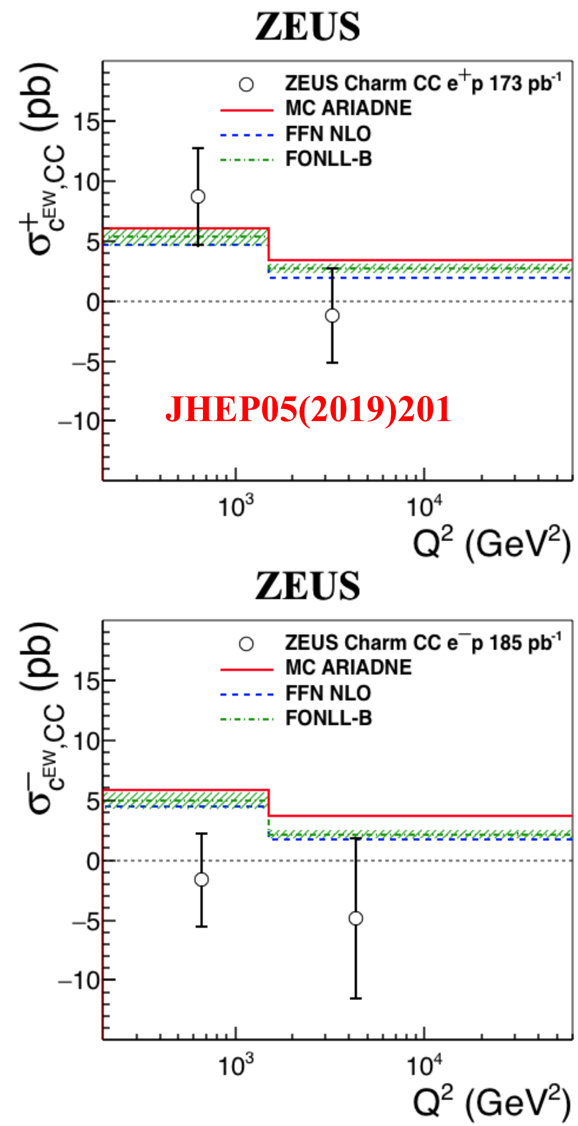
Charm production in CCDIS at EIC

Jae D. Nam

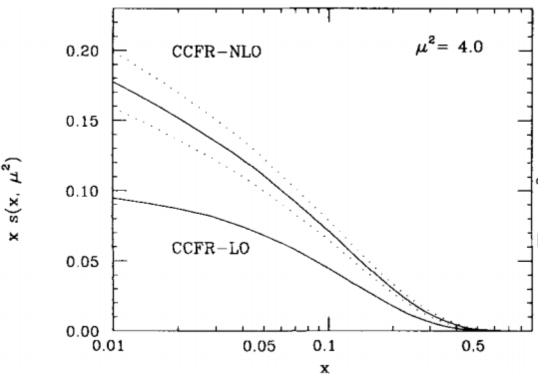
Temple Univ.

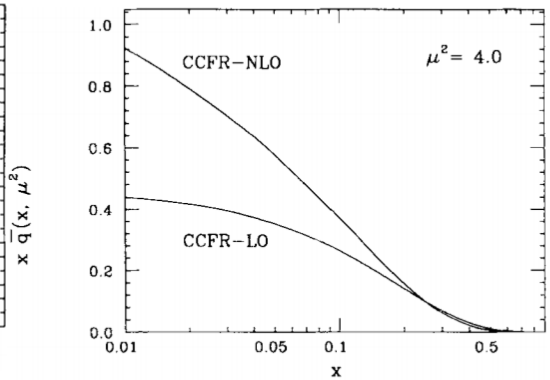
Overview

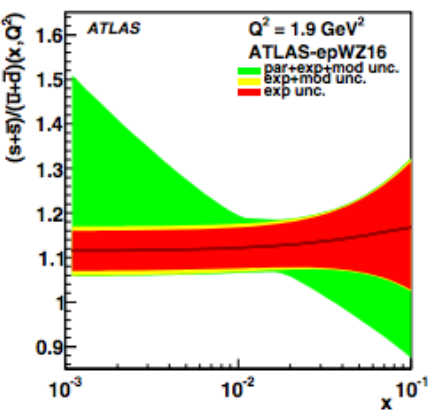
- **Motivation**
  - The strange quark content of the proton is largely unknown and there exist measurements in disagreement (different kinematic regions).
  - An attempt was made at ZEUS/HERA in order to provide a complementary measurement to contribute to the investigation, but was statistically-limited.
- **ZEUS/HERA**
  - The theory calculations suggest 10-20% variation in charm cross section in CCDIS depending on the assumptions behind strange content of the proton.
  - The measurement was statistically-limited ($\delta_{syst}\sim$ 10% can be brought down to 3%, $\delta_{stat}\sim$100%).
- **EIC**
  - This topic can be revisited since we expect much higher luminosity to be achieved in EIC (2~4 orders higher than HERA).

