Monte Carlo Studies of the HERMES RICH in SBS

Andrew Puckett, LANL

SBS Session, Hall A Collaboration Meeting

12/10/2010

Outline

- Introduction to the HERMES/SBS RICH detector
- Planned Experiments
  - SIDIS on transversely polarized ^{3}He
  - Other SIDIS physics + ...?
- Performance in HERMES
- Expected performance in SBS
  - GEANT simulation
  - Results
- Summary/Conclusion

The HERMES RICH Detector

An Overview

Figures: Akopov et al.; NIM A 479, 511 (2002)

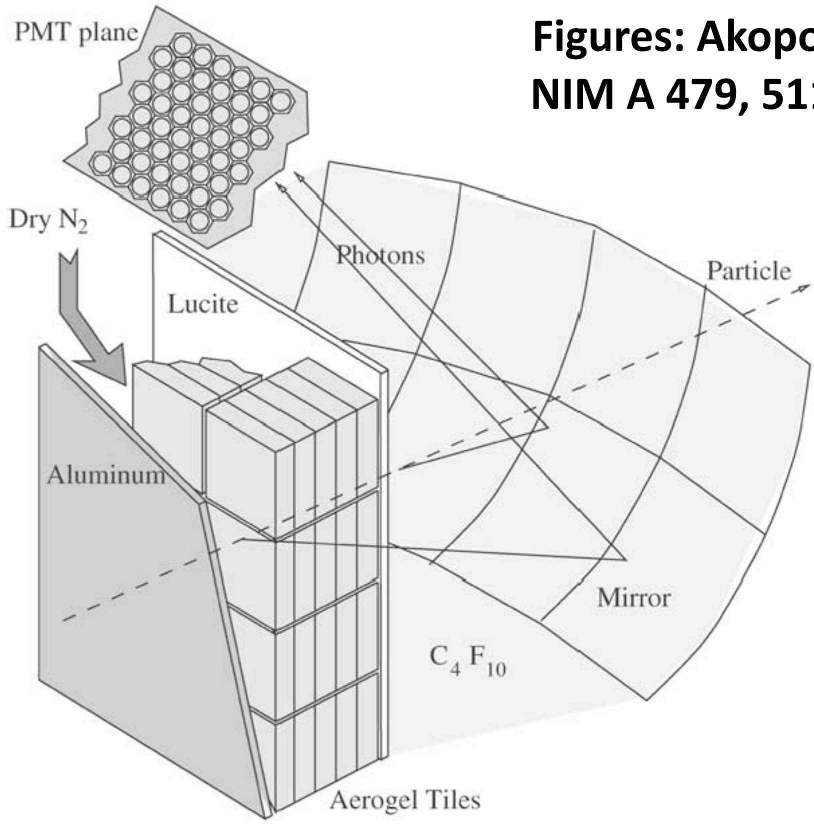


Fig. 4. Basic geometry and radiator configuration for the HERMES dual radiator RICH (not to scale).

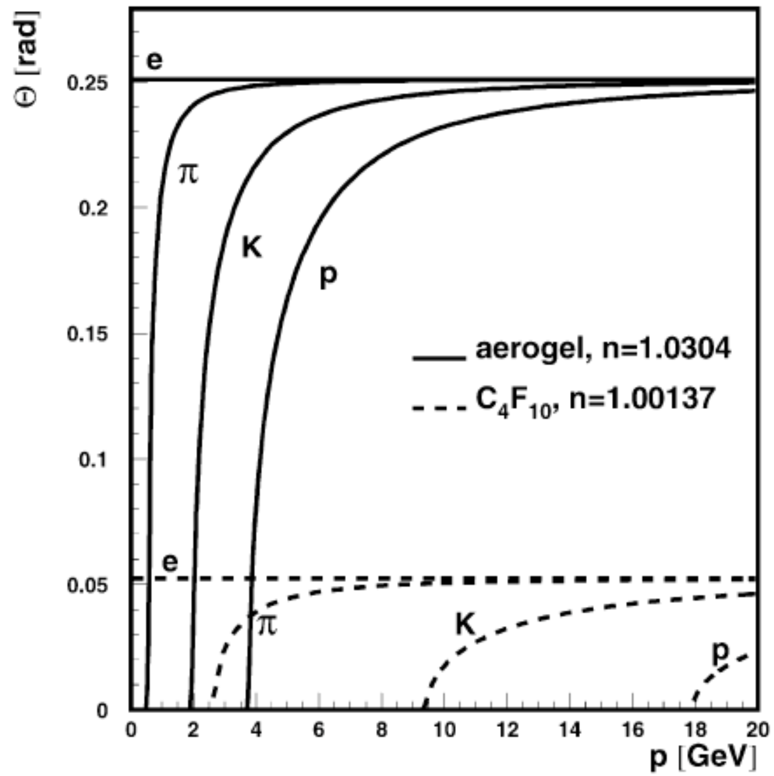


Fig. 2. The Cherenkov angle θ versus hadron momentum for the aerogel and C_4F_{10} gas radiators.

- PID requirements in HERMES: π/K/p separation for momenta 2-15 GeV
- PID requirements in SBS: π/K/p separation for momenta 2-10 GeV (p_{max} ~7 GeV for SIDIS z<.7)
- **HERMES PID capability and geometry ideally suited for SBS**
- Dual radiator design; separate particles based on both threshold and Cherenkov angle θ_C
    - Aerogel; index of refraction n=1.0304
    - C_4F_{10}; index of refraction n = 1.00137

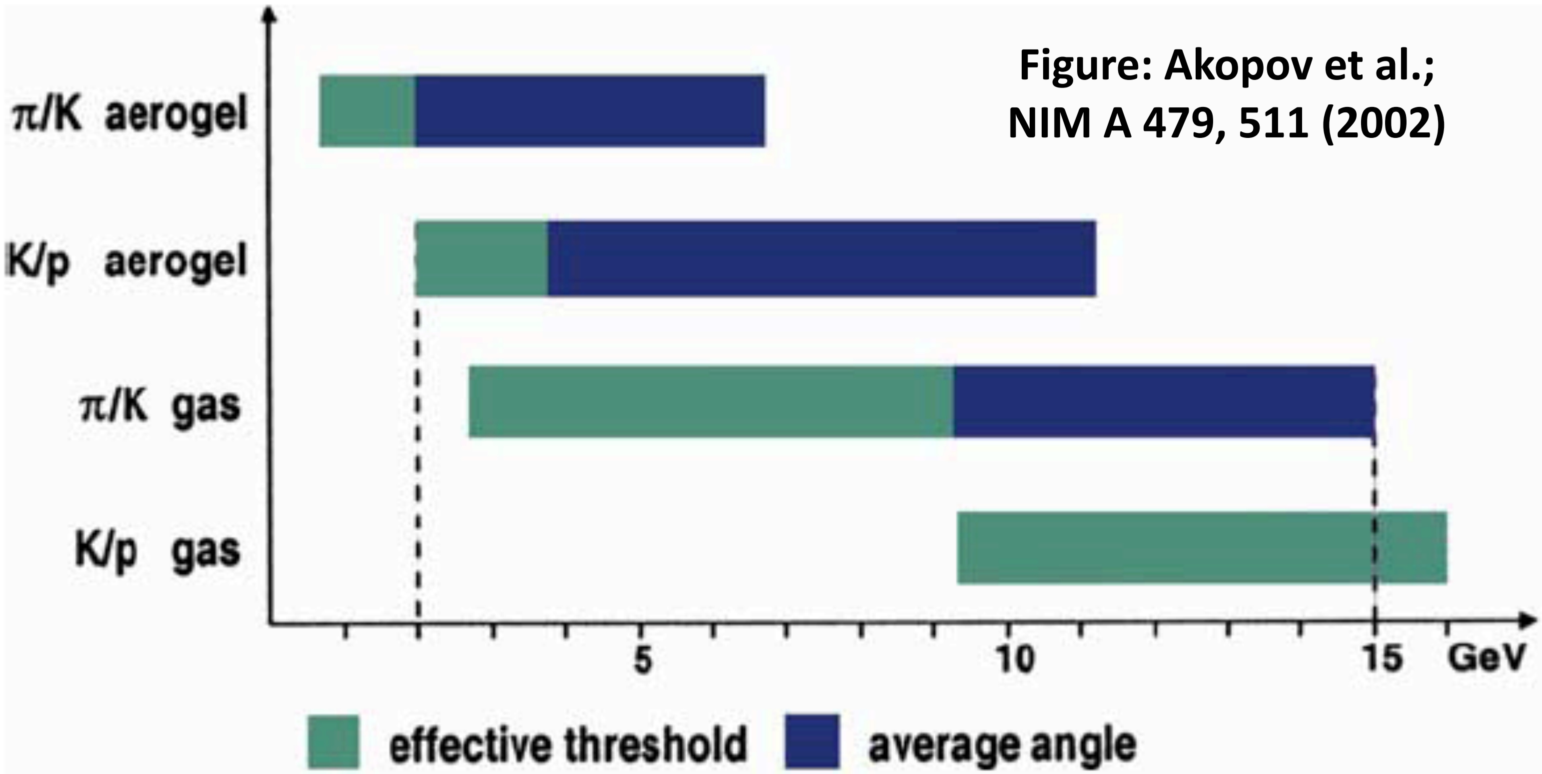


Fig. 3. Momentum ranges for hadron separation in aerogel and C_4F_{10}. Between the dashed lines the hadrons can be separated.

- Dual radiator design provides overlapping coverages for π/K/p separation based on Cherenkov threshold and average angle between 2-15 GeV:
    - K threshold in aerogel sets minimum momentum of 2 GeV for K/p separation
    - θ_C resolution sets upper limit for π/K separation in gas at 15 GeV (4.6σ separation)

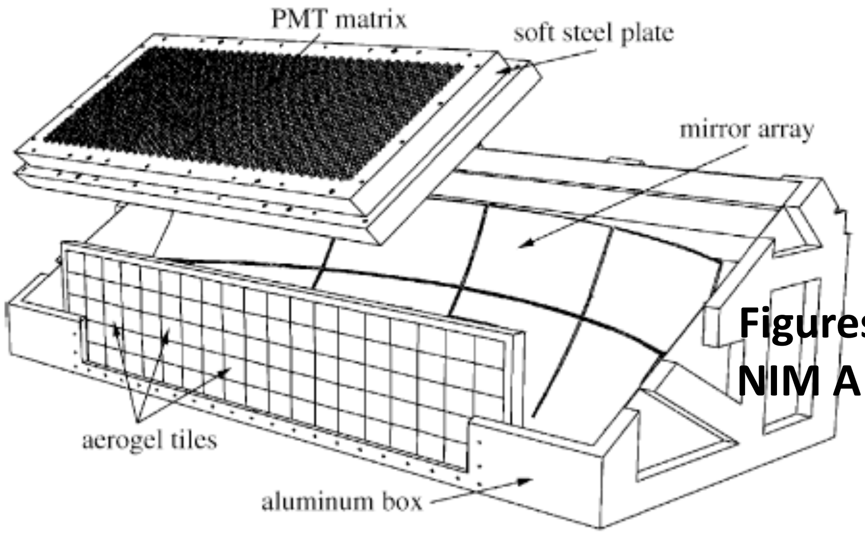


Fig. 5. A cutaway schematic view of the (top) RICH counter.

Figures: Akopov et al.; NIM A 479, 511 (2002)

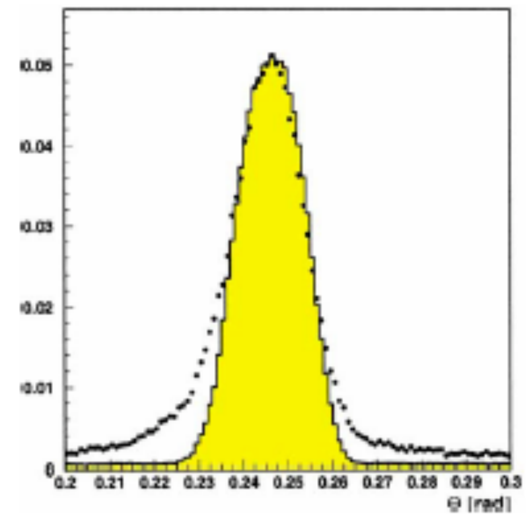


Fig. 21. Normalized distributions of reconstructed aerogel angles for single, low background electrons ($p > 5$ GeV). Histogram: MC, points: data.

