TMD Measurements in *hadron-hadron* and in e^+-e^- Collisions

Almo Collegio Borromeo, Pavia – May, 23-2022

e^+e^-

BELLE BABAR BESIII

Fixed target Drell-Yan

COMPASS SeaQuest

Polarizded Proton Collider BRAHMS

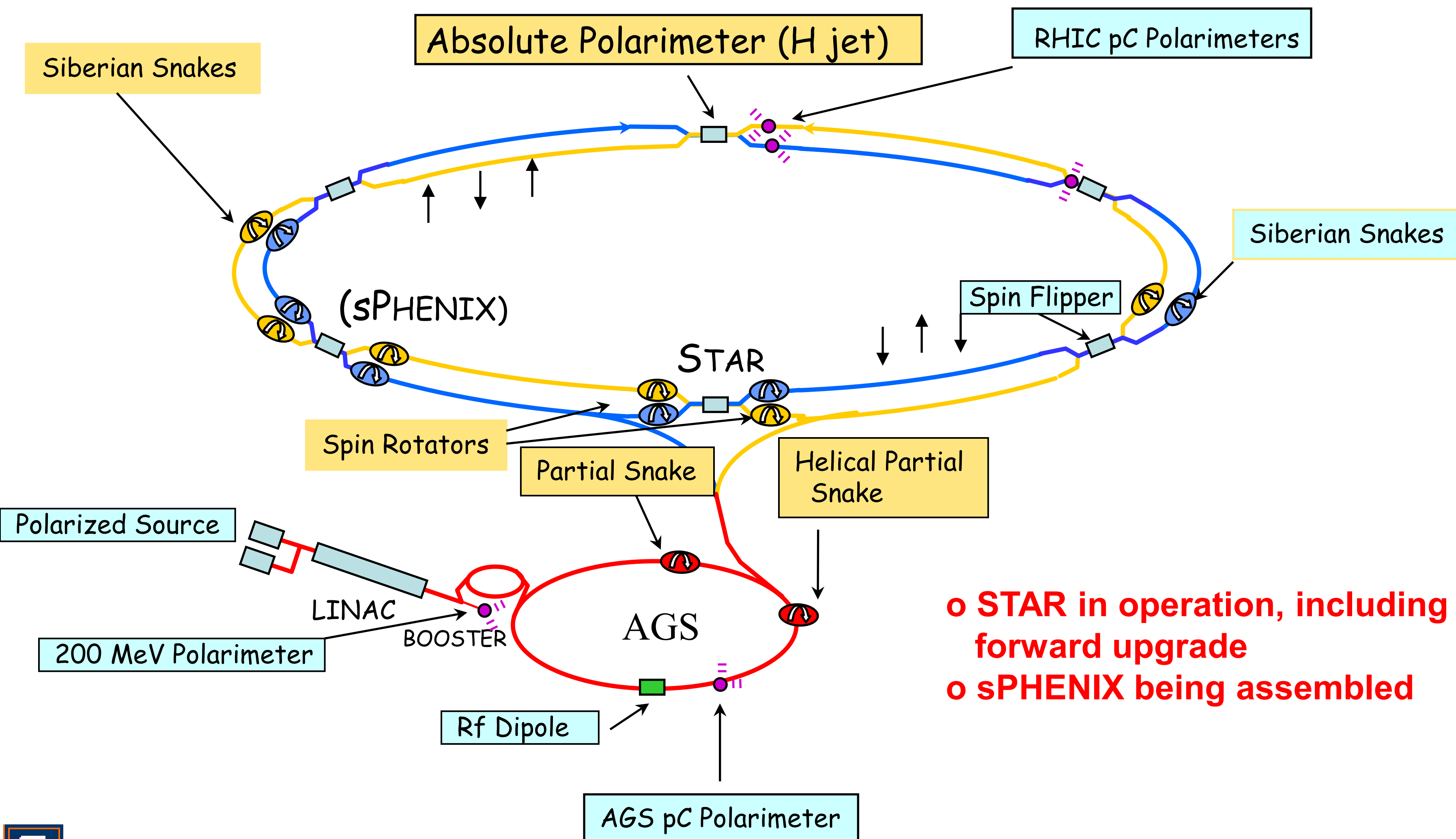
PHENIX STAR

M. Grosse Perdekamp, University of Illinois

Outline

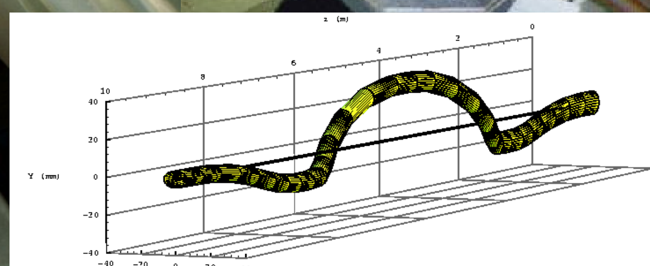
- Polarized p-p
- Observation of Large A_N and TMD Mechanisms
  - A_N of inclusive hadrons
  - A_N for forward neutrons at RHIC
- The Sivers effect
- Constraining Transversity
  - Transverse spin dependent hadron fragmentation
  - Collins in jets and di-hadrons
  - Measurements with Lambdas

Technology from a Happy Past: Polarization in RHIC as US-Japanese-Russian Technology Development



- **STAR in operation, including forward upgrade**
- **sPHENIX being assembled**

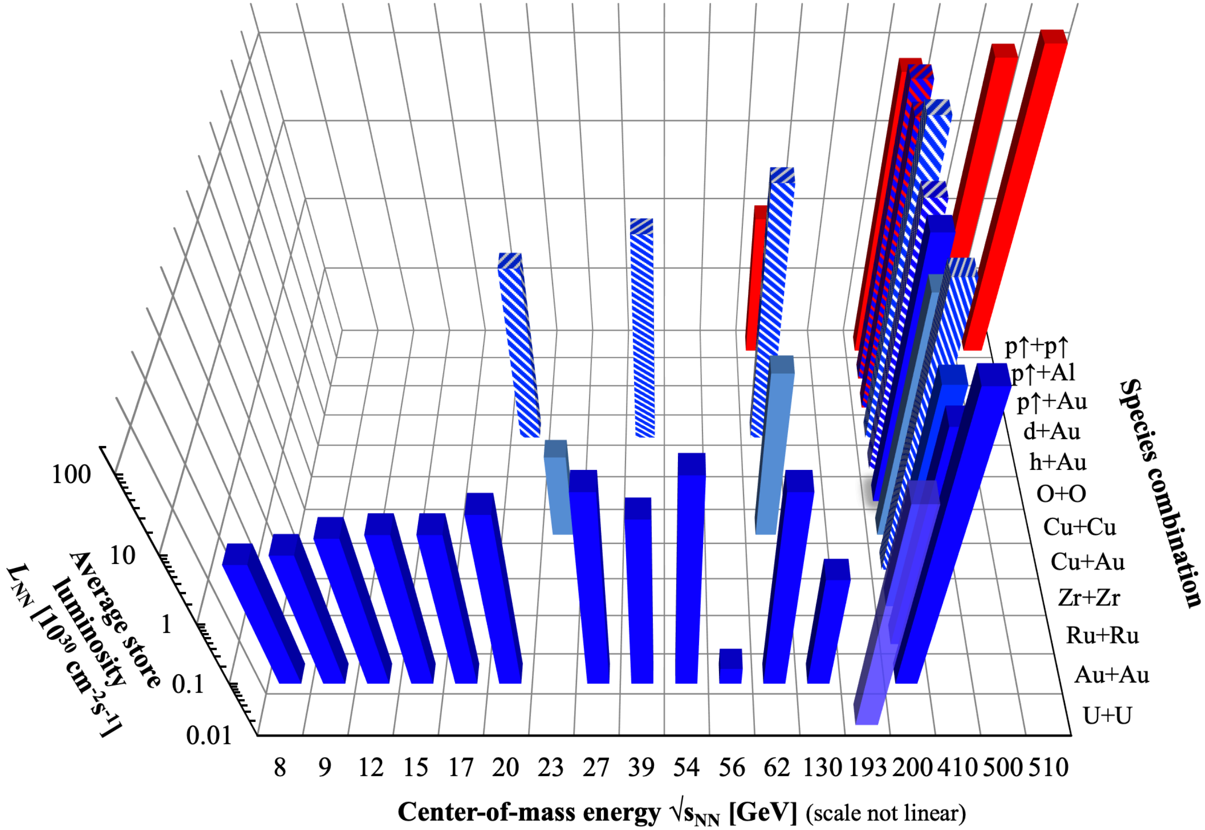
Example: Siberian Snakes



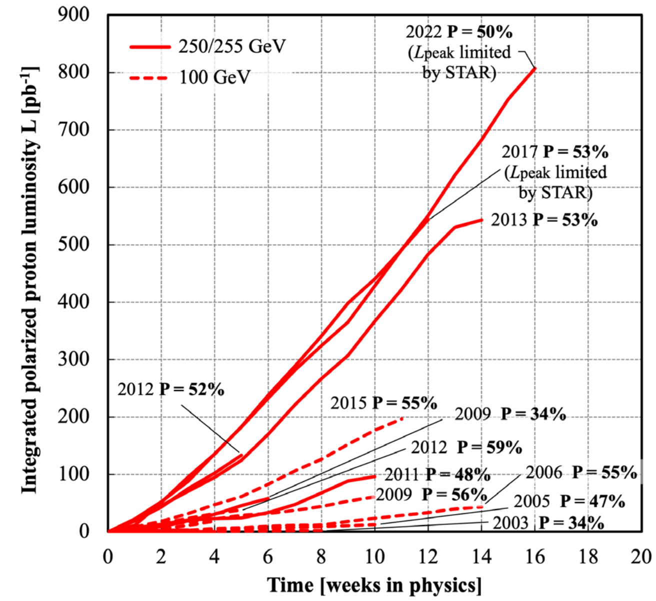
Field rotates by 180°
Snake like p-trajectories

RHIC Versatile Polarized p-p and Heavy Ion Collider

RHIC Runs 2001 to 2022
Energies – Particle Species and Luminosities

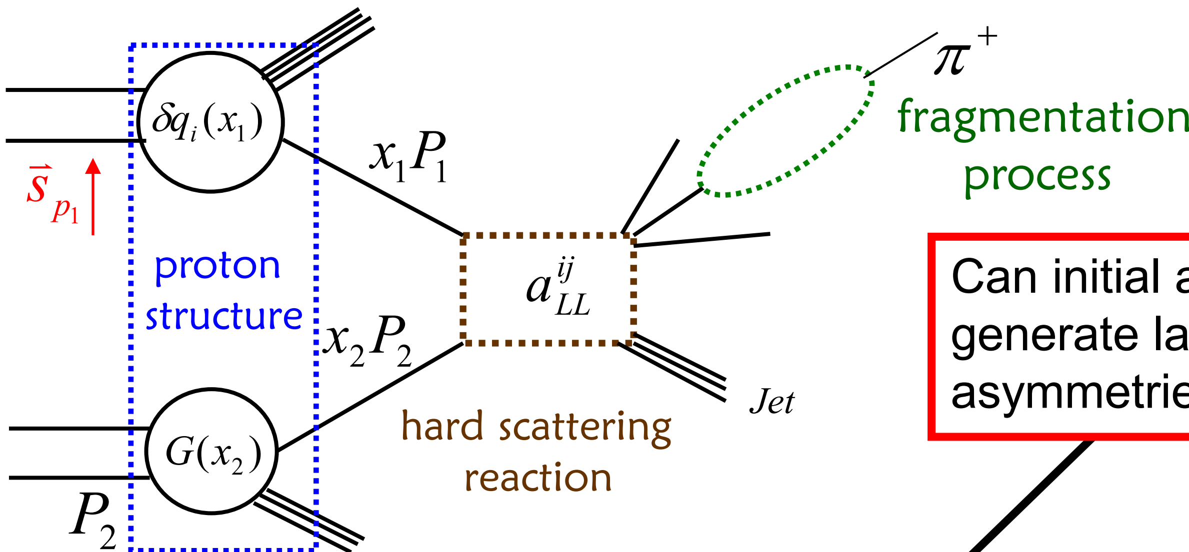


Polarized Protons:
Integrated Luminosity
vs Time



Single Transverse Spin Asymmetries A_N in Hadron-Hadron Collisions

Origin of Large SSA → Inspect Factorized Components of Cross Section



Can initial and/or final state effects generate large transverse spin asymmetries? ($A_N \sim 10^{-1}$)

pQCD

$$\frac{d^3\sigma^{\uparrow}\left(pp^{\uparrow} \rightarrow \pi^+ X\right)}{dx_1 dx_2 dz} \propto \boxed{q_i^{\uparrow}(x_1, k_{q,T}) \cdot G(x_2)} \times \boxed{\frac{d^3\hat{\sigma}^{\uparrow}(q_i q_j \rightarrow q_k q_l)}{dx_1 dx_2}} \times FF_{q_{k,l}}(z, p_{h,T})$$

