Spin Physics at the STAR Experiment

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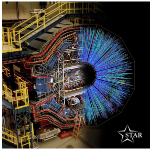
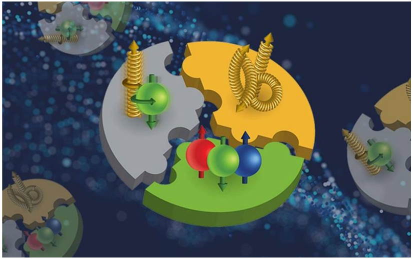


Outline

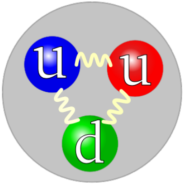
- **The proton structure**
  - Proton helicity structure
    1. Gluon polarization: inclusive jet, and di-jet production
    2. Sea quark polarization: $W^{\pm}/Z$ boson production
  - 3D Structure of the proton
    1. TMD parton distribution function
    2. Transversity and TMD fragmentation function, identified hadrons in jets
- **Future STAR measurements**
  - STAR forward upgrade at η as large as 4
- **Conclusion**

Proton Helicity Structure from Longitudinally Polarized Proton Beam



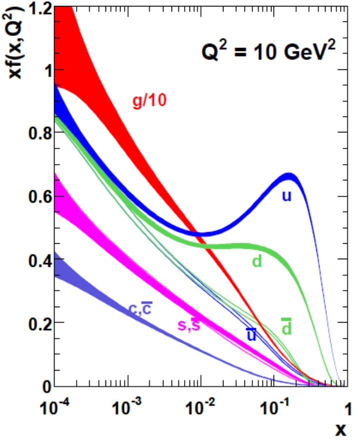
The Proton Structure

- **Constituents**: quarks and gluons



- **Parton distribution functions**: $f(x, Q^2)$, the probability of a probe at momentum transfer Q^2 encountering a parton in the proton with momentum fraction x
- gluons dominate at low x

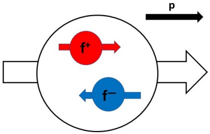
- $xf(x, Q^2 = 10\ \mathrm{GeV}^2)$ vs. x for quarks and gluons, MSTW, EPJC63, 189



Proton spin sum rule:

$$S_z = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_{q,g}$$

- In longitudinally polarized proton, PDF also depends on parton helicity
- Quark: $\Delta\Sigma(Q^2) = \int_0^1 dx \Delta f_q(x, Q^2) = \int_0^1 dx(f_q^+(x, Q^2) - f_q^-(x, Q^2))$
- Gluon: $\Delta G(Q^2) = \int_0^1 dx \Delta g(x, Q^2) = \int_0^1 dx(g^+(x, Q^2) - g^-(x, Q^2))$



Deep inelastic scattering:

- Quark contribution $\Delta\Sigma$: constrained

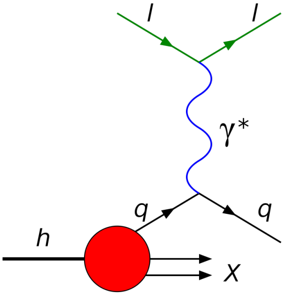
  $\Delta\Sigma = 0.254 \pm 0.042$, Leader et al, PRD 82, 114018

- Gluon contributions ΔG: **poorly** constrained

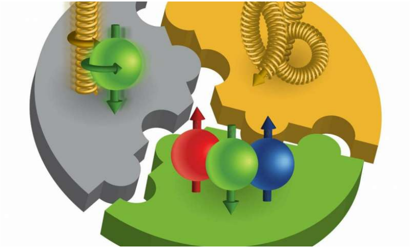
  Fixed targets experiments → Limited in $x - Q^2$ space

  Constrained through scaling violation

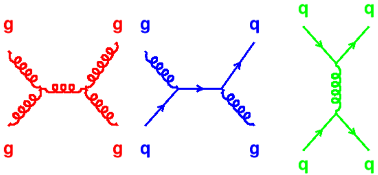
- Orbital angular momentum contribution, $L_{q,g}$: not constrained



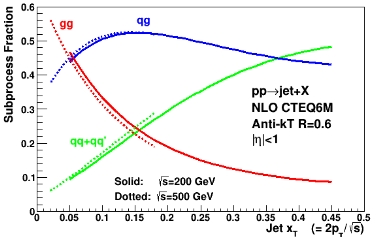
Gluon Polarization at RHIC



- Asymptotic freedom at short distances → parton-parton scattering
- At RHIC, jets, clusters of collimated particles, are dominated by *gg* and *qg* processes, therefore allow direct access to Δg



PRD86, 094009

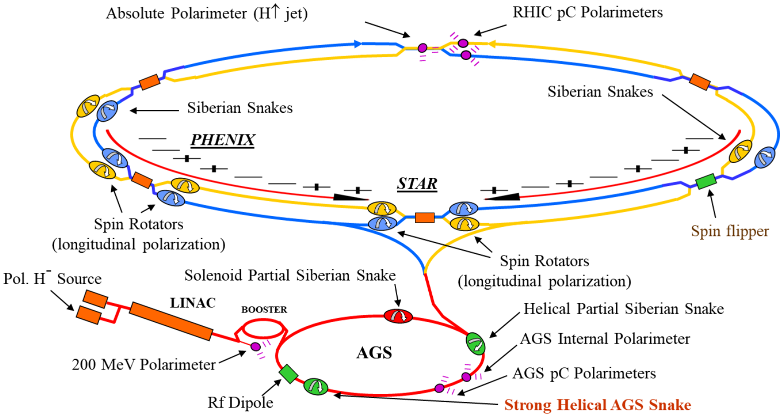


- Define longitudinal double-spin asymmetry A_{LL}:

