Paper Preview:
Measurements of W^+/W^- cross-section ratio in pp Collisions at RHIC

Jae Nam, Matt Posik, Bernd Surrow

Temple Univ.

Information

- **Title**: Measurements of W^+/W^- cross-section ratio in pp collisions at RHIC
- **Target Journal**: PRD
- **PA**: Jae Nam, Matt Posik, Bernd Surrow
- **Webpage**: link
- **Analysis Note**: link
- **Paper draft**: link
- **Previous Publications**:
  - Z cross section and AN, PLB 854 (2024) 138715
  - Unpol W/Z cross section + ratio, PRD 103 (2021) 1, 012001
  - W-AL, PRD 99 (2019) 5, 051102
  - W/Z-AN, PRL 116 (2016) 13, 132301

Abstract

We report measurements of $W^{\pm} \to e^{\pm}\nu$ production cross sections and their ratio in unpolarized pp collisions at a center-of-mass energy of $\sqrt{s} = 510$ GeV. The measurements were performed within the fiducial region defined by the charged-lepton pseudorapidity $-1 < \eta_e < 1.5$, and transverse energy 25 GeV $< E_{\mathrm{T},e} <$ 50 GeV. The cross-section ratio, $\sigma^{\mathrm{fid}}(W^+ \to e^+\nu)/\sigma^{\mathrm{fid}}(W^- \to e^-\nu)$ and differential cross sections, $d\sigma(W^{\pm} \to e^p m\nu)/d\eta_e$, are sensitive to the unpolarized sea quark ratio, $\bar{d}/\bar{u}$, and are measured as a function of the leptonic pseudorapidity within the studied region. The results are based on pp collision data collected with the STAR detector at RHIC in 2017, which correspond to an integrated luminosity of 340 pb^{-1}, and found to be consistent with previous STAR publications. Perturbative predictions at $\mathcal{O}(\alpha_s^1)$ accuracy based on the ResBos2 framework with the latest global fit results, supplemented with next-to-leading-log corrections and resummation, are compared to the combined STAR data. While the predicted cross-section ratio describes the data well, the predictions for the differential cross sections overestimate the measurements by approximately 2σ.

Abstract

We report measurements of $W^{\pm} \to e^{\pm}\nu$ production cross sections and their ratio in unpolarized pp collisions at a center-of-mass energy of $\sqrt{s} = 510$ GeV. The measurements were performed within the fiducial region defined by the charged-lepton pseudorapidity $-1 < \eta_e < 1.5$, and transverse energy 25 GeV $< E_{\mathrm{T},e} <$ 50 GeV. The cross-section ratio, $\sigma^{\mathrm{fid}}(W^+ \to e^+\nu)/\sigma^{\mathrm{fid}}(W^- \to e^-\nu)$ and differential cross sections, $d\sigma(W^{\pm} \to e^p m\nu)/d\eta_e$, are sensitive to the unpolarized sea quark ratio, $\bar{d}/\bar{u}$, and are measured as a function of the leptonic pseudorapidity within the studied region. The results are based on pp collision data collected with the STAR detector at RHIC in 2017, which correspond to an integrated luminosity of 340 pb^{-1}, and found to be consistent with previous STAR publications. Perturbative predictions at $\mathcal{O}(\alpha_s^1)$ accuracy based on the ResBos2 framework with the latest global fit results, supplemented with next-to-leading-log corrections and resummation, are compared to the combined STAR data. While the predicted cross section ratio describes the data well, the predictions for the differential cross sections overestimate the measurements by approximately 2σ.

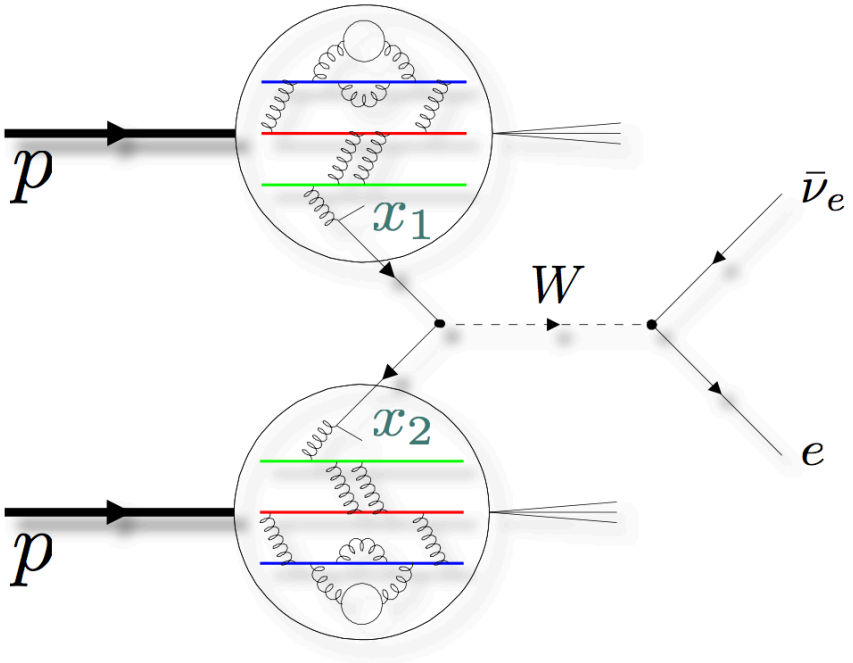
Close communication with PAs (Pavel Nadolsky, et al.)
For this presentation, **FEWZ** framework is used (w/o NLL)

This is also the case for unpol. W/Z Run 2011-13
Run 17 Z pub. under investigation

Motivation

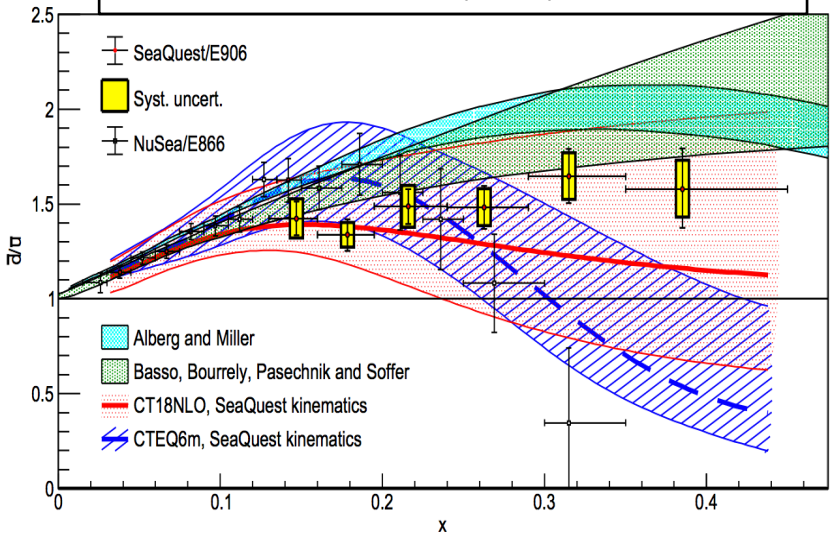
- W ($W \to e\nu$) in pp at LO
  - $d\sigma^{W+} \propto u(x_1)\bar{d}(x_2) + u(x_2)\bar{d}(x_1)$
  - $d\sigma^{W-} \propto \bar{u}(x_1)d(x_2) + \bar{u}(x_2)d(x_1)$

$$\to R_W = \frac{\sigma^{W+}}{\sigma^{W-}} \sim \frac{u(x_1)\bar{d}(x_2) + u(x_2)\bar{d}(x_1)}{\bar{u}(x_1)d(x_2) + \bar{u}(x_2)d(x_2)}$$



- Sensitive to non-perturbative SU(2) $\bar{d}/\bar{u}$ asymmetry
- Momentum scale set by the W mass, complementary to fixed-target experiments
- Provides robustness test of STAR W/Z reconstruction scheme
- Key features of $W \to e\nu$ in pp
  - High p_T electron.
  - Large imbalance in p_T due to missing ν.

SeaQuest, Nature 590 (2021) 7847, 561-565

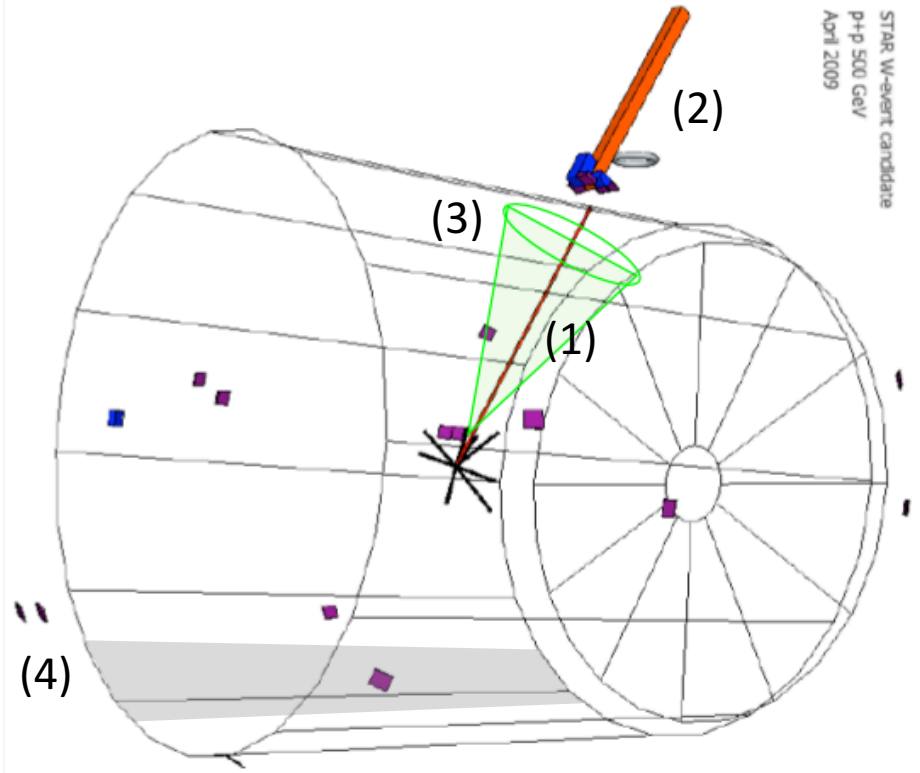


Data & MC

- Data: STAR Run 2017 pp $\sqrt{s} = 510$ GeV
- Trigger set: pp500_production_2017
- Production tag: P20ic
- Trigger: L2BW || L2EW
- Run list: /star/u/jaenam/W2017/lists/runnumber.list
  (2691 runs, 340 pb^{-1})
  - 2.6% correction based on Xiaoxuan's luminosity study
  - 352 pb^{-1} (Jamie's table) $-2.6\% = 343$ pb^{-1}; reporting as 340 pb^{-1})
  - Same has been done for previous publication
- TPC Sec 20 masked out
- Simulation: Request ID 20201502 (link)
  - Pythia 6, CTEQ5L,
    STAR Tune based on Perugia 2012 (minimally affected)

Event Reconstruction

Event Display of typical W event



1) A high momentum track is identified ($p_T > 10$ GeV)

2) Energy cluster is formed (2×2 towers, each covering 0.05×0.05 in $\eta\times\phi$; cluster: 0.1×0.1)

3) Isolation requirement ($E_T^{2\times2}/E_T^{\Delta R<0.7}\sim1$, $E_T^{2\times2}/E_T^{4\times4}\sim1$)

4) Backward (neutrino direction) energy flow requirement ($E_T^{\Delta\phi\sim\pi} < 11$ GeV)

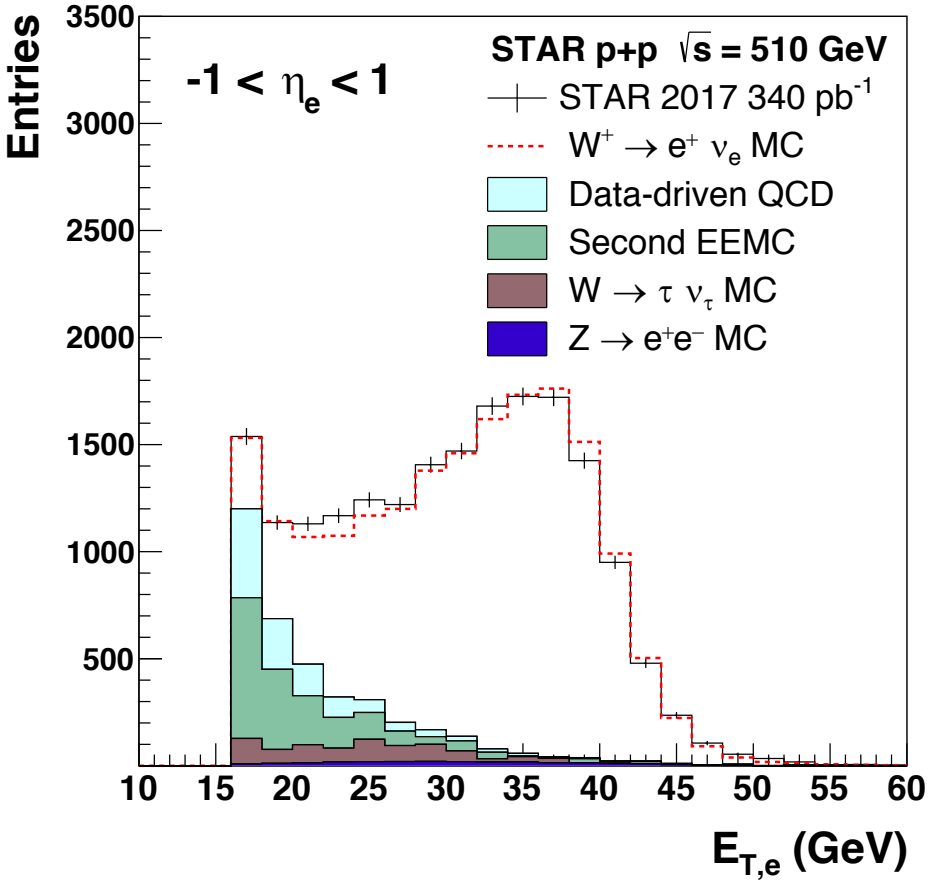
5) Energy imbalance ($p_{T,bal}$) ($\hat{p}_{T,e}\cdot\left(\vec{p}_{T,e}+\sum\vec{p}_{T,jet}\right) > 16$ GeV)