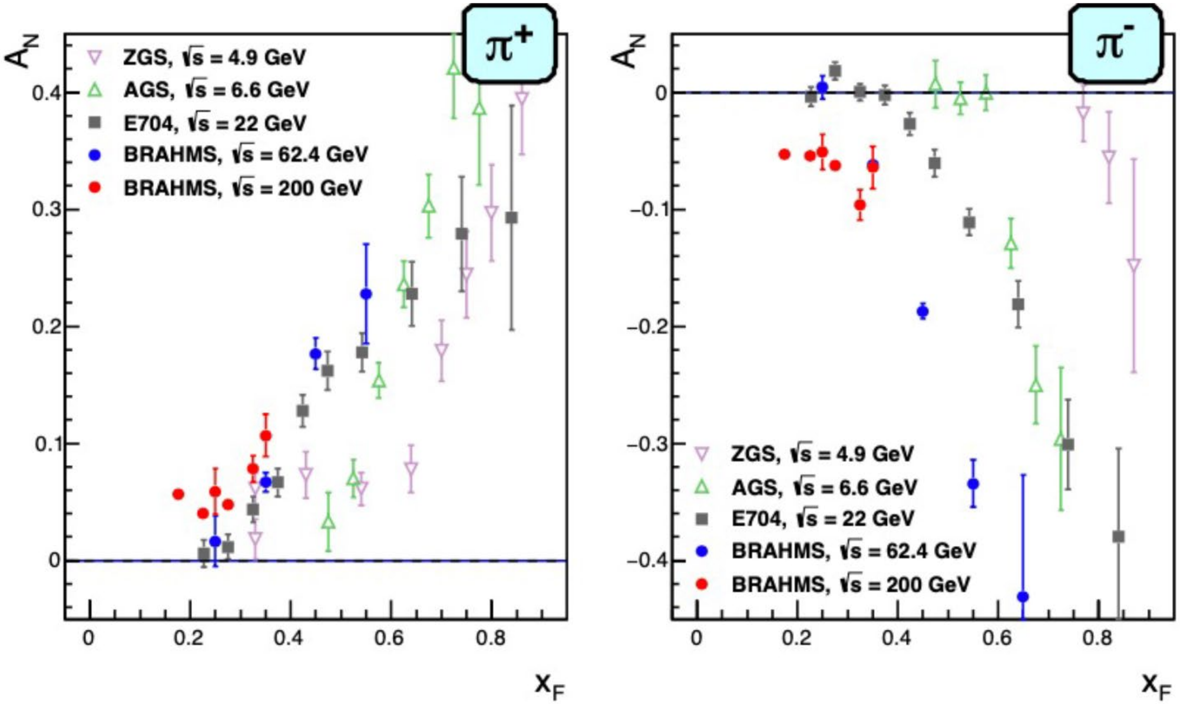
Initial state – proton structure

Kane, Pumplin, Repko → $a_{LL} \sim 10^{-4}$

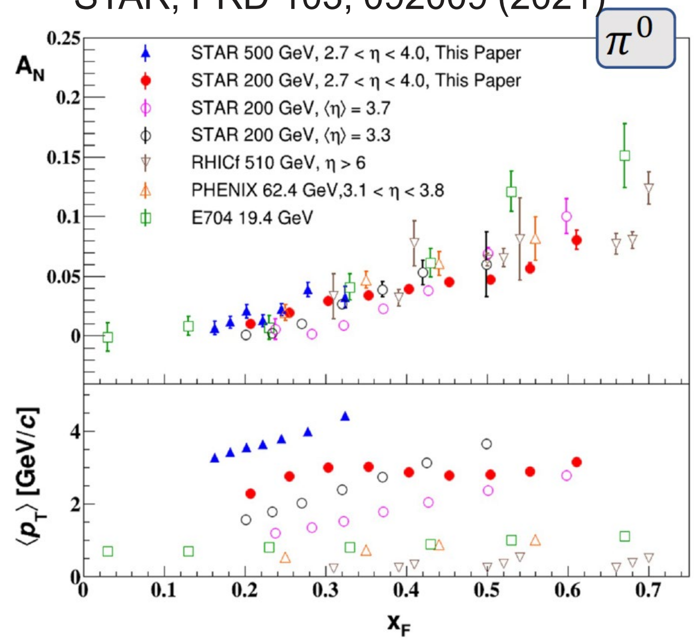
Final state – hadron fragmentation

A_N for Pions for ZGS to RHIC

RHIC Cold QCD Plan 2017-23 arXiv:1602.03922



STAR, PRD 103, 092009 (2021)



JAM fit to A_N^h

JAM, PHYSICAL REVIEW D 102, 054002 (2020)

A_N^h	$p^\uparrow + p \to (\pi^+, \pi^-, \pi^0) + X$	$h_1(x), F_{FT}(x,x) = \frac{1}{\pi} f_{1T}^{\perp(1)}(x), H_1^{\perp(1)}(z)$	$66.5/60 = 1.11$

Origin of single transverse-spin asymmetries in high-energy collisions

Justin Cammarota,[1,2,*] Leonard Gamberg,[3,†] Zhong-Bo Kang,[4,5,6,‡] Joshua A. Miller,[2,§] Daniel Pitonyak,[2,‖] Alexei Prokudin,[3,7,¶] Ted C. Rogers,[7,8,**] and Nobuo Sato[7,††]

(Jefferson Lab Angular Momentum (JAM) Collaboration)

Observable	Reactions	Nonperturbative function(s)	$\chi^2/N_{\mathrm{pts.}}$	Refs.
$A_{\mathrm{SIDIS}}^{\mathrm{Siv}}$	$e + (p,d)^\uparrow \to e + (\pi^+, \pi^-, \pi^0) + X$	$f_{1T}^\perp(x, k_T^2)$	$150.0/126 = 1.19$	[65,66,68]
$A_{\mathrm{SIDIS}}^{\mathrm{Col}}$	$e + (p,d)^\uparrow \to e + (\pi^+, \pi^-, \pi^0) + X$	$h_1(x, k_T^2), H_1^\perp(z, z^2 p_\perp^2)$	$111.3/126 = 0.88$	[66,68,71]
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$A_{\mathrm{DY}}^{\mathrm{Siv}}$	$\pi^- + p^\uparrow \to \mu^+\mu^- + X$	$f_{1T}^\perp(x, k_T^2)$	$5.96/12 = 0.50$	[73]
$A_{\mathrm{DY}}^{\mathrm{Siv}}$	$p^\uparrow + p \to (W^+, W^-, Z) + X$	$f_{1T}^\perp(x, k_T^2)$	$31.8/17 = 1.87$	[72]
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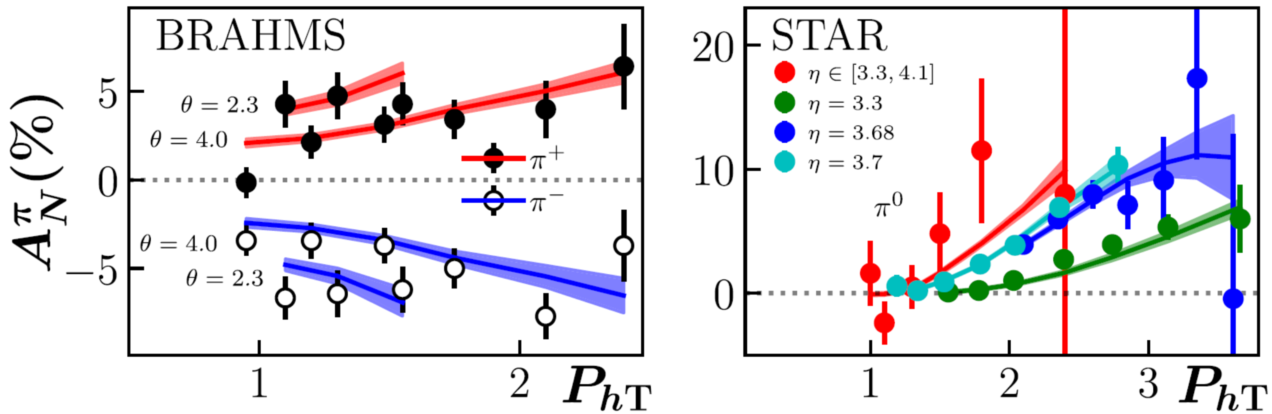
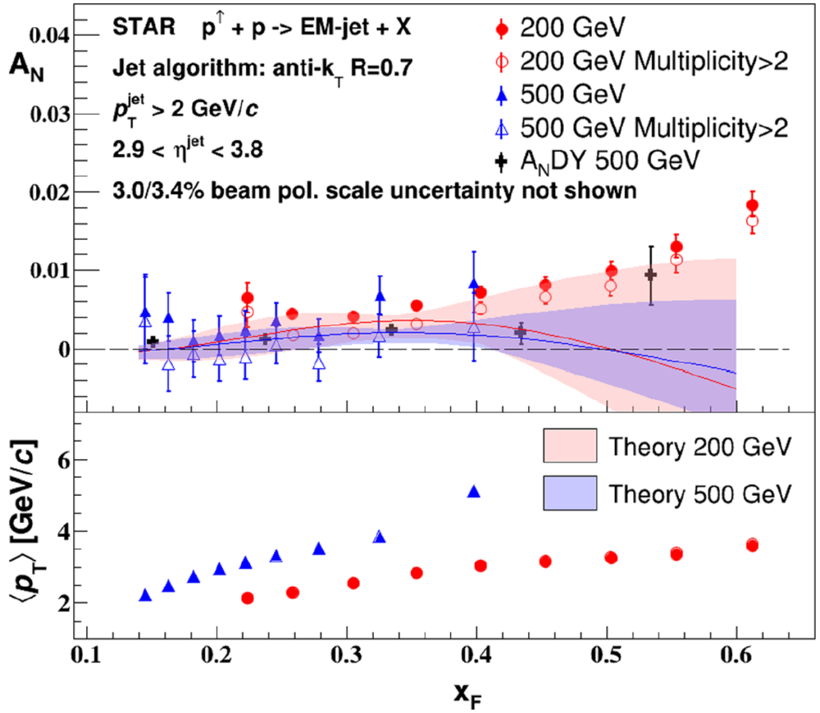


A_N : inclusive Jets, inclusive π^0s, isolated π^0s, Collins π^0s

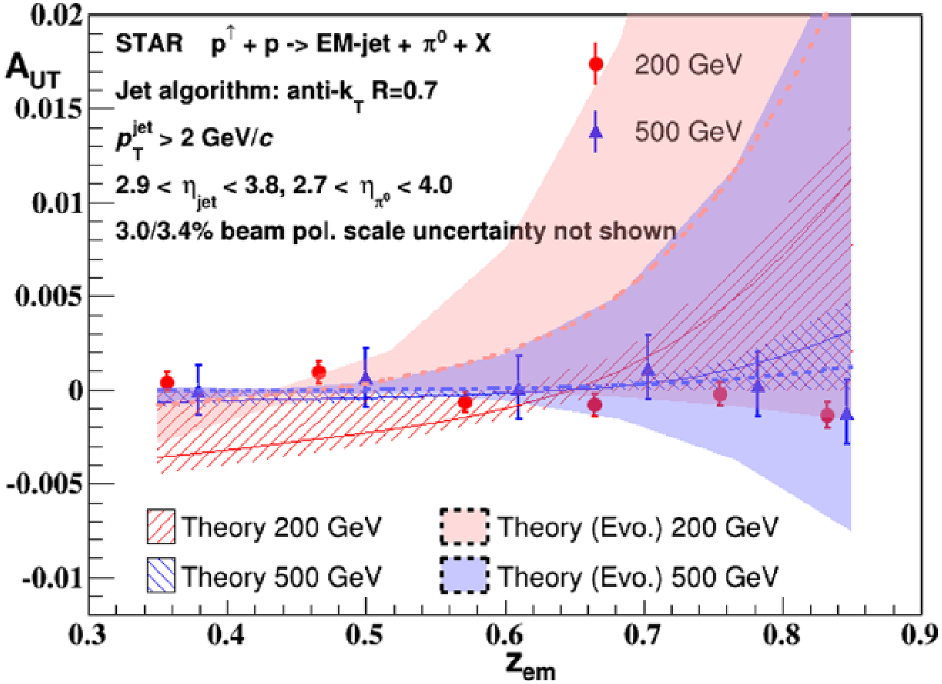
STAR PRD 103, 092009 (2021)

STAR A_N^{jet}(EM) is small
-> small Sivers contribution



Compare different final state topologies to discriminate between different mechanisms leading to SSA

STAR Collins for π^0s in jets is small
-> small Collins ?

