

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

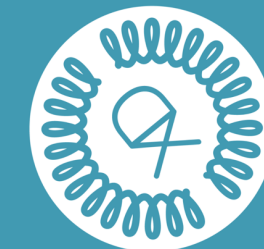
Xiaoxuan Chu (for the STAR Collaboration)
Brookhaven National Laboratory
24-30 Sep 2022



U.S. DEPARTMENT OF
ENERGY

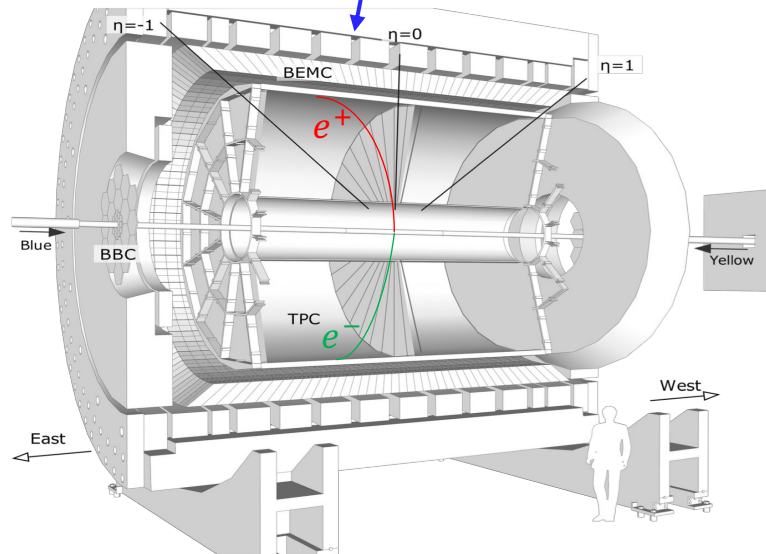
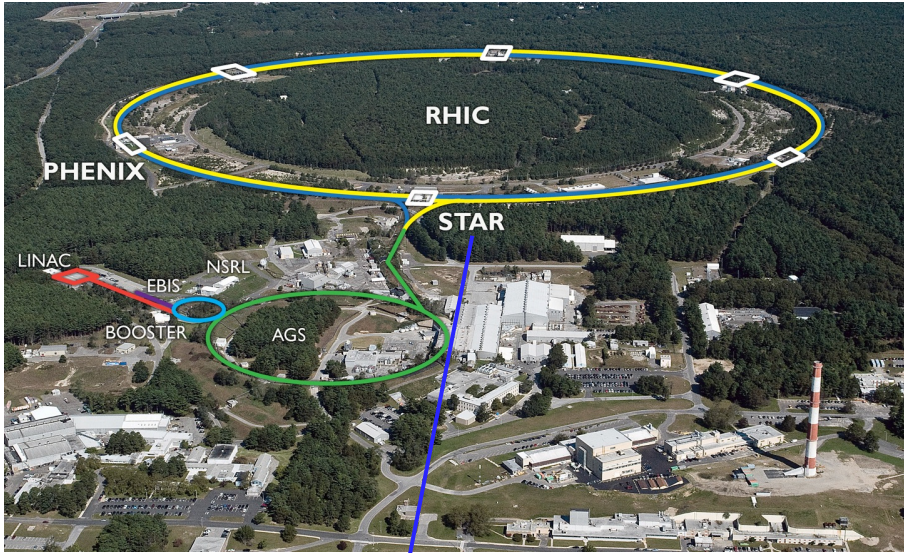
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The STAR detector at RHIC



- 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: $|\eta| < 1, 0 \leq \phi < 2\pi$
 - Tracking, PID, vertex reconstruction
- Electromagnetic Calorimeter: $-1 < \eta < 2, 0 \leq \phi < 2\pi$
 - 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

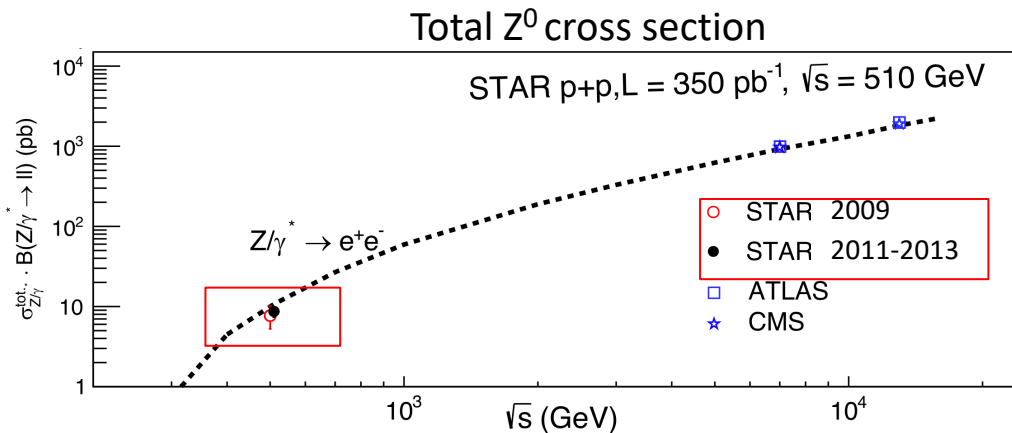


Motivation of cross section measurement

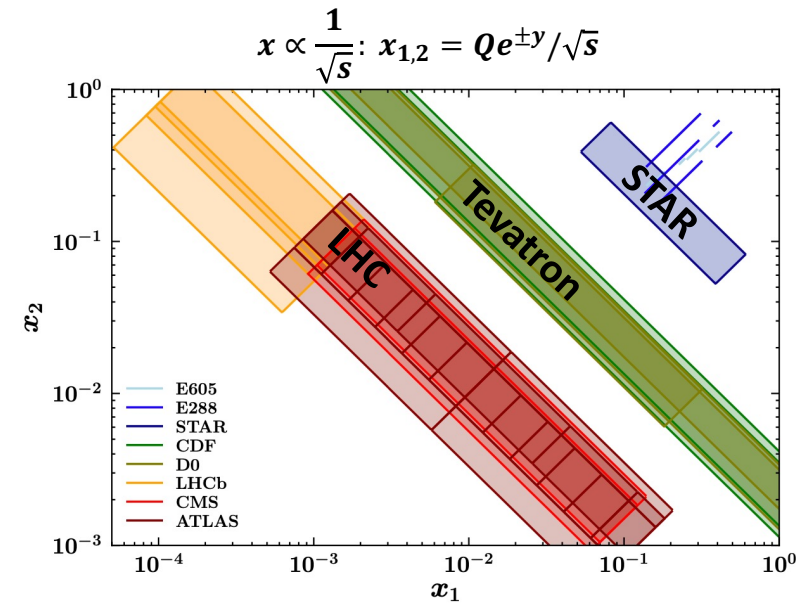
- Unpolarized cross section of Z^0 in 500/510 GeV $p+p \rightarrow Z^0+X$ is measured to extract **unpolarized TMDs***

