THE RHIC SPIN PROGRAM

ACHIEVEMENTS AND FUTURE OPPORTUNITIES

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BROOKHAVEN NATIONAL LABORATORY
a passion for discovery

U.S. DEPARTMENT OF ENERGY | Office of Science

SPIN: FUNDAMENTAL QUANTUM NUMBER

SPIN is one of the fundamental properties of matter
all elementary particles, but the Higgs carry spin
Studying Spin revealed many surprises in physics
→ proton anomalous magnetic moment → substructure
cannot be explained by a static picture of the proton

Proton Spin:

It is more than the number $\frac{1}{2}$! It is the interplay between the intrinsic properties and interactions of quarks and gluons

If we do not understand the proton spin in QCD,
we do not fully understand QCD !

need a polarized collider to have full access to the proton dynamics

FUNDAMENTAL QUESTIONS

- How do quarks and gluons conspire to provide the proton's spin 1/2

$$\frac{1}{2}\hbar = \left\langle P,\frac{1}{2}\middle| J^z_{QCD} \middle| P,\frac{1}{2}\right\rangle = \underbrace{\sum_q \frac{1}{2}S^z_q}_{\text{total quark spin}} + \overbrace{S^z_g}^{\text{gluon spin}} + \underbrace{\sum_q L^z_q + L^z_g}_{\text{angular momentum}}$$

Gluons account for 50% to the proton's momentum

Gluons and sea quarks dominate the proton structure at x<0.2

Remember: x-distribution of PDF provides insight of pertubative vs. non-pertubative effects

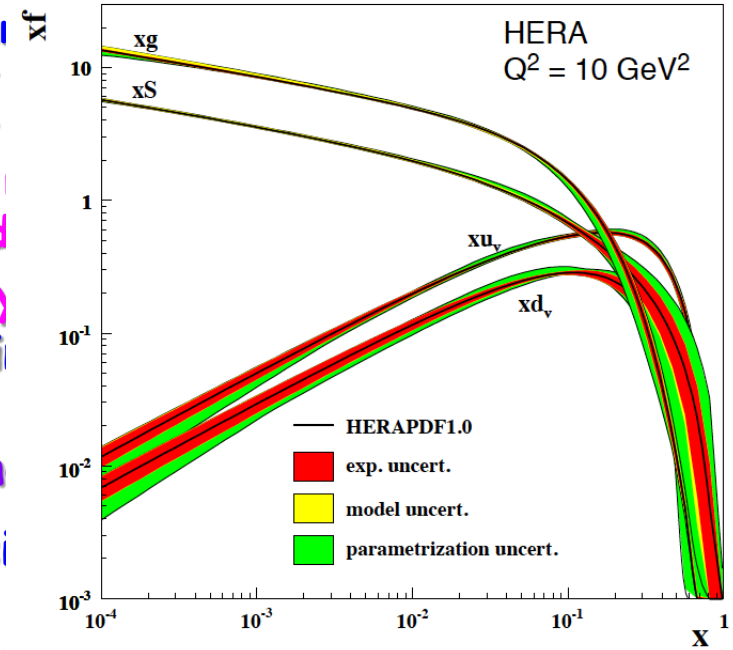
Can qua

→ what

→ what

→ How

need



RHIC SPIN

- What is the dy

2D+1 picture i

Visualize color

collective phen

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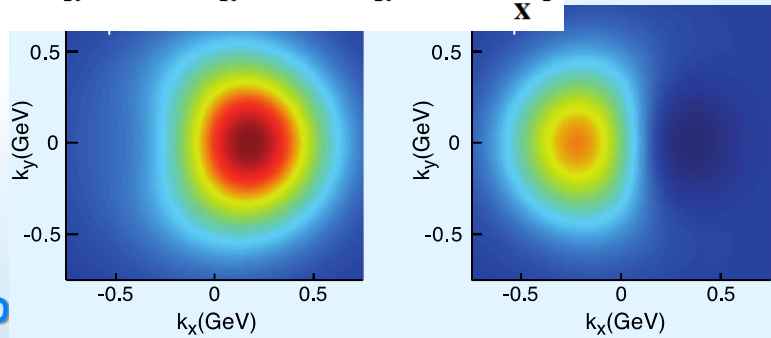
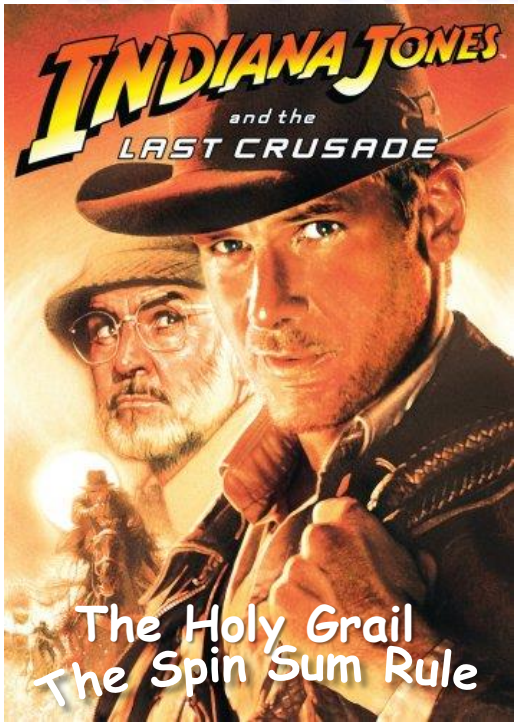
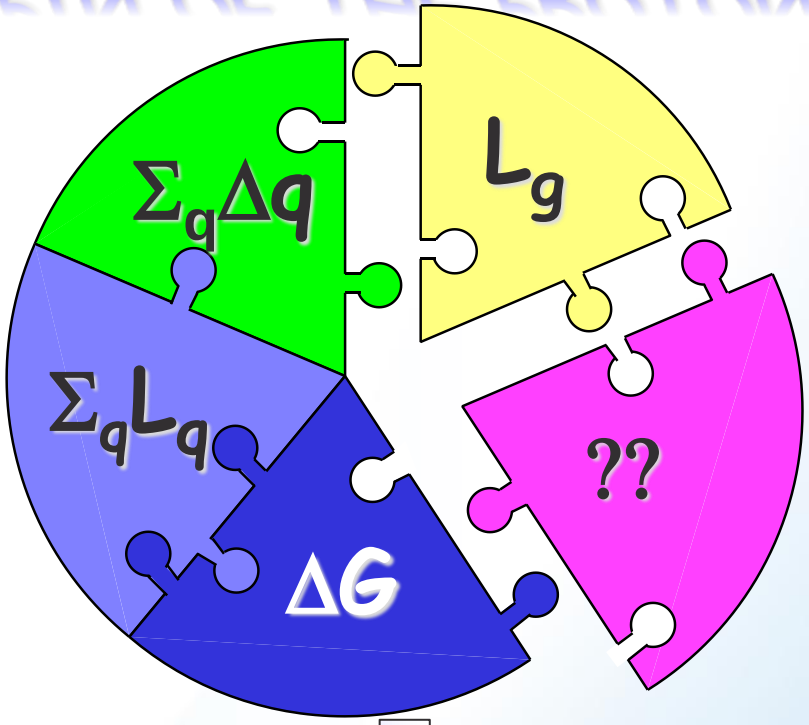


WHAT COMPOSES THE SPIN OF THE PROTON





"Helicity sum rule"

$$\frac{1}{2}\hbar = \left\langle P,\frac{1}{2}\middle| J^z_{QCD} \middle| P,\frac{1}{2}\right\rangle = \overbrace{\sum_q \frac{1}{2} S^z_q}^{\text{total quark spin}} + \overbrace{S^z_g}^{\text{gluon spin}} + \overbrace{\sum_q L^z_q + L^z_g}^{\text{angular momentum}}$$

Can quarks and gluons explain all the spin?

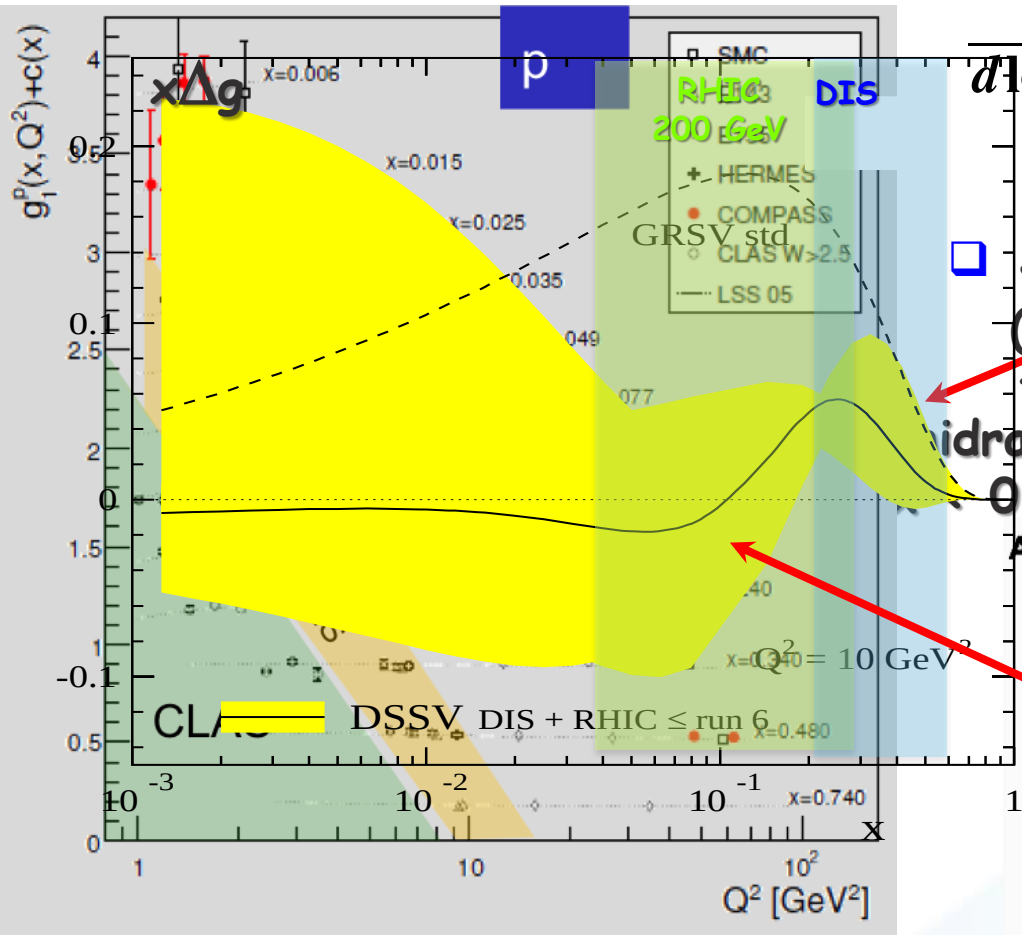
→ what is the role of gluons?

→ what is the role of sea quarks?

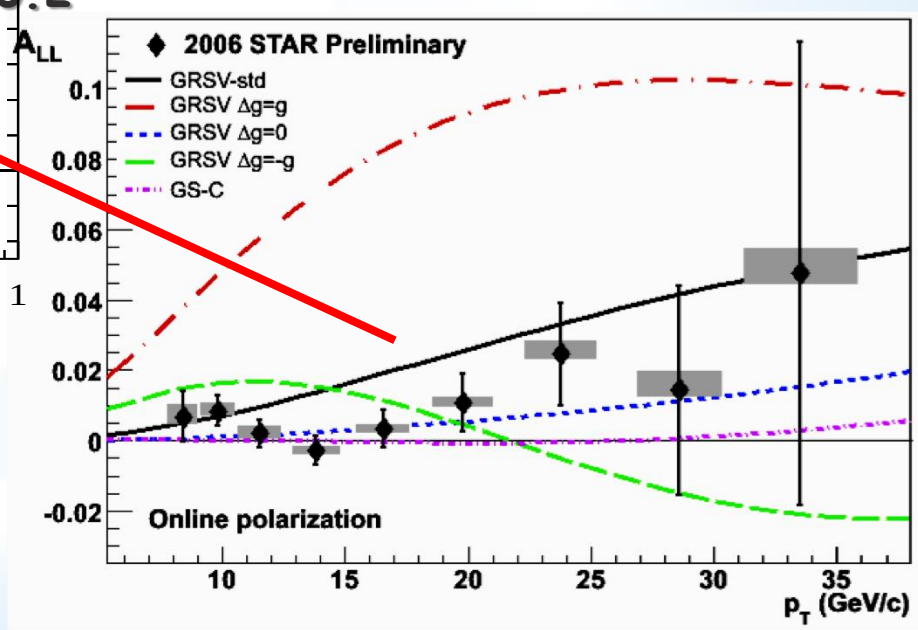
→ How much orbital angular momentum is needed?

ΔG FROM EARLY DIS AND POLARIZED p+p DATA

$$\frac{dg_1}{d\log(Q^2)} \sim -\Delta g(x,Q^2)$$



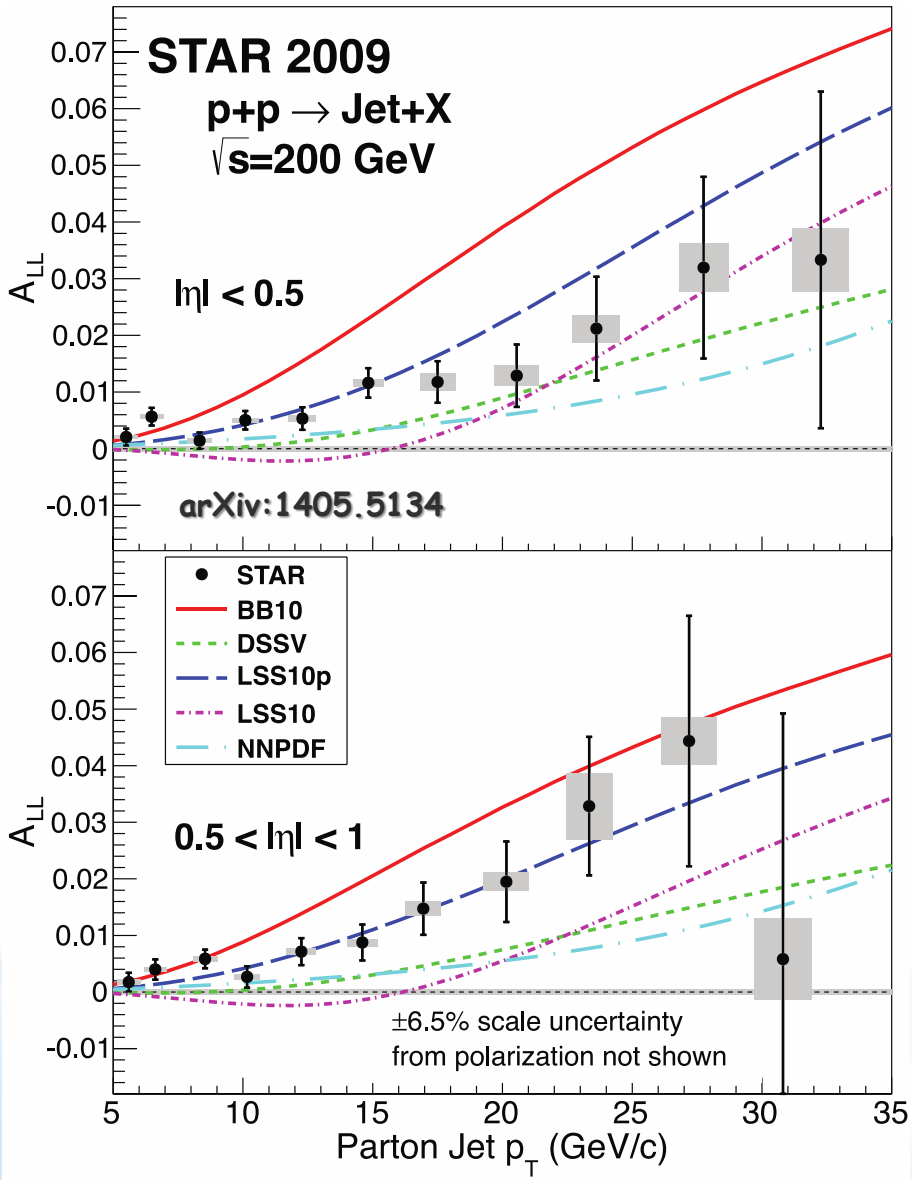
- Scaling violations of g_1 (Q^2-dependence) give indirect access to the gluon distribution via DGLAP evolution.
- Hadron rapidity: direct access to gluons (gg,qg)



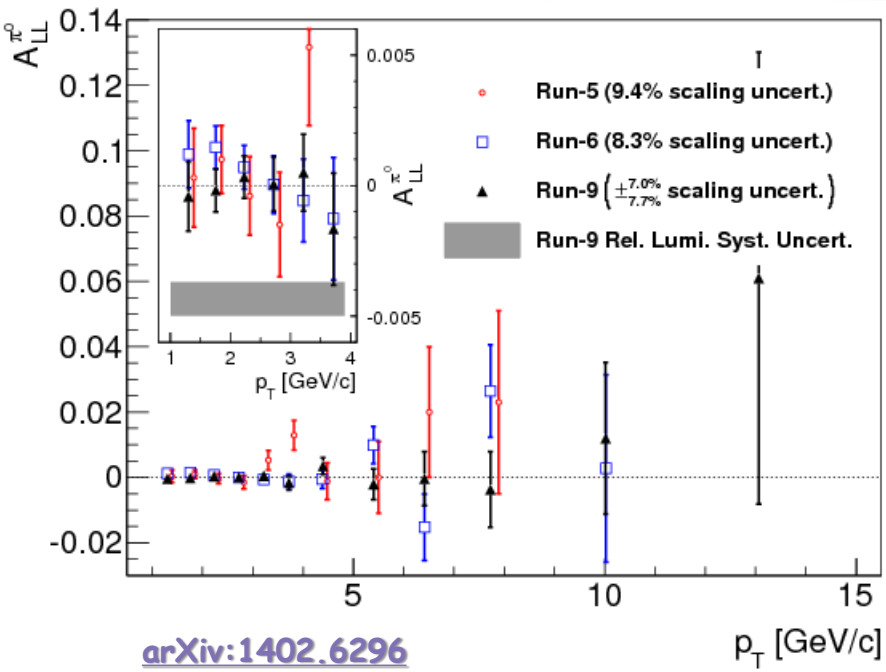
Integral in RHIC x-range:

$$\int_{0.05}^{0.2} dx\Delta g \sim 0.005 \pm^{0.129}_{0.164} \text{ @ } 10\ \text{GeV}^2$$

HIGH PRECISION 2009 RHIC DATA→∫Δg(X)



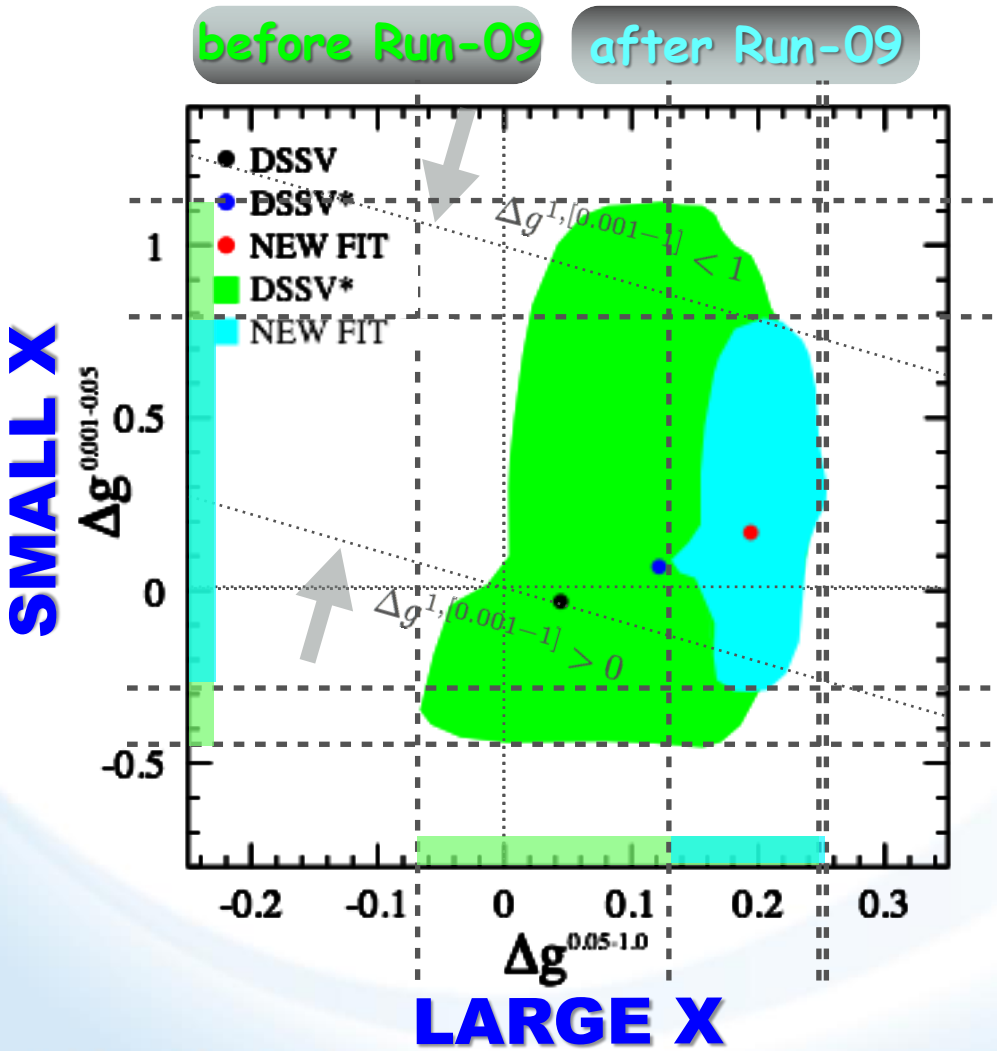
PHENIX



EXTRACTION OF $\int \Delta g(X)$

QCD analysis of world data; especially new 2009 RHIC data

DSSV: arXiv: 1404.4293, PRL 113, 012001



gluon contribution (down to x ~10^{-3}) looks positive and smaller than 1

$$\int_{0.05}^{1.0} dx \Delta g \sim 0.2 \pm^{0.06}_{0.07} @\ 10\ \mathrm{GeV}^2$$

First time a significant non-zero $\Delta g(x)$

what about very small x (x < 10^{-3})? how can we reduce the uncertainty?

