LA-UR-20-23799

LANL open heavy flavor and quarkonia simulation updates for the EIC Yellow Report preparation

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Outline

- Motivation.
- Open heavy flavor simulation updates and plan.
- Quarkonia simulation updates and plan.
- Summary

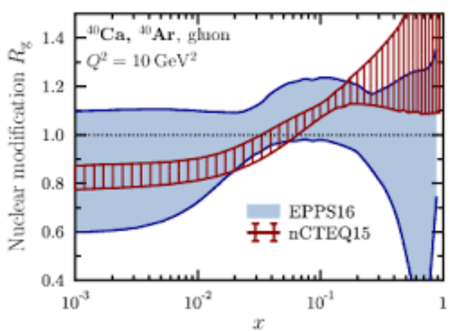
One of the major EIC physics goals

- Measurement of heavy flavor hadrons, jets which can be treated as surrogates of initial quarks/gluons and their correlations in the hadron/nuclei going (forward) direction at the EIC.

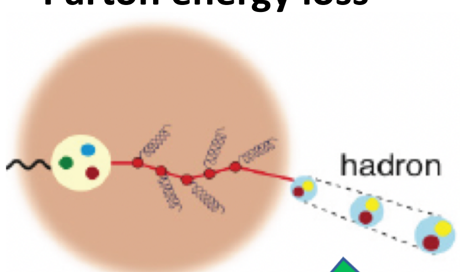
arXiv:1610.08536 **Phys. Rev. D 96, 114005 (2017)**

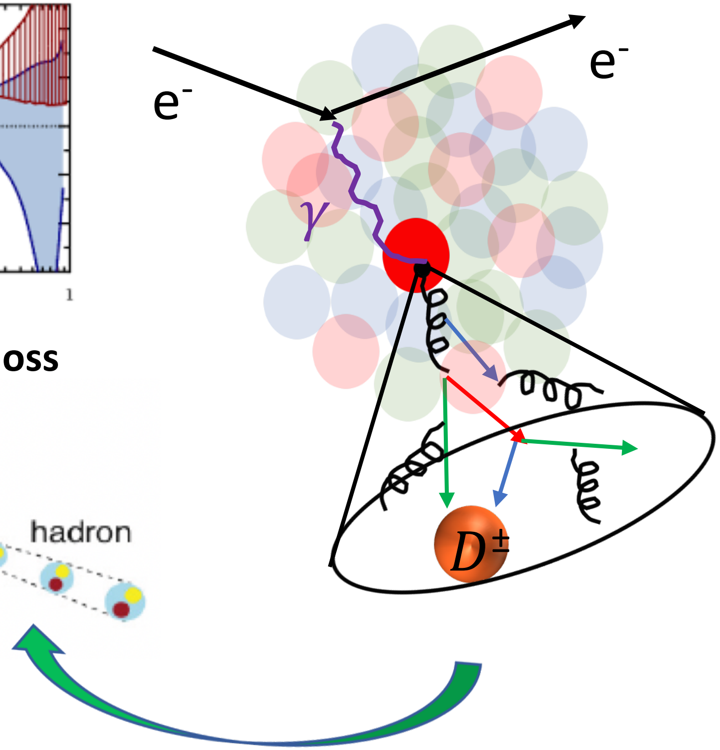
arXiv:2002.05880 $e^- + \mathrm{Au} \rightarrow e^- + jet(D^\pm) + X$

nPDF modification



Parton energy loss

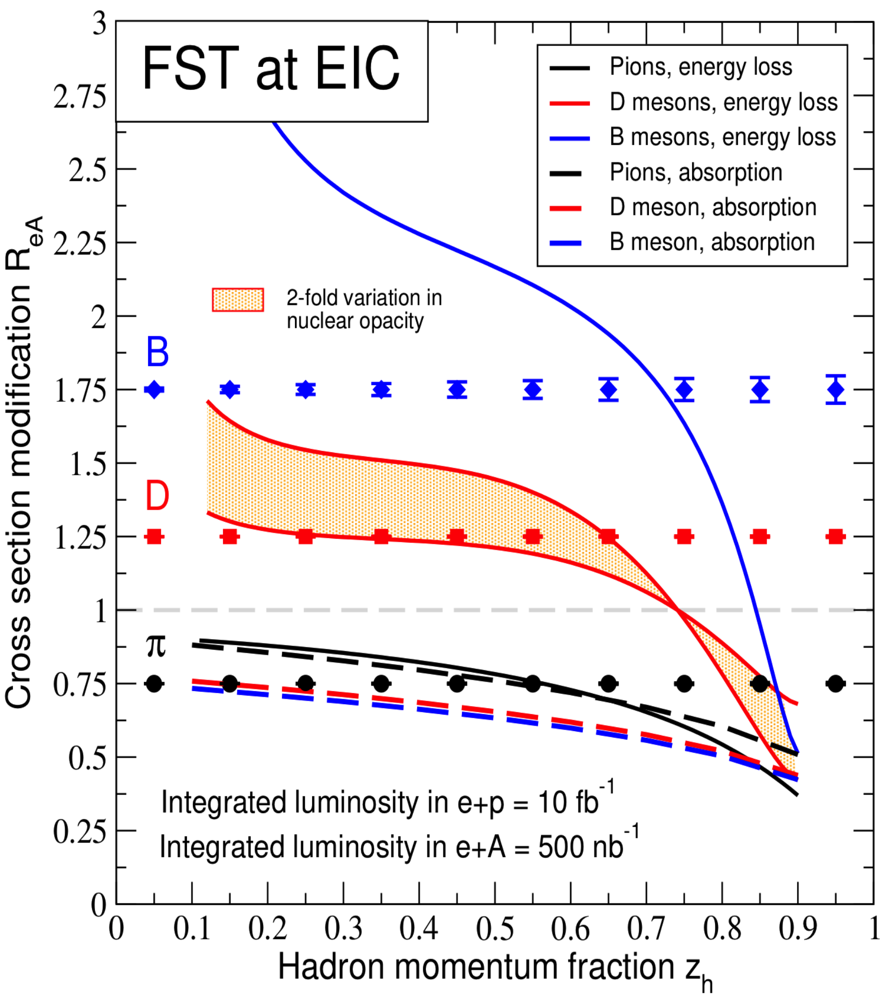




- To understand the nuclear medium effects on hadron production such as modification on nuclear PDFs, parton energy loss mechanisms and hadronization processes through the comparison of measured heavy flavor hadron/jet cross section between e+p and e+A collisions.

Key EIC physics observables are under study

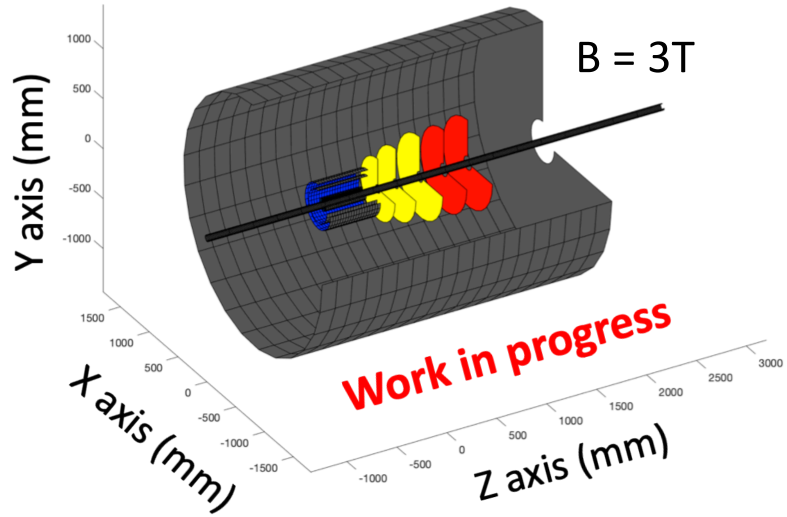
- Competing models of nuclear modification in DIS reactions with nuclei (e.g HERMES data). Differentiation not possible with light hadrons.
  - Hadronization inside nuclear matter (dashed lines).
  - Energy loss of partons, hadronization outside (solid lines).
- Heavy mesons have very different fragmentation functions and formation times
  - Easy to discriminate between larger suppression for D/B mesons (in-medium hadronization) and strong/intermediate z enhancement (E-loss).
  - Enhanced sensitivity to the transport properties of nuclei.



