Studying the Proton "Radius" Puzzle with μp Scattering

1) Exciting Physics

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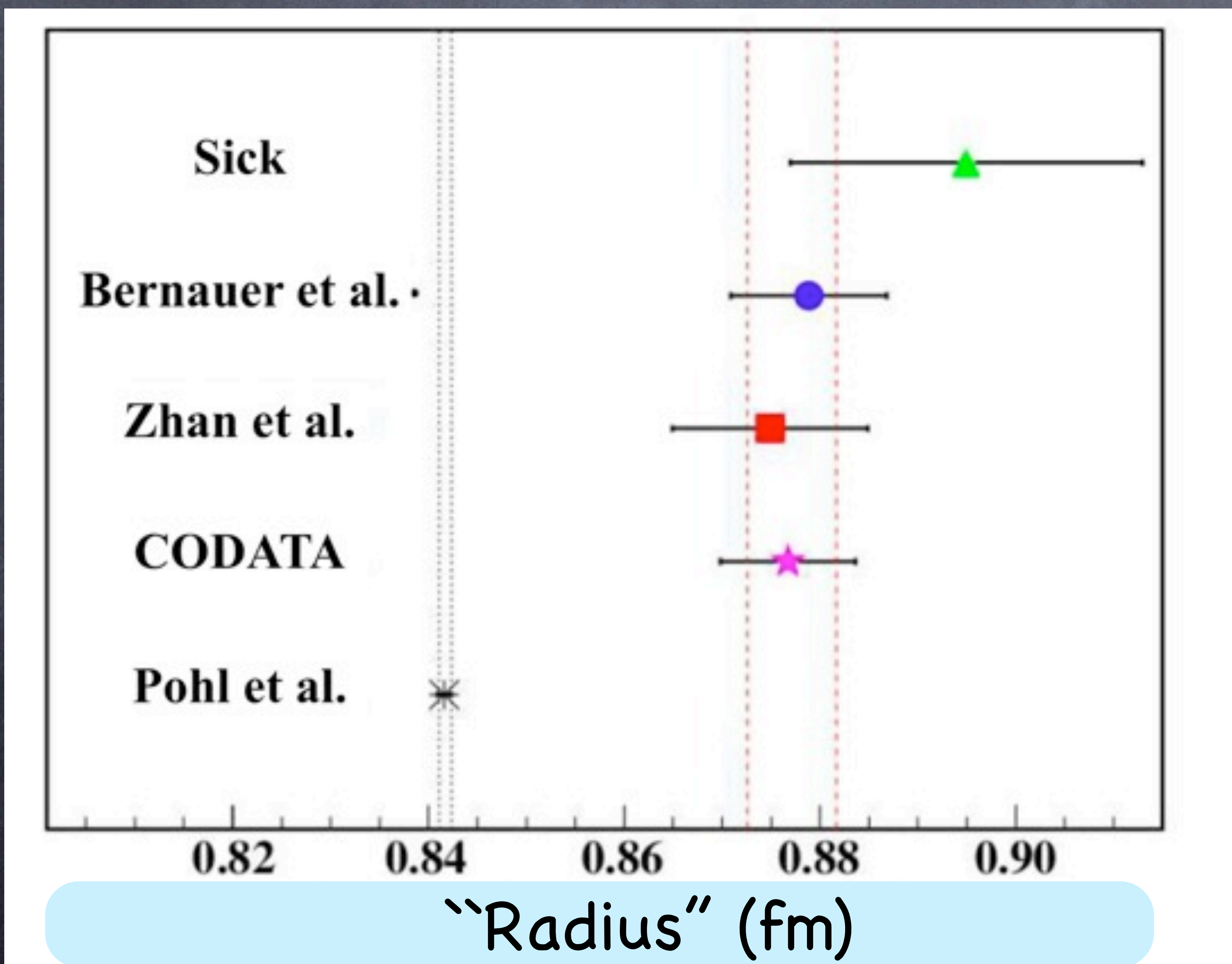
The Proton "Radius" Puzzle

Muonic hydrogen disagrees with ep atomic physics and scattering determinations of the slope of FF at $Q^2 = 0$. The difference (#5 vs #6) is 7σ. This is a high-profile issue - Nature paper, APS plenary & many invited talks, PSAS2012 Symposium, Trento ECT* Workshop Nov 2012

What could explain the difference?



#	Extraction	$\langle r_E \rangle^2$ (fm)
1	Sick	0.895±0.018
2	Bernauer Mainz	0.879±0.008
3	Zhan JLab	0.870±0.010
4	CODATA	0.877±0.007
5	Combined 2-4	0.876±0.005
6	Muonic Hydrogen	0.842±0.001

Possible Resolutions to the Puzzle / Critiques

- The μp result is wrong. No doubts about the experiment, but some discussion about the theory and proton structure for extracting the proton radius.
- The ep (scattering) results are wrong. The fit procedures are not good enough. Perhaps the data do not go to low enough Q^2, and there are structures in the form factors.
- Proton structure issues in theory. Theory critique of theory - off-shell proton in two-photon exchange leads to enhanced effects differing between μ and e, or leads to theoretically unjustified sticking-in-form-factor models.
- Novel beyond-Standard-Model Physics differentiates μ and e. But constraints on novel physics exist, and there seems to be no generally accepted solution at present.

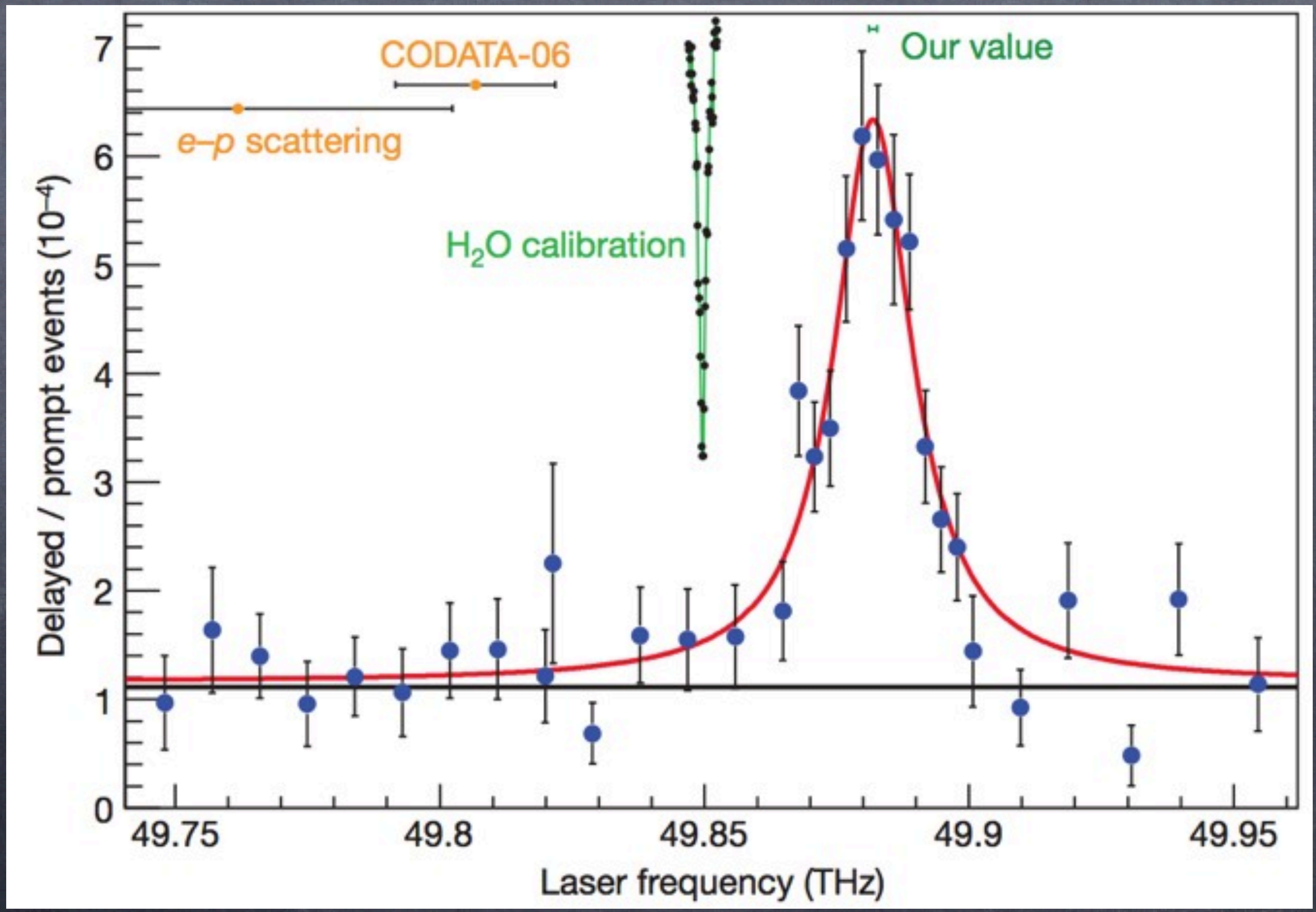
PSI Muonic Hydrogen Measurements

R. Pohl et al., Nature 466, 09259 (2010): 2S⇨2P Lamb shift

ΔE (meV) = 209.9779(49) - 5.2262 r_p^2 + 0.0347 r_p^3

⇨ r_p = 0.842 ± 0.001.

Possible issues: atomic theory & proton structure



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Possible issues: atomic theory & proton structure

Proton structure: De Rujula suggested r_p^3 could be anomalously large. Miller & Cloet and Distler, Bernauer & Walcher showed that this is inconsistent with modern form factor fits. Wu & Kao showed if you add narrow peaks in unmeasured low-Q^2 regions you can get different results. There is no reason at present to believe such structures exist - and we would also expect them to affect the ep atom and scattering determinations of the radii.

Examples of Atomic Physics Calculations

Carlson & Vanderhaeghen (2011): box diagram corrections essentially agree with Pachucki and with Martynenko, although individual terms within the evaluation vary.

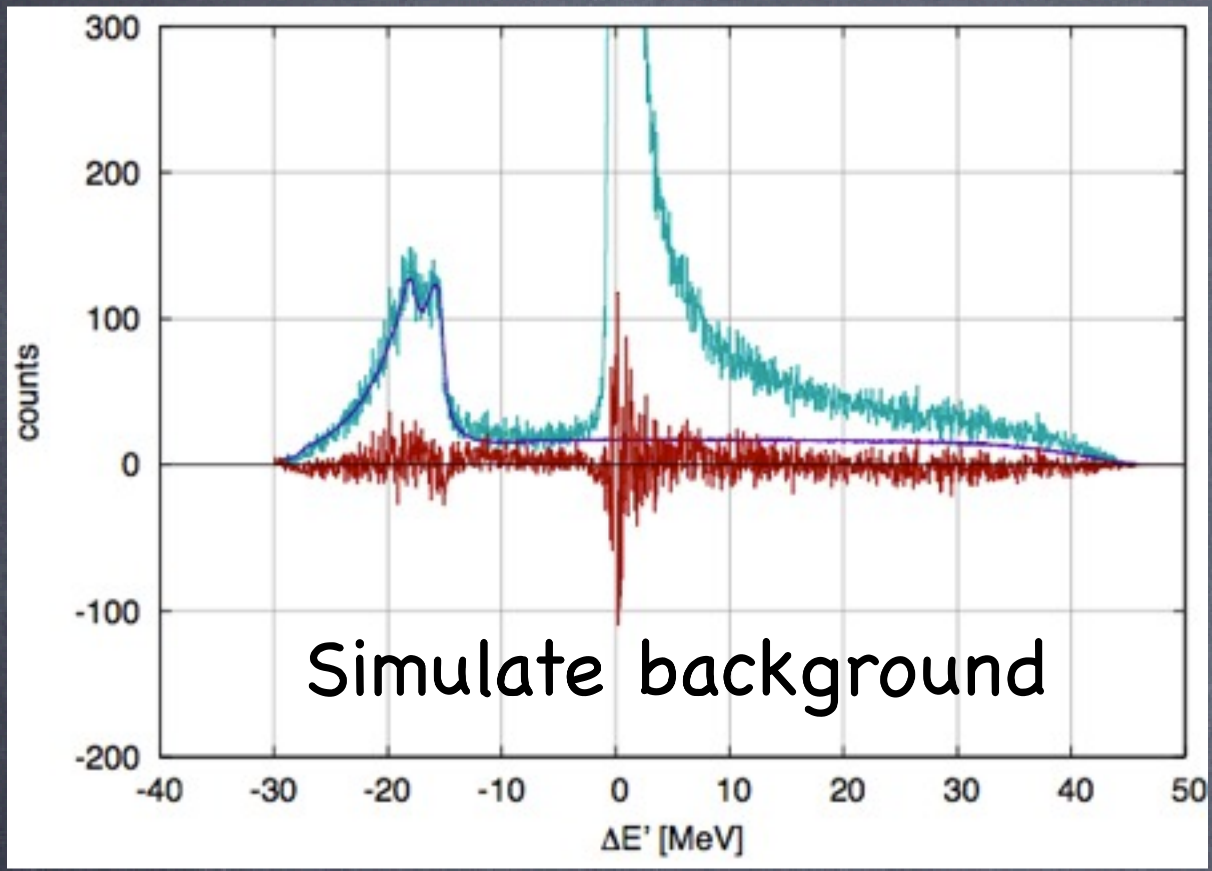
Hill & Paz (2011): Elastic contribution of C&V and others from SIFF model. Real part of inelastic not under good theoretical control and have nonphysical limiting behaviors in existing models. Numerical values given not all that different from others.

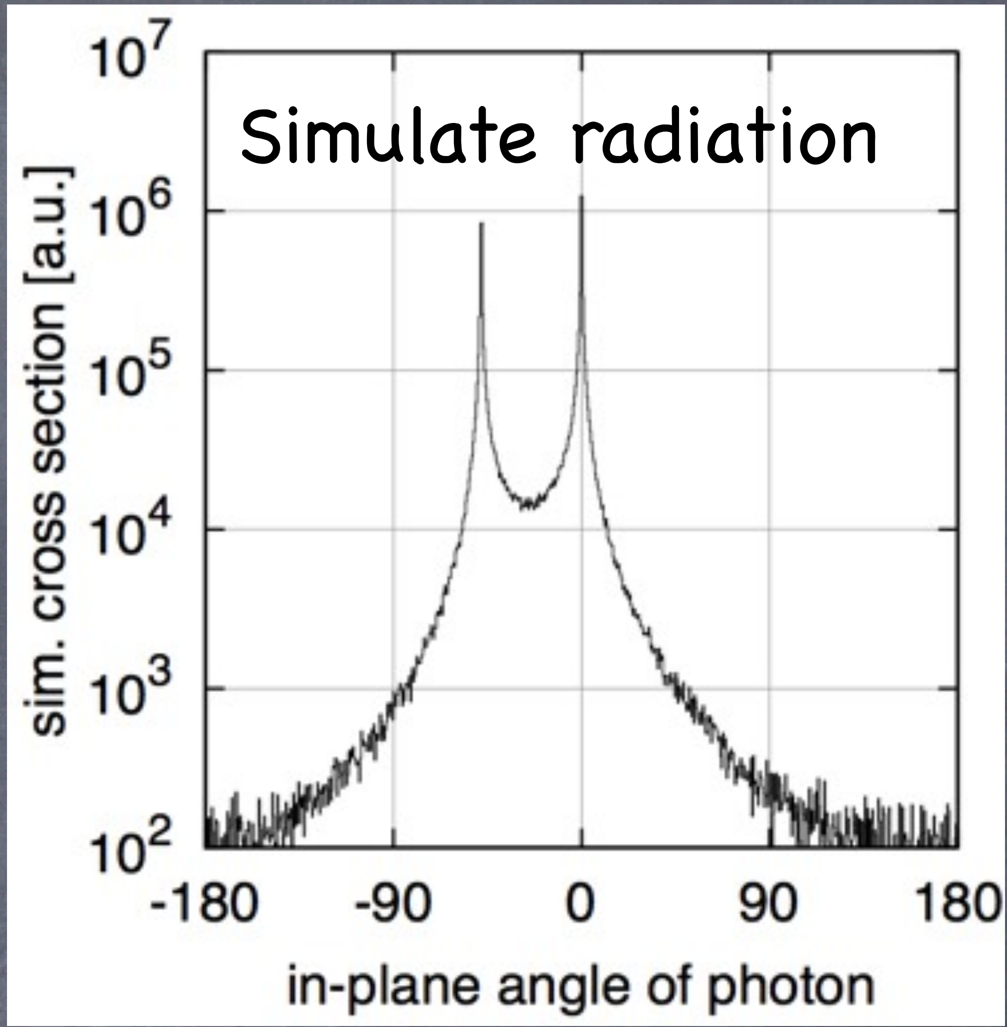
The SIFF criticism has also been made by Miller, Thomas, Carroll, & Rafelski, who point out that it has been made for many years.

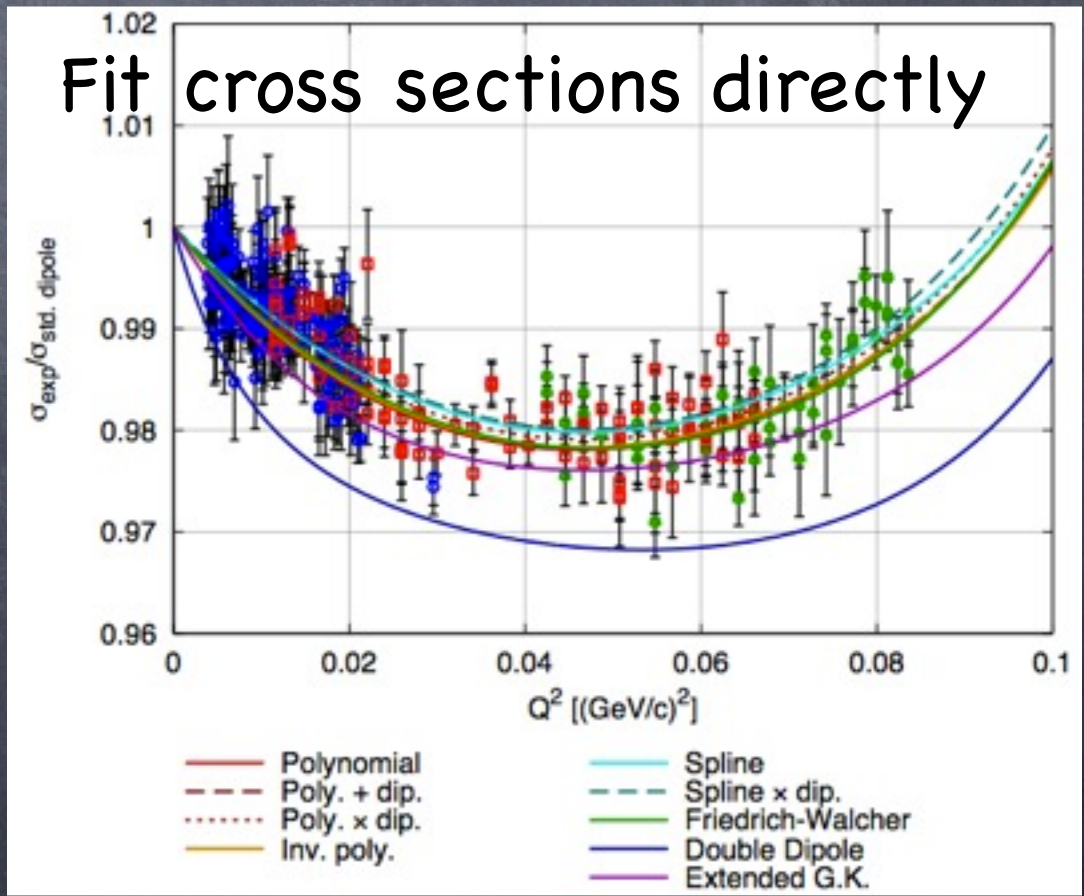
But the issue remains under dispute.

Mainz A1 ep Elastic Scattering Data

J. Bernauer et al., PRL 105, 242001 (2010)



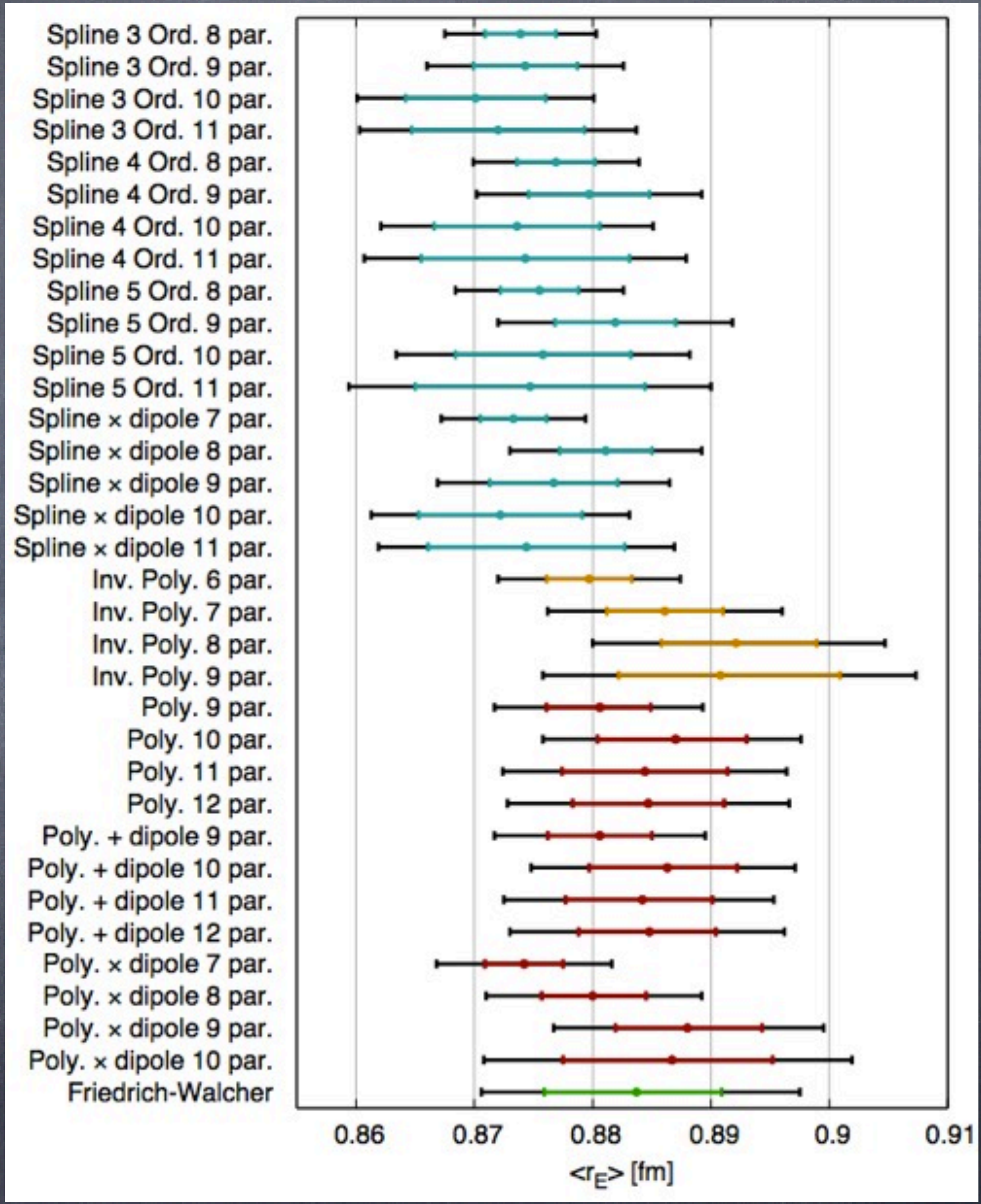




- Cross sections $\Rightarrow_{\text{corrections}}$ form factors $\Rightarrow_{\text{fits}}$ radius
- Figures from J. Bernauer's Ph.D. thesis.
- 0.5% absolute uncertainty proposed, few % achieved, data normalized to $G_E = 1$ at $Q^2 = 0$.

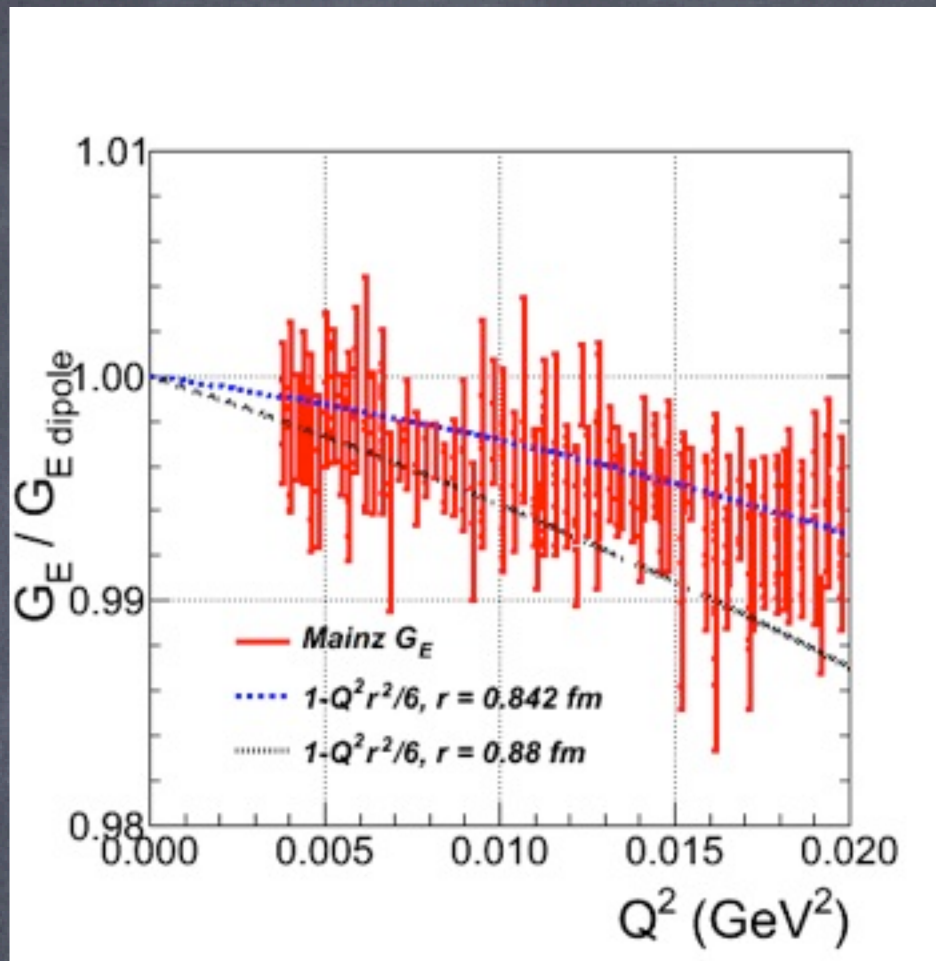
Mainz A1 Data

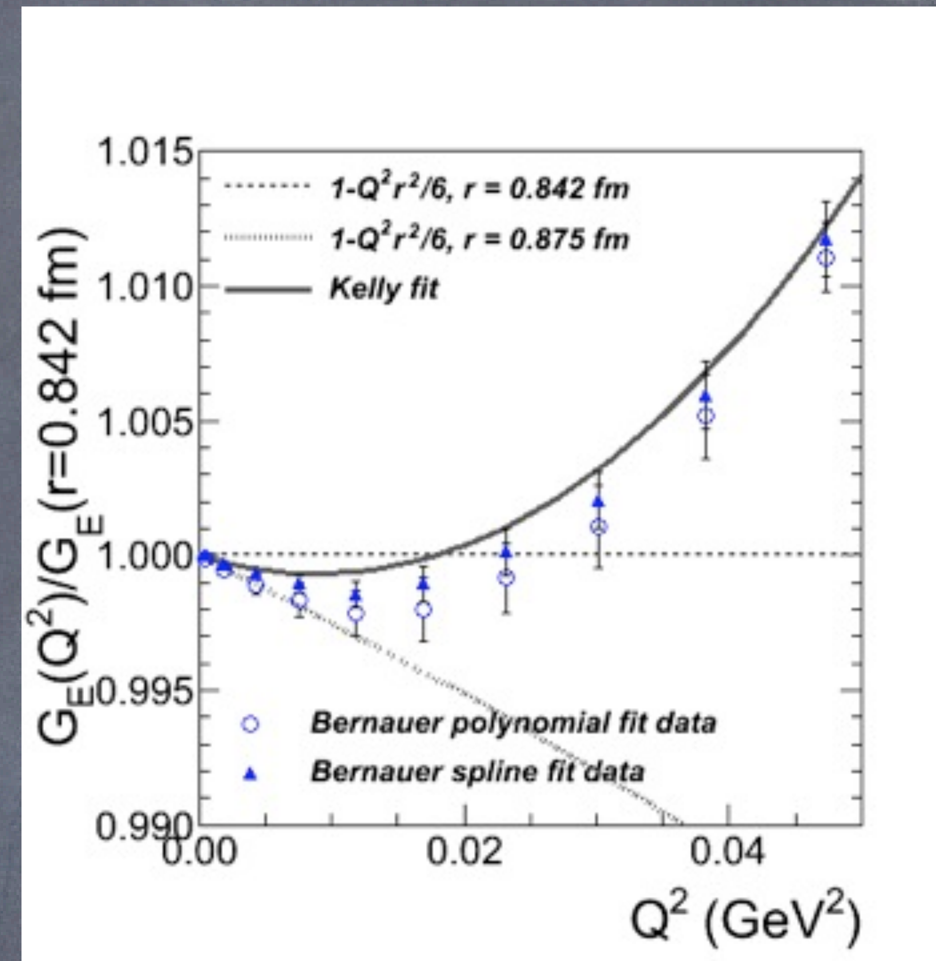
- From J. Bernauer's Ph.D. thesis: spline fits tend to give r ≈ 0.875 fm, vs polynomial fits with r ≈ 0.883 fm. Uncertainties are statistics + <u>linearly</u> added systematics.
- Reported r is an average of these, with statistical, systematic, and model uncertainties.



Mainz A1 Data

$G_E(Q^2) = 1 - Q^2r^2/6 + \ldots$



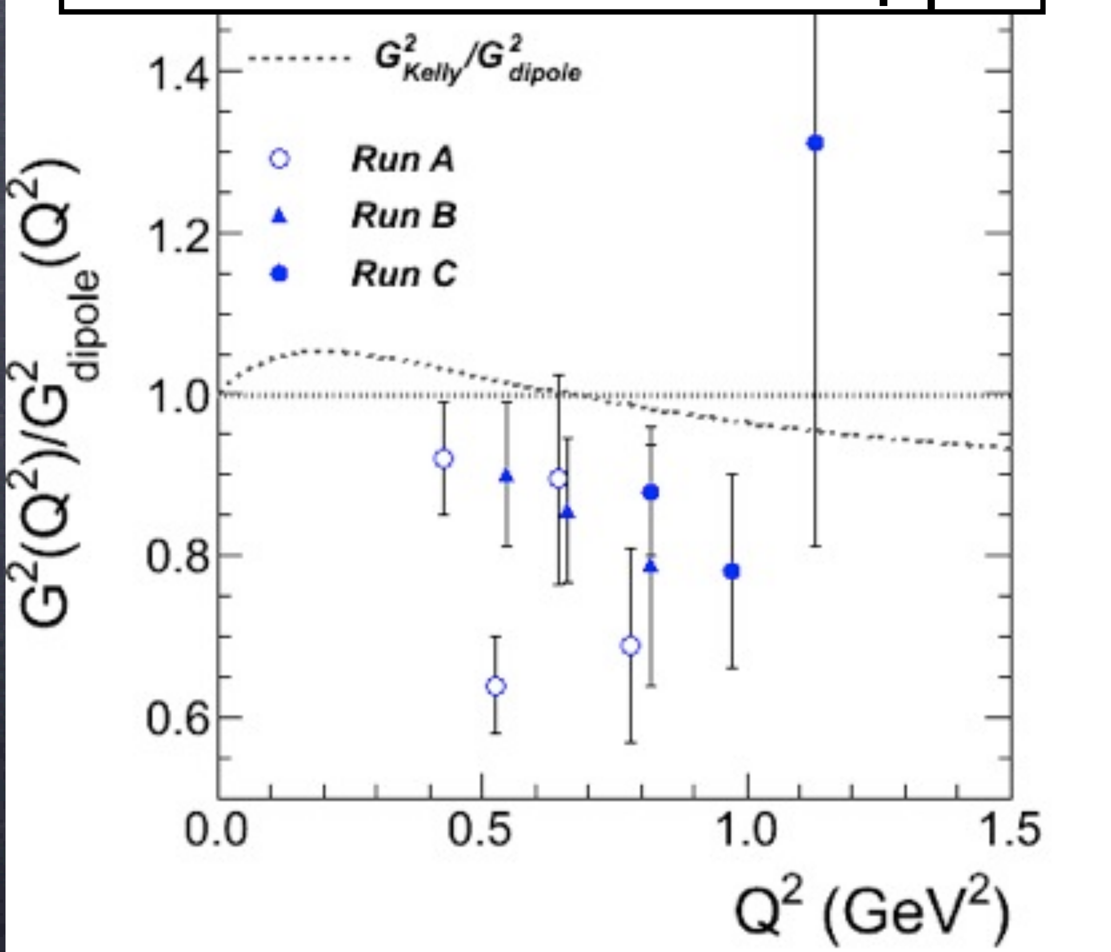


- Low Q^2 Mainz data: left - raw data, right- rebinned G_E
- Conclusion: in principle, the differences between r = 0.84 and 0.88 fm are large, but a precise experiment is needed, similar to Mainz, rather than a lower precision one aimed at only at distinguishing r = 0.84 fm from r = 0.88 fm.

