

Recent results from the STAR cold QCD program

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For the STAR collaboration
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Polarized proton beam with $\sqrt{s} = 200$ and $500/510$ GeV

- Longitudinal
 - Jets & $\pi \rightarrow$ Gluon polarization
 - W & $Z \rightarrow \Delta\bar{d}$ and $\Delta\bar{u}$
- Transverse
 - W & Z , EM-jet \rightarrow Sivers effect
 - π^0 in pp, pAl and pAu \rightarrow Nuclear dependence of A_N
 - π^\pm in jet \rightarrow Collins effect
 - $\pi^+ \pi^-$ pair \rightarrow Interference FF
- Unpolarized
 - W & $Z \rightarrow \bar{d}$ and \bar{u}
 - Di- $\pi^0 \rightarrow$ Gluon saturation

PROSPECTS FOR SPIN PHYSICS AT RHIC

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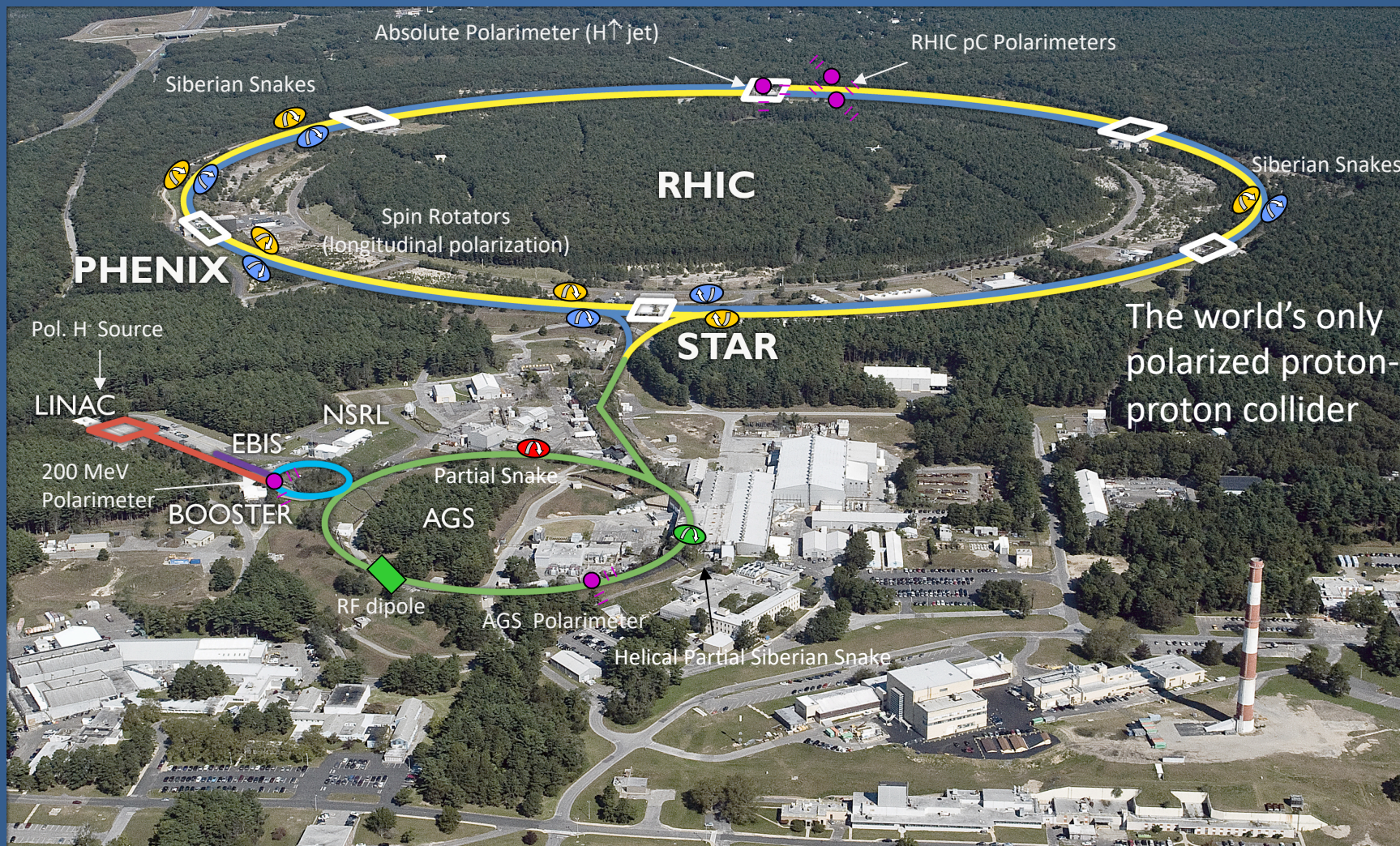
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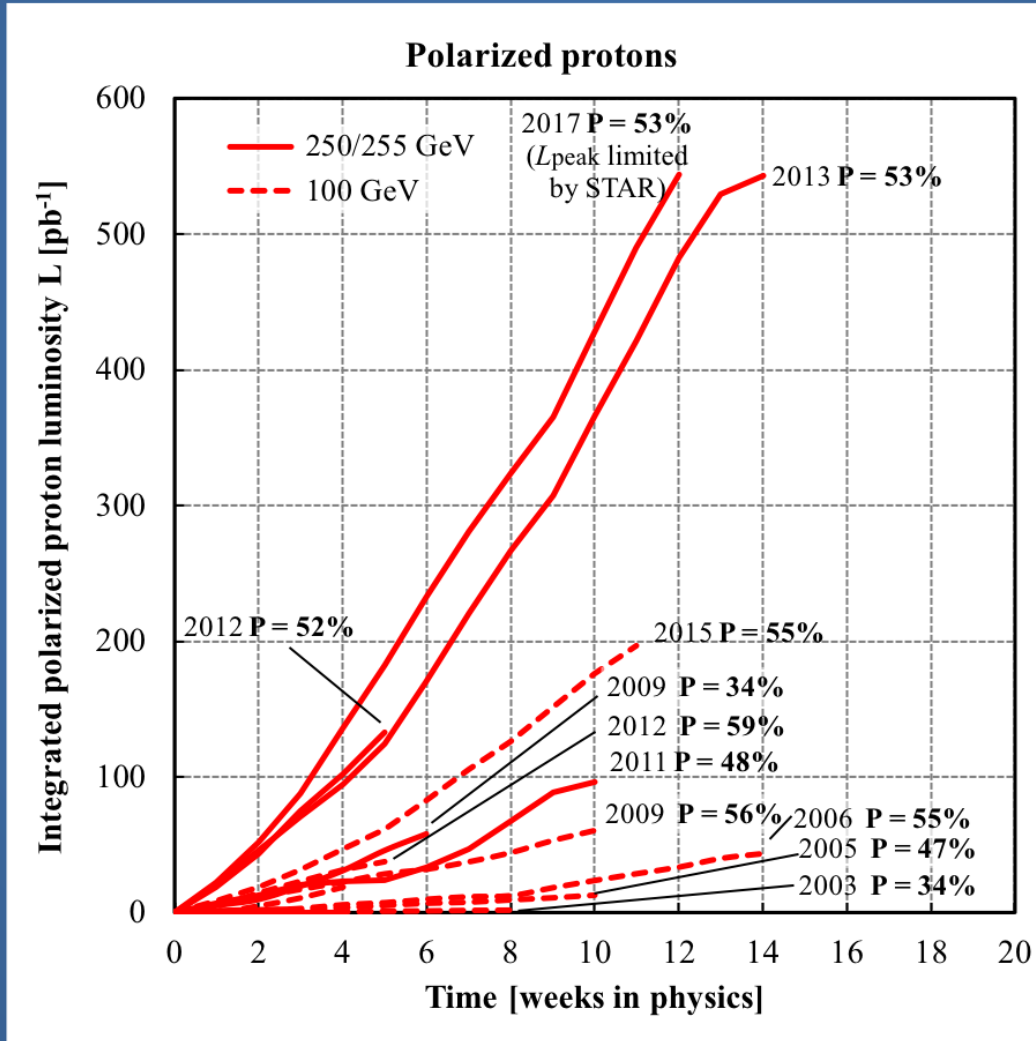
Key Words proton spin structure, spin asymmetries, quantum chromodynamics, beyond the standard model

■ **Abstract** Colliding beams of 70% polarized protons at up to $\sqrt{s} = 500$ GeV, with high luminosity, $L = 2 \times 10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$, will represent a new and unique laboratory for studying the proton. RHIC-Spin will be the first polarized-proton collider and will be capable of copious production of jets, directly produced photons, and W and Z bosons. Features will include direct and precise measurements of the polarization of the gluons and of \bar{u} , \bar{d} , u , and d quarks in a polarized proton. Parity violation searches for physics beyond the standard model will be competitive with unpolarized searches at the Fermilab Tevatron. Transverse spin will explore transversity for the first time, as well as quark-gluon correlations in the proton. Spin dependence of the total cross section and in the Coulomb nuclear interference region will be measured at collider energies for the first time. These qualitatively new measurements can be expected to deepen our understanding of the structure of matter and of the strong interaction.

Relativistic Heavy Ion Collider



Polarized proton runs at RHIC



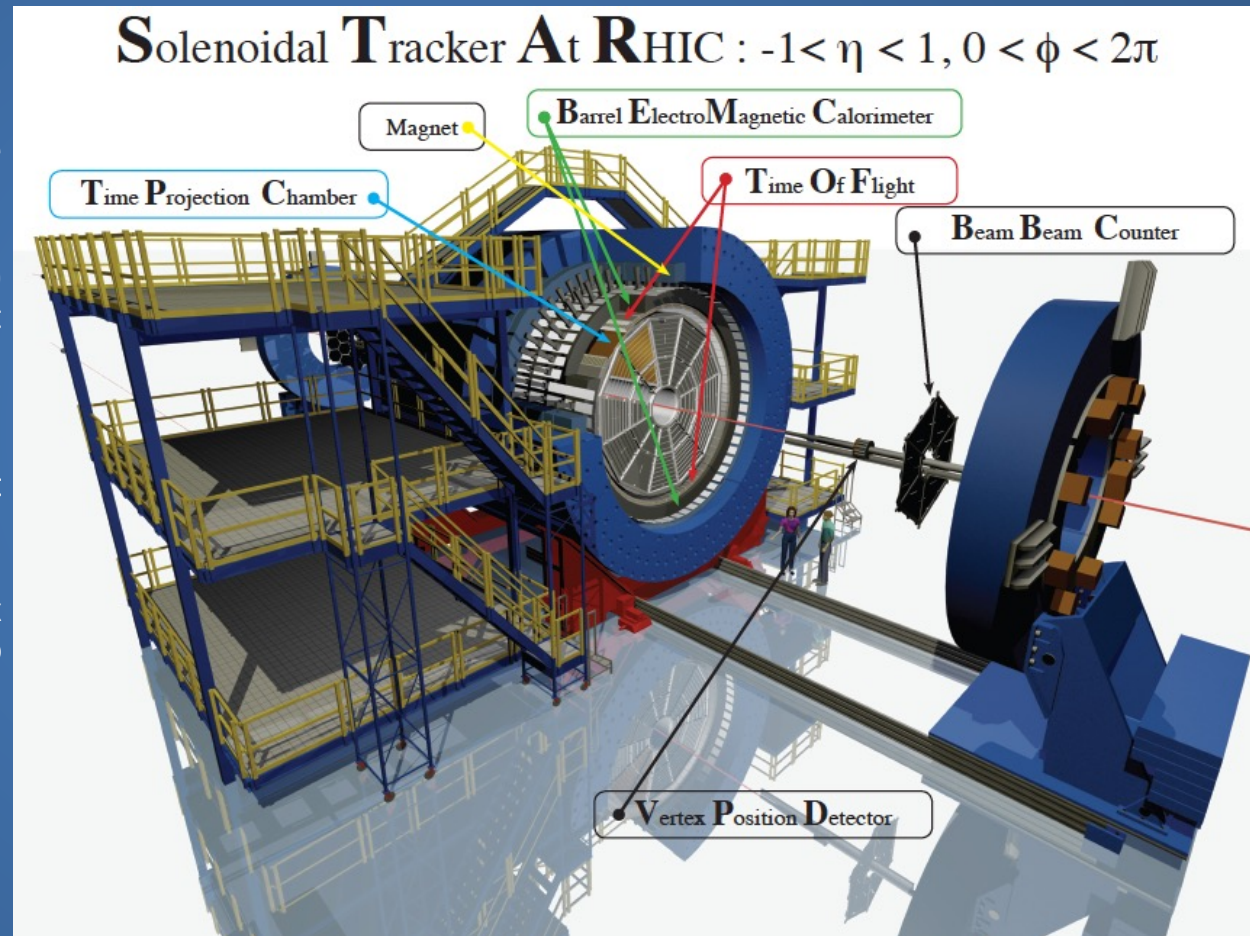
STAR detector

The main tracking device is a Time Projection Chamber (TPC) at $|\eta| \leq 1$.