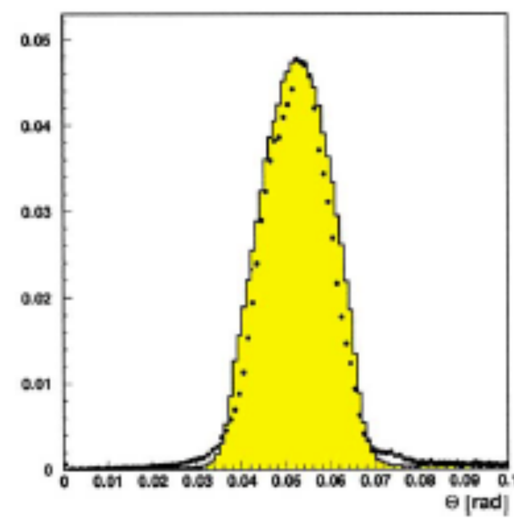


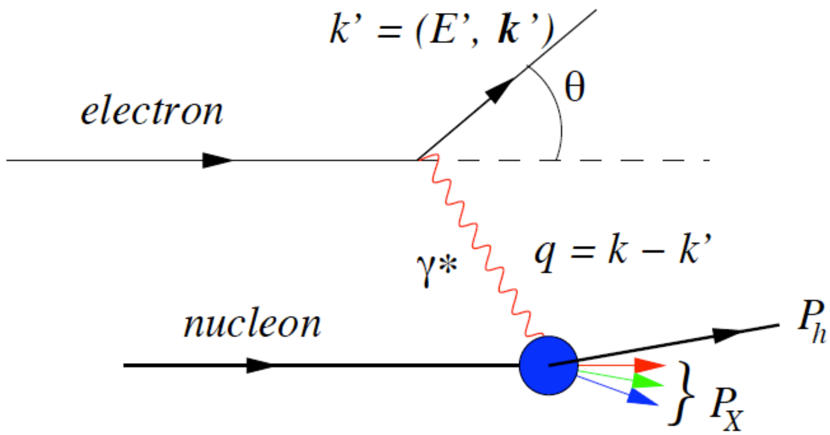
Fig. 22. Normalized distributions of reconstructed gas angles for single, low background electrons ($p > 5$ GeV). Histogram: MC, points: data.

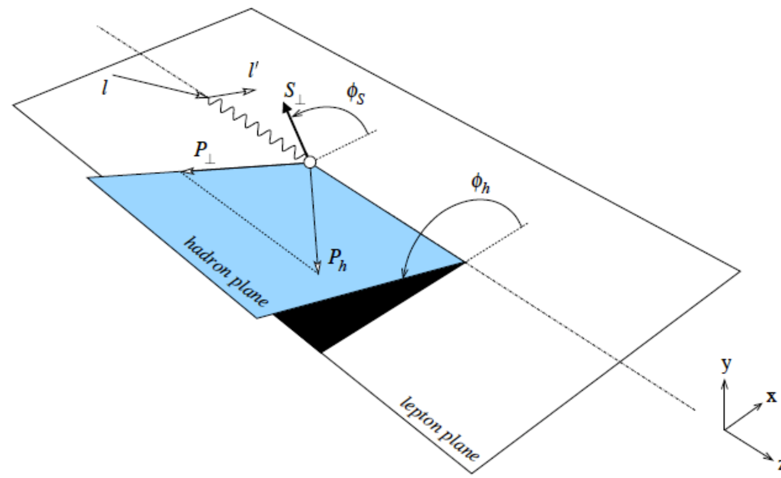
- Photon detector: rectangular array of 1,934 0.75” diameter XP1911UV PMTs
- Optics: large-acceptance spherical mirror
- Above: schematic of the full detector
- Right—Comparison of simulated and experimental ring angle resolution for low-background, high-p electrons:
    - Top: Aerogel
    - Bottom: Gas
- For both radiators, angle resolution of ~7.5 mrad dominated by pixel size

Planned experiments using the SBS RICH

SIDIS on a transversely Polarized ^{3}He Target—C12-09-018

- Second-generation transversity experiment
- **Conditionally approved by PAC34, resubmitted to PAC37 for full approval**
- In two-month run, will achieve ~10X greater stat. precision ***on the neutron*** than representative first-generation experiments (e.g., HERMES/COMPASS/Hall A 6 GeV transversity)
- Collins and Sivers asymmetries in a multi-dimensional kinematic grid (x,z/p_T,Q^2)
- Excellent PID capability using HERMES RICH (subject of this talk)
- Two beam energies: 11 GeV and 8.8 GeV; provide Q^2 dependence at fixed x
- Vertical orientation of detectors behind SBS magnet = up/down symmetric acceptance+optics, simultaneous collection of $\pi^\pm$/$K^\pm$ data; periodic reversal of magnet polarity will cancel any residual systematic acceptance differences between positive and negative charged hadron species.





		quark		
		U	L	T
nucleon	U	q		$h_1^{\perp}$
	L		Δq	$h_{1L}^{\perp}$
	T	$f_{1T}^{\perp}$	$g_{1T}^{\perp}$	δq / $h_{1T}^{\perp}$

• Separate different effects by measuring characteristic azimuthal dependences:

$$d\sigma_{UT} = d\sigma_{UU}\left[1 + A_{UT}^{Collins}\sin(\phi+\phi_S) + A_{UT}^{Sivers}\sin(\phi-\phi_S)\right]$$

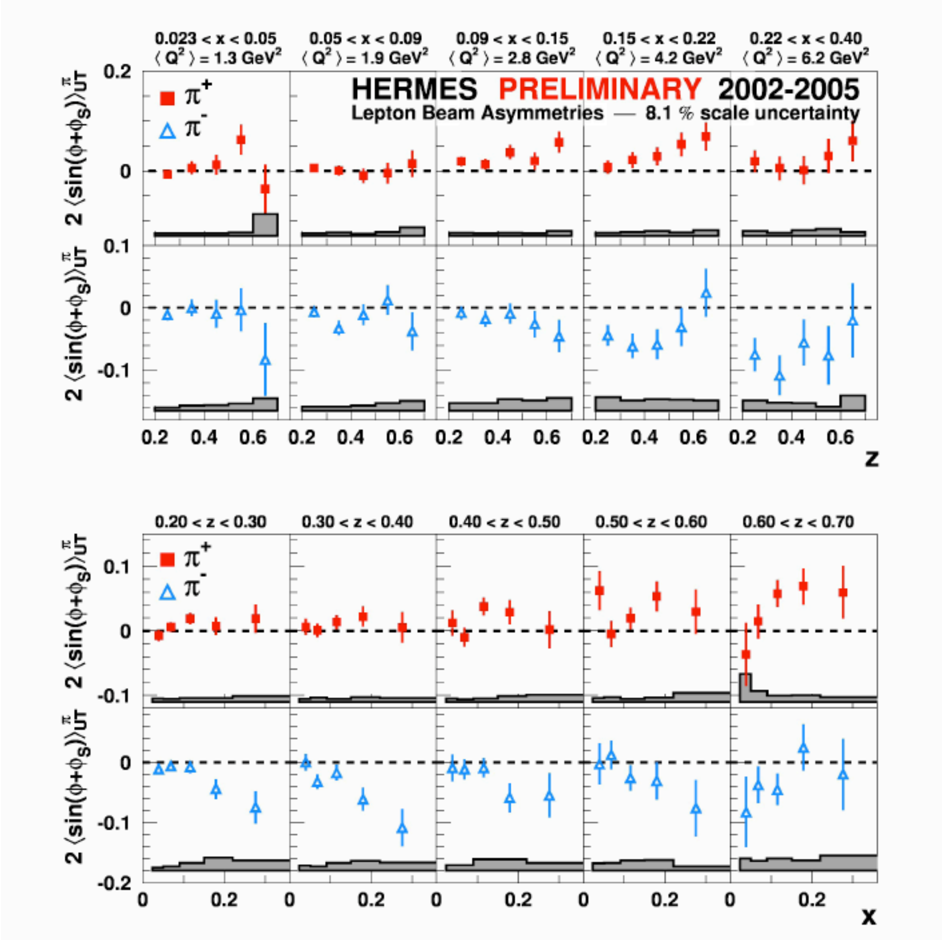
• Transverse target spin-dependent cross section for SIDIS

• Three leading-twist TMDs:

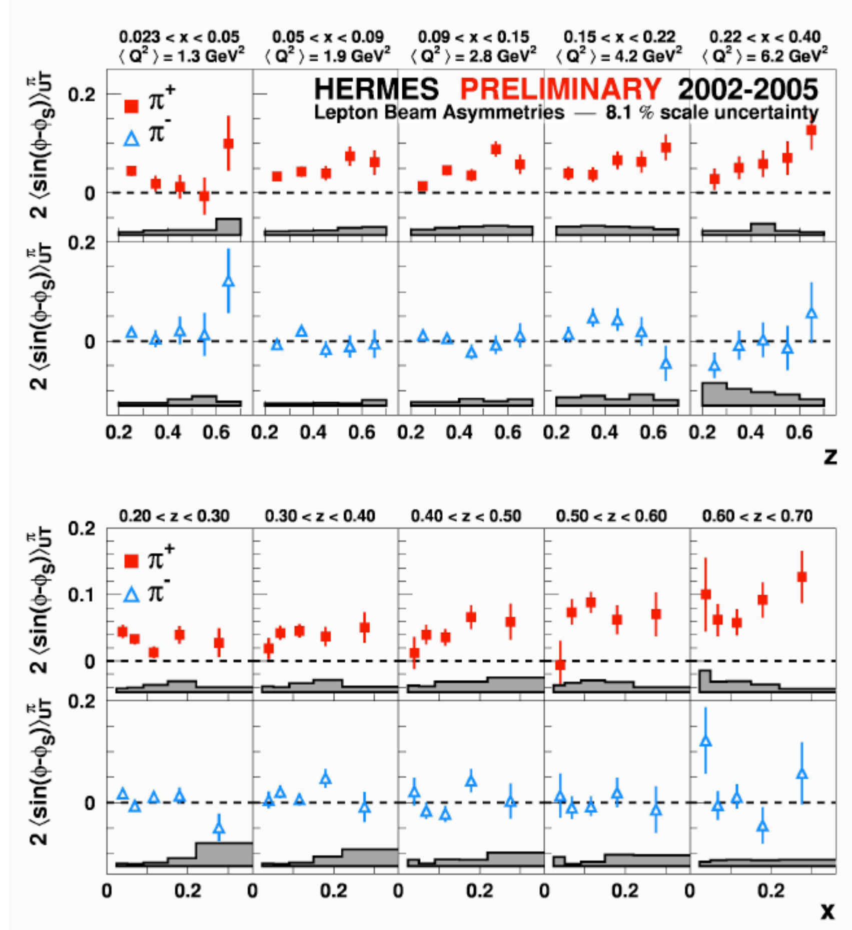
  • Collins effect: chiral-odd quark transversity distribution; observable in SIDIS through convolution with chiral-odd Collins fragmentation function, describes quark transverse polarization in a transversely polarized nucleon

  • Sivers effect: describes correlation between nucleon transverse spin and the transverse momentum of unpolarized partons, related to quark OAM

  • "Pretzelosity"

