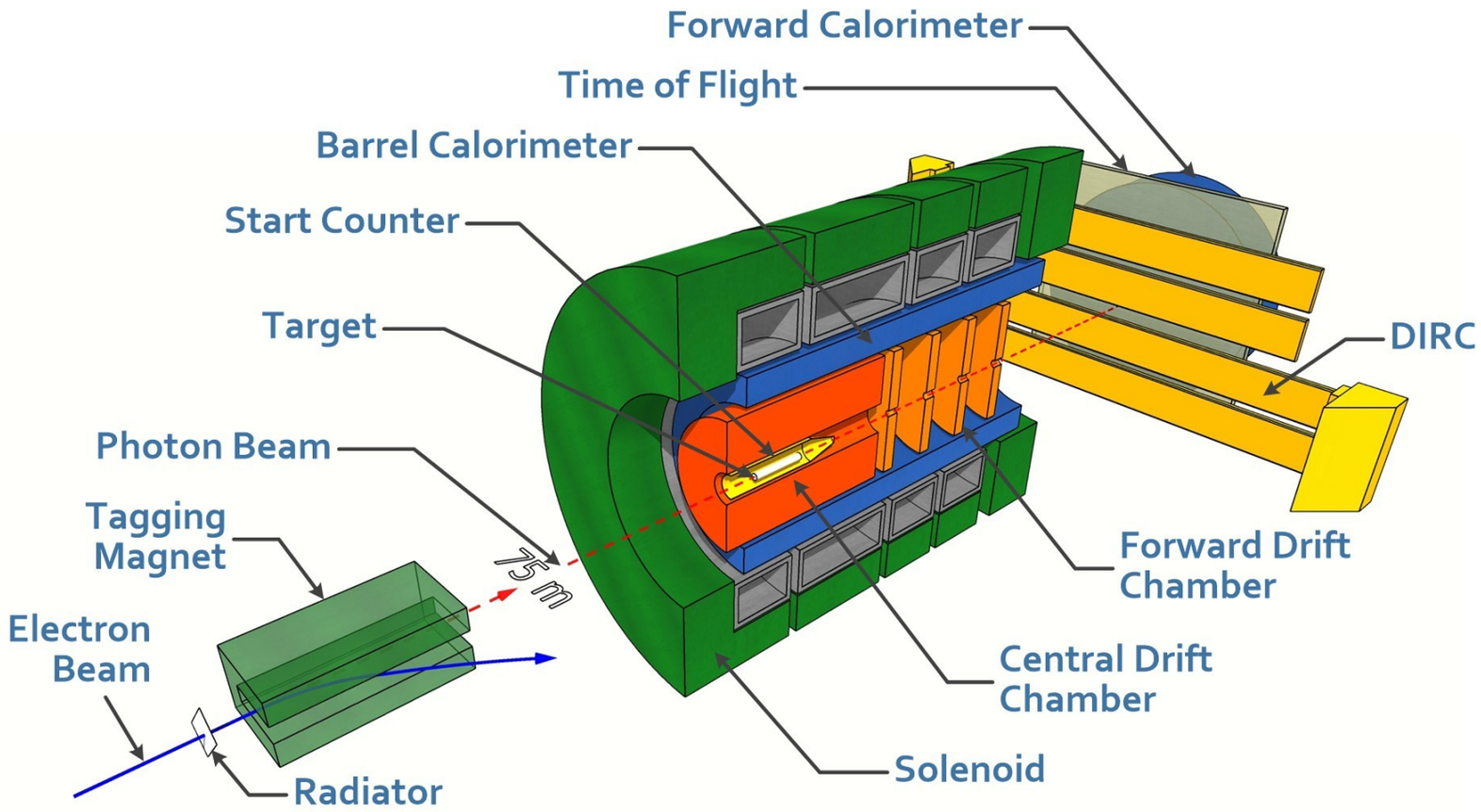
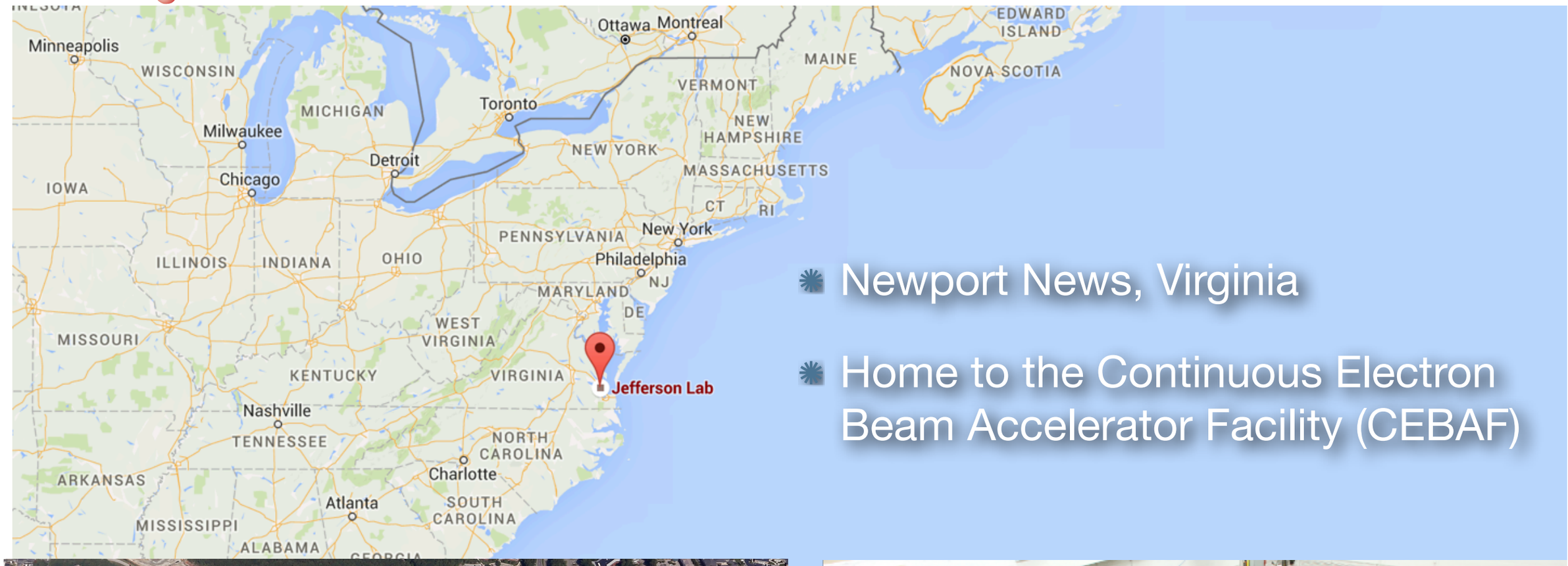


Status and Performance of the GlueX DIRC

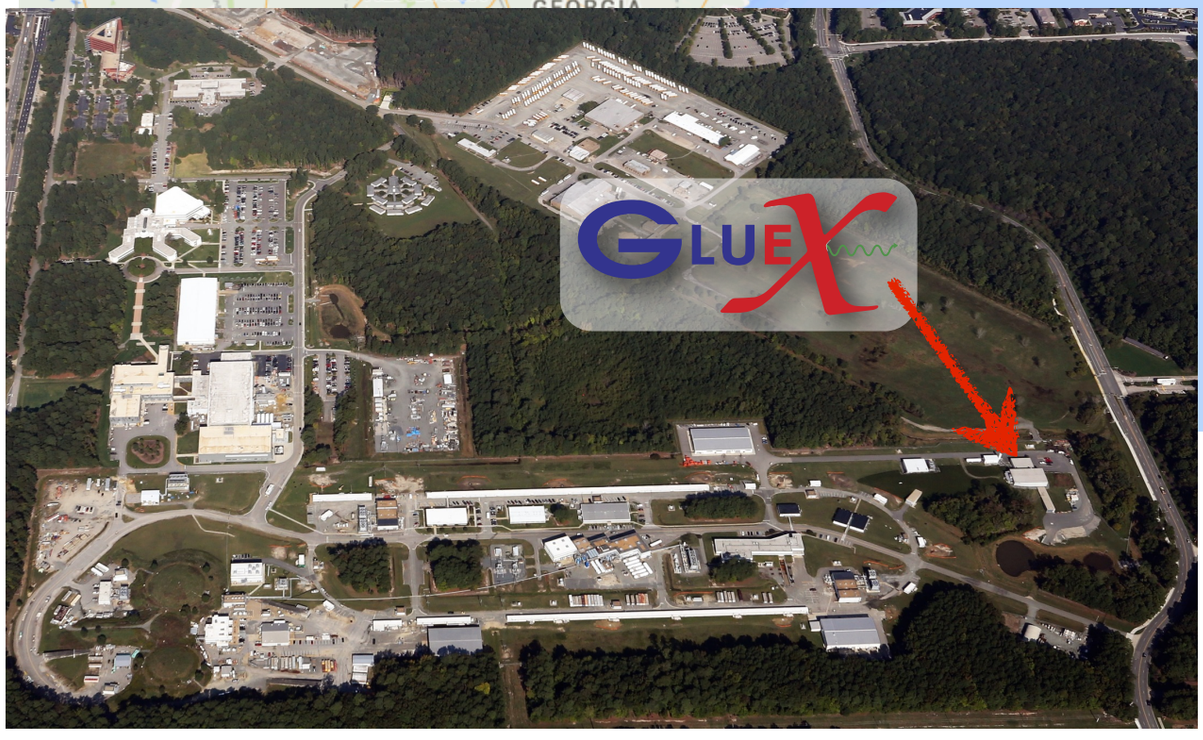
Justin Stevens

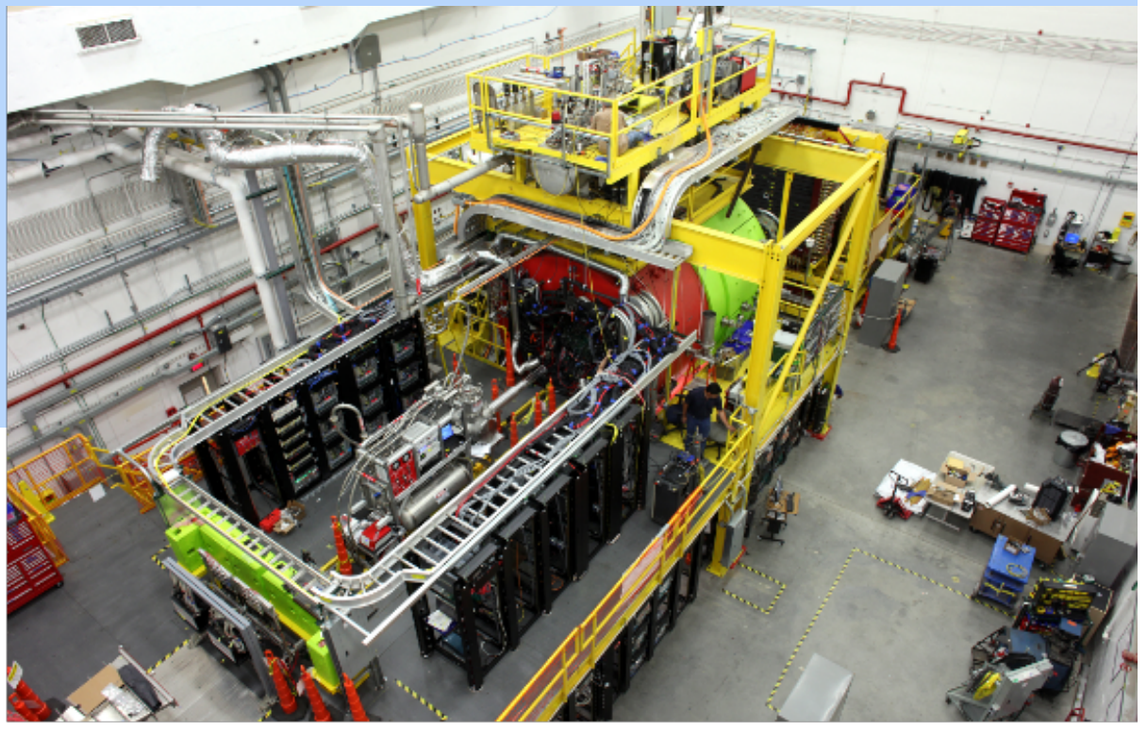
William & Mary
CHARTERED 1693

Jefferson Lab (JLab)



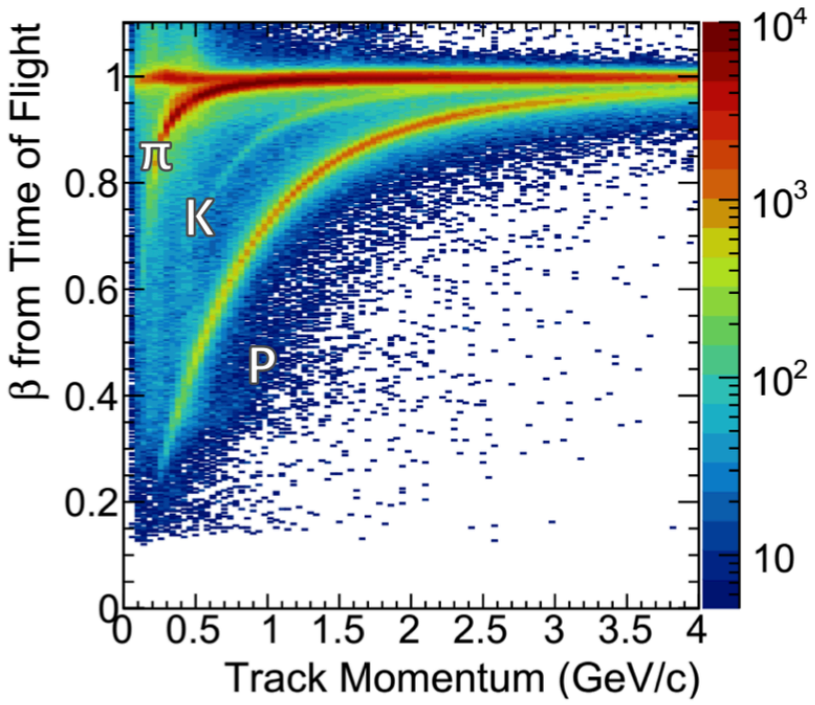
- Newport News, Virginia
- Home to the Continuous Electron Beam Accelerator Facility (CEBAF)

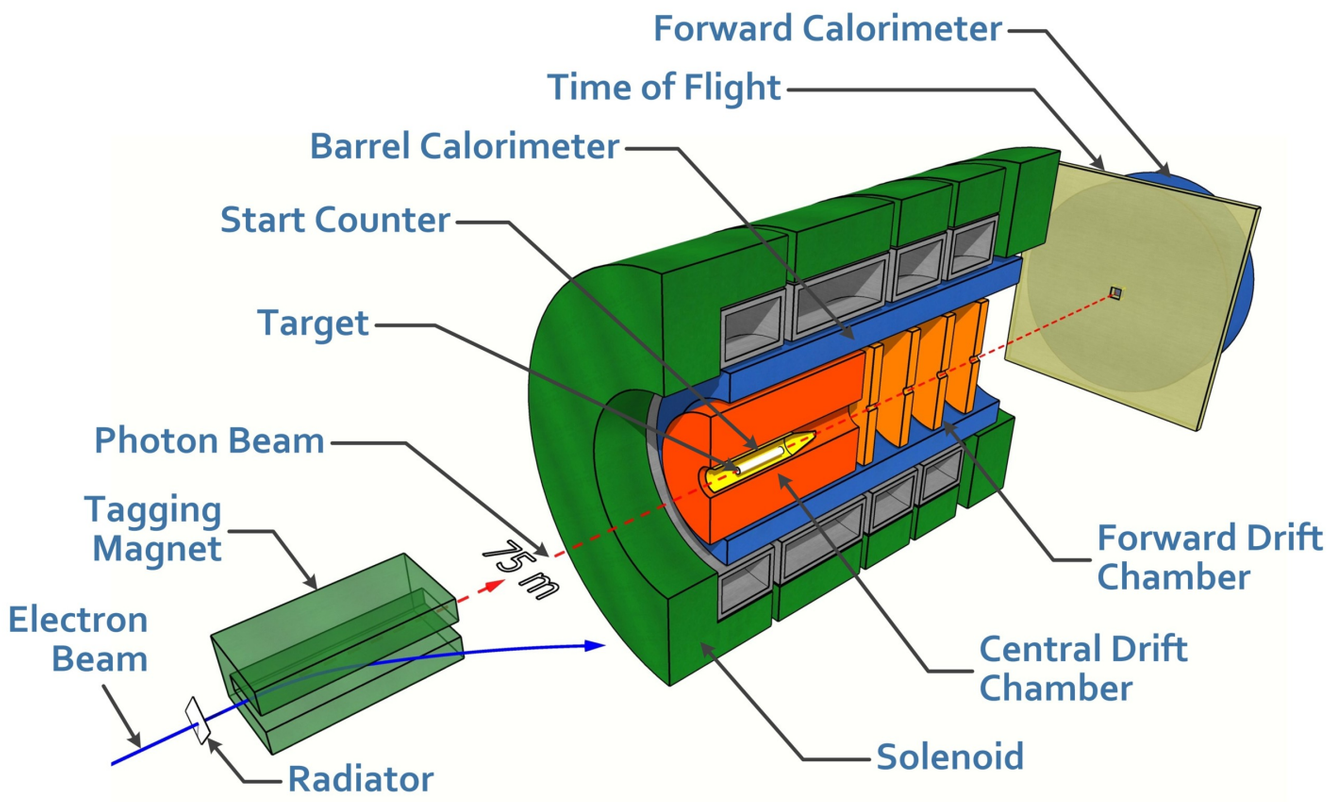




GlueX at JLab

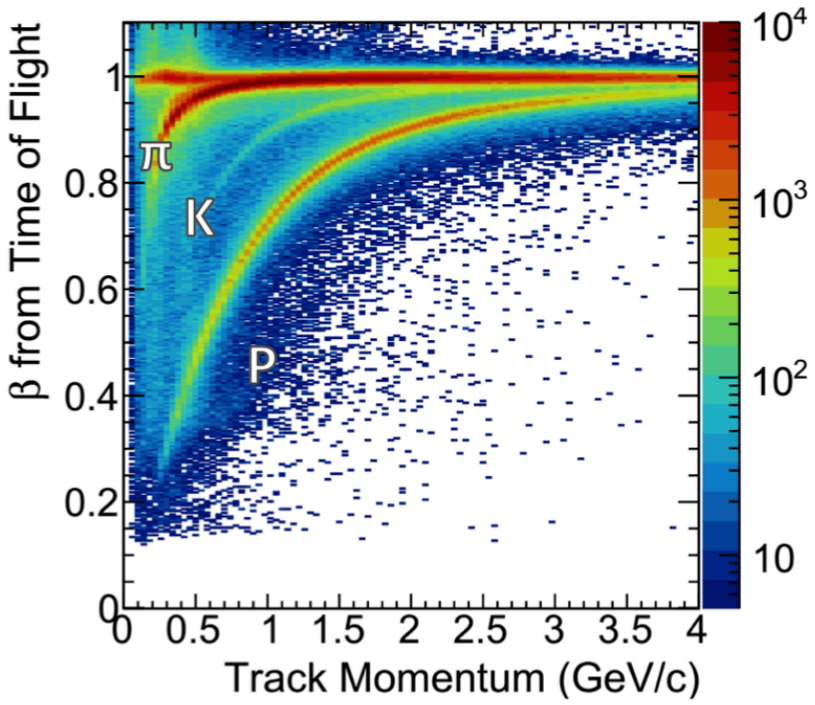
- Designed for light quark meson spectroscopy: 9 GeV linearly-polarized photon beam on LH_2 target
- GlueX-I: π/K separation up to ~2 GeV provided by time-of-flight