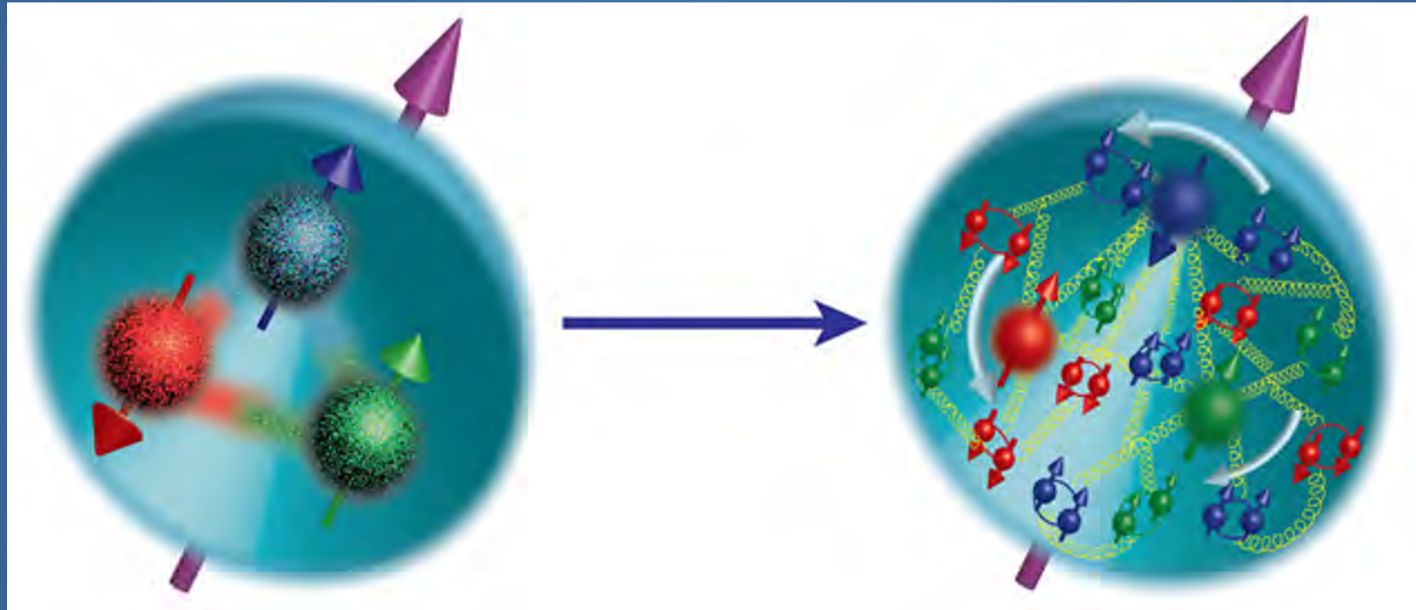
Electromagnetic calorimeters ($-1 \leq \eta \leq 2$) are used to trigger high momentum jet via EM energy deposit.

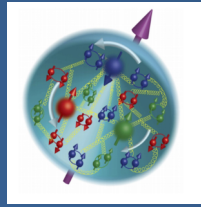
Forward Meson Spectrometer (FMS) is a lead-glass EM calorimeter used to detect π^0 at $2.5 \leq \eta \leq 4.2$.

Luminosity is measured with the Vertex Position Detector (VPD) and the Zero Degree Calorimeter (ZDC).

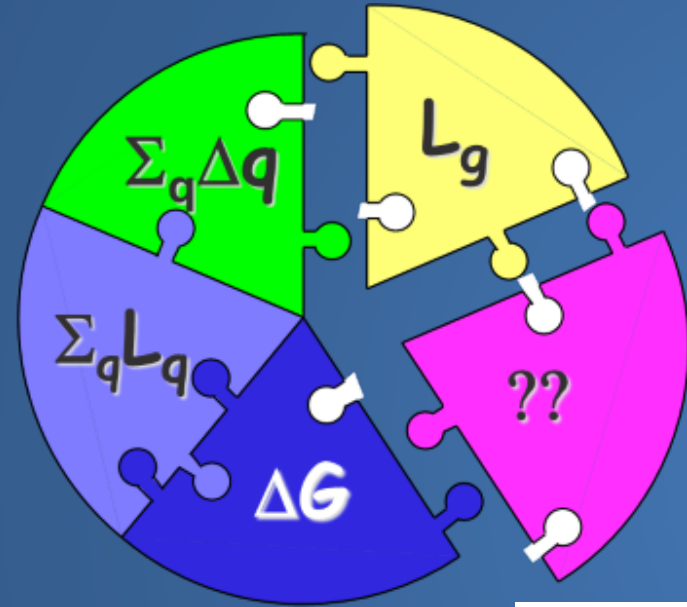


Constraining Polarized PDF





Proton Spin Puzzle



Measure the individual contributions of quarks, antiquarks and gluons, to the spin of the proton.

The proton spin sum rule (Jaffe-Manohar 1990):

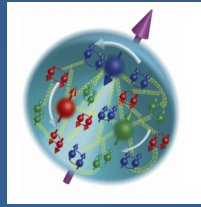
$$\langle S_p \rangle = \frac{1}{2} = \frac{1}{2} \Delta\Sigma + \Delta G + L_q + L_g$$

- Polarized DIS results $\Delta\Sigma \approx 0.3$
- Flavor separation from **STAR**, *Phys. Rev. D* 99 (2019) 051102

Gluon polarization

Quark and gluon orbital angular momentum contribution

poorly constrained 7/24



Gluon helicity distribution

$$\langle S_p \rangle = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g$$

- Gluon polarization can be measured using A_{LL} of jets in proton collisions.

- Dominating processes at RHIC gg and qg scattering.



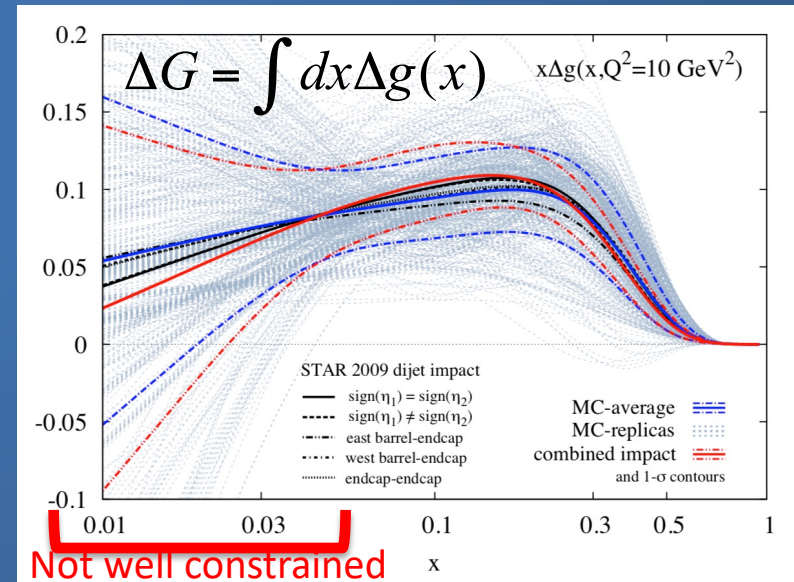
\sqrt{s}	Run	Central Jets ($ \eta < 1$)	Central Dijets ($ \eta < 1$)	Inter. Dijets ($0.8 < \eta < 1.8$)
200	2009	Published $x > 0.05$	Published $x > 0.05$	Published $x > 0.01$
200	2015	Published $x > 0.05$	Published $x > 0.05$	
510	2012	Published $x > 0.015$	Published $x > 0.015$	Preliminary $x > 0.004$
510	2013	In preparation for publication $x > 0.015$		In Progress $x > 0.004$

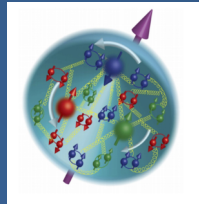
- Collection of longitudinally polarized data concluded in 2015.

- Also neutral pions A_{LL} measurement at $\sqrt{s} = 200$ & 510 GeV.

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \propto \frac{\Delta f_a \Delta f_b}{f_a f_b} \hat{a}_{LL}$$

