Study of heavy flavor hadronization in eA collision via BeAGLE simulation

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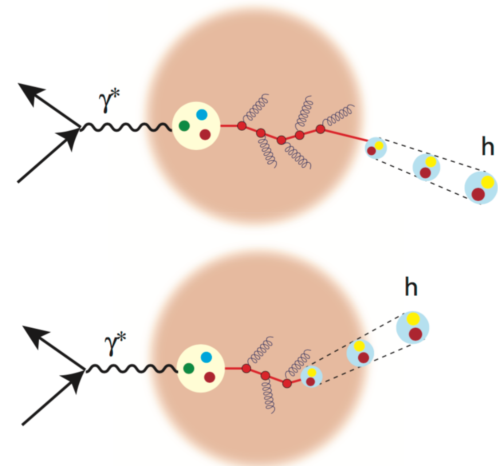
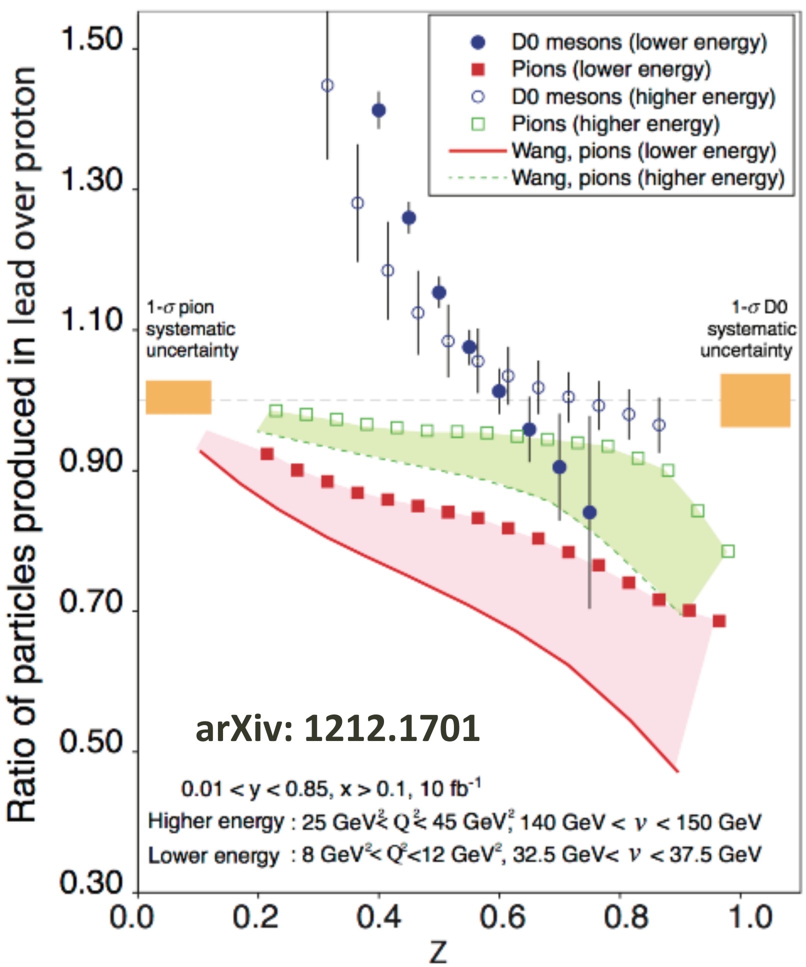
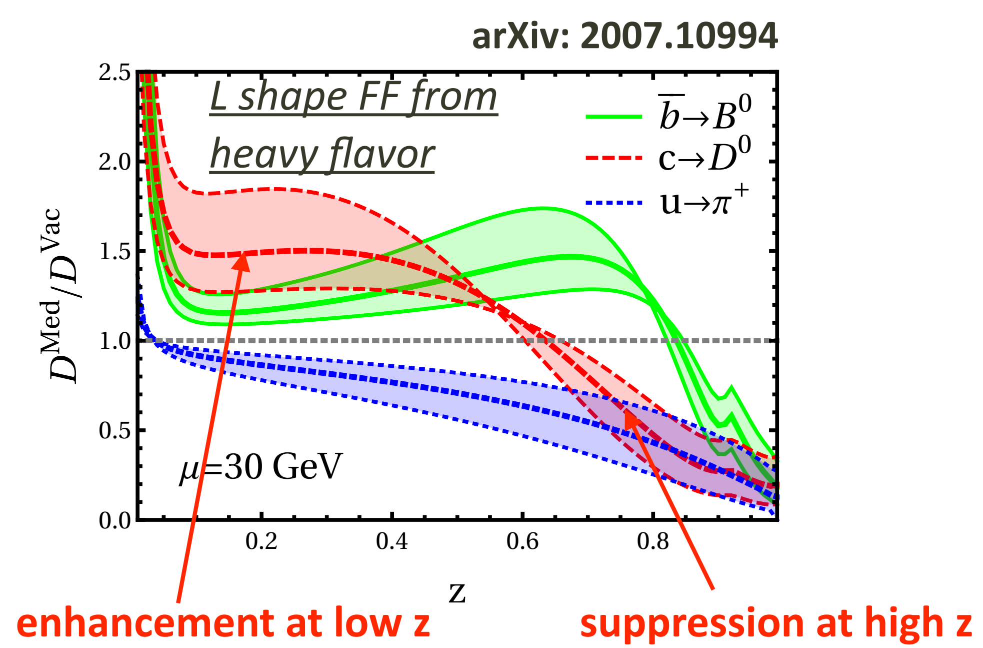
California consortium meeting, 07/19/2022

- **Study nuclear modification of (light and heavy) hadrons in different eA system**
  - **Hadronization scale**
  - **Energy loss mechanism inside nucleus**

