Probing nuclear gluons with heavy flavors at an Electron-Ion Collider

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Overview

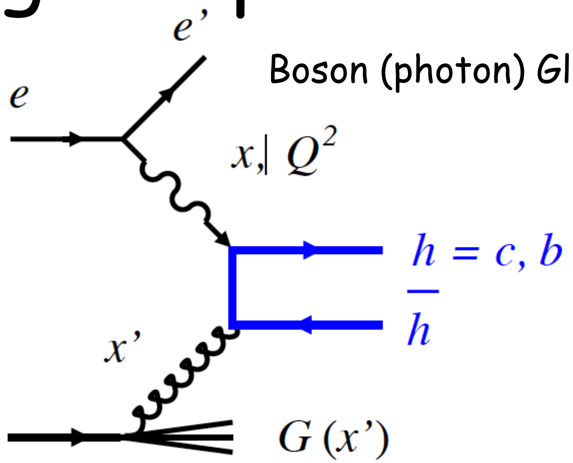
AIM: Study feasibility of direct measurements of nuclear gluons at $x >\sim 0.1$ using heavy quark probes with a future Electron-Ion Collider

- Nuclear modification of gluons
- Open charm/beauty as direct probe
- Simulation tools and methods
- PID and Vertex detectors at JLEIC
- EIC simulation results

Introduction

- At HERA ep collider measurements of open charm and beauty were performed at $x_B<0.01$
- The high luminosity beam at EIC would permit measurements of open charm/beauty production with extending kinematic coverage to the large $x_B \sim 0.1$ and rare processes, such as high PT jets.
- At EIC for the first time and with a full control of initial state:
  - heavy quark production on nuclear targets
  - heavy quark propagation through cold nuclear matter

Open charm/beauty production as a direct gluon probe



Boson (photon) Gluon Fusion (BGF)

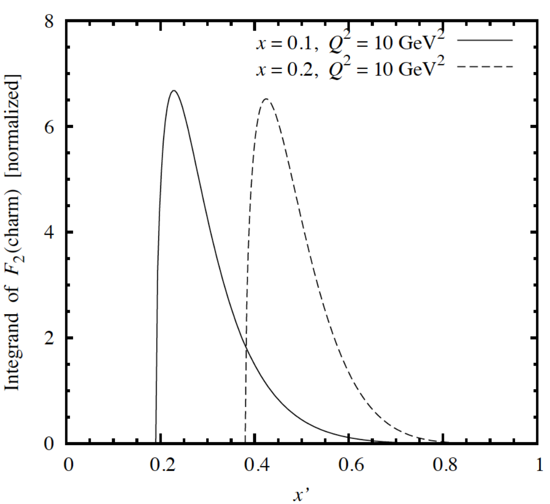
$$F_2^h(x, Q^2) = \int_{ax}^{1} \frac{dx'}{x'} \, x' G(x') \, \hat{F}_g^h(x/x', Q^2, m_h^2, \mu^2)$$

coefficient function

$$a = 1 + \frac{4m_h^2}{Q^2}$$

sets limit of x' integral

A



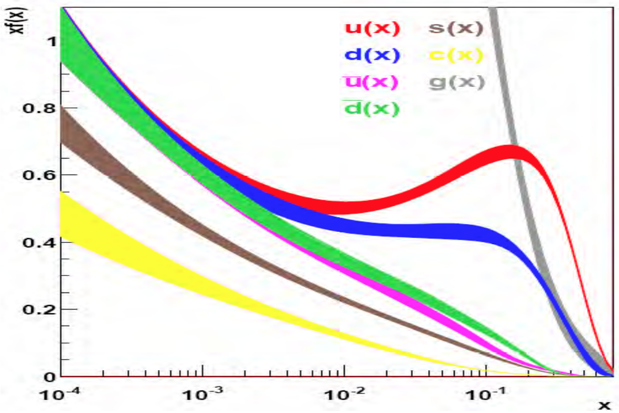
- Heavy quark production probes large-x' gluons "almost locally" at $x'_{glue} \geq x_{BJ}\,(1+4m^2_h/Q^2)$

- NLO corrections calculated, theory uncertainties quantified

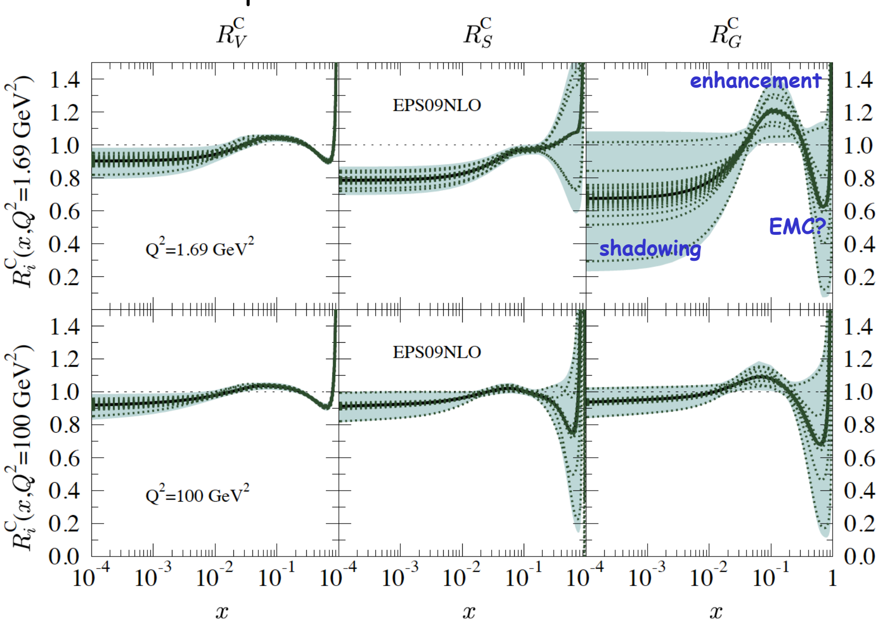
Laenen, Riemersma, Smith, Van Neerven 93+, Kawamura et al. 12, Alekhin, Moch et al. 93+