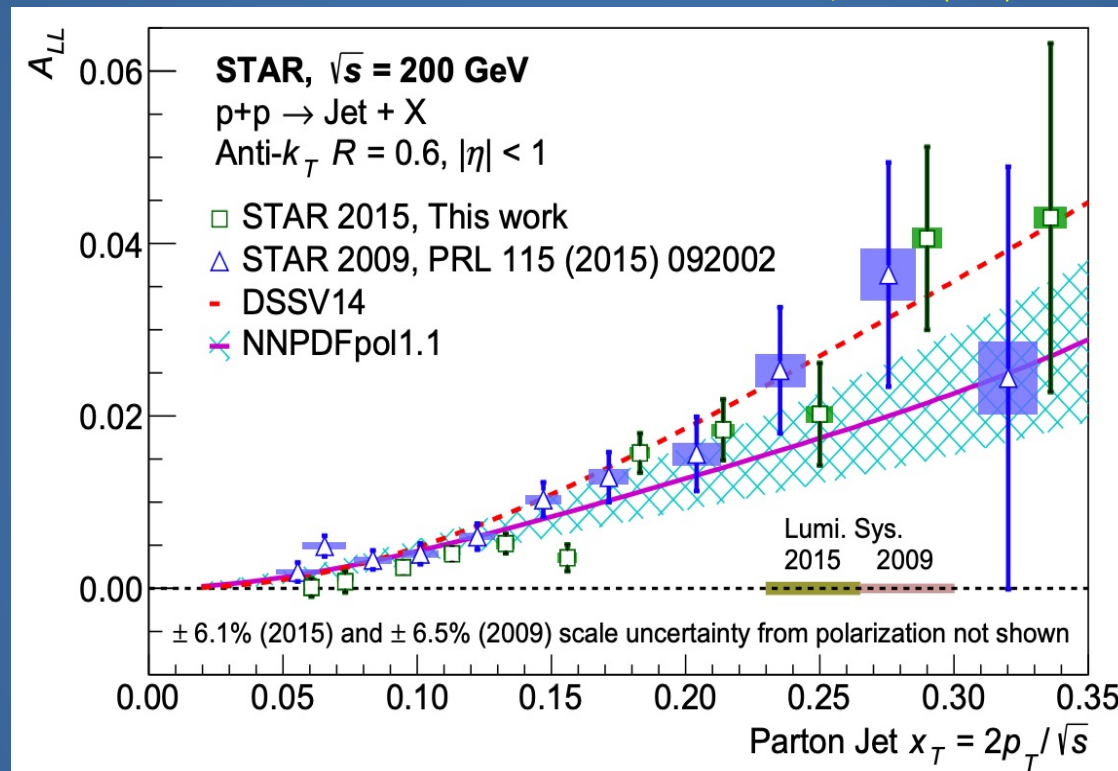
DSSV, Phys. Rev. D 11 (2019) 114027



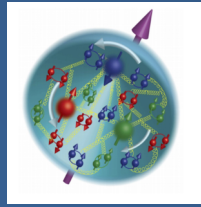


Inclusive jets

STAR, PRD 103 (2021) L091103

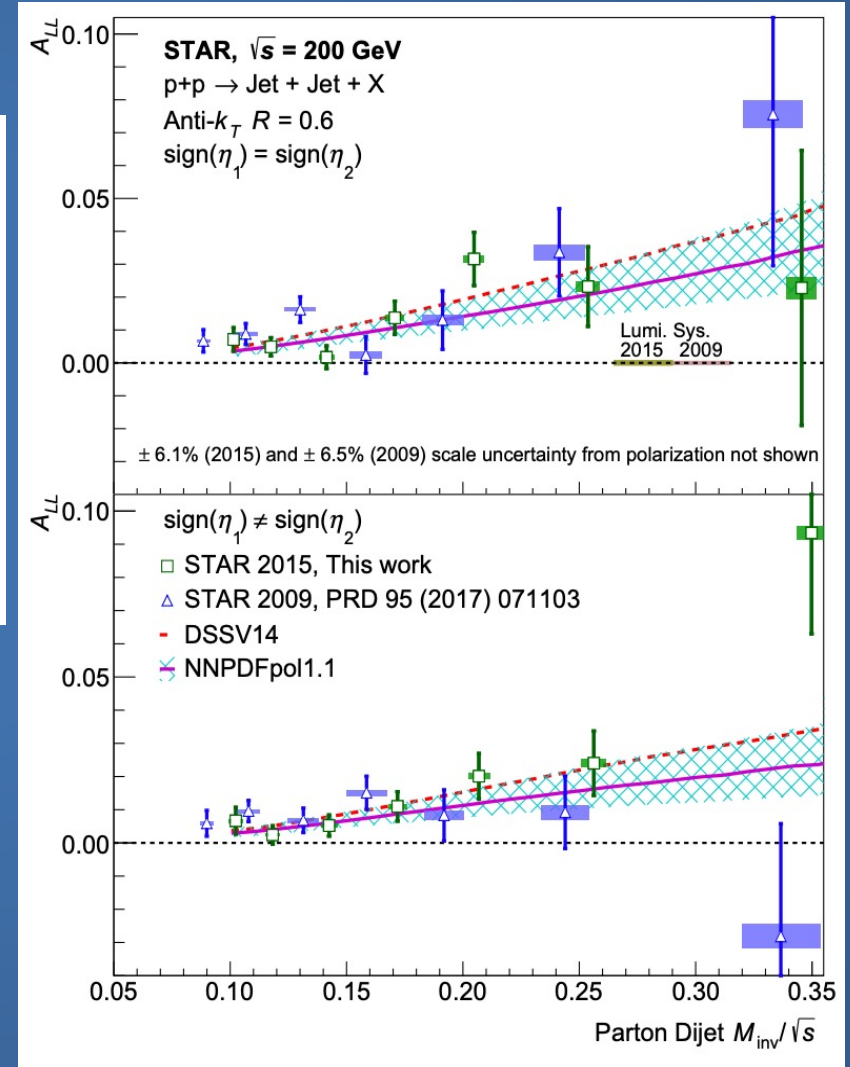
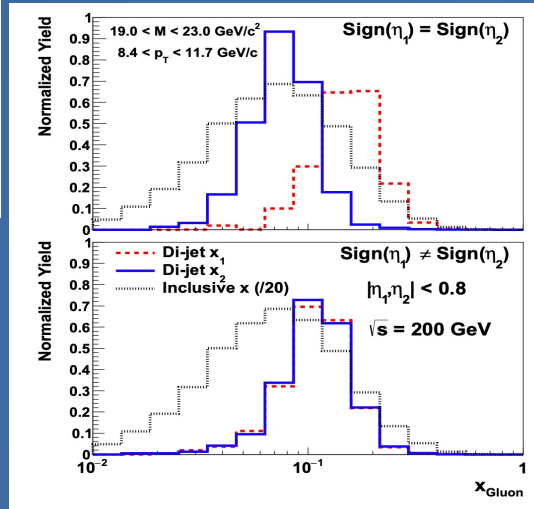
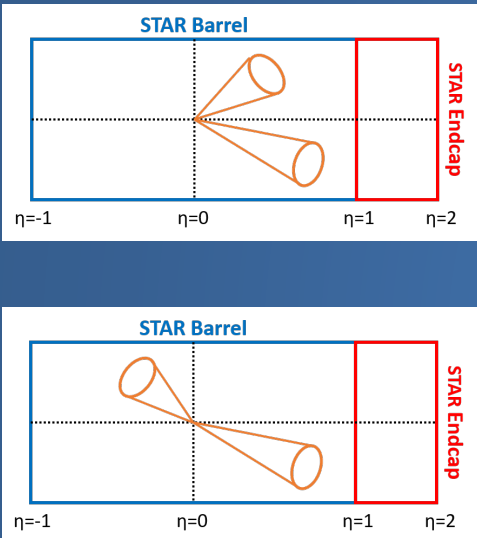


- Inclusive jet A_{LL} results from 2015 data, consistent with previous STAR result and global fits.
- Twice larger figure of merit with improved systematics.
- This result will reduce uncertainty of gluon polarization for $x > 0.05$.
- Inclusive jet at 510 GeV provides constraints for $x > 0.015$ STAR, PRD 100 (2019), 052005.



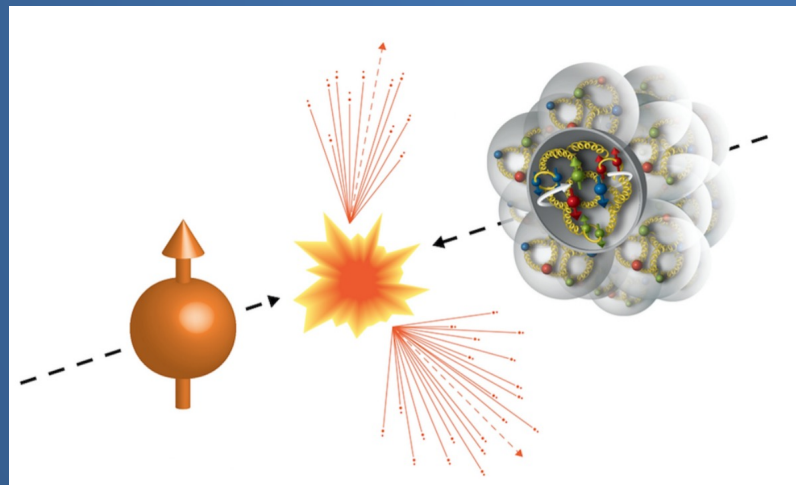
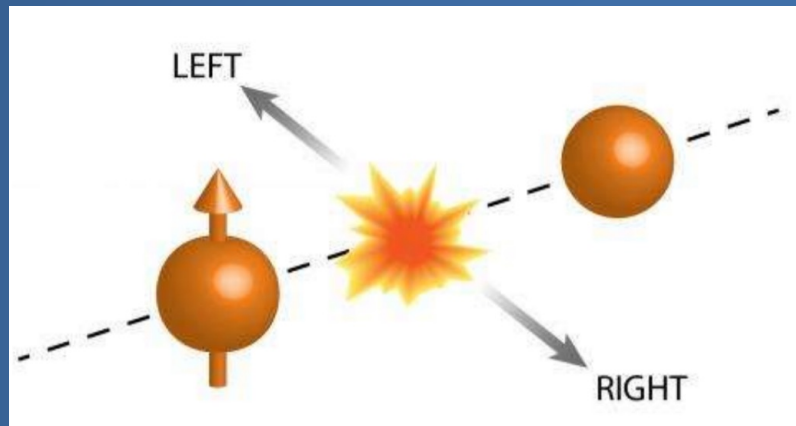
Dijets

STAR, PRD 103 (2021) L091103

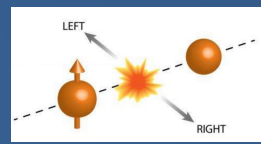


- Dijet A_{LL} results from 2015 data, consistent with previous STAR result and global fits.
- Dijet production constrains the gluon polarization in narrower x regions than inclusive jets..

Transverse Single-Spin Asymmetries (TSSA)

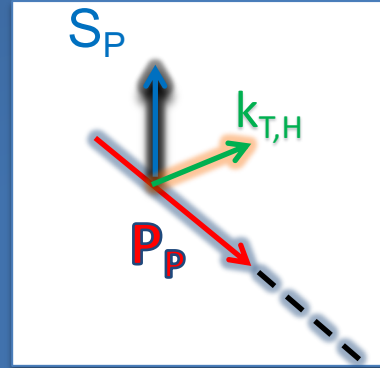


$$A_N = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

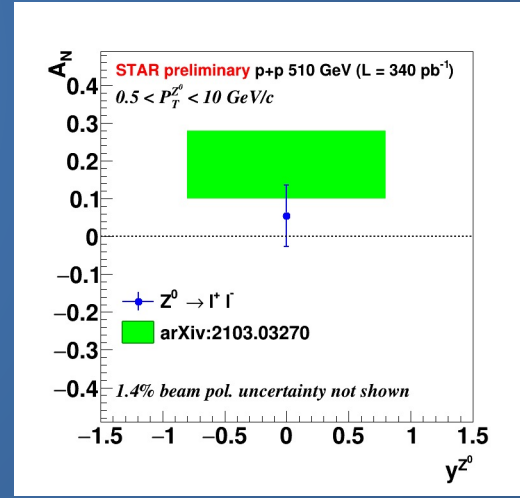
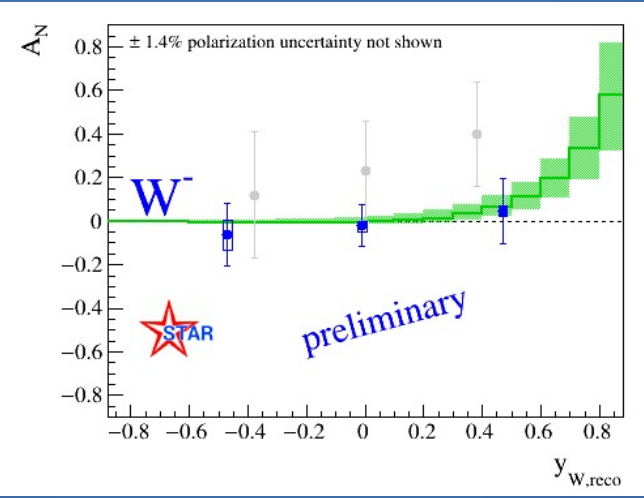
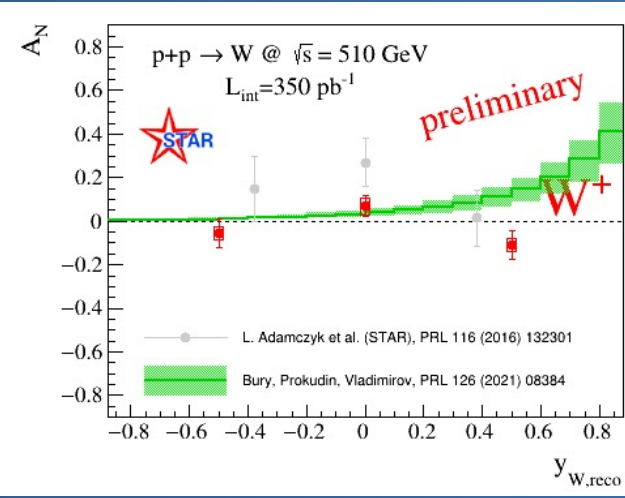


New A_N preliminary for W and Z

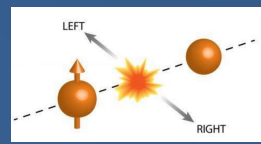
Sivers effect: correlation between transverse momentum of a parton and transverse spin of the proton.



$$\langle \vec{S}_{proton} \cdot (\vec{P}_{proton} \times \vec{k}_T) \rangle \neq 0$$