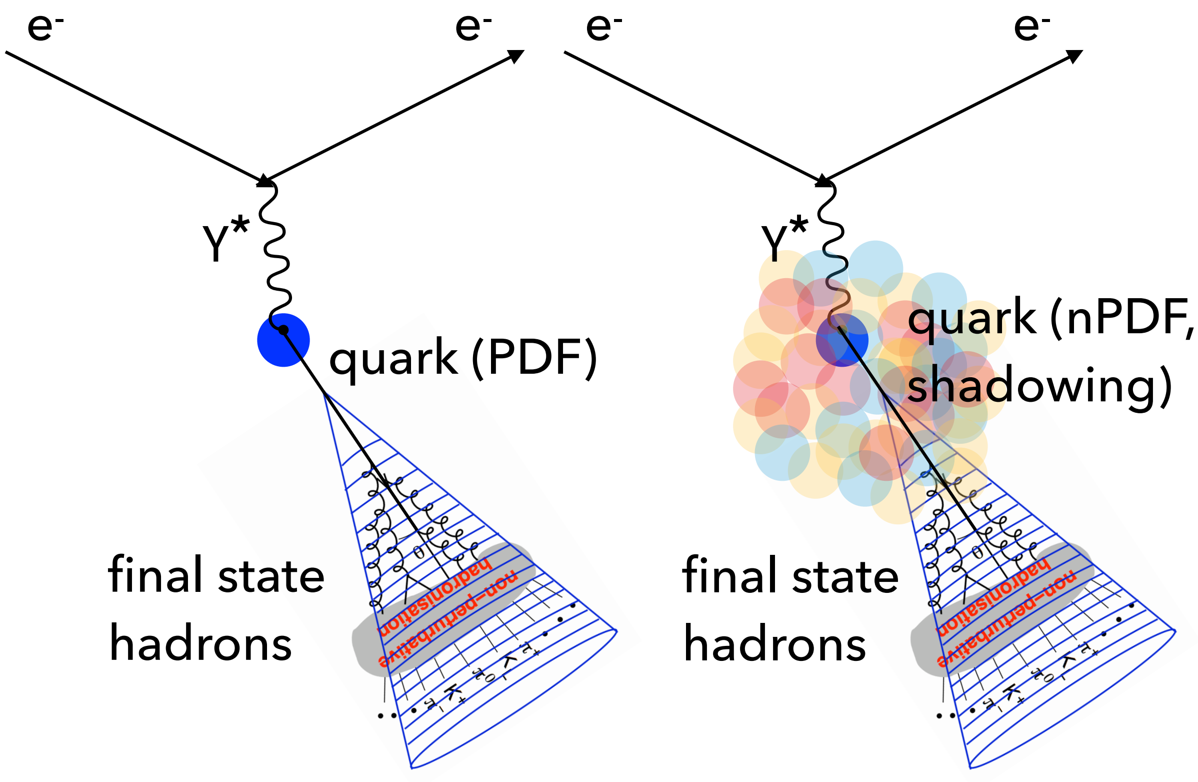




Would be interesting to also look at Λ_c (Eloss on parton level or hadron level or mixed?)



Hadron multiplicity ratio (double ratio) $R_{eA}{}^{h}$



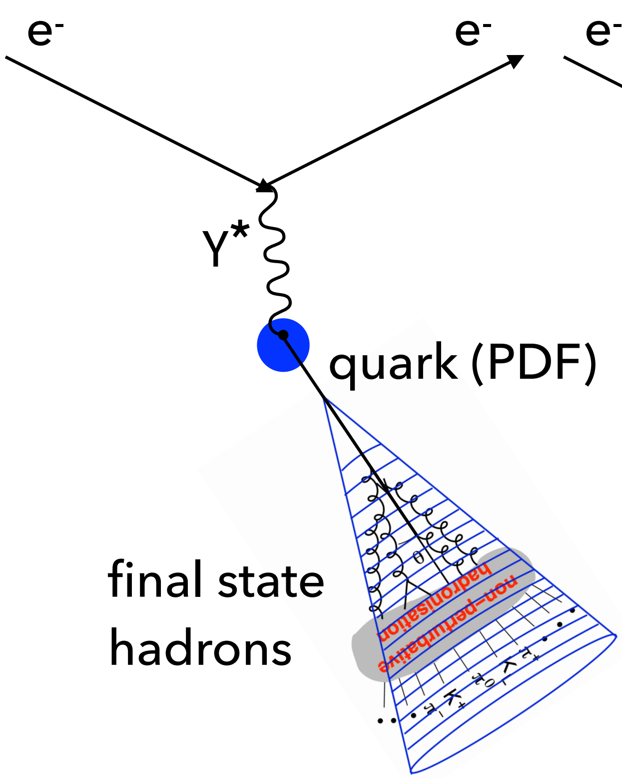
arXiv: 0704.3270

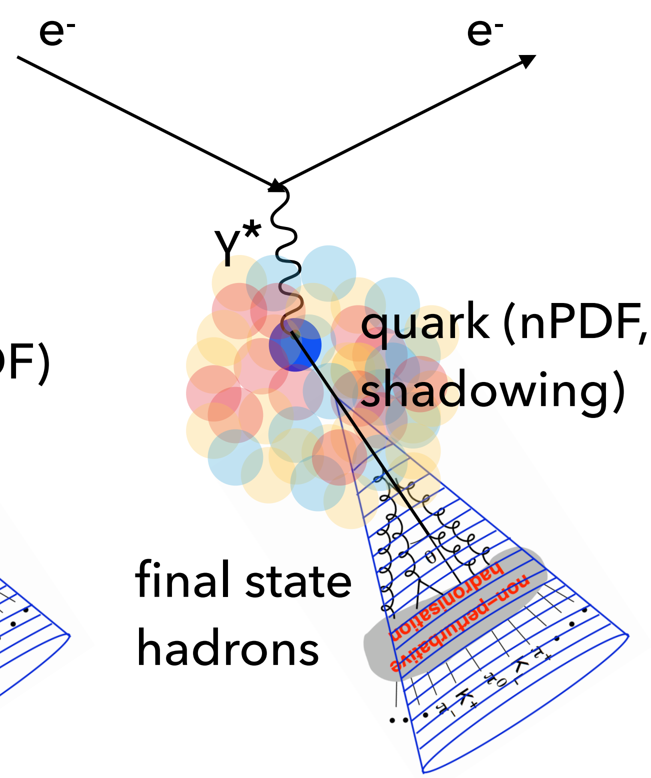
Fractional energy of the final state hadron z: $z = \frac{P \cdot p}{P \cdot q} \overset{\text{lab}}{=} \frac{E_h}{\nu}$

$$R_{eA}(x, Q^2, z) = \frac{\left(\frac{N^h(x,Q^2,z)}{N^e(x,Q^2)}\right)_{e+A}}{\left(\frac{N^h(x,Q^2,z)}{N^e(x,Q^2)}\right)_{e+p}}$$