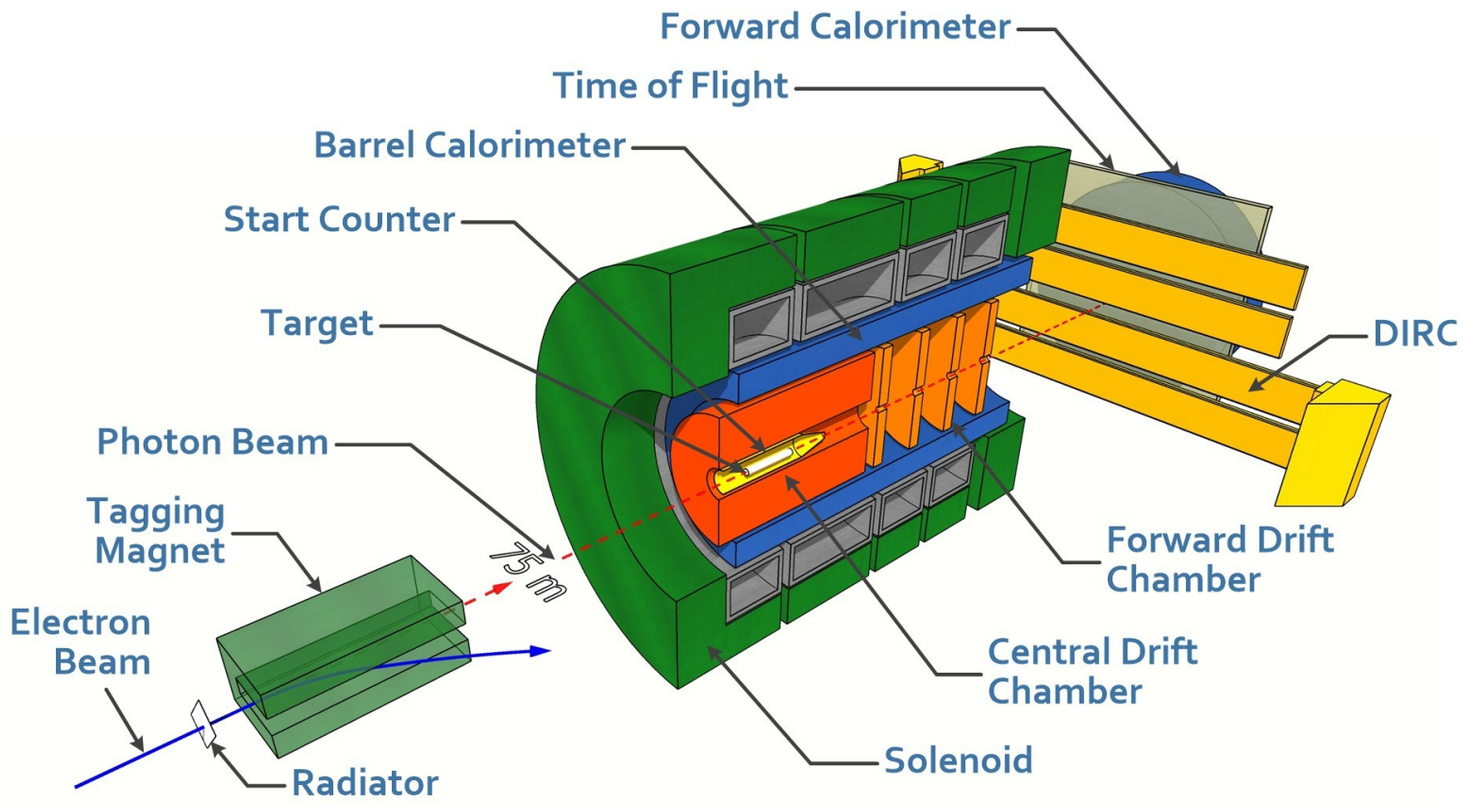




GlueX at JLab

- Designed for light quark meson spectroscopy: 9 GeV linearly-polarized photon beam on LH_2 target
- GlueX-I: π/K separation up to ~2 GeV provided by time-of-flight
- GlueX-II: high luminosity with DIRC PID with 3σ up to 3.7 GeV

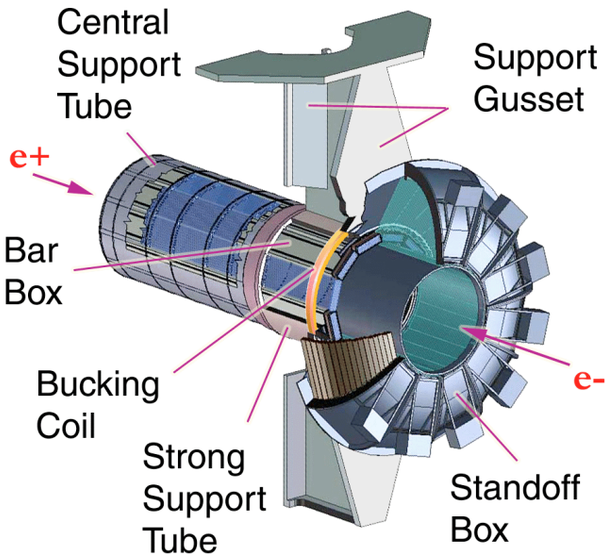




Recycling DIRC bar boxes

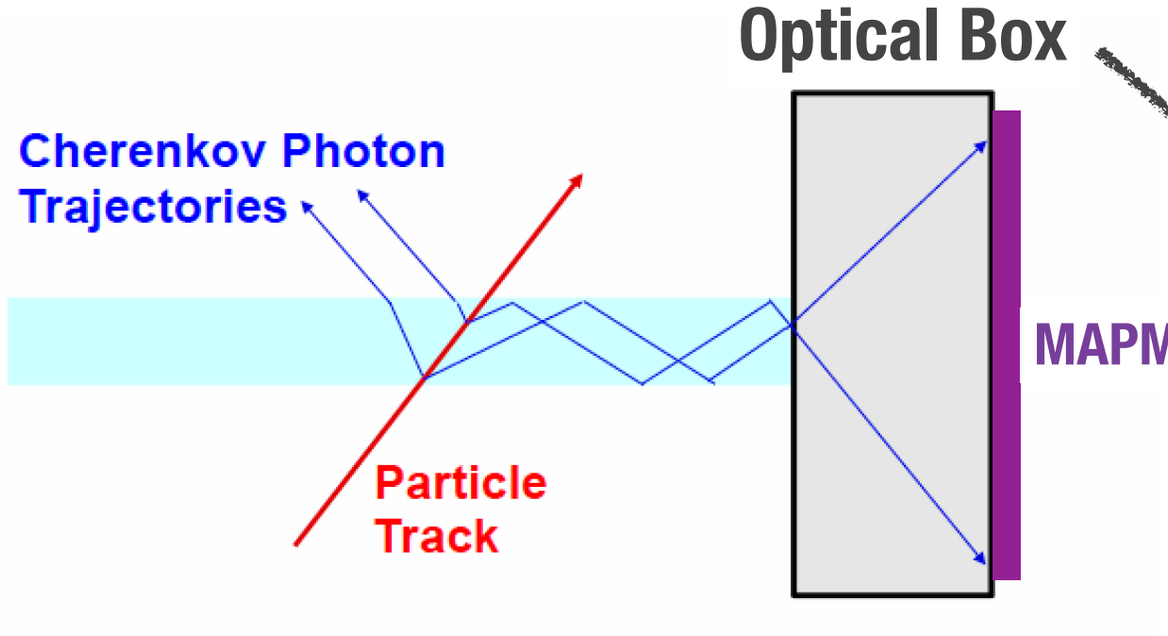
RECYCLE

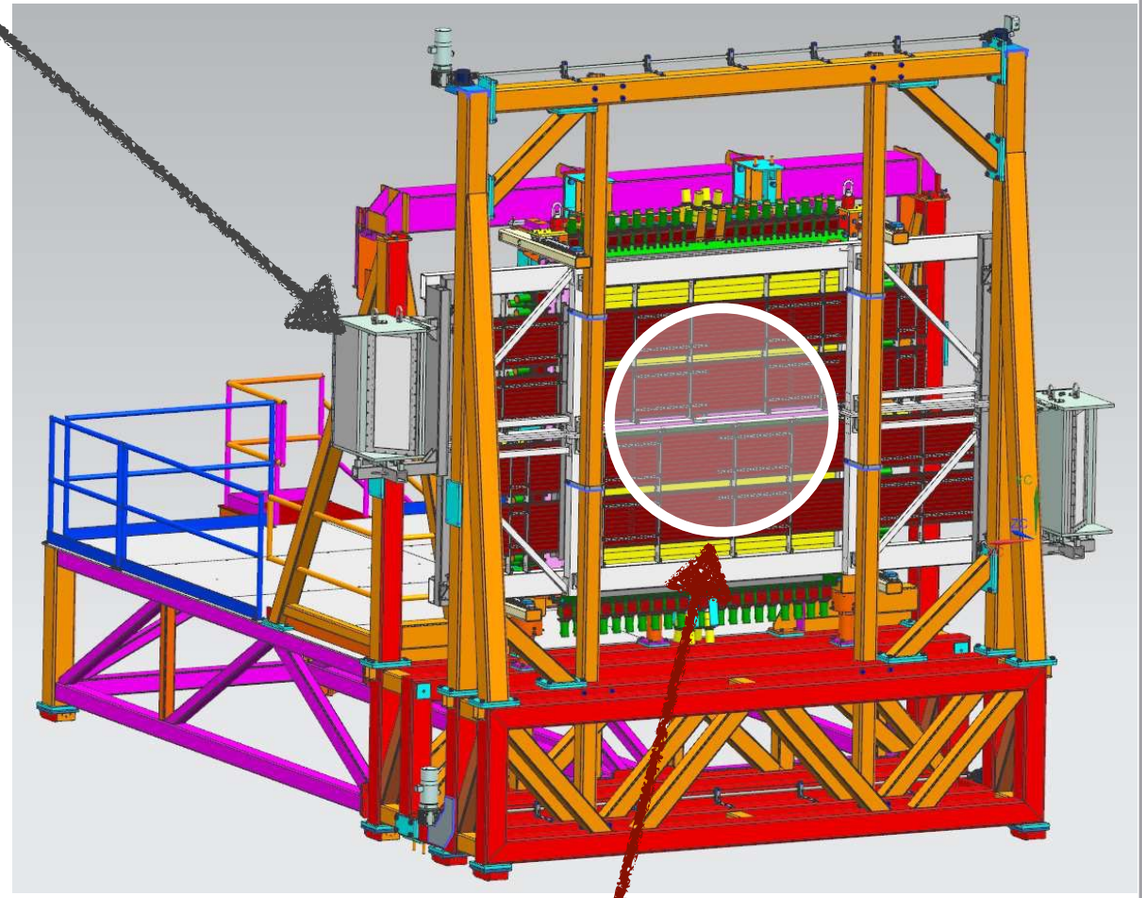
Transported 1/3 of BaBar DIRC radiators to JLab



Cameras, accelerometers, etc. provided real time feedback to trail car

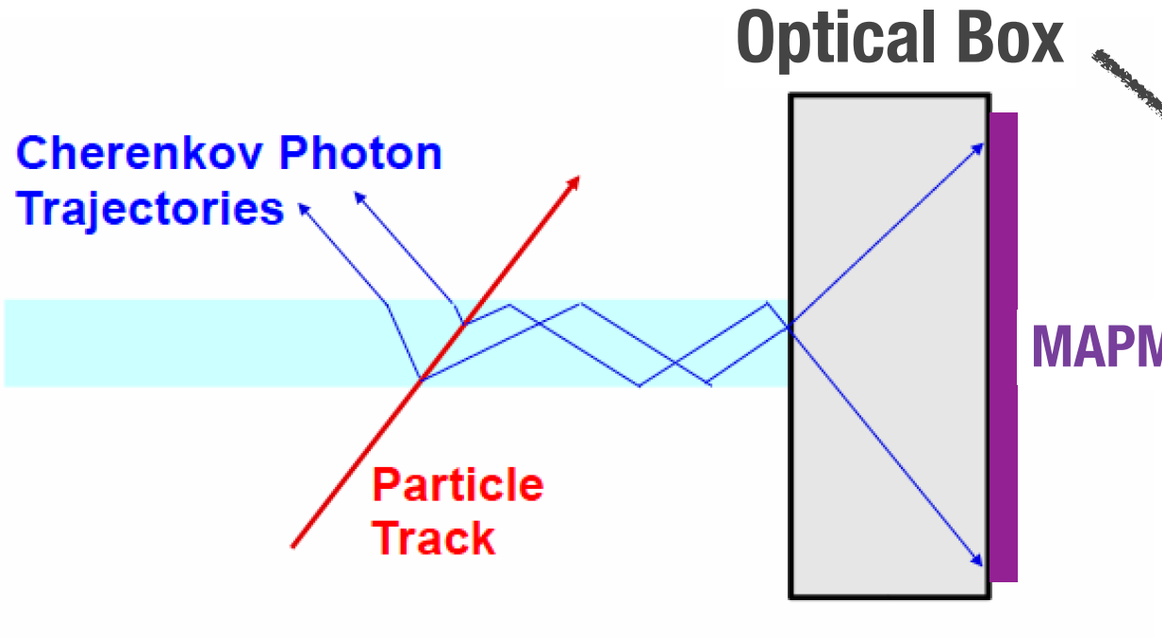
GlueX DIRC

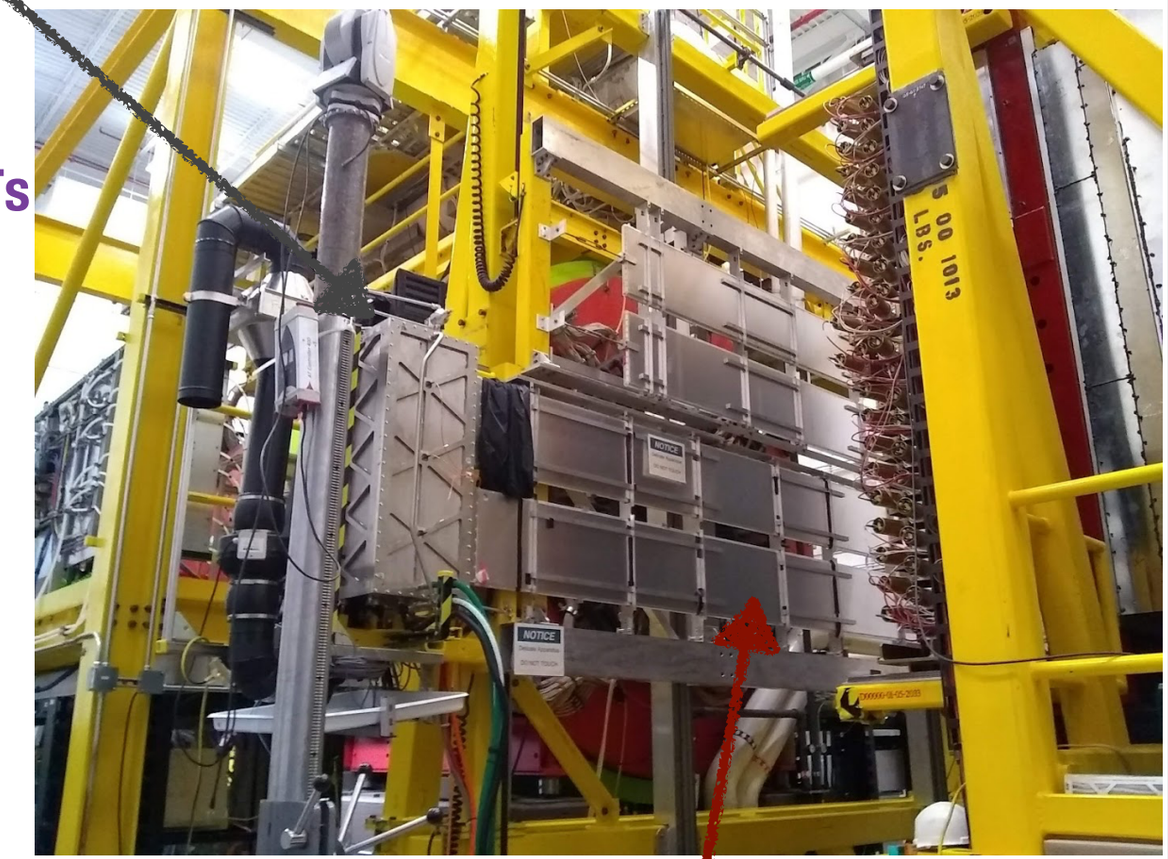




48 fused silica radiator bars installed, covering 2<θ<11°

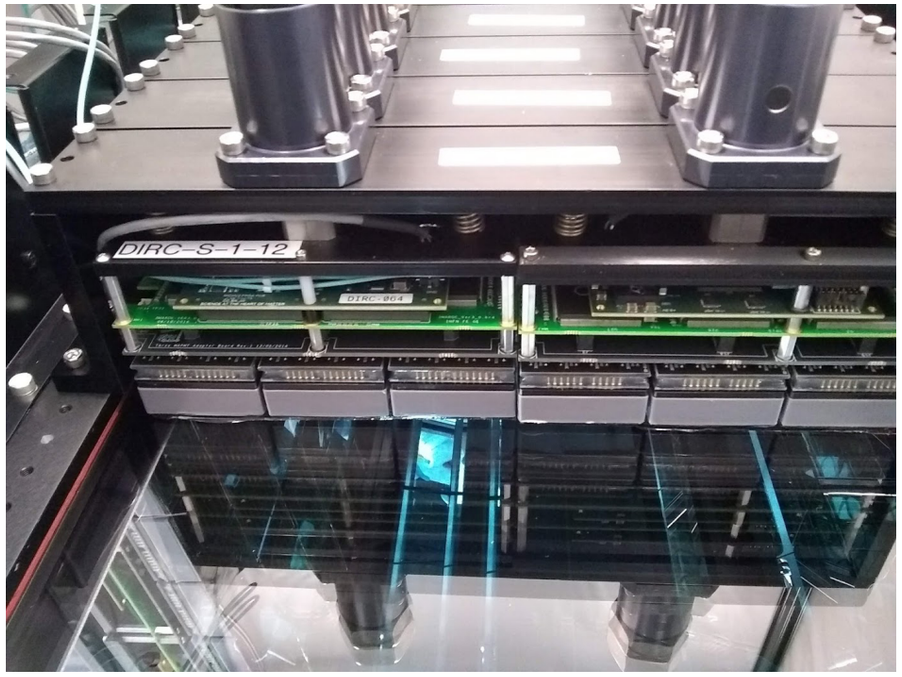
GlueX DIRC

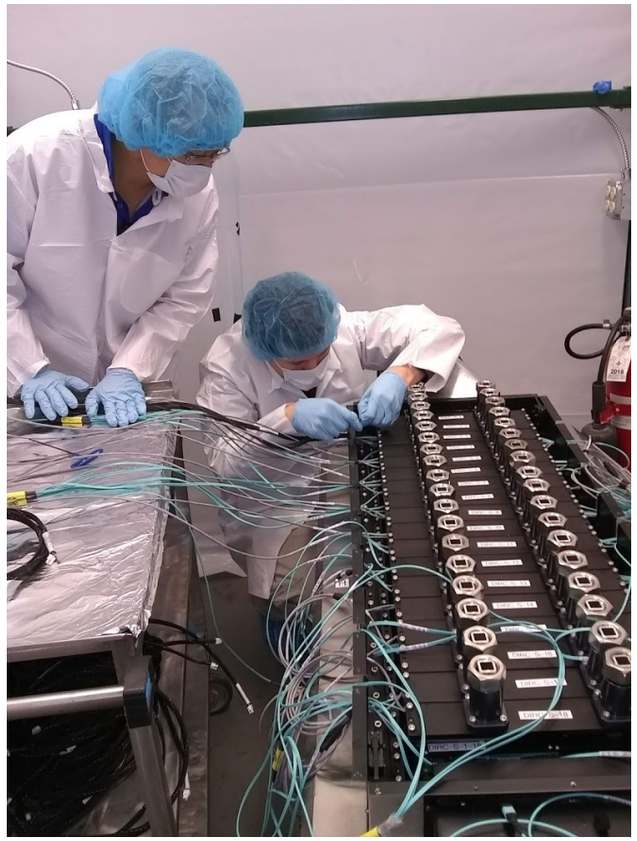




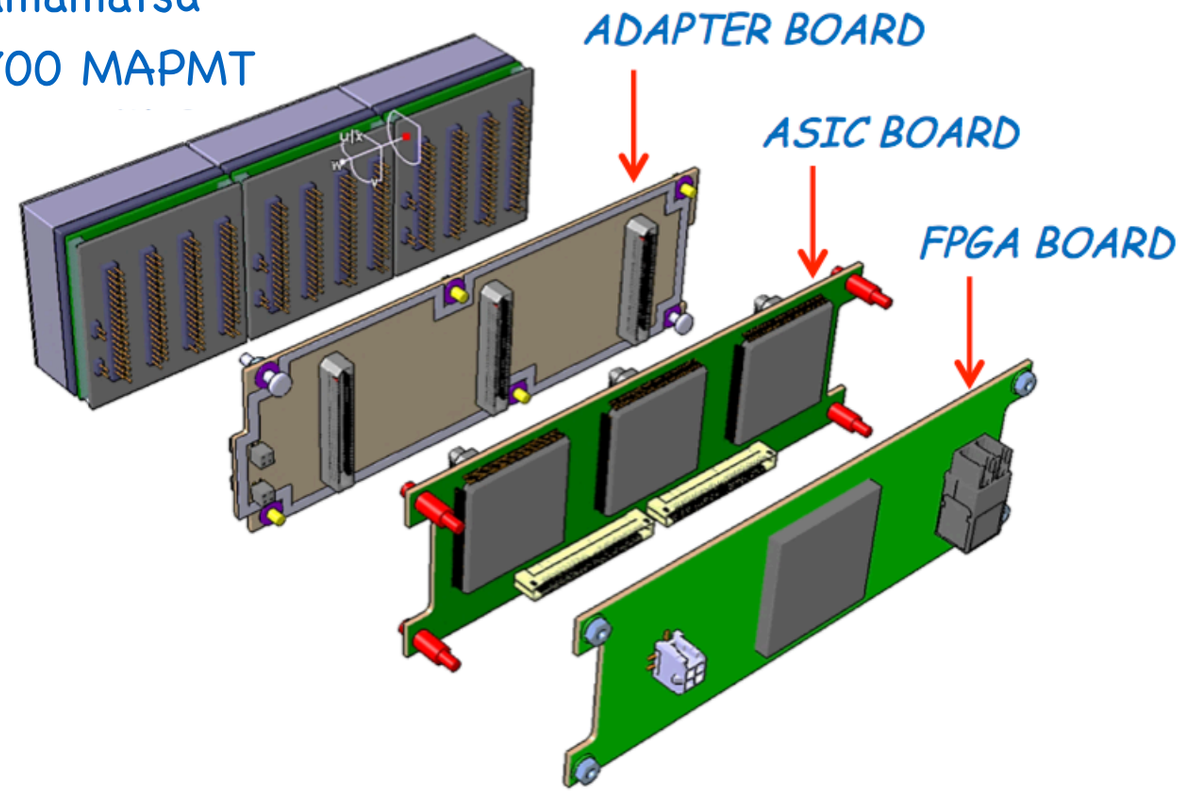
48 fused silica radiator bars installed, covering 2<θ<11°

