Measurements of W^+/W^- cross-section ratio in pp collisions at STAR

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For the STAR collaboration

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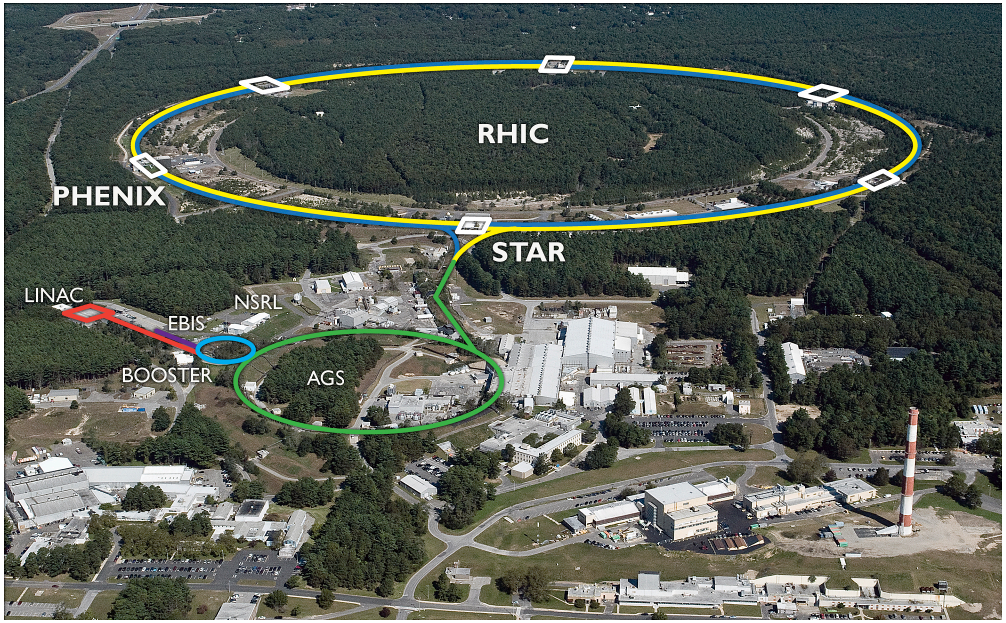
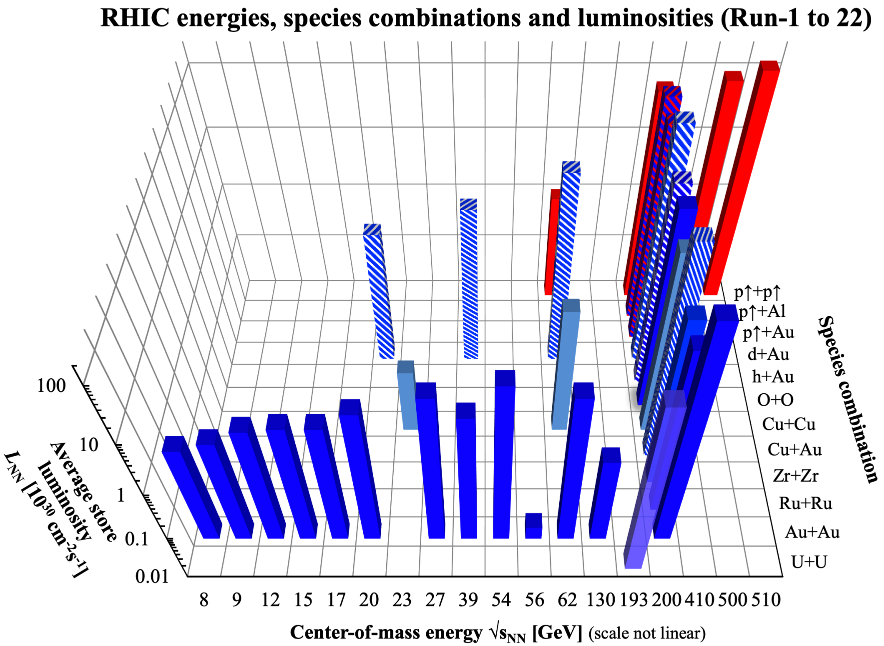
Relativistic Heavy Ion Collider



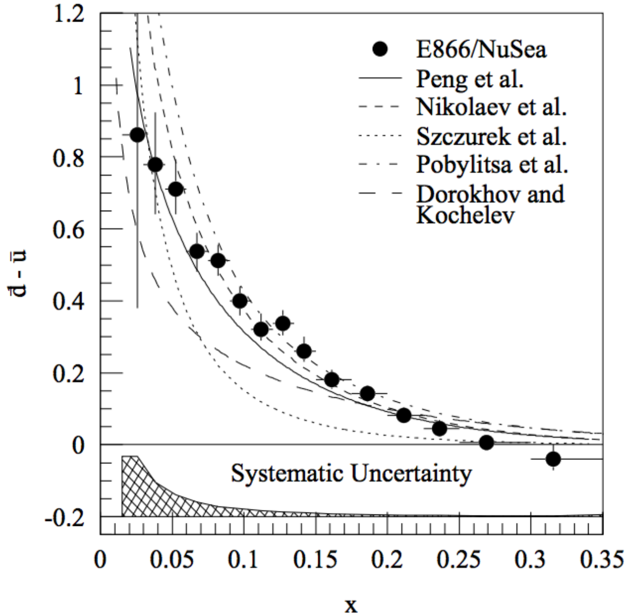


- RHIC continues to serve as the world's first and only polarized pp collider.
- Features pp collisions at $\sqrt{s} = 500/508/510$ GeV and $\sqrt{s} = 200$ GeV.
- pA $\sqrt{s_{NN}} = 200$ GeV and AA $\sqrt{s_{NN}} = 3\sim200$ GeV collisions.

