Selected results from measurement of jets at STAR experiment at different rapidities

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International Workshop on Forward and Jet Physics at LHC

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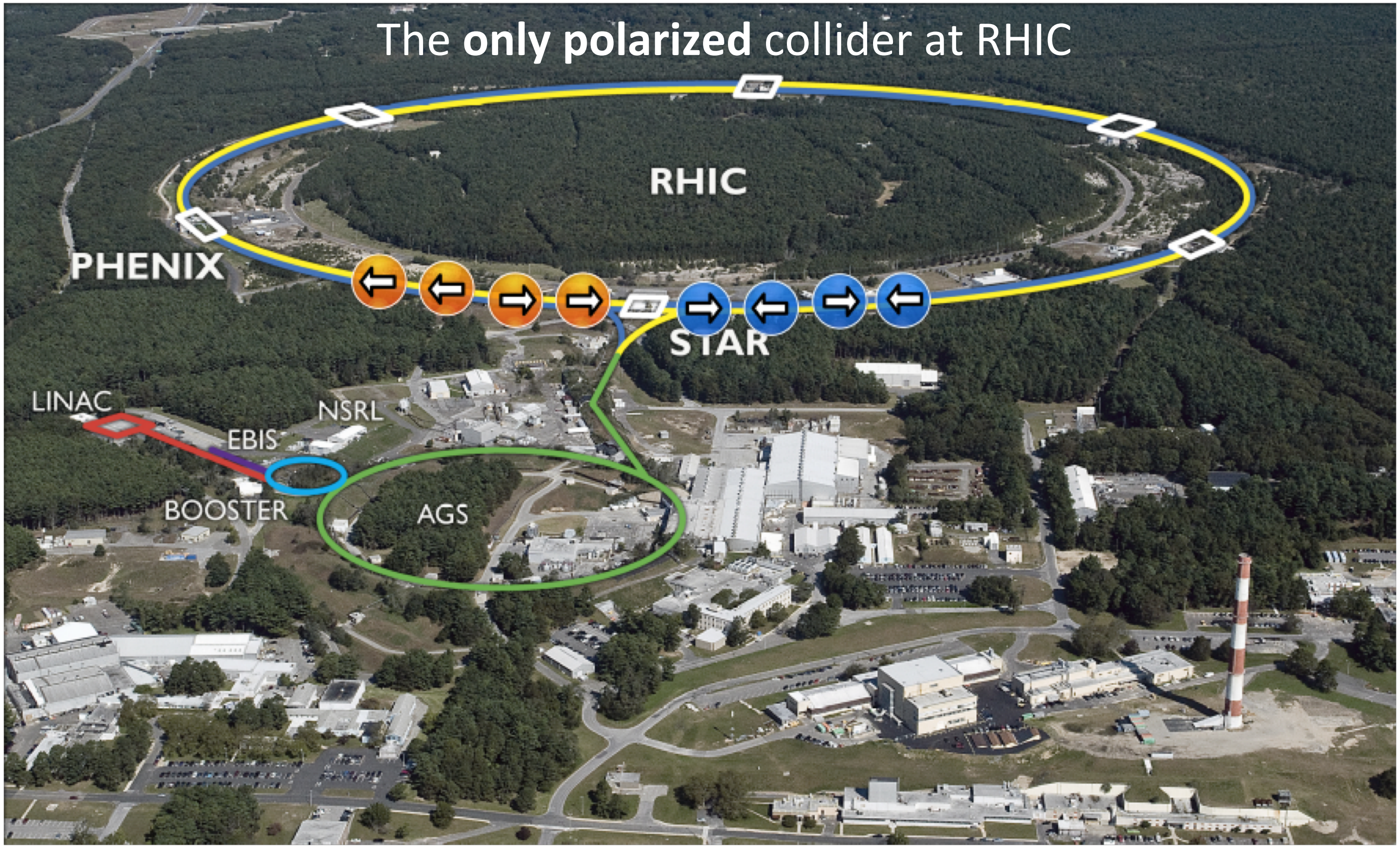
Outline

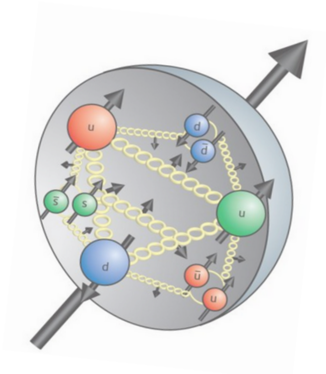
- RHIC contributes significantly in heavy ion and spin physics
- STAR contribution in spin structure of Nucleon
  - Longitudinal spin via Helicity Asymmetries
    - Jets, neutral pions and W
  - Transverse spin via Single Spin Asymmetries
    - **Electromagnetic Jets**, W
- Gluon saturation with forward jets@p+A 200GeV
- Physics with STAR in 2021+
- Summary

Relativistic Heavy Ion Collider (RHIC)



I. **Heavy ion** : Phases of QCD matter from high temp to high baryon density
II. **Spin physics** : Probing the Spin structure of Nucleon
III. **Cold QCD and Forward physics** : Study of low x properties and search for CGC
IV. **Tagged forward physics** : Elastic inelastic processes, search for gluonic matter

ΔG measurement at STAR



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

$$\Delta\Sigma = \int (\Delta u + \Delta d + \Delta s + \Delta\bar{u} + \Delta\bar{d} + \Delta\bar{s} + \cdots)dx$$

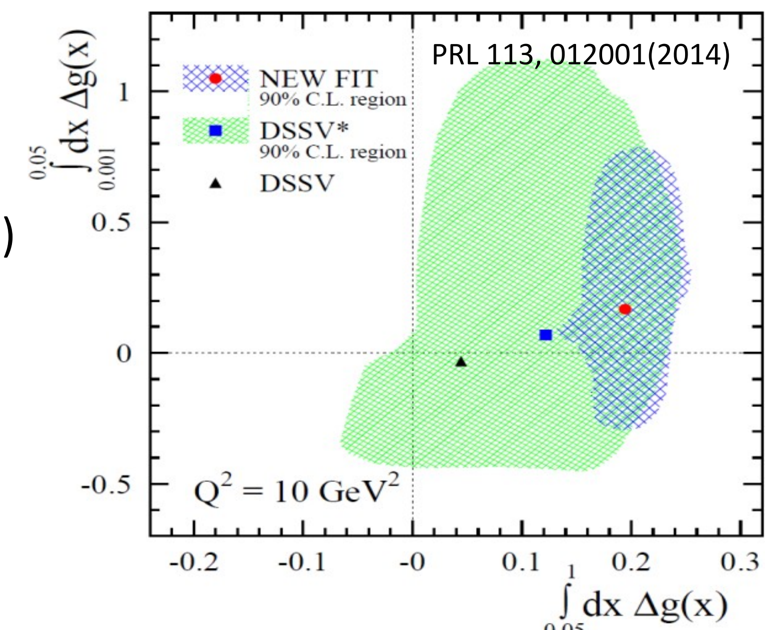
$$\Delta G = \int \Delta g dx$$

From DIS, ΔΣ≈30% (spin crisis)

Rest must come from gluon's spin (ΔG) and orbital angular momentum (L) of the partons

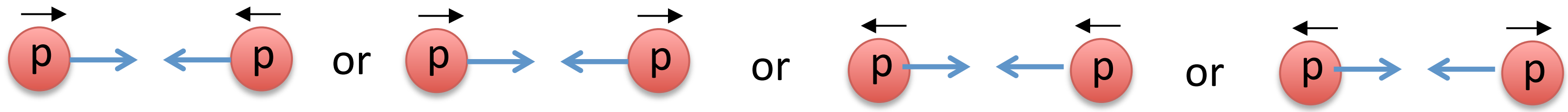
DSSV and NNPDF global analyses found the first evidence of nonzero gluon polarization for x>0.05 from STAR 2009 inclusive jet results (PRL 115.09202)

Low x behavior and shape of Δg(x) are still poorly constrained. Recent data will extend our reach in low x using forward pion and jet results, and also using higher collision energies.

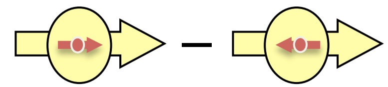


$$\int_{0.05}^{1} dx\, \Delta g(x) = 0.20\ ^{+0.06}_{-0.07}$$ at 90 % C.L.

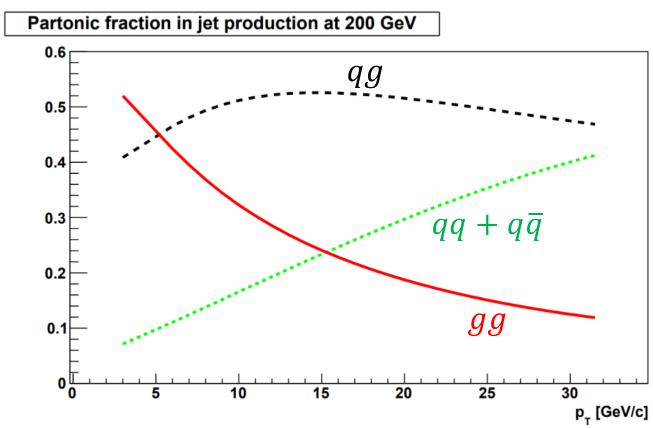
Helicity asymmetries



Helicity distributions : ΔΣ, ΔG



$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} = \frac{\sum_{a,b,c} \Delta f_a \otimes \Delta f_b \otimes d\hat{\sigma}^{f_a f_b \to f_c X} \cdot \hat{a}_{LL}^{f_a f_b \to f_c X} \otimes D_{f_c}^{h}}{\sum_{a,b,c} f_a \otimes f_b \otimes d\hat{\sigma}^{f_a f_b \to f_c X} \otimes D_{f_c}^{h}}$$



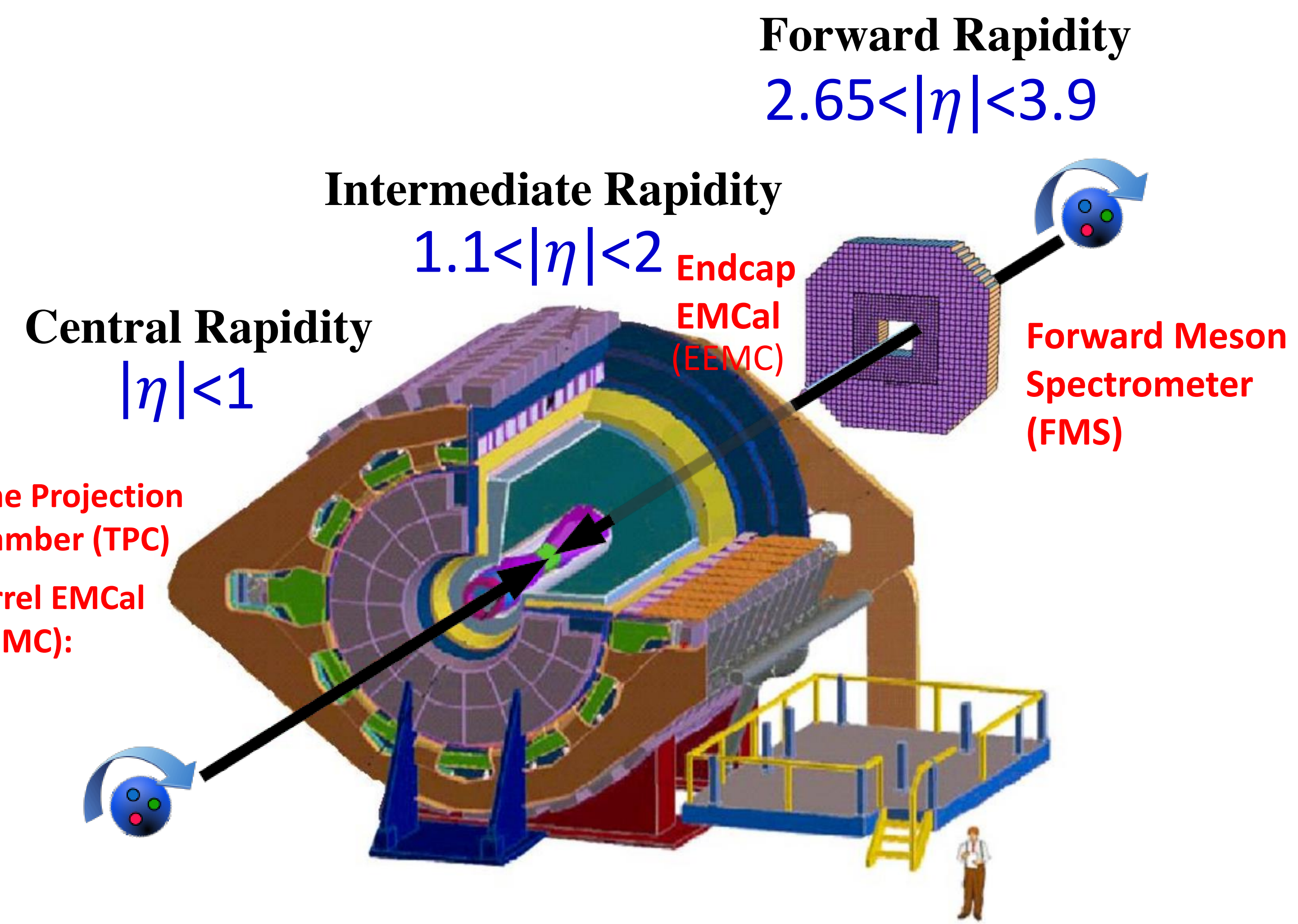
Needed for hadrons but not for jets

Contribution in A_{LL} arising from

$$A_{LL} \approx f_{gg} a_{gg} \Delta g \Delta g + f_{qg} a_{qg} \Delta q \Delta g + f_{qq} a_{qq} \Delta q \Delta q'$$