NEW DATA

Reduce uncertainties:

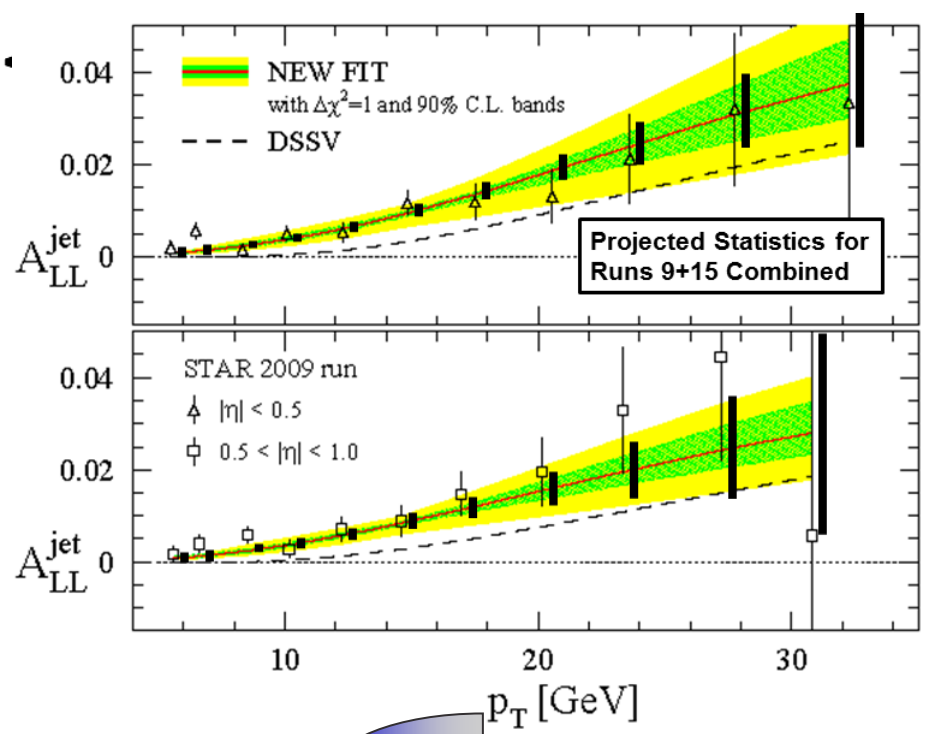
at low x → higher beam energy → new 500 GeV data at mid-rapidity

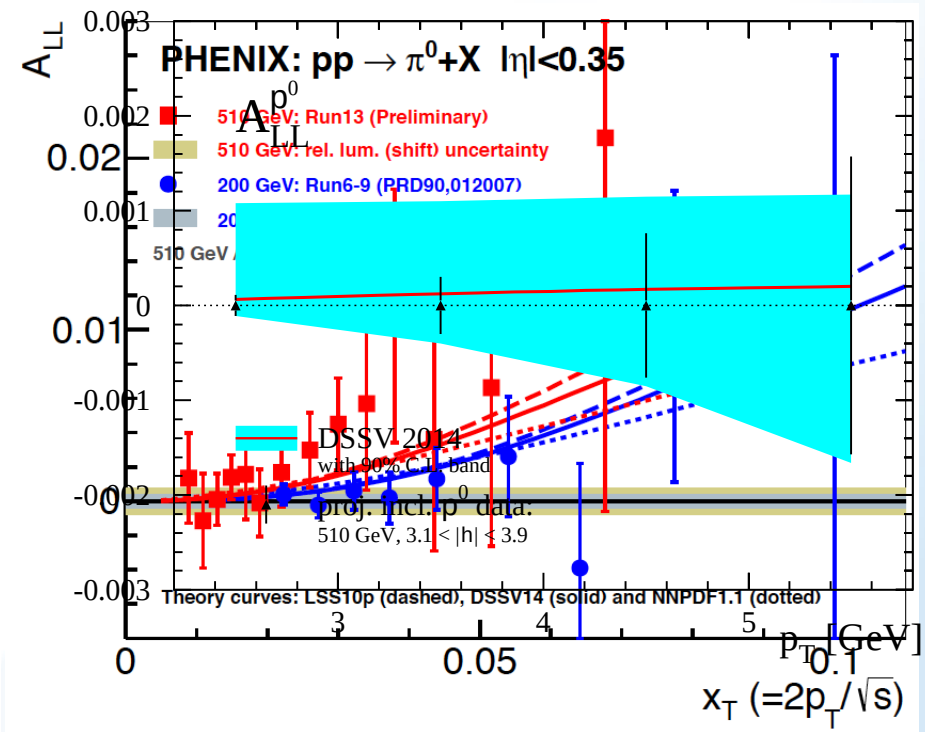
→ go to forward rapidities $|\eta| > 1$

overall: more statistics

several other channels, i.e. di-jets, charged pions, J/Ψ, …..

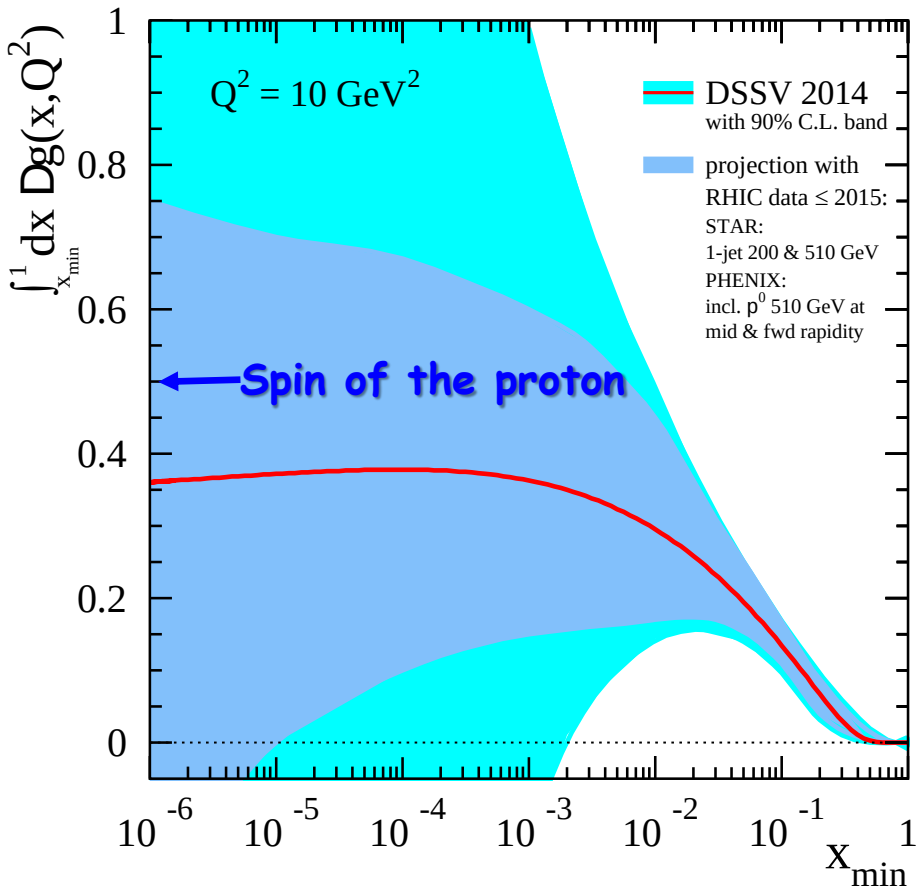
sometimes lower statistics, but very different systematics





New data sets will have a high impact

FURTHER IMPROVED KNOWLEDGE ON $\Delta g(x, Q^2)$



factor 2 reduced uncertainties at $x \sim 10^{-3}$

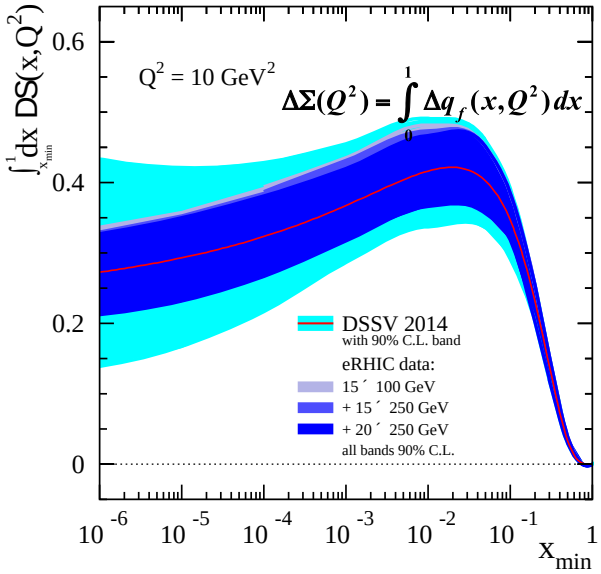
Gluons: ~72%

$$\int_{10^{-6}}^{1.0} dx \Delta g \sim 0.36 @\ 10\ GeV^2$$

Lets see what RHIC can teach us about Δq_f

WHY IS SEPARATING QUARK FLAVORS IMPORTANT?

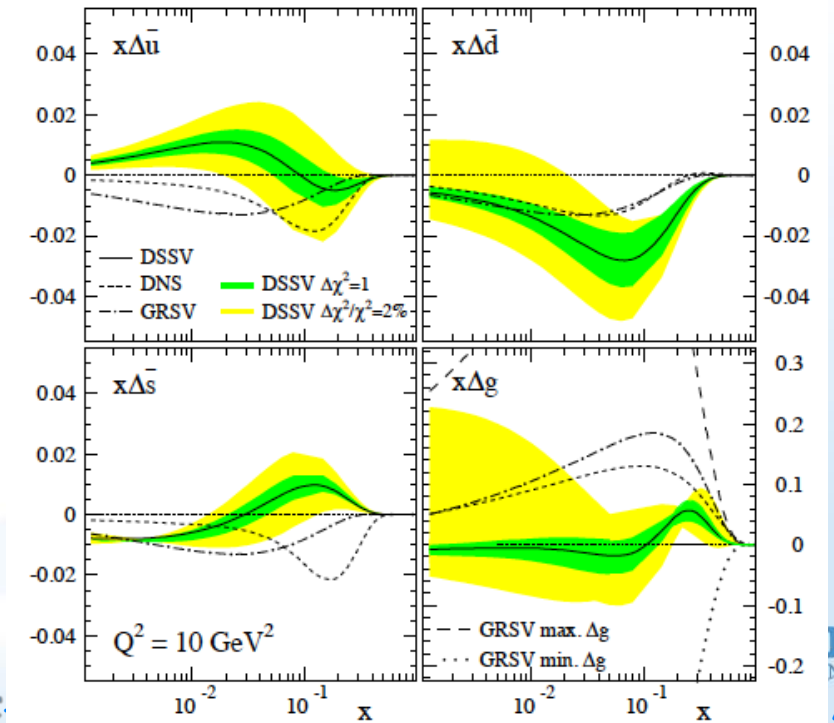
- nuclear structure is encoded in PDF
- understand dynamics of the quark-antiquark fluctuations
- flavor asymmetry in the light quark sea in the proton
  unpolarized: ubar ≠ dbar → caused by non-pertubative effects
  polarized case ?
- shape of polarized sea-quark PDFs critical for quark contribution to spin



Drop of integral due to shape of polarized sea quark PDFs at low x
→ forced by 3F-D constrain in PDF fits

$$\int_{0.001}^{1} dx\Delta\Sigma \sim 0.366 \pm^{0.042}_{0.062} @10GeV^2$$

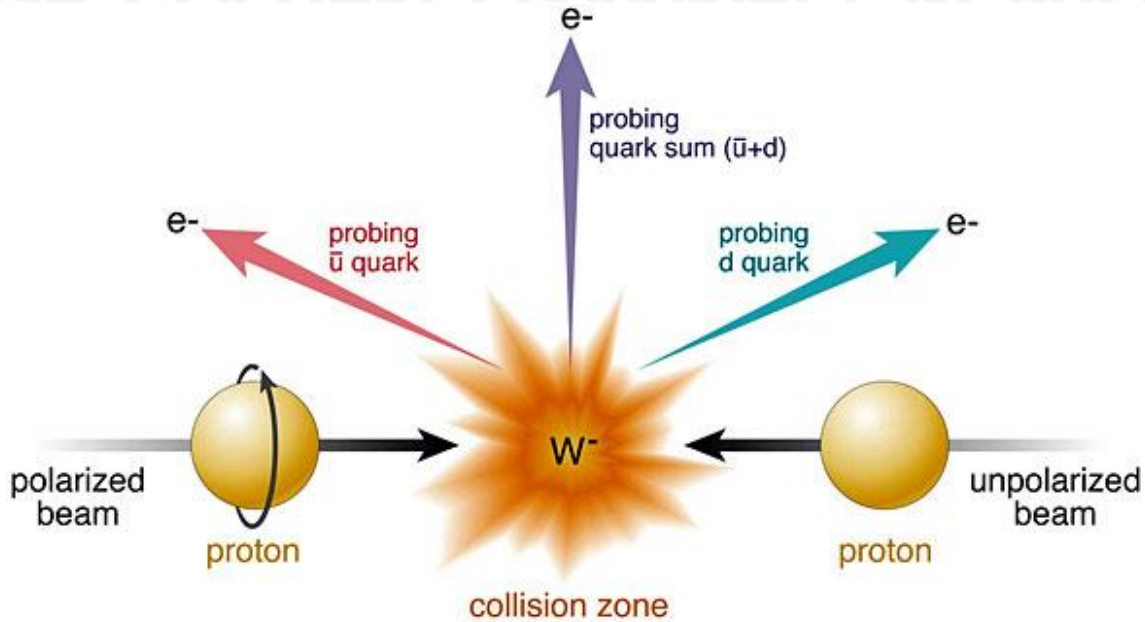
$$\int_{0}^{1} dx\Delta\Sigma \sim 0.242 @10GeV^2$$



THE GOLDEN CHANNEL: W PRODUCTION

$u\bar{d} \rightarrow W^+$

$d\bar{u} \rightarrow W^-$

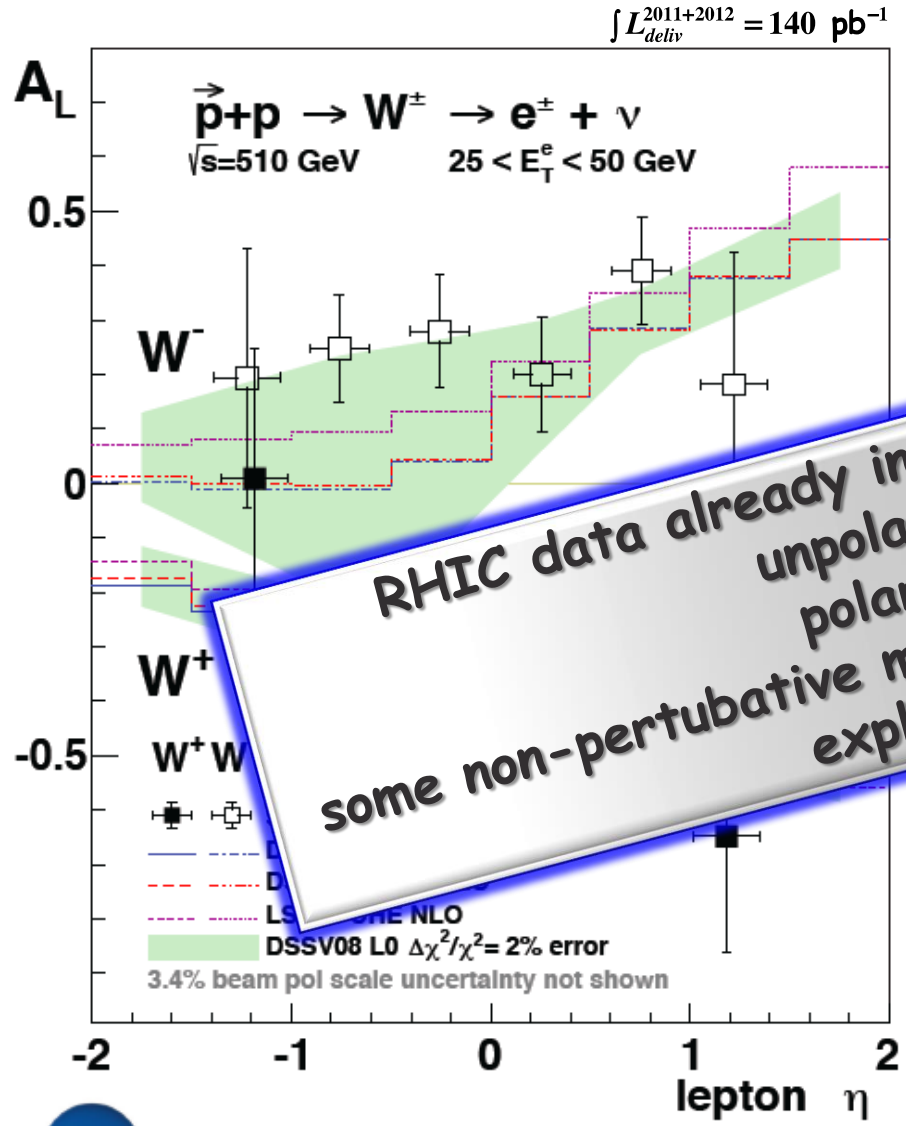


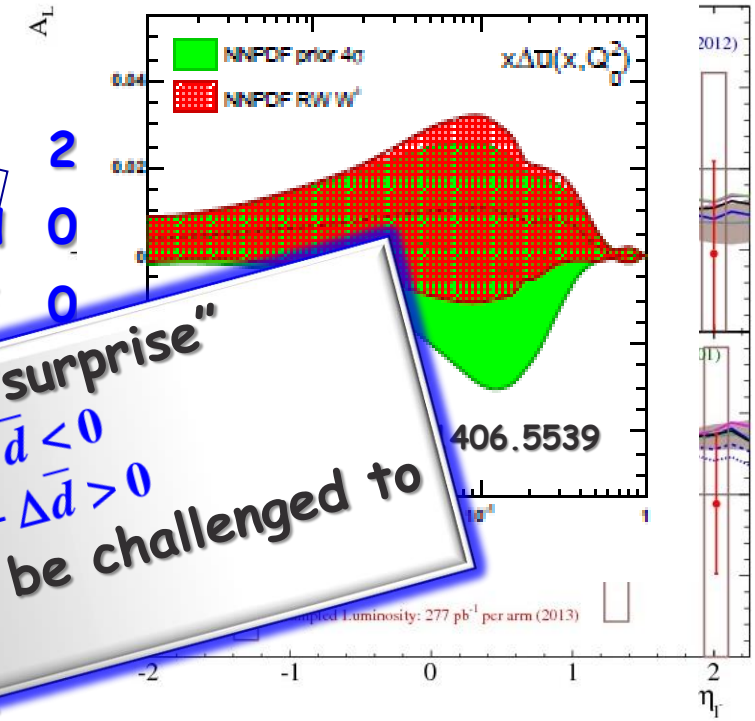
Ws naturally separate quark flavors
→ rapidity: sea vs. valence quarks

Ws are maximally parity violating
→ Ws couple only to one parton helicity

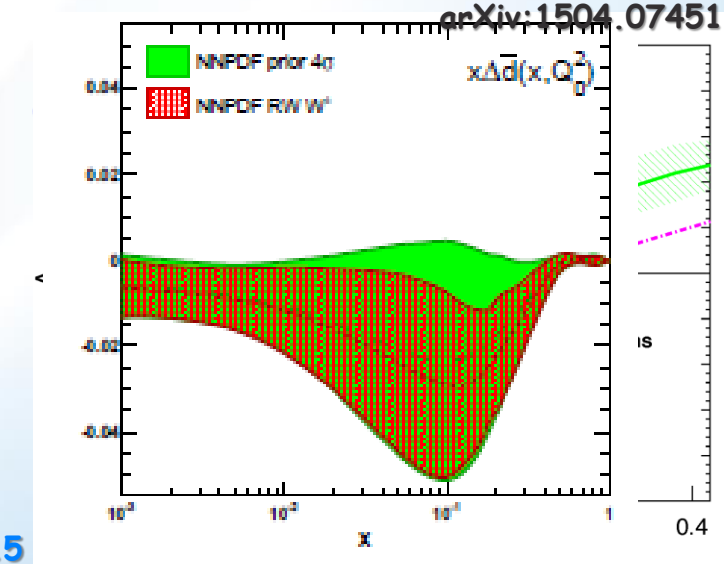
Complementary to SIDIS:
very high Q^2-scale 6400 GeV^2
extremely clean theoretically
No Fragmentation function
→ stringent test on theory approach for SIDIS
UNIVERSALITY of PDFs

CURRENT W-RESULTS





arXiv:1504.07451



P 2
H 0
E 0

$\Delta\bar{u}$

$\Delta\bar{d}$ u

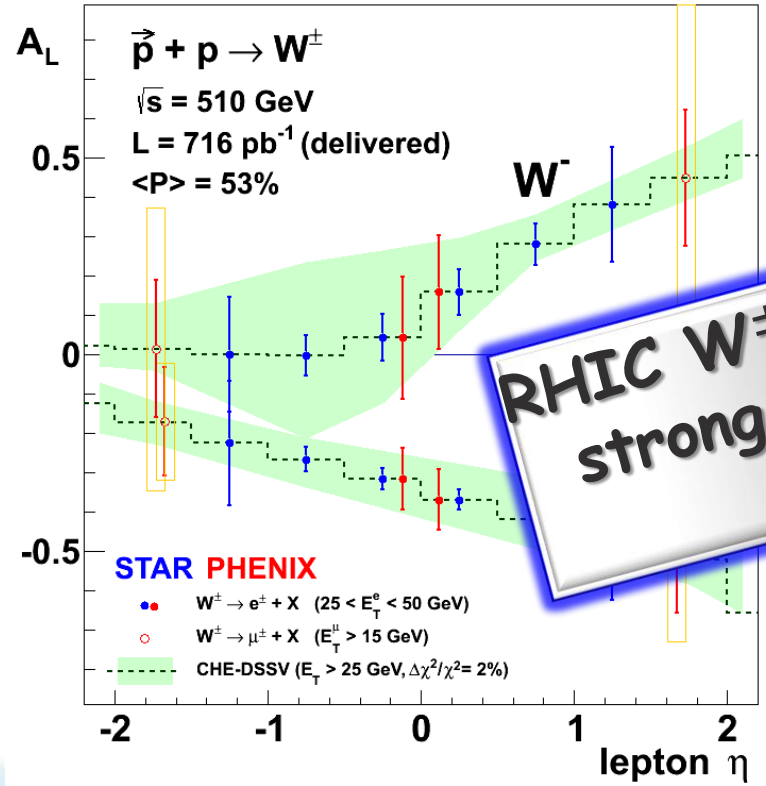
n

RHIC data already indicate a "surprise"
unpolarised: $\bar{u} - \bar{d} < 0$
polarised: $\Delta\bar{u} - \Delta\bar{d} > 0$
some non-pertubative models will be challenged to explain this

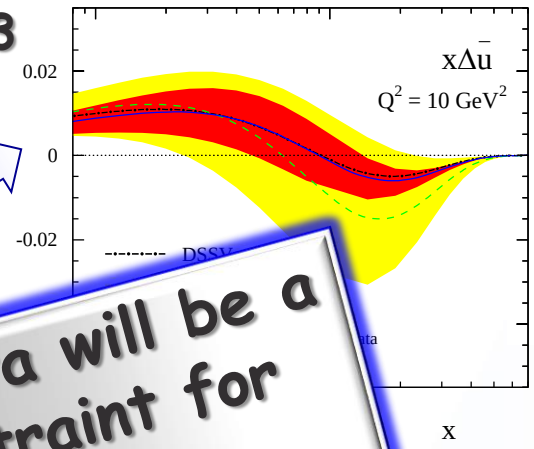
NEW arXiv:1404.6880

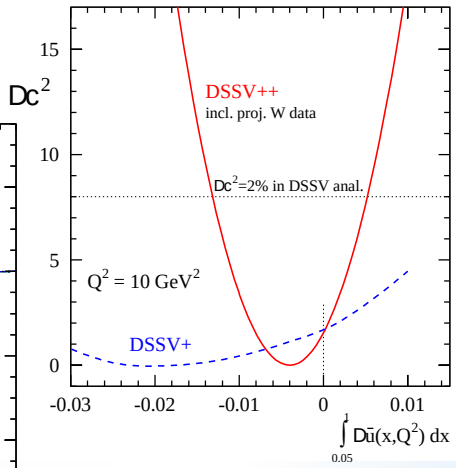
IF THE RUN-13 DATA ARE FULLY ANALYZED

pseudo-data randomized around DSSV uncertainties correspond to 2009-2013



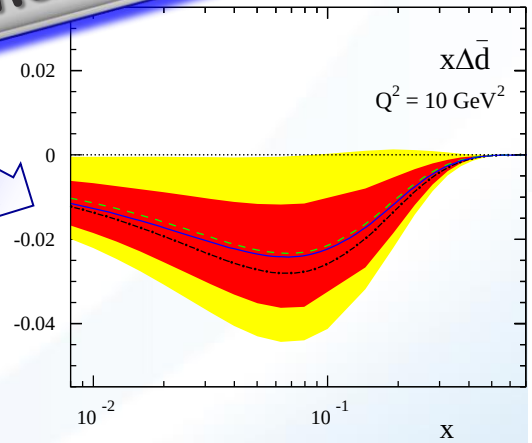
$\Delta\bar{u}$

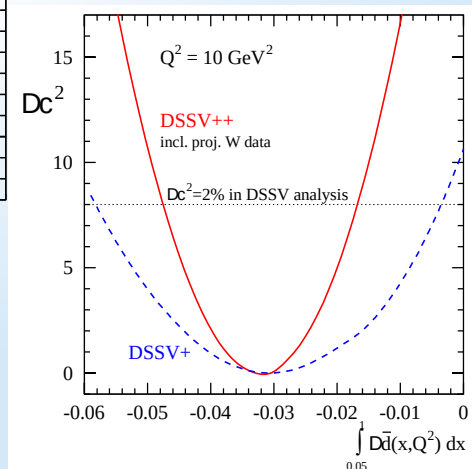




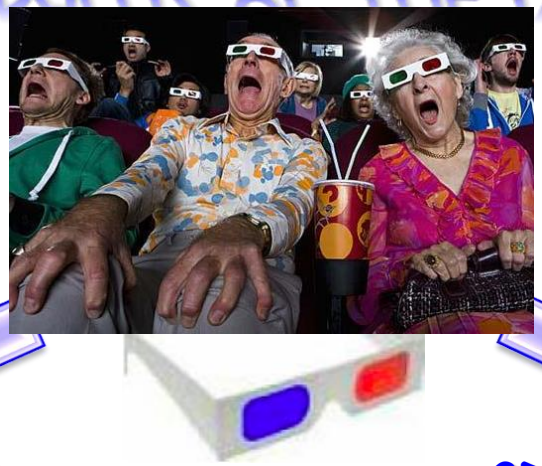
RHIC $W^{\pm}$-data will be a strong constraint for $\Delta\bar{u}$ and $\Delta\bar{d}$

$\Delta\bar{d}$





QUANTUM TOMOGRAPHY OF THE NUCLEONS & NUCLEI



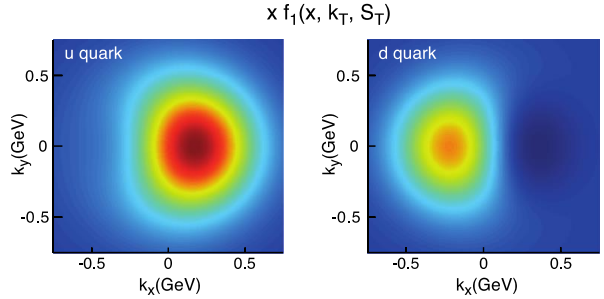
Join the real
3D experience !!