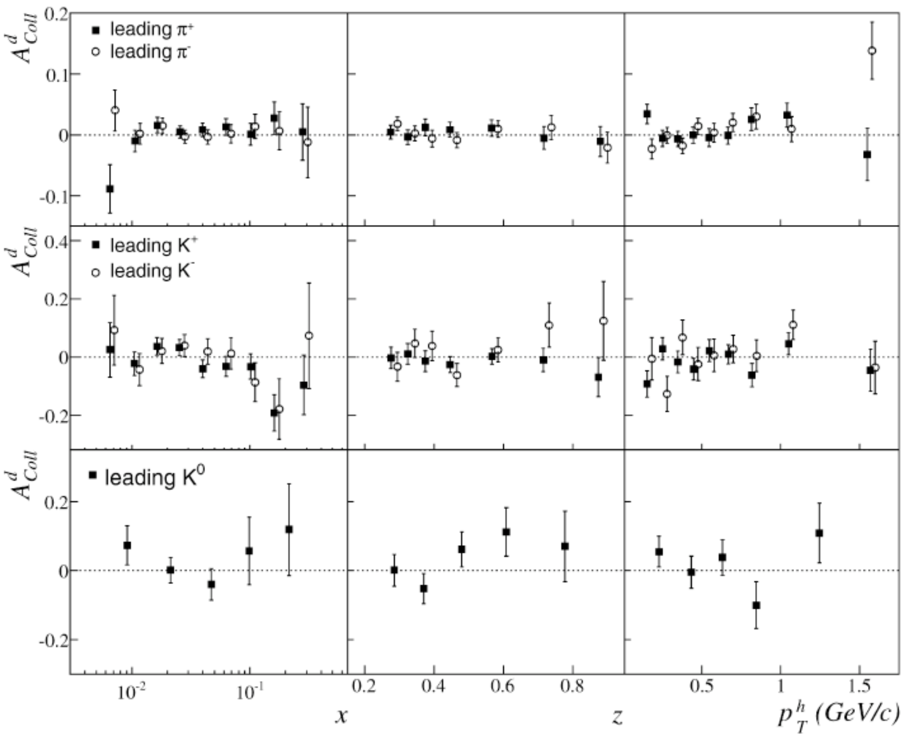


HERMES data on proton Collins Moments, 2D x-z binning

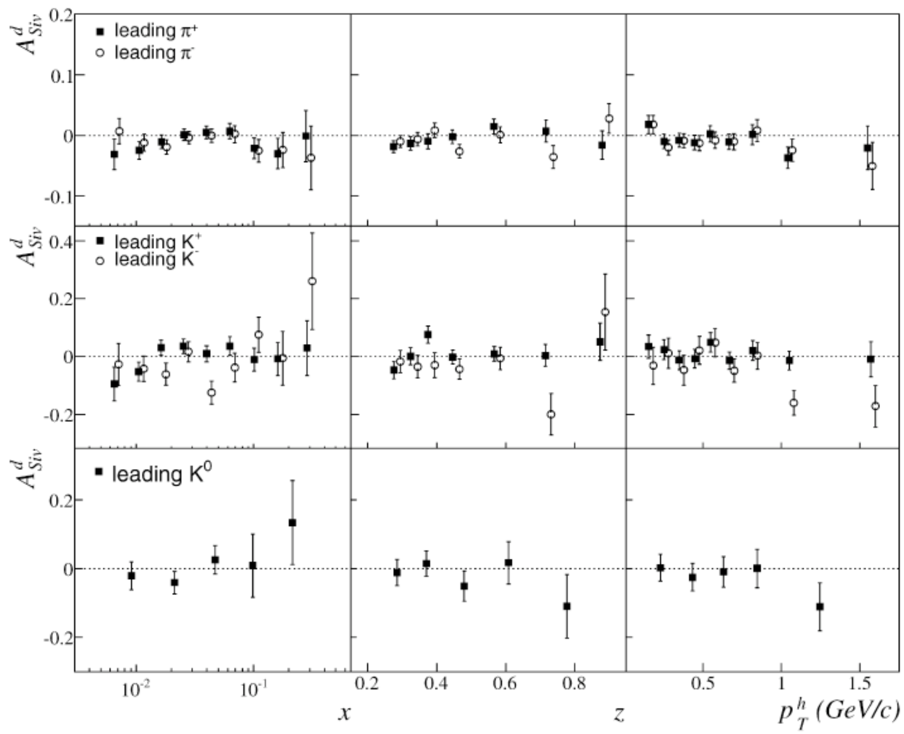


HERMES data on proton Sivers Moments, 2D x-z binning

M. Contalbrigo talk at SPIN2008

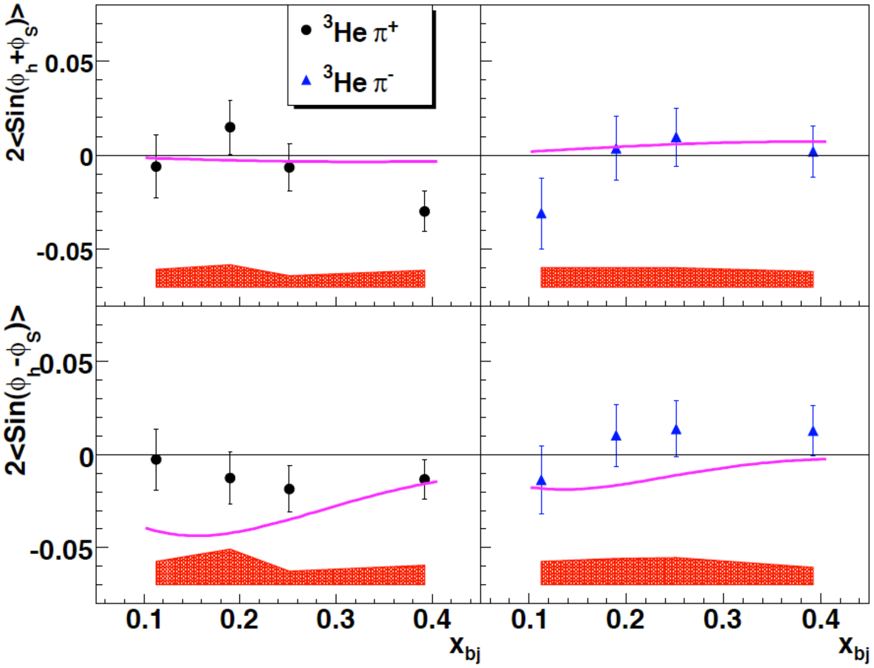


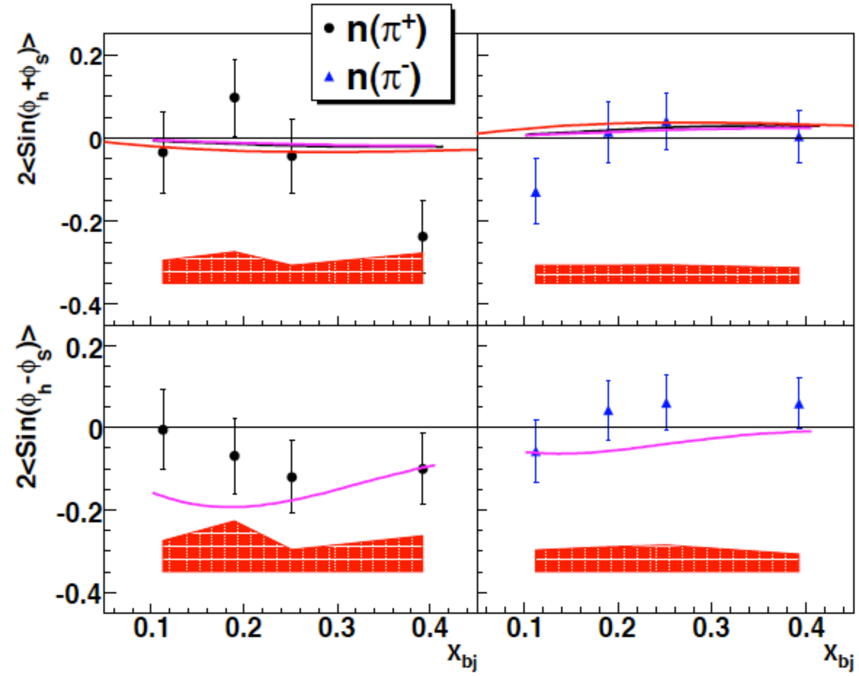
COMPASS Collins asymmetry on deuteron target



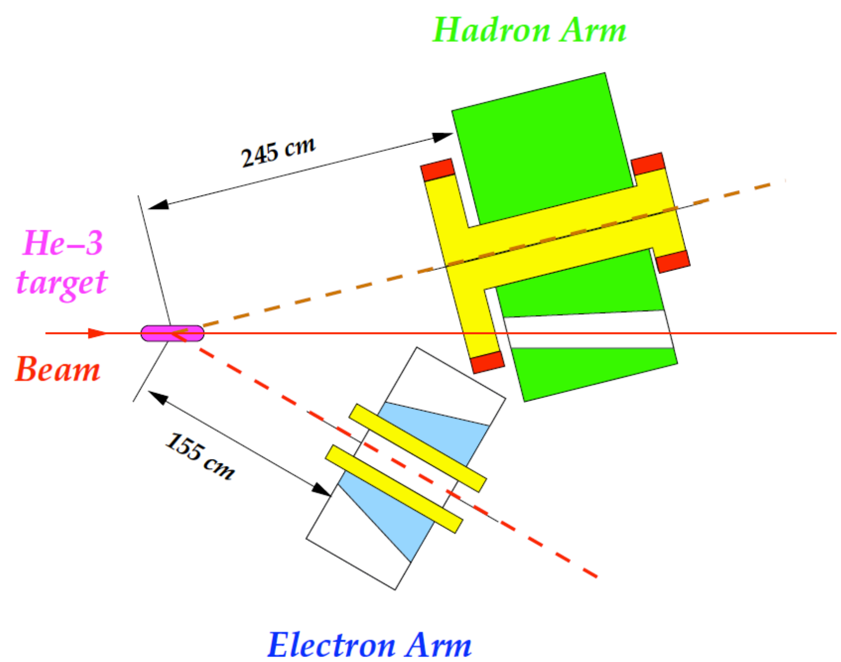
COMPASS Sivers asymmetry on deuteron target

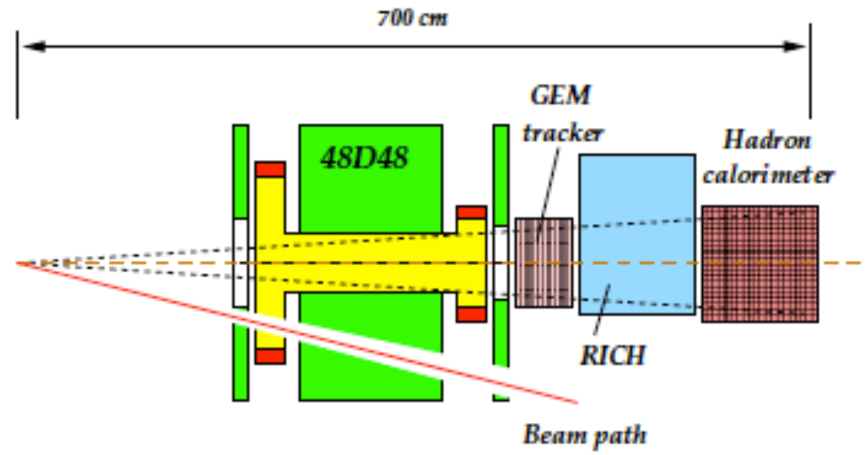
- COMPASS results on transversely polarized ^{6}LiD target; Collins/Sivers for pions and kaons: PLB
- Measured asymmetries generally small;
- Comparison to HERMES proton data suggests cancellation between proton and neutron due to opposite sign of Sivers effects for u/d quarks
- Leads to expectation of significant signal for the neutron, opposite to that seen for the proton

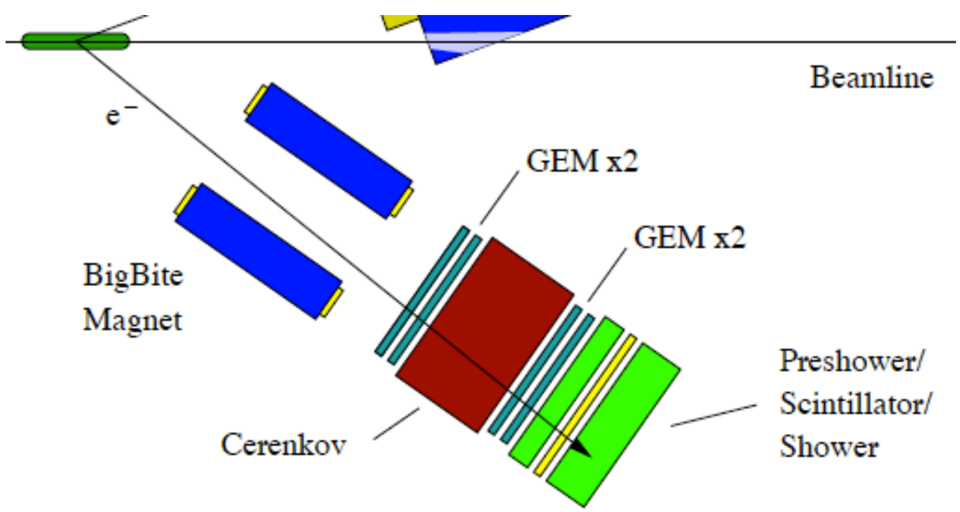




- **PRELIMINARY** results of Hall A E06-010 (transversity) for ^{3}He (left) and neutron (right)
- Neutron results are based on the method of the effective polarization in ^{3}He and the measured yield ratio of hydrogen to ^{3}He, combined with a Monte Carlo simulation
- At the level of precision of the data, the asymmetries are compatible with zero and/or naive expectation (curve) based on global analysis of HERMES p and COMPASS d data; (perhaps slightly smaller than expected for the π^+ Sivers, but the theoretical uncertainties are quite large.)
- **Clearly, it is imperative to increase the precision of the neutron data!**

