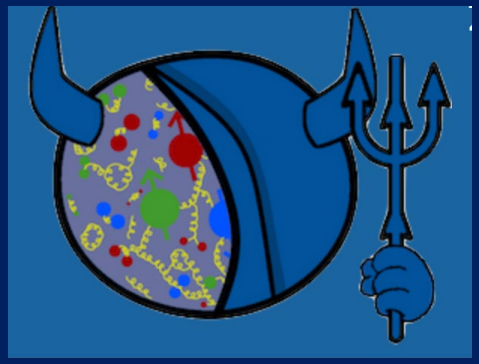
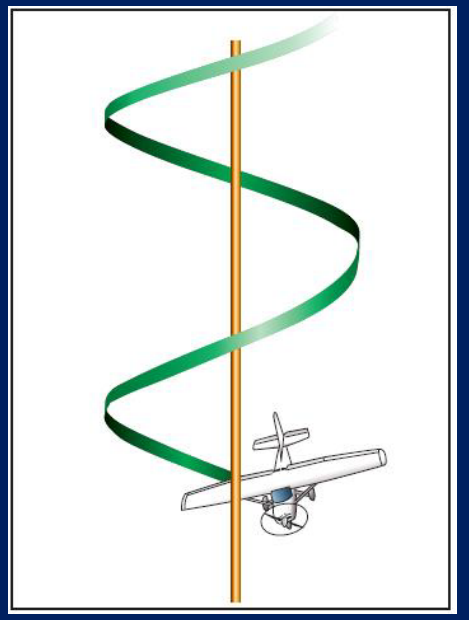


http://www.faa.gov/library/manuals/aircraft/airplane_handbook/media/faa-h-8083-3a-3of7.pdf



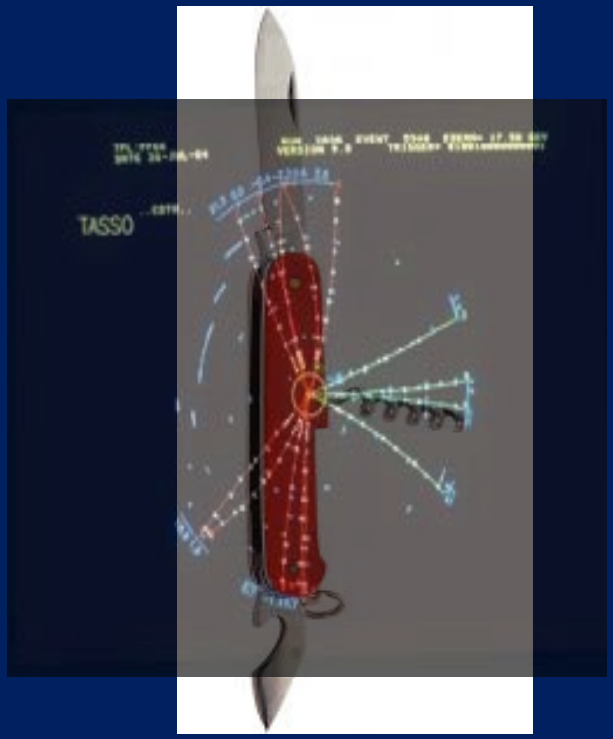
Jets for Spin Physics: An Experimental Perspective

Christine A. Aidala
University of Michigan

25th International Spin Symposium
Durham, NC
September 28, 2023

Jets have become versatile multipurpose tools . . .


TASSO


TASSO


alamy
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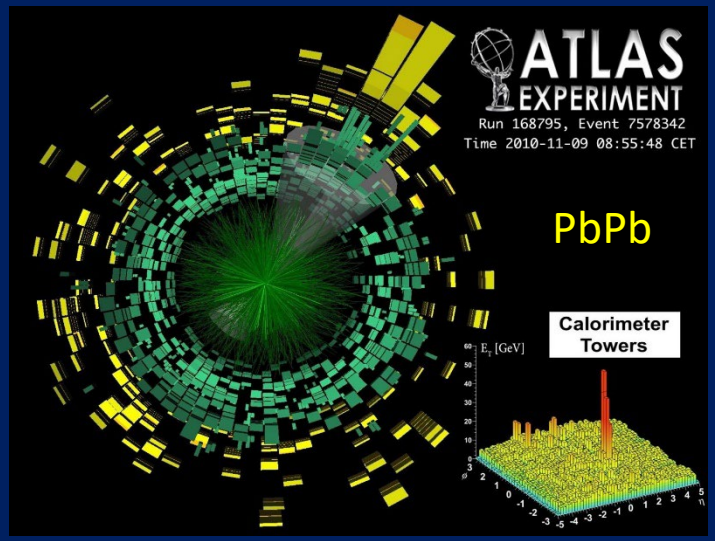
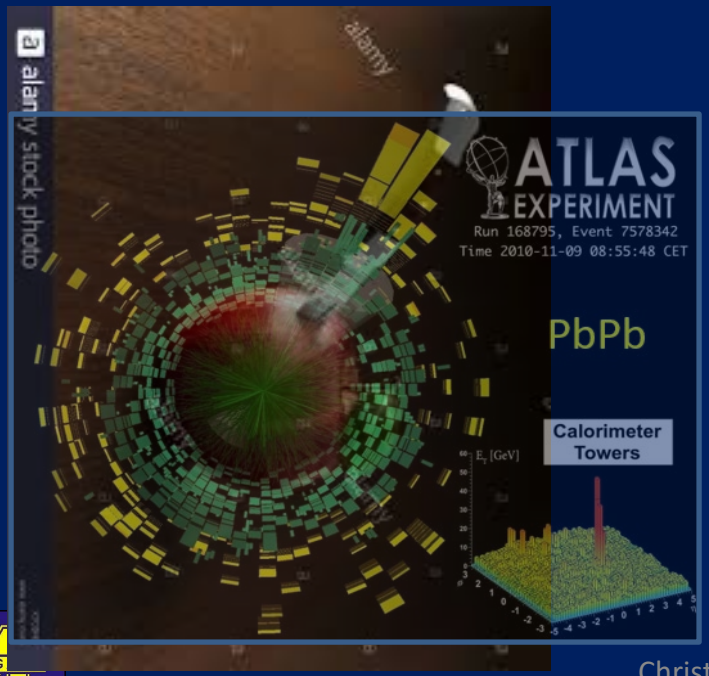
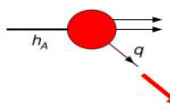

ATLAS
EXPERIMENT
Run 168795, Event 7578342
Time 2010-11-09 08:55:48 CET
PbPb
Calorimeter Towers
E_T [GeV]

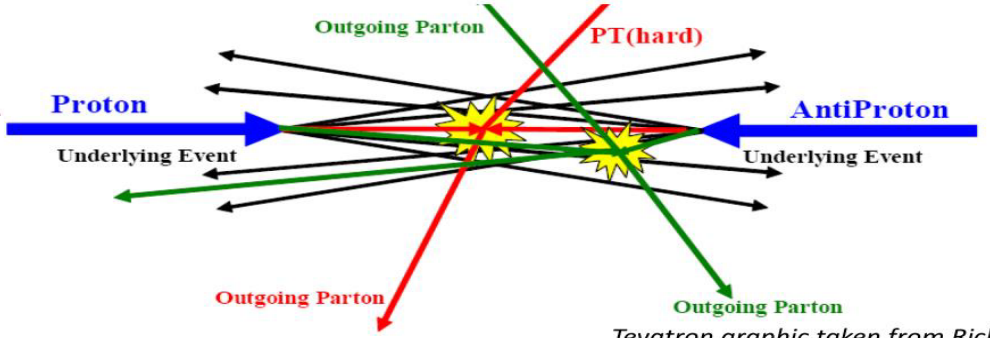

alamy
alamy stock photo
ATLAS
EXPERIMENT
Run 168795, Event 7578342
Time 2010-11-09 08:55:48 CET
PbPb
Calorimeter
Towers

...+ multi-parton scattering +...



proton remnants.

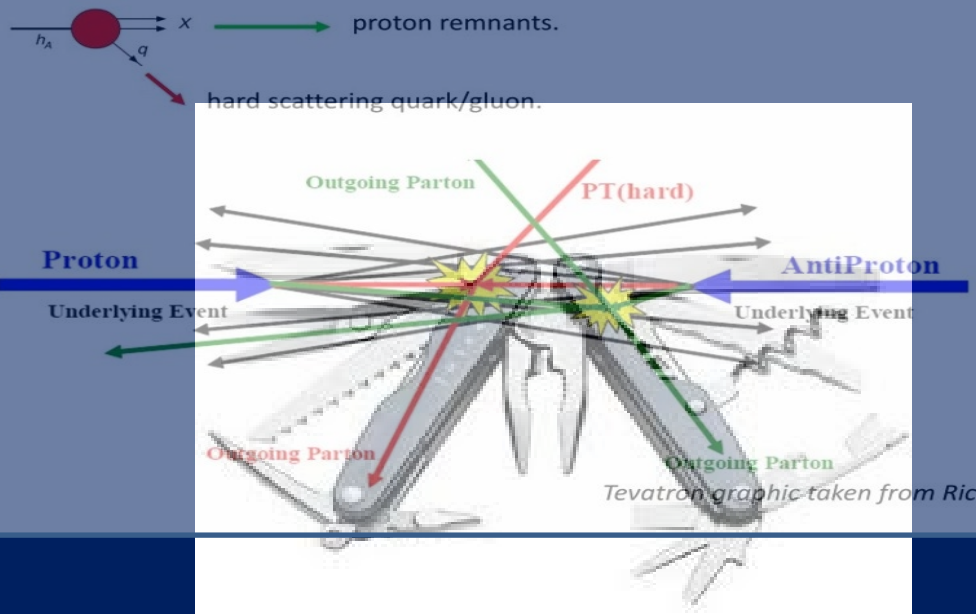
hard scattering quark/gluon.



Tevatron graphic taken from Rick Field

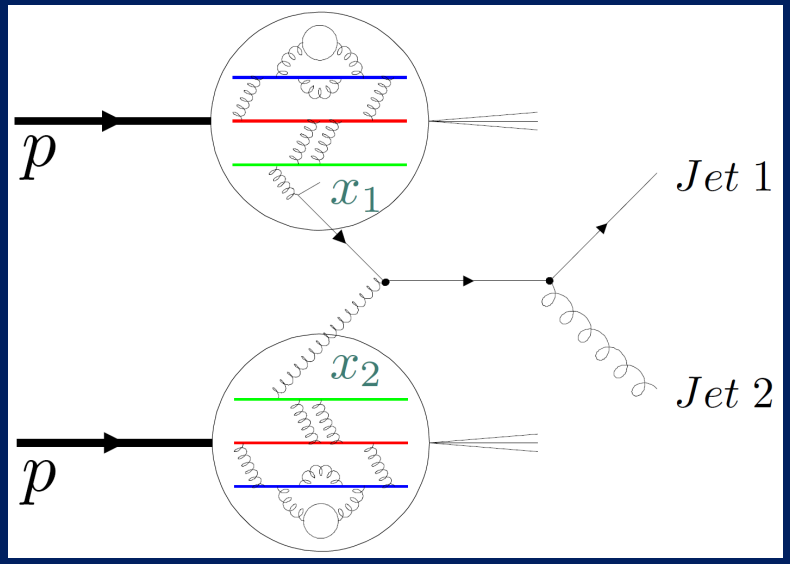
From talk by Harald Ita

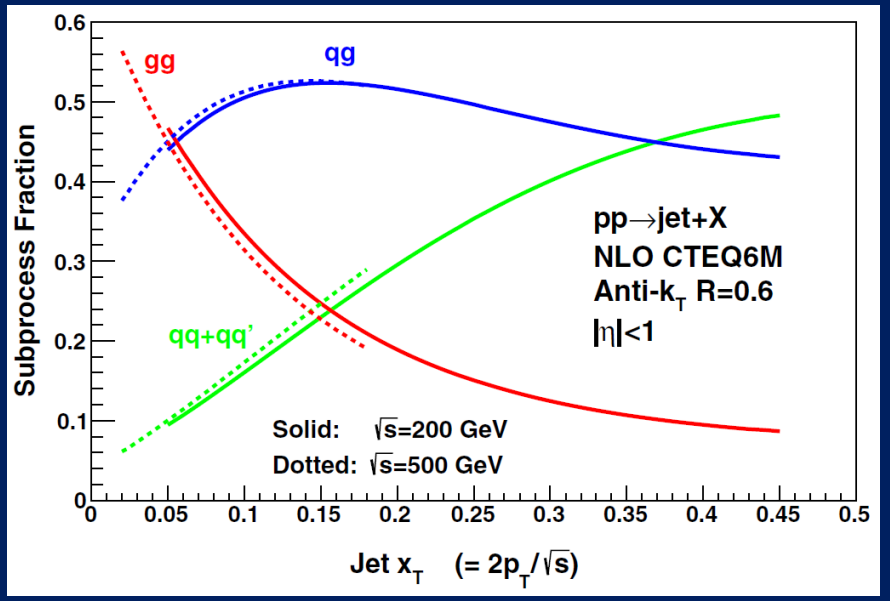
...+ multi-parton scattering +...



From talk by Harald Ita

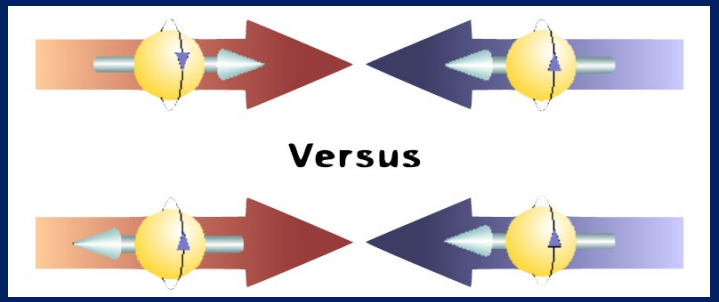
Jet production in polarized p+p collisions at RHIC





- Access gluons at leading order in p+p collisions
- (Polarized) PDFs and fragmentation functions
- E.g. access gluon helicity PDF via:

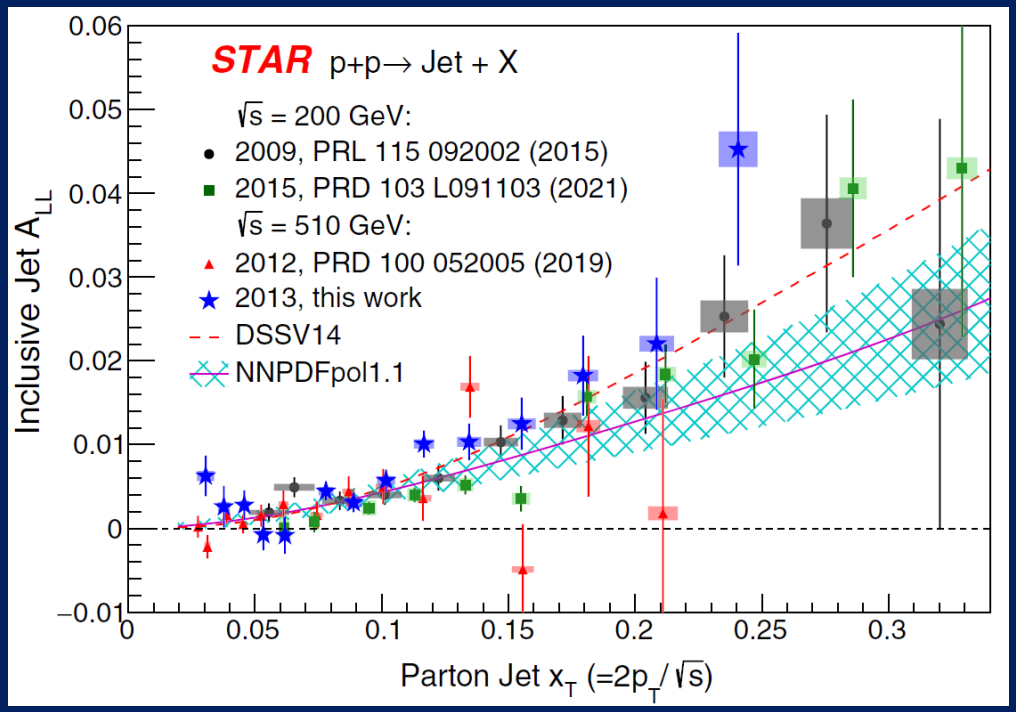
$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}}$$

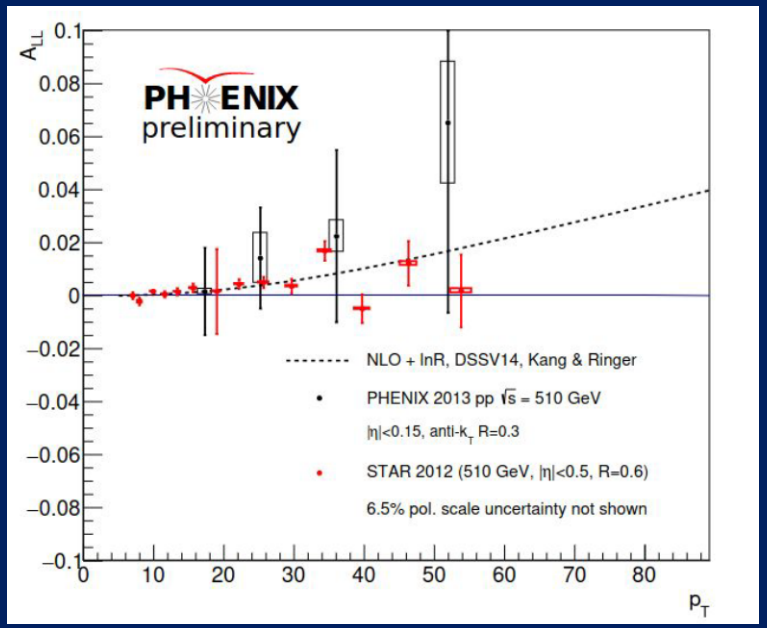


Using jets to probe the gluon helicity distribution

Ting Lin, Monday

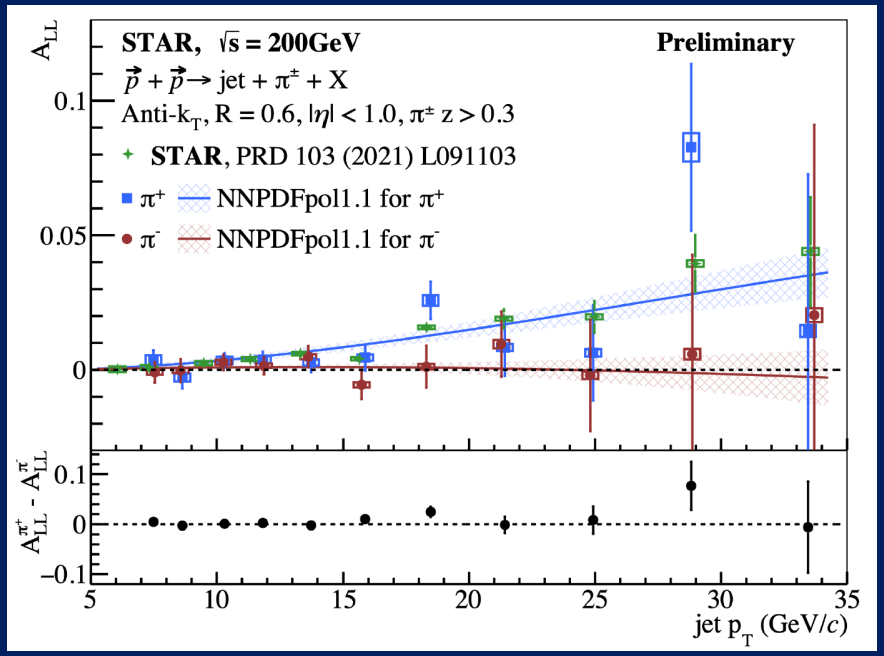
PRD105, 092011 (2022)



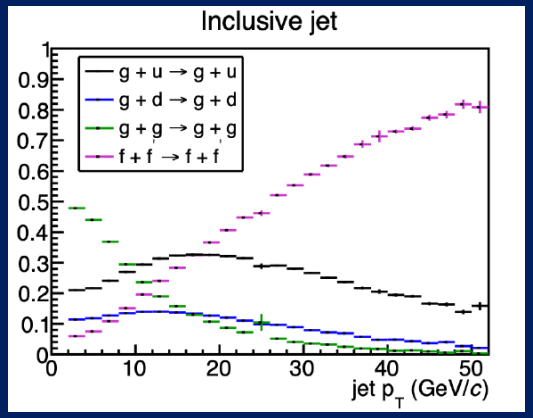


Latest results from STAR including both 200 and 510 GeV p+p data. Further evidence of a positive $\Delta g(x, Q^2)$ for gluons carrying >~5% of the proton's momentum.

