Charm Production in CC DIS at HERA

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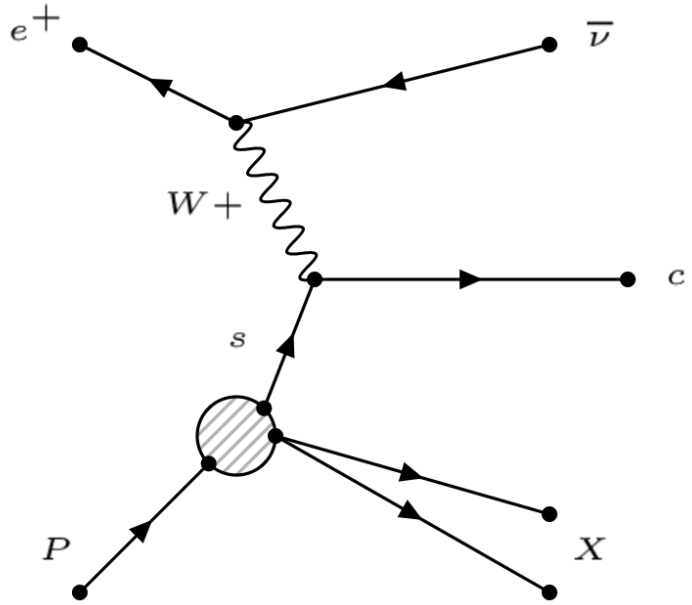
Motivations

- Charm cross section measurement in high-Q^2 charged current (CC) DIS.
  → Constraints on $s(x, Q^2)$



← 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.

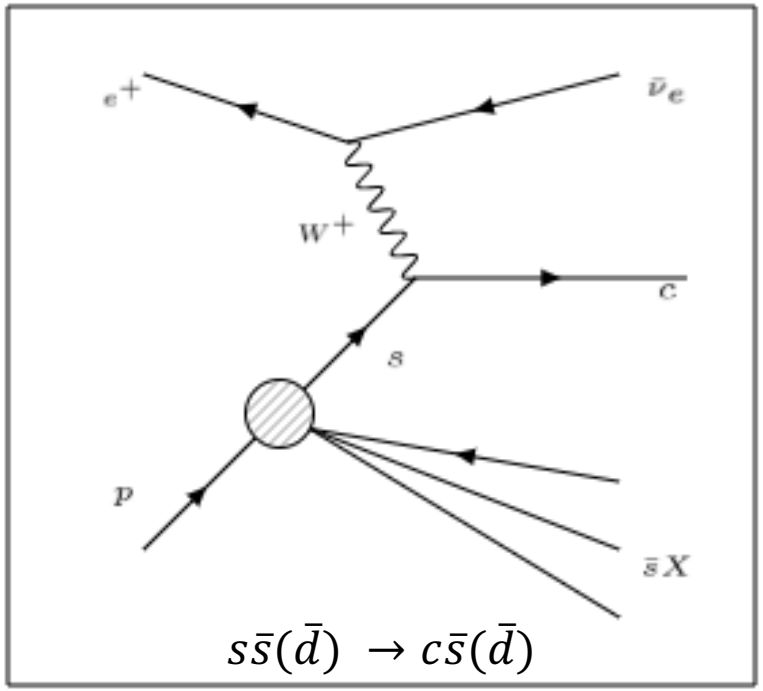
$$y_{JB} = \frac{\sum_h (E - p_z)_h}{2E_{e,beam}} \qquad Q^2_{JB} = \frac{p^2_{T,h}}{1 - y_{JB}} \qquad x_{JB} = \frac{Q^2_{JB}}{s y_{JB}}$$

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

→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

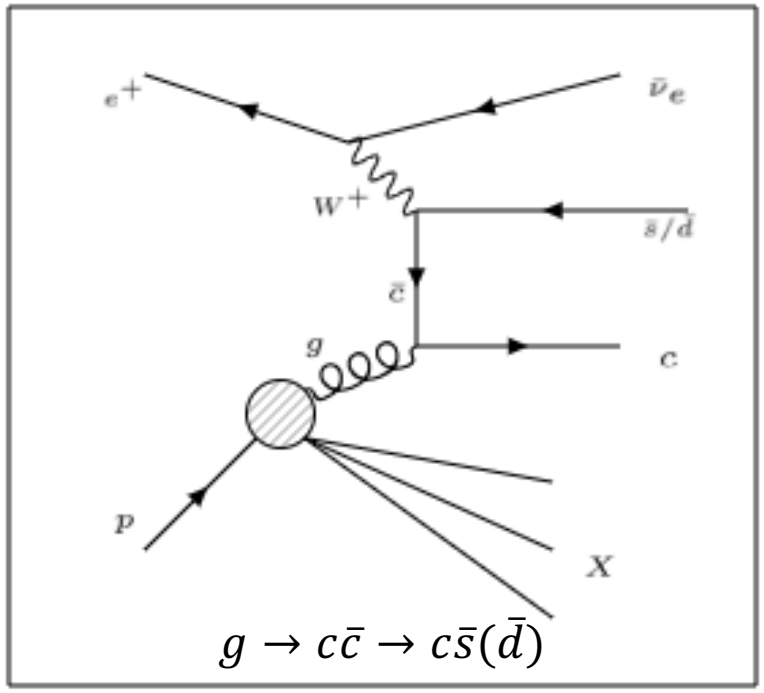
→ATLAS : $\frac{s+\bar{s}}{\bar{u}+\bar{d}} = 1.13 \pm 0.05$ $(Q^2 = 1.9\ GeV^2, x = 0.023)$ **Eur. Phys. J. C 77 (2017) 367

Charmed Sub-processes



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

- LO quark-initiated process (QI)
  - sensitive to strange content.



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

- NLO boson-gluon fusion (BGF)
  - sensitive to gluon 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 Summary (Ciesielski & Oliver)

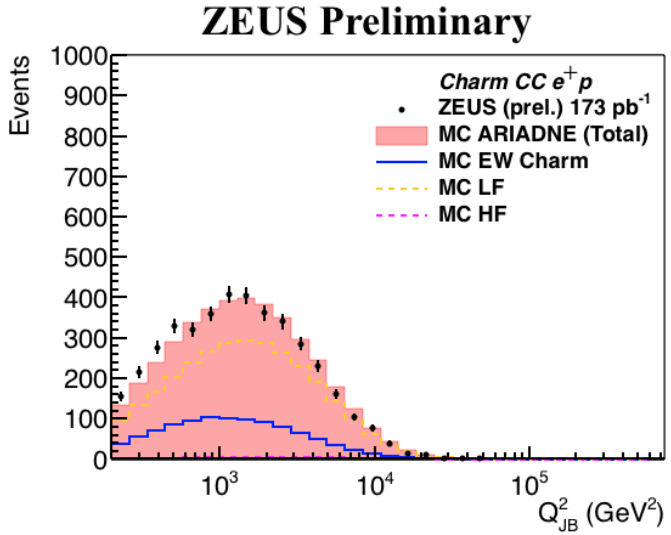
General Selection	
Trigger	FLT 60 || 63 || 39 || 40 || 41 || 43 || 44 SLT EXO 4 TLT EXO 2 || EXO 6 DST 34
DQ	EVTAKE, POLTAKE, MVDTAKE, STTTAKE
p_T	p_T > 12 GeV p'_T > 10 GeV
Kinematic	200 < Q2 < 60,000 GeV2 y < 0.9
Tracking Based Selection	
Vertex	|Zvtx| < 30 cm
ϕcal - ϕtrk	dϕ < 90 degrees
Beam Gas Trk	Ntrkvtx > 0.125 * (Ntrk - 20)

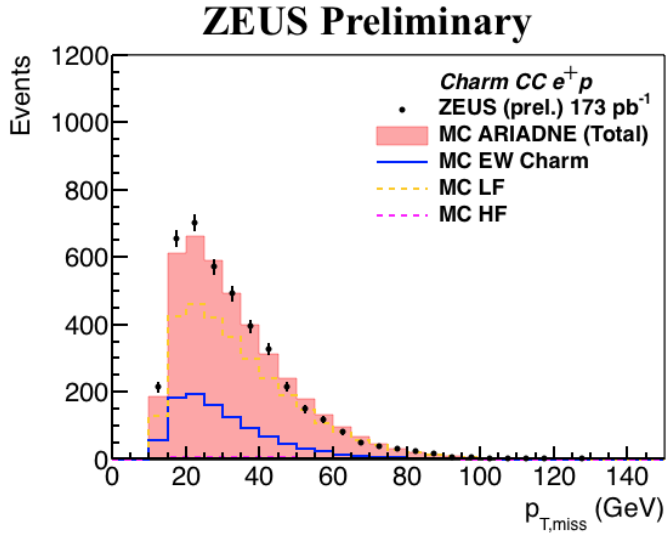
Calorimeter Based Selection	
Timing	Consistent with ep interaction
PhP, Beam Gas	Vap/Vp < 0.25 if (Pt < 20 GeV) Vap/Vp < 0.35 else
Cosmics	Reject if: Ncell < 40 or (BAC/BRMU cosmic muon) or E_RCAL > 2 GeV and f_RHAC > 0.5 or E_BCAL > 2 GeV and f_BHAC > 0.85 or f_BHAC1 > 0.7 or f_BHAC2 > 0.4 or E_FCAL > 2 GeV and f_FHAC < 0.10 or f_FHAC > 0.85 or f_FHAC1 > 0.7 or f_FHAC2 > -.6
Halo Muon	Reject if: MaxEtCell_nr <= 16384 and RCAL asosE > 0.3 GeV (FCAL) or Tsu_halo > 0 (TSUBAME in BCAL) or (BAC/BRMU halo muon)
NC DIS	Reject if: PT < 30 GeV&& E-Pz > 30 GeV && E_e > 4 GeV && E_in < 5 GeV && (Ptrk/Ee > 0.25 for 15 < θe < 164 or Ete > 2 GeV for θe > 164)

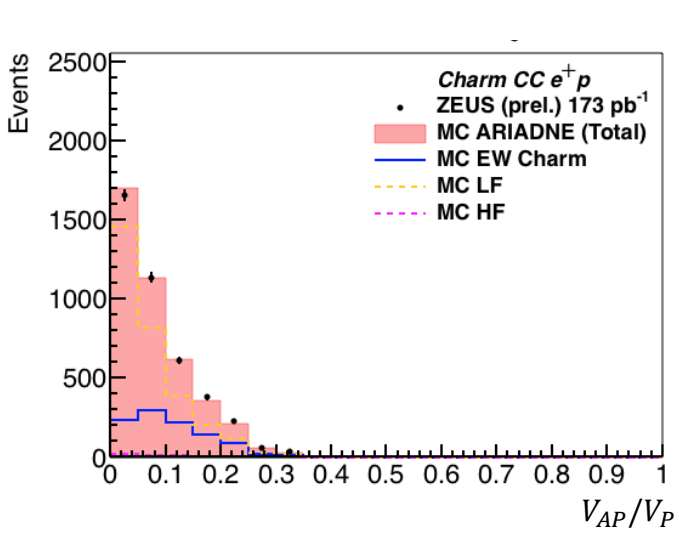
yellow – Varies between run periods
-STTTAKE = 0 for 05e data
-FLT 63 active after run 54115

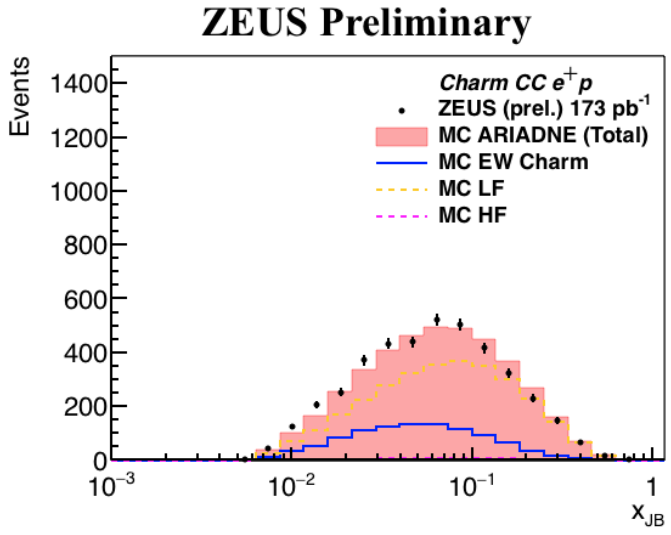
green – Only applied on data
-Timing cut only on data

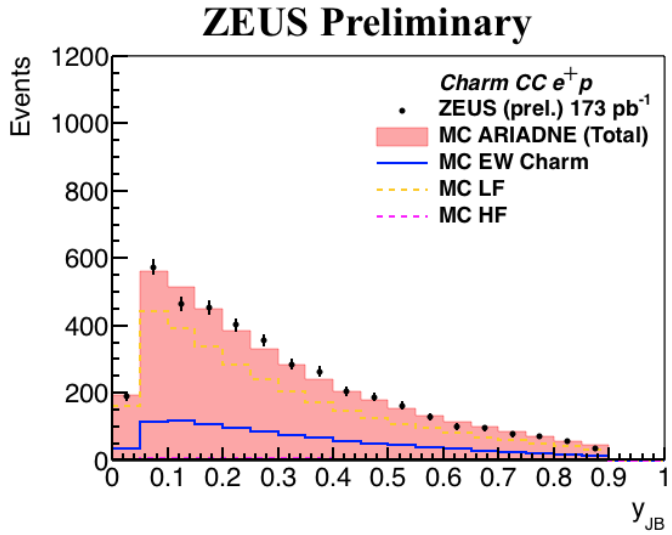
Control Plots – Event (e^+p)

