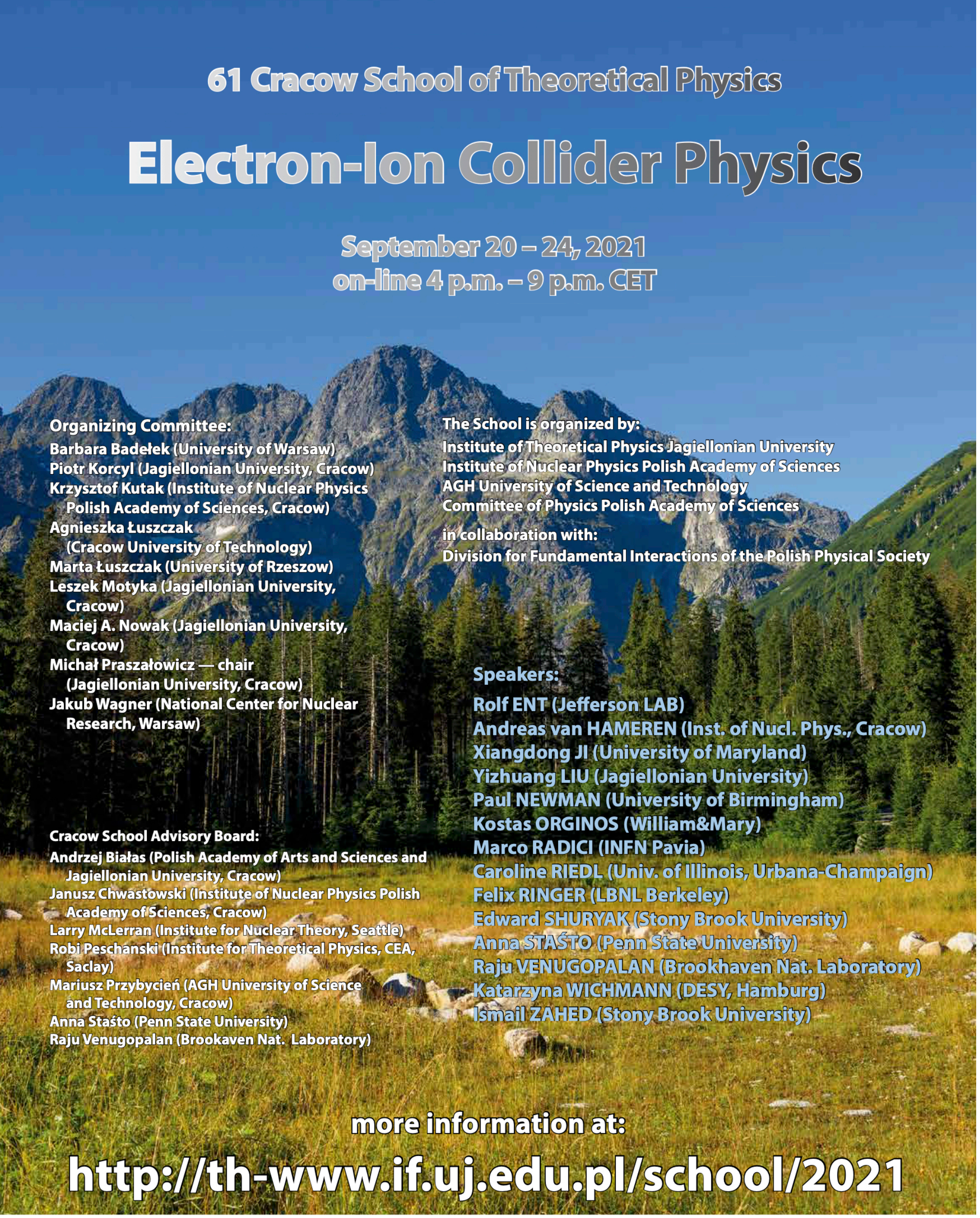


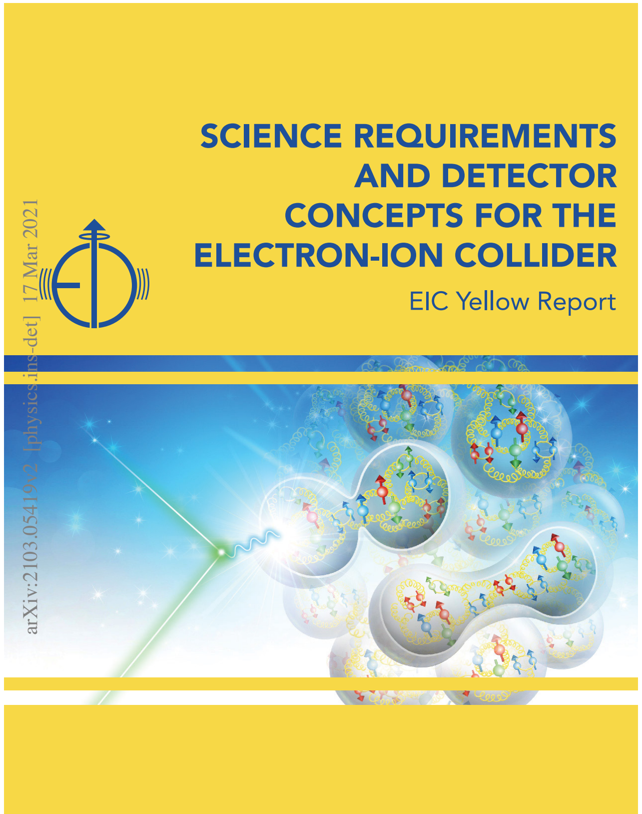
Ministry of Education and Science

Charm production in charged current DIS

Jae Nam

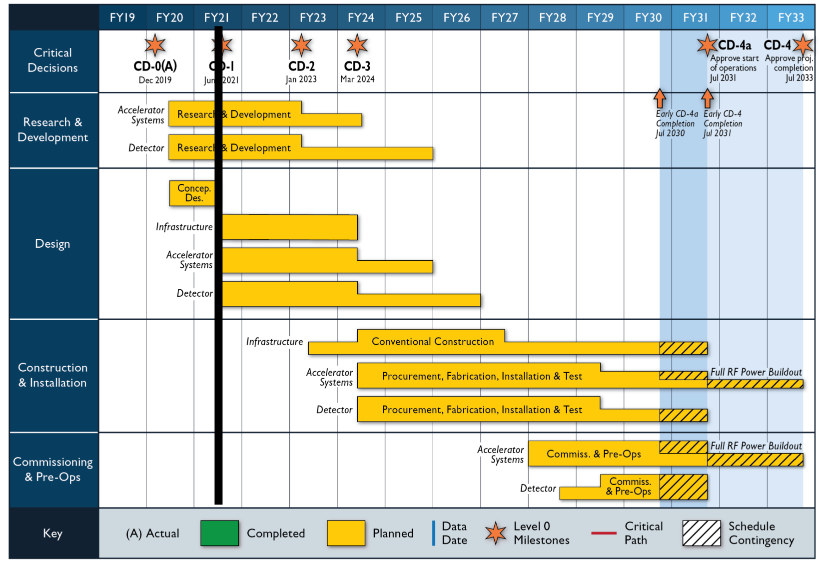
TEMPLE UNIVERSITY

EIC on the horizon



Electron-Ion Collider Achieves Critical Decision 1 Approval

CD-1 milestone marks start of project execution phase for next-generation nuclear physics facility that will probe the smallest building blocks of visible matter



T. Hallman, EICUGM 2021

EIC collaboration

The EIC will be an international facility, attracting expertise from around the world. The growing EIC User Group already includes 251 member institutions from 33 countries—with 88 U.S. institutions representing 27 states, Puerto Rico, and Washington, D.C.

