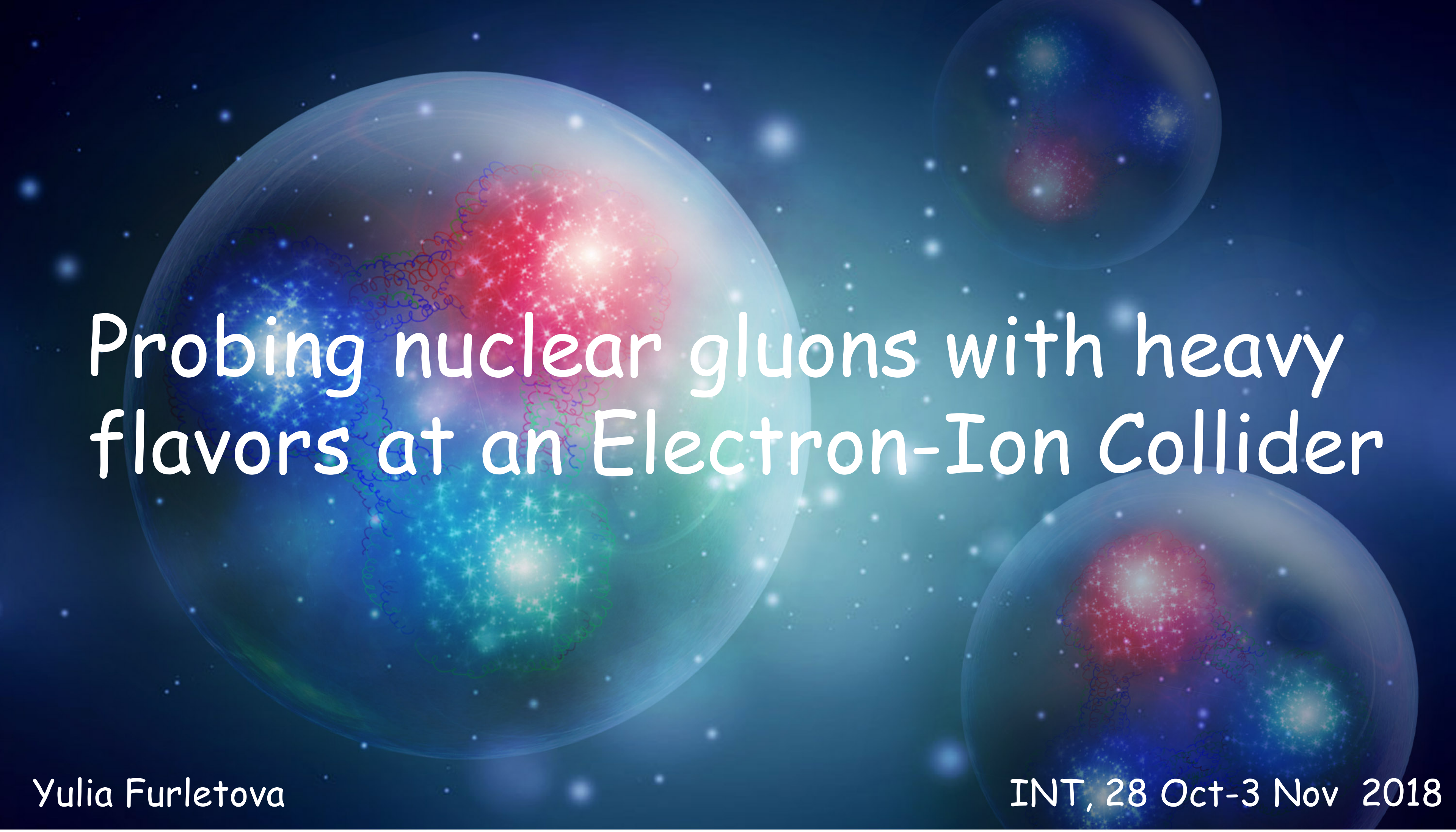


Probing nuclear gluons with heavy flavors at an Electron-Ion Collider

Yulia Furletova

INT, 28 Oct-3 Nov 2018

LDRD- 1601/1701 project
("Nuclear gluons with charm at EIC")

E. Chudakov, D. Higinbotham, Ch. Hyde, S. Furletov,
Yu. Furletova, D. Nguyen, N.Sato, M. Stratmann, M.Strikman,
C. Weiss

https://wiki.jlab.org/nuclear_gluons/
[arXiv:1610.08536], [arXiv:1608.08686]

Overview

- Nuclear modification of gluons (large-x)
- Open charm/beauty as direct probe
- Charm reconstruction at EIC
  - Charm production rate at large-x
  - Charm reconstruction
  - PID and Vertex detectors at EIC
- Impact on nuclear gluons
- … and in addition "Other processes with heavy flavor at EIC"

Nuclear partons: Physics interest

- DIS processes on nuclei $A > 1$ probe nuclear PDFs

Quark/gluon densities of entire nucleus
Nuclear matrix elements of QCD quark/gluon operators, DGLAP evolution

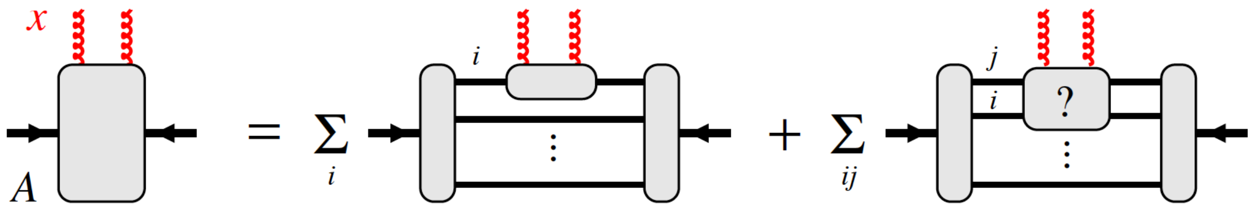
- Fundamental physics interest

➢ Compare quark/gluon densities of nucleus with those of a system of free nucleons: $A \neq \sum N$, "nuclear modifications"

➢ Learn about QCD substructure of nucleon interactions — how they emerge from the microscopic theory?

➢ "Next step" after exploring single nucleon structure!

Nuclear partons: Nucleon interactions



Hard process, QCD factorization

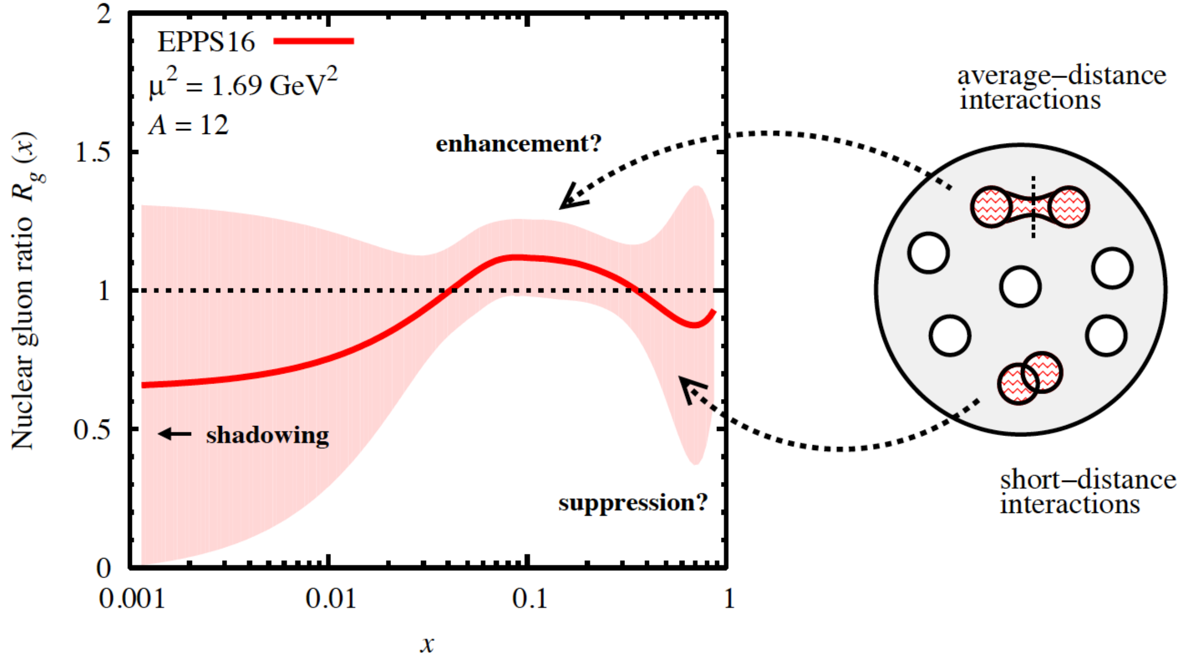
Nuclear matrix element <A| Twist-2 |A>

- 1-nucleon contribution < N| Twist-2 |N> — nucleon PDF, Fermi motion
- 2-nucleon contribution <NN| Twist-2 |NN> — nucleon interactions!
- Well-defined operator, scale dependence μ2, matching with LQCD, nuclear EFT

Physics questions:

- How do interactions modify quarks/gluons with different x?
- What are the relevant distances in the NN interactions?
- What are the relevant intermediate states? Non-nucleonic DoF!

Nuclear partons: Nucleon interactions



0.3 < x < 0.8	Suppression? EMC effect	Interactions at short distances cf. short-range NN correlations JLab 6/12 GeV
0.05 < x < 0.2	Enhancement? Antishadowing	Interactions at average distances
$x \ll 0.1$	Shadowing	Coherent interactions enabled by diffraction Gribov 70s Suppression effect calculable Frankfurt, Strikman Guzey 12+ Observed in J/ψ photoproduction on nuclei ALICE, CMS Suggests large antishadowing

Nuclear partons: Probing gluons

- Determine nuclear gluon density at large x (> 0.05)!
- Nuclear gluon probes:

eA/μA/νA	Q^2 dependence of F_{2A}, F_{LA} + DGLAP
eA/γA	Heavy quark production – direct probe! ⇐
pA/eA/γA	Jets?

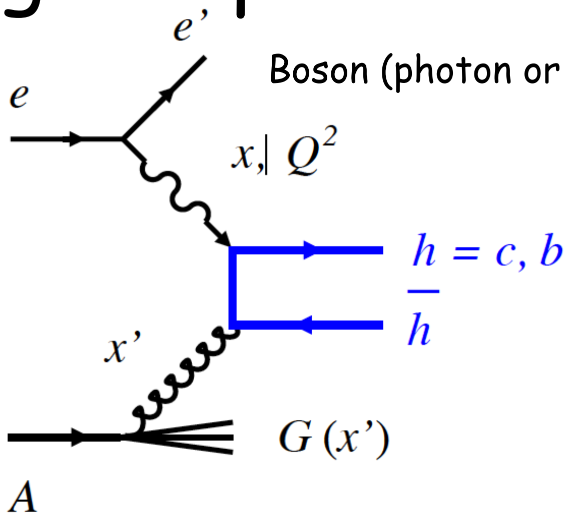
- EIC capabilities

Nuclear beams A = 2–208
CM energy $\sqrt{s}$ (eN) ~ 20–100 GeV
Luminosity L ~ 10^{34} cm^{-2} s^{-1}
Next generation of detectors with PID and vertex

⇔

first eA collider
coverage at large x_B
rare processes
final states

Open charm/beauty production as a direct gluon probe



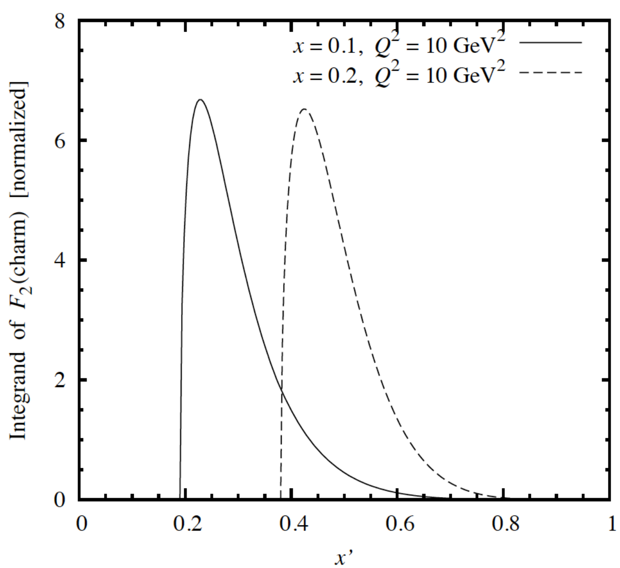
Boson (photon or Z) Gluon Fusion (BGF)

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

coefficient function

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

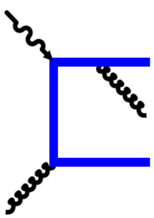
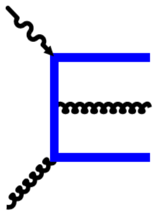
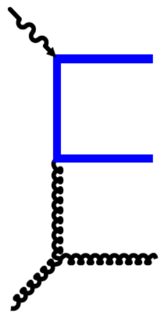
sets limit of x' integral



- Heavy quark production probes large-x' gluons "almost locally" at $x'_{glue} \geq x_{BJ}\,(1+4m_h^2/Q^2)$
- NLO corrections calculated, theory uncertainties quantified