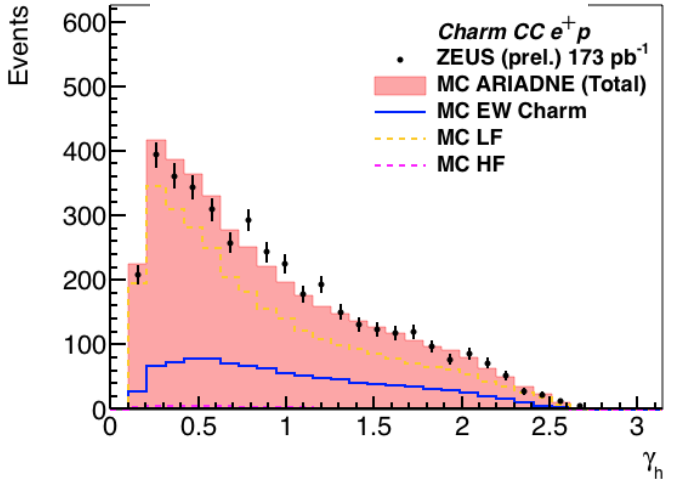




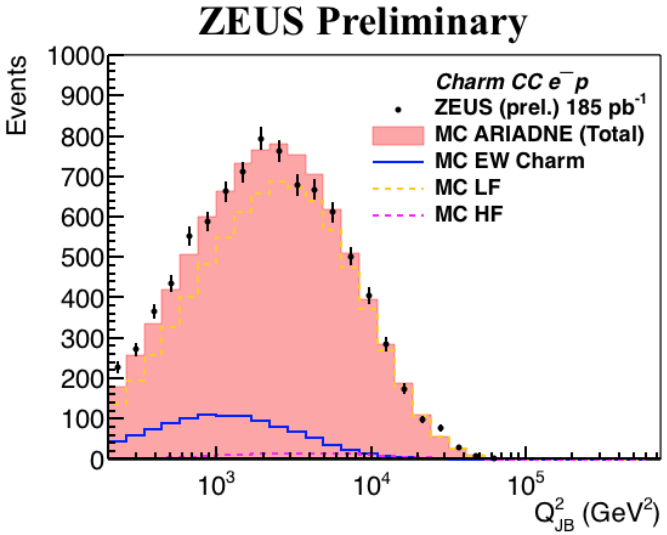


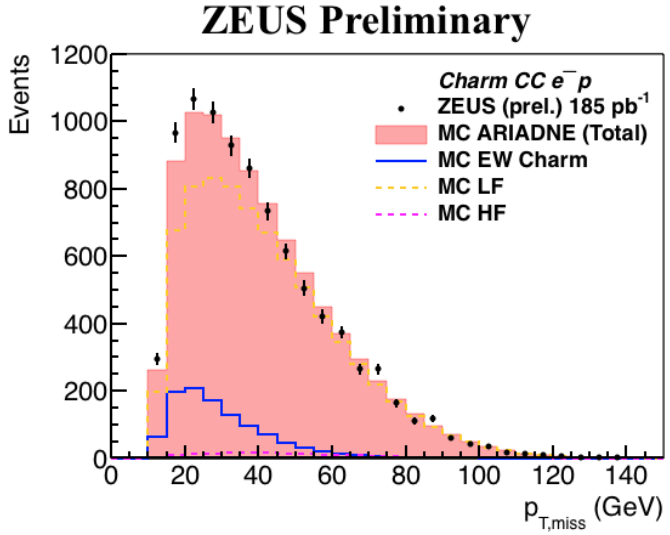


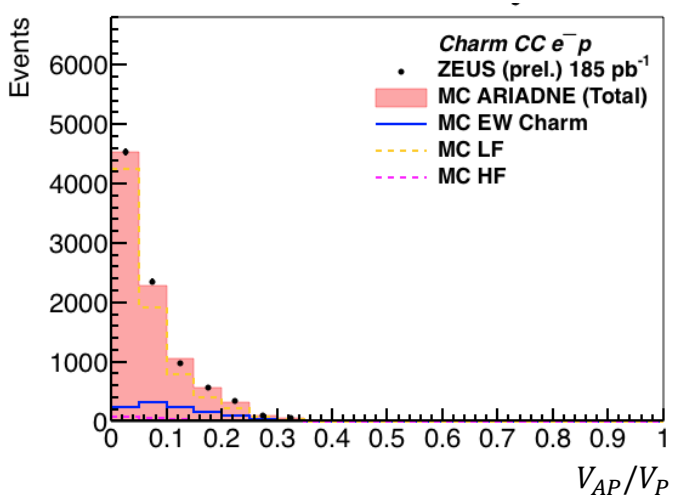


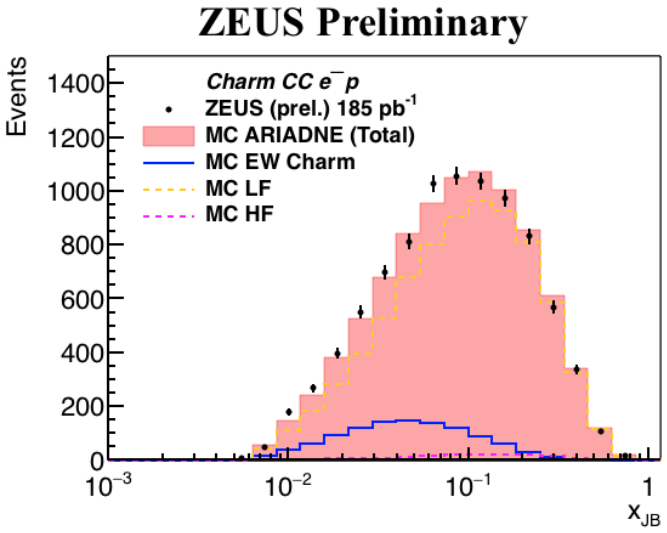


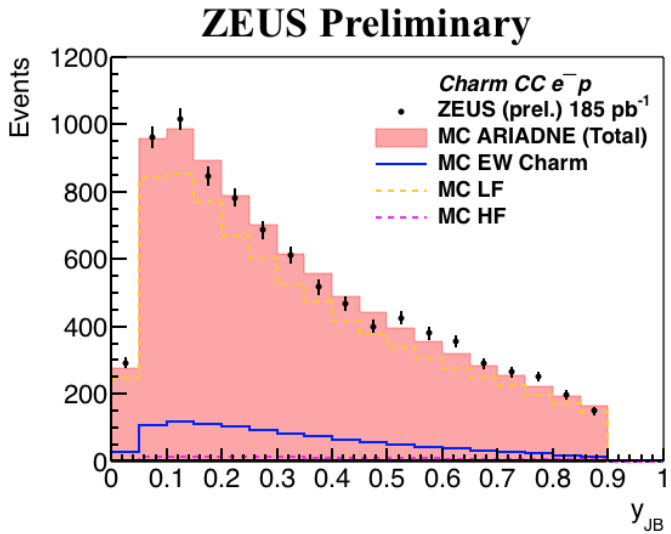
Control Plots – Event ($e^- p$)

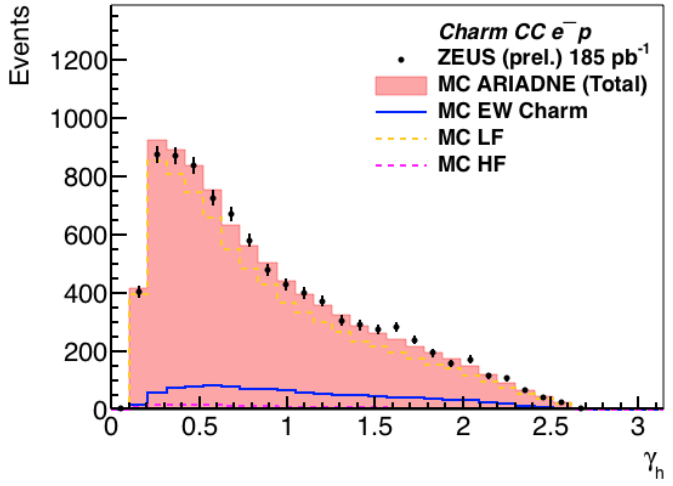












Charm Identification

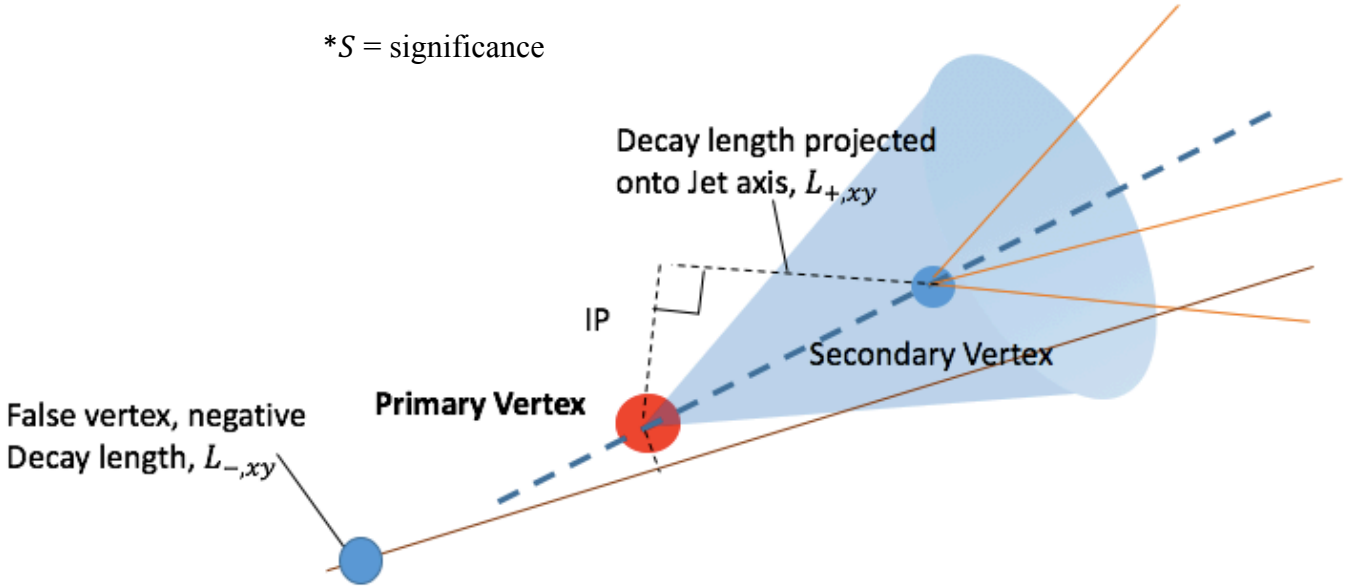
Lifetime-tagging Method

- 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

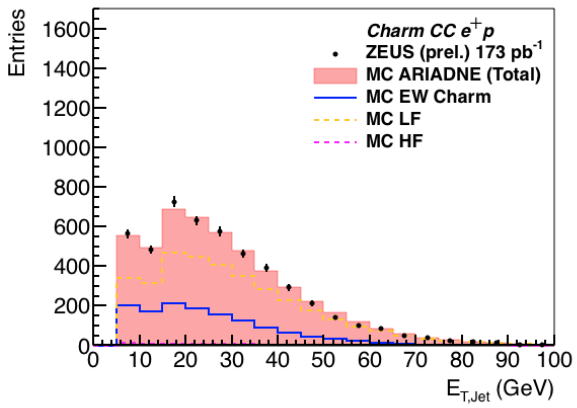


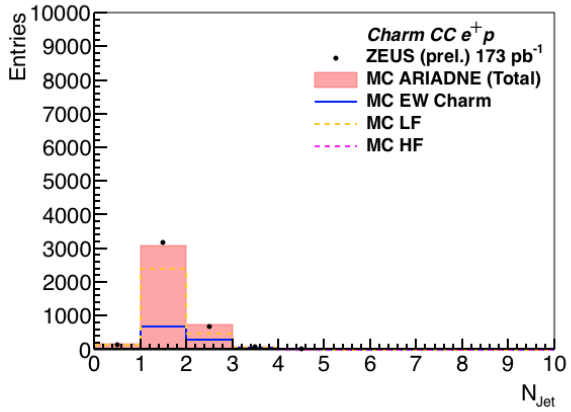
Jet Selection	Reconstructed by using kT algorithm in massive mode.
	$E_T^{jet} > 5\ GeV$
	$-2.5 < \eta^{jet} < 2.5$
SecVtx Selection	$\chi^2/N_{dof} < 6$
	$\lvert Z_{secvtx} \rvert < 30\ cm$
	Distance to beamspot $\sqrt{\Delta x^2 + \Delta y^2} < 1\ cm$

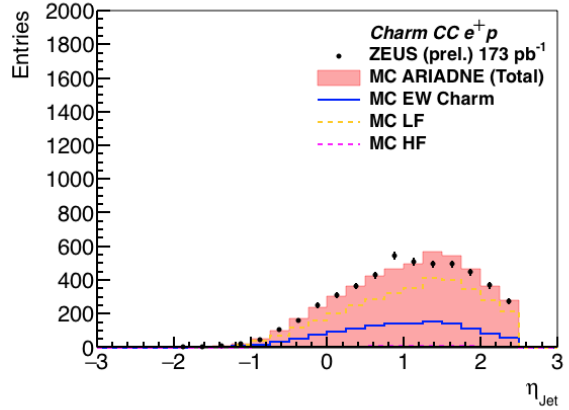
- E_T^{jet} and η^{jet} cuts further define the kinematic phase space of the measurement.

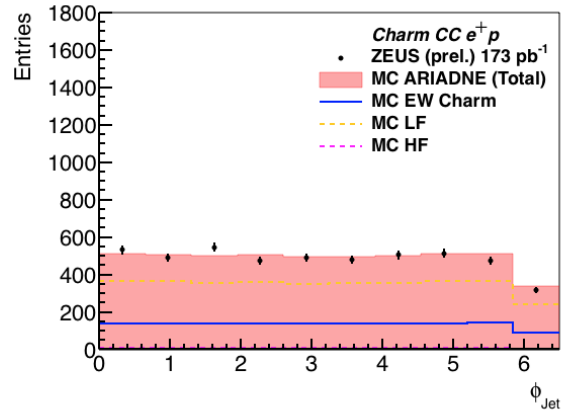
Control Plots – Jet

e^+p

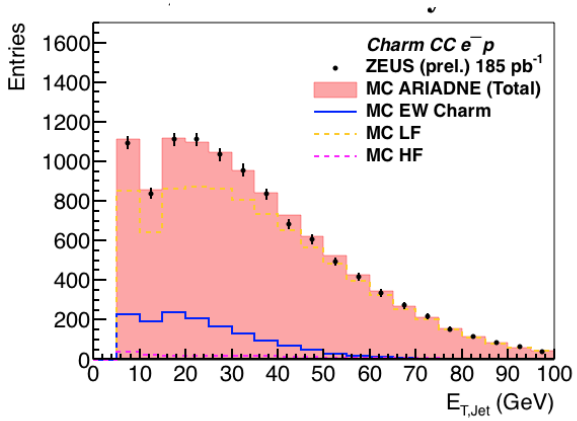


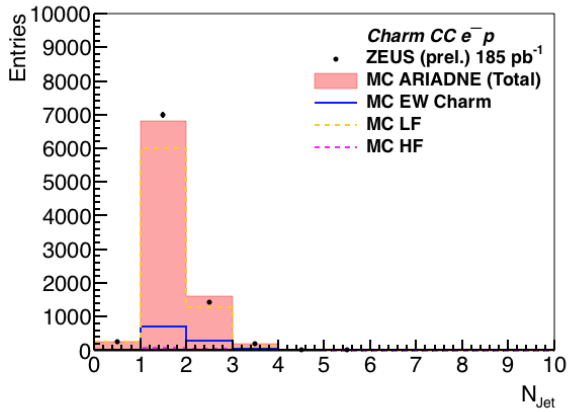


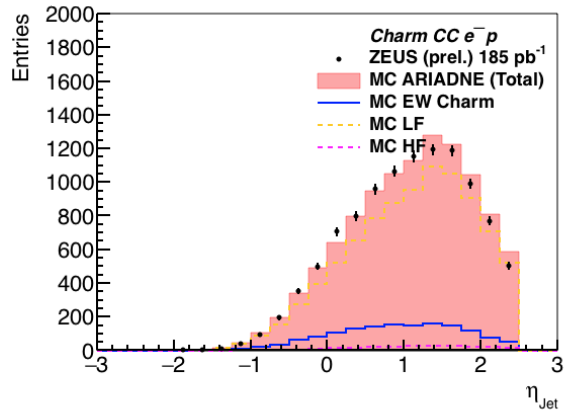


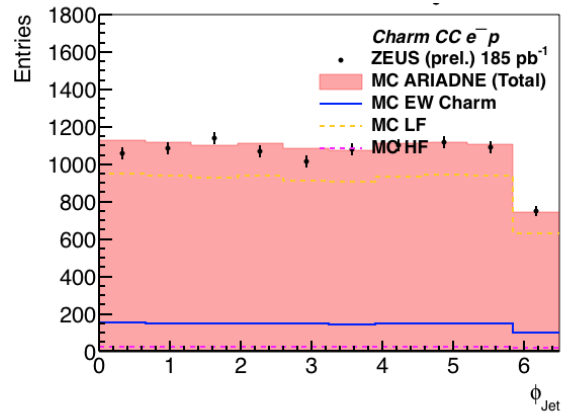


e^-p



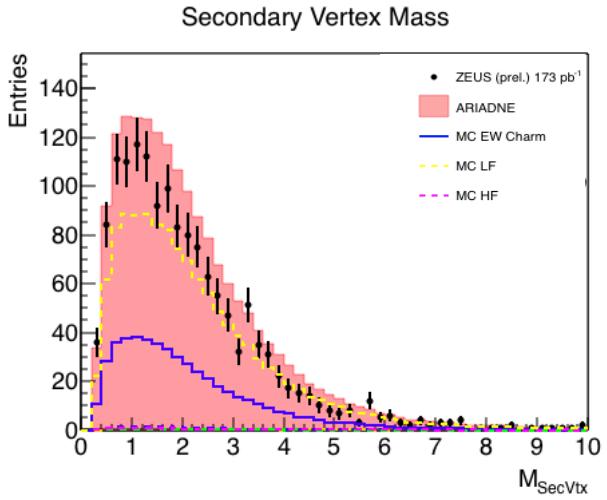


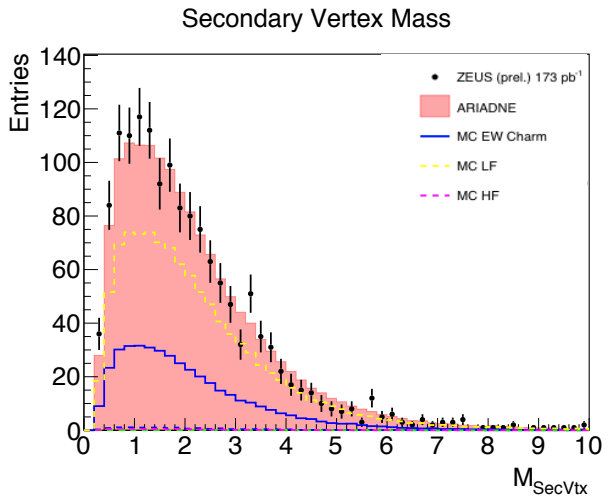


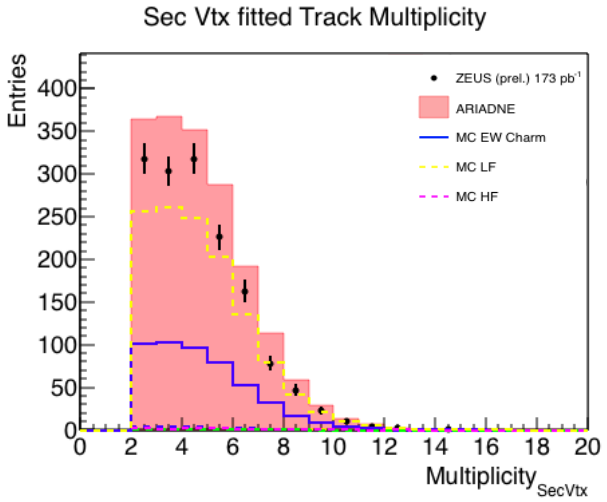


Secondary Vertex Scaling

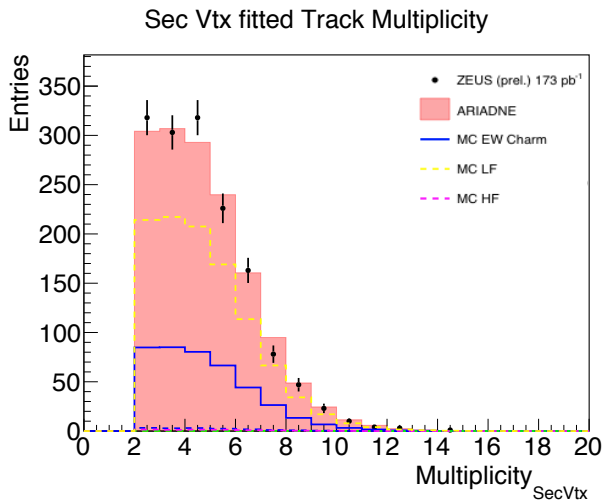
(0607p)