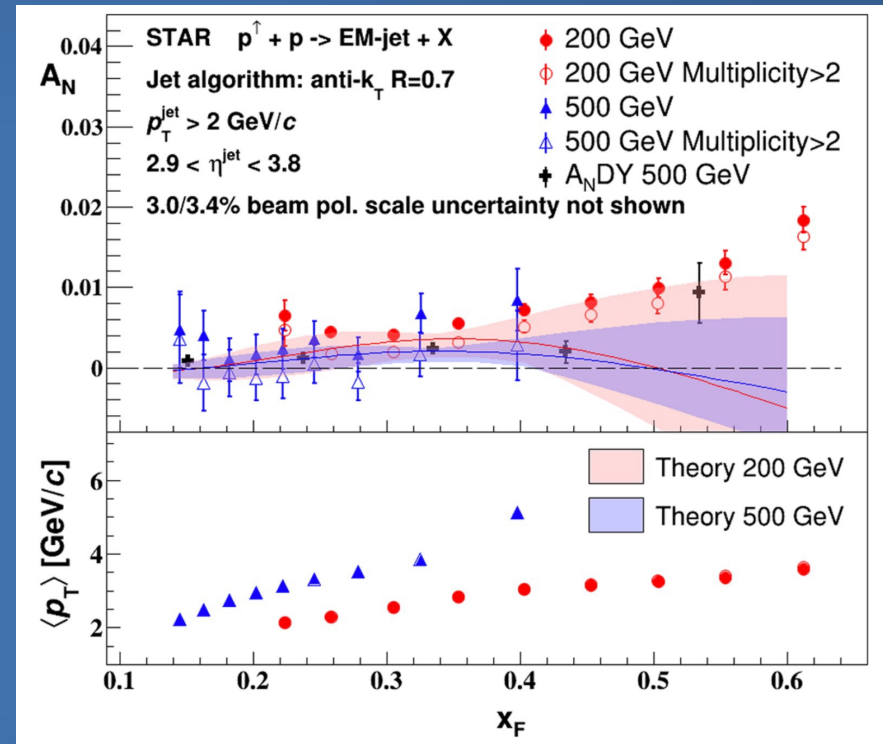
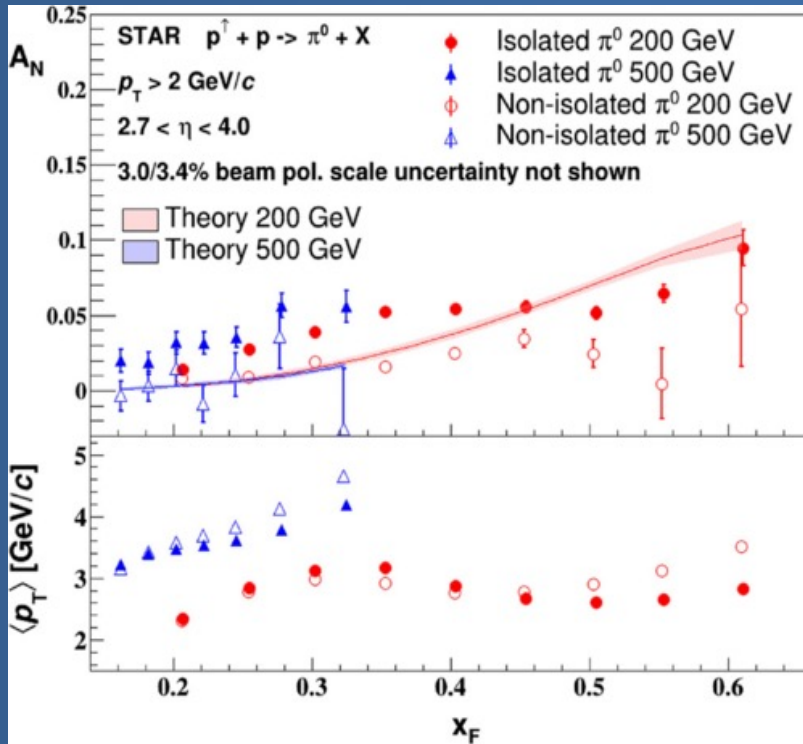


- Sensitive to Sivers sign-change and TMD evolution effects.
- New STAR preliminary results improve significantly statistical uncertainty on previous data from 2011.

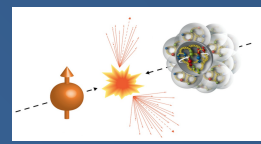


Forward A_N

STAR, Phys. Rev. D 103 (2021) 92009

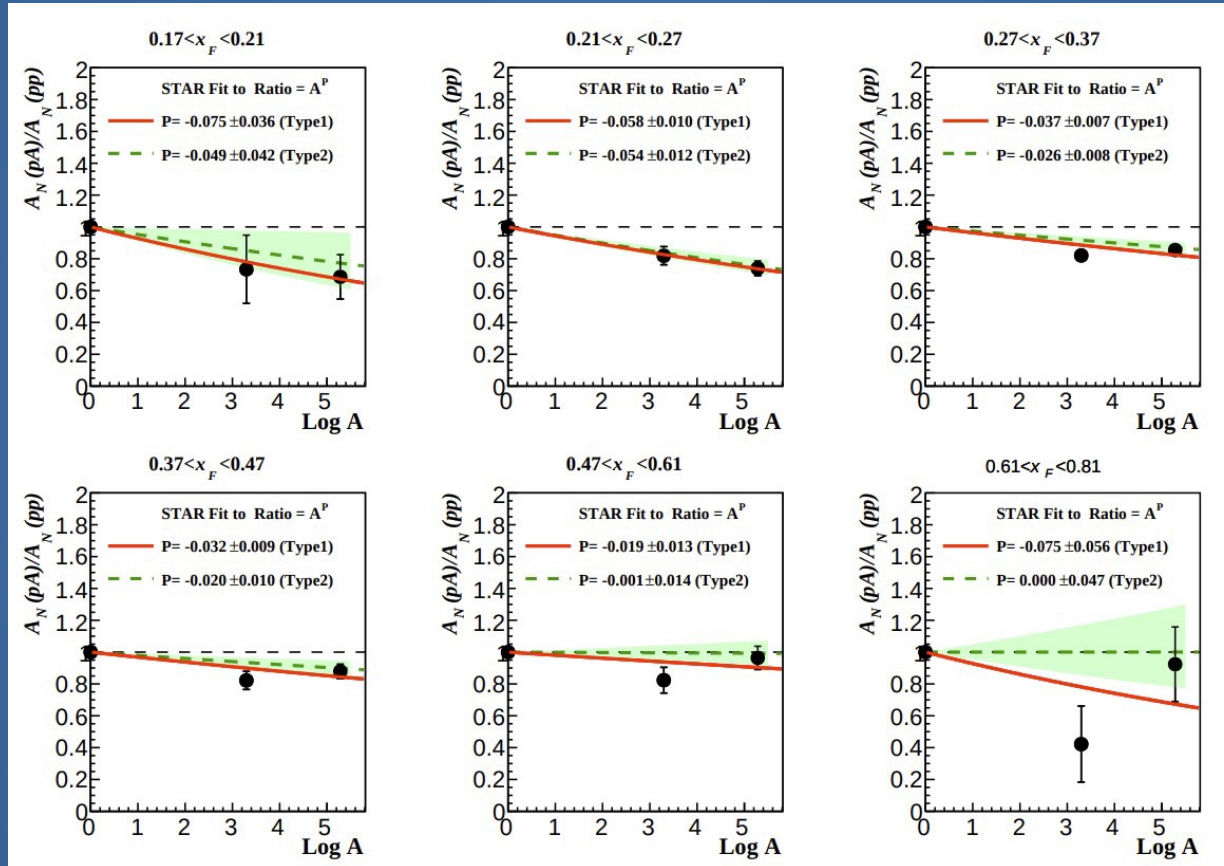


- Larger asymmetry for isolated π^0 than non-isolated π^0 .
- Forward inclusive EM-jet result shows small but non-zero signal at 200 GeV.
- Significantly reduces the uncertainty of the quark Sivers function in a recent global fit [M.Boglione et.al., PLB 815, 136135 \(2021\)](#).



Nuclear dependance of A_N

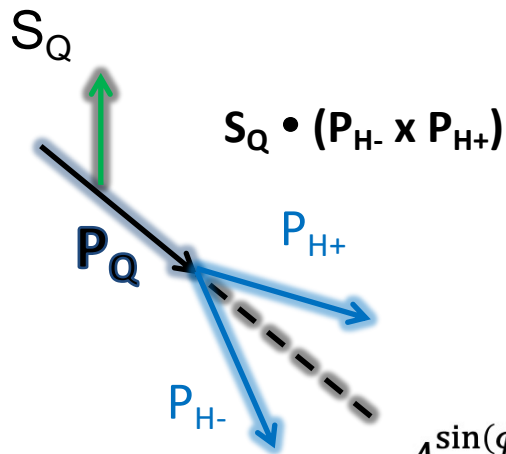
STAR, PRD103 (2021) 072005



- Forward $\pi^0 A_N$ ($2.6 < \eta < 4.0$) for pp, pAl and pAu.
- Suppression of A_N in nuclei but no strong A dependence.

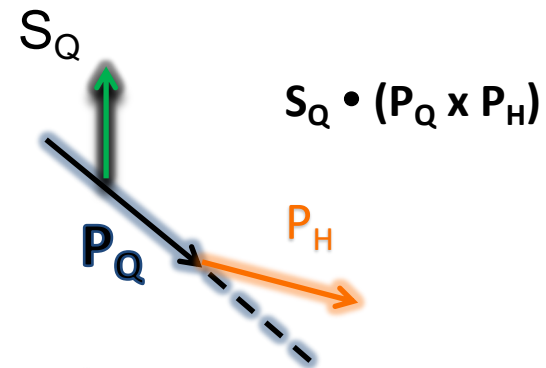
Transversity

Interference Fragmentation Functions (FF)

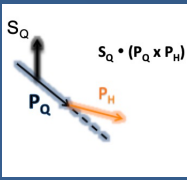


$$A_{UT}^{\sin(\phi)} \sin(\phi) = \frac{\sigma^{\uparrow}(\phi) - \sigma^{\downarrow}(\phi)}{\sigma^{\uparrow}(\phi) + \sigma^{\downarrow}(\phi)}$$

Collins Fragmentation Functions (FF)

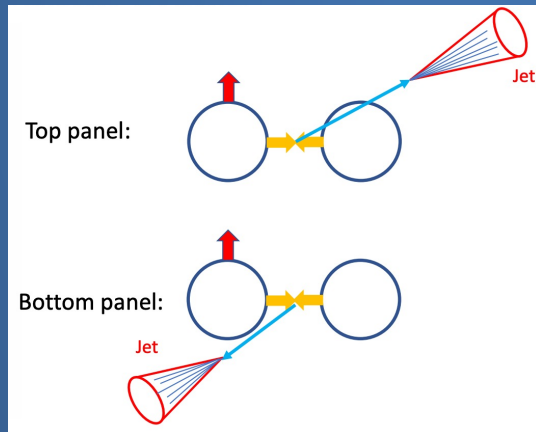


Transversity \otimes Collins FF

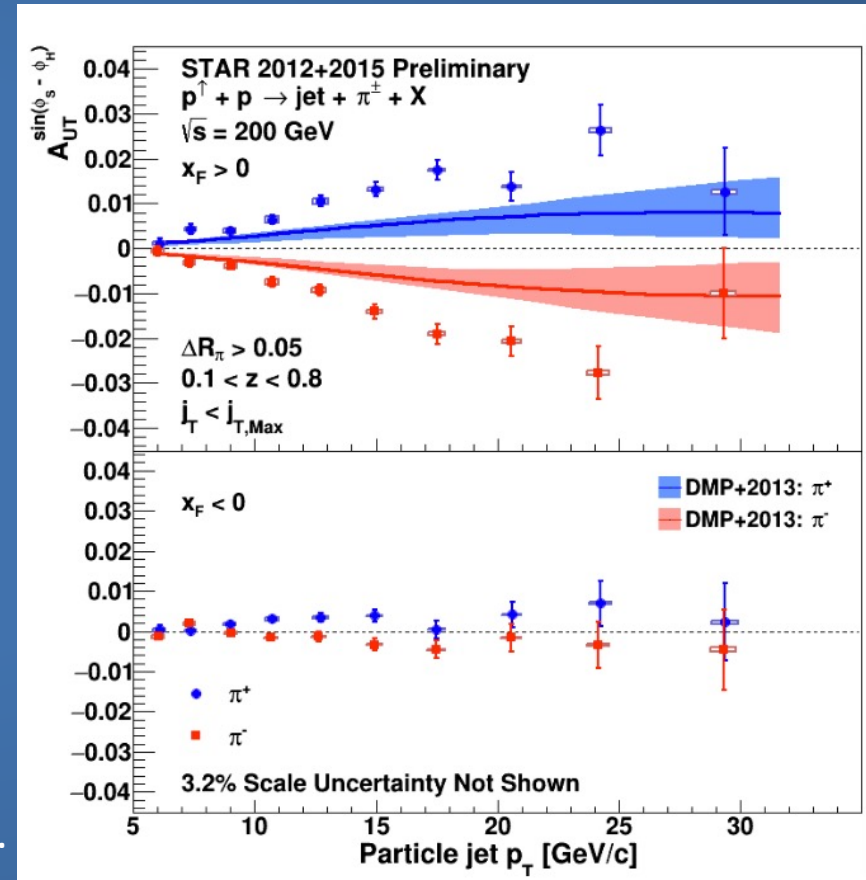


Transversity: transversely polarized quark in transversely polarized nucleon, which is chiral-odd so requires coupling to another chiral-odd object.