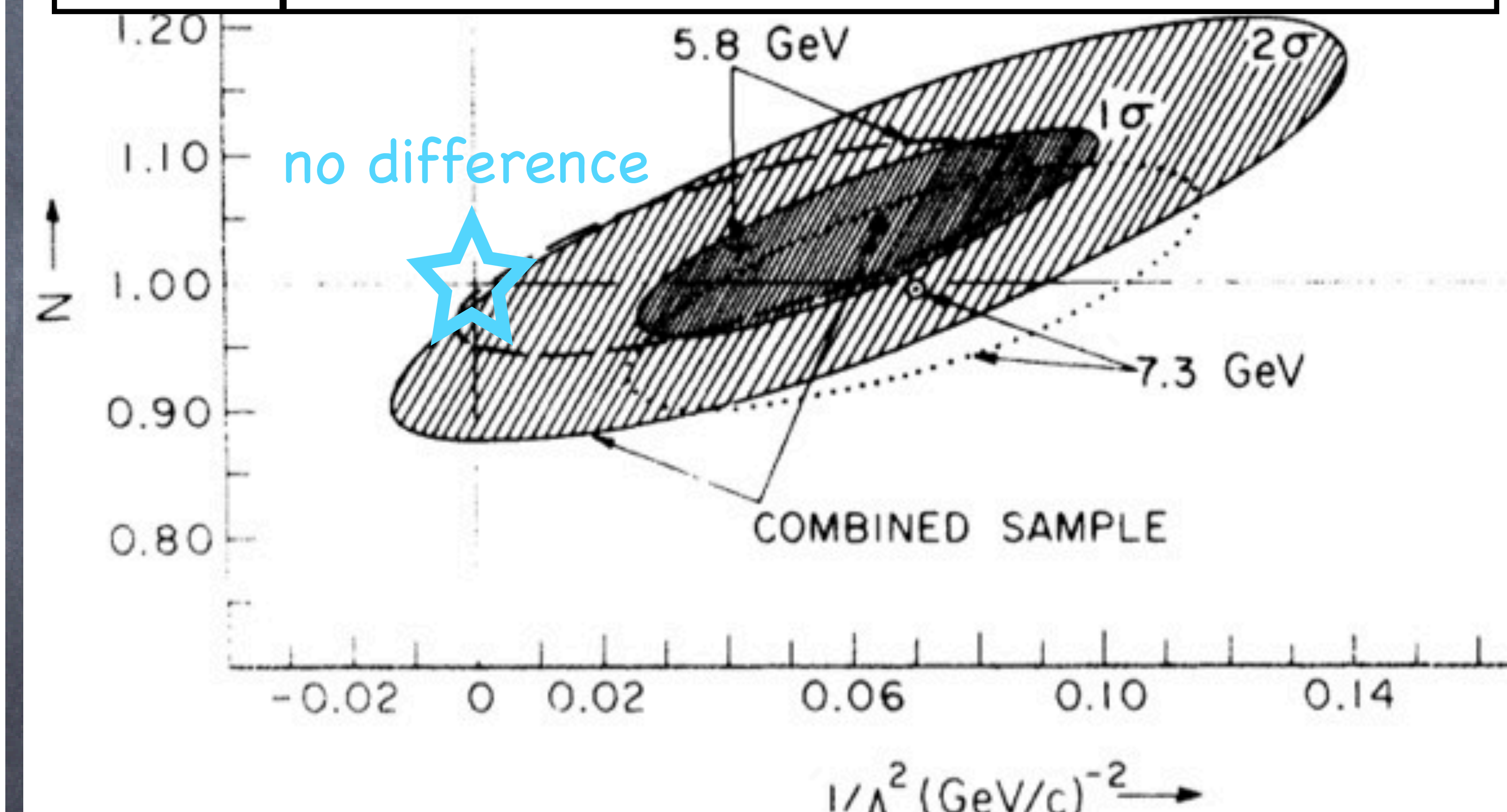
e-μ Universality

In the 1970s / 1980s, there were several experiments that tested whether the ep and μp interactions are equal. They found no convincing differences, once the μp data are renormalized up about 10%. In light of the proton "radius" puzzle, the experiments are not as good as one would like.

Ellsworth et al.: form factors from elastic μp



Kostoulas et al. parameterization of μp vs. ep elastic differences



Entenberg et al DIS: $\sigma_{\mu p}/\sigma_{ep} \approx 1.0 \pm 0.04$ ($\pm$8.6% systematics)

e-μ Universality

The ^{12}C radius was determined with ep scattering and μC atoms. The results agree:

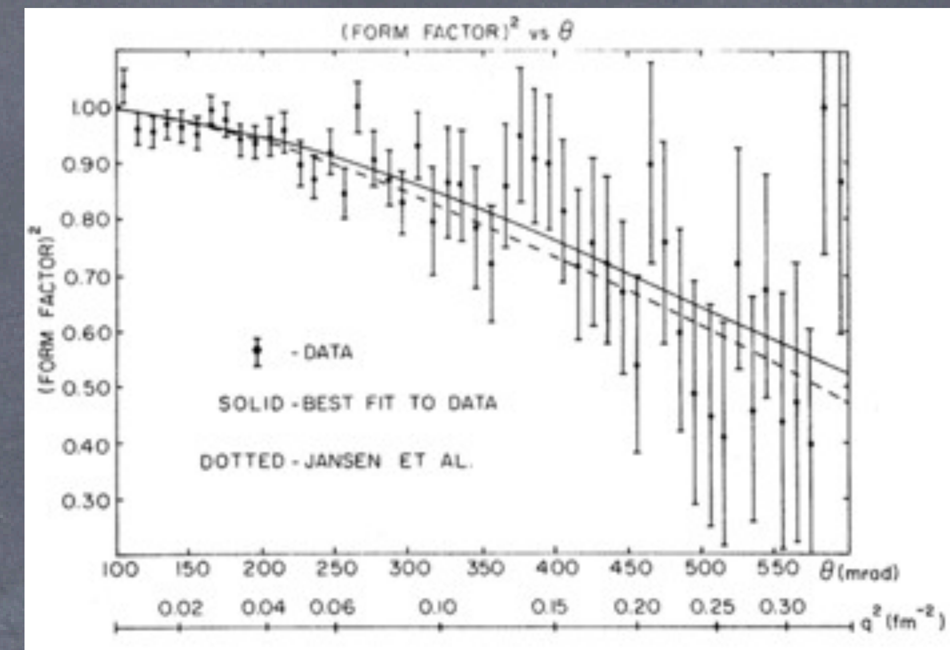
Cardman et al. eC: 2.472 ± 0.015 fm

Offermann et al. eC: 2.478 ± 0.009 fm

Schaller et al. μC X rays: 2.4715 ± 0.016 fm

Ruckstuhl et al. μC X rays: 2.483 ± 0.002 fm

Sanford et al. μC elastic: 2.32 $^{+0.13}_{-0.18}$ fm



Perhaps carbon is right, e's and μ's are the same.

Perhaps hydrogen is right, e's and μ's are different.

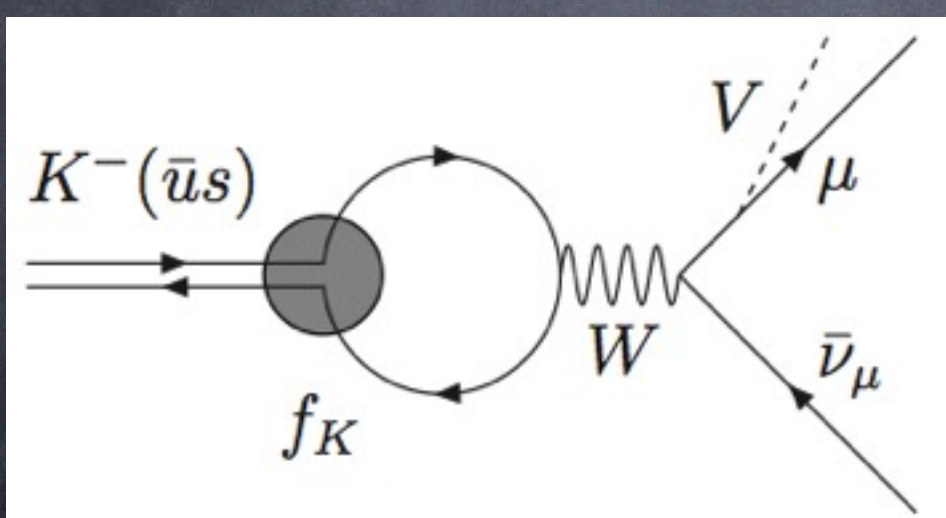
Perhaps both are right - opposite effects for proton and neutron cancel with carbon.

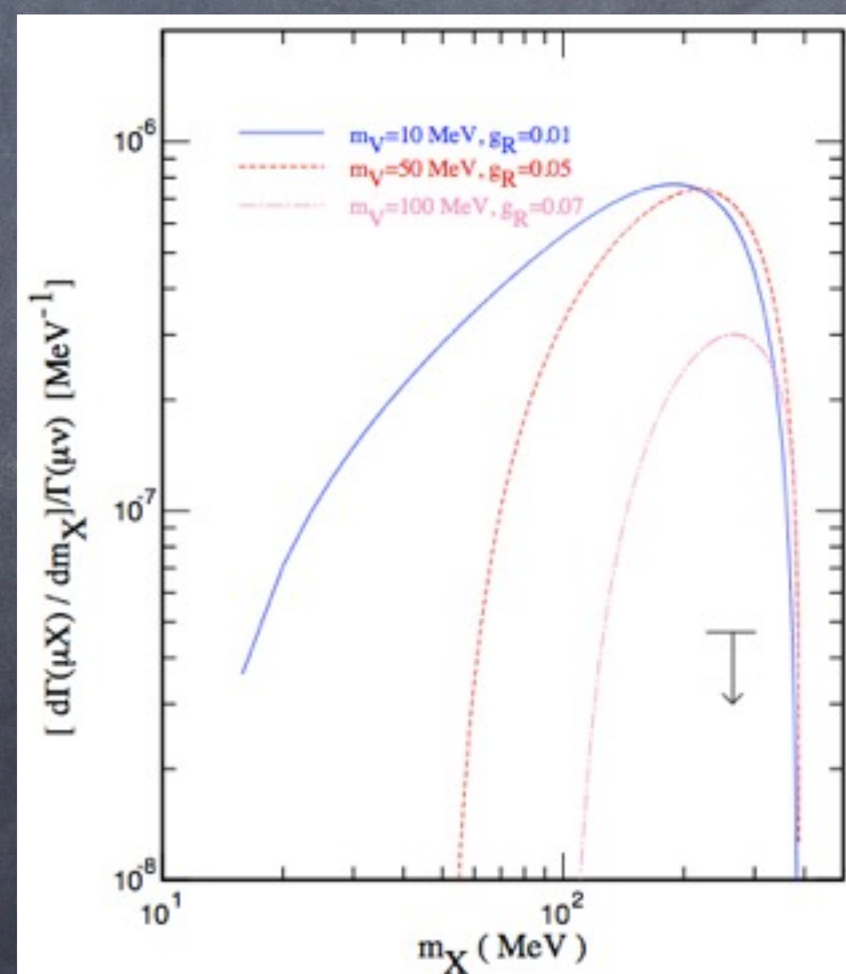
But perhaps the carbon radius is insensitive to the nucleon radius, and μd or μHe would be a better choice.

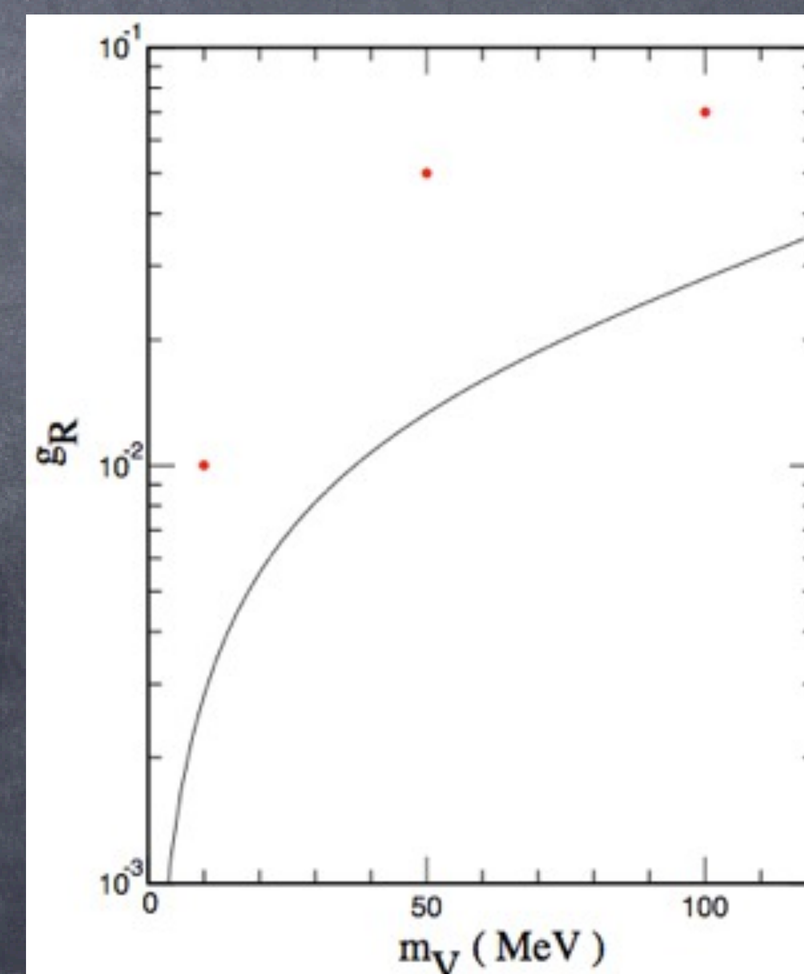
Example of Beyond Standard Model

Batell, McKeen, Pospelov propose new e/μ differentiating force with ≈ 100 MeV force carriers (guage boson V + complex scalar field), leading to large PV μp scattering. Two forces are needed to keep consistency with g_μ-2 data.

Barger, Chiang, Keung, Marfatia indicate that the $K \rightarrow \mu\nu$ decay which could radiate V, and constrains its parameters.



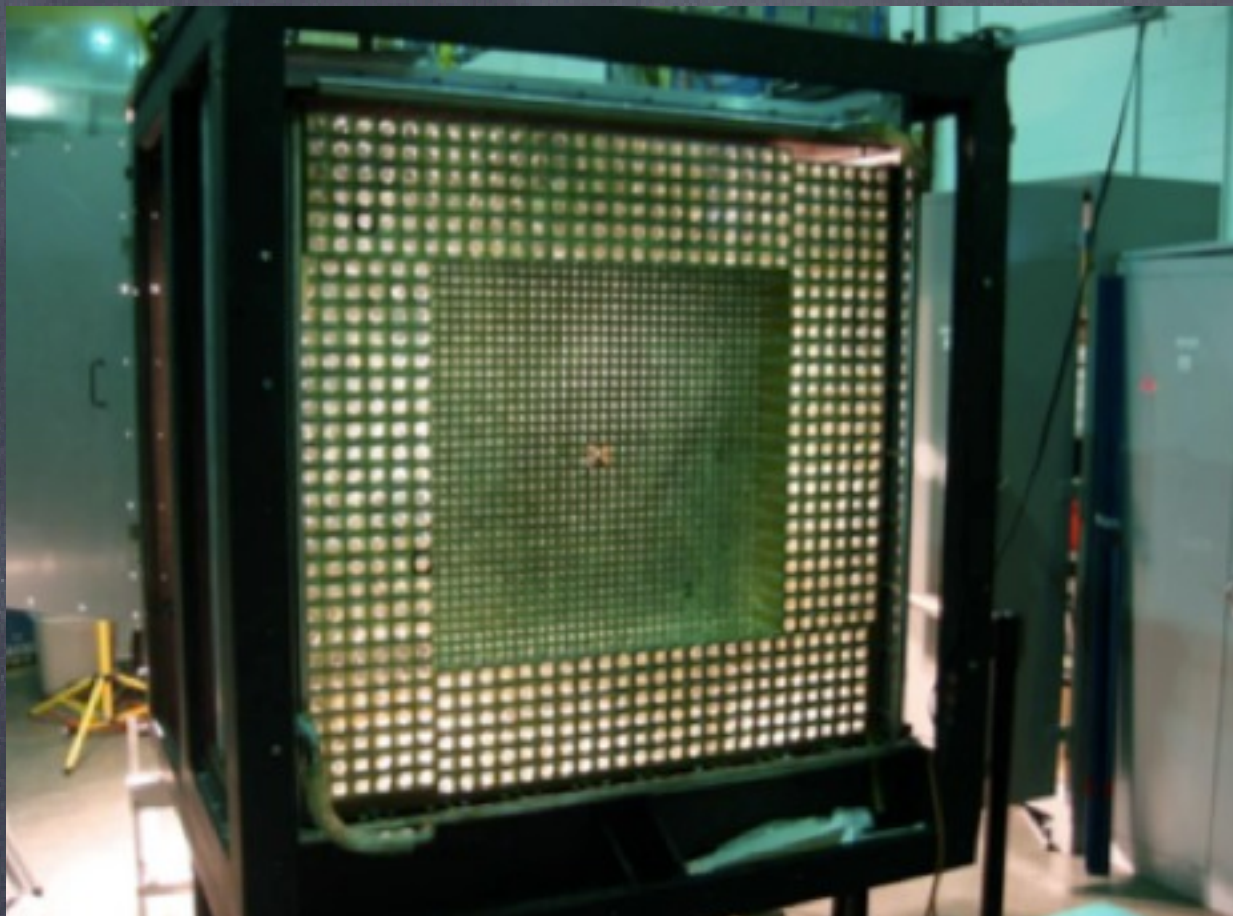


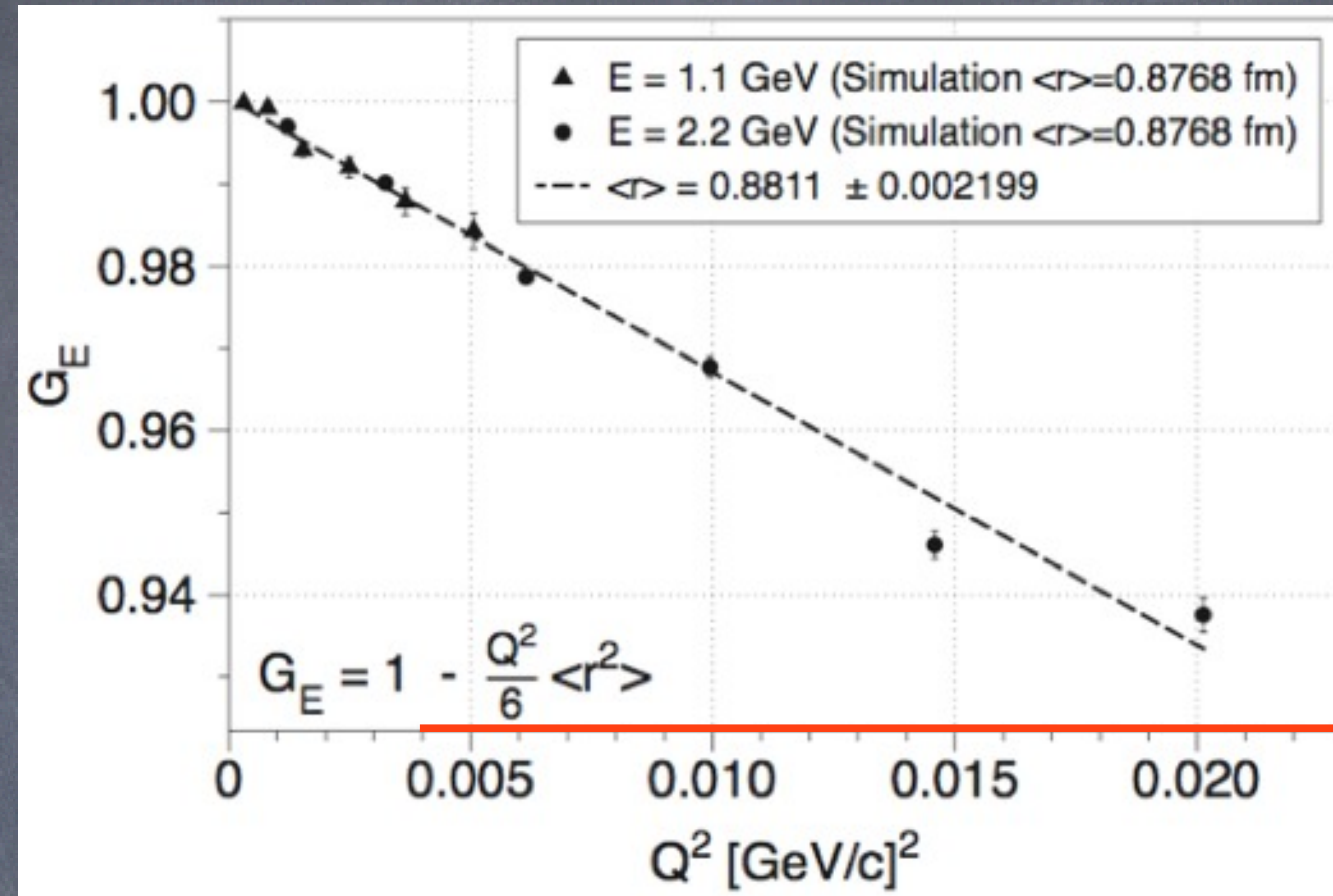


Possible Way to Resolve Puzzle: New ep Experiments

- Obvious 1st guess: high energy proton beam (FNAL?) on atomic electrons, akin to low Q^2 pion form factor measurements - difficult - only goes to 0.01 GeV^2.
- With MEIC/EIC, etc., obvious alternative in the longer term: use a ring with bending magnets to provide access to near 0 degree scattering - perhaps in several years
- Very low Q^2 JLab experiment, near 0° using ``PRIMEX'' setup: A. Gasparian, D. Dutta, H. Gao et al.

The ``PrimEx'' Proposal



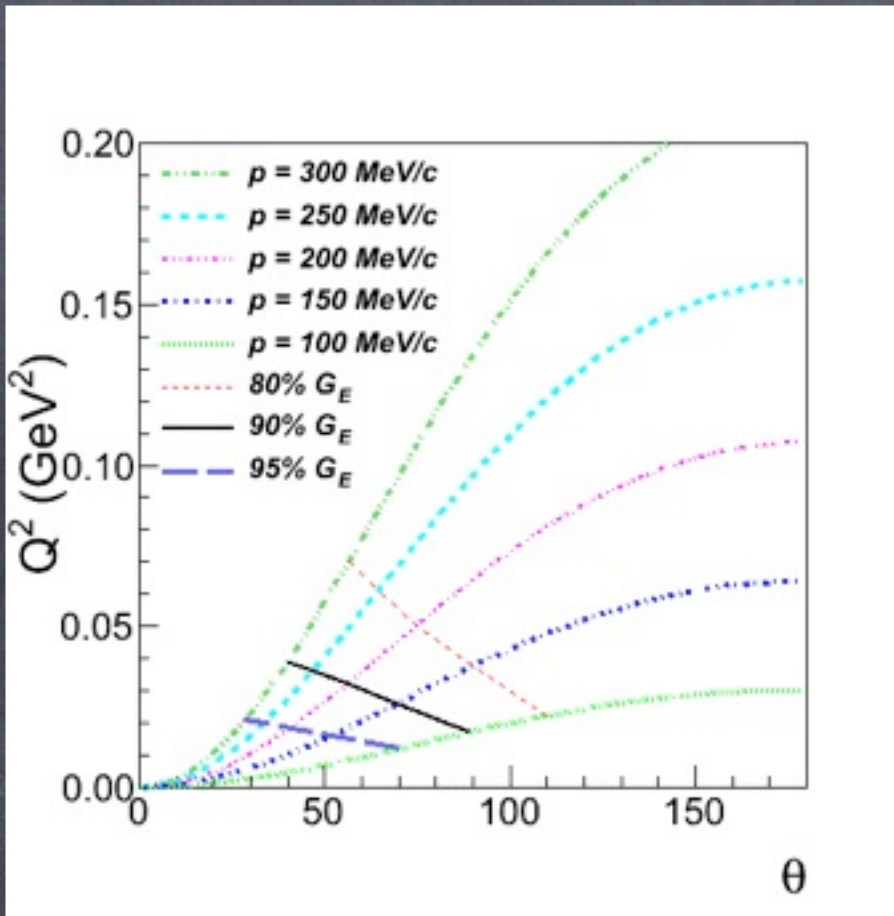


- Low intensity beam in Hall B into windowless gas target.
- Scattered ep and Moller electrons into HYCAL at 0°.
- Lower Q^2 than Mainz. Very forward angle, insensitive to 2γ, G_M.
- Conditionally approved by August 2011 PAC: ``Testing of this result is among the most timely and important measurements in physics.'' Unlikely to run until 2016 or so (my estimate).

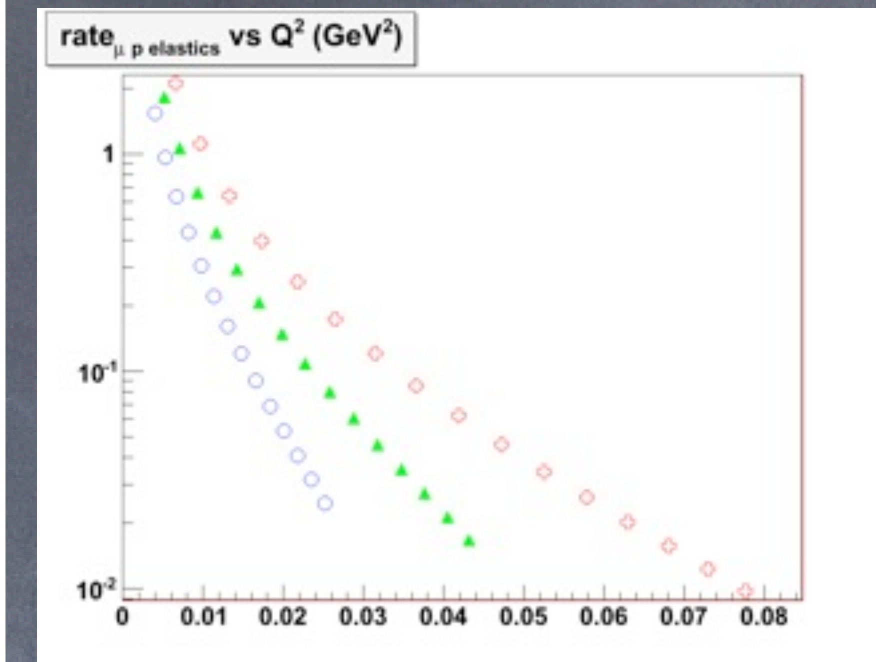
This proposal: μp Scattering at PSI

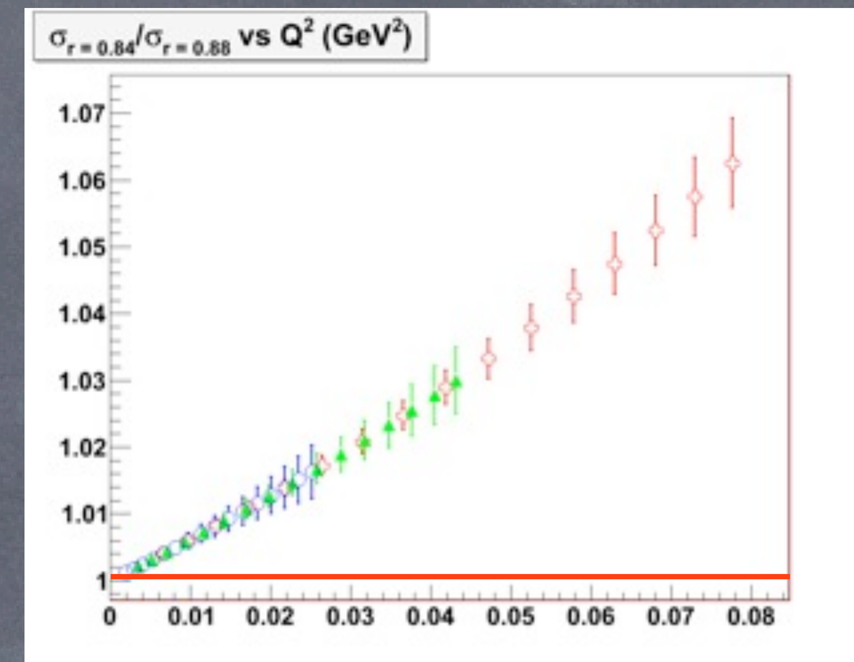
- Directly test the most interesting possibility, that μp and ep scattering are different:
  - to higher precision than previously,
  - in the low Q^2 region (same as Mainz and a JLab experiment now starting) for sensitivity to radius
  - with $\mu^\pm$ to study possible 2γ mechanisms, but with improved sensitivity from low energy and large angle
  - measuring both $\mu^\pm p$ and $e^\pm p$ to have direct comparison and a robust, convincing result.
- Depending on the results, 2nd generation experiments (lower Q^2, $\mu^\pm n$, higher Q^2, ...) might be desirable or unneeded.

The Results!



