TMDs in SIDIS, p+p and e^+e^-– Experimental Review

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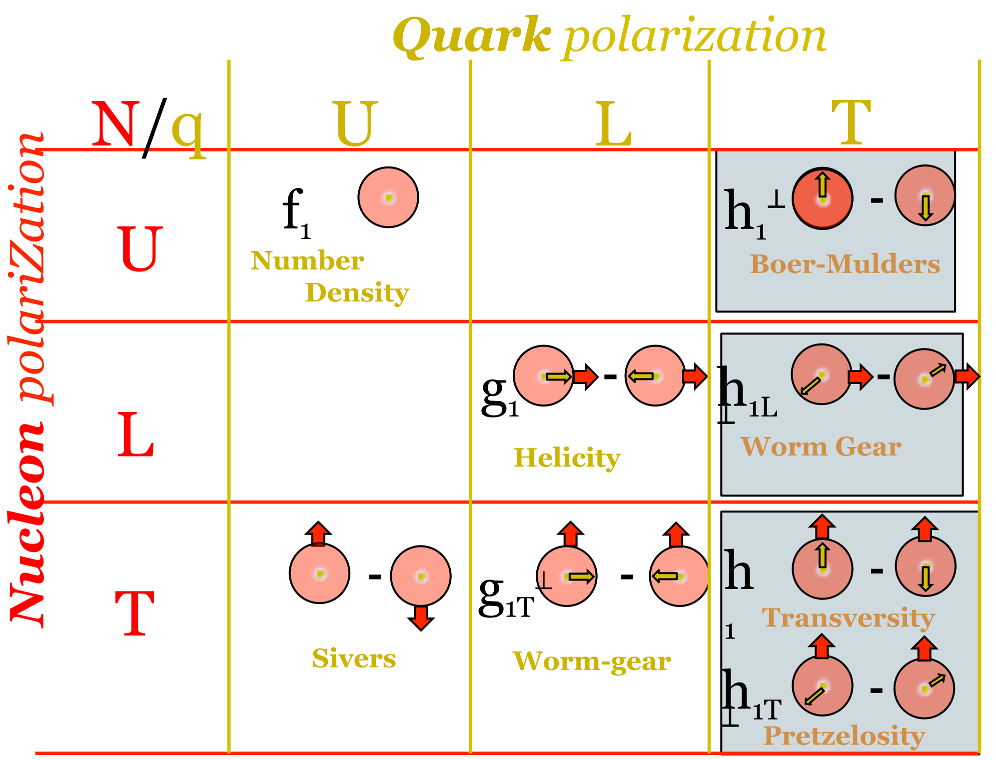
Matrix of spin dependent TMD Distribution Functions

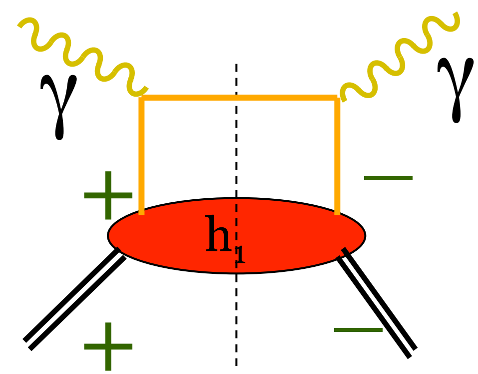
Quark *polarization*

Nucleon *polariZation*

N/q	U	L	T
U	f_1 Number Density		$h_1^{\perp}$ Boer-Mulders
L		g_1 Helicity	$h_{1L}^{\perp}$ Worm- Gear
T	$f_{1T}^{\perp}$ Sivers	$g_{1T}^{\perp}$ Worm-gear	h_1 Transversity $h_{1T}^{\perp}$ Pretzelosity

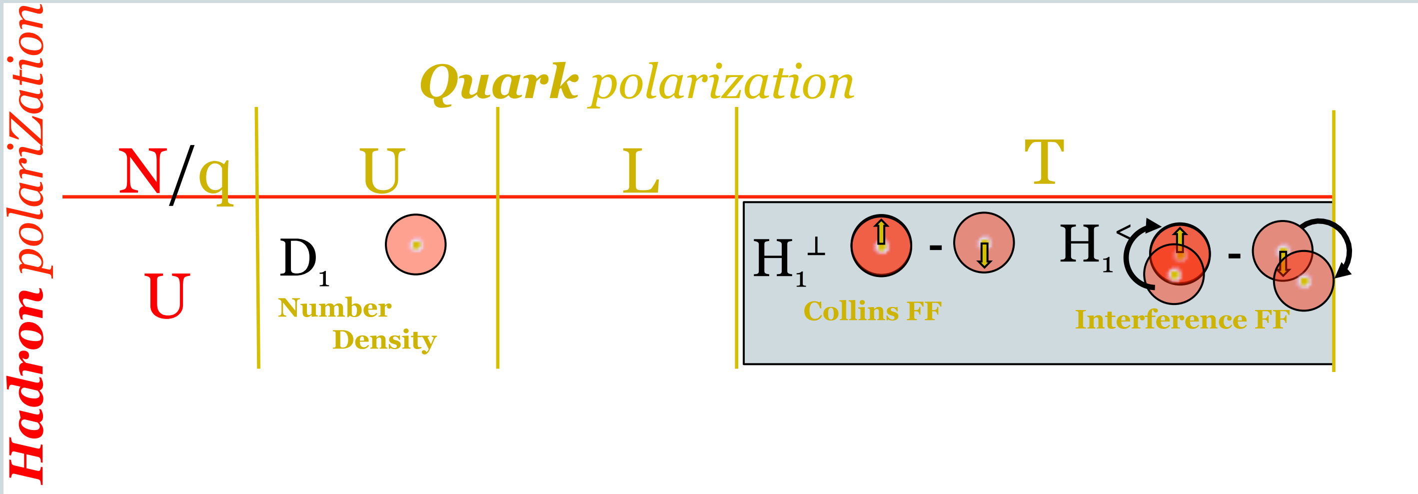
Chiral odd PDFs need Partner

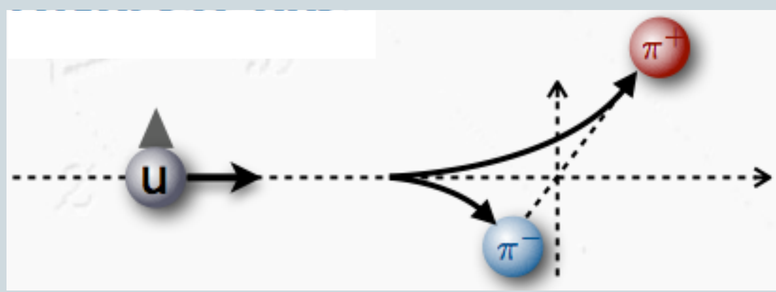




Transversity handbag diagram

Spin dependent TMD Fragmentation Functions

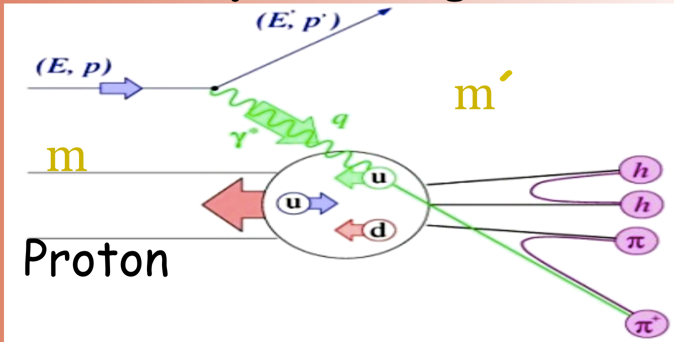




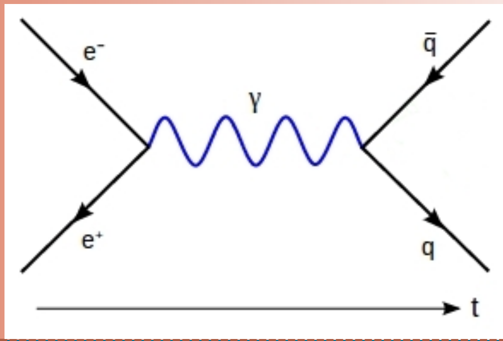
- Correlation between fragmenting quark spin and hadron transverse momentum

Lepton and Hadron Probes of TMDs

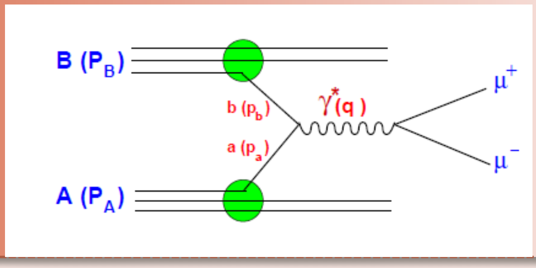
SIDIS
- Most explored
- Clean probe
- So far only fixed target (lim. Kin.)



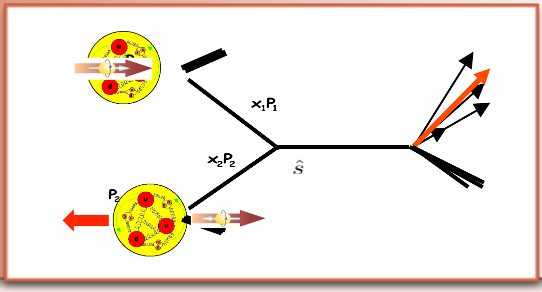
e+e-
- Clean
- Needed for chiral-odd TMD FFs



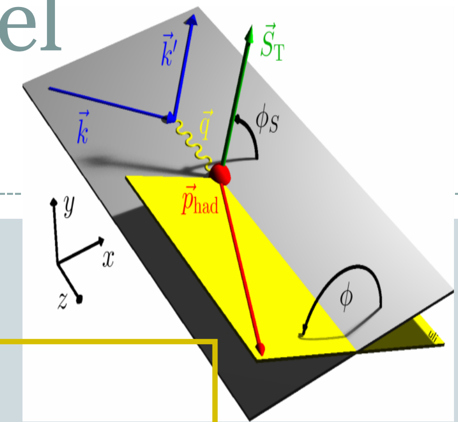
Drell Yan
- Initial vs. final state effects
- Needs dedicated experimental setup

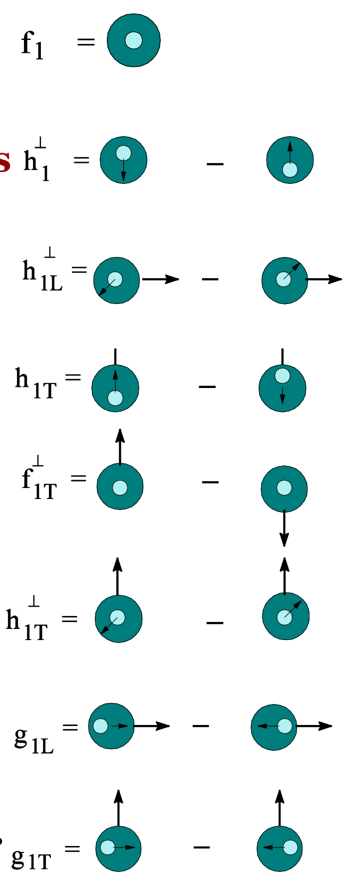


Polarized proton collisions
- Rich, collider kinematics
- Gluonic degrees of freedom
- Challenging for theory and exp.



SIDIS X-section in the Parton Model





$$d^6\sigma = \frac{4\pi\alpha^2 sx}{Q^4}\times$$

Unpolarized

$$\{[1+(1-y)^2]\sum_{q,\bar{q}} e_q^2 f_1^q(x) D_1^q(z,P_{h\perp}^2)$$

$$+(1-y)\frac{P_{h\perp}^2}{4z^2 M_N M_h}\cos(2\phi_h^l)\sum_{q,\bar{q}} e_q^2 h_1^{\perp(1)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

Polarized target

$$-|S_L|(1-y)\frac{P_{h\perp}^2}{4z^2 M_N M_h}\sin(2\phi_h^l)\sum_{q,\bar{q}} e_q^2 h_{1L}^{\perp(1)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

$$+|S_T|(1-y)\frac{P_{h\perp}}{zM_h}\sin(\phi_h^l+\phi_S^l)\sum_{q,\bar{q}} e_q^2 h_1^q(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

$$+|S_T|(1-y+\frac{1}{2}y^2)\frac{P_{h\perp}}{zM_N}\sin(\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 f_{1T}^{\perp(1)q}(x) D_1^q(z,P_{h\perp}^2)$$

$$+|S_T|(1-y)\frac{P_{h\perp}^3}{6z^3 M_N^2 M_h}\sin(3\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 h_{1T}^{\perp(2)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

Polarzied beam and target

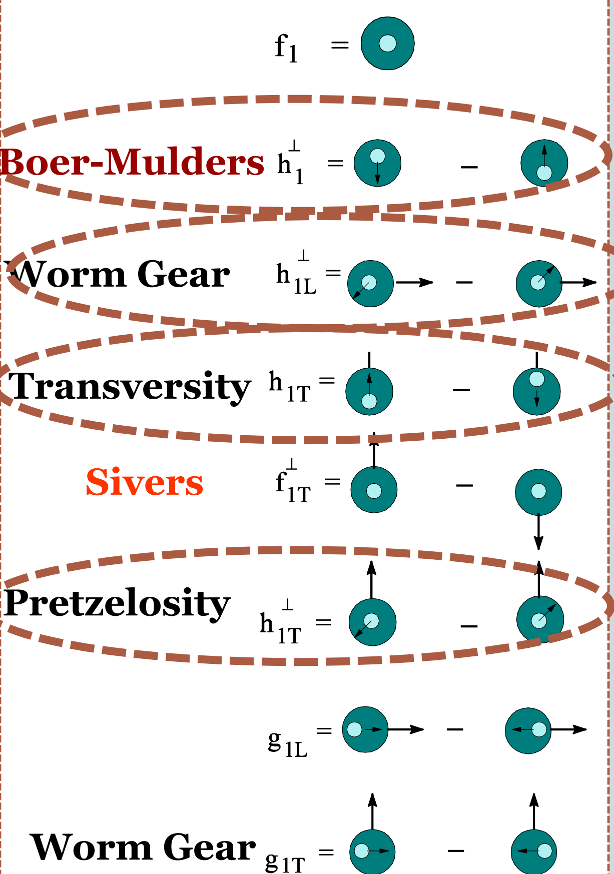
$$+\lambda_e|S_L|y(1-\frac{1}{2}y)\sum_{q,\bar{q}} e_q^2 g_1^q(x) D_1^q(z,P_{h\perp}^2)$$

$$+\lambda_e|S_T|y(1-\frac{1}{2}y)\frac{P_{h\perp}}{zM_N}\cos(\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 g_{1T}^{(1)q}(x) D_1^q(z,P_{h\perp}^2)\}$$

S_L and S_T: Target Polarizations; λe: Beam Polarization

x: momentum fraction carried by struck quark, z: fractional energy of hadron

Chiral Odd TMDs

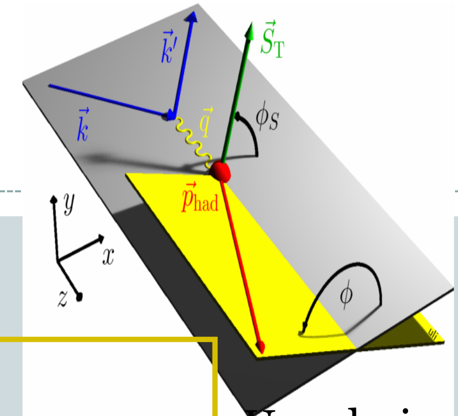


$$d^6\sigma = \frac{4\pi\alpha^2 sx}{Q^4}\times$$

$$\{[1+(1-y)^2]\sum_{q,\bar q} e_q^2 f_1^q(x) D_1^q(z,P_{h\perp}^2)$$

$$+(1-y)\frac{P_{h\perp}^2}{4z^2 M_N M_h}\cos(2\phi_h^l)\sum_{q,\bar q} e_q^2 h_1^{\perp(1)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

Unpolarized



$$-|S_L|(1-y)\frac{P_{h\perp}^2}{4z^2 M_N M_h}\sin(2\phi_h^l)\sum_{q,\bar q} e_q^2 h_{1L}^{\perp(1)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

$$+|S_T|(1-y)\frac{P_{h\perp}}{zM_h}\sin(\phi_h^l+\phi_S^l)\sum_{q,\bar q} e_q^2 h_1^q(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

$$+|S_T|(1-y+\frac{1}{2}y^2)\frac{P_{h\perp}}{zM_N}\sin(\phi_h^l-\phi_S^l)\sum_{q,\bar q} e_q^2 f_{1T}^{\perp(1)q}(x) D_1^q(z,P_{h\perp}^2)$$

$$+|S_T|(1-y)\frac{P_{h\perp}^3}{6z^3 M_N^2 M_h}\sin(3\phi_h^l-\phi_S^l)\sum_{q,\bar q} e_q^2 h_{1T}^{\perp(2)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

Polarized target

$$+\lambda_e|S_L|y(1-\frac{1}{2}y)\sum_{q,\bar q} e_q^2 g_1^q(x) D_1^q(z,P_{h\perp}^2)$$

$$+\lambda_e|S_T|y(1-\frac{1}{2}y)\frac{P_{h\perp}}{zM_N}\cos(\phi_h^l-\phi_S^l)\sum_{q,\bar q} e_q^2 g_{1T}^{(1)q}(x) D_1^q(z,P_{h\perp}^2)\}$$

Polarzied beam and target

S_L and S_T: Target Polarizations; λe: Beam Polarization

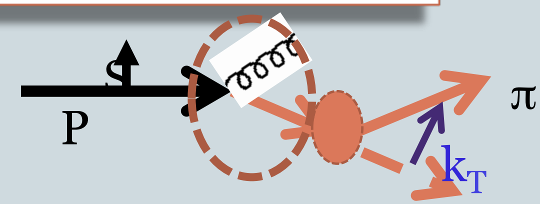
Example: Collins Extraction of Transversity: Transverse momentum dependence is essential!

Spin Asymmetry extraction:
Moments normalized to spin independent x-section

$$\frac{N^{\uparrow}-N^{\uparrow}}{N^{\uparrow}+N^{\uparrow}} \propto 1+\sum_i A_i \cos(\varphi_i), i \in \{Coll, Siv, \ldots\}, \qquad A_i = \frac{f_i \otimes D_i}{f \otimes D}$$

cancels detector effects →no MC needed

Including p_T dependence e.g:



transversity Collins FF

$$A_{UT}^{Collins} = \frac{\sum_q e_q^2 \int d\varphi_S \, d\varphi_h d^2 k_\perp h(x,k_\perp) \frac{d(\Delta\sigma)}{dy} H_{1,q}^{\perp}(z,p_\perp) \sin(\varphi_S+\varphi+\varphi_q^h)\sin(\varphi_S+\varphi_h)}{\sum_q e_q^2 \int d\varphi_S \, d\varphi_h d^2 k_\perp q(x,k_\perp) \frac{d(\Delta\sigma)}{dy} D_q^h(z,p_\perp)}$$

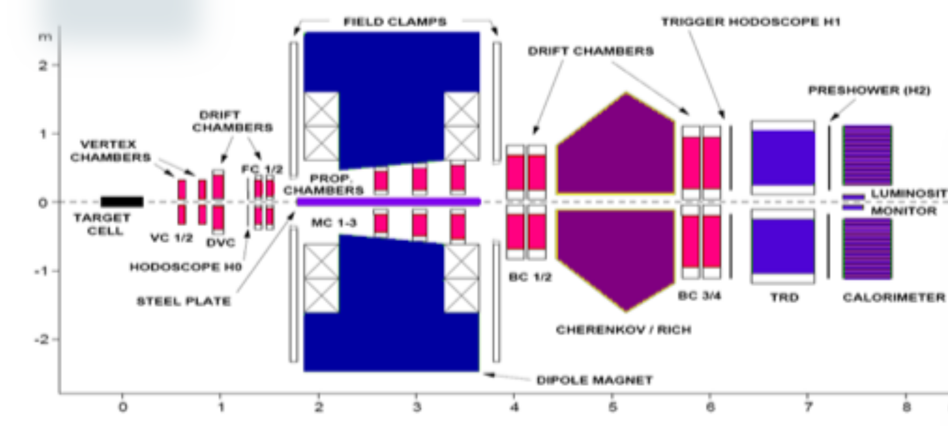
quark pdf hadron FF

$k_\perp$ transverse quark momentum in nucleon
$p_\perp$ transverse hadron momentum in fragmentation

Anselmino, Boglione, D'Alesio, Kotzinian, Murgia, Prokudin, Turk Phys. Rev. D75:054032,2007

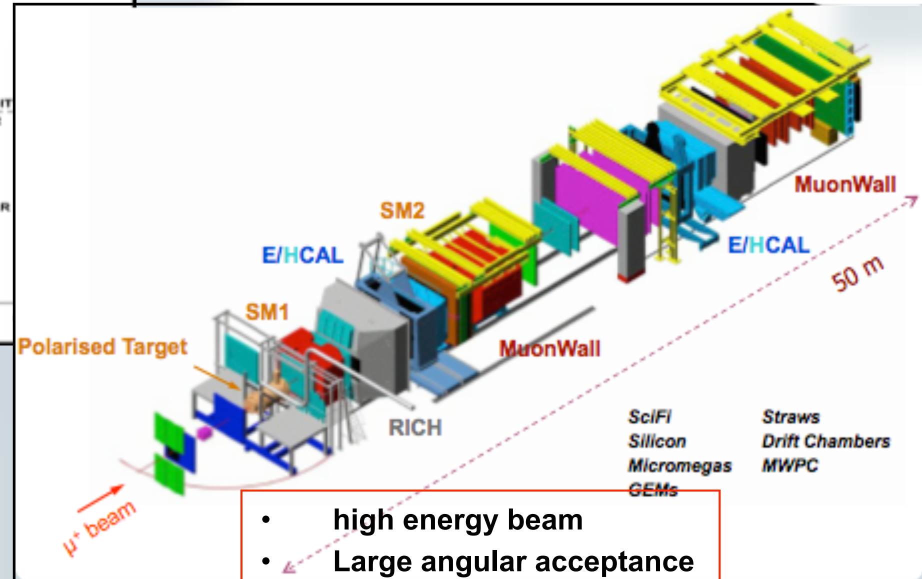
The transverse momentum dependencies are still unknown→usual Gauss assumed
→Need to measure p_T dependence

