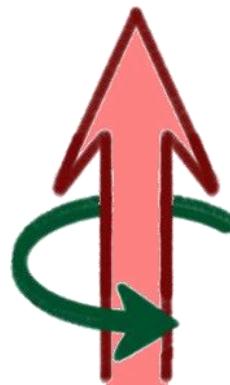


Experimental Overview of Transverse Spin Physics



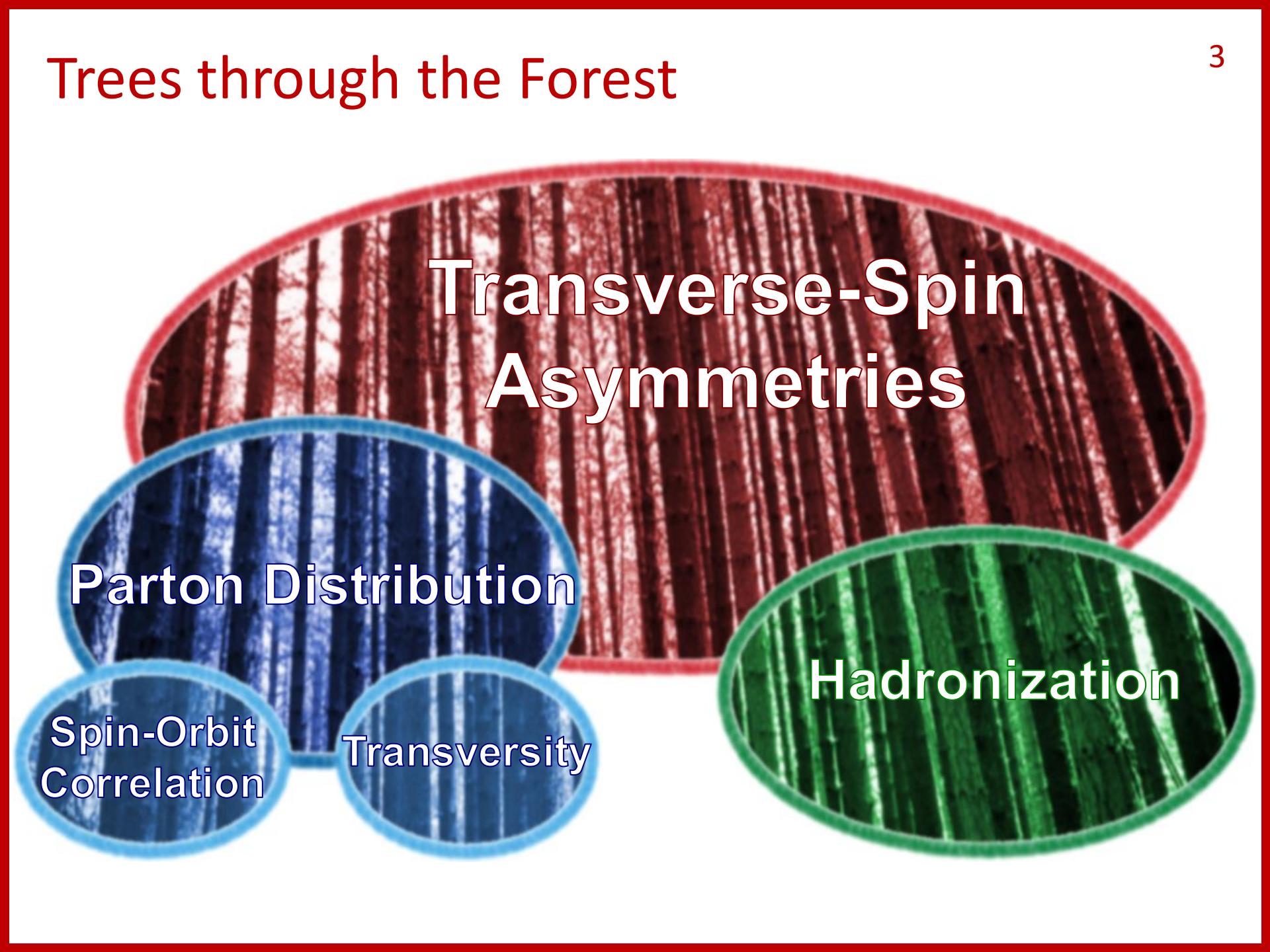
Oleg Eyser

22nd International Spin Symposium
University of Illinois / Indiana University
September 25-30, 2016

Cutting Questions

- What is the transversity distribution?
- How do we separate initial from final state effects?
- Do TMD distributions factorize?
- Are TMD distributions universal?
- How do TMD distributions evolve with Q^2 ?
- What can we learn about the color flow in QCD?
- Can other effects cause transverse spin asymmetries?
- What can we learn about gluon saturation?

Trees through the Forest



Transverse-Spin Asymmetries

Parton Distribution

Spin-Orbit
Correlation

Transversity

Hadronization

The Toolbox



$e^+ + e^-$

$l + N$

$p + p$



BESIII

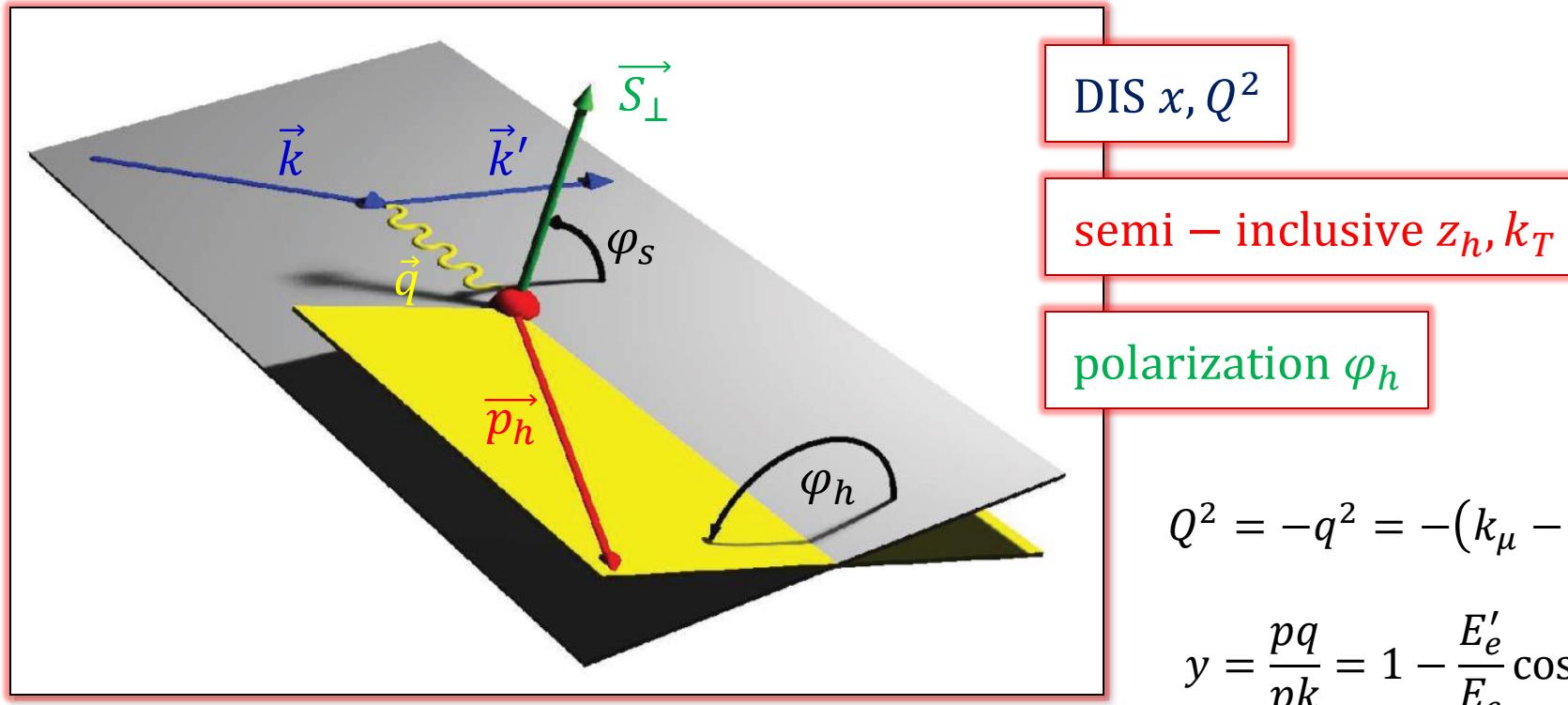


Jefferson Lab



This talk: status and recent results; no projections or plans
→ talks by E. Aschenauer, V. Burkert, C. Quintans

Semi-Inclusive Deep Inelastic Scattering

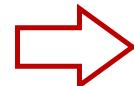


$$Q^2 = -q^2 = -(k_\mu - k'_\mu)^2$$

$$y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e} \cos^2 \frac{\theta_e}{2}$$

$$\frac{d^6\sigma}{dx_B dy dz_h d\phi_S d\phi_h dp_{h\perp}^2} = \frac{\alpha_{em}^2}{8Q^4} \frac{y}{z_h} L_{\mu\nu} W^{\mu\nu}$$

$$x_B = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$



Parameterized in 18 structure functions

Polarization Effects in Nucleons / Partons

Leading twist transverse momentum dependent distributions

		quark		
		U	L	T
nucleon	U	f_1		h_1^\perp
	L		g_1	h_{1L}^\perp
	T	f_{1T}^\perp	g_{1T}	h_1, h_{1T}^\perp

		quark		
		U	L	T
hadron	U	D_1		H_1^\perp
	L			G_{1L}
	T	H_{1T}^\perp	G_{1T}	H_1, H_{1T}^\perp

Sivers function

$$F_{UT,T}^{\sin \phi_h - \phi_S} = \mathcal{C} \left[-\frac{\hat{h} \cdot k_T}{M} f_{1T}^\perp D_1 \right]$$

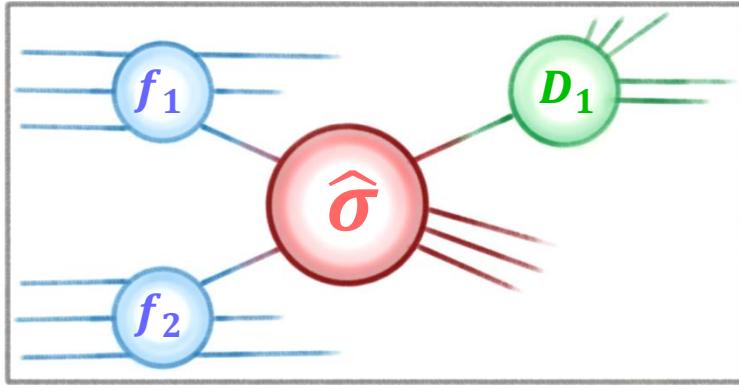
Transversity \times Collins function

$$F_{UT}^{\sin \phi_h + \phi_S} = \mathcal{C} \left[-\frac{\hat{h} \cdot \kappa_T}{M} h_1 H_1^\perp \right]$$

Boer-Mulders function
 \times Collins function

$$F_{UU}^{\cos 2\phi_h} = \mathcal{C} \left[-\frac{2(\hat{h} \cdot k_T)(\hat{h} \cdot \kappa_T) - k_T \cdot \kappa_T}{MM_h} h_1^\perp H_1^\perp \right]$$

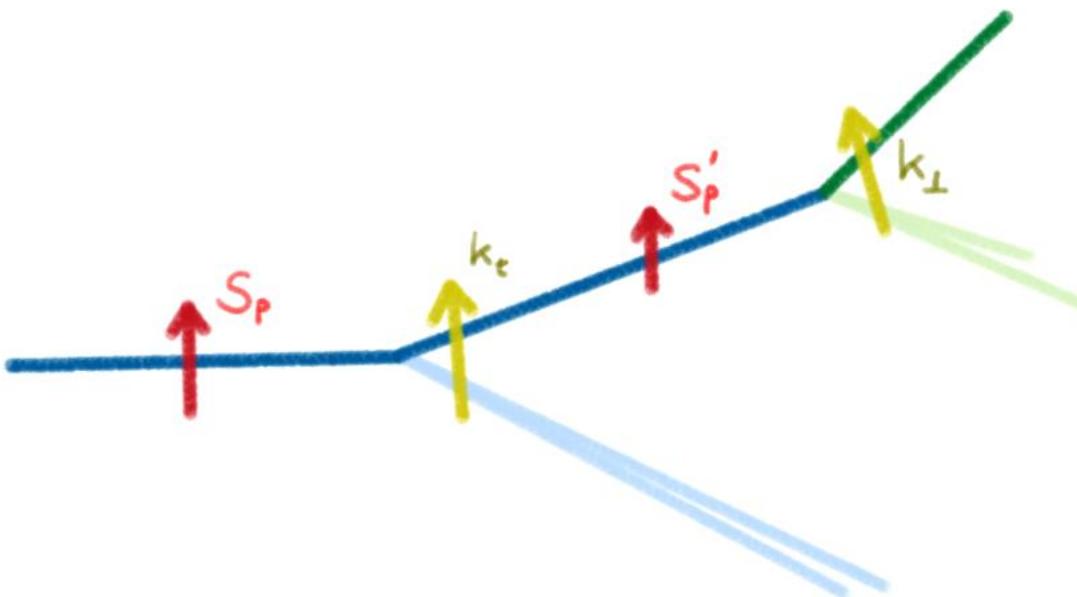
Hadroproduction



$$\left. \begin{array}{l} f_{1T}^\perp \otimes f_1 \otimes D_1 \\ h_1 \otimes h_1^\perp \otimes D_1 \\ h_{1T}^\perp \otimes h_1^\perp \otimes D_1 \\ h_1 \otimes f_1 \otimes H_1^\perp \\ f_{1T}^\perp \otimes h_1^\perp \otimes H_1^\perp \\ h_{1T}^\perp \otimes f_1 \otimes H_1^\perp \end{array} \right\}$$

final state initial state

...



- Inclusive hadrons
- Direct photons
- Jets
- Jet structure
- Hadron correlations
- Interference fragmentation
- Drell-Yan
- W-bosons

Beyond the Collinear Picture

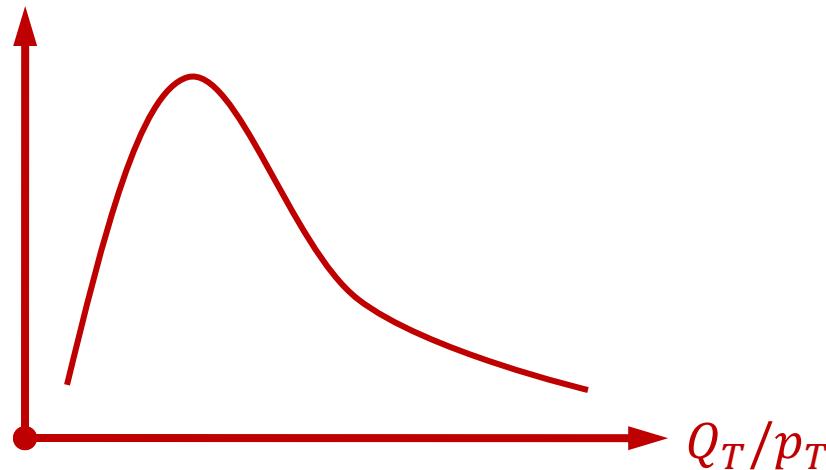
Transverse Momentum
Dependent Effects

or

Twist-3
Effects

$$Q \gg Q_T \gtrsim \Lambda_{QCD}$$

$$Q, Q_T \gg \Lambda_{QCD}$$

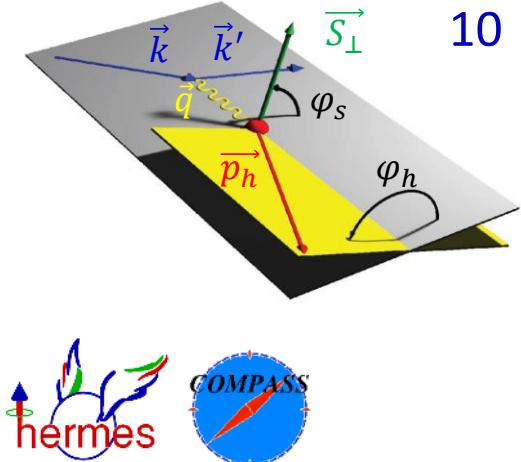
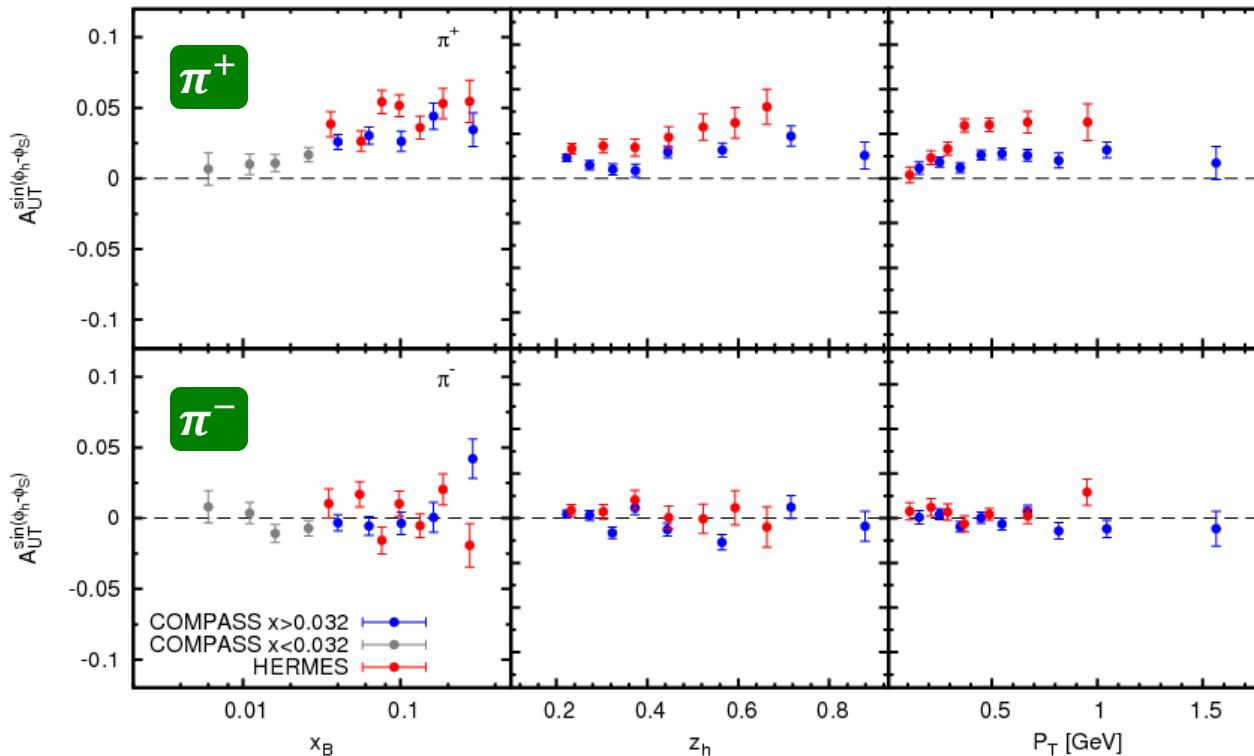


$$-\int d^2 k_\perp \frac{|k_\perp^2|}{M} f_{1T}^{\perp q}(x, k_\perp^2) = T_{q,F}(x, x)$$