Photosensors and readout





Hamamatsu
H12700 MAPMT

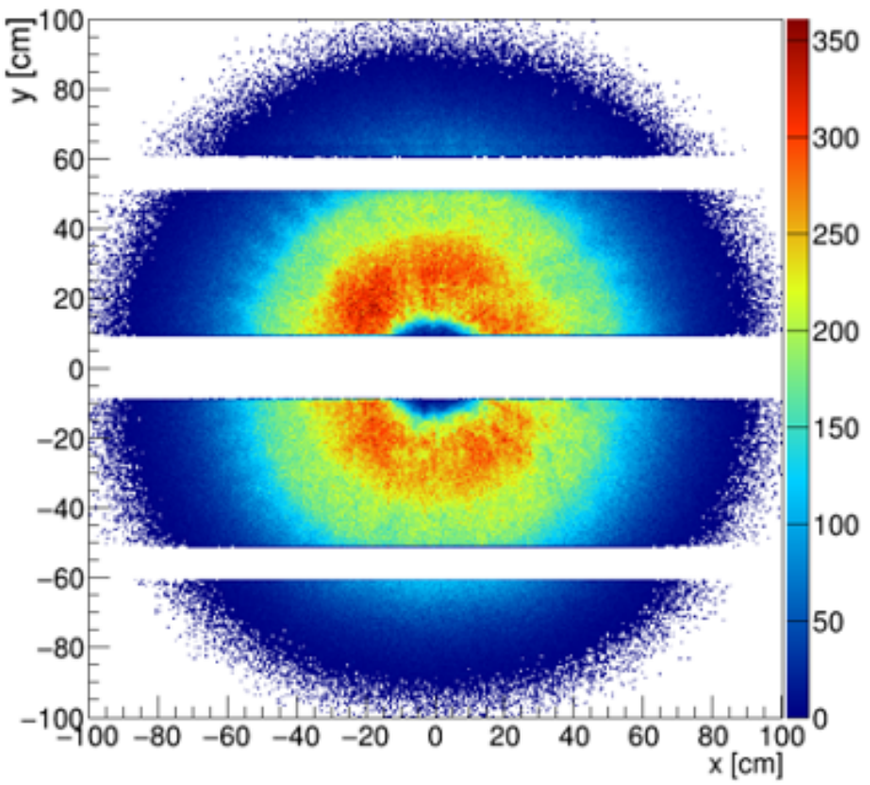


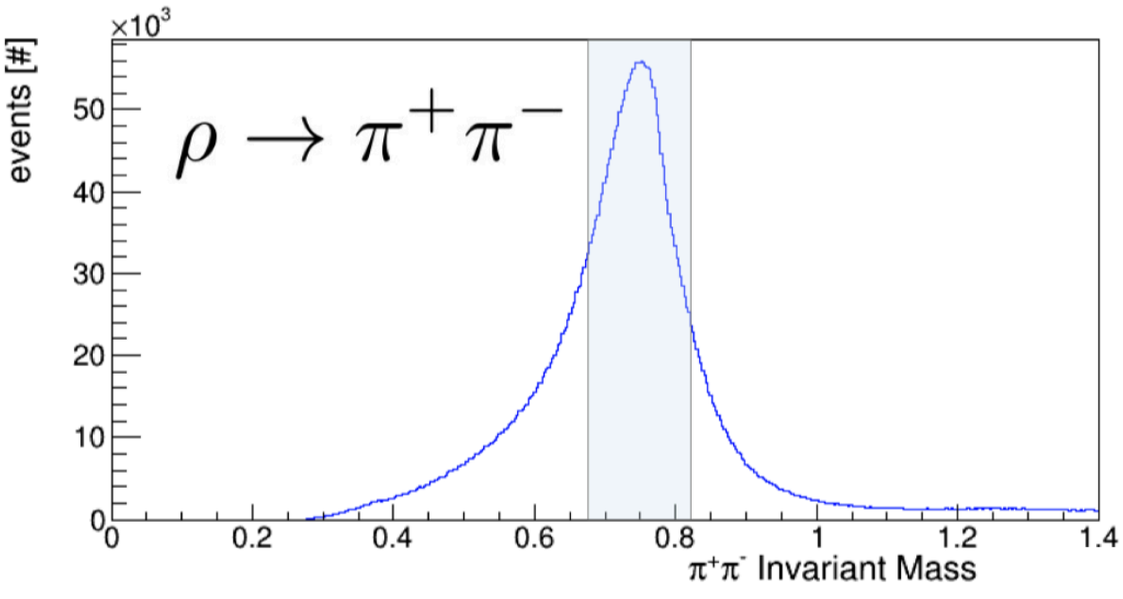
- Small magnetic field and limited timing resolution requirements to other DIRCs
- MAPMTs coupled to quartz window by optical cookies (a la Belle II)
- Utilized CLAS12 RICH readout with very similar requirements (see Marco's talk)

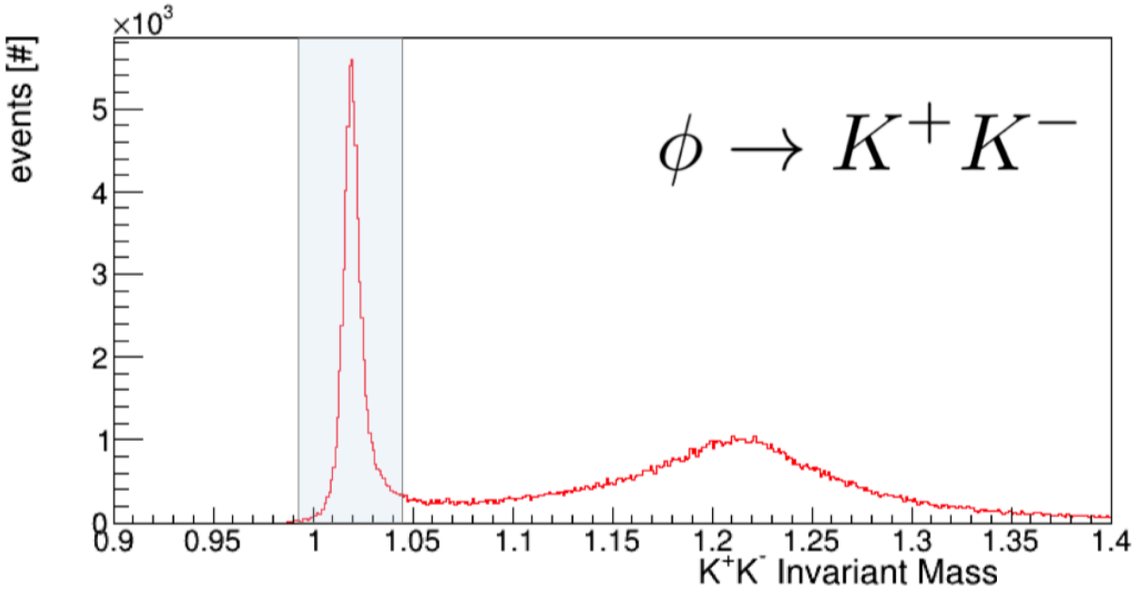
Timeline and performance evaluation

- 2020: GlueX-II production running for 6 months (COVID interruption), collected $\mathscr{L} \sim 0.35\ fb^{-1}$
- Additional data in 2023 and 2025 which are currently being analyzed
- GlueX-II samples of exclusive ρ and ϕ photoproduction provide pure samples of $\pi^{\pm}$ and $K^{\pm}$ tracks for PID studies

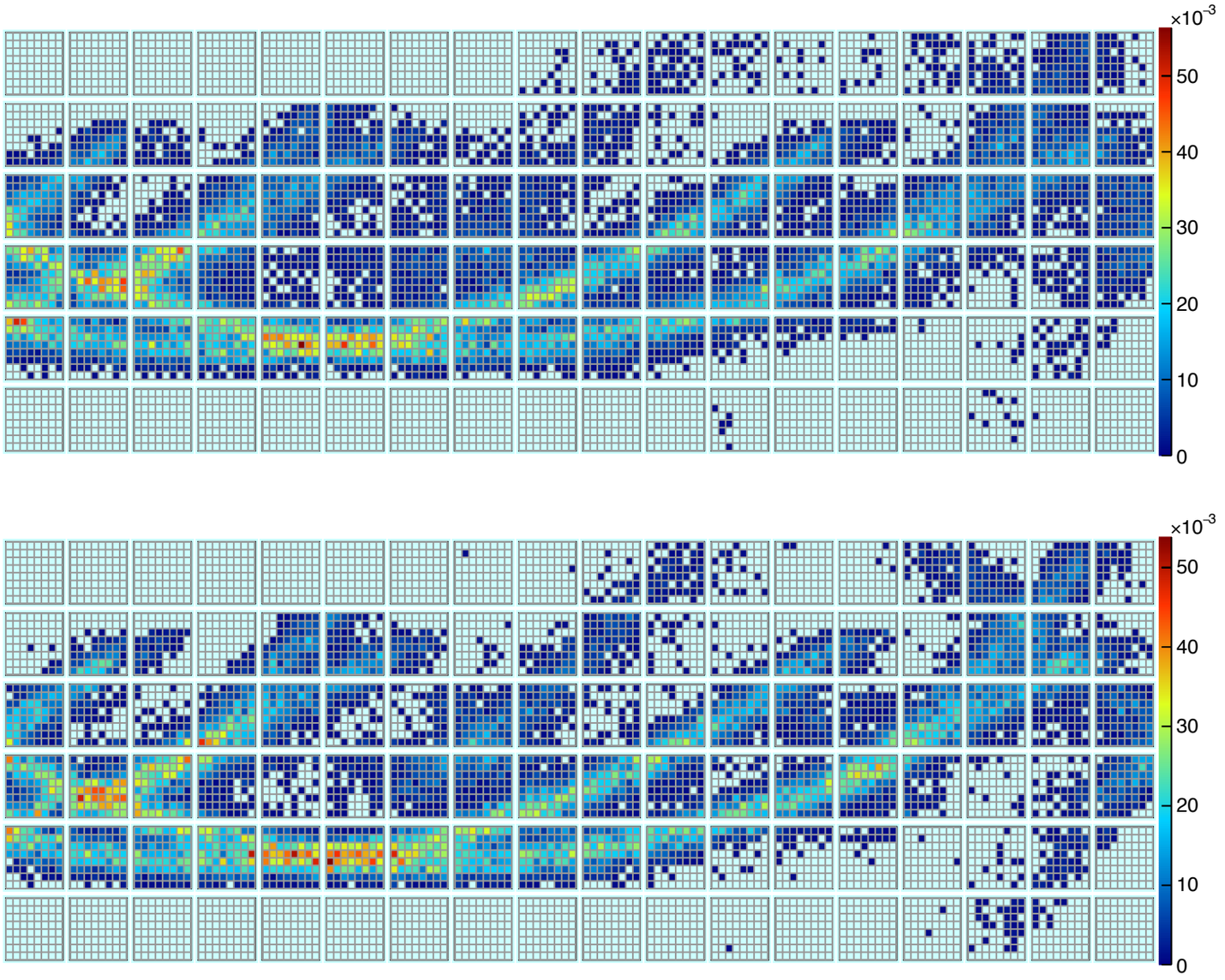
Track hit locations on DIRC plane







Photon hit patterns: **pions**

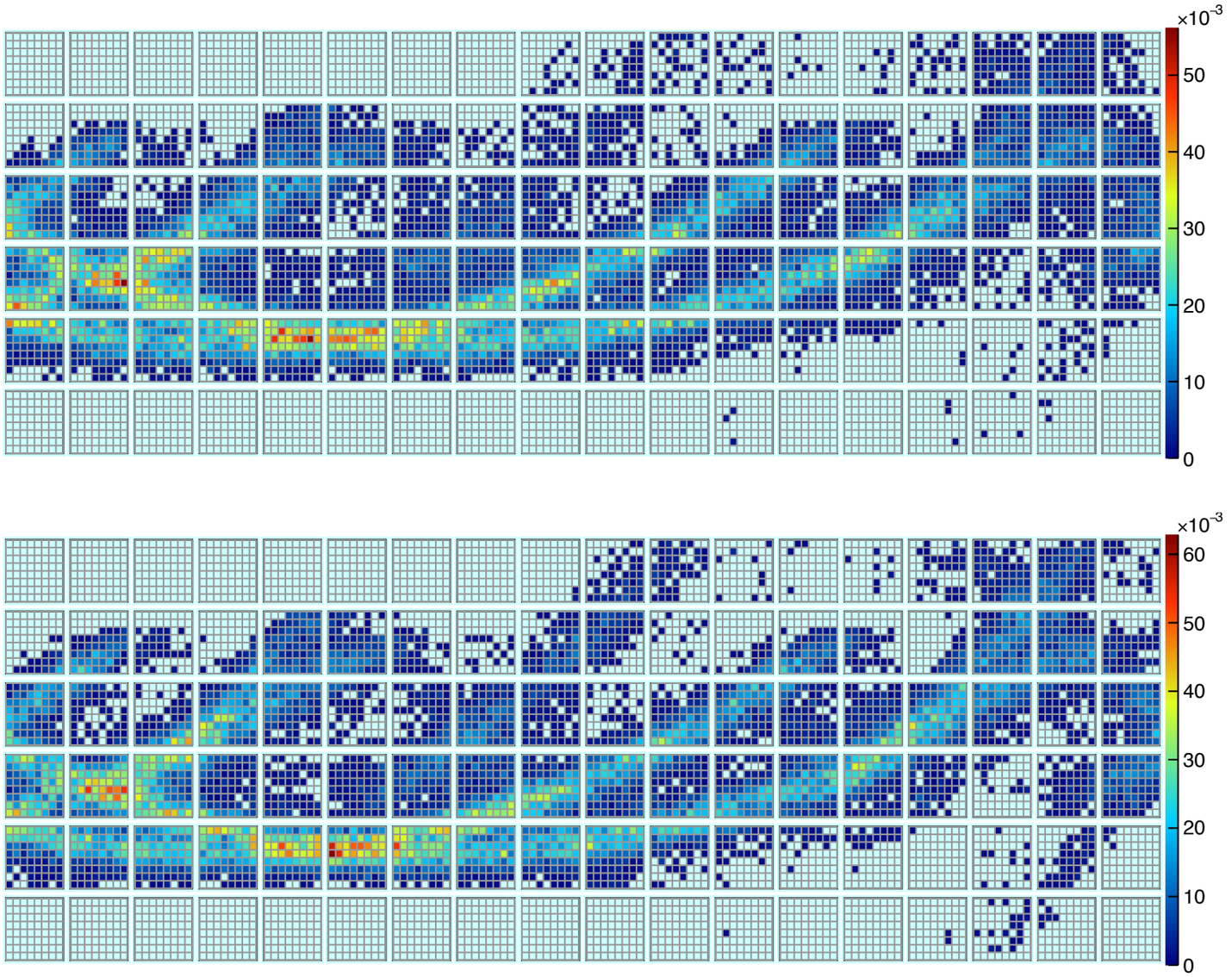


GlueX-II Data

Geant4 Simulation

- Hit patterns from 1000 identified pion tracks with p = 3.5 GeV/c
- Good agreement between beam data and simulations

Photon hit patterns: **kaons**



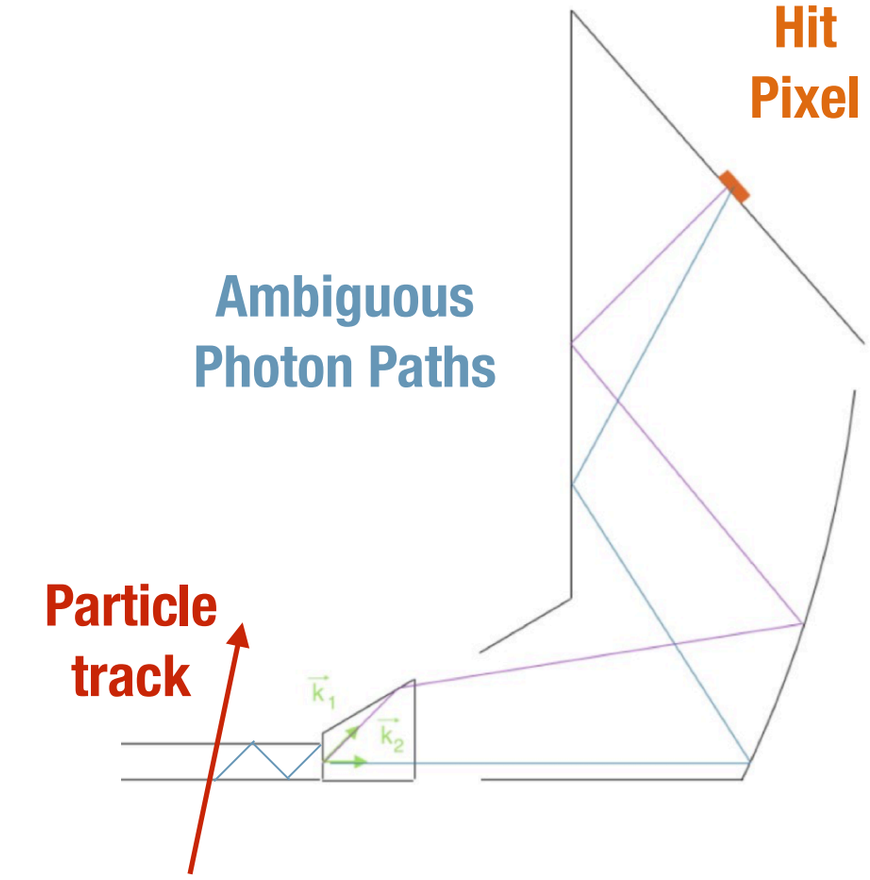
GlueX-II Data

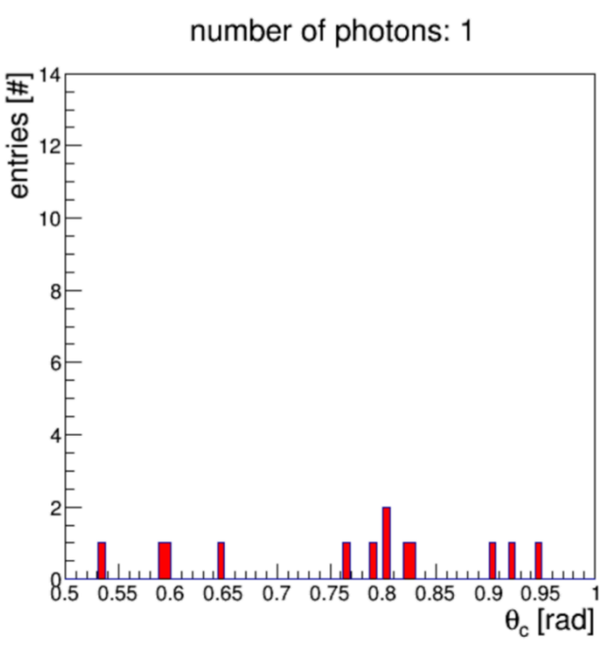
Geant4 Simulation

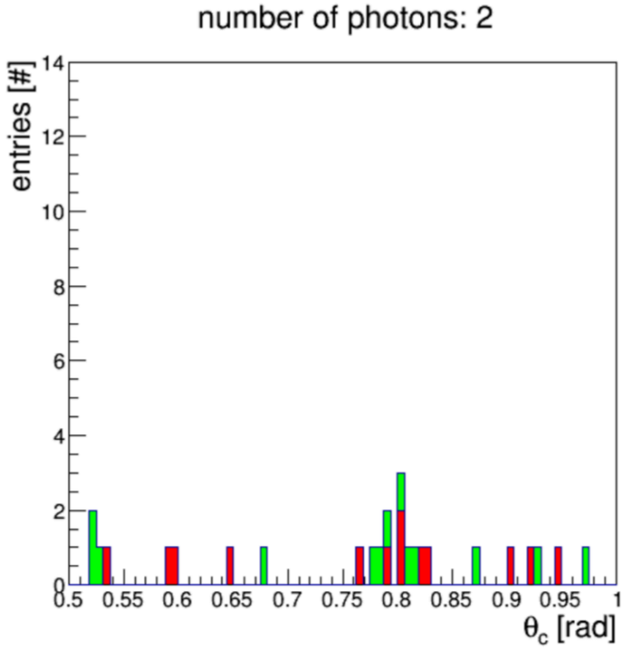
- Hit patterns from 1000 identified kaons tracks with p = 3.5 GeV/c
- Good agreement between beam data and simulations