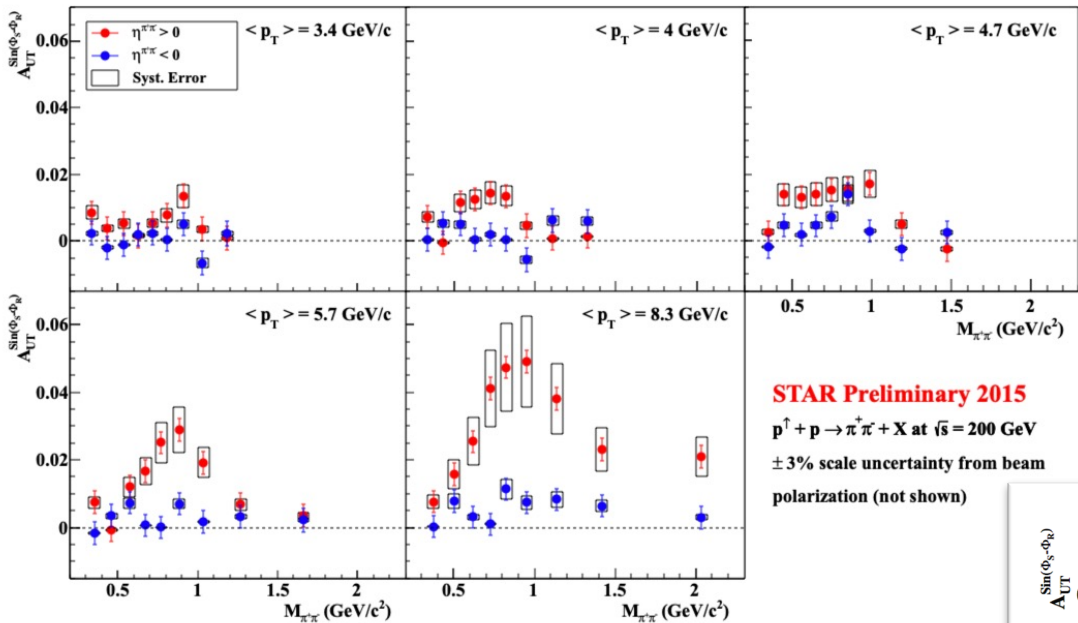
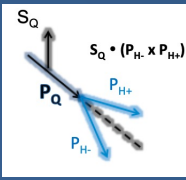
Collins FF: correlation between spin of transversely polarized quark and transverse momentum of the fragmented hadron.



- Preliminary results for STAR 2012 and 2015 data.
- Significant non-zero asymmetries
- Provide insight on TMD evolution.



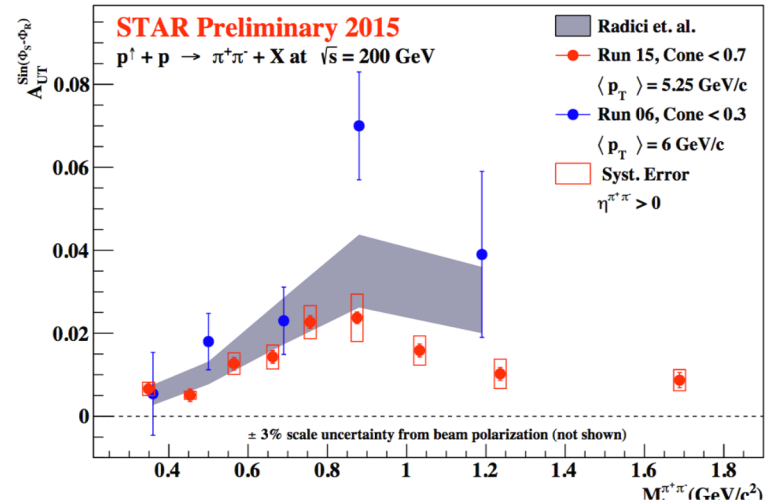
Transversity \otimes IFF



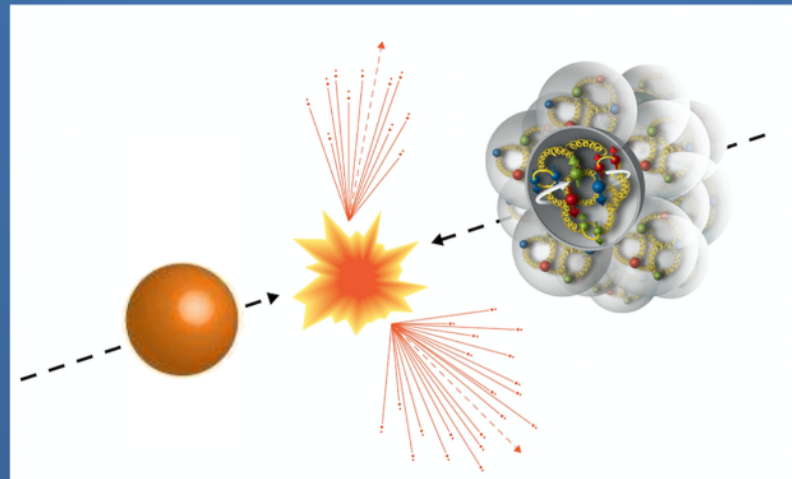
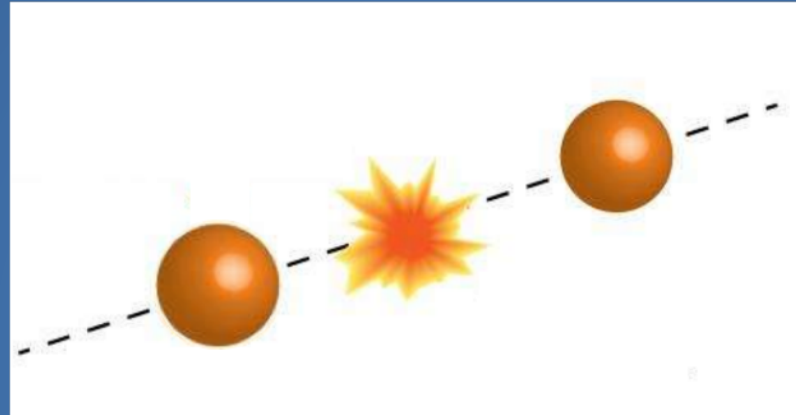
STAR Preliminary 2015
 $p^+ + p \rightarrow \pi^+ \pi^- + X$ at $\sqrt{s} = 200$ GeV
 $\pm 3\%$ scale uncertainty from beam polarization (not shown)

Interference FF: Correlation of transverse spin of fragmenting quark and momentum cross-product of di-hadron pair.

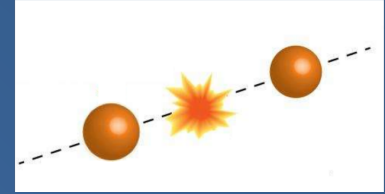
- Preliminary results with STAR 2015 data.
- Measurement carried out in five p_T bins.
- Signal enhanced around ρ -meson mass, but small in the backward region.
- Data agree with theoretical predictions.



Unpolarized results

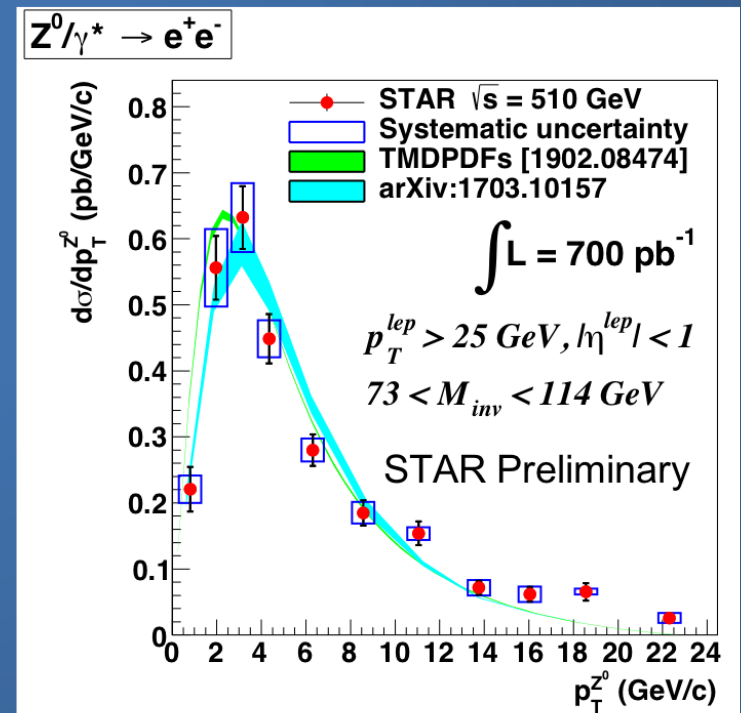
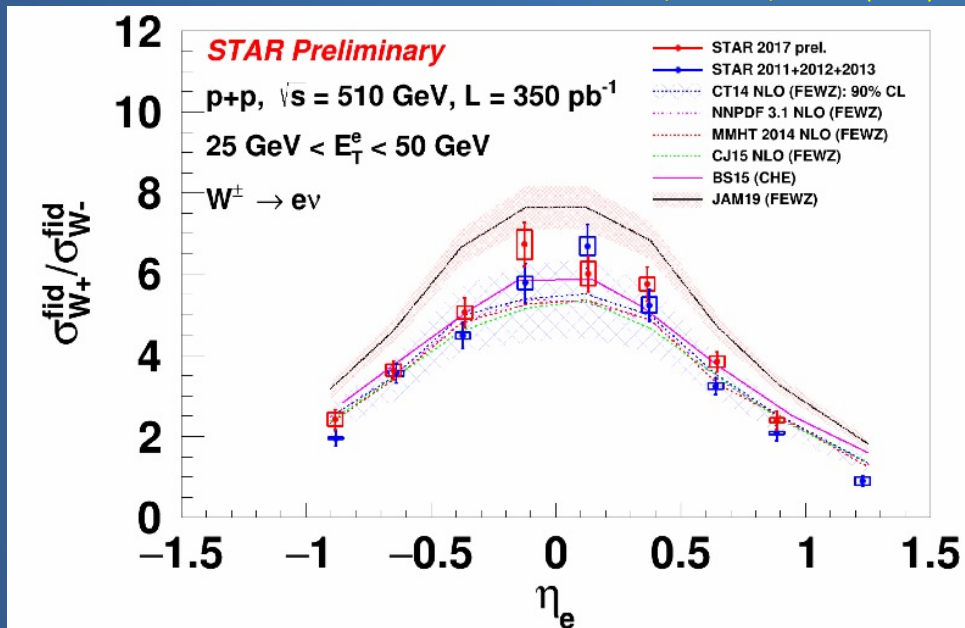


W and Z cross section

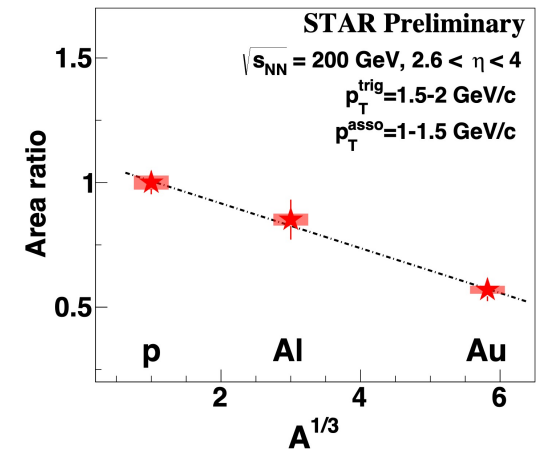
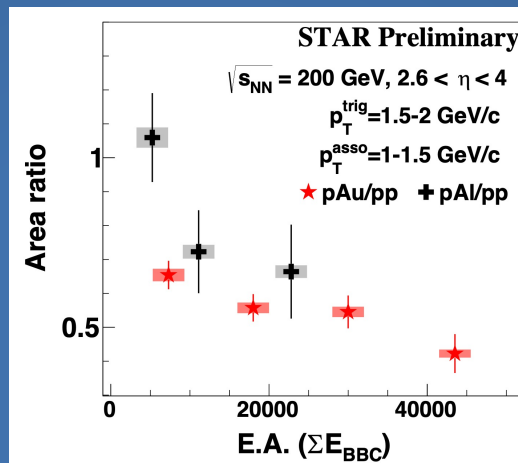
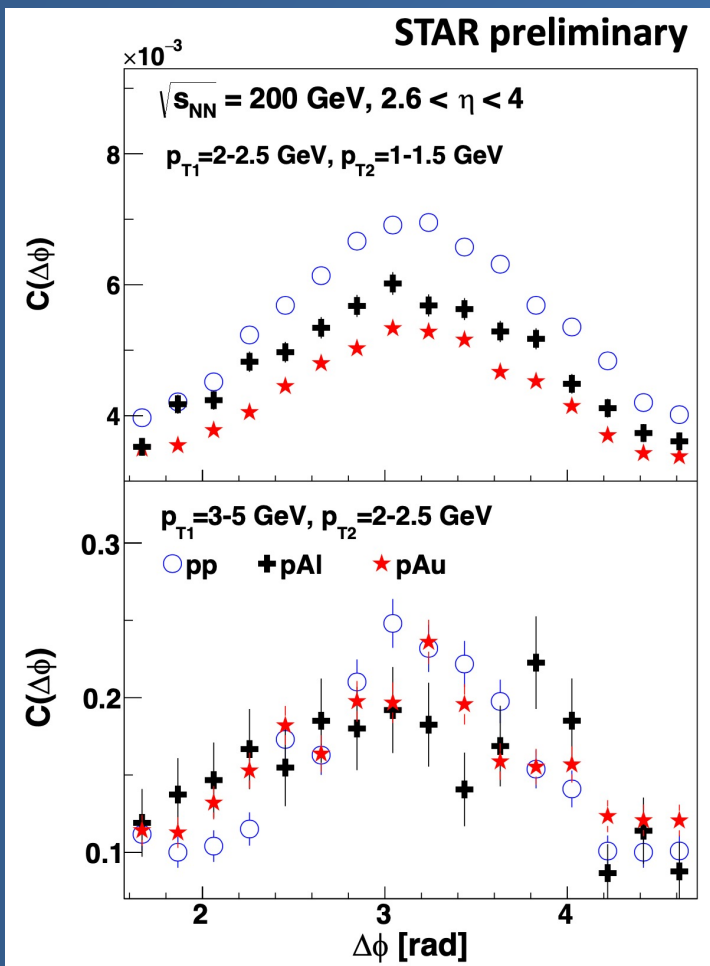
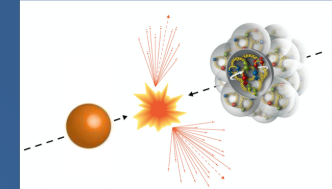


