Diffraction and low-x 2022

Measurements of unpolarized cross section and transverse single spin asymmetry of Z^0 in 500/510 GeV p+p collisions

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Brookhaven National Laboratory
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Supported by

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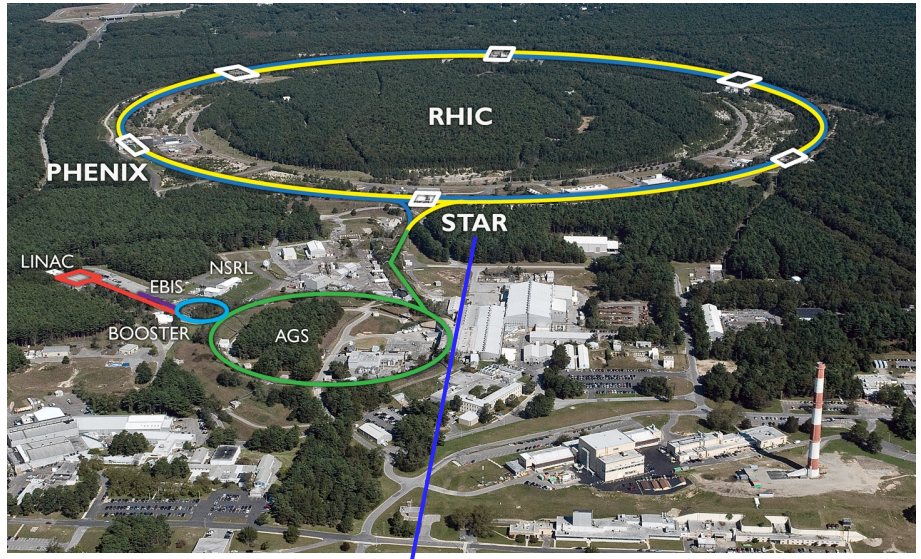
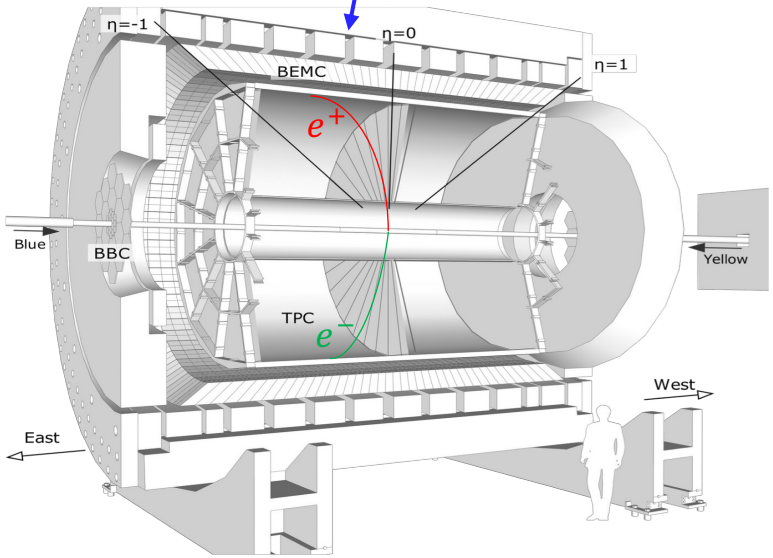
Diffraction and Low-x

The STAR detector at RHIC





- **RHIC** is the world's **first and only polarized hadron collider;** its top energy is sufficient to produce weak bosons

- **STAR detector**
  - Time Projection Chamber: $|\eta| < 1$, $0 <= \phi < 2\pi$
    - Tracking, PID, vertex reconstruction
  - Electromagnetic Calorimeter: $-1 < \eta < 2$, $0 <= \phi < 2\pi$
    - Energy measurement

  Complemented by many ancillary subsystems:
  - Beam-Beam Counter
  - Time-of-Flight
  - Vertex Position Detector
  - Zero Degree Calorimeter
  - Roman Pots
  - Forward Meson Spectrometer

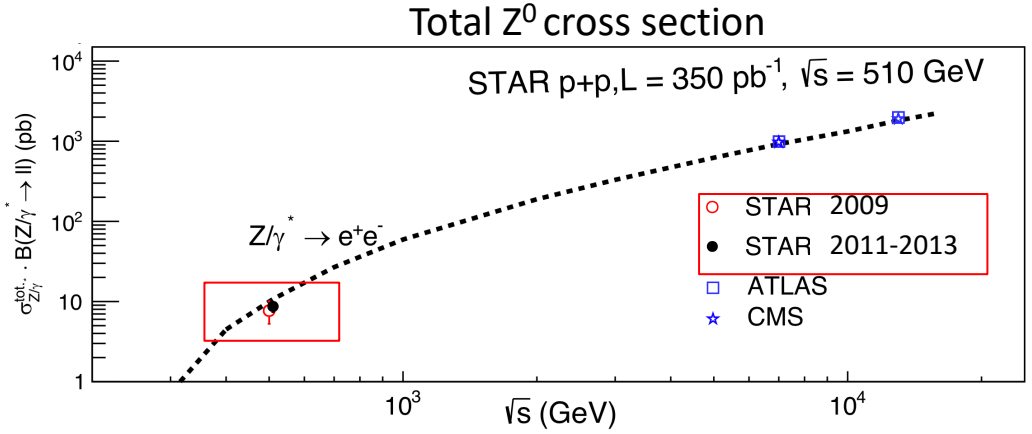
- Through $Z^0 \rightarrow e^+e^-$ we measured
  - Unpolarized cross section of Z^0
  - Transverse single spin asymmetry of Z^0

Motivation of cross section measurement

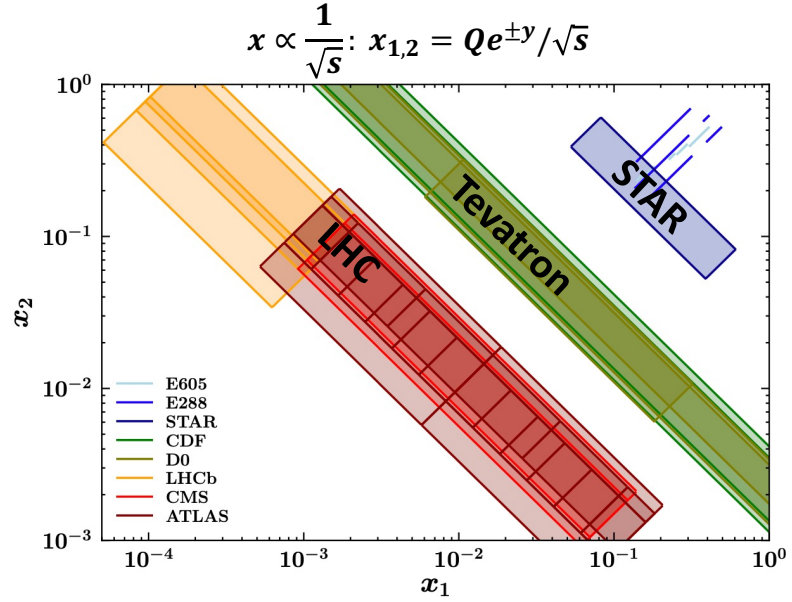
- Unpolarized cross section of Z^0 in 500/510 GeV p+p→Z^0+X is measured to extract unpolarized TMDs*

$$\frac{d\sigma}{dQdydp_T} \propto \int dk_{\perp 1}^2\, dk_{\perp 2}^2\, f_1(x_1, k_{\perp 1}^2, Q^2)\, f_2(x_2, k_{\perp 2}^2, Q^2)\, \delta(k_{\perp 1}, k_{\perp 2})$$