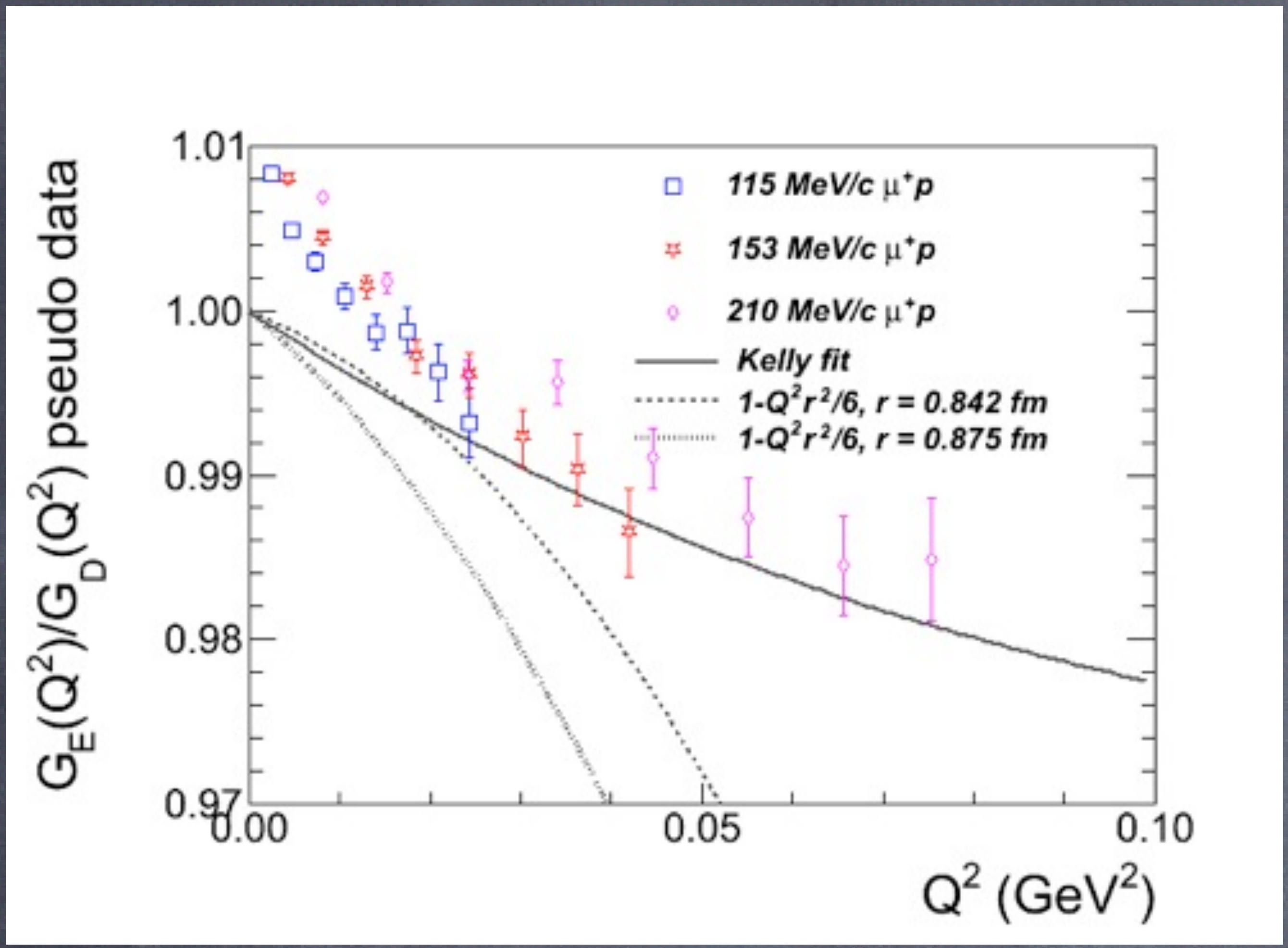
projected μ^+p

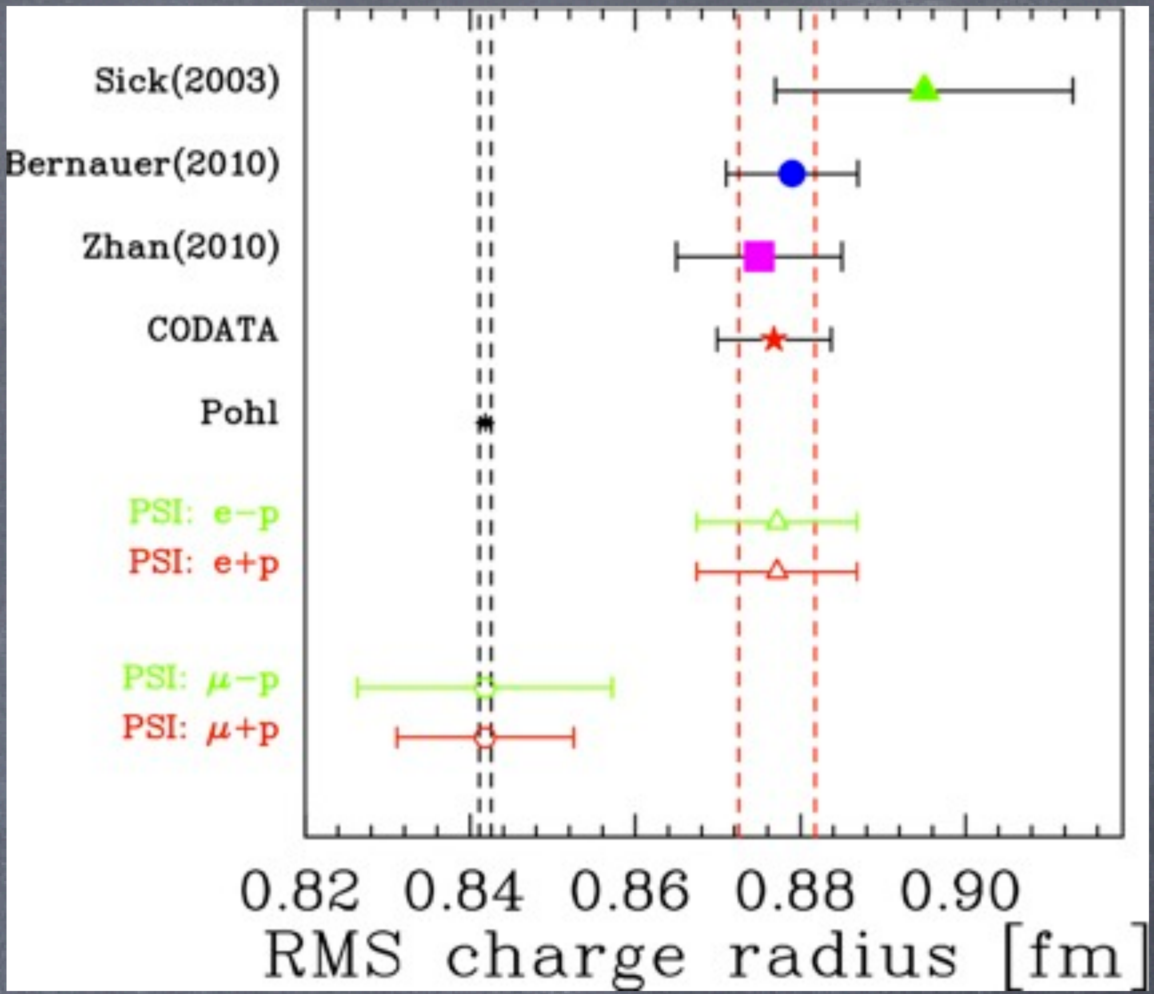




- πM1 channel, with p_{in} = 115, 153, and 210 MeV/c: PID reasons.
- Choose $\theta_{scatter}$ = 20 - 100°: rates, backgrounds, systematics.
- ΔR = 4% ⇨ $\Delta G'$ = 8% ⇨ $\Delta\sigma'$ = 16%.
- Statistics shown with estimated systematics lead to $\Delta R \approx$ 0.01 fm for μ^+, $e^\pm$, but about 0.015 fm for μ^-.
- Un-answered question: if radius differences are real, are cross section differences really this large?

More Results





- Left: pseudo-random data (10° bins) showing effect of a large angle offset.
- Right: Estimate of uncertainties on extracted radius - systematic uncertainties dominate
  - Relative e-μ radius has decreased uncertainties, estimated to be a factor of 2 or more.

Experimental Issues Studied

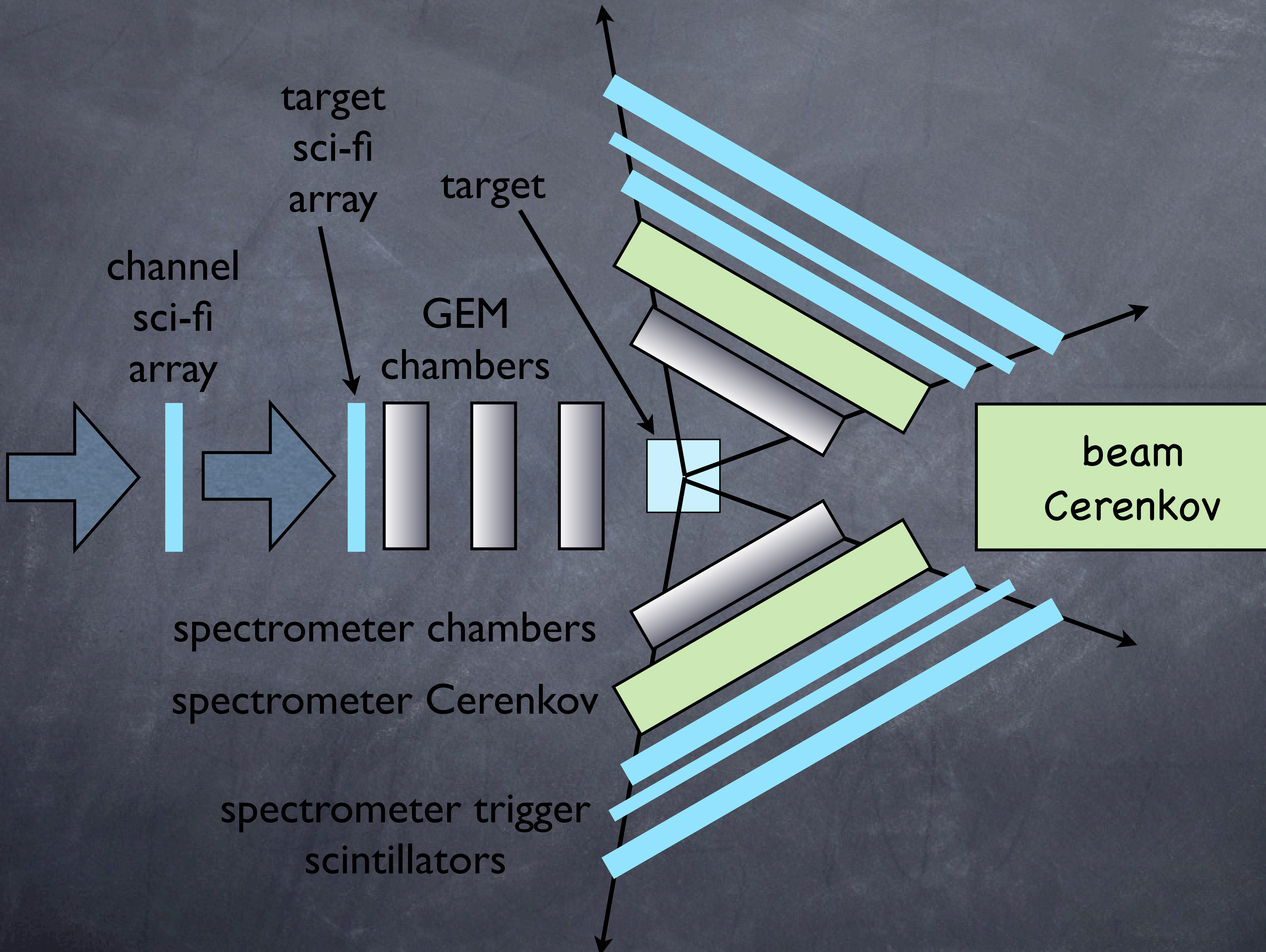
- Backgrounds: Moller & Bhabha scattering, π elastic scattering, π and μ decay in flight, scattering from cell walls
- Rate issues: determining event by event properties of 10 MHz of beam particles, singles rates in detectors, trigger rates
- Systematic uncertainties: angle determination, beam momentum determination, multiple scattering effects, determining flux and efficiency
- Detectors: GEMs, Sci-Fis, beam Cerenkov, wire chambers, threshold Cerenkov, scintillators, certain issues in triggering and DAQ
- Management: cost, time line, possible funding

What do we need to do?

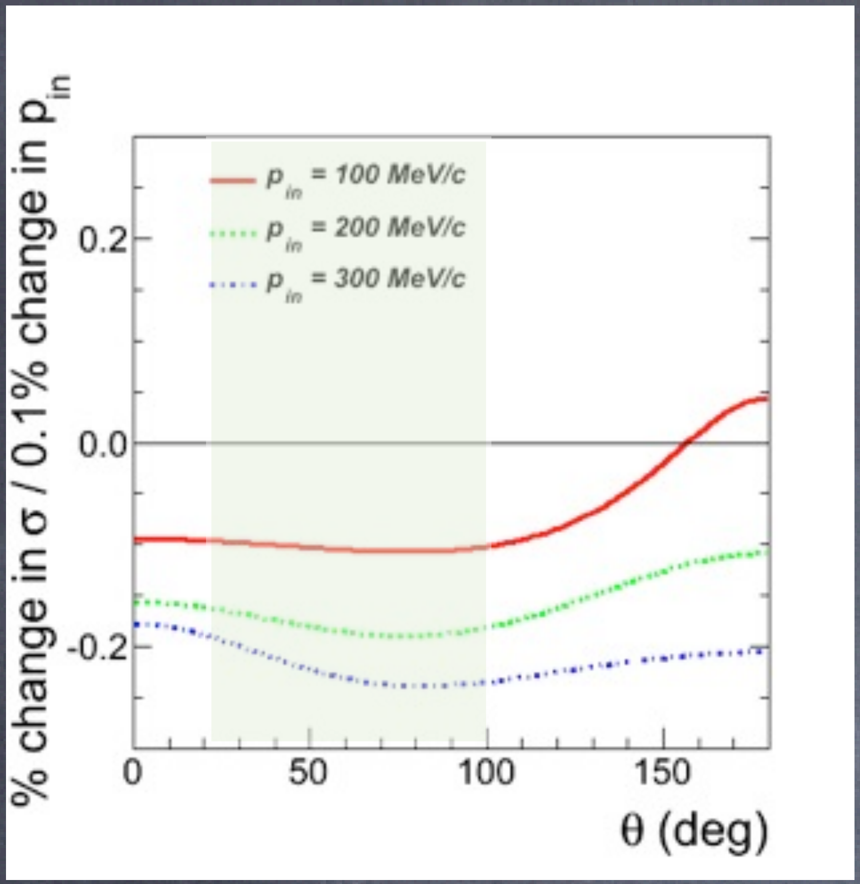
Basic goal: close to 1% experiment absolute, sub 1% relative, to minimize the amount of improvement needed in fitting out offsets

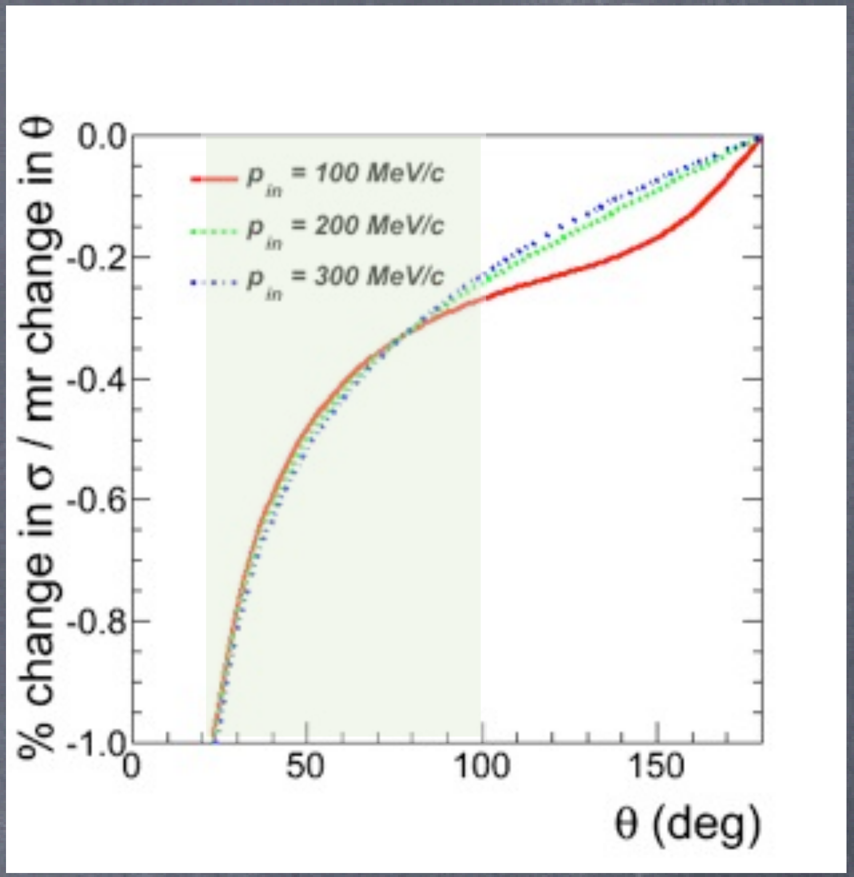
Operate at ≈10 MHz beam rates w/ 50 MHz beam
Know flux of μ's and e's to ≈0.1%
PID at trigger and analysis level
2nd PID method for redundancy and consistency
Know chamber orientation to < 1 mr
Determine event scattering angle to ≤ 10 mr event by event
Reject ghosts and accidentals
Know average incident momentum of particles to 0.1%
Trigger off ≈100 MeV/c μ's, e's, not π's, Mollers, Bhabhas, ...
Redundancy for high and well-known efficiencies - trigger and tracking

Detector Cartoon



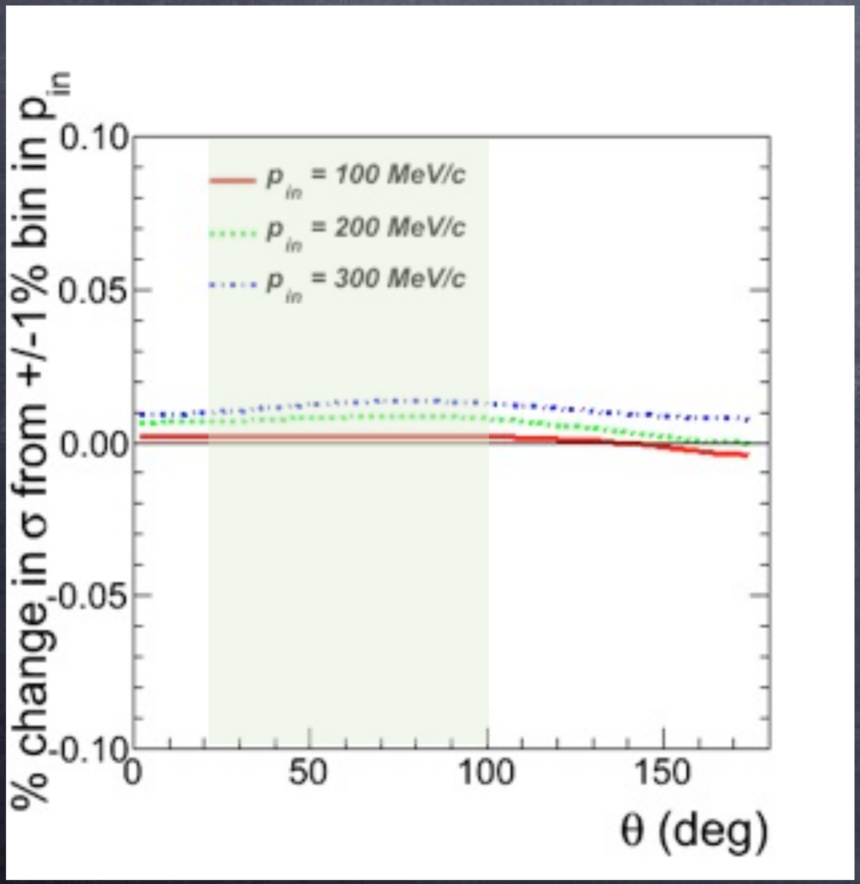
Some Systematics to Control

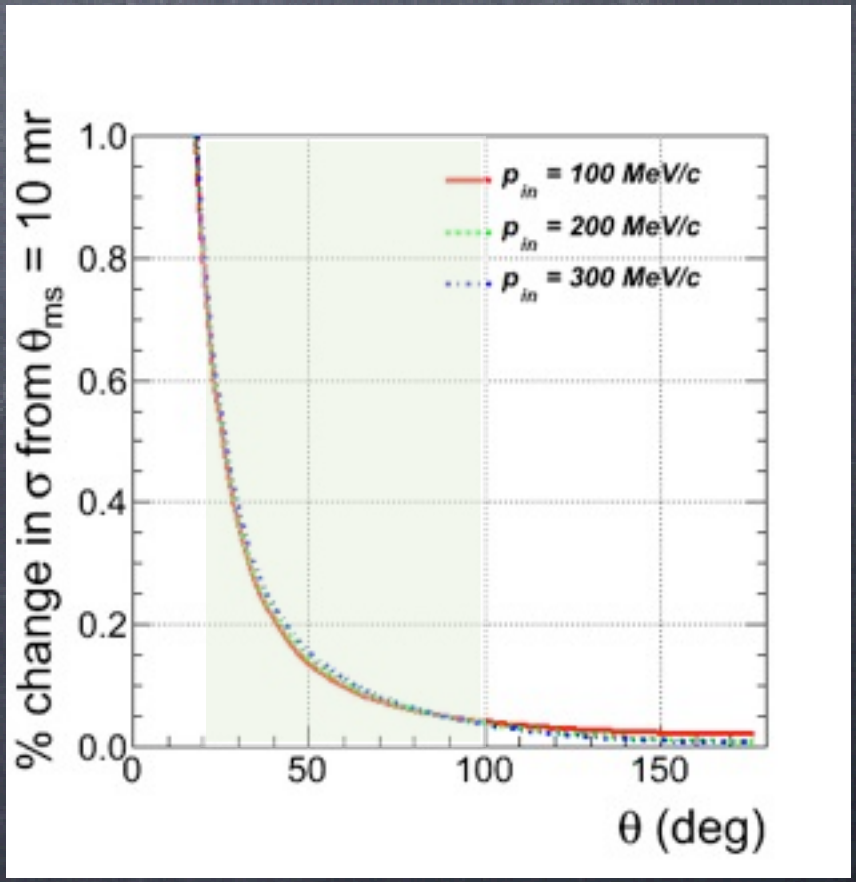




Left: should know central momentum to tenths of a percent, but can average over a few percent bin. Can "fit this out".

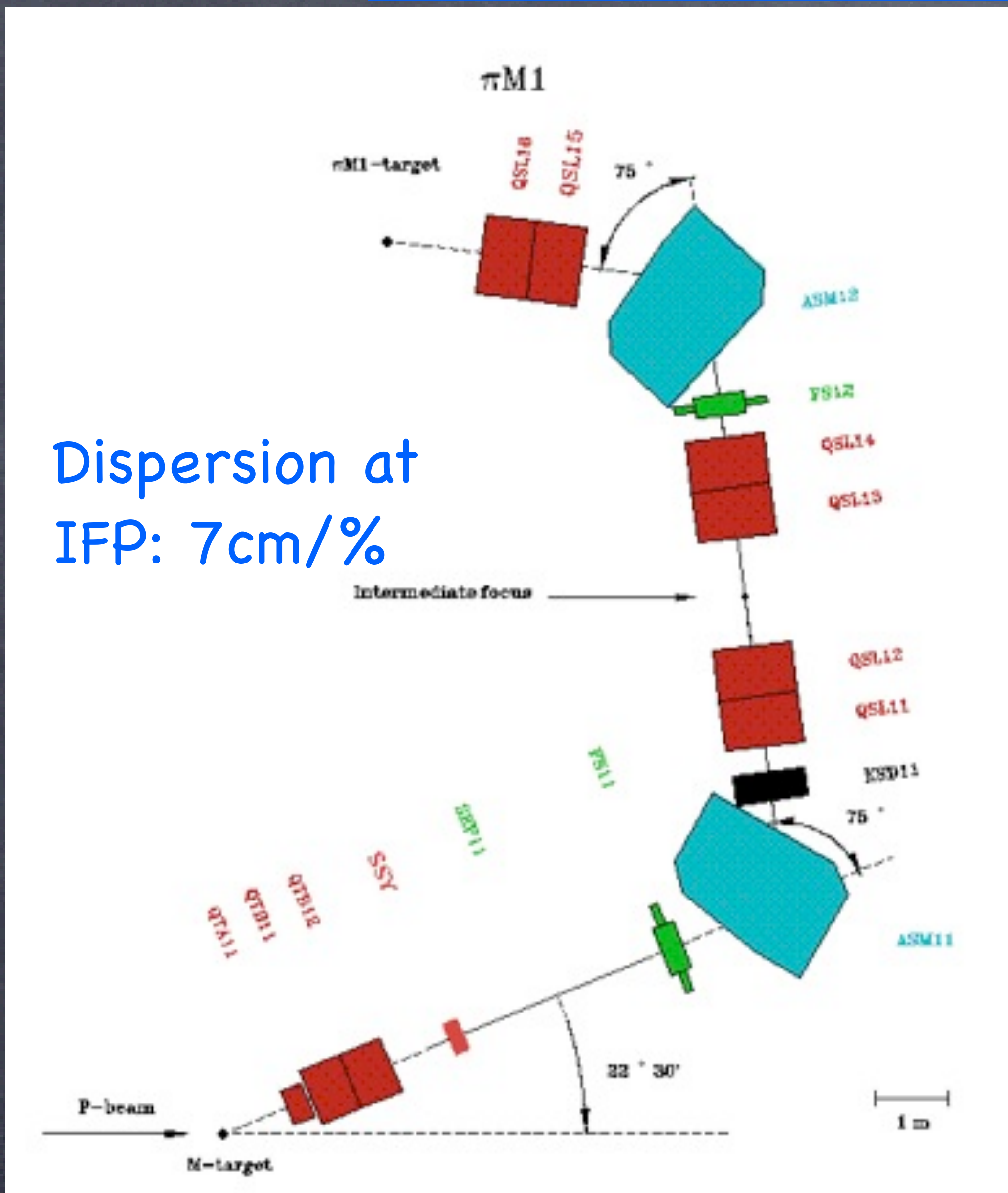
Right: should know central angle to mr level, but can average over several mr. Can ``fit out" offset and correct cross sections for resolution.



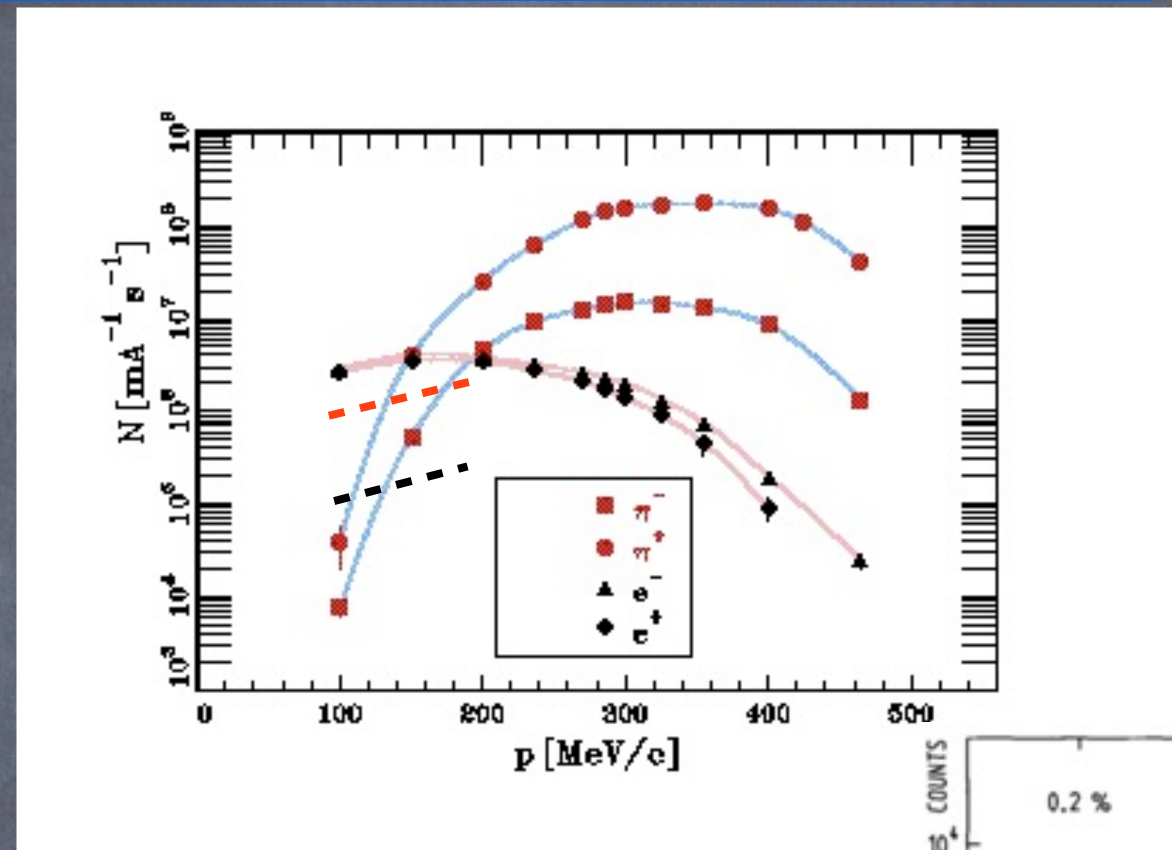


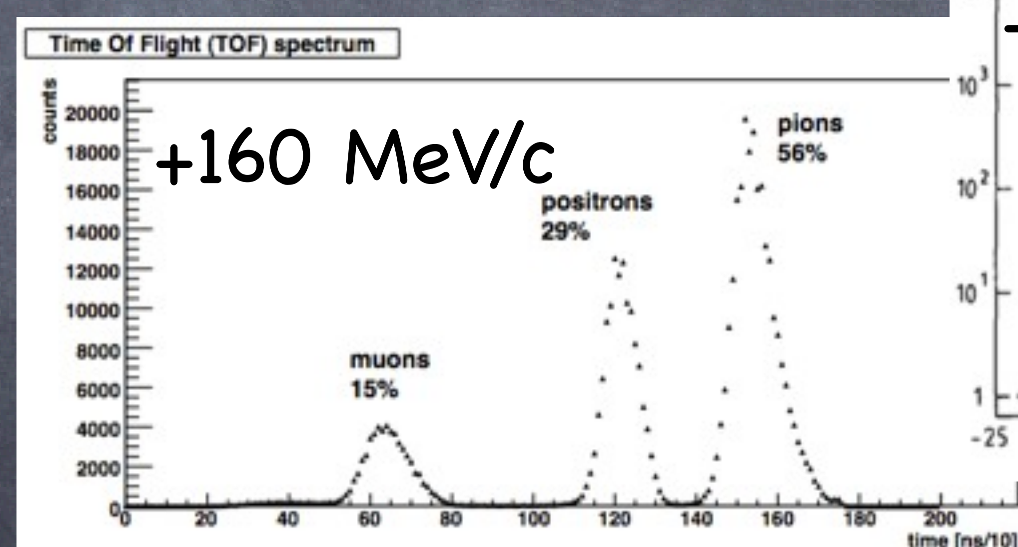
πM1 Channel - Nominal Characteristics

≈100 - 500 MeV/c mixed beam of μ's + e's + π's

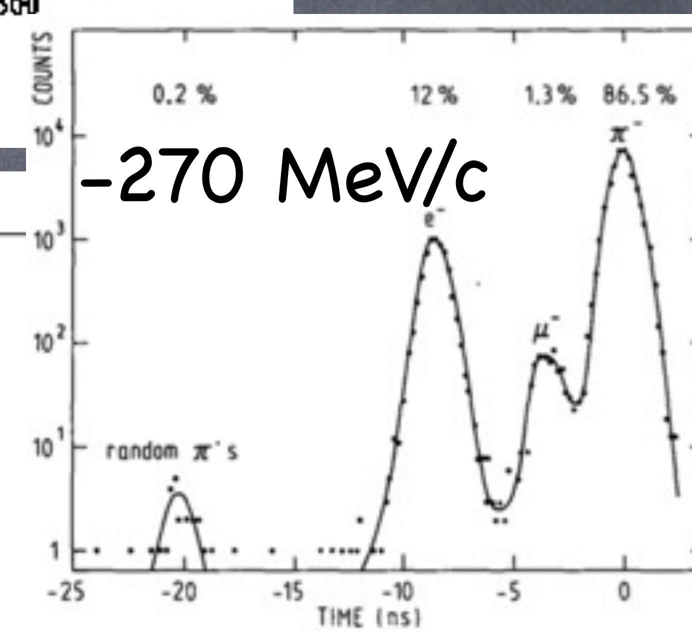


Dispersion at IFP: 7cm/%





+160 MeV/c



−270 MeV/c

Beam spot (nominal):
1.5 cm X x 1 cm Y,
35 mr X′ x 75 mr Y′

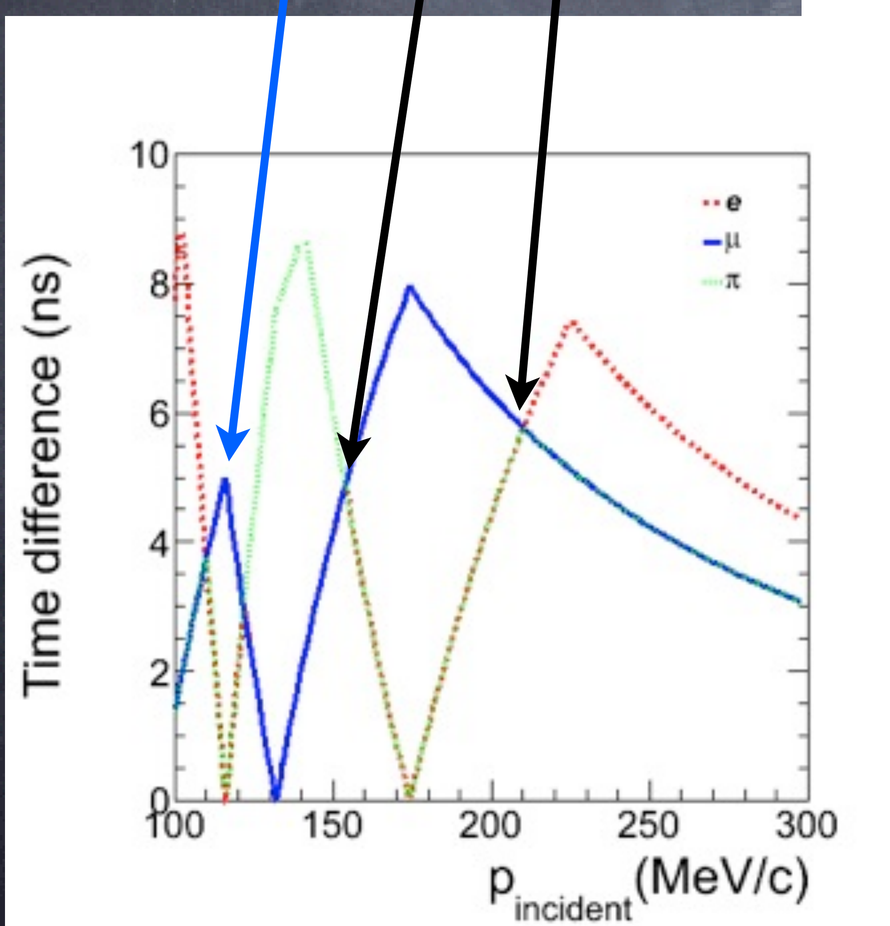
Momentum acceptance: 3% resolution: 0.1%

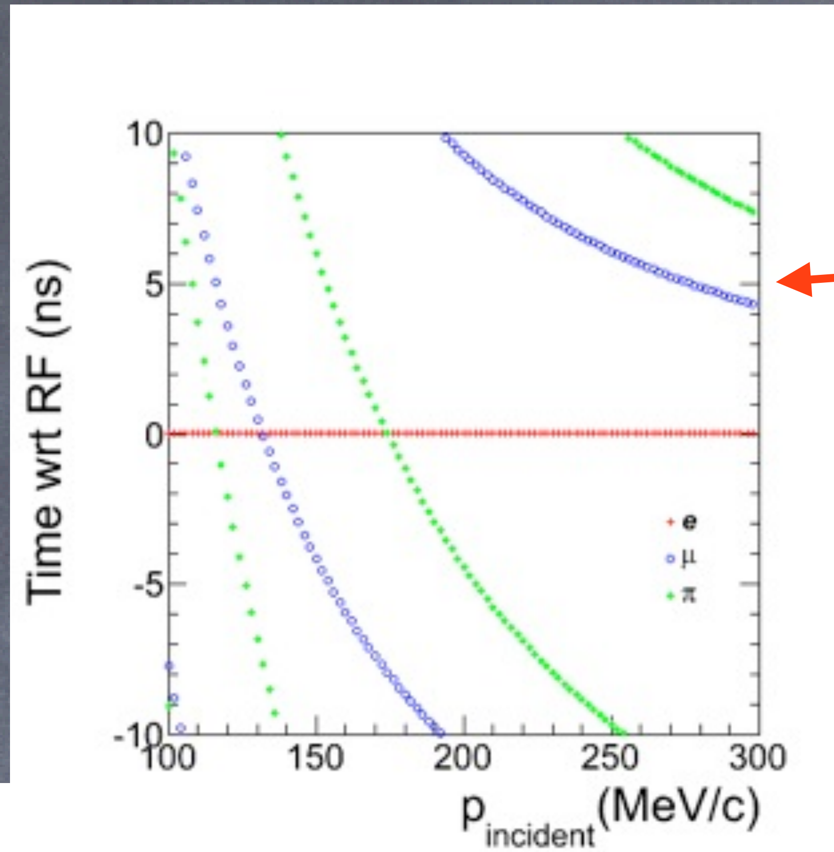
Spots from 0.7x0.9 cm^2 up to 16x10 cm^2, and Δp/p from 0.1-3.0%, used previously.