MC scaling factor
$= 0.834$

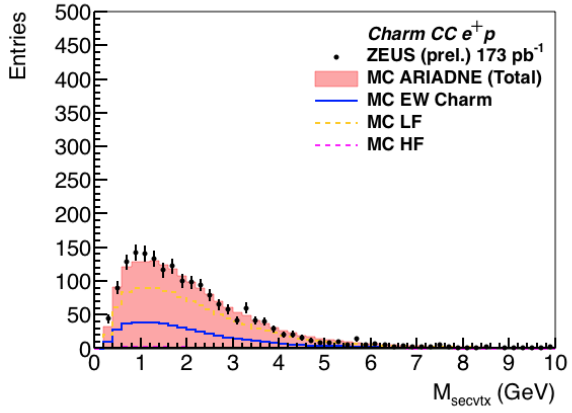


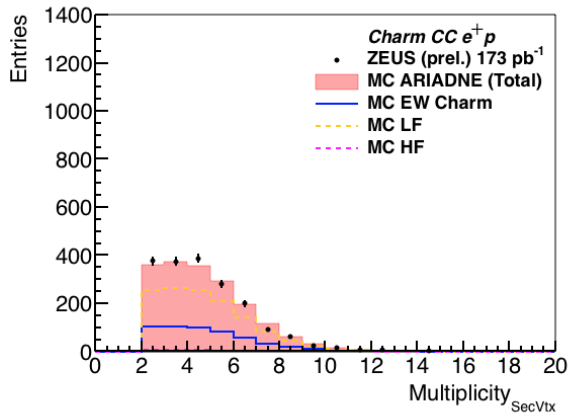
- MC overestimates trackings & secondary vertices.
- A secondary scaling applied to MC to match Data.

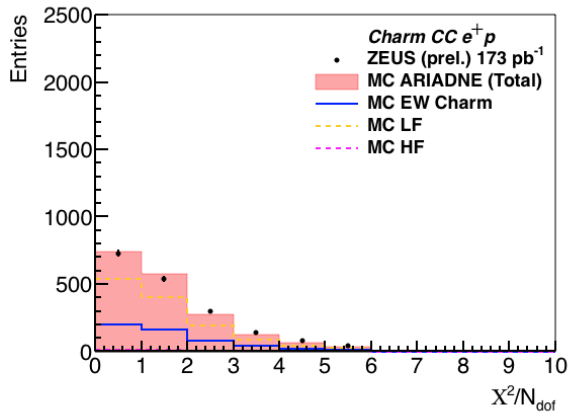
$$N_{SecVtx}^{DATA}/N_{SecVtx}^{MC} = 0.686 \ (0304p)$$
$$= 0.802 \ (05e)$$
$$= 0.810 \ (06e)$$
$$= 0.834 \ (0607p)$$

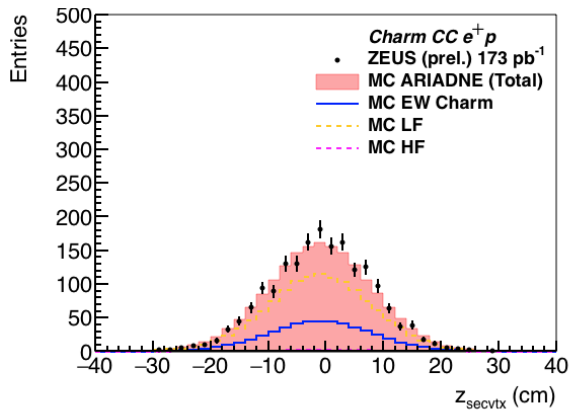
Control Plots – Secondary Vertex

e^+p

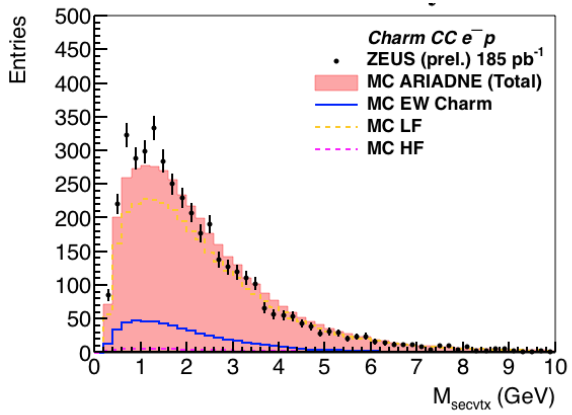


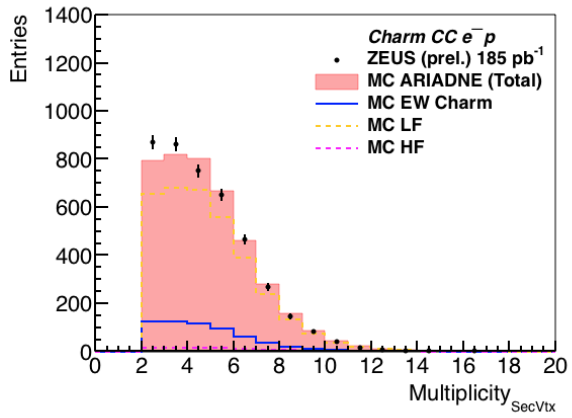


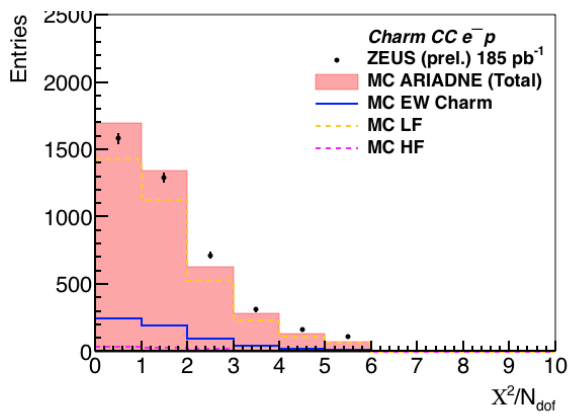


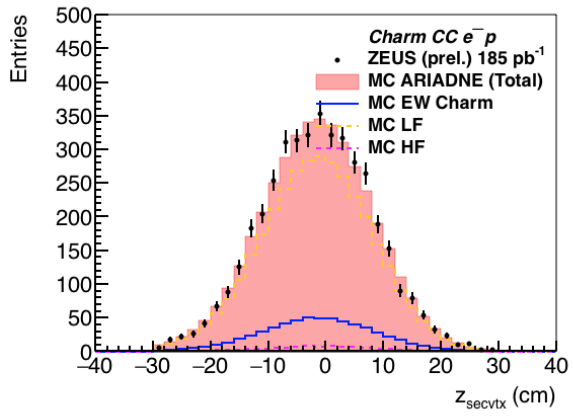


e^-p

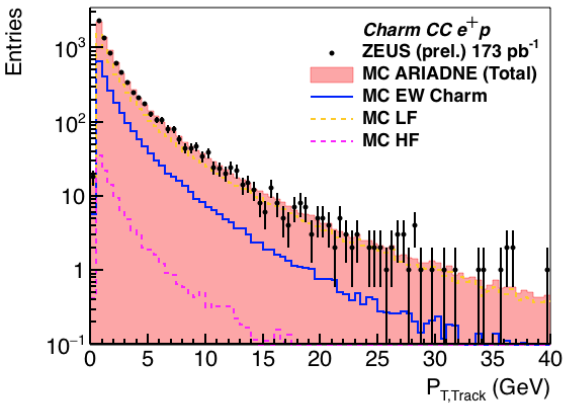


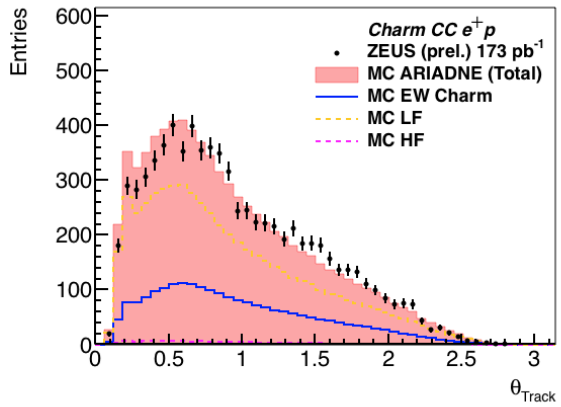


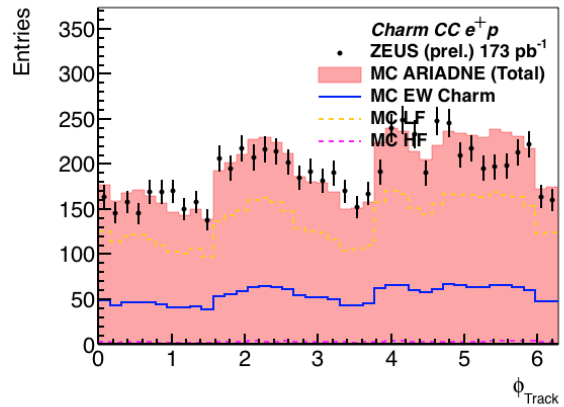


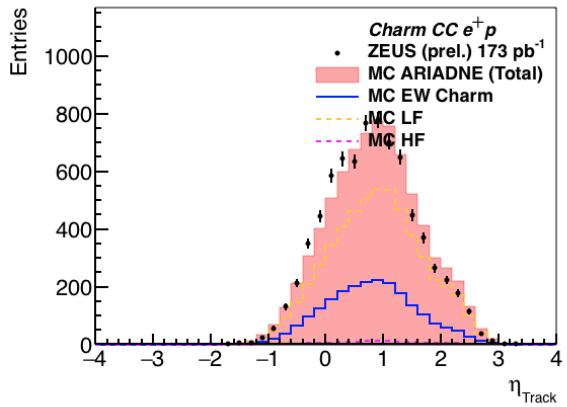


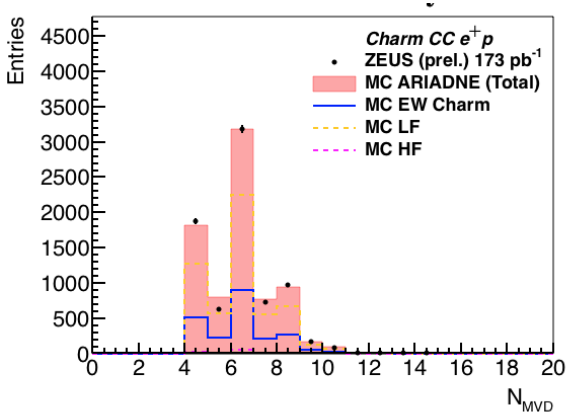
Control Plots – Tracks (e^+p)

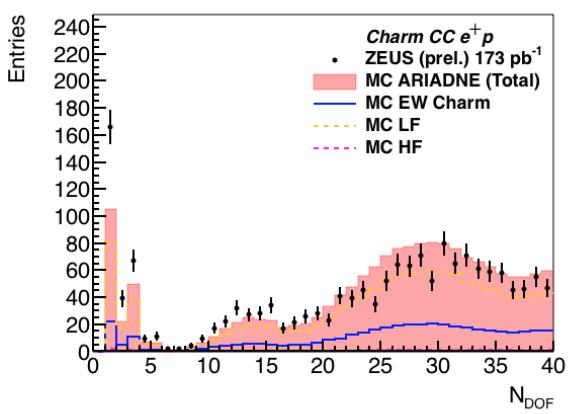


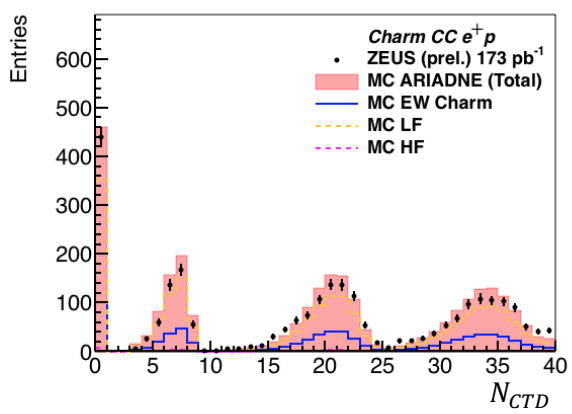


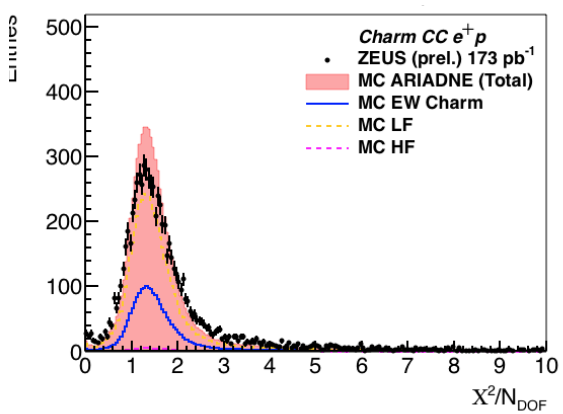




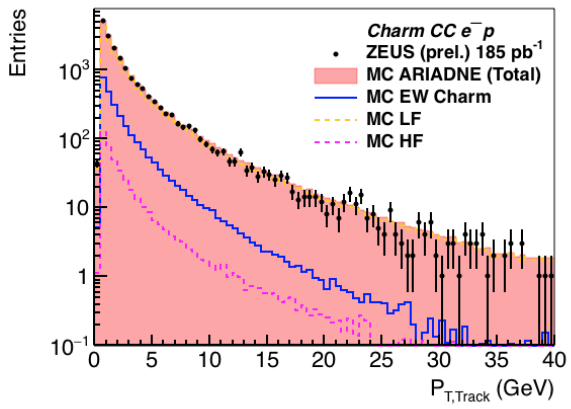


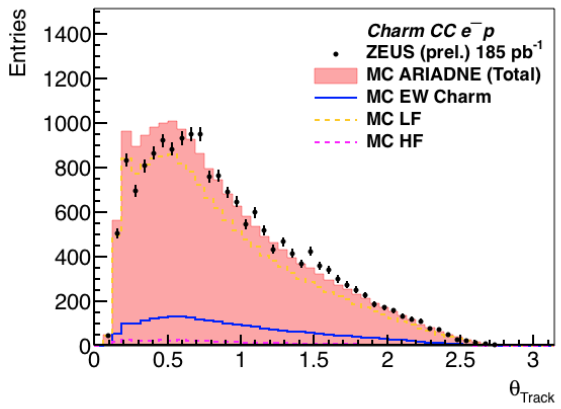


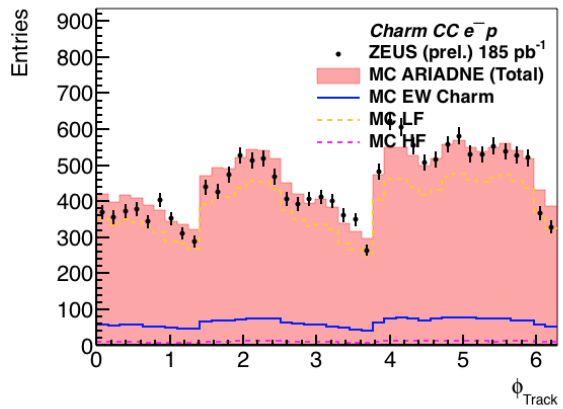


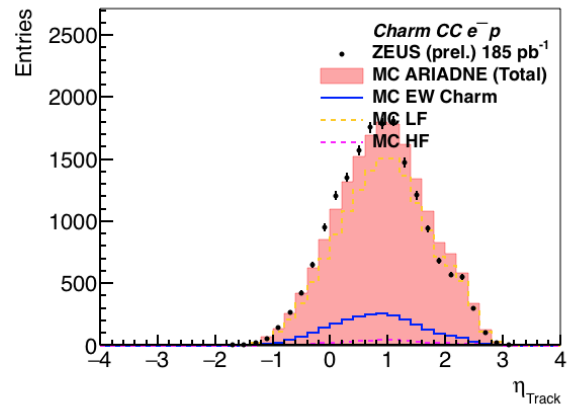


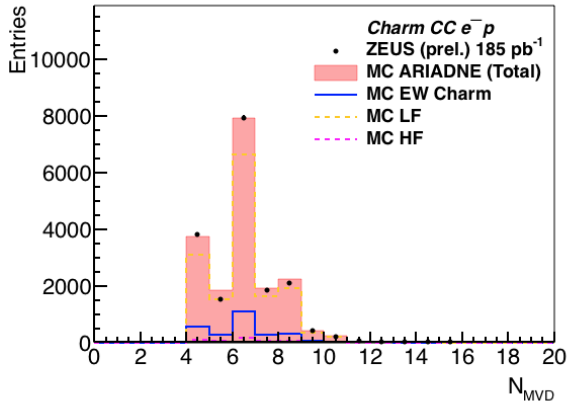
Control Plots – Tracks ($e^- p$)