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

Heavy quark production: Higher orders

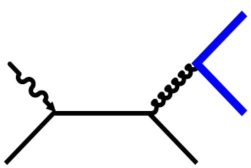
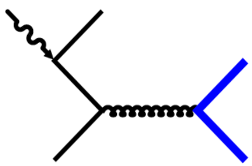
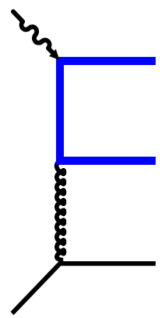




gluons $e g^2$

Heavy quark production at NLO

- Sensitivity to light quarks at O(ehg2)
- LO photon-gluon fusion large at x > 0.1
- Theoretical uncertainties quantified

Laenen, Riemersma, Smith Van Neerven, Harris 93+.
Alekhin, Moch, Bl¬umlein, Vogt, Kawamura et al. 11+

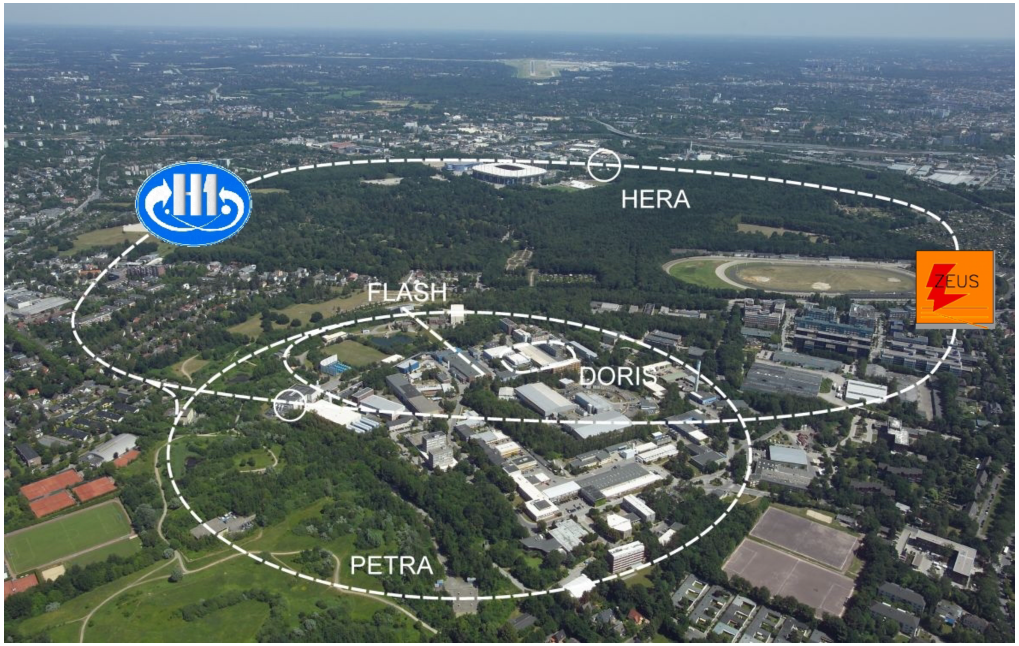




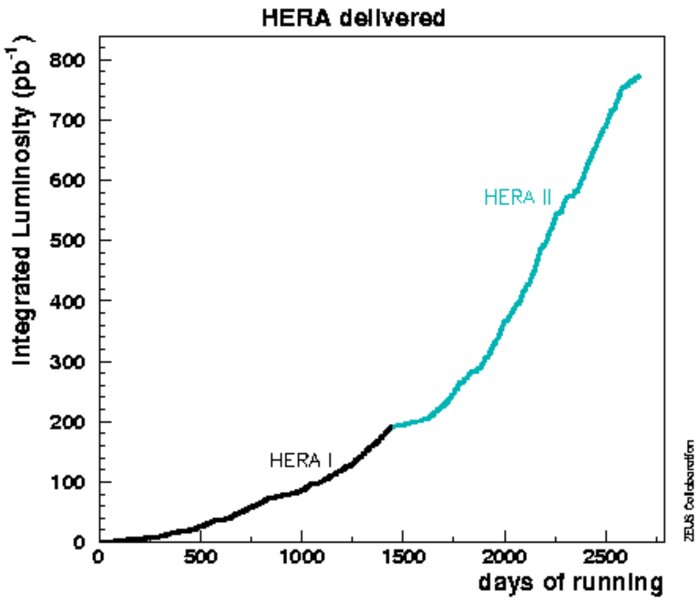
quarks $e g^2$

Perturbative stability LO → NLO

- Good stability of F^c_2 with choice of effective LO scale Gluck, Reya, Stratmann 94
- Rapidity, pT distributions more sensitive

Heavy quark production at HERA





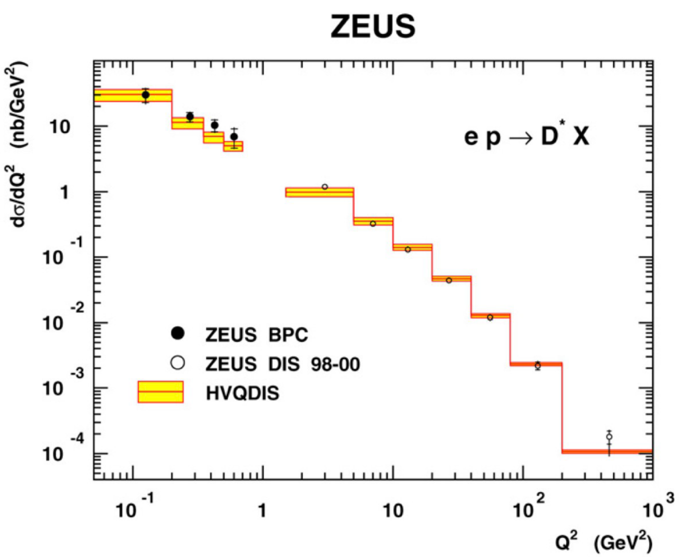
HERA: 27.5 GeV electrons/positrons with 920 GeV protons

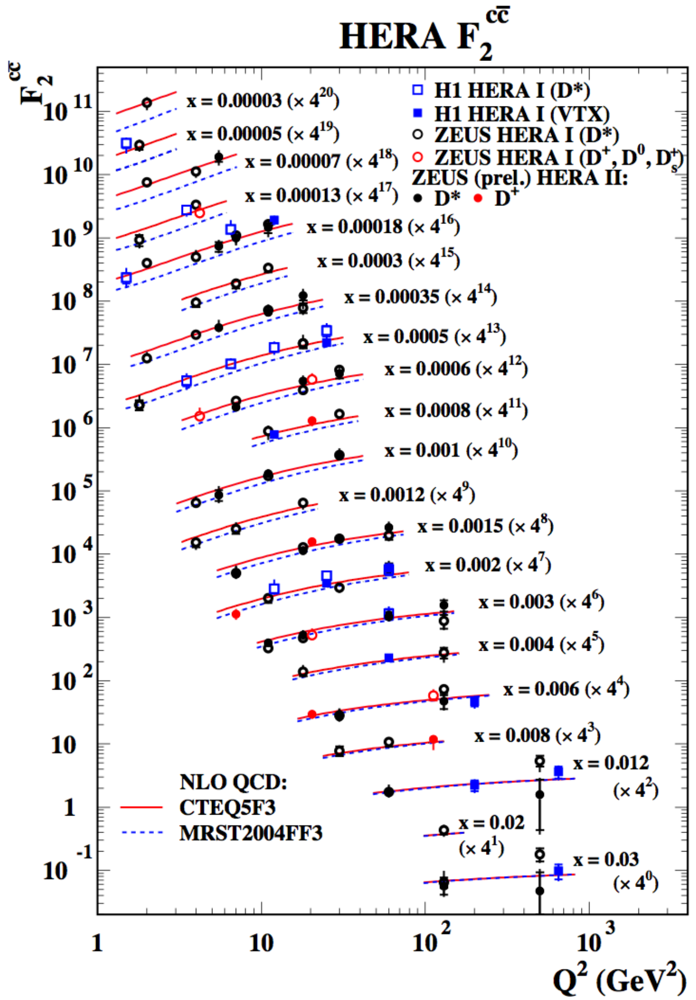
ZEUS: ~ 0.5 fb^{-1} after 10 years of operation

At EIC (10-100 fb^{-1}/year) which is 100-1000 times higher then at HERA

Heavy quarks at HERA

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



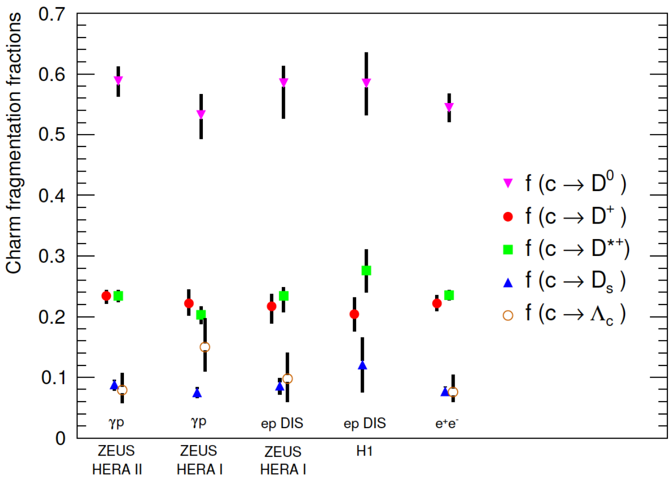


- The HVQDIS calculation produces a good description of the measured data.
- In particular, NLO QCD describes the dependence on Q^2 of the data over 4 orders of magnitude in Q2

- Mostly $x < 10^{-2}$

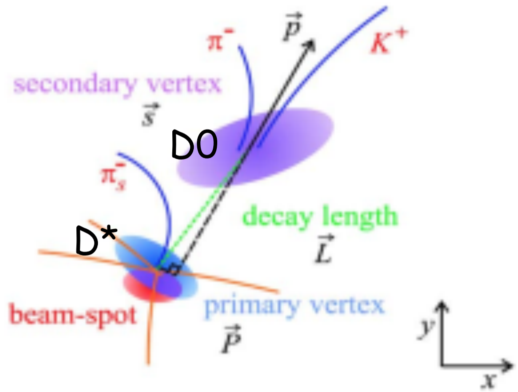
Heavy quarks at HERA

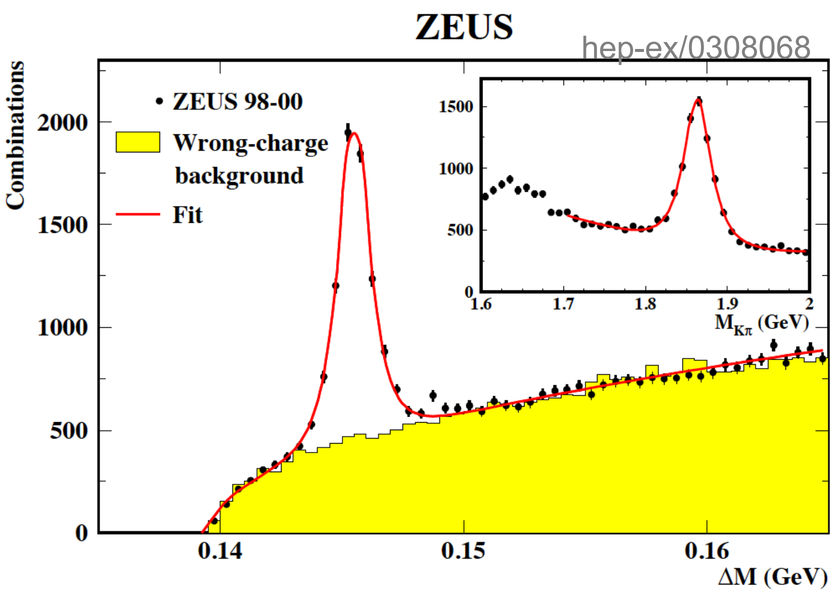
$D^{*+} \to D^o \pi_s^+ \ , \ D^o \to K^- \pi^+$



Abramowicz, H., et al. (ZEUS Collaboration), 2013b, J. High Energy Phys. 09, 058.

c-> D*+ (20%)
D*+ ->D0 π+$_{slow}$ (67.7%)
D0 -> K- π+ (3.9%)





$c\bar{c}$, $b\bar{b}$ production in ep/γp

- Various reconstruction methods
- Extensive tests of theory
- Measurements of c → D and