Cancel out initial state effect

Hadron multiplicity ratio (double ratio) R_{eA}^{h}





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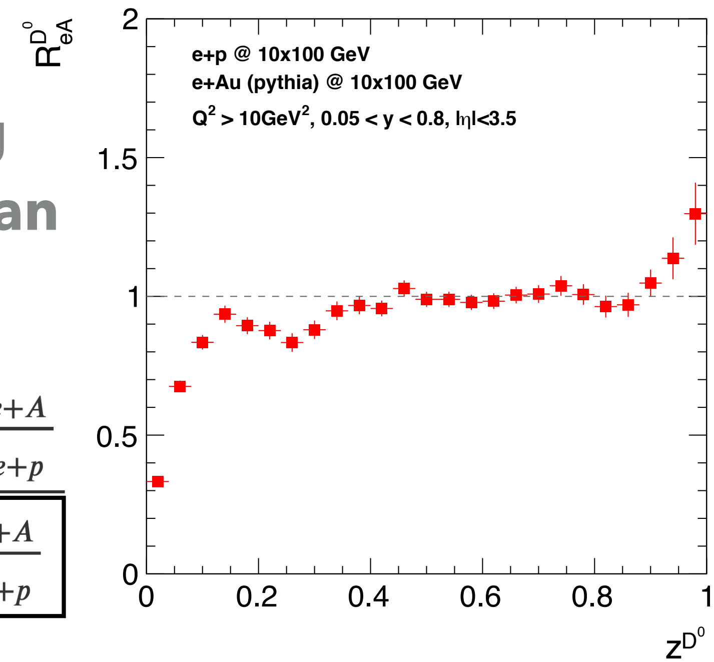
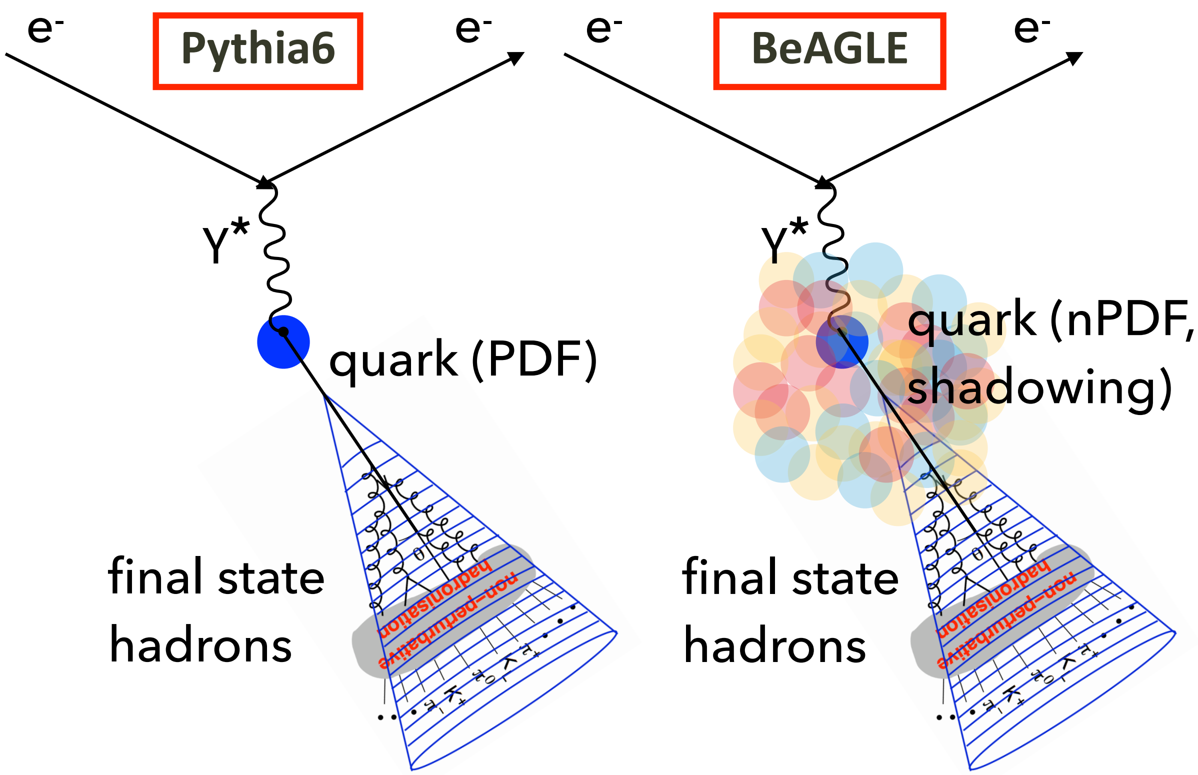
Cancel out initial state effect

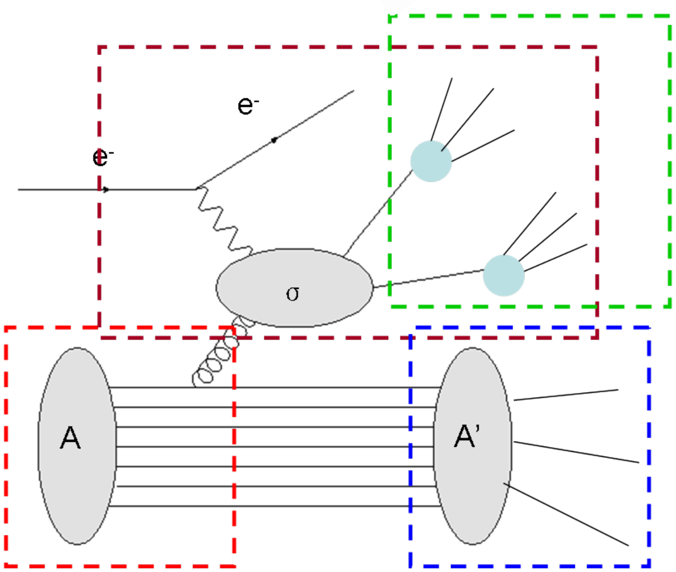
- For charm hadron modification, normalizing the charm cross section is a better choice than the inclusive cross section

$$R_{eA}(x, Q^2, z) = \frac{\left(\frac{N^h(x,Q^2,z)}{N^{c\bar{c}}(x,Q^2)}\right)_{e+A}}{\left(\frac{N^h(x,Q^2,z)}{N^{c\bar{c}}(x,Q^2)}\right)_{e+p}} = \frac{\frac{N^h(x,Q^2,z)_{e+A}}{N^h(x,Q^2,z)_{e+p}}}{\frac{N^{c\bar{c}}(x,Q^2)_{e+A}}{N^{c\bar{c}}(x,Q^2)_{e+p}}} \neq \frac{\frac{N^h(x,Q^2,z)_{e+A}}{N^h(x,Q^2,z)_{e+p}}}{\frac{N^e(x,Q^2)_{e+A}}{N^e(x,Q^2)_{e+p}}}$$



Nuclear modification in e+A events generated by BeAGLE





A hybrid model consisting of DPMJet and PYTHIA with nPDF EPS09.

Nuclear geometry by DPMJet and nPDF provided by EPS09.

Parton level interaction and jet fragmentation completed in PYTHIA.