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

- Z^0 channel: RHIC sits in an intermediate energy range
 - Complementary to the LHC and Tevatron
 - STAR data probe large x region \rightarrow 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

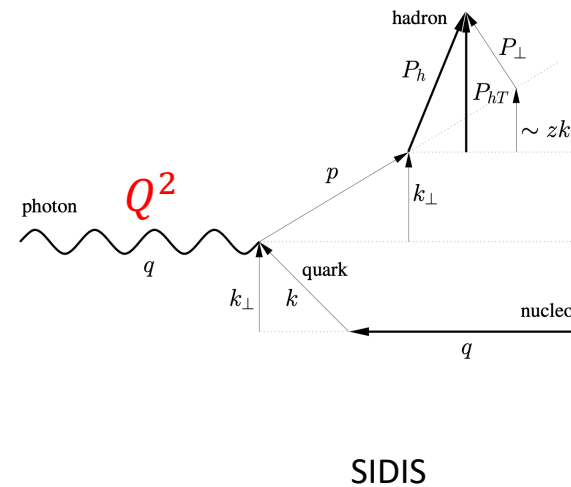
*Transverse momentum dependent parton distribution functions (TMDs): $f(x, k_{\perp}, Q^2)$



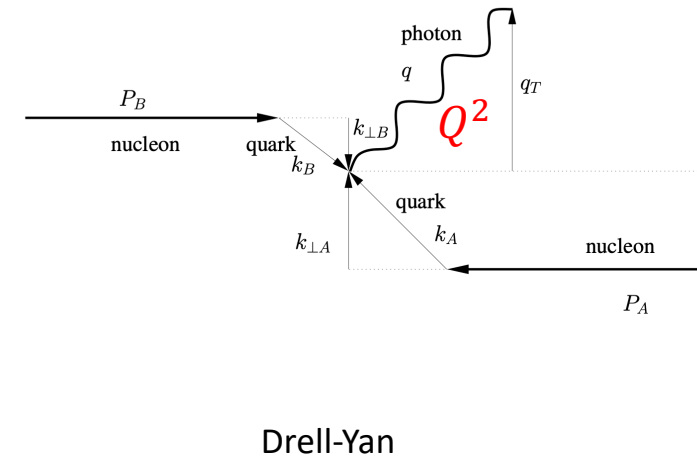
Motivation of cross section measurement

- Z^0 channel + semi-inclusive DIS (SIDIS) + Drell-Yan
 - Universality properties of TMDs
 - Different channel probes different $Q^2 \rightarrow$ 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

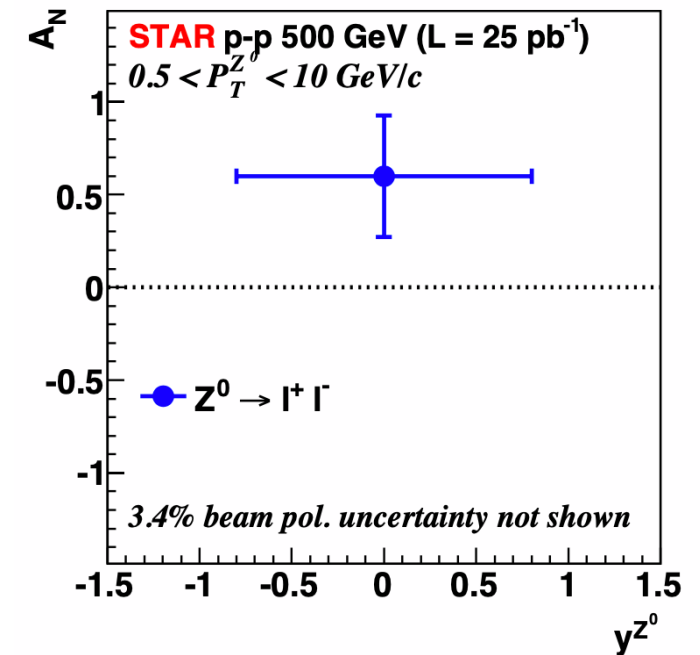
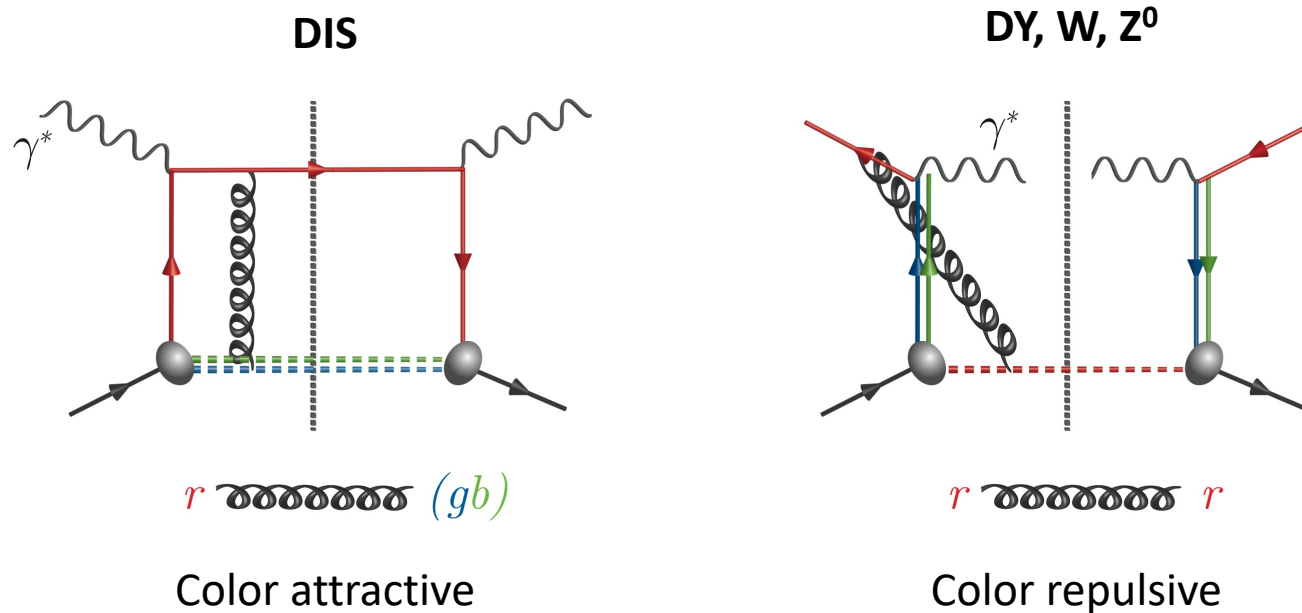