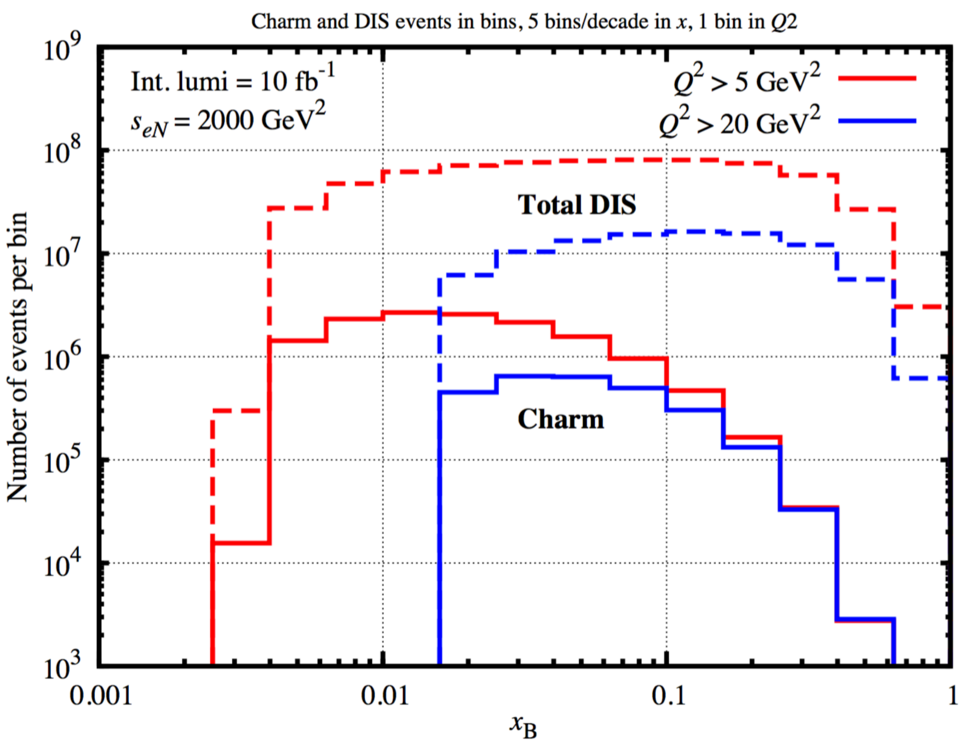
b → B fragmentation functions

Charm production rate at large x at EIC

Differential cross sections using LO QCD formulas

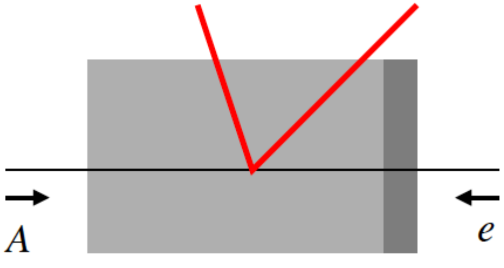
$$d\sigma(e+N \to e'+X) = \text{Flux}(x,y,Q^2)\, F_2(x,Q^2)\, dx\, dQ^2 \quad (1)$$

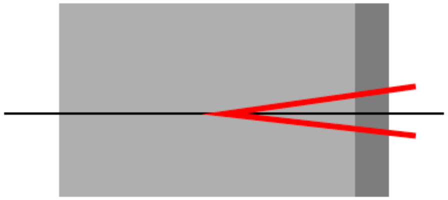
$$d\sigma(e+N \to e'+c\bar{c}+X') = \text{Flux}(x,y,Q^2)\, F_2^{c\bar{c}}(x,Q^2)\, dx\, dQ^2 \quad (2)$$

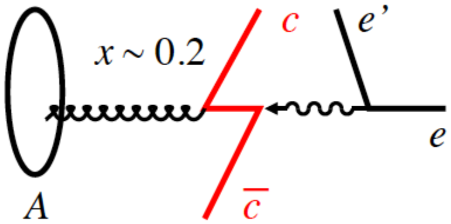


- Charm production rates drop rapidly at large x
- Charm production rates 10^5 at x~0.1 (int. lumi 10 fb^{-1})
  Defines charm reconstruction efficiency needed for physics
- Charm/DIS ratio 2-3 % at x ~0.1
  Defines charm reconstruction environment
- Nuclear rates comparable: Structure function $F^c_{2A} \sim AF^c_{2N}$, but luminosity $L_A \sim L_N/A$

Charm momentum and angle distributions



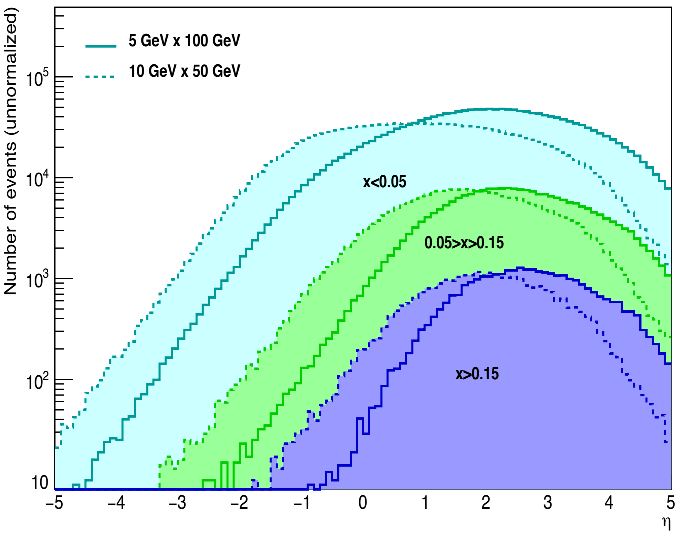




50 GeV/N 10 GeV
Low ep/eA ratio colliders

High ep/eA ratio colliders

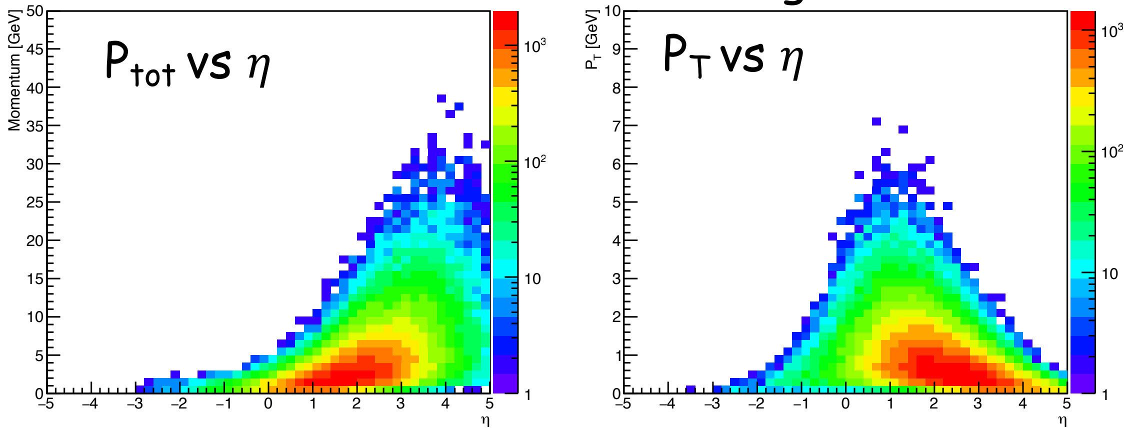
- Large-x $c\bar{c}$ pairs produced almost at rest in low-ratio collider
  Example: Gluon with x = 0.2 at
  10GeV e on 50 GeV/N
  Contrast with high-ratio collider!
- π/K produced at large angles, with typical momenta ~ 5 GeV
  Favorable situation!
- Good PID and momentum resolution available in central detector
  Enables "new" methods of charm reconstruction



EIC: charm event reconstruction

- Exclusive D-meson decays
- Inclusive decays with displace vertex

Kaons from charm at large-x



Questions

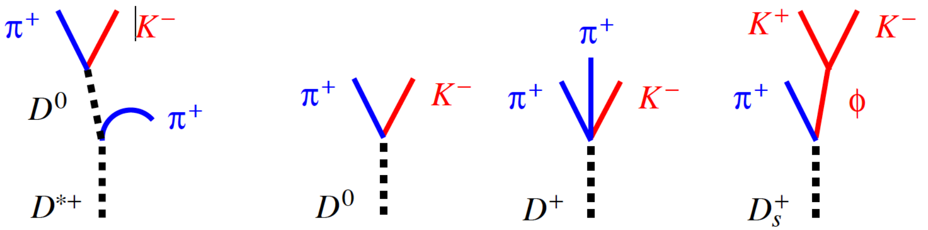
- How well do the methods work at large x?
- What are the overall efficiencies and uncertainties?
- What detector performance is required?

Simulations at different levels

1) Theoretical estimates of reconstruction efficiency
2) Model acceptance and PID performance, describe resolution effects through smearing of vertex and momentum distributions
3) Tracking and vertexing based on schematic JLEIC detector model

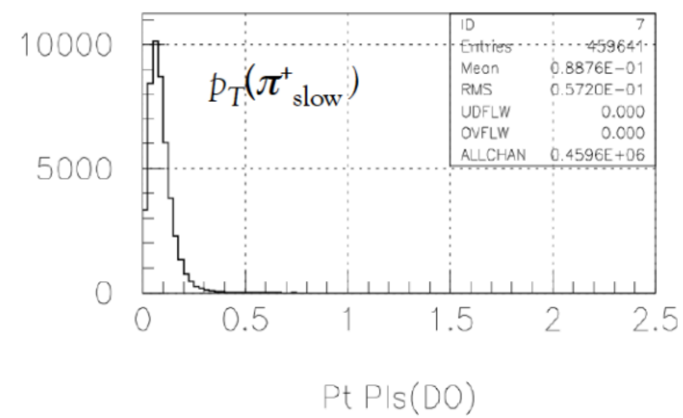
EIC: Charm reconstruction with exclusive D's

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%	$(K^-\pi^+)_{D0}\ \pi^+_{slow}$	2.6%
		$(K^-\pi^+\pi^+\pi^-)_{D0}\ \pi^+_{slow}$	5.5%
D_s^+	9%	$(K^+K^-)_\phi\ \pi^+$	2.3%
Λ_c^+	8%	$pK^-\pi^+$	5.0%

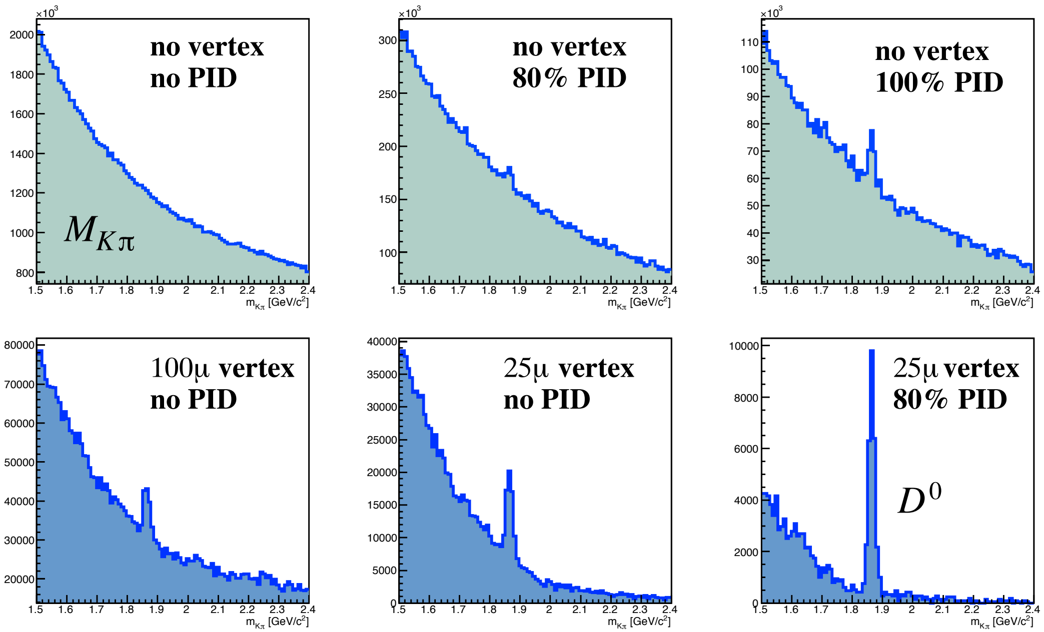


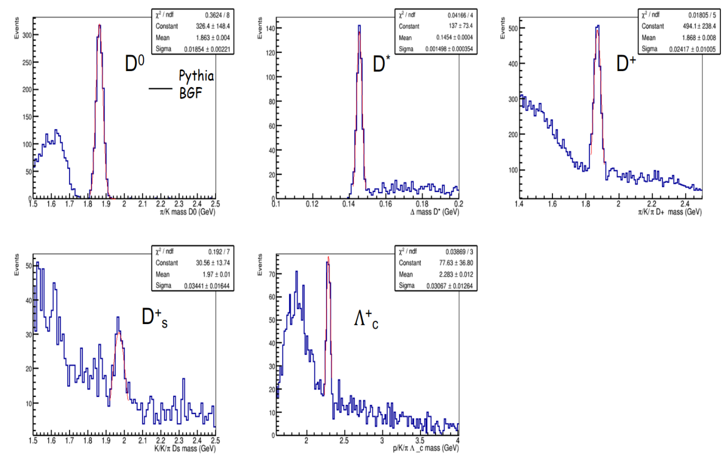
- Simple exclusive channel $D^{*+} \to \pi^+_{slow} + (K^-\pi^+)_{D0}$
- For reconstruction need to provide good vertex and PID
- At HERA1: no PID, no vertex => Efficiency < 1%
  HERA2: no PID + vertex => Other channels, incl.
- At EIC: PID + vertex detection
  => allow use of other exclusive channels D^0,D^+,D^+_s
- Theoretical efficiency ~ 10% summed over channels
  Fragmentation ratio f ~ Branching ratio BR

π_{slow} is really slow at EIC!