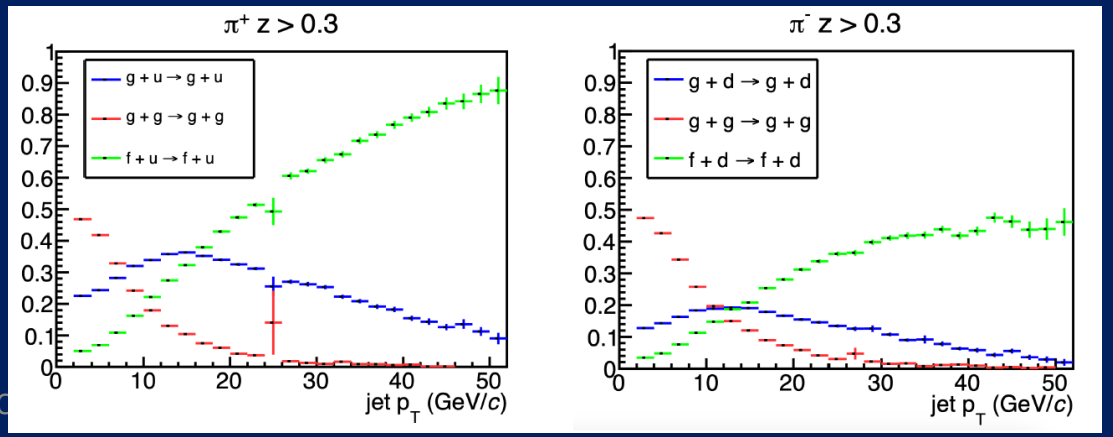
*Using **pion-tagged** jets to probe the gluon **and light flavor** helicity distributions*



Yi Yu, Tuesday



Tagging jets containing a high-momentum π^+ or π^- changes the mix of parton flavors

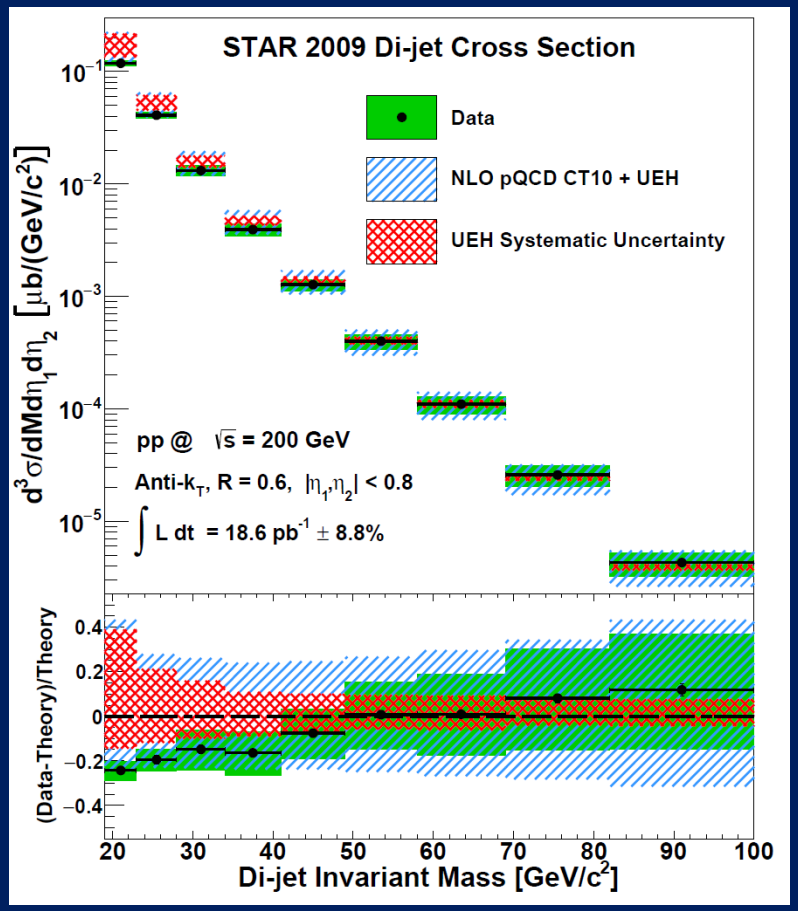


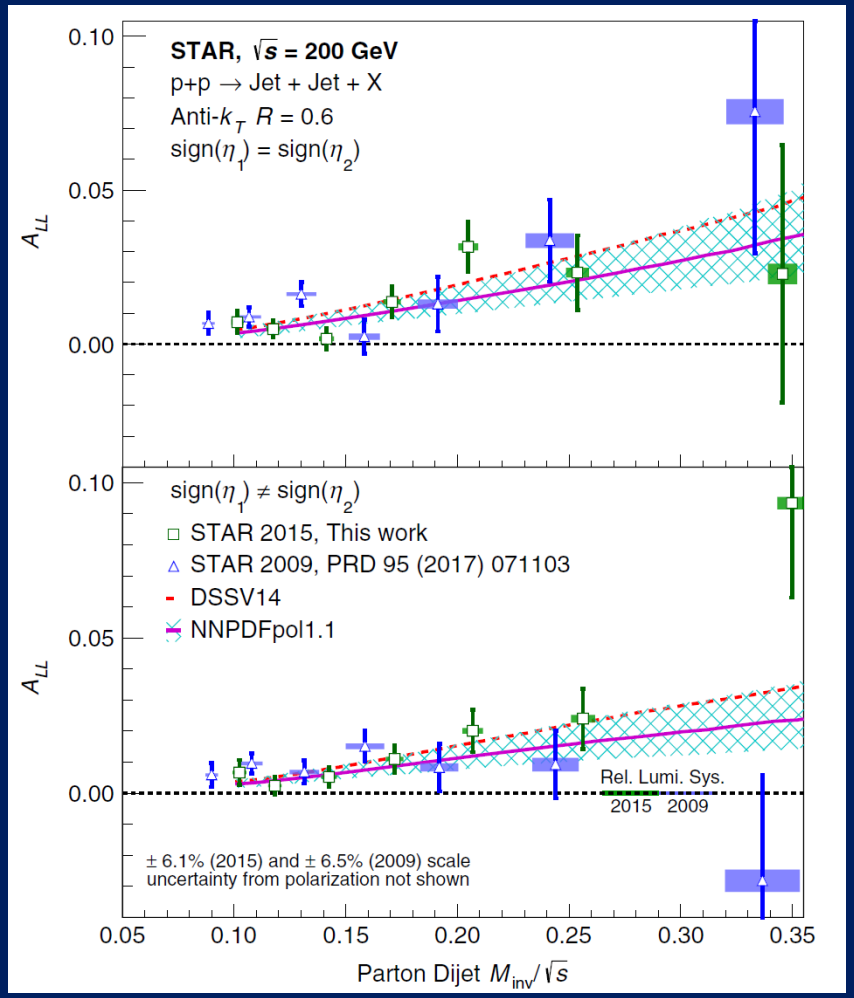
*Using **dijets** to probe the gluon helicity distribution*

Ting Lin, Monday

PRD95, 071103 (2017)

PRD103, L091103 (2021)

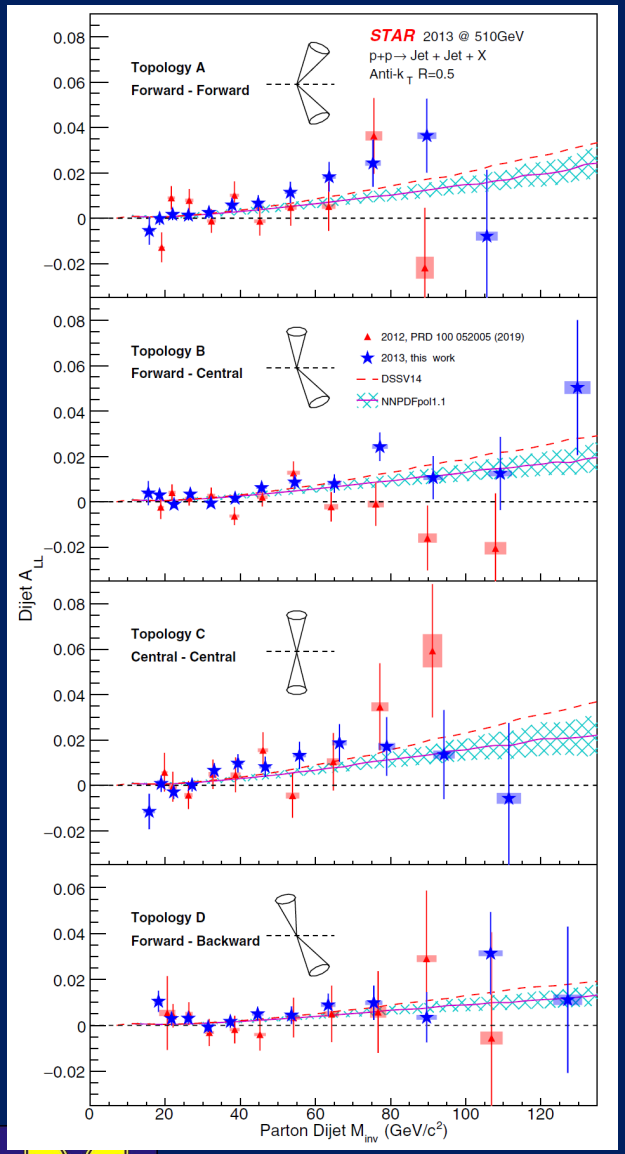




Dijets provide tighter constraints on the parton momentum fractions probed in the two protons

*Using **dijets** to probe the gluon helicity distribution*

Ting Lin, Monday



Inclusive jets:

$$x \approx \frac{2p_T}{\sqrt{s}} e^{\pm\eta}$$

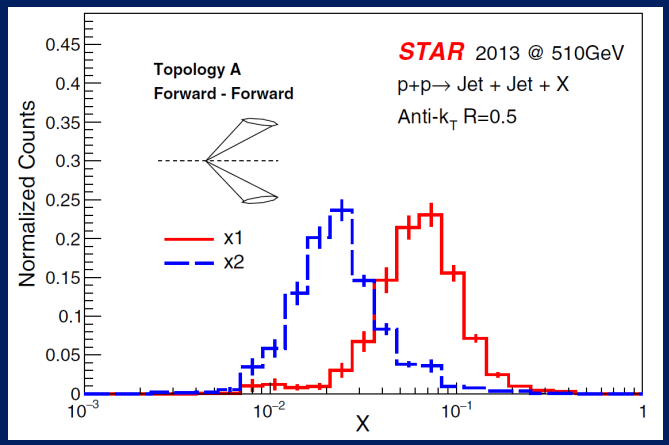
Dijets:

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

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

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

Different dijet configurations probe different combinations of parton momentum fractions in the two protons . . .

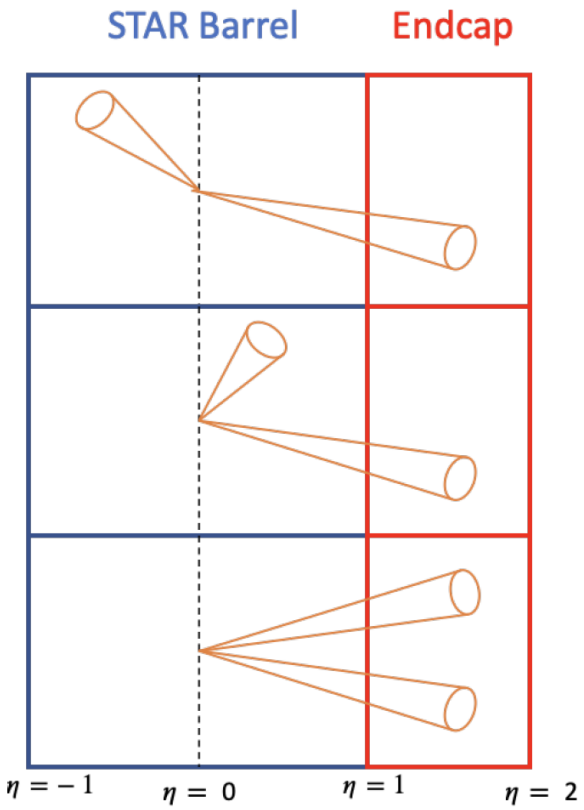


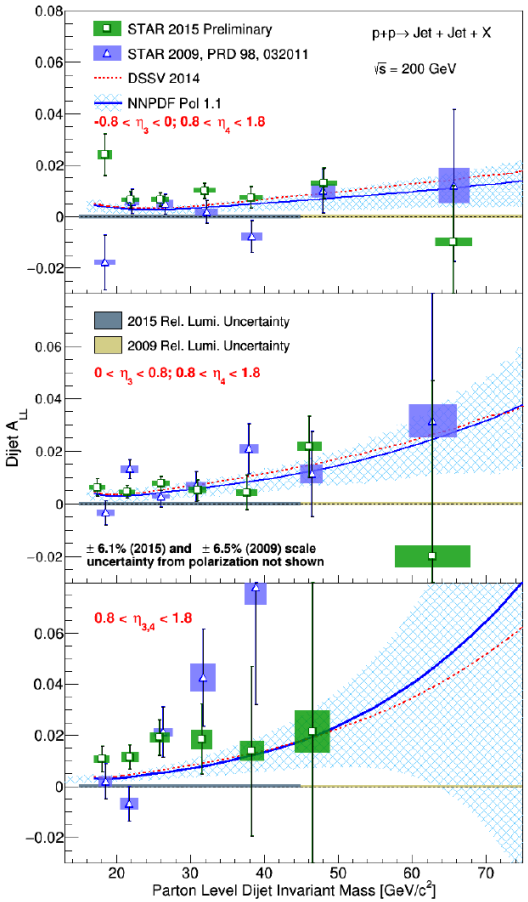
Bin	η_3 and η_4 regions	Physics description
A	$0.3 < \lvert\eta_{3,4}\rvert < 0.9;\ \eta_3 \cdot \eta_4 > 0$	Forward-forward
B	$\lvert\eta_{3,4}\rvert < 0.3;\ 0.3 < \lvert\eta_{4,3}\rvert < 0.9$	Forward-central
C	$\lvert\eta_{3,4}\rvert < 0.3$	Central-central
D	$0.3 < \lvert\eta_{3,4}\rvert < 0.9;\ \eta_3 \cdot \eta_4 < 0$	Forward-backward

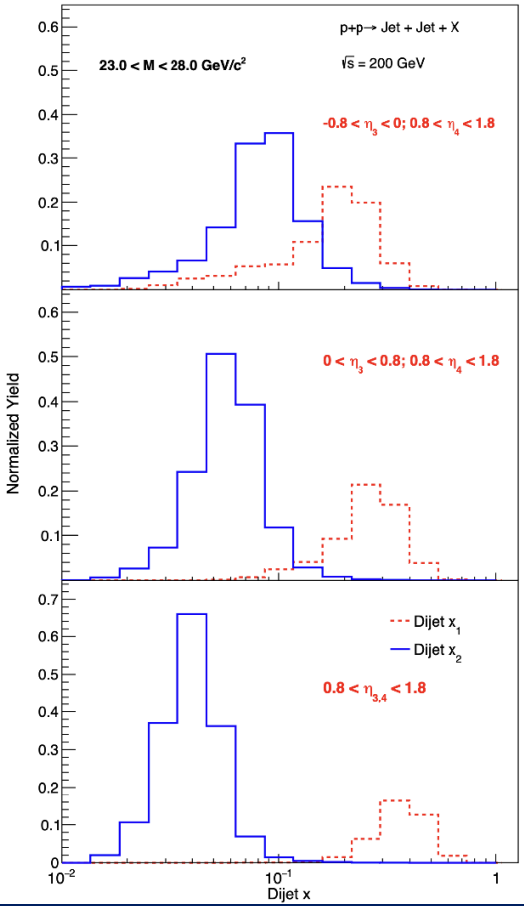
PRD105, 092011 (2022)

*Using **dijets** to probe the gluon helicity distribution*

Ting Lin, Monday





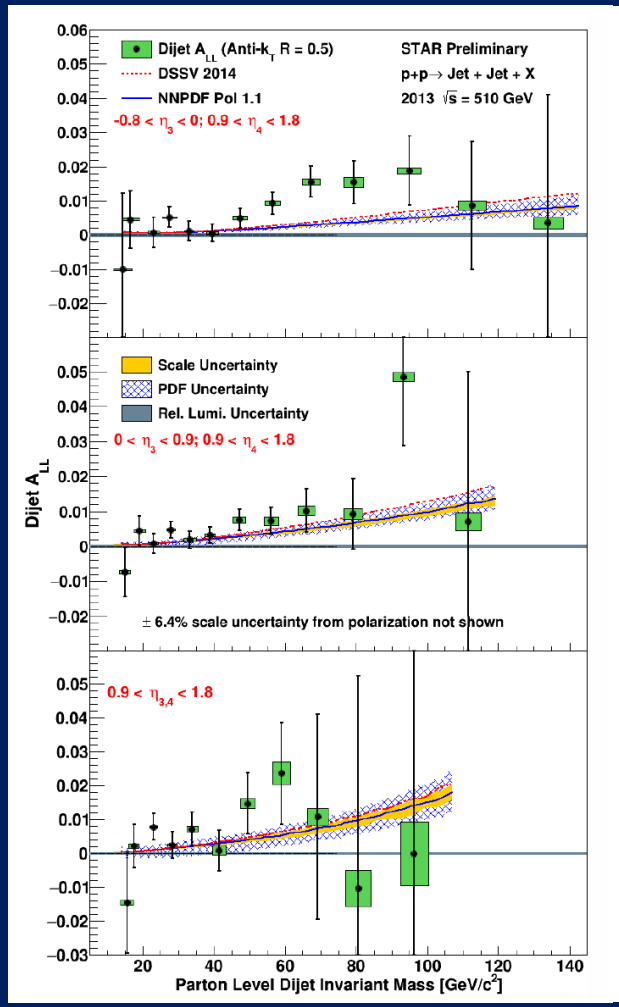


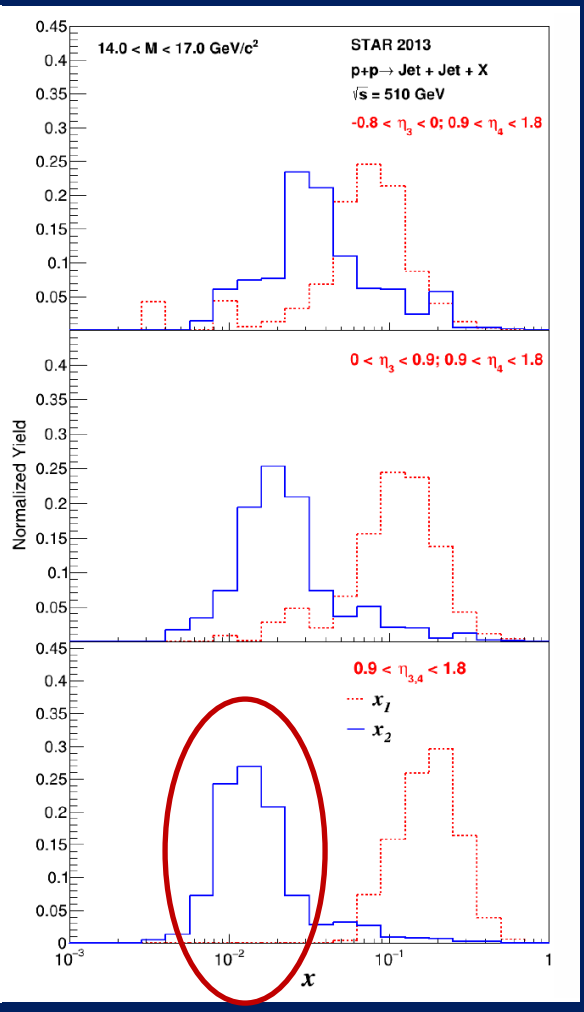
Latest STAR 200 GeV dijet A_{LL} results including the Endcap Calorimeter—access higher x in one beam, lower in the other

*Using **dijets** to probe the gluon helicity distribution*

Ting Lin, Monday

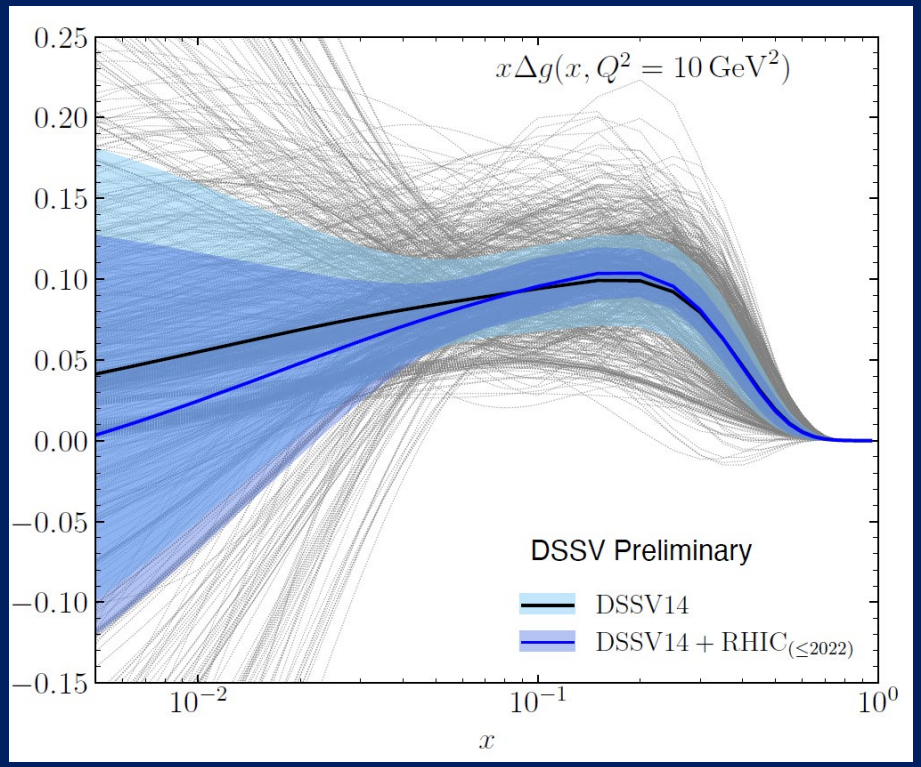
Latest STAR **510** GeV dijet A_{LL} results including the Endcap Calorimeter. Access lowest x_{gluon}~0.01 by going both to higher $\sqrt{s}$ and to more forward rapidity.

