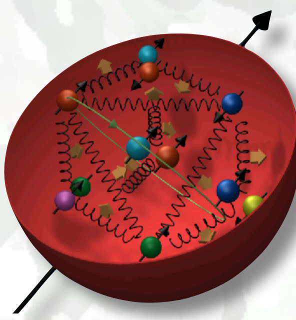
Helicity-constraining measurements from STAR at mid-rapidity in polarized proton-proton collisions at $\sqrt{s} = 200$ and $510\,\mathrm{GeV}$ at RHIC

Bernd Surrow

TEMPLE UNIVERSITY®



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DOE NP contract: DE-SC0013405

Thank you, Daniel and Werner, for the invitation to give this presentation!

Workshop: Precision QCD Predictions for ep Physics at the EIC (II)

Sep 18 – 22, 2023
CFNS
US/Eastern timezone

Enter your search term

- Overview
- Timetable
- Contribution List
- Registration
- Participant List
- Code of Conduct
- Organizing Committee
- Remote Zoom Instruction
- Lodging information
- Workshop venue and direction

Contact
cfns_contact@stonybro...

This event is part of the CFNS workshop/ad-hoc meeting series. See the CFNS conferences page for other events.

The discussions at our workshop will feature the following topics

- Precision fixed-order calculations of polarized and unpolarized hard-scattering cross sections for the EIC. This includes QCD corrections at NLO and beyond for inclusive and semi- inclusive scattering, for jet, hadron or photon final states;
- QCD threshold resummation for EIC cross sections and their impact on phenomenology;
- Techniques for extraction of PDFs and FFs from future EIC data in the context of global analyses, and the status and prospect for "joint" global analyses that aim at simultaneous extractions of PDFs and FFs;
- High-pT observables at the EIC and their interplay with TMD physics.
- See other topics in the EIC Wish List prepared in the previous edition of the workshop.

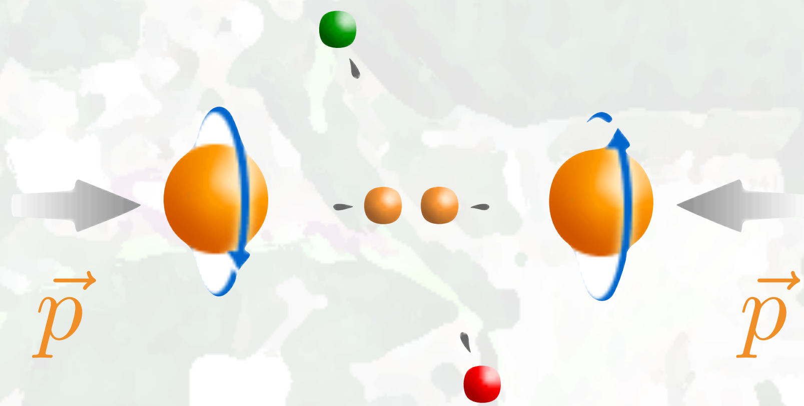
Starts Sep 18, 2023, 8:00 AM
Ends Sep 22, 2023, 7:00 PM
US/Eastern

CFNS

EIC-Wish-List.pdf

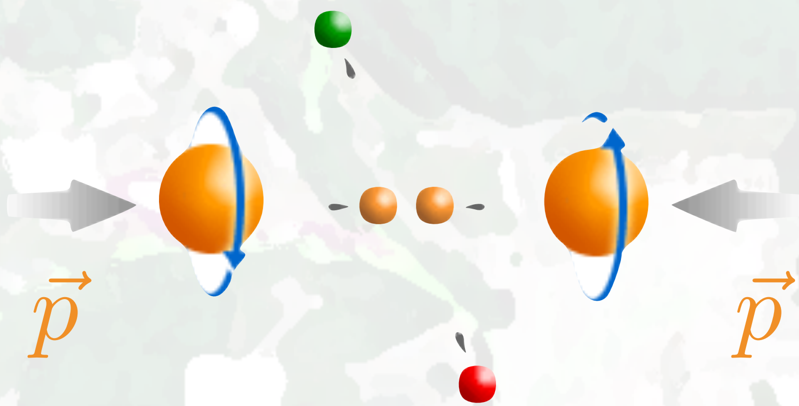
Outline

Outline



Outline

- Theoretical foundation



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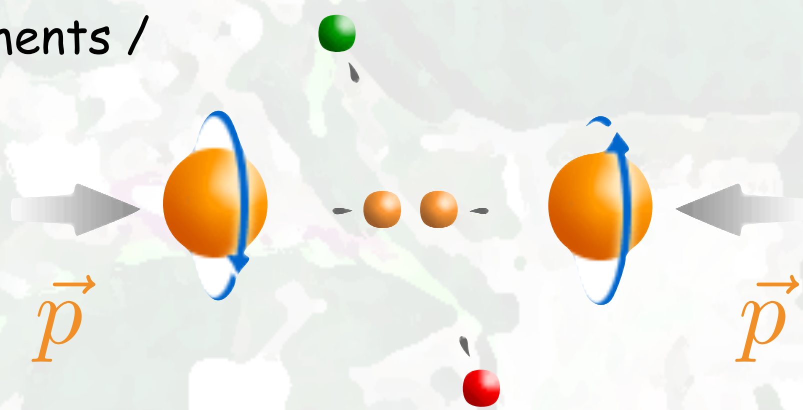
- Experimental aspects: Asymmetry measurements / RHIC / STAR

- Theoretical foundation



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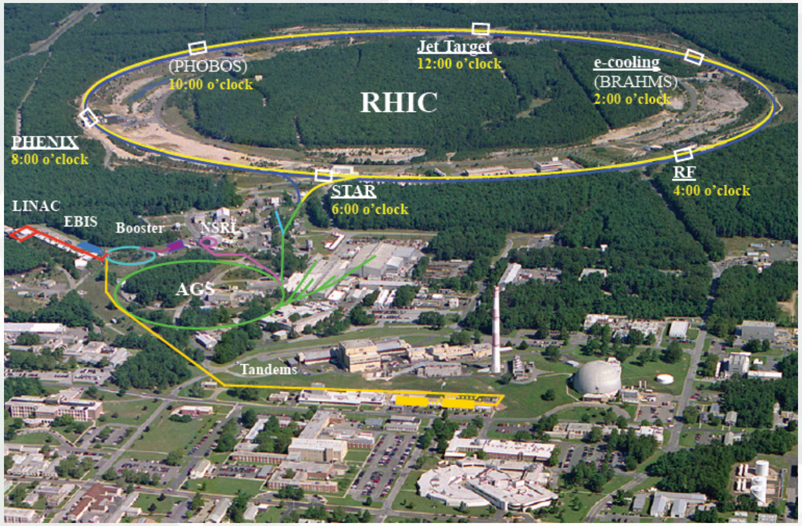

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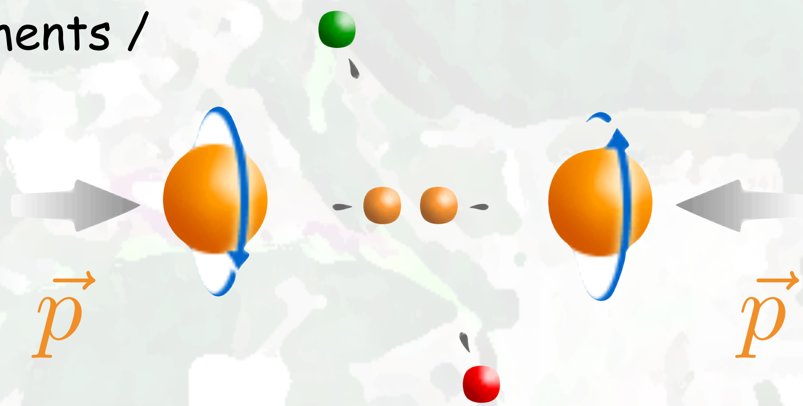

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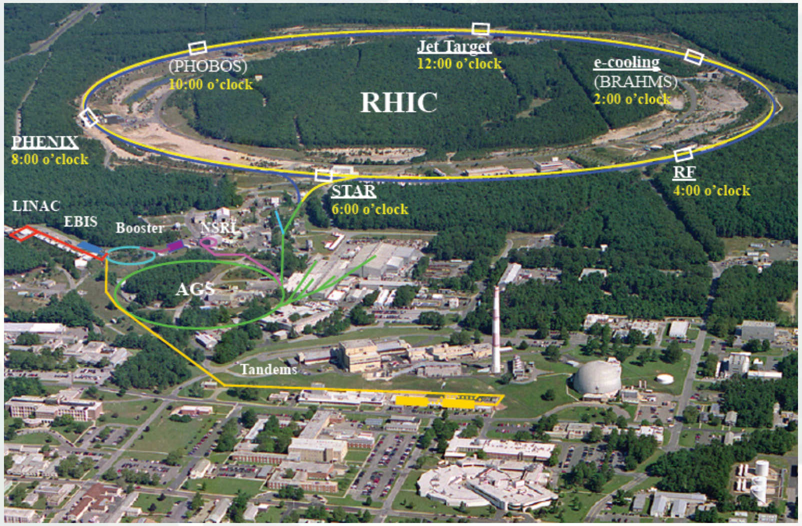

- Measurement of:
  Inclusive Jet and Dijet double spin asymmetry A_{LL} and cross-sections

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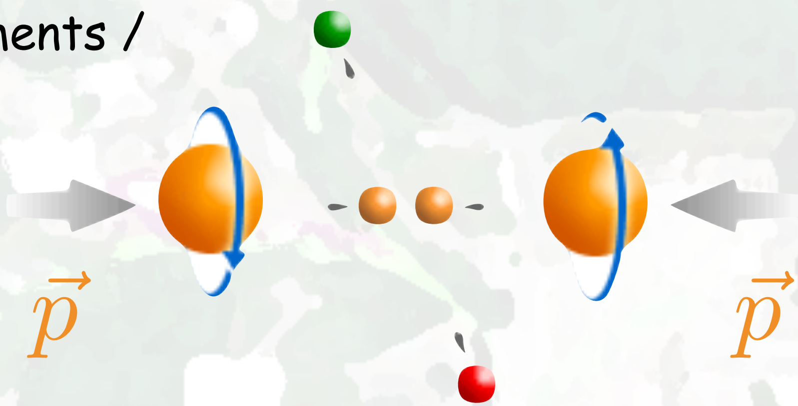

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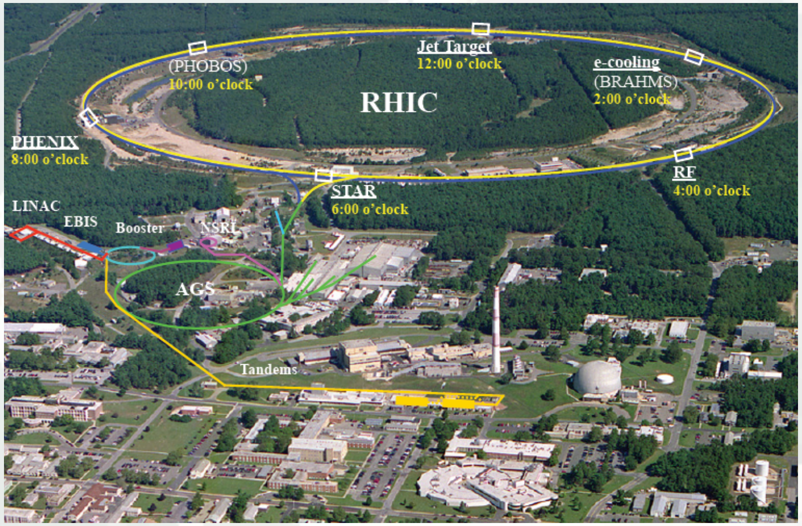

- Measurement of:
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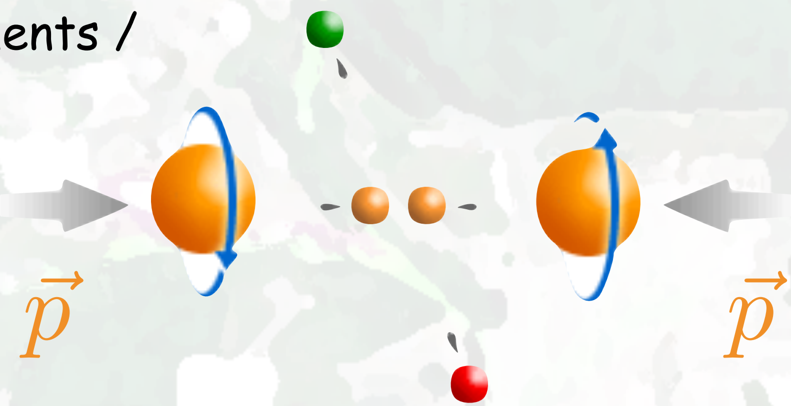

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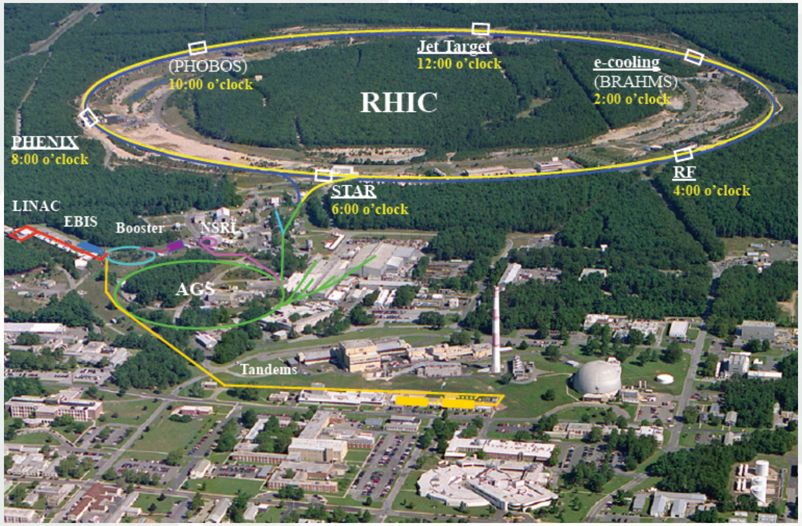

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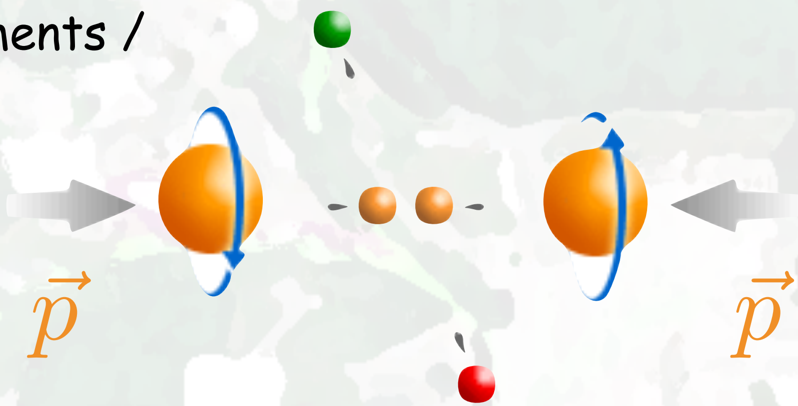

- Summary and Outlook

Theoretical foundation - Probing PDFs

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- How do we probe the structure and dynamics of matter in ep / pp scattering?

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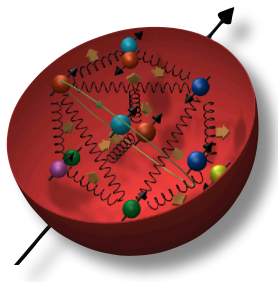

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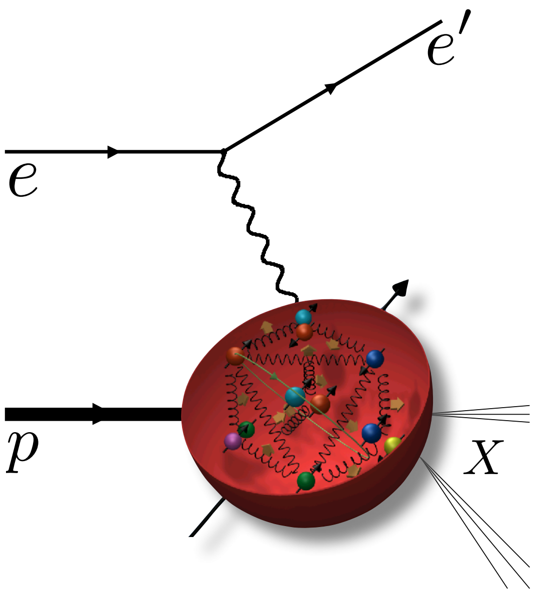

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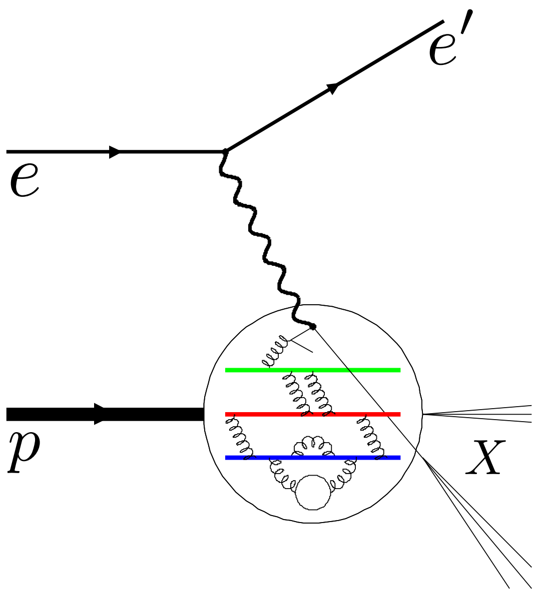

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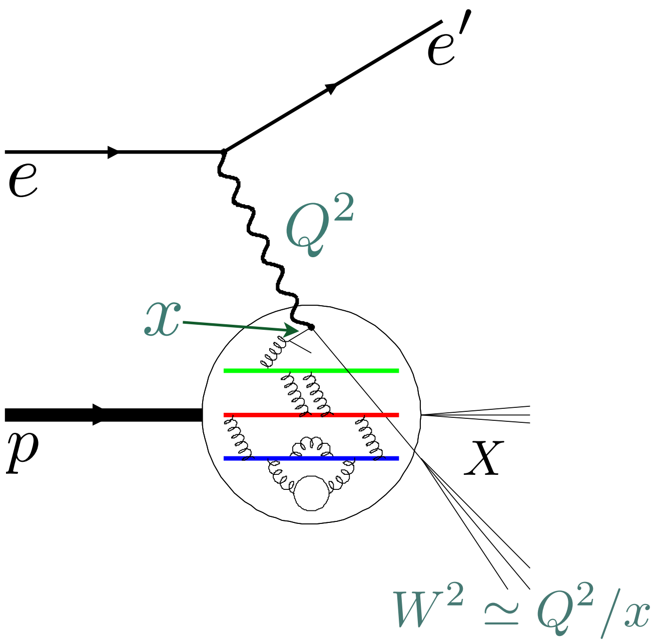

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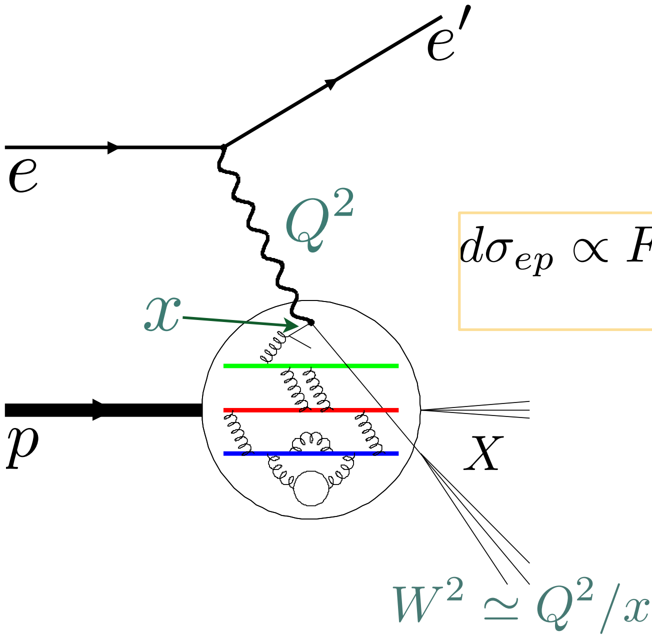

$$d\sigma_{ep} \propto F_2 = \sum_q x e_q^2 f_q(x)$$

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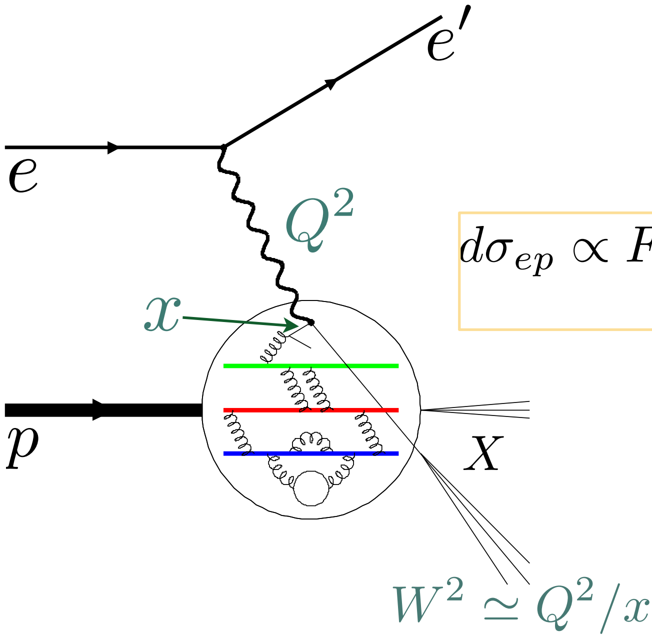

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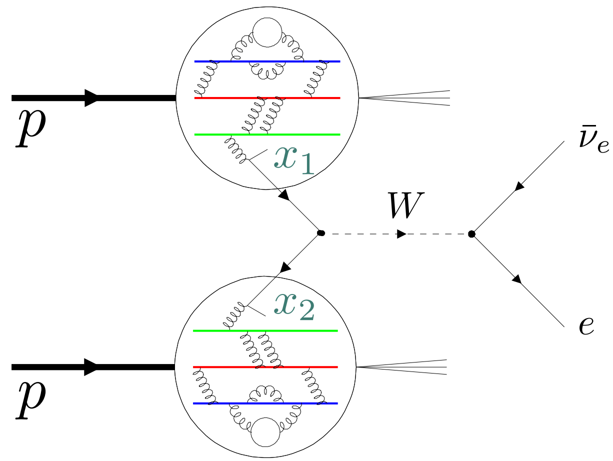

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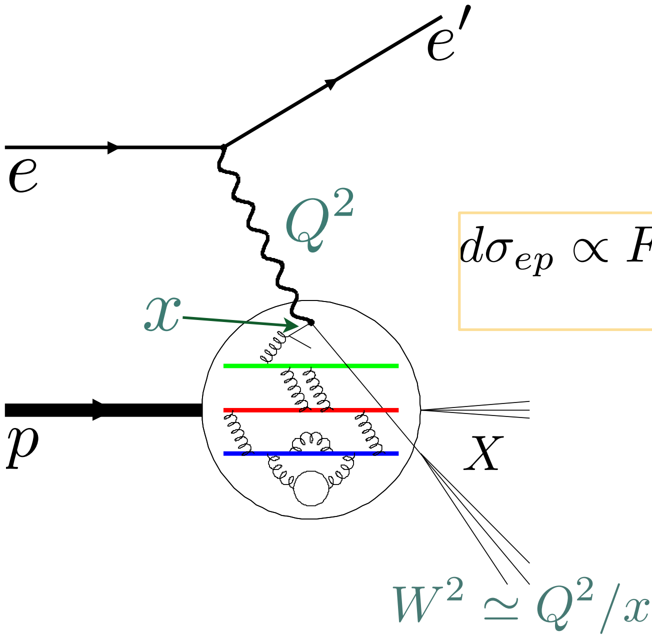

