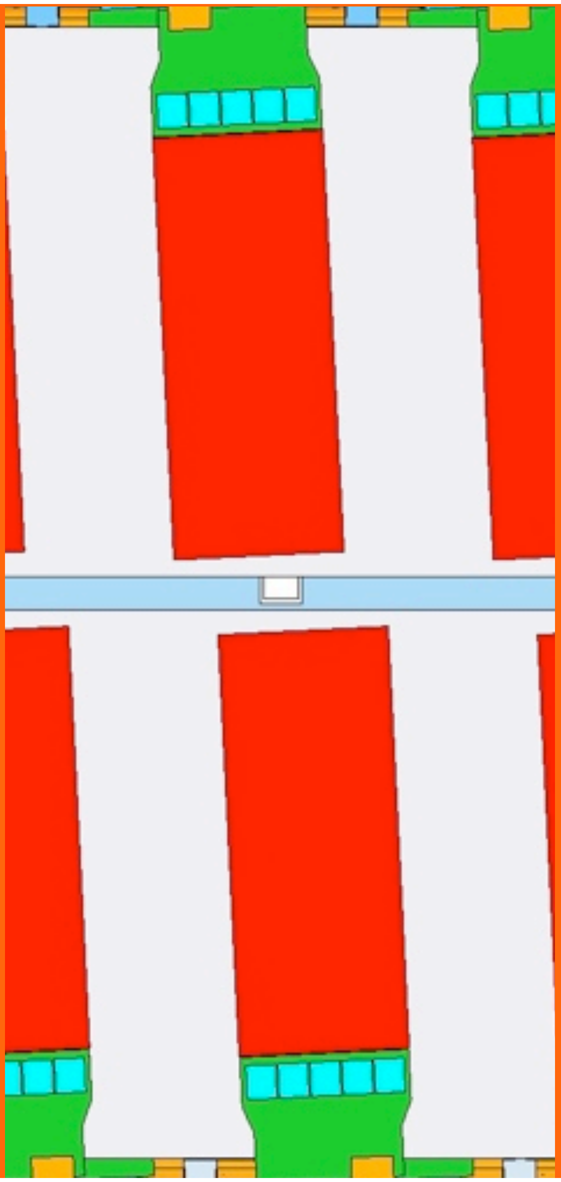
The Search for a Dark Photon at JLab



***Tim Nelson* - SLAC**

on behalf of the HPS collaboration

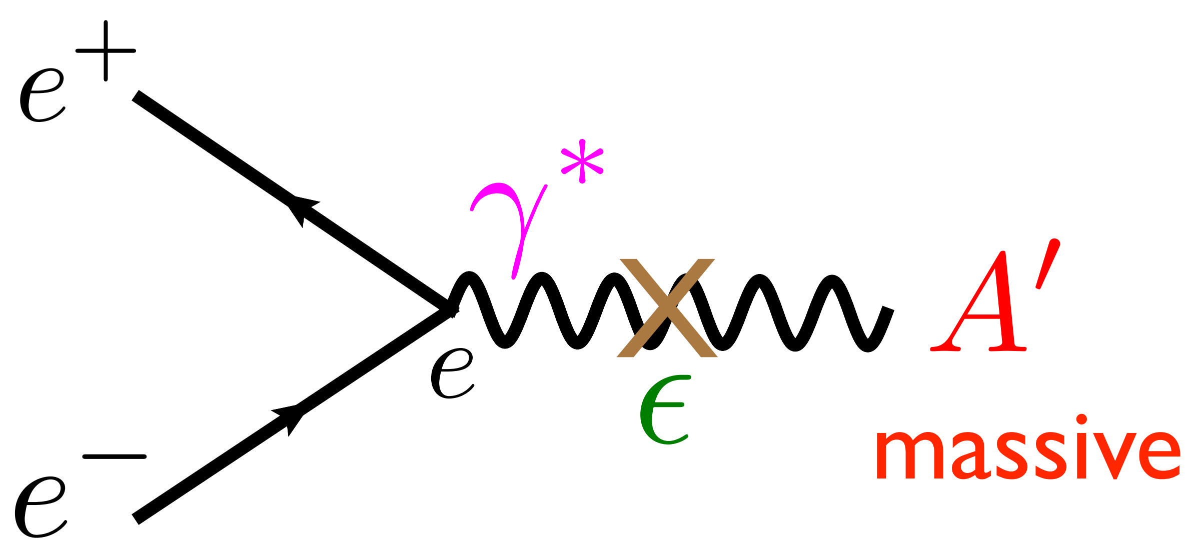
Harvard LPPC Seminar - October 27, 2010

"Dark Photon?"

Standard Model | **Hidden Sector?**

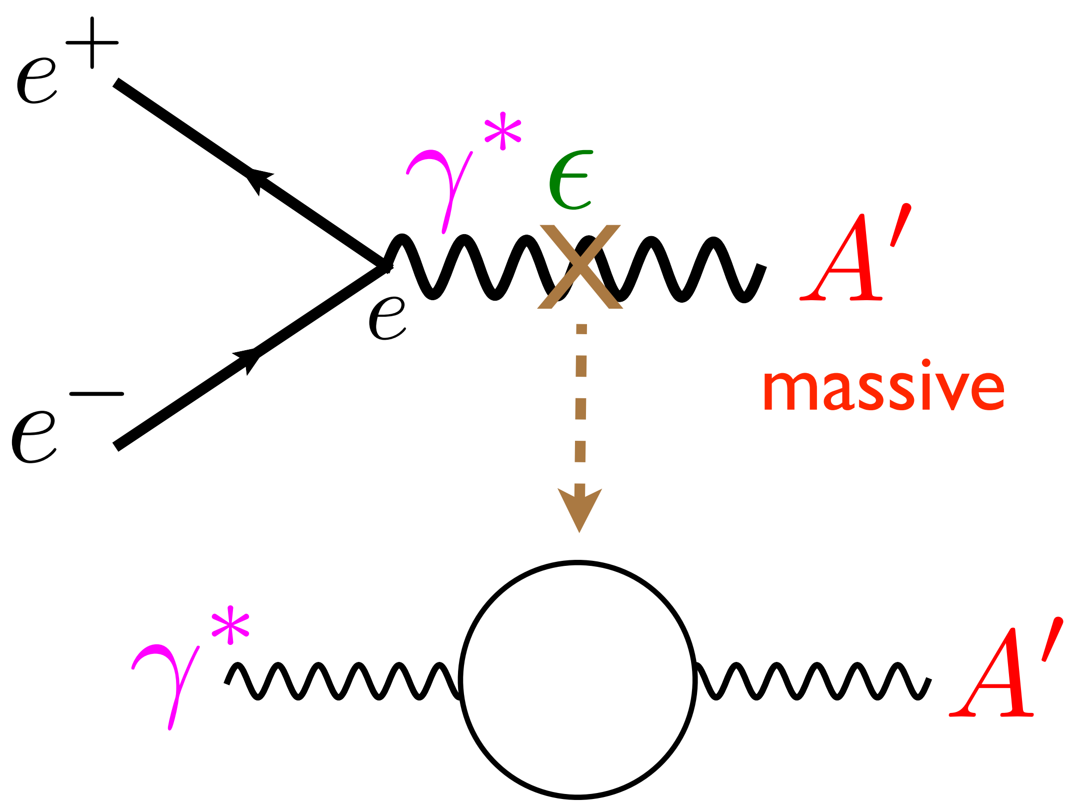
strong	weak	electromagnetic	new force?
g	$W^{\pm}, Z$	γ	A'

Photon can mix with a new vector boson A′



Hidden Sector
U(1)

How Does it Work?



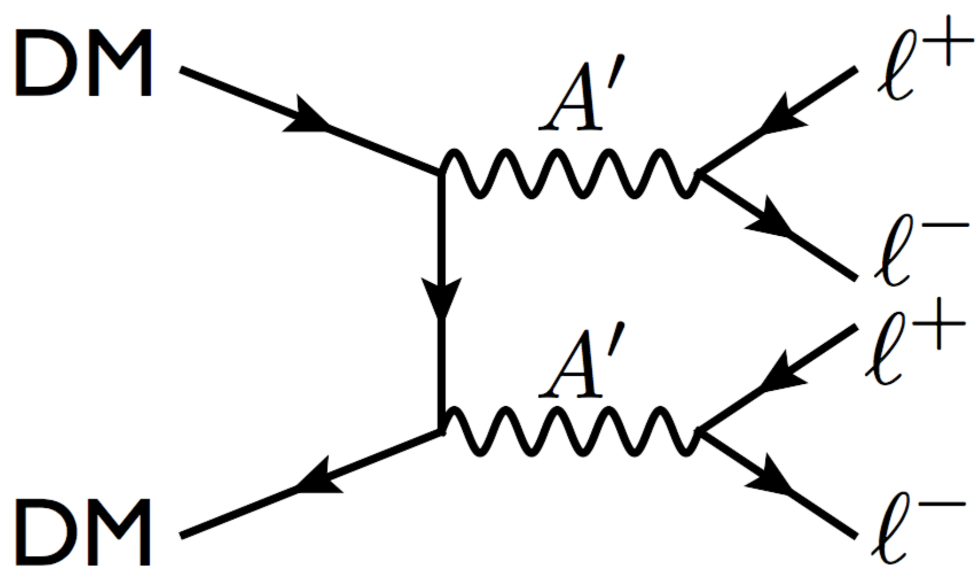
$$\epsilon = \sqrt{\frac{\alpha'}{\alpha}}$$

$$\Delta\mathcal{L} = \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}$$

"Kinetic Mixing" generated by heavy particles interacting with γ and A' [Holdom - 1986]

quarks & charged leptons have $e{\cdot}\epsilon$ coupling to A′

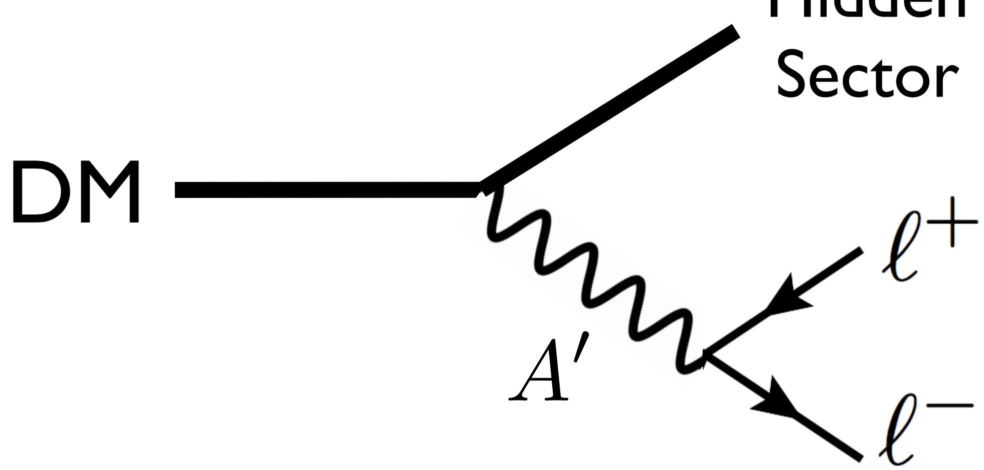
What Makes It Interesting?



m_{DM} ~ TeV $m_{A'}$ ~ GeV

What if dark matter annihilates to A′ ??

Arkani-Hamed, Finkbeiner, Slatyer, Weiner
Pospelov & Ritz



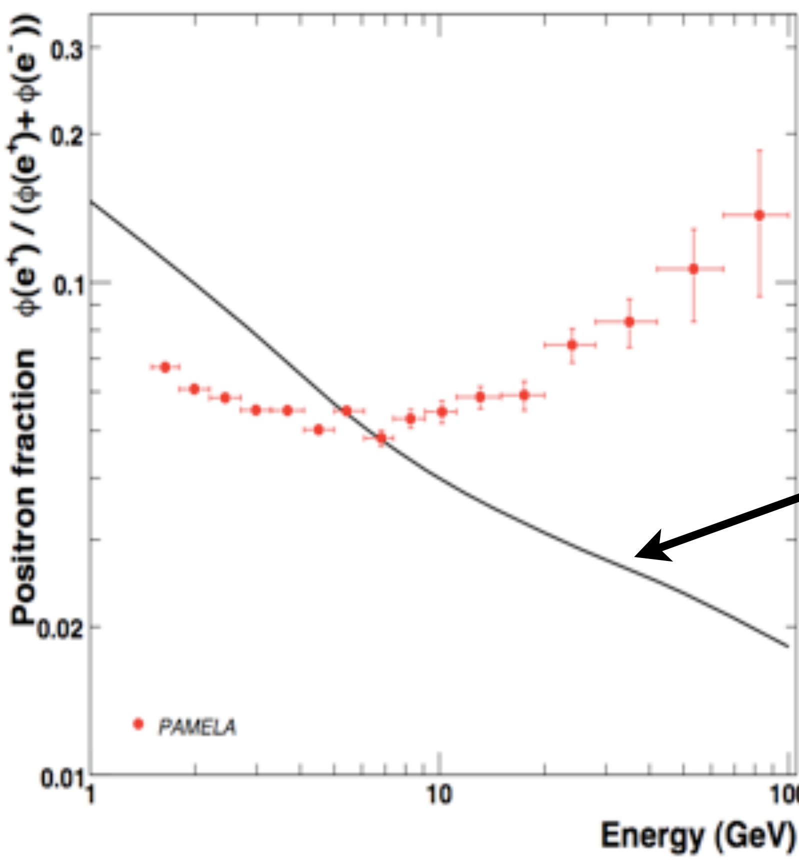
What if dark matter decays to A′ ??

[Ruderman, Volansky]

[Essig, Kaplan, Schuster, Toro]

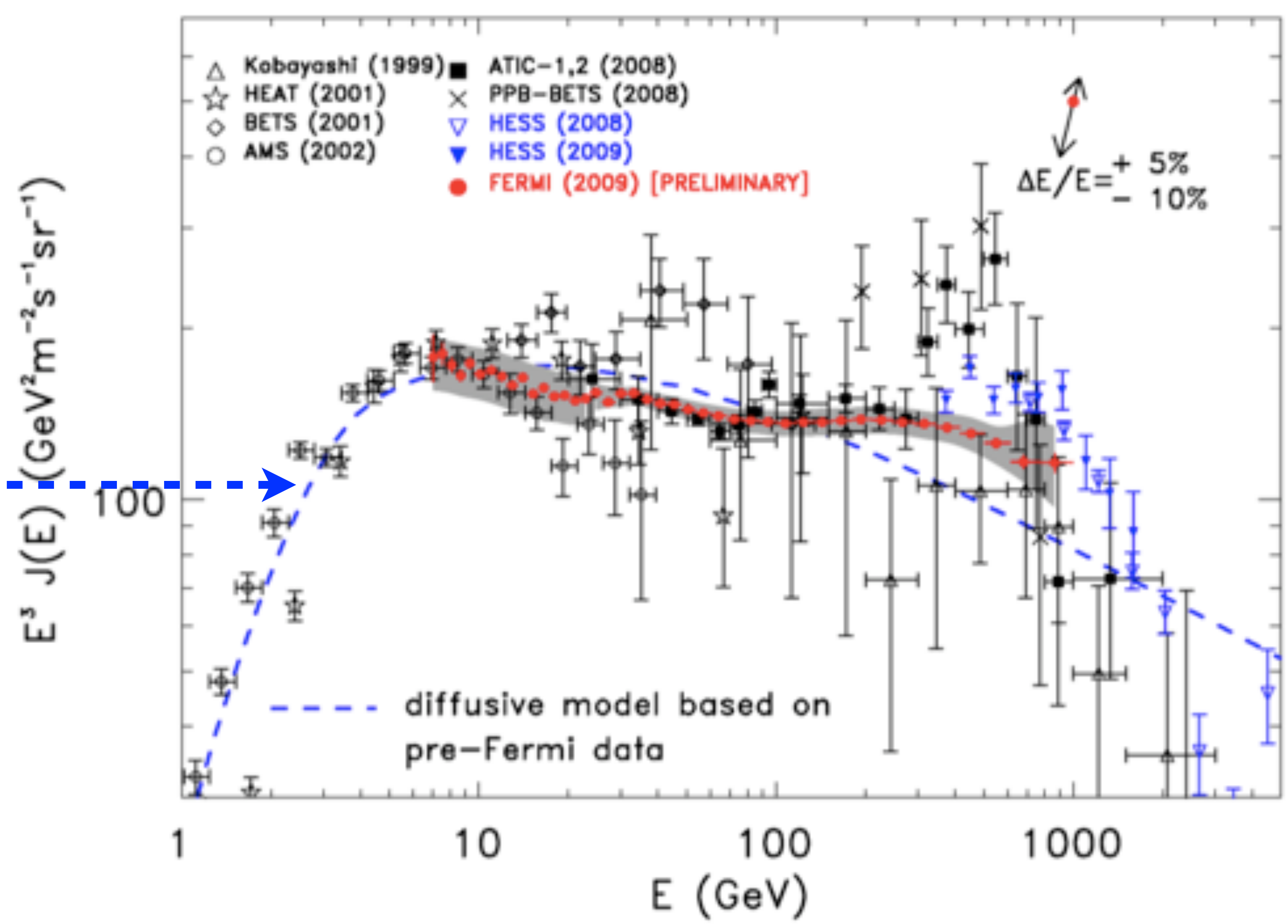
Explains Observed Excesses

PAMELA: e^+ fraction



theory expectation

Fermi: $e^+ + e^-$ flux



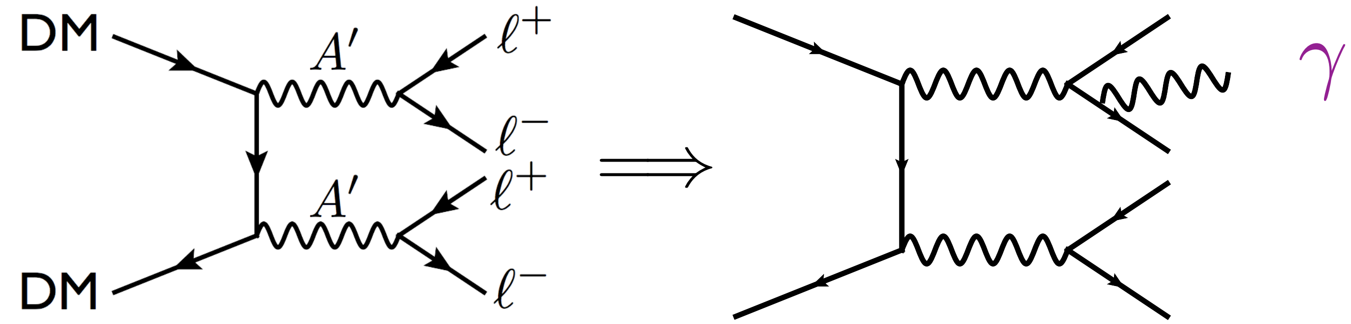
no accompanying proton excesses ⇒ $m_{A'} < 2m_p$

(Improved measurements from AMS-02 ~1-2 year)

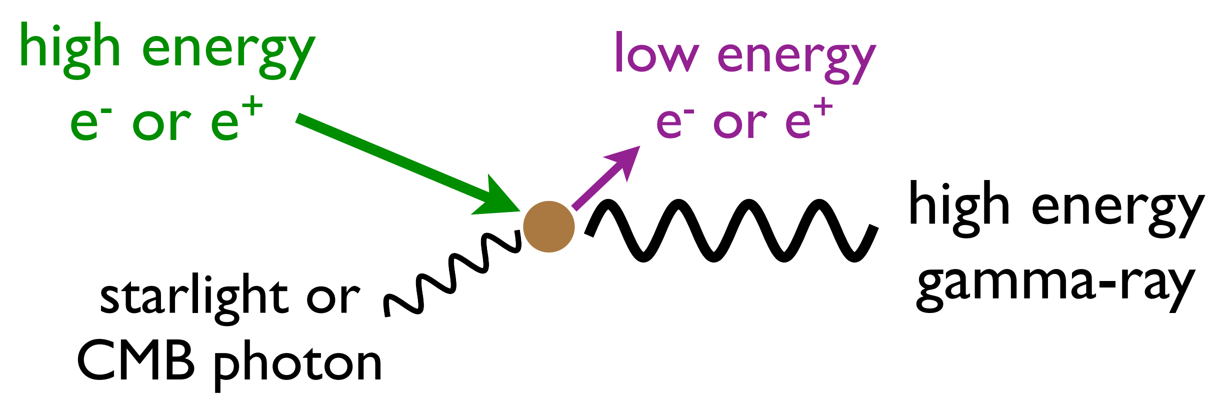
More Indirect Searches

- Expect gammas (Fermi, Cherenkov Telescopes...)

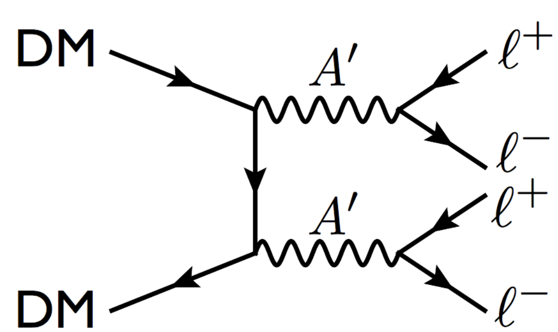
final-state radiation



inverse compton scattering



- Possibly neutrinos (IceCube, Super-K...)



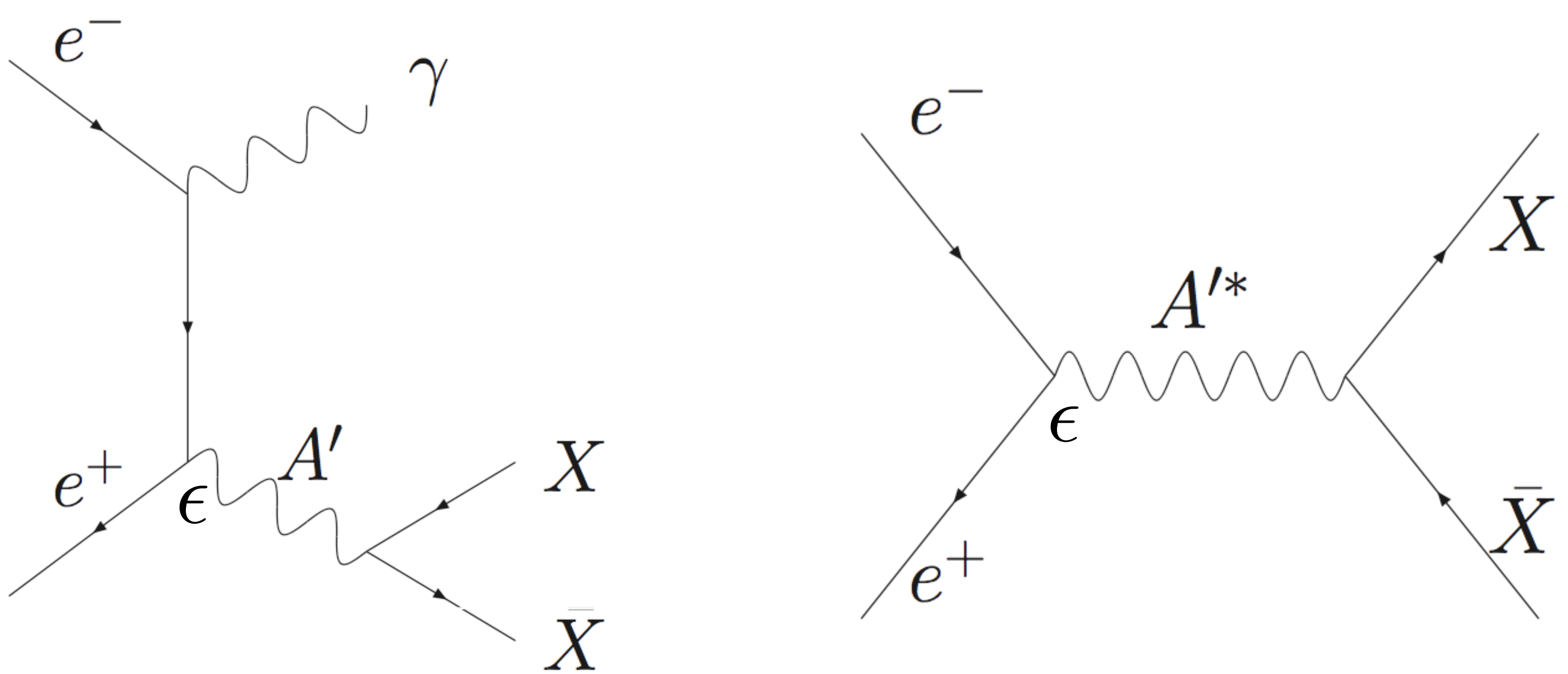
$$\ell = \mu, \tau$$

$$\tau \rightarrow \mu\nu_\mu\nu_\tau$$

$$\mu \rightarrow e\nu_e\nu_\mu$$

Searches underway, nothing conclusive yet.

Direct Searches: production



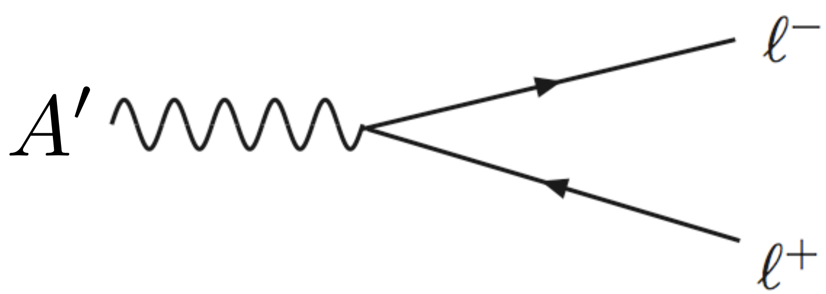
Essig, Schuster, Toro
Batell, Pospelov, Ritz
Reece, Wang

X = Standard Model or hidden-sector particle

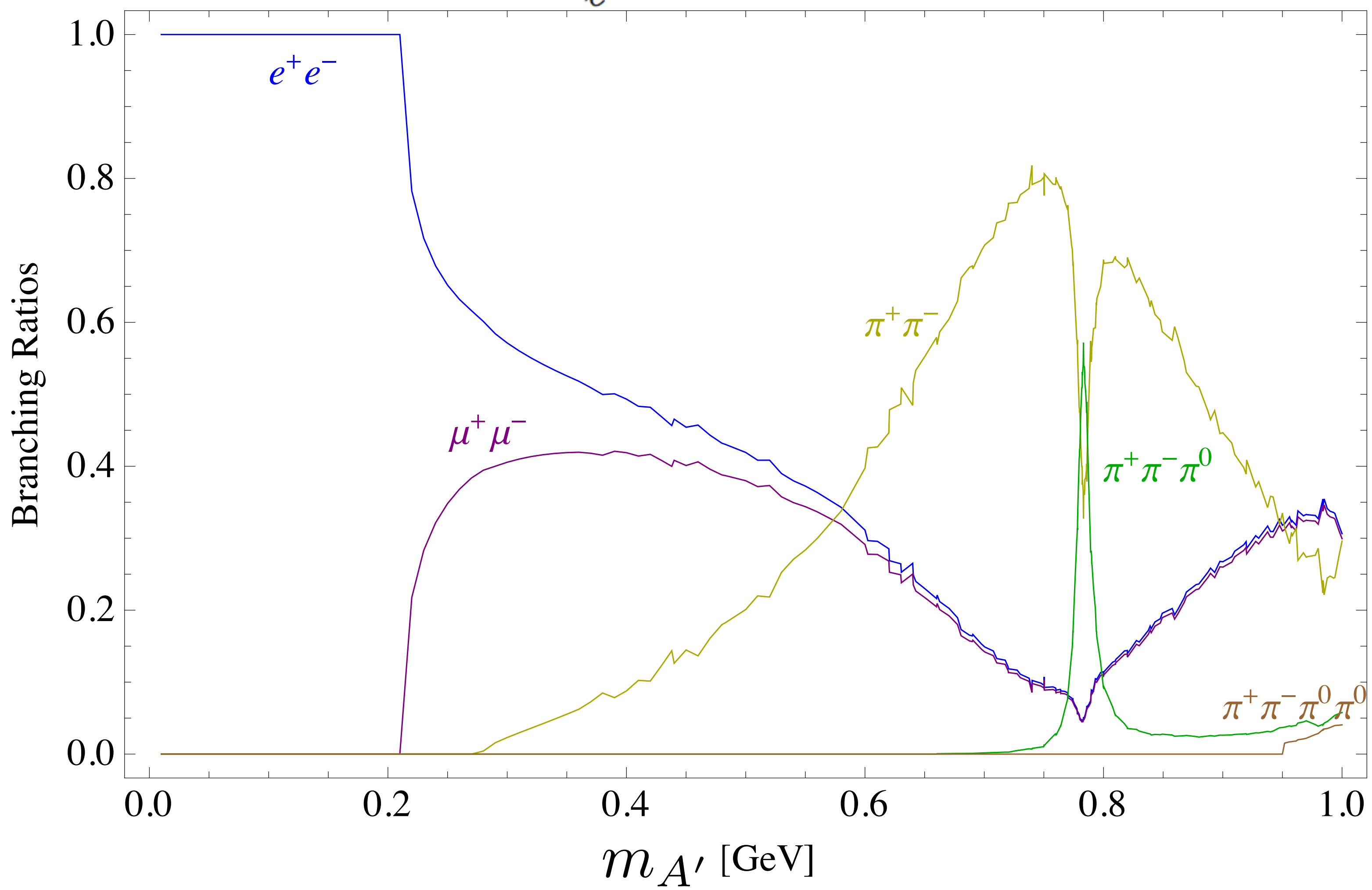
$$\sigma \propto \frac{\epsilon^2}{E_{cm}^2} \Longrightarrow$$ want low-energy, high-luminosity collider

(BaBar, BELLE, KLOE, CLEO-c, BESIII, ...)