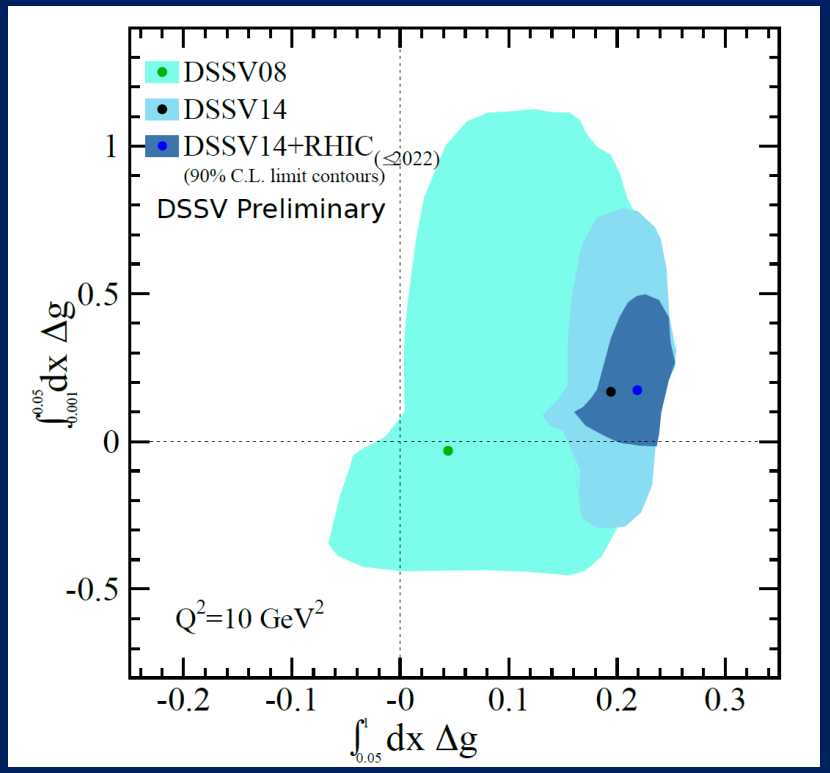




Latest extraction of gluon helicity

RHIC Cold QCD White Paper - arXiv:2302.00605





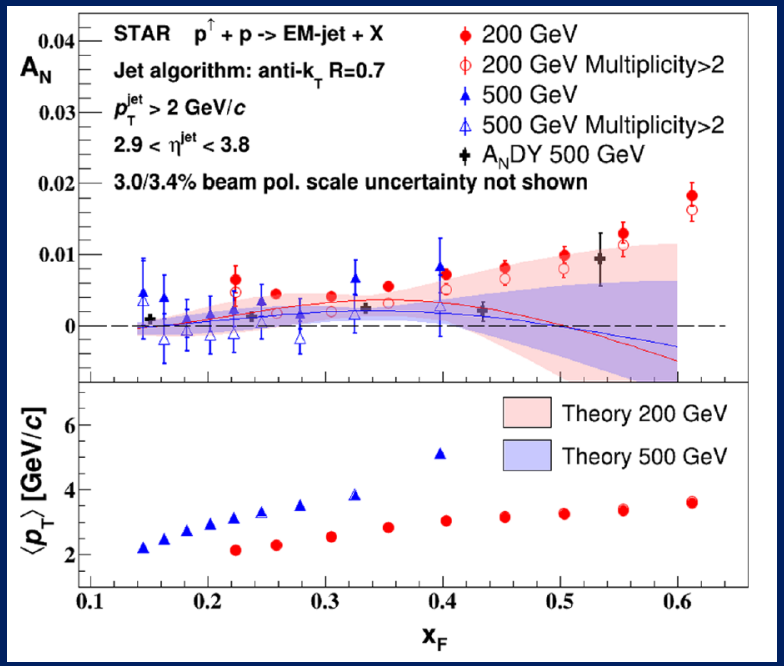
- Fit includes RHIC data released as of 2022, i.e. jets, dijets, and pions
  - See also fits by JAM collaboration (PRD105, 074022 (2022)), which use inclusive jet data
- The longitudinally polarized p+p program at RHIC concluded with 510 GeV running in 2013 and 200 GeV in 2015 – final publications forthcoming!

Jets and transverse spin effects: Inclusive jet transverse single-spin asymmetries

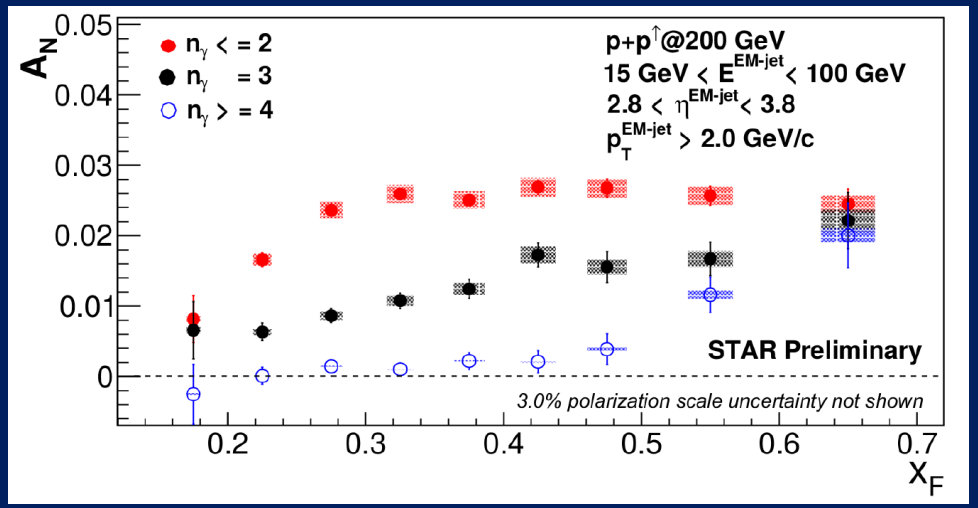
- Constrain collinear twist-3 correlators for gluons and quarks in transversely polarized protons
  - Twist-3 correspondent of Sivers TMD PDF

Xilin Liang, Monday

Nonzero but small at forward rapidity



Larger asymmetries at forward rapidity in electromagnetic jets with fewer photons



Theory curves: Gamberg, Kang, Prokudin, PRL110, 232301 (2013)

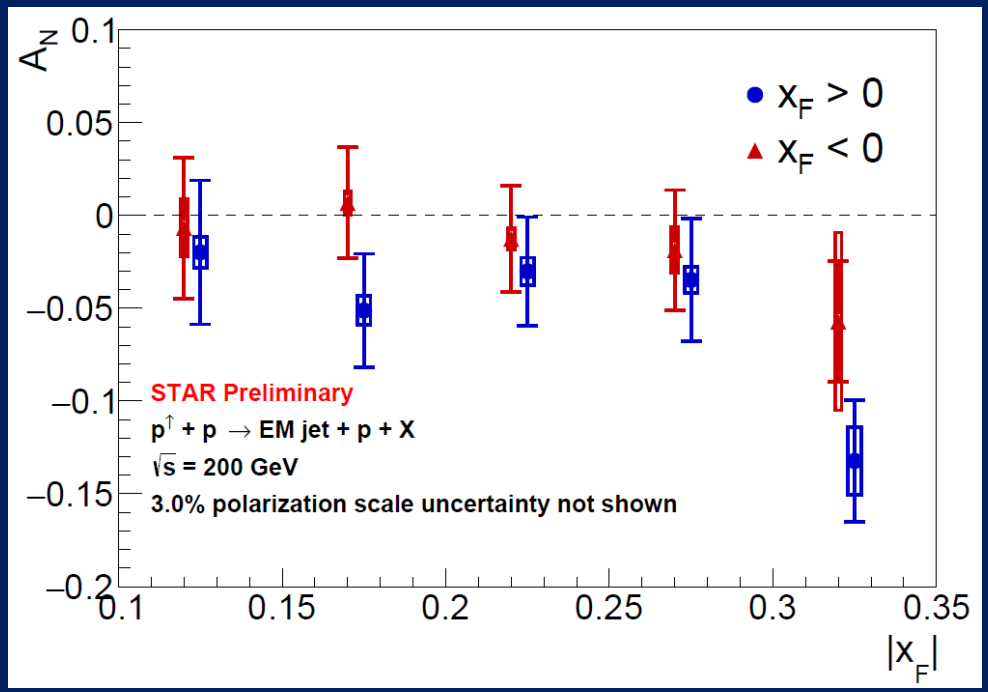
PRD103, 092009 (2021)
A_NDY: PLB750, 660 (2015)

Jets and transverse spin effects: Inclusive jet transverse single-spin asymmetries

- Constrain collinear twist-3 correlators for gluons and quarks in transversely polarized protons
  - Twist-3 correspondent of Sivers TMD PDF

Xilin Liang, Monday

But negative asymmetry for forward diffractive jets?!

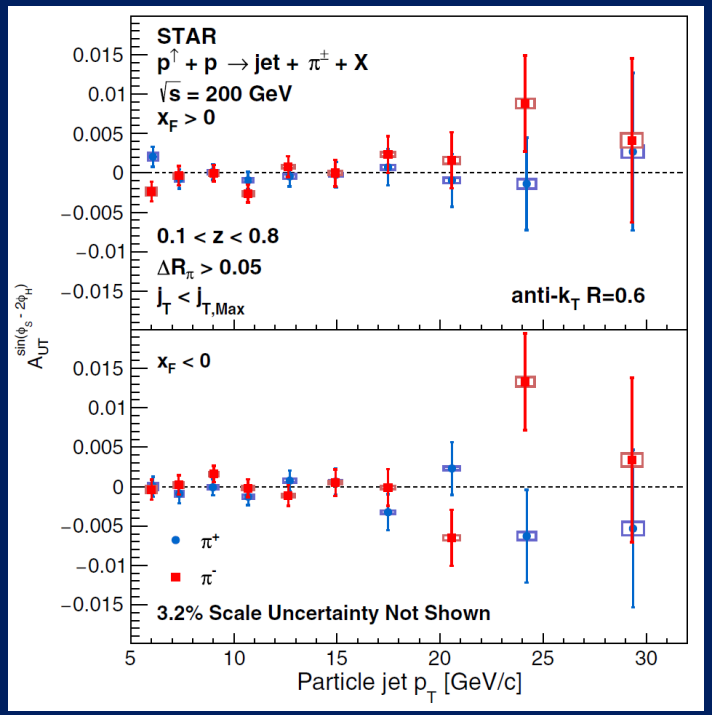


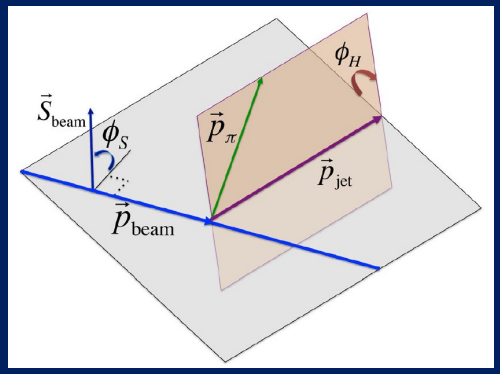
Jets and transverse spin effects: Hadron-in-jet transverse single-spin asymmetries

$$\frac{d\sigma^{\uparrow}(\phi_S,\phi_H) - d\sigma^{\downarrow}(\phi_S,\phi_H)}{d\sigma^{\uparrow}(\phi_S,\phi_H) + d\sigma^{\downarrow}(\phi_S,\phi_H)}$$
$$\propto A_{UT}^{\sin(\phi_S)} \sin(\phi_S)$$
$$+ A_{UT}^{\sin(\phi_S-\phi_H)} \sin(\phi_S - \phi_H)$$
$$+ A_{UT}^{\sin(\phi_S-2\phi_H)} \sin(\phi_S - 2\phi_H)$$
$$+ A_{UT}^{\sin(\phi_S+\phi_H)} \sin(\phi_S + \phi_H)$$
$$+ A_{UT}^{\sin(\phi_S+2\phi_H)} \sin(\phi_S + 2\phi_H).$$

Hadron and jet: enough vectors to define various azimuthal modulations!

SIDIS – hadron and scattered lepton



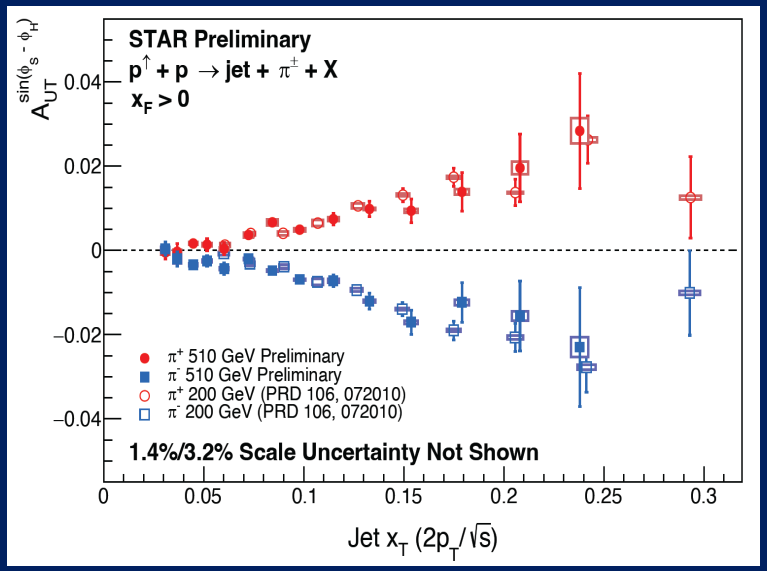


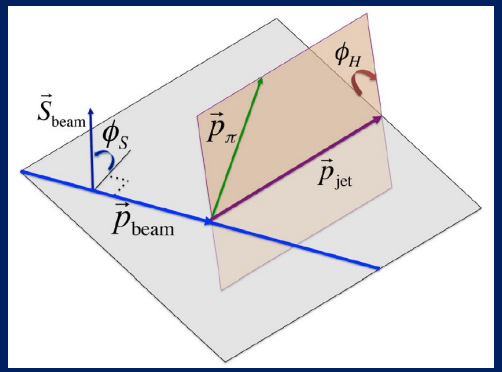
Consistent with zero. Constrains linearly polarized gluons in transversely polarized protons as well as analog of Collins TMD FF for gluon-initiated jets.

PRD106, 072010 (2022)

Jets and transverse spin effects: Hadron-in-jet transverse single-spin asymmetries

$$\frac{d\sigma^{\uparrow}(\phi_S,\phi_H) - d\sigma^{\downarrow}(\phi_S,\phi_H)}{d\sigma^{\uparrow}(\phi_S,\phi_H) + d\sigma^{\downarrow}(\phi_S,\phi_H)} \propto A_{UT}^{\sin(\phi_S)} \sin(\phi_S) + \boxed{A_{UT}^{\sin(\phi_S-\phi_H)} \sin(\phi_S-\phi_H)} + A_{UT}^{\sin(\phi_S-2\phi_H)} \sin(\phi_S-2\phi_H) + A_{UT}^{\sin(\phi_S+\phi_H)} \sin(\phi_S+\phi_H) + A_{UT}^{\sin(\phi_S+2\phi_H)} \sin(\phi_S+2\phi_H).$$



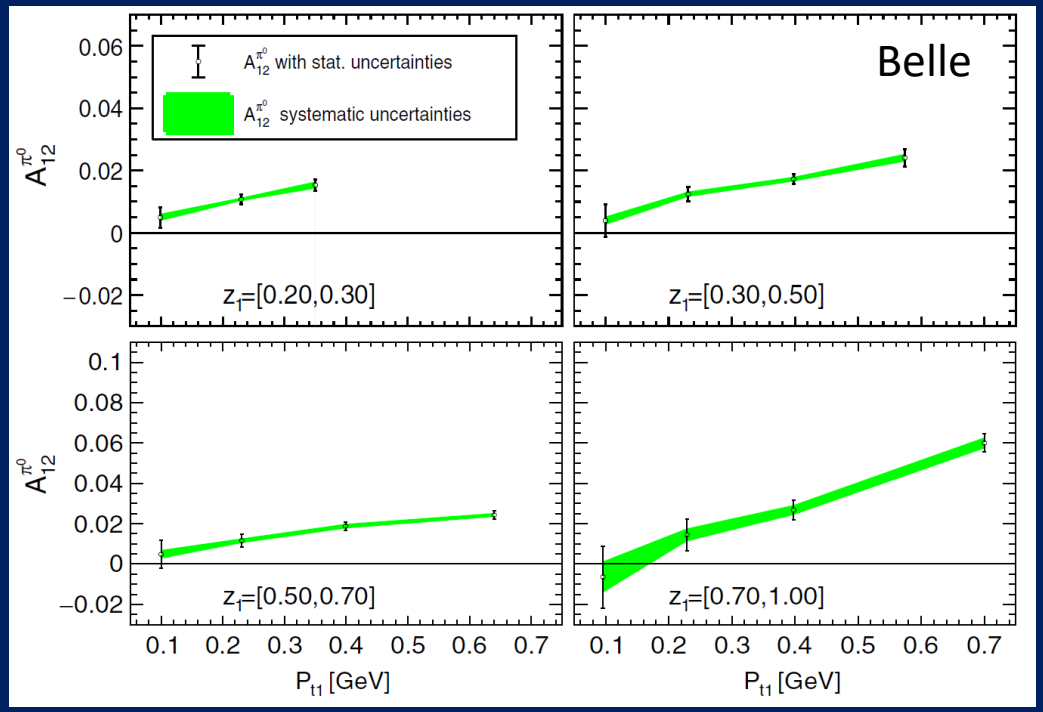


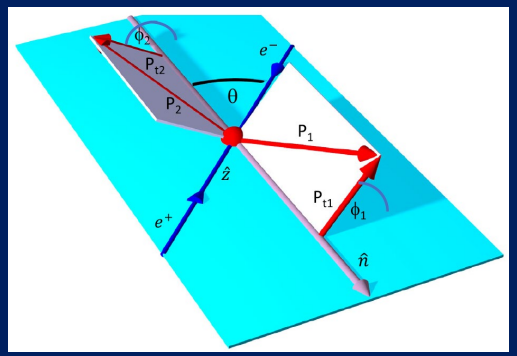
Yixin Zhang, Monday

Significant asymmetries observed for $x_F > 0$ jets, with opposite sign for π^+ and π^-. Constrains transversity PDF x Collins TMD FF.

New 510 GeV preliminary results compared to published 200 GeV results show little to no energy dependence.