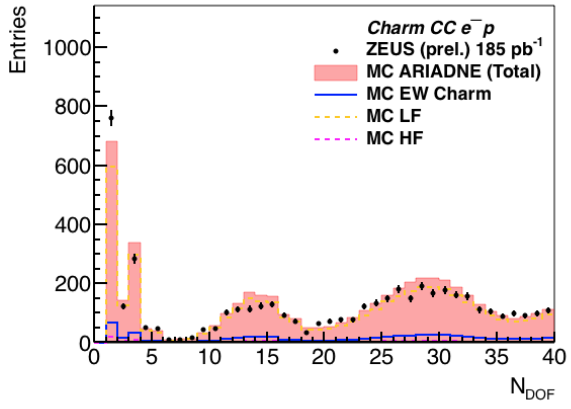


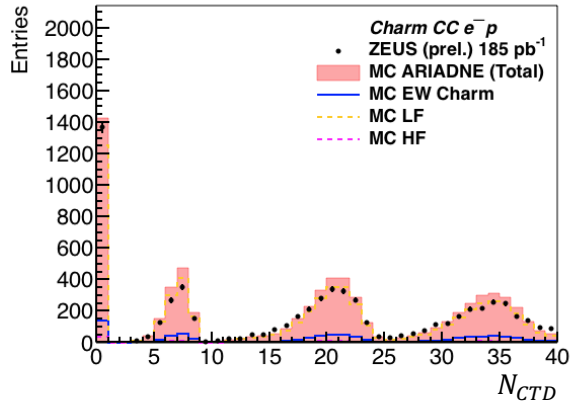


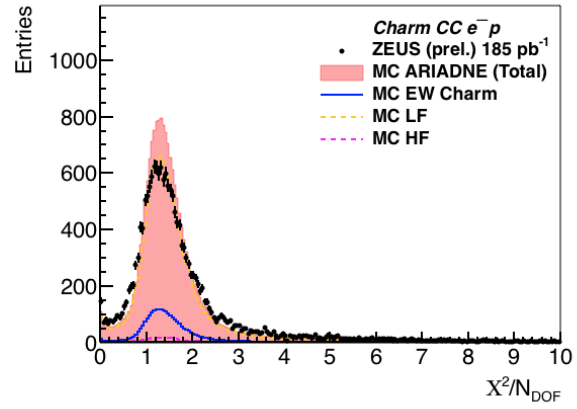






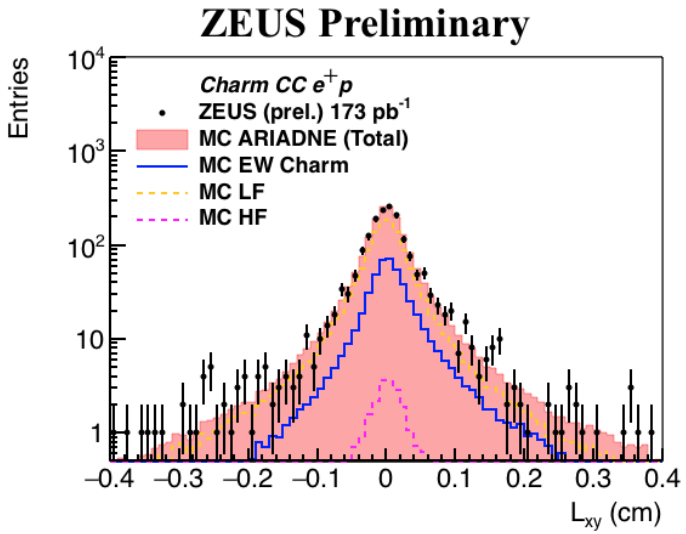


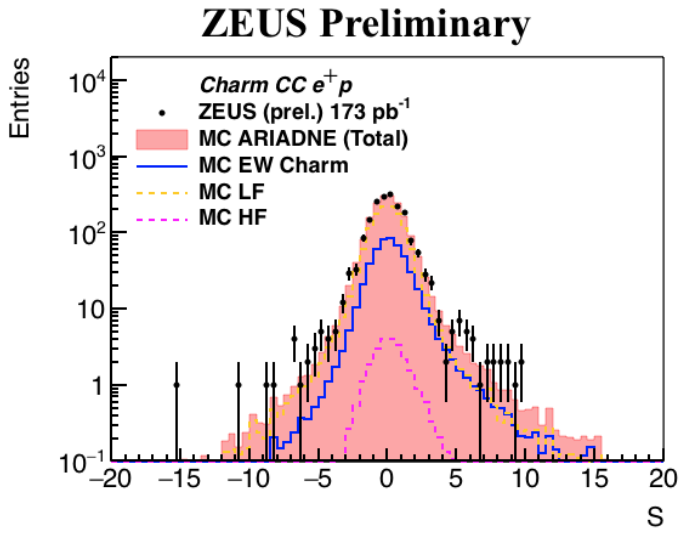




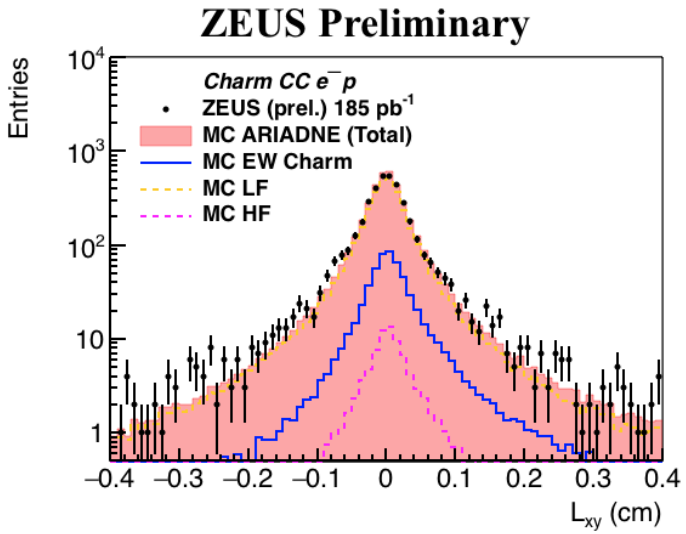
Decay Length Plots

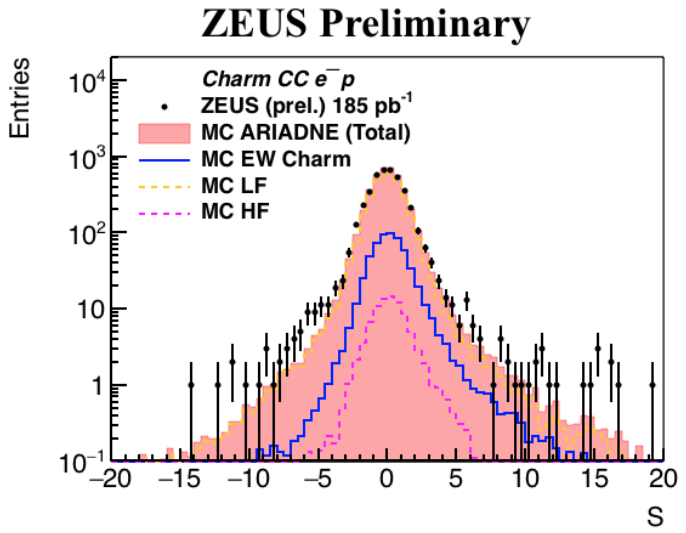
e^+p





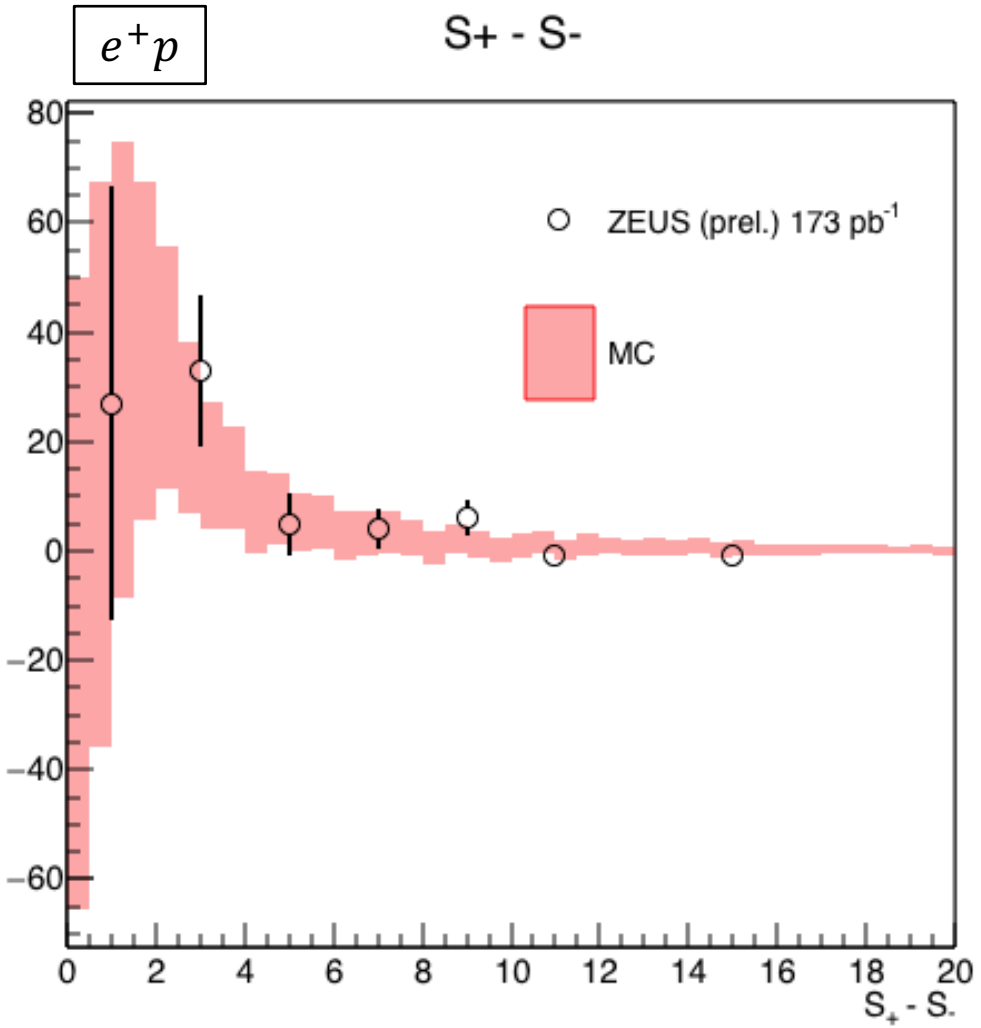
e^-p

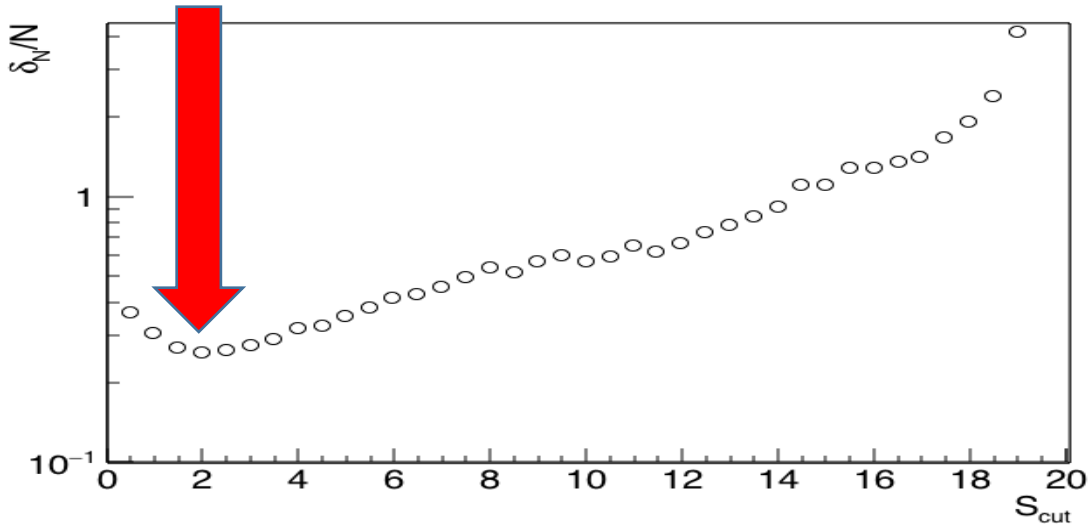




- Asymmetric charm signal observed.
- The high symmetry and large statistics around $S \sim 0$ contributes to a large statistical uncertainty in the low bin regions in S.
- A significance threshold cut was applied to reduce overall statistical uncertainty.

Significance Threshold

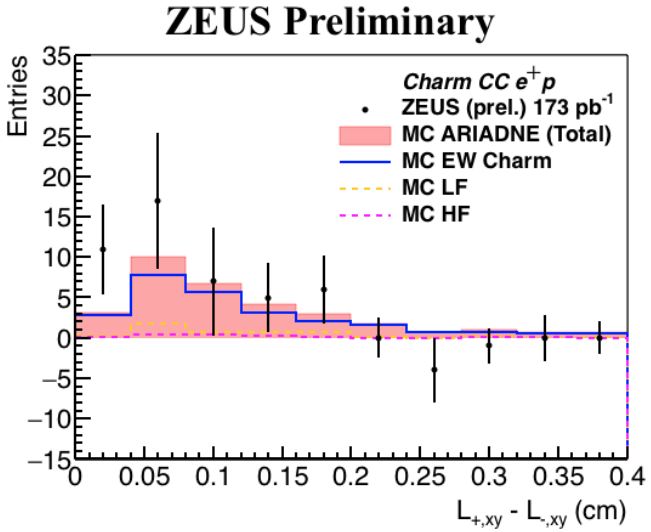


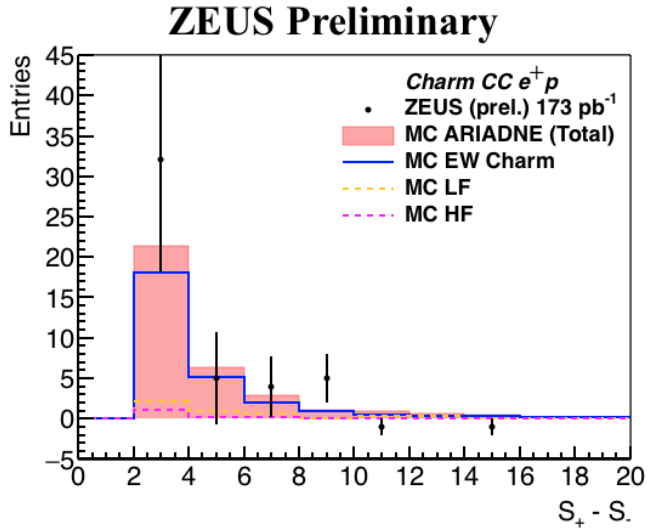


- The high symmetry and large statistics around $S \sim 0$ contributes to a large statistical uncertainty.
- A significance threshold cut was applied to reduce overall statistical uncertainty.
- From MC, the lowest δ/N is achieved if cut were to be applied at $S = 2$.