Selection cuts

*same as PRD 103 (2021) 1, 012001

	Barrel ($-1 < \eta < 1$)	Endcap ($1 < \eta < 1.5$)
Trigger	L2BW	L2EW
Vertex	Rank > 0 $\lvert Z_{vtx}\rvert < 100\ cm$	
Track	$p_T > 10\ GeV$ $N_{hit} > 15$ $N_{hit}/N_{pos} > 0.51$ $R_{TPC,in} < 90\ cm$ $R_{TPC,out} > 160\ cm$	$p_T > 7\ GeV$ $N_{hit} > 5$ $N_{hit}/N_{pos} > 0.51$ $R_{TPC,in} < 120\ cm$ $R_{TPC,out} > 70\ cm$
Cluster	$\Delta R_{trk,cls} < 7\ cm$ $E_T^{2\times2} > 16\ GeV$	$\Delta R_{trk,cls} < 10\ cm$ $E_T^{2\times2} > 16\ GeV$ $N_{ESMD} > 20$
Isolation	$E_T^{2\times2}/E_T^{2\times2} > 0.96$ $E_T^{2\times2}/E_T^{\Delta R<0.7} > 0.82$	$E_T^{2\times2}/E_T^{2\times2} > 0.97$ $E_T^{2\times2}/E_T^{\Delta R<0.7} > 0.88$ $R_{ESMD}^{7\times7/41\times41} > 0.6$
W Selection	signed-$p_{T,bal} > 16\ GeV$ $E_T^{\Delta\phi\sim\pi} < 11\ GeV$ $\lvert Q\times E_T p_T\rvert < 3.0$ $25\ GeV < E_{T,e}(\equiv E_T^{2\times2}) < 50\ GeV$	signed-$p_{T,bal} > 20\ GeV$ $\lvert Q\times E_T p_T\rvert < 2.5$ $25\ GeV < E_{T,e}(\equiv E_T^{2\times2}) < 50\ GeV$

Fig 1: Signal + BG description



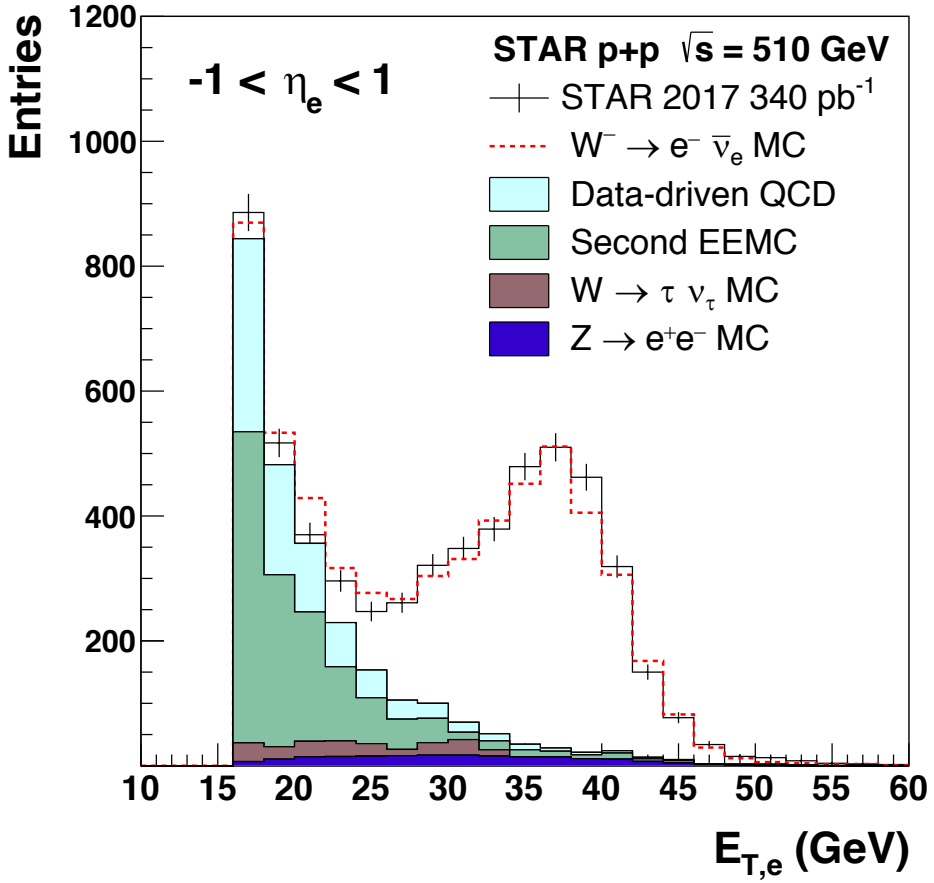
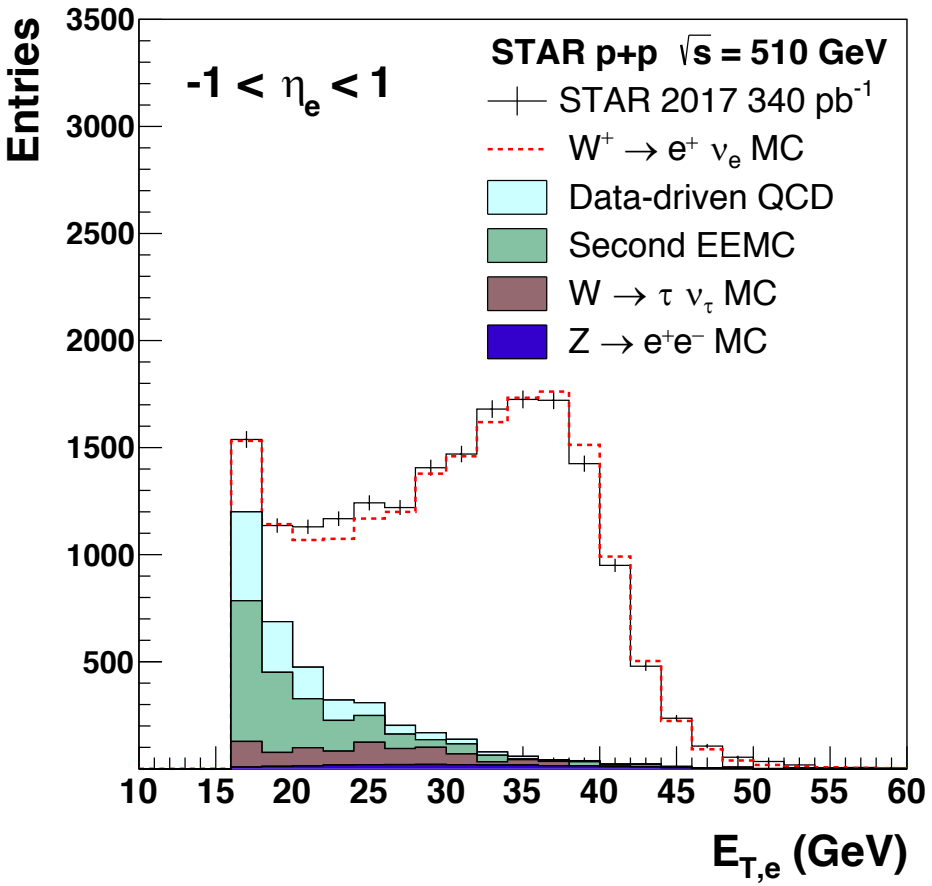


Fig 1: Signal + BG description



$$N_{sig}^{data} = N_{sel}^{data} - \sum N_{bg,i}$$

Remaining background

- $Z \rightarrow e^+e^-$
  - with one electron outside STAR acceptance
  - Indistinguishable experimentally → Estimated based on MC
- $W \rightarrow \tau$
  - $\tau \rightarrow e$ decay within STAR volume
  - Same as $Z \rightarrow e^+e^-$ (MC-based)
- QCD processes (dijets)
  - One jet in dijet events outside STAR acceptance
  - Data-driven method (signed-$p_{T,bal}$ < threshold)
  - Using existing EEMC ($-2 < \eta < -1$)
  - Systematic uncertainty for data-driven QCD background selection and normalization

Fig 2: Signal + BG description (W+)

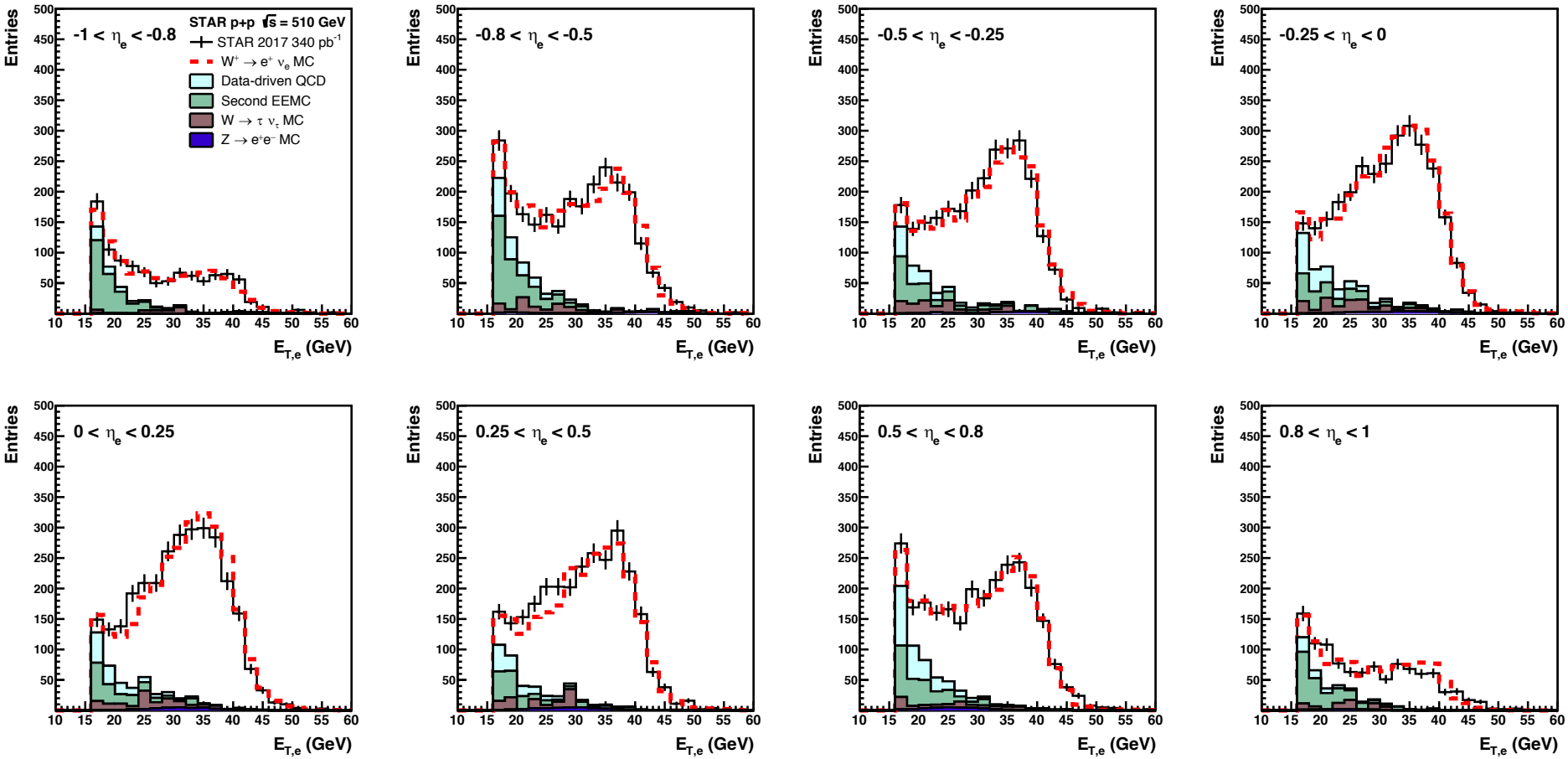


Fig 3: Signal + BG description (W-)