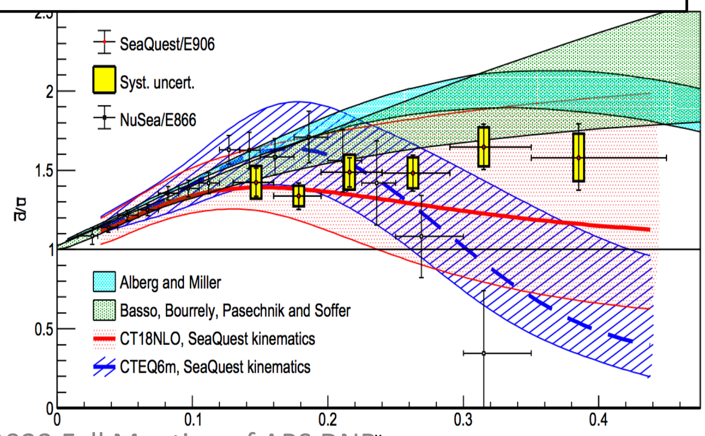
- At RHIC, protons can be polarized either:
  - Longitudinally (along the direction of the beam)
    - → Proton spin composition
  - Transversely (perpendicular to the beam)
    - → 3D image of the proton
  - Or can be unpolarized
    - → **Parton distribution functions**
    - → Non-linear gluon effects

Physics case: $\bar{d}/\bar{u}$ asymmetry

NuSea, Phys.Rev.D 64 (2001) 052002



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



- While the valence quark (d, u) structure of the proton is well understood, the anti-quark counterpart $(\bar{d}, \bar{u})$ is much less constrained.
- Non-diminishing asymmetry between the anti-quarks in the proton sea $\bar{d}, \bar{u}$ is a purely non-perturbative phenomenon.
- The anti-quark ratio $\bar{d}/\bar{u}$ is typically measured in Drell-Yan type experiments with deuterons.
- Inconsistencies among these measurements have been found, especially in the proton momentum fraction range $x > 0.2$.
- W measurements at RHIC may provide insight around the same x region at higher Q^2.

W production in pp collisions

- $W^{\pm}$ cross sections at LO
  - $d\sigma^{W+} \propto u(x_1)\bar{d}(x_2) + u(x_2)\bar{d}(x_1)$
  - $d\sigma^{W-} \propto \bar{u}(x_1)d(x_2) + \bar{u}(x_2)d(x_1)$

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

- At LO, momentum scale set by the W mass, $Q^2 \sim M_W^2$.
- Leptonic decay via $W \rightarrow e\nu$
  - $\frac{d\sigma(W^{\pm}\rightarrow e\nu)}{dp_{T,e}^2} \propto \frac{(1\pm\cos\theta)^2}{M_W \cos\theta}$

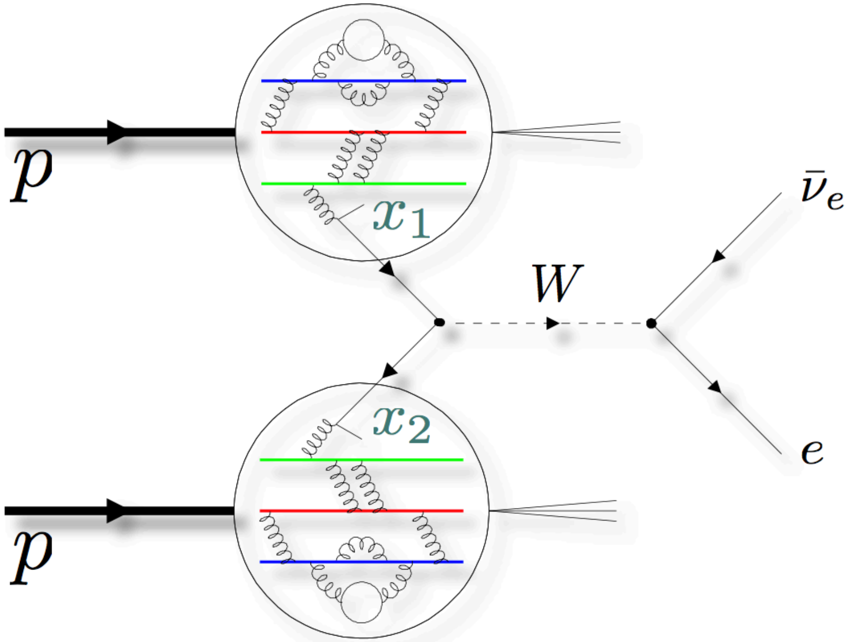
*θ = angle between W pol. and electron

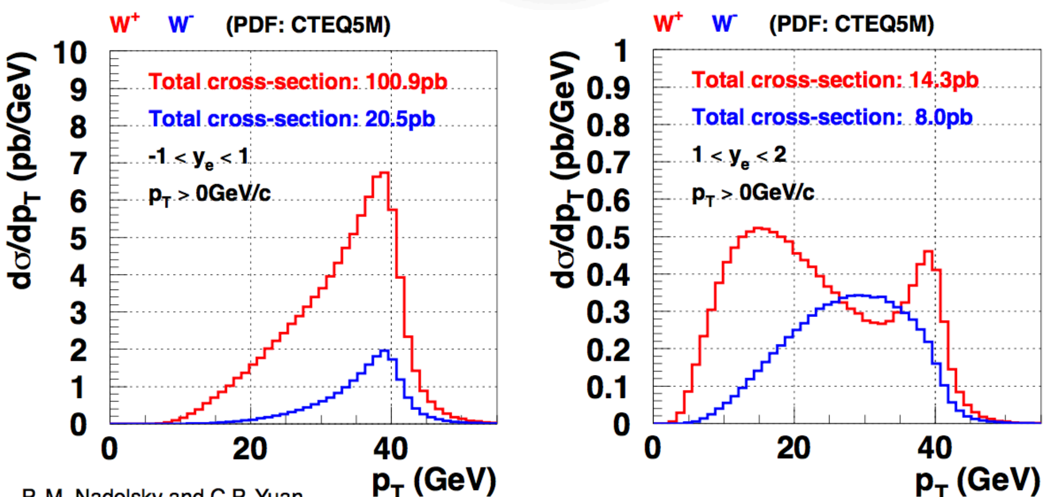
  - $p_{T,e} \sim \frac{M_W}{2}\sin\theta$

  $\rightarrow$ Jacobian peak at $p_{T,e} \sim M_W/2$
  - $y_e \sim y_W + \frac{\ln 1+\cos\theta}{\ln 1-\cos\theta}$

  $\rightarrow$ Charge discrimination as a function of y_e.