Nuclear modification of partonic structure

CTEQ6 nucleon PDF parametrization



Nuclear PDF parametrization EPS09 Eskola et al. 2009



See talk by Nestor Armesto

- For nucleon:
  - ~50% of gluon momentum sum rule from region x > 0.1
  - g(x) ≈ d(x) quarks at x ≥ 0.3 within errors
- Nucleon's partonic structure is modified in nucleus: NN interactions, non-nucleonic degrees of freedom
- Open questions concerning gluons:
  1. Is the nuclear gluon density suppressed at x > 0.3 (EMC effect) ?
  2. Are gluons enhanced at x ~ 0.1 (antishadowing) ?
- Strong gluon shadowing at x < 0.01 observed in the LHC Alice AA data suggests compensating antishadowing at x ~ 0.1

Nuclear gluons with heavy quarks

ZEUS Collaboration / Physics Letters B 649 (2007) 111–121

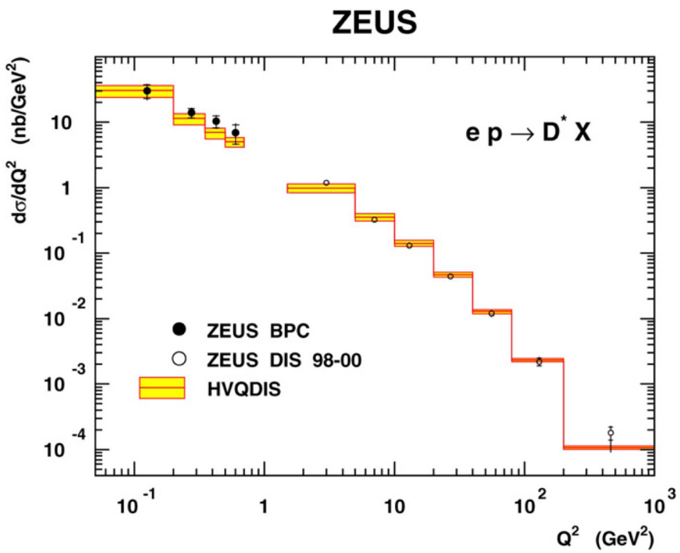
JLab 2016/17 LDRD Project LD1601

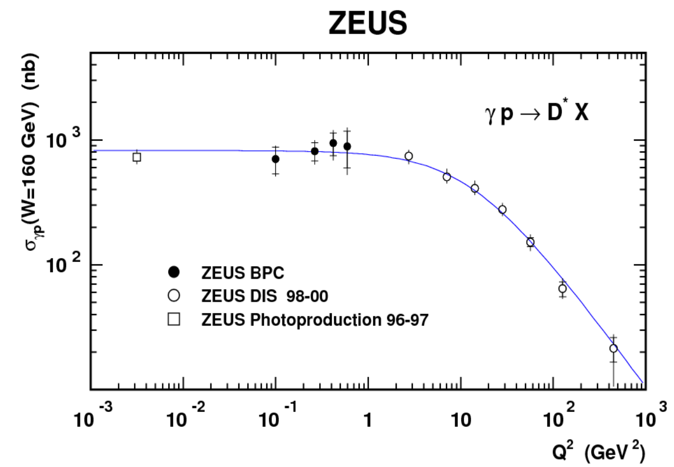
- Adapt heavy quark simulation tools (for example HVQDIS) to eN at EIC
  - The HVQDIS calculation produces a good description of the measured HERA data and describes the dependence on Q2 of the data over 4 orders of magnitude in Q2

- Estimate experimental conditions for open charm/beauty production in eN at EIC, using different reconstruction methods

  Stage 1: Generic assumptions about heavy quark reconstruction
  Stage 2: Idealized simulations of heavy quark reconstruction with PYTHIA/HERWIG, including acceptance, background
  Stage 3: Realistic simulations including resolution from detector specs