A′ Decays

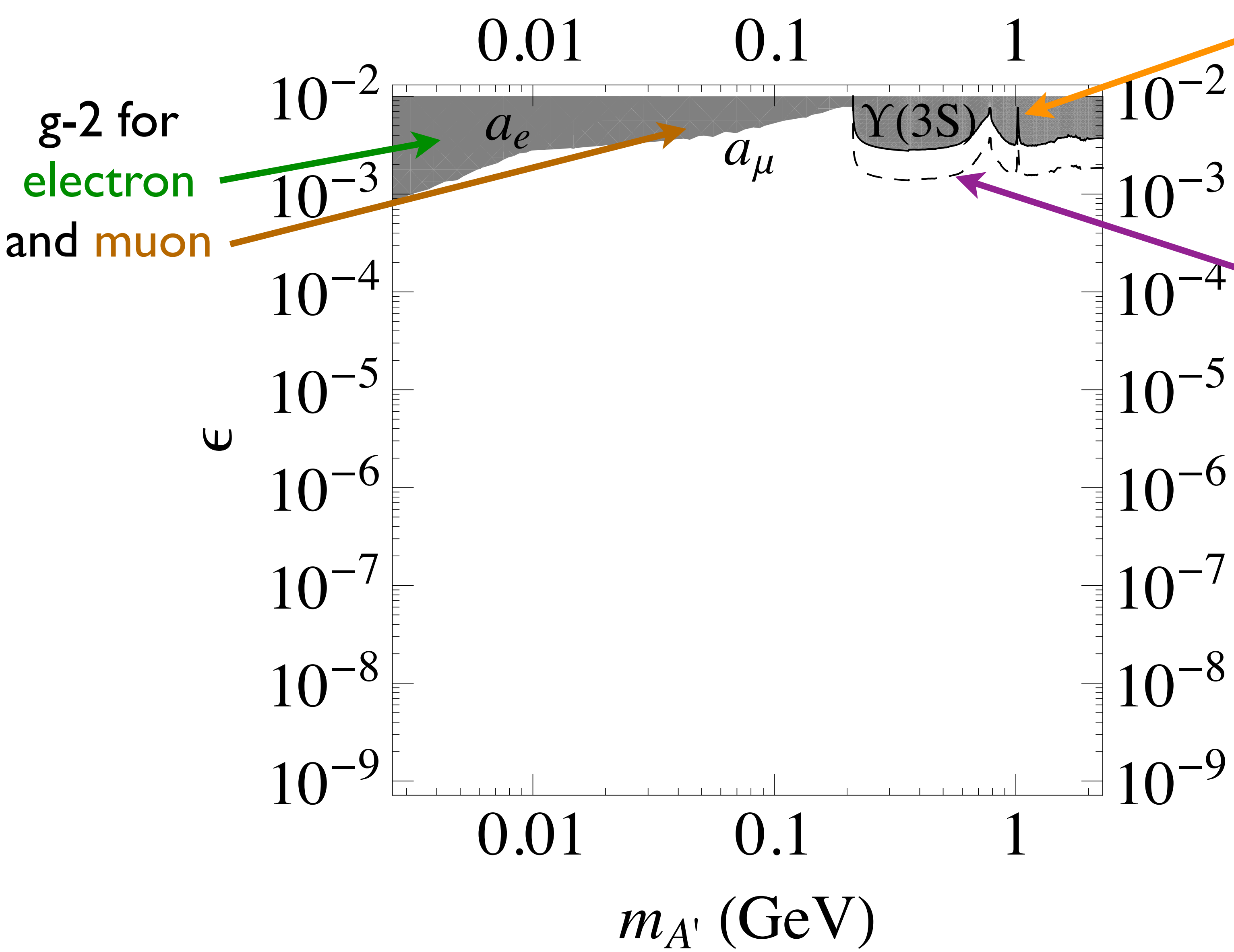


Can decay directly to Standard Model



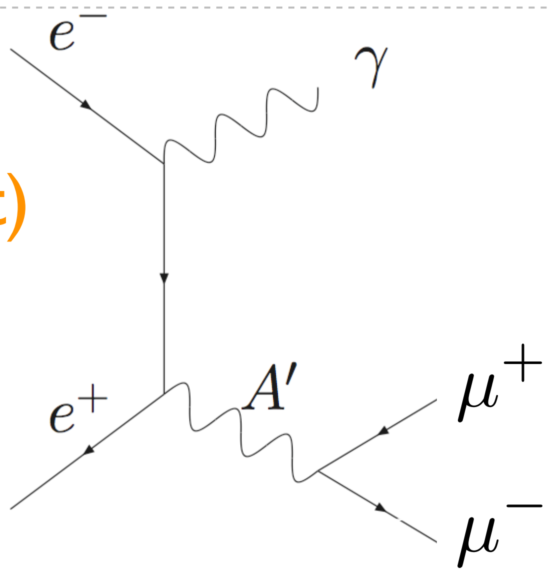
[used without permission from Meade]

Direct Searches: e^+e^-



BaBar $\gamma\mu^+\mu^-$
(partial data set)
Done

Belle
(full dataset)
not yet



Direct Searches: meson decays

$\pi^0 \to \gamma A' \to \gamma e^+ e^-$

BaBar $\sim$ few $\times\ 10^9\ \pi^0$

(analysis ongoing)

KTeV $\sim 10^{10}\ \pi^0$

(sensitivity [over?]estimated)

$\phi \to \eta A' \to \eta e^+ e^-$

KLOE $\sim 10^{10}\ \eta^0$

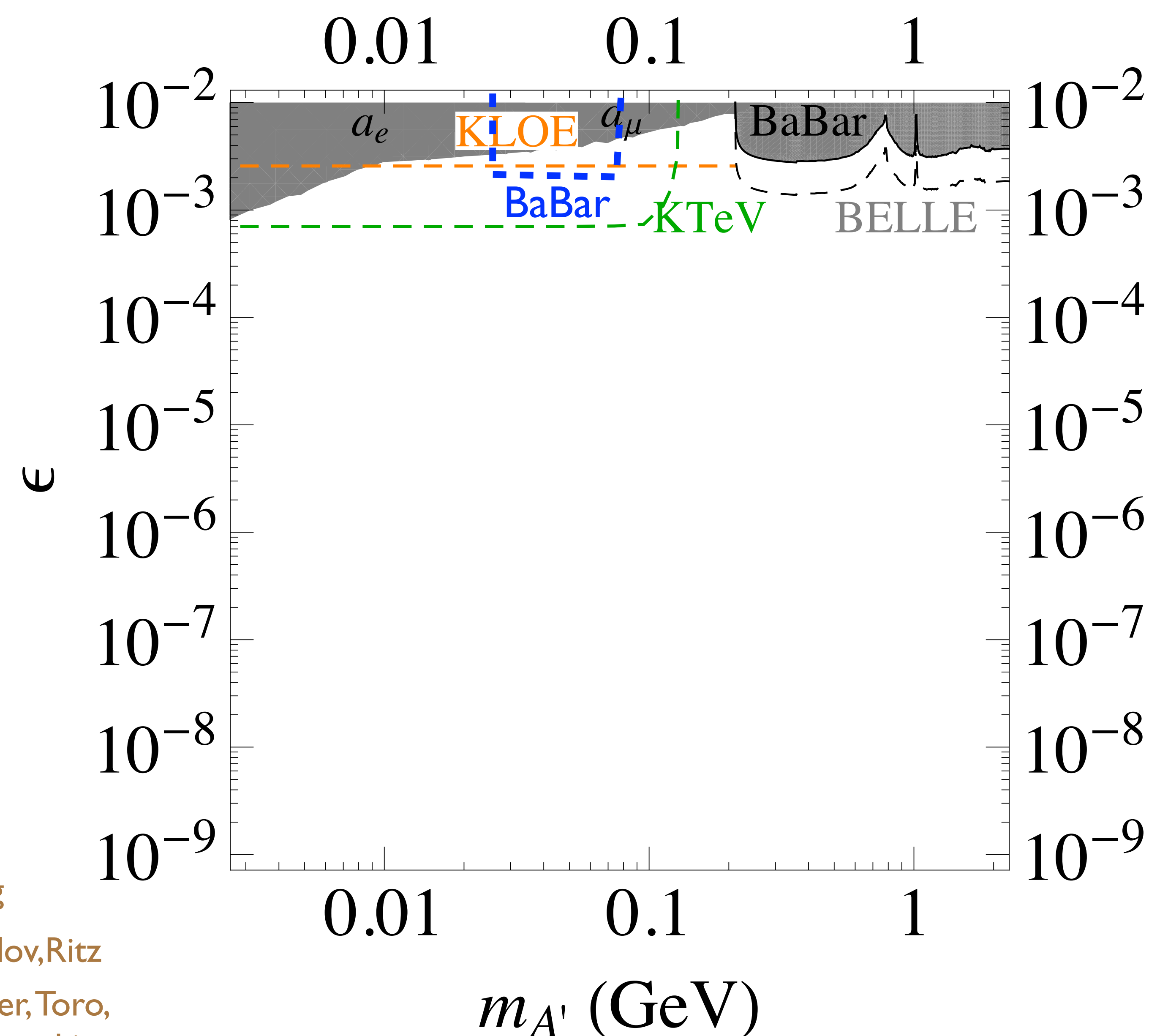
(analysis underway)

Pospelov

Reece, Wang

Batell, Pospelov, Ritz

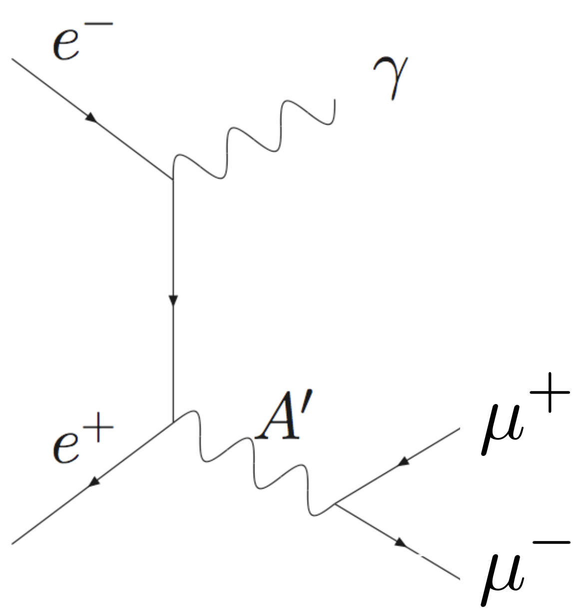
Essig, Schuster, Toro, Wojtsekhowski

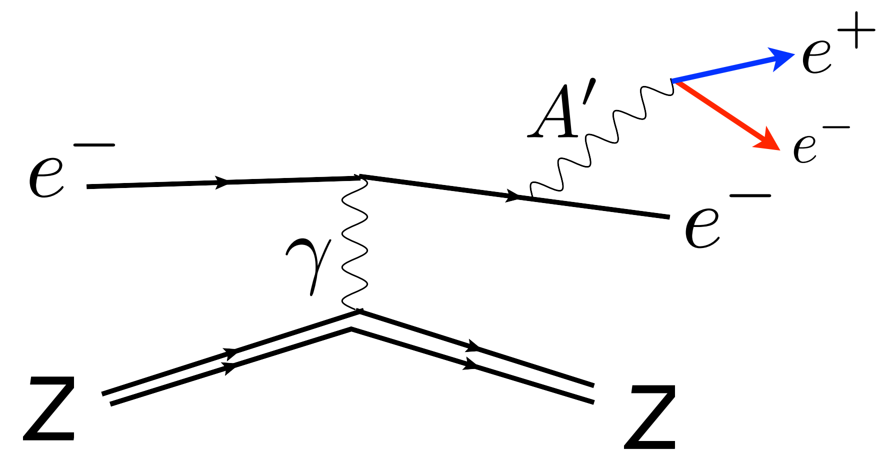


Fixed Target

[Bjorken, Essig, Schuster, Toro]
[Batell, Pospelov, Ritz]
[Reece & Wang]

Collider vs. Fixed Target





$$\sigma \sim \frac{\alpha^2 \epsilon^2}{E^2} \sim O(10\ fb)$$

$$\sigma \sim \frac{\alpha^3 Z^2 \epsilon^2}{m^2} \sim O(10\ pb)$$

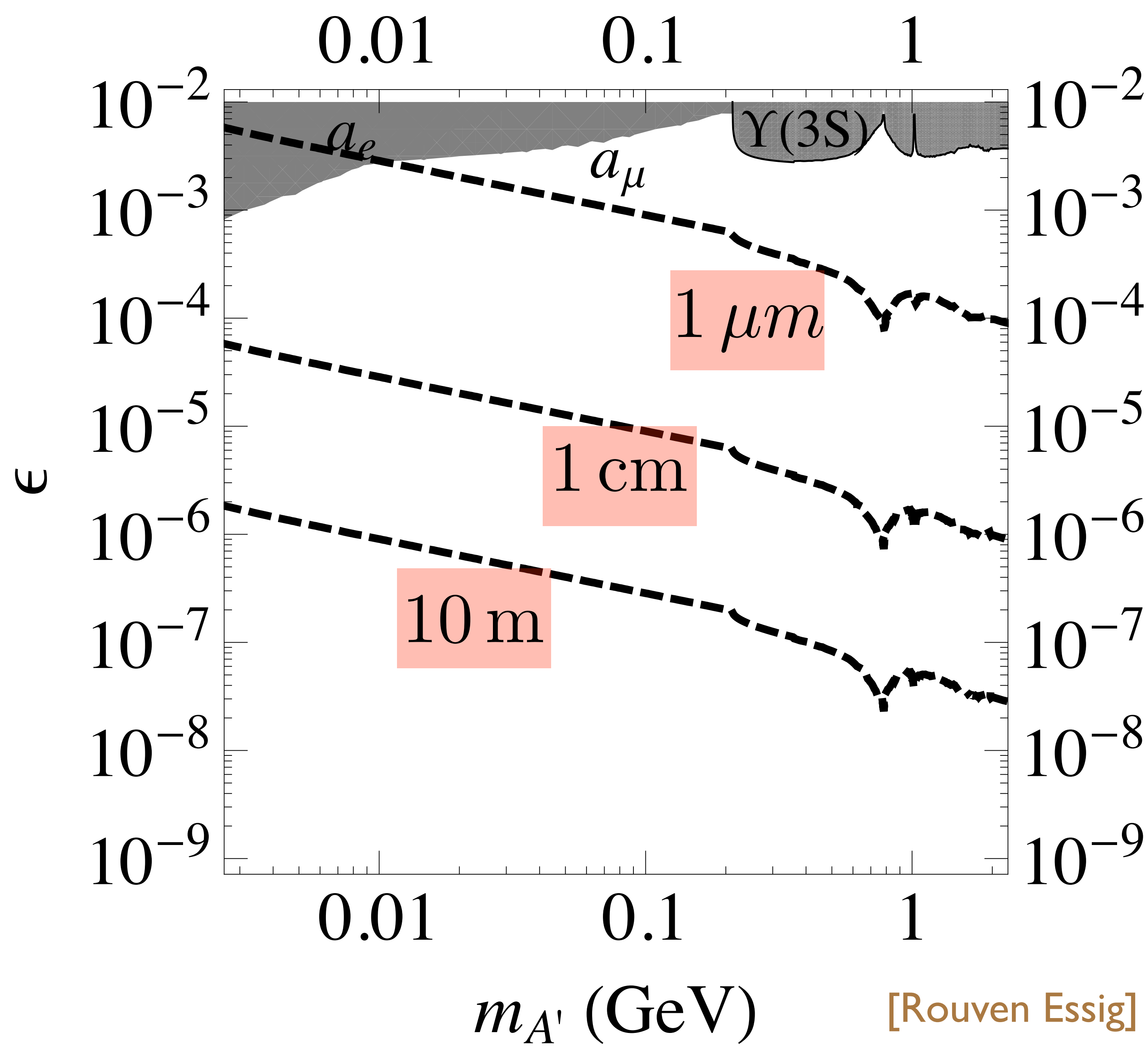
$O\ ab^{-1}$ per decade

$O\ ab^{-1}$ per day

A′ Lifetime

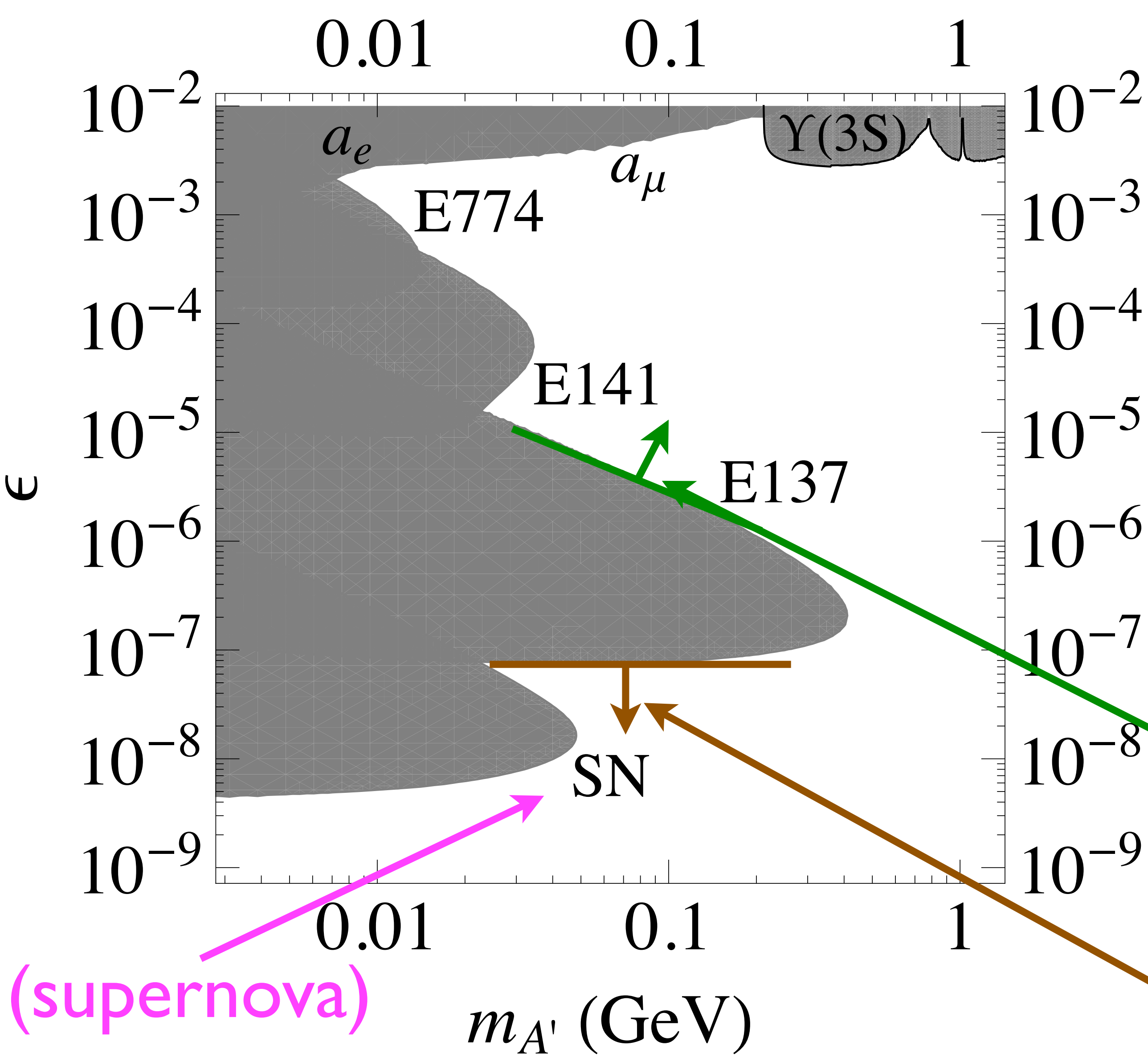
$$\gamma c\tau \propto \left(\frac{10^{-4}}{\epsilon}\right)^2 \left(\frac{100\ \mathrm{MeV}}{m_{A'}}\right)^2$$

At small couplings,
A′ is long-lived!



[Rouven Essig]

Fixed Target: Beam Dump



(supernova)

[Bjorken, Essig, Schuster, Toro]

	Shield (m)	E_{beam} (GeV)	Lumi (e^-)
E137	200	20	10^{20}
E141	0.12	9	2×10^{15}
E774	0.3	275	5×10^{9}

- A′ decay products decay in shield (since lifetime too small)
- luminosity too small (since cross-section too small)

New Experiments?

HIPS: e⁻ beam dump at DESY

[A. Ringwald, S. Andreas, E. Garutti, P. Bechtle, A. Lindner, C. Niebuhr, S. Ghazaryan, H. Ehrlichmann]

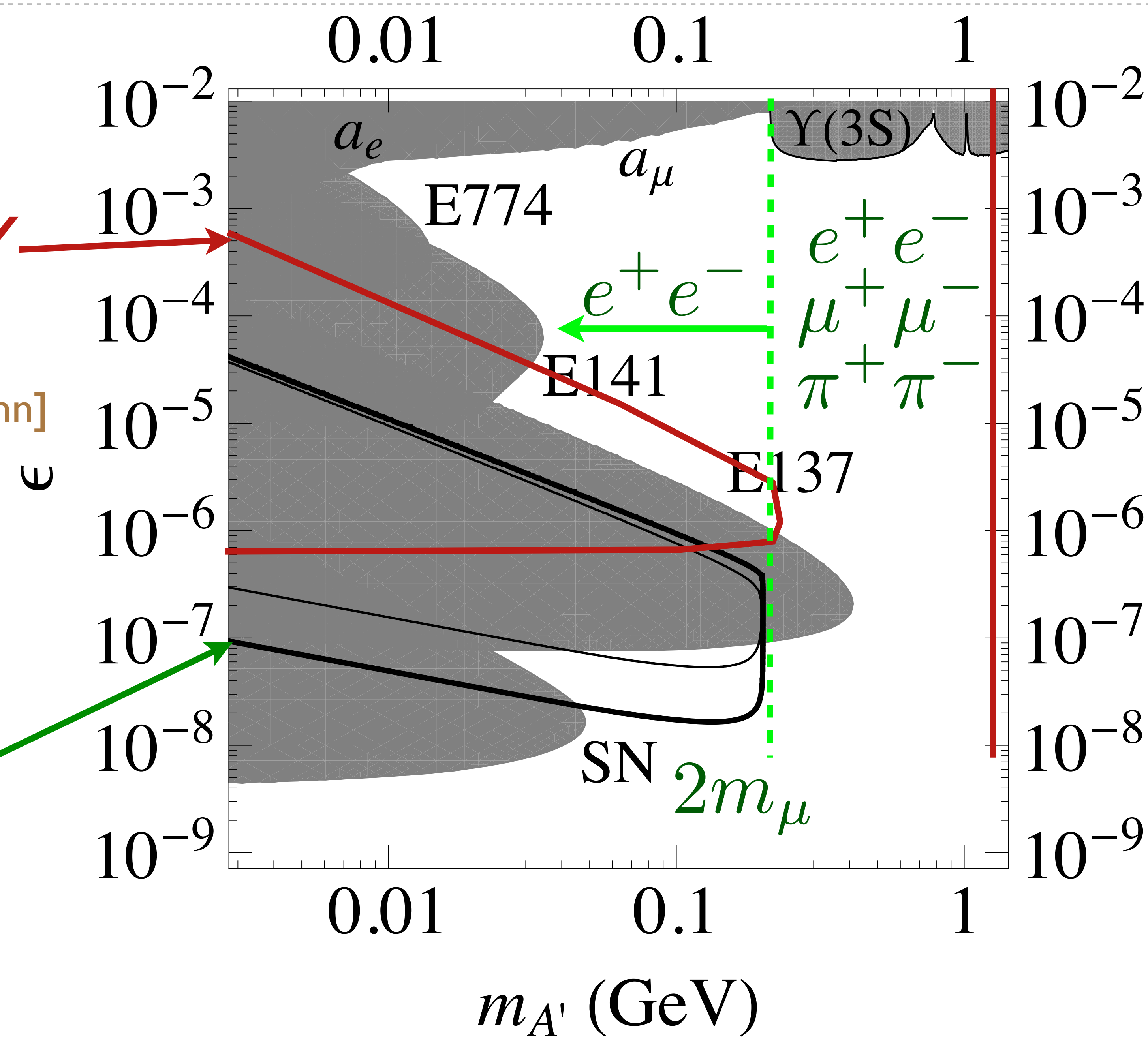
Proton beam dumps

$$\pi^0 \to \gamma A' \to \gamma e^+ e^-$$

e.g. LSND ~ 10^{22} pions

[Batell, Pospelov, Ritz]

[Essig, Harnik, Kaplan, Toro]

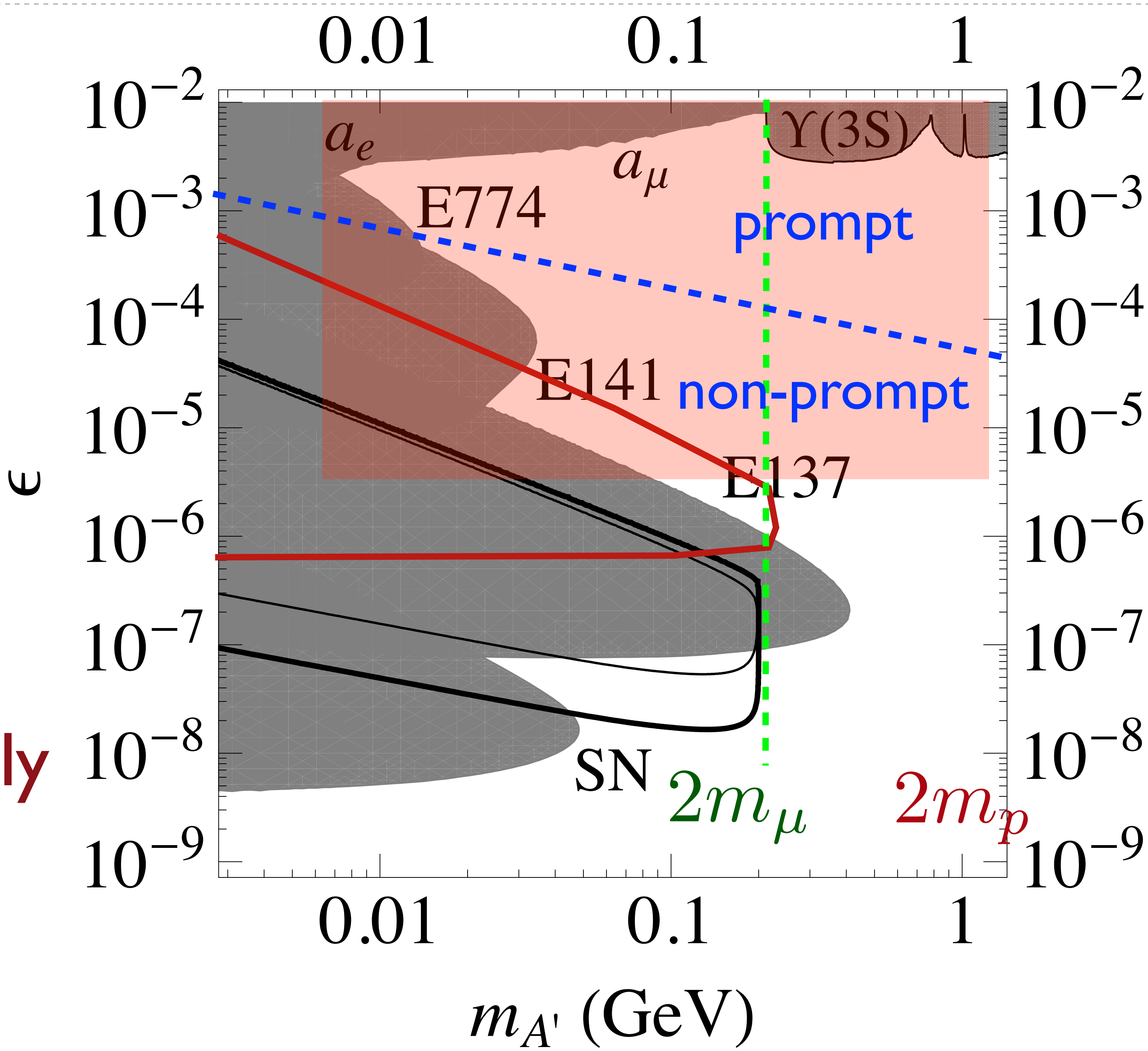


New Experiments?