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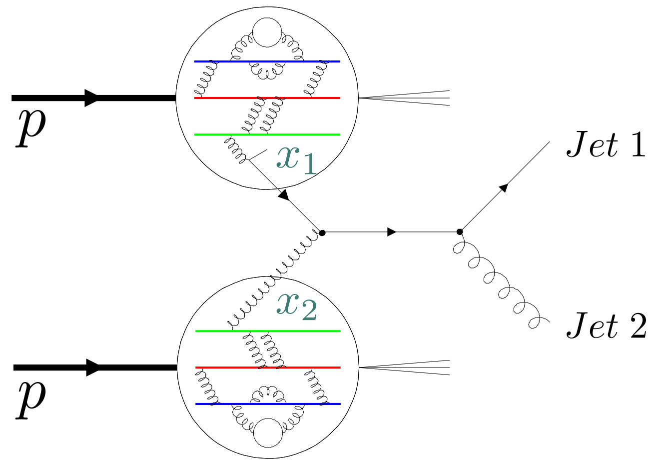

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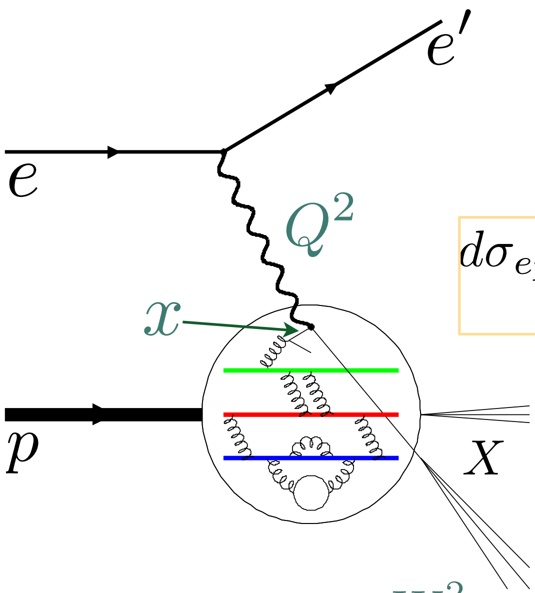

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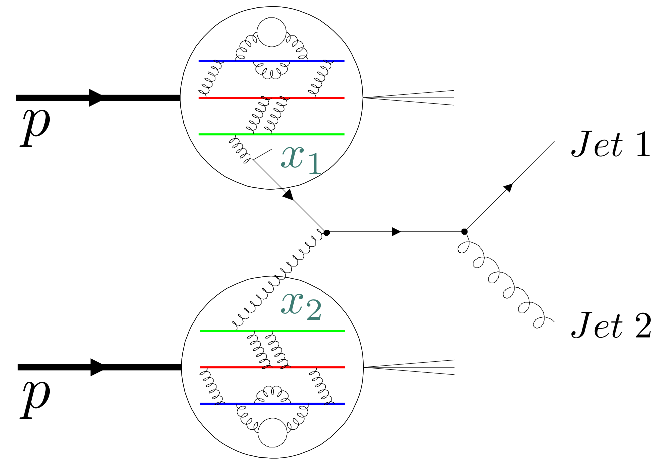
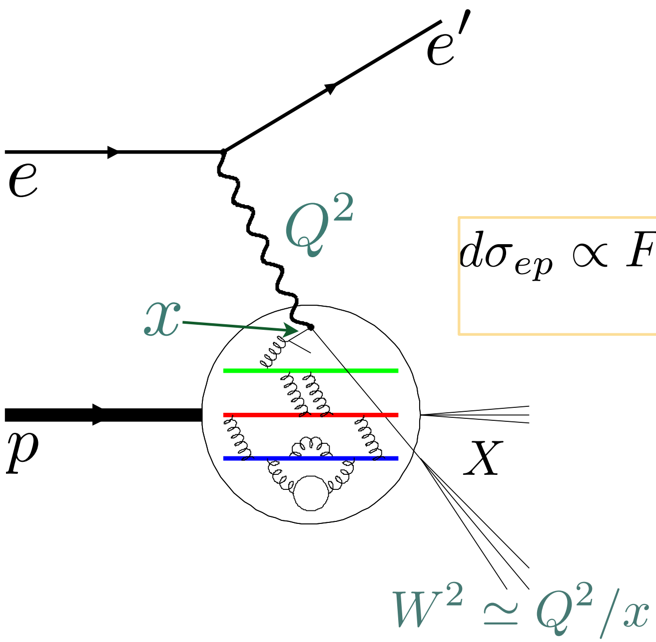


$$d\sigma_{pp} \propto f_1 \otimes f_2 \otimes \sigma_h \otimes D_f^h$$

Factorization

Theoretical foundation - Probing PDFs

- How do we probe the structure and dynamics of matter in ep / pp scattering?



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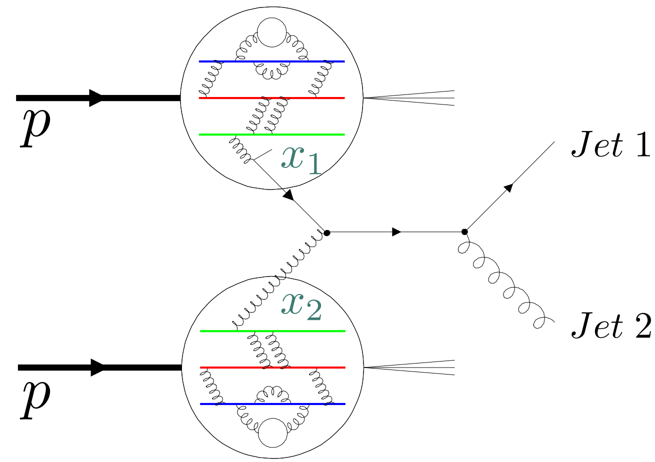
Universality



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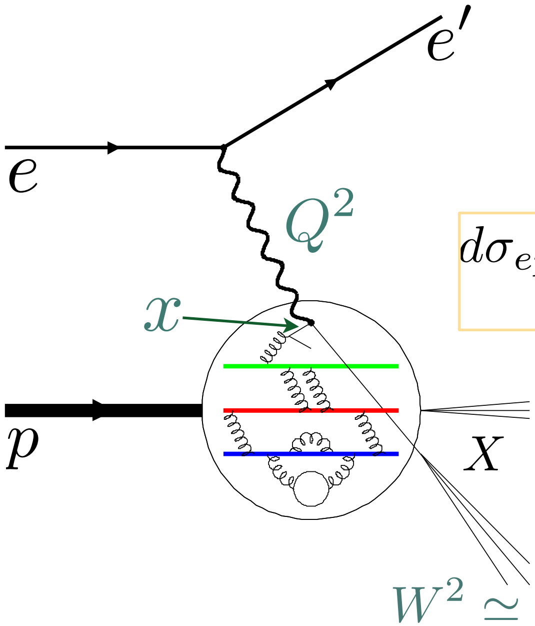

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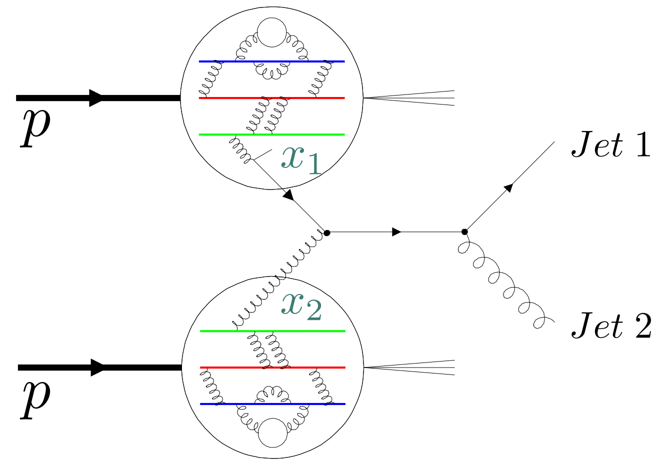

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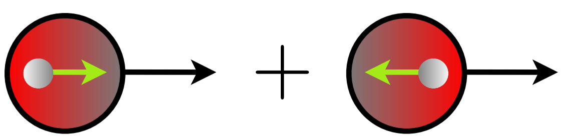
Factorization

Momentum contribution

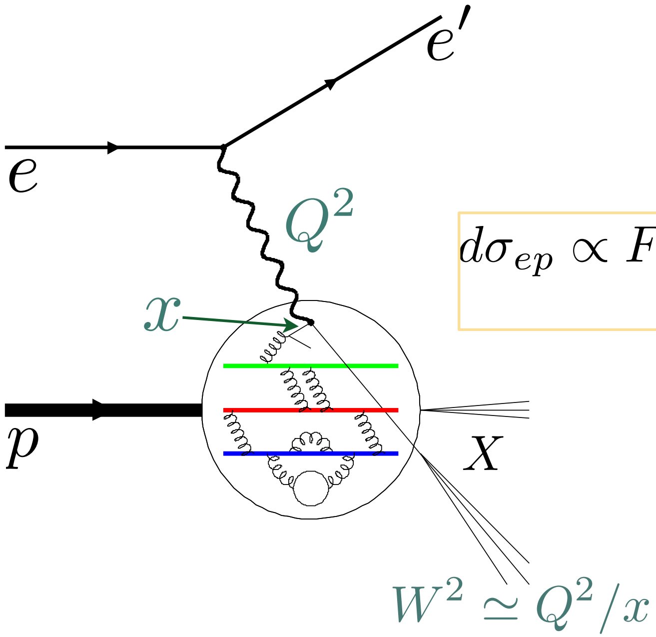
$$f(x) =$$



$$f^+(x) + f^-(x)$$

Theoretical foundation - Probing PDFs

- How do we probe the structure and dynamics of matter in ep / pp scattering?



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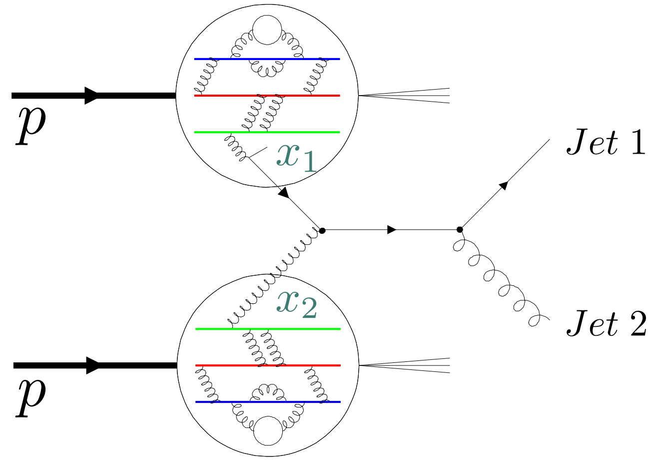

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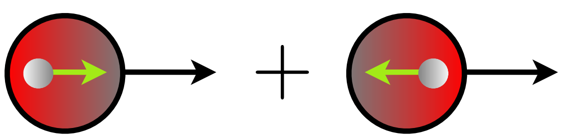
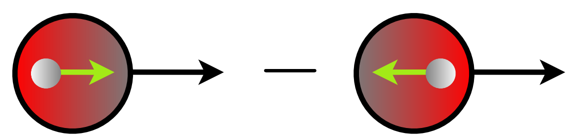


$f^+(x) + f^-(x)$

$\Delta f(x) =$

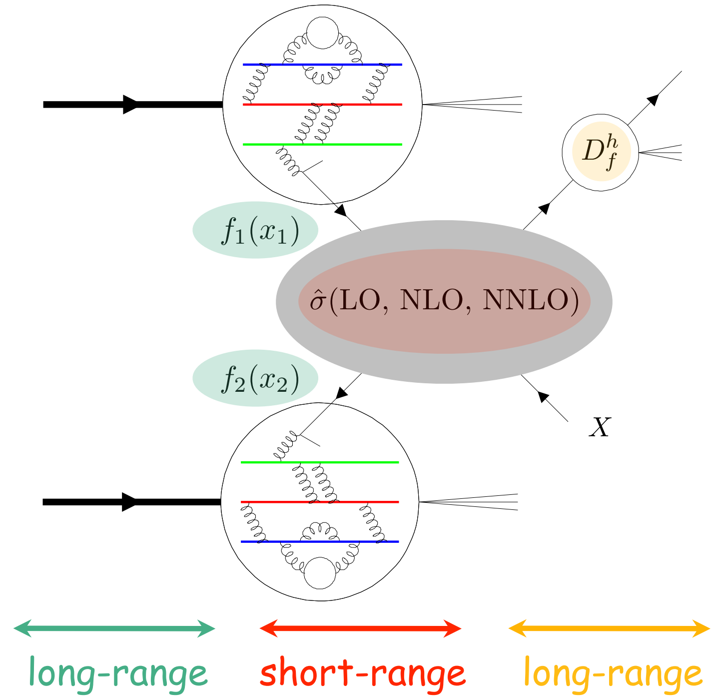


$f^+(x) - f^-(x)$

Spin contribution

Theoretical foundation - PDF access

- Probe gluon helicity via Jet/hadron production
  - Observable: Longitudinal double-spin asymmetry A_{LL} ➜ Probe gluon helicity distribution function $\Delta g(x, Q^2)$ through Inclusive Jet/Dijet production in global analysis!



$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}}$$

Colliding beam helicities!

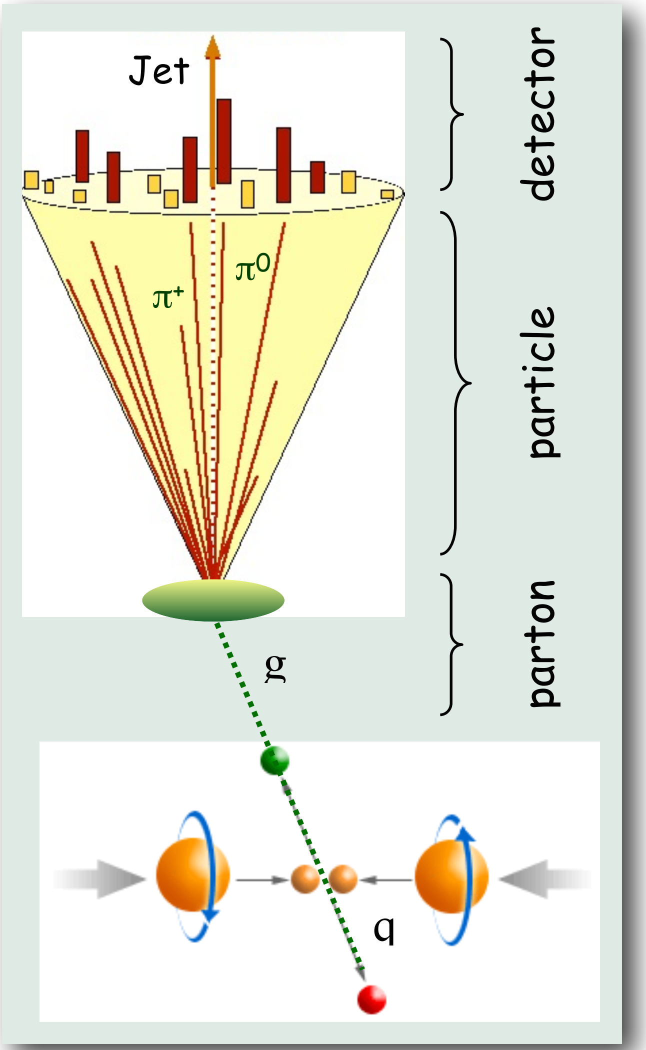
$$a_{LL} = \frac{\Delta\sigma_h}{\sigma_h}$$

$$= \frac{\Delta f_1 \otimes \Delta f_2 \otimes \sigma_h \cdot a_{LL} \otimes D_f^h}{f_1 \otimes f_2 \otimes \sigma_h \otimes D_f^h}$$

Input

Theoretical foundation - QCD processes in pp

- Process contribution for jet-type measurements



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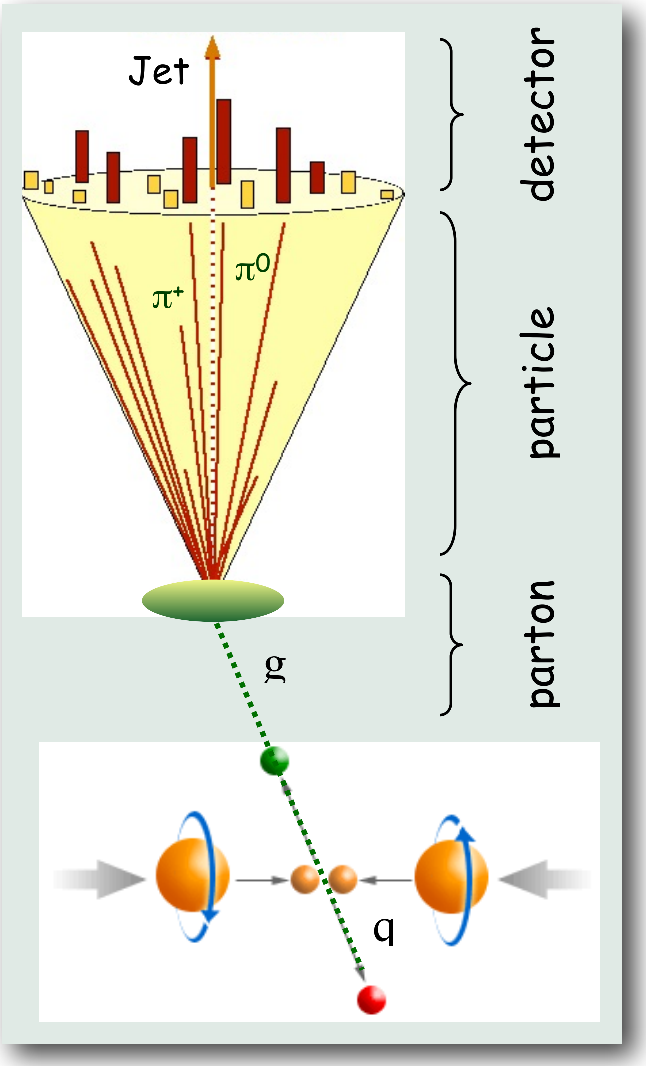

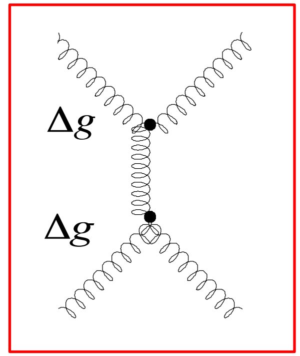

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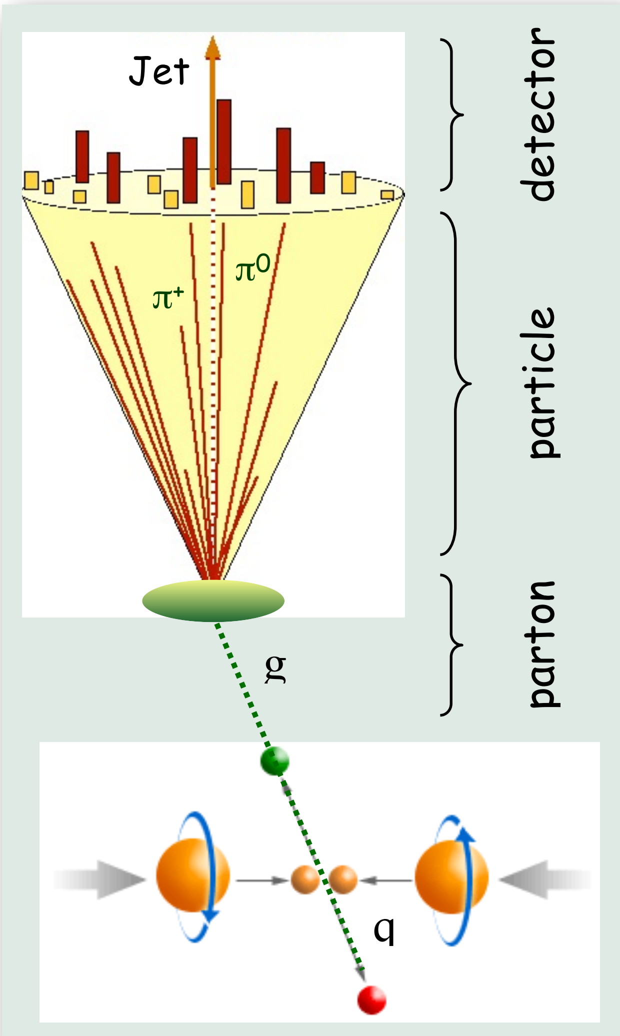

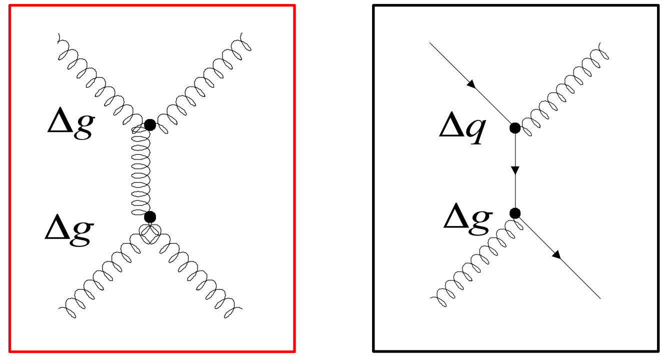

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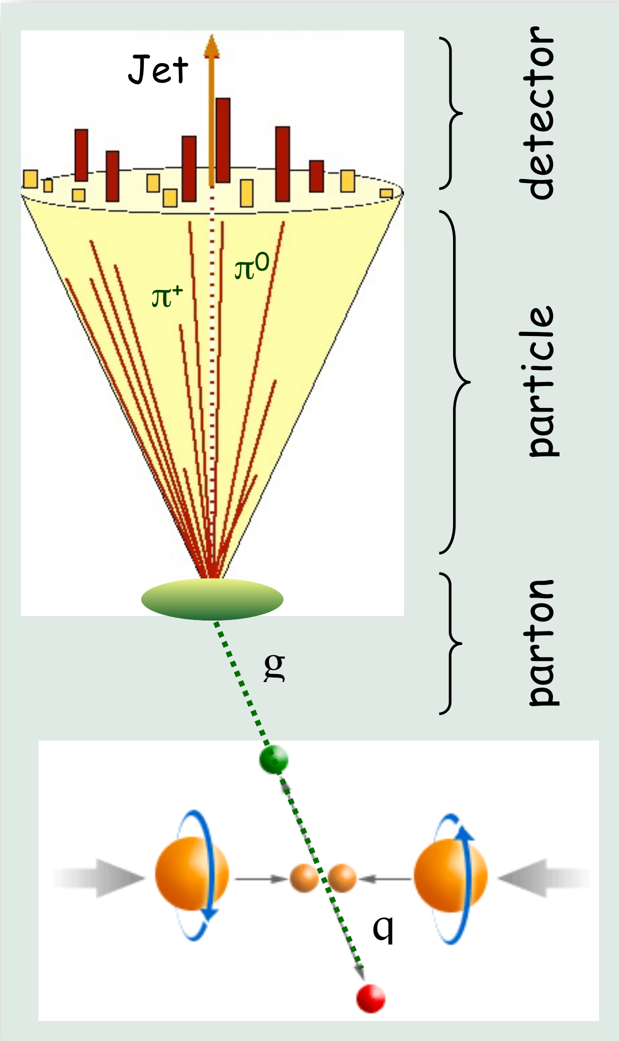