- Simulate nuclear ratio measurements: Stat/sys errors, impact on nuclear PDFs



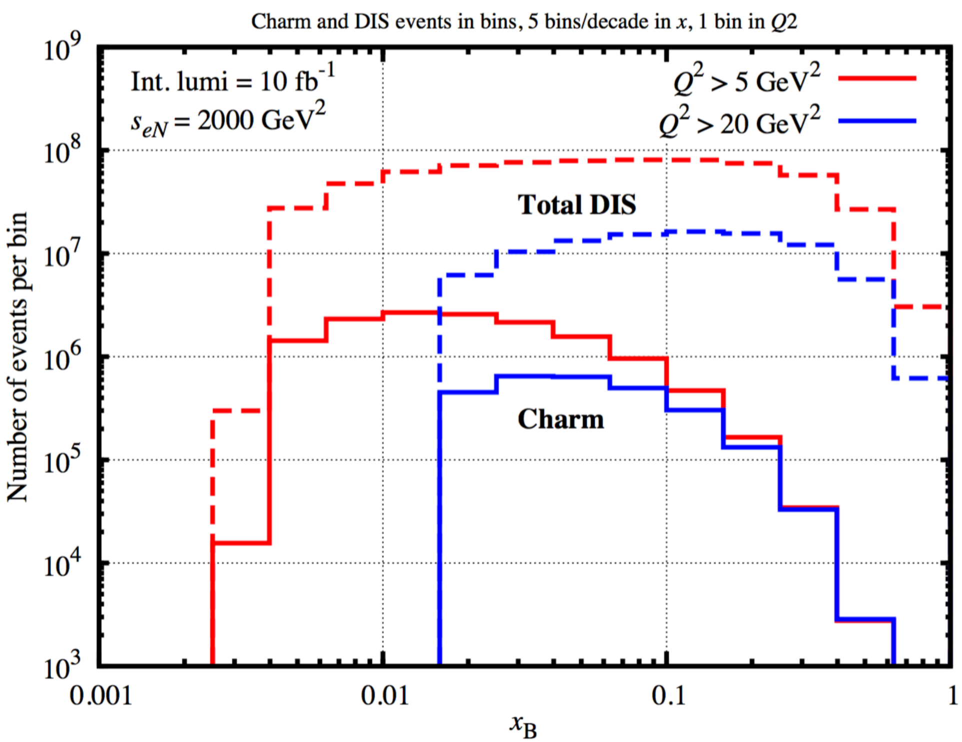


Charm and DIS cross-sections

Calculate differential cross sections using LO QCD formulas and integrate cross section over defined x and Q2 bins

$$d\sigma(e + N \to e' + X) \quad = \quad \mathrm{Flux}(x, y, Q^2)\ F_2(x, Q^2)\ dx\ dQ^2 \qquad (1)$$

$$d\sigma(e + N \to e' + c\bar{c} + X') \quad = \quad \mathrm{Flux}(x, y, Q^2)\ F_2^{c\bar{c}}(x, Q^2)\ dx\ dQ^2 \qquad (2)$$



- Charm production rates drop rapidly at large x
- Charm production rates 10^5 at x~0.1 (int. lumi 10 fb^{-1})
  Defines charm reconstruction efficiency needed for physics
- Charm/DIS ratio 2-3 % at x ~0.1
  Defines charm reconstruction environment

Methods of Charm reconstruction

1. Charm reconstruction using exclusive D-meson decays into charged π/K
   - $D^{*+} \rightarrow \pi^{+}_{slow} + (K^{-} \pi^{+})_{D0}$ used at HERA-I w/o PID and vertex , efficiency < 1%.
   - PID and vertex open up other exclusive channels (D) with theoretical charm efficiency up to 10%

2. Charm reconstruction using inclusive modes with displaced vertex

   D–meson decay length significance distribution used at HERA-II with vertex detector. Potentially much higher efficiency ~ 30% (E. ASCHENAUER, "Large-x at EIC"-workshop Oct. 2016)

   Relies essentially on vertex detection. Requires model of vertex detector.

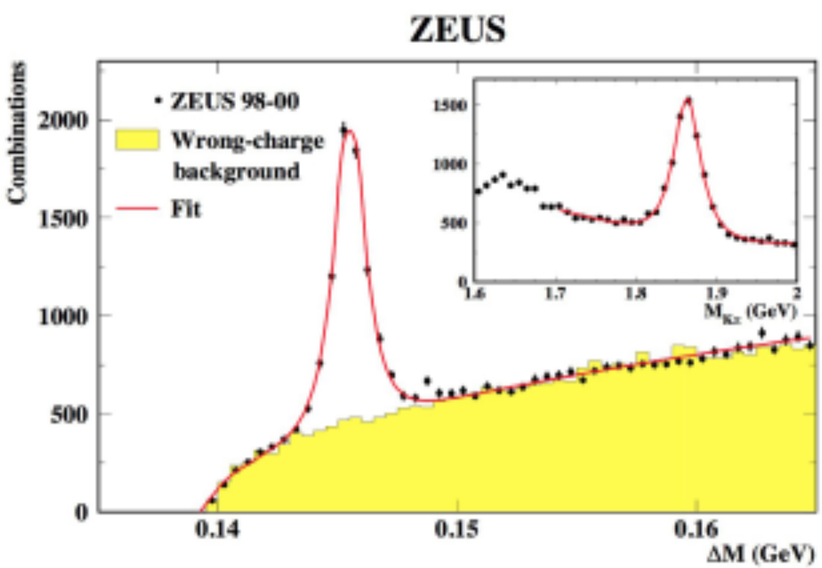
3. Charm reconstruction using high–pT $c\bar{c}$ pairs

