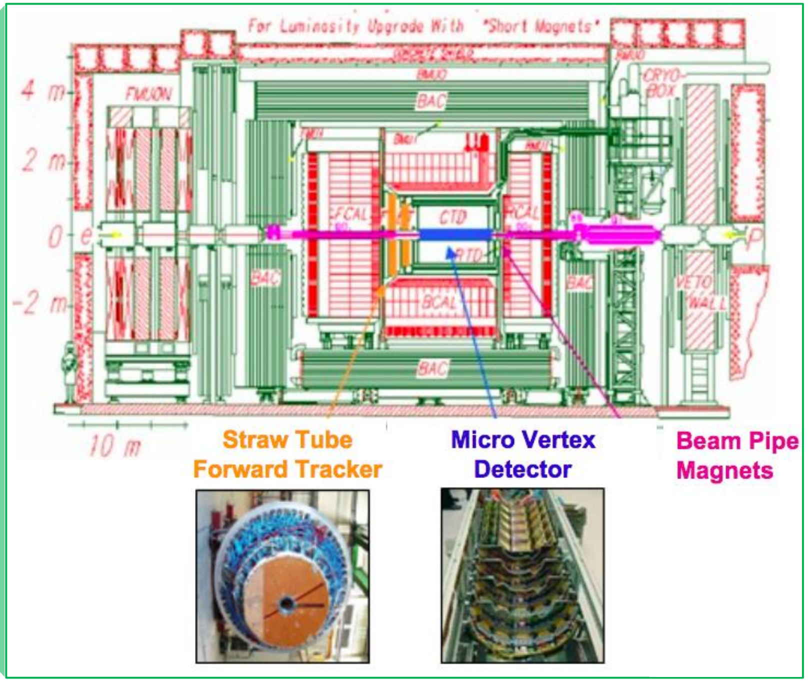
Charm Production in Charged Current DIS at HERA

Jae D. Nam

Temple Univ.

HERA accelerator & ZEUS detector



HERA accelerator (Hamburg, Germany)

- $e^{\pm}p$ collider with $\sqrt{s} = 318\ GeV$.
- Luminosity upgrade during HERA II period (2003-2007)

ZEUS detector (South side of HERA)

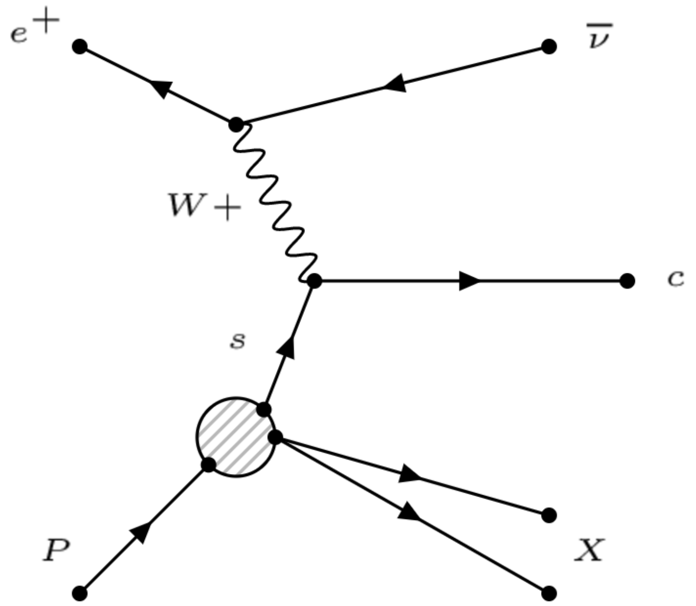
- Asymmetric with extended coverage of the proton beam direction.
- Installation of a microvertex detector (MVD) during HERA upgrade.

Data stored at ZEUS provides a great testing ground for future EIC projects!

Motivations

- Charm cross section measurement in high-Q^2 charged current (CC) DIS.

  $\rightarrow$ Constraints on $s(x, Q^2)$



$\leftarrow$ LO Charm production Feynman diagram

- Allows for $s(x, Q^2)$ measurement.
- The process via d is Cabibbo-suppressed.
- Due to the final state neutrino, a large missing P_T is observed.
- Charmed particle has a long lifetime since it decays weakly.
- Invariant kinematic variables (x, y, Q^2) defined by using Jacquet-Blondel Method.