- Key features in experiment
  - High p_T electron.
    - Electron/hadron discrimination needed.
  - Large imbalance in p_T due to missing ν.

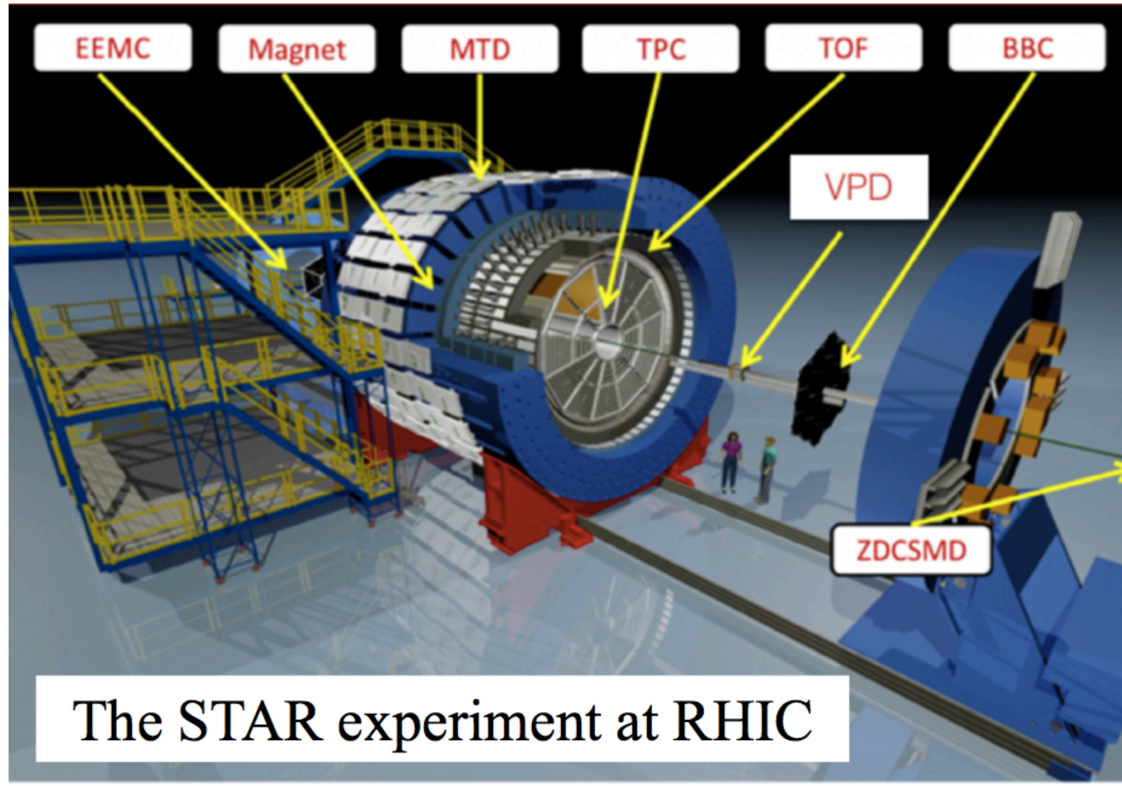




P. M. Nadolsky and C.P. Yuan, Nucl.Phys. B666 (2003) 31.

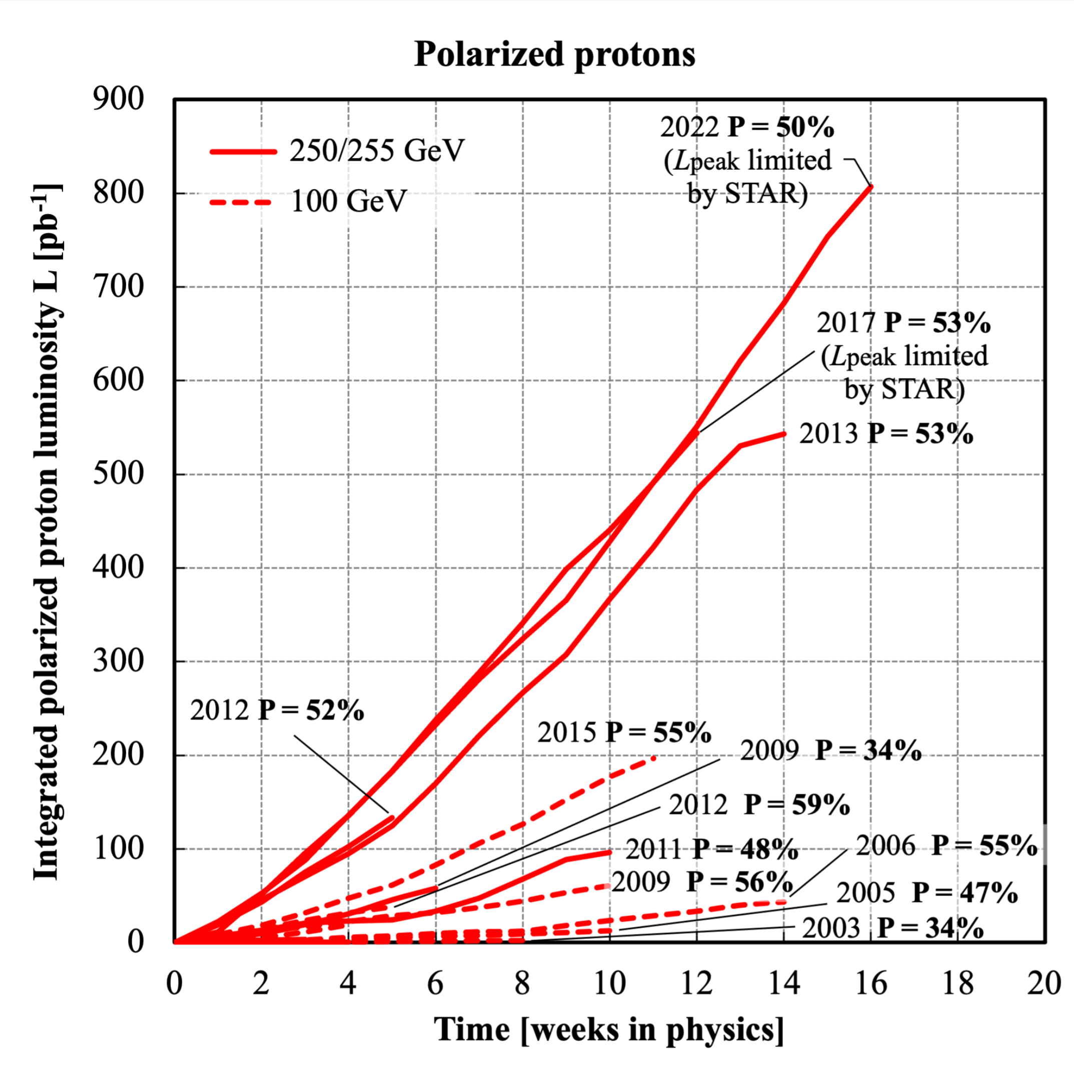
Solenoid Tracker At RHIC (STAR)

