Charm Production in CC DIS at HERA

(DESY-19-054, arXiv:1904.03261)

Jae D. Nam

Temple Univ. & ZEUS

DIS 2019 TORINO

8-12 April

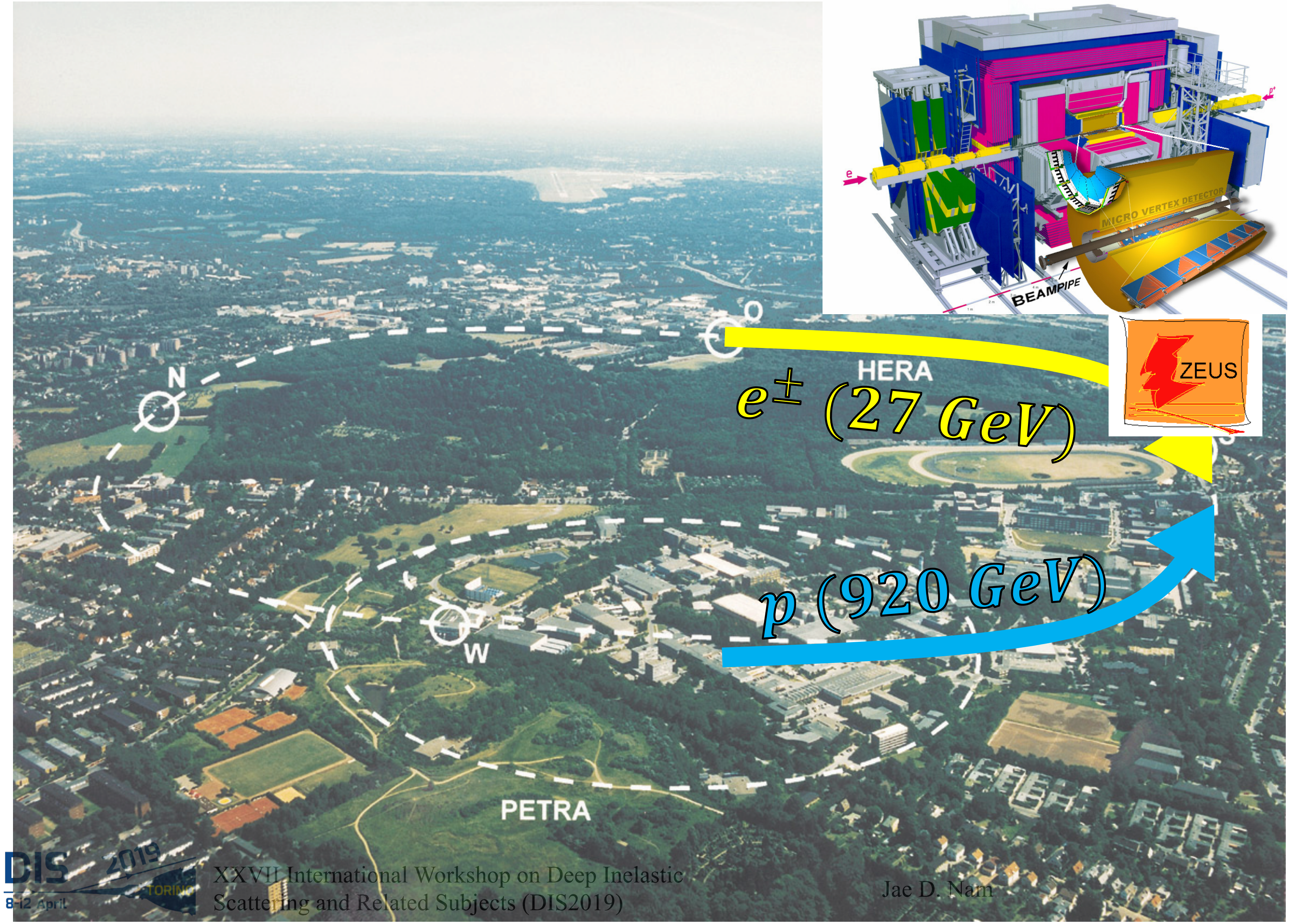
ZEUS

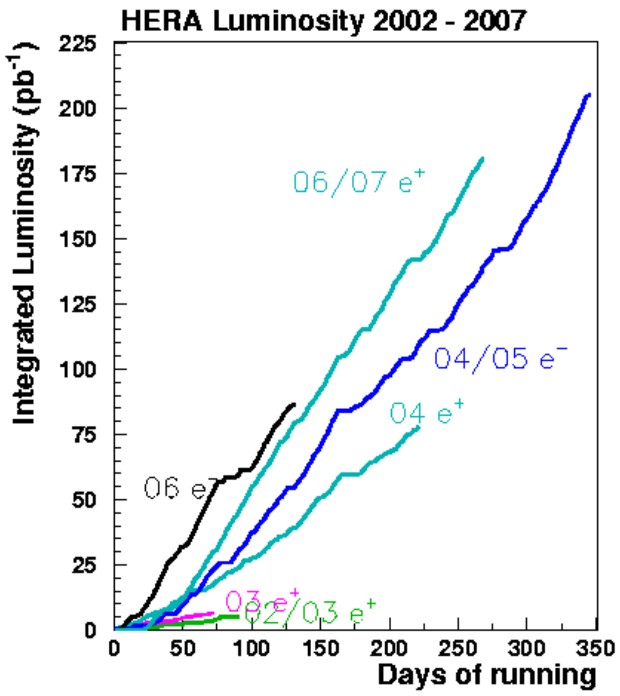
TEMPLE UNIVERSITY

U.S. DEPARTMENT OF ENERGY

DOE NP contract: DE-SC0013405

Hadron-Electron Ring Accelerater

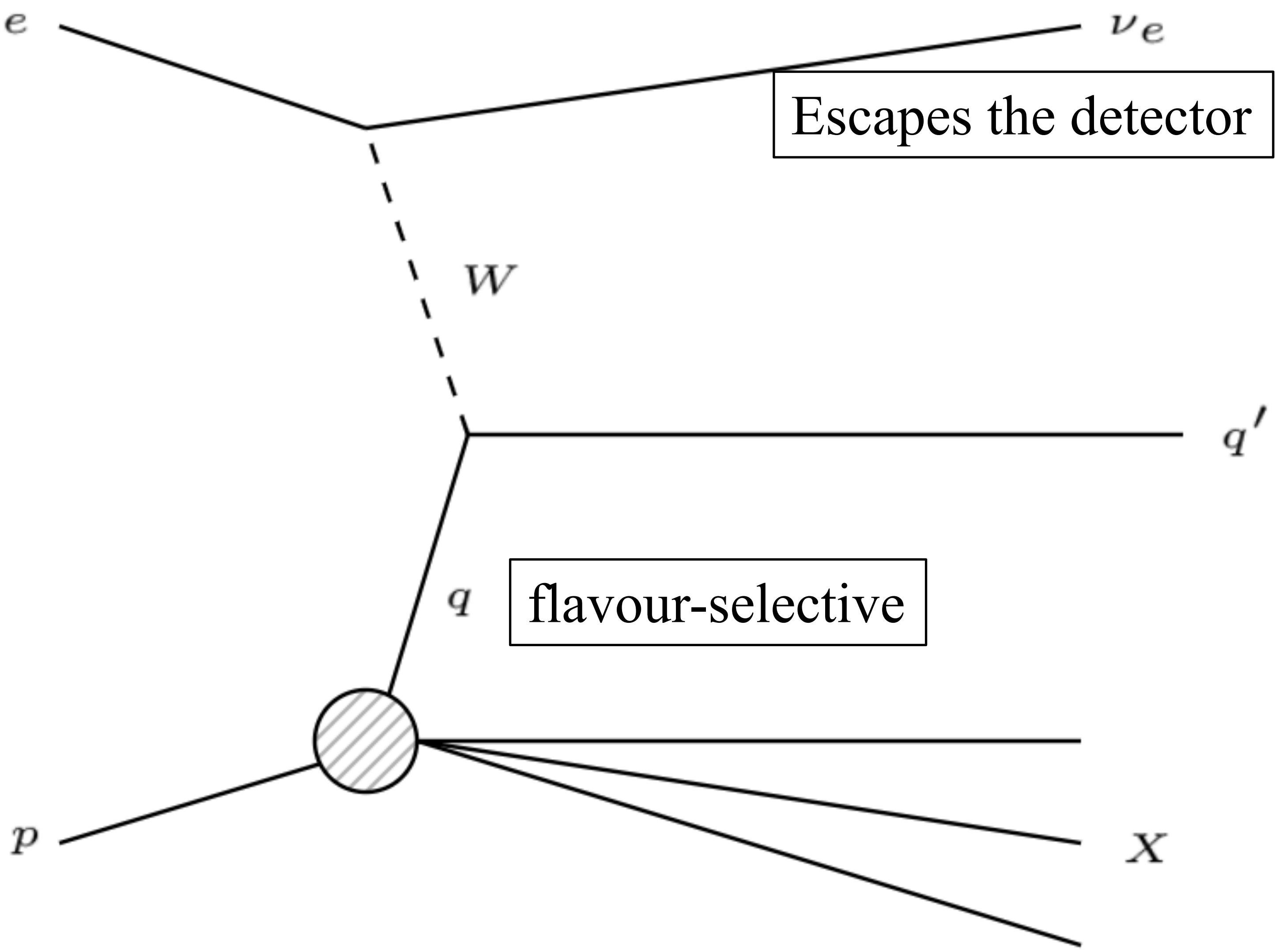




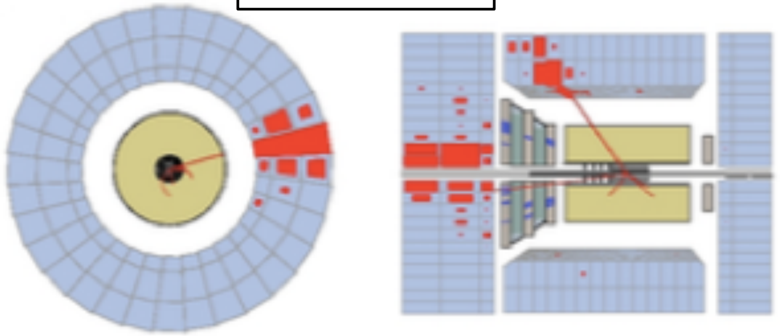
HERA upgrade

- Luminosity upgrade.
  - HERA I : 120 pb^{-1}
  - HERA II : 360 pb^{-1}
- Higher particle tagging capabilities through MVD & STT.