   Extreme configurations: Low rate, but clean signal. Photoproduction possible

Charm with exclusive D-meson decays

- First HERA-I measurements without microvertex – D* golden channel

$$D^{*+} \rightarrow D^o \pi_s^+ \;,\; D^o \rightarrow K^- \pi^+$$



EIC offers:

- High luminocity beam (L~ 10^{34} cm^{-2} s^{-1})
  - Charm production rates drop rapidly at large x
- Close to 100% acceptance
  - including far-forward area
- PID for charged hadrons
- Vertex detector

h_c	f	Decay	BR
D^0	59%	$K^-\pi^+$	3.9%
		$K^-\pi^+\pi^+\pi^-$	8.1%
D^+	23%	$K^-\pi^+\pi^+$	9.2%
D^{*+}	23%	$(K^-\pi^+)_{D0}\ \pi^+_{\mathrm{slow}}$	2.6%
		$(K^-\pi^+\pi^+\pi^-)_{D0}\ \pi^+_{\mathrm{slow}}$	5.5%
D_s^+	9%	$(K^+K^-)_\phi\ \pi^+$	2.3%
Λ_c^+	8%	$pK^-\pi^+$	5.0%

D0 : 2.3 % + 4.8%
D+ : 2.1 %
D*: 0.6% + 1.2%
Ds: 0.2 %
Λc: 0.4%

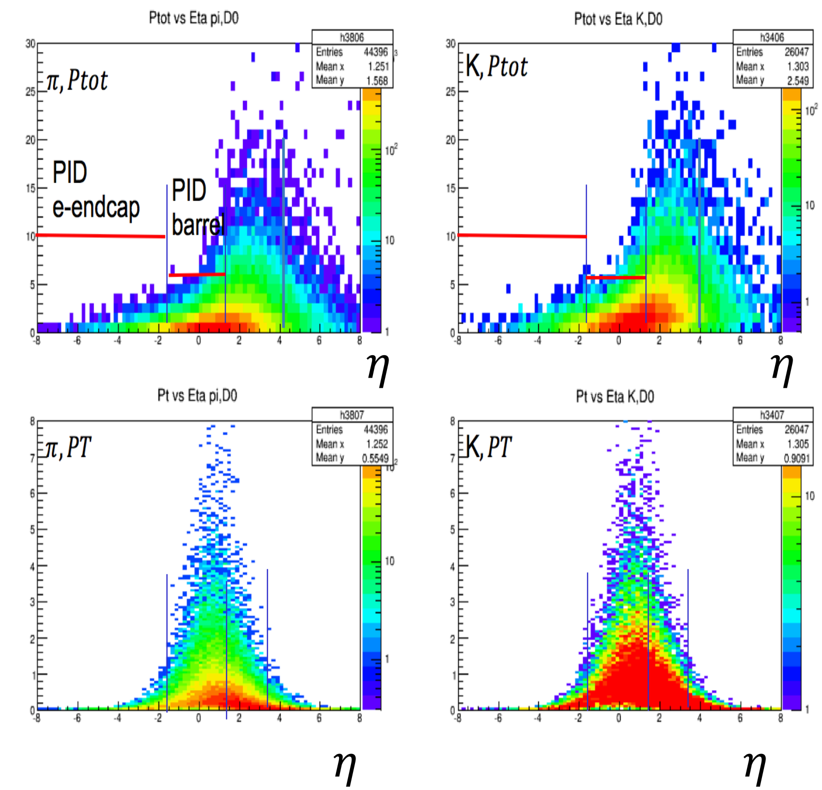
Total: ~10%

Particle identification at JLEIC

Energy ratio Ep/Ee ~ 5-10 places large-x
$c\bar{c}$ jets in central detector: Pythia

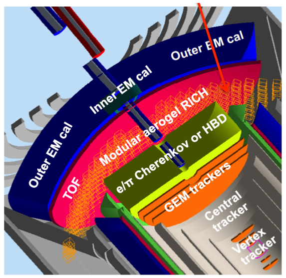
Electron end-cap: ~1.5% Barrel: ~78%
Hadron end-cap: ~20% Far-forward:< 0.5 %

π and K from D0 decay
Total momentum and PT vs pseudorapidity



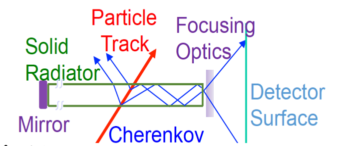
Yulia Furletova

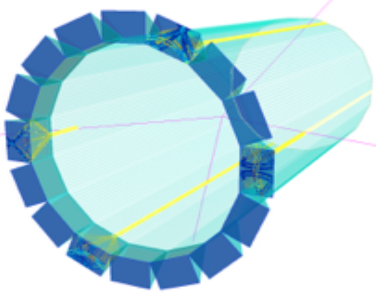
Electron end-cap: Modular RICH



- Modular aerogel RICH (eRD14 detector R&D)
- π/K separation up to ~10 GeV

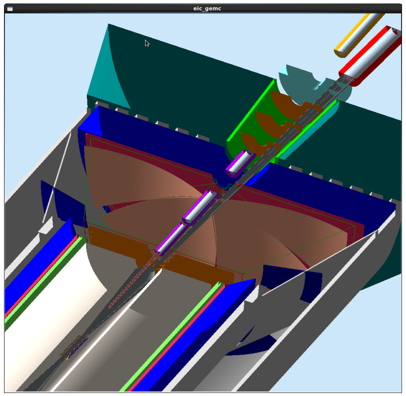
Barrel: DIRC





- radially compact (2 cm) Cherenkov detector
- Particle identification (3σ) p/K < 10 GeV, π/K < 6 GeV, e/π < 1.8 GeV
- eRD14 R&D program (test beam with PANDA), radiation hardness test