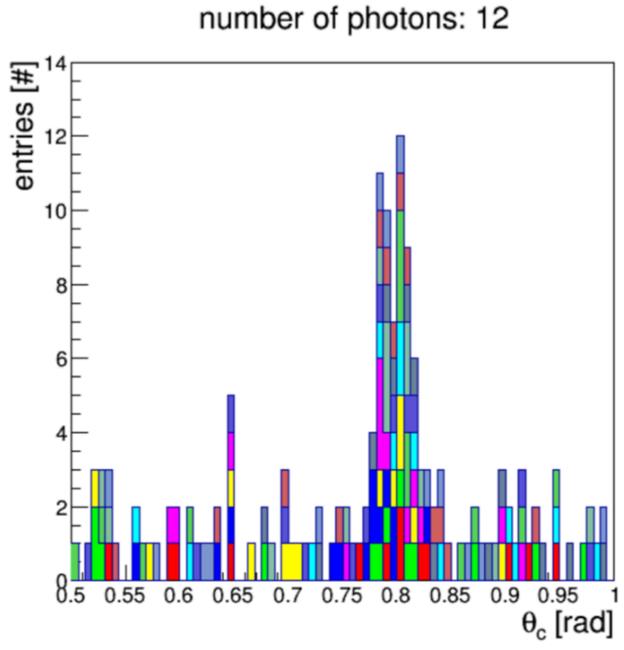
Geometric reconstruction

- Adapted from BaBar, then PANDA Barrel DIRC reconstruction
- Each detected photon has multiple ambiguous paths with different Cherenkov angles, computed using look up tables
- Compute likelihood for π and K mass hypothesis over all detected photons



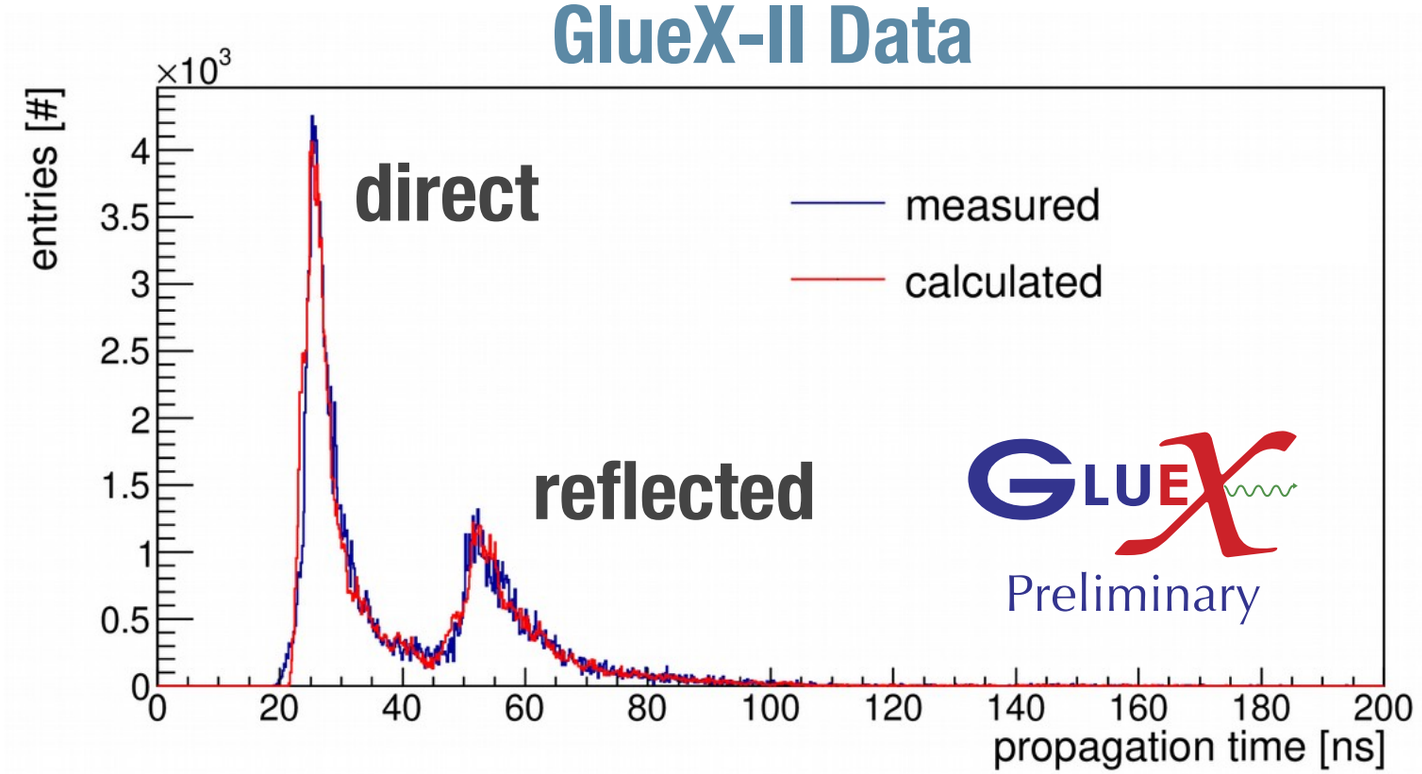


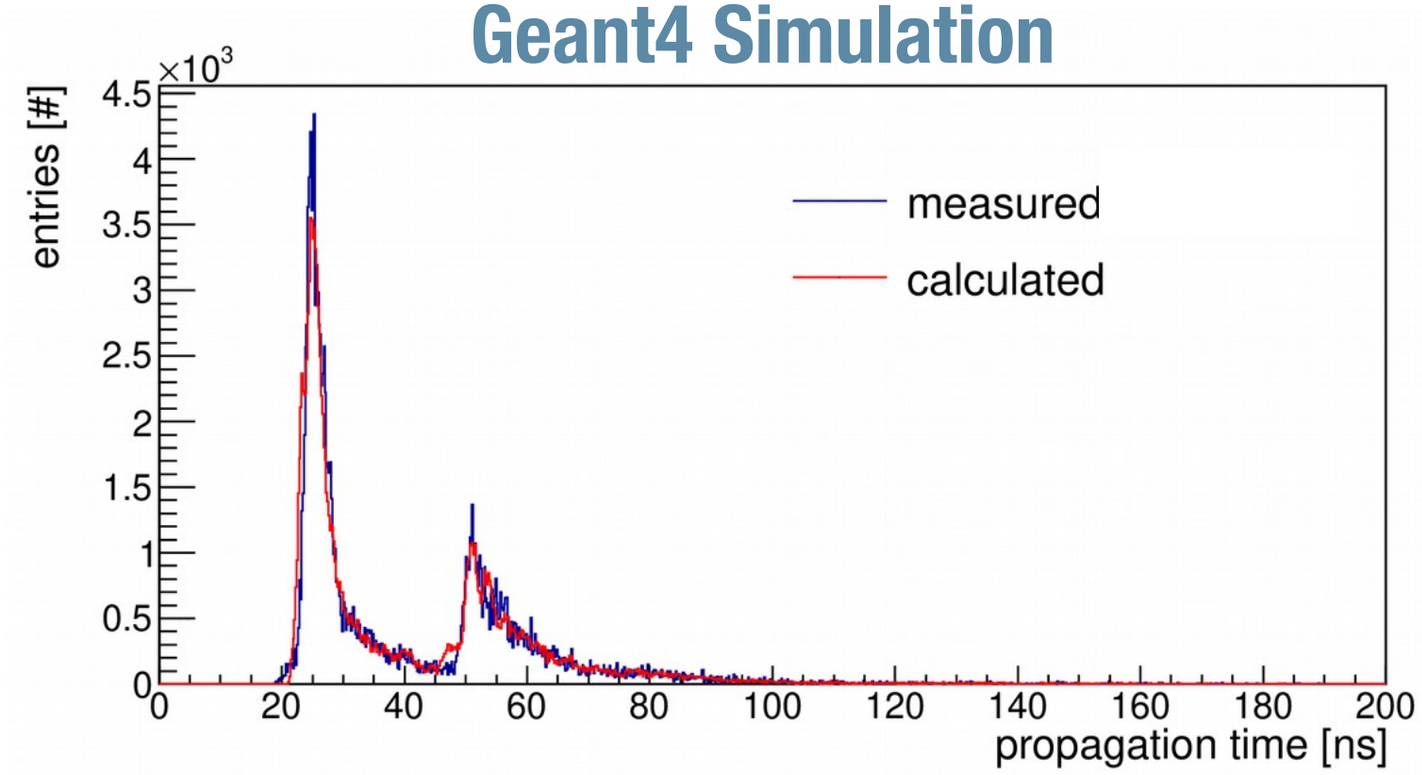




Photon Propagation Time

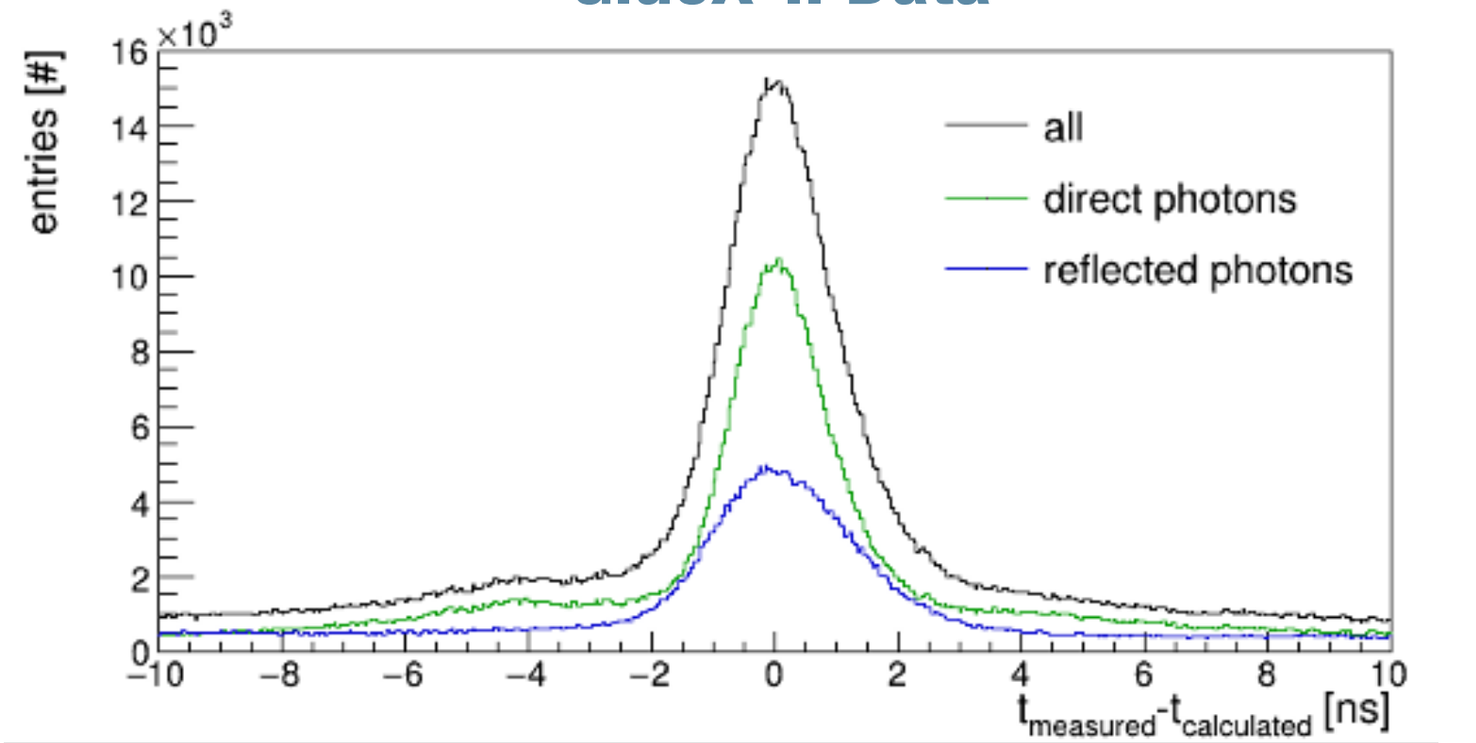
Propagation time: direct and reflected photons separable, reasonable data/MC agreement

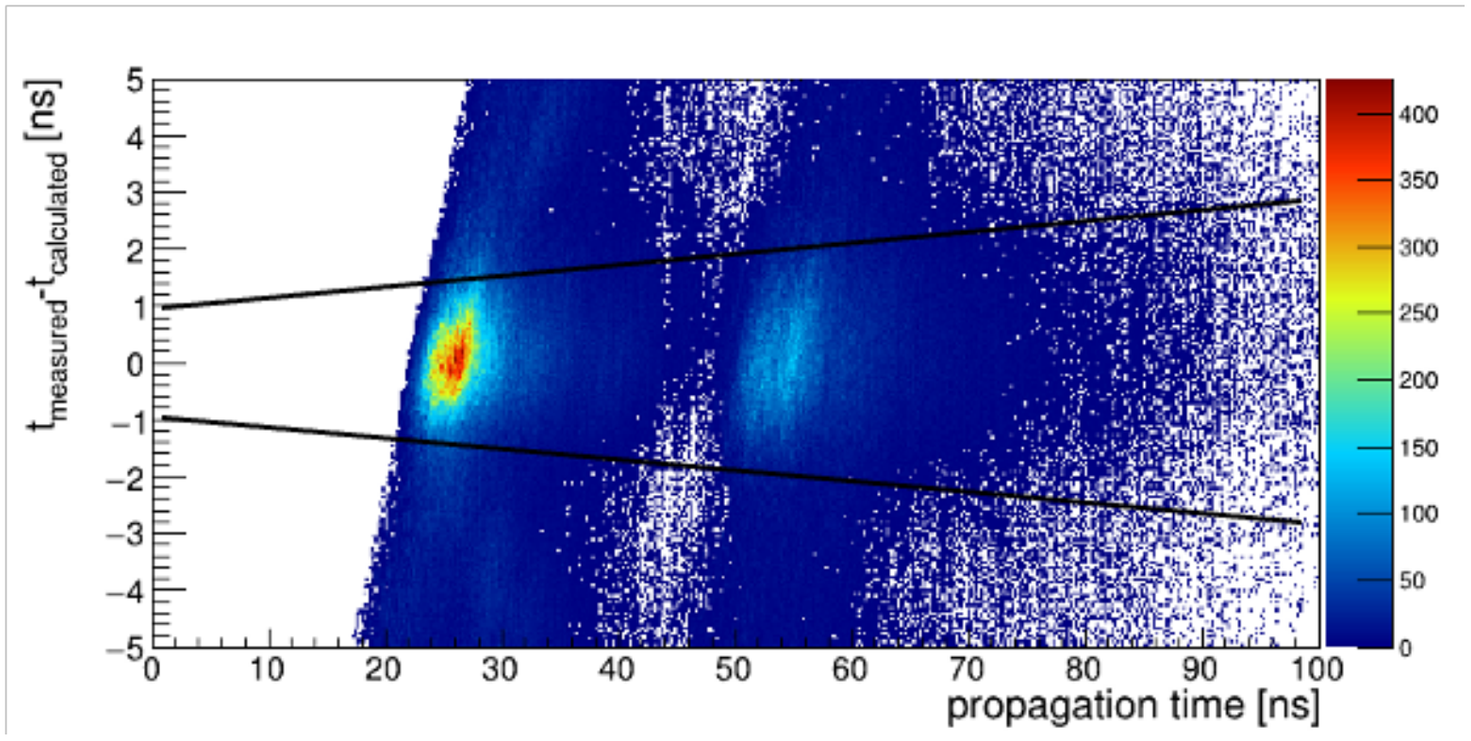




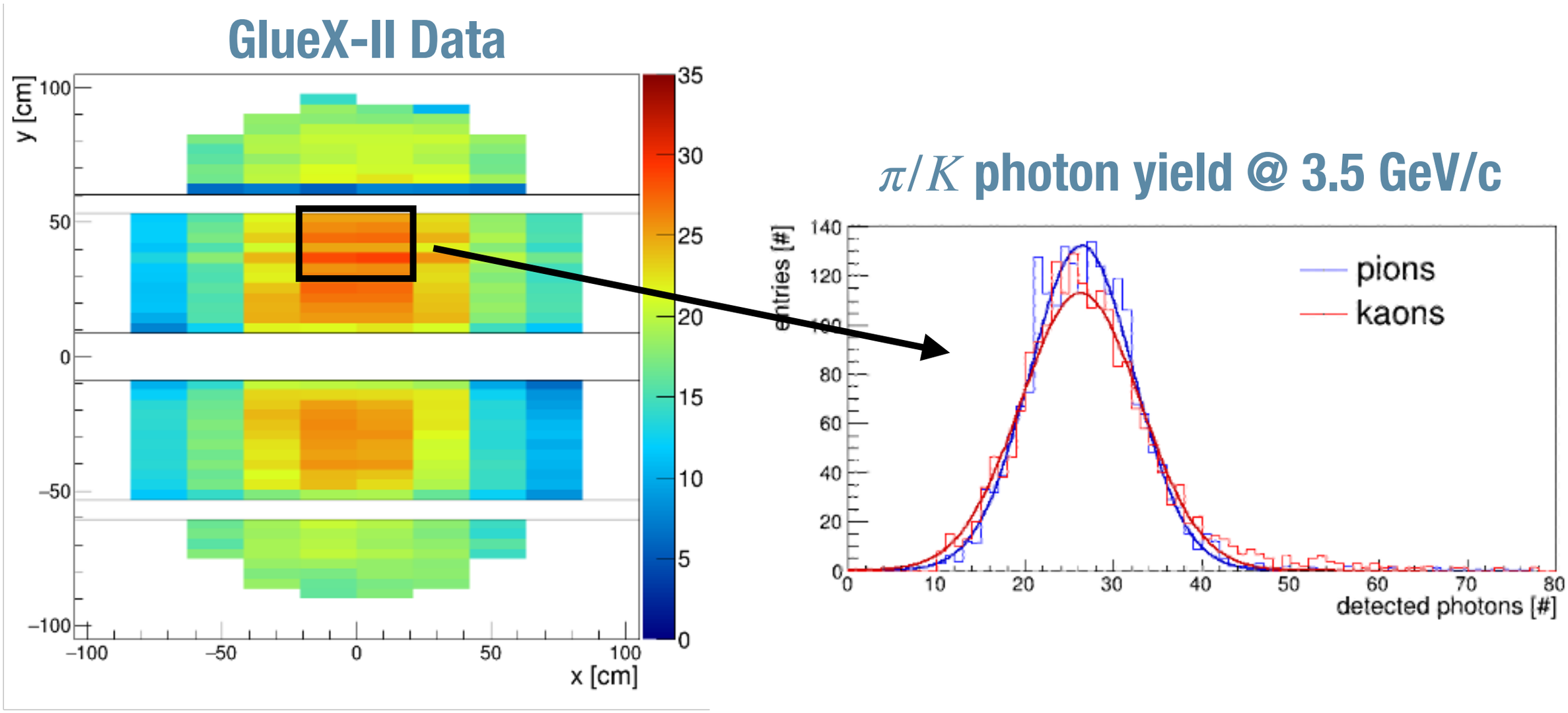
Photon Propagation Time

Propagation time: direct and reflected photons separable, reasonable data/MC agreement