EIC: Charm reconstruction with exclusive D's



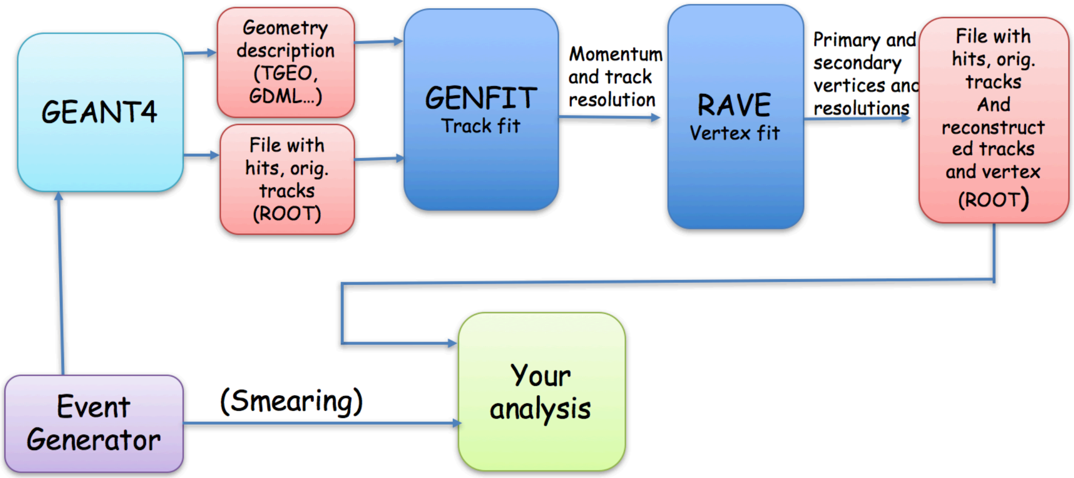


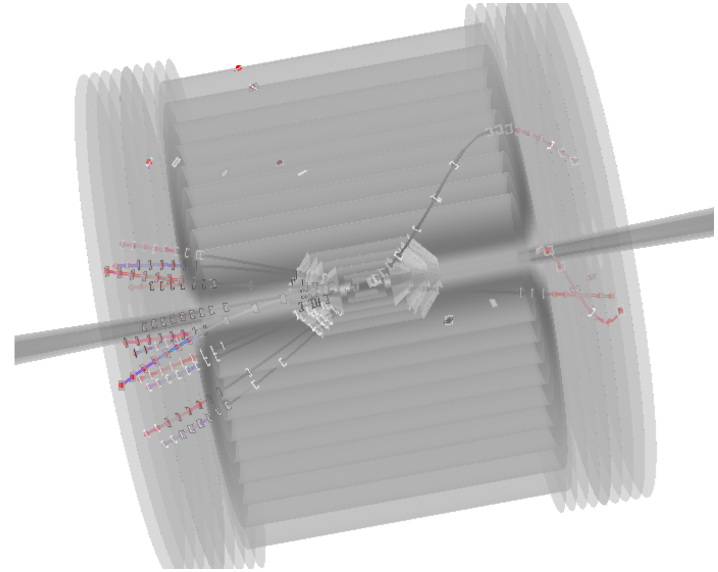
Example: D0 meson reconstruction using exclusive decay
$D^0 \rightarrow K^- \pi^+$
ep (10 GeV x100 GeV) , $Q^2 > 10$ GeV^2 and $x_B > 0.05$,
vertex cut > 100 μm

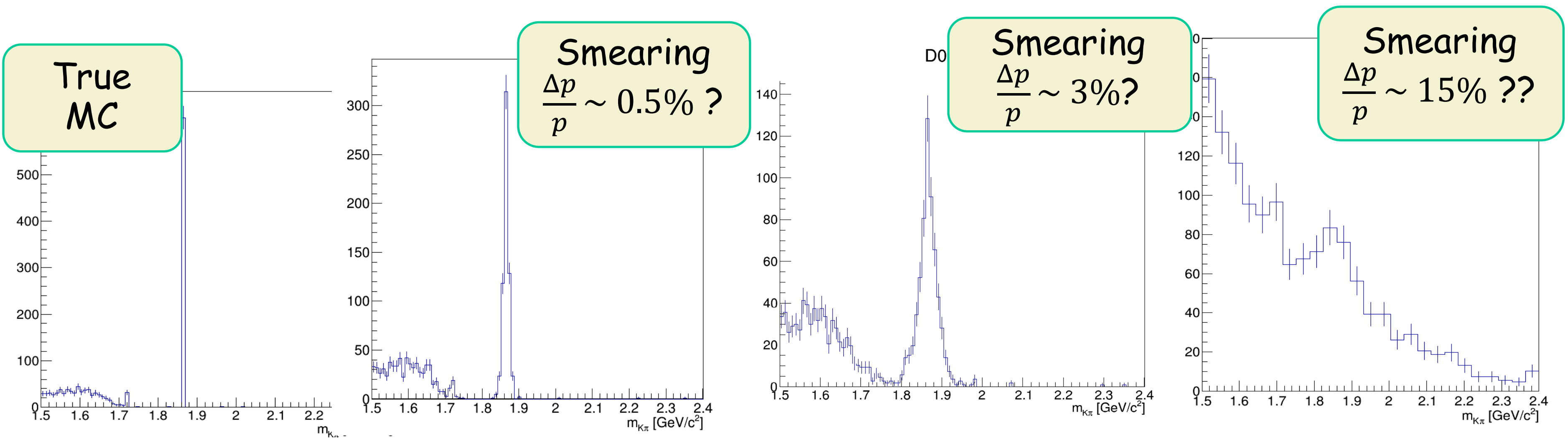
simulation with mass/momentum and vertex smearing
Impact of PID and vertex detection

Reconstruction chain

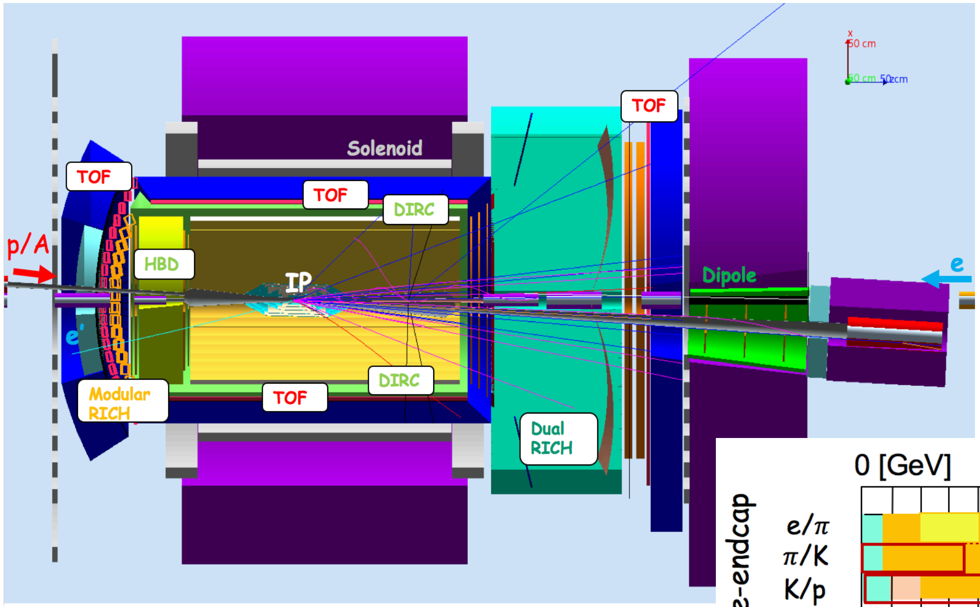
GEANT4 and Track/Vertex reconstruction



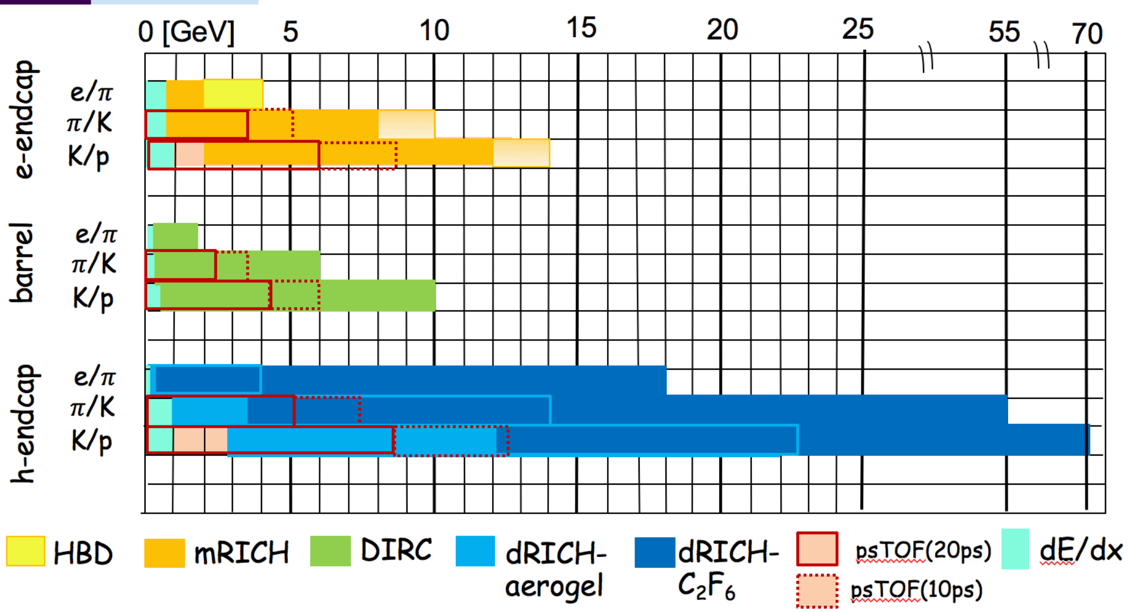




PID detectors

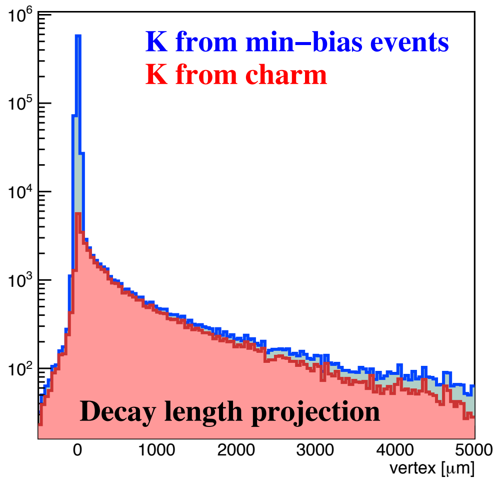


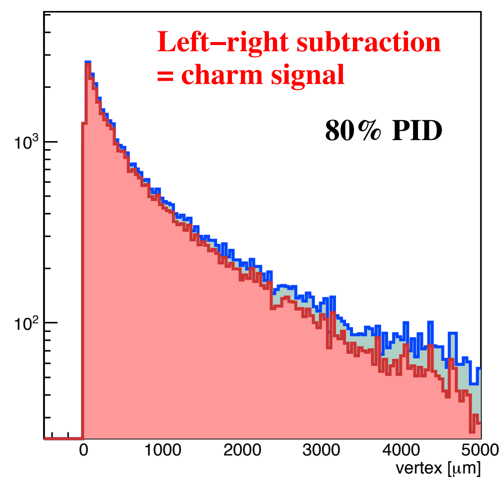
JLEIC design

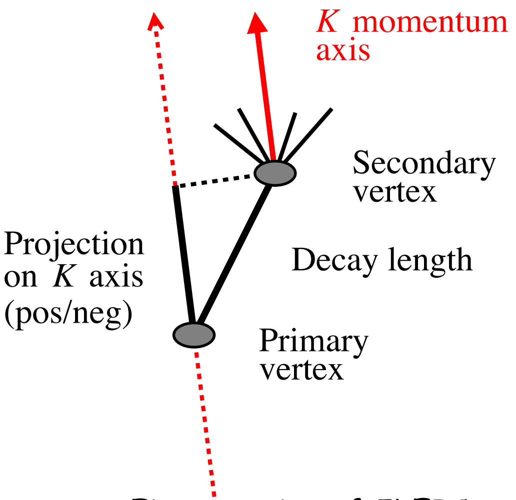


** Here, electron/hadron separation only from Cherenkov detectors is shown. Main e/h rejection is done by calorimeters.

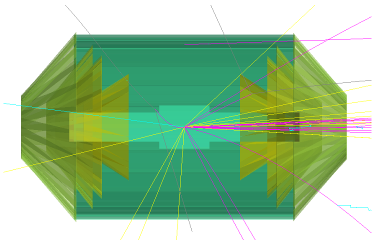
EIC: Charm reconstruction with inclusive modes







First version of JLEIC vertex detector

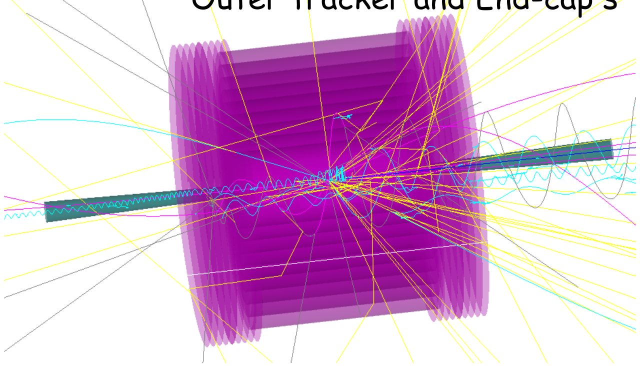


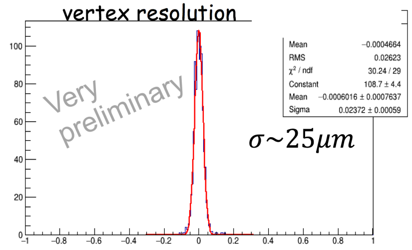
Decay length significance distribution:
- Establish secondary vertex
- Project decay length on jet axis, positive/negative

Identify D-meson decays through positive projection
- Used at HERA-I with vertex detector
- Use for charm at EIC

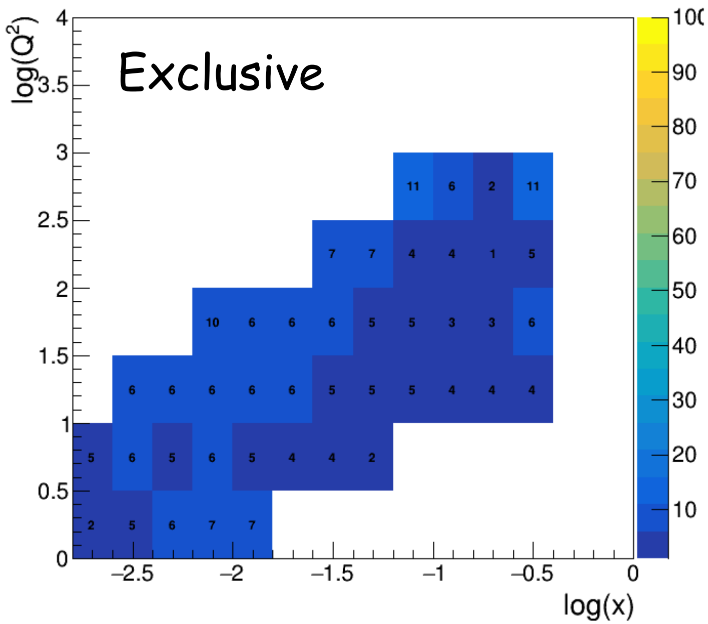
Identified K from PID.