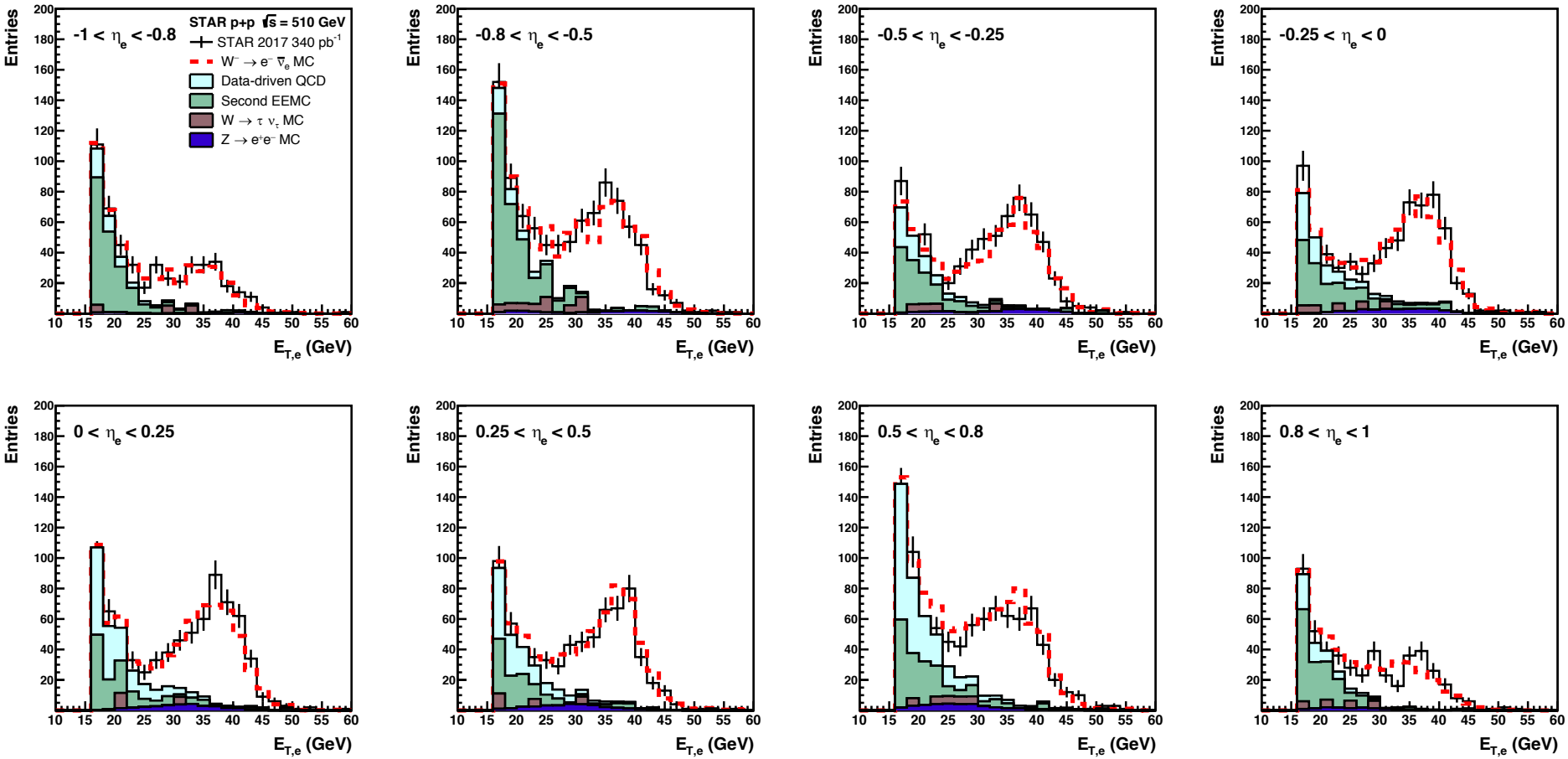
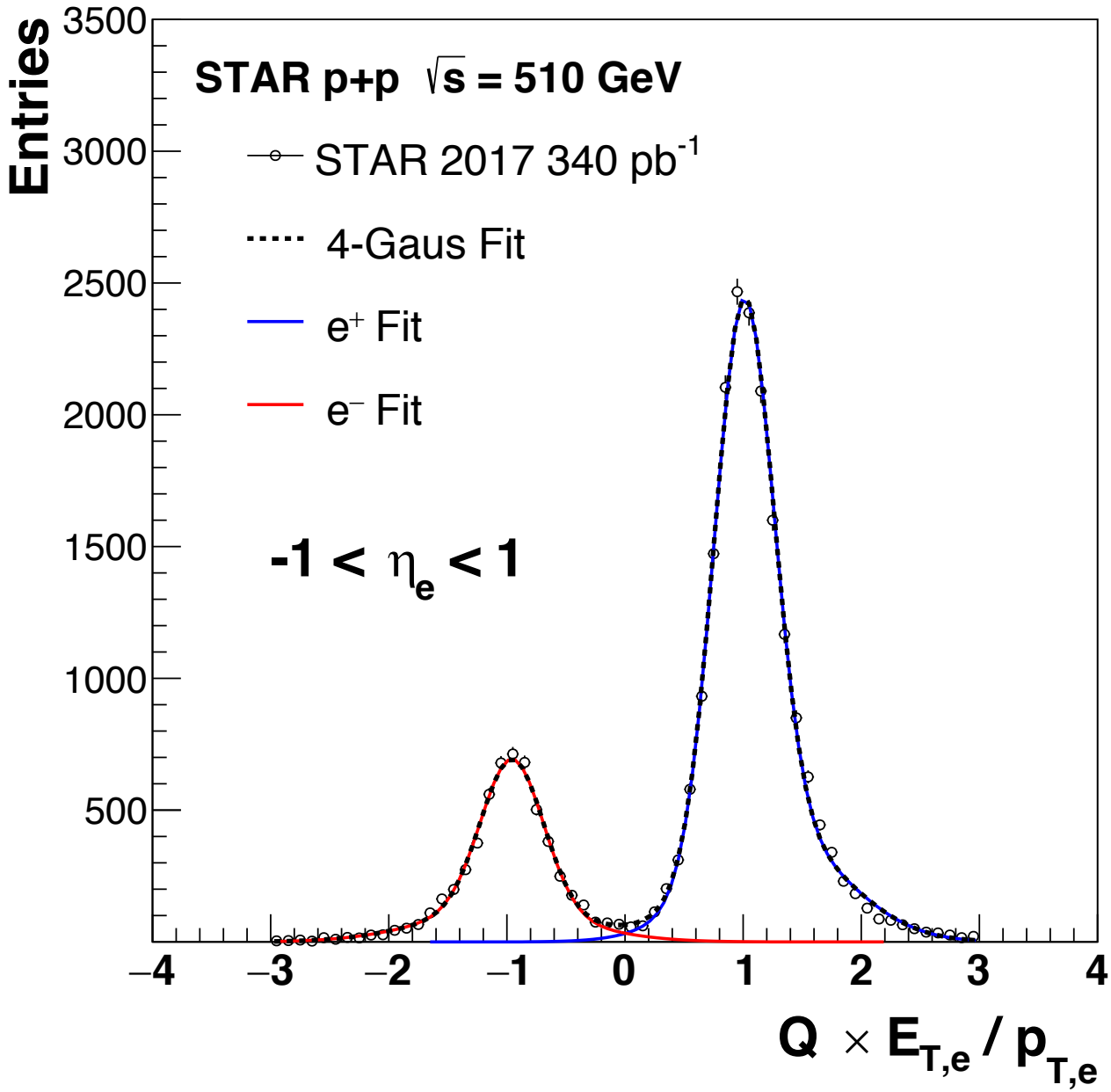


Fig 4: Charge Mis-ID (Barrel, Comb)



- Charge mis-ID correction based on 4-Gaus fit of $Q \times E_T / p_T$
- 2-Gaus for each sign to describe signal and background
- $c_q^+ = \frac{N^{fit+}}{N_{q>0}^{fit+} + N_{q>0}^{fit-}}$

$$N_{sig,cor}^{data} = c_q \times N_{sig}^{data}$$

Fig 5: Charge Mis-ID (Barrel)

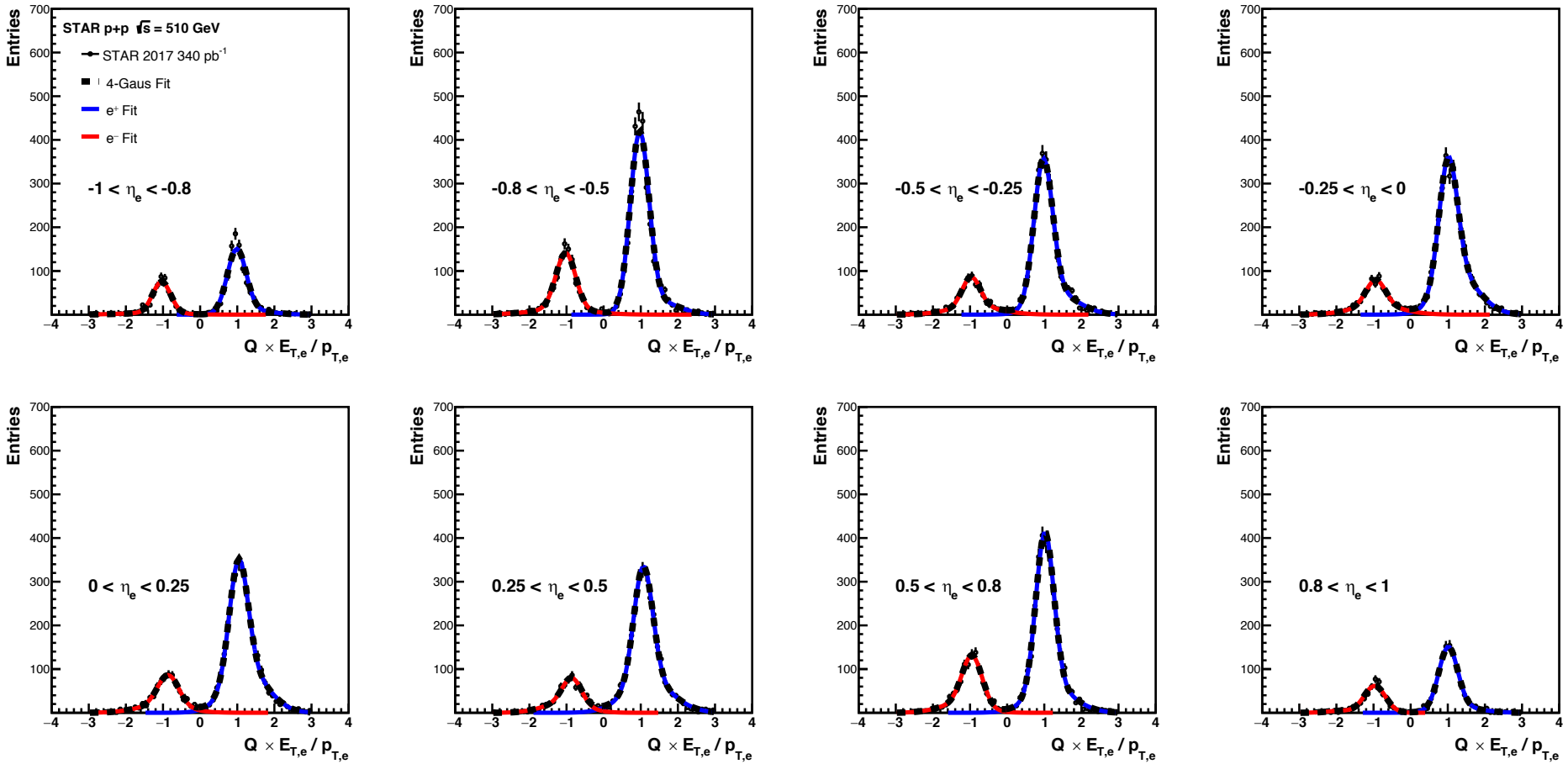
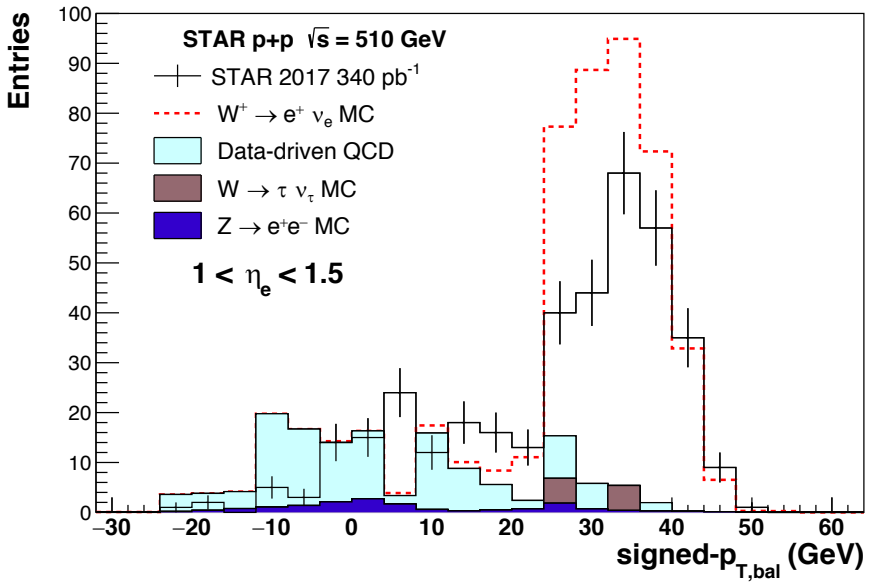
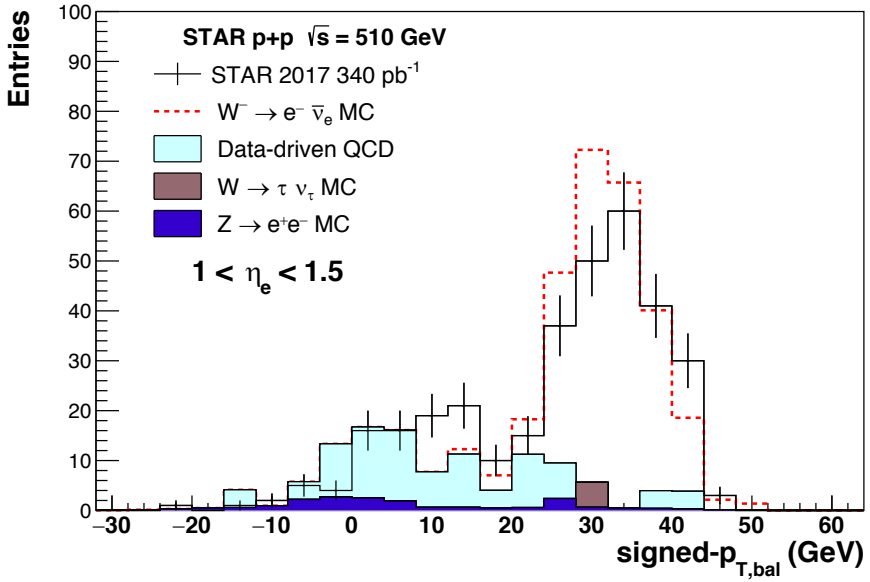
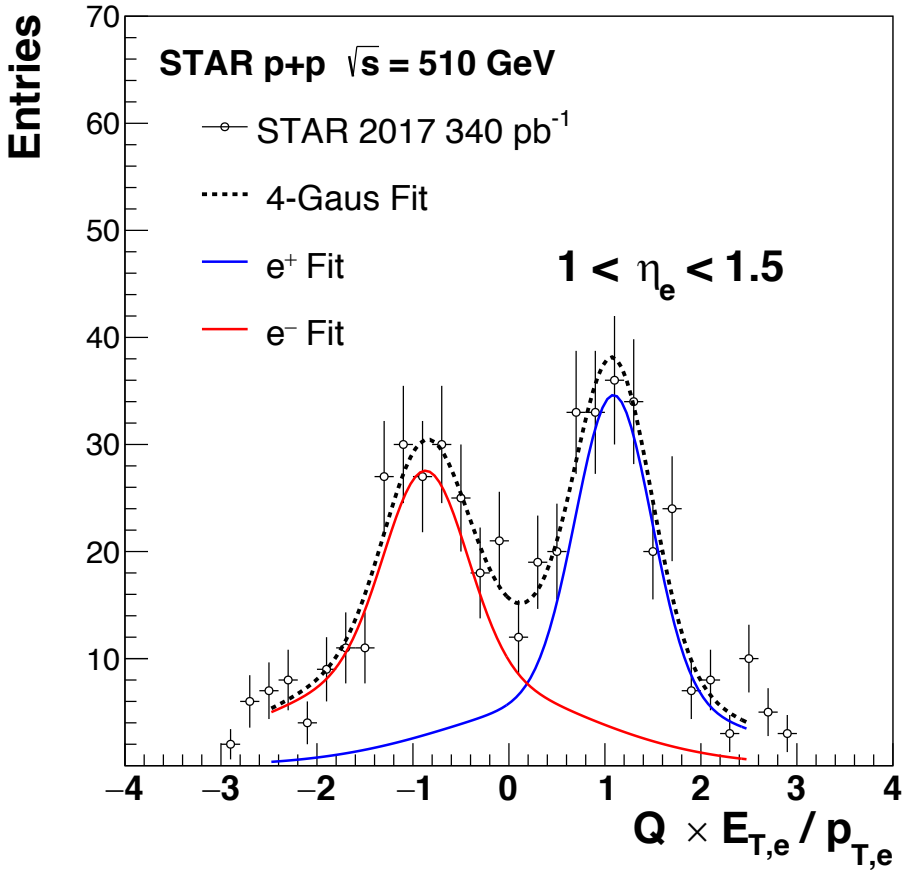