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

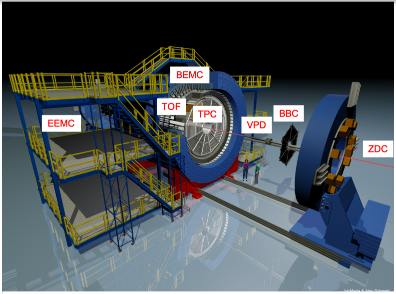
- Theory predicts large partonic $\hat{a_{LL}}$ involving *gg* and *qg* processes
- **Making A_{LL} sensitive to gluon polarization**

RHIC Facilities, World-only Polarized Collider



- 2.4 mile in circumference, two lane "racetrack"
- 120 bunches around each ring
- Polarization orientation varies from bunch to bunch to minimize systematic uncertainty
- Spin rotators provide choice of polarization orientation (longitudinal or transverse).
- Beam polarizations are around 55 to 65%

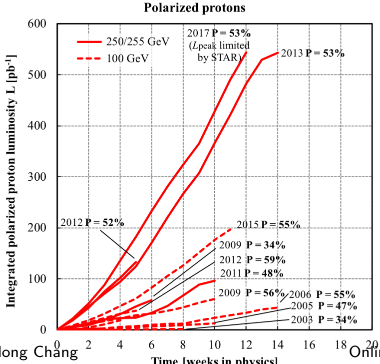
STAR Detectors



- Full 2π coverage in azimuthal
- Tracking with TPC: $|\eta| < 1.3$
- EM energy and triggering with:

  BEMC: $-1.0 < \eta < 1.0$,
  EEMC: $1.0 < \eta < 2.0$
- Spin-sorted relative luminosity monitoring detectors:

  VPD, BBC and ZDC

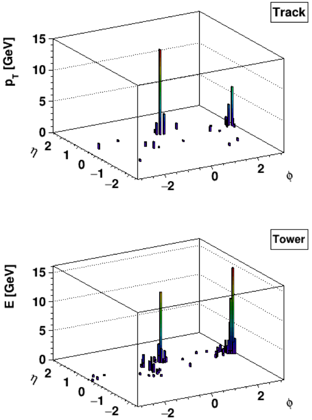


- Polarized *pp* dataset collected at RHIC over the past two decades
- At both $\sqrt{s} = 200$ GeV and $\sqrt{s} = 500/510$ GeV
- Two large dataset collected in 2013 (longitudinally polarized) and 2017 (transverse polarized) at 510 GeV
- Recent 200 GeV data from 2015 have equal amount of transverse and longitudinal polarizations

- Inputs to jet finder, reconstructed charged TPC tracks and electromagnetic towers
- Anti-k_T algorithm with $R = 0.6$ for 200 GeV and $R = 0.5$ for 510 GeV
- Count number of jets when beams have the same and the opposite helicity, N^{++} and N^{+-}
- Measure:

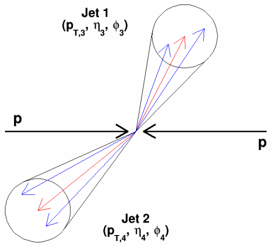
$$A_{LL} = \frac{N^{++} - RN^{+-}}{P_B P_Y (N^{++} + RN^{+-})}$$

$P_{B(Y)}$: beam polarizations, and
$R = \frac{L^{++}+L^{--}}{L^{+-}+L^{-+}}$: spin-sorted relative luminosity



Dijet Events at STAR

- Two leading p_T jets in an event
- $p_{3,T} > 6$ GeV/c, $p_{4,T} > 8$ GeV/c, theoretical consideration
- Opening angle $\Delta\phi = \phi_3 - \phi_4 > \frac{2\pi}{3}$, remove hard gluon emissions
- $|\Delta\eta| = |\eta_3 - \eta_4| < 1.6$, limit detector acceptance
- Dijets are measured in topology bins defined by η_3 and η_4
- Topology bins sample different pairs of x_1 and x_2 and scattering angles $cos\theta^*$, therefore constrain the shape of $\Delta g(x)$



$$x_1 = \frac{1}{\sqrt{s}}(p_{T,3}e^{\eta_3} + p_{T,4}e^{\eta_4})$$

$$x_2 = \frac{1}{\sqrt{s}}(p_{T,3}e^{-\eta_3} + p_{T,4}e^{-\eta_4})$$

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

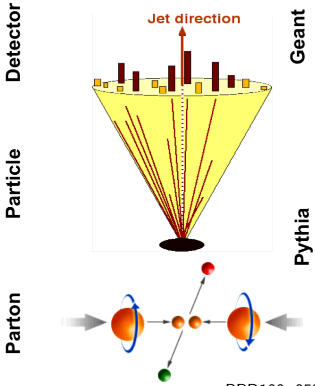
$$|cos\theta^*| = tanh\frac{|\eta_3 - \eta_4|}{2}$$

- Data-driven modified PYTHIA6 Perugia 2012 Tune with reduced $P_{90} = 0.213$ from 0.24