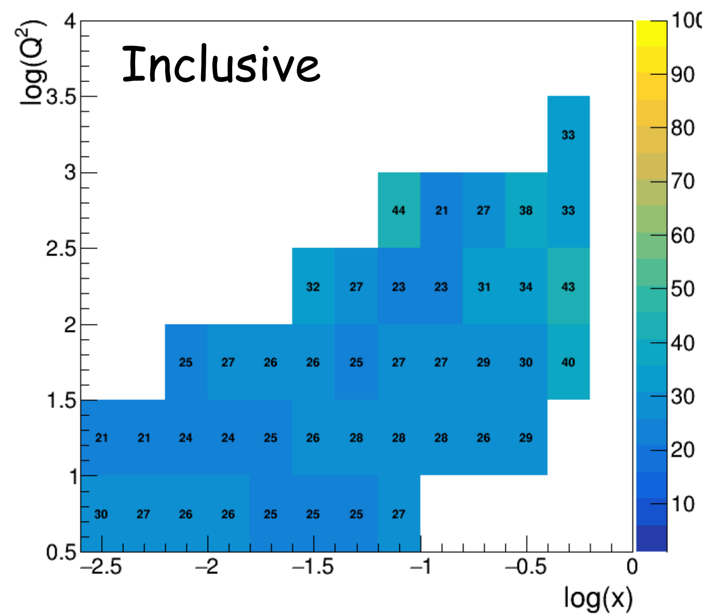
Outer tracker and End-cap s





EIC: Charm reconstruction efficiency





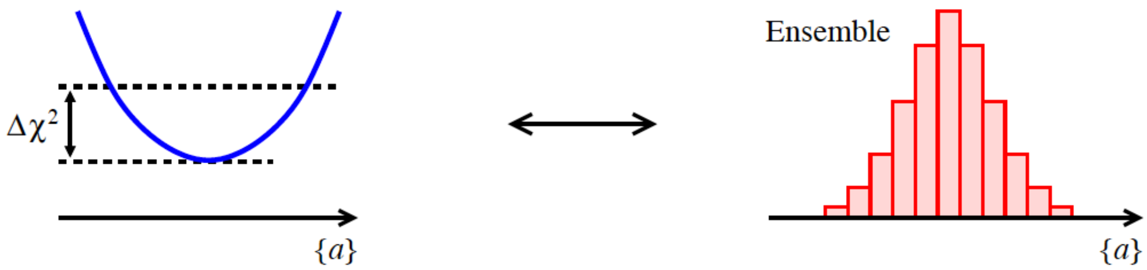
Total efficiency estimated:

~5-6% exclusive, ~25-30% inclusive

- Little kinematic variation in (x,Q_2) region of interest

- Systematic uncertainties? HERA ≲10%
- Both vertex detection and PID are essential for charm reconstruction

Charm impact: PDF reweighting



PDF reweighting

- Method for quantifying impact of new (pseudo-) data on existing global fit

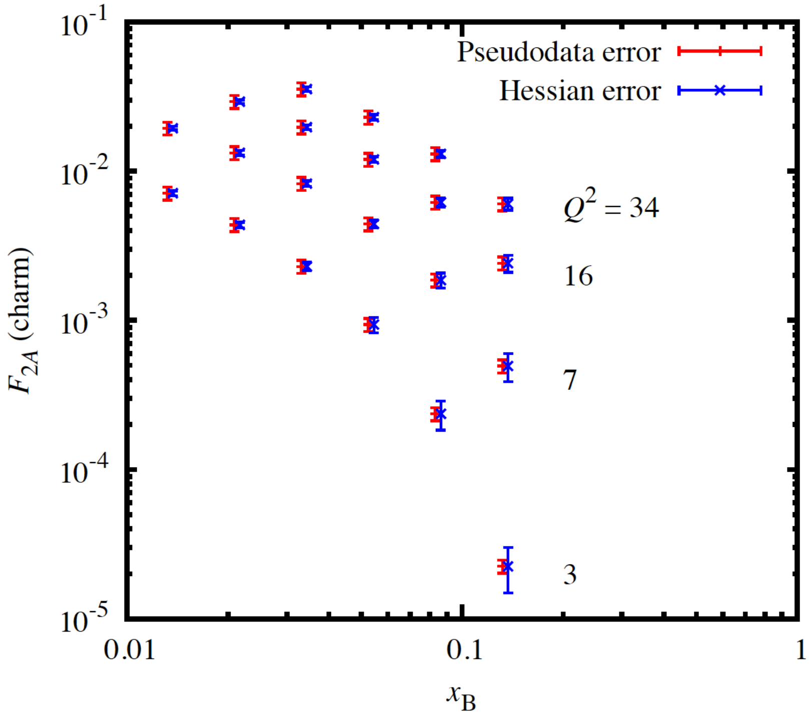
Giele, Keller 98; NNPDF Collab Ball et al 11; Paukkunen, Zurita 14; Sato et al 16

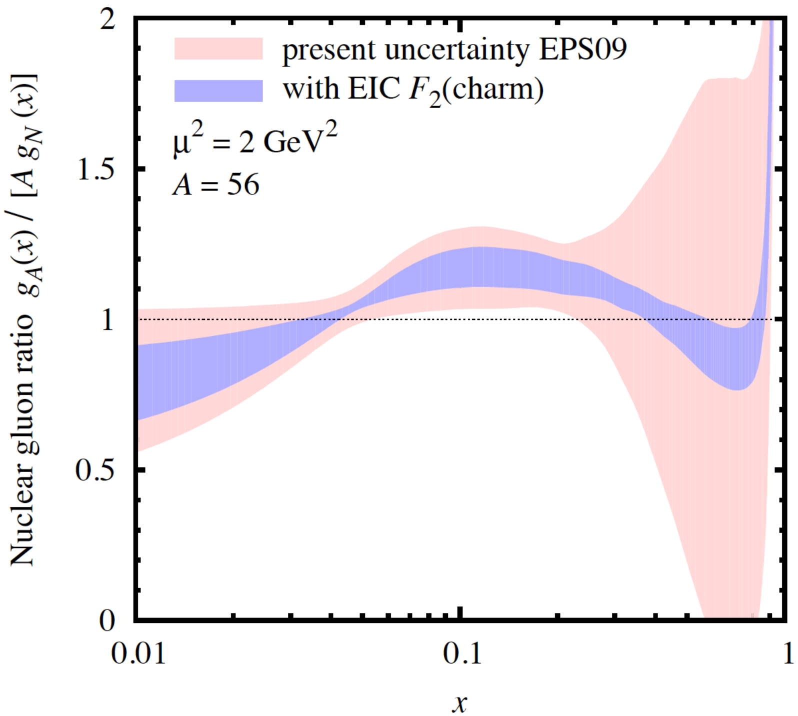
- Represents existing fit as statistical ensemble, uses Bayes' theorem
- Avoids costly re-fitting
- Widely used in PDF analysis, HEP

Implemented for charm pseudodata from EIC

- Presently F_{2c}, can be extended to other observables

Charm impact: Large-x gluons





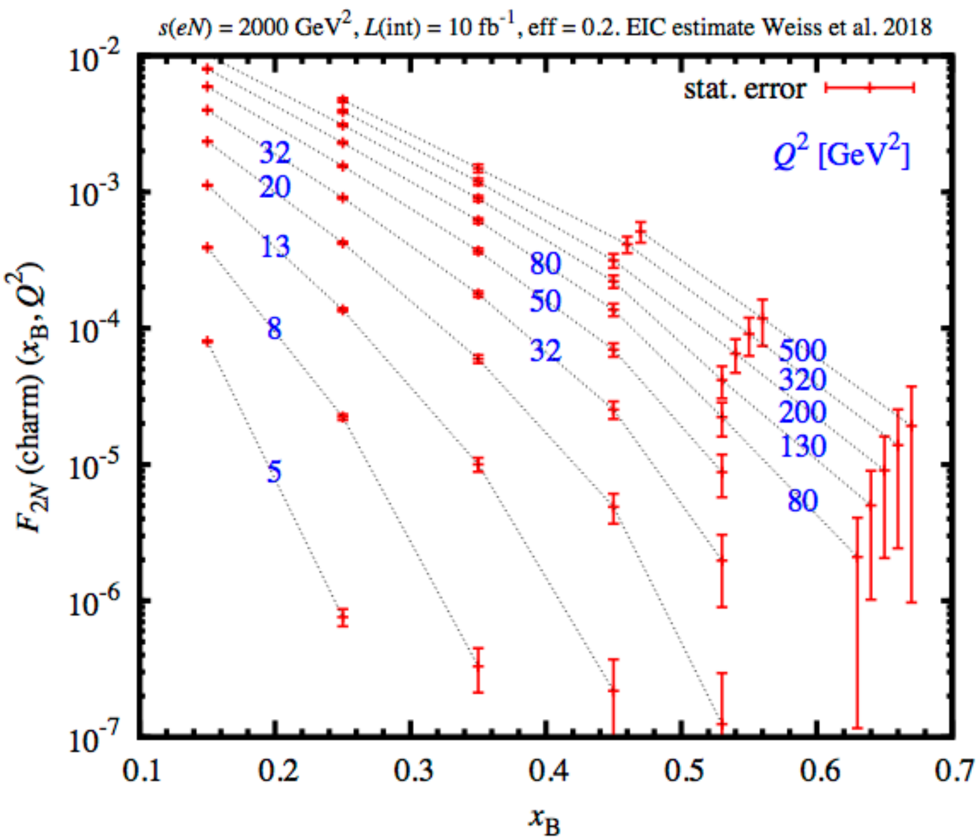
- Charm pdeudodata
  Fc2 (x,Q2), assumed 10% total uncertainty, dominated by systematics, point-to-point
  Here EPS09, LO approximation. To be updated/refined
- Substantial impact on large–x nuclear gluons

See also: Aschenauer et al, PRD 96 114005 (2017)

- Theoretical uncertainties to be estimated
- Nuclear final-state interactions vs. initial-state modifications
- Uncertainties of nuclear ratios

Other applications

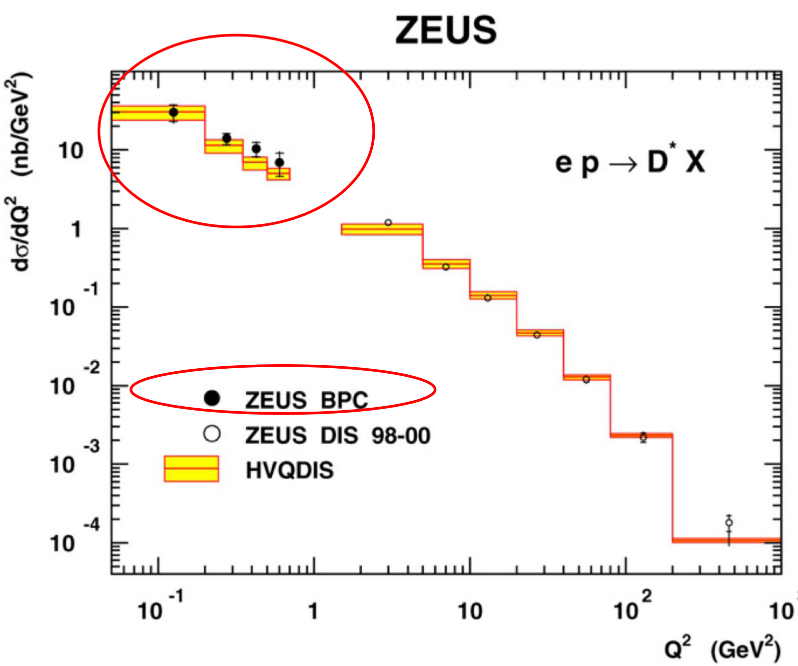
F2 charm in high-x region at EIC

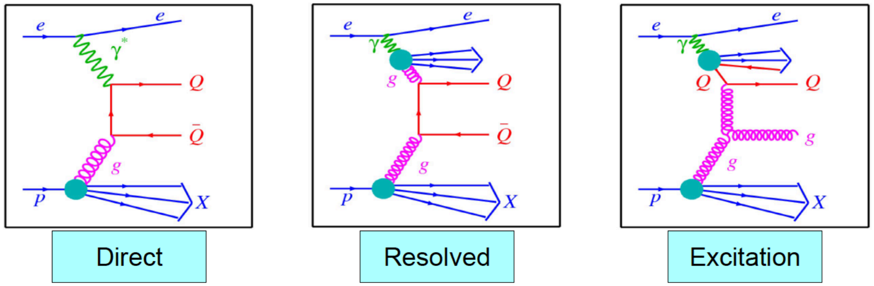


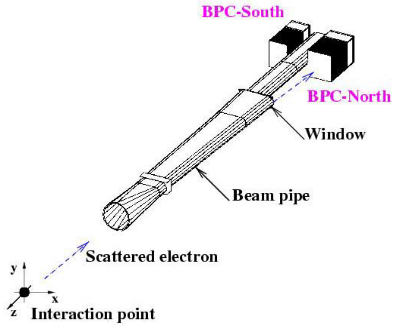
Int lumi 10 fb^{-1}, 10x100 GeV
charm reconstruction efficiency 20%