Fig 6: Signal + Charge (Endcap)







- MC overestimates W+,
  also seen in previous publication
- Systematics for data-driven QCD
  (same as barrel) and charge correction

Fig 7: Efficiency

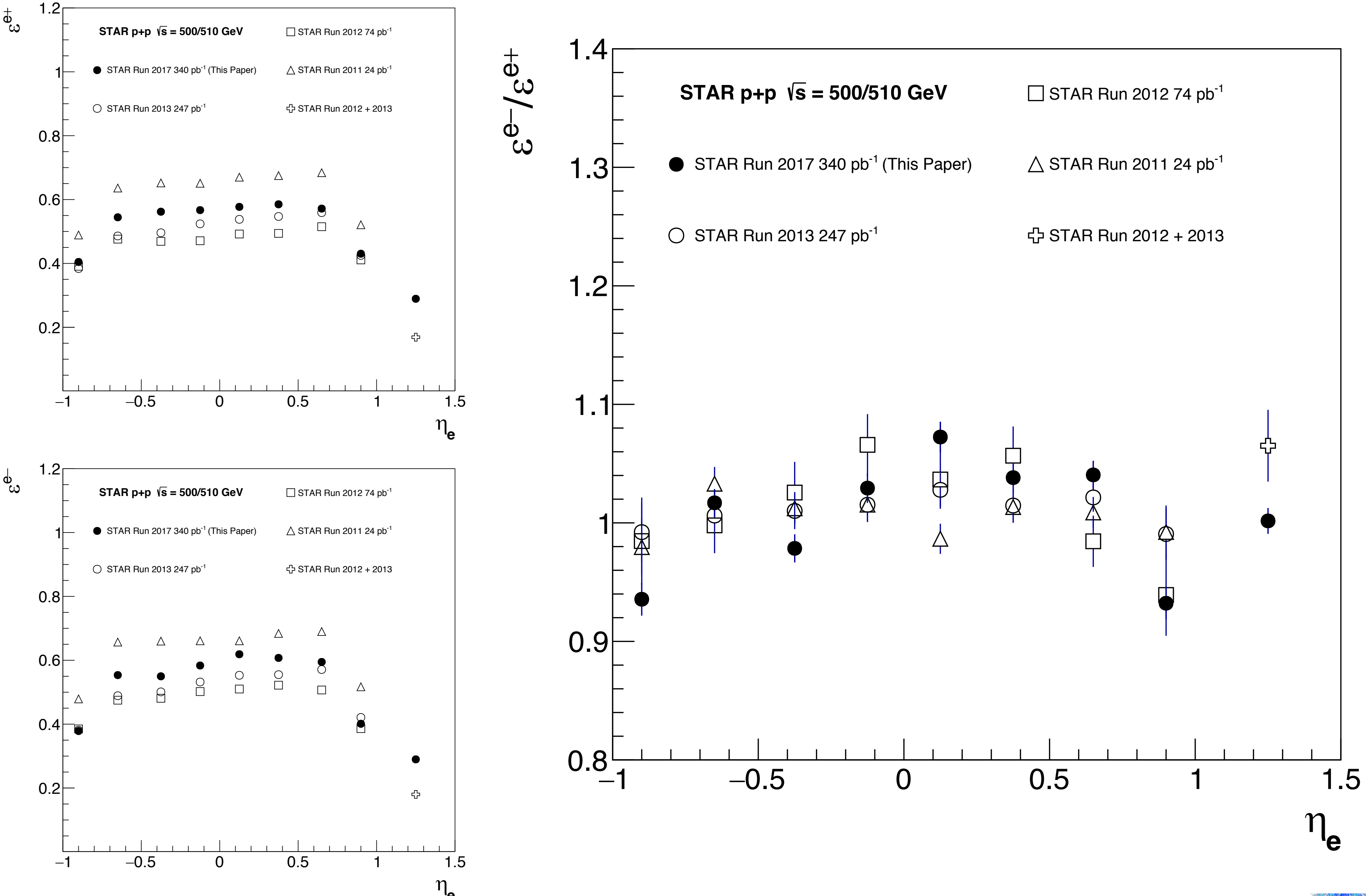
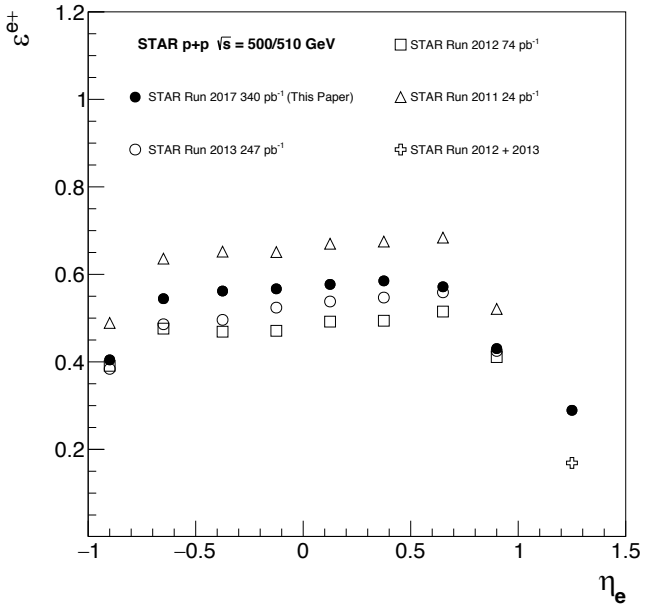
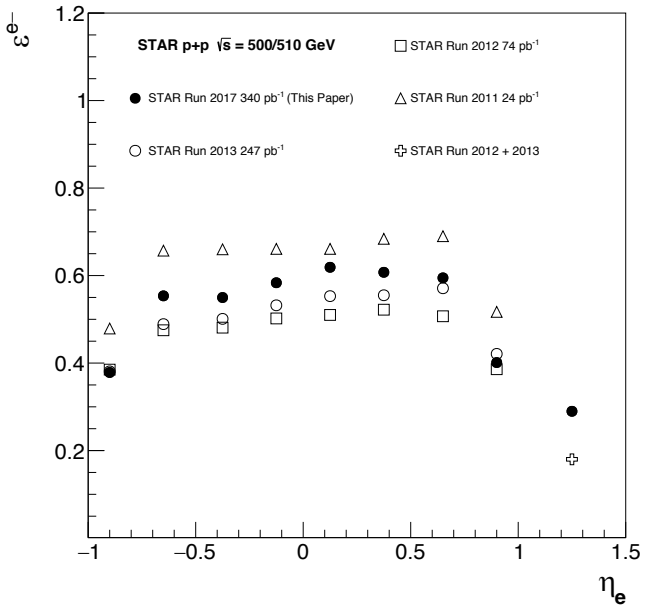


Fig 7: Efficiency

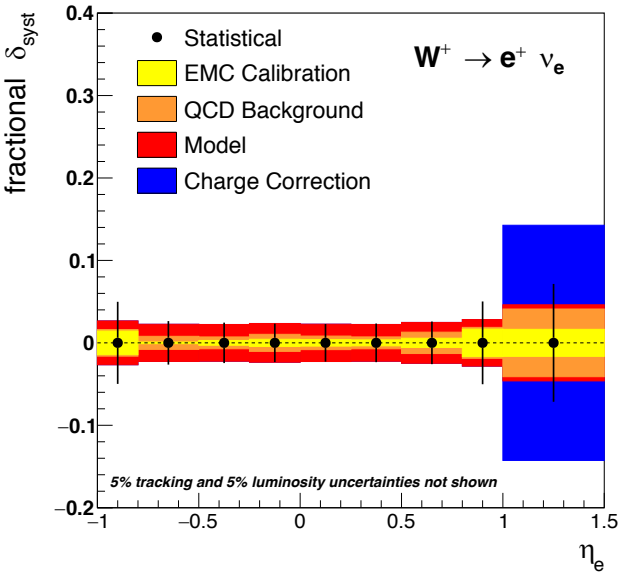


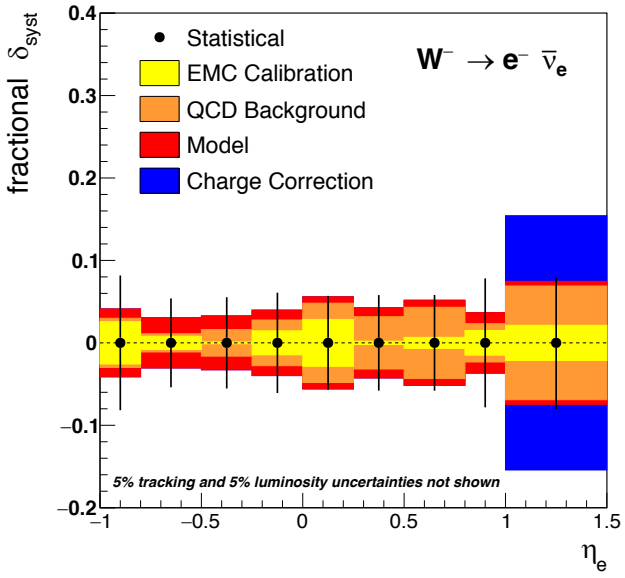


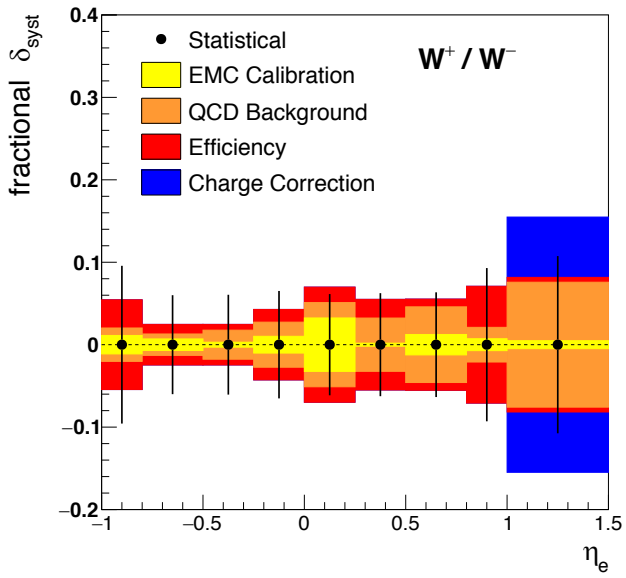
- Run 2011
  - Low material budget
  - Low instantaneous luminosity
- Run 2012 & 2013
  - High material budget (HFT, FGT, support)
  - High instantaneous luminosity
  - STI track algo Run 11, 12 vs STICA Run 13
- Run 2017
  - Low material budget
  - High instantaneous luminosity
  - STICA algo
- Asymmetric in η_e due to TPC Sec 20
  - Sec 20 issue addressed in Run 18 (→ Run 22)

$$\left(\frac{d\sigma}{d\eta}\right)_i = \frac{1}{\epsilon_i}\frac{N_{sig,cor,i}}{\delta\eta_{e,i}L}$$

Fig 8: Systematics

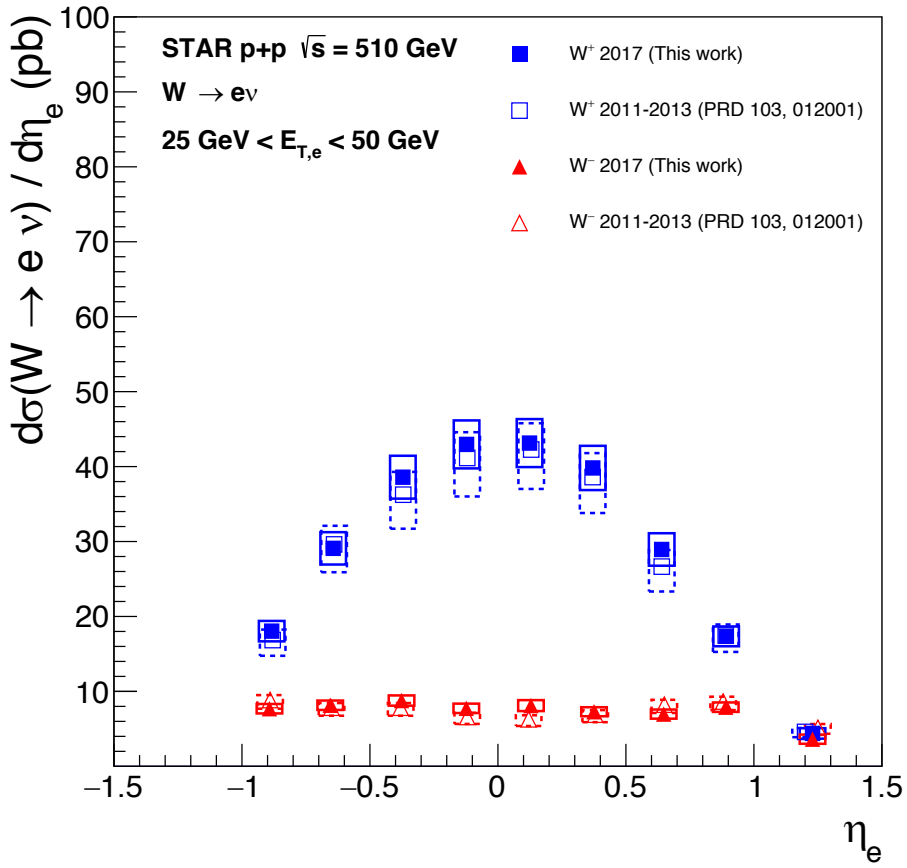


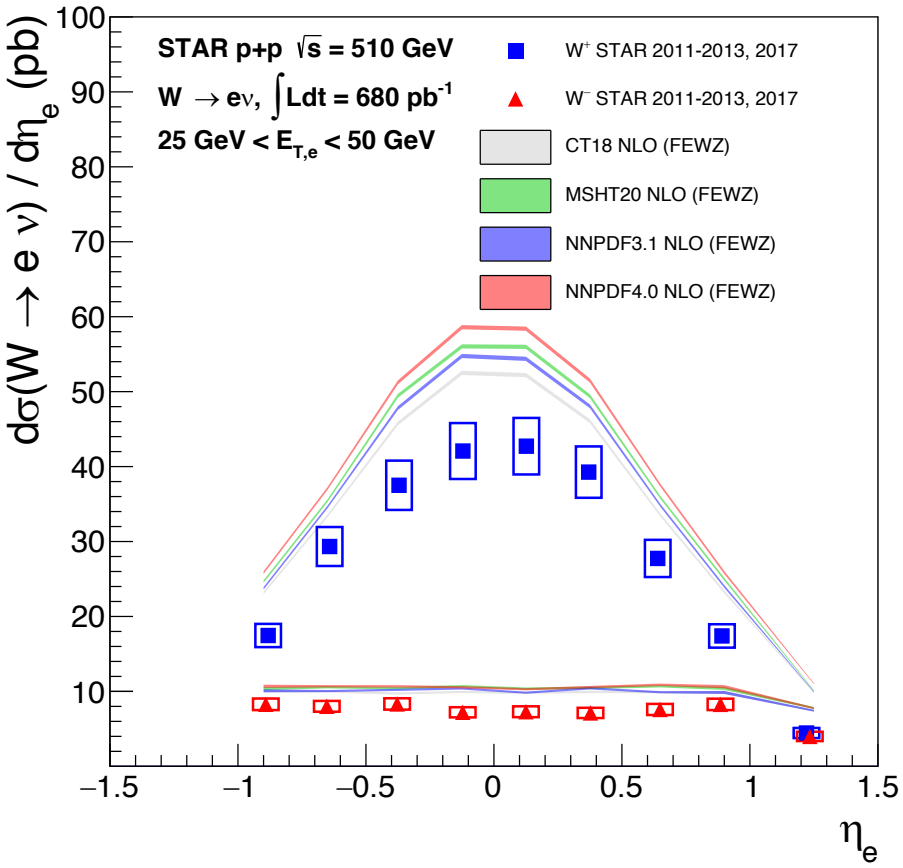




- EMC Calibration
  - BEMC/EEMC gains varied by reported uncertainties in calibration
- QCD Background
  - Data-driven QCD background identification and normalization
- Charge Correction (Endcap only)
  - Fit function and range
- Model
  - Mis-estimated $E_T^{\Delta R<0.7}$, $E_T^{\Delta\phi\sim\pi}$, and signed-$p_{T,bal}$ selection efficiency
  - $\sim 2.5\%$ correction and 2.5% uncertainty
- Efficiency (ratio only): deviation from 1
- Luminosity (cross section only) $\sim 5\%$
- Tracking (cross section only) $\sim 5\%$