Hadron end-cap: dual-radiator RICH



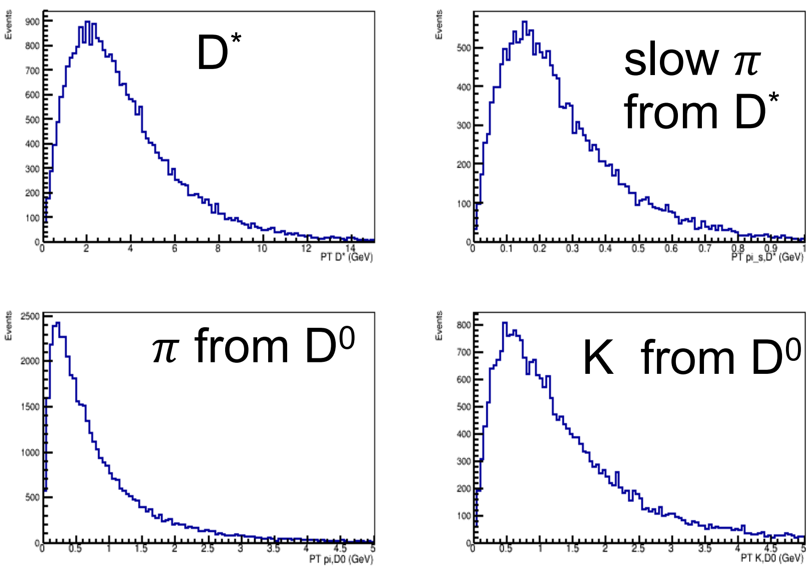
- JLEIC design geometry constraint: ~160 cm length
- Aerogel in front, followed by CF4
- covers energy for π/K up to 50GeV
- Sensitive to magnetic field=>
- New 3T solenoid minimized a field in RICH region

Exclusive D-meson decays

<u>Selection Cuts:</u>

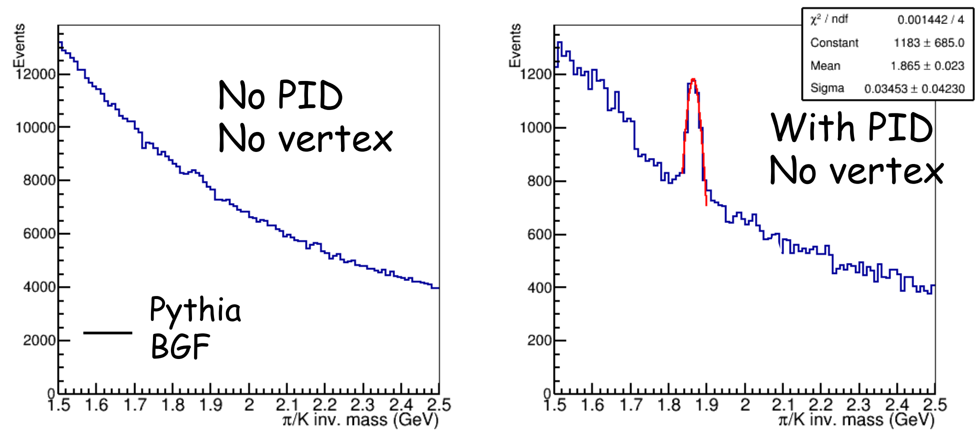
- Pythia 6 (ep 10 GeV x 100 GeV)
- Kinematic cuts: Q^2>10 GeV^2, x>0.05
- Pt >0.1 GeV
- VTX cut (D0~ 100 μm, D+ ~300 μm Ds ~150 μm)
- PID cut

-4 < η <-1.5	pt<10 GeV	(e-endcap, Modular RICH)
-1.5 < η <1.5	pt<6 GeV	(barrel, DIRC)
1.5 < η <4	pt<50GeV	(h-endcap, dual-RICH)