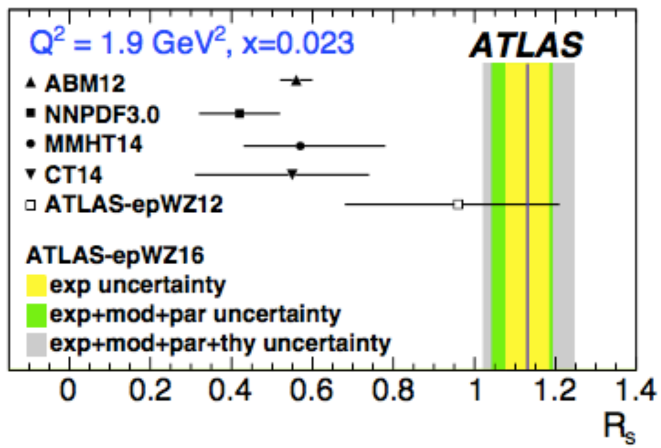


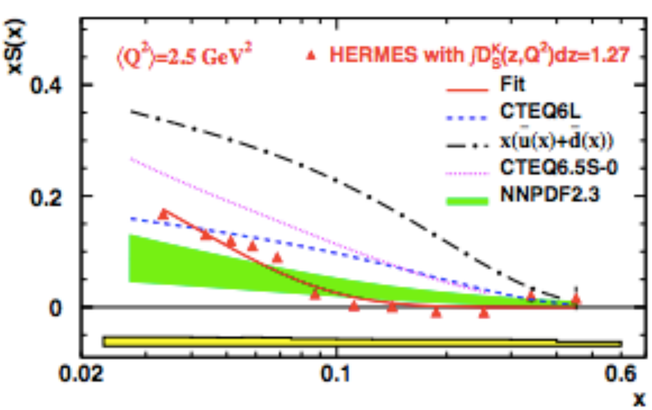
Previous measurements of $s(x, Q^2)$





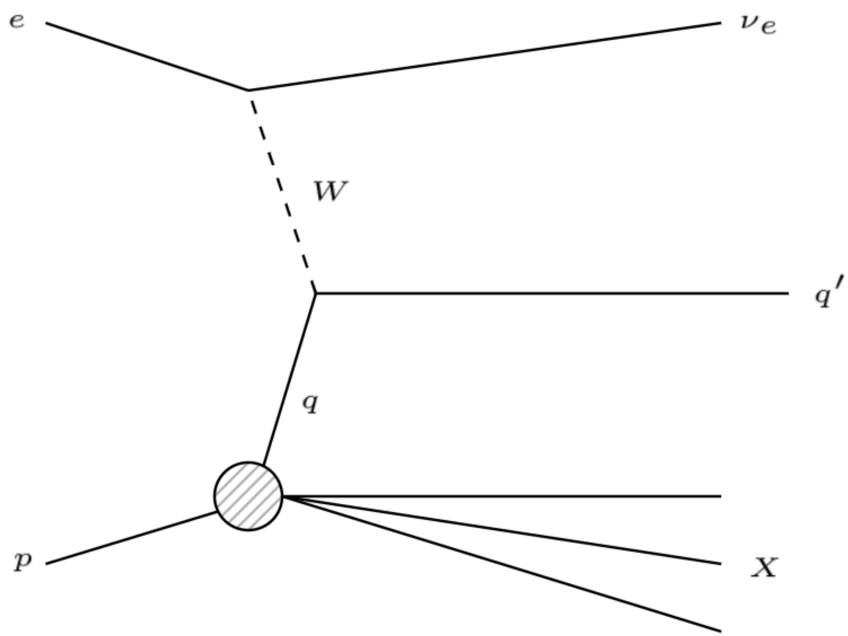






- Suppressed ($s/d \sim 0.5$)
  - Neutrino experiments e.g. CCFR/NuTeV
  - For large-x_{Bj}
- Unsuppressed ($s/d \sim 1$)
  - W/Z measurement by ATLAS,
  - $W + c$ measurement by CMS
  - For low-x
  - Disagreement btw. ATLAS and CMS in some kinematic region.
- x-dependent
  - HERMES
  - Suppressed strangeness at high-x and unsuppressed in low-x regime.

Charged current DIS (CCDIS)



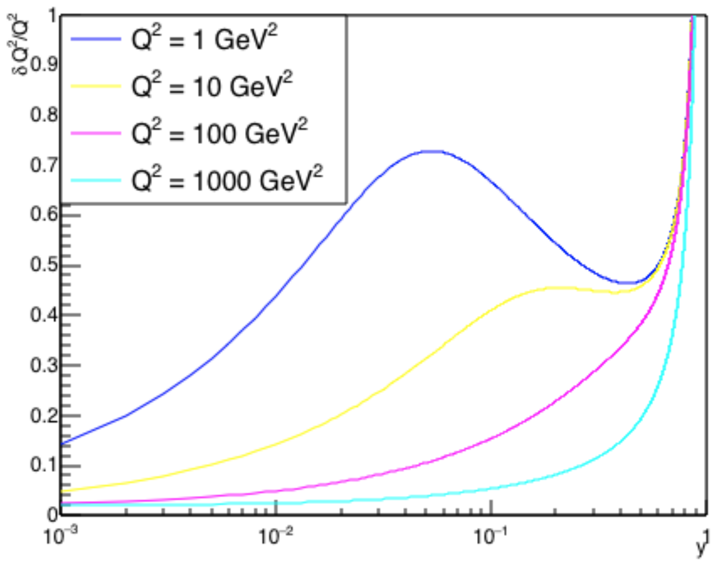
- Characteristics include…
  - Clear signature (ν_e)
  - Flavor selective
  - Low production rate

- Kinematic quantities can only be reconstructed via JB method.