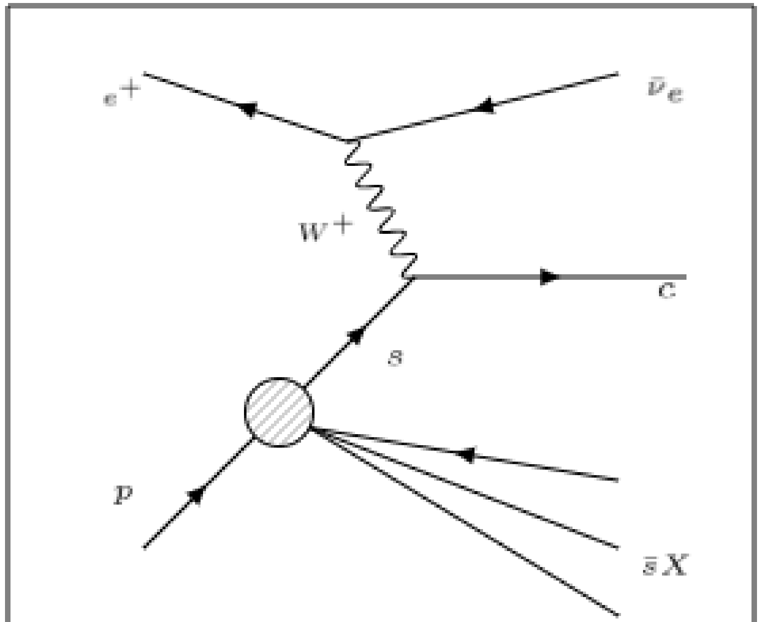
$$y_{JB} = \frac{\sum_h (E - p_z)_h}{2E_{e,beam}} \qquad Q^2_{JB} = \frac{p^2_{T,h}}{1 - y_{JB}} \qquad x_{JB} = \frac{Q^2_{JB}}{s y_{JB}}$$

- Complementary measurement (high-Q^2) to the previous analyses at low-Q^2.

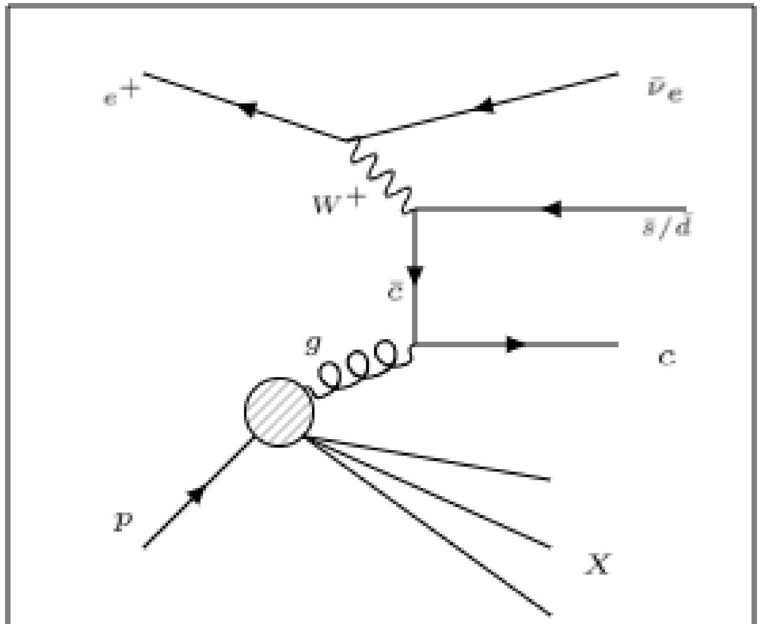
  $\rightarrow$CCFR/NuTeV : $\frac{\int_0^1 dx[xs + x\bar{s}]}{\int_0^1 dx[x\bar{u} + x\bar{d}]} = 0.477^{+0.063}_{-0.053}$ $(Q^2 = 4\ GeV^2)$ **Z.Phys.C65:189-198,1995

  $\rightarrow$ATLAS : $\frac{s + \bar{s}}{\bar{u} + \bar{d}} = 1.13 \pm 0.05$ $(Q^2 = 1.9\ GeV^2, x = 0.023)$ **Eur. Phys. J. C 77 (2017) 367

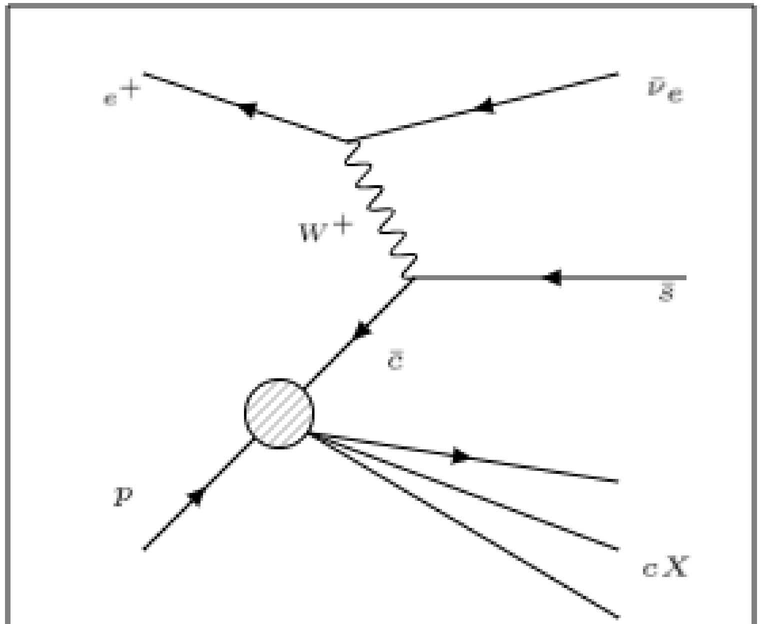
Charmed Sub-processes



$s\bar{s}(\bar{d}) \rightarrow c\bar{s}(\bar{d})$



$g \rightarrow c\bar{c} \rightarrow c\bar{s}(\bar{d})$



$c\bar{c} \rightarrow c\bar{s}(\bar{d})$

- LO quark-initiated process (QI)
  - sensitive to strange content.
- NLO boson-gluon fusion (BGF)
  - sensitive to gluon content.
- LO, strange production
  - sensitive to charm content.