Jets and transverse spin effects: Transverse single-spin asymmetries in e^+e^-



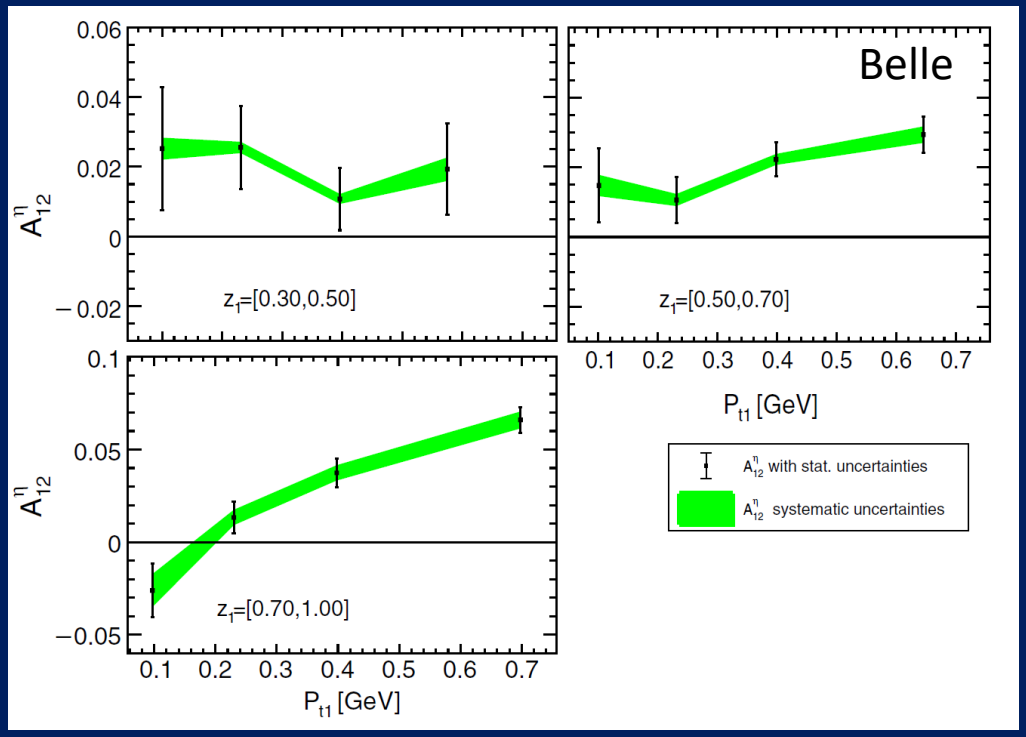


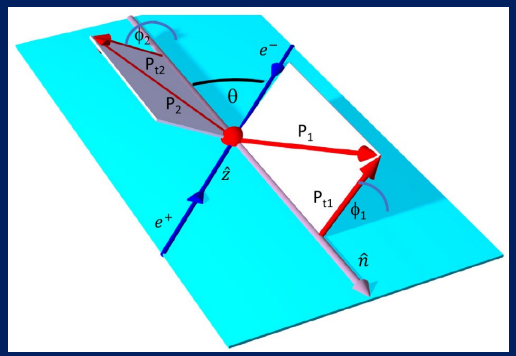
Collins asymmetries for π^0 as a function of p_T in bins of momentum fraction z.

Measurement uses the thrust axis and a pair of back-to-back hadrons.

PRD100, 092008 (2019)

Jets and transverse spin effects: Transverse single-spin asymmetries in e^+e^-





Collins asymmetries for η as a function of p_T in bins of momentum fraction z.

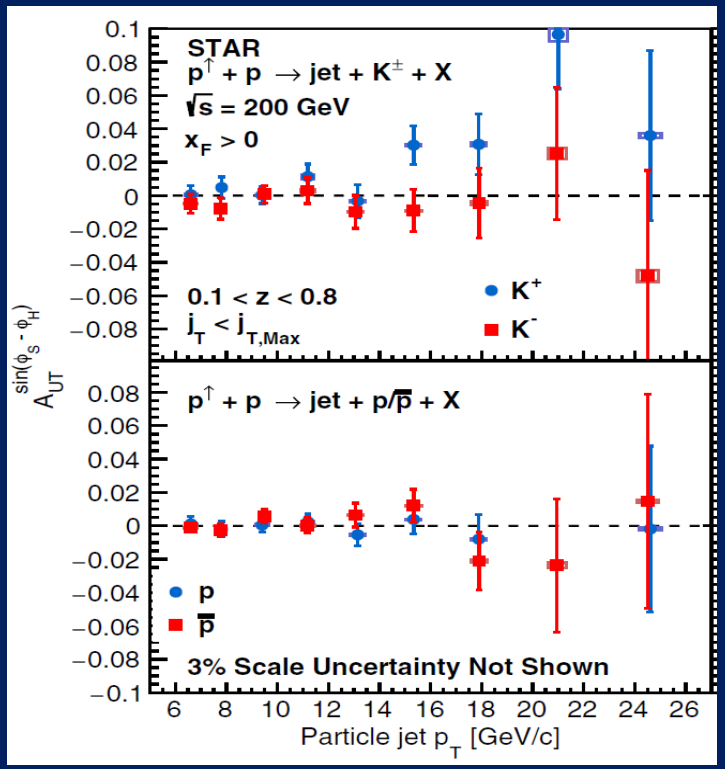
Slightly larger than for π^0, consistent with hints from p+p transverse single-spin asymmetry data. Due to strangeness?? Isospin??

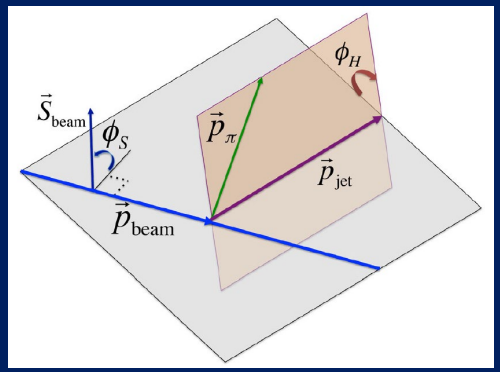
Measurement uses the thrust axis and a pair of back-to-back hadrons.

PRD100, 092008 (2019)

Jets and transverse spin effects: Hadron-in-jet transverse single-spin asymmetries

$$\frac{d\sigma^{\uparrow}(\phi_S,\phi_H) - d\sigma^{\downarrow}(\phi_S,\phi_H)}{d\sigma^{\uparrow}(\phi_S,\phi_H) + d\sigma^{\downarrow}(\phi_S,\phi_H)}$$
$$\propto A_{UT}^{\sin(\phi_S)} \sin(\phi_S)$$
$$+ A_{UT}^{\sin(\phi_S-\phi_H)} \sin(\phi_S-\phi_H)$$
$$+ A_{UT}^{\sin(\phi_S-2\phi_H)} \sin(\phi_S-2\phi_H)$$
$$+ A_{UT}^{\sin(\phi_S+\phi_H)} \sin(\phi_S+\phi_H)$$
$$+ A_{UT}^{\sin(\phi_S+2\phi_H)} \sin(\phi_S+2\phi_H).$$





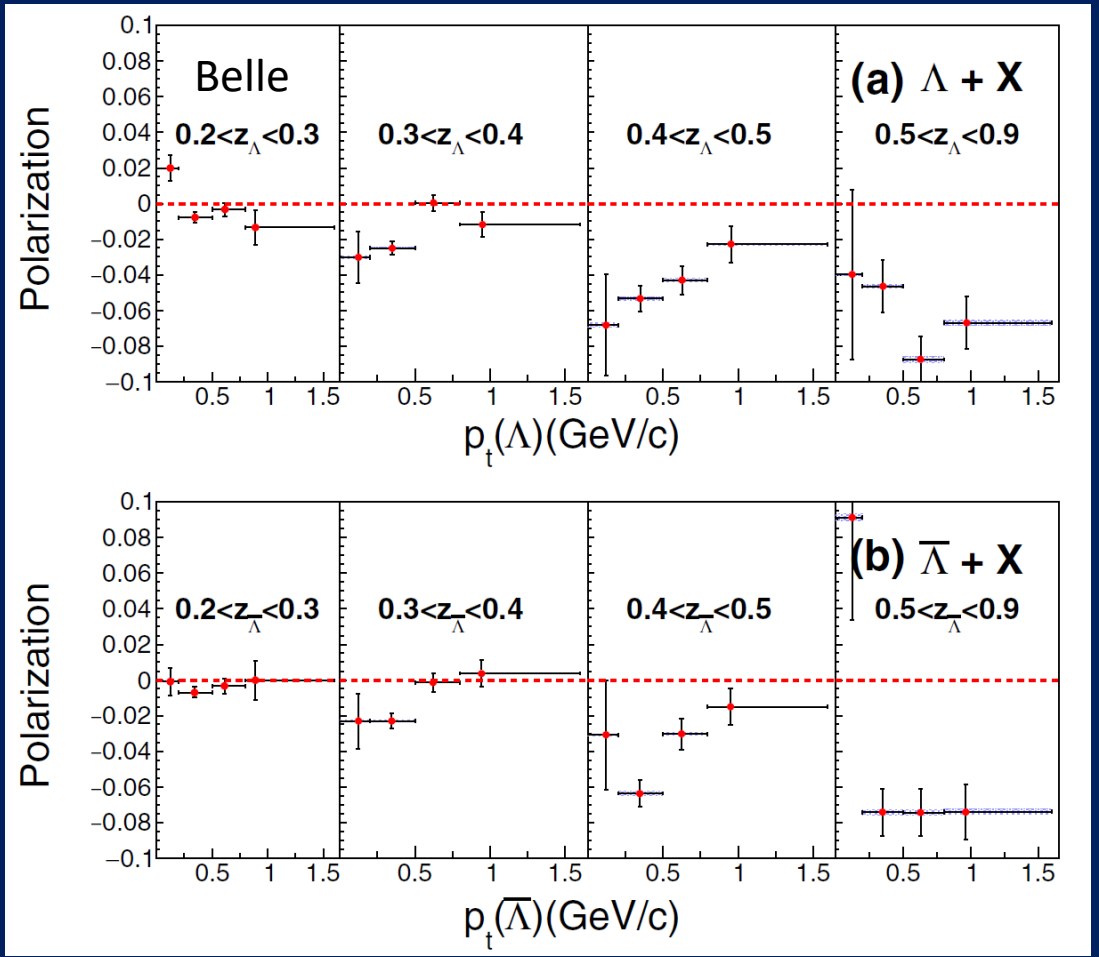
Significant Collins asymmetries observed also for K^+, but consistent with zero for K^-, p, and $\bar{p}$. Gives further insight into flavor dependence.

First measurement of kaon and proton Collins asymmetries in p+p collisions!

PRD106, 072010 (2022)

Λ, $\overline{\Lambda}$ *polarization in* e^+e^-

- Belle measurement of nonzero Λ and $\overline{\Lambda}$ transverse polarization
  - How does this relate to zero $\overline{\Lambda}$ polarization for inclusive production in hadronic collisions??
- Sensitive to polarizing TMD FF

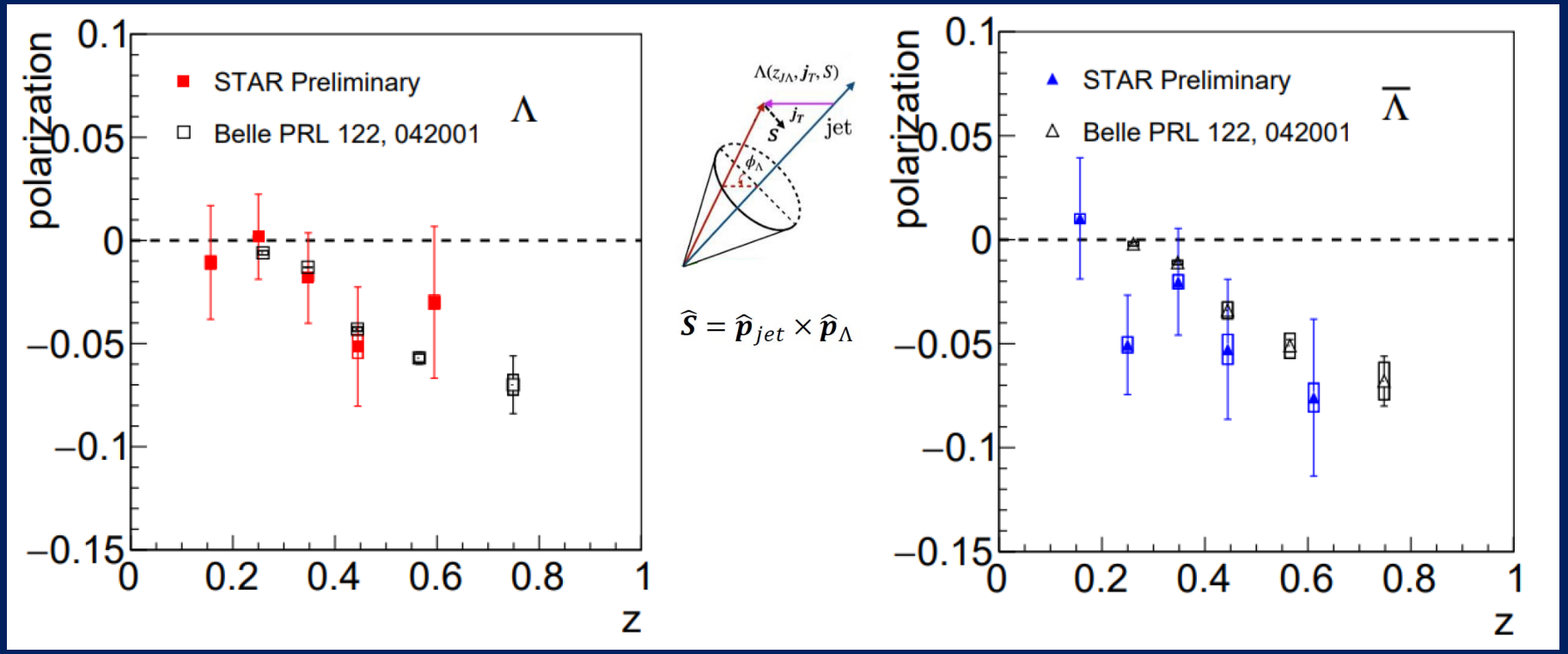


PRL122, 042001 (2019)

p_T with respect to thrust axis or an associated light hadron in the opposite hemisphere.

Λ, $\bar{\Lambda}$ polarization in jets in p+p

Taoya Gao, Tuesday



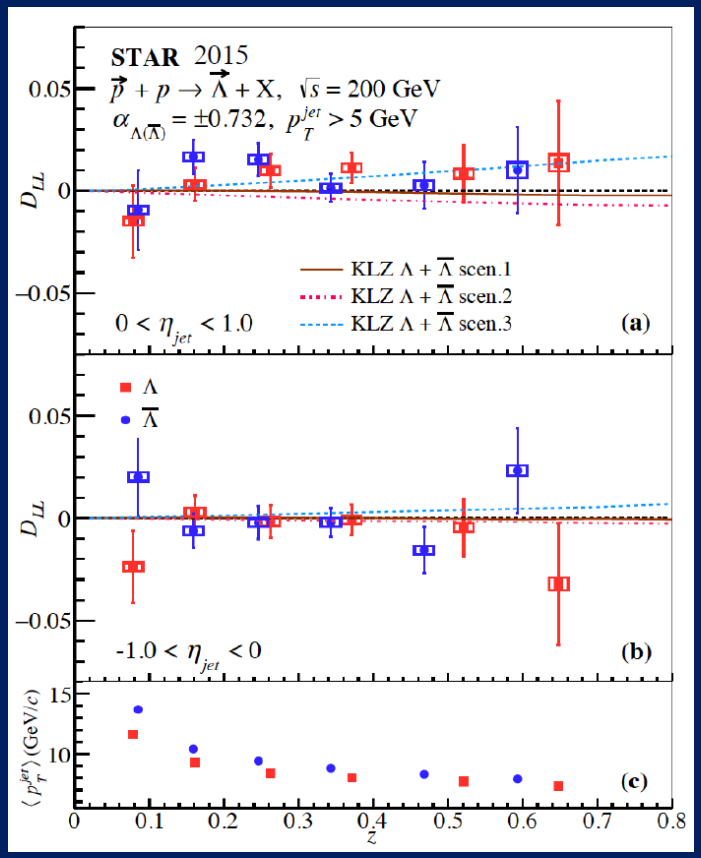
New preliminary results from STAR on transverse Λ and $\bar{\Lambda}$ polarization in jets shown for the first time this week! Consistent with Belle results.

J/ψ polarization in jet analysis underway at LHCb…

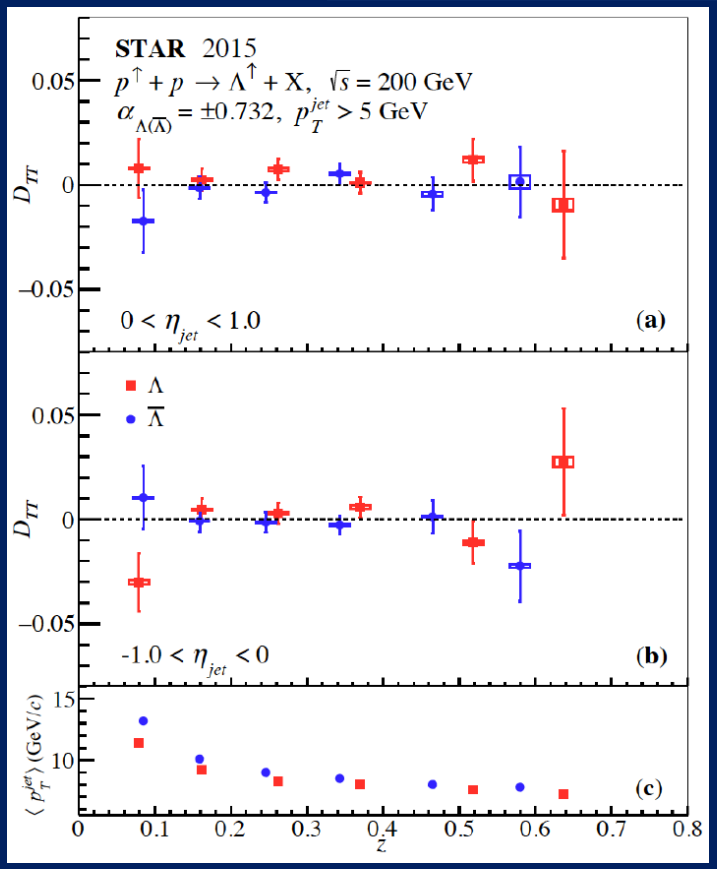
Spin transfer to Λ, $\bar{\Lambda}$ in jets

arXiv:2309.14220

Qinghua Xu, Tuesday



Theory: PLB809, 135756 (2020)



Using a longitudinally or transversely polarized proton beam at RHIC, can study longitudinal (left) or transverse (right) spin transfer to (anti-)lambdas in jets.

Future polarized measurements with jets at RHIC

- STAR took a large transversely polarized dataset in 2022 with their forward upgrade in place

  Carl Gagliardi, Thursday

- The new sPHENIX experiment now fully installed and took commissioning data with Au+Au collisions this year

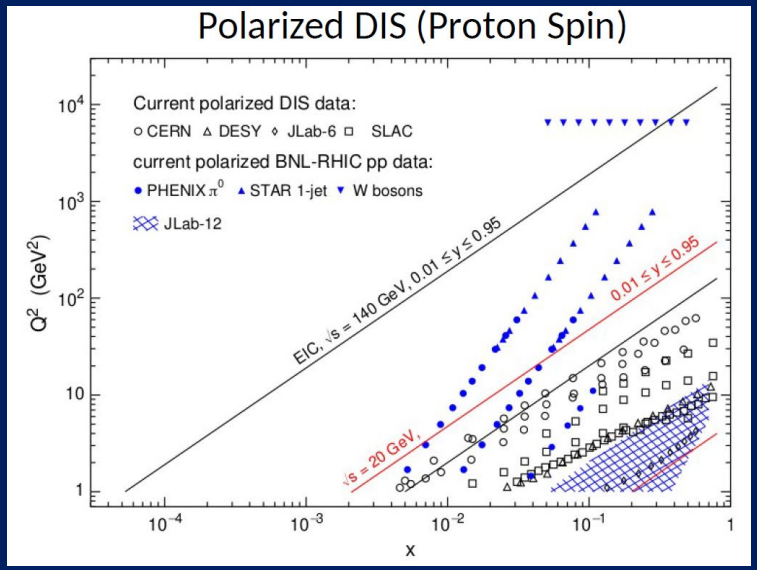
  Devon Loomis, Gregory Mattson posters

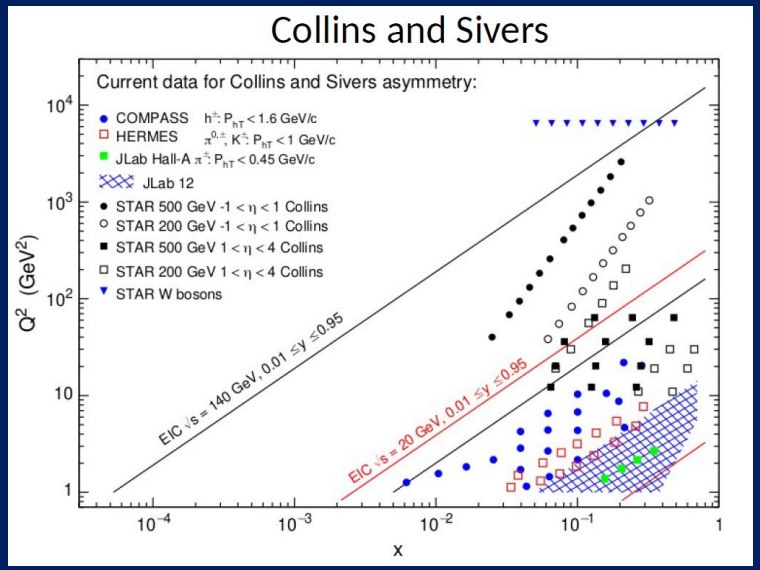
- Last polarized proton running at RHIC 2024—transverse polarization planned for both sPHENIX and STAR
  - Last year of RHIC operations 2025, then transitioning to Electron-Ion Collider construction . . .