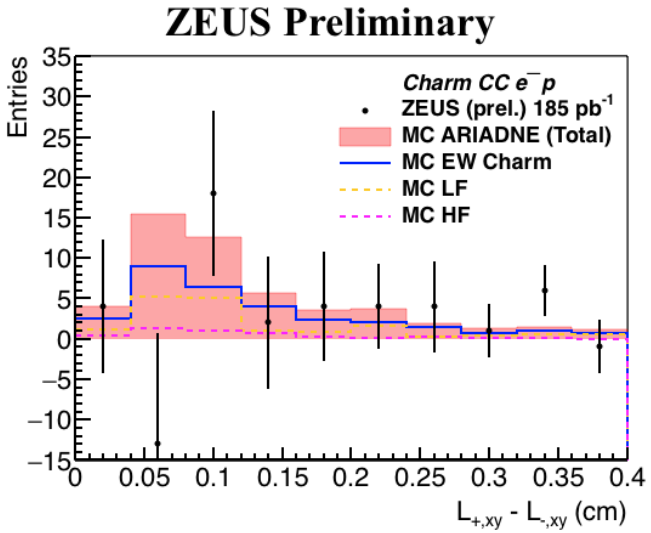
Mirrored Decay Length

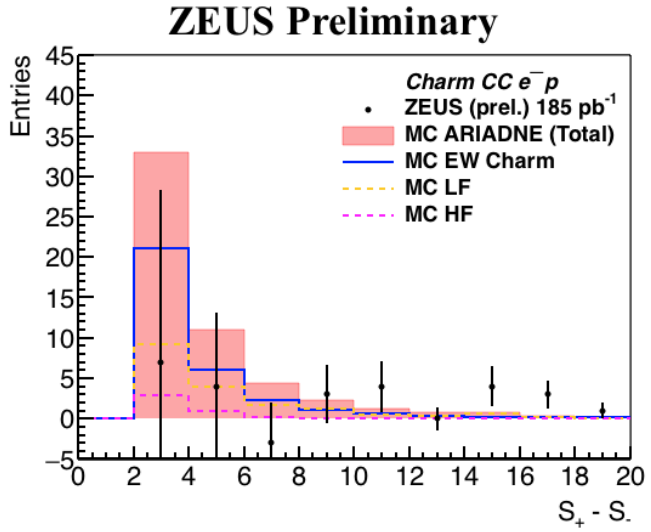
e^+p





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, $\sigma_{charm,CC}$.

Inverse correlation matrix

- Good agreement between True and Reconstructed Q^2.

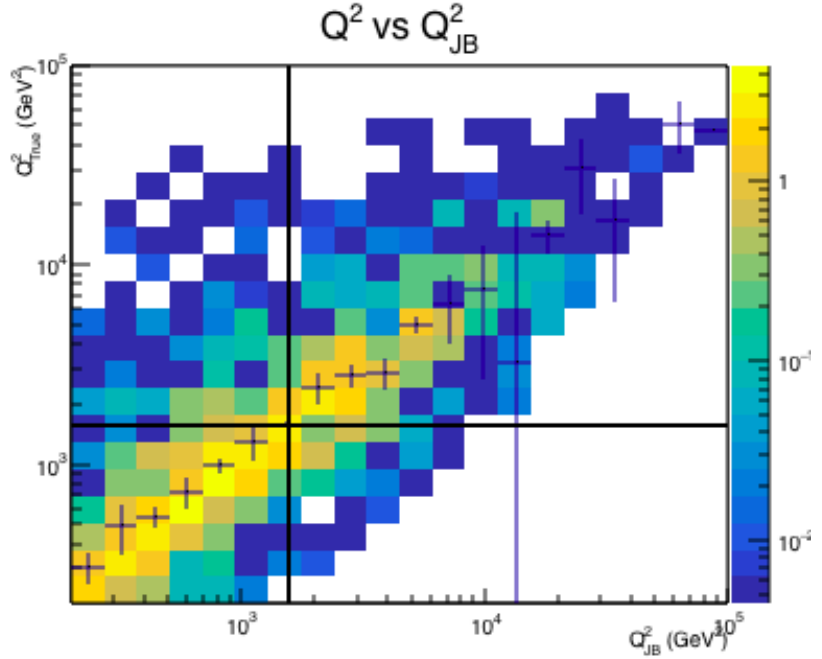
$$N_i = \sum_j C_{ij}^{-1} M_j$$

$N_i = true\ number\ of\ entries\ in\ bin\ i$
$M_i = reconstructed\ number\ of\ entries\ in\ bin\ i$
$C_{ij}^{-1} = inverse\ correlation\ matrix\ element\ for\ bin\ i,j$

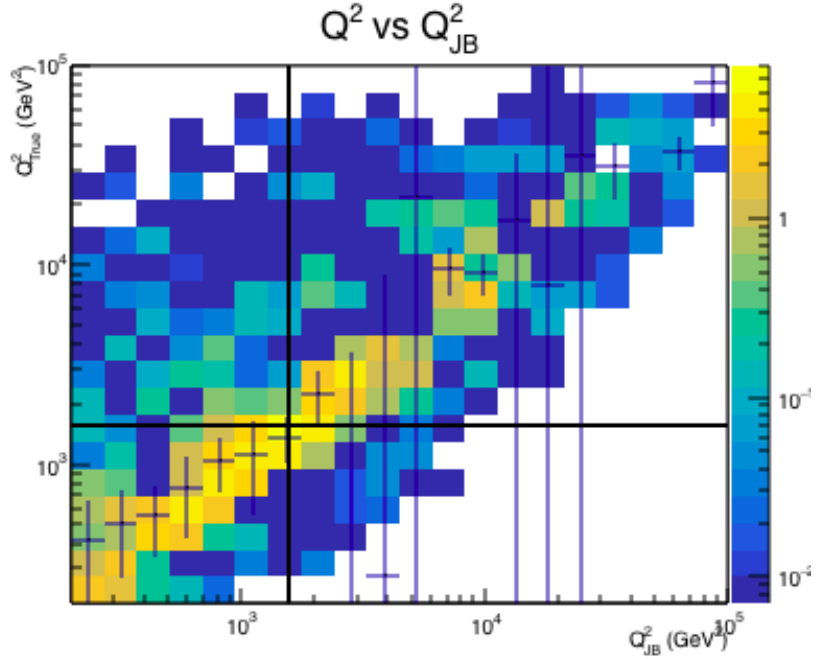
$C_{ij}^{-1}\ (e^+p)$	$j=1$	$j=2$
$i=1$	0.90	0.07
$i=2$	0.10	0.93

$C_{ij}^{-1}\ (e^-p)$	$j=1$	$j=2$
$i=1$	0.91	0.13
$i=2$	0.09	0.87

$e^+ p$



$e^- p$



Systematic Uncertainty

Source	Variable	Nominal Value	Variation	e^+p $\delta_{\sigma_{vis}}(pb)$	e^-p $\delta_{\sigma_{vis}}(pb)$
DIS Selection	P_T	12 GeV	11 GeV	-0.03	-0.02
			13 GeV	-0.10	0.03
	Z_{vtx}	30 cm	25 cm	0.44	0.67
			35 cm	0.00	-0.01
Calorimeter	E_T^{jet}	5 GeV	-3%	0.02	0.02
			$+3\%$	0.02	-0.03
Background	M_{bg}		-30%	0.58	1.70
			$+30\%$	-0.58	-1.70
SecVtx Rescaling	Rescaling only applied to LF			-0.66	0.95
Signal Extraction	S_{cut}	2	± 1	± 2.6	± 5.9
Luminosity	L			$\pm$ 2%	
Sum (exclud. Luminosity)				2.70	6.25
				2.75	6.14

δ_1 DIS Selection

- Criteria associated with more than 1% uncertainty is listed.

δ_2 Calorimeter

- Due to imperfect calibration of hadronic calorimeter (HAC). Uncertainty in E_T^{jet} is known to be $\pm 3\%$. The reconstructed E_T^{jet} cut was varied 3% for MC events.

δ_3 Background

- Asymmetry in LF decay length due to long-lived LF particles.
- Due to the higher background count, the uncertainty due to background contribution is larger in e^- beam periods. It is expected that the uncertainty from this criterion will go down as the optimization progresses.

δ_4 Secondary Vertex Rescaling

- More secondary vertices survive in MC than in data. Rescaling was only applied to the light-flavor signal to account for different causes of the discrepancy.
- Also higher in e^- beam periods due to the large LF background count.

δ_5 Signal Extraction

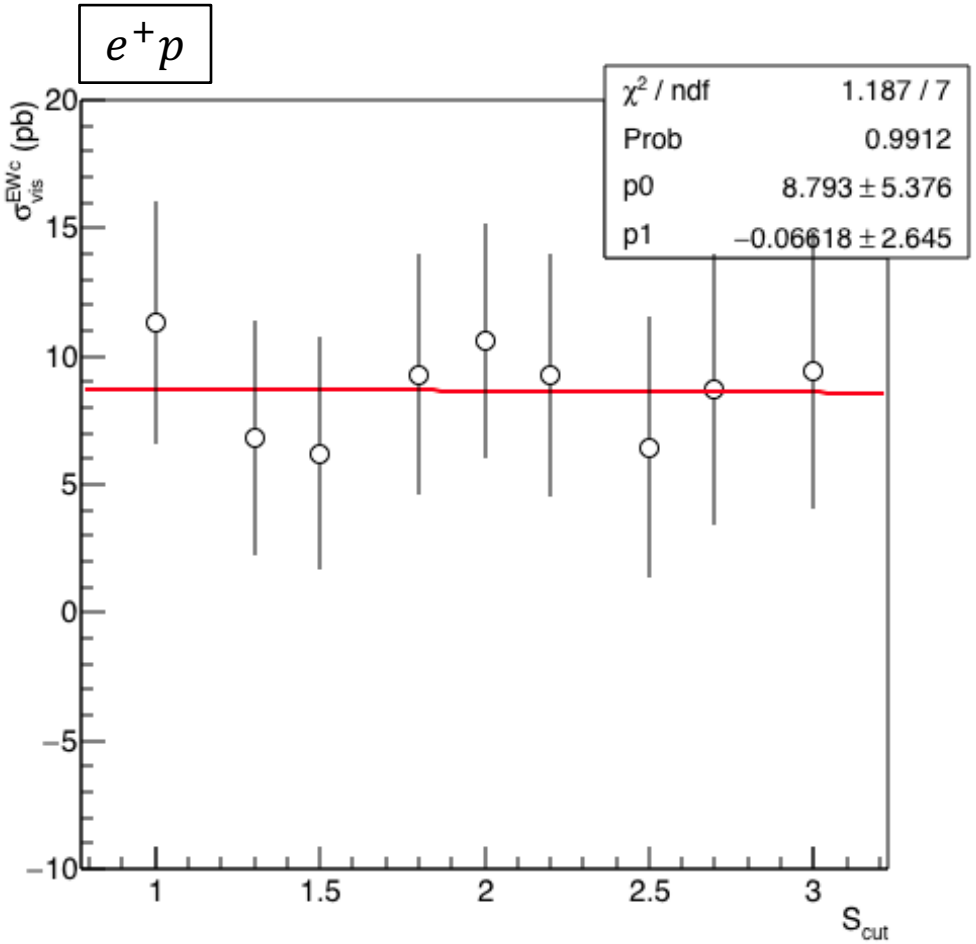
- Significance cut value was varied by 0.5 up and down. Due to the low statistics & high fluctuation in data, further study was performed. This will be discussed in the following slide.

Variation	e^+p $\delta_{\sigma_{vis}}(pb)$	e^-p $\delta_{\sigma_{vis}}(pb)$
1.5	-4.41	-2.89
2.5	-4.16	8.04

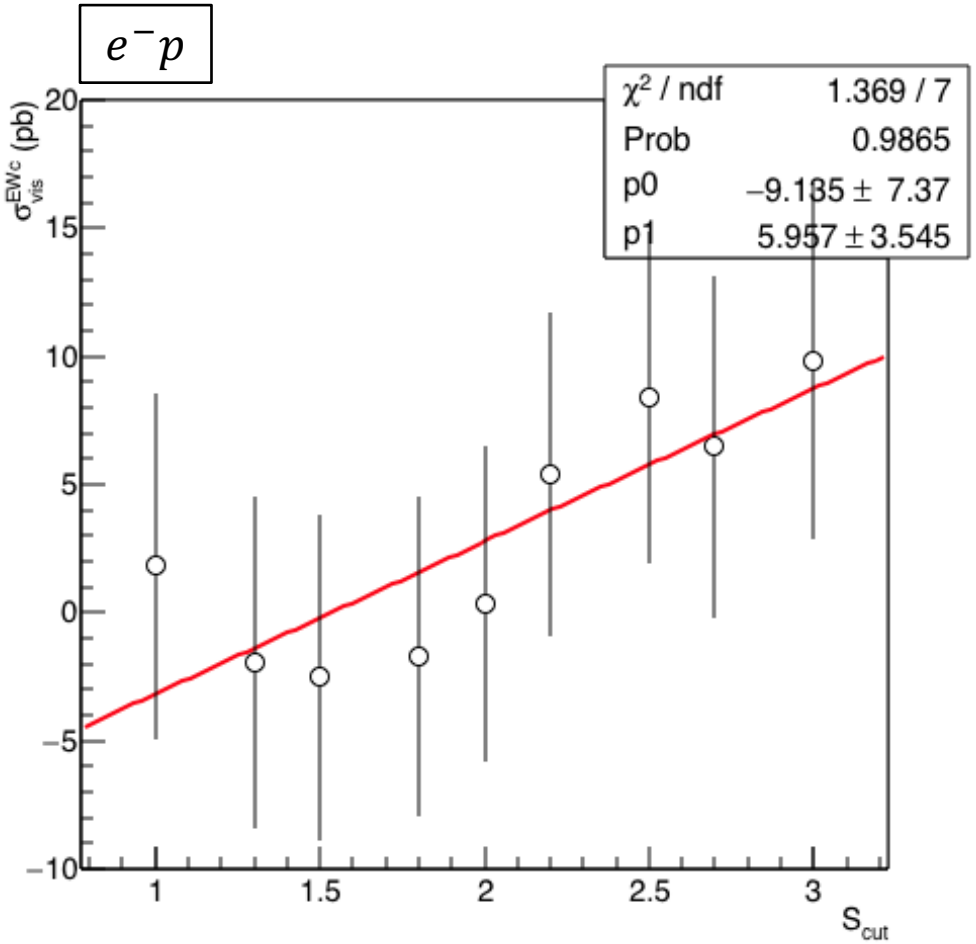
δ_6 Luminosity

- Uncertainty in ZEUS luminosity measurement. Known to be $\pm 2\%$.

