THE REDTOP EXPERIMENT: RARE ETA DECAYS TO EXPLORE NEW PHYSICS

*R*are *E*ta *D*ecays with a
*T*pc for *O*ptical *P*hotons

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Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

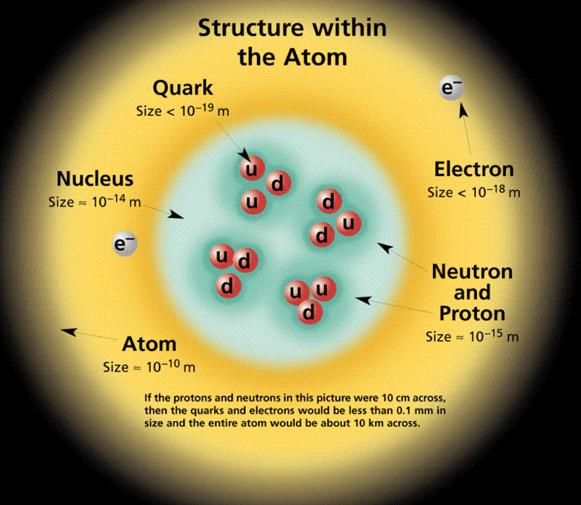
Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $= 1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge
Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons
One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction
The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$

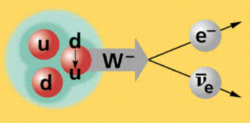
Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Matter and Antimatter
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

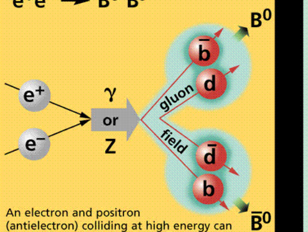
Figures
These diagrams are an artist's conception of physical processes. They are ***not*** exact and have ***no*** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

$n \rightarrow p\, e^-\, \bar{\nu}_e$



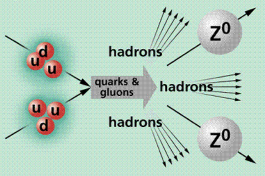
A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

$e^+e^- \rightarrow B^0\, \bar{B}^0$



An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.

$p\,p \rightarrow Z^0Z^0$ + assorted hadrons



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure
Visit the award-winning web feature *The Particle Adventure* at
http://ParticleAdventure.org

This chart has been made possible by the generous support of:
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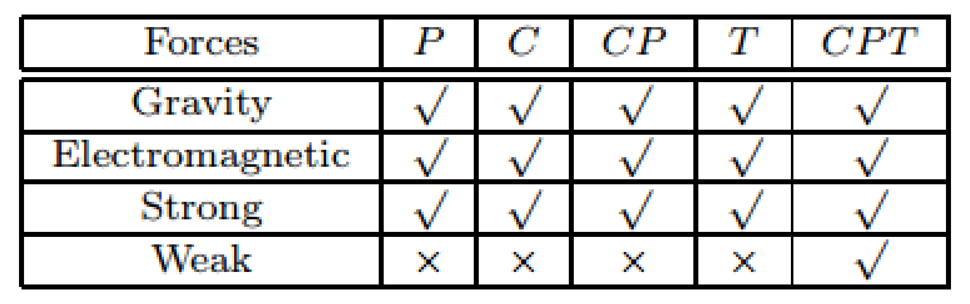
Symmetries of the Standard Model

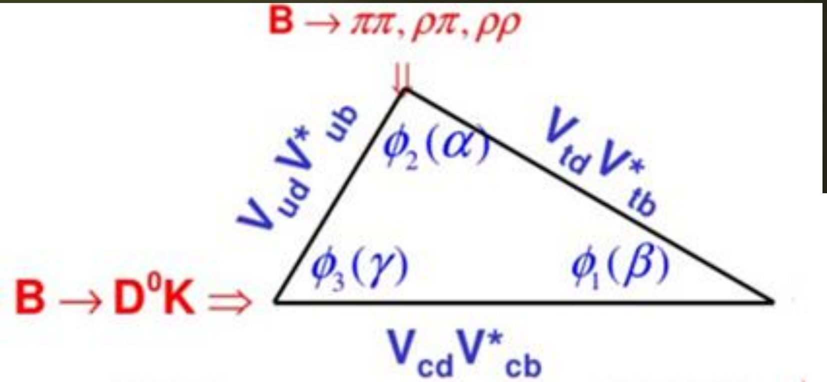
- In the Standard Model, CP violation is described by a unique physical phase in the CKM quark mixing matrix
- CPT is conserved
- T violation is a consequence of the above

Symmetry conservation in the Standard Model



Forces	P	C	CP	T	CPT
Gravity	√	√	√	√	√
Electromagnetic	√	√	√	√	√
Strong	√	√	√	√	√
Weak	×	×	×	×	√

CP Violation in the Standard Model



$V_{ub} = |V_{ub}|e^{-i\gamma}$ ← see Wolfenstein parametrization

Quarks

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$V_{td} = |V_{td}|e^{-i\beta}$

CP violating phase

Antiquarks:

$$\begin{pmatrix} \bar{d}' \\ \bar{s}' \\ \bar{b}' \end{pmatrix} = \begin{pmatrix} V^*_{ud} & V^*_{us} & V^*_{ub} \\ V^*_{cd} & V^*_{cs} & V^*_{cb} \\ V^*_{td} & V^*_{ts} & V^*_{tb} \end{pmatrix} \begin{pmatrix} \bar{d} \\ \bar{s} \\ \bar{b} \end{pmatrix}$$

Phase angle≠0: complex CKM matrix

⬇

Different mixing for quarks and anti-quarks

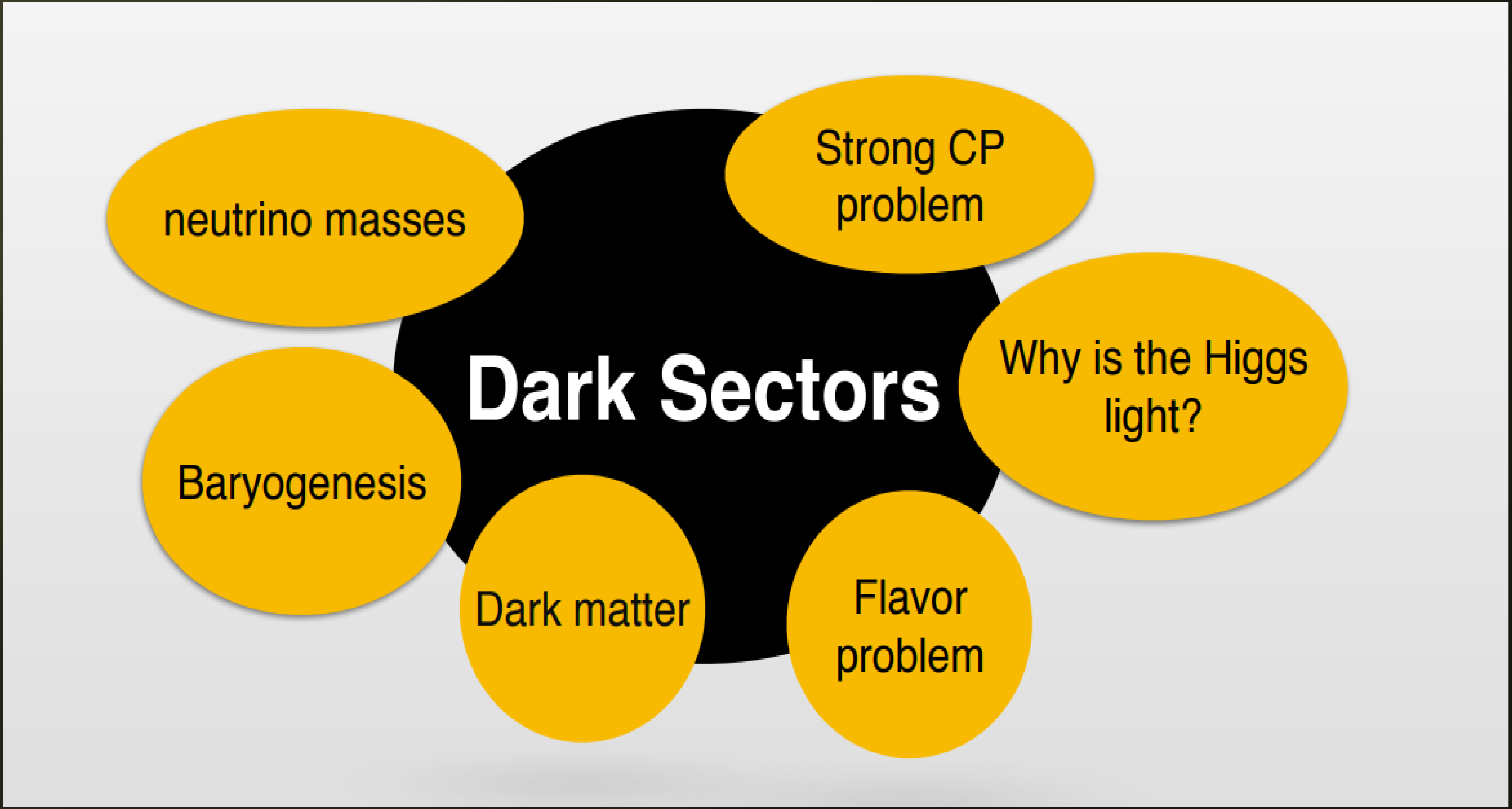
⬇

Origin of CP Violation (CPV)

Strength of CPV: Characterized by Jarlskog invariant: $J = \text{Im}\left(V_{ij} V_{kl} V^*_{il} V^*_{kj}\right) \neq 0$

In SM: $J = \text{Im}[V_{us}V_{cb}V^*_{ub}V^*_{cs}] = A^2\lambda^6\eta\left(1-\lambda^2/2\right)+O(\lambda^{10}) \sim 10^{-5}$

The Shortfalls of The Standard Model



Dark Sectors

neutrino masses

Strong CP problem

Why is the Higgs light?

Baryogenesis

Dark matter

Flavor problem

Limits of the Standard Model - I

Necessary ingredients are:

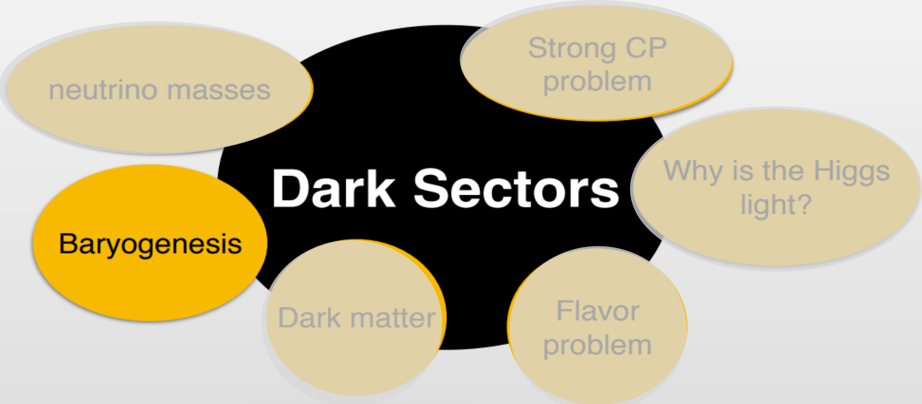
- Baryon number violation
- Thermal non-equilibrium
- C and CP violation

Sakarov - conditions

All of these ingredients were present in the early Universe!

- Do we understand the cause of CP violation in particle interactions?
- Can we calculate the BAU from first principles?

1975 Nobel Peace Prize



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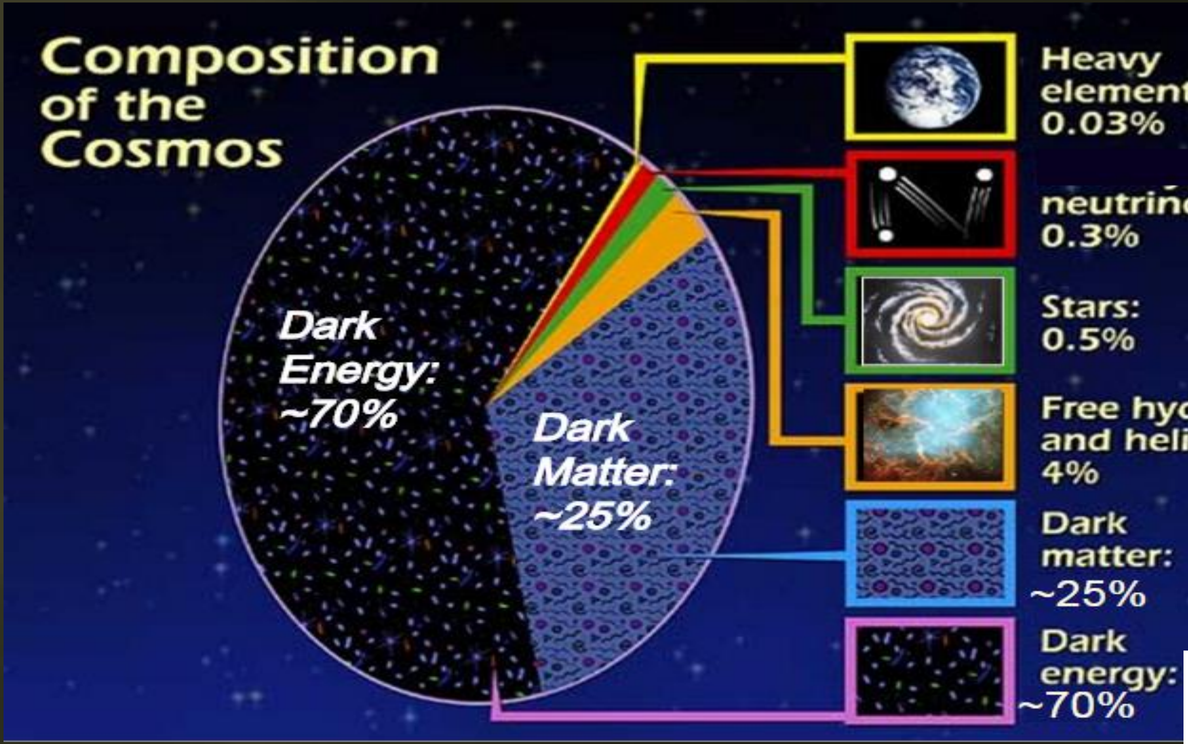
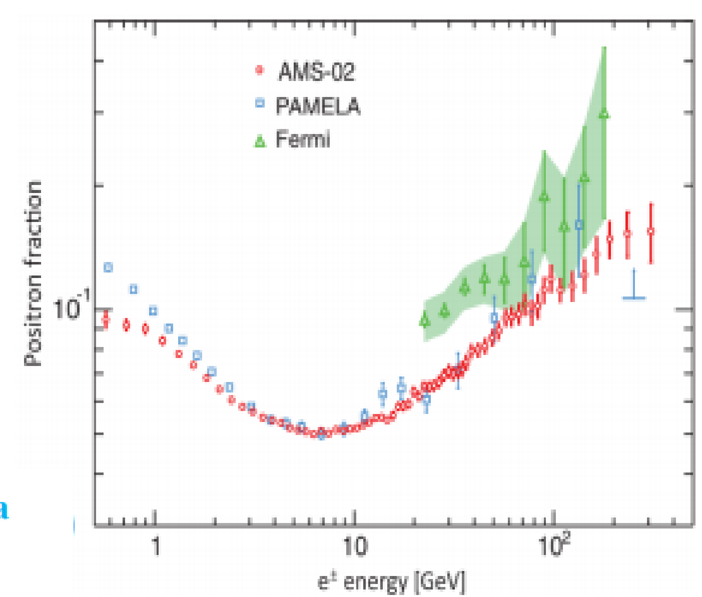
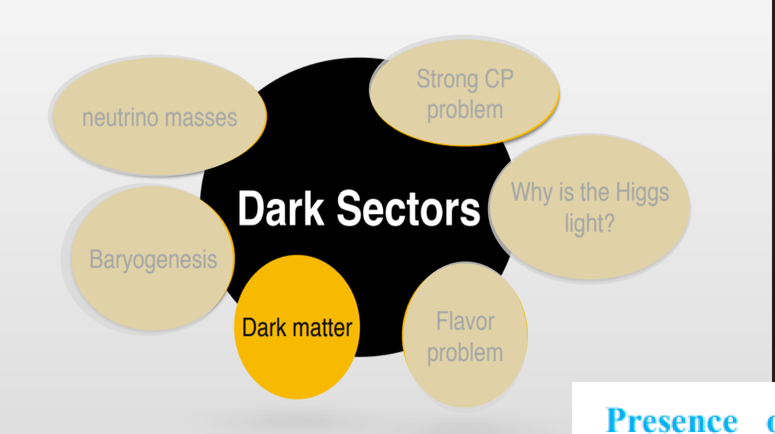
N. Roe

Limits of the Standard Model - II



No dark matter with the required properties observed on cosmology (might require new particles)

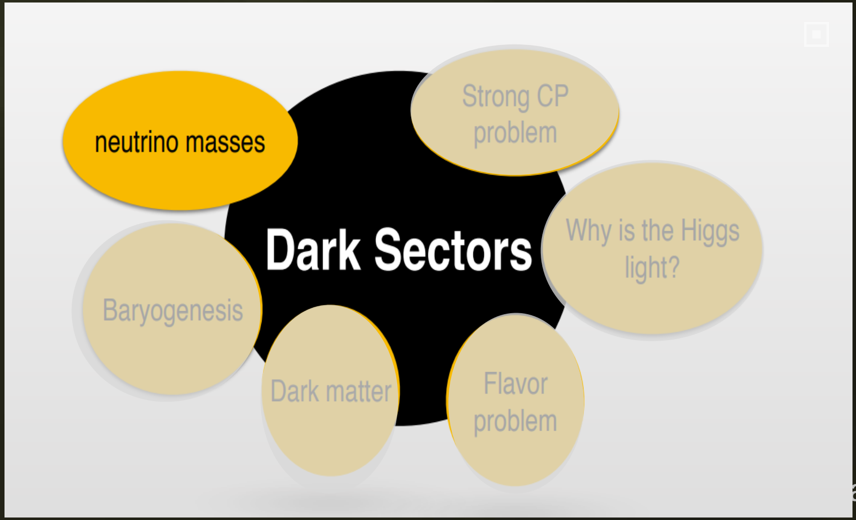




Presence of DM is inferred via gravitational effect only.

Limits of the Standard Model - III

- Neutrino mass = 0 (while we know they oscillate)
- Expansion of the universe is accelerating (might require new forces)
- Value of particle masses are not in the model
- No full theory of gravitation as described in the general relativity
  - Simply adding a graviton to the SM does not reproduce the experimental observations
  - SM is widely considered ***incompatible*** with the current general relativity



- Plank’s limit: the Standard Model is only a "low energy" approximation to a more fundamental theory

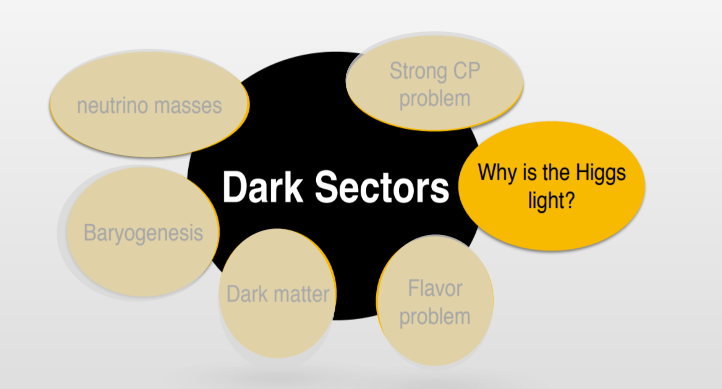
Theoretical Problems of the SM

- The hierarchy problem
  - It is the huge difference in the strength of fundamental forces or the wide range in mass for the elementary particles.
  - Why is there such a wide spectrum of masses among the building blocks of matter? Imagine having a Lego set containing bricks as disparate in size as that!
- The hierarchy problem is also related to the Higgs boson mass.
  - Corrections to the Higgs mass are proportional to the mass of the contributing quark
  - The top quark being the heaviest particle, it adds such a large correction to the *theoretical* Higgs boson mass that theorists wonder how the *measured* Higgs boson mass can be as small as it was found.

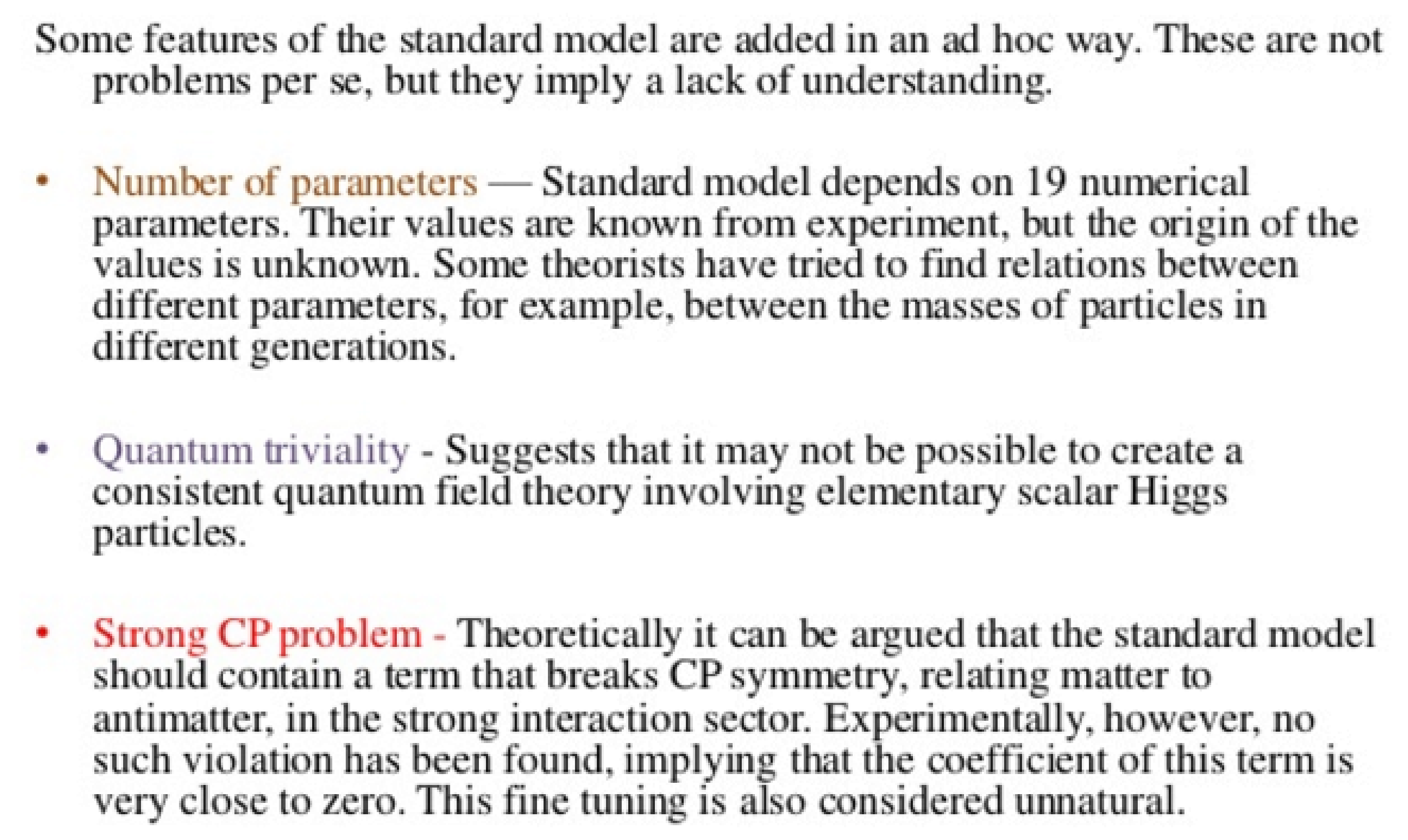
- The naturalness problem (hint: it is a consequence of the hierarchy problem)
  - the cosmological constant [often referred to as "dark `energy' " in public settings] is amazingly small, compared to what you'd naturally expe
  - the hierarchy between the strength of gravity and the

    strengths of the other forces is amazingly big,

    compared to what you'd expect



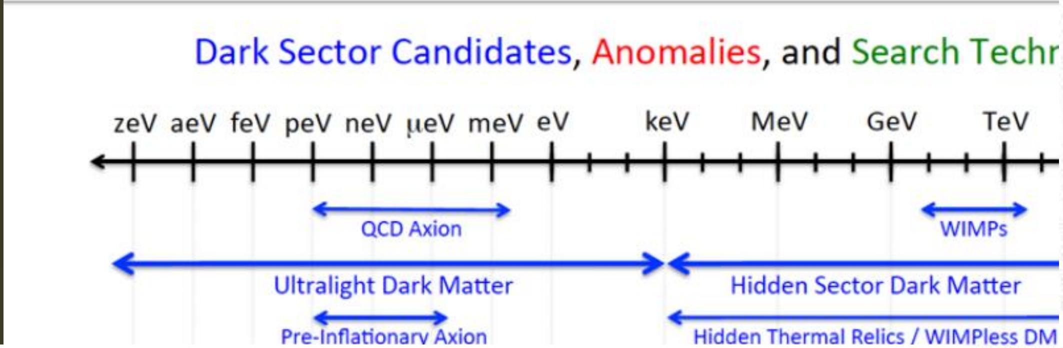
Theoretical Problems of the SM – cont'd

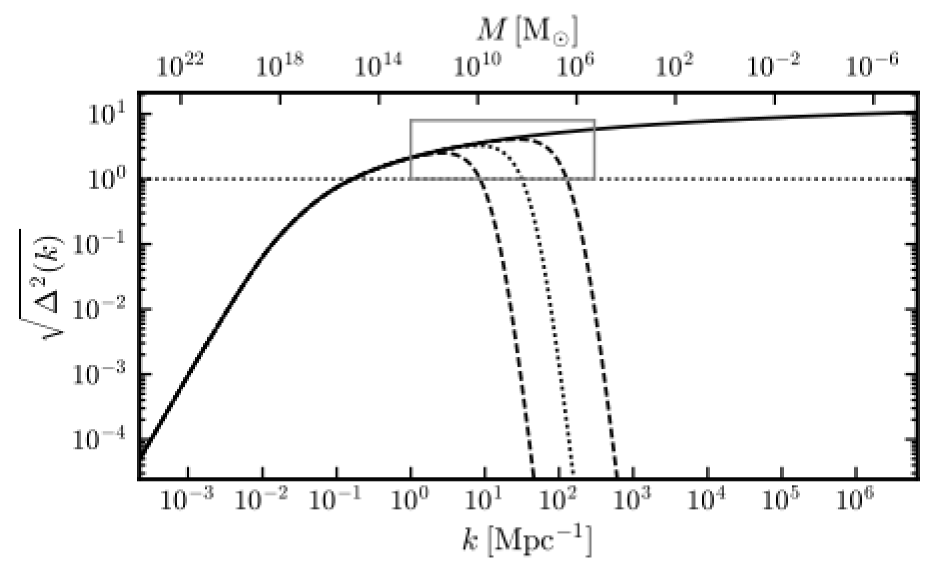


Some features of the standard model are added in an ad hoc way. These are not problems per se, but they imply a lack of understanding.

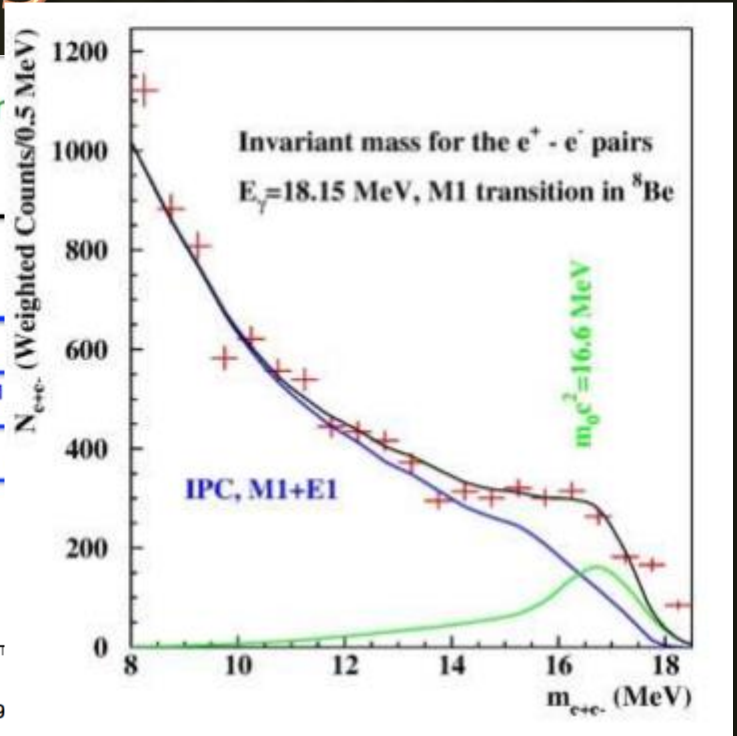
- **Number of parameters** — Standard model depends on 19 numerical parameters. Their values are known from experiment, but the origin of the values is unknown. Some theorists have tried to find relations between different parameters, for example, between the masses of particles in different generations.
- **Quantum triviality** - Suggests that it may not be possible to create a consistent quantum field theory involving elementary scalar Higgs particles.
- **Strong CP problem** - Theoretically it can be argued that the standard model should contain a term that breaks CP symmetry, relating matter to antimatter, in the strong interaction sector. Experimentally, however, no such violation has been found, implying that the coefficient of this term is very close to zero. This fine tuning is also considered unnatural.

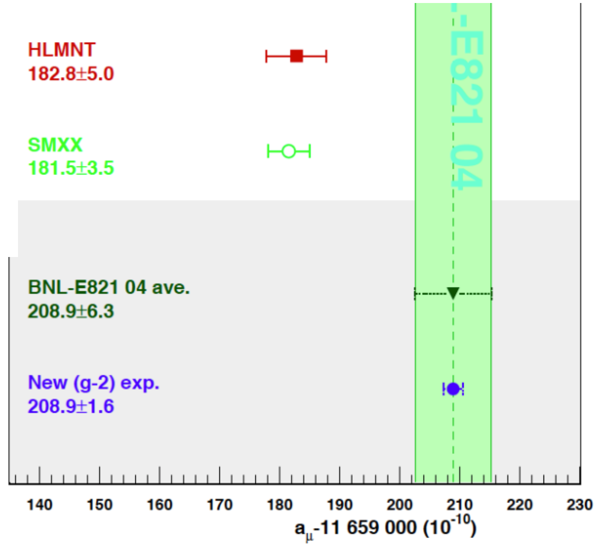
Current Outstanding Anomalies





From Cosmic Visions community study



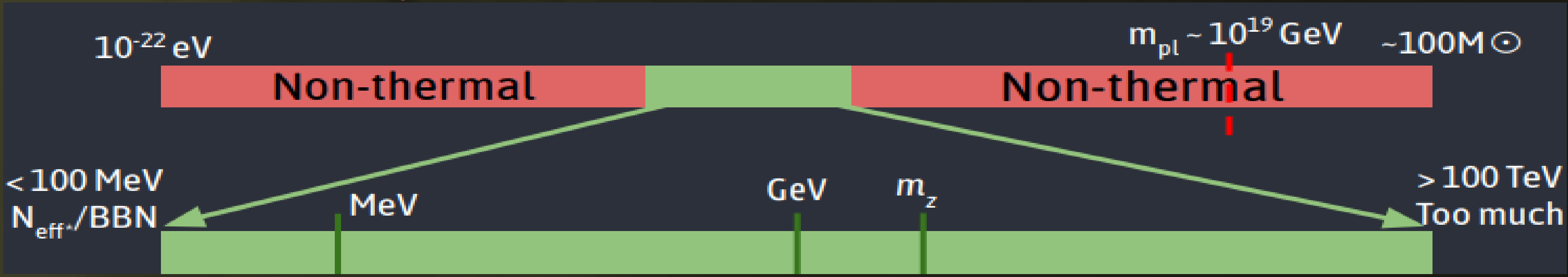


4 events, BR(K_L → $\pi\nu\nu$) ~ $2x10^{-9}$, BR(K_L →

The bottom line

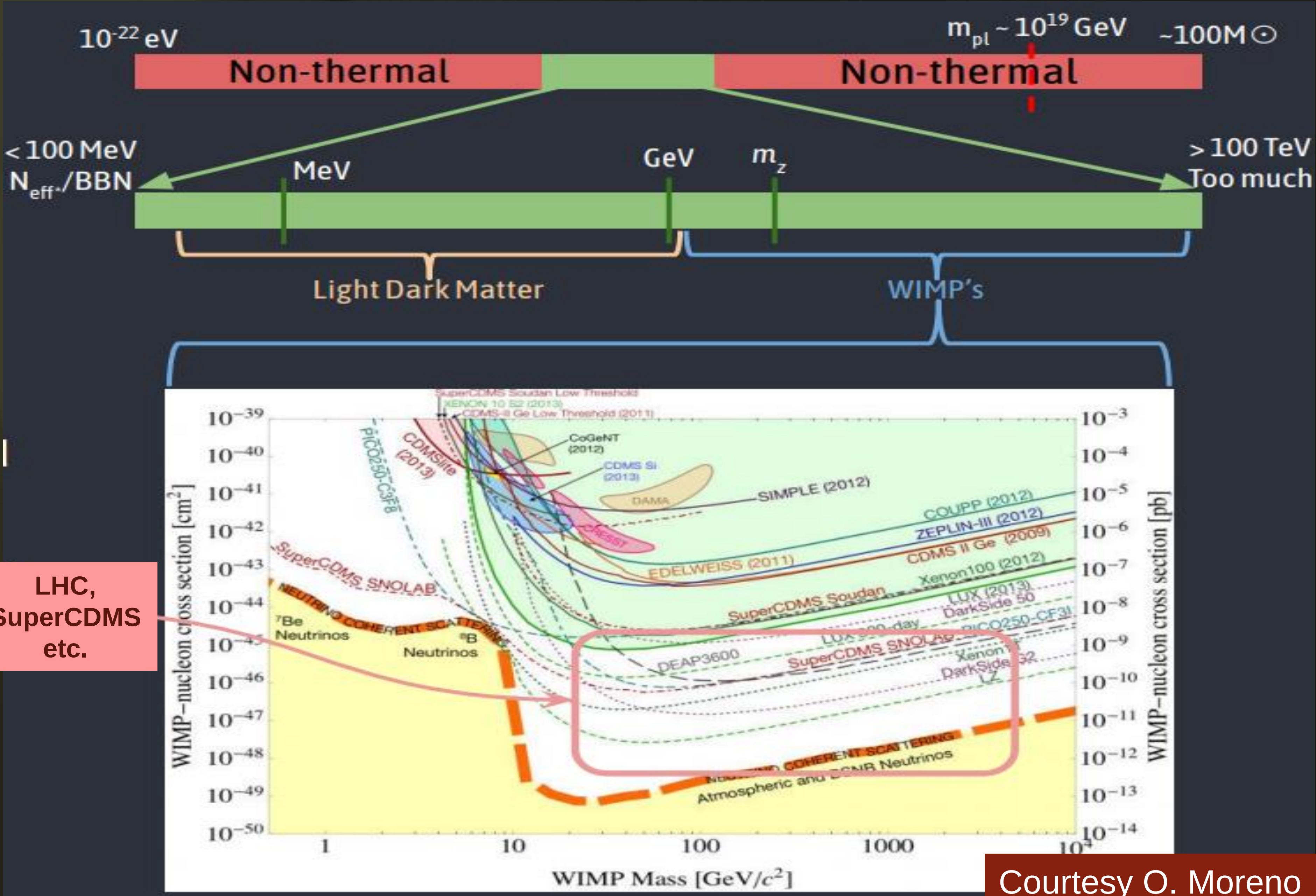
- SM ingredients are insufficient to explain the nature beyond the SM. Most likely we need:
    - new forces (with adequate CP violation)
    - new particles
- Mass of possible New Physics spans 40 order of magnitude
- We don't have a clue of what's beyond the Standard Model
- Scientists are hard pressed to design new experiments for understanding what's going on

The Quest for Dark Matter



Courtesy O. Moreno

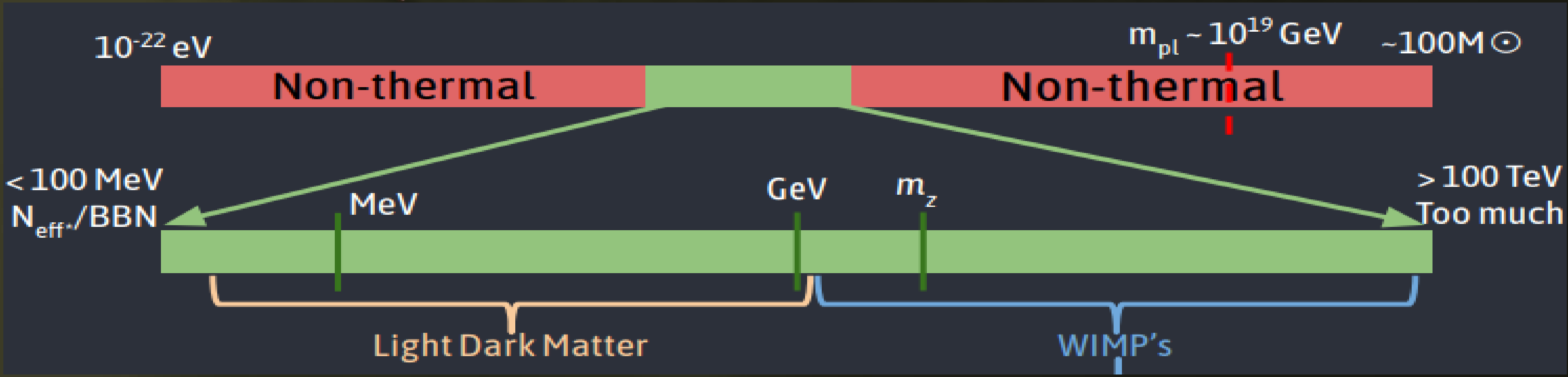
The Quest for Dark Matter

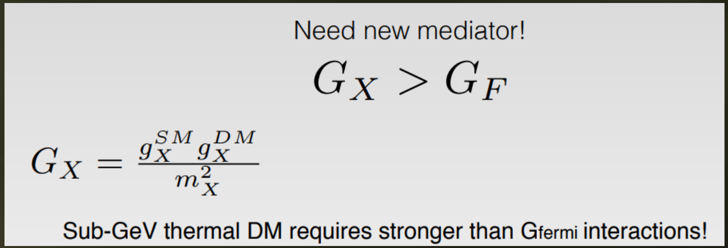


LHC, SuperCDMS etc.

Courtesy O. Moreno

The Quest for Dark Matter





Need new mediator!

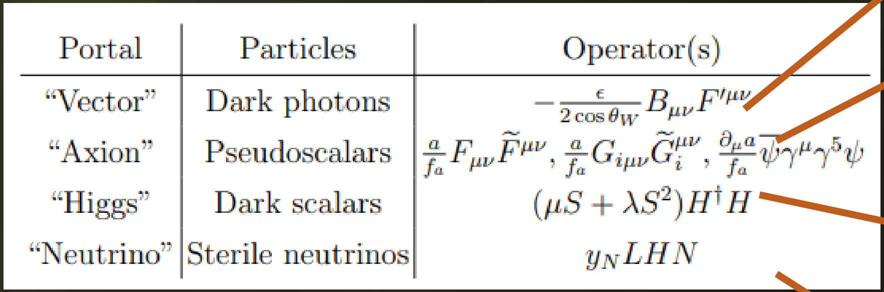
$$G_X > G_F$$

$$G_X = \frac{g_X^{SM} g_X^{DM}}{m_X^2}$$

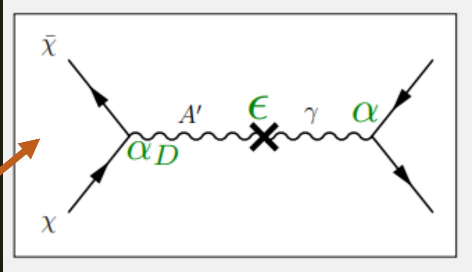
Sub-GeV thermal DM requires stronger than G$_{\text{fermi}}$ interactions!

