

Monte Carlo Simulation of the SBS RICH Detector

Andrew Puckett

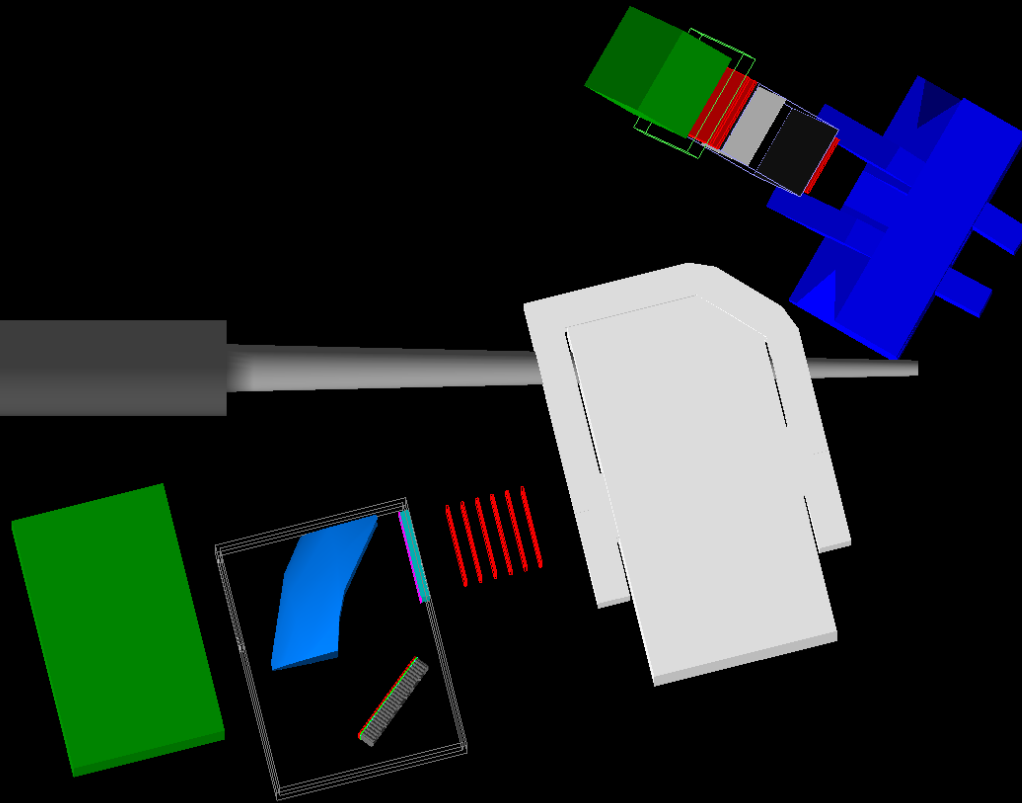
UConn

SBS Weekly Meeting, 5/21/2014

Outline

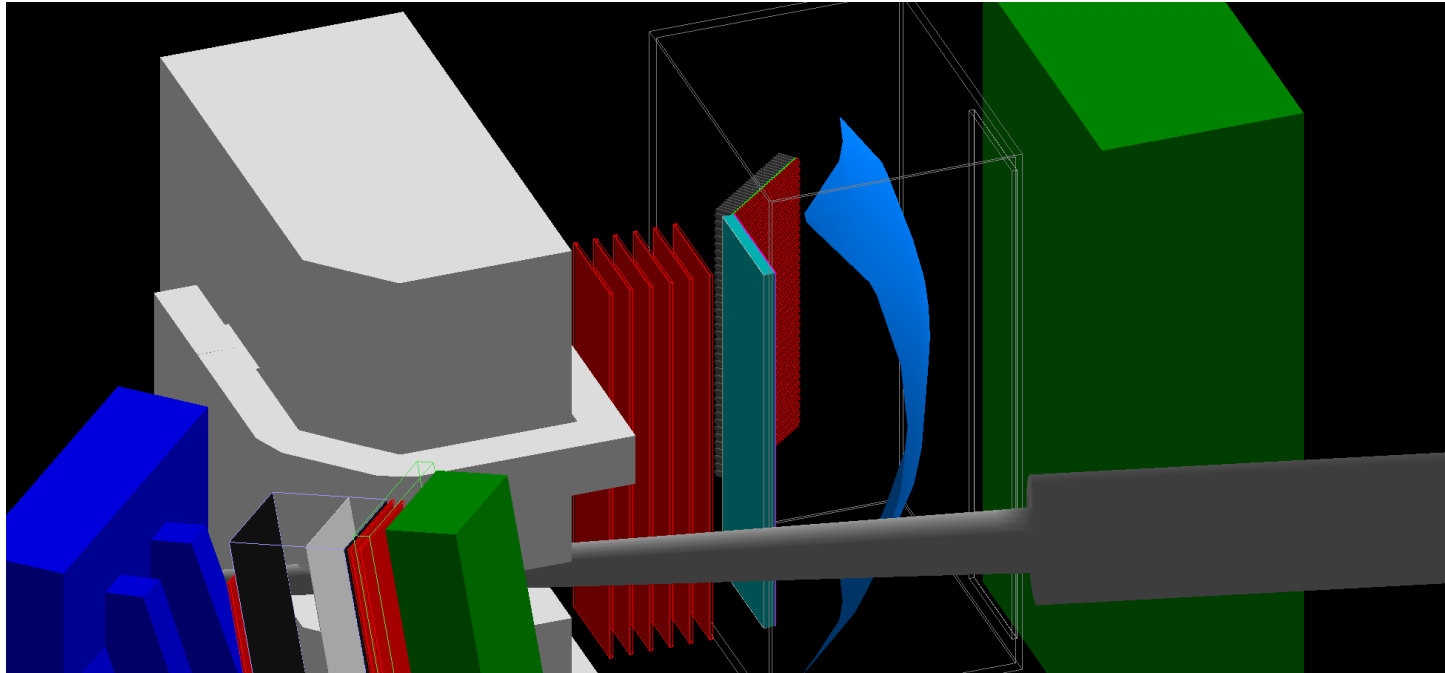
- Layout of SBS SIDIS experiment in GEANT4
- Details of RICH geometry in GEANT4
 - Geometry
 - Optical properties
 - Physics processes
- SBS and BigBite optics and resolution studies
 - Fitting of reconstruction matrix elements
- Simulations of RICH PID performance
 - Reconstruction of Cherenkov emission angles—inverse ray tracing
 - PID assignment—IRT “likelihood” calculation and PID performance
- New Simulations of RICH Background Rates
 - Results
 - Comparison to old GEANT3 work

Layout of E12-09-018 in GEANT4



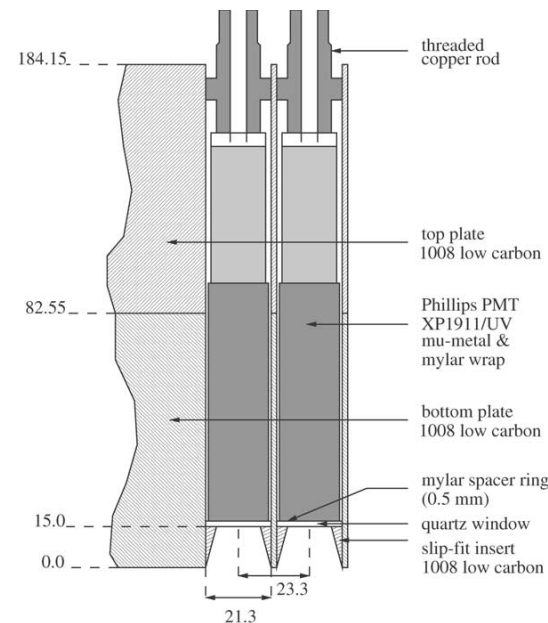
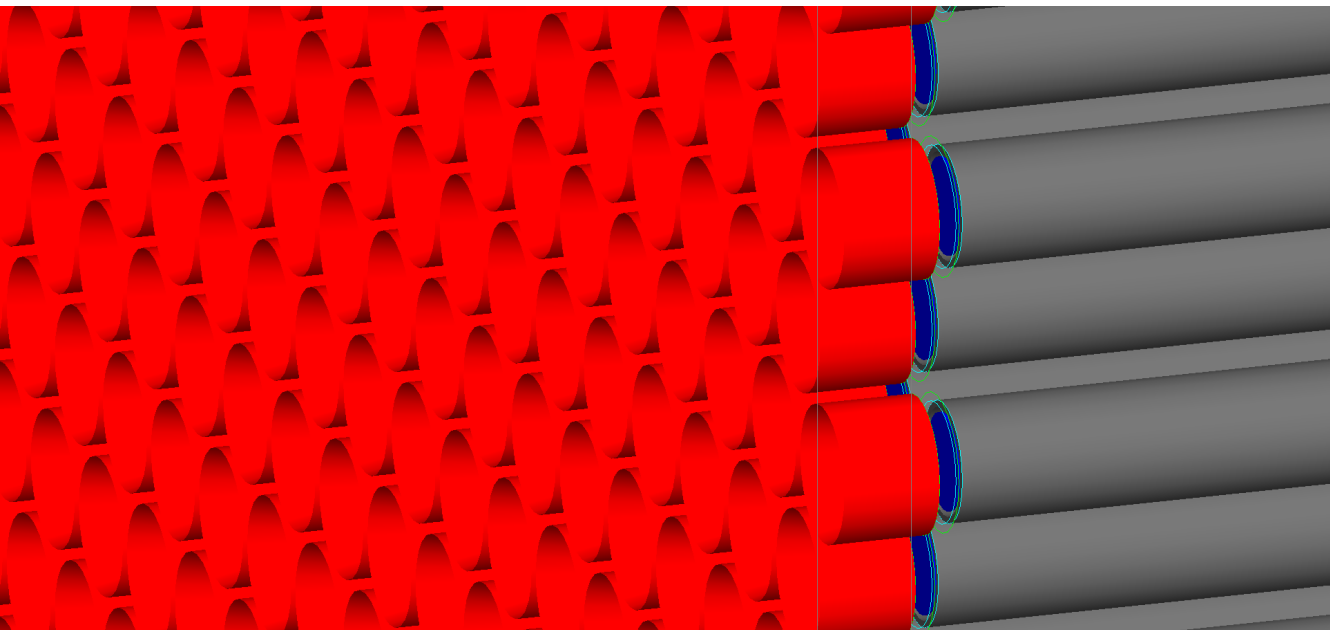
- BigBite at 30 degrees on beam right—detector package includes four-plane GEM tracker, calorimeter, Cherenkov gas volume; some details still missing (GRINCH, calorimeters, hodoscopes)
- SBS at 14 degrees beam left—detector package includes six GEM planes (50 x 200 cm²), RICH and HCAL; details of HCAL missing.
- Field clamps and beamline lead shielding missing from SIDIS model.
- Helium-3 target cell: 60 cm, 10.5 atm, all glass for now