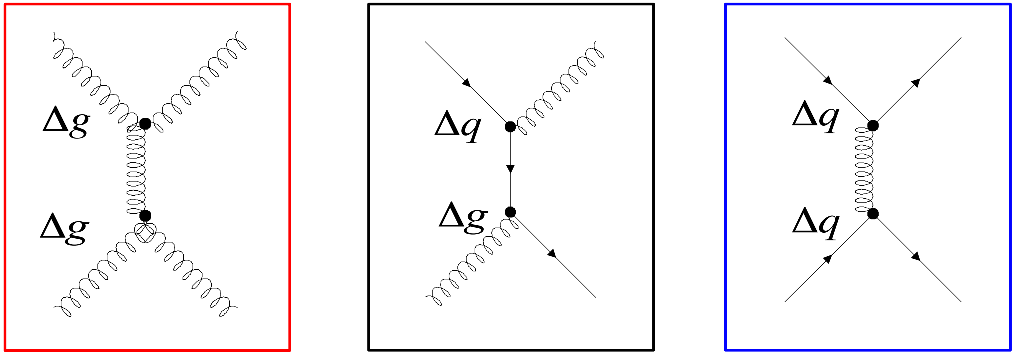

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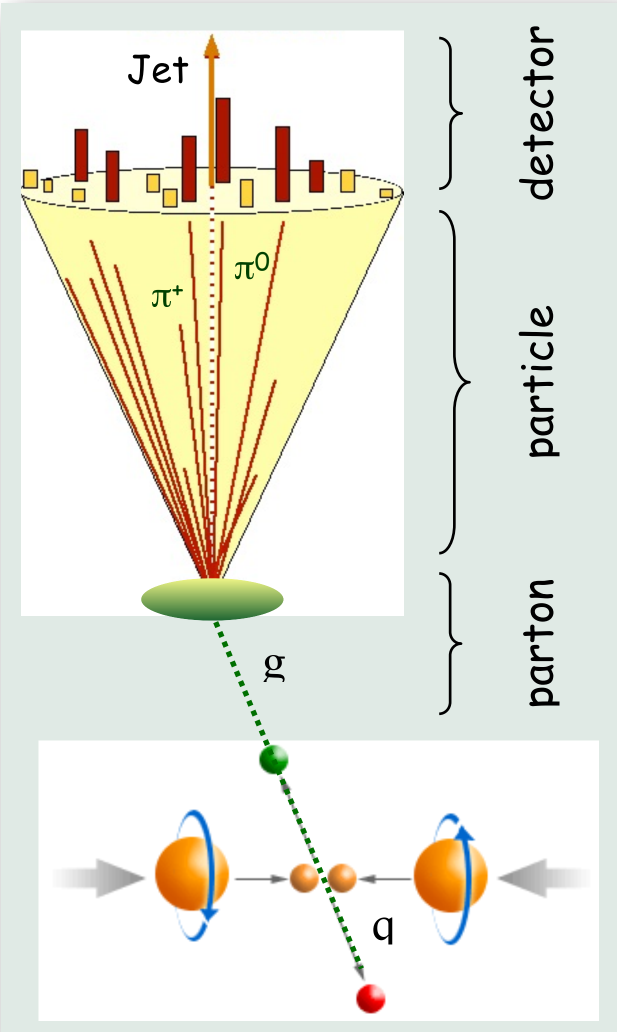

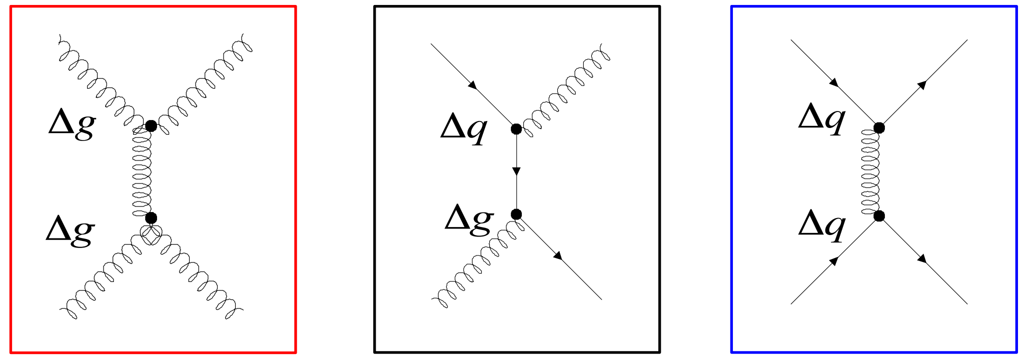

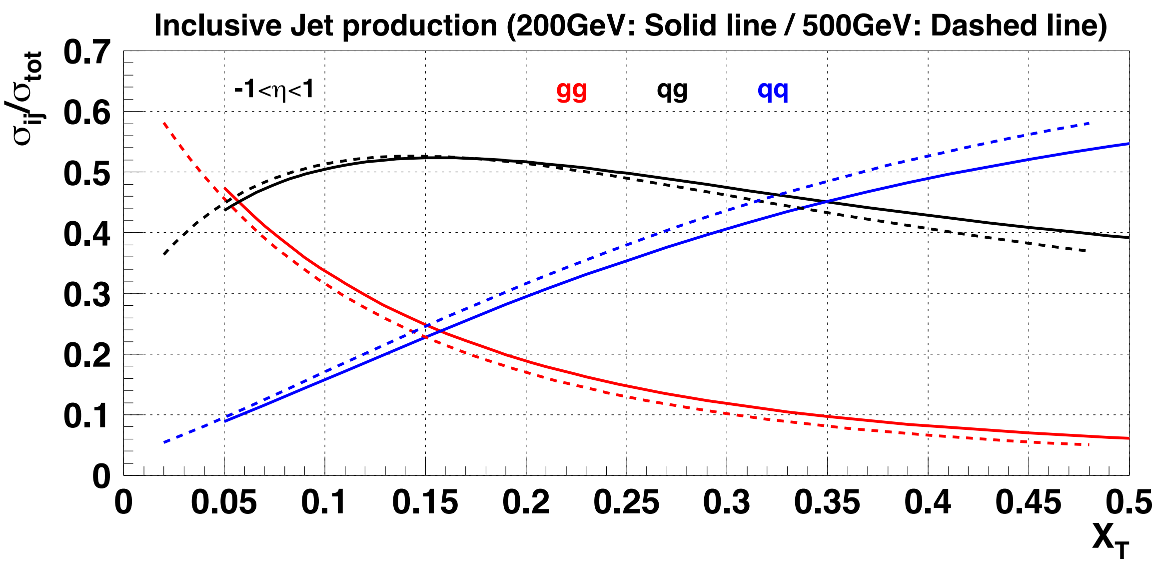

$$x_T = \frac{2p_T}{\sqrt{s}} \quad \text{(x value at } \eta = 0\text{)}$$

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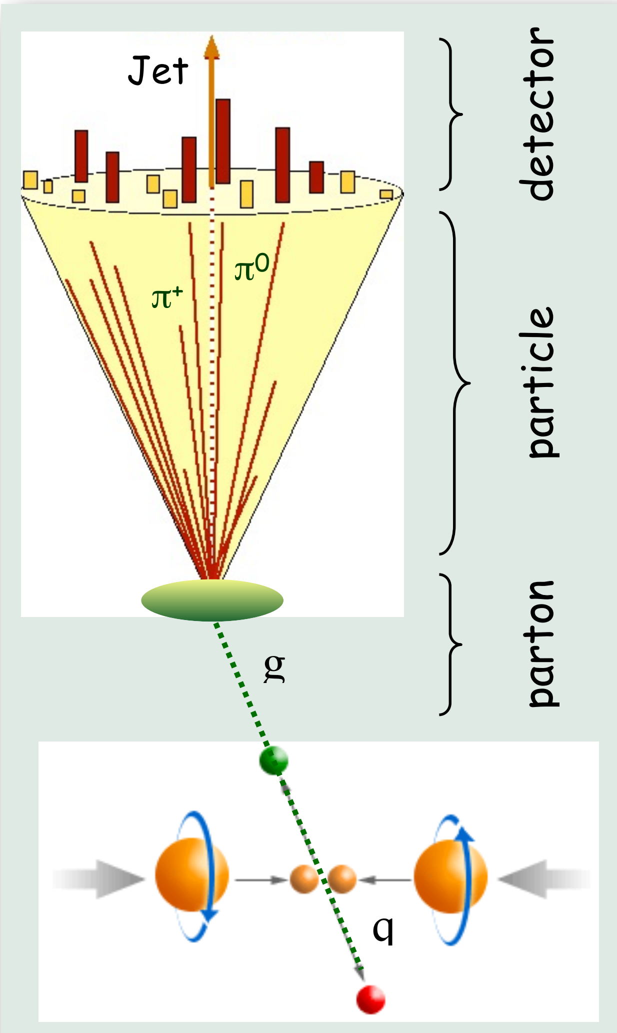

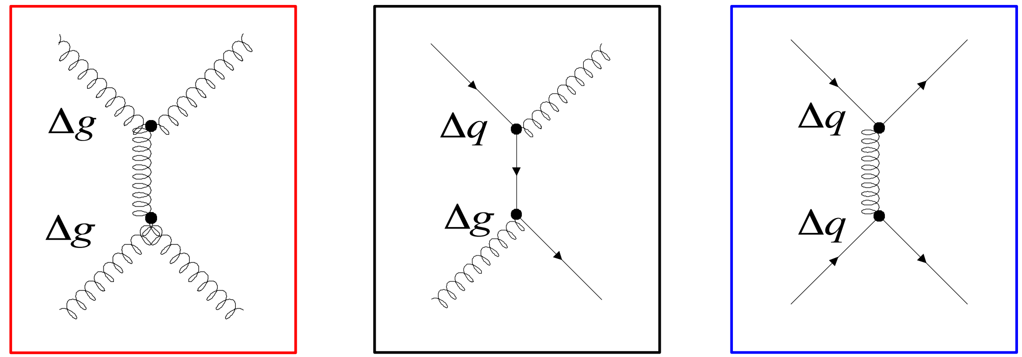

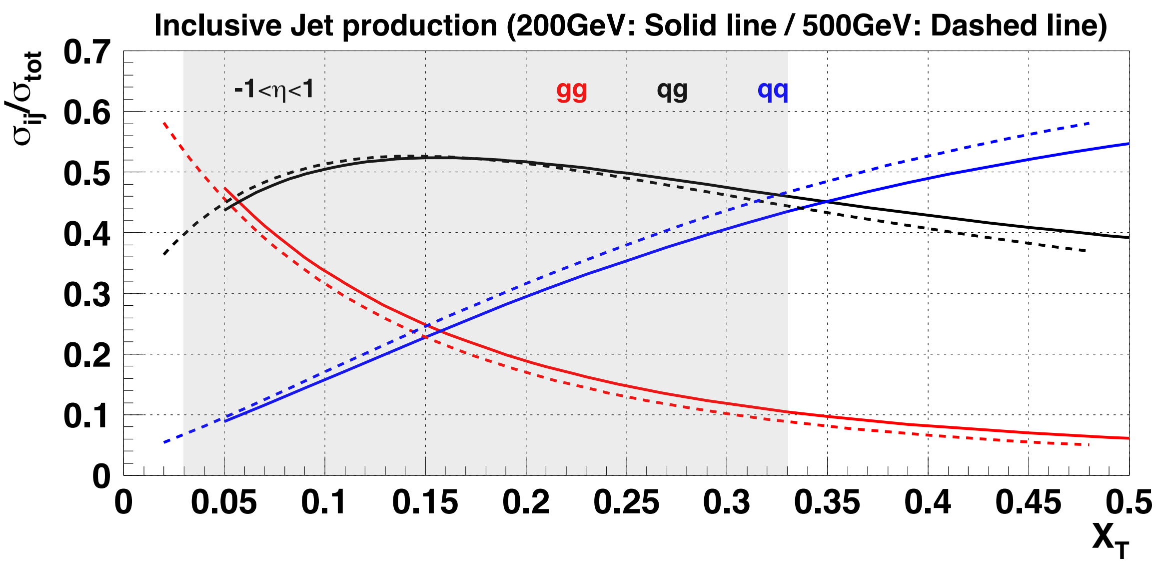

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Theoretical foundation - pp Dijet measurements

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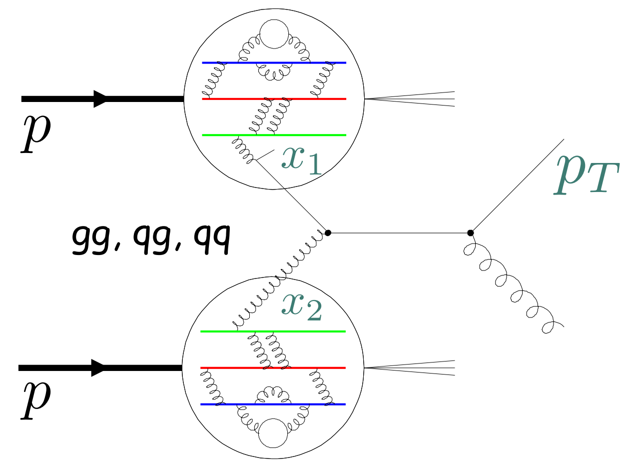
- Correlation Measurements: Dijet production

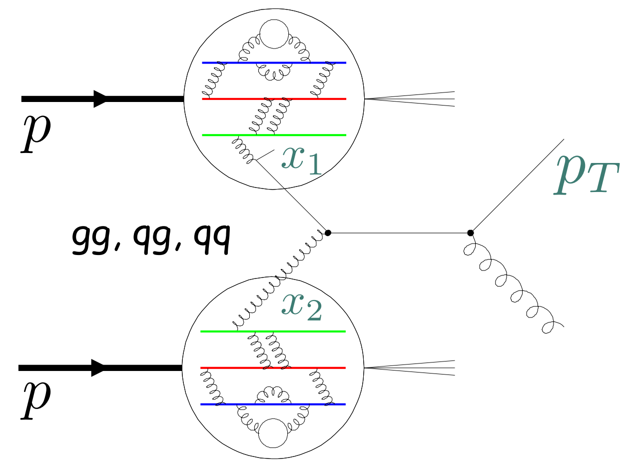


Dijet production

Theoretical foundation - pp Dijet measurements

- Correlation Measurements: Dijet production
  - Correlation measurements provide access to LO partonic kinematics through Dijet/Hadron production and Photon-Jet production:

$$x_{1\,(2)} = \frac{1}{\sqrt{s}}\left(p_{T_3}e^{\eta_3(-\eta_3)} + p_{T_4}e^{\eta_4(-\eta_4)}\right)$$



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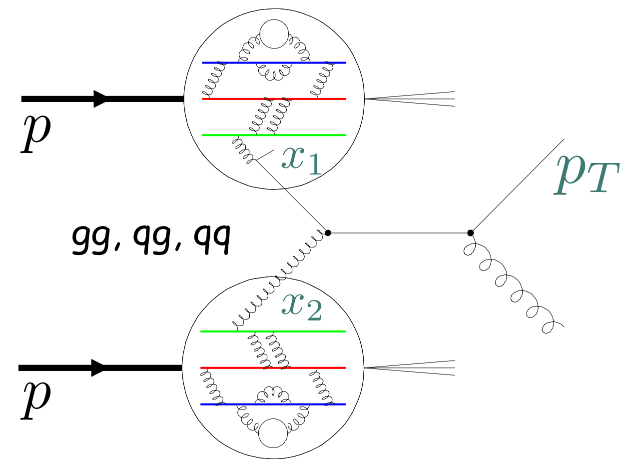
- Bjorken x-coverage:



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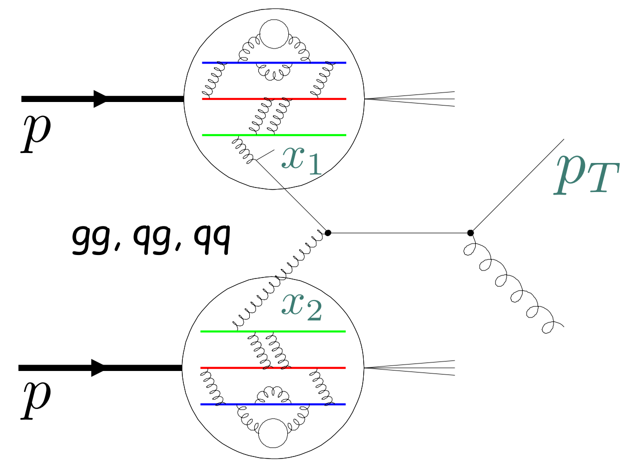

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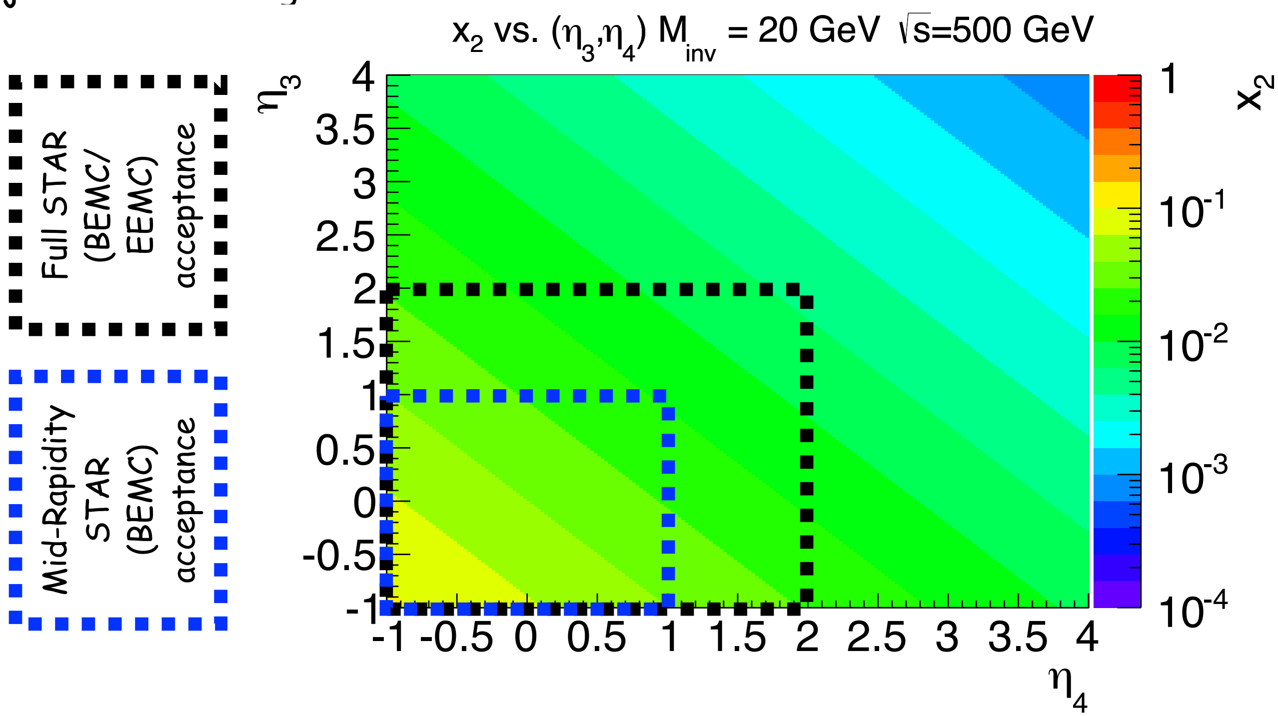


$$\eta_3 + \eta_4 = \ln\frac{x_1}{x_2}$$

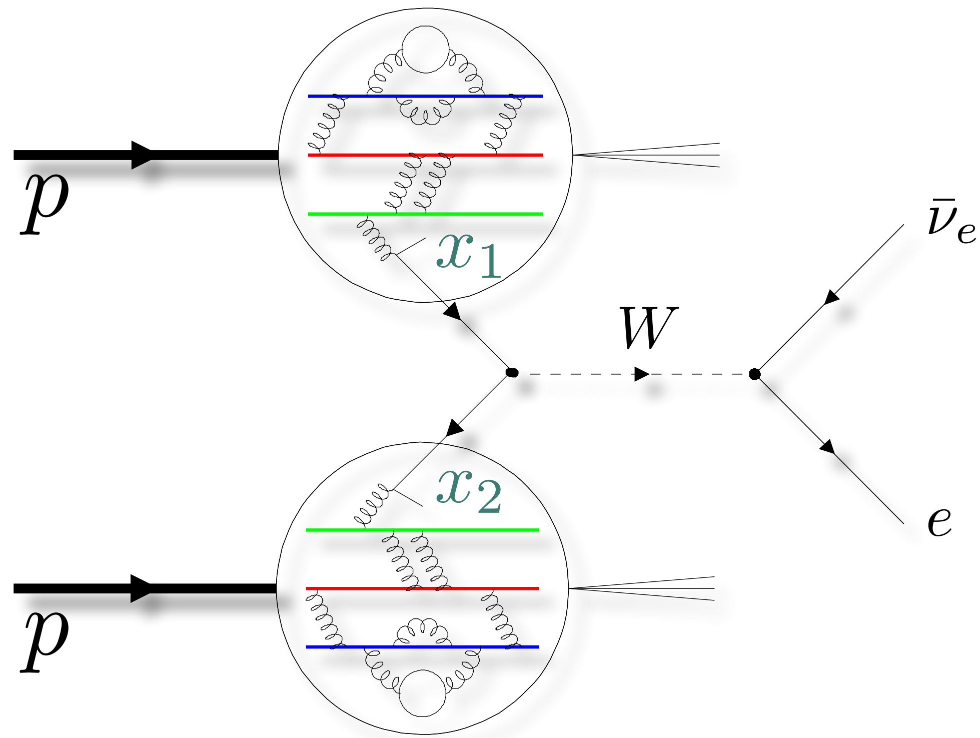
$$M = \sqrt{s}\sqrt{x_1 x_2}$$

Theoretical foundation - PDF access

- Probe quark/anti-quark helicity via W production

Theoretical foundation - PDF access

- Probe quark/anti-quark helicity via W production

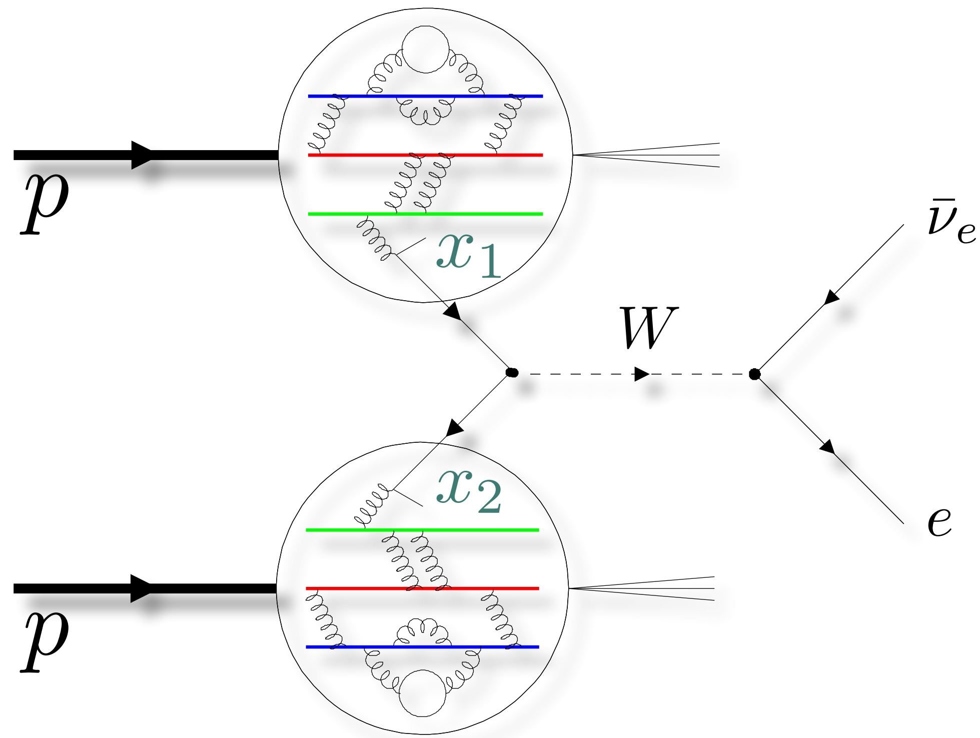


Theoretical foundation - PDF access

- Probe quark/anti-quark helicity via W production
  - Observable: Quark/Anti-quark polarization (W production)
    - Longitudinal single-spin asymmetry A_L

$$A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

    - Parity (Spatial inversion) violating for W production!