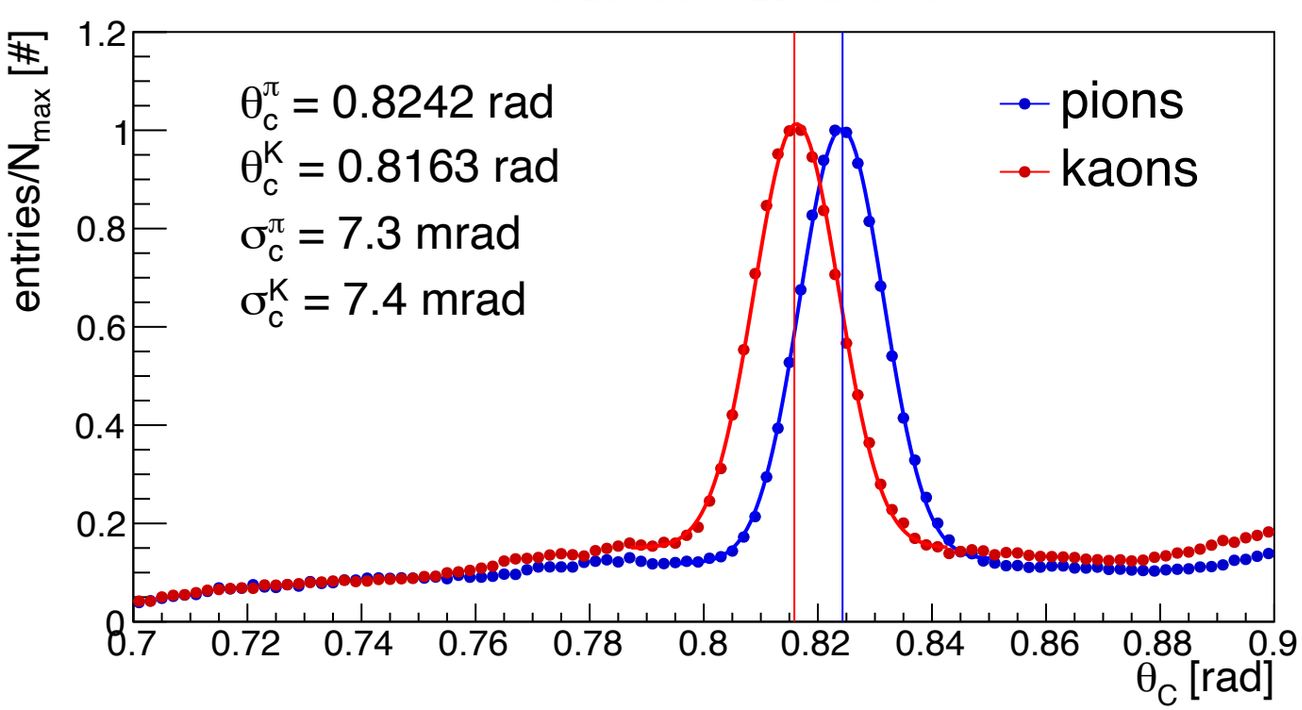
Photon Yield

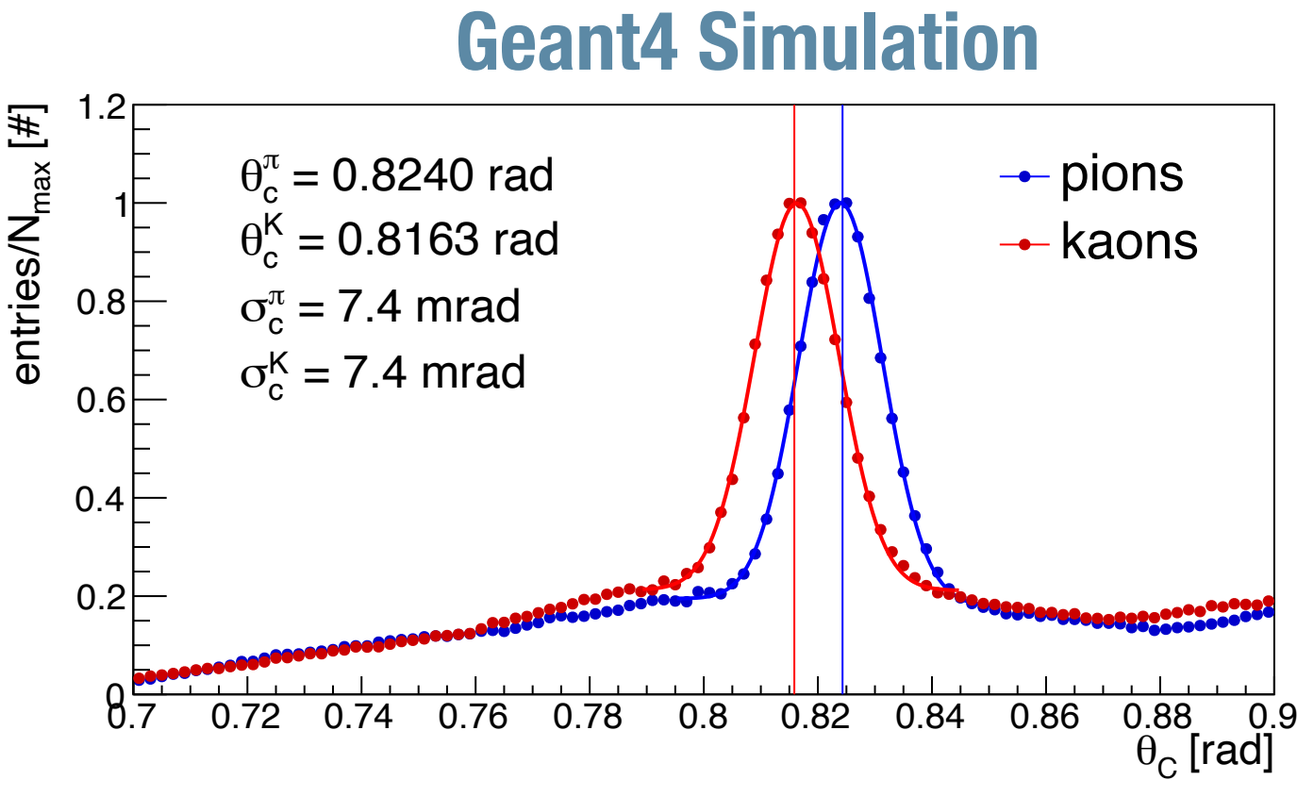


- ~15-30 photons per track, dependent on intersection point with DIRC plane and incident angle

Single photon resolution

Single Photon Resolution: example at 3.5 GeV/c, in good agreement with expectations from simulation

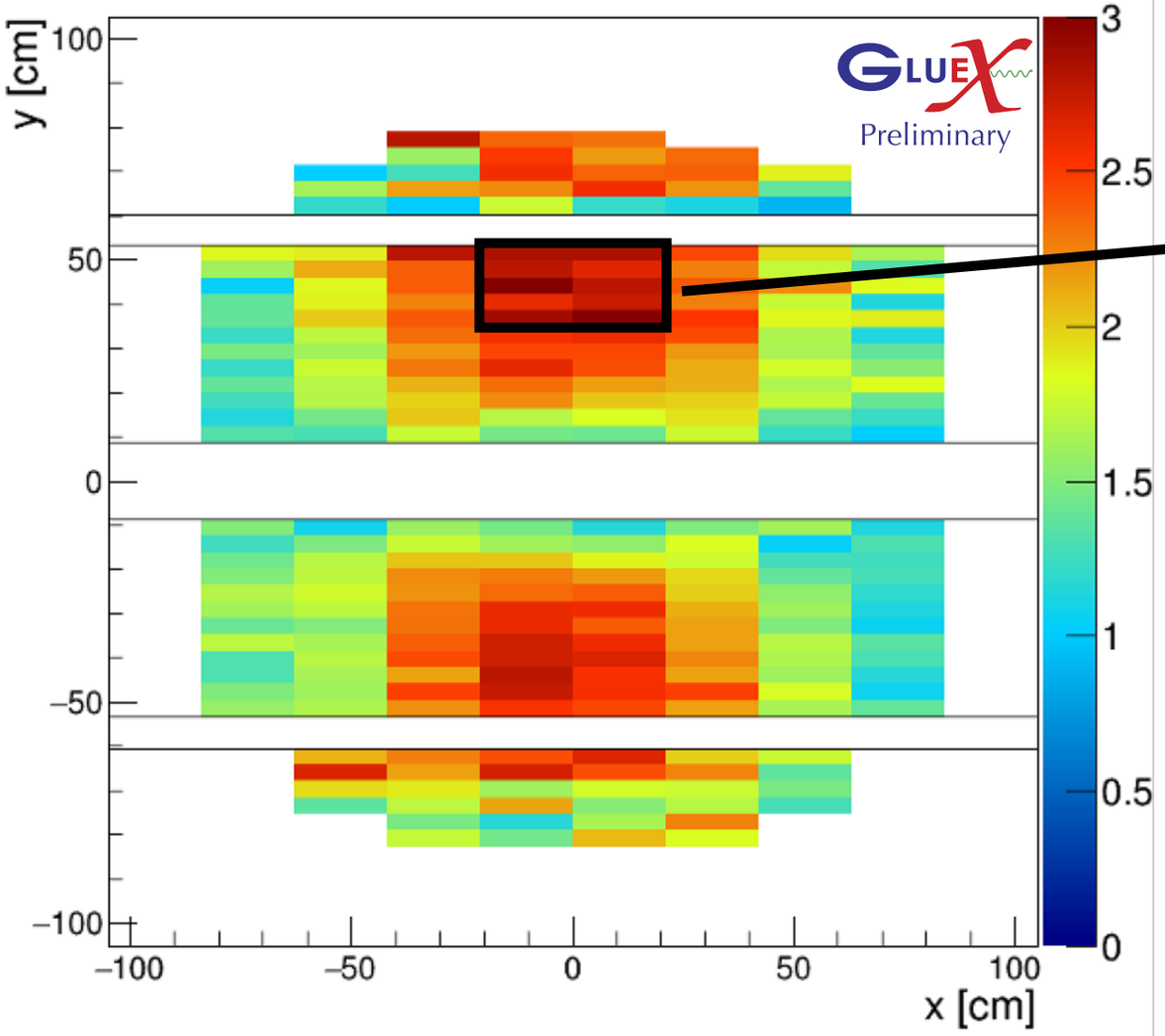


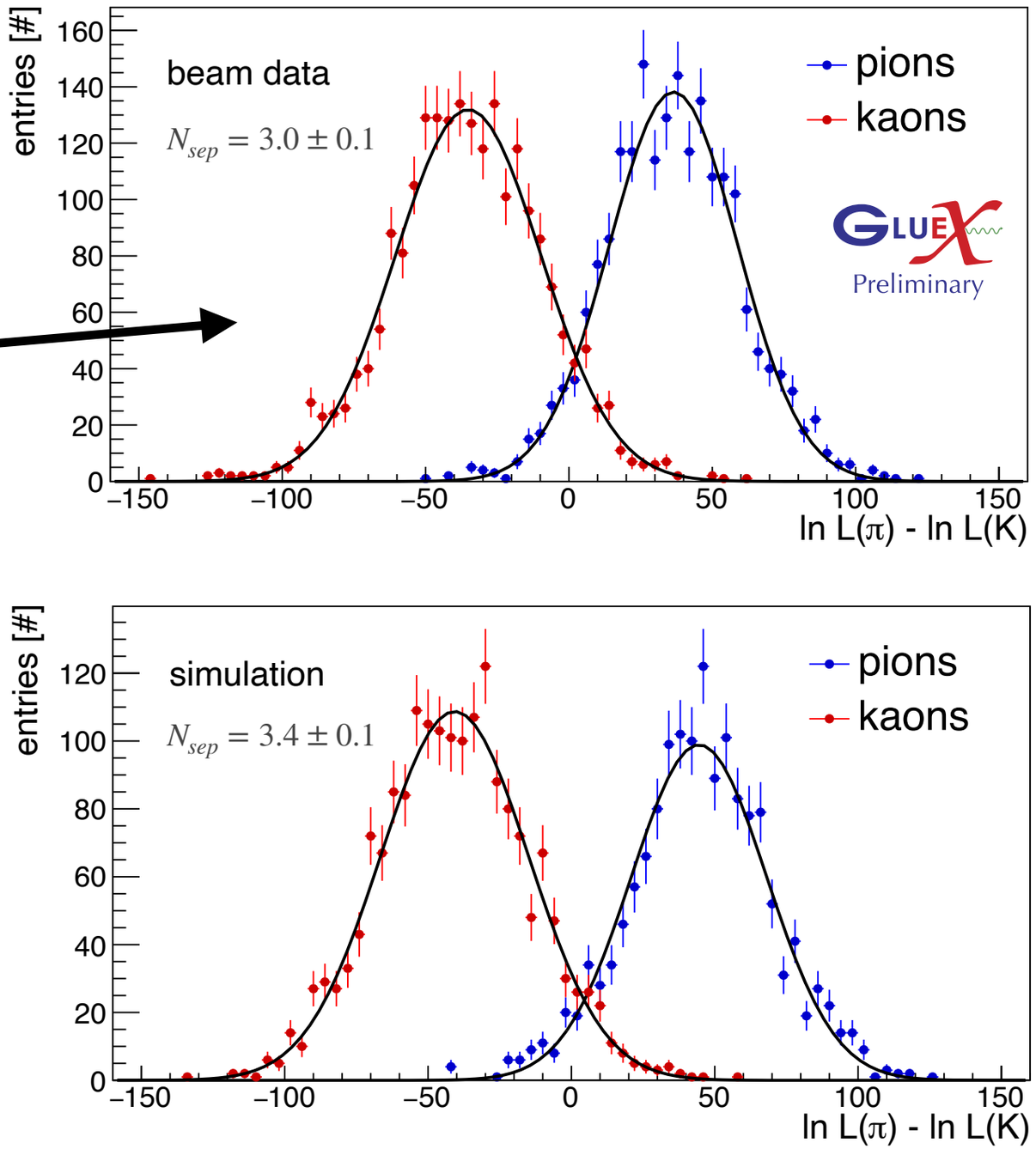


Separation power

$$N_{sep} = \frac{|\mu_\pi - \mu_k|}{0.5(\sigma_\pi + \sigma_k)}$$

π/K separation power @ 3.5 GeV/c





J.Phys.Conf.Ser. 2374 (2022)

Application of Machine Learning

Deep(er) Reconstruction of Imaging Cherenkov Detectors with Swin Transformers and Normalizing Flow Models

C. Fanelli, J. Giroux, JRS
MLST 6 (2025) 1, 015028

- **Goal:** demonstrate proof of principle with single particle simulation for
  - Fast simulation → Normalizing Flows (NF)
  - Particle identification → NF and Swin Transformer

Normalizing Flows (NF)

MLST 6 (2025) 1, 015028

- Learn likelihood function by change of variables from unknown PDF $p(\boldsymbol{x}, \boldsymbol{k})$
  - $\boldsymbol{x}$ = photon with position x, y and time t
  - $\boldsymbol{k}$ = conditional track kinematics: $|\vec{p}\,|, \theta, \phi$
- To a Gaussian representation of $\boldsymbol{x}$ through Neural Network (NN) transformation

$$\boldsymbol{x_k} = f(\boldsymbol{z}, \boldsymbol{k}) = f_N \circ f_{N-1} \circ ... f_1(\boldsymbol{z_0}, \boldsymbol{k}),$$

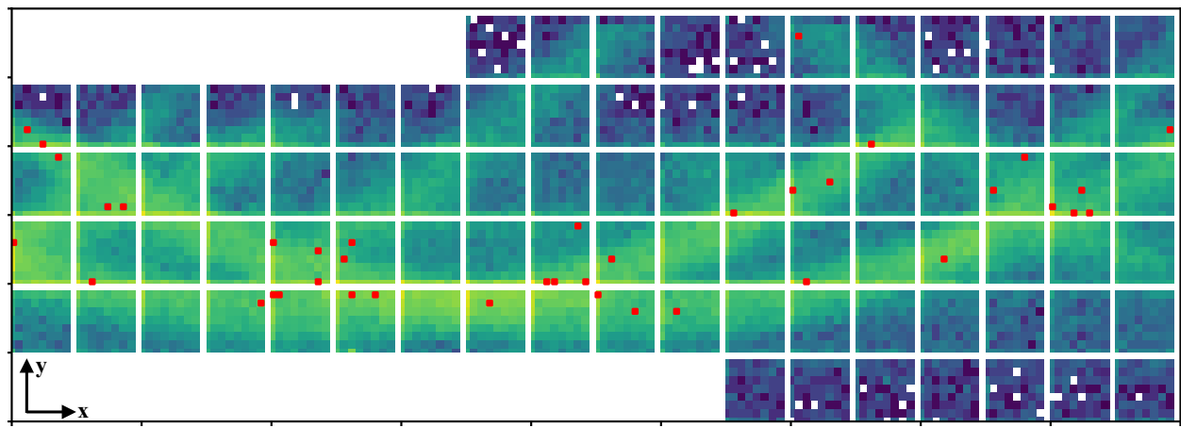
- Train NN with loss function from transformed likelihood

$$\log p(\boldsymbol{x}|\boldsymbol{k}) = \log q(f^{-1}(\boldsymbol{x})|\boldsymbol{k}) + \sum_{i=1}^{N} \log \left| det \left(\frac{\partial f_i^{-1}(\boldsymbol{x})}{\partial \boldsymbol{x}} \right) \right|$$

Normalizing Flows (NF)

MLST 6 (2025) 1, 015028

- Learn likelihood function by change of variables from unknown PDF $p(\boldsymbol{x}, \boldsymbol{k})$
  - $\boldsymbol{x}$ = photon with position x, y and time t
  - $\boldsymbol{k}$ = conditional track kinematics: $|\vec{p}\,|, \theta, \phi$



Training Data: individual photons

$$\begin{pmatrix} x_1 & y_1 & t_1 \\ x_2 & y_2 & t_2 \\ \vdots & \vdots & \vdots \\ x_{N_\gamma} & y_{N_\gamma} & t_{N_\gamma} \end{pmatrix} \qquad \begin{pmatrix} |\vec{p}\,| \\ \theta \\ \phi \end{pmatrix}$$

- Train NN with loss function from transformed likelihood

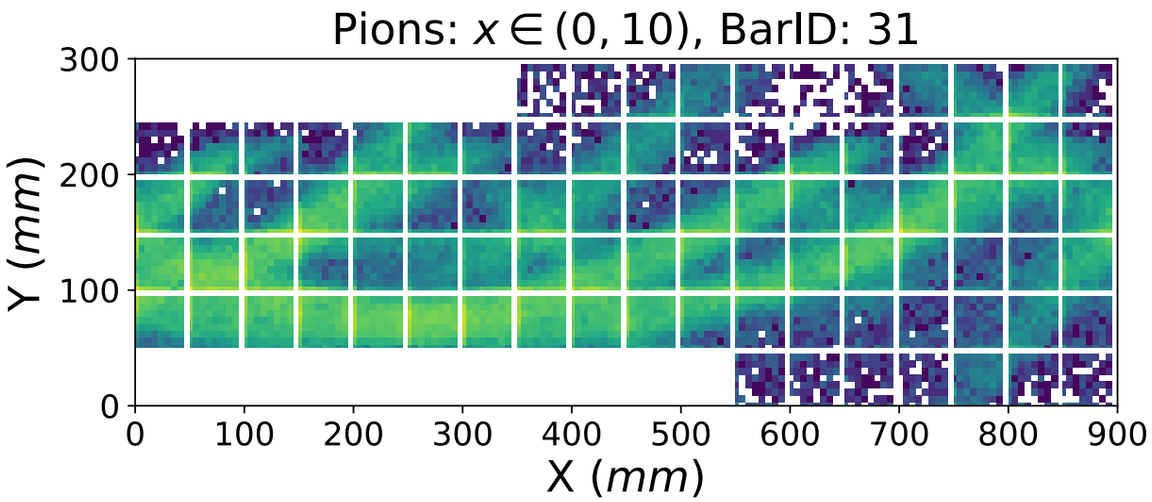
$$\log p(\boldsymbol{x}|\boldsymbol{k}) = \log q(f^{-1}(\boldsymbol{x})|\boldsymbol{k}) + \sum_{i=1}^{N} \log \left| det \left(\frac{\partial f_i^{-1}(\boldsymbol{x})}{\partial \boldsymbol{x}} \right) \right|$$