TMDs

GPDs

2D+1 picture in momentum space

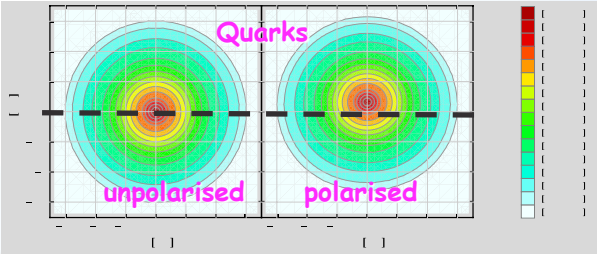
transverse momentum dependent PDFs



2D+1 picture in coordinate space

generalized parton distributions

→ exclusive reaction



Spin as vehicle to do tomography of the nucleon

What is the dynamic structure of the proton and nuclei

2D+1 picture in momentum and coordinate space

Visualize color interactions in QCD

collective phenomena and correlations in fragmentation

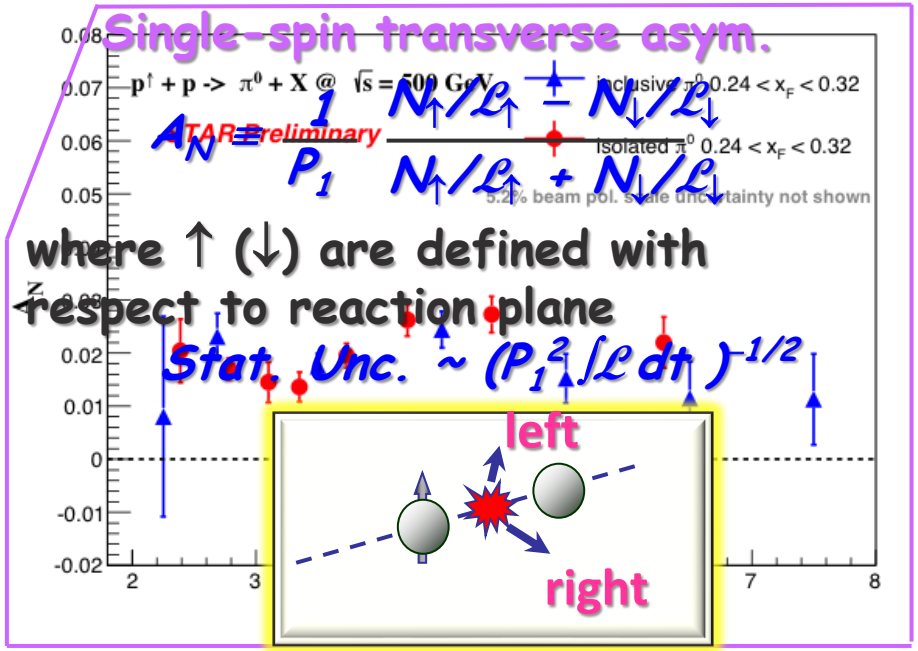
New physics aspects due to confined motion

TRANSVERSE SPIN STRUCTURE

using spin to unravel
the secrets / dynamics of QCD

Resolving the new spin puzzle
of the 21st century
The legacy of transverse polarized pp:
What causes A_N at forward rapidities?

NEW SURPRISE IN SPIN: LARGE A_N AT HIGH $\sqrt{s}$

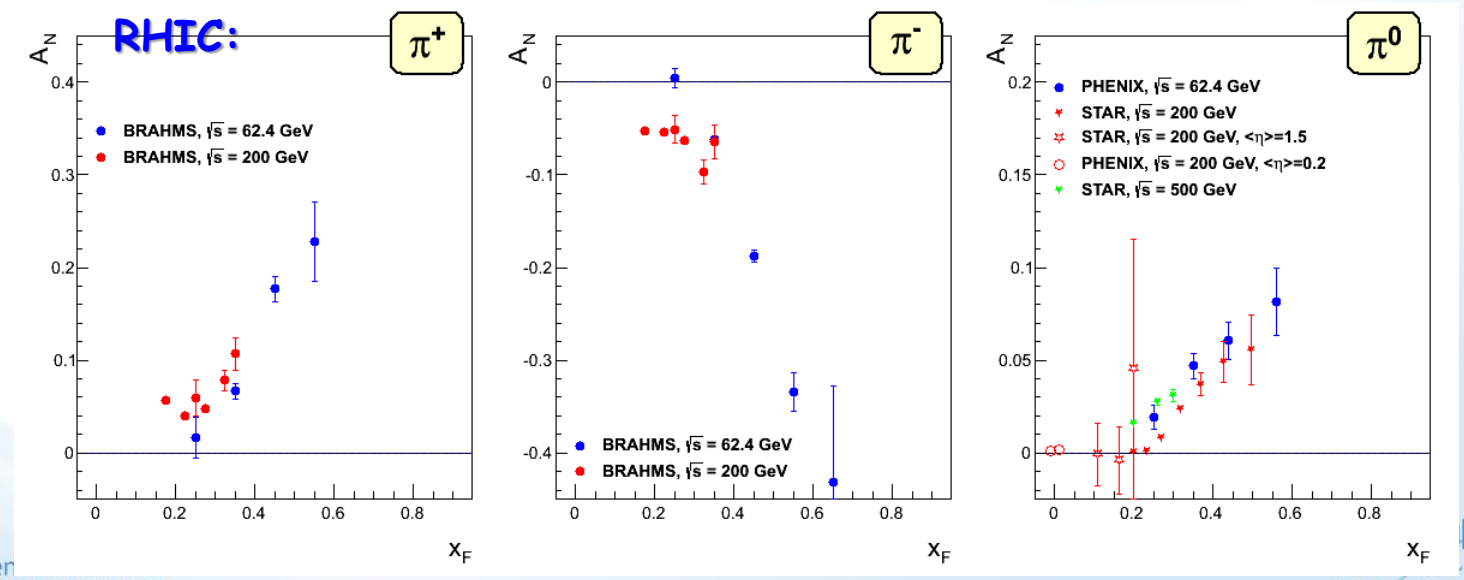


Big single spin asymmetries in p⇧p !!

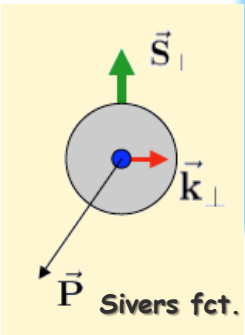
Naive pQCD (in a collinear picture) predicts $A_N \sim \alpha_s m_q/\mathrm{sqrt}(s) \sim 0$

Do they survive at high $\sqrt{s}$? YES
Is observed p_t dependence as expected naively from p-QCD? NO

What is the underlying process?

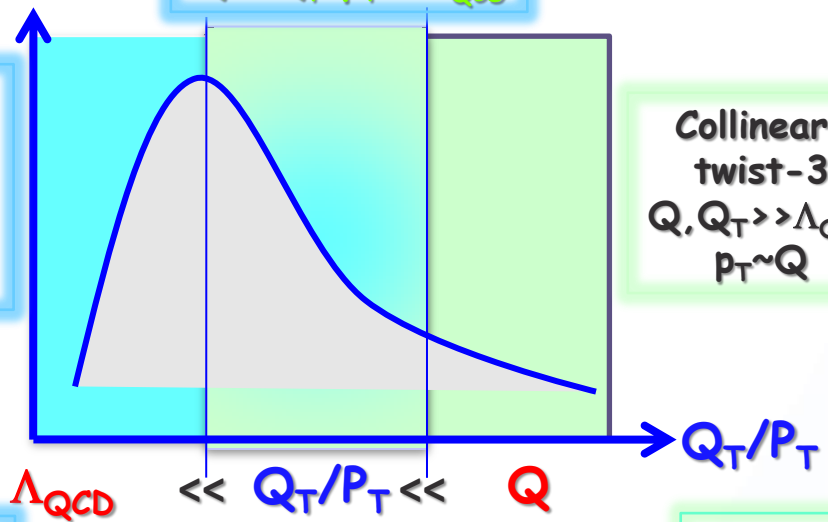


INITIAL STATE: TMDs VS. TWIST-3

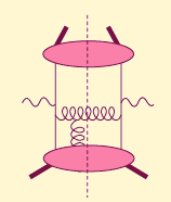


Transverse momentum dependent
$Q >> Q_T >= \Lambda_{QCD}$
$Q >> p_T$

Intermediate Q_T
$Q >> Q_T/p_T >> \Lambda_{QCD}$



Collinear/ twist-3
$Q, Q_T >> \Lambda_{QCD}$
$p_T \sim Q$



Efremov, Teryaev; Qiu, Sterman
or
Twist-3 FF

Need 2 scales
Q^2 and p_t
Remember pp:
several observables one scale
Exception:
DY, W/Z-production

Need only 1 scale
Q^2 or p_t
But
should be of reasonable size

should be applicable to pp observables
$A_N(\pi^0/\gamma/\text{jet})$

related through

$$-\int d^2k_\perp \frac{|k_\perp^2|}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{SIDIS} = T_{q,F}(x,x)$$

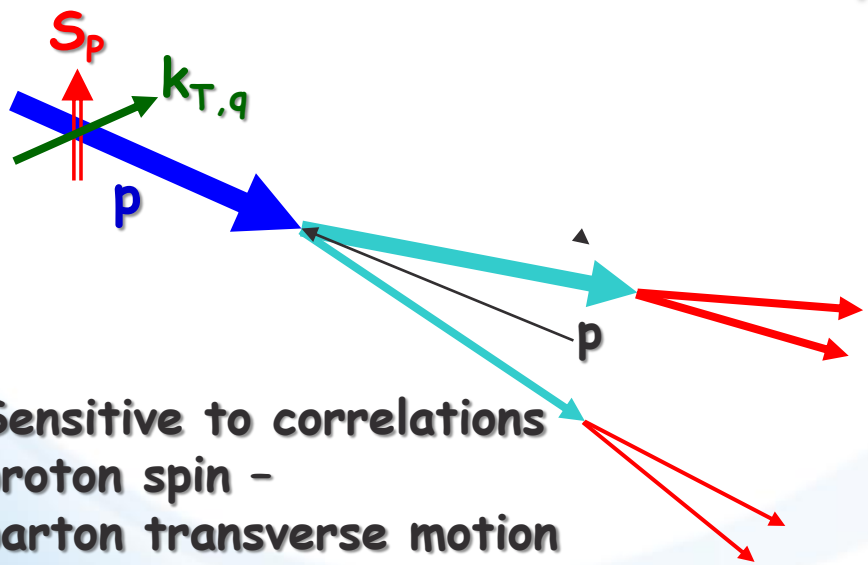
A_N: HOW TO GET TO THE UNDERLYING PHYSICS

measure less inclusive

Initial State

SIVERS/Twist-3

- A_N for jets, direct photons
- A_N for heavy flavour → gluon
- A_N for $W^{+/-}$, Z^0, DY



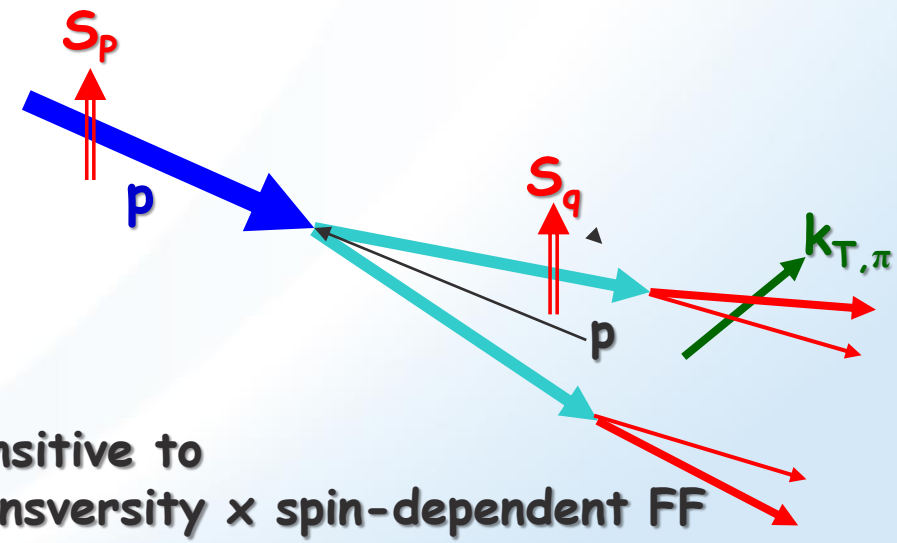
Sensitive to correlations
proton spin –
parton transverse motion

not universal between SIDIS & pp

Final State

Collins Mechanism

- asymmetry in jet fragmentation
  - $\pi^{+/-}\pi^0$ azimuthal distribution in jets
  - Interference fragmentation function
- A_N for pions
  → Novel Twist-3 FF Mechanisms

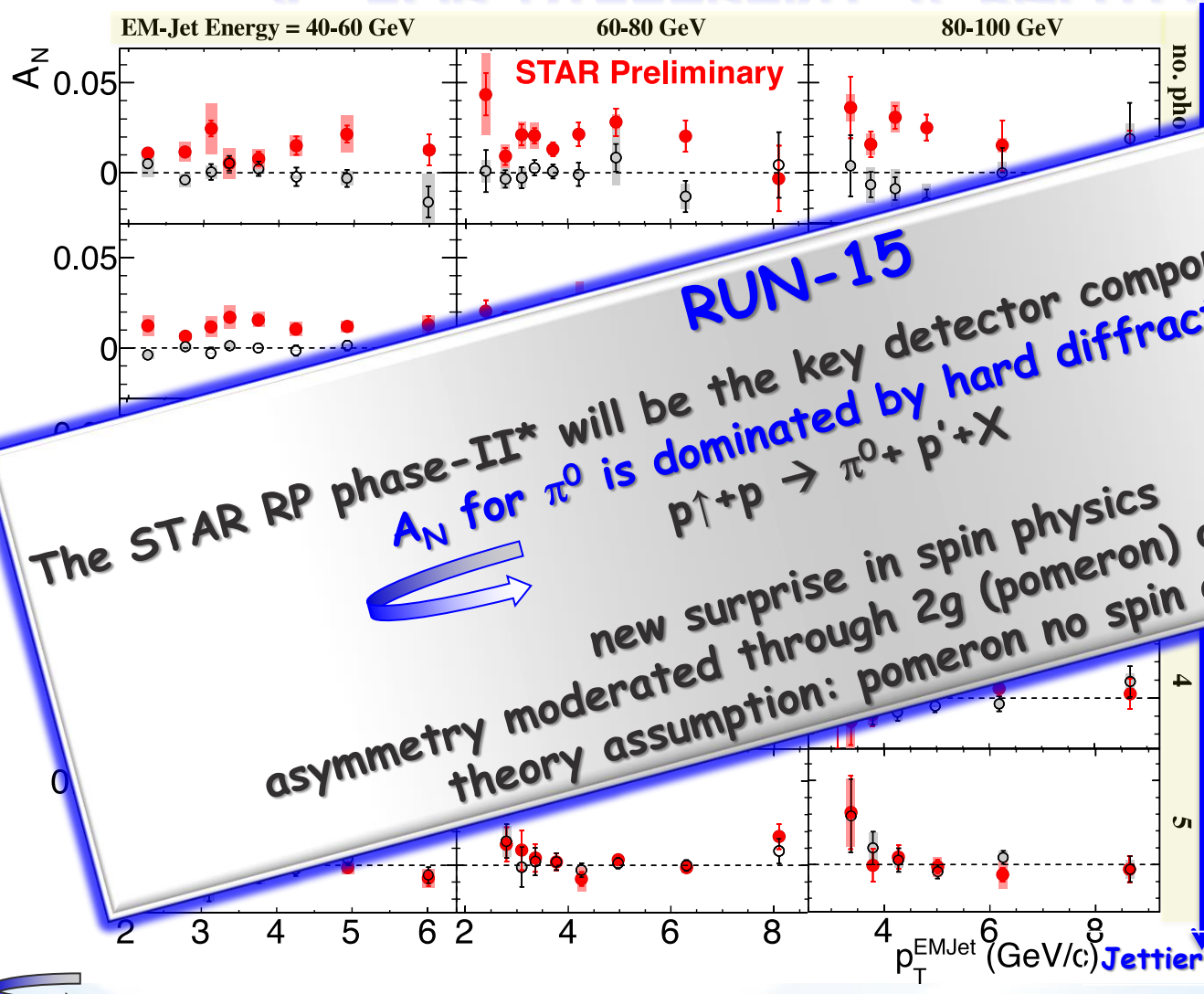


Sensitive to
transversity x spin-dependent FF

universal between SIDIS & pp & e+e-

Results at forward rapidities
$\eta \gtrsim 2.5$

A_N FOR DIFFERENT # PHOTONS IN EM-JETS



RUN-15

The STAR RP phase-II* will be the key detector component to investigate A_N for π^0 is dominated by hard diffraction

$p\uparrow + p \rightarrow \pi^0 + p' + X$

new surprise in spin physics

asymmetry moderated through 2g (pomeron) or 3g exchange

theory assumption: pomeron no spin effects

smaller than for isolated π^0's

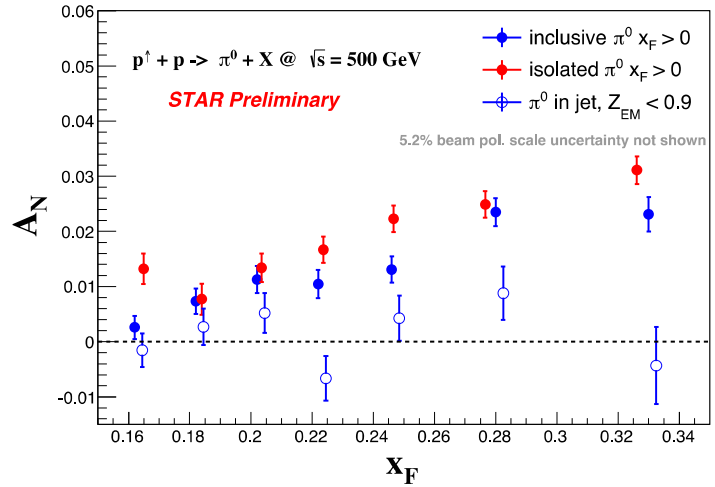
- A_N decreases as the event complexity increases (i.e., the "jettiness"
- A_N for #photons >5 is similar to that for #photons = 5

Jettier events

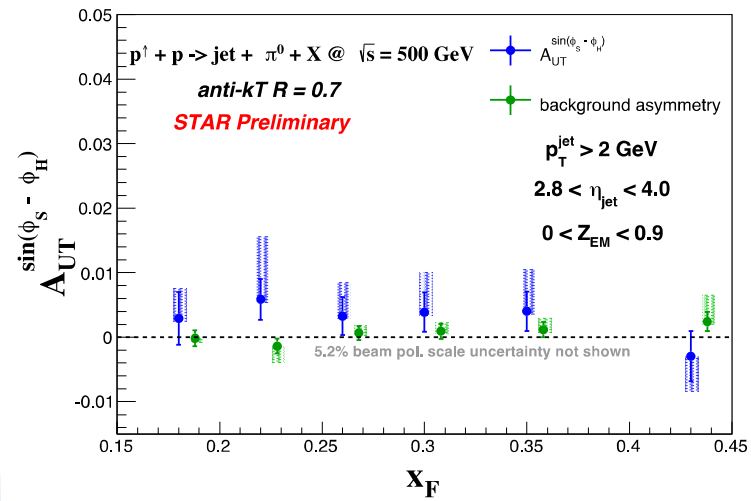
Several other Asymmetries for jettier events are also very small

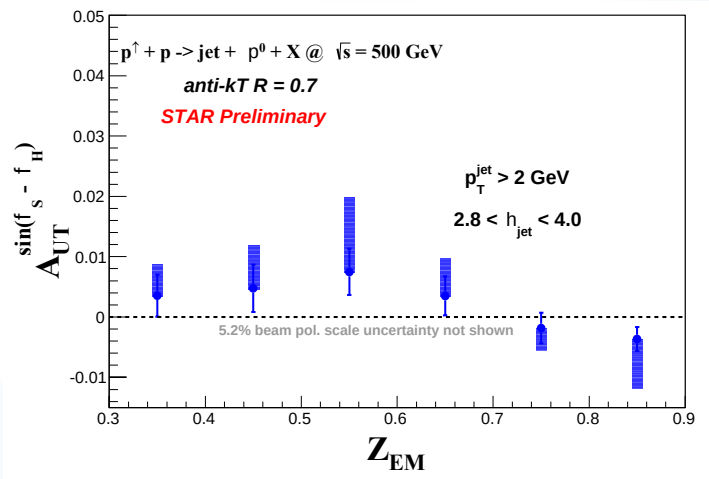
these dependences raise serious questions how much of the large forward π^0 A_N comes from 2 → 2 parton scattering

COLLINS ASYMMETRIES FOR π^0 RELATIVE TO JET AXIS



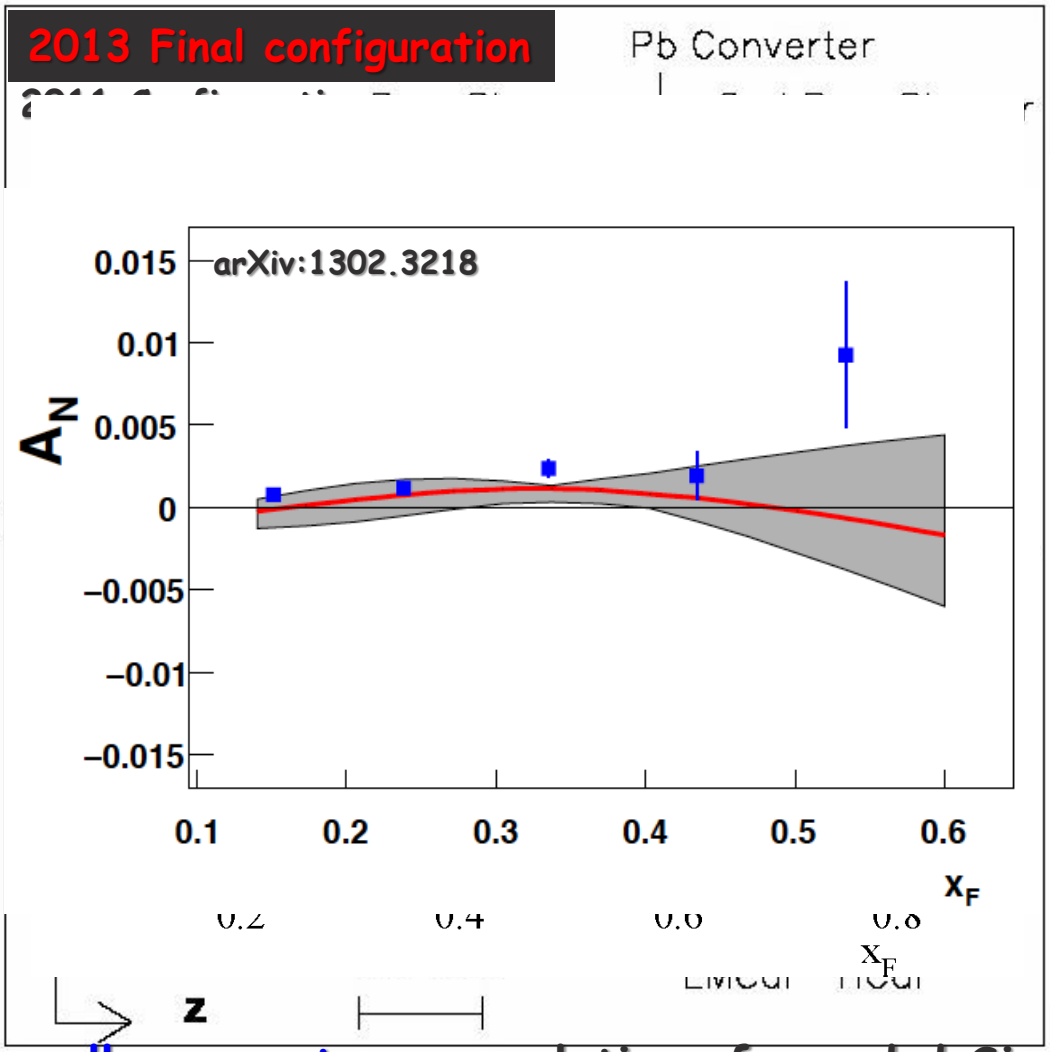
- Calculated A_N for jet-isolated π^0, background subtracted A_N for inclusive π^0 and π^0 in EM-jet
- Isolation defined by anti-k_T jet algorithm with R = 0.7
- Longitudinal momentum fraction z of π^0 is calculated w.r.t the EM-jet as Z_{EM}
- Asymmetries of less exclusively produced π^0 (Z_{EM} < 0.9) is smaller than isolated π^0

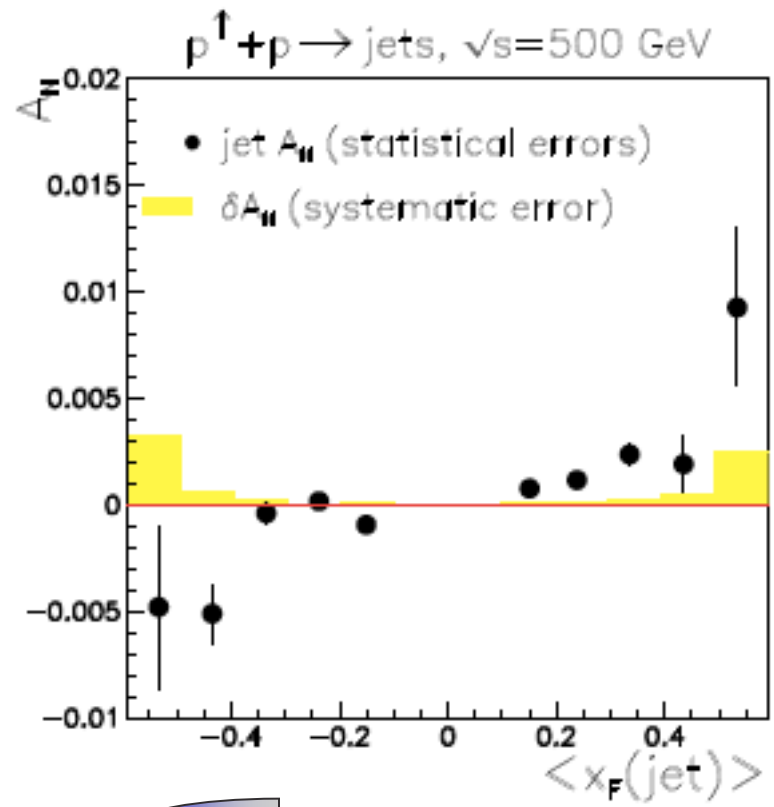




Total of Sivers and Collins asymmetries of EMjet and π^0 relative to jet axis are found to be insufficient to account for the observed inclusive π^0 single spin asymmetries.