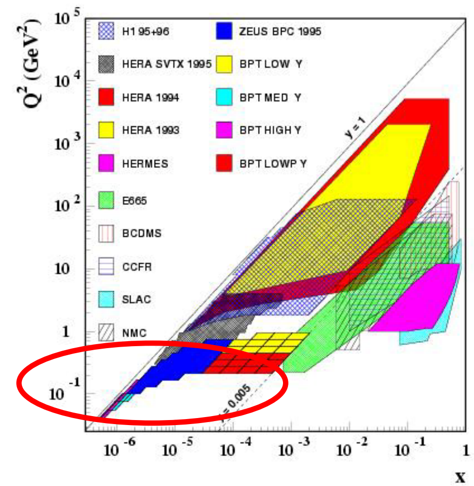
Statistical errors only

Charm in Photo production









- ✓ Cross section is much higher then for DIS
- ✓ High P_T charm pair.
- ✓ Need far-rear instrumentation (for low-Q^2 e′ measurements)

Beauty production

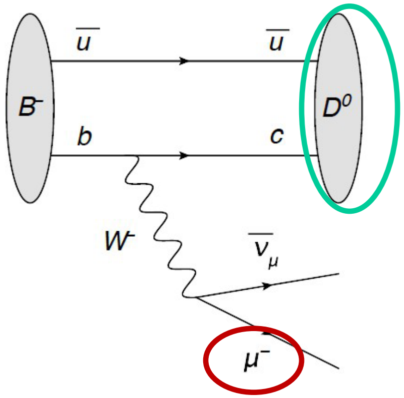
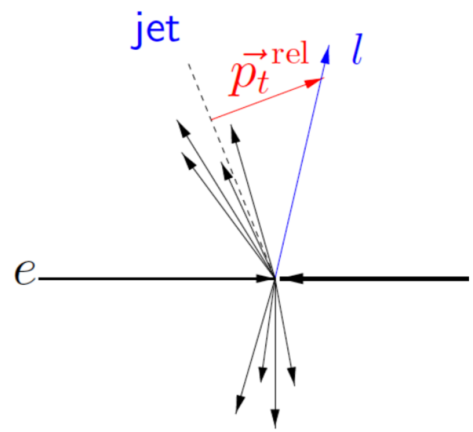
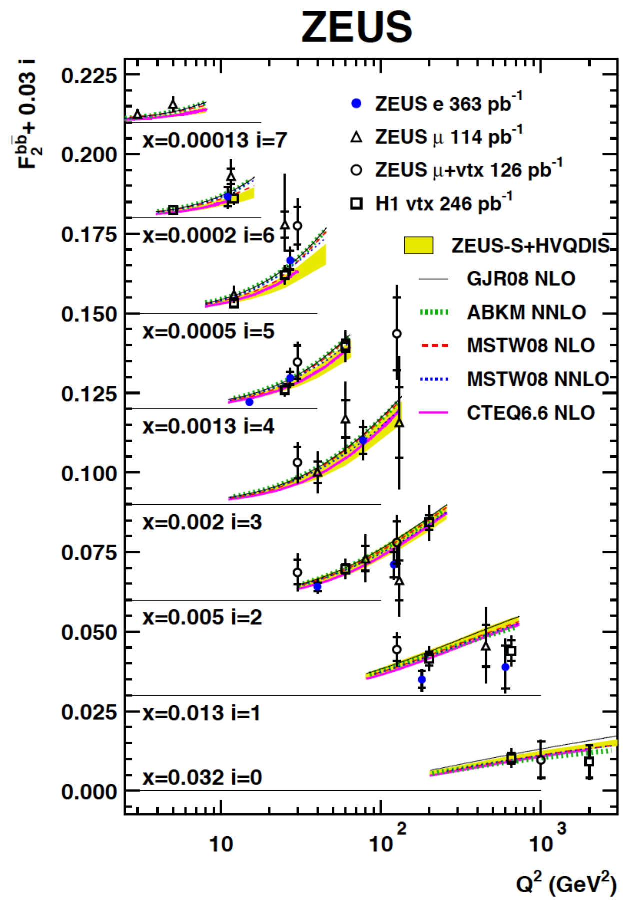


Figure 2.15.: Quark level diagram for the decay $B^- \to D^0\mu^-$

For the identification:
D^0 and muon





At HERA, before the use of silicon microvertex detectors, the principal way to identify beauty events was to reconstruct leptons and measure their momentum p^{rel}_T perpendicular to the axis of an associated jet.

Lessons learned at HERA:

- Beauty production at HERA is suppressed by 2 order of magnitude with respect to charm, due to the larger mass and smaller electric charge of the b quark.
- Total cross section is dominated by photoproduction
- Final states: steeply falling pT spectrum -> challenge for secondary vertex.

Semi-leptonic channels for heavy quark identification

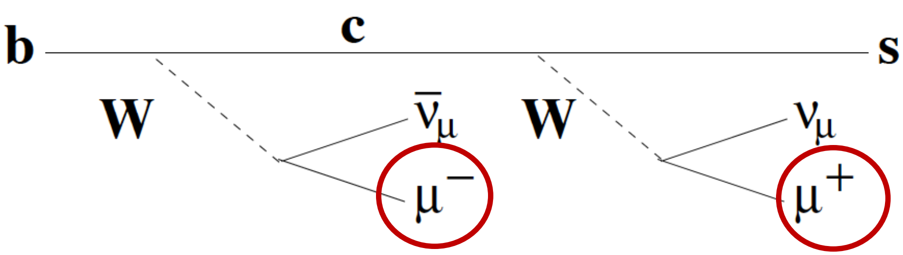


Figure 2.12: *Cascade decay of a beauty quark.*

HERA:
σ(e+p -> e+b X) ~ 1.6 ±0.4 nb

σ(e+p -> $b\bar{b}$X -> μX) ~ 160 ± 30 pb (PhP: Q^2<1 GeV^2)
σ(e+p ->$b\bar{b}$X -> μX) ~ 30 ± 8 pb (DIS)

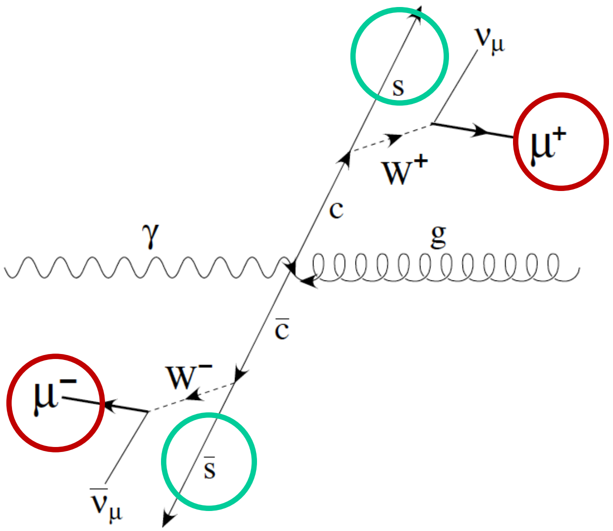
σ(ep -> e$b\bar{b}$X -> ejj μeX) ~ 9.4 ± 1.2 pb
σ(ep -> e$b\bar{b}$X -> ejj μμX) ~ 10.4 ± 1.5 pb

HVQDIS for EIC (ep 10x100 GeV), no fragmentation
m ~4.18 GeV Q^2> 1GeV 0<x<1
σ(e+p -> e+b X)~ 0.11805 nb
m ~4.18 GeV Q^2> 1GeV x > 0.1
σ(e+p -> e+b X) ~1.0229 10^{-3} nb

Semi-leptonic channels for charm

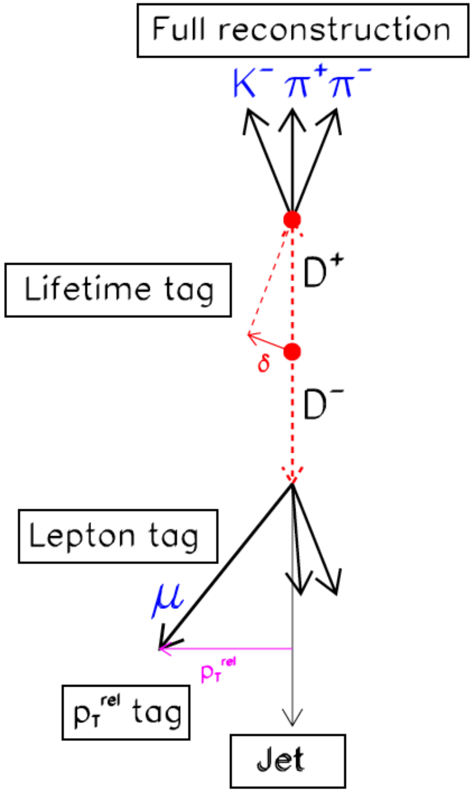
Olaf Behnke

Di-charm events via
semi-leptonic channels

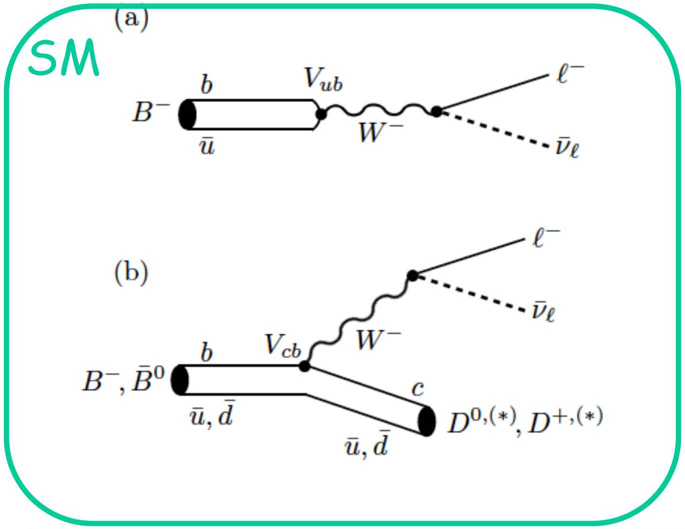


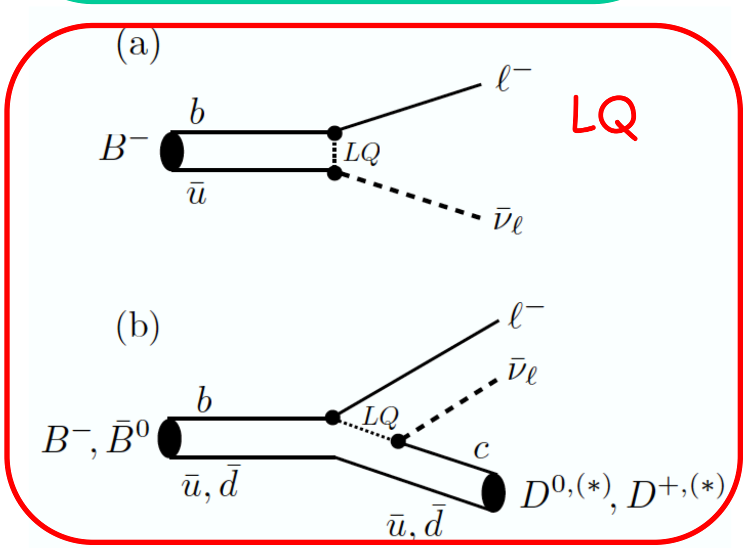
BR: c-> lepton + X (~ 17% ?)