Initial State Effects



Sivers Asymmetries in SIDIS



Phys. Rev. Lett. 103 (2009)

Phys. Lett. B744 (2015)

Kaon asymmetries similar;
 $K^+ > \pi^+$

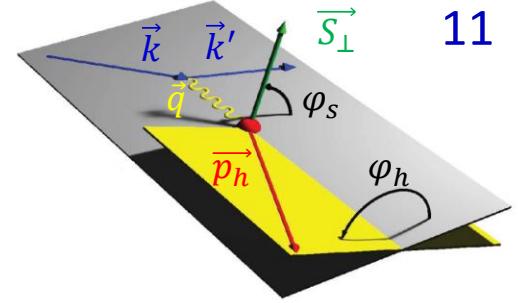
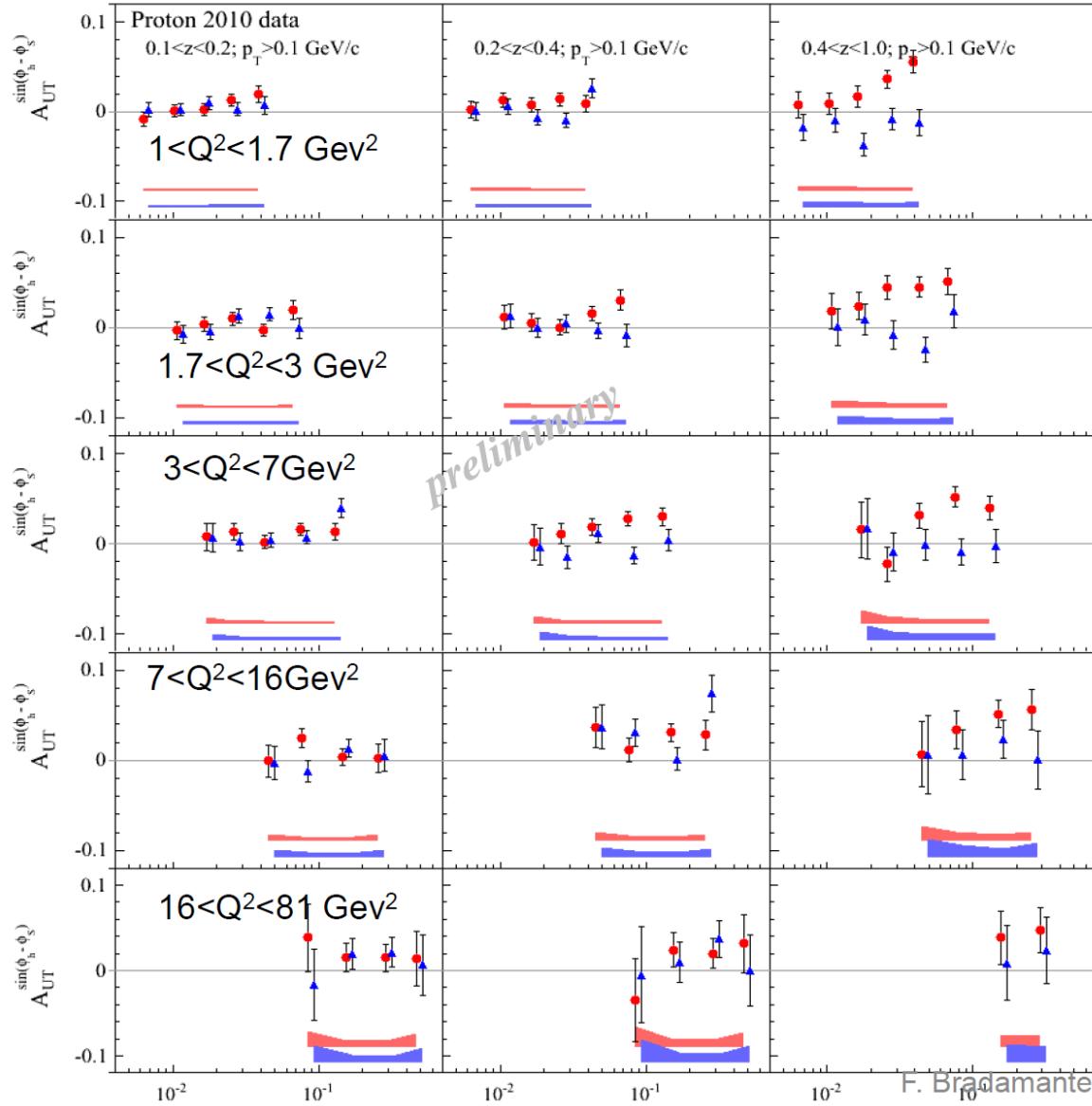
Nucl. Phys. B765 (2007)

- COMPASS d^\uparrow
- consistent with zero

Hall A

Phys. Rev. Lett. 107 (2007)

Sivers Asymmetries in SIDIS



Multidimensional binning

$(x, Q^2; z, p_T)$

2010 proton data

Also for Drell-Yan Q^2 ranges

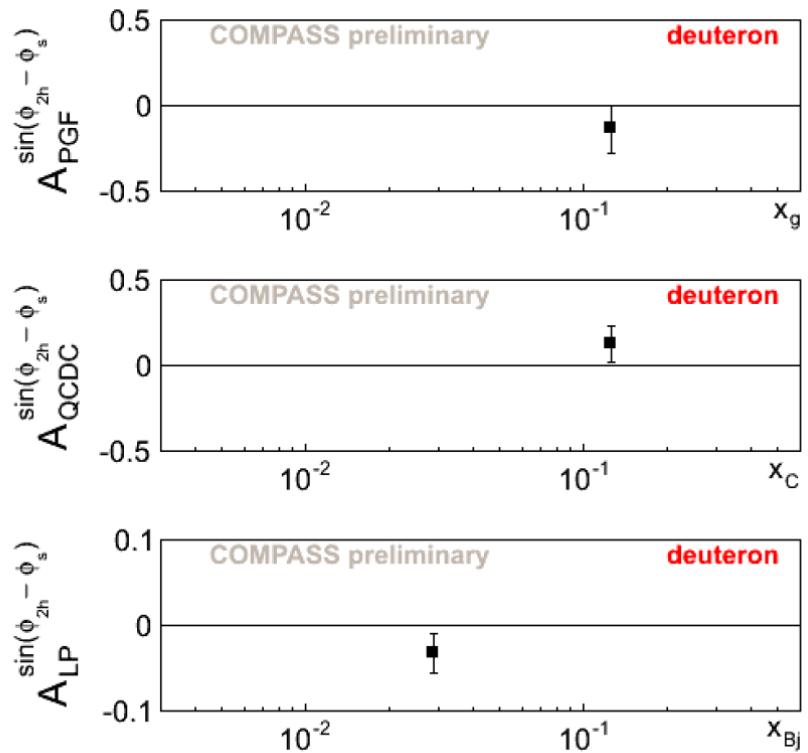
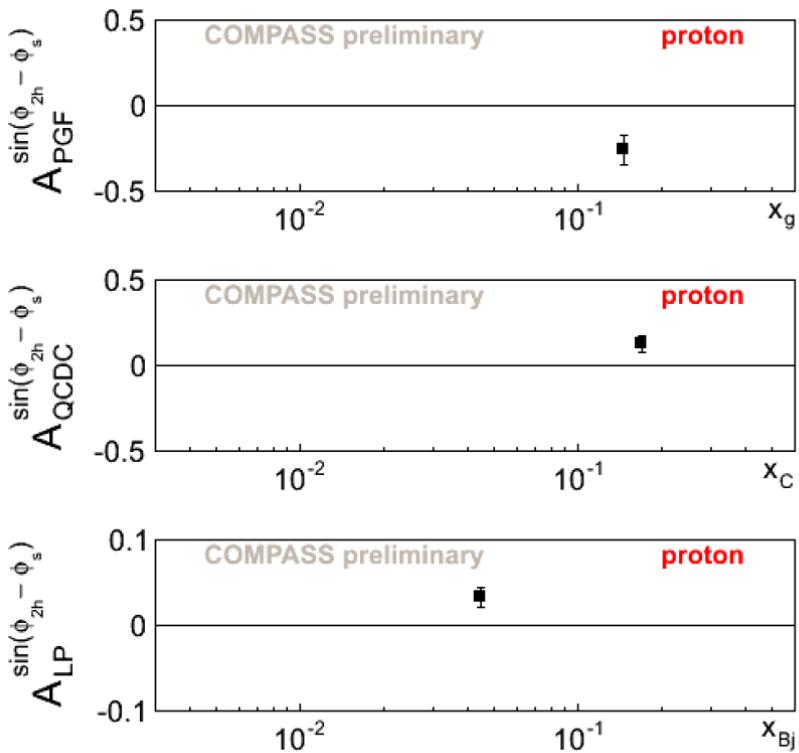
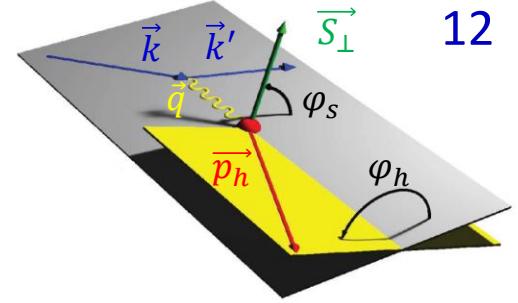
arxiv:1609.07374

Talks by
F. Bradamante & B. Parsamyan

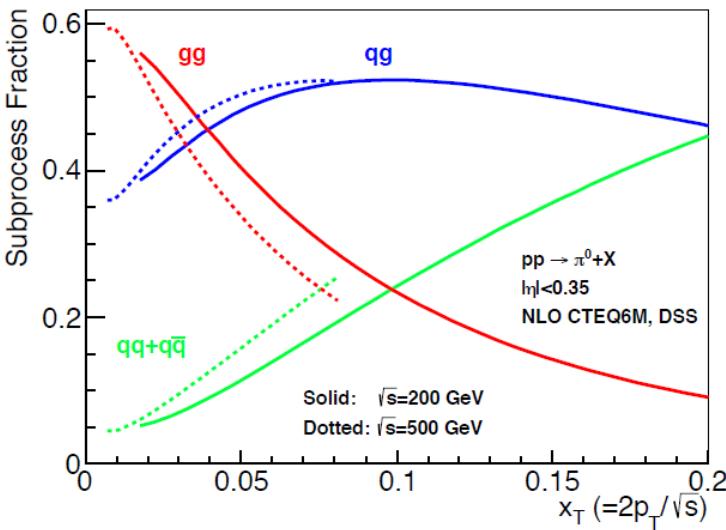
→ C. Quintans

Gluon Sivers in SIDIS

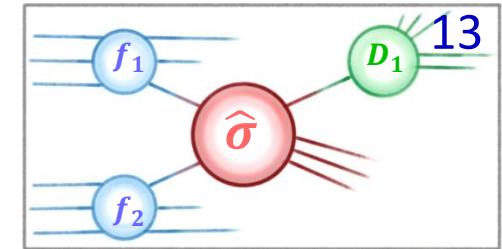
- High- p_T hadron pair enhances photon-gluon fusion process and parton (gluon)
- Event-by-event weighting by neural network
- Statistically very challenging
- Talk by L. Silva



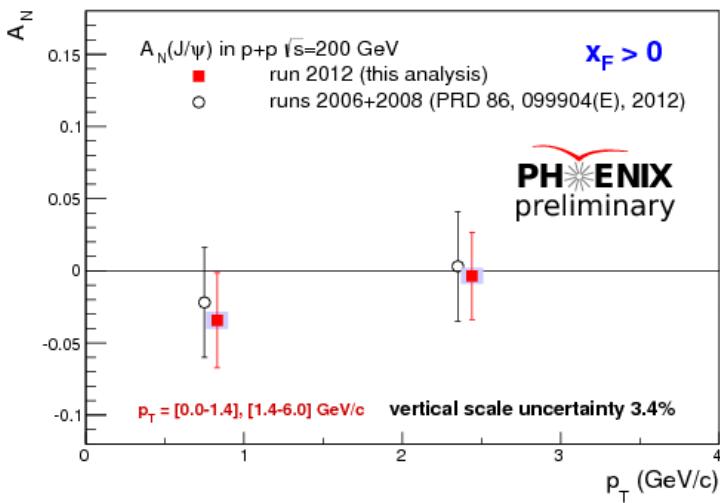
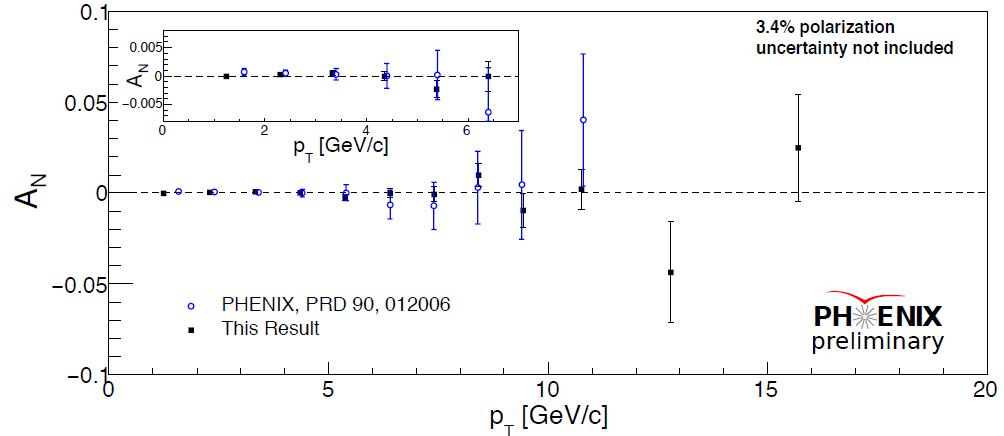
Gluon Sivers in $p + p$



PHENIX



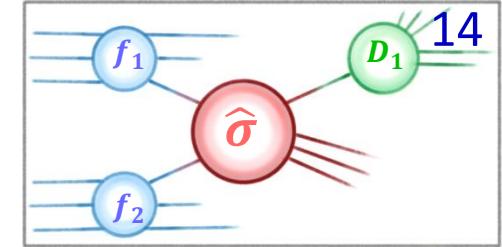
$p+p \rightarrow \pi^0 + X @ 200$ GeV, $|\eta| < 0.35$



- Constrain gluon Sivers function in twist-3 formalism
- Phys. Rev. D90, 012006 (2014)
- Talk by N. Novitzky
- Also single μ result (heavy flavor)

W -Boson Production in $p + p$

$$p + p \rightarrow W^\pm \rightarrow e^\pm + \nu$$



Requires full reconstruction of W^\pm kinematics

Missing transverse momentum from recoil

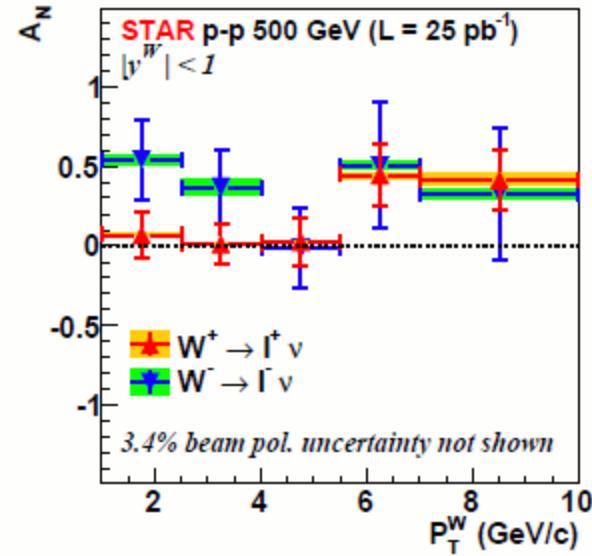
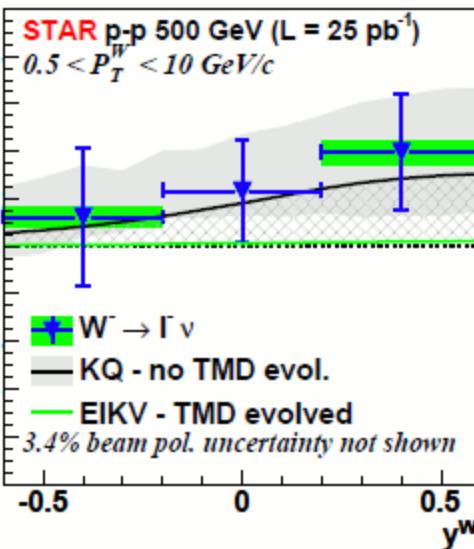
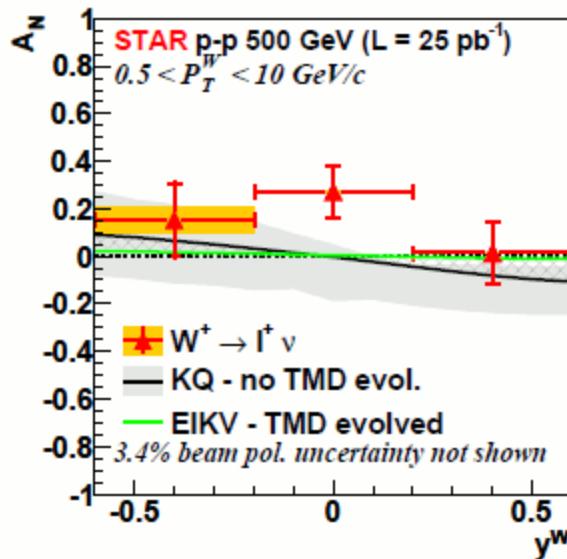
$$P_T^W = P_T^e + P_T^\nu = P_T^{recoil}$$

Phys. Rev. Lett. 116 (2016)