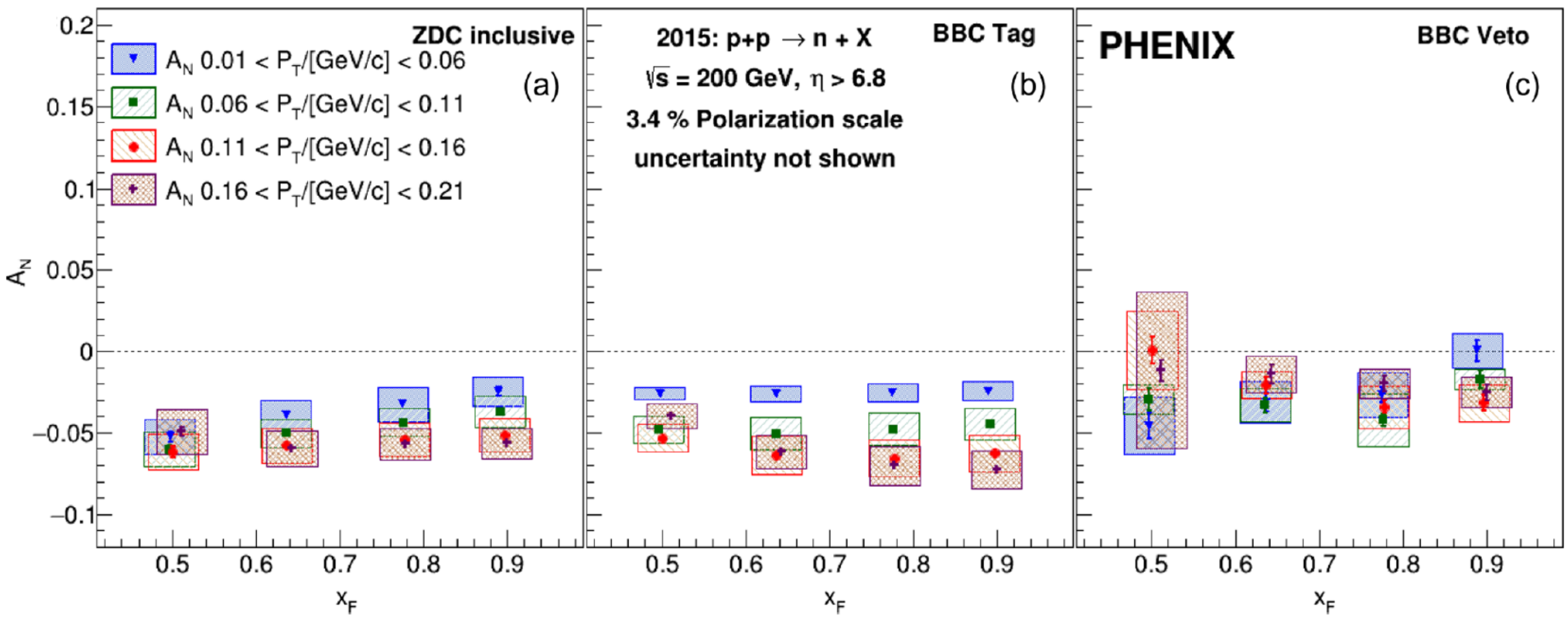


limitations from EM-Jets: resolution of jet-axis fluctuations
➔ STAR 2022 run + forward upgrades

A_N for neutrons , $\eta > 6.8$

PHENIX PRD 105, 032004 (2022)

Compare samples with enhanced UPC (BBC veto) to events with lower UPC contributions (BBC Tag)



A_N for neutrons , $\eta>6.8$

PHENIX PRD 105, 032004 (2022)

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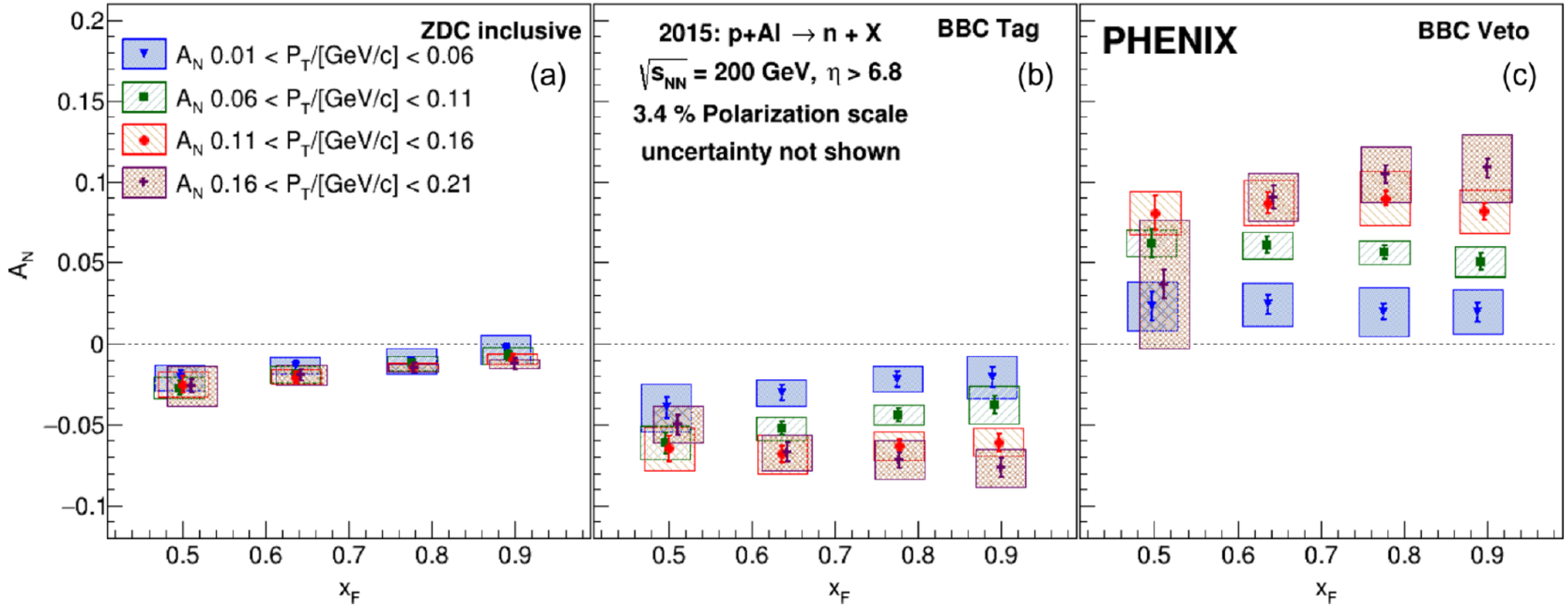

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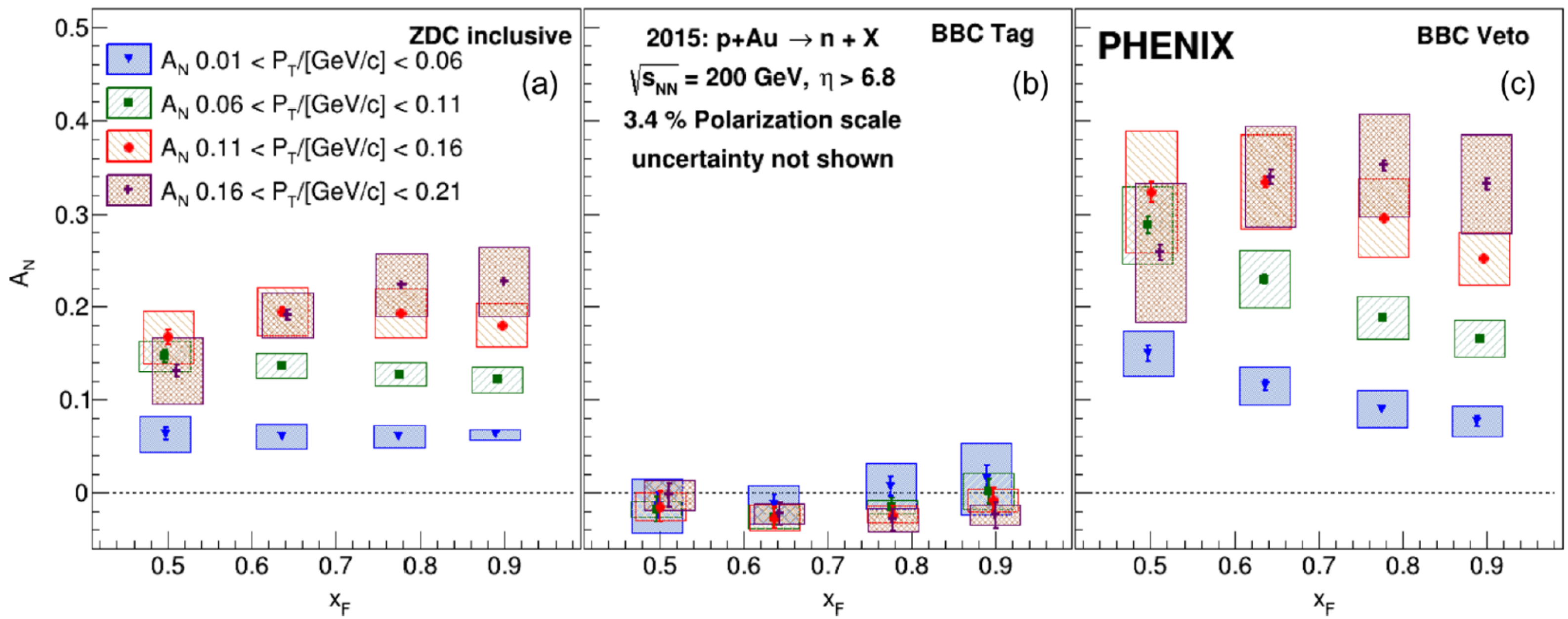

Competing mechanisms contributing to A_N !

The Sivers Effect in h-h Collisions

Constraining Sivers Functions

JAM, PHYSICAL REVIEW D 102, 054002 (2020)

Origin of single transverse-spin asymmetries in high-energy collisions

Justin Cammarota,[1,2,*] Leonard Gamberg,[3,†] Zhong-Bo Kang,[4,5,6,‡] Joshua A. Miller,[2,§] Daniel Pitonyak,[2,∥] Alexei Prokudin,[3,7,¶] Ted C. Rogers,[7,8,**] and Nobuo Sato[7,††]

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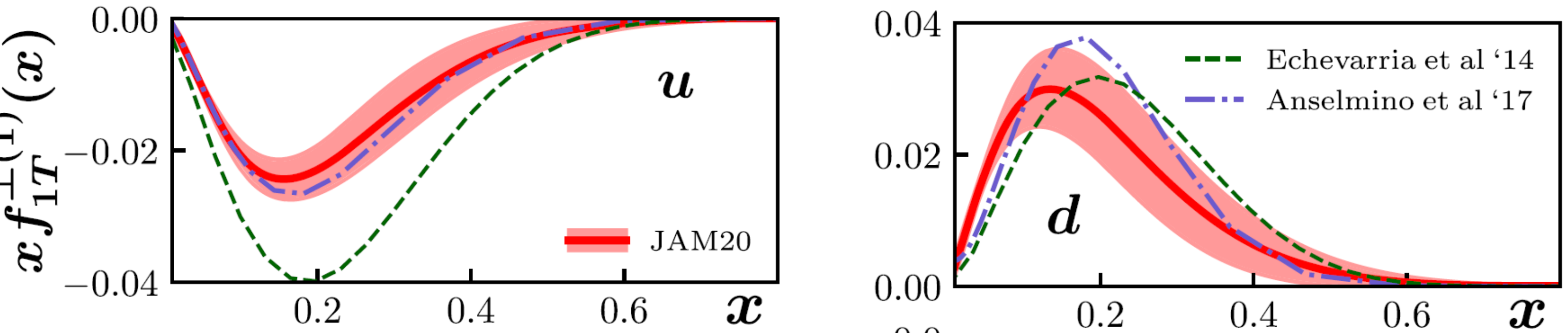
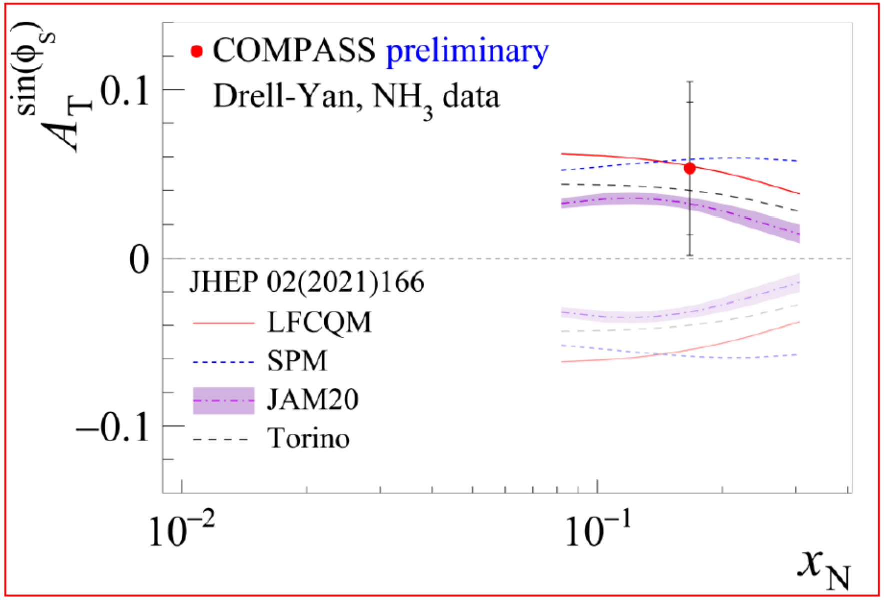