$$y_{JB} = \frac{\sum_h (E - p_z)_h}{2E_{e,beam}}$$

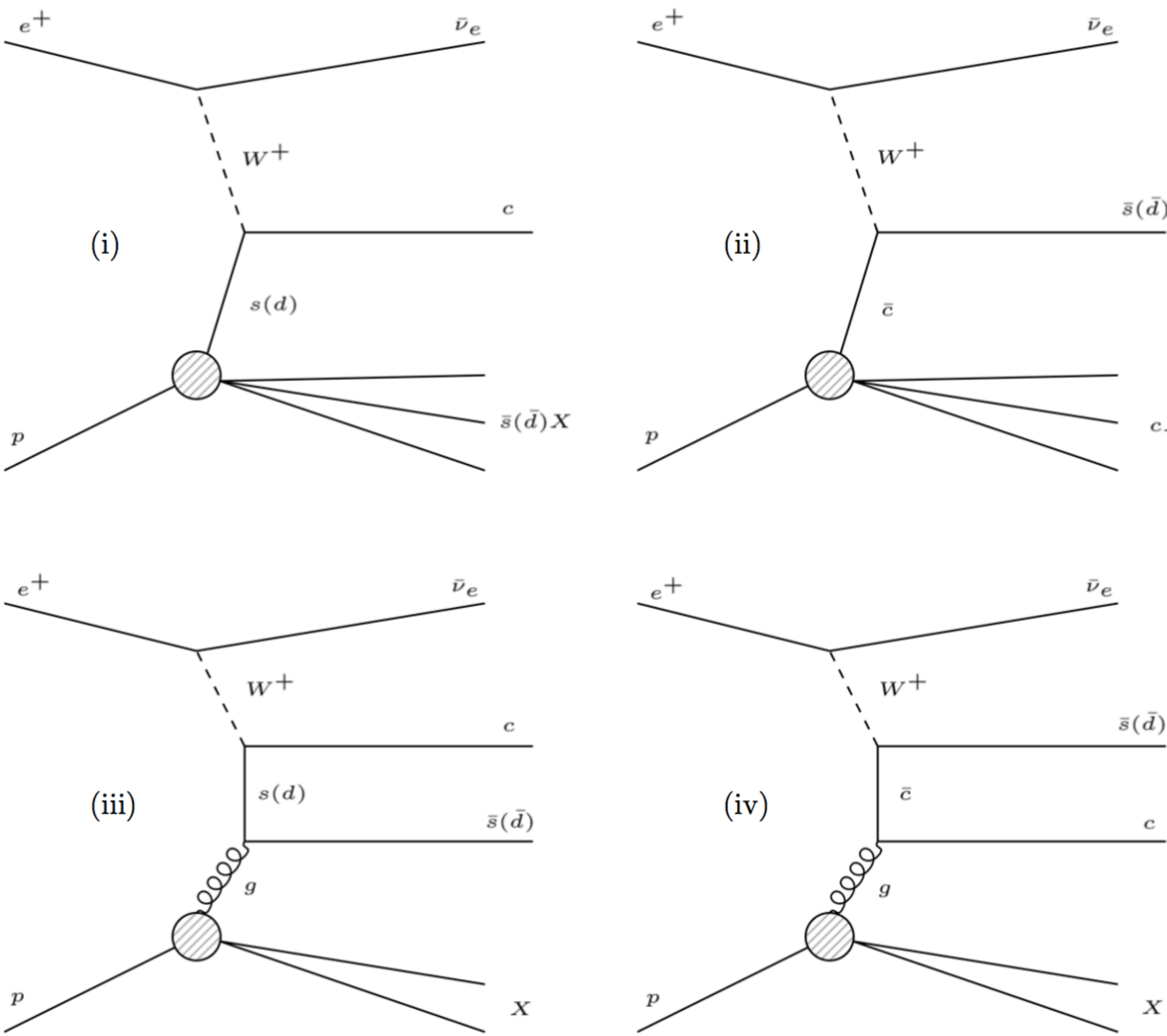
$$Q^2_{JB} = \frac{p^2_{T,h}}{1 - y_{JB}}$$

$$x_{JB} = \frac{Q^2_{JB}}{s y_{JB}}$$



- Limited resolution in **high-*y*** & **low-Q^2**

Charm production in CCDIS



- Contributions from different subprocesses.
  - Process (i) sensitive to strangeness.
  1. $s \rightarrow c$: (i) and (iii)
  2. $d \rightarrow c$: (i) and (iii) via d
  3. $c \rightarrow s(d)$: (ii) and (iv)
- BGF contributions in low-x and high-η.
- $s \rightarrow c$ process was not isolated at ZEUS.

  $\rightarrow$ model-dependent

  - ZM-VFNS: relative variation in $\sigma^{c,CC}$ with different $s(x, Q^2)$
  - FFN & GM-VFNS: comparison to data.

Strategy

- Charm cross section was estimated with a range of $s(x, Q^2)$ based on different assumptions on the proton strangeness.

- A projection on charm yield $N^{c,CC}$ in EIC can be made with information on
  - Beam energies
  - Vertex detection resolution

$$N^{c,CC}_{EIC} = \underbrace{\frac{\sigma^{c,CC}_{EIC}}{\sigma^{c,CC}_{ZEUS}}}_{\underbrace{\frac{\sigma^{CC}_{EIC}}{\sigma^{CC}_{ZEUS}}}_{\text{CCDIS } \sigma \text{ ratio}} * \underbrace{\frac{r^{c}_{EIC}}{r^{c}_{ZEUS}}}_{\text{Charmed event ratio}}} * \underbrace{\frac{\epsilon_{EIC}}{\epsilon_{ZEUS}}}_{\text{Charm-tagging efficiency}} * N^{c,CC}_{ZEUS}$$

*another useful quantity: $\frac{r^{s\to c}_{EIC}}{r^{s\to c}_{ZEUS}} = s \to c$ charm ratios

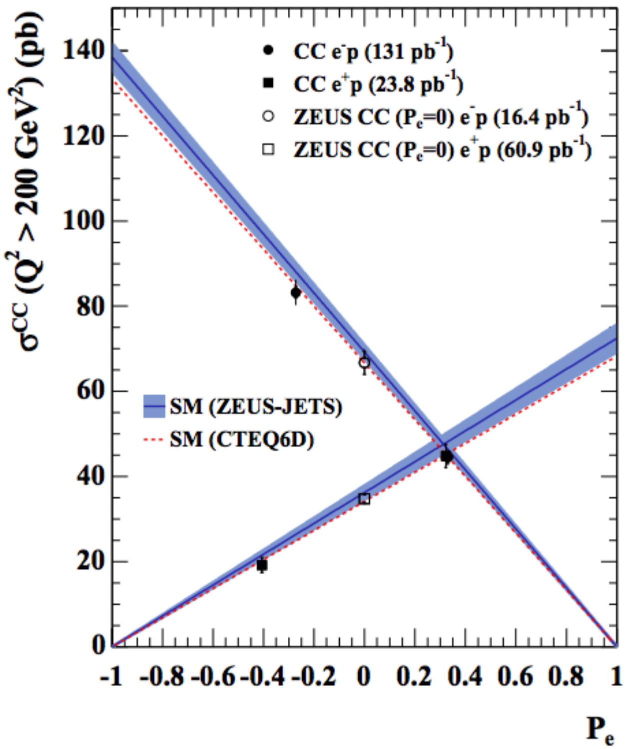
Pseudo data

- Summary
  - 4 pseudo data samples have been generated with DJANGOH 4.6.10 and Pythia 8.2.
  - Main process: $2 \rightarrow 2$ via W.
  - $2 \times$ HERA and $2 \times$ EIC samples with different Q^2, y ranges
  - Unpolarized (subject to change)

E_e/E_p (GeV)	$\sqrt{s}$ (GeV)	$Q^2_{min}(GeV^2)$	y_{max}	
27.5 / 920	318	200	1.0	HERA CCDIS measurement
27.5 / 920	318	200	0.9	HERA Charm in CCDIS
18 / 275	141	200	0.9	Direct comparison to HERA
18 / 275	141	0	0.9	Extended Q^2 range

  - These samples have not been smeared nor G4-simulated.