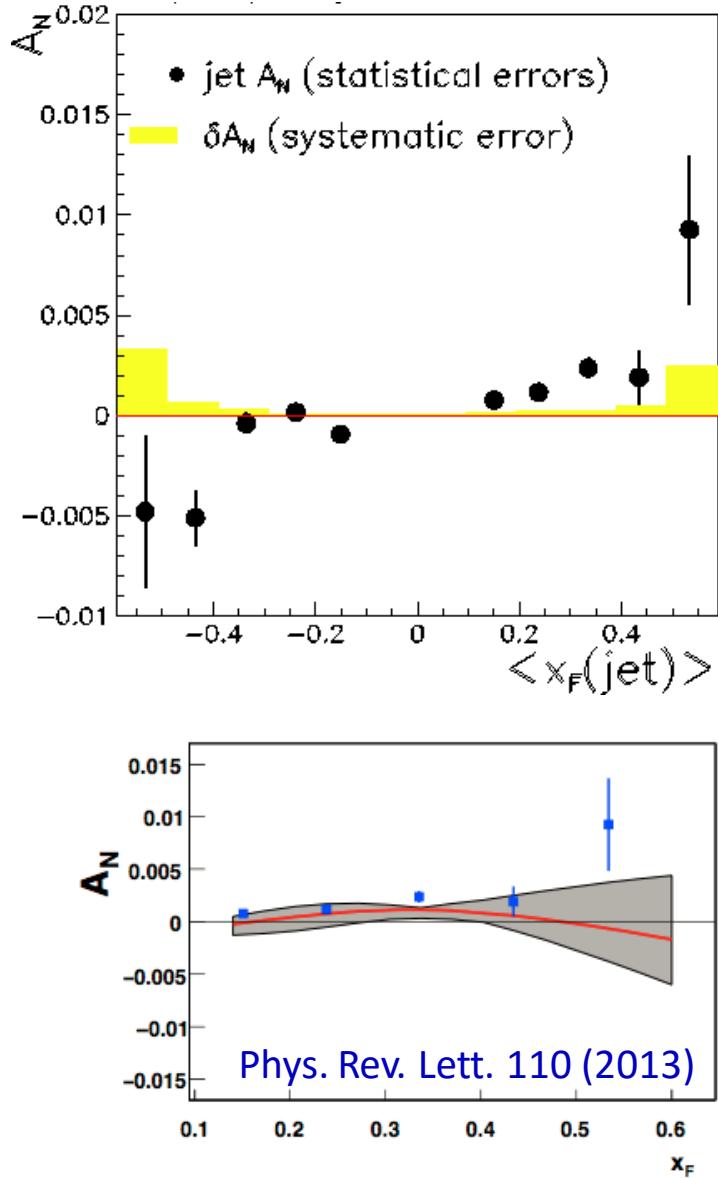
Talk by A. Ogawa



Test non-universality
of Sivers effect similar
to Drell-Yan
→ C. Quintans



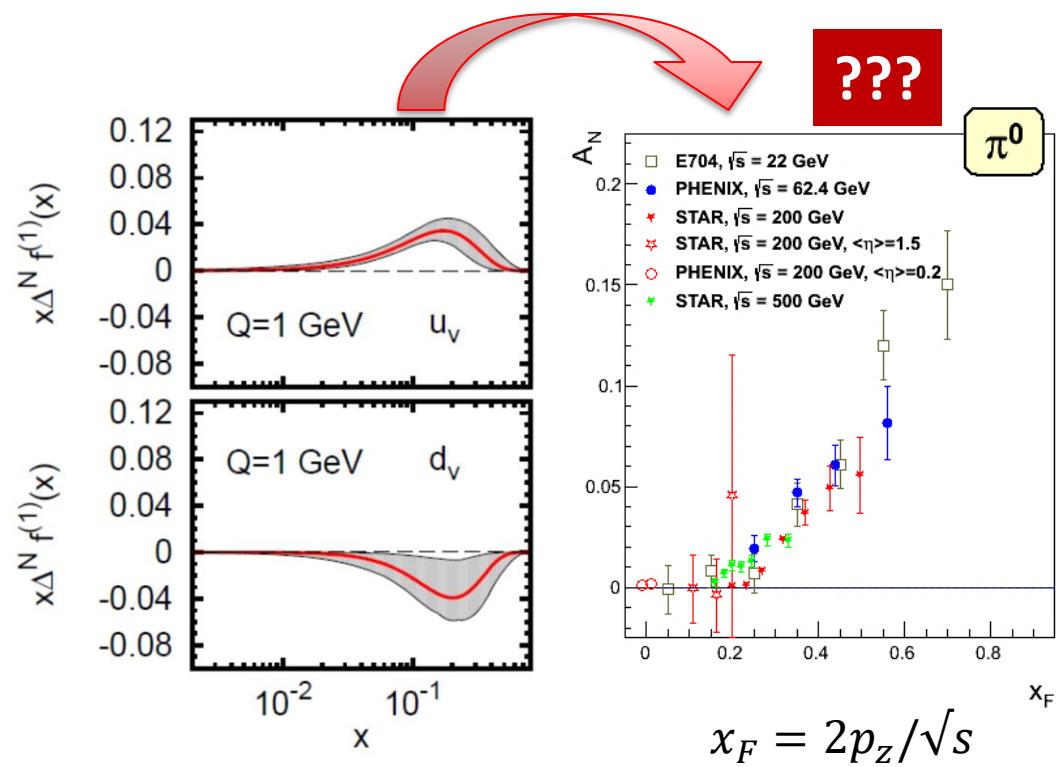
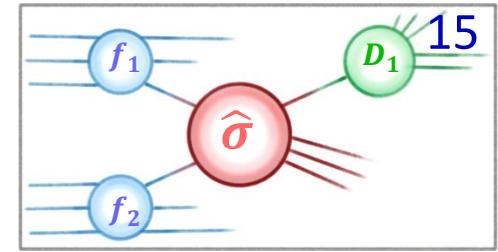
Inclusive Jets in $p + p$



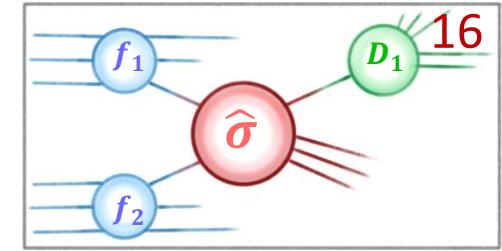
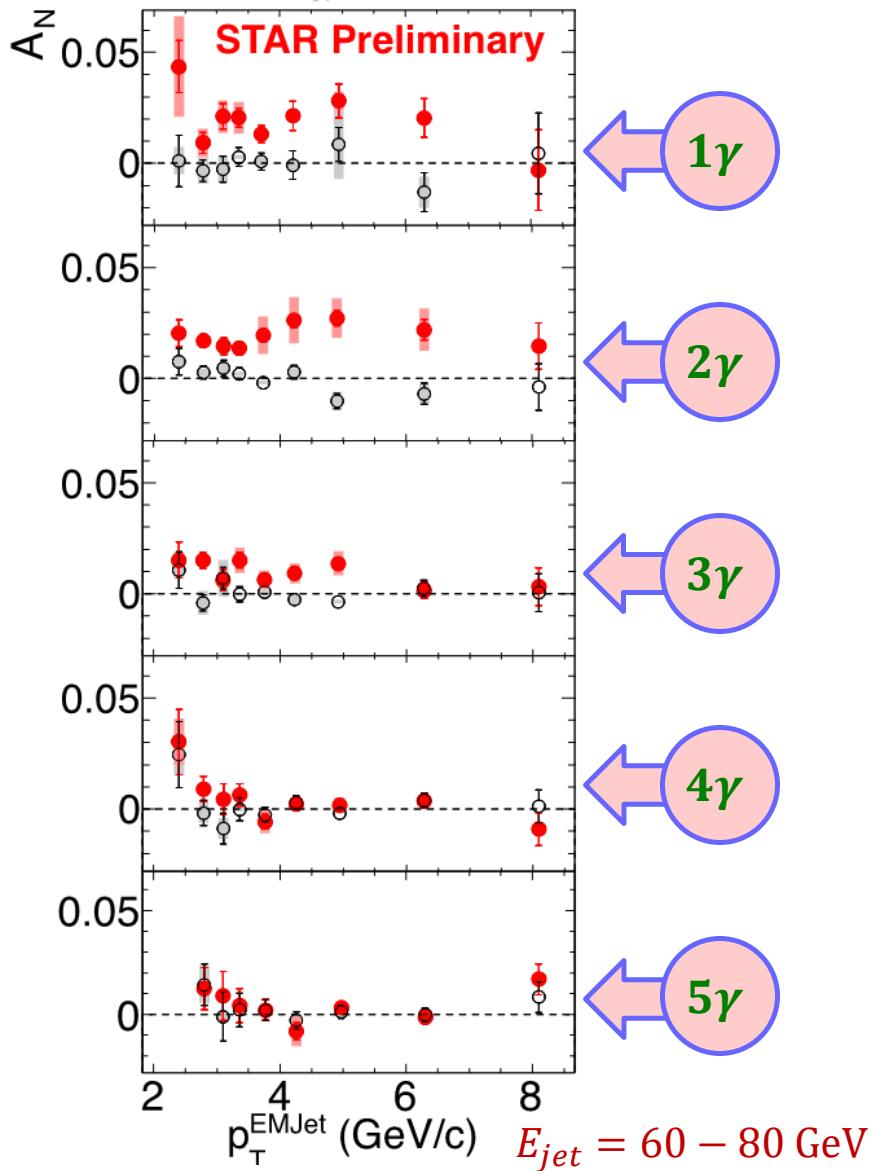
AnDY @ RHIC

$\sqrt{s} = 500 \text{ GeV}$

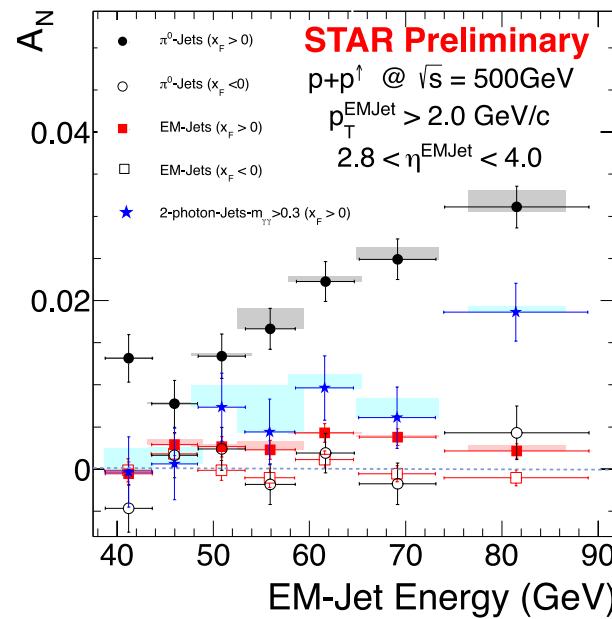
Very small asymmetry
as expected from theory



Event Topology in $p + p$



- $\sqrt{s} = 500 \text{ GeV}$
- Forward rapidity, $2.8 < \eta < 4.0$

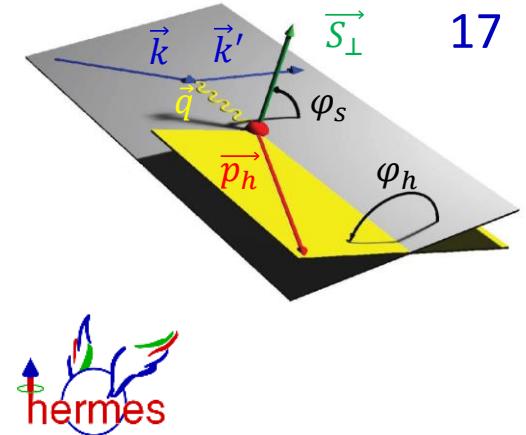
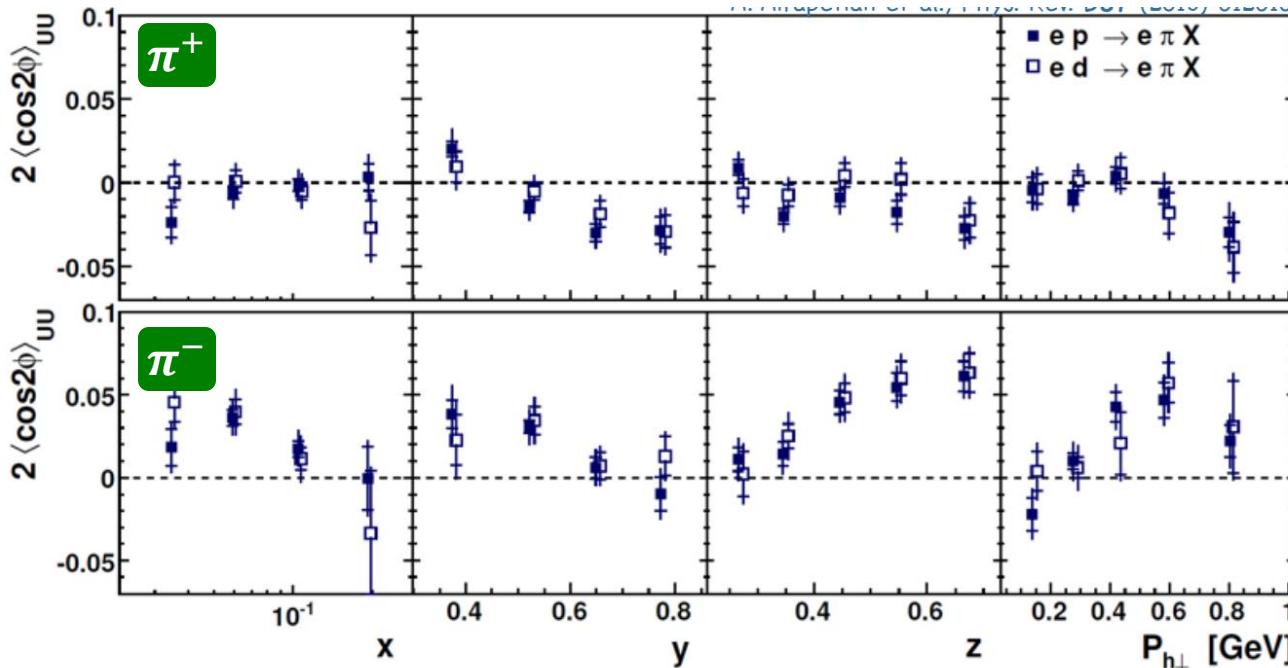


Event complexity increases

Possibly diffraction? Or a combination with hadronization effects?

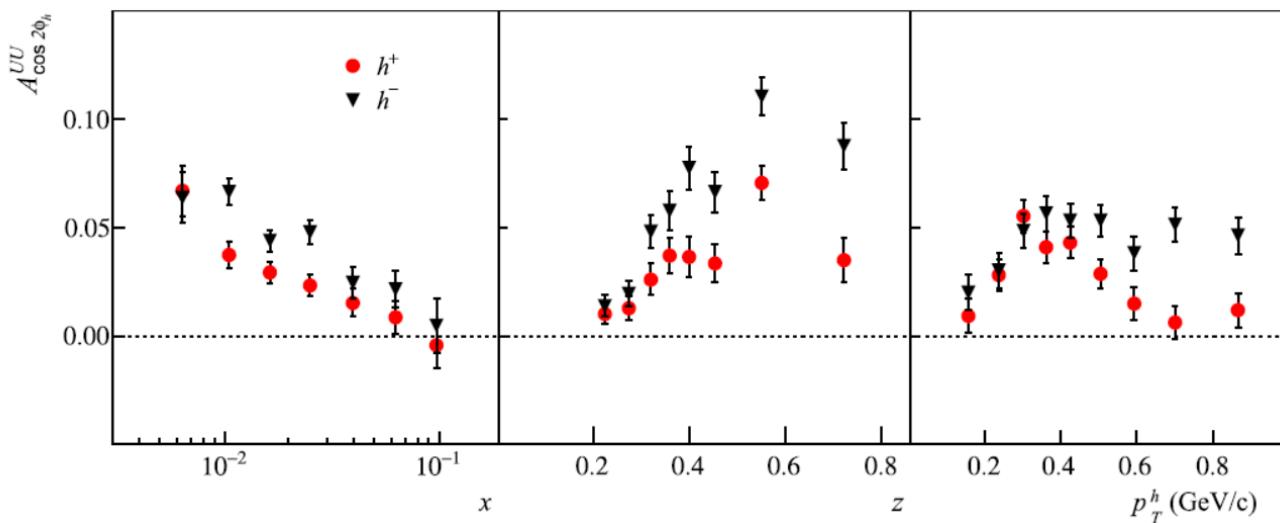
Boer-Mulders Effect in SIDIS

17



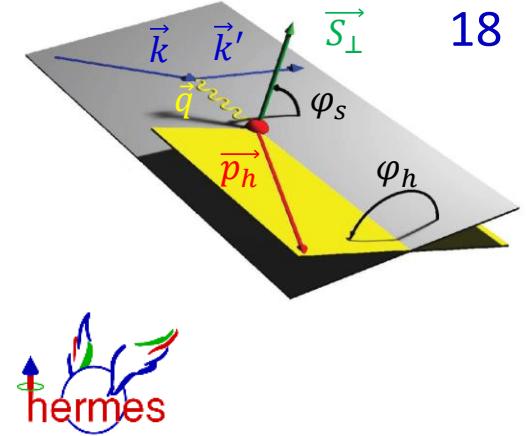
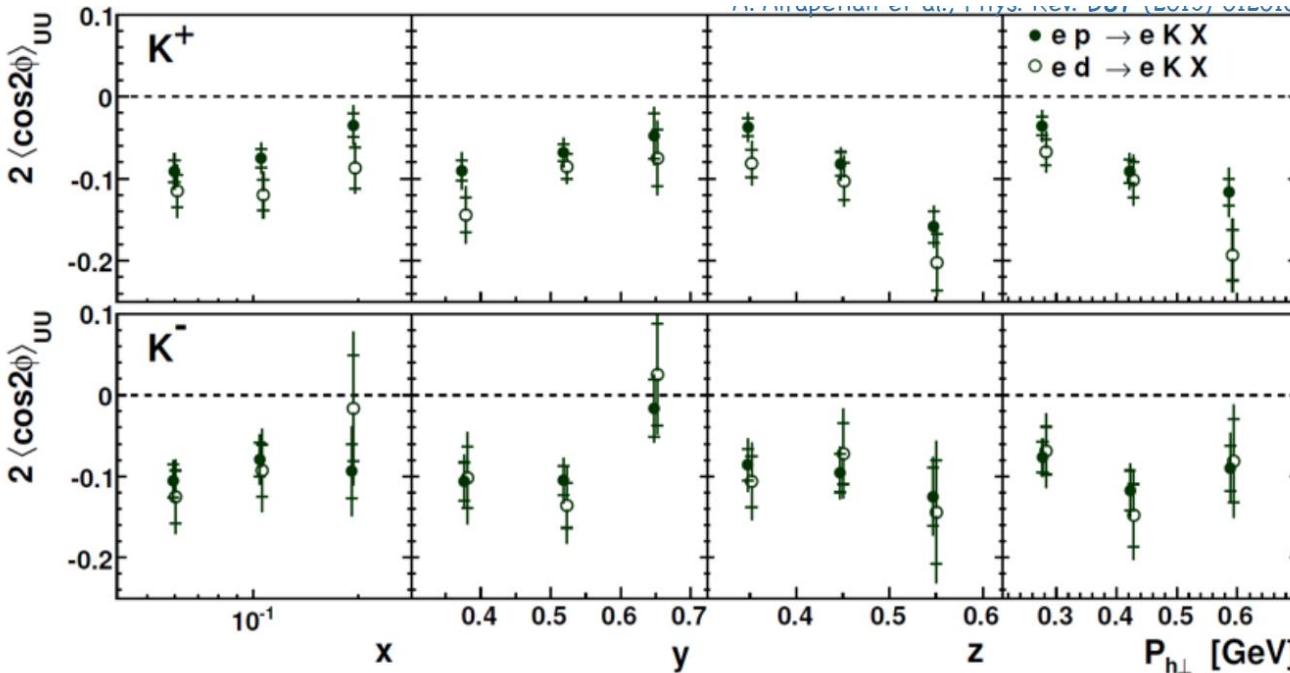
Phys. Rev. D87 (2013)

$$A_p \approx A_d \\ \rightarrow h_1^\perp(u) \approx h_1^\perp(d)$$



Nucl. Phys. B886 (2014)