Determining Particle Type - RF Time

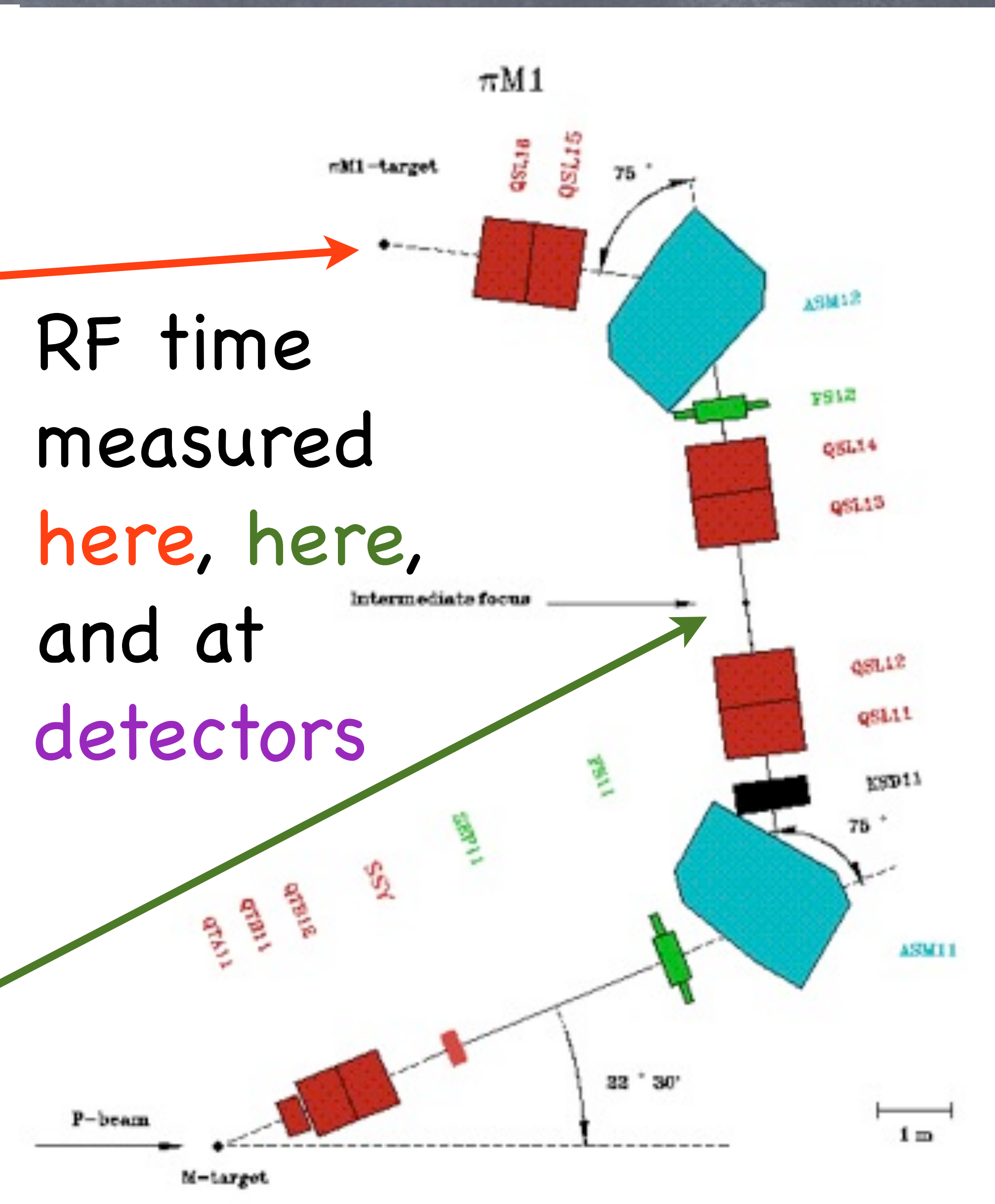
μ separated from π and e

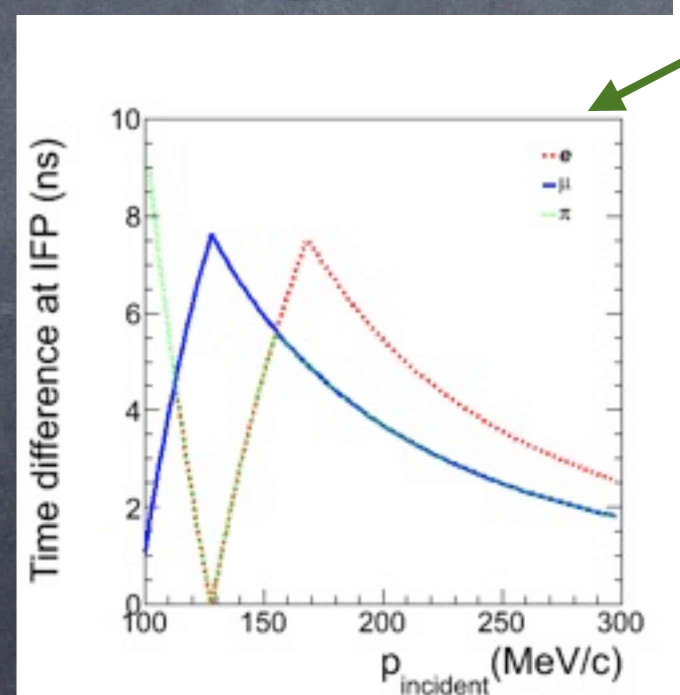
π, μ, e all separated





RF time measured here, here, and at detectors





If random (non-scattered) particle at IFP is a different particle type, the position and momentum of the triggering particle can still be determined.

Rate Considerations

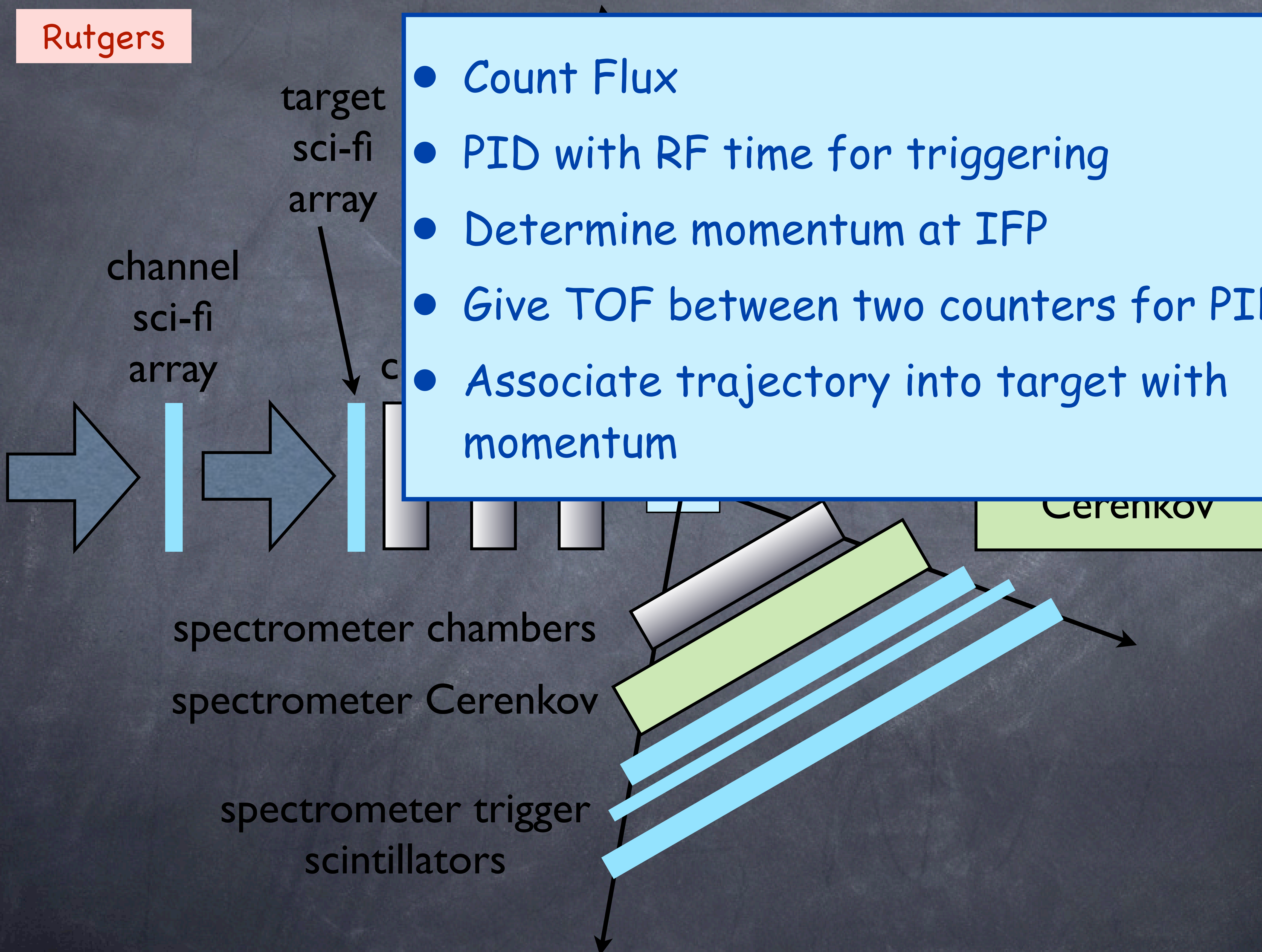
- At 10 MHz rate with 50 MHz beam, 82% chance clean, 16% chance 2 particles, 2% chance >2 particles in RF bucket.
- Reduce acceptance to cut rates for +210, 153 MeV/c.
- 250 ns chamber time scale ➪ 2.5 background trajectories on average each event.
- Desirable to be able to handle 2nd particle in same RF bucket as μ trigger. Not absolutely needed.

p (MeV/c)	+/-	π (MHz)	μ (MHz)	e (MHz)	Σ (MHz)
115	+	0.6	2	6	9
153	+	8	2	8	18
210	+	60	5	6	70
115	-	0.06	0.2	6	6
153	-	0.7	0.2	8	9
210	-	6	0.5	6	12

Beam Sci-Fi

Rutgers

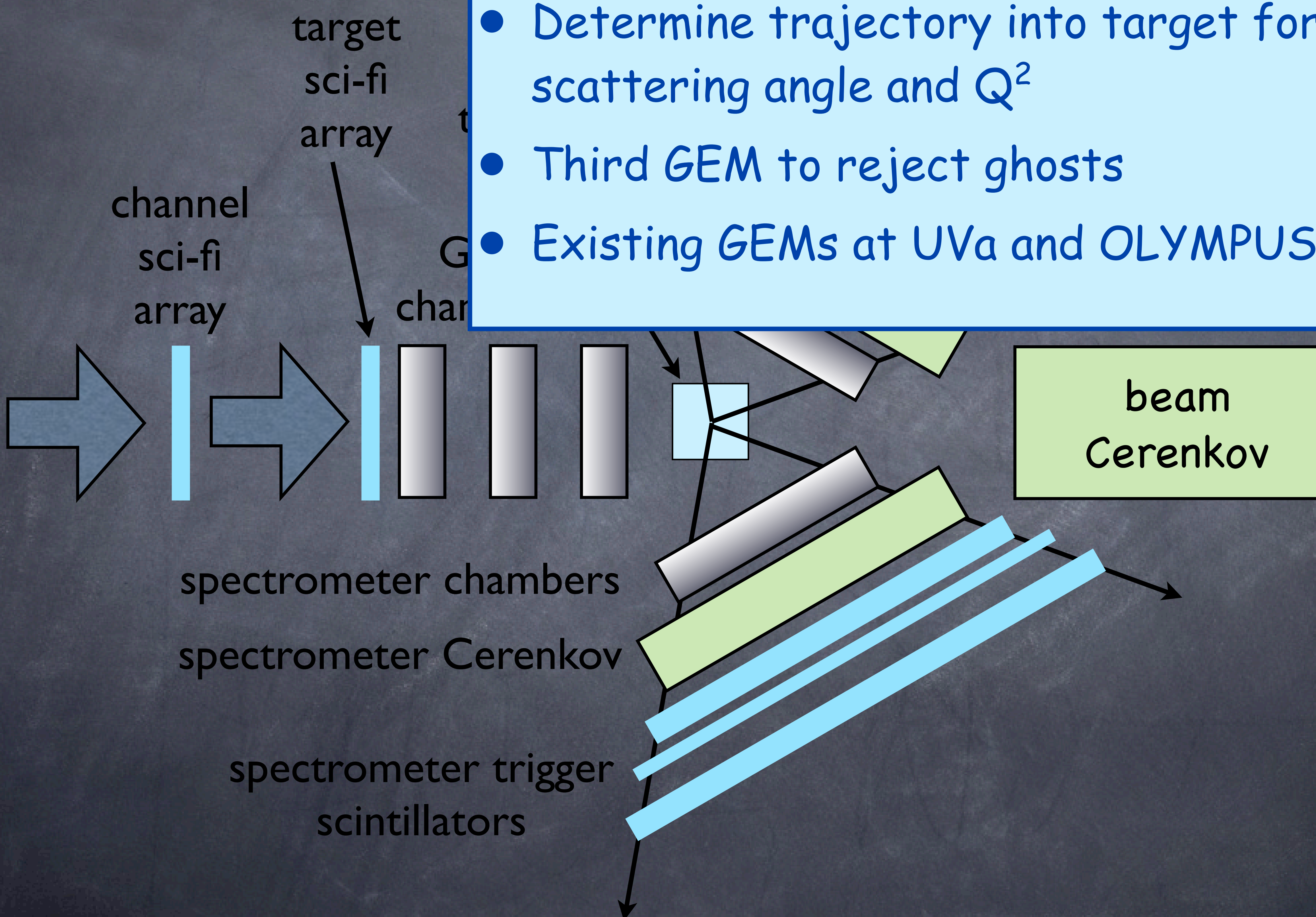
- Count Flux
- PID with RF time for triggering
- Determine momentum at IFP
- Give TOF between two counters for PID
- Associate trajectory into target with momentum



GEMs

Hampton, UVa

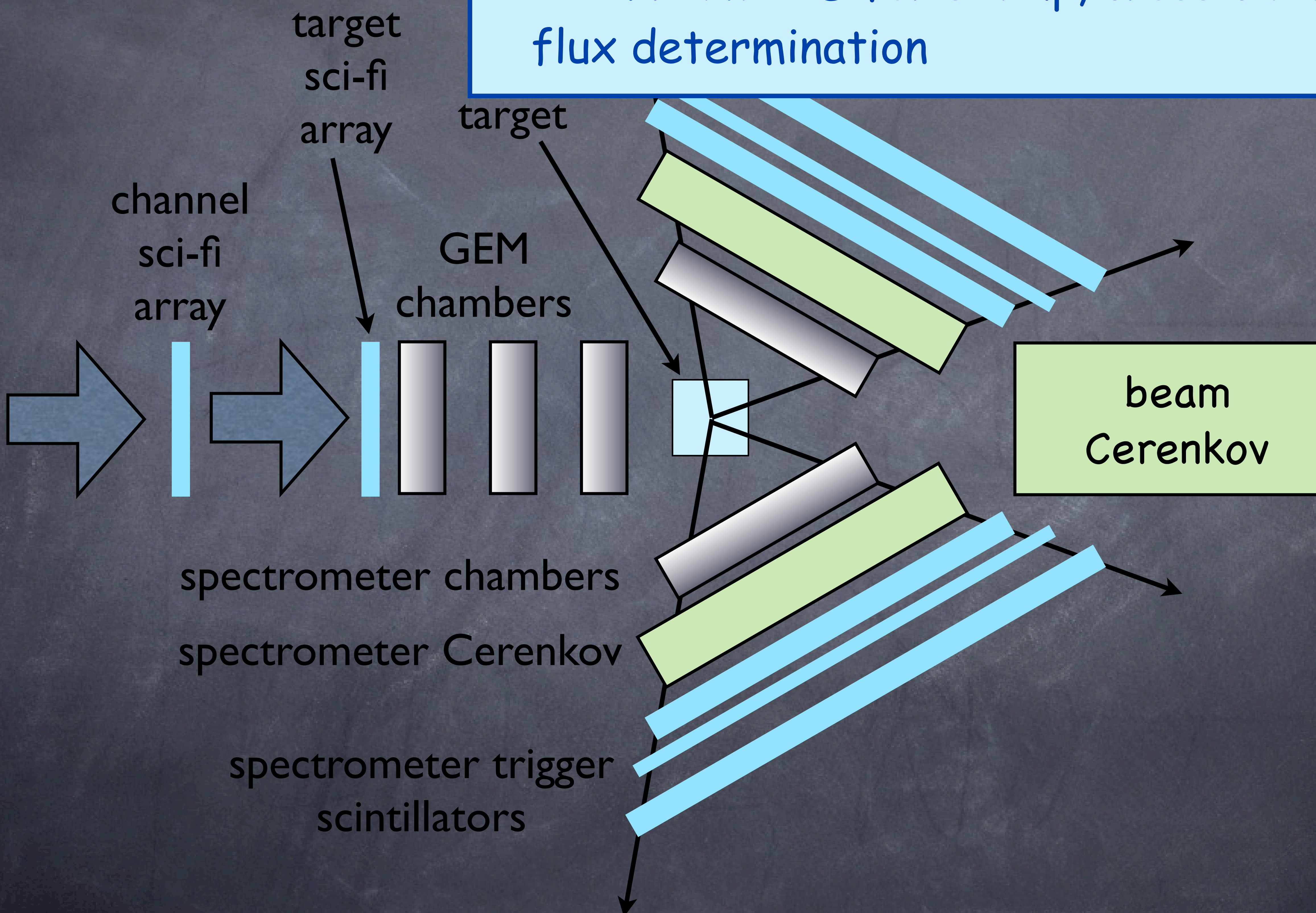
- Determine trajectory into target for scattering angle and Q^2
- Third GEM to reject ghosts
- Existing GEMs at UVa and OLYMPUS



Beam Cerenkov

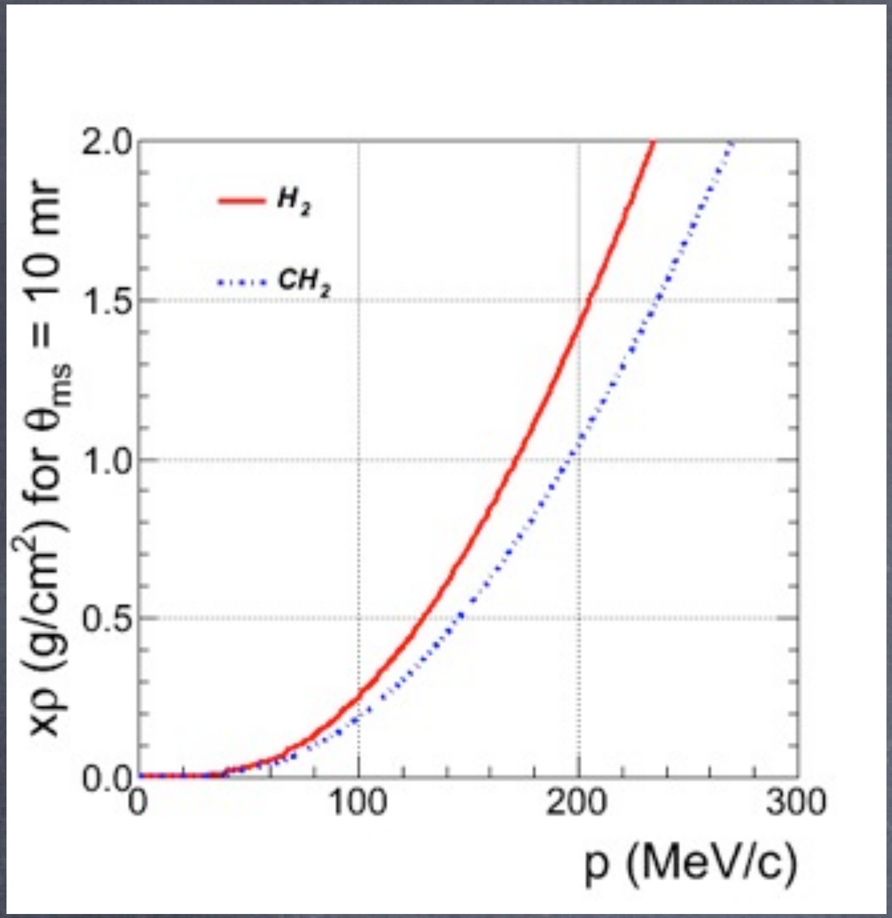
Temple

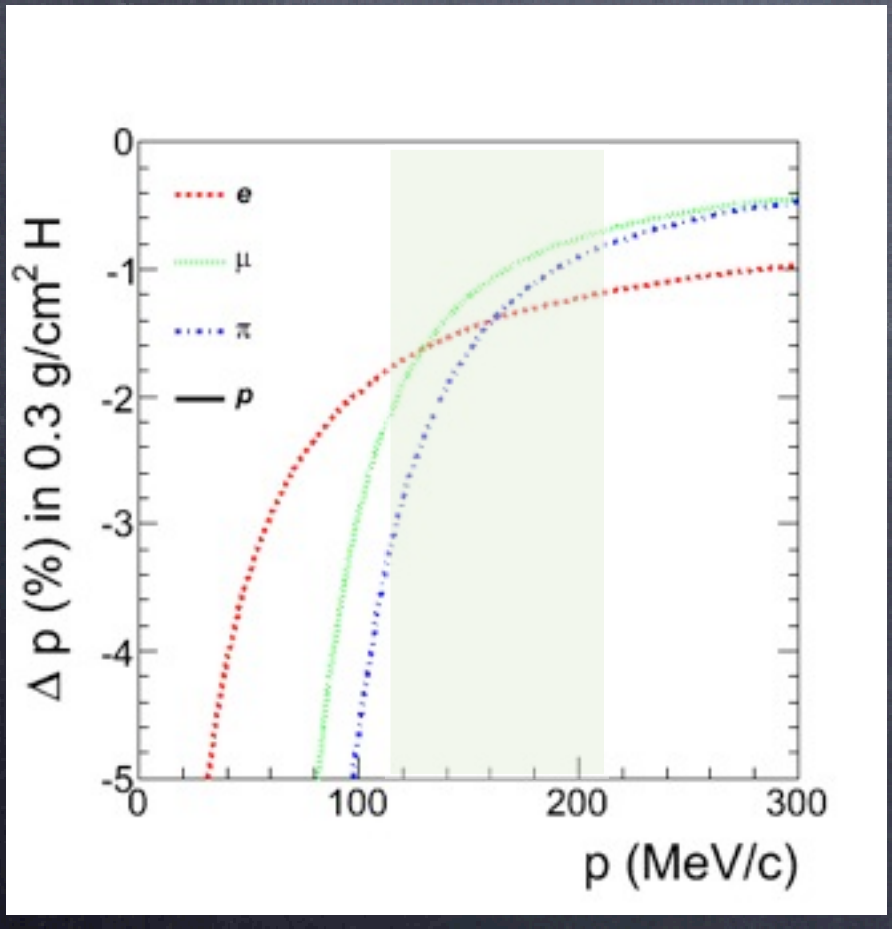
- Redundant PID for set up, cross checks, flux determination



πM1 Channel - Target

MIT, Rutgers, PSI



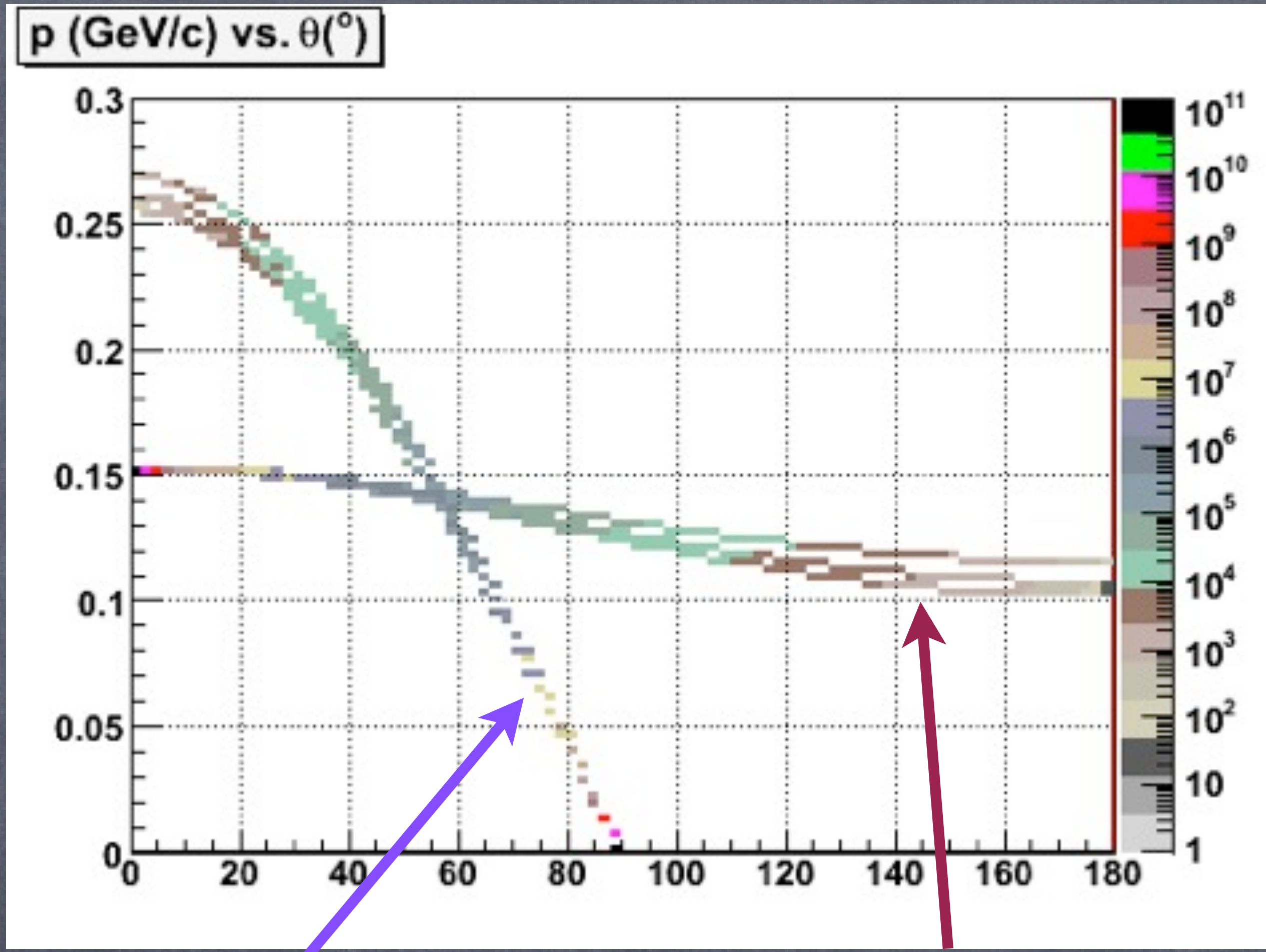


- Use 4-cm LH_2 target, ≈ 0.3 g/cm². (0.5% L_{rad})
- ≈10x as much H as CH_2 target with same multiple scattering.
- $\theta_{MS\ plane}$ ≈ 10 mr @ 115 MeV/c, 6.5 mr @ 153 MeV/c, 4 mr @ 210 MeV/c.
- Copy recent E906 target design?

Due to E loss in target, μ's and e's average over ≈ ±0.5 - 1% bin in momentum.

Scattered Particles

- p vs. θ for 153 MeV/c μ's + e's + π's incident on protons.



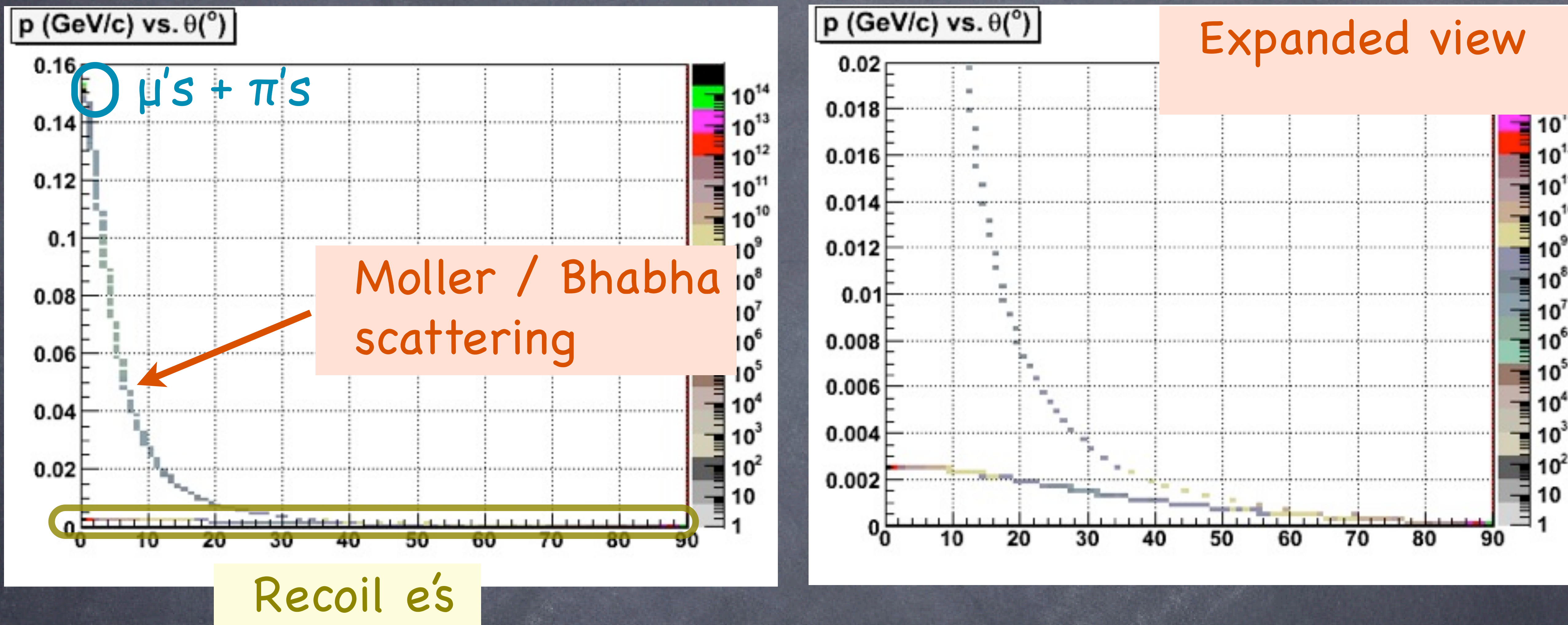
Recoil protons.

