Hall A SIDIS

Jefferson Lab

Hall A/C collaboration Meeting
June 24 2016

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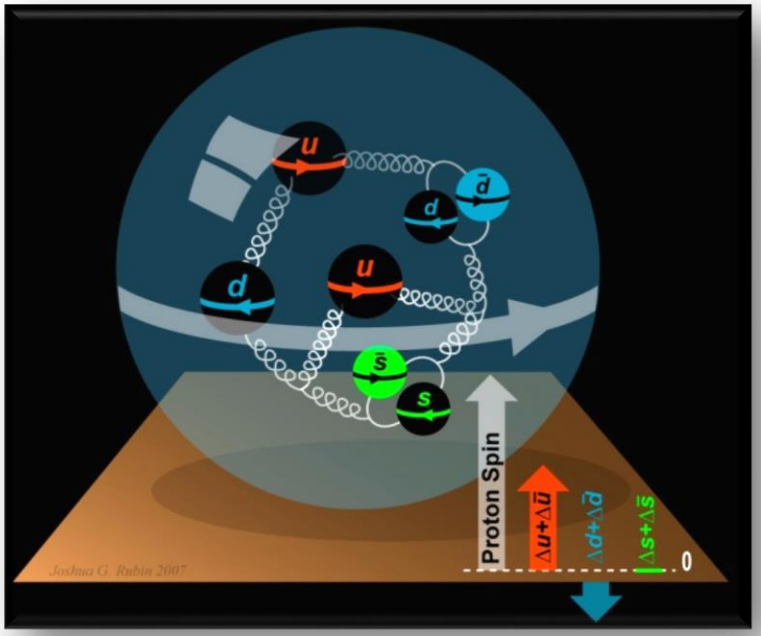
E06-010 Collaboration
Hall A collaboration

Duke UNIVERSITY

TUNL

The Incomplete Nucleon: Spin Puzzle

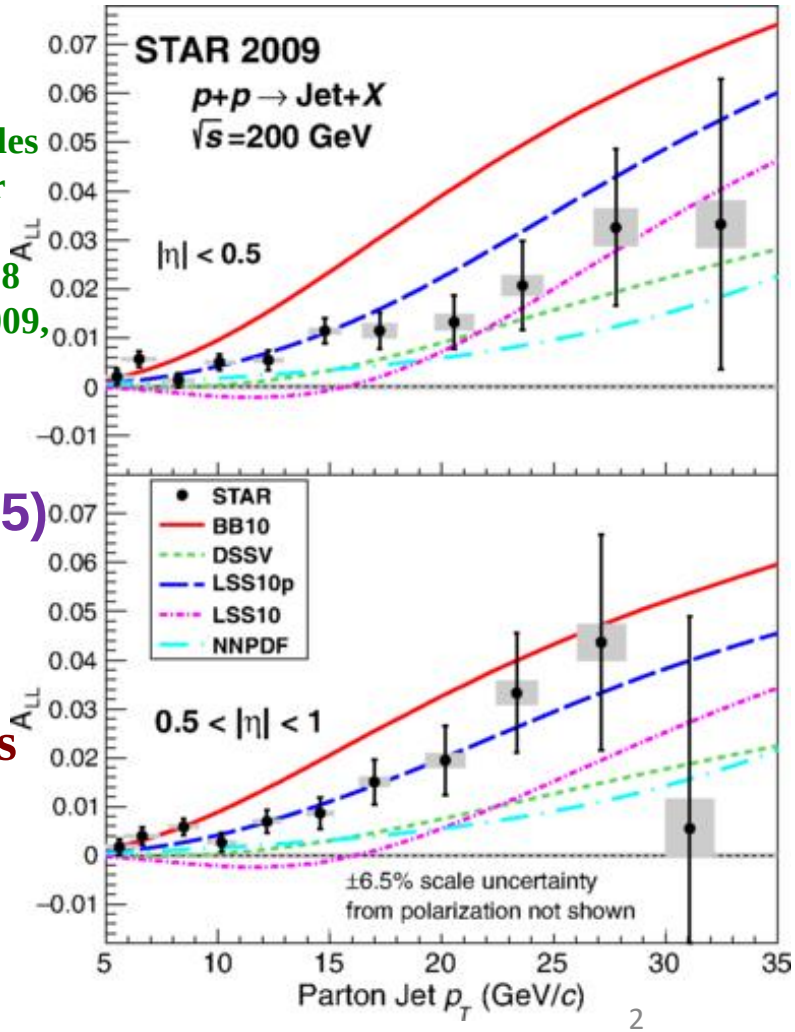


$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma(\mu) + L_q(\mu) + J_g(\mu)$$

[X. Ji, 1997]

Other spin sum rules
- Jaffe-Manohar 1990
- Chen et al. 2008
- Wakamatsu 2009, 2010

PRL 115, 092002 (2015)



- DIS → $\Delta\Sigma \cong 0.30$
- RHIC + DIS → Δg not small
- → L_q

Orbital angular momentum of quarks and gluons is important

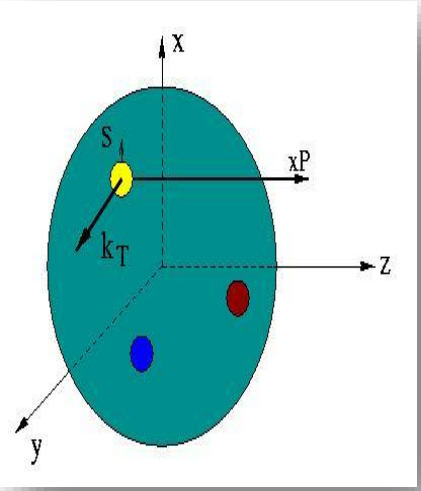
Understanding of spin-orbit correlations (atomic hydrogen, topological insulator…..)

How to access OAM?

Unified View of Nucleon Structure

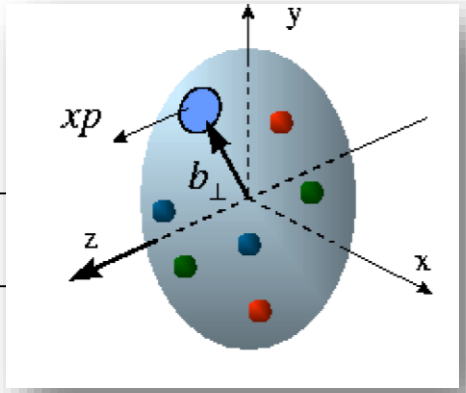
$W_p^u(x,k_T,\boldsymbol{r_T})$ Wigner distributions

5D Dist.



$d^2\boldsymbol{r_T}$

d^2k_T



TMD PDFs
$f_1^u(x,k_T)$, ..
$h_1^u(x,k_T)$

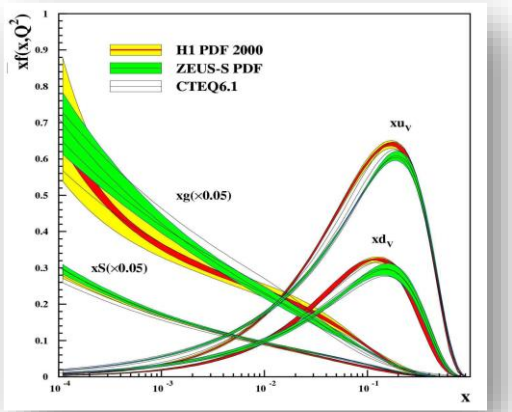
GPDs/IPDs

3D imaging

d^2k_T

d^2r_T

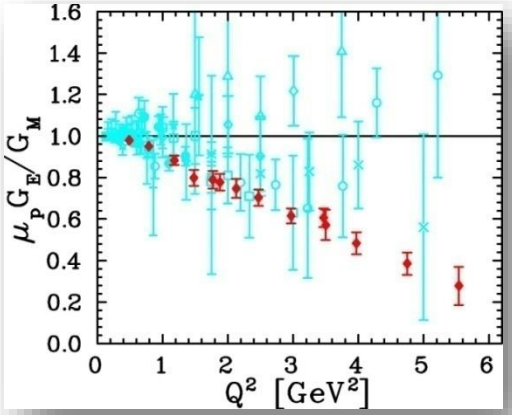
dx &
Fourier Transformation



PDFs
$f_1^u(x)$, ..
$h_1^u(x)$

1D

Form
Factors
$G_E(Q^2)$,
$G_M(Q^2)$



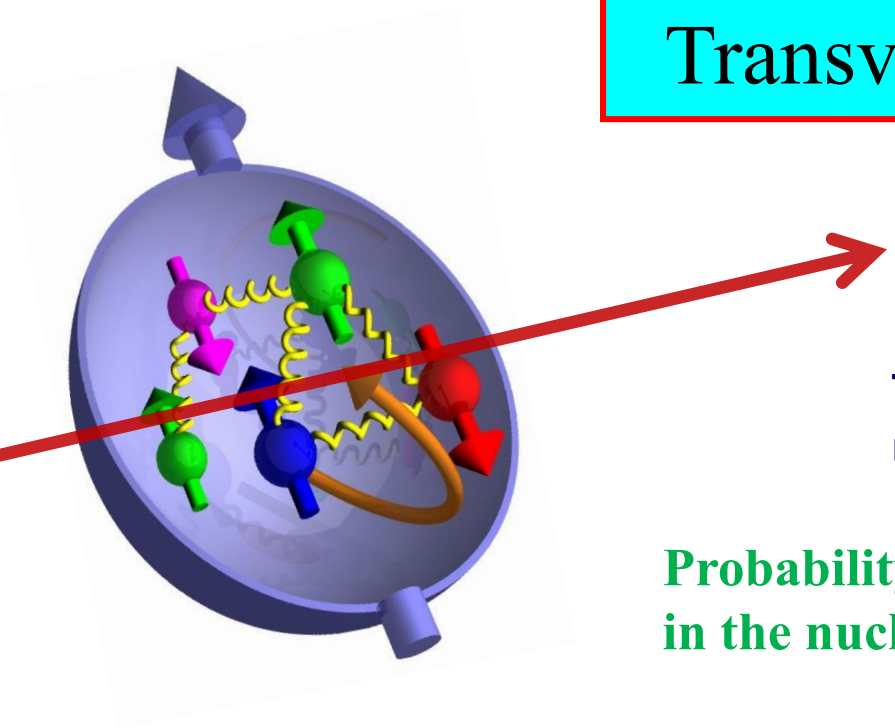
Leading-Twist TMD PDFs

Nucleon Spin

Quark Spin

Nucleon Polarization	Quark polarization: Unpolarized (U)	Quark polarization: Longitudinally Polarized (L)	Quark polarization: Transversely Polarized (T)
U	f_1		$h_1^{\perp}$ – **Boer-Mulders**
L		g_1 – **Helicity**	$h_{1L}^{\perp}$ – **Long-Transversity**
T	$f_{1T}^{\perp}$ – **Sivers**	g_{1T} – **Trans-Helicity**	h_1 – **Transversity** $h_{1T}^{\perp}$ – **Pretzelosity**

Transverse Spin Structure



Longitudinal Spin structure function: g_{1L}
Its transverse spin counter part
(**Transversity**): h_{1T}

They are not the same due to relativity: rotation and boost do not commute

Probability for quark polarized in the nucleon spin direction

Q: how to probe it?

Transversity: Chiral-odd

No mixing with gluon
Simpler evolution effect

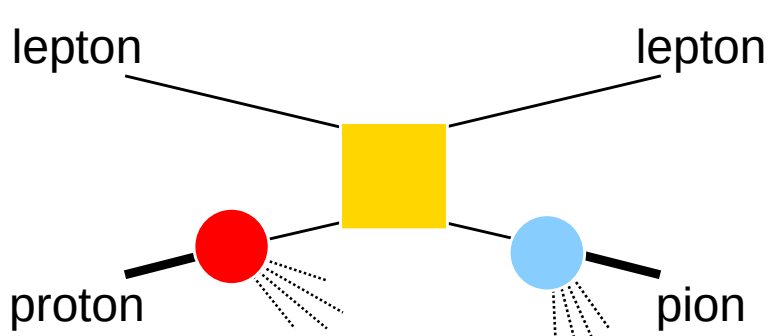
Not accessible via DIS process
Must couple to another chiral-odd function: e.g. Collins function

Semi-inclusive deep inelastic scattering (SIDIS)

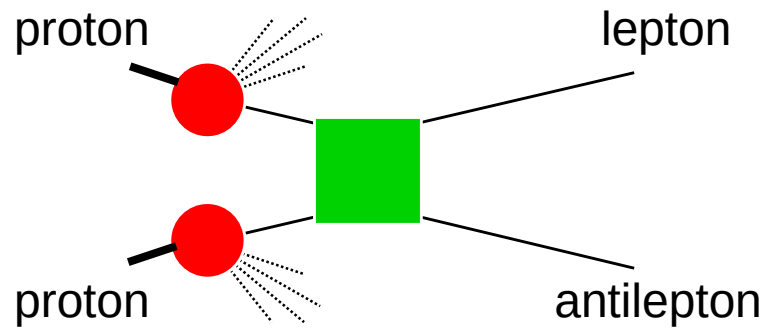
Measure the single spin asymmetry (SSA)

Transverse Momentum-dependent parton distributions (TMDs)