Jets at each p_T bin is a mixture of subprocesses

STAR at RHIC



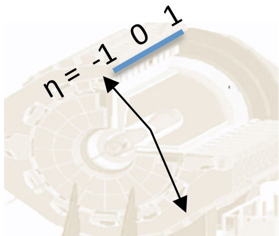
- Measurement with jets in p+p in STAR with TPC+BEMC+EEMC is well established
- Jet measurement extended to very forward rapidity with FMS (electromagnetic energy)

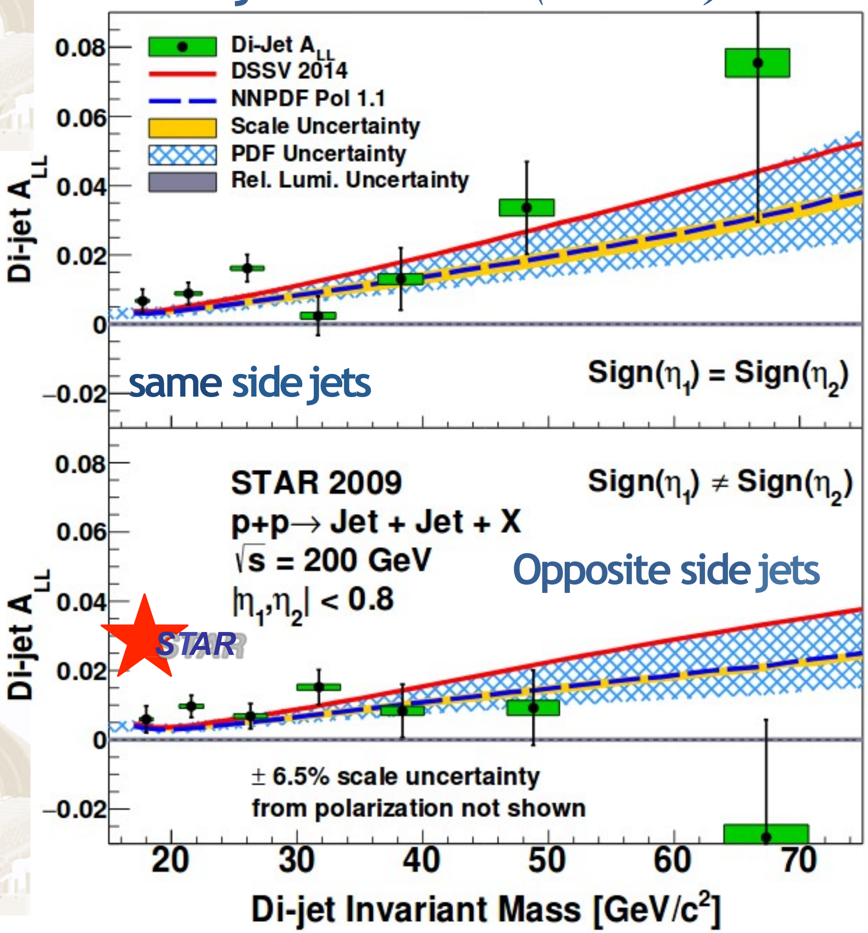
Gluon polarization (central jets and dijets)

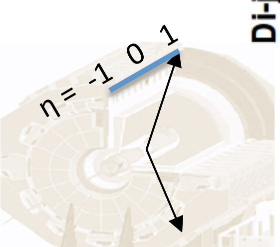
Phys.Rev. D95, 071103 (2017)

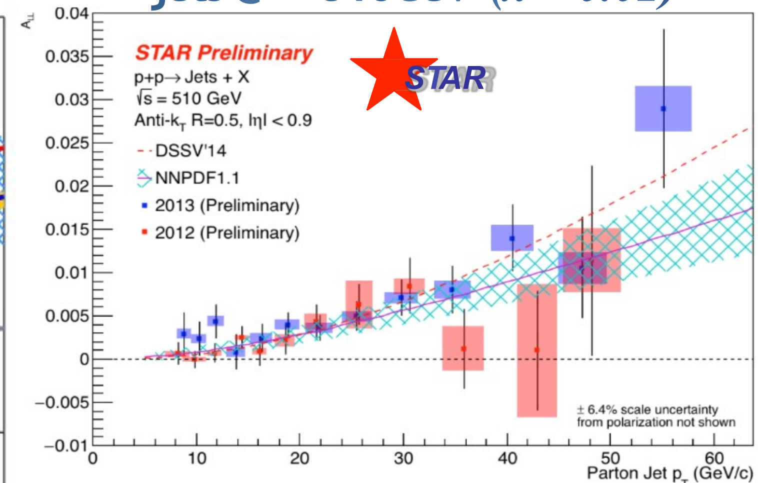
dijets @ 200GeV $(x > 0.05)$

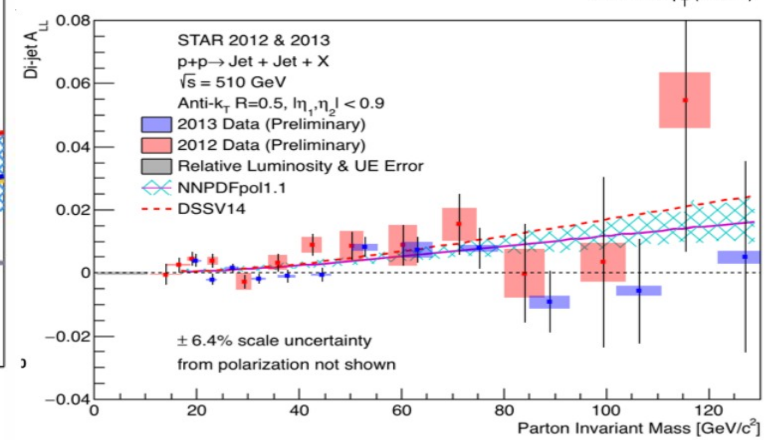
jets @ 510GeV $(x > 0.02)$



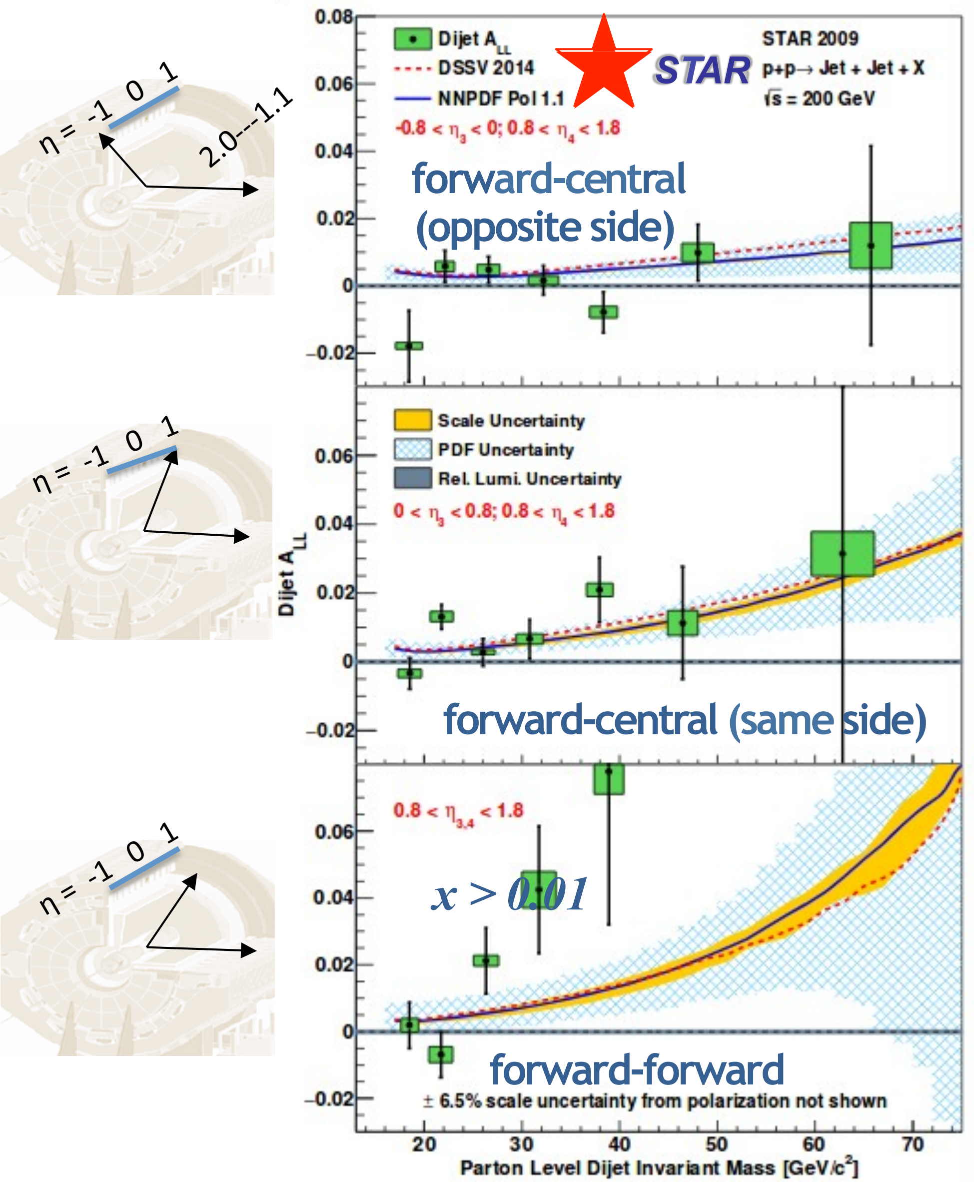








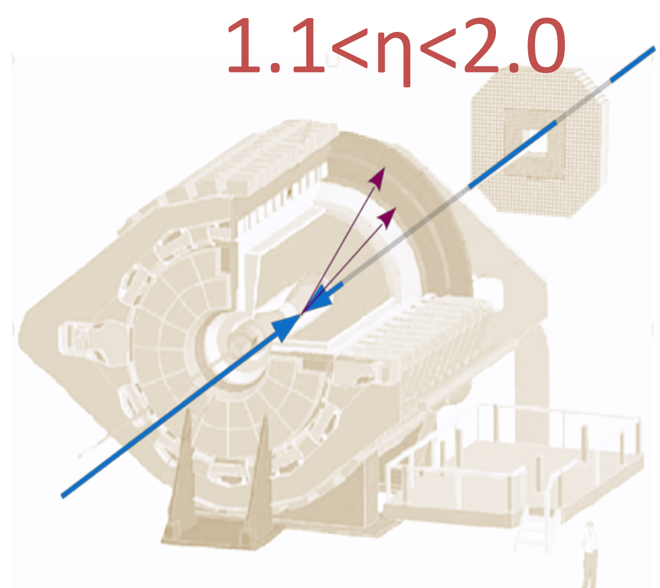
Gluon polarization (intermediate rapidity)



Dijets at 200 GeV in 2009 : Phys.Rev. D98, 032011 (2018)