Sign Change of Sivers-Function Between SIDIS and Drell-Yan

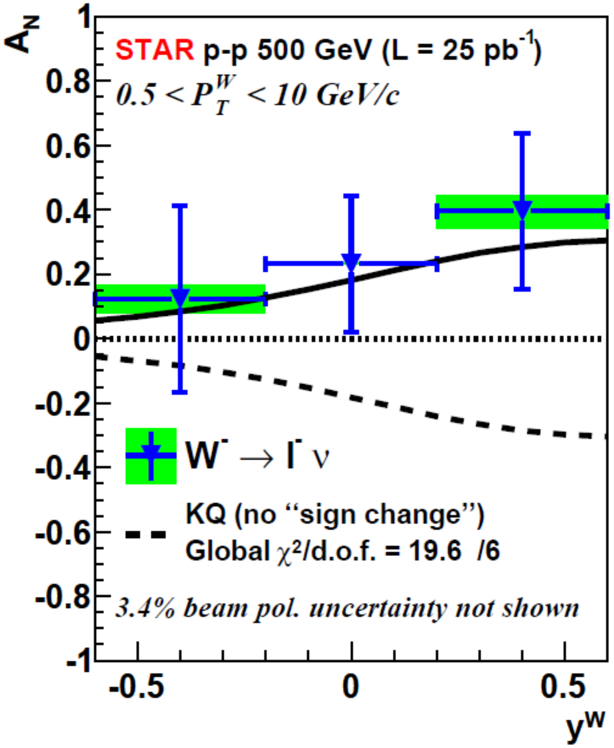
COMPASS 2015+2018 π-p Drell-Yan

DIS 2022: Bakur Parsamyan



STAR W-> lν

PRL, 116, 132301 (2016)



Sign Change preferred,
also compatible with zero.
Data taking complete.

More data to come!!

Constraining Transversity

Knowledge of Transversity and Tensor Charge Requires Measurements in p-p, lepton-p and e^+e^-

SIDIS

~ $\delta q(x)$ x $CFF(z)$

~ $\delta q(x)$ x $IFF(z)$

e^+e^-

~ $CFF(z_1)$ x $CFF(z_2)$

~ $IFF(z_1)$ x $IFF(z_2)$

pp → jets

~ $G(x_1) x \delta q(x_2)$ x $CFF(z)$

pp → $h^+ + h^- + X$

~ $G(x_1) x \delta q(x_2)$ x $IFF(z)$

pp → Λ + X

~ $G(x_1)$ x $\delta q(x_2)$ x $\Lambda FF(z)$

Transversity, $\delta q(x)$
Tensor Charge

Theory

Lattice QCD: Tensor Charge = $\Sigma_{q=u,d}\int_0^1 \delta q(x)dx$

Constraining Transversity & Collins

JAM, PHYSICAL REVIEW D 102, 054002 (2020)

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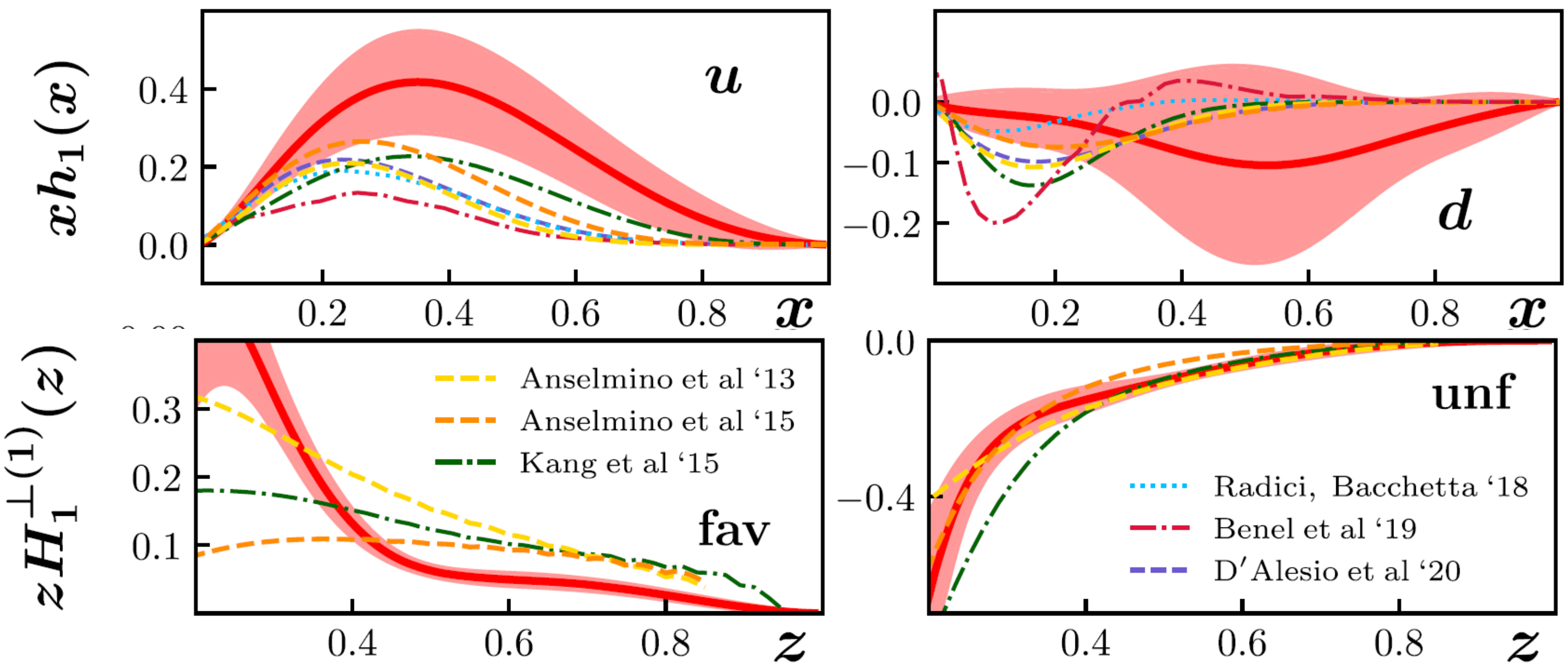


Constraining the Tensor Charge

JAM, PHYSICAL REVIEW D 102, 054002 (2020)

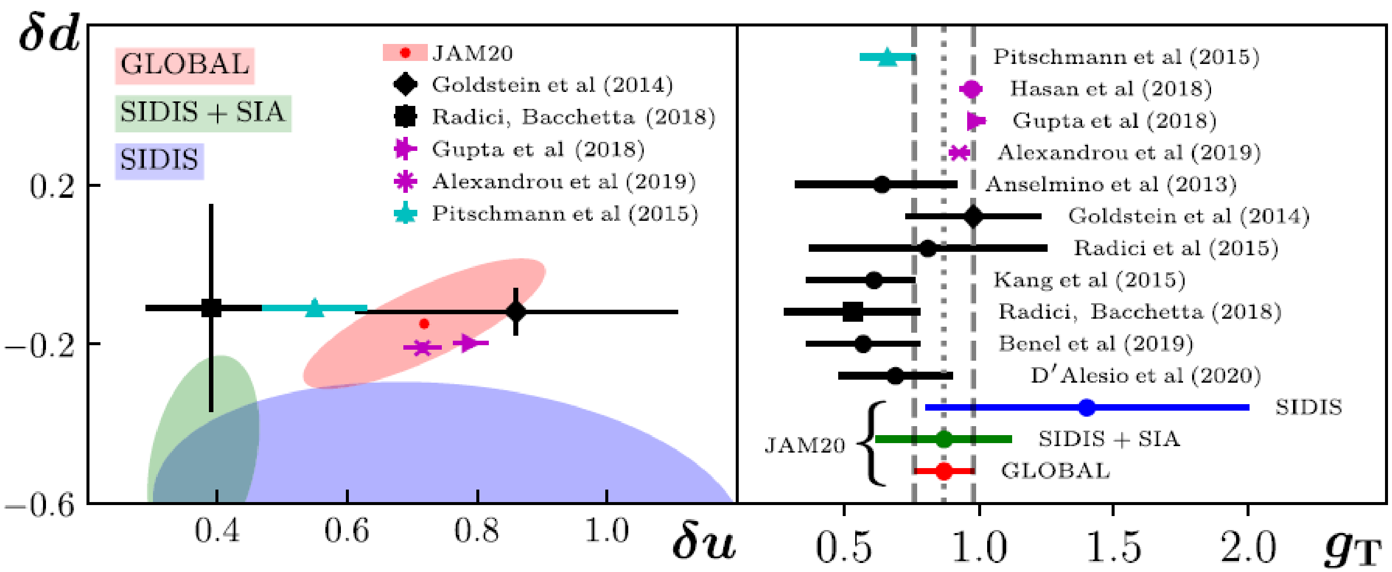
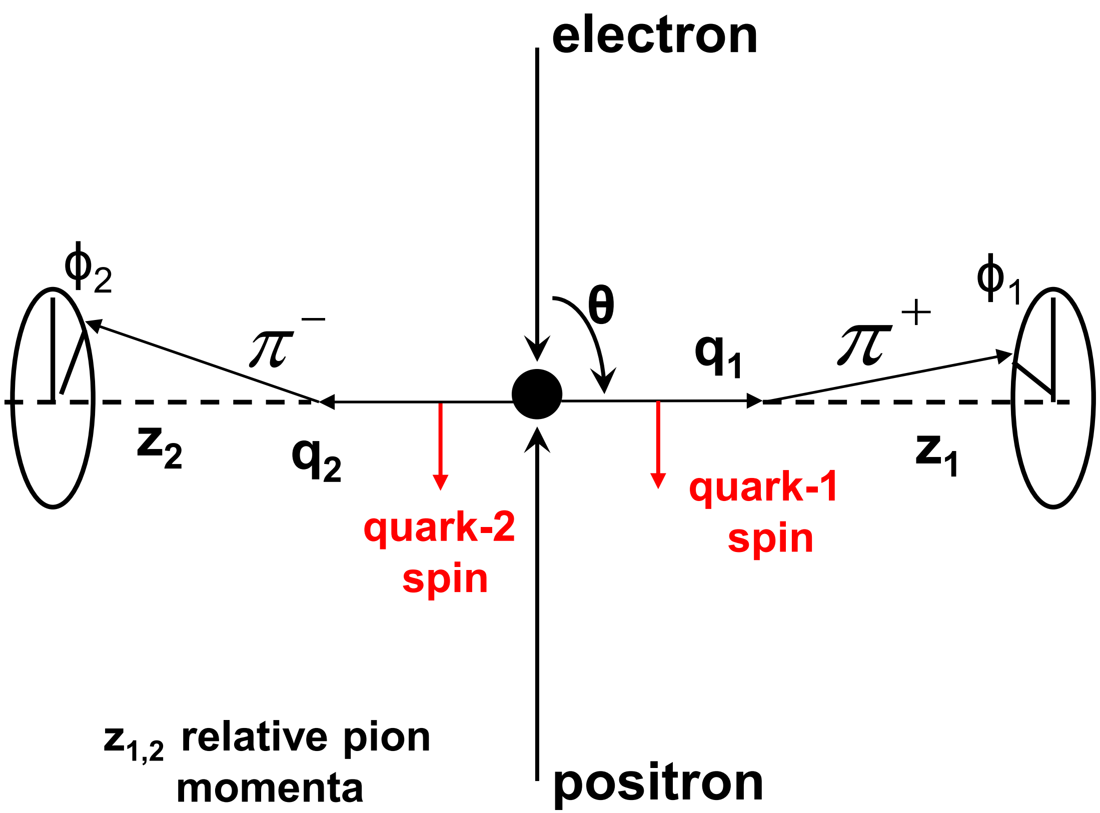


FIG. 6. The tensor charges δu, δd, and g_T. Our (JAM20) results at $Q^2 = 4\ \mathrm{GeV}^2$ along with others from phenomenology (black), lattice QCD (purple), and Dyson-Schwinger (cyan).