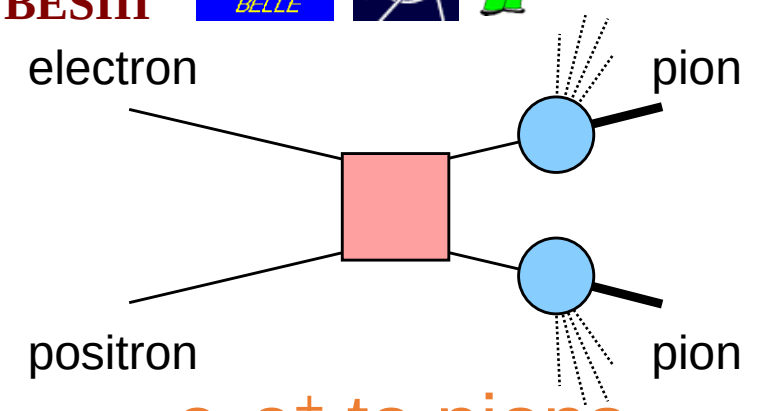
Access TMDs through Hard Processes



SIDIS



Drell-Yan



e^-e^+ to pions

Partonic scattering amplitude

Fragmentation amplitude

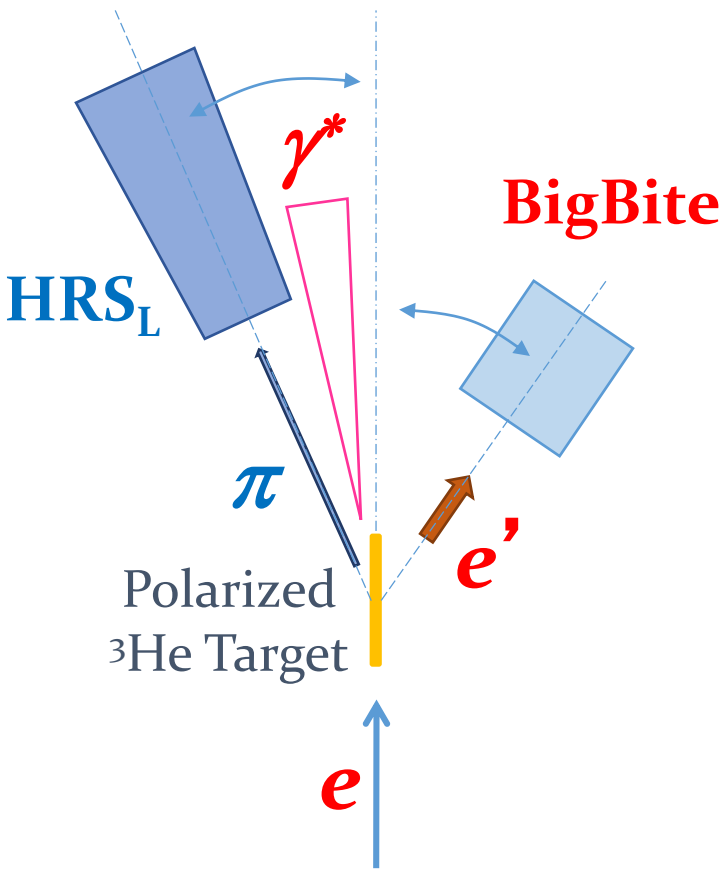
Distribution amplitude

$$f_{1T}^{\perp q}(\mathrm{SIDIS}) = -f_{1T}^{\perp q}(\mathrm{DY})$$

$$h_1^{\perp}(\mathrm{SIDIS}) = -h_1^{\perp}(\mathrm{DY})$$

RHIC Transverse Spin Program

E06-010: experimental configuration



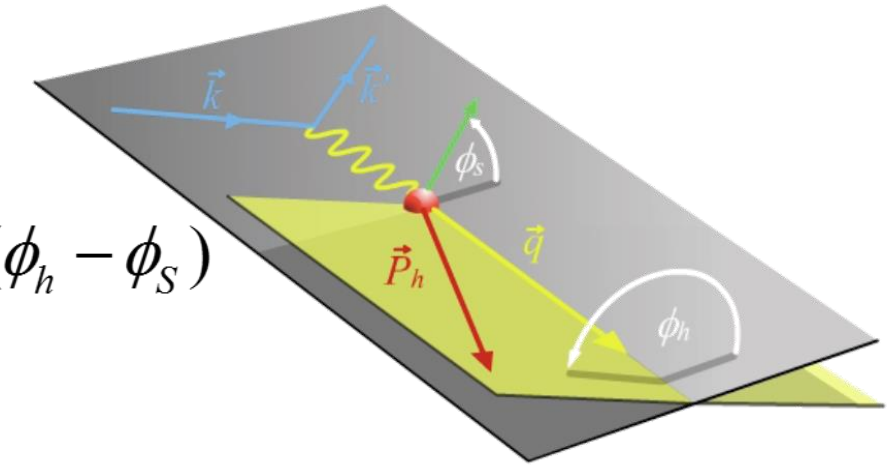
- ***First*** **neutron** data in SIDIS **SSA&DSA**
  - Similar Q^2 as HERMES experiment
- Results on SIDIS **unpolarized differential cross section**
- Electron beam: $\boldsymbol{E}$ = 5.9 GeV
  - High luminosity L ~ 10^{36} $cm^{-2}s^{-1}$
  - 40 cm transversely polarized ^{3}He target
  - Average beam current 12 uA (max: 15 uA as in proposal)
- BigBite at 30° as **electron** arm: $\boldsymbol{P_e}$ = 0.6 ~ 2.5 GeV/c
- HRSL at 16° as **hadron** arm: $\boldsymbol{P_h}$ = 2.35 GeV/c

Separation of Collins, Sivers and pretzelocity effects through angular dependence

$$A_{UT}(\varphi_h^l, \varphi_S^l) = \frac{1}{P}\frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$

$$= A_{UT}^{Collins} \sin(\phi_h + \phi_S) + A_{UT}^{Sivers} \sin(\phi_h - \phi_S)$$

$$+ A_{UT}^{Pretzelosity} \sin(3\phi_h - \phi_S)$$



$$A_{UT}^{Collins} \propto \langle \sin(\phi_h + \phi_S) \rangle_{UT} \propto h_1 \otimes H_1^{\perp}$$

Collins frag. Func. from e^+e^- collisions

$$A_{UT}^{Sivers} \propto \langle \sin(\phi_h - \phi_S) \rangle_{UT} \propto f_{1T}^{\perp} \otimes D_1$$

$$A_{UT}^{Pretzelosity} \propto \langle \sin(3\phi_h - \phi_S) \rangle_{UT} \propto h_{1T}^{\perp} \otimes H_1^{\perp}$$

SIDIS SSAs depend on 4-D variables (x, Q^2, z and P_T)
Large angular coverage and precision measurement of asymmetries in 4-D phase space is essential.

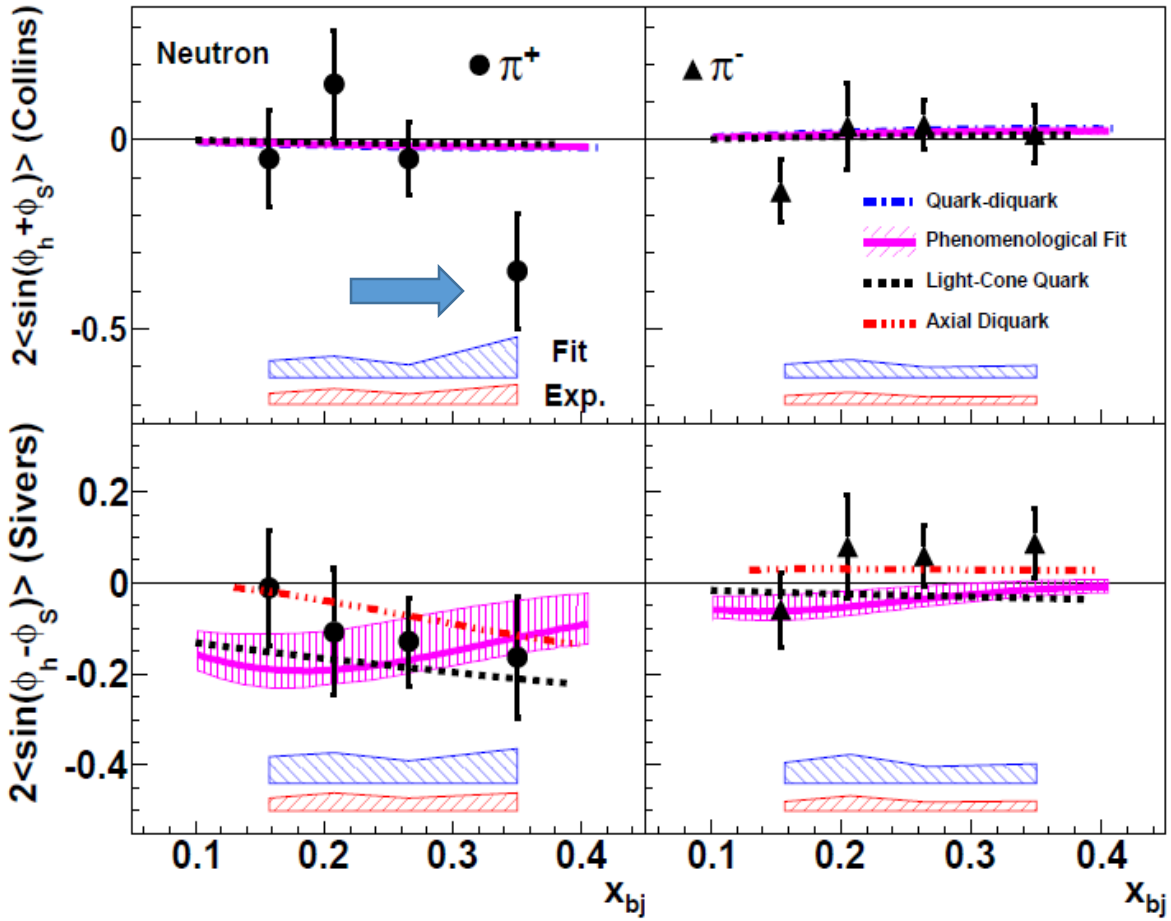
Published results from E06-010

- SIDIS Single Spin Asymmetries (SSA)
  - X. Qian *et al*, Phys. Rev. Lett. 107, 072003 (2011): sizable π^+ Collins asymmetry at x=0.34 & negative π^+ Sivers asymmetries of neutrons
  - Y. Zhang et al. Phys. Rev. C 90, 055209 (2014): Pretzelosity asymmetries consistent with 0 (within experimental uncertainties)
  - Y. X. Zhao et al. Phys. Rev. C 90, 055201 (2014): $K^{\pm}$ Collins & Sivers asymmetries
- Inclusive Single Spin Asymmetries (SSA)
  - K. Allada, et al. Phys. Rev. C 89, 042201 (2014): SSA for K^- & proton consistent with 0, SSA for $\pi^{\pm}$ has opposite sign from ^{3}He & neutron
- Double Spin Asymmetries (DSA)
  - J. Huang et al., Phys. Rev. Lett. 108, 052001 (2012): None-zero SIDIS $\pi^{\pm}$ $A_{LT}^{\cos(\phi_h-\phi_s)}$ DSA of neutrons, in CQ model → non-zero quark OAM
  - Y. X. Zhao et al. Phys. Rev. C 92 015207 (2015): $\pi^{\pm}$, $K^{\pm}$ & Proton Inclusive A_{LT}

Results on Neutron

- Sizable Collins π^+ asymmetries at x=0.34?
  - Sign of violation of Soffer's inequality?
  - **Data are limited by stat. Needs more precise data!**

- Negative Sivers π^+ Asymmetry
  - Consistent with HERMES/COMPASS



  - **demonstration of negative d quark Sivers function.**

Model (fitting) uncertainties shown in blue band.
Experimental systematic uncertainties: red band
X. Qian *et al*, Phys. Rev. Lett. 107, 072003 (2011)

Unpolarized differential cross section of Semi-Inclusive DIS

$$\frac{d\sigma}{dx dy d\phi_S dz d\phi_h dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)} \cdot \{\boldsymbol{F_{UU}}$$

Twist-2: no ϕ_h dependence

$$+\sqrt{2\epsilon(1-\epsilon)}\cos\phi_h \cdot \boldsymbol{F_{UU}^{cos\phi_h}}$$

Twist-3 Cahn effect: $\cos\phi_h$ dependence

$$+\epsilon\cos(2\phi_h) \cdot \boldsymbol{F_{UU}^{cos2\phi_h}}\}$$

Boer-Mulders & twist-4 Cahn : $cos2\phi_h$ dependence

- Cahn effect $\propto f_1 \otimes D_1$
  - Non-zero Cahn effect **solely require non-zero quark transverse momentum**
  - Related to quarks' **intrinsic transverse momentum distribution**
- Boer-Mulders effect $\propto h_1^\perp \otimes H_1^\perp$
  - Boer-Mulders TMD PDF: transversely polarized quarks in unpolarized nucleon
- Twist-4 Cahn effect could have similar size of contribution to $\langle\cos(2\phi_h)\rangle$ as Boer-Mulders [Phys. Rev. D. 81:114026 (2010) based on HERMES/COMPASS results]

Naïve x-z factorization & Gaussian ansatz

$$\boldsymbol{F_{UU}} = \sum_q e_q^2 x f_1(x) D_1(z) \exp\left(-\frac{P_t^2}{\langle P_T^2 \rangle}\right) / [\pi \langle P_T^2 \rangle]$$

$$\boldsymbol{F_{UU}^{cos\phi_h}}|_{Cahn} = -2\frac{P_T}{Q}\sum_q e_q^2 x\, f_1(x) D_1(z) \exp\left(-\frac{P_t^2}{\langle P_T^2 \rangle}\right) \frac{z\langle k_\perp^2 \rangle}{\pi \langle P_T^2 \rangle^2}$$

$$\boldsymbol{F_{UU}^{cos2\phi_h}}|_{Cahn} = 2\frac{P_T^2}{Q^2}\sum_q e_q^2 x f_1(x) D_1(z) \exp\left(-\frac{P_t^2}{\langle P_T^2 \rangle}\right) \frac{z^2 \langle k_\perp^2 \rangle^2}{\pi \langle P_T^2 \rangle^3}$$

$$\langle P_t^2 \rangle = \langle p_\perp^2 \rangle + z^2 \langle k_\perp^2 \rangle$$ Gaussian widths

$$f_1(x, k_\perp) = f_1(x)\, \frac{e^{-k_\perp^2/\langle k_\perp^2 \rangle}}{\pi \langle k_\perp^2 \rangle}$$ TMD PDF with Gaussian ansatz

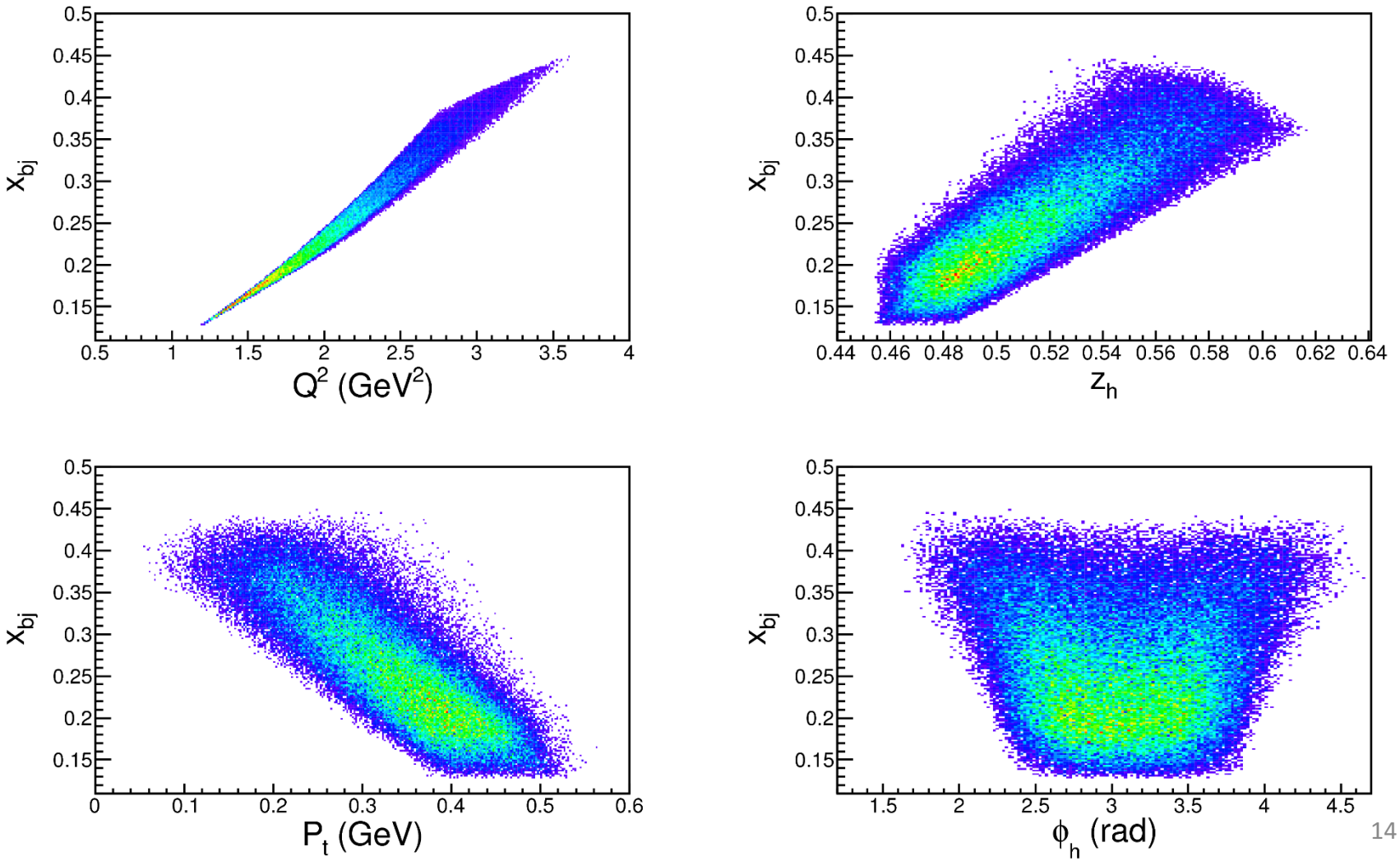
$$D_1(z, k_\perp) = D_1(z)\, \frac{e^{-p_\perp^2/\langle p_\perp^2 \rangle}}{\pi \langle p_\perp^2 \rangle}$$ TMD FF with Gaussian ansatz