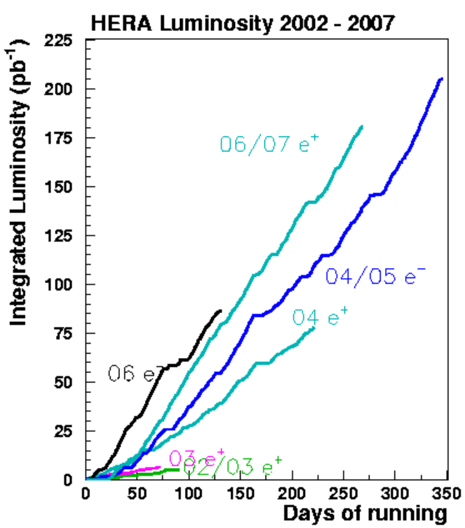
- A lot of progresses have been made to realize EIC.
- Naturally, one wants to study EIC capabilities at the phenomenology level.
- Many physics topics of HERA are relevant in EIC.

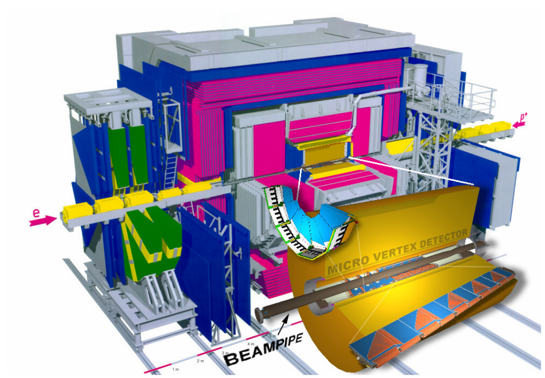
→ Lessons from HERA

Hadron-**E**lektron **R**ing**A**nlage (**HERA**)

HERA

- First and only ep collider
- Featuring both $e^{-}p$ and $e^{+}p$
- In operation 1992-2007
- HERA II (2003-2007)
  - $\sqrt{s} = 318\ GeV$
  - $L \sim 360\ pb^{-1}$ (stored at ZEUS)



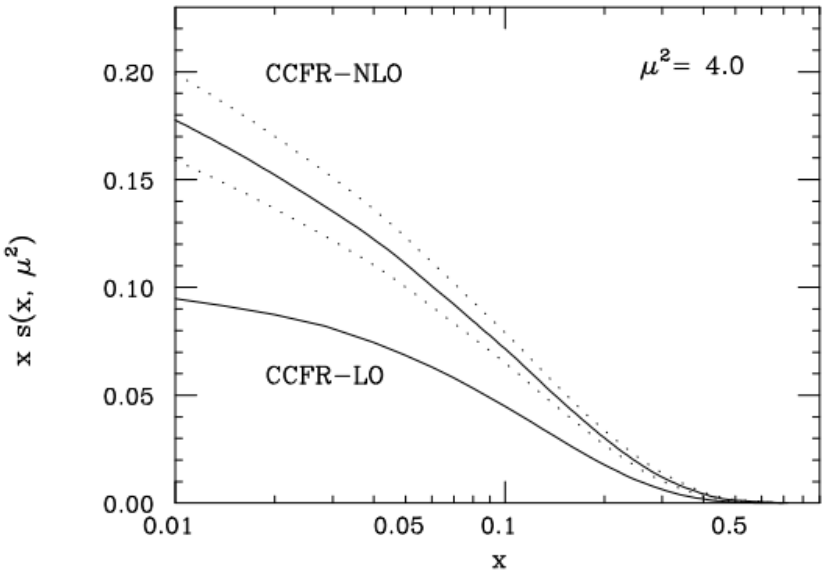


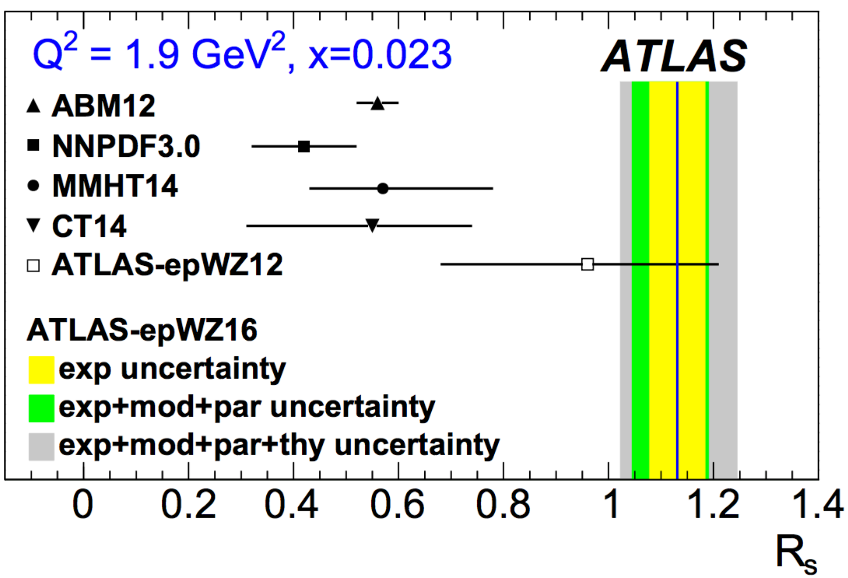
e (27 GeV) → ← p (920 GeV)

ZEUS

- General purpose detector
- High particle tagging capabilities via MVD.
- Two independent luminosity measurements, $\delta(L)/L \sim 3\%$