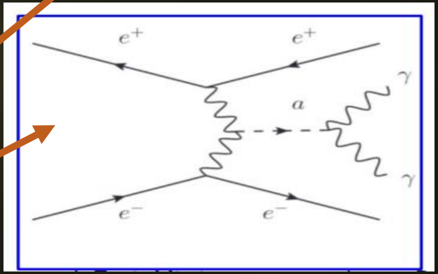
- *Newest theoretical models prefer gauge bosons in MeV-GeV mass range as "…many of the more severe astrophysical and cosmological constraints that apply to lighter states are weakened or eliminated, while those from high energy colliders are often inapplicable" (B. Batell , M. Pospelov, A. Ritz – 2009)*

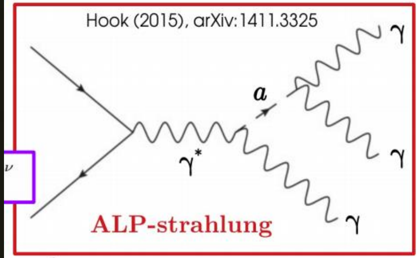
Connections between Standard and Dark Matter

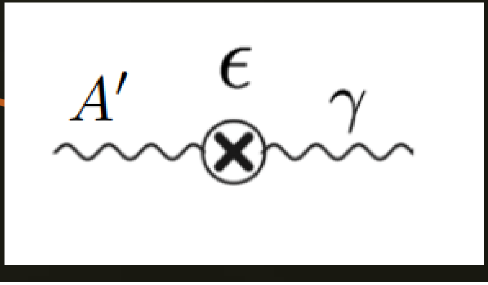


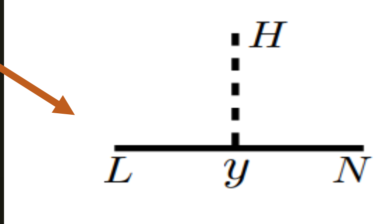
Portal	Particles	Operator(s)
“Vector”	Dark photons	$-\frac{\epsilon}{2\cos\theta_W}B_{\mu\nu}F'^{\mu\nu}$
“Axion”	Pseudoscalars	$\frac{a}{f_a}F_{\mu\nu}\widetilde{F}^{\mu\nu}$, $\frac{a}{f_a}G_{i\mu\nu}\widetilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
“Higgs”	Dark scalars	$(\mu S+\lambda S^2)H^\dagger H$
“Neutrino”	Sterile neutrinos	$y_N LHN$







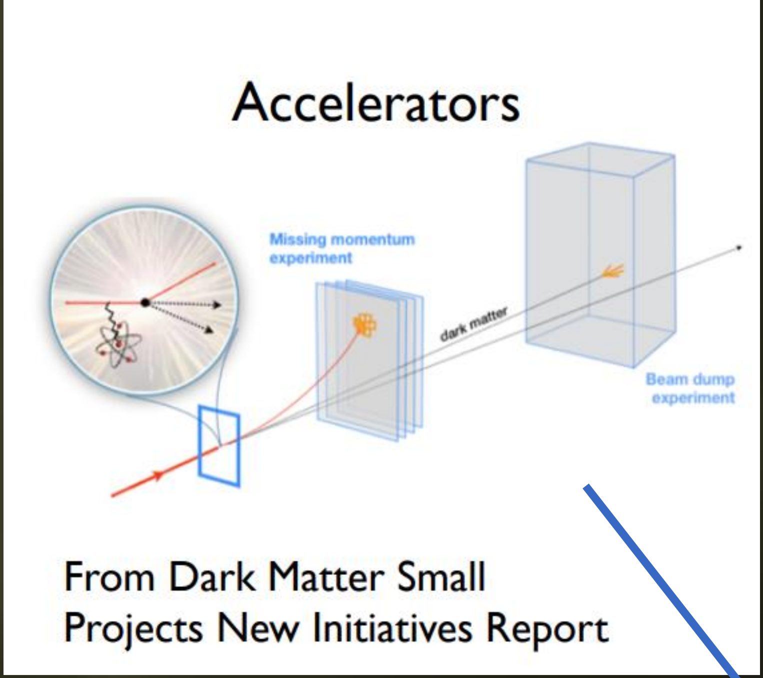




Current Experimental Searches

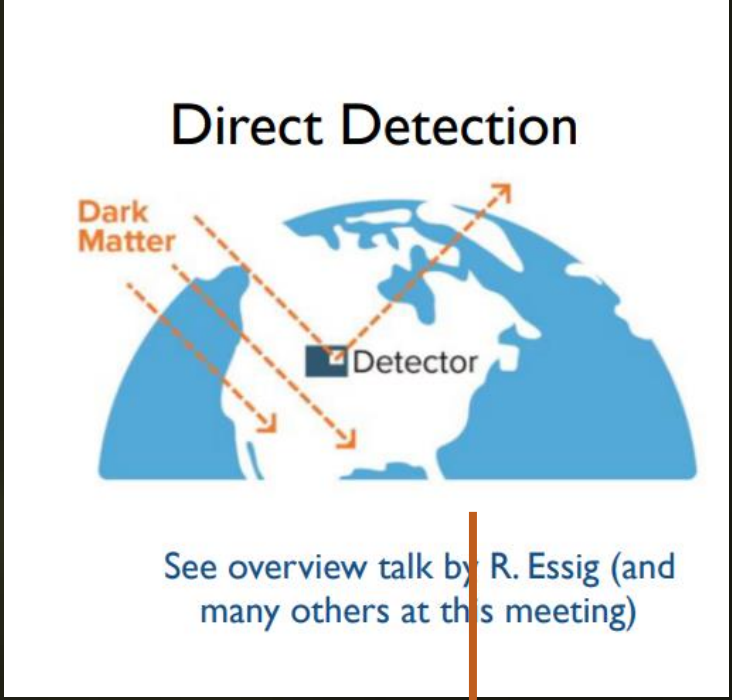
- Direct searches
- Proton beam dump
- Electron beam dump
- Fixed target electron scattering
- Fixed target proton experiments
- Colliders

Direct detection vs Accelerator



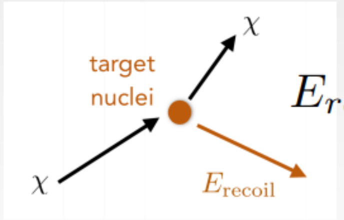
Accelerators

From Dark Matter Small Projects New Initiatives Report

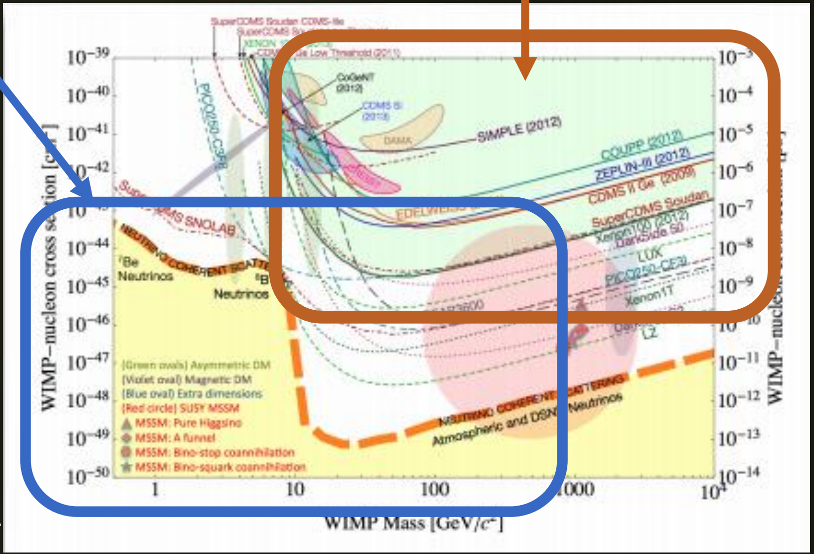


Direct Detection

See overview talk by R. Essig (and many others at this meeting)



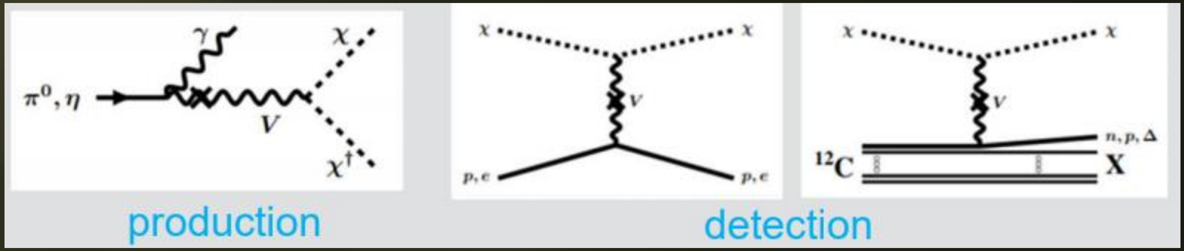
$$E_{rec} = \frac{q^2}{2m_N} \sim \frac{m_{DM}^2 v^2}{2m_N}$$

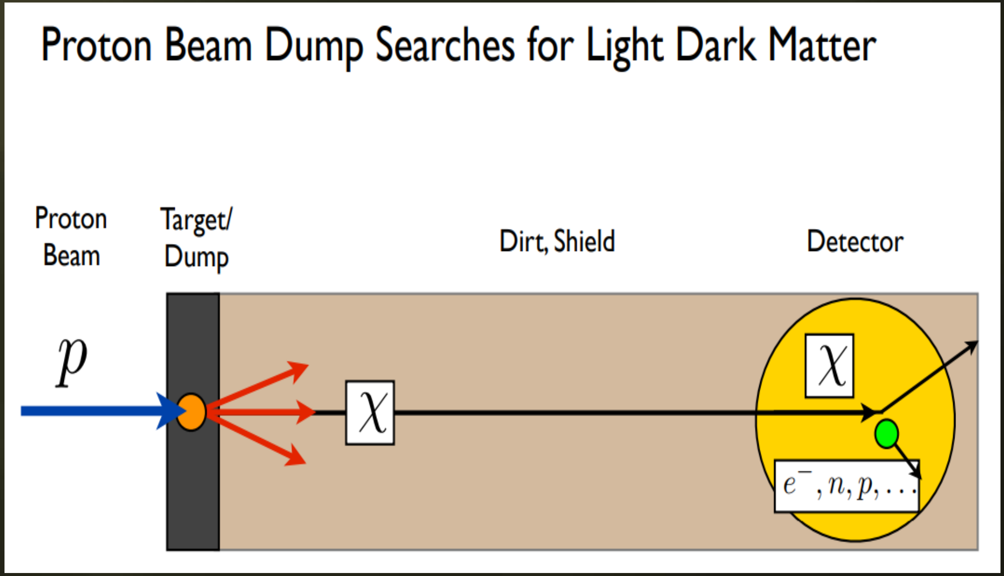


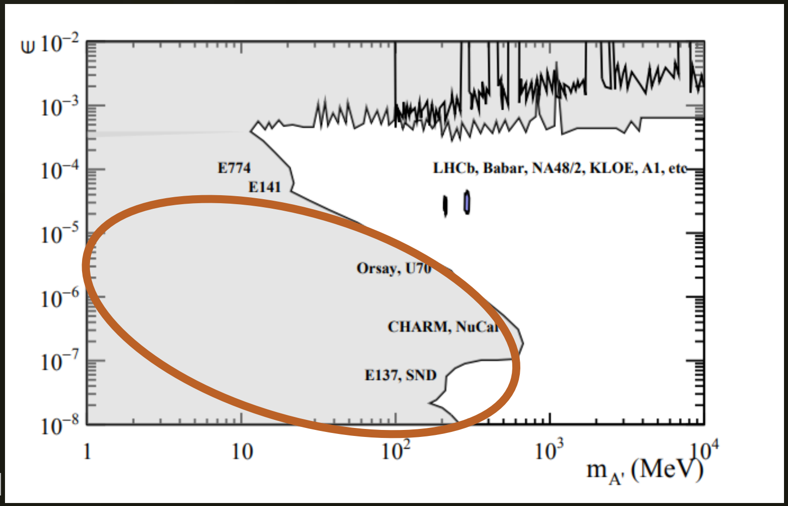
▣ Complementary approach

They are required for a full understanding of the structure of the dark sector

The Proton Beam Dump Technique

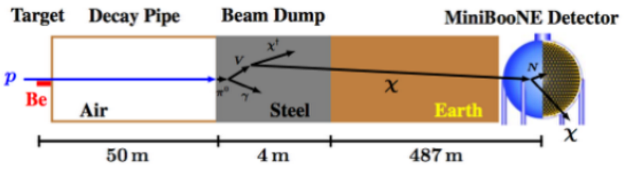



Proton Beam Dump Searches for Light Dark Matter

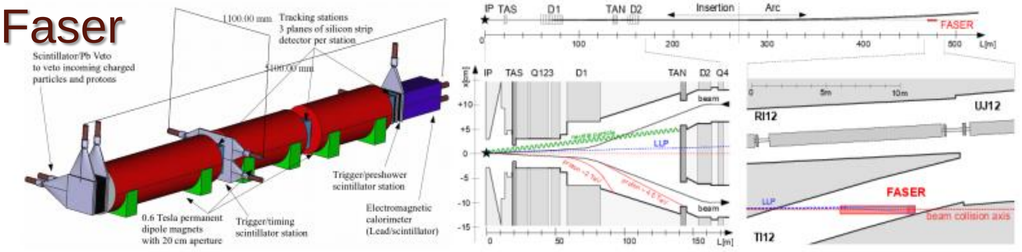


Proton Beam Dump Experiments

MiniBooNE-DM @ FNAL



Faser

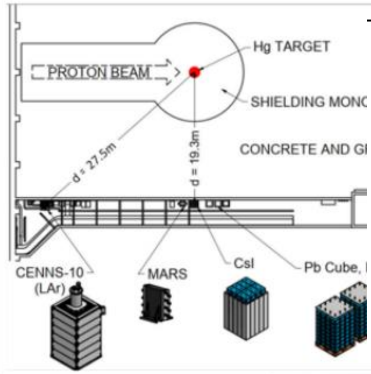


COHERENT @ ORNL

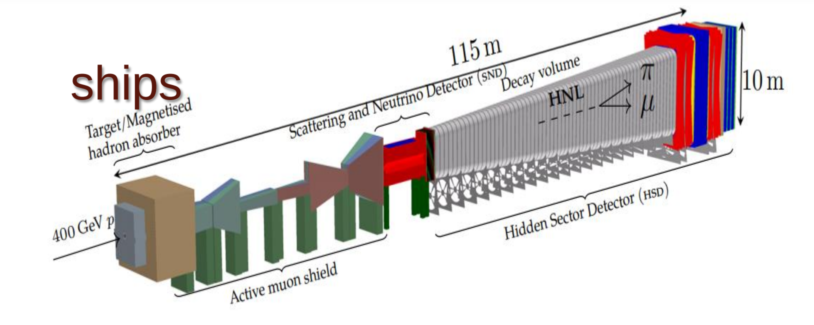
- First observation of Coherent Elastic Neutrino Nucleus Scattering (CEvNs)

  [Science 357 (2017) no.6356, 1123-1126]

- COHERENT also sensitive to sub-GeV dark matter [deNiverville, Pospelov, Ritz] [Ge, Shoemaker]

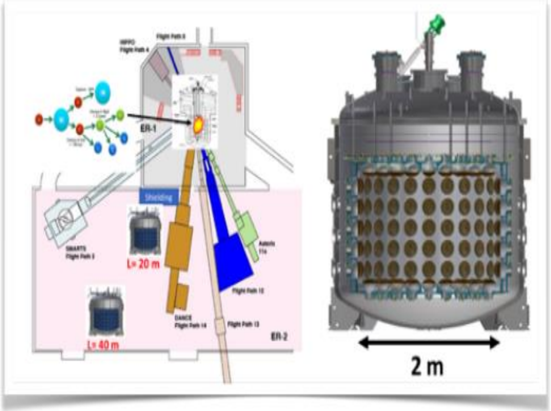


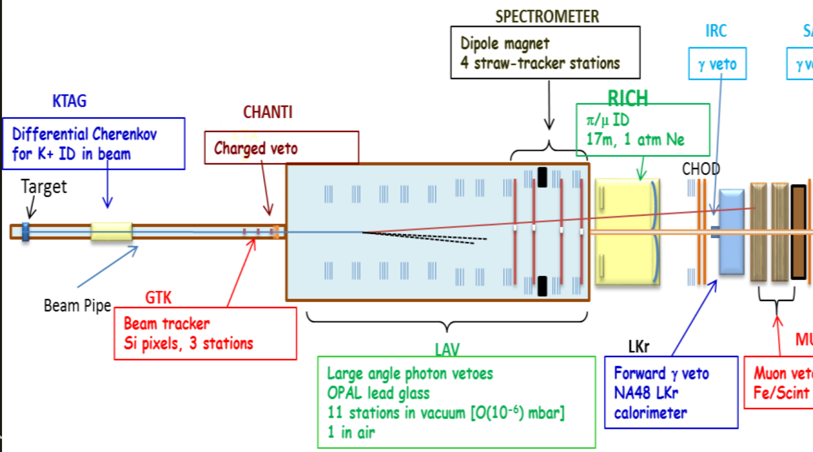
ships



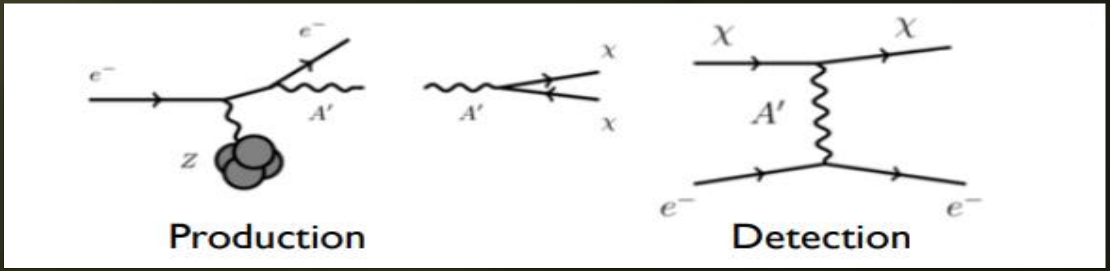
CCM @ LANL

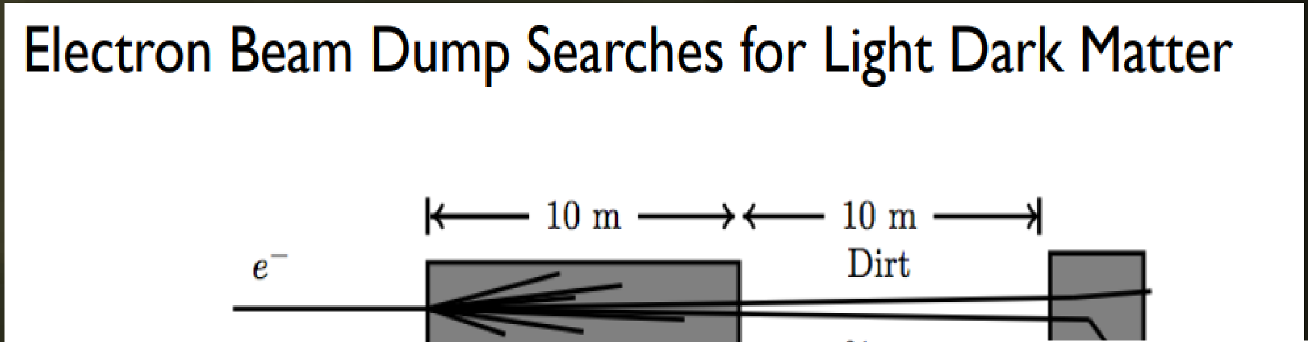
- Primary goal: measure CEvNS and search for eV - scale sterile neutrinos
- 800 MeV protons on tungsten target
- 10 ton Liquid Argon Scintillation detector x 2 (near and far locations)

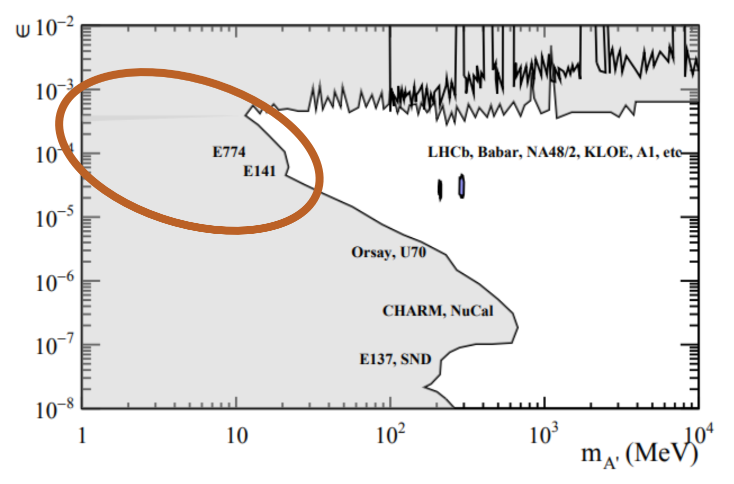




The Electron Beam Dump Technique





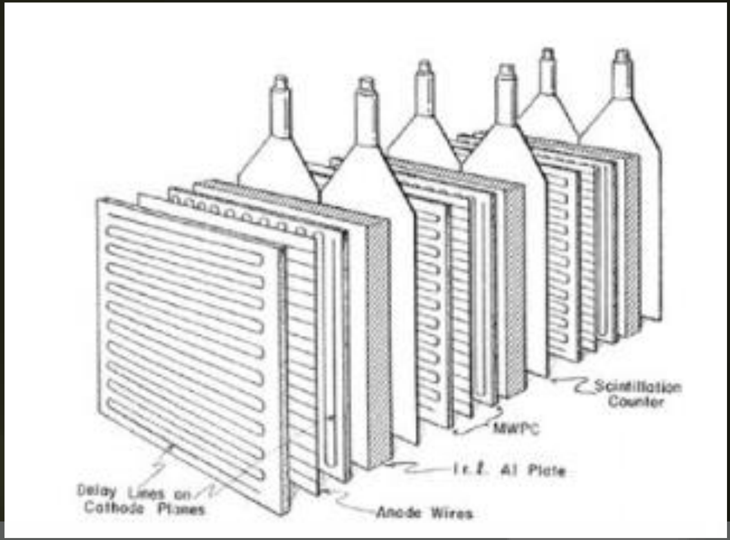


- Advantages:
  - Cleaner backgroundvs p-beam dump:
- Disadvantages:
  - Lower Yield

Electron Beam Dumb Experiments

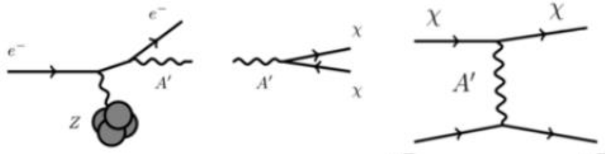
SLAC Beam Dump E137

- 20 GeV electron beam; 30 C dumped
- Water - aluminum target
- Shower calorimeter, 400 m from dump



BDX @ JLAB

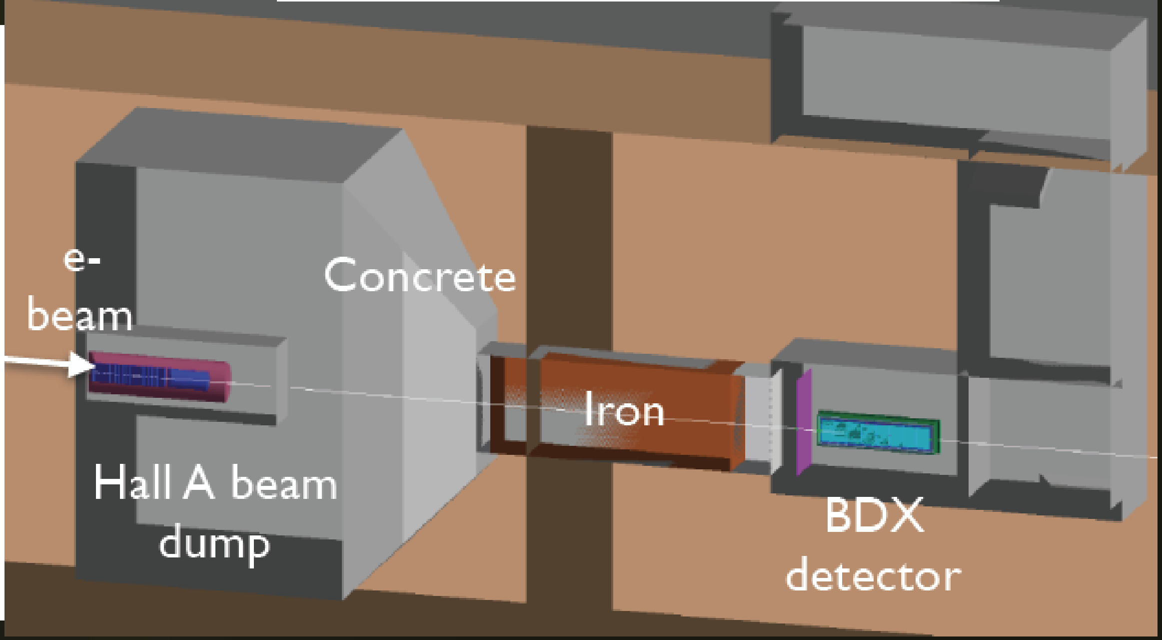
- 11 GeV electron beam on Water-Aluminum dump
- ECAL detector located 20m downstream



Production

Detection

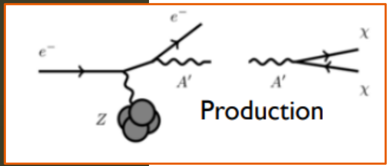
- Approved by JLAB PAC for 10^{22} EOT run



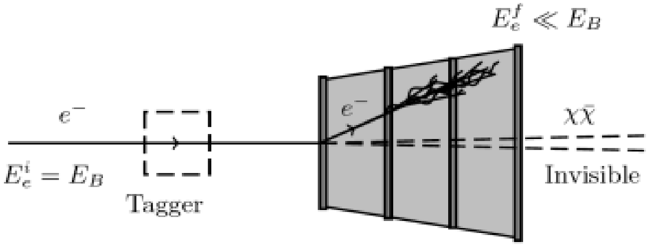
Fixed Target e^- Techniques

Two complementary approaches

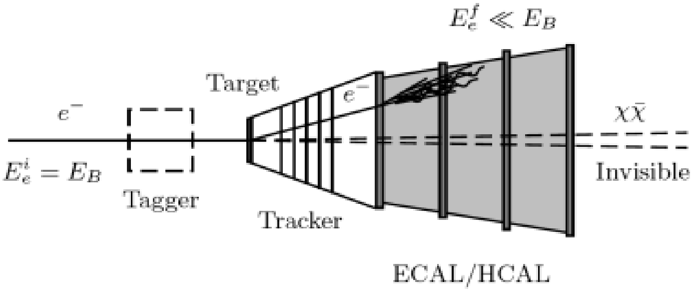
Courtesy A. Celentano



missing energy



missing momentum

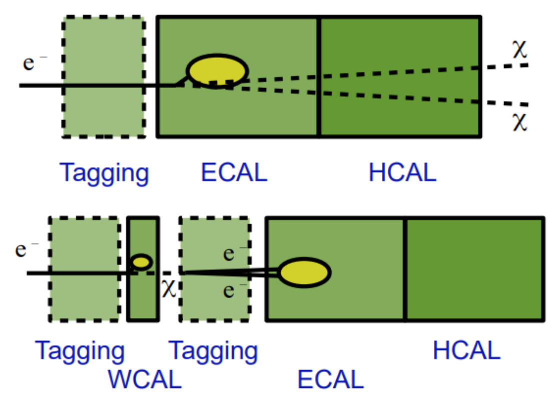


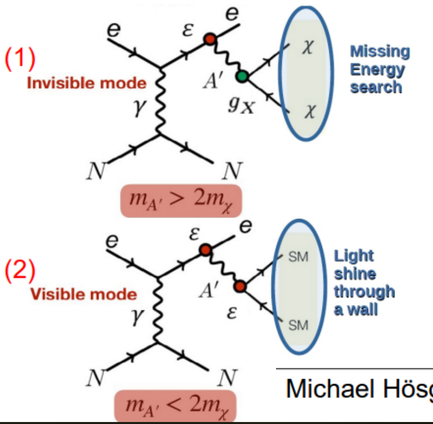
Missing Energy

- Higher yield (thick target)
- Higher acceptance

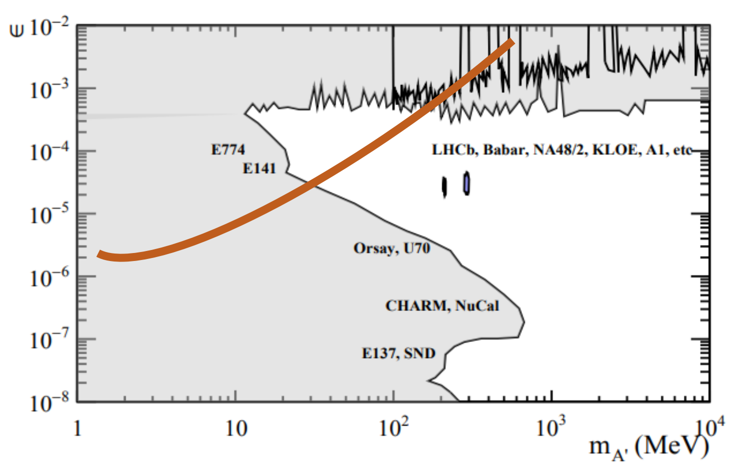
Missing Momentum

- Lower yield (thin target), but includes a missing energy experiment
- p_T as background discriminator and signal identifier





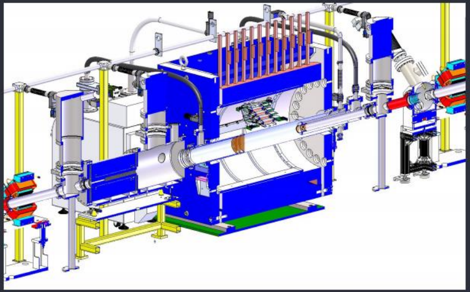
Michael Hösgen



Missing Momentum e^- Experiments

DarkLight @ Jefferson Lab (>2021)

Arxiv: 1903.02648



2016 (Phase IA): Explored operation of LERF with prototype detector installed

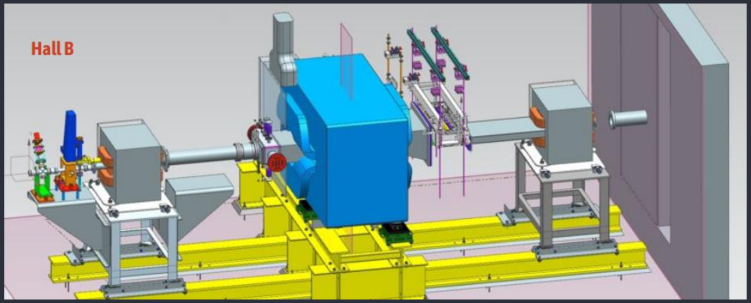
2017 (Phase IB): Target design was improved and assembled for test at Bates

Phase IC: Proof-of-principal detector focused on low mass A'

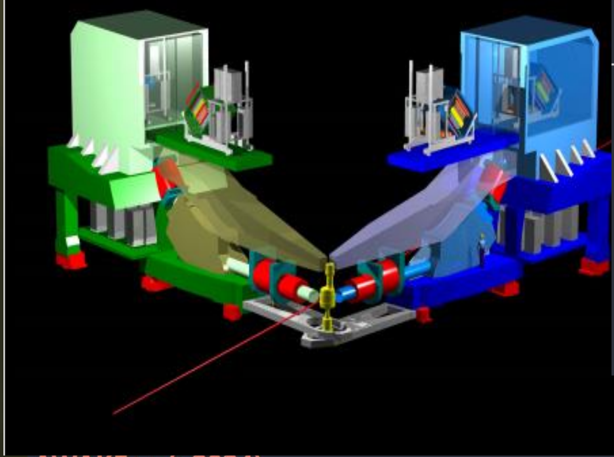
HPS @ Jefferson Lab

e^- fixed target experiment installed in Hall B at Jefferson Lab searching for dark photons in the mass range 19 MeV - 500

- Makes use of CEBAF electron beam → Energy range 1.1 - 6.6 GeV Current: 50 nA - 500 nA



Apex @ JLAB

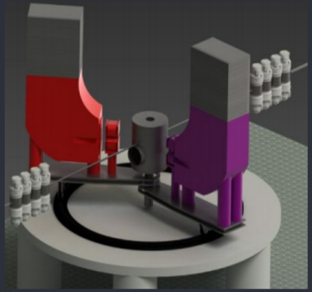


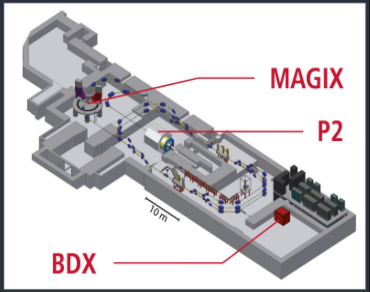
MAGIX @ MESA (> 2023)

Arxiv: 1809.07168

MAGIX e^- fixed target experiment making use of the energy recovery line of the MESA accelerator (E_{max} = 105 MeV @ > 1 mA) to search for dark photons in the mass range 10 - 60 MeV ($\epsilon > 5 \times 10^{-5}$)

- Dark bremsstrahlung in a gas jet target (H, Ar, O_2, N_2, Xe) with thickness of 10^{19} atoms/cm^2
- Coincident measurement of e^+e^- using





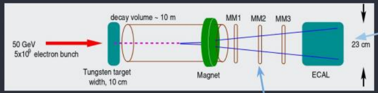
AWAKE++ (>2024)

Arxiv: 1812.11164

AWAKE++ is investigating the use of the proton-driven plasma wakefield acceleration scheme for future particle physics applications

- Using self-modulated SPS proton beam to drive strong wakefield in plasma
- Run 1 (2016-2018): Successfully demonstrated acceleration of externally injected electrons to a few GeV using protor driven plasma wakes
- Run 2 (2021 - 2024): Demonstrate the scalability of the acceleration scheme (high charge bunches accelerated to ~10 GeV)

LS3: NA64 like e^- fixed target experiment using 10^{16} EoT (collected in 3 months)

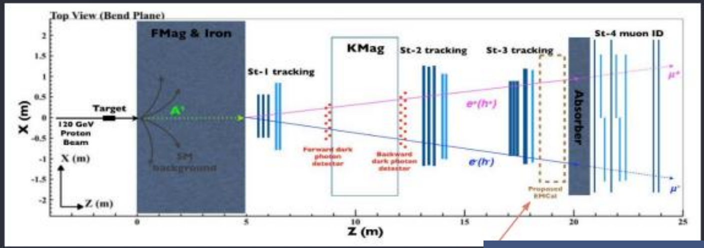


Tungsten-plastic ECAL

Micromegas tracker planes

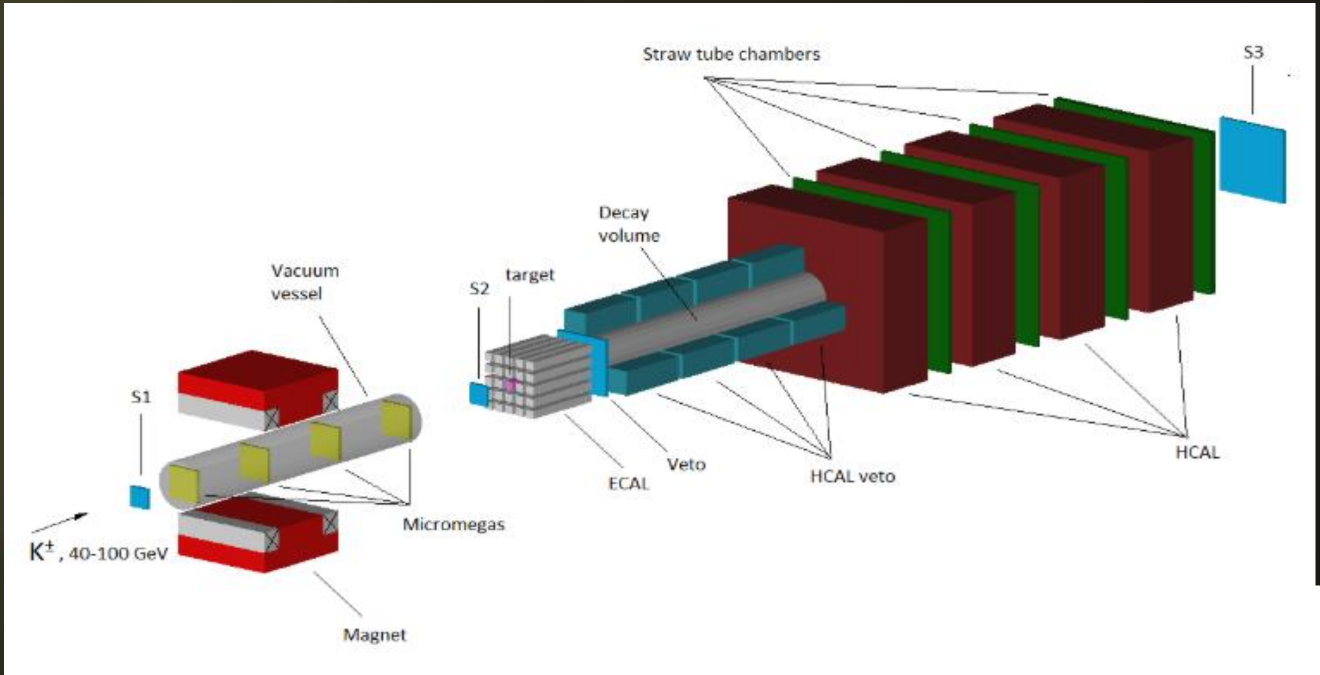
DarkQuest (>2023)

Possible upgrade to PID using a single PHENIX EMCal sector will add sensitivity to dielectron channel