Details of RICH geometry in GEANT4



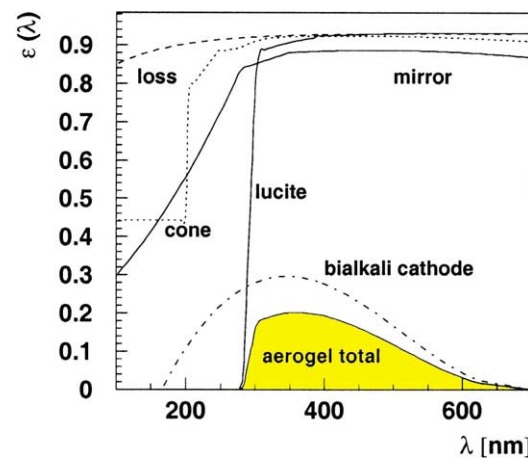
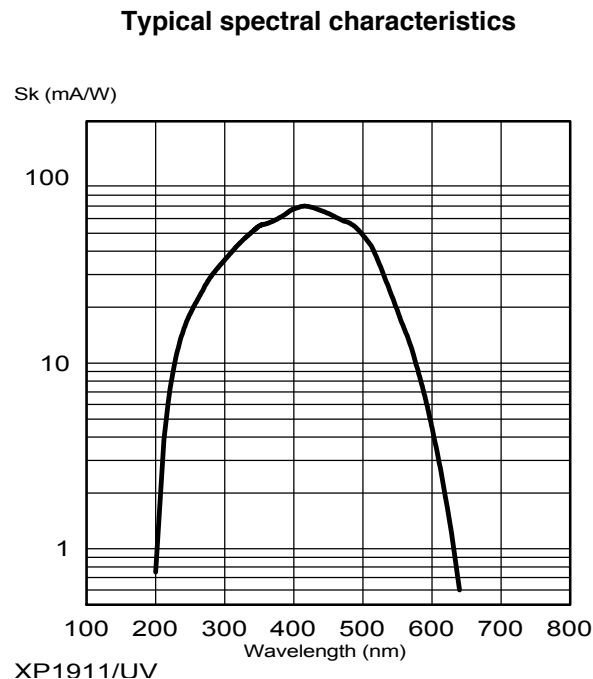
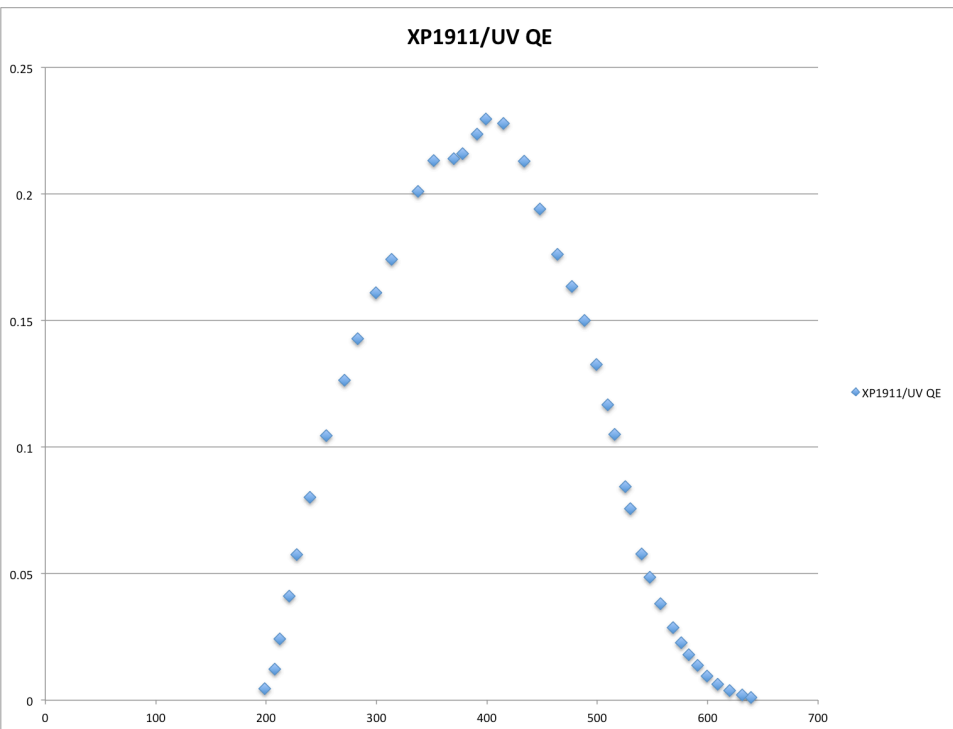
- Simplified geometry of containment volume: 1"-thick aluminum rectangular box with cutouts for entry and exit windows of 1 mm-thick aluminum—filled with C_4F_{10} , $n = 1.00137$
- Aerogel wall—5 (W) x 17 (H) x 5 (D) tiles with average dimensions of HERMES tiles
 - Separated by 1-mil thick “Tedlar” spacers (absorb photons crossing stack boundaries)
- 3.2 mm-thick UVT-lucite window between aerogel and C_4F_{10} —absorbs Rayleigh-scattered UV photons produced in aerogel—Cherenkov photons emitted in lucite trapped by total internal reflection
- Spherical mirror—geometry approximated by a spherical shell of carbon with uniform thickness equal to average thickness of carbon-fiber composite used in actual HERMES RICH mirrors
- PMT matrix—more details next slide

Details of RICH geometry in GEANT4—PMTs



- PMTs are Philips XP1911UV, with 19 mm diameter, (15 mm active photocathode diameter)
- Bi-alkali photocathode w/UV glass window (PMT window assumed 1 mm-thick, but this is a guess—note too important for simulation purposes).
- Cathode diameter 15 mm, defines sensitive volume for GEANT4 hits/output
- Additional quartz window provides seal between PMT and C_4F_{10} environment (3 mm thick, from HERMES RICH CAD drawings)
- Light collection cone: “Steel” covered with aluminized plastic foil—increase light collection efficiency/packing fraction from ~38% of PMT matrix area to ~60%
- “Steel” tube—19 mm-diameter, 87 mm length, 2 mm wall thickness—defines PMT body: only purpose in the MC is to block “stray” light from reaching PMT photocathode and approximate surrounding shielding materials without a full description of the steel plate that holds the PMT matrix

RICH Optical Properties—PMT Quantum Efficiency

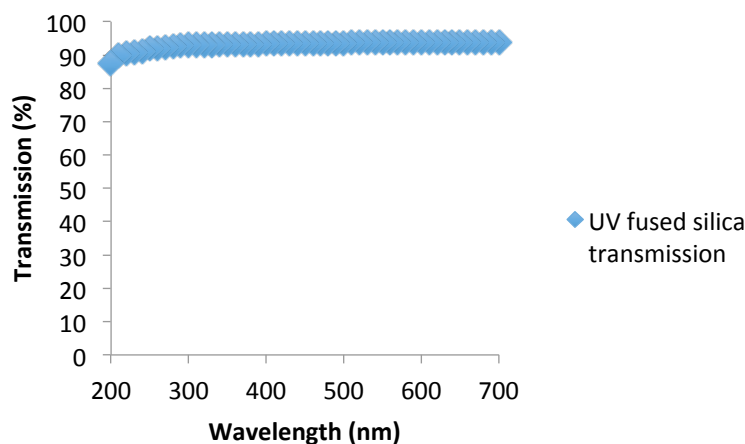


- Top right: spectral sensitivity of XP1911UV in mA/W vs. wavelength, from XP1911UV data sheet
- Top left: converted to quantum efficiency—this curve used in GEANT4 for detection probability
- Bottom right: QE curve from HERMES RICH NIM paper shows slightly higher QE peaking at slightly lower wavelength.
- If HERMES curve is correct, our simulation will slightly underestimate signal strength