Nuclear evaporation (gamma dexcitation/nuclear fission/fermi break up) treated by DPMJet

Energy loss effect from routine by Salgado&Wiedemann to simulate the nuclear fragmentation effect in cold nuclear matter

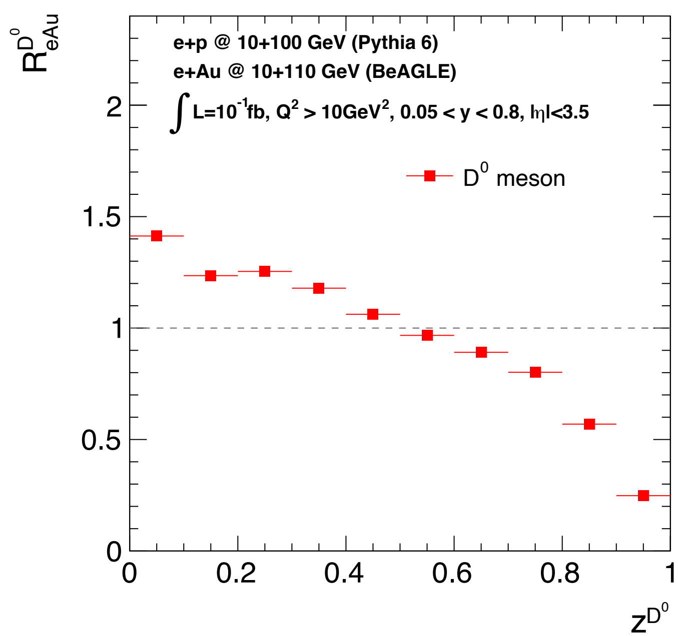
- **PythiaeRHIC (Pythia6) for ep collisions**
- **BeAGLE for eA collisions**
  - **Initial hard scattering and fragmentation by Pythia6**
  - **Nuclear evaporation, intra-nuclear cascade etc handled by DPMJet**
  - **Partonic energy loss by PyQM**

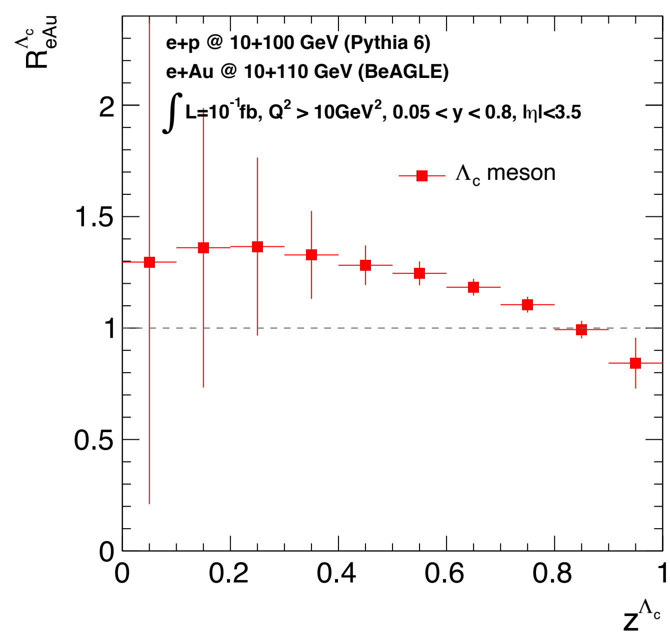
wiki page

arXiv:2204.11998

Final state effects in BeAGLE

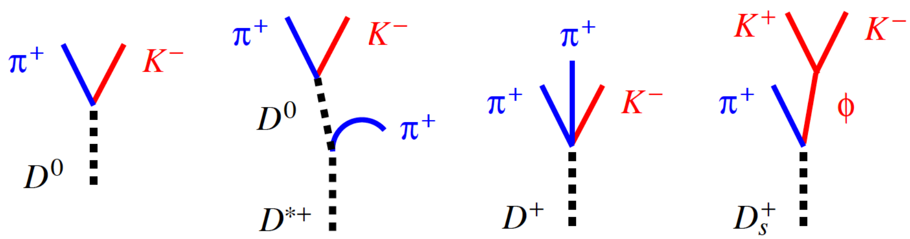
- Intra-nuclear cascade handled by DPMJet (FLUKA)
  - Intra-nuclear cascade: secondary low-energy interactions with spectator nucleons
- Energy loss effect handled by PyQM
  - This module applies energy loss to the partons after they have been simulated by Pythia, but before they have been hadronized
  - Turned off in our studies so far
  - Not in the previous version of BeAGLE we were using (v1.01). Available in the latest version (v1.02), but still under test





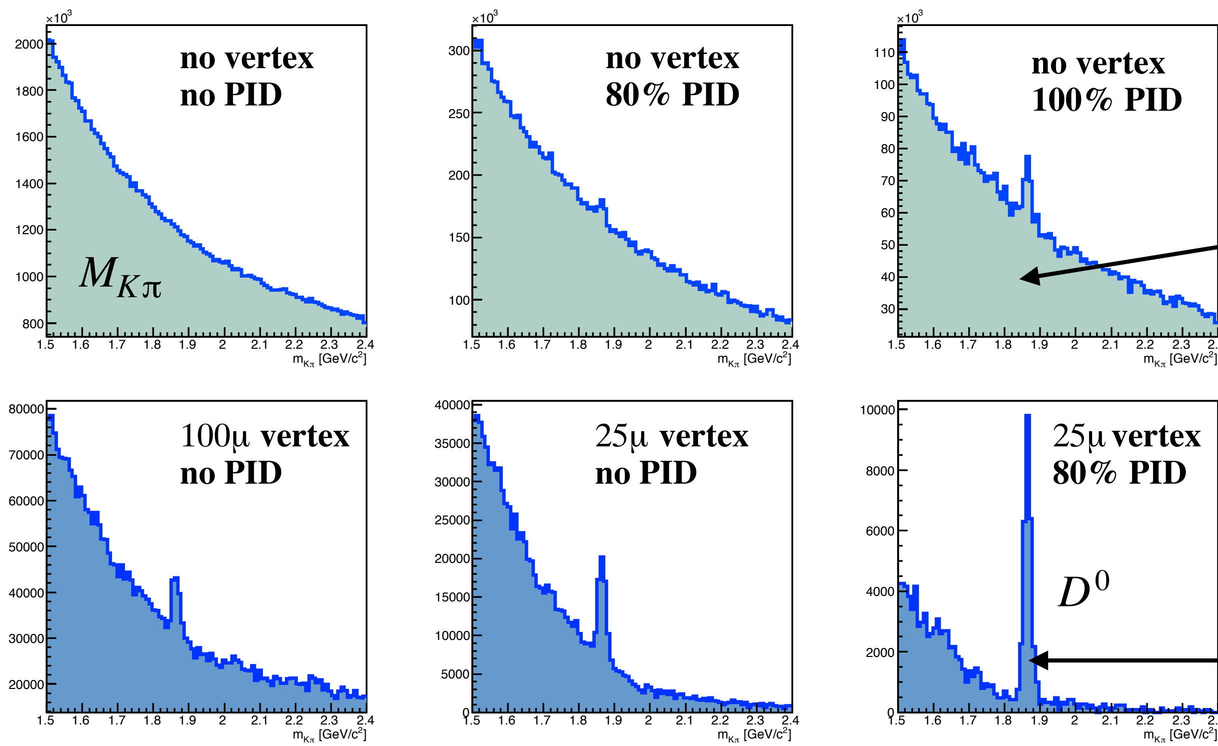
Charm hadron reconstruction via hadronic decays