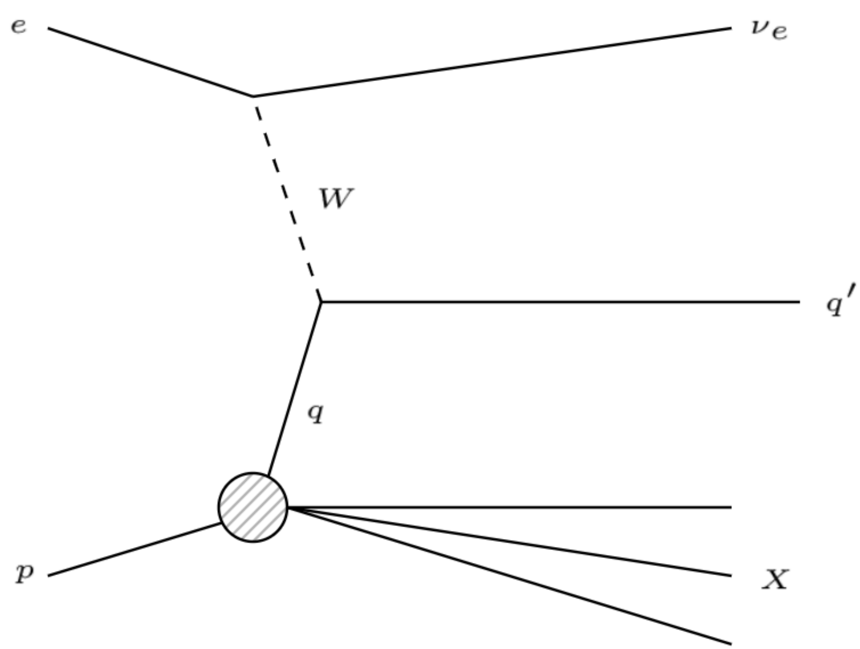
Strangeness of the proton

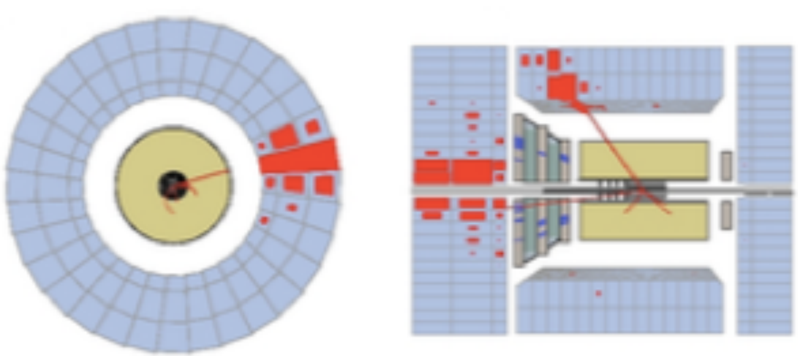




- Strange quark is the least known LF in the proton.
- Previously, largely relied on neutrino DIS, e.g., CCFR/NuTeV, NOMAD, CHORUS.
  - Consistent with the assumption of strange mass-suppression, $\frac{s}{s+\bar{d}} \sim 0.3$.
- Recent LHC measurements of W/Z and $W+c$ production.
  - Consistent with the unsuppressed strangeness assumption, $\frac{s}{s+\bar{d}} \sim 0.5$.
- Charm production in CCDIS can provide complementary measurements.
  - Start from HERA measurement [*JHEP* 05 (2019) 201] and extrapolate to EIC.

Charged Current DIS (CCDIS)





- The CCDIS structure functions
  - $F_2 = 2x \sum e_q^2[q + \bar{q}]$
  - $xF_3 = 2x \sum e_q^2[q - \bar{q}]$
  - Provides a great probe of PDFs due to the simplicity of F^{CC} and some cancellation.

- The phase space of the rotated quark state given by the CKM matrix.

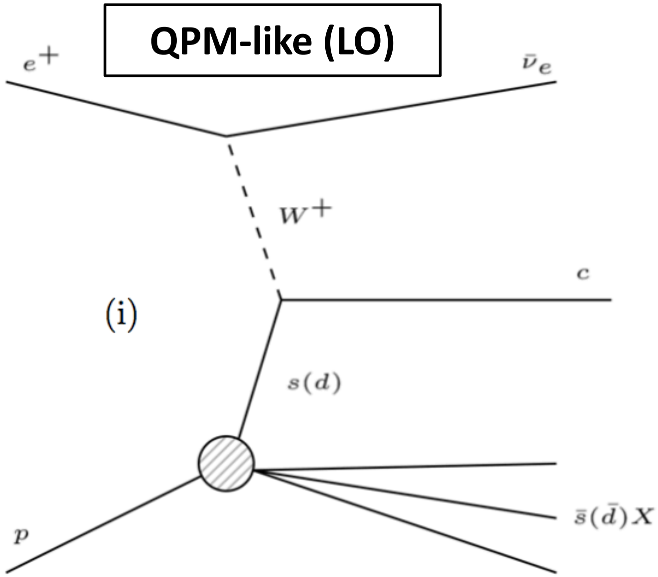
$$|q_i{}'\rangle = V_{i1}|q_1\rangle + V_{i2}|q_2\rangle + V_{i3}|q_3\rangle$$

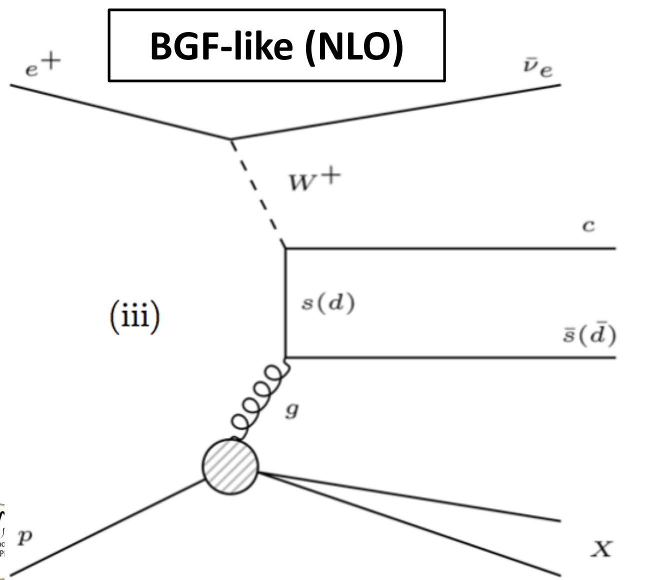
- CCDIS suppression in low Q^2,

$$\frac{\sigma^{CC}}{\sigma^{NC}} \sim \frac{Q^4}{(Q^2 + M_W^2)^2}$$

- Final-state neutrino
  - Clean identification by imbalance in the calorimeter energy deposit.
  - Impaired vertex reconstruction.

Charm production in CCDIS





- LO: QPM-like process
  - $sW \rightarrow c$ (Cabbibo-favored) or $dW \rightarrow c$ (Cabbibo-suppressed).
  - Sensitive to strange density.
- NLO: BGF-like process
  - $g \rightarrow s\bar{s},\ g \rightarrow d\bar{d},\ g \rightarrow c\bar{c}$
  - Sensitive to gluon density
  - Overcomes its high pQCD order in low-x regime.
- LO and NLO share the same final state.
  - Differing contributions to different regions in kin. phase space.
  - At HERA, no attempt made to disentangle them due to limited stat.
  - Distinction depends purely on the choice of QCD scheme.
  - Model-dependent extraction of $s(x, Q^2)$.

Data, MC, Theory

- HERA II data
  - $L(e^-p) \sim 185\ pb^{-1}$
  - $L(e^+p) \sim 173\ pb^{-1}$
- MC
  - Inclusive CCDIS, DJANGOH 1.6, ARIADNE 4.12, CTEQ-5D
  - Negligible non-CC background after DIS selection.
- Kinematics
  - Parton-level (electron method):

$$Q^2 = -(k - k')^2 \qquad x_{Bj} = \frac{Q^2}{2pq} \qquad y = \frac{pq}{pk}$$

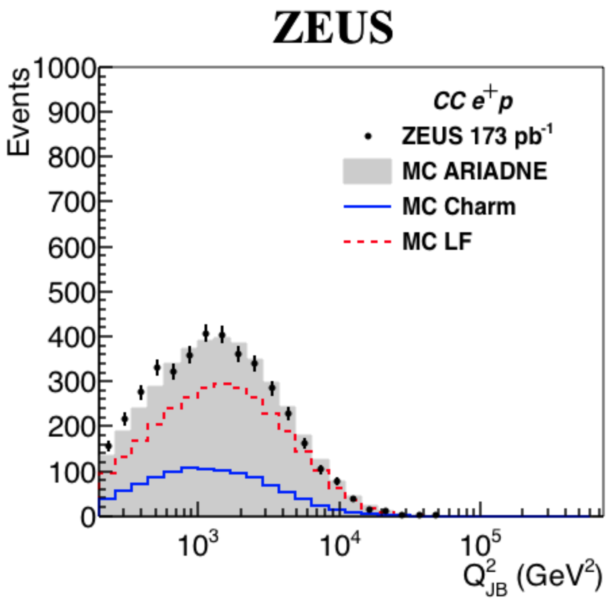
  - Hadron-level (Jacquet-Blondel method):