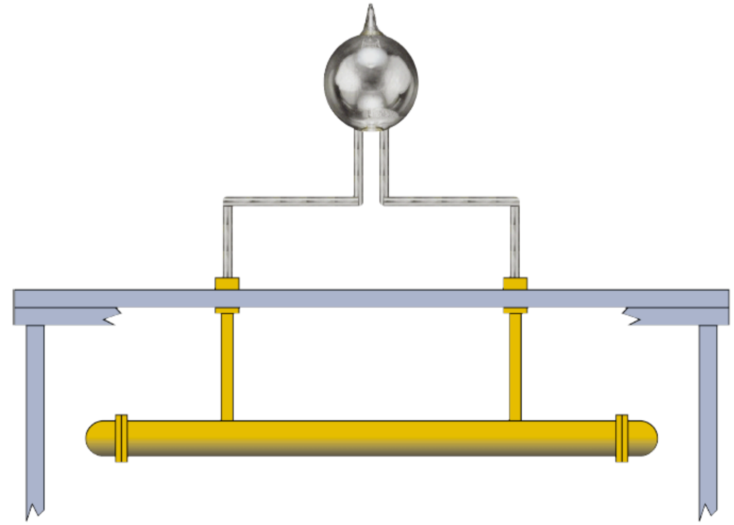


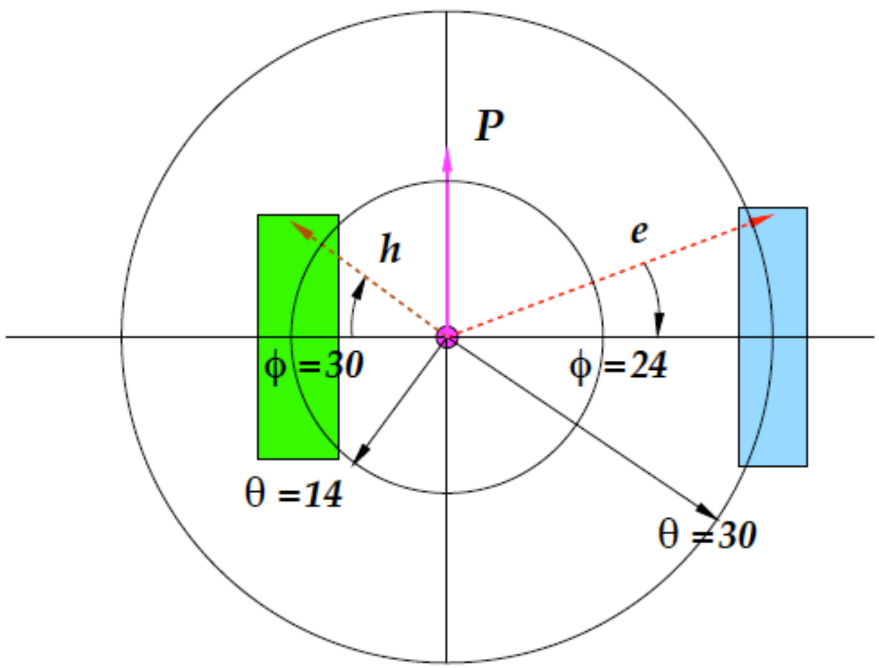




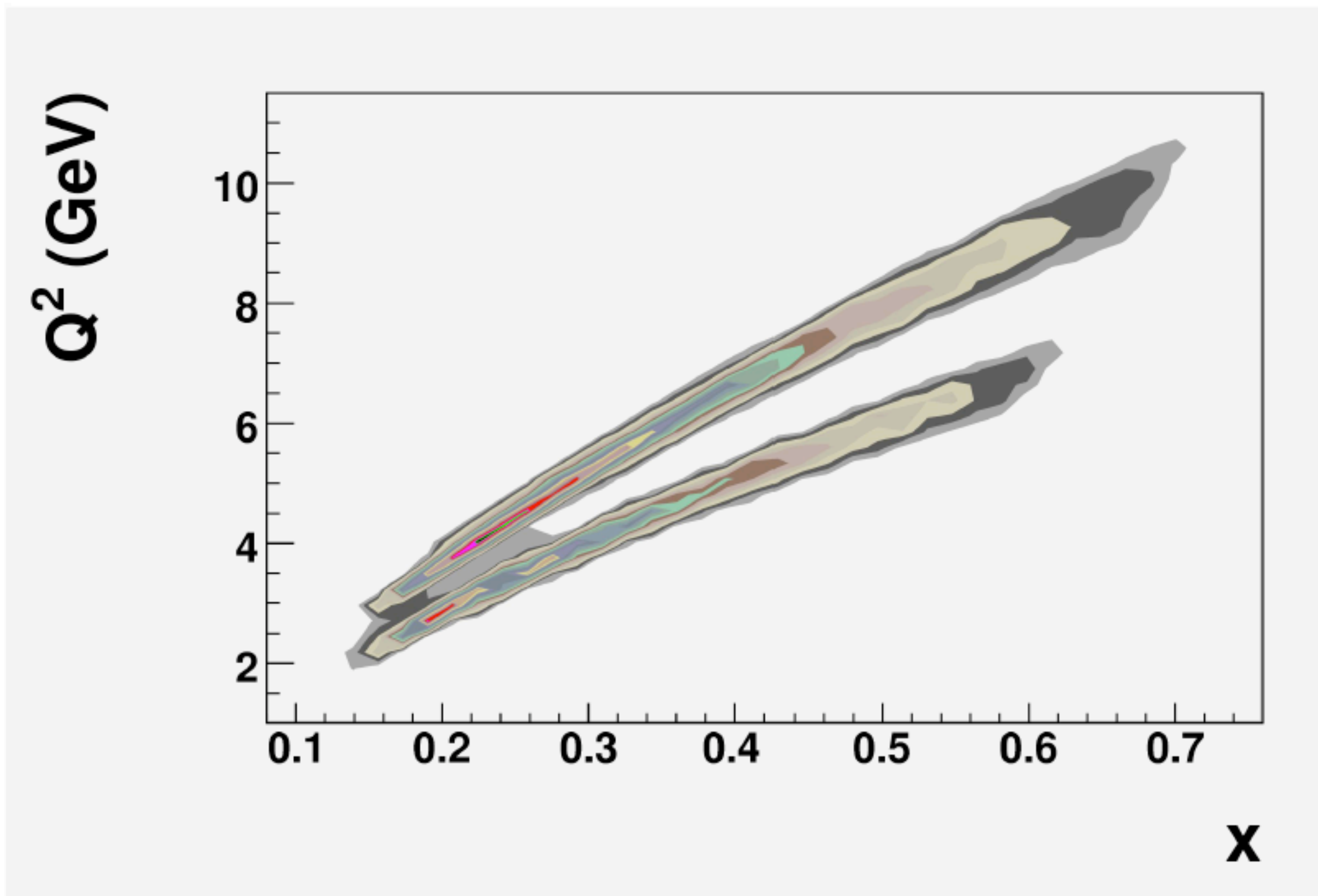
- Experimental Setup:
  - e arm: BigBite at 30° at a distance of 155 cm
  - h arm: SBS at 14° at a distance of 245 cm
- BigBite detector upgrades: similar to GEn-II
  - GEM trackers replace MWDCs, increase rate capability and resolution
  - Gas Cherenkov: provide online and offline pion rejection
  - Preshower/shower: trigger and offline pion rejection
- SBS detector:
  - GEMs: tracking before RICH; also after (not shown)
  - HCAL: trigger
  - RICH: hadron ID

- GEn-II high-luminosity polarized ^{3}He target:
  - Convection-driven flow allows operation at higher luminosity; faster replacement of target chamber gas depolarized by beam with gas polarized in pumping chamber
  - Allows greater physical separation between target and pumping chambers;
  - Metal target cell in evacuated scattering chamber
- **With all improvements, expected electron-neutron luminosity is $4{\times}10^{36}$ cm^{-2}s^{-1}**

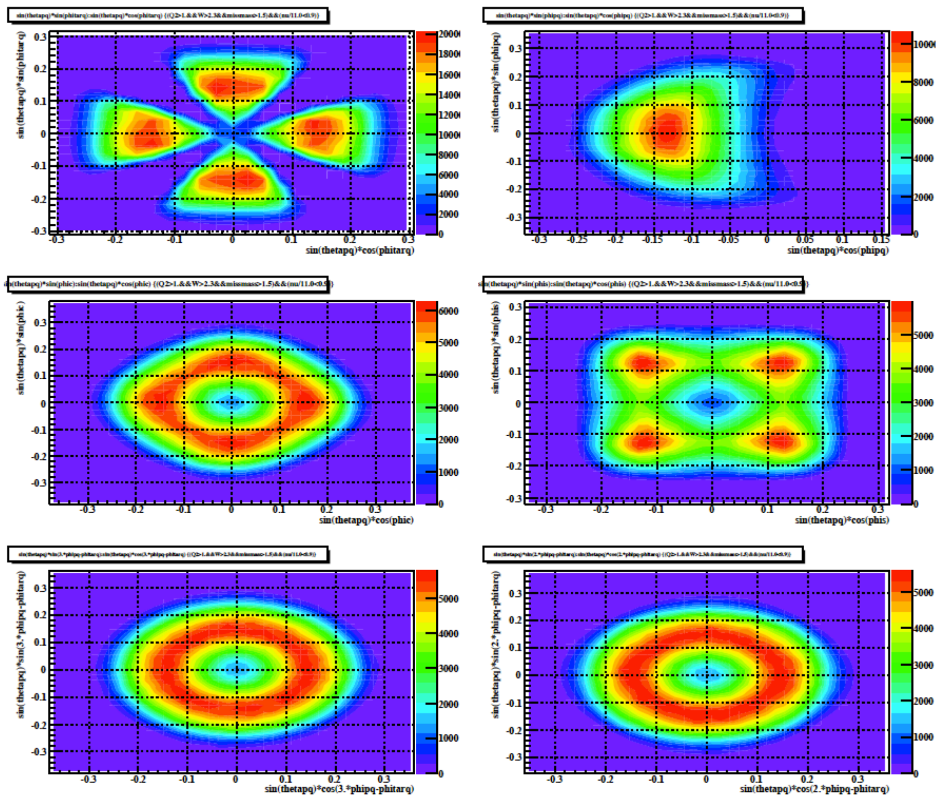




- Schematic angular acceptance of our setup
- Large out-of-plane angle acceptance (±24° for BigBite and ±30° for SBS) leads to relatively large azimuthal coverage for ϕ_h: approximately 1/3rd of 2π, roughly independent of kinematics
- Target spin can be oriented in virtually any direction; with 4 (or 8) spin orientations, cover very close to full 2π azimuthal acceptance in all relevant ϕ_S-dependent angles

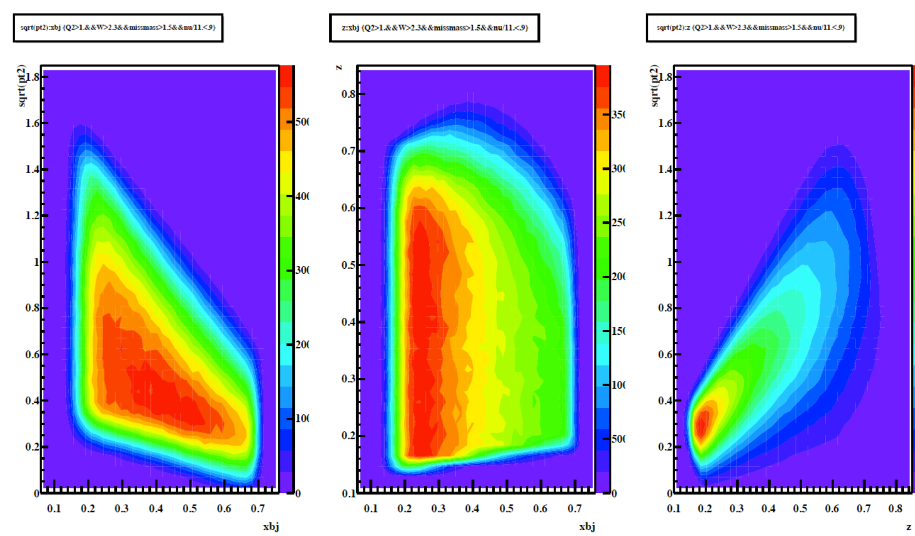


Q^2 vs x coverage, E=11 GeV (upper stripe) and E=8.8 GeV (lower stripe)