- **Key of precision heavy flavor hadron reconstruction**
  - High luminosity + detector acceptance
  - Good pointing/vertexing resolution
  - Good π/K/p separation power



Heavy flavor hadron w/ longer life time

Particle	cτ
D^0	123 μm
$D^{\pm}$	312 μm
B^0	456 μm
$B^{\pm}$	491 μm
Λ_c	60 μm



D0→K/π multiplicity vs background K/π multiplicity

purity: BG/SG

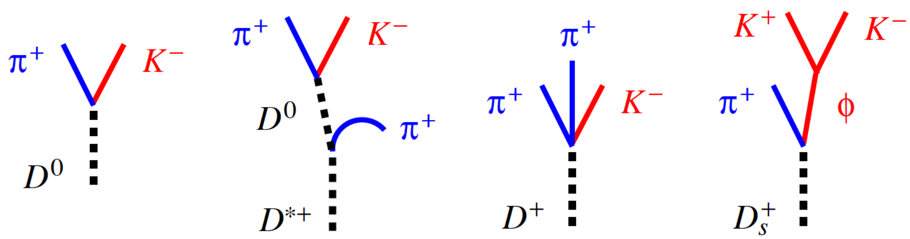
peak width: momentum resolution

Charm hadron reconstruction via hadronic decays

- **Key of precision heavy flavor hadron reconstruction**
  - High luminosity + detector acceptance ← High statistics **(increase SG)**
  - Good pointing/vertexing resolution ← High purity **(decrease BG/SG)**
  - Good π/K/p separation power ← High purity **(decrease BG/SG)**

To reduce Stat. Err.

Stat. Err. = √(SG+BG)/SG = √(1/SG+BG/SG)



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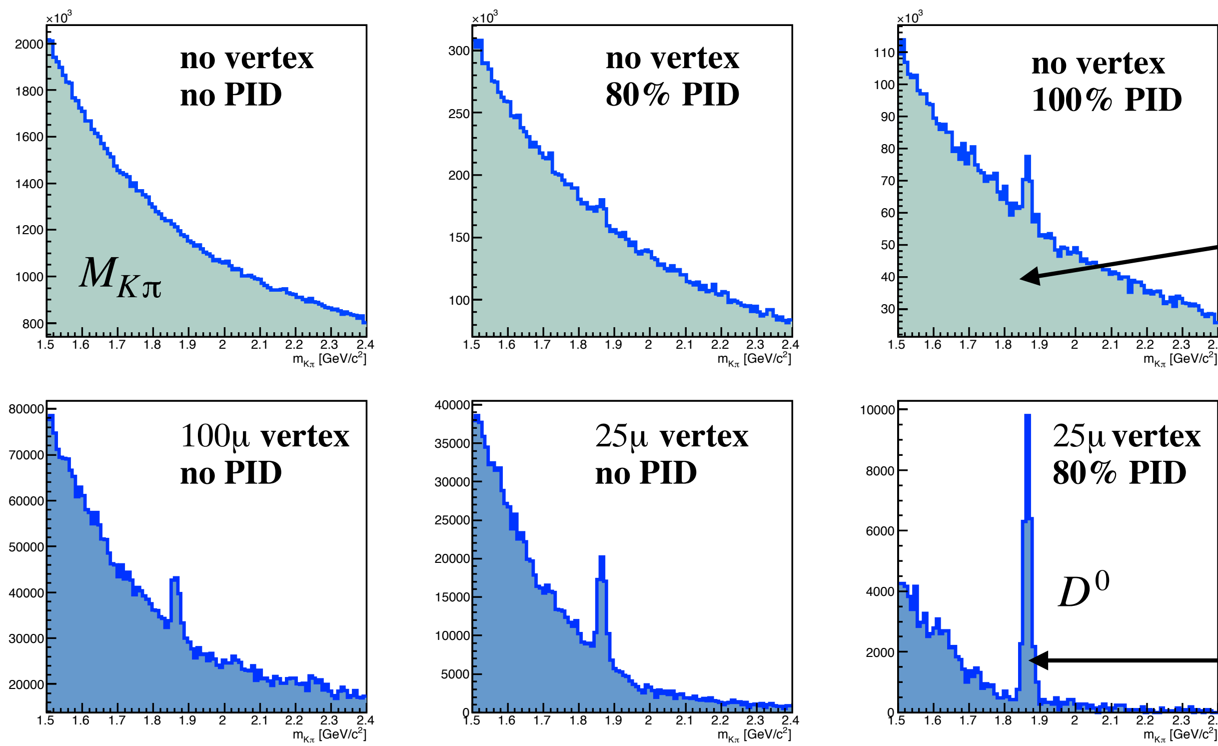