Barone, et al. PRD 91 074019 (2015)

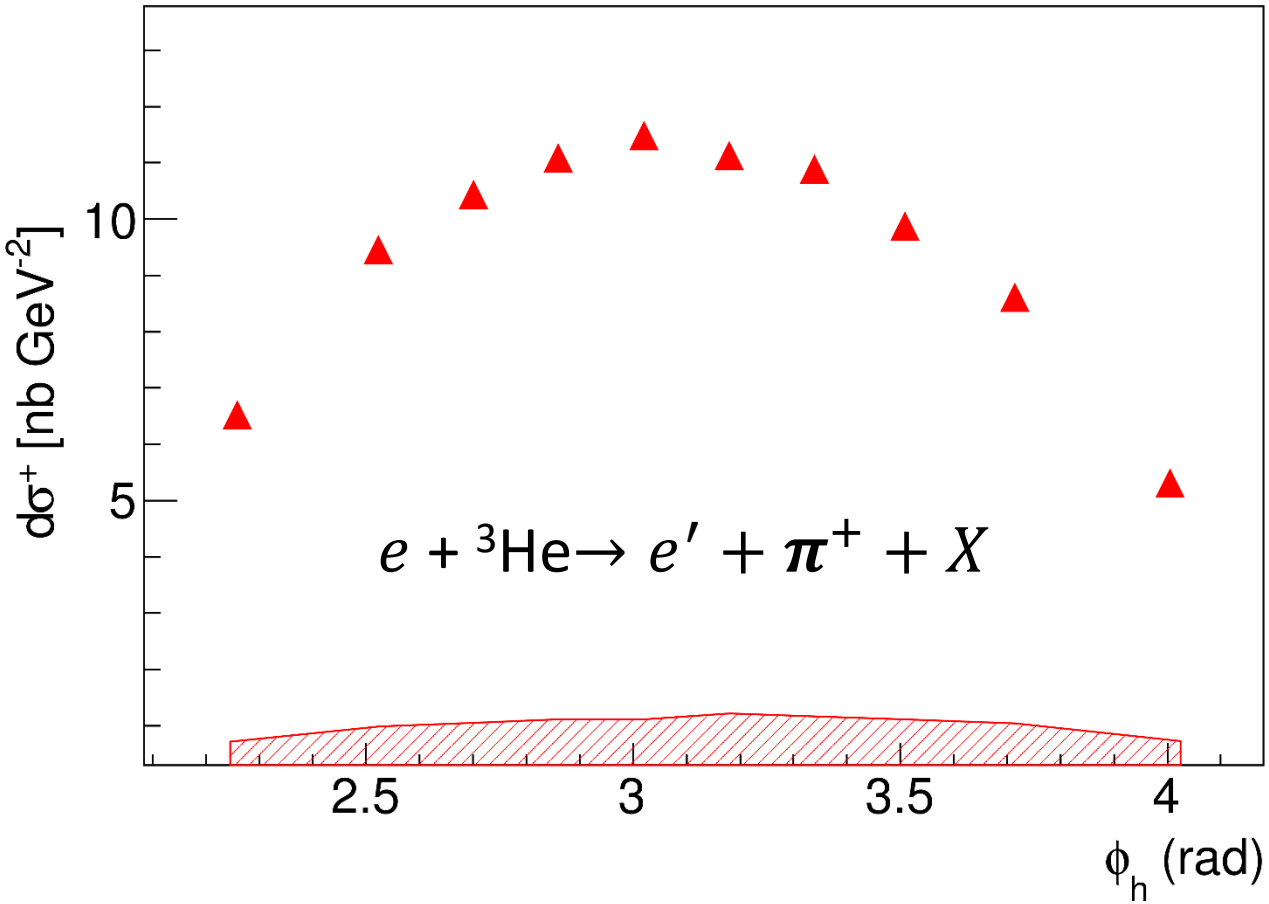
Unpolarized differential cross section

- Combine data with different target and beam polarizations for unpolarized cross section analysis
  - Radiative correction for unpolarized process
- Detector models in simulation for description of experimental acceptance
  - Simulation vs. data in HRS and BigBite detector individually: inclusive DIS and elastic e-p processes
- Updated efficiency and contamination study with higher precision than SSA & DSA analysis (Sys. Uncertainty control)

Experimental acceptance & kinematic correlation

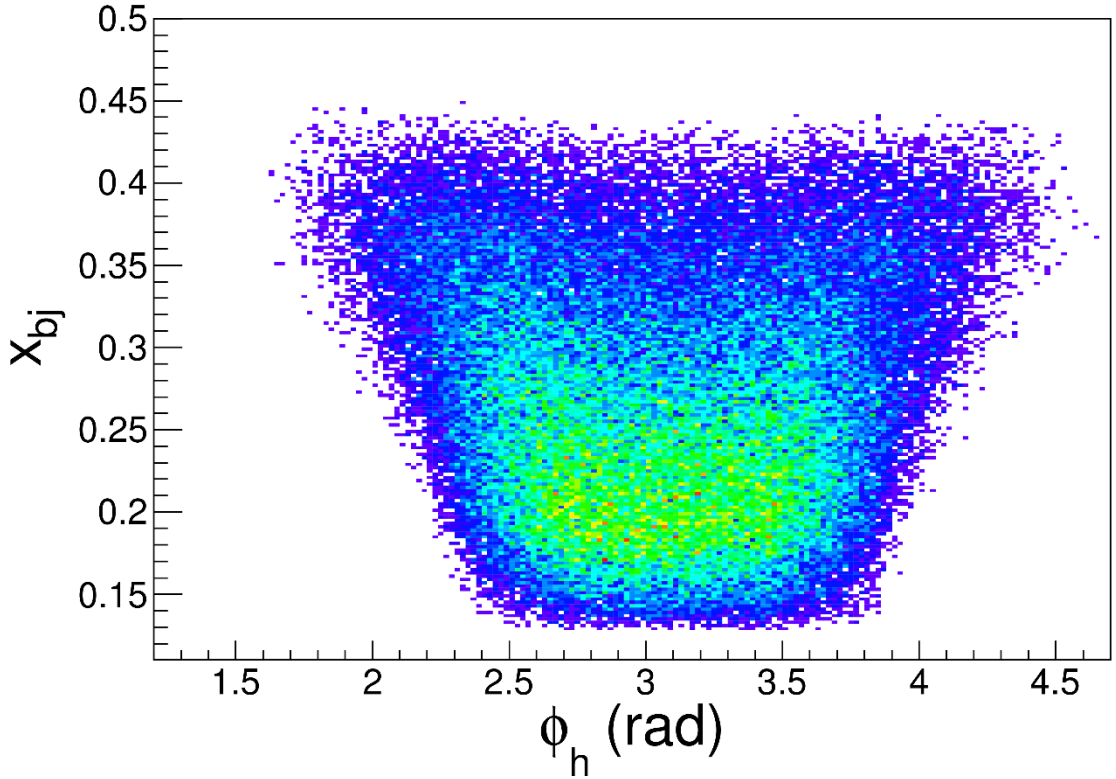


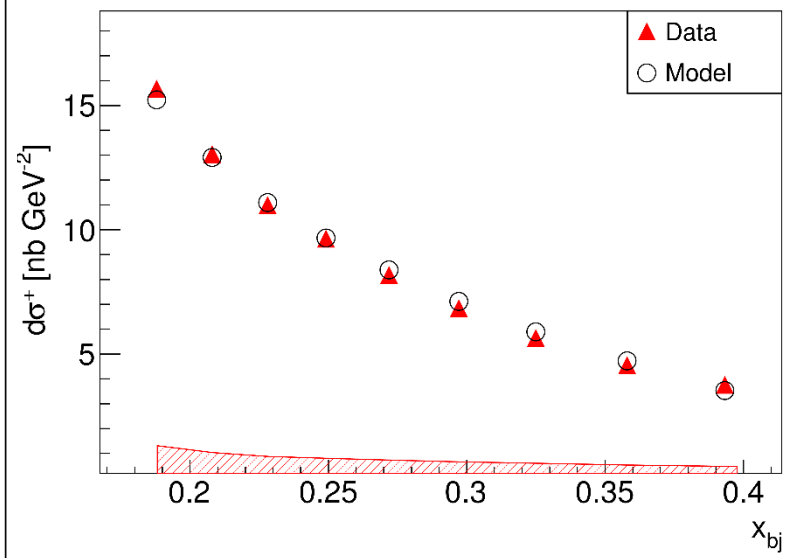
SIDIS differential cross section from data in 1D ϕ_h bins



- The $cos\phi_h$-like behavior is due to kinematic correlation
- If use model to do bin center correction (BCC) here: big model dependence
- Solution: multi-dimensional binning & BCC in small range

$\cos\phi_h$-like signal: x vs. ϕ_h and x dependence of cross section





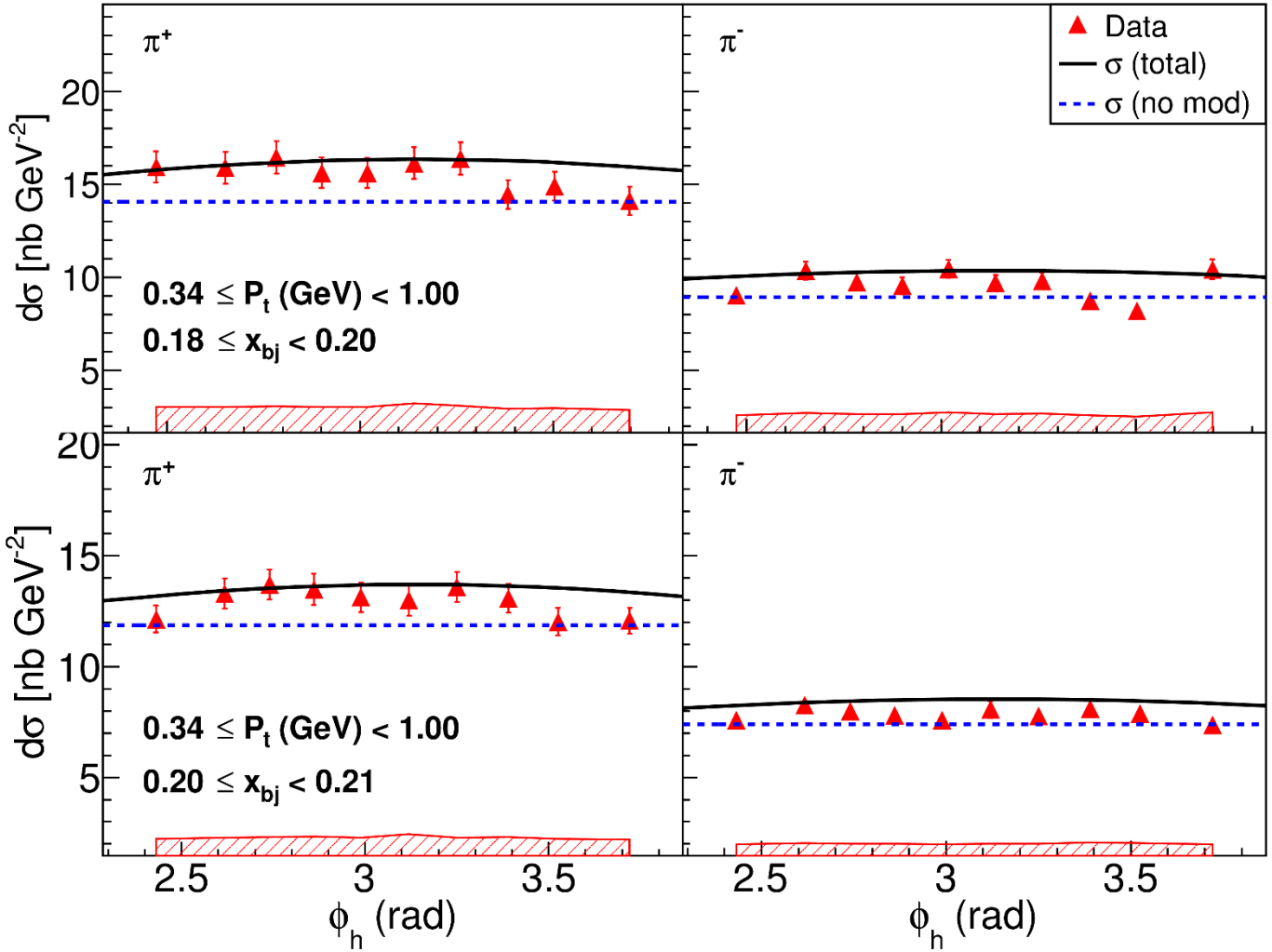
ϕ_h farther away from π corresponds to larger x: lower cross section with/without modulation, look ~like $\cos\phi_h$

3D binning

- Pt (2 bins) vs. x (5 bins) vs. ϕ_h (10 bins)
- Approximately equal statistical uncertainty in bins

- SIDIS unpolarized differential cross section from data vs. models

3D binning results



- Theory: cross section model in Bacchetta, et al. PRL 107 212001 (2011)
- Naïve x-z factorization
- Gaussian ansatz

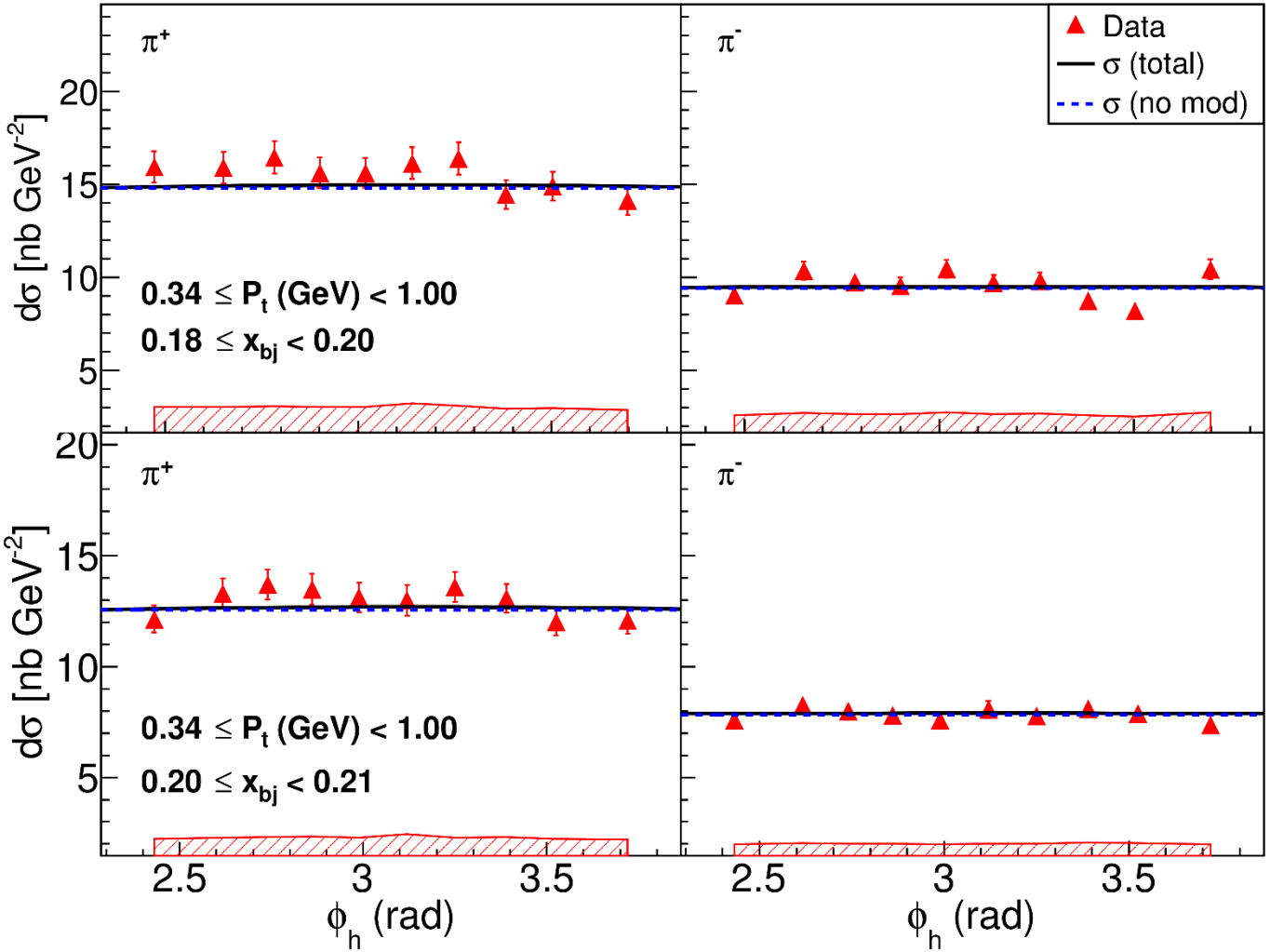
- Data in Pt (2) vs. x (5) vs. ϕ_h (10) bins