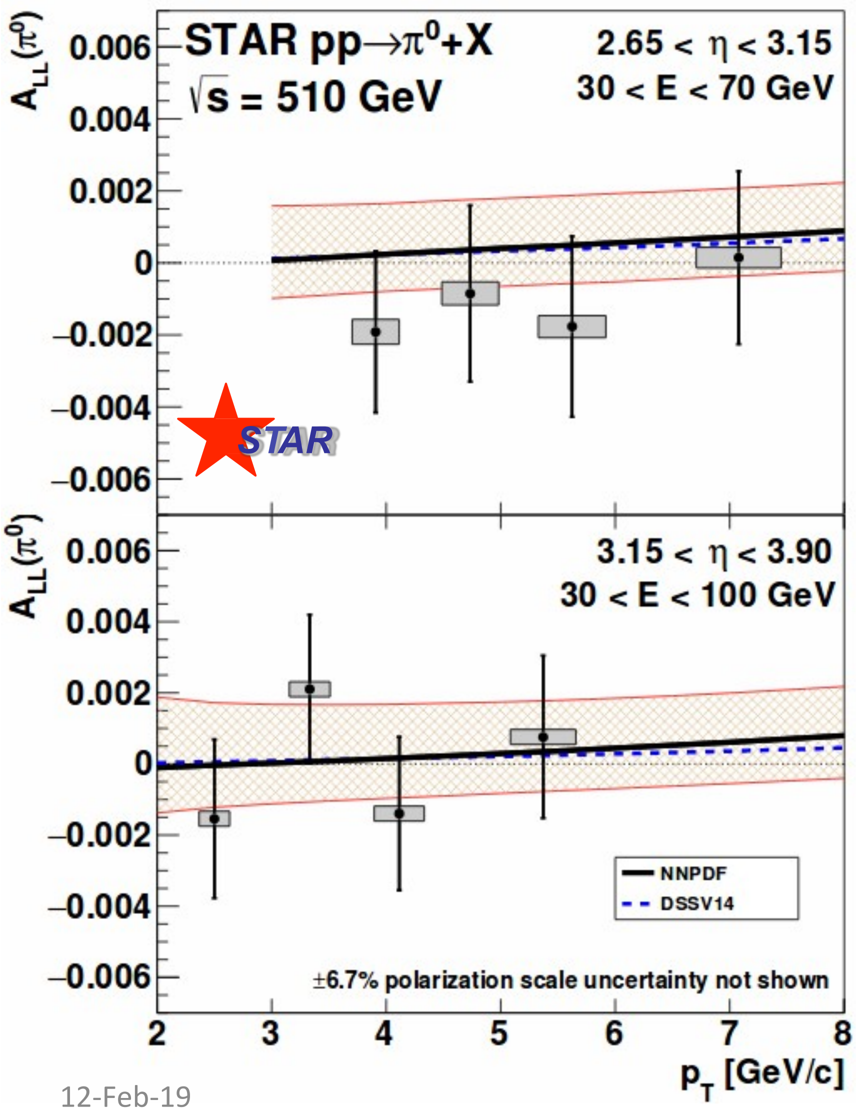
- More-forward production probes lower x, down to 0.01
- Provides tighter constraints to size and especially shape of Δg(x) for x<0.05

Pions at 200 GeV in 2006 : Phys.Rev.D89, 012001 (2014)
Pions at 510 GeV in 2012 and 2013 : analysis underway

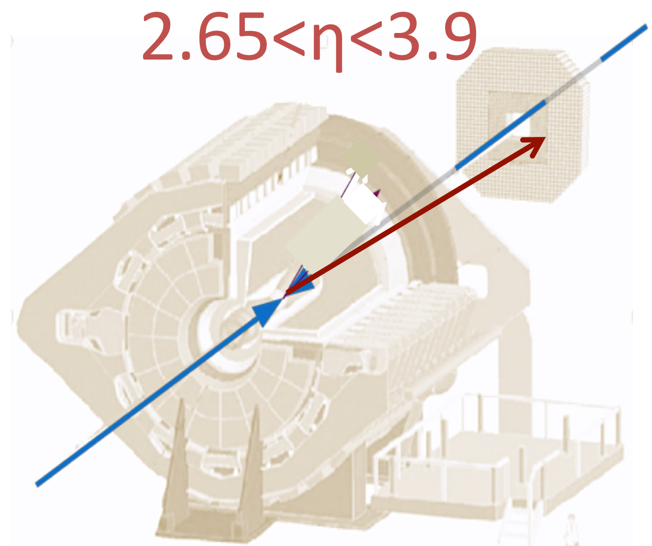


Gluon polarization (forward Pions)

Phys.Rev.D 98, 032013 (2018)



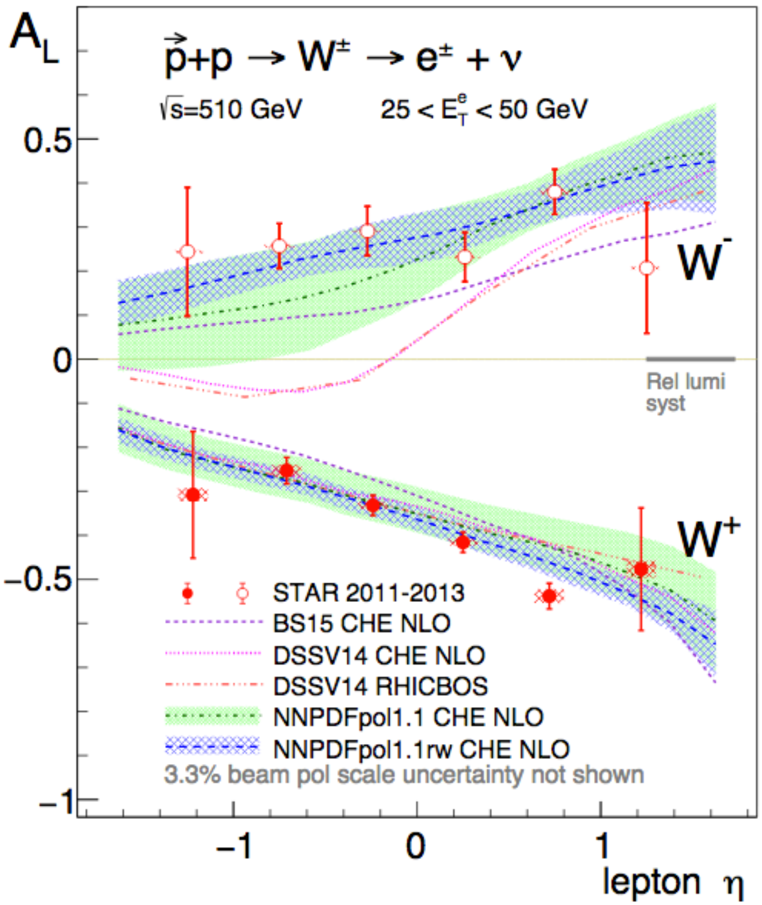
- Pushing farther forward probes x down to 0.001
- Provides constraints to the unexplored low-*x* region, which is *abundant* with soft gluons
- Shown for two pseudorapidity regions
- Analysis for 200GeV is underway



need enhance forward capabilities in measuring full jets

Sea quark polarization - $A_L(W)$

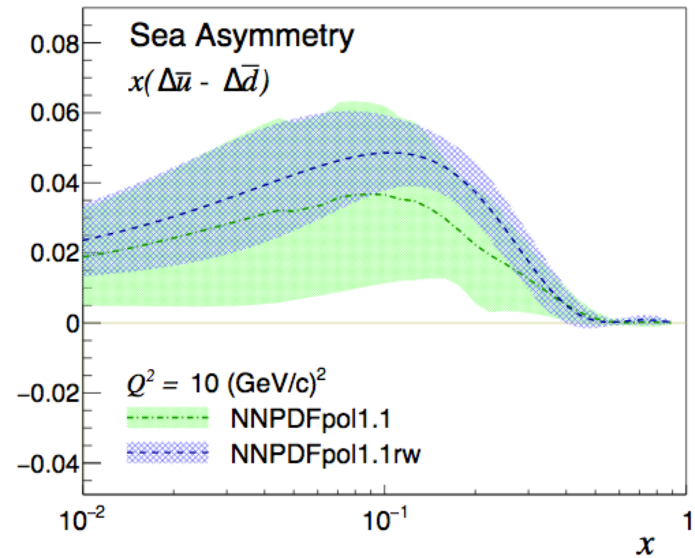
(accepted - PRD rapid)
arXiv:1812.04817



STAR 2011-2012: PRL113, 072301(2014)

- STAR 2013 results are the most precise measurements of W A_L so far
- Provide constrains on sea quark helicity

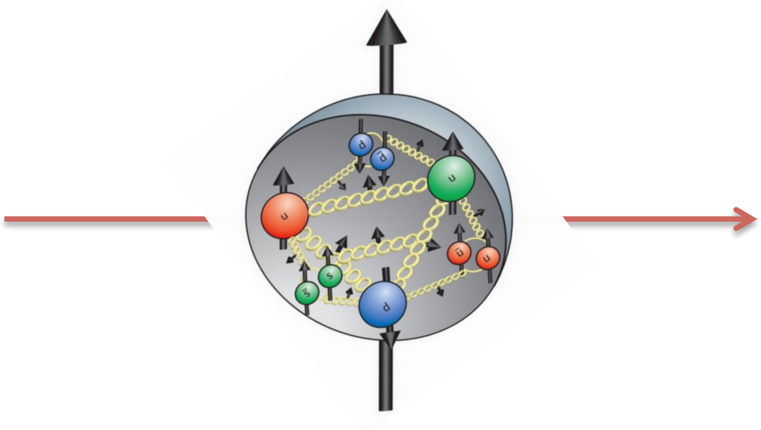
arXiv:1812.04817



---- Nucl. Phys.457B887, 276 (2014)
---- 2013 $W^{\pm}$ data included

$$\Delta\bar{u} > \Delta\bar{d}$$

reversed from the unpolarized distributions that have $\bar{d} > \bar{u}$



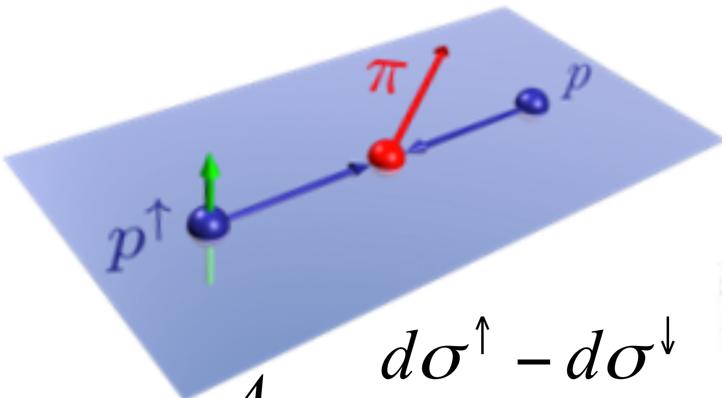
Transverse spin structure of proton

Forward rapidity measurements

Transverse spin structure via single spin asymmetry (A_N)

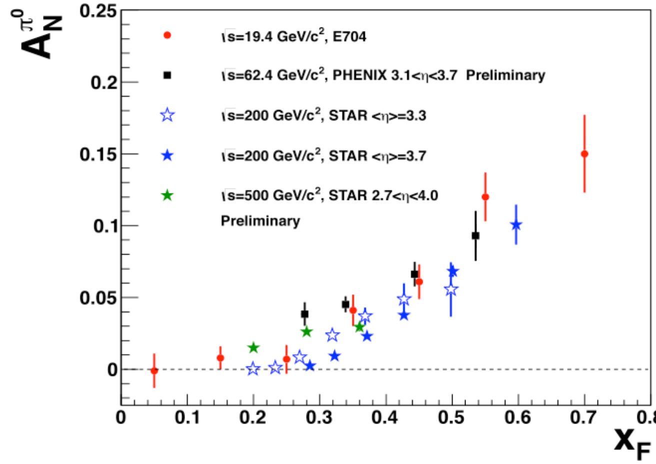
Transverse single spin asymmetry

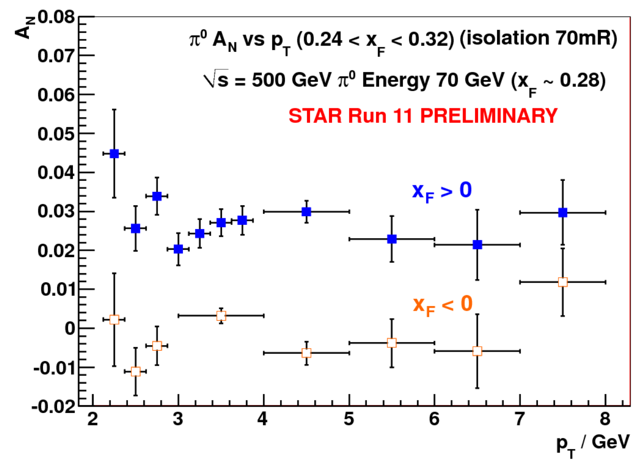
(left-right asymmetry)