- For measurements of W bosons, it is important to achieve near-4π detector acceptance.
- Time Projection Chamber(TPC)
  - Acceptance of $|\eta| < 1.3$.
  - Provides tracking & PID.
  - charge discrimination
- Electro-Magnetic Calorimenter
  - Barrel (BEMC): $|\eta| < 1$.
  - Endcap (EEMC): $1 < \eta < 2$.
  - Assists in electron/hadron discrimination.
  - Assists in electron charge discrimination.



- The W bosons detected in the TPC + BEMC (barrel region) arise from a kinematic region of $0.1 < x < 0.3$.
- EEMC provides coverage in the intermediate rapidity region $1 < \eta < 2$, extending the kinematic reach to $0.06 < x < 0.4$.

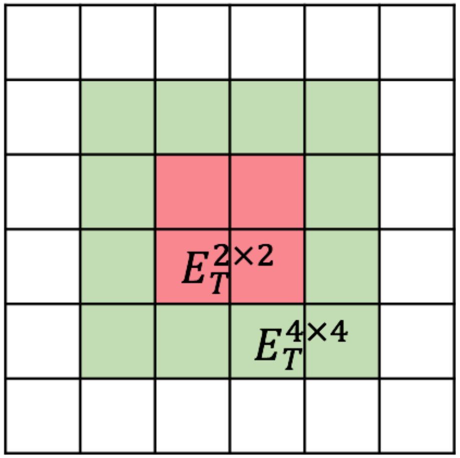
RHIC $pp\ \sqrt{s} = 500/510$ GeV Run Overview



Run	$\sqrt{s}\ (GeV)$	$L\ (pb^{-1})$
2009	500	10
2011	500	25
2012	510	75
2013	510	250
2017	510	350
2022	508	400

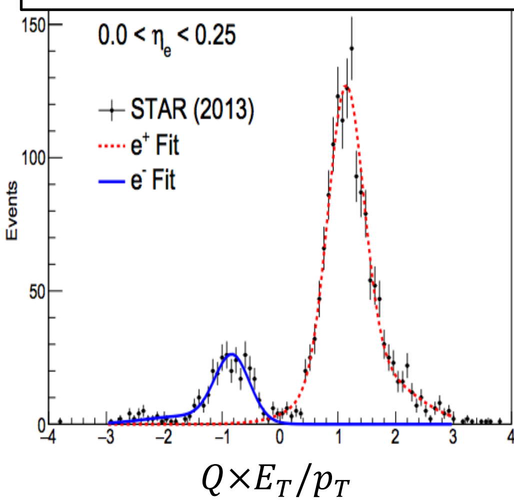
- $L \sim 700 + 400\ pb^{-1}$ of pp collisions with $\sqrt{s} \sim 500$ GeV has been collected at STAR.
- Initial measurement based on Run 2009 with $L \sim 10\ \text{pb}^{-1}$. (STAR, PRD 85 092010)
- Follow up study with Run 2011-2013 with $L \sim 350\ \text{pb}^{-1}$ has been published. (STAR, PRD 103,012001)
- Preliminary study based on Run 2017 with $L \sim 350\ \text{pb}^{-1}$.
- New dataset with $L \sim 450\ \text{pb}^{-1}$ from Run 2022.