- Z^0 channel: RHIC sits in an intermediate energy range
  - Complementary to the LHC and Tevatron
  - STAR data probe large x region → study the TMD evolution on x



CMS, JHEP 01 (2011) 080; JHEP12 (2019) 061
ATLAS, JHEP 12 (2010) 060; PLB 759, 601 (2016)
STAR 2009: PRD 85(2011) 092010
STAR 2011-2013: PRD 103 (2021) 012001



A. Bacchetta et al., JHEP 07(2020) 117

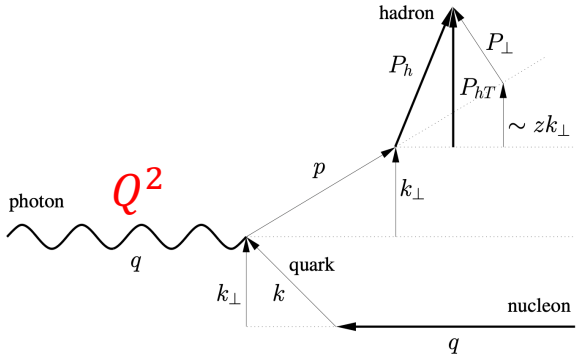
*Transverse momentum dependent parton distribution functions (TMDs): $f(x, k_\perp, Q^2)$

Motivation of cross section measurement

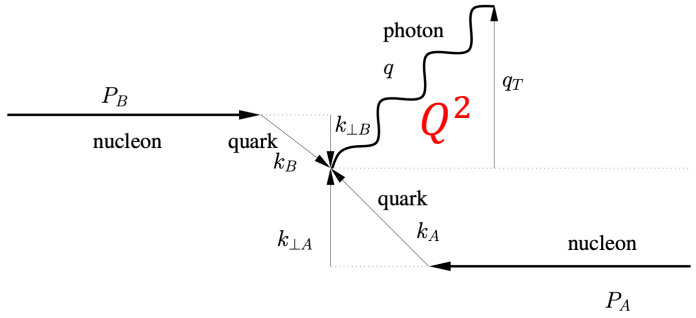
- Z^0 channel + semi-inclusive DIS (SIDIS) + Drell-Yan
  - Universality properties of TMDs
  - Different channel probes different Q^2 → study the TMD evolution on Q^2

Channels	Experiments	$\sqrt{s}$
Z^0 boson	STAR CDF, D0 ATLAS, CMS, LHCb	500/510 GeV 1.8, 1.96 TeV 7, 8 TeV
SIDIS	Hermes Compass	27.6 GeV 160 GeV
Drell-Yan	E288, E605, E772 PHENIX ATLAS D0	19.4 – 38.8 GeV 200 GeV 8 TeV 1.96 TeV

A. Bacchetta et al., JHEP 06(2017) 081



SIDIS



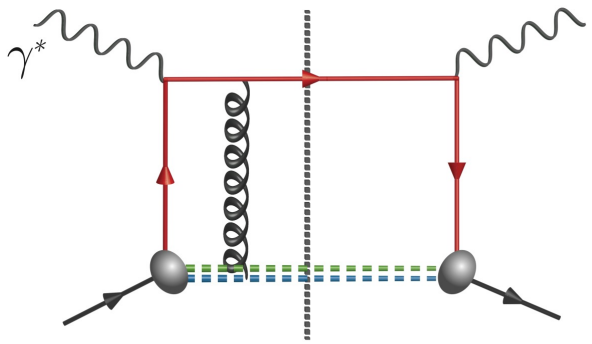
Drell-Yan

*Transverse momentum dependent parton distribution functions (TMDs): $f(x, k_\perp, Q^2)$

Motivation of TSSA measurement

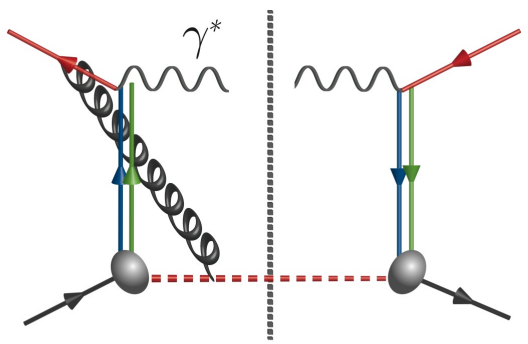
- Transverse single spin asymmetry (TSSA) of Z^0 in 500/510 GeV p+p collisions
  - Sensitive to the correlation of transverse proton spin and parton transverse motion – Sivers function (one of the polarized TMDs)
  - Test the non-universality of the Sivers function: sign change from p+p→W/Z+X to SIDIS
  - Limited statistics for STAR 2011 data to provide definitive test on the "sign change" hypothesis