A_NDY: "JETS" AT η>3





arXiv: 1304.1454

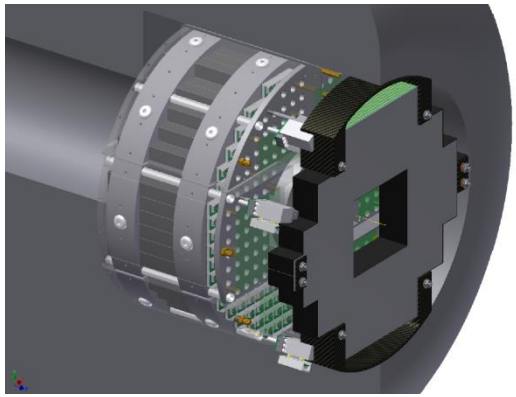
small asymmetry: cancelation of u and d Sivers TMDs

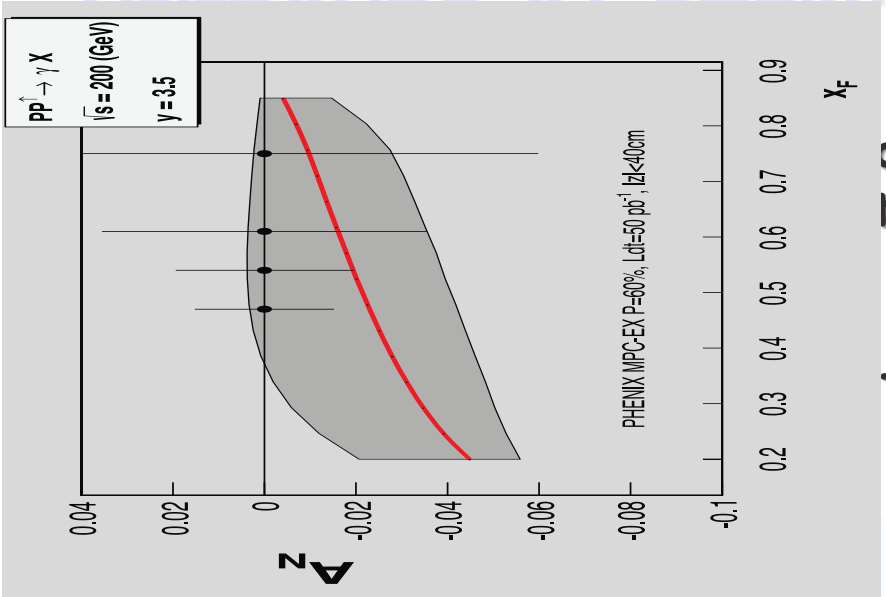
Determine A_N(jet) at same rapidity of big $A_N(\pi^0)$ η>3

RUN-11: A_NDY collected ~ 6.5/pb

UPGRADES AT PHENIX AND STAR

PHENIX MPC-EX:

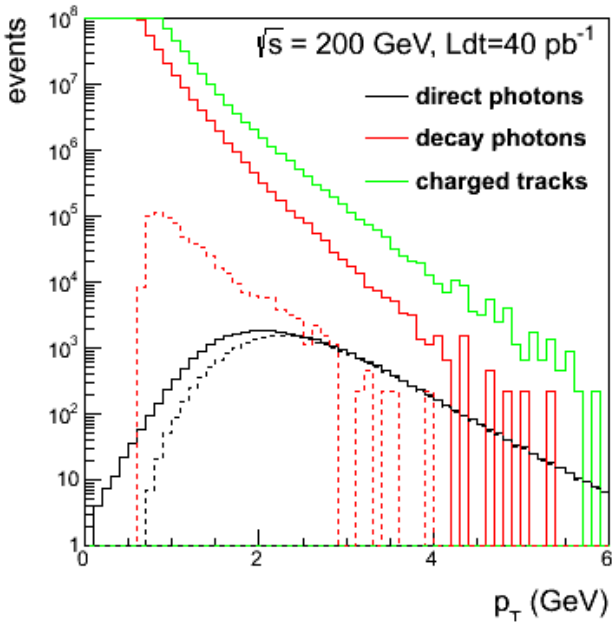


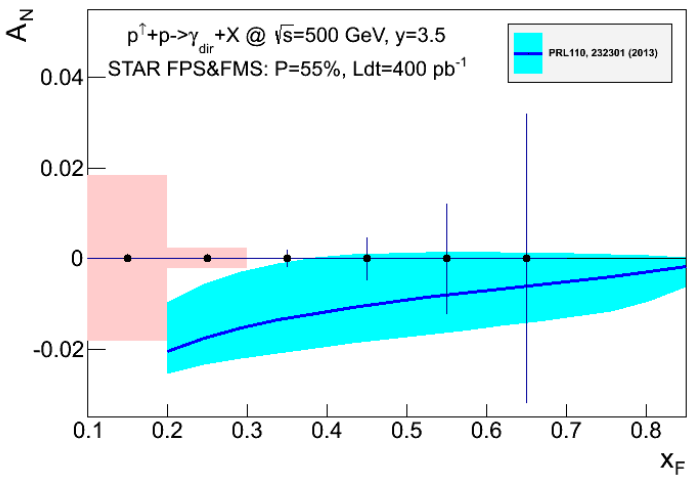


dwich pre-shower
tromagnetic

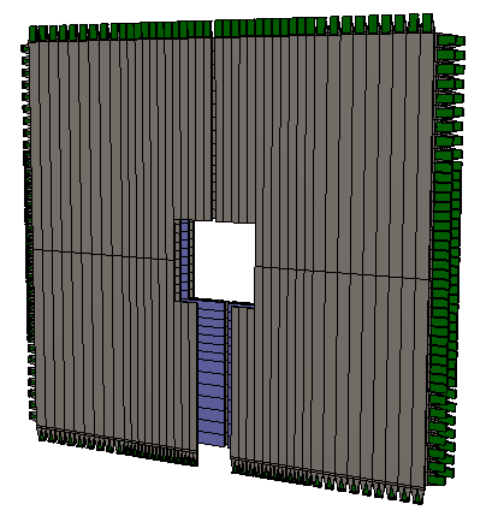
to >80GeV)

STAR FMS-PreShower:





s



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FINDINGS FROM FORWARD RAPIDITY

- A_N decreases as the event complexity increases(i.e., the "jettiness")
- Isolated π^0 asymmetries are smaller when there is a correlated EM-jet at mid-rapidity.
- A_N of forward jets are small
  → cancellation of u and d Sivers TMD

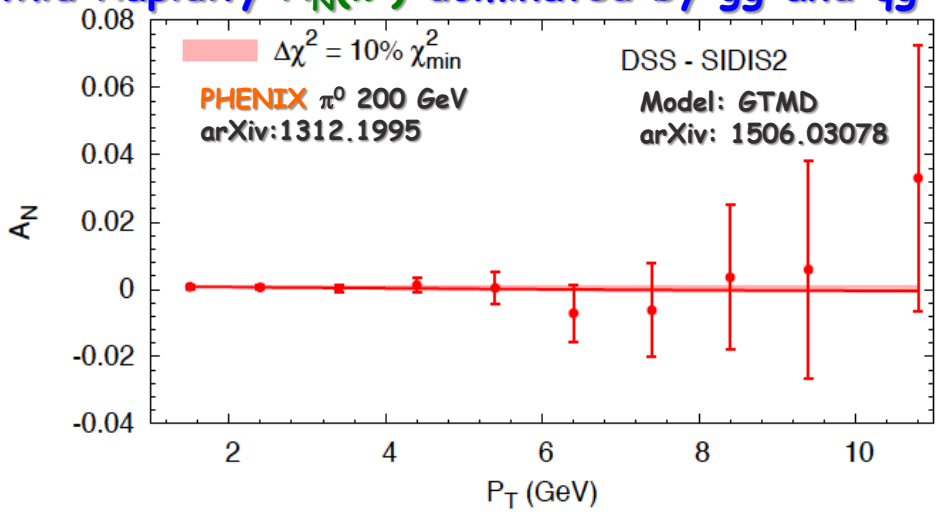
Total of Sivers and Collins asymmetries of EMjet and π^0 relative to jet axis are found to be insufficient to account for the observed inclusive π^0 single spin asymmetries.

These dependences raise serious question about how much of the large forward π^0 A_N have 2 → 2 parton scattering as underlying process (diffractive events?).

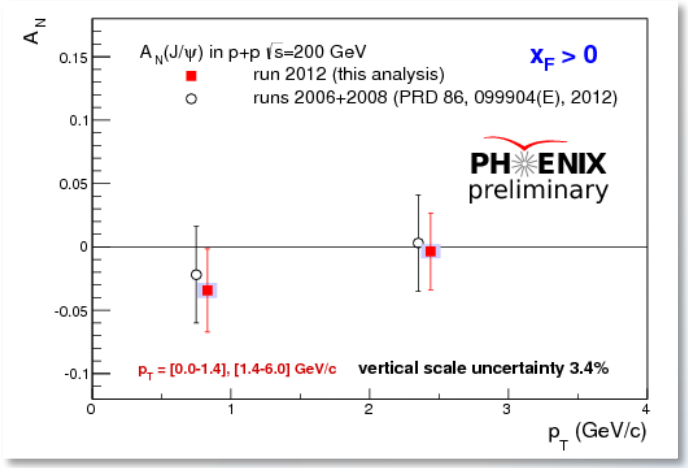
Results at mid rapidity

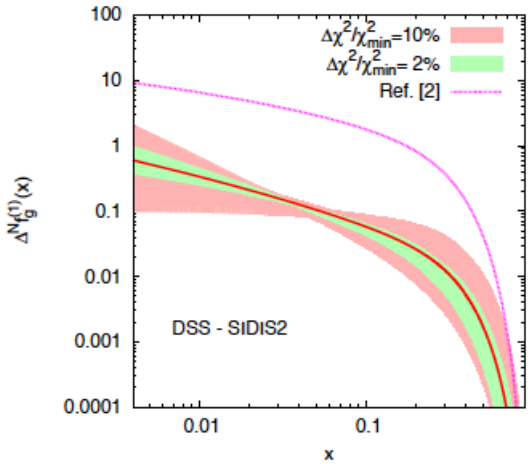
HINTS FOR GLUON SIVERS /TWIST-3

Mid Rapidity $A_N(\pi^0)$ dominated by gg and qg

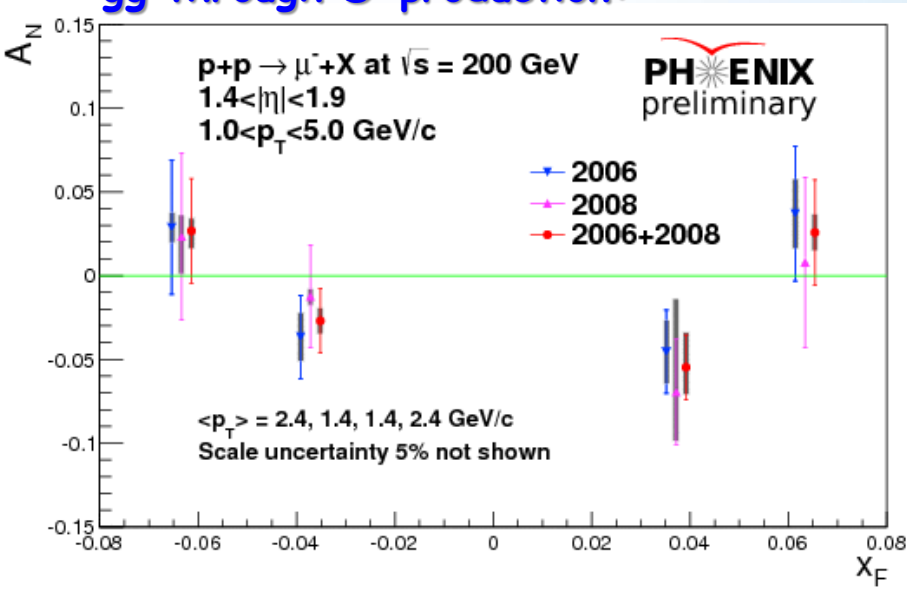


Forward Rapidity $A_N(J/\psi)$ only gg:





Forward Rapidity $A_N(\mu)$ dominated by gg through D-production:



no hint of a non-zero $A_N(\pi^0)$, $A_N(J/\psi)$ and $A_N(\mu)$

→ gluon Sivers ~ 0

→ Twist-3 gg correlator ~0 ?

INTERFERENCE FRAGMENTATION FUNCTION (IFF)

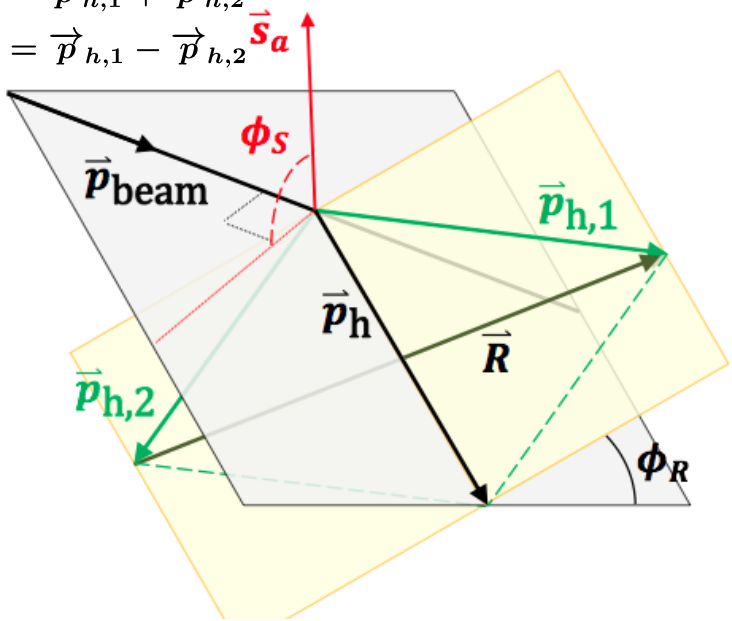
$p\uparrow + p \rightarrow \pi^+\pi^- + X$ → transversity × IFF survives in collinear framework

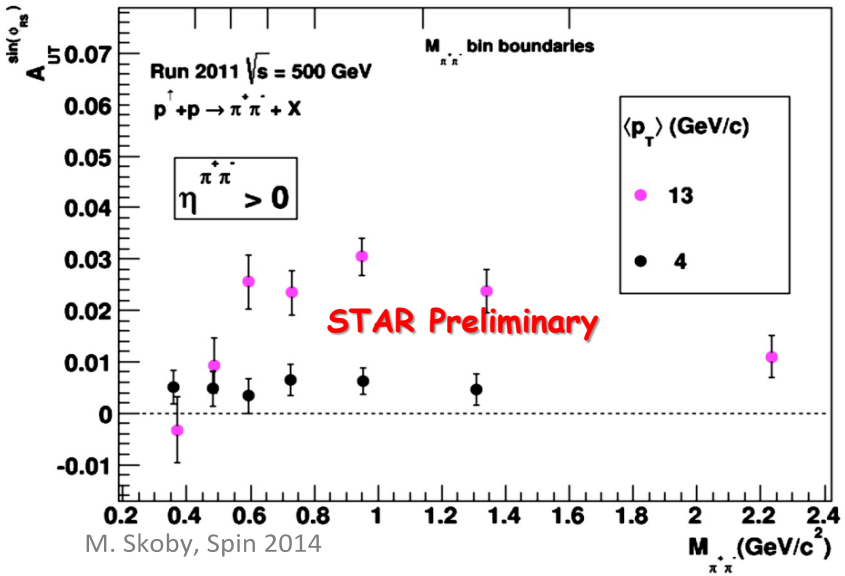
$$A_{UT}\sin(\phi_{RS}) = \frac{1}{Pol}\frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow}$$

$\phi_{RS} = \phi_R - \phi_S$

$\vec{p}_h = \vec{p}_{h,1} + \vec{p}_{h,2}$

$\vec{R}_h = \vec{p}_{h,1} - \vec{p}_{h,2}$

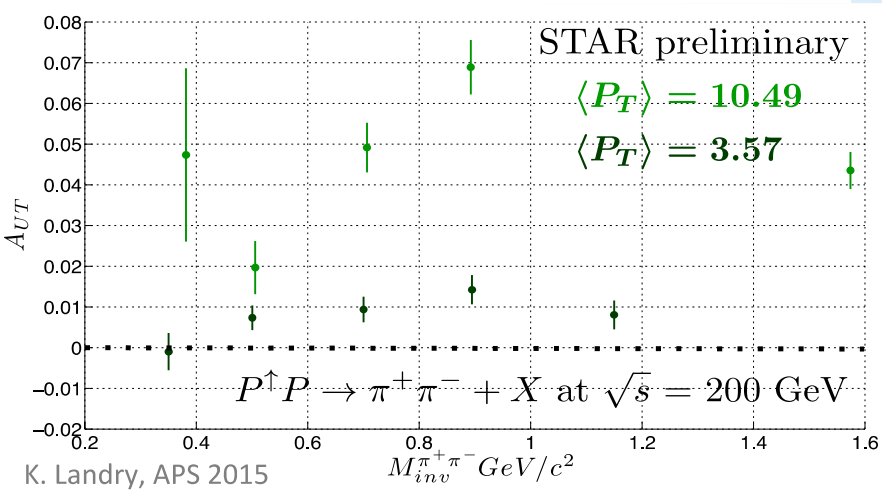




M. Skoby, Spin 2014

—"Interference Fragmentation Function"

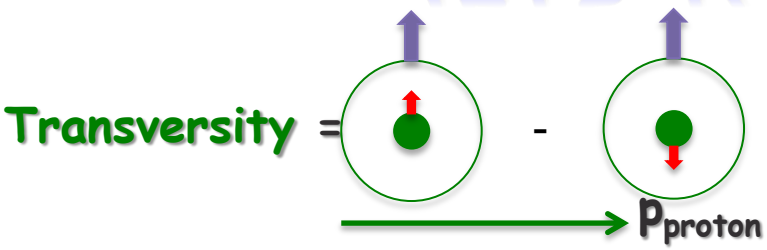
e.g. Bacchetta and Radici, PRD 70, 094032 (2004)



K. Landry, APS 2015

- Significant di-hadron asymmetries both at √s=200GeV and √s=500GeV
- Increasing with p_T
- Enhancement to asymmetry is seen around ρ mass

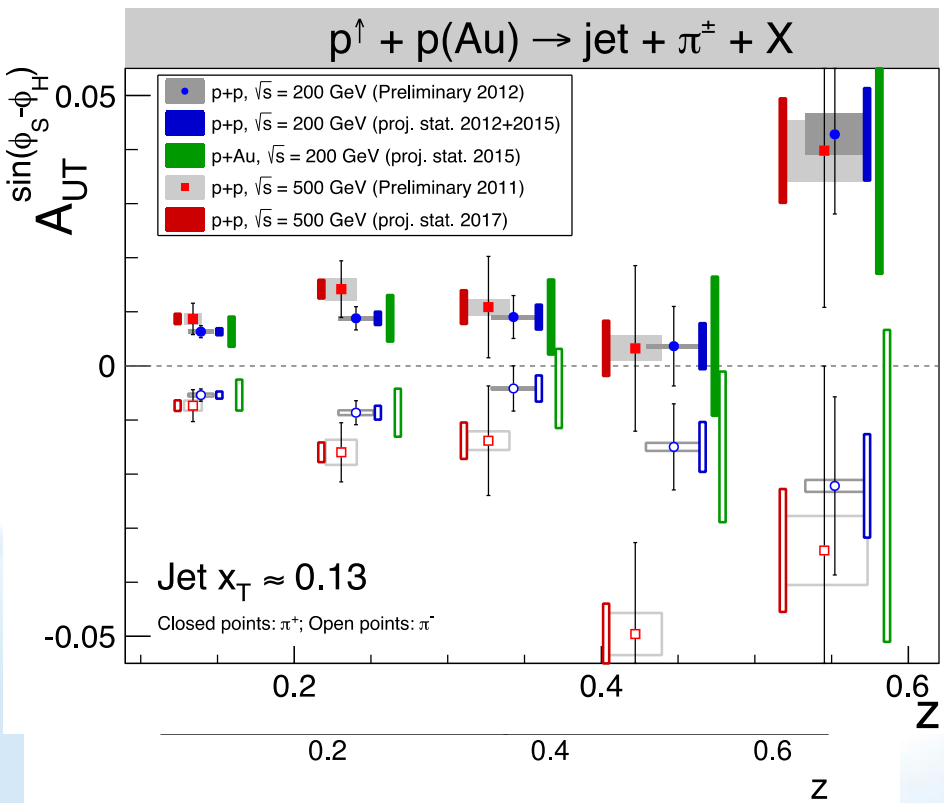
JETS TO ACCESS TRANSVERSITY



$$A_{UT}^{p^\pm} \approx \frac{h_1^{q_1}(x_1,k_T) f_{q_2}(x_2,k_T)\hat{s}_{UT}(\hat{s},\hat{t},\hat{u}) D_{q_1}^{p^\pm}(z,j_T)}{f_{q_1}(x_1,k_T) f_{q_2}(x_2,k_T)\hat{s}_{UU} D_{q_1}^{p^\pm}(z,j_T)}$$

Key search in region x (0.1 < x < 0.35)

- dependence of the Collins FF on pion transverse momentum (j_T)
- Collins asymmetry universal?
- do these asymmetries evolve with $\sqrt{s}$?