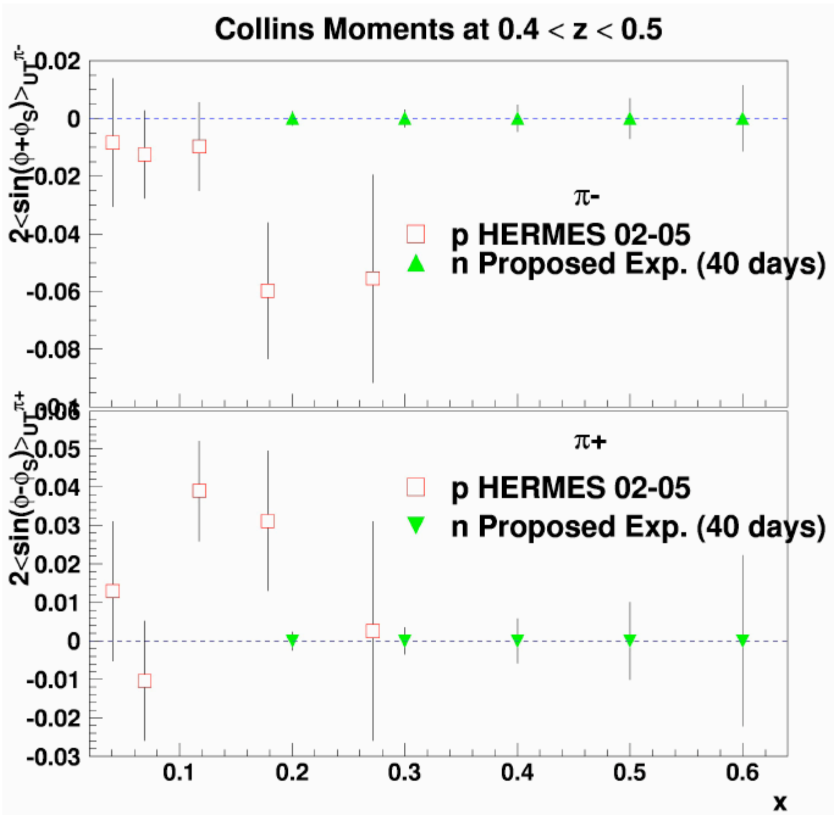


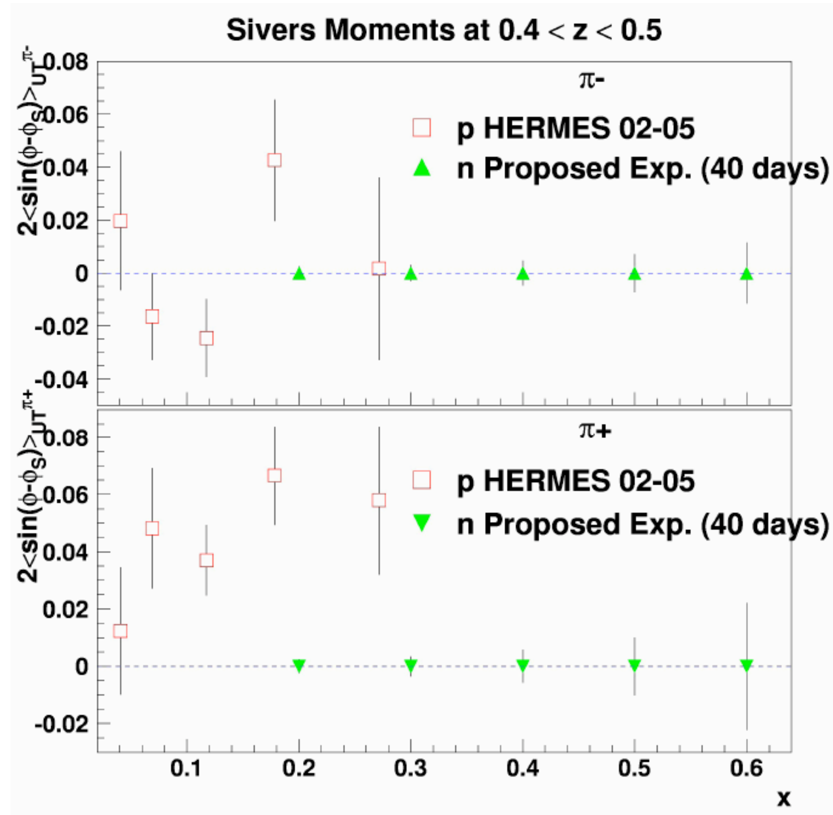
- Azimuthal phase space coverage with four (up, down, left, right) target spin directions, 11 GeV beam (8 directions even better):
- Top left: ϕ_S
- Top right: ϕ_h
- Mid left: $\phi_h+\phi_S$ (Collins)
- Mid right: $\phi_h-\phi_S$ (Sivers)
- Bottom left: $3\phi_h-\phi_S$ (Pretzelosity)
- Bottom right: $2\phi_h-\phi_S$ (Higher-twist)

- Kinematics coverage, E=11 GeV
- Left: p_T vs. x
- Mid: z vs. x
- Right: p_T vs. z



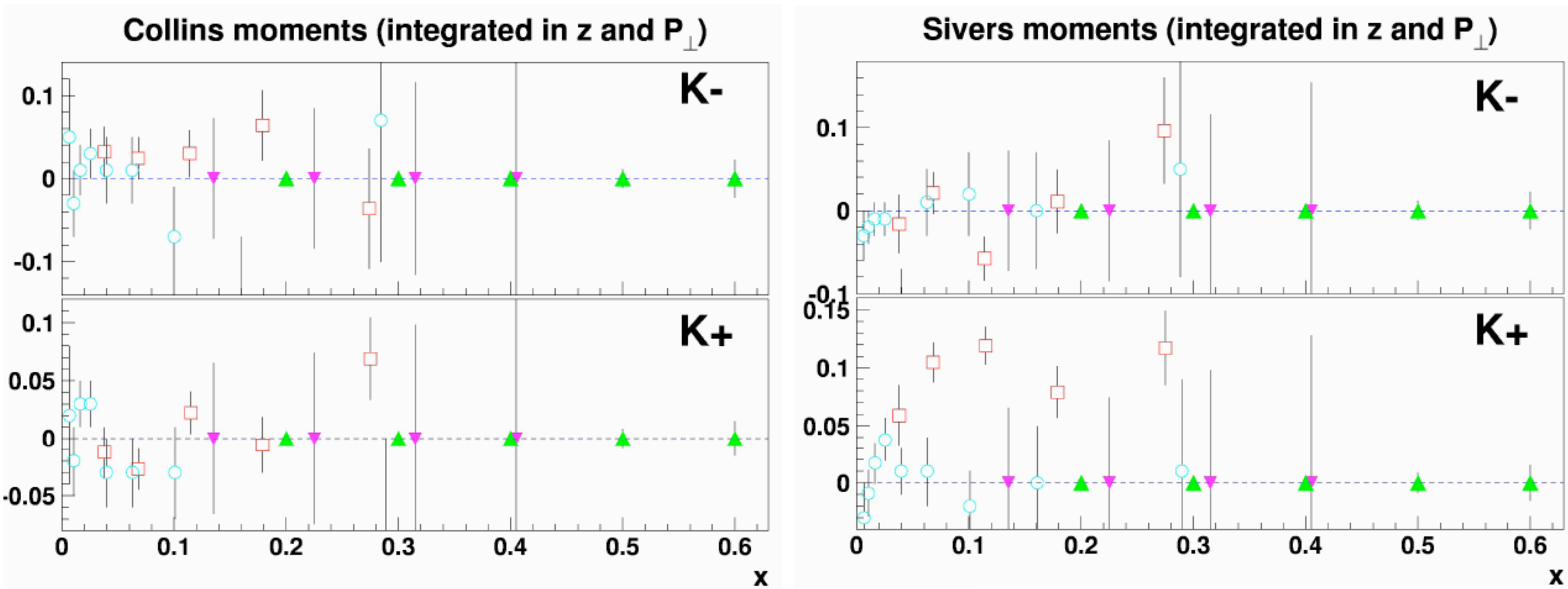
Projected Statistical Precision, pions

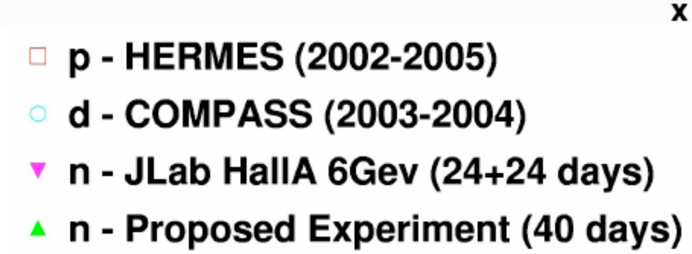




- High x region, overlapping with HERMES
- At least 2D binning in (x,z,p_T), with Q^2 dependence from two beam energies

Projected Statistical Precision, kaons





- Highest-quality kaon data

Other Experiments Using SBS RICH

- SIDIS-transversity using p+d targets?
  - Unlike high-lumi ^{3}He case, CLAS12 could be competitive with SBS+BB because target limits luminosity; OTOH, transverse polarized target could be much more challenging in CLAS12 case.
- SIDIS physics beyond transversity
  - SIDIS A_1^h measurements on ^{3}He (also; flavor decomposition of polarized PDFs
  - Precise unpolarized SIDIS measurements on ^{3}He/^{3}H; look to constrain partonic charge symmetry violation
  - ...?

Performance of the HERMES RICH

• Average number of PMTs fired per aerogel ring for β➔1 particles suffering no acceptance effects is ~10.

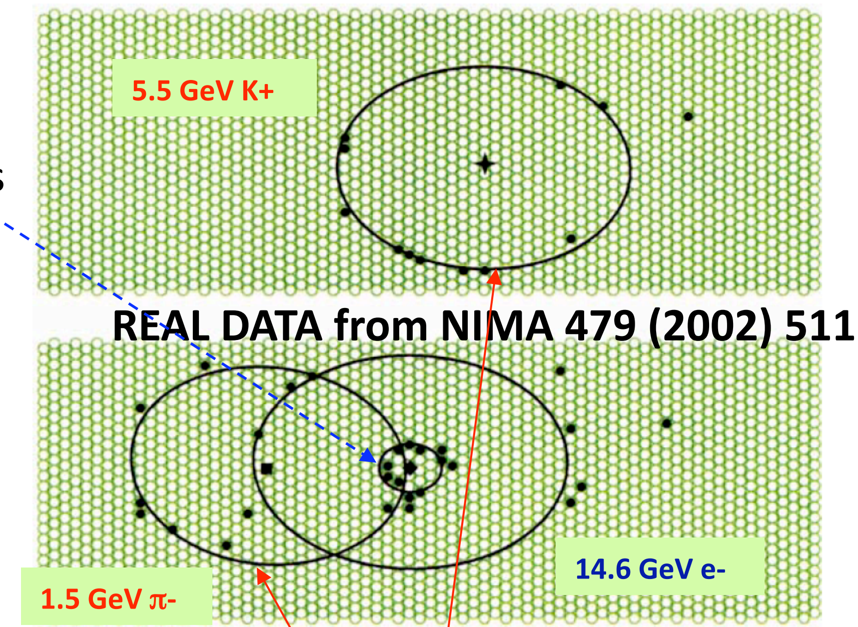
• Number of Cherenkov photons emitted per unit path length in aerogel is:

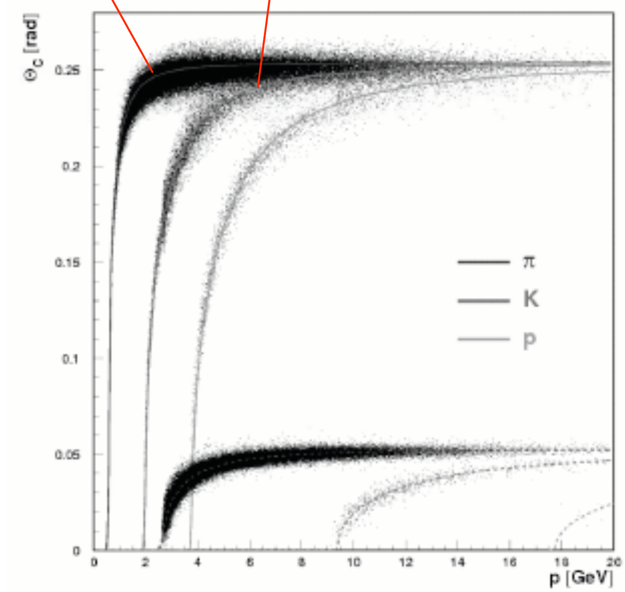
$$\frac{d^2N}{dx\,d\lambda} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right)$$