Syst. unc. from signal extraction

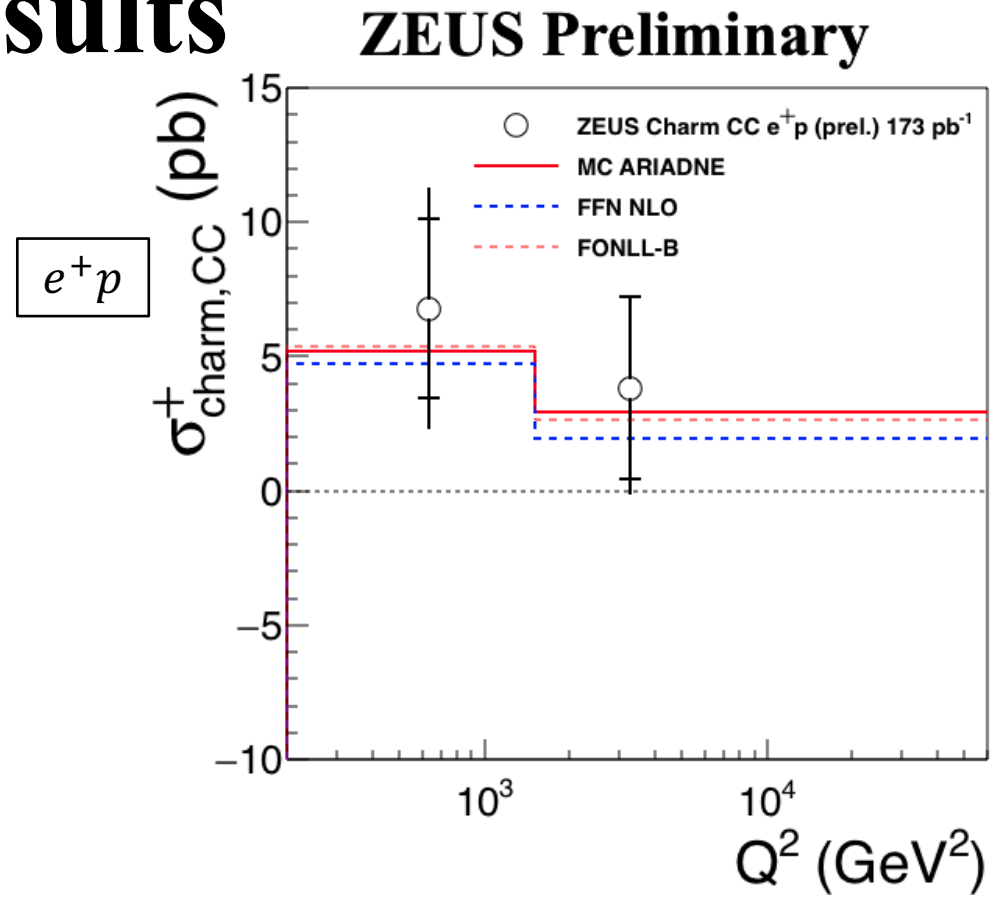


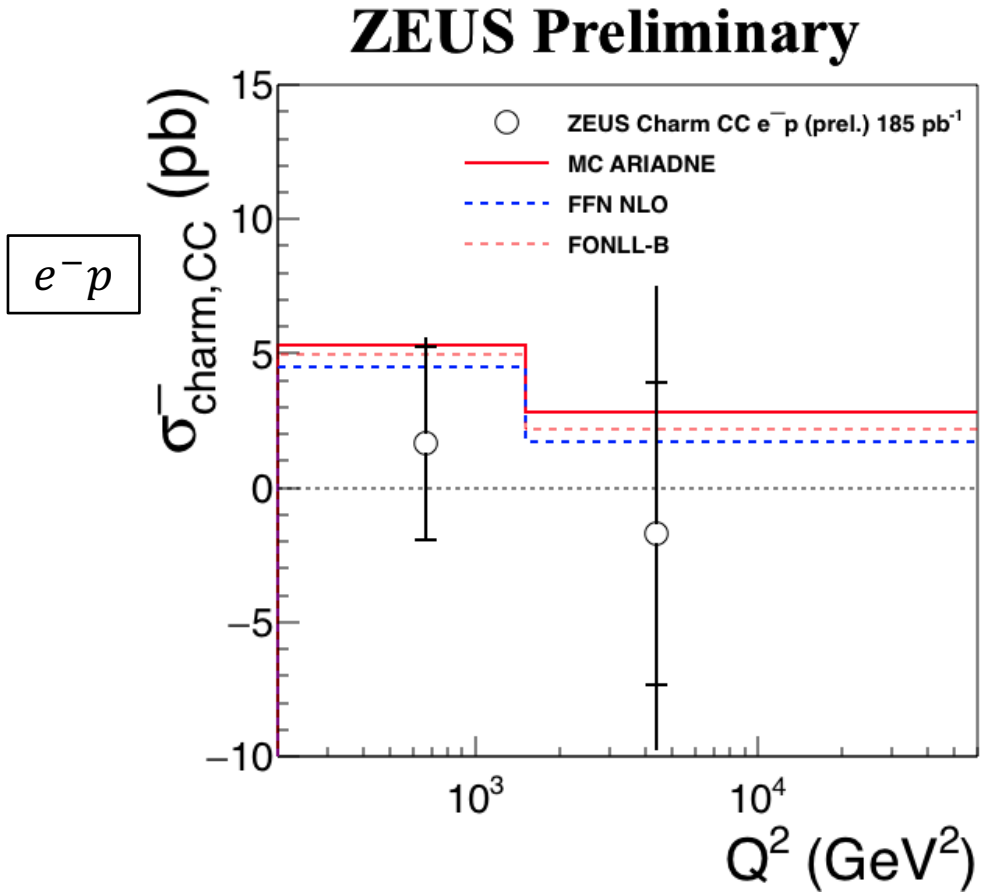
- Systematic uncertainty taken from the uncertainty in slope.



- Systematic uncertainty taken from the slope.

Results

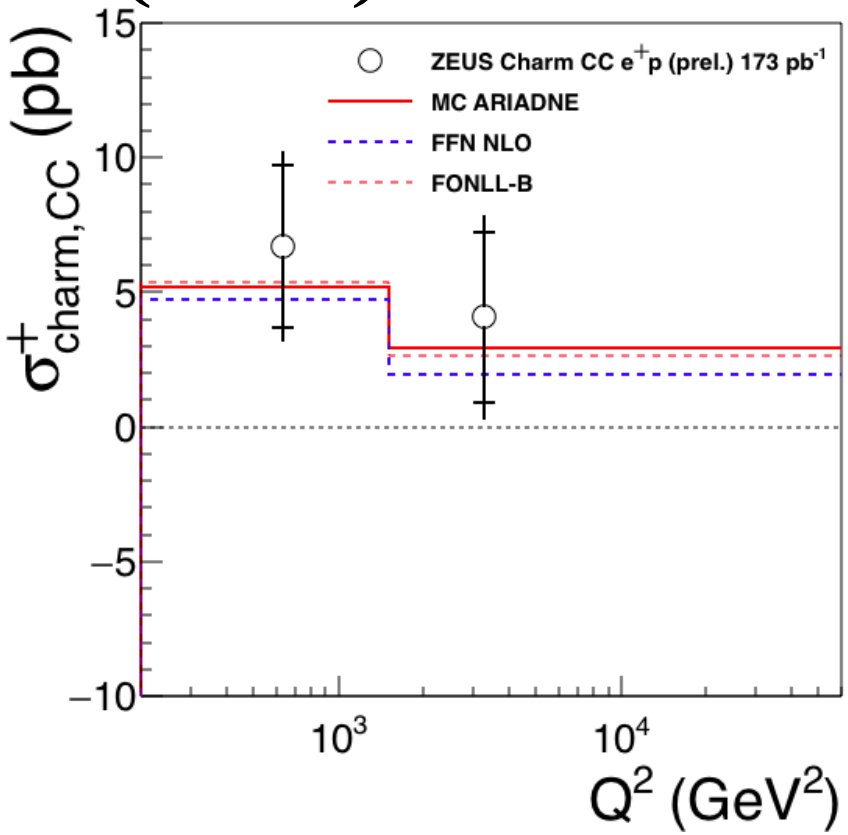


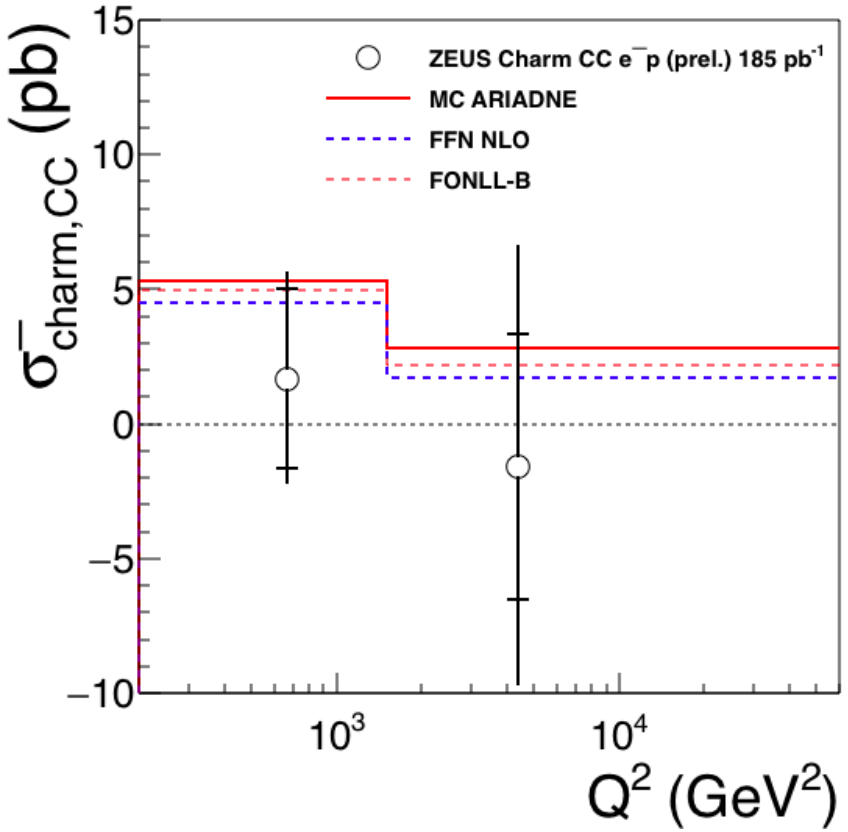


- EW charm cross sections have been measured.
- Reasonable agreement between data, MC & theory with a large uncertainty.
- MC & theory predictions suggest that the contributions from QI and BGF processes are about equal.

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

Results (new)



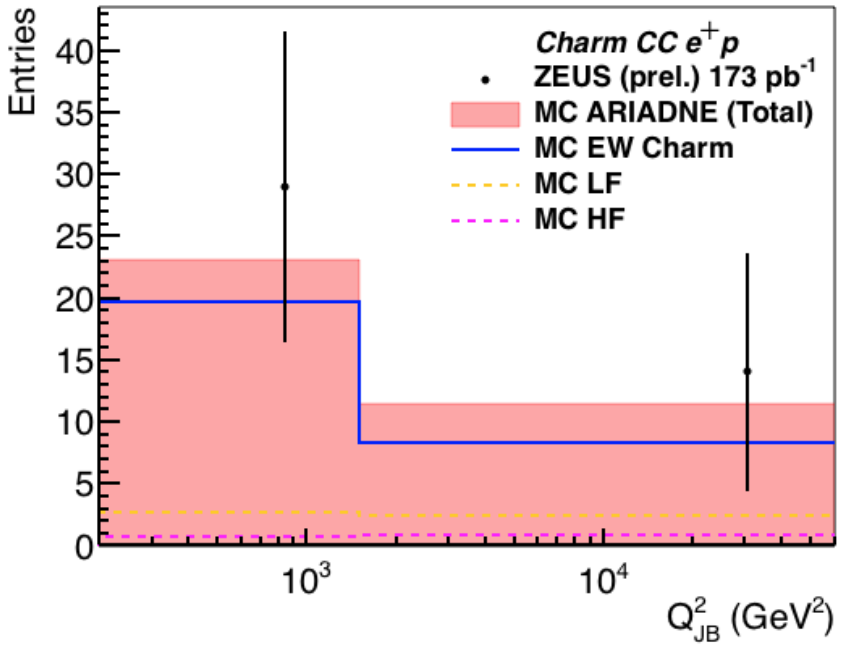


- Inverse correlation matrix was used, instead of bin-by-bin correction.
- New values for systematic uncertainties from signal extraction were used.
  - Note that syst. unc.'s have not been recalculated with inverse matrix applied.

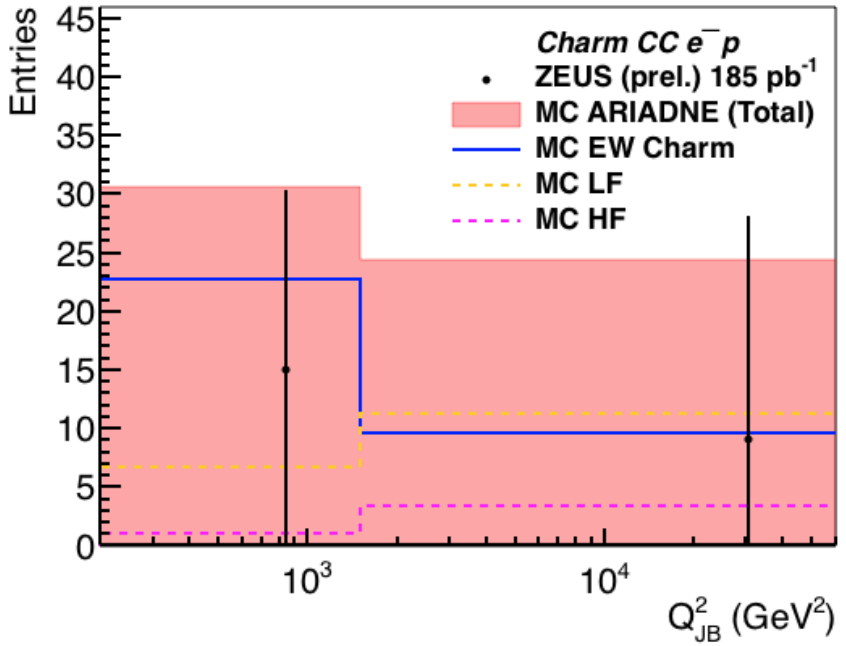
Remaining Tasks…

- LF background
  - A good contribution from LF background survives the decay length mirroring.
  - What they are needs to be identified. e.g. longer-lived LF particles?
  - Further cuts have been investigated to reduce this background contribution.

e^+p



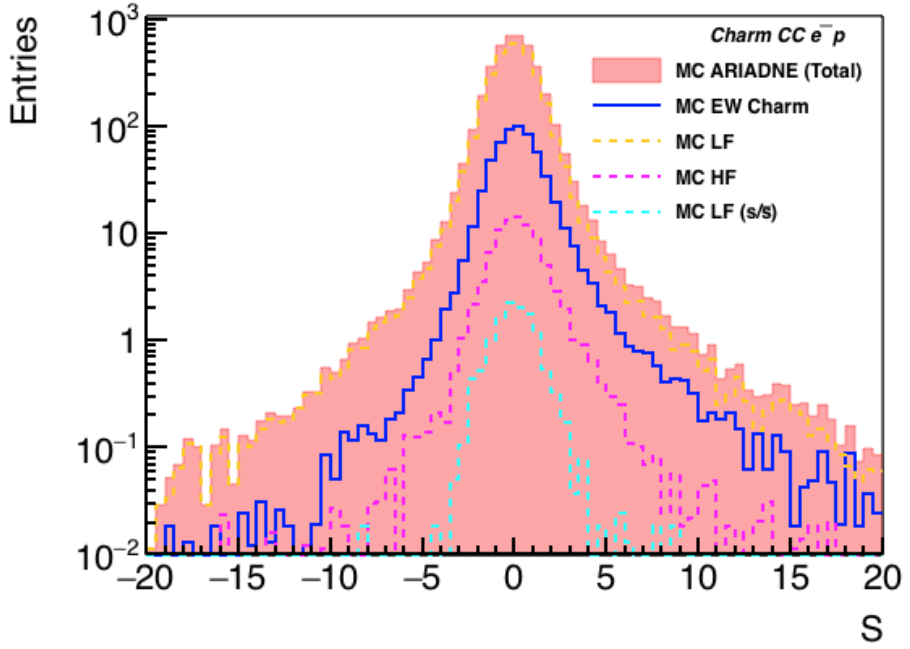
e^-p

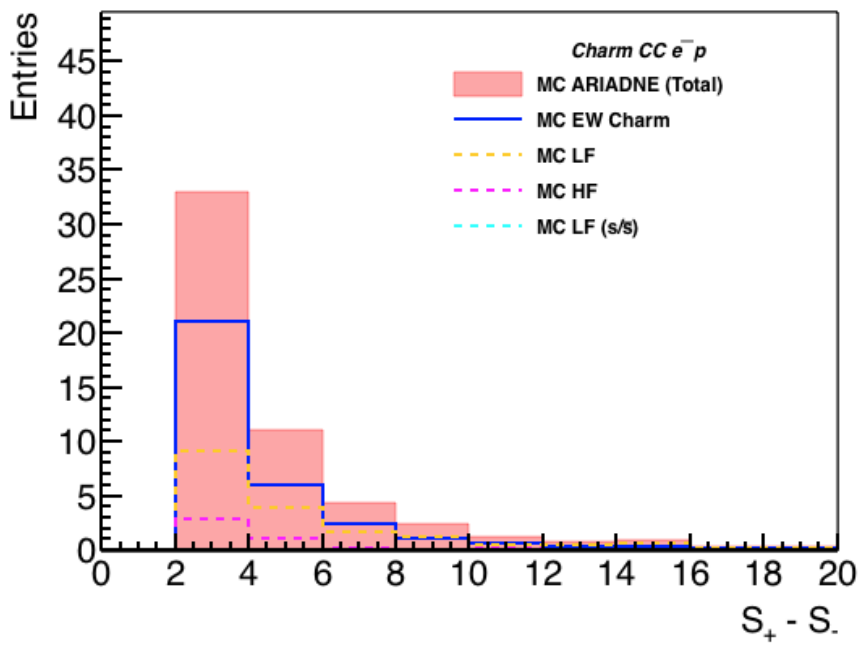


LF Background – Initial Thought

- Some LF particles have a long lifetime, which then allows them to survive after the mirroring.
- The longer-lived particles (K's, Λ's, etc) were separated from LF background (Cyan).