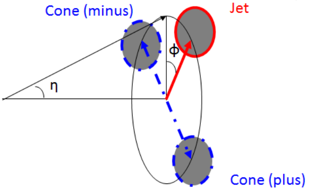
$$\sigma \sim \frac{1}{(p_T^2 + p_{T,0}^2)^2}$$

$$p_{T,0} = p_{T,ref} \times (\frac{\sqrt{s}}{\sqrt{s_{ref}}})^{P_{90}}$$

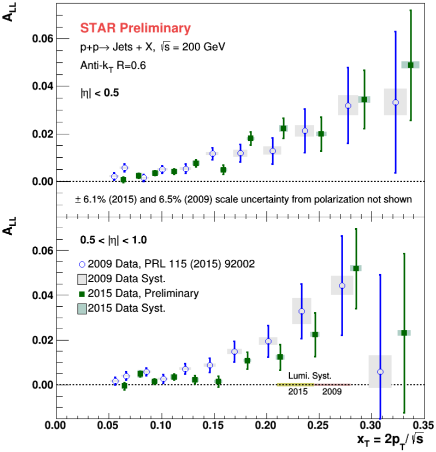
- Jet reconstruction at three levels: simulated detector response, PYTHIA particle and parton jets
- Simulated jet quantities match data very well
- Two off-axis cones centered at $\pm\frac{\pi}{2}$ away in ϕ and the same η relative to a given jet are used to estimate underlying event for that jet, ALICE, PRD 91, 112012
  1. Corrected the measured jet energy due to underlying event contribution
  2. Estimated the underlying event contribution to jet A_{LL}



PRD100, 052005



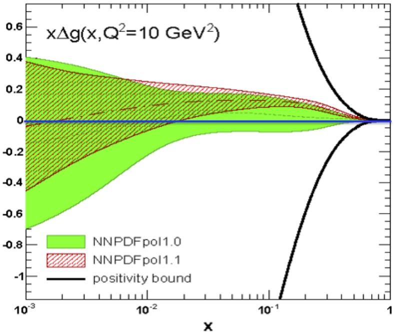
- Inclusive jet A_{LL} at $\sqrt{s} = 200$ GeV



- Reduced statistical uncertainty from the recent 2015 data comparing to the 2009 data

NNPDF, NPB887, 276

- $x\Delta g(x, Q^2)$ vs. x at $Q^2 = 10\mathrm{GeV}^2$
- With STAR 2009 data only:
  $\int_{0.05}^{0.5} dx \Delta g(x) = 0.23 \pm 0.07$

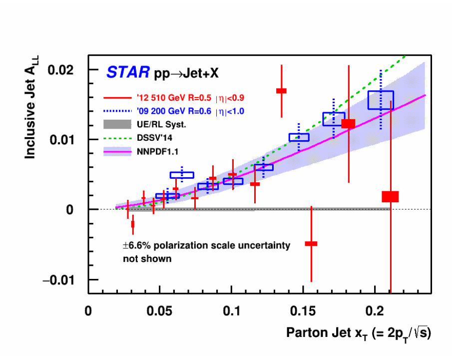


- Significant impact on $x\Delta g(x, Q^2)$
- Uncertainty on $x\Delta g$ still large when $x < 0.05$
- To constrain $x\Delta g$ at $x < 0.05$ better: increasing $\sqrt{s}$

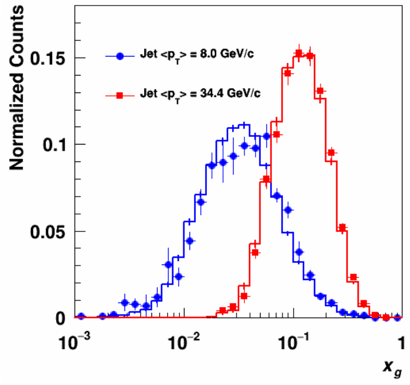
STAR Inclusive Jet A_{LL} Results at $\sqrt{s} = 510$ GeV

- Inclusive jet A_{LL} vs. jet $x_T = \frac{2p_T}{\sqrt{s}}$ together with 2009 200 GeV results,

  PRD100, 052005



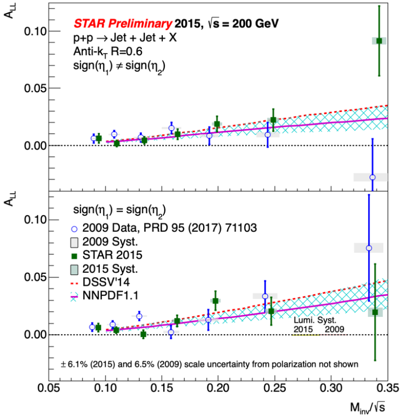
- Sampled x_g distribution by jet with $< p_T >= 8$ GeV/c and 34.4 GeV/c



- Agree with previously published data at $\sqrt{s} = 200$ GeV
- Also agree well with pQCD calculation with recent polarized PDF
- At 510 GeV, access $\mathbf{x_g}$ as low as **0.015**