Boer-Mulders Effect in SIDIS



Phys. Rev. D87 (2013)

$$h_1^\perp(u) \approx h_1^\perp(d)$$

Very significant asymmetries for Kaons:

$$H_1^\perp(u \rightarrow K^+) > H_1^\perp(u \rightarrow \pi^+)$$

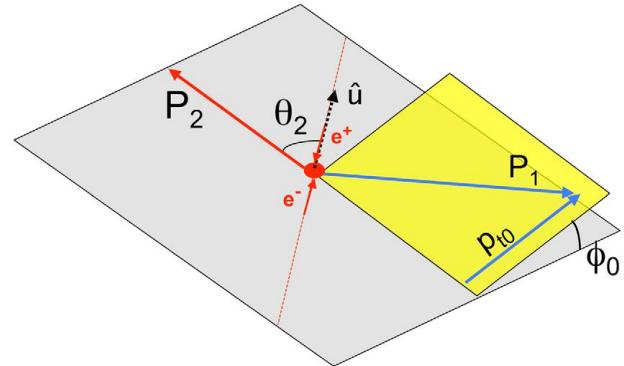
s -quarks behave very different in string breaking
(Artru model, Z Phys. C73, 1997)

Final State Effects



Collins Effect in e^+e^-

$$e^+ + e^- \rightarrow h_1 + h_2 + X$$



Similar to Gottfried-Jackson frame in Drell-Yan production

$$A_0^{\cos 2\phi} \propto H_1^\perp \overline{H_1^\perp}$$

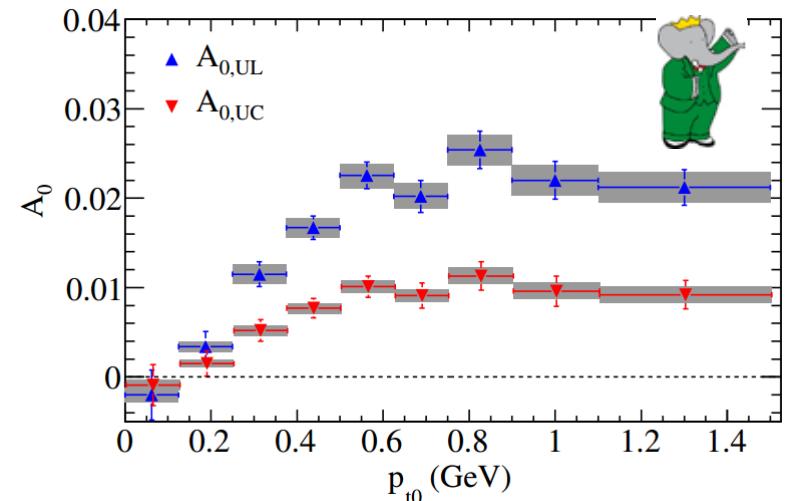
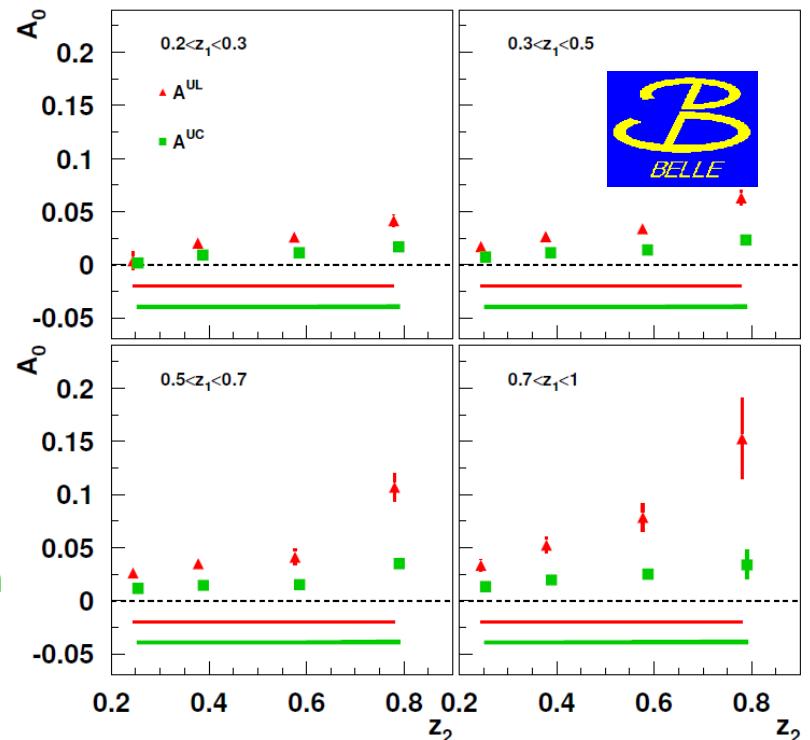
Belle: Phys. Rev. D78, 032011 (2008),
Phys. Rev. D90, 052003 (2014)

Babar: Phys. Rev. D92, 111101 (2015)

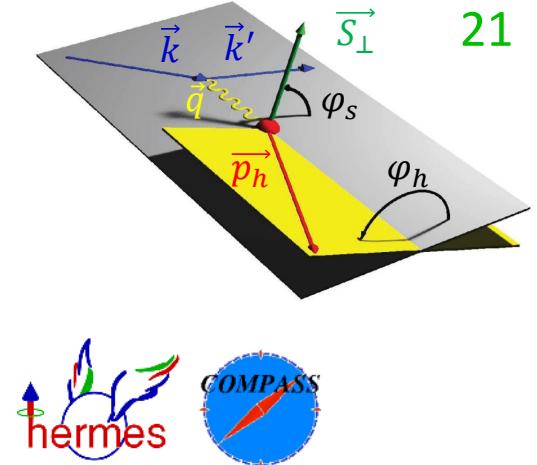
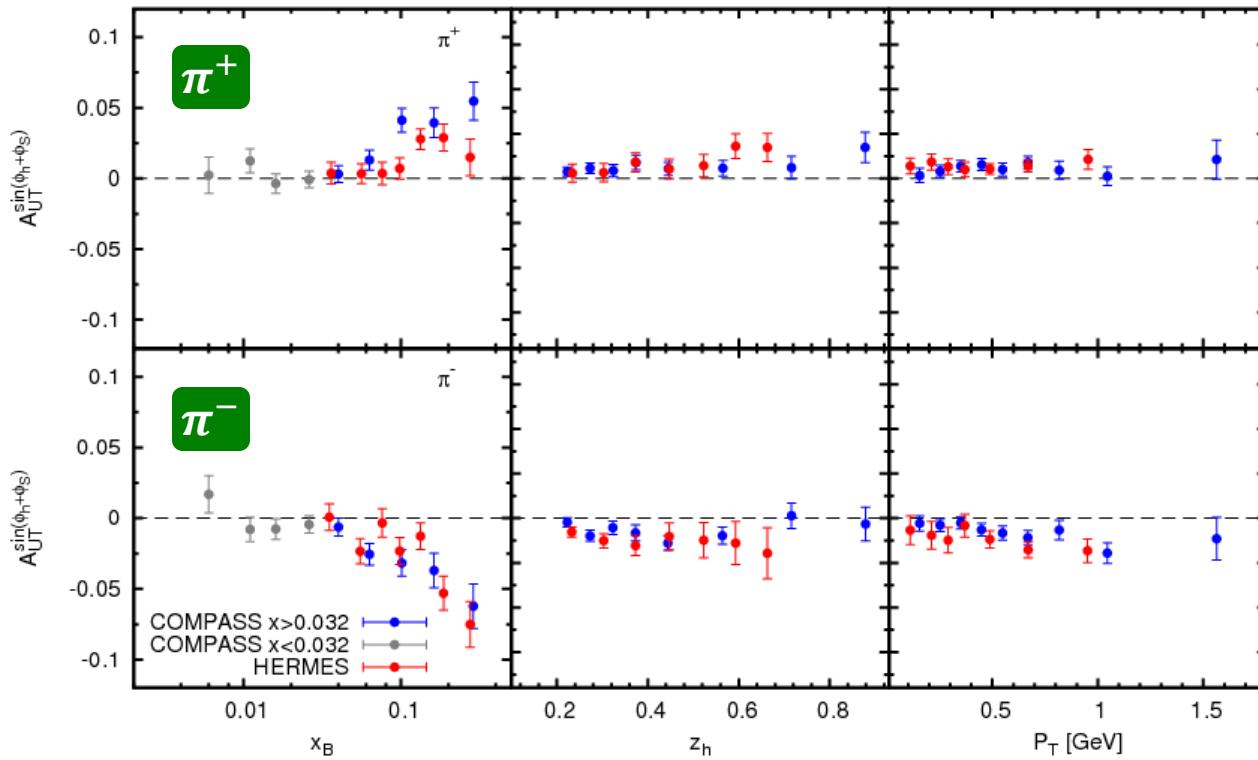
BES III: Phys. Rev. Lett. 116, 042001 (2016)

Kaon asymmetries slightly larger than π

Talk by F. Anulli



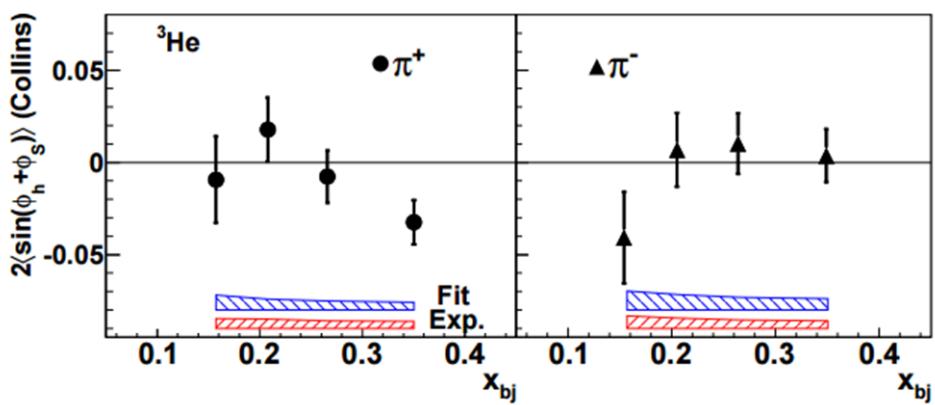
Collins Asymmetries in SIDIS



Phys. Lett. B693 (2010)

Phys. Lett. B744 (2015)

$$H_1^{\perp,fav} \approx -H_1^{\perp,unfav}$$

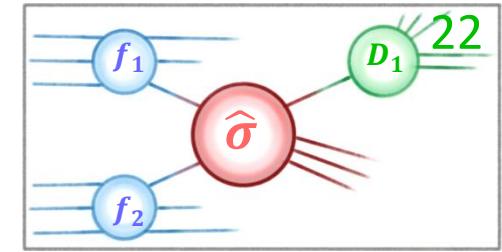


Hall A

Phys. Rev. Lett. 107 (2007)

Collins Effect in $p + p$

Azimuthal distribution of hadrons in jets



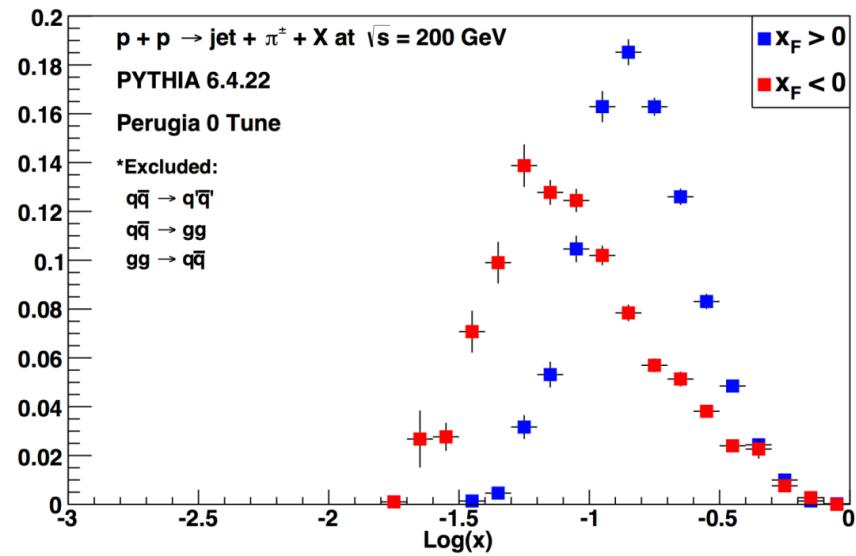
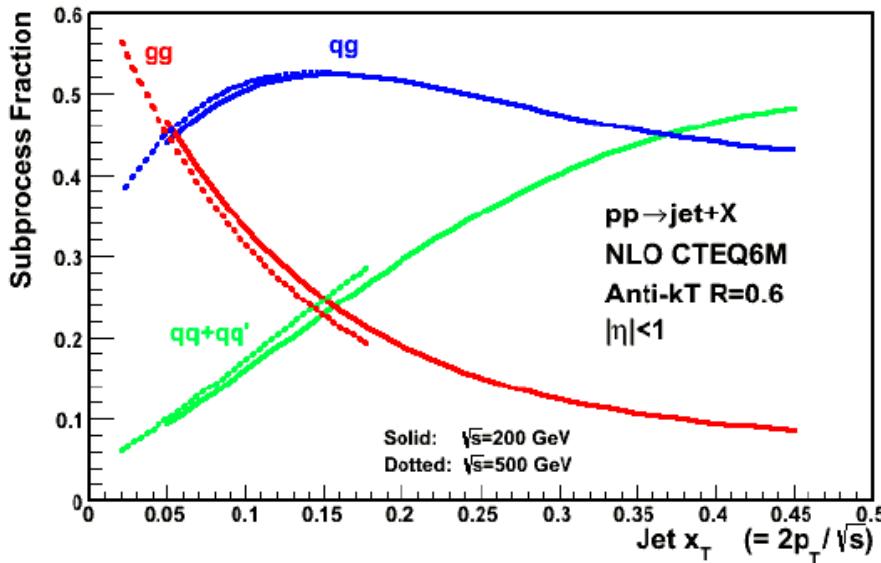
Fragmentation effect only; no initial state effects

Provides two scales that are necessary for TMD framework

$$h_1 \otimes H_{1T}^\perp$$

High- p_T for reduced gluon contribution

Central rapidity: $|\eta| < 1$



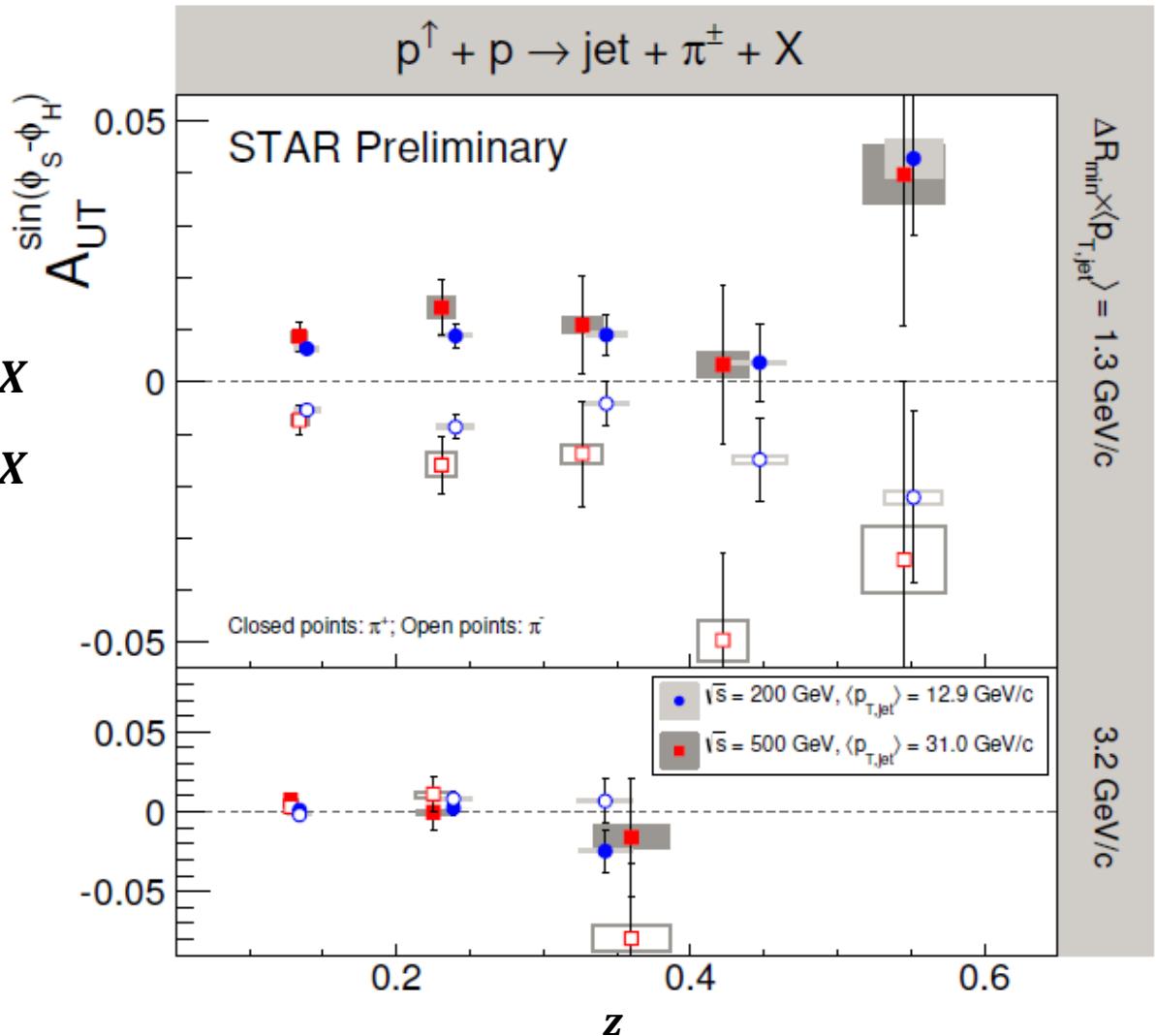
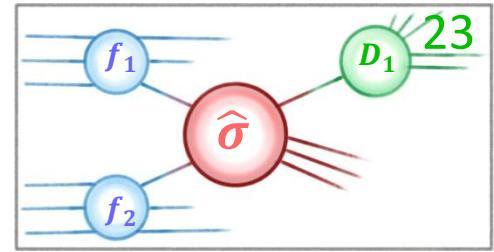
Collins Effect in $p + p$