CCDIS



- CCDIS cross section

$$\sigma^{CC}(P_e = +0.30 \pm 0.01) = 47.1 \pm 1.1(\text{stat.}) \pm 2.2(\text{syst.})\ \text{pb},$$

$$\sigma^{CC}(P_e = -0.27 \pm 0.01) = 83.1 \pm 1.2(\text{stat.}) \pm 3.3(\text{syst.})\ \text{pb}.$$

- Unpolarized cross section expected to be:

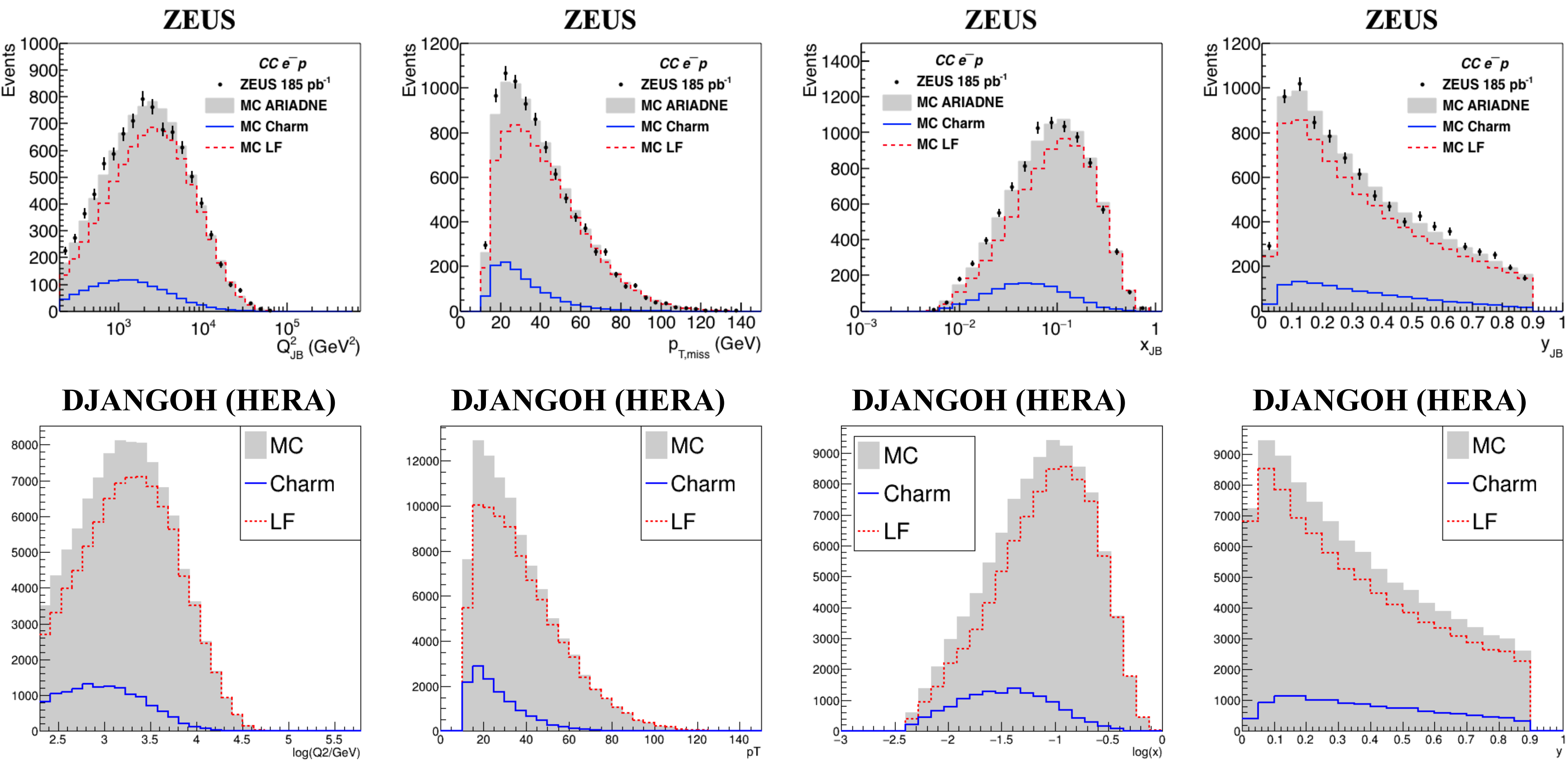
$$\boxed{\sigma^{CC}(P_e = 0) \sim 66 \pm 4\, pb}$$

- DJANGOH & Pythia w/ HERA kinematics

$$\boxed{\begin{array}{c}\sigma^{CC}_{DJANGOH} = 57.6\, pb \\ \sigma^{CC}_{Pythia} = 63.6\, pb\end{array}}$$

$E_e/E_p\ (GeV)$	$\sqrt{s}\ (GeV)$	$Q^2_{min}(GeV^2)$	y_{max}	$\sigma^{CC}_{DJANGOH}$ / σ^{CC}_{Pythia} (pb)	$\sigma^{CC}/\sigma^{CC}_{nominal}$ (DJ/Py)
27.5 / 920	318	200	1.0	57 / 64	
27.5 / 920	318	200	0.9	54 / 61	**1.00 / 1.00**
18 / 275	141	200	0.9	17 / 19	**0.31 / 0.31**
18 / 275	141	0	0.9	24 / 25	**0.44 / 0.39**