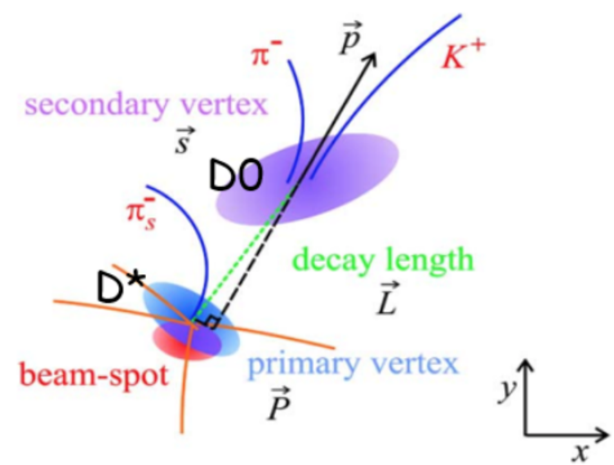
arXiv:2002.05880

Simulation setup

- Updated central+forward silicon tracker detector design in fast simulation to evaluate the tracking performance, which will be used for smearing in generated events.

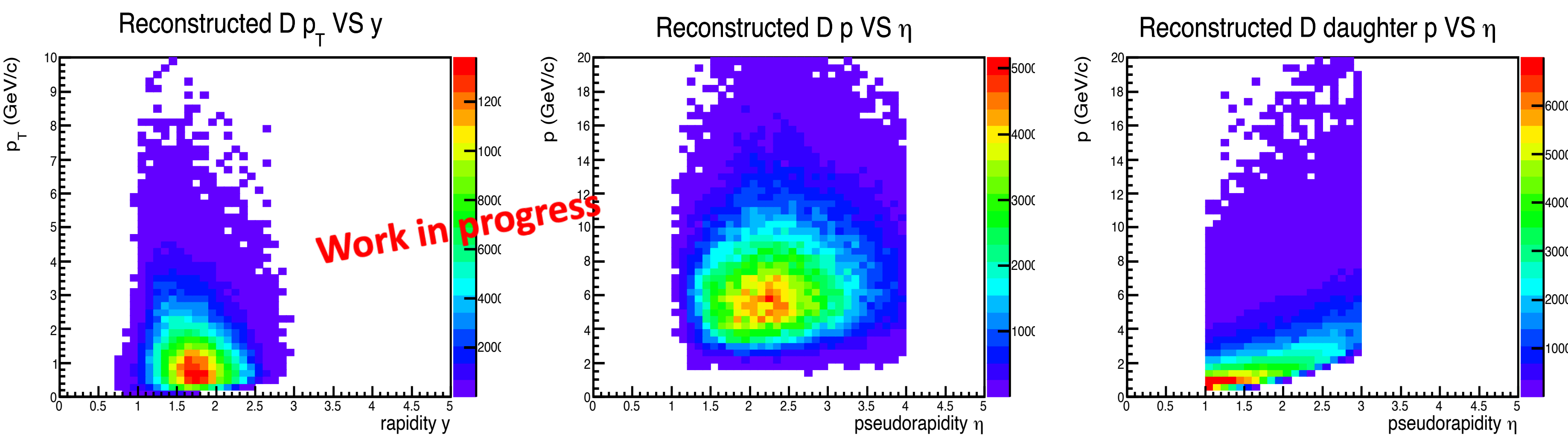


- The full analysis framework which includes the event generation (PYTHIA8), detector response in fast simulation, beam remnant interaction background embedding, and hadron reconstruction have been setup.
- Start with heavy flavor hadron reconstruction and we are working on the inclusive method as well.



Reconstructed D mesons in PYTHIA8 simulation

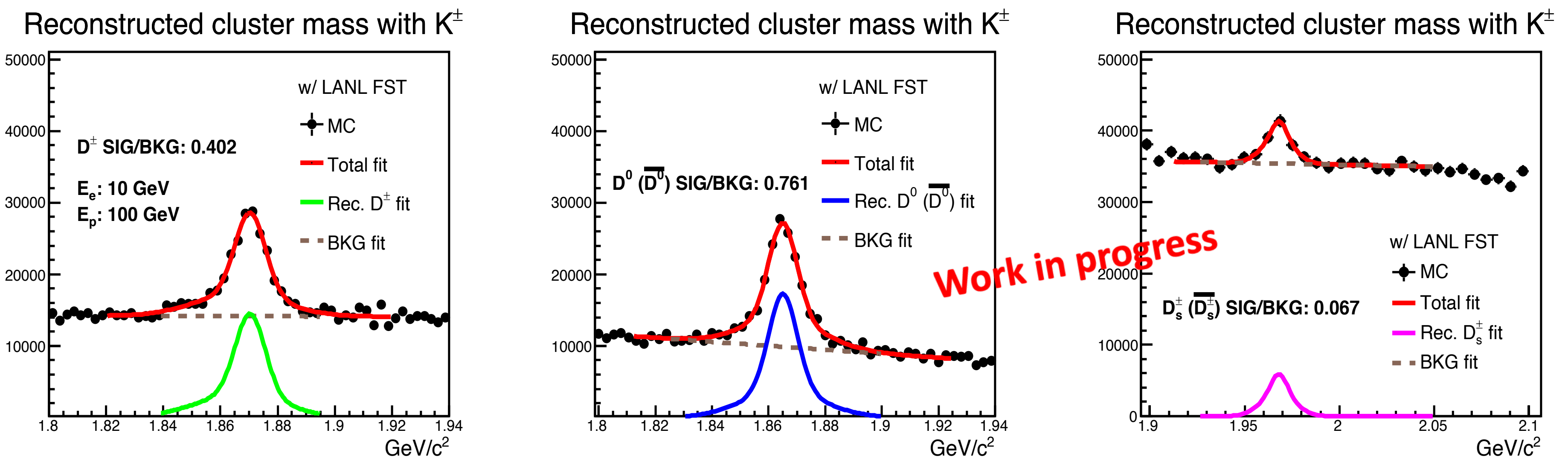
- In 10 GeV electron and 100 GeV proton collisions with integrated luminosity: 10 fb^{-1}.
- Reconstructed D meson kinematic distributions:
  - Tracking η cut: 1 to 3 and track efficiency set at 95%.
  - The performances are based on 100% K/π/p separation.
  - Reconstructed D-meson p_T VS rapidity (left), momentum VS pseudorapidity (middle) and the momentum VS pseudorapidity distribution for the D-meson decayed daughters (right).



- Most particles from forward D-meson decay have p<10 GeV/c.

Reconstructed D mesons in PYTHIA8 simulation

- In 10 GeV electron and 100 GeV proton collisions with integrated luminosity: 10 fb^{-1}.
- Reconstructed D meson mass distributions.
  - Tracking η cut: 1 to 3 and track efficiency set at 95%.
  - The performances are based on 100% K/π/p separation.
  - Charged track clusters that contain K$^{\pm}$ with a decay length (DCA) cut.