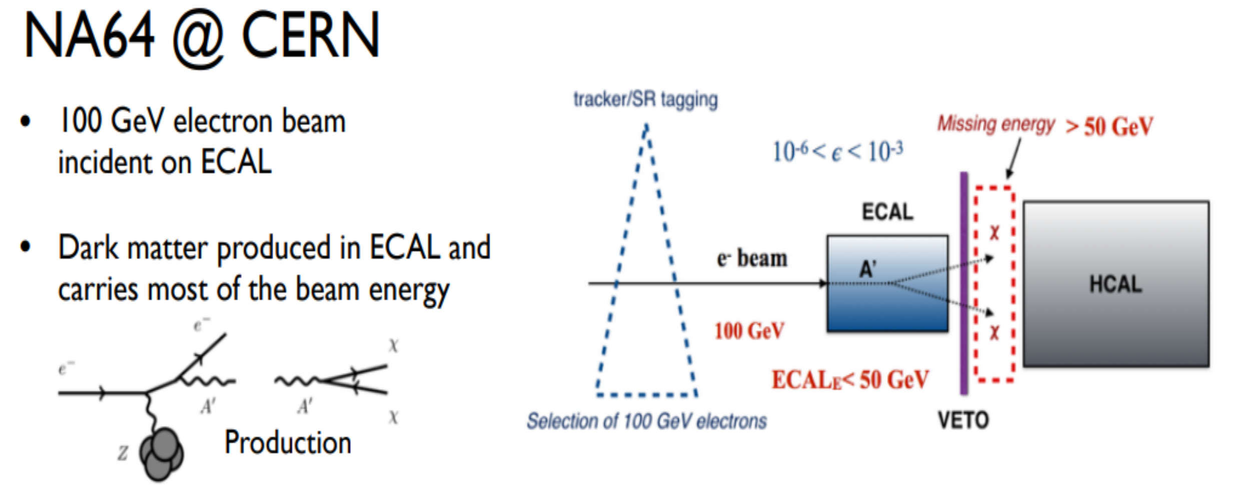


Courtesy O. Moreno

Missing Energy e^- Experiments

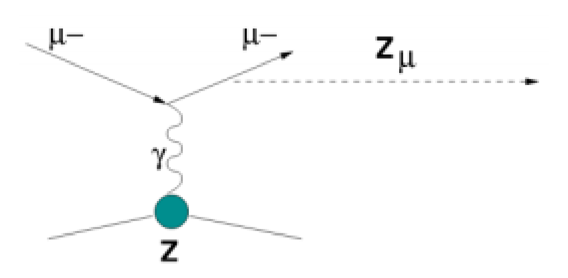


- $\mathrm{NA64}\mu$: 150 GeV beam, 10^12 MOT

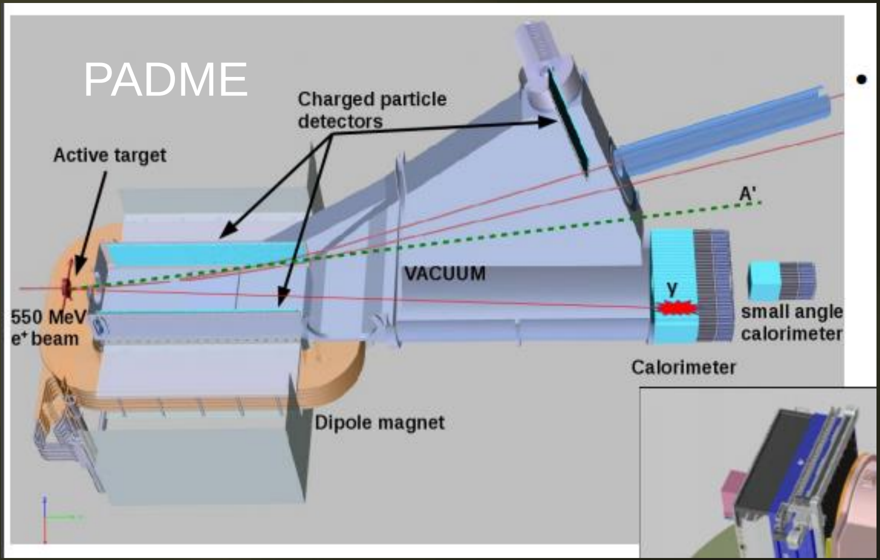


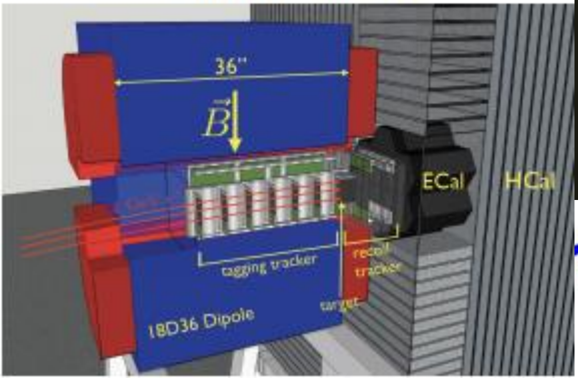
NA64 @ CERN

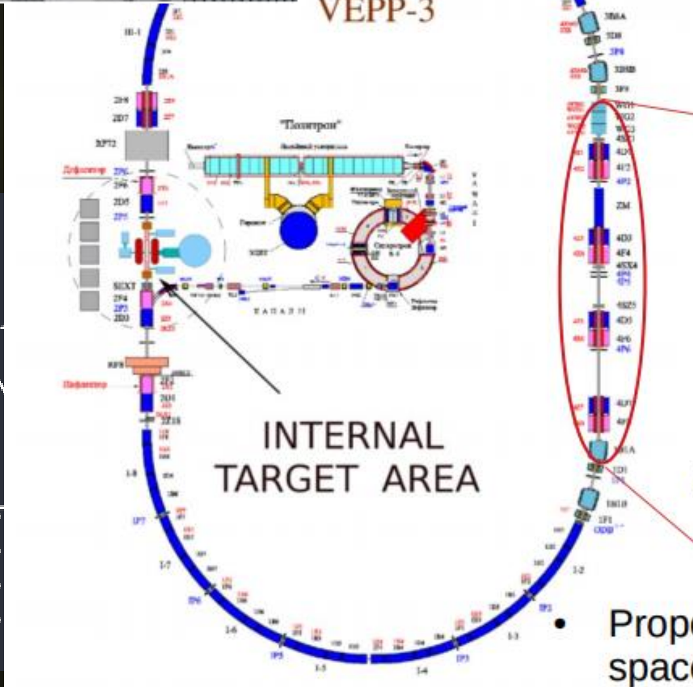
- 100 GeV electron beam incident on ECAL
- Dark matter produced in ECAL and carries most of the beam energy



Missing Momentum e- Experiments


PADME

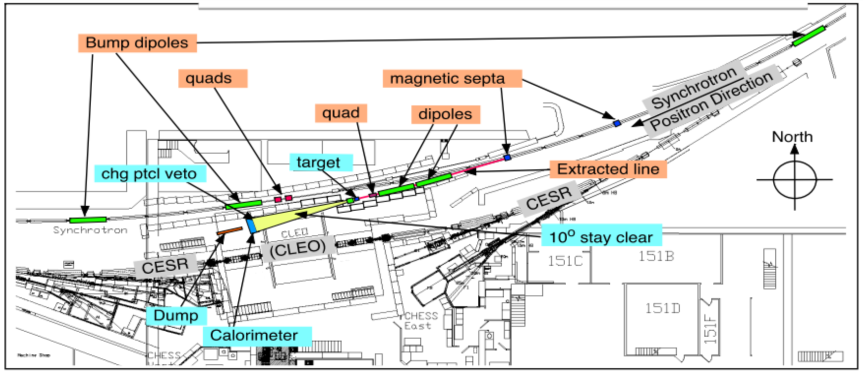
LDMX-SLAC




- Prop
spac

Cornell positron beam

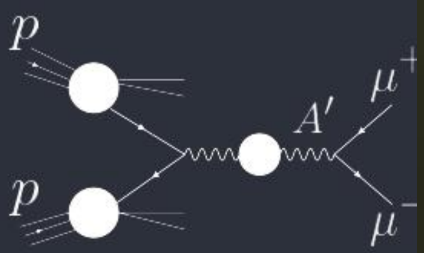
EPJ Web Conf. 142 (2017) 0100



Hadron Colliders

- Bump-hunt in a very noisy background

pp Colliders



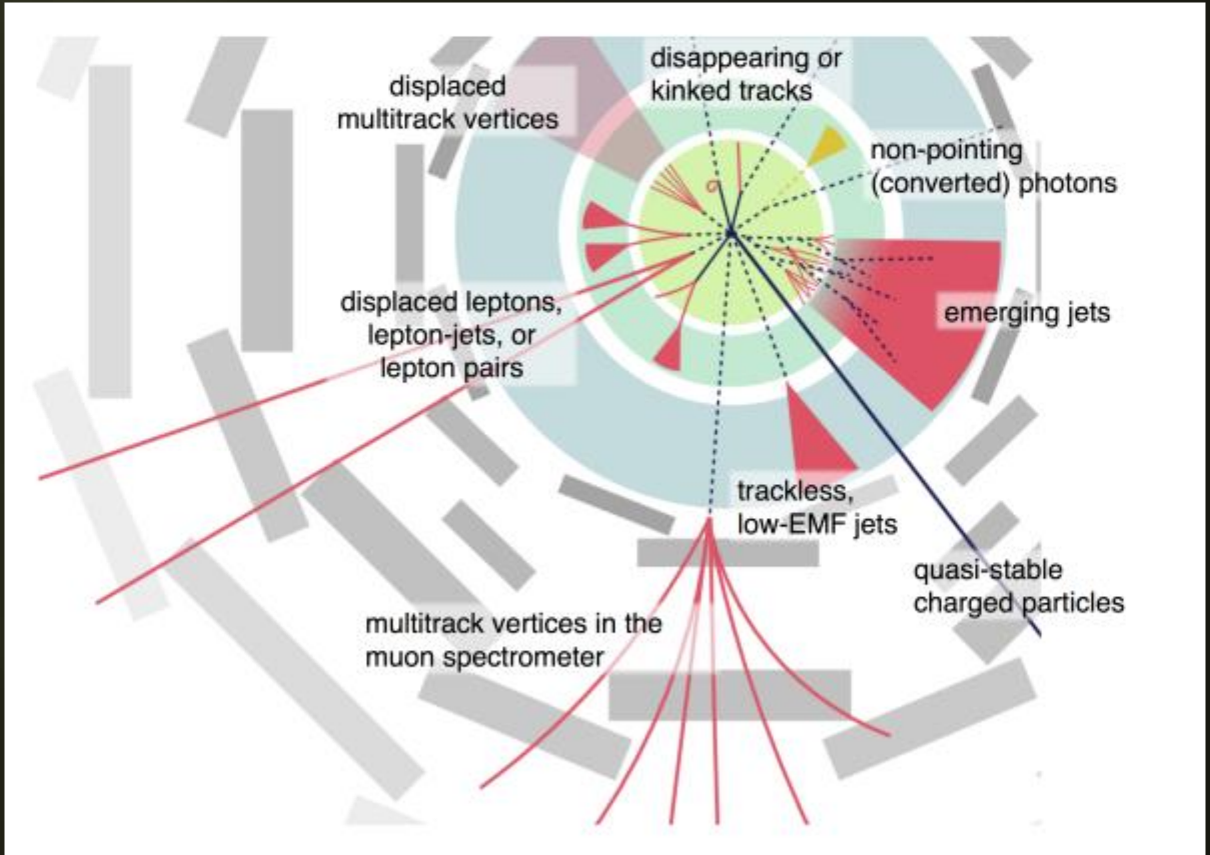
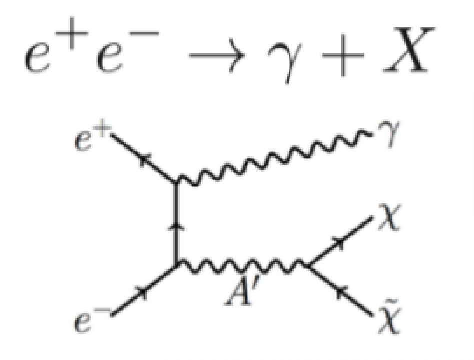
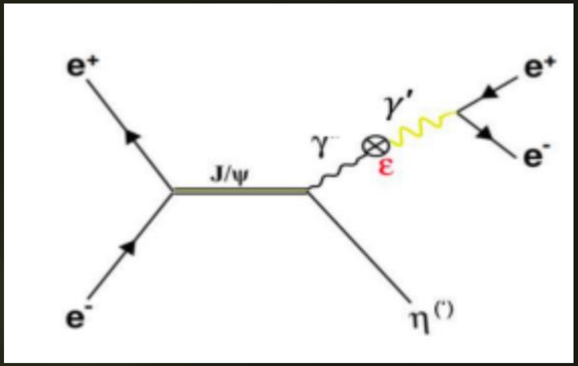


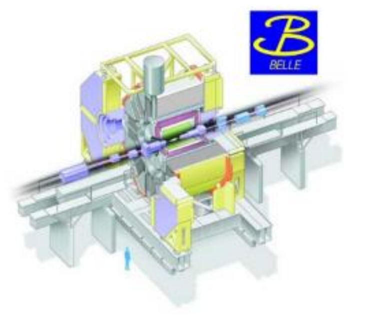
Fig: Heather Russel, 2017

Electron-Positron Colliders

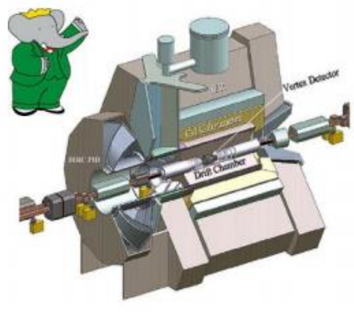
- Actually, a missing mass technique


$$e^+e^- \to \gamma + X$$

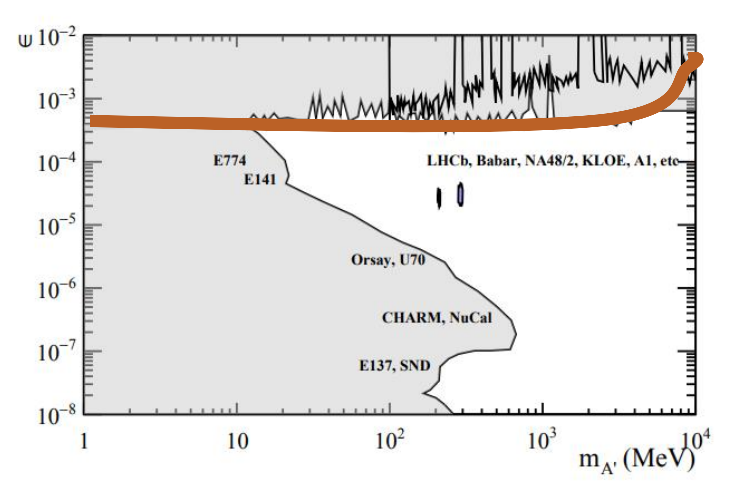




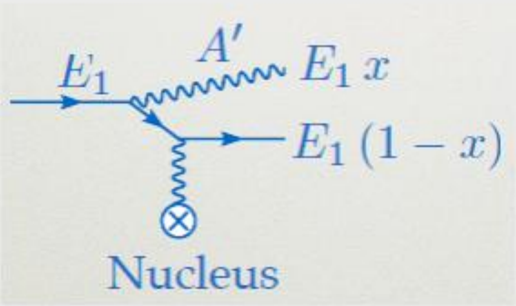
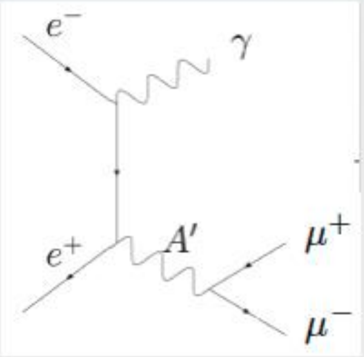
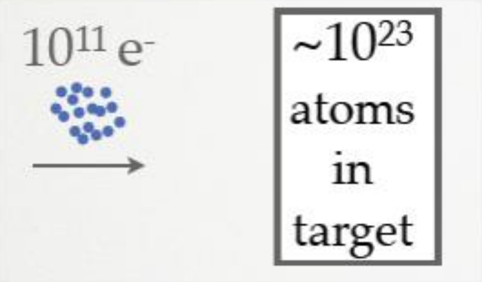
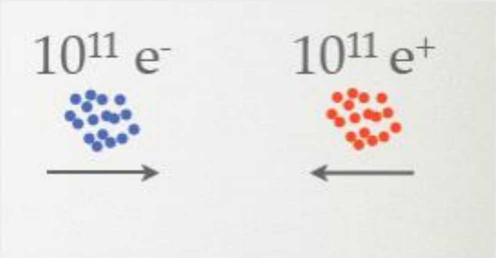
at the KEKB collider
(KEK, Japan)



at the PEP II collider
(SLAC, California)



Fixed Target vs Collider

	Fixed Target	e+e- colliders
Process		
Luminosity	 10^{11} e$^-$ ~10^{23} atoms in target	 10^{11} e$^-$ 10^{11} e$^+$
Cross-Section	$\sigma \sim \frac{\alpha^3 Z^2 \epsilon^2}{m^2} \sim O(10\ pb)$	$\sigma \sim \frac{\alpha^2 \epsilon^2}{E^2} \sim O(10\ fb)$

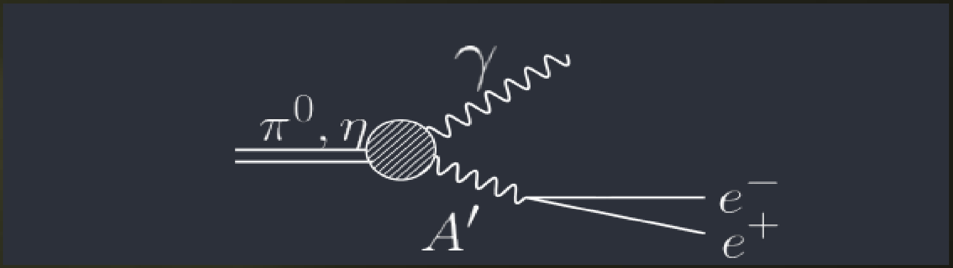
∗1/M$_{A'}$ .vs.1/E$_{beam}$

∗Coherent scattering from Nucleus (~Z^2)

- high backgrounds
- limited A’ mass

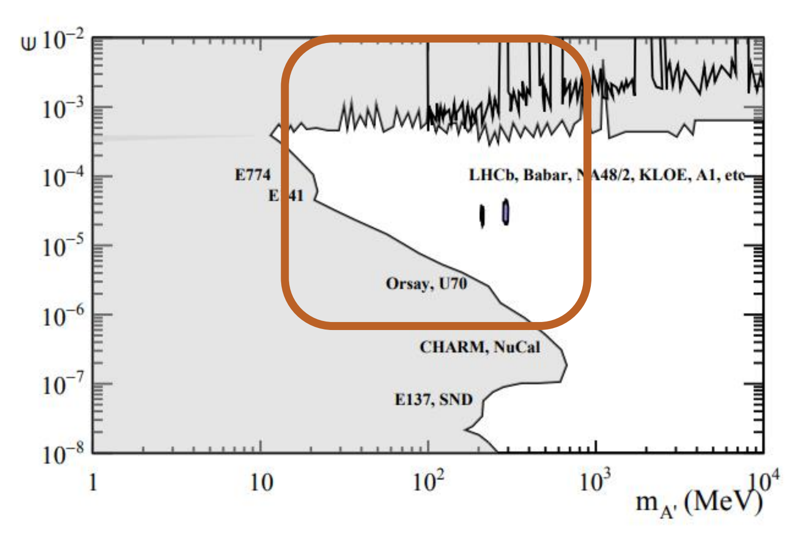
- low backgrounds
- higher A’ mass

Meson Decays



10^9 η mesons

10^{13} η
10^{11} η‘ mesons



The Physics Landscape for REDTOP

- *SM is showing its age*
    - *SM matter: Dark matter:Dark energy=5%:25%:70%*
    - *Baryon Asymmetry of the Universe*
    - *Expansion of the universe is accelerating (hint to more forces)*
    - . . . .
- *New physics is elusive: probability of processes where new physics is coupled to SM physics is low*
- *LHC found no hint of new physics at high energy so far*
    - *New physics could be at much lower energy*
    - *Colliders have insufficient luminosity ($\mathcal{O}(10^{41})$ cm^{-2} vs $\mathcal{O}(10^{44})$ cm^{-2} for 1–mm fixed target)*
- *Newest theoretical models prefer gauge bosons in MeV-GeV mass range as "…many of the more severe astrophysical and cosmological constraints that apply to lighter states are weakened or eliminated, while those from high energy colliders are often inapplicable" (B. Batell , M. Pospelov, A. Ritz – 2009)*

High intensity-low energy experiments are growing in popularity (Fixed target and beam dump)

REDTOP Key Points

The experiment will yield 2.5 x 10^{13} η mesons/year and 2 x 10^{11} η' mesons/year – Good physics opportunities start at ~10^{11} η mesons

That is a consequence of a relatively large η/η' hadro-production cross section (10-20 mbar in the 2 GeV beam energy region and 0.1 mbar at 3 GeV)

Requires a detector blind to protons and slow pions

Near-4π detector can be used with beams of different energy and/or particles

Why the η meson is special?

▣ It is a Goldstone boson	Symmetry constrains its QCD dynamics
▣ It is an eigenstate of the C, P, CP and G operators (very rare in nature): $I^G J^{PC} = 0^+ 0^{-+}$	It can be used to test C and CP invariance.
▣ All its additive quantum numbers are zero $Q = I = j = S = B = L = 0$	Its decays are not influenced by a change of flavor (as in K decays) and violations are "pure"
▣ All its possible strong decays are forbidden in lowest order by P and CP invariance, G-parity conservation and isospin and charge symmetry invariance. ▣ EM decays are forbidden in lowest order by C invariance and angular momentum conservation	It is a very narrow state (Γ_η=1.3 KeV vs Γ_ρ=149 MeV) Contributions from higher orders are enhanced by a factor of ~100,000 Excellent for testing invariances
▣ The η decays are flavor-conserving reactions	Decays are free of SM backgrounds for new physics search

η is an excellent laboratory to search for physics Beyond Standard Model

Detecting BSM Physics with REDTOP (η/η' factory)

Assume a yield ~10^{13} η mesons/yr and ~10^{11} η' mesons/yr

C, T, CP-violation

- CP Violation via Dalitz plot mirror asymmetry: $\eta \to \pi^o \pi^+ \pi^-$
- CP Violation (Type I – P and T odd , C even): η–> $4\pi^o \to 8\gamma$
- CP Violation (Type II - C and T odd , P even): $\eta \to \pi^o \ell^+\ell^-$ **and** $\eta \to 3\gamma$
- Test of CP invariance via μ longitudinal polarization: $\eta \to \mu^+\mu^-$
- Test of CP invariance via $\gamma*$ polarization studies: $\eta \to \pi^+\pi^-e^+e^-$ and $\eta \to \pi^+\pi^-\mu^+\mu^-$
- Test of CP invariance in angular correlation studies: $\eta \to \mu^+\mu^-e^+e^-$
- Test of T invariance via μ transverse polarization: $\eta \to \pi^o\mu^+\mu^-$ and $\eta \to \gamma\mu^+\mu^-$
- CPT violation: μ polariz. in $\eta \to \pi^+\mu^-\nu$ vs $\eta \to \pi^-\mu^+\nu$ and γ polarization in $\eta \to \gamma\gamma$

New particles and forces searches

- Scalar meson searches (charged channel): $\eta \to \pi^o H$ with $H \to e^+e^-$ and $H \to \mu^+\mu^-$
- Dark photon searches: $\eta \to \gamma A'$ with $A' \to \ell^+\ell^-$
- Protophobic fifth force searches : $\eta \to \gamma X_{17}$ with $X_{17} \to e^+e^-$
- New leptophobic baryonic force searches : $\eta \to \gamma B$ with $B \to e^+e^-$ or $B \to \gamma\pi^o$
- Indirect searches for dark photons new gauge bosons and leptoquark: $\eta \to \mu^+\mu^-$ and $\eta \to e^+e^-$
- Search for true muonium: $\eta \to \gamma(\mu^+\mu^-)|_{2M_\mu} \to \gamma e^+e^-$

Other discrete symmetry violations

- Lepton Flavor Violation: $\eta \to \mu^+e^- +$ c.c.
- Double lepton Flavor Violation: $\eta \to \mu^+\mu^+e^-e^- +$ c.c.

Other Precision Physics measurements

- Proton radius anomaly: $\eta \to \gamma\mu^+\mu^-$ vs $\eta \to \gamma e^+e^-$
- All unseen leptonic decay mode of η / η' (SM predicts 10^{-6} -10^{-9})

Non-η/η' based BSM Physics

- Dark photon and ALP searches in Drell-Yan processes: qqbar $\to A'/a \to l^+l^-$
- ALP's searches in Primakoff processes: $p\,Z \to p\,Z\,a \to l^+l^-$ (F. Kahlhoefer)
- Charged pion and kaon decays: $\pi+ \to \mu^+\nu A' \to \mu^+\nu e^+e^-$ and $K+ \to \mu^+\nu A' \to \mu^+\nu e^+e^-$
- Neutral pion decay: $\pi^o \to \gamma A' \to \gamma e^+e^-$

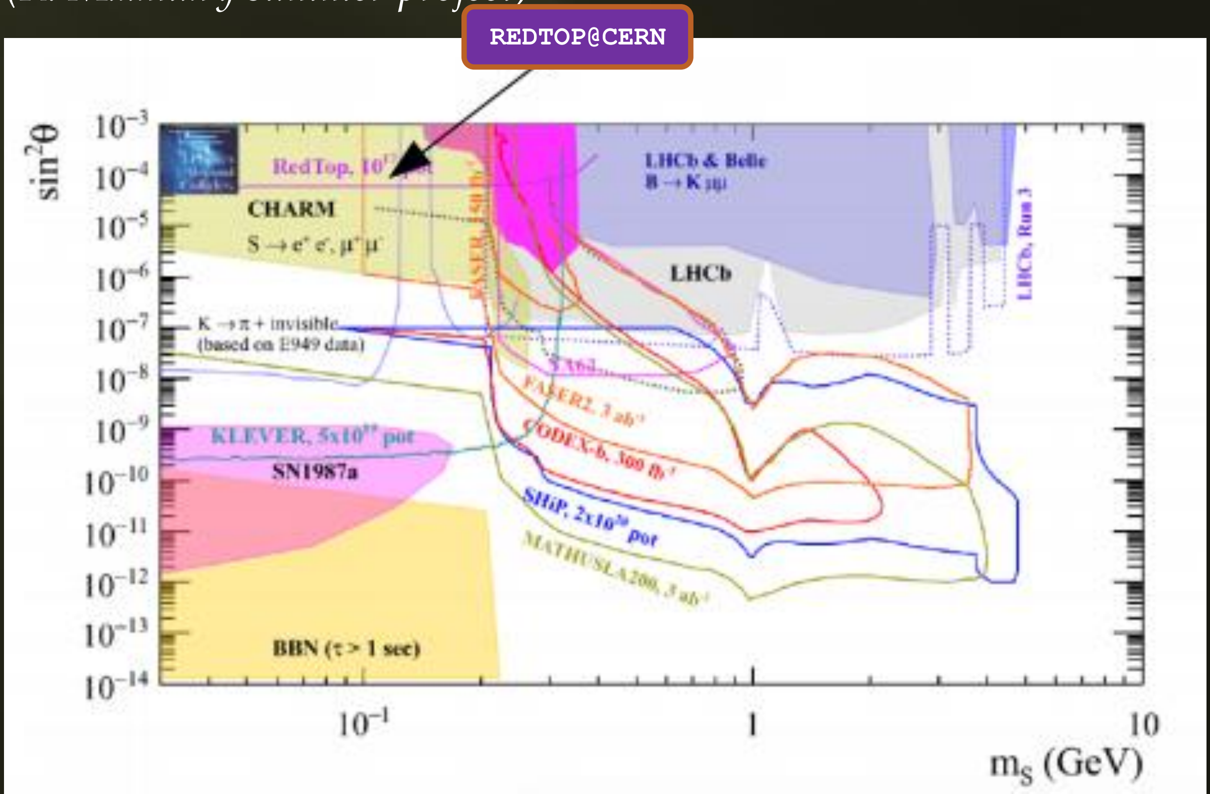
High precision studies on medium energy physics

- Nuclear models
- Chiral perturbation theory
- Non-perturbative QCD
- Isospin breaking due to the u-d quark mass difference
- Octet-singlet mixing angle
- Electromagnetic transition form-factors (important input for g-2)

Searches for light scalar mesons

$\eta \rightarrow \pi^o H \quad with\ H \rightarrow \mu^+ \mu^- \ and \quad e^+ e^-$

- *Viable DM candidate (in certain circumstances) coupling to Higgs portal - M. Pospelov, A. Ritz and M. Voloshin, Phys. Rev. D 78, 115012 (2008)*
- *Studied within the "Physics Beyond Collider" program at CERN for 10^{17} POT*
- *FNAL and BNL can provide 10x more POT*
- *Only "bump hunt analysis". Adding vertexing improve the sensitivity to physics BSM by 1000x (K. Maamary summer project)*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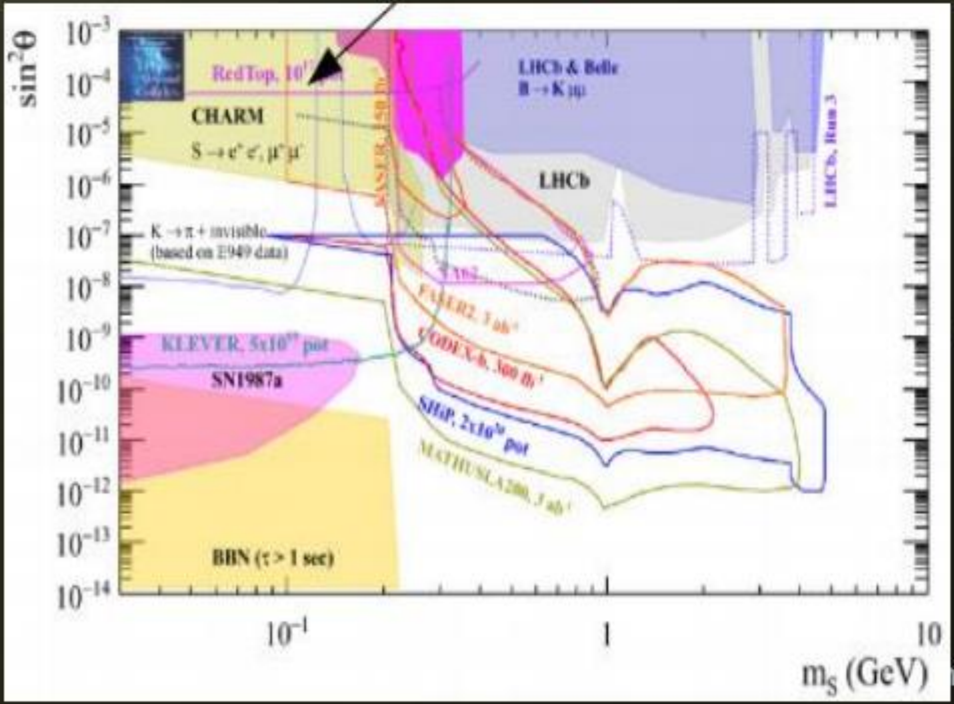
Searches for light scalar mesons

Minimal SM Higgs extension

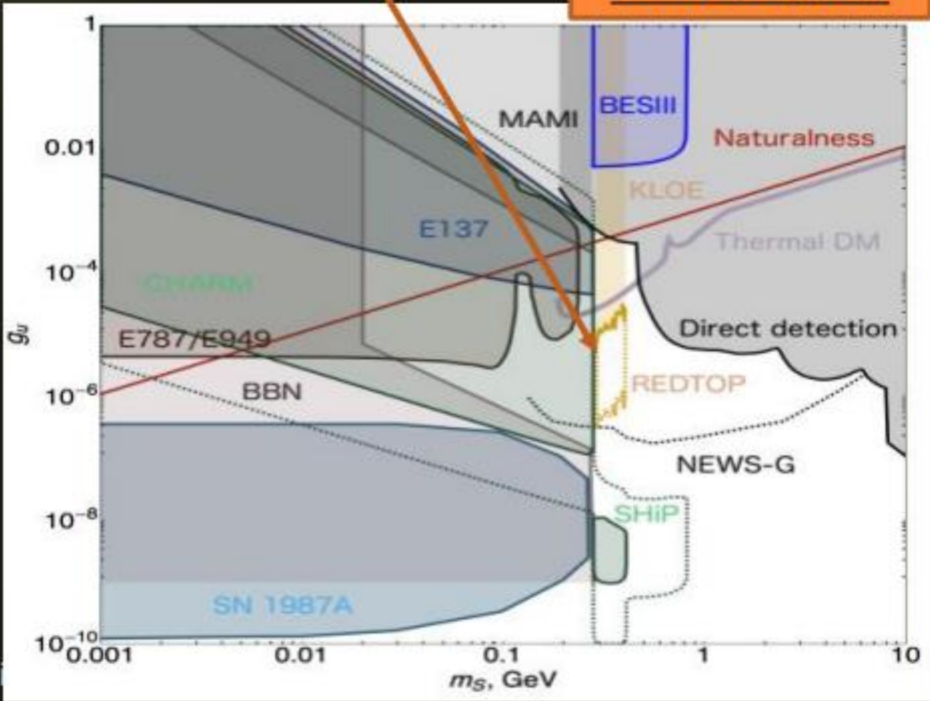
- *Studied within the "Physics Beyond Collider" program at CERN for 10^{17} POT*
- *FNAL and BNL can provide 10x more POT*
- *Only "bump hunt analysis". Vertexing add 10x more sensitivity*

Hadrophilic Scalar Mediator

- *Studied in* **arXiv:1812.05103**
- *Only bump hunt - no vertexing*



REDTOP@CERN



REDTOP@Fermilab

arXiv:1812.05103

Searches for ALPs with fermion or gluon coupling

- *Beam emitted ALP's from the following processes:*
  - *Drell-Yan processes:* *qqbar* → A'/a → l^+l^-
  - *Proton bremsstrahlung processes: p N* → p N A'/a *with* A'/a → l^+l^- *(J. Blümlein and J. Brunner)*
  - *Primakoff processes: p Z* → p Z a → l^+l^- *(F. Kahlhoefer, et. Al.)*
- *Only "bump hunt analysis" with 10^{17} POT (CERN). Will add vertexing+timing to the analysis.*
- *Redtop@PIP-II will provide x100 sensitivity (ALPACA study).*

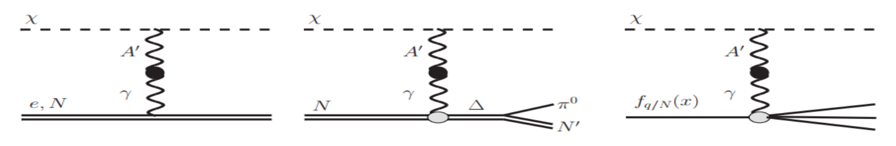
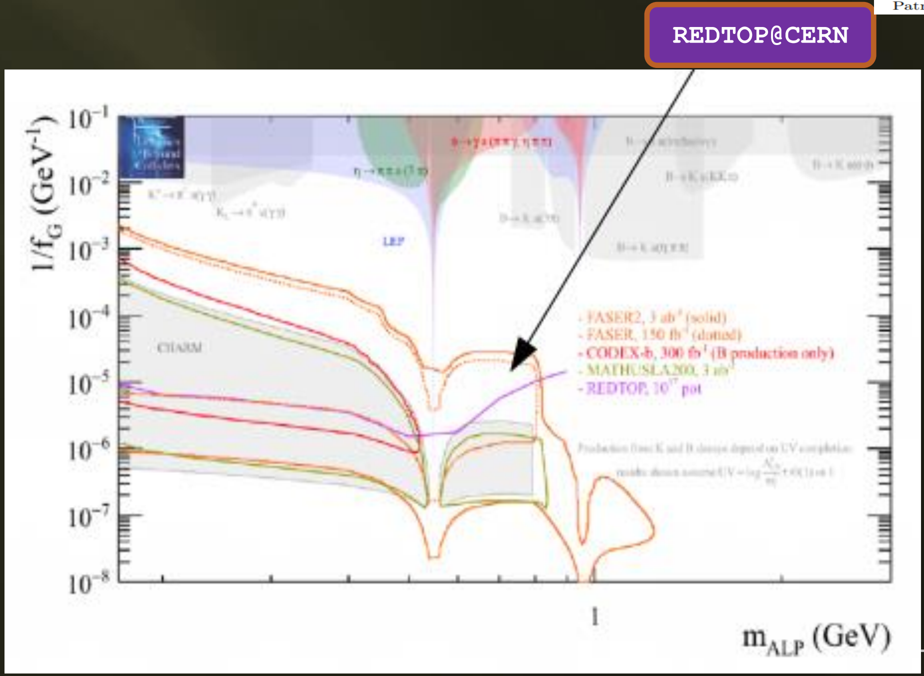
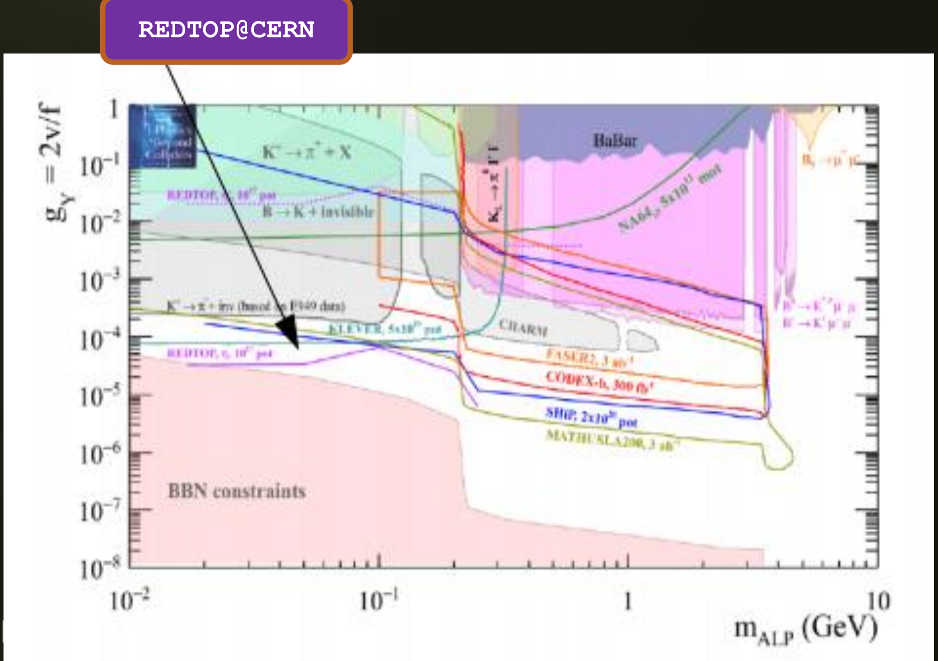


FIG. 4. Scattering channels analyzed: from left to right, elastic scattering on electrons or nucleons, quasielastic (incoherent) single pion production, and deep inelastic scattering.

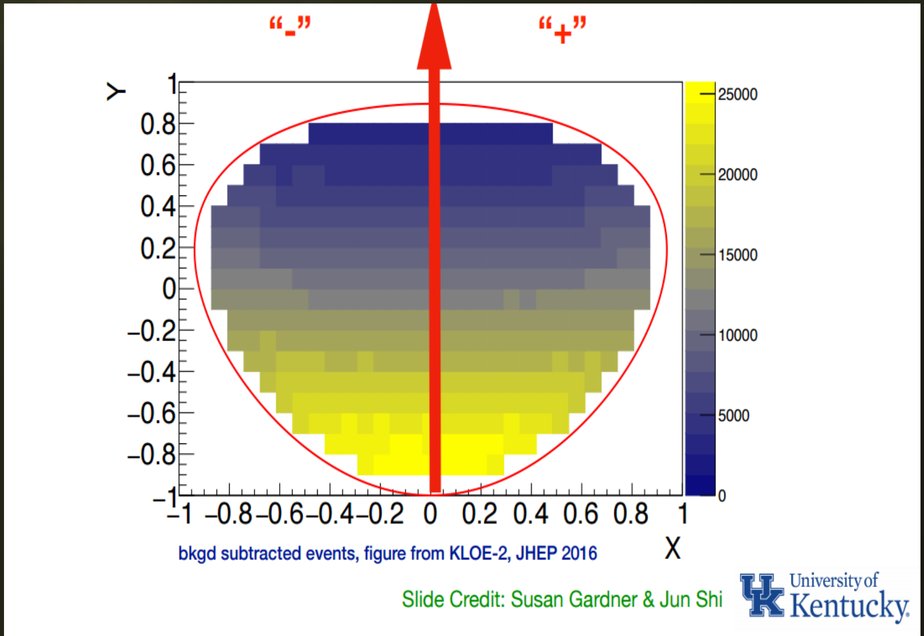
Patrick deNiverville,[1] Chien-Yi Chen,[1,2] Maxim Pospelov,[1,2] and Adam Ritz[1]





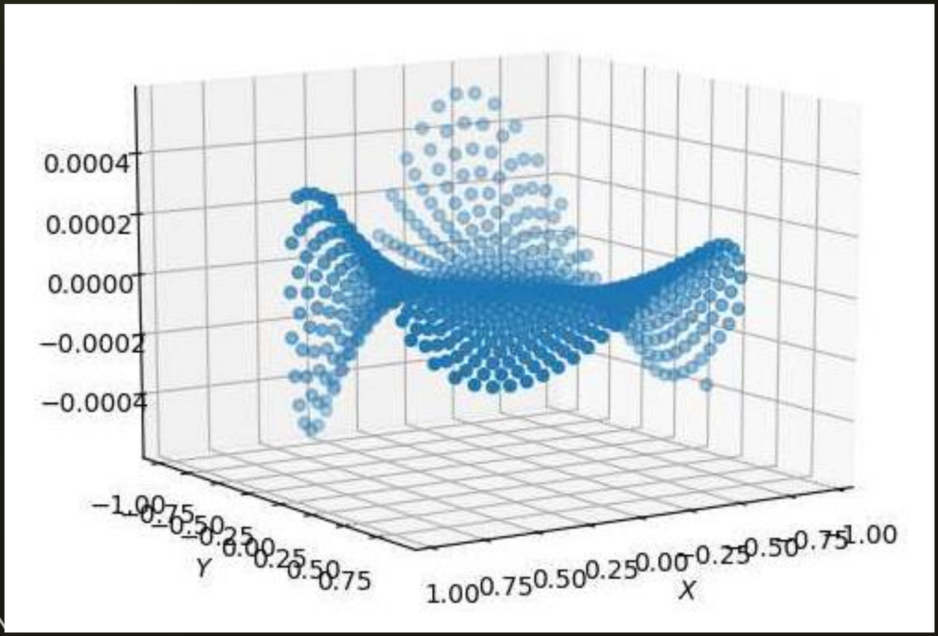
CP Violation from Dalitz plot mirror asymmetry in $\eta -> \pi^+\pi^-\pi^0$

- *CP-violation from this process is not bounded by EDM as is the case for the $\eta \rightarrow 4\pi$ process.*
- *Complementary to EDM searches even in the case of T and P odd observables, since the flavor structure of the eta is different from the nucleus*
- *Current PDG limits consistent with no asymmetry*
- *REDTOP will collect 4x10^{11} such decay (factor 100 in stat. error)*
- *New model in GenieHad (collaboration with S. Gardner & J. Shi – UK) based on* https://arxiv.org/abs/1903.11617



bkgd subtracted events, figure from KLOE-2, JHEP 2016

Slide Credit: Susan Gardner & Jun Shi



BSM Physics Program (η and η' factory)

Non-η/η' based BSM Physics

- *Dark photon and ALP searches in Drell-Yan processes:* $qqbar \rightarrow A'/a \rightarrow l^+l^-$
- *Dark photon and ALP searches in proton bremsstrahlung processes:* $p\,N \rightarrow p\,N\,A'/a$ *with* $A'/a \rightarrow l^+l^-$ *(J. Blümlein and J. Brunner)*
- *ALP's searches in Primakoff processes:* $p\,Z \rightarrow p\,Z\,a \rightarrow l^+l^-$ *(F. Kahlhoefer)*

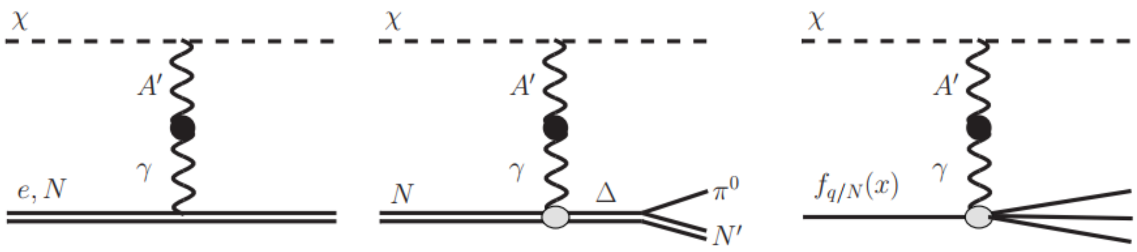


FIG. 4. Scattering channels analyzed: from left to right, elastic scattering on electrons or nucleons, quasielastic (incoherent) single pion production, and deep inelastic scattering.