$D^0 \rightarrow K/\pi$ multiplicity vs background K/π multiplicity

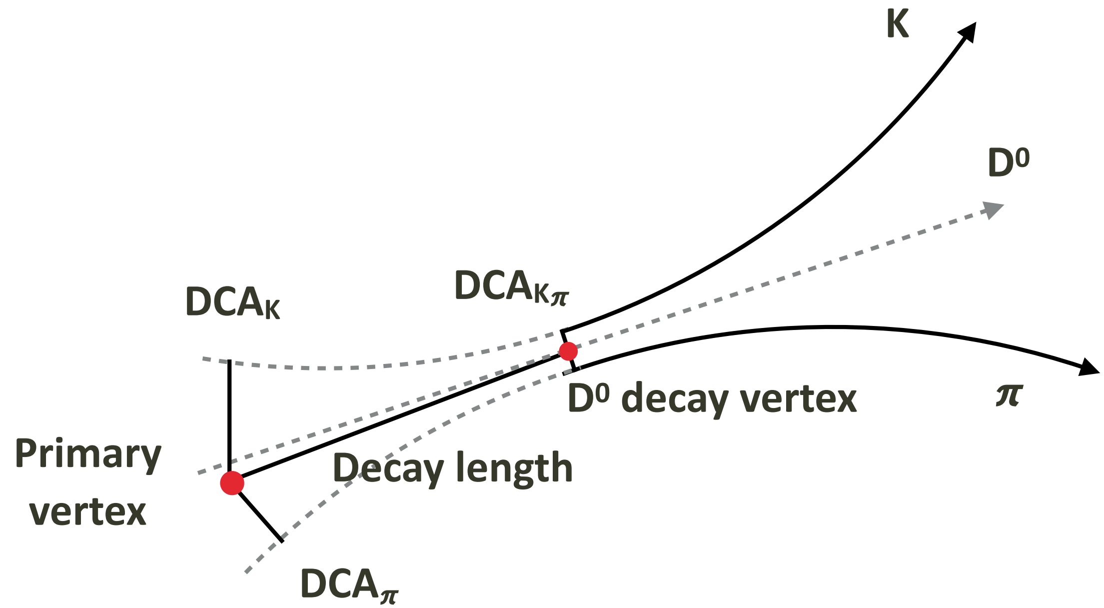
purity: BG/SG

peak width: momentum resolution

ATHENA smearing and analysis selection

- **Single track smearing benchmarked by ATHENA single particle simulation**
  - **p (magnitude) smeared by p resolution along the true p direction**
  - **Vertex position smeared by $DCA_{r\phi}$ and DCA_z**
- **Primary vertex smearing from multi-track fitting (Matt Kelsey's study)**
- **DIS event selection**
  - **$Q^2 > 10$ GeV^2 (event generated with $Q^2>10$ GeV^2)**
  - **$0.05 < y < 0.8$**
- **D^0 selection**
  - **p > 0.5GeV**
  - **Pair identified $K\pi$ tracks**
  - **$DCA_{pair} < 130\mu m$**
  - **Decay length > 40μm**
  - **$\cos\theta_{r\phi} > 0.8$**

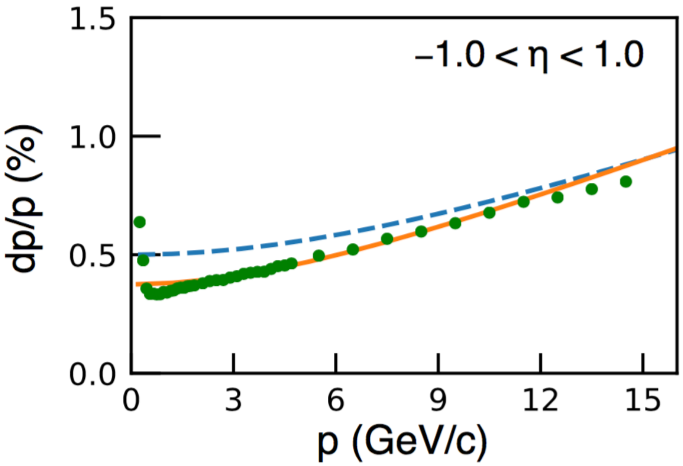
<u>*All topological cuts in transverse plane*</u>

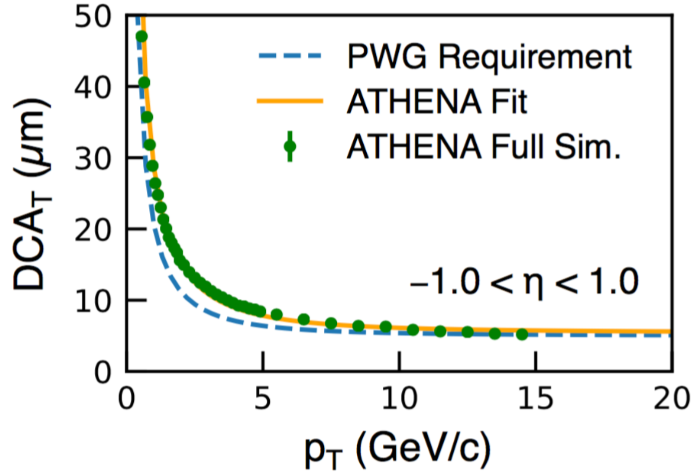


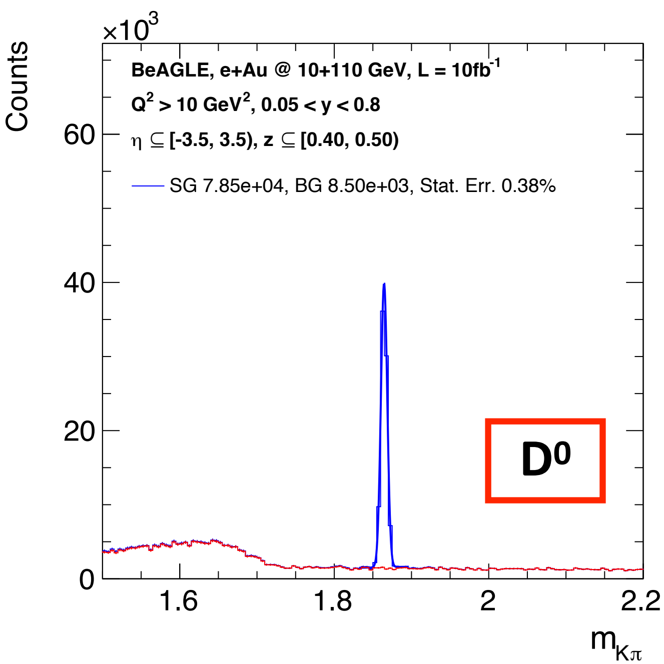
Why not full simulation yet?

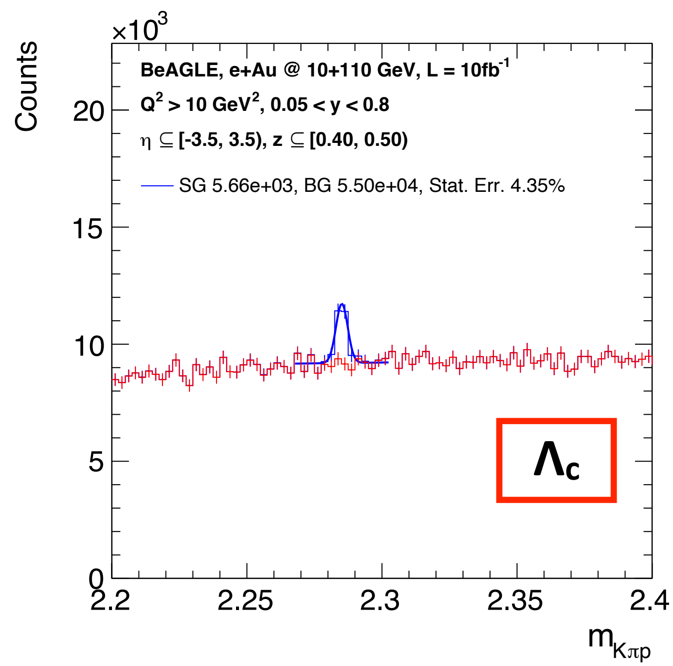
- DD4HEP + juggler: Canyonland 2.1 tag, DIS, $Q^2 > 10 GeV$
  - Pythia events, beam crossing
  - Event vertex distribution: σ_x = 0.13mm, σ_y = 0.008mm, σ_z = 35.6mm
- Available info
  - Reconstructed particle momentum and matched MC true particles
- Missing info
  - No ancestry information for MC true particles (cannot tag the decay ancestry)
  - **Reconstructed PID (currently using truth)**
  - **No reconstructed primary vertex, no reconstructed secondary vertex**
  - DCA values currently calculated w.r.t (0,0,0) rather than the true event vertex
- Because of the missing info, it was very difficult to apply topology cuts