$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

$$p_{\uparrow} + p \longrightarrow \pi^0 + X$$





- ✧ Rising A_N with X_F
- ✧ A_N nearly independent of √s
- ✧ **No evidence of fall in A_N with increasing P_T**

TMD - Sivers and Collins effect

D. Sivers, Phys. Rev. D **41**, 83 (1990)

Sivers effect : the correlation between the **transverse momentum (k_t)** of the struck quark and the **spin (S)** and **momentum (p)** of its parent nucleon

Sivers distribution

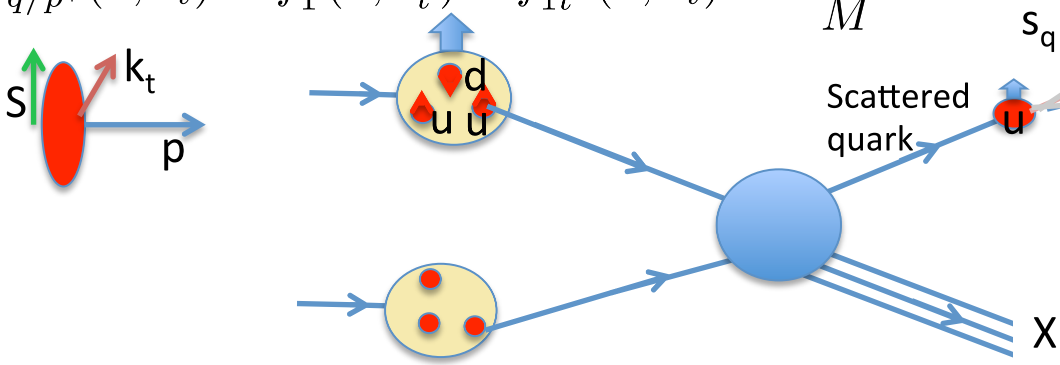
$$f_{q/p^{\uparrow}}(x,k_t) = f_1^q(x,k_t^2) - f_{1t}^{\perp q}(x,k_t)\frac{\mathbf{S}\cdot(\mathbf{k_t}\times\hat{\mathbf{p}})}{M}$$

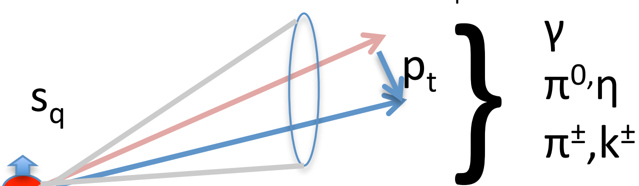
J. C. Collins, Nucl. Phys. **B396**, 161 (1993)

Collins effect :spin-momentum correlation in the hadronization process

$$\mathbf{s_q}\cdot(\mathbf{k_q}\times\mathbf{p_t})$$

Fragmentation, ΔD^h_q





s_q = spin fragmenting of quark
k_q = momentum direction of the quark
p_t = transverse momentum of hadron with respect to the direction of the fragmenting quark

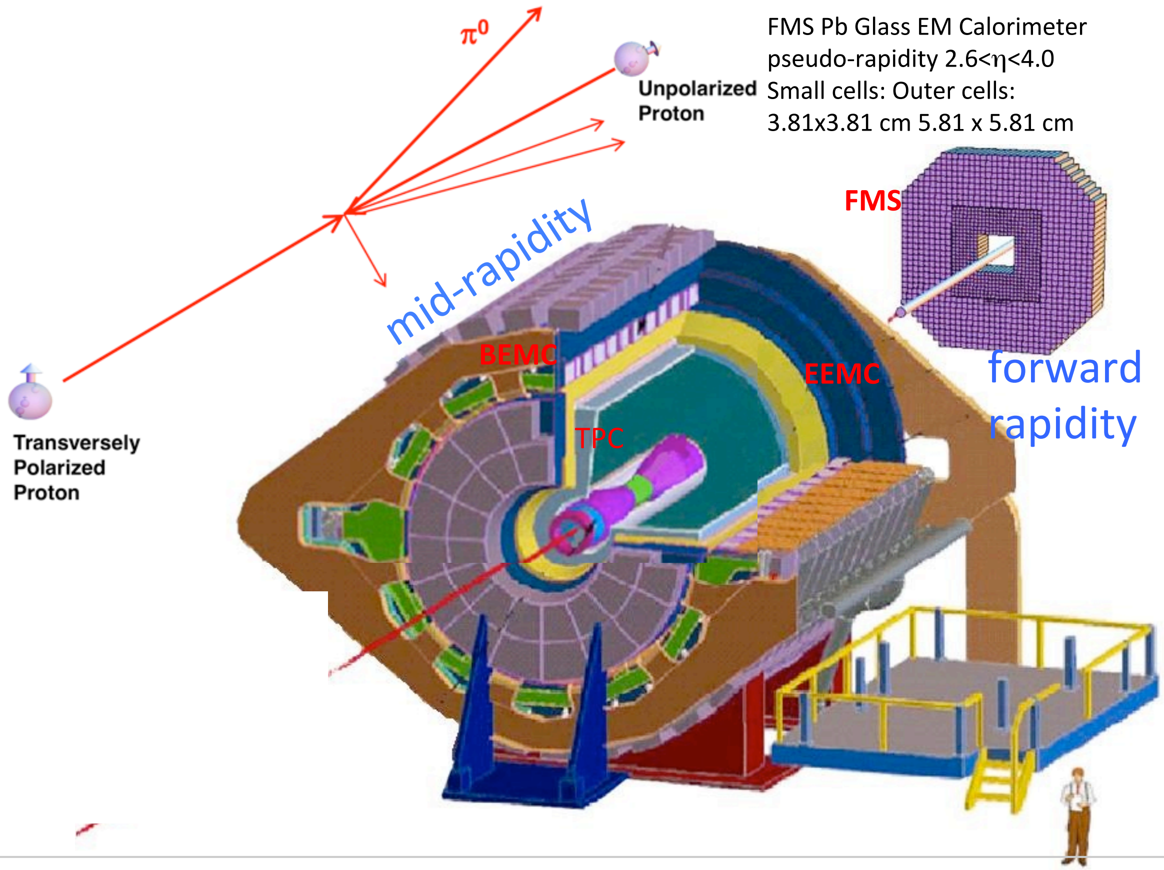
$$A_N = \quad \propto \underbrace{\bar{f}_{1T}^{\perp q}(x,k_\perp^2)}_{\text{Sivers distribution}}\cdot D_q^h(z) \;+\; \propto \underbrace{\delta q(x)}_{\text{Quark transverse spin distribution}}\cdot \underbrace{H_1^\perp(z_2,\bar{k}_\perp^2)}_{\text{Collins FF}}$$

need to move beyond inclusive production

- Sivers effect : full jets, direct photons, Drell-Yan
- Collins effect : azimuthal orientation of particles within a jet
- **Separating Sivers and Collins effects**

measurements from jets can give an access to Sivers effect

Forward EM Calorimeter in STAR

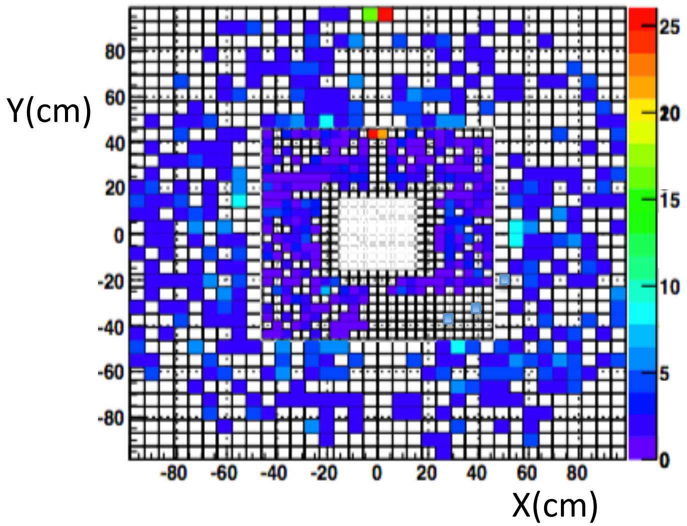


Forward Meson Spectrometer (FMS) :

- Pb glass EM calorimeter covering 2.6<η< 4.0
- Detect π^0,η, **direct photons** and jet-like events in the kinematic region where transverse spin asymmetries are known to be large

- FMS : A trigger detector : defined for **π^0/Jet-rich, Di- π^0/Jet-rich like triggers**

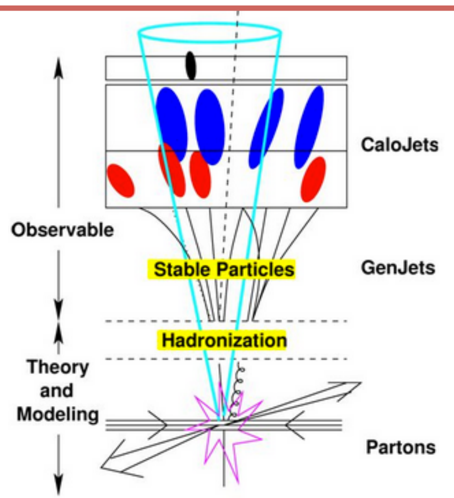
Jet in FMS: A tool implemented to access parton level kinematics



FMS photon reconstruction :

1. Towers energy
2. Clusters
3. Photons (shower shape fitting)

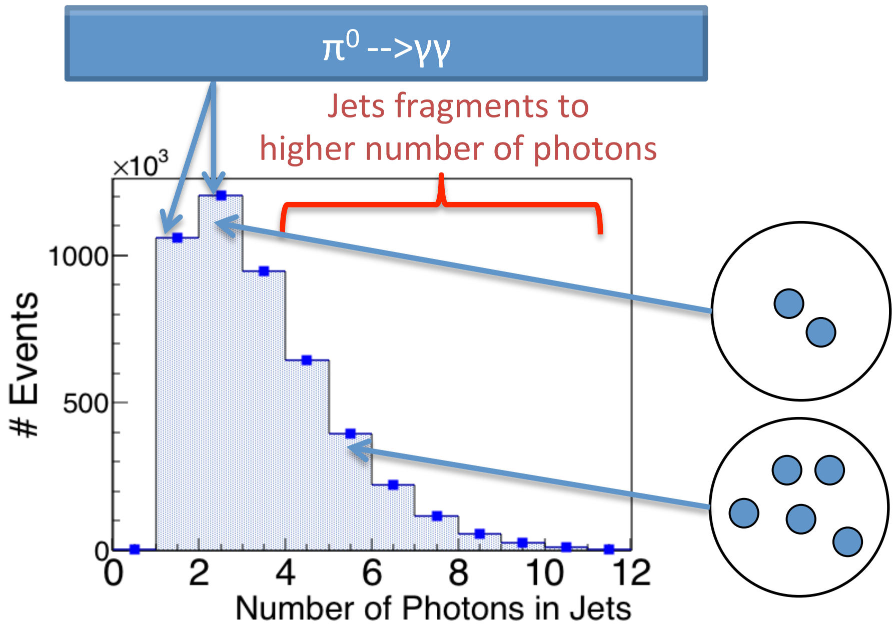
Reaching to the parton!!