$\boxed{e^- p}$

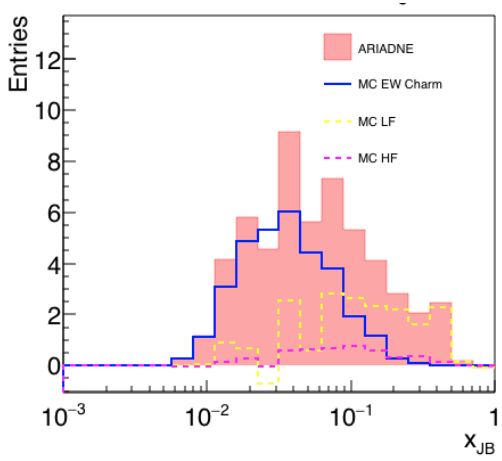


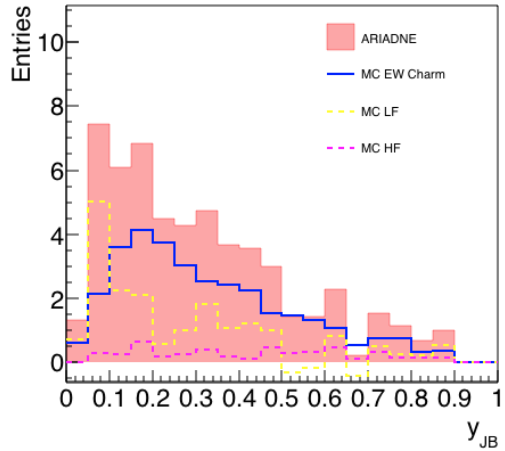


- No significant contribution from these events were observed.

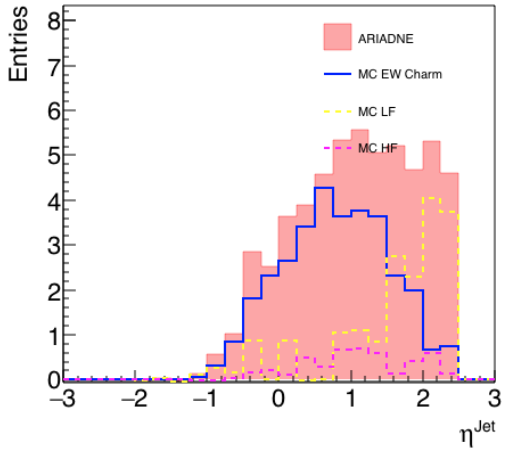
LF Background

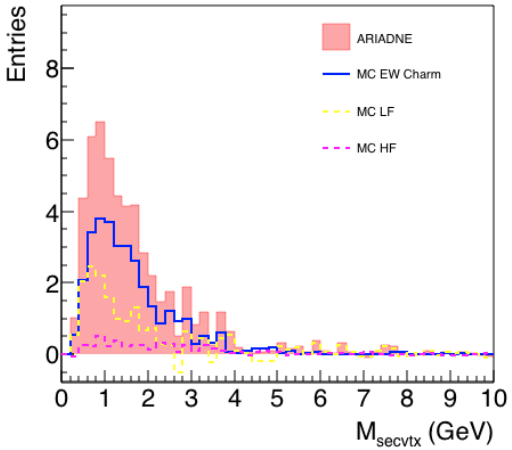
- The LF discriminating variables have been discussed in the preliminary presentation.
  - $x > 0.1, \quad y < 0.2$
  - $\eta^{jet} > 1.5$
  - $m_{secvtx} < 1\ GeV, \quad N_{trk\ per\ secvtx} < 3$

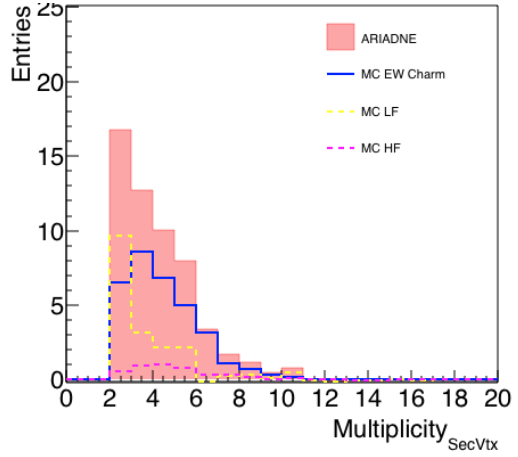




- Particle level MC info does not suggest anything in particular.
  (Info stored in ~namjae/public/updates/update_20180829/particleList_0304p, 05e, 06e, 0607p)

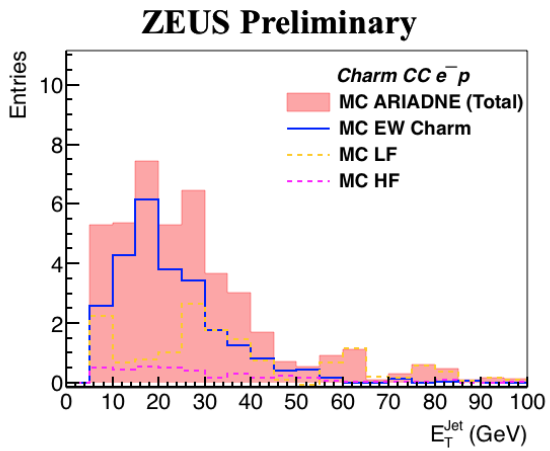


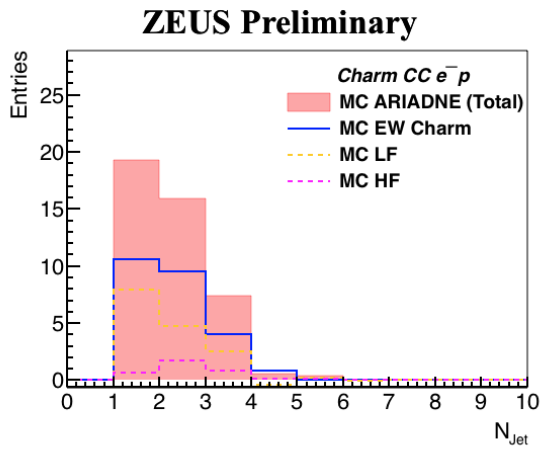


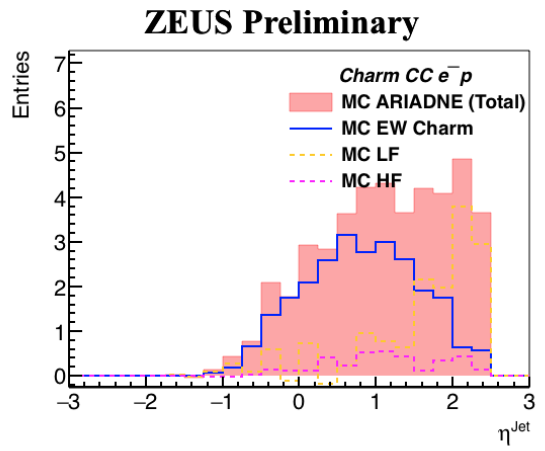


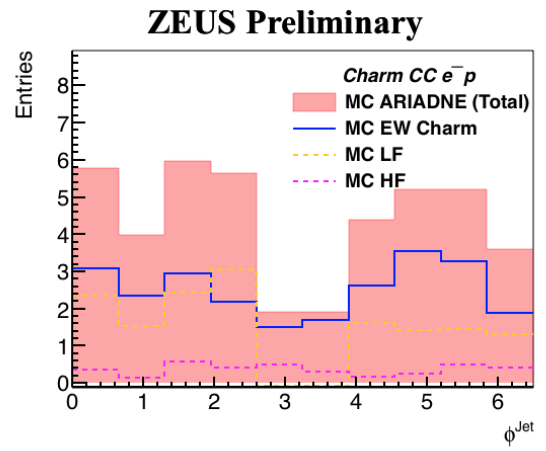
Mirrored Control Plots – Jets

05e

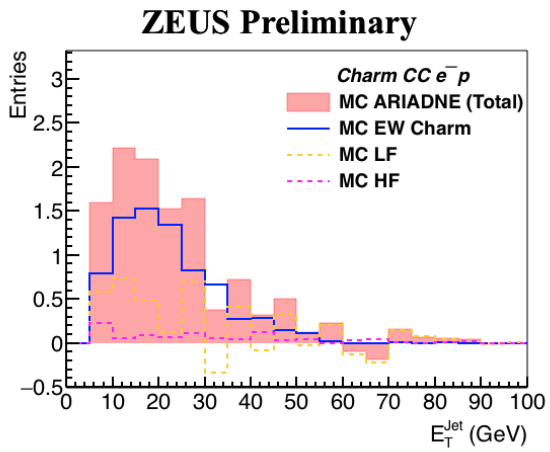


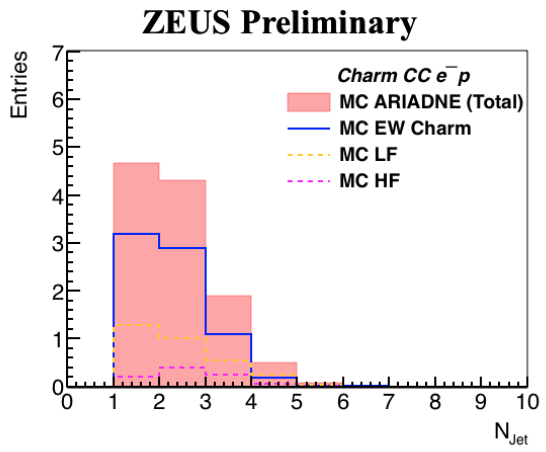


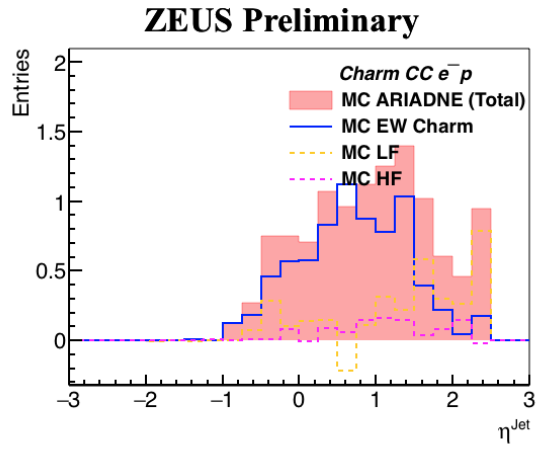


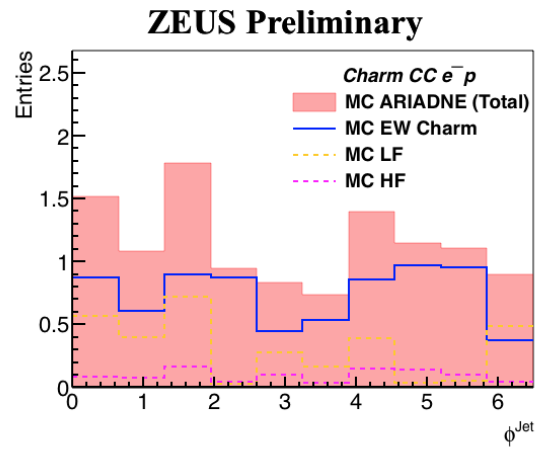


06e



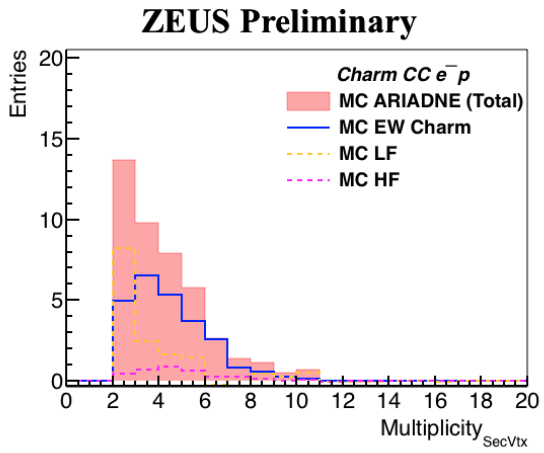


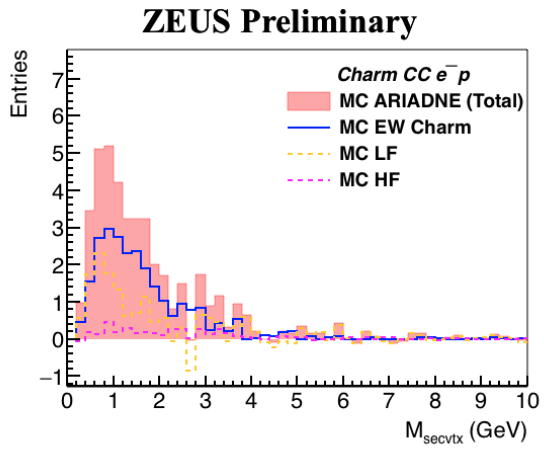


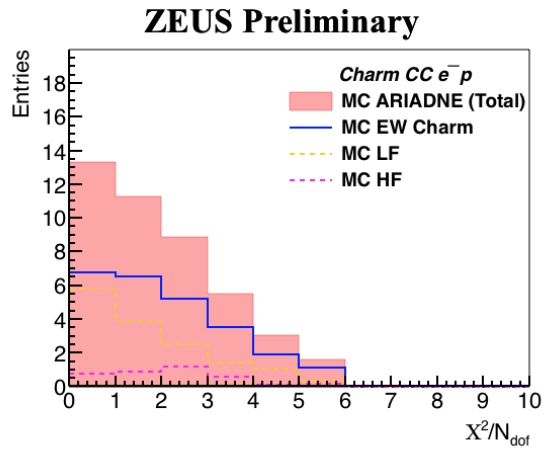


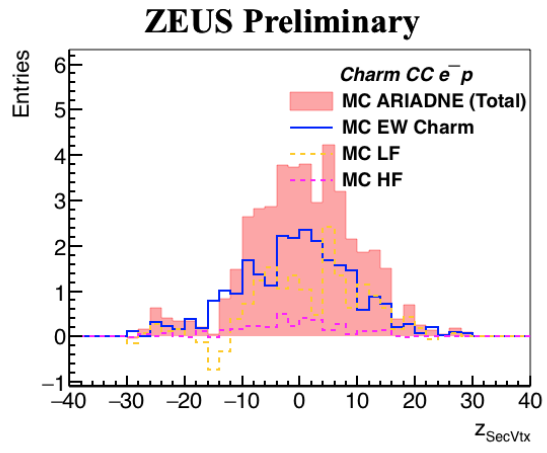
Mirrored Control Plots – Sec Vtx.