Collins Effect in di-Hadron Correlations In e^+e^- Annihilation into Quarks!



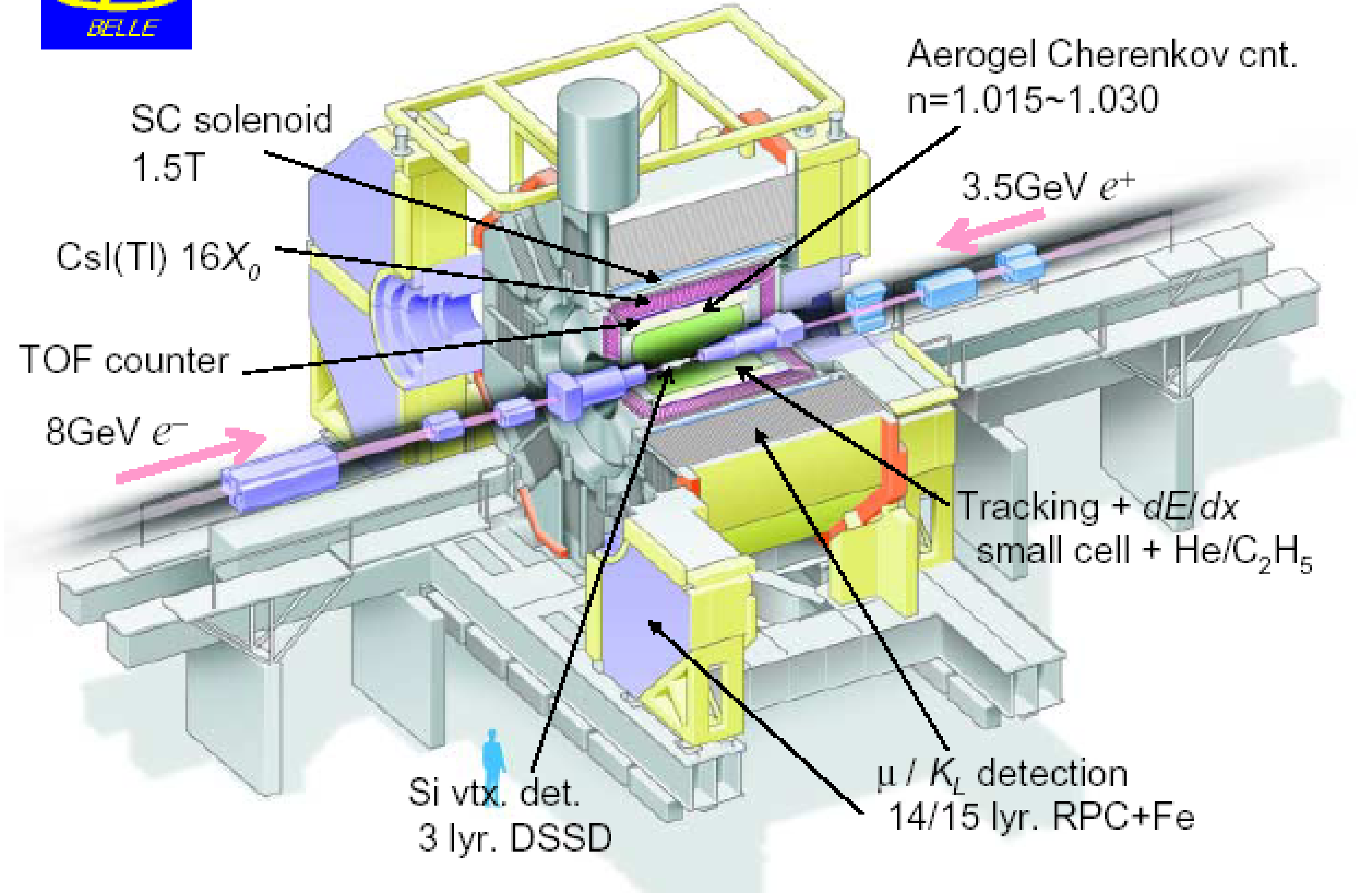
Collins effect in e^+e^- quark fragmentation will lead to azimuthal asymmetries in di-hadron correlation measurements:

$$N_{\pi_1,\pi_2}(\phi_1+\phi_2) \sim a_{12}\cos(\phi_1+\phi_2)$$

Experimental requirements:

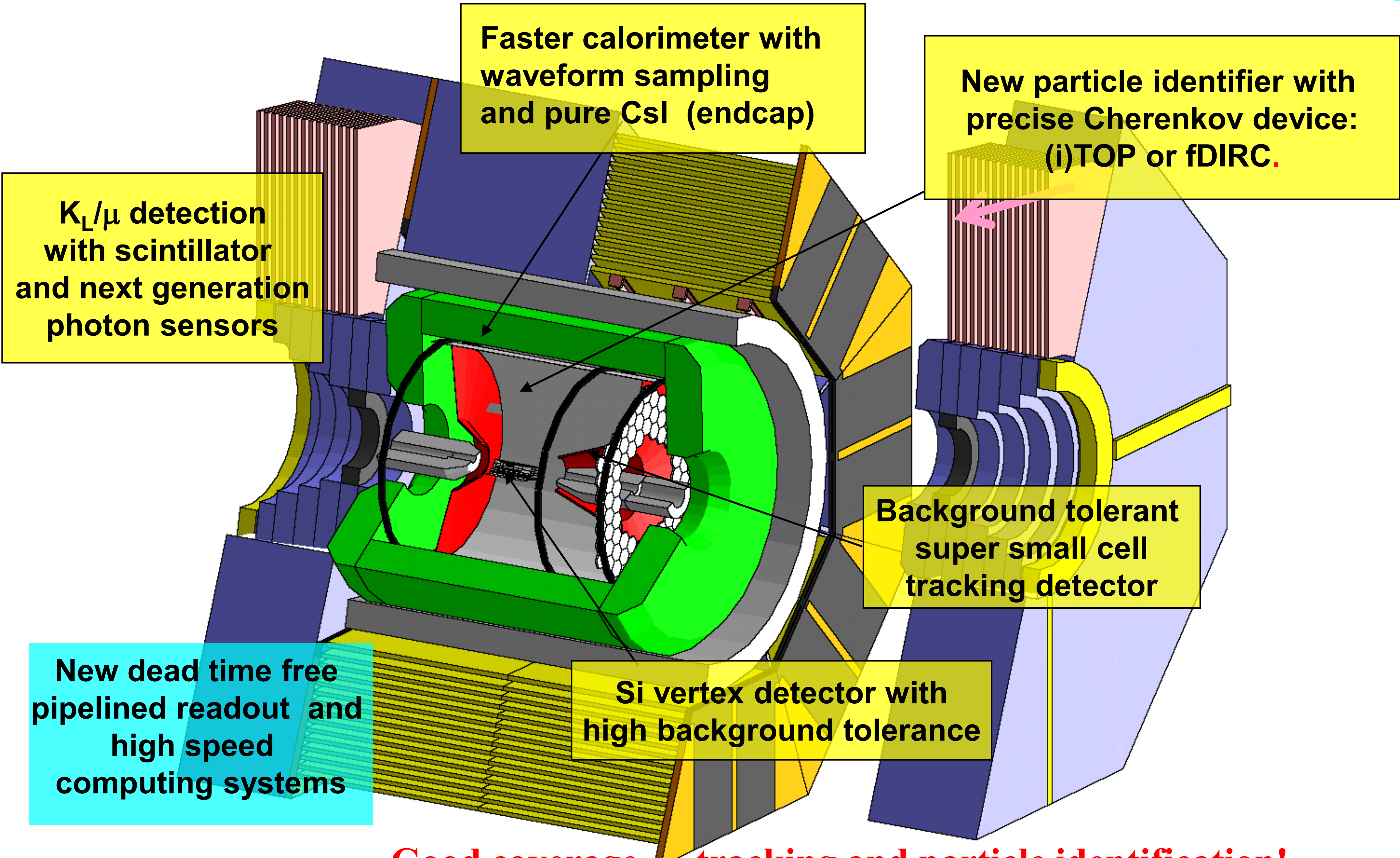
- Small asymmetries ➔ very large data sample!
- Good particle ID to high momenta.
- Hermetic detector
- Events with back-to-back jets

Belle Detector



Good coverage, tracking and particle identification!

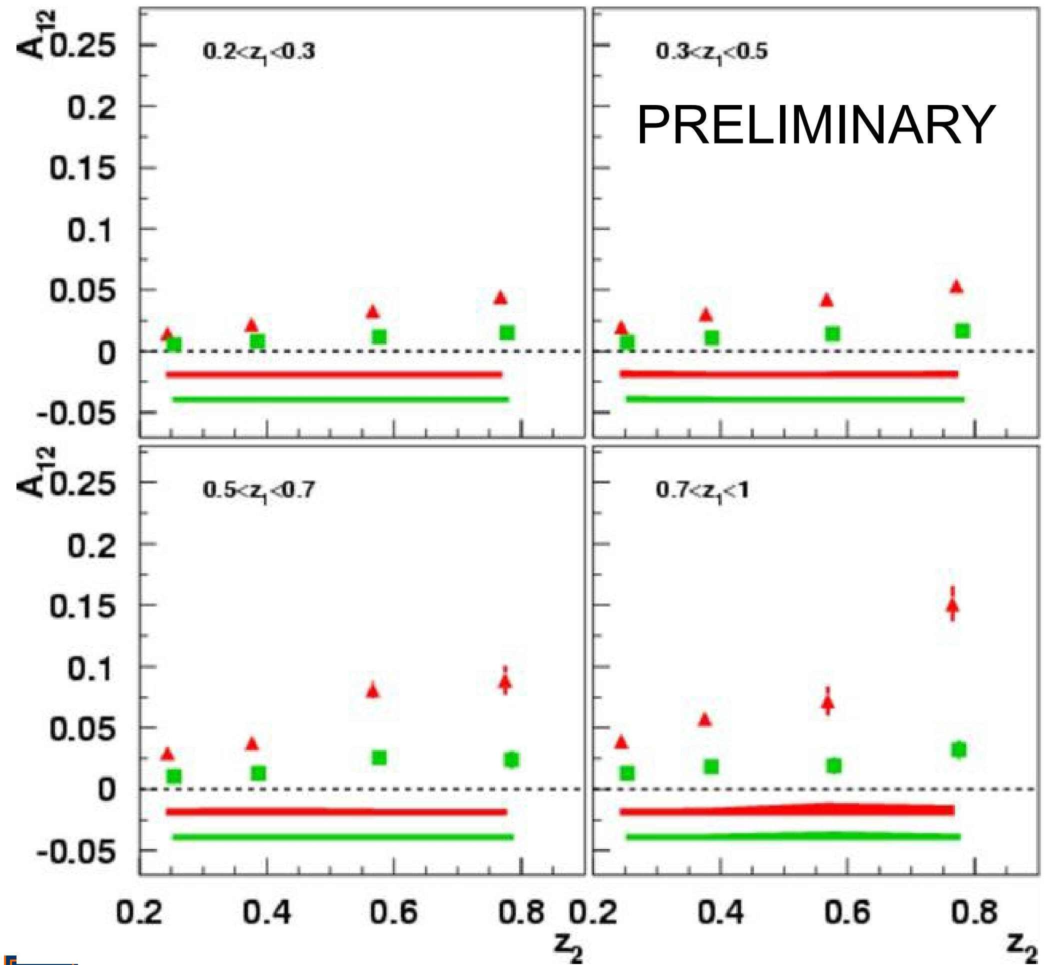
Super Belle: detector for SuperKEKB



Good coverage, tracking and particle identification!