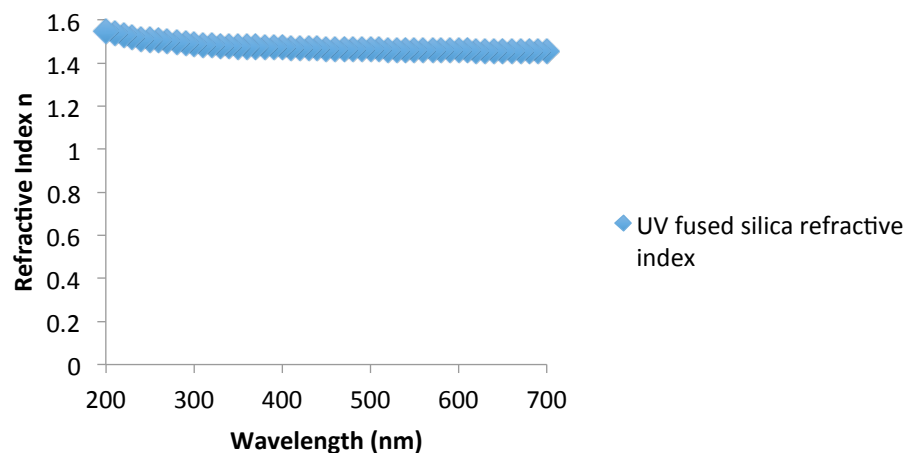
RICH optical properties—PMT windows

- Presently, refractive index and transparency of UV glass and quartz windows are assumed identical to those of fused silica.
- For now, the 0.5 mm gap between PMT window and quartz window is not included in the simulation (not including this gap means neglecting the small losses due to reflections at the boundaries)

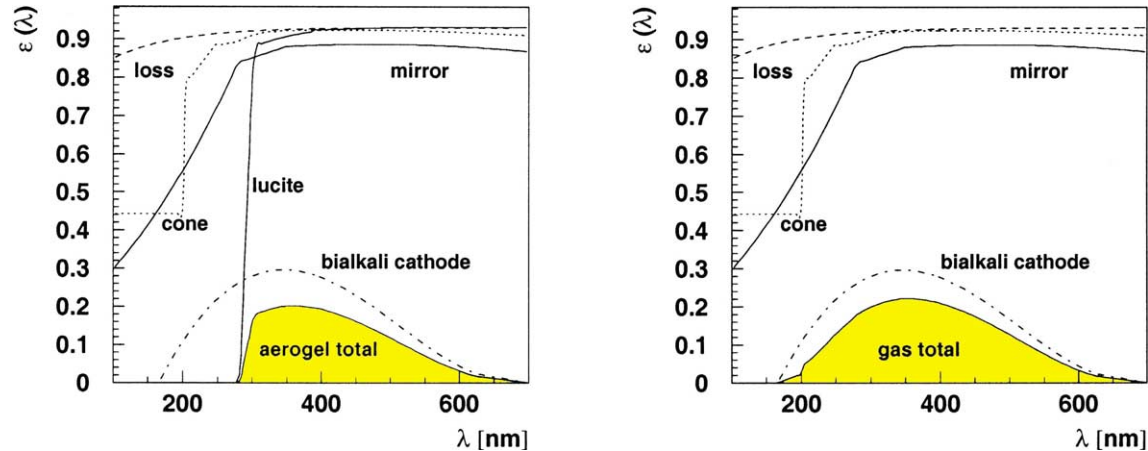
UV fused silica transmission



UV fused silica refractive index



RICH Optical Properties: Mirror reflectivity and Lucite transparency



- The curve labeled “mirror” from HERMES RICH NIM paper was used for the reflectivity of both the spherical mirror and the light collection funnels, even though actual funnel reflectivity is slightly higher
- UVT-lucite window between aerogel and gas has a sharp cutoff in transparency at ~ 300 nm. This is included in simulation; absorbs deep-UV photons emitted in aerogel, which suffer from Rayleigh scattering (cross section proportional to $1/\lambda^4$)
- **Caveat: while making this talk, I discovered an error in the code that caused mirror reflectivity to be 100% instead of using the curve, so actual Cherenkov yields will be approximately 10% less than what is shown in this talk. On the other hand, the PMT QE may be underestimated, so these effects partially offset each other**

RICH Optical Properties: Aerogel and C_4F_{10}

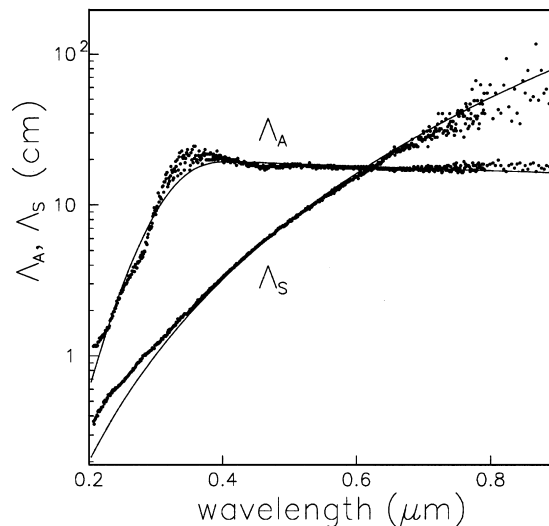
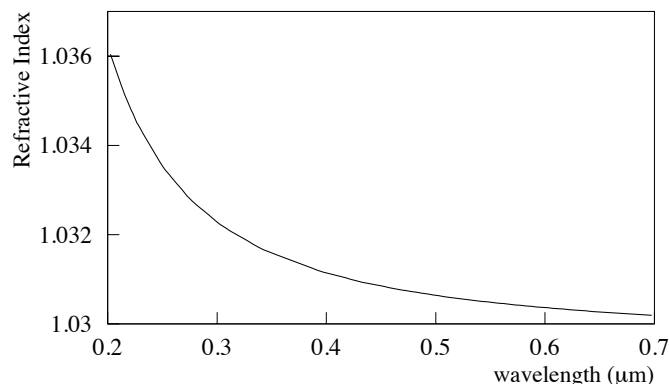
$$n_{aerogel}(\lambda) = An_{Air}(\lambda) + Bn_{quartz}(\lambda)$$

$$A = 0.944$$

$$B = 0.056$$

$$\lambda_{Rayleigh} = \frac{\lambda^4}{C}$$

$$C \approx 885 \text{ nm}^3$$

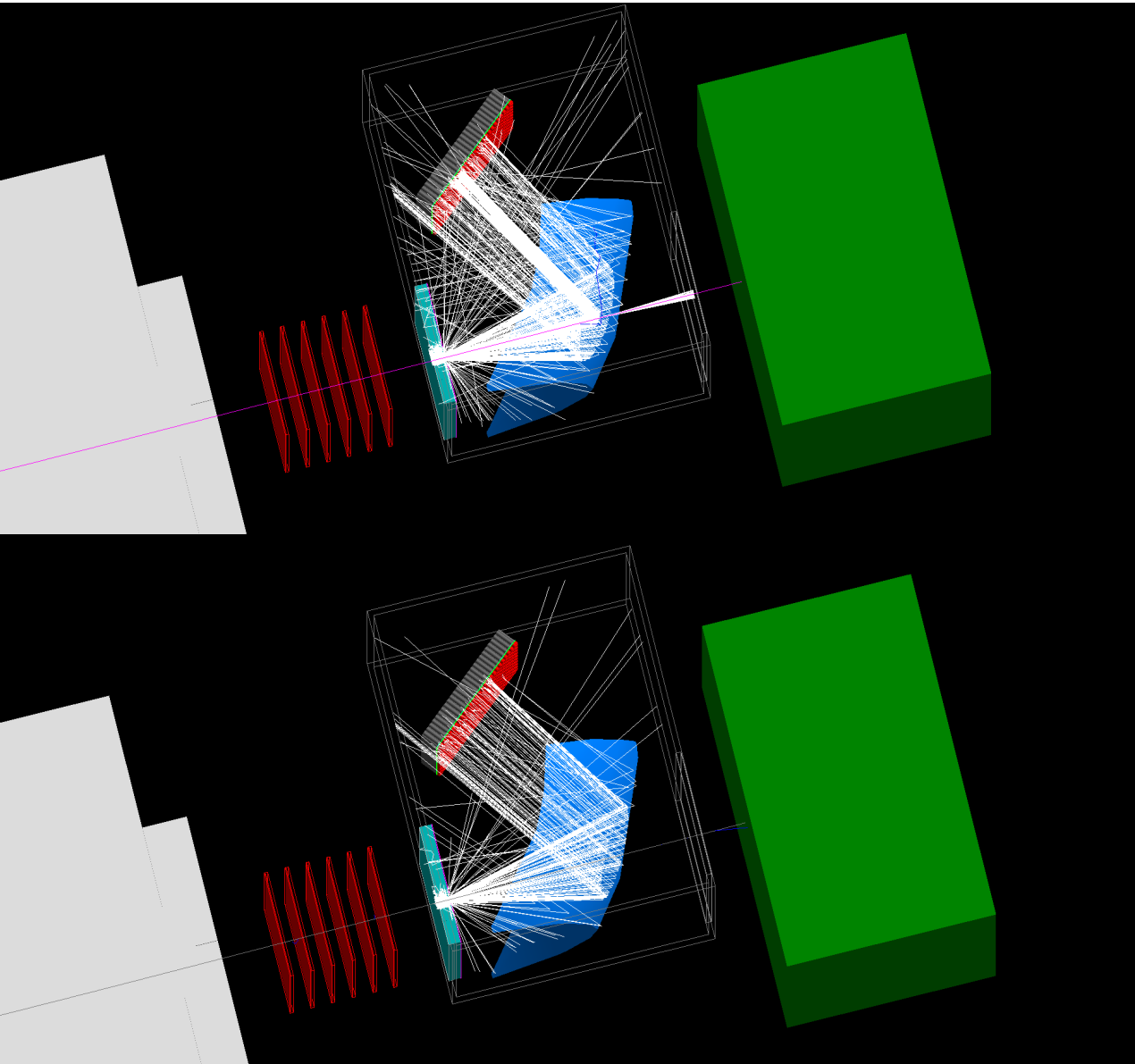


- Optical dispersion in aerogel limits resolution of Cherenkov emission angle/PID performance (*not* the dominant source of error)
- Light losses in aerogel dominated by Rayleigh scattering
- Constant refractive index $n=1.00137$ assumed for gas for the time being