Patrick deNiverville,[1] Chien-Yi Chen,[1,2] Maxim Pospelov,[1,2] and Adam Ritz[1]

- *Charged pion and kaon decays:* $\pi+ \rightarrow \mu^+ \nu A' \rightarrow \mu^+ \nu e^+e^-$ *and* $K+ \rightarrow \mu^+ \nu A' \rightarrow \mu^+ \nu e^+e^-$
- *Neutral pion decay:* $\pi^0 \rightarrow \gamma A' \rightarrow \gamma e^+e^-$

Experimental Techniques- η/η' production+detection

- *Incident proton energy ~1.8 GeV (3.5 GeV for η')*
- *CW beam, 10^{17}-10^{18} POT/yr (depending on the host laboratory)*
- *η/η' hadro-production from inelastic scattering of protons on Li or Be targets*
- *Use multiple thin targets to minimize combinatorics background*

Charged tracks detection

- ***Option 1: Optical-TPC***
  - *Baryons and most pions are below Č threshold*
  - *Electrons and most muons are detected and reconstructed*
- ***Option 2: LGAD tracker***
  - *4D tracker in high interaction rate environement*
  - *TOF will help to reject the barions*

γ detection

- *Use **ADRIANO2** calorimeter (Calice+T1015) for reconstructing EM showers*
- *$\sigma_E/E < 5\%/\sqrt{E}$*
- *PID from dual-readout to disentangle showers from γ/μ/hadrons*
- *96.5% coverage*

- *Fiber tracker (LHCB style) for rejection of background from γ-conversion and reconstruction of secondary vertices ($\sim 70\mu$m resolution)*

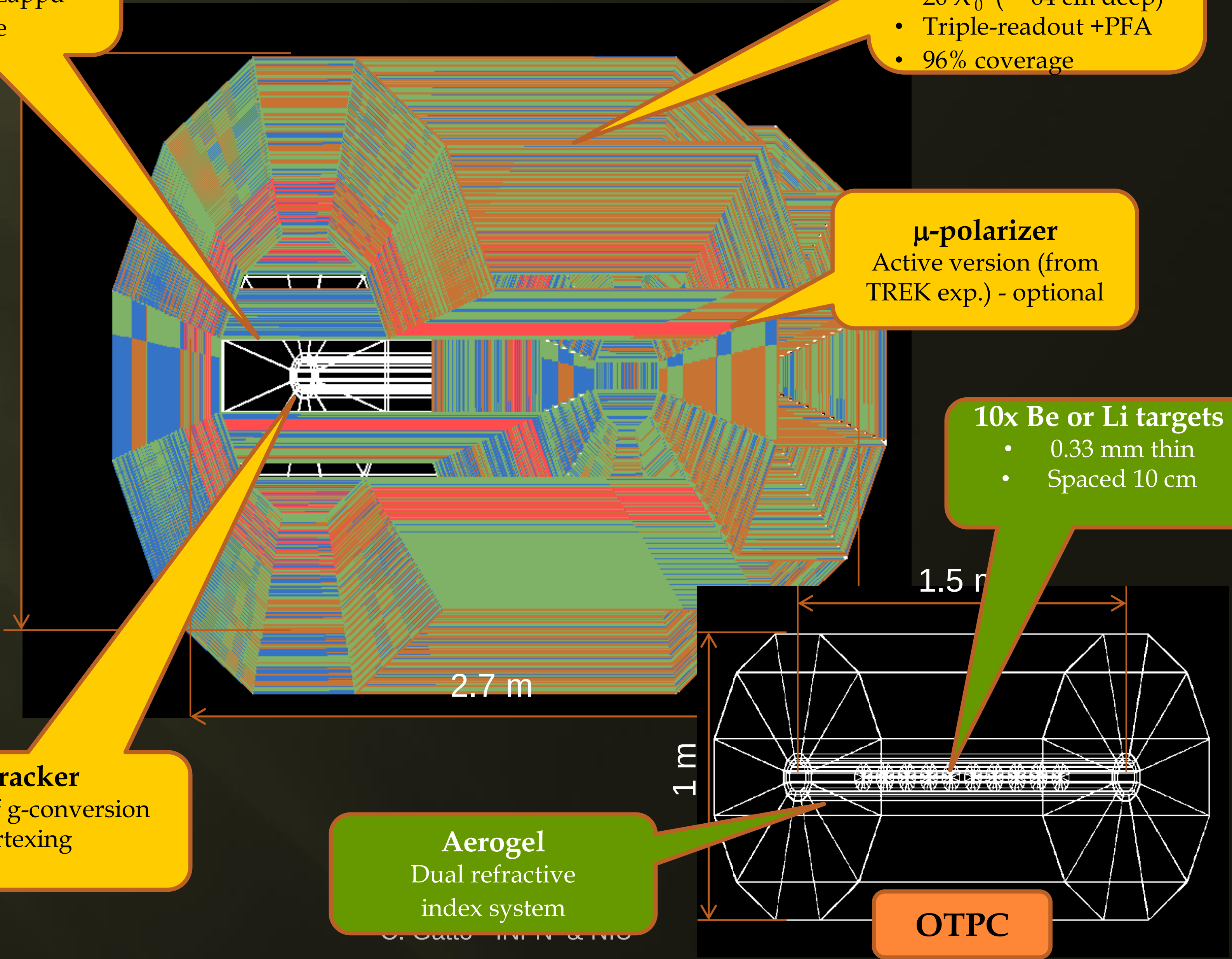
Present & Future η Samples

	Technique	$\eta \to 3\pi^0$	$\eta \to e^+e^-\gamma$	Total η
CB@AGS	$\pi^- p \to \eta\, n$	9×10^5		10^7
CB@MAMI-B	$\gamma p \to \eta\, p$	1.8×10^6	5000	2×10^7
CB@MAMI-C	$\gamma p \to \eta\, p$	6×10^6		6×10^7
KLOE	$e+e- \to \Phi \to \eta\gamma$	6.5×10^5		5×10^7
WASA@COSY	$pp \to \eta\, pp$ $pd \to \eta\, ^3He$			$>10^9$ (untagged) 3×10^7 (tagged)
CB@MAMI 10 wk (proposed 2014)	$\gamma p \to \eta\, p$	3×10^7	1.5×10^5	3×10^8
Phenix	$d\, Au \to \eta\, X$			5×10^9
Hades	$pp \to \eta\, pp$ $p\, Au \to \eta\, X$			4.5×10^8
Near future samples				
GlueX@JLAB (just started)	$\gamma_{12\,\mathrm{GeV}} p \to \eta\, X \to$ neutrals			5.5×10^7/yr
JEF@JLAB (recently approved)	$\gamma_{12\,\mathrm{GeV}} p \to \eta\, X \to$ neutrals			3.9×10^5/day
REDTOP@FNAL (proposing)	$p_{1.8\,GeV} Li \to \eta\, X$			2.5×10^{13}/yr

REDTOP Requirements

- *Medium energy proton beam 1.5 – 4 GeV*
- *Proton economics:*
    - *Min: 10^{17} POT/yr - CERN*
    - *Optimal: 10^{18} POT/yr - FNAL or BNL*
    - *Produce ~10^{13} η mesons/yr – reco eff > 10%*
    - *Produce ~10^{11} η' mesons/yr– reco eff > 10%*
- *Efficient detection of the leptonic decays of the η*
- *Blind to protons and low energy charged pions.*
- *Neutron rejection (via dual-readout)*
- *near 4π detector acceptance.*

REDTOP detector



Optical TPC
- ~ 1m x 1.5 m
- CH_4 @ 1 Atm
- $5x10^5$ Sipm/Lappd
- 98% coverage

ADRIANO2 Calorimeter (tiles)
- Scint. + heavy glass sandwich
- 20 X_0 (~ 64 cm deep)
- Triple-readout +PFA
- 96% coverage

μ-polarizer

Active version (from TREK exp.) - optional

10x Be or Li targets
- 0.33 mm thin
- Spaced 10 cm

Fiber tracker

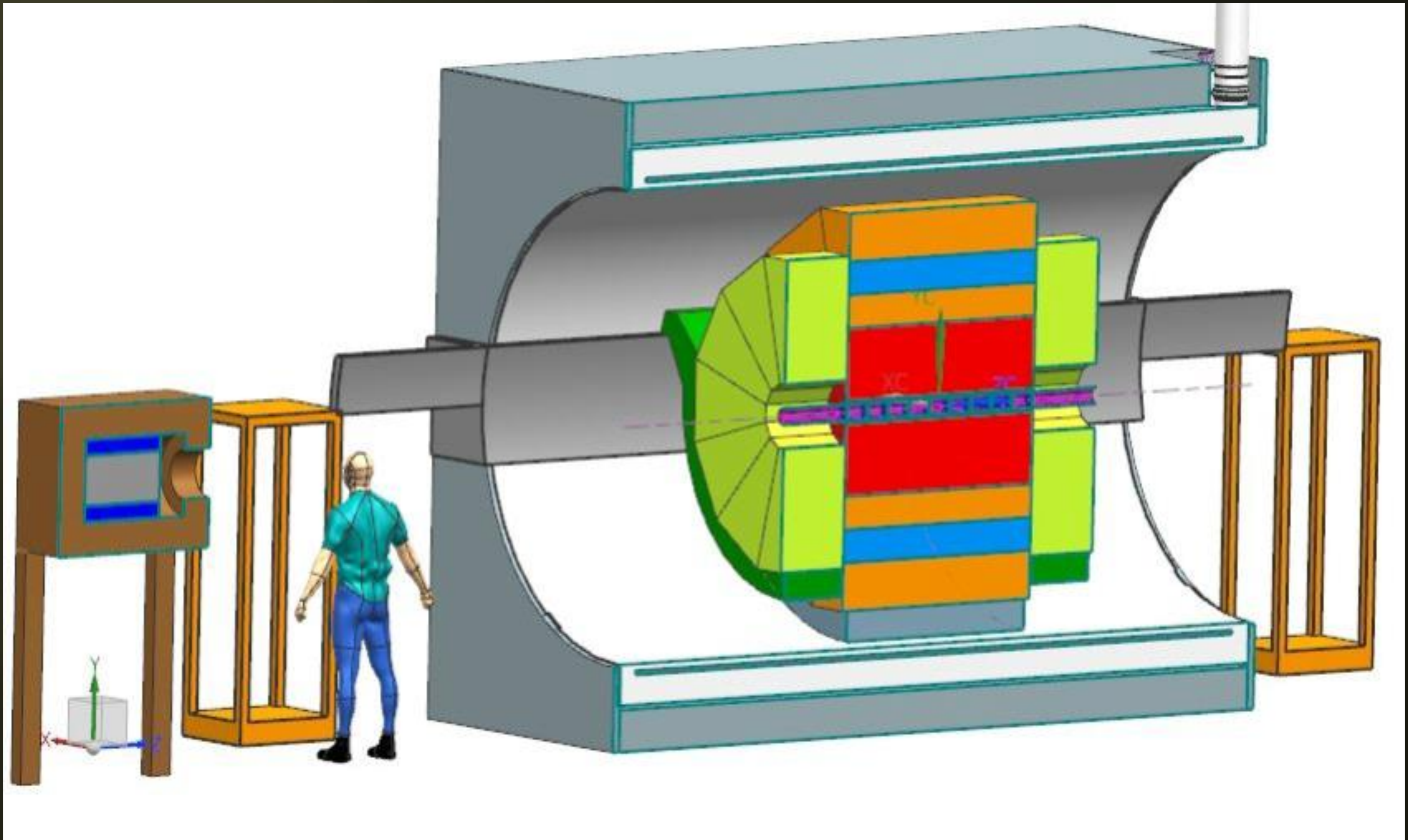
for rejection of g-conversion and vertexing

Aerogel

Dual refractive index system

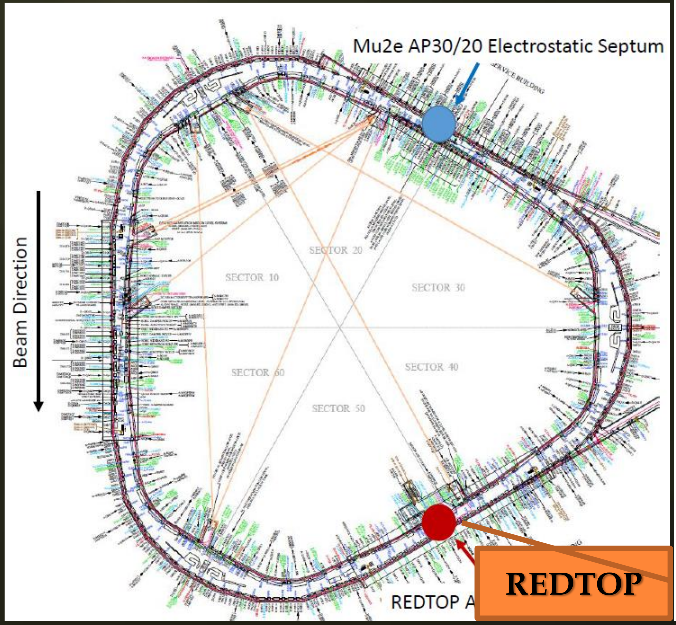
OTPC

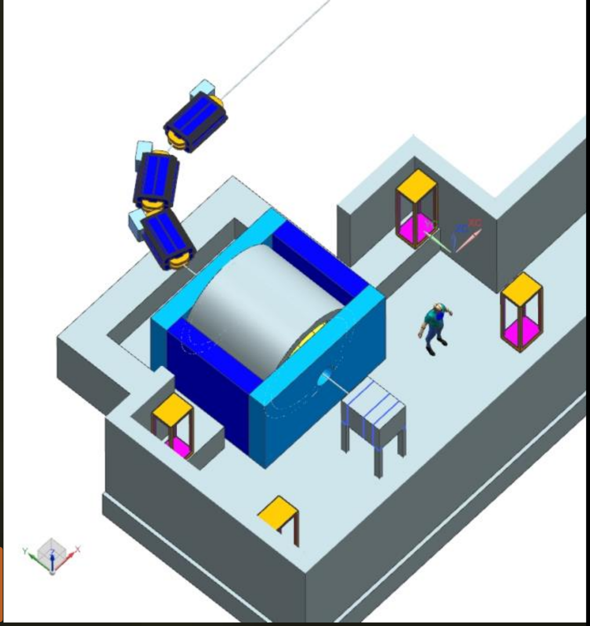
REDTOP Detector+ Magnet



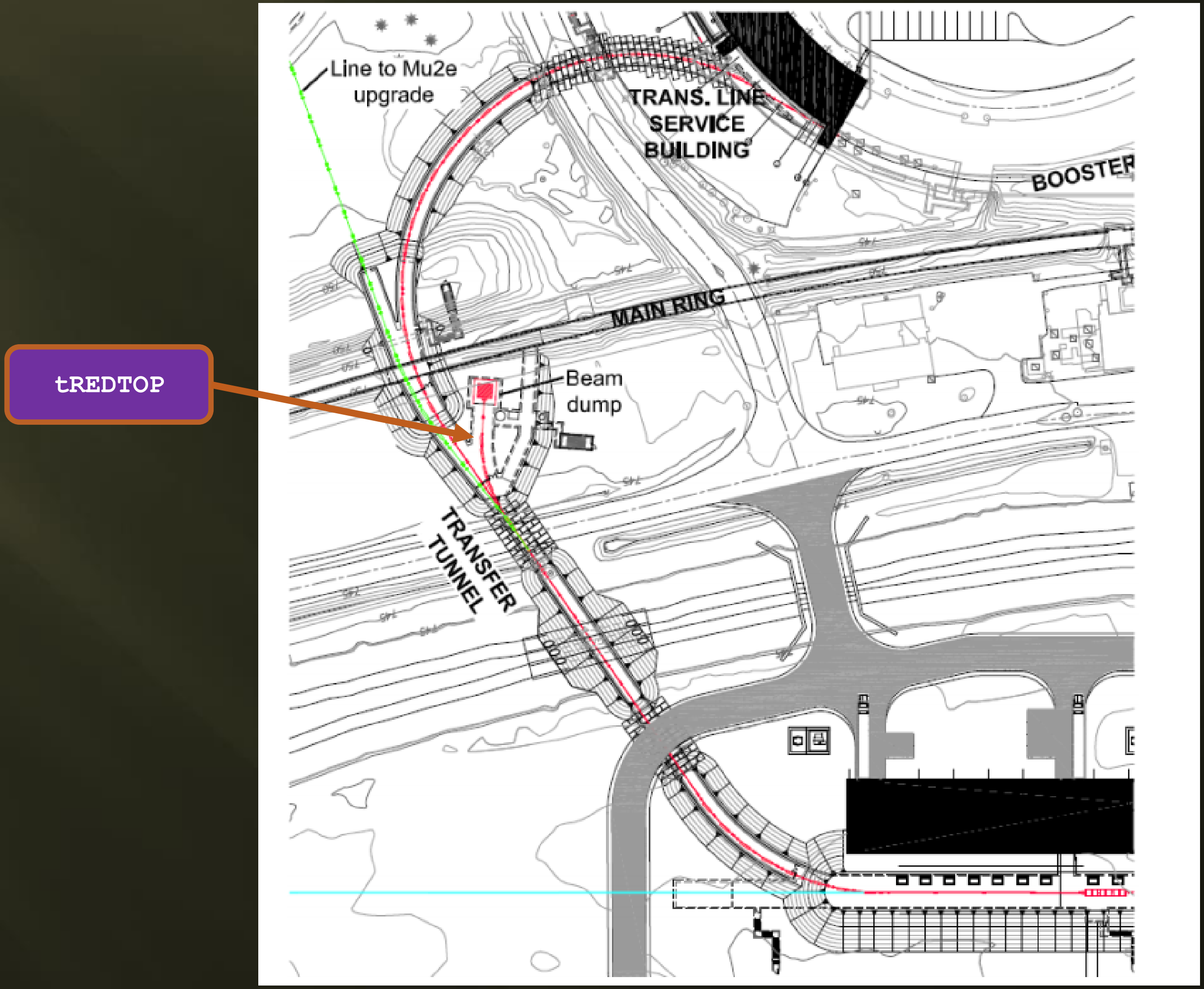
Acceleration Scheme for Run-I (M. Syphers)

- *Single p pulse from booster ($\leq 4x10^{12}$ p) injected in the DR (former debuncher in anti-p production at Tevatron) at fixed energy (8 GeV)*
- *Energy is removed by adding 1-2 RF cavities identical to the one already planned (~5 seconds)*
- *Slow extraction to REDTOP over ~40 seconds.*
- *The 270^o of betatron phase advance between the Mu2e Electrostatic Septum and REDTOP Lambertson is ideal for AP50 extraction to the inside of the ring.*
- *Total time to decelerate-debunch-extract: 51 sec: duty cycle ~80%*





Tagged REDTOP Run-II at PIP-III
The ultimate eta factory



Expected η/η' Yield

- *Assume: $1x10^{11}$ POT/sec – CW*
  - *Beam power @ 3 GeV: 10^{11} p/sec × 1.9 GeV × 1.6 × 10^{-10} J/GeV = 30 Watts (48 W for η')*
- *Target system : 10 x 0.33mm Be or 0.5 mm Li foils, spaced 10 cm apart*
  - *Be is thinner (better vertex resolution) but makes more primary hadrons (final state hadron multiplicity ≈ $A^{1/3}$)*
  - *Prob(p + target → X) ~ 0.5% or 5× 10^8 p-Be inelastic collisions per second*

⬇

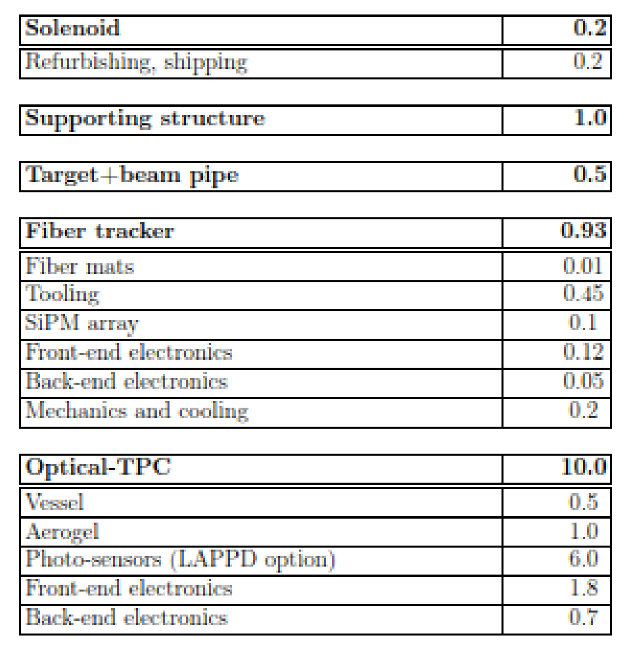
- *p-inelastic production: 5 x 10^8 evt/sec (1 interaction/2 nsec in any of the 10 targets)*
- *Probability of 2 events in the same target in 2 nsec: 7%*
- *η production: 2.5 x 10^6 η/sec (2.5 x 10^4 η'/sec) or 2.5 x 10^{13} η/yr (2.5 x 10^{11} η' /yr)*
- *Preliminary di-lepton reconstruction efficiency (no-vertexing/timing): 30-50%*
- *Preliminary background rejection (no-vertexing/timing): < 10^{-8} (from QCD) or ≈ 0.1% from η (need to improve 100x with vertexin+timing)*

Timeline & Costing

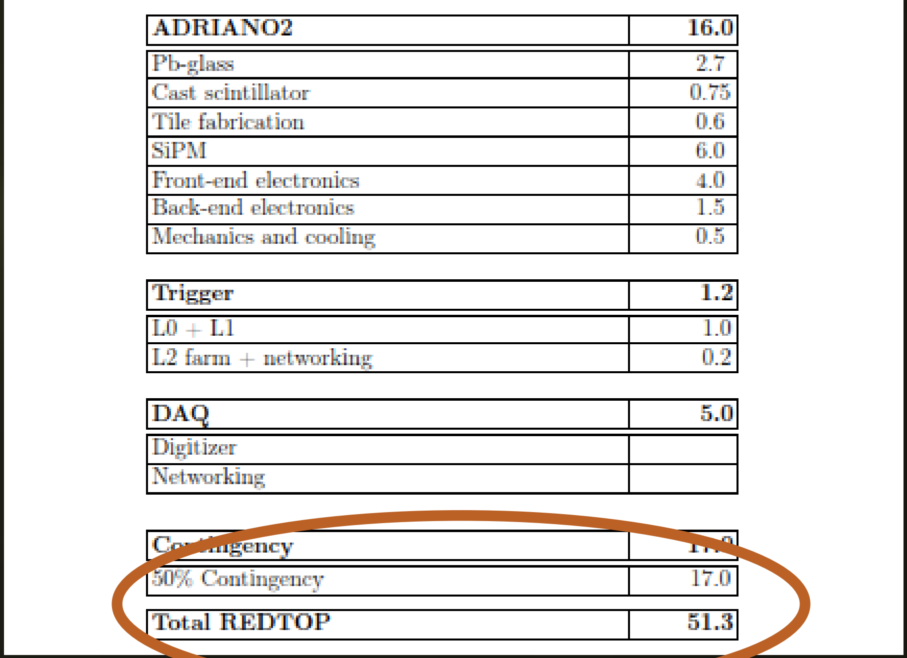
- *Once approved and funded, REDTOP needs:*
  - *2-3 years detector R&D*
  - *1 year detector design*
  - *2-3 yrs construction*
- *Accelerator mods requires:*
  - *BNL: <1yr (only requiring a new electronics for the extraction line (C4)*
  - *CERN: need further studies*
  - *FNAL: ~1yr (add a SC cavity to the DR and build an extraction line*
- *Total cost (for ESPP): ~50 M$ (including 50% contingency)*
  - *Solenoid and ¾ of Pb-Glass for ADRIANO in-kind contributions from INFN (Finuda and NA64 experiments)*
  - *Construction at participating institutions*
  - *Assembly at hosting laboratory*

Cost (estimate for ESPP)

- *In kind contribution from INFN*
  - *Solenoid (from Finuda experiment at Frascati)*
  - *¾ of Pb-glass (from NA62)*



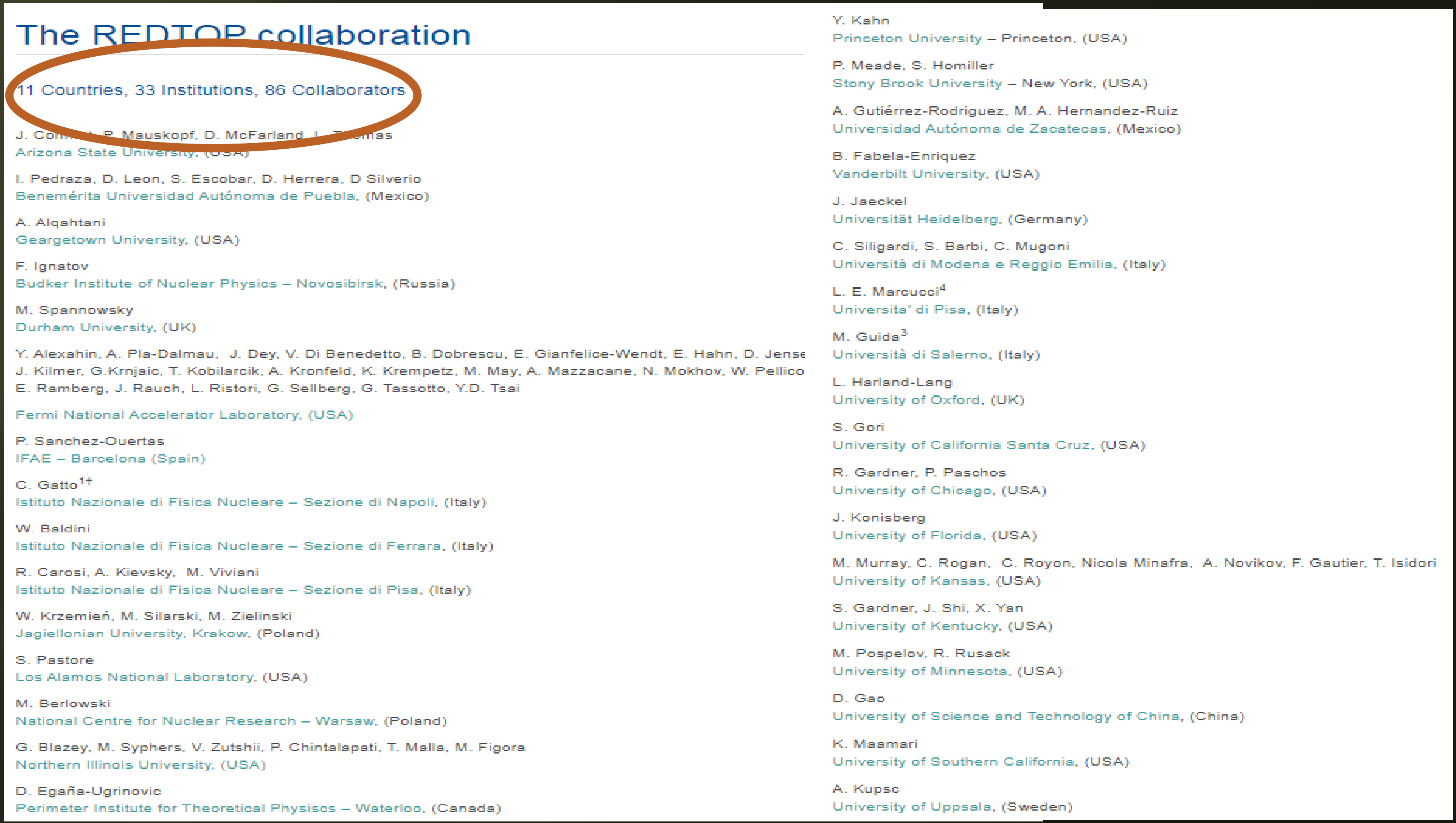
Solenoid	**0.2**
Refurbishing, shipping	0.2
Supporting structure	**1.0**
Target+beam pipe	**0.5**
Fiber tracker	**0.93**
Fiber mats	0.01
Tooling	0.45
SiPM array	0.1
Front-end electronics	0.12
Back-end electronics	0.05
Mechanics and cooling	0.2
Optical-TPC	**10.0**
Vessel	0.5
Aerogel	1.0
Photo-sensors (LAPPD option)	6.0
Front-end electronics	1.8
Back-end electronics	0.7



ADRIANO2	**16.0**
Pb-glass	2.7
Cast scintillator	0.75
Tile fabrication	0.6
SiPM	6.0
Front-end electronics	4.0
Back-end electronics	1.5
Mechanics and cooling	0.5
Trigger	**1.2**
L0 + L1	1.0
L2 farm + networking	0.2
DAQ	**5.0**
Digitizer	
Networking	
Contingency	**17.0**
50% Contingency	17.0
Total REDTOP	**51.3**

- *For Fermilab*
  - *Add labor and accelerator (R.F.cavities and EM septum are available at Fermilab)*
  - *Adjust contingency from 50% to 25%*

Status of the collaboration



The REDTOP collaboration

11 Countries, 33 Institutions, 86 Collaborators

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University of Uppsala, (Sweden)

- *Potential hosting laboratories: BNL, CERN, FNAL (either DR and/or PIP-II)*

Future Prospects

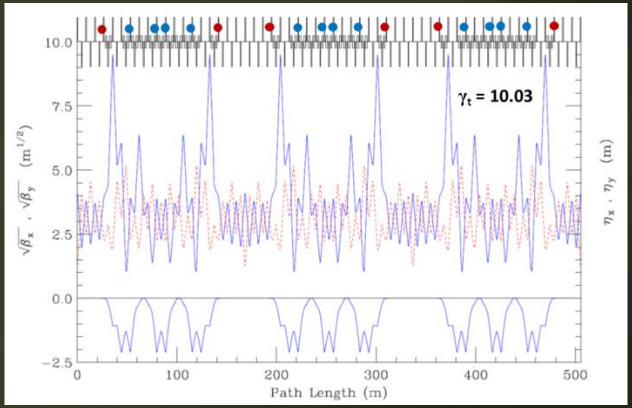
- *The Collaboration is currently engaged in the ESPP process and preparing for the P5-Snowmass process*
- *Endorsement by the community and/or laboratories is needed to fund detector R&D activities*
- *Current activities aim at the preparation of a full proposal in a timeframe consistent with the ESPP and Snowmass-P5*
    - *Detector optimization and sensitivity studies are well established and ongoing. Goal is maximize* $S/\sqrt{B}$
    - *Detector R&D is minimal (ADRIANO2 only, at present)*
- *Competition from several other experiments (LHCB, et. Al.)*
    - *But, REDTOP experimental techniques is substantially different*
- ***More details: https://redtop.fnal.gov***

Summary

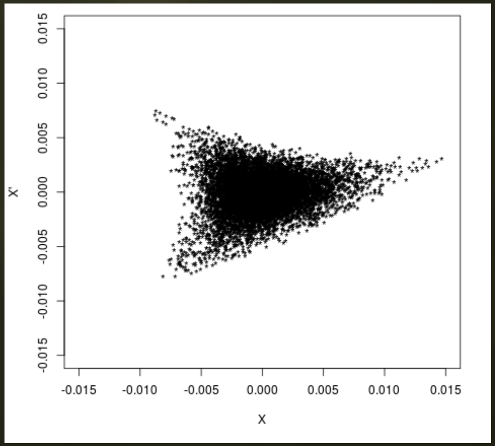
- *The η / η' meson is a excellent laboratory for studying rare processes and physics BSM*
- *Existing world sample not sufficient for breaching into decays violating conservation laws or searching for new particles*
- *REDTOP goal is to produce ~10^{13} η mesons/yr in phase I and ~ 10^{11} η' /year in phase II*
- *More running phases could use different beam species:*
  - *PIP-II for a tagged-η experiment*
- *Several labs could host the experiment (FNAL is the most optimal)*
- *New detector technique would set the stage for next generation High Intensity experiments*
- *Moderate cost (50-60 M$)*

Backup slides

Accelerator Physics Issues



- *Transition Energy*
  - γ_t is where $\Delta f/f = 1/\gamma 2 - \langle D/\rho \rangle = 0$; synchrotron motion stops momentarily, can often lead to beam loss
  - beam decelerates from $\gamma = 9.5$ to $\gamma = 3.1$
  - original Delivery Ring $\gamma_t = 7.6$
  - a re-powering of 18 quadrupole magnets can create a $\gamma_t = 10$, thus avoiding passing through this condition
    - Johnstone and Syphers, *Proc. NA-PAC 2016*, Chicago (2016).

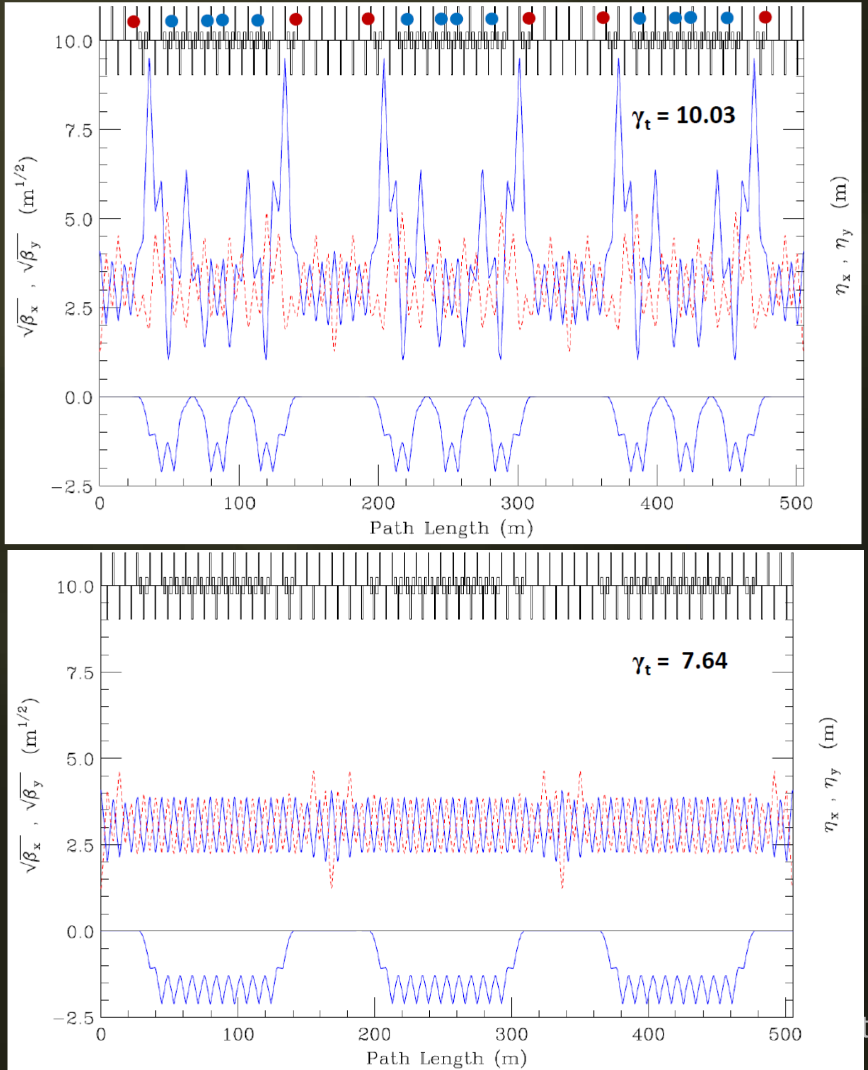


- *Resonant Extraction*
  - Mu2e will use 1/3-integer resonant extraction
  - REDTOP can use same system, with use of the spare Mu2e magnetic septum
  - initial calculations indicate sufficient phase space, even with the larger beam at the lower energies
- *Vacuum*
  - REDTOP spill time is much longer than for Mu2e
  - though beam-gas scattering emittance growth rate 3 times higher at lower energy, still tolerable level

Ring Optics through Deceleration (J. Johnstone)

Transition is avoided by using select quad triplets to boost γt above beam γ by 0.5 units throughout deceleration until γ_t = 7.64 and beam γ = 7.14 (5.76 GeV kinetic).