Observation of the Collins Effect in e^+e^- Annihilation with Belle

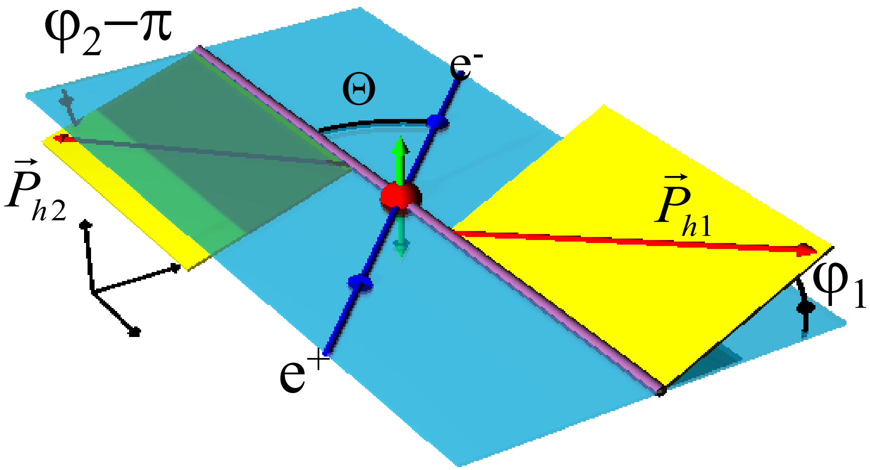
R. Seidl, Belle, Phys.Rev.Lett. 96 (2006) 232002



Collins Asymmetries in e^+e^- annihilation into hadrons

$$e^+ + e^- \rightarrow \pi^+ + \pi^- + X$$

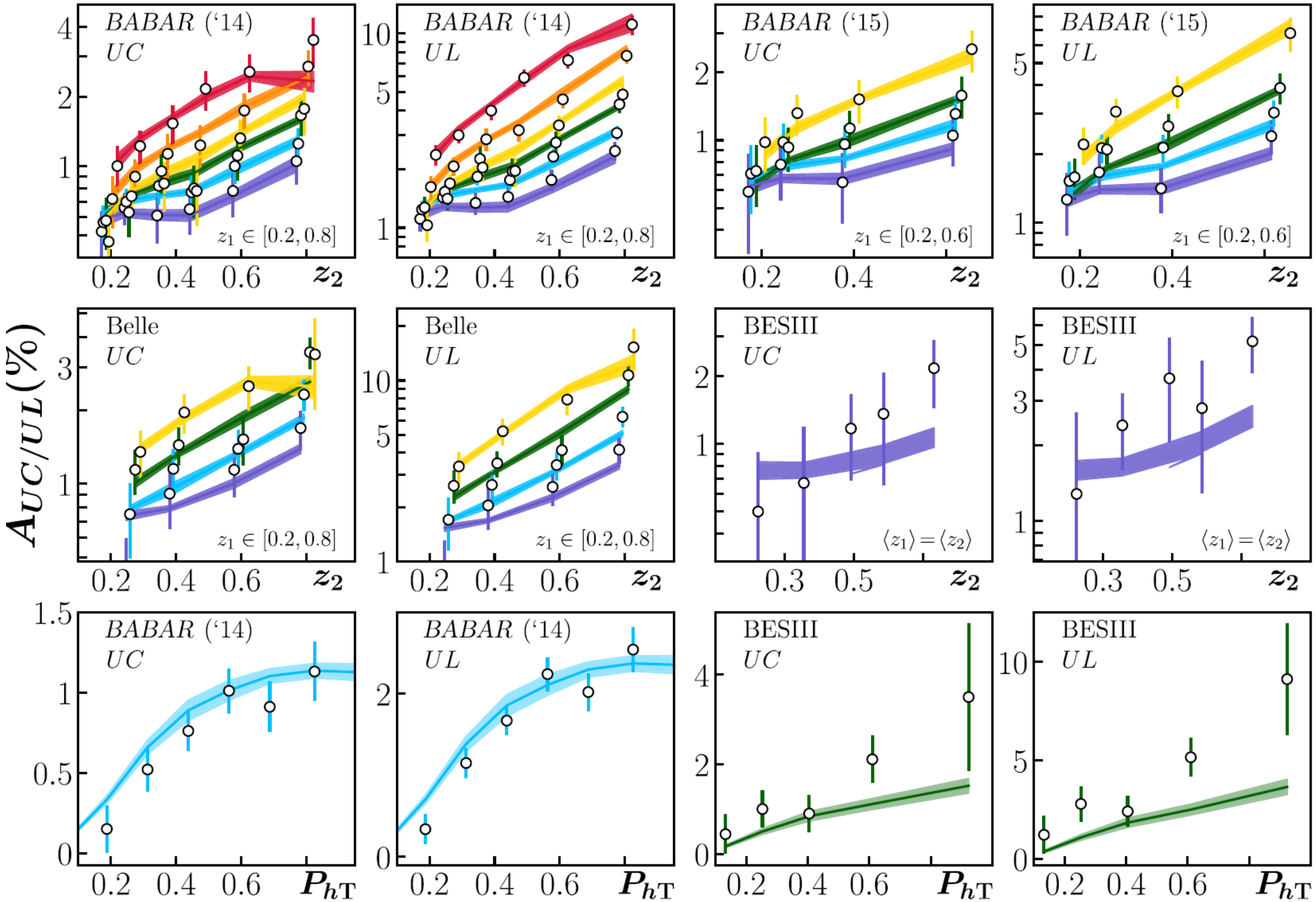
~ *Collins(z_1) x Collins (z_2)*



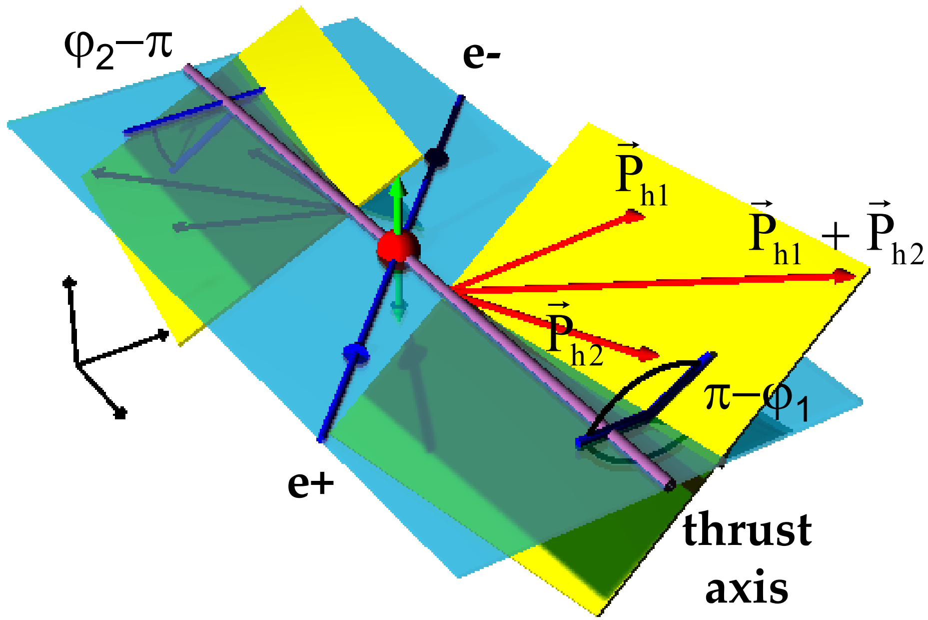
$A_{12} \cos(\phi_1 + \phi_2)$

JAM fit to e+e- JAM, PHYSICAL REVIEW D 102, 054002 (2020)

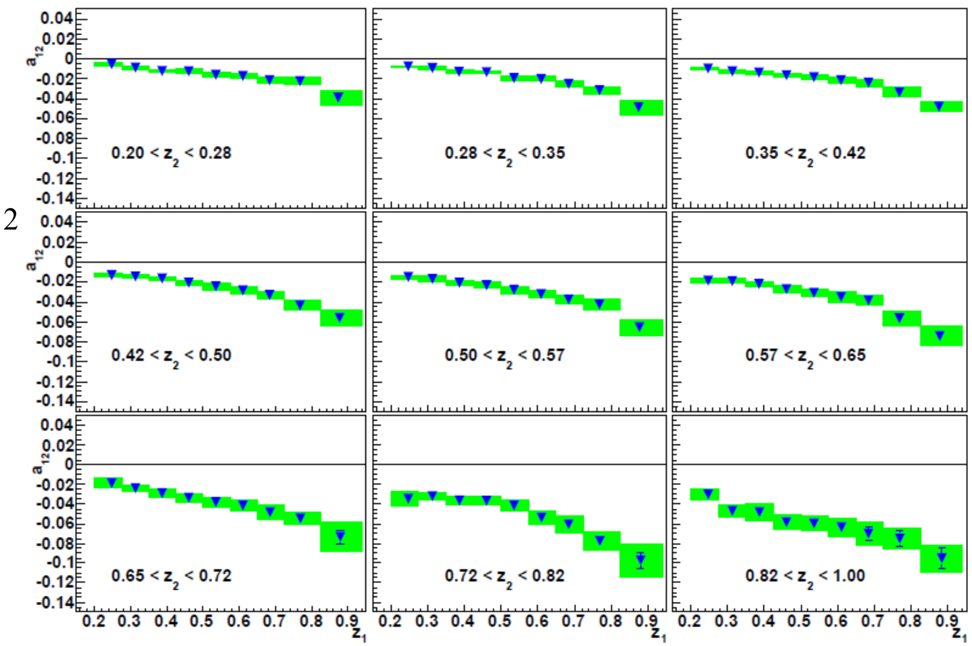
$A_{\mathrm{SIA}}^{\mathrm{Col}}$	$e^+ + e^- \to \pi^+\pi^-(UC, UL) + X$	$H_1^\perp(z, z^2 p_\perp^2)$	$154.5/176 = 0.88$



IFF measurement at BELLE



A. Vossen, Belle, Phys. Rev. Lett. 107(2011)



$$e^+e^- \rightarrow (\pi^+\pi^-)_{jet1}(\pi^+\pi^-)_{jet2}X$$

$$A \propto H_1^{\sphericalangle}(z_1, m_1)H_1^{\sphericalangle}(z_2, m_2)\cos(\phi_1+\phi_2)$$

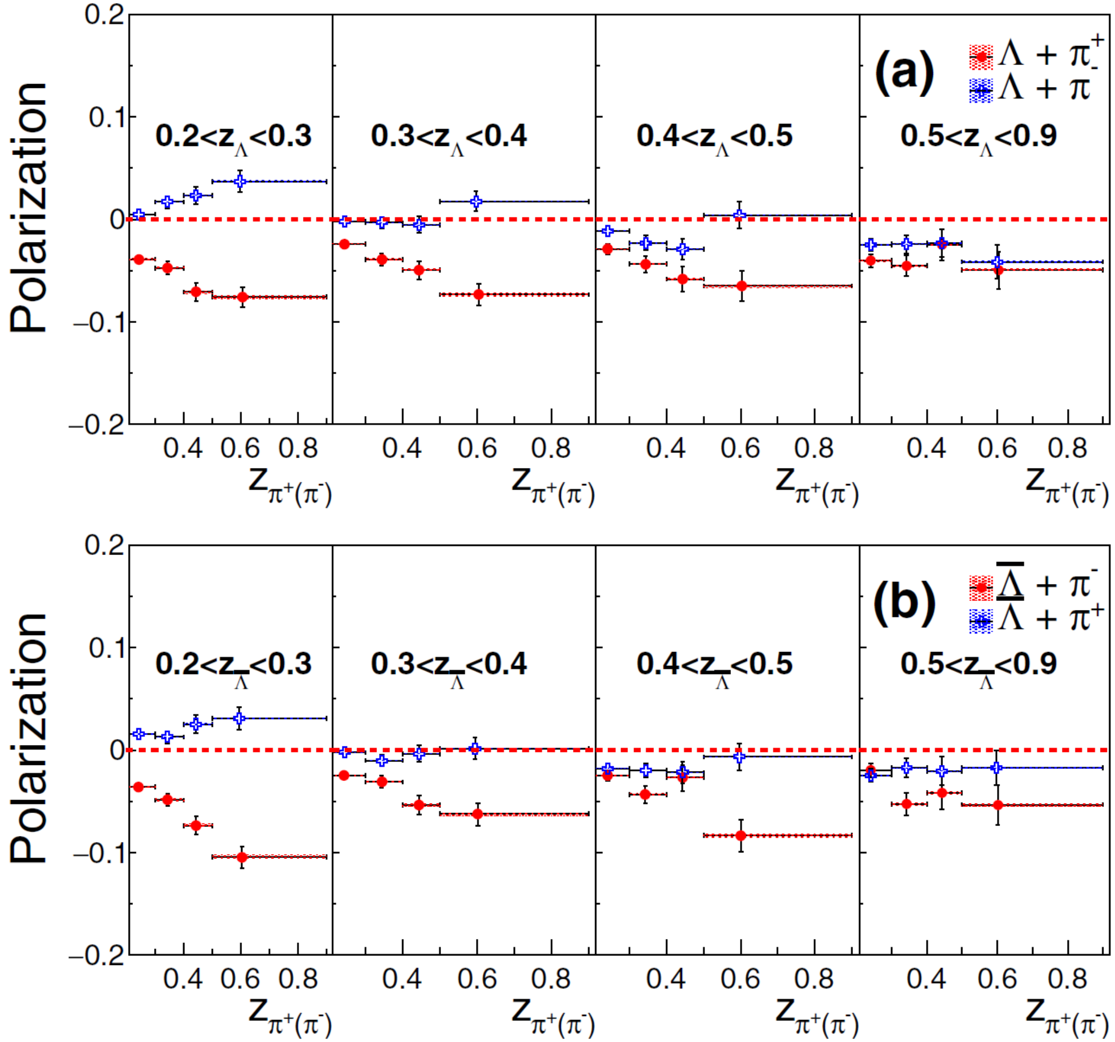
Artru and Collins, *Z. Phys. C69, 277 (1996)*