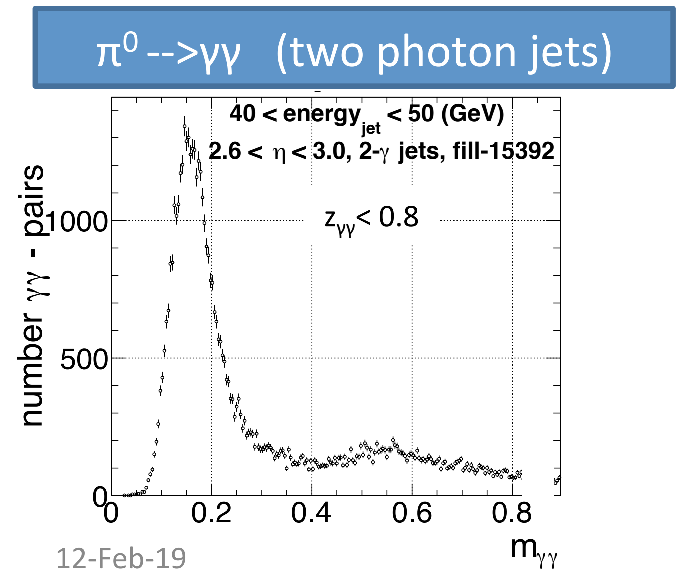


Jet Reconstruction :

- **STAR code for jet reconstruction developed for forward rapidity : neutral energy jet (EM Jet)**
- **anti-kt**
- **R=0.7**

Forward EM-jet



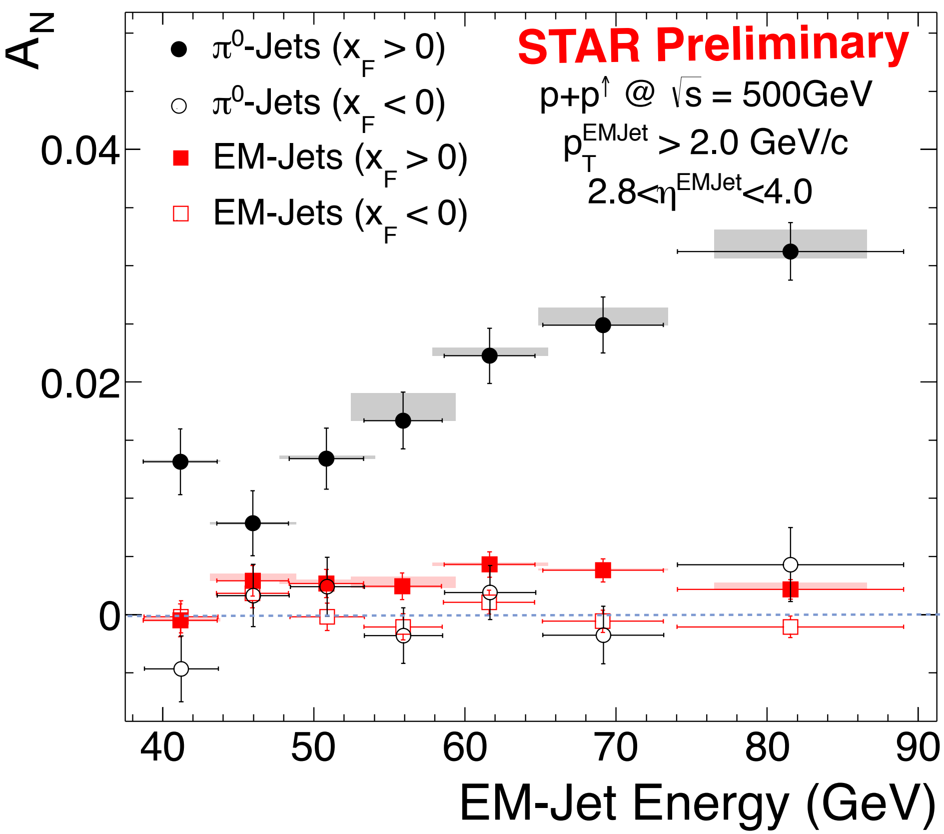


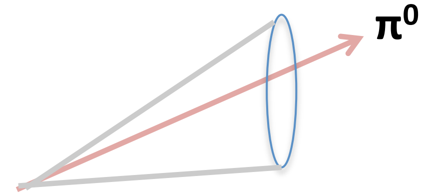
Two photon jets are mostly from π^0 –an isolated neutral pion

Looking for :

- How the asymmetry depends on energy (x_F)
- How the asymmetry depends on p_T
- How it varies when there is a correlated central jet - does isolated π^0 come from different production mechanism ?

A_N vs. EM-jet energy





π^0-Jets –

2γ-EM-Jets with

$m_{\gamma\gamma}$ <0.3

$Z_{\gamma\gamma}$ <0.8

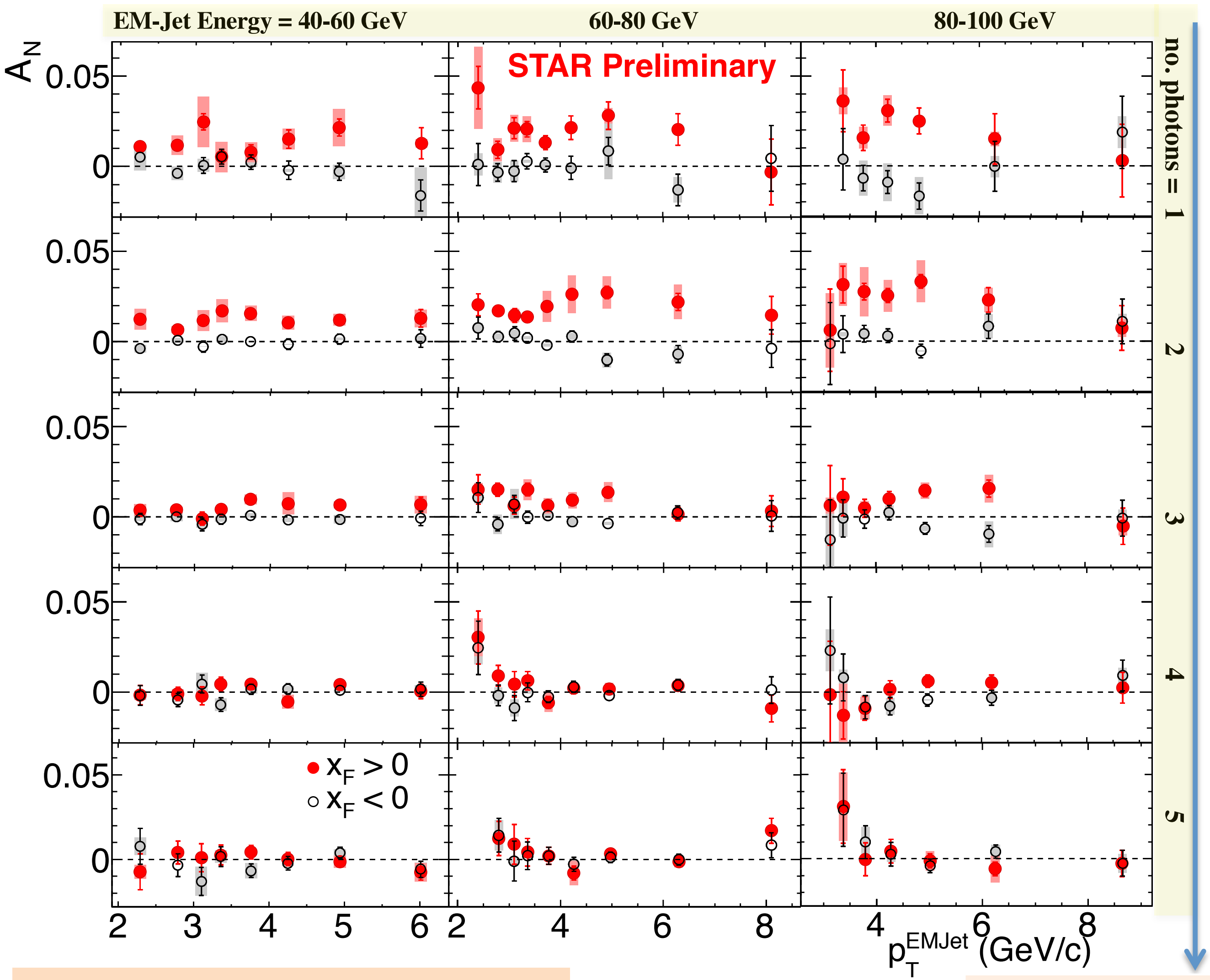
EM-Jets –

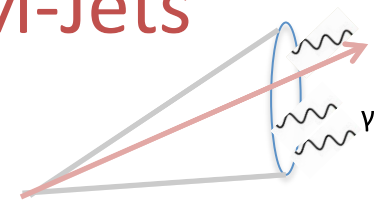
With number of photons >2

Asymmetries for single π^0 –jets events are much higher compared to jets with higher number of photons

M. M. Mondal [for STAR Coll.] PoS DIS 2014, 2016 (2014)

A_N for different # photons in EM-Jets



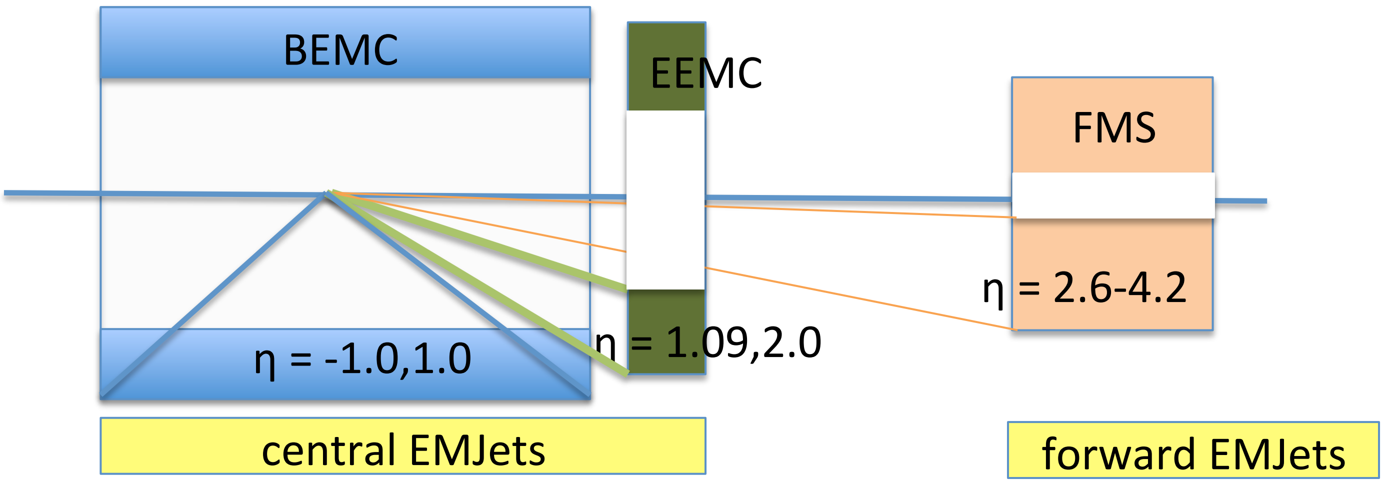


- ✧ 1-photon events, which include a large π^0 contribution in this analysis, are similar to 2-photon events
- ✧ Three-photon jet-like events have a clear non-zero asymmetry, but substantially smaller than that for isolated π^0's
- ✧ A_N decreases as the event complexity increases (jet like)
- ✧ A_N for #photons >5 is similar to that for #photons = 5