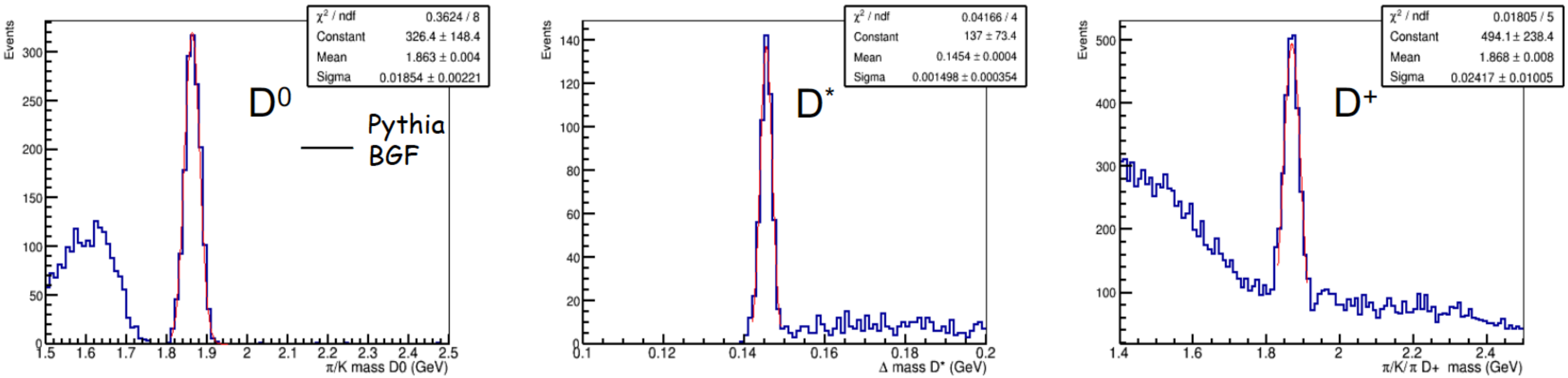
D0 mass plots:

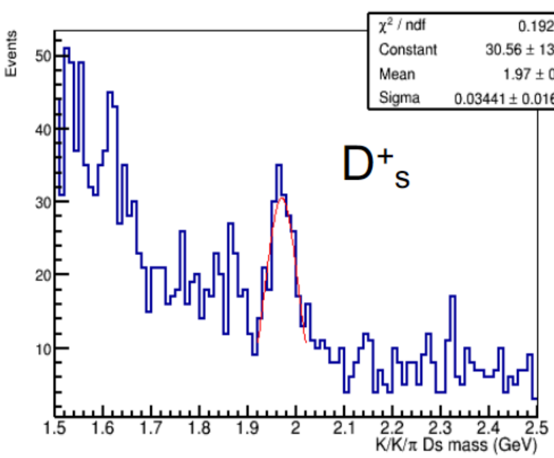
$D^o \to K^- \pi^+$

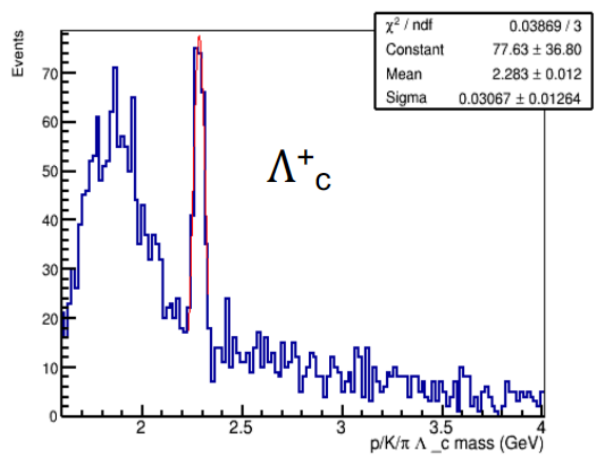


- ➢ **Simulations in progress:** incl. DIS background
- ➢ **Pion/kaon identification:** Substantially reduces combinatorial background
- ➢ **Vertex detection:** can further improve signal/background, but reduces overall efficiency

Other D-mesons







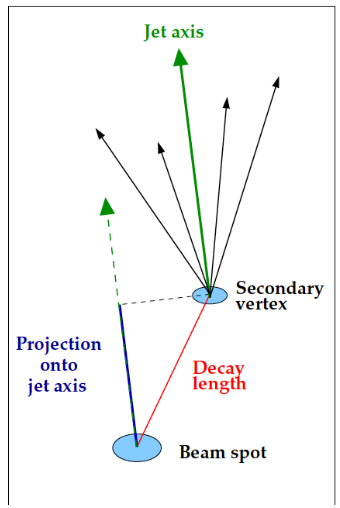
	Expected F*B	Reconstructed efficiency
D0	2.3%	0.88%
D*	0.6%	0.32%
D+	2.1%	1.14%
Ds	0.2%	0.07%
Λ^+_c	0.4%	0.13%

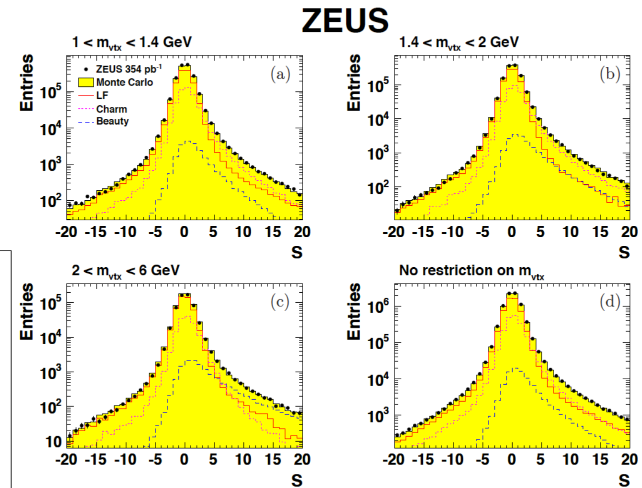
Next steps: DIS background, overall efficiency and systematics, optimization