Di-charm events,
Combination of inclusive and
exclusive decays

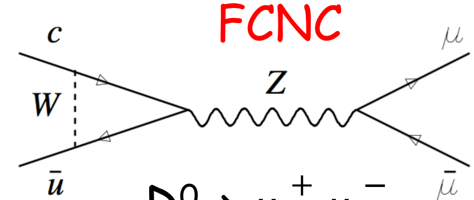


Semi-leptonic channels for BSM





- Enhance of semi-leptonic decay BRs via **Leptoquark** process
- Comparisons of e vs μ decays
- Comparisons (c/c-bar, b/b-bar) rates (mixing)
- Rare decay processes (FCNC, LFV, etc)



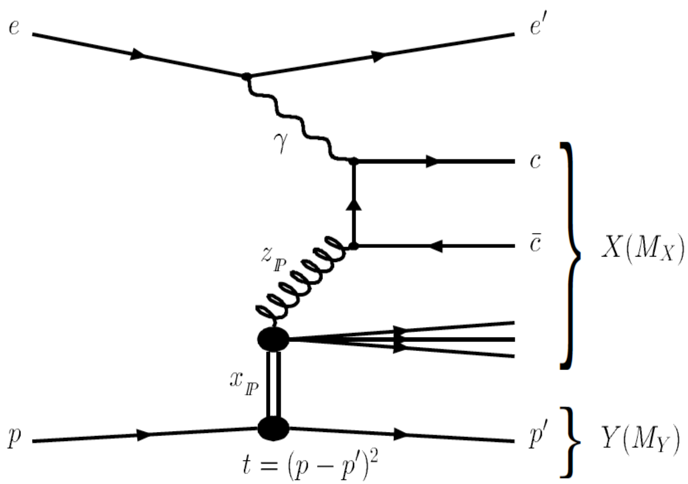
LFV

$D^0 \to e^+ \mu^-$

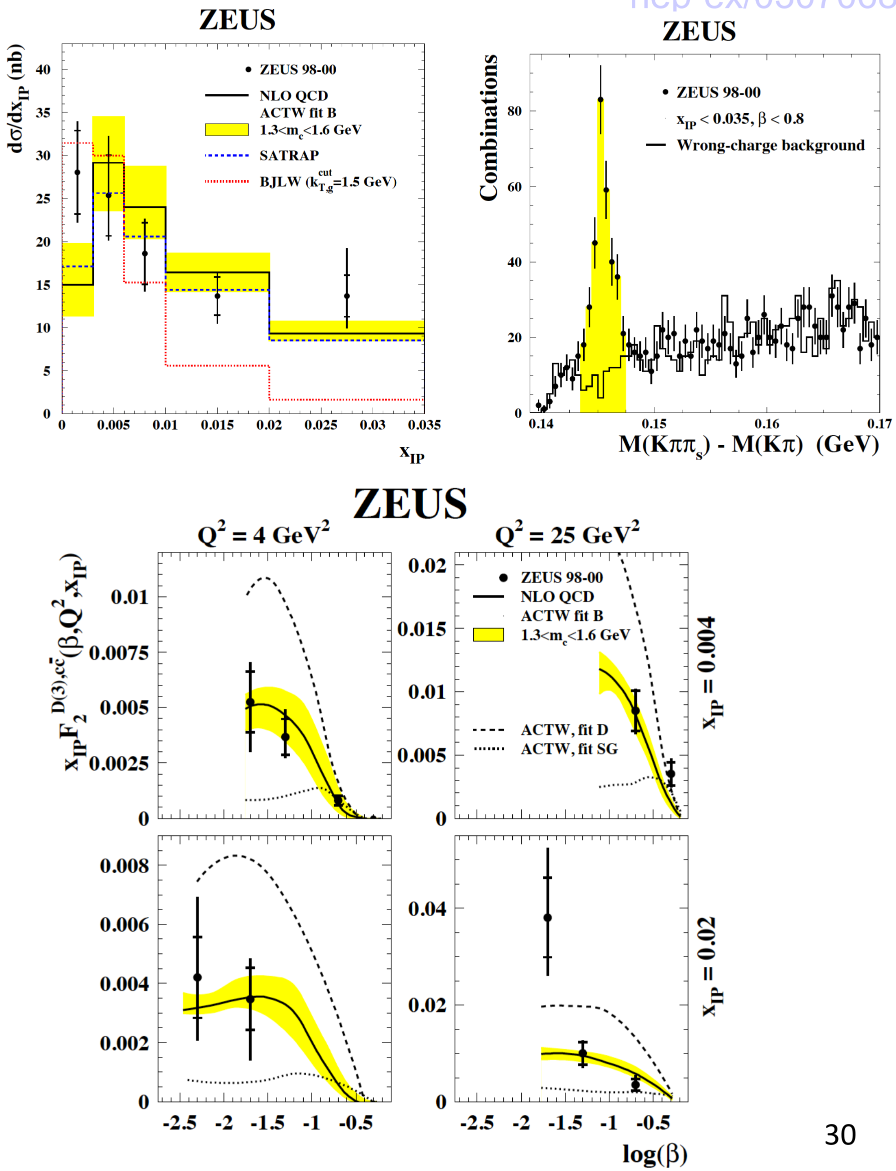
arXiv:1703.01766v3
G. Ciezare and etc.

"Rare D Meson Decays at HERA " C. Grab

Charm in diffractive processes



hep-ex/0307068



BGF process with Heavy flavors could be used as a probe of a gluon content of a diffractive (pomeron) exchange.

Diffractive gluon density (DPDF).
Nuclear diffractive gluon density (nDPDF)

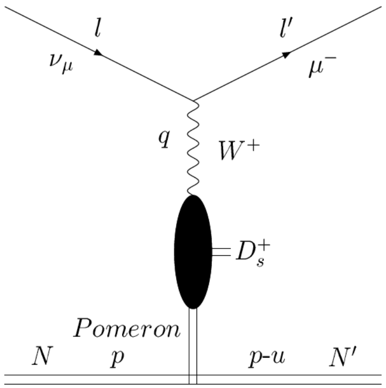
Charm in diffractive Ds production in Charged Current DIS

Neutrino facilities

$\nu_\mu + N \rightarrow \mu^- + N' + D^+_s$.

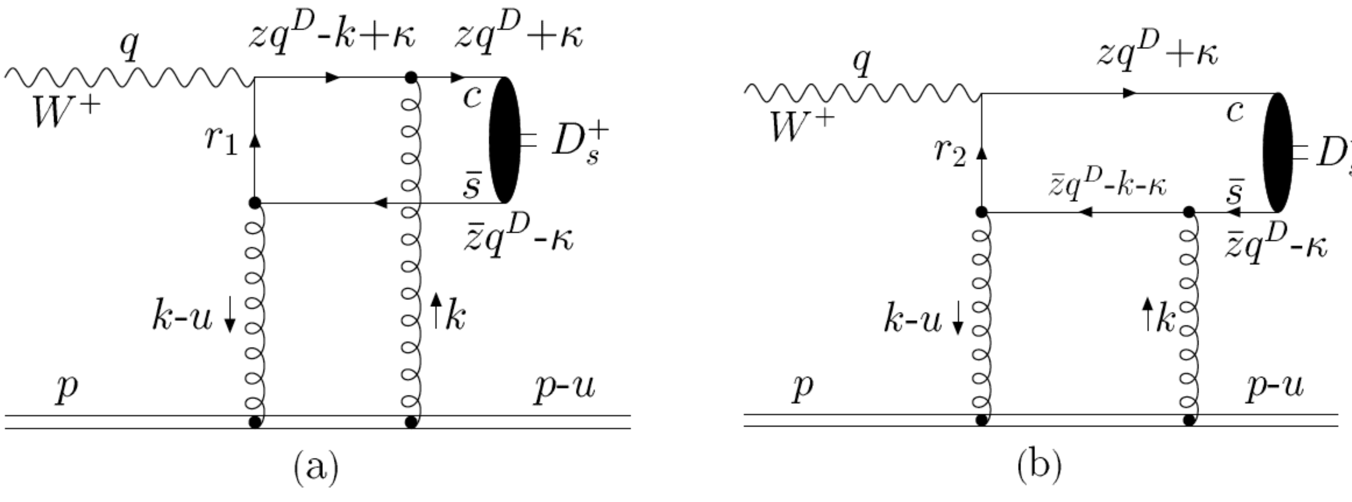
hep-ph/0112192

(Zhongzhi Song (PKU), Kuang-Ta Chao)

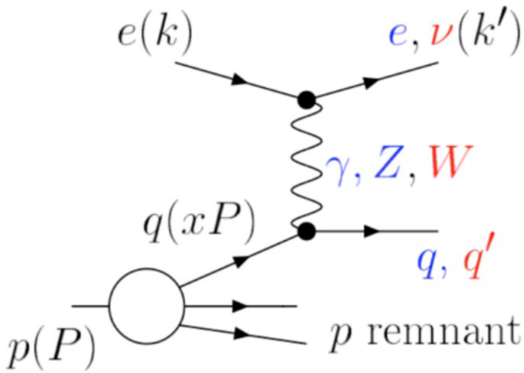


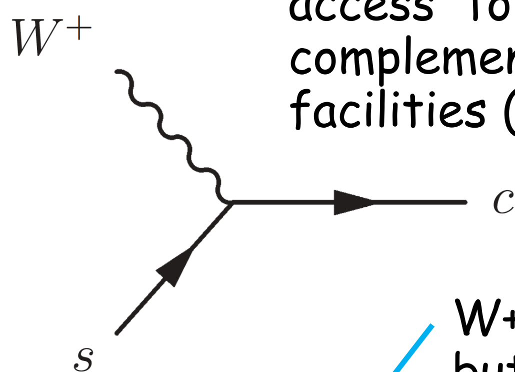
At ep (charged current) :

$e + N \rightarrow \nu_e + N' + D^+_s$.



Charm in Charged Current reactions





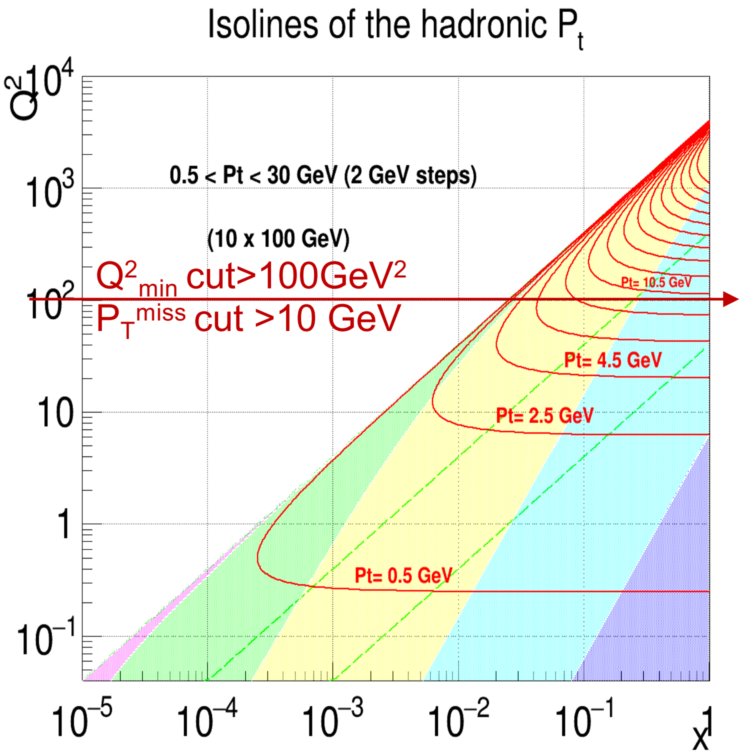
Positron beam allows to access to the strange PDFs, complementary to neutrino facilities (νN).

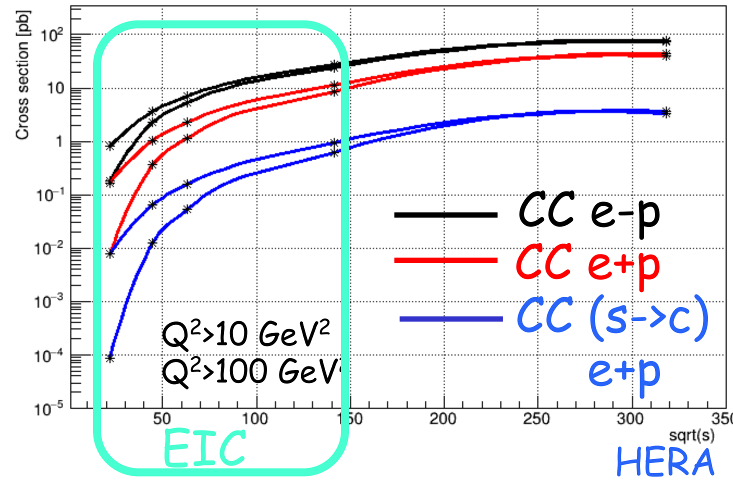
W+d → c is suppressed, but should be taken into account at high-x region

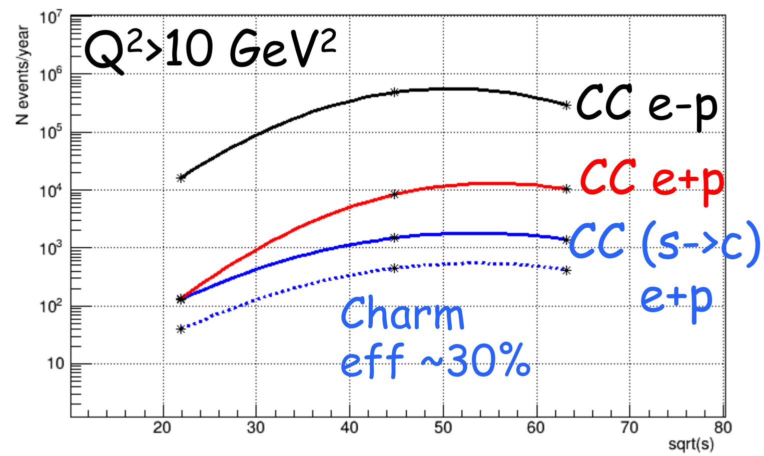
$$s' = |V_{cs}|^2 s + |V_{cd}|^2 d + |V_{cb}|^2 b.$$

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 0.97 & 0.22 & 0.0037 \\ 0.22 & 0.97 & 0.042 \\ 0.094 & 0.040 & 1.0 \end{pmatrix}$$