Scattered μ's + e's + π's

Rates of scattered e's and μ's of interest are small - a few 10's of Hz over the planned acceptance. PID is needed at the trigger level to keep the rate of π triggers manageable.

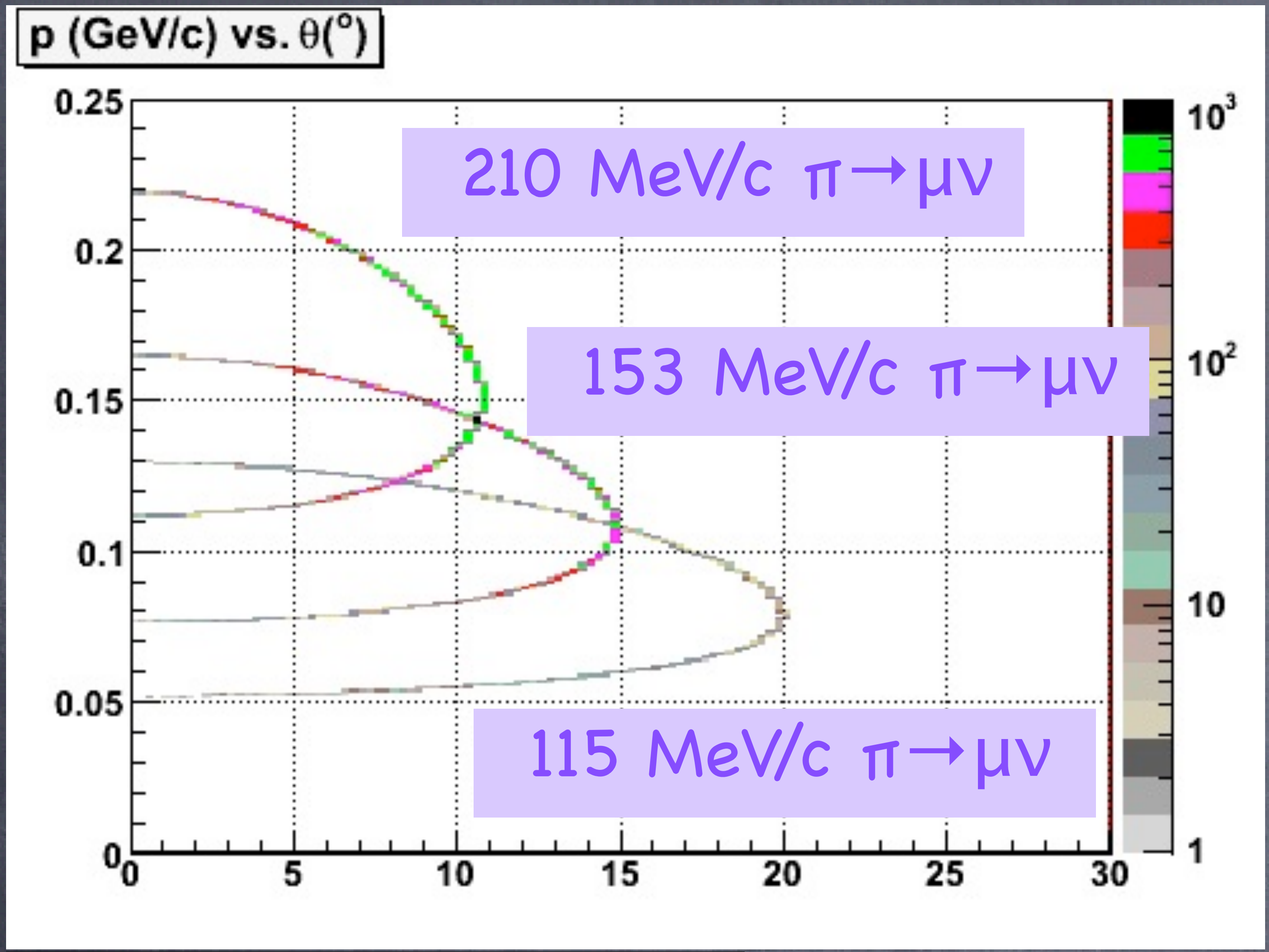
Moller / Bhabha / δ-ray Background

- p vs. θ for 153 MeV/c μ's + e's + π's incident on electrons.

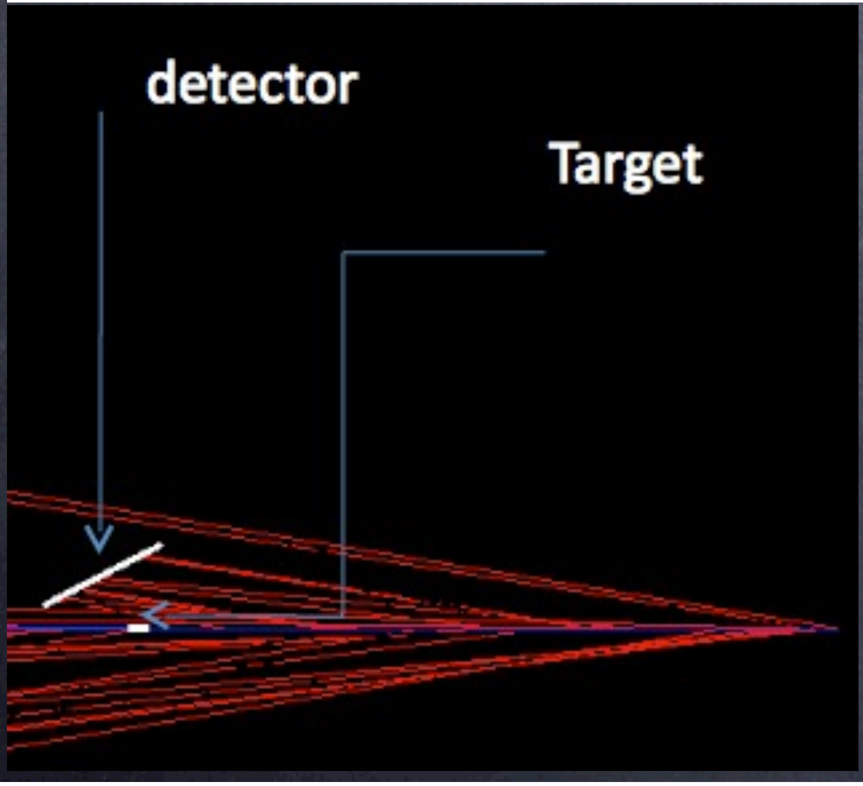


Scattered electrons are low energy and generate ≈40 kHz of tracks into chambers, but not triggers.

π Decay Background

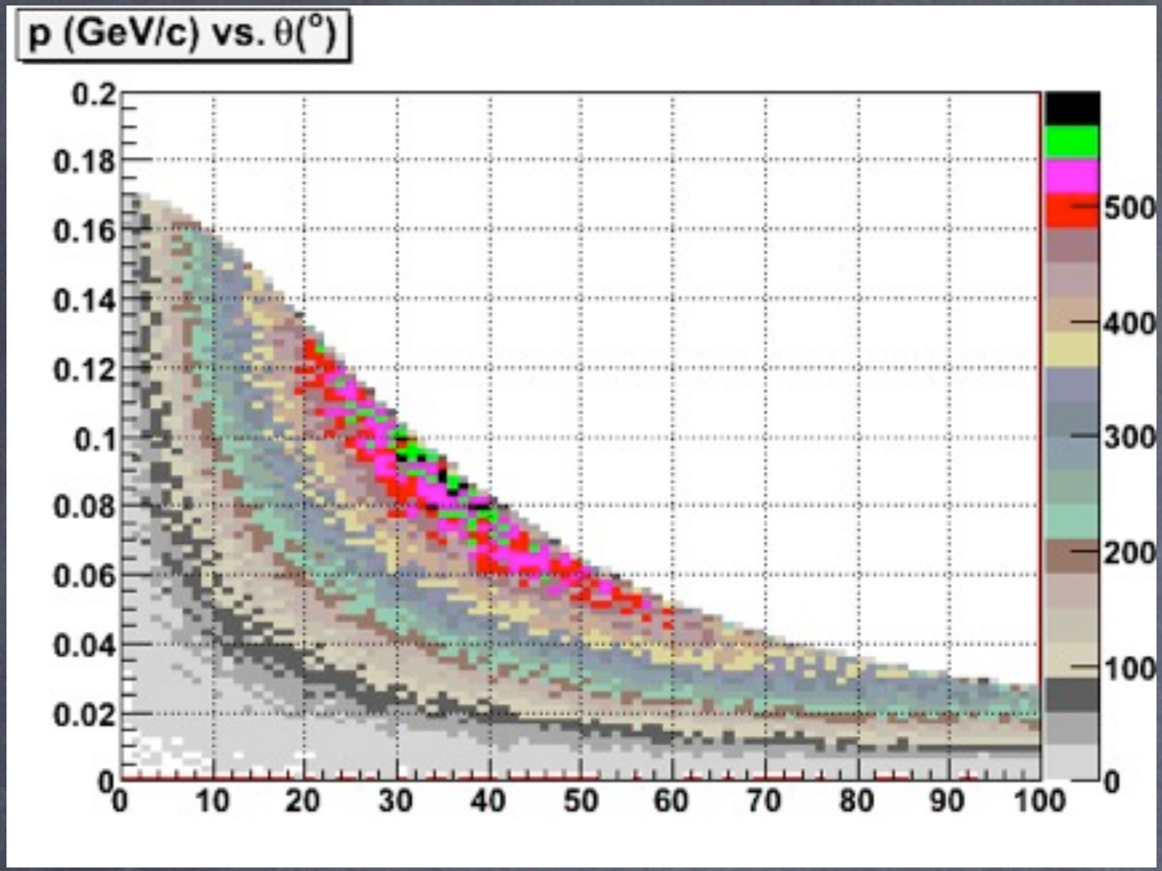


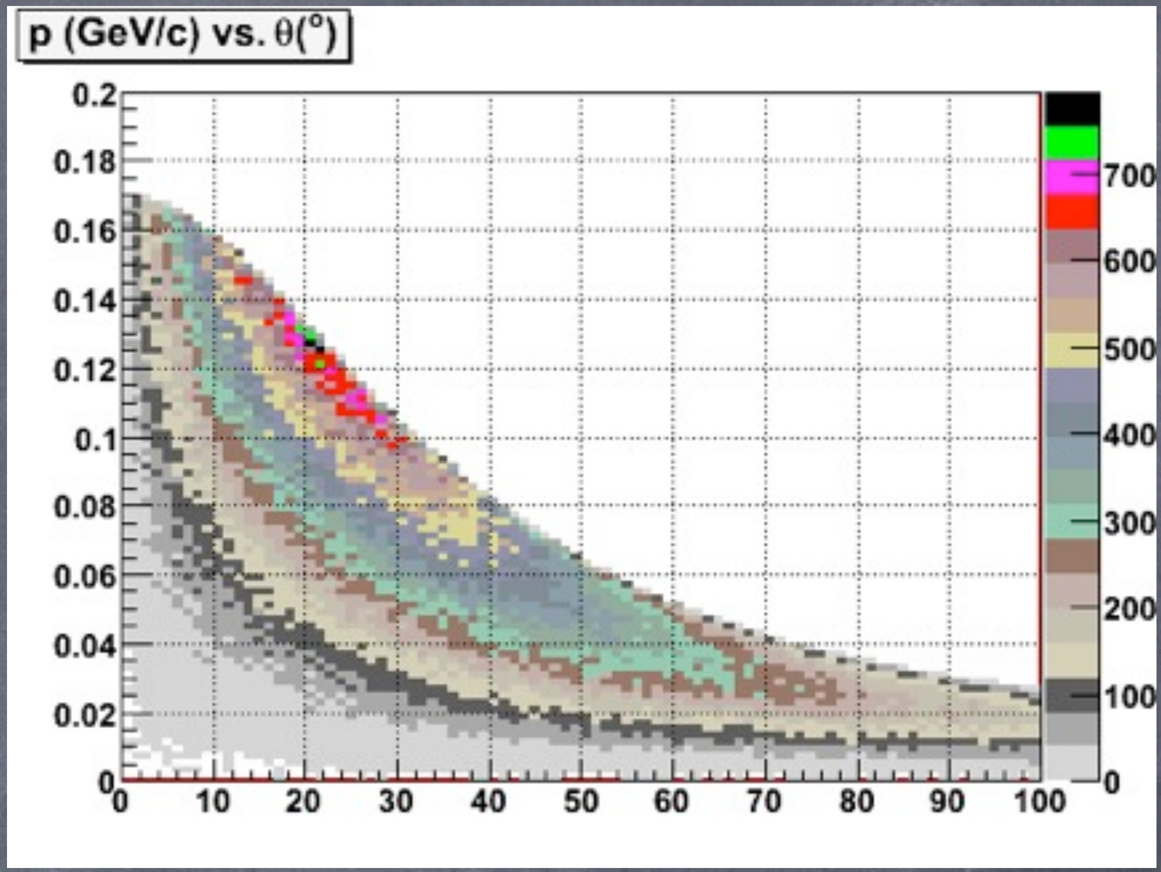
μ's from π decay go forward of detectors ➪ π decays near the target are not an issue. A simple GEANT gives a singles rate from 4 m of beam line in the wire chambers as 30, 150, 20 kHz. At the trigger level, these events are suppressed at least 3 orders of magnitude since they have a π RF time, and do not tend to strike two scintillator paddles that point back to the target.



At the analysis level, these events would be further suppressed by tracking back to the target, refined RF time determination, and lack of a GEM track. Their characteristics can be cross checked with empty target measurements.

μ Decay Background



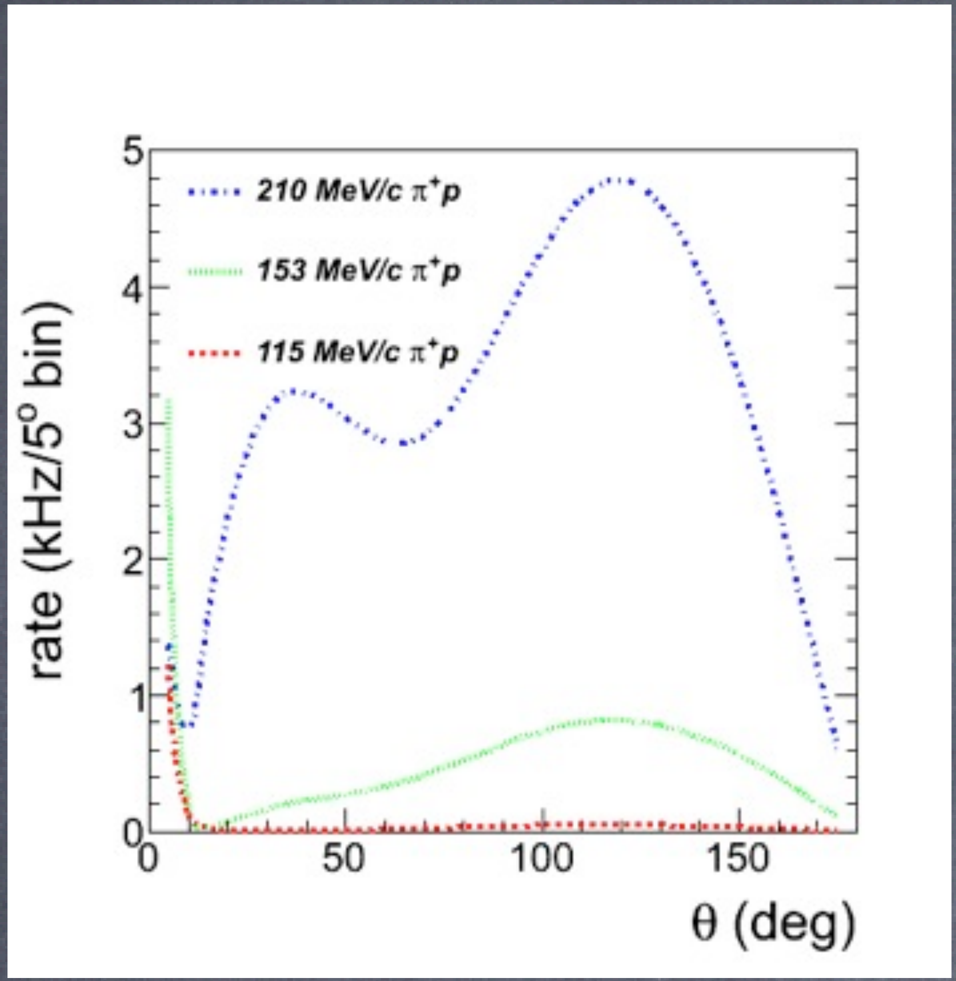


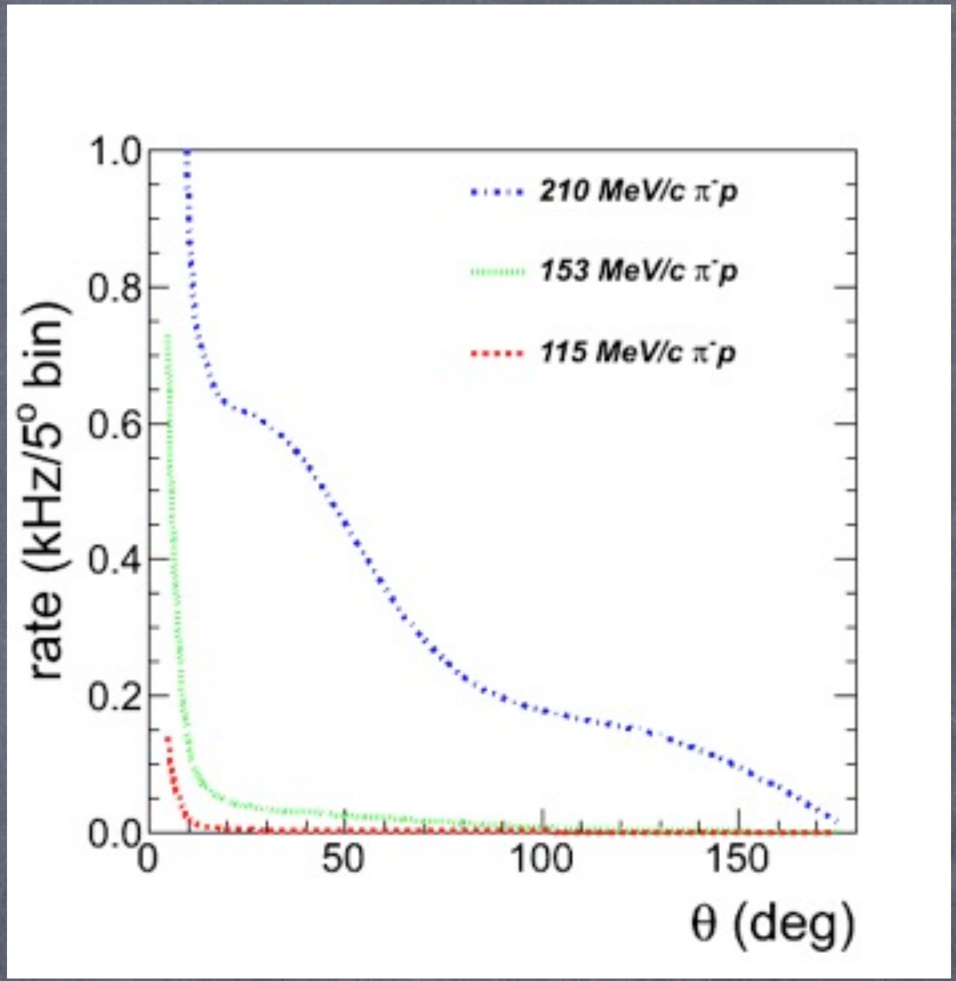
Distribution of electrons from 153 MeV/c μ decay.

Distribution modified if μ polarized - here for S || p.

$\mu^+ \rightarrow e^+\nu_\mu\nu$ gives several kHz track rate and ≈400 Hz e^+ background trigger rate. Rejected at analysis level by requiring tracks from the target, and μ RF time from the detector - the decay electrons will be ≈ 0.8 ns faster than μ scattering events. Rate can be directly measured with empty target.

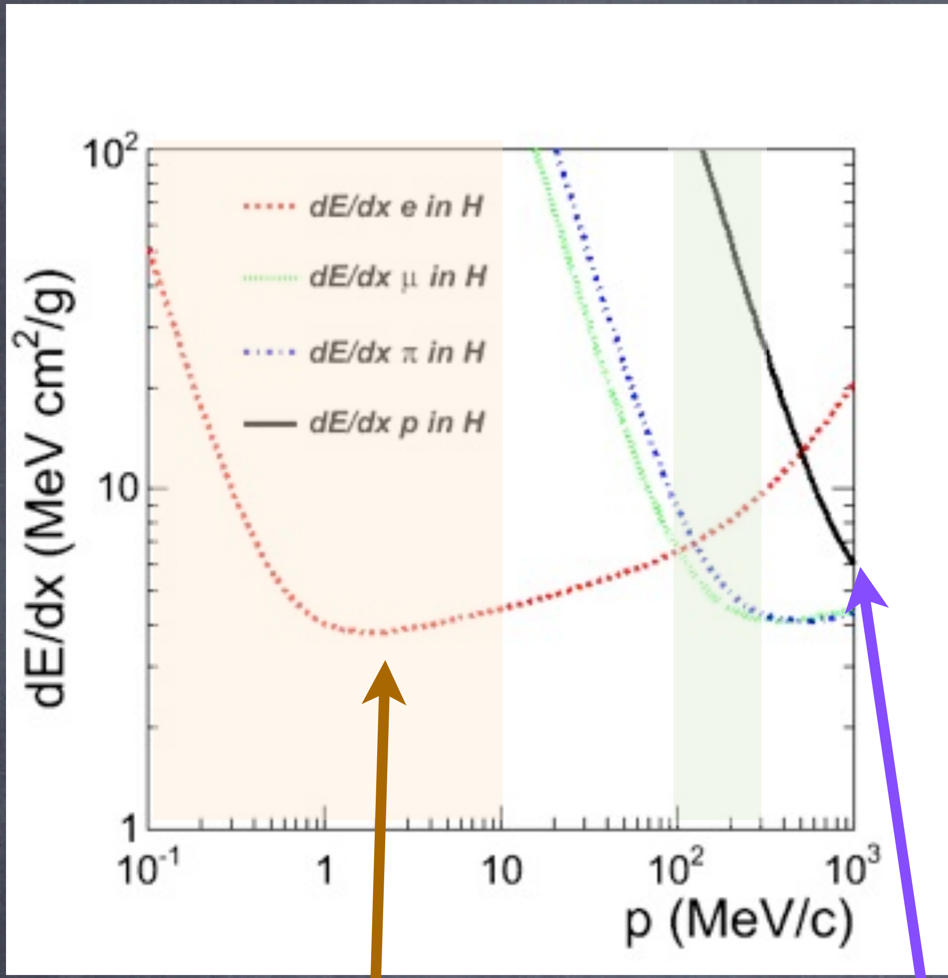
Hadronic Scattering of π

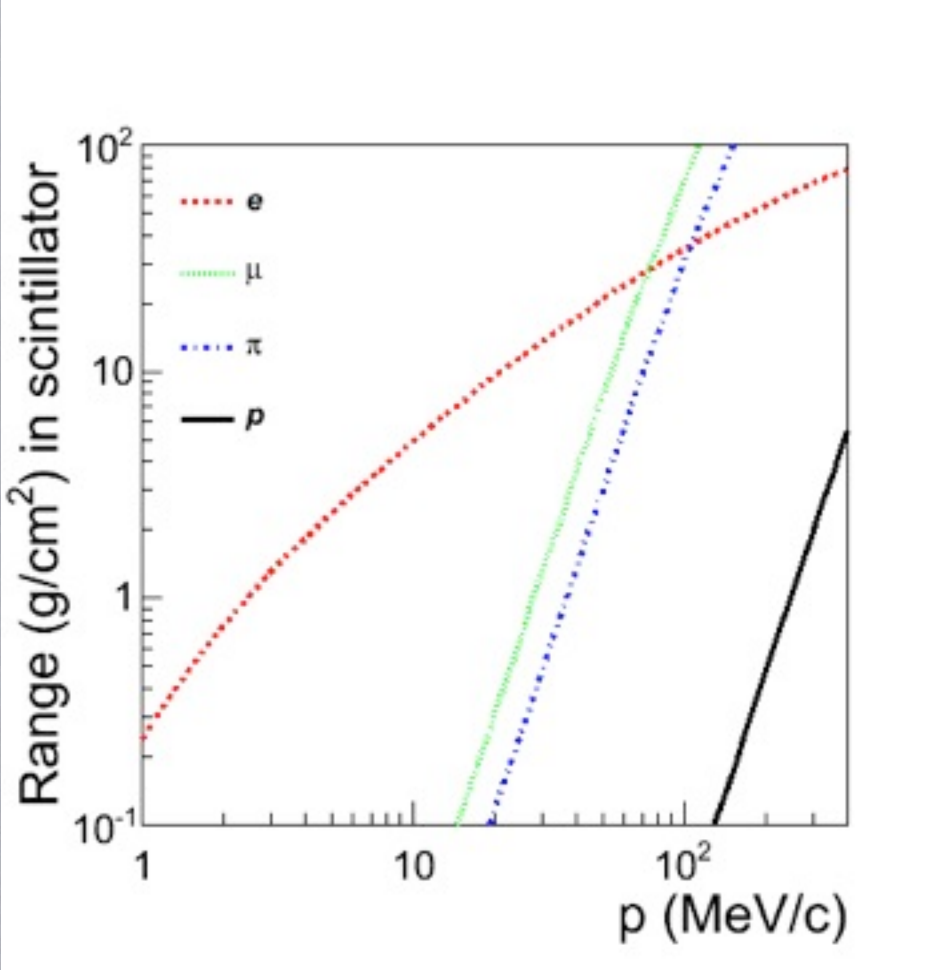




πp scattering rates calculated with cross sections from SAID and expected luminosities, assuming 2π azimuthal acceptance. Up to a few tens of kHz chamber rates, plus a DAQ rate issue for some kinematics, if not suppressed at the trigger level.

Scattered Particle Considerations





Large angle, very low energy Moller / Bhabha e's lose large fraction of energy in target

Recoil protons E loss so large that all except forward angle recoil protons stopped in target.

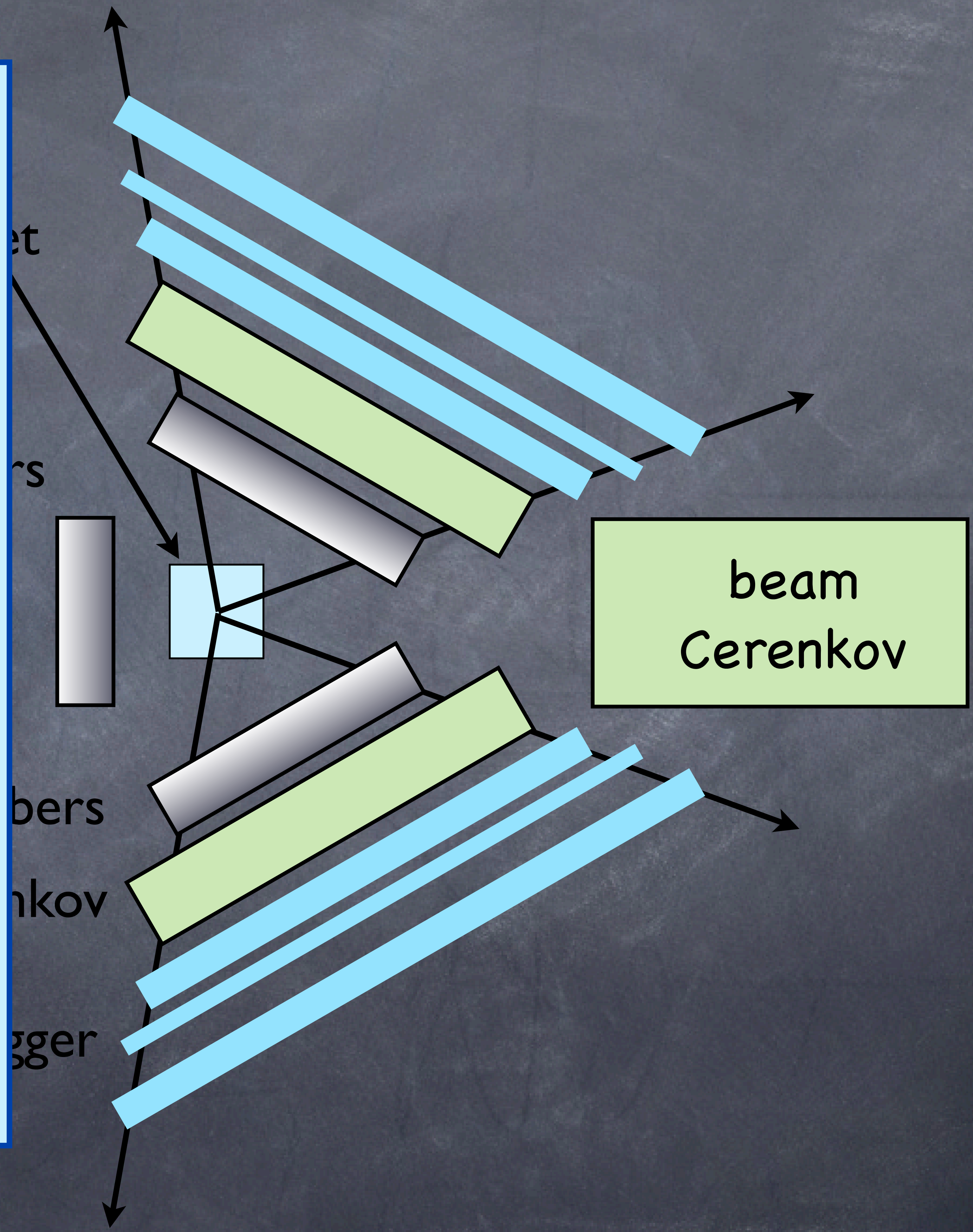
All the low-energy electron and proton backgrounds are ranged out in the first scintillator layer.

Scintillator dE/dx plot looks the same, except curves down a factor of ≈2.

So. Carolina, Tel Aviv

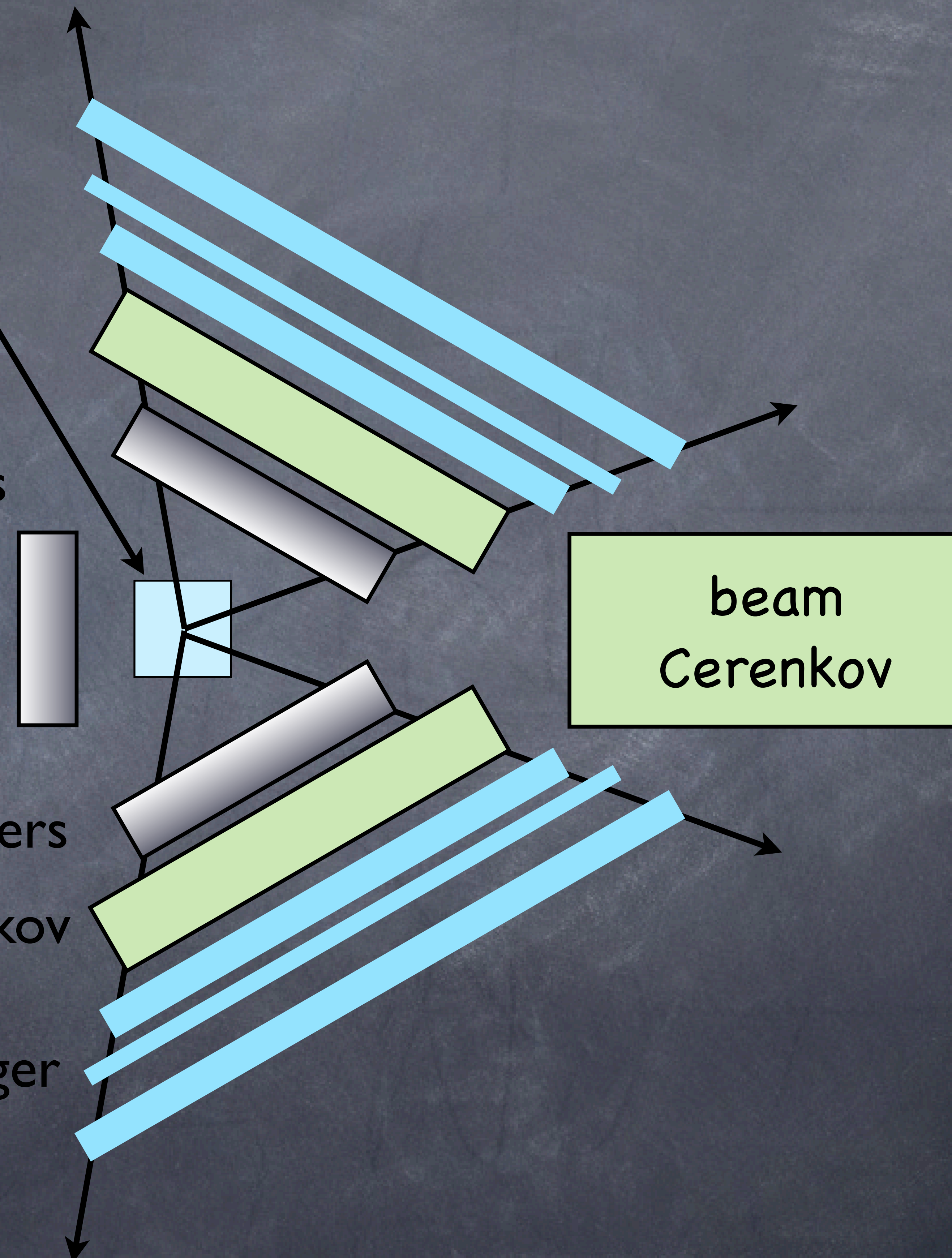
Scintillators

- Adopting So Carolina design: 2 planes of 6 cm x 6 cm scintillator paddles with < 60 ps time resolution.
- 3rd plane from BLAST / OLYMPUS.
- FPGA trigger to require paddles track back to target, to suppress cosmic and decay in flight backgrounds.