- All three schemes have the same initial & final state and are EW processes.

  → hard to disentangle theoretically.

DATA & Monte Carlo Samples

Data

- HERA II ($L \cong 360\ pb^{-1}$)
  - $e^{-}p$: $05e, 06e$ w/ $L \cong 185\ pb^{-1}$
  - $e^{+}p$: $0304p, 0607p$ w/ $L \cong 173\ pb^{-1}$

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

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.

DIS Selection Summarized

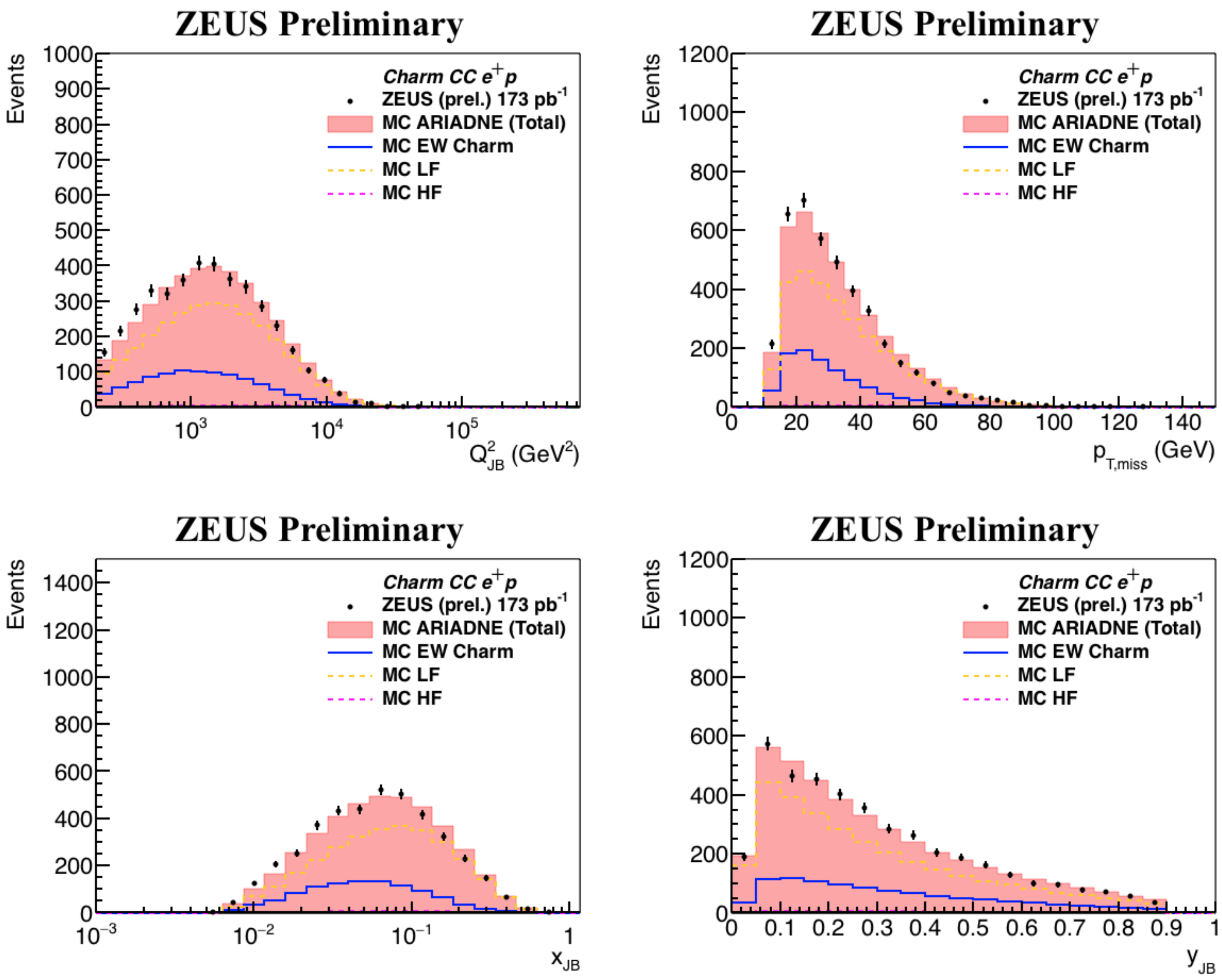
- Kinematic Selection
  - $200\ GeV^2 < Q_{JB}^2 < 60{,}000\ GeV^2$
  - $y_{JB} < 0.9$
  - Confines the sample in a region where the detector resolution is well understood and has a low background.

- Charged Current Selection
  - $p_T > 12\ GeV$ $**$ missing transverse momentum $p_{T,miss} = -p_T$
  - $p_T' > 10\ GeV$ $**$ $p_T' = p_T$ excluding the ones measured by CAL cells adjacent to the beam hole.

- Further background rejection (NC, Photoproduction, etc)

- ~4,000 CC events from e^+ periods and ~9,000 from e^- periods.