Data: all kinematic ranges

- $\chi^2(\sigma_{total})$=249
- $\chi^2(\sigma_{no\ mod})$=440

Theory in comparison: $\langle k_\perp^2 \rangle$ =0.14 GeV², $\langle p_\perp^2 \rangle = 0.42 \times z^{0.54}(1-z)^{0.37}$ GeV²

3D binning results



- Theory: best fit of data
- Naïve x-z factorization
- Gaussian ansatz

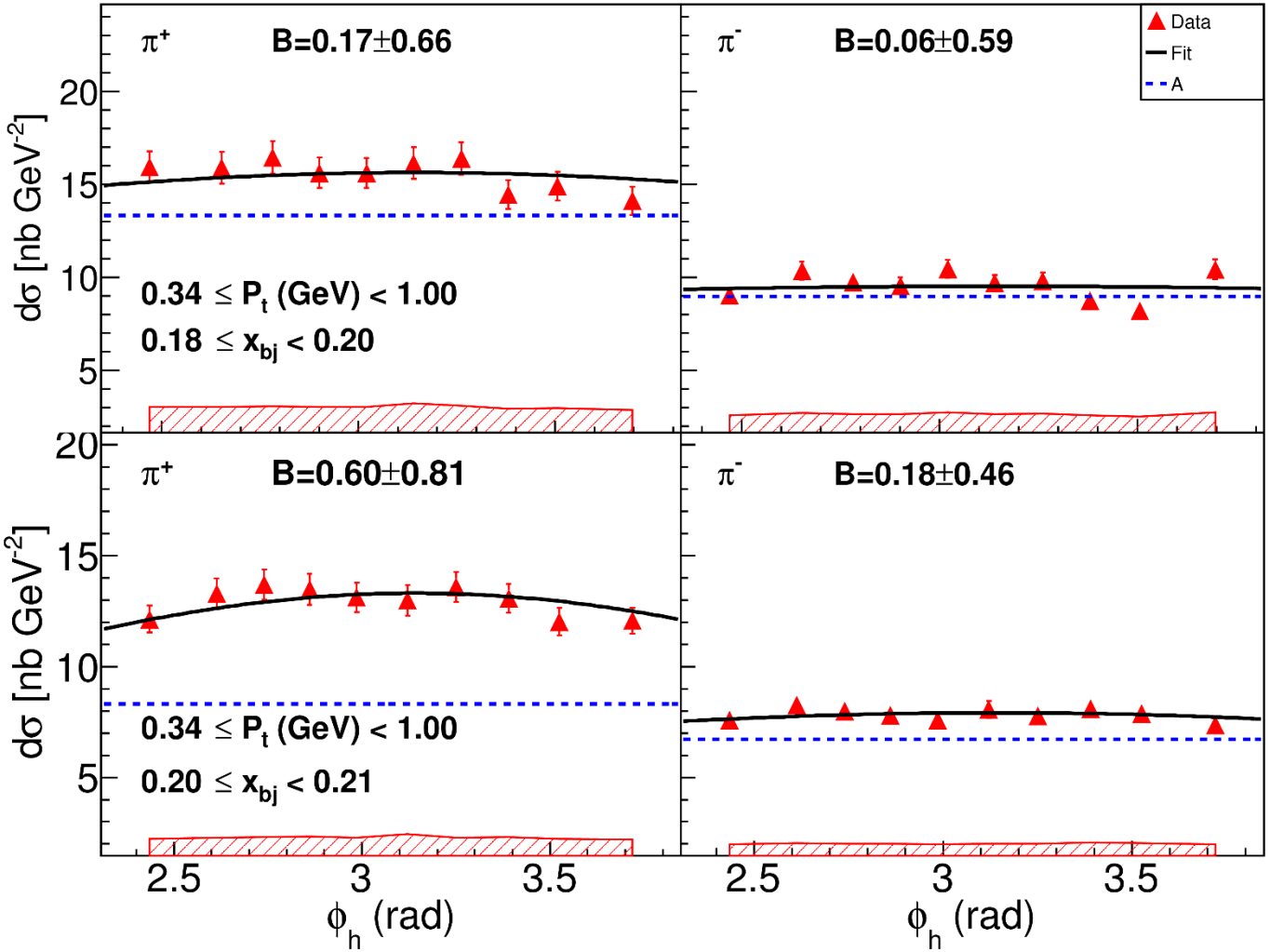
- Data in Pt (2) vs. x (5) vs. ϕ_h (10) bins

Data: all kinematic ranges

- $\chi^2(\sigma_{total})$=128
- $\chi^2(\sigma_{no\ mod})$=128

Theory in comparison: $\langle k_\perp^2 \rangle$ =0.006 GeV², $\langle p_\perp^2 \rangle = 0.214$ GeV²

3D binning results

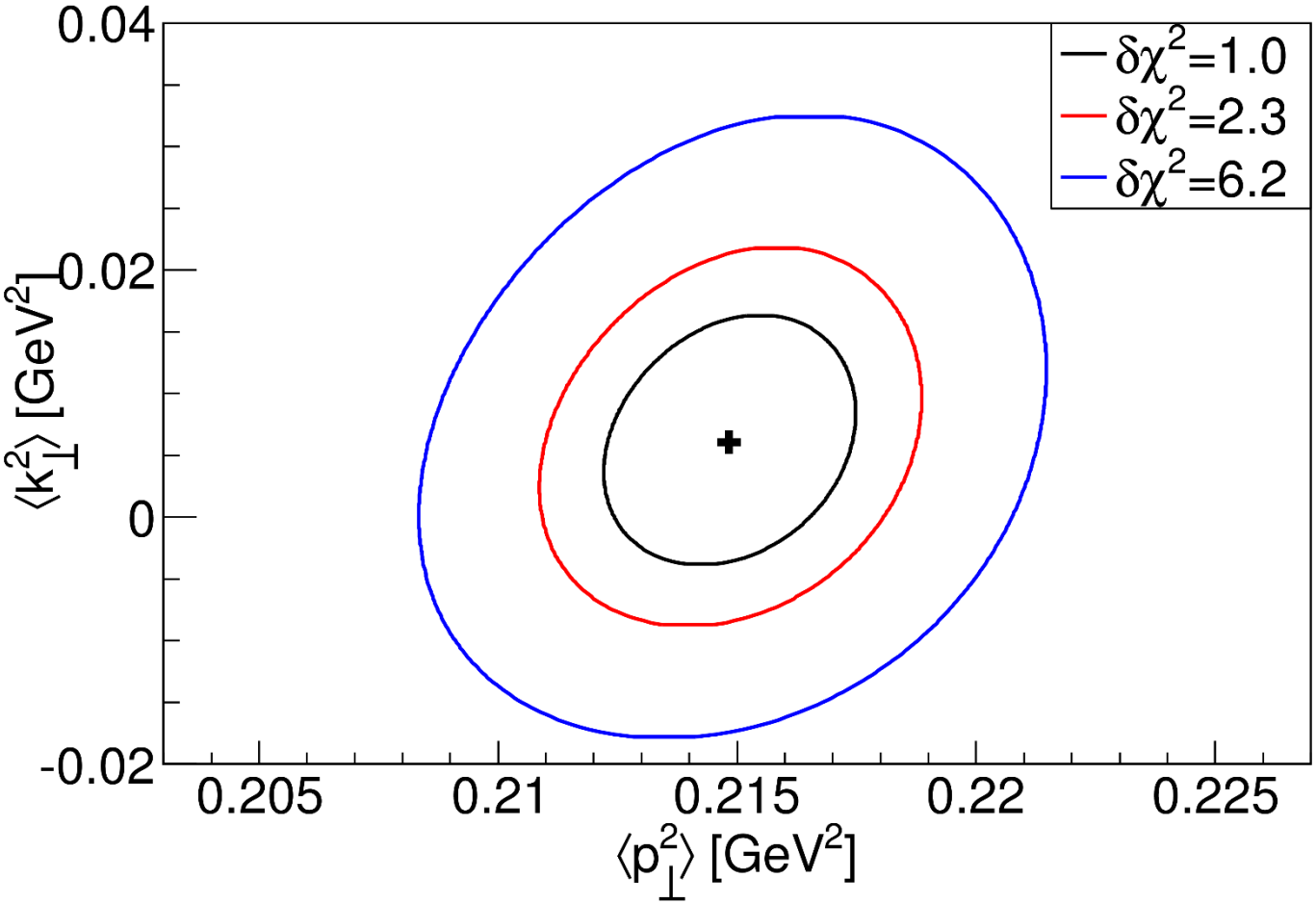


- Data in Pt (2) vs. x (5) vs. ϕ_h (10) bins
- Fit data with $f(\phi_h) = A(1 - B \cdot cos\phi_h)$
- Limited data points provide loose constraints on A & B in each kinematic range
- Limited shape change due to cosine term in kinematic range

Constraint for SIDIS parameters with stand-alone data (E06-010)

- SIDIS cross section with modulation
  - Cahn effect $\propto \langle k_\perp^2 \rangle$ (Gaussian ansatz in convolution)
  - Preferable: large ϕ_h range in data for fitting Cahn effect ($\cos\phi_h$: sign change)
- SIDIS cross section without azimuthal modulation ($F_{UU}^{cos\phi_h}$=0 & $F_{UU}^{cos2\phi_h}$=0)
  - $\langle k_\perp^2 \rangle$ & $\langle p_\perp^2 \rangle$ only appear as one variable $\langle p_\perp^2 \rangle + z^2 \langle k_\perp^2 \rangle$
  - When z in very small range (as in E06-010), data will not constrain both simultaneously with good quality

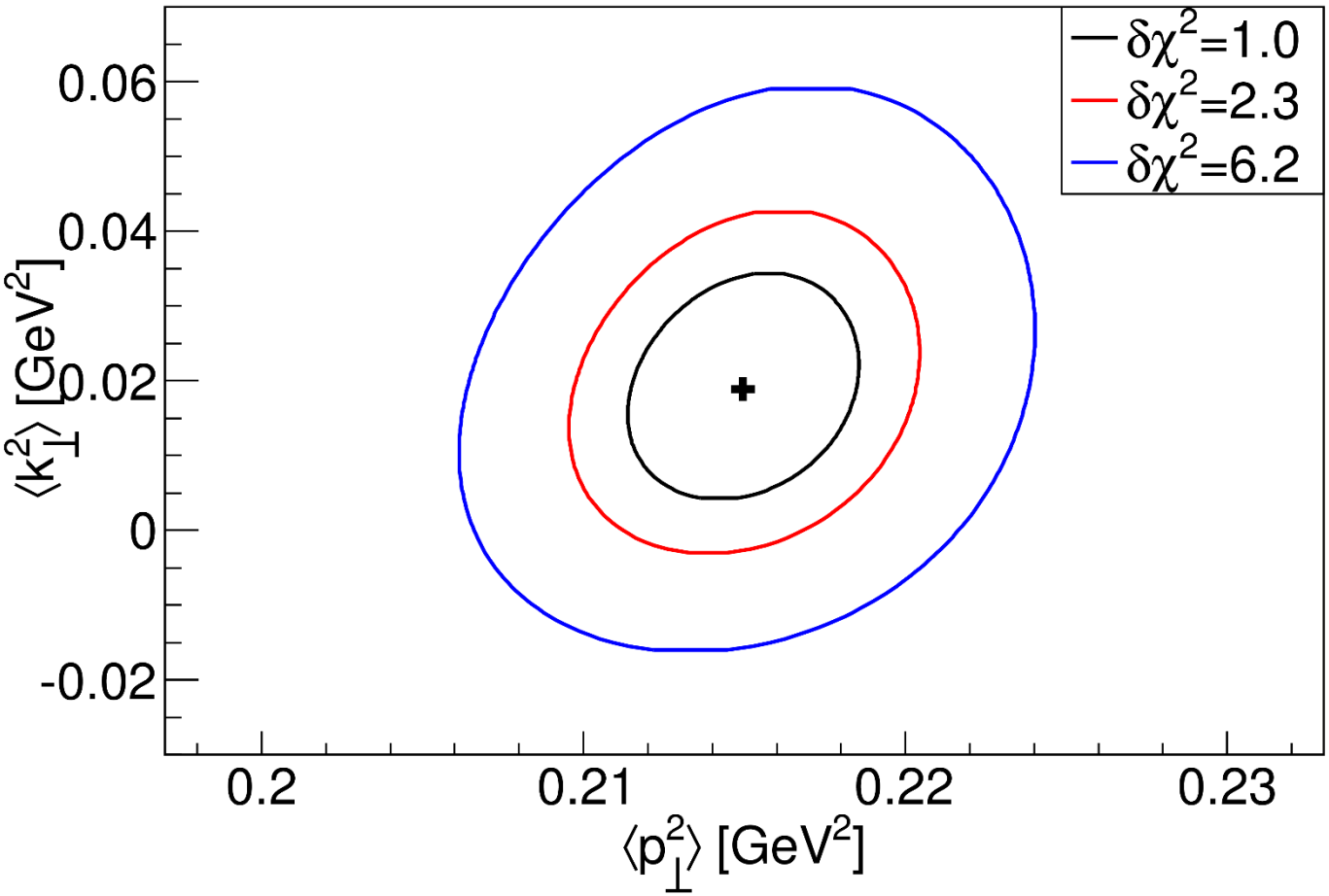
$\delta\chi^2$ contours: with modulation ($\pi^{\pm}$)



- $\delta\chi^2$ contours
- Best fit: solid cross

- 200 data points SIDIS $\boldsymbol{\pi}^+$ (100) & $\boldsymbol{\pi}^-$ (100) production in Pt (2) vs. x (5) vs. ϕ_h (10) bins
- Best fit: $\langle k_\perp^2 \rangle = 0.006$ GeV^2, $\langle p_\perp^2 \rangle = 0.215$ GeV^2
  - Conservative systematic uncertainty estimation: minimal $\chi^2 = 128$