DIS

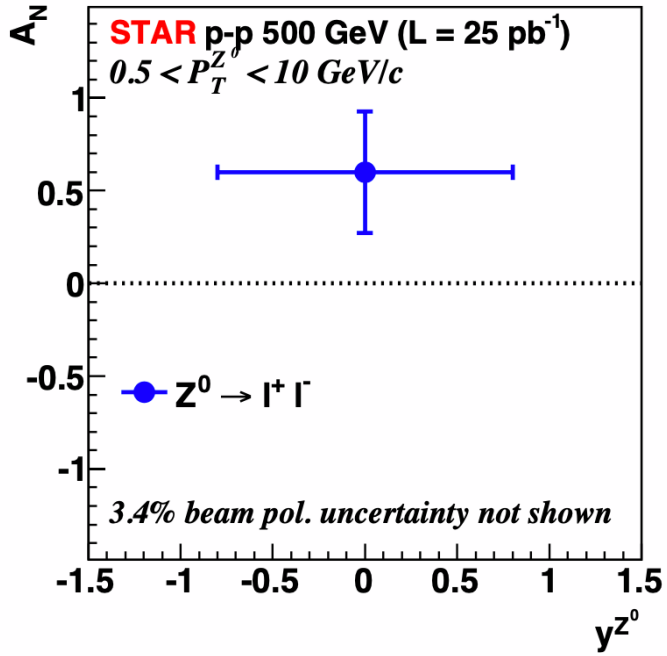


Color attractive

DY, W, Z^0



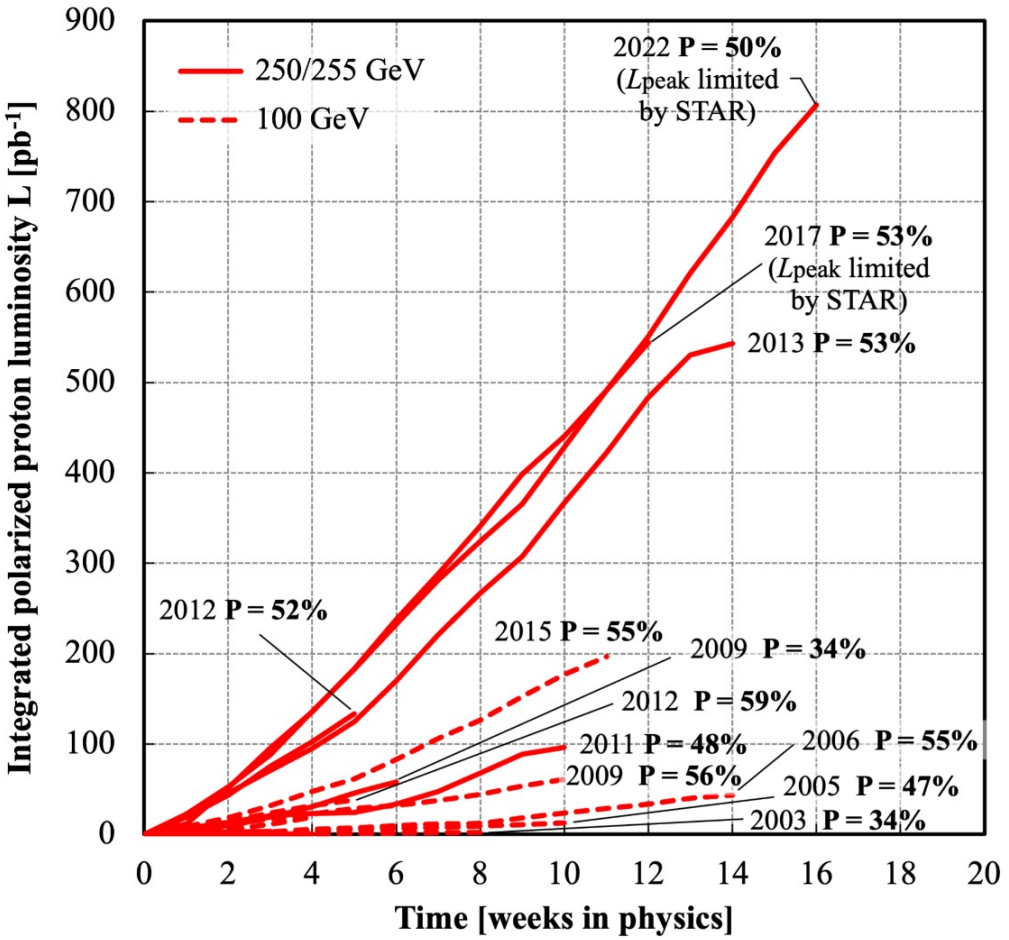
Color repulsive



STAR 2011: PRL 116 (2016) 132301

RHIC p+p data collection overview

Delivered Luminosity



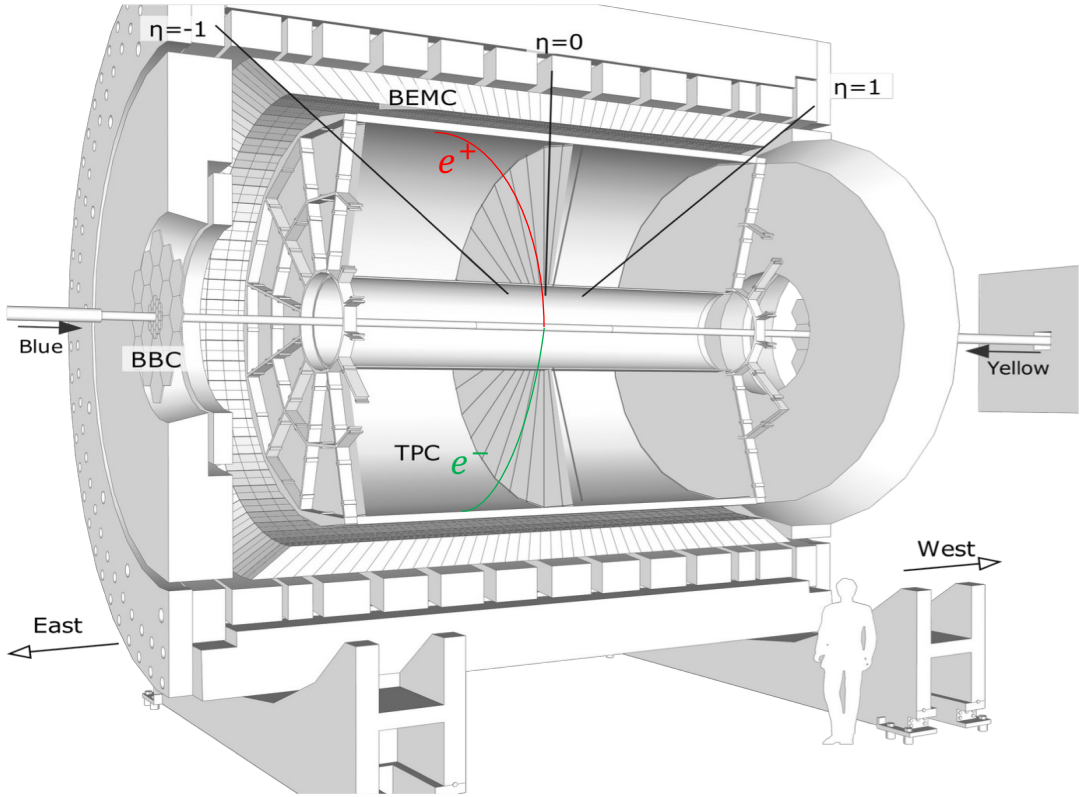
Sampled Luminosity

Year	$\sqrt{s}$ (GeV)	$L\ (pb^{-1})$	Results of Z^0
2009	500	10	Total cross section: STAR, PRD 85 (2011) 092010
2011	500	25	TSSA: STAR 2011, PRL 116 (2016) 132301 Total cross section: STAR 2011-2013, PRD 103 (2021) 012001 Cross section on p_T: preliminary
2012	510	75	
2013	510	250	
2017	510	340	Cross section on p_T and TSSA: preliminary
2022	508	450	Recently completed data taking

- What we present in this talk:
  - Cross section on p_T: not measured before
  - TSSA from 2017 data → ~14 times statistics of 2011 data
- Recently completed data taking for 2022 → last 508 GeV p+p data at STAR for Z^0 analysis