Control Plots – Event (e^+p)



Legend Info

- EW Charm/Anticharm

  Charm from electroweak reaction either in the initial or final state.

- LF

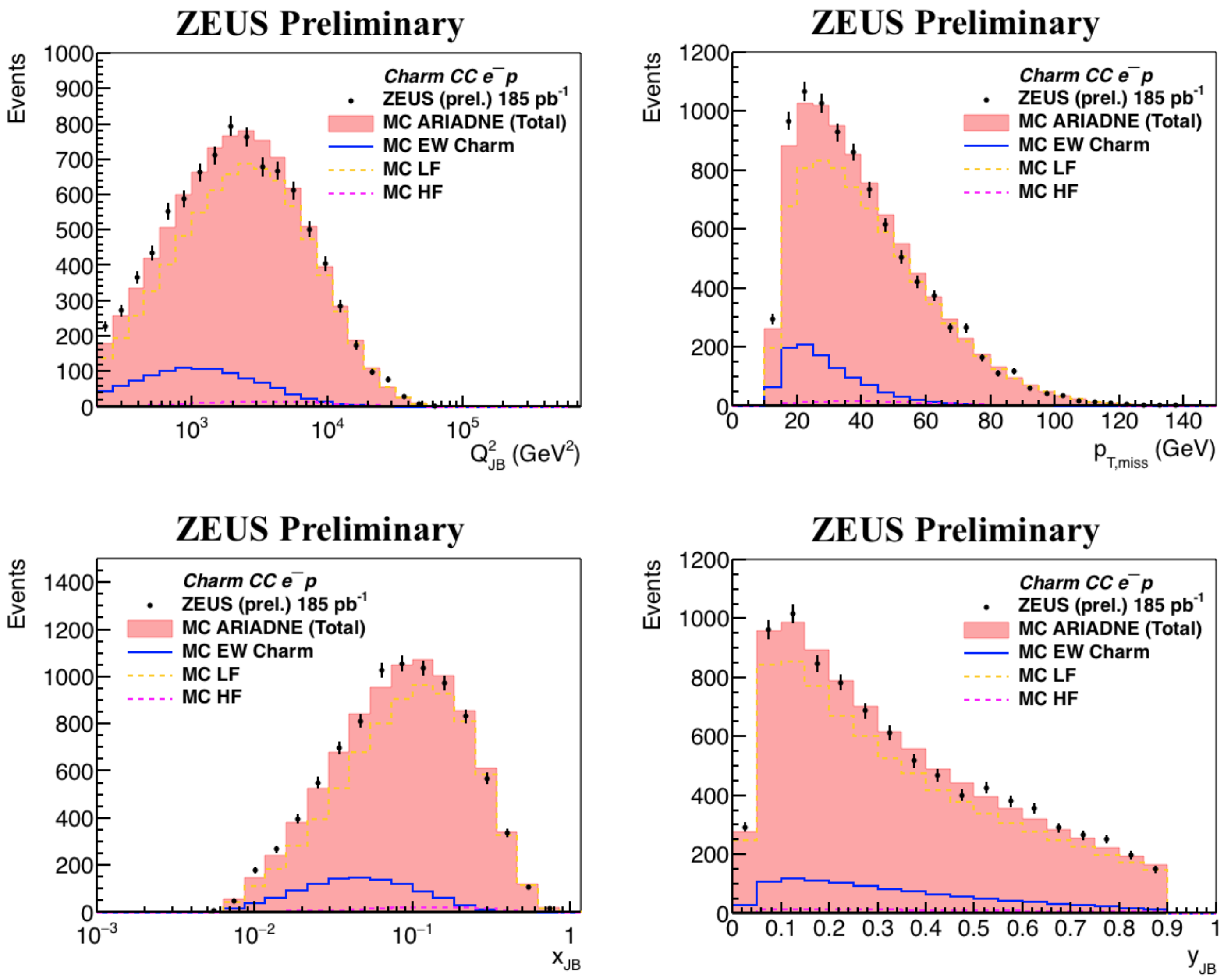
  Light-flavor contribution.

  Major source of background.

- HF

  Heavy Flavor events that do not involve EW charm.

Control Plots – Event ($e^{-}p$)



- A good consistency between MC and data.
- LF content higher in e^{-} periods due to W-coupling valence quarks.
- EW charm content:
  ~25 % in e^{+} periods
  ~15% in e^{-} periods.