In simple models, expect:

- $\epsilon \sim 10^{-5} - 10^{-2}$
- $m_{A'} \sim \sqrt{\epsilon} M_W \sim \text{MeV} - \text{GeV}$ for Higgs-like U(1)′ breaking.

An interesting region not easily explored with beam dumps!



HPS: The Elevator Pitch

Sensitivity in this region relies upon abilities to *precisely*...

- determine invariant mass of A' decay products (estimate momentum vectors)
- distinguish A' decay vertexes as non-prompt (extrapolate tracks to origin)

Placement of a tracking and vertexing system immediately downstream from a target and inside an analyzing magnet provides both measurements with high acceptance from a single, relatively compact detector.

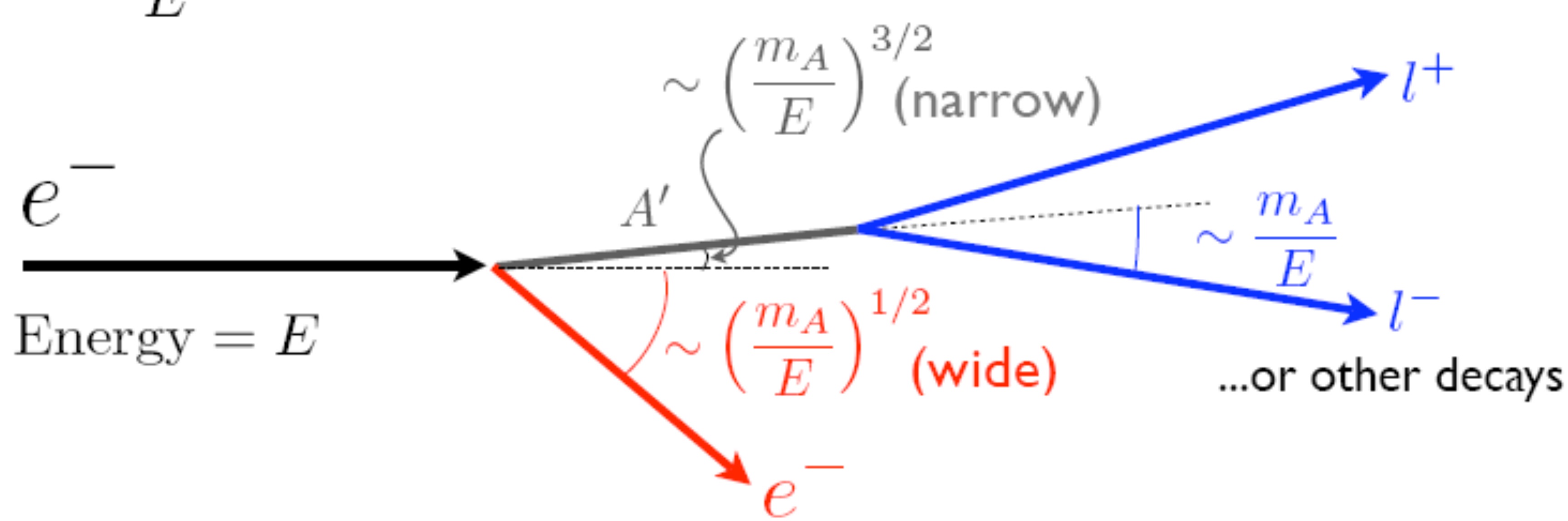
"If they don't like our proposal I'll show them the kittens. Everybody likes kittens."

Fixed Target A′ Kinematics

$$\frac{d\sigma}{dx} \propto \frac{\alpha^3}{\pi} \frac{\epsilon^2}{m_e^2 \cdot x + m_A^2 (1-x)/x}$$

$$x = \frac{E_A}{E}$$

Kinematics **very different** from massless photon bremsstrahlung

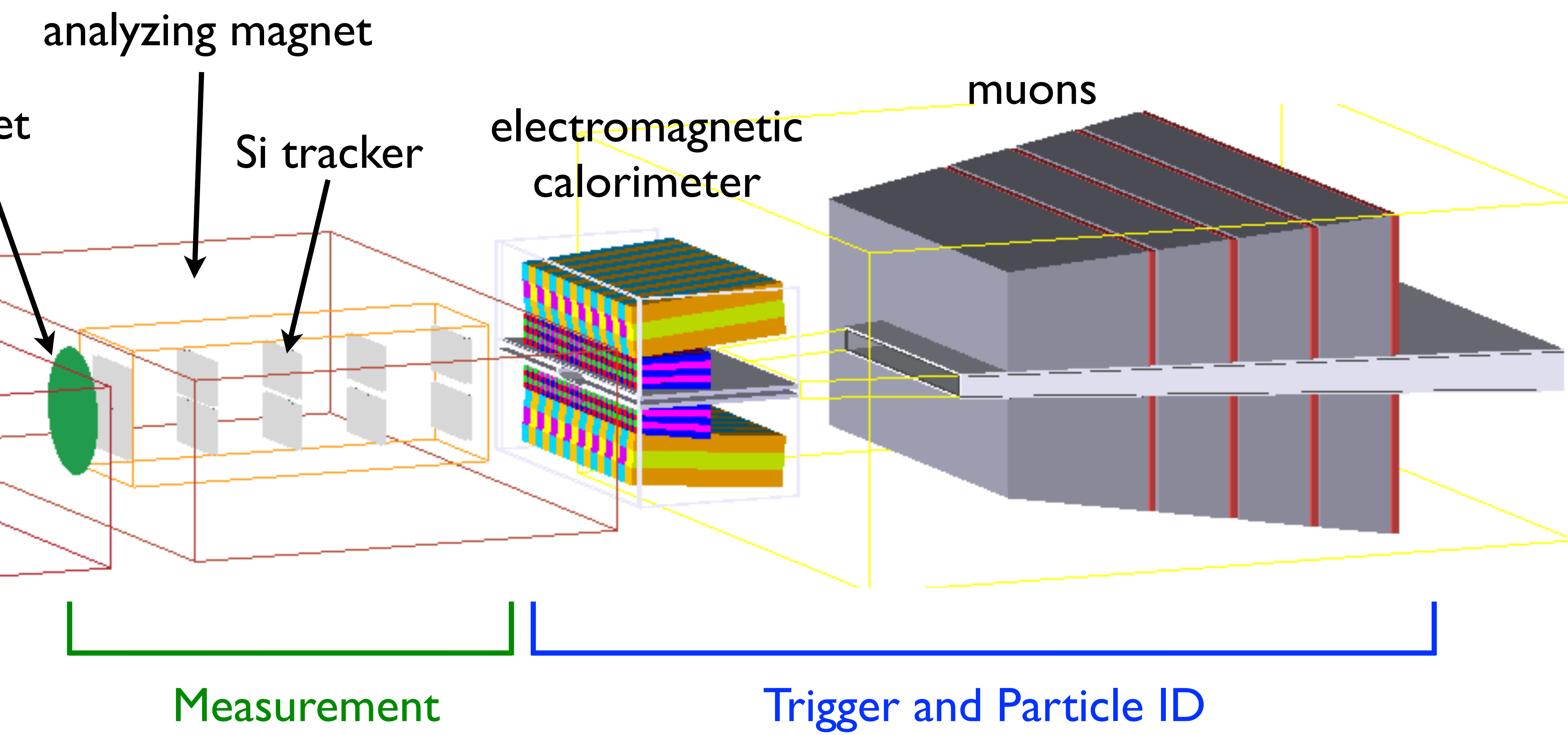


Heavier product (here A') takes most of beam energy

$E_A \sim E - m_A$
$E_e \sim m_A$

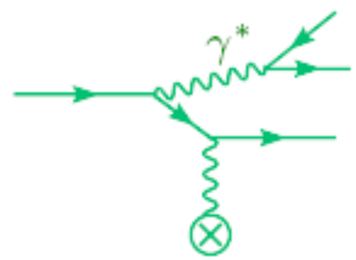
Efficient reconstruction of A' decays needs large, forward acceptance:
$\theta_{decay} = m_{A'}/E_{A'}$ (~200 MeV/6 GeV = 33 mrad)

HPS Concept

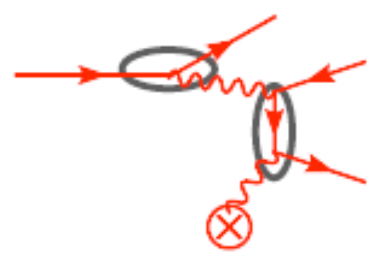

analyzing magnet
target
Si tracker
electromagnetic
calorimeter
muons
Measurement
Trigger and Particle ID

Backgrounds

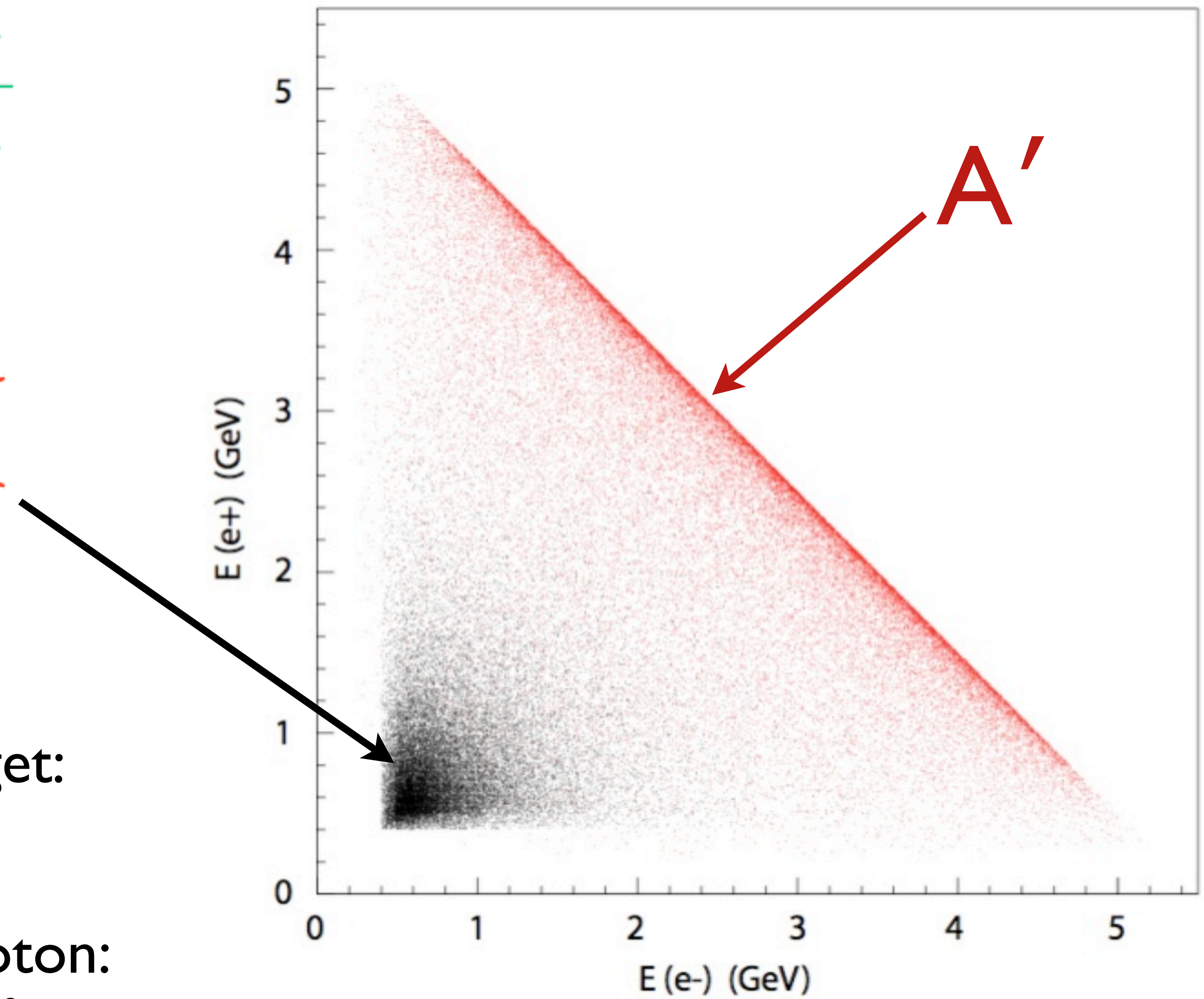
- virtual photon conversion: irreducible



- Bethe-Heitler: dominant



- multiple coulomb scattering in target
- secondary particle production in target: bremstrahlung and delta-rays
- pair conversion of bremstrahlung photon: two-step process: α (target thickness)^2



Experimental Requirements

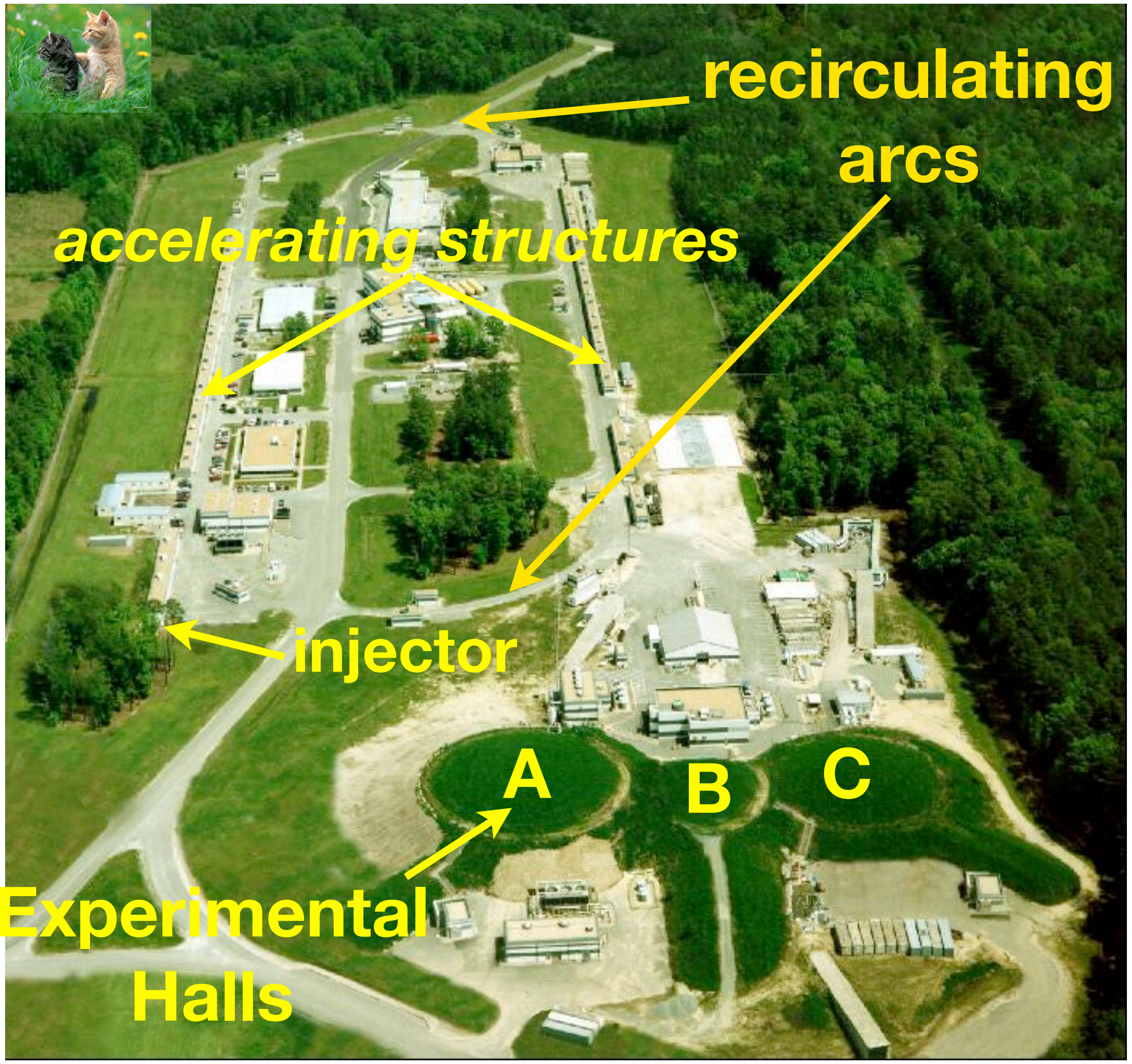
- Thin targets need to reduce backgrounds require high beam current to probe small cross sections: Q_{tot} ~ 1C for T=0.25% X_0
- Manageable occupancies require ~DC beam to spread out background from 1C of angry electrons as much as possible.
- Need fast detectors and electronics, fast and efficient trigger algorithms
- Good mass and vertex resolution are at the heart of sensitivity

CEBAF at JLab

Simultaneous delivery of electron beams at different energies and intensities in three experimental halls.

- $E_{\text{beam}} = n \times 1.1$ GeV, n≤5 (5.5 GeV Max)
- $I_{\text{beam}} < 100\ \mu$A (A&C), <300 nA (B)
- bunch separation: 2.004 ns
- energy upgrade complete 2014: $E_{\text{beam}} = n \times 2.2$ GeV, n≤5 (11 GeV max)

Ideal for this experiment.

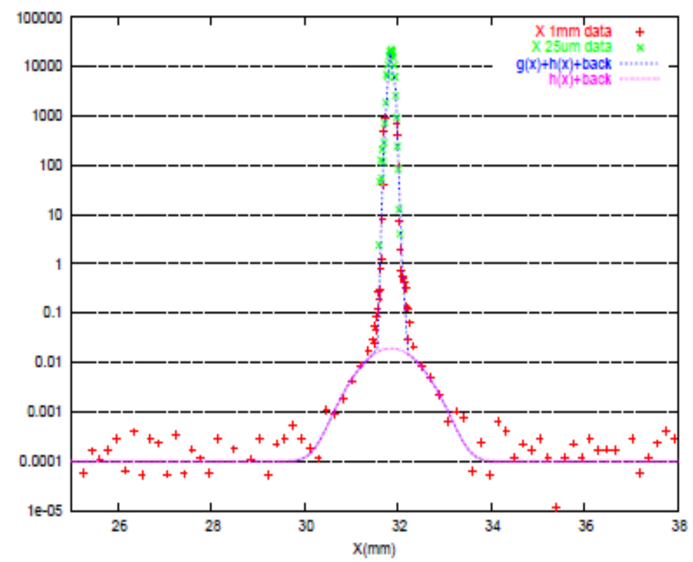


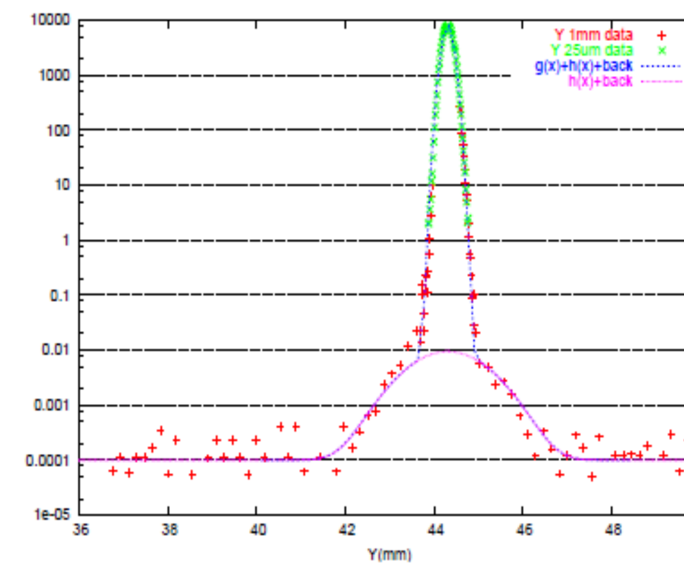
JLAB

Beamline

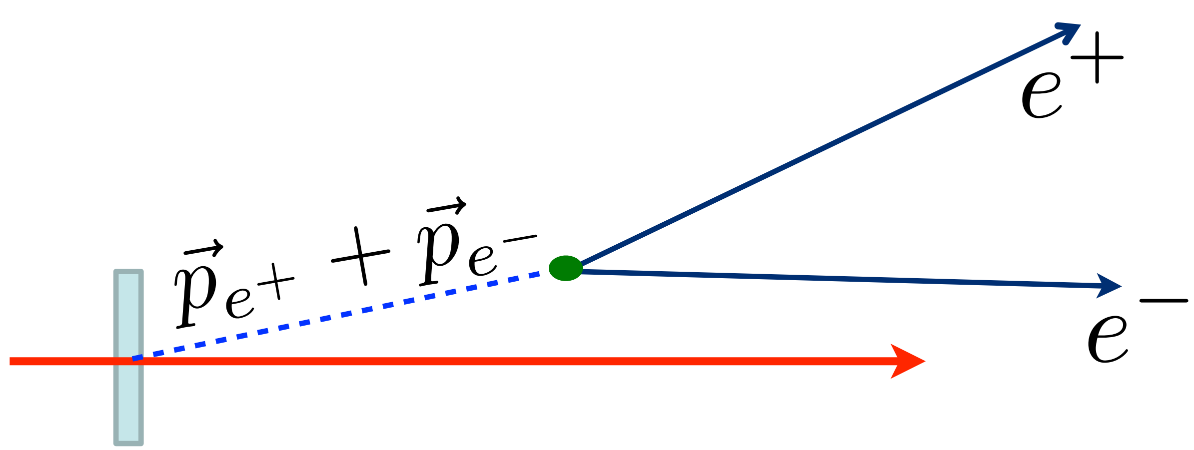
- Excellent beam quality, stability

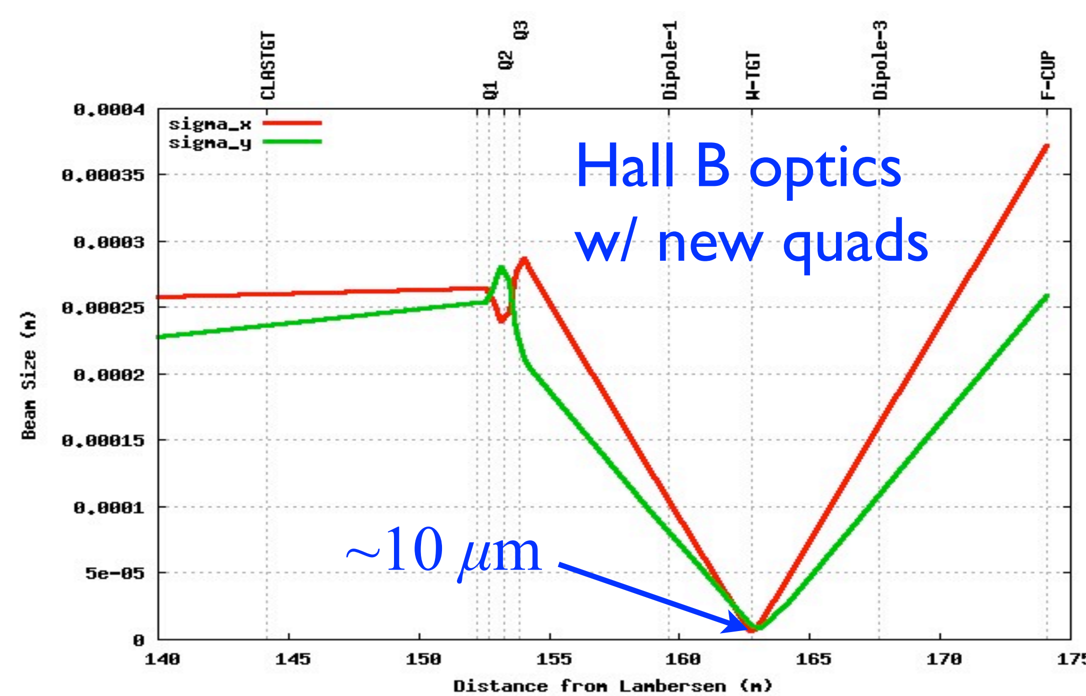
Beam Tail ~ 10^{-5}





- $10\ \mu m$ spot possible with additional quads: constrains A′ trajectory, reducing background





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Tracking/Vertexing Challenges

- At relevant beam energies and interesting A' masses, decay products tend to be electrons with momenta order a few GeV. Multiple scattering...
  - dominates both mass and vertexing measurement errors
  - leads to pattern recognition mistakes in dense environments
- Proximity to target means primary beam must pass through apparatus.
  - scattered beam sweeps out a "dead zone" of extreme occupancy and radiation, compounded by beam-gas interactions
  - puts low-mass acceptance in opposition to longevity and tracking purity
- Long-lived A' signal very small: vertexing must be exceedingly pure to eliminate fakes.