Complementarity of RHIC and EIC

Maria Zurek, Monday

Barak Schmookler, Thursday

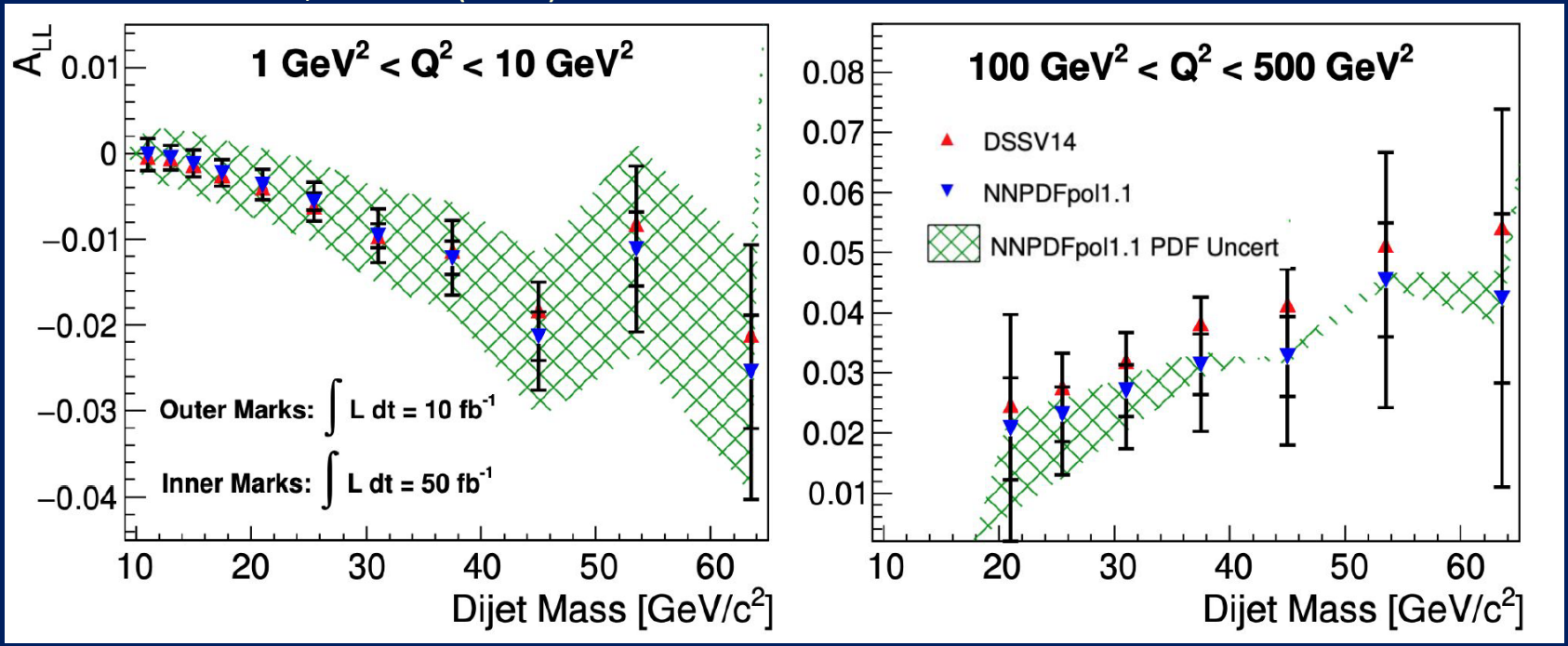




- Overlapping kinematic range relevant to helicity and transverse spin observables at RHIC and the EIC
  - Study universality, TMD-factorization breaking effects
- Extensive kinematic reach of EIC
  - Study TMD evolution
  - Jets will play an important complementary role to semi-inclusive DIS in which a single hadron is measured

EIC: Double-longitudinal asymmetry for dijets to probe gluon helicity

PRD101, 072003 (2020)

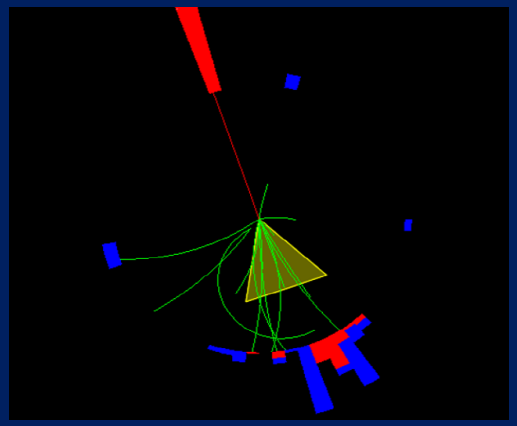


Complementary measurement to inclusive polarized DIS structure function g_1

Also proposals to access gluon orbital angular momentum at EIC via single and double spin asymmetry in diffractive dijet production: PRL118, 192004 (2017), PRL128, 182002 (2022)

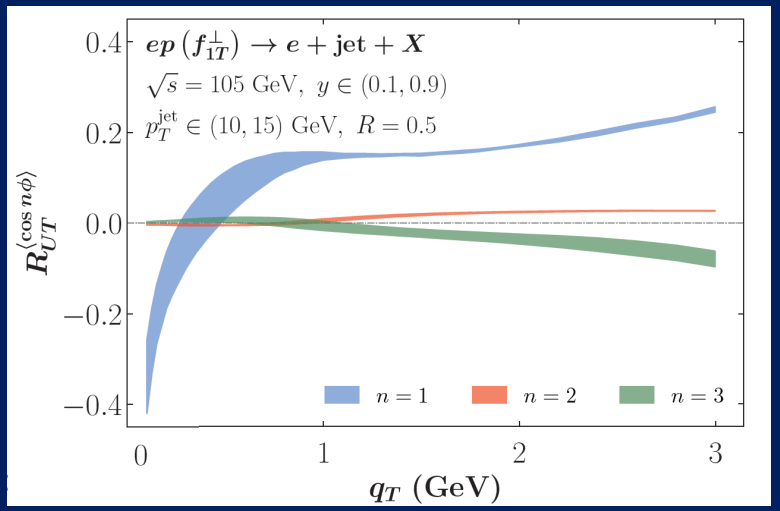
EIC: Nearly back-to-back electron-jet to probe Sivers TMD PDF

Fanyi Zhao, Tuesday

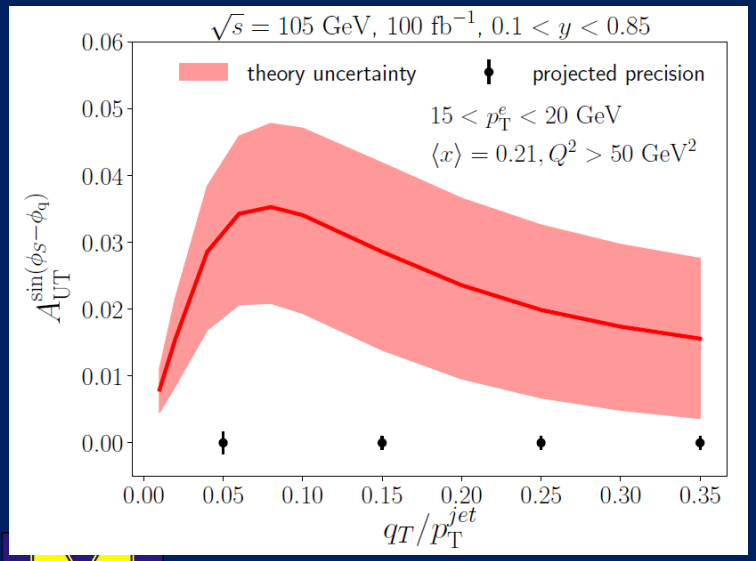


$$F_{UT}^{\sin(\phi_q-\phi_S)} = \sum_{n=0}^{\infty} A_n^{\text{Sivers}}$$

$$R_{UT}^{\langle\cos(n\phi)\rangle} = \frac{\int A_n^{\text{Sivers}} \cos(n\phi)\frac{d\phi}{2\pi}}{\int A_0^{\text{Sivers}}\frac{d\phi}{2\pi}},$$



EIC Yellow Report (2021)

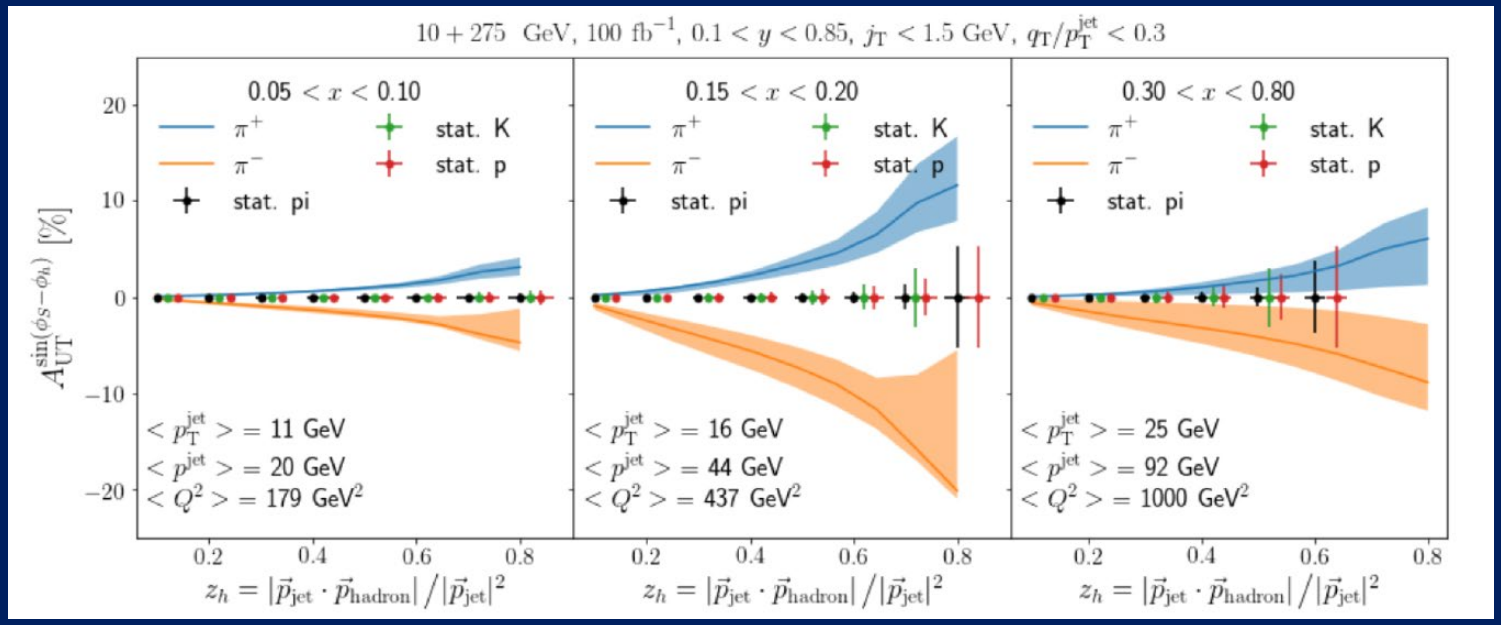


See also recent STAR Sivers dijet measurement with jet charge tagging: arXiv:2305.10359

(And various recent ideas about how to improve jet flavor tagging!)

EIC: Collins asymmetries for identified hadrons in jets

EIC Yellow Report (2021)

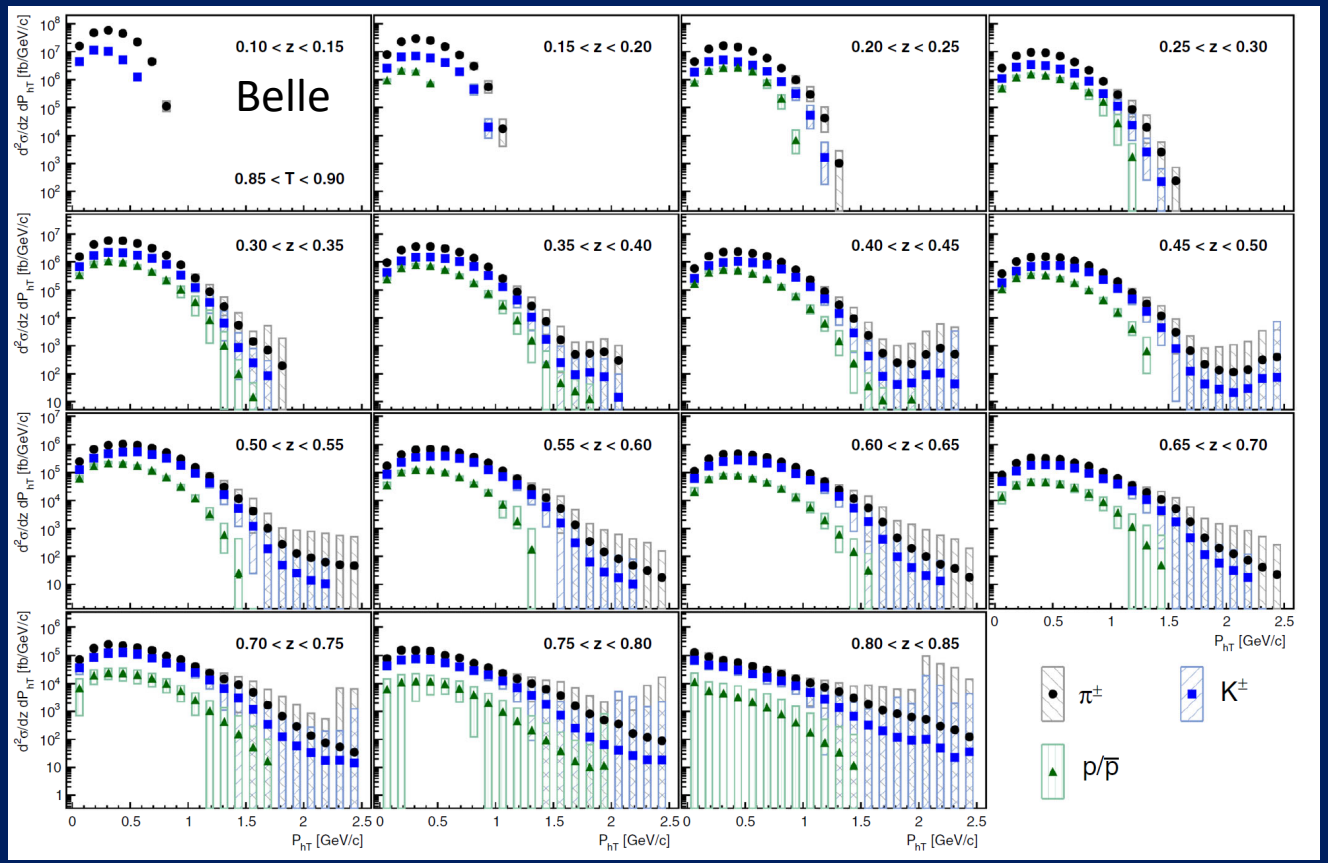


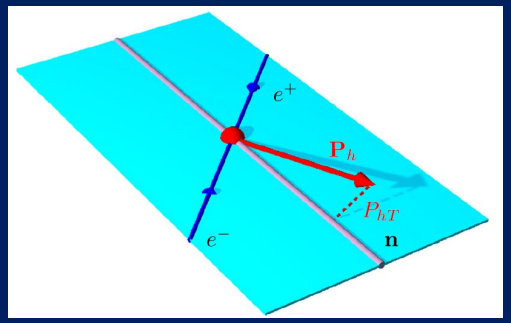
Access transversity quark distribution × Collins TMD FF

Also proposals to access linearly polarized gluons in transversely polarized protons at EIC via $J/\psi + jet$ (PRD100, 094016 (2019)) and $D + jet$ (PRD108, 034005 (2023))

(Unpolarized) TMD fragmentation functions for identified hadrons in e^+e^-

PRD99, 112006 (2019)



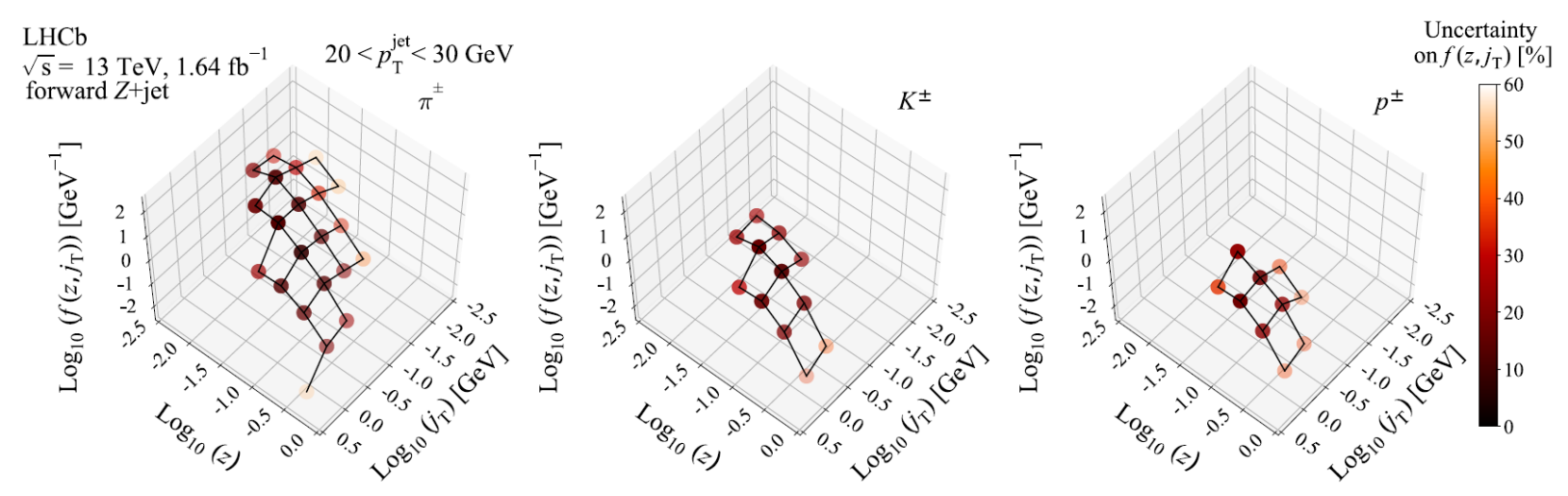


Differential cross sections for pions, kaons, and protons as a function of p_T in bins of momentum fraction z.

p_T defined relative to thrust axis.