- Preliminary results on W+/W- ratio at 510 GeV from 2017 data, together with published results from 2011-2013 data.
- W+/W- is sensitive to \bar{d} and \bar{u} distribution.
- Z cross section can constrain unpolarized TMD PDFs.

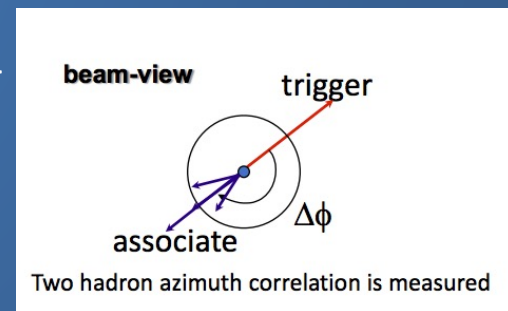
STAR Run11-13, PRD 103, 012001(2021)



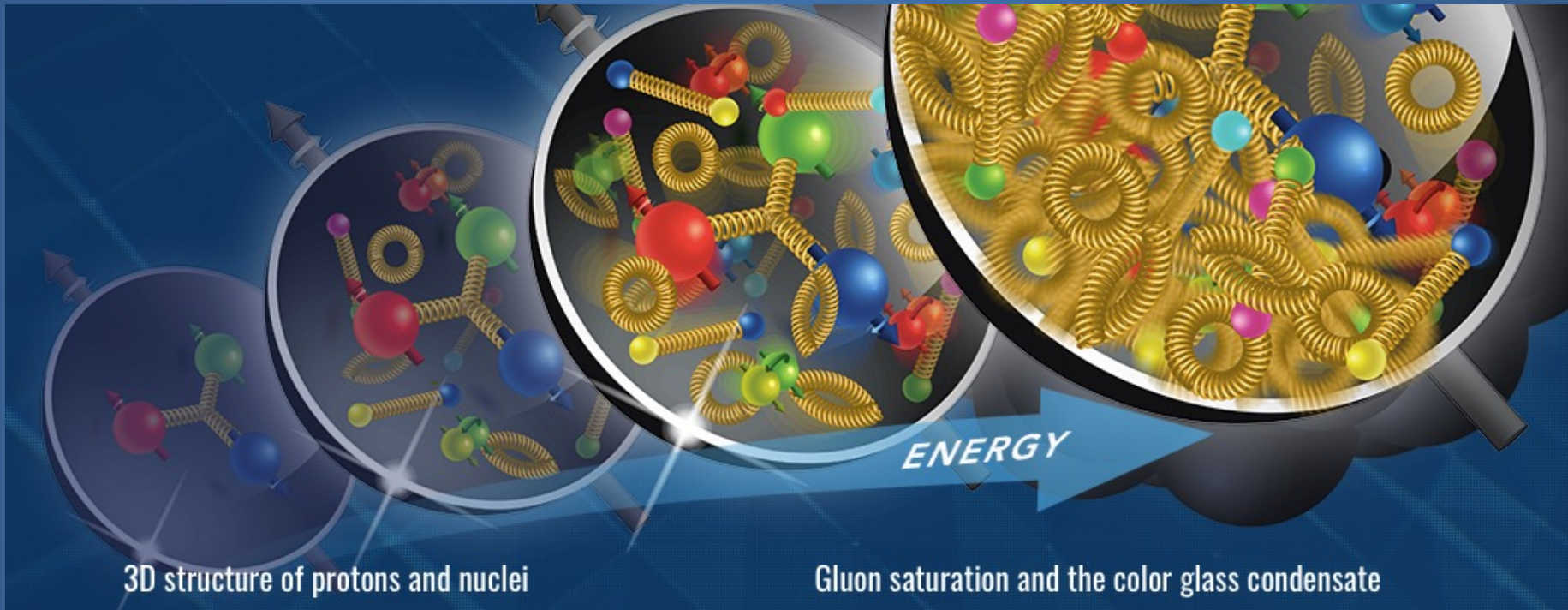
Di-hadron correlations



- Di- π^0 azimuth correlation with 2015 pp, pAl, and pAu data.
- Clear suppression of back-to-back yields.
- Suppression follows $A^{1/3}$ nuclear dependence.
- Consistent with predictions from gluon saturation model [Nucl. Phys. A748 \(2005\) 627-640](#).



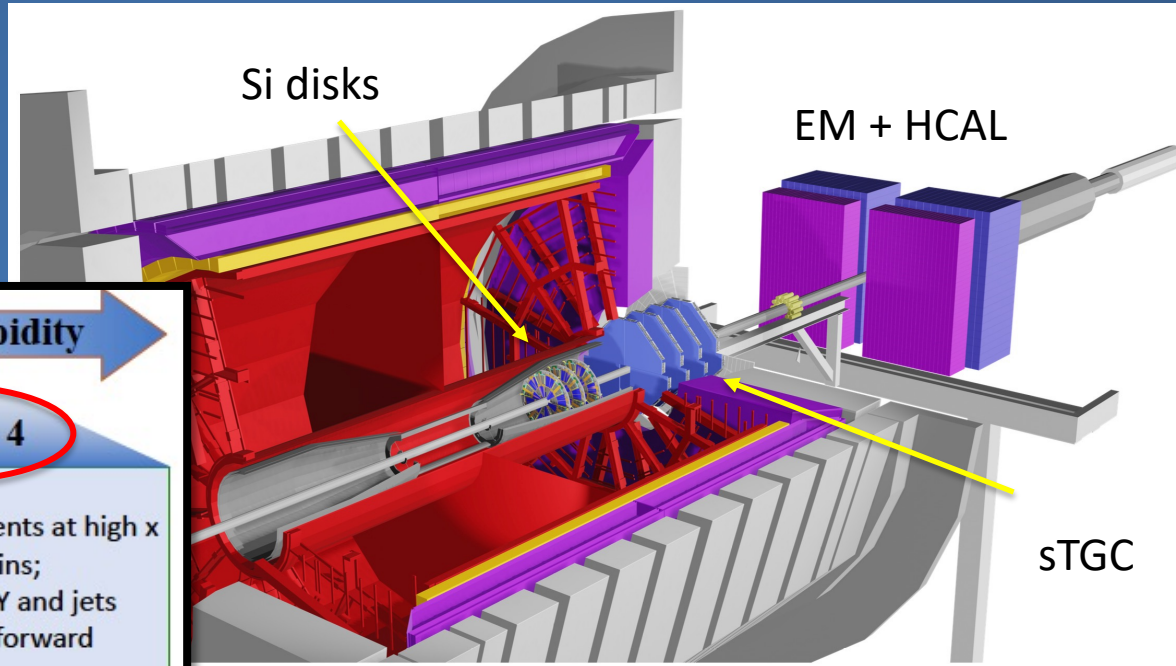
Future upgrades





STAR Forward Upgrade

Ready for proton-proton running in 2022



Mid Rapidity

Forward Rapidity

$$-1.5 < \eta < 1.5$$

Physics Topics:

Improve statistical precision:

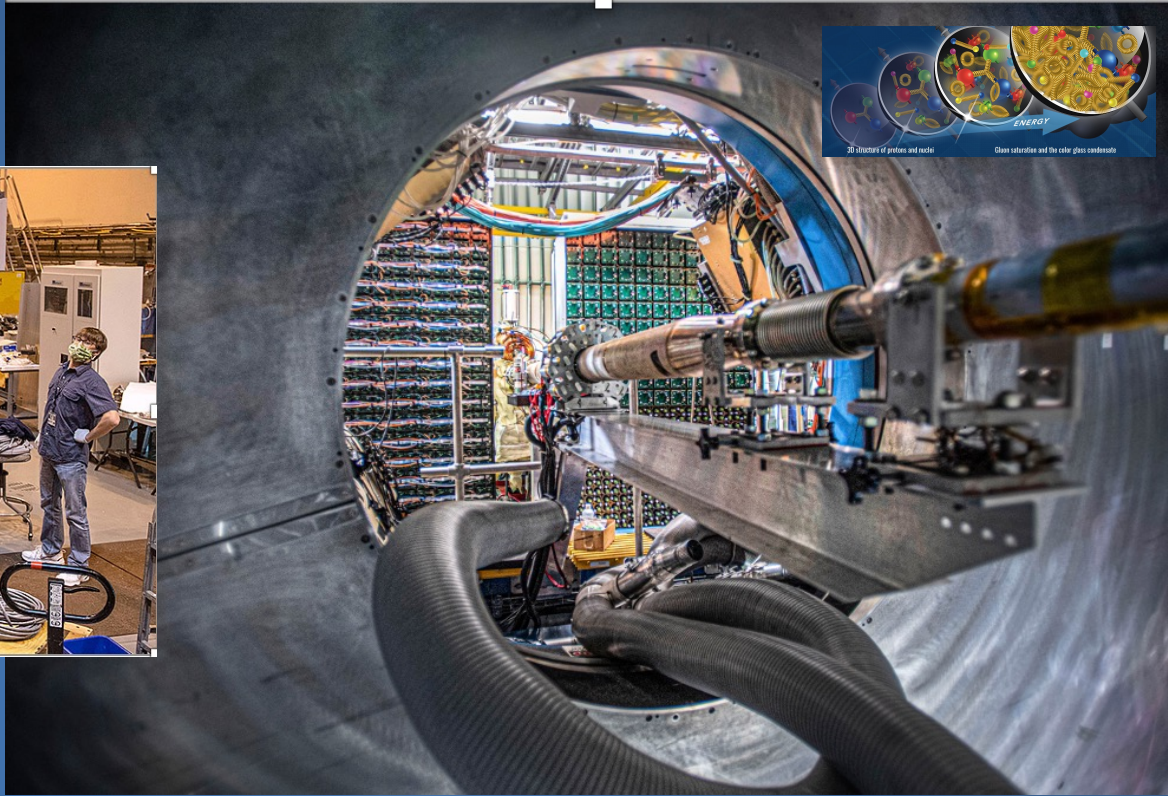
- Sivers effect in dijet and W/Z production;
- Collins effect for hadrons in jets;
- Transversity and IFF
- Diffractive studies for spatial imaging of nucleon
- Measurement of GPD E_g through UPC J/ ψ
- Nuclear PDF and fragmentation function;

$$2.5 < \eta < 4$$

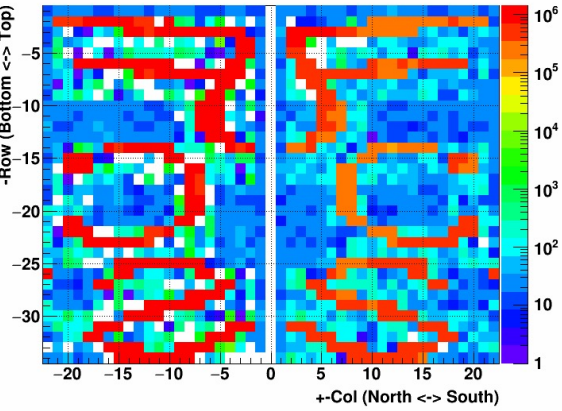
Physics Topics:

- TMD measurements at high x
 - Transversity, Collins;
 - Sivers through DY and jets
 - UPC J/ ψ GPD at forward rapidity;
 - Nuclear PDFs and FF:
 - R_{pA} for direct photons & DY, and hadrons
 - Gluon Saturation through di-hadrons, γ -Jets, di-jets
- All of these measurements are critical to the scientific success of EIC to test universality and factorization

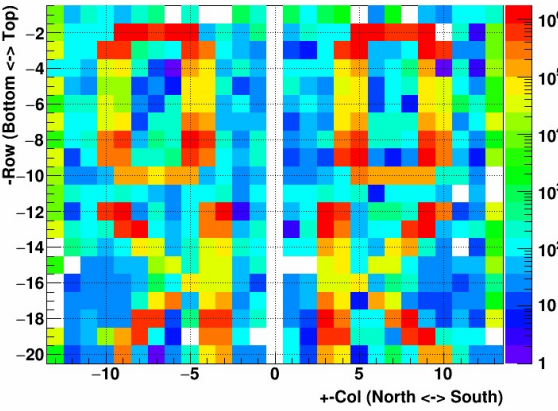
- Three silicon microstrip disks plus four small-strip Thin Gap Chamber (sTGC) for tracking.
- Electromagnetic and hadronic calorimeters.