Optical Physics Processes Included in the MC

- Production of optical photons:
 - Cherenkov effect—production of optical photons requires “RINDEX” to be defined as a property of the medium
- Propagation of optical photons:
 - Requires “RINDEX” to be defined
 - Bulk absorption—requires definition of “ABSLENGTH” for the medium of propagation
 - Rayleigh scattering—if “RAYLEIGH” is defined (aerogel only)
 - Reflection, refraction and transmission at boundaries:
 - Dielectric-dielectric interface: if “RINDEX” is defined for both media, then boundary interaction is handled automatically via Fresnel equations
 - Dielectric-metal interface: if “REFLECTIVITY” is defined for the metal surface or complex RINDEX, then reflect/absorb with appropriate probabilities
- See <http://geant4.web.cern.ch/geant4/UserDocumentation/UsersGuides/ForApplicationDeveloper/html/ch05s02.html#sect.PhysProc.Photo> for more details

Putting it all together..



RICH response to a 5 GeV pion (top) and a 5 GeV kaon (bottom) moving on identical trajectories

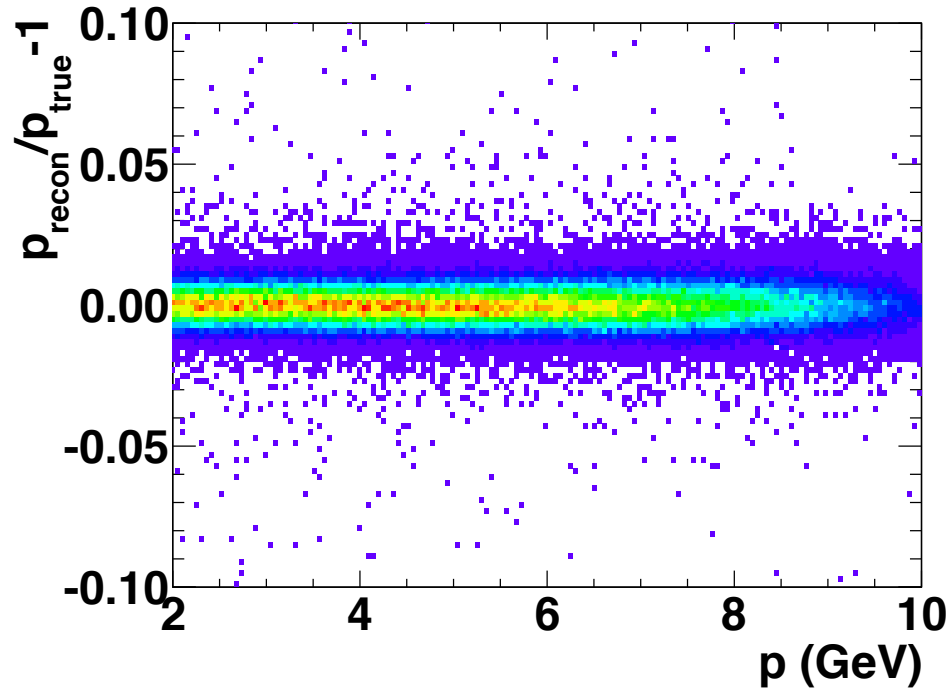
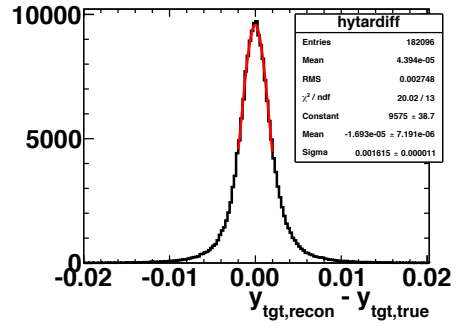
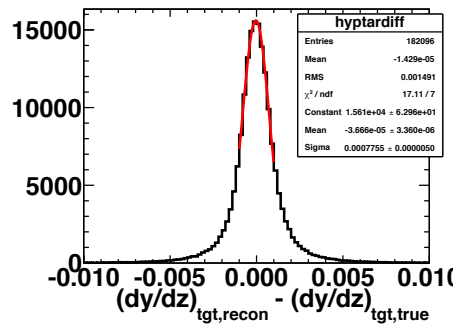
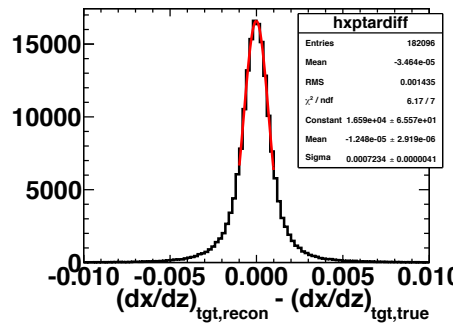
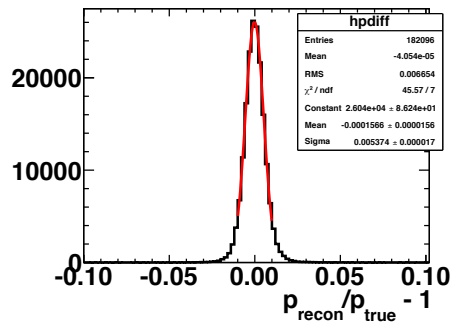
BigBite and SBS optics from GEANT4

- For a realistic simulation of RICH PID performance, we need to reconstruct the particle momentum from measured track, so that PID analysis is done with realistic momentum resolution
- Magnetic field layout:
 - BigBite: realistic field map (map_696A.dat)
 - SBS: Uniform 1.4 T field (for now, will use TOSCA-generated maps later)
- GEM hits are smeared by 70 μm coordinate resolution of GEMs, then a straight-line track is fitted.
- Since “true” track parameters are known in GEANT4, we can use the classic Hall A/C method of expanding the reverse transport matrix in a power series in the measured track parameters:

$$(x'_{tgt}, y'_{tgt}, y_{tgt}, 1/p) = \sum_{i+j+k+l+m \leq 6} C_{x', y', y, 1/p}^{ijklm} x_{fp}^i y_{fp}^j x'_{fp}{}^k y'_{fp}{}^l x_{tgt}^m$$