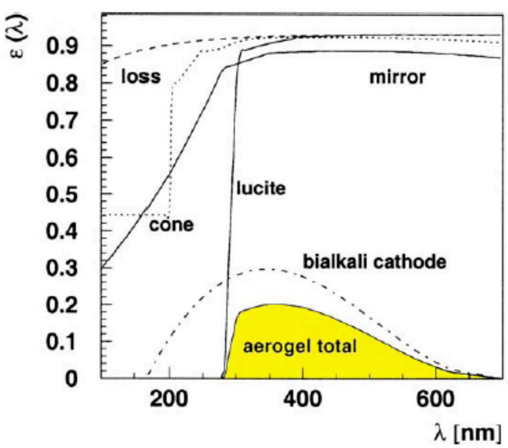
• Assume constant n, integrate from ~250 to 700 nm, then in 5.65 cm aerogel, total number of emitted photons for β=1 is approximately 193

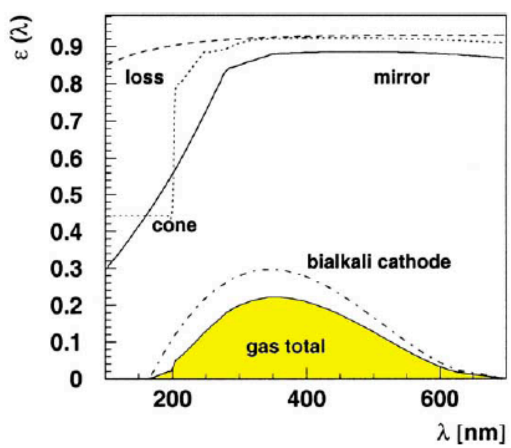
• Compare contributions to efficiency below; not including PMT packing fraction, ~60% (full PMT area) or 38% (active photocathode area)

C4F10 gas

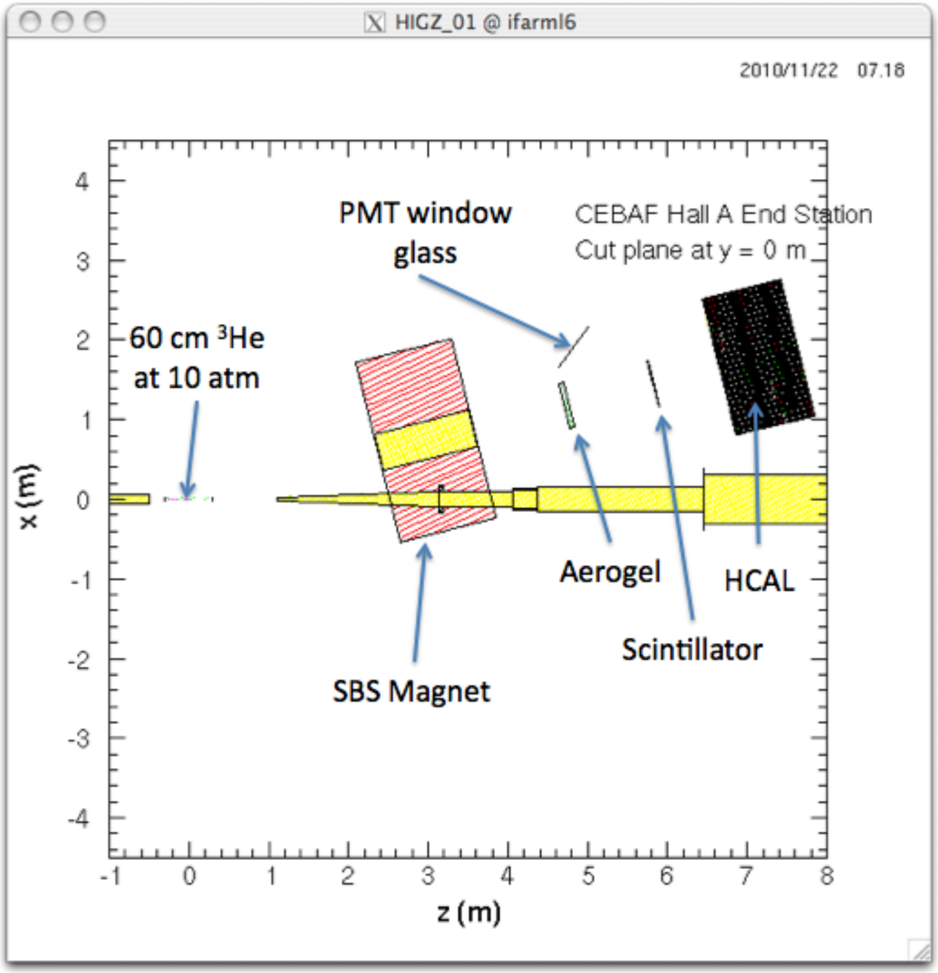


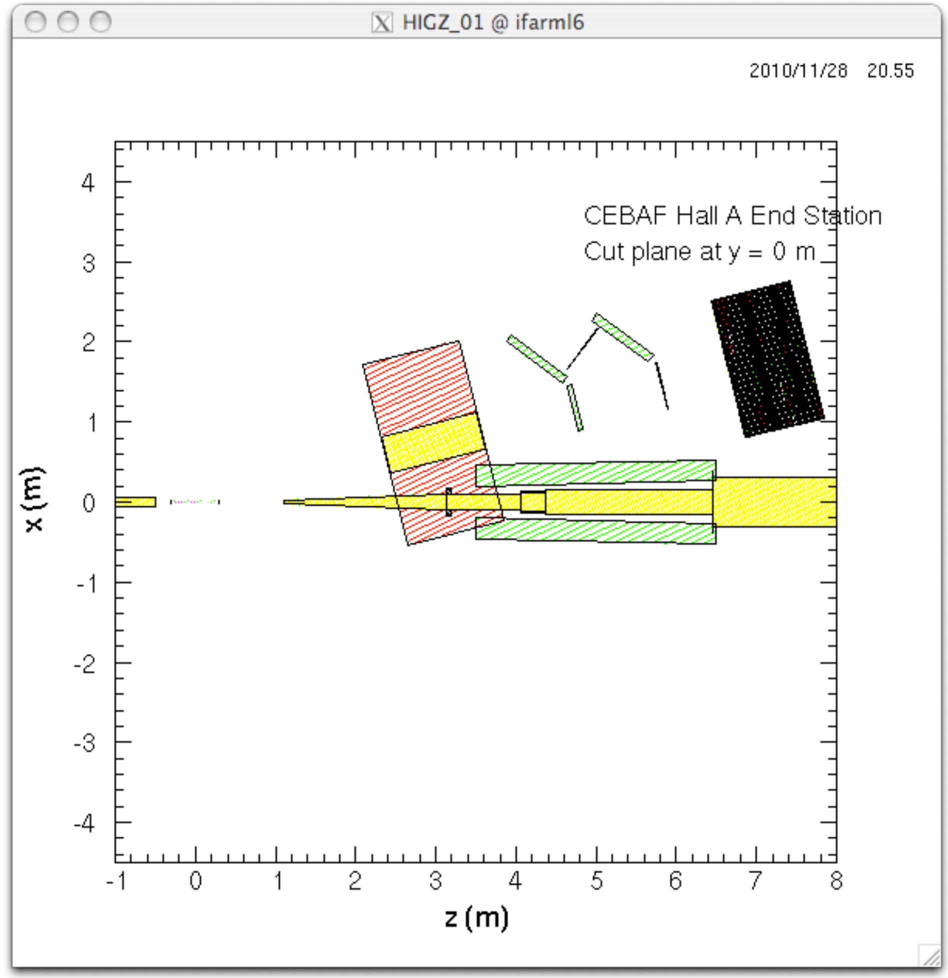






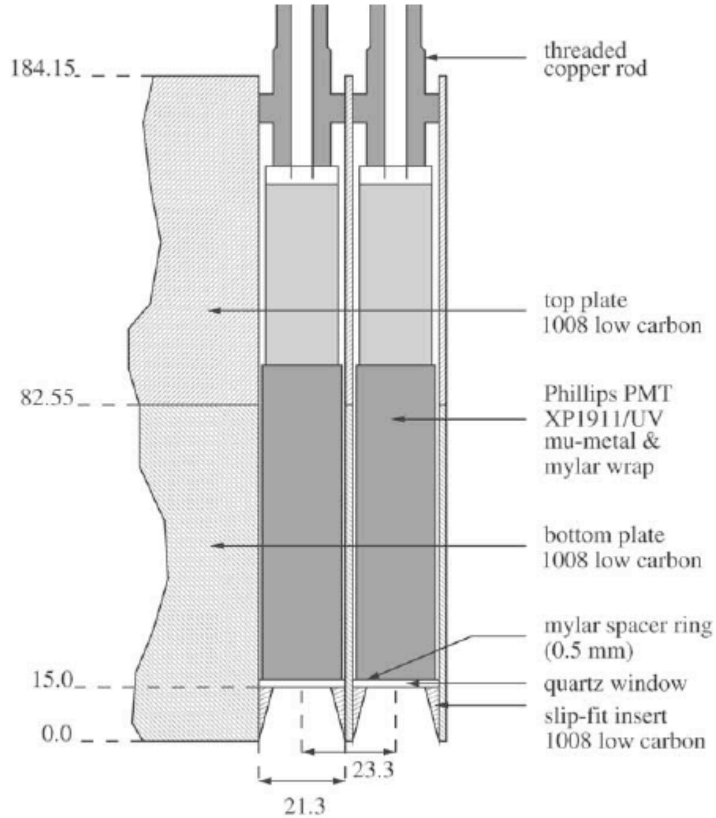
GEANT Simulation of SBS RICH Background Counting Rates





- MCWORKS: GEANT3.21-based framework for JLab rad. budget and background simulations (P. Degtiarenko), widely used throughout JLab.
- Left: SBS layout in GEANT with target, magnet, RICH aerogel, PMT window glass + Quartz window, and HCAL
- Right: Same layout with added lead shielding of the beamline and detectors

General Considerations:

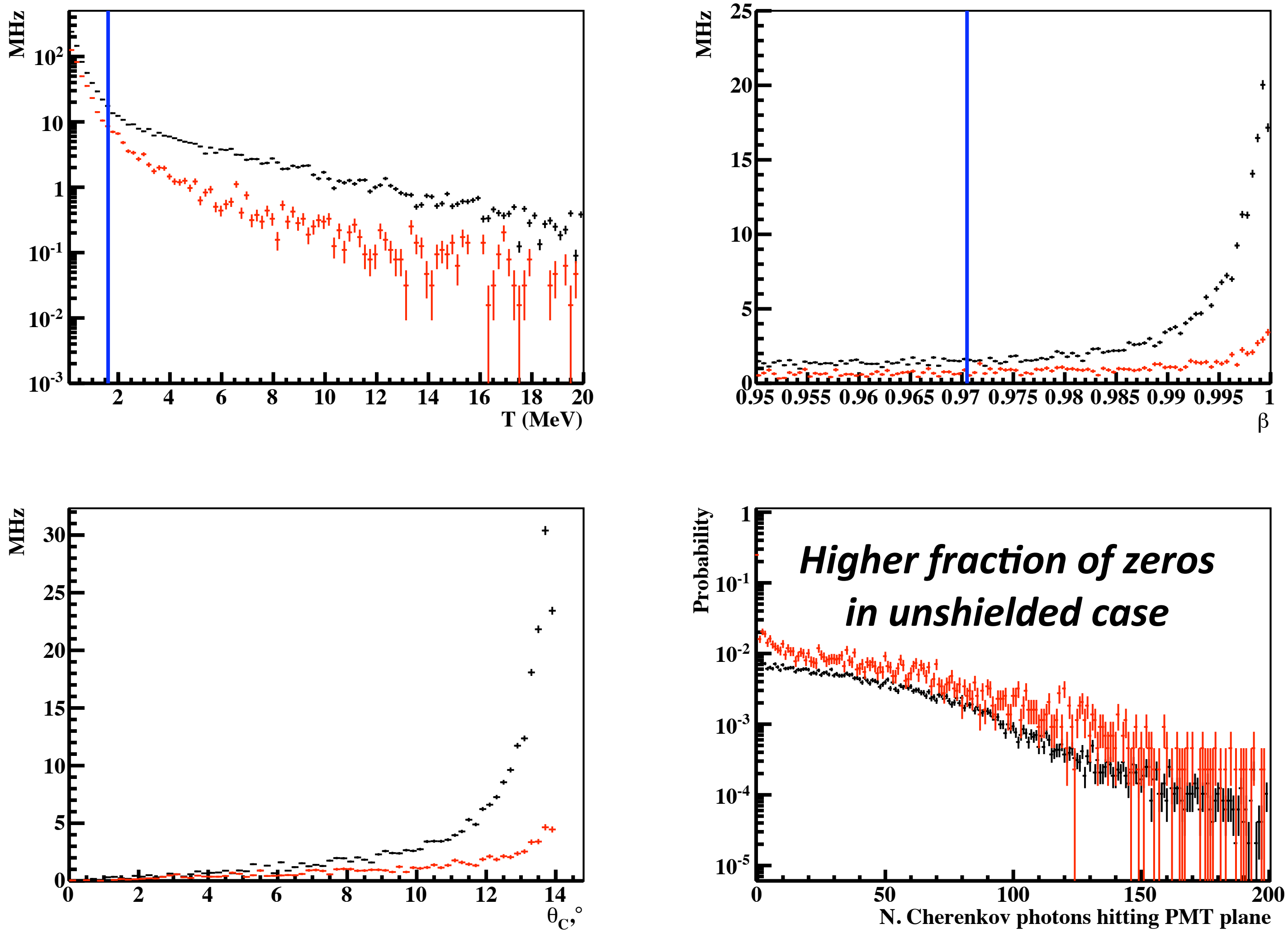


- Closeup section of PMT matrix:
- Soft-steel, close-packed hexagonal matrix
- Quartz window ~2 mm thick provides gas seal for individual PMT cavities
- PMT window 3 mm thick borosilicate UV-enhanced glass