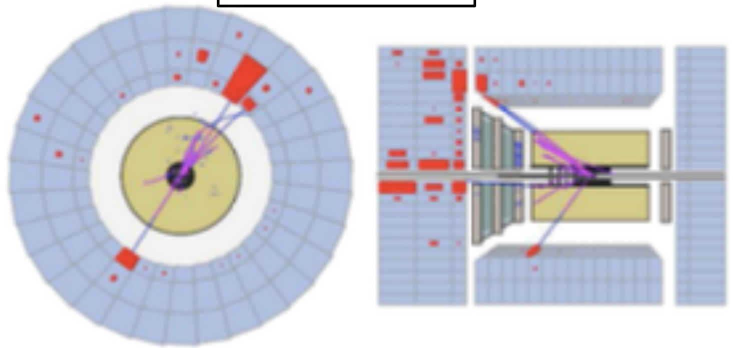
Charged Current (CC) DIS at HERA



CC DIS



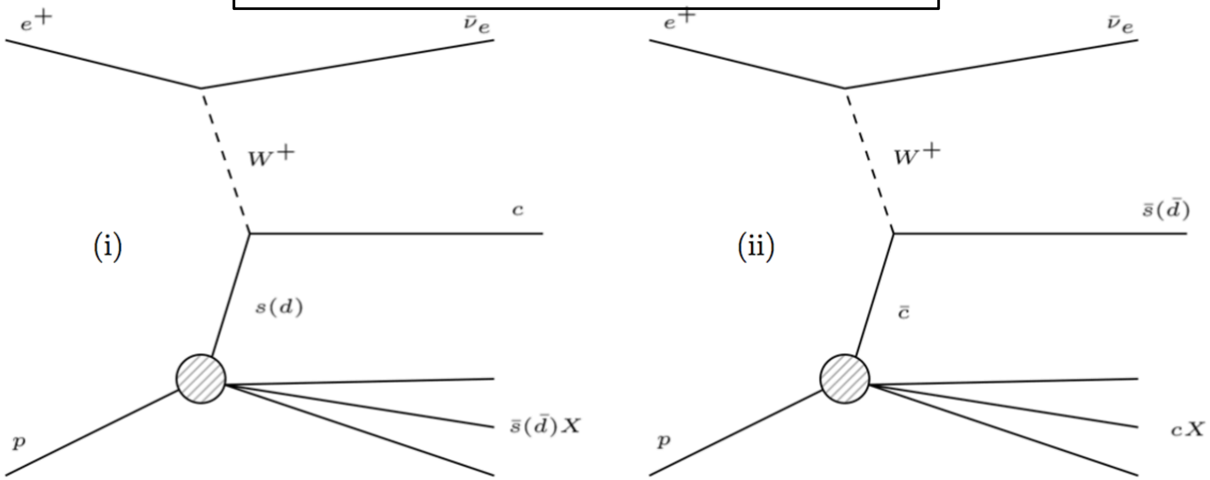
NC DIS



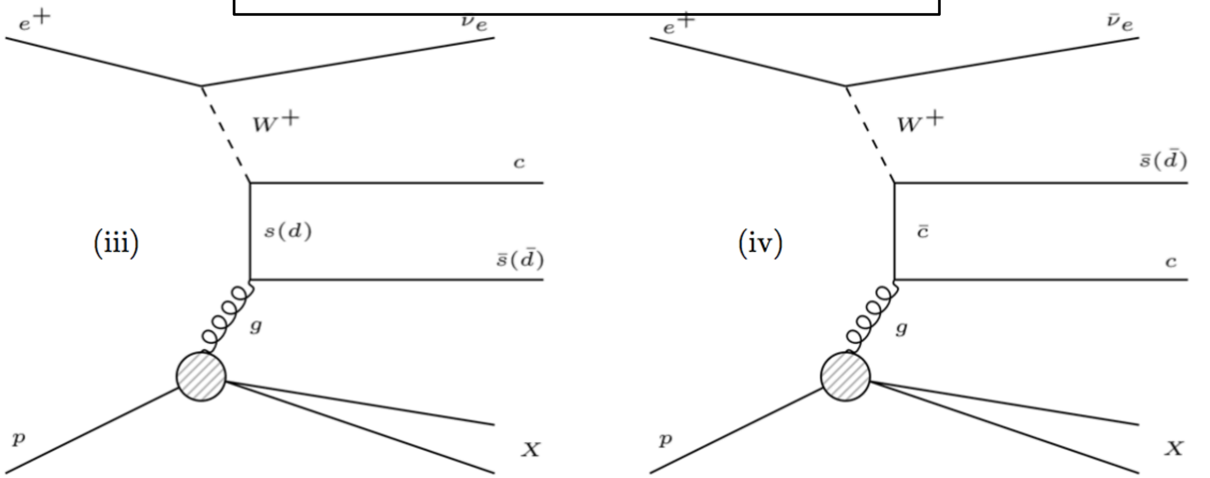
- Large missing p_T due to neutrino.
- Powerful probe of flavour-specific PDFs.
- Low production rate.

Charm production in CCDIS

QPM-like



BGF-like



- Charm production processes in e^+p CCDIS

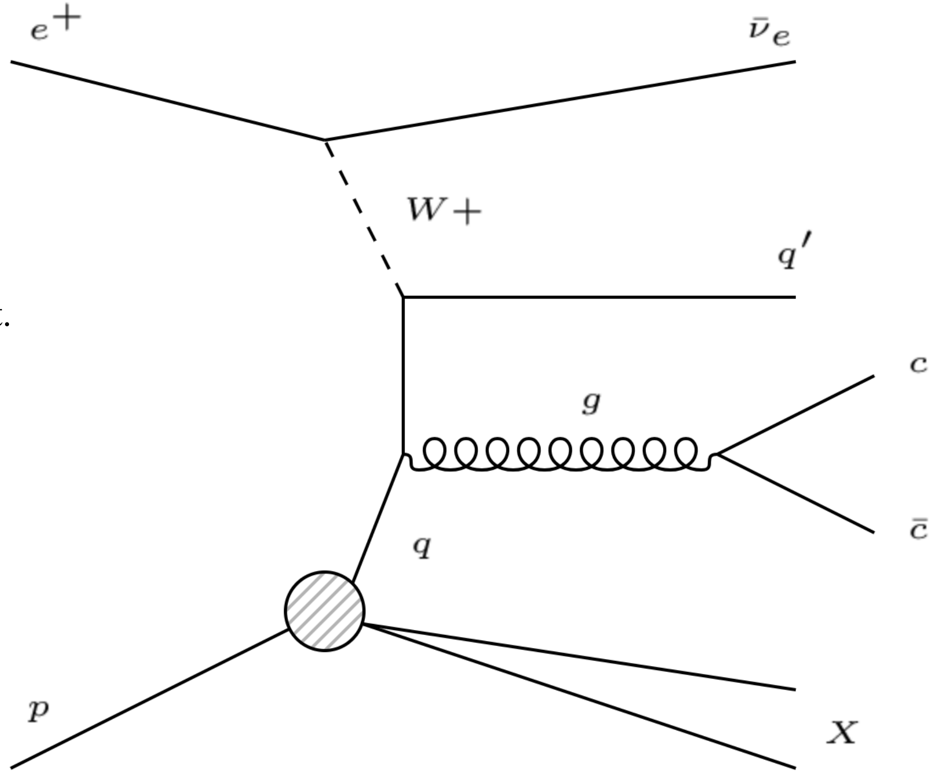
QPM-like
  - *i.* $s\bar{s}(d\bar{d})W^+ \rightarrow c\bar{s}(\bar{d})$
  - *ii.* $c\bar{c}W^+ \rightarrow c\bar{s}(\bar{d})$

BGF-like
  - *iii.* $g \rightarrow s\bar{s}(d\bar{d})$
  - *iv.* $g \rightarrow c\bar{c}$

- Subprocess (i) is directly sensitive to the strangeness of the proton.
- However, the distinction of these processes depends on the choice of QCD scheme.
  → Extraction of $s(x, Q^2)$ is model dependent.