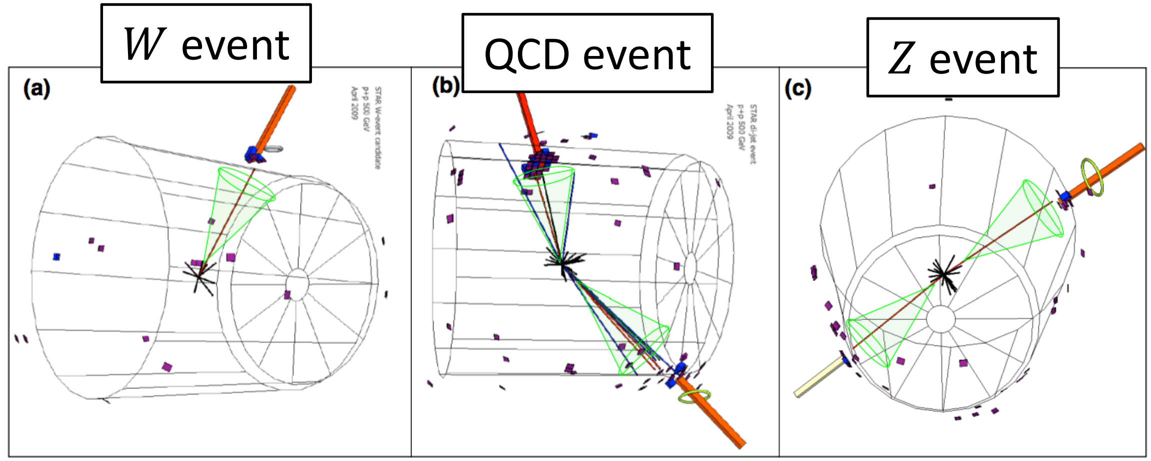
W tagging method



TPC track extrapolated to BEMC tower grid

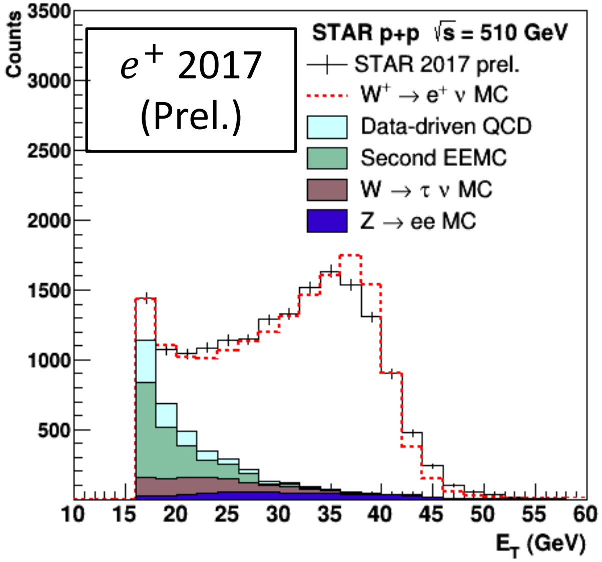
STAR, PRD 103 (2021) 1, 012001

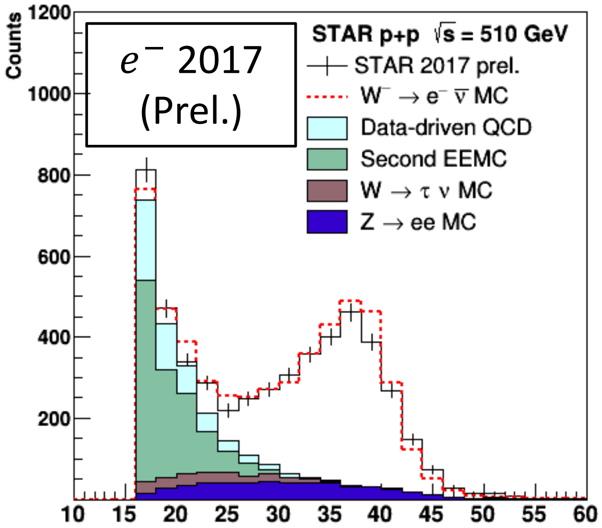




- W bosons that undergo the leptonic decay process, $W \rightarrow e\nu$, are tagged.
- Imbalance in p_T due to the missing neutrino. High $\vec{p}_{T,bal}$ ($= \vec{p}_{T,e} + \Sigma\vec{p}_{T,recoil}$) events are selected.
- Unlike hadrons, electrons deposit their energy in a highly concentrated region in the EMC. This isolated electron energy deposit is selected by requiring $E_T^{2\times2}/E_T^{4\times4} \sim 1$.
- Charge separation from TPC + EMC ($Q_e\times E_T/p_T$).