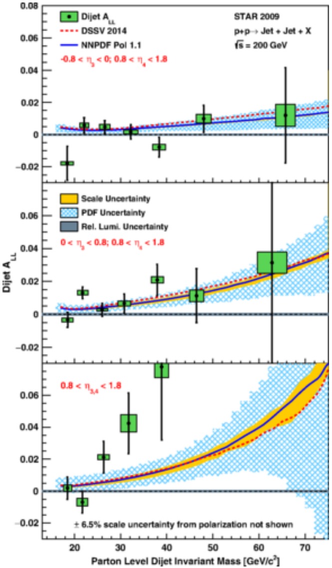
STAR Dijet A_{LL} Results at $\sqrt{s} = 200$ GeV

- Dijet A_{LL} in $|\eta| < 0.8$, **barrel region**



- With STAR 2009 dijet results, the DSSV study shows PRD100, 114027: $\int_{0.01}^{1} \Delta g(x, Q^2 = 10GeV^2) = 0.296 \pm 0.108$

- Dijet A_{LL} for $\eta < 1.8$, **endcap region**



STAR Dijet A_{LL} Results at $\sqrt{s} = 510$ GeV

- Dijet A_{LL} vs. M_{inv} in four η topology bins
- Topology bins sample x_1, x_2 and $cos\theta^*$ bins

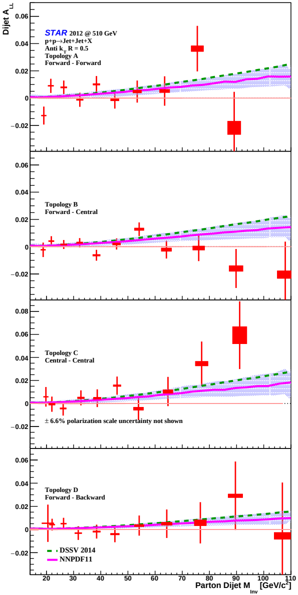
$$x_1 = \frac{1}{\sqrt{s}}(p_{T,3}e^{\eta_3} + p_{T,4}e^{\eta_4})$$

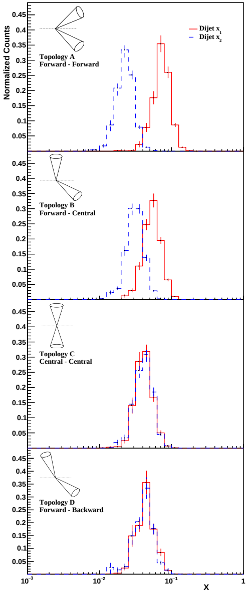
$$x_2 = \frac{1}{\sqrt{s}}(p_{T,3}e^{-\eta_3} + p_{T,4}e^{-\eta_4})$$

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

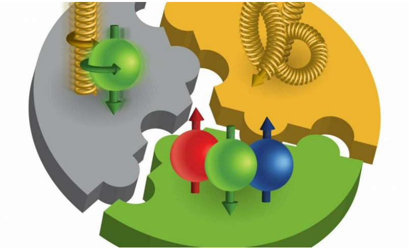
- Constrain the shape of $\Delta g(x)$

- More inclusive jet and dijet results from 2013 at $\sqrt{s} = 510$ GeV will come out soon





Sea Quark Polarization at RHIC

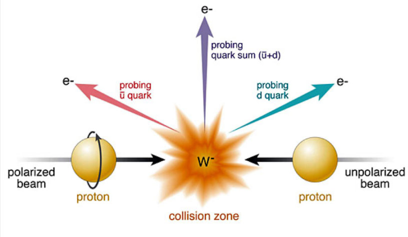


W Production in Longitudinally Polarized *pp* Collisions

- Ws are produced through left-handed quarks and right-handed anti-quarks
- W are identified from $e^{\pm}$ with:
  1. Large isolated energy deposition in EM-cal
  2. Large p_T imbalance due to missing neutrino
- Longitudinal single-spin asymmetry, $A_L = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$

$$A_L^{W^-} \sim \frac{-\Delta d(x_1)\bar{u}(x_2) + \Delta\bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2)}$$

$$A_L^{W^+} \sim \frac{-\Delta u(x_1)\bar{d}(x_2) + \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}$$

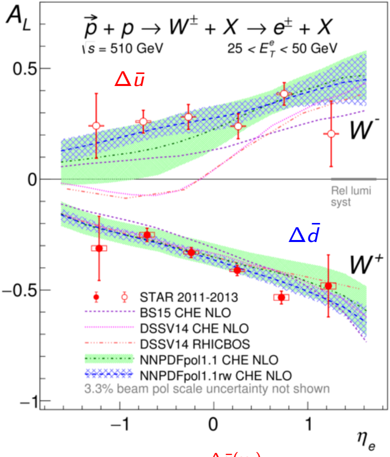


- W^- with backward e^-:
  $A_L^{W^-} \approx \frac{\Delta\bar{u}(x_1)}{\bar{u}(x_1)}$, $y_{W^-} \ll 0$ $(x_1 \ll x_2)$
- W^+ with forward e^+:
  $A_L^{W^+} \approx \frac{\Delta\bar{d}(x_1)}{\bar{d}(x_1)}$, $y_{W^+} \ll 0$ $(x_1 \ll x_2)$

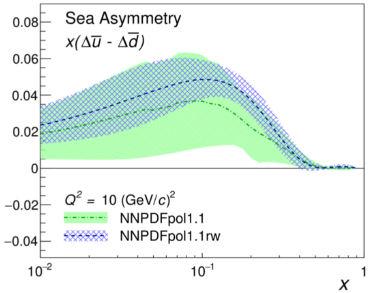
$W^{\pm}$ A_L sensitive to **sea quark** polarization