(Unpolarized) TMD fragmentation functions for identified hadrons in jets

PRD108, L031103 (2023)



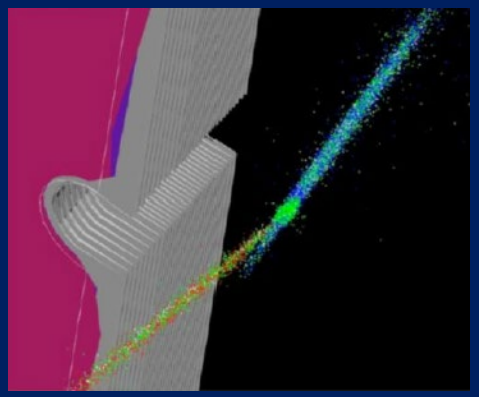
- LHCb: forward spectrometer with tracking, electromagnetic and hadronic calorimetry, hadron PID

- Doubly differential measurement for identified pions, kaons, and protons in forward jets produced back-to-back with a Z boson—predominantly light quark jets
- Larger longitudinal momentum fraction z correlated with larger transverse momentum w.r.t. jet axis j_T - differs from typical phenomenological assumption that they're uncorrelated

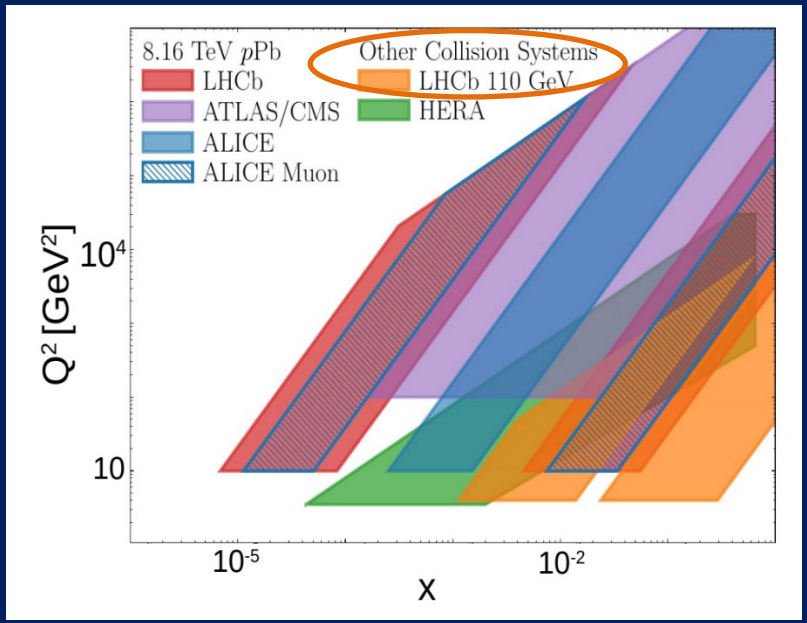
LHCb fixed-target capabilities

"Fixed-target-like" geometry well suited for . . . fixed-target physics!

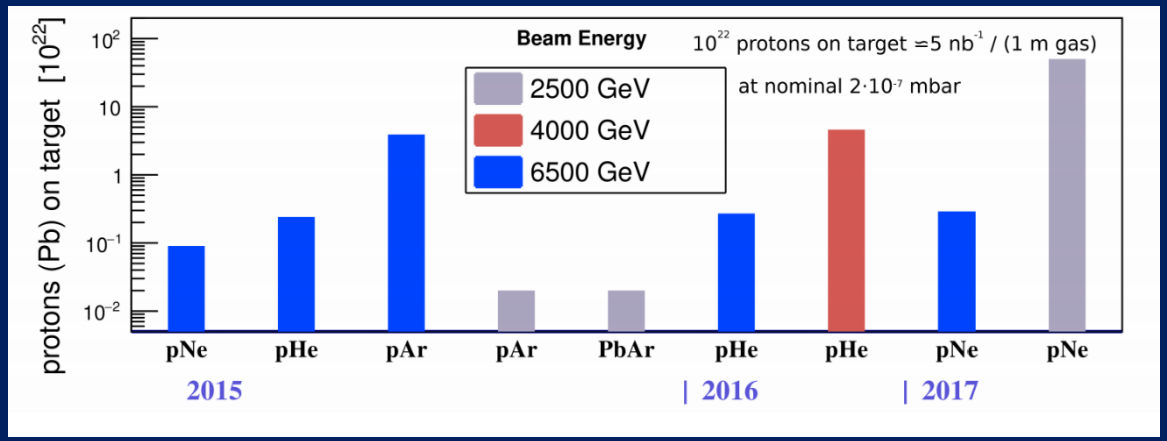
- System for Measuring Overlap with Gas (SMOG) allowed injection of small amounts of noble gas into LHC beam pipe around LHCb collision region. Luminosity up to 10^{30} cm^{-2} s^{-1}



- Collisions at $\sqrt{s_{NN}} = \sqrt{2E_{beam}M_p}$ 41-110 GeV for E_{beam}= 0.9-6.5 TeV
  - Between SPS and top RHIC energies
- Overlap with EIC energies

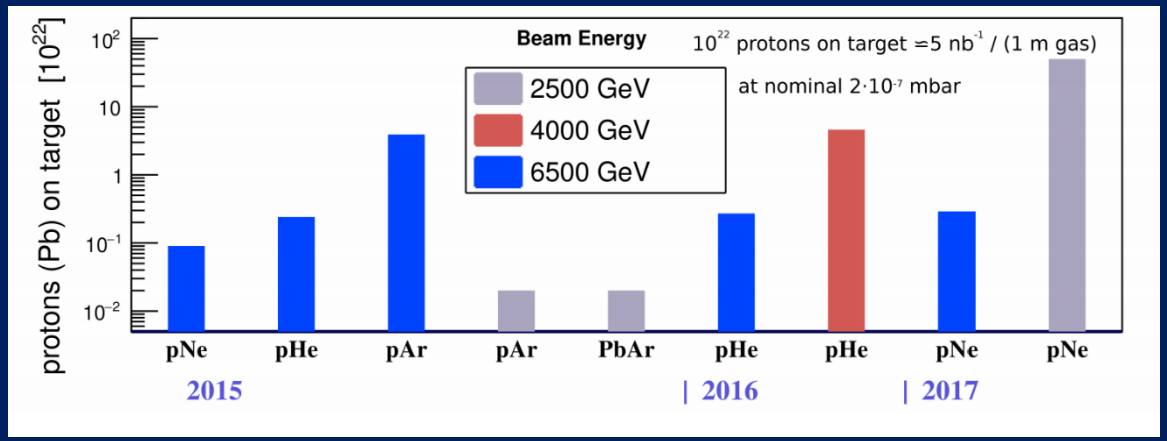


LHCb fixed-target capabilities



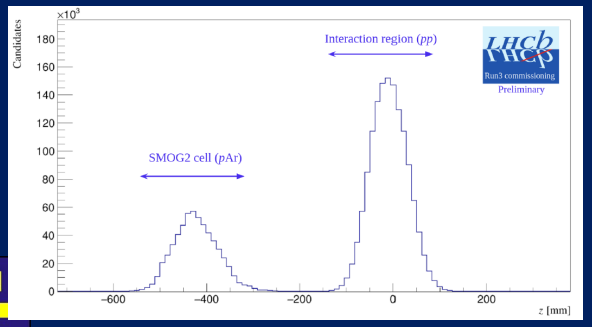
LHCb-PUB-2018-015

LHCb fixed-target capabilities



LHCb-PUB-2018-015

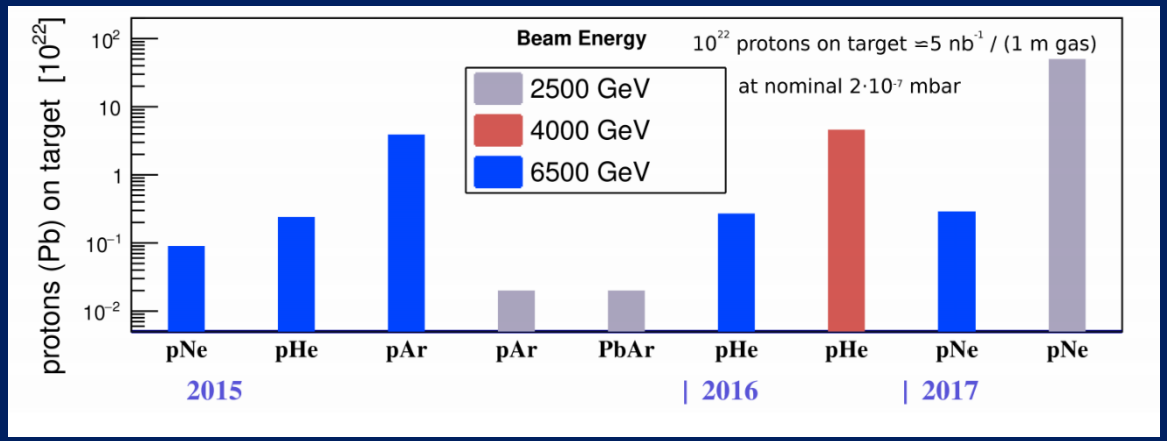
- Target storage cell installed Aug 2020: Up to 2 orders of magnitude higher luminosity, improved lumi determination, reduced backgrounds, wider variety of target species: H_2, D_2, He, N_2, O_2, Ne, Ar, Kr, Xe



Run collider and fixed-target mode simultaneously. Excellent vertex separation seen!

LHCb-FIGURE-2023-001

LHCb fixed-target capabilities



LHCb-PUB-2018-015

Pasquale Di Nezza, Friday

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- LHCSpin: Proposal for transversely polarized gas target at LHCb!

Conclusions

- Jets have become extremely versatile tools in high-energy nuclear and particle physics over the last ~15 years!
  - Rapid expansion of new theoretical ideas and experimental measurements
- They offer a range of ways to access effects due to spin-spin and spin-momentum correlations in nucleon structure and in the process of hadronization

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- Jet measurements at RHIC have been instrumental in constraining gluon helicity and exploring transverse spin phenomena
- More results to come from RHIC, e^+e^-, and the future EIC!

Conclusions

- Jets have become extremely versatile tools in high-energy nuclear and particle physics over the last ~15 years!
  - Rapid expansion of new theoretical ideas and experimental measurements
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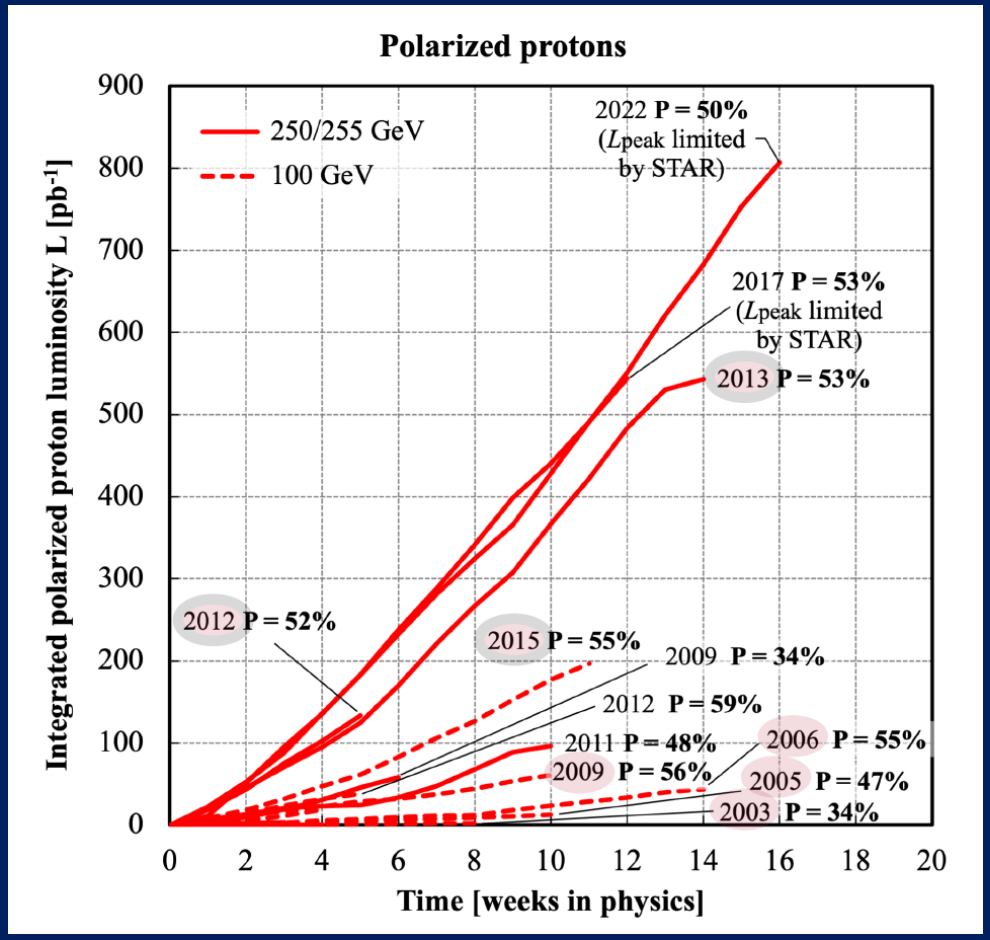
Extra

Jets have become versatile tools!

- Anti-k_T jet reconstruction algorithm has opened up many new possibilities to make robust comparisons of jets between theory and experiment – Cacciari, Salam, Soyez, JHEP 04, 063 (2008)
- Lots of subsequent developments!
  - Healthy interplay between experiment and theory, in particular given the wealth of jet data from pp and heavy ion collisions at the LHC

- Parton energy loss in hot or cold nuclear matter
- Study the *Z, W,* τ, top quark, Higgs
- Probe color coherence
- Probe factorization breaking/limits of factorization
- Constrain α_s
- Search for new resonances in dijet mass spectrum
- Constrain collinear/transverse-momentum-dependent, polarized/unpolarized PDFs
- Probe polarization of a fragmenting quark
- Diffractive imaging of protons and nuclei
- …

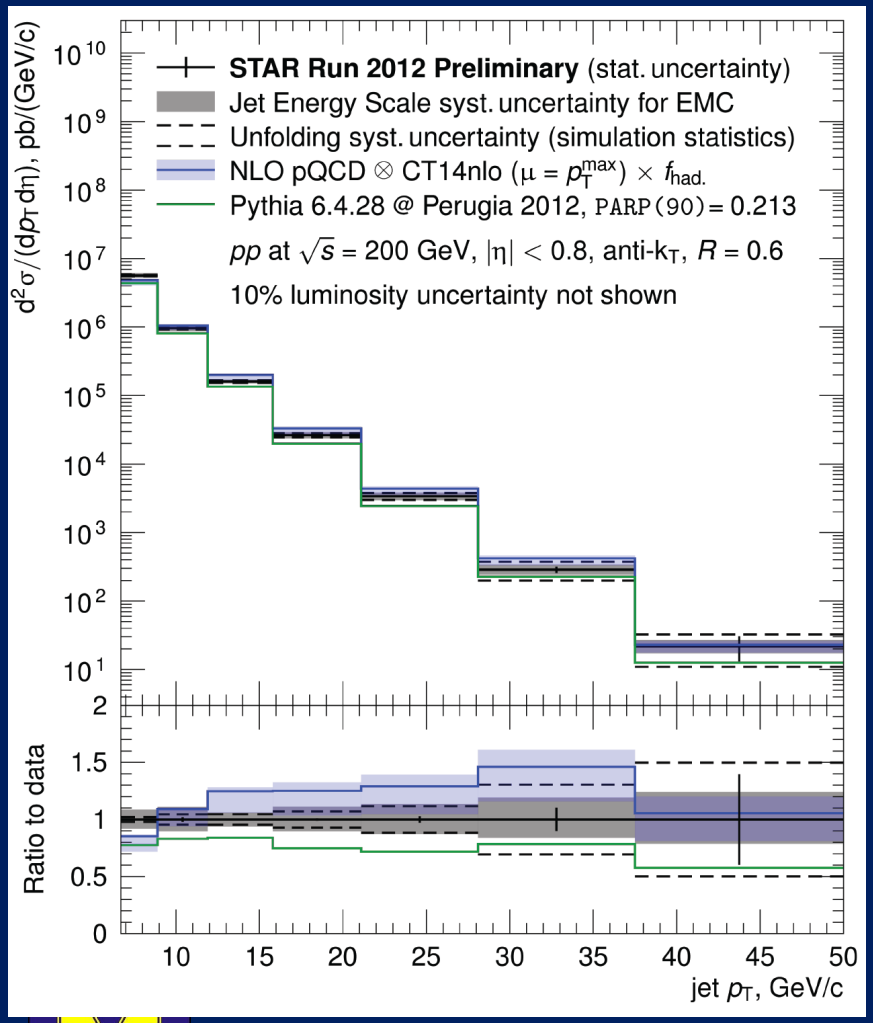
Polarized proton running at RHIC

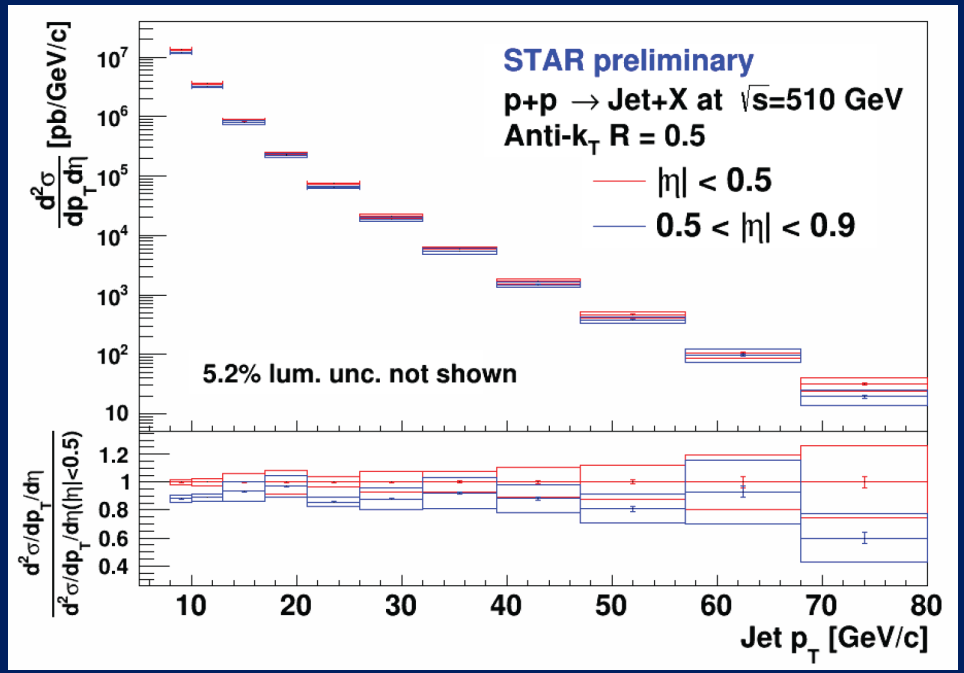


Final polarized proton run will be 2024!

200 GeV, transverse polarization planned for both STAR and sPHENIX

Inclusive jet cross section measurements





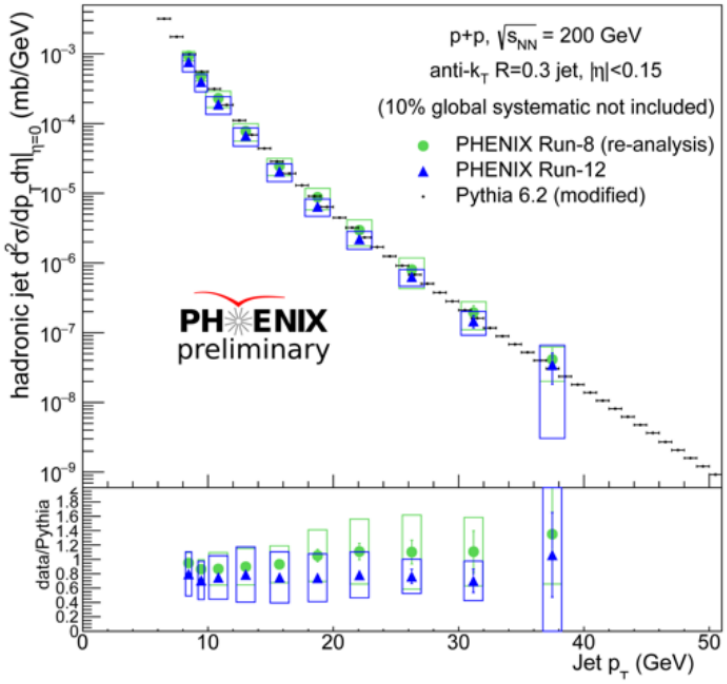
Latest inclusive jet cross section measurements vs. p_T from STAR for 200 GeV (left) and 510 GeV (right). 510 GeV measurement in two bins of pseudorapidity.