Signal/background description

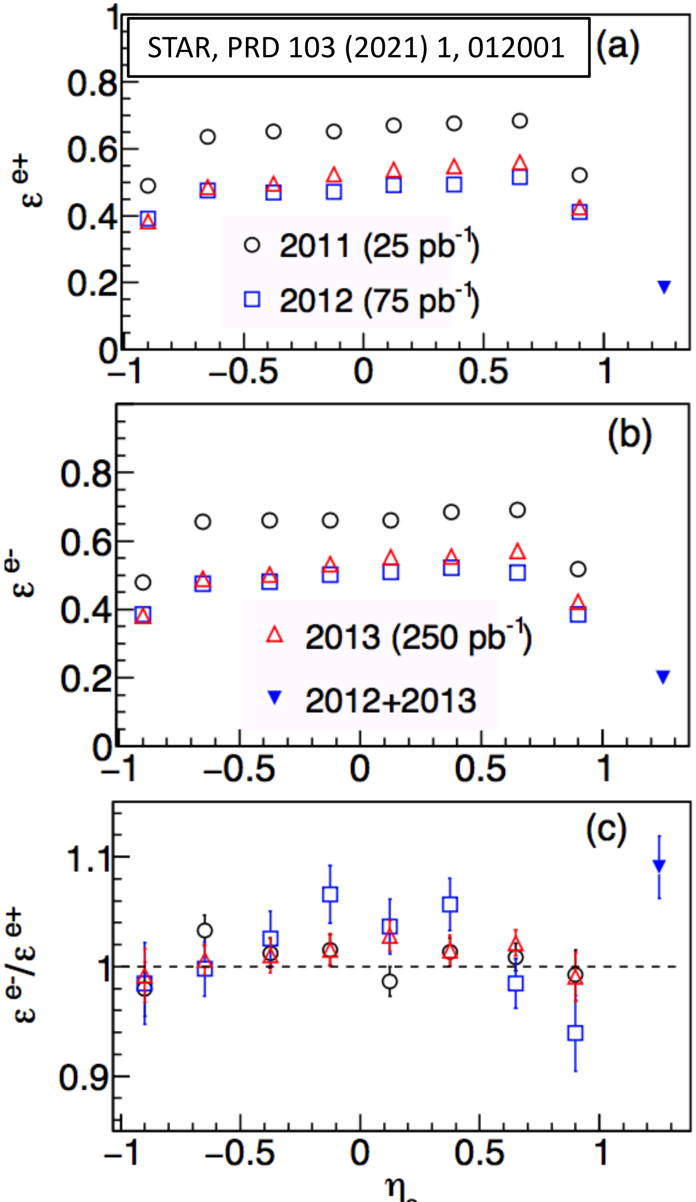




- Electroweak $(N_{Z\to ee},\ N_{W\to\tau\nu})$ background
  - Z decays with one unidentified electron
  - Leptonic decay of τ^W
  - Estimated with MC (Pythia)

- QCD background
  - Due to the limited acceptance and kinematic coverage, imbalance in p_T may appear in QCD events.
  - Two methods employed to estimate their contributions:
  - Second EEMC (N_{EEMC})
    - Accounts for missing backward coverage $(-2 < \eta < -1)$
    - Estimated by mirroring the effect of existing EEMC in the forward direction.
  - Data-driven QCD (N_{QCD})
    - Remaining background contribution that passes the selection process.
    - Distribution obtained by using events that do not pass the $p_{T,bal}$ cut.

Efficiencies



- In the W cross-section ratio measurement, the expression of the ratio reduces to:

$$\sigma_{W^+}/\sigma_{W^-} = \frac{N_{obs}^{+}}{\epsilon^{+}\int Ldt} / \frac{N_{obs}^{-}}{\epsilon^{-}\int Ldt}$$

$$= \frac{\epsilon^{-}}{\epsilon^{+}} \cdot \frac{N_{sig}^{+} - N_{bg}^{+}}{N_{sig}^{-} - N_{bg}^{-}}$$

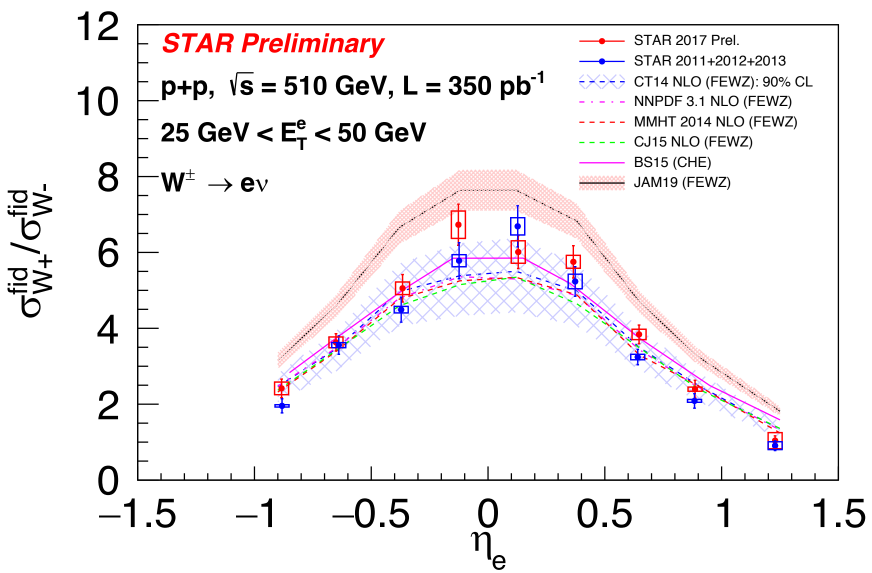
  where ϵ represents the product of the efficiencies of our selection process.

- Lower efficiency in Run 2012 and 2013 (compared to Run 2011) due to higher material budget and event pile-up caused by higher instantaneous luminosity.

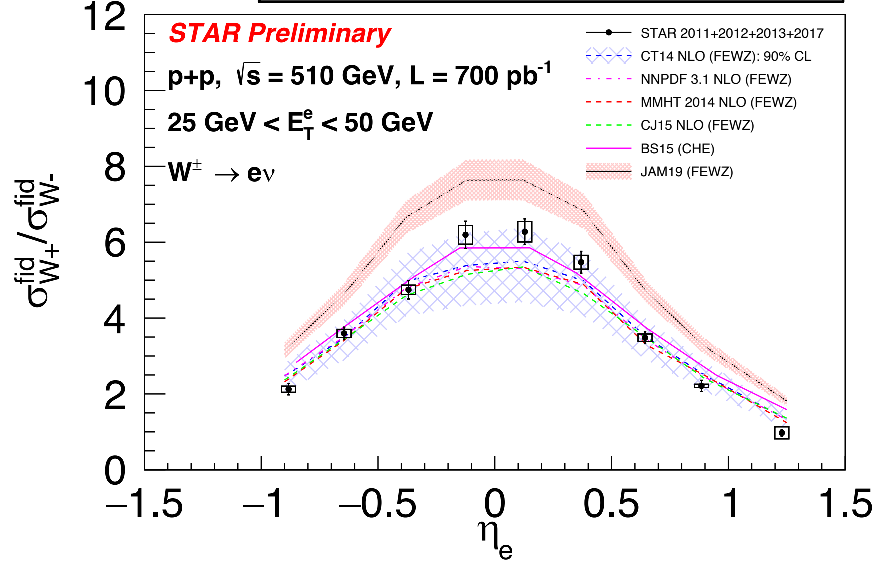
- Higher tracking efficiency in 2013 than in 2012 due to improvements in tracking algorithm.

- MC study suggests that the efficiency ratio $\epsilon^{-}/\epsilon^{+}$ is consistent with unity and the deviation from unity is taken as a source of systematic uncertainty.