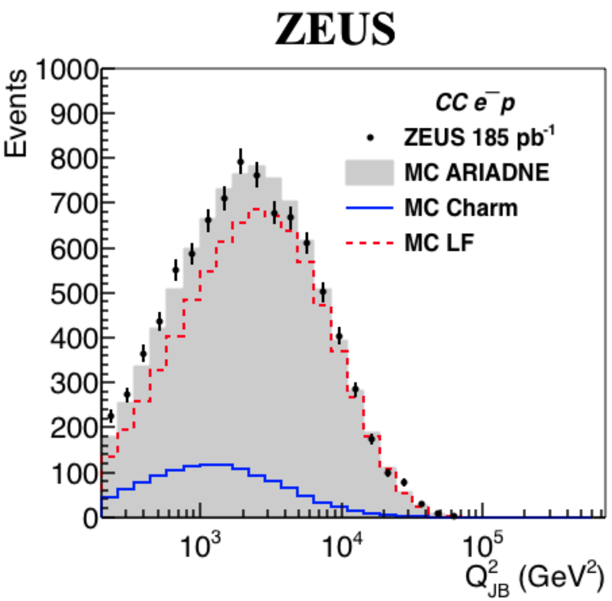
$$y_{JB} = \frac{\sum_h (E - p_z)_h}{2E_e} \qquad Q^2_{JB} = \frac{p^2_{T,h}}{1 - y_{JB}} \qquad x_{JB} = \frac{Q^2_{JB}}{s y_{JB}}$$

- QCD schemes
  - Zero-mass Variable Flavor Number (ZMVFNS; QCDNUM, HERAPDF2.0 & ATLAS epWZ16 PDF sets):
    - For relative comparison of different assumptions on the strange quark density.
  - NLO Fixed-Flavor Number (FFNS; OPENQCDRAD, ABMP16.3 NLO PDF sets):
    - No charm arising from the proton, compensated by a larger gluon content.
  - General-mass VFNS (GMVFNS; FONLL-B scheme, APFEL, NNPDF3.1)
    - Interpolates FFNS and ZMVFNS at the charm mass region.

DIS selection

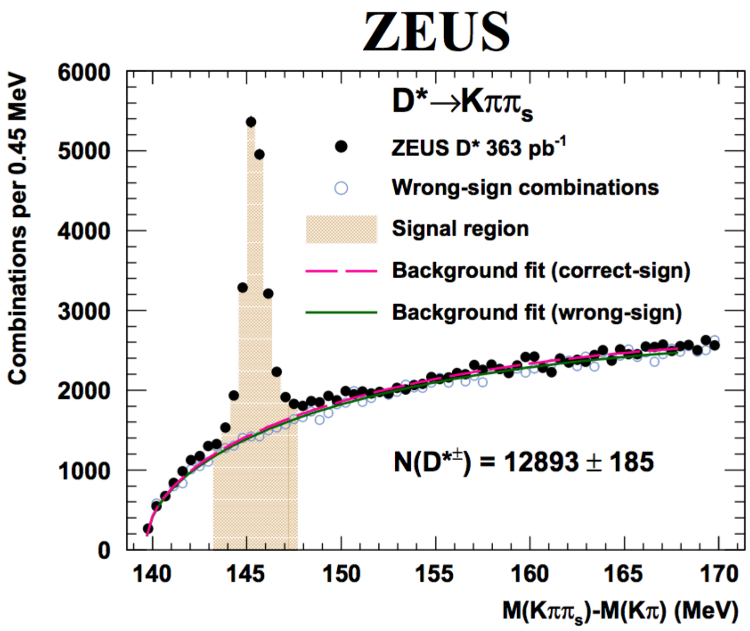
- Kinematic selection
  - Limitations of JB method
  - $Q^2 > 200\ GeV^2, \quad y < 0.9$
- Undetected neutrino momentum
  - $p_{T,miss} > 10\ GeV$
- Non-ep/non-CC reaction rejection.
- Result consistent with expectations.
  - ~4000 (e^+p) and ~9000 (e^-p) CC evts.
  - Each producing ~1000 charm evts.