Fig 9 Cross Section

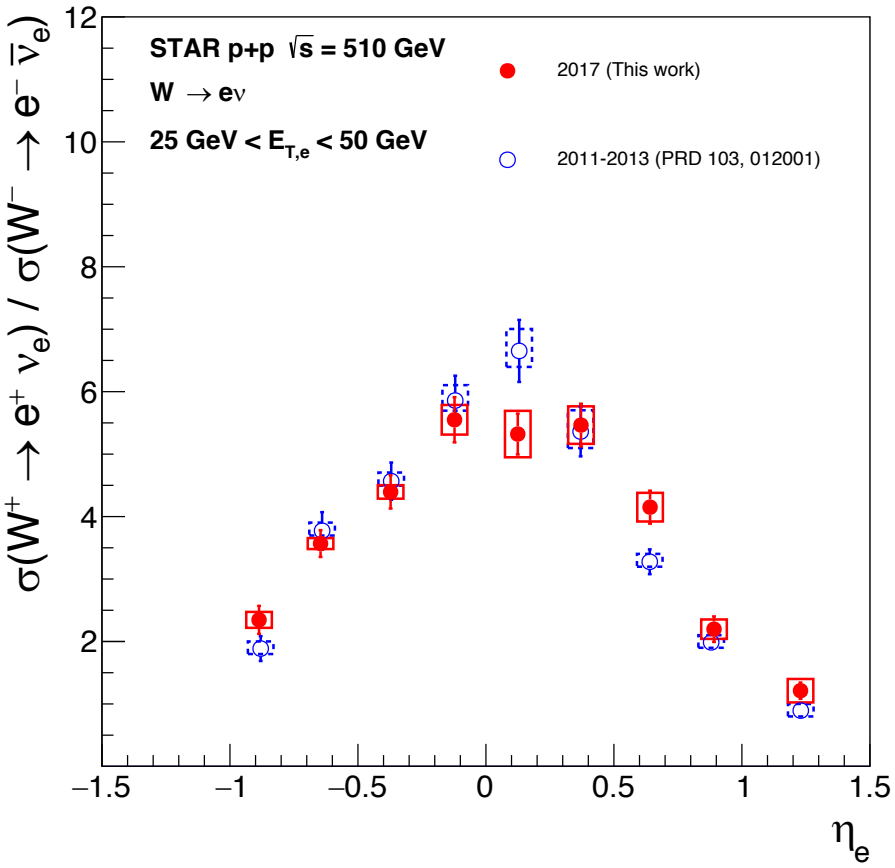


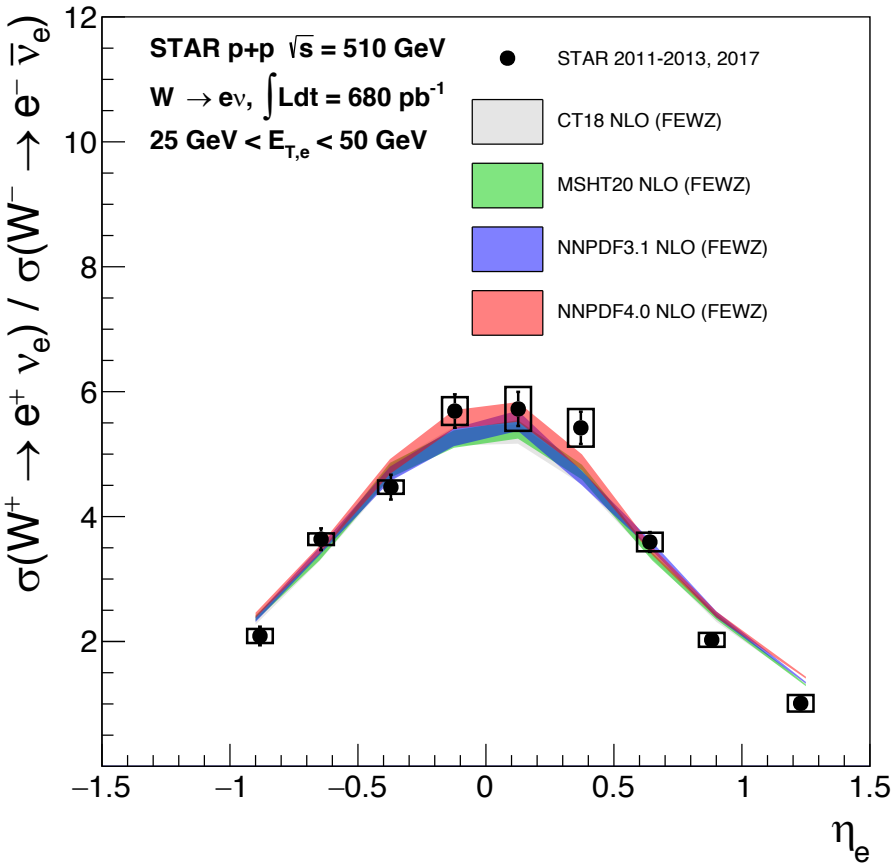


- ~3% shift between Run 17 and previous datasets based on χ^2 minimization
- Systematic uncertainties with strong bin-wise correlation
  - Luminosity (5%, strongly correlated btw datasets)
  - Tracking (5%, different detector conditions, changes in tracking algo, etc.)

- 30% scale mismatch between STAR and pQCD
  - ~10% uncertainty in data, spread btw. PDF sets
- Currently using FEWZ calculation
  - ResBos2 calculation in agreement with FEWZ
  - PDF dependence WIP

Fig 10: Cross Section Ratio





- Run 17 result consistent previous STAR publication;
  p > 0.05 based on T test, t value = 1.2199 with NDF = 9 − 1 → p value = 0.257242
- Modest improvement (expected) from fitting SeaQuest data
  ($\chi^2 = 16.1 \rightarrow 14.9$ with NNPDF3.1 → 4.0 in the barrel region from FEWZ)
- Tension in the endcap region still persists ($\chi^2 = 7.0$ and 4.5 with NNPDF 4.0 and 3.1)

13 Conclusion

The $W^{\pm} \to e\nu$ cross sections and their ratio have been measured with RHIC pp $\sqrt{s} = 510$ GeV collision data collected at STAR in 2017, corresponding to an integrated luminosity of 340 pb^{-1}. The measurements were performed as a function of the leptonic pseudorapidity η_e within the kinematic region defined by leptononic pseudorapidity $-1.0 < \eta < 1.5$ and transverse energy 25 GeV $< E_{T,e} <$ 50 GeV. The resulting cross sections and ratio are consistent with previous STAR publications. These measurements provide independent constraints for the non-perturbative SU(2) $\bar{d}/\bar{u}$ asymmetry at a higher momentum scale ($\sim M_W$), complementary to existing pp/pd Drell-Yan data, and a low-$\sqrt{s}$ and high-x (~ 0.2) reference for LHC W/Z programs.

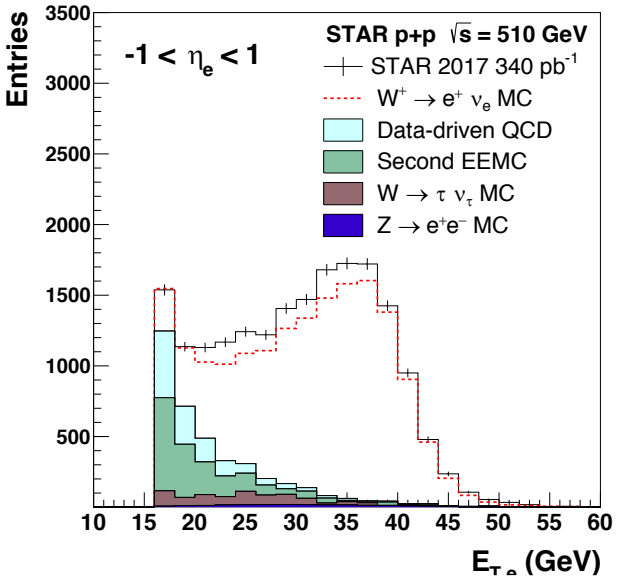
Perturbative calculations at NLO+NLL accuracy with latest PDF sets implemented in the ResBos2 framework [PLACEHOLDER] have been compared to the data. The prediction with the NNPDF4.0 PDF set [11] that includes the latest SeaQuest data [12] in the global fit shows an improvement over the previous NNPDF3.1 PDF set [13] in describing the W^+/W^- cross-section ratio observed at STAR. However, all calculations overestimate the differential cross sections $d\sigma(W^{\pm} \to e\nu)/d\eta_e$ throughout the studied η_e range.

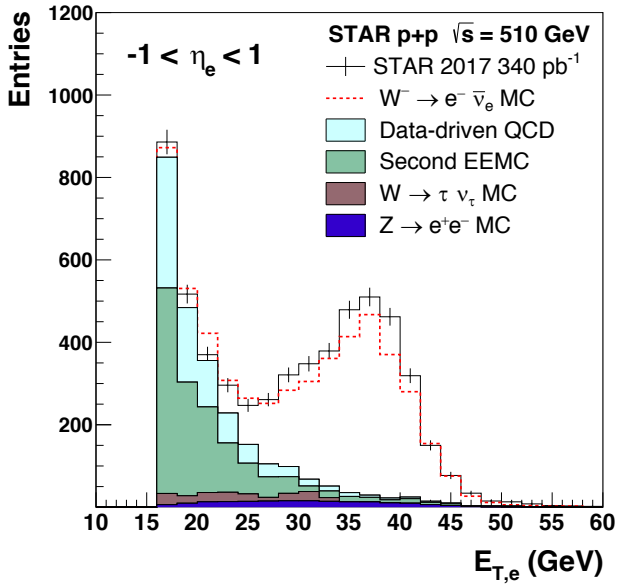
Summary

- Data well described by MC + background estimation
- Further corrections well understood
- Consistency between STAR datasets
- pQCD predictions overestimate STAR cross section by $\sim 2\sigma$
- Modest improvement (expected) in description of STAR cross-section ratio by fitting SeaQuest (NNPDF3.1 $\rightarrow$ 4.0)
- Tension in the Endcap region

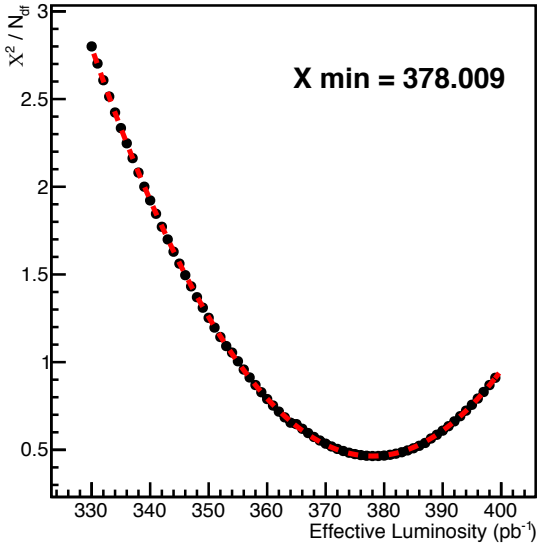
MC Normalization

L = 343 pb-1 (352 pb – 2.6%)