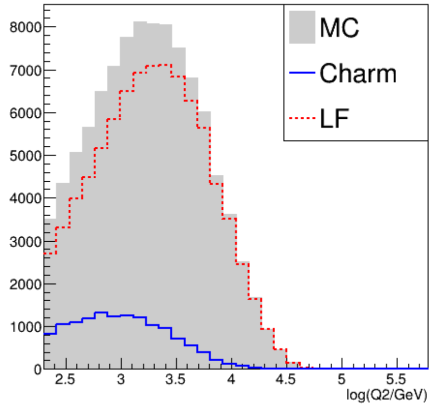
Event level quantities



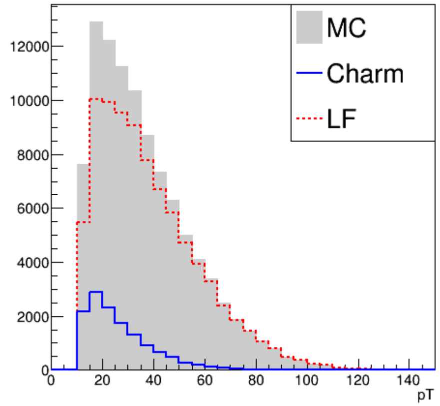
- A good description of ZEUS by both DJANGOH & Pythia at the DIS level.
- Discrepancy in $p_{T,miss} \sim 20\ GeV$, overall y.
    - Possibly due to missing DIS selection cuts.

Event level quantities (EIC)

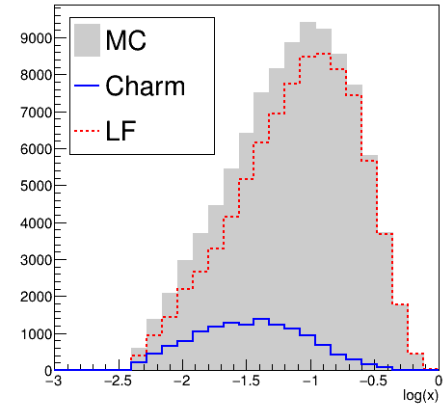
DJANGOH (HERA)



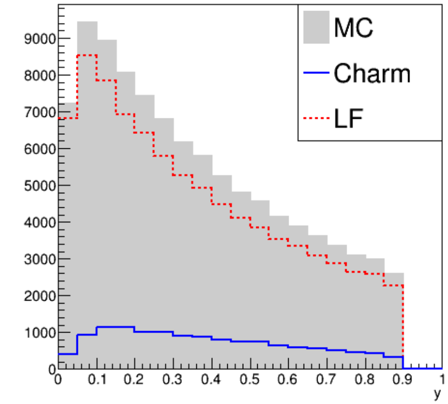
DJANGOH (HERA)



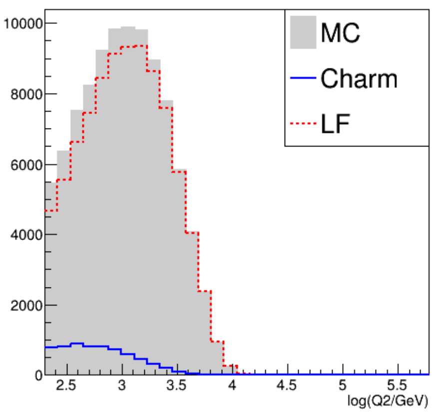
DJANGOH (HERA)



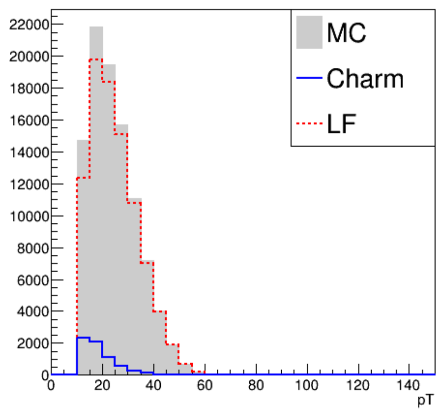
DJANGOH (HERA)



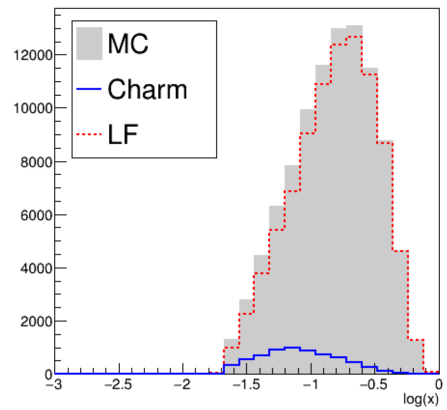
DJANGOH (EIC)



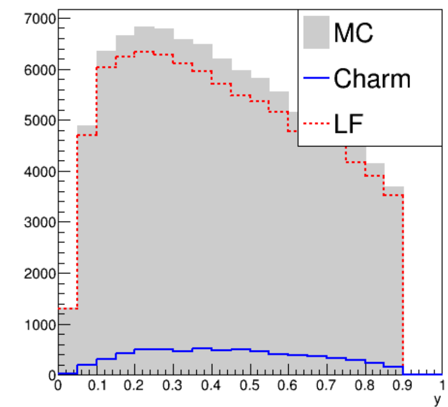
DJANGOH (EIC)



DJANGOH (EIC)



DJANGOH (EIC)



- Change in kinematic sensitivity
  - $< x > \sim 0.1 \rightarrow 0.2,\; x_{min} \sim 0.005 \rightarrow 0.05$
  - W/Z measurement by ATLAS evolves to $x \approx 0.02$
  - ν-scattering experiment at CCFR integrates x around $x \approx 0.1$

Charmed event ratio

- **HERA ($Q^2 > 200\ GeV$)**

25% in the e^+p periods and 12% in the e^-p periods

e^-p	Contribution (%)					
	$200 < Q^2 < 1500\,\text{GeV}^2$			$1500 < Q^2 < 60000\,\text{GeV}^2$		
	$\bar{d} \to \bar{c}$	$\bar{s} \to \bar{c}$	$c \to s(d)$	$\bar{d} \to \bar{c}$	$\bar{s} \to \bar{c}$	$c \to s(d)$
ARIADNE MC	3	37	60	2	29	69
FFN NLO ABMP16.3	4	51	45	5	49	46
FONLL-B NNPDF3.1	4	43	53	4	33	63

- Charmed event ratio r_c~12% is expected from HERA and this is achieved by both event generators.
- The $s \to c$ process ratio, however, differs by a factor of ~2 between DJANGOH and Pythia.