Motivations

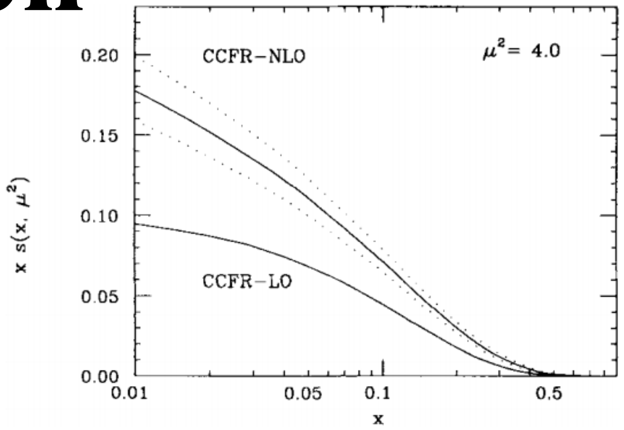
- Charm in CCDIS with high-Q^2 HERA $e^{\pm}p$ collision data collected at ZEUS.
  - Probe strangeness in the proton by measuring EW part of inclusive charm cross section in CCDIS.
  - Charm quark from final-state QCD radiation is indistinguishable due to lack of charm charge measurement & low statistics.

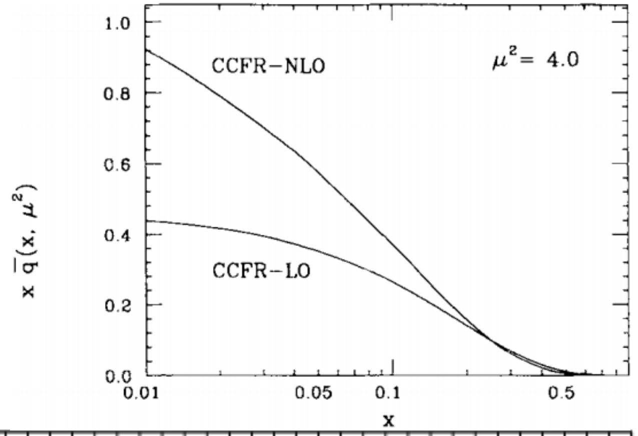


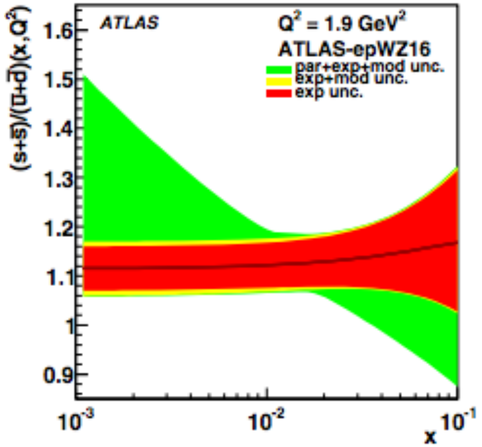
- Theory predictions
  - Zero-mass variable-flavour-number scheme (ZM-VFNS)
    - QCDNUM, HERAPDF2.0 & ATLAS $epWZ16$ PDF sets.
    - Used for relative comparison of different assumptions on the strange content.
  - Fixed-flavour number scheme (FFN)
    - No charm quark content in the proton & larger gluon content.
    - OPENQCDRAD, ABMP16.3 NLO PDF sets.
  - General-mass VFN scheme (GM-VFNS)
    - FONLL-B scheme.
    - APFEL, NNPDF3.1 sets.

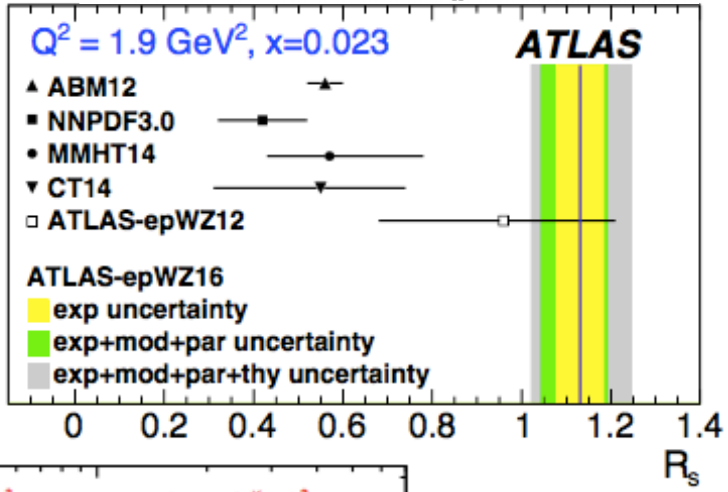
Strangeness in the proton

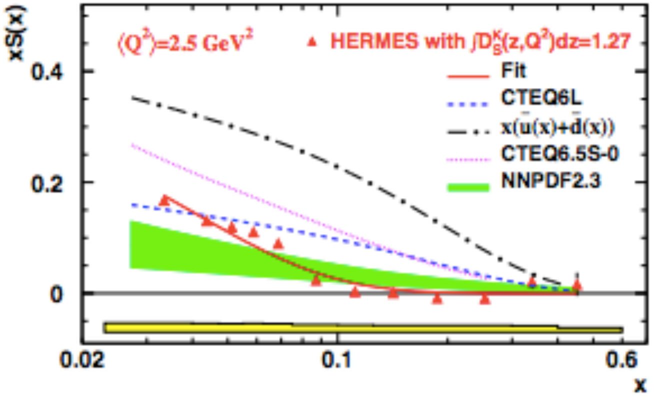
- Mass-suppressed strangeness : $f_s \left(\equiv \frac{s}{s+\bar{d}}\right) \sim 0.3$
  - For large x_{Bj}, experimentally supported by neutrino-scattering experiments (CCFR/NuTeV, NOMAD, CHORUS).
- Unsuppressed strangeness : $f_s \sim 0.5$
  - For small x_{Bj}, experimentally supported by high-precision W/Z production measurement (ATLAS) & $W + c$ data (CMS).
- x-dependent strangeness
  - As suggested by HERMES
  - $x\bar{s} = f_s' \, 0.5 \tanh\left(-20\,(x - 0.07)\right) x\bar{D}$











DATA & MC

Data

- HERA II ($L \cong 360\, pb^{-1}$)
  - $e^{-}p : L \cong 185\, pb^{-1}$
  - $e^{+}p : L \cong 173\, pb^{-1}$

Year	Collision	Integrated Luminosity (pb^{-1})
2003/04	$e^{+}p$	~ 38
2004/05	$e^{-}p$	~ 133
2006	$e^{-}p$	~ 52
2006/07	$e^{+}p$	~ 135

- Kinematic variables (x, y, Q^2) defined by using Jacquet-Blondel Method.

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

MC

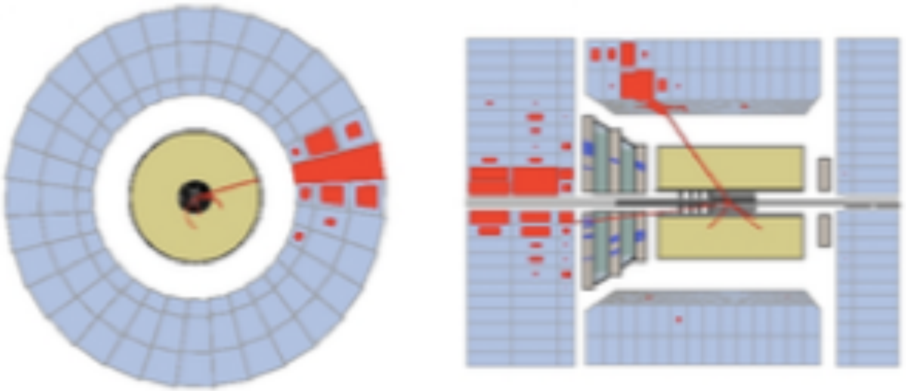
- DIS
  - Inclusive CCDIS MC, DJANGOH 1.6, ARIADNE 4.12, CTEQ-5D.
- Background
  - Inclusive NCDIS MC: DJANGOH 1.6, ARIADNE 4.12, CTEQ-5D
  - Photoproduction MC: HERWIG, resolved & direct
  - Background contribution was found to be negligible.

- The kinematic variables (x, y, Q^2) obtained from the lepton information.