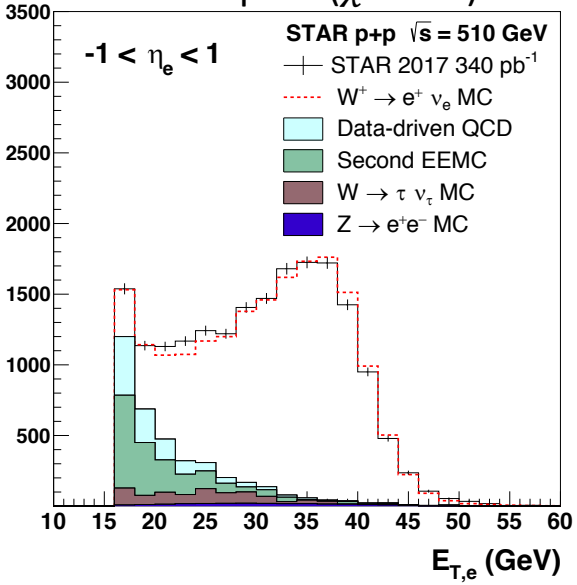




W⁺ + W⁻

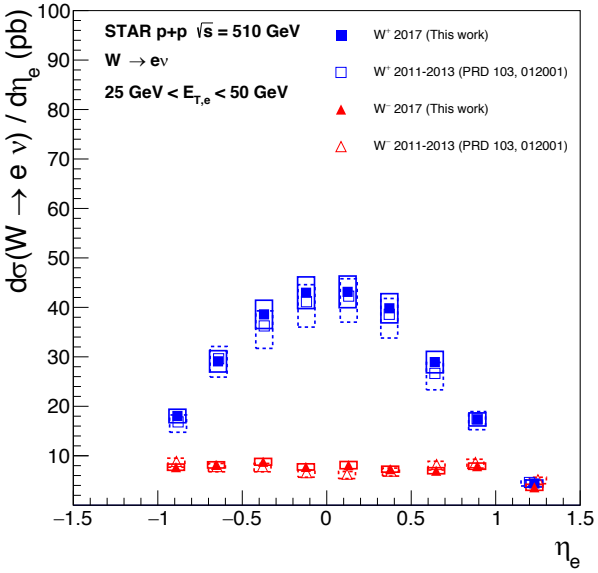


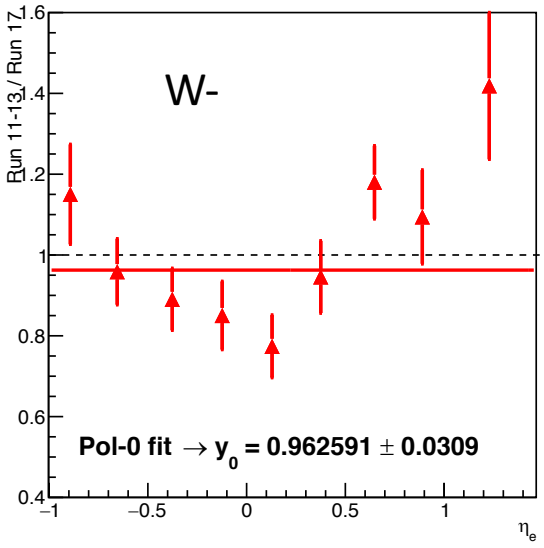
L = 378 pb-1 (χ^2-min)

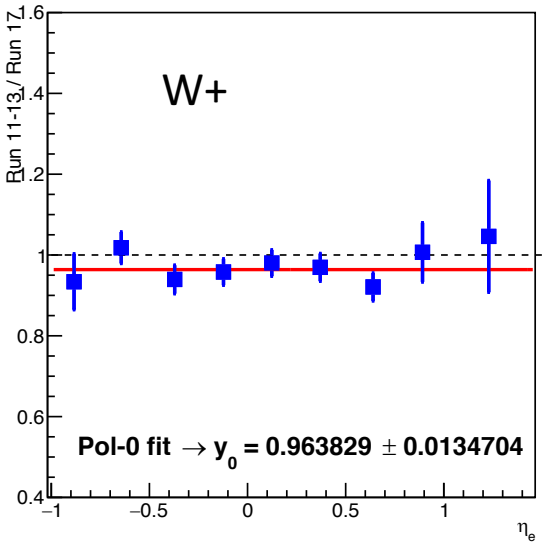


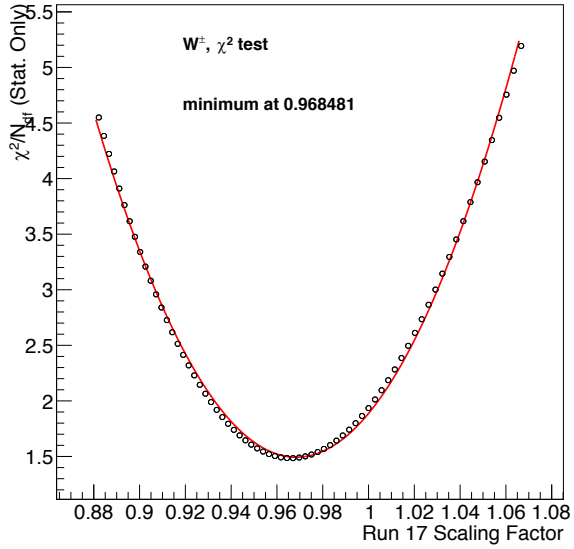
- Luminosity based on Jamie's table $352\ pb^{-1}$
- Systematic shift between MC and data
- Lumi correction + Changes in analysis details (MC gain smearing, etc.)
- χ^2 test minimzing effective luminosity $= 378\ pb^{-1}$
- Well within (lumi + track) $352\ (\pm 9\% \pm 5\%)\ pb^{-1}$
- Around 1.4σ within $343\ (\pm 5\% \pm 5\%)\ pb^{-1}$
- Dropping claims about "MC normalized to data luminosity"
- Instead, "MC normalization based on χ^2 minimization"

Systematic shift between Run 17 and 11-13





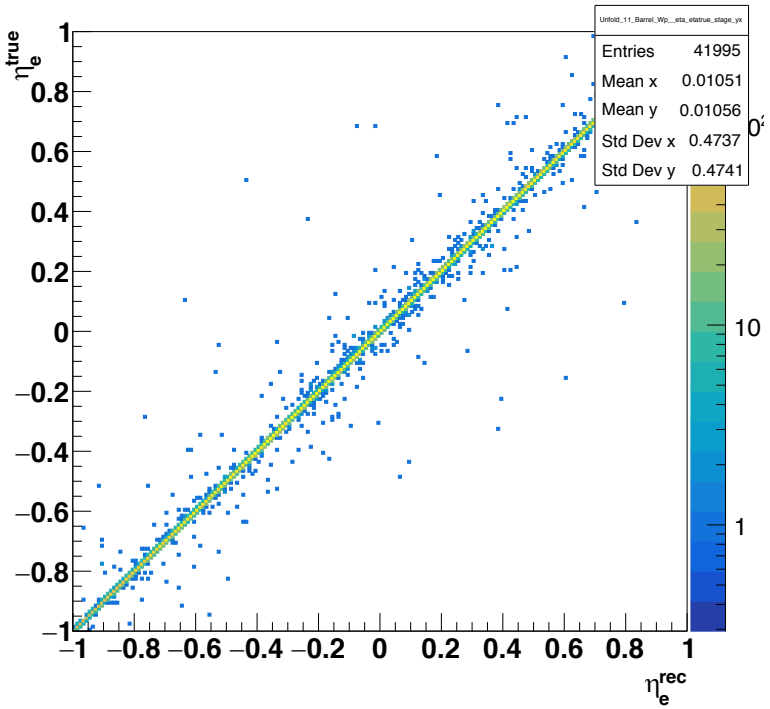


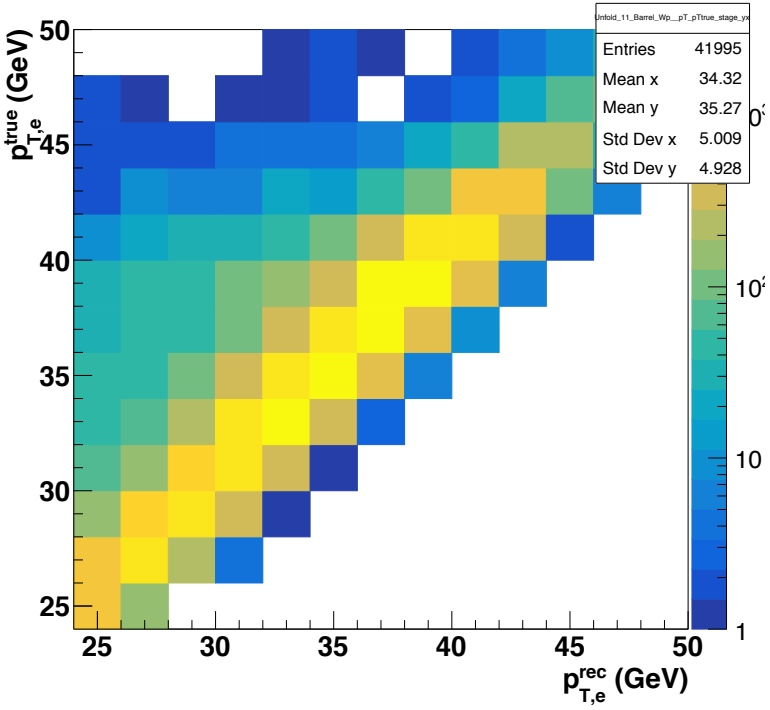


- 2.6% luminosity correction included for both Run 17 and 11-13
- $> 2\sigma$ shift based on pol-0 fit of W+
- χ^2 scan (based on statistical uncertainty) suggests there is 3.2% systematic shift between Run 11-13 and Run 17

Backup

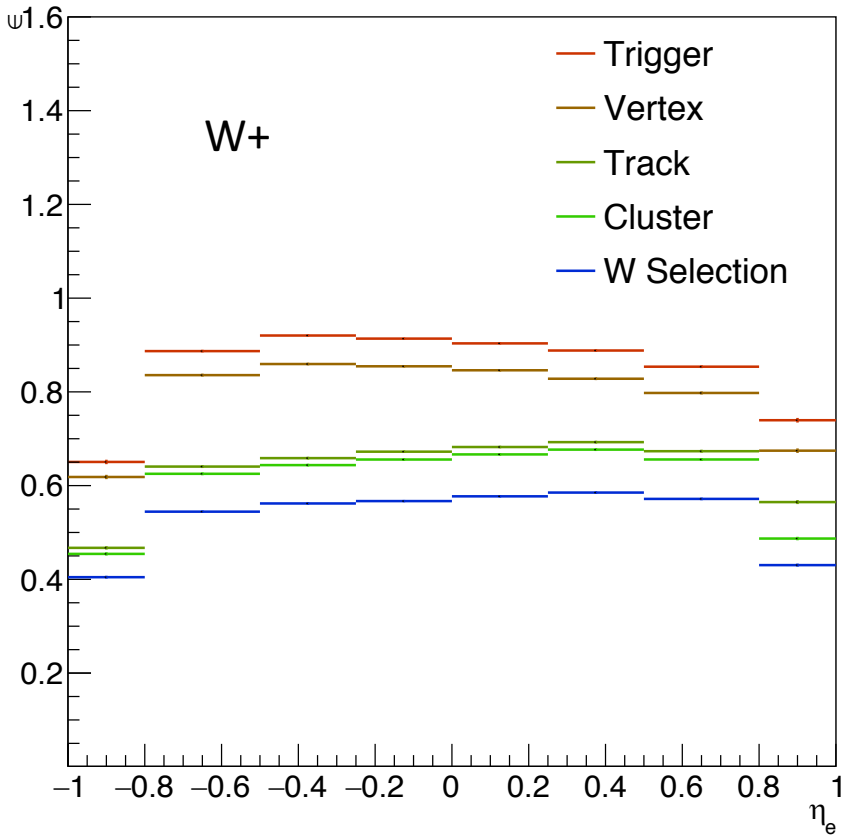
Bin migration correction?

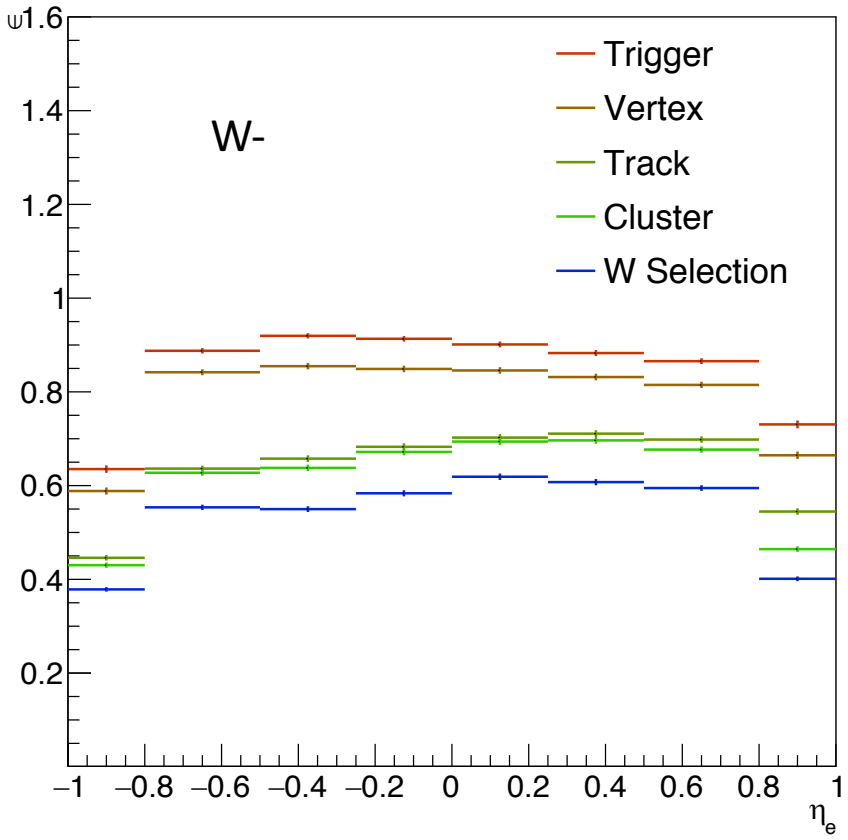




- Good reconstruction of η and E_T
- Binwise correction factor $\sim 0.5\%$
- Ignored; not included in the calculation, and was not considered as systematics