Jet like events

M. M. Mondal [for STAR Coll.] PoS DIS 2014

A_N with midrapidity activities



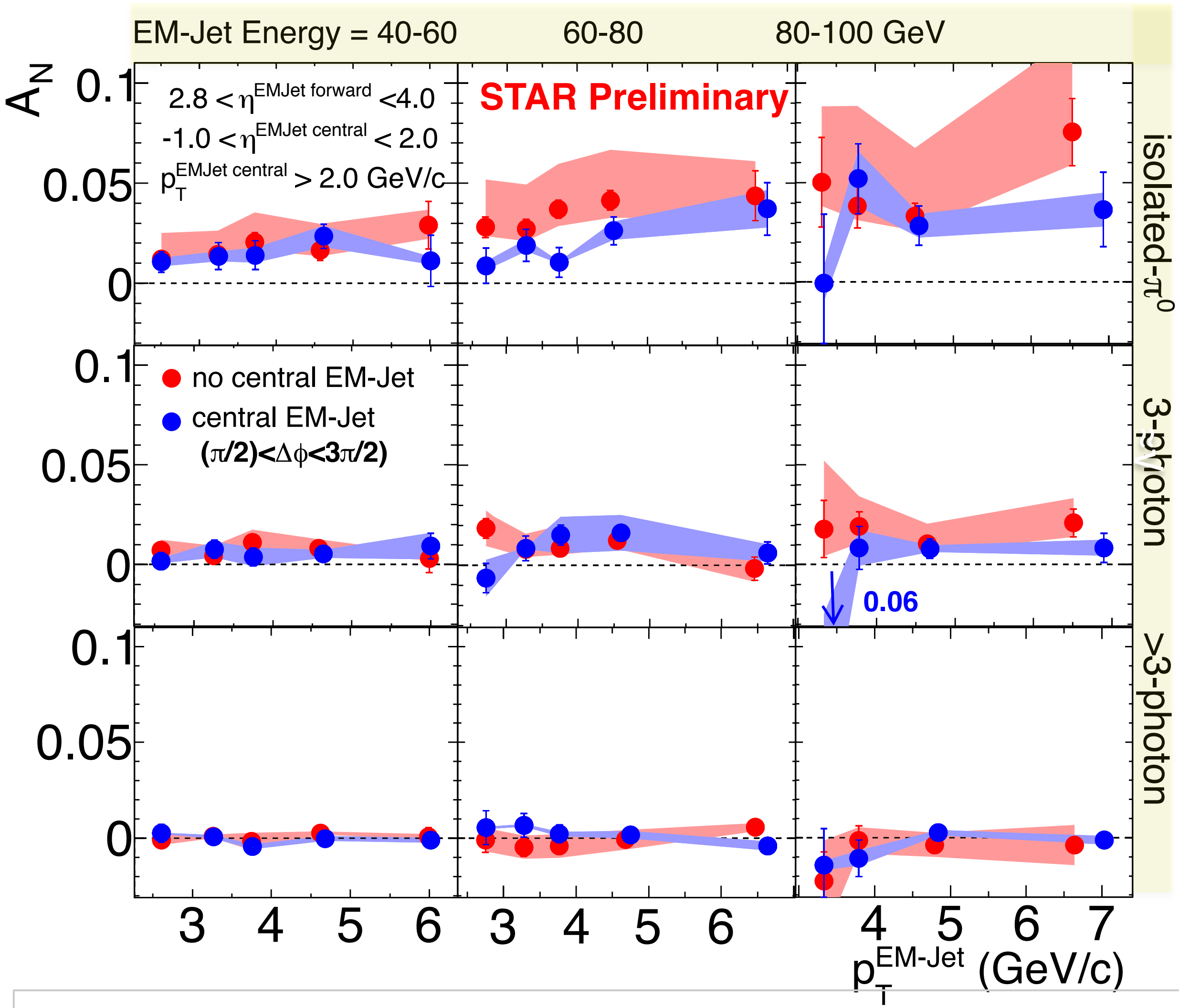
Midrapidity EM Jets

Jet algorithm : anti-k_T, R = 0.7
$p_T^{EM\text{-}Jet} > 2.0$ GeV/c, $-1.0 < \eta^{EM\text{-}Jet} < 2.0$

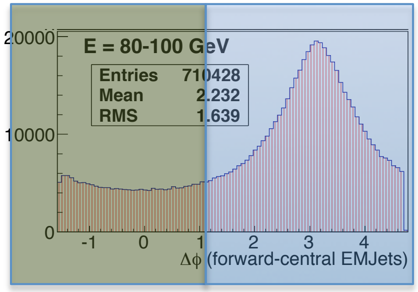
Inputs for central EMJets : towers from BEMC and EEMC

Leading central EM-Jets : Jet with highest p_T

A_N for correlated central jets and no central jet cases



Near and away side



Correlated central EM-Jet

✧ Asymmetries for the forward isolated π^0 are lower when there is a correlated away-side jet.

Summary on TSSA for EM jets

- Jets with **isolated π^0 have large asymmetry**
- **A_N decreases as the event complexity increases**
- Isolated π^0 **asymmetries are smaller when there is a correlated EM-jet** at mid-rapidity

- **Both of these dependences raise serious question how much of the large forward π^0 A_N comes from 2 → 2 parton scattering**

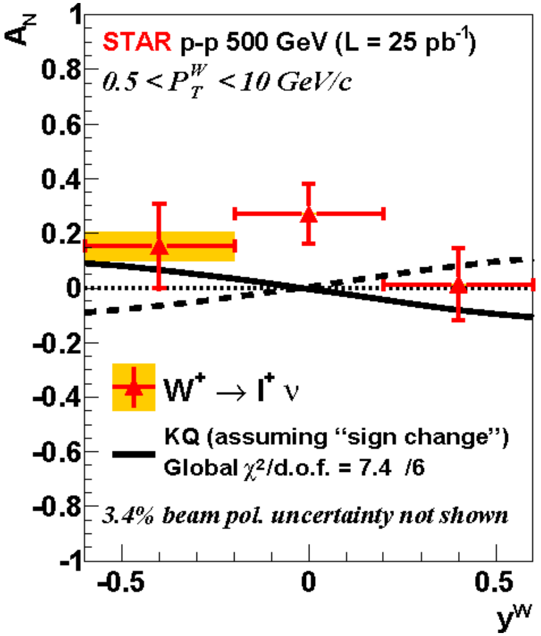
Diffractive Events ??

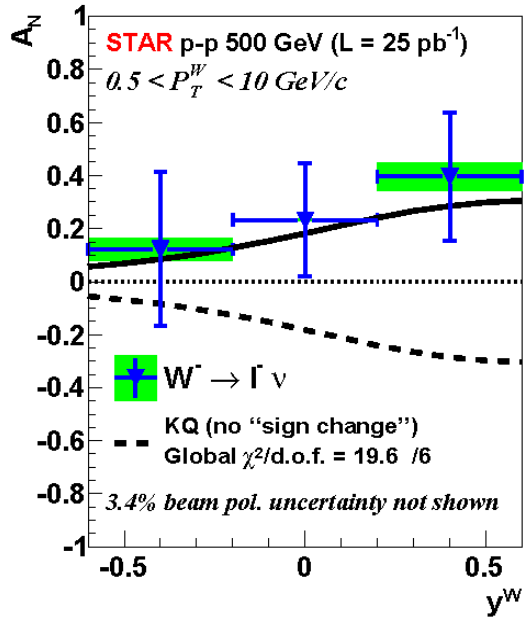
Forward upgrade for the STAR experiment - necessary to have better understanding

- Roman pots – tagging diffractive events
- FMS upgrade : with Forward pre-shower detector (direct photons) and post-shower detector (Drell-Yan)
- In 2020's STAR plan to have tracking and full calorimetry to detect **full jets in forward rapidity**

Other measurements related to transverse spin

Transverse: Sivers $A_N(W)$





PRL 116, 132301 (2016)

Run 2011: $A_N(W)$@500GeV
W kinematics fully reconstructed
Sign change compared to DIS

$Sivers_{DIS} = -Sivers_{Drell\text{-}Yan}$

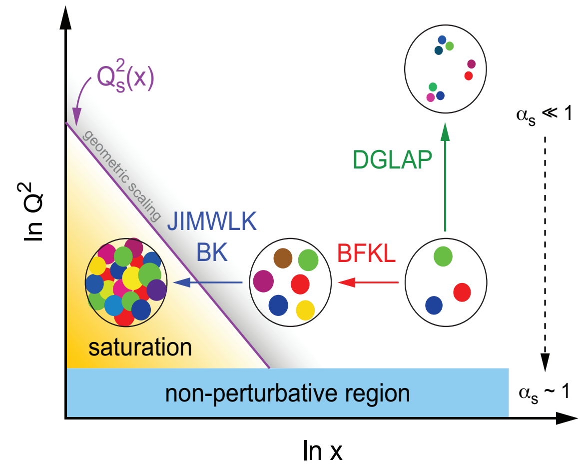
Run 2017 data : $A_N(W)$, $A_N(DY)$, $A_N(\gamma)$
See the sign change
Probe anti-quark Sivers function for the first time
Directly measure the evolution effect

Transversity from midrapidity jets

- Di-hadron interference fragmentation function (IFF)
- Collins fragmentation

Gluon saturation at RHIC

- Densities of gluons and sea quarks are high at low x
- Leading to Saturation of parton density, called Color Glass Condensate (CGC)



pA@200GeV : **Nuclei** may allow access to the saturation region at moderate p_T

$$(Q_s^A)^2 \approx cQ_0^2 \left(\frac{A}{x} \right)^{1/3}$$

Smll x :**Forward rapidity** :

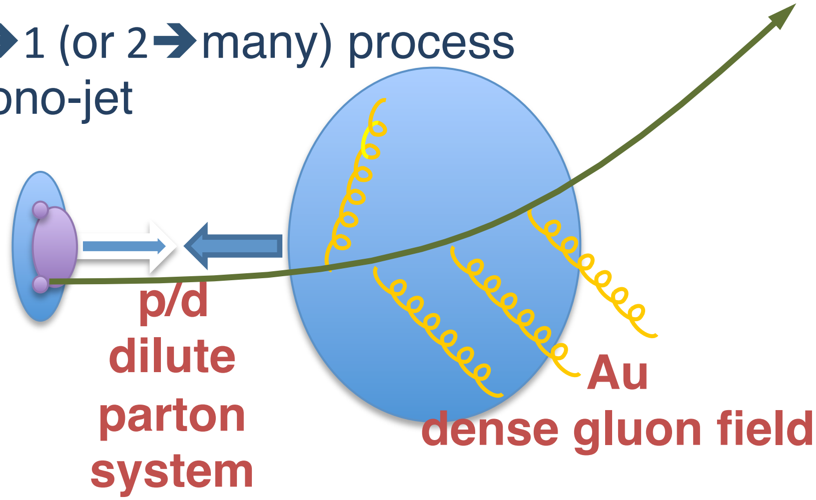
$$x \sim \frac{2p_T}{\sqrt{s}} e^{-y}$$

Back-to-back angular correlations at RHIC

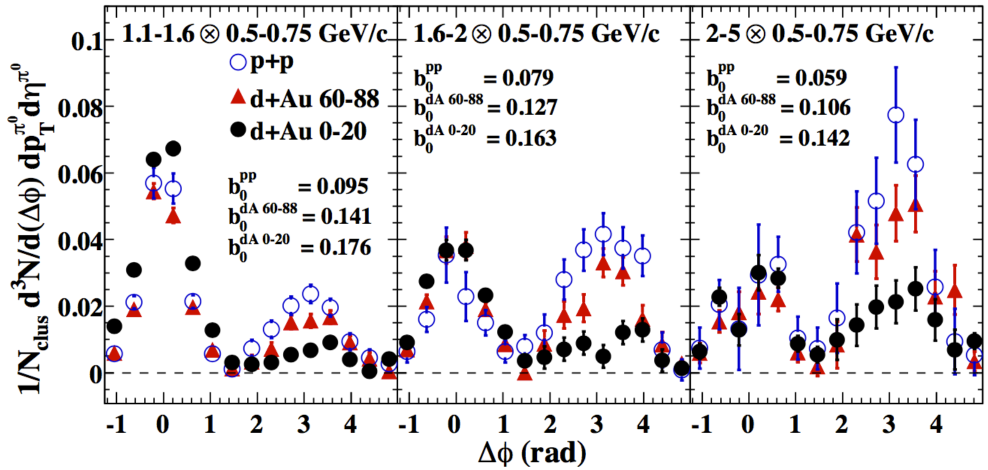
Kharzeev, Levin, McLerran (NPA748, 627)

Jet Azimuthal Correlation : Suppression

2➔1 (or 2➔many) process
Mono-jet



PHENIX, PRL 107, 172301



CGC predicts suppression of the away-side peak : PHENIX observed suppression of the away-side peak in 0-20% d+Au collisions at (√s = 200 GeV)

STAR data 2015 : p+p, p+Al, p+Au at √s = 200 GeV

- analyzed for π^0- π^0 and EM jet – EM jet azimuthal correlations
- Ongoing Work on FMS gain uniformity and stability

Physics with STAR in 2021+

Opportunity :

- Unique program addressing several fundamental questions in QCD

Motivation: (The RHIC Cold QCD Plan for 2017 to 2023: A Portal to the EIC (arXiv: 1602.03922))

- Central to the mission of the RHIC physics program in cold and hot QCD
- Fully realize the scientific promise of the EIC
  - Lay the groundwork for the EIC, both scientifically and by refining the experimental requirements
  - Test EIC detector technologies under real conditions, i.e SiPMs

Take full advantage of STAR's unique capability including upgrades for BES-II:

- Midrapidity program based on existing STAR detector utilizing iTPC, eToF and EPD upgrades (https://drupal.star.bnl.gov/STAR/starnotes/public/sn0669)
- Forward rapidity program based on upgrade consisting of Hcal + Ecal+ Tracking (Si + sTGCs) at $2.5 < \eta < 4$ (https://drupal.star.bnl.gov/STAR /starnotes/public/sn0648)

Goal: Complete upgrade for potential polarized pp@500 GeV run in 2021 and the sPHENIX data taking periods

Summary

- STAR play important role in measuring gluon contribution in proton's spin and transverse spin structure of proton

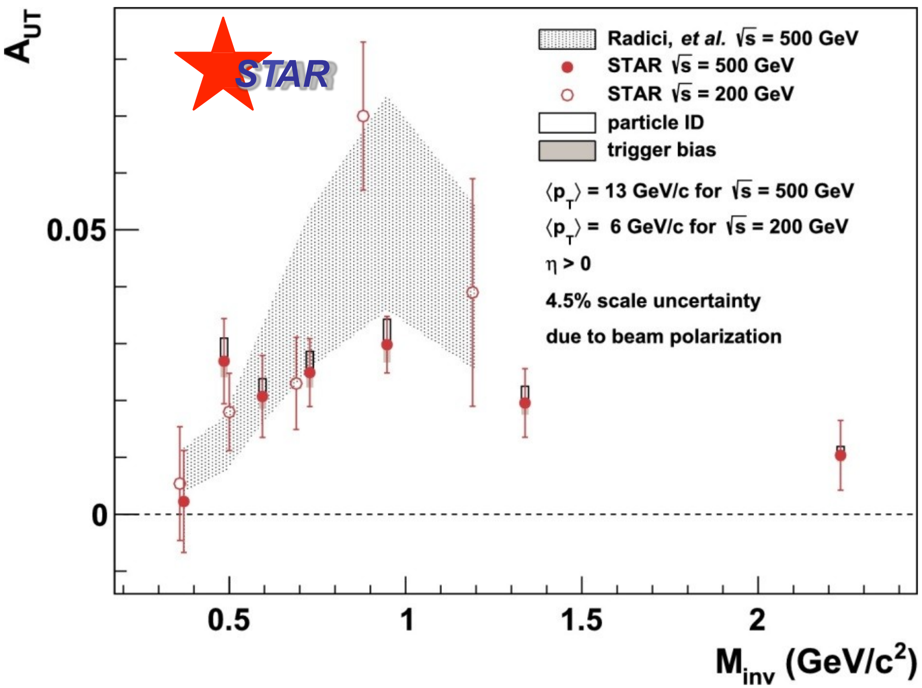
- STAR had rich data from 2015 and 2017 :
  - spin data which are under analysis $A_N(W)$, $A_N(DY)$, $A_N(\gamma)$, A_N(EM Jets, neutral pions) with forward tagged protons
  - p+A data for saturation physics

- STAR forward upgrade (2021+) adds capability of forward full jet measurements
  - to address critical questions
  - To fully realize the scientific promise of the future EIC

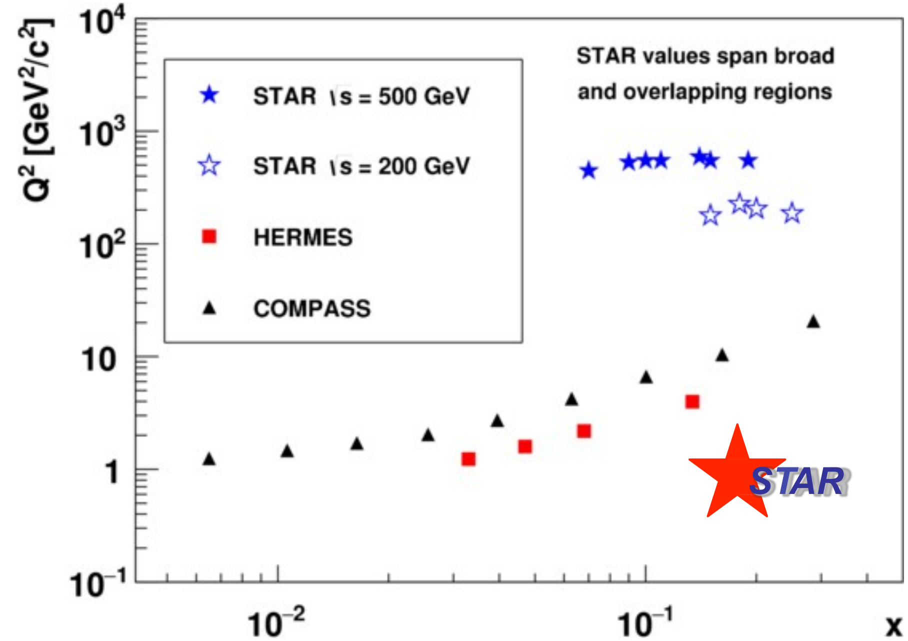
Thank you

Transverse: *IFF Transversity Measurements*

PLB 780, 332 (2018)



PLB 780, 332 (2018)



- **STAR measurements provide the first observations of transversity at very high scales**
- ***STAR*** IFF measurements in 200 and 500 GeV pp collisions are well described by recent IFF calculations

Transverse: Collins

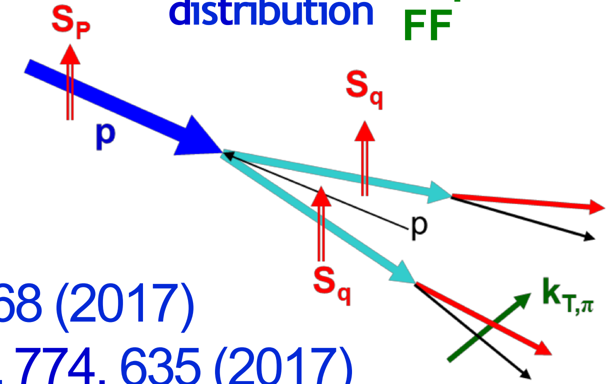
$\propto \delta q(x) \times H_1^{\perp}(z_2, \bar{k}_{\perp}^2)$

Quark transverse spin distribution

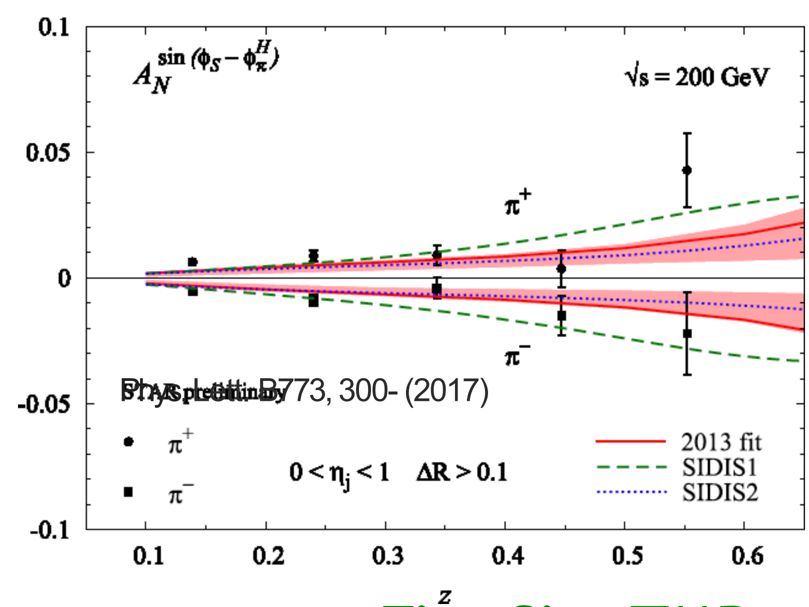
"Collins" spin dependent FF

200 vs. 500 GeV Comparison:

- Evolution: 200 GeV ⟷ 500 GeV factor 3 in Q
- Test of factorization & Universality
  - → compare with transversity from IFF
  - → compare with SIDIS and e+e-
- Inspired a lot of theory work
  - → Proof of factorization: Kang et al. JHEP1711, 068 (2017)
  - → Asymmetry calculation: Kang et al. Phys.Lett B. 774, 635 (2017)
  - → Universality: D'Alesio et al. Phys.Lett. B773, 300 (2017)

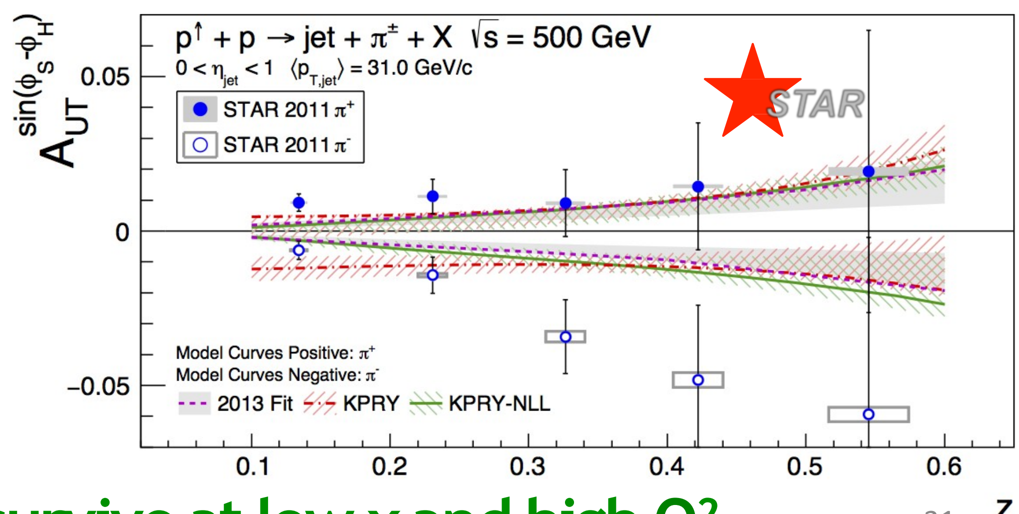


final state effect



$\pi^{\pm}$ **azimuthal distribution in jets**

STAR: PRD 97, 032004 (2018) (arXiv:1708.07080)

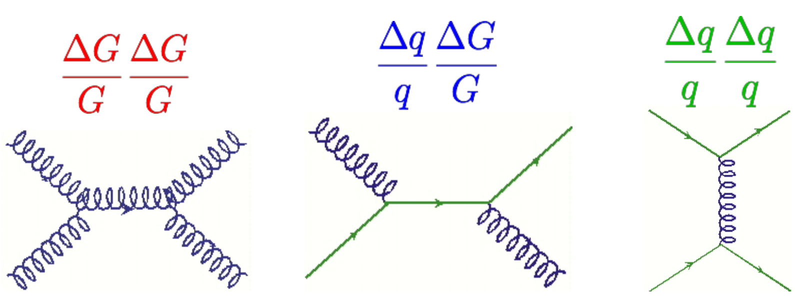


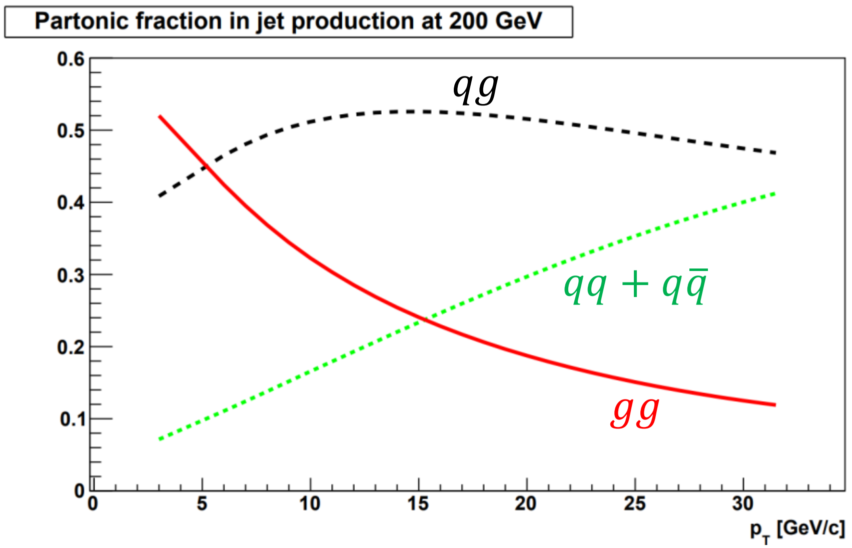
First Sign TMDs survive at low x and high Q^2