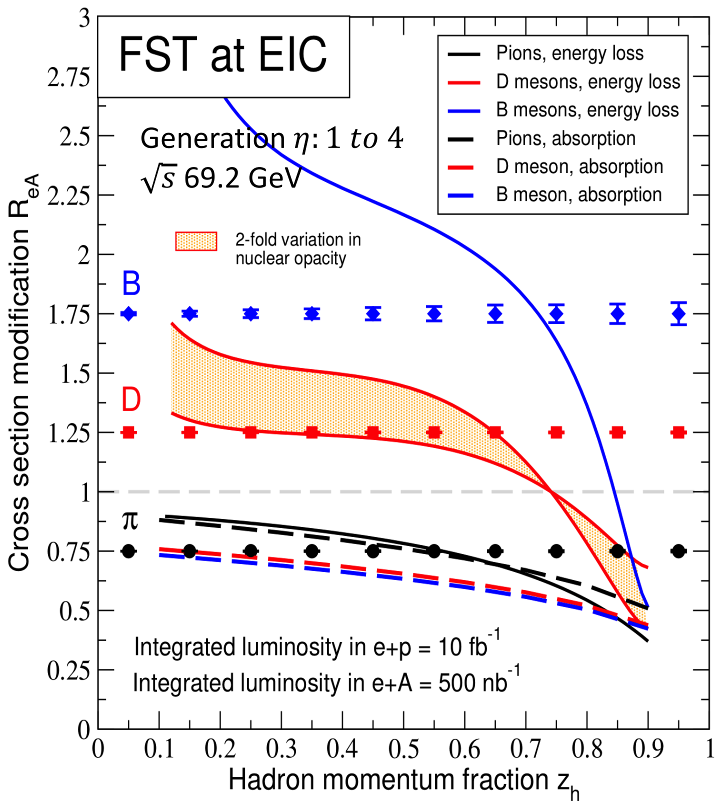


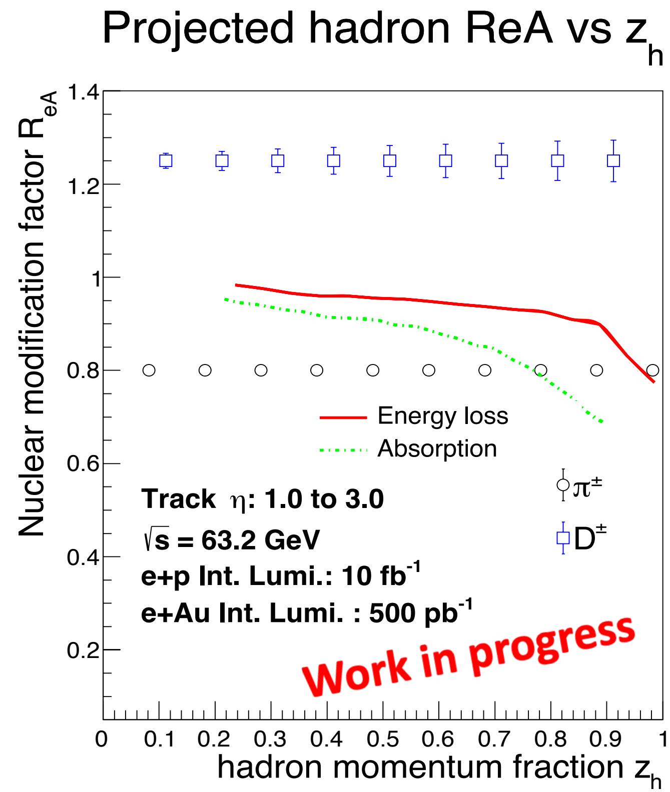
- Clear D-meson signal can be determined from combinatorial background and beam remnant background with one of the initial silicon tracker designs.

Money plot: Flavor dependent R_{eA} projections

Stat. uncertainty evaluated at generation level, w/ wide kinematic coverage

Stat. uncertainty evaluated at reconstruction level, w/ tighter kinematic coverage

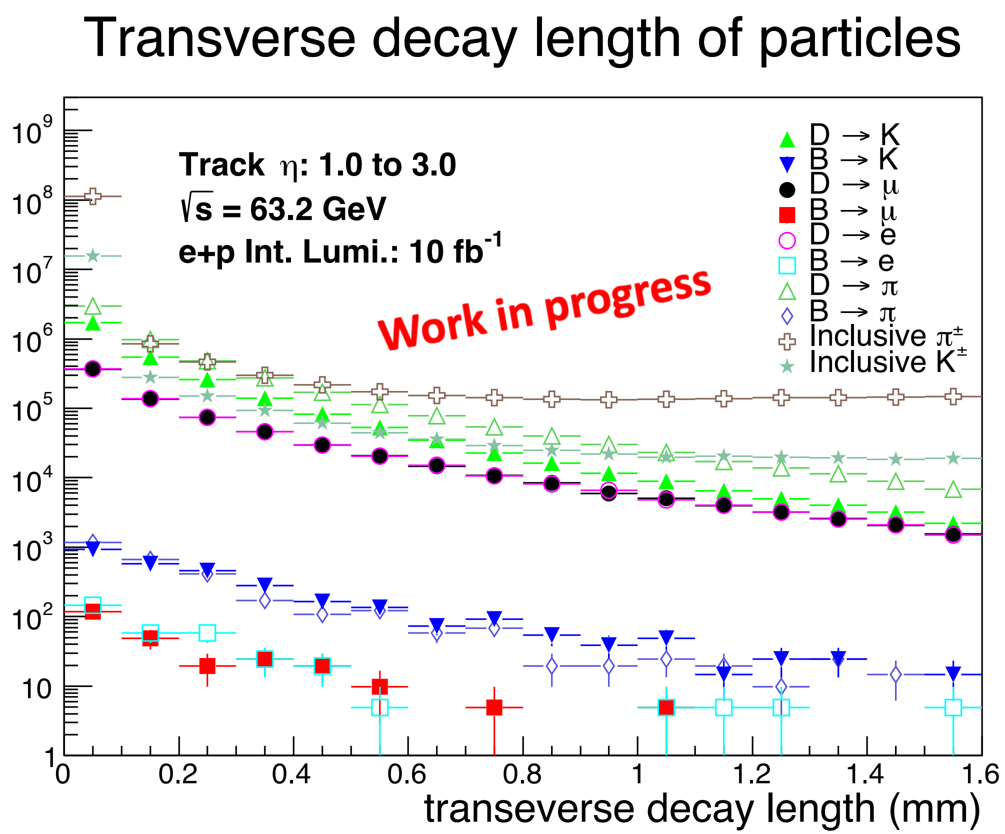




- Projected precision of the forward reconstructed light/heavy flavor hadrons can help separate different model predictions.
- Will implement updated detector performance and add the updated theoretical calculations.

Inclusive method to tag heavy flavor products

- Tag the heavy flavor decayed particles based on the decay length or Distance of Closest Approach (DCA) measurements.
- In 10 GeV electron and 100 GeV proton collisions with integrated luminosity: 10 fb^{-1}.



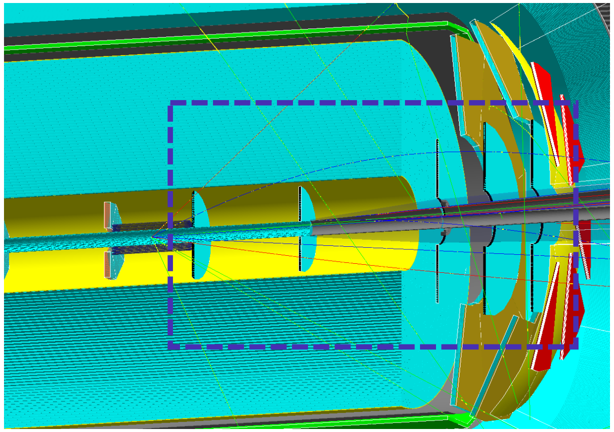
- Clear shape differences in the transverse decay length for light and heavy flavor decay products.
- Studies on heavy flavor hadron and jet tagging with different kinematic regions and different collision energies are underway.

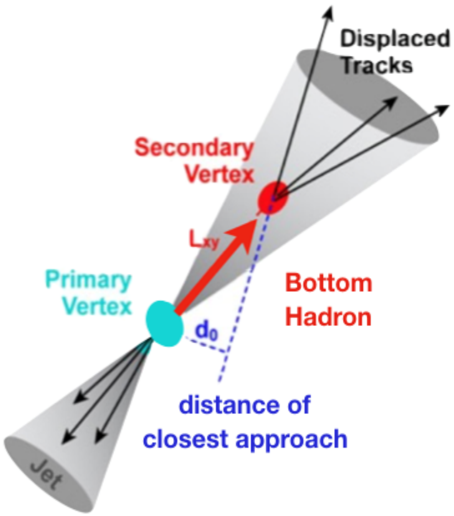
Detector requirements for heavy flavor measurements at the future EIC

- For fully reconstructed heavy flavor hadrons/jets:
  - Precise primary vertex and decay vertex measurements (vertex resolution <50μm).
  - Better than 3 sigma separation of the PID identification.
  - Good tracking momentum resolution in the central (<2%$\Delta p/p$) and forward (<10%$\Delta p/p$) pseudorapidity region.
  - Good time resolution (<10ns) to reduce background.
- For jet sub-structure:
  - Fast tracker which can provide synchronized readout with the calorimetry system.
  - Wide pseudorapidity and full azimuthal coverage.
  - Tracker that can provide good spatial resolution (<100 μm).
  - Better than 3 sigma separation of the PID identification.

Open heavy flavor simulation plan

Initial design of the forward silicon tracker implemented into the Fun4All w/ Babar magnet.