Z^0 reconstruction with STAR detector

$$p + p \rightarrow Z^0 \rightarrow e^+ e^-$$



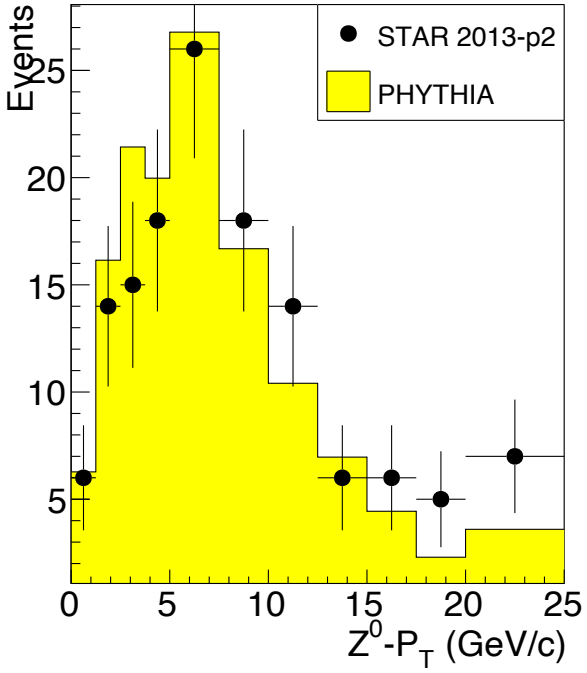
- **Main subsystems used from STAR detector**
  - Time Projection Chamber: |η| < 1, 0 <= ϕ < 2π
    - Lepton's charge, momentum
  - Barrel Electromagnetic Calorimeter: |η| < 1, 0 <= ϕ < 2π
    - Energy measurement
- **Cuts:** STAR 2011 analysis, PRL 116,132301 (2016)
  - Two high-p_T leptons: lepton p_T^{lep} > 25 GeV/c
  - Two leptons must have opposite charge
  - Invariant mass of two leptons within: 73 – 114 GeV/c^2
- Clean experimental reconstruction of Z^0 with small background

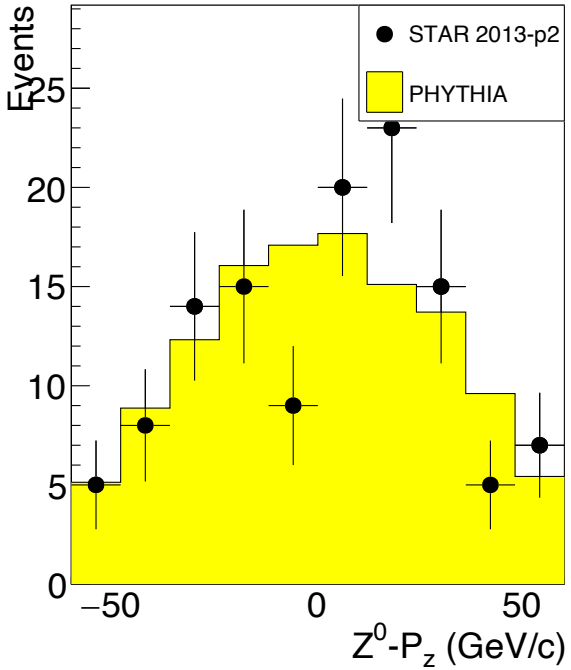
Technical details

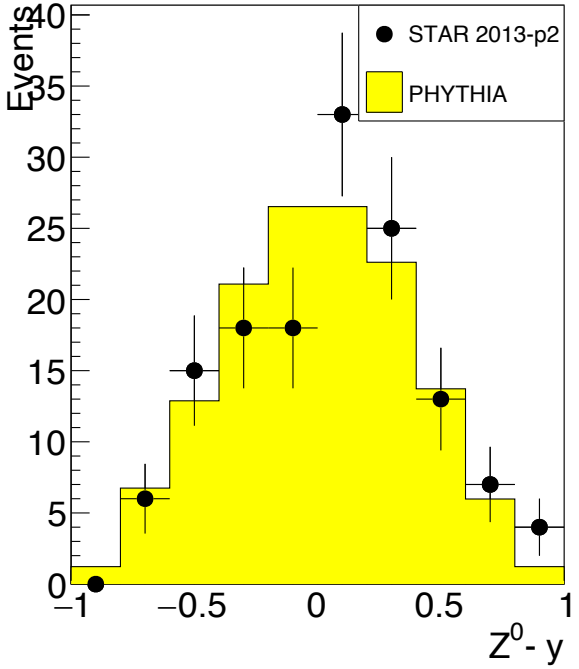
Monte Carlo

- PYTHIA passed through GEANT simulated STAR detector
- Perugia0 tune with hard p_T > 10 GeV/c
- PYTHIA embedded into real zero-bias p+p events