Fast Simulation with NF

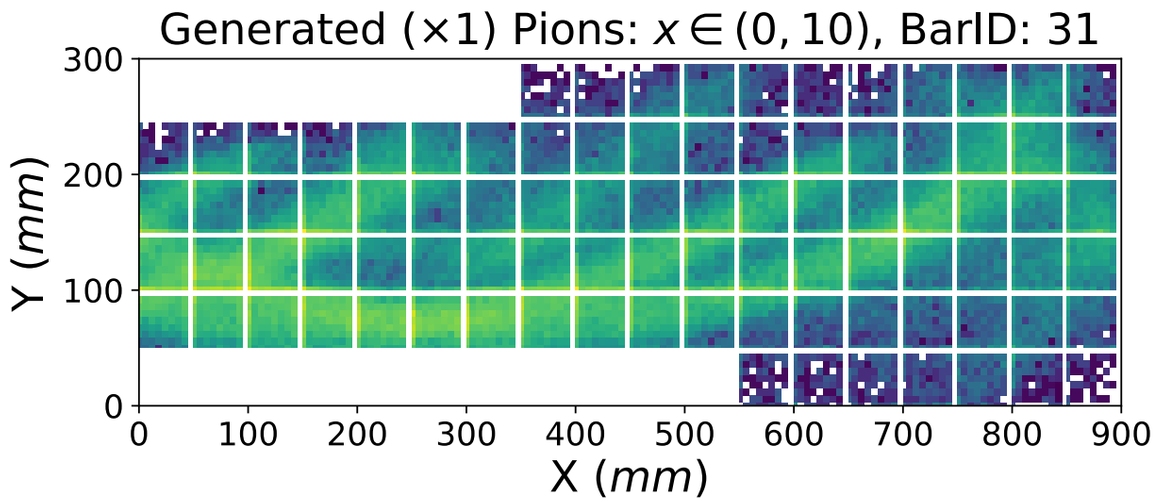
MLST 6 (2025) 1, 015028

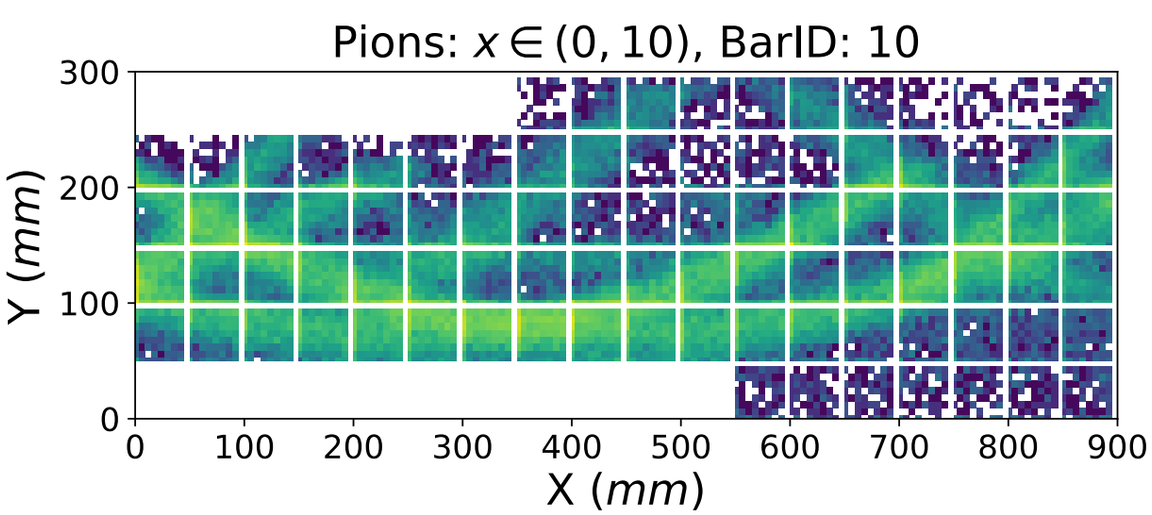
- With known NF transformation, straightforward to generate photons for each track
- Potential to learn transformation directly from data

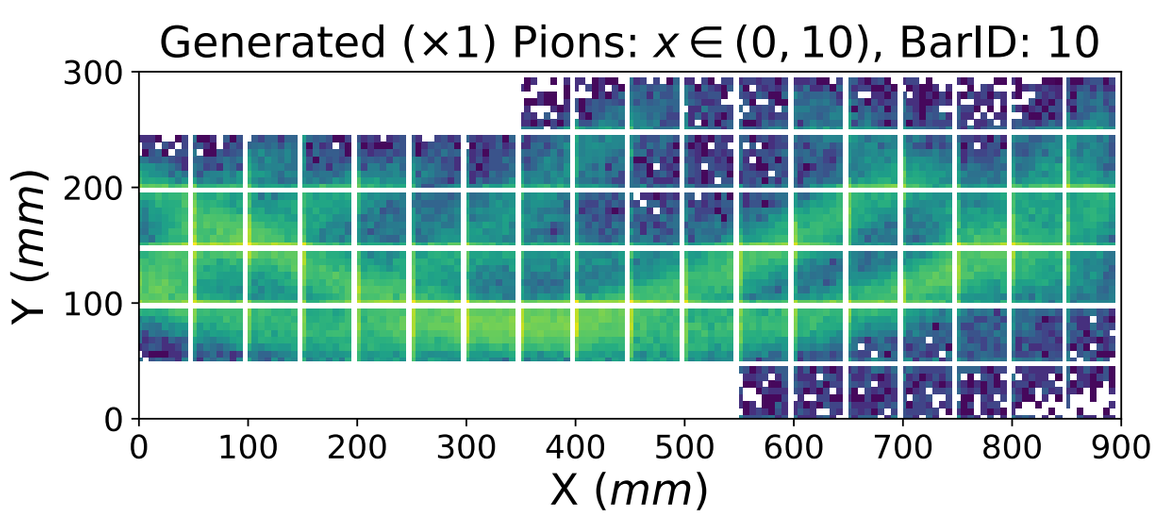
Geant4 Truth Distribution



NF Generated Distribution

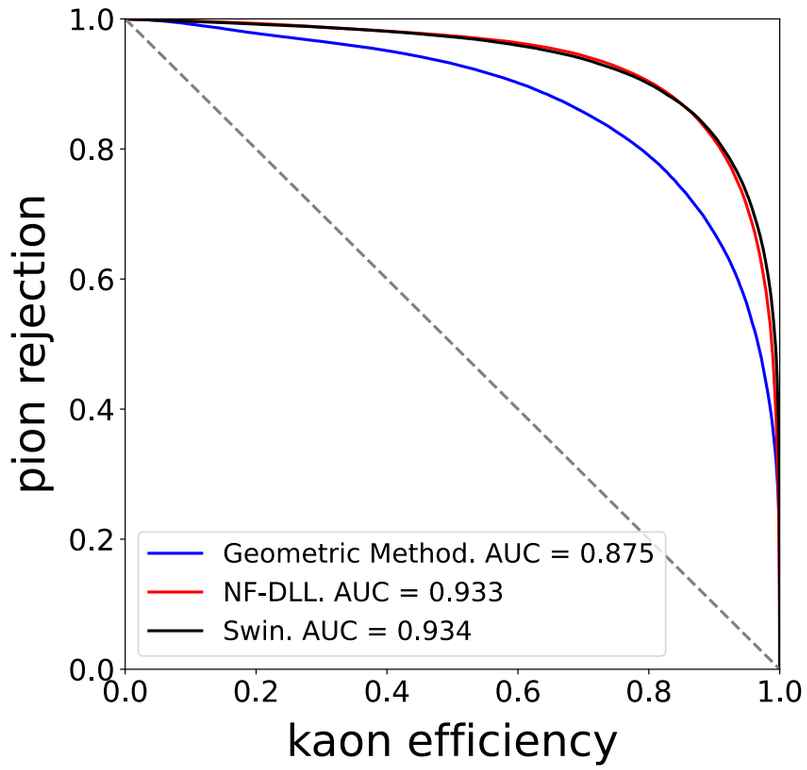


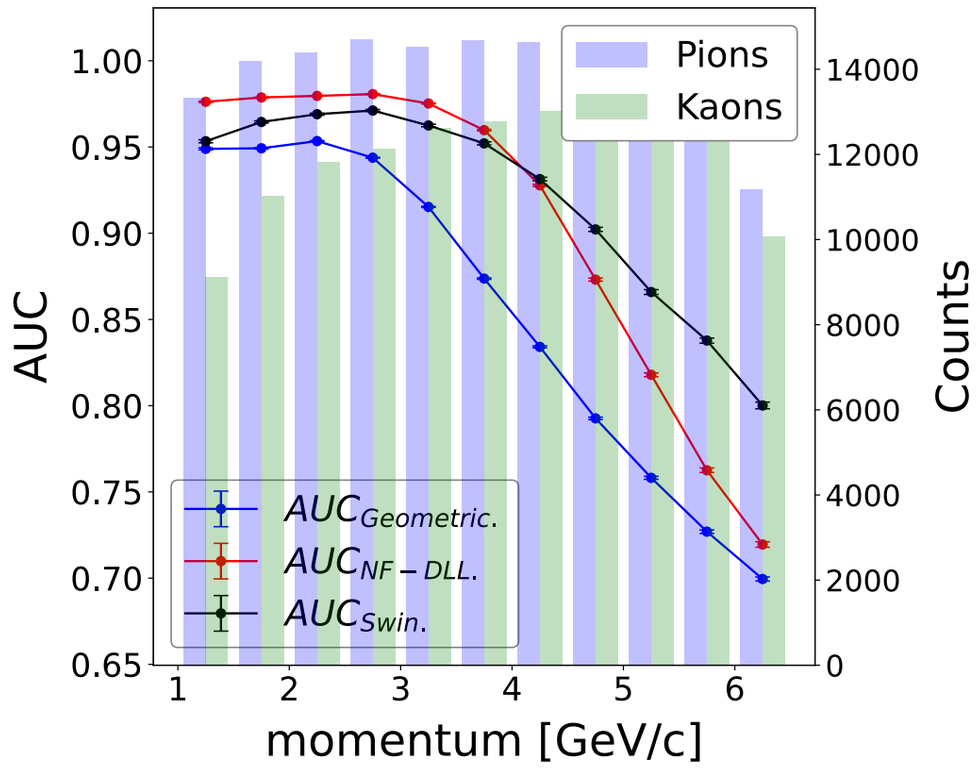




Classification with NF

MLST 6 (2025) 1, 015028





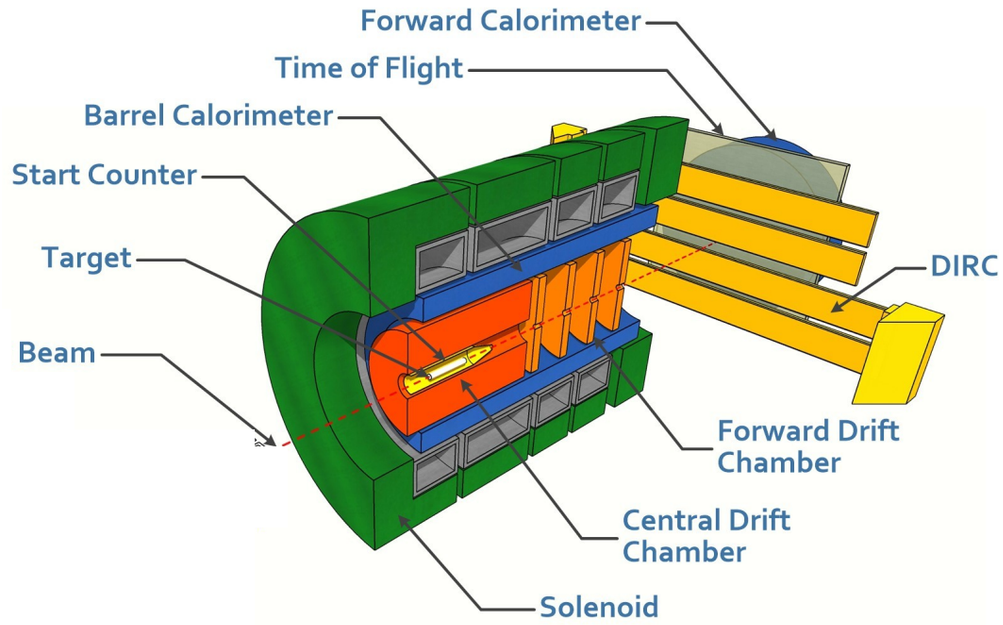
- NF also provides analytic likelihood function to directly compute traditional log likelihood difference

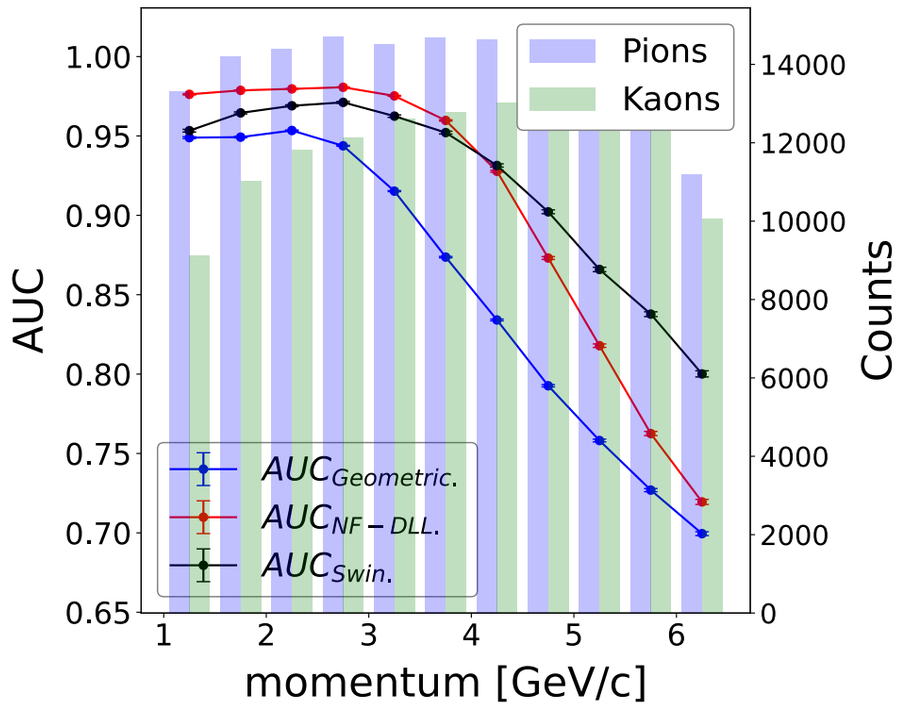
$$\Delta \log \mathcal{L}_{K\pi} = \sum_{i}^{N} \log p(\vec{x}_i|\vec{k}, K) - \sum_{i}^{N} \log p(\vec{x}_i|\vec{k}, \pi)$$

- Use Area Under the Curve (AUC) for pion rejection vs kaon efficiency to quantify performance

Summary

- The second phase of GlueX is a multi-year effort with data taking from 2020 to 2026
- Recently completed 2025 run with new $PbWO_4$ calorimeter, will continue in 2026
- Initial performance evaluation: 3σ π/K separation at 3.5 GeV/c
- Recent machine learning work demonstrates proof of principle with single particle simulations





Supported by DE-SC0023978

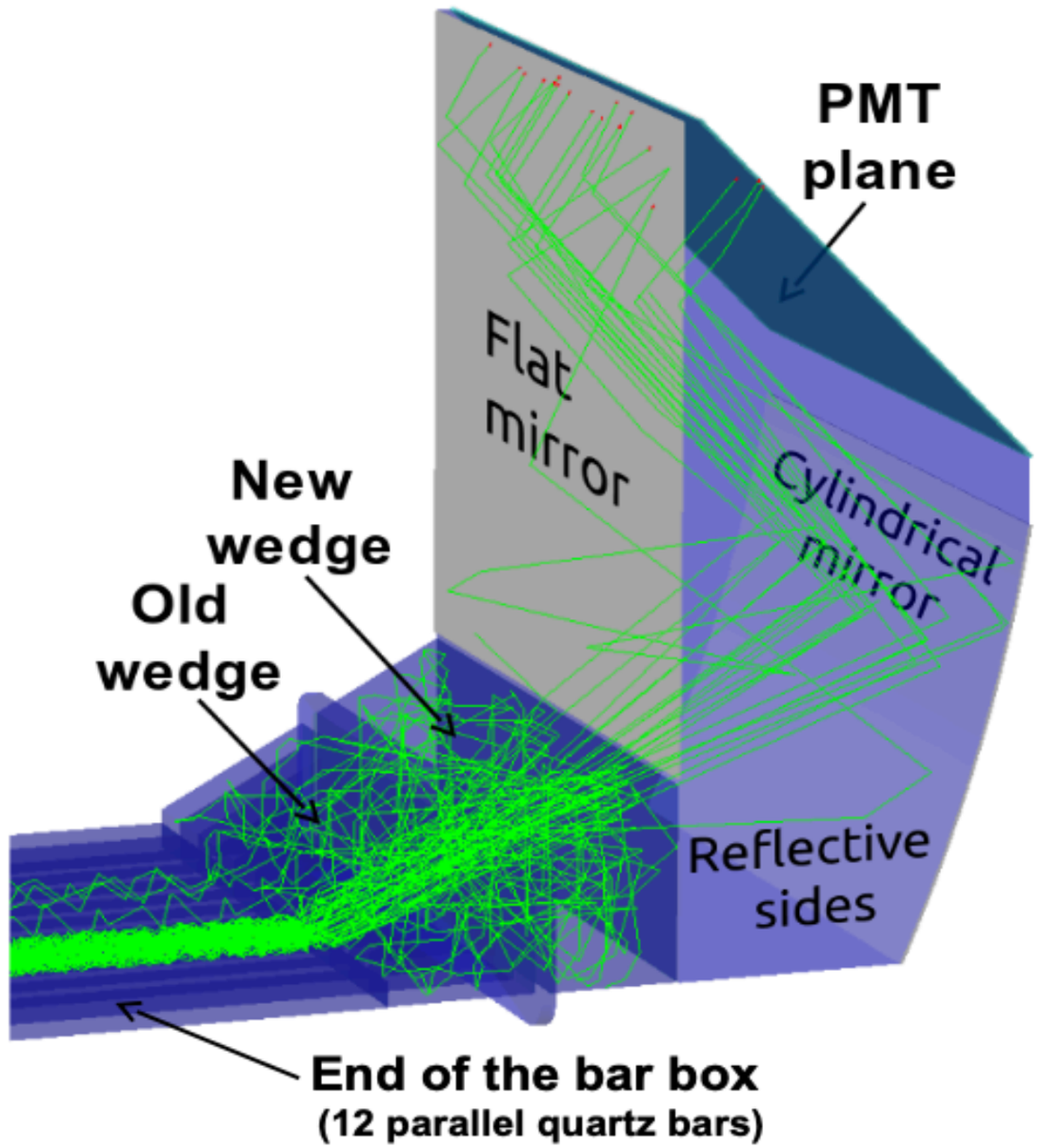
U.S. DEPARTMENT OF ENERGY | Office of Science

Backup

Optical box design

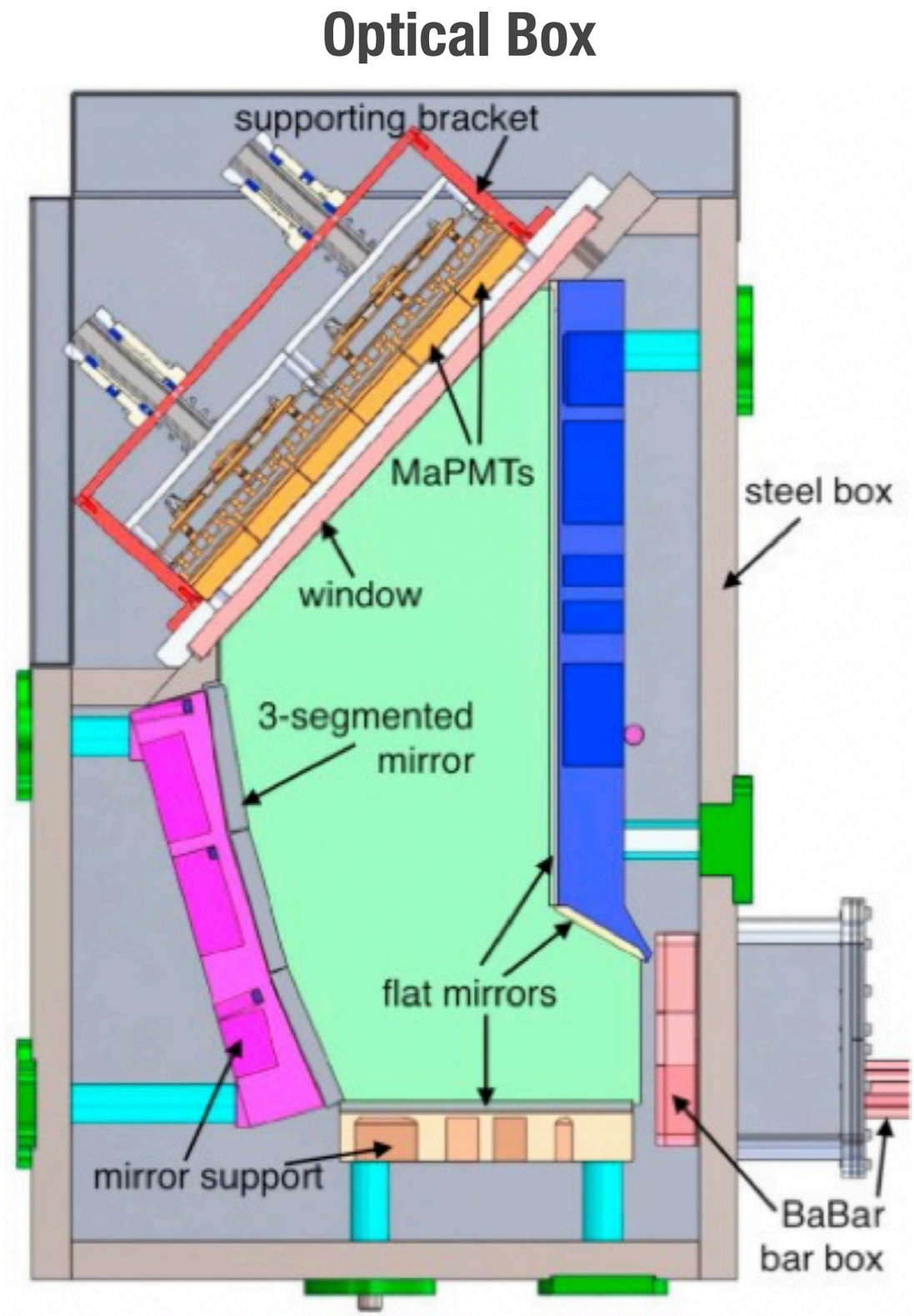
- Design based on SLAC FDIRC prototype
  - Replace fused silica block from FDIRC prototype with mirrors contained in water
  - Replace of cylindrical mirror with 3-segment flat mirror
- Similar coupling of bar boxes to water volume as used at BaBar