Threshold Cerenkov

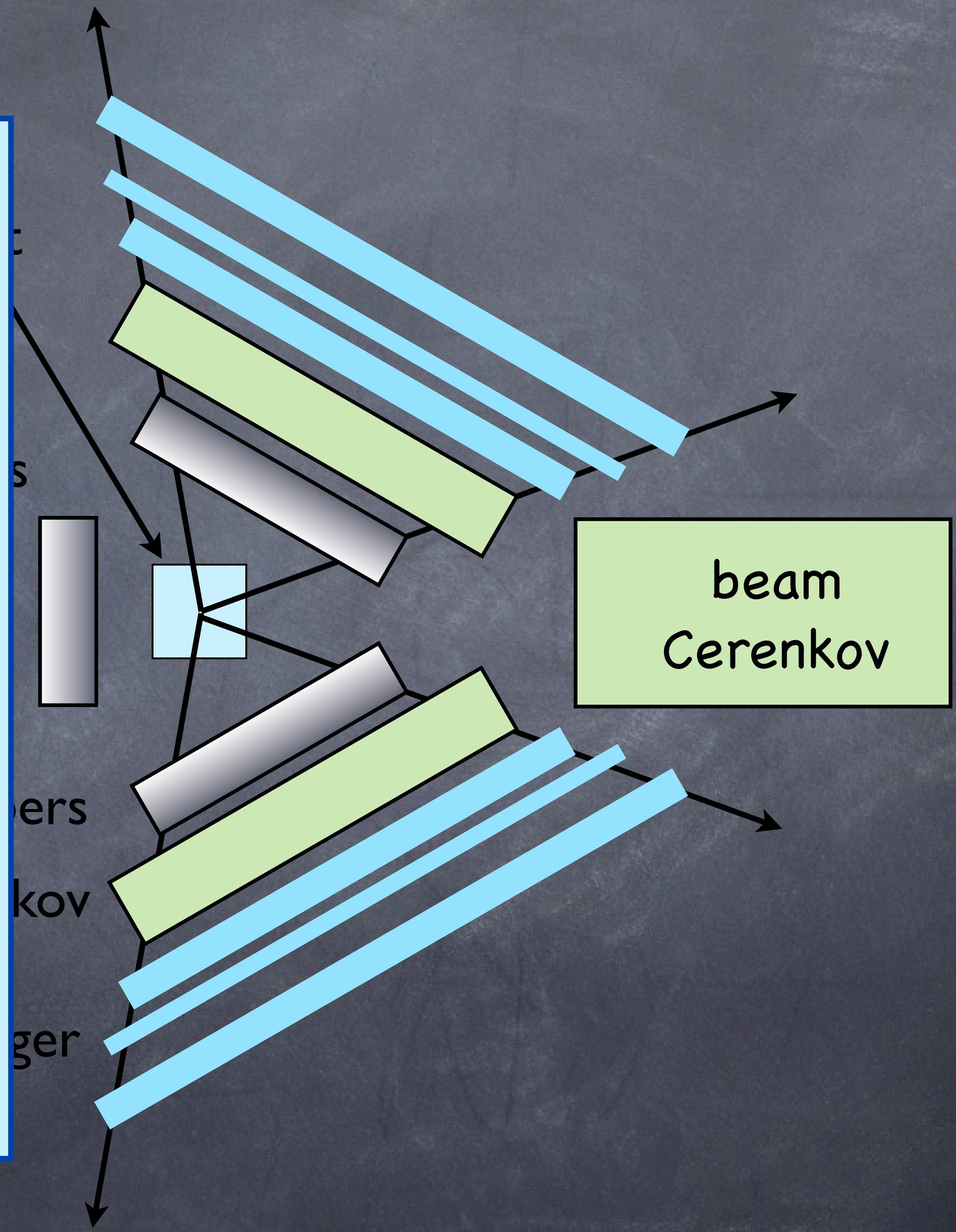
- Additional PID to supplement SF RF time for π rejection at trigger level
- Media of quartz/lucite for 115 MeV/c, water/teflon for 153 MeV/c, pinhole dried aerogel for 210 MeV/c



MIT

Wire Chambers

- Positioned to determine tracks at 1 mr level (central), but several mr level event by event.
- Need more or less standard wire position precisions of 100 - 200 μm.
- Need chambers positions at the few tenths of mm level.



Summary of Equipment

Beam Sci-Fi	Rutgers	100 k
Beam GEMs	Hampton, UVa	existing
Beam Cerenkov	Temple	50 k
Target	MIT/...	300 k
Wire Chambers	MIT	200 k
Cerenkovs	Jerusalem	100 k
Scintillators	So Carolina, Tel Aviv	220 k
Scintillators	Hampton	existing
Trigger	Rutgers	100 k
DAQ	-	?

Time Line

Feb 2012	Physics Approval
August 2012	PAC/PSI Technical Review
September 2012	Funding proposals to US agencies*
fall 2012	test measurement in πM1 beamline
spring 2013	finalize designs
summer 2013	money arrives - start construction
fall 2014	start assembling equipment at PSI
late 2014 / early 2015	experiment ready to run
2015	6 month experiment run

* Tel Aviv + Jerusalem already applied for ERC advanced grant

Summary

- The proton radius puzzle is a high-profile issue - APS plenary talk & invited sessions, PSAS2012 Symposium, Trento ECT* Workshop Nov 2012
  - Explanation unclear, theoretically or experimentally.
  - Electron scatterers interested in going to lower Q^2: checks $R_{ep\ scattering}$, proton structure
  - Atomic physicists interested in other μ atoms.
  - PSI μp scattering directly tests interesting possibilities: Are μp and ep interactions different? If so, does it arise from 2γ exchange effects ($\mu^+ \neq \mu^-$) or BSM physics ($\mu^+ \approx \mu^- \neq e^-$).
- Request:
  - physics approval.
  - technical review about end of summer, 2012: very helpful in proposing funding.
  - Test time in fall 2012, check of beam properties and plans.

Backup Slides Follow

Basics: The Proton ``Radius"

The proton has several ``radii": electric, magnetic, axial, gravitational, ...

They are defined within non-relativistic quantum mechanics as root mean square (rms) radii. E.g.:

$$r_E = (r_E{}^2)^{1/2} = (\int d^3r \; r^2 \; \rho_E(r))^{1/2}$$

where $\rho_E(r)$ is the normalized charge distribution.

In relativistic QM, the radius is a model-dependent quantity - the impact parameter is not. We will ignore this issue for simplicity, and because it does not fundamentally change the physics importance of the proposal.

Notes

- In NRQM, the FF is the 3d Fourier transform (FT) of the Breit frame spatial distribution, but the Breit frame is not the rest frame, and doing this confuses people who do not know better. The low Q^2 expansion remains.
- Boost effects in relativistic theories destroy our ability to determine 3D rest frame spatial distributions. The FF is the 2d FT of the transverse spatial distribution.
- The slope of the FF at $Q^2 = 0$ continues to be called the radius for reasons of history / simplicity / NRQM, but it is not the radius.
- Nucleon magnetic FFs crudely follow the dipole formula, $G_D = (1+Q^2/0.71\ \mathrm{GeV}^2)^{-2}$, which a) has the expected high Q^2 pQCD behavior, and b) is amusingly the 3d FT of an exponential, but c) has no theoretical significance.

Simple Overview of Techniques

Atomic Physics:

Atomic 1/r potential modified by finite size of proton, shifting energy levels.

Effect bigger for muons than electrons due to smaller size of muonic atom orbitals.

Polarization

Determine transition energies and use theory to infer proton radius.

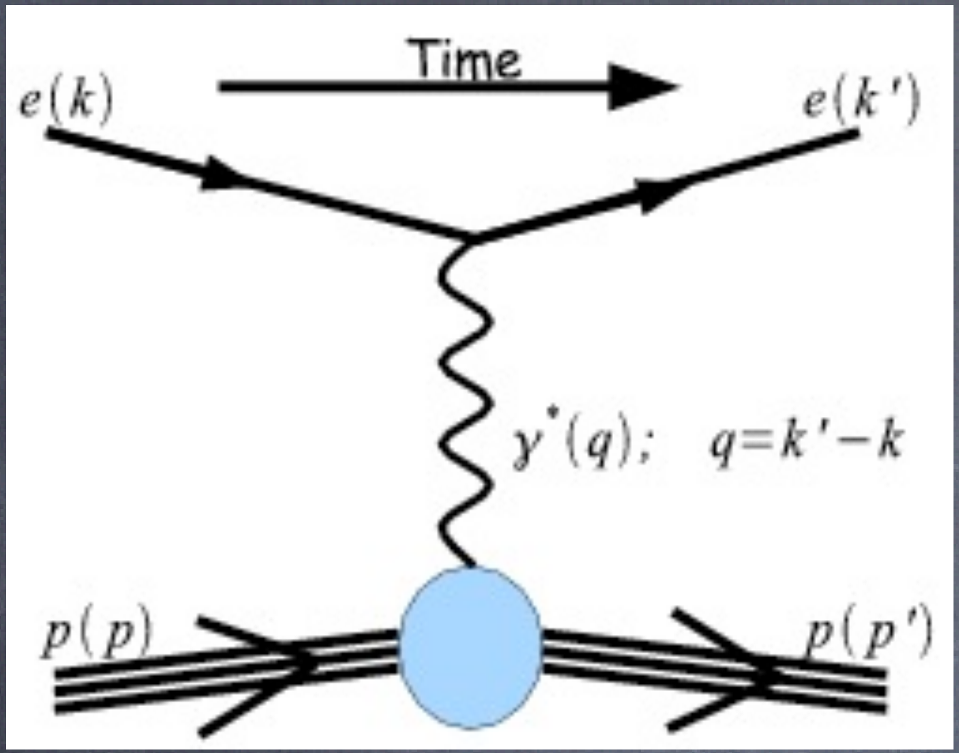
Lepton scattering:

Scattering cross section depends on form factor, the Fourier transform of spatial charge distribution.

Use corrected scattering cross section to determine form factors, and fit to determine proton radii.

For low four-momentum transfer Q^2:
$F(Q^2) = 1 - Q^2r^2/6 + Q^4r^4/120$ ...

ep Scattering Basics: 1



currents

$$J_e^\mu = \overline{u}(k')[\gamma^\mu]u(k)$$

$$J_p^\mu = \overline{u}(p')[F_1(Q^2)\gamma^\mu + i\frac{\kappa}{2M}F_2(Q^2)\sigma^{\mu\nu}q_\nu]u(p)$$

algebra

cross sections

$$\sigma_R \equiv \epsilon(1+\tau)\frac{d\sigma/d\Omega}{d\sigma_{Mott}/d\Omega} = \epsilon G_E^2(Q^2) + \tau G_M^2(Q^2)$$

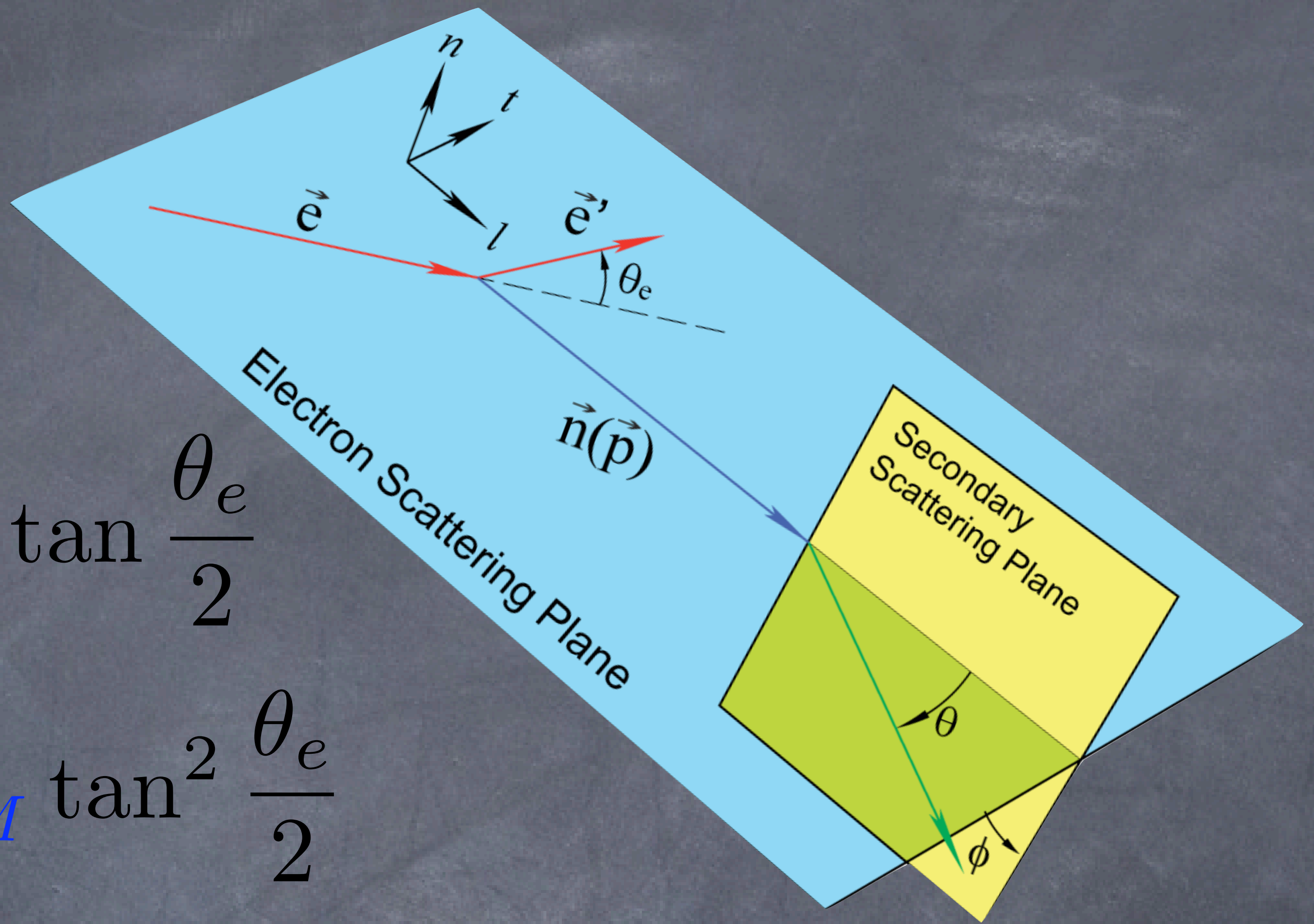
with form factors: $G_E = F_1 - \tau\kappa F_2 \qquad G_M = F_1 + \kappa F_2$

$$F_1 = \frac{G_E + \tau G_M}{1+\tau} \qquad F_2 = \frac{G_M - G_E}{\kappa(1+\tau)}$$

and kinematic factors: $\tau = Q^2/4M^2 \quad \epsilon^{-1} = 1 + 2(1+\tau)\tan^2\frac{\theta}{2}$

Polarizations: 1

Use polarizations for form factor ratios



$$I_0 P_t = -2\sqrt{\tau(1+\tau)}G_E G_M \tan\frac{\theta_e}{2}$$

$$I_0 P_l = \frac{E_e + E_{e'}}{M}\sqrt{\tau(1+\tau)}G_M^2 \tan^2\frac{\theta_e}{2}$$

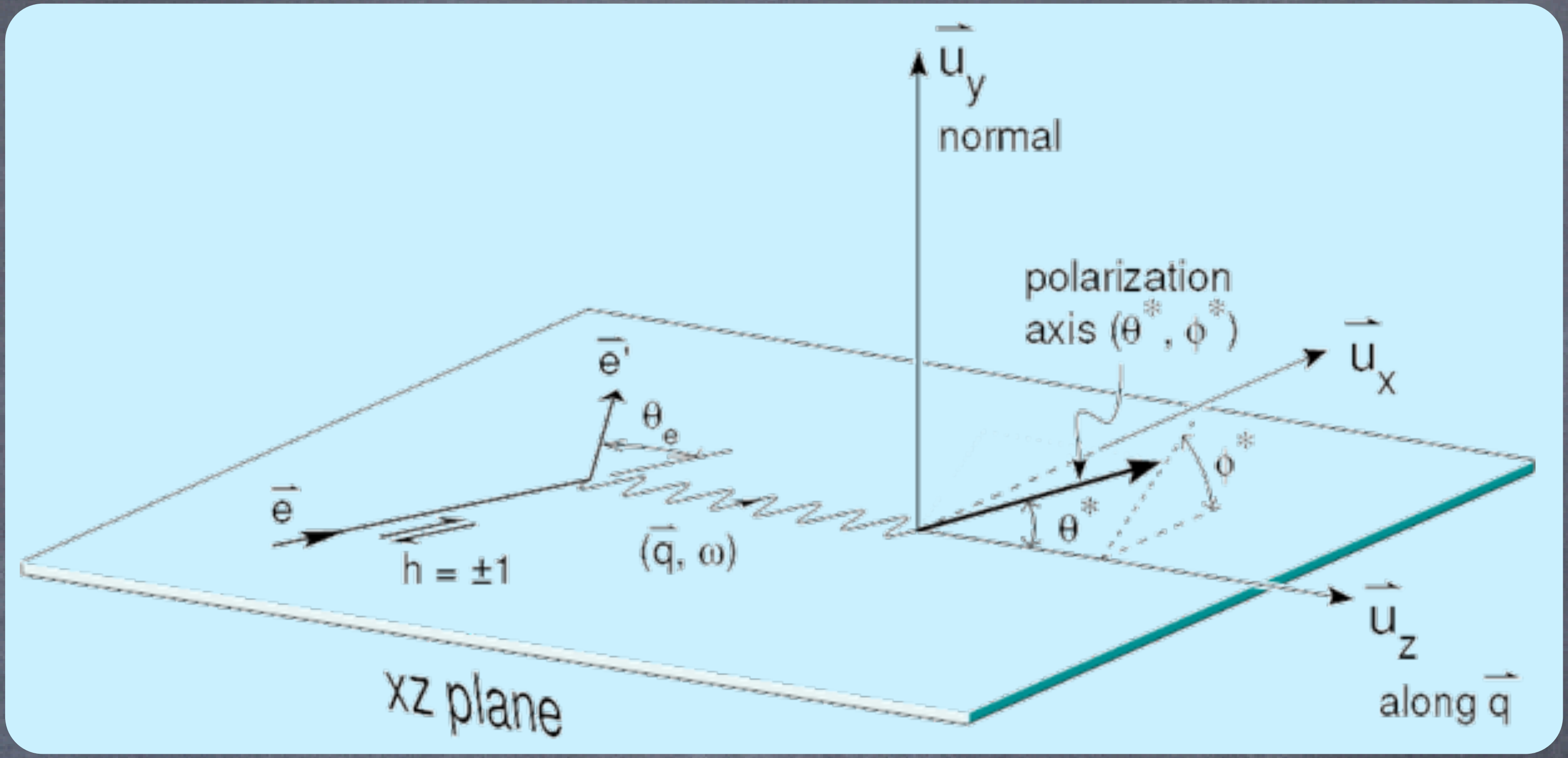
$$P_n = 0 \ (1\gamma)$$

$$\mathcal{R} \equiv \mu_p \frac{G_E}{G_M} = -\mu_p \frac{P_t}{P_l}\frac{E_e + E_{e'}}{2M}\tan\frac{\theta_e}{2}$$

Sensitive to spin transport, insensitive to almost everything else ... but needs large statistics

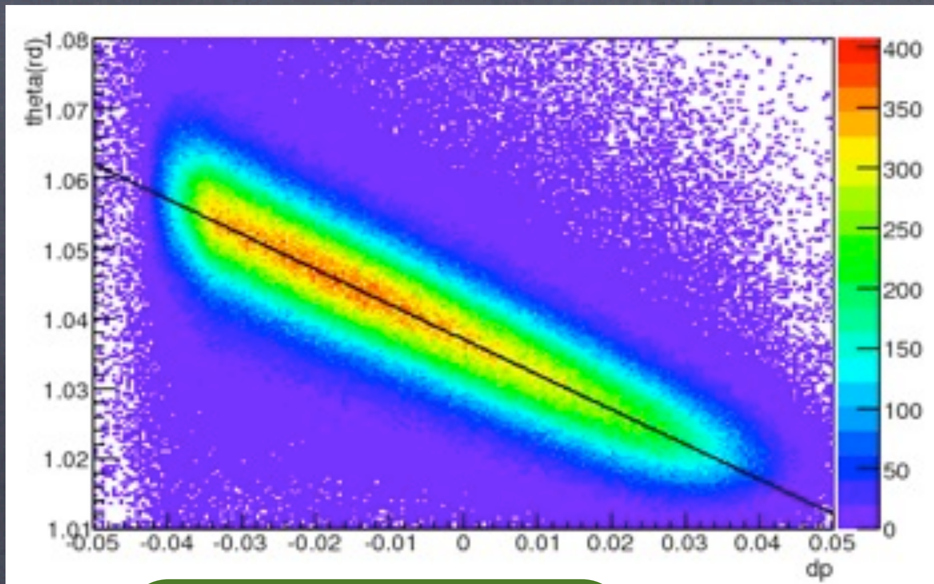
Polarizations: 2

$$\mathcal{A} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$



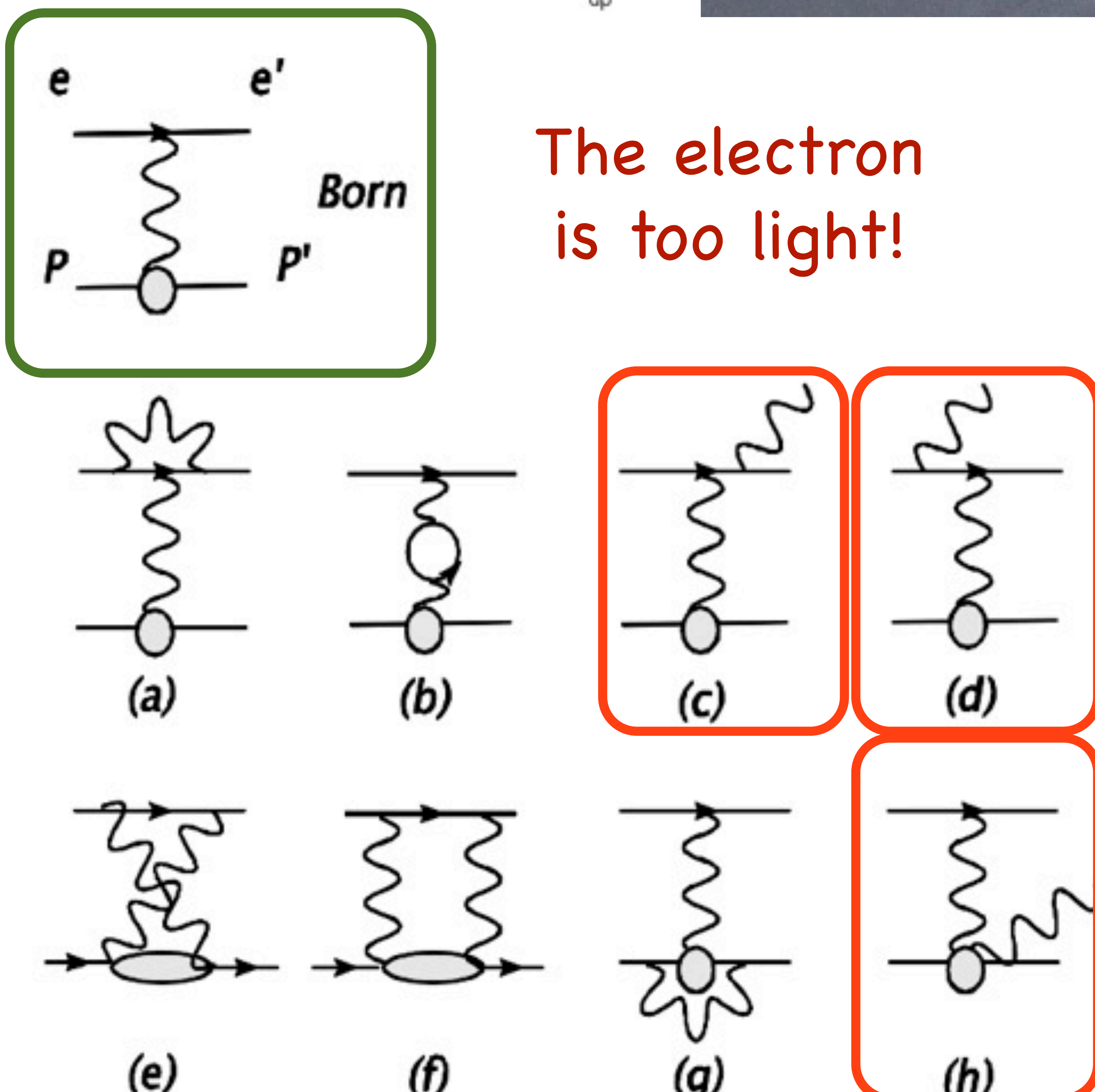
$$\mathcal{A} = f P_b P_t \frac{\overbrace{a\, cos\theta^* G_M^2}^{A_T} + \overbrace{b\, sin\theta^*\, cos\phi^* G_E G_M}^{A_{LT}}}{c G_M^2 + d G_E^2}$$

Measuring two angles at the same time allows a ratio to be made, reducing sensitivity to P_bP_t, which can vary by 20% or more over time.

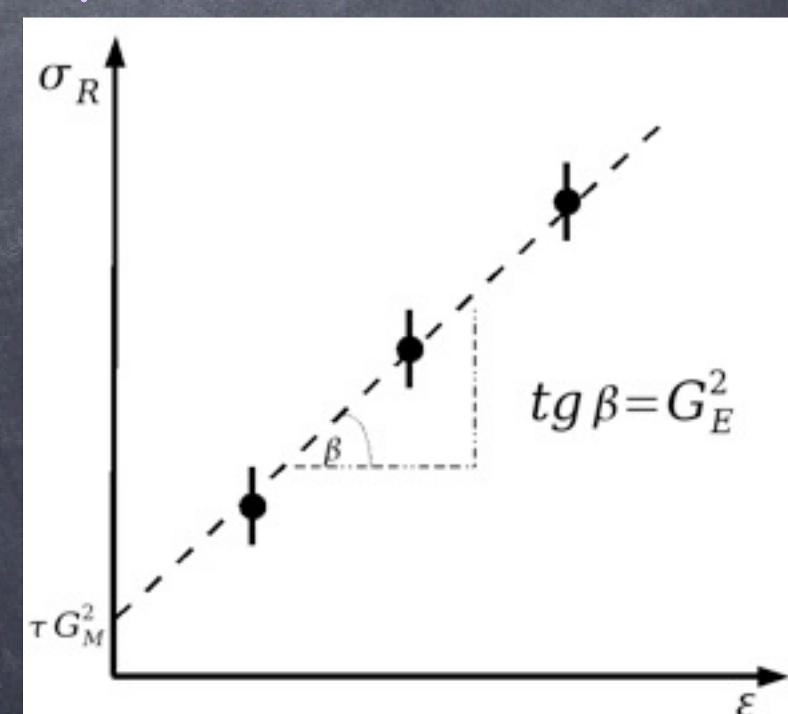


ep Scattering Procedure

- Measure cross sections
- Perform radiative corrections: (c) and (d) depend on experiment cuts, (h) is very small, (a), (b), (e), (f), (g) change cross section, not kinematics
- Do Rosenbluth separations - or - fit world data with form factor parameterization



The electron is too light!

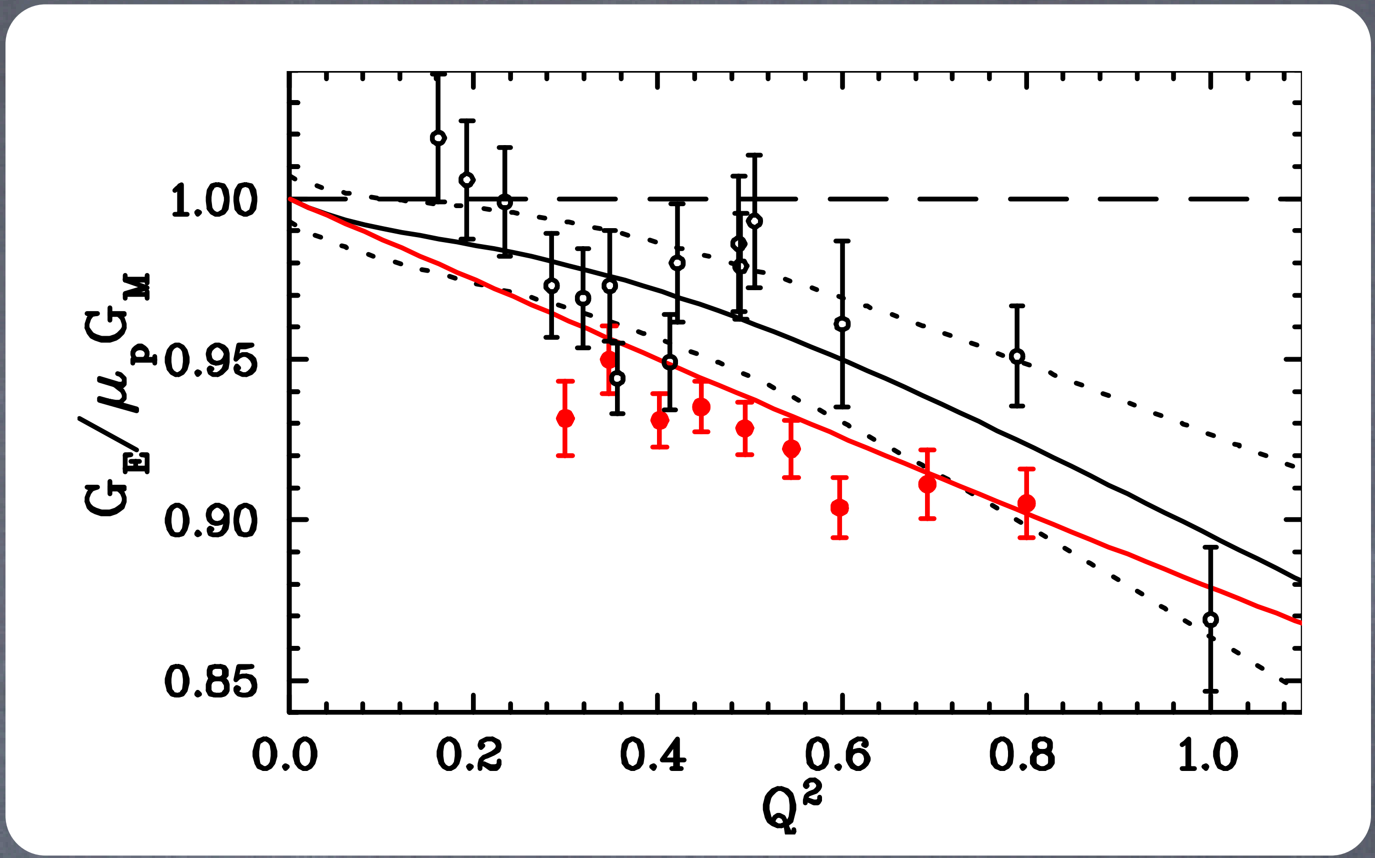


Wednesday, February 22, 2012

JLab E08-007 Data

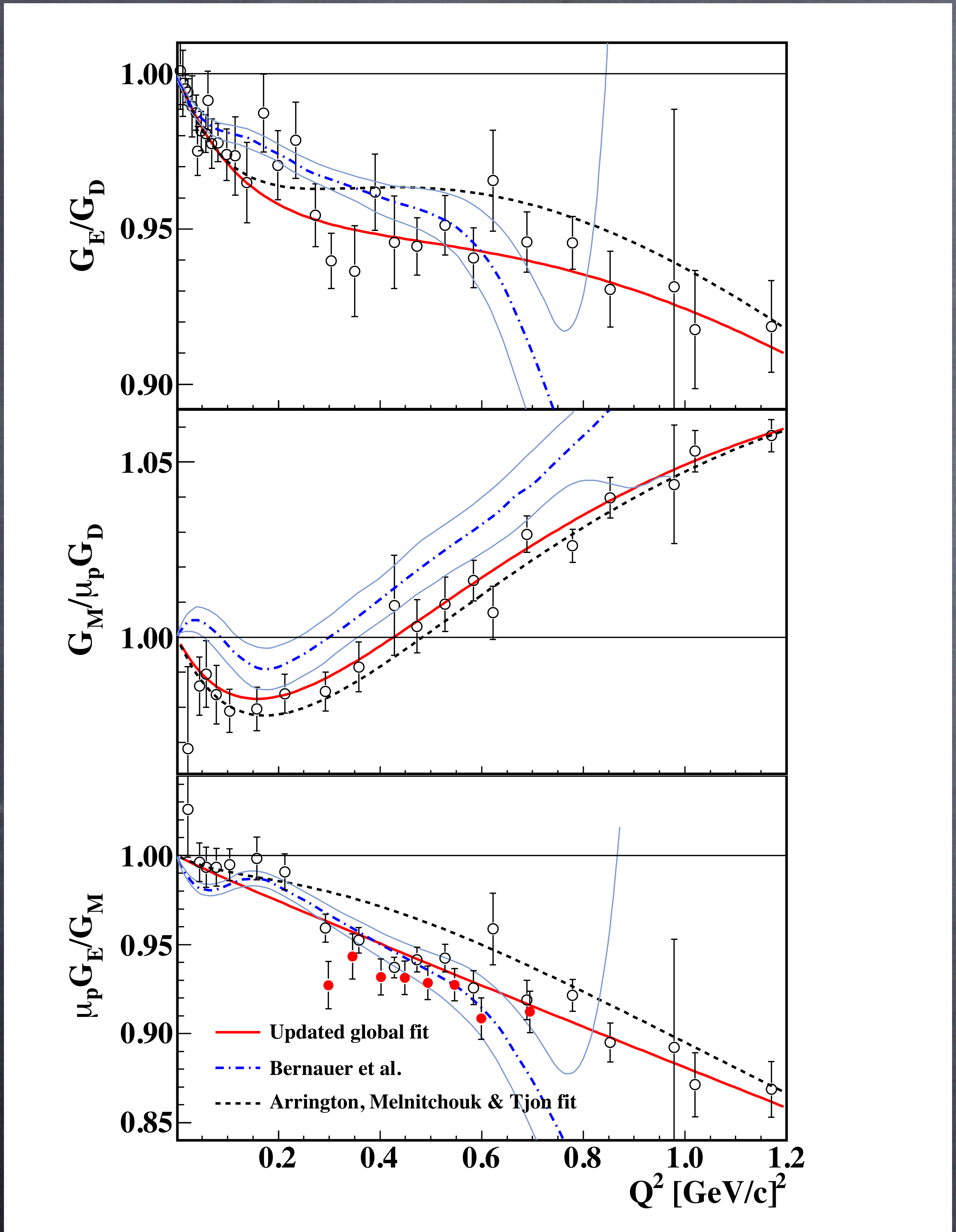
X. Zhan et al., PLB 705, 59 (2011).