Example of data and MC comparison for the second period of 2013 data

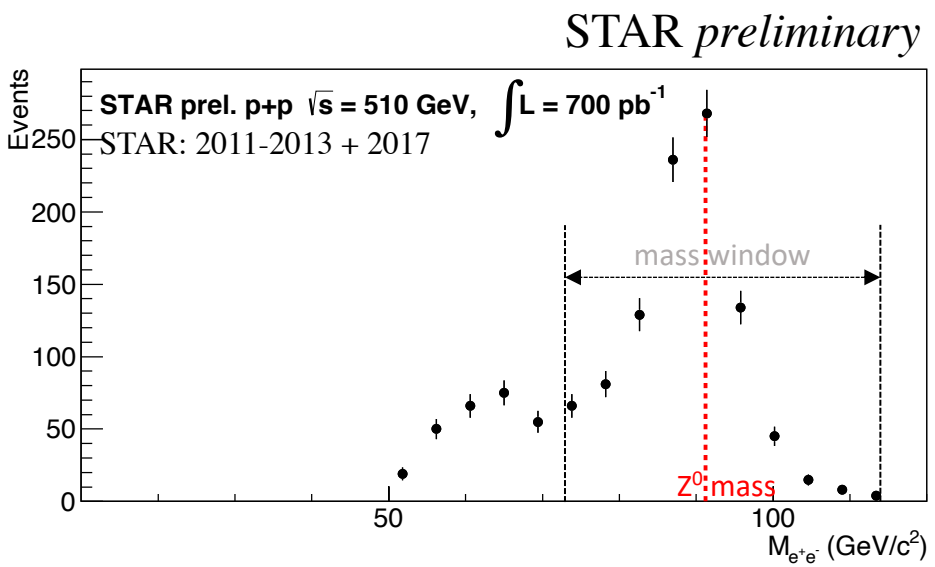






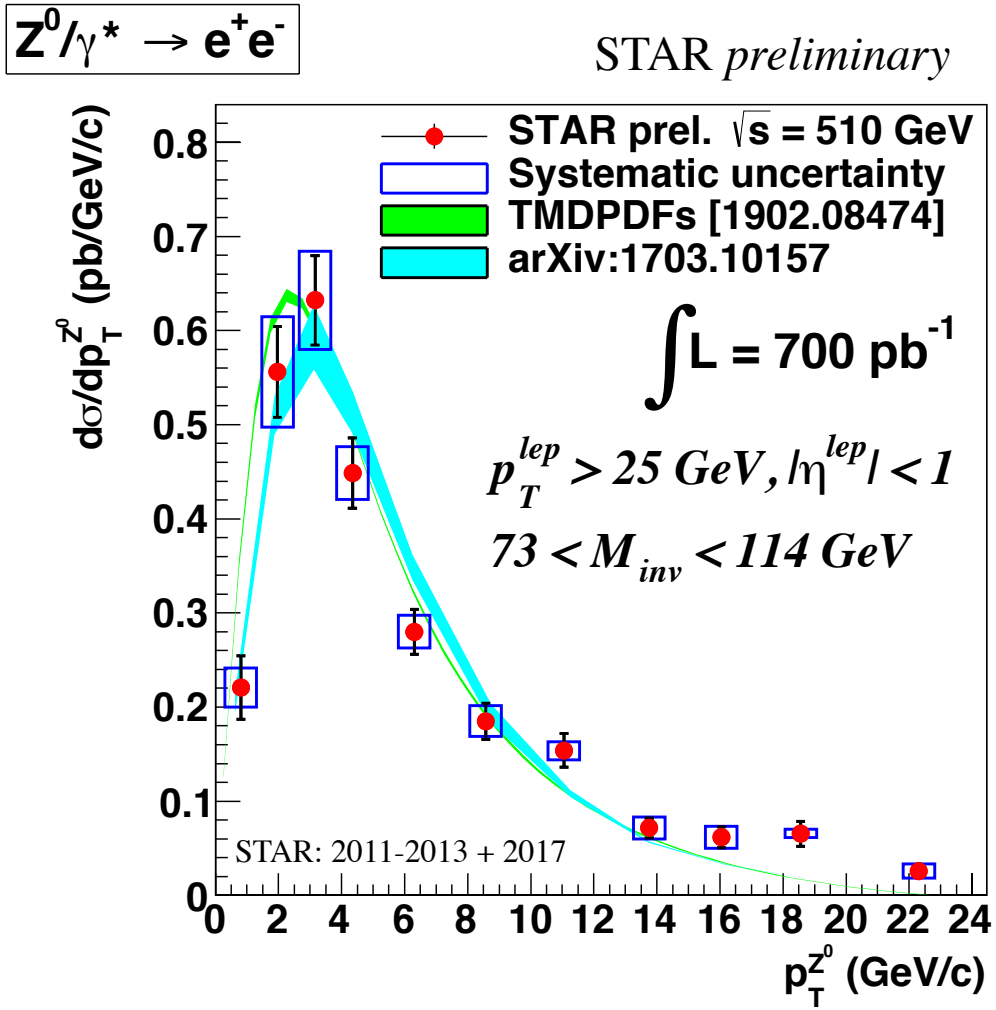
Z^0 p_T spectrum is obtained as the following: p_T distribution → p_T unfolding → detector efficiency correction → normalization by luminosity and dp_T

Preliminary unpolarized Z^0 results



Z^0 p_T spectrum:

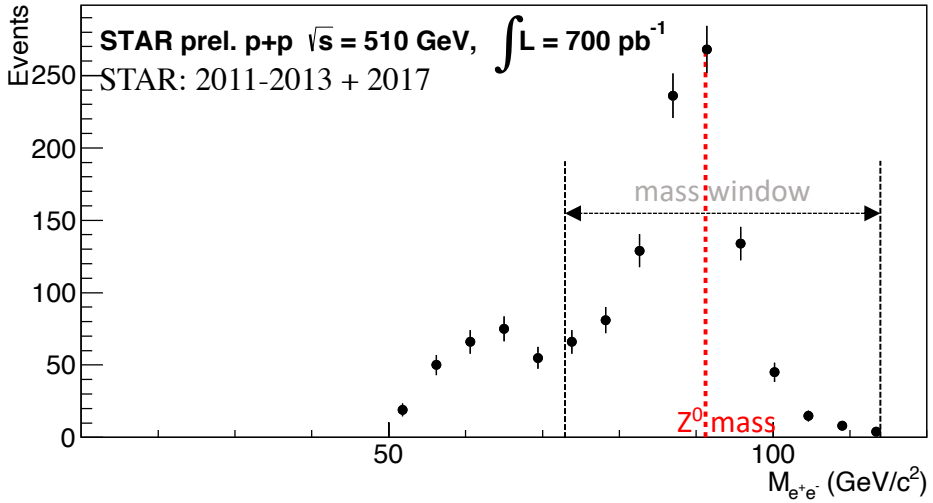
- systematics evaluated by varying p_T^{lep} and energy resolution
- key input to global fits of unpolarized TMDs
- agreement with calculations from
  - Regensburg group (V. Bertone et al.) based on NNLO TMD evolution
  - Pavia group (A. Bacchetta et al.) based on NLO TMD evolution



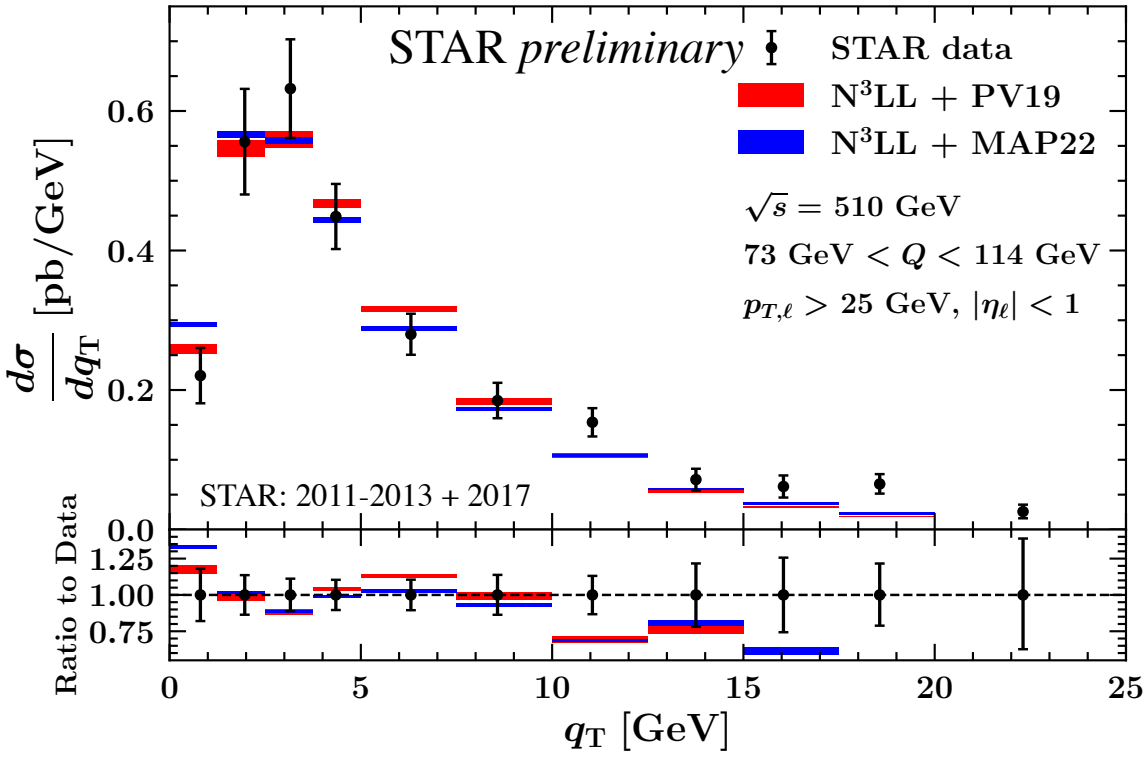
1902.08474: V. Bertone et al., JHEP06 (2019) 028
1703.10157: A. Bacchetta et al., JHEP06 (2017) 081