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

DIS selection

- CCDIS selection based on $p_{T,miss}$
  - $p_{T,miss} > 12\ GeV$
  - $p'_{T,miss} > 10\ GeV$ (excld. cells adjacent to beam pipe)



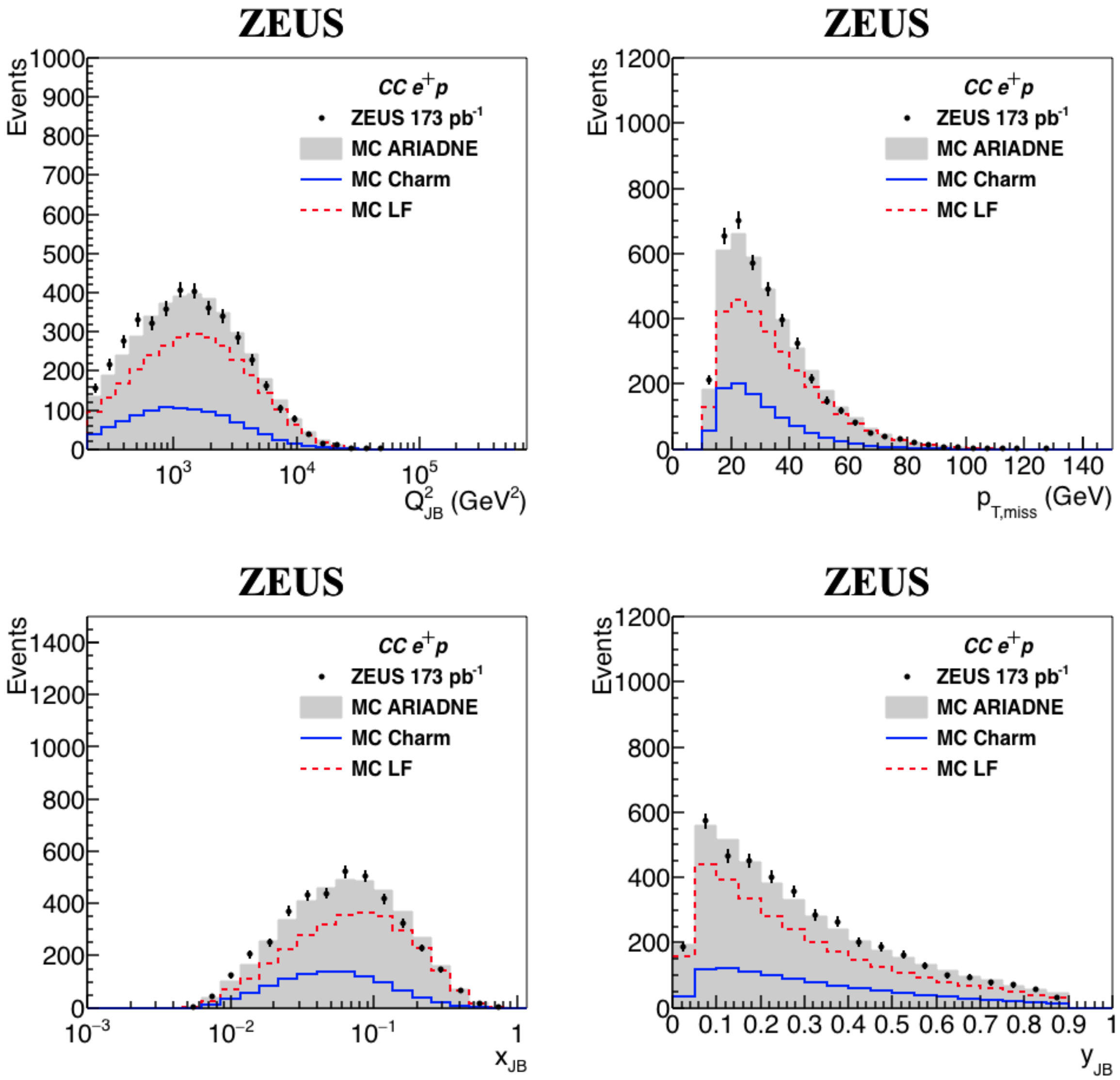
- Non-CC DIS rejection (arXiv:1008.3493)

- Non-*ep* background (beam-gas, beam-halo muon, cosmic) rejection

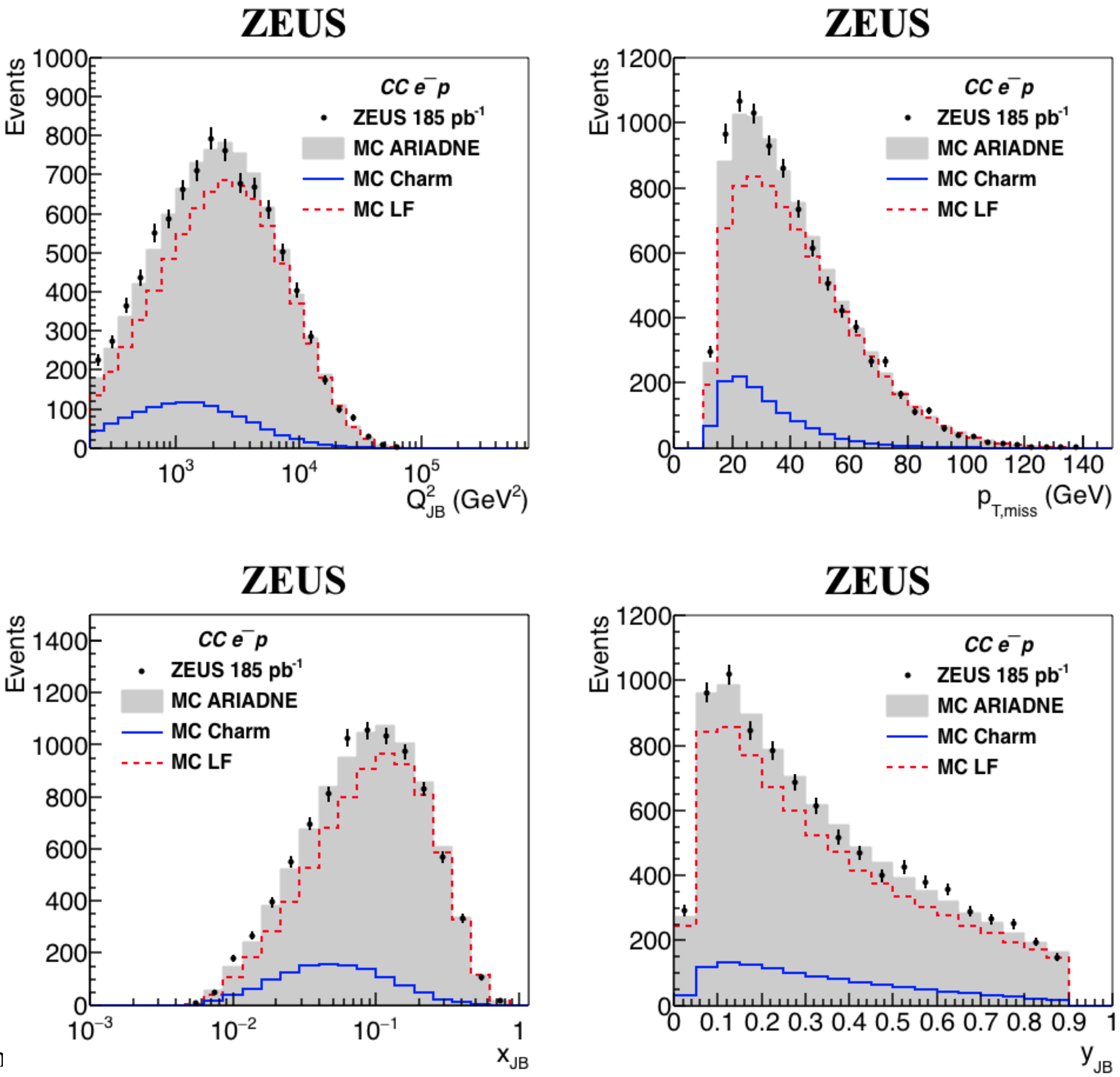
- Kinematic selection cut
  - $200 < Q^2 < 60000\ GeV^2$
  - $y < 0.9$
  - For optimal detector resolution & low background.
  - Full kinematic range of the measurement

DIS control plots

e^+p collisions



e^-p collisions



Charm identification

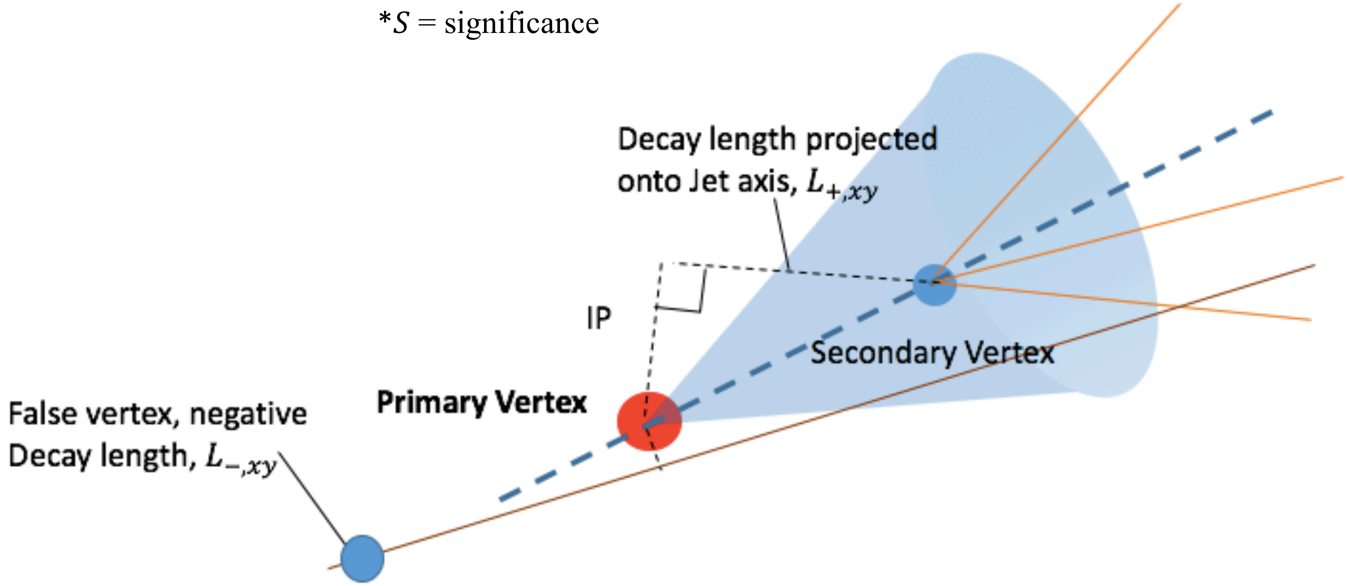
Lifetime-tagging Method

- 2D decay length (L_{xy}) projected onto Jet axis.
  - LF → Prompt, Symmetric decay length dist.
  - Charm → Weakly-decaying, Asymmetric dist.