Inclusive jet cross section: PHENIX 200 GeV

Purpose: p + p baseline

Additional: modify simulation to better follow the data

- Found that Pythia prefers more charged particles in its jets than are present in data
  - Can affect unfolding for structure quantities & uncertainty
- Method:
  1. Find ratio of data/unmodified-Pythia for the distribution of charged particles w.r.t. the jet axis
  2. Randomly remove constituent particles from the jets (charged and neutral) according to that distribution
  3. Re-scale for the lost momentum
- Plot: cross-section unfolding with corrected/tuned simulation

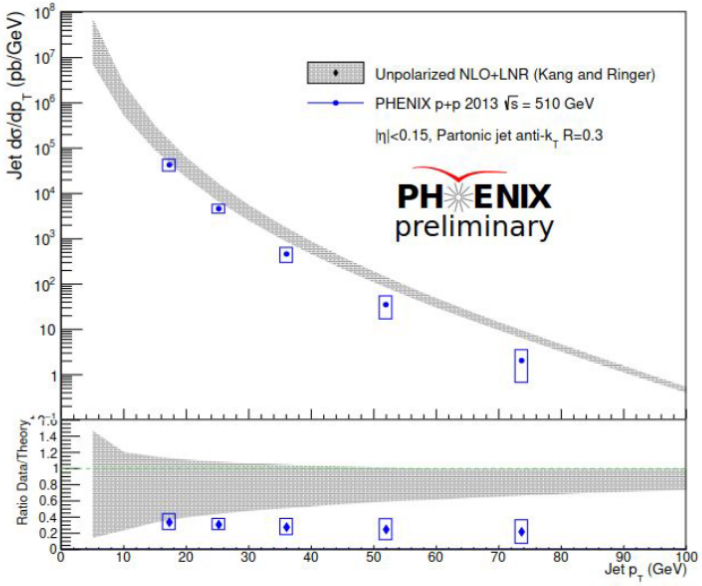


Inclusive jet cross section: PHENIX 510 GeV

PHENIX

Midrapidity jet cross section

- Small jet radius R=0.3 with anti-kT jet clustering algorithm
- NLO + ln(R) resummation theory calculation overestimates data for small R jets
  - Partonic level calculation does not account for MPI and hadronization effects
  - Similar effect found in CMS, ALICE small R jets



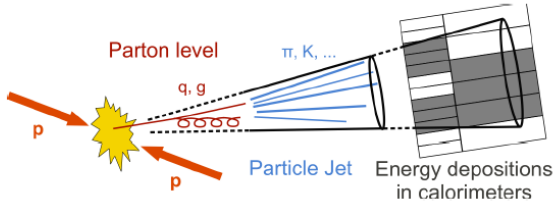
UNIVERSITY OF MICHIGAN

Jet substructure from PHENIX

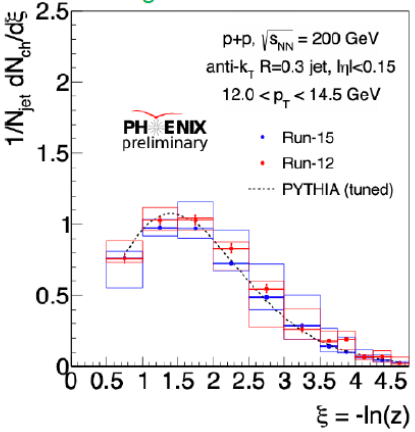
Jets

PHENIX New Analysis Results (Preliminary)

Jet substructure in p+p collisions

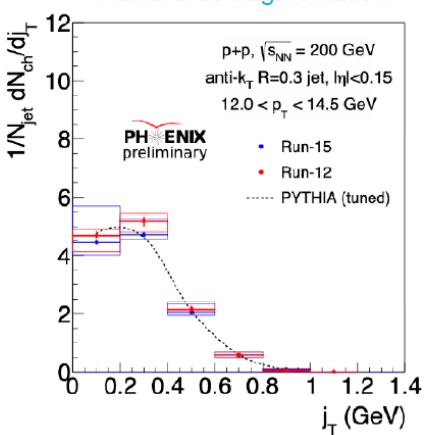


Fragmentation function



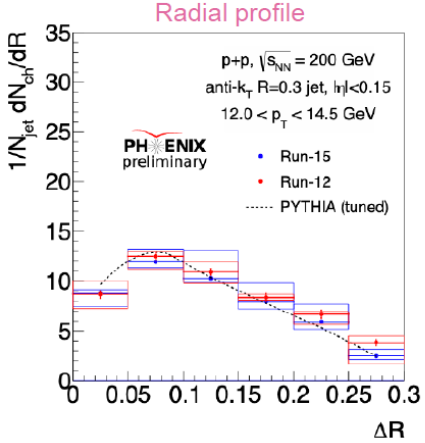
$\xi = -\ln(z) = \ln(p_{T,jet}/p_{T,h})$

Transverse fragmentation



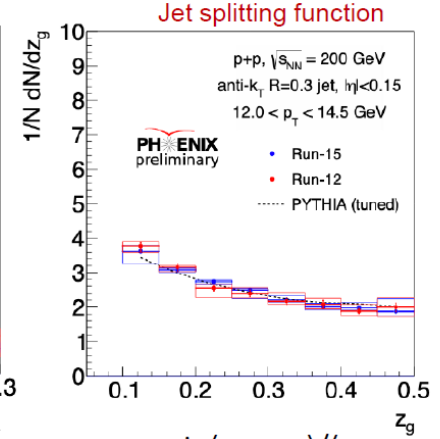
$j_T = |p_{jet} \times p_{track}| / |p_{jet}|$

Radial profile



$\Delta R = \sqrt{(\Delta\phi^2 + \Delta\eta^2)}$

Jet splitting function



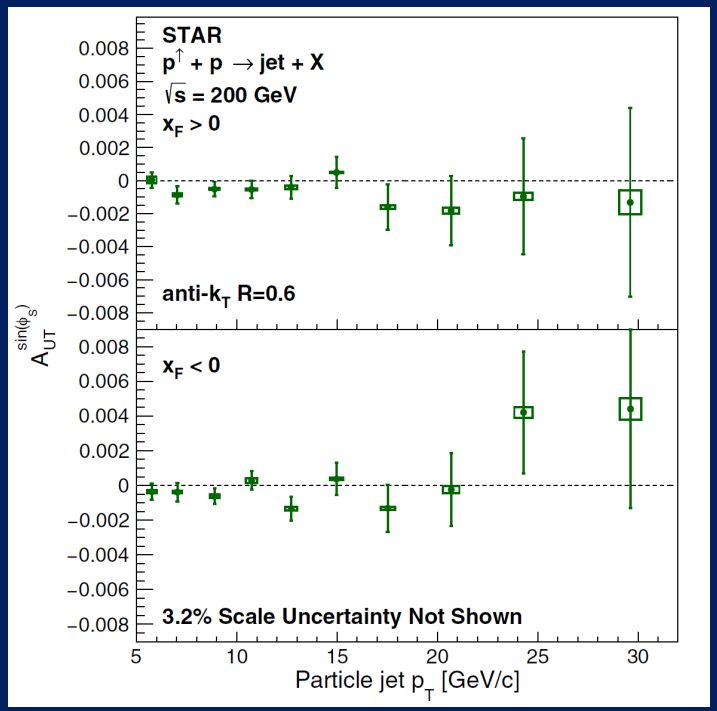
$z_g = \min(p_{T1}, p_{T2})/(p_{T1} + p_{T2})$

- PHENIX measured jet substructure in pp (shown for 12 < p_T < 14.5 GeV jets)
- pp data from Run 12, 15 ; 2D unfolding and tuned PYTHIA (dashed lines)
- Baseline for ongoing jet substructure measurements in p+A and A+A

Jets and transverse spin effects: Inclusive jet transverse single-spin asymmetries

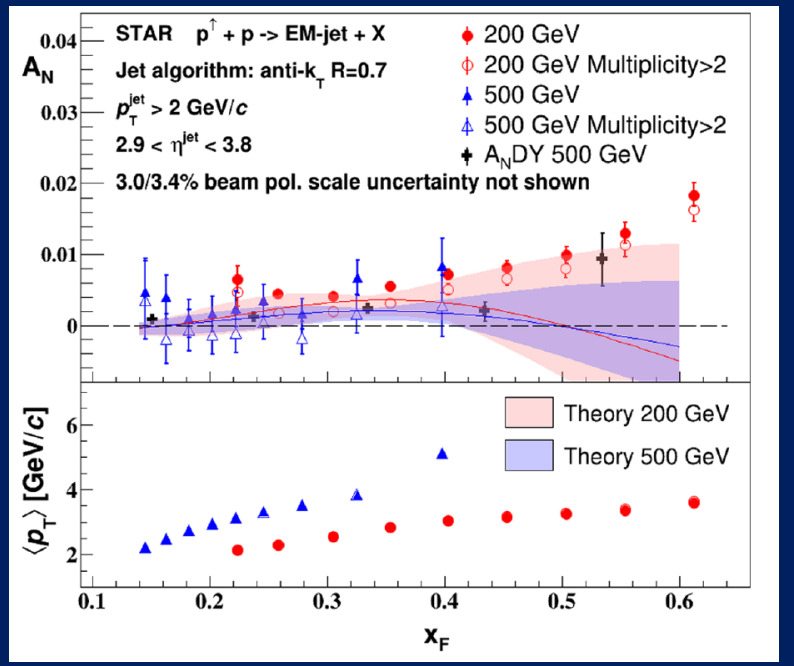
- Constrain collinear twist-3 correlators for gluons and quarks in transversely polarized protons
  - Twist-3 correspondent of Sivers TMD PDF

Xilin Liang, Monday



Consistent with zero at midrapidity

Nonzero but small at forward rapidity

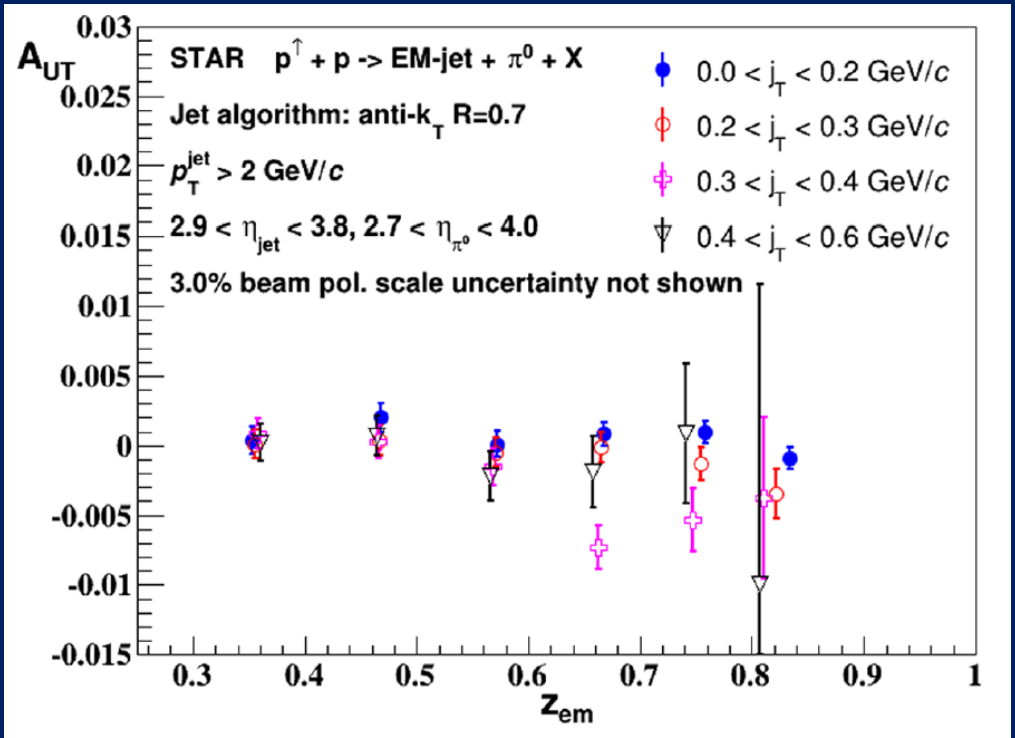


Theory curves: Gamberg, Kang, Prokudin, PRL110, 232301 (2013)

PRD106, 072010 (2022)

PRD103, 092009 (2021)
A_NDY: PLB750, 660 (2015)

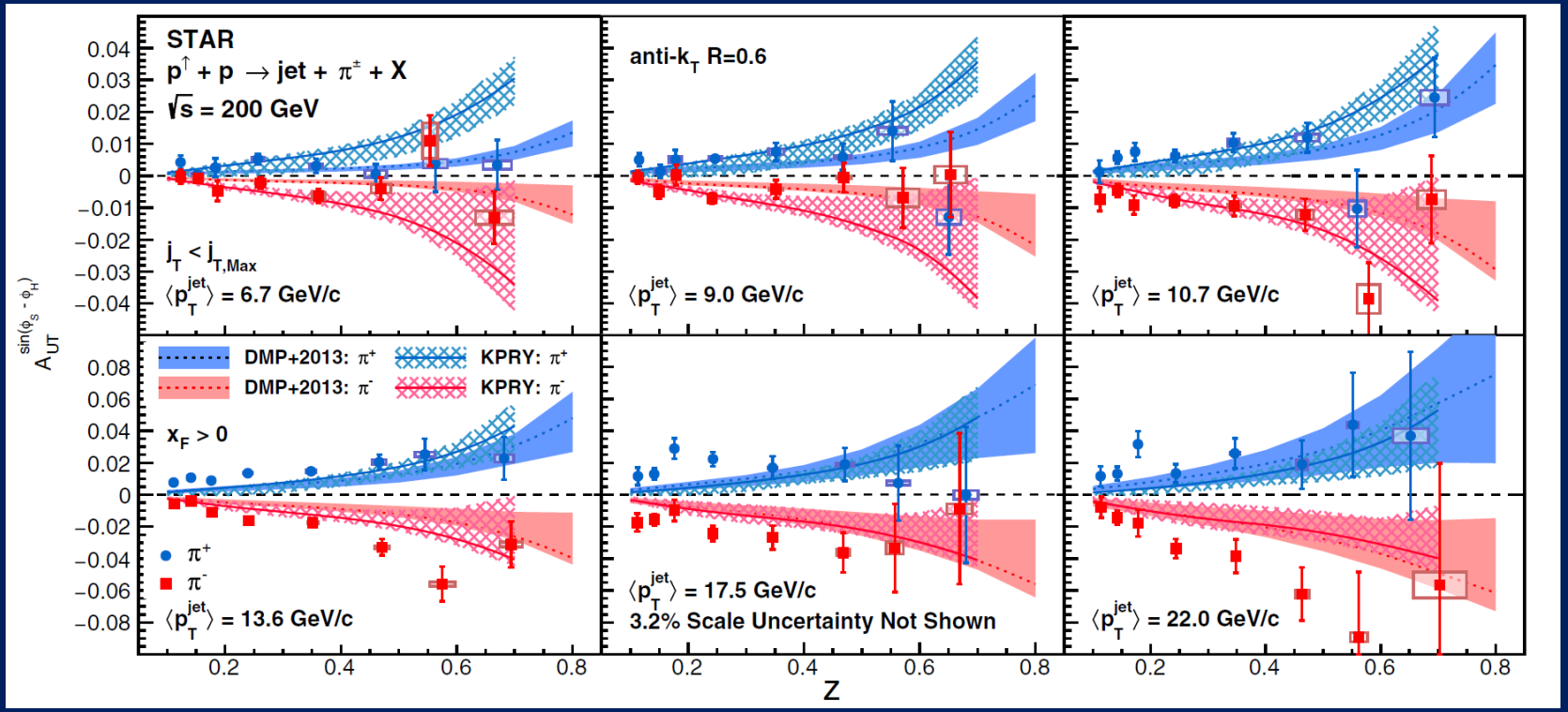
Jets and transverse spin effects: Forward electromagnetic jet transverse single-spin asymmetries



Collins asymmetries for π^0 in forward electromagnetic jets as a function of longitudinal momentum fraction z of the pion in the jet, in bins of pion transverse momentum with respect to the jet axis j_T.

PRD103, 092009 (2021)

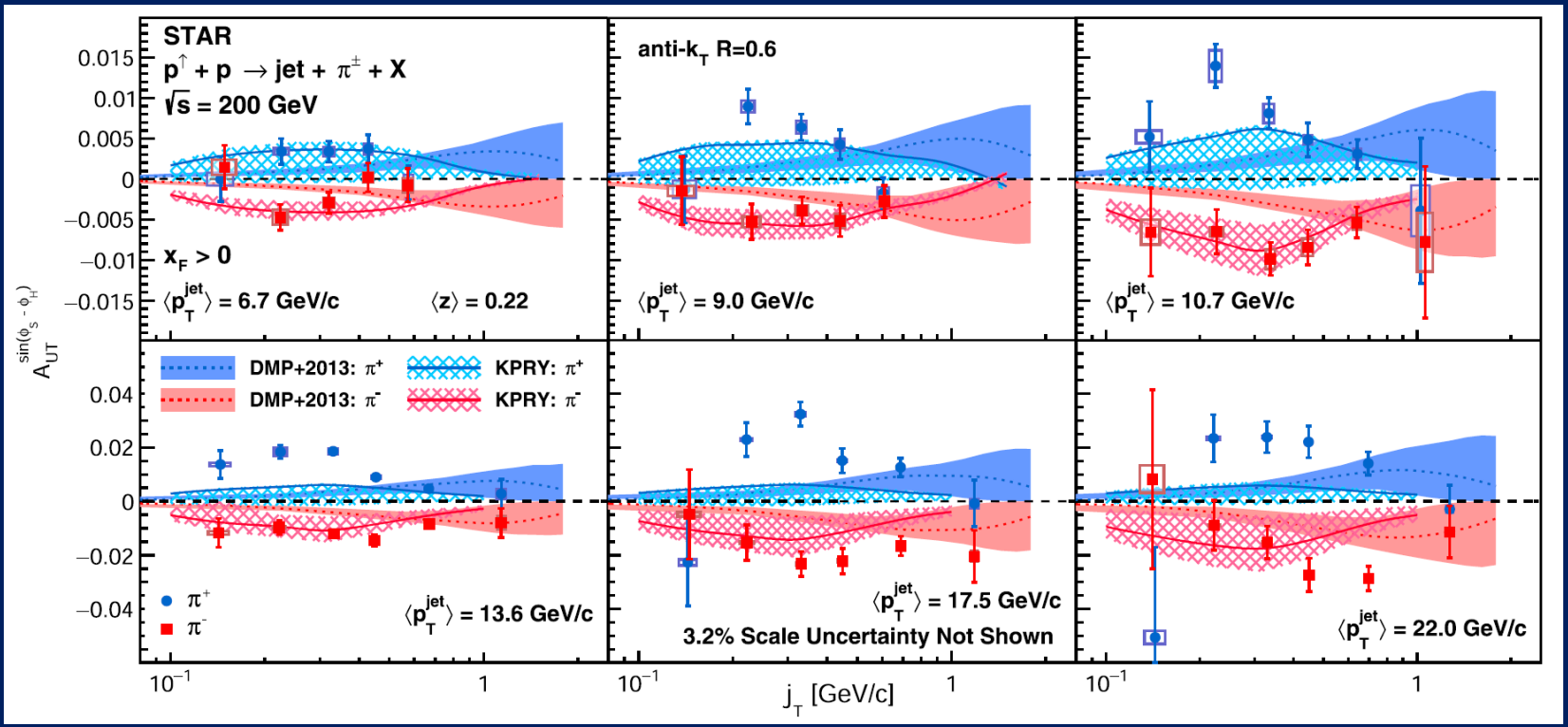
Jets and transverse spin effects: Hadron-in-jet transverse single-spin asymmetries



Collins asymmetries for π^+ and π^- as a function of longitudinal momentum fraction z of the pion in the jet, in bins of jet p_T.