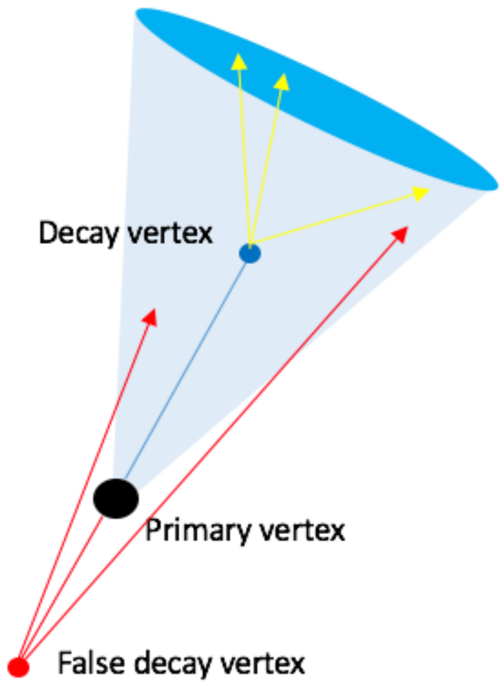
- **DJANGOH & Pythia**

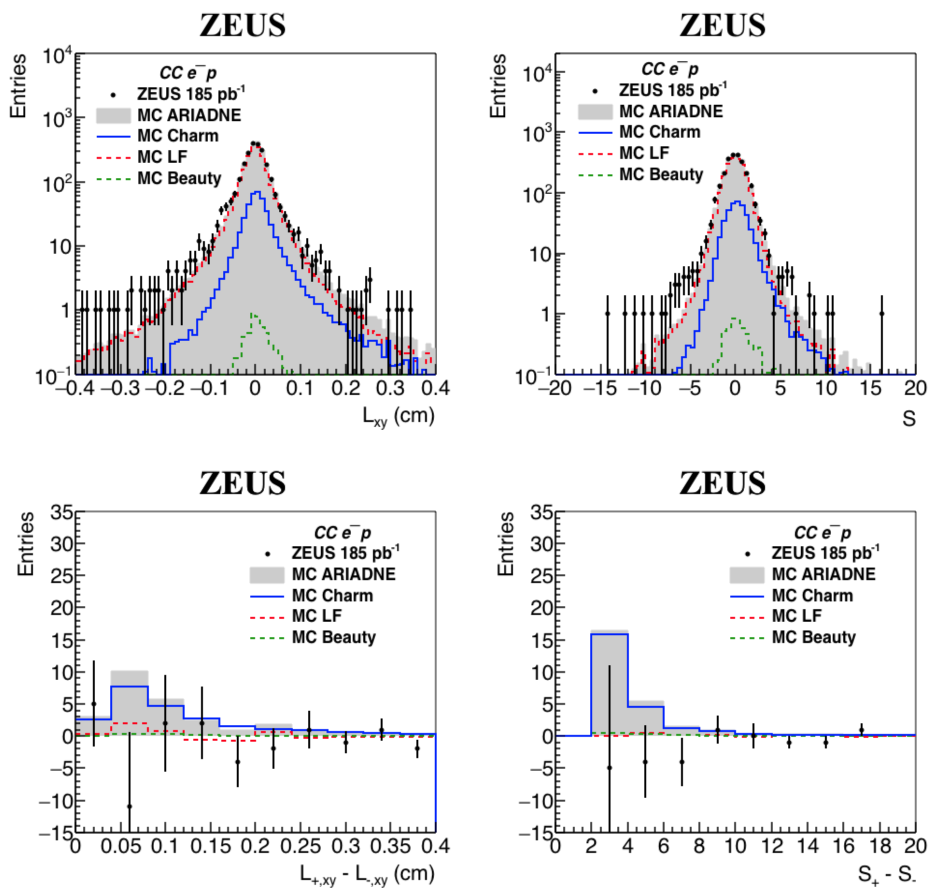
HERA ($Q^2 > 200\ GeV^2$)	r_c	$d \to c$	$s \to c$	$c \to s(d)$
DJANGOH	13.7	2.8	50.4	46.8
Pythia	10.7	3.6	26.7	69.6

EIC ($Q^2 > 200\ GeV^2$)	r_c	$d \to c$	$s \to c$	$c \to s(d)$
DJANGOH	7.2	2.6	51.0	46.4
Pythia	5.2	2.8	26.4	70.8

- Nonetheless, the $s \to c$ ratio is constant going from HERA to EIC, and r_c goes down by half.