- SBS magnet shields detectors from low-energy charged particles
- Because detectors are in direct view of the target, neutral background (photon) interactions in detectors can cause problems
- Thickest detector material in direct view of target = aerogel ~.8 g/cm^2
- Cherenkov threshold for electrons in aerogel is about 2.1 MeV total, 1.5 MeV kinetic
- Soft photon backgrounds produce secondary electrons in aerogel through Compton scattering+pair production
- Low Cherenkov threshold = high rate
- Also direct interation in PMT window glass and quartz window (not in direct view of the target, but much higher n (~1.5) than aerogel = lower Cherenkov threshold)

Overall Strategy of Monte Carlo

- Trigger a large number of beam electrons;
  - All e+/e-/gamma above .15 MeV (threshold in window glass) traced
  - Since all particles are traced down to a very low cutoff energy, simulation is slow, inefficient
  - Large statistics not needed for basic rate estimate.
- Record all electrons and positrons produced in or entering aerogel, glass/quartz, storing full energy, coordinate and track information
- For aerogel case, need secondary analysis to estimate Cherenkov yield.
- For glass/quartz case, any electron entering or produced in the glass will fire the PMT with a large average probability (39% based on bench tests with a PMT and radioactive source).
- Results on following slides



- GEANT primary and secondary e+/e- in aerogel (with/**without lead shielding**):
  - Top left(right): Kinetic energy(beta=v/c); ***blue line = Cherenkov threshold***
  - Bottom left = Cherenkov angle
  - Bottom right = distribution of number of photons hitting PMT plane

Calculation of the Photon Yield

$$\frac{d^2N}{dx d\lambda} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right)$$

Assume constant n:

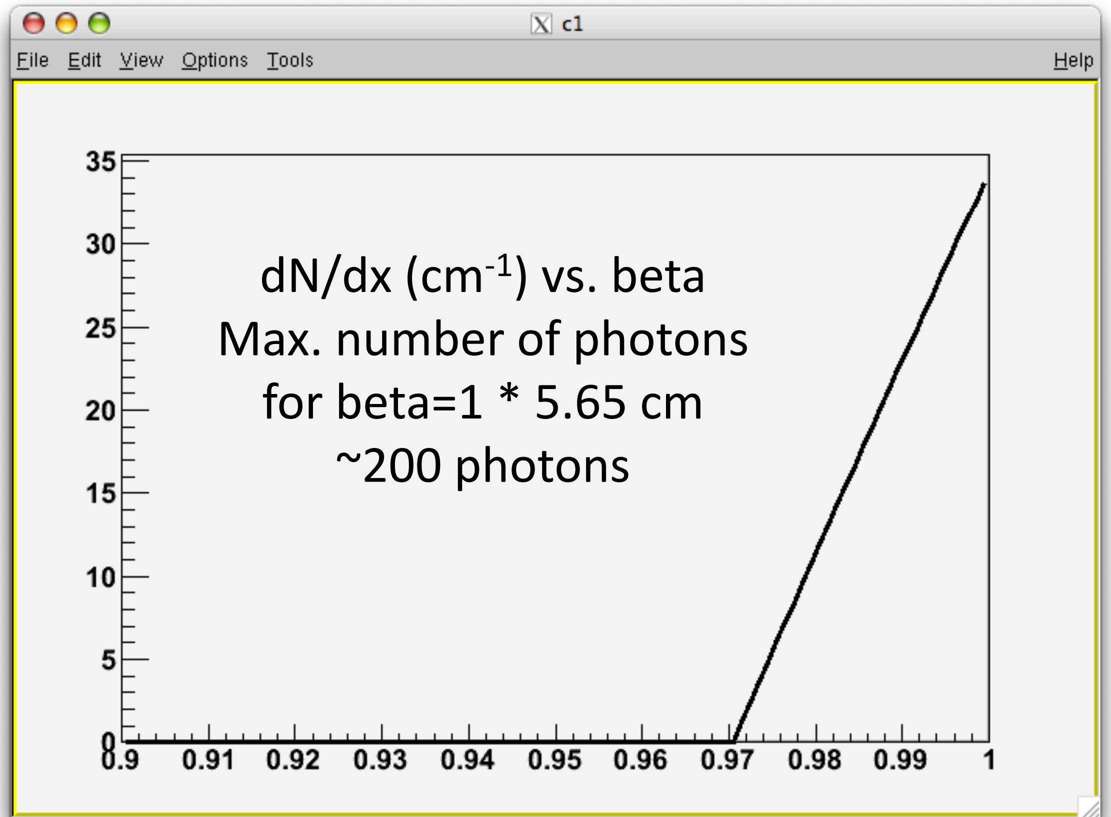
$$\frac{dN}{dx} = \pi\alpha\frac{\lambda_2 - \lambda_1}{\lambda_2\lambda_1}\left(1 - \frac{1}{\beta^2 n^2}\right)$$

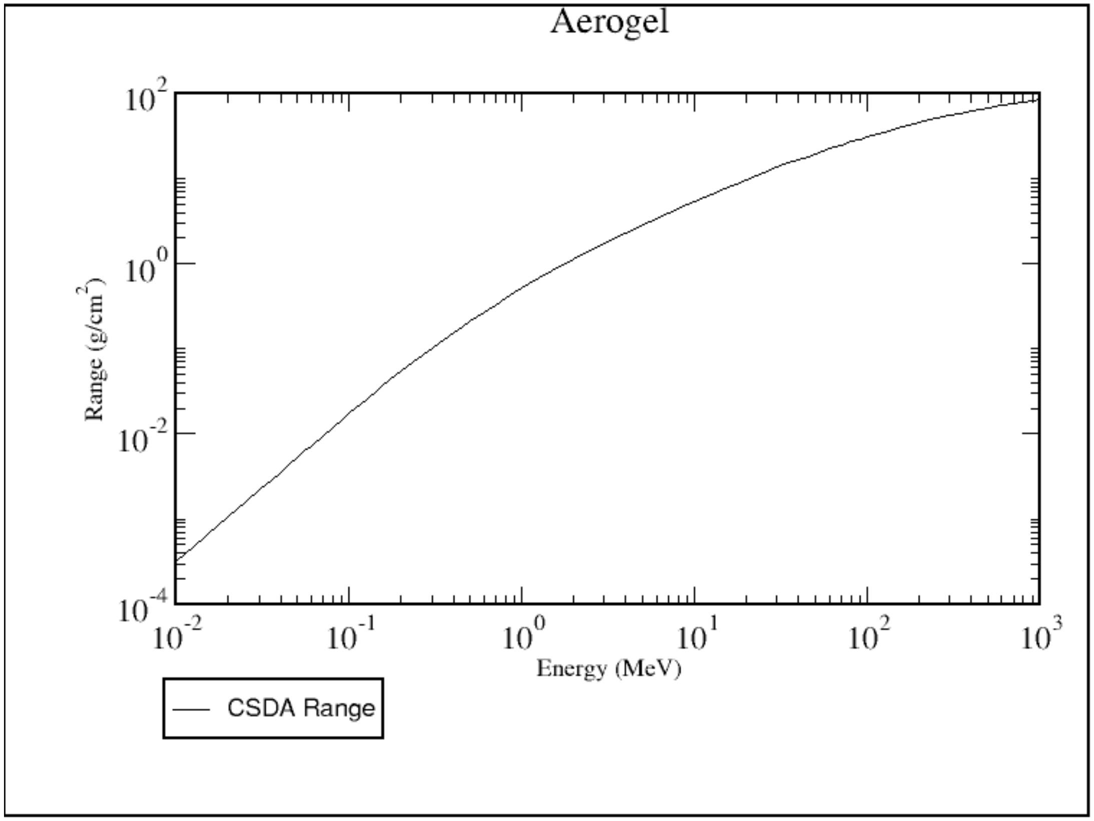
λ_1=250 nm

λ_2=700 nm

(Sensitive range of PMT)

Need to know path length of electrons in aerogel!



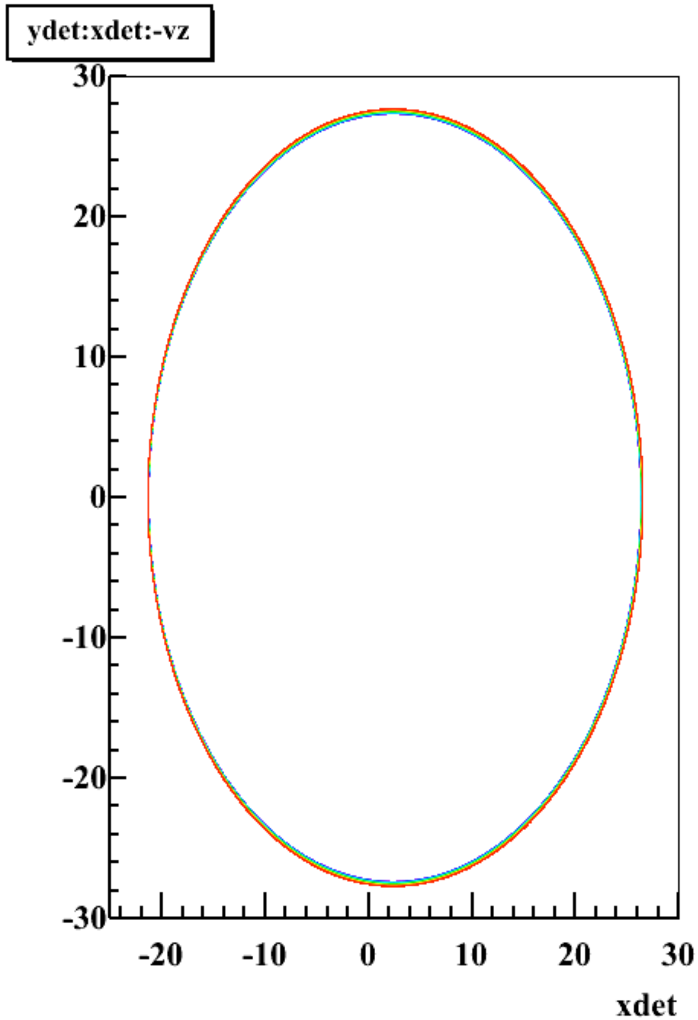


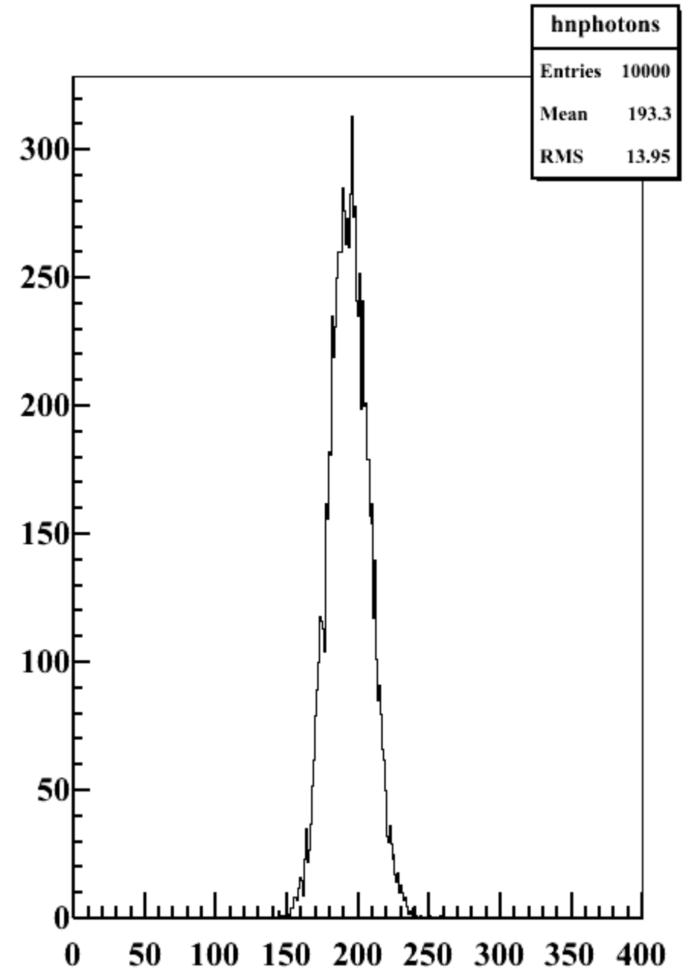
Between 1.5 MeV and 10 MeV kinetic energy, electron range in aerogel varies from ~.8 grams to about 6 grams (aerogel wall is about .8 grams)