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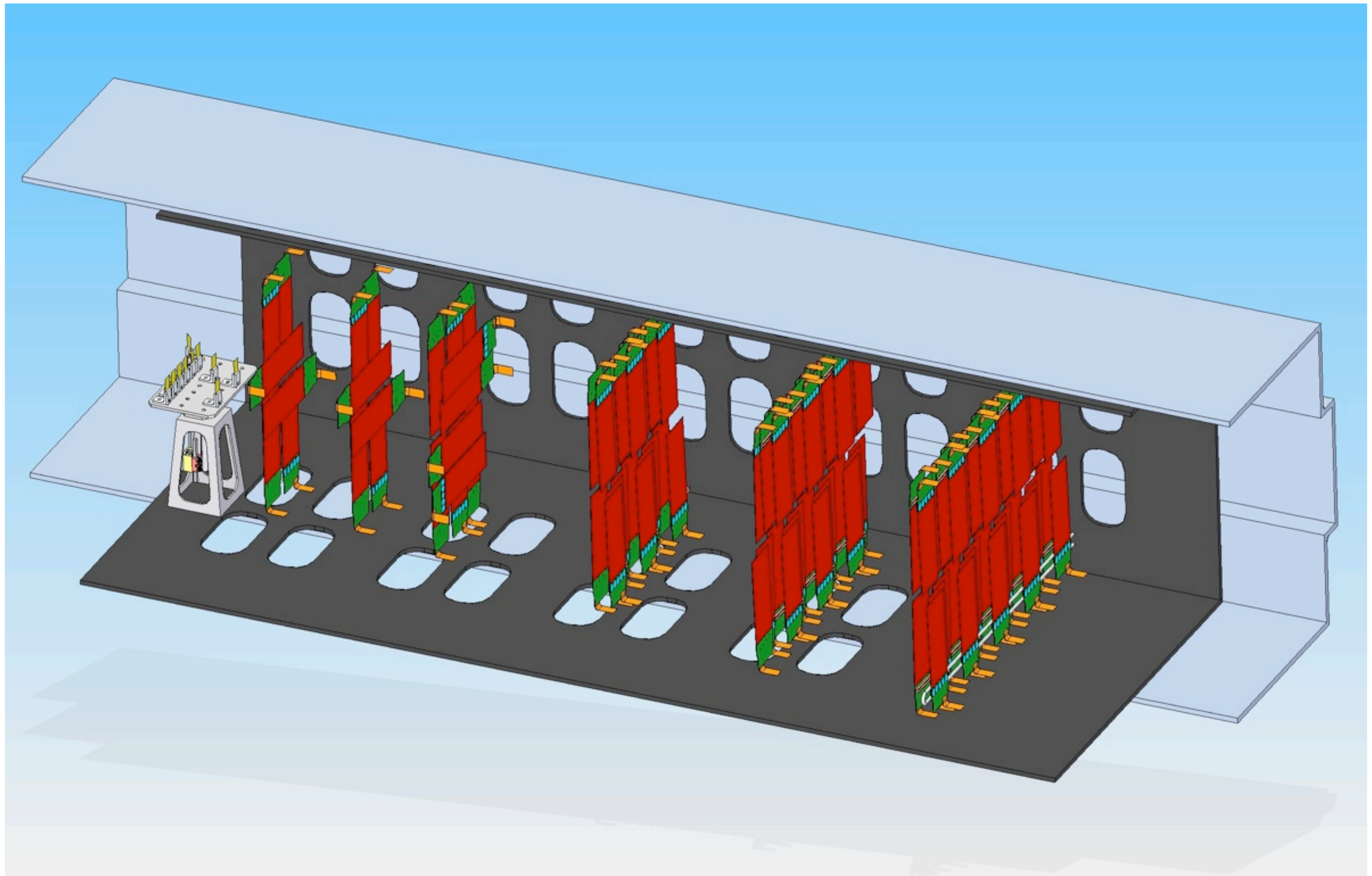
Challenges ⇒ Design Principles

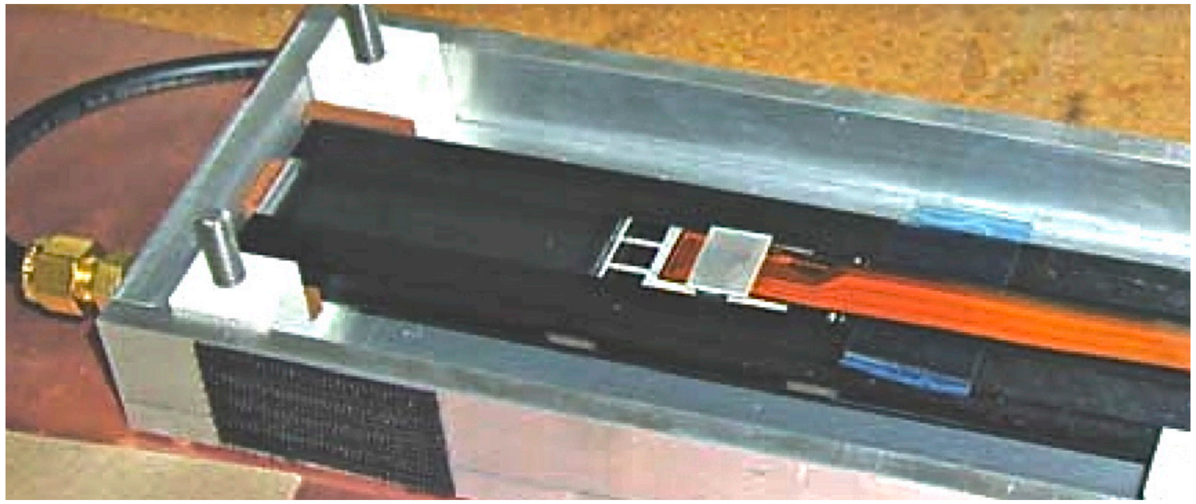
- Mass and vertex resolution
  - low-mass construction
- Occupancies and radiation
  - fast, robust sensors / readout
  - movability / replaceability
  - operation in vacuum
- Acceptance/Purity
  - optimized sensor layout



FNAL

Light, Fast, Robust Sensors

- pixels too massive, costly, complex: microstrips are the simple, lightweight solution
- Production Tevatron RunIIb sensors
  - many capable of 1000V bias: fully depleted to $> 4\times10^{15}$ e$^-$/cm^2
  - Fine readout granularity
  - Available in sufficient quantity



Cut Dimensions (L×W)	100 mm × 40.34mm
Active Area (L×W)	98.33 mm × 38.34mm
Readout (Sense) Pitch	60μm (30μm)
# Readout (Sense) Strips	639 (1277)
Breakdown Voltage	>350V
Total Interstrip Capacitance	<1.2 pF/cm
Defective Channels	<1%

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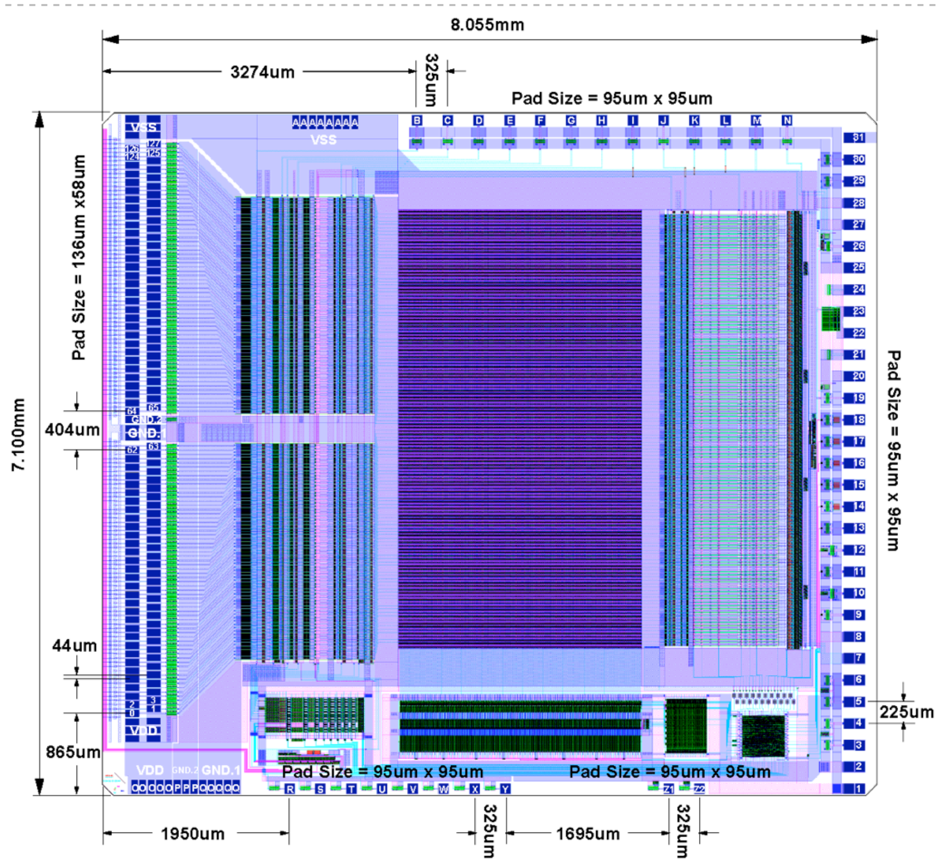
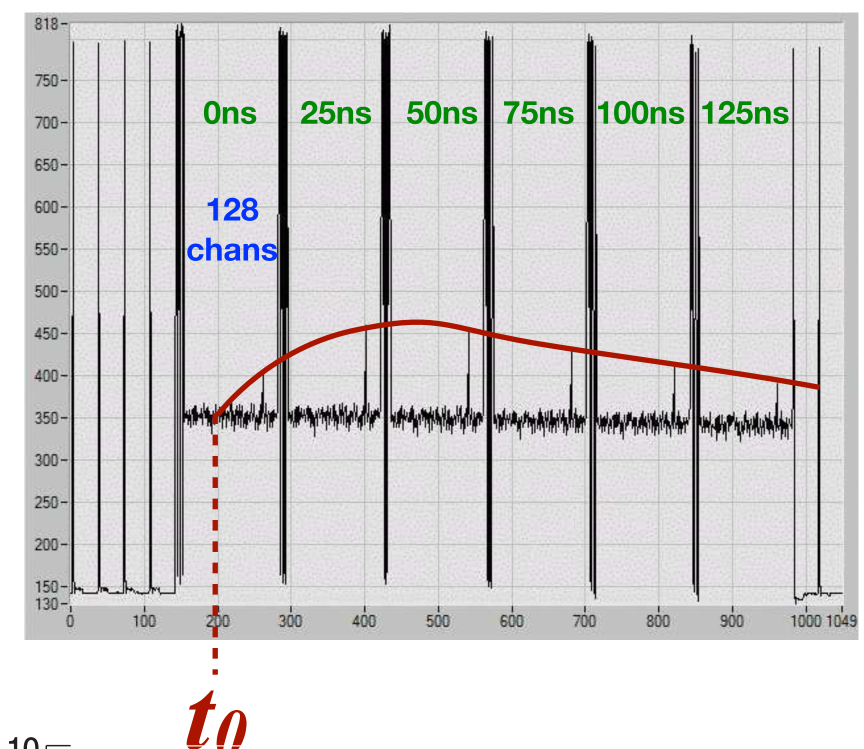
Fast Readout Electronics: APV25

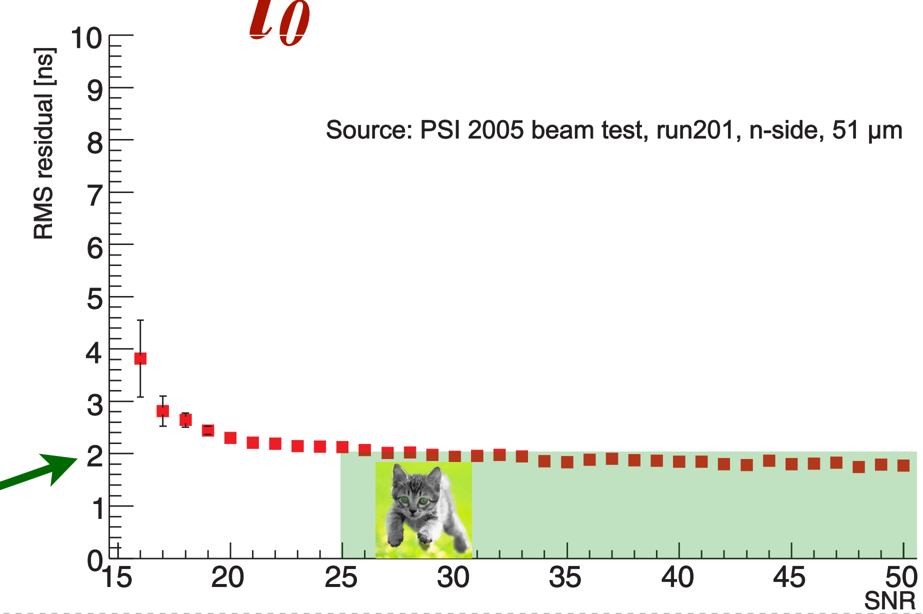


Developed for CMS

- readily available
- radiation tolerant
- low noise: S/N = 34
- 2 ns t_0 resolution

# Readout Channels	**128**
Input Pitch	**44 µm**
Shaping Time	**50ns nom. (35ns min.)**
Noise Performance	**270+36×C(pF) e⁻ ENC**
Power Consumption	**345 mW**





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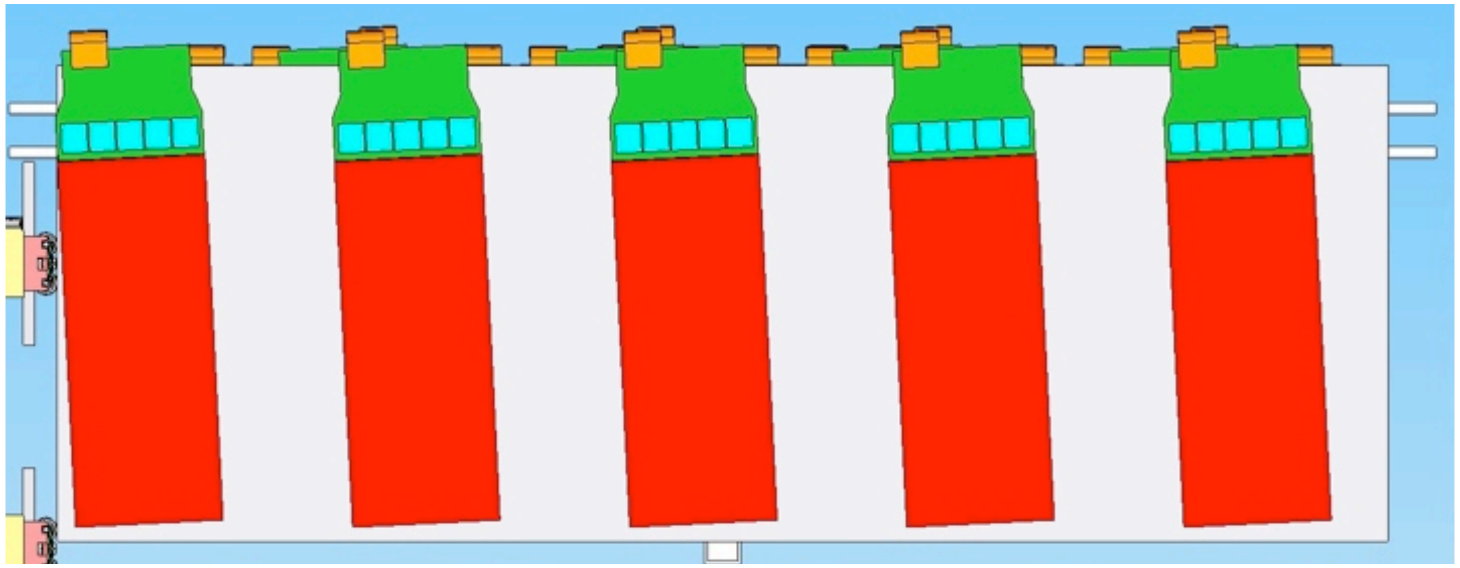
Low Mass Support/Cooling

- CF-composite/rohacell-foam
  - 1.0% X_0/layer
  - dominated by Si
- H_20/glycol at -10°C
  - outside tracking volume
  - vacuum minimizes heat load on sensors



	Radiation Length (mm)	Thickness (mm)	Coverage/Unit Acceptance	Scattering Material (% X_0)
Silicon	**93.6**	**0.320**	**1.2**	**0.410**
Rohacell Foam	13800	3.0	0.5	0.011
Carbon Fiber	242	0.150	0.5	0.031
PGS Passivation	256	0.101	1.25	0.049
Epoxy	290	0.050	0.5	0.009
Total	-	-	-	**0.510**

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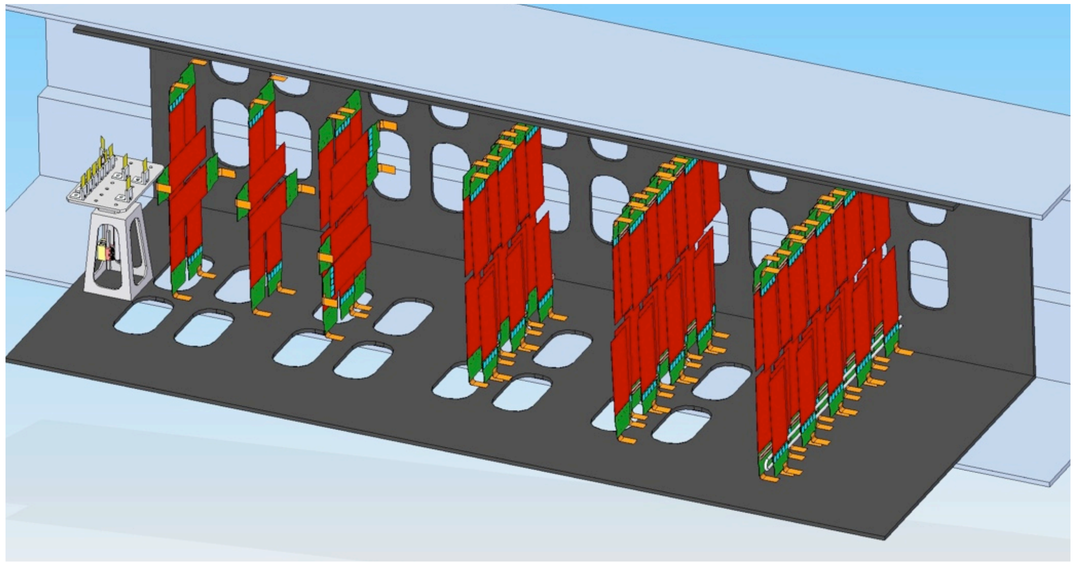
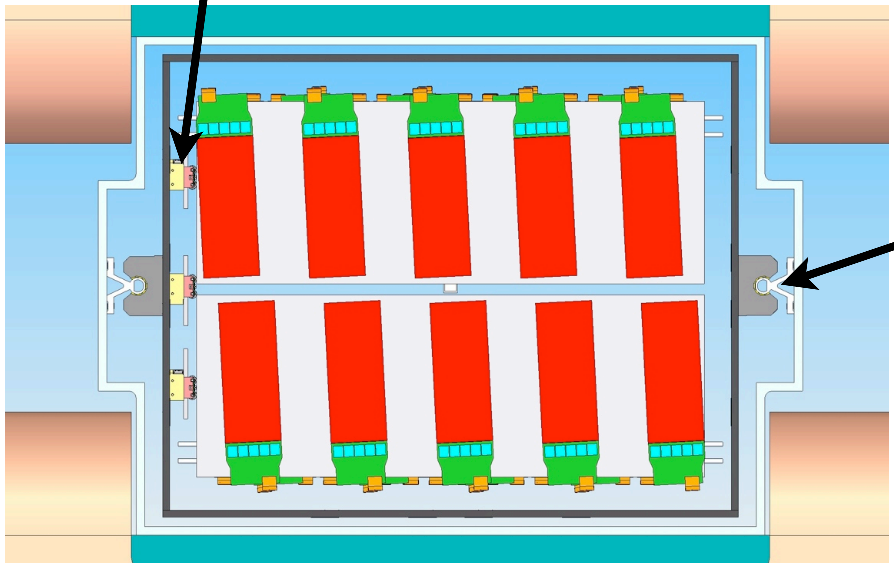
Moveable/Replaceable

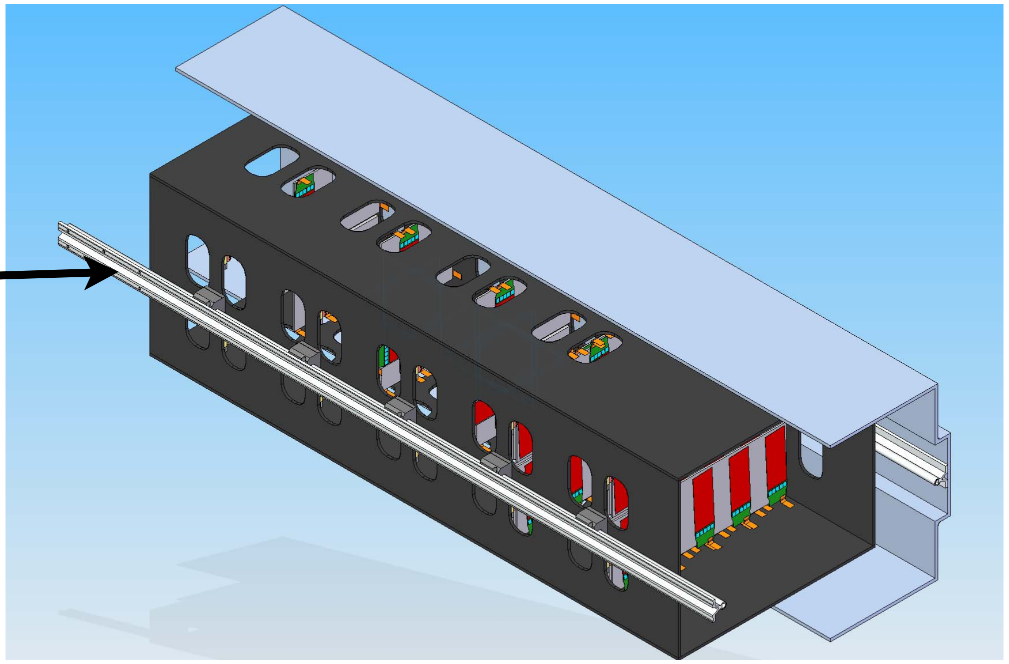


carbon fiber support box inside vacuum chamber

piezo motors allow retraction of planes



rail system for easy removal of tracker



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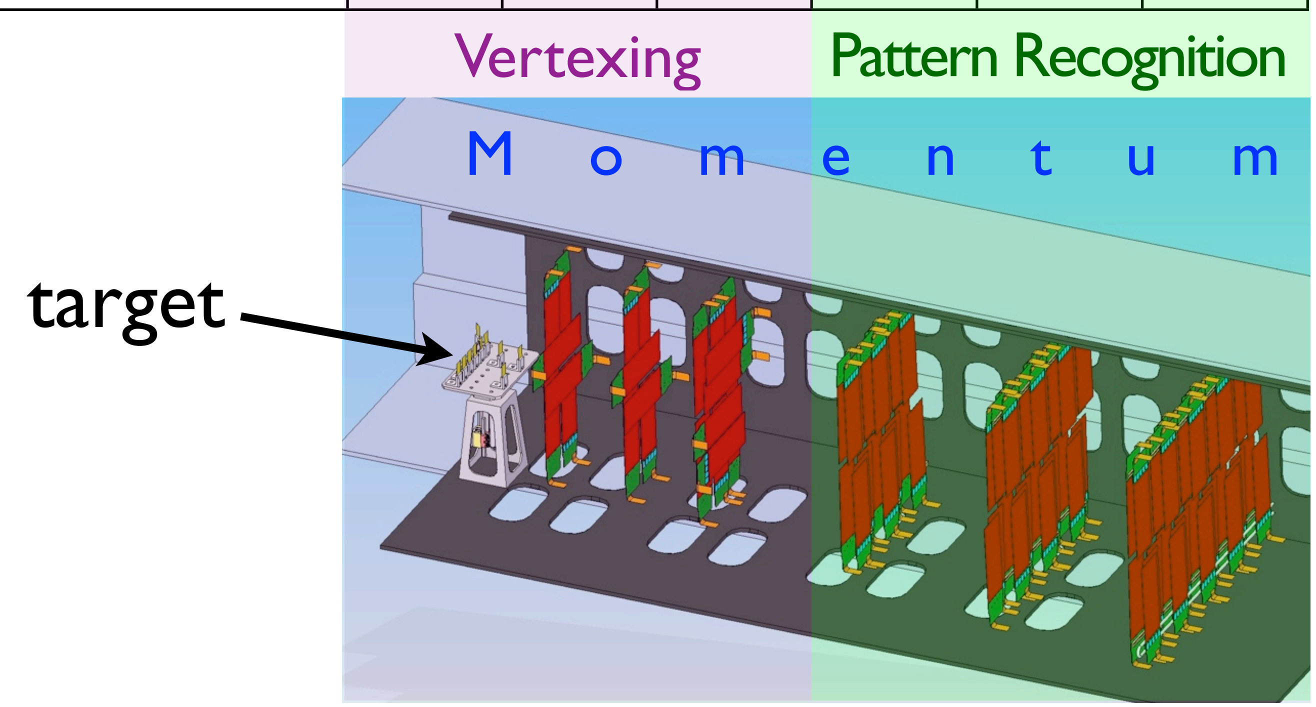
Detector Layout

- Layers 1-3: vertexing
- Layers 4-6: pattern recognition with adequate pointing into Layer 2.
- Bend plane measurement in all layers: momentum
- 106 sensors/hybrids
- 530 APV25 chips
- 67840 channels

	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6
z position, from target (cm)	10	20	30	50	70	90
Stereo Angle	90 deg.	90 deg.	90 deg.	50 mrad	50 mrad	50 mrad
Bend Plane Resolution (μm)	≈ 6	≈ 6	≈ 6	≈ 6	≈ 6	≈ 6
Stereo Resolution (μm)	≈ 6	≈ 6	≈ 6	≈ 120	≈ 120	≈ 120
# Bend Plane Sensors	4	4	6	10	14	18
# Stereo Sensors	2	2	4	10	14	18
Dead Zone (mm)	±1.5	±3.0	±4.5	±7.5	±10.5	±13.5
Power Consumption (W)	10.5	10.5	17.5	35	49	63