Charm tagging

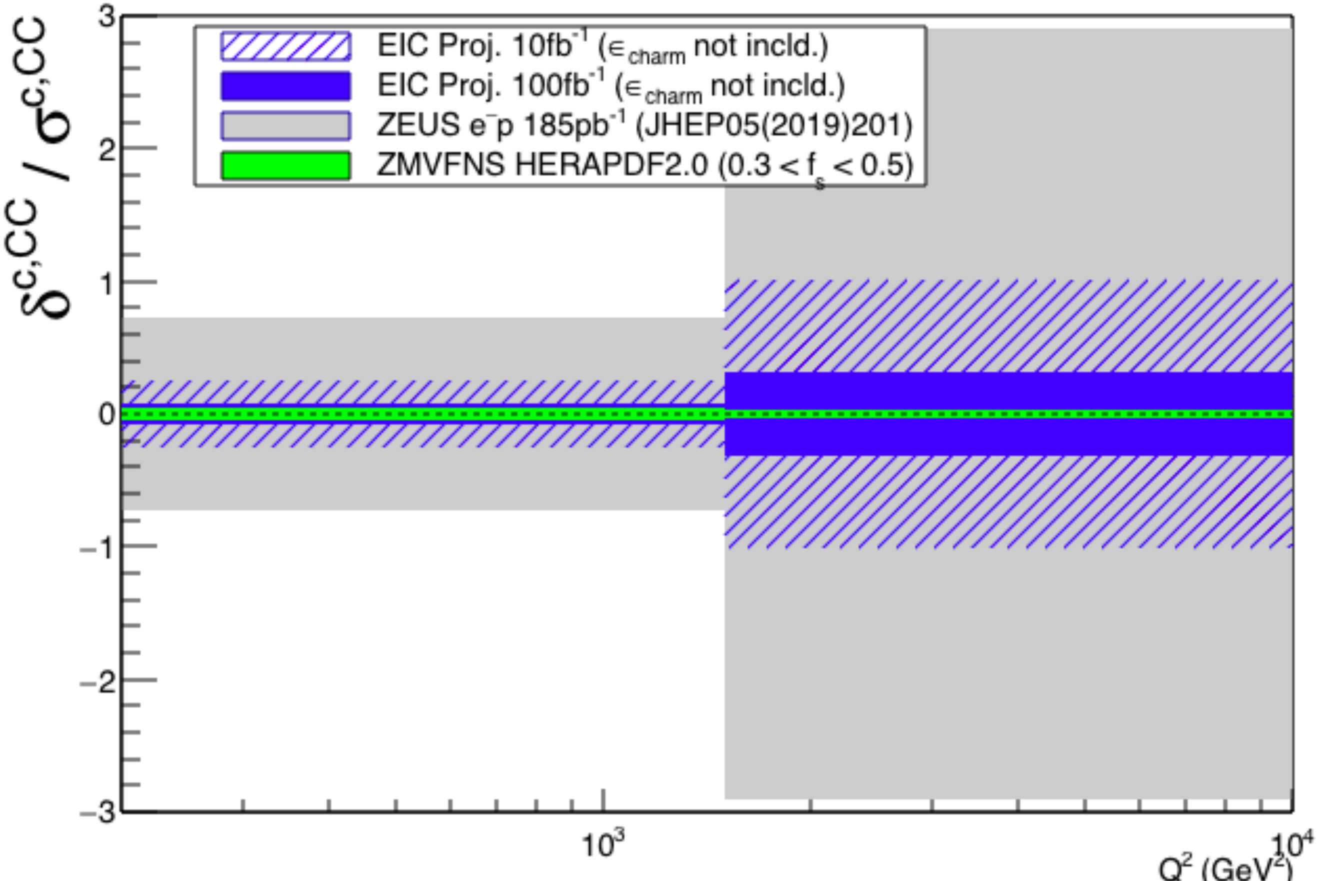




Lifetime-tagging Method

- 2D decay length (L_{xy}) projected onto Jet axis.
  - LF → Prompt, Symmetric decay length distribution due to finite vertex detection resolution
  - Charm → Weakly-decaying, Asymmetric distribution.
- LF contribution (background) suppressed by mirroring decay length distribution about $L_{xy} = 0$.
- Tagging efficiency ~ 2%

Projection



- Projection for EIC
  - Charm tagging efficiency ratio not included.
  - The relative variation in $\sigma^{c,CC}$ assumed to be identical.
  - Optimal binning for EIC needs to be studied.

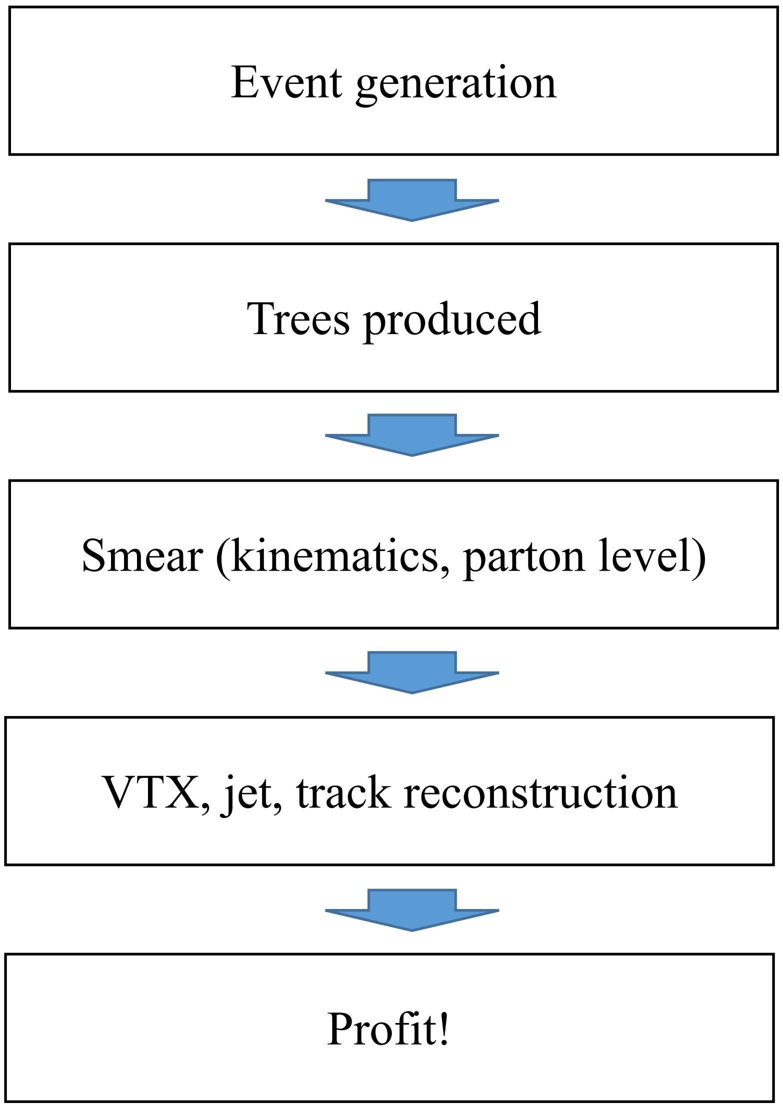
Summary

- Charm in CCDIS cross section, thus δ_{stat}, for EIC can be extrapolated from ZEUS measurement by understanding:
  1. CCDIS cross section at EIC kinematics
  2. Charmed event fraction in CCDIS
  3. Tagging efficiency
  4. (Luminosity)
  - Criteria 1, 2 and 4 suggest the tagging efficiency at EIC needs to be up to 1~10 times better than ZEUS to be decisive on the subject.