HERMES@DESY

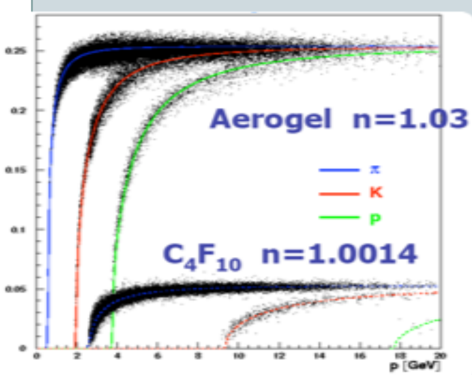


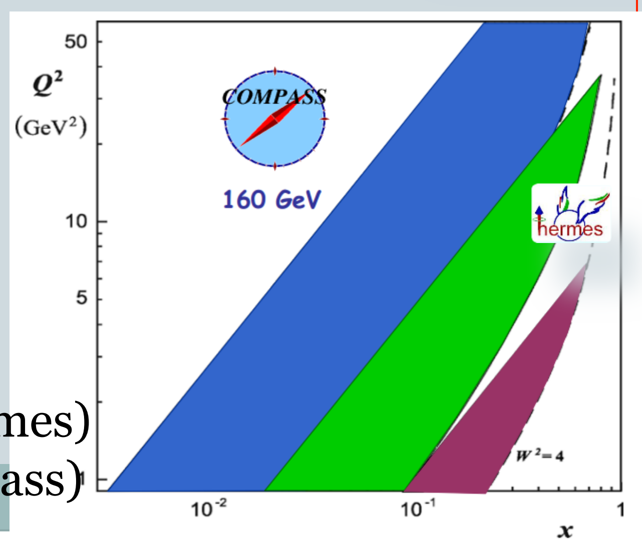
- Pioneering TMD/GPD experiment
- Moderate energy beam
- L/T proton/deuteron targets 27.6 GeV e^- beam

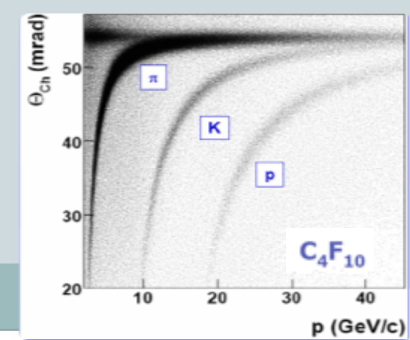
COMPASS@CERN



- high energy beam
- Large angular acceptance
- Broad kinematical range – 2 stage spectrometer
- 160 GeV μ^+ beam off ^{6}LiD/ NH^3 L/T target







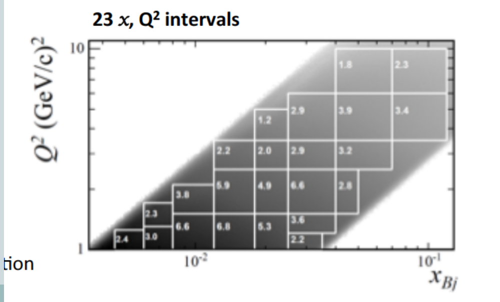
- Measurements for
  - π^{+-},K^{+-},π^0,η (Hermes)
  - π^{+-},K^{+-},K_S (Compass)
- Here mostly π^{+-}

Baseline Multiplicities, $M(x,p_T) \approx \sum_q e_q^2 f_1^q(x,p_T) \otimes D(z,k_T) \,/\, \sum_q e_q^2 f_1^q(x)$

- Access to intrinsic quark k_T, e.g. (gauss) $\langle P_\perp^2\rangle = z^2\langle k_T^2\rangle + \langle p_T^2\rangle$
- Test of TMD factorization
- Unpolarized measurement: Needs very good understanding of acceptance
- Hermes, Compass use Lepto+Jetset/Pythia + GEANT to model acceptance

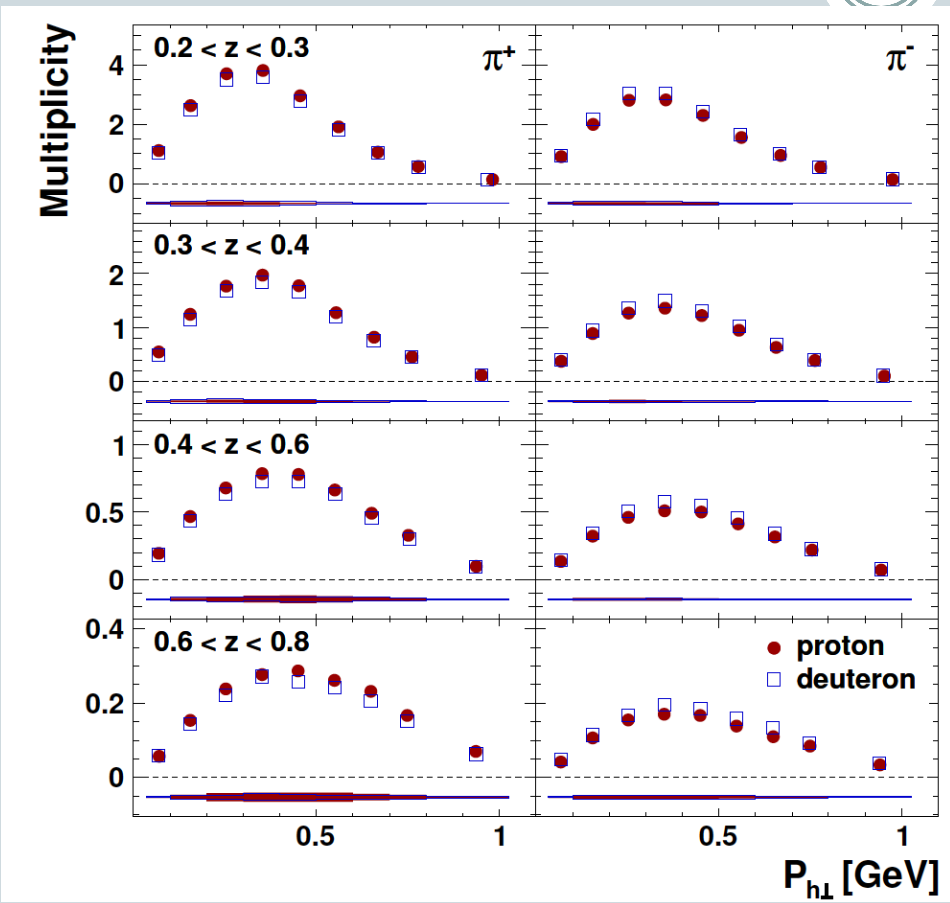
- from MC: $\varepsilon(\phi,\Omega) = \varepsilon(\phi,\Omega)\,\sigma(\phi,\Omega) \,/\, \sigma(\phi,\Omega)$, $\Omega \in x,y,z\ldots$
- $\varepsilon(\phi) = \int d\Omega\, \varepsilon(\phi,\Omega)\,\sigma(\phi,\Omega) \,/\, \int d\Omega\, \sigma(\phi,\Omega)$
- →x-section cancels if multi dimensional binning with small enough Bins…

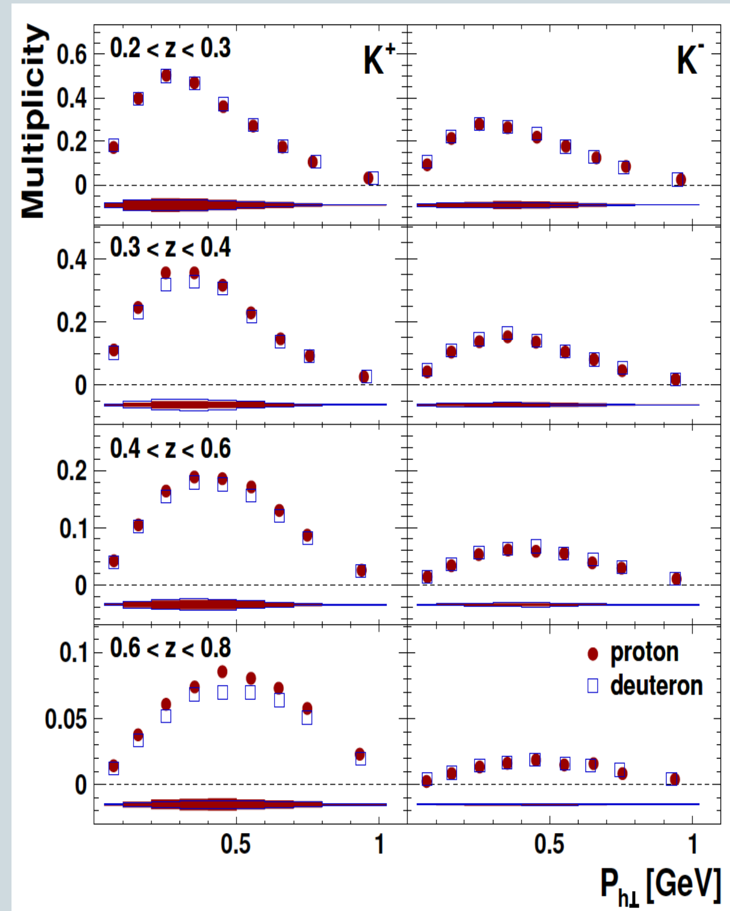
○ **→Fully differential analysis!**



Compass binning

Hermes Results on Multiplicities for id. π/K



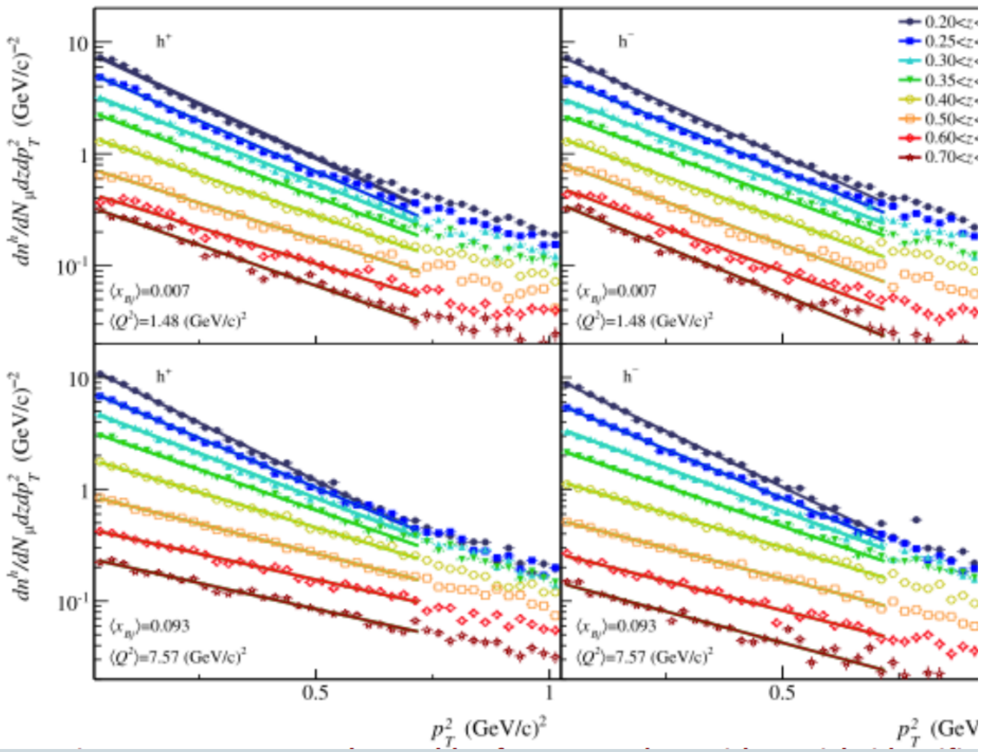


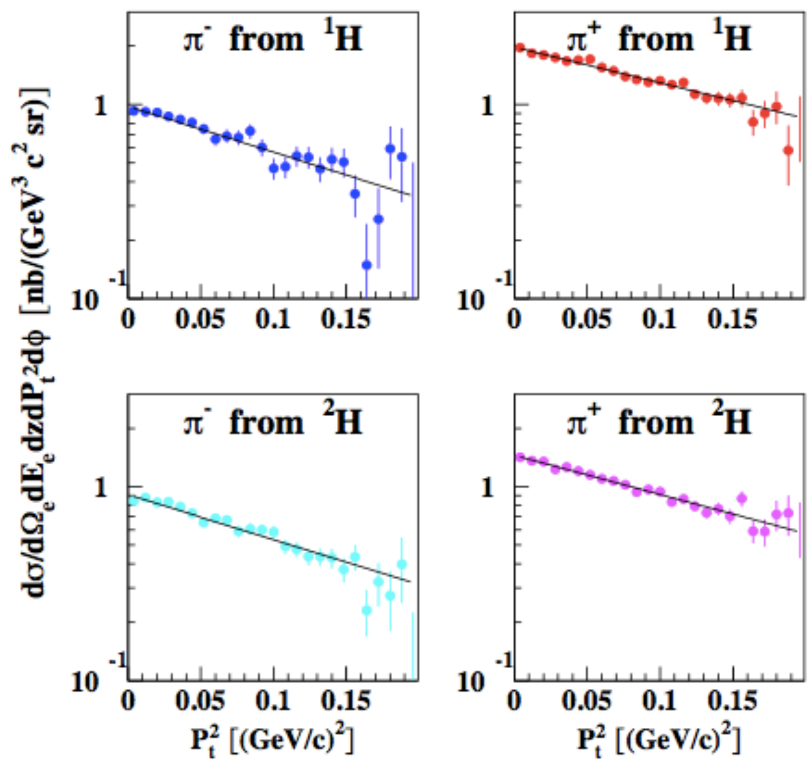
3-4 % sys error from varying jetset parameters

Flavor dependence of TMDs (Signori, Bacchetta, Radici, Schnell, doi:10.1007 JHEP 11(2013)194)

Compass/Jlab results

EPJC 73(2013) 2531



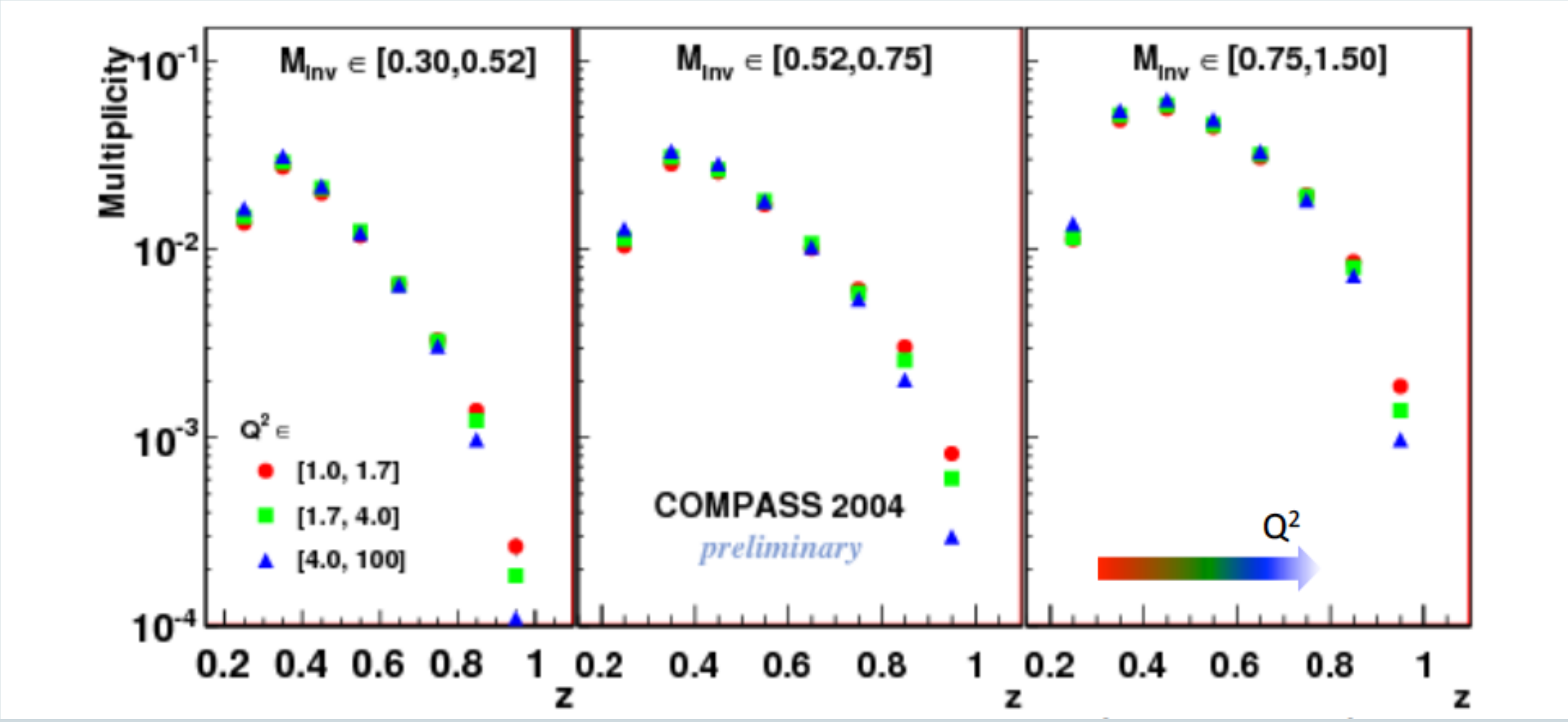


+ bins in z and pT→4D acceptance corrections
See Zhangbo's talk for fits using TMD evolution of Hermes, Compass, Jlab data

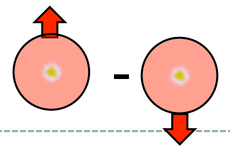
JLAB6 Hall C
E00108 (HMS)
Q2>1.5

Compass 2H Multiplicities

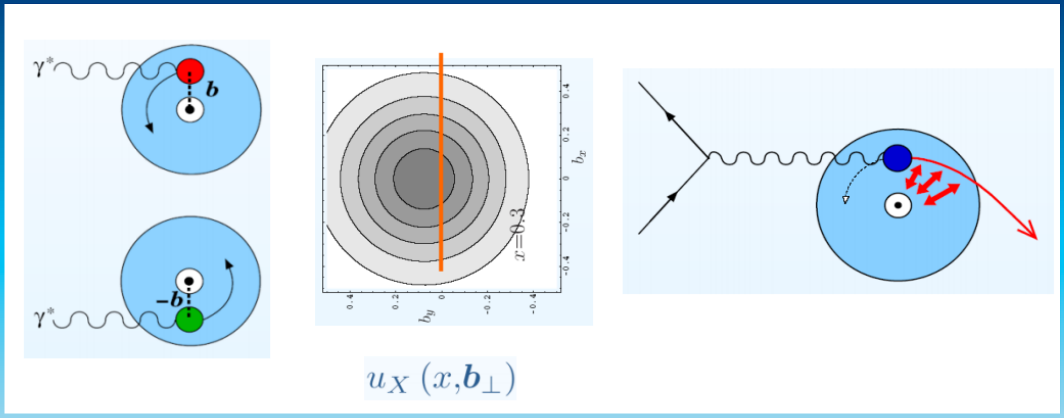
- Needed for transversity from di-hadron correlations



Sivers Asymmetries $A_{Siv} \sin(\phi_h - \phi_S)$



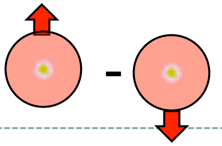
- The 'original TMD', Sivers 1990
- Correlation between quark k_T and nucleon spin
- Naïve T-odd: Needs final state interaction



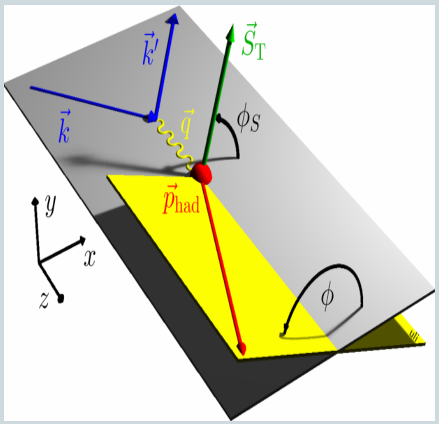
Burkardt:
"Chromodynamic Lensing"

- Model dependent connection to OAM

Sivers Asymmetries, $A^{\sin(\phi h-\phi S)} \propto f^{\perp}_{1} \otimes D_{1}$