Charm Identification

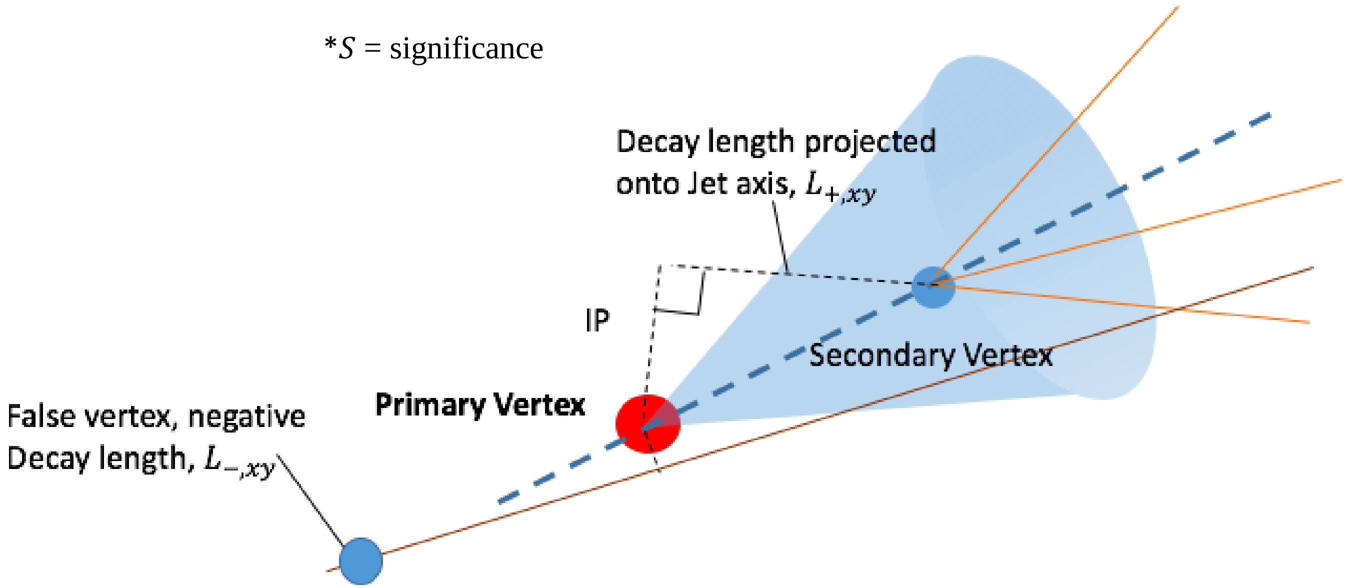
Lifetime-tagging Method

- 2D decay length (L_{xy}) projected onto Jet axis.
  - LF → Short-lived, Symmetric decay length.
  - Charm → Long-lived, Asymmetric.

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

$$(M_{L+} - M_{L-}, M_{S+} - M_{S-})$$

$*S$ = significance



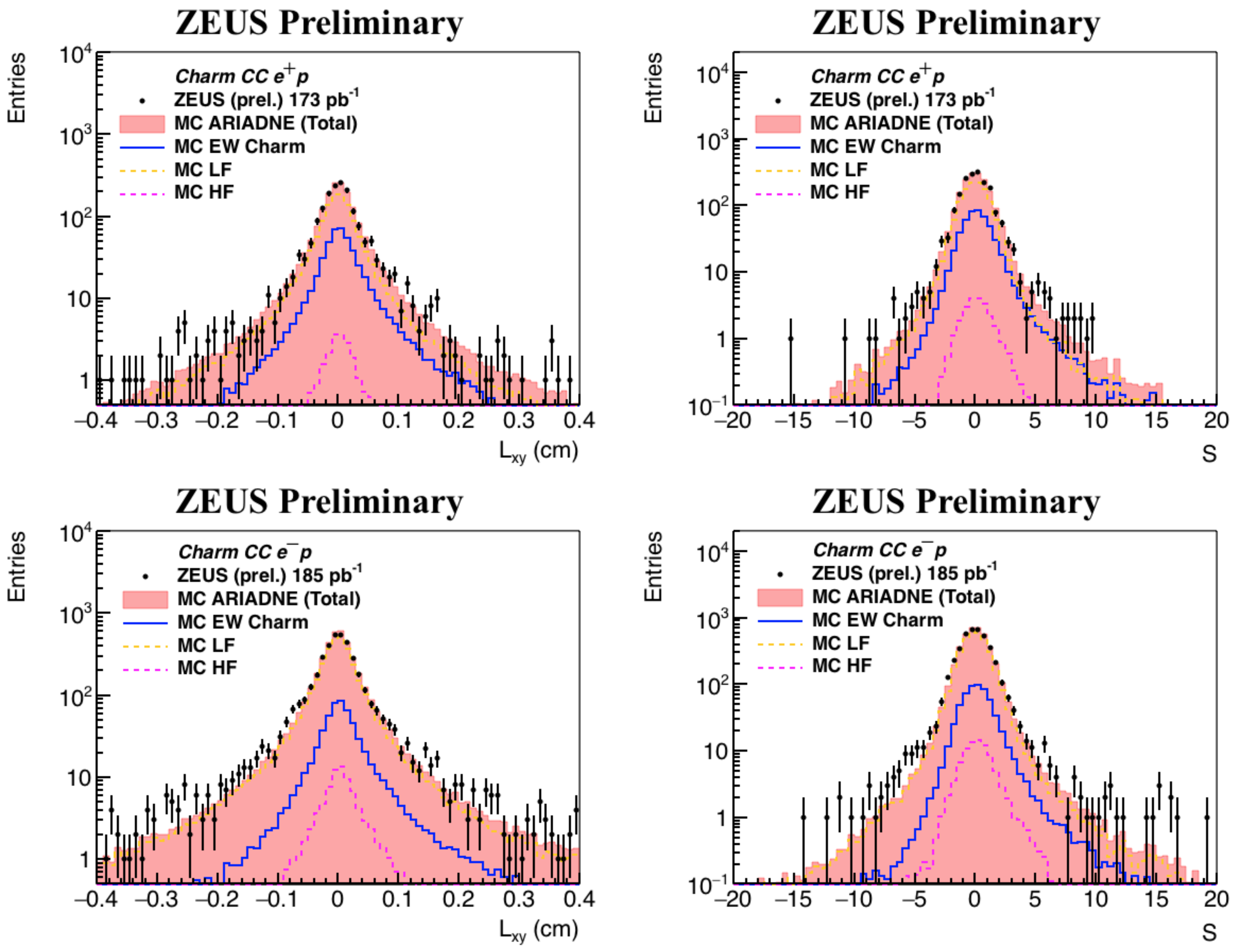
Jet Selection	Reconstructed by using kT algorithm in massive mode.
	$E_T^{jet} > 5\ GeV$
	$-2.5 < \eta^{jet} < 2.5$
SecVtx Selection	$\chi^2/N_{dof} < 6$
	$\lvert Z_{secvtx} \rvert < 30\ cm$
	Distance to beamspot $\sqrt{\Delta x^2 + \Delta y^2} < 1\ cm$