- LF contribution (background) suppressed by mirroring decay length distribution about $L_{xy} = 0$.

  $(L_+ - L_-, S_+ - S_-)$

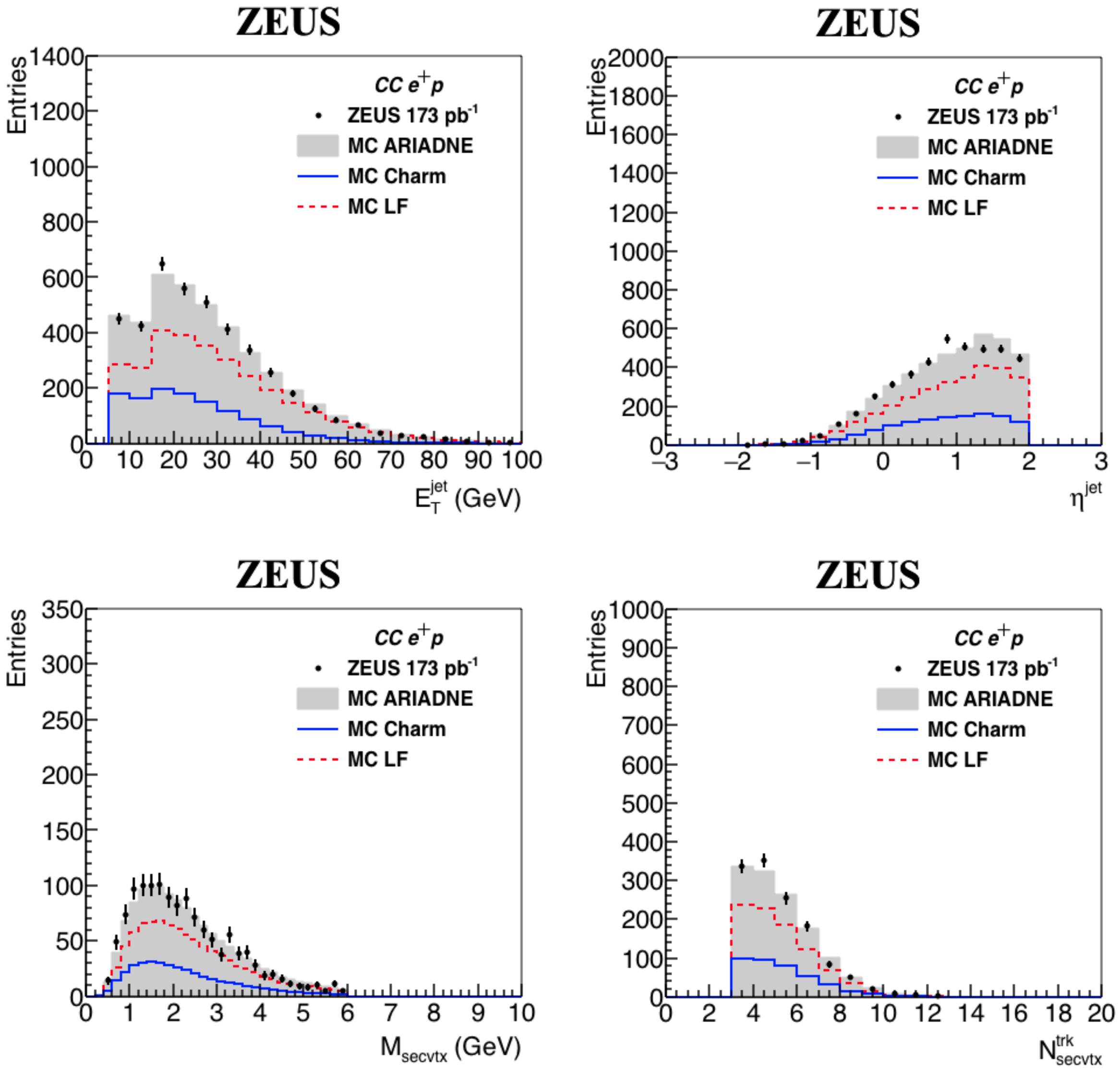
  *S = significance



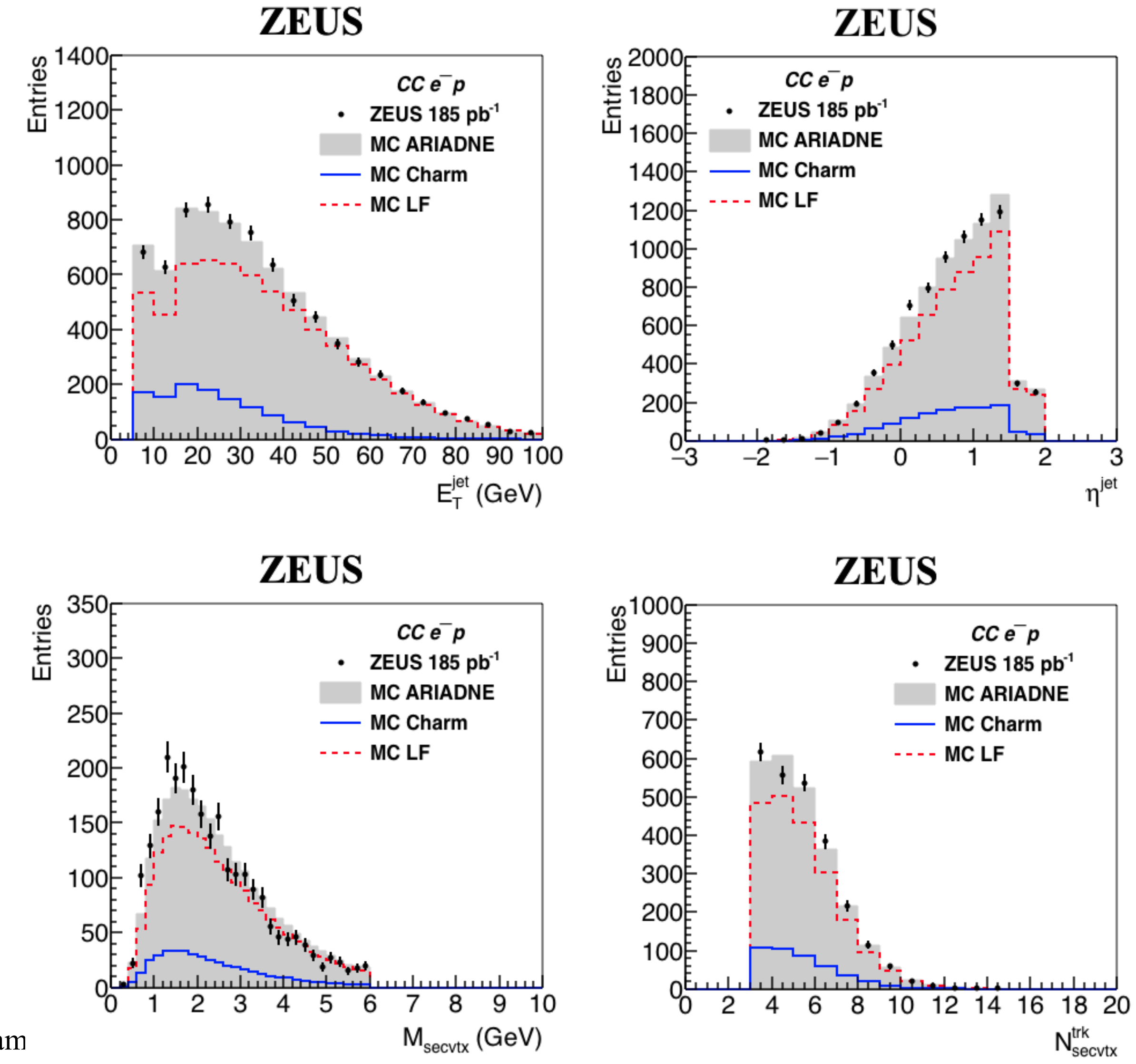
Jet Selection	Reconstructed by using k_T-cluster algorithm in the massive mode.
	$E_T^{jet} > 5\ GeV$
	$-2.5 < \eta^{jet} < 2.0\ (1.5\ for\ 05e)$
	Defines "visible" kinematic region.
SecVtx Selection	$\chi^2/N_{dof} < 6$
	$\lvert Z_{secvtx}\rvert < 30\ cm$
	Distance to beam spot $\sqrt{\Delta x^2 + \Delta y^2} < 1\ cm$
	$M_{secvtx} < 6\ GeV$
	$N_{secvtx}^{trk} > 2$