Results



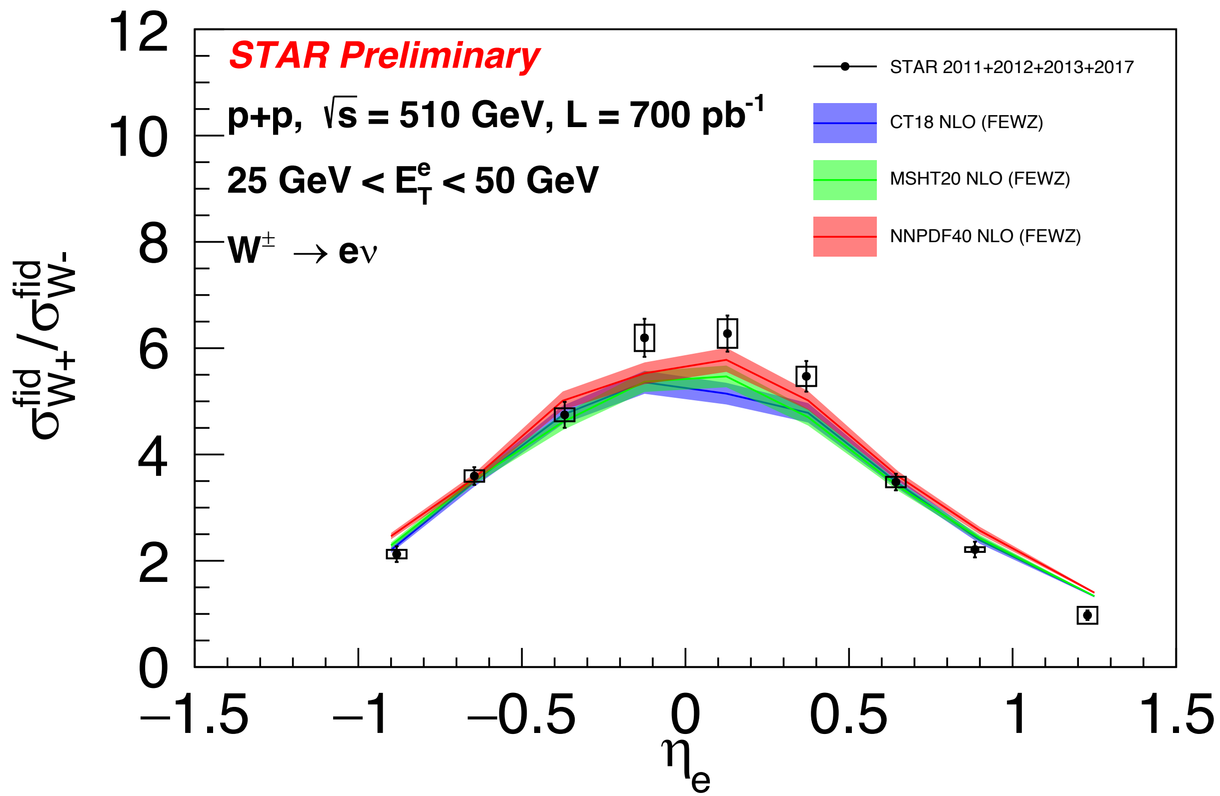
Combined published + preliminary results



- Measurement with STAR 2011-2013 data set has been published (PRD 103 (2021) 1, 012001).
- Additional data set taken in 2017 has been analyzed and is in preliminary release.
- These measurements are consistent with each other within their uncertainties.
- Overall good agreement with the PDF distributions.
  - Unlike the other predictions, JAM19 result extracts both FF and sea quarks.

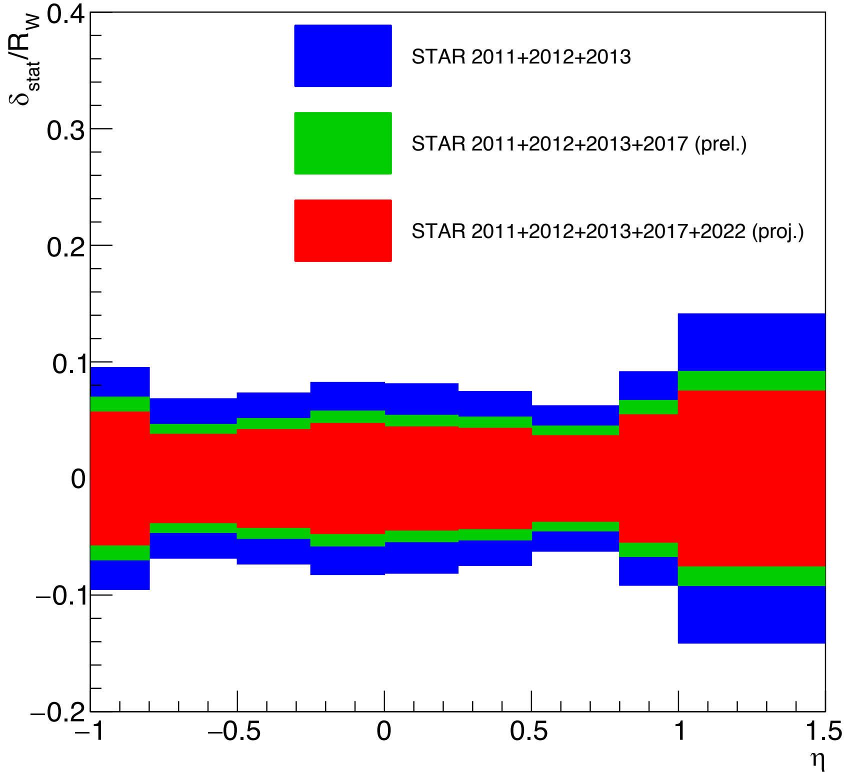
Results (continued)

Featured PDF sets:
CT18: arXiv:1908.11394
MSHT20: EPJC 81 (2021) 4, 341
NNPDF4.0: EPJC 82 (2022) 5, 428



- SeaQuest data (NNPDF4.0) improves description of STAR data.
- However the improvement is mostly seen in $\eta_e \sim 0$.
- The endcap ($1 < \eta_e < 1.5$) still underestimated.
- Calculations at NNLO accuracy will be included in the final paper.