More calculations on p_T spectrum

STAR *preliminary*



Plot from M. Radici



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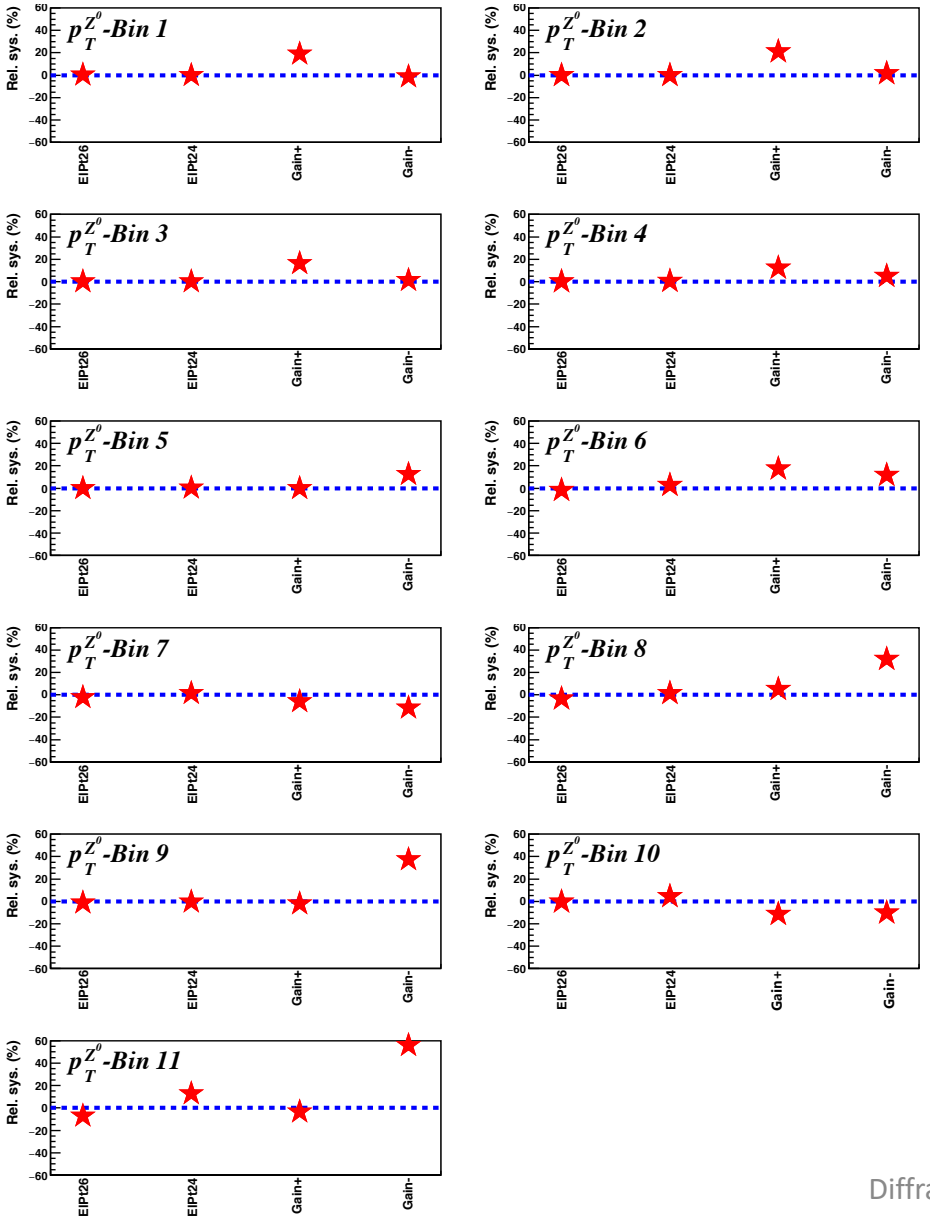
More calculations:

N^{3}LL+PV19: A. Bacchetta et al., JHEP07 (2020) 117, DY data

N^{3}LL+MAP22: A. Bacchetta et al., 2206.07598, DY+SIDIS data

Systematic uncertainties

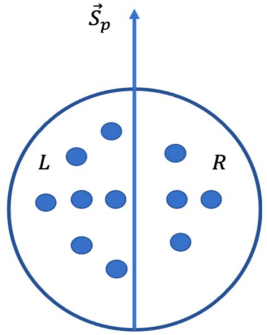


Source for systematic uncertainty bin by bin in p_T (11 p_T bins)

- Source 1: p_T^{lep} > 26 GeV/c
- Source 2: p_T^{lep} > 24 GeV/c
- Source 3: BEMC gains $+4\%$
- Source 4: BEMC gains -4%

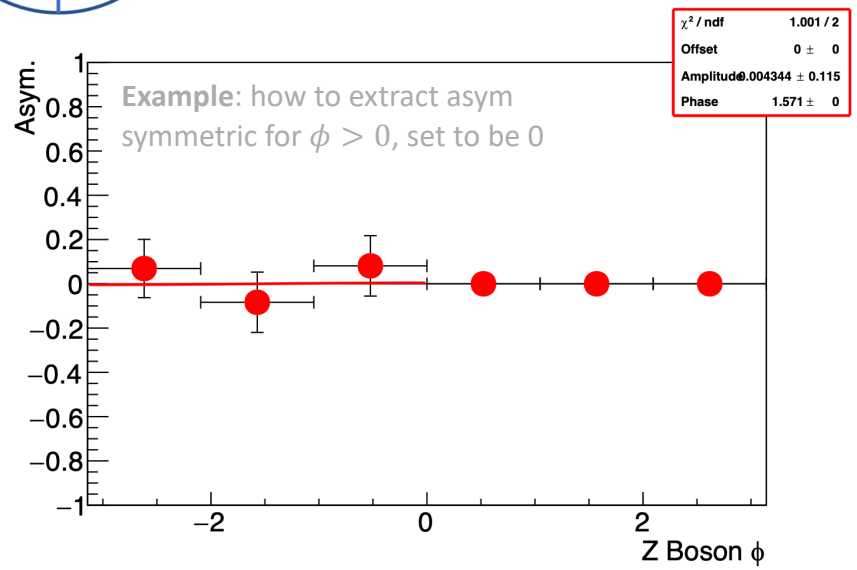
Systematic uncertainties dominated by energy resolution