Below 5.76 GeV the DR lattice reverts to the nominal design configuration



8 GeV injection energy (top) and <5.8 GeV (bottom)

- Blue & red circles indicate sites of the γ_t quad triplets.

p (GeV/c)	8.89	8.33	7.76	7.20	6.63
KE (GeV)	8.00	7.45	6.88	6.32	5.76
γ_{BEAM}	9.53	8.93	8.33	7.74	7.14
$\gamma_{transition}$	10.03	9.43	8.83	7.74	7.64
β_{max} (m)	94.9	72.5	49.5	30.1	15.1
q (m^{-1})	.0697	.0573	.0416	.0236	0.0
3σ (mm)	15.0	13.6	11.6	9.4	6.9

Variation of γ_t, β_{max}, and the 15π 99% beam envelope through deceleration

"J.Johnstone, M.Syphers, NA-PAC, Chicago (2016)"

Expected η/η' Yield

- *Assume: 1x10^{11} POT/sec – CW*
  - *Beam power @ 3 GeV: 10^{11} p/sec × 1.9 GeV × 1.6 × 10^{-10} J/GeV = 30 Watts (48 W for η')*
- *Target system : 10 x 0.33mm Be or 0.5 mm Li foils, spaced 10 cm apart*
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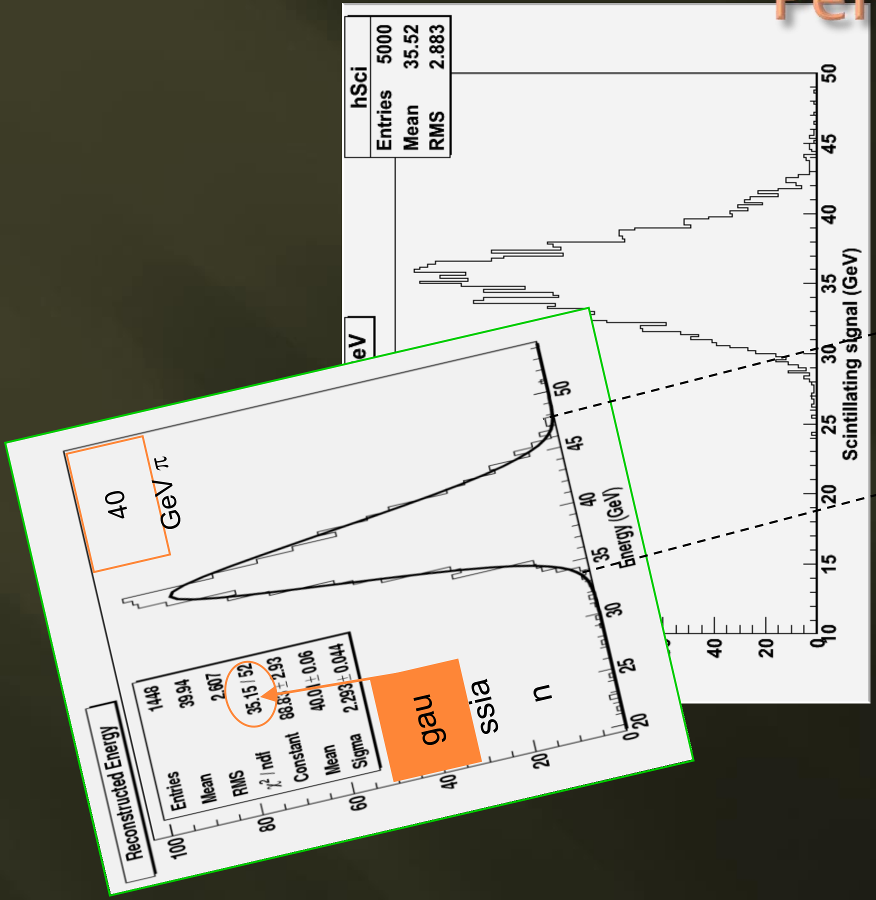
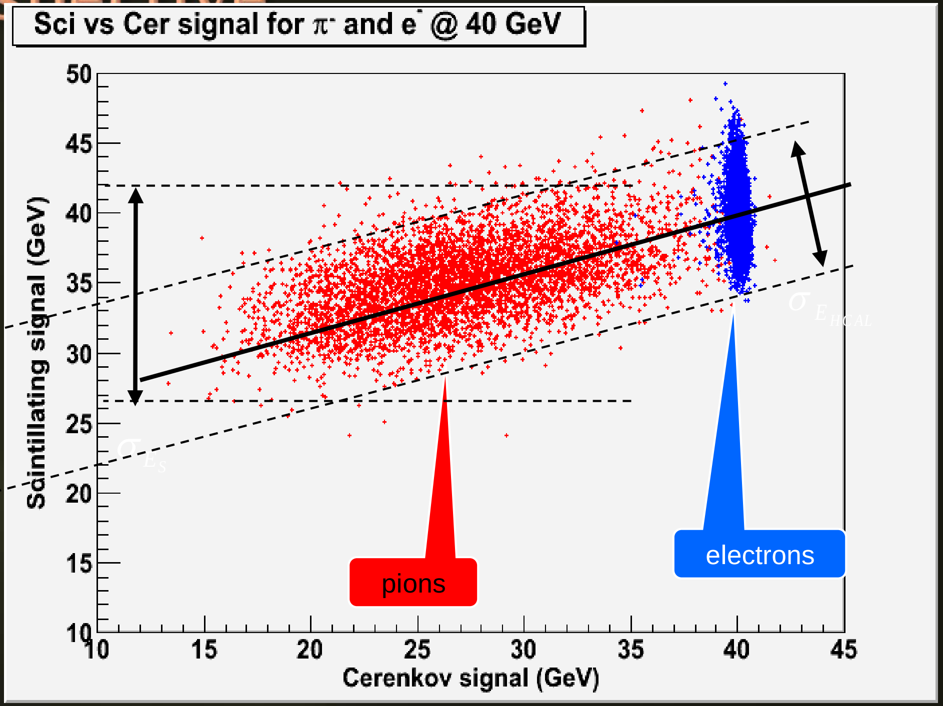
The ADRIANO2 Calorimeter

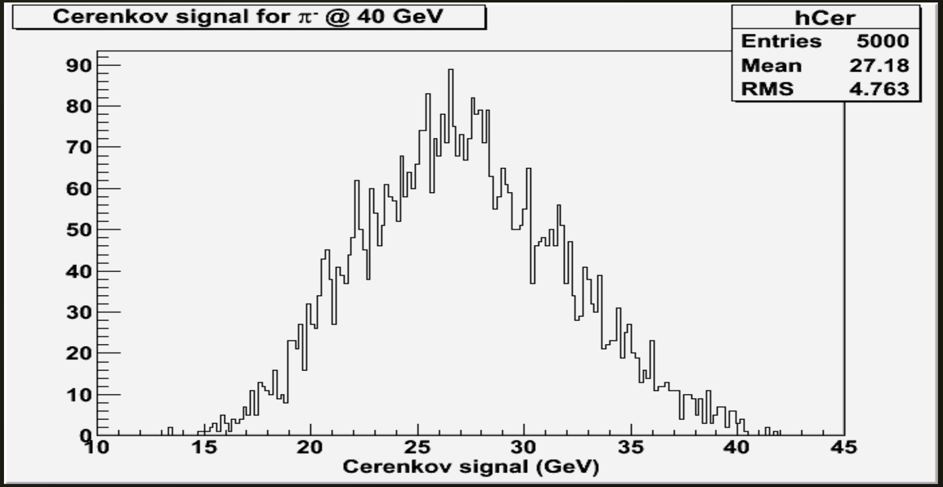
- *Sandwich of Pb-glass and scintillating plastic tiles with direct SiPM reading*
  - *Evolution of ADRIANO dual-readout calorimeter (A Dual-Readiut Integrally Active Non-segmented Option)*
- *Triple-readout obtained from waveform analysis*

- *Rationale for multiple readout calorimetry at η -factory*
  - *Particle identification (see next)*
  - *Integrally active (no sampling)*
  - *Prompt Cerenkov light fed to L) trigger*
  - *Good granularity helps disentangling overlapping showers*

Dual Readout Calorimetry from a Different Perspective

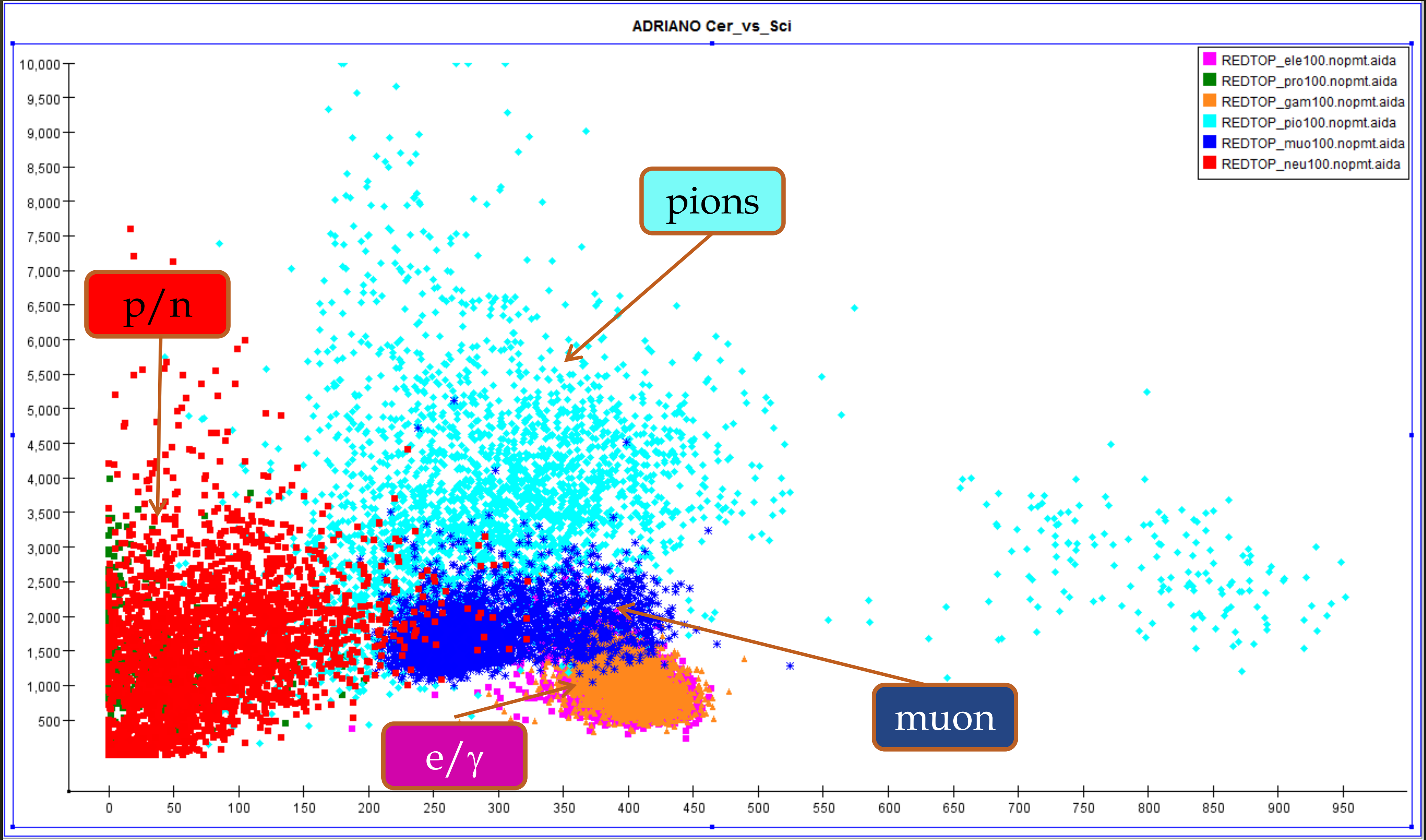






Triple-readout adds the measurement of the neutron component improving the energy resolution even further

ADRIANO PID @ 100MeV



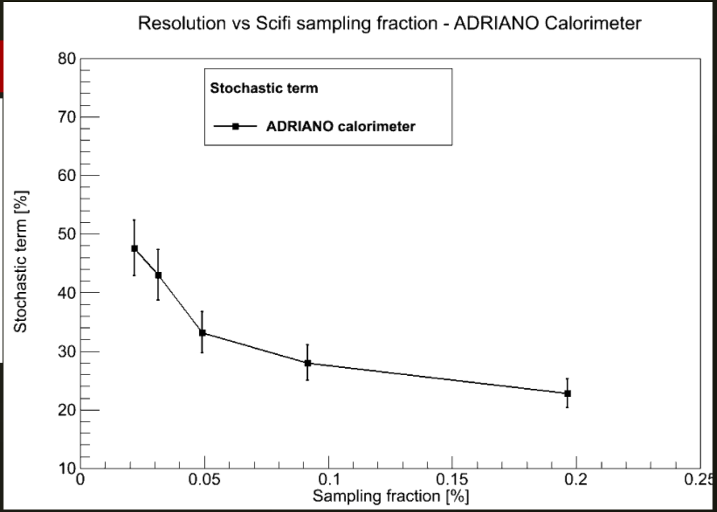
ADRIANO Light Yield and Resolution

Integrally Active with Double side readout (*ADRIANO*)								**Sampling**
Pitch [mm^2] Diameter	2x2 1mm	3x3 1mm	4x4 1mm	5x5 1mm	6x6 1mm	4x4 1.4mm	4x4 2mm	4x4 capillry	Sampling
<pe$_S$/GeV>	1053	430	254	163	124	500	110	250	200
<pe$_C$/GeV>	340	360	360	355	355	355	350	350	7.5

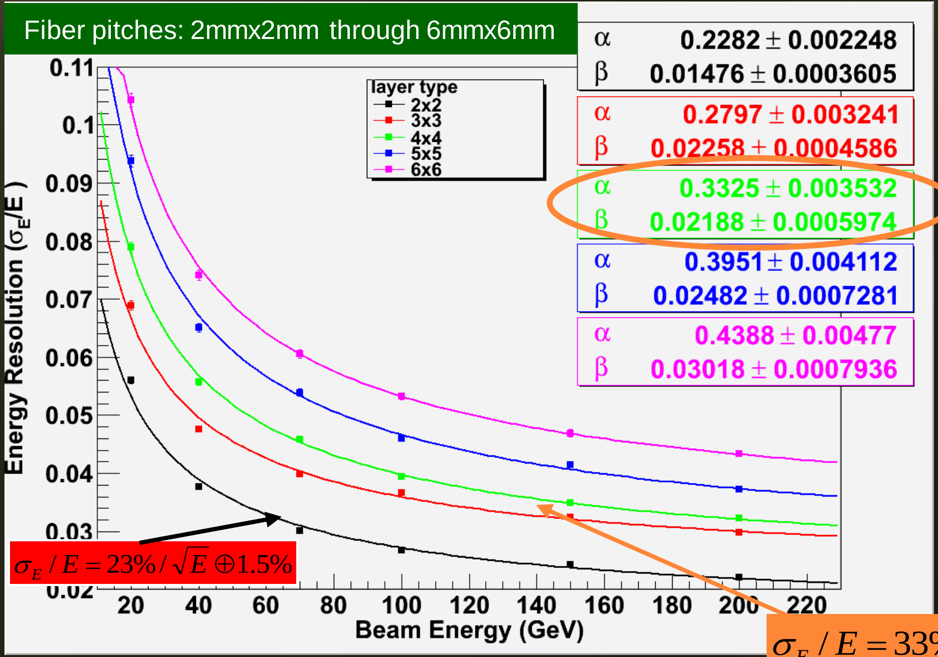
Baseline configuration

ILCroot simulations

1-side readout

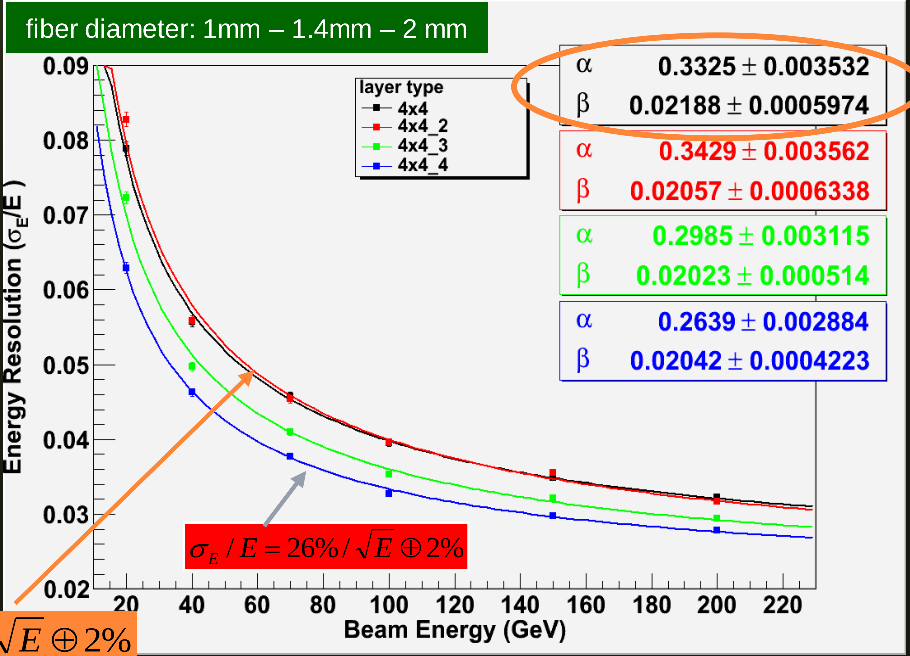


Fiber pitches: 2mmx2mm through 6mmx6mm



$\sigma_E / E = 23\% / \sqrt{E} \oplus 1.5\%$

fiber diameter: 1mm – 1.4mm – 2 mm



$\sigma_E / E = 26\% / \sqrt{E} \oplus 2\%$

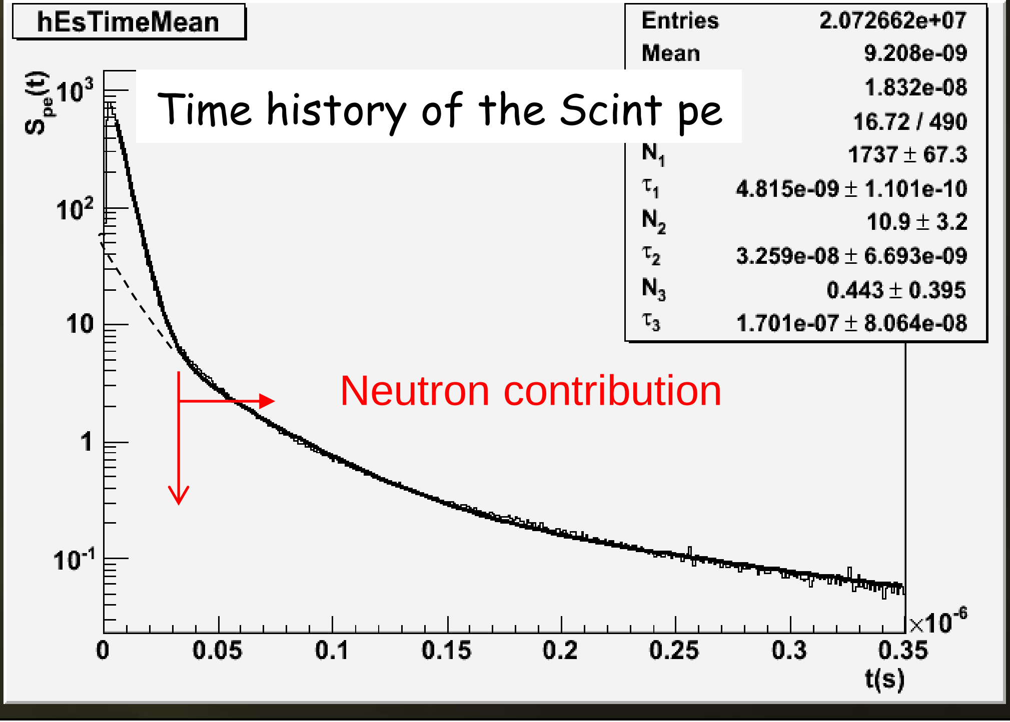
$\sigma_E / E = 33\% / \sqrt{E} \oplus 2\%$

All numbers include the effect of photodetector QE

From Dual to Triple Readout

Disentangling neutron component from waveform

40 Gev pions



ILCroot simulations

Time history of the scintillation signal in *ADRIANO* for π^-@40 GeV.

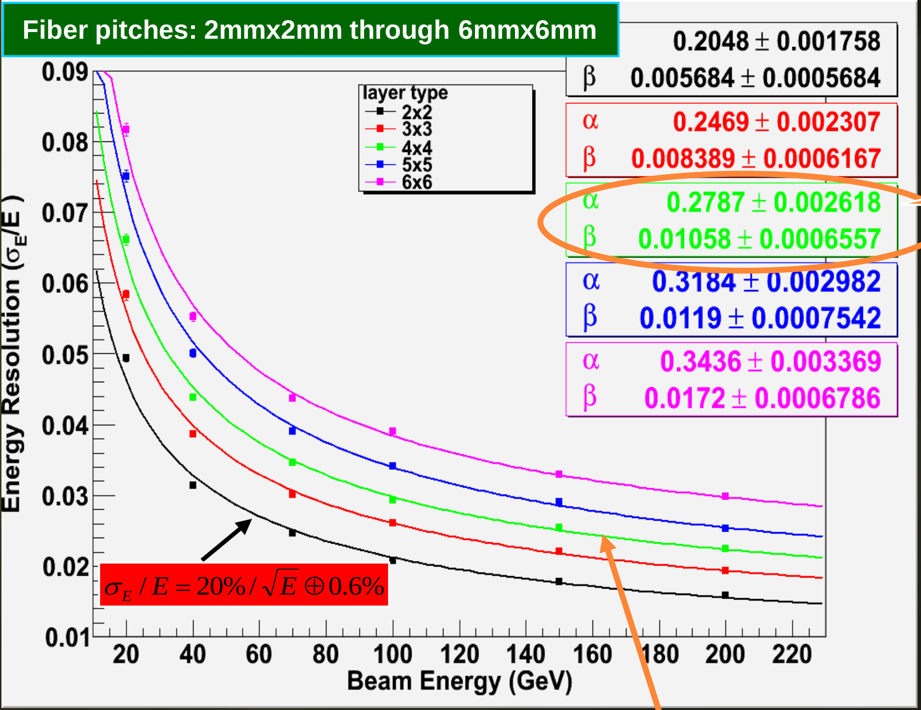
The contribution after 35 ns is from neutrons only. The distribution has been fitted with a triple exponential function .

$$E_{HCAL} = \frac{\eta_S \cdot E_S \cdot (\eta_C - 1) - \eta_C \cdot E_C \cdot (\eta_S - 1)}{\eta_C - \eta_S} + \eta_n \cdot E_{neutrons}$$

Triple Readout aka Dual Readout with time history readout

ADRIANO in Triple Readout configuration

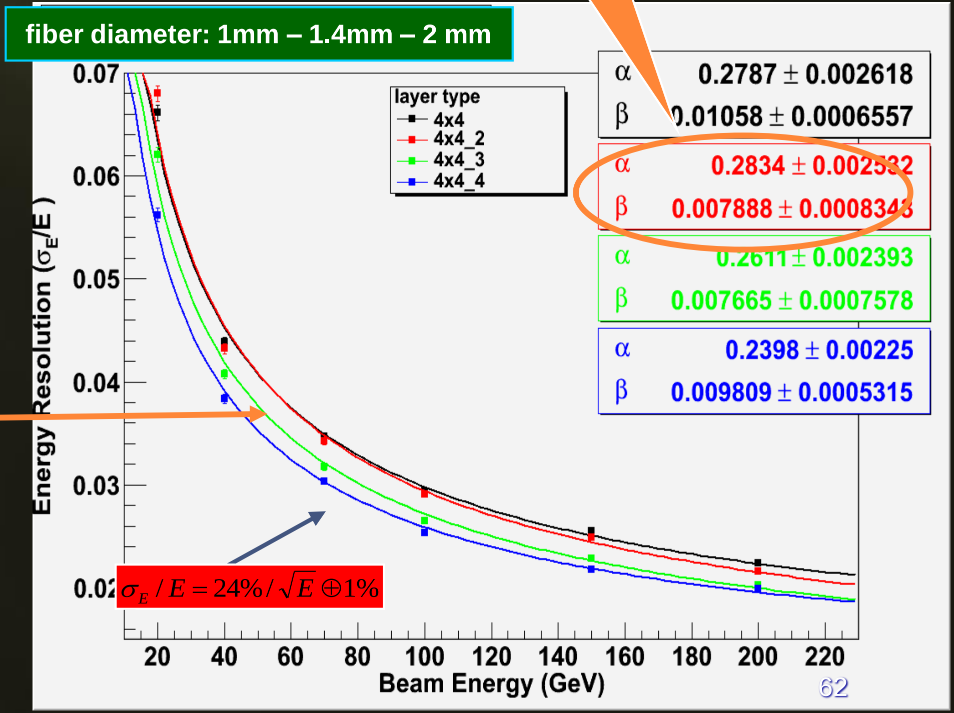
Fiber pitches: 2mmx2mm through 6mmx6mm



Baseline configuration

Pion beams

fiber diameter: 1mm – 1.4mm – 2 mm



ILCroot simulations

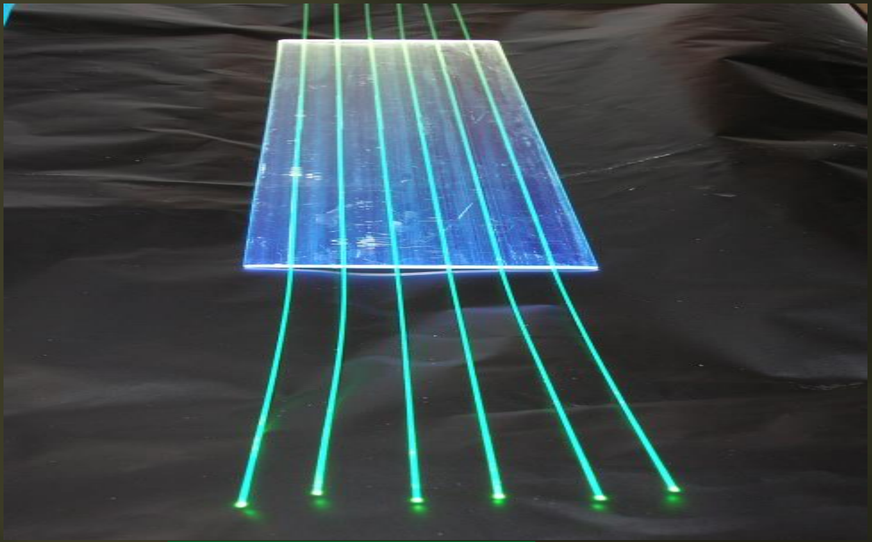
$$\sigma_E / E = 28\% / \sqrt{E} \oplus 1\%$$

ompare to ADRIANO in Double Readout configuration

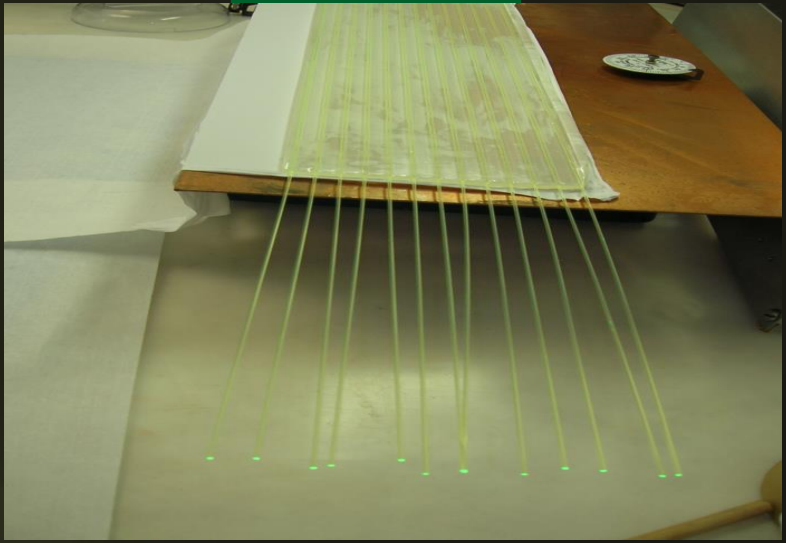
$$\sigma_E / E = 33\% / \sqrt{E} \oplus 2\%$$

ADRIANO for ORKA Construction

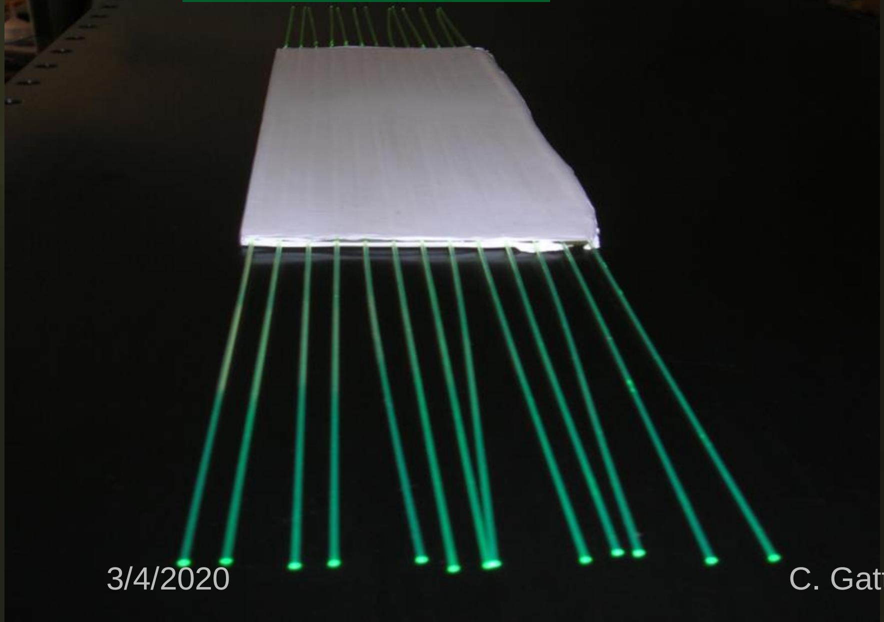
WLS + scintillator



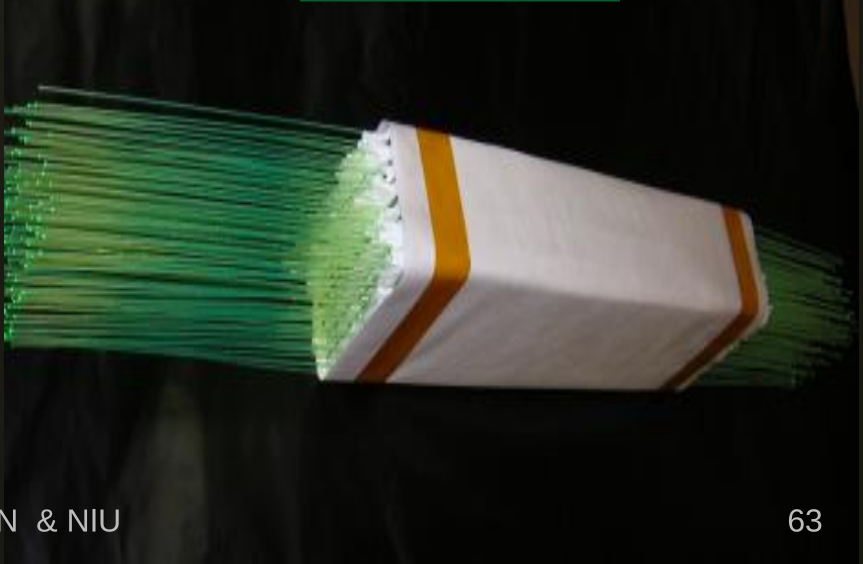
WLS + glass



Teflon wrapping

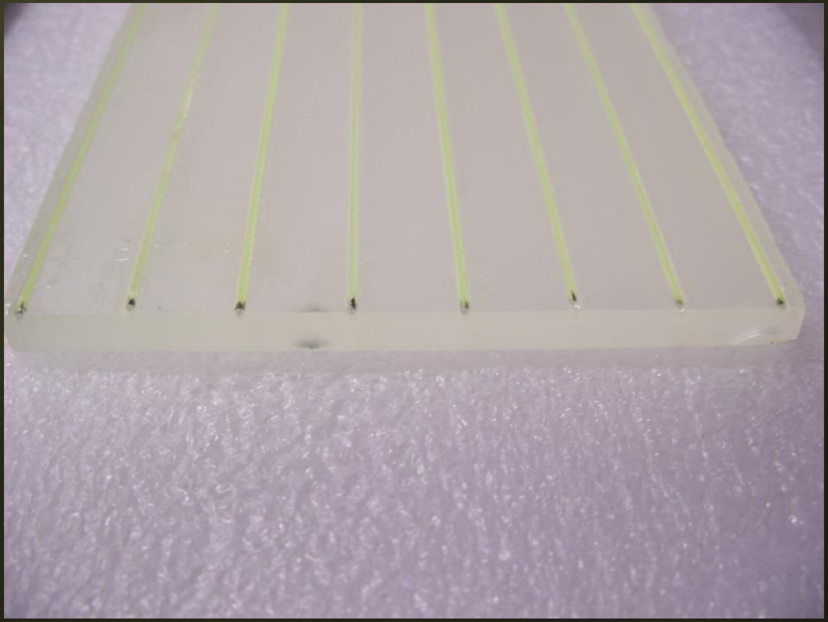


Final detector

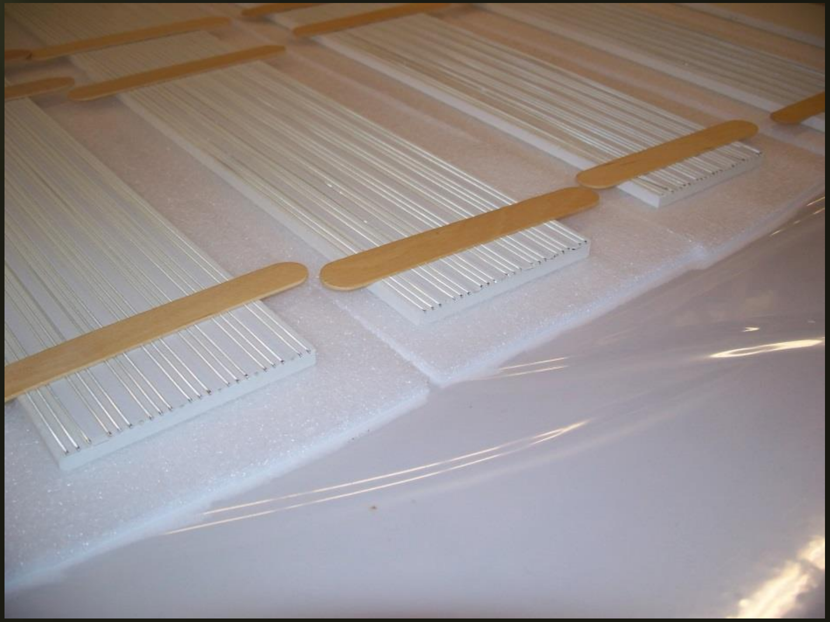


ADRIANO-2014

- Two versions built: scifi and scintillating plates
- 10 x 8 x105 cm3 long prototypes, about 50 Kg each
- 4 cells total, front and back readout
- Hopefully , we will be able to test the dual-readout concept with integrally active detectors



ADRIANO 2014A: 8 grooves



ADRIANO 2014B: 23 grooves

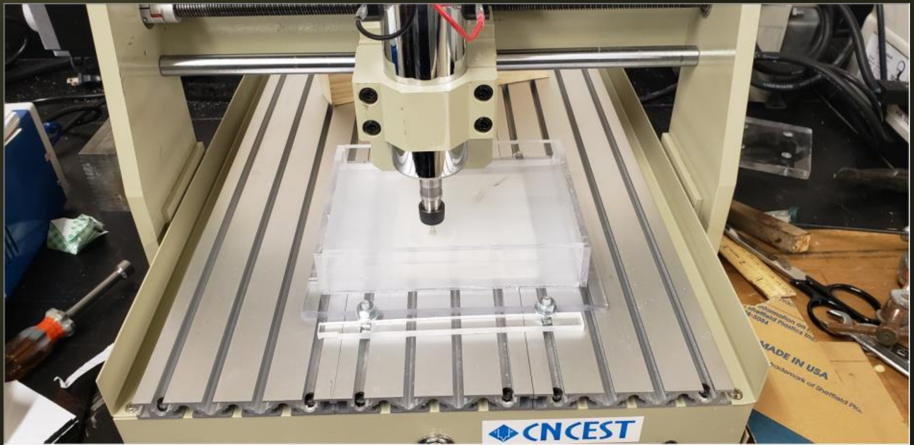
ADRIANO for High Energy

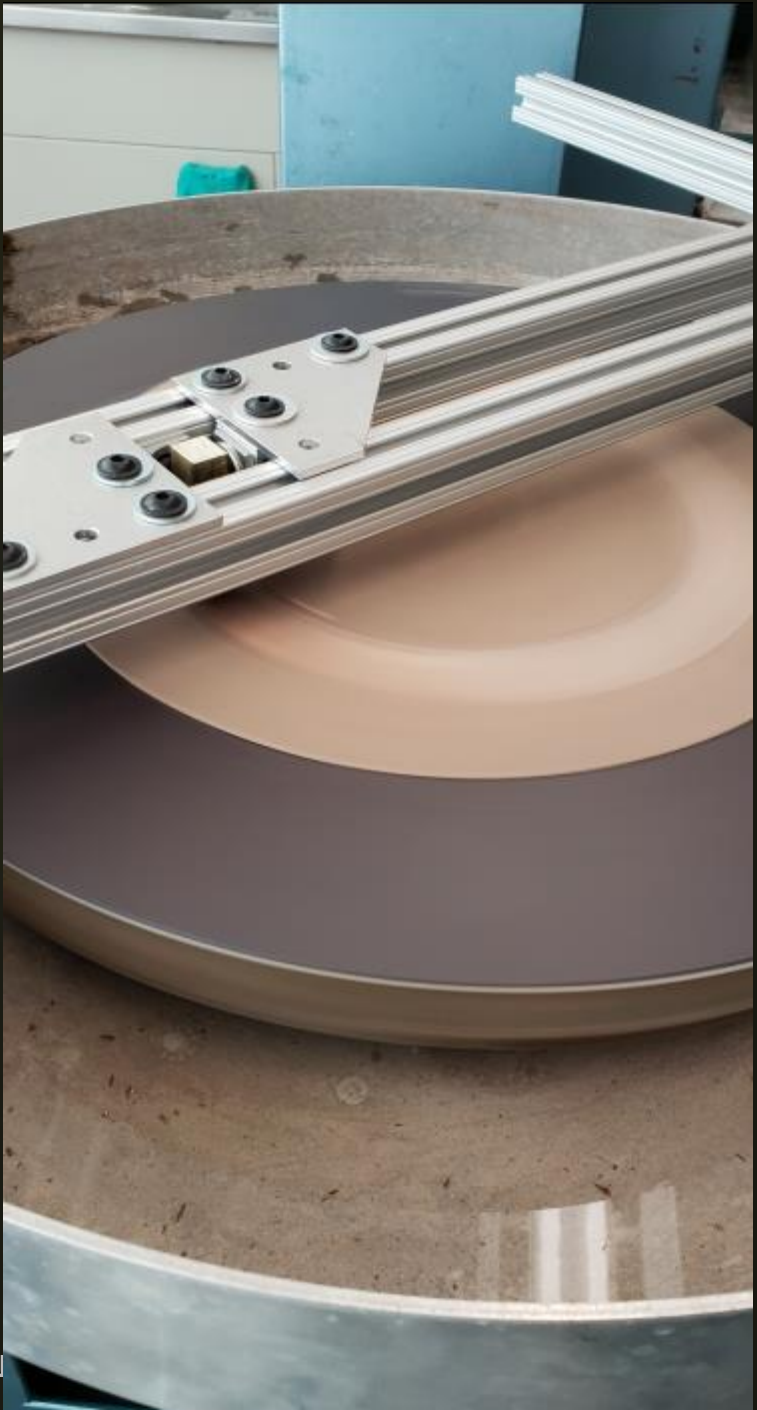
Nov. 2015 test Beam at Fermilab

ADRIANO2 R&D

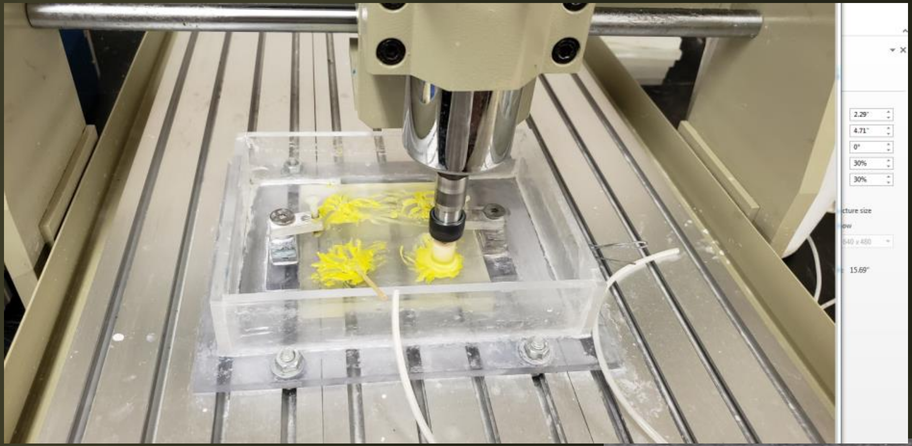
- Evolution of ADRIANO: log layout->tiles
- Sandwich of 3mm scintillating plastics and 10 mm Pb-glass (10cm x 10cm transverse size)
- WLS light capture -> SiPM directly coupled to glass and plastic
- Prompt Cerenkov signal used in L0 trigger
- Granularity can be made extremely fine
- 16 layers – prototype (64 ch) under construction at NIU
- Will be tested in Fall 2019 at FTBF
- At present, Fermilab-INFN-NIU-UMN Collaboration