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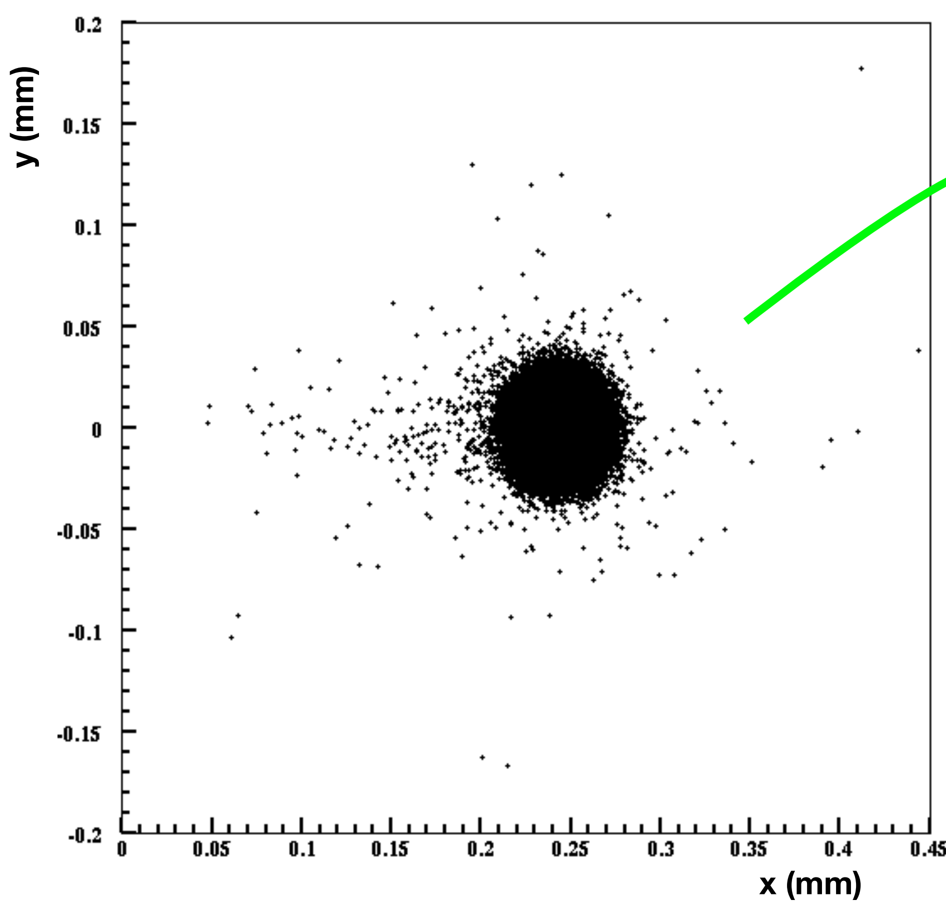
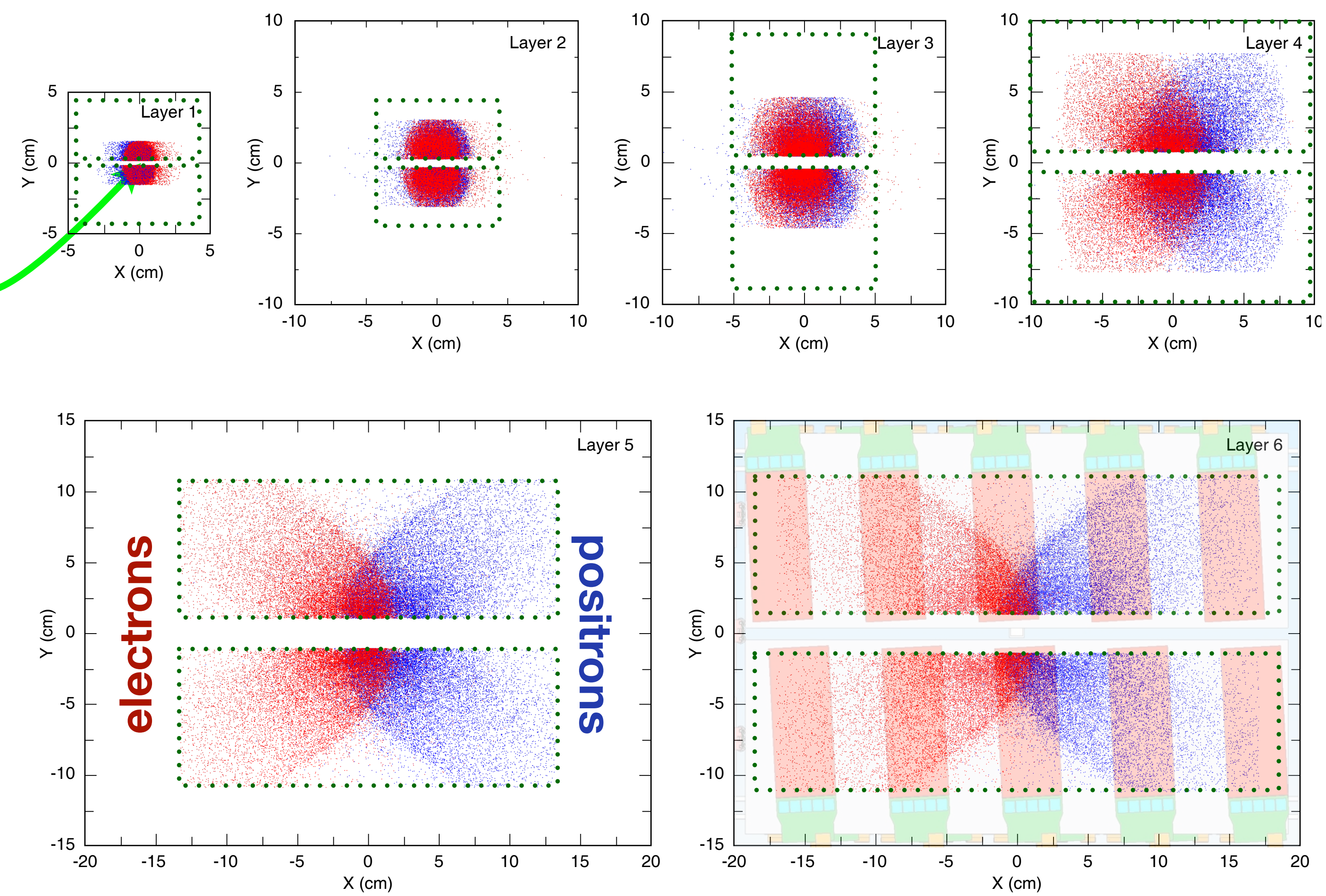
Dead Zone and Acceptance

Hits from A′ daughters within acceptance;
E_{beam}=5.5 GeV, $m_{A'}$ = 300 MeV/c^2

75 ns of beam at Layer 1





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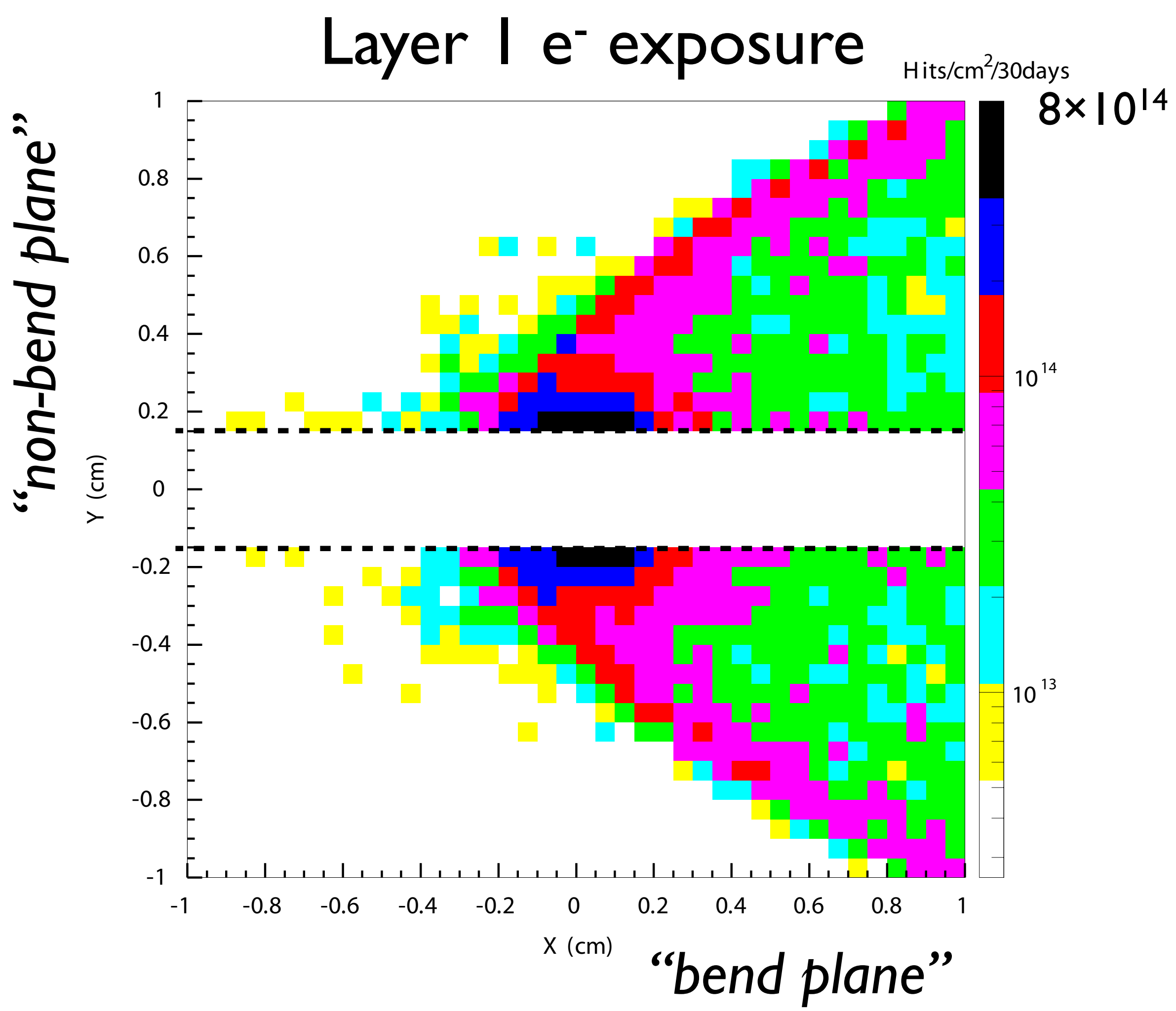
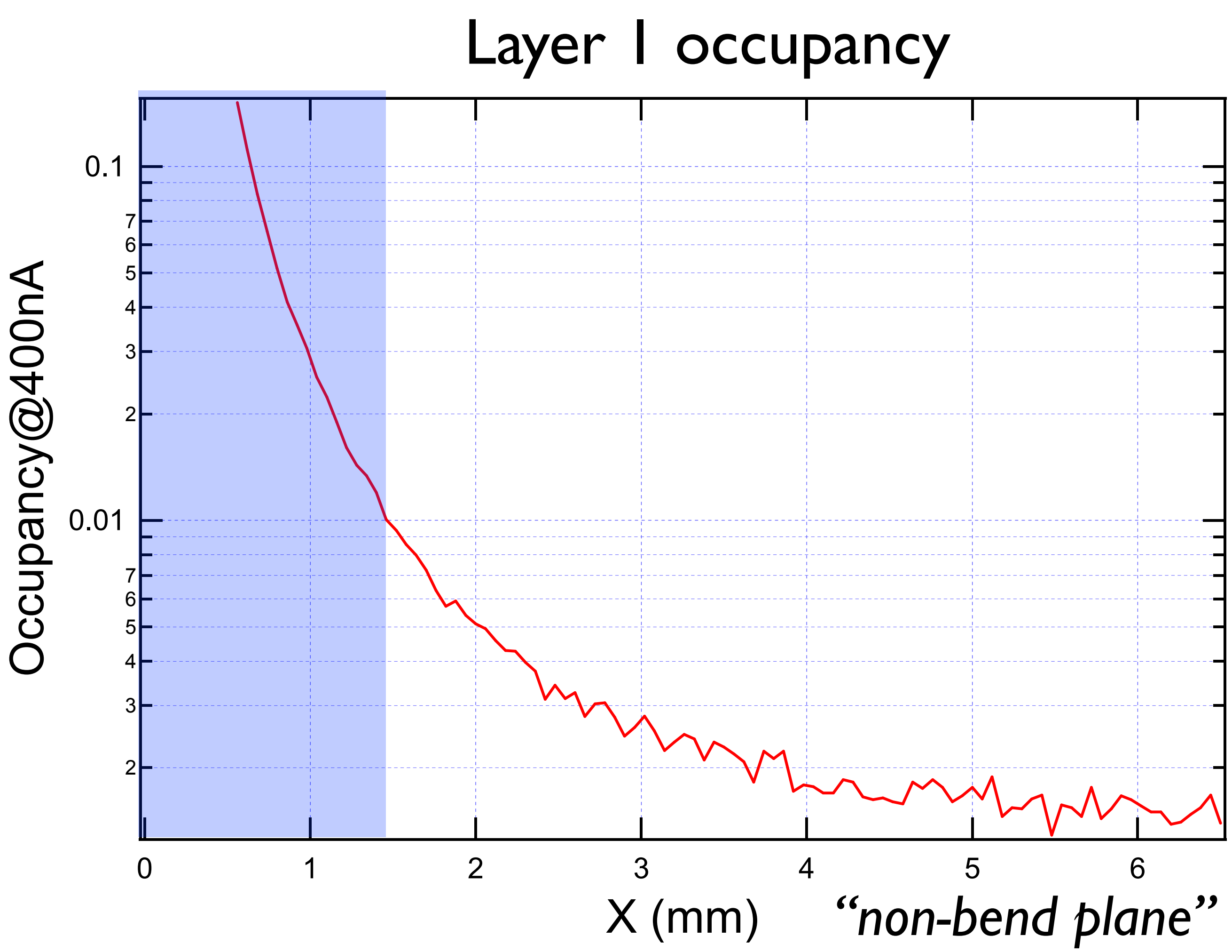
Dead Zone Limits





Layer 1 dead zone <±1.5 mm (15 mrad) allows for ~8 months running at acceptable occupancies.

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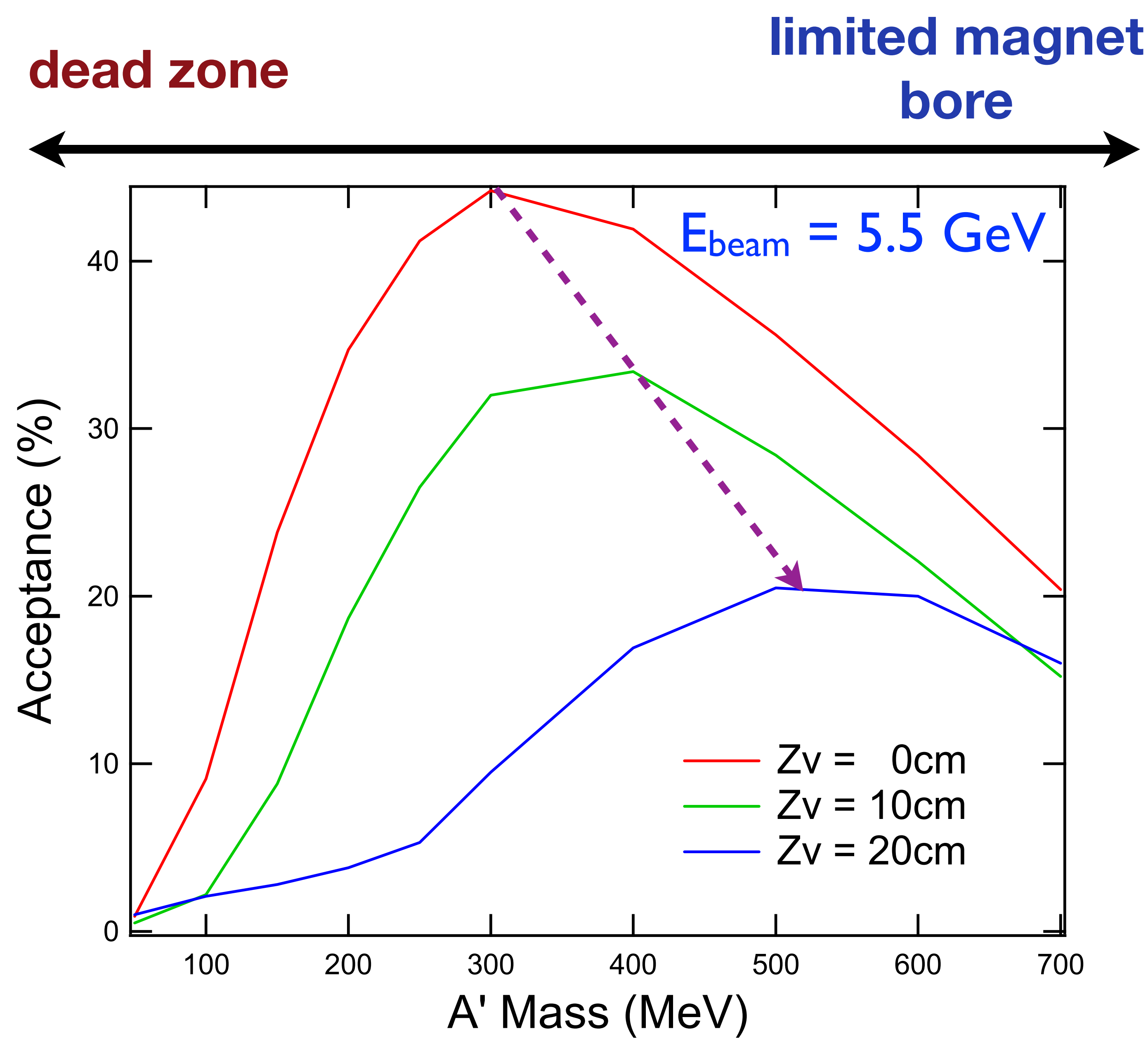
Tracker Acceptance

- At smaller masses, dead-zone limits acceptance
- At larger masses, losses due to limited coverage in layers 5 and 6 become important.
- Solid angle of dead zone increases with increasing z-vertex position

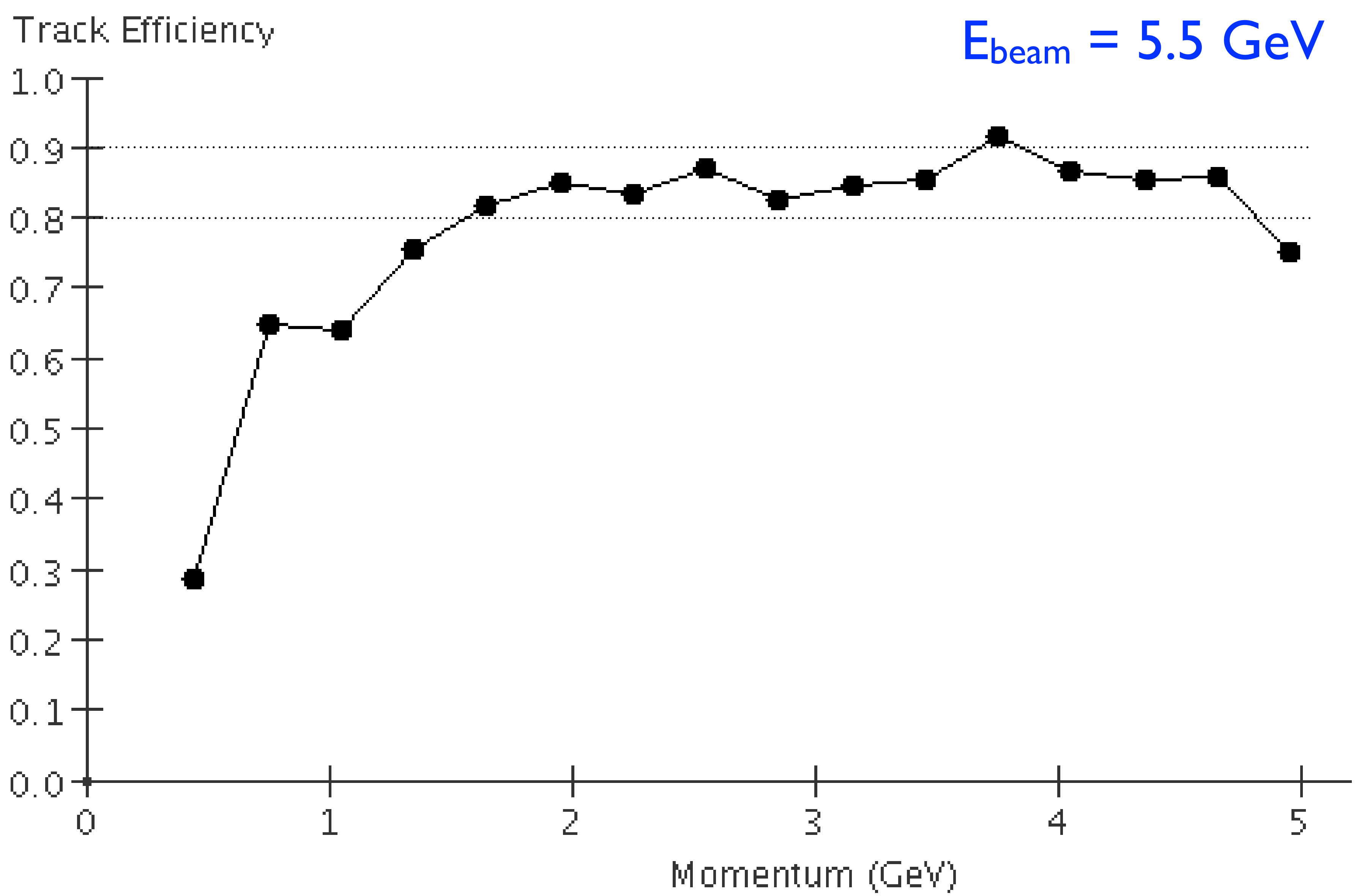


Matt Graham - SLAC

Tracking Efficiency

after selections

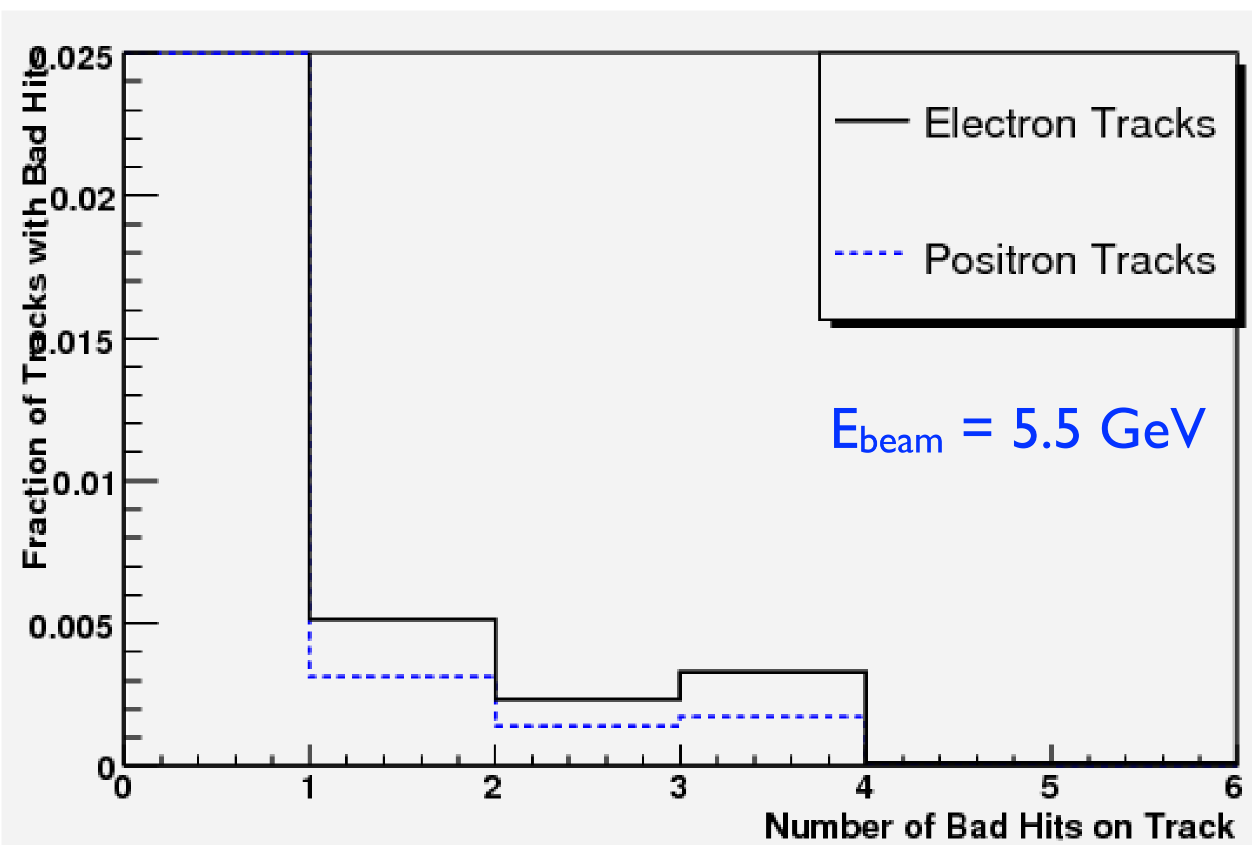
$\chi^2 < 20$

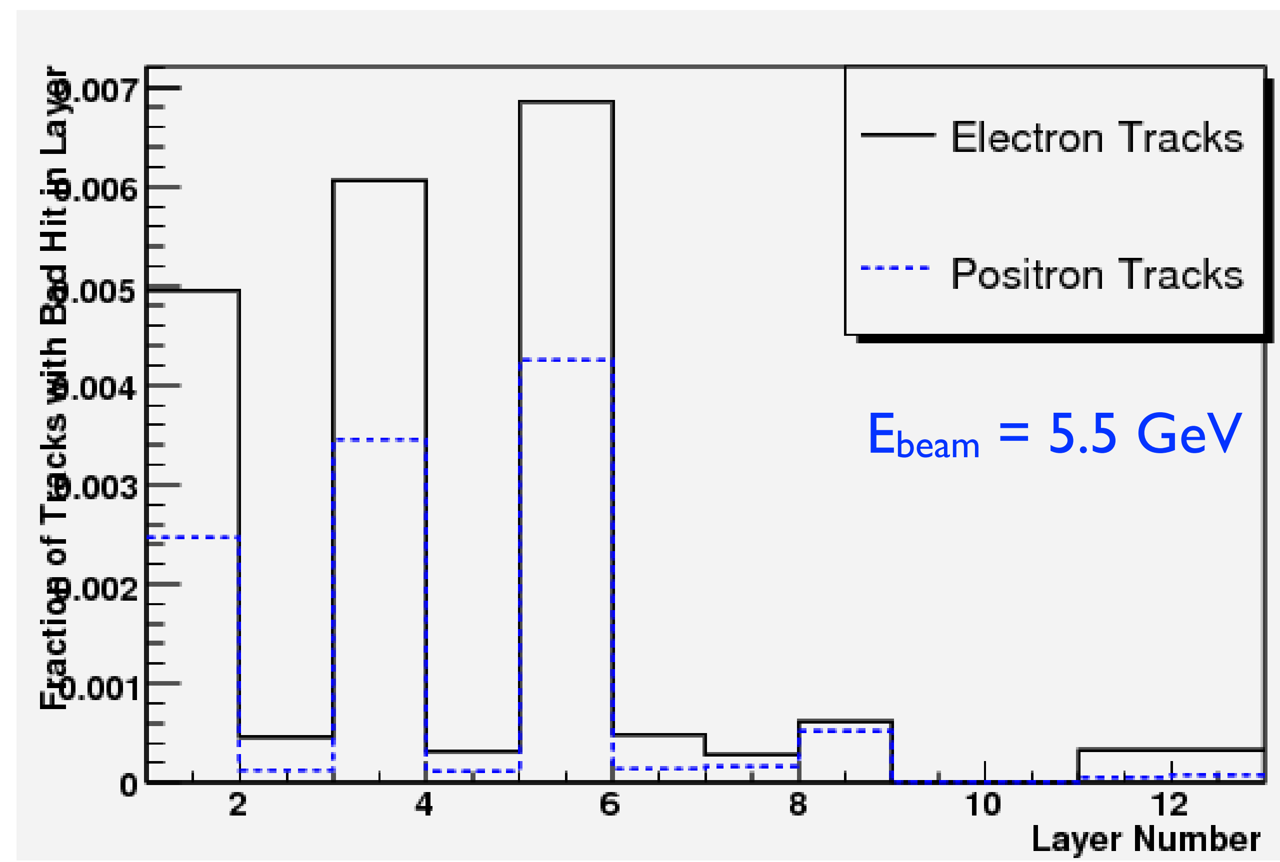


Matt Graham - SLAC

Tracking Purity

~99% tracks have 12/12 hits assigned correctly

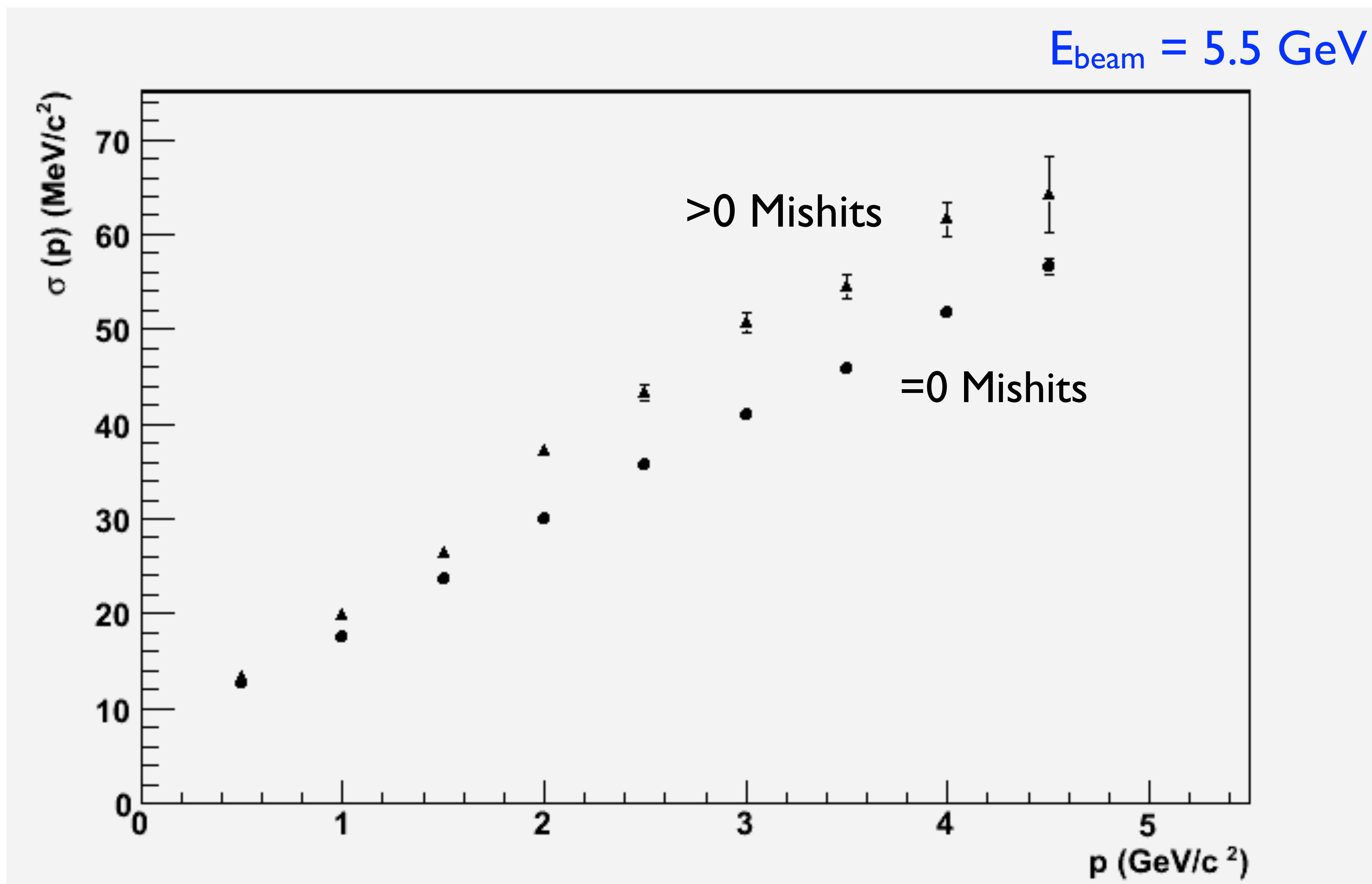




Mis-assigned hits mostly in high-occupancy view of 90-degree stereo layers.