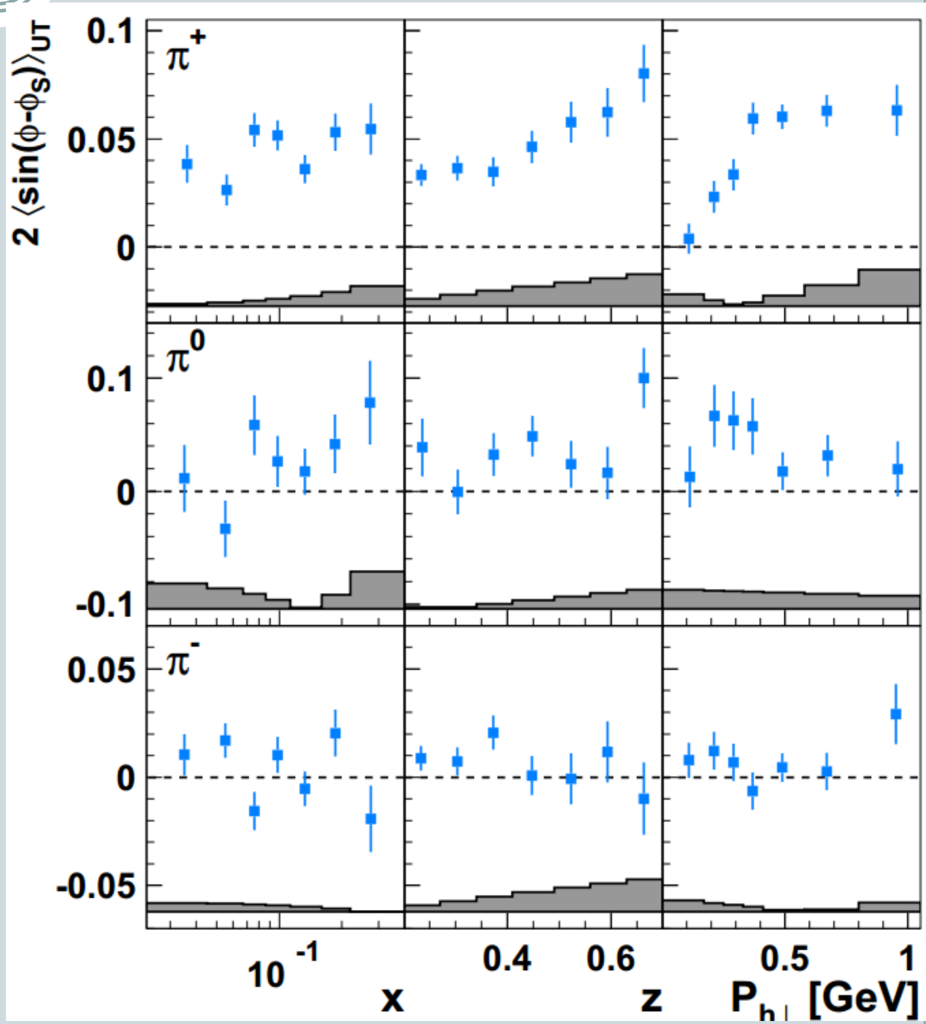


- HERMES sees significant signal on proton

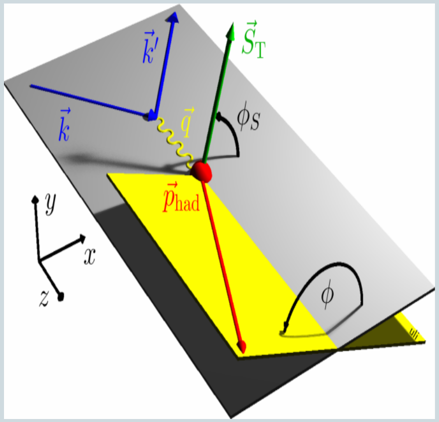


$\sigma_{UT} \propto \sigma_{UU} + A_{siv}\sin(\phi_h-\phi_S)+....$

$A_{siv} \propto f^{\perp}_{1} \otimes D_{1}$

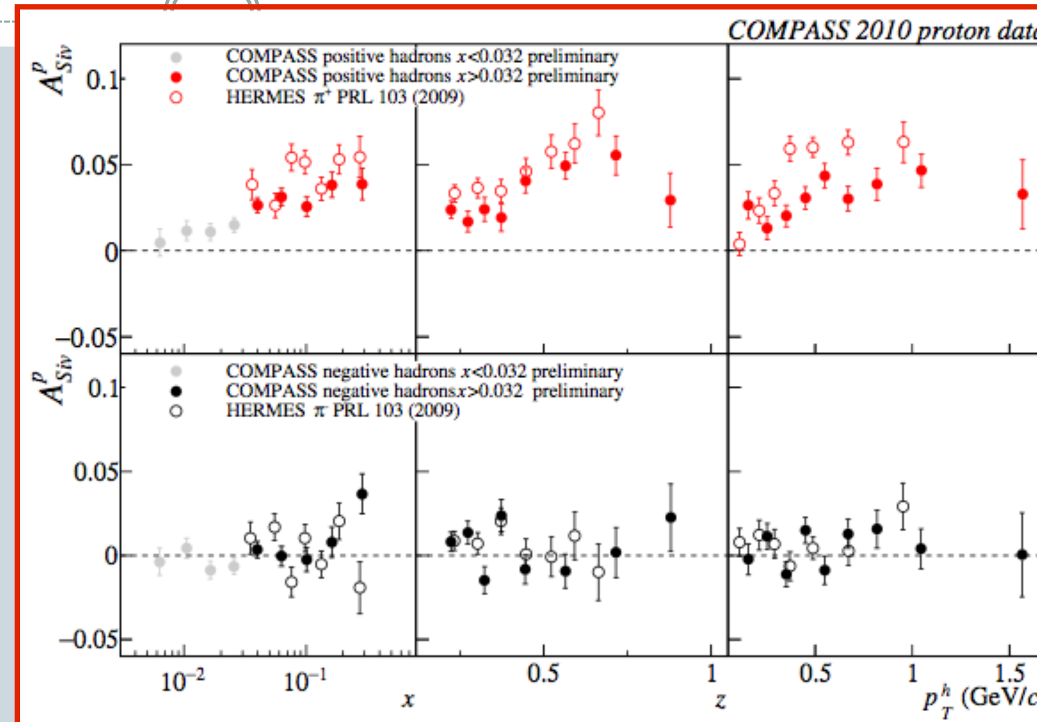


COMPASS and HERMES see significant signal on proton

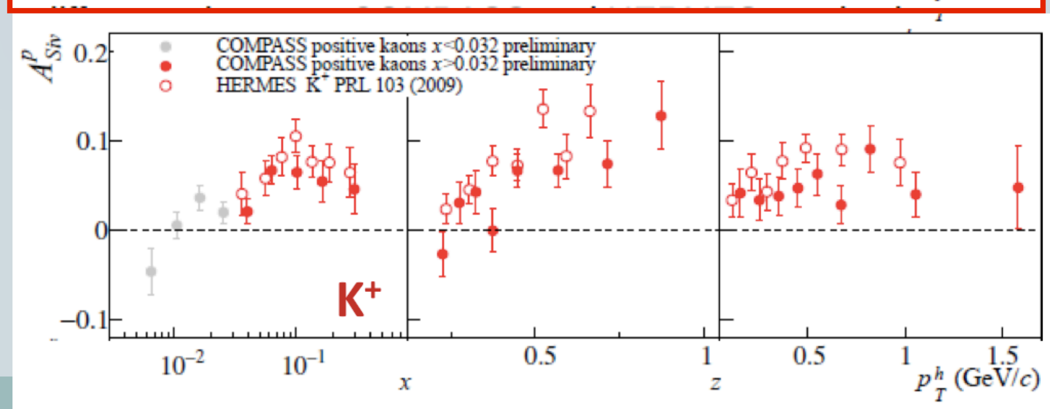


$$\sigma_{UT} \propto \sigma_{UU} + A_{siv}\cos(\phi_h - \phi_S) + \ldots.$$

$$A_{siv} \propto f^{\perp}_1 \otimes D_1$$

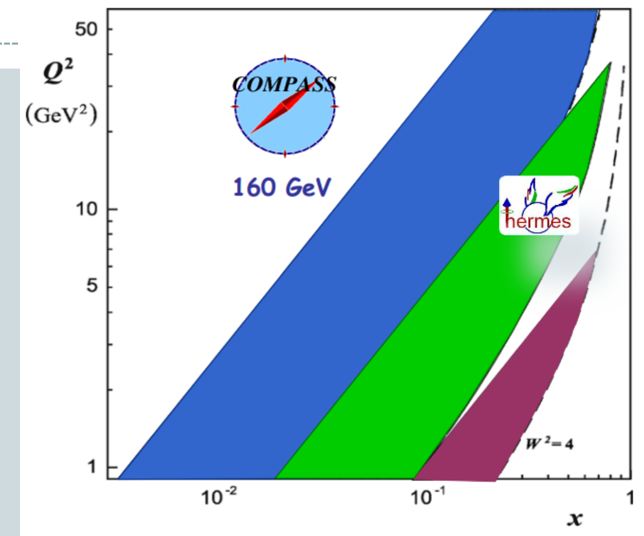


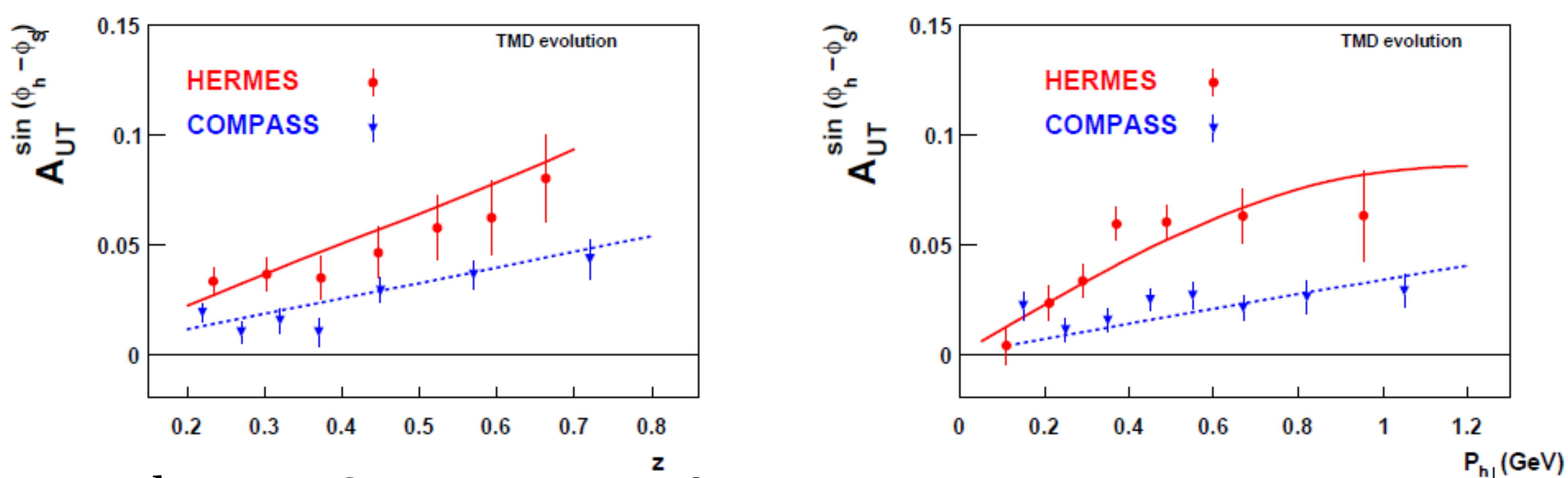
- Larger
  Kaon Signal…



TMD evolution

- TMD evolution, see Zhongbo Kang's talk
- Work from
  - Anselmino, Boglione, Melis
  - Aybat, Prokudin, Rogers,
  - Sun, Yuan,
  - Echevarria, Idilbi, Kang, Vitev

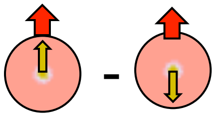




Compass k_T=0.25 GeV, Hermes 0.18

Aybat, Prokudin, Rogers, arXiv: 1112.4423

Collins Effect, $A^{\sin(\phi h+\phi S)} \propto h_1 \otimes H_1$

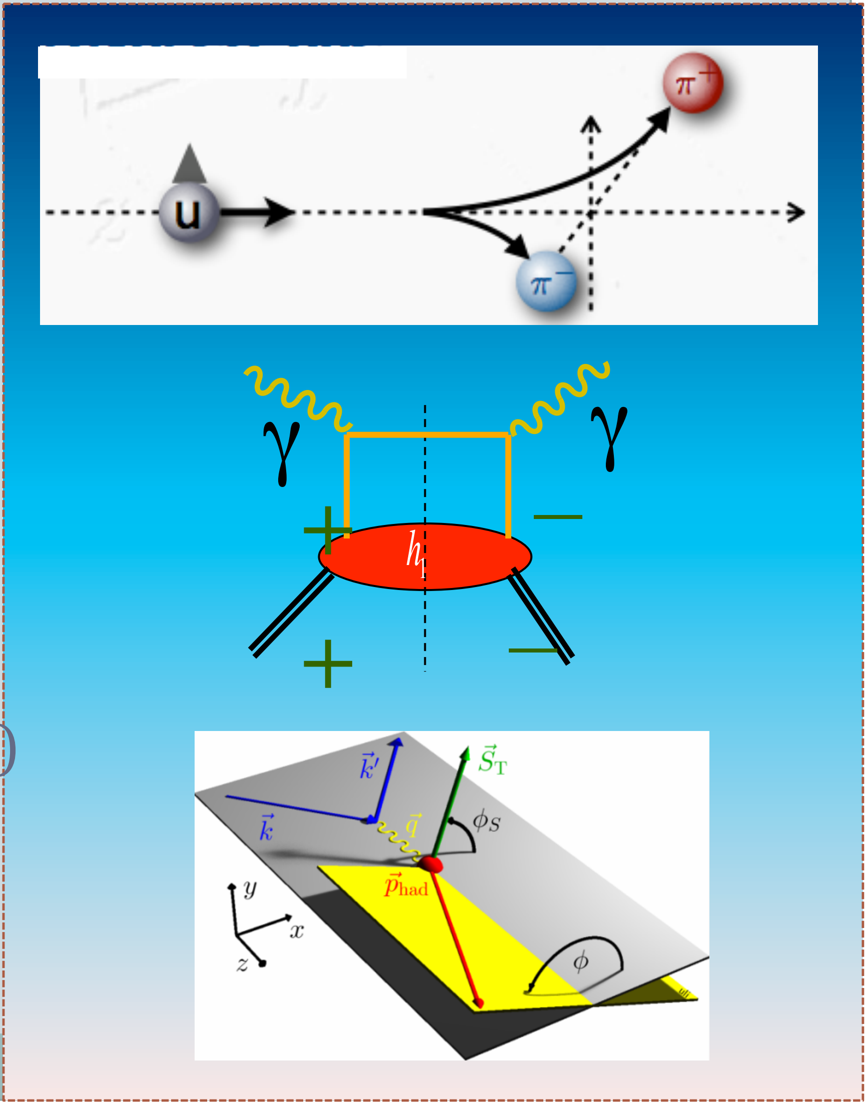


- Collins (1993)

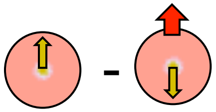
  $\sigma_{UT} \propto \sigma_{UU} + A_{Cols}\sin(\phi_h+\phi_S)+....$

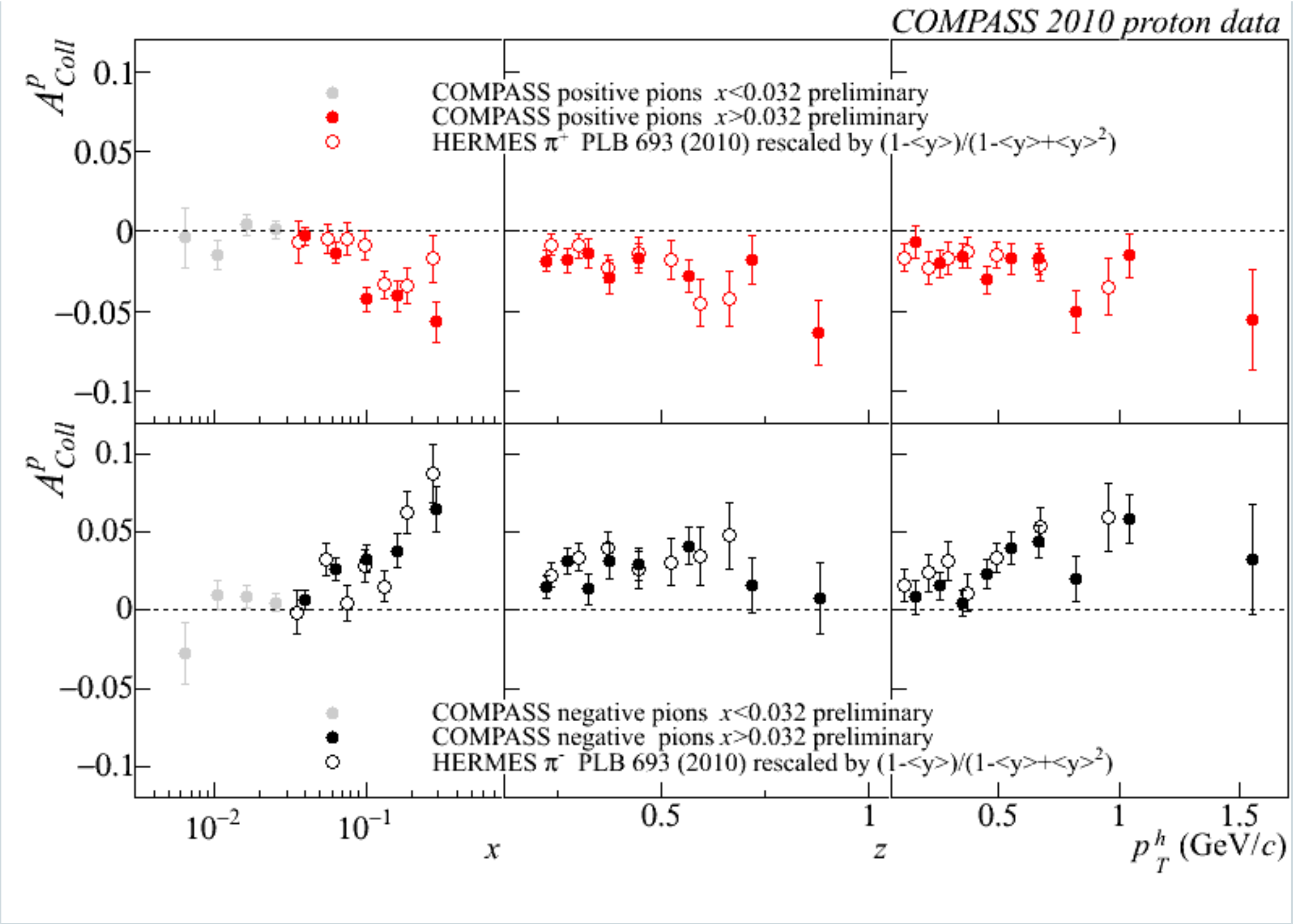
  $A_{Col} \propto h_1 \otimes H_1$

- Access to transversity:
- Least well known collinear PDF
  - Chiral odd quantity
  - $\int h_1(x)dx$=Tensor charge (Lattice)
- Needs chiral odd partner FF as "Quark polarimeter)