Jet & Secondary vertex

e^+p collisions



e^-p collisions

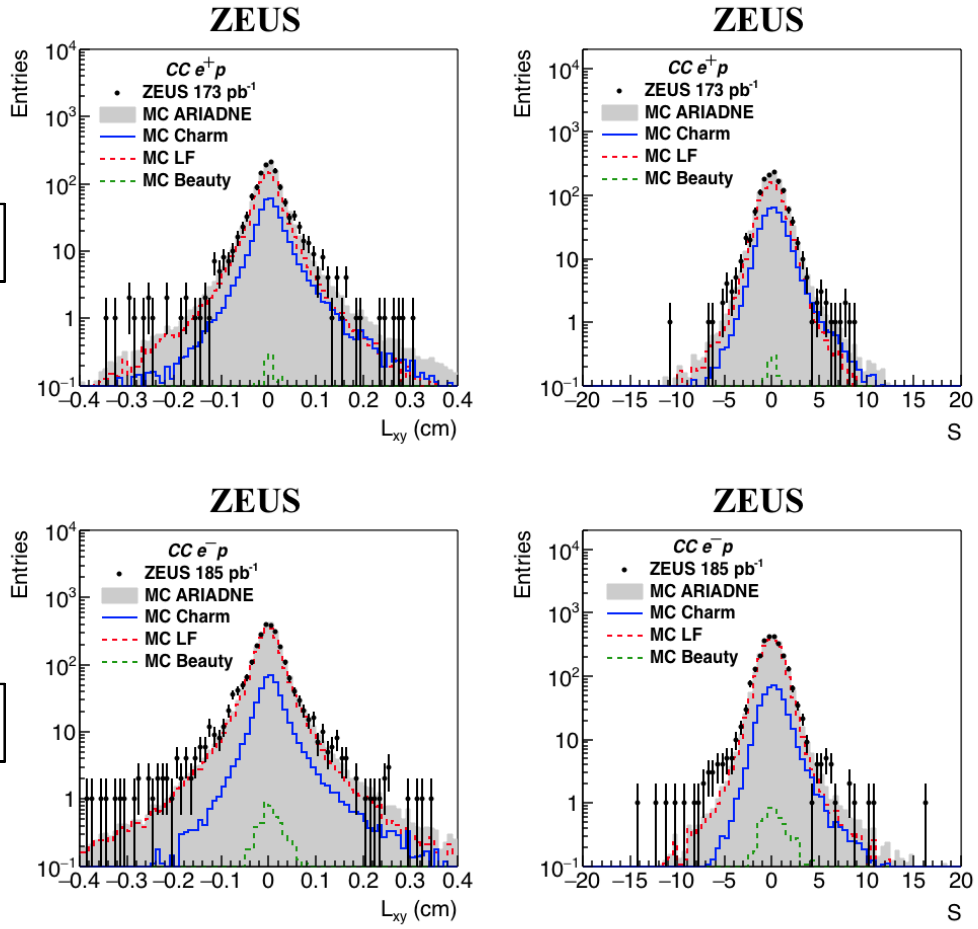


Decay length

- Asymmetric charm distribution observed.
- Significance cut, $S > 2$, to improve statistical uncertainty.

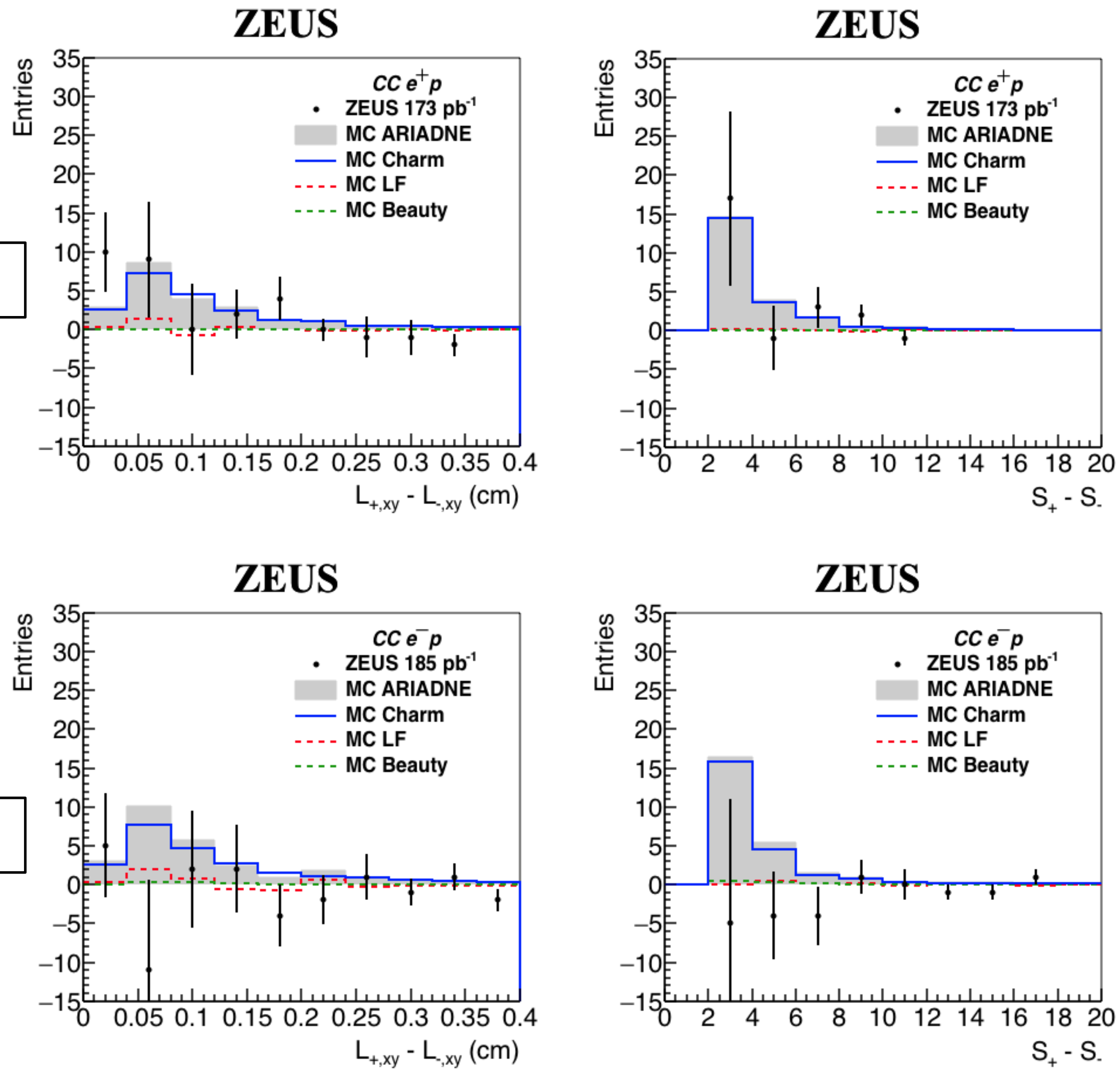
e^+p

e^-p



e^+p

e^-p



Charm cross section

- Visible charm cross section

$$\sigma_{c,vis} = \frac{N^{data} - N^{MC}_{bg}}{N^{MC}_{c}} * \sigma^{MC}_{c} = \frac{N^{data} - N^{MC}_{bg}}{N^{MC}_{c}} * \frac{N_{vis}}{L}$$

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

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

- Visible EW charm cross section is taken from subtracting the QCD part.

$$\sigma_{c^{EW},vis} = \sigma_{c,vis} - \sigma_{c^{QCD},vis}$$

- EW charm cross section is extrapolated via $C_{ext} = N^{EW}_{full}/N^{EW}_{vis}$

$$\sigma_{c^{EW}} = C_{ext}\sigma_{c^{EW},vis}$$

Charm cross section

- Visible charm cross section

$$\sigma_{c,vis} = \frac{N^{data} - N_{bg}^{MC}}{N_c^{MC}} * \sigma_c^{MC}$$
$$= \frac{N^{data} - N_{bg}^{MC}}{N_c^{MC}} * \frac{N_{vis}}{L}$$

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

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

- Visible EW charm cross section is not measured. Instead, the QCD part is taken as a systematic.

- ARIADNE predicts QCD part to be small. But, the QCD calculation here is cannot be considered reliable.

- EW charm cross section is extrapolated via $C_{ext} = N_{full}^{EW}/N_{vis}^{EW}$

$$\sigma_{c^{EW}} = C_{ext}\sigma_{c,vis}$$

Charm cross section

- Visible charm cross section

$$\sigma_{c,vis} = \frac{N^{data} - N^{MC}_{bg}}{N^{MC}_{c}} * \sigma^{MC}_{c} = \frac{N^{data} - N^{MC}_{bg}}{N^{MC}_{c}} * \frac{N_{vis}}{L}$$

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

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

- Visible EW charm cross section is not measured. Instead, the QCD part is taken as a systematic.

- EW charm cross section is extrapolated via $C_{ext} = N^{EW}_{full}/N^{EW}_{vis}$

$$\sigma_{c^{EW}} = C_{ext}\sigma_{c,vis}$$

- Higher contribution from strange-sensitive QPM process in the visible range.