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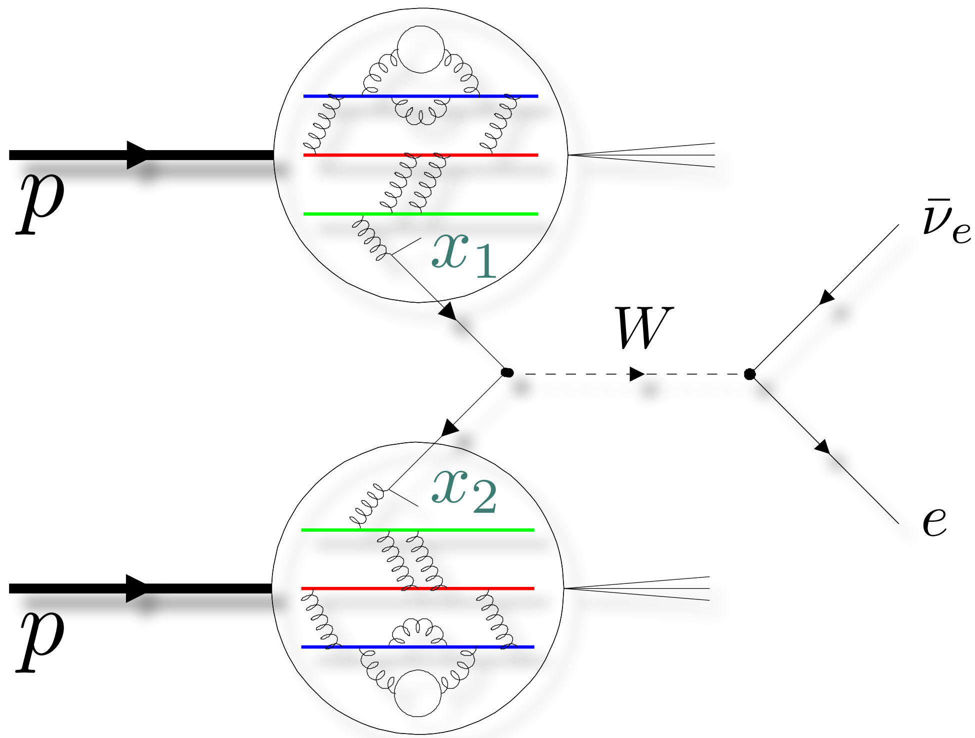
    - Parity (Spatial inversion) violating for W production!
  - Features of W boson production probing parton distributions:
    - Direct sensitivity to quark (u/d) / anti-quark (ubar/dbar) distributions
    - Large scale defined by W mass (~80GeV)
    - Simple final state of charged leptons: No dependency on fragmentation functions



Theoretical foundation - PDF access

- Probe quark/anti-quark helicity via W production
  - Observable: Quark/Anti-quark polarization (W production)
    - Longitudinal single-spin asymmetry A_L

$$A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

    - Parity (Spatial inversion) violating for W production!
  - Features of W boson production probing parton distributions:
    - Direct sensitivity to quark (u/d) / anti-quark (ubar/dbar) distributions
    - Large scale defined by W mass (~80GeV)
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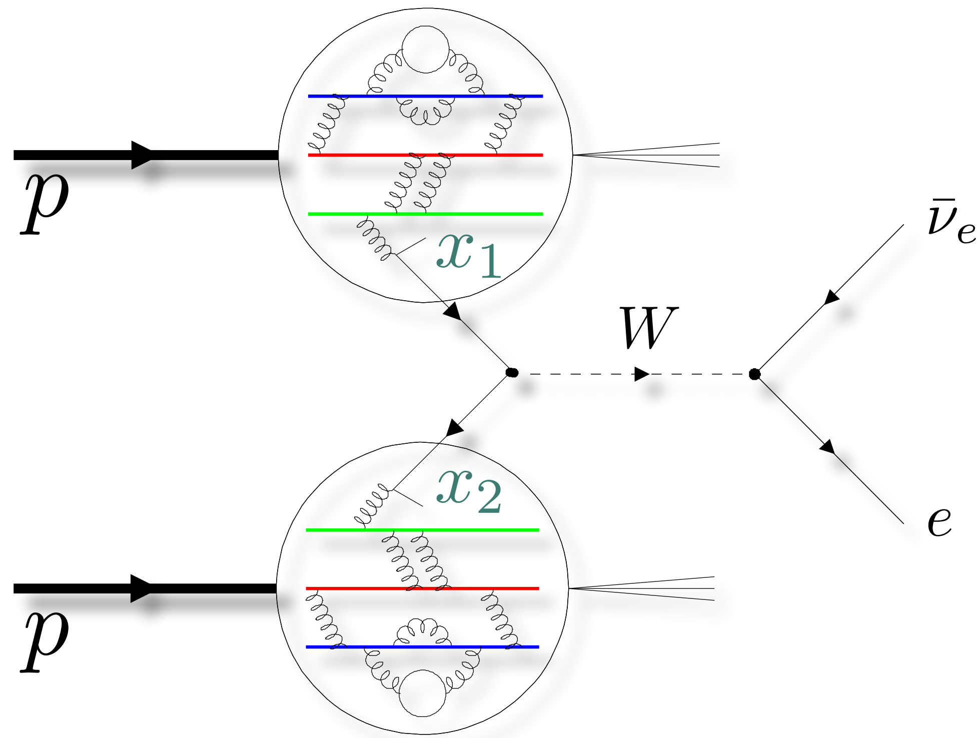
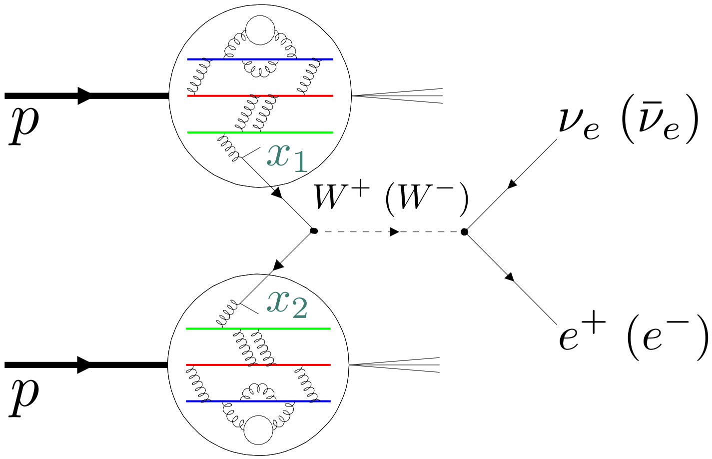


- Polarized and unpolarized partonic cross-sections known at NLO/NNLO - W A_L asymmetry results powerful input for global analyses such as DSSV and NNPDF at NLO level!

Theoretical foundation

- Probing the quark flavor structure: W boson production (1)



$$y_l = y_W + \underbrace{\frac{1}{2}\ln\frac{1+\cos\theta^*}{1-\cos\theta^*}}_{y_l^*}$$

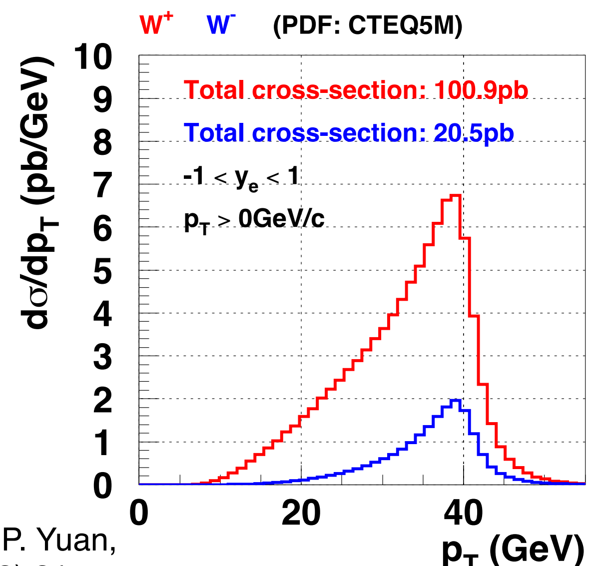
$$x_1 = \frac{M_W}{\sqrt{s}} e^{y_W}$$

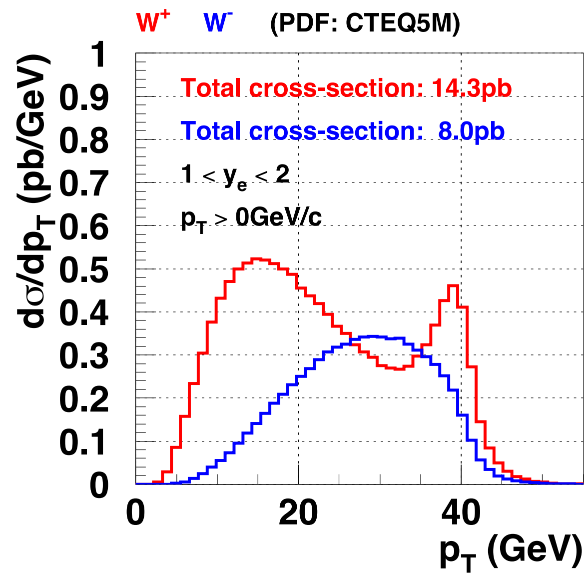
$$x_2 = \frac{M_W}{\sqrt{s}} e^{-y_W}$$

$$p_T = p_T^* = \frac{M_W}{2}\sin\theta^*$$

$$\frac{M_W}{\sqrt{s}} = 0.16$$

- Key signature: High p_T lepton (e^-/e^+)(Max. $M_W/2$) - Selection of W^+/W^- : Charge sign discrimination of high p_T lepton
- Required: Lepton/Hadron discrimination



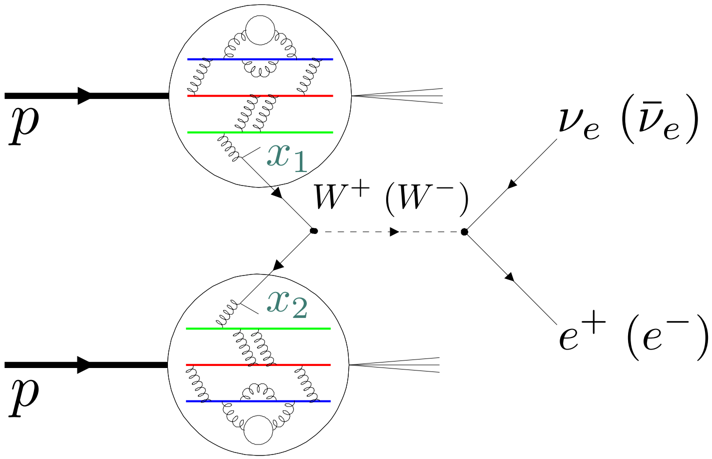


P. M. Nadolsky and C.P. Yuan, Nucl.Phys. B666 (2003) 31.

Total ($\sqrt{s}$=500GeV) $\sigma(W^+)$=135pb and $\sigma(W^-)$=42pb

Theoretical foundation

Probing the quark flavor structure: W boson production (1)



$$y_l = y_W + \underbrace{\frac{1}{2}\ln\frac{1+\cos\theta^*}{1-\cos\theta^*}}_{y_l^*}$$

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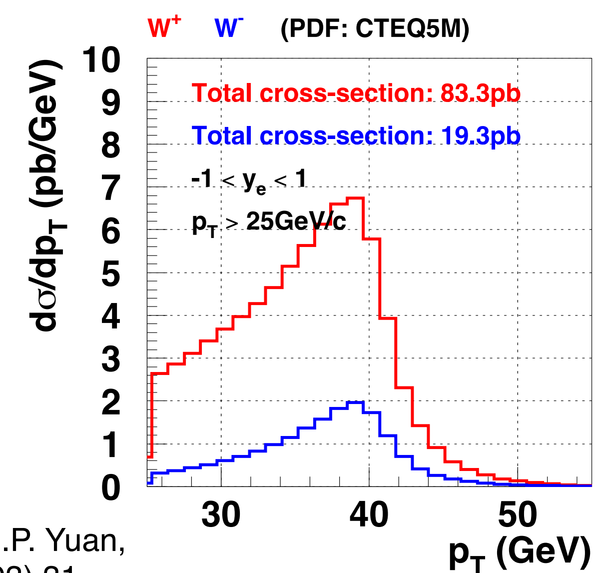
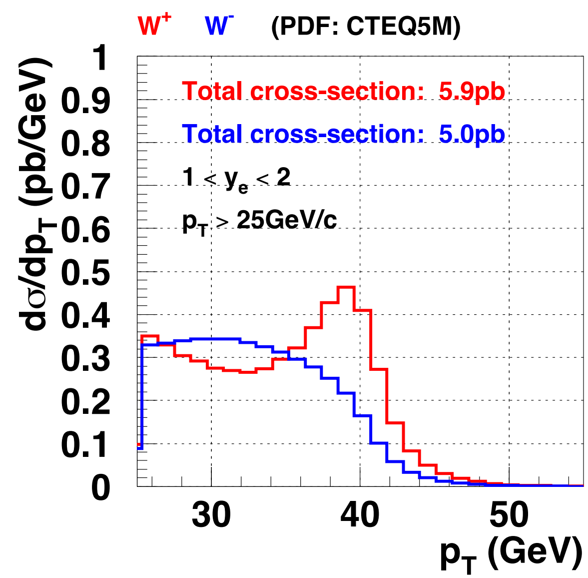


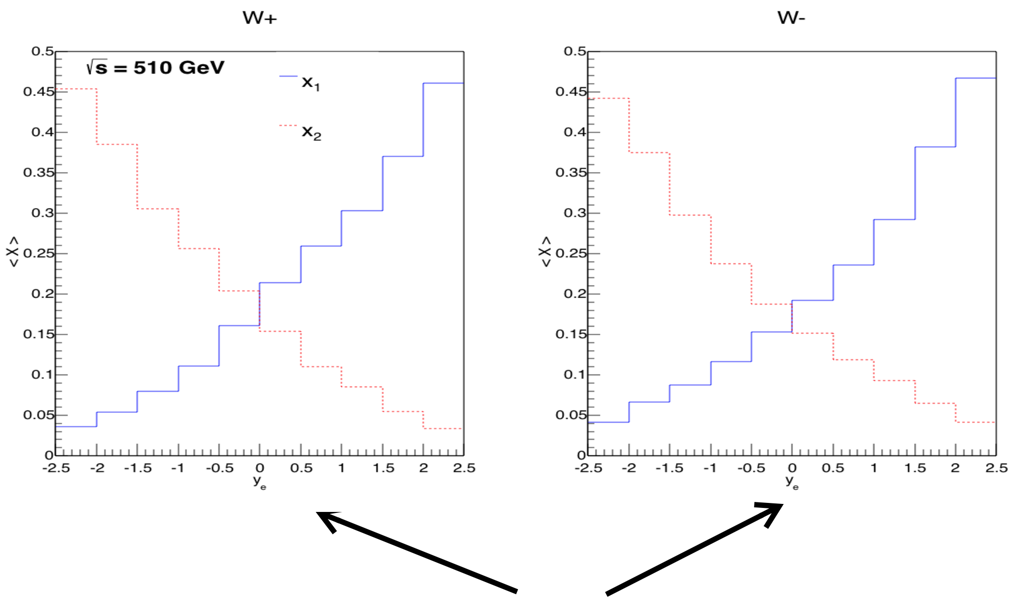


P. M. Nadolsky and C.P. Yuan, Nucl.Phys. B666 (2003) 31.

Total ($\sqrt{s}$=500GeV) $\sigma(W^+)$=135pb and $\sigma(W^-)$=42pb

Theoretical foundation

- Probing the quark flavor structure: W boson production (2)

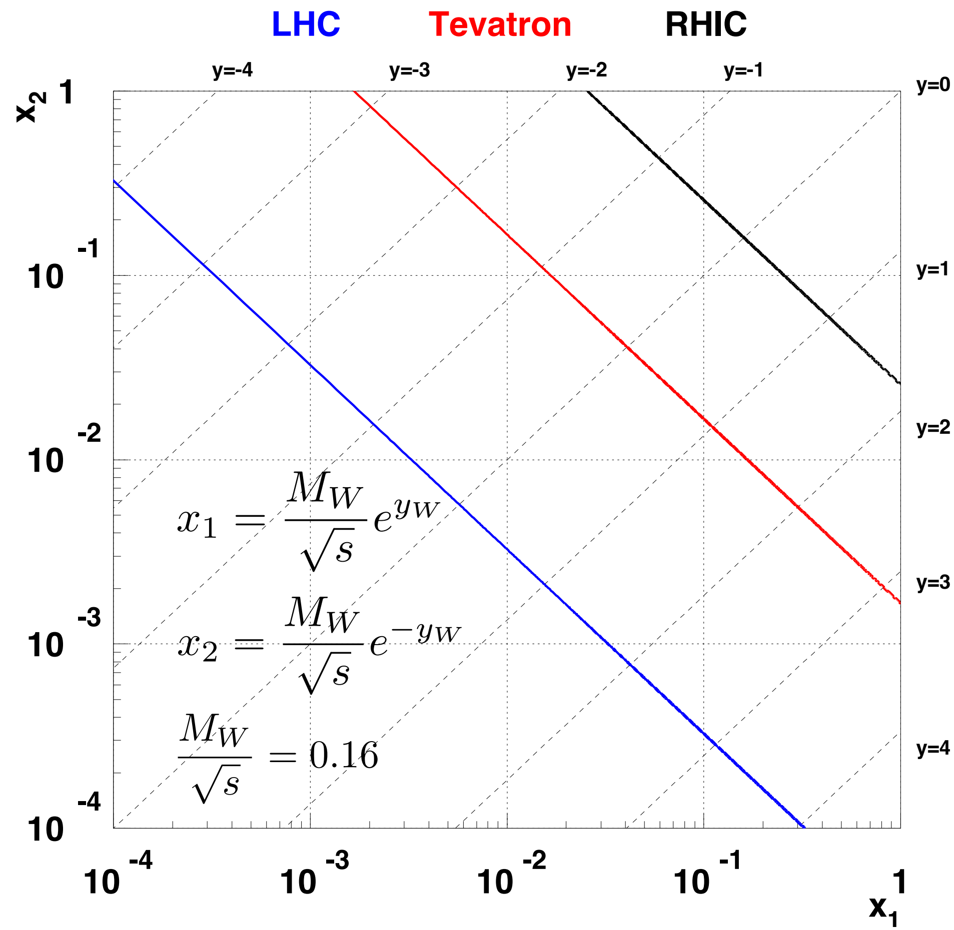


$e^{+/-}$ pseudo-rapidity

- Approximate kinematic range at RHIC:

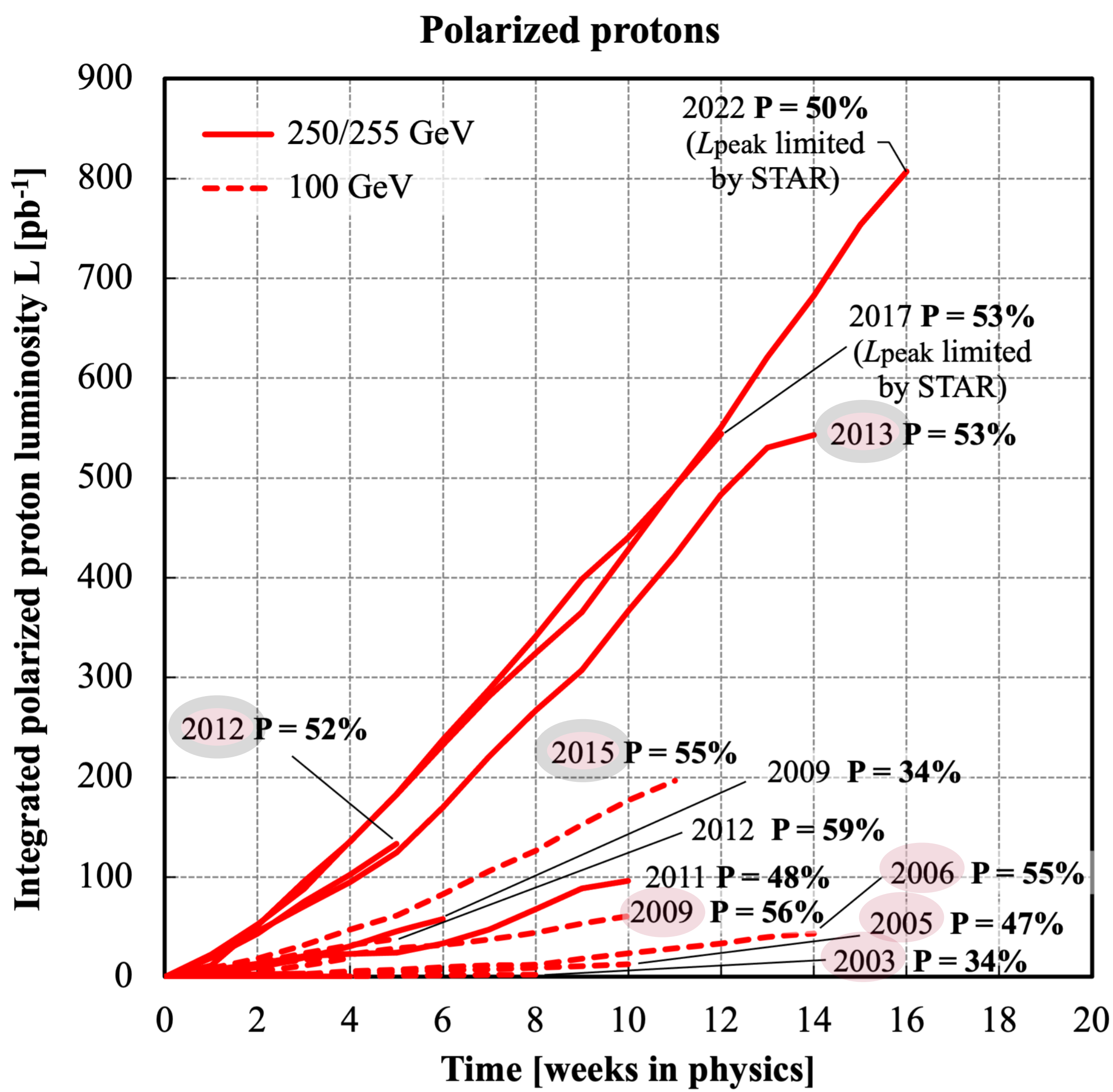
  0.06 < x < 0.4 for -2 < η < 2

- Measurement at LHC in high-x range would require very forward measurements



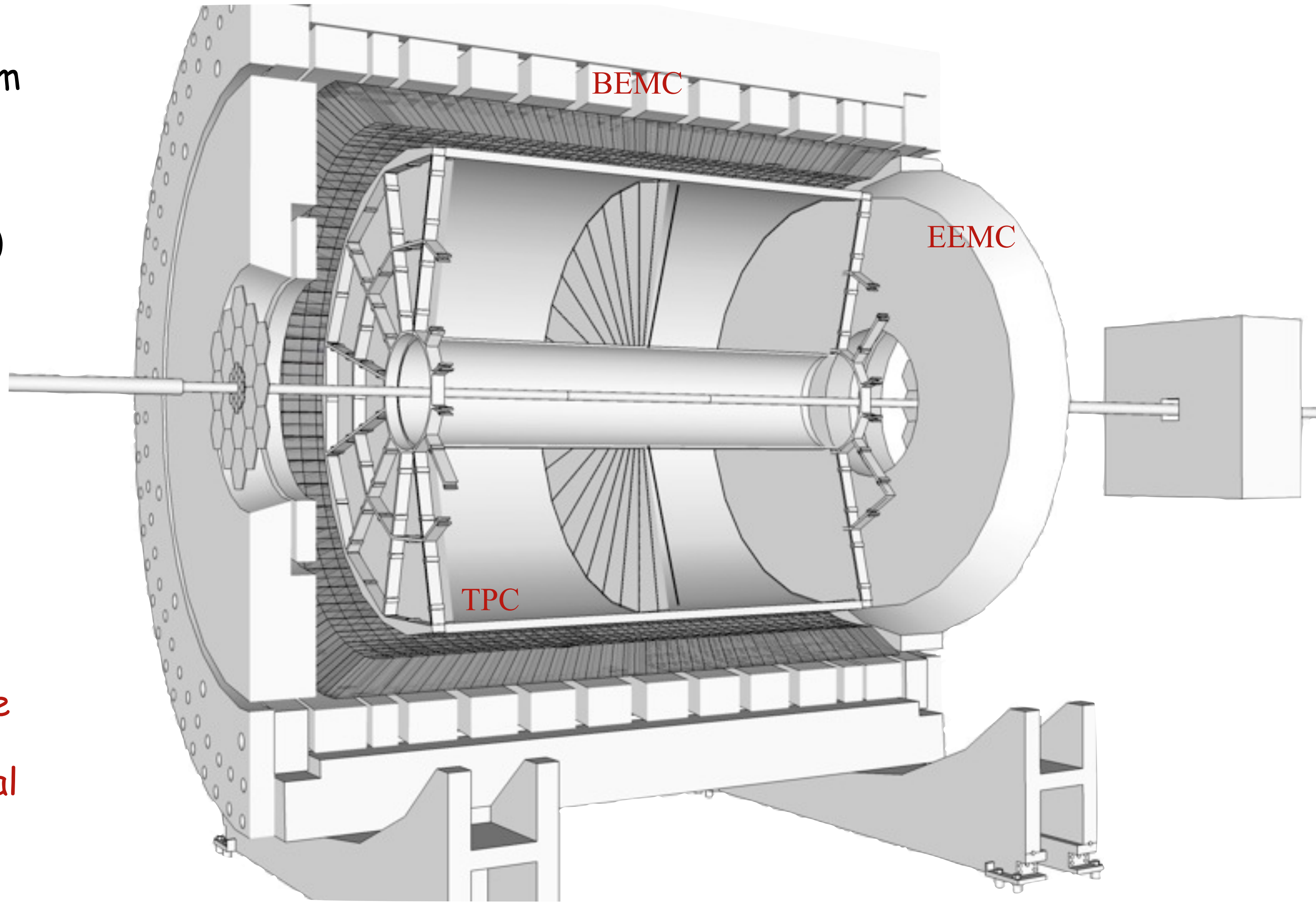
Experimental aspects - RHIC

- Polarized p+p collisions
  - Production runs at √s=200 / 500 / 510GeV (long. polarization) in 2003/2004, 2005, 2006, 2009, 2012, 2013 and 2015: Inclusive Jet and Dijet production and W production
  - Results will be shown from Run 13 (510GeV) in comparison to Run 12 (510GeV) and Run 15 (200GeV)