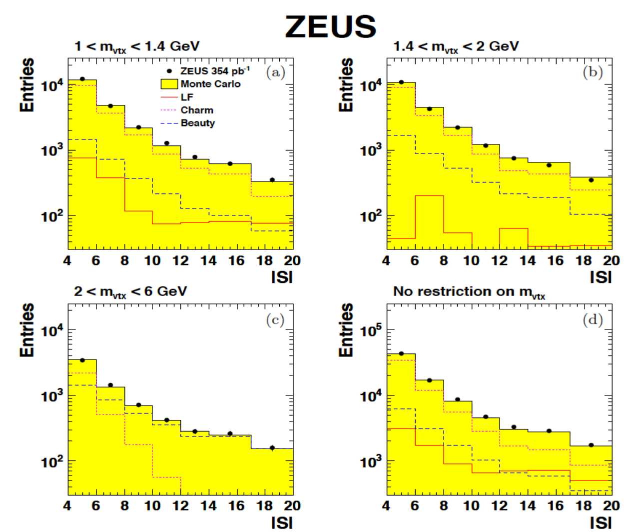
Charm reconstruction using inclusive modes with displaced vertex

- D-meson decay length significance distribution used at HERA-II with vertex detector.
- Potentially much higher efficiency ~ 30% (E. ASCHENAUER, "Large-x at EIC"-workshop Oct. 2016)

- Reconstruct jet
- Reconstruct vtx
- Decay length projection on jet axis
- (-) if in wrong semisphere
- Decay length significance S=d/δd
- M_{vxt} (assuming all tracks are charged pions)
- Subtract LF from wrong sign
- S in Mvtx bin







2014 ZEUS paper: JHEP09(2014)127

JLEIC Vertex detector

-Reconstruction of primary and secondary vertices
-improve momentum resolution of outer tracker
-provide stand-alone measurements of low-Pt particles
-dE/dx measurements (PID) for low Pt particles

2 layers of pixel detector
5 layers of double-sided Si strip det.

- Vertex detector is closest to IP. Background increases occupancy, therefore high granularity detector is needed (pixels).
- Multiple scattering: low material budget detector
- Beam related background could cause radiation damage.

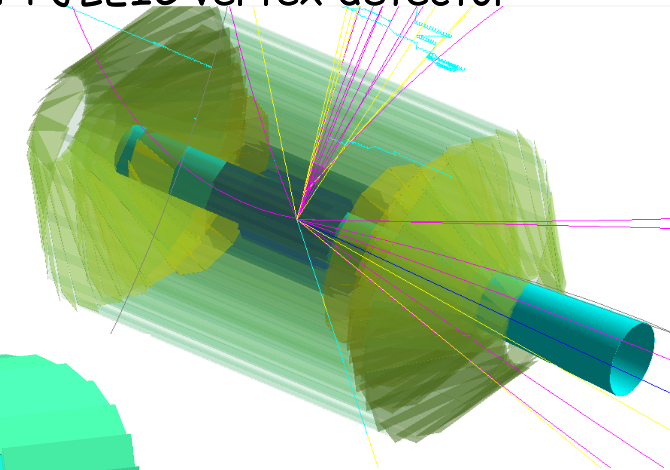
- MAPS (STAR, ALICE)

EIC R&D is ongoing

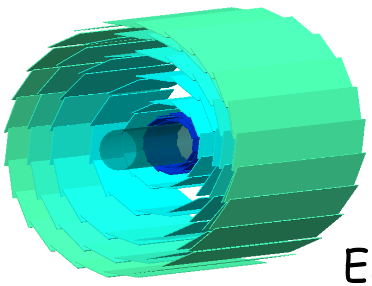
- DEPFET: BelleII PXD

1 ladder : 0.19 % X_0
-thickness 50μm
-Integration time ~10μs
-Vertex resolution ~23μm

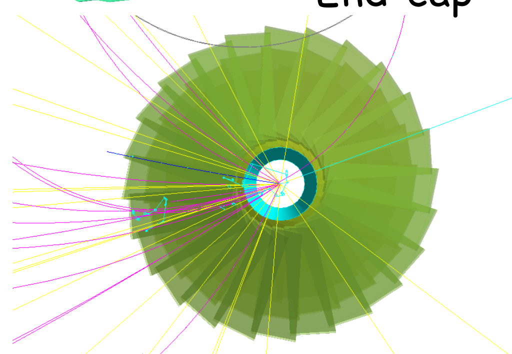
GEANT4 JLEIC vertex detector

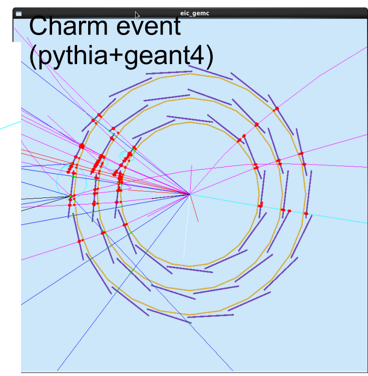


Barrel



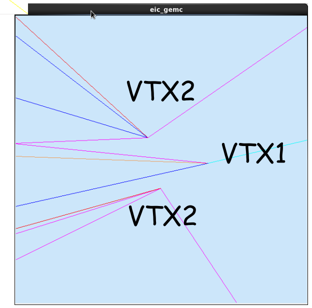
End-cap





Stand-alone measurements of low Pt particles:

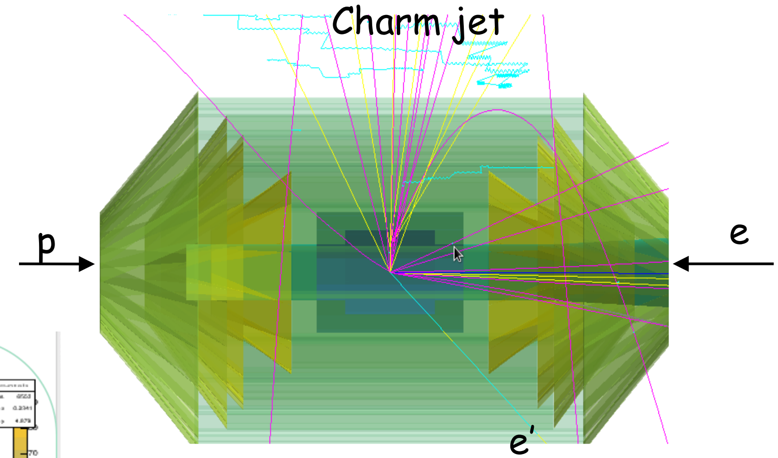
13.5 MeV < pt < 160 MeV
(for 1.5 Tesla field)
27 MeV < pt< 300 MeV
(for 3 Tesla field).

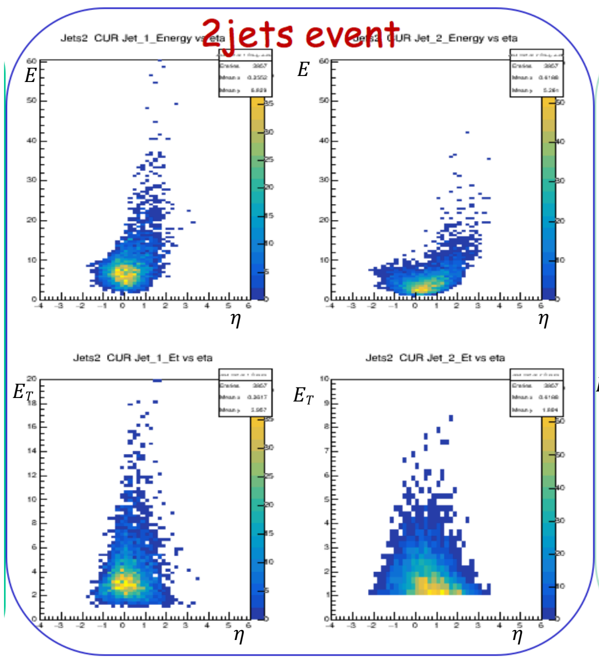


Decay length significance

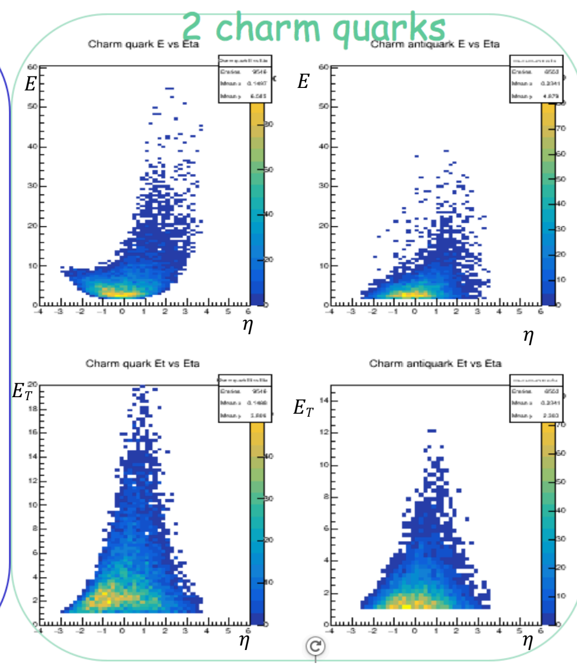
- Vertex detector design: GEANT4
- Tracking and vertex reconstruction: GENFIT + RAVE
- Jet reconstruction: FASTJET

High-x, High-Q2 charm event





Reconstructed charm jets: Pythia6 /BGF + FASTJET



Initial charm quarks : Pythia6/BGF

- Simulations in progress

Summary

- Prospect of direct measurements of nuclear gluons at x >~ 0.1 using heavy quark production at EIC
- Luminosity ~10^{34}cm^{-2} s^{-1} is essential for charm production at x>0.1
- Challenge to identify charm/beauty with overall efficiency of ~10%, and in kinematics with ~100 times larger DIS background
- PID and high-resolution vertex detector can significantly improve charm reconstruction efficiency and overall charm to background ratio and should be integrated into EIC detector design
- Studies of charm reconstruction and physics impact in progress

Materials publicly available on Wiki:
https://wiki.jlab.org/nuclear_gluons/
Preliminary results presented in:
E. Chudakov et al., BEACH 2016 Proceedings [arXiv:1610.08536]
E. Chudakov et al., DIS 2016 Proceedings [arXiv:1608.08686]

Backup