$\sqrt{s} = 200 \text{ GeV}$
 $\sqrt{s} = 500 \text{ GeV}$

- ● $p + p \rightarrow \text{jet} + \pi^+ + X$
- ○ $p + p \rightarrow \text{jet} + \pi^- + X$

- No strong effect of TMD evolution observed
- Talk by J. Drachenberg



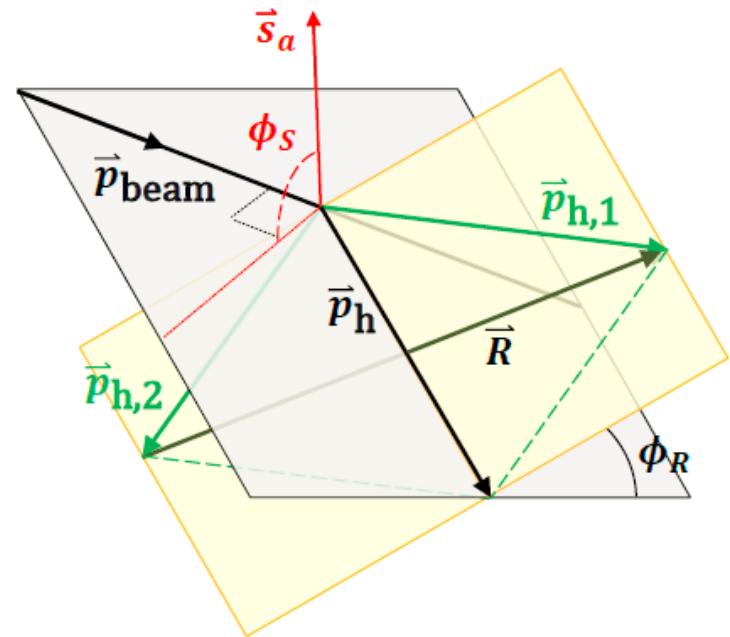
Interference Fragmentation Functions

- Angular correlation of particles

$$p_h = p_1 + p_2$$

$$R = p_1 - p_2$$

- Independent access to transversity
- Collinear description
- Evolution well known: DGLAP
- Expected to be universal

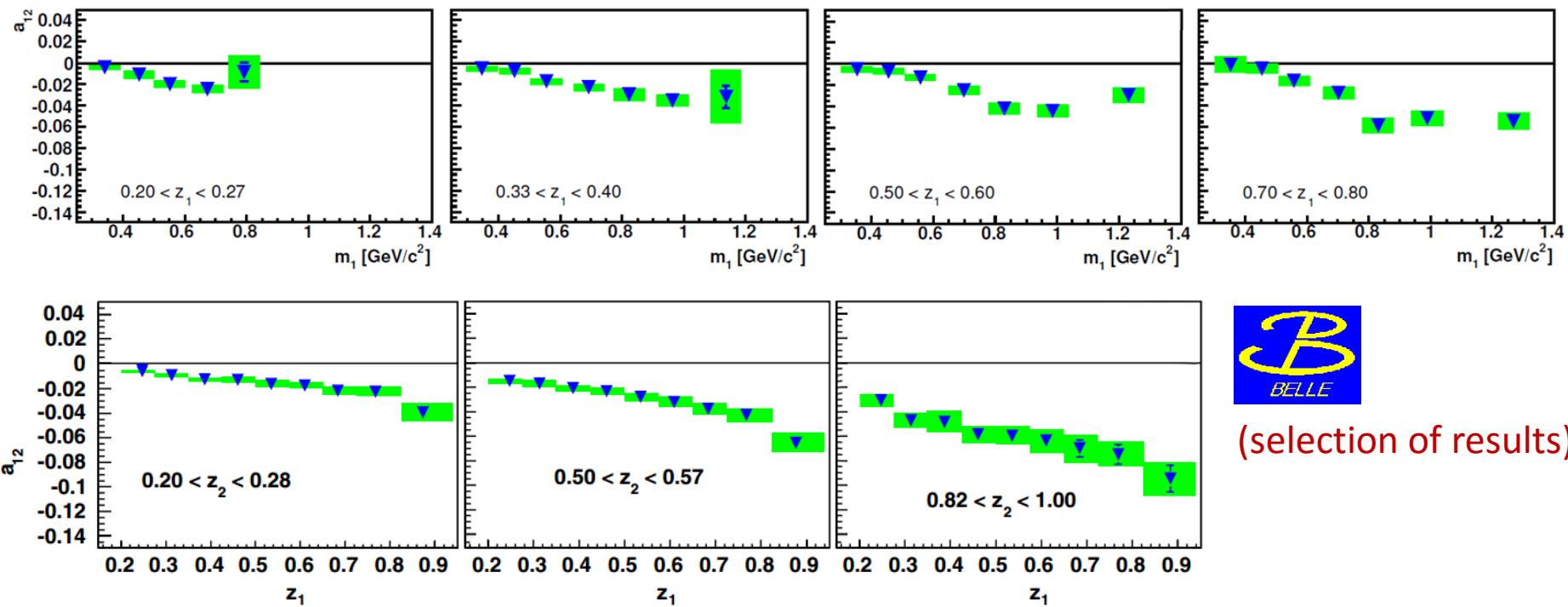
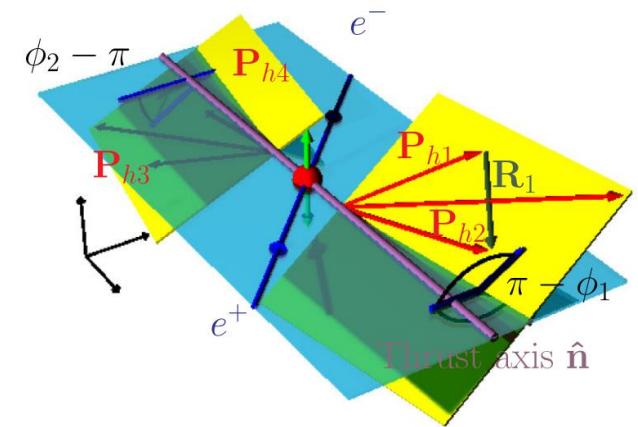


$$A_{SIDIS}^{\sin \phi_R + \phi_S}(x, z, M_h^2) \propto -\frac{\sum_q e_q^2 h_1^q(x) \frac{|R_T|}{M_h} H_{1,q}^4(z, M_h^2)}{e_q^2 f_1^q(x) D_{1,q}(z, M_h^2)}$$

- Point-by-point extraction of transversity
- Depends on invariant mass

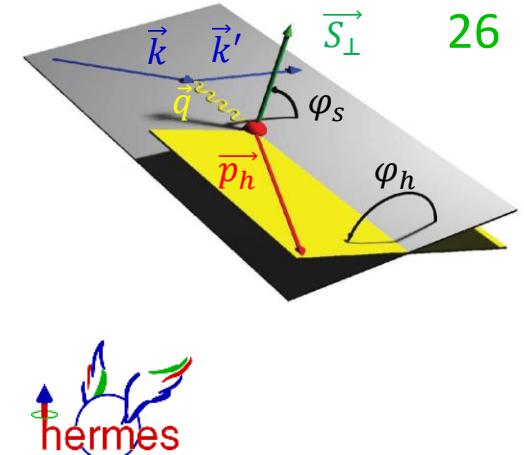
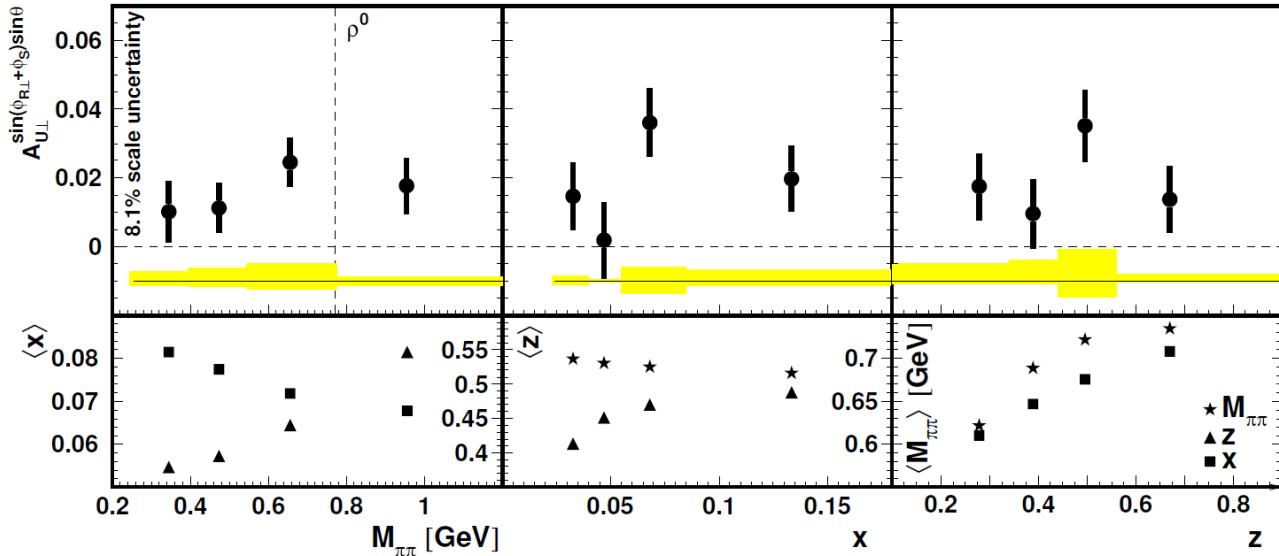
Interference Fragmentation in e^+e^-

- Correlations between hadron pairs from back-to-back jets
- Phys. Rev. Lett. 107 (2011)
- Very precise data, multidimensional binning
- Input for point-by-point extraction of transversity

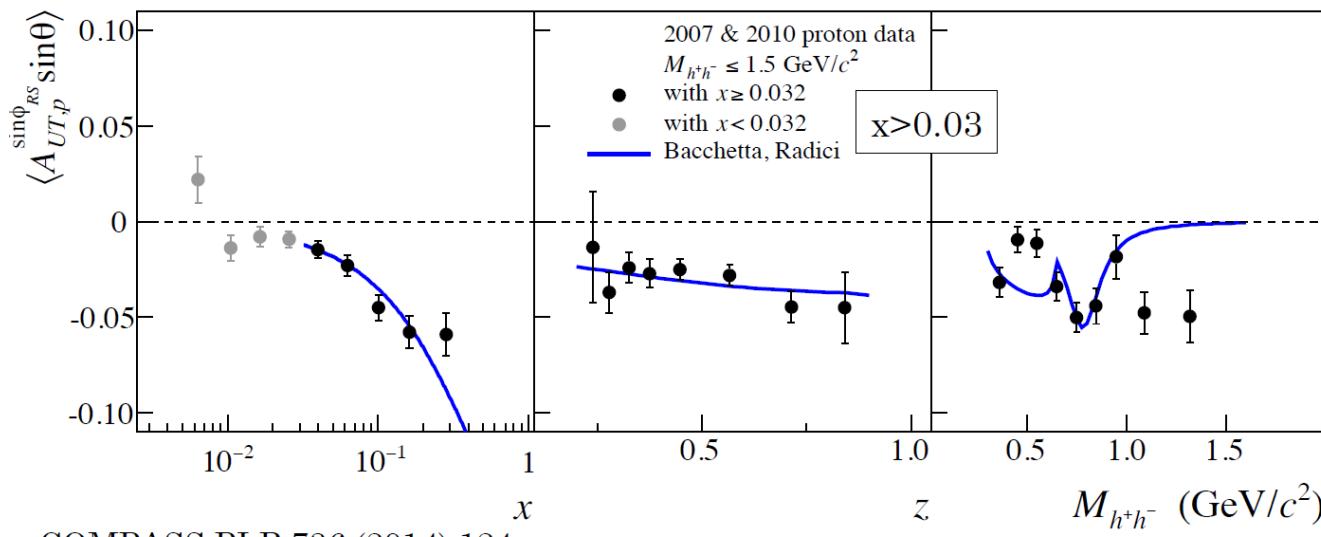


IFF in SIDIS

26

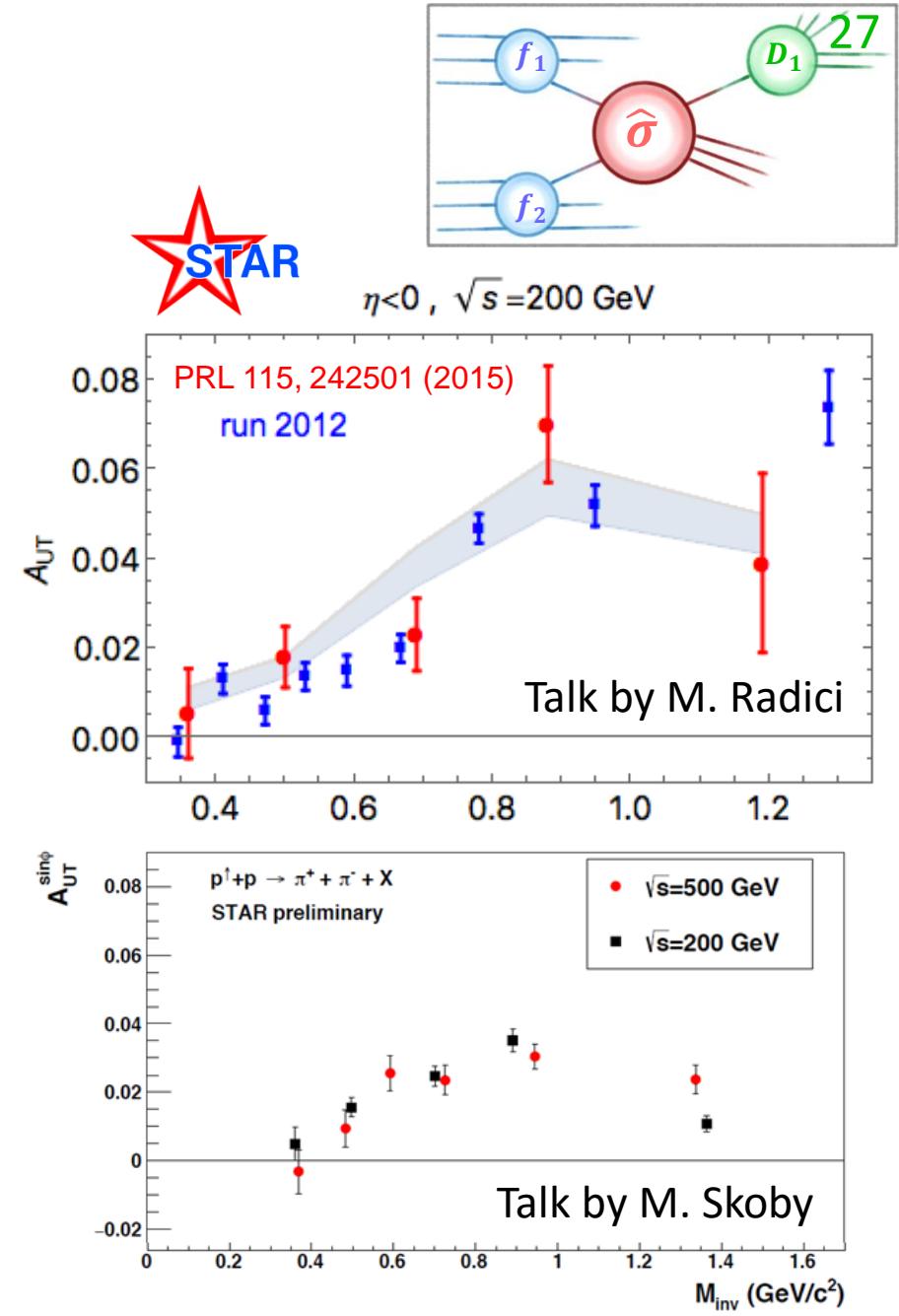
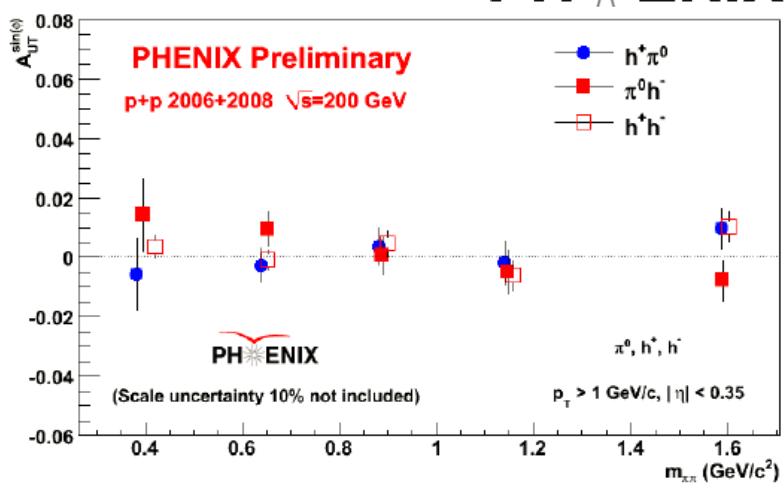
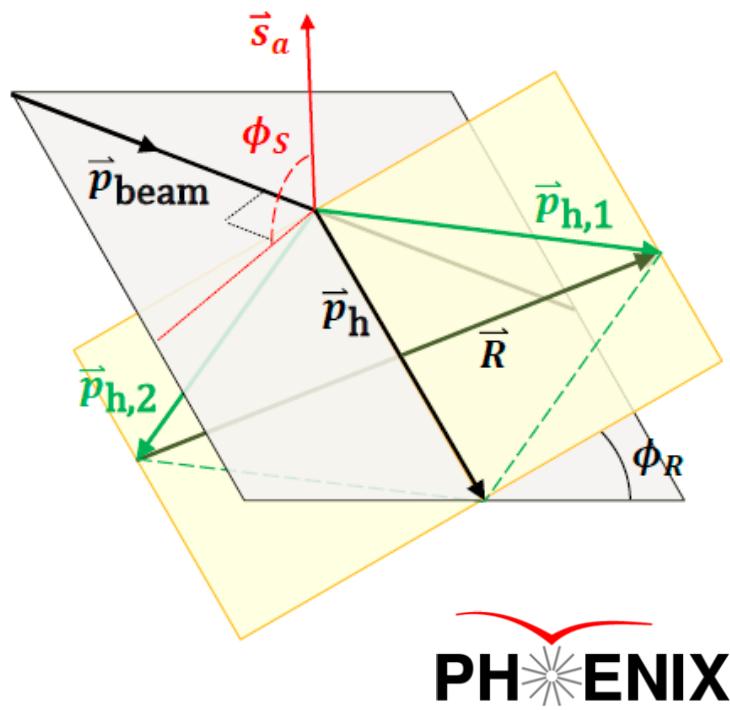