W A_L from 510 GeV pp Collisions and its Impact

- W A_L vs. η_e, STAR, PRD 99, 051102



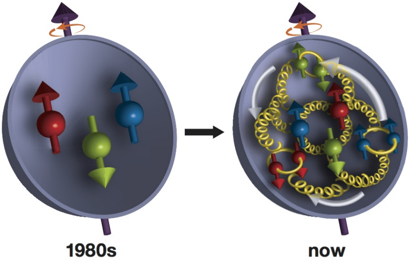
- $\Delta\bar{u} - \Delta\bar{d}$ vs. x, NNPDF, NPB887, 276



- W^-, $\eta_e < 0 \approx \frac{\Delta\bar{u}(x_1)}{\bar{u}(x_1)}$
- W^+, $\eta_e > 0 \approx \frac{\Delta\bar{d}(x_1)}{\bar{d}(x_1)}$

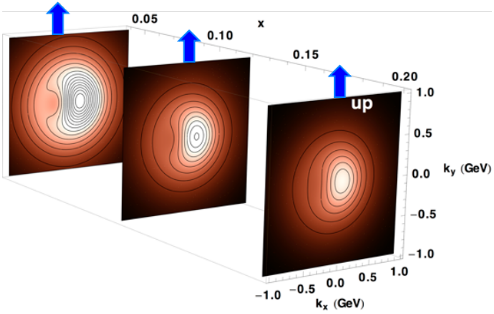
- By reweighting NNPDF replicas at $Q^2 = 10\ \mathrm{GeV}^2$: $\Delta\bar{u} > \Delta\bar{d}$ unlike $\bar{d} > \bar{u}$

Proton 3D Structure from Transversely Polarized Beam

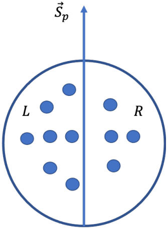


Transverse Structure of the Proton

- At given Q^2, described by transverse momentum dependent (TMD) parton distribution function, $f(x, k_T)$

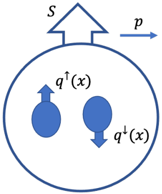


- In polarized case, becoming spin dependent
- Predict single spin azimuthal asymmetry $A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$, for example jets, hadron in jets, W/Z bosons, and so on

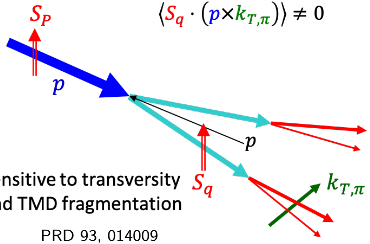


Transversity

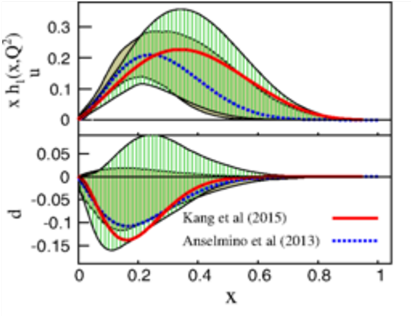
- Definition: $\delta q(x) = q^{\uparrow}(x) - q^{\downarrow}(x)$



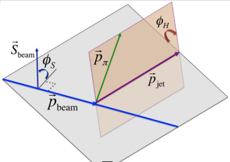
- Chiral odd, need to couple with another chiral-odd distribution, TMD fragmentation function (FF)
- TMD FF is universal for example Collins FF
- Large uncertainties from DIS measurements



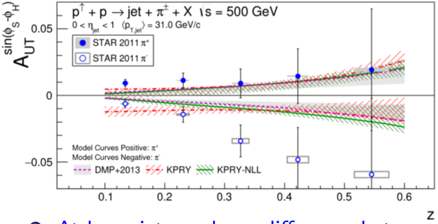
PRD 93, 014009



Collins Asymmetry for $\pi^{\pm}$ in Jets

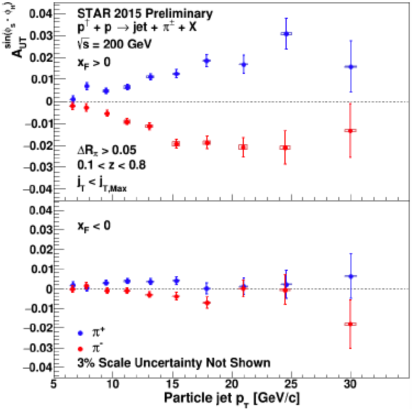


- Transverse azimuthal asymmetry:
  $d\sigma^{\uparrow} - d\sigma^{\downarrow} \sim d\Delta\sigma_0 sin\phi_S + d\Delta\sigma_1^- sin(\phi_S - \phi_H) +$
  $d\Delta\sigma_1^+ sin(\phi_S + \phi_H) + d\Delta\sigma_2^- sin(\phi_S - 2\phi_H) + d\Delta\sigma_2^+ sin(\phi_S + 2\phi_H)$
  PRD, 83, 034021
- Collins asymmetry: $A_{UT}^{sin(\phi_S - \phi_H)} \sim d\Delta\sigma_1^-$
  - $A_{UT}^{sin(\phi_s - \phi_h)}$ vs z (longitudinal momentum fraction of $\pi^{\pm}$ relative to the jet), at $\sqrt{s} = 500$ GeV
  - $< p_T >= 31$ GeV/c PRD 97, 032004