- **Single track smearing benchmarked by ATHENA single particle simulation**





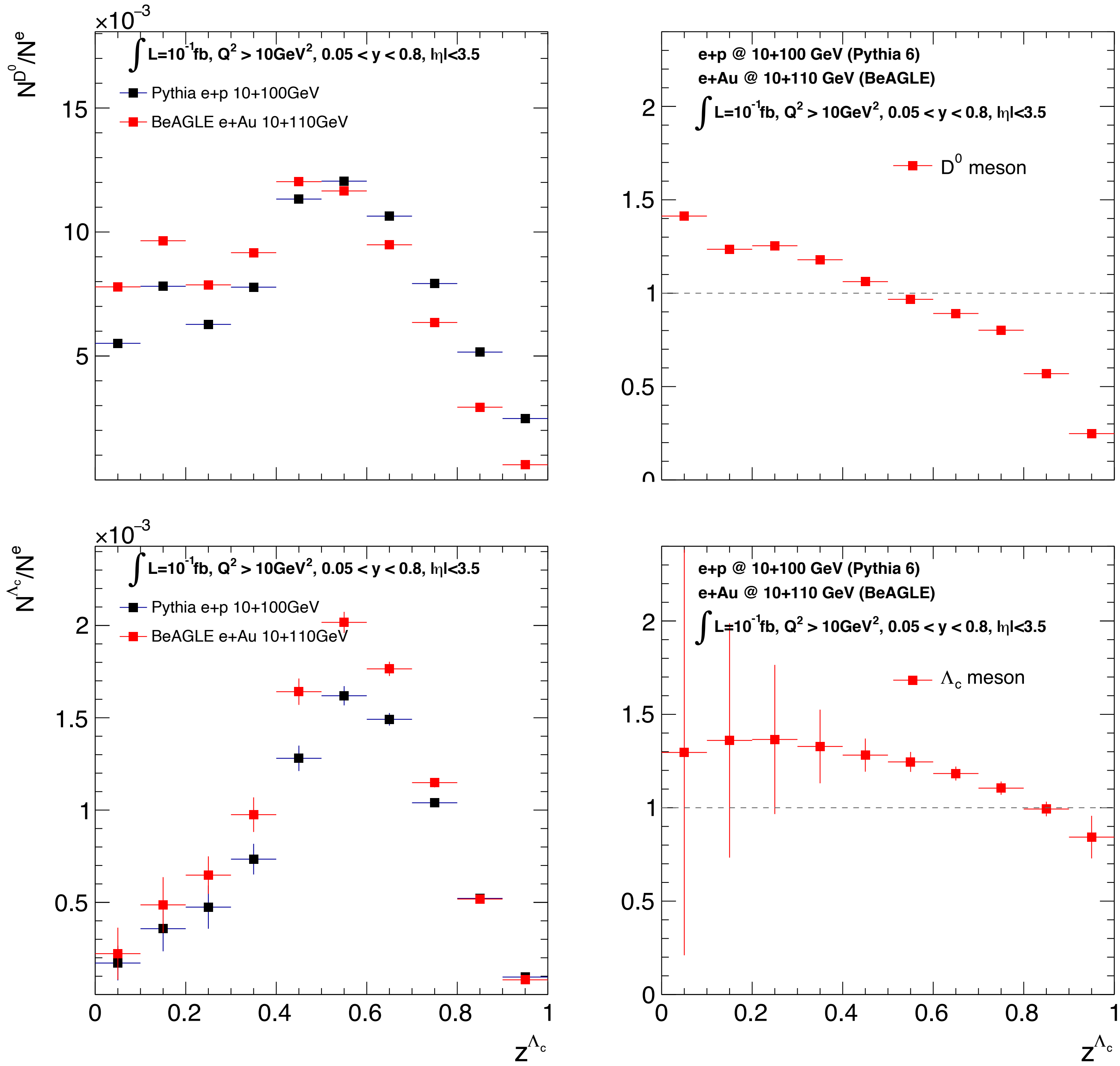




Much worse sig/bkg ratio for reconstructed Λ_c → worse statistical accuracy

R_{eA} of D^0 and Λ_c with statistical uncertainty

- Using the generator results as central value
- Using the projected statistical uncertianty as the uncertainty