Transversity: $A_{Col} \propto h_1 \otimes H_1$

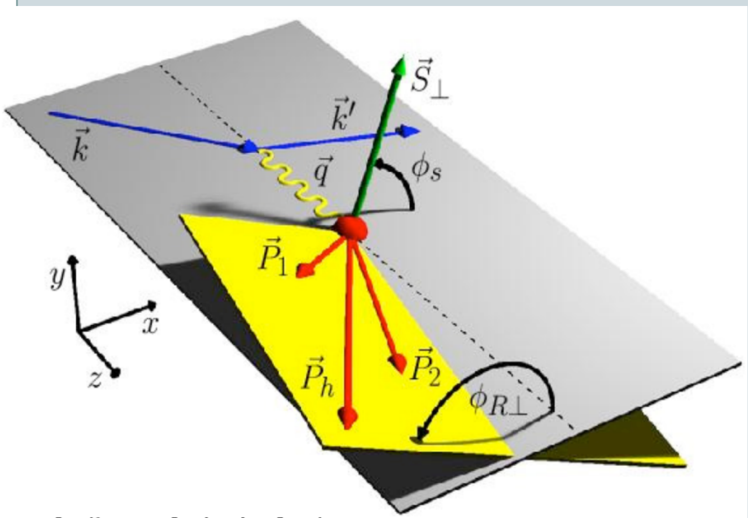


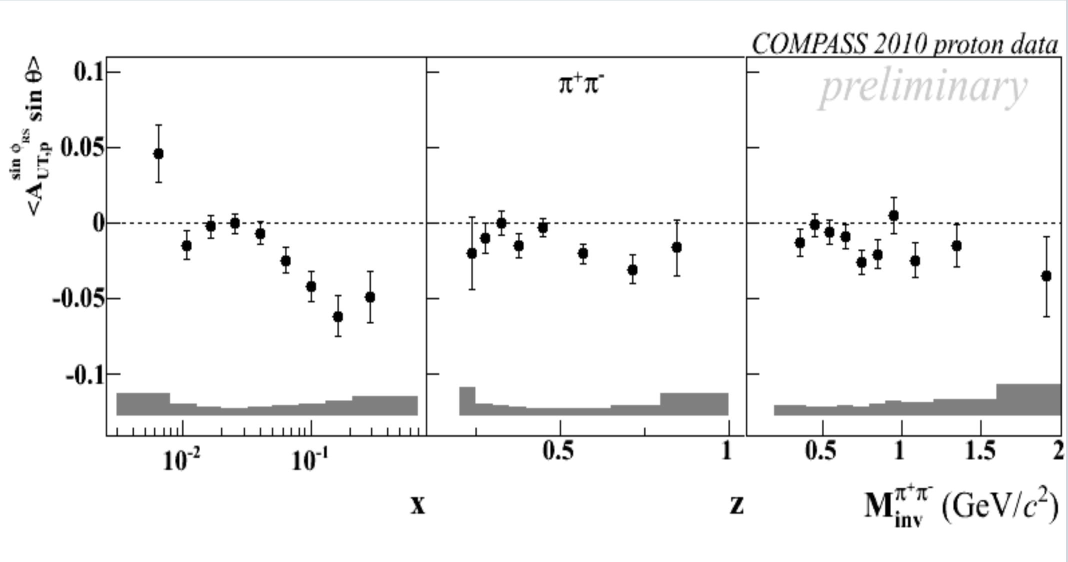


Agreement, no TMD evolution of h_1

Di-hadron Asymmetries: $A^{\sin(\phi R+\phi S)} \propto h_1 \bullet H_1^{<}$

- Collinear framework

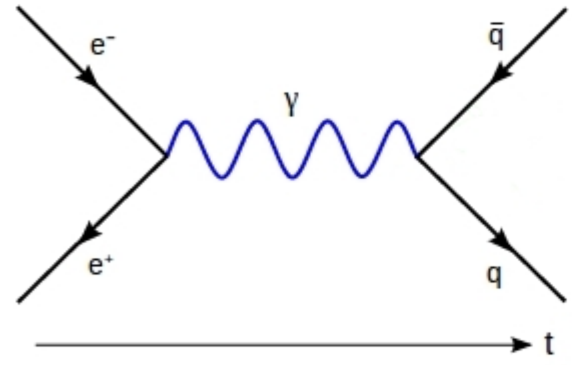




$A_{UT} \propto h_1 \bullet H_1^{<}$

Measurements of Fragmentation Functions in e+e- at Belle and Babar

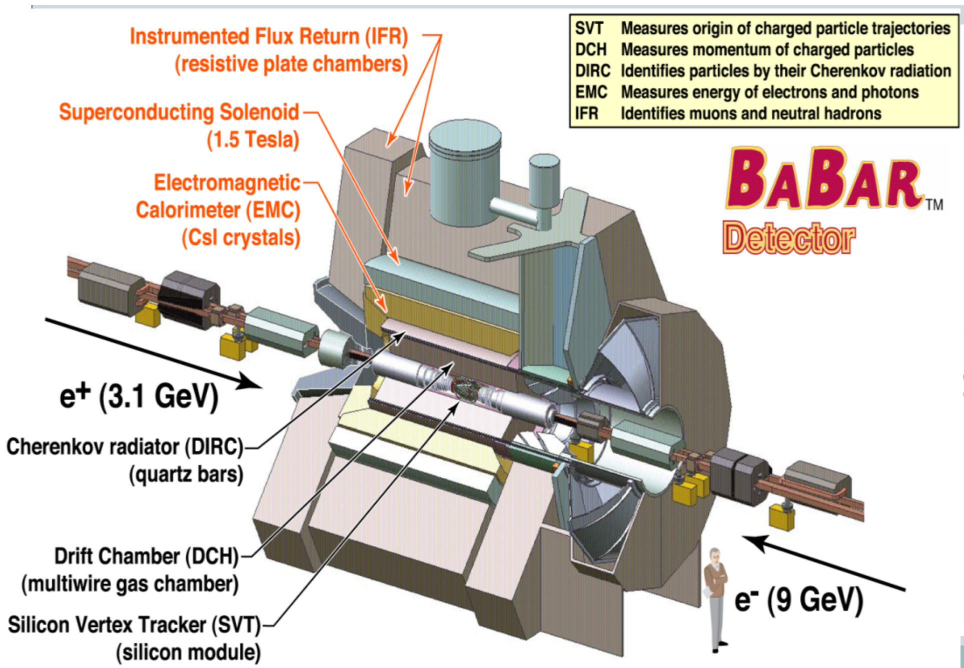
- B-Factories: asym. e^+ (3.5/3.1 GeV) e^- (8/9 GeV) collider:
  - **-$\sqrt{s}$ = 10.58 GeV,** $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B$ anti-B
  - -$\sqrt{s}$ = 10.52 GeV, e+e-→ qqbar (u,d,s,c) 'continuum'
- ideal detector for high precision measurements:
  - Azimuthally symmetric acceptance, high res. Tracking, P

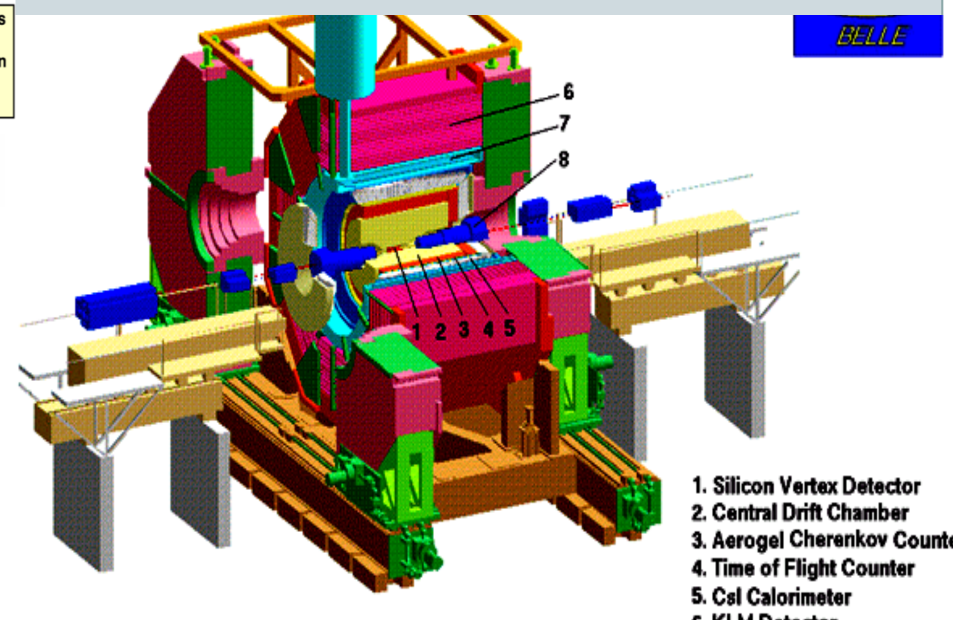


Available data (Belle, Babar similar):

~1.8 $*10^9$ events at 10.58 GeV,

~220 $*10^6$ events at 10.52 GeV





Measurements of Fragmentation Functions in e+e- at Belle and Babar

• B-Factories: asym. e^+ (3.5/3.1 GeV) e^- (8/9 GeV) collider :

  -$\sqrt{s}$ = 10.58 GeV, $e^+e^-\rightarrow \Upsilon(4S)\rightarrow$ B anti-B

  -$\sqrt{s}$ = 10.52 GeV, e+e-→ qqbar (u,d,s,c) 'continuum'

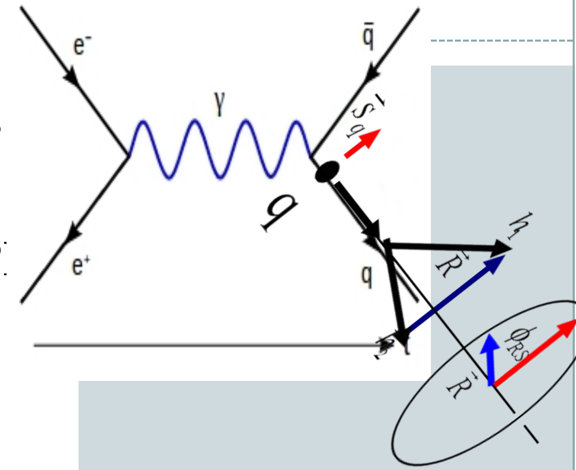
• ideal detector for high precision measurements:

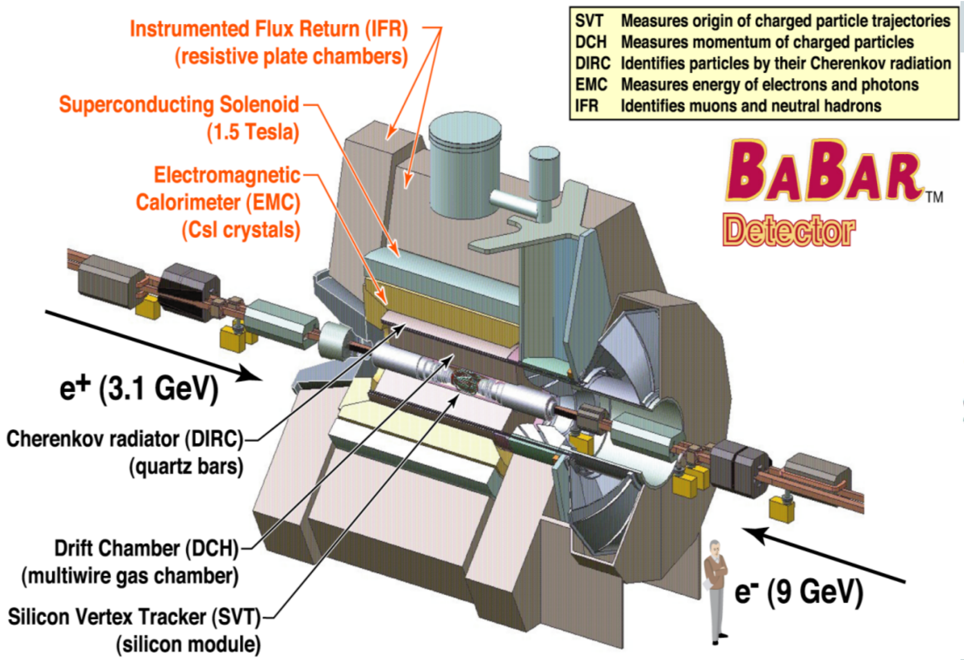
  - Azimuthally symmetric acceptance, high res. Tracking, P

Available data (Belle, Babar similar):

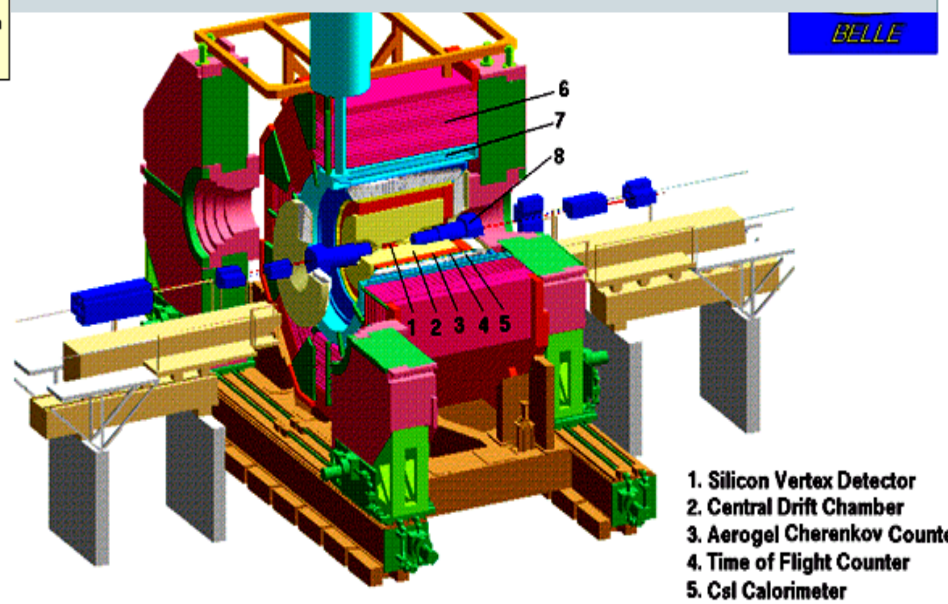
  ~1.8 $*10^9$ events at 10.58 GeV,

  ~220 $*10^6$ events at 10.52 GeV

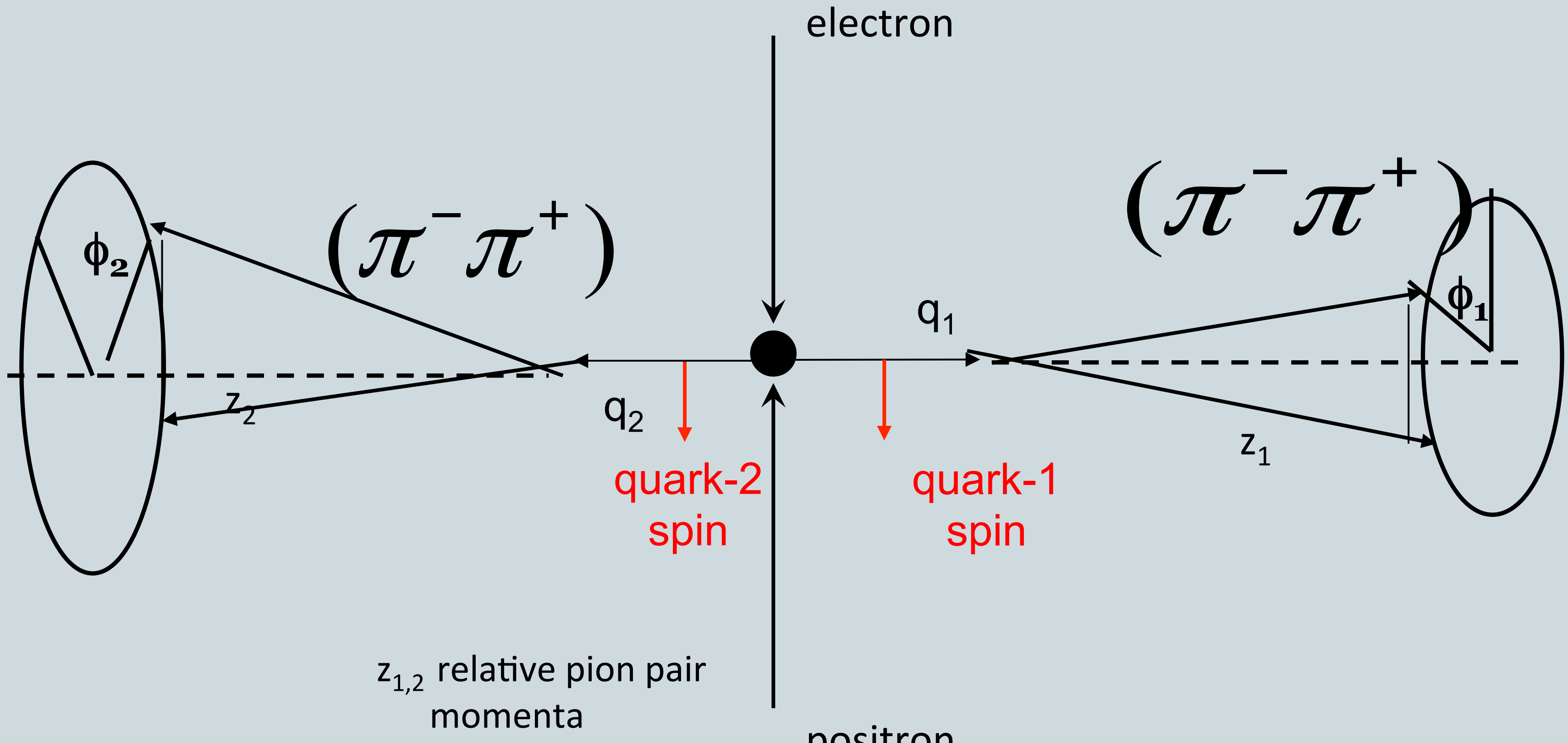




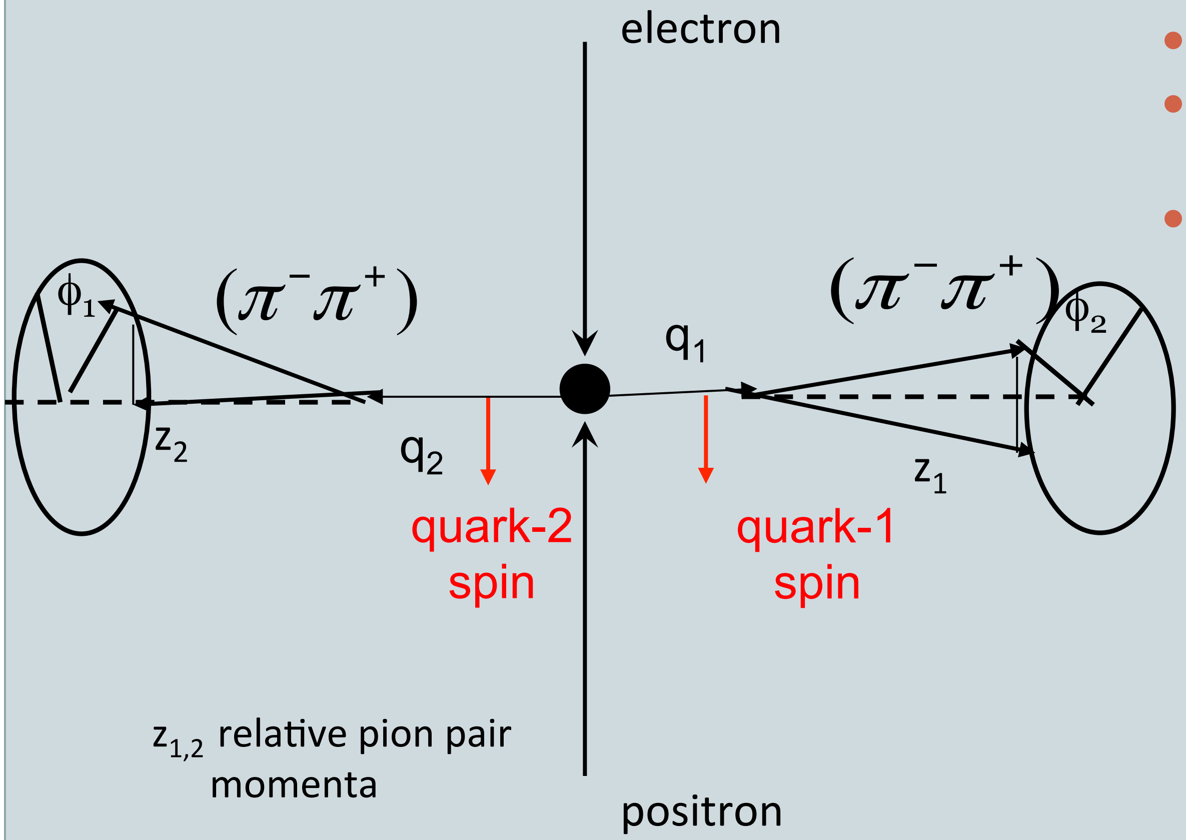
SVT	Measures origin of charged particle trajectories
DCH	Measures momentum of charged particles
DIRC	Identifies particles by their Cherenkov radiation
EMC	Measures energy of electrons and photons
IFR	Identifies muons and neutral hadrons



Measuring Spin Dependent FFs in unpolarized e+e- collisions using angular correlations

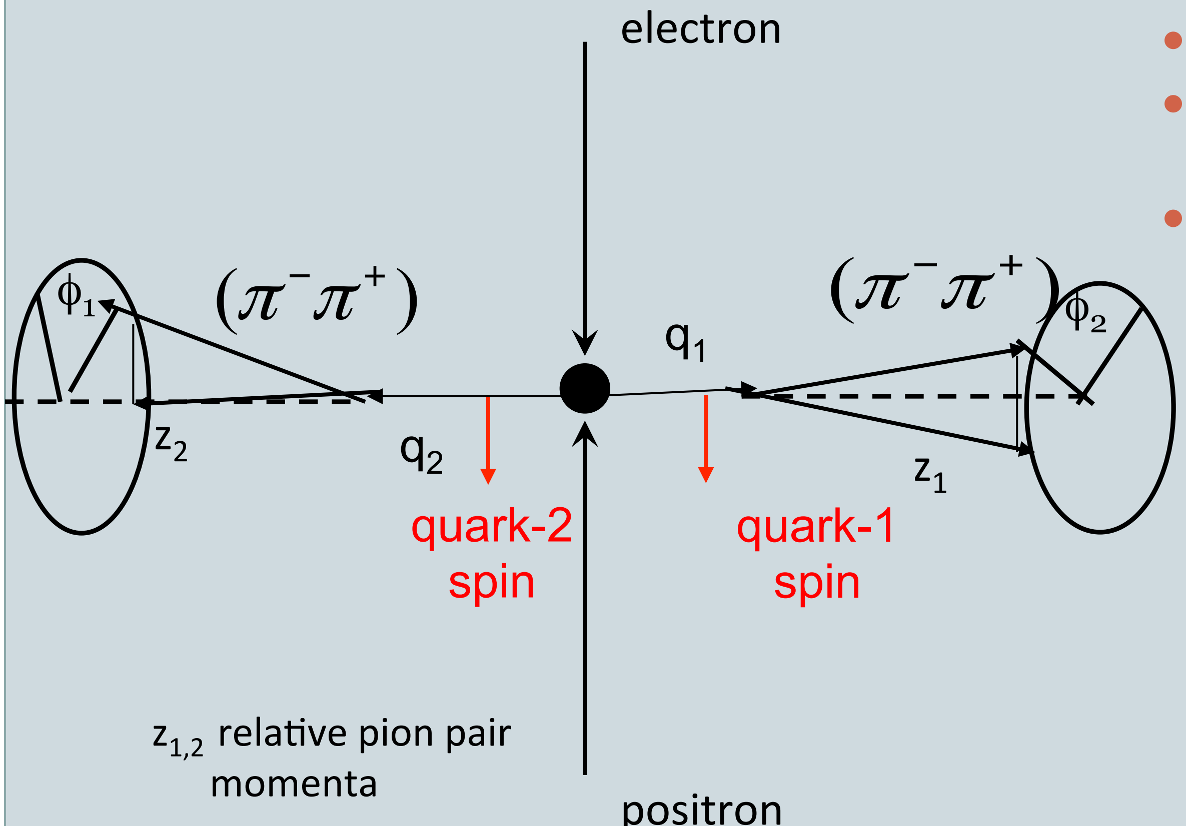


Measuring Spin Dependent FFs in unpolarized e+e- collisions using angular correlations



- $e^+e^- \rightarrow (\pi^+\pi^-)_{jet1}(\pi^+\pi^-)_{jet2}X$
- Find pion pairs in opposite hemispheres
- Observe angles φ_1, φ_2 between the event-plane (beam, jet-axis) and the two two-pion planes.