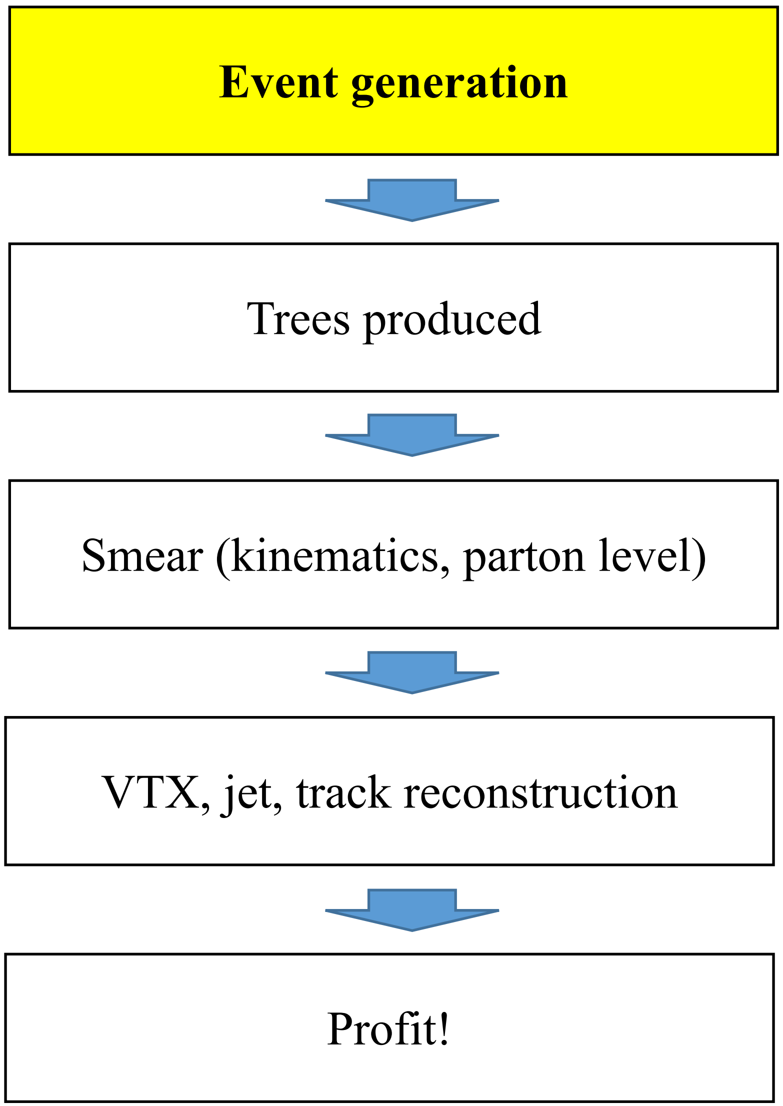
- Remaining tasks
  - Jet & 2nd vertex reconstruction.
  - Choosing optimal kinematic bins.

- Suggestions
  - A general purpose pseudo-data for high-Q^2 CCDIS
  - Consensus on G4 simulation package (Fun4All / G4E)
  - Theory input for EIC kinematic range will be most welcome.
    - For EIC η_{jet} range (Up to $\eta_{jet} < 4?$).
    - High Q^2 ($> 200\ GeV^2?$) & y ($< 0.9?$, optional)

Flow chart


Event generation
Trees produced
Smear (kinematics, parton level)
VTX, jet, track reconstruction
Profit!

Flow chart



- Event generation
  - DJANGOH 4.6.10
    - Interfaced in /afs/…/eic/
  - Beam energies (HERA)
    - $E_e = 27.5GeV, E_p = 920GeV$
    - $\sqrt{s} = 318\ GeV$
  - Beam energies (EIC)
    - $E_e = 18GeV, E_p = 275GeV$
    - $\sqrt{s} = 141\ GeV$
  - Sample info
    - 100,000 events each

$\sqrt{s}\ (GeV)$	$Q^2_{min}(GeV^2)$	y_{max}
318 (HERA)	200	0.9
318 (HERA)	200	1.0
141 (EIC)	200	0.9
141 (EIC)	0	0.9

Flow chart

Event generation

↓

Trees produced

↓

Smear (kinematics, parton level)

↓

VTX, jet, track reconstruction

↓

Profit!

- Tree production and smearing at the parton level & thus kinematics is done by **EIC-smear**.
  - interfaced in: /afs/…/eic/
- A selection of detector configuration available. (may not be up to date)
  - BeAST, ePHENIX, eSTAR…
- At the end, tree contains:
  - Event kinematics
  - Particle info

Flow chart

- Event generation
- ↓
- Trees produced
- ↓
- Smear (kinematics, parton level)
- ↓
- **G4, vtx/jet/track reconstruction**
- ↓
- Profit!

- **Fun4All** comes with Geant4 based simulation.
  - Interfaced in: /afs/…/eic/
  - ePHENIX detector configuration available.
  - Seems highly capable.
    - StRoot-like environment
    - Does Jet reconstruction using anti-k_T algorithm. (k_T, ZEUS)
    - 2nd-vertex reconstruction.
    - Vertices reconstructed with a defined(?) resolution.
    - True (generated) & reconstructed quantities available.
    - Detector response studies (Not utilized here).