Experimental aspects - STAR

- Overview
  - Calorimetry system with 2π coverage: BEMC ($|\eta| < 1.0$) and EEMC ($1.1 < \eta < 2.0$)
  - TPC: Tracking and particle ID
  - VPD/ZDC: Relative luminosity and local polarimetry



$$\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$

Experimental aspects - STAR

- Overview
  - Calorimetry system with 2π coverage: BEMC ($|\eta| < 1.0$) and EEMC ($1.1 < \eta < 2.0$)
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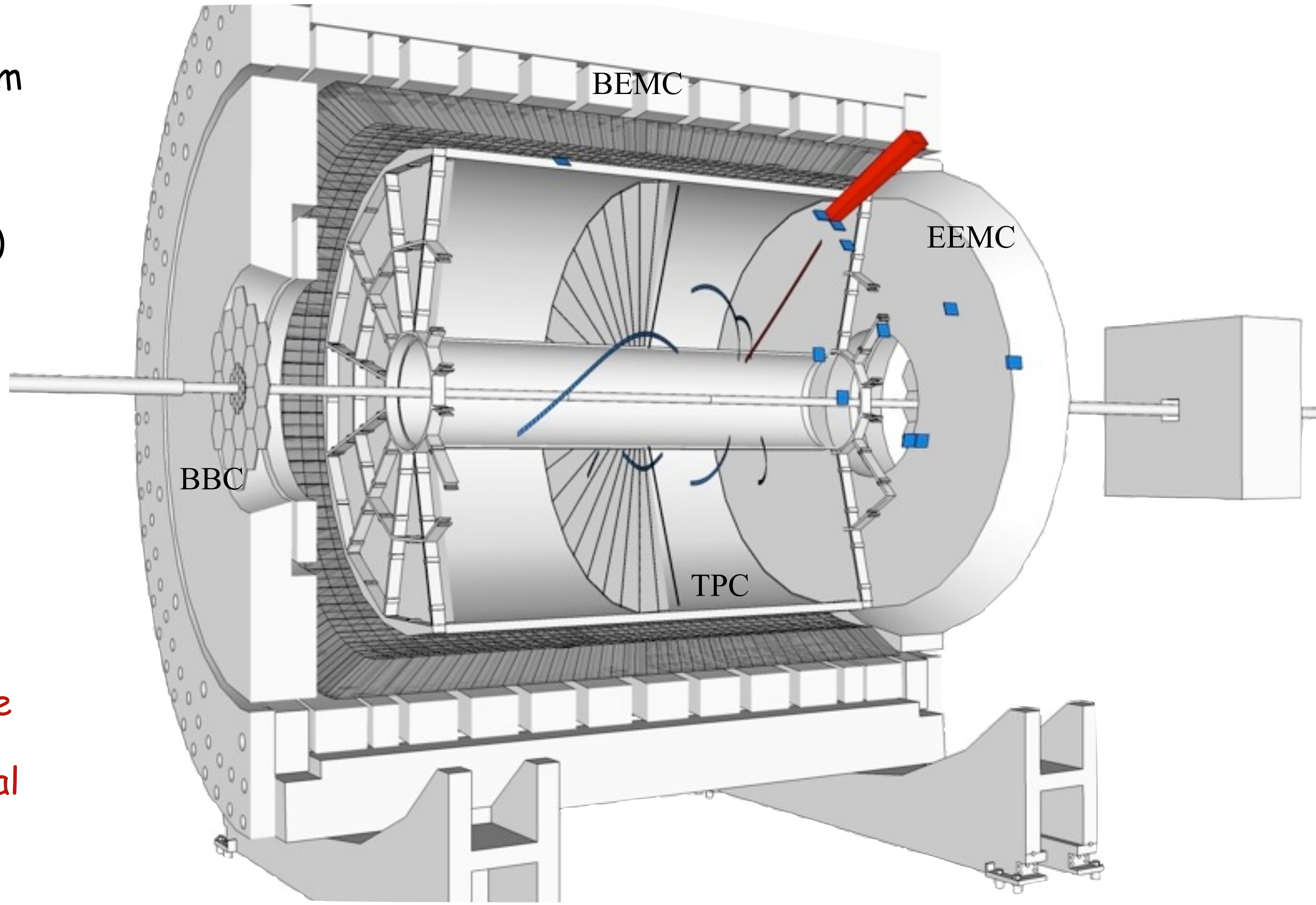
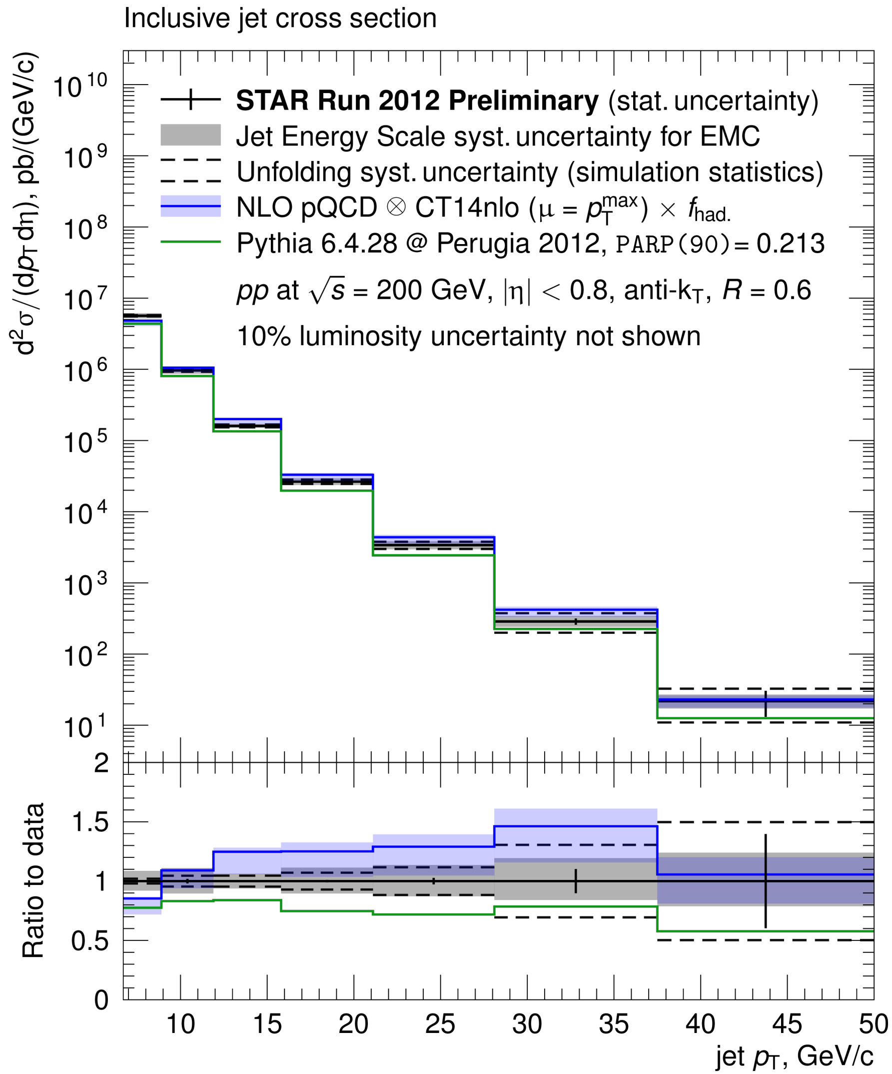
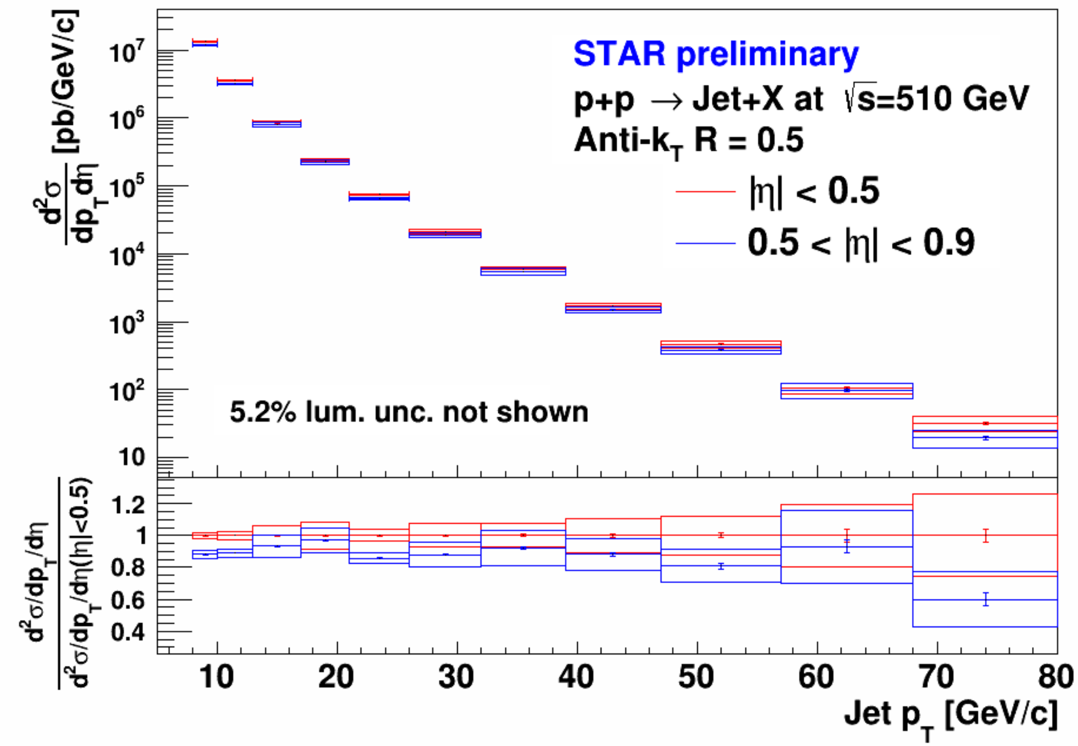


$$\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$

STAR Results: Inclusive Jet Cross-section

- Mid-rapidity Inclusive Jet cross-sections at 200GeV / 510GeV



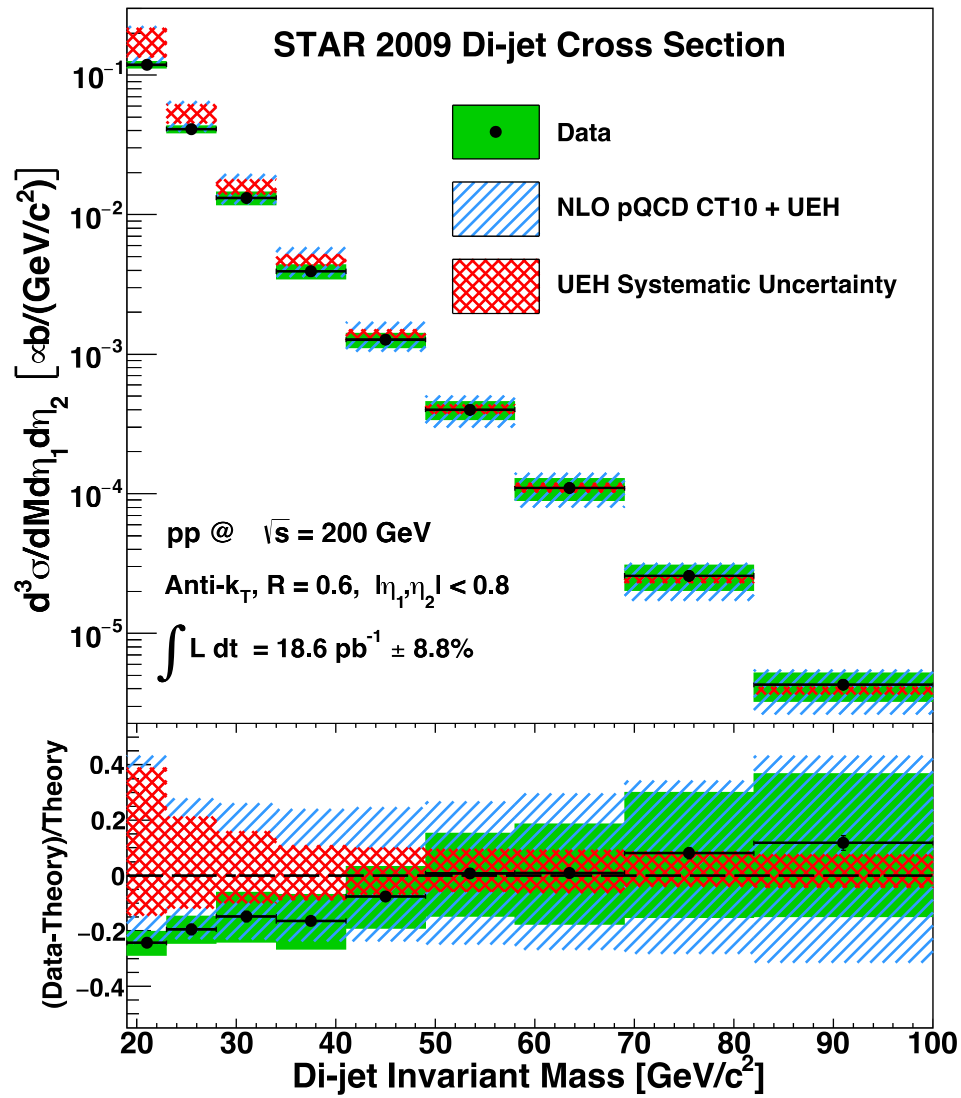


- Double-differential cross-section in jet p_T for $|\eta| < 0.8$ at $\sqrt{s} = 200\,\text{GeV}$ and for $|\eta| < 0.5$ and $0.5 < \eta < 0.9$ at $\sqrt{s} = 510\,\text{GeV}$
- Sys. uncertainties: EMC response to photon/electrons & hadrons (Dom. contr.) / TPC track mom. resolution / TPC tracking efficiency / Unfolding bias - Luminosity scale (Not shown)

STAR Results: Dijet Cross-section

- Mid-rapidity Dijet cross-section
  - Differential cross-section in dijet invariant mass for $|\eta_1, \eta_2| < 0.8$ at $\sqrt{s} = 200\,\text{GeV}$
  - Sys. uncertainties: EMC tower energy scale / TPC tracking efficiency / Track p_T resolution / Unfolding bias - Luminosity scale (Not shown)
  - Theory comparison: Cross-section corrected for underlying event and hadronization (UEH) effects / Theory uncertainty

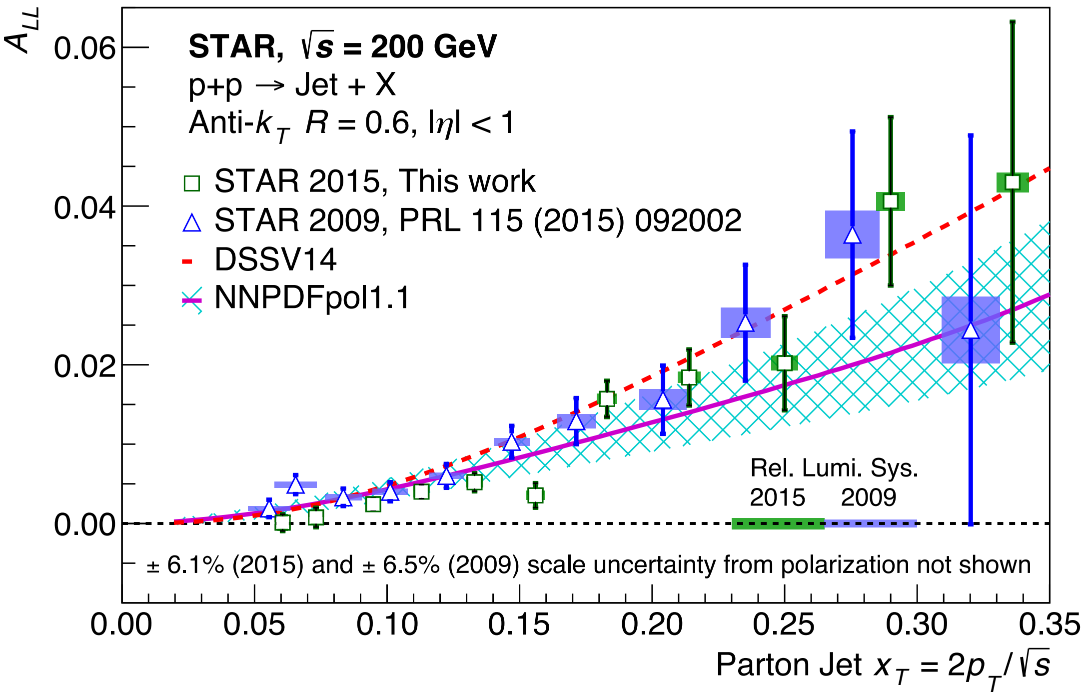
J. Adamczyk *et al.* (STAR Collaboration), *Phys. Rev.* **D 95** (2017) 7, 071103.