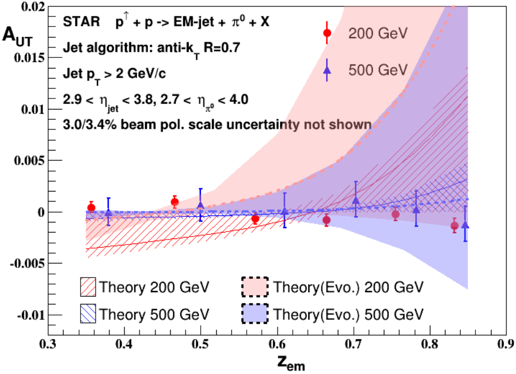
  - At large jet p_T, large difference between π^+ and π^- in forwarding moving jets
  - First indication of transversity in pp collisions

- $A_{UT}^{sin(\phi_s - \phi_h)}$ vs jet p_T at $\sqrt{s} = 200$ GeV
- $0.1 < z < 0.8$



Collins Asymmetry for π^0 in EM-Jets

- A_{UT} vs. z_{EM} for π^0 in electromagnetic jets in forward region at $\sqrt{s} = 200$ and 500 GeV, arXiv2012.11428
- $2.9 < \eta_{jet} < 3.8$, $2.7 < \eta_{\pi^0} < 4.0$

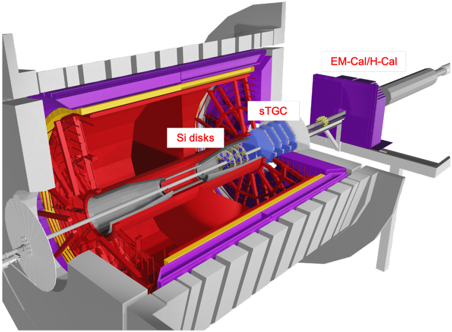


- Small asymmetry over measured z_{EM}
- Compared with theory predictions with and without TMD evolutions, PLB774, 635

STAR Forward Upgrade

STAR Forward Upgrade

- STAR forward upgrade has been fully funded and approved in time for polarized 510 GeV run in 2022
- Forward Calorimeter System (FCS), an EMCal and a HCal
- Forwarding Tracking System (FTS), silicon detectors (Si) and small thin gap chamber (sTGC)
- Lay the groundwork for the realization of the future Elector Ion Collider (EIC)

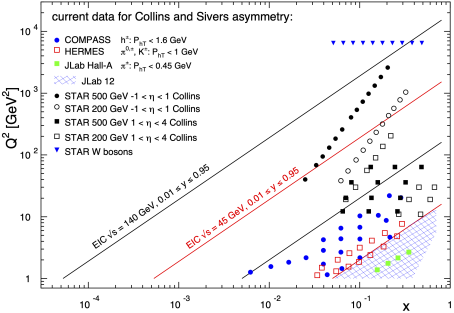


https://drupal.star.bnl.gov/STAR/starnotes/public/sn0648

Future Plan with STAR Forward Upgrade

- FCS system has been fully installed and is ready for test in the upcoming run
- STAR will be continuing running till 2025, including two sets of transversely polarized *pp* collisions at $\sqrt{s} = 200$ and 510 GeV

Year	$\sqrt{s}$ (GeV)	Sampled Luminosity (pb^{-1})	Polarization	Duration
2022	510	400	Transverse	16 weeks
2024	200	235	Transverse	TBD



- Extend coverage of valence quark up to $x > 0.3$, where no current experiment has probed

Conclusion

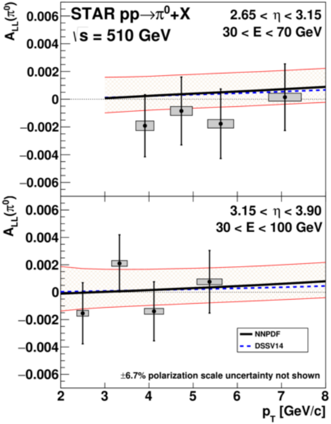
- STAR longitudinal program has been complete
  - STAR inclusive jet and dijet A_{LL} measurements have provided evidence of positive gluon polarization in the proton, with $\sqrt{s} = 510$ data pushing gluon polarization at $x < 0.02$
  - $W^{\pm}$ A_L at $\sqrt{s} = 510$ GeV measures the sea quark polarization and shows that $\Delta\bar{u} > \Delta\bar{d}$
- STAR transverse program is a great tool to test universality and factorization breaking in TMD formalism from pp collisions
  - STAR $A_{UT}^{sin(\phi_S - \phi_H)}$ provided first evidence of transversity
  - More new results coming out soon including dijet Sivers asymmetry, $W^{\pm}/Z$ boson A_N from 2017 data, etc.
- The forward upgrade will further explore the transverse spin structure for valence quark at new regime, $x > 0.3$

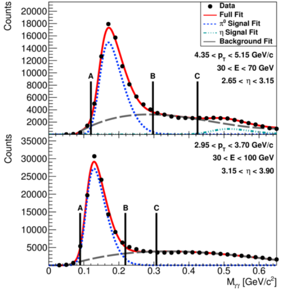
Expect Another 5 Successful Years at STAR