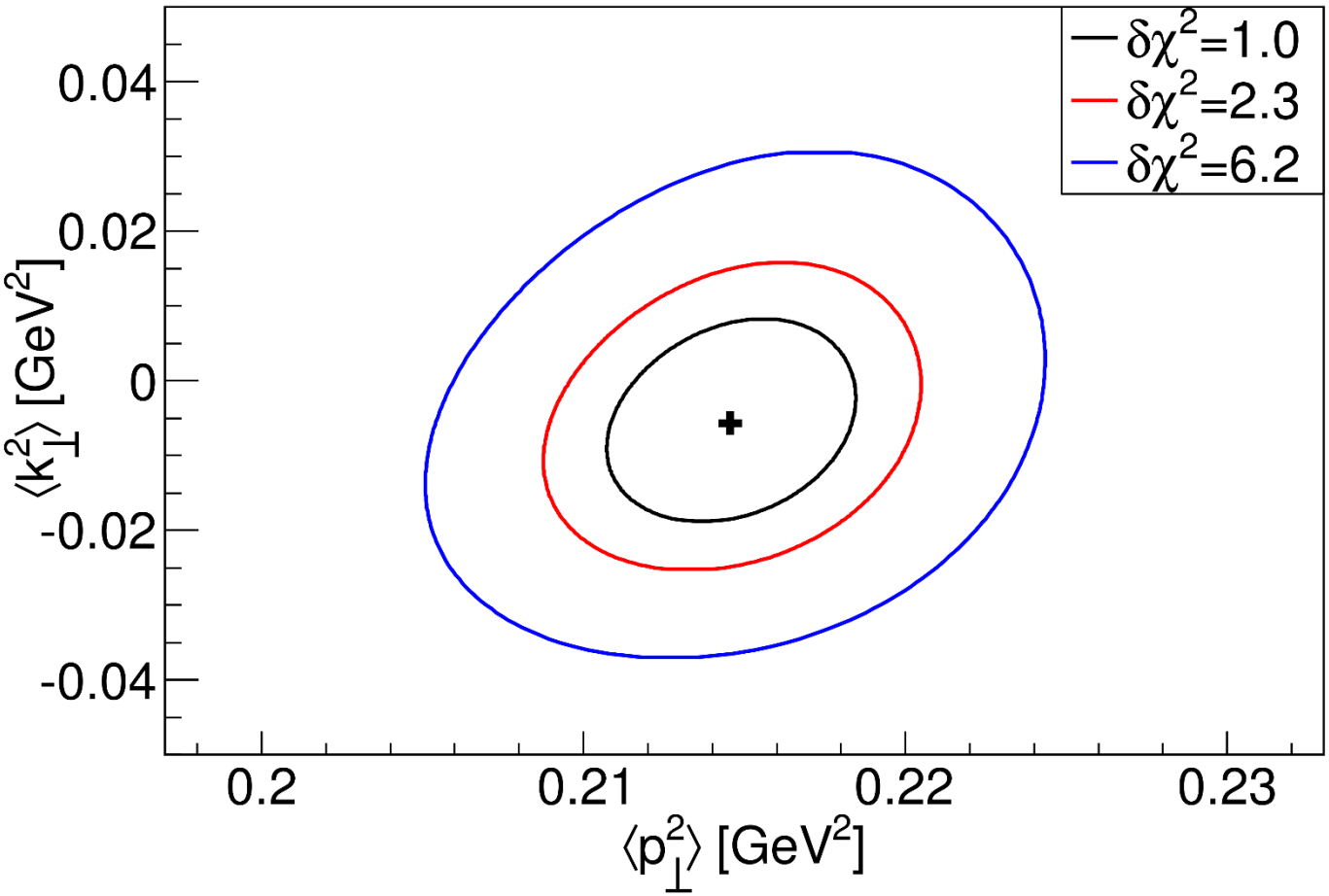
$\delta\chi^2$ contours: with modulation (π^+)



- $\delta\chi^2$ contours
- Best fit: solid cross

- 100 data points SIDIS $\boldsymbol{\pi}^+$ (100) production in Pt (2) vs. x (5) vs. ϕ_h (10) bins
- Best fit: $\langle k_\perp^2 \rangle = 0.019$ GeV², $\langle p_\perp^2 \rangle = 0.215$ GeV²
  - Conservative systematic uncertainty estimation: minimal $\chi^2 = 60.6$

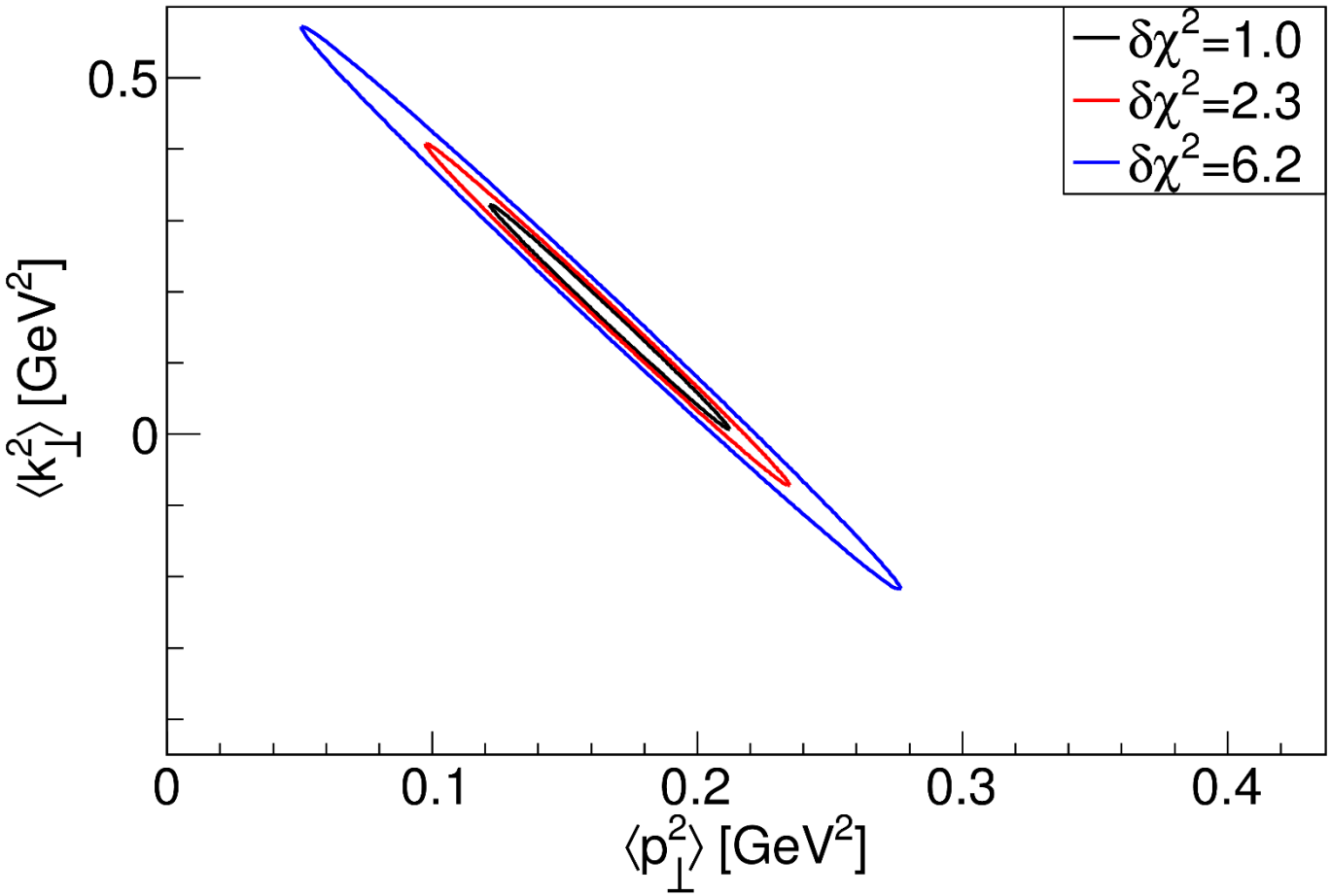
$\delta\chi^2$ contours: with modulation (π^-)



- $\delta\chi^2$ contours
- Best fit: solid cross

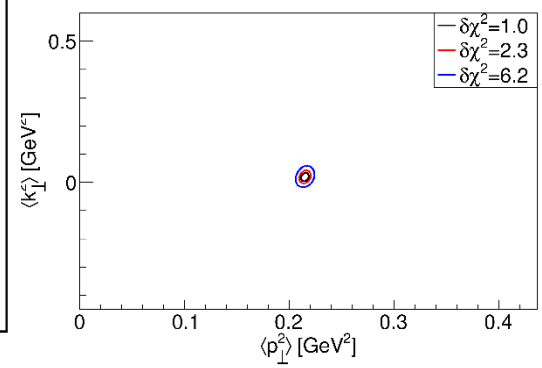
- 100 data points SIDIS $\boldsymbol{\pi}^-$ (100) production in Pt (2) vs. x (5) vs. ϕ_h (10) bins
- Best fit: $\langle k_\perp^2 \rangle = -0.06$ GeV², $\langle p_\perp^2 \rangle = 0.215$ GeV²
  - Conservative systematic uncertainty estimation: minimal χ^2 =65.5

$\delta\chi^2$ contours: no modulation (π^+)



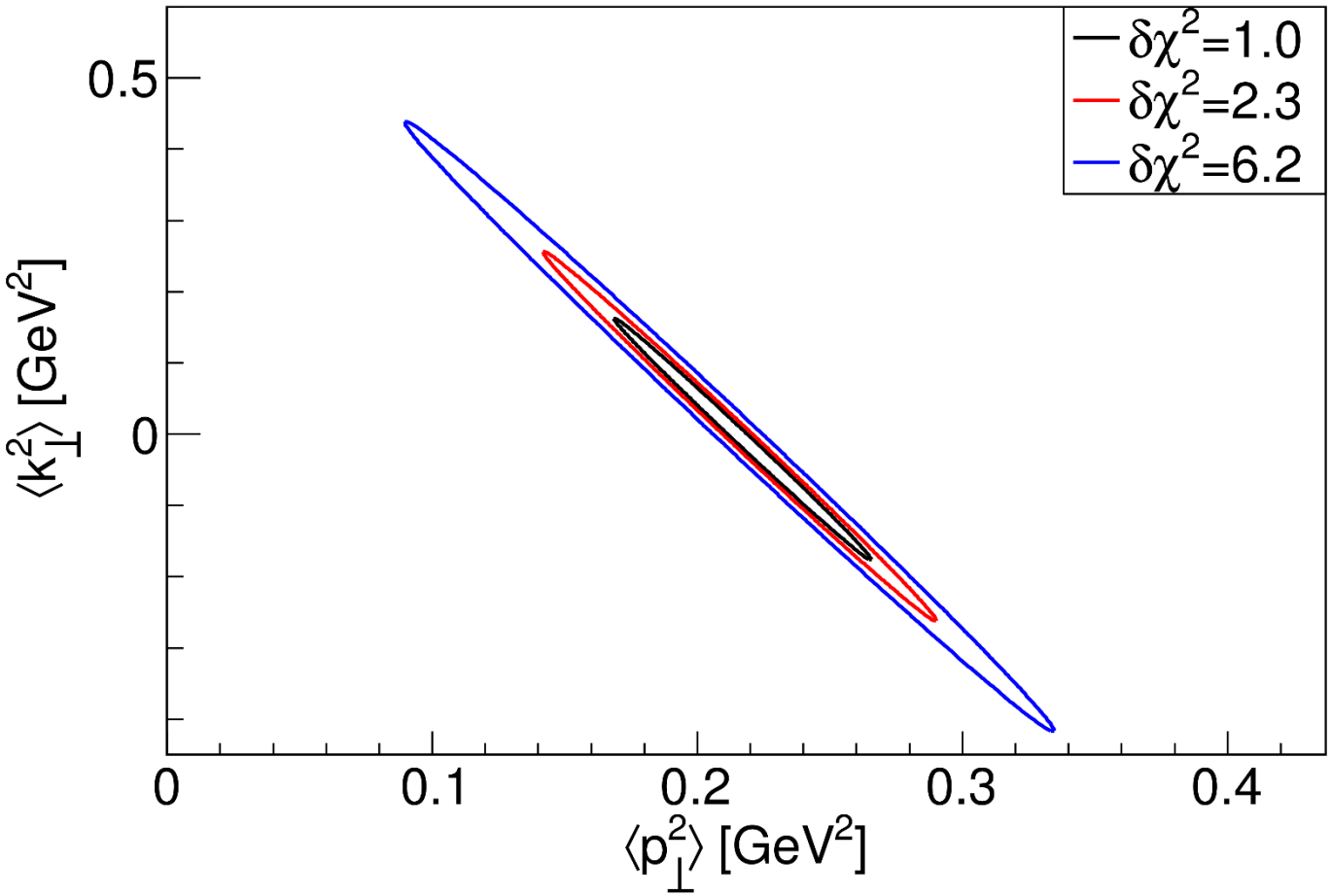
- $\delta\chi^2$ contours
- Best fit: solid cross

Previous plot on same scale



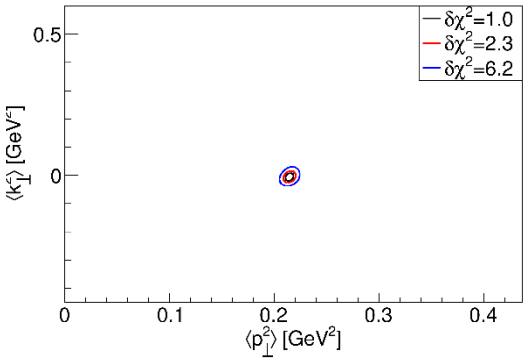
- 100 data points SIDIS $\boldsymbol{\pi}^+$ (100) production in Pt (2) vs. x (5) vs. ϕ_h (10) bins
- Best fit: $\langle k_\perp^2 \rangle = 0.163$ GeV², $\langle p_\perp^2 \rangle = 0.167$ GeV²
  - Conservative systematic uncertainty estimation: minimal $\chi^2 = 60.5$

$\delta\chi^2$ contours: no modulation (π^-)



- $\delta\chi^2$ contours
- Best fit: solid cross

Previous plot on same scale



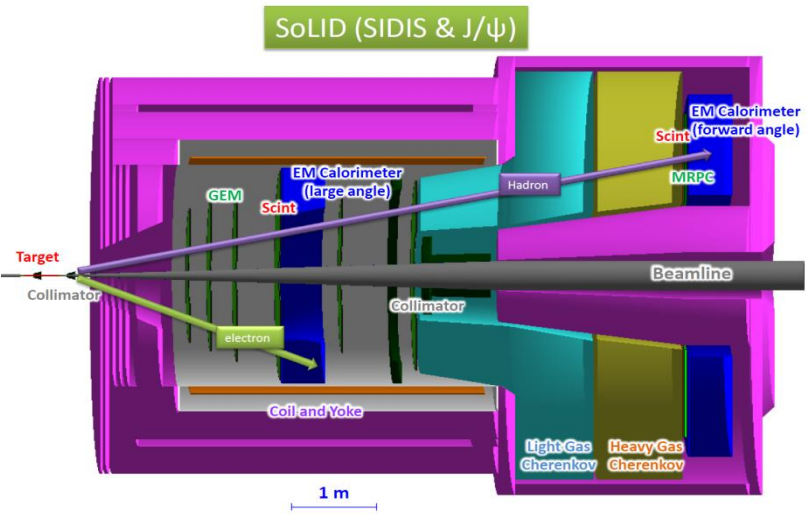
- 100 data points SIDIS $\boldsymbol{\pi}^-$ (100) production in Pt (2) vs. x (5) vs. ϕ_h (10) bins
- Best fit: $\langle k_\perp^2 \rangle = -0.011$ GeV², $\langle p_\perp^2 \rangle = 0.218$ GeV²
  - Conservative systematic uncertainty estimation: minimal $\chi^2 = 65.7$

Summary and outlook

- Published work on SSA & DSA from E06-010 (Transversity)
- Unpolarized SIDIS cross section extraction
  - 1st measurement using ^{3}He target
  - Consistent with (naïve) x-z factorization
  - Constraints on different theoretical functional forms