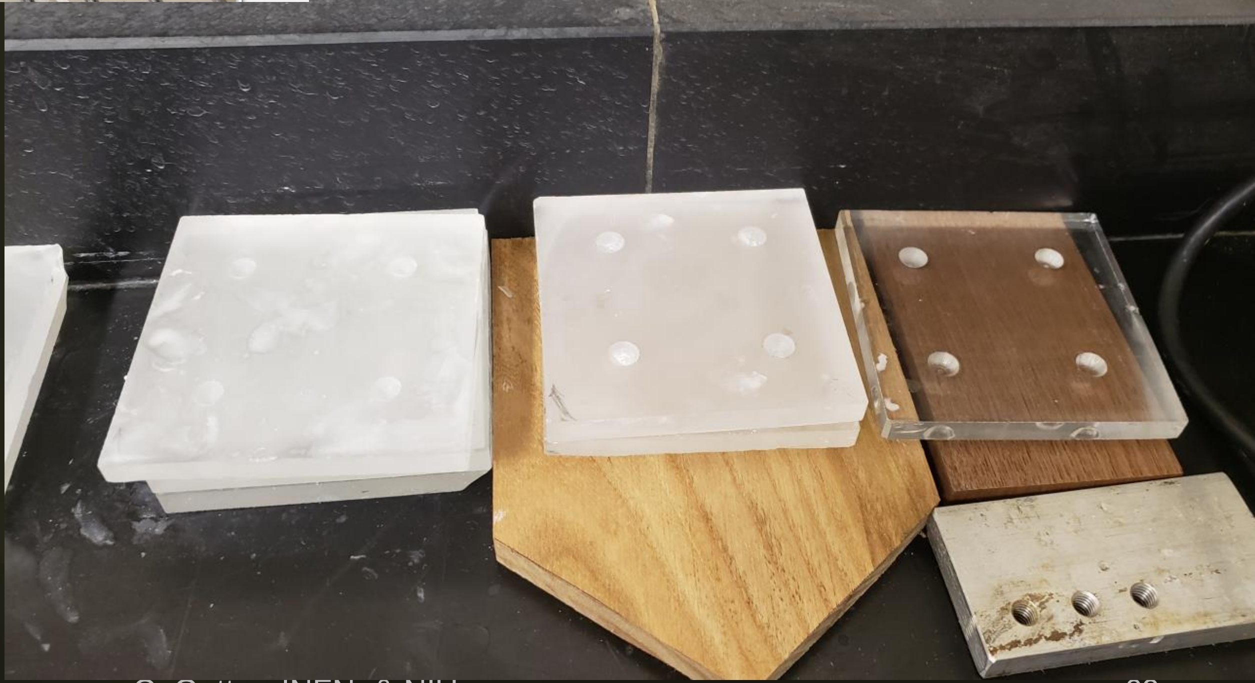
Glass preparation



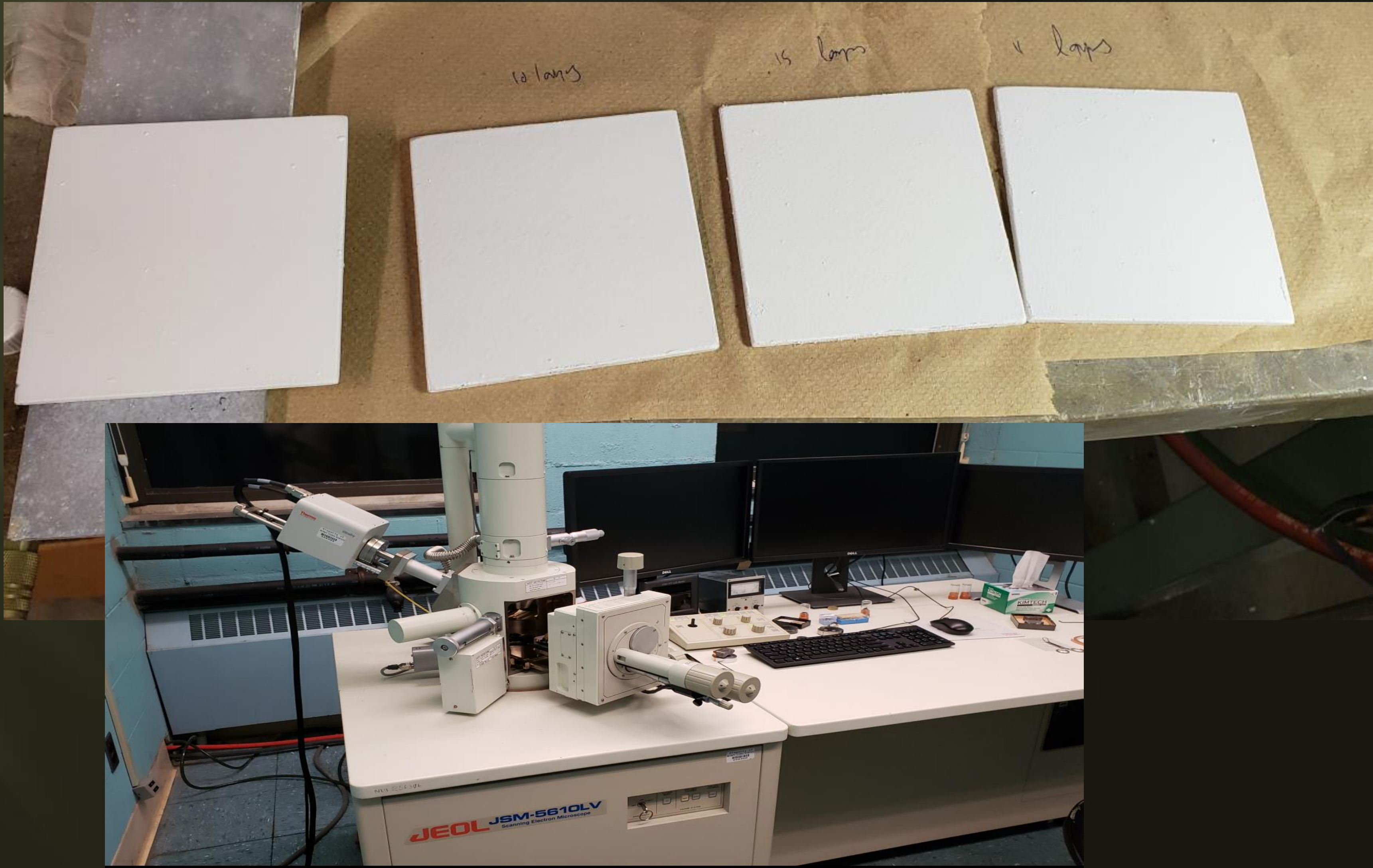


Polishing





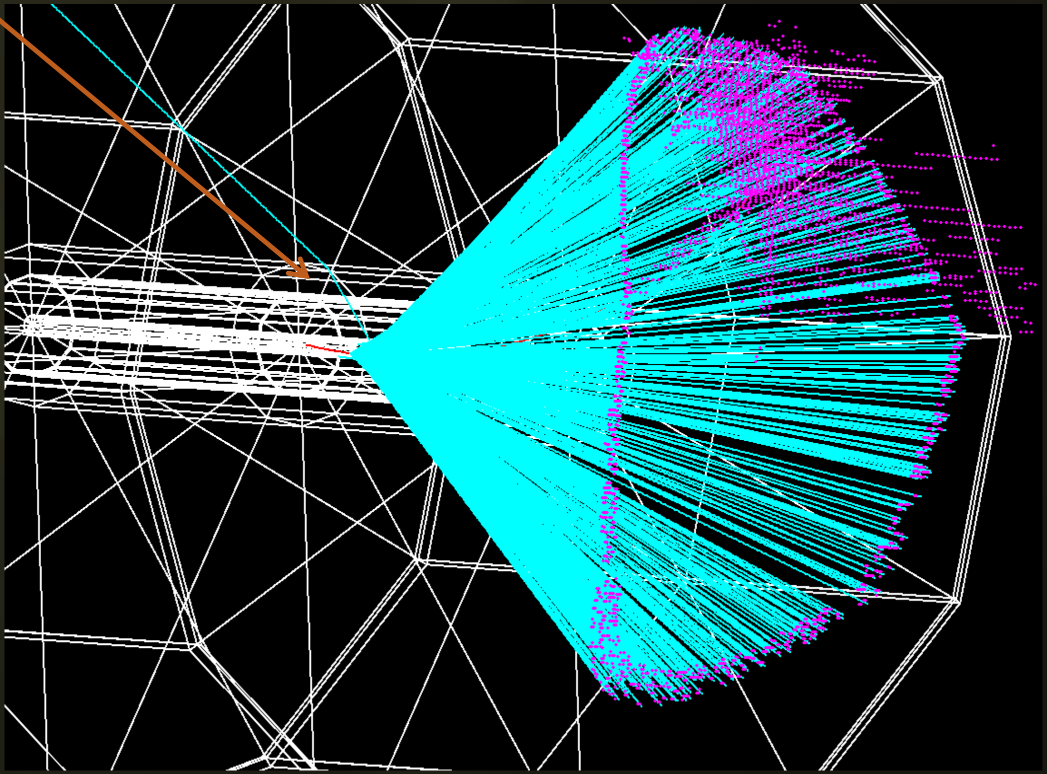
Coating and testing



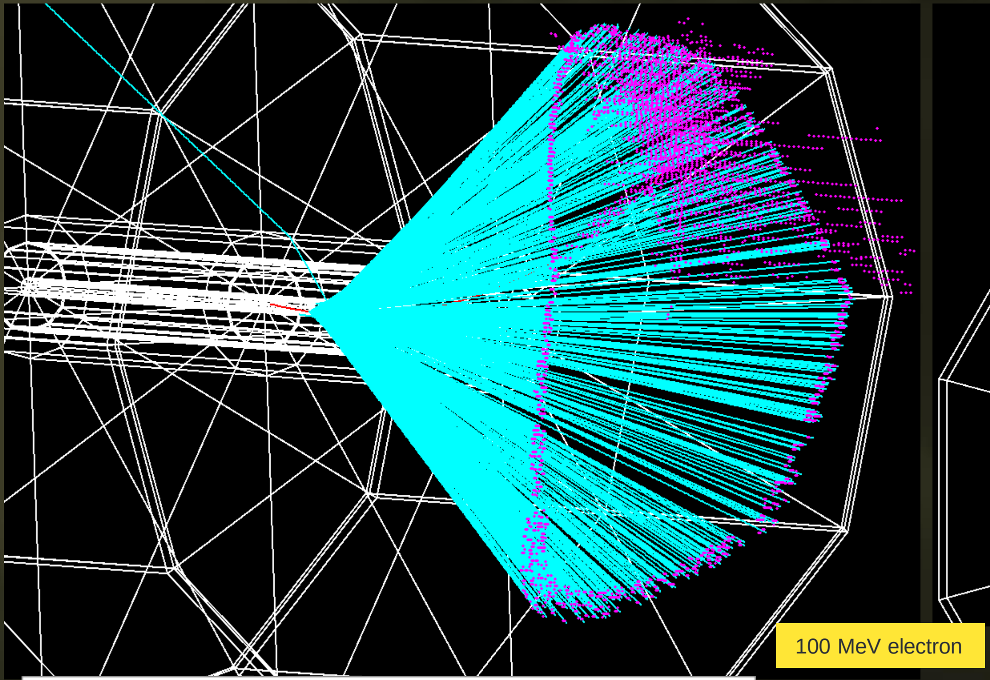
The Optical TPC Concept

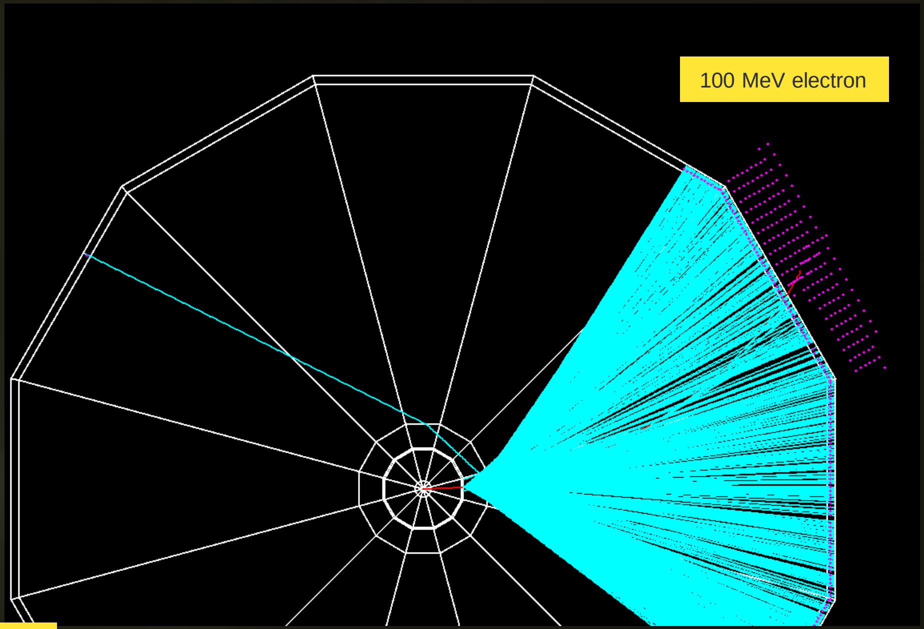
Rationale for an Optical- TPC

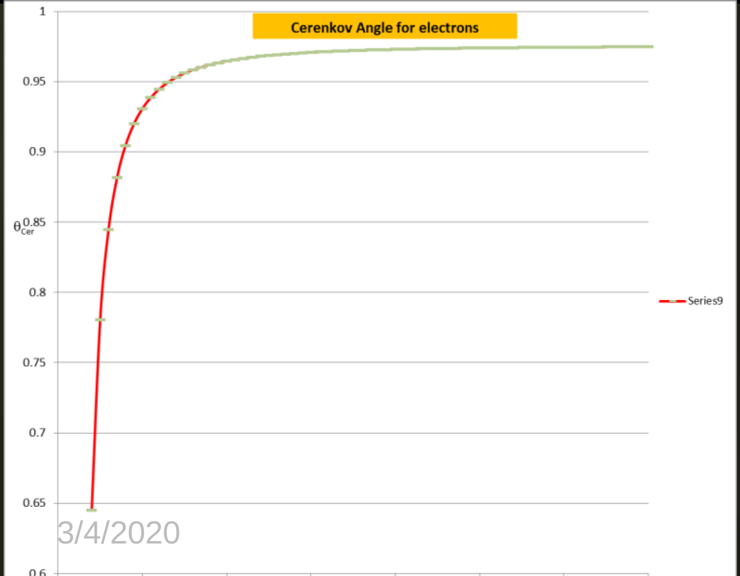
- *At 1 GHz inelastic interaction rate, a conventional, gas detector is suboptimal*
- *Hadronic particles (p, ion remnants, slow pions, etc.) will clutter the tracker*
- *Use the Cerenkov effect to detect the fast (leptons and fast pions) tracks*
- *Prompt signal is also fed to the L0 trigger for fast selection of event with leptons*



Electron Detection







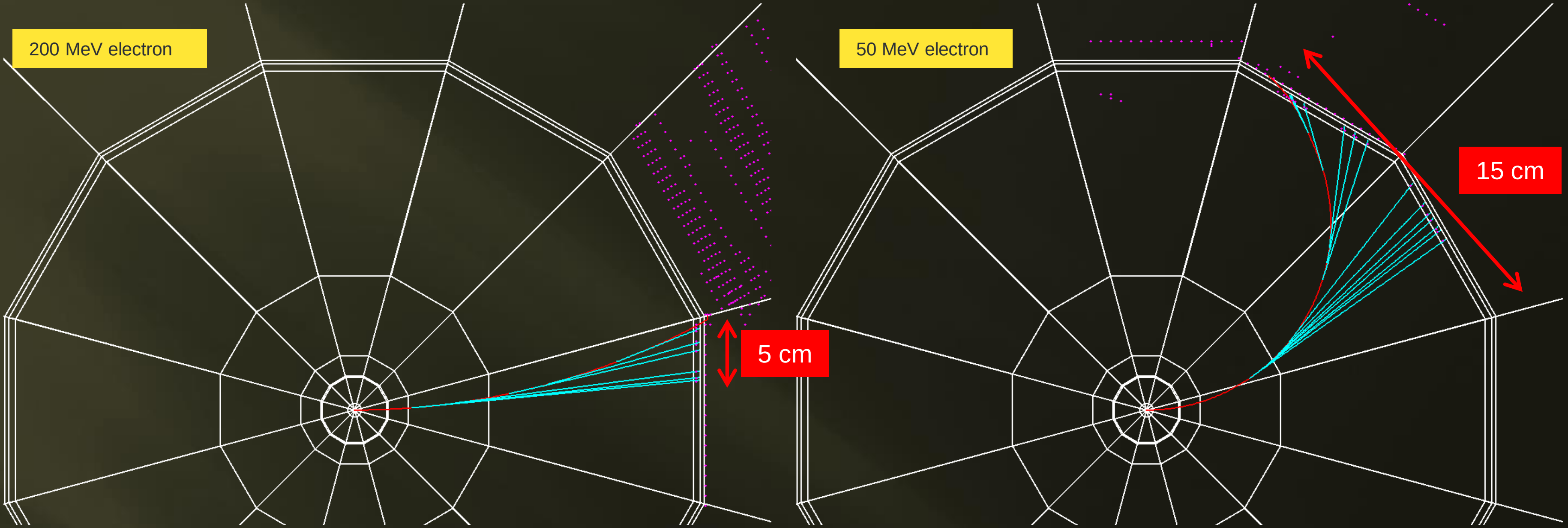
$n_D(N_2@2.7psi)=1.000145$

Č threshold for e- in N_2: P=40 mev

n_D(aerogel1)=1.12

n_D(aerogel2)=1.22

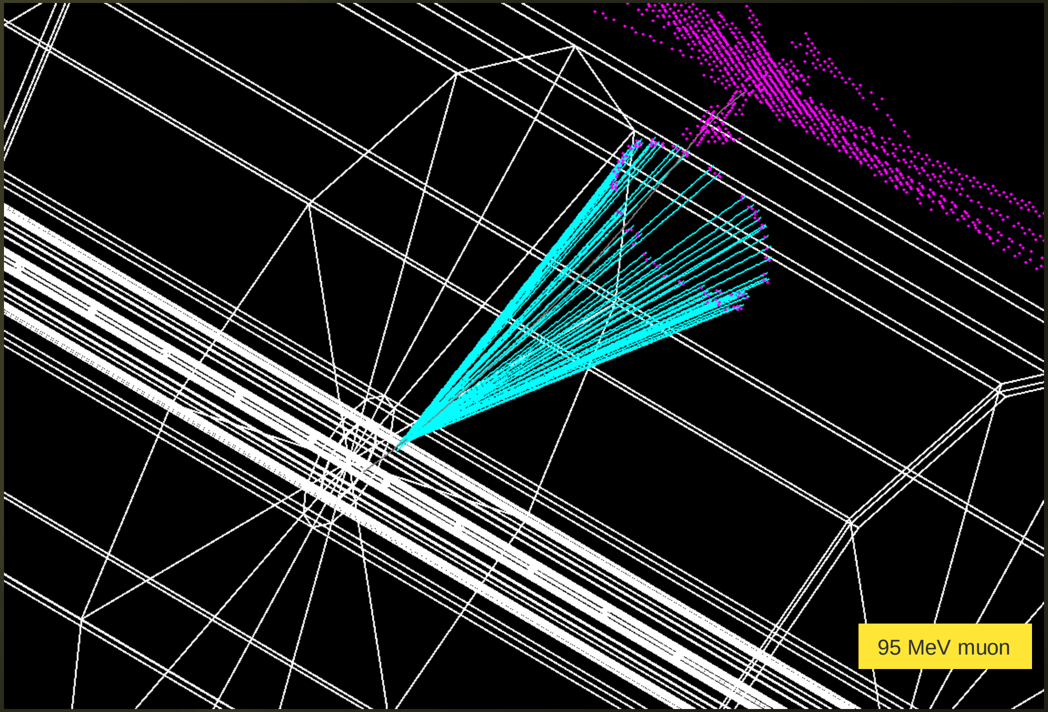
Electron Momentum Reconstruction

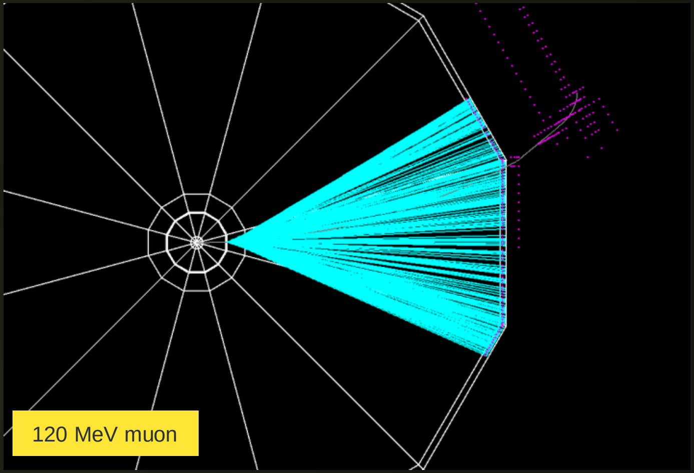


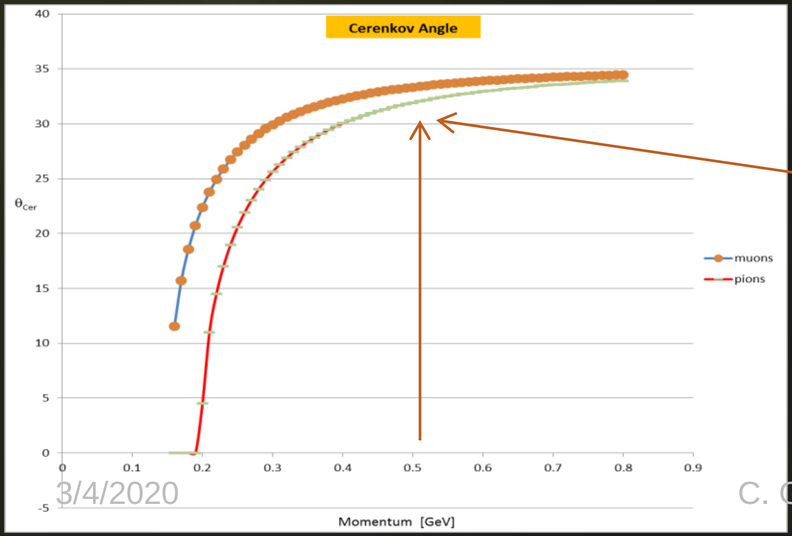
- Electrons are recognized by:
  1. a large (>30 cm dia) circle of photons generated in the aerogel
  2. A sweep of photons circles with dia < 1cm and several cm long (depends on P_t)
  3. An EM shower in ADRIANO (identified by Č vs S)

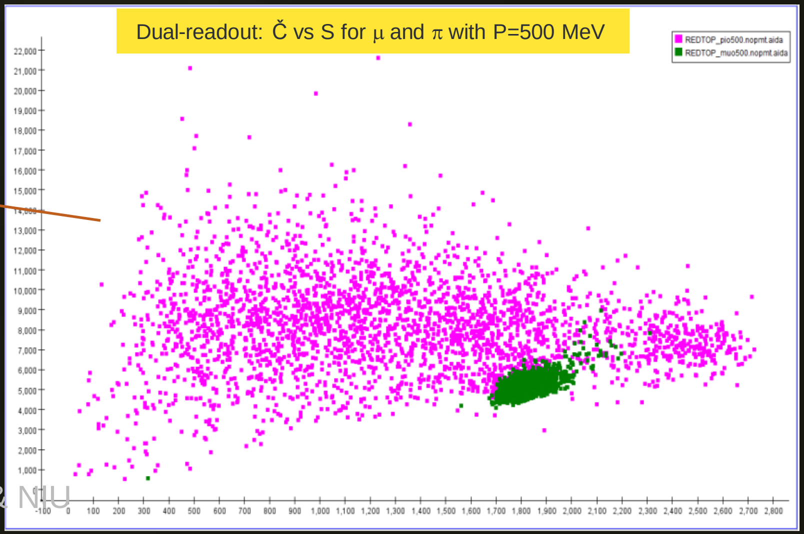
Muon/pion Detection

- n_D(aerogel)=1.22/1.12
- Č threshold for muons: P=160 mev
- Č threshold for pions: P=200 mev

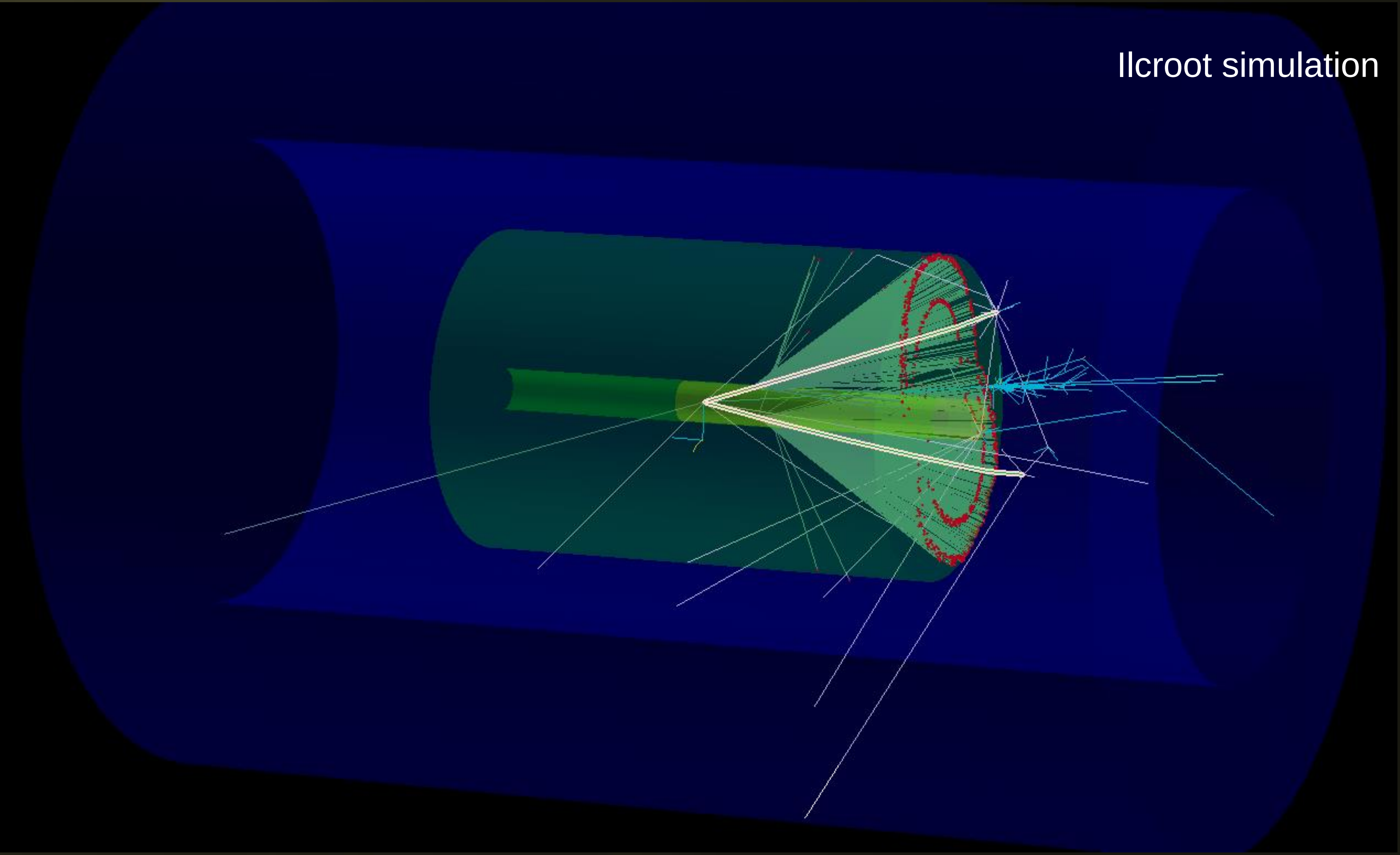






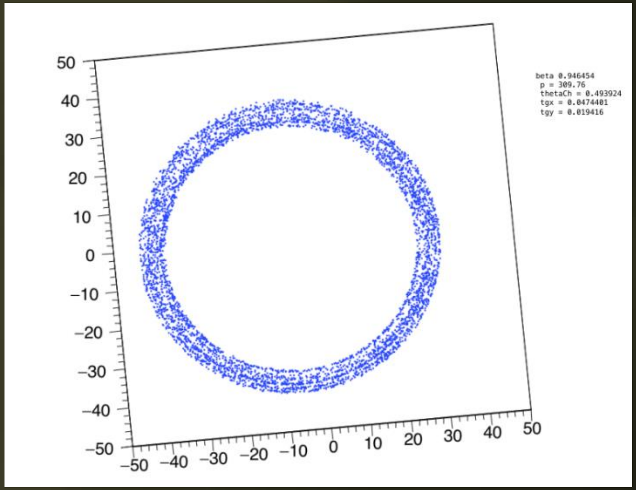


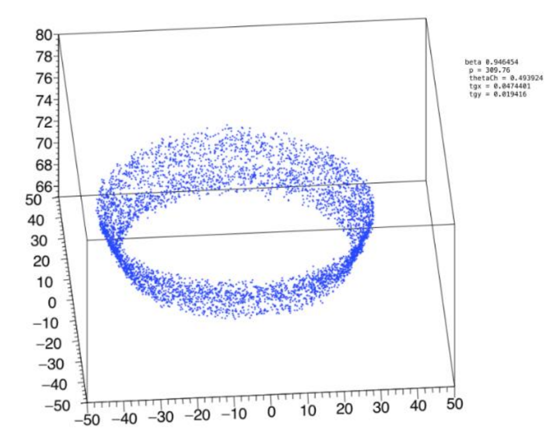
$\eta -> \pi^{+}\pi^{-}\pi^{o}$



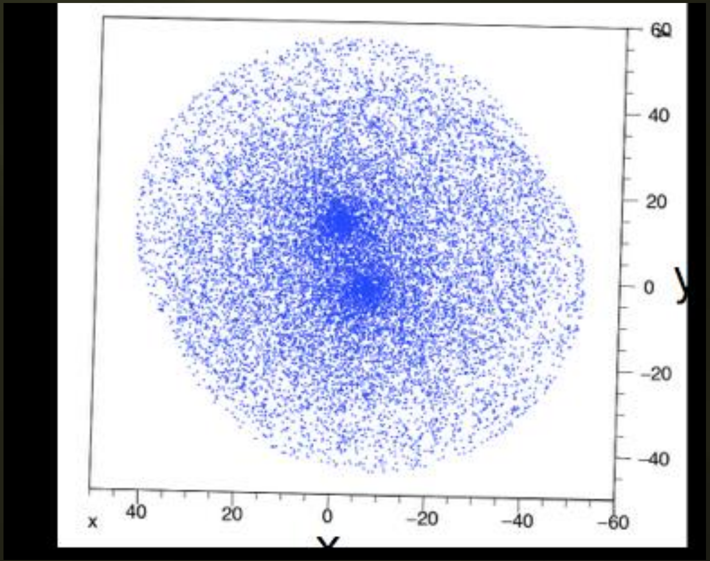
Improvement with timing (~10 nsec)

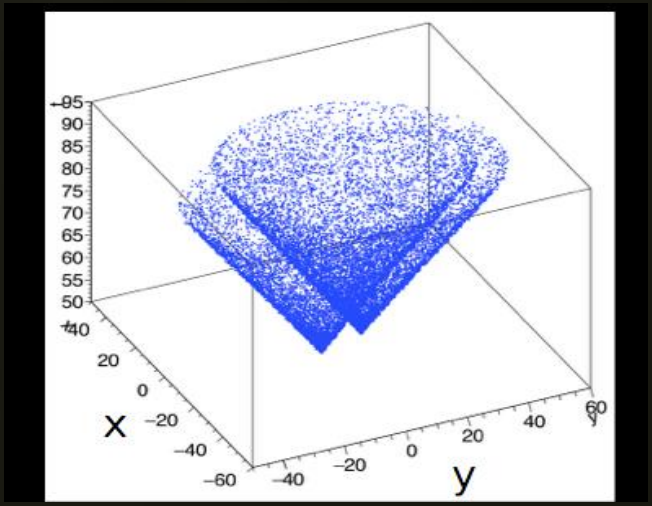
- *Uncertainty on the photon origin*





- *Two-track separation*

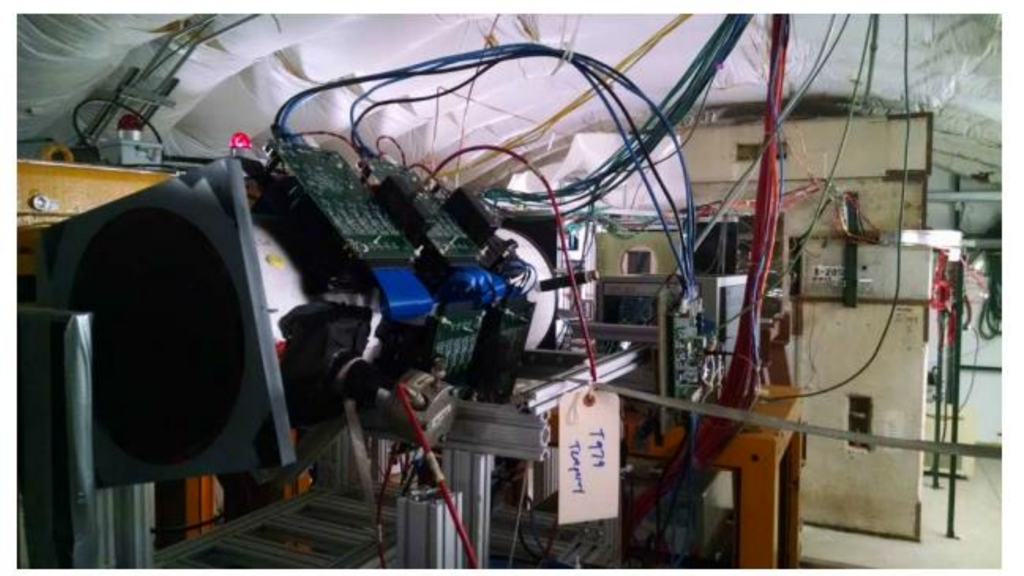


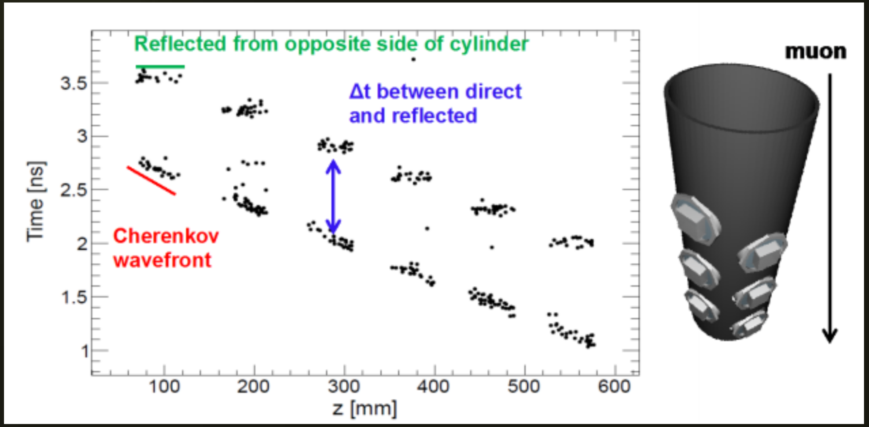


Detector R&D: OTPC

Fnal –T1059 (H. Frisch, E. Oberla)

- *Successful proof of principle in 2015 at FTBF*
- *Instrumented with an MCP photo-detector, three boards each with thirty channels of 10 GSPS waveform digitizing readout*
- *http://ppd.fnal.gov/ftbf/TSW/PDF/T1059_tsw.pdf*



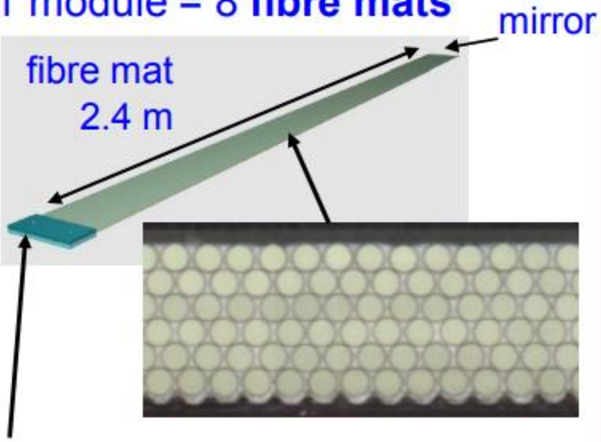


It requires a robust and dedicated R&D (LDRD)

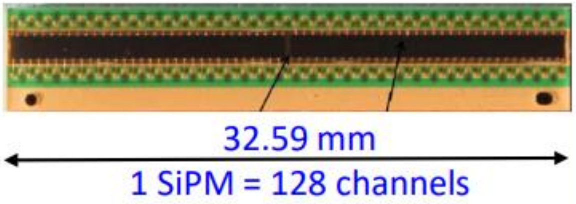
The Fiber Tracker – LHCb design

128 modules (0.5 x 5 m^2)
arranged in 3 stations × 4 layers
(XUVX)

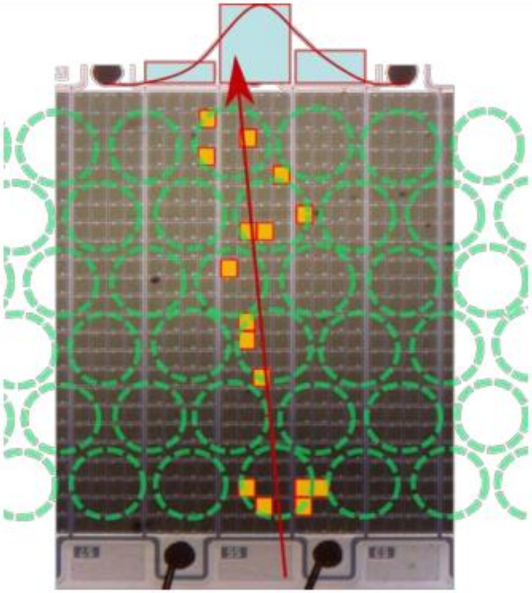
1 module = 8 **fibre mats**



4 silicon photomultipliers (SiPM)



128 modules (0.5 x 5 m^2)
arranged in 3 stations × 4 layers
(XUVX)



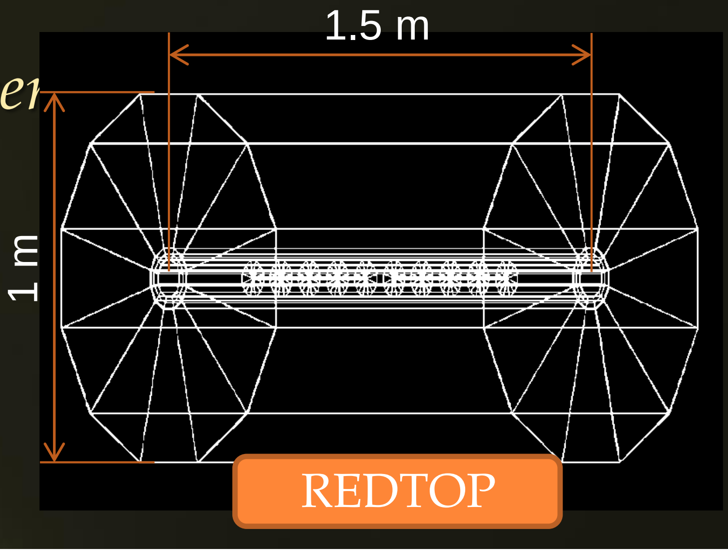
Light yield for 6-layer mat:
16–20 photo-electrons
(for particles near mat mirror)

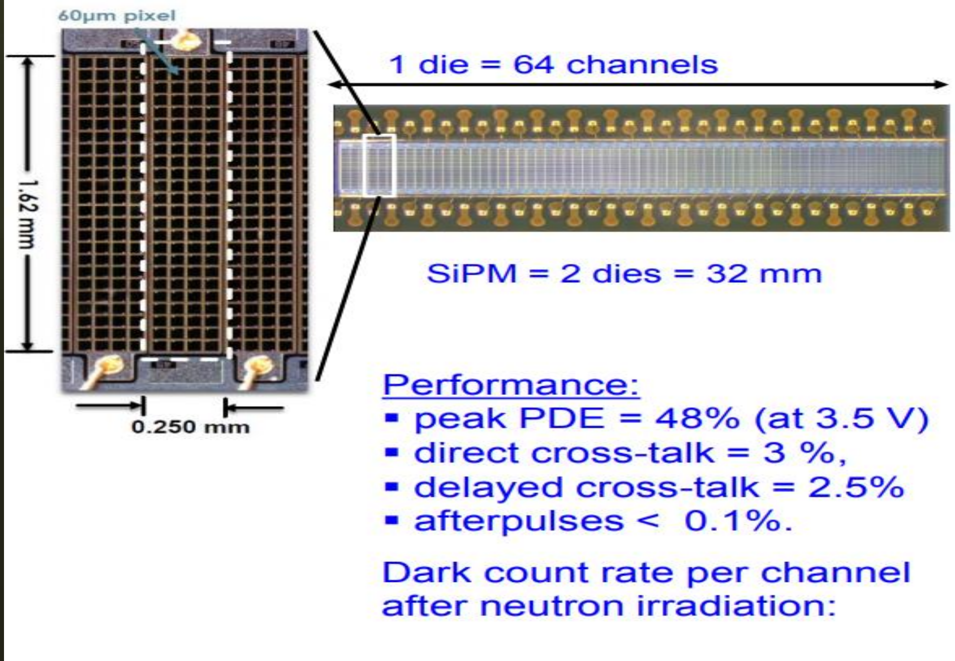
Ulrich Uwer

Layout for LHCb vs REDTOP

Input parameter

- ~ 360 m^2 vs 0.24m^2
- 1152 mats vs 36 mats
- 524,000 vs 18,000 channels





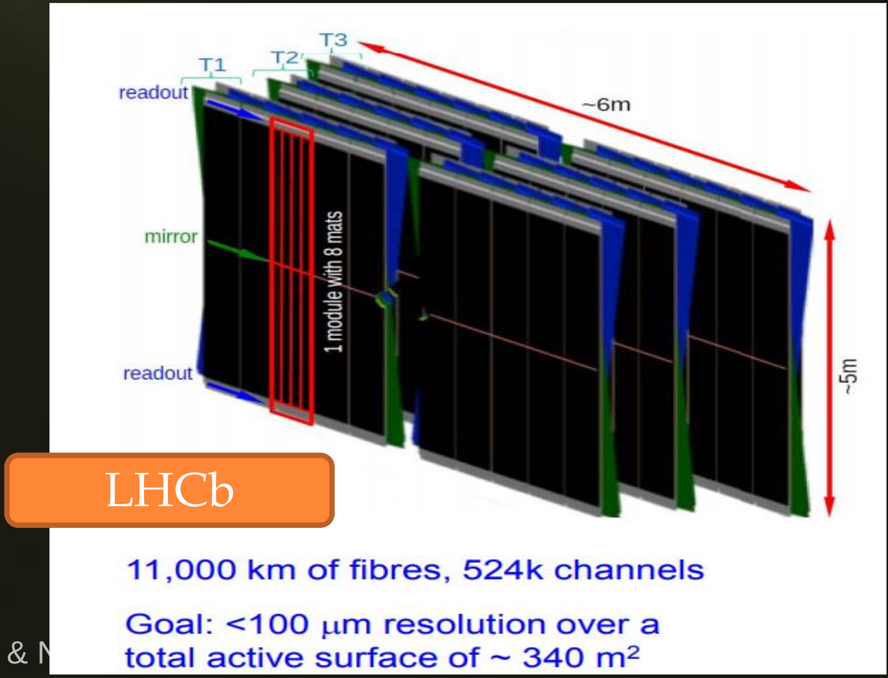
1 die = 64 channels

SiPM = 2 dies = 32 mm

Performance:

- peak PDE = 48% (at 3.5 V)
- direct cross-talk = 3 %,
- delayed cross-talk = 2.5%
- afterpulses < 0.1%.