Gluon polarization at RHIC

$$\Delta G = \int \Delta g(x)dx$$

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

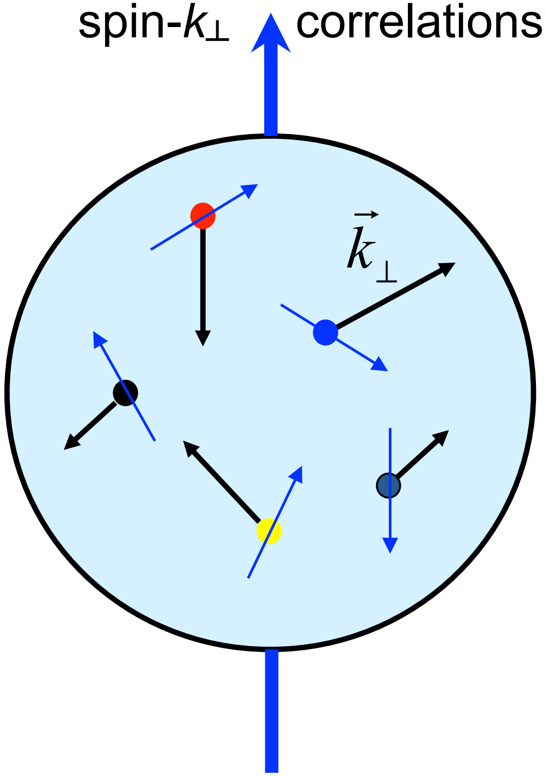




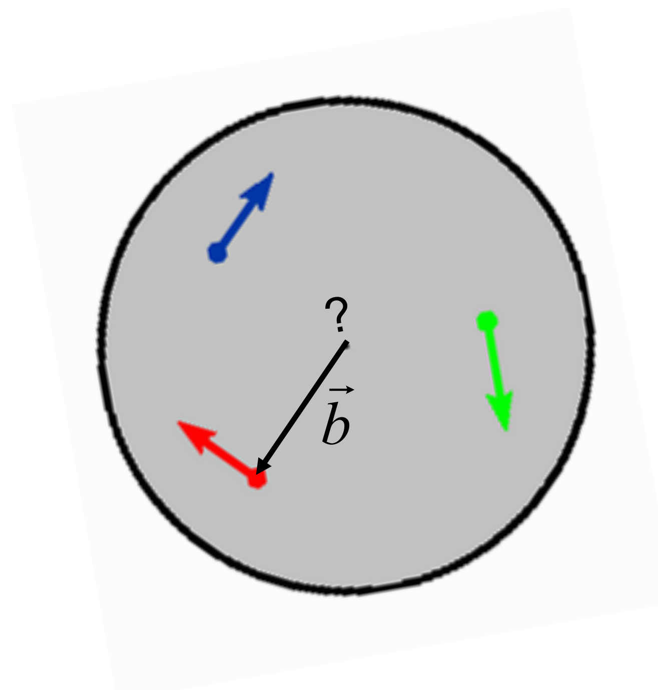
For most RHIC kinematics, qg, gg dominates making A_{LL} for jets sensitive to gluon polarization

Transverse spin structure is less studied

spin-$k_\perp$ correlations?



orbiting quarks?



Transverse Momentum Dependent distribution functions

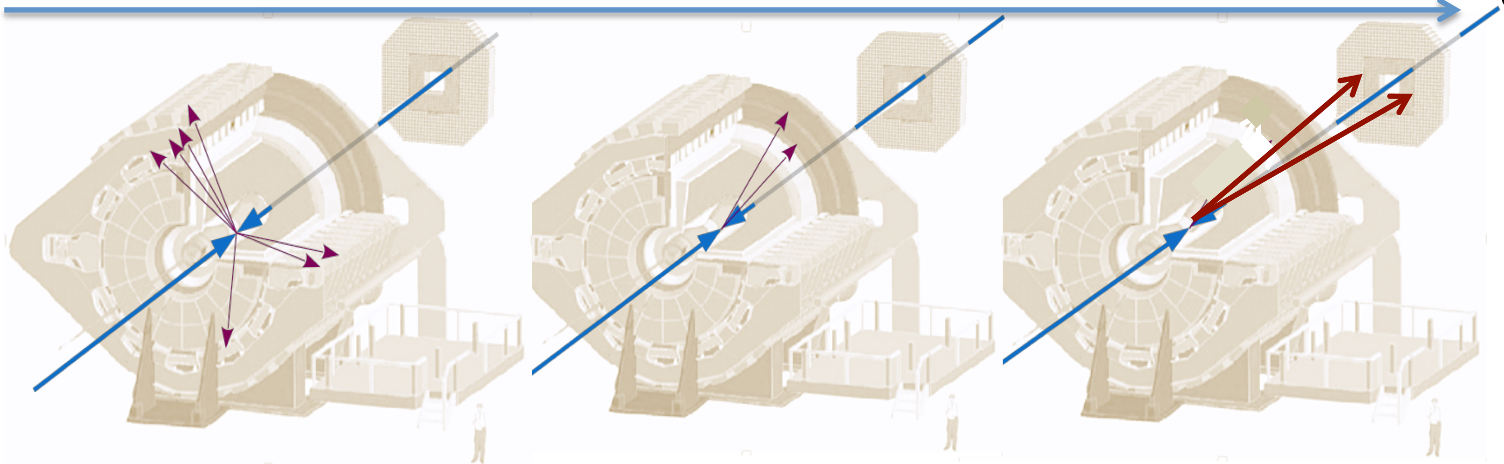
$$q(x, \boldsymbol{k}_\perp; Q^2)$$

Space dependent distribution functions

$$q(x, \boldsymbol{b}; Q^2)$$

x reach in in STAR experiment

Probing smaller in x



Di-jet give better control in kinematics

$$x_1 = \frac{1}{\sqrt{s}}\left(p_{T3}e^{\eta_3} + p_{T4}e^{\eta_4}\right)$$

$$x_2 = \frac{1}{\sqrt{s}}\left(p_{T3}e^{-\eta_3} + p_{T4}e^{-\eta_4}\right)$$

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

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

$$|\cos\theta^*| = \tanh\left|\frac{\eta_3 - \eta_4}{2}\right|$$

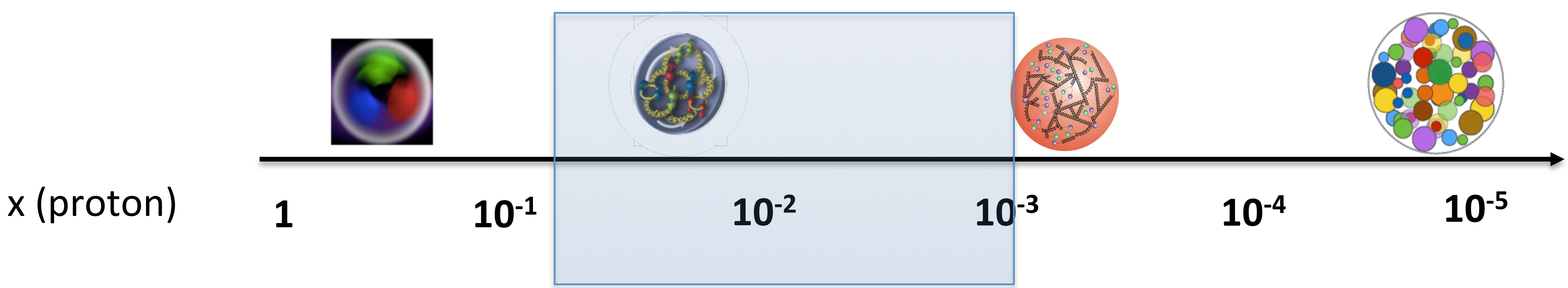
$x > 0.05$ | $x > 0.01$ | $x > 0.001$

Few-body/ valence quark Regime

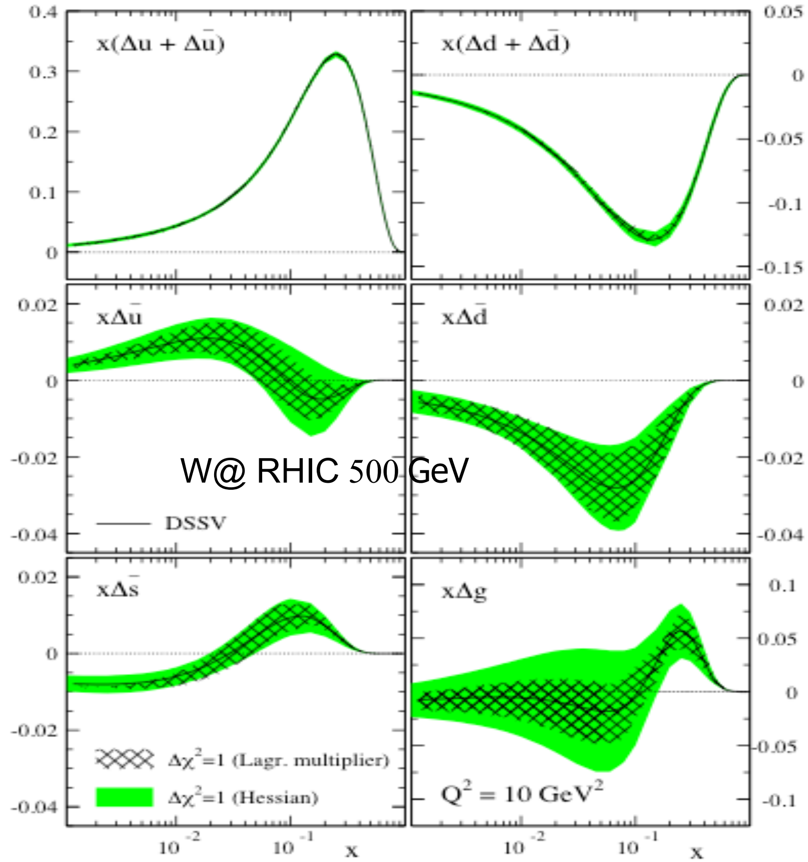
Many-body Regime

QCD radiation dominated Regime

non-linear dynamic Regime



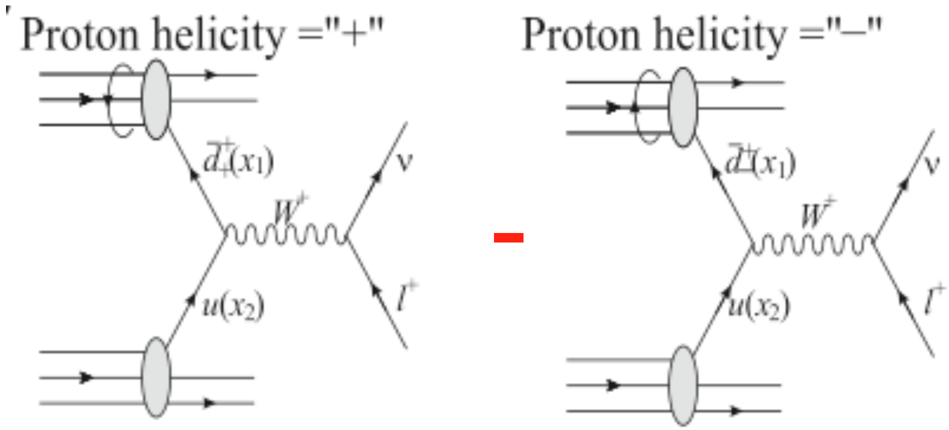
Sea quark polarization not well constrained by DIS data yet



D. de Florian, R. Sassot, M. Stratmann, W. Vogelsang, PRD80 (2009)034030

Probing sea quark polarization via W production

- Quark polarimetry with W's in p+p collision (example of W^+):



$$\propto \Delta\bar{d}(x)u(x)$$

W-detection through high energy lepton

- Spin asymmetry measurements:

$$A_L^{W^+} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{-\Delta u(x_1)\bar{d}(x_2) + \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)} = \begin{cases} -\dfrac{\Delta u(x_1)}{u(x_1)}, & y_{W^+} >> 0 \\ \dfrac{\Delta\bar{d}(x_1)}{\bar{d}(x_1)}, & y_{W^+} << 0 \end{cases}$$

$$A_L^{W^-} = \begin{cases} -\dfrac{\Delta d(x_1)}{d(x_1)}, & y_{W^-} >> 0 \\ \dfrac{\Delta\bar{u}(x_1)}{\bar{u}(x_1)}, & y_{W^-} << 0 \end{cases}$$