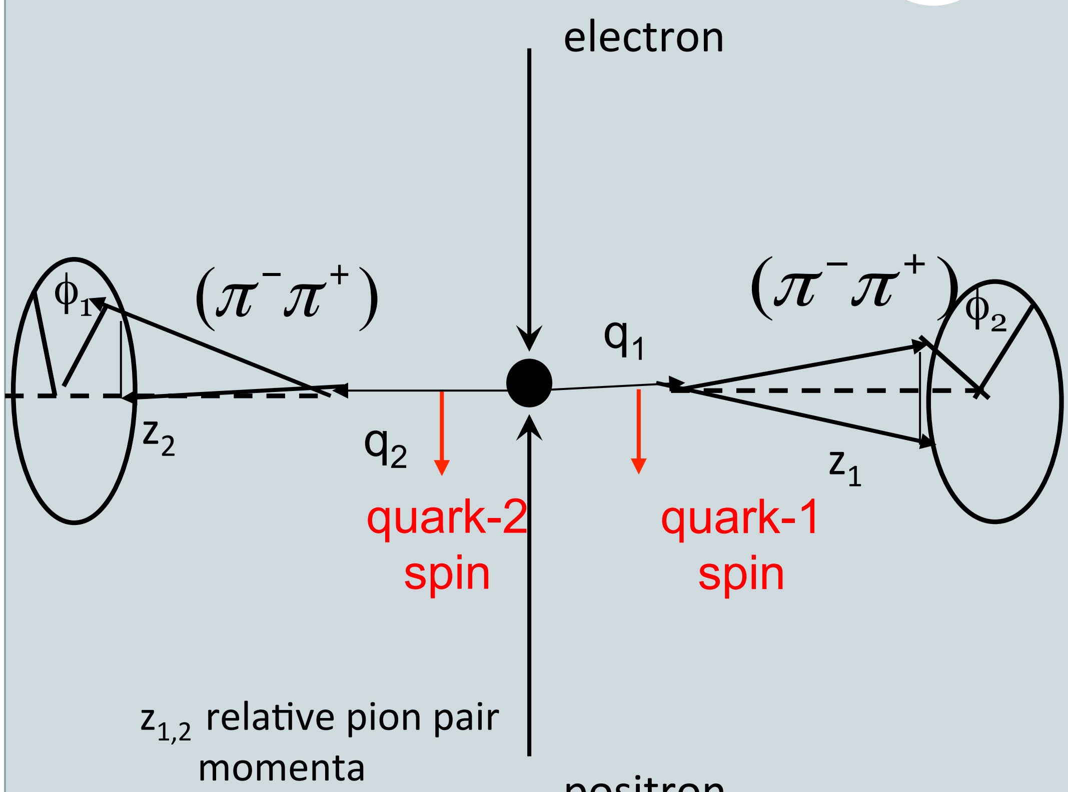
Measuring Spin Dependent FFs in unpolarized e+e- collisions using angular correlations



- $e^+e^- \rightarrow (\pi^+\pi^-)_{jet1}(\pi^+\pi^-)_{jet2}X$
- Find pion pairs in opposite hemispheres
- Observe Yield $N(\varphi_1, \varphi_2)$, φ_1, φ_2 between the event-plane (beam, jet-axis) and the two single/di-pion planes.

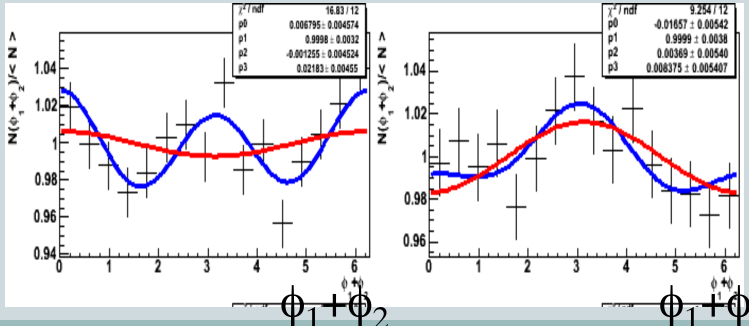
e.g. $A^{\cos(\phi1+\phi2)}_{UT} \propto H_1^{<} \bullet H_1^{<}$
Or $H_1 \bullet H_1$ for single hadrons

Measuring Spin Dependent FFs in unpolarized e+e- collisions using angular correlations



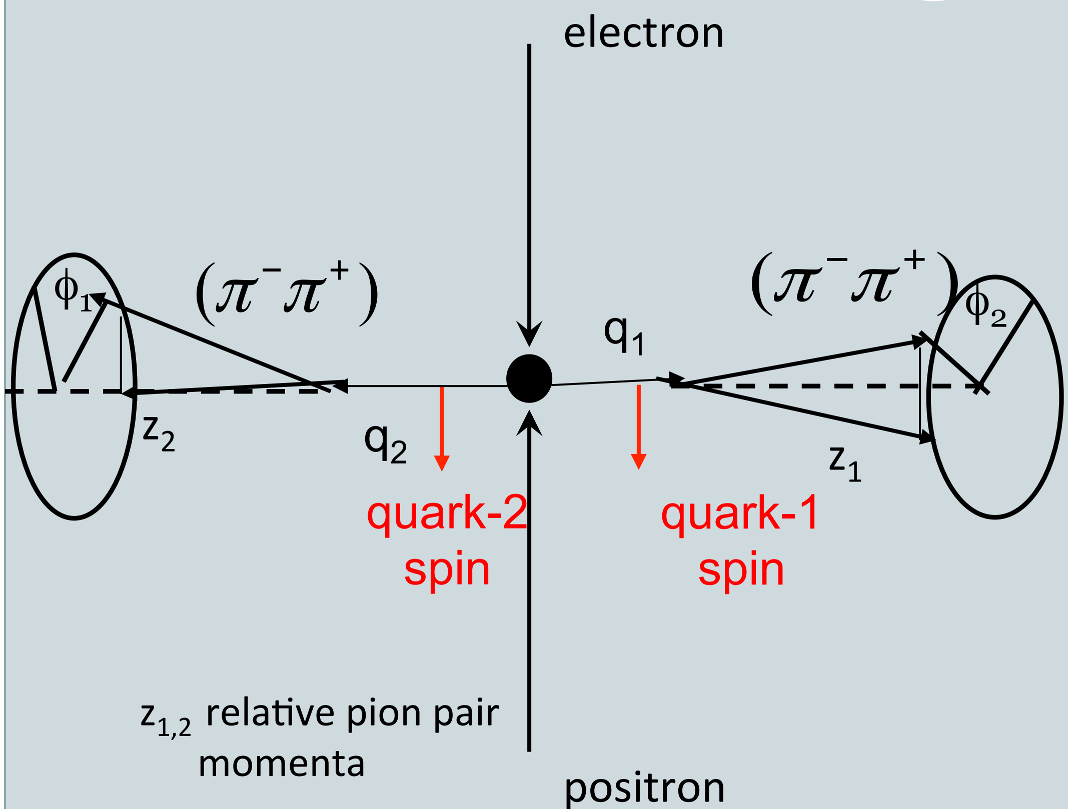
- $e^+e^- \rightarrow (\pi^+\pi^-)_{jet1}(\pi^+\pi^-)_{jet2}X$
- Find pion pairs in opposite hemispheres
- Observe angles φ_1, φ_2 between the event-plane (beam, jet-axis) and the two two-pion planes.

e.g. $A^{\cos(\phi1+\phi2)}_{UT} \propto H_1^< \bullet H_1^<$
Or $H_1 \bullet H_1$ for single hadrons



Fit counts... done...

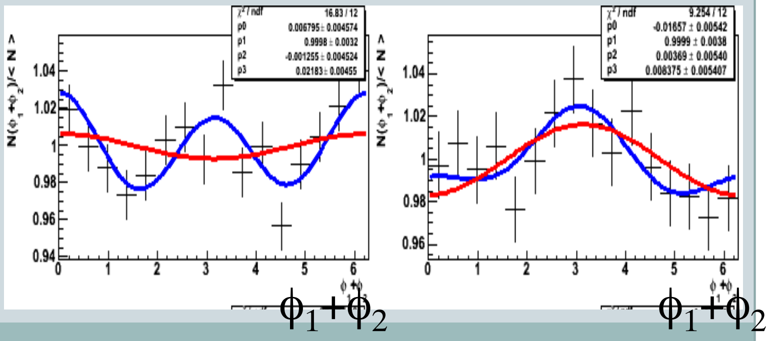
Measuring Spin Dependent FFs in unpolarized e+e- collisions using angular correlations



- $e^+e^- \rightarrow (\pi^+\pi^-)_{jet1}(\pi^+\pi^-)_{jet2}X$
- Find pion pairs in opposite hemispheres
- Observe angles φ_1, φ_2 between the event-plane (beam, jet-axis) and the two two-pion planes.

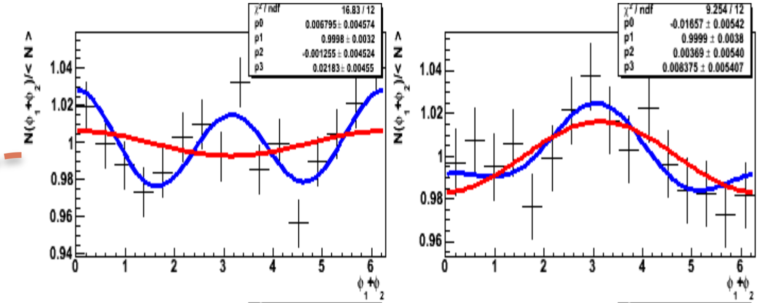
e.g. $A^{\cos(\phi1+\phi2)}{}_{UT} \propto H_1^{<} \bullet H_1^{<}$

Or $H_1 \bullet H_1$ for single hadrons

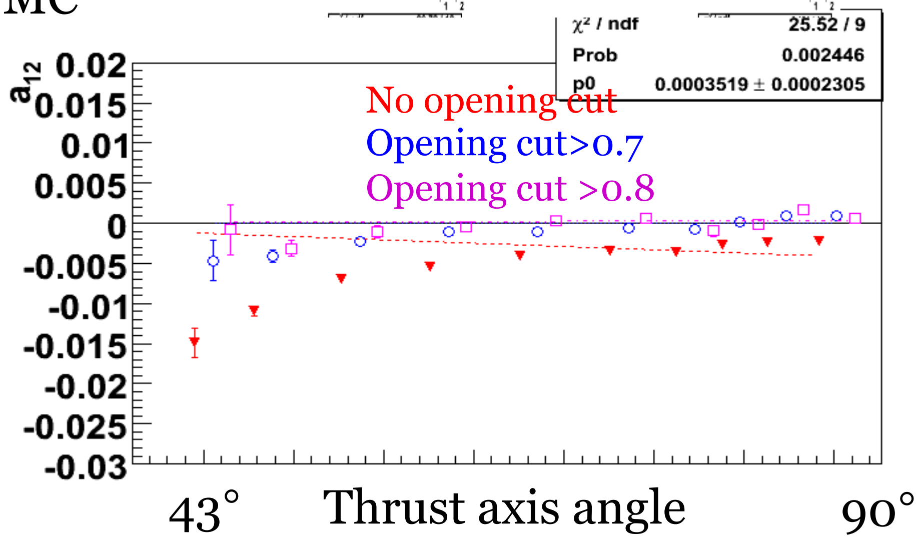


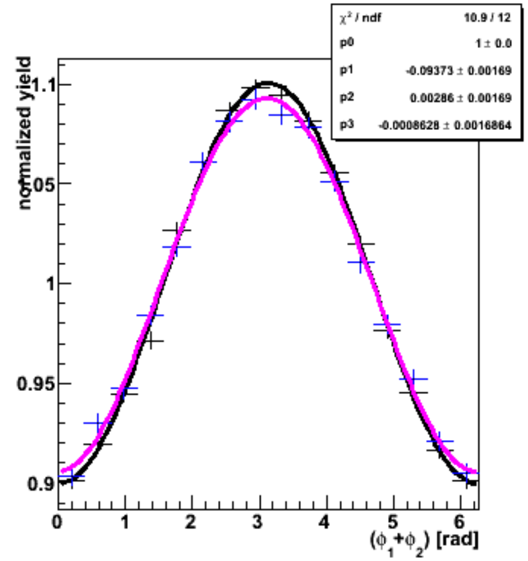
Fit counts… done… or not?

Extraction of $A^{\cos(\phi_1+\phi_2)}$~$H_1^{<}H_1^{<}$,Zero tests: MC



In MC

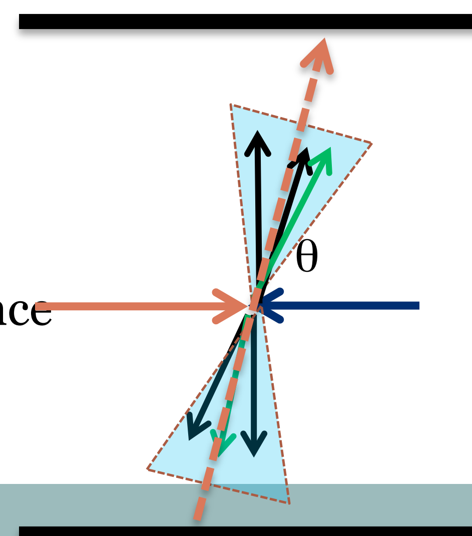




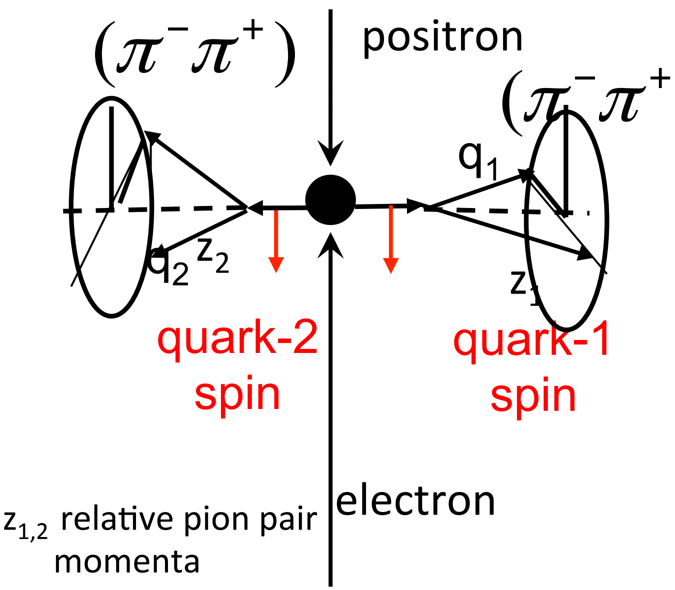
Thrust axis reconstruction:
94% of asymmetry Is reconstructed

- A small asymmetry seen due to acceptance effect
- Mostly appearing at boundary of acceptance
- Opening cut in CMS of 0.8 (~37 degrees) reduces acceptance effect to the sub-per-mille level
- θ>56°

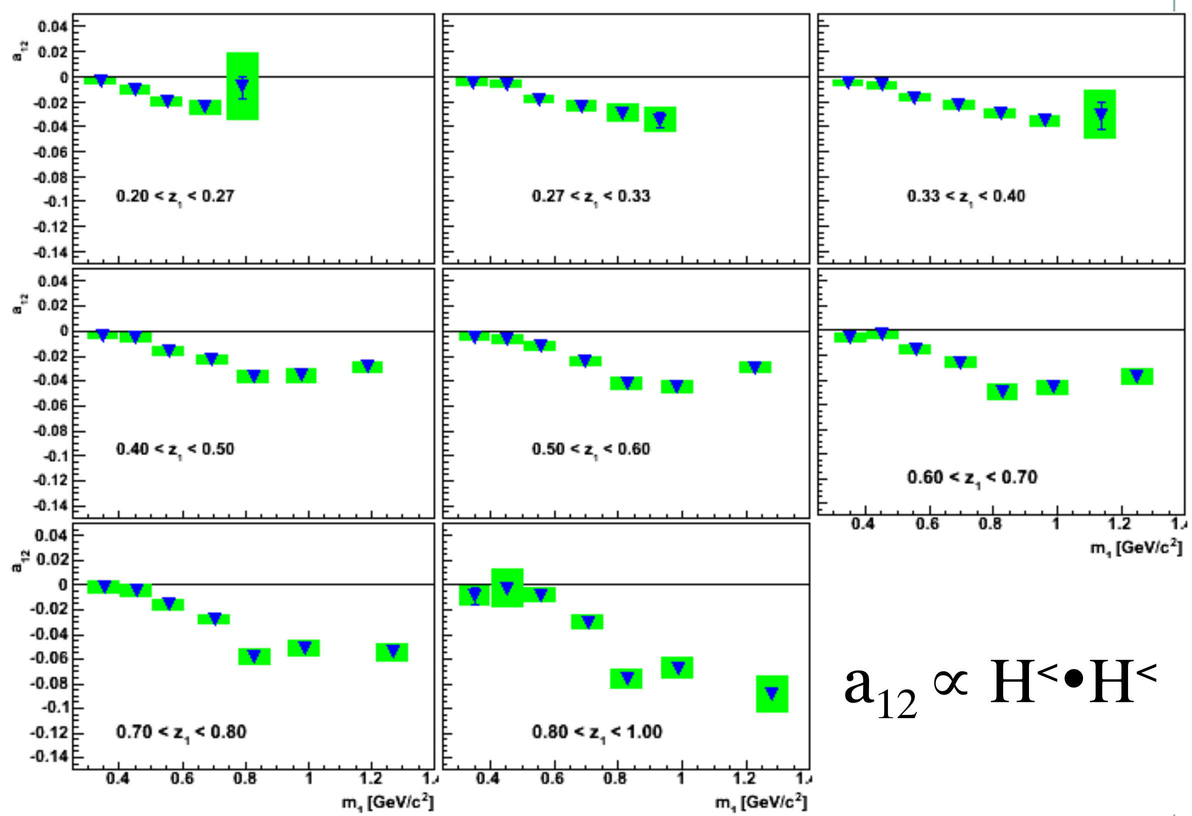
$$\frac{P_h \bullet \hat{n}}{|P_h|} = \cos(P,n)$$



Measuring the spin dependent $H^{<}_1$ in e^+e^-



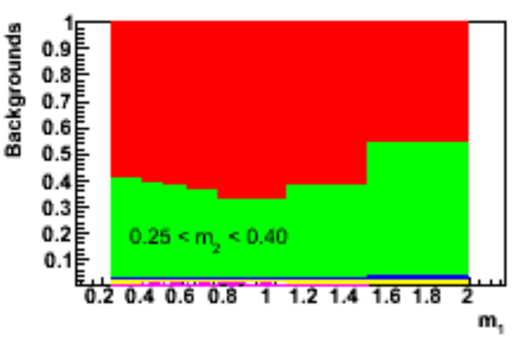
$z_{1,2}$ relative pion pair momenta



$a_{12} \propto H^{<} \bullet H^{<}$

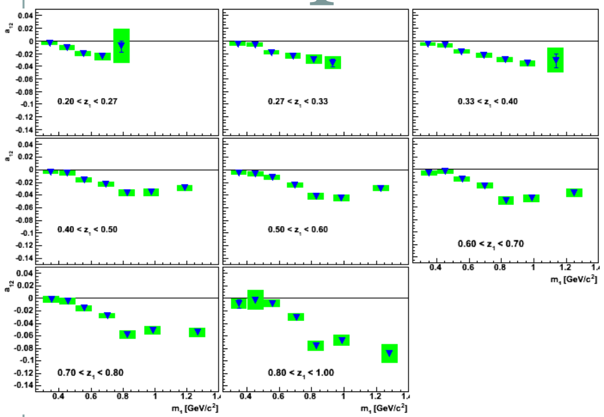
$A_{UT} \propto H^{<}(z_1,m_1)H^{<}(z_2,m_2)\cos(\phi_1+\phi_2)+\ldots.$

No double ratios!