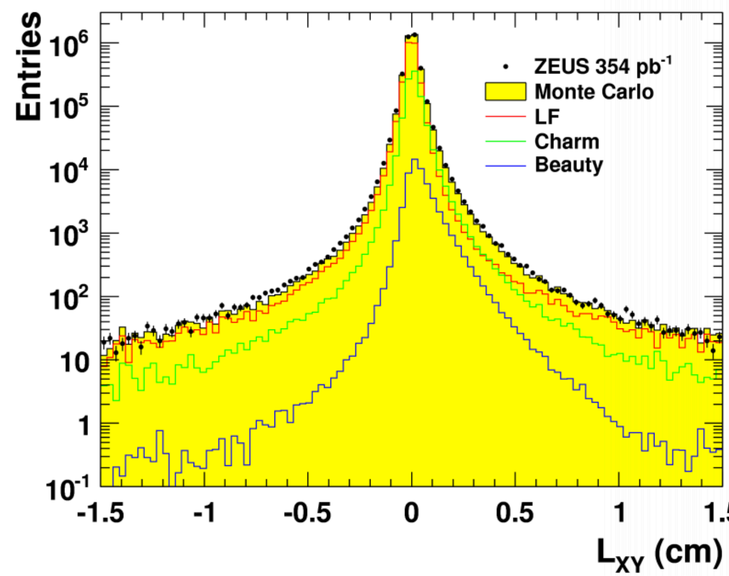




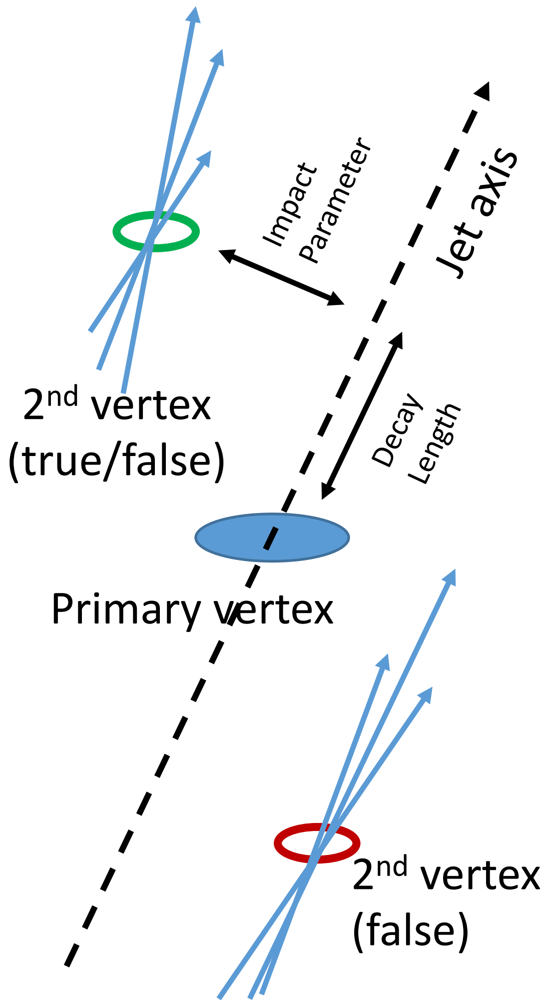
Charm quark tagging at HERA

- Semi-inclusive DIS (SIDIS)
  - Final state hadrons containing charm are identified.
    - e.g., $D^* \to D^0\pi_s \to K\pi\pi_s$ (The Golden Channel)
  - Pros
    - Simpler identification of final state hadrons with charm
    - Great signal-to-background ratio
  - Cons
    - Generally, suffers from low statistics from corresponding branching ratios.
    - Additional uncertainty from hadronization model/fragmentation function.
- Lifetime based methods (more inclusive approaches)
  - Use decay length of hadrons with charm (this), impact parameter (PRD 103 (2021) 7, 074023)
  - Pros
    - Simpler theory calculations
    - Generally, larger statistics and lower syst. unc.
  - Cons
    - Heavily reliant on the detector resolution as this approach requires reconstruction of jets, vertices.

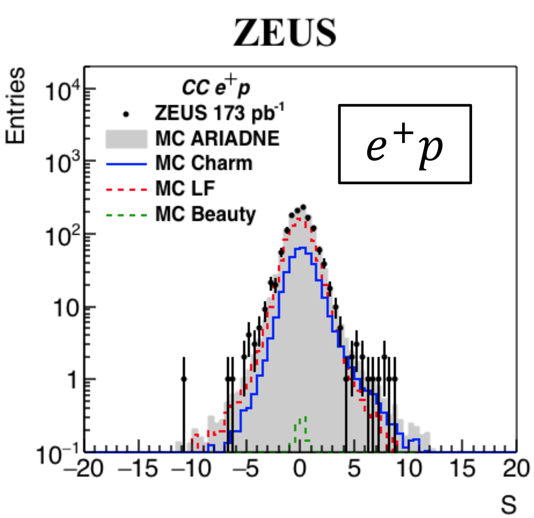


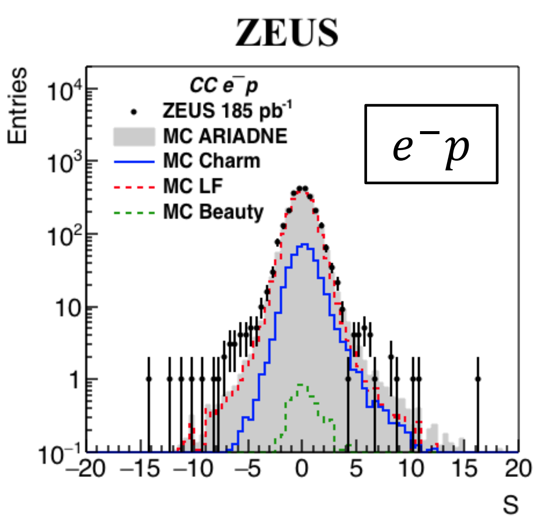


Lifetime-based tagging

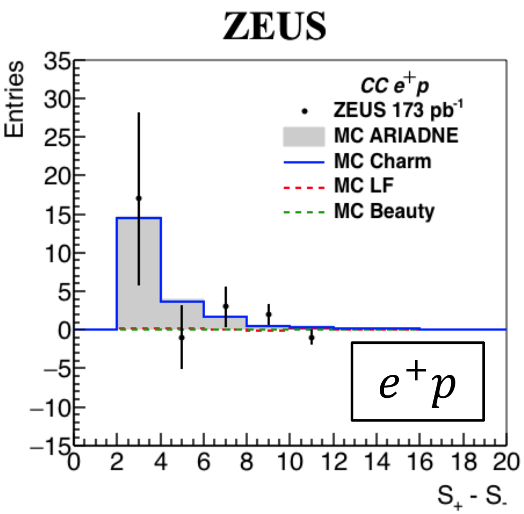


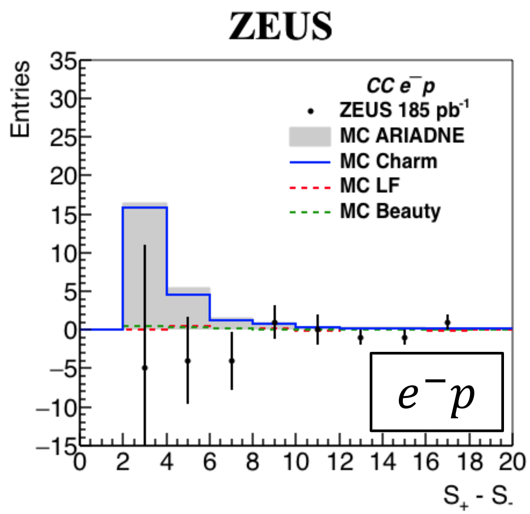
- Lifetime information
  - LF: Produced promptly
  - HF: longer lifetime due to weak decay
- lifetime difference + finite resolution of vertex detector result in:
  - LF: symmetric decay length distribution
  - HF: asymmetric distribution





Charm signal extraction



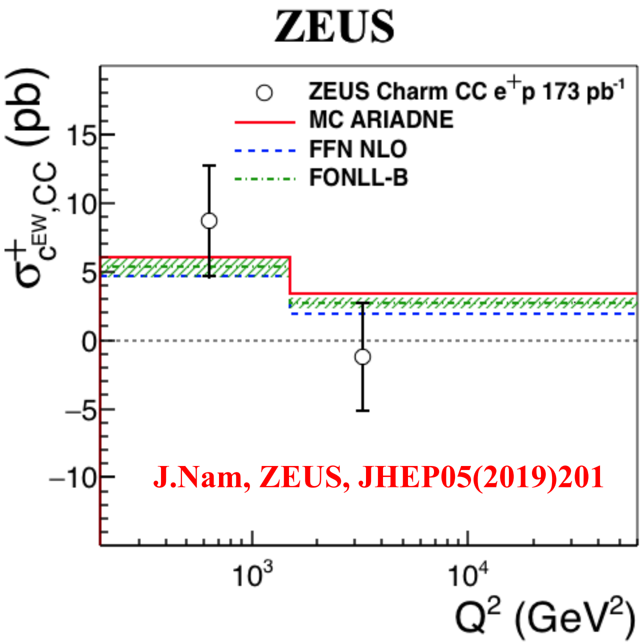


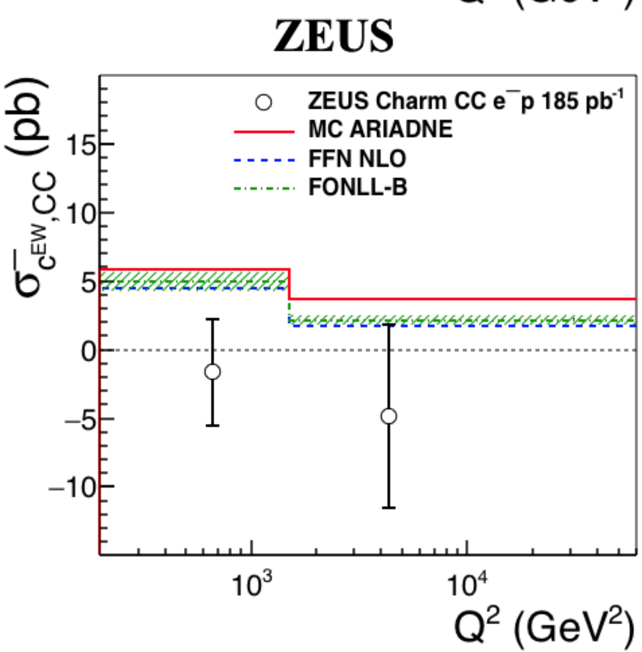
e^+p	MC Contribution (%)			
	$d \to c$	$s \to c$	$\bar{c} \to \bar{s}(\bar{d})$	$g \to c\bar{c}$
$\sigma^{MC}_{c,vis} + \sigma(g \to c\bar{c})$	9	45	40	6
$\sigma^{MC}_{cEW} + \sigma(g \to c\bar{c})$	7	31	58	4