Boer, Jakob, and Radici, PRD67, 094003 (2003)

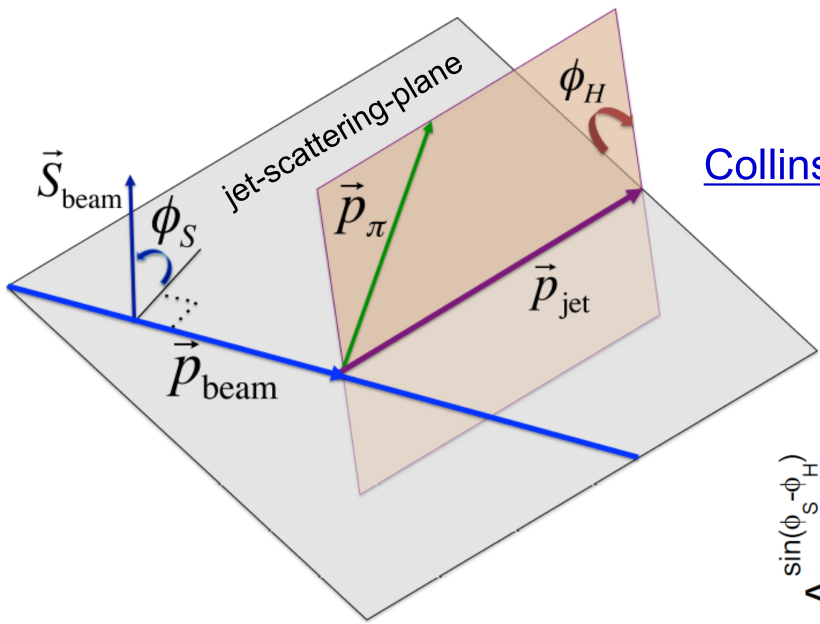
No double ratios needed to cancel radiative and acceptance effects!

Observation of Lambda Polarization in e^+e^- Annihilation with Belle

Y. Guan, Belle PRL 122, 042001 (2019)

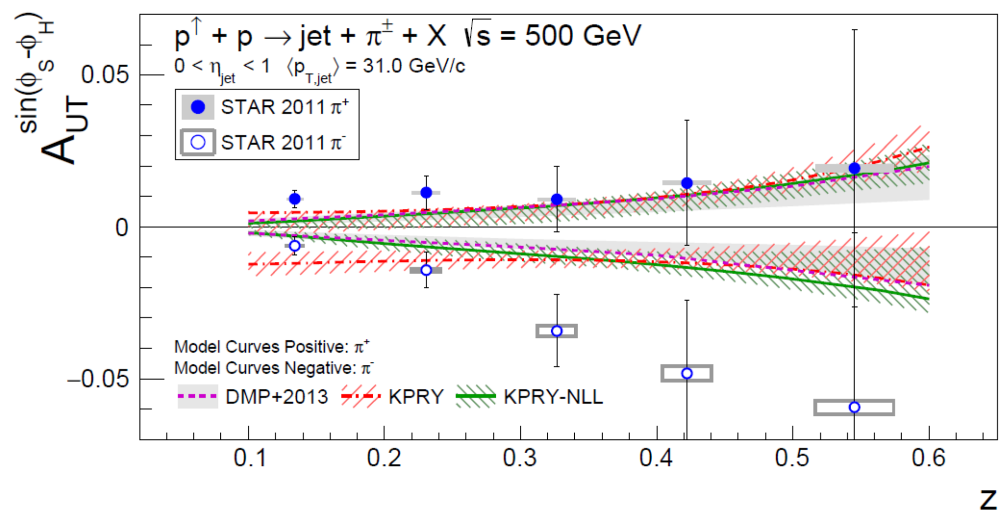


STAR: Collins in jets – 500 GeV



$$d\sigma^{\uparrow}(\phi_S,\phi_H) - d\sigma^{\downarrow}(\phi_S,\phi_H)$$
$$\sim d\Delta\sigma_0 \sin(\phi_S) \text{ Sivers}$$
$$\text{Collins } + d\Delta\sigma_1^{-}\sin(\phi_S-\phi_H) + d\Delta\sigma_1^{+}\sin(\phi_S+\phi_H)$$
$$+ d\Delta\sigma_2^{-}\sin(\phi_S-2\phi_H) + d\Delta\sigma_2^{+}\sin(\phi_S+2\phi_H)$$

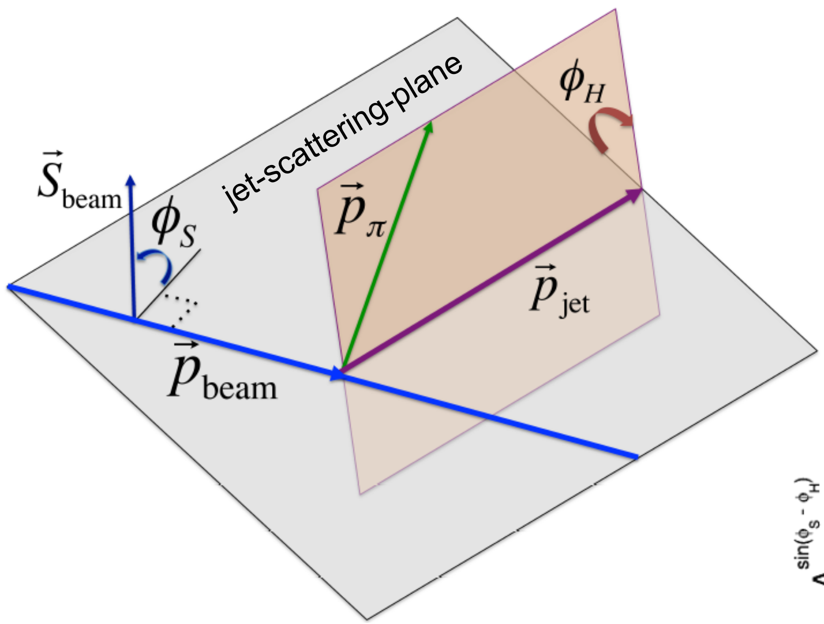
Charged pion Collins-modulations in jets



First measurement of Collins effect in jets!

STAR, Phys.Rev. D97 (2018) no.3, 032004

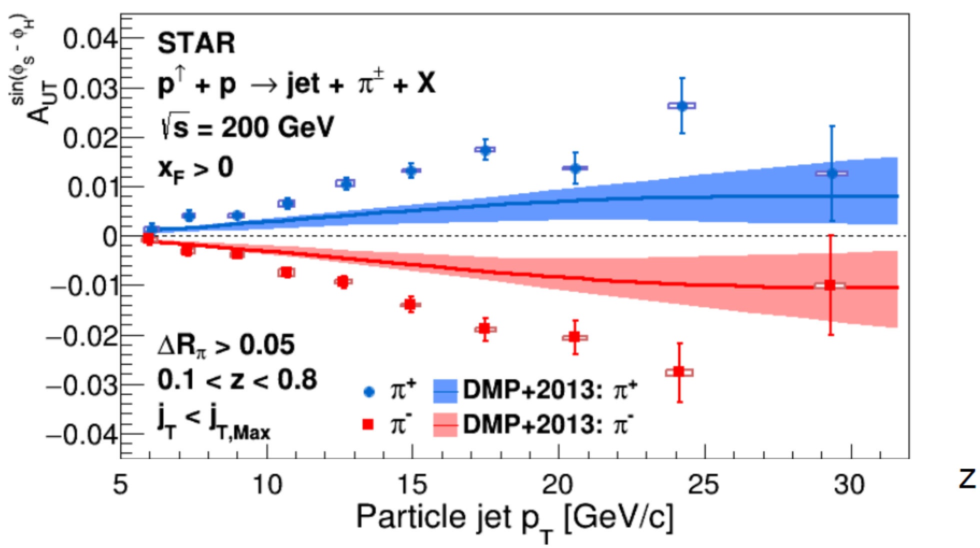
STAR: Collins in Jets – 200 GeV



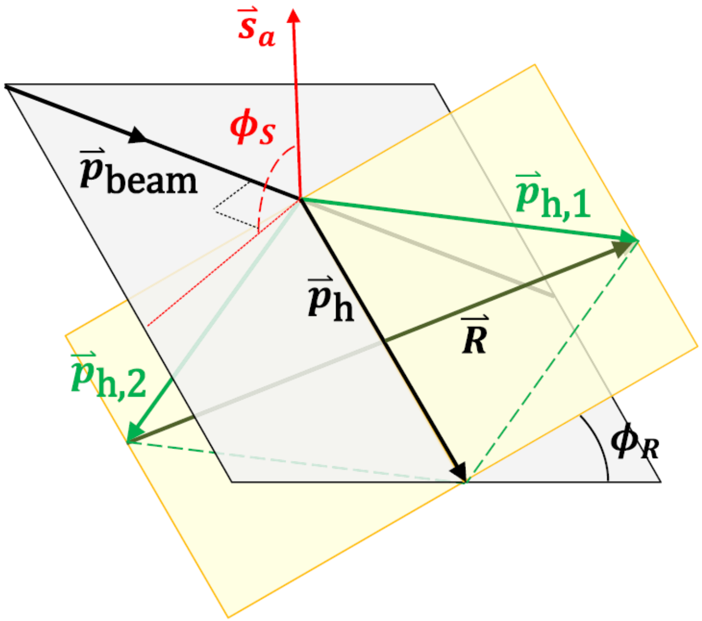
Runs 2012+2015, 200 GeV
Collins in Jets

Ting Lin, STAR, DIS 2022

Charged pion Collins-modulations in jets

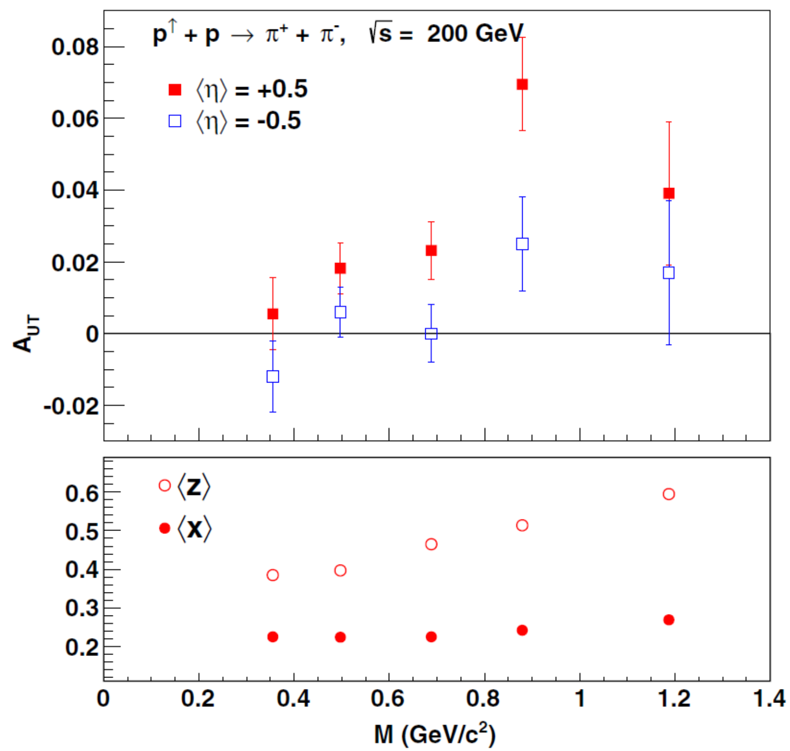


STAR: First IFF – 200 GeV



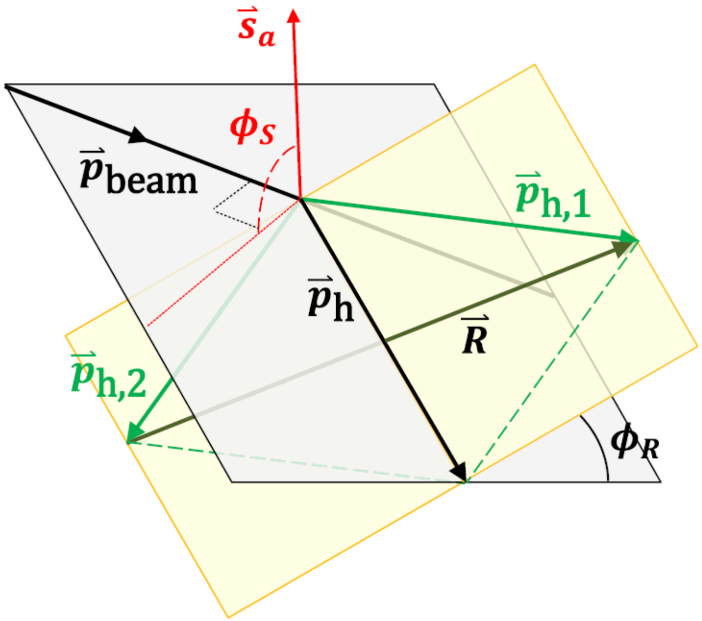
STAR PRL 115, 242501 (2015)

IFF – pion pairs vs invariant mass



First measurement of IFF at 200 GeV!