JHEP 0806 (2008)



Phys. Lett. B 736 (2014)

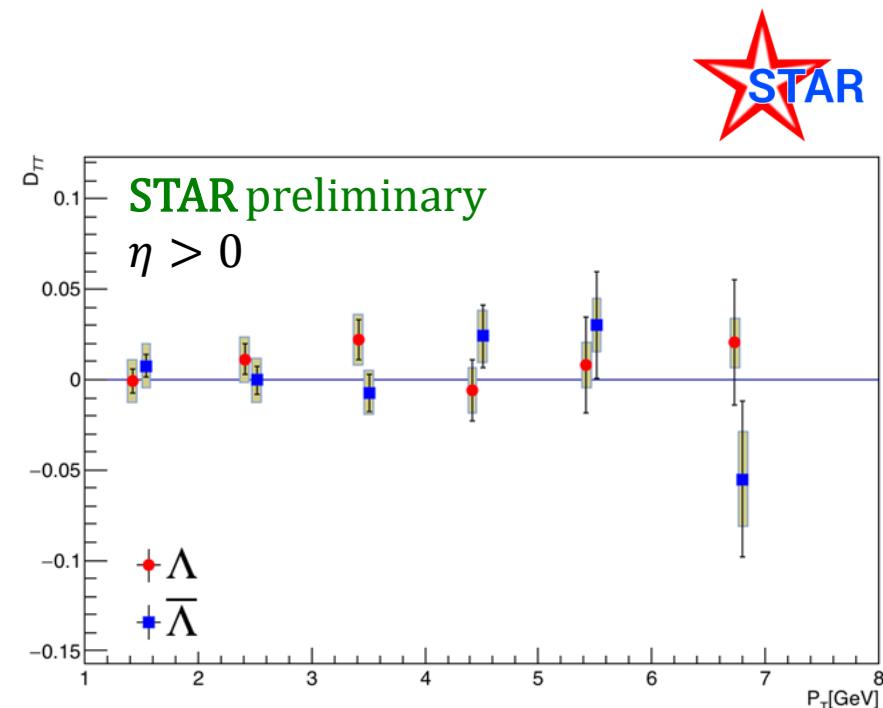
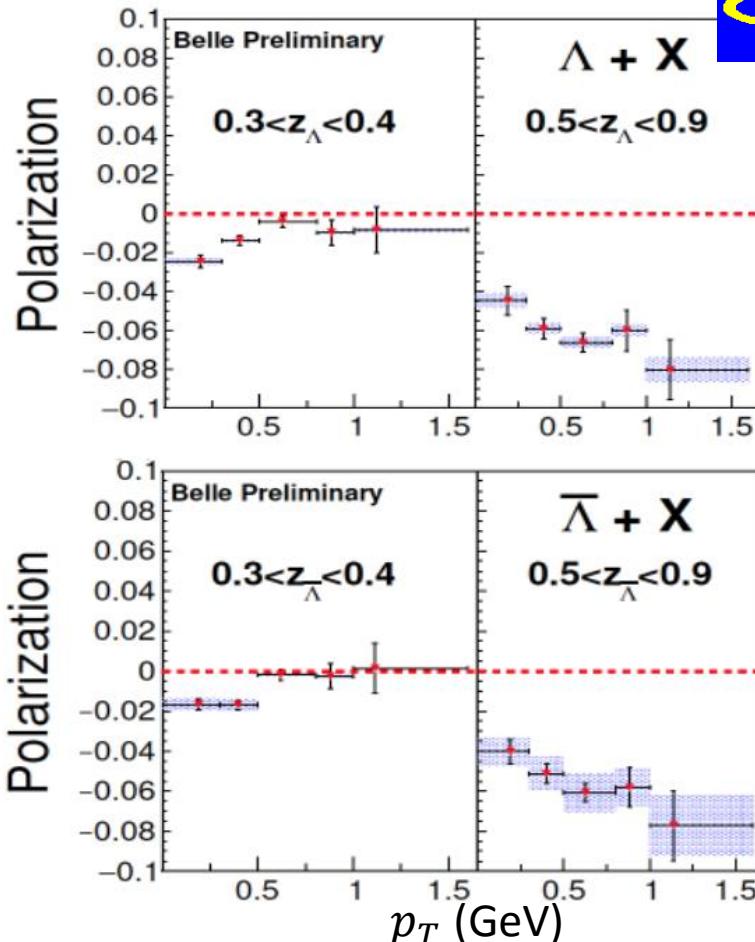
IFF in $p + p$



Outside the Box



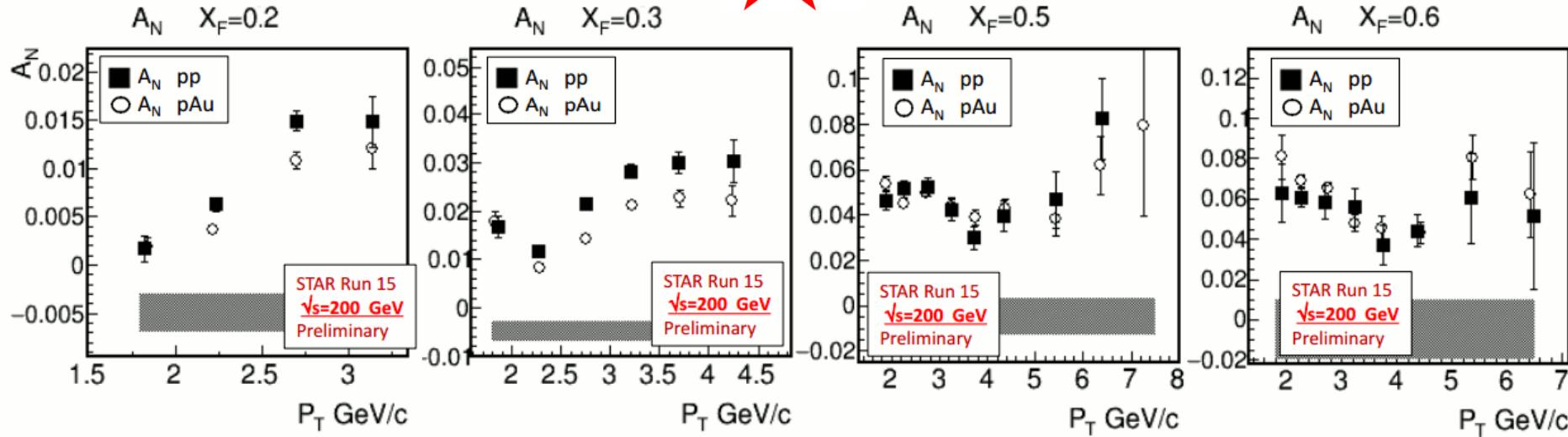
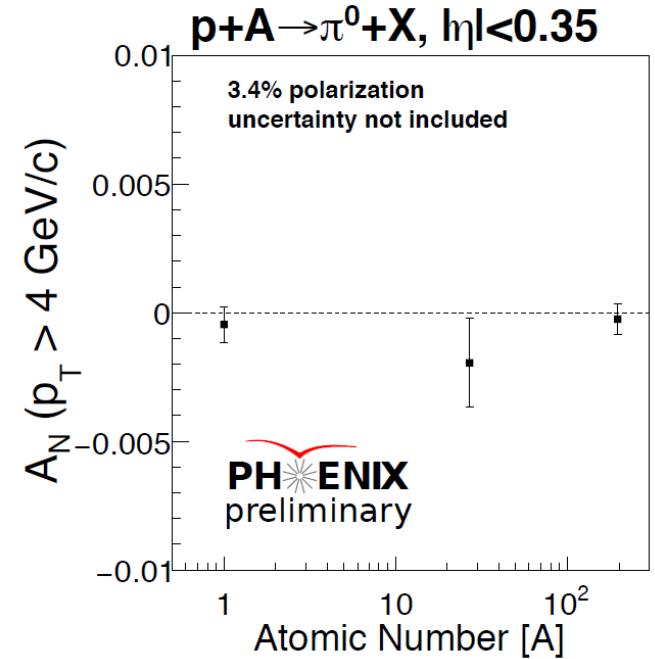
$\Lambda/\bar{\Lambda}$ Polarization



- Access to transversity \otimes fragmentation
- Transverse spin transfer coefficient D_{TT} (w.r.t. jet as quark proxy)
- Similar results in backward direction
- Talk by Y. Guan
- Talk by J. Mei
- Also flavor tagged results:
 $\Lambda/\bar{\Lambda} + \pi^\pm/K^\pm$

Cold Nuclear Matter Effects

- Polarized $\vec{p} + A$ collisions
- Possibly gluon saturation effects
- Nuclear effects on fragmentation process
- Talks by C. Xu, S. Heppelmann, N. Novitzky
- $A_N^{J/\Psi} < 0$; 2σ sigma significance



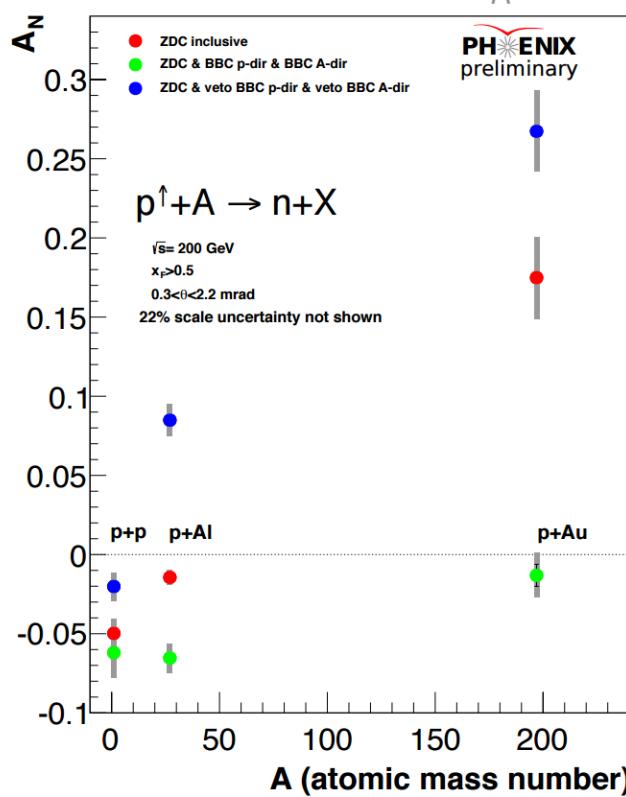
Recent Transverse Spin Surprises

$$p^\uparrow + A \rightarrow n + X$$

Very forward rapidities in ZDC

Unexpected strong A-dependence

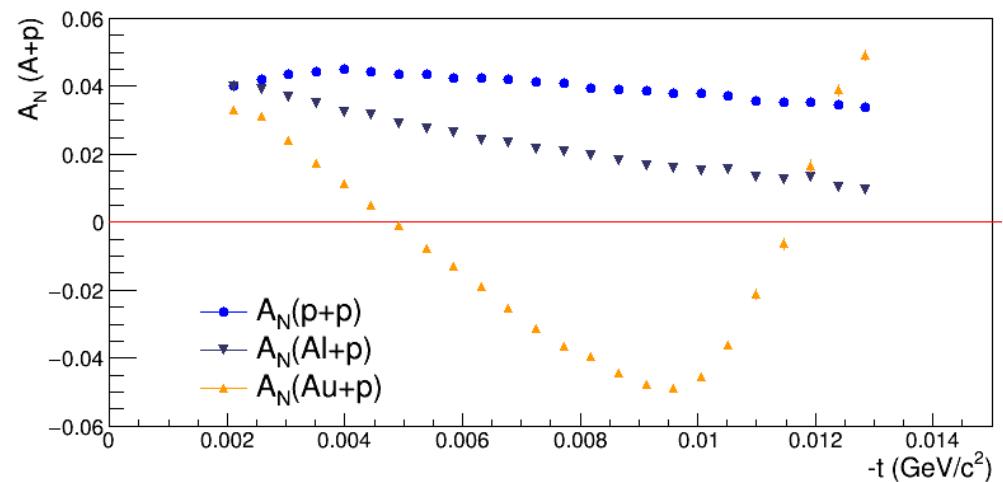
Talk by M. Kim

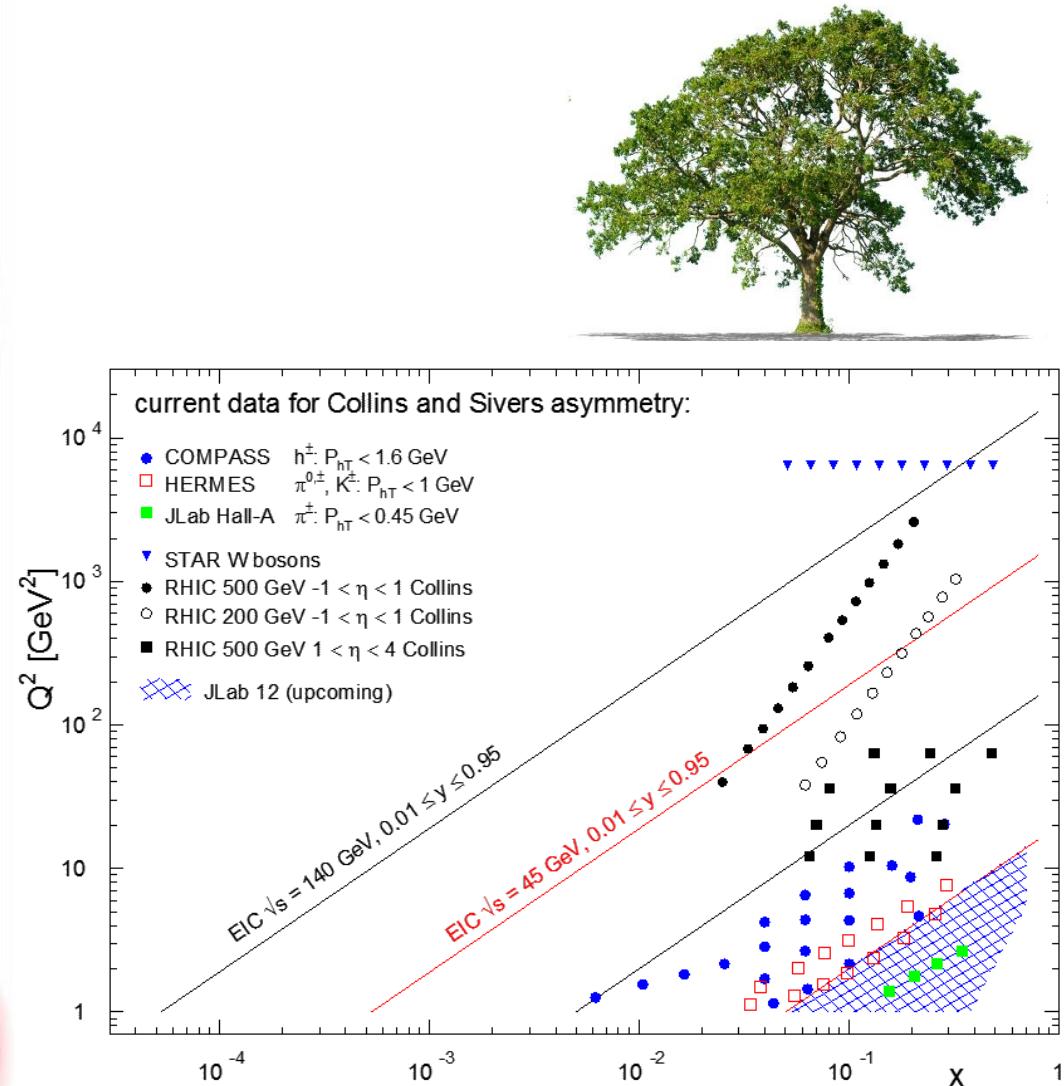
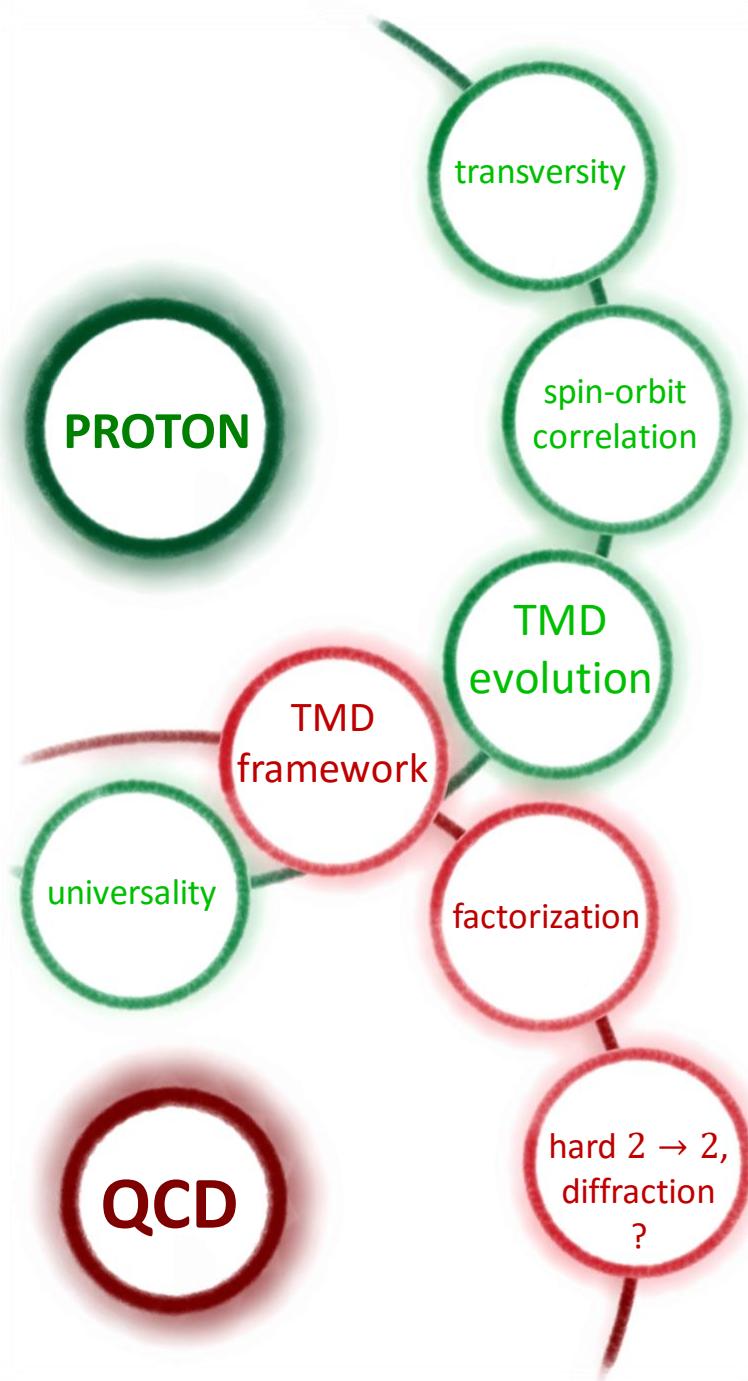