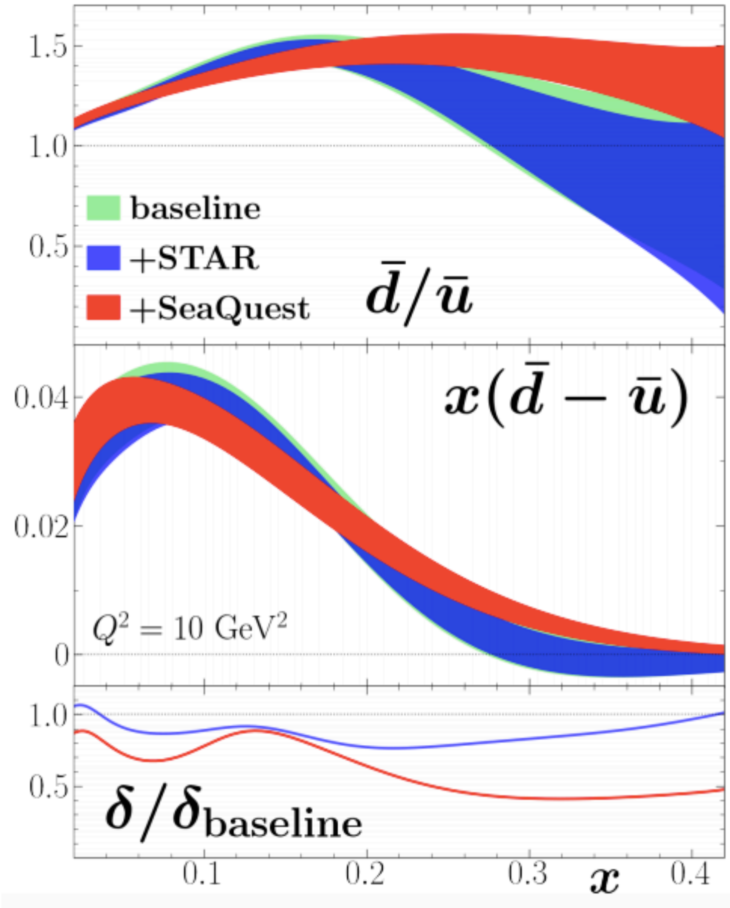
Results (projection)



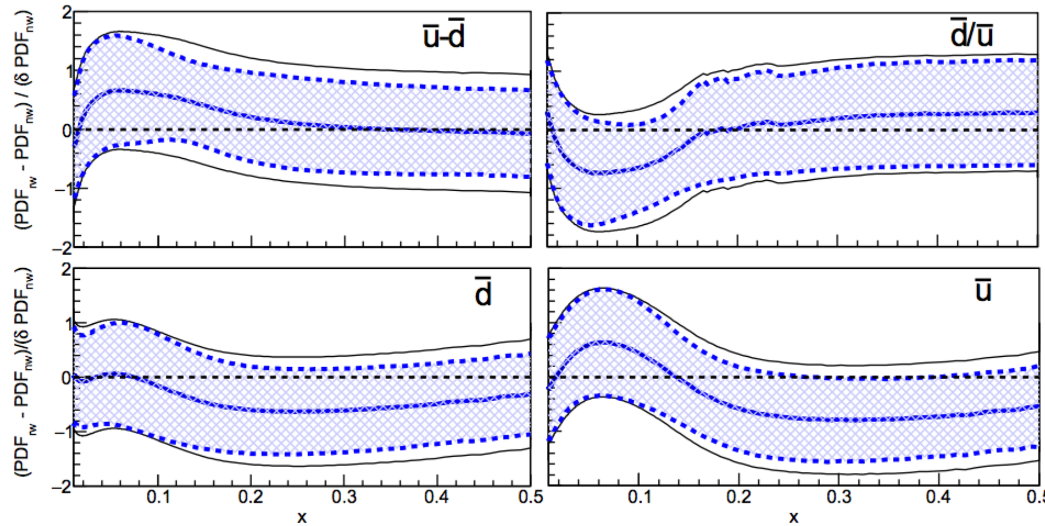
- Projection for STAR 2022 data set
  - Combined statistics $\sim 1.1\ \mathrm{fb}^{-1}$, concluding $500/510\ GeV\ pp$ program at STAR
  - Data preparation (detector calibrations, etc.) has been initiated.

PDF impacts

JAM, PRD 104 (2021) 7, 074031



STAR, PRD 103 (2021) 1, 012001
*(uses CT14MC2NLO)



- Recent publication (STAR 2011+2012+2013) has been included in global fits.
- STAR data have a moderate impact on the sea quark distributions around $x \sim 0.2$, reducing the uncertainty by $\sim$20 %.

Summary & Outlook

- W^+/W^- cross-section ratio has been measured with STAR pp $\sqrt{s} = 500, 510$ GeV datasets.
  - Probe $\bar{d}/\bar{u}$ asymmetry in the proton sea at higher Q^2, complementary to Drell-Yan measurements.
  - Results based on STAR 2011+2012+2013 ($L \approx 350\ \mathrm{pb}^{-1}$) have been published.
  - STAR 2017 (adds additional $L \approx 350\ \mathrm{pb}^{-1}$) dataset in preliminary state.
  - Combined results consistent with the current PDF distributions.
  - Reduction of uncertainty by $\sim 20\%$ seen from global fit analyses.

- Outlook
  - STAR 2017 results nearing publication.
  - New STAR 2022 dataset currently being calibrated.