e^-p	MC Contribution (%)			
	$\bar{d} \to \bar{c}$	$\bar{s} \to \bar{c}$	$c \to s(d)$	$g \to c\bar{c}$
$\sigma^{MC}_{c,vis} + \sigma(g \to c\bar{c})$	3	45	40	12
$\sigma^{MC}_{cEW} + \sigma(g \to c\bar{c})$	2	31	57	10

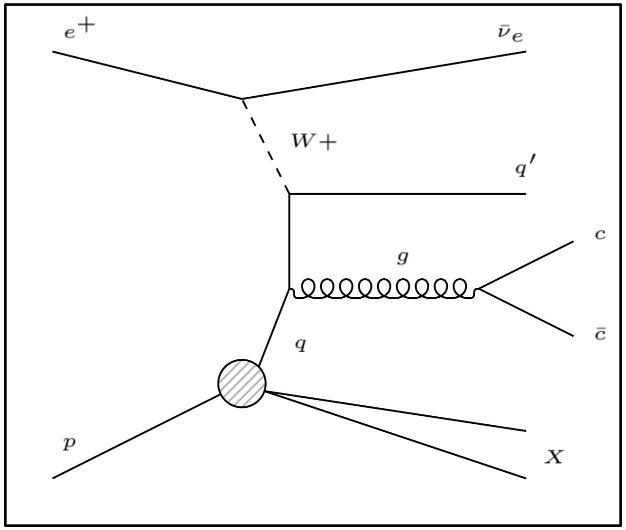
- Charm extraction by decay length subtraction
  - $S = L_{xy}/\delta(L_{xy})$
  - Resulting charm isolation > 0.96
- Due to limited statistics, negative number of charm from e^-p period.
  - $\sigma(e^-p \to sWX \to cX)$ consistent with 0 with a large unceratinty.
- Differing contributions from different subproccesses
  - Smaller BGF contribution in the visible region
    - $-2.5 < \eta^{jet} < 2.0\ (1.5)$,
    - $E_T^{jet} > 5\ GeV$

Results





- EW charm cross section measured at HERA
  - Consistent with theory predictions with large statistical uncertainty
  - Manageable systematics
    - ~10% effect mostly from simulation (ZEUS-specific) and QCD charm.
  - Negative cross section for $e^{-}p \rightarrow cX$ process ($\bar{s}$-sensitive) due to low-statistics behavior of the tagging method.



Theory predictions

Q^2 range (GeV^2)	NLO Predictions (pb)					
	HERAPDF2.0					ATLAS-epWZ16
	$f_s = 0.4$ (nominal)	$f_s = 0.3$	$f_s = 0.5$	$f'_s =$ HERMES$^-$	$f'_s =$ HERMES$^+$	
e^+p						
200 – 1500	5.67	5.40	5.96	5.05	5.38	6.41
1500–60000	2.57	2.47	2.65	2.16	2.20	3.07
e^-p						
200 – 1500	5.41	5.15	5.70	4.79	5.12	6.14
1500–60000	2.30	2.21	2.37	1.89	1.93	2.78

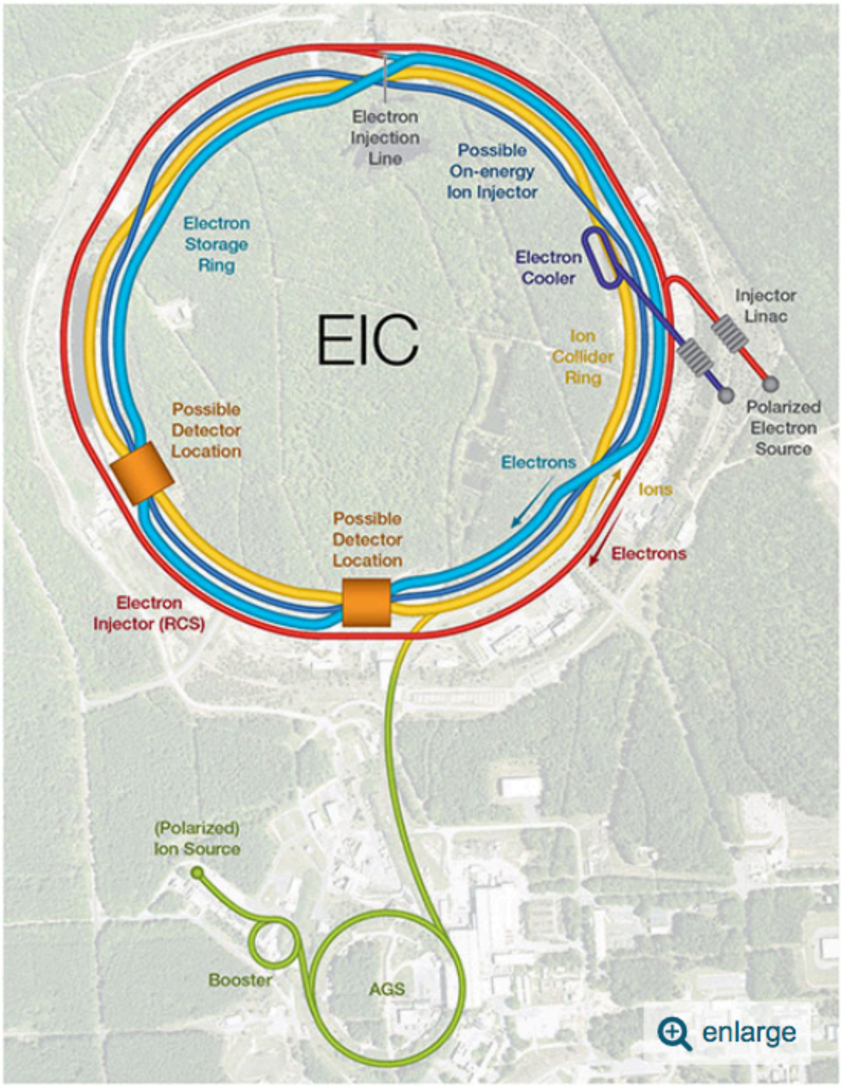
Q^2 range (GeV^2)	NLO Predictions (pb)							
	FFN ABMP16.3				FONLL-B NNPDF3.1			
	σ	uncertainties			σ	uncertainties		
		PDF	scale	mass		PDF	scale	mass
e^+p								
200 – 1500	4.72	± 0.05	$^{+0.31}_{-0.23}$	± 0.02	5.37	± 0.21	$^{+0.68}_{-0.73}$	± 0.00
1500–60000	1.97	± 0.03	$^{+0.18}_{-0.13}$	± 0.01	2.66	± 0.23	$^{+0.37}_{-0.26}$	± 0.00
e^-p								
200 – 1500	4.50	± 0.05	$^{+0.31}_{-0.23}$	± 0.02	4.98	± 0.22	$^{+0.66}_{-0.71}$	± 0.00
1500–60000	1.73	± 0.03	$^{+0.18}_{-0.13}$	± 0.01	2.16	± 0.22	$^{+0.33}_{-0.21}$	± 0.00