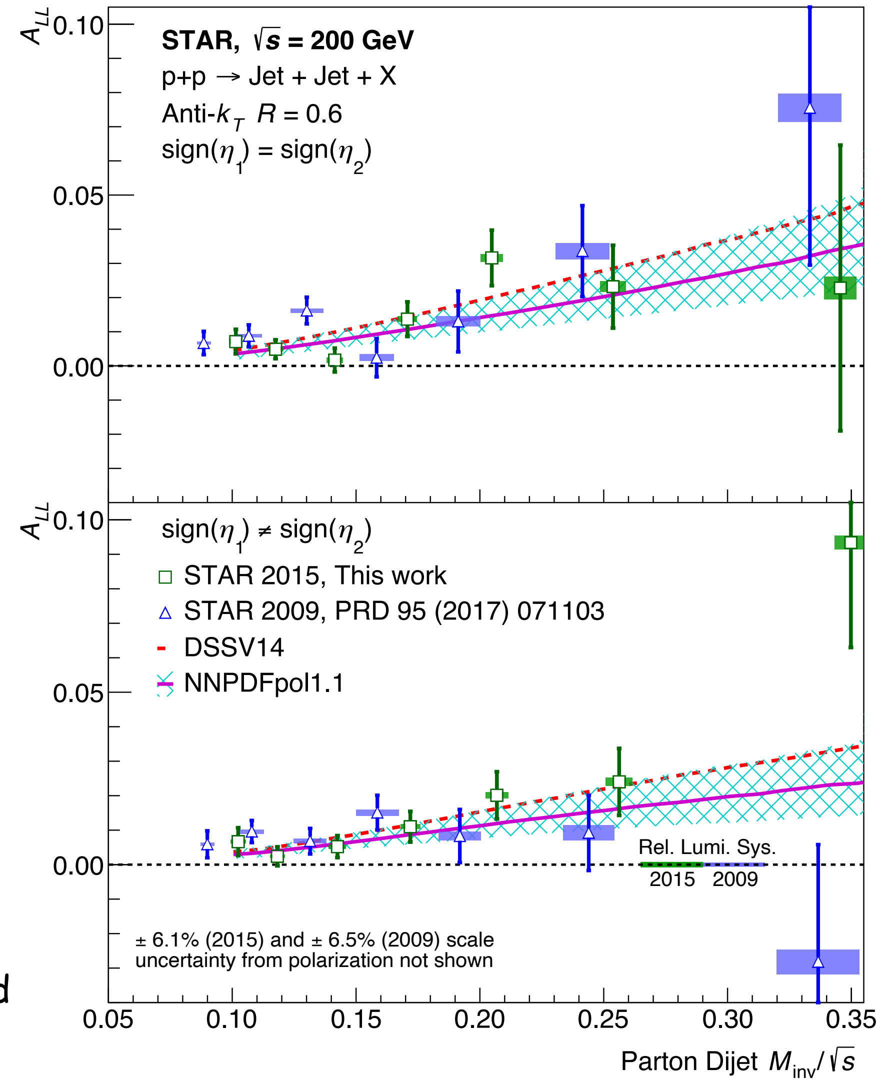


STAR Results: Run 15 Jet results at 200 GeV

Mid-rapidity Incl. Jet and Dijet A_{LL}

J. Adam *et al.* (STAR Collaboration), *Phys. Rev.* **D 103** (2021) 9, L091103.



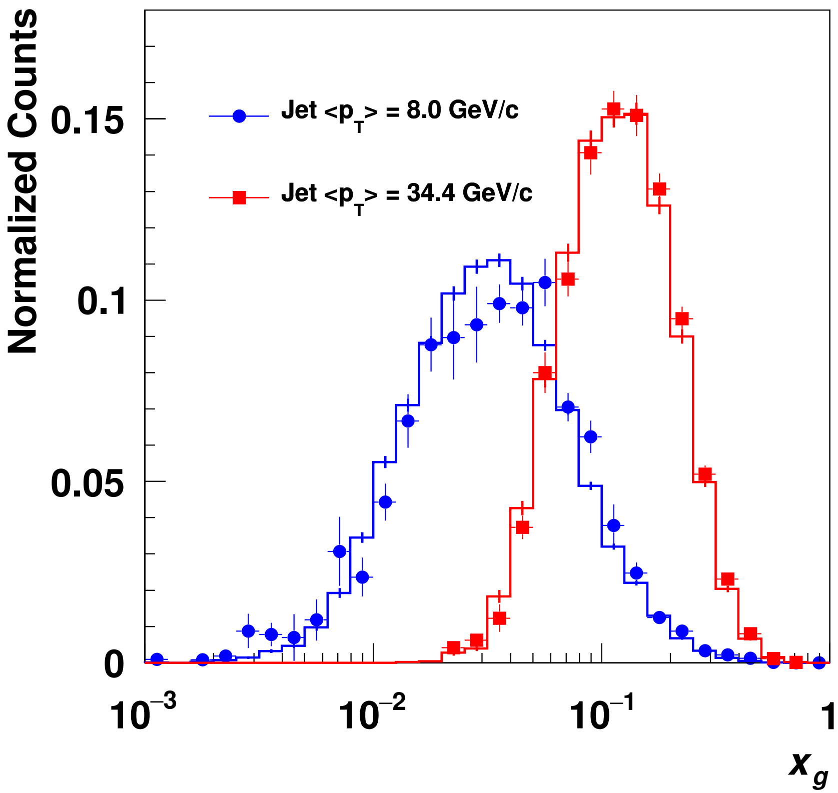


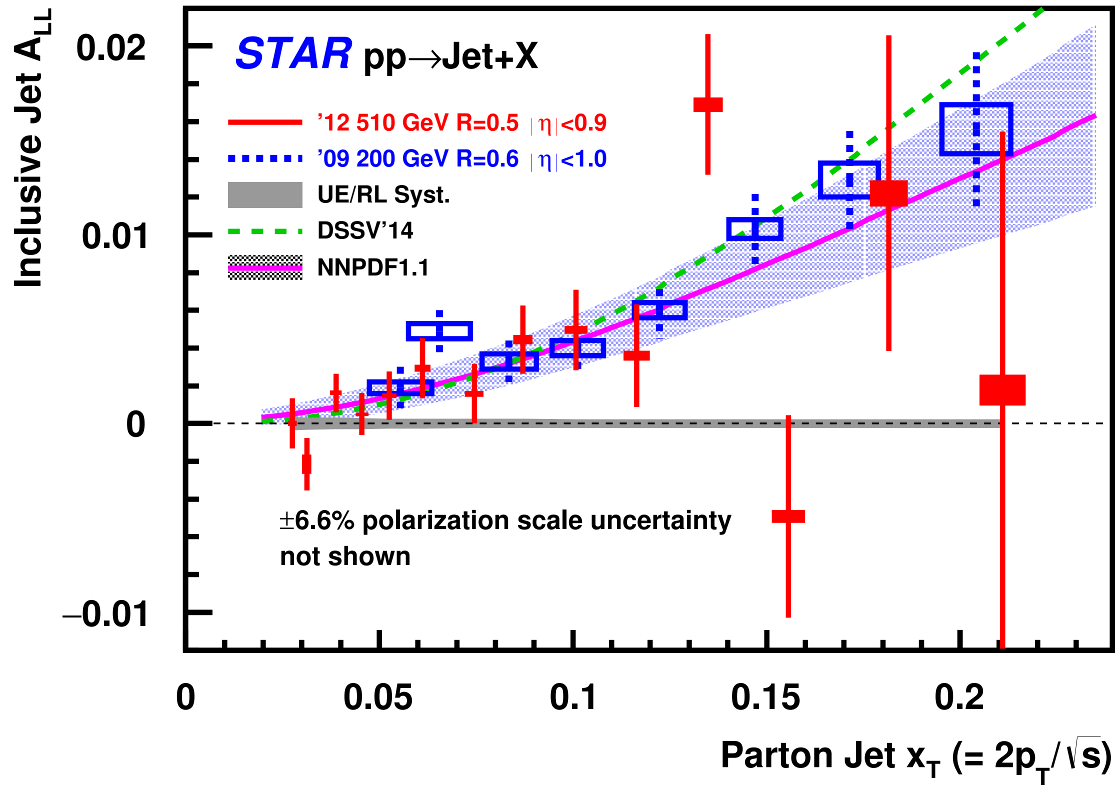
- A_{LL} inclusive and dijet measurements for Run 15 in good agreement with Run 9 measurements - Further evidence for positive $\Delta g(x, Q^2)$ for $x > 0.05$!
- Good agreement with NLO calculations based on DSSV14 and NNPDFpol1.1 PDF set

STAR Results: Run 12 Inclusive Jet results at 510 GeV

Mid-rapidity Inclusive Jet A_{LL}

J. Adam *et al.* (STAR Collaboration), *Phys. Rev.* **D 100** (2019) 5, 052005.





- A_{LL} inclusive jets vs. x_T for Run 12 510GeV in good agreement with Run 9 200GeV measurements - Probing $\Delta g(x, Q^2)$ at smaller x ($x \approx 0.015$)!
- Good agreement with NLO calculations based on DSSV14 and NNPDFpol1.1 PDF set

STAR Results: Run 12 Dijet results at 510GeV

Mid-rapidity Dijet A_{LL}

J. Adam *et al.* (STAR Collaboration), *Phys. Rev.* **D 100** (2019) 5, 052005.

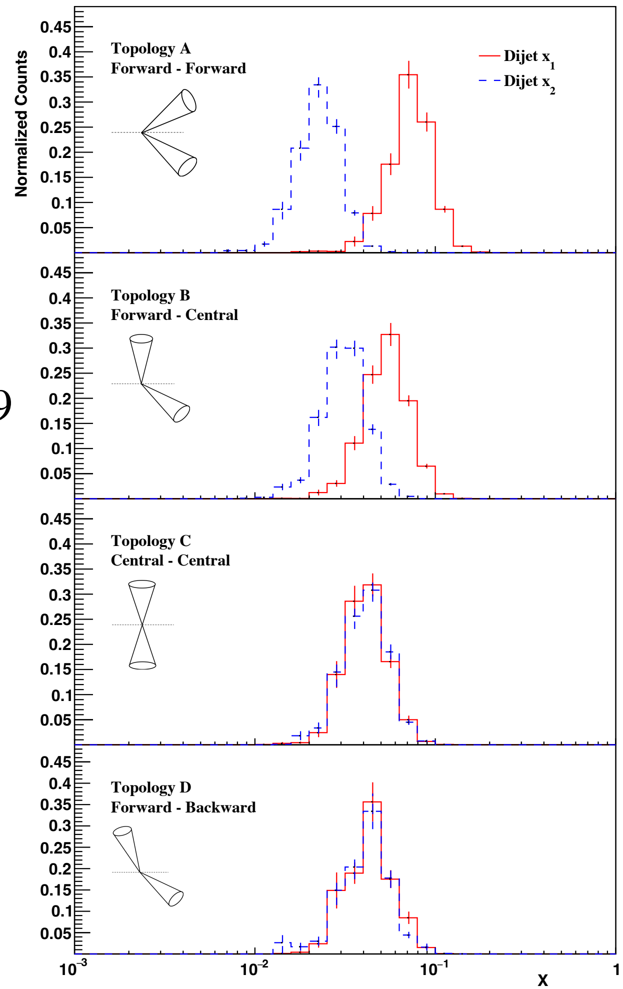
- 4 Topological configurations probing different kinematic regions in x:
  - A: Forward-Forward

    $0.3 < |\eta_{3,4}| < 0.9;\ \eta_3 \cdot \eta_4 > 0$
  - B: Forward-Central

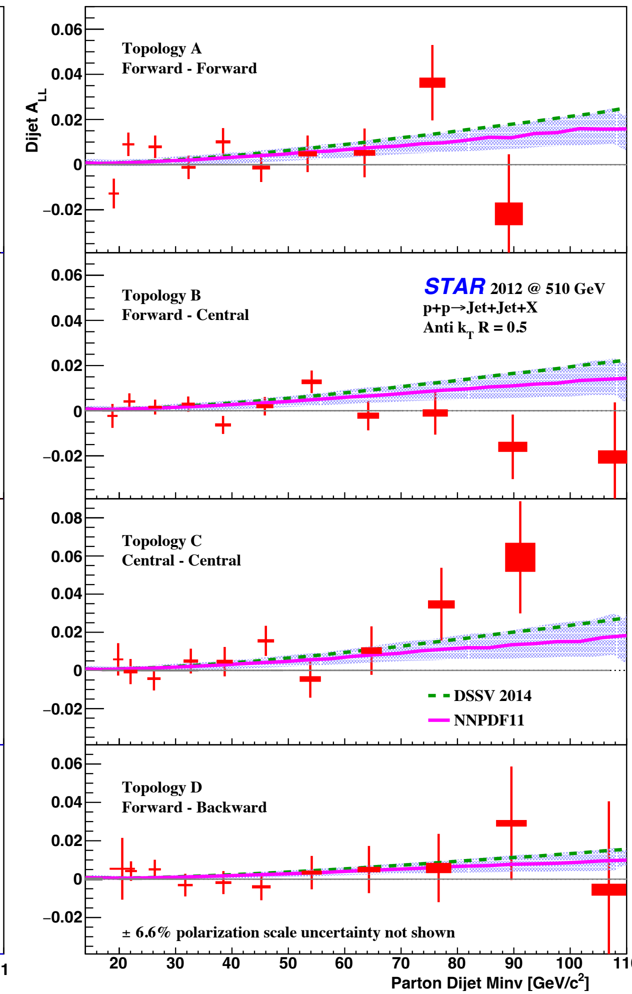
    $|\eta_{3,4}| < 0.3;\ 0.3 < |\eta_{3,4}| < 0.9$
  - C: Central-Central

    $|\eta_{3,4}| < 0.3$
  - D: Forward-Backward

    $0.3 < |\eta_{3,4}| < 0.9;\ \eta_3 \cdot \eta_4 < 0$
- Good agreement with NLO calculations based on DSSV14 and NNPDFpol1.1 PDF set



$M_{inv} = 17 - 20\ \mathrm{GeV}/c^2$



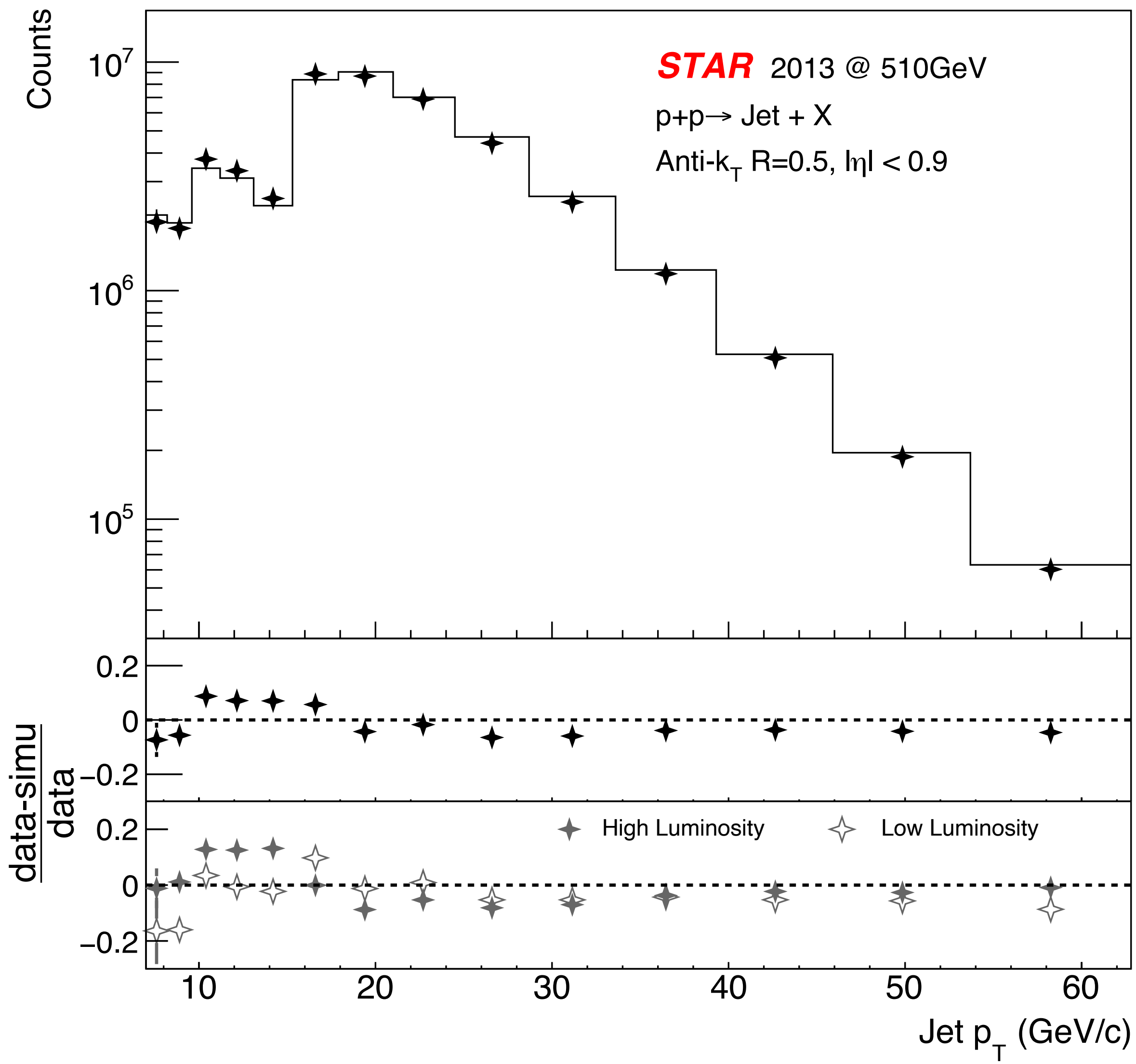
STAR Results: Run 13 data set / Selection cuts

- Overview of data size / beam conditions / selection cuts for Run 13 data
  - Data size: ~250 pb^{-1} X 3 times as large compared to Run 12 data sample
  - Beam polarization: Average beam polarization P_B = 56% and P_Y = 54% / Scale uncertainty from polarization $\pm 6.4\,\%$
  - Selection cuts:
    - Trigger: Jet Patch ($\Delta\eta \times \Delta\phi = 1 \times 1$) (JP0 / JP1 / JP2) / Dijet trigger JP0dijet & JP1dijet
    - Jet reconstruction: Anti-k_T and FastJet package (R=0.5) - TPC: $p_T > 0.2\,\mathrm{GeV/c}$ EMC : $E_T > 0.2\,\mathrm{GeV/c}$
    - DCA (Distance of Closest Approach) to vertex: < 2cm for $p_T < 0.5\,\mathrm{GeV/c}$ and < 1cm for $p_T > 1.5\,\mathrm{GeV/c}$ and linearly interpolated in-between
    - R_{EM} (Fraction of jet energy detected in calorimeter): $R_{EM} < 0.95$
    - Inclusive Jet sample: Only JP0, JP1, and JP2 triggers
    - Dijet sample: Two largest p_T jets and $|\Delta\eta| < 1.6 \;\; \Delta\phi > 120^{\circ}$ asymmetric p_T cuts of 5.0 / 7.0GeV/c
  - Systematics:
    - Jet Energy Scale systematics impacting p_T / M_{inv} (Horizontal):
      - TPC tracking efficiency and resolution effects
      - Electromagnetic response
      - Difference between data and simulation for underlying-event correction
      - Differences between nominal PYTHIA tunes and other tunes
    - Total A_{LL} systematic uncertainty (Vertical): Quadrature sum of trigger and reconstruction bias, underlying event correction, plus relative luminosity uncertainty of $4.7 \cdot 10^{-4}$

STAR Results: Run 13 Data/MC comp. Incl. Jets / Syst.

- Data/MC comparison Incl. Jets
  - Comparison between data (points) and embedded simulation for inclusive jet events as a function of p_T at detector level
  - Middle: Ratio of relative differences between all data runs and simulation
  - Botton: Ratio of relative differences between data and simulation separated into high and low luminosity runs
  - Statistical uncertainties are smaller than most of the points!

J. Adam *et al.* (STAR Collaboration), *Phys. Rev.* **D 105** (2022) 9, 092011.

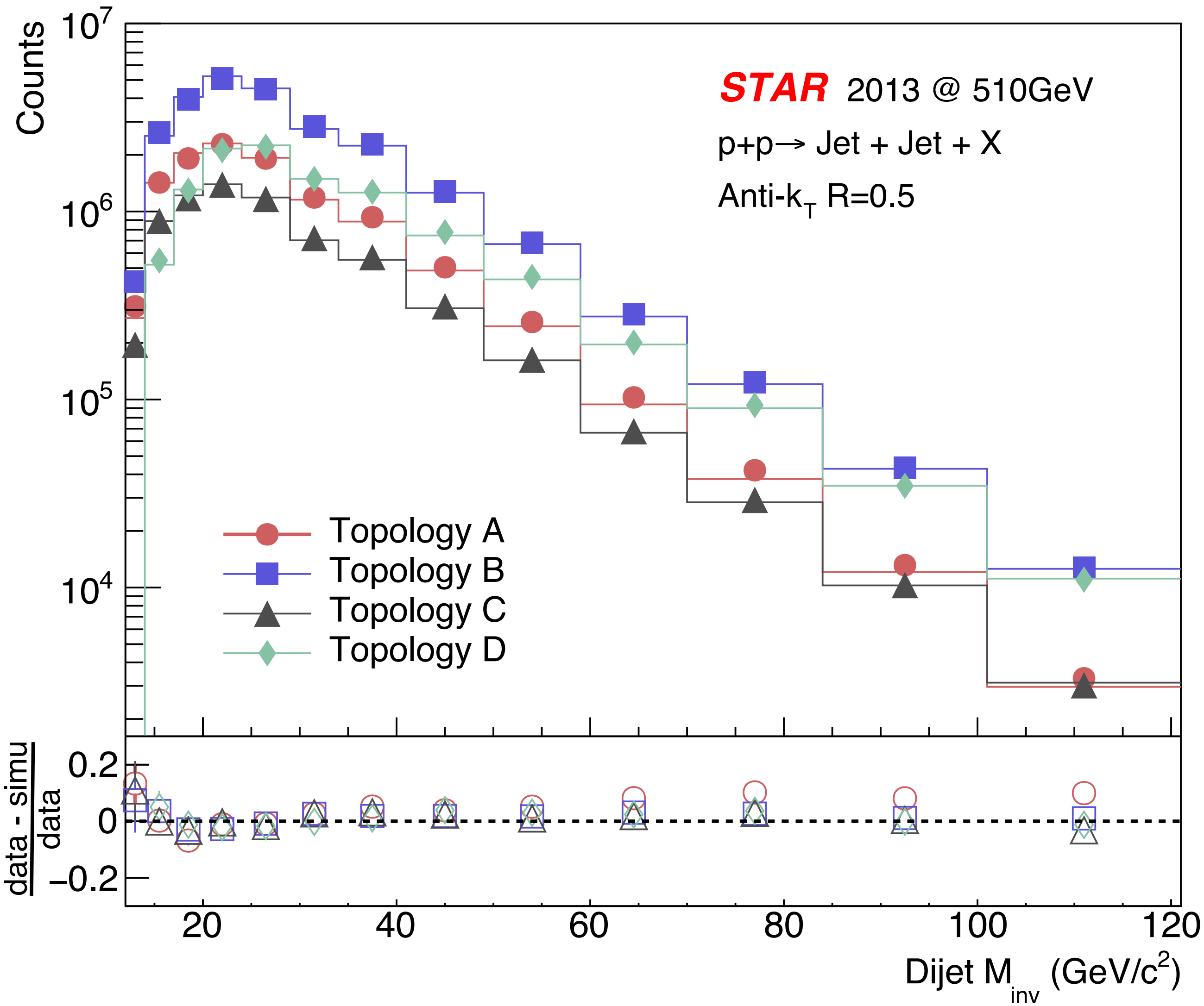


STAR Results: Run 13 Data/MC comp. Dijets / Syst.

Data/MC comparison Dijets

J. Adam *et al.* (STAR Collaboration), *Phys. Rev.* **D 105** (2022) 9, 092011.

- Comparison between data (points) and embedded simulation for dijet as a function of the dijet invariant mass for 4 topological configurations (A-D)
- Botton: Ratio of relative differences between data and simulation
- Statistical uncertainties are smaller than most of the points!

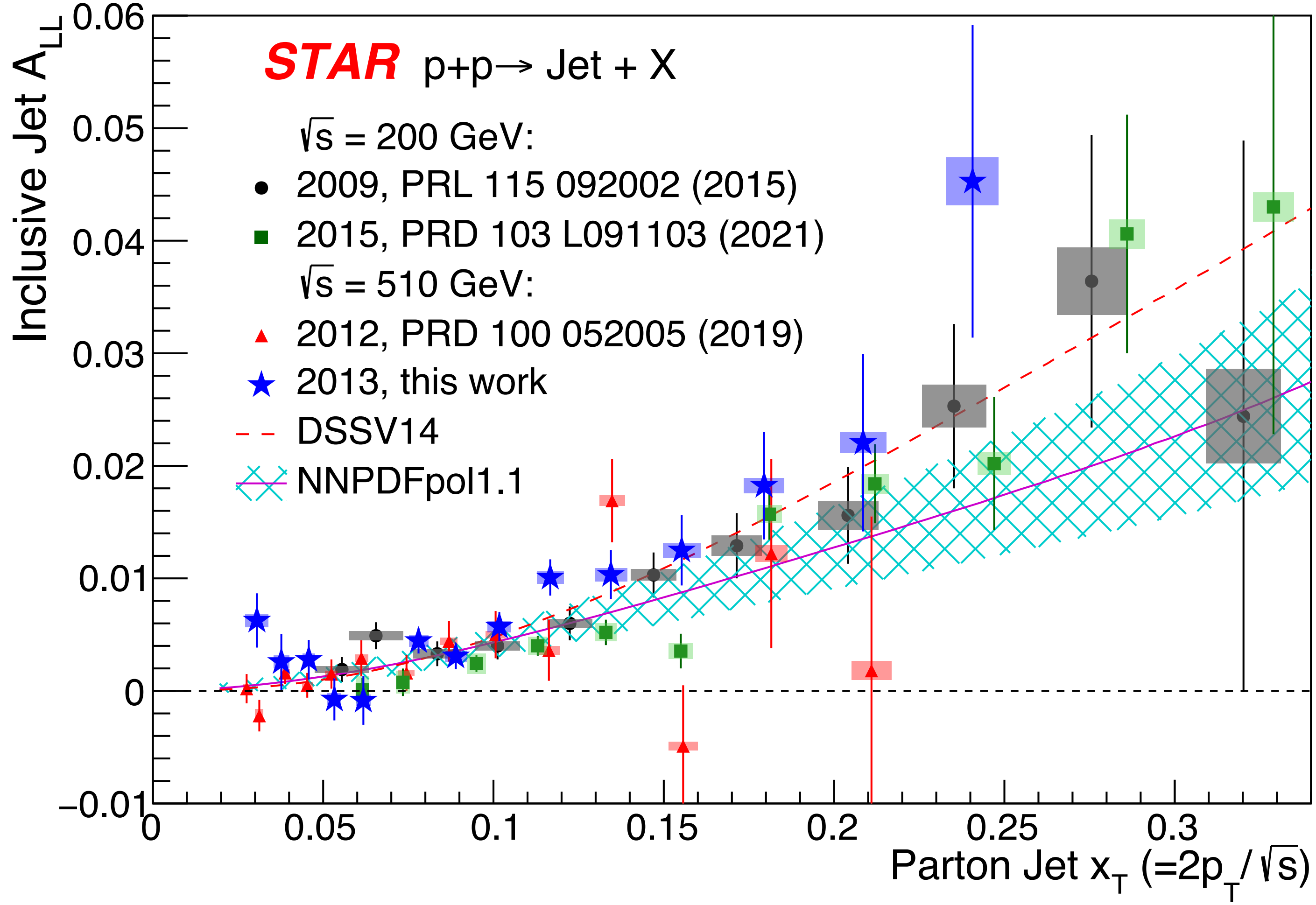


STAR Results: Run 13 Inclusive Jet results at 510 GeV

Mid-rapidity Incl. Jet A_{LL}

J. Adam *et al.* (STAR Collaboration), *Phys. Rev.* **D 105** (2022) 9, 092011.

- Inclusive Jet A_{LL} versus x_T in comparison to 200 GeV (Run 9 / Run 15) results and 510 GeV results (Run 12) -
- Good agreement between Run 13 and previous measurements
- Good agreement with NLO calculations based on DSSV14 and NNPDFpol1.1 PDF set