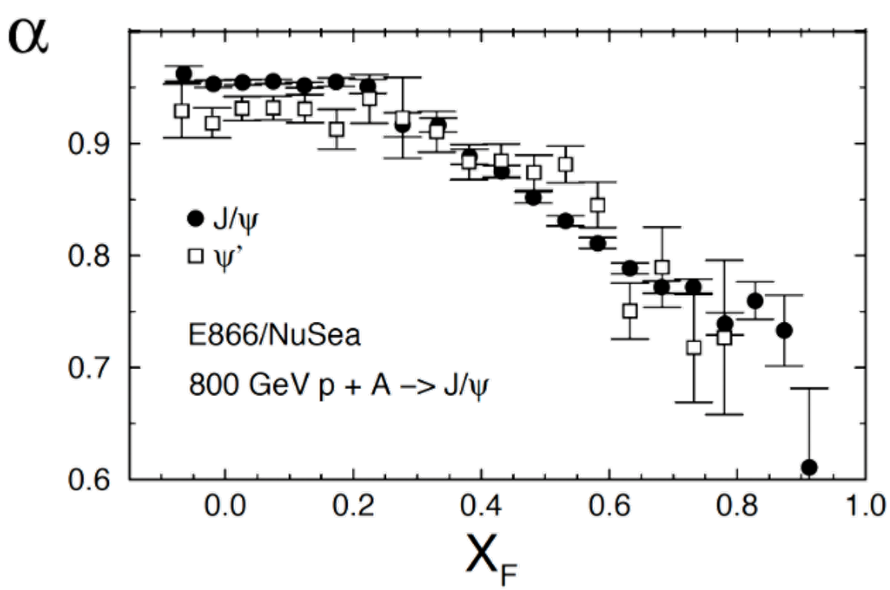


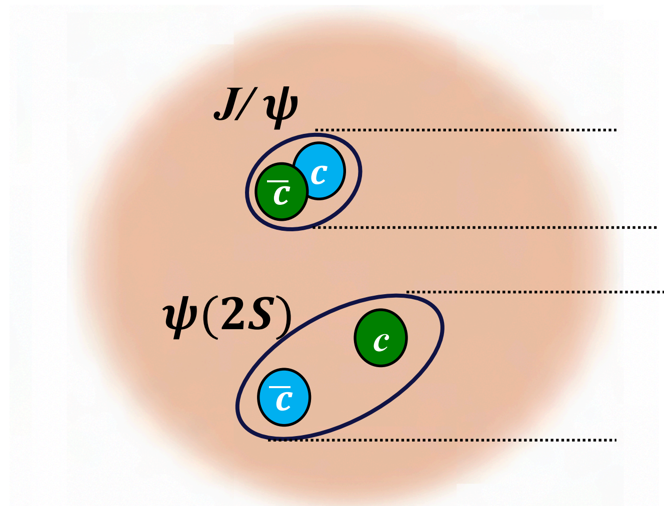
- We have completed the projected stat. uncertainties for one of the golden measurements: flavor dependent R_{eA} for reconstructed hadrons with updated detector geometries.
- Implementing the updated vertex and tracking performance in the heavy flavor and jet studies is underway.
- Work on the projected stat. uncertainties of the nuclear modification factor R_{eA} with different collision energies, different kinematic regions is in progress.
- Will work on the flavor tagged jet cross sections and jet sub-structure studies in e+p and e+A collisions.

Quarkonia Interactions Inside the Nucleus

- Quarkonia and open heavy flavor experience similar initial state effects due to nPDF, energy loss, etc when produced in nuclei
- However, quarkonia is uniquely subject to breakup – suppression due to disruption of the $Q\bar{Q}$ pair

E866, PRL 84 (2000) 3256-3260





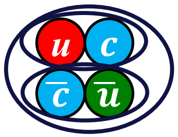
Larger (weakly bound) states sample a larger volume of the nucleus while passing through – larger absorption cross section
Explains trends observed in fixed target data at FNAL, SPS

Arleo, Gossiaux, Gousset, Aichelin PRC 61 (2000) 054906

Study Exotic Hadron Structure at the EIC

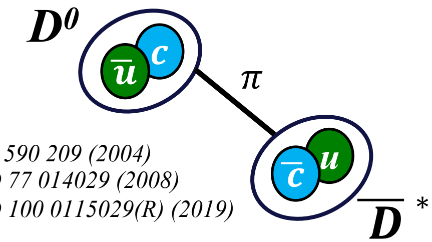
- The structure of exotic quarkonia states such as X(3872) is not known:

Compact Tetraquark (relatively tightly bound)



Diquark-diantiquark
PRD 71, 014028 (2005)
PLB 662 424 (2008)

Hadronic Molecule (weakly bound)



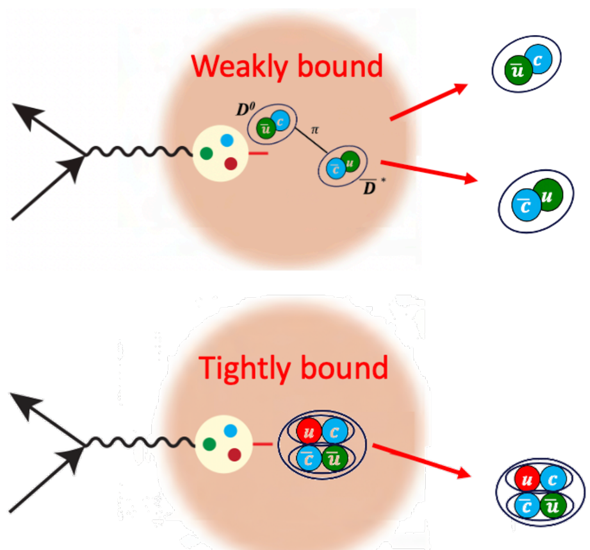
PLB 590 209 (2004)
PRD 77 014029 (2008)
PRD 100 0115029(R) (2019)

Mixtures
exotic + conventional states

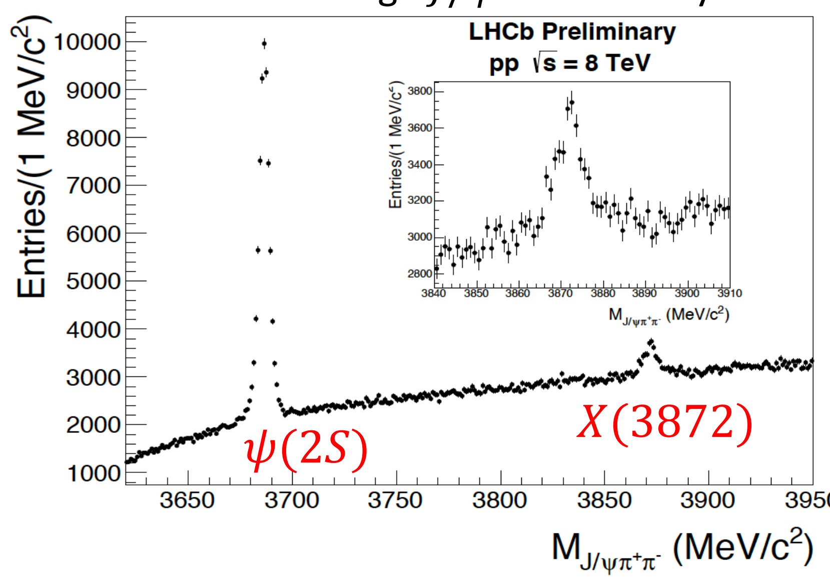
$$X = a\,|c\bar{c}\rangle + b\,|c\bar{c}q\bar{q}\rangle$$

PLB 578 365 (2004)
PRD 96 074014 (2017)

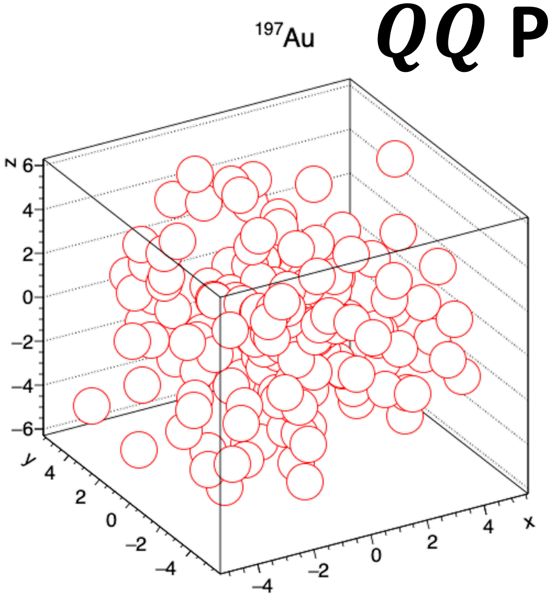
- Breakup of X(3872) in nuclei should depend on its radius
- Therefore, exotic structure can be studied by measuring suppression in eA collisions.