PRD106, 072010 (2022)

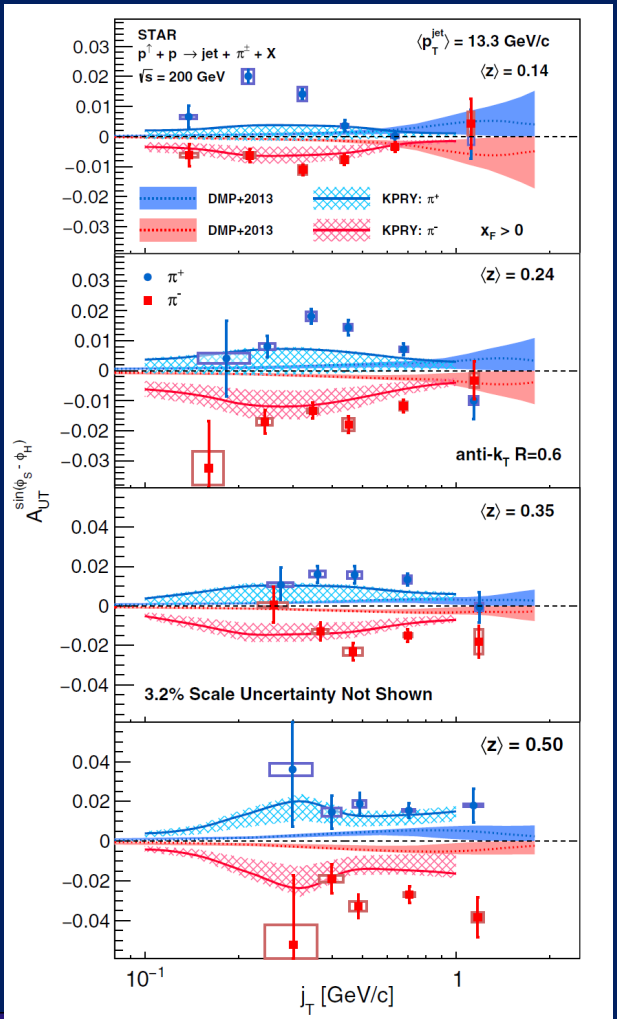
Jets and transverse spin effects: Hadron-in-jet transverse single-spin asymmetries

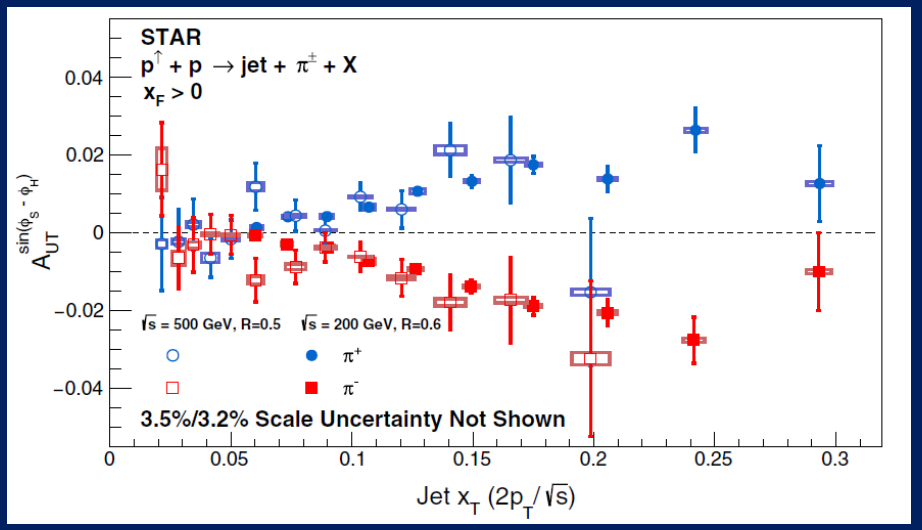


Collins asymmetries for π^+ and π^- as a function of pion transverse momentum j_T with respect to the jet axis, in bins of jet p_T.

PRD106, 072010 (2022)

Jets and transverse spin effects: Hadron-in-jet transverse single-spin asymmetries



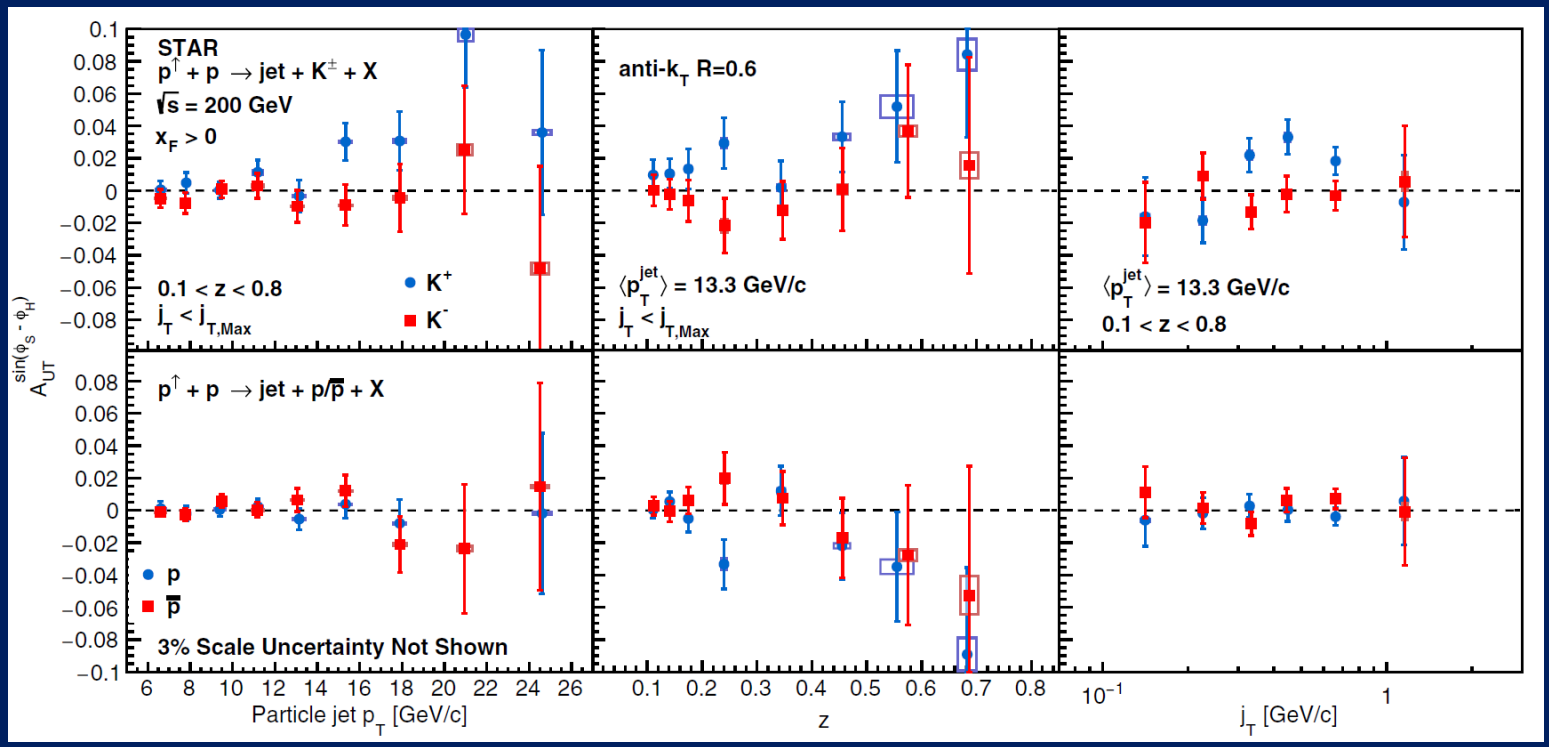


Collins asymmetries for π^+ and π^- as a function of jet $x_T = \frac{2p_T}{\sqrt{s}}$, for 200 and 500 GeV p+p collisions.

Collins asymmetries for π^+ and π^- as a function of pion transverse momentum j_T with respect to the jet axis, in bins of longitudinal momentum fraction z of the pion in the jet.

PRD106, 072010 (2022)

Jets and transverse spin effects: Hadron-in-jet transverse single-spin asymmetries

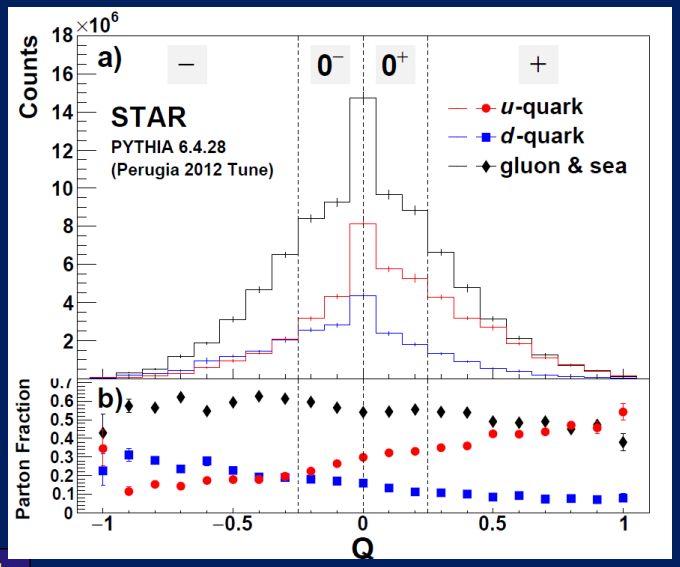


Collins asymmetries for K^+, K^-, p, and $\bar{p}$ as a function of jet p_T, longitudinal momentum fraction z, and hadron transverse momentum j_T with respect to the jet axis.

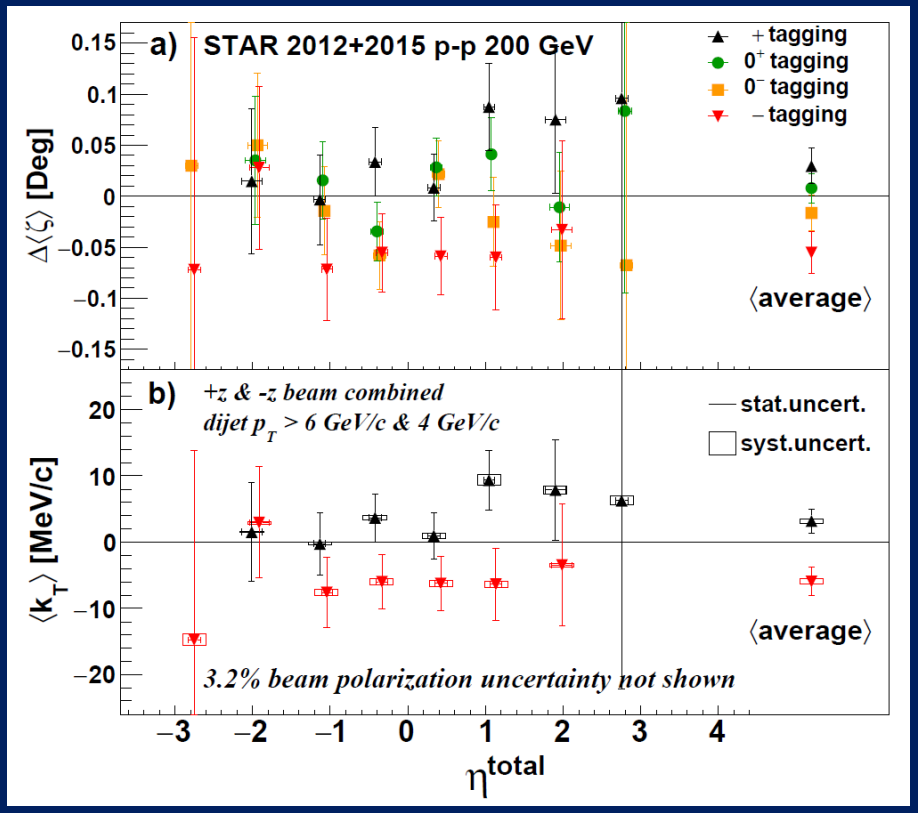
PRD106, 072010 (2022)

Jets and transverse spin effects: Spin-dependent dijet momentum imbalance

- Sensitive to Sivers TMD PDF
- Nonzero if separate by jet charge to enhance up-quark vs. down-quark jet fractions

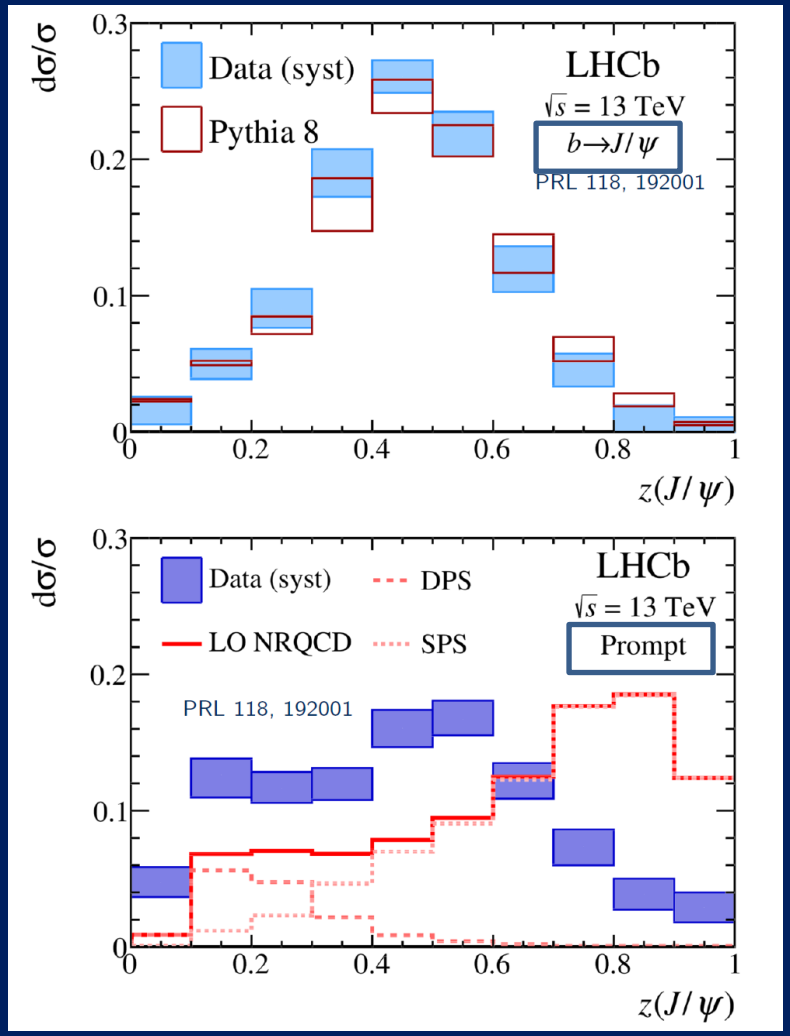


arXiv:2305.10359



Toward hadron-in-jet polarization measurements

- LHCb has measured J/ψ-in-jet
  - J/ψ from b decay well described by PYTHIA
  - Prompt J/ψ-in-jet not. Can shed light on prompt J/ψ production mechanism(s).
- LHCb analysis of J/ψ polarization in jets ongoing
- Could also measure hyperon polarization in jets, sensitive to polarizing TMD FFs

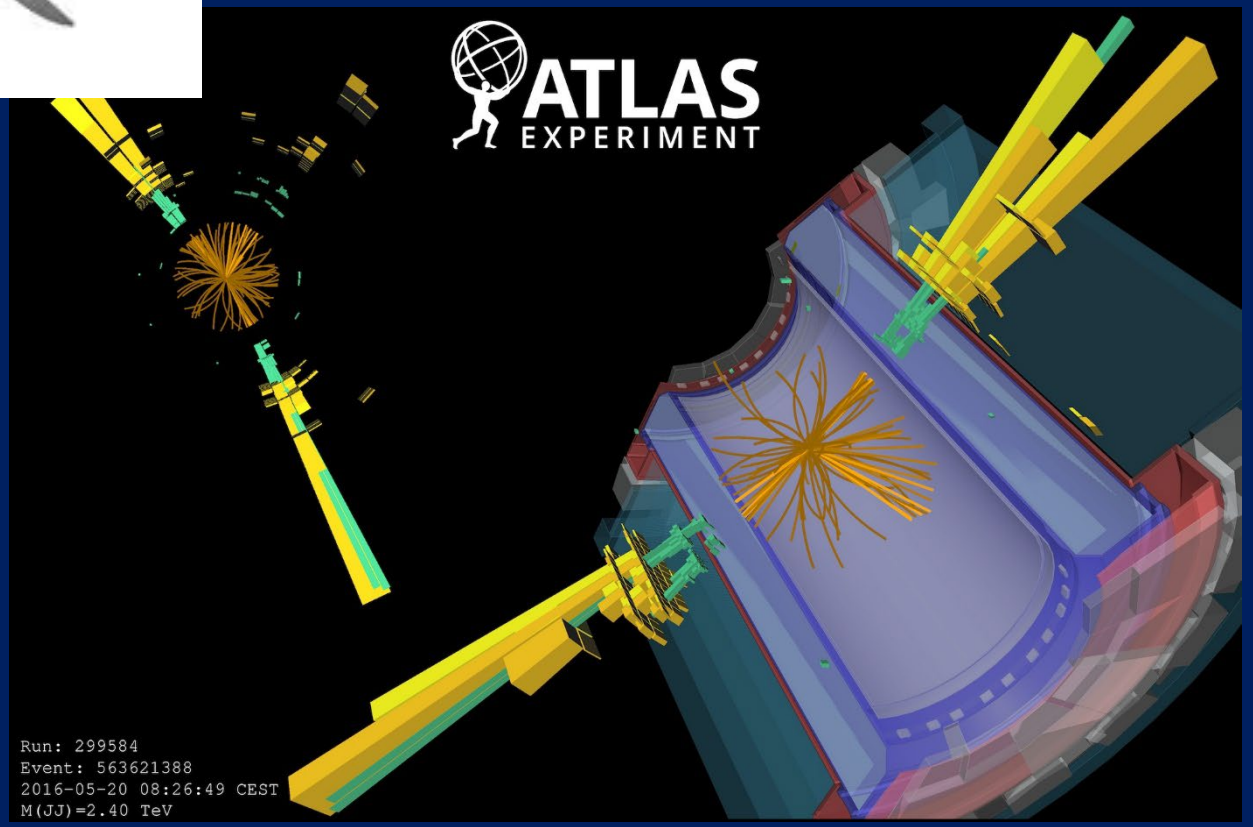


$$z \equiv \frac{p_T^{J/\psi}}{p_T^{jet}}$$

PRL 118, 192001 (2017)

Other new and old ideas

- "Celestial blocks and transverse spin in the three-point energy correlator" – JHEP09, 199 (2022)
- "Determining the polarized parton distributions of the proton via jet handedness" – PLB295, 277 (1992)
  - Measure 3 particles in the jet
- "The time-reversal-odd side of a jet" – Fundamental Research 3, 346 (2023)
- "Collins-type energy-energy correlators and nucleon structure" – arXiv:2307.06953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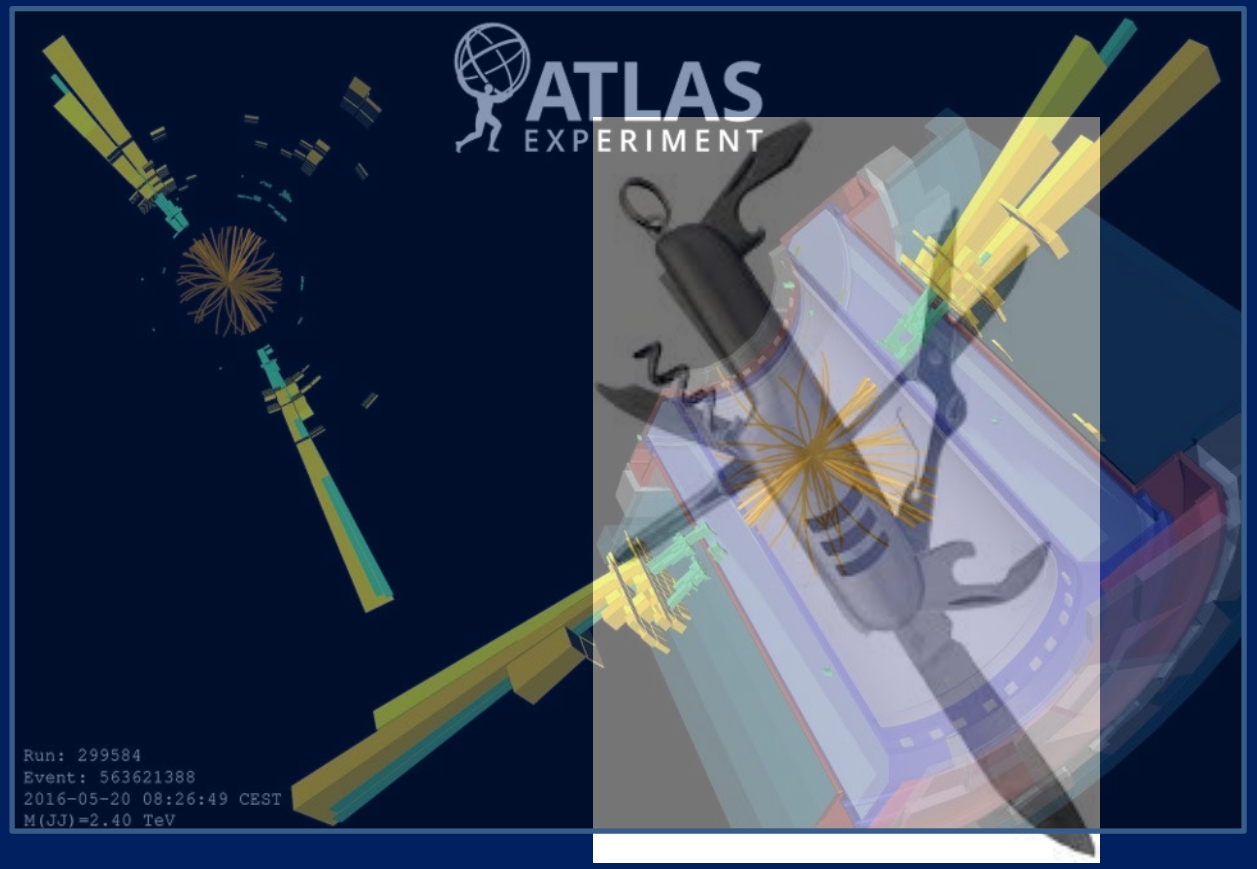
M(JJ)=2.40 TeV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