200 vs. 500 GeV Comparison:

- These measurements coupled with the interference fragmentation function (IFF) measurements at both 200 and 500 GeV will provide insight into the Q^2 evolution and universality of TMD functions.
- These results could lend sensitivity to the size of potential factorization-breaking in Collins in p+p.

VISUALIZE COLOR INTERACTIONS IN QCD.

Measure non-universality of sivers-functi

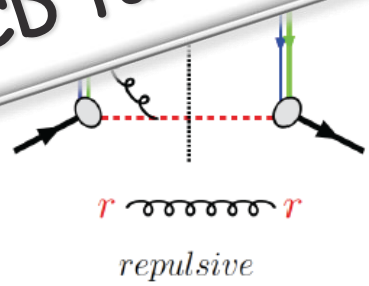
QCD:

DIS:
γq-scattering
attractive FSI

Critical test of factorization in QCD

no sign change

→ need to rethink QCD factorization



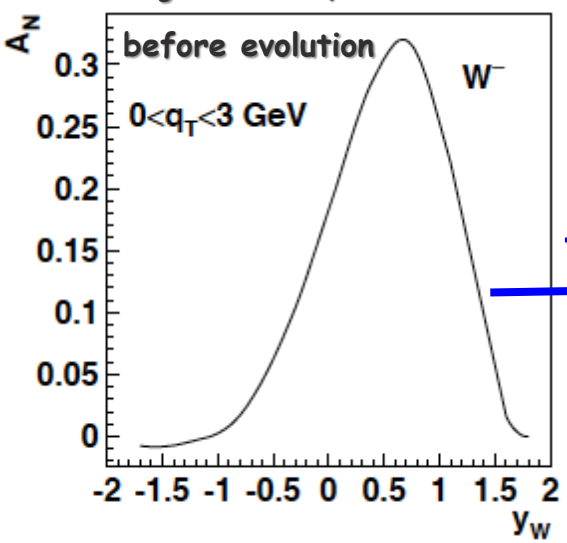
$$\text{Sivers}_{DIS} = - \left(\text{Sivers}_{DY} \text{ or } \text{Sivers}_{W} \text{ or } \text{Sivers}_{Z0}\right)$$

A_N(direct photon) measures the sign change in the Twist-3 formalism

All three observables can be approached
at 500 GeV at RHIC

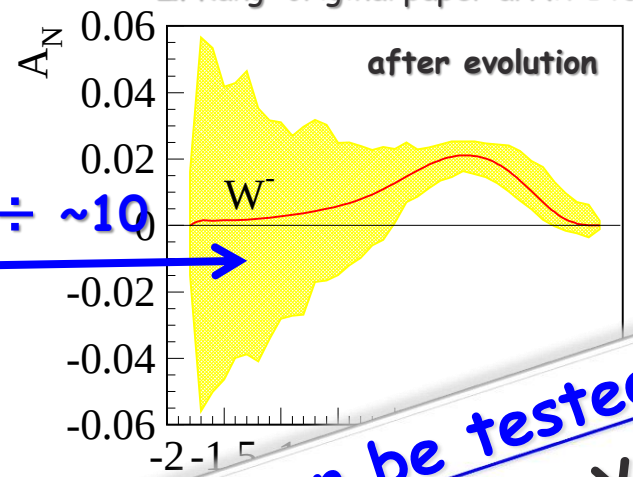
SURPRISE: TMD EVOLUTION

Z.-B. Kang & J.-W. Qui arXiv:0903.3629



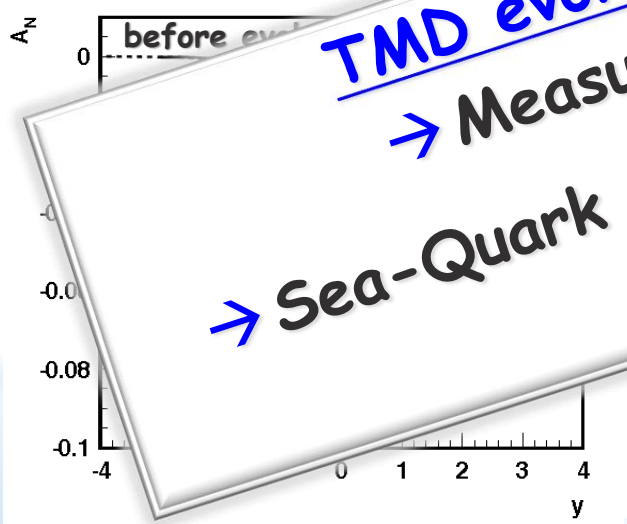
÷ ~10

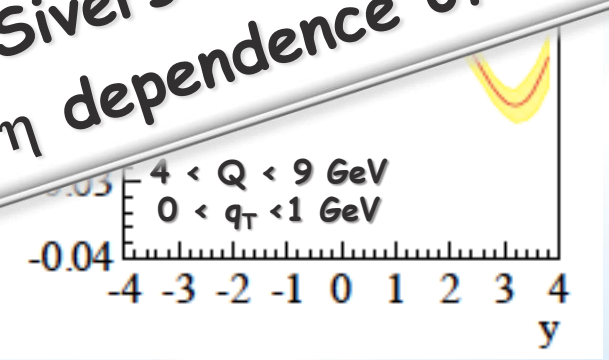
Z. Kang: original paper arXiv:1401.5078



much stronger than any other known evolution effe

Z.-B. Kang & J.-W. Qui Phys.Rev





TMD evolution can be tested at RHIC

→ Measure A_N through DY and W/Z

→ Sea-Quark Sivers fct. can be accessed through η dependence of $A_N(W)$

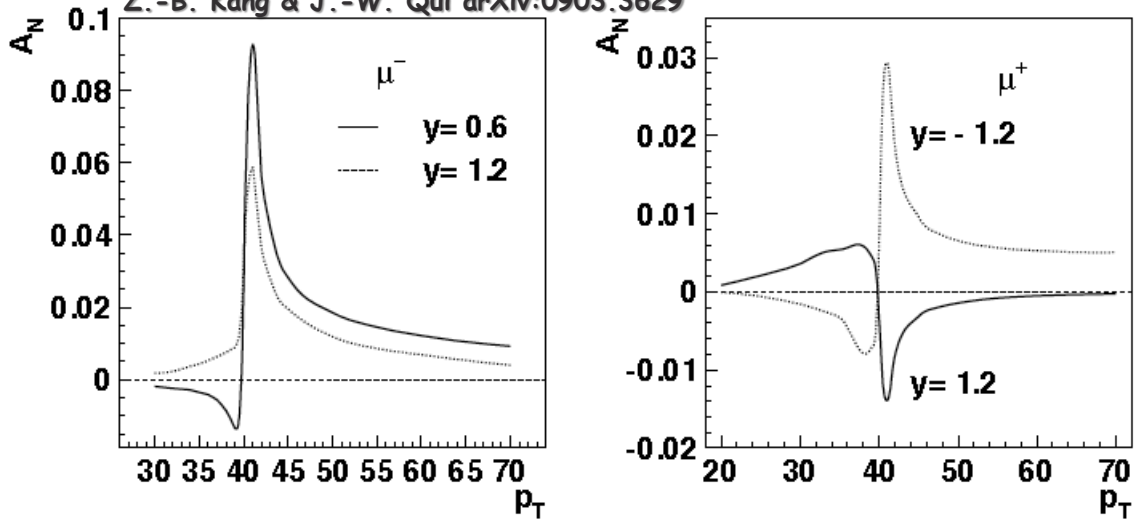
all lever arm in Q^2 & p_t

NOTE:
the same evolution applies to TMD FFs, i.e. Collins and to e^+e^-, SIDIS → eRHIC

ANALYSIS TECHNIQUE FOR A_N W

Need to reconstruct W kinematics as lepton asymmetry is suppressed and the kinematic dependences are difficult to resolve
→ resolution effects and statistics

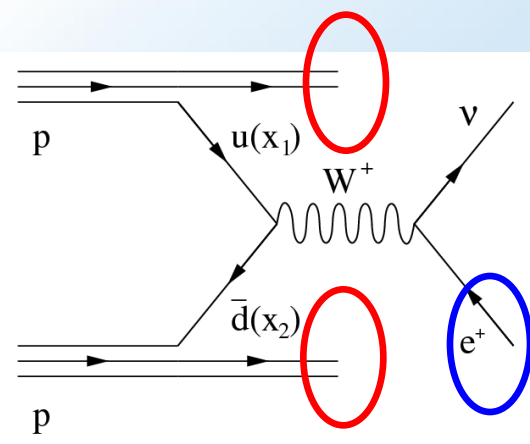
Z.-B. Kang & J.-W. Qui arXiv:0903.3629



Apply analysis technique developed at the Tevatron and used at LHC i.e. CDF PRD 70, 032004 (2004)

Philosophy:

W → l+ν as ν is not seen
→ reconstruct W kinematics through lepton and hadronic recoil



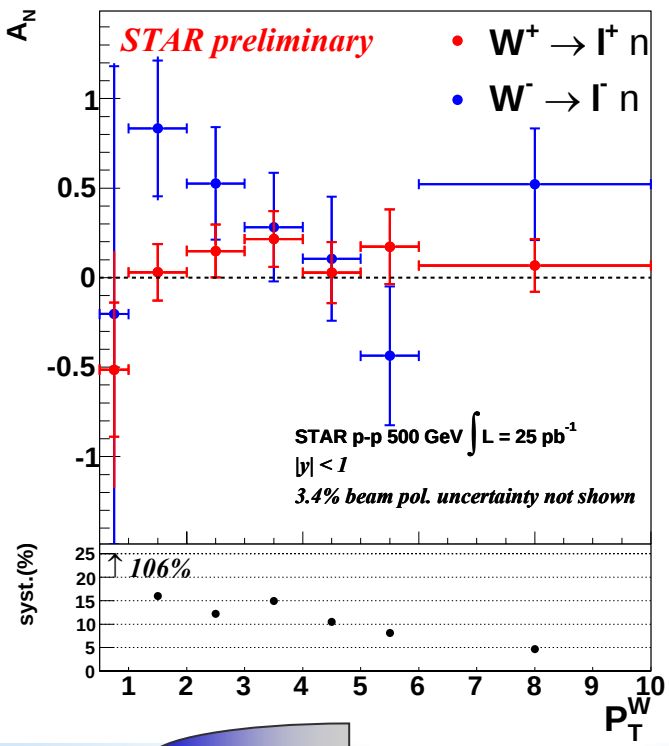
STAR: A_N^W

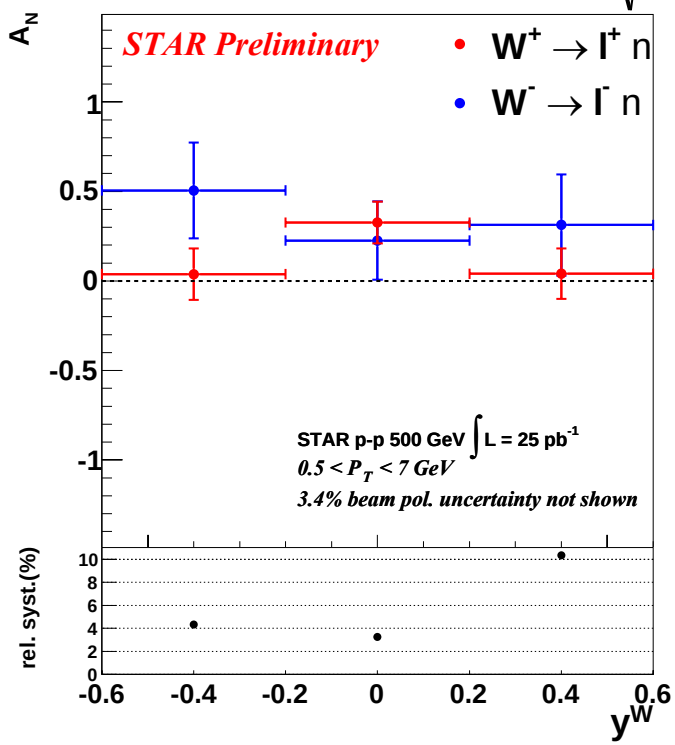
- ✓ fit sin(ϕ) modulation with phase = π/2
- ✓ Average RHIC polarization for 2011 transverse p-p data → P = 53%
- ✓ Systematics estimated via a Monte Carlo challenge

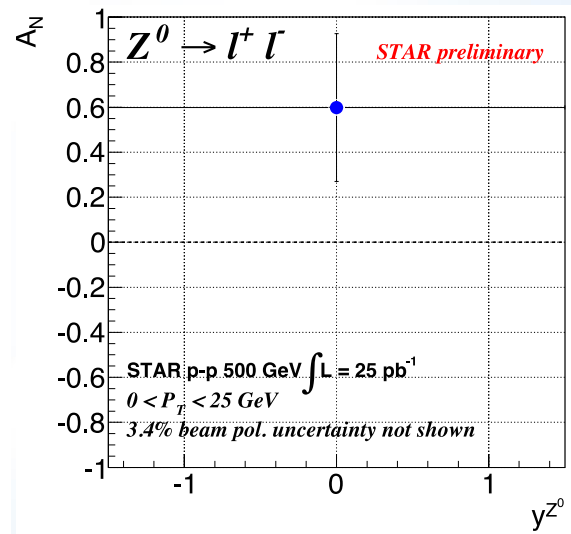
input asymmetries from arXiv:1401.5078 and reconstruct it back

We use the "left-right" formula to cancel dependencies on geometry and luminosity

$$A_N \approx \frac{1}{P}\frac{\sqrt{N_R^+ N_L^-} - \sqrt{N_L^+ N_R^-}}{\sqrt{N_R^+ N_L^-} + \sqrt{N_L^+ N_R^-}}$$







Asymmetry sign consistent with Sivers fct. sign change

WHAT CAN WE DO ... -17

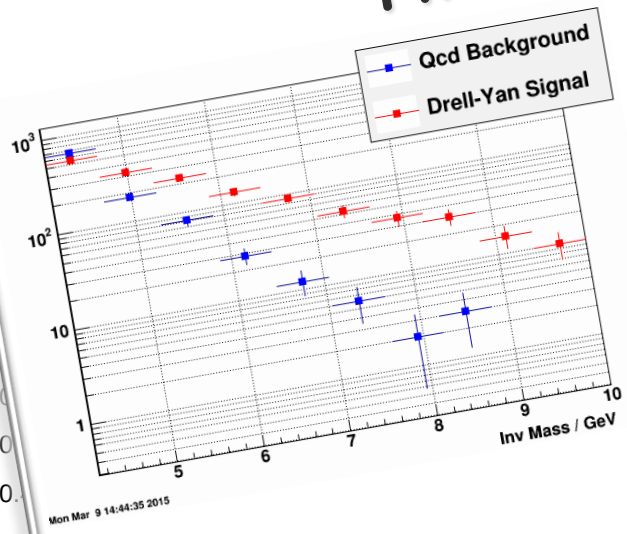
Assumptions:

integrated delivered lumin...

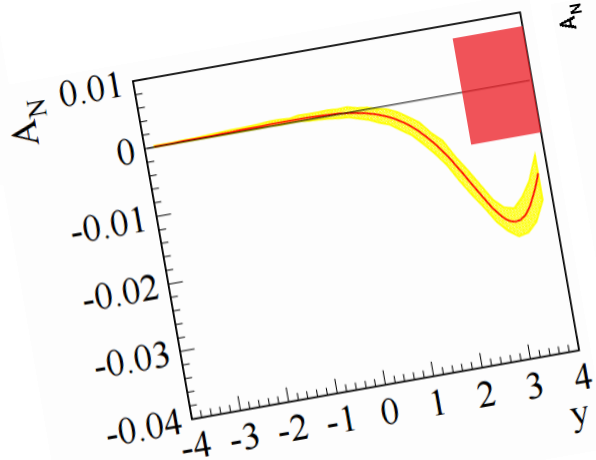
→ 7 weeks ...

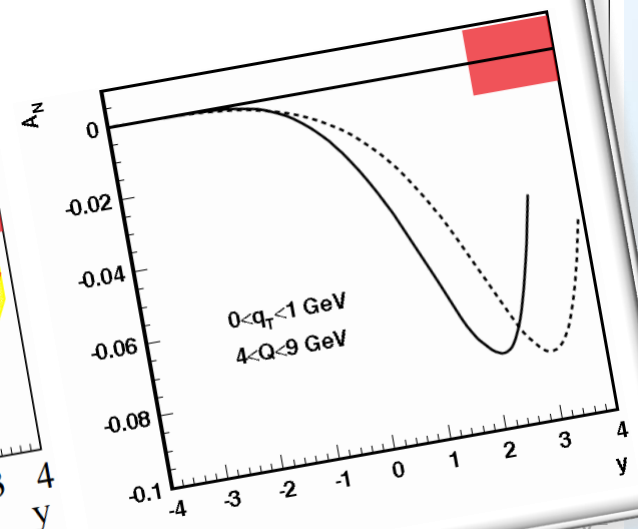
Measuring the sign change through DY

STAR has investigated in detail the option FMS & Pre- and Post-shower



Results for a run-17





...evolution

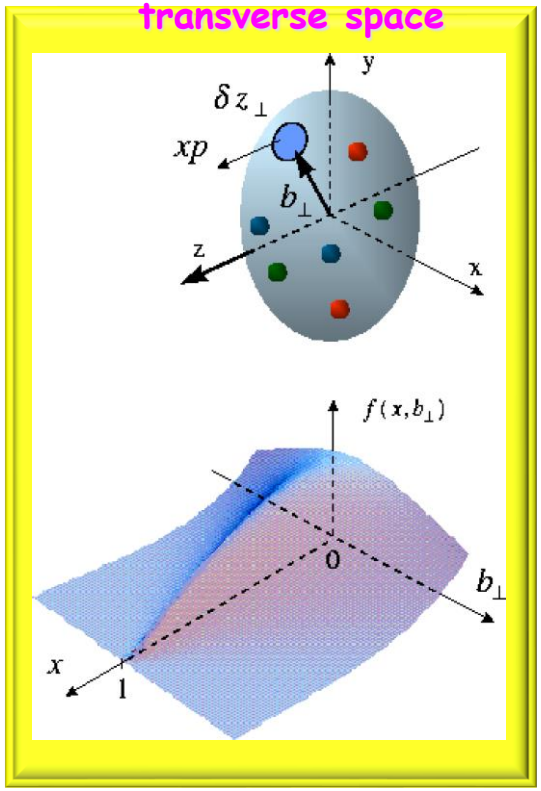
sea-quark Sivers fct

...sign-change if TMD evolution ÷ ~5 or less

OUTLOOK

THE MISSING PIECE: ORBITAL ANGULAR MOMENTUM

GPDs: PDFs that correlated parton momentum and their distributions in transverse space



exclusive reactions the vehicle to access L_q & L_g
golden channel: J/Ψ

new theoretical concept: Generalized Parton Distributions

Spin-Sum-Rule in PRF:

$$\frac{1}{2} = J_q^z + J_g^z = \frac{1}{2}\Delta\Sigma + \sum_q \mathcal{L}_q^z + J_g^z$$

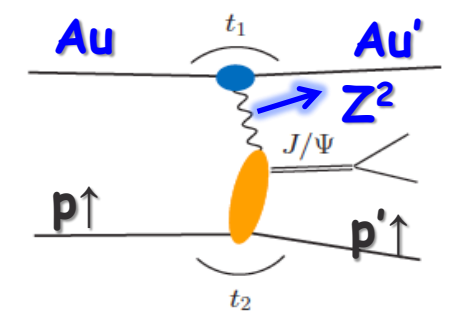
$$J_{q,g}^z = \frac{1}{2}\left(\int_{-1}^{1} x\,dx\left(H^{q,g} + E^{q,q}\right)\right)_{t\to 0}$$

responsible for orbital angular momentum

J/Ψ production in p↑Au UPC
→ world wide only access to GPD E for gluons

$$A_{UT}(t,t) \sim \frac{\sqrt{t_0 - t}}{m_p}\frac{\mathrm{Im}(E^* H)}{|H|} \qquad t = \frac{M_{J/\Upsilon}^2}{s}$$

Run-15: 7000 J/Ψ



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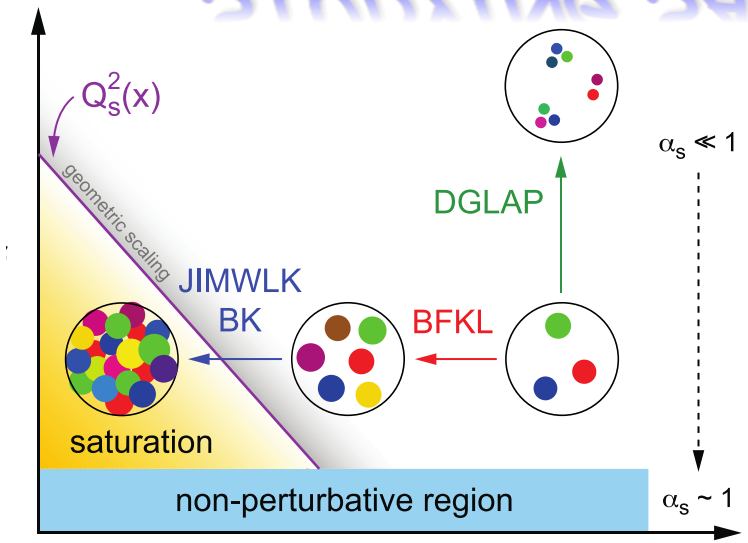
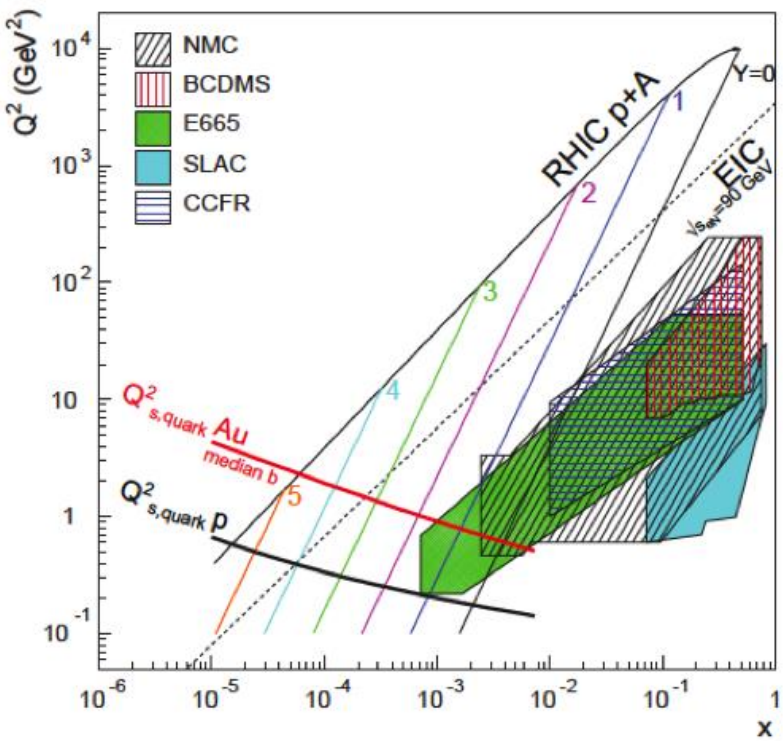
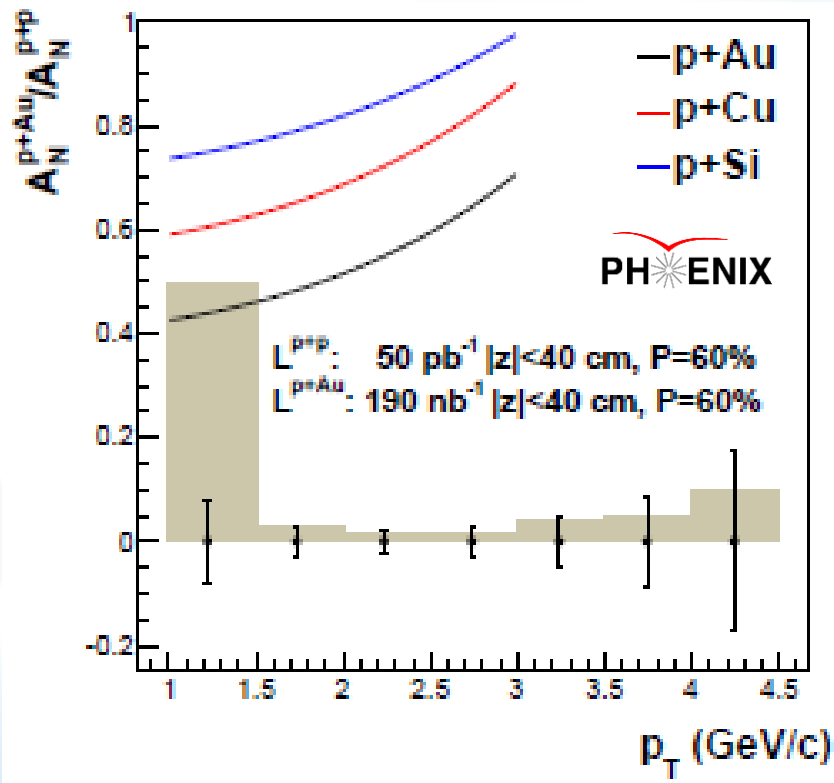
STUDYING SATURATION THROUGH SPIN



- Very unique RHIC possibility p↑A
- Synergy between CGC based theory and transverse spin physics
- Suppression of A_N in p↑A provides sensitivity to Q_s.