05e

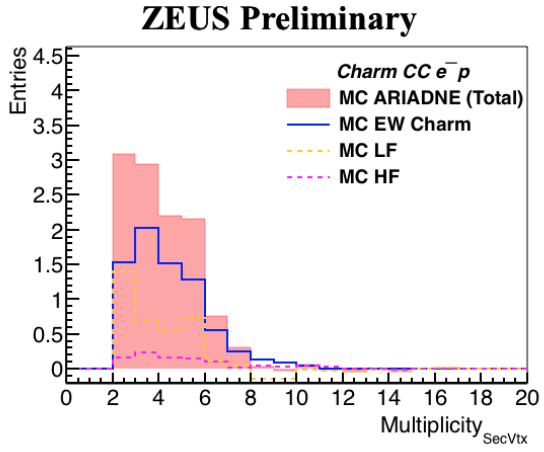


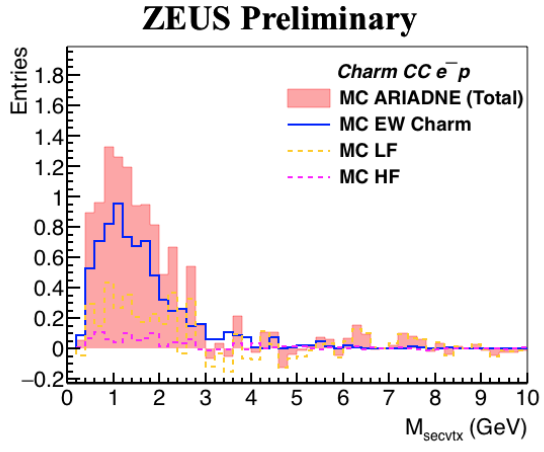


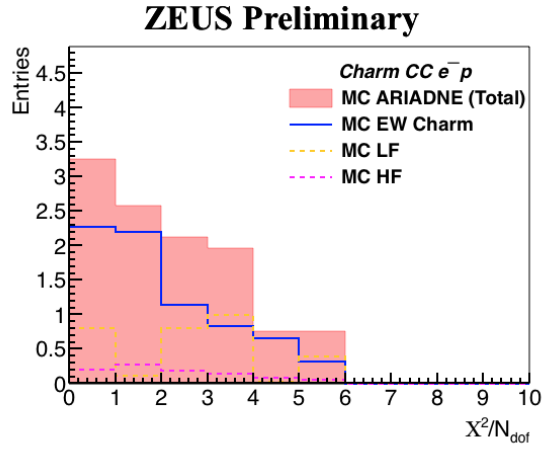


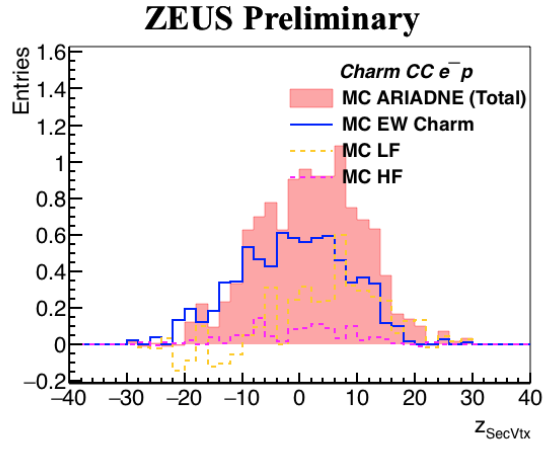


06e

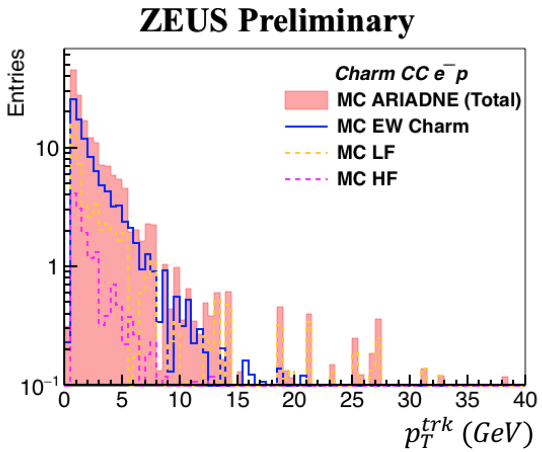


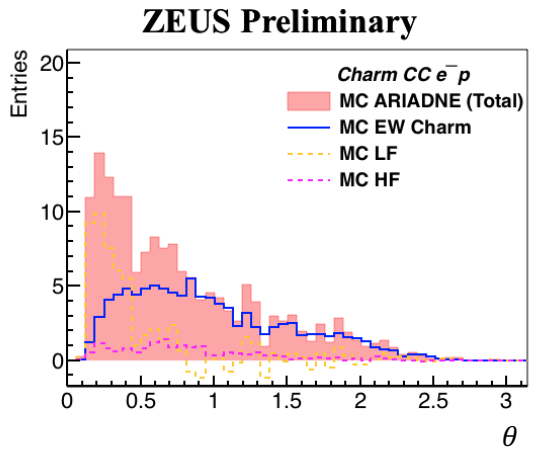


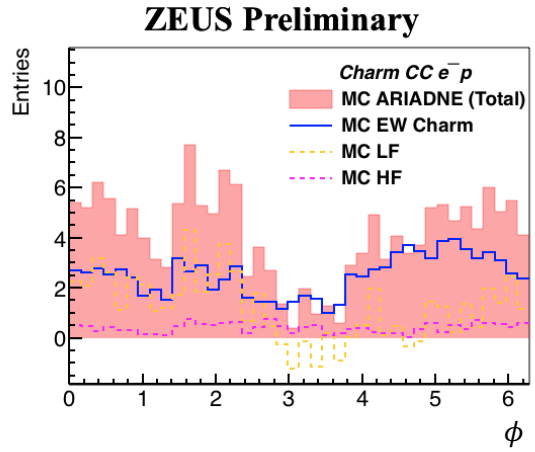


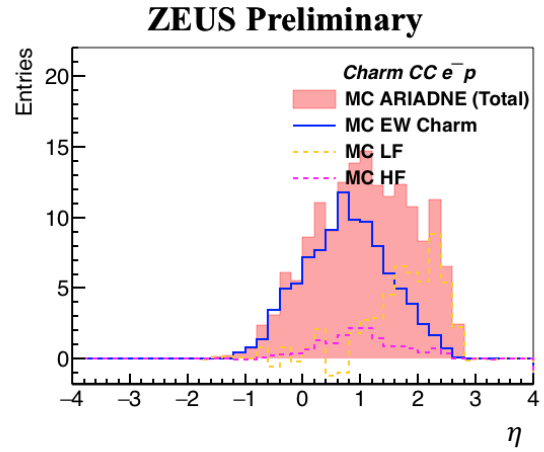


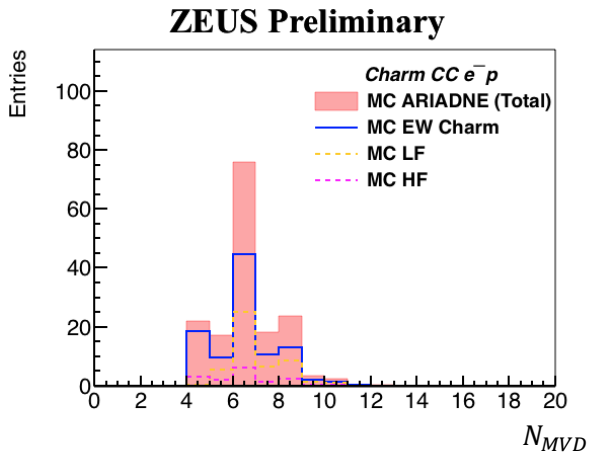
Mirrored Control Plots – Tracks (05e)

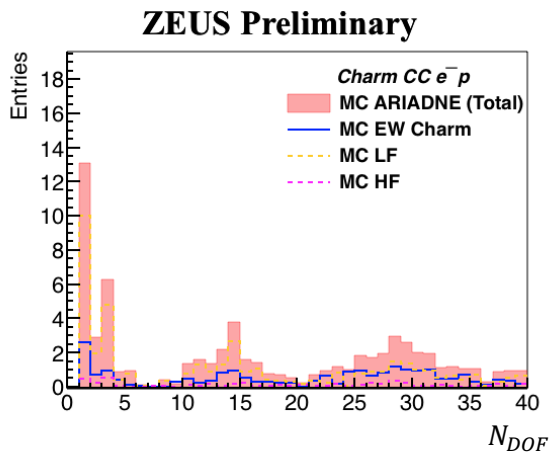


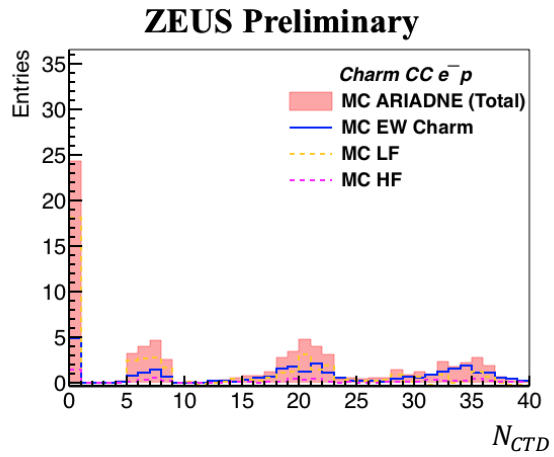


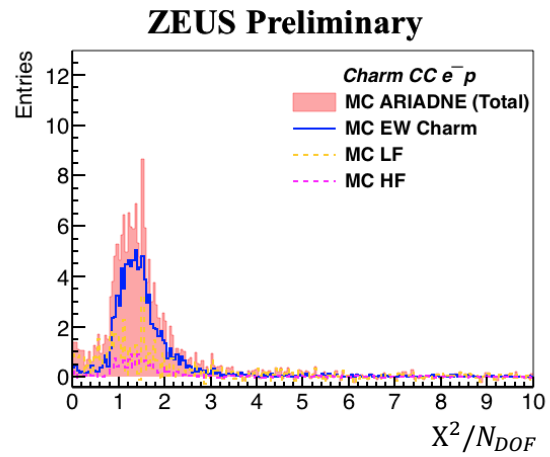




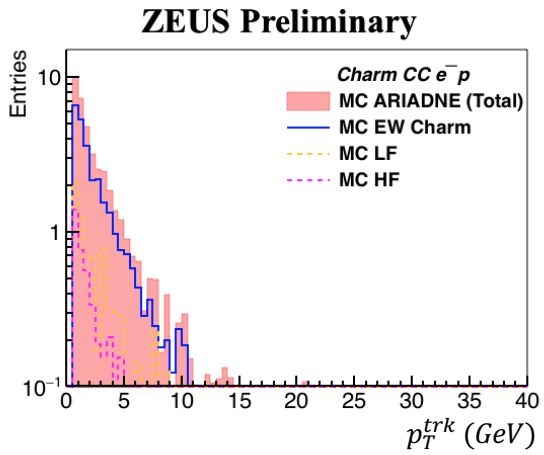


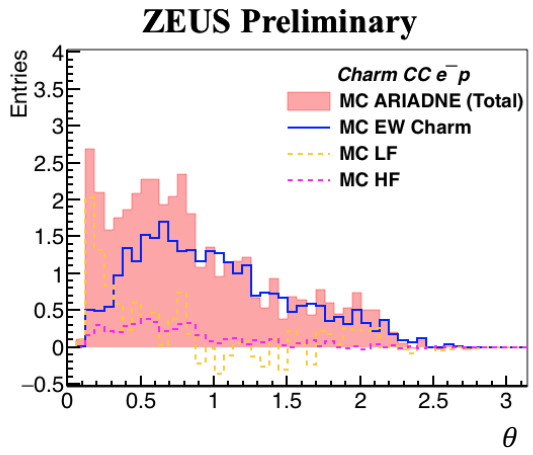


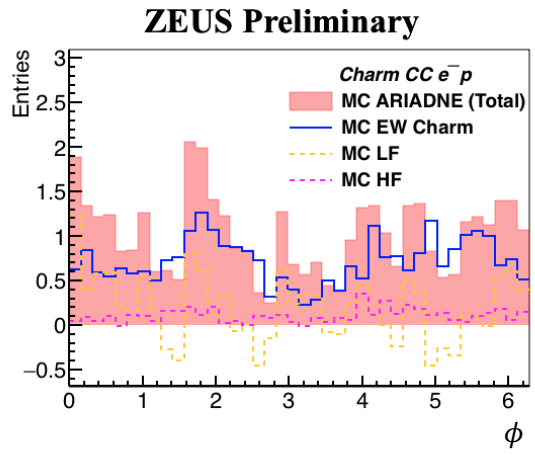


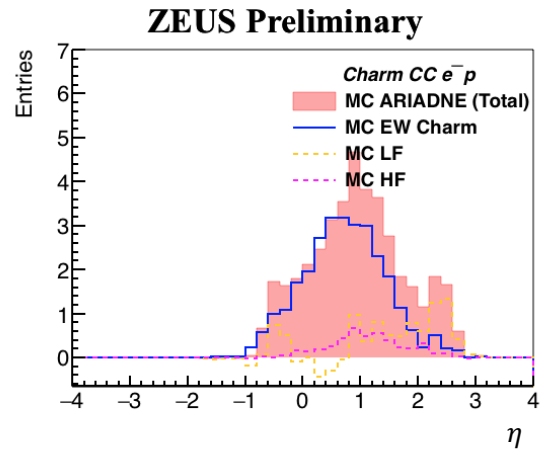


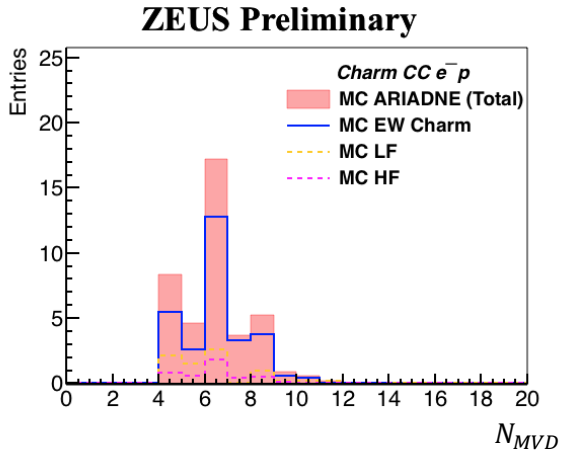
Mirrored Control Plots – Tracks (06e)

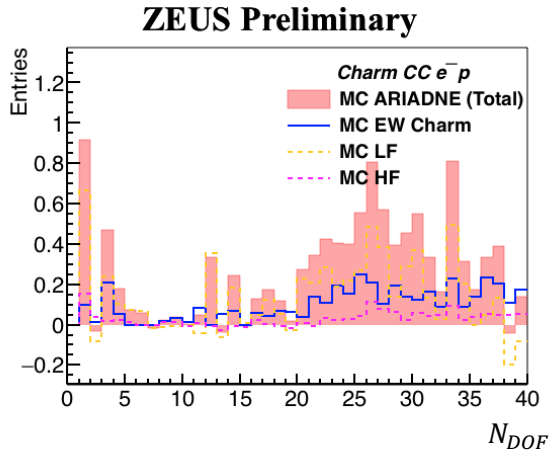


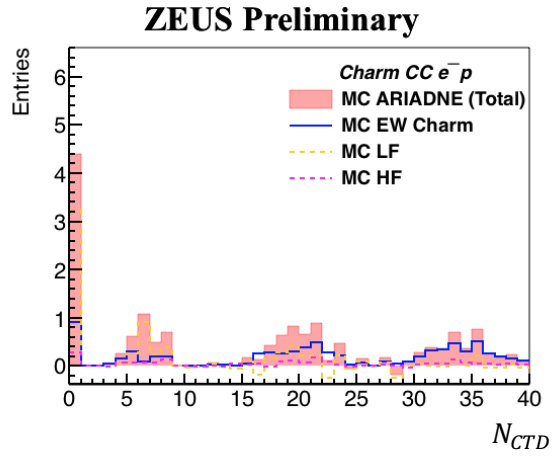


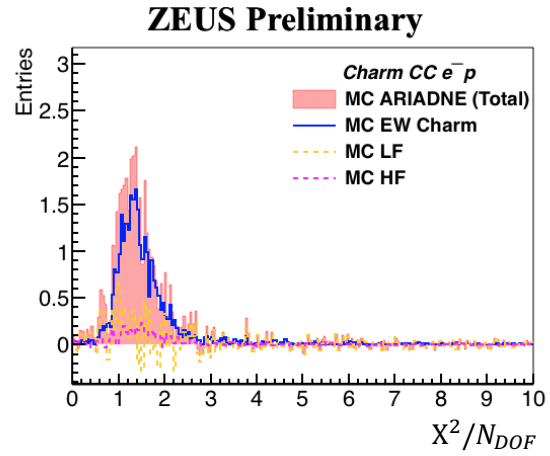












Summary

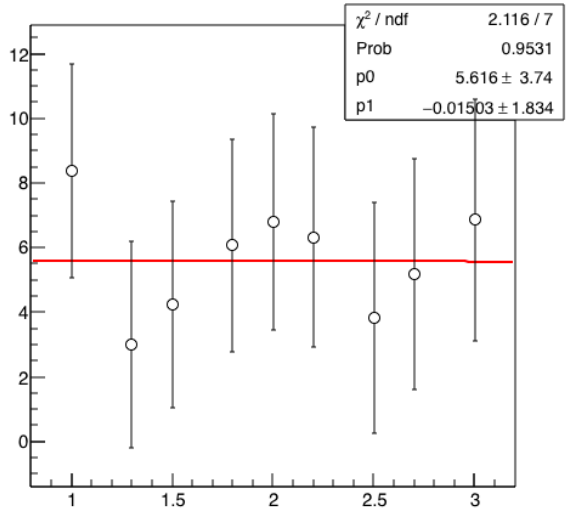
- Inverse correlation matrix has been quantified for both electron and positron beam periods.
- Systematic uncertainty associated with signal extraction has been estimated by fitting the repeated cross section measurement with different threshold location.
- LF background in $e^- p$ period has been looked into.
  - It was observed that longer-lived LF particles do not contribute to the large LF background in electron beam periods
  - A number of LF discriminating variables have been identified and particle lists have been produced. But, no significant pattern was observed.

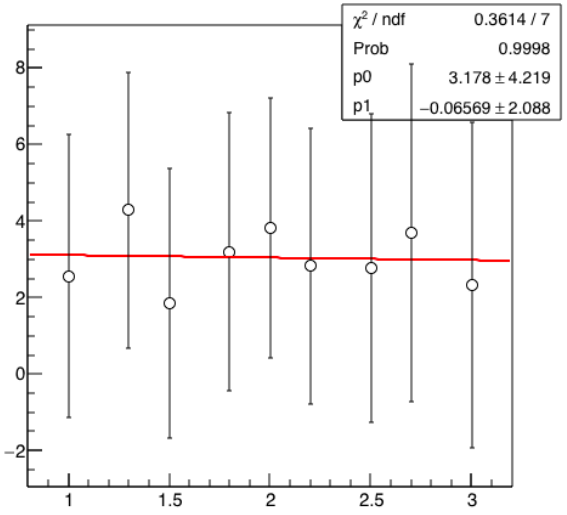
Back-up slides

Significance cut

Bin 1 | Bin 2

e^+p





e^-p