- E_T^{jet} and η^{jet} cuts further define the kinematic phase space of the measurement.

Decay Length Plots

e^+p

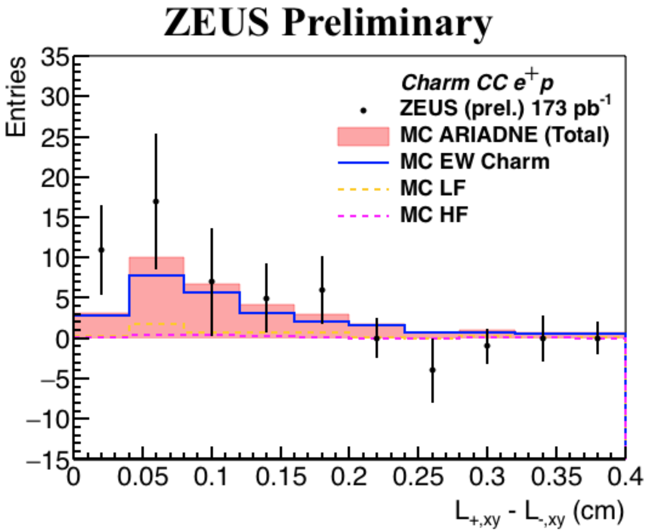
e^-p

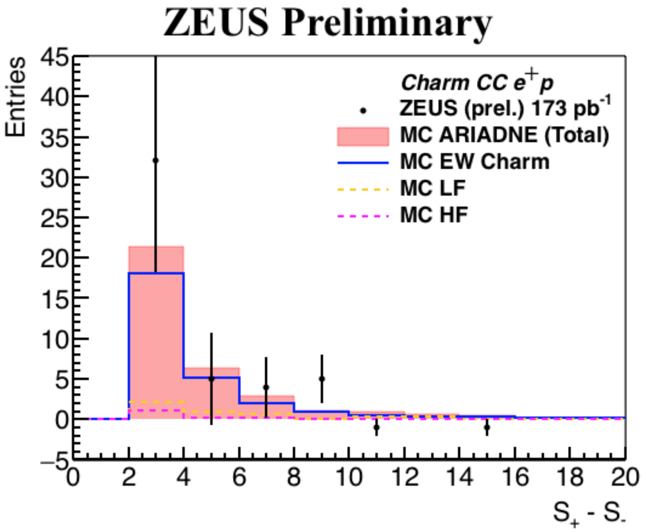


- Asymmetric charm signal observed.
- The high symmetry and large statistics around $S \sim 0$ contributes to a large statistical uncertainty in the low bin regions in S.
- A significance threshold cut was applied to reduce overall statistical uncertainty.