*Transverse momentum dependent parton distribution functions (TMDs): $f(x, k_\perp, Q^2)$



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 $p+p \rightarrow W/Z+X$ to SIDIS
 - Limited statistics for STAR 2011 data to provide definitive test on the “sign change” hypothesis

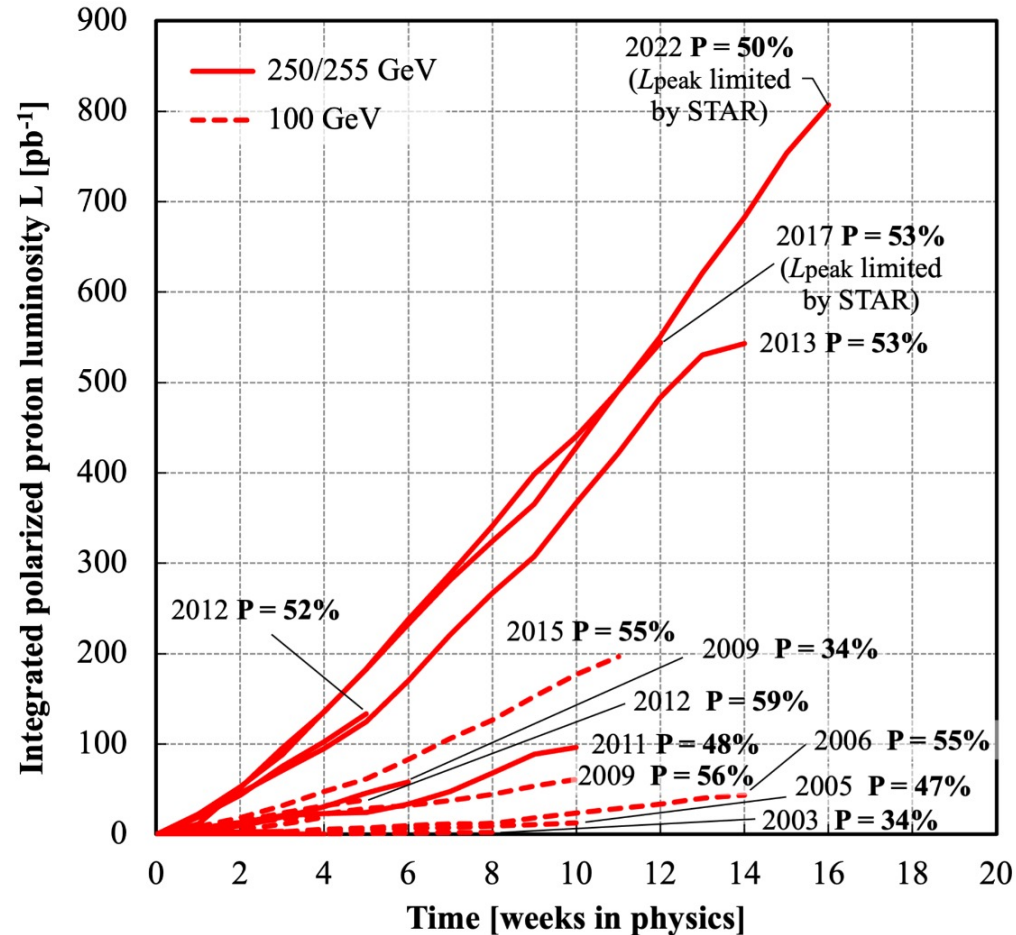


STAR 2011: PRL 116 (2016) 132301



RHIC p+p data collection overview

Delivered Luminosity



Sampled Luminosity

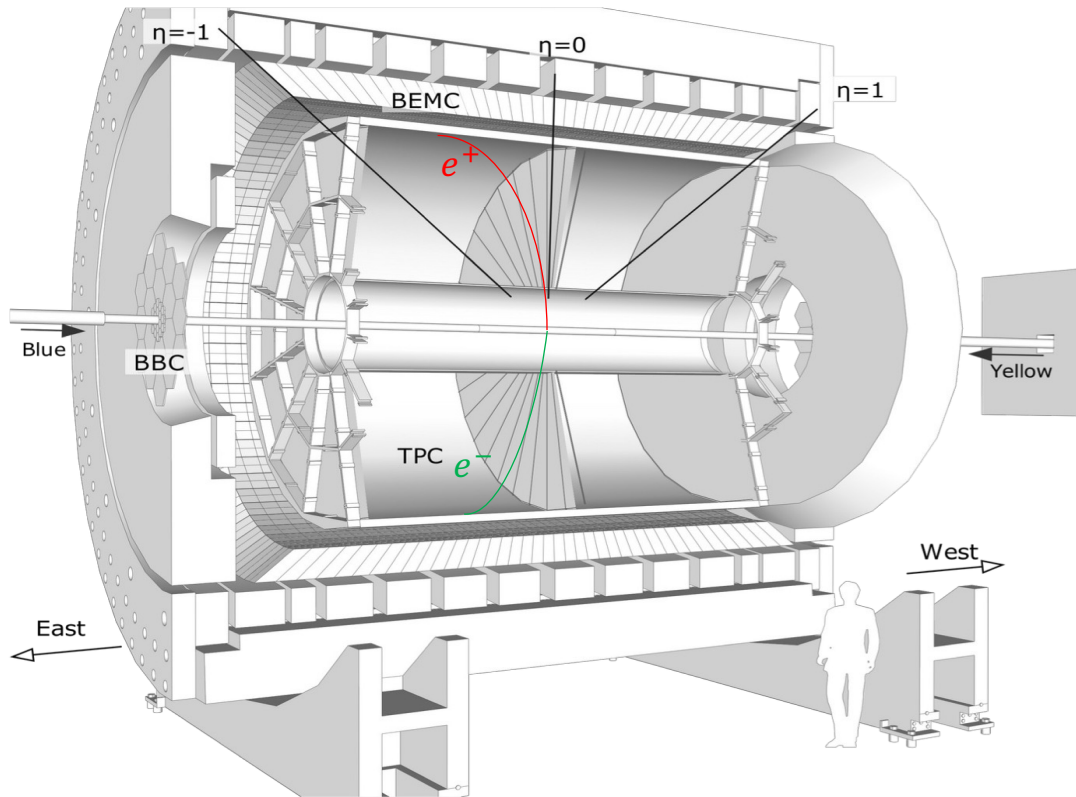
Year	\sqrt{s} (GeV)	L (pb^{-1})	Results of Z^0
2009	500	10	Total cross section: STAR, PRD 85 (2011) 092010
2011	500	25	TSSA: STAR 2011, PRL 116 (2016) 132301
2012	510	75	Total cross section: STAR 2011-2013, PRD 103 (2021) 012001
2013	510	250	Cross section on p_T : preliminary
2017	510	340	Cross section 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 \rightarrow ~ 14 times statistics of 2011 data
- Recently completed data taking for 2022 \rightarrow last 508 GeV p+p data at STAR for Z^0 analysis