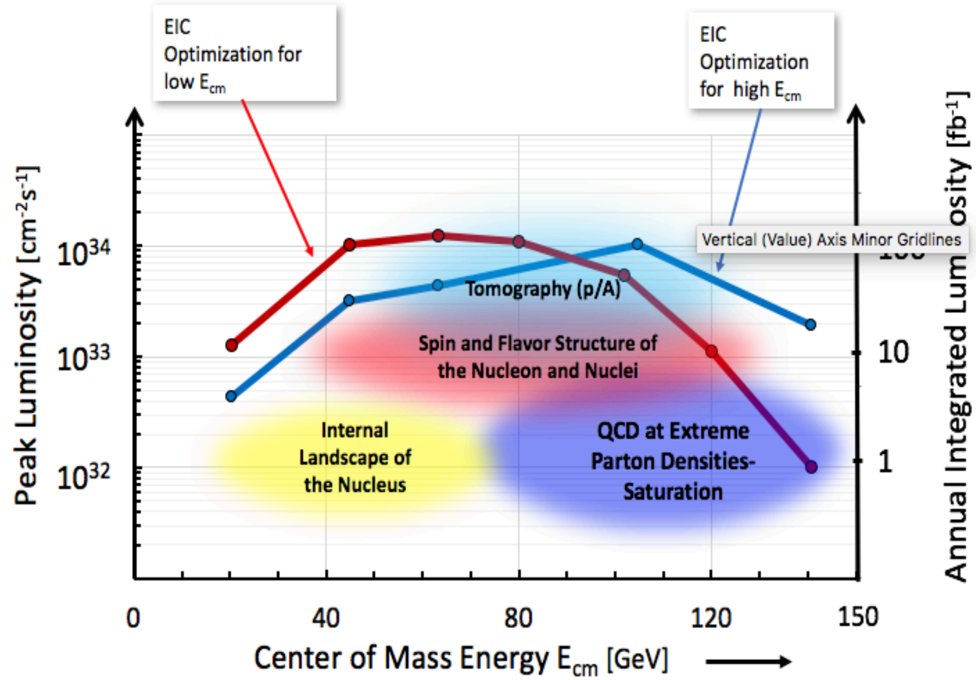
- Assumptions
  - $f_s = 0.3 - 0.5$ with HERAPDF2.0
  - HERMES x-dependent $\bar{s}(x, Q^2)$ normalized to $f_s = 0.3(-), 0.5(+)$
  - ATLASepWZ16
- 10-20% variation with different assumptions on strange content
  - Need 2 OoM larger statistics
- 10-20% uncertainty in theory prediction
  - Also need improvements in theory calculations.

Lessons from HERA

- CCDIS with lifetime based tagging can be used as a probe of proton strangeness, complementarily to νDIS, W production in pp, and SIDIS.
- Good tracking and vertexing are crucial in HF studies, not limited to charm.
- Non-trivial, but essential phenomenological calculations

Electron Ion Collider (EIC)





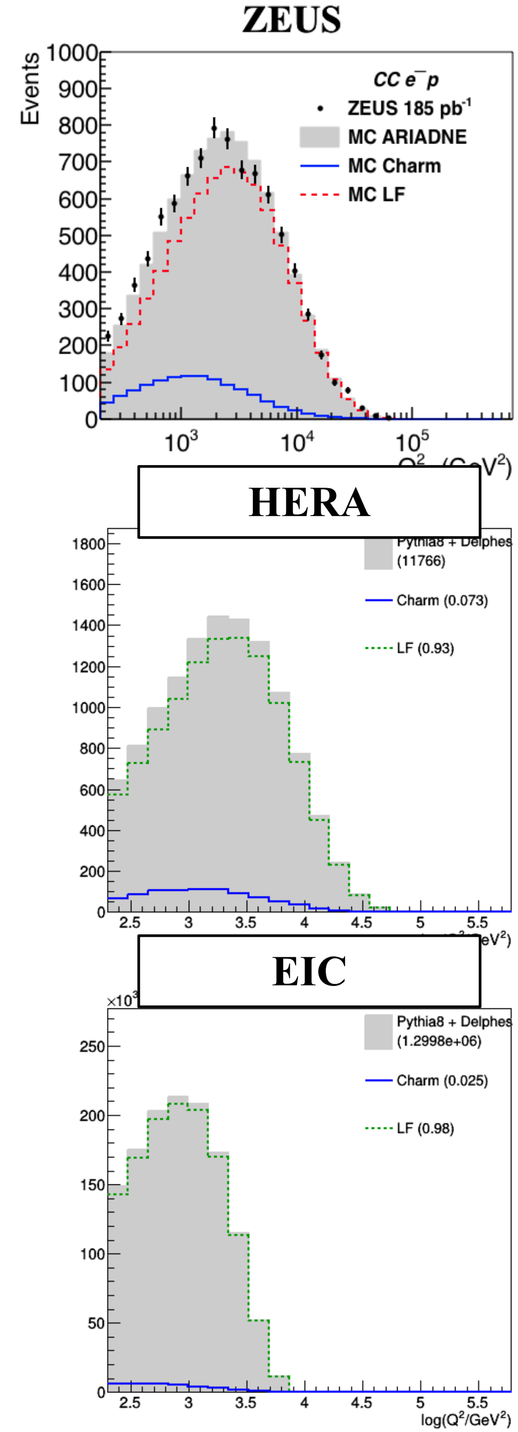
- eRHIC design was selected.
- Feature ep/eA collisions at varying $\sqrt{s} = 20 - 140\ GeV$
- Up to ~1000 times L_{HERA}.
- Detector design in progress

EIC Simulation

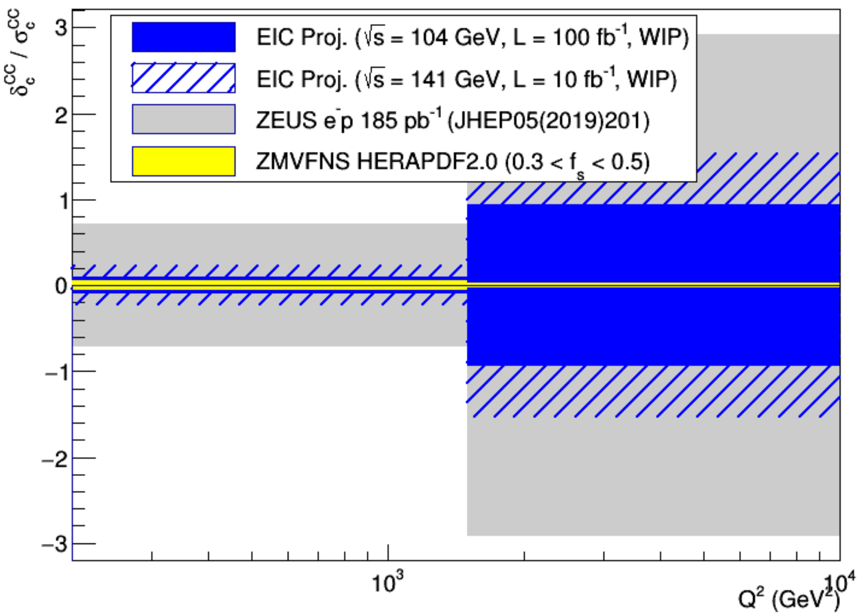
- HERA result was statistically-limitted.
- Feasibility of this measurement at EIC can be estimated in terms of charm yield as