Matt Graham - SLAC

Momentum Resolution



$$\frac{\sigma_p}{p} \simeq 1 - 1.5\%$$

multiple-scattering dominates errors

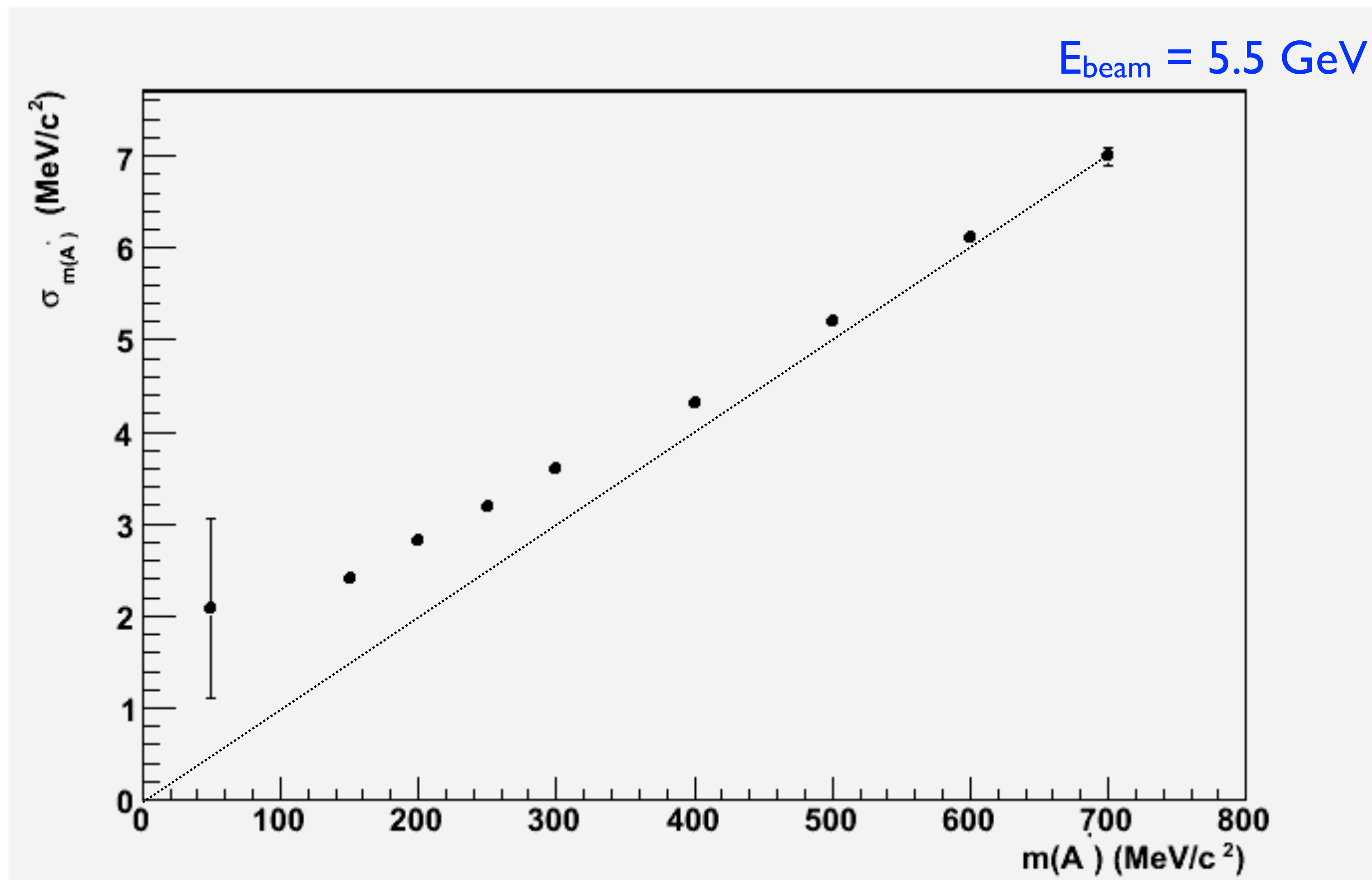
Matt Graham - SLAC

Mass Resolution

naively, $\sigma_m \propto \frac{m}{E}$

Angular resolution
at vertex dominates error:
limited by multiple scattering

Expect significant
improvement from
constraining track to vertex



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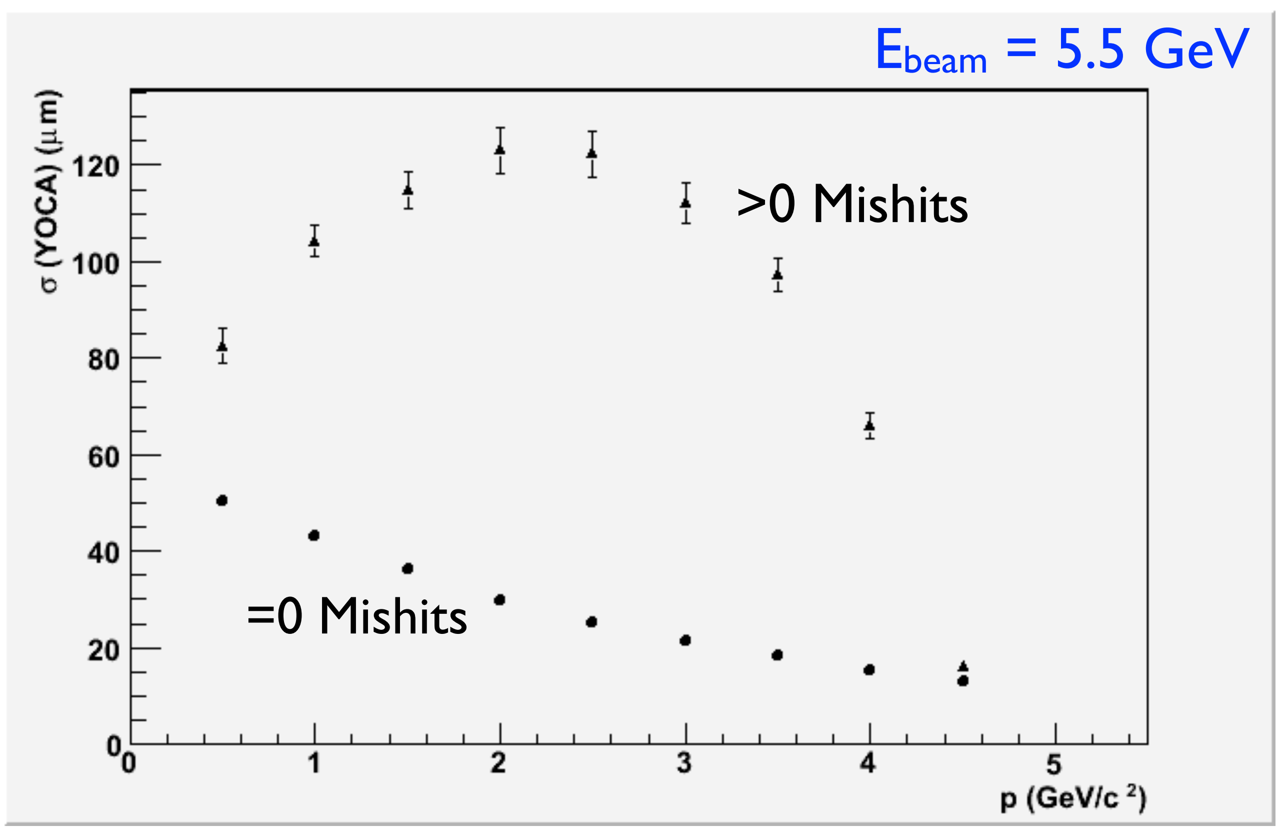
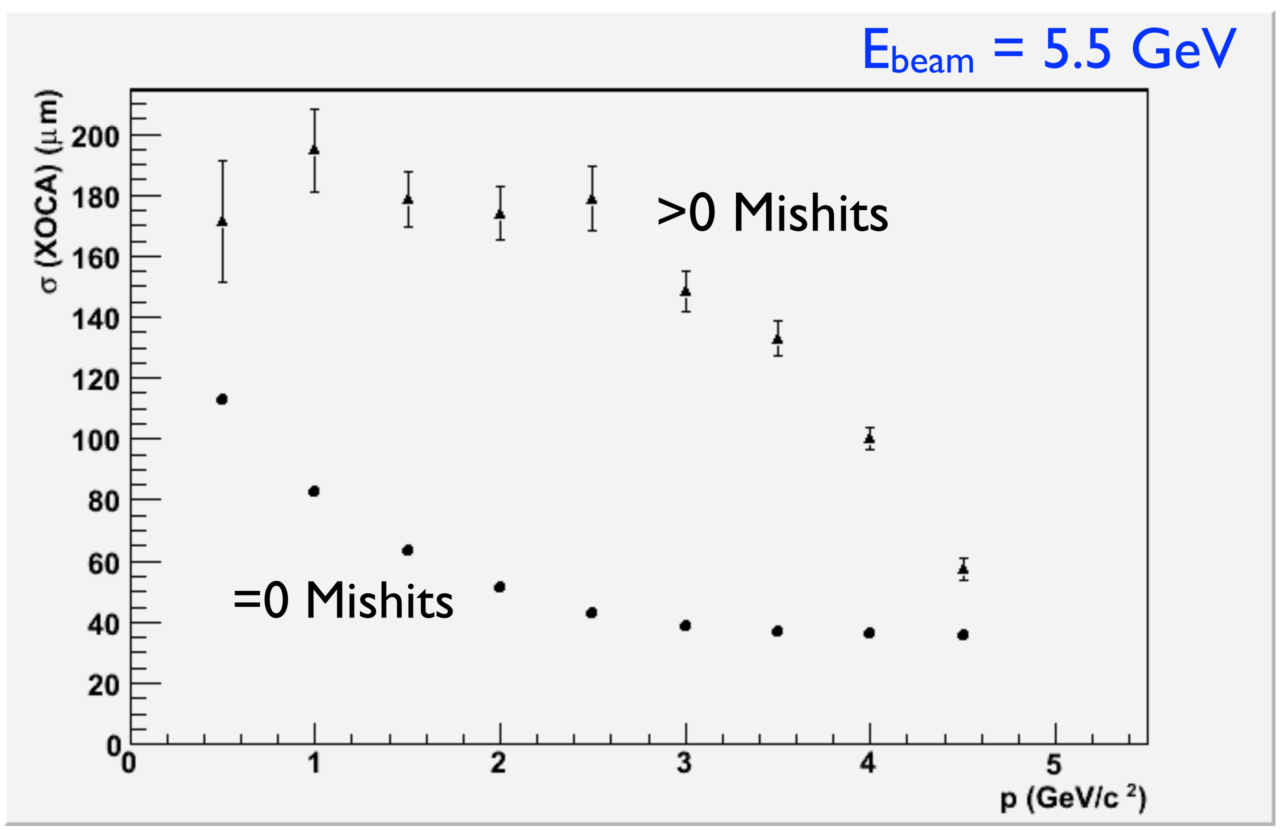
Impact Parameter Resolution

Non-Bend Plane

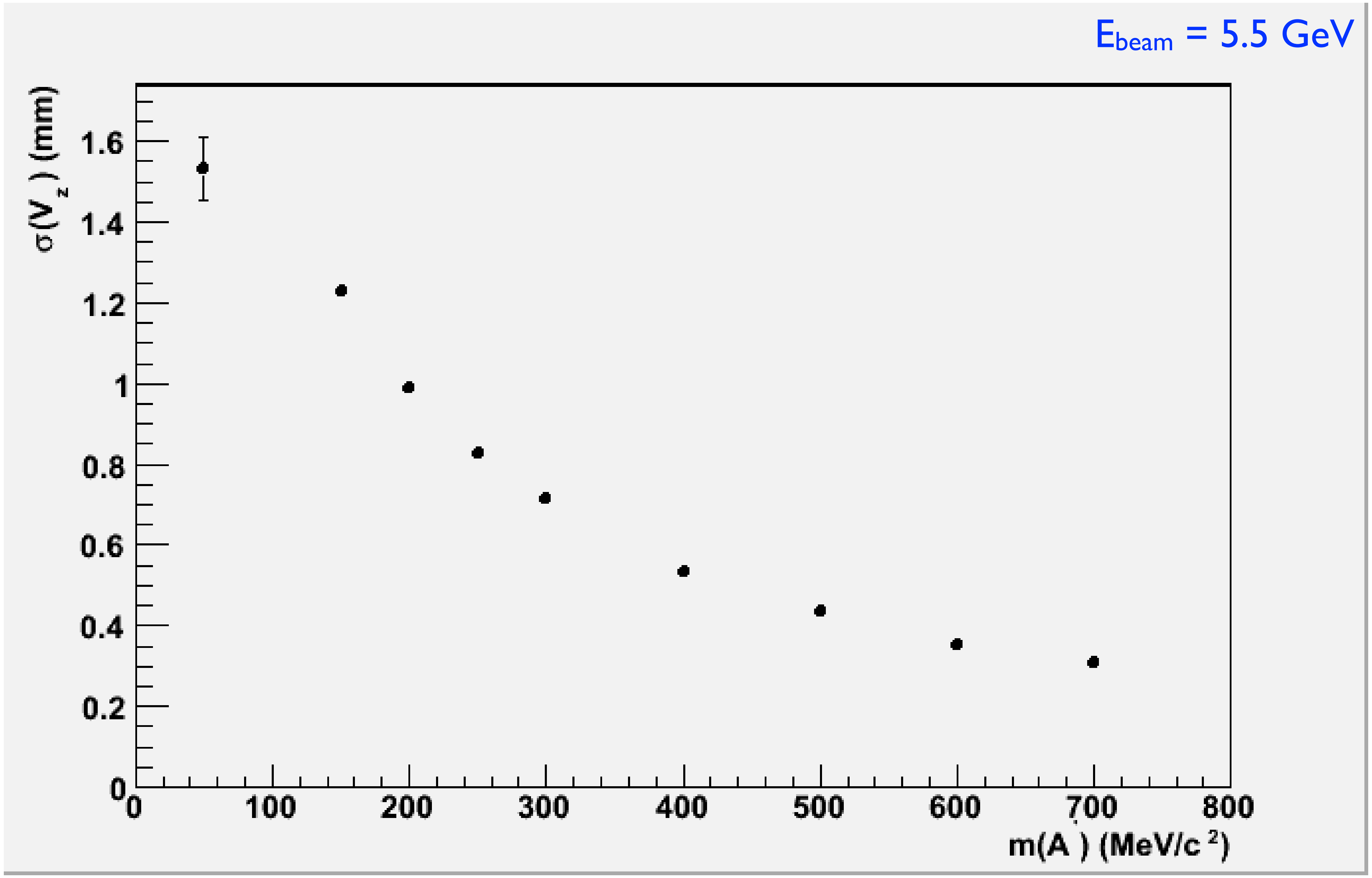


Bend Plane



Matt Graham - SLAC

Vertex Resolution



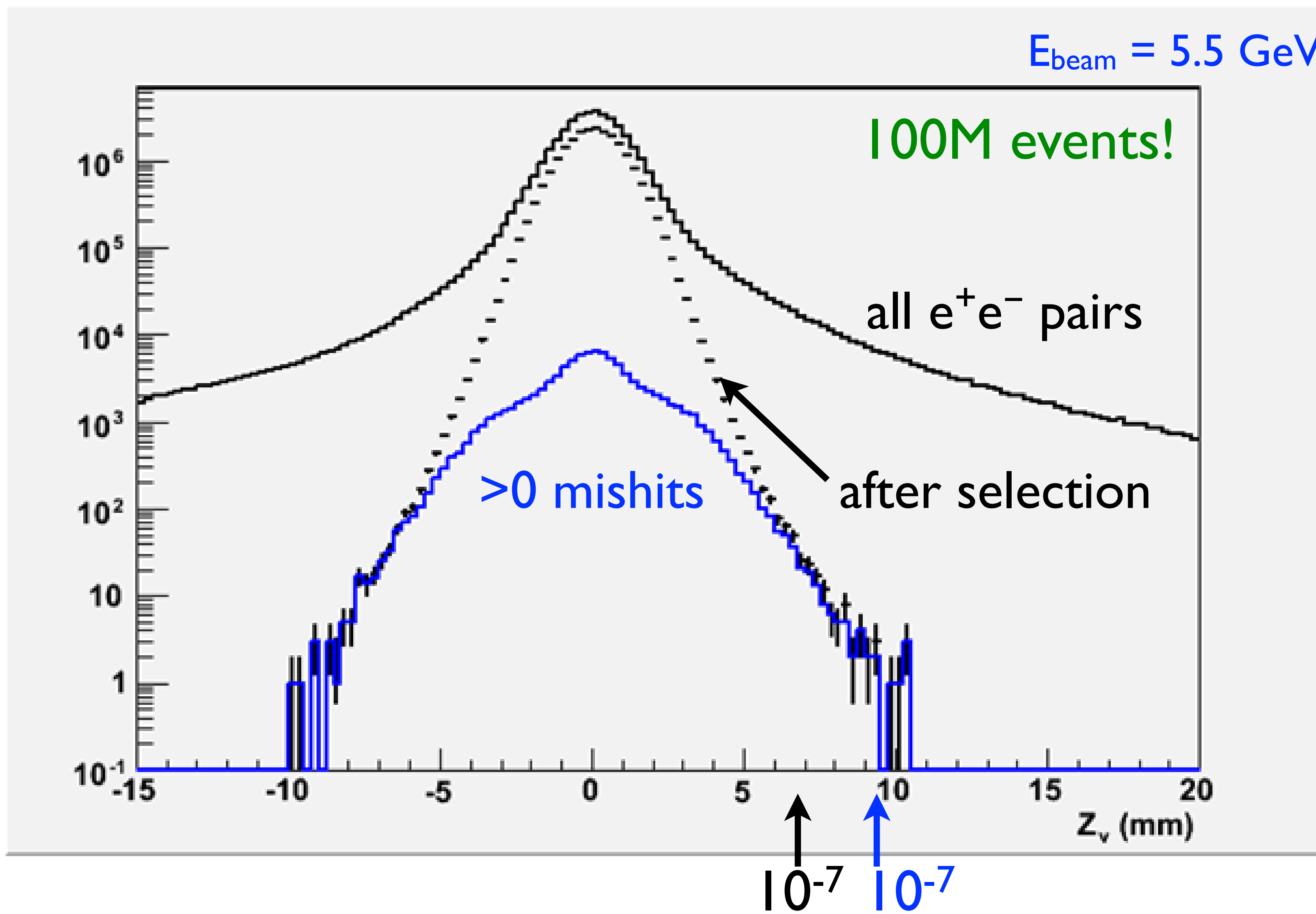
Matt Graham - SLAC

Prompt Vertex Rejection

need ~10^{-7} rejection for sensitivity to small signals

$$\chi^2_{\text{track}} < 20$$
$$|p_{A'}| < E_{\text{beam}}$$
$$|v_{x,y}| < 400\mu\text{m}$$
$$\chi^2_{\text{vertex}} < 15$$

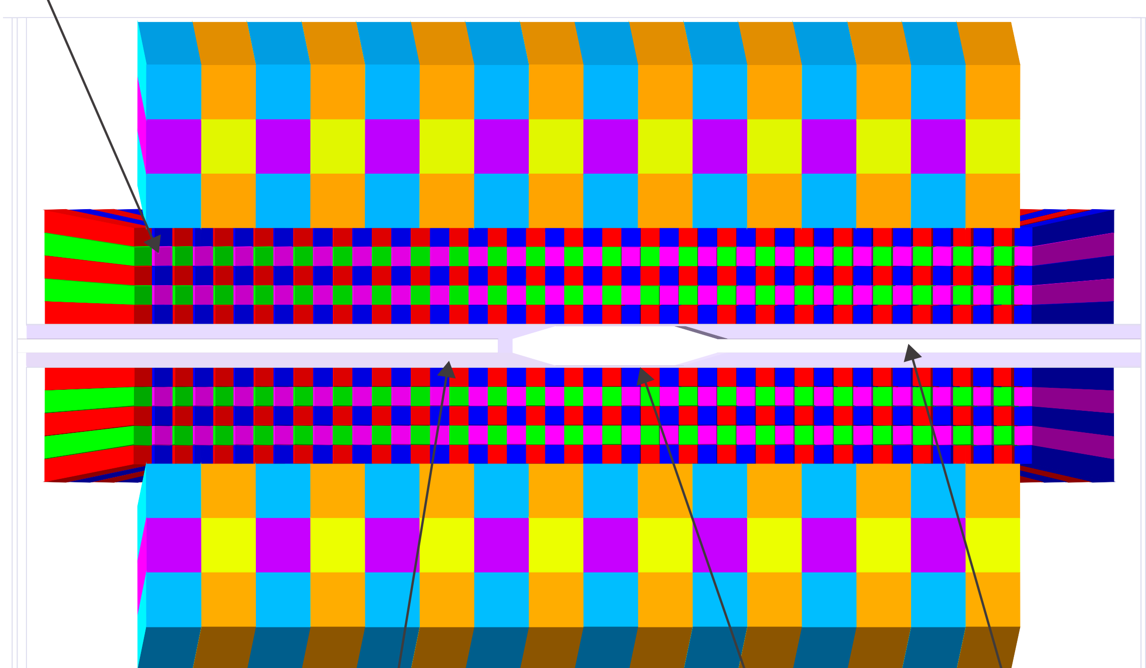
Efficiency ≅50%



Maurik Holtrop - UNH

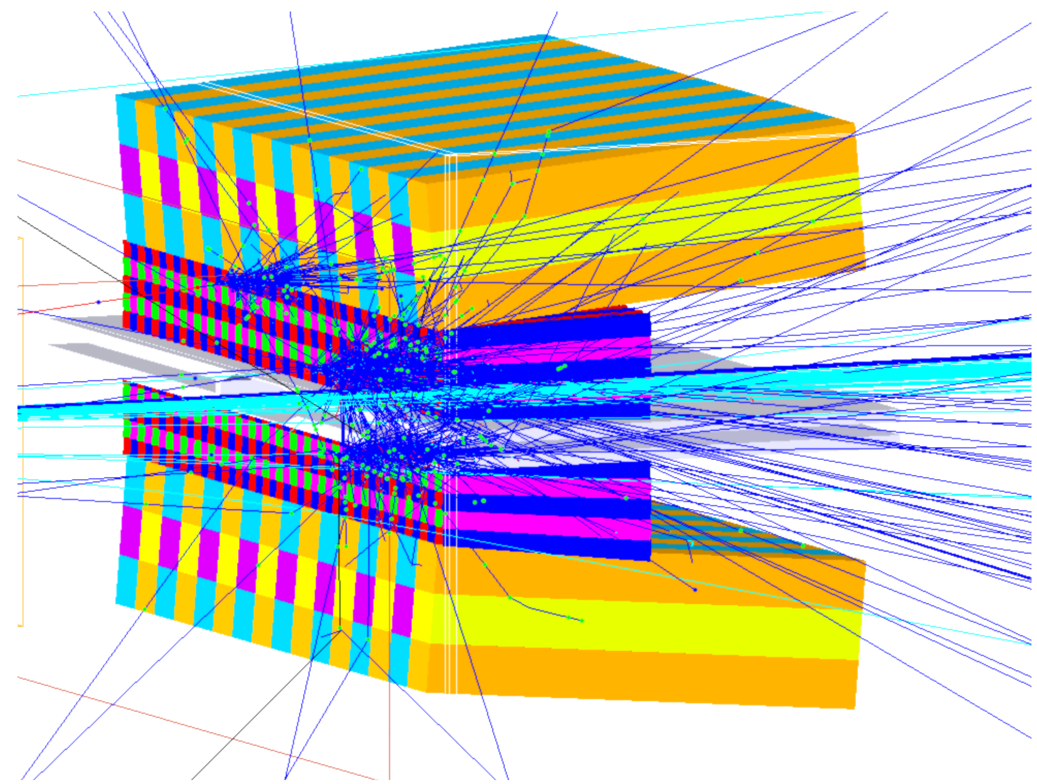
Hybrid Calorimeter

Lead Tungstate crystals
SHASLYK crystals



Positron side - air
Electron side - vacuum
1 cm aluminum plate
1 mm aluminum plate

250 MeV A′ event



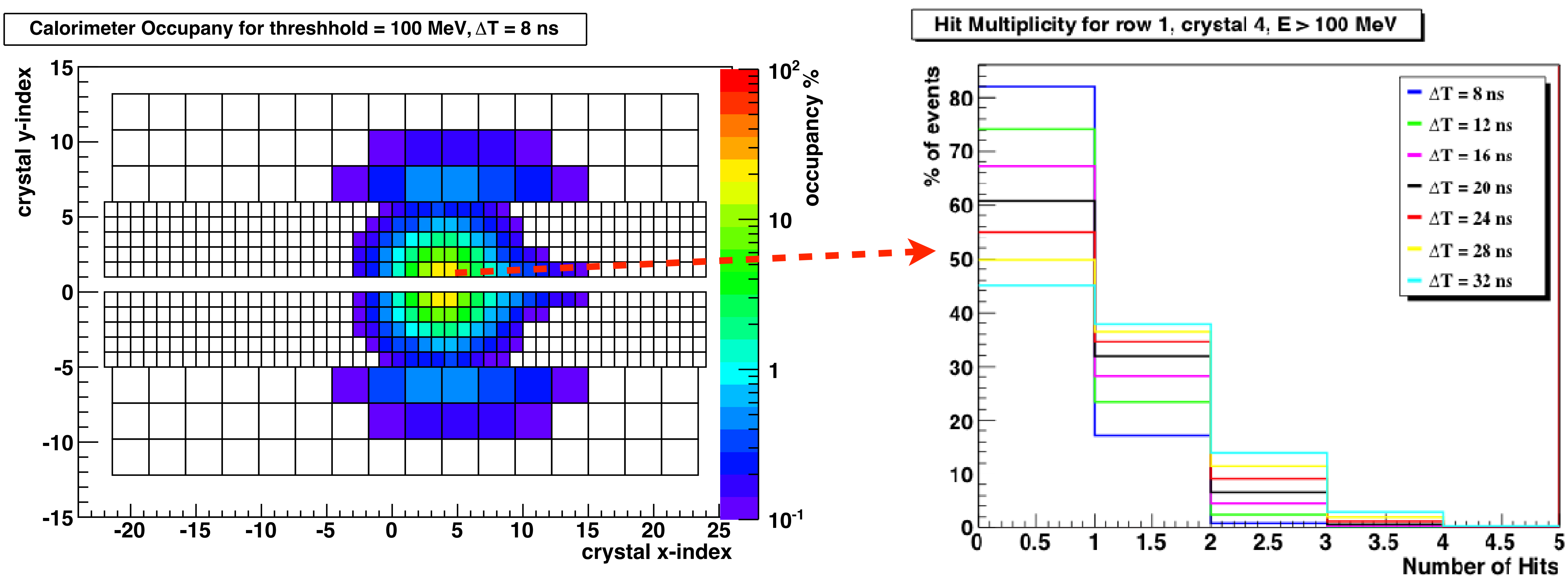
Design criteria: highest acceptance with readily available crystals, low background.