Preliminary Z^0 TSSA results



Left-right asymmetry

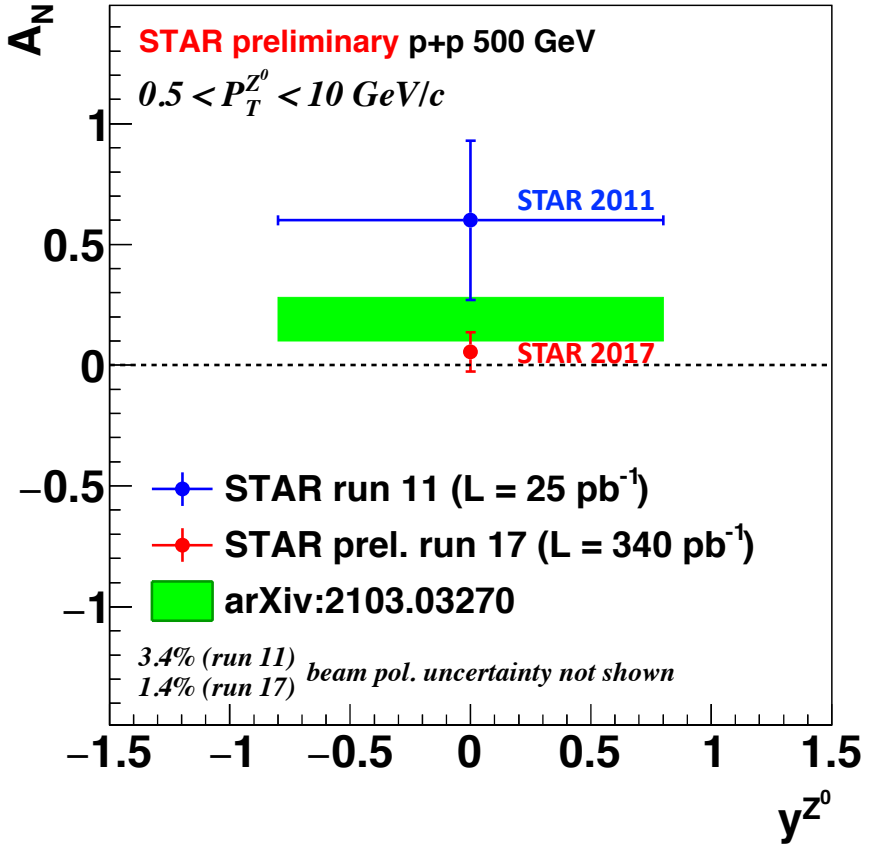
$$Asym^* = \frac{1}{P}\frac{\sqrt{N_R^{\uparrow}N_L^{\downarrow}} - \sqrt{N_L^{\uparrow}N_R^{\downarrow}}}{\sqrt{N_R^{\uparrow}N_L^{\downarrow}} + \sqrt{N_L^{\uparrow}N_R^{\downarrow}}}$$



Azimuthal modulations:
Sine function fit→ $\boldsymbol{p_1}\times\sin(\phi + p_2)$

*↑ ↓: spin up or down; P: polarization fraction
* L,R: left or right with respect to spin direction

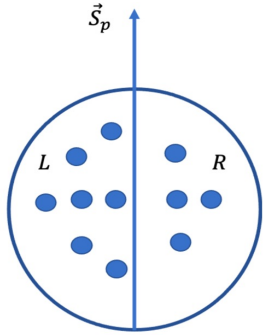
Measured TSSA of Z^0



Much more statistics in 2017 than 2011

2103.03270: M. Bury et al., JHEP05 (2021) 151

Preliminary Z^0 TSSA results



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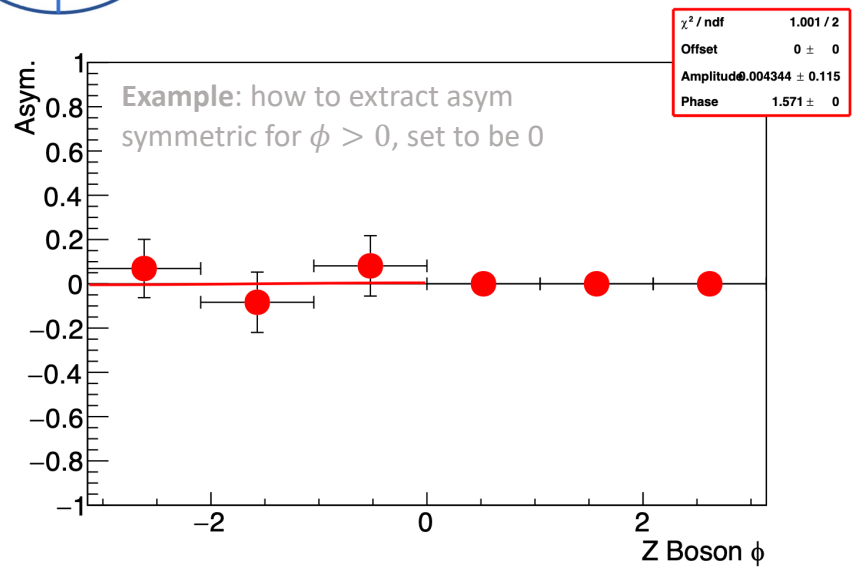