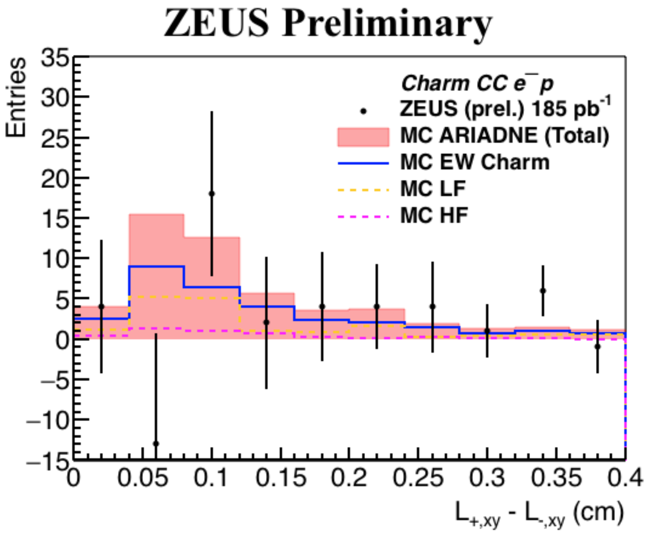
Mirrored Decay Length

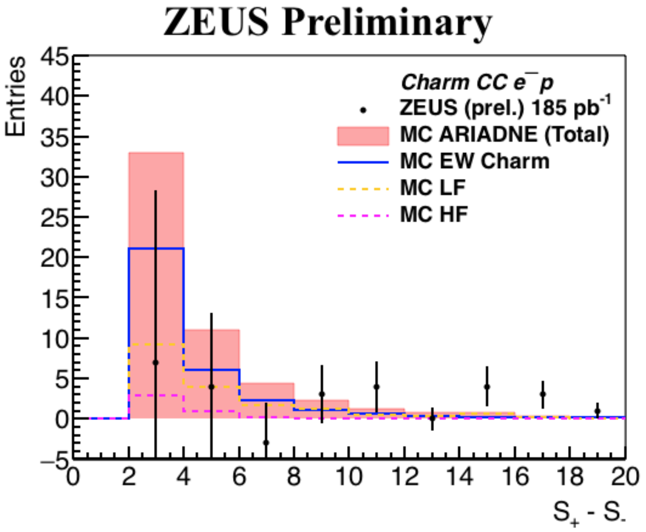
$e^{+}p$





$e^{-}p$





- Significance cut applied at $S > 2$.
- Charm signal observed with LF contribution (Background) suppressed.
- Surviving events are split into 2 bins in Q^2 to unfold charm production cross section, $\sigma_{charm,CC}$.

Cross Section Unfolding

$$\sigma_{i,charm,CC} = \frac{M_{i,meas} - M_{i,meas}^{bg}}{M_{i,meas}^{MC}} \sigma_{i,charm,CC}^{MC}$$

- The charm cross section is measured by extrapolating the cross section measured in MC samples with a factor $\frac{M_{meas,i} - M_{meas,i}^{bg}}{M_{meas,i}^{MC}}$.
- Here, M denotes the number of entries in reconstructed Q_{JB}^2 distribution.

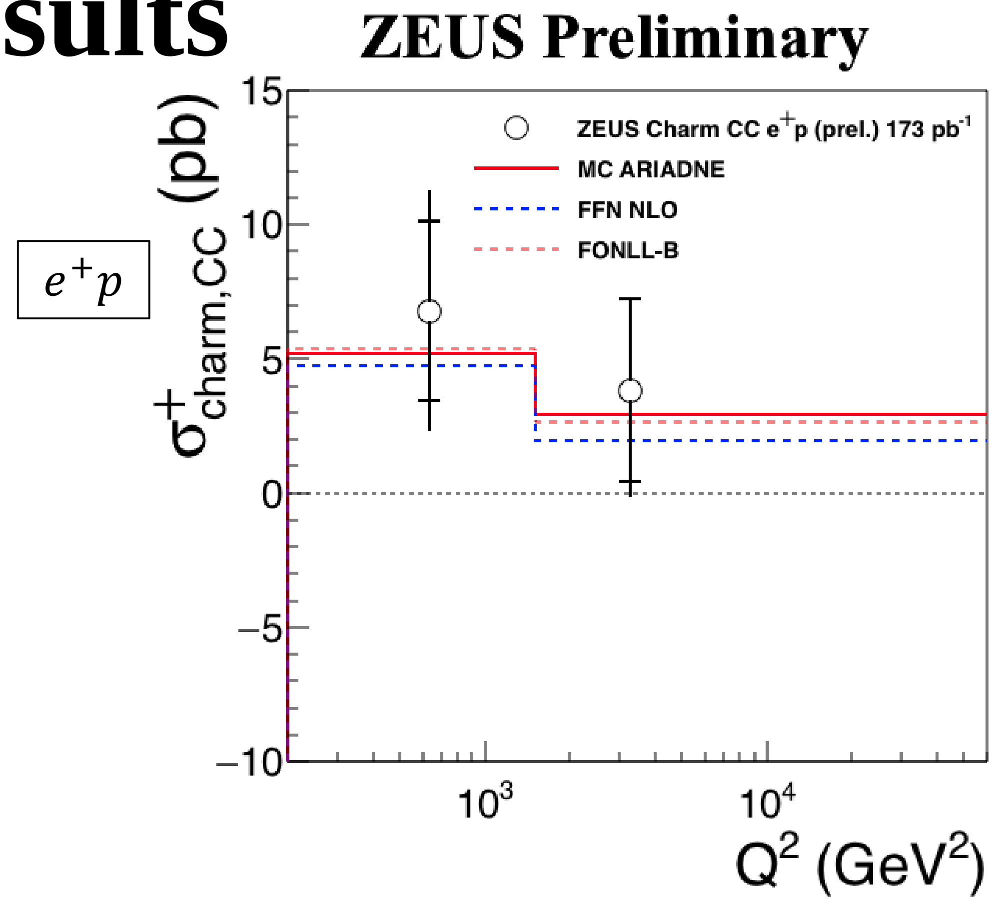
$$\sigma_{i,charm,CC}^{MC} = \frac{N_{i,charm,CC}^{MC}}{L}$$