conventional $\psi(2S)$ and exotic X(3872) accessible through $J/\psi\pi^+\pi^-$ decays



$Q\bar{Q}$ Propagation through Nuclei



- In Monte Carlo simulation, populate a Glauber nucleus, using parameters from PHOBOS model: arXiv:1408.2549
- Randomly select starting point for $Q\bar{Q}$ pair
- Propagate $Q\bar{Q}$ along z axis
- Following model of Arleo *et al.* in Phys Rev C, 61 054906 (2000), expand $Q\bar{Q}$ radius as a function of time:

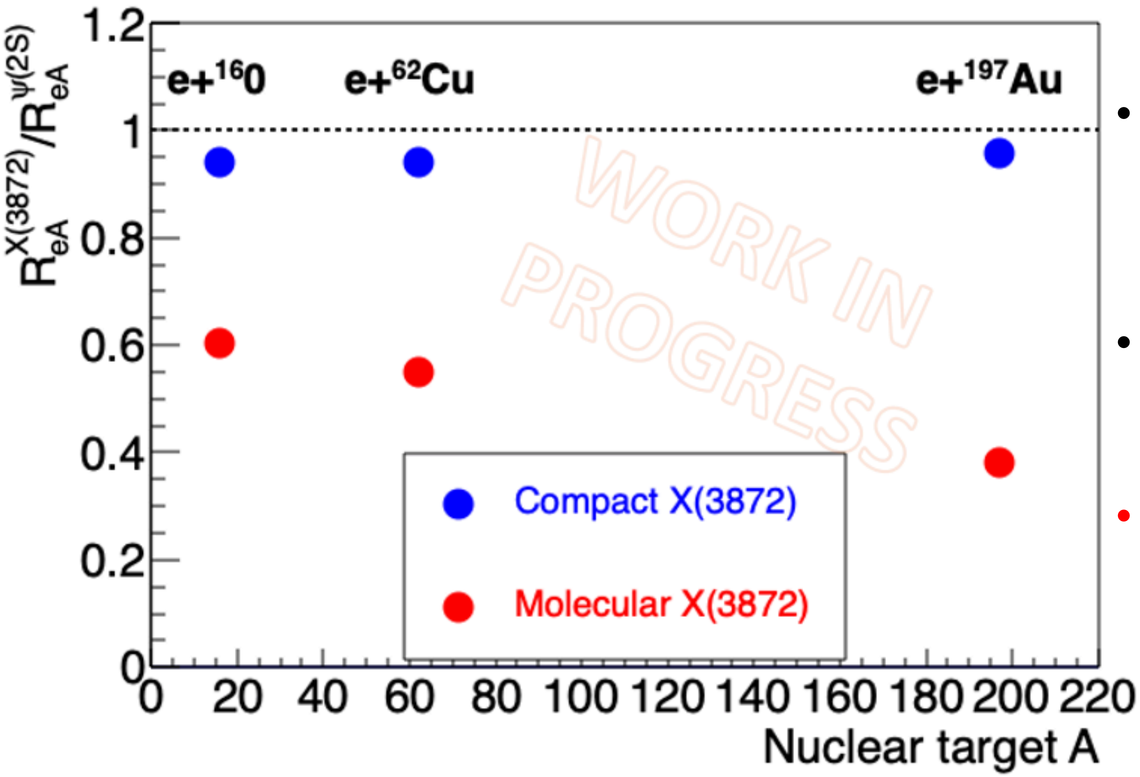
$$r_{c\bar{c}}(\tau) = \begin{cases} r_0 + v_{c\bar{c}} \ \tau & \text{if } r_{c\bar{c}}(\tau) \leqslant r_i \\ r_i & \text{otherwise} \end{cases}$$

- Calculate radius-dependent cross section:

$$\sigma_{(c\bar{c})_1 N} = \sigma_{\psi N}(s) \cdot (r_{c\bar{c}}/r_{\psi})^2$$

- Three cases: $\psi(2S)$ with radius 0.87 fm, compact X(3872) with radius 1 fm, molecular X(3872) with radius 7 fm
- If $Q\bar{Q}$ comes within a distance of $\sqrt{\sigma_{c\bar{c}}/\pi}$ to a nucleon, consider it disrupted.

Work in Progress:
Relative modification of X(3872)/ $\psi(2S)$



- Little difference in suppression between model of compact X(3872) and $\psi(2S)$, as expected.
- Large difference between model of molecular X(3872) and $\psi(2S)$.
- **Potential for decisive discrimination between X(3872) structure models at the EIC.**

Next steps, currently in progress:

- Calculate uncertainties based on expected yields in eA collisions
- Implement $\mathrm{X}(3872), \psi(2) \rightarrow J/\psi\pi^+\pi^-$ in simulation to study detector effects/requirements in detail

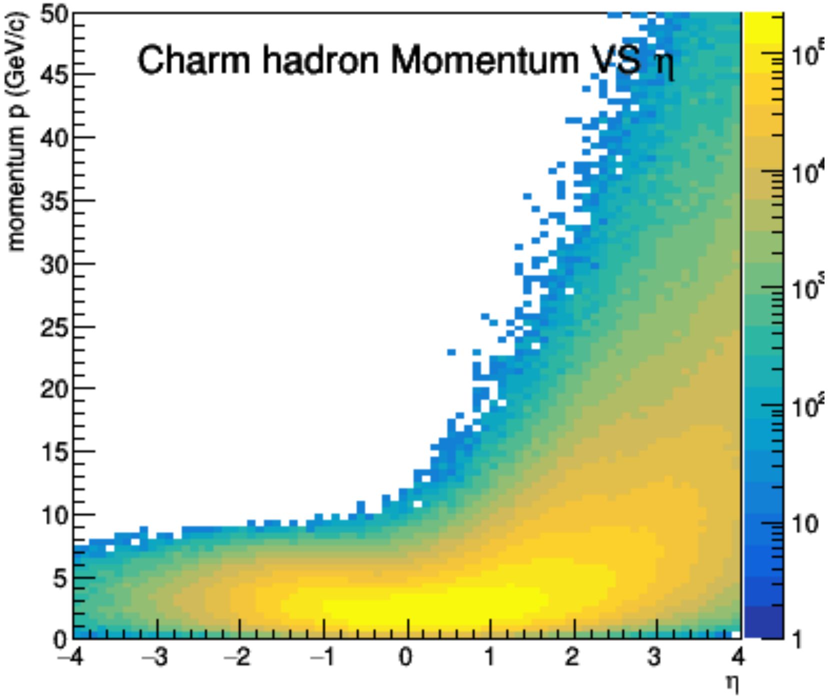
Summary

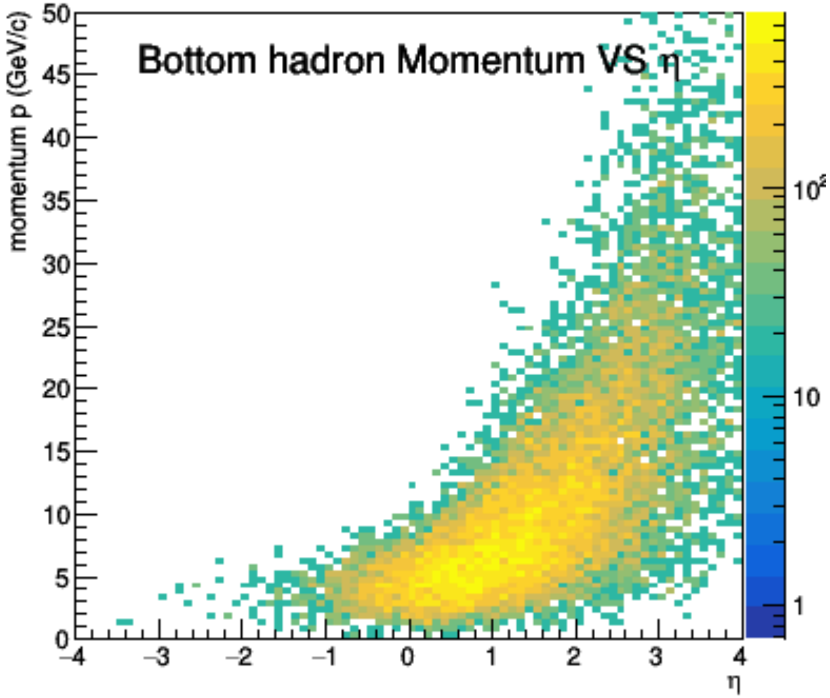
- The nuclear environment at the EIC provides an opportunity to study fundamental QCD physics:
  - Hadronization process
  - Parton/hadron transport in the nucleus
  - Allowed configurations of quarks bound inside hadrons
- First projected statistical uncertainties of nuclear modification factor R_{eA} for reconstructed light/heavy flavor hadrons has been delivered.
- Initial predictions of the X(3872)/ $\psi(2S)$ nuclear modification in different e+A collisions have been achieved.
- Additional work on realistic simulation studies and updated projections is underway.