Z^0 reconstruction with STAR detector

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



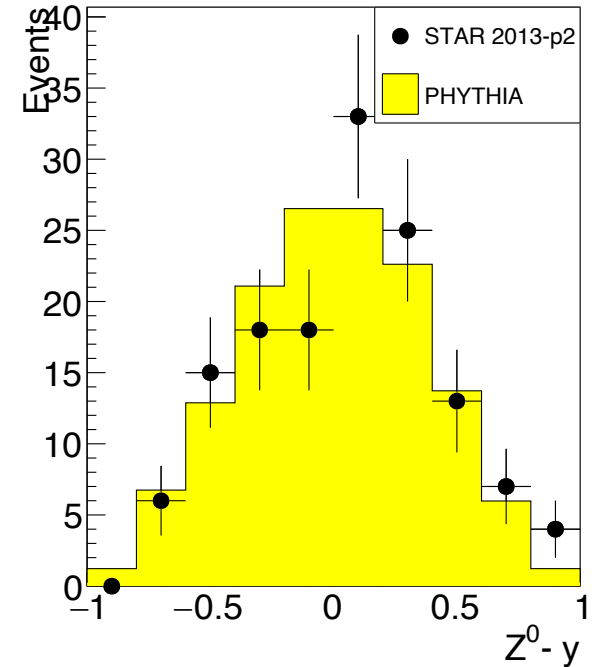
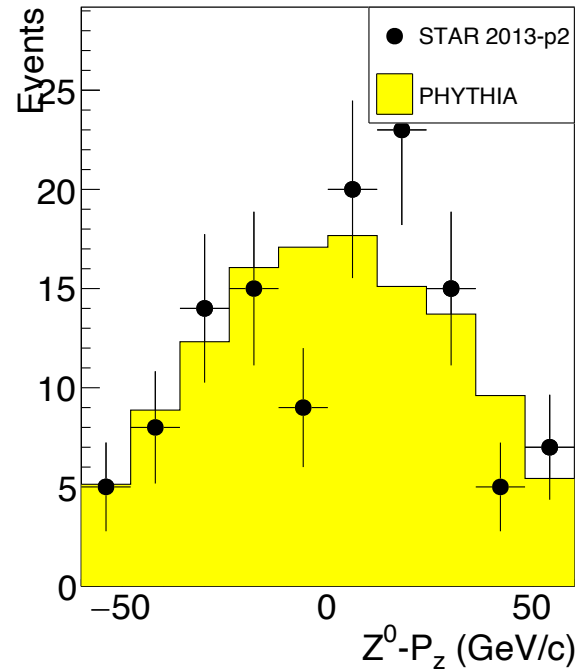
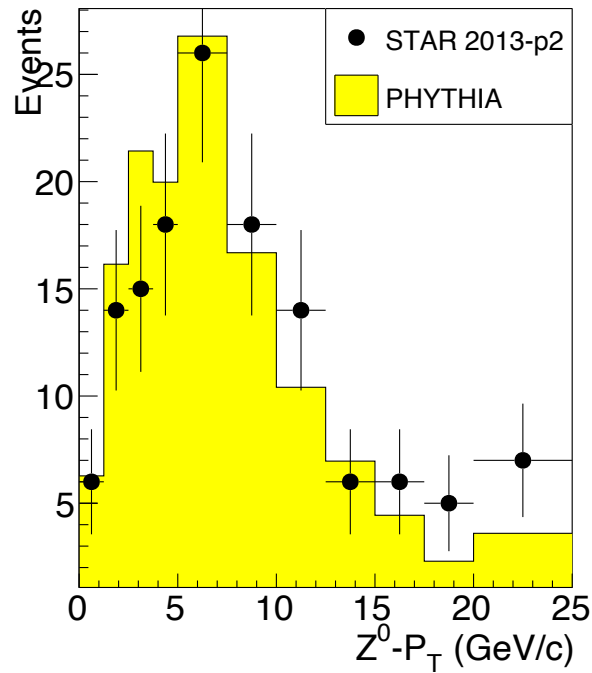
- **Main subsystems used from STAR detector**
 - Time Projection Chamber: $|\eta| < 1, 0 \leq \phi < 2\pi$
 - Lepton's charge, momentum
 - Barrel Electromagnetic Calorimeter: $|\eta| < 1, 0 \leq \phi < 2\pi$
 - Energy measurement
- **Cuts:** STAR 2011 analysis, PRL 116,132301 (2016)
 - Two high- p_T leptons: lepton $p_T^{\text{lep}} > 25 \text{ GeV}/c$
 - Two leptons must have opposite charge
 - Invariant mass of two leptons within: $73 - 114 \text{ GeV}/c^2$
- 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

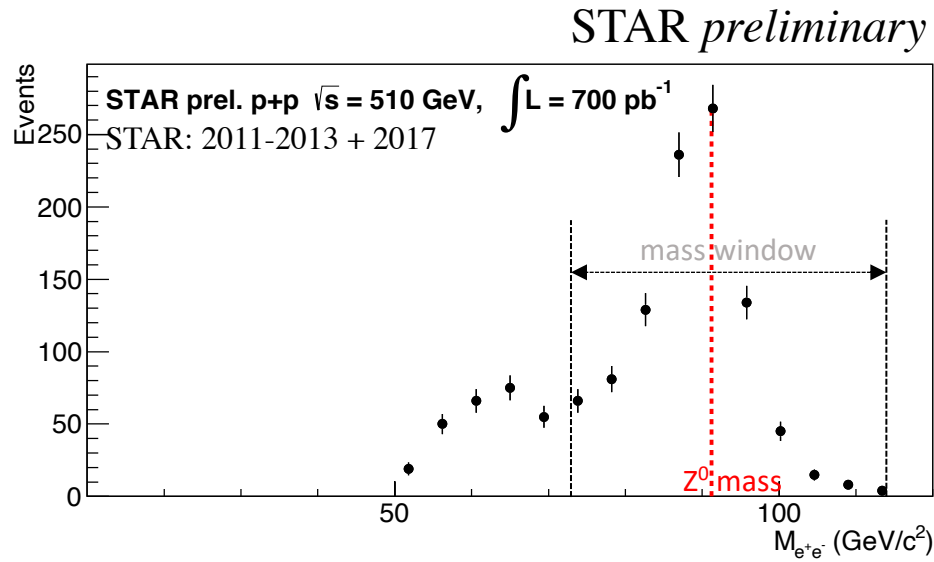
Example of data and MC comparison for the second period of 2013 data