M. Paolone et al., Phys Rev Lett 105, 072001, 2010 (Q^2 = 0.8 GeV^2)



- Polarization techniques determine a ratio of electric to magnetic form factors to ≈1% total uncertainty
- Decreased ratio compared to earlier data prompted 2 years of systematics studies: cuts, spin transport, backgrounds, ...
- Does not get to low enough Q^2, but suggests $r_E > r_M$
- E08-007 part 2, dedicated polarized beam - polarized target measurements to cover the range about 0.015 - 0.16 GeV^2 with high precision, running late Feb - May 2012.

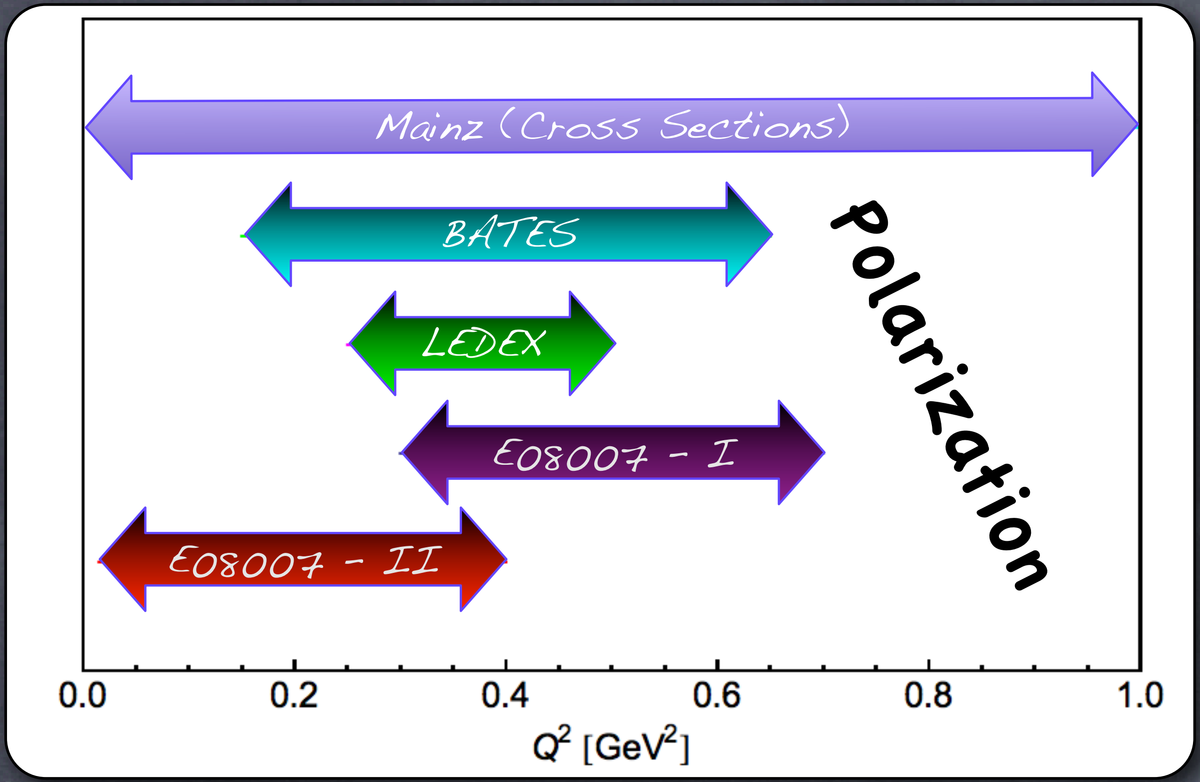
Some tension between Mainz and JLab

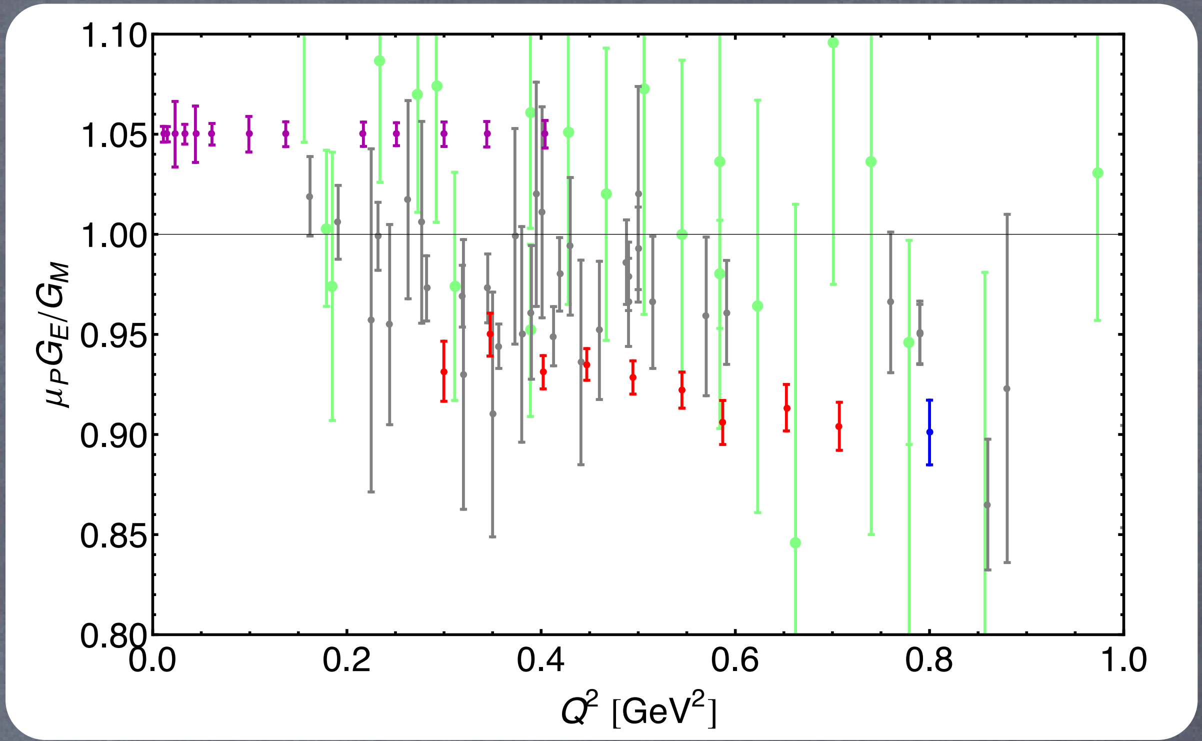


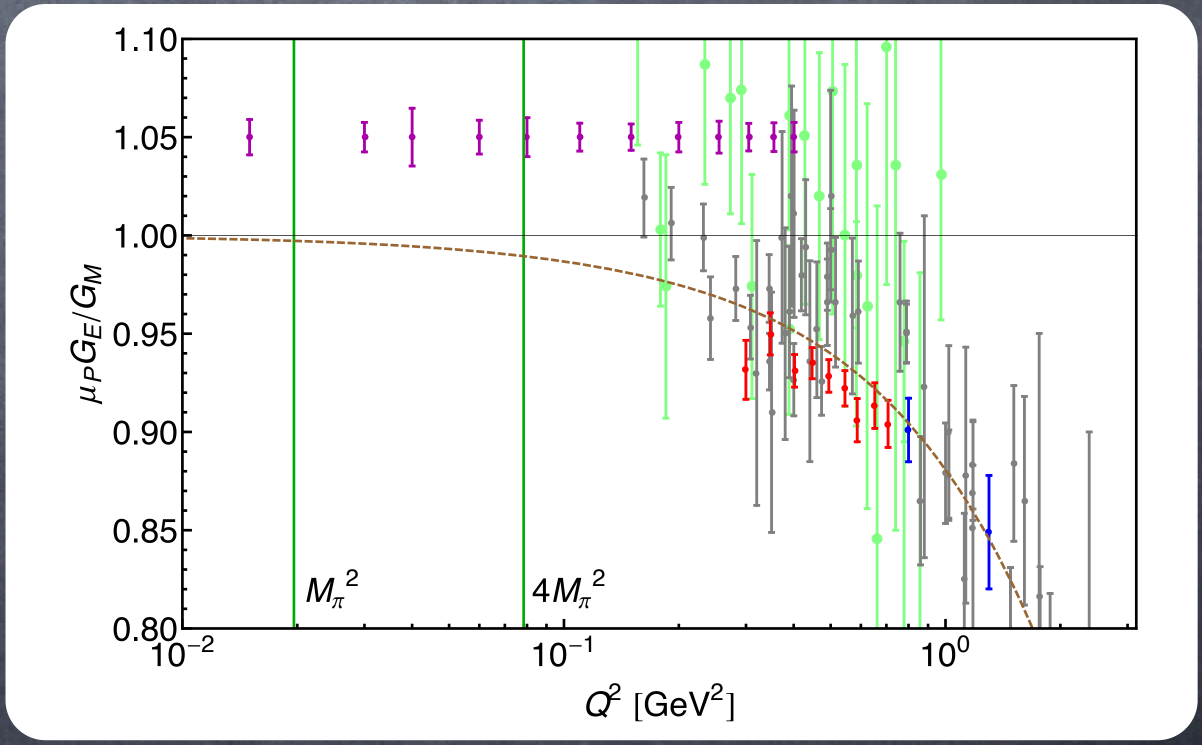
Note that the JLab and Mainz experiments agree better for the FF ratio than the for individual form factors. Thus much of the difference in the FF's must arise from Mainz vs. "world" cross sections.

Is there an issue in the FF ratio at the low Q^2 limit, or is it an end-point problem / statistics? We will know better once we have the polarized target results.

E08-007 Phase II

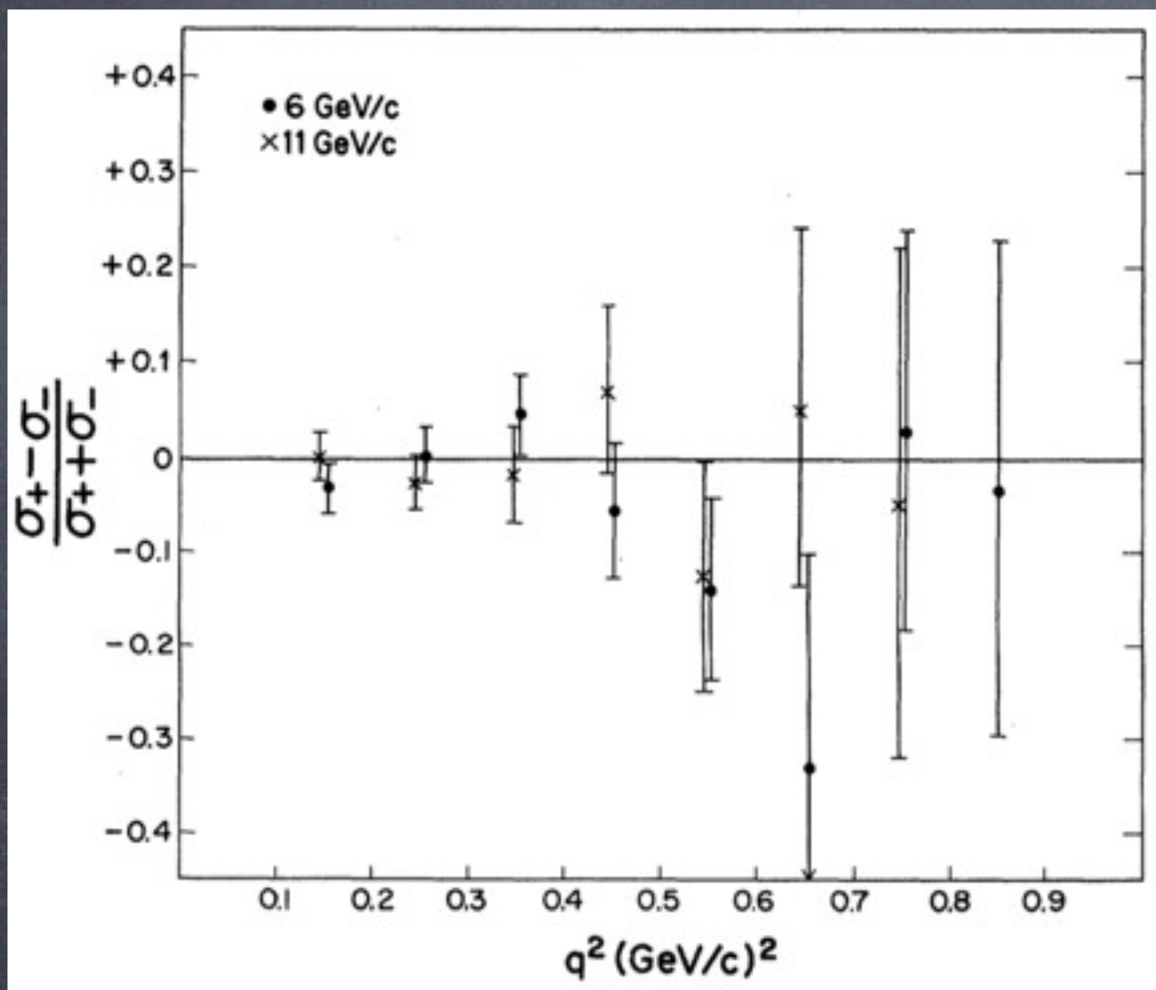






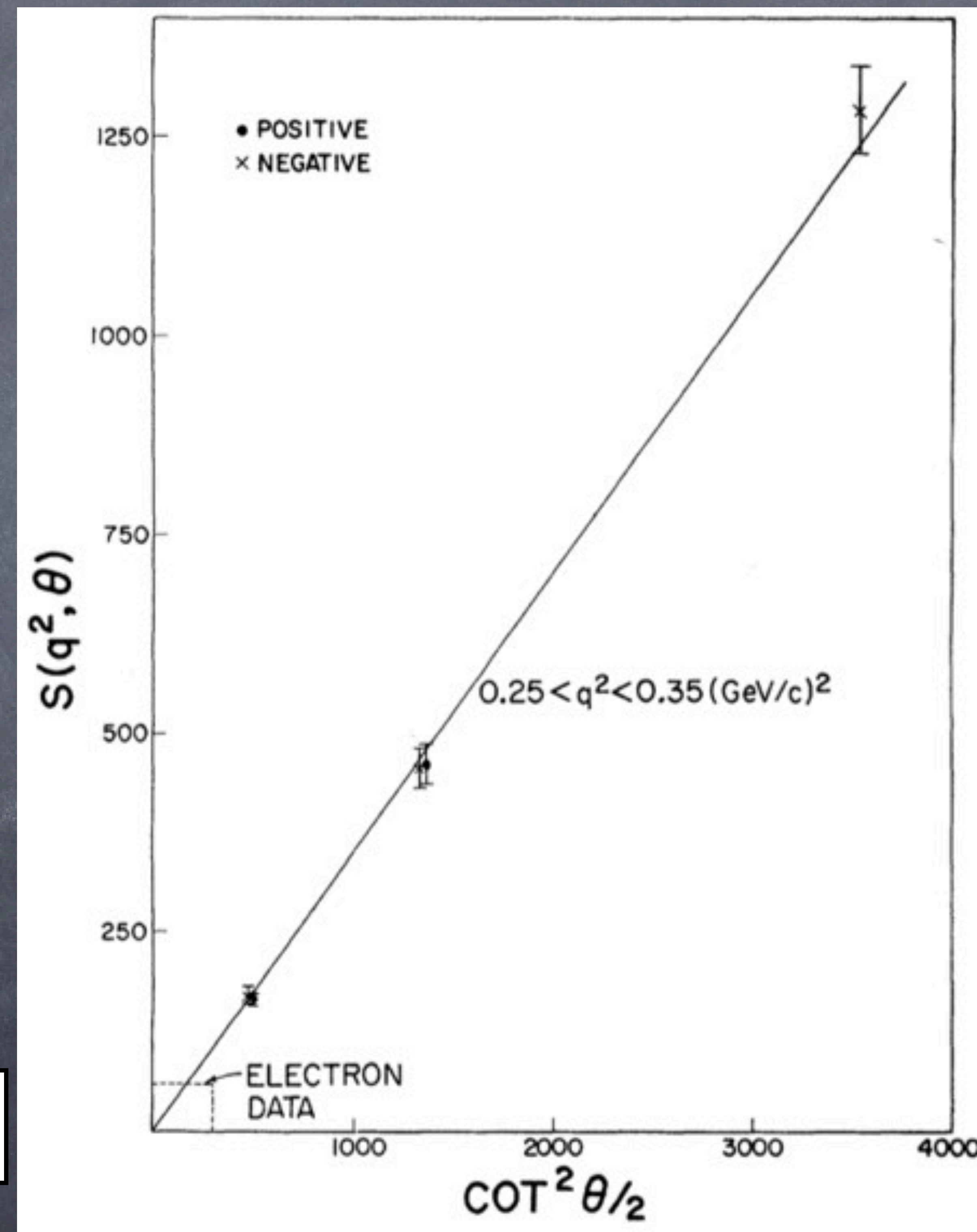
Two-photon exchange tests in μp elastics

Camilleri et al. PRL 23: No evidence for two-photon exchange effects, but very poor constraints by modern standards.

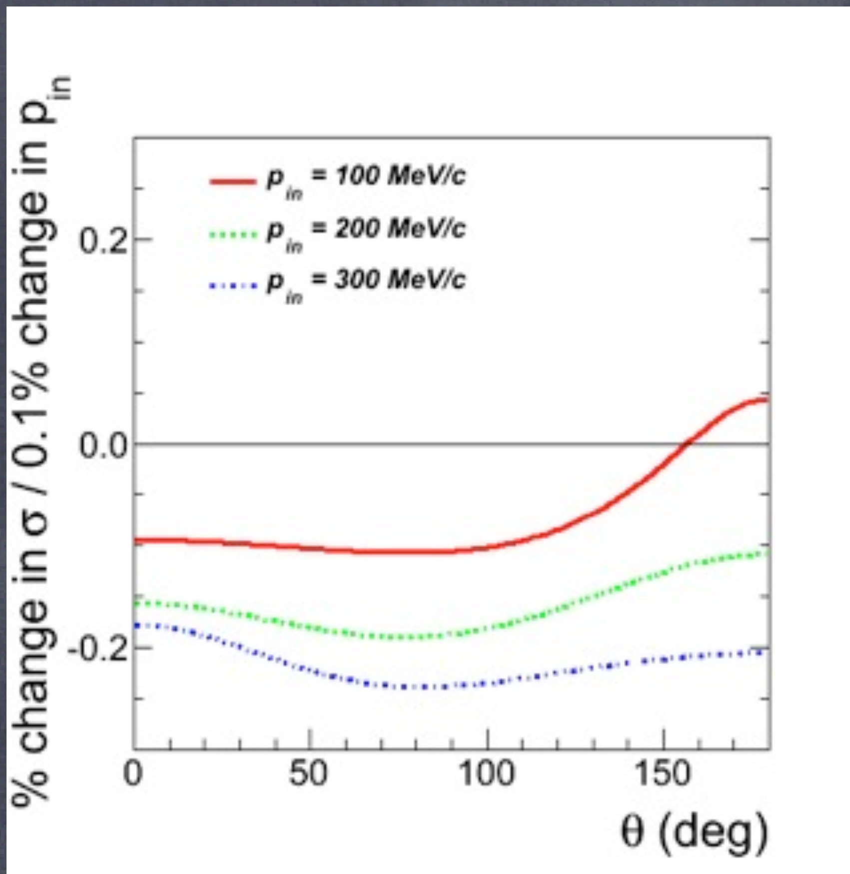


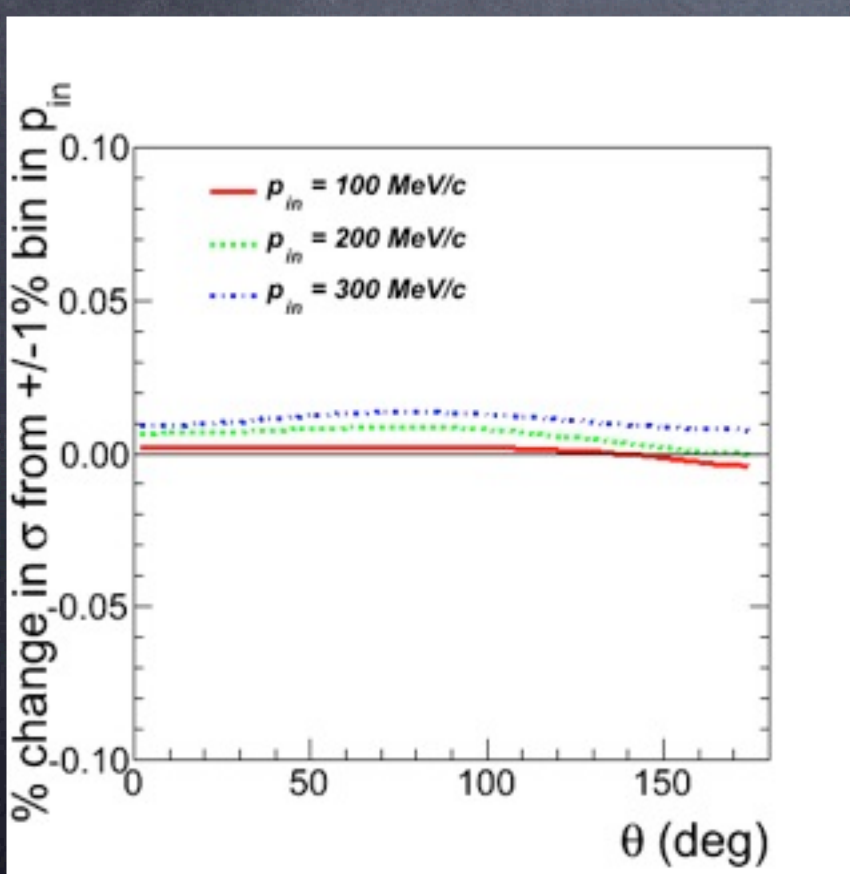
No difference between μ^+p and μ^-p elastic scattering

Rosenbluth plot is linear.



Determining Momentum at High Rate

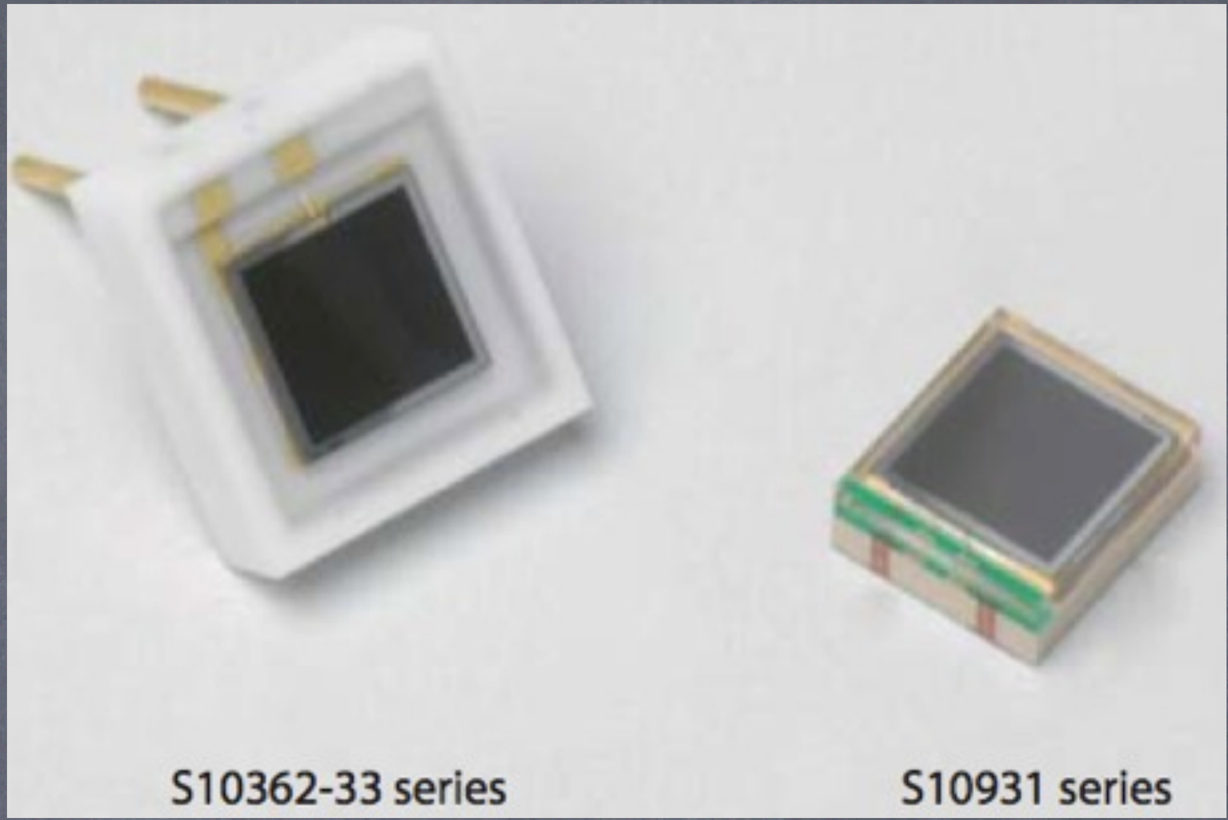




- Need to know $p_{central}$ to 0.1% level, but can average over "large" range.
- Determine p at IFP with XX' Sci-Fi array: 7 cm / % dispersion ➪ need position to 7 mm. Plan to use ≈110 2 mm square fibers / layer. At 10 MHz, ≈0.1% chance multiple tracks in same X and X'. Rate in each fiber about 0.1 MHz.
- 2nd particles can be rejected by RF time if it is a different type from triggering particle.

Sci-Fi Technical Details

Rutgers



- SF: St. Gobain
- Cladding thickness makes each layer ≈96% efficient, offset layers allows high efficiency and its determination.
- Fibers give ≈30 photons at readout / mm thickness of fiber.

- Multi Pixel Photon Counters: Hamamatsu (Si-PMT).
- About 50% efficiency for 400 - 500 nm photons.
- Timing: 0.25 ns FWHM for 1x1 mm^2, 0.55 ns FWHM for 3x3 mm^2
- Insensitive to B fields

Determining Flux - RF Time

Rutgers

The Sci-Fi signals will be discriminated and sent to TDCs in the DAQ and an FPGA. We have started a conceptual design for an FPGA that will have the Sci-Fi inputs plus RF time and gate inputs, to:

- act as a scaler, counting hits in 16 1.25 ns time bins relative to the RF
- output signals for programmed time bins corresponding to the 3 different particle types, for input to the trigger

This will allow us to identify events coming from μ, e, and π beam particles and treat them differently. We want all μ triggers. The e trigger rate is several times higher and can be suppressed if needed. The π events are not wanted for physics, but will be sampled for determining backgrounds, etc.

Determining Flux - Muon Decays

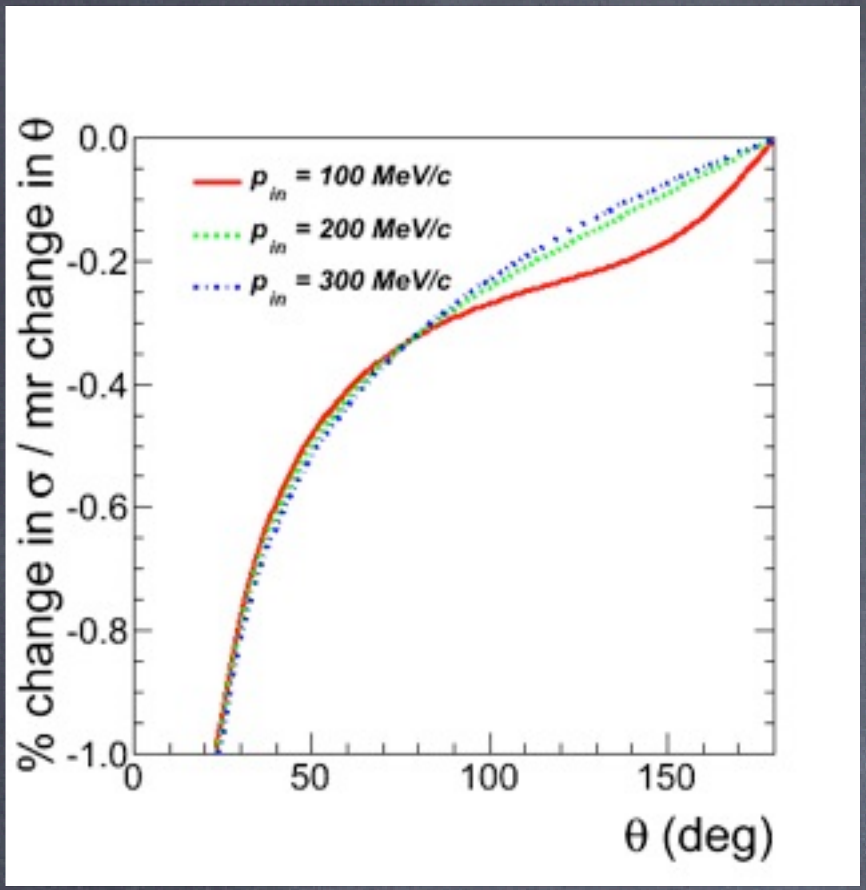
The flux determined by the Sci-Fi at the IFP has to be corrected for μ decays between the counter and the target, and for trajectories that do not make it to the target, so a 2nd Sci-Fi will be used near the target.