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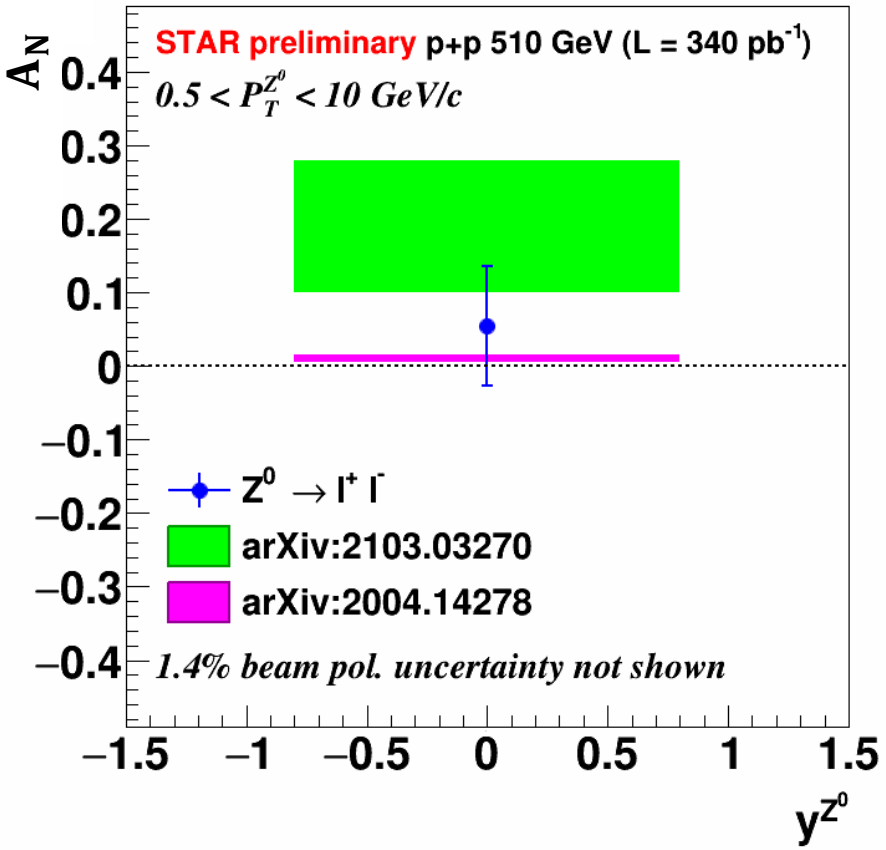


Current data not precise enough to distinguish two models

2103.03270: M. Bury et al., JHEP05 (2021) 151
2004.14278: A. Bacchetta et al., PLB 827 (2022) 136961

Conclusion

- Measurement of unpolarized cross section of Z^0 in 500/510 GeV p+p collisions, using 2011-2013 and 2017 STAR data with the total luminosity of 700 pb^{-1}:
  - Important input to unpolarized TMDs, especially at large x
  - Access to TMD evolution on x and Q^2 together with results from other experiments

- Measurement of TSSA of Z^0 in 500/510 GeV p+p collisions, using 2017 data with the total luminosity of 340 pb^{-1}:
  - Sensitive to one of the polarized TMDs – Sivers function
  - Current STAR data cannot conclusively verify the "sign change" hypothesis (non-universality between W/Z production and SIDIS)

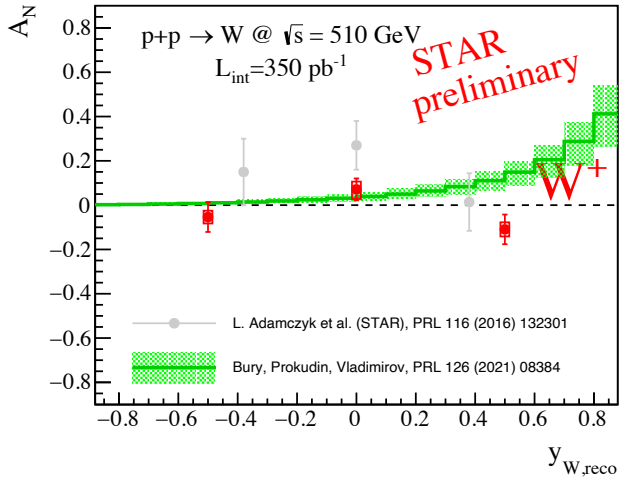
- Stay tuned for STAR 2022 data with the total luminosity of 450 pb^{-1}
  - Highest precision in combination with previous data

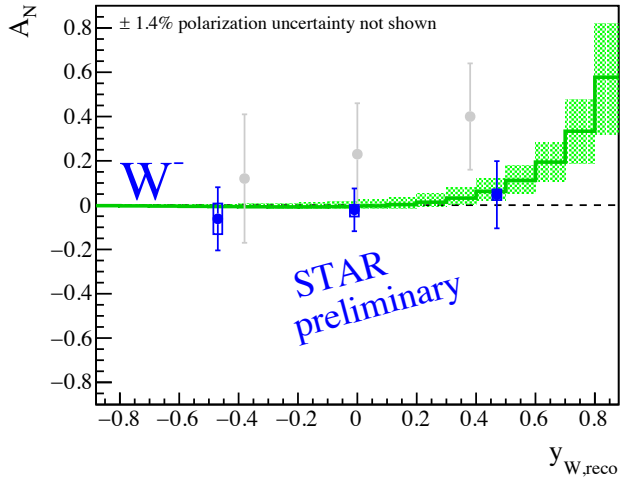
STAR also performed measurements with high precision using W boson, results can be found in the backup

Thank you for your attention!

Backup

TSSA of W

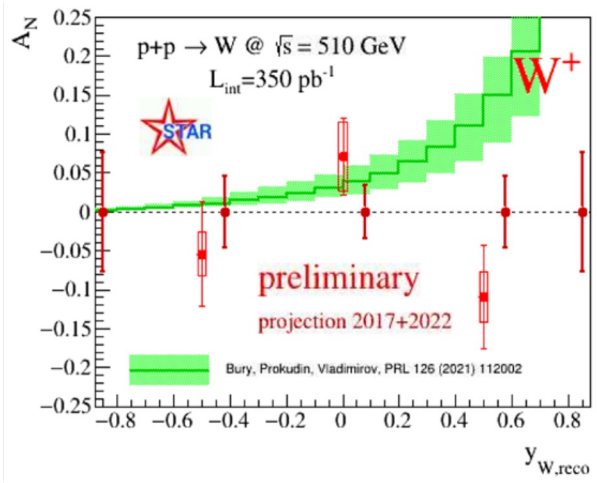


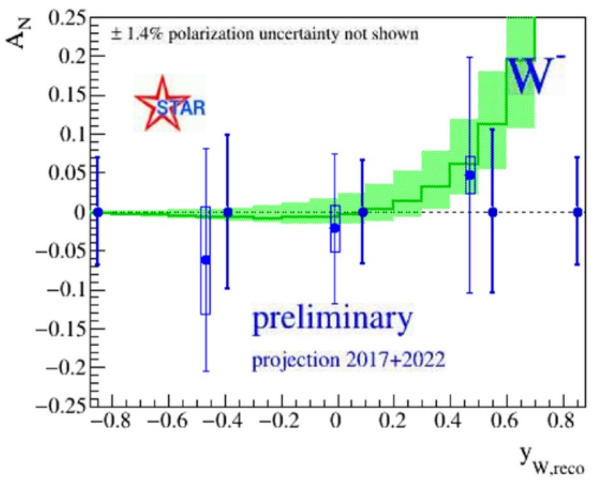


Data from run 2011 and 2017

zoom in

Data from run 2017 and projection from 2017+2022





- Improved statistic from run 2011 25 pb^{-1} to run 2017 350 pb^{-1}
- 450 pb^{-1} more data from run 2022 with Forward Upgrade and extended η coverage by STAR iTPC