STAR: High Statistics IFF – 200 GeV



Navagyan Ghimire, STAR DIS 2022

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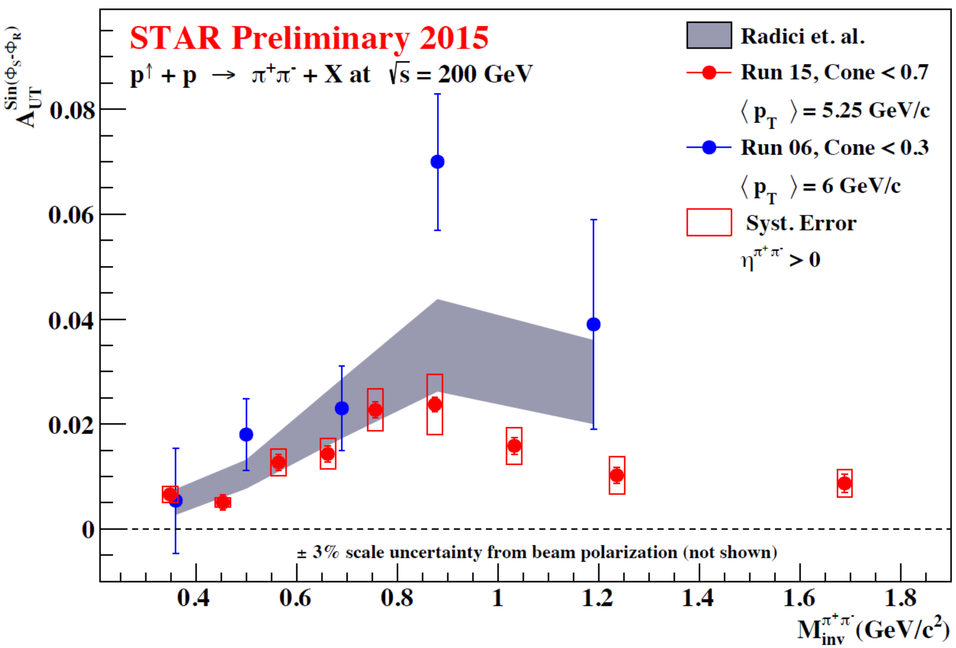
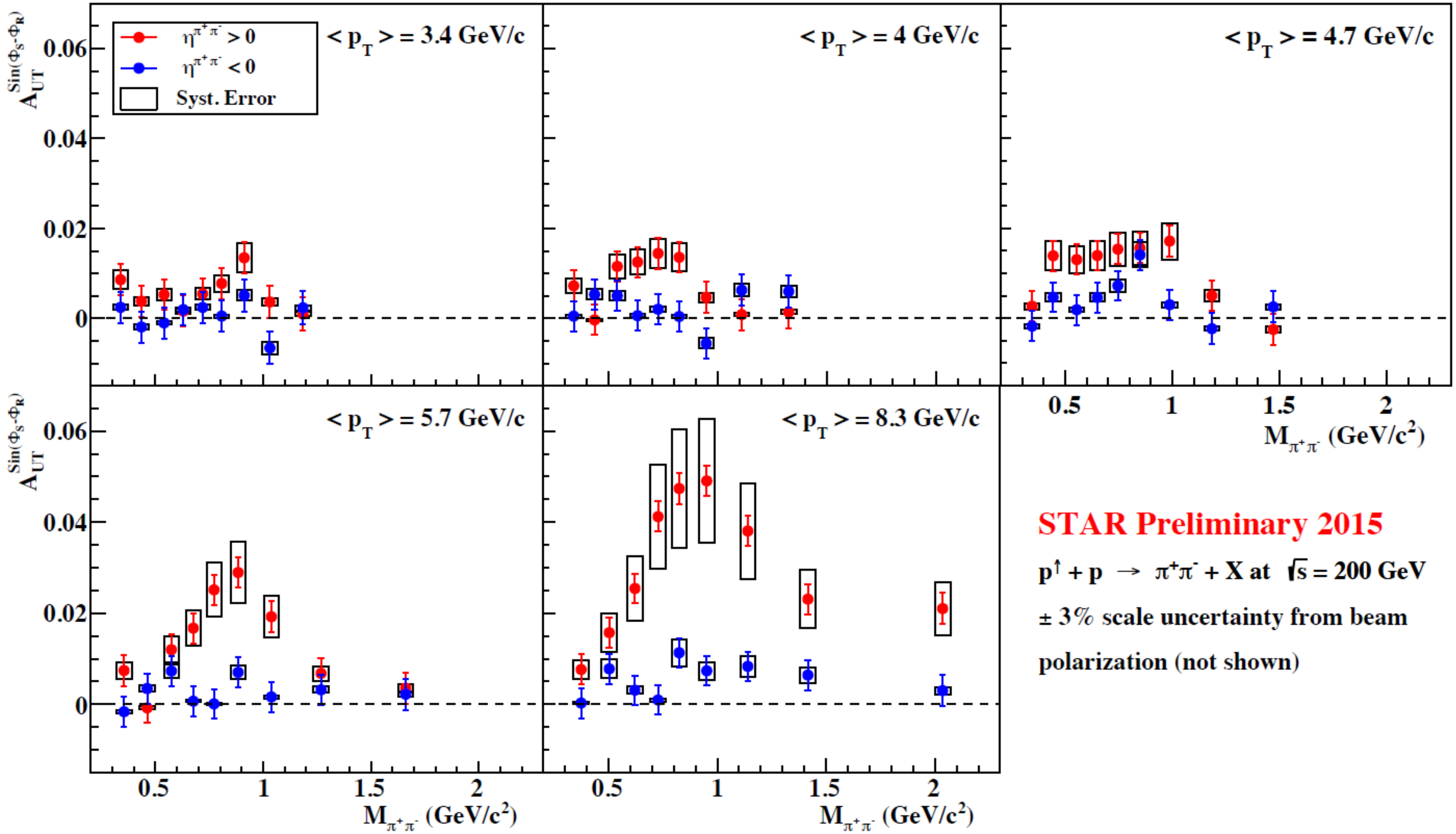


Significantly improved statistics from run 2015!

STAR: High Statistics IFF, p_T dependence of A_{UT} vs $M_{\pi+\pi-}$



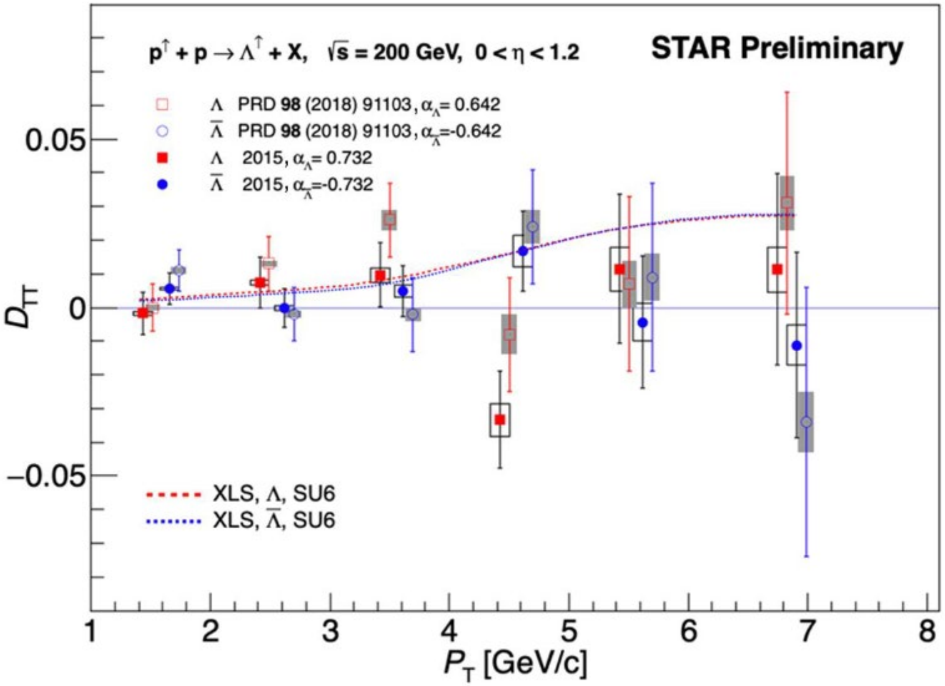
STAR Preliminary 2015

$p^{\uparrow} + p \rightarrow \pi^+\pi^- + X$ at $\sqrt{s} = 200$ GeV

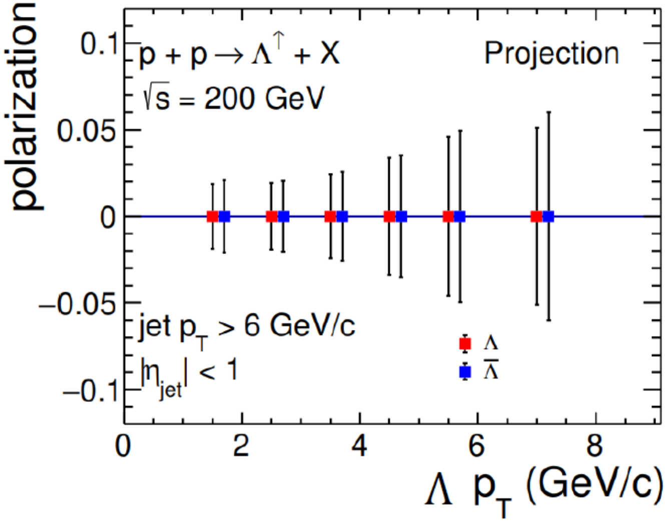
± 3% scale uncertainty from beam polarization (not shown)

STAR: High Statistics IFF, p_T dependence of A_{UT} vs $M_{\pi+\pi-}$

Current D_{TT} measurement with $\int Ldt=52pb^{-1}$



Projected P measurement with $\int Ldt=104pb^{-1}$

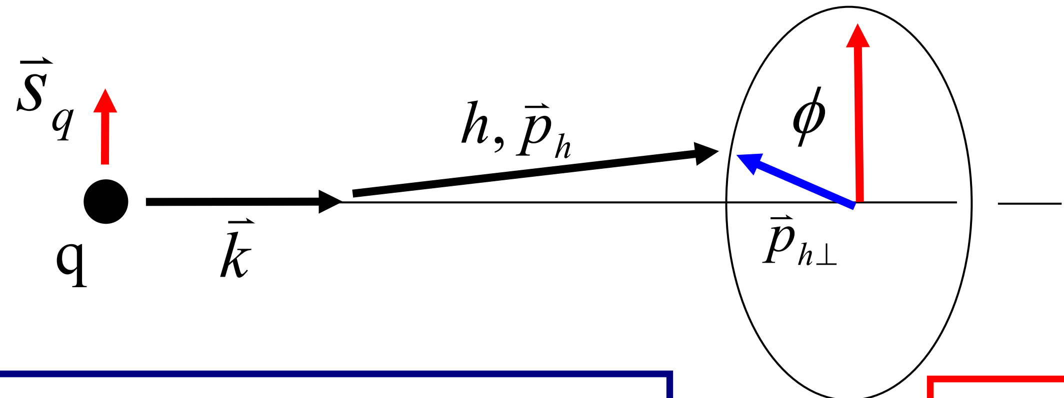


Summary:

- Large TMD-dependent observables in e+e- and hadron-hadron.
- Consistent description also including SIDIS, eg JAM, resulting in extraction of tensor charge
- TMDs continue to be measured in jets with improving statistics and sytematics: STAR, sPHENIX
- Increasingly precise measurements using di-hadron interference fragmentation functions!
- More data & results to come from RHIC before EIC

Collins Effect in Quark Fragmentation

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



$\vec{k}$: quark momentum

$\vec{s}_q$: quark spin

$\vec{p}_h$: hadron momentum

$\vec{p}_{h\perp}$: transverse hadron momentum

$\mathrm{z_h} = E_h / E_q$

$= 2\,E_h / \sqrt{s}$: relative hadron momentum

Collins Effect:
Fragmentation of a transversely polarized quark *q* into spin-less hadron *h* carries an azimuthal dependence:

$$\propto \left(\vec{k} \times \vec{p}_{h\perp}\right) \cdot \vec{s}_q$$

$$\propto \sin\phi$$