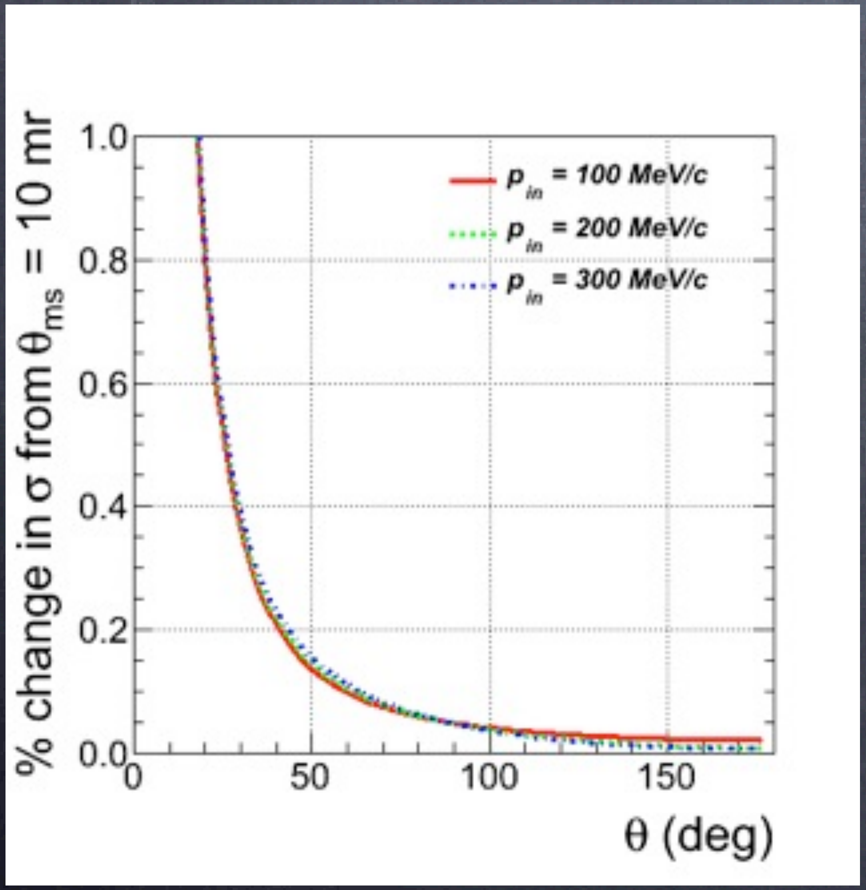
The decay correction is:

$N_{target} = N_{counter}\ e^{-t/\gamma\tau} = N_{counter}\ e^{-d/\beta\gamma c\tau} = N_{counter}\ e^{-dm/pc\tau}$.

About 10^{-5} of the muons decay per cm of flight path, or about 1% decay from the IFP array to the target. The decaying fraction can be calculated to ≈0.1%, the survival fraction much more precisely to ≈0.001%.

Tracking Requirements



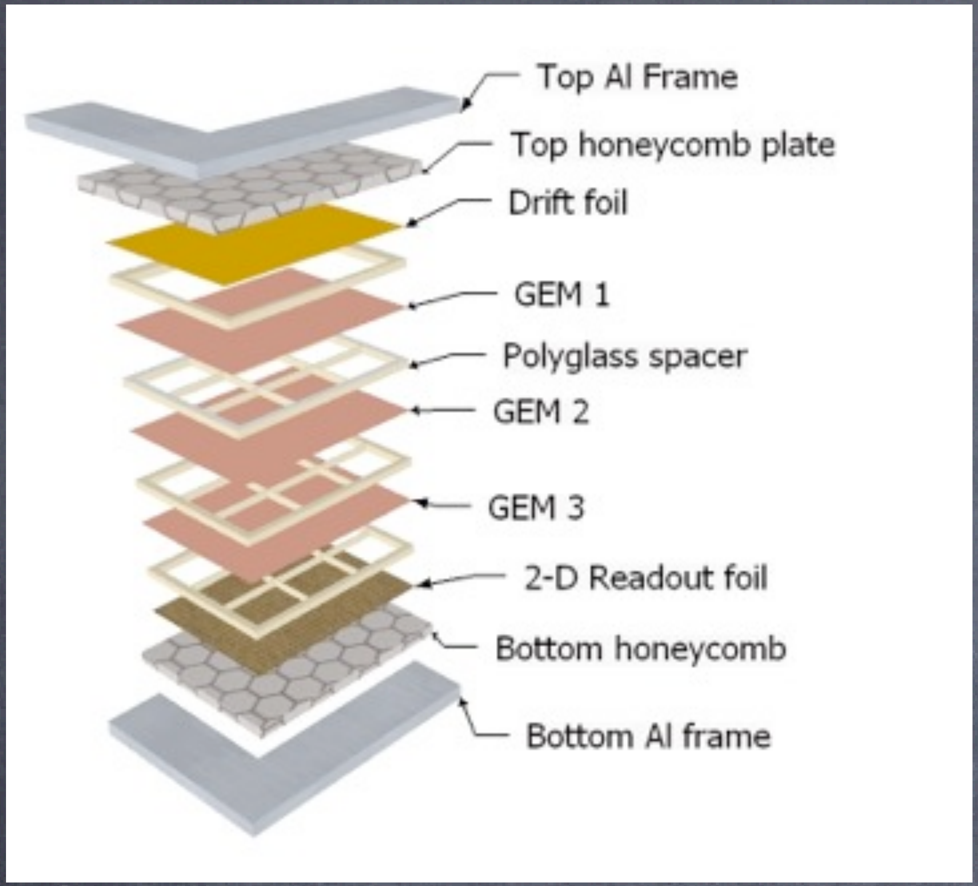


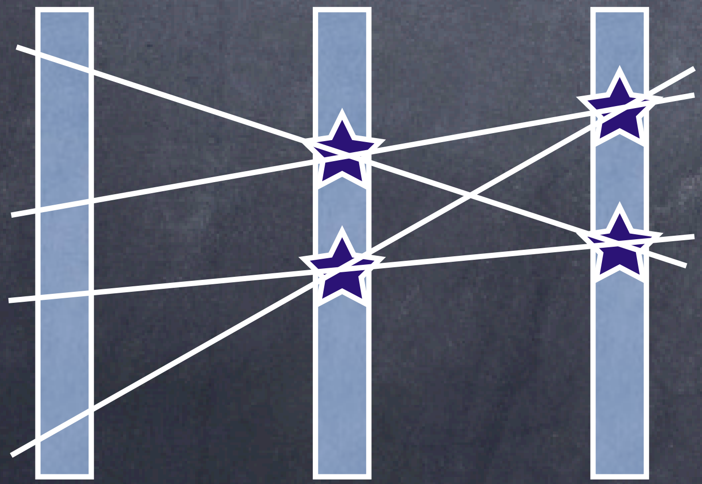
Nominal emittance:
1.5 cm X x 1 cm Y,
35 mr X′ x 75 mr Y′

- Need central scattering angles at mr level, but event by event angles at several mr level.
- Large variation in angles in secondary beam ➪ incident particles need to be measured for each event. High rates ➪ GEM chambers.

GEM Chambers

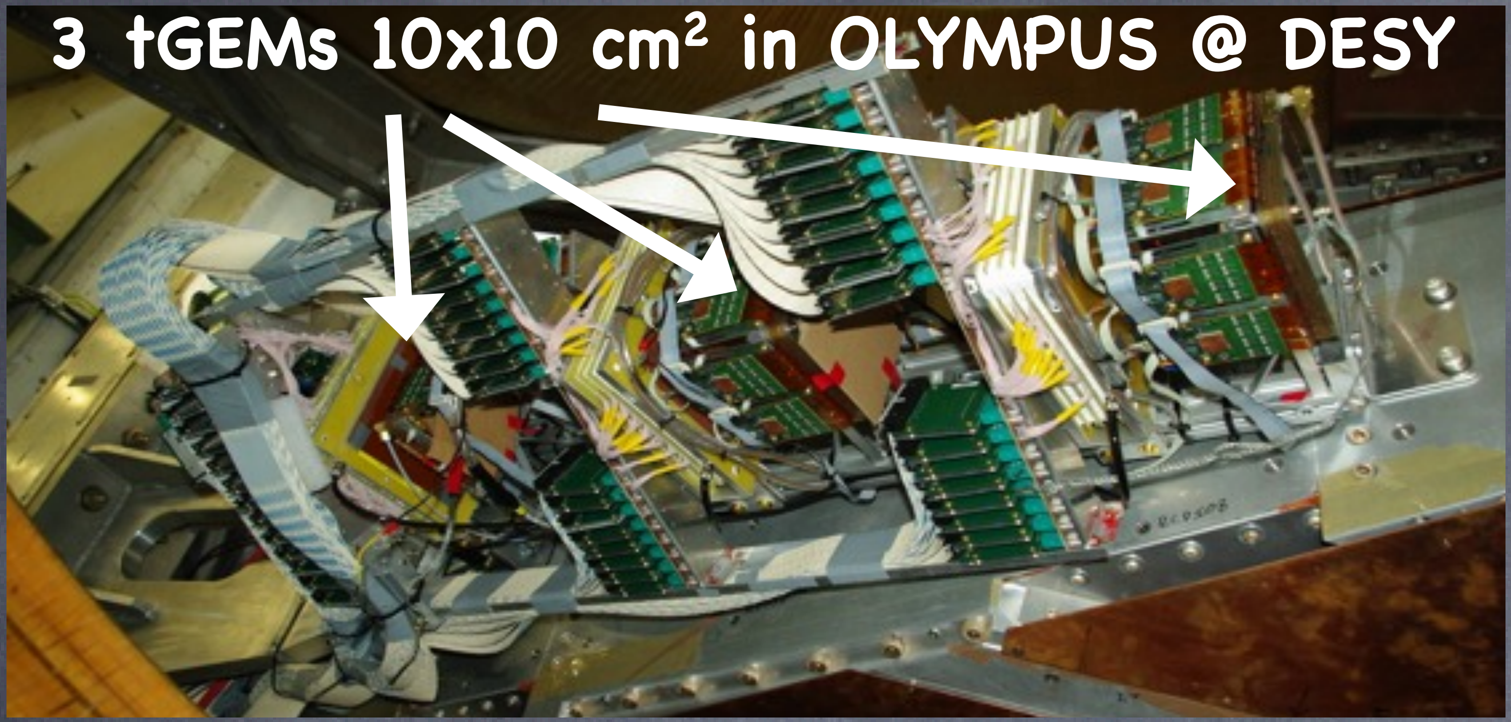
Hampton, UVa

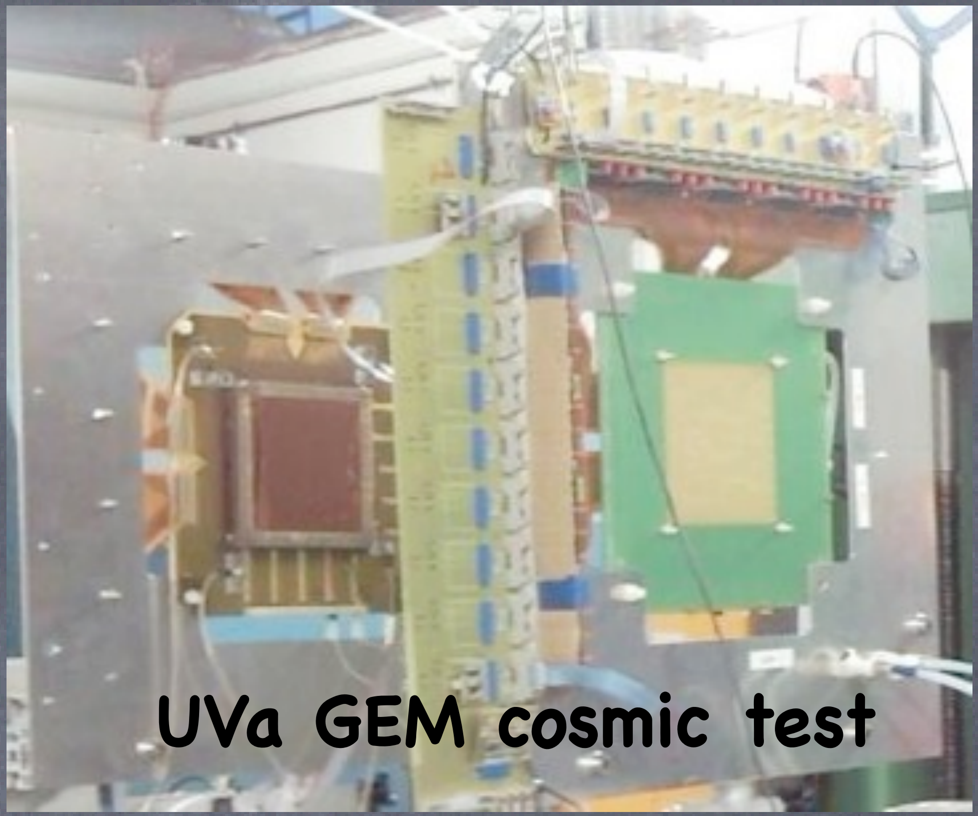




- COMPASS GEMs routinely operated to ≈2.5 MHz/cm^2.
- Tests by various groups have gone up to several 10s of MHz/cm^2.
- We are assuming 10 MHz/1.5 cm^2 = 6.7 MHz/cm^2 (average) rate.
- Gas avalanche is in a ≈ 100 μm wide – the 1.5 cm^2 πM1 beam spot is "100 x 150 pixels" in size, so the 2-3 random coincidence trajectories have negligible probability of overlap.
- Angle divergence of beam leads to ghosts, which can be removed by a 3rd chamber. (Rotation not needed.)
- Electronics might allow removal of particles from other RF buckets.

Available GEMs



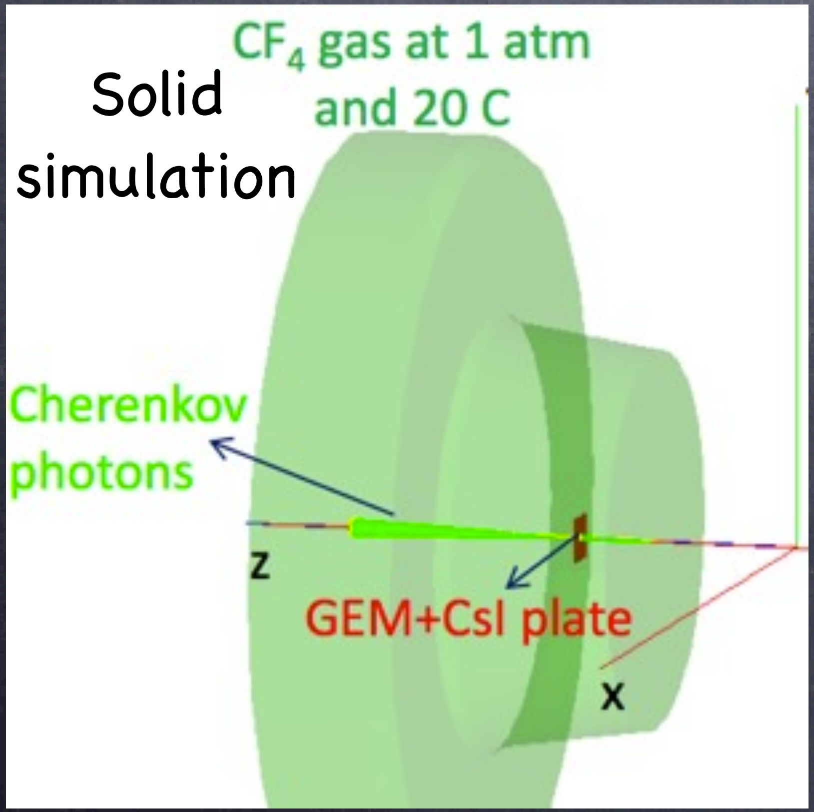


- Access to OLYMPUS (e^+p/e^-p at DESY) GEMS through Hampton. Available at end of 2012. FPGA controlled APV front-end readout (INFN Rome). Well tested and tuned. -or-
- UVa has 2 GEMs available as part of JLab SBS project. New GEMS about \$10,000 - \$30,000 each.
- Can determine absolute wire positions in Hall to 100 - 200 μm ⇨ know central angle to ≈ 200 μm / 40 cm = 0.5 mr.

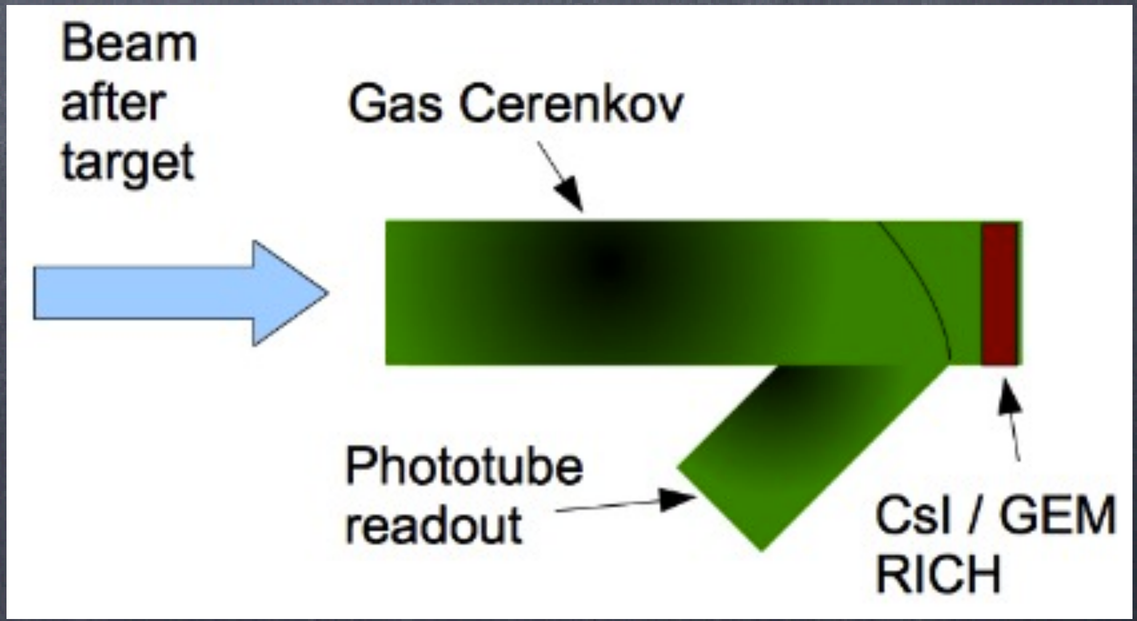
Channel Particle Identification

Temple

- Hybrid gas threshold + RICH Cerenkov
- Gas threshold efficiently detects electrons and can be used with PID FPGA as cross check of RF time calibration for efficient setup.
- RICH likely uses JLab SOLID scheme of CsI radiator.
- Dedicated Cerenkov run and prescaled readout allows RF time PID to be cross checked at analysis level for non-scattered particles.



Configuration under discussion



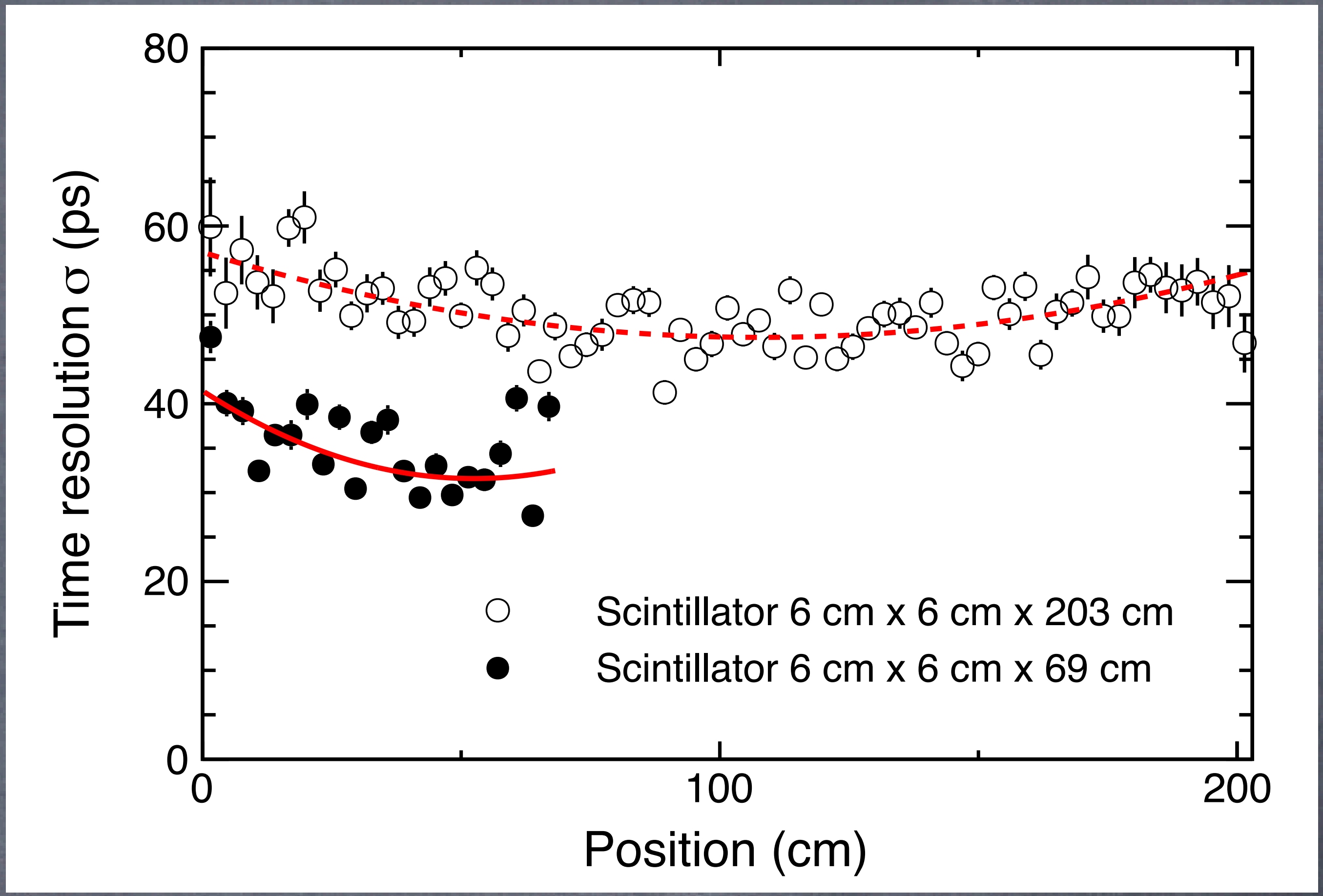
Rutgers

Target Sci-Fi array

- The channel Sci-Fi + 2 GEMs are sufficient to determine the incoming momentum vector for events with one track.
- For events with background tracks, a 3rd GEM resolves ghosts. But we also need to correlate the momentum and PID at the channel IFP with the trajectory at the target.
- A Sci-Fi near the target with 2 mm XYU fibers ("40 pixels") can
  - Measure RF time
  - Measure TOF over a ≈9 m flight path
  - Correlate GEM tracks to momentum measurement in channel for essentially all particles from different RF buckets and nearly all particles from the same RF bucket.
- Expect to put SciFi upstream of GEMs, but will study if SciFi array can be put downstream of the target.

Scintillators

So. Carolina, Tel Aviv



Cosmic ray test of some of the 400 JLAB CLAS12 Forward Time of Flight scintillators being built at So. Carolina by R. Gothe et al.

Time Resolution with BC-404 scintillator and Hamamatsu R9779 PMT is σ_{avg} = 51 ps for 203 cm bars, 34 ps for 69 cm bars.

Scintillators

So. Carolina, Tel Aviv

Copying the So. Carolina 6 cm x 6 cm scintillator paddle design with 2 scintillator planes 70 and 100 cm from the target requires planes made of 20 1.4-m long scintillators and 28 2-m long scintillators. The system cost is ≈220 k$.

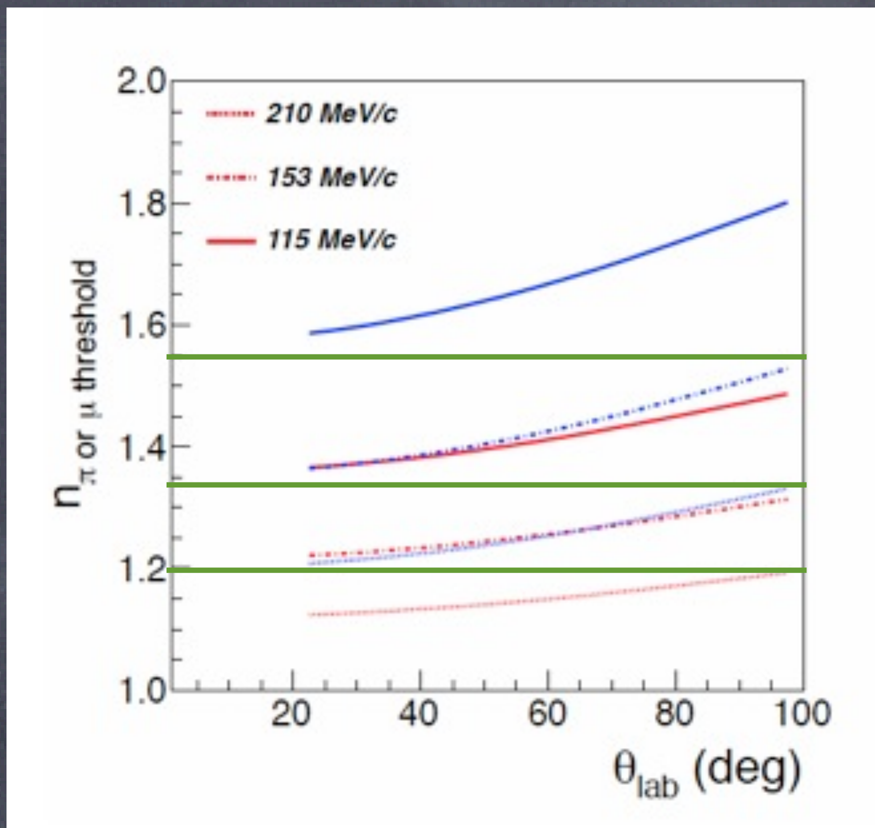
Although the SC scintillators are highly efficient, we will add one scintillator plane from existing OLYMPUS scintillator paddles, to save cost and give redundancy & efficiency data.

For triggering, an FPGA (e.g., CAEN v1495) will require tracks that roughly point to the target, and allow for inefficiencies.

Cannot use RF time of scintillator hits for triggering. In the analysis, 60 ps resolution separates particles by RF time by > 4 ns / 60 ps ≈ 70σ. Electrons coming from muon decay in flight are separated from scattered muons by 0.4 - 1.5 ns, or 7σ - 25σ in the analysis.

Threshold Aerogel Detector

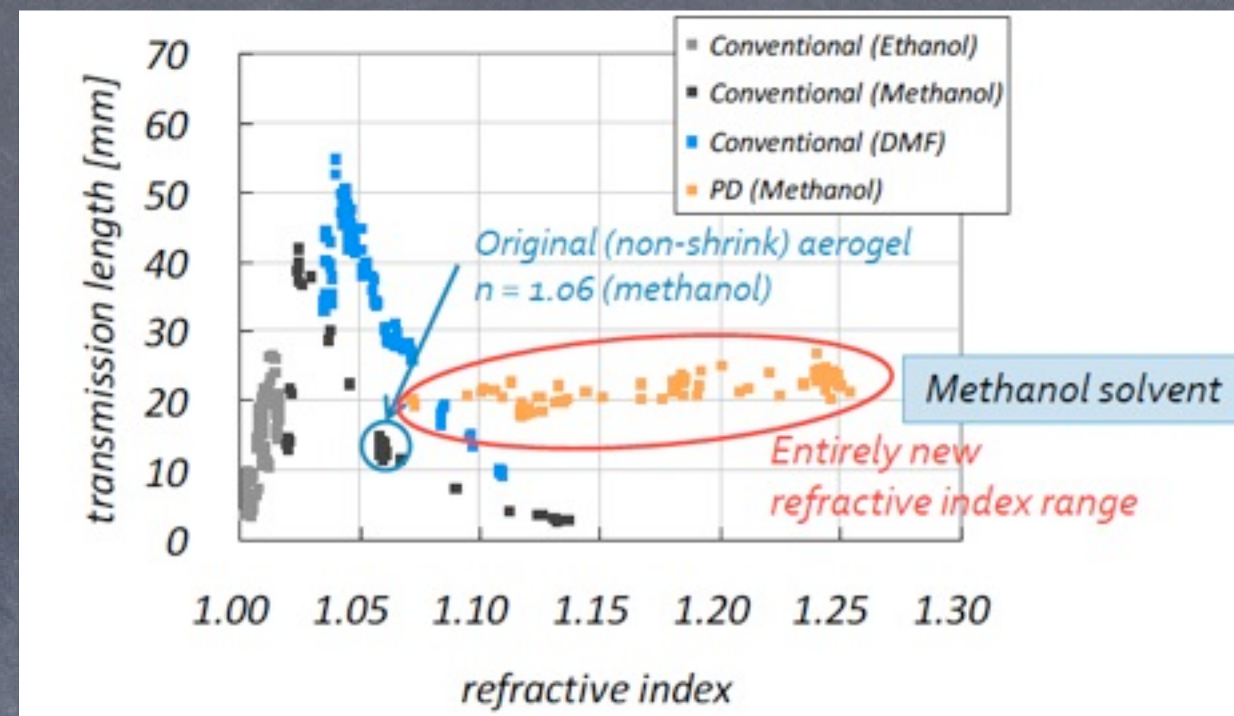
Jerusalem



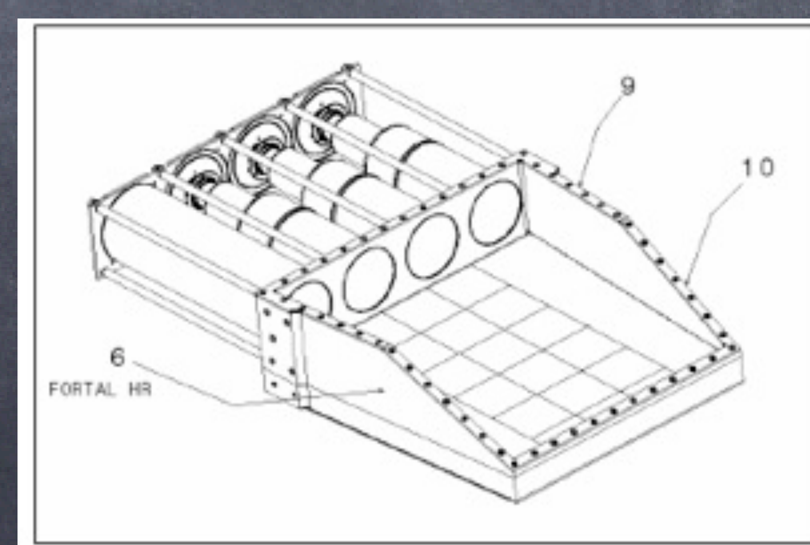
Beam	$n_{threshold}$	Material
210	1.19-1.20	pinhole dried Aerogel
153	1.32-1.36	water / teflon
115	1.50-1.58	quartz/ lucite

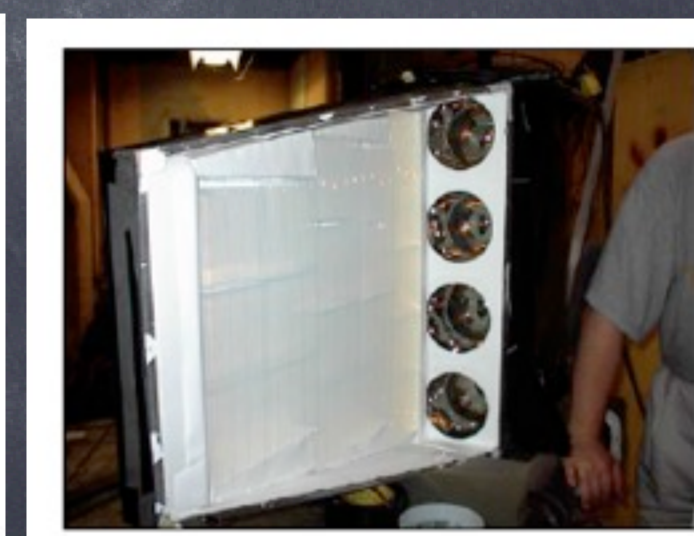
Additional suppression of pion triggers

from: M. Tabata, Japan Aerospace Exploration Agency, talk at TIPP2011, Chicago



Expect design to be similar to Qweak Cerenkov





Wire Chambers

MIT

Scattered particle wire chambers have moderate total rates, about 400 khZ in total system, as long as $\theta_{min} > 20^o$. Most of the rate is low energy electrons / positrons from the target, and μ's from in-flight beam π decays upstream of the target. With chambers close to the target, the wire lengths will be short, and position resolution of 100 μm and angle resolution of <1 mr (neglecting multiple scattering) should be achievable. The main issue being thought about it how to keep the relative angle of the GEMs and scattered particle wire chambers under control.

GEANT Monte Carlo

So Carolina,
Tel Aviv

We have started development of a simulation of the experiment, so that backgrounds and detector design trade offs can be better understood. It remains under development at this stage.