Backup

Charm/Bottom hadron

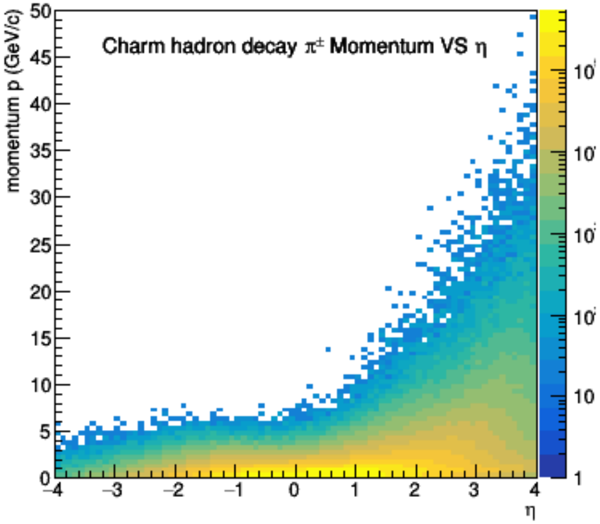
- 10 GeV electron + 100 GeV proton with integrated luminosity at 10 fb^{-1}
- At generation level:

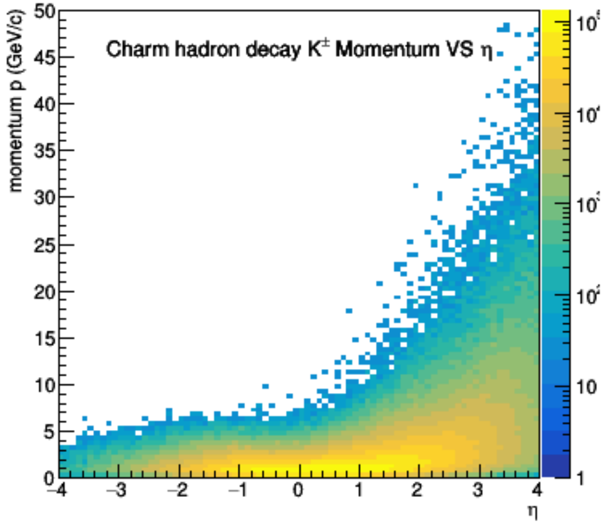


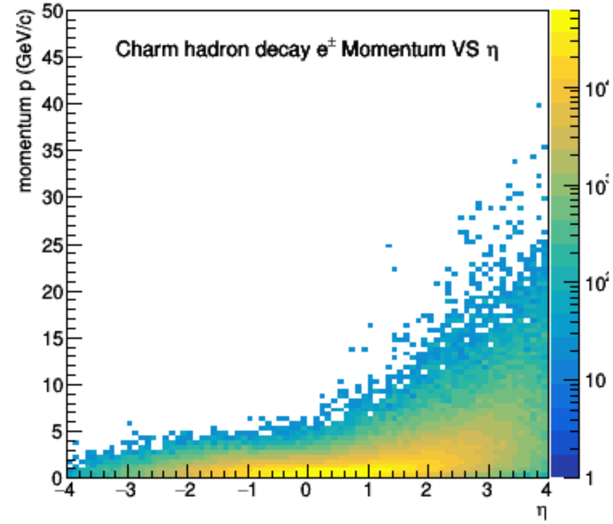


Charm hadron decay particles

- 10 GeV electron + 100 GeV proton with integrated luminosity at 10 fb^{-1}
- At generation level:

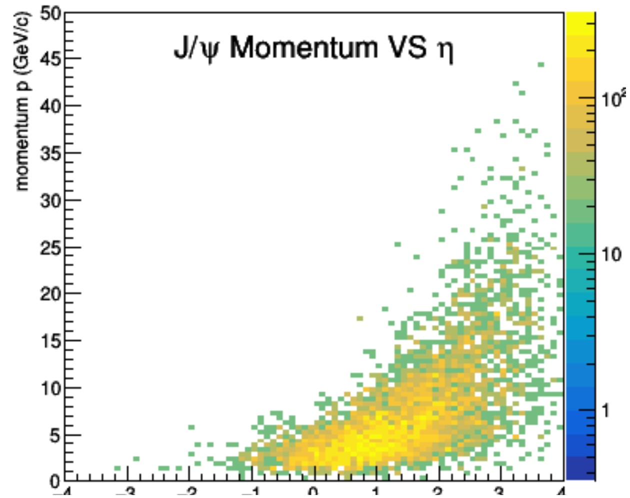


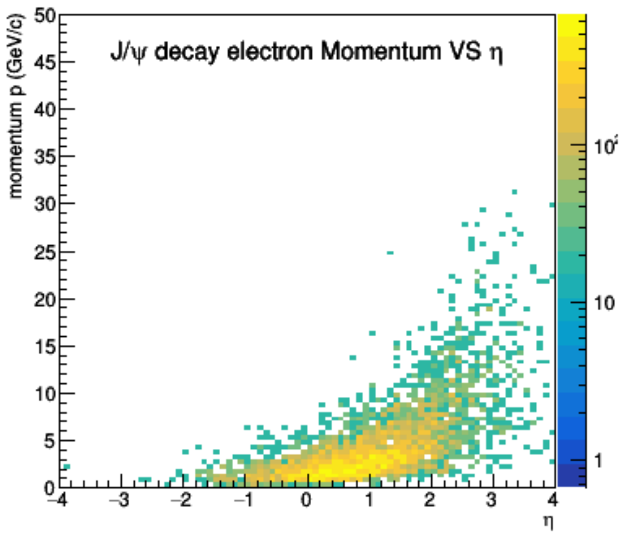


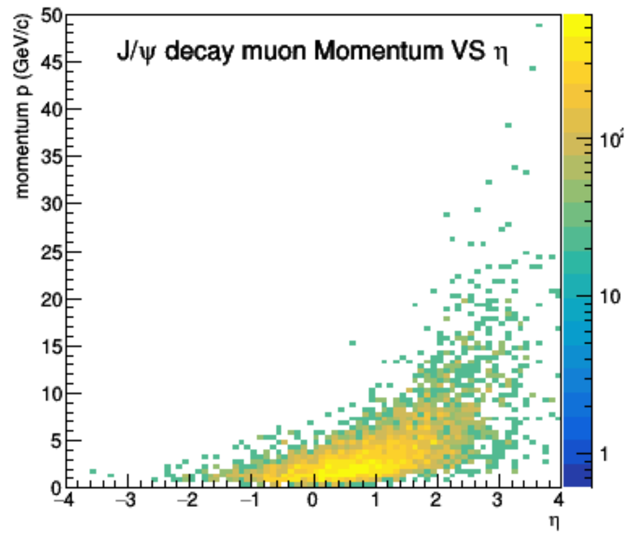


J/ψ and its decay particles

- 10 GeV electron + 100 GeV proton with integrated luminosity at 10 fb^{-1}
- At generation level:

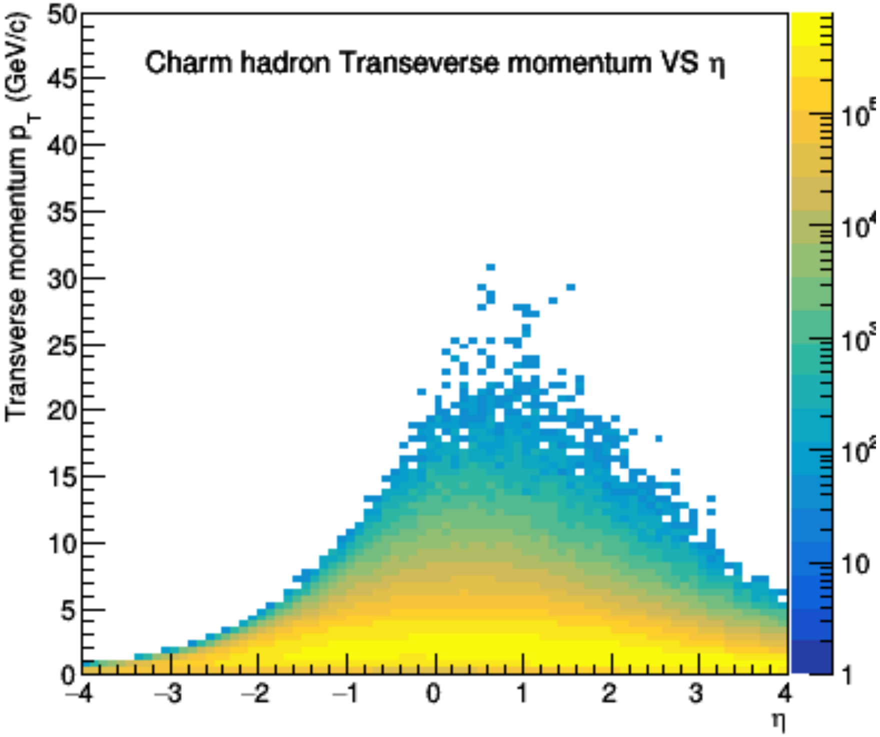


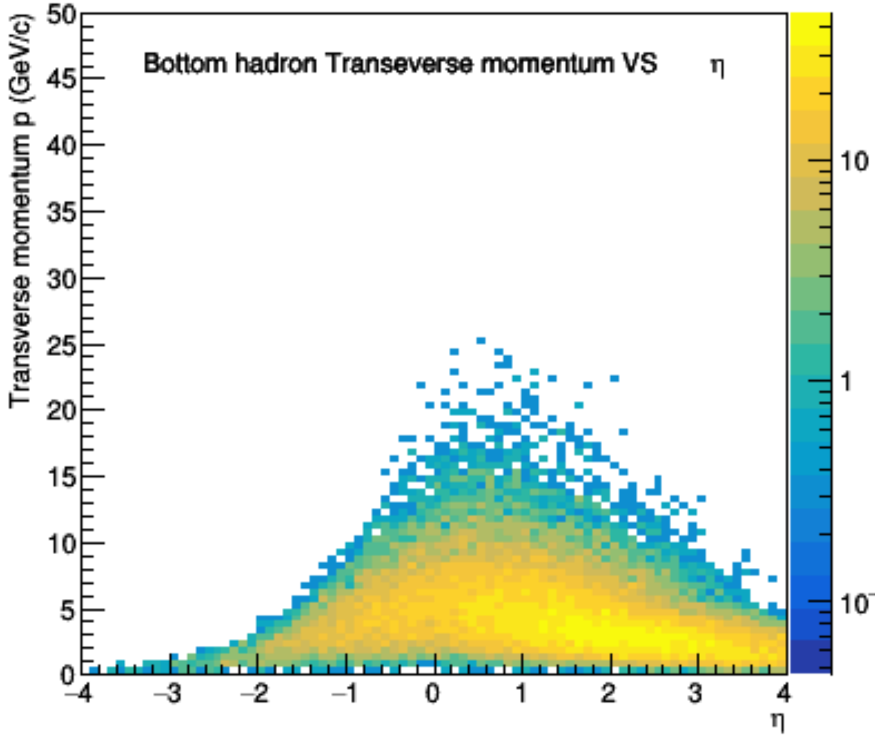




Charm/Bottom hadron

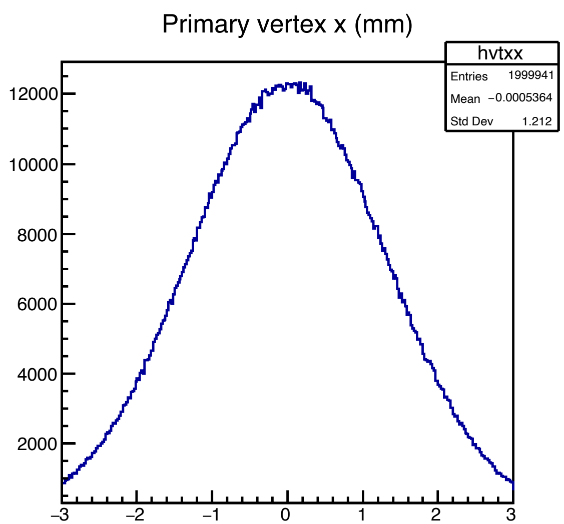
- 18 GeV electron + 275 GeV proton with integrated luminosity at 10 fb^{-1}
- At generation level:





Smeared vertex distributons

- In 18 GeV electron and 100 GeV proton collisions:



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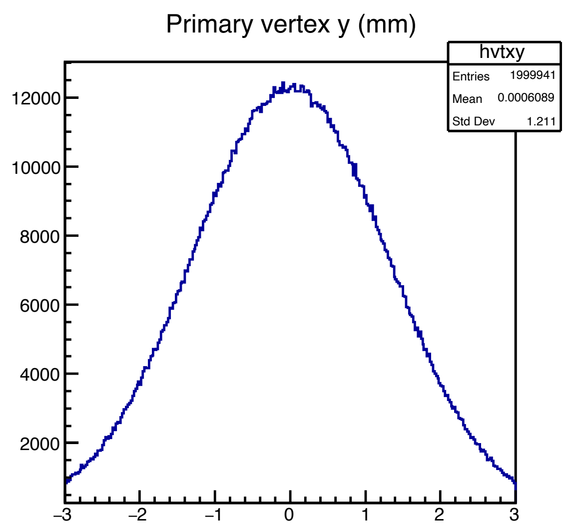

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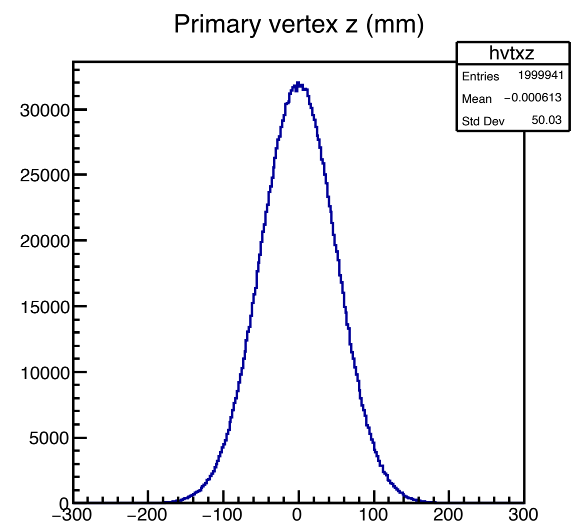