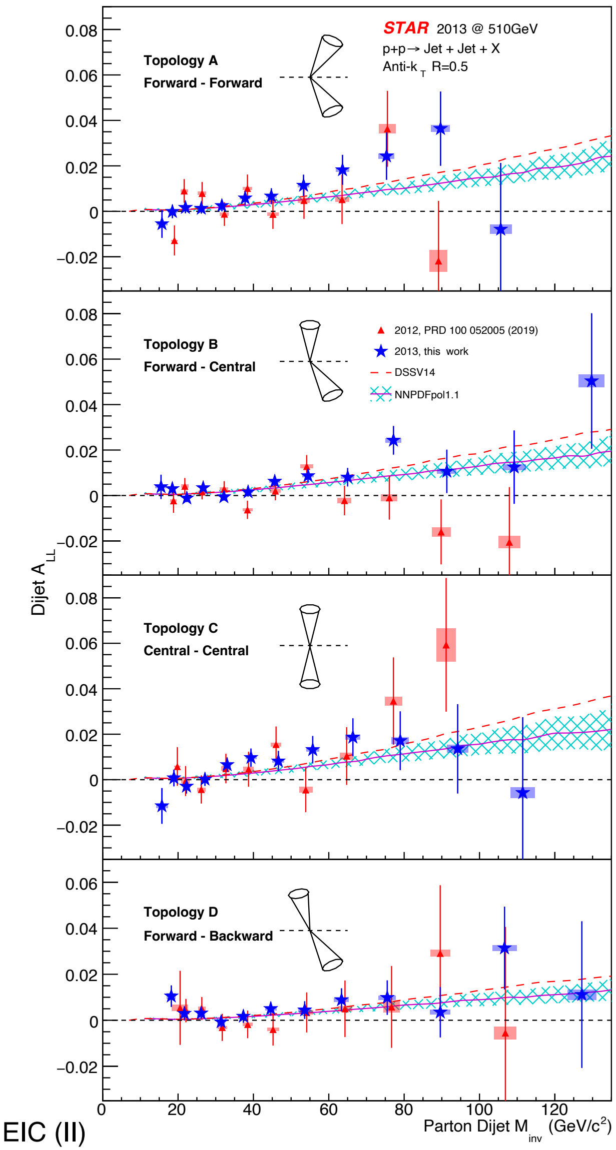


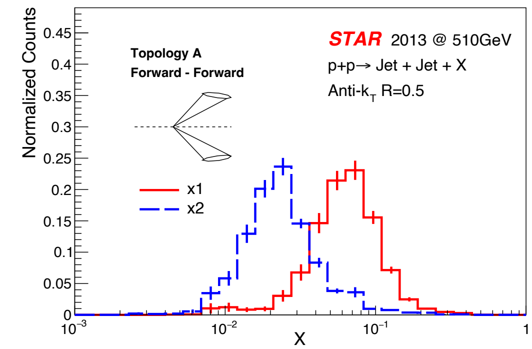
STAR Results: Run 13 Dijet results at 510GeV

- Mid-rapidity Dijet A_{LL}

J. Adam *et al.* (STAR Collaboration), *Phys. Rev.* **D 105** (2022) 9, 092011.

- Good agreement between Run 13 and Run 12 measurements
- Good agreement with NLO calculations based on DSSV14 and NNPDFpol1.1 PDF set
- Higher precision measurement will provide valuable input constraining $\Delta g(x, Q^2)$ at small x ($x \approx 0.015$)!





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- D: Forward-Backward

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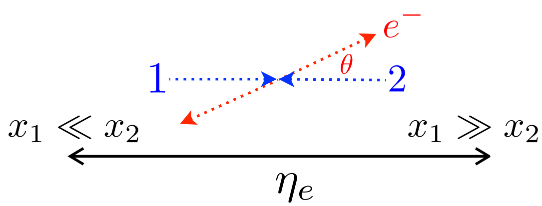
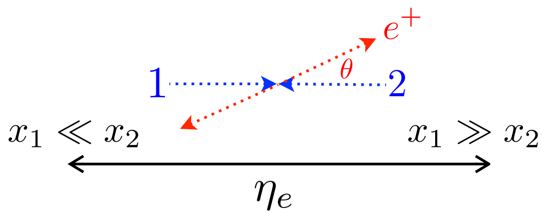
STAR Results: W boson production

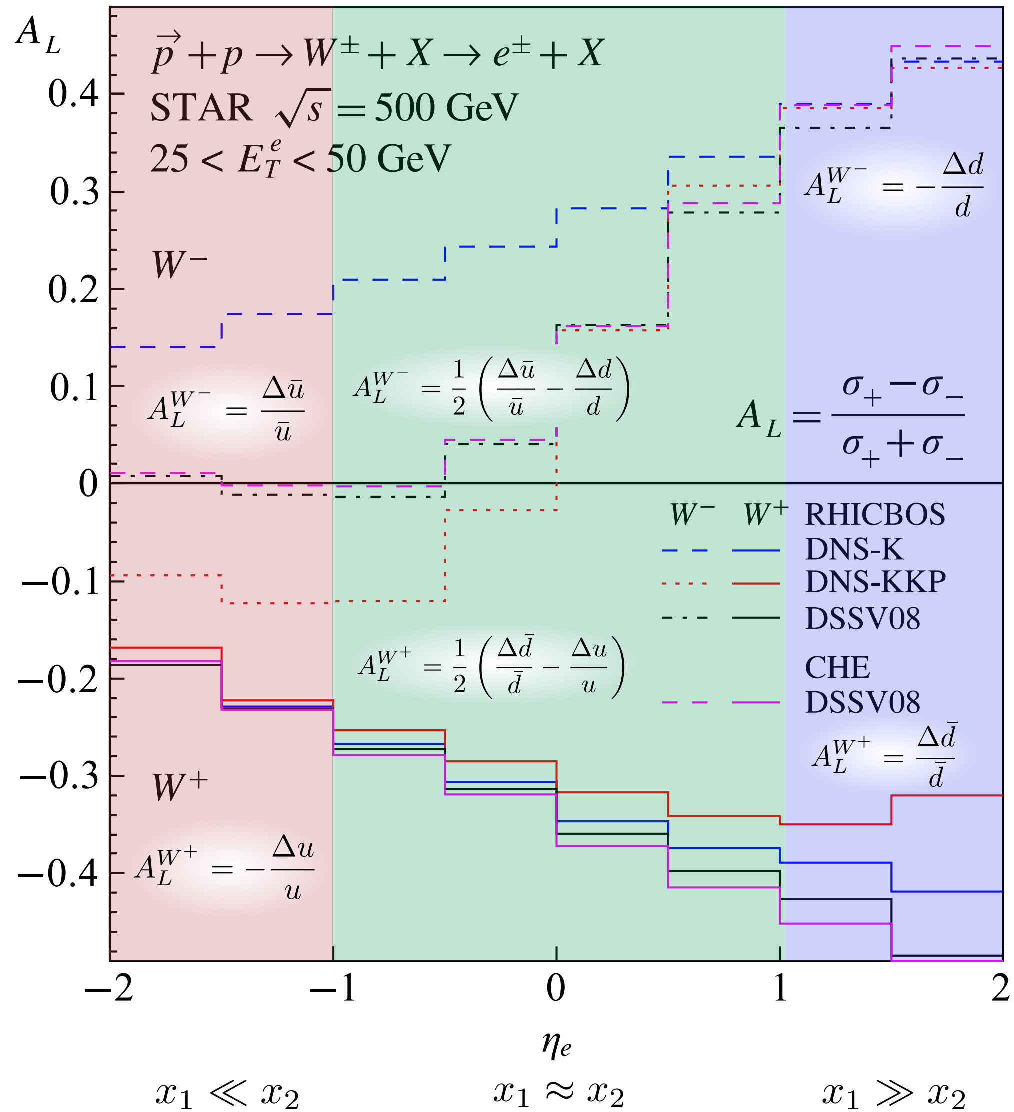
- RHIC Probing the quark flavor structure using W boson production

$$A_L^{e^-} \approx \frac{\int_{\otimes(x_1,x_2)} [\Delta\bar{u}(x_1)d(x_2)(1-\cos\theta)^2 - \Delta d(x_1)\bar{u}(x_2)(1+\cos\theta)^2]}{\int_{\otimes(x_1,x_2)} [\bar{u}(x_1)d(x_2)(1-\cos\theta)^2 + d(x_1)\bar{u}(x_2)(1+\cos\theta)^2]}$$



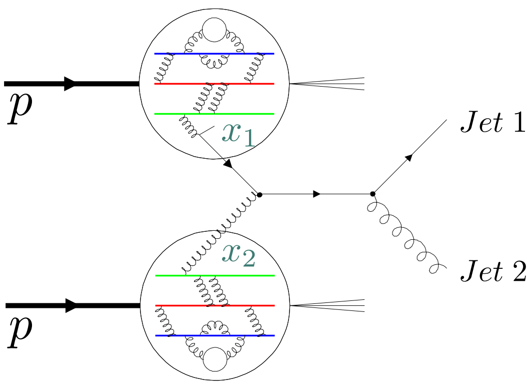
$$A_L^{e^+} \approx \frac{\int_{\otimes(x_1,x_2)} [\Delta\bar{d}(x_1)u(x_2)(1+\cos\theta)^2 - \Delta u(x_1)\bar{d}(x_2)(1-\cos\theta)^2]}{\int_{\otimes(x_1,x_2)} [\bar{d}(x_1)u(x_2)(1+\cos\theta)^2 + u(x_1)\bar{d}(x_2)(1-\cos\theta)^2]}$$

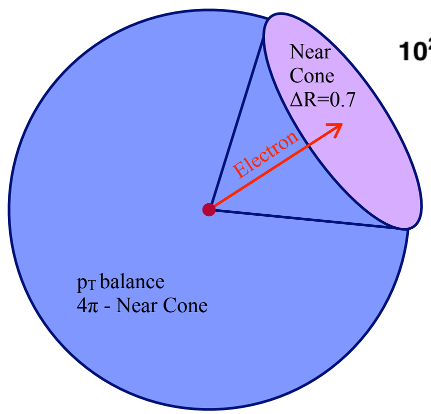




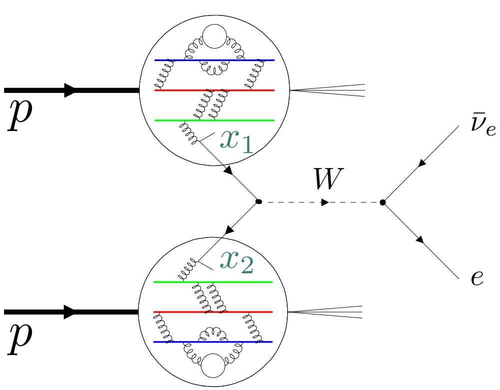
STAR Results: W boson production

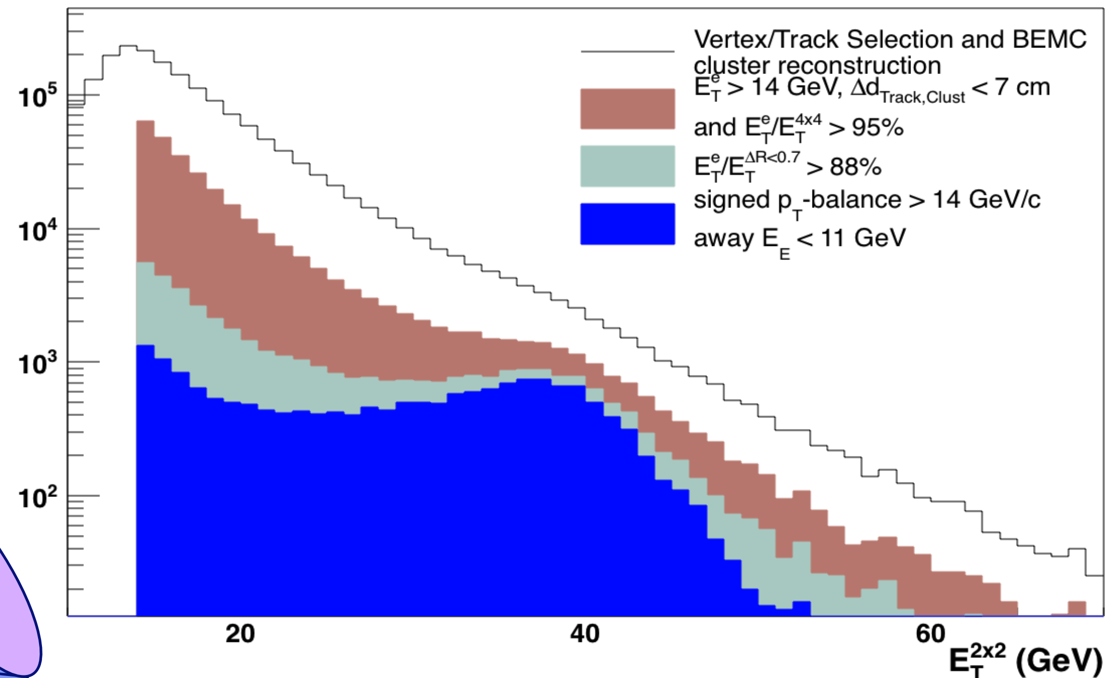
- W boson reconstruction at STAR





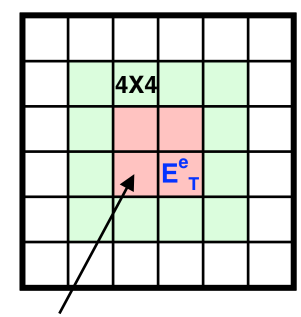
Transverse plane view





$$\vec{p_T}^{\,bal} = \vec{p_T}^{\,e} + \sum_{\Delta R>0.7} \vec{p_T}^{\,jets}$$

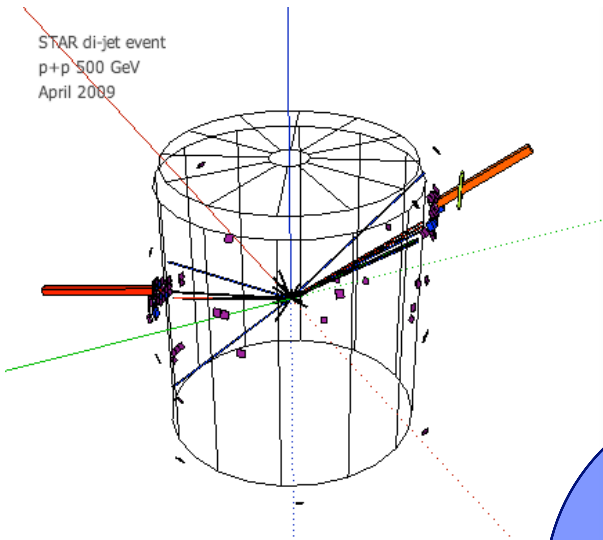
$$P_T\text{-balance}\cos(\phi) = \frac{\vec{p}_T^{\,e} \cdot \vec{p}_T^{\,bal}}{|\vec{p}_T^{\,e}|}$$

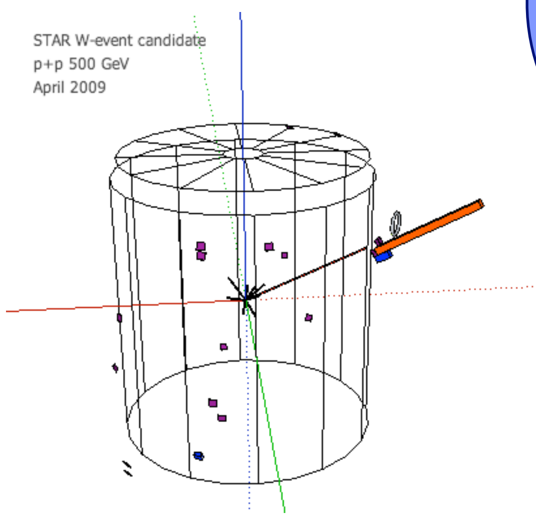


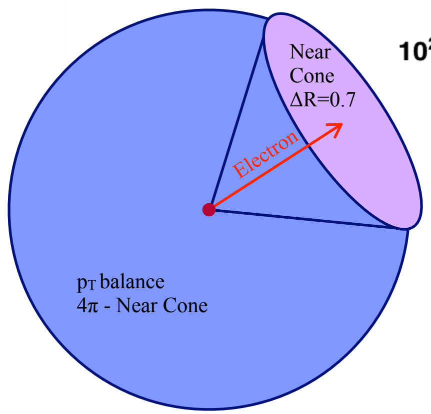
TPC track extrapolated
to Barrel calorimeter tower grid

STAR Results: W boson production

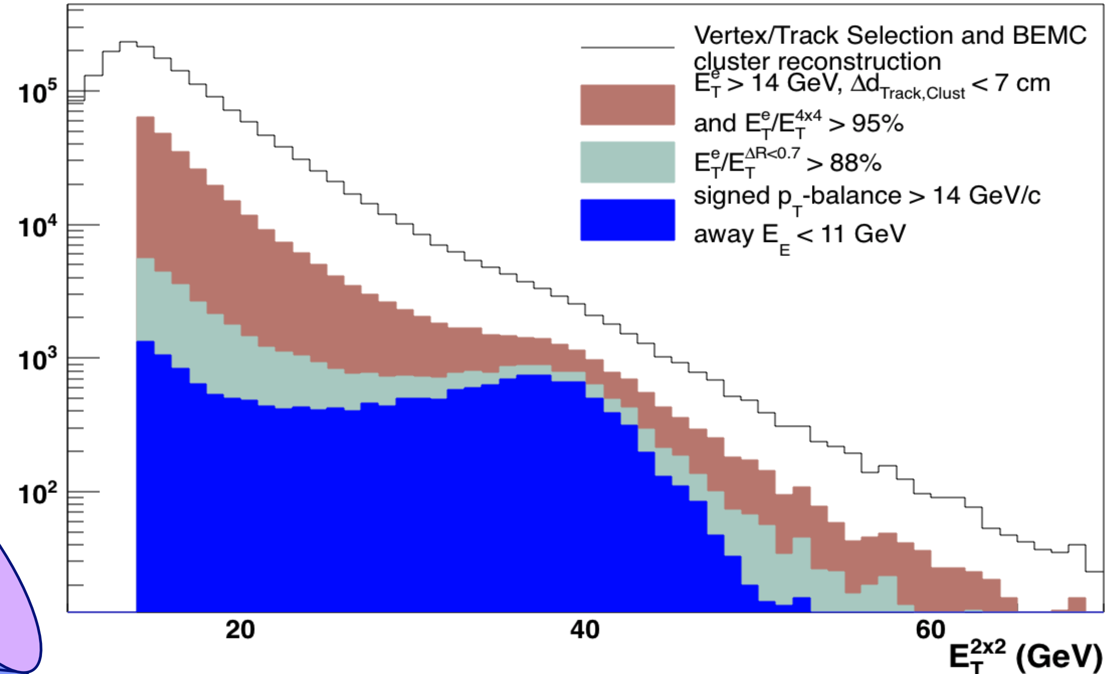
W boson reconstruction at STAR





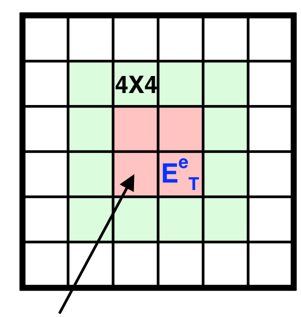


Transverse plane view



$$\vec{p_T}^{bal} = \vec{p_T}^{e} + \sum_{\Delta R>0.7} \vec{p_T}^{jets}$$

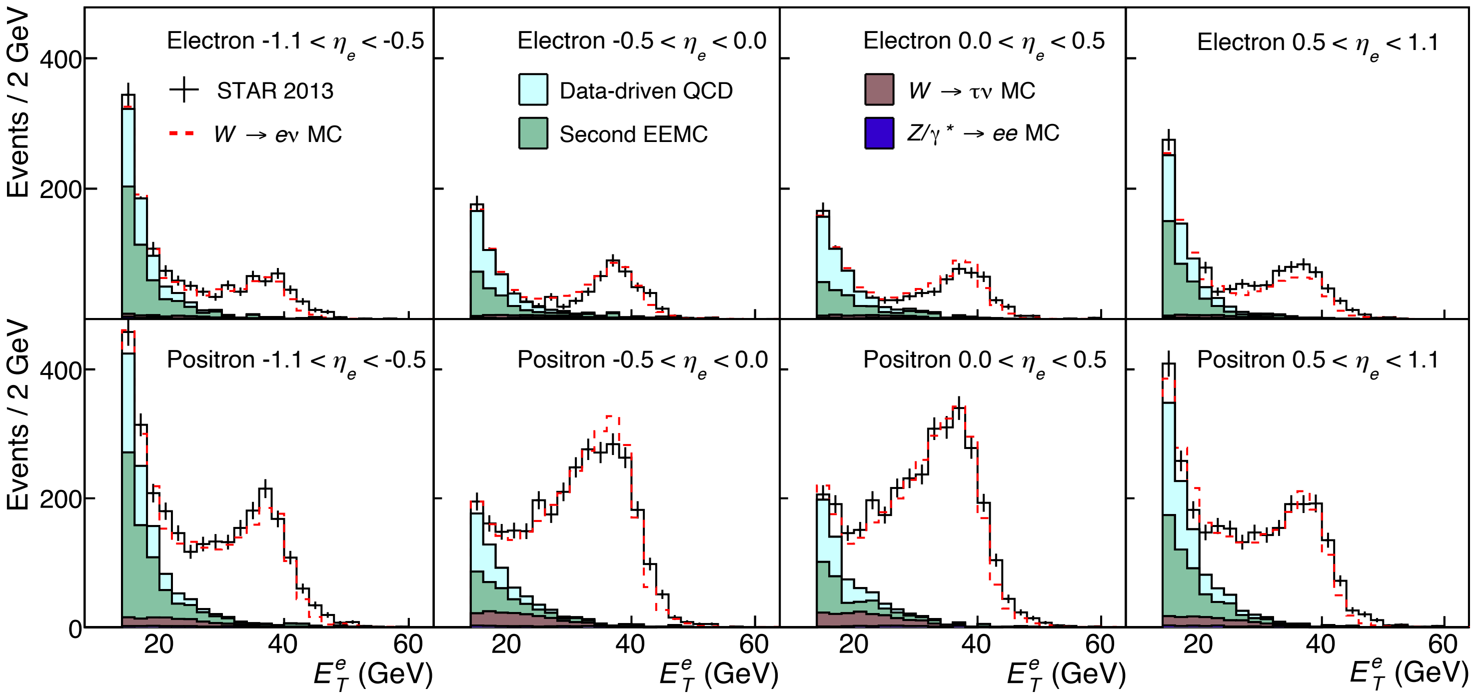
$$P_T\text{-balance}\cos(\phi) = \frac{\vec{p_T}^{e} \cdot \vec{p_T}^{bal}}{|\vec{p_T}^{e}|}$$



TPC track extrapolated to Barrel calorimeter tower grid

STAR Results: W boson production

- Mid-rapidity W^+ / W^- signal distributions / Background determination



STAR E_T distributions for W^-/W^+ candidate events well described by $W \rightarrow e + \nu$ (W-e decay) signal events and data-driven QCD background estimation plus electro-weak background events in four mid-rapidity η bins

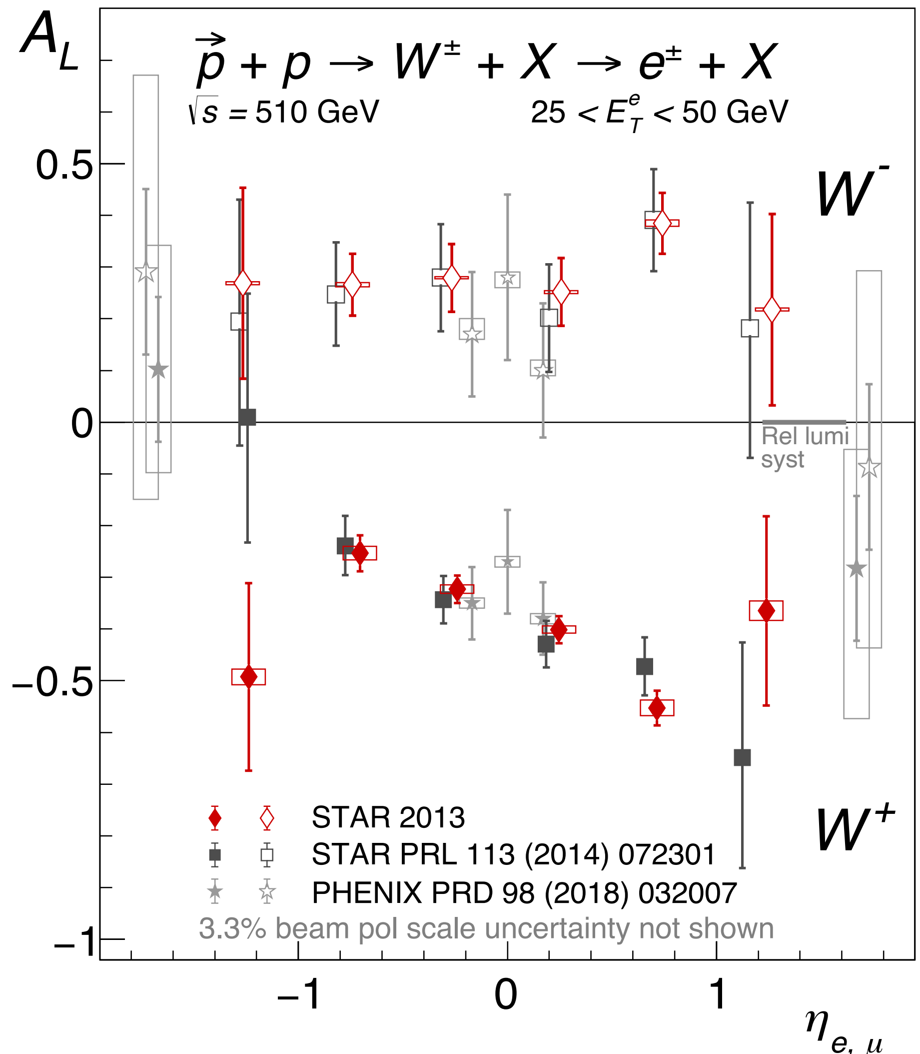
J. Adam et al. (STAR Collaboration), Phys. Rev. D **99** (2019) 51102.