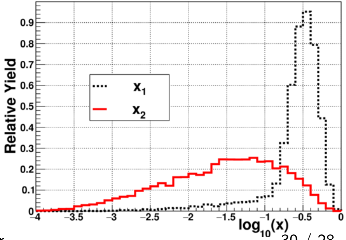
Backup

Forward Neutral Pions at $2.7 < \eta < 3.9$ from 510 GeV Collisions

- Reconstructed π^0 from its γ decays, STAR, PRD 98, 032013
- Access $\mathbf{x_g}$ as low as **0.001**

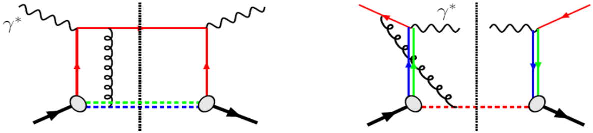






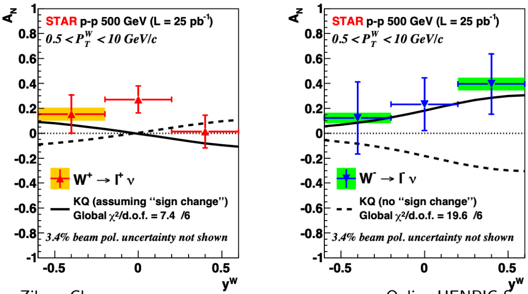
Sivers Function

- DIS, final state interaction, opposite colors attract
- Drell-Yan, $W^{\pm}/Z^0$, initial state interaction, same colors repel



- $Sivers_{DIS} = -Sivers_{Drell-Yan}$ or, $-Sivers_{W^{\pm}}$ or $-Sivers_{Z^0}$
- $A_N = \frac{1}{P_{beam}} \frac{\sqrt{N^{\uparrow}(\phi)N^{\downarrow}(\phi+\pi)} - \sqrt{N^{\uparrow}(\phi+\pi)N^{\downarrow}(\phi)}}{\sqrt{N^{\uparrow}(\phi)N^{\downarrow}(\phi+\pi)} + \sqrt{N^{\uparrow}(\phi+\pi)N^{\downarrow}(\phi)}}$, where $cos(\phi) = \frac{\vec{S_p}\cdot(\overrightarrow{p_{T,W}} \times \overrightarrow{p_{beam}})}{|p_{T,W}|}$

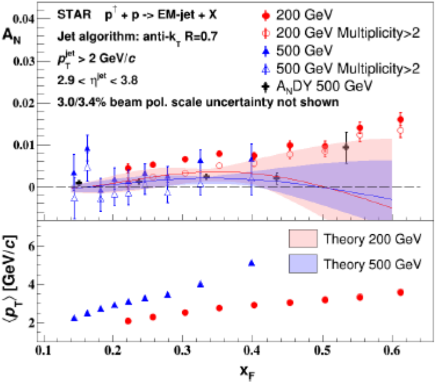
PRL 106, 62002



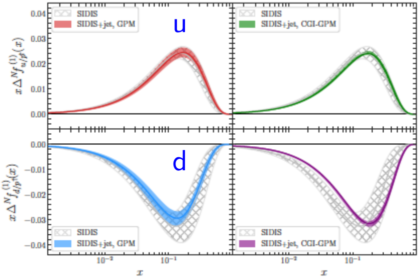
- Cross ratio formula cancels out left-right detector efficiency and relative luminosity
- $W^{\pm}$ A_Ns favor sign change if no TMD evolution effect
- New measurements from 2017 dataset will reduce statistical uncertainty by a factor of 4

A_N for EM-Jet at $\sqrt{s} = 200$ and 500 GeV

- $A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$ as a function of Feynman-x, at $2.9 < \eta^{jet} < 3.8$ arXiv2012.11428

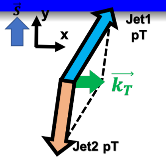


- Sivers first k_T moments as a function of x, top u quark and down: d quark, arXiv2101.03955

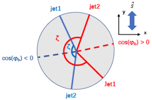


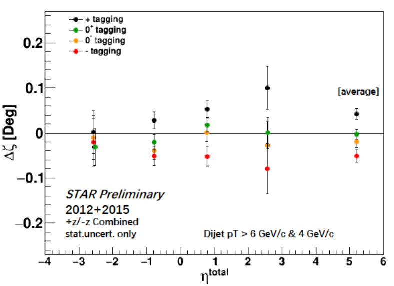
- Small EM-jet A_N as seen in STAR inclusive π^0 A_N
- STAR EM-jet has a big impact on constraining the Sivers function than SIDIS data especially at large x

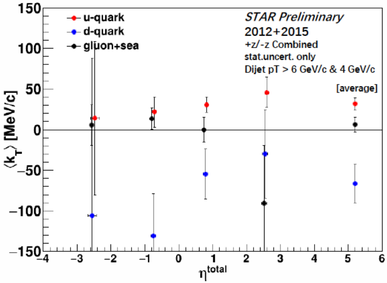
Dijet Sivers Asymmetry at $\sqrt{s} = 200$ GeV



- Parton k_T leads to asymmetry in the centroid of dijet signed opening angle, ζ
- Measure $\Delta\zeta = \frac{<\zeta>^{\uparrow} - <\zeta>^{\downarrow}}{P_{beam}}$ vs. $\eta_{total} = \eta_{jet,1} + \eta_{jet,2} \sim ln(\frac{x_1}{x_2})$
- Associate jet with the polarized beam through the jet motion along the beam
- Weighted charge tagging to separate quark flavors u and d