- Future JLab programs: exploration → precision

SoLID-Spin: SIDIS on ^{3}He/Proton @ 11 GeV

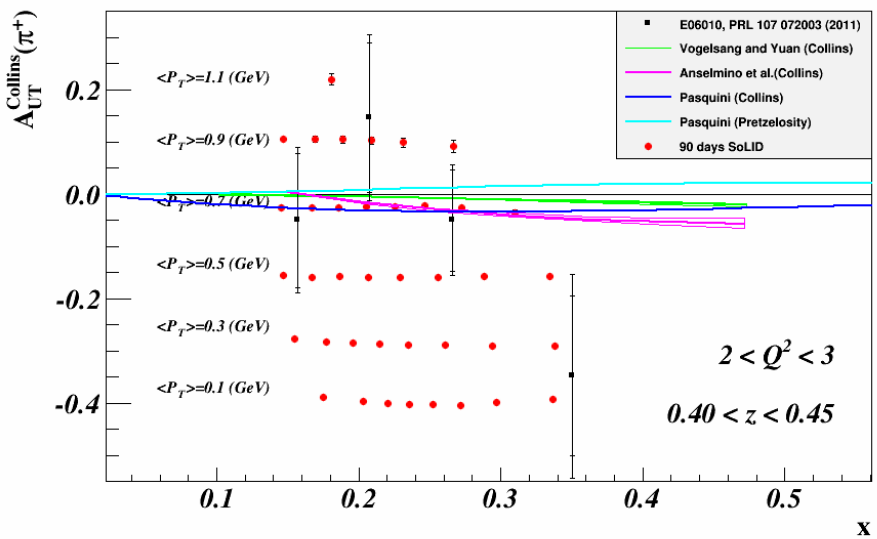


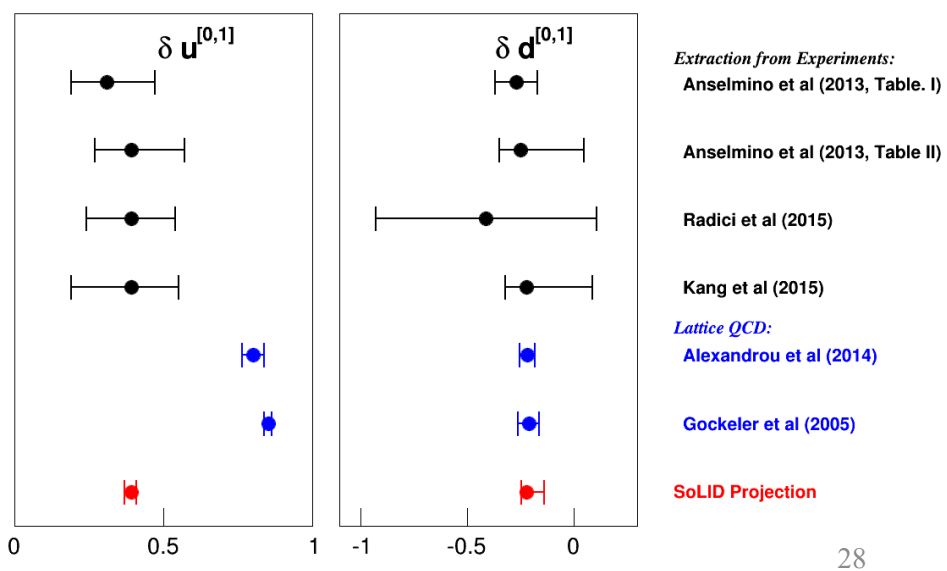
E12-10-006: Single Spin Asymmetry on Transverse ^{3}He, **rating A**

E12-11-007: Single and Double Spin Asymmetries on ^{3}He, **rating A**

E12-11-108: Single and Double Spin Asymmetries on Transverse Proton, **rating A**

Two run group experiments: DiHadron and Ay

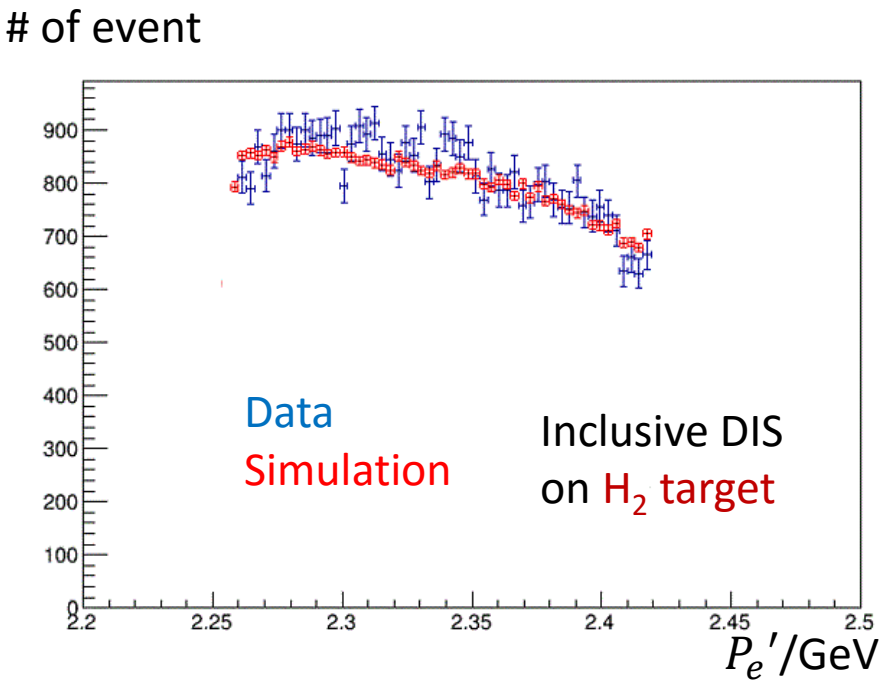


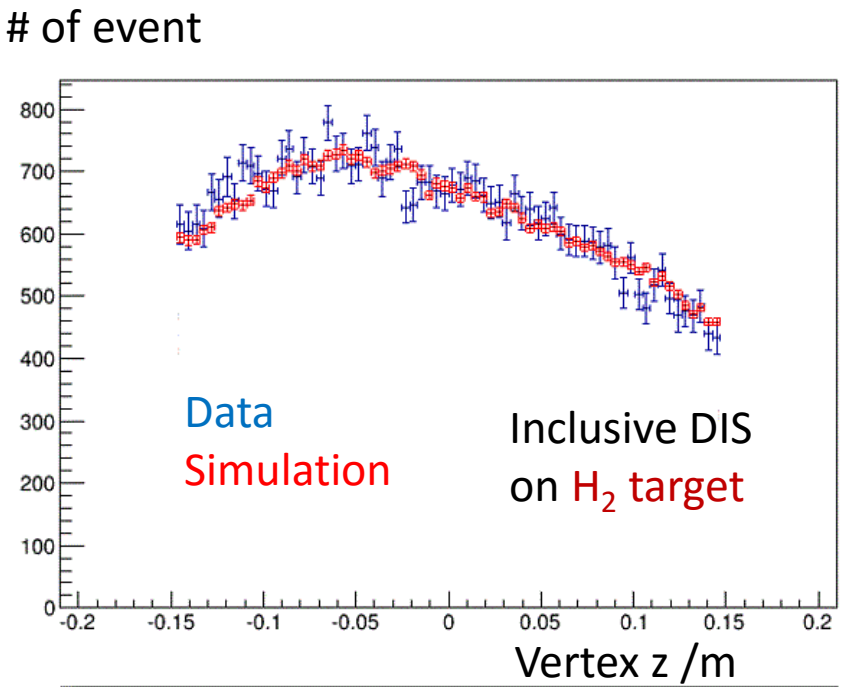


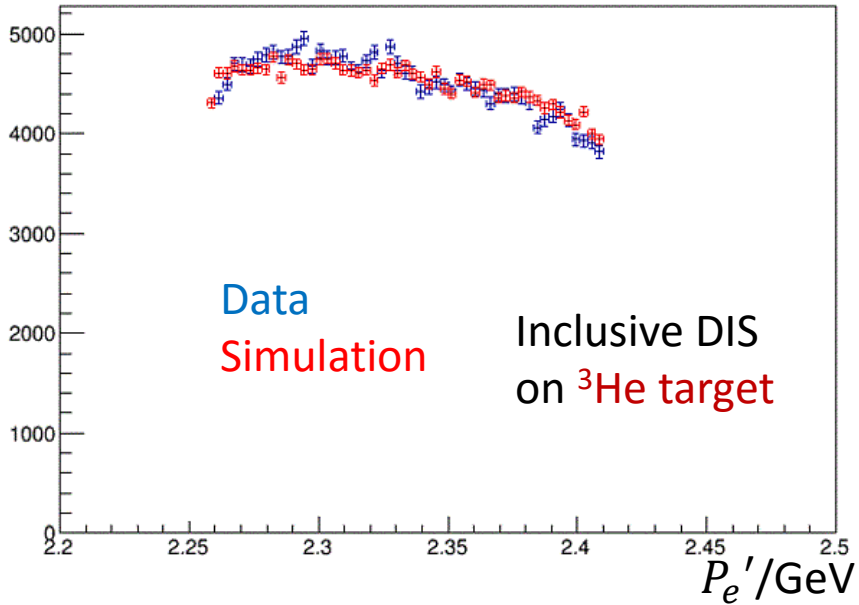
Thank you!