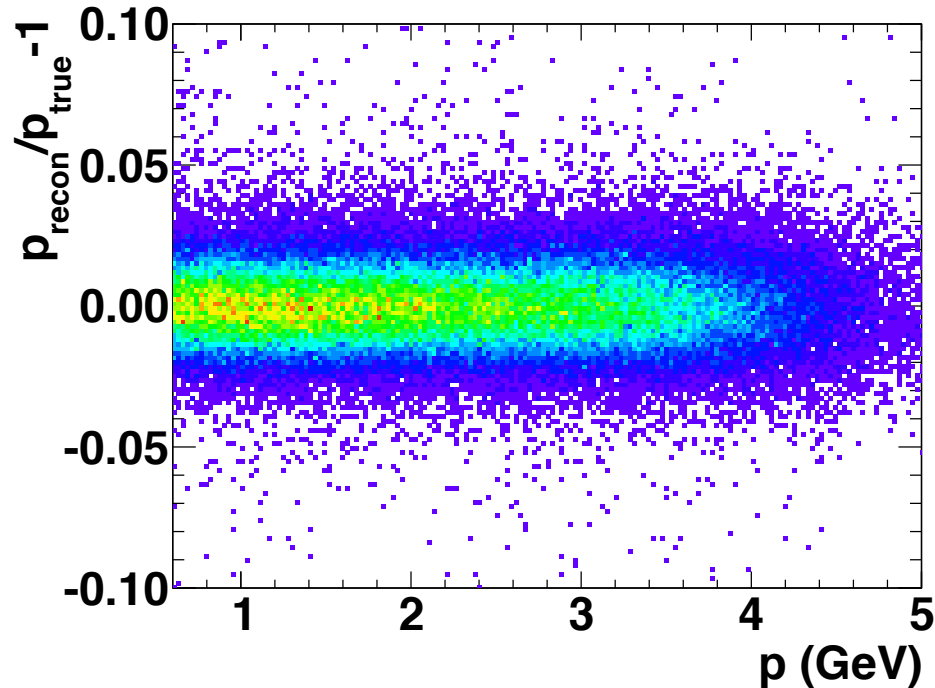
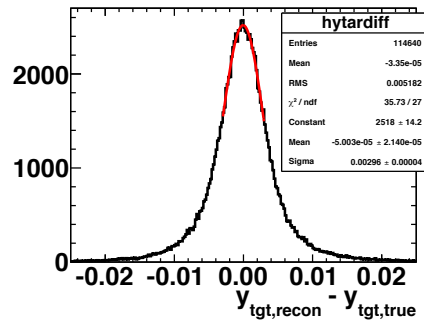
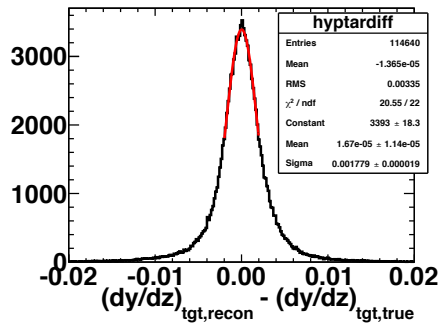
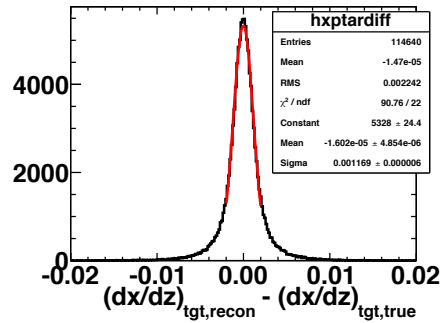
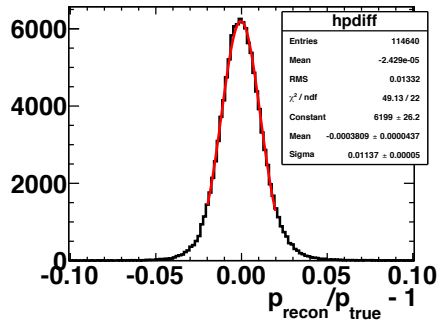
- Track parameters at the target are **linear** functions of the expansion coefficients
 - Use standard linear algebra libraries, e.g., SVD, to fit the coefficients, avoid pitfalls of nonlinear fitting/numerical minimization
- Why fit $1/p$ instead of p or the traditional $\delta = 100 \times (p/p_0 - 1)$ in the expansion?
 - SBS/BigBite are large-acceptance spectrometers—range of delta can equal or exceed $\pm 100\%$
 - Expansion of $1/p$ converges much more quickly— x_{fp} , x'_{fp} are almost linear in $1/p$ for dipole magnets
- In principle, the transport matrix for a uniform, rectangular field volume can be calculated analytically, but it is nonetheless useful to develop the general formalism

SBS resolution from optical reconstruction of GEANT4 events



- Average momentum resolution: $\sim 0.54\%$, angular resolution ~ 0.7 mrad (vertical) and ~ 0.8 mrad (horizontal), vertex resolution (y_{tar}): ~ 1.6 mm
- Multiple scattering (including target cell walls) appears to dominate the momentum/angle/vertex resolution in SIDIS configuration; GEM resolution contribution insignificant

BigBite resolution from GEANT4



- Average momentum resolution: $\sim 1.1\%$, angular resolution ~ 1.2 mrad (vertical) and ~ 1.8 mrad (horizontal), vertex resolution (y_{tar}): ~ 3 mm
- Multiple scattering (including target cell walls) appears to dominate the momentum/angle/vertex resolution in GEANT4; GEM resolution contribution insignificant

RICH PID analysis—Inverse Ray Tracing Approach

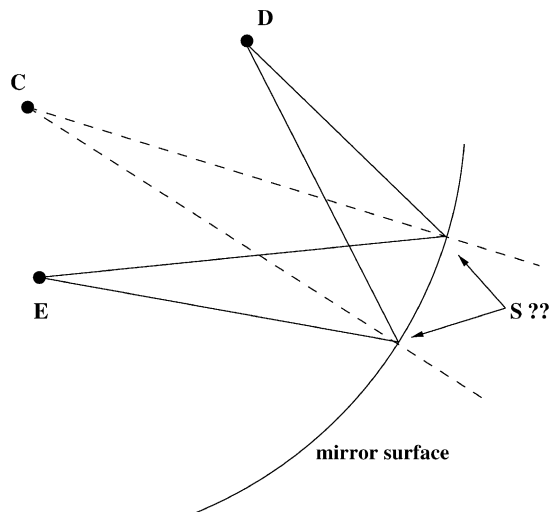
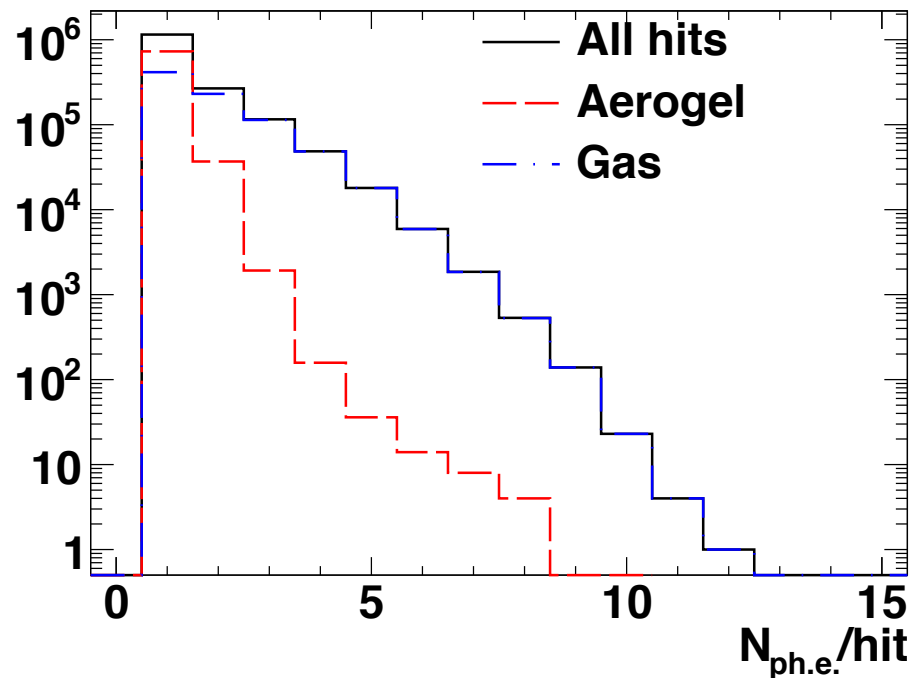
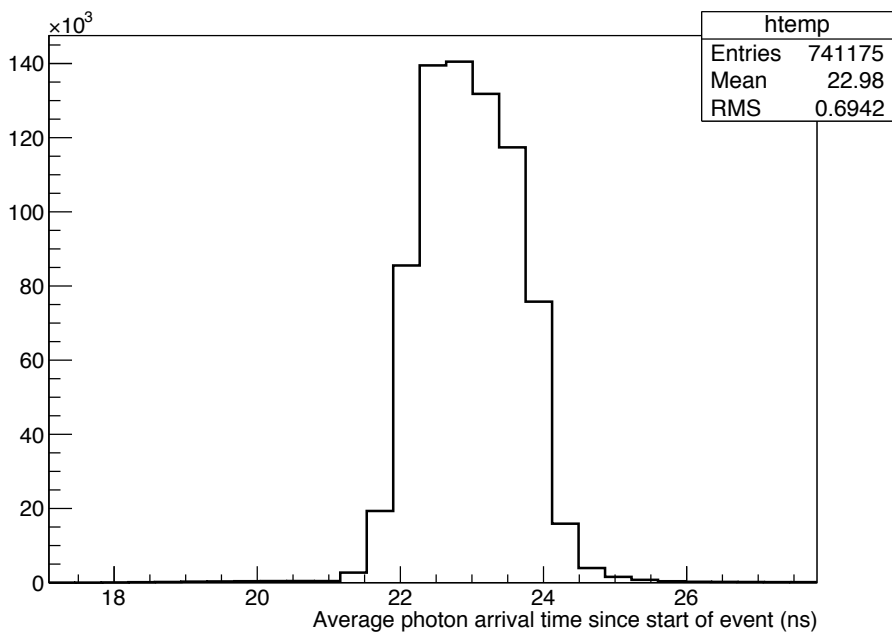
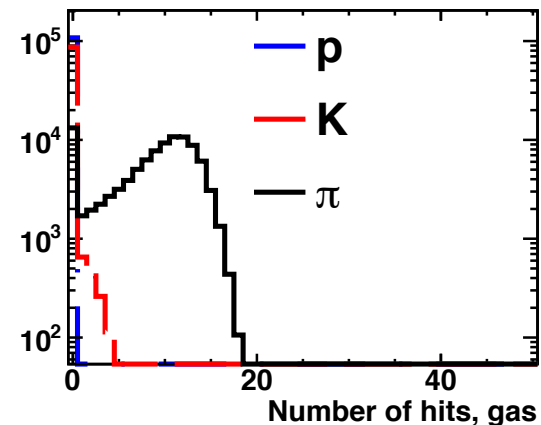
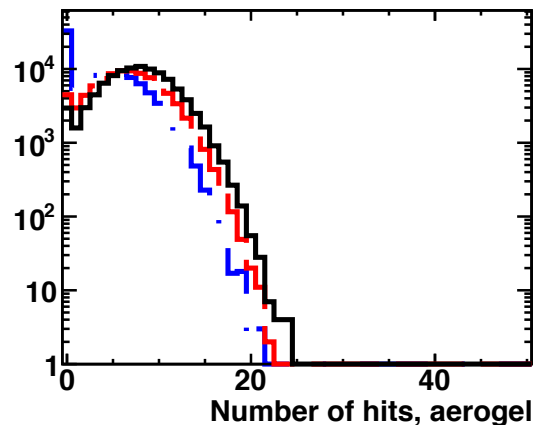
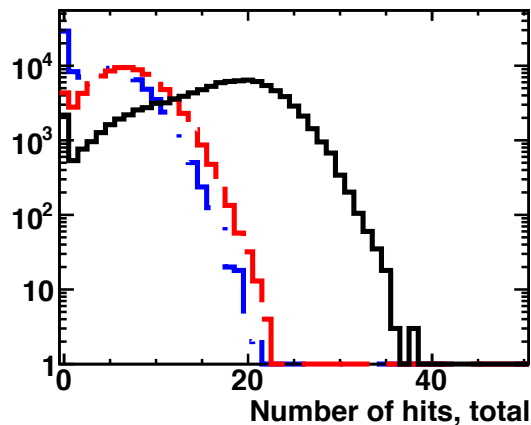