Vacuum box: 1 cm aluminum plate with cutout area for beam.
5 rows of 46 lead-tungstate crystals, total: 460
3 rows of 16 lead-glass or Shashlyk crystals, total: 96

In hand from other experiments

Maurik Holtrop - UNH

ECal Occupancy/Multiplicity



Acceptable occupancy and multiplicity can be achieved in all crystals with100 MeV threshold and 8 ns time window.

Maurik Holtrop - UNH

Trigger Selection

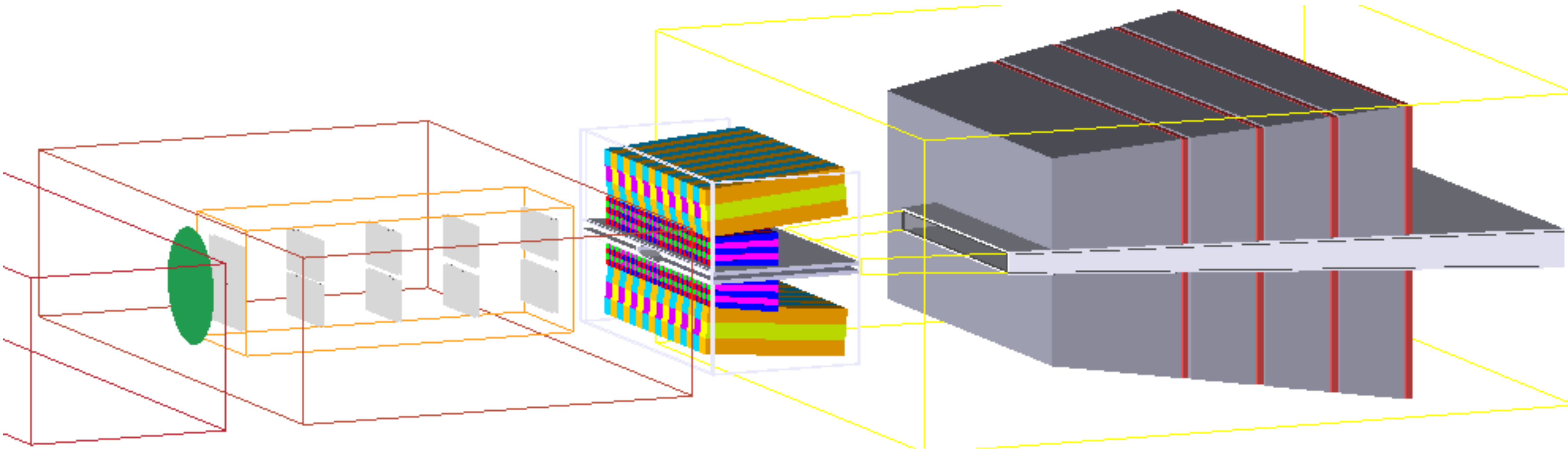
- Total trigger budget estimated at 20 kHz
- Simple 3×3 clustering with 50 MeV seed threshold

Trigger Requirement	A′ (250 MeV) Acceptance	Background Acceptance	Background Rate
Events with least two opposite clusters	44.6%	1.26%	1.6 MHz
Cluster energy > 0.5 GeV and < 4.4 GeV	46.4 %	0.239%	0.3 MHz
Energy sum < 5.1 GeV	46.4 %	0.0959%	120 kHz
Energy difference < 3.2 GeV	46.1 %	0.0823%	102 kHz
Lower energy - distance slope cut	45.4%	0.0601%	75 kHz
Clusters coplanar to 45°	44.6%	0.0344%	43 kHz
Eliminate crystals in row 1, column 0,3,4	41.3 %	0.0158%	20 kHz
Not counting double triggers	38.1%	0.0135%	17 kHz

A’ Mass (MeV)	50	100	200	250	300	400	500	600	700
Trigger Acceptance	3.1%	18.5%	33.7%	38.1%	40.5%	36.3%	30.3%	25.1%	21.3%

Maurik Holtrop - UNH

Muon Detector



Conceptual design:

Location ~ 2m from target

Iron absorbers: 30 cm + 3x15 cm

Four segmented hodoscopes, 1.5 cm thick

Maurik Holtrop - UNH

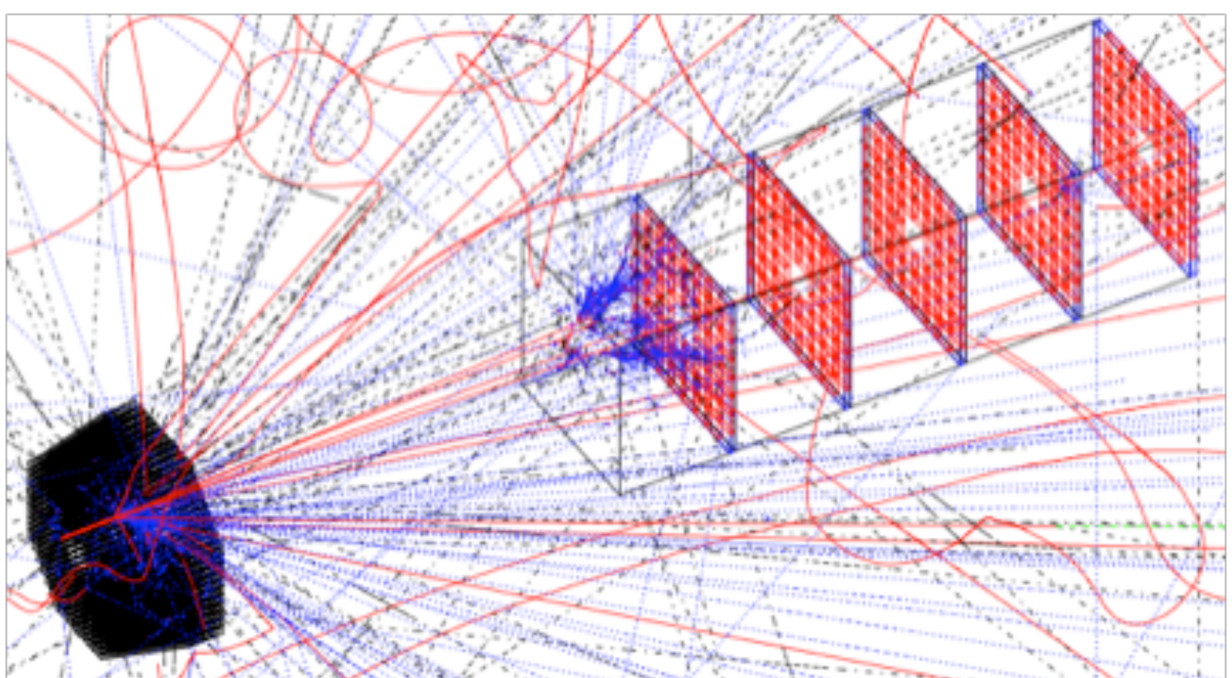
Muon Detector Optimization

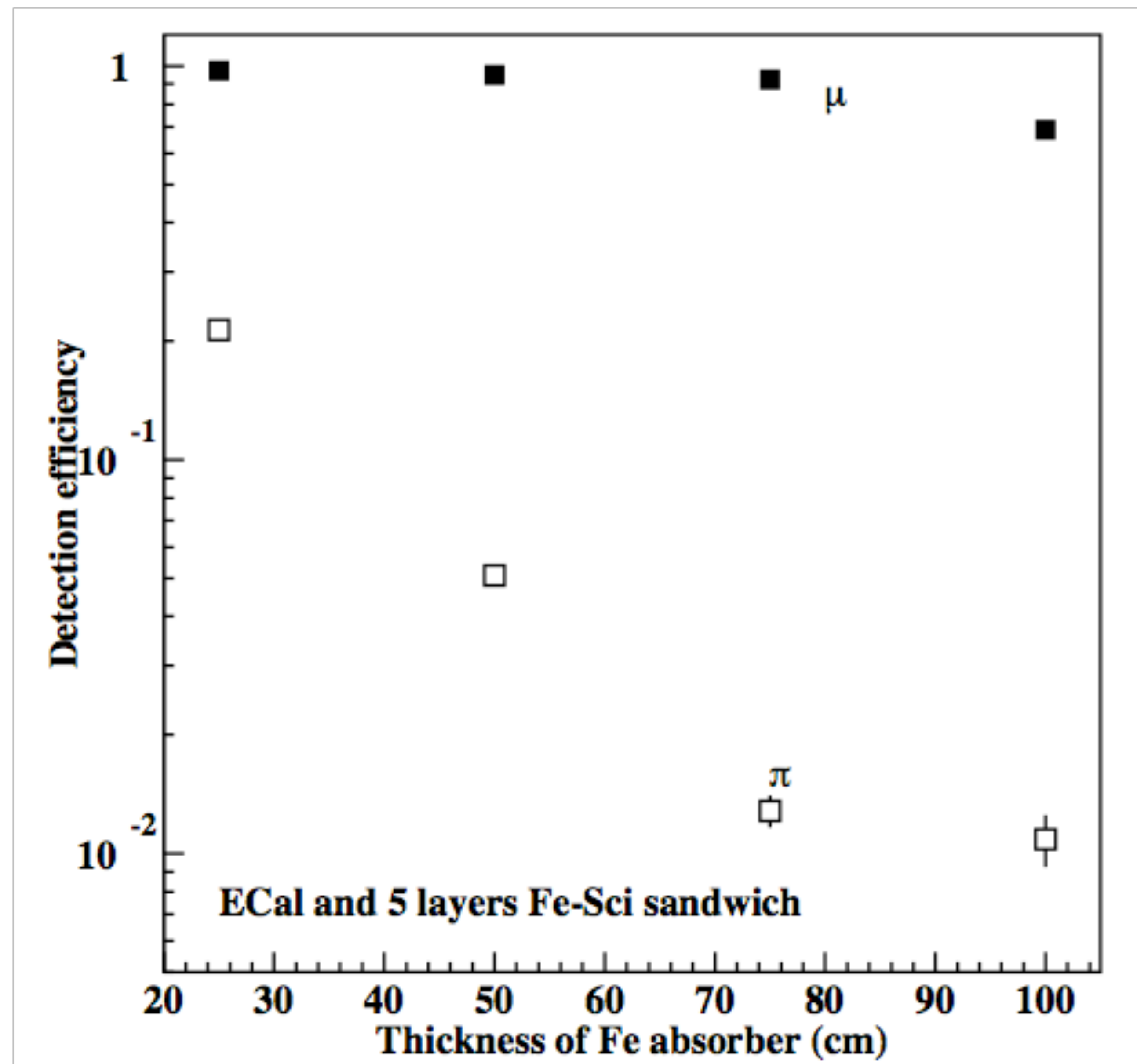
In progress:

Est. background trigger rate

≈ 250 Hz (0.1 MeV threshold)

≈ < 1 Hz (0.4 MeV threshold)





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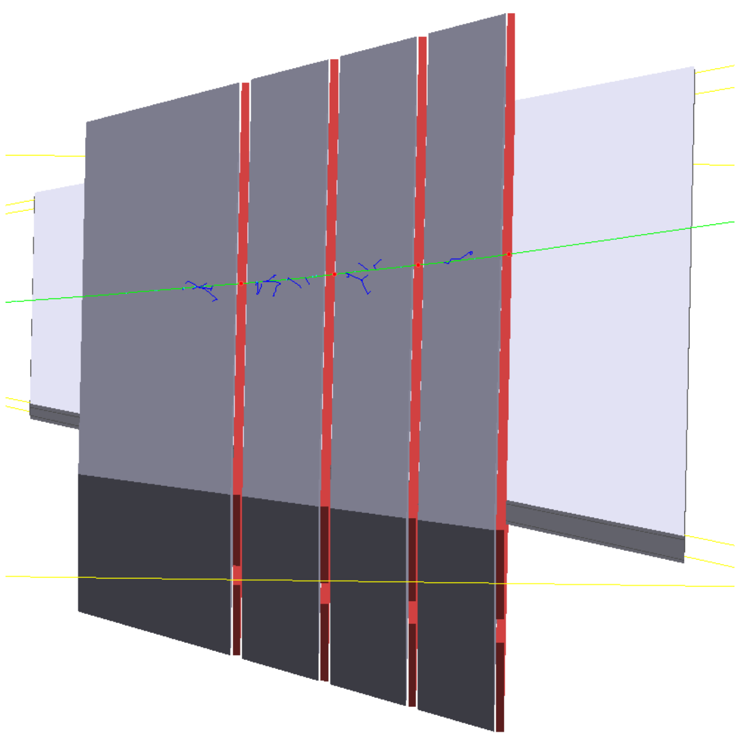
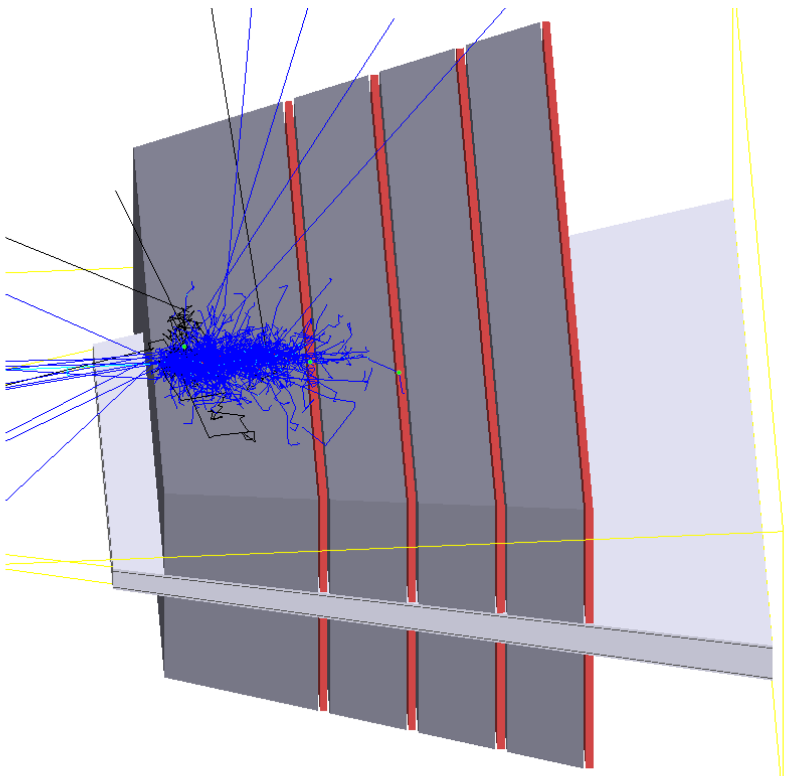
Pions?

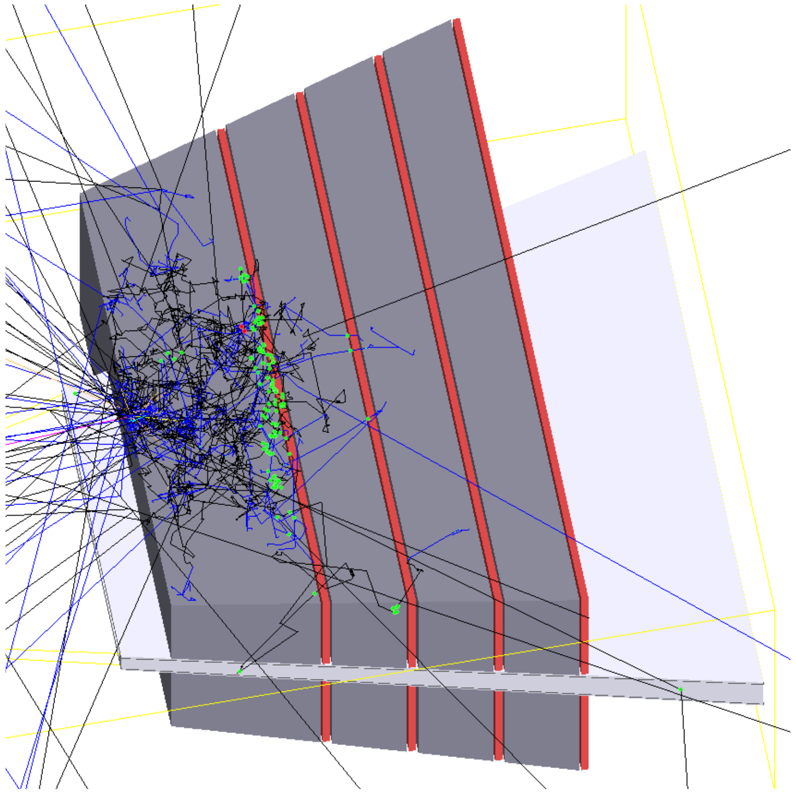
muon



electron



pion



Pion rates lower than predicted? Trigger may be manageable

Add more shallow planes to improve pion trigger/ID?

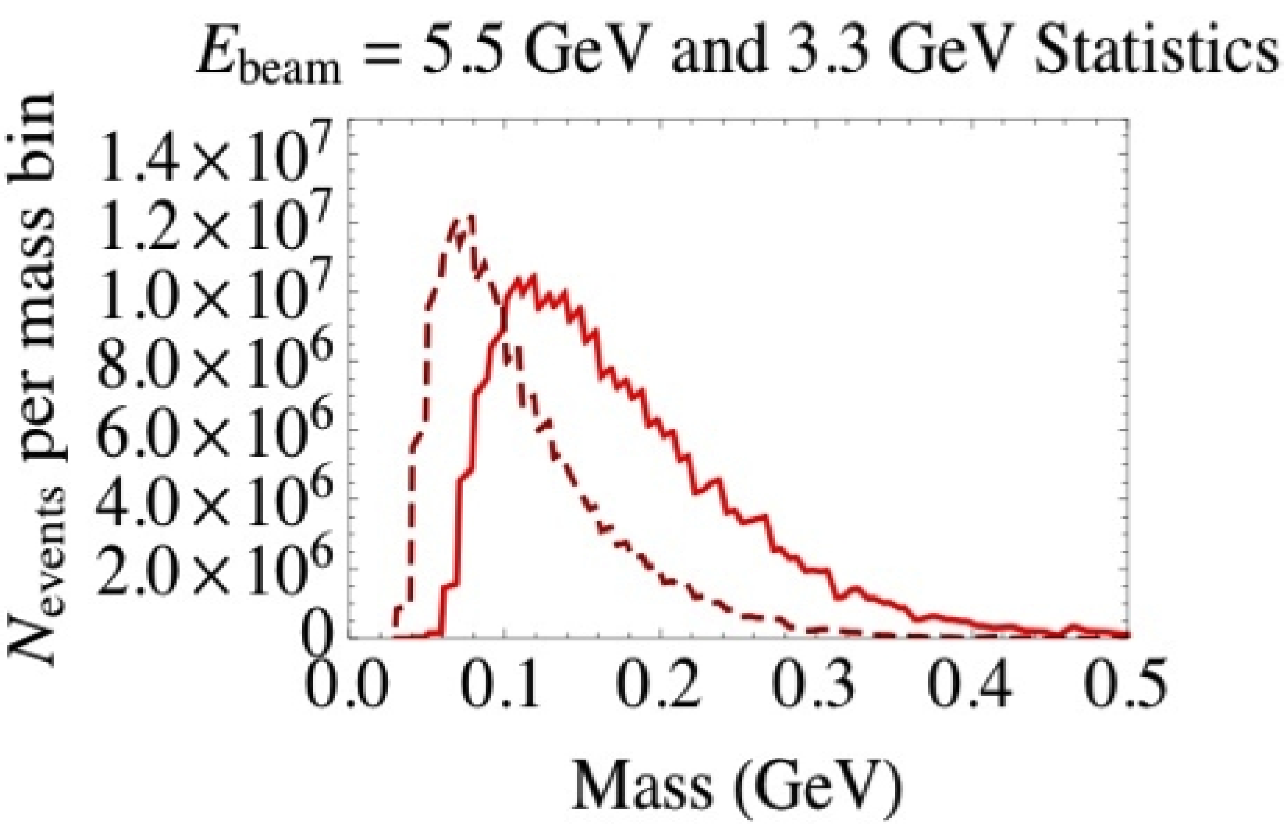
Phil Schuster - SLAC

Reach Estimates

bump hunt

$$\frac{d\sigma(e^- Z \to e^- Z\,(A' \to e^+ e^-))}{d\sigma(e^- Z \to e^- Z\,(\gamma^* \to e^+ e^-))} = \left(\frac{3\pi\epsilon^2}{2\,N_{eff}\,\alpha}\right)\left(\frac{m_{A'}}{\delta m_{A'}}\right)$$

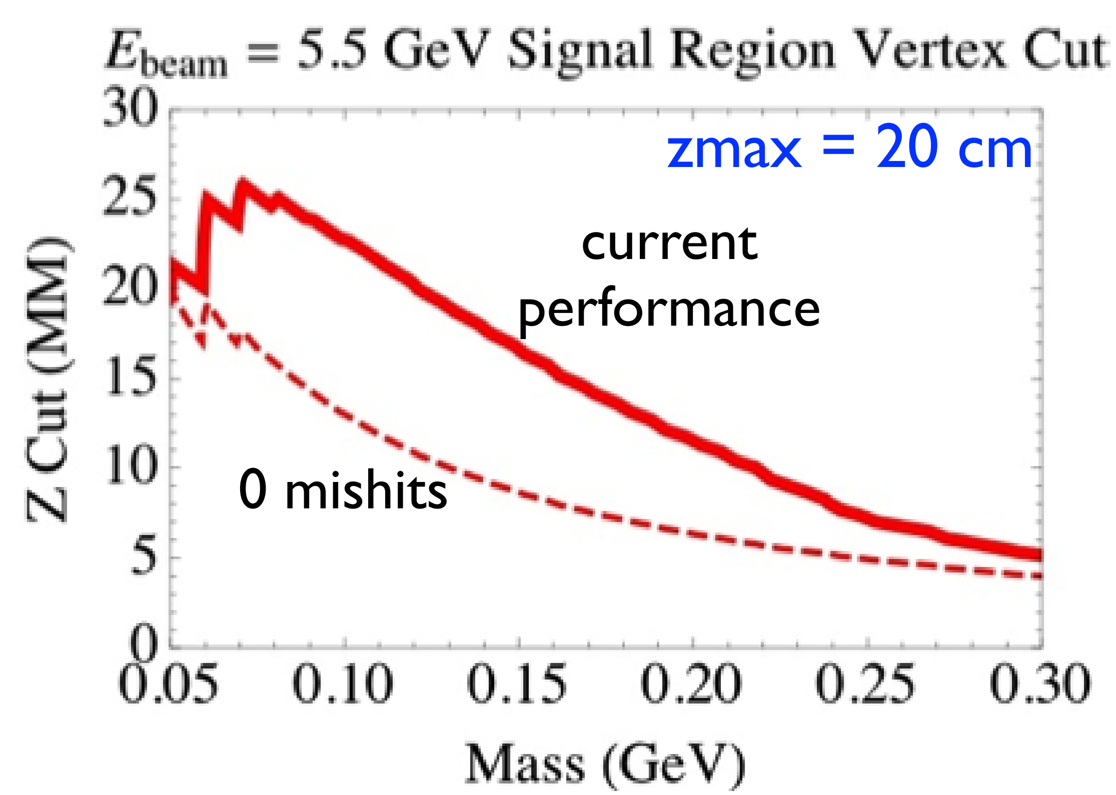
$$\left(\frac{S}{\sqrt{B}}\right)_{bin} = \left(\frac{N_{radiative}}{N_{total}}\right)\sqrt{N_{bin}}\left(\frac{3\pi\epsilon^2}{2\,N_{eff}\,\alpha}\right)\left(\frac{m_{A'}}{\delta m_{A'}}\right)\epsilon_{bin}$$



bump hunt + vertexing

$$\left(\frac{S}{\sqrt{B}}\right)_{bin,zcut} = \left(\frac{S}{\sqrt{B}}\right)_{bin}\frac{\epsilon_{sigeff}(zcut)}{\sqrt{\epsilon_{rejection}(zcut)}}$$

$$\epsilon_{sigeff}(zcut) \cong \epsilon_{vtx} \times \left(e^{-\left(\frac{zcut}{\gamma c\,\tau}\right)} - e^{-\left(\frac{zmax}{\gamma c\,\tau}\right)}\right)$$



Phil Schuster - SLAC

HPS Reach: one month run

E_{beam} = 5.5 (3.3) GeV

I_{beam} = 400nA

Target = 0.25% (0.125%) W

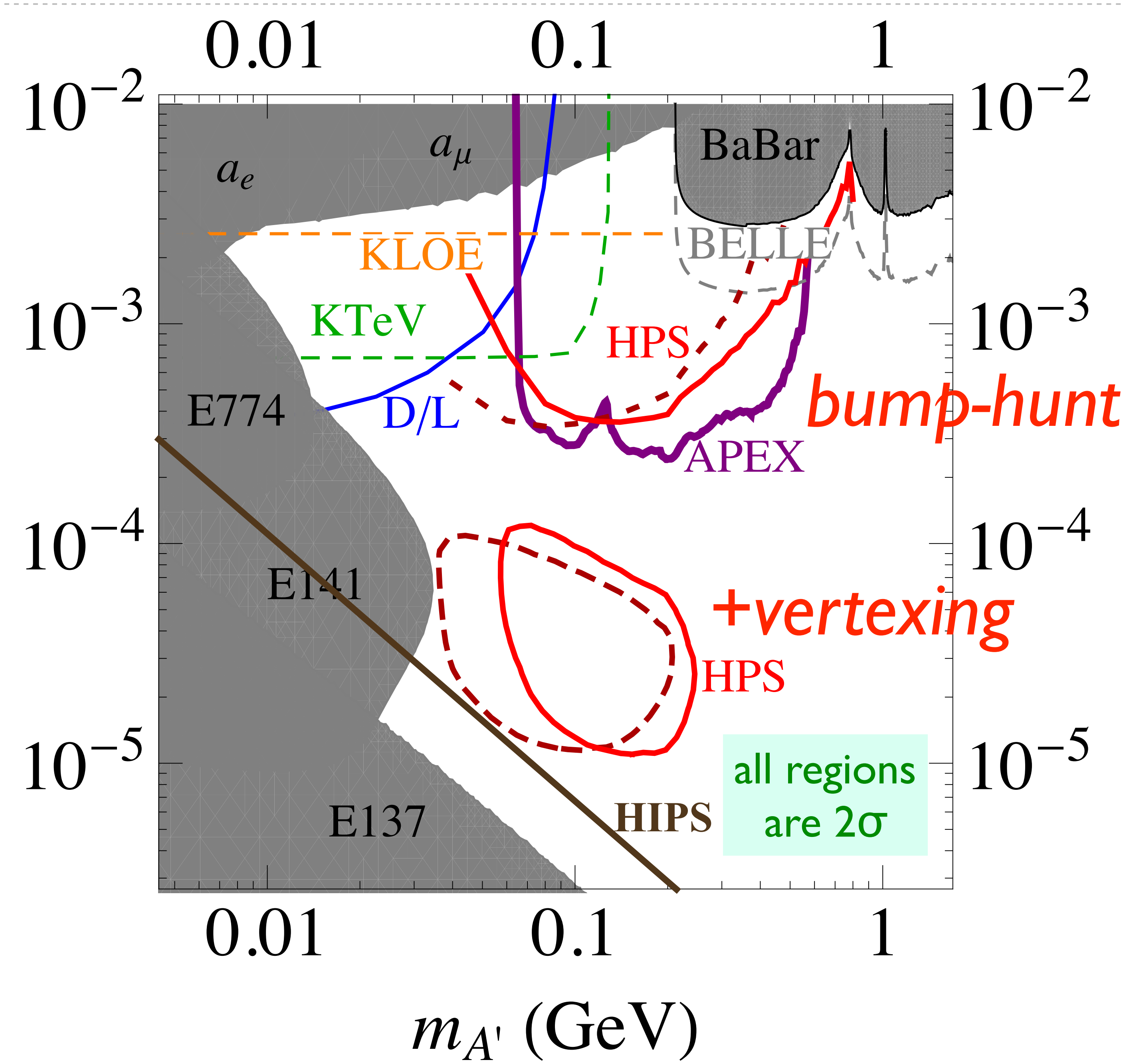
Time = 3x10^6 s (~1 month)

5.5 GeV

3.3 GeV (prelim.)

APEX: "A-prime Experiment" *m*(e^+e^-) bump-hunt using Hall A two-arm spectrometer.