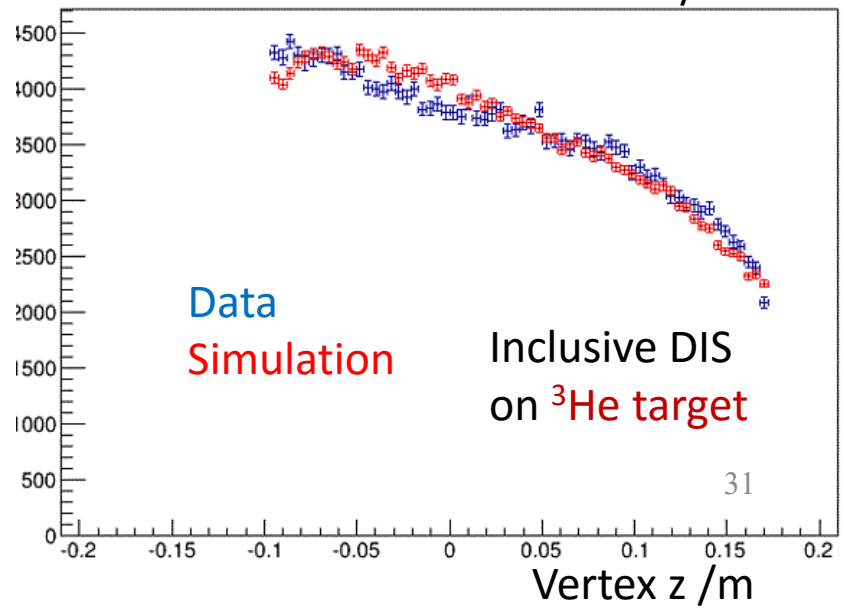
Back up

HRS simulation vs. data

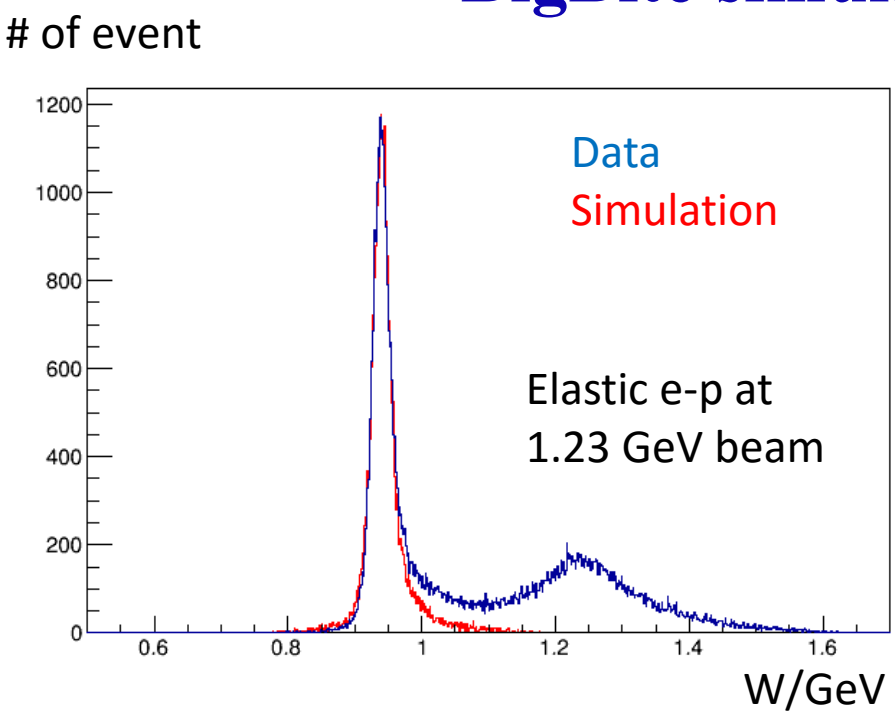


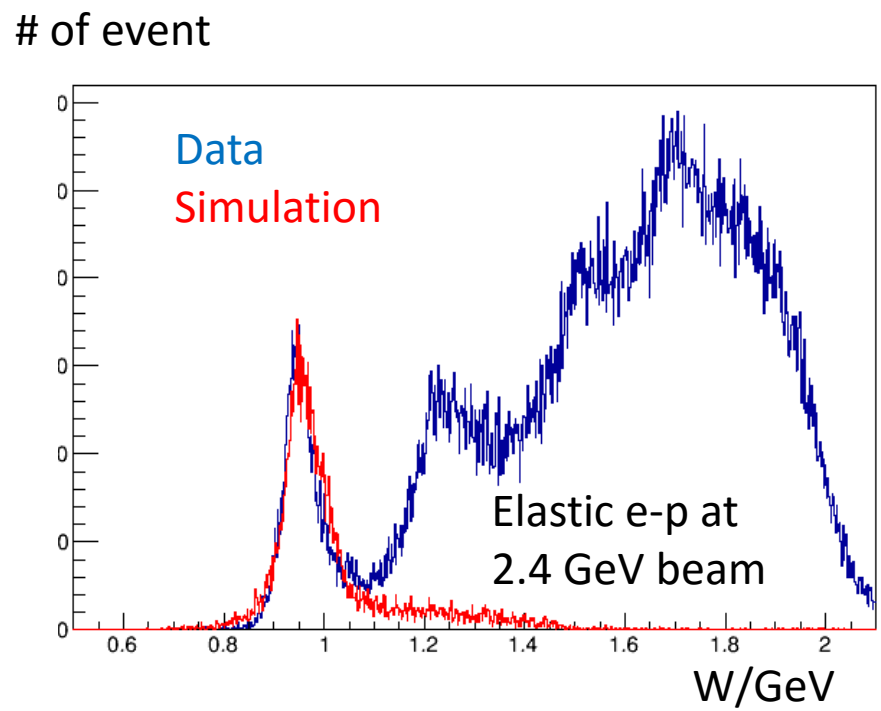


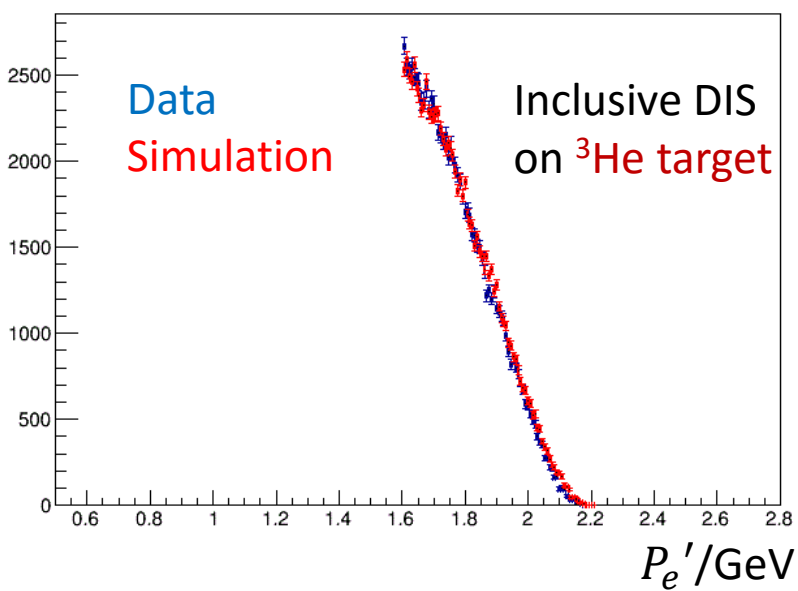


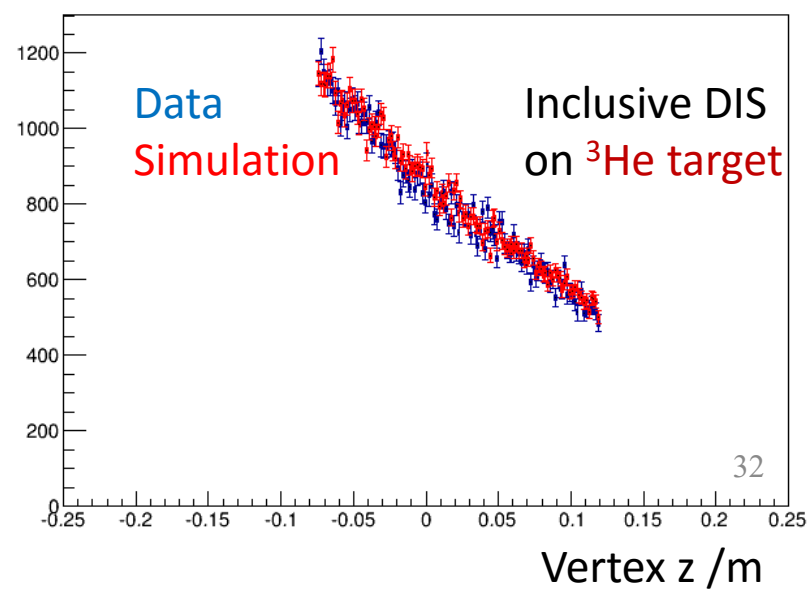


BigBite simulation vs. data

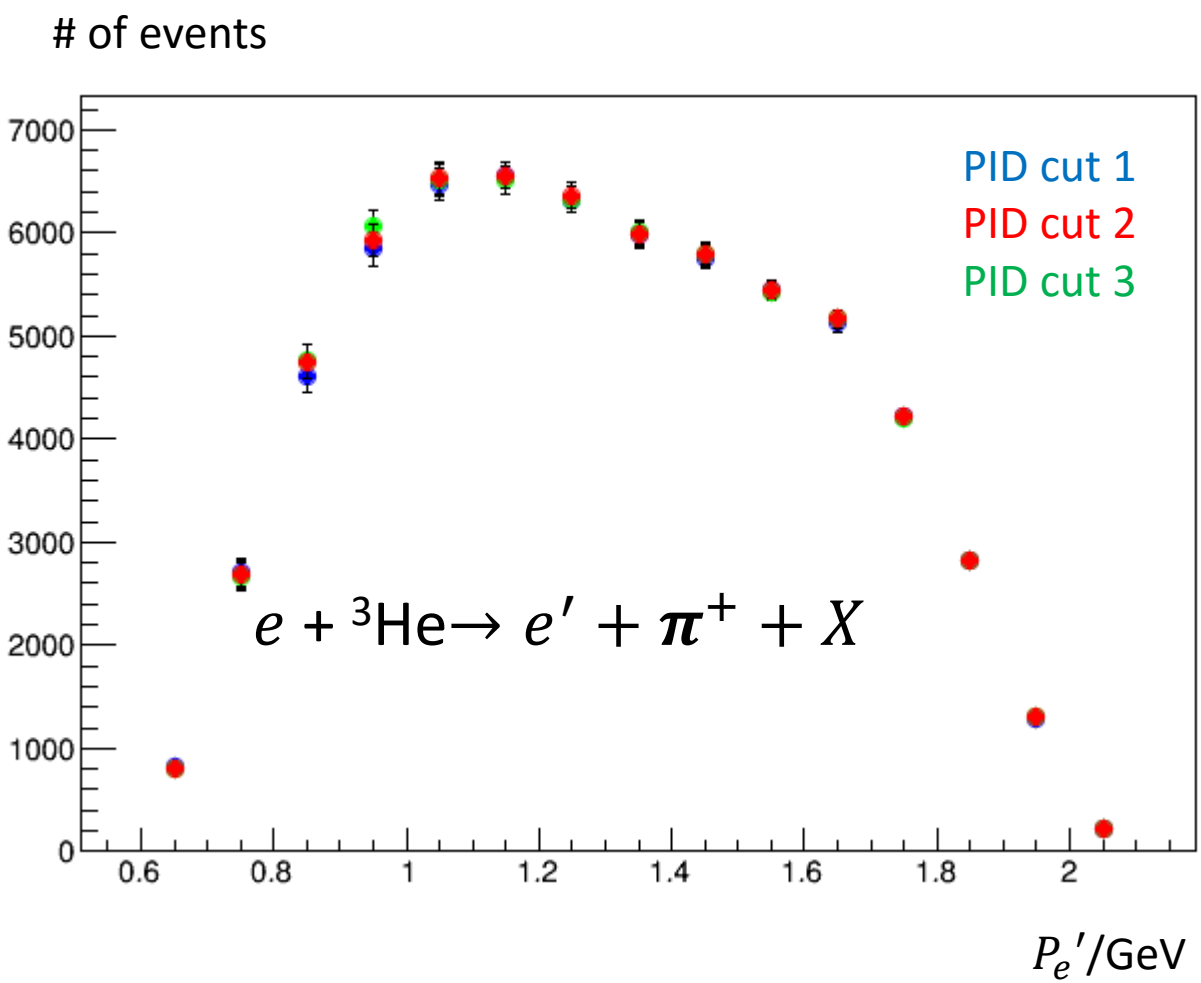








Data with efficiency/contamination correction in SIDIS channel



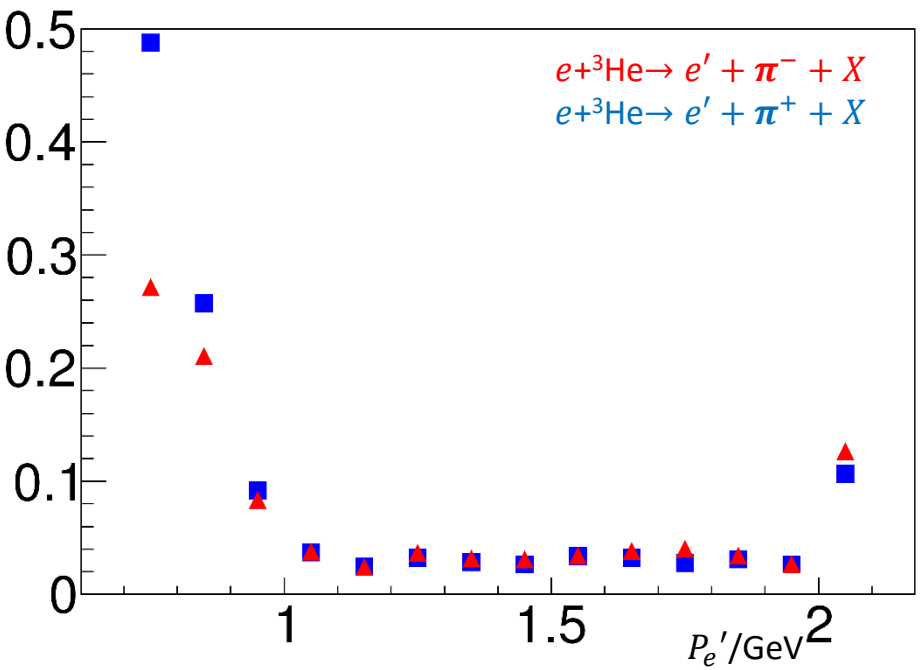
- PID cut 1-3: lower π^- contamination & higher loss of e' in BigBite
- Consistency: data under 3 different PID cuts, corrected by related contamination and efficiency, respectively

- SIDIS channel: $e + {}^3\mathrm{He} \rightarrow e' + \pi^+ + X$
  - e' detected by BigBite
  - π^+ detected by HRS

Dominant systematic uncertainty: from BigBite

- Acceptance description: 2-7% (most bins), up to 10% (edge bins) with kinematics dependence
- Efficiency & contamination: 2 - 50% for π^+ channel, 2-30% for π^-

Relative systematic uncertainty



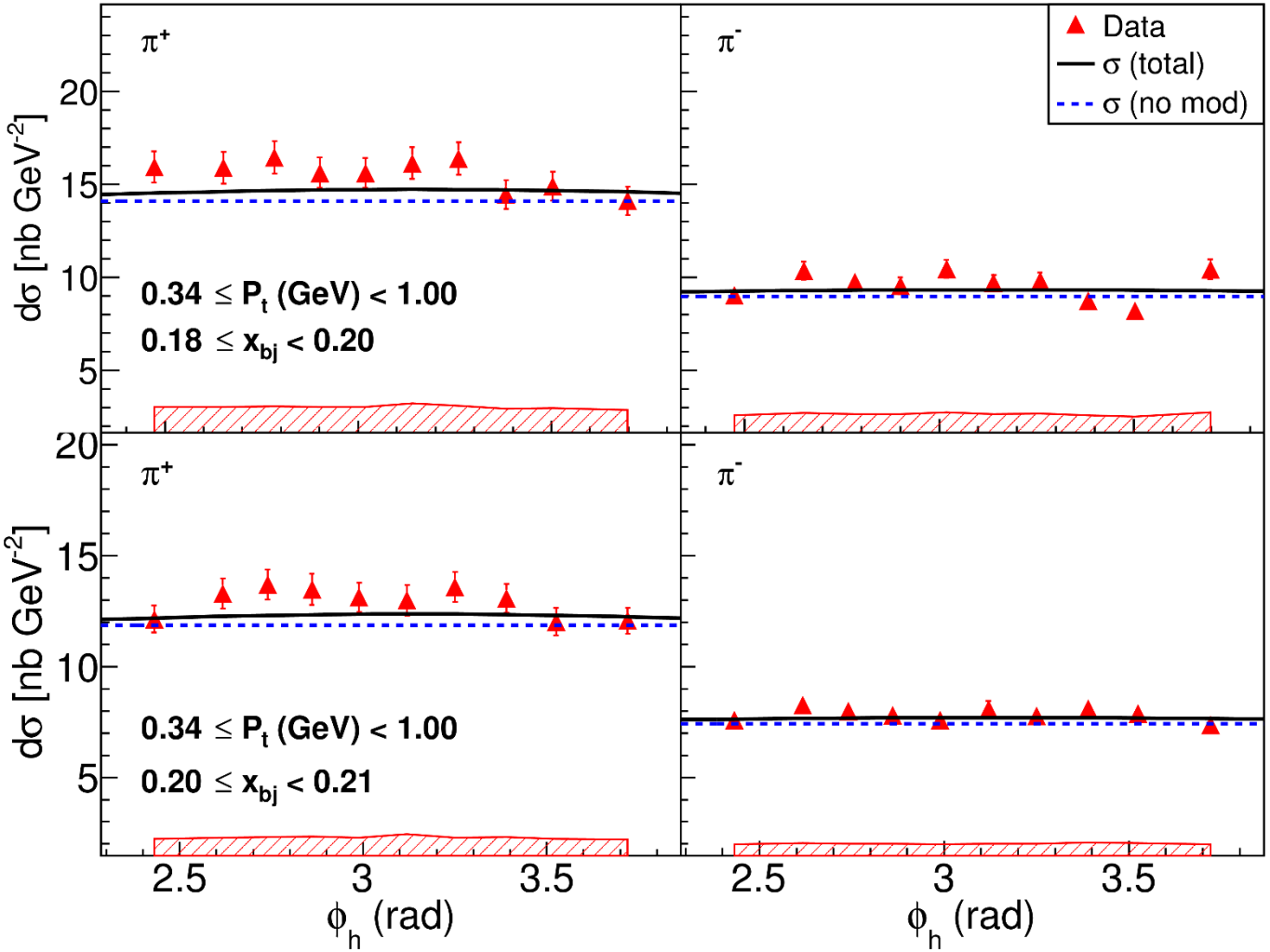
P_e'<0.9 GeV range has large sys uncertainty

- Trigger: shower threshold non-uniform drift during experiment; off-line cut & loss of efficiency description unprecise
- Photon-induced e^- contamination: up to 40% & contain large uncertainty
- If NOT cut away low P range, unreasonably large uncertainty will go to multiple bins in other variables x, z, Q^2, etc.

Exclusive tail & radiative correction

- Exclusive channel cross section model: in SIMC from JLab π form factor experiments
  - H. P. Blok et al. PRC 78 045202 (2008): $Q^2 \in (0.6, 2.45)$ GeV^2, W=1.95 &2.22 GeV
  - V. Tadevosyan et al. PRC 75 055205 (2007): $Q^2 \in (0.6, 1.6)$ GeV^2
  - T. Horn et al. PRL 97 192001 (2006) $Q^2 \in (1.6, 2.45)$ GeV^2, W=2.22 GeV
  - $\boldsymbol{Q^2 \in (1.3,\ 3.5)}$ **GeV^2** in E06-010
- Determined exclusive tail proportion consistent with R. Asaturyan et al. Phys. Rev. C 85, 015202 (2012) in overlapping kinematics range (Hall C SIDIS results)
- Radiative correction based on HAPRAD: SIDIS model iterative tuning

3D binning results



- Theory: cross section model in Barone, et al. PRD 91 074019 (2015)
- Naïve x-z factorization
- Gaussian ansatz