RICH2016: Dey, Ratcliff and Va'vra
NIMA 876 (2017) 141

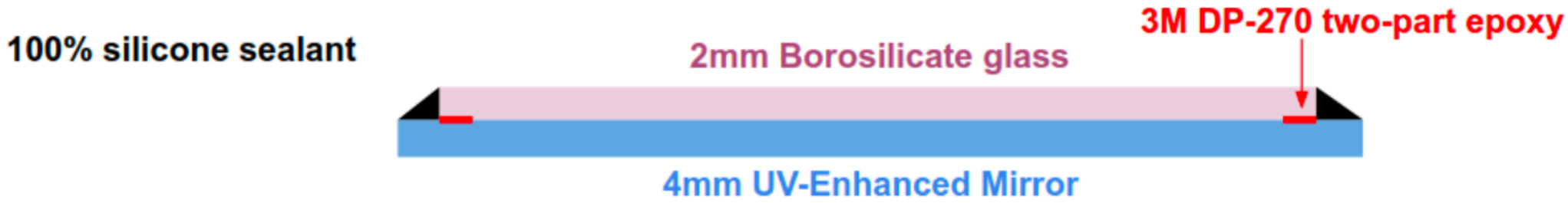


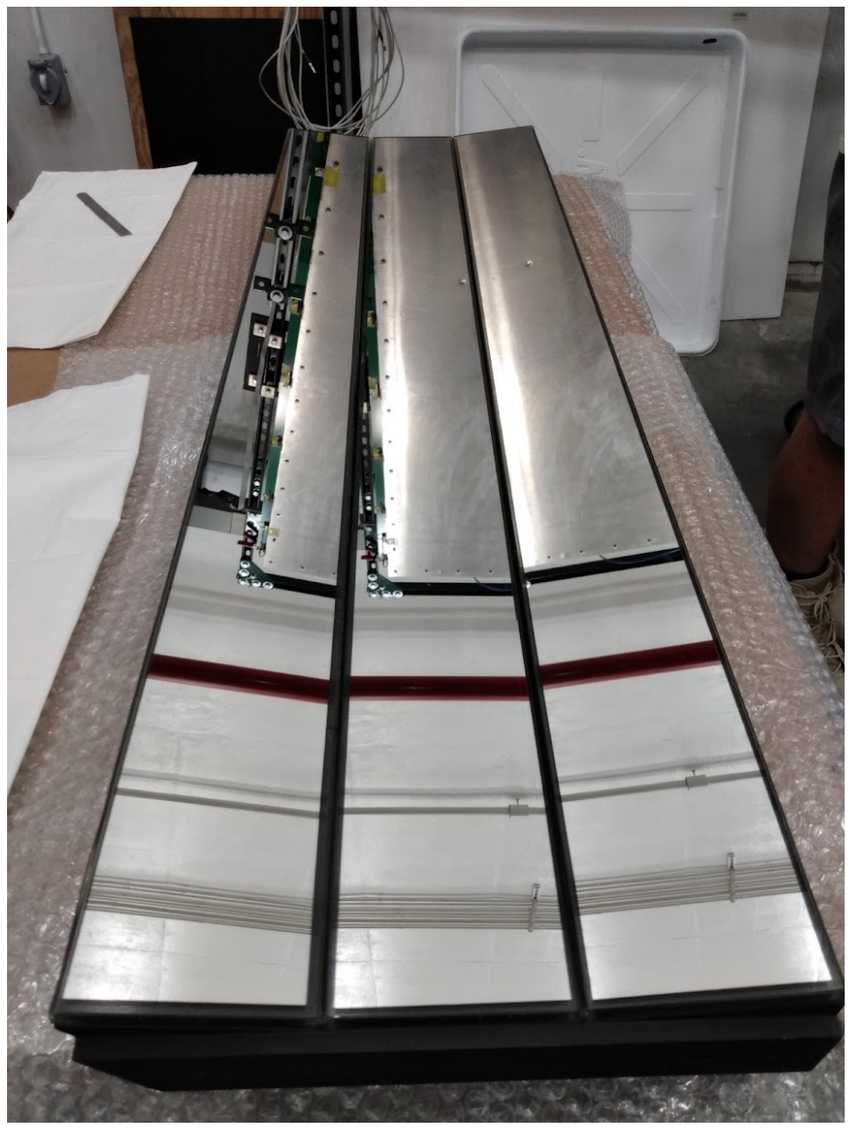
Optical box design

- Design based on SLAC FDIRC prototype
  - Replace fused silica block from FDIRC prototype with mirrors contained in water
  - Replace of cylindrical mirror with 3-segment flat mirror
- Similar coupling of bar boxes to water volume as used at BaBar



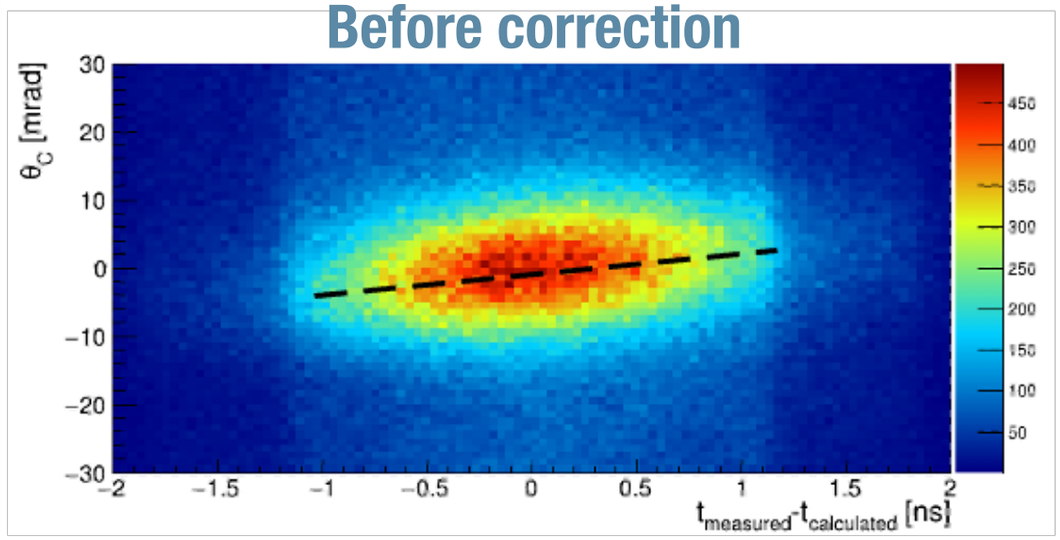
Mirror water protection

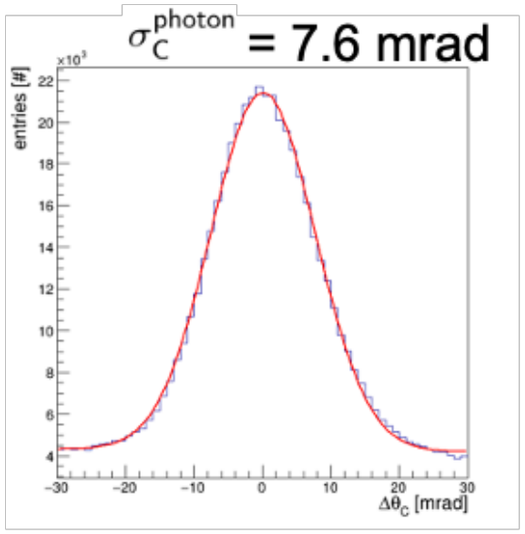


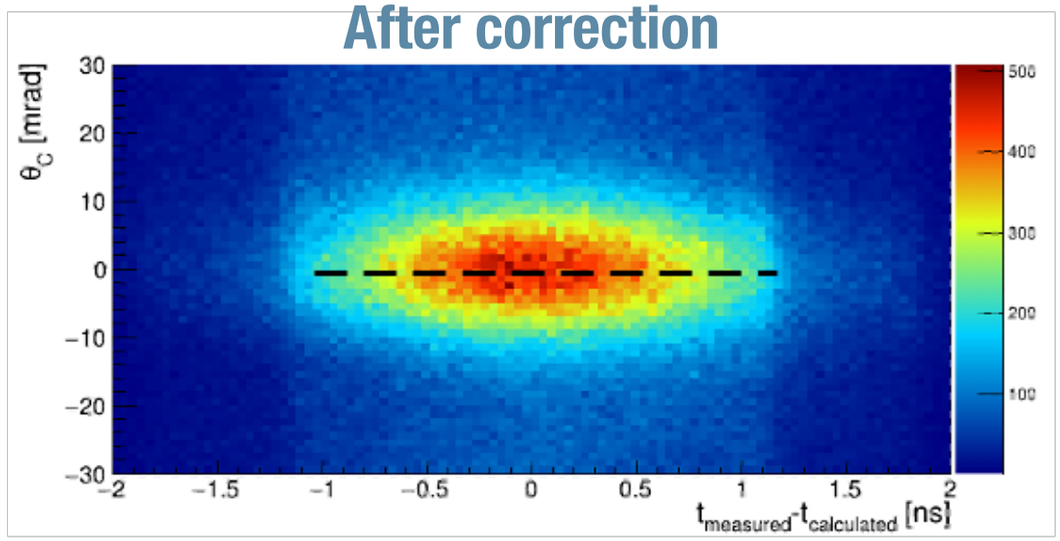


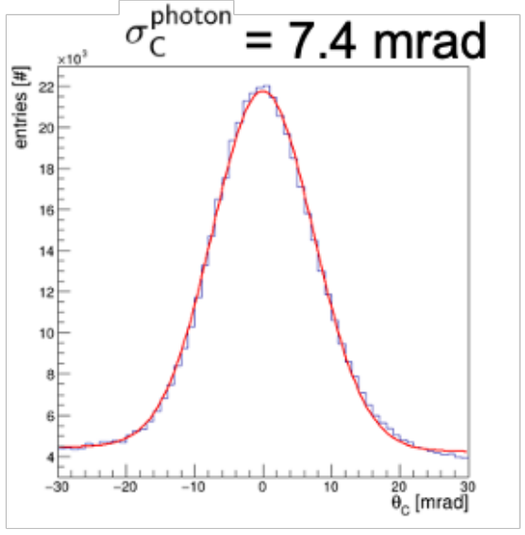
- Borosilicate bonding improved with etched mirror surface
- Silicone seal improved for redundant protection from water

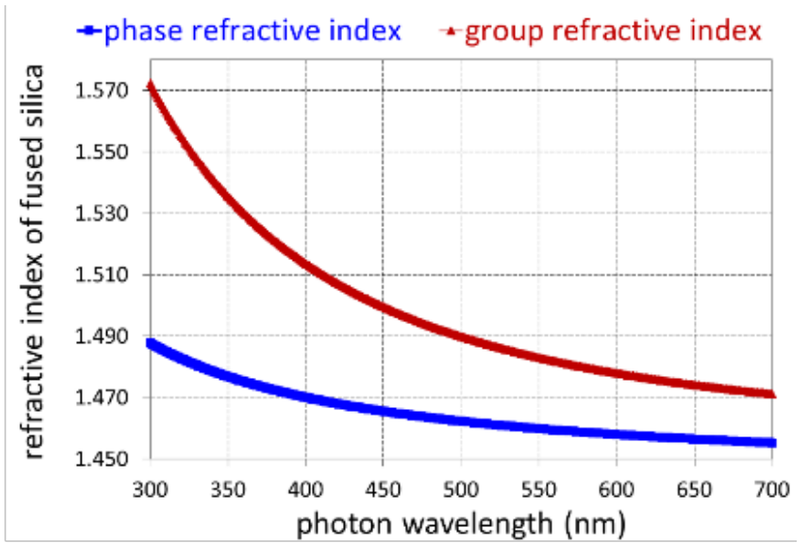
Chromatic correction





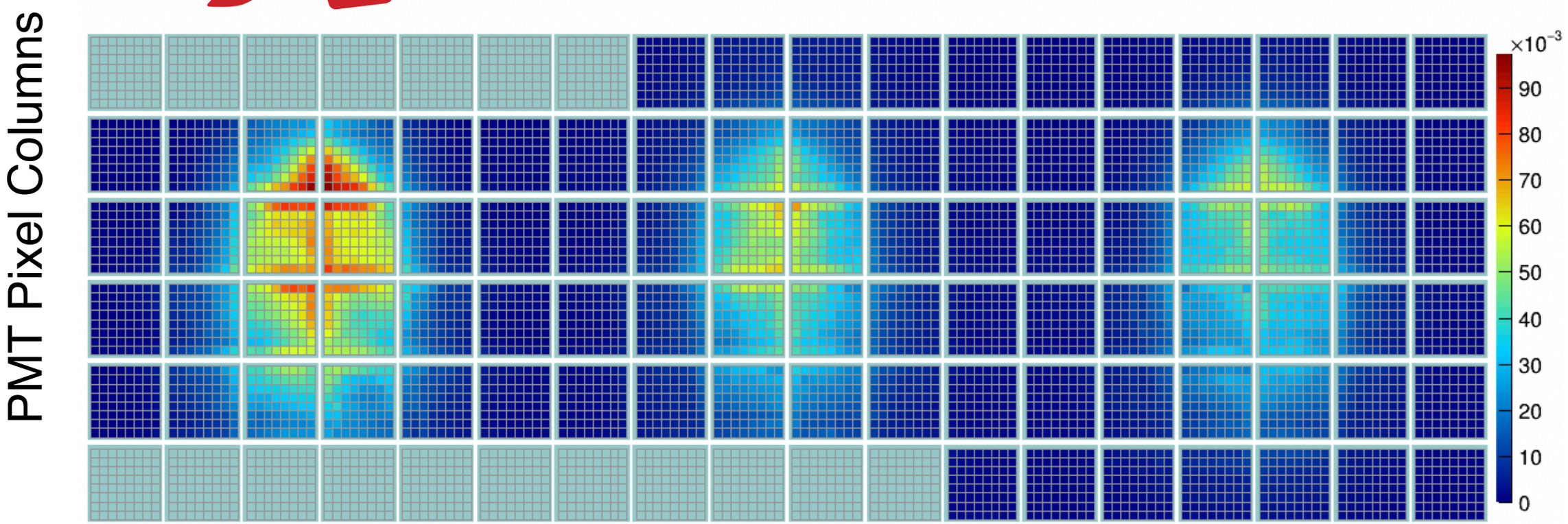




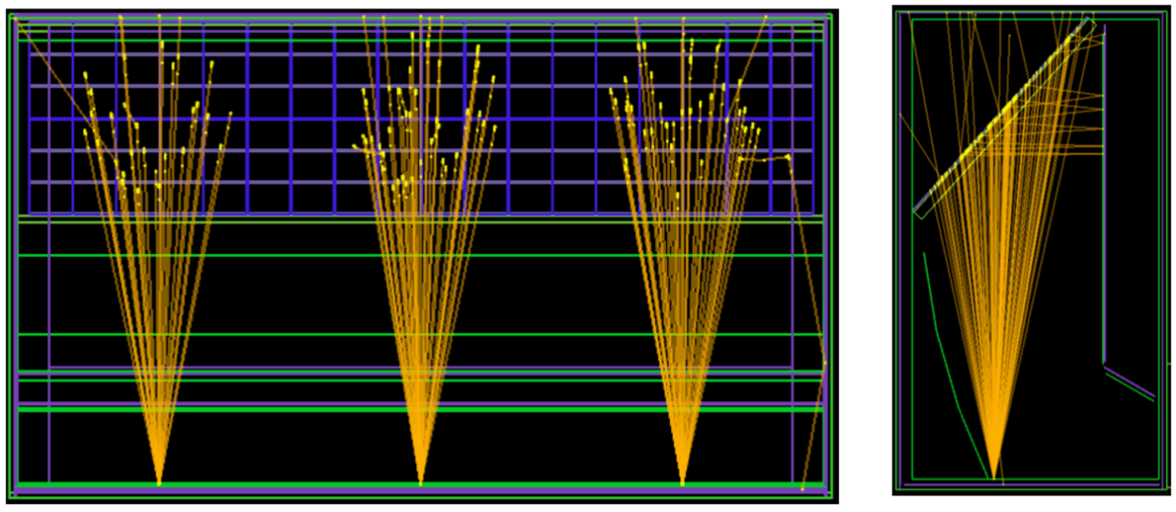


- Refractive index dependence on wavelength corrected by photon propagation time with limited ~1 ns resolution
- Improvement of single photon resolution after correction

DIRC calibration system

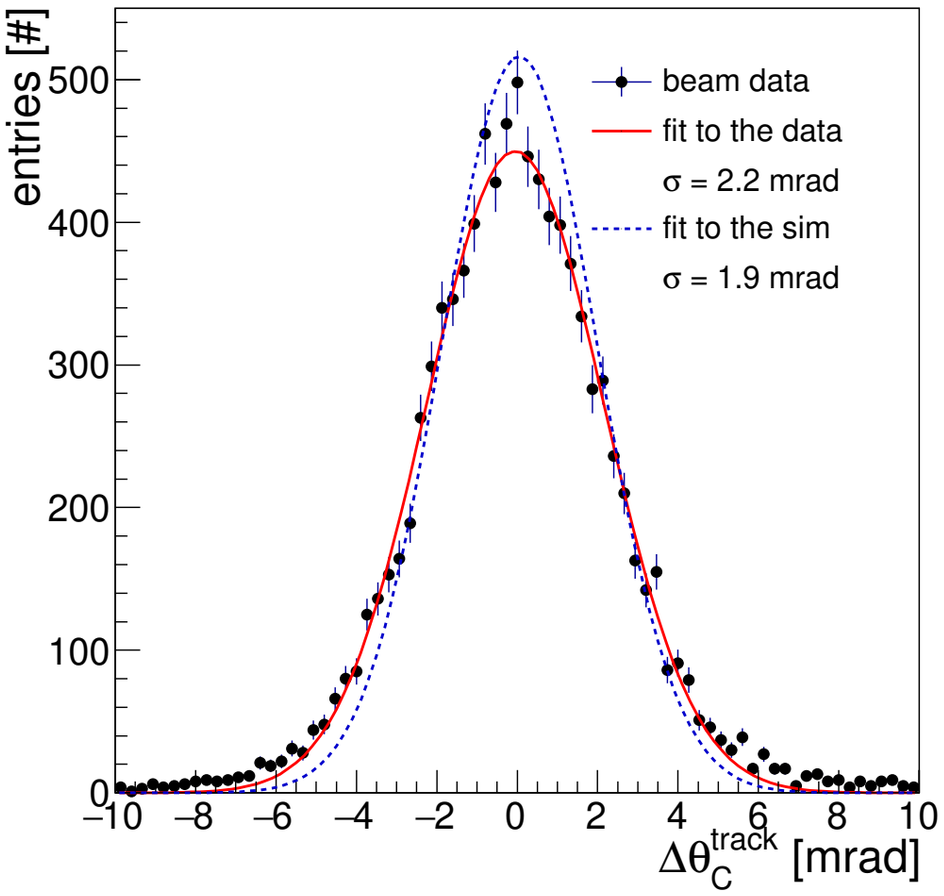


- 405 nm LED pulser with 840 ps rise time, split over 3 fibers with 25° opening angle to cover the full MAPMT array
- Run in parallel with physics trigger for continuous monitoring