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



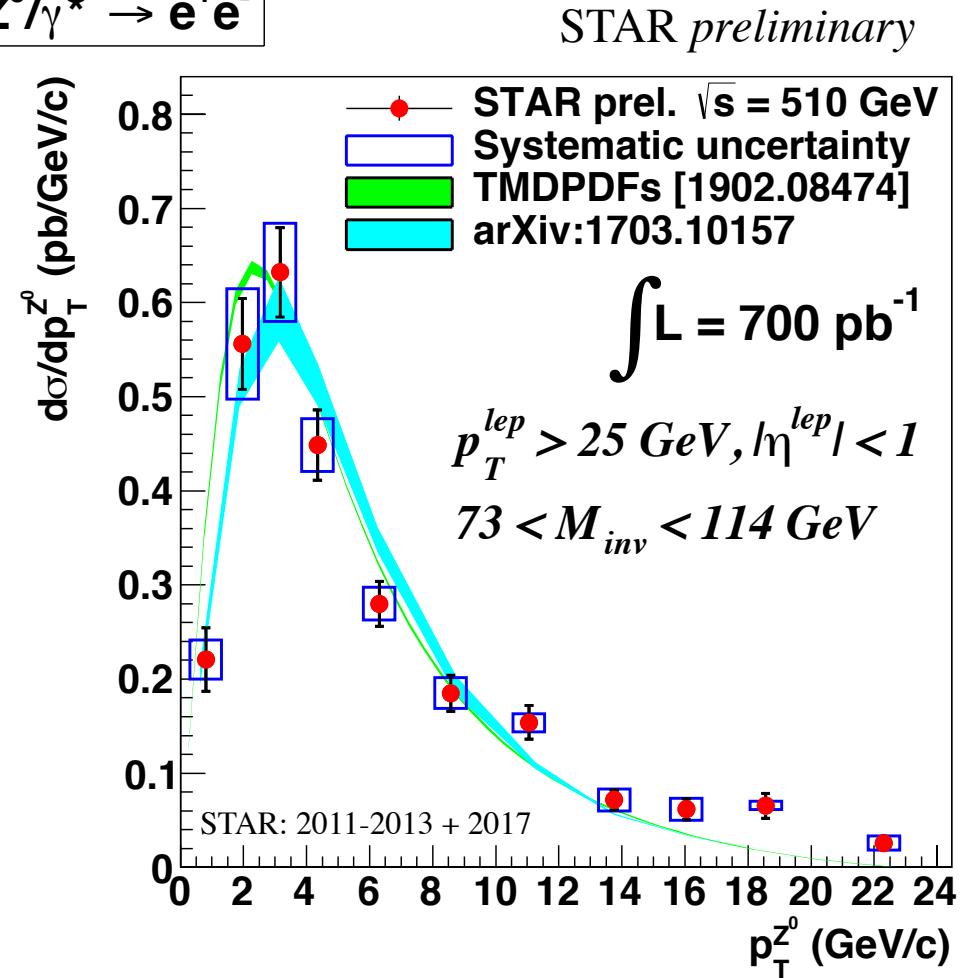
Preliminary unpolarized Z^0 results



$Z^0 p_T$ 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

$Z^0/\gamma^* \rightarrow e^+e^-$

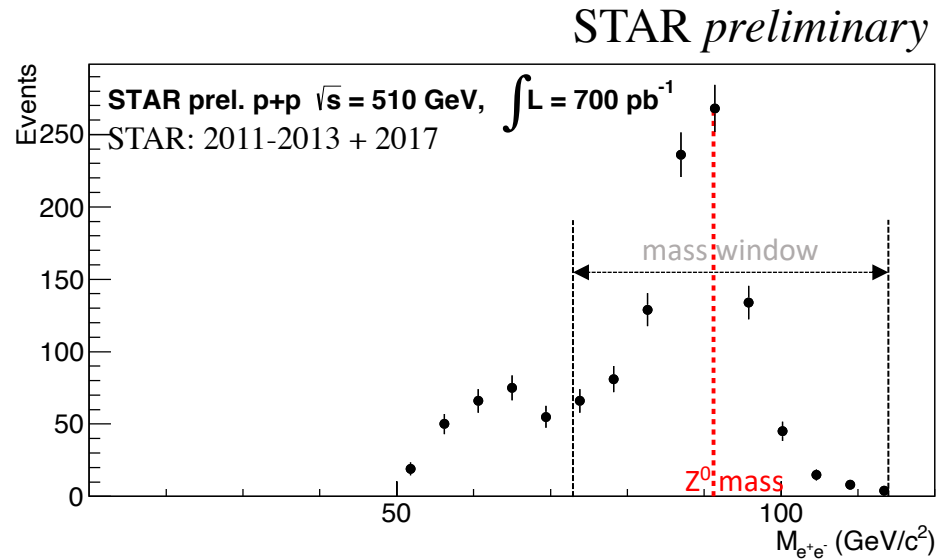


1902.08474: V. Bertone et al., JHEP06 (2019) 028

1703.10157: A. Bacchetta et al., JHEP06 (2017) 081

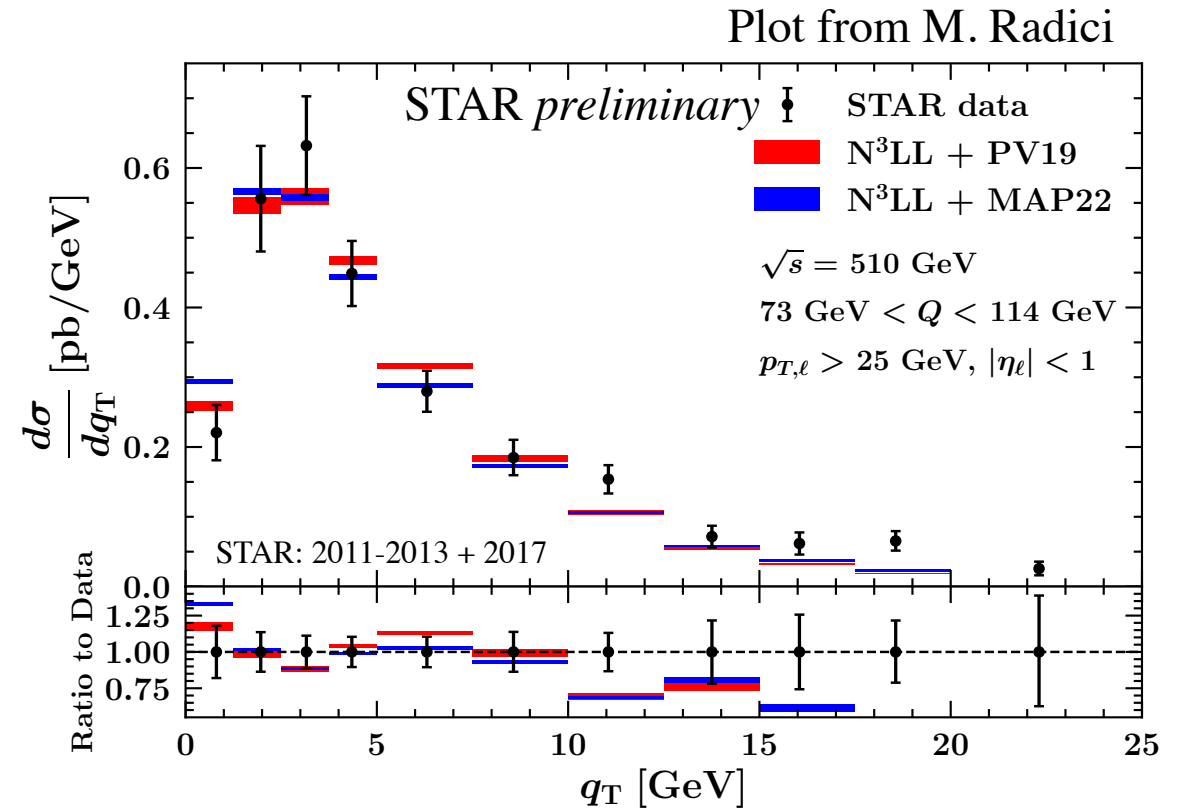


More calculations on p_T spectrum



Z^0 p_T spectrum:

- systematics evaluated by varying p_T^{lep} and energy resolution
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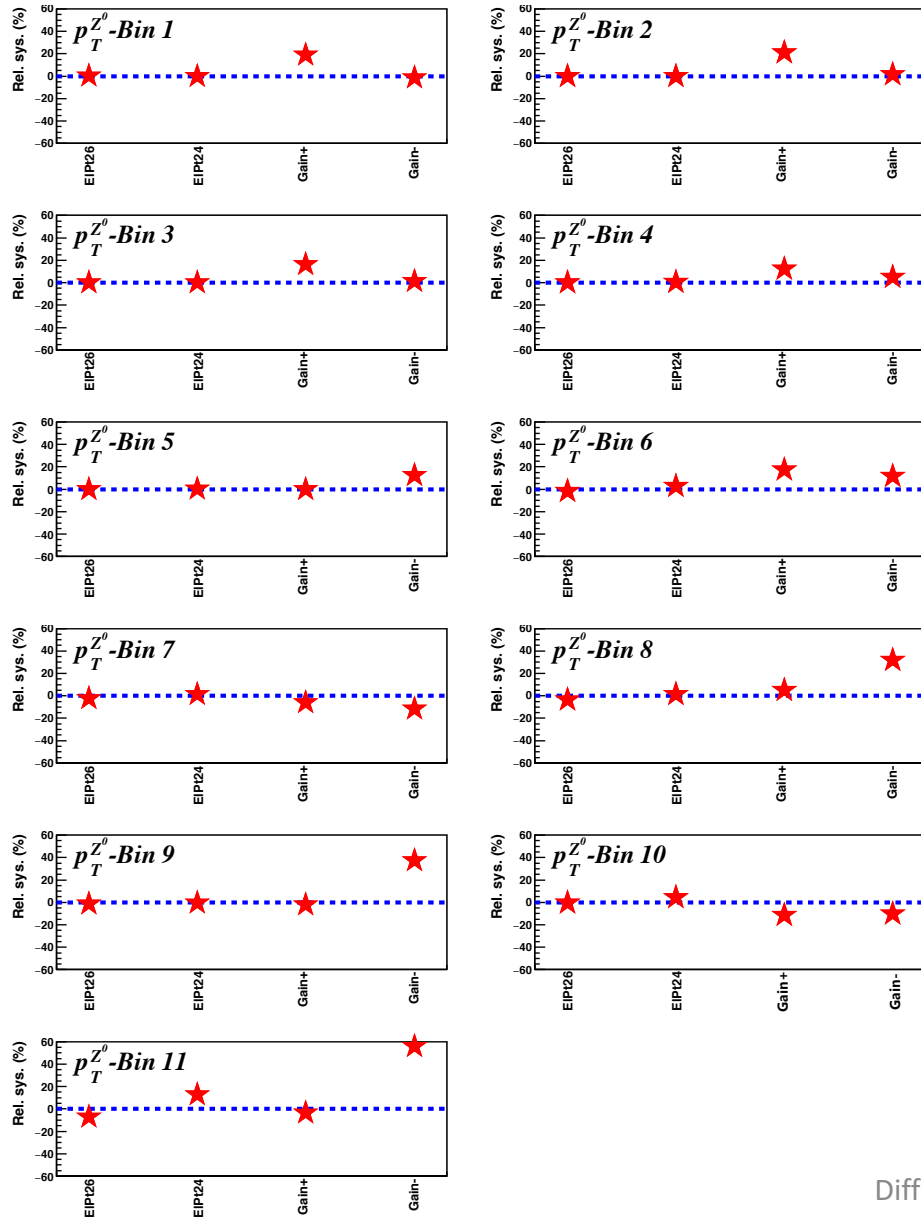


More calculations:

$N^3\text{LL} + \text{PV19}$: A. Bacchetta et al., JHEP07 (2020) 117, DY data
 $N^3\text{LL} + \text{MAP22}$: A. Bacchetta et al., 2206.07598, DY+SIDIS data



Systematic uncertainties



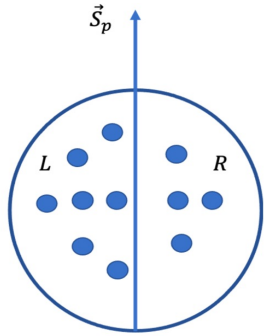
Source for systematic uncertainty bin by bin in p_T (11 p_T bins)