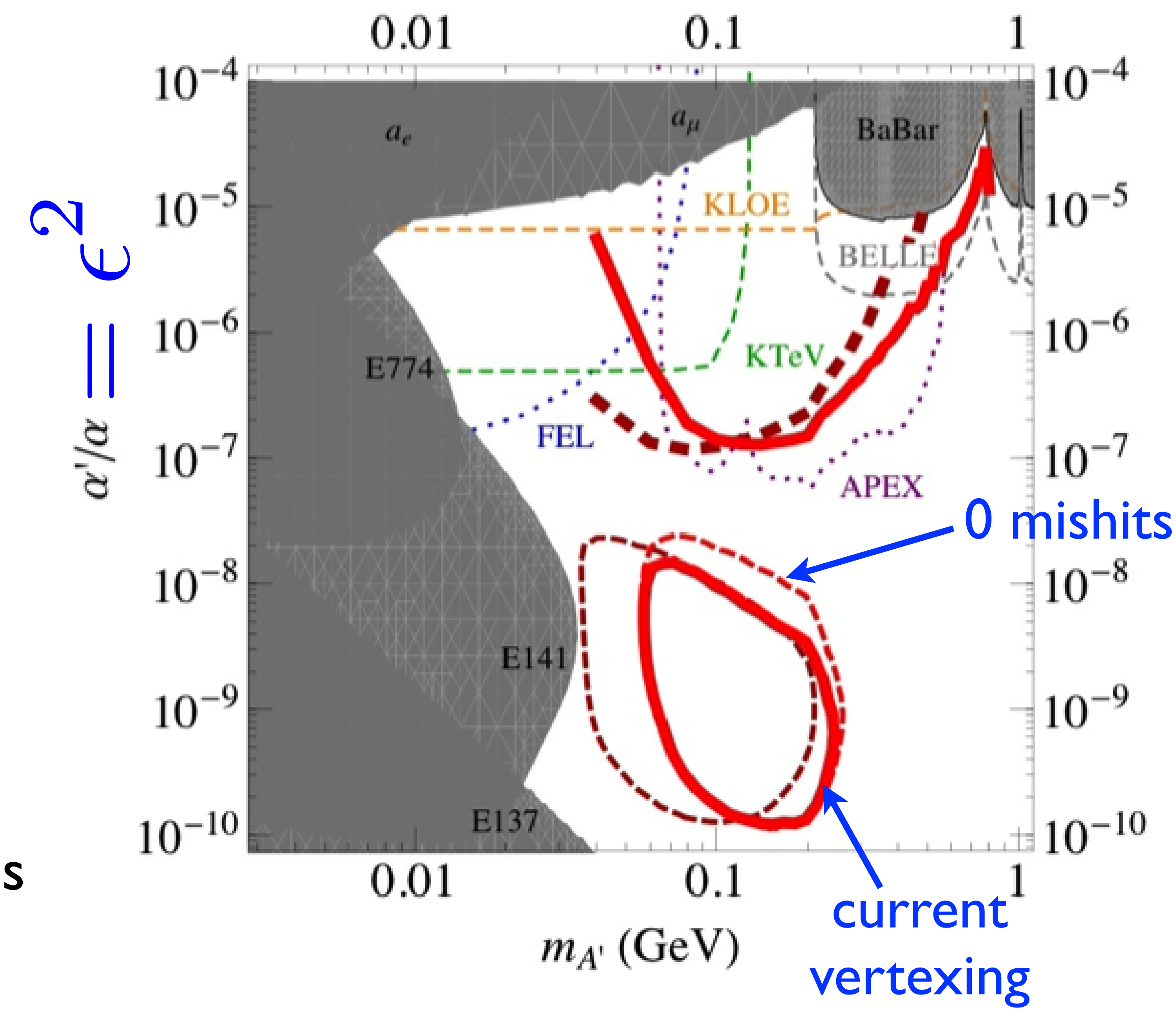
D/L = DarkLight: full kinematic reconstruction using JLab FEL and H-gas target



Phil Schuster - SLAC

Expected Improvements

- Further elimination of tracks with mishits
- Vertex-constrained mass
- Likelihood fit to decay length distributions
- Optimization of muons, addition of pions
- Addition of more beam energies



https://confluence.slac.stanford.edu/display/hpsg/Heavy+Photon+Search+Experiment

HPS
HEAVY PHOTON SEARCH

A Proposal to Search for Massive Photons at Jefferson Laboratory

Fermilab Jefferson Lab Thomas Jefferson National Accelerator Facility SLAC NATIONAL ACCELERATOR LABORATORY

September 10, 2010

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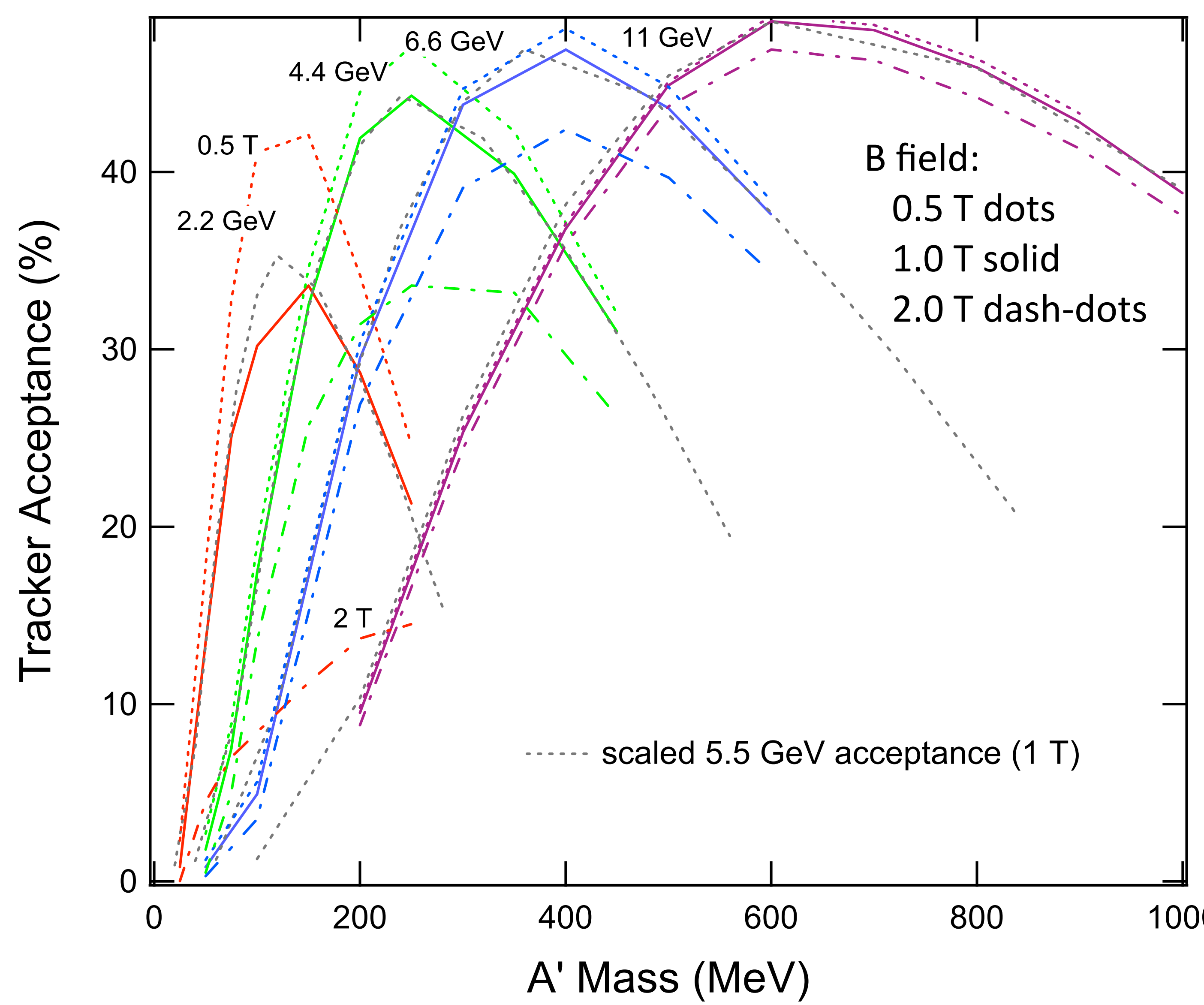
Status

- Proposal presented at JLab workshop "Boson 2010"
  http://conferences.jlab.org/boson2010/
- Estimated cost: $3.1M (includes contingency)
- No time "on the floor" in the 6GeV schedule:
  main run period likely to be in 12 GeV era.
- Going before PAC at JLab in January
- Pulling up the sofa cushions to continue development work

Plans

- Testing reach at 12GeV energies
- Investigating alternate magnets
- Hard at work on the targets that will be needed
- Broadening trigger and reach to include pions, optimize muons
- Tracking/vertexing improvements
- APV25 readout and DAQ development getting underway



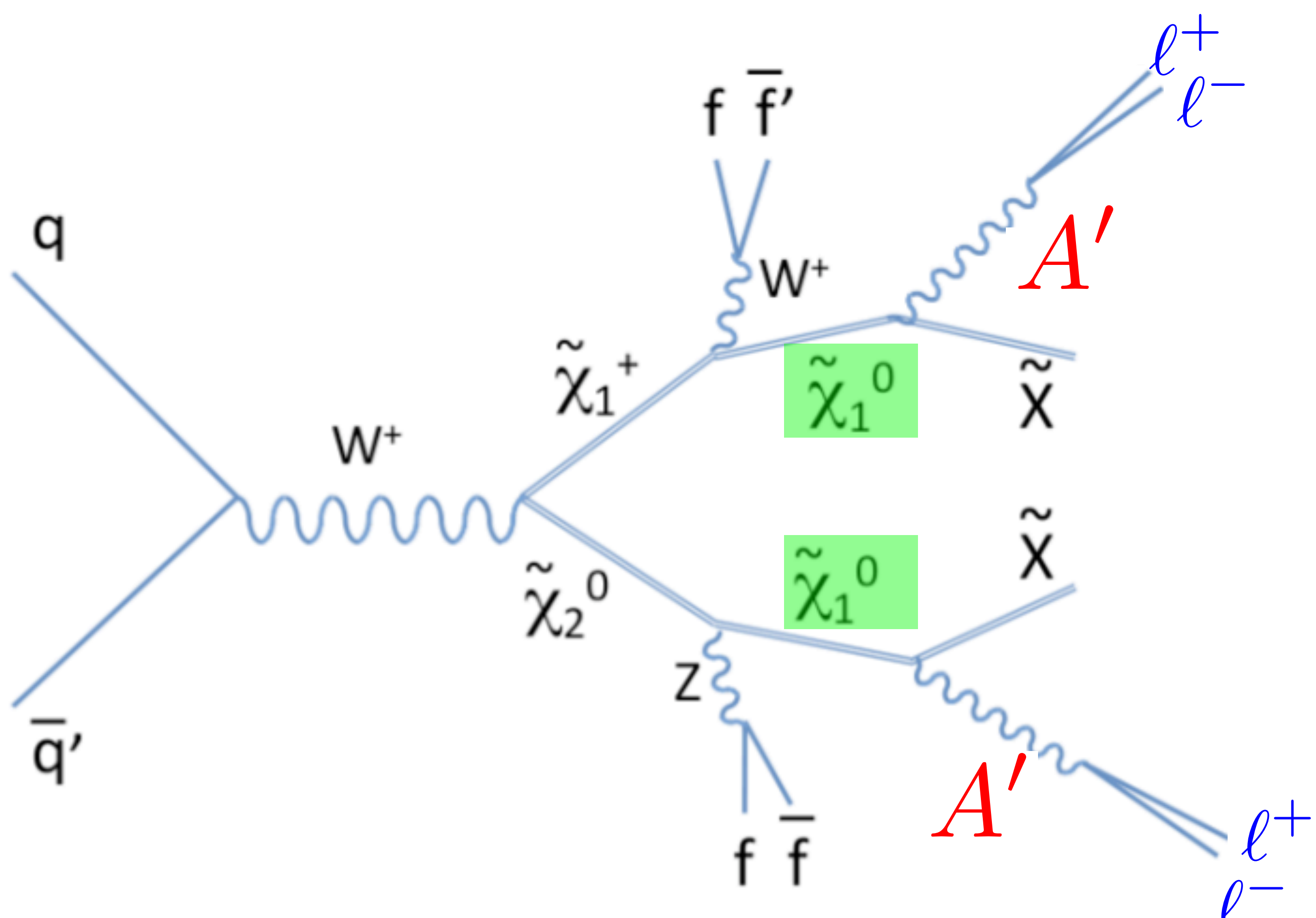
Summary

- Compelling reasons to look for a hidden, low-mass U(1)
- JLab has two excellent instruments for these searches: CEBAF and FEL
- HPS has unique capability to probe intermediate couplings: complimentary to other efforts
- Interesting reach already demonstrated: *how much better can we make it?*


Backup Slides

Direct Searches: Tevatron/LHC

Lightest SUSY particle ("LSP") not stable,
and can decay to A′ + hidden sector



"lepton jet"

some searches at Tevatron completed (no signal)

others planned

"lepton jet"

Arkani-Hamed, Weiner

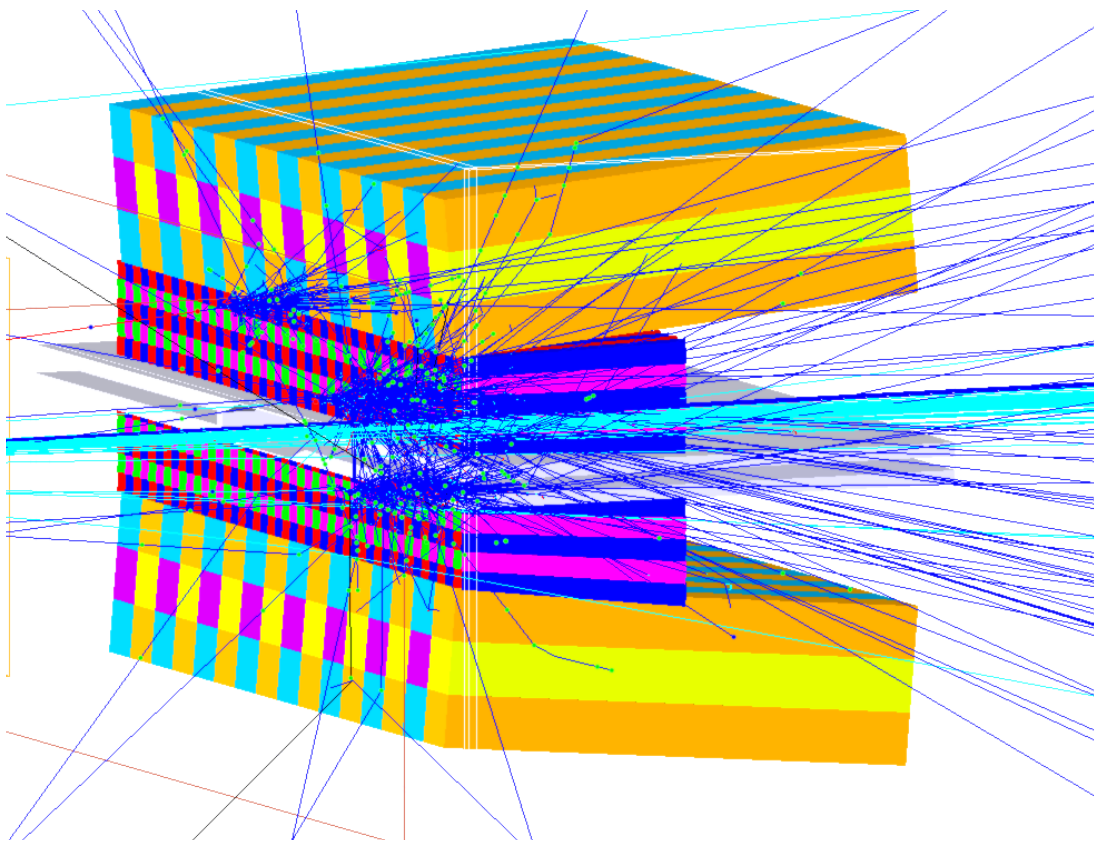
Bumgart, Cheung, Ruderman, Wang, Yavin

D-zero, arXiv: 1008.3356

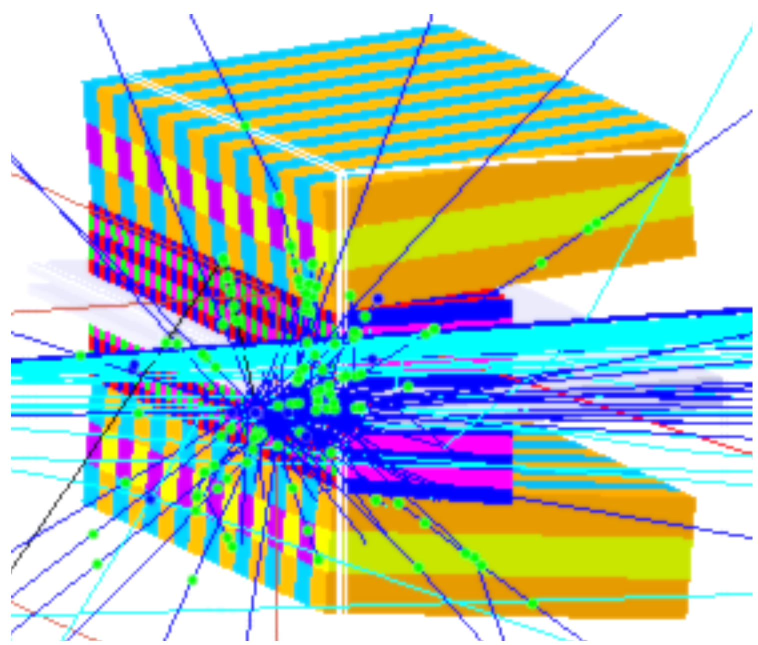
Maurik Holtrop - UNH

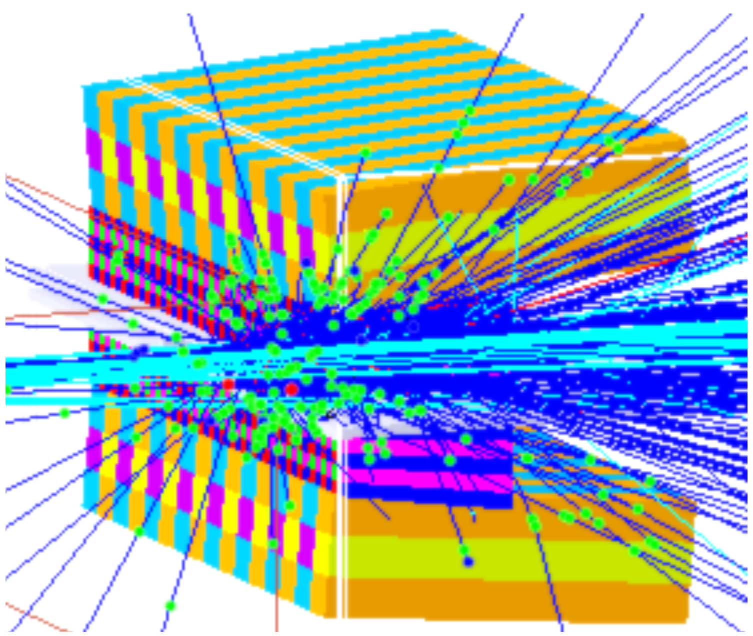
ECal Trigger

250 MeV A′ event



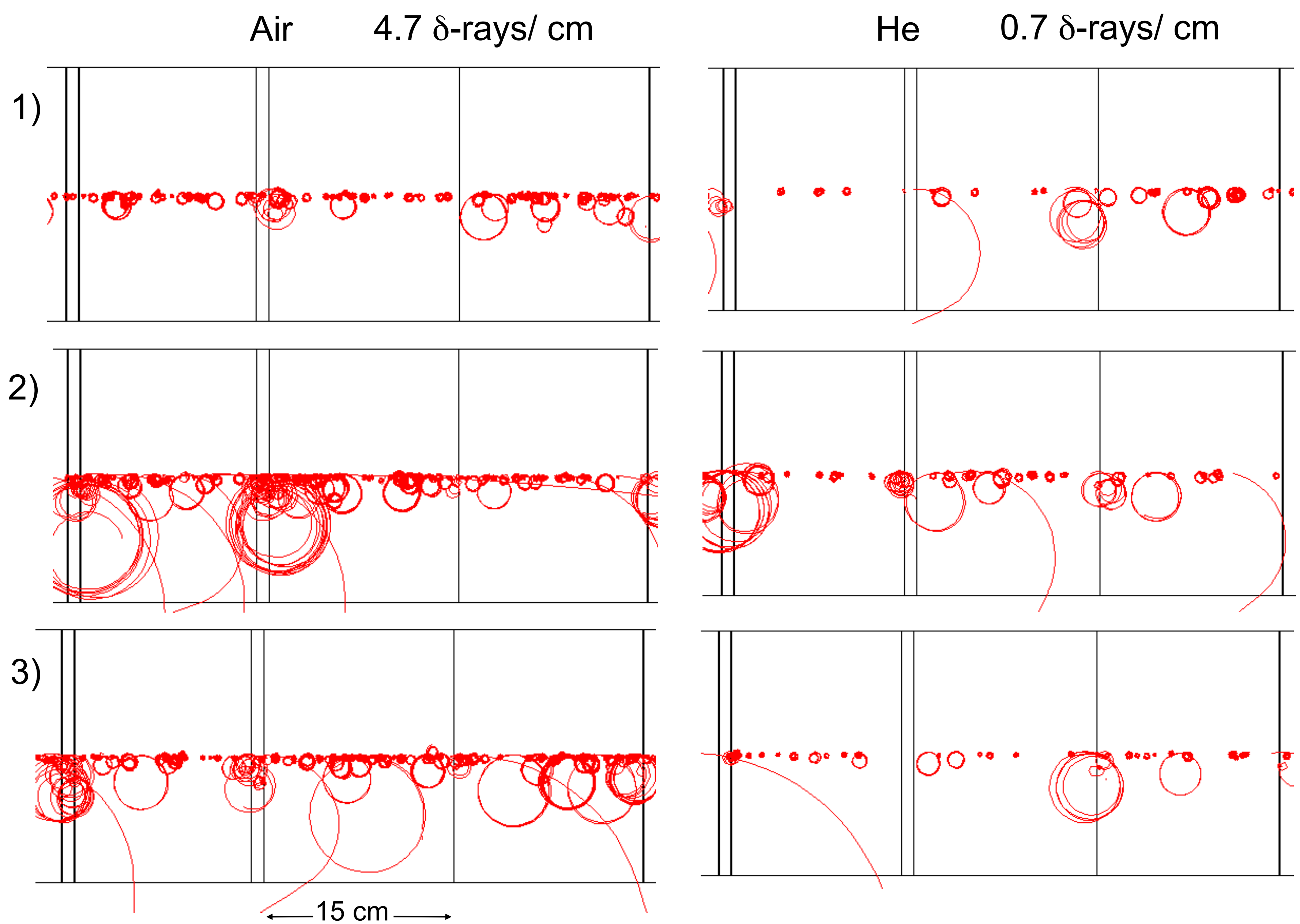
background events





Why Vacuum?

δ-ray background in 25 ns



Upgrade?

Thin silicon in Layers 1 and 2?

- Reduces material budget by 0.15% X_0 / plane: 30% of total.
- S/N still ~22: timing resolution degrades by only ~10%.
- Cost: $37.5k for silicon per copy
- Should be possible to use same hybrids, partially populated, with a pitch adapter
- Additional risk for parts not in hand. Risk in working with Micron, but minimal for such a small production of single-sided sensors.

HPS? REALLY?

- HPS: "Heavy Photon Search" - John Jaros (co-spokesperson)
- MaDPhoX: "Massive Dark Photon Experiment" - Tim Nelson
- MassiVE: "Massive Photon Vertex Experiment" - Maurik Holtrop

Having too much fun for a mutiny, so for now at least, HPS it is!