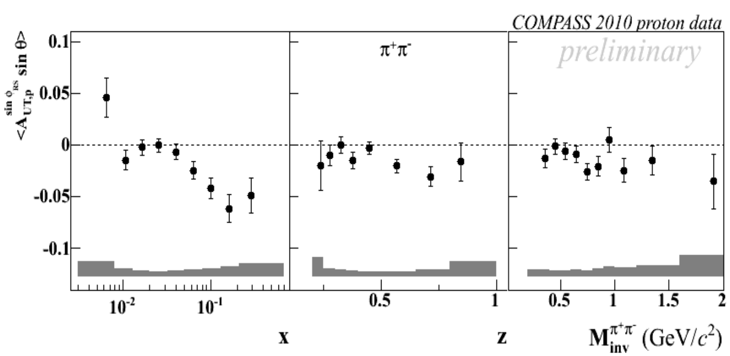
Uds/charm ratio
From MC

Measurement at Belle leads to first point by point extraction of Transversity



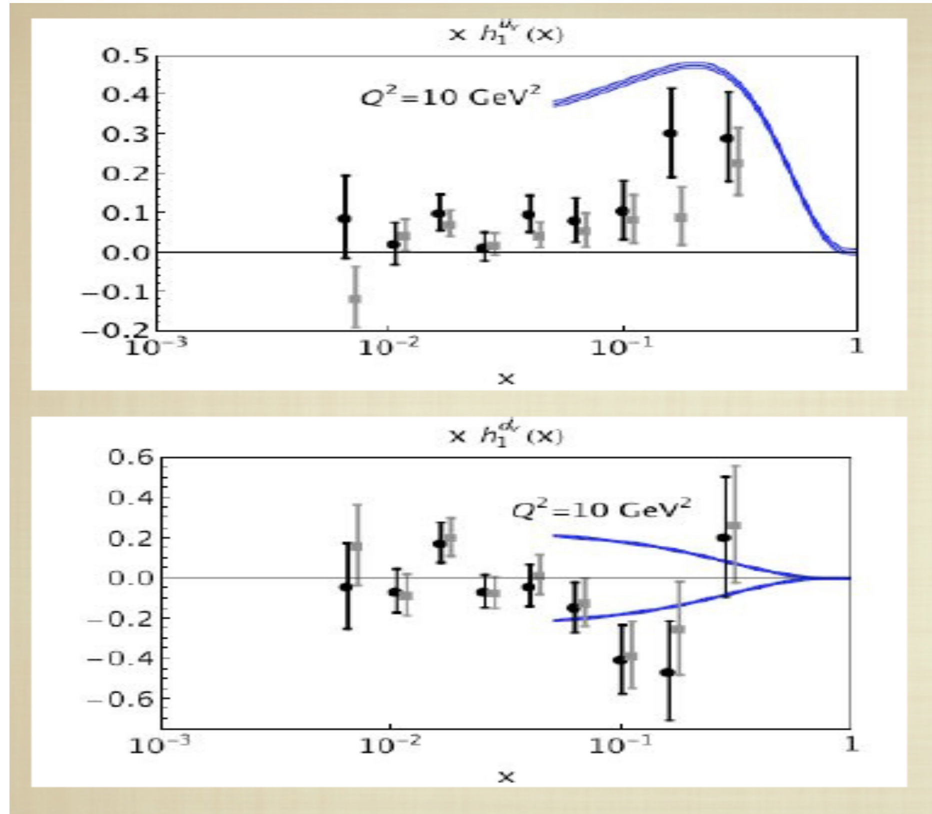
$a_{12} \propto H^{<} \bullet H^{<}$

+



$A_{UT} \propto h_1 \bullet H_1^{<}$

M. Radici at FF workshop, RIKEN, 11/2012
See also: Courtoy: Phys. Rev. Lett. 107:012001,2011



Is Soffer Bound violated?
h(x)<|f(x)+g(x)|/2

Future experiments (Jlab, Star):
Increase x range

Di-hadron Cross Section from Boer,Jakob,Radici[PRD 67,(2003)]

- Expansion of Fragmentation Matrix Δ: encoding possible correlations in fragmentation (k: $P_{h1}+P_{h2}$)

$$\frac{1}{32z}\int dk^{+}\Delta(k;P_h,R)\Big|_{k^-=P_h^-/z,\mathbf{k}_T}$$

$$= \frac{1}{4\pi}\frac{1}{4}\Big\{D_1^a(z,\xi,\boldsymbol{k}_T^2,\boldsymbol{R}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{R}_T)\,\not{n}_- - G_1^{\perp\,a}(z,\xi,\boldsymbol{k}_T^2,\boldsymbol{R}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{R}_T)\,\frac{\epsilon_{\mu\nu\rho\sigma}\,\gamma^\mu\,n_-^\nu\,k_T^\rho\,R_T^\sigma}{M_1M_2}\,\gamma_5$$

$$+ H_1^{\sphericalangle\,a}(z,\xi,\boldsymbol{k}_T^2,\boldsymbol{R}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{R}_T)\,\frac{\sigma_{\mu\nu}\,R_T^\mu\,n_-^\nu}{M_1+M_2} + H_1^{\perp\,a}(z,\xi,\boldsymbol{k}_T^2,\boldsymbol{R}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{R}_T)\,\frac{\sigma_{\mu\nu}\,k_T^\mu\,n_-^\nu}{M_1+M_2}\Big\}\,.$$

$$\langle\cos(2(\phi_R-\phi_{\overline{R}}))\rangle = \sum_{a,\overline{a}} e_a^2\,\frac{3\,\alpha^2}{2Q^2}\,z^2\overline{z}^2\,A(y)\,\frac{1}{M_1M_2\overline{M}_1\overline{M}_2}\,G_1^{\perp a}(z,M_h^2)\,\overline{G}_1^{\perp a}(\overline{z},\overline{M}_h^2)\;.$$

$$\langle\cos(\phi_R+\phi_{\overline{R}}-2\phi^l)\rangle = \sum_{a,\overline{a}} e_a^2\,\frac{3\alpha^2}{Q^2}\,\frac{z^2\overline{z}^2\,B(y)}{(M_1+M_2)(\overline{M}_1+\overline{M}_2)}\,H_{1\,(R)}^{\sphericalangle a}(z,M_h^2)\,\overline{H}_{1\,(R)}^{\sphericalangle a}(\overline{z},\overline{M}_h^2)\,.$$

Measure $\mathrm{Cos}(\phi_{R1}+\phi_{R2})$, $\mathrm{Cos}(2(\phi_{R1}-\phi_{R2}))$ Modulations!

Di-hadron Cross Section from Boer,Jakob,Radici[PRD 67,(2003)]

- Δ: Fragmentation Matrix, encoding possible correlations in fragmentation
- k: $P_{h1}+P_{h2}$

Spin independent part

from Boer,Jakob,Radici[PRD 67,(2003)]

$$\frac{1}{32z}\int dk^+ \Delta(k;P_h,R)\Big|_{k^-=P_h^-/z,\mathbf{k}_T}$$

$$= \frac{1}{4\pi}\frac{1}{4}\Big\{D_1^a(z,\xi,\boldsymbol{k}_T^2,\boldsymbol{R}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{R}_T)\,\not{n}_- - G_1^{\perp a}(z,\xi,\boldsymbol{k}_T^2,\boldsymbol{R}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{R}_T)\,\frac{\epsilon_{\mu\nu\rho\sigma}\,\gamma^\mu\, n_-^\nu\, k_T^\rho\, R_T^\sigma}{M_1 M_2}\,\gamma_5$$

$$+ H_1^{\sphericalangle a}(z,\xi,\boldsymbol{k}_T^2,\boldsymbol{R}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{R}_T)\,\frac{\sigma_{\mu\nu}\,R_T^\mu\, n_-^\nu}{M_1+M_2} + H_1^{\perp a}(z,\xi,\boldsymbol{k}_T^2,\boldsymbol{R}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{R}_T)\,\frac{\sigma_{\mu\nu}\,k_T^\mu\, n_-^\nu}{M_1+M_2}\Big\}\,.$$

$$\langle\cos(2(\phi_R-\phi_{\overline{R}}))\rangle = \sum_{a,\overline{a}} e_a^2\,\frac{3\,\alpha^2}{2Q^2}\,z^2\overline{z}^2\,A(y)\,\frac{1}{M_1M_2\overline{M}_1\overline{M}_2}\,G_1^{\perp a}(z,M_h^2)\,\overline{G}_1^{\perp a}(\overline{z},\overline{M}_h^2)\,.$$

$$\langle\cos(\phi_R+\phi_{\overline{R}}-2\phi^l)\rangle = \sum_{a,\overline{a}} e_a^2\,\frac{3\alpha^2}{Q^2}\,\frac{z^2\overline{z}^2\,B(y)}{(M_1+M_2)(\overline{M}_1+\overline{M}_2)}\,H_{1\,(R)}^{\sphericalangle a}(z,M_h^2)\,\overline{H}_{1\,(R)}^{\sphericalangle a}(\overline{z},\overline{M}_h^2)\,.$$

Cross Section

- Δ: Fragmentation Matrix, encoding possible correlations in fragmentation

Correlation of transverse spin with Di-hadron plane

$$\frac{1}{32z}\int dk^+ \Delta(k;P_h,R)\Big|_{k^-=P_h^-/z,\mathbf{k}_T}$$

$$= \frac{1}{4\pi}\frac{1}{4}\Big\{D_1^a(z,\xi,\boldsymbol{k}_T^2,\boldsymbol{R}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{R}_T)\,\not{n}_- - G_1^{\perp a}(z,\xi,\boldsymbol{k}_T^2,\boldsymbol{R}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{R}_T)\,\frac{\epsilon_{\mu\nu\rho\sigma}\,\gamma^\mu n_-^\nu\, k_T^\rho R_T^\sigma}{M_1M_2}\,\gamma_5$$

$$+ H_1^{\sphericalangle a}(z,\xi,\boldsymbol{k}_T^2,\boldsymbol{R}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{R}_T)\,\frac{\sigma_{\mu\nu}\,R_T^\mu n_-^\nu}{M_1+M_2} + H_1^{\perp a}(z,\xi,\boldsymbol{k}_T^2,\boldsymbol{R}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{R}_T)\,\frac{\sigma_{\mu\nu}\,k_T^\mu n_-^\nu}{M_1+M_2}\Big\}\,.$$

$$\langle\cos(2(\phi_R-\phi_{\overline{R}}))\rangle = \sum_{a,\overline{a}} e_a^2\,\frac{3\,\alpha^2}{2Q^2}\,z^2\overline{z}^2\,A(y)\,\frac{1}{M_1M_2\overline{M}_1\overline{M}_2}\,G_1^{\perp a}(z,M_h^2)\,\overline{G}_1^{\perp a}(\overline{z},\overline{M}_h^2)\,.$$

$$\langle\cos(\phi_R+\phi_{\overline{R}}-2\phi^l)\rangle = \sum_{a,\overline{a}} e_a^2\,\frac{3\alpha^2}{Q^2}\,\frac{z^2\overline{z}^2\,B(y)}{(M_1+M_2)(\overline{M}_1+\overline{M}_2)}\,H_{1\,(R)}^{\sphericalangle a}(z,M_h^2)\,\overline{H}_{1\,(R)}^{\sphericalangle a}(\overline{z},\overline{M}_h^2)\,.$$

Di-hadron Cross Section from Boer,Jakob,Radici[PRD 67,(2003)]

- Δ: Fragmentation Matrix, encoding possible correlations in fragmentation
- k: $P_{h1}+P_{h2}$

Helicity dependent correlation of Intrinsic transverse momentum with Di-hadron plane

$$\frac{1}{32z}\int dk^+ \Delta(k;P_h,R)\Big|_{k^-=P_h^-/z,\mathbf{k}_T}$$

$$= \frac{1}{4\pi}\frac{1}{4}\Big\{D_1^a(z,\xi,\boldsymbol{k}_T^2,\boldsymbol{R}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{R}_T)\,\not{n}_- - G_1^{\perp a}(z,\xi,\boldsymbol{k}_T^2,\boldsymbol{R}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{R}_T)\,\frac{\epsilon_{\mu\nu\rho\sigma}\,\gamma^\mu\,n_-^\nu\,k_T^\rho\,R_T^\sigma}{M_1M_2}\,\gamma_5$$

$$+ H_1^{\sphericalangle a}(z,\xi,\boldsymbol{k}_T^2,\boldsymbol{R}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{R}_T)\,\frac{\sigma_{\mu\nu}\,R_T^\mu\,n_-^\nu}{M_1+M_2} + H_1^{\perp a}(z,\xi,\boldsymbol{k}_T^2,\boldsymbol{R}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{R}_T)\,\frac{\sigma_{\mu\nu}\,k_T^\mu\,n_-^\nu}{M_1+M_2}\Big\}.$$

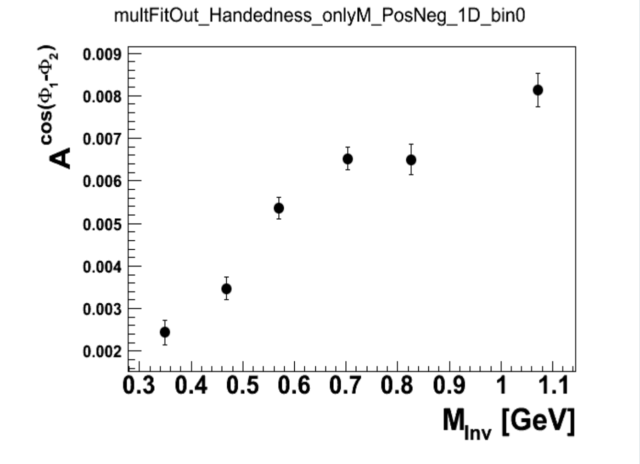
$$\langle\cos(2(\phi_R-\phi_{\overline{R}}))\rangle = \sum_{a,\bar{a}} e_a^2\,\frac{3\,\alpha^2}{2Q^2}\,z^2\bar{z}^2\,A(y)\,\frac{1}{M_1M_2\overline{M}_1\overline{M}_2}\,G_1^{\perp a}(z,M_h^2)\,\overline{G}_1^{\perp a}(\bar{z},\overline{M}_h^2)\ .$$

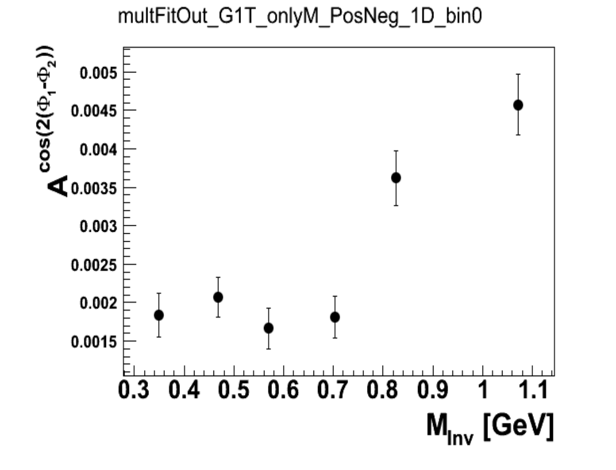
$$\langle\cos(\phi_R+\phi_{\overline{R}}-2\phi^l)\rangle = \sum_{a,\bar{a}} e_a^2\,\frac{3\alpha^2}{Q^2}\,\frac{z^2\bar{z}^2\,B(y)}{(M_1+M_2)(\overline{M}_1+\overline{M}_2)}\,H_{1\,(R)}^{\sphericalangle a}(z,M_h^2)\,\overline{H}_{1\,(R)}^{\sphericalangle a}(\bar{z},\overline{M}_h^2)\,.$$

Measure $\mathrm{Cos}(\phi_{R1}+\phi_{R2})$, $\mathrm{Cos}(2(\phi_{R1}-\phi_{R2}))$ Modulations and additional $\mathrm{Cos}(\phi_{R1}-\phi_{R2})$ (handedness, non pQCD related)

Study of $A^{\cos(\varphi 1-\varphi 2)}$ and $A^{\cos(2(\varphi 1-\varphi 2))}$ Asymmetries in Belle MC

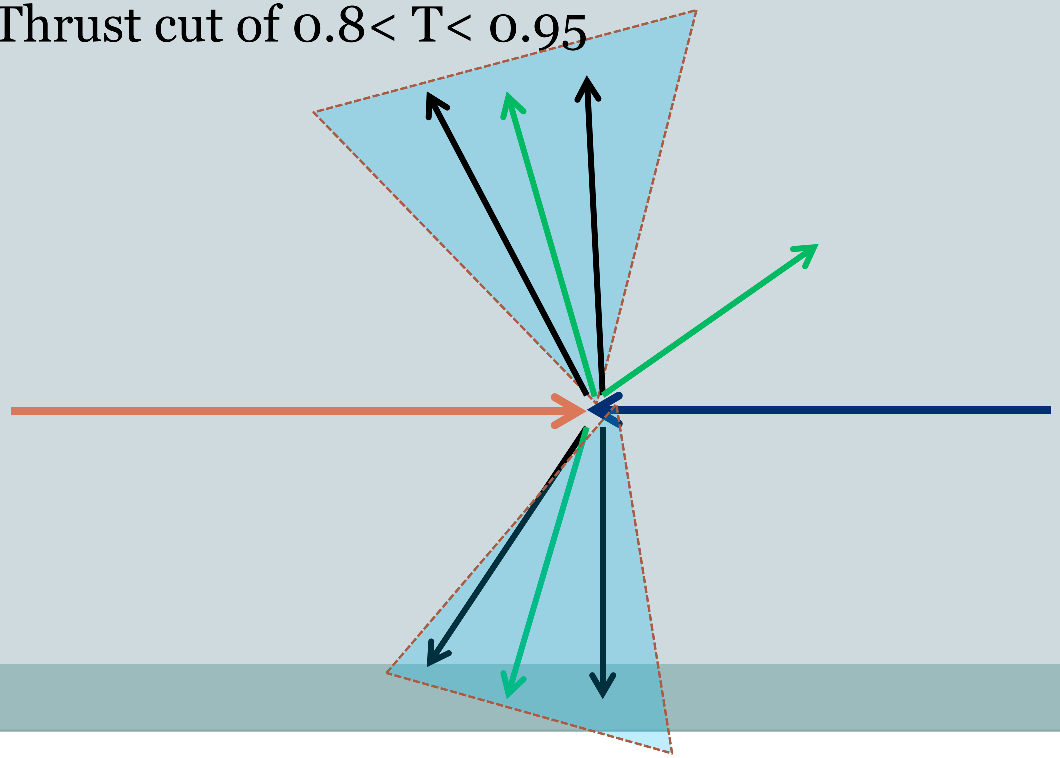
- Belle uses Pythia+Evtgen (implements decay tables)
- After detector asymmetries of the order of 1% (0.5%) are left.
- Pythia w/o detector is consistent with shows similar effect
- Possible culprits: gluon radiation, weak decays, detector effects



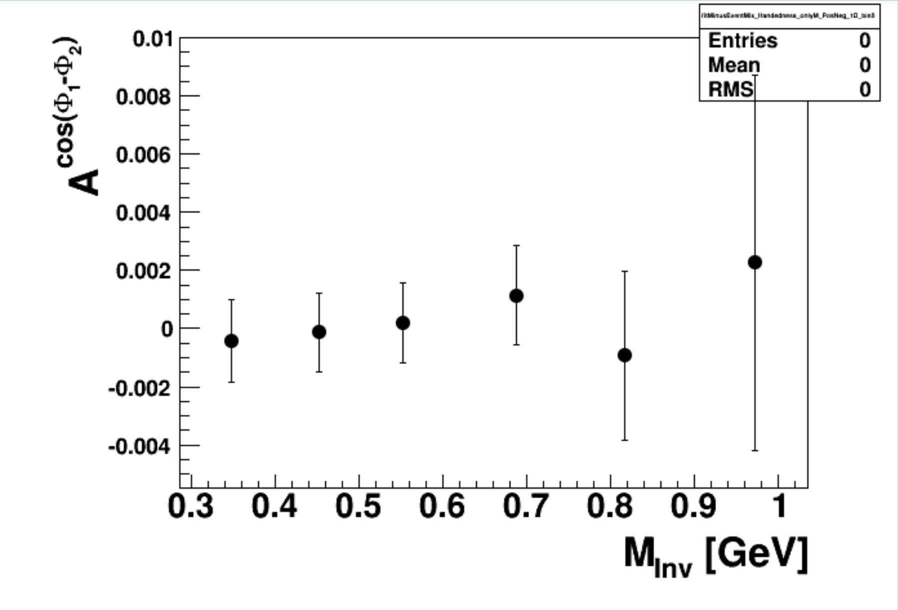


New: Use Jet Reconstruction at Belle

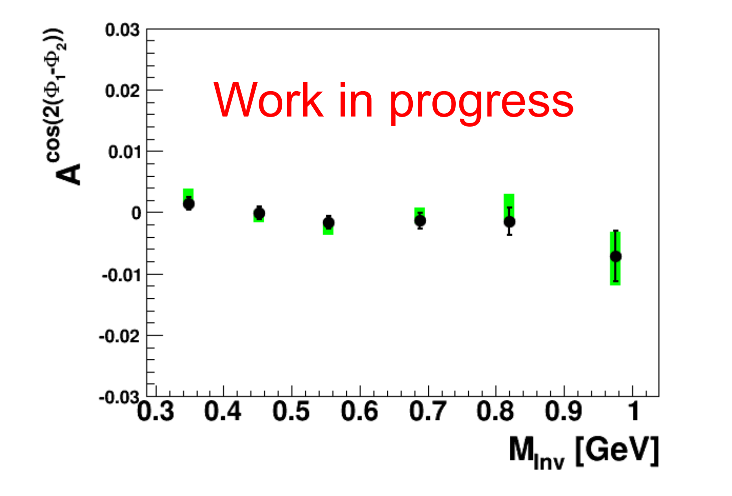
- Robust vs. final state radiation
- We use anti-kT algorithm implemented in fastjet
- Cone radius R=0.55
- Min energy per jet 2.75 GeV→ suppress weak decays
- Only allow events with 2 jets passing energy cut (dijet events)
- Only particles that form the jet are used in the asymmetry calculation
- Thrust cut of 0.8< T< 0.95