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

Systematic uncertainties dominated by energy resolution

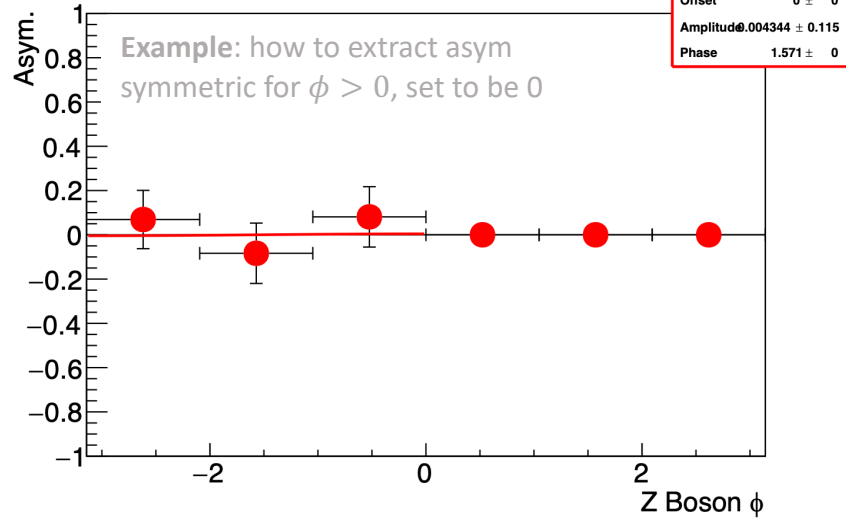


Preliminary Z⁰ TSSA results



Left-right asymmetry

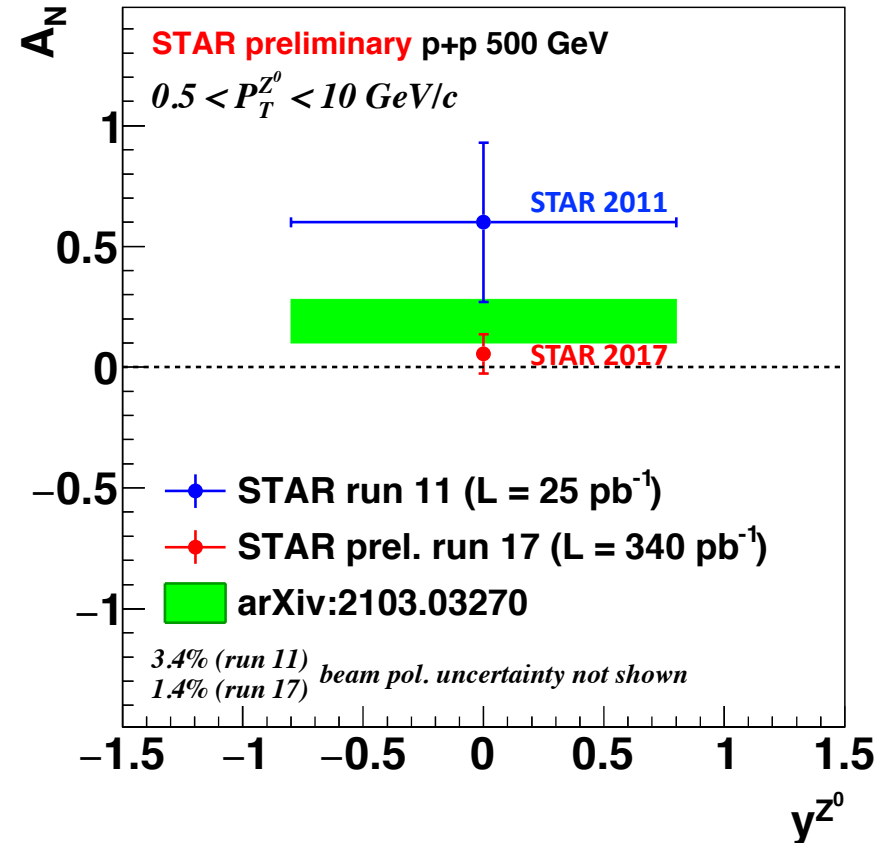
$$Asym^* = \frac{1}{P} \frac{\sqrt{N_R^\uparrow N_L^\downarrow} - \sqrt{N_L^\uparrow N_R^\downarrow}}{\sqrt{N_R^\uparrow N_L^\downarrow} + \sqrt{N_L^\uparrow N_R^\downarrow}}$$



Azimuthal modulations:
Sine function fit $\rightarrow p_1 \times \sin(\phi + p_2)$

- * $\uparrow \downarrow$: spin up or down; P: polarization fraction
- * L,R: left or right with respect to spin direction

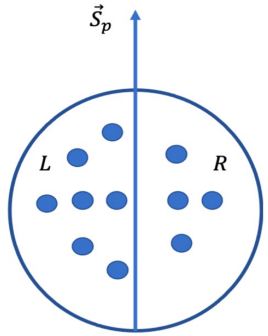
Measured TSSA of Z⁰



Much more statistics in 2017 than 2011
2103.03270: M. Bury et al., JHEP05 (2021) 151