Charm in Charged Current reaction at EIC





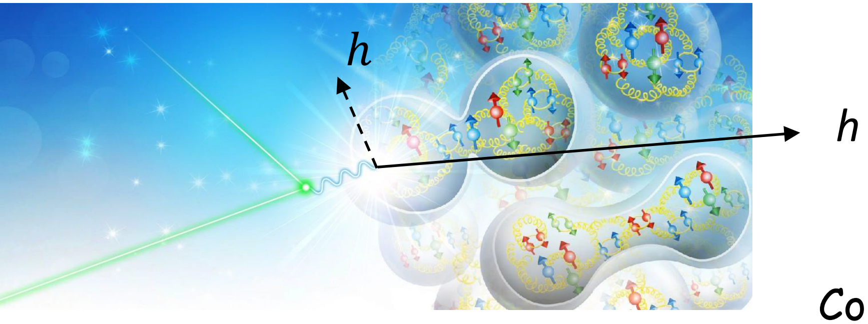


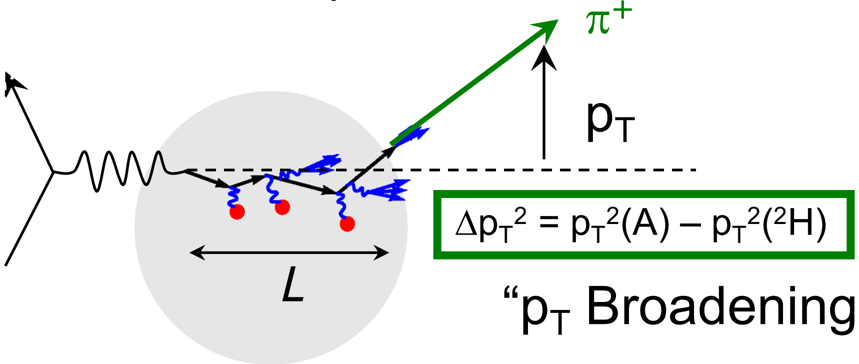
At EIC (Q^2>10GeV²):

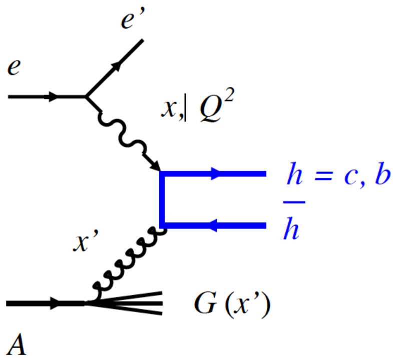
σ(e+p -> ν_e + X ~ 10 pb
σ(e+p -> ν_e +c +X) ~ 0.15 pb

with 10fb^{-1} /year (goal for positron beam)
⇒ ~ 1500 (s->c) events/year
⇒ ~ 500 (s->c) reconstructed events/year with 30% eff for charm reconstruction

Propagation within nuclear matter



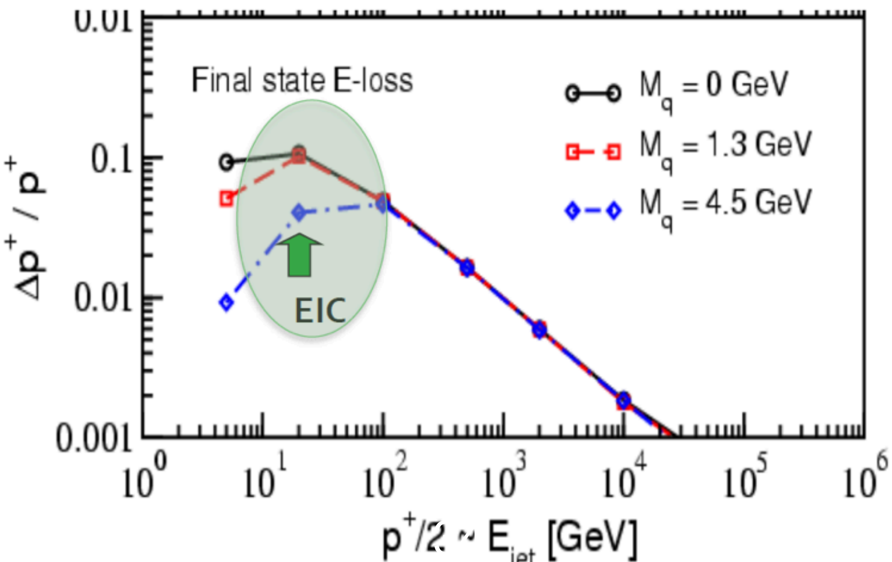




Comprehensive studies possible:

- wide range of energy ν = 10-1000 GeV
- wide range of Q^2: evolution
- P_T broadening, multiple scattering
- Hadronization length

Ivan Vitev



At EIC for the first time - will be able to study in-medium propagation and hadronization of heavy quarks (charm and beauty)

Summary

- Open charm production at EIC can constrain nuclear gluons at large–x
  Natural measurement for medium-energy collider
- Nuclear PDFs opens window on nucleon interactions in QCD
- High Luminosity (~10^{34}cm^{-2} s^{-1}) is essential for charm production at x>0.1
- Challenge to identify charm/beauty with overall high efficiency and in kinematic region with ~100 times larger DIS background
- PID and high-resolution vertex detector significantly improve charm reconstruction efficiency and overall charm to background ratio and should be integrated into EIC detector design
- Many other applications for heavy-quarks at EIC: Photoproduction, diffraction, Charged current, Jets, BSM …

Backup

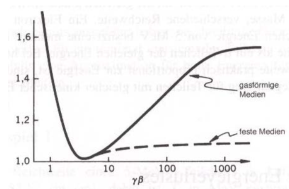
Energy loss of quarks (jets)

Interaction of Charged Particles with Matter:

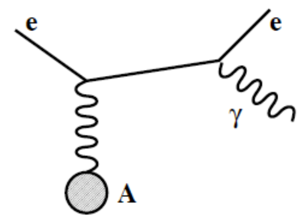
- Interaction with atomic electrons: Ionization and excitation

Energy loss is independent of the mass a charge and velocity of the incoming particle. Relatively independent of the absorber (Z/A). At βγ≈3.5 energy loss in the mimimum : (MIP)

$$\left.\frac{dE}{dx}\right|_{min} \approx 1.5\frac{MeV \cdot cm^2}{g}$$

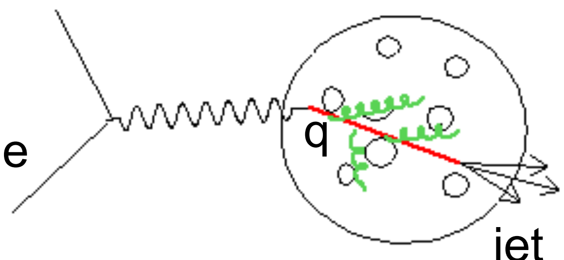


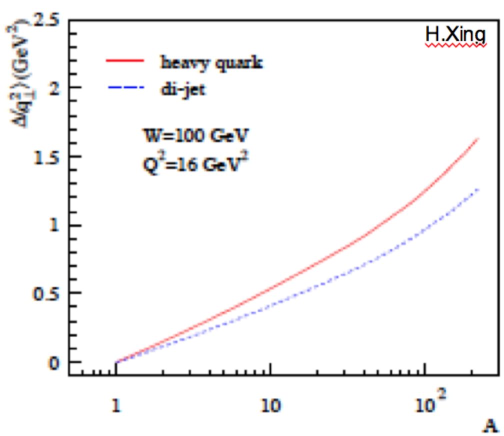
- Interaction with atomic nucleus: Bremsstrahlung (for high energy charged particles) , i. e. radiation of photons, in the Coulomb field of the atomic nuclei



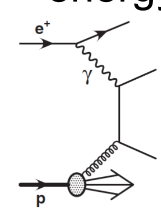
ELECTROMAGNETIC

- At EIC - energy loss of quarks.
- Gluon bremsstrahlung





- Z/A dependence (ep vs eA)
- Energy loss measurements as a function of initial quark energy and type of quark

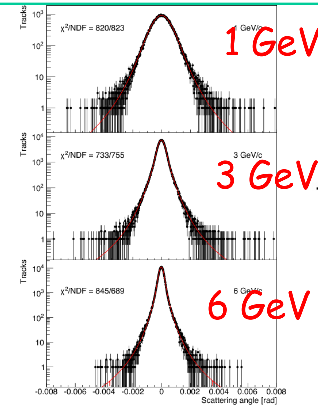


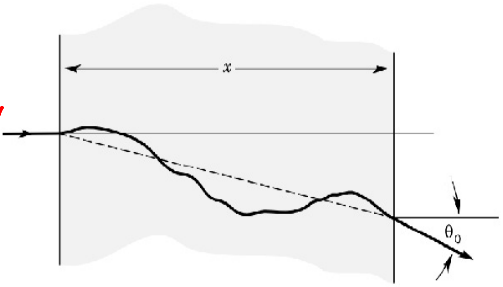
STRONG

Yulia Furletova

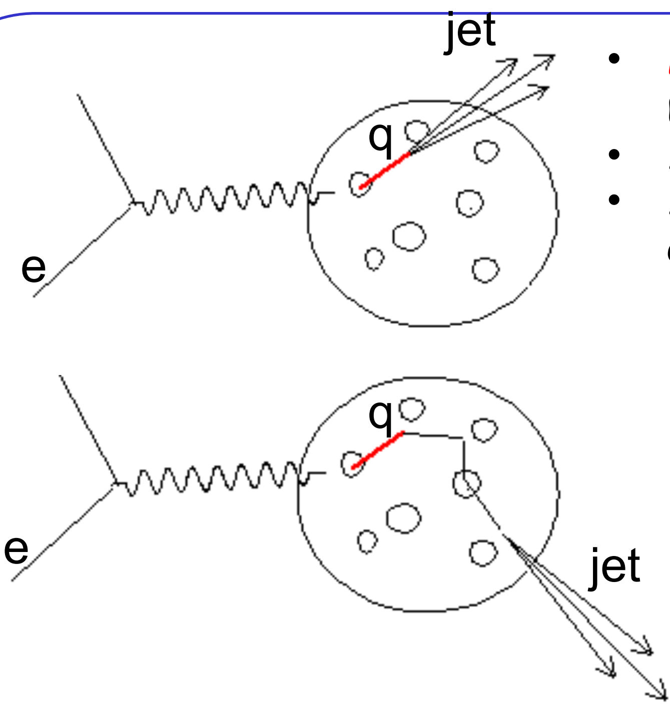
Multiple scattering of quarks (jets)

A charged particle traversing a medium is deflected by many small-angle scatters. Most of this deflection is due to Coulomb scattering from nuclei, and hence the effect is called multiple Coulomb scattering.

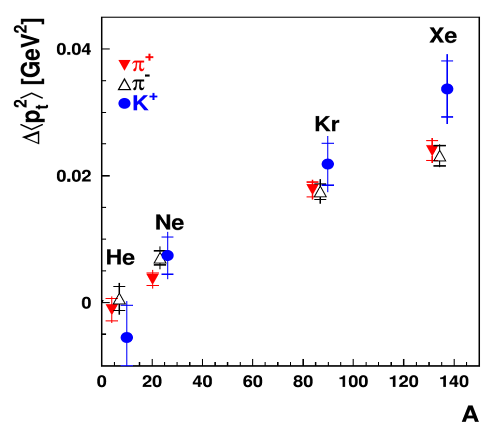




ELECTROMAGNETIC



- Multiple scattering of quarks in strong interacting matter.
- At low/medium energy this effect is more visible?
- Angular distribution, Z/A dependence (ep vs eA), quark energy (mass) dependence

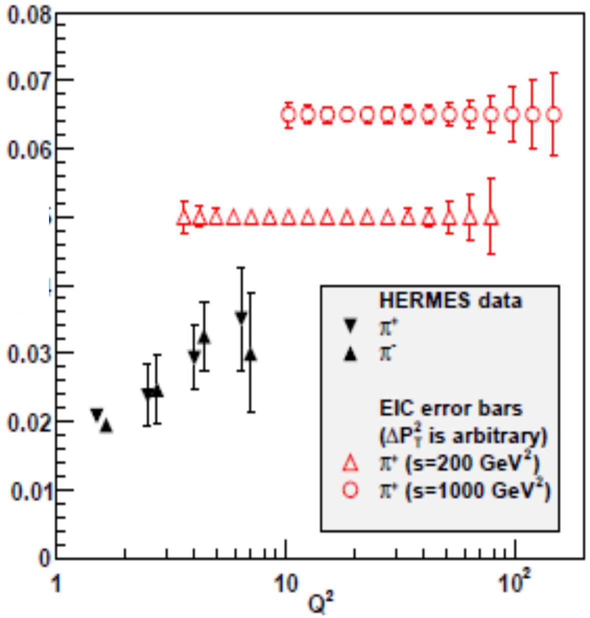


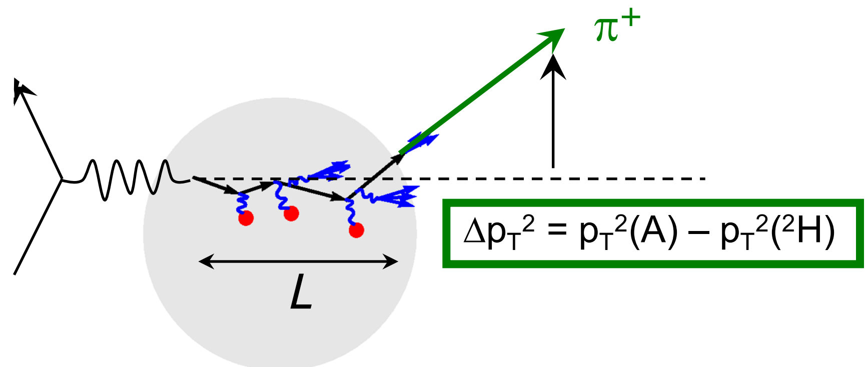
HERMES, A.Accardi,et c.

STRONG

PARTON PROPAGATION IN MATTER

Accardi, Dupre





Comprehensive studies possible:
- wide range of energy ν = 10-1000 GeV
- wide range of Q^2: evolution
- High luminosity for 3D and correlations

At EIC for the first time - will be able to study in-medium propagation and hadronization of heavy quarks (charm and beauty)