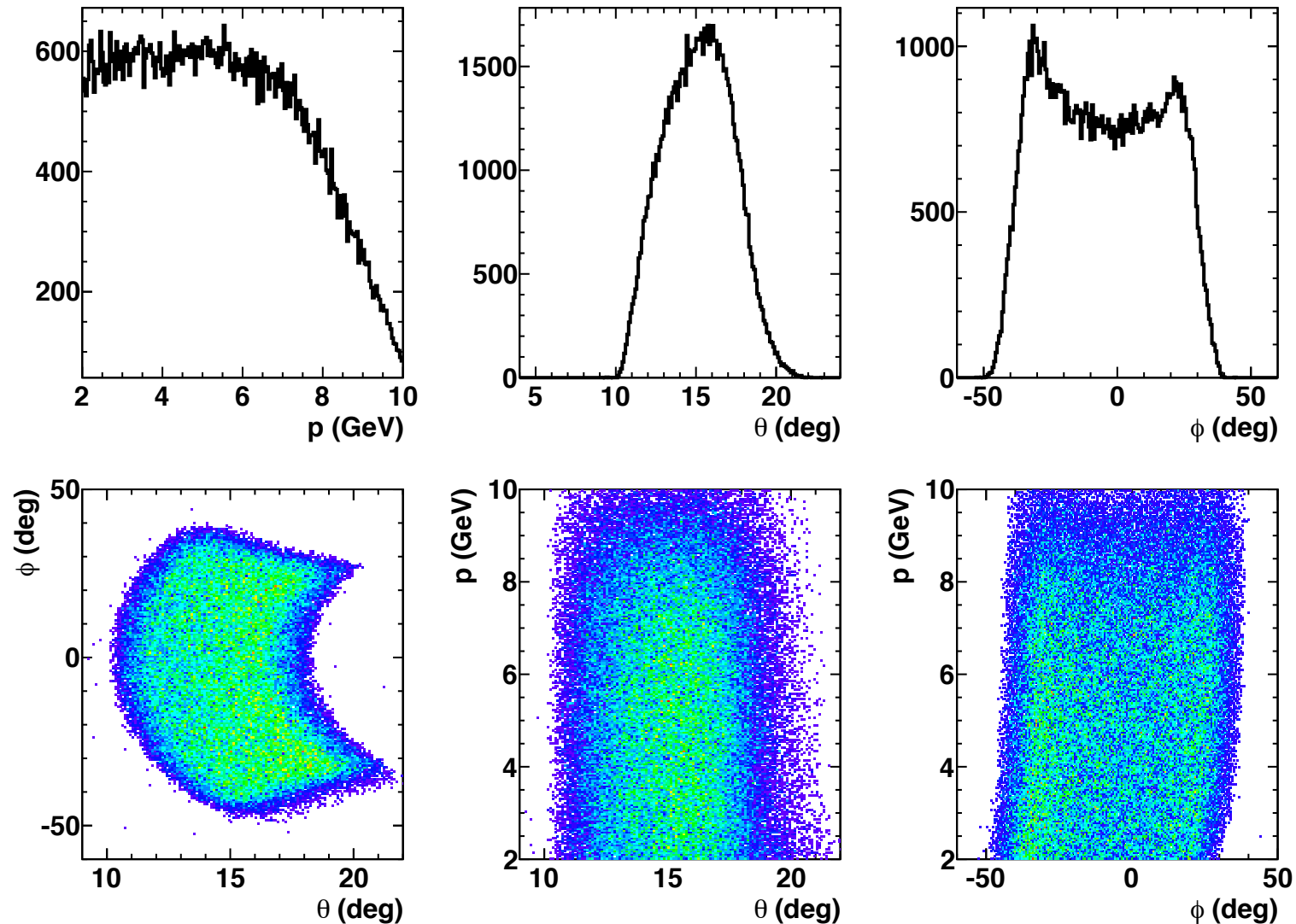
Fig. 13. The problem of inverse ray tracing.

- Defining the problem of RICH reconstruction:
 - Given a particle track in the GEM with known (reconstructed) momentum, and a hit in a RICH PMT, what is the emission angle for Cherenkov radiation?
- Knowns:
 - Particle trajectory (emission point must be located along the track)
 - Particle momentum
 - Hit position
 - Center of spherical mirror and radius of curvature
- Unknowns:
 - Emission point along particle trajectory (must be estimated)
 - Particle type (what we are trying to find out)
 - In which radiator the photon was emitted
- Geometry facts:
 - Emission point, reflection point, detection point and sphere center all lie in the plane of incidence
 - Reflection angle = Incidence angle
 - Leads to transcendental equation for θ_C that can be solved numerically in small number of iterations.

SBS RICH signal strength

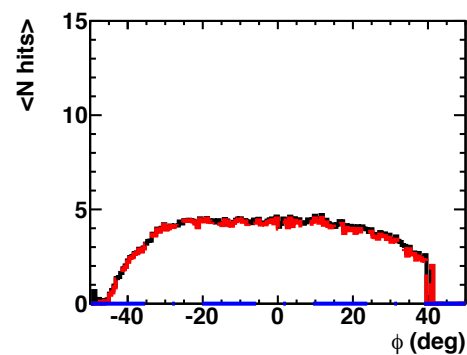
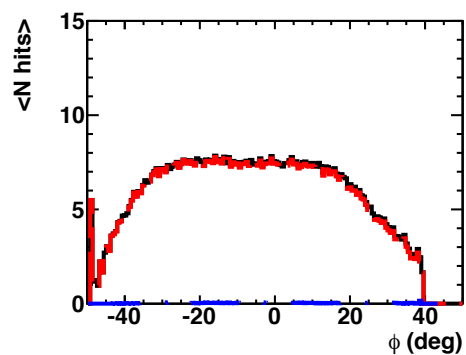
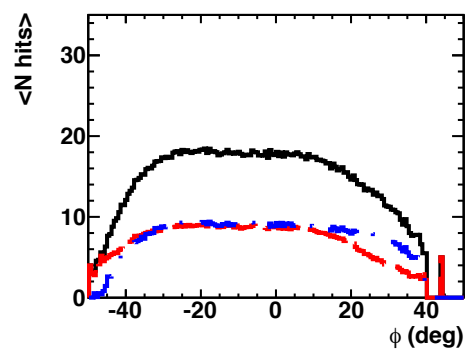
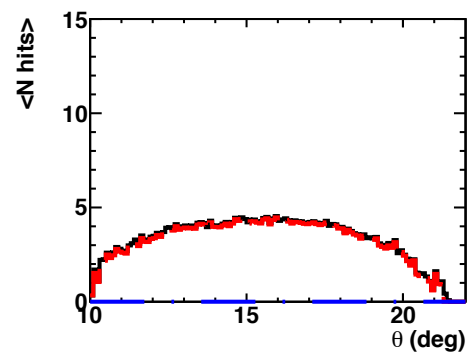
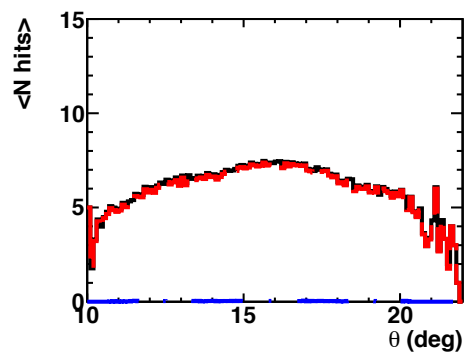
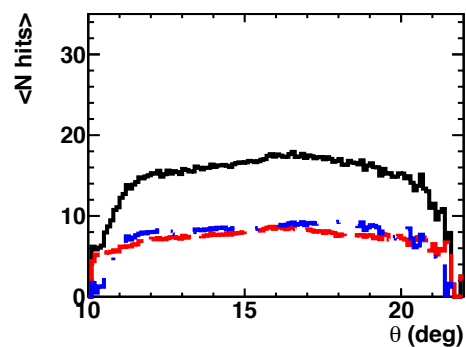
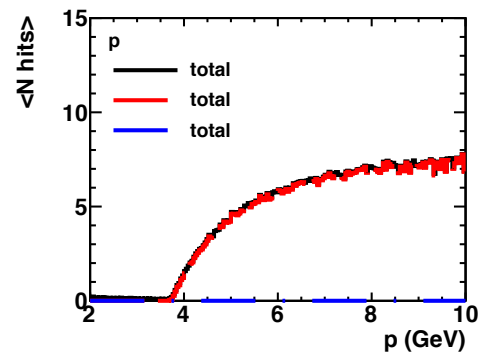
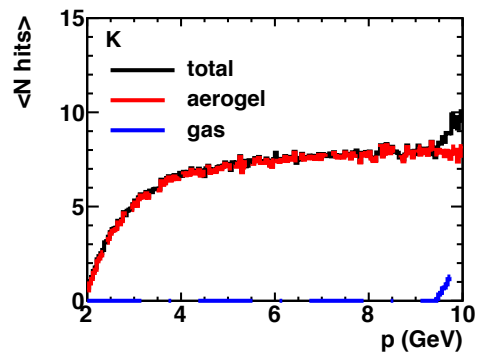
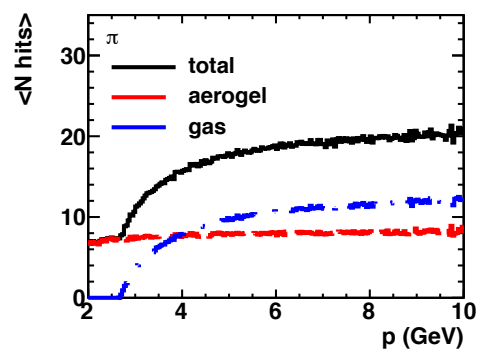