Systematic uncertainties

δ_1 Vertex rescaling

- More secondary vertex in MC. For the nominal result, a rescaling is applied for both N_c and N_{bg}. For systematic, this was only applied on N_{bg}.

δ_2 EW charm fraction

- QCD contribution to MC charm signal is taken as a systematic uncertainty.

δ_3 LF background

- Uncertainty associated with remaining LF background was estimated by varying N_{bg} by $\pm 30\%$.

δ_4 CC DIS selection

- Taken from previous ZEUS analysis. (arXiv:1008.3493)

δ_5 Jet energy scale

- Uncertainty associated with calorimeter is ~3%. Measurement was repeated with E_T cut varied by $\sim 3\%$ in the MC.

δ_6 Luminosity (**Not included**)

- Uncertainty in ZEUS luminosity measurement is ~2%.

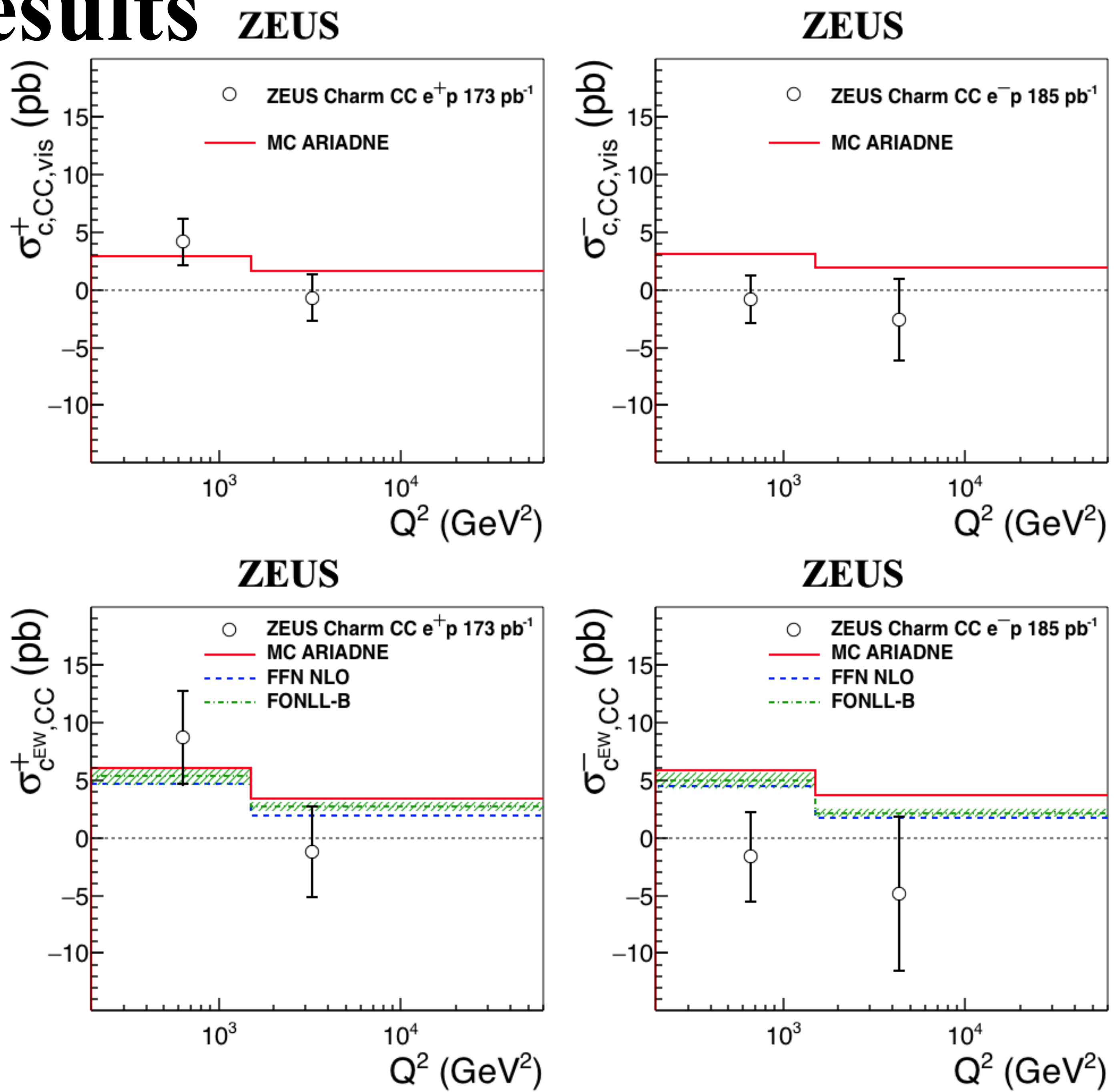
δ_7 Signal extraction method & secvtx selection (**Not included**)

- This could only be tested with the low statistics available at the cross section stage and was not included in the final number. It could be as large as $\pm 6\ pb$.

Sources	$\delta\sigma^{+}_{cEW}\ (pb)$	$\delta\sigma^{-}_{cEW}\ (pb)$
Rescaling	-1.2	$+0.9$
QCD charm fraction	-0.6	-1.1
LF background	± 0.1	± 0.3
DIS selection	± 0.2	± 0.1
Calorimeter	± 0.0	± 0.1
Total	$+0.2$	$+1.0$
	-1.3	-1.2

- In MC, $\sigma_{cEW} \sim 9\ pb$

Results

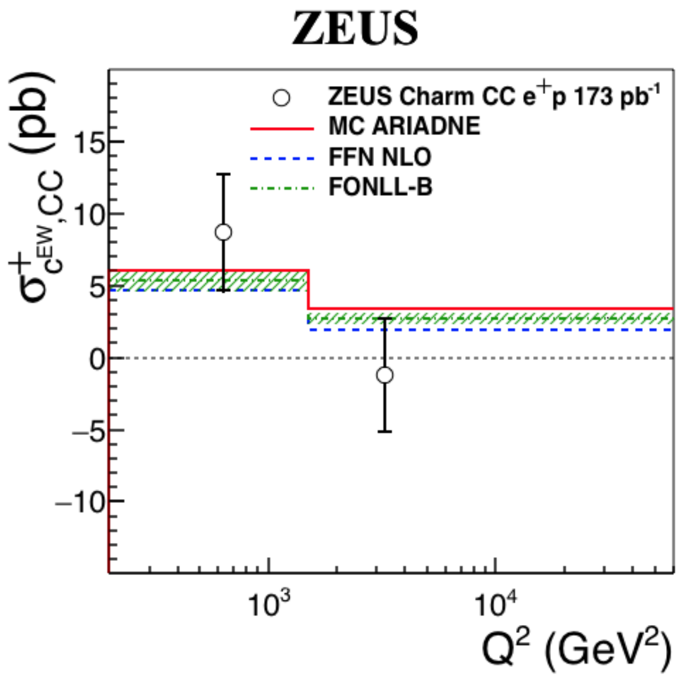


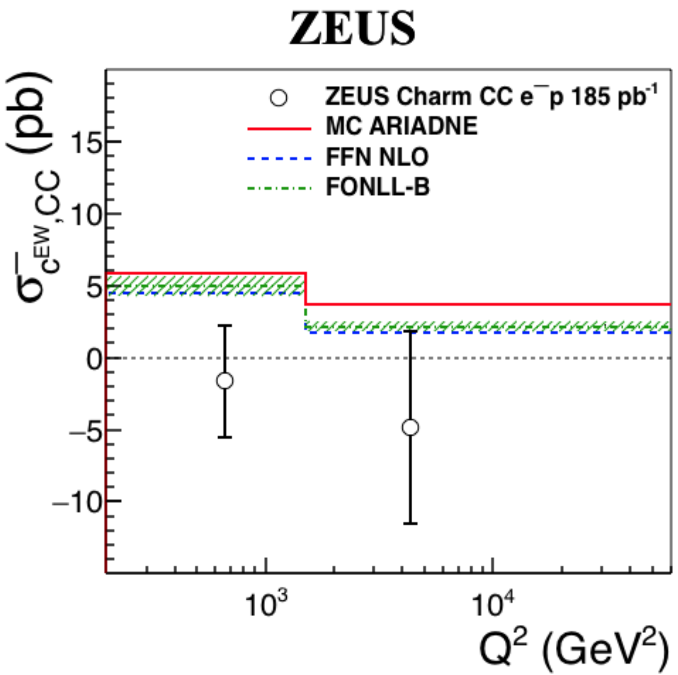
- EW charm production in CCDIS is measured with HERA II data.
  - Consistent with theory predictions, although statistically limited.

Re

e^+p	Contribution (%)					
	$200 < Q^2 < 1500\,\mathrm{GeV}^2$			$1500 < Q^2 < 60000\,\mathrm{GeV}^2$		
	$d \to c$	$s \to c$	$\bar{c} \to \bar{s}(\bar{d})$	$d \to c$	$s \to c$	$\bar{c} \to \bar{s}(\bar{d})$
ARIADNE MC	6	36	58	10	26	64
FFN NLO ABMP16.3	8	49	43	16	43	41
FONLL-B NNPDF3.1	8	43	40	12	37	51

e^-p	Contribution (%)					
	$200 < Q^2 < 1500\,\mathrm{GeV}^2$			$1500 < Q^2 < 60000\,\mathrm{GeV}^2$		
	$\bar{d} \to \bar{c}$	$\bar{s} \to \bar{c}$	$c \to s/d$	$\bar{d} \to \bar{c}$	$\bar{s} \to \bar{c}$	$c \to s/d$
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

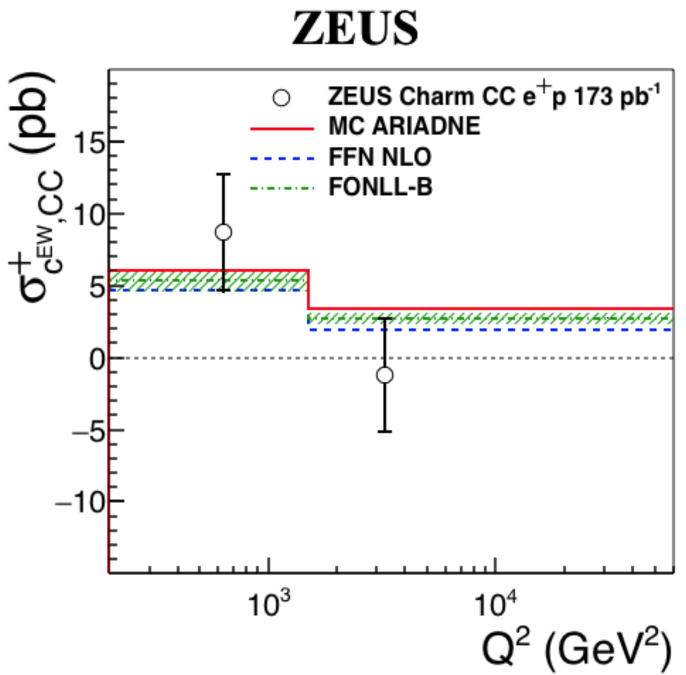


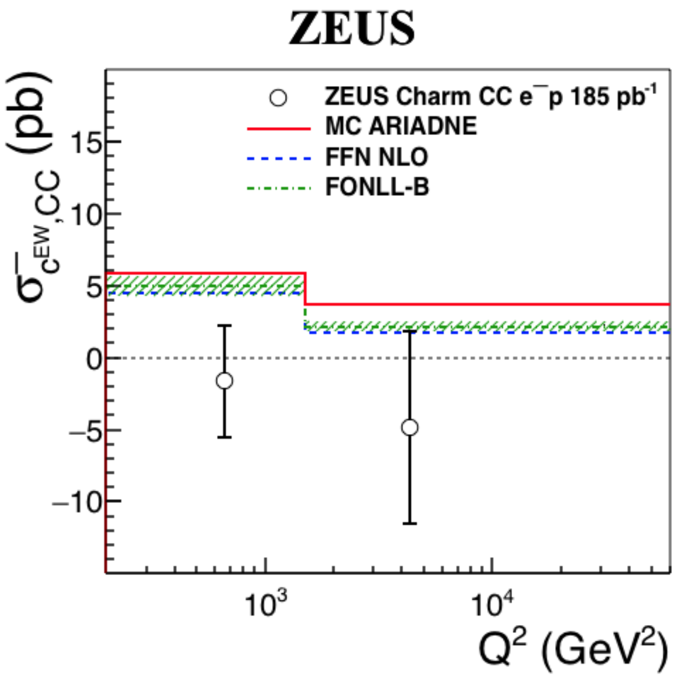


- EW charm production in CCDIS is measured with HERA II data.
  - Consistent with theory predictions, although statistically limited.
  - About the same contribution shared between QPM-like and BGF-like processes. Varies between different theory models.

Results

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





EW charm production in CCDIS is measured with HERA II data.

- Consistent with theory predictions, although statistically limited.
- About the same contribution shared between QPM-like and BGF-like processes. Varies between different theory models.
- Different assumptions on the strangeness in the proton results in $\Delta\sigma_{c^{EW}} \sim 1\, pb$.

→ ~ 2 orders of magnitude higher statistics to be decisive.

Results

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

EW charm production in CCDIS is measured with HERA II data.

- Consistent with theory predictions, although statistically limited.
- About the same contribution shared between QPM-like and BGF-like processes. Varies between different theory models.
- Different assumptions on the strangeness in the proton results in $\Delta\sigma_{c\,EW} \sim 1\,pb$.

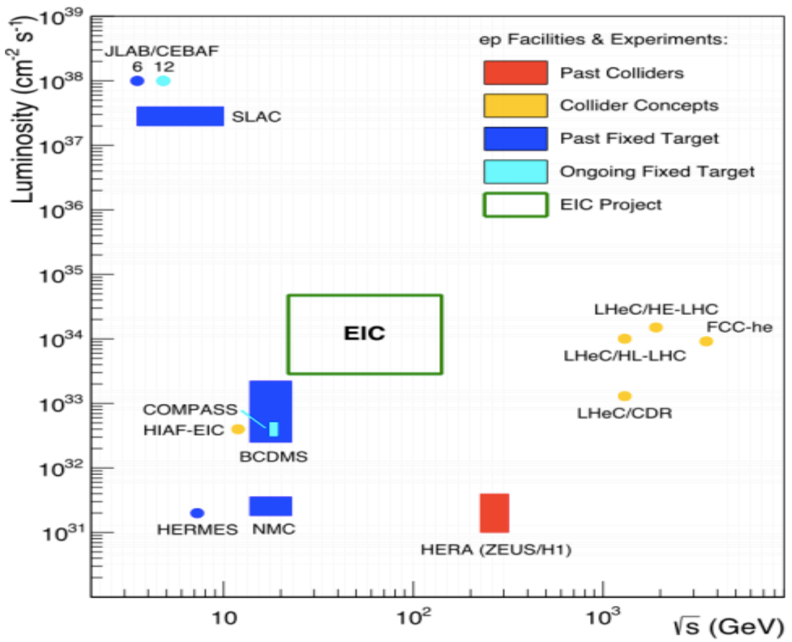
→ ~ 2 orders of magnitude higher statistics to be decisive.

- The uncertainty in the theory predictions $\delta\sigma_{c\,EW} \sim 1\,pb$.

→ some improvements in theory needed.

Summary & Outlook

- EW charm production in high-Q^2 $e^{\pm}p$ CCDIS at HERA has been measured for the first time.
  - Consistent with theory predictions, although statistically limited.
  - Manageable systematic uncertainties.
  - Higher contribution from strange-sensitive process in the visible kinematic region than in the full range.
- Theory predictions with different assumptions of the strangeness in the proton.
  - ~ 2 orders of magnitude higher statistics required to investigate the strangeness in the proton, which could be achieved by higher luminosity & better vertex detection resolution in future colliders.
  - Some improvements in theory calculations.
- Potential of DIS has been tested.
  - Better understanding of the strangeness in the proton expected in future lepton-ion collider experiments, such as EIC in the U.S., LHeC at CERN, and EicC in China.



Backup

Q^2 range (GeV^2)	$\sigma_{c,\mathrm{vis}}$ (pb)	$\sigma_{c\mathrm{EW}}$ (pb)
	e^+p	
200–1500	$4.1 \pm 2.0\ (\mathrm{stat.})\ ^{+0.1}_{-0.6}\ (\mathrm{syst.})$	$8.7 \pm 4.1\ (\mathrm{stat.})\ ^{+0.2}_{-1.4}\ (\mathrm{syst.})$
1500–60000	$-0.7 \pm 2.0\ (\mathrm{stat.})\ ^{+0.2}_{-0.0}\ (\mathrm{syst.})$	$-1.2 \pm 3.9\ (\mathrm{stat.})\ ^{+0.3}_{-0.3}\ (\mathrm{syst.})$
	e^-p	
200–1500	$-0.9 \pm 2.1\ (\mathrm{stat.})\ ^{+0.2}_{-0.0}\ (\mathrm{syst.})$	$-1.7 \pm 3.9\ (\mathrm{stat.})\ ^{+0.3}_{-0.3}\ (\mathrm{syst.})$
1500–60000	$-2.6 \pm 3.5\ (\mathrm{stat.})\ ^{+0.5}_{-0.1}\ (\mathrm{syst.})$	$-4.8 \pm 6.7\ (\mathrm{stat.})\ ^{+0.9}_{-0.8}\ (\mathrm{syst.})$

$$\sigma^+_{c,\mathrm{vis}} = 4.0 \pm 2.8\ (\mathrm{stat.})\ ^{+0.1}_{-0.6}\ (\mathrm{syst.})\ \mathrm{pb}, \qquad \sigma^+_{c\mathrm{EW}} = 8.5 \pm 5.5\ (\mathrm{stat.})\ ^{+0.2}_{-1.3}\ (\mathrm{syst.})\ \mathrm{pb},$$

$$\sigma^-_{c,\mathrm{vis}} = -3.0 \pm 3.8\ (\mathrm{stat.})\ ^{+0.5}_{-0.1}\ (\mathrm{syst.})\ \mathrm{pb}, \qquad \sigma^-_{c\mathrm{EW}} = -5.7 \pm 7.2\ (\mathrm{stat.})\ ^{+1.0}_{-1.2}\ (\mathrm{syst.})\ \mathrm{pb}.$$