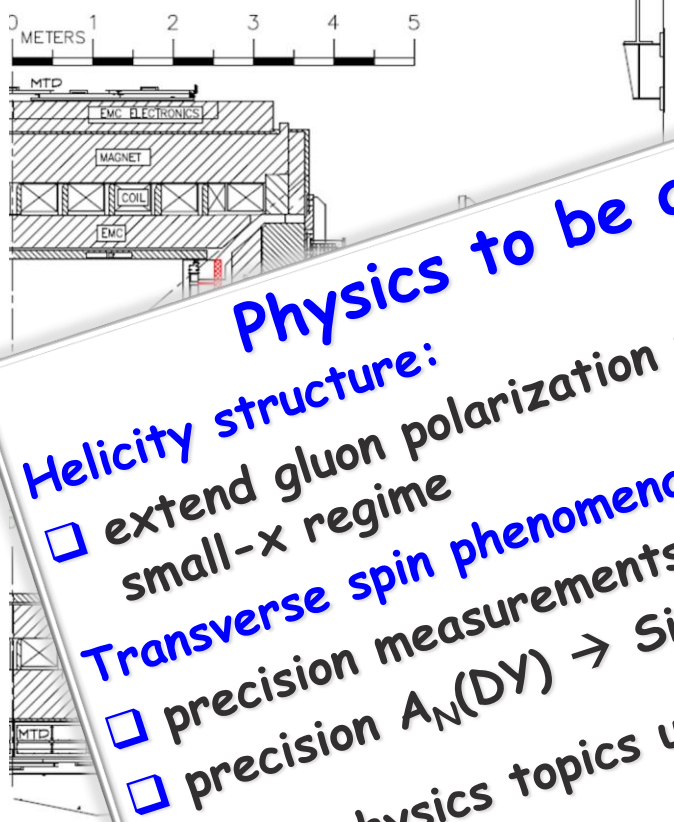
arXiv:1106.1375 & arXiv:1201.5890





PHENIX AND STAR FORWARD UPGRADES

STAR



Physics to be addressed with the upgrades

Helicity structure:

- ❑ extend gluon polarization measurements to the presently unconstrained small-x regime

Transverse spin phenomena:

- ❑ precision measurements of TMDs through jets at forward η
- ❑ precision $A_N(DY) \rightarrow$ Sivers fct.

several physics topics utilizing p+A collisions not discussed here

Details:

PHENIX-LoI: https://indico.bnl.gov/getFile.py/access?resId=0&materialId=5&confId=764

STAR-LoI: https://indico.bnl.gov/getFile.py/access?resId=0&materialId=4&confId=764

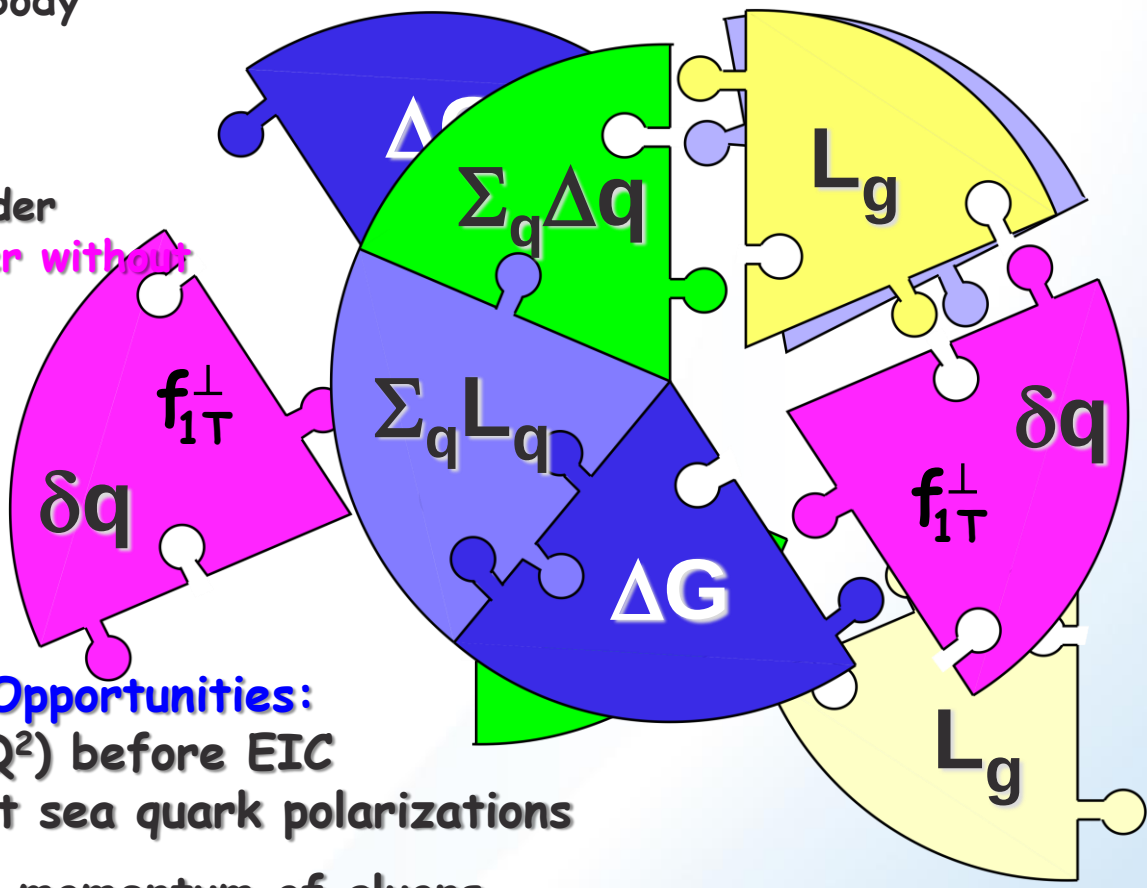
ECal:
Tungst... integrated in the
HCal: ...PHENIX detector
Lead an...
Tracking:
Silicon mi... detector or GEM-Tracker

RHIC SPIN Program:

SUMMARY

spin to study how a complex many-body system such as the proton arises from the vacuum structure of QCD

uniquely tied to a polarized pp-collider never been measured before & never without



many Achievements and future Opportunities:

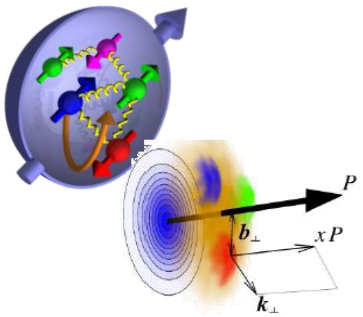
- the best constraint on $\Delta g(x,Q^2)$ before EIC
- strong constraints on the light sea quark polarizations
- a first look to orbital angular momentum of gluons
- mystery on what is the underlying process of forward A_N will be solved
- tests of TMD evolution and color interactions in QCD
- Spin as tool to test saturation models through $p\uparrow A$

BACKUP

FUNDAMENTAL QUESTIONS

How are sea quarks and gluons and their spin distributed in space and momentum inside the nucleon?

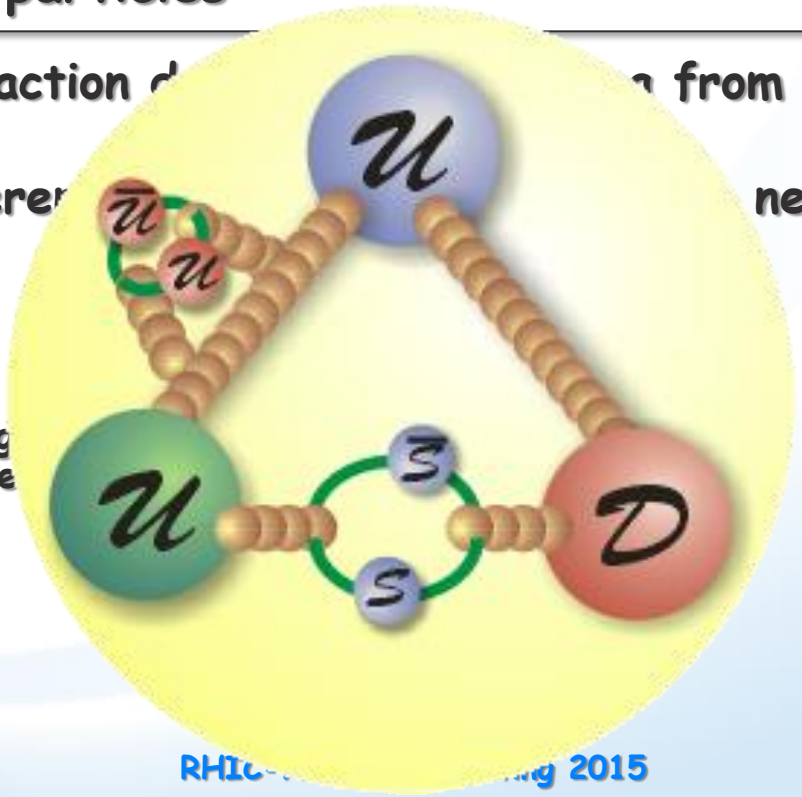
- How are these quark and gluon distributions correlated with the over all nucleon properties, such as spin direction?
- What is the role of the motion of sea quarks and gluons in building the nucleon spin?



How do quarks and gluons hadronize into final-state particles

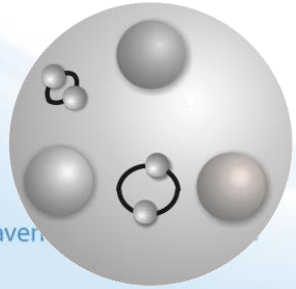
To separate interaction d **from intrinsic properties**

differen **needed**



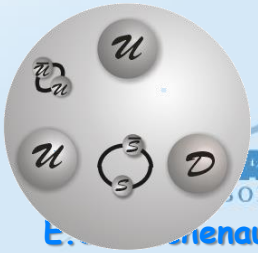
EM interaction

- Photon
- Sensitive to electric charg
- Insensitive to color charge



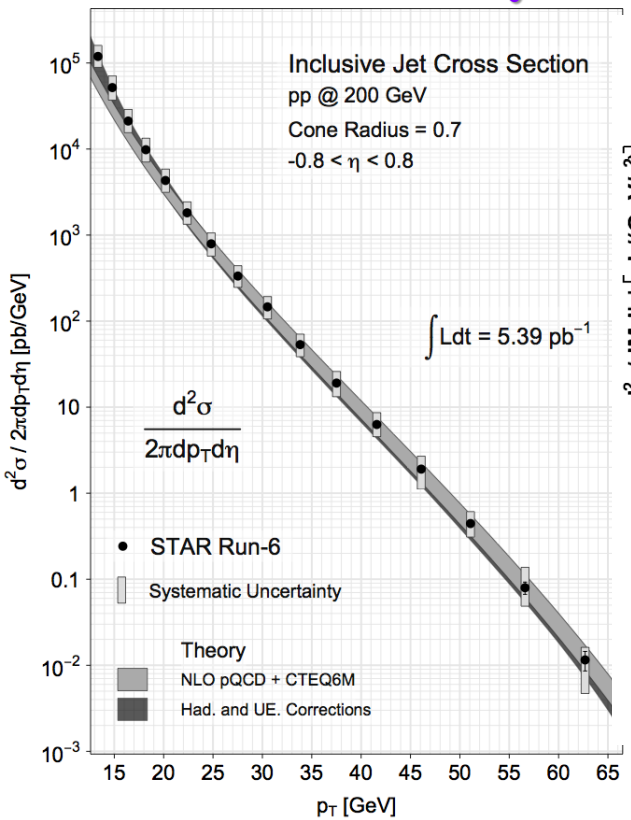
Weak Interaction

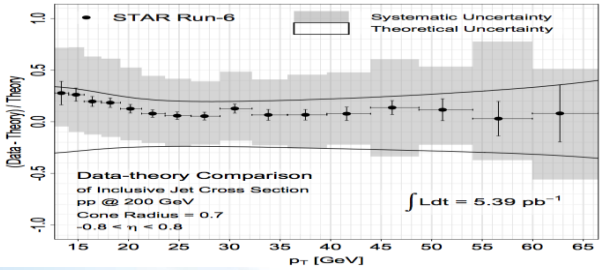
- Weak Boson
- Sensitive to weak charge ~flavor
- Insensitive to color



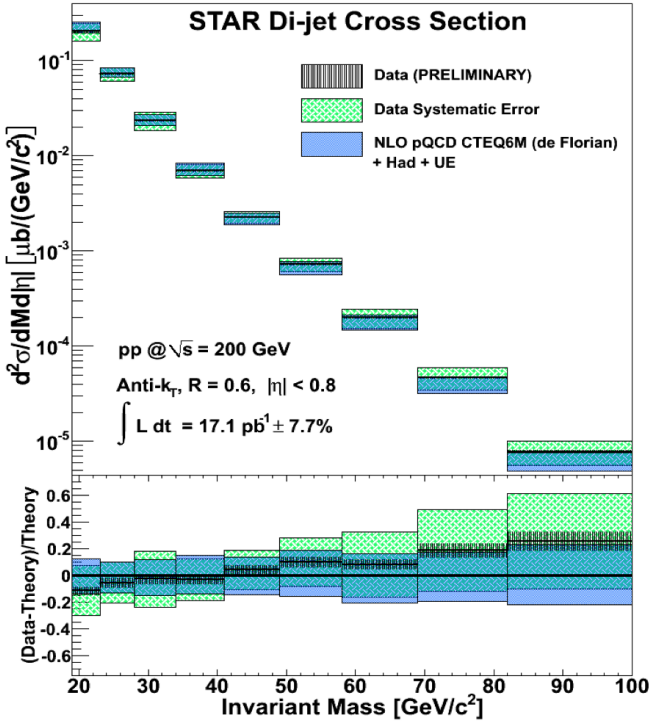
JET-CROSS SECTIONS

√s=200 GeV inclusive jets

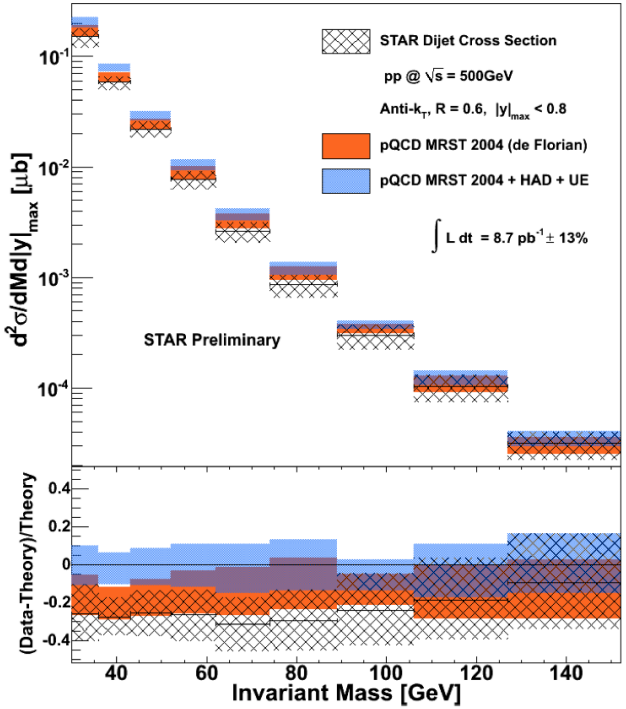




√s=200 GeV Di-jets



√s=500 GeV Di-jets

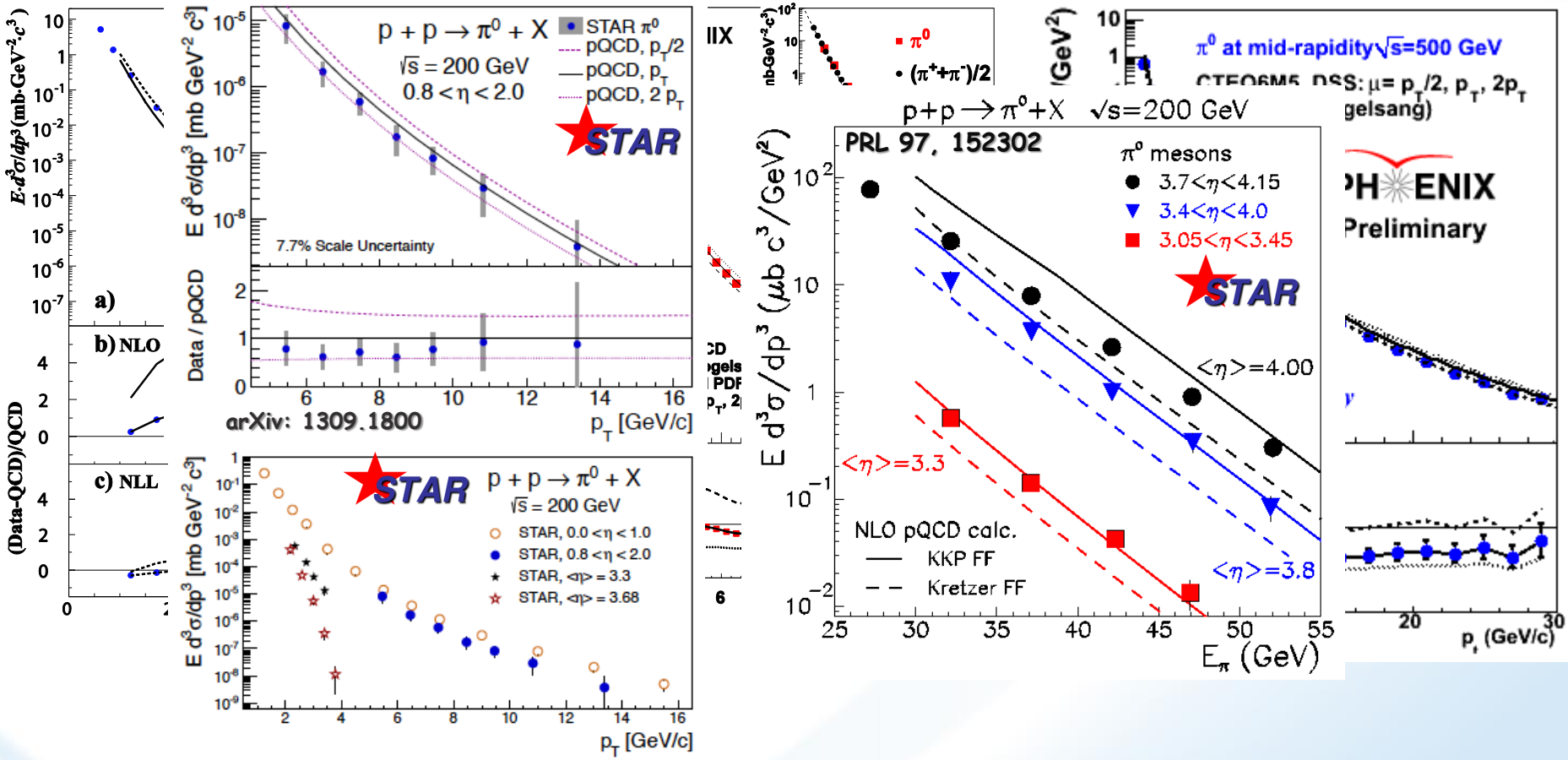


Data compared to NLO pQCD calculations:

- Inclusive jet and di-jet cross section results in p+p collisions are consistent with NLO pQCD calculations after Had+UE corrections

π^0-CROSS SECTIONS

√s=62 GeV (PRD79, 012003) √s=200 GeV (PRD76, 051106) √s=500 GeV (Preliminary)



Data compared to NLO pQCD calculations:

- √s=62 GeV calculations may need inclusion of NLL (effects of threshold logarithms)
- √s=200 and 500 GeV: NLO agrees with data within ~30%
- good agreement also for η>1
- Input to qcd fits of gluon fragmentation functions → DSS

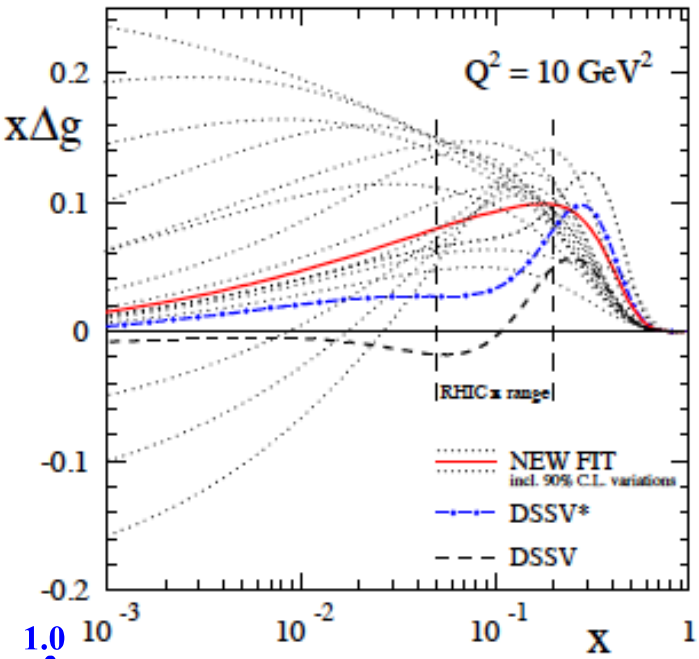
HIGH PRECISION 2009 RHIC DATA→∫Δg(X)

DSSV: arXiv: 1404.4293, PRL 113, 012001

DSSV: arXiv:0904.3821

DSSV*: DSSV + all new (SI)DIS

DSSV: DSSV* & RHIC 2009

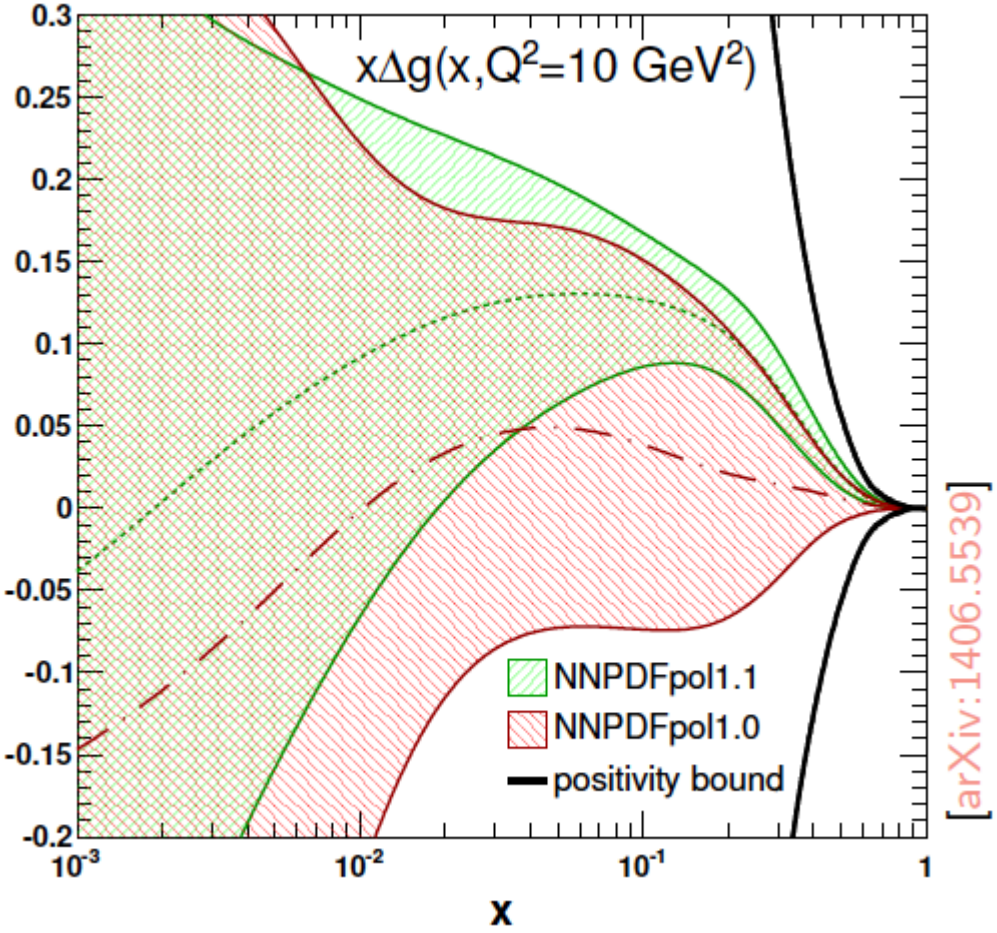


$$\int_{0.05}^{1.0} dx\Delta g \sim 0.2 \pm^{0.06}_{0.07} @\ 10\ GeV^2$$

First time a significant non-zero Δg(x)

- strong constrain on $\int \Delta g(x)$
- first $\int \Delta g(x) > 0$
- completely consistent with DSSV* in 90% C.L.