Elastic proton scattering $A + p^\uparrow$

From RHIC polarimeter

Strong A-dependence with sign change





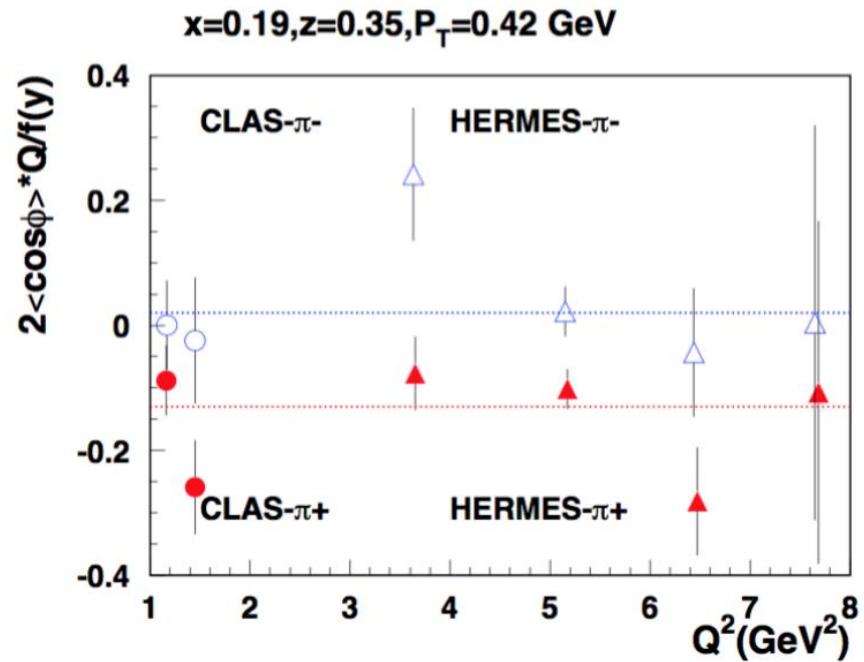


BACK UP

Boer-Mulders $\cos \phi_h$ Moments

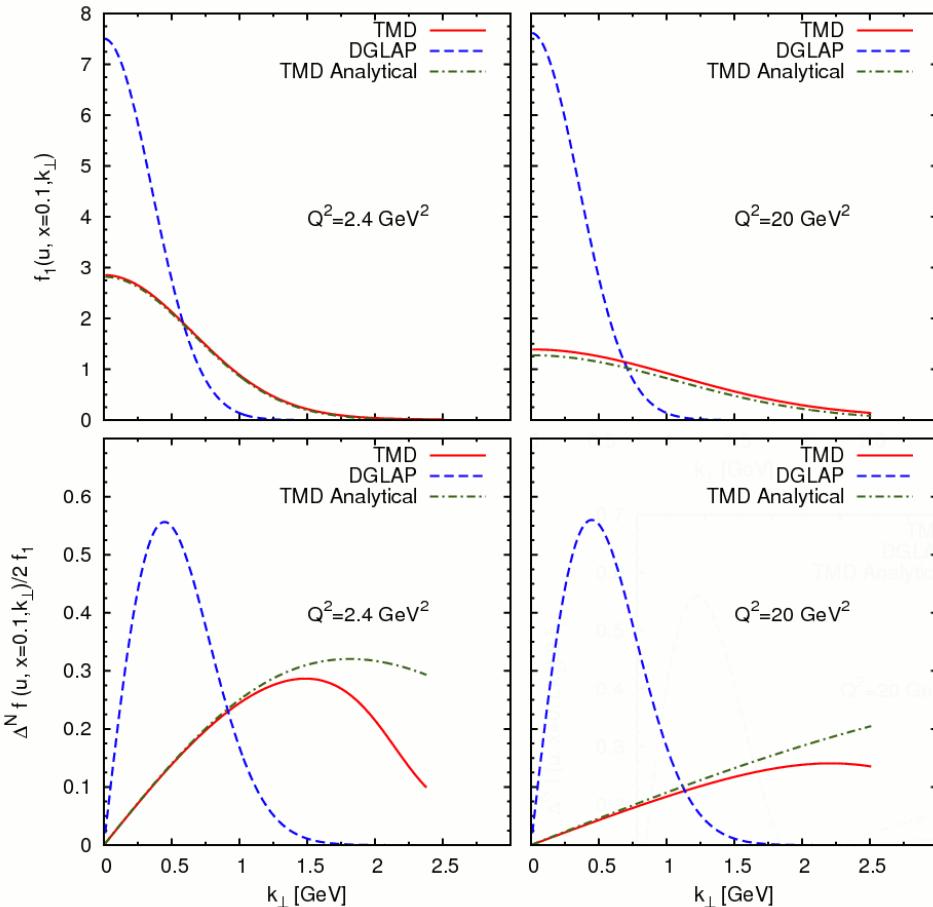
$$F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon) \cos \phi_h F_{UU}^{\cos \phi_h}}$$

$$F_{UU}^{\cos \phi_h} = \frac{2M}{Q} \mathcal{C} \left[\frac{\hat{h} \cdot p_\perp}{z M_h} \frac{k_\perp^2}{M^2} h_1^\perp H_1^\perp - \frac{\hat{h} \cdot k_\perp}{M} z f_1 D_1 \right]$$



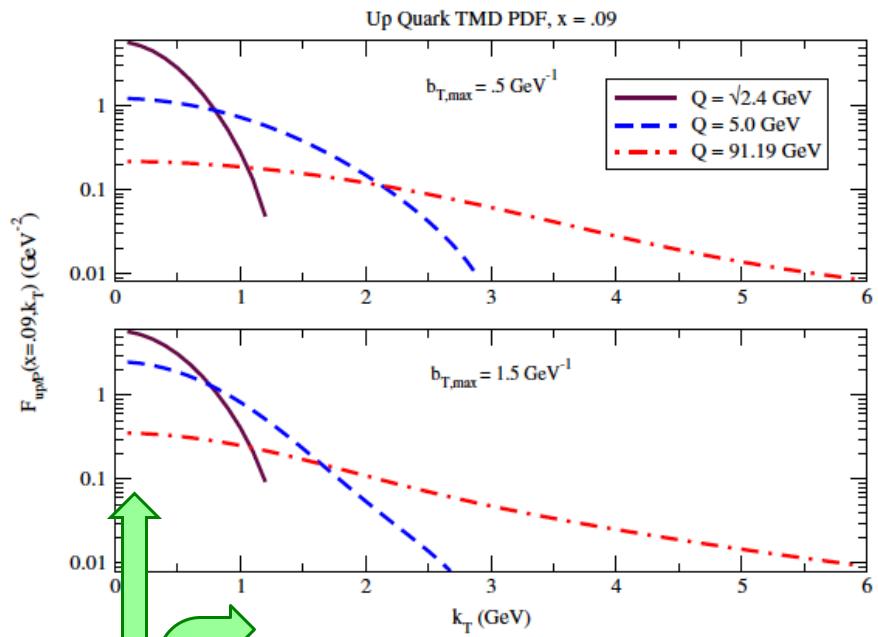
Q^2 Evolution

PDF evolution
TMD evolution
Twist-3 evolution



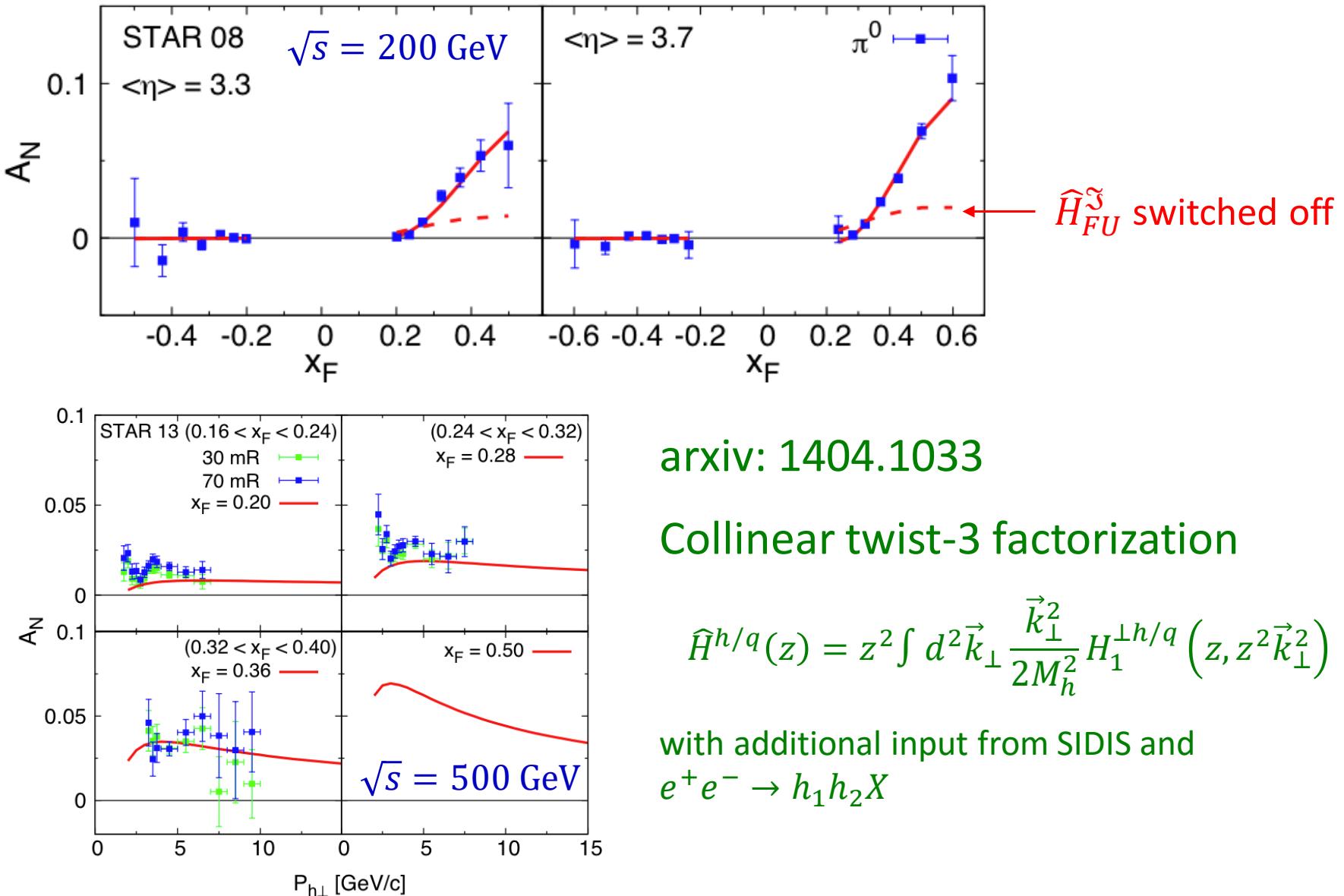
$$Q_0^2 = 1 \text{ GeV}^2$$

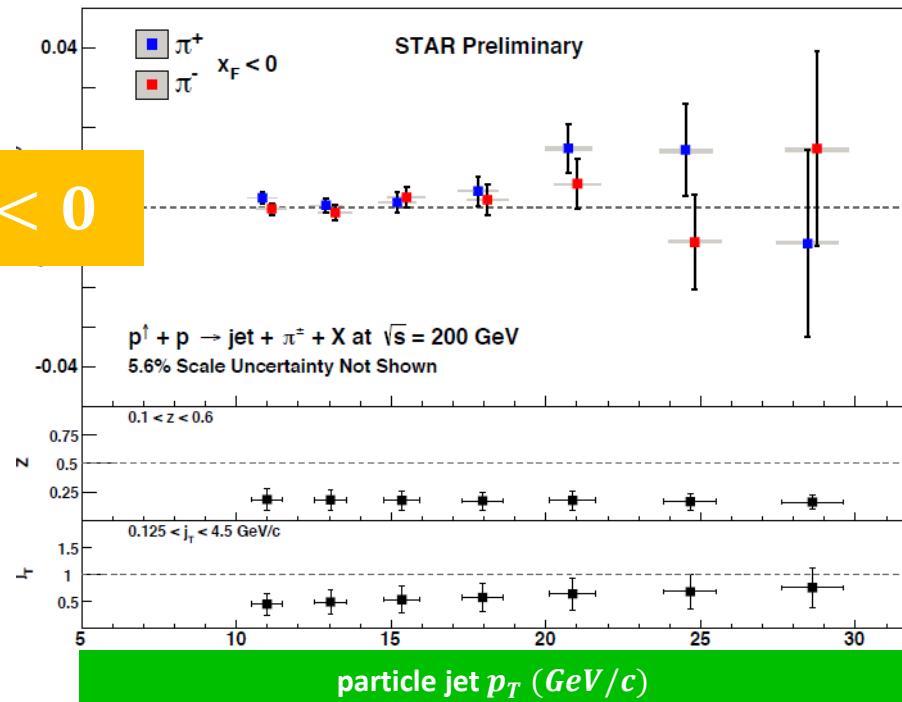
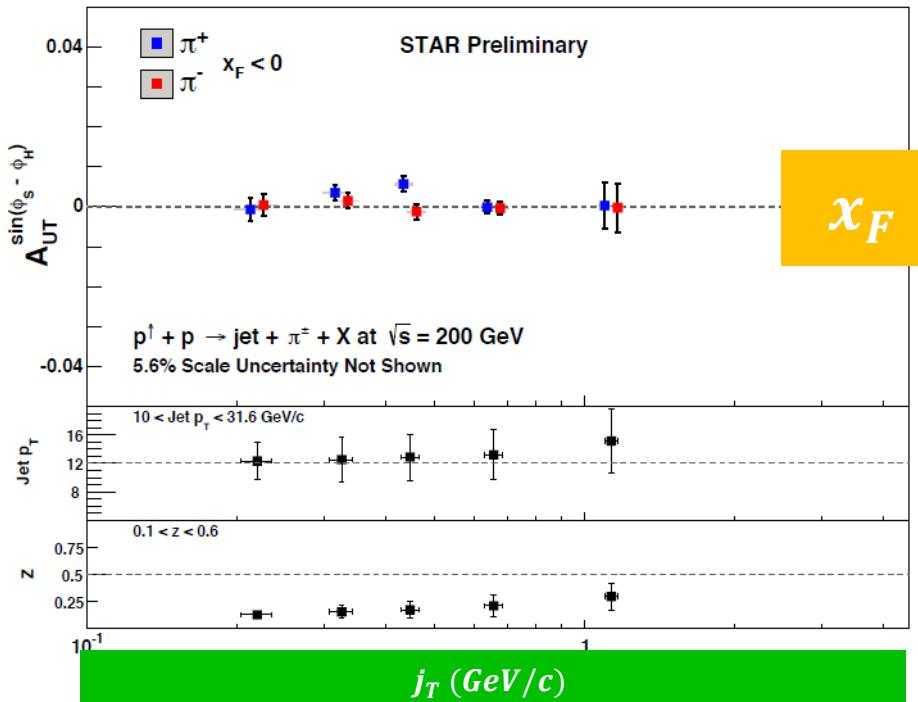
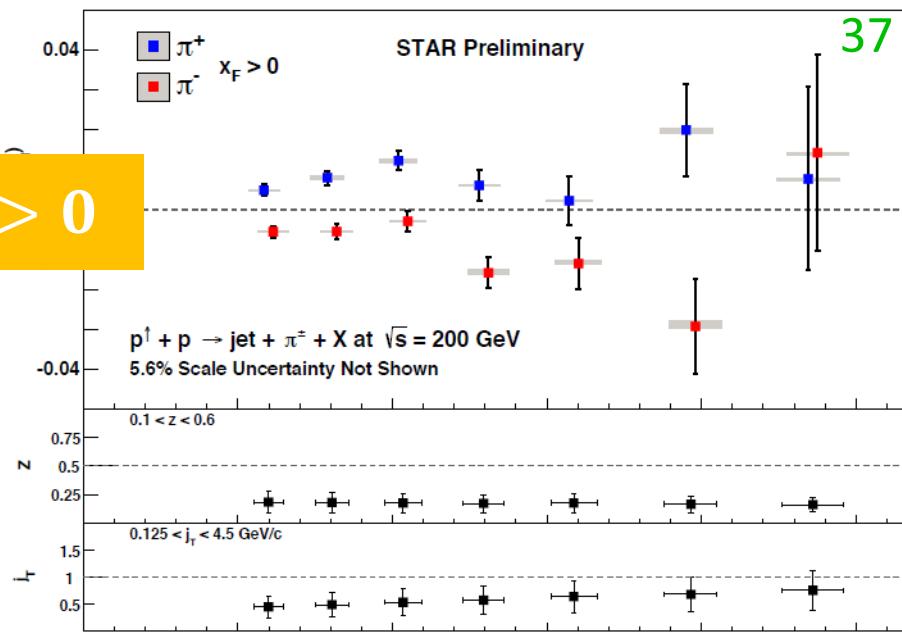
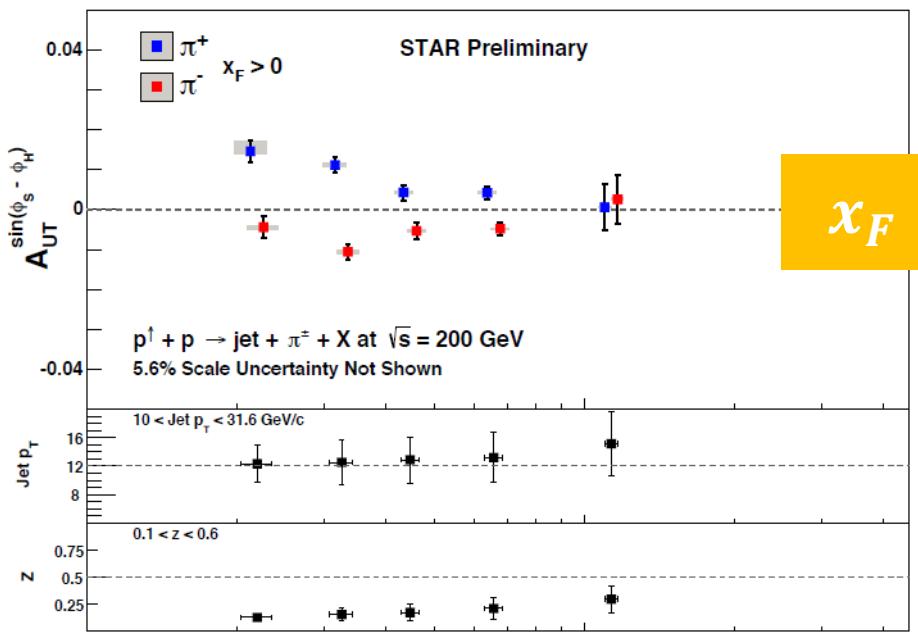
Phys Rev D86, 014028 (2012)



non-perturbative part is empirical input for evolution kernel

Fragmentation Effects



 $j_T (\text{GeV}/c)$ particle jet $p_T (\text{GeV}/c)$

Ideally...