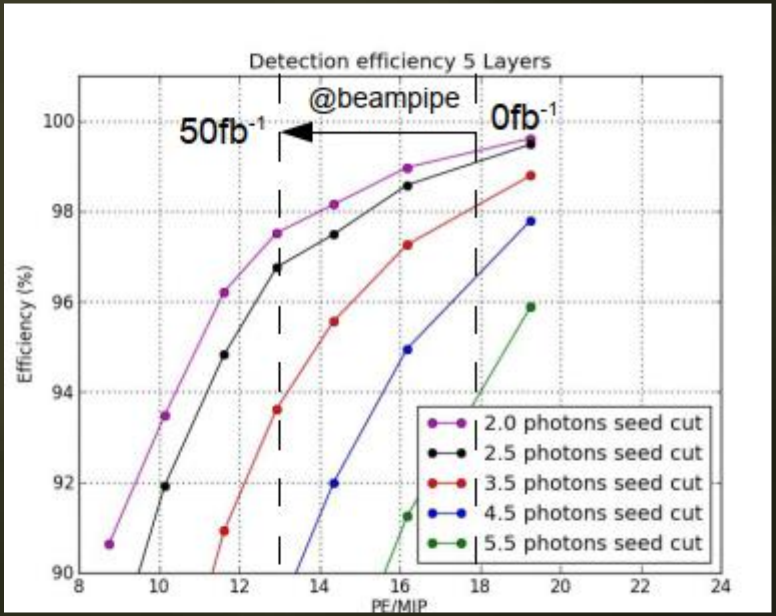
Dark count rate per channel after neutron irradiation:

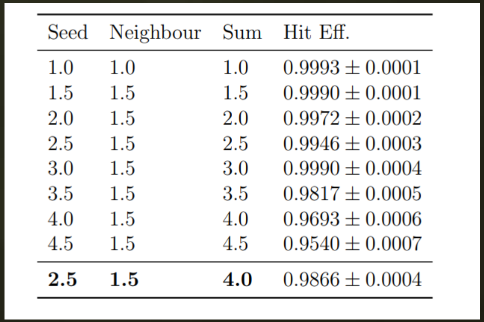


11,000 km of fibres, 524k channels

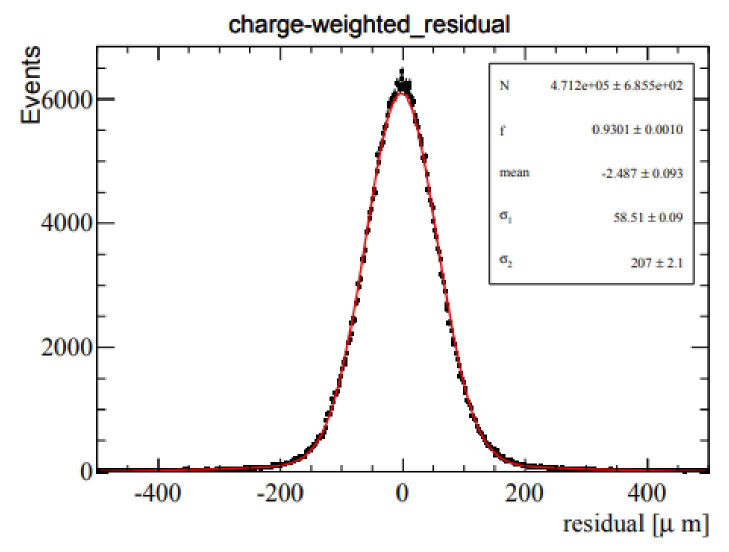
Goal: <100 µm resolution over a total active surface of ~ 340 m^2

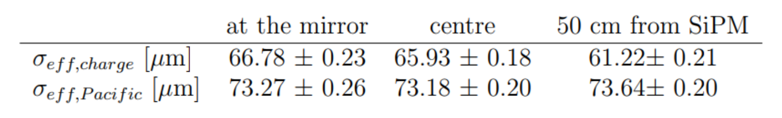
Reselts from LHCb Test Beam





Seed	Neighbour	Sum	Hit Eff.
1.0	1.0	1.0	0.9993 ± 0.0001
1.5	1.5	1.5	0.9990 ± 0.0001
2.0	1.5	2.0	0.9972 ± 0.0002
2.5	1.5	2.5	0.9946 ± 0.0003
3.0	1.5	3.0	0.9990 ± 0.0004
3.5	1.5	3.5	0.9817 ± 0.0005
4.0	1.5	4.0	0.9693 ± 0.0006
4.5	1.5	4.5	0.9540 ± 0.0007
2.5	**1.5**	**4.0**	0.9866 ± 0.0004

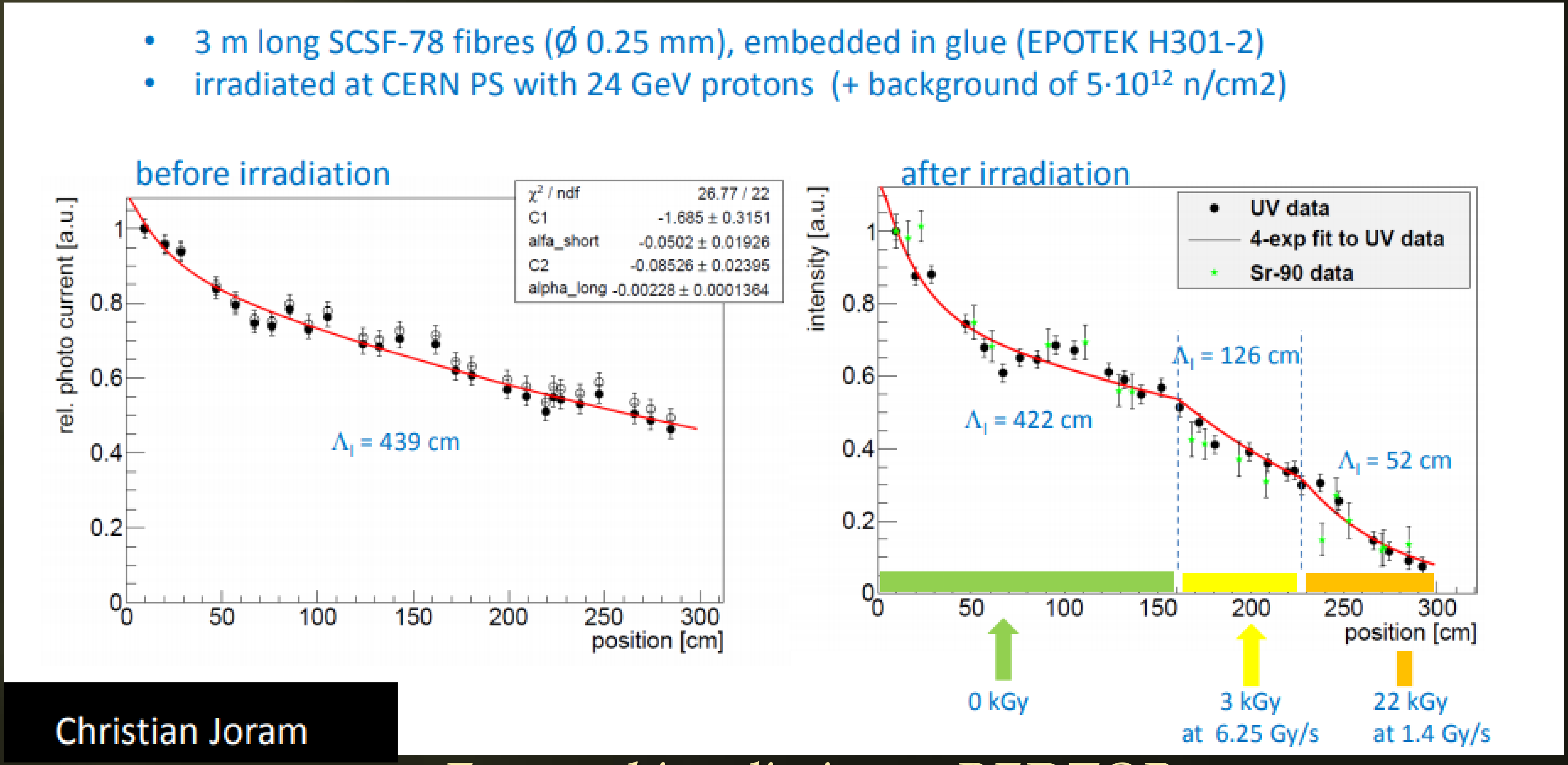




	at the mirror	centre	50 cm from SiPM
$\sigma_{eff,charge}$ [μm]	66.78 ± 0.23	65.93 ± 0.18	61.22± 0.21
$\sigma_{eff,Pacific}$ [μm]	73.27 ± 0.26	73.18 ± 0.20	73.64± 0.20

Christian Joram

Fiber Tracker Radiation Hardness



- 3 m long SCSF-78 fibres (Ø 0.25 mm), embedded in glue (EPOTEK H301-2)
- irradiated at CERN PS with 24 GeV protons (+ background of 5·10^{12} n/cm2)

before irradiation

after irradiation

Christian Joram

Expected irradiation at REDTOP

- Worst case (forward detector): ~10^{13} n/cm^2
- Average: ~10^{12} n/cm^2

Trigger & DAQ

Input parameters

- ~5 × 10^8 p-Be inelastic collisions per second
- ~2.5× 10^6 (10^4)produced η (η') per second

Trigger requirements (L. Ristori)

Level	**Algo**	**Detectors**	**Hardware**	**Rejection factor**
L0	Σ OTPC & ADRIANO-Cer	OTPC, ADRIANO	Fast sum	100
L1	identification of a pair of leptons, γ-conversion rejection	OTPC, ADRIANO, Fiber Tracker	FPGA	100
L2	Reco	All	2000 CPU-cores	>100

Expected data rates

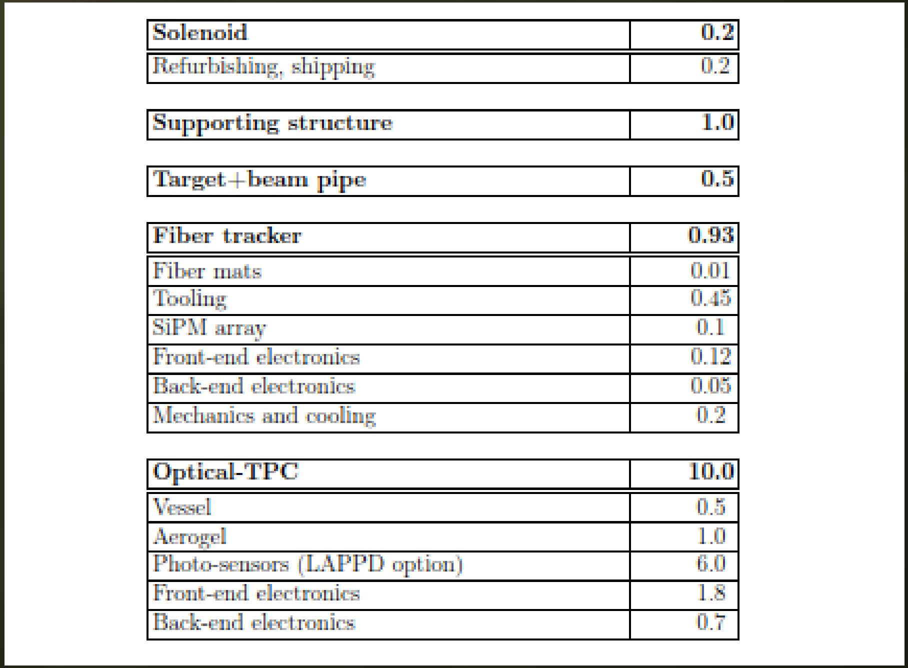
- About 100 Hz to be stored on tape
- ~1 MB/sec from L2
- ~5 PB/year to tape (assume 5 kb event size)

Recent History of the Project

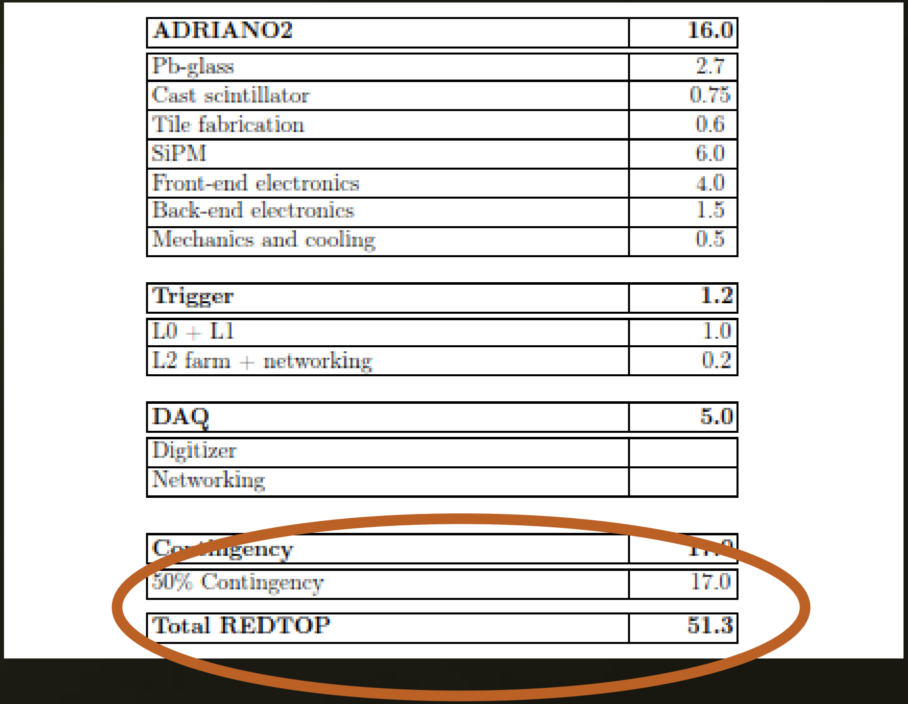
- *Sept. 2017*
  - *LOI submitted to Fermilab's PAC in Sept. 2017*
  - *PAC recommendation: "The PAC finds that the science goals of the experiment are very interesting….., the PAC does not recommend that the Laboratory invest resources into furthering the REDTOP proposal at this time."*
  - *Fermilab's Director recommended a two-year waiting period (still ongoing).*
- *Jan. 2018*
  - *REDTOP admitted into the "Physics Beyond Colliders" program to explore a possible implementation at CERN*
  - *Near full simulations studies indicate very good sensitivity studies to physics BSM for 3 out of 4 "portals"*
  - *Final report from PBC indicate that the experiment is feasible at CERN, but with lower (1/10x) beam luminosity and larger impact on existing physics program cfr. FNAL*
- *Dec. 2018*
  - *EOI submitted to European Strategy for Particle Physics*

Cost (estimate for ESPP)

- ## *In kind contribution from INFN*
  - *Solenoid (from Finuda experiment at Frascati)*
  - *¾ of Pb-glass (from NA62)*



Solenoid	**0.2**
Refurbishing, shipping	0.2
Supporting structure	**1.0**
Target+beam pipe	**0.5**
Fiber tracker	**0.93**
Fiber mats	0.01
Tooling	0.45
SiPM array	0.1
Front-end electronics	0.12
Back-end electronics	0.05
Mechanics and cooling	0.2
Optical-TPC	**10.0**
Vessel	0.5
Aerogel	1.0
Photo-sensors (LAPPD option)	6.0
Front-end electronics	1.8
Back-end electronics	0.7



ADRIANO2	**16.0**
Pb-glass	2.7
Cast scintillator	0.75
Tile fabrication	0.6
SiPM	6.0
Front-end electronics	4.0
Back-end electronics	1.5
Mechanics and cooling	0.5
Trigger	**1.2**
L0 + L1	1.0
L2 farm + networking	0.2
DAQ	**5.0**
Digitizer	
Networking	
Contingency	**17.0**
50% Contingency	17.0
Total REDTOP	**51.3**

- ## *For Fermilab*
  - *Add labor and accelerator (R.F.cavities and EM septum are available at Fermilab)*
  - *Adjust contingency from 50% to 25%*

History of the Project

- *Dec. 2014*
  - *Born at FTBF (A. M., C. G. , H. F.)*
- *Sept. 2017*
  - *LOI submitted to Fermilab's PAC in Sept. 2017*
  - *PAC recommendation: "The PAC finds that the science goals of the experiment are very interesting….., the PAC does not recommend that the Laboratory invest resources into furthering the REDTOP proposal at this time."*
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- *Dec. 2018*
  - *EOI submitted to European Strategy for Particle Physics*

REDTOP Possible Running Phases

- Phase I: η-factory. Goal is ~10^{13} η /yr
  - T_{beam}: 1.8-2.1 GeV
  - Power: 30 W
  - Target: 10 x 0.33 mm Be
- Phase II: η ’-factory. Goal is ~10^{11} η' /yr
  - T_{beam}: 3.5-4.5 GeV (to be optimized)
  - Power: 60 W
  - Target: 10 x 0.33 mm Be
- Phase III: Dark photons radiating form muons. Goal is > 1.0 $\times 10^{13}$ μ/yr
  - (G. Krnjaic and Y. Kahn)
  - T_{beam}: 1< <3 GeV (to be optimized)
  - Target: H_2 gas
- Phase IV: Muon Scattering Experiment. Goal is > 2.0 $\times 10^{12}$ μ/yr
  - T_{beam}: 0.2< <0.8 GeV (to be optimized)
  - Muon yield: >1.6 $\times 10^{-8}$ μ/p
  - Target: 1 x 100 mm graphite
- Phase V: tagged REDTOP. Goal is > 2.0 $\times 10^{13}$ η/yr
  - T_{beam}: 1.2 GeV at PIP-II
  - Muon muon yield: >1.6 $\times 10^{-8}$ μ/p
  - Target: ^3H
- Phase VI: Rare Kaon Decays: $K^+ \to \pi^+ \nu \underline{\nu}$ Goal is > 1×10^{14} KOT/yr
  - T_{beam}: K^+ from 8 GeV protons
  - K^+/π yield: 1 /13 (neglecting very soft pions – factor 1.8 better than p@92 GeV)
  - Target: primary (PT: for K production) + secondary (active: scintillating plastics)

It could be made unnecessary by NA62+ and JPARC

Intermediate Phases

Pre-REDTOP with OTPC only

- $p\ ^{7}Li \rightarrow\ ^{8}Be^{*} \rightarrow e^{+} e^{-} X$
  - At 2.5 MeV IOTA proton source (Fermilab)
  - Confirm 17 MeV bump found in Prague experiment
- $p\ D \rightarrow\ ^{3}He\ e^{+} e^{-}$ (M. Viviani ,L. E. Marcucci and A. Kievsky)
  - At 40 MeV Fermilab p linac (Fermilab) or ATLAS facility (ANL)
- $p\ ^{9}Be \rightarrow\ ^{8}Be^{*} + X \rightarrow e^{+} e^{-} X$
  - At MCenter 2 GeV p beam (Fermilab)
- μ^{+} Nucleus scattering in fixed target mode
  - 1.5-3 GeV muon campus – Fermilab
- μ^{+} Nucleus in beam dump mode
- e^{-} Nucleus in fixed target mode
  - 250-500 MeV, 50 mA IOTA facility – Fermilab
- e^{-} Nucleus in beam dump mode
- OTPC test with 2 GeV protons dumped by g-2 - Fermilab

Ongoing activities - simulations

- *Event generation*
  - *GenieHad (Genie add-on) event generator interfaces to: Urqmd, Gibuu, Phsd, Abla, Gemini, SMM, G4EM processes, Incl++, IAEA tables, LELAPS*
  - *New interfaces to JAM (JPARC) and ALPS (for PIP-II simulations) in preparation*
- *Simulation, digitization, reconstruction and analysis*
  - *Based on ILC frameworks (slic, lcsim and ilcroot)*
  - *Full simulation in place (except for OTPC-reco and vertexing)*
- *Detector optimization and sensitivity studies are ongoing*
  - *Improvement on BSM physics from detached vertices*

Ongoing activities – detector R&D

- *ADRIANO*
  - *ADRIANO2 prototype under construction at NIU (INFN-NIU-UMN collaboration). FNAL probably joining (J. Freeman)*
  - *Inherits from 10+ years R&D by T1015*
- *O-TPC*
  - *UC (H. Frish) only existing prorotype*
  - *Requires a more structured collaboration*
- *Fiber tracker*
  - *No R&D needed: technology is exact copy of LHCB's new tracker*
  - *In talk with Aachen-RWTH for joining*
  - *Otherwise, technology&tools transfer to REDTOP*

Timeline

- *Once approved and funded, REDTOP needs about 2-3 years detector R&D + 1 year detector construction*
  - *Solenoid and ¾ of Pb-Glass for ADRIANO in-kind contributions from INFN (Finuda and NA64 experiments)*
- *Accelerator mods requires:*
  - *BNL: <1yr (only requiring a new electronics for the extraction line (C4)*
  - *CERN: need further studies*
  - *FNAL: ~1yr (add a SC cavity to the DR and build an extraction line*

Future Prospects

- *The Collaboration is currently engaged in the ESPP and P5-Snowmass processes*
- *Endorsement by the community and/or laboratories is needed to fund detector R&D activities*
- *Current activities aim at the preparation of a full proposal in about 2-3 years (corresponding to the ESPP conclusion)*
  - *Fermilab best : either DR or PIP-II (tREDTOP)*
  - *Detector optimization and sensitivity studies*
  - *Detector R&D*
- *Competition from several other experiments (LHCB, et. Al.)*
  - *However, experimental techniques are quite different*
- ***More details: https://redtop.fnal.gov***

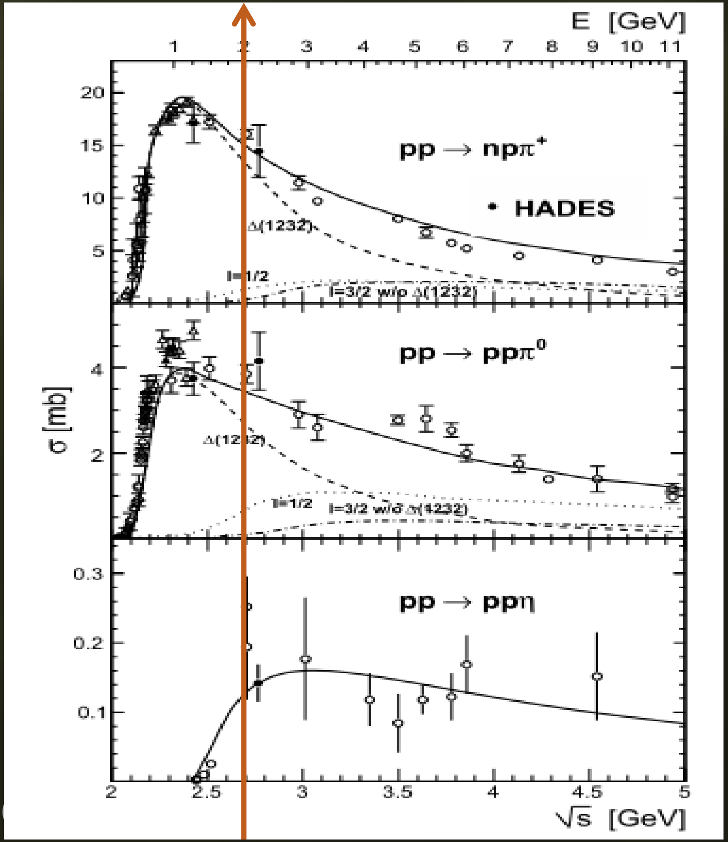
Summary

- *The η/η' meson is a fantastic laboratory for studying rare processes and physics BSM*
- *Existing world sample not sufficient for breaching into decays violating conservation laws or searching for new particles*
- *REDTOP goal is to produce ~10^{13} η mesons/yr in phase I and ~ 10^{11} η' /year in phase II*
- *More running phases could use different beam species:*
  - *PIP-II for a tagged-η experiment*
- *Several labs could host the experiment (FNAL is the most optimal)*
- *New detector technique would set the stage for next generation High Intensity experiments*
- *Moderate cost*

Beam Requirements for η-factory (1)

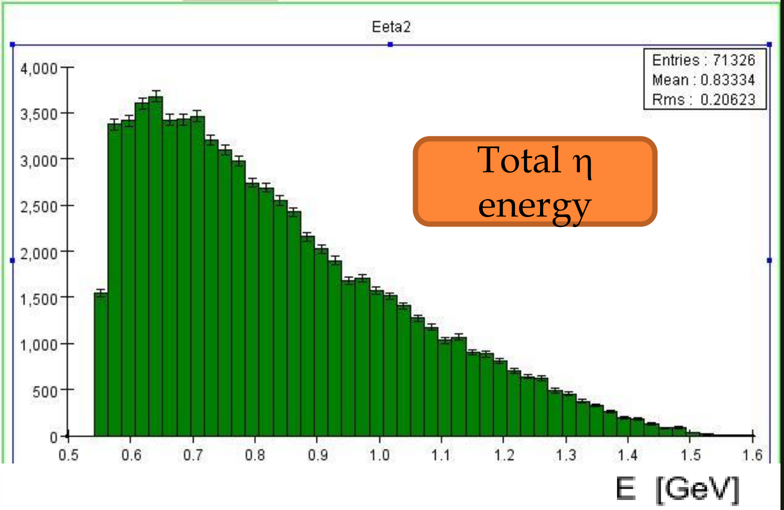
Beam energy

- *Constraints:*
  - *Beam energy large enough to get $\Gamma(\eta)/\Gamma(pX) \sim 1\%$*
  - *Beam energy low enough to make slow baryons (minimize background)*
  - *η meson energy low enough to make slow pions*
- *T_{beam} = 1.8 – 2.1 GeV (still under optimization but 1.9 GeV seems preferred)*



G. Agakishiev et al.
PHYSICAL REVIEW. C, NUCLEAR
PHYSICS 2012, 48, 74-1

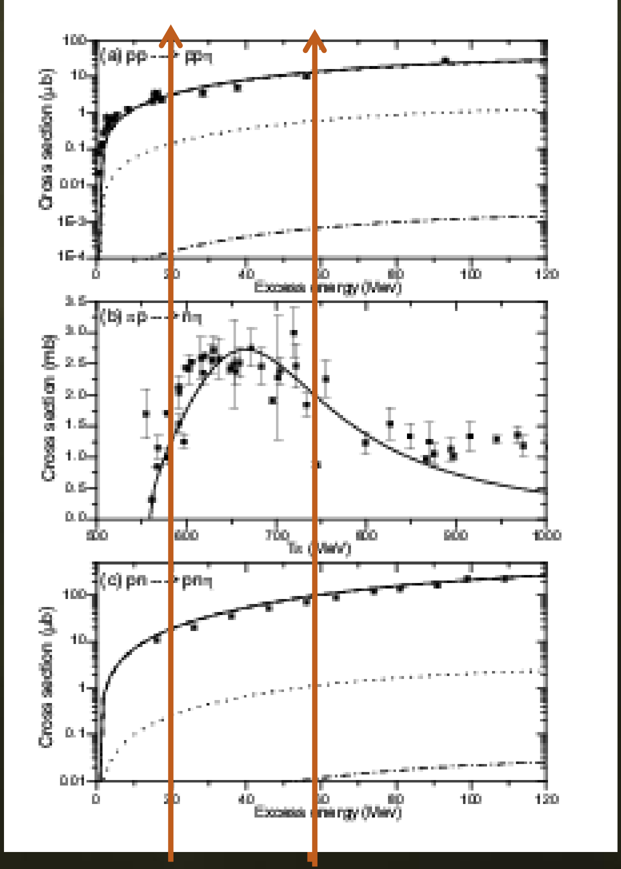
Total cross sections @ 2 GeV
$pp \rightarrow pp\eta$
140 μbarn
Total inelastic cross sections @ 2 GeV
About 200x



Total η energy

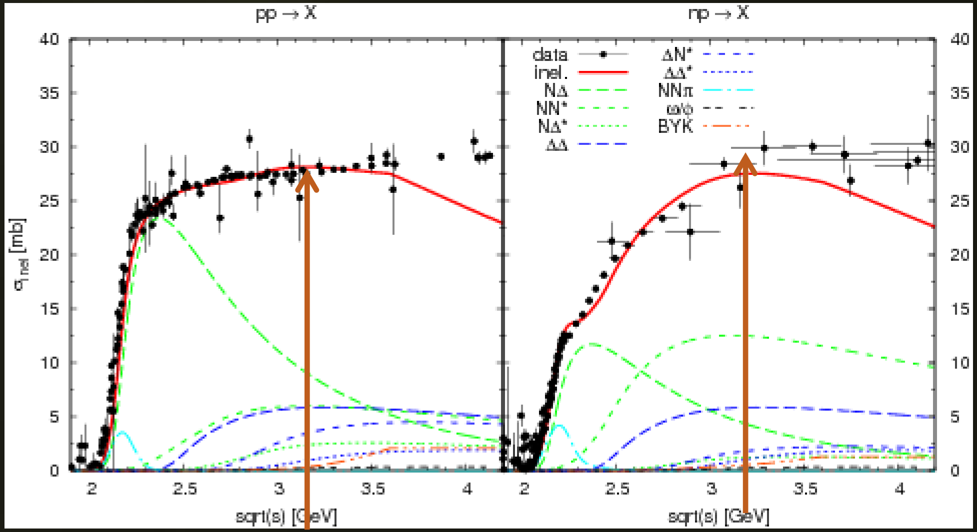
Beam Considerations for η' -factory

- *Constraints:*
  - *Same as for η-factory*
- *E_{beam} = 3.0 – 4.0 GeV (yet to be optimized)*
- $R_{\eta'} = \sigma(pp \rightarrow pn\eta')/\sigma(pp \rightarrow pp\eta')$ slightly lower than R_η



Xu Cao and Xi-Guo Lee
Phys. Rev. C 78, 035207 –2008

Total cross sections @ 3.8 GeV
$pp \rightarrow pp\eta'$
1 μbarn
Total inelastic cross sections @ 2 GeV
About 25,000x



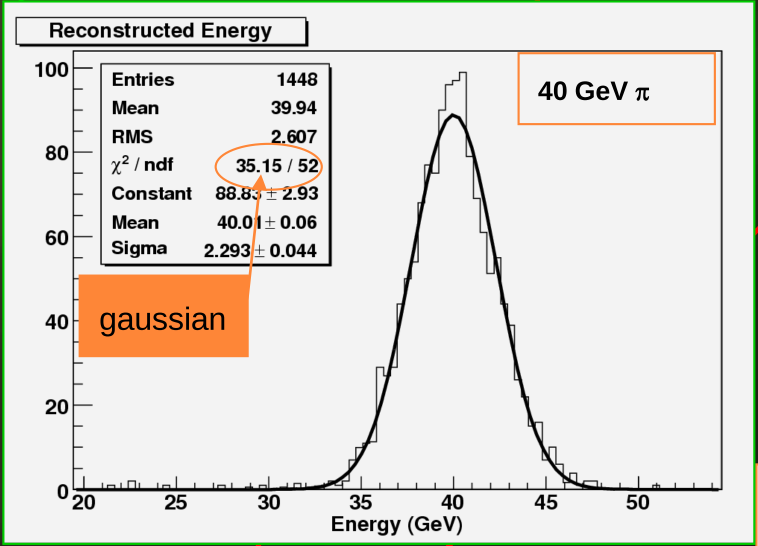
Transitionless Deceleration in the Delivery Ring (J. Johnstone)

- Large beam losses will occur if beam is decelerated from injection @ 8 GeV (γ = 9.53) to 2 GeV (γ = 3.13) through the DR natural transition energy γ_t = 7.64.
- Transition is avoided by using select quad triplets to boost γt above beam γ by 0.5 units throughout deceleration until γ_t = 7.64 and beam γ = 7.14 (5.76 GeV kinetic).
- Below 5.76 GeV the DR lattice reverts to the nominal design configuration
- Optical perturbations are localized within each triplet
- Straight sections are unaffected thereby keeping the nominal M3 injection beamline tune valid.

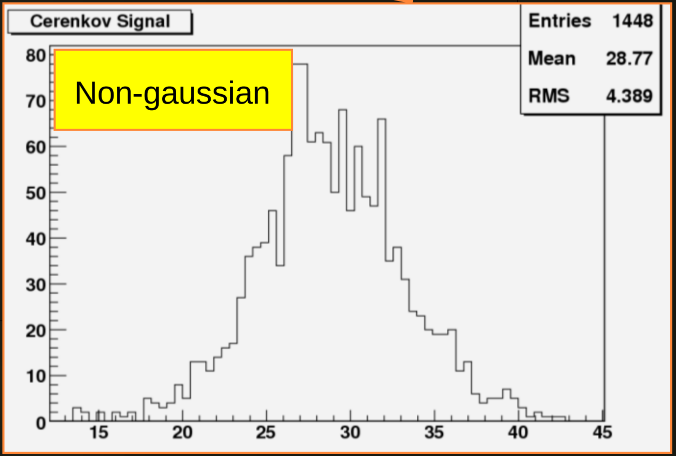
Dual Readout Calorimetry

Total calorimeter energy: use two measured signals and two, energy-independent, calibration constants.

$$E_{HCAL} = \frac{\eta_S \cdot E_S \cdot (\eta_C - 1) - \eta_C \cdot E_C \cdot (\eta_S - 1)}{\eta_C - \eta_S}$$



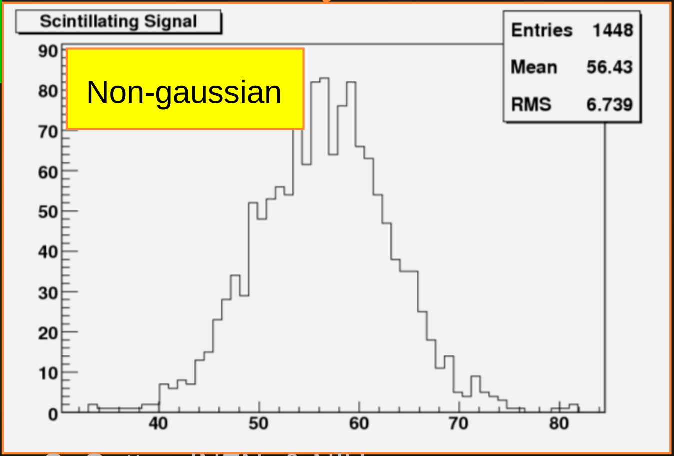
ILCroot simulations



$$\eta_c = \left(\frac{e}{h}\right)_C \quad \eta_S = \left(\frac{e}{h}\right)_S$$

From calibration

@ 1 Energy only



Dual readout calorimeter is two distinct calorimeters sharing the same absorber. Measured energy is gaussian because of compensation event by event.