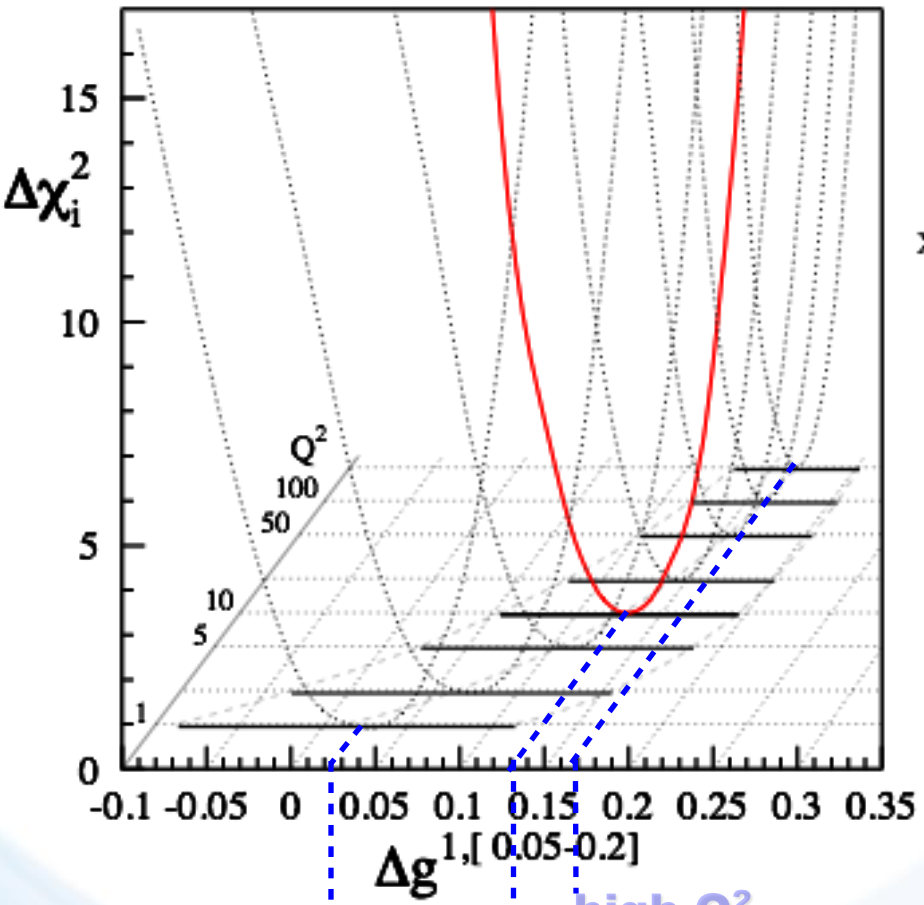
Impact in NNPDF

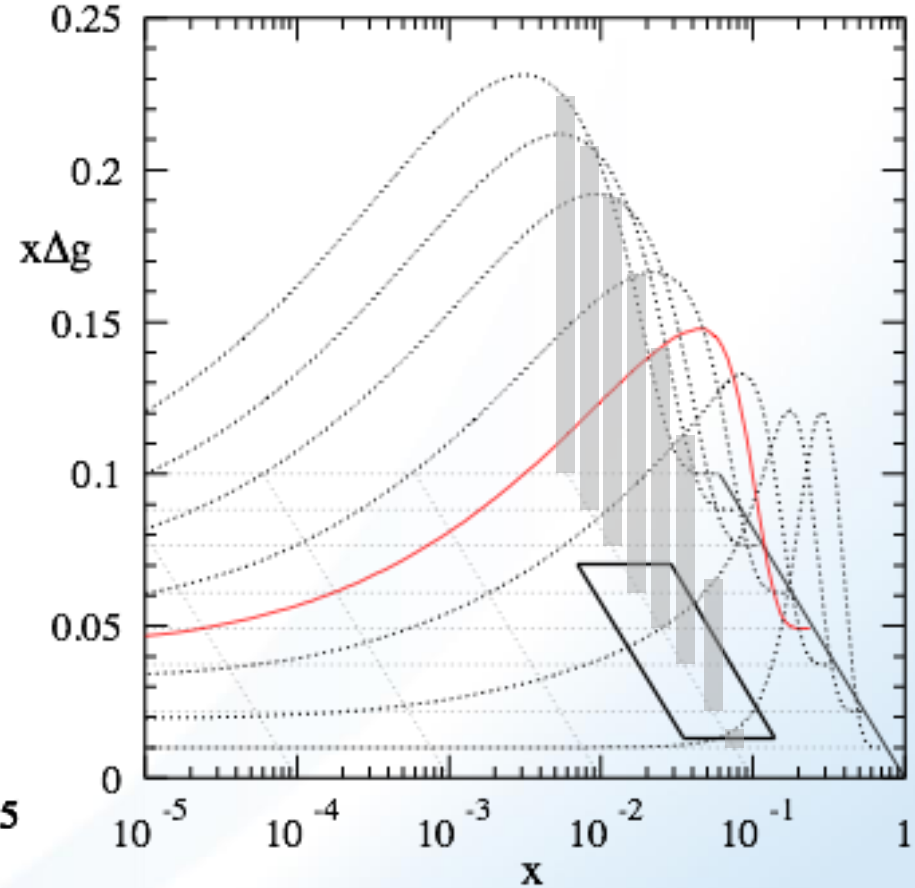


only STAR jets included

Q^2 DEPENDENCE

$$\Delta g^{1,[0.05-0.2]}(Q^2) \equiv \int_{0.05}^{0.2} \Delta g(x, Q^2)\, dx$$





high Q^2

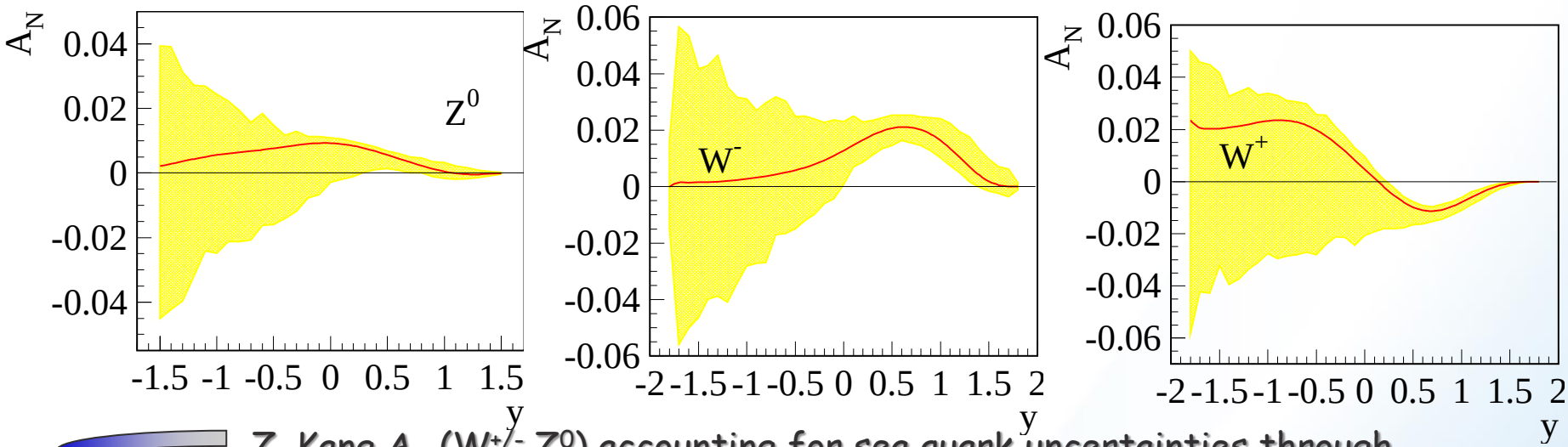
medium Q^2

low Q^2

very fast evolution
in RHIC kinematics

WHAT ELSE CAN WE LEARN

- What is the sea-quark Sivers fct.?
  - → W's ideal → rapidity dependence of A_N separates quarks from antiquarks
  - → no constraint from existing SIDIS data



Z. Kang A_N ($W^{+/-}$,Z^0) accounting for sea quark uncertainties through positivity bounds
all plots after evolution (arXiv:1401.5078)

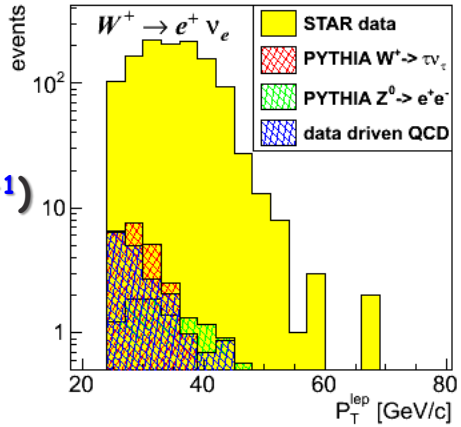
STAR: A_N^W

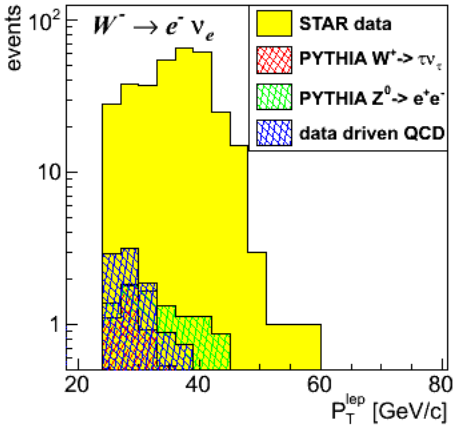
Analysis Strategy to fully reconstruct Ws:

Follow the analysis steps of the A_L

→ W candidate selection via high p_t lepton

Data set: 2011 transverse 500 GeV data (25 pb^{-1})





✓ **In transverse plane:** $\vec{P}_T^W = \vec{P}_T^e + \vec{P}_T^n = \vec{P}_T^{recoil}$

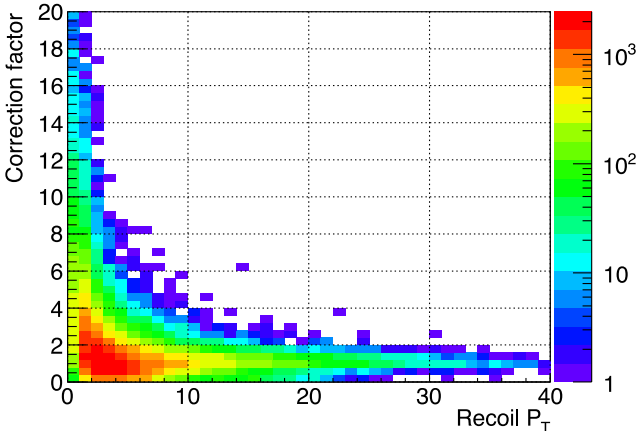
✓ **Recoil reconstructed using tracks and towers:** $\sum_{i=tracks+trackless-clusters} \vec{P}_T^i$

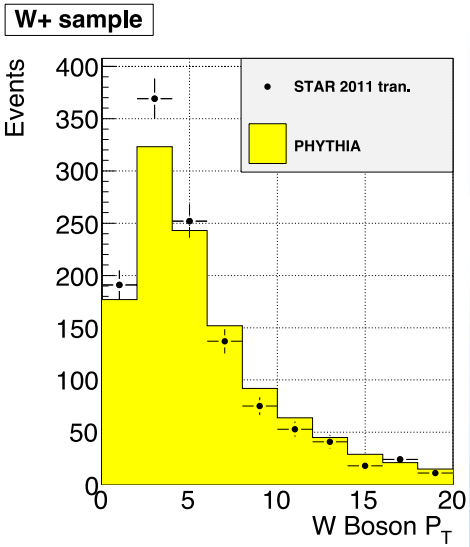
✓ **Part of the recoil not within STAR acceptance**

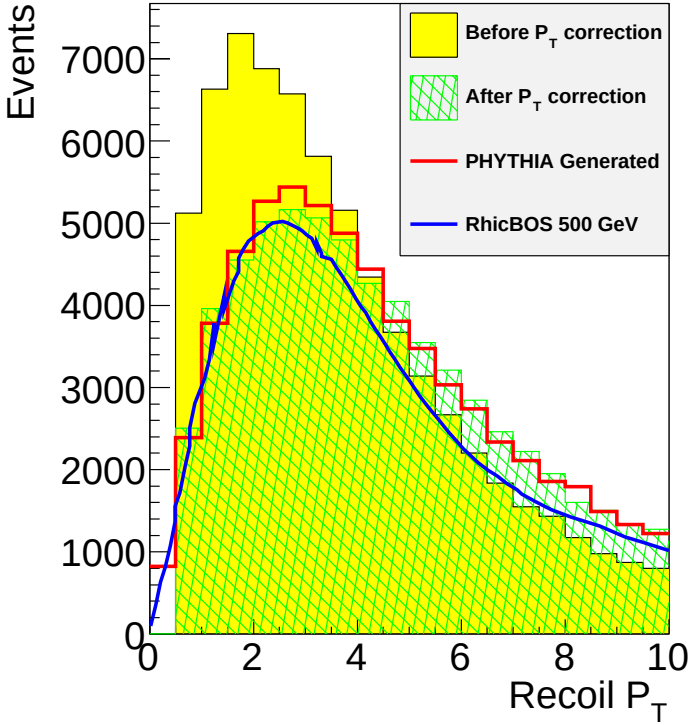
→ correction through MC (Pythia)

→ MC-correction

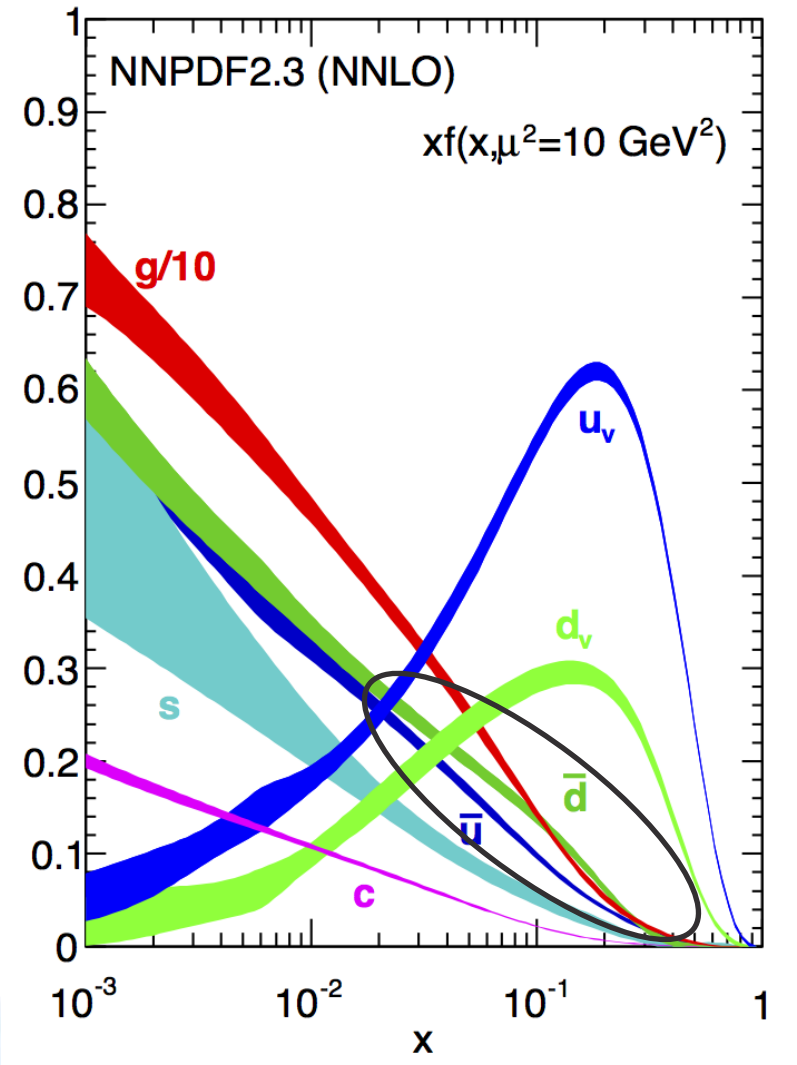
$$k_i = \frac{P_{T,i}^W(true)}{P_{T,i}^{Recoil}(reconstructed)}$$







ARE SEA QUARKS FLAVOR-SYMMETRIC?



at which x-range are sea quarks flavor symmetric ?

High precision high-x PDFs critical for searches at high masses at the LHC

→ RHIC

mid-rapidity jet cross sections
→ high x gluons (200 GeV)
W^+/W^-: u, d, ubar, dbar PDFs

UNPOLARIZED W+/W- RATIOS

- What will we learn?
  - d-bar/u-bar in PDFs

LO:

$$A\left(W^+/W^-\right) = \frac{u(x_1)\bar{d}(x_2)+\bar{d}(x_1)u(x_2)}{\bar{u}(x_1)d(x_2)+d(x_1)\bar{u}(x_2)}$$

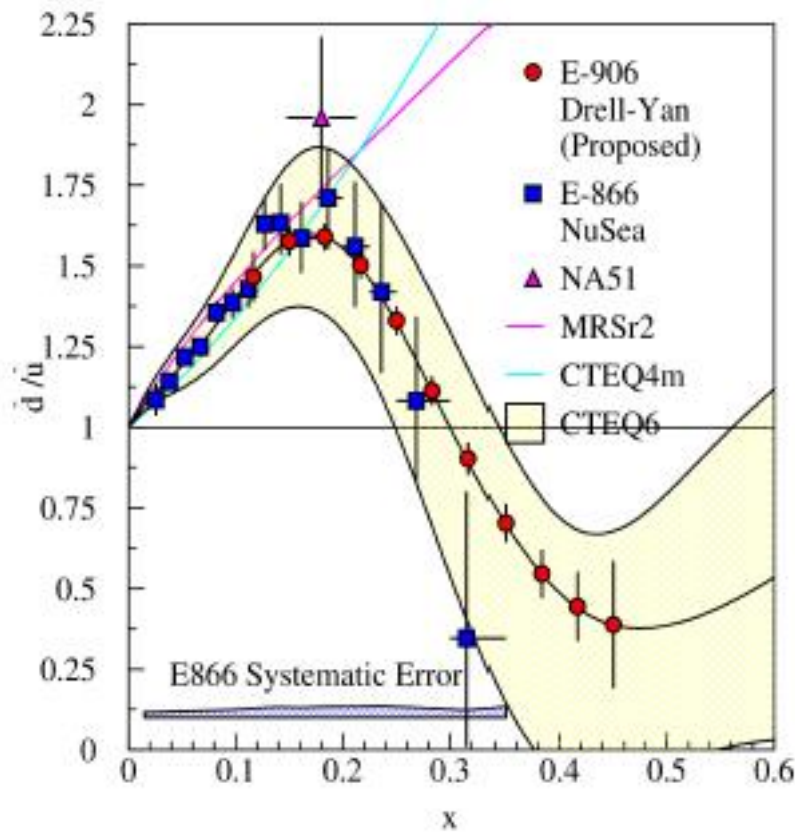
LHC coverage: ~10^{-3} < x < 10^{-1}

RHIC coverage: x > ~10^{-1}

- Current data: E866/NuSea (Drell-Yan)

$$\bar{d}(x)/\bar{u}(x) \text{ for } 0.015 \leq x \leq 0.35$$

  - included in all NLO global PDF fits



✧ Unpolarized asymmetries:

✧ Quantitative calculation of Pauli blocking does not explain $\bar{d}/\bar{u}$ ratio

THE UNPOLARIZED W+/W- CROSS SECTION RATIO

What we measure

$$RW = \frac{s(W+)}{s(W-)} = \frac{N_{obs}^{W+} - N_{bkg}^{W+}}{N_{obs}^{W-} - N_{bkg}^{W-}} \times \frac{e^{W-}}{e^{W+}}$$

N_{obs} = observed W events
N_{bkg} = background events
ε = efficiency

- Same selection as for A_N
- Background estimated in the same way
- W boson kinematics are reconstructed in the same way
- We do not care of the polarization direction in measuring RW
  - We could add the STAR 2012 data at $\sqrt{s}$= 510 GeV
  - and will add run 13

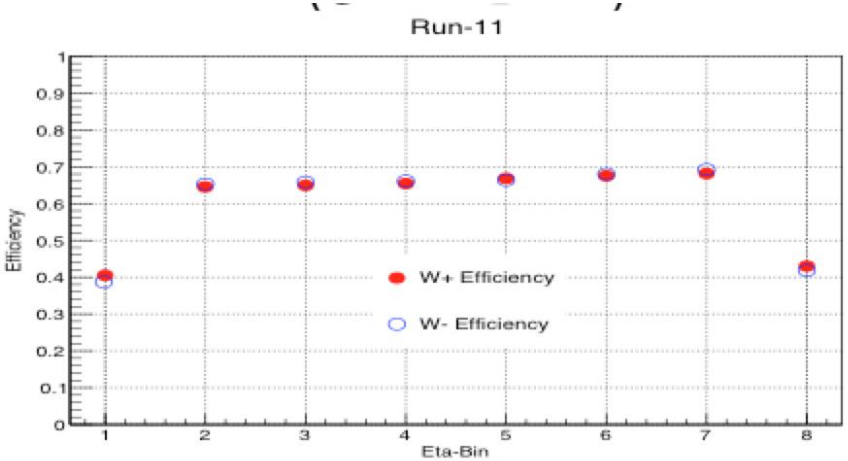
Data sample

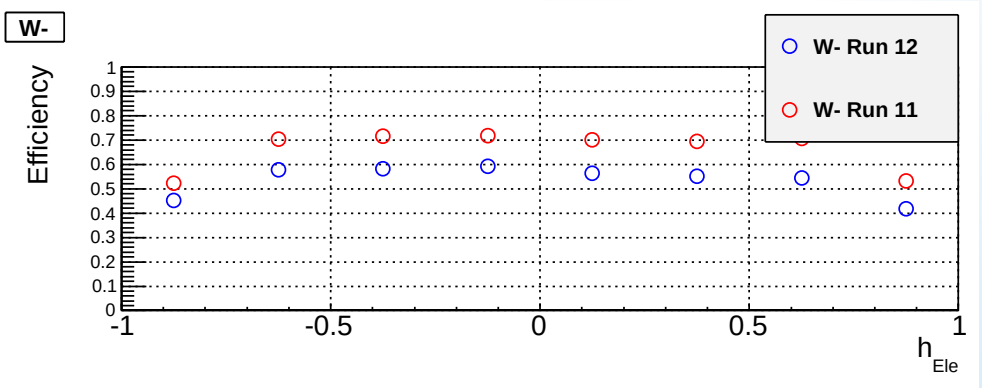
- pp – run11 transverse @ $\sqrt{s}$=500 GeV Integrated Luminosity ~25 pb^{-1}
- pp – run12 long @ $\sqrt{s}$=510 GeV Integrated luminosity: ~ 77 pb^{-1}
- Total Int. lumi: 102 pb^{-1}

EFFICIENCY STUDY

$$e = \frac{\#evt(reconstructed)}{\#evt(generated)}$$

Uncertainties calculated binomially (not visible)