SBS Acceptance



SBS acceptance in SIDIS expt. @14 deg., $d = 2.5$ m, up-bending particles

RICH average signal strength vs. kinematics



Comparison to HERMES real data

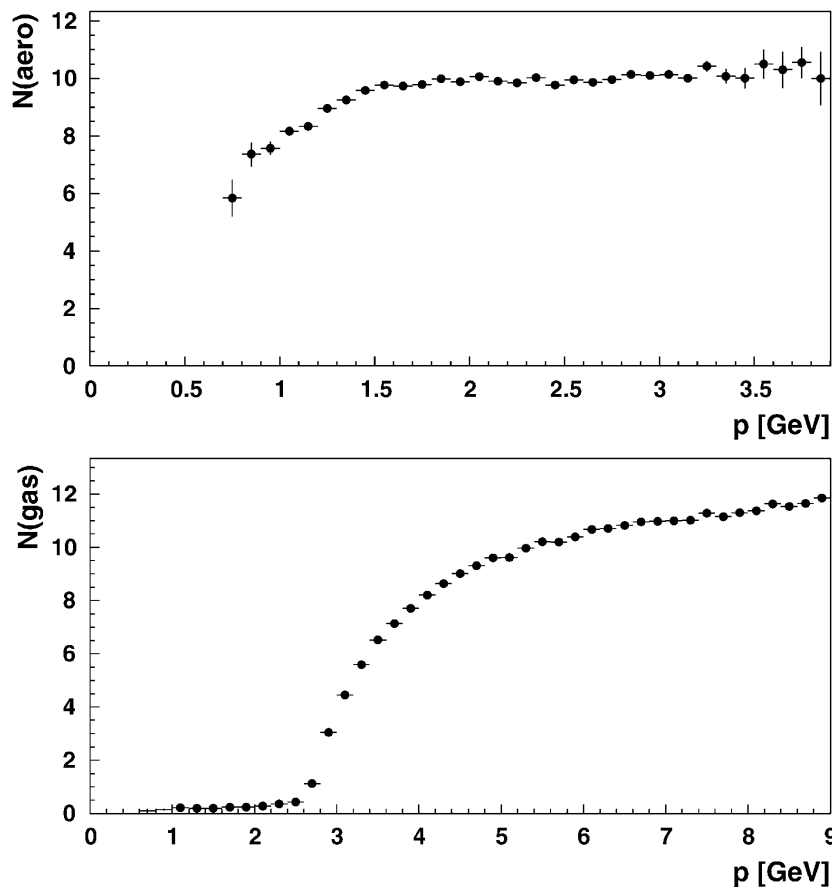
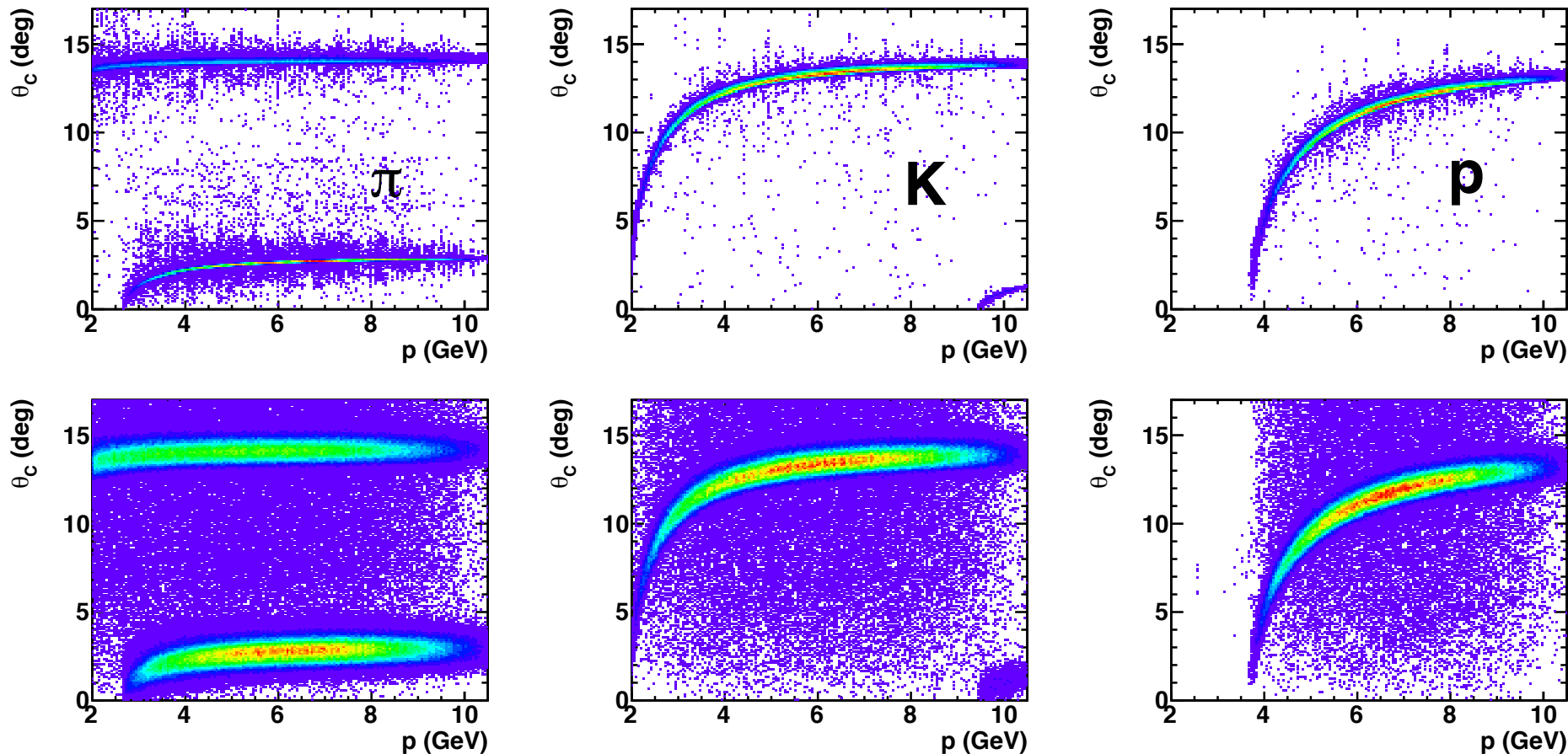


Fig. 18. Number of fired aerogel (top) and gas PMTs (bottom) versus particle momentum for 'ideal' pion tracks.

- From HERMES RICH long NIM paper:
 - Average number of aerogel PMTs fired for “ideal” pion tracks = 10
 - Average number of aerogel PMTs including acceptance effects = 8
 - ***Our simulations: ~8 (includes acceptance effects)***
 - Average number of gas PMTs fired for “ideal” pion tracks ~12
 - ***Our simulations: ~12***
- Known defects of our simulation:
 - Underestimate PMT Q.E.
 - Overestimate mirror reflectivity due to coding error
- Effects approximately cancel in the final yields, so our results are close to reality

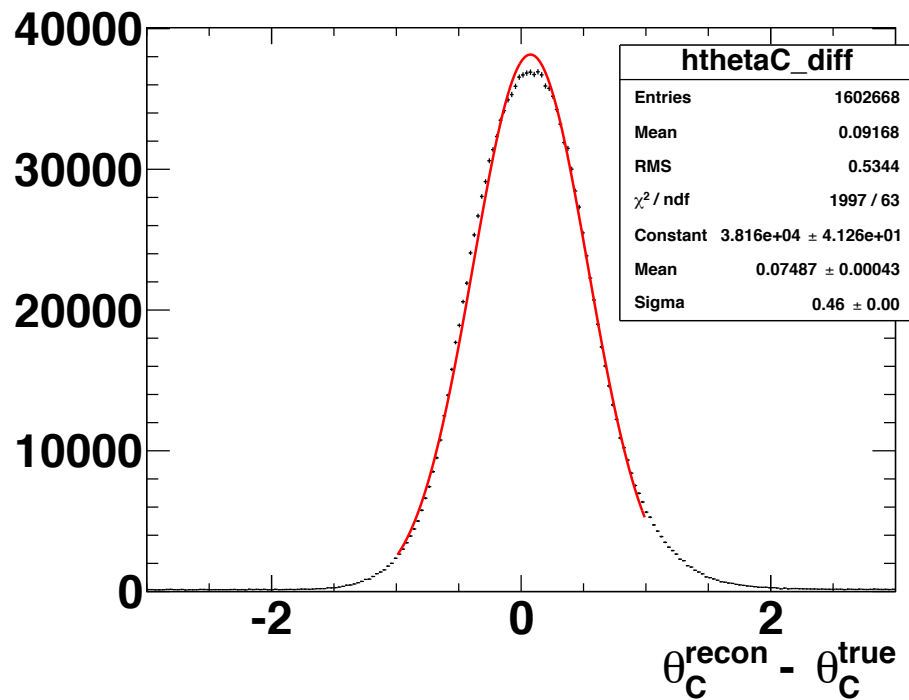
Emission Angles: True and reconstructed (IRT)