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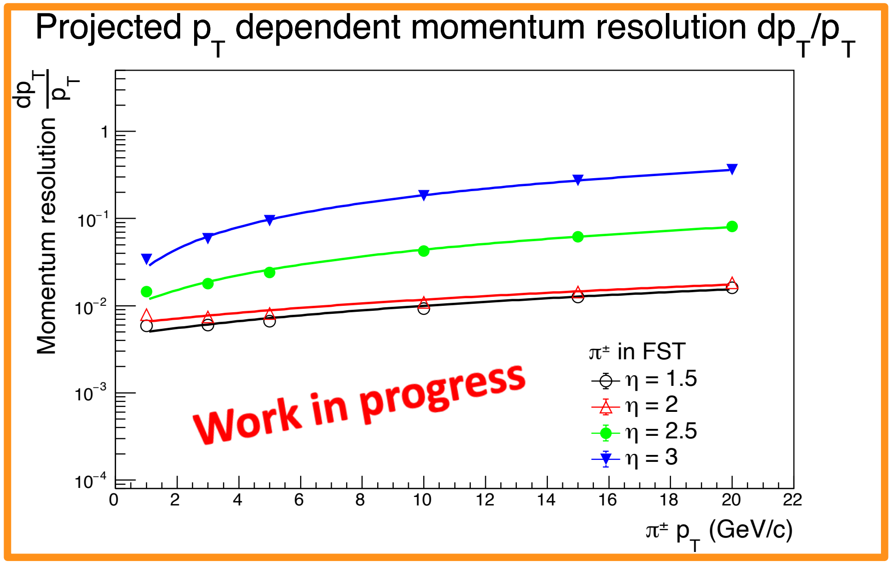
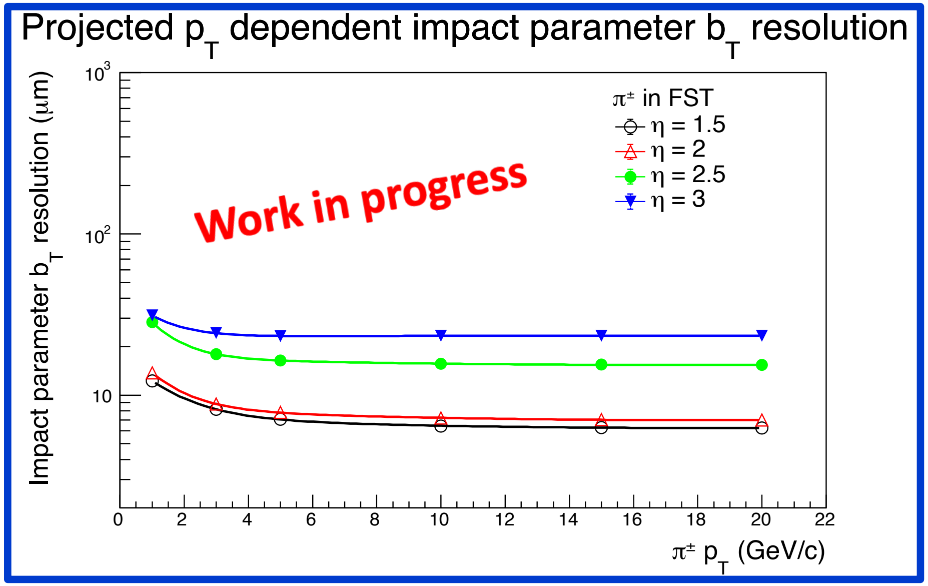
Single track performance in fast simulation

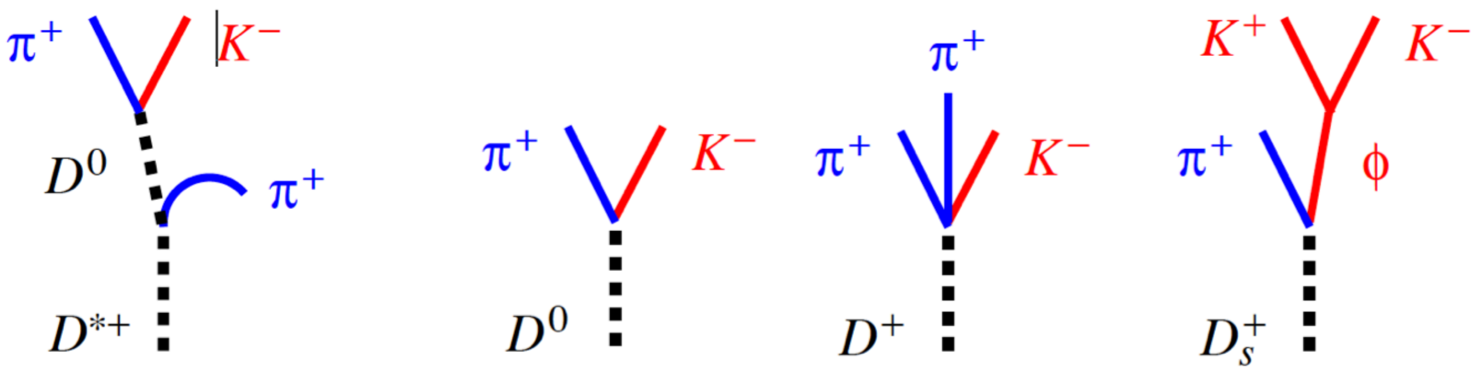
- Track performance from the FST with average pixel pitch at 30 μm, materials per detector layer: MAPS 0.4%X_0 and HV-MAPS 0.8%X_0 and the readout rate is at 500 kHZ, same for the central barrel layers:





- Better than 40 μm resolution can be achieved by the initial FST design for the transverse decay length b_T measurements for tracks with p_T > 1 GeV/c over the 1.5<η<3.0 region.
- The momentum resolution dp_T/p_T are better than or consistent with the forward tracking requirements from the EIC detector handbook.

D-meson decay channels



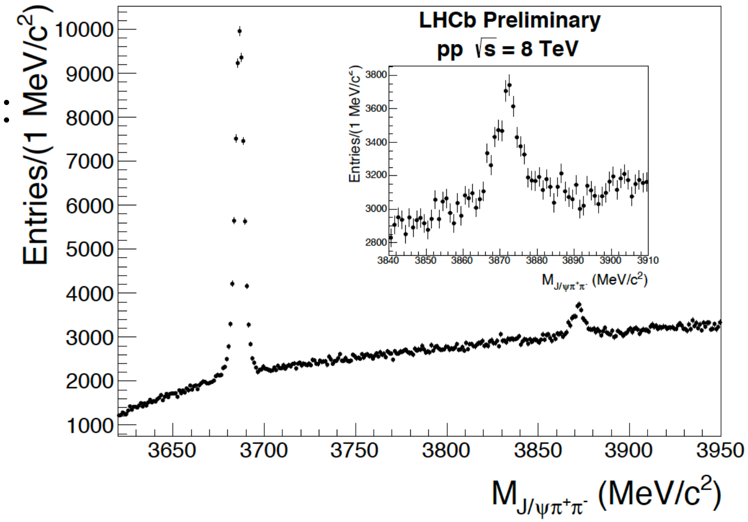
Possible breakup of X(3872) - LHCb

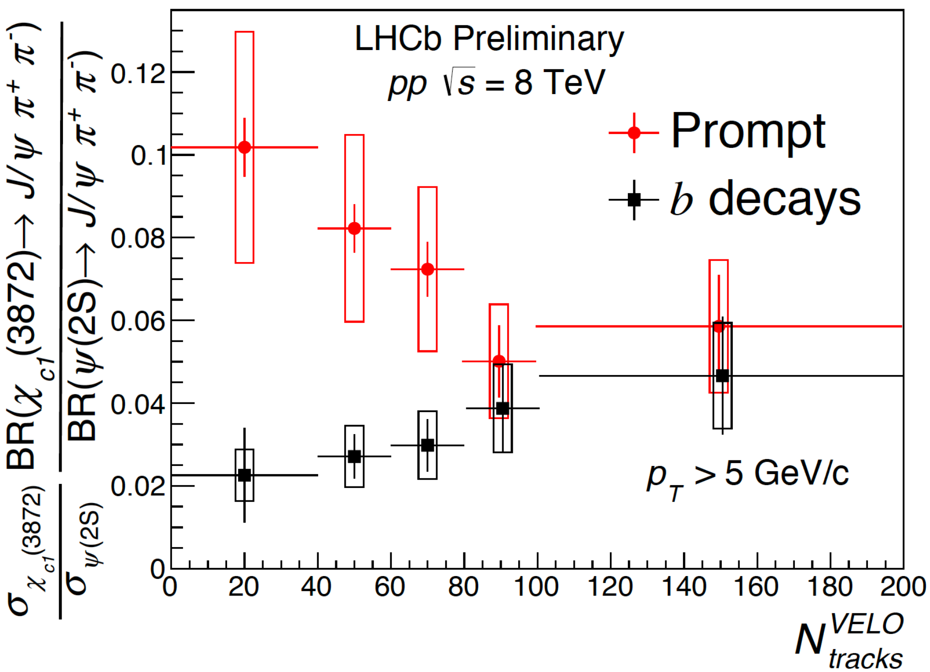
LHCb-CONF-2019-005, arXiv:2002.01551

Reconstruct the $\boldsymbol{\mu^+\mu^-\ \pi^+\pi^-}$ final state from the decays:

$$\boldsymbol{X(3872) \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\rho(\rightarrow \pi^+\pi^-)}$$

$$\boldsymbol{\psi(2S) \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\pi^+\pi^-}$$





Prompt Component:
Increasing suppression of $\boldsymbol{X(3872)}$ production relative to $\boldsymbol{\psi(2S)}$ as event activity increases

***b*-decay component:**
No significant change in relative production, as expected for decays in vacuum. Ratio is set by ***b*** decay branching fractions.
Consistent with ATLAS measurement
R = 0.0395±0.0032±0.0008
(p_T>10GeV/c)