Ecal View from Back

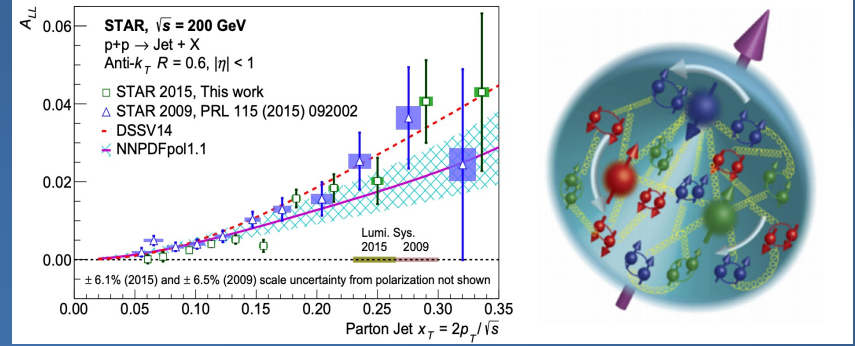


Hcal View from Back



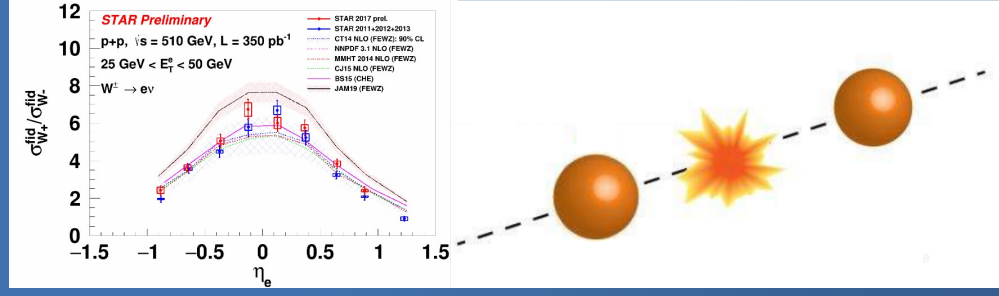
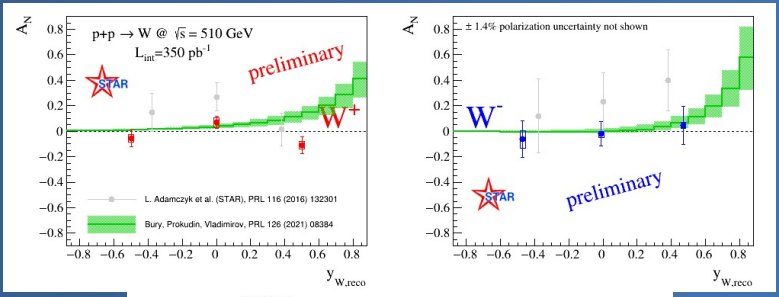
<https://www.bnl.gov/newsroom/news.php?a=217681>

Summary:
 - New measurements
 - Improved precision

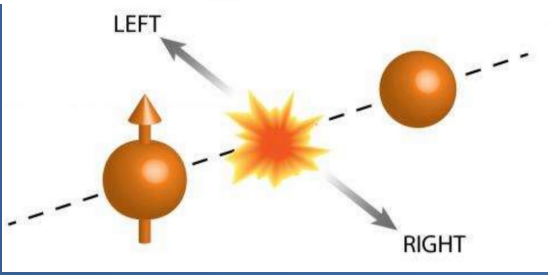


Gluon spin contributes significantly to the proton spin (~50%)

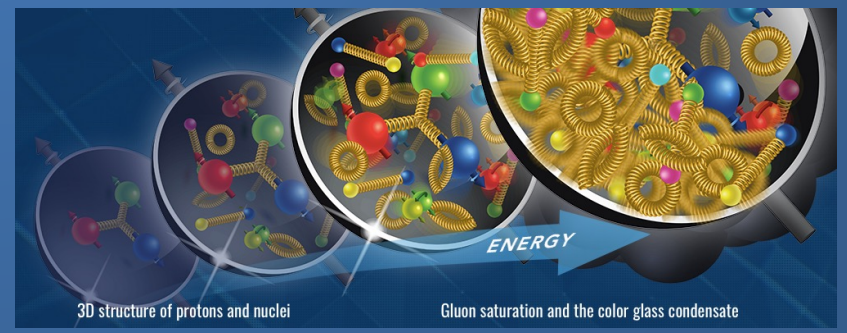
Several channels sensitive to TMDs



Constraining unpolarized PDFs


















Forward STAR upgrade enables unique QCD physics before EIC



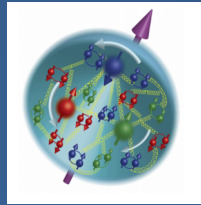
Backup

Observables

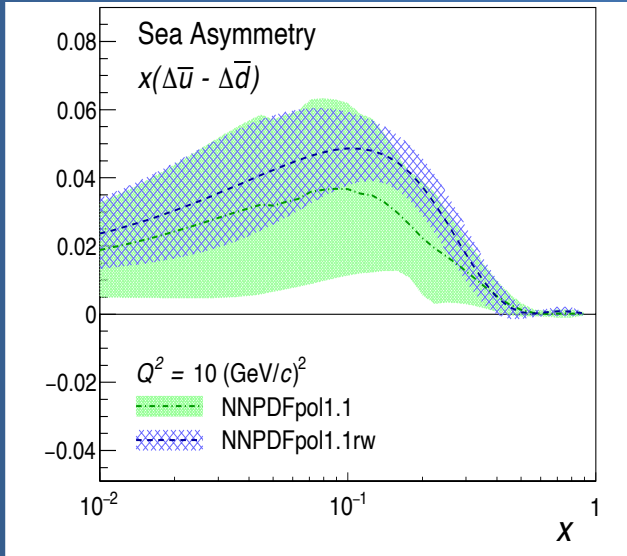
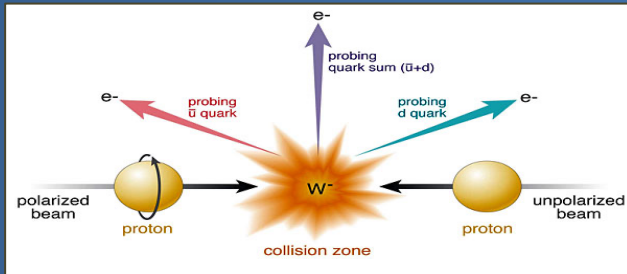
		Leading Twist TMDs		
		Quark Polarization		
		Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 =$ 		$h_1^\perp =$  —  Boer-Mulders
	L		$g_{1L} =$  —  Helicity	$h_{1L}^\perp =$  — 
	T	$f_{1T}^\perp =$  —  Sivers	$g_{1T}^\perp =$  — 	$h_1 =$  —  Transversity $h_{1T}^\perp =$  — 

*From Yuri Kovchegov

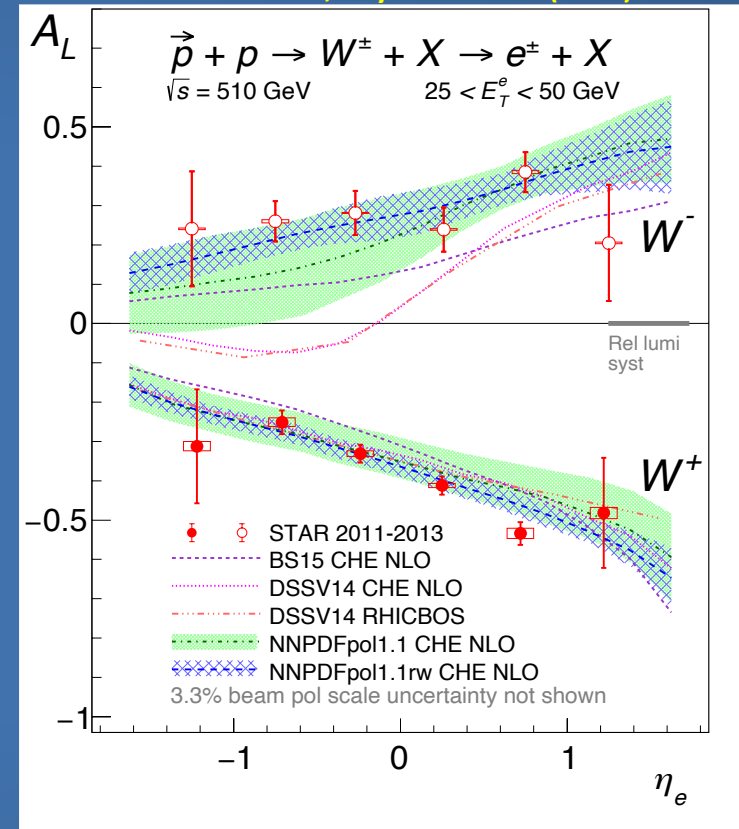
Quark Helicity Distributions



$$\langle S_p \rangle = \frac{1}{2} = \frac{1}{2} \Delta\Sigma + \Delta G + L_q + L_g$$