- Top row: true Cherenkov emission angle vs. momentum for pions, kaons and protons
- Bottom row: reconstructed Cherenkov emission angle vs. momentum for pions, kaons and protons (with “cheating”; i.e., using known radiator information of hit to guess emission point)

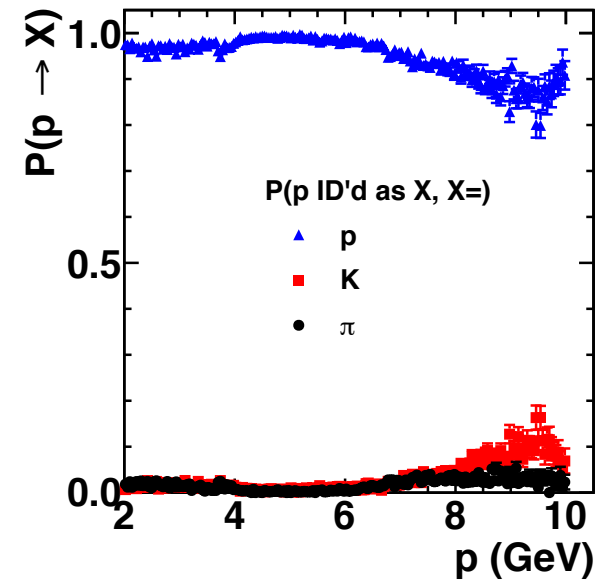
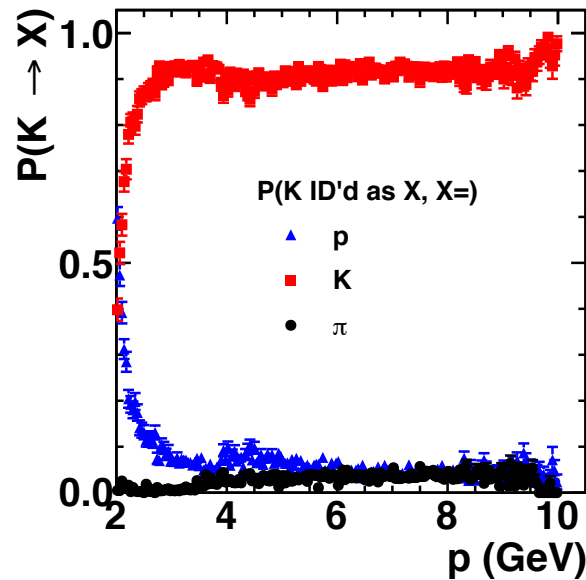
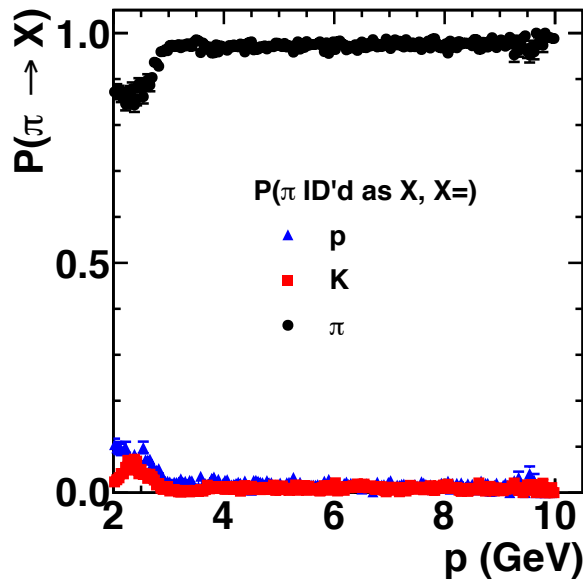
Notes on θ_C reconstruction using IRT method

- Photon energy is unknown, therefore constant refractive index is assumed—fit average “true” θ_C vs. p to $N \times \sin^2 \theta_C(\beta, n)$ to extract average refractive index taking into account emission spectrum and detection efficiency
- Correct “raw” reconstructed θ_C of aerogel hits for refraction at aerogel-gas boundary (aerogel-lucite refraction is cancelled by lucite-gas refraction in first approximation)
- For aerogel (gas) hypothesis, fix emission point to half thickness of aerogel (gas) traversed by particle track



- Above: difference between reconstructed and “true” emission angles, including effects of SBS momentum & tracking resolution
 - Result ~ 8 mrad; consistent with HERMES results, dominated by pixel size

From reconstructed hits to PID assignment



- Above: P_{ij} vs. momentum (probability to identify particle type i as type j) using a simple modified version of IRT likelihood algorithm (see various HERMES NIM papers and these for more details)
 - **This includes all tracks in SBS acceptance, so P_{ij} includes effects of acceptance mismatch**
- More details of algorithm on next slide...

Details of (very preliminary) PID algorithm

$$\mathcal{L}_{rad}^{PID} = e^{-\frac{(\langle \theta_C \rangle - \theta_C^{PID}(p))^2}{2\sigma_\theta^2}}$$

$$\sigma_\theta = \sigma_1 / \sqrt{N_{hit}}$$

$$\mathcal{P}_{rad}^{PID}(N_{hit}) = \frac{\langle N(p) \rangle^{N_{hit}} e^{-\langle N(p) \rangle}}{N_{hit}!}$$

$$\mathcal{L}_{combined}^{PID} = \mathcal{L}_{aero} \mathcal{L}_{gas} \mathcal{P}_{aero} \mathcal{P}_{gas} + 1 \times (\text{Any aerogel?}) + 1 \times (\text{Any gas?})$$

- For each radiator/PID hypothesis, count number of hits within $\pm 4\sigma$ of expected θ_C and compute average reconstructed θ_C , compute likelihood as above
- If above threshold and no hits consistent with this PID/radiator hypothesis, compute Poisson probability that no hits would occur based on the expected average number of hits
- Regardless of above/below threshold and observed hits or not, compute Poisson probability that the actual observed number of hits would occur.
- Add 1 to combined likelihood if any hits consistent with a given radiator/PID hypothesis occurred; this favors tracks with RICH hits over tracks without hits, even if track is below threshold for a given PID/radiator
- Assign PID based on the highest combined likelihood

Pitfalls and Future improvements

- Approach on slide 23, which was used in generating the PID results on slide 22, was applied to simulated events with no beam background; may not work in a higher-background environment
- An alternative for higher purity at the expense of efficiency is to *require* RICH hits in order to make ANY PID assignment.
 - This approach would reject all protons below the proton aerogel threshold of ~ 3.8 GeV and reduce kaon detection efficiency from 2-3 GeV where the number of aerogel hits is low, but would improve purity of kaon sample from 2-4 GeV
- Need to re-do simulation w/ realistic background and gain from HERMES collaboration experience/expertise for optimization of PID algorithm

Conclusions and To-Do List—RICH

- SBS RICH simulation includes most details of geometry and optics, and predicted yields agree with HERMES
- Preliminary PID results with a crude PID algorithm with room for improvement/optimization already show that RICH acceptance does not significantly reduce useful SBS acceptance for SIDIS hadrons
- Need new background calculations with GEANT4 MC to cross-check earlier GEANT3 work
 - Need to define/implement beam-line shielding for SIDIS configuration in G4SBS
- Time to start preparing the RICH for Hall A experiments

Advertisement—New SBS+BB SIDIS proposal to PAC42

- Working draft available at:
 - https://userweb.jlab.org/~puckett/PAC42_deltaq/main_Deltaq.pdf
- Main features:
 - SIDIS on longitudinally polarized Helium-3—measure double-spin asymmetries A_{LL}
 - Almost identical configuration to SBS+BB transversity
 - Data taking at SBS 10 degrees, slightly larger distance (need background rate estimates, check geometry compatibility)
 - 30 days production on Helium-3
 - 20 days @11 GeV
 - 10 days @8.8 GeV
 - Provide highest-precision A_{1n}^h data for ${}^3\text{He}(e,e'h)X$ —sensitivity to sea quark polarization; input to spin-flavor decomposition in NLO global QCD analysis
 - Neutron target most sensitive to d and dbar polarization
 - Vertical detectors, symmetric acceptance for +/- hadrons. With SBS polarity reversals, acceptance is identical
 - Precise extraction of charge-sum and difference asymmetries
 - Charge difference asymmetries cancel effects of fragmentation functions at leading-order—robust extraction of Δq_v and Δq_{bar}
- Send email to Xiaodong Jiang or Andrew Puckett if interested in joining.