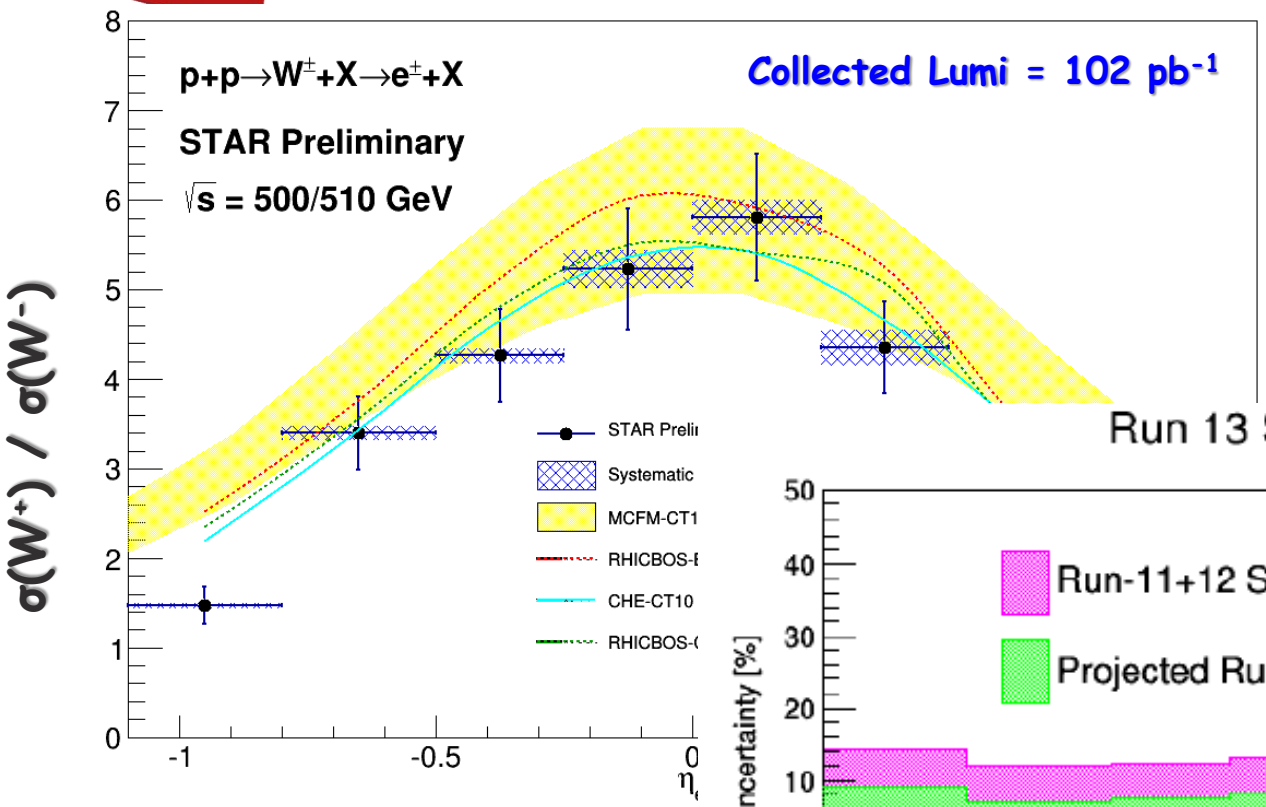
The efficiency depends very little on the charge

→ it plays negligible role in this measurement

The efficiency depends on the period

Run 12 less efficient than run 11 because of the lower reconstruction efficiency at higher rates due to pile up effects in the TPC

W+/W- RATIO AS FCT. OF LEPTON RAPITITY

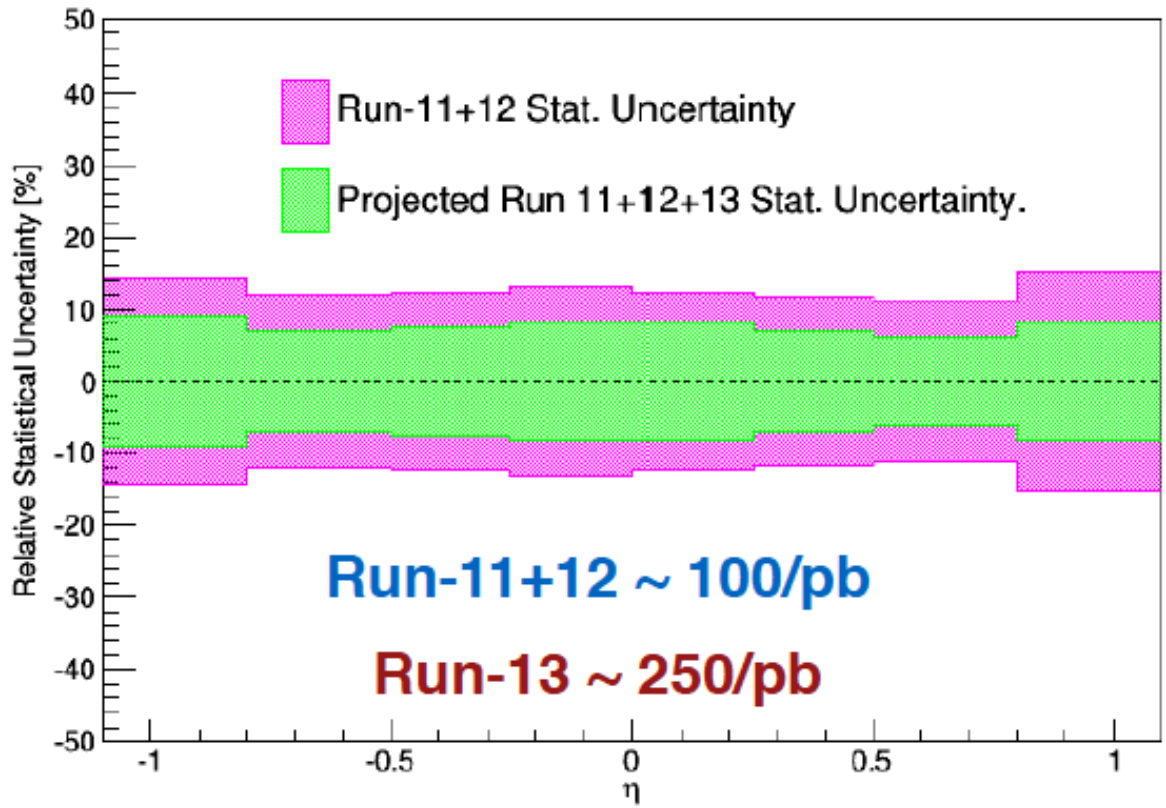


Systematics much smaller than statistical uncertainties

Systematic uncertainties (blu

- QCD background varied th
- Z^0 -> ee background vary

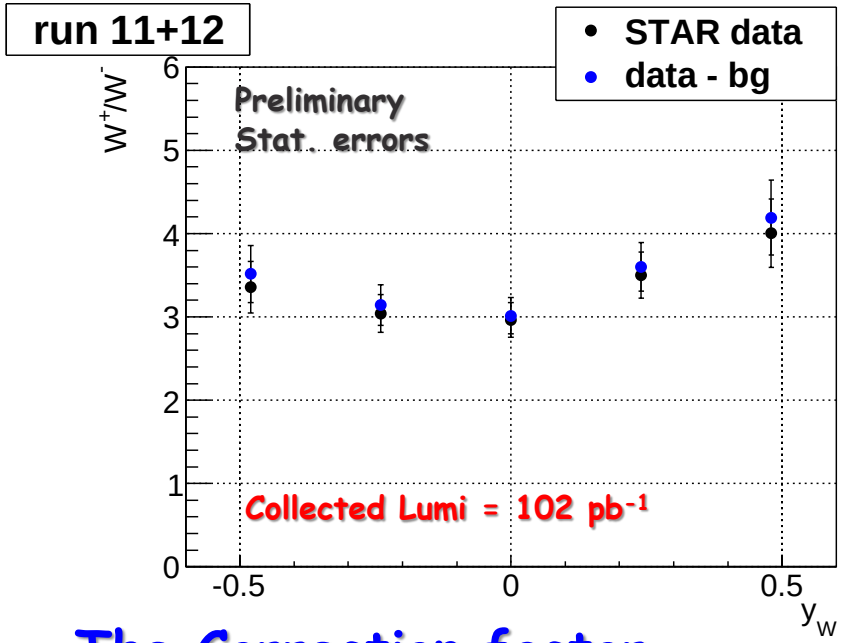
Run 13 Statistical Impact



W+/W- VS BOSON RAPIDITY

Why to use fully reconstructed Ws for charge ratio:

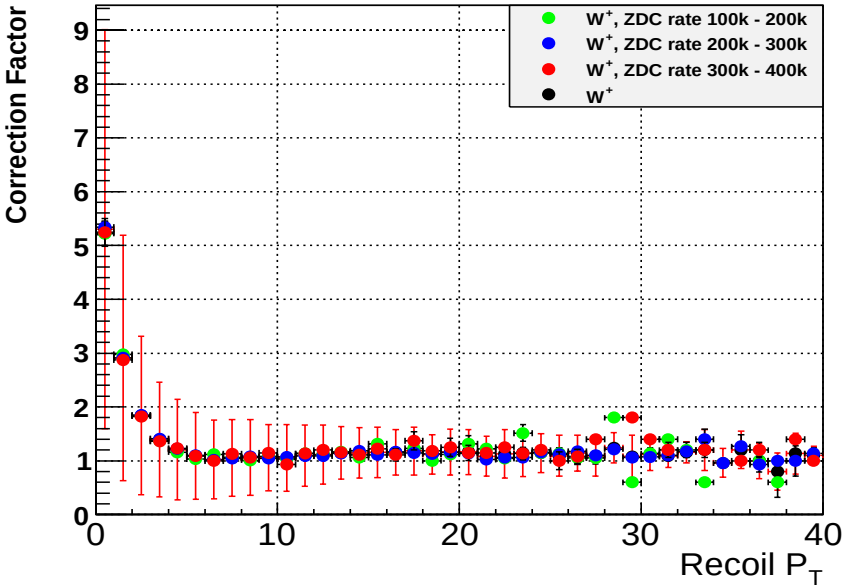
- no smearing in x compared to "lepton asymmetry"
- access to higher x compared to "lepton asymmetry"
- Cross check of CDF measurements



Follow the same procedure to reconstruct W kinematics as for A_N

Blue points: After background subtraction

- Impact of background subtraction smaller than statistical uncertainties



The Correction factor

Is not charge-dependent

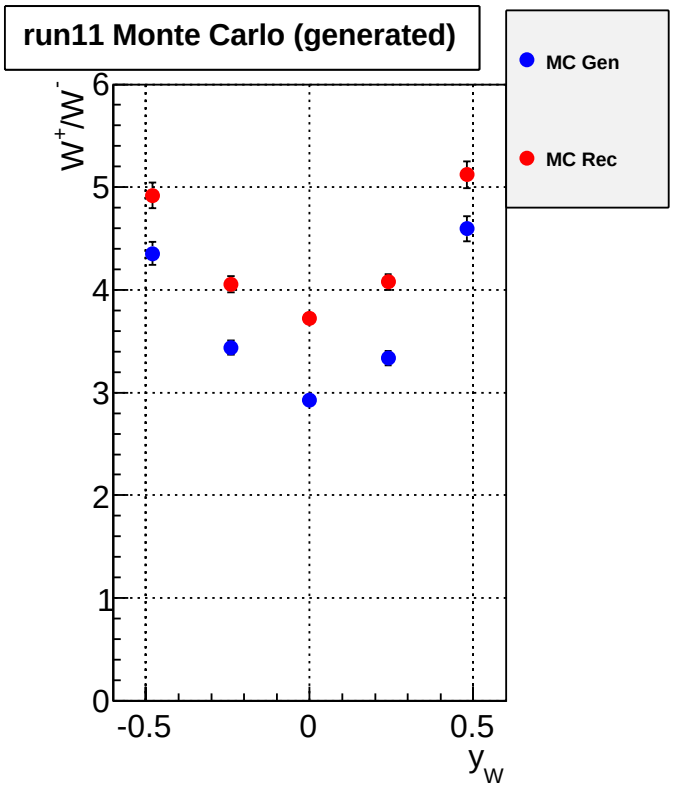
→ does not impact the W+/W- ratios !

Is not interaction-rate dependent

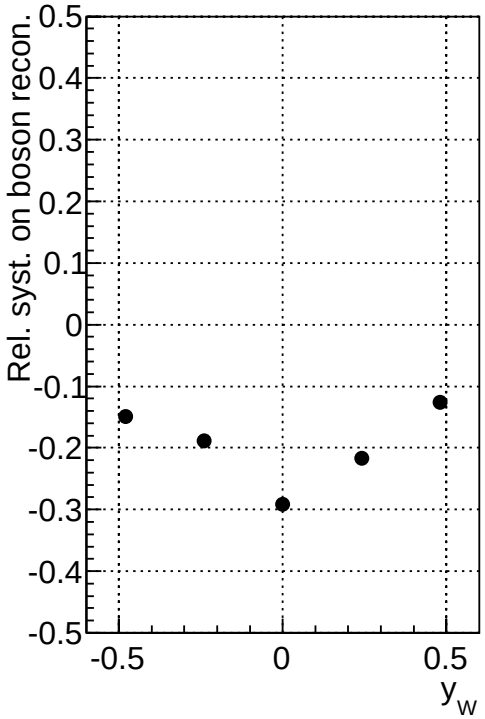
→ we can combine different run periods

SYSTEMATICS FOR W RECONSTRUCTION

- Systematics on background subtraction (as for the decay lepton)
- Systematics on the reconstruction smearing
  - Calculate the ratio with generated pure MC
  - Calculated the ratio with reconstructed MC after all the analysis
  - Assign the difference as systematic uncertainty

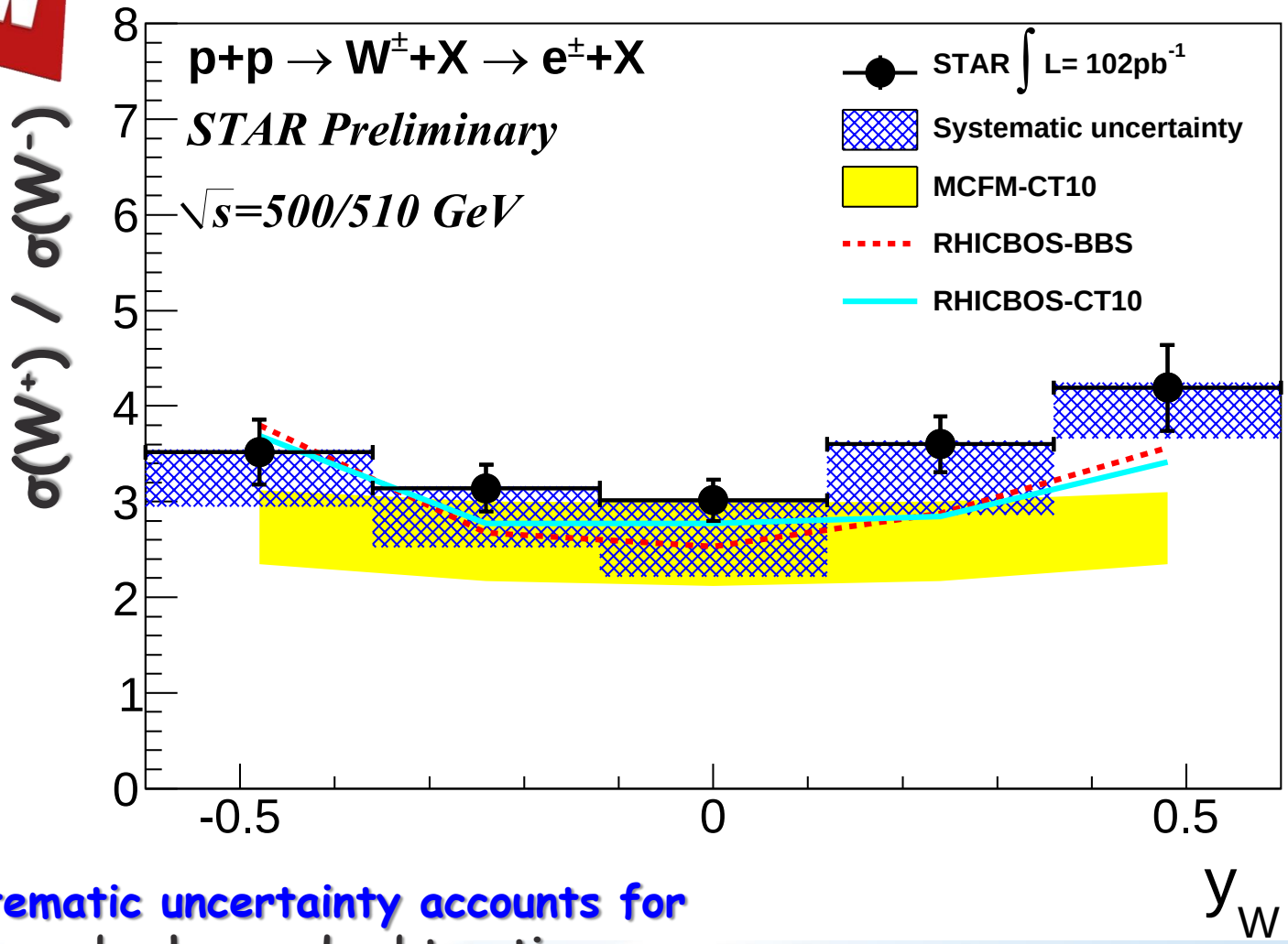


Relative Systematics



W^+/W^- AS FUNCTION OF BOSON RAPIDITY

New

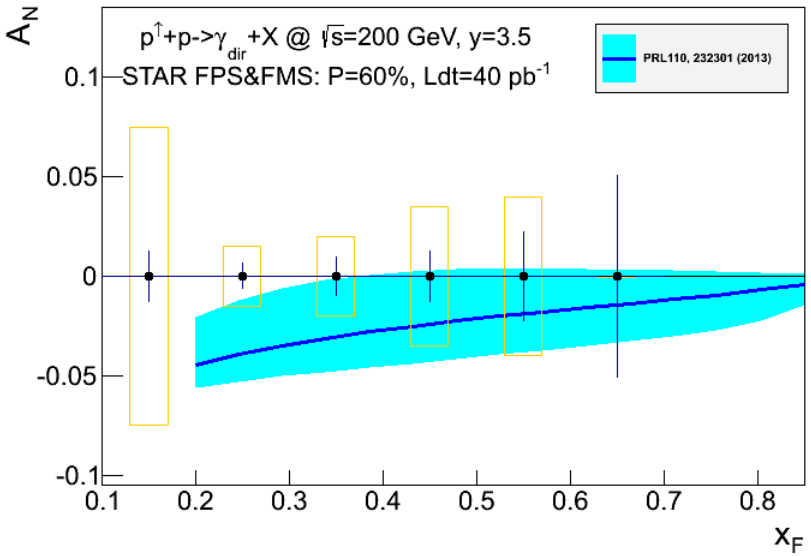


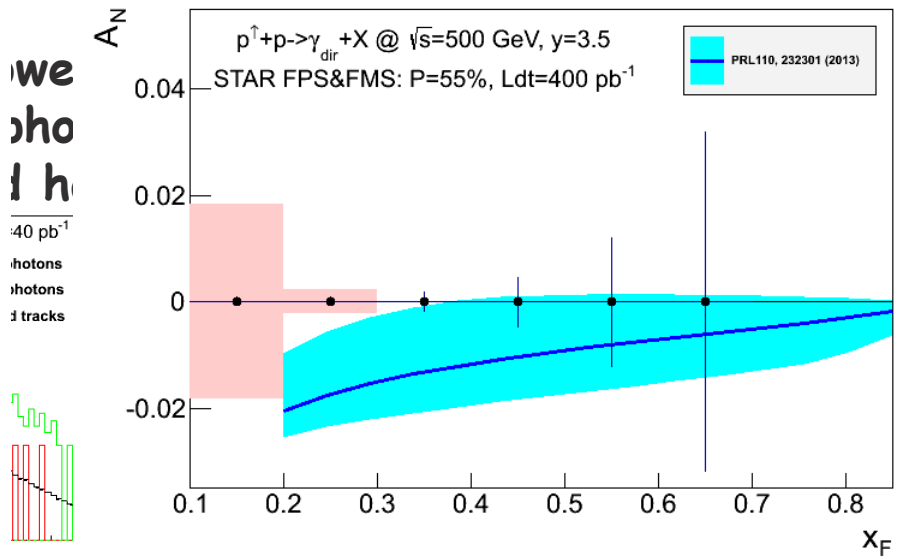
Total systematic uncertainty accounts for

- Syst. from background subtraction
- Syst. from W reconstruction

COMPLEMENTARY CHANNEL

STAR FMS-PreShower:





p_T (GeV)

A_N for direct photon production:

- sensitive to sign change, but in TWIST-3 formalism
- not sensitive to TMD evolution
- no sensitivity to sea-quarks; mainly u_v and d_v at high x
- collinear objects but more complicated evolutions than DGLAP
- indirect constraint on Sivers fct.

$$-\int d^2k_\perp \frac{|k_\perp^2|}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{SIDIS} = T_{q,F}(x,x)$$

Not a replacement for $A_N(W^{+/-}, Z^0, DY)$ measurement but an important complementary piece in the puzzle

STAR POSSIBILITIES

	$A_N(W^{+/-},Z^0)$	$A_N(DY)$	$A_N(\gamma)$
sensitive to sign change through TMDs	yes	yes	no
sensitive to sign change through Twist-3 $T_{q,F}(x,x)$	no	no	yes
sensitive to TMD evolution	yes	yes	no
sensitive to sea-quark Sivers fct.	yes	yes	no
need detector upgrades	no	yes FMS postshower	no
biggest experimental challenge	integrated luminosity	background suppression & integrated luminosity	---------

$A_N(DY,W^{+/-},Z^0,\gamma)$ clean and proven probes sensitive to all questions in a timely way without the need for upgrades

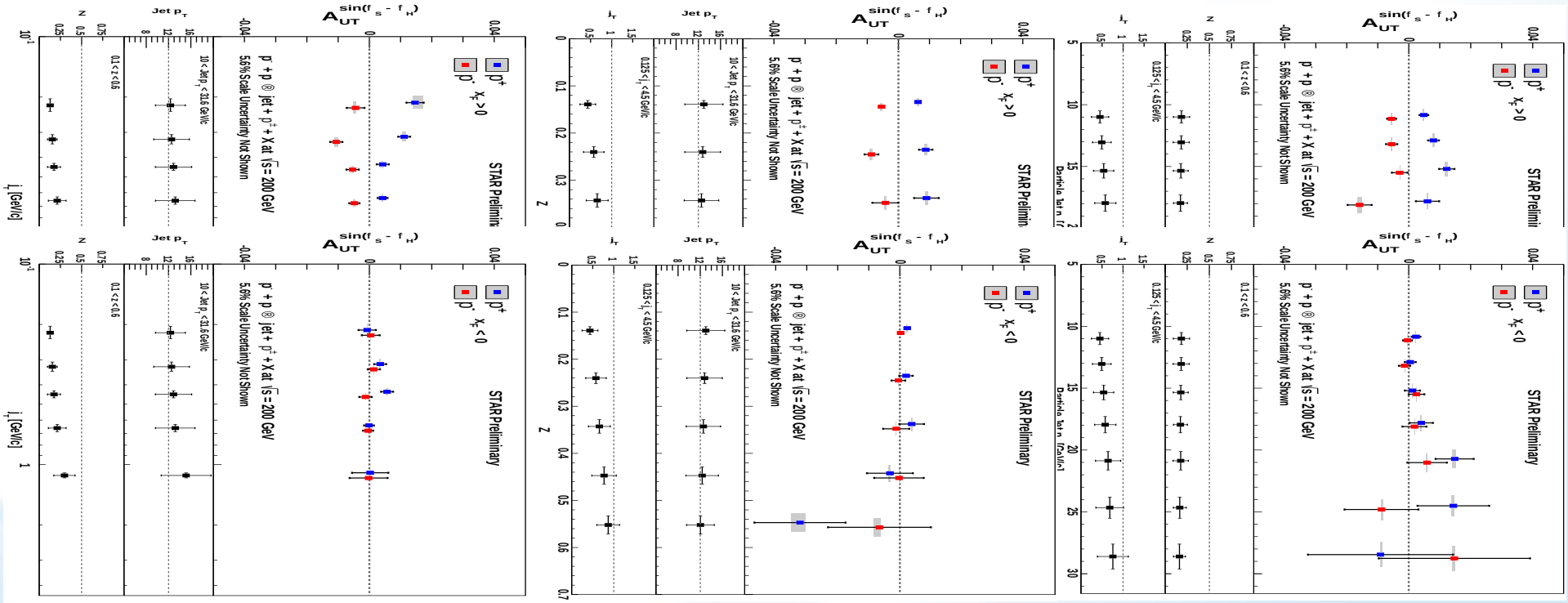
- 20 pb^{-1} transversely polarized p+p collisions at $\sqrt{s}$ = 200 GeV

  Average event weighted polarization: 63%

  Anti-k_T (R = 0.6) jet reconstruction $|\eta_{jet}| < 1$

  Jet p_T > 10 GeV/c (x_T > 0.1) reduces gluon contamination ΔR_{min} > 0.1

A_{UT} vs. j_T A_{UT} vs. z A_{UT} vs. p_T



The first statistically significant non-zero Collins asymmetries in pp collisions