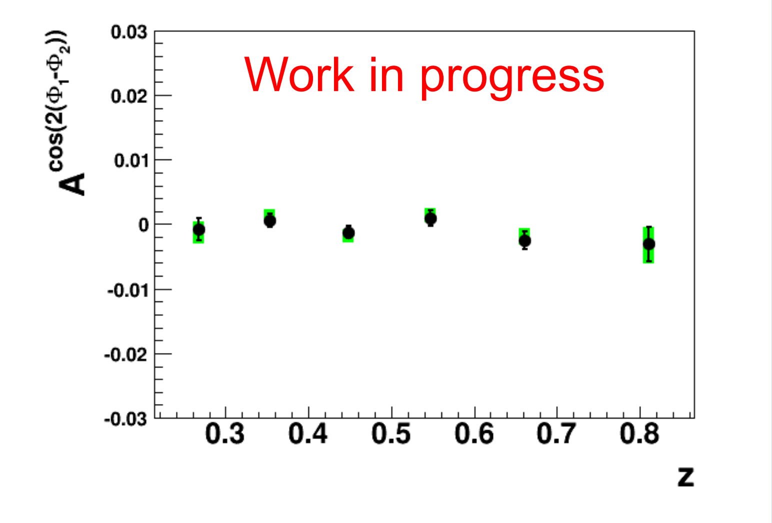


- Mixed event subtracted flattens acceptance related false asymmetries
- Remaining asymmetries in MC+their stat error used to estimate systematics

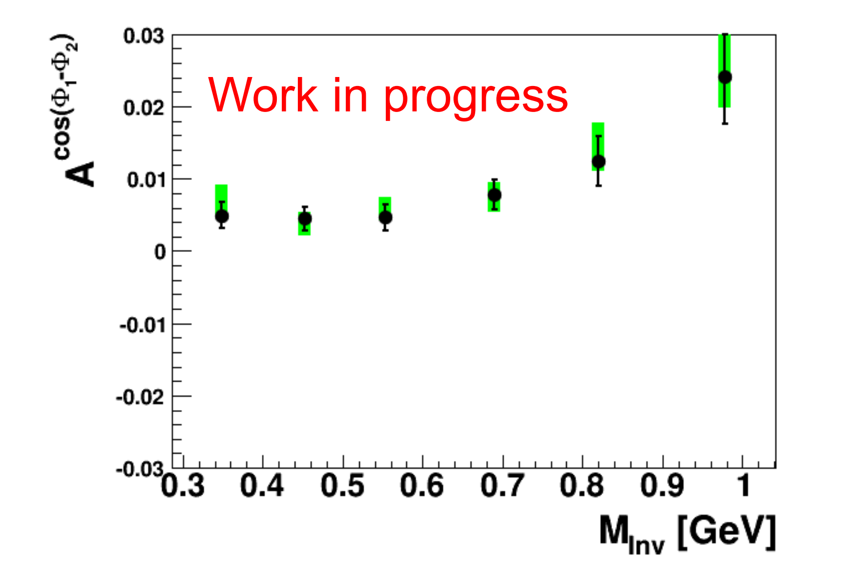


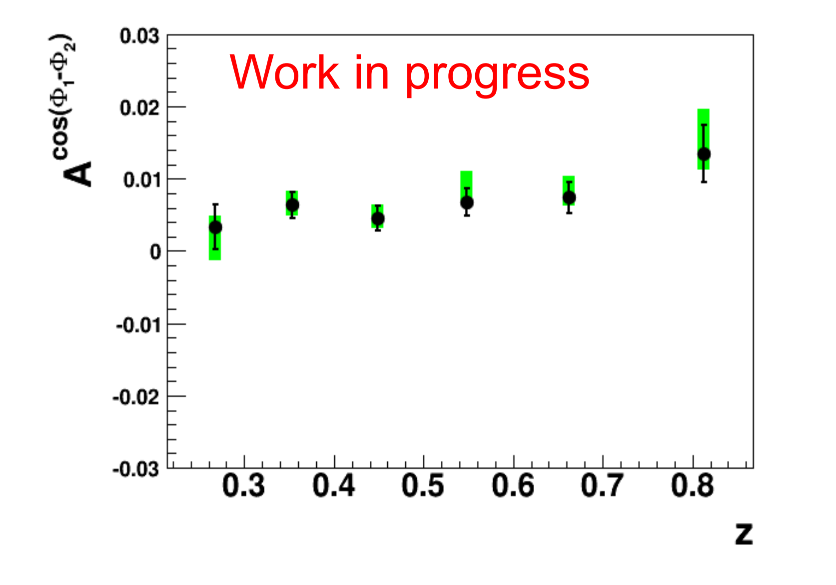
Asymmetries for Cos($2(\phi_{R1}-\phi_{R2})$) ($G_1^{\perp}$) small





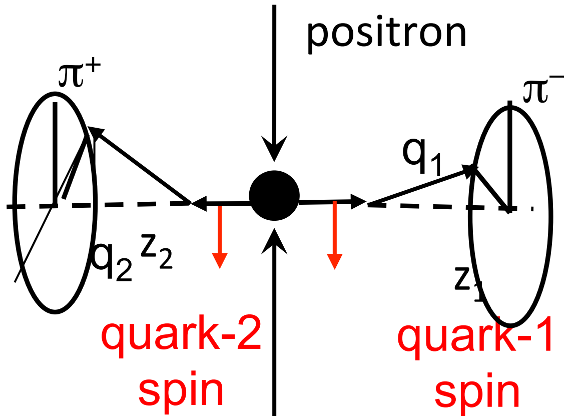
Asymmetries in Data persists for Cos(ϕ_{R1}-ϕ_{R2})





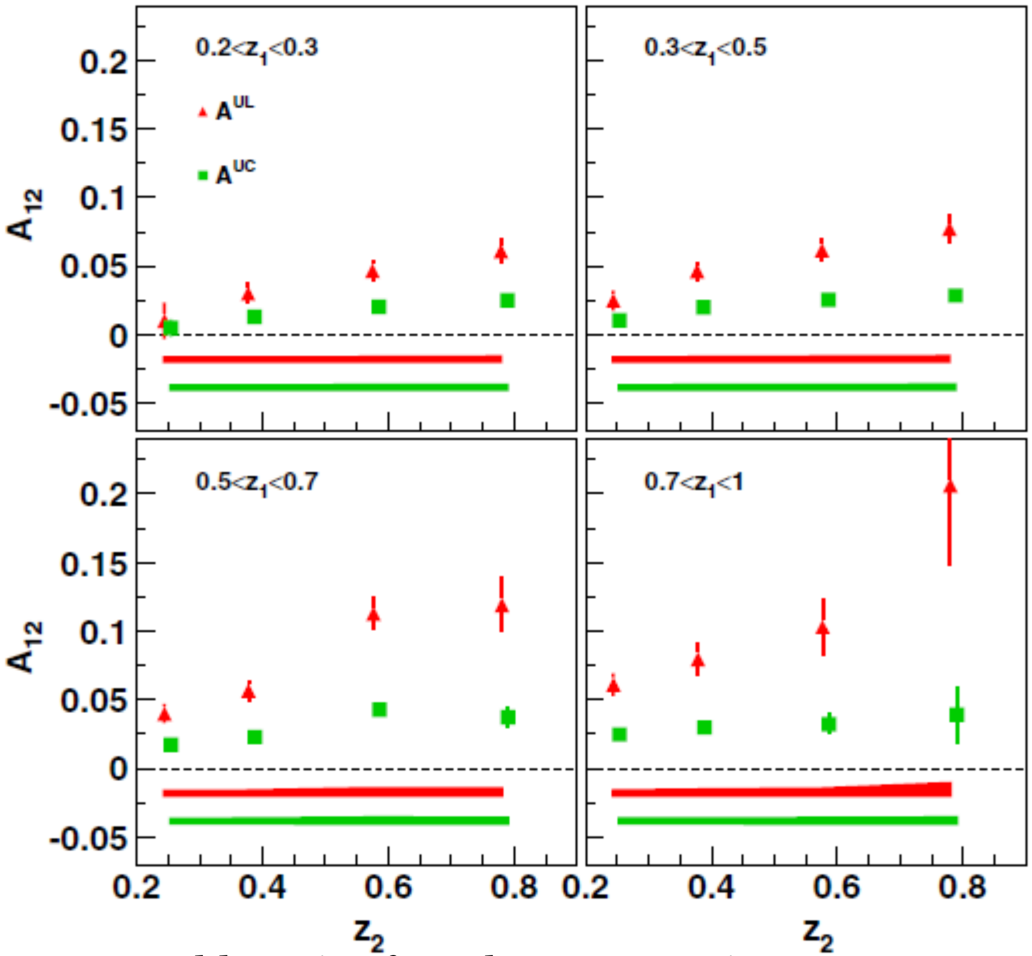
- Systematics driven by MC…

Measuring the spin dependent H_1 in e^+e^-



$z_{1,2}$ relative pion pair momenta

$$A_{12} \propto H_1(z_1)H_1(z_2)\cos(\phi_1+\phi_2)+....$$



Double ratios for robustness against Detector Effects:

A_{UL}: unlike over like sign pions

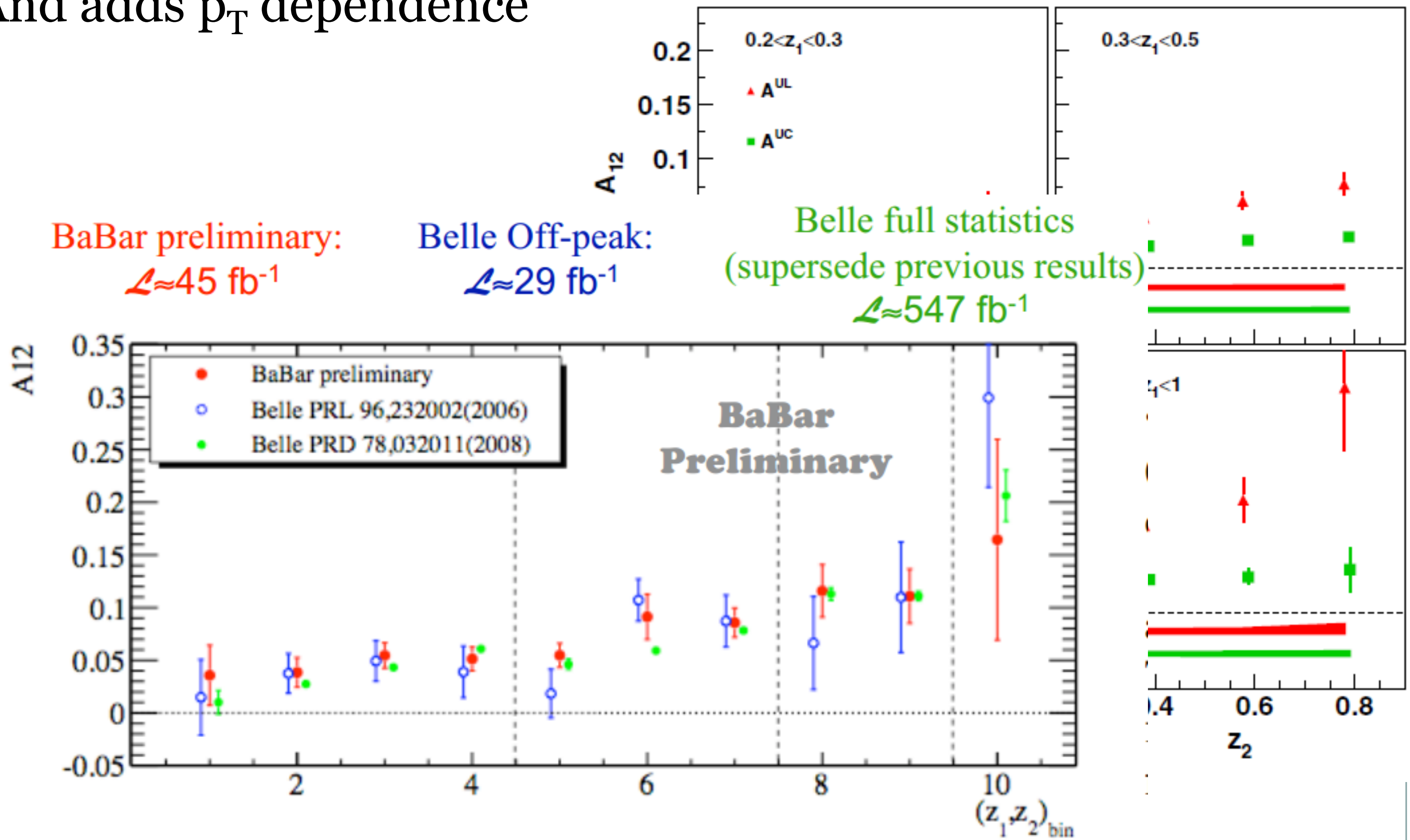
A_{UC}: unlike over charge integrated pions

BaBar confirms Belle measurement!
And adds p_T dependence

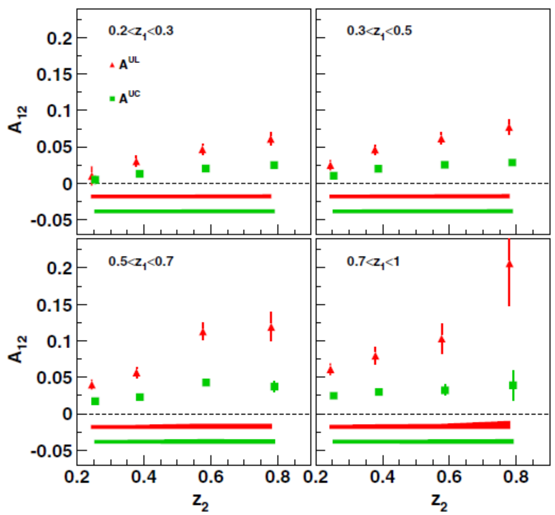
BaBar preliminary: $\mathcal{L}\approx 45\ fb^{-1}$

Belle Off-peak: $\mathcal{L}\approx 29\ fb^{-1}$

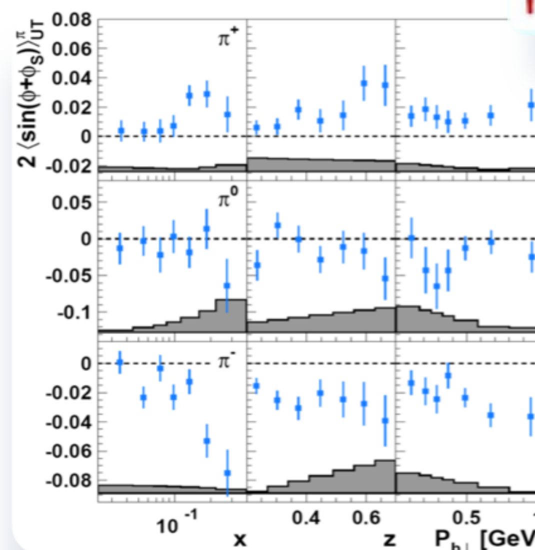
Belle full statistics (supersede previous results) $\mathcal{L}\approx 547\ fb^{-1}$



First Extraction of Transversity from

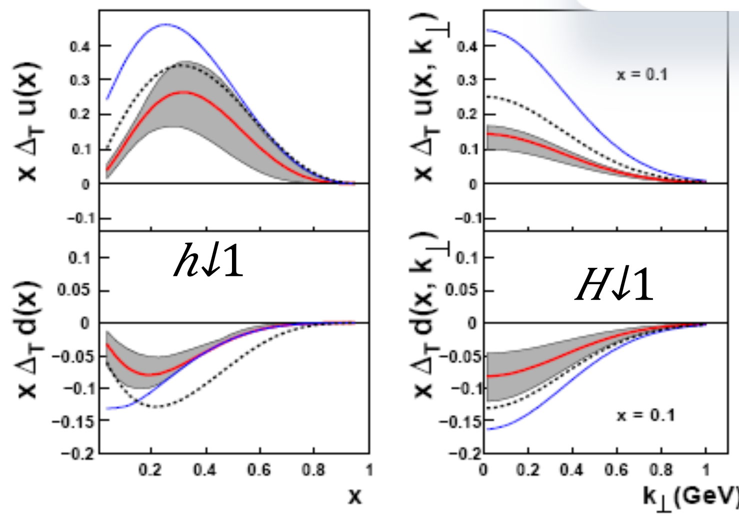


+



$A_{12} \propto H_1 \otimes H_1$

$A_{12} \propto h_1 \otimes H_1$



$H_1^{fav} \sim -H_1^{ufav}$

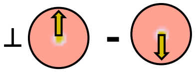
$h_1^u \sim -h_1^d$

Anselmino et. al.

Nucl. Phys. Proc. Suppl. **191** (2009)

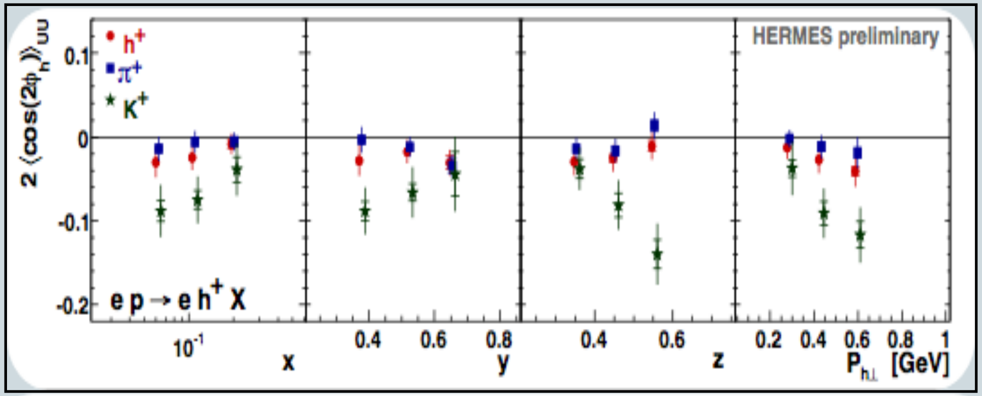
Boer-Mulders Function and Cahn effect

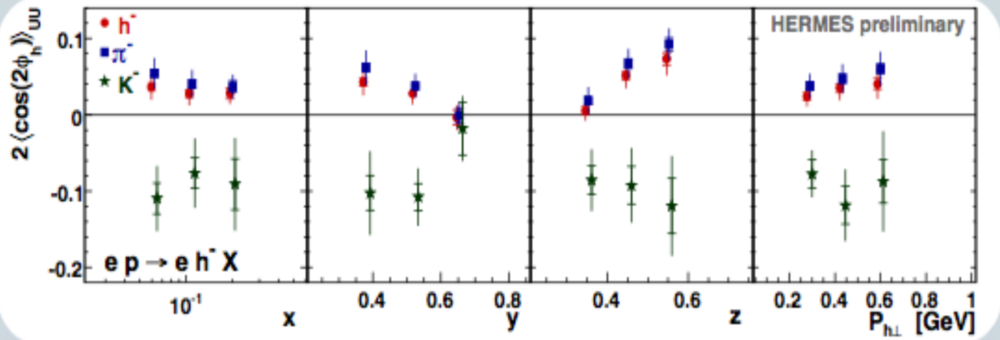
$A^{\cos(2\phi h)} \propto h_1^{\perp} \otimes H_1$



- Correlation of transverse polarization of quark with k_T: $\overrightarrow{s_{Tq}} \cdot (\boldsymbol{P} \times \boldsymbol{k_T})$
- Unpolarized asymmetry: Needs very good understanding of acceptance
  - →Fully differential analysis (similar to Multiplicity extraction)
- Boer-Mulders: naïve T-odd **and** chiral odd, transversely polarized quarks in unpolarized nucleon: Need OAM and Collins FF:

$A_{UU}^{cos2\phi} \propto h_1^{\perp} H_1^{\perp}$

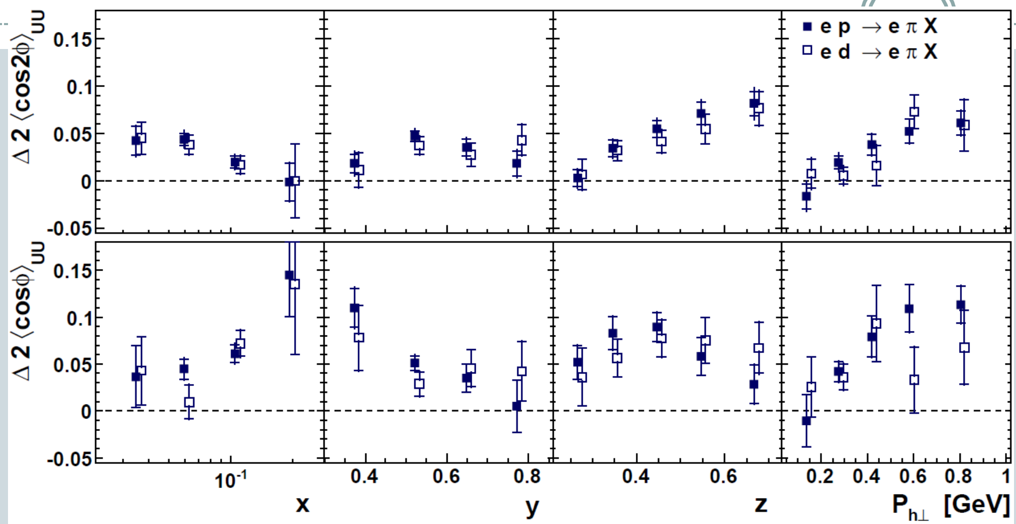




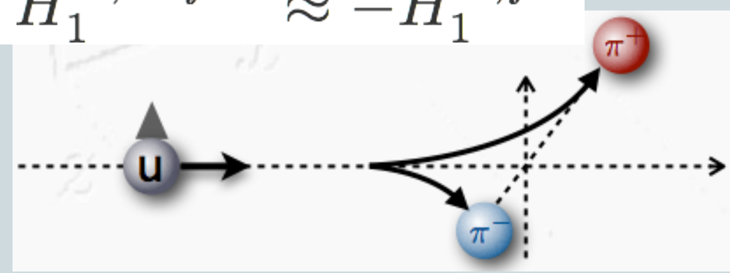
Large Kaon signal
→flavor dependent
CFF?