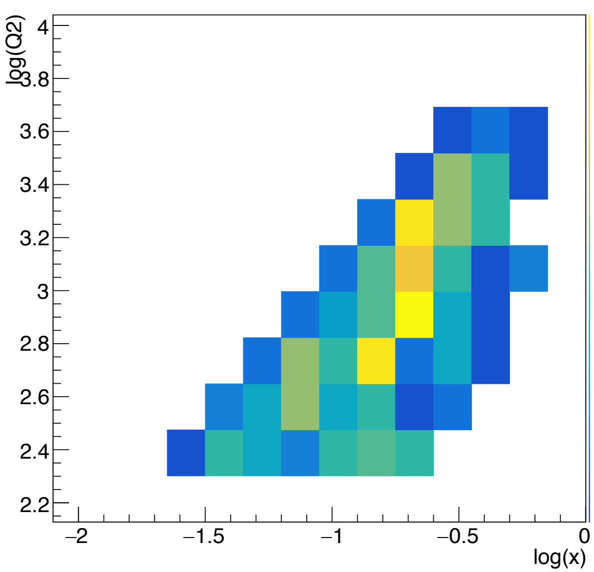
$$\frac{N_{c,CC}^{EIC}}{N_{c,CC}^{HERA}} = \frac{L^{EIC}}{L^{HERA}} \times \frac{\sigma_{CC}^{EIC}}{\sigma_{CC}^{HERA}} \times \frac{r_c^{EIC}}{r_c^{HERA}} \times \frac{\epsilon^{EIC}}{\epsilon^{HERA}}$$

- Pythia interfaced in Delphes
  - No BGF contribution → ~50% charm
  - Good description of HERA II data (yield, shape, charm fraction)
  - 7~15% charm yield of HERA per unit luminosity depending on $\sqrt{s}$.



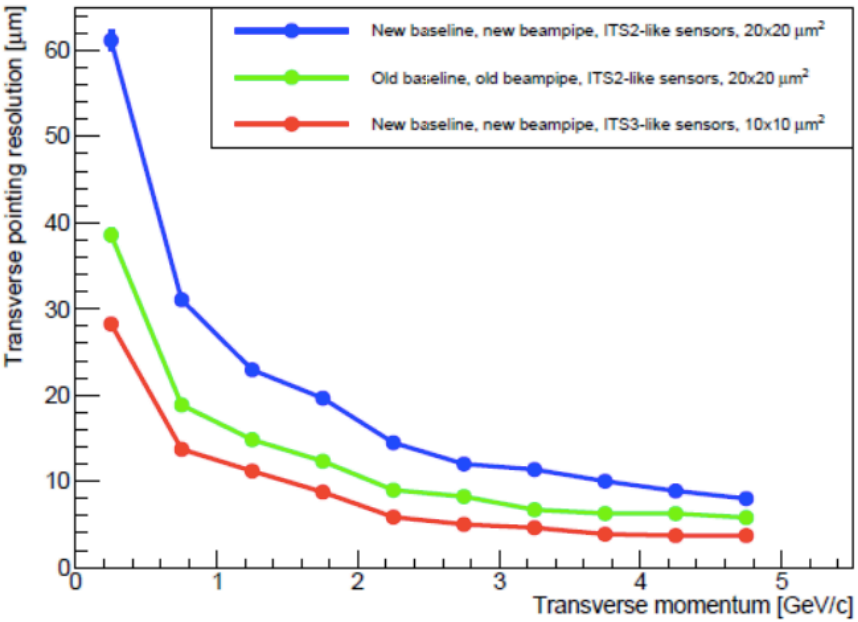
EIC projection

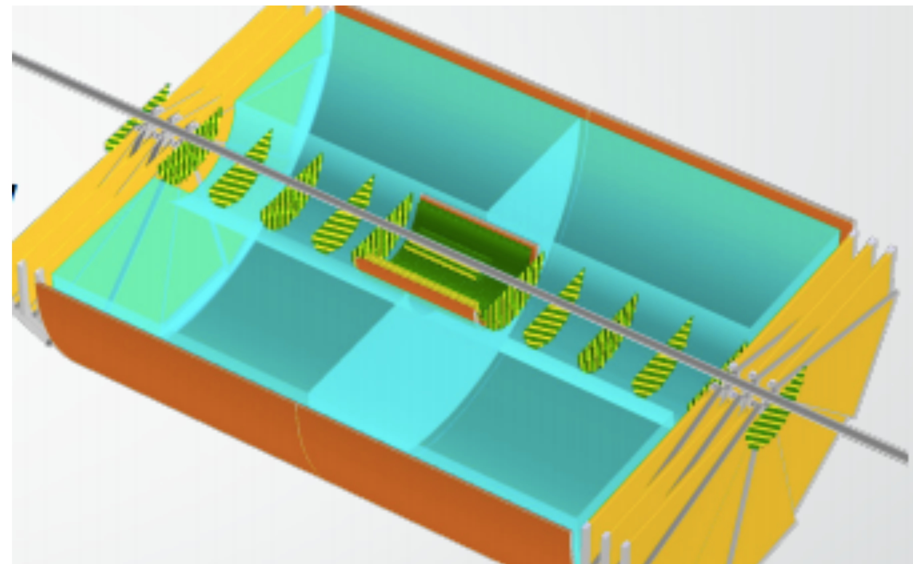




- EIC projection compared to variation in theory (HERAPDF2.0, $0.3 < f_s < 0.5$)
- Assumes no improvement in tagging efficiency
- Promising result with nominal sample
  - $\sqrt{s} = 100\ GeV$
  - $L = L_{1year} = 100\ fb^{-1}$
- Sensitive to strangeness in $0.05 < x < 0.5, \quad \langle x \rangle = 0.15$

Improvements at EIC





O. Evdokimov, CFNS Summer 2021

- Silicon pixel sensor technology for EIC produces a better vertexing resolution ($\sim 10\ \mu m$) than ZEUS ($> 20\ \mu m$).
    - Impact at the measurement level needs to be verified.
- Large interest in improving vertexing detector & algorithm.

Summary

- Charm production in CCDIS can be used to study strangeness.
  - Different techniques available that allow for many complementary measurements
- Lifetime based measurement at ZEUS with HERA II data
  - Good charm isolation
  - Limited statistics, efficiency $\sim 2\%$
  - Can be improved in future experiments with (1) high luminosity, (2) better vertex detector and (3) better vertexing algorithm.
- EIC is the perfect place to test all three improvements
  - Improvement in luminosity alone estimated to generate enough enhancement in statistics to produce conclusive result.
  - Impact from improved vertexing needs to be verified.