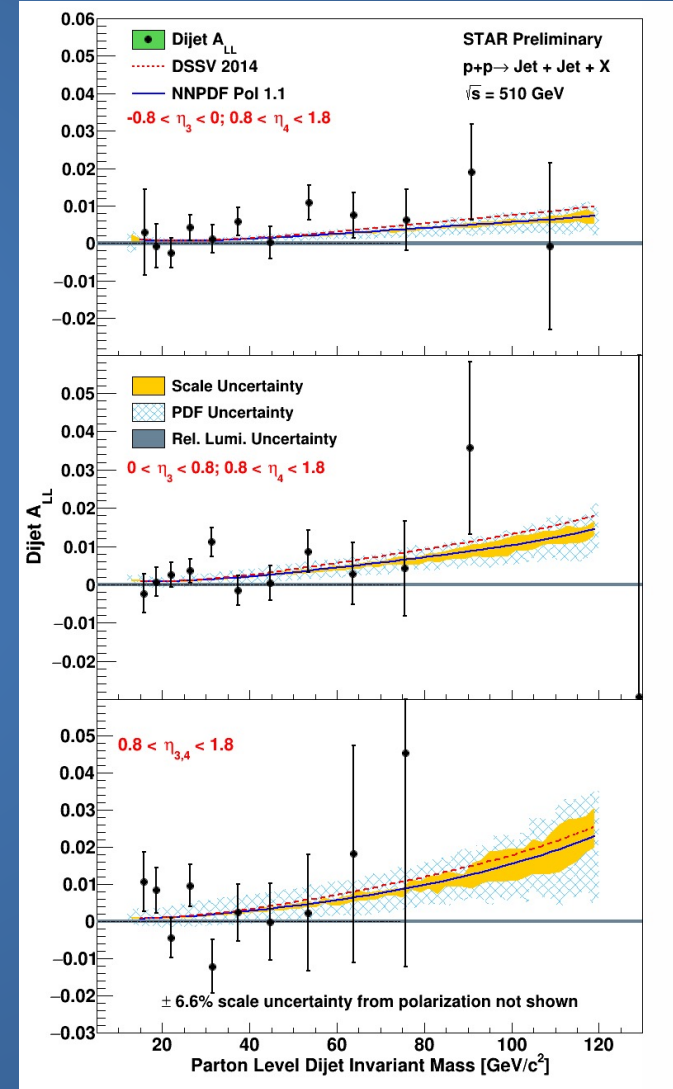
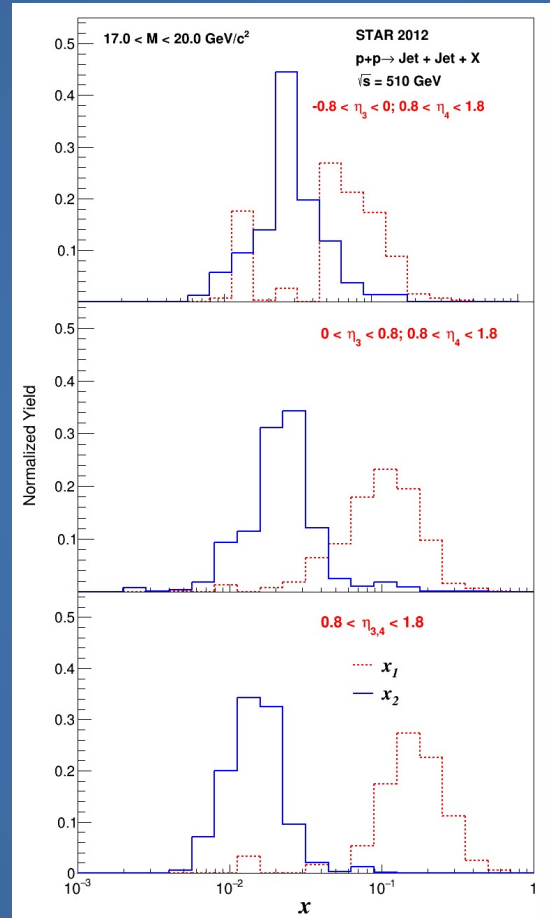
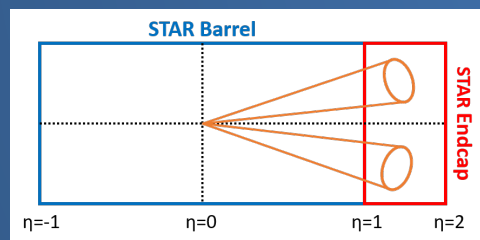
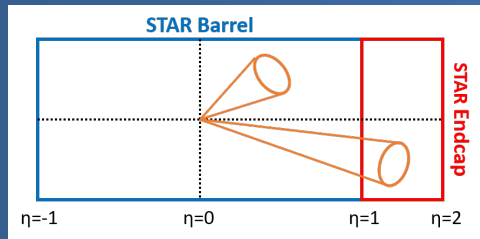
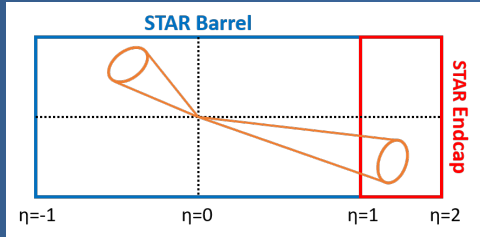
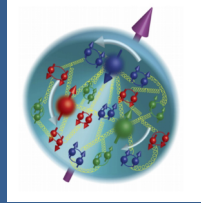


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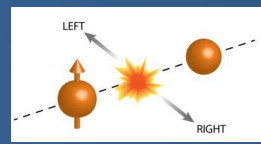
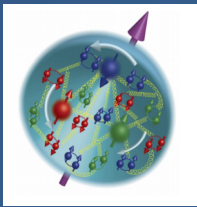


- All RHIC results are consistent with each other.
- New data reduced uncertainty by 40%.
- First clear evidence of the flavor asymmetry in the polarized quark sea.

Intermediate Dijets

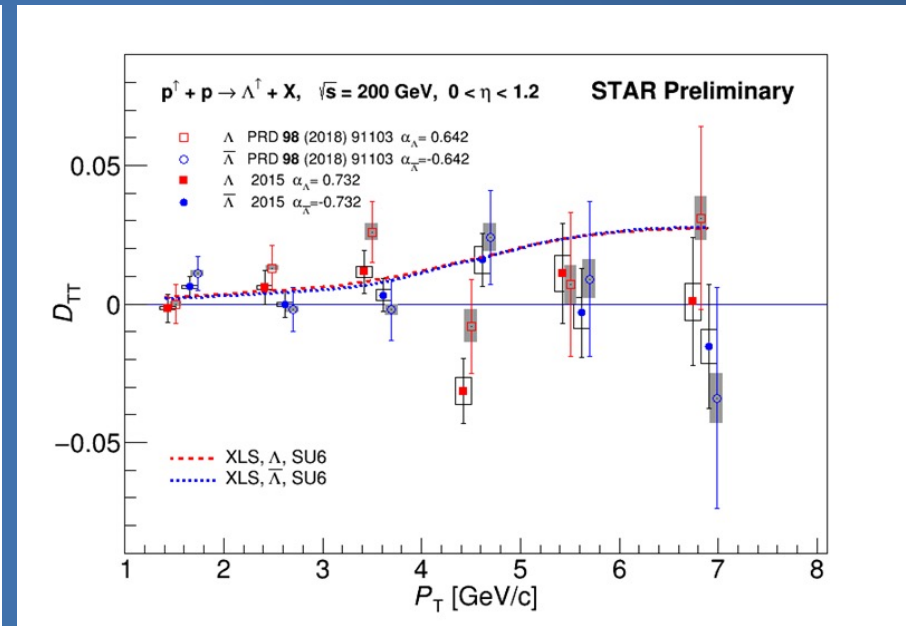
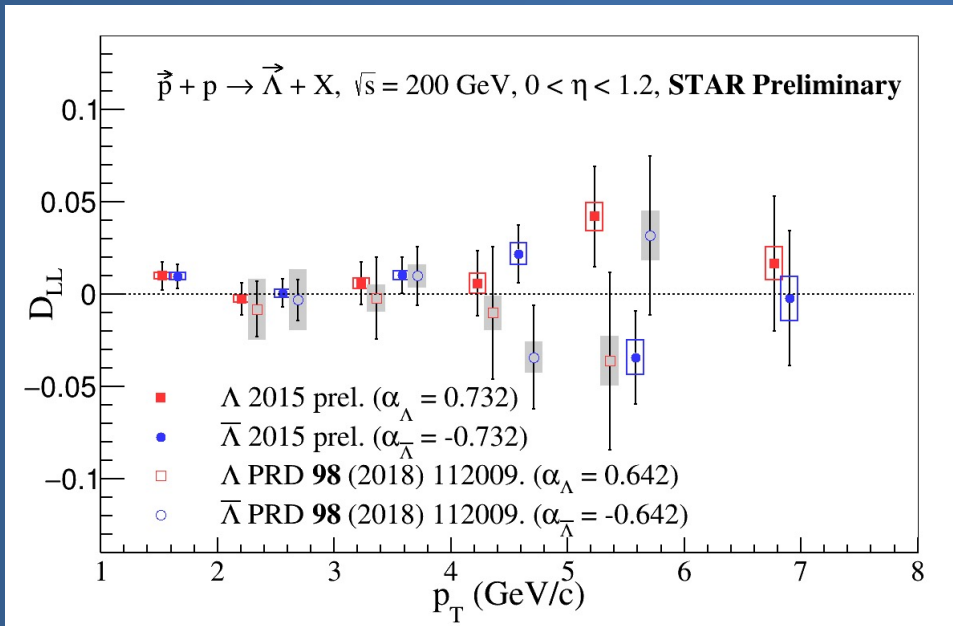


- Preliminary result using 2012 data
- Expecting ~2.5x higher statistics for 2013 data



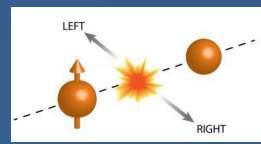
Hyperon spin transfer

- Preliminary results from 2015 data



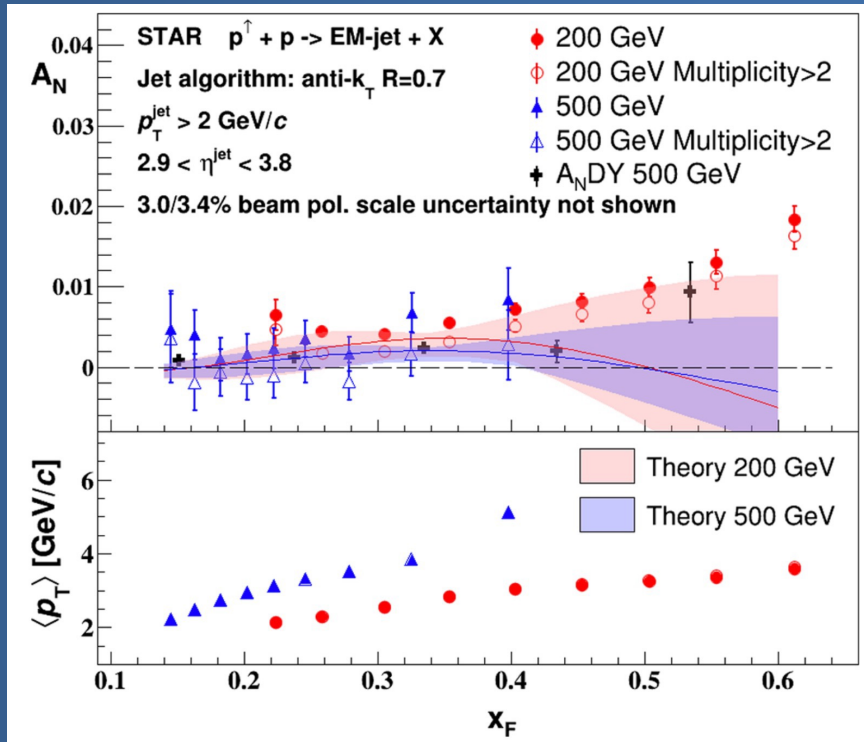
- Sensitive to strange quark helicity

- Sensitive to strange quark transversity

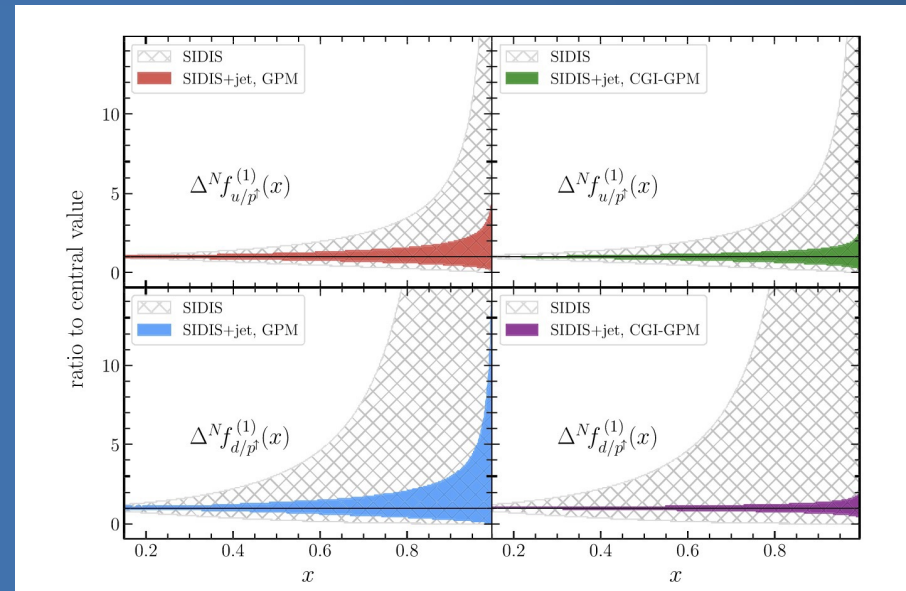


Forward EM-jet A_N

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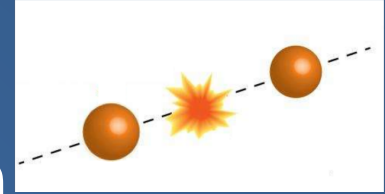


M. Boglione et al., PLB 815, 136135 (2021)



- Forward inclusive EM-jet result shows small but non-zero signal at 200 GeV.
- Significantly reduces the uncertainty of the quark Sivers function on a recent global fit.

Inclusive jet cross section



- Preliminary inclusive jet cross sections at 200 and 510 GeV using 2012 data
- Will help to constrain unpolarized gluon PDF at high x