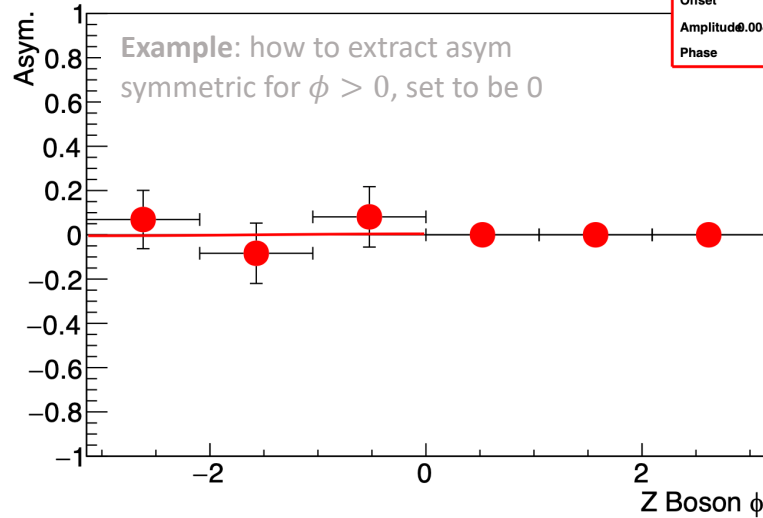


Preliminary Z^0 TSSA results



Left-right asymmetry

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

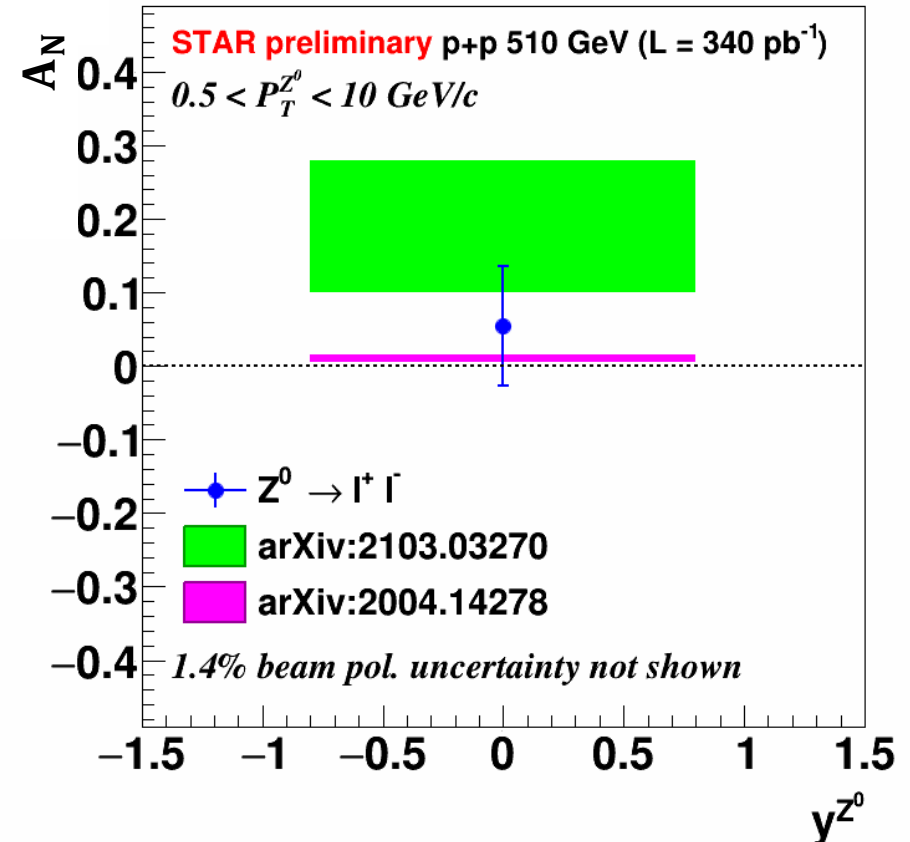


Example: how to extract asym
symmetric for $\phi > 0$, set to be 0

Azimuthal modulations:
Sine function fit $\rightarrow p_1 \times \sin(\phi + p_2)$

- * $\uparrow \downarrow$: spin up or down; P: polarization fraction
- * L,R: left or right with respect to spin direction

Measured TSSA of Z^0



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

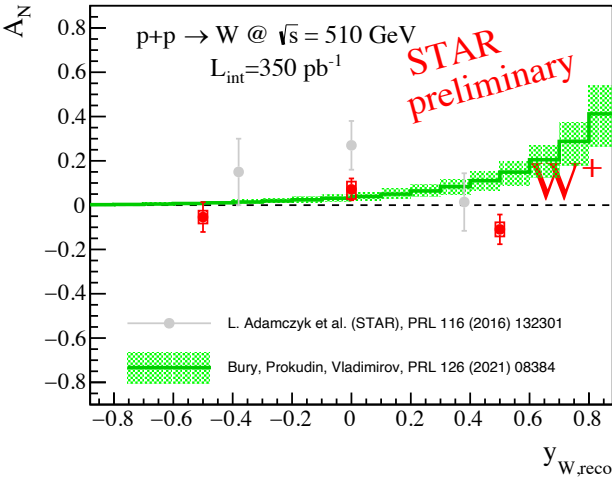
STAR also performed measurements with high precision using W boson, results can be found in the backup

Thank you for your attention!

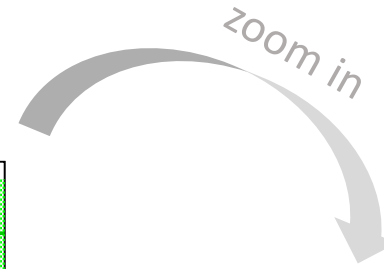
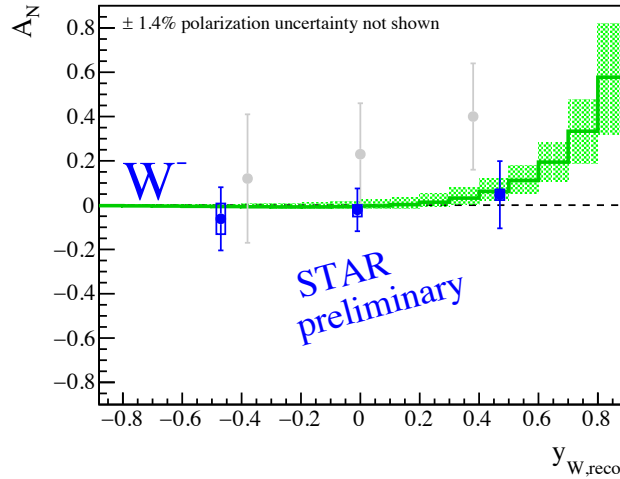


Backup

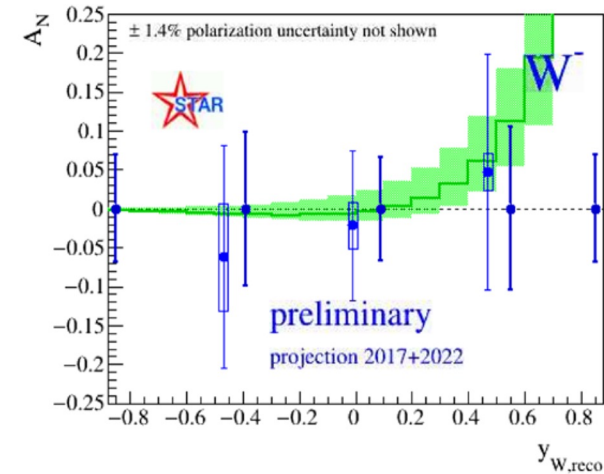
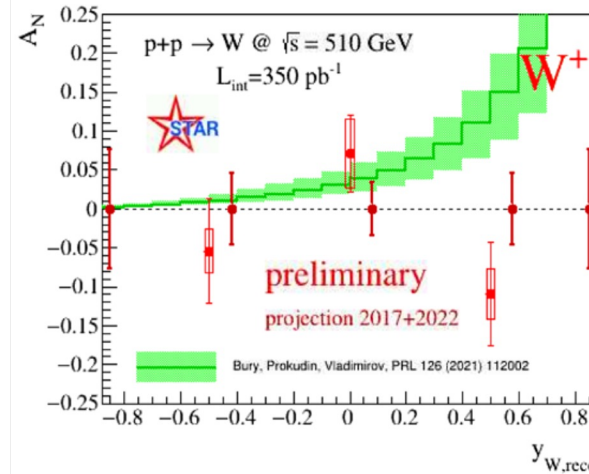
TSSA of W



Data from run 2011 and 2017



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