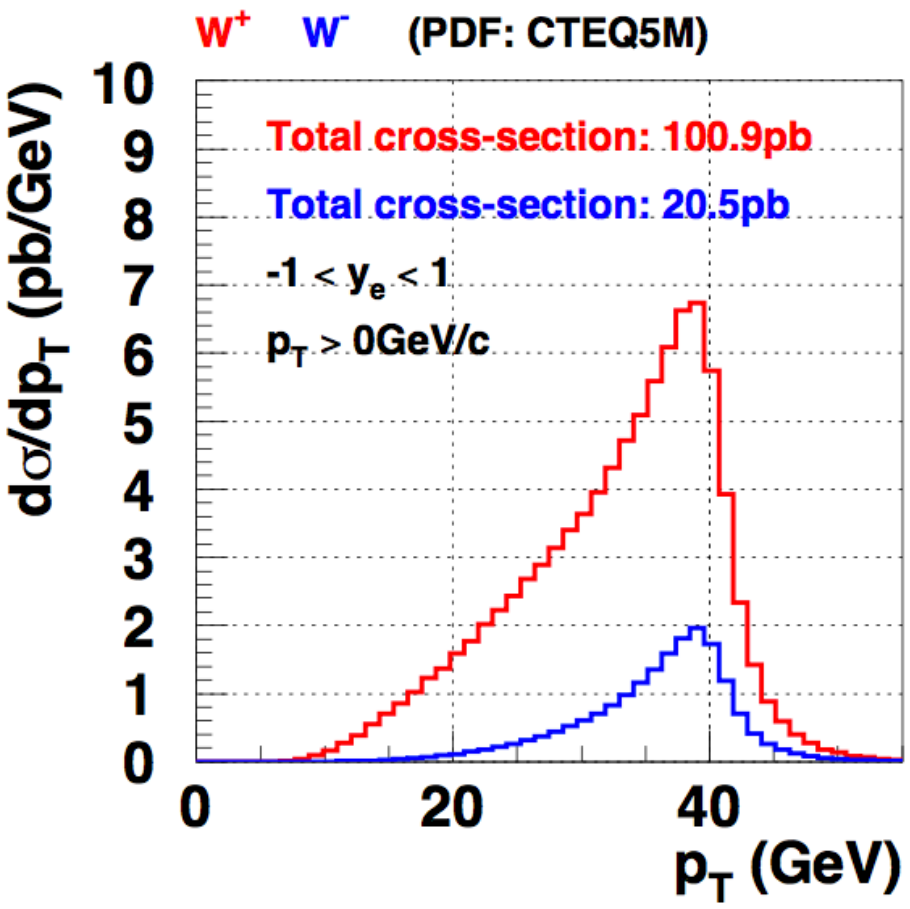
Efficiency breakdown

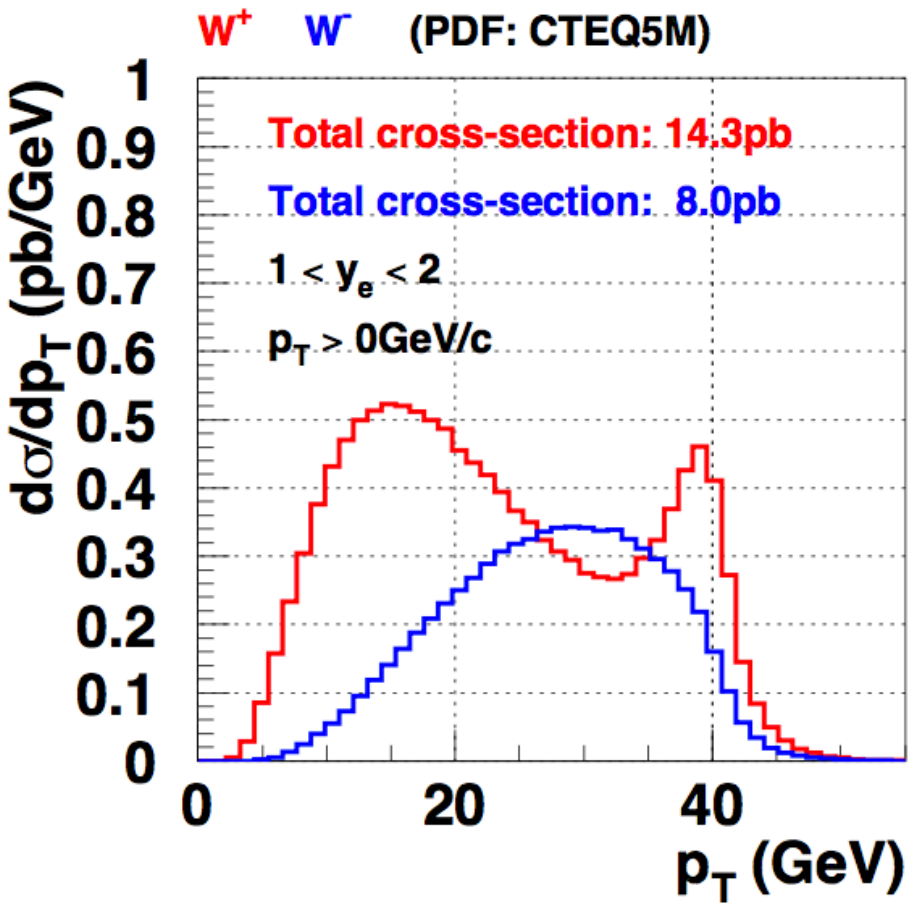




Why not one value for certain syst.?

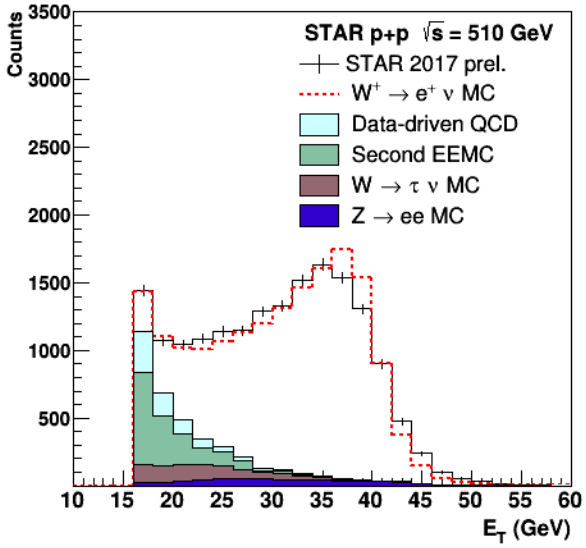
P. M. Nadolsky and C.P. Yuan,
Nucl.Phys. B666 (2003) 31.

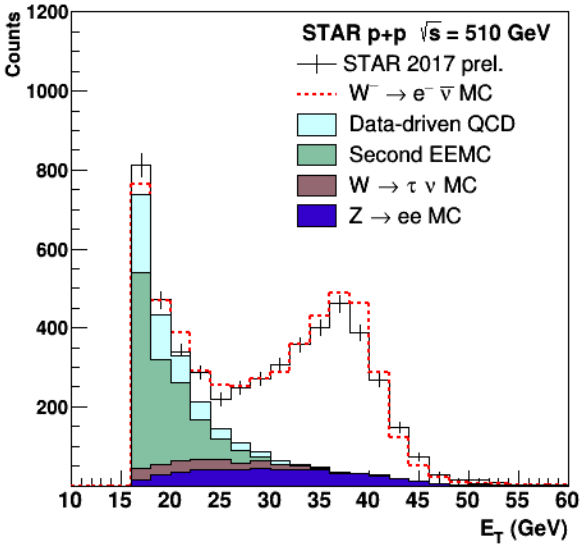


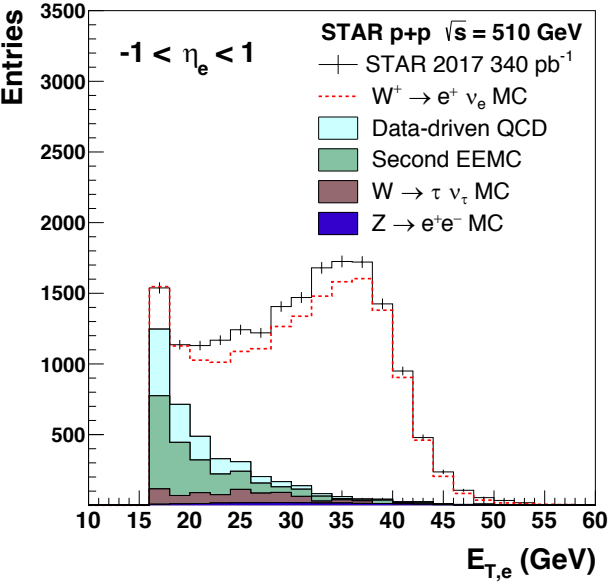


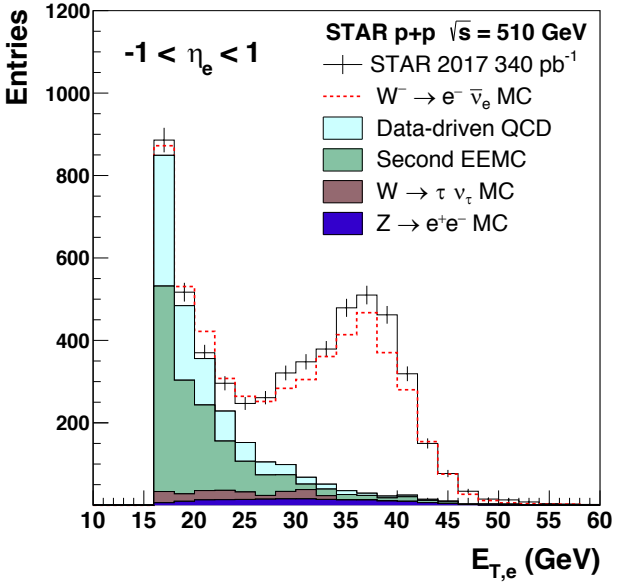
- The shape of Jacobian peak, and thus EMC/Efficiency systematics, should depend on η_e

Comparison to Preliminary





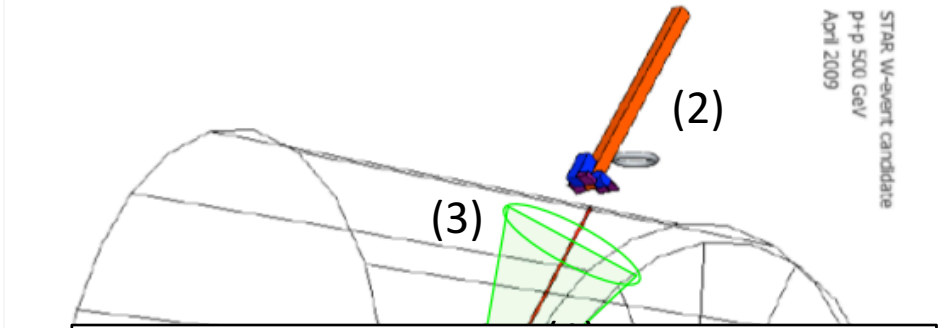




- Top: Preliminary
  - MC normalized to $352\ pb^{-1}$
- Bottom: Publication
  - MC normalized to $343\ pb^{-1}$
  - Includes MC gain smearing of 5%
  - Software-level inconsistency corrections (analysis note)

Review of Event Reconstruction

Event Display of typical W event



$E_T^{\Delta R<0.7}$ and $E_T^{\Delta\phi\sim\pi}$ are formed with track momentum and EMC tower energy (p of particles reconstructed in detector)

(4) $p_{T,bal}$ is reconstructed with objects (jets) reconstructed with anti-kT clustering algorithm (E-scheme, $R = 0.6$, min-p_T =3.5 GeV)

Relevant studies in:
https://drupal.star.bnl.gov/STAR/system/files/userfiles/6368/Nam_20250326(1).pdf
https://drupal.star.bnl.gov/STAR/system/files/userfiles/6368/Nam_20250409.pdf
https://drupal.star.bnl.gov/STAR/system/files/userfiles/6368/Nam_20250423(1).pdf
https://drupal.star.bnl.gov/STAR/system/files/userfiles/6368/Nam_20250604.pdf

1) A high momentum track is identified ($p >$ threshold)

2) Energy cluster is formed (2×2 towers, each covering 0.05×0.05 in $\eta\times\phi$; cluster: 0.1×0.1)

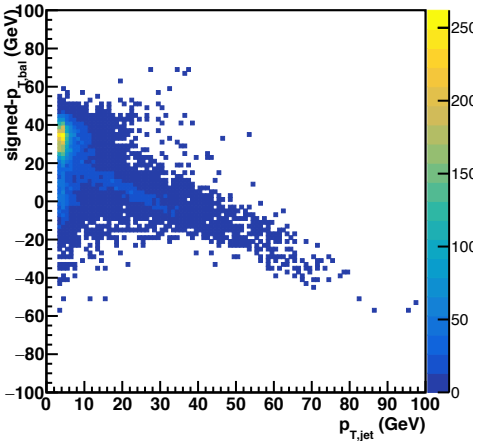
3) Isolation requirement ($E_T^{2\times2}/E_T^{\Delta R<0.7}\sim1$, $E_T^{2\times2}/E_T^{4\times4}\sim1$)

4) Backward (neutrino direction) energy flow requirement ($E_T^{\Delta\phi\sim\pi} <$ threshold)

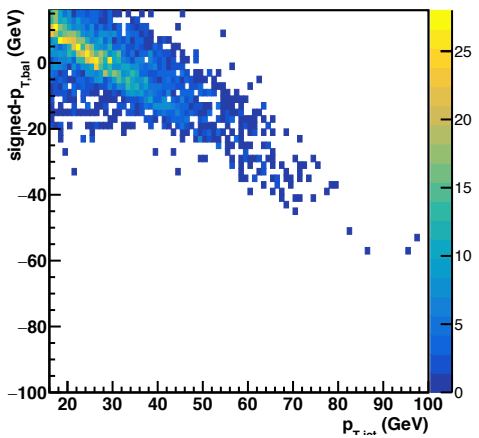
5) Energy imbalance ($p_{T,bal}$) ($\hat{p}_{T,e}\cdot\sum[\vec{E}_T$ and $\vec{p}_T] >$ threshold)

Signed-$p_{T,bal}$ and Jet p_T (W+)

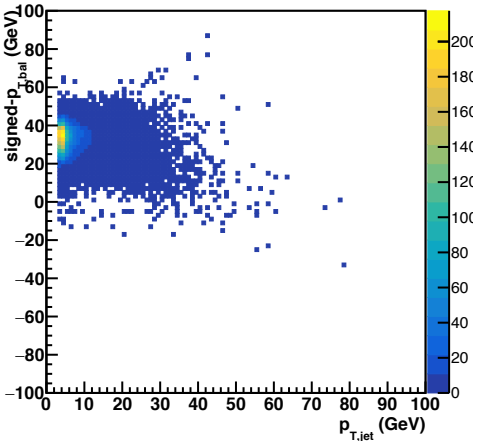
Data W+



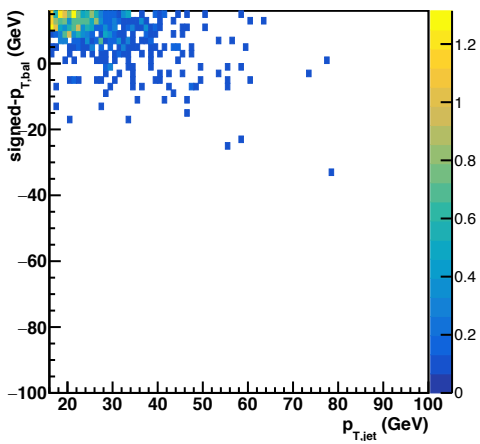
Data W+ (Zoomed in)

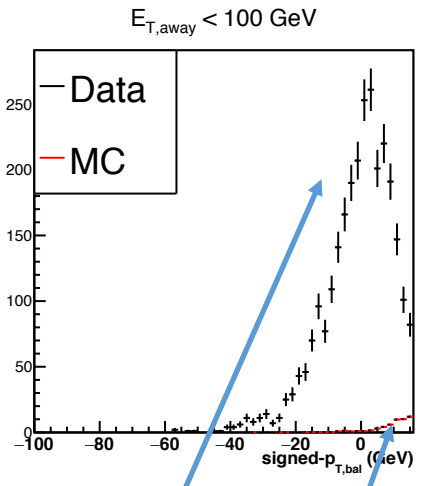


MC W+



MC W+ (Zoomed in)