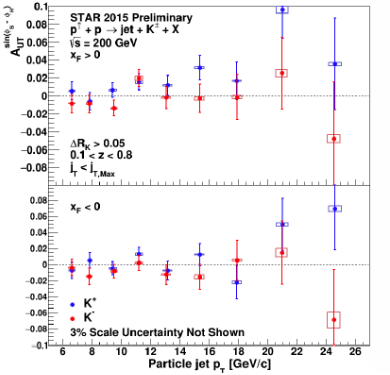




- $\Delta\zeta$: 5 σ separation between $+$ tagging and $-$ tagging
- Unfold $\Delta\zeta$ to k_T: at $Q^2 = 160 GeV^2$, $k_{T,u} > 0$, $k_{T,d} < 0$ and $k_{T,gluon} \approx 0$
- $|\frac{<k_{T,d}>}{<k_{T,u}>}| \sim 2$

Collins Asymmetry for $K^{\pm}$ in Jets at $\sqrt{s} = 200$ GeV

- Jet p_T and asymmetries are corrected for underlying event contribution
- Integrated over hardron $0.1 < z < 0.8$

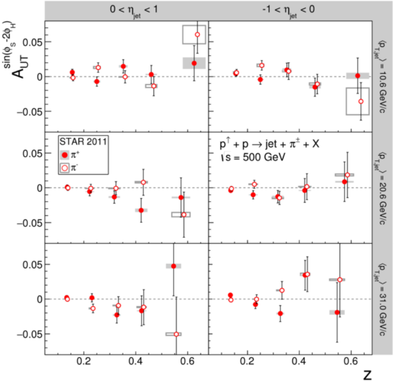


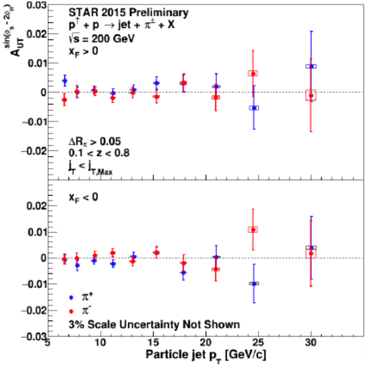
- Like π^+, K^+ in the forward moving jets shows positive asymmetry

Collins-like Asymmetry for $\pi^{\pm}$ in Jets

- Transverse azimuthal asymmetry:
  $d\sigma^{\uparrow} - d\sigma^{\downarrow} \sim d\Delta\sigma_0 sin\phi_S + d\Delta\sigma_1^{-} sin(\phi_S - \phi_H) + d\Delta\sigma_1^{+} sin(\phi_S + \phi_H) + d\Delta\sigma_2^{-} sin(\phi_S - 2\phi_H) + d\Delta\sigma_2^{+} sin(\phi_S + 2\phi_H)$ PRD, 83, 034021
- Collins-like asymmetry: $sin(\phi_S - 2\phi_H)$ modulation, $A_{UT}^{sin(\phi_S - 2\phi_H)} \sim d\Delta\sigma_1^{-}$
- Sensitive to gluon linear polarization

PRD 97, 032004

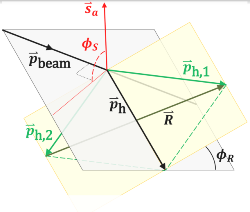


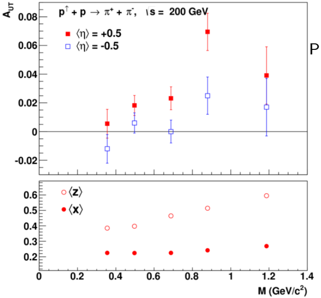


- At both $\sqrt{s} = 500$ and 200 GeV, Collins-like asymmetries are consistent with zero

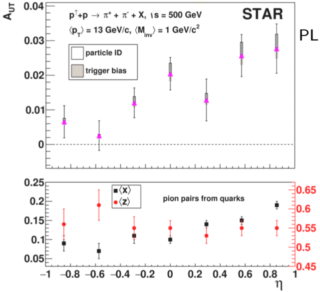
Transverse Spin-dependent Azimuthal Correlation of Charged Pion Pairs

- $\phi_{RS} = \phi_R - \phi_S$: ϕ_S angle between polarization and production plane, ϕ_R angle between production plane and hadron plane
- $\frac{N^{\uparrow}(\phi_{RS}) - rN^{\downarrow}(\phi_{RS})}{N^{\uparrow}(\phi_{RS}) + rN^{\downarrow}(\phi_{RS})} = P_{beam} \cdot A_{UT} \cdot sin(\phi_{RS})$, where $r = \frac{L^{\uparrow}}{L^{\downarrow}}$
- Pion selected by TPC $\frac{dE}{dx}$: purity of pion $> 95\%$





PRL115, 242501



PLB780, 332

- For $\sqrt{s} = 200$ and 500 GeV, backward pairs corresponding to quarks with smaller x have smaller asymmetries
- At $\sqrt{s} = 200$ GeV, enhancement around ρ mass due to vector meson decay

Future plan with STAR Forward Upgrade

- A_N of $\pi^{\pm}$ in the forward region
- In the meantime with recently installed iTPC which will improve particle identification, STAR will measure $\pi^{\pm}$ Collins asymmetry more precisely