- Most electrons produced in aerogel above threshold are at low energy (few MeV)
- Path length in grams assuming constant velocity is comparable to total range.
- Approximation: take the lesser of range *R* and distance *d* to aerogel boundary along electron trajectory as pathlength: ***path = min(d,R)***
- Since electrons are losing energy continuously, we ***overestimate*** the photon yield by assuming a constant velocity **(upper limit = GOOD from the point of view of our background estimates)**

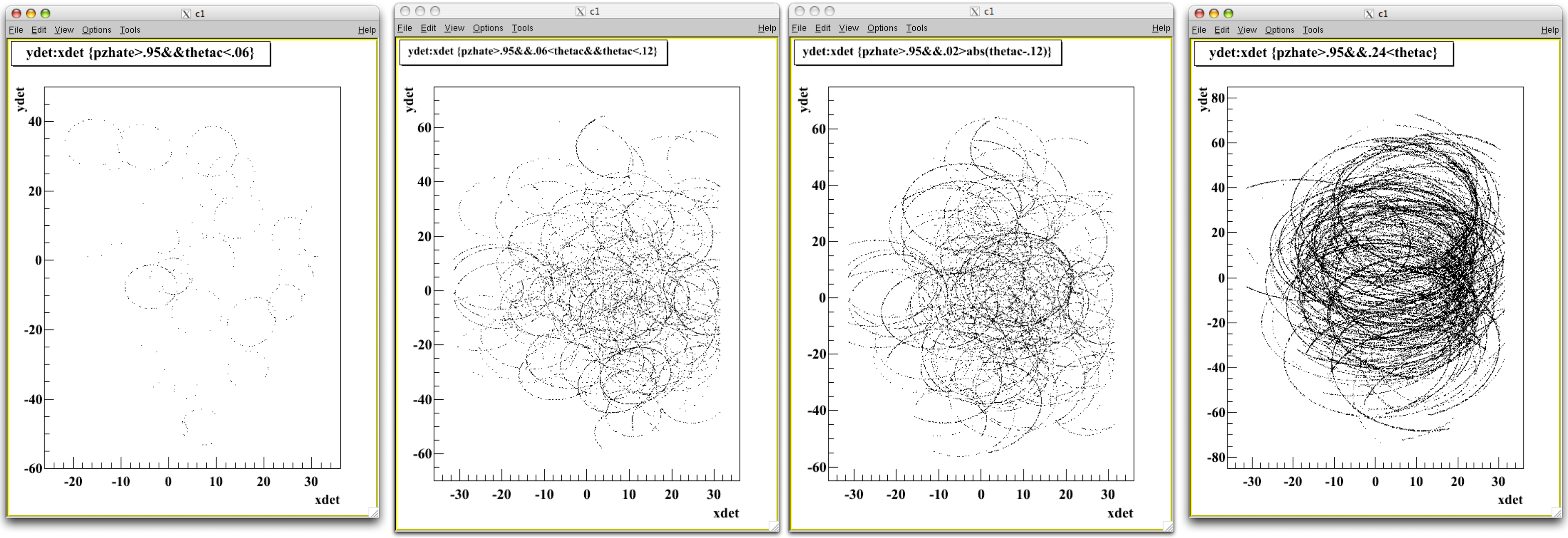
Raytracing/light collection

- Equipped with the spectrum of electrons in aerogel, do secondary Monte Carlo of Cherenkov photons for each electron in the following steps:
  1. Sample number of emitted photons from a Poisson distribution about the average calculated using standard formula
  2. Sample emission vertex randomly along electron track in aerogel
  3. Sample azimuthal emission angle randomly in 2π
  4. Calculate polar angle from beta
  5. Project photon tracks to mirror
  6. Calculate reflected photon tracks
  7. Project reflected tracks to detector plane
  8. Check whether photon hits active area





- Validation of raytracing Monte Carlo:
  - Left: ring pattern of position at the PMT plane of photons emitted by 100 GeV muons moving along the central axis of the aerogel ("rainbow" color scale correlates with position of emission vertex)
  - Right: spectrum of number of emitted photons for said 100 GeV muons; average ~193



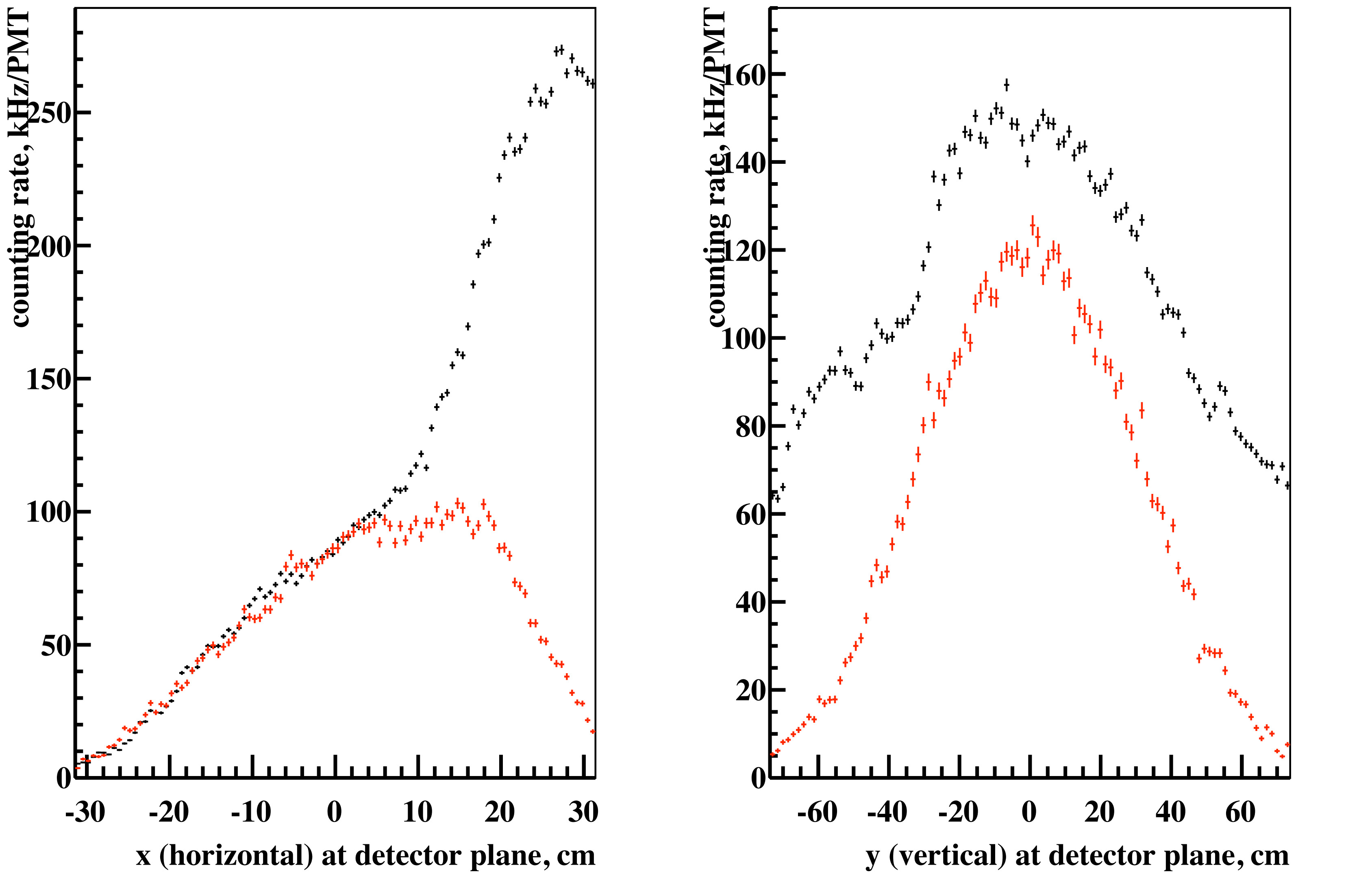
- Ring images for background photons with different cuts on β, in order of increasing β from left to right in raytracing Monte Carlo:
- Confirms expectations:
  - low β = small rings, low number of photons,
  - high β = large rings, many photons
- In these plots, we only show the position of photons hitting the PMT plane
- We need to normalize results for detection efficiency/packing fraction!

$$\pi R^2 = 2.85 \text{ cm}^2$$

- Packing fraction = ratio of $N_{PMT} * A_{PMT}$ / total detector plane area = 60%
- 60% number is for total window area
- For active photocathode area, packing fraction is only ~38%
- PMT aluminized plastic funnels increase light collection efficiency, reduce dead area.
- For overall normalization, we used 60% for packing fraction;
- **Since packing fraction enters both the overall normalization and the collection efficiency, choice does not affect results!!!!**

Beamline+detector Pb shielding?	No	Yes
Total rate of $n\beta > 1$ electrons in aerogel (MHz)	244	73
Area of PMT (cm^2)	2.85	2.85
Total detector area (cm^2)	9257	9257
Number of PMTs	1934	1934
Packing fraction (%)	60	60
Monte Carlo $N_{Cherenkov}$ ($\beta = 1$)	115	115
HERMES $N^{aerogel}_{PMThit}(\beta = 1)$	10	10
Normalization factor	0.087	0.087
$< dN/dt >_{background}$, Aerogel (kHz/PMT)	111	65
$< dN/dt >_{background}$, Glass+Quartz (kHz/PMT)	28	17
Average total rate (kHz/PMT)	139	82
Average PMT occupancy ($\Delta t = 10$ ns) (%)	0.139	0.082

- Overall normalization by comparing actual performance of HERMES RICH = 10 PMTs fired per high-energy aerogel ring
- 193*60% = 115 emitted photons
- 10 PMTs/115 photons = 8.7% total collection and detection efficiency (compare plots on slide 21, which do not include acceptance/packing fraction effects)
- **Rate of PMT hits due to background = Rate of photons hitting PMT plane from raytracing Monte Carlo * packing fraction * overall efficiency**
- ***Average occupancy per PMT at the 10^{-3} level for 10 ns window (TDC readout correlated with HCAL timing)!***



Distribution of background counting rate at the detector plane, ***Pb SHIELDING/No SHIELDING***

Shielding reduces average rate by ~2, but concentrated on one side of detector

Remaining background mostly from target

Summary/Conclusions

- Realistic, GEANT3-based simulations of background counting rate in SBS RICH look very good; 10^{-3} occupancy would result in high S/N ratio under experimental conditions
- Worst case: β=1 aerogel rings; 100 PMTs on expected rings from tracks, 10 signal hits, 0.1 noise hits (on average); S/N = 100:1
- For π/K in 2-7 GeV momentum range, β<1, smaller rings, even cleaner!
- Highly encouraging for planned SIDIS experiments!