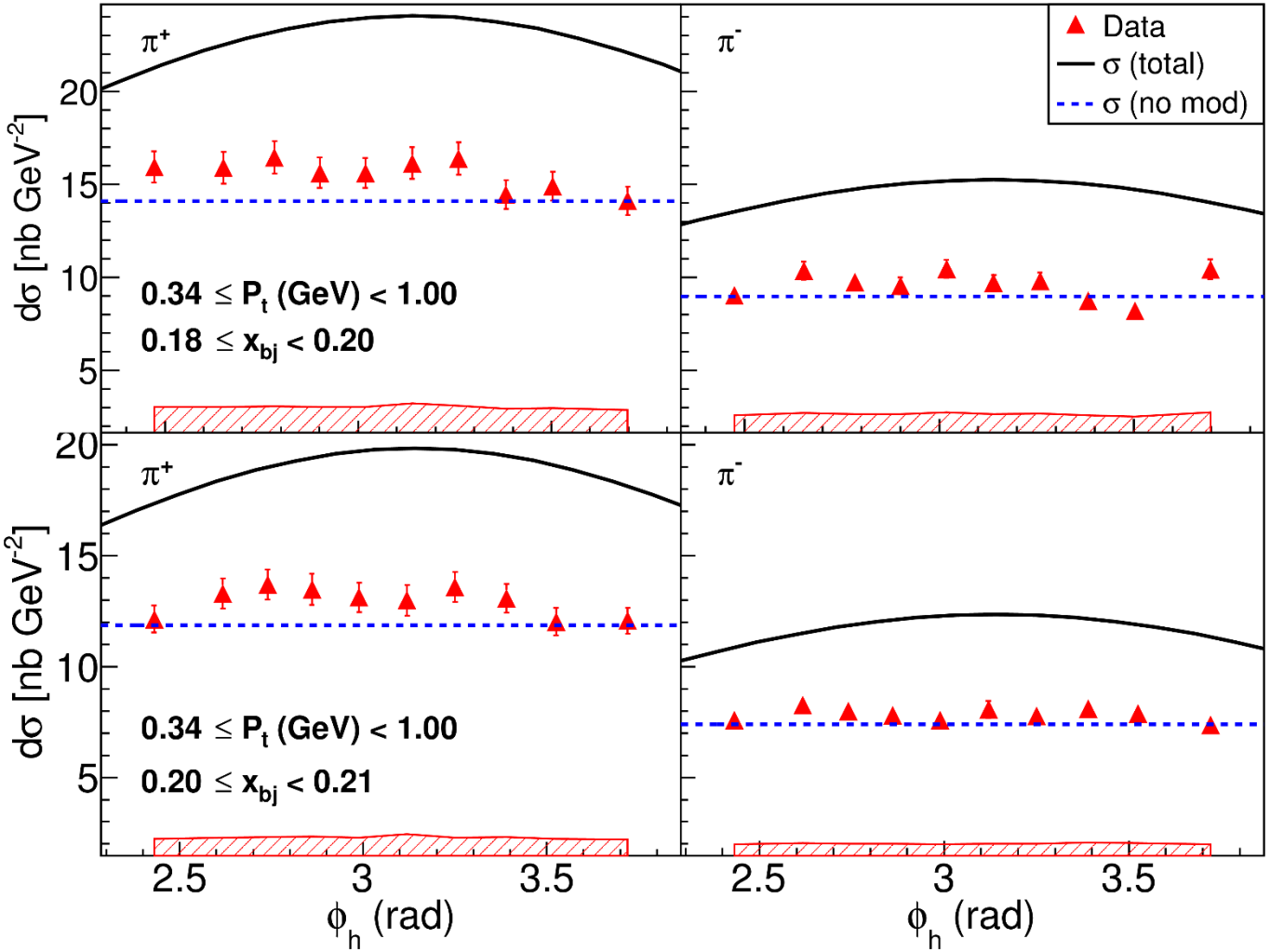
- Data in Pt (2) vs. x (5) vs. ϕ_h (10) bins

Data: all kinematic ranges

- $\chi^2(\sigma_{total})$=486
- $\chi^2(\sigma_{no\ mod})$=611

Theory in comparison: $\langle k_\perp^2 \rangle$ =0.037 GeV², $\langle p_\perp^2 \rangle = 0.126 + 0.506z^2$ GeV²

3D binning results



- Theory: cross section model in Anselmino, et al. JHEP 04 (2014) 005
- Naïve x-z factorization
- Gaussian ansatz

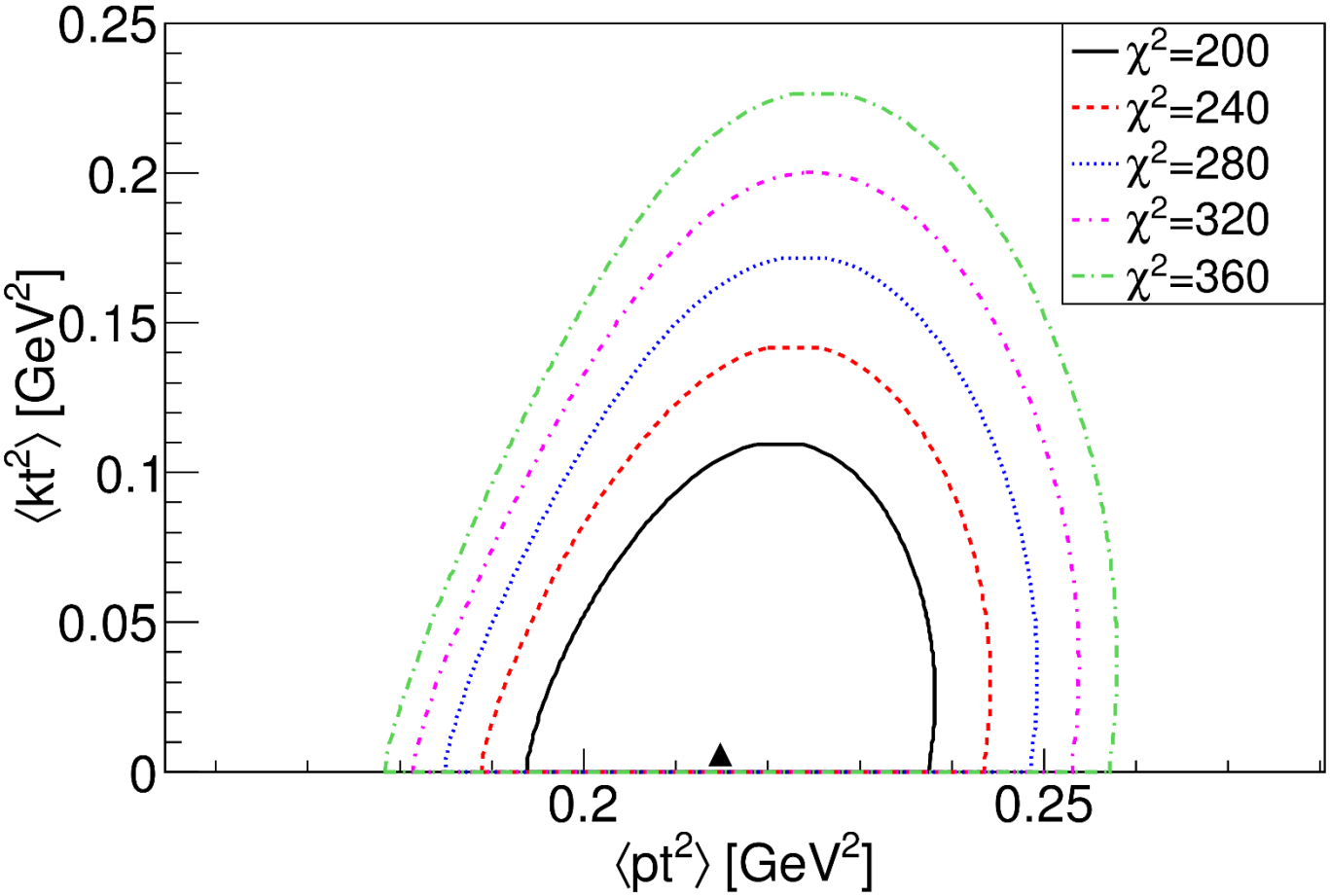
- Data in Pt (2) vs. x (5) vs. ϕ_h (10) bins

Data: all kinematic ranges

- $\chi^2(\sigma_{total})$=3780
- $\chi^2(\sigma_{no\ mod})$=632

Theory in comparison: $\langle k_\perp^2 \rangle$ =0.57 GeV², $\langle p_\perp^2 \rangle = 0.12$ GeV²

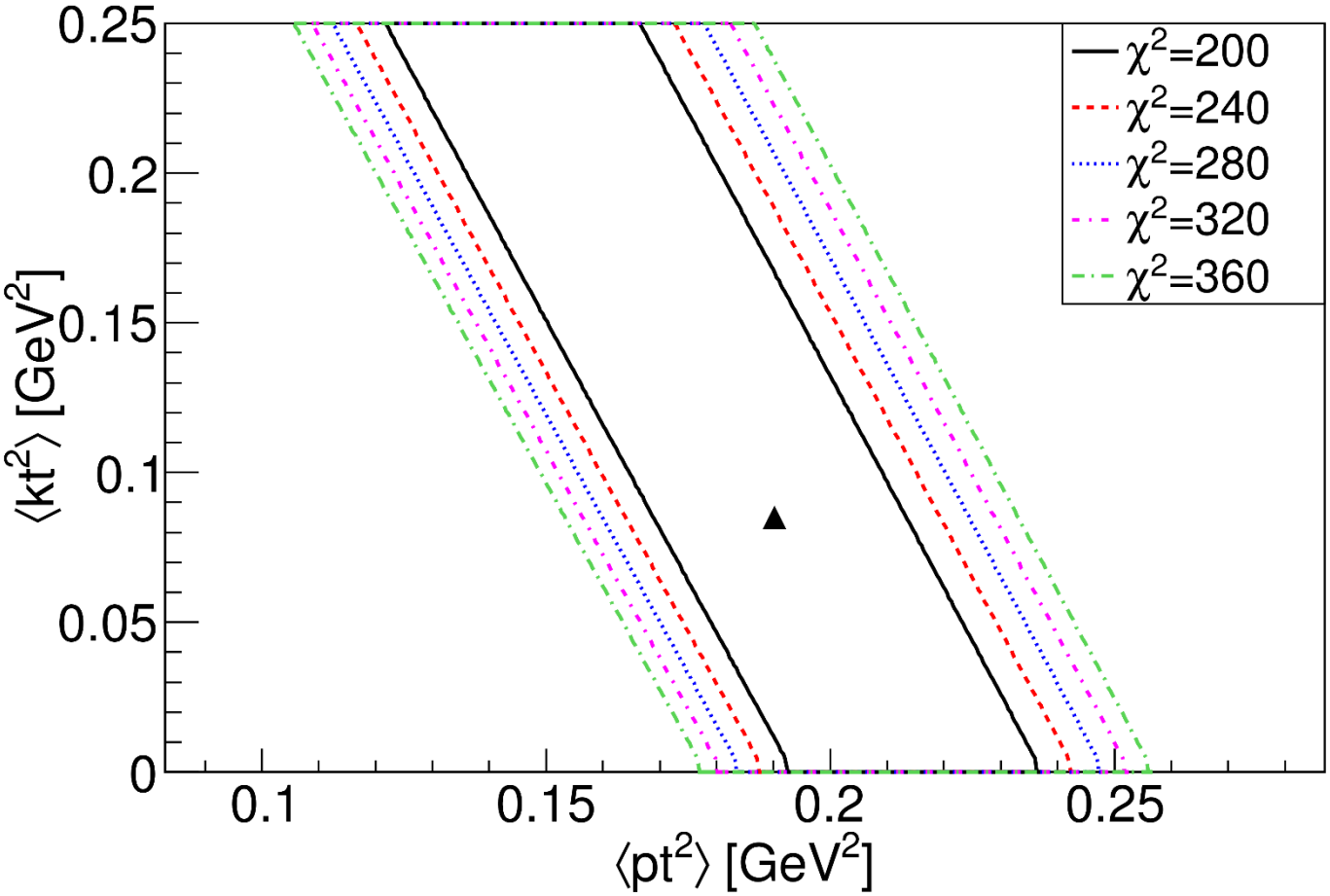
Constraints: with modulation



- Constant χ^2 contours
- Best fit: solid triangle

- 200 data points SIDIS π^+ (100) & π^- (100) production in Pt (2) vs. x (5) vs. ϕ_h (10) bins
- Best fit: $\langle k_\perp^2 \rangle = 0.006$ GeV², $\langle p_\perp^2 \rangle = 0.214$ GeV²
  - Conservative systematic uncertainty estimation: minimal $\chi^2 = 128$
  - If use stat uncertainty only: $\chi^2 > 700$

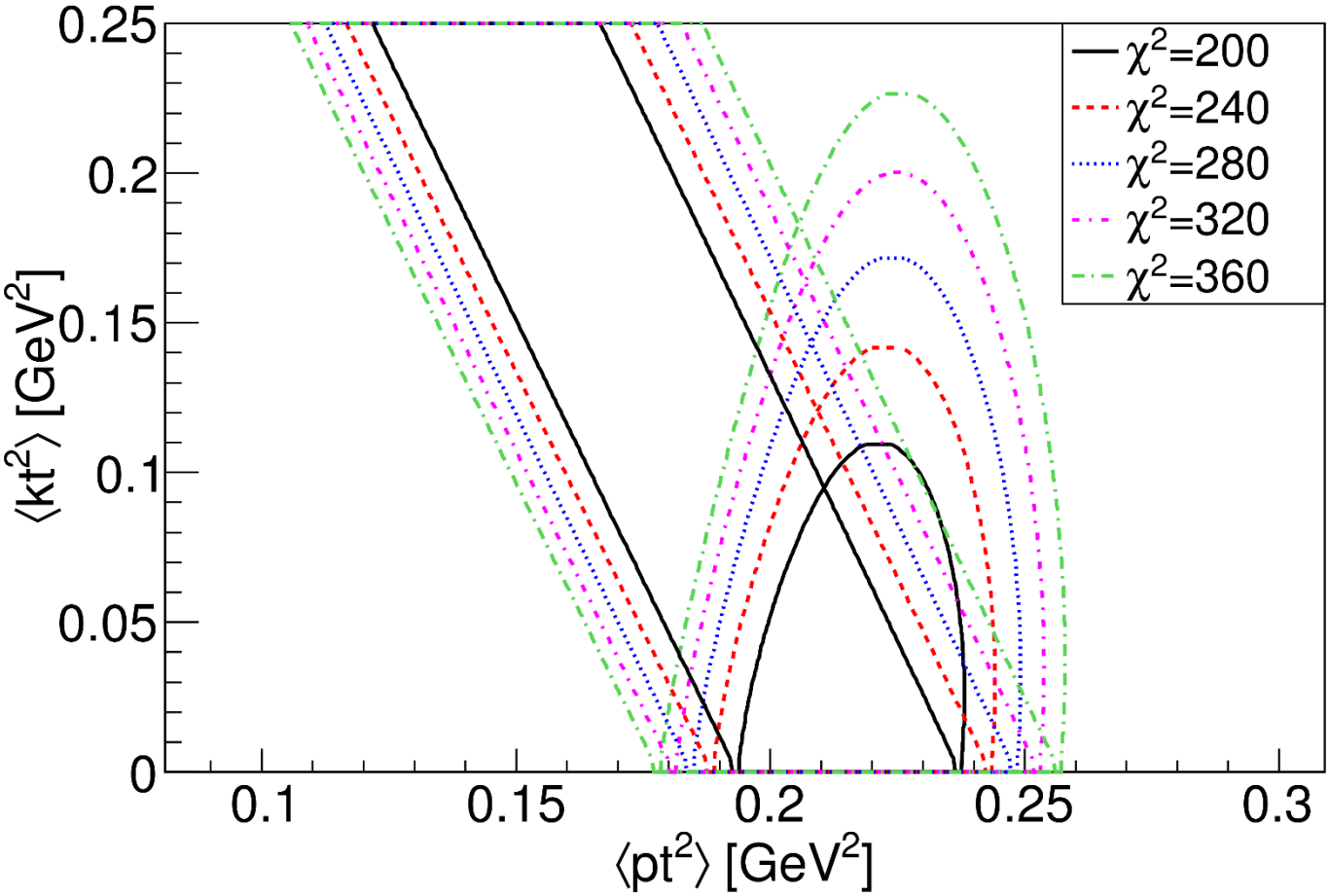
Constraints: no modulation



- Constant χ^2 contours extends beyond $k_\perp^2$=0.25 GeV²
- Best fit: solid triangle

- 200 data points SIDIS π^+ (100) & π^- (100) production in Pt (2) vs. x (5) vs. ϕ_h (10) bins
- Best fit: $\langle k_\perp^2 \rangle = 0.085$ GeV², $\langle p_\perp^2 \rangle = 0.190$ GeV²
  - Conservative systematic uncertainty estimation: minimal $\chi^2 = 127$
  - If use stat uncertainty only: $\chi^2 > 700$

Comparison at low $\langle k_\perp^2 \rangle$



- Constant χ^2 contours

- 200 data points SIDIS π^+ (100) & π^- (100) production in Pt (2) vs. x (5) vs. ϕ_h (10) bins