Dual Readout Calorimetry from a Different Perspective

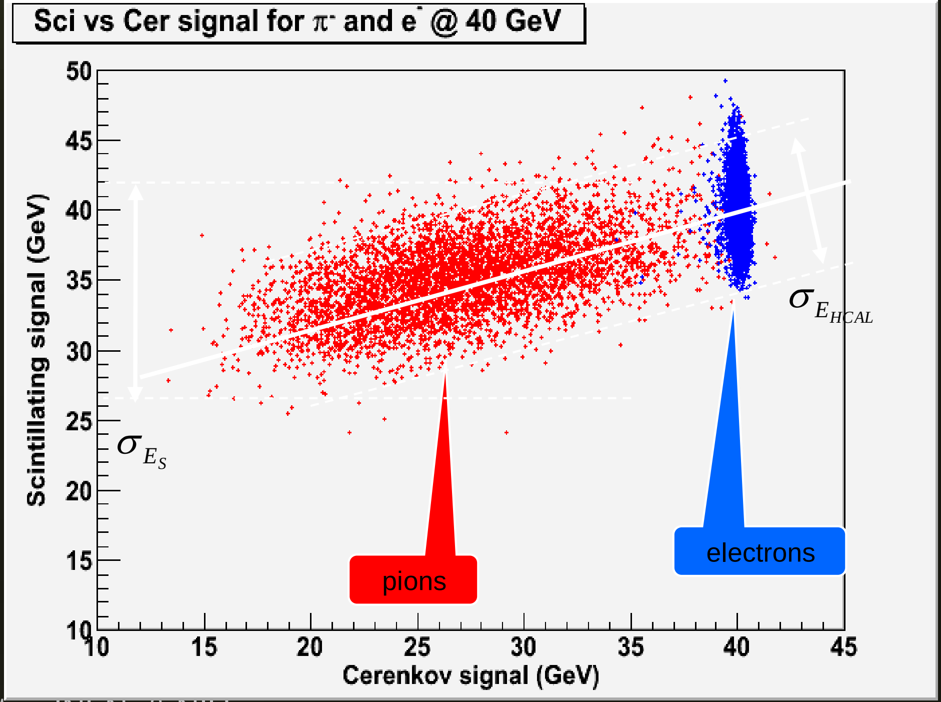
$$E_{HCAL} = \frac{\eta_S \cdot E_S \cdot (\eta_C - 1) - \eta_C \cdot E_C \cdot (\eta_S - 1)}{\eta_C - \eta_S}$$

$$\left(\eta_S = \left(\frac{e}{h}\right)_s \quad ; \quad \eta_C = \left(\frac{e}{h}\right)_C \right)$$

$$\begin{cases} E_S = \left[fem + \frac{(1 - fem)}{\eta_S} \right] \cdot E_{HCAL} \\ E_C = \left[fem + \frac{(1 - fem)}{\eta_C} \right] \cdot E_{HCAL} \end{cases}$$

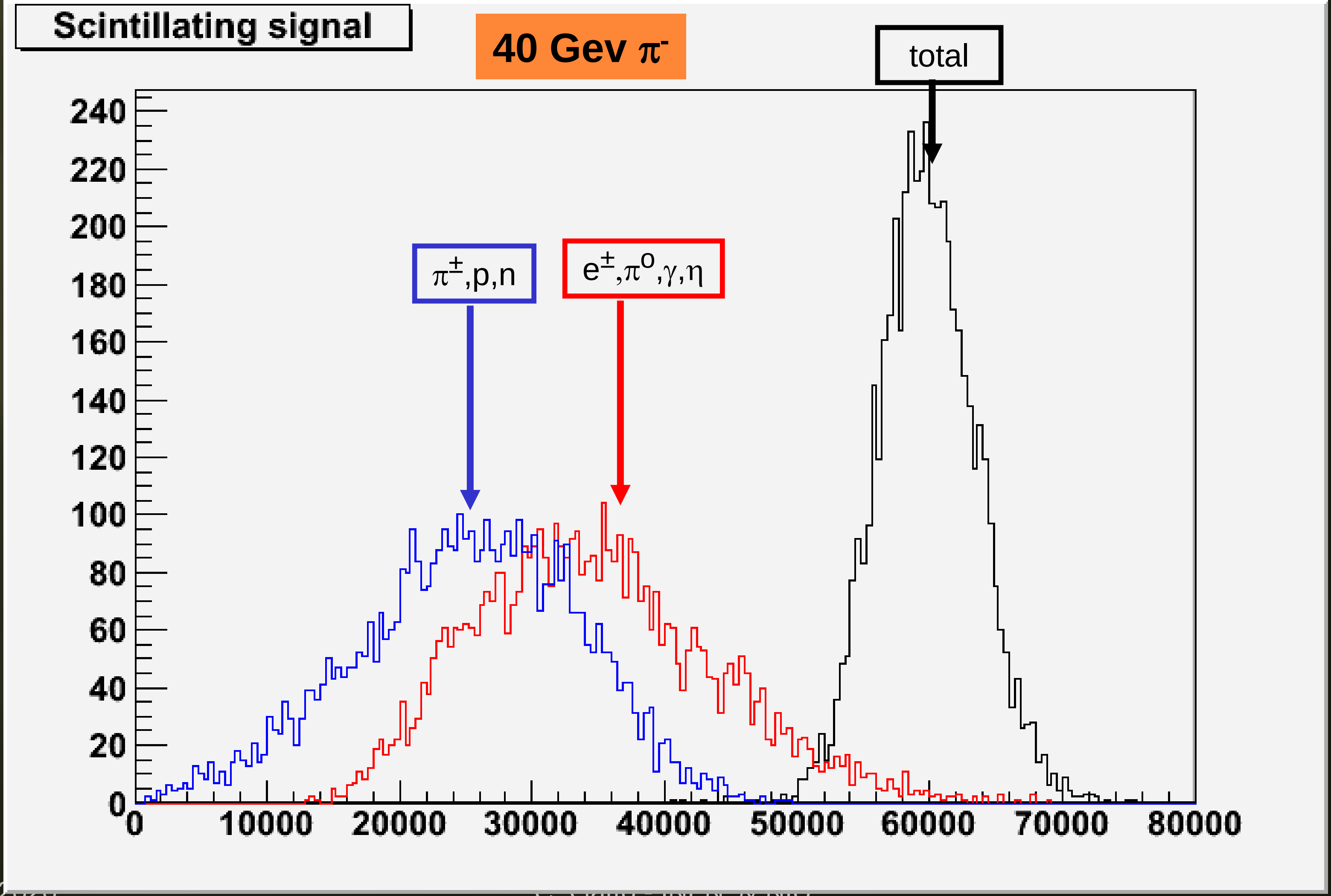
If $\eta_s \neq \eta_c$ then the system can be solved for E_{HCAL}

ILCroot simulations



Dual Readout is nothing but a rotation in E_S - E_C plane

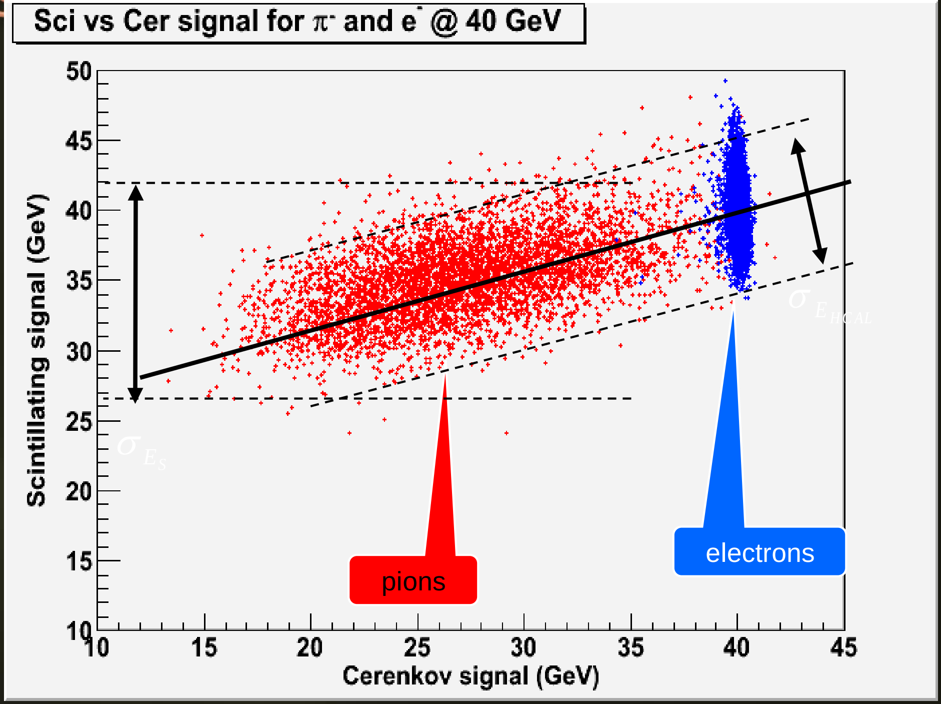
The major source of fluctuations: *fem*



Dual Readout Calorimetry from a Different Perspective

Dual Readout is nothing but a rotation in E_S - E_C plane

ILCroot simulations



$$E_{HCAL} = \frac{\eta_S \cdot E_S \cdot (\eta_C - 1) - \eta_C \cdot E_C \cdot (\eta_S - 1)}{\eta_C - \eta_S}$$

$$\left(\eta_S = \left(\frac{e}{h}\right)_s \quad ; \quad \eta_C = \left(\frac{e}{h}\right)_C \right)$$

$$\begin{cases} E_S = \left[fem + \frac{(1 - fem)}{\eta_S} \right] \cdot E_{HCAL} \\ E_C = \left[fem + \frac{(1 - fem)}{\eta_C} \right] \cdot E_{HCAL} \end{cases}$$

If $\eta_s \neq \eta_c$ then the system can be solved for E_{HCAL}

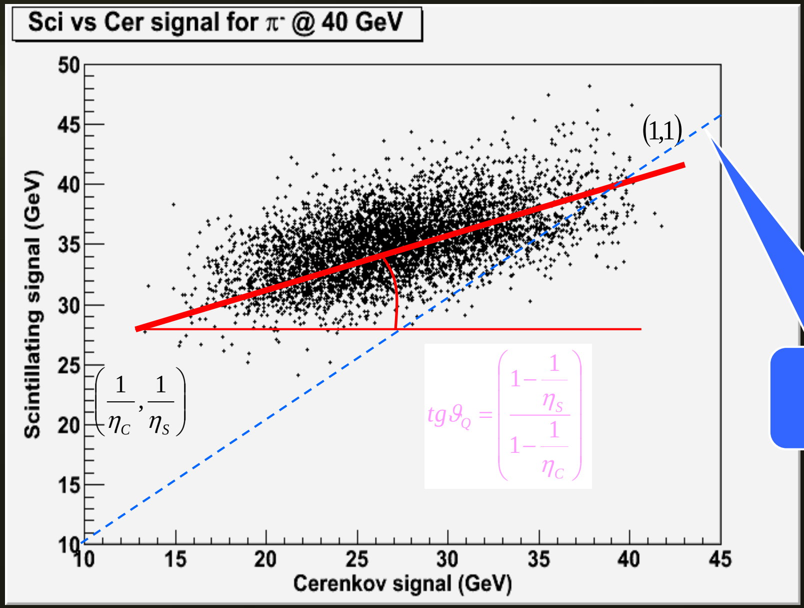
Figures of Merit for Dual-Readout Calorimeter

- Large pe/GeV: must be much greater than 45 pe/GeV (corresponding to 15% (teoretical limit) contrubution to stochastic term
- System is solvable only when $\eta_S \neq \eta_C$. The larger the compensation asymmetry the better. Aka, $tg(\theta_{S/Q})$ much diferent from 1

$$\sigma^2_{E_{corr}} = \left(\frac{1}{1-\chi}\right)^2 \sigma^2_S + \left(\frac{\chi}{1-\chi}\right)^2 \sigma^2_Q$$

$$\chi \equiv tan(\theta_{S/Q}) = \frac{1-1/\eta_C}{1-1/\eta_S}$$

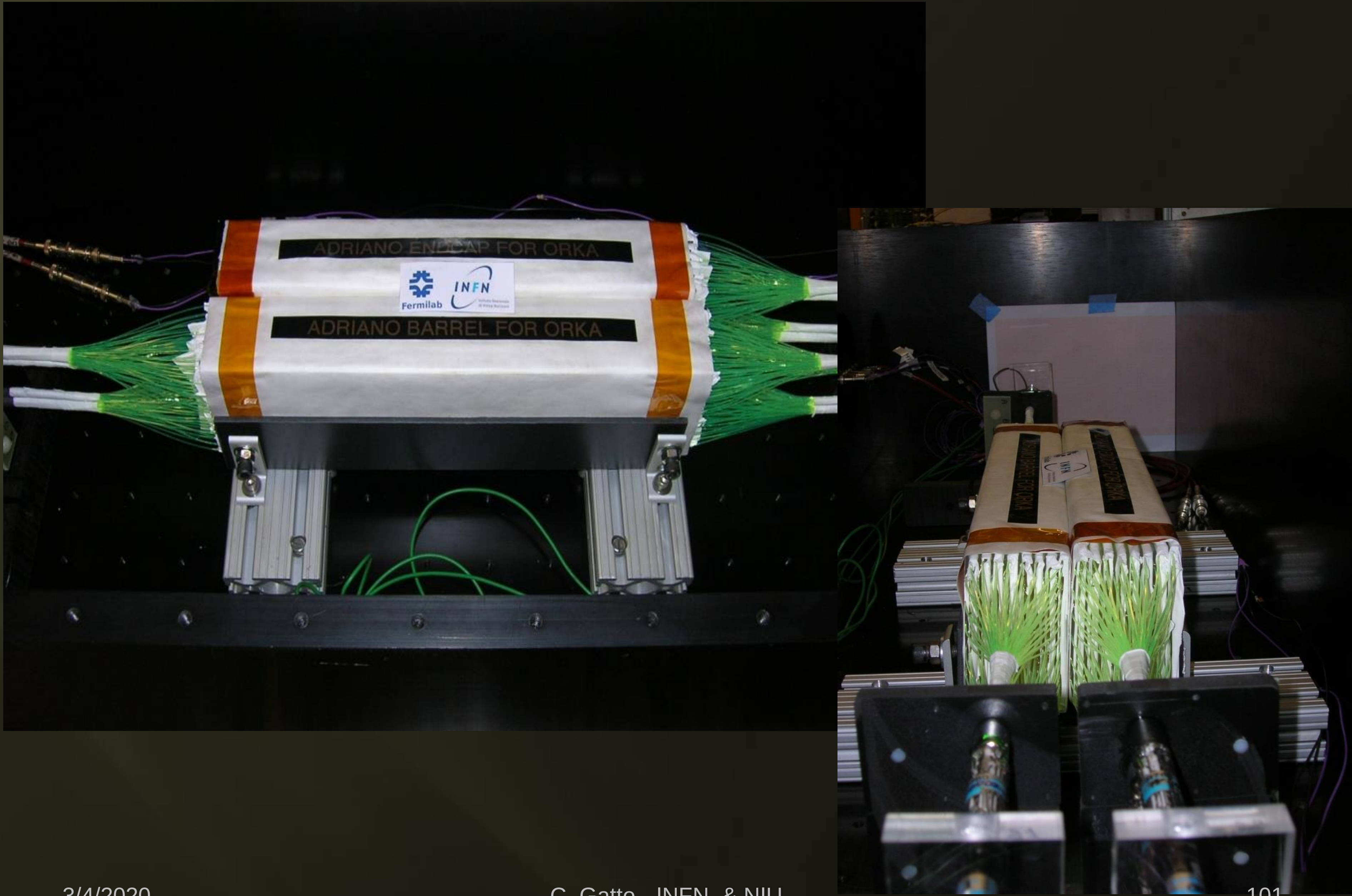
ILCroot simulations



$\eta_S = \eta_C$

- Small Γ = photodetector area/calorimeter area. Γ_{DREAM} = 24%. Γ_{4th} = 21%. Goal is Γ < 10%.
- Small mixing of S and C components

ADRIANO for ORKA Final Prototypes



High Energy vs High Intensity Layouts

High Energy

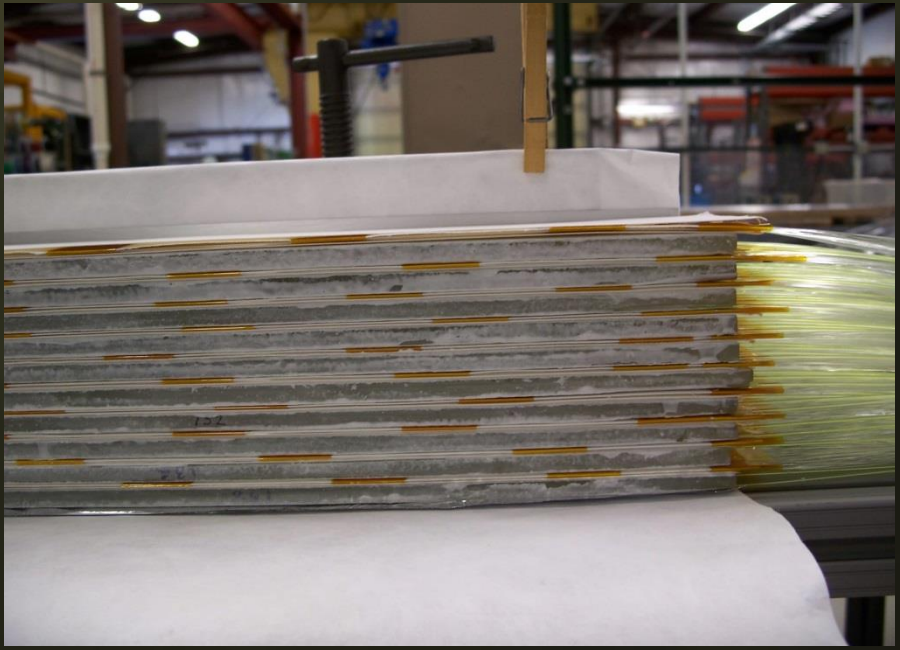
- Detection of Hadronic and EM showers with large S and Č light production
- Optimized for maximum shower containment (i.e. max detector density)

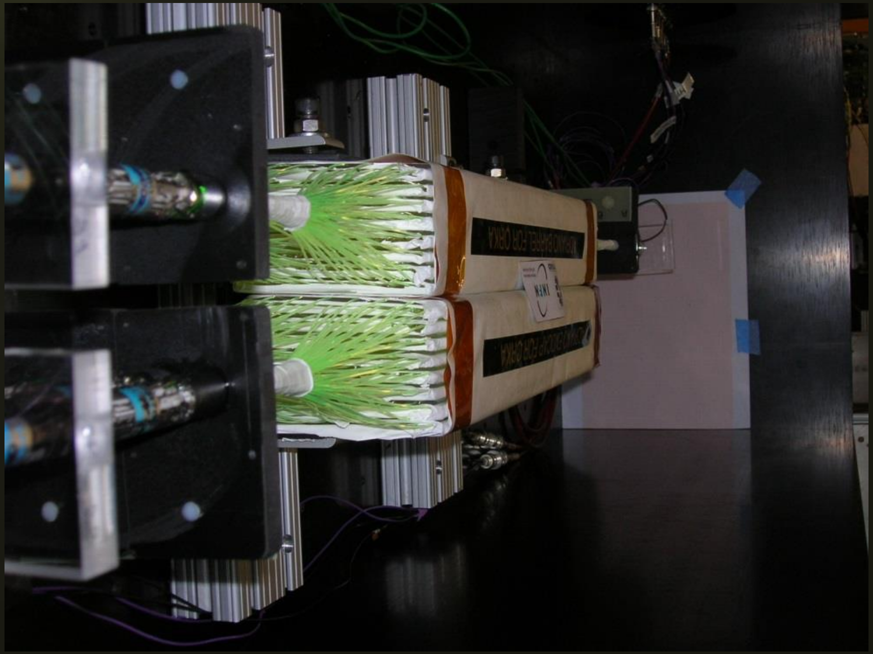
- Thicker glass
- Thin scintillating fibers or ribbons
- Fewer WLS fibers

High Intensity

- Detection of EM showers only with small S and Č light production
- Optimized for high sensitivity in the 10 MeV range (i.e. max detector granularity)

- Thinner glass
- Thicker scintillator plates
- More WLS fibers





15 Prototypes Performance Summary

Prototype	Year	Glass	gr/cm^3	Čerenkov L. Y./GeV	Notes
5 slices, machine grooved, unpolished, white	2011	Schott SF57HHT	5.6	82	SiPM readout
5 slices, machine grooved, unpolished, white, v2	2011	Schott SF57HHT	5.6	84	SiPM readout
5 slices, precision molded, unpolished, coated	2011	Schott SF57HHT	5.6	55	15 cm long
2 slices, ungrooved, unpolished, white wrap	2011	Ohara BBH1	6.6	65	
5 slices, scifi silver coated, grooved, clear, unpolished	2011	Schott SF57HHT	5.6	64	15 cm long
5 slices, scifi white coated, grooved, clear, unpolished	2011	Schott SF57HHT	5.6	120	
2 slices, plain, white wrap	2011	Ohara	7.5	-	DAQ problem
10 slices, white, ungrooved, polished	2012	Ohara PBH56	5.4	30	DAQ problems
10 slices, white, ungrooved, polished	2012	Schott SF57HHT	5.6	76	
5 slices, wifi Al sputter, grooved, clear, polished	2012	Schott SF57HHT	5.6	30	2 wls/groove
5 slices, white wrap, ungrooved, polished	2012	Schott SF57HHT	5.6	158	Small wls groove
ORKA barrel	2013	Schott SF57	5.6	2500/side	molded
ORKA endcaps	2013	Schott SF57	5.6	4000	molded
10 slices – 6.2 mm thick, scifi version	2014	Schott SF57	5.6	338	molded
10 slices – 6.2 mm thick, sci-plate version	2014	Schott SF57	5.6	354	molded

On CP violation (CPV) in $\eta \rightarrow \pi^+\pi^-\pi^0$ decay

Unlike η→π π decay, CPV can appear via amplitude interference

➡ CPV effect would be linear in a CPV parameter

Multiple observables appear through the Dalitz plot

- Recall early discussions of C violation, possibly through EM interactions [TD Lee & L Wolfenstein,1965; Lee, 1965; Nauenberg, 1965] [Bernstein, Feinberg, & Lee, 1965; Barshay ,1965]
- C violation can be discovered through a "charge asymmetry" in the Dalitz plot (difference in the π^+ / π^- energy spectra)

Note left-right (+/-) asymmetry — and asymmetries to probe if I is non-zero as well [Note also Layter et al. PRL1972 and, e.g., KLOE-2, JHEP 2016]

* New! Note structure of possible CPV interferences in decay rate

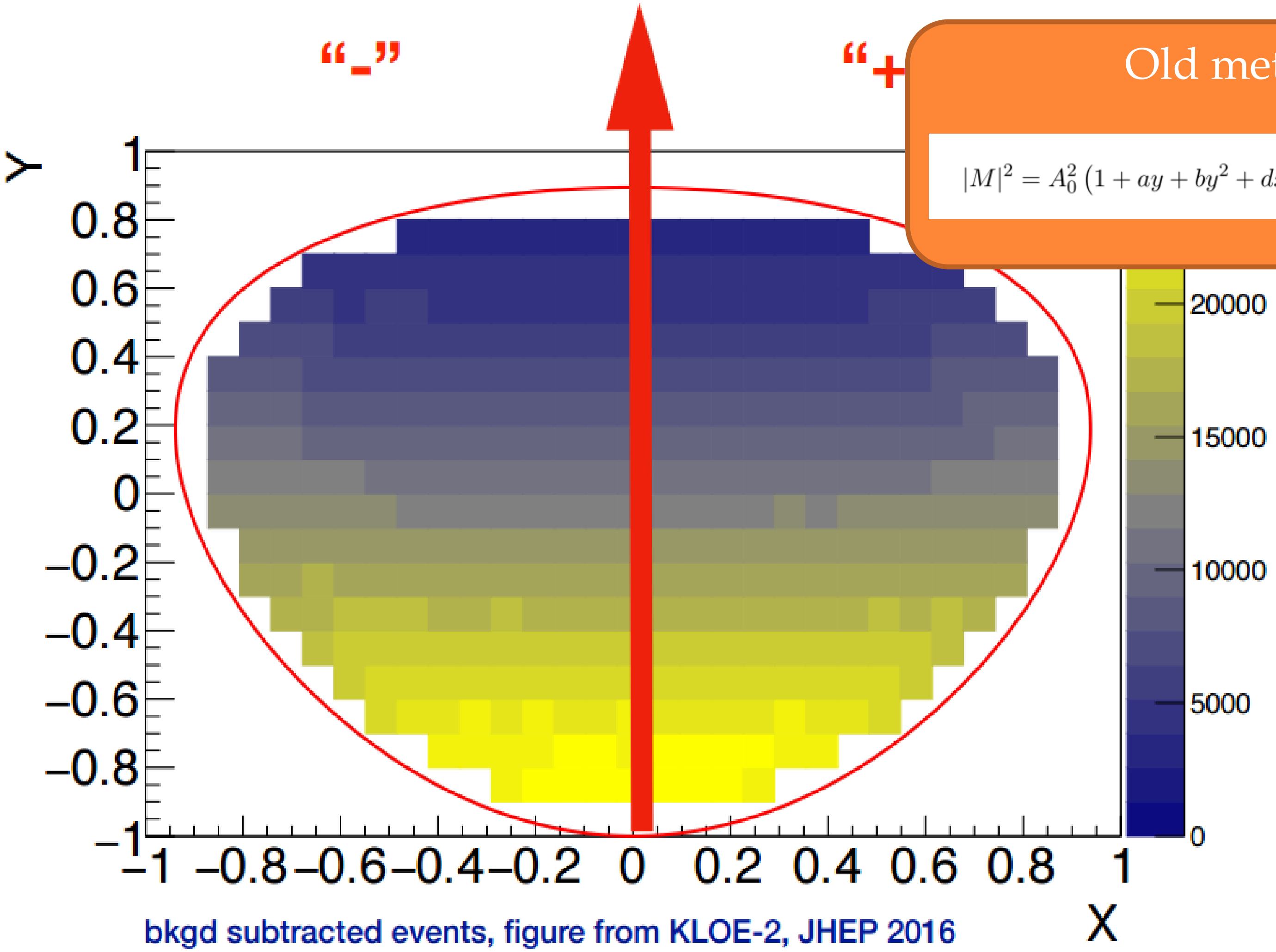
[Note Gardner & Tandean, 2004; Gardner & Shi, 2017, to appear]

Slide Credit: Susan Gardner & Jun Shi

On CP violation (CPV) in $\eta \to \pi^+\pi^-\pi^0$ decay

Terms in $|A|^2$ that are odd in X generate a charge (+/-) asymmetry

Can also fit Dalitz distribution for these X odd terms



Old method

$$|M|^2 = A_0^2\left(1 + ay + by^2 + dx^2 + fy^3 + gx^2y + \cdots\right) .$$

bkgd subtracted events, figure from KLOE-2, JHEP 2016

Slide Credit: Susan Gardner & Jun Shi

University of Kentucky

Theoretical Analysis: $\eta \to \pi^+\pi^-\pi^0$

C and CP violation poorly constrained in flavor diagonal processes

New way to construct CPV amplitudes in $\eta \to \pi^+\pi^-\pi^0$

- Use NLO ChPT result & project it to the isospin basis of two pions (I=0,1,2)

[Gasser & Leutwyler, 1985; note also Anisovich & Leutwyler, 1996; Bijnens & Ghorbani, 2007]

- Add CP violating terms controlled by "a" and "b"

$$A(s,t,u) = M_0(s) + (s-u)M_1(t) + (s-t)M_1(u) + M_2(t) + M_2(u) - \frac{2}{3}M_2(s)$$
$$+a[(s-u)M_1(t) - (s-t)M_1(u)] + b[M_2(t) - M_2(u)]$$

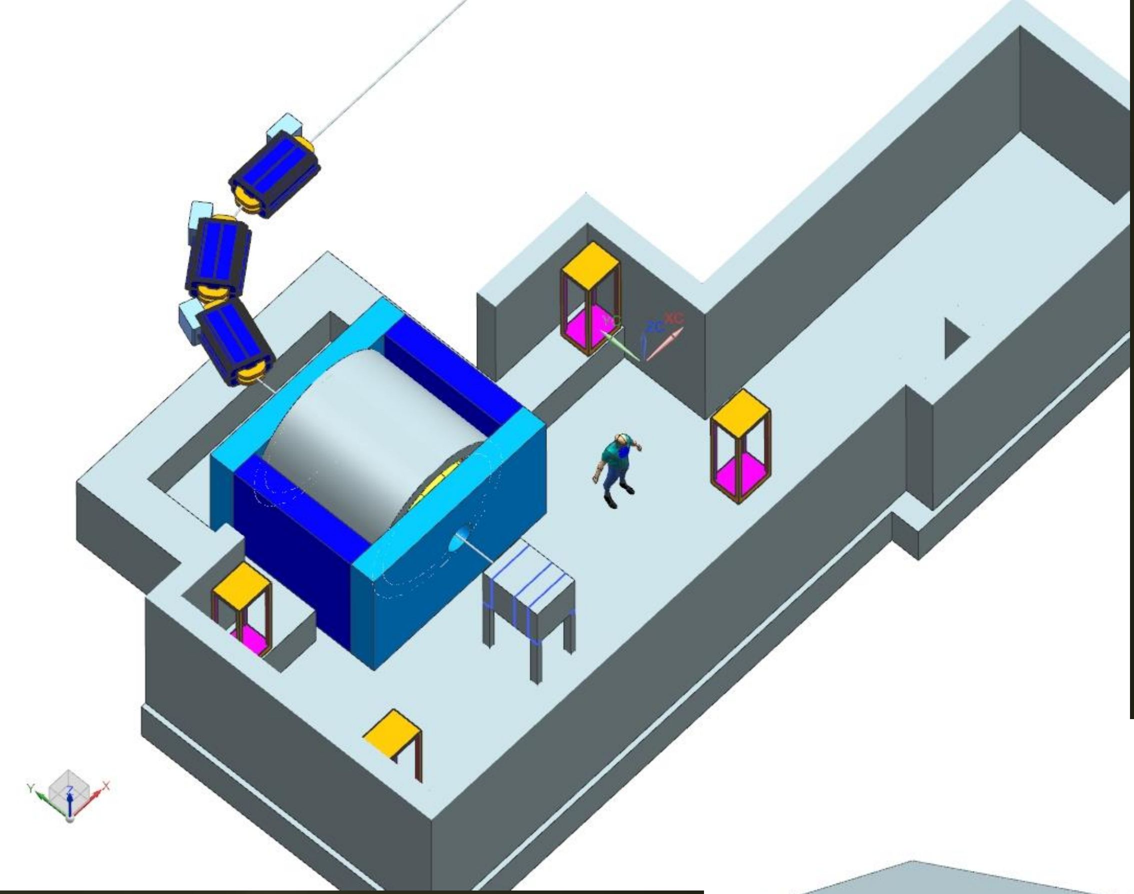
- Expand 8 CPV interferences in $|A(s,t,u)|^2$ in terms of (X, Y)=(0,0)

- Can fit the Dalitz plot to get Re(a), Im(a), Re(b), Im(b) and/or study charge asymmetries

Preliminary analysis shows the largest CPV contributions could come from the interference with $M_0(s)$

[Gardner & Shi, 2017, to appear]

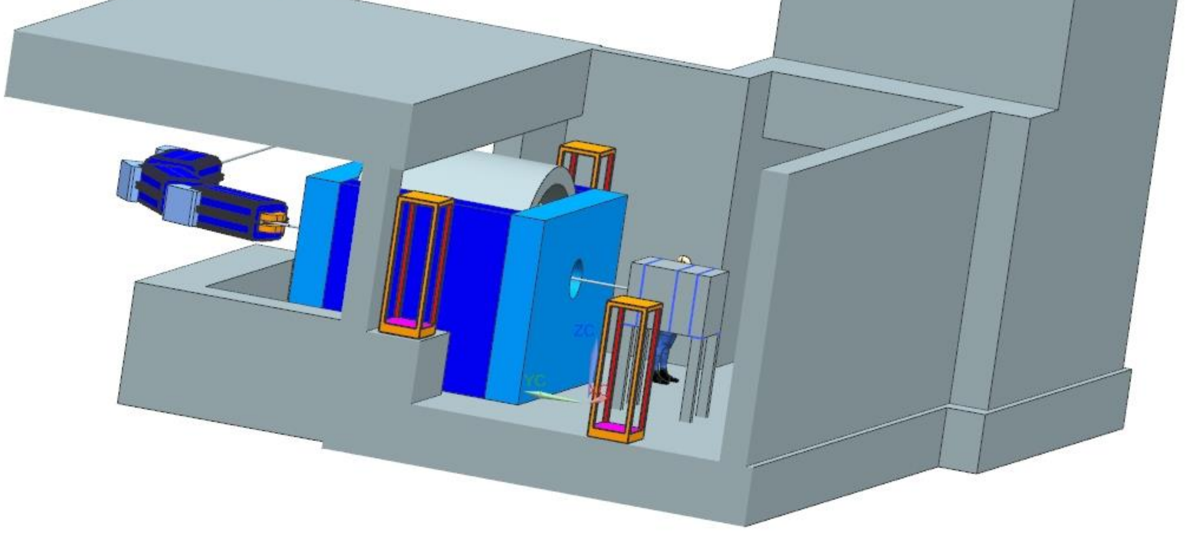
Slide Credit: Susan Gardner & Jun Shi



REDTOP detector in AP50

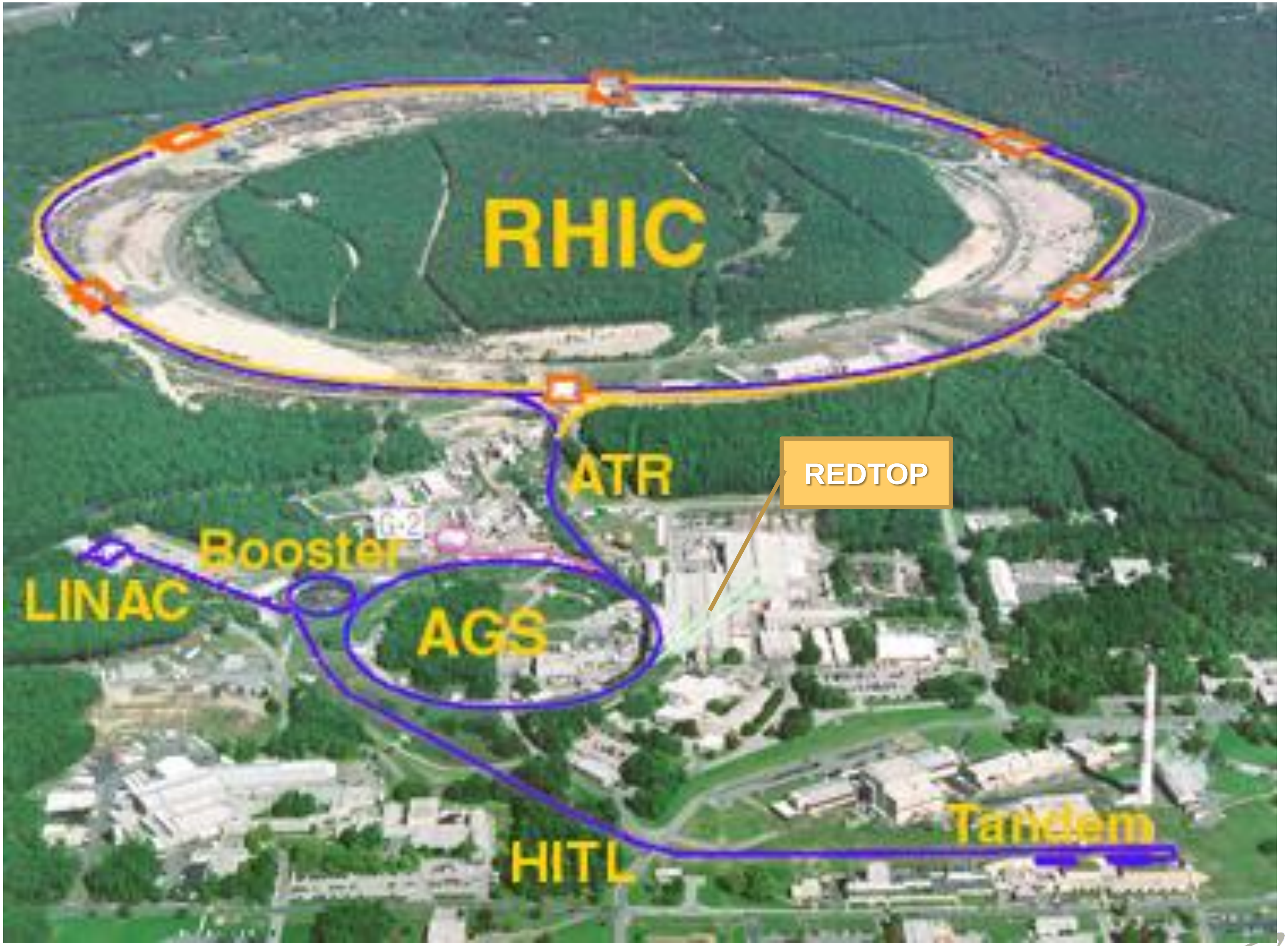
J. Kilmer
J. Rauch
E. Barzi (Solenoid and yoke)

(Many thanks to K. Krempetz, as well)

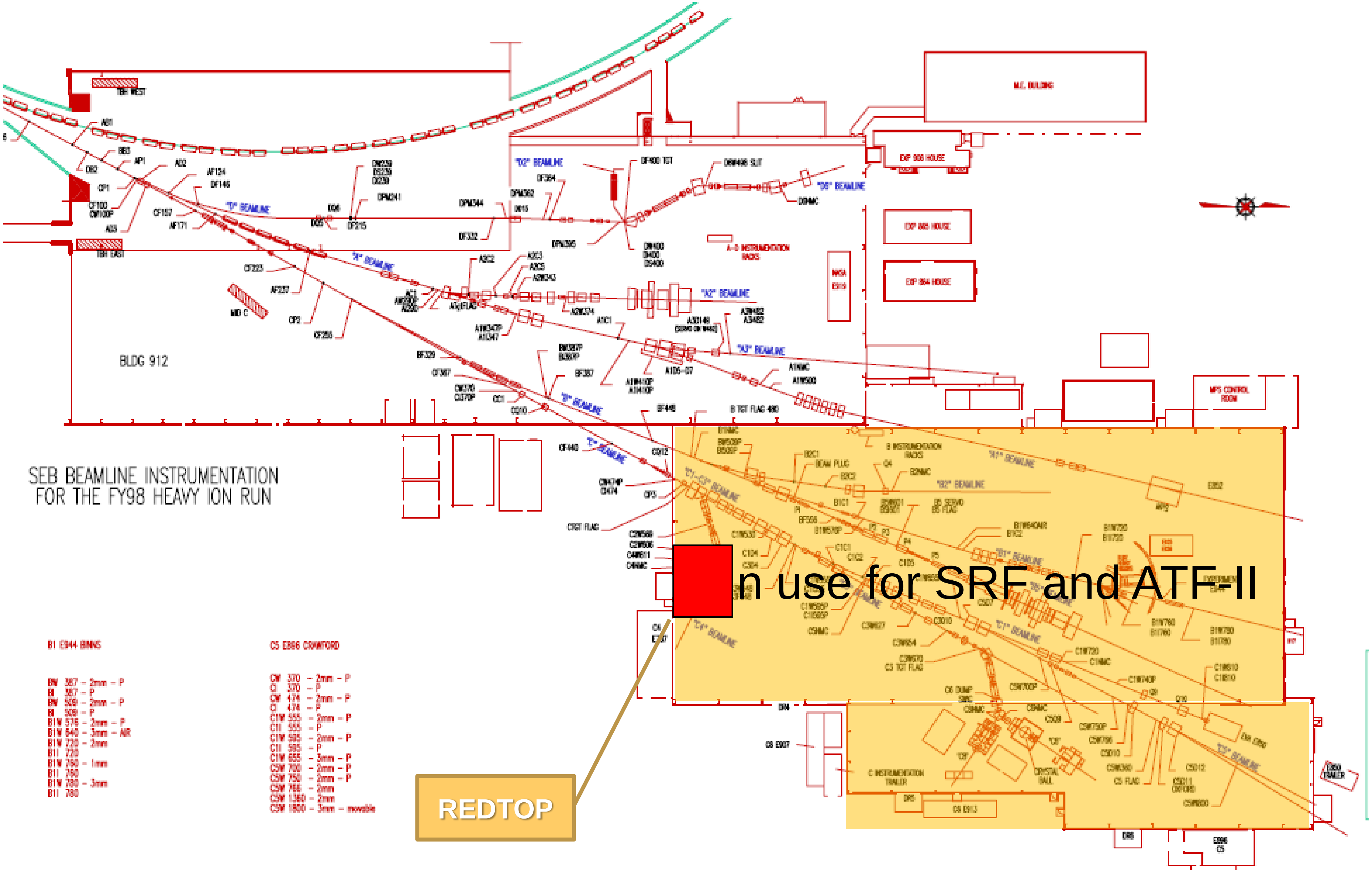


3/4/2020

BNL hadron complex



Building 912 AGS Experimental Area (1998)



n use for SRF and ATF-II

REDTOP