- QCD background:
  - Data-driven QCD background estimate: Background which satisfy $e^{\pm}$ candidate isolation cuts
  - Second EEMC QCD background estimate: Background ("Jet") at non-existing calorimetric coverage for $-2 < \eta < 1.1$ based on instrumented calorimetric coverage with STAR EEMC for $1.1 < \eta < 2$
- Electro-Weak background: $Z \rightarrow e^+ + e^-$ (Z decay) and $W \rightarrow \tau + \nu$ (W-Tau decay) / PYTHIA-MC estimation!

STAR Results: W boson production Run 11/12 + 13

- W A_L measurements at STAR 2013 and 2011+2012 and PHENIX

  - STAR 2013 W A_L results is the most precise measurement of W A_L up to date.
  - STAR 2013 W A_L results consistent with published 2011+2012 results
  - Statistical uncertainties (Dominant uncertainties) were reduced by 40-50% compared to published 2011+2012 results / Similar systematic uncertainties.
  - Results consistent with published PHENIX mid-rapidity measurements.



J. Adam et al. (STAR Collaboration), Phys. Rev. D **99** (2019) 51102.

STAR Results: W boson production Run 11/12 + 13

- W A_L measurements: Combination of 2011+2012+2013

  - STAR 2013 W A_L results is the most precise measurement of W A_L up to date.
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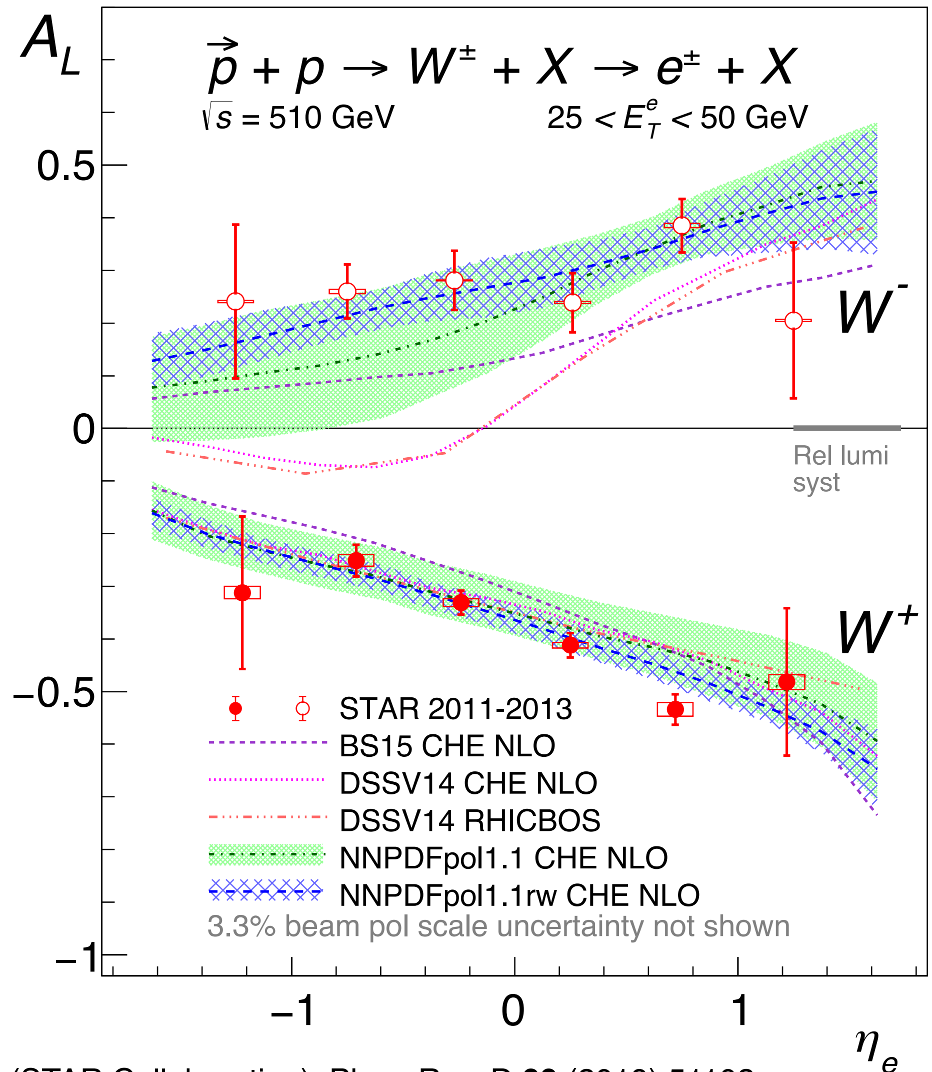
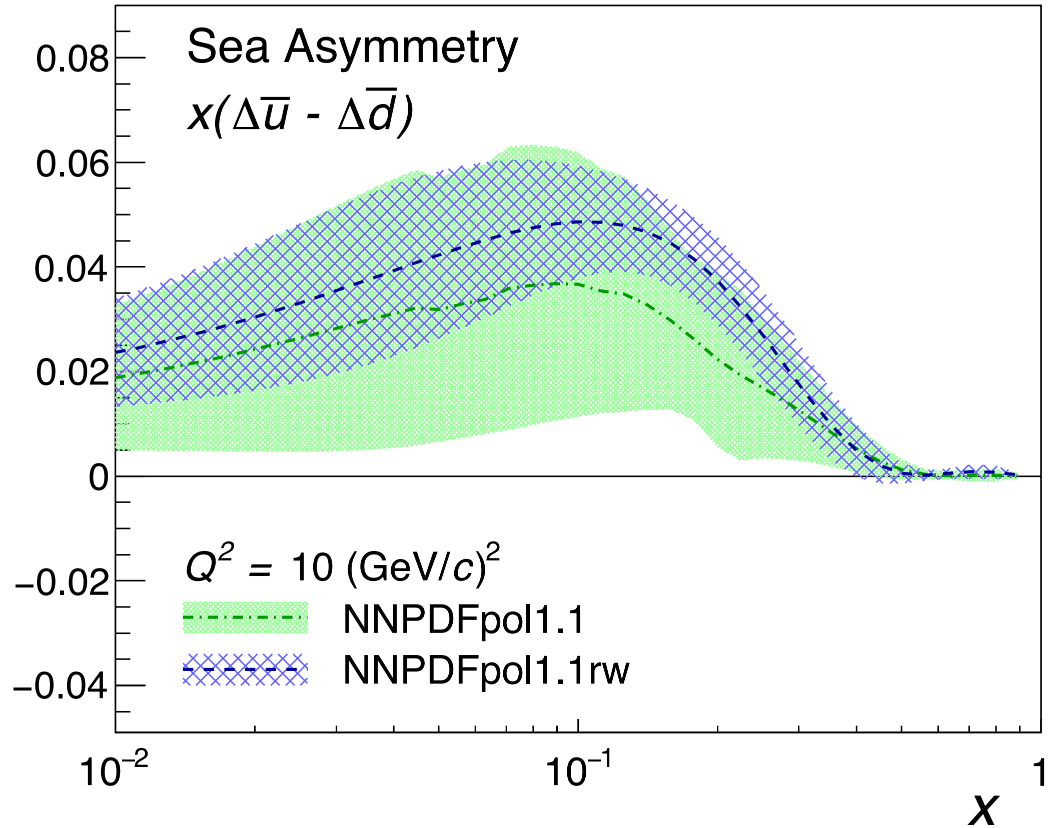


J. Adam et al. (STAR Collaboration), Phys. Rev. D **99** (2019) 51102.

STAR Results: W boson production Run 11/12 + 13

- Impact of STAR W A_L measurements on $\Delta\bar{u}$ and $\Delta\bar{d}$:

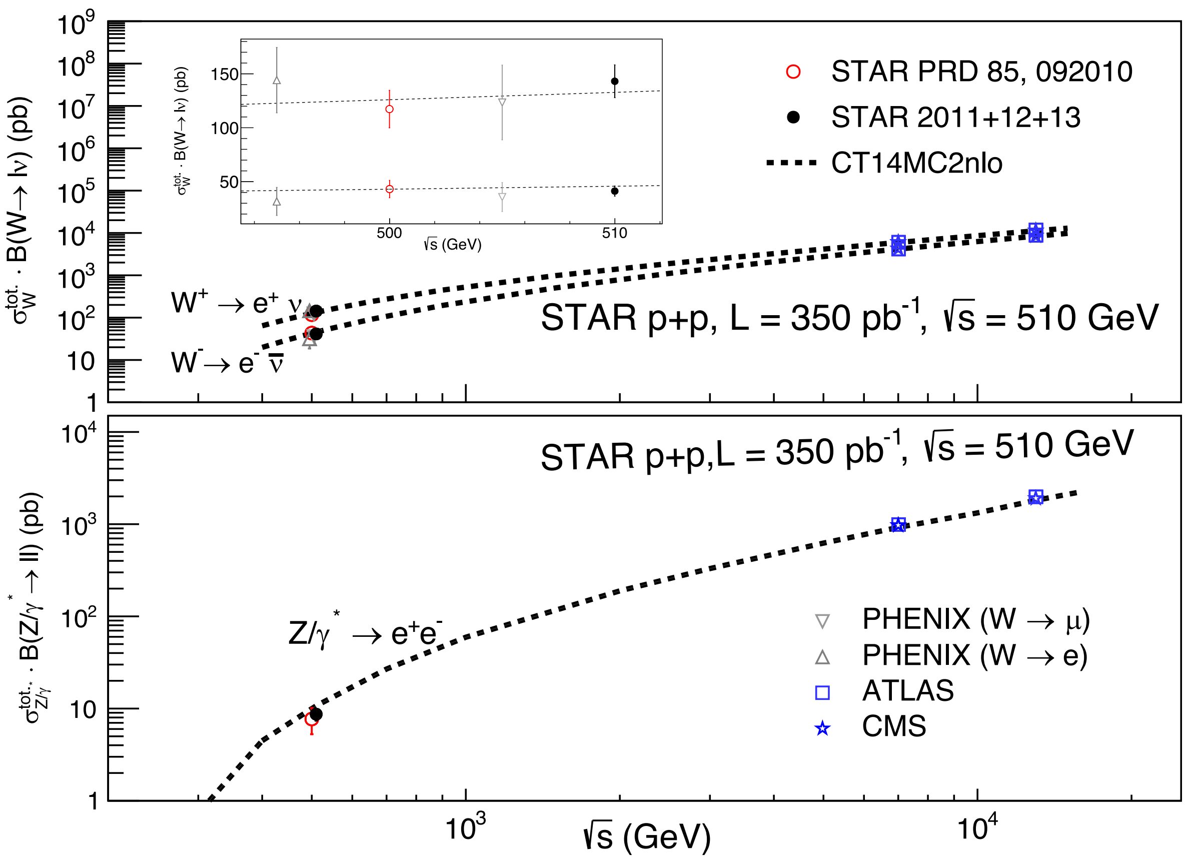
J. Adam et al. (STAR Collaboration), Phys. Rev. D **99** (2019) 51102.

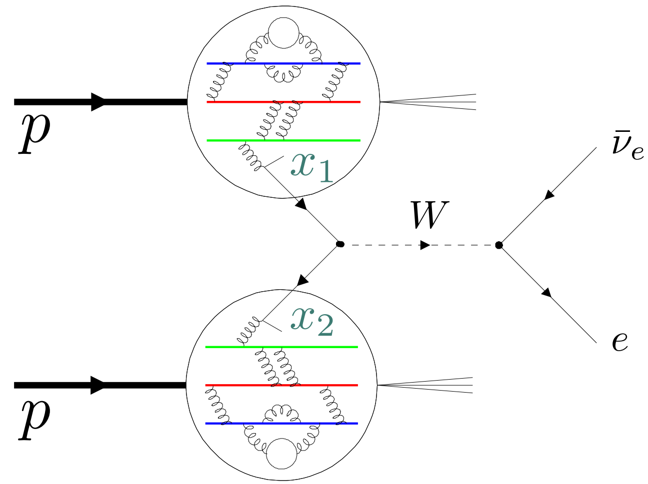


- Significant constraint for $\Delta\bar{u}$ and $\Delta\bar{d}$: $\Delta\bar{u} > \Delta\bar{d}$ at intermediate Bjorken-x $(M_W/\sqrt{s} \simeq 0.16)$
- Polarized flavor asymmetry $\Delta\bar{u} - \Delta\bar{d}$ of similar size, but opposite sign compared to unpolarized asymmetry $\bar{u} - \bar{d}$

STAR Results: W boson production Run 11/12 + 13

- W/Z cross-section measurements at collider experiments



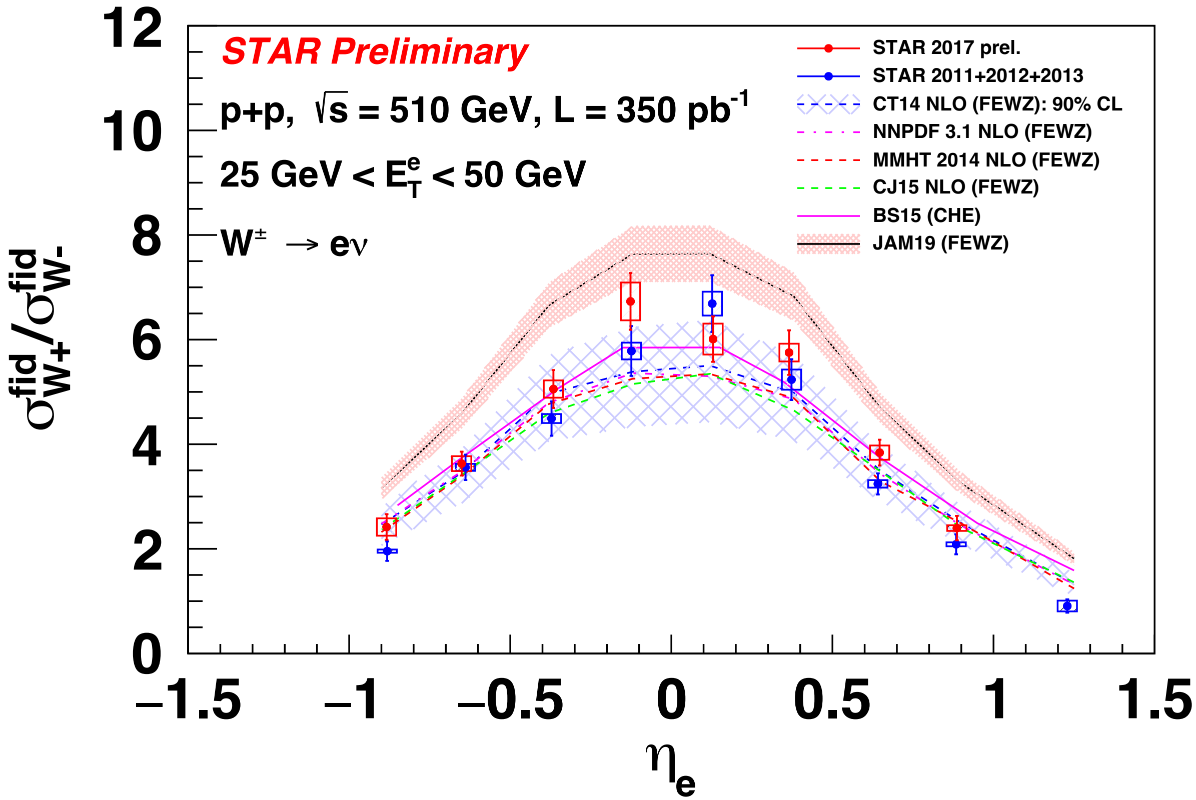


J. Adam et al. (STAR Collaboration), Phys. Rev. D **103** (2021) 012001.

- Measured and theory evaluated cross-sections agree within uncertainties
- Theory calculations: FEWZ and CT14MC2nlo

STAR Results: W boson production Run 11/12 + 13

- STAR: W cross-section ratio measurements: Run 11+12+13 and Run 17

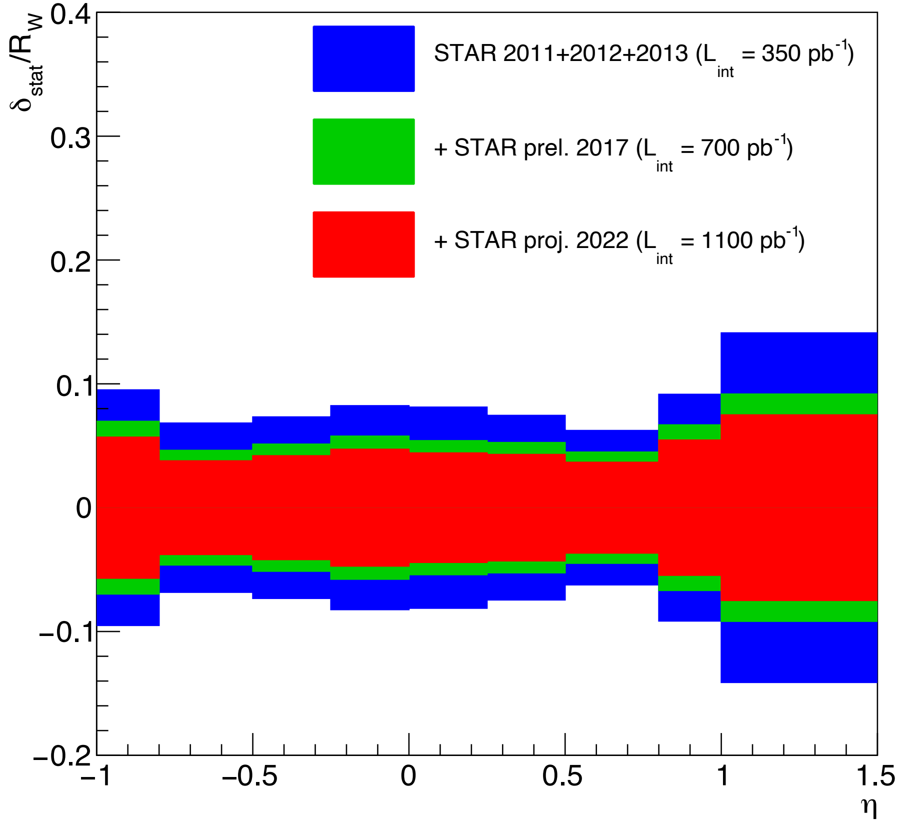


J. Adam et al. (STAR Collaboration), Phys. Rev. D **103** (2021) 012001.

- Run 11 + 12 + 13 published results
- Preliminary results: Run 17 data sample of ~400pb^{-1}

STAR Results: W boson production - Projections

- STAR: W cross-section ratio measurements Run 11+12+13, Run 17, and Run 22



- Run 11 + 12 + 13 published results ~350pb^{-1}
- Preliminary results: Run 17 data sample of ~400pb^{-1}
- Projections for Run 22: Data sample of ~400pb^{-1}

Summary / Outlook

- Helicity-related results at STAR - Mid-rapidity
  - The RHIC Spin program was an enormous success resting on the synergy of accelerator physics, experimental measurements, and fundamental theory calculations to deepen understanding of the proton spin structure and dynamics
  - After about 20 years, the longitudinally polarized p+p program concluded with the last measurement at 200 GeV in Run 15 and at 510 GeV in Run 13
  - The RHIC Spin gluon polarization provided evidence that $\Delta g(x, Q^2)$ is positive for x > 0.05 with further improvements in kinematic coverage and precision
  - Significant constraint for $\Delta\bar{u}$ and $\Delta\bar{d}$ through W boson production $\Delta\bar{u} > \Delta\bar{d}$ at intermediate x $(M_W/\sqrt{s} \simeq 0.16)$
- Future
  - The last RHIC Spin program is scheduled for Run 24 at 200 GeV of transversely polarized p+p collisions
  - The future is bright with the advent of the EIC program at BNL. The conclusion of the RHIC operation is scheduled for June 2025!

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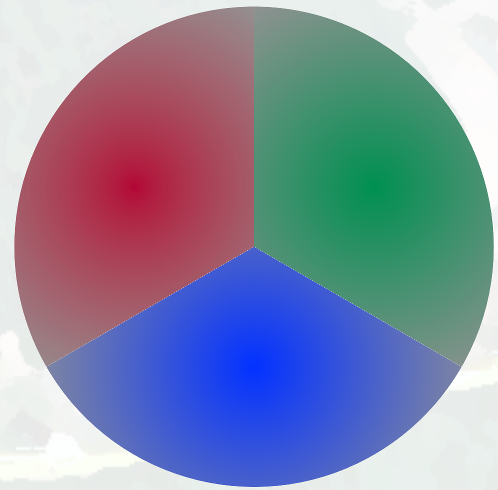
- I want to express my deep gratitude to various groups who made the RHIC SPIN program a success:
  - RHIC SPIN machine group
  - RHIC Polarimetry group
  - STAR / PHENX collaborators
  - Numerous theory groups, providing higher-order calculations (Hadron/Jets and EW bosons), along with global analysis groups: DSSV, JAM, and NNPDF



  - Special thanks to lots of very talented graduate students and postdocs!