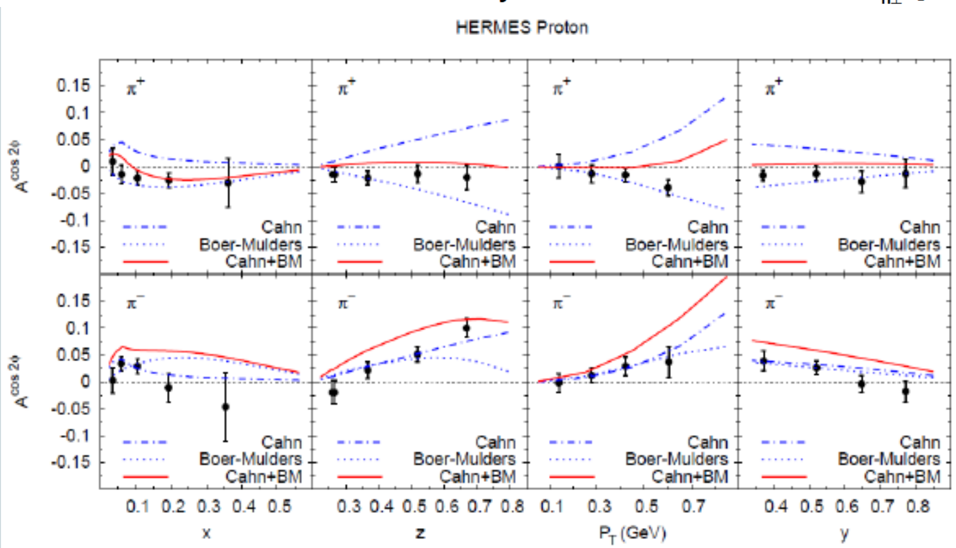
- Purely kinematic Cahn effects contribution at order $(k/Q)^2$ same magnitude !

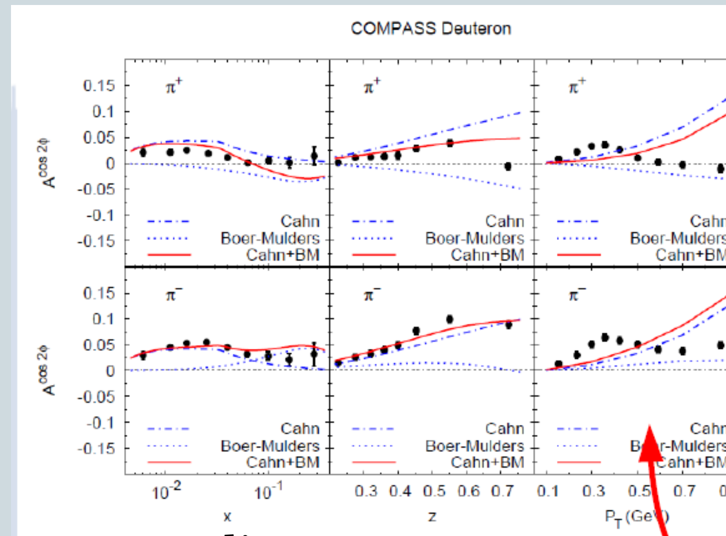
Disentangling Cahn and Boer-Mulders



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





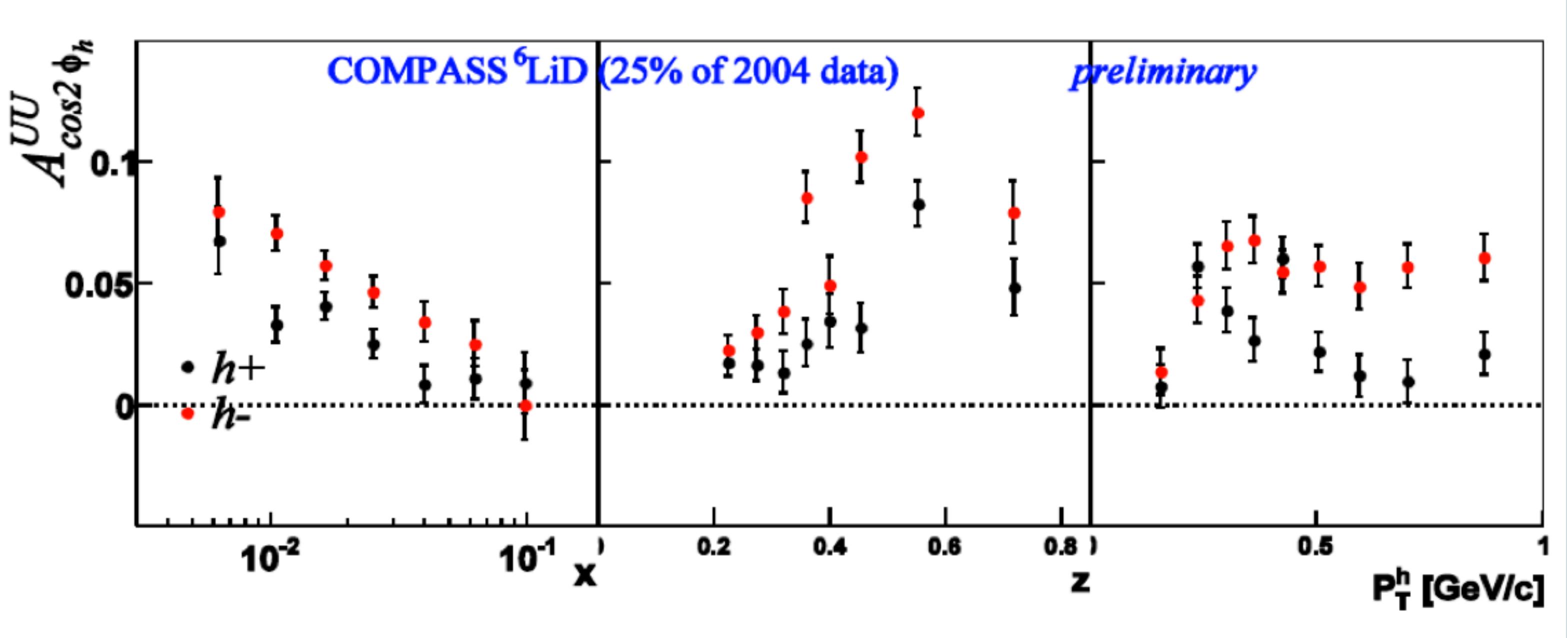


Compass k_T=0.25 GeV, Hermes 0.18

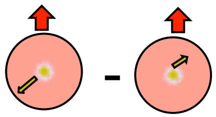
S. Melis,
ECT 2012

New Compass Analysis does not agree with Hermes anymore

- Caused by complex kinematic dependencies+cuts?

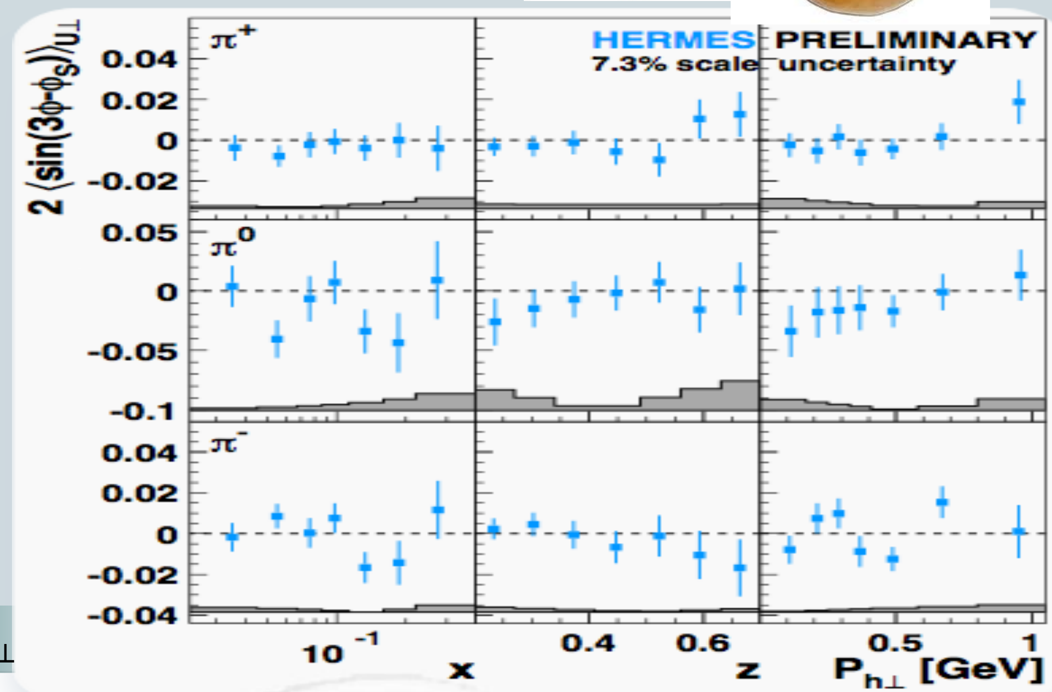


Pretzelosity, $A^{\cos(3\phi h-\phi S)} \propto h_{1T}^{\perp} \otimes H_1$

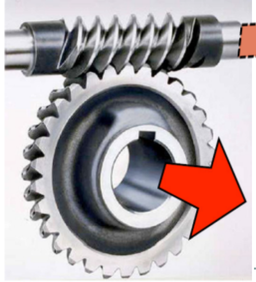


- Related to amplitude where OAM changes by two units
  - p-p or s-d interference → gives information about shape of quark distribution (oblate, prolate: peanut, bagel, maybe pretzel?)

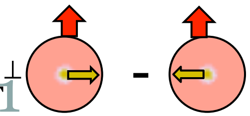
$$A_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{1T}^{\perp} \otimes H_{1q}^{h}$$



$h_{1T}^{\perp}$



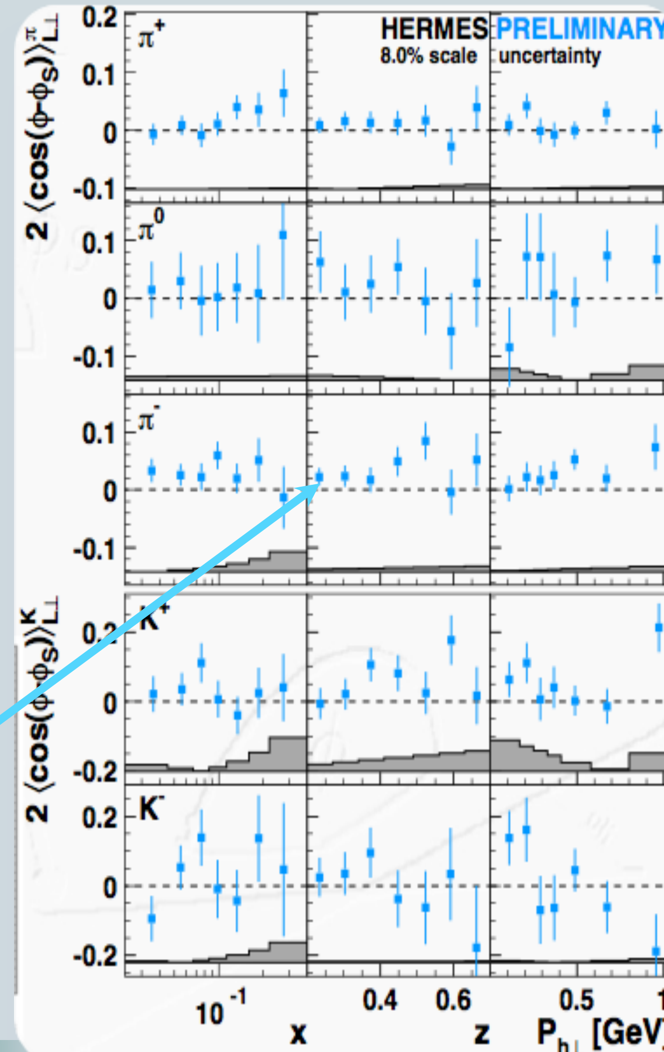
Worm Gear, $A_{LT}^{\cos(\phi h-\phi S)} \propto g_{1T}^{\perp} \otimes D_1$



- From Lattice $h_{1L}^{\perp} = -g_{1T}^{\perp}$
- Not T-odd, no FSI
- No GPD correspondence: real OAM effect

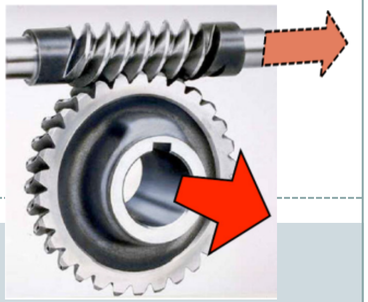
$$A_{LT}^{\cos(\phi_h - \phi_s)} \propto g_{1T}^{q} \otimes D_{1q}^{h}$$

- Interference of amplitudes with one unit OAM difference (real part) (Sivers, Boer-Mulders imaginary part)



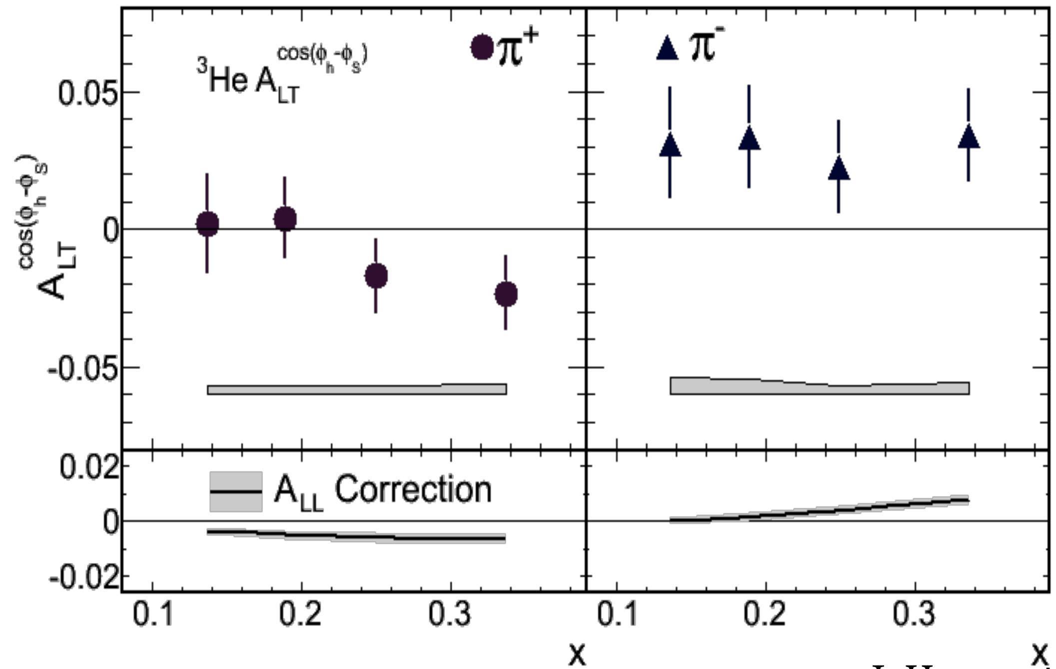
- Results consistent with zero
- Hint of non zero signal?

CLAS @Jlab 6GeV on He



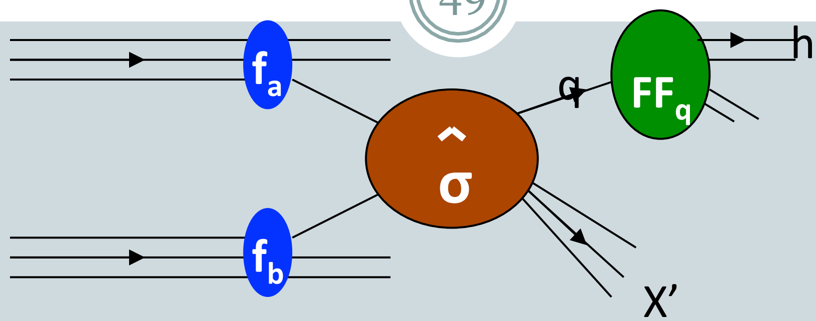
$$A_{LT}^{\cos(\phi_h - \phi_s)} \propto g_{1T}^q \otimes D_{1q}^h$$

- ^{3}He A_{LT} : Positive for π-



J. Huang et al., PRL. 108, 052001 (2012).

TMDs in P+P: Rich and Challenging



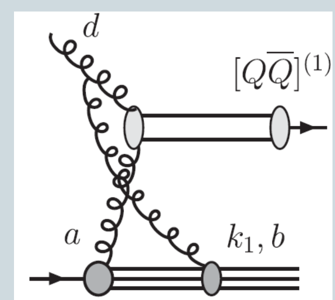
Proton Structure

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

fragmentation function

TMD factorization challenging:

$T_{q,F}, T_G^{(f)}$



- Color 'entanglement' is predicted to lead to process dependence
- Higher twist at high p_t

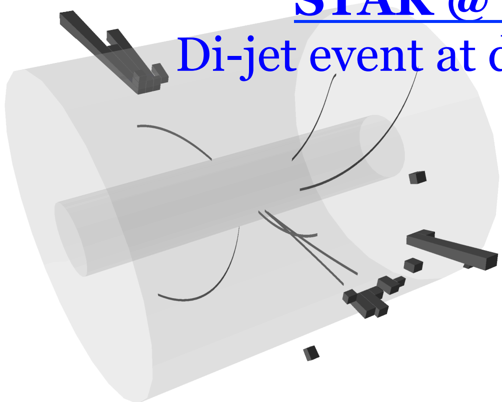
Experimentally challenging: reconstruct 2-2 scattering kinematics: → need ~Jets !

Jet Reconstruction in STAR

Data jets

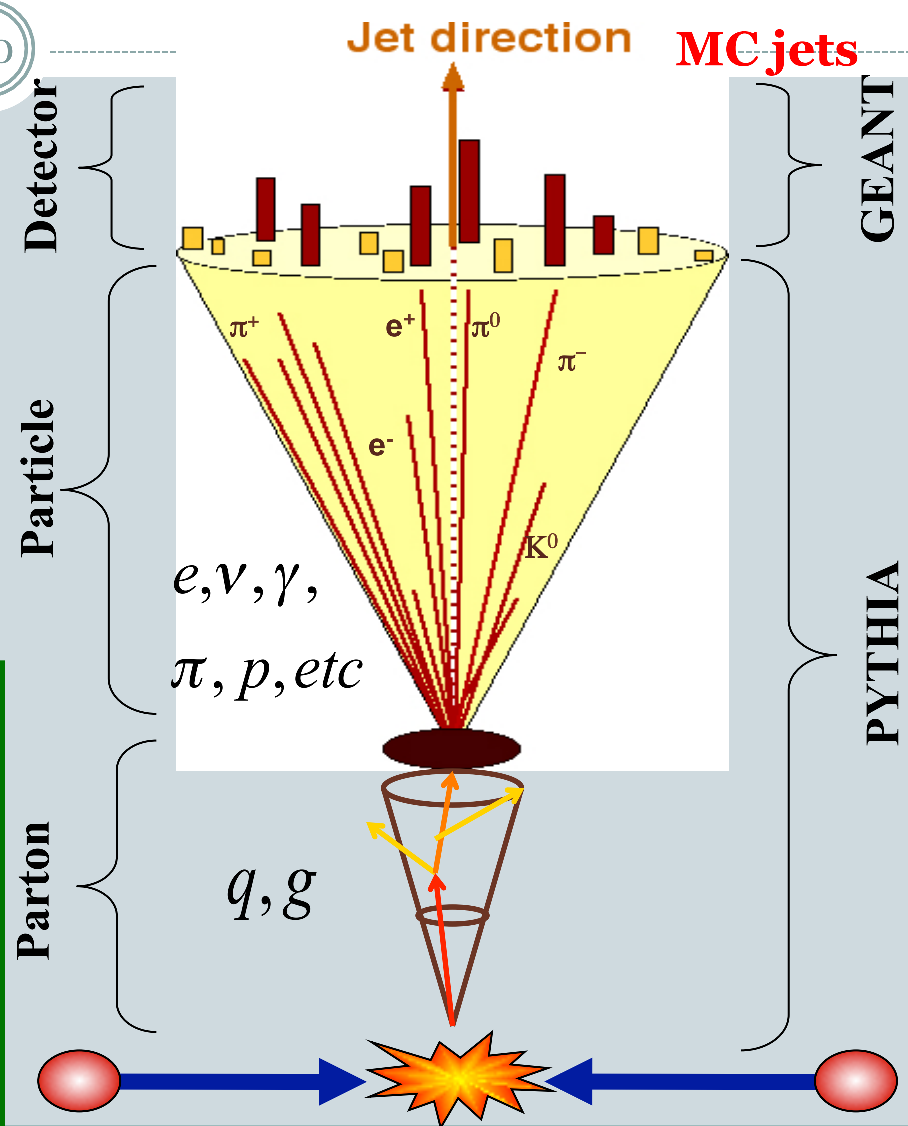
STAR @ RHIC:

Di-jet event at detector-level



e.g. Anti-k_T algorithm

JHEP 0804, 063 (2008)