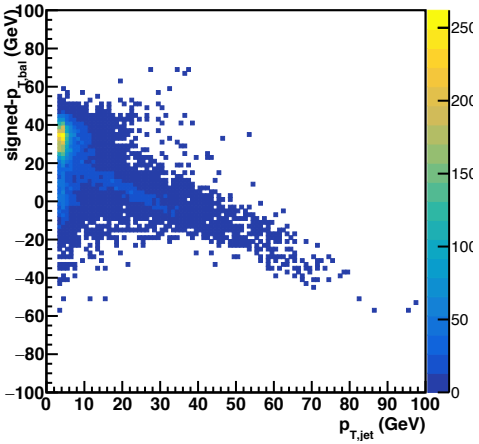
Asymmetric low-spTbal tail of W

Symmetric contribution dominated by Z, QCD-dijet

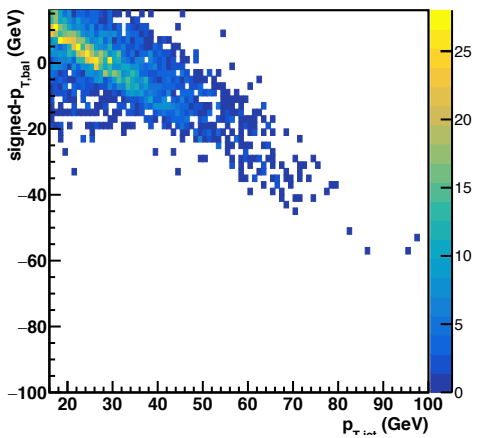
- Looking at signed-$p_{T,bal} < 16\ GeV$, $p_{T,jet} > 16\ GeV$

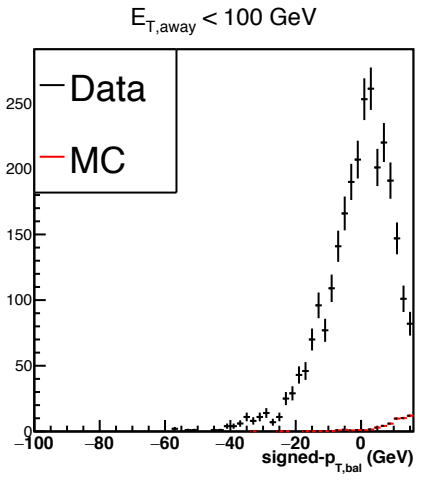
Signed-$p_{T,bal}$ and Jet p_T (W+)

Data W+

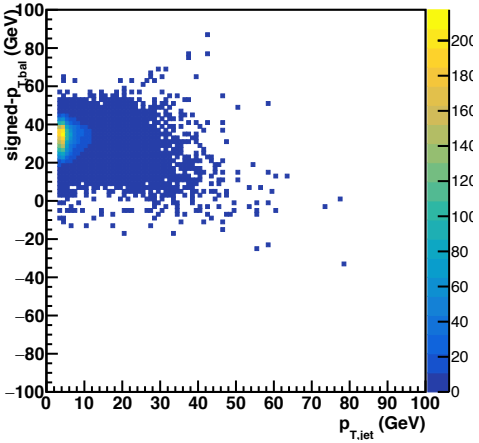


Data W+ (Zoomed in)

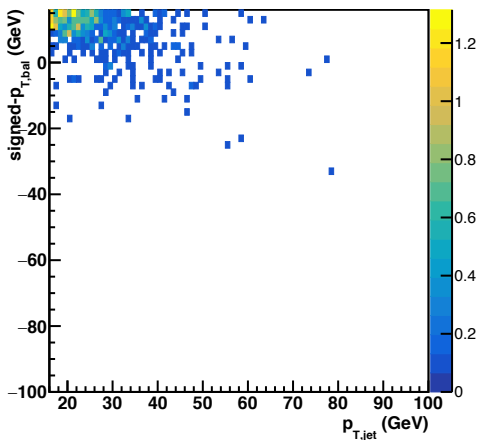


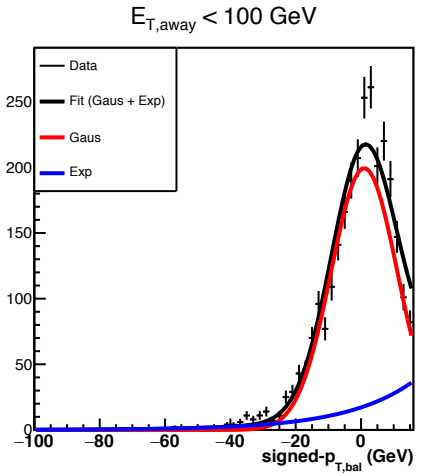


MC W+



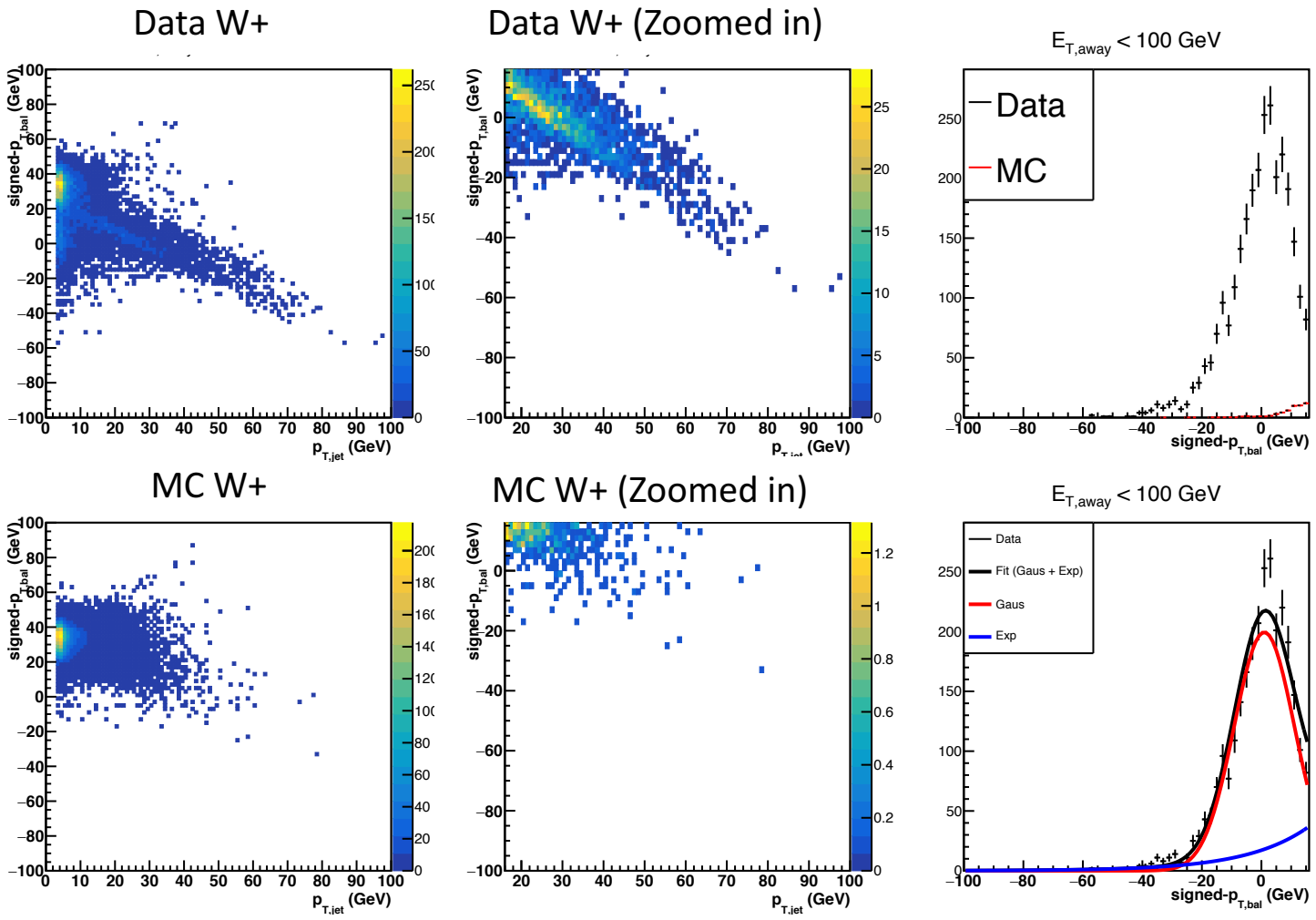
MC W+ (Zoomed in)





- Symmetric (QCD/Z) and asymmetric (possible $W \rightarrow e$ or $W \rightarrow \tau$) fits
- No justification behind choice of fit function (Gaus, Exp)

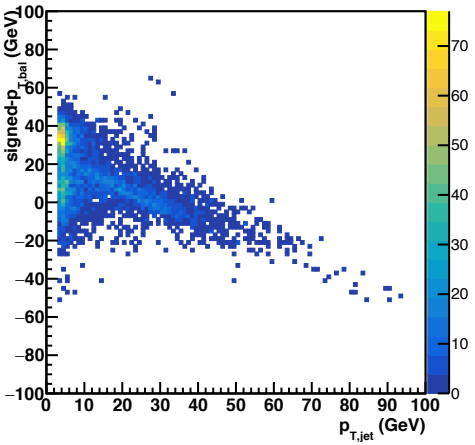
Signed-$p_{T,bal}$ and Jet p_T (W+)



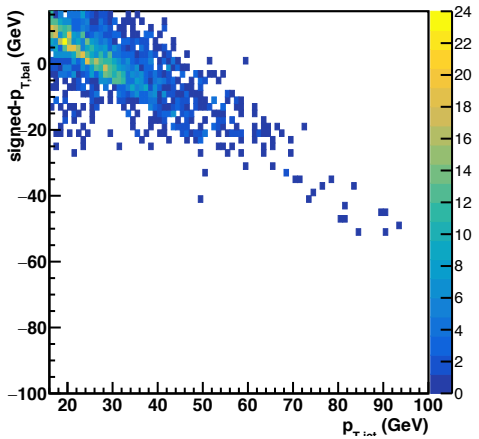
- Asymmetric contribution can be as large as ~5% of signal

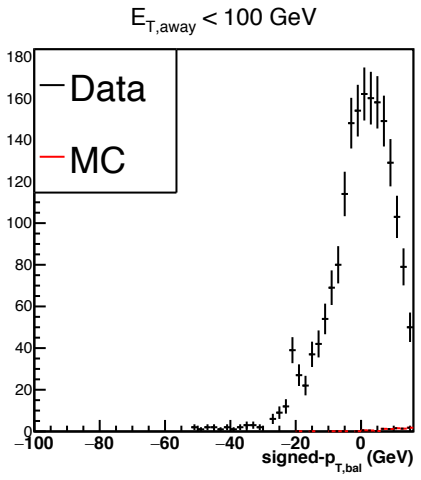
Signed-$p_{T,bal}$ and Jet p_T (W-)

Data W-

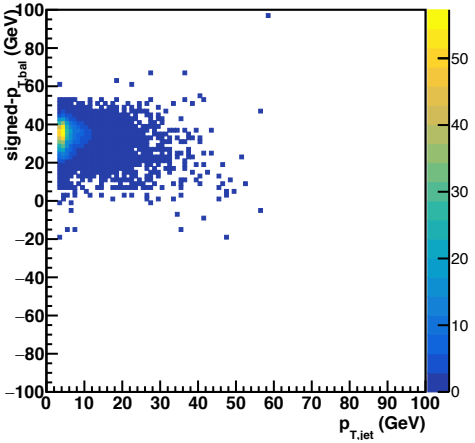


Data W- (Zoomed in)

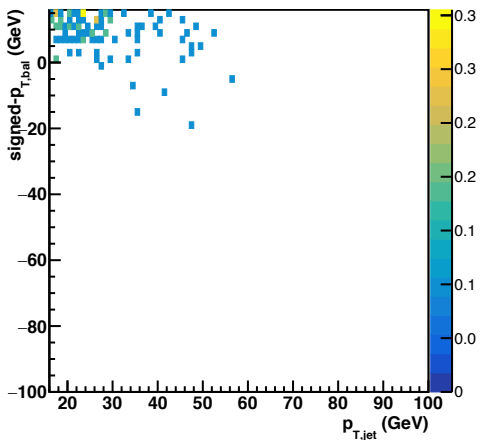


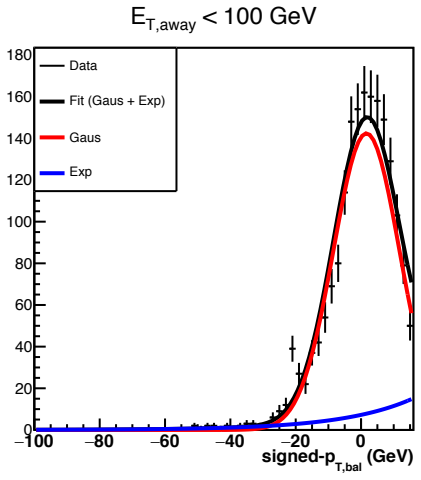


MC W-



MC W- (Zoomed in)





- Similar observation with W-
  (Asymmetric contribution can be as large as ~5% of signal)

Summary of Model Uncertainty

- Mock W study with new QCD jet definition suggests **no significant** mis-estimation of signed-$p_{T,bal}$ cut
- Similar study was repeated with W data and found that the mis-estimation effect can **only be as large as** $\sim\mathbf{5}\%$

→ No significant contribution from signed-$p_{T,bal}$ and $E_{T,away}$

- The following lines will be added In the text,
  - Emission of soft and hard gluons simulated with LO+PS models, such as Pythia, is subject to uncertainties originating from the underlying assumptions behind parton showering algorithms, and cannot be trusted entirely.
  - The resulting misdescription of soft and hard QCD radiation may appear as an incorrect estimation of the reconstruction efficiency in equation (X).
  - The inefficiency of selection criteria based on the activity within a large area of the detector, such as $\boldsymbol{E_T^{\Delta R<0.7}}$ and $\boldsymbol{E_T^{\Delta\phi\sim\pi}}$, and the description of reconstructed jets, such as **signed-$\boldsymbol{p_{T,bal}}$**, have been re-evaluated using reconstructed W and Z samples from data without these requirements.
  - The impact of the misestimation of the reconstruction efficiency to the overall cross section was found to be less than 5% and taken as a **systematic uncertainty**.