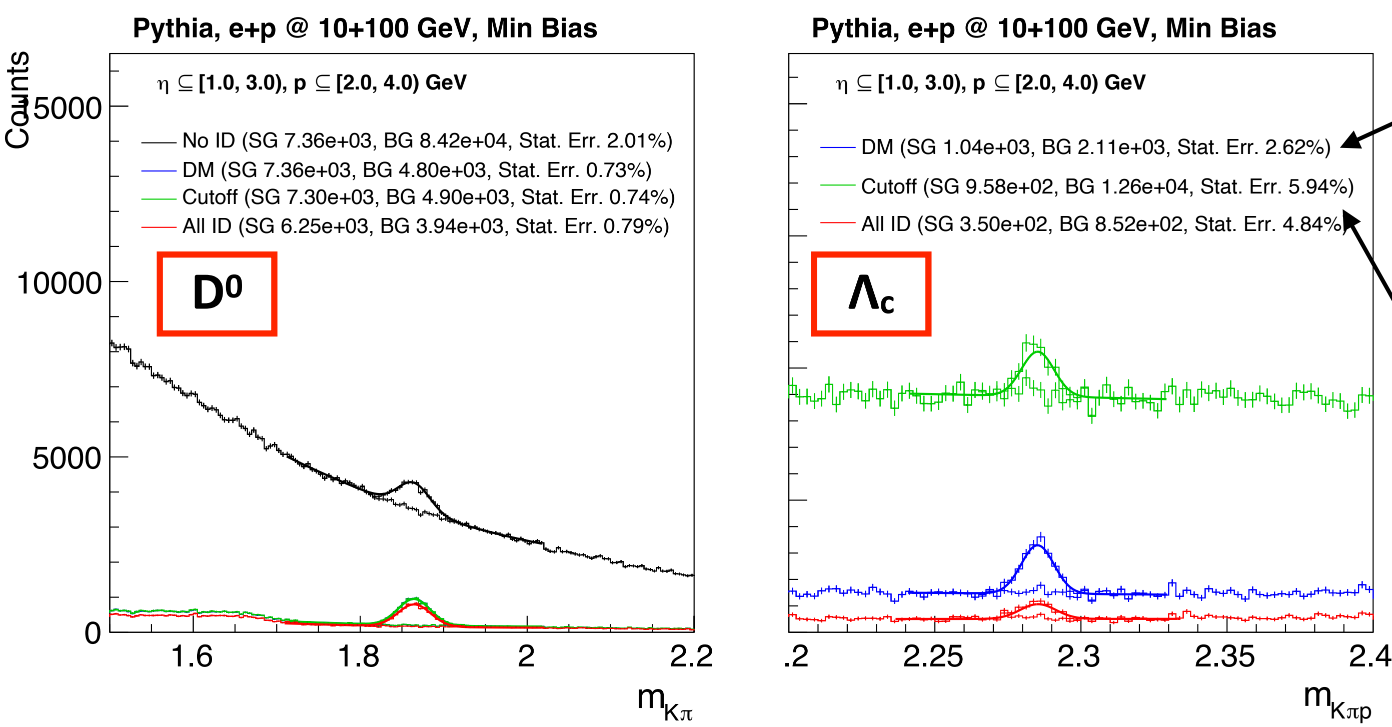


Detector effects

- Acceptance/efficiency (tracking+PID)
- Tracking and pointing resolution
- PID (π/K/p separation power)

B field

Detector setup



Deterctor Matrix	
Barrel	< 6 GeV
Forward	< 10 GeV
Backward	< 50 GeV

More realistic: take into consideration of the firing threshold and acceptance of Cherekov detectors

Low p cutoff using DIRC+dRICH as PID does not affect D^0 significantly, but it affects Λ_c significantly, especially at low pT and |η|>1

Summary

- **Fast smearing framework with ATHENA detector parameters**
  - No realistic reconstructed PID info yet
  - Update the smearing parameters with the Detector1 tracking setup
  - Switching to full simulation if all the necessary information are available

- **More investigation on the final state effects in BeAGLE**
  - Collision geometry
  - Intra-Nuclear Cascade (INC) effect
  - Energy loss model: PyQM (https://arxiv.org/pdf/2203.16665.pdf)

- **Model comparison**
  - Different mechanism, qhat

arXiv: 2204.11998

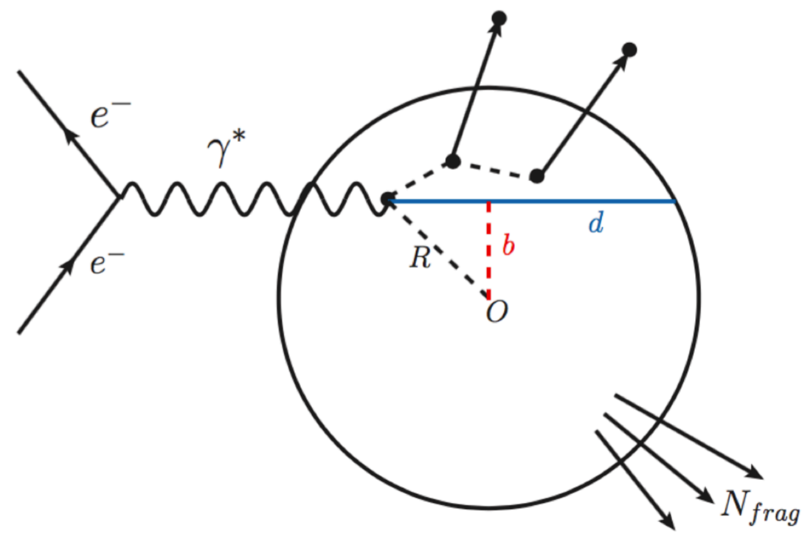


FIG. 11. Relevant quantities to describe the collision geometry. The effective interaction length, d, is the distance between the photon-nucleon interaction point and the edge of the nucleus in the direction of the virtual photon, weighted by the nuclear density. The variable b is the impact parameter between d and the center of the nucleus.

Thanks! + Questions?

Detector effects: PID

- Using fast simulation to check the detector effects on D0 and Λ_c reconstruction
- Particle identification (PID)
  - No PID
  - Detector Matrix (DM) PID: no low p cutoff (can be covered by TPC and TOF)
  - DIRC+dRICH: with low p cutoff (1.4T and 3T), including or excluding mis-identified particles
  - Caveat: assume perfect electron ID, ignore muons

Deterctor Matrix	
Barrel	< 6 GeV
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EICUG YR

radiator	index	Threshold (GeV/c) e	π	K	p
quartz (DIRC)	1.473	0.00048	0.13	0.47	0.88
aerogel (mRICH)	1.03	0.00207	0.57	2.00	3.80
aerogel (dRICH)	1.02	0.00245	0.69	2.46	4.67
C_2F_6 (dRICH)	1.0008	0.01277	3.49	12.34	23.45
CF_4 (gRICH)	1.00056	0.01527	4.17	14.75	28.03

Table 11.23: Table of Cherenkov thresholds for various media.

Fast simulation for DIRC and RICH

- **Fast simulation for DIRC and dRICH**
  - If particles can not reach DIRC ($p_T >$ 0.19GeV for 1.4T, 0.40GeV for 3T), can be smaller if put DIRC closer to All-Si
  - If particles momentum is below the firing threshold for π/K/p

Veto mode: if track momentum above pion threshold but not firing the detector, then it cannot be pion

<table>
<tr><th>True particle</th><th>Pion</th><th>Kaon</th><th>Proton</th></tr>
<tr><td>p < 0.13 (0.69)</td><td colspan="3">prob(π/K/p) = 0.7, 0.2, 0.1</td></tr>
<tr><td>p < 0.47 (2.46)</td><td rowspan="4">prob(π/K/p) = 1, 0, 0</td><td colspan="2">prob(π/K/p) = 0, 0.6, 0.4</td></tr>
<tr><td>p < 0.88 (4.67)</td><td rowspan="3">prob(π/K/p) = 0, 1, 0</td><td rowspan="3">prob(π/K/p) = 0, 0, 1</td></tr>
<tr><td>p < 6 (50)</td></tr>
</table>

probability assigned according to multiplicity of different charged particles