Drell-Yan Production

$$p^\uparrow + p \rightarrow \gamma^* \rightarrow l^+ + l^-$$

$$\sqrt{s} = 500 \text{ GeV}$$

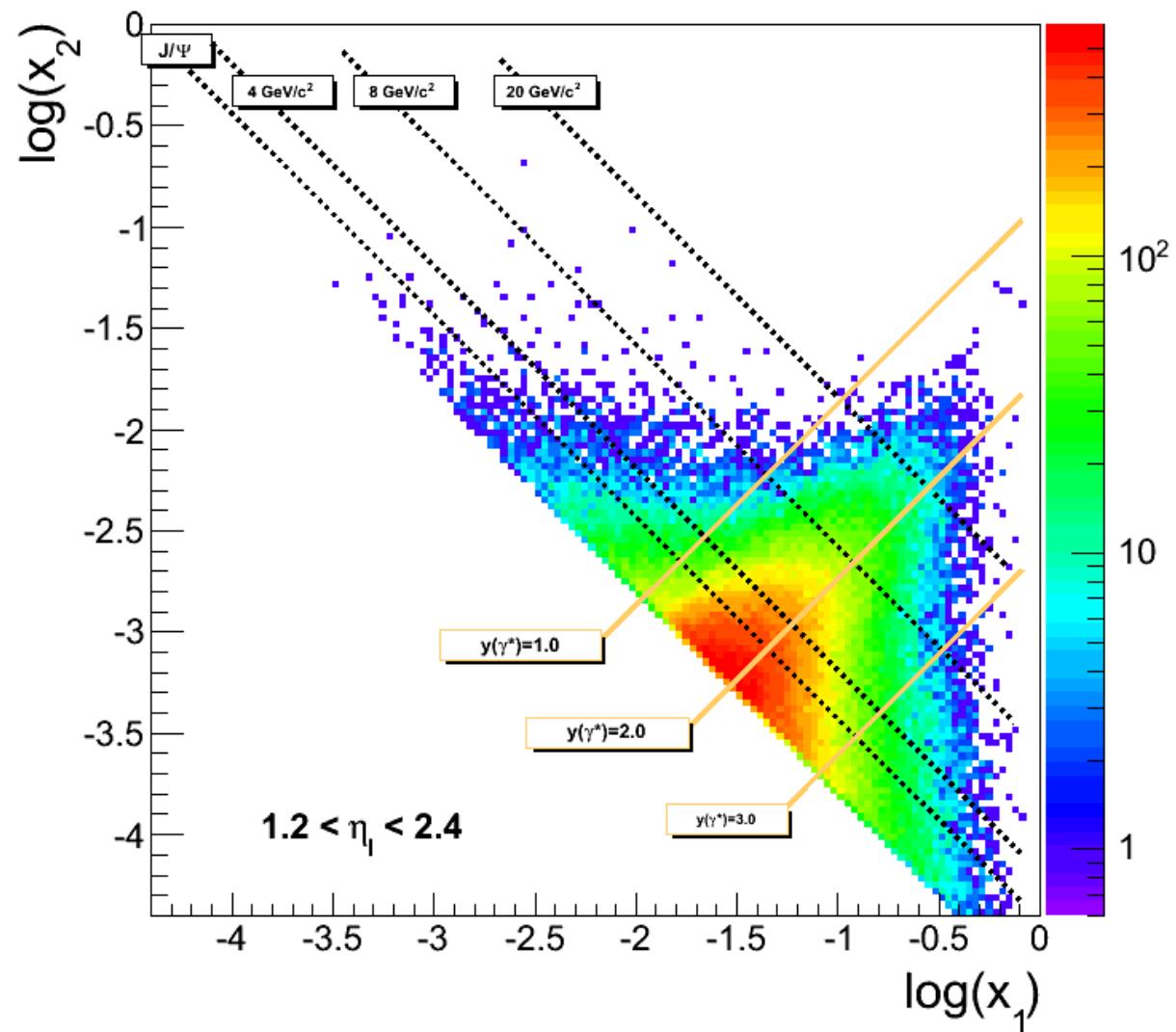
$$Q^2 = M^2 \gg p_T^2$$

Get rid of background

Scan x with rapidity

Accumulate a few fb^{-1}

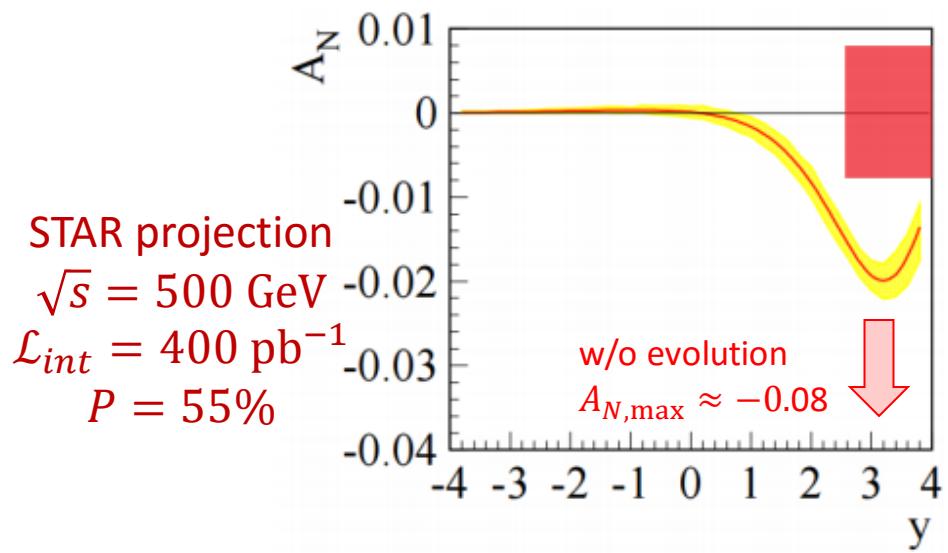
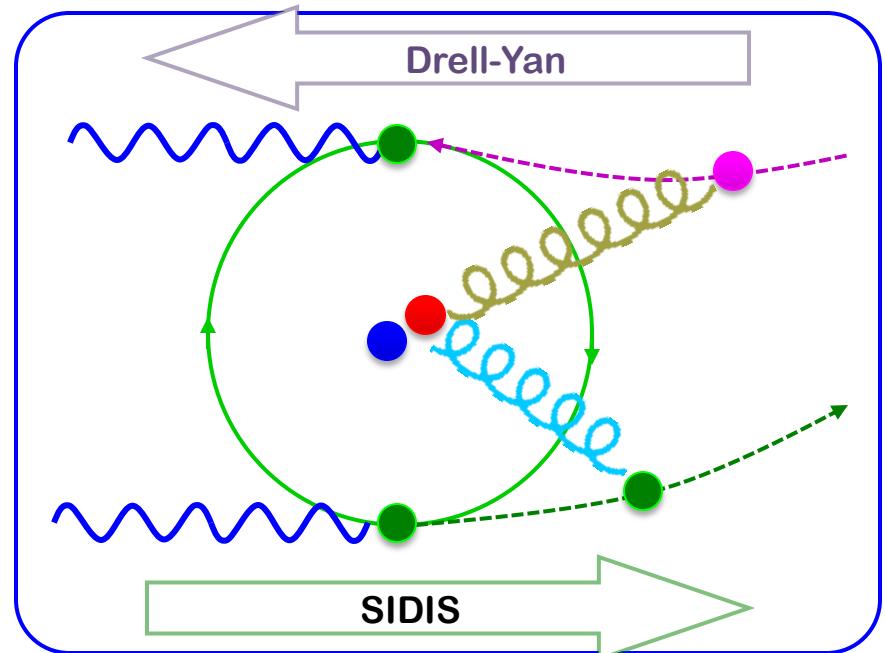
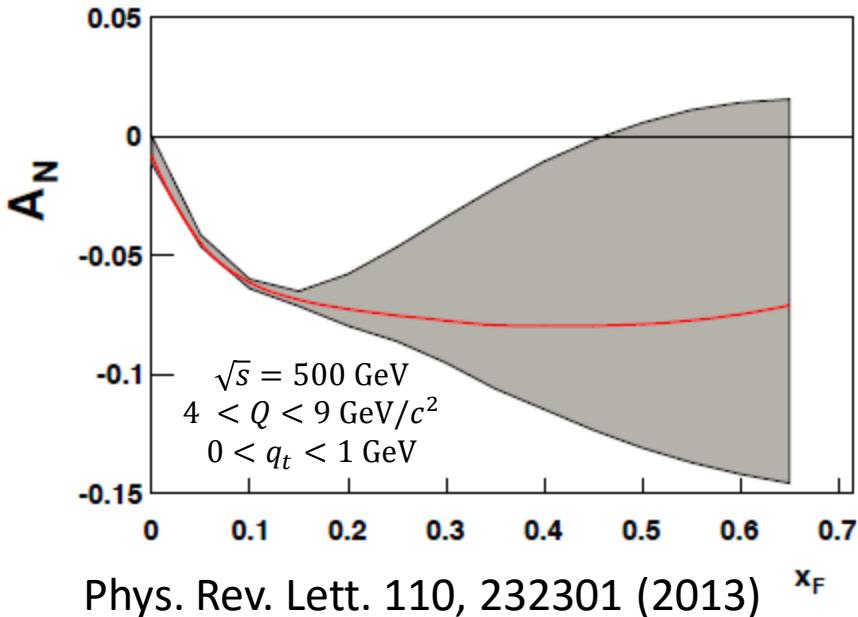
...



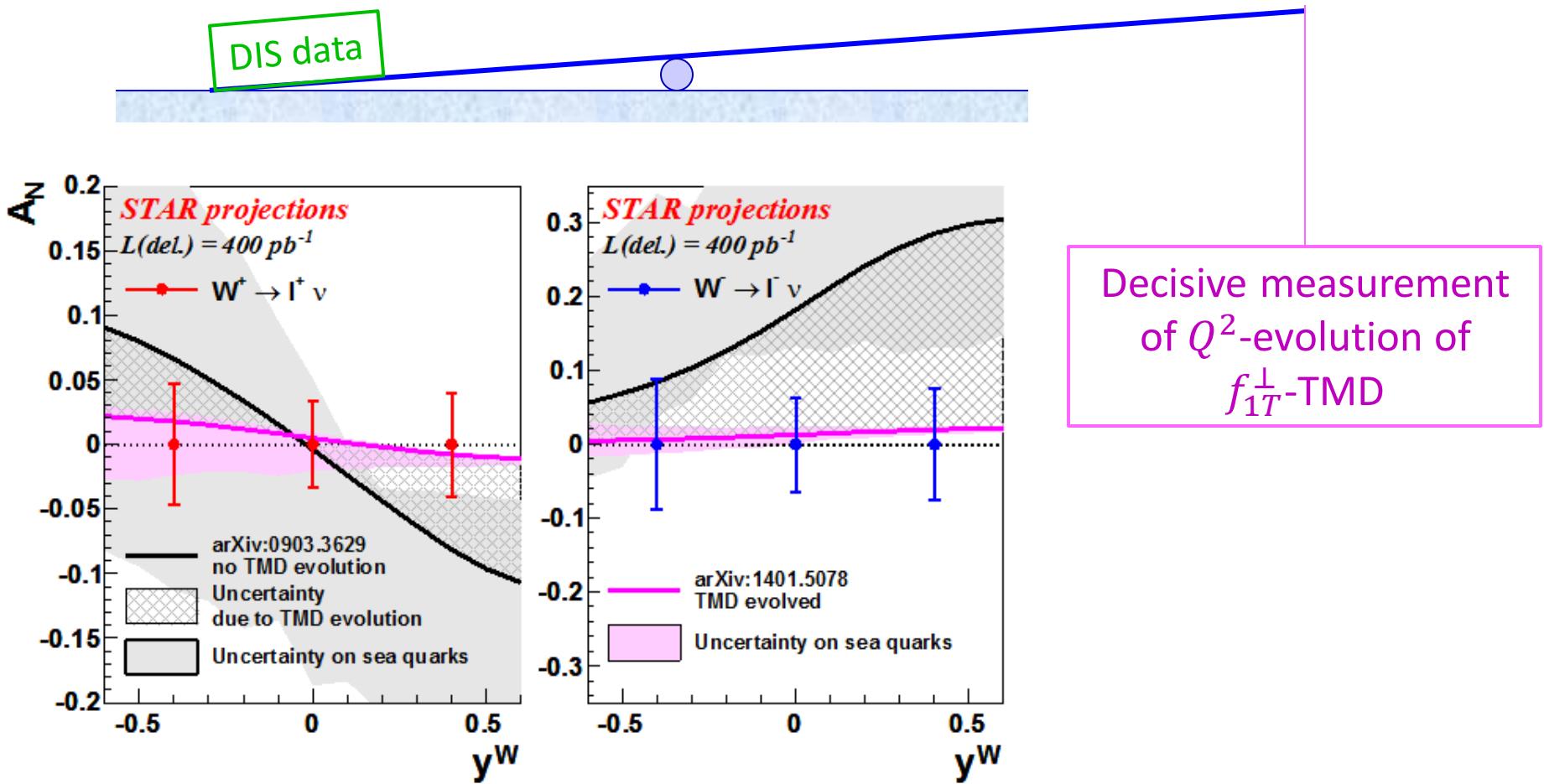
Factorization & Universality

Compare SIDIS and Drell-Yan production

- expect a sign-change in the asymmetry from spin-orbit correlations
- Non-universality of Sivers function (and others)

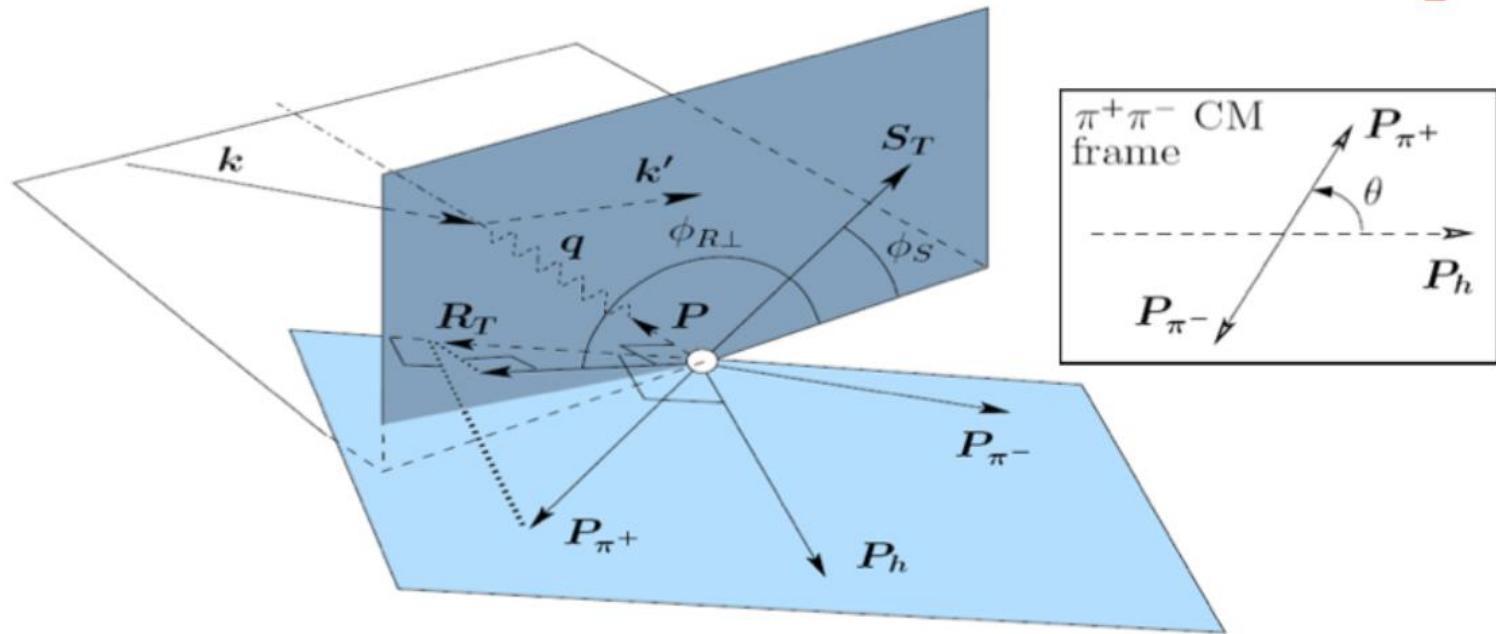


More W-Bosons in 2017...



Address universality of f_{1T}^\perp in combination with Drell-Yan, Z^0 , and direct photons
 (current W^\pm favors sign change 7.4 vs. 19.6 [per 6 n.d.f.])

Interference Fragmentation in SIDIS



$$\vec{P}_h = \vec{P}_1 + \vec{P}_2$$

$$\vec{R} = \frac{1}{2}(\vec{P}_1 - \vec{P}_2)$$

$$\vec{R}_T = \vec{R} - \frac{\vec{R} \cdot \vec{P}_h}{|\vec{P}_h|^2} \vec{P}_h$$

angles $\phi_{R\perp}$ and θ