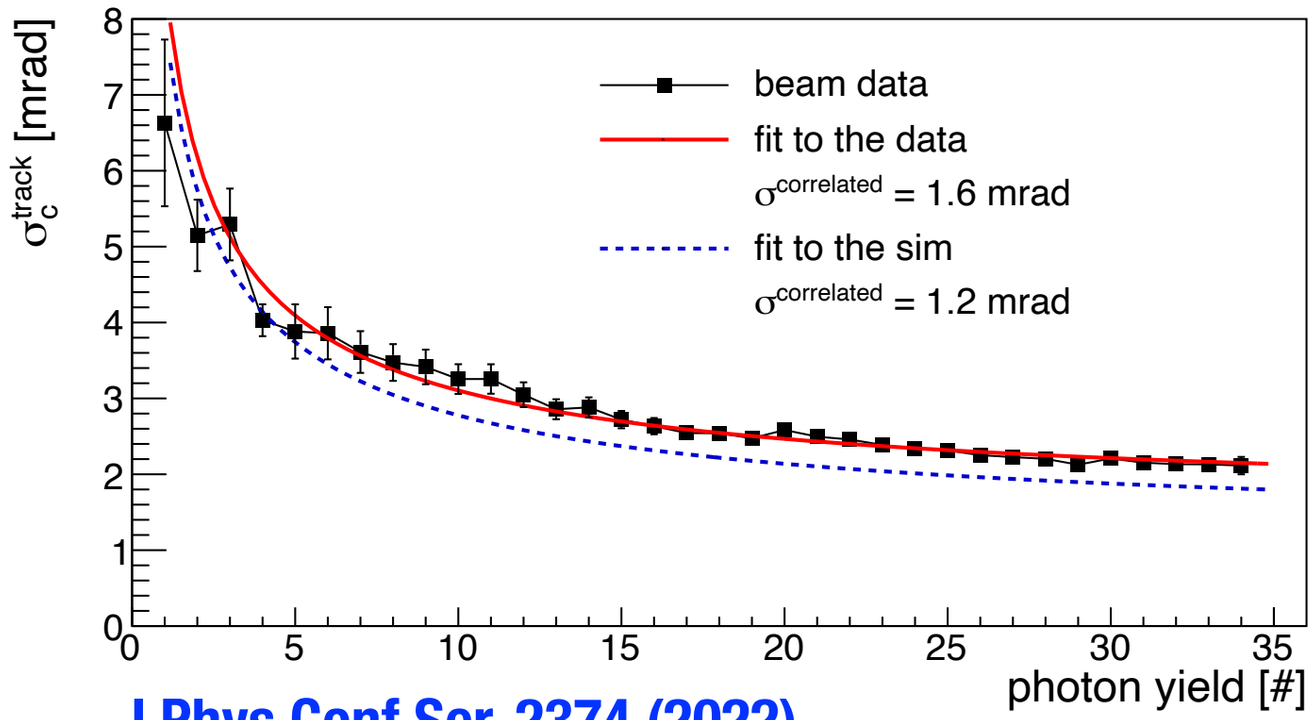


Cherenkov Track Resolution

π track resolution @ 3.5 GeV/c



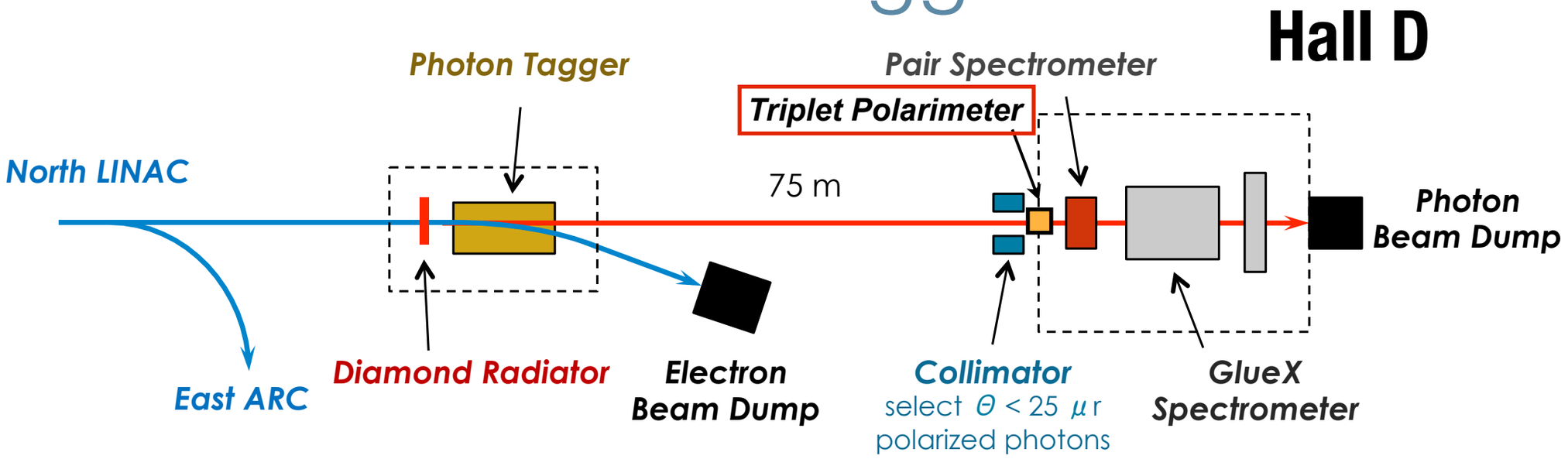
$$\sigma_C^{track} = \sqrt{\left(\frac{\sigma_C^{photon}}{\sqrt{N_{photons}}}\right)^2 + \left(\sigma^{correlated}\right)^2}$$



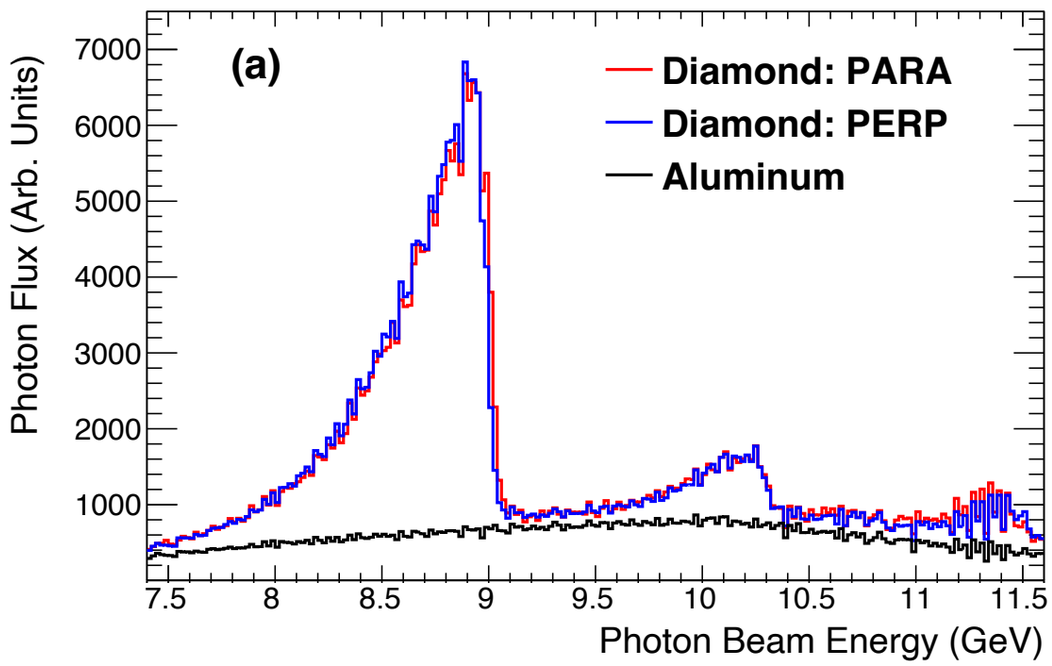
J.Phys.Conf.Ser. 2374 (2022)

- Resolution for each track to separate per-photon and correlated contributions
- With 2.2 mrad resolution, expect 3.8σ π/K separation at 3.5 GeV/c, but so far only 3.0σ achieved: non-guassian tails contribute to reducing performance
- Simulation predicts 1.2 mrad for correlated term, improvements are possible

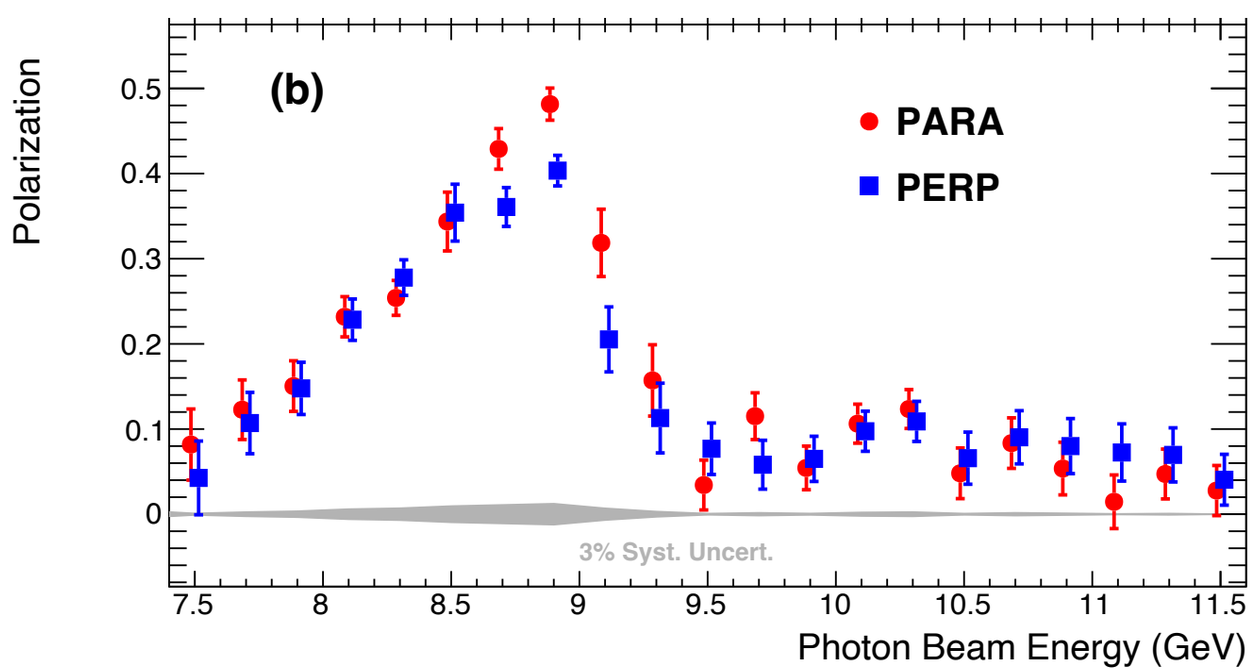
Photon Beam and Tagger



Measured Flux



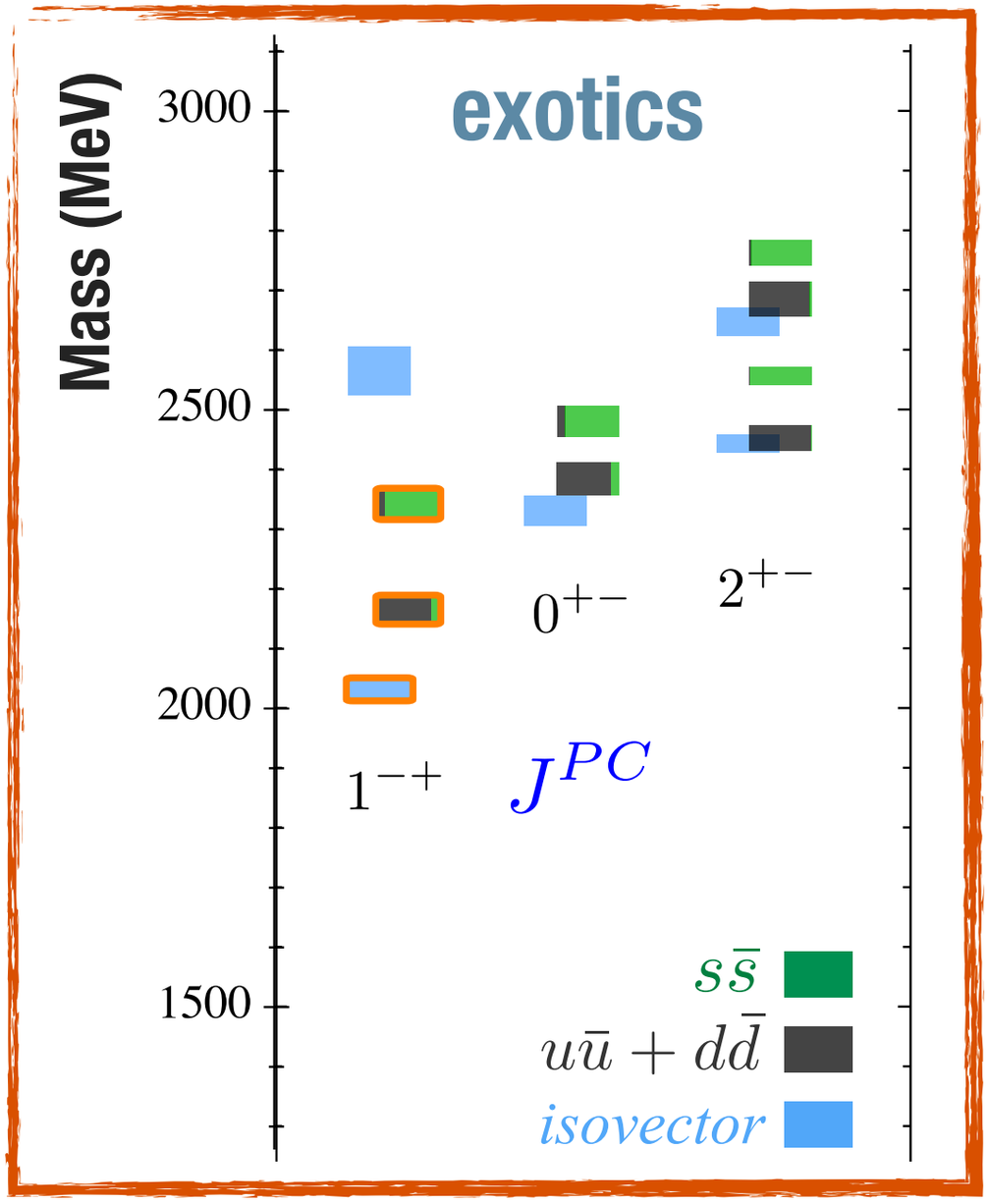
Measured Polarization



Filter on production mechanism

Strangeness program

- Lattice predicts **strange** and **light** quark content for mesons
- Search for a **pattern** of hybrid states in many final states
- Requires clean identification of charged pions and kaons

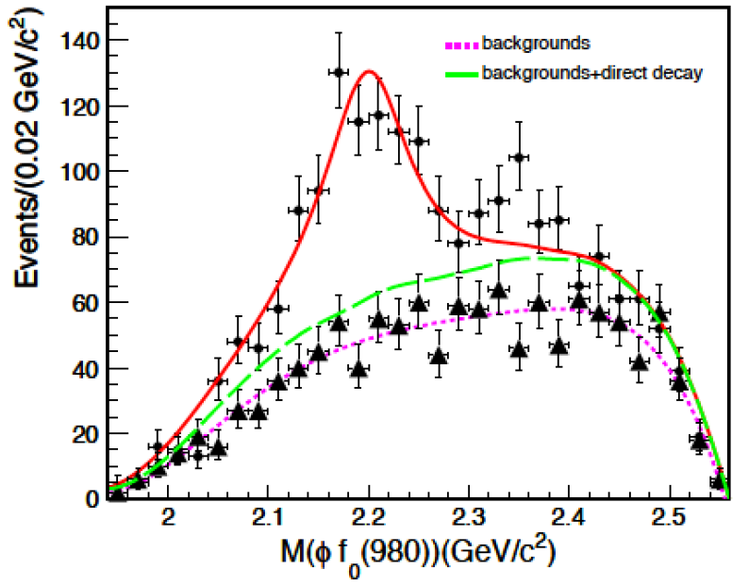


PRD 88 (2013) 094505

	Final States
π_1	$\omega\pi\pi$, 3π , 5π, $\eta 3\pi$, $\eta'\pi$
η_1	4π, $\eta 4\pi$, $\eta\eta\pi\pi$
η_1'	$KK\pi\pi$, $KK\pi$, $KK\omega$

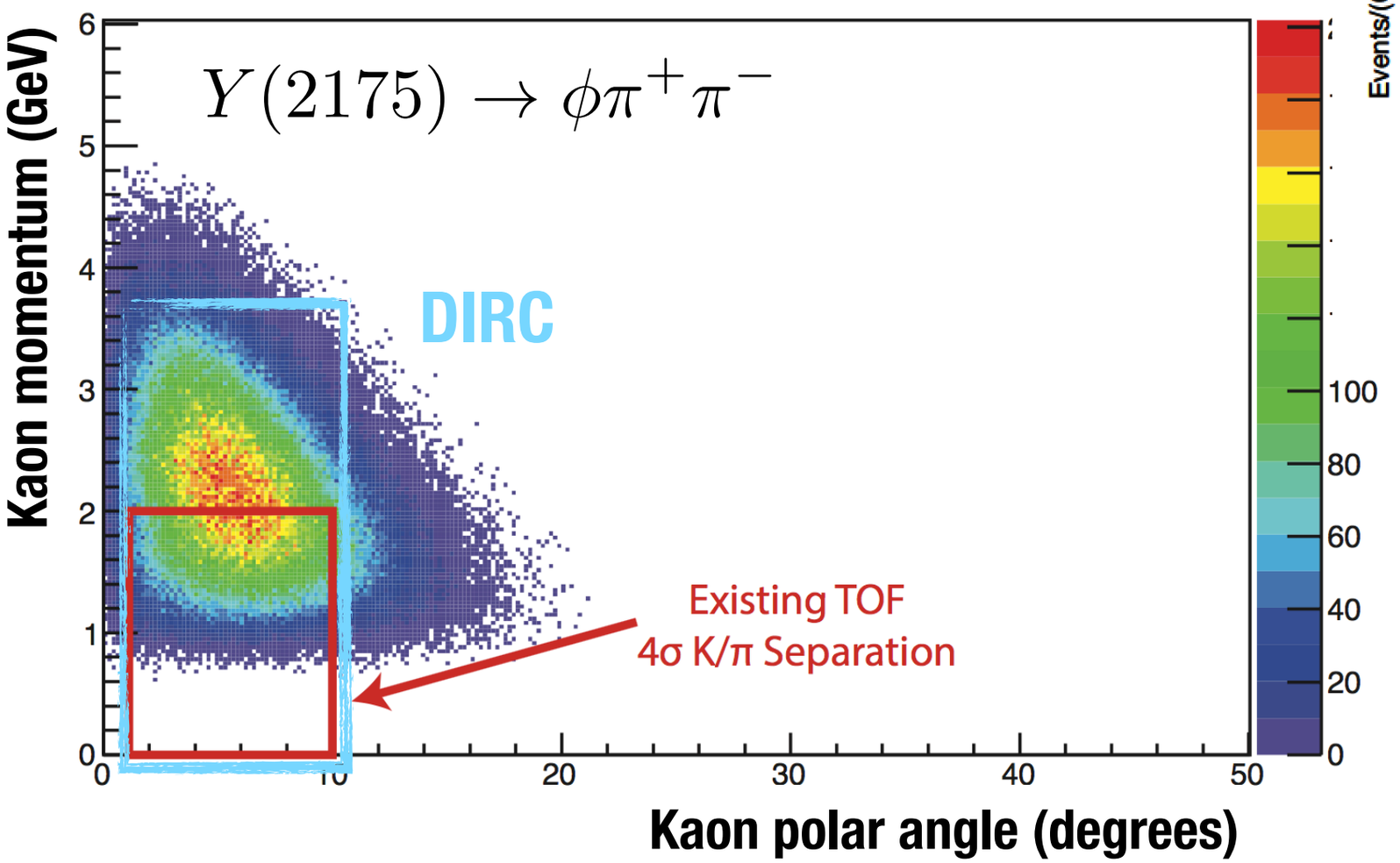
Expected DIRC performance

BES III: $J/\psi \to \eta\phi\pi^+\pi^-$



PRD 91, 052017 (2015)

GlueX Simulation



- Significantly extends reach in search for exotic hadrons (hybrid, multi-quark, etc.) containing strange quarks