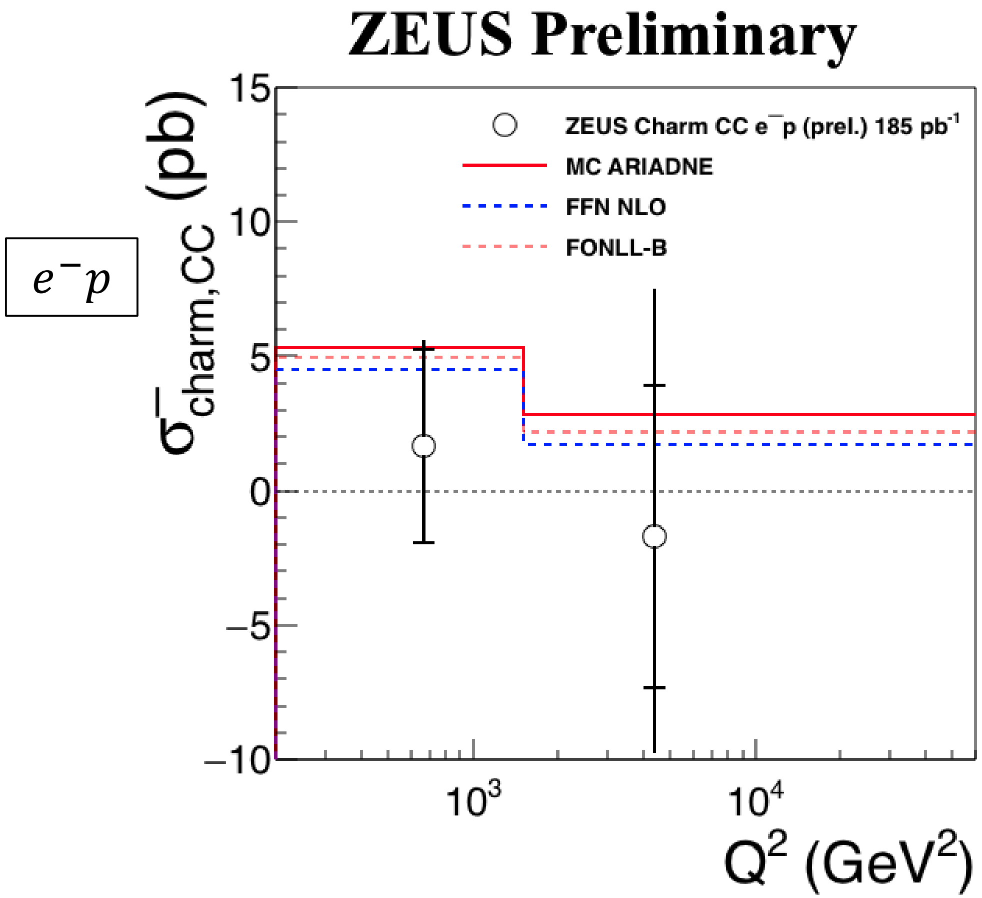
- The MC cross section is given by the equation on the left, where N denotes the number of entries in true Q^2 distribution.
- The discrepancy between N and M is found to be in the order of ~1%.

$$\sigma_{charm,CC}^{tot} = C_{ext}\, \sigma_{charm,CC}^{vis}$$

- The total cross section can then be extrapolated via an extrapolation factor $C_{ext} := N_{charm}^{full} / N_{charm}^{kin}$, the ratio of the number of generated charm versus that of visible charm.

Results





- EW charm cross sections have been measured.
- Reasonable agreement between data, MC & theory with a large uncertainty.
- MC & theory predictions suggest that the contributions from QI and BGF processes are about equal.

- Theory predictions
  - FFN scheme:
    - ABMP16.3 NLO pdf set, OPENQCDRAD
  - FONLL scheme:
    - NNPDF31 NLO pdf set, APFEL
  - Both are interfaced in xFitter.

Summary

- Measurement of charm cross sections in a kinematic region ($Q^2 > 200\ GeV^2, y < 0.9, E_T^{jet} > 5\ GeV, |\eta^{jet}| < 2.5$) has been performed with the ZEUS detector with HERA II data.

- Charm production cross section is 30-50% sensitive to strange quark content in proton, as suggested by MC and theoretical calculations (FFN NLO, FONLL-B).

- Further signal optimization to suppress LF content, especially in e^- periods, is in progress.

- With orders of magnitude higher instant luminosity and better vertex detection resolution projected to be implemented in the future EIC, this analysis can further constrain strange quark content in proton.

Thank you!

Special thanks to…

- ZEUS Collaboration
- NUPAX group at Temple (Bern Surrow, et al.)

Back up

Charm Production in CC

- Charged current events are always weak interactions.

$$\frac{d^2\sigma_{Born}^{CC,e^{\pm}p}}{dxdQ^2} = (1 \pm P_e)\frac{G_F^2}{4\pi x}\left(\frac{M_W^2}{M_W^2 + Q^2}\right)^2 \tilde{\sigma}_{CC}^{e^{\pm}p}$$

- The double-differential cross section is sensitive to different quark densities.

$$\tilde{\sigma}_{CC}^{e^+p} = x[\bar{u} + \bar{c} + (1-y)^2(d \boxed{+ \boldsymbol{s}})]$$
$$\tilde{\sigma}_{CC}^{e^-p} = x\left[u + c + (1-y)^2\left(\bar{d} \boxed{+ \bar{\boldsymbol{s}}}\right)\right]$$

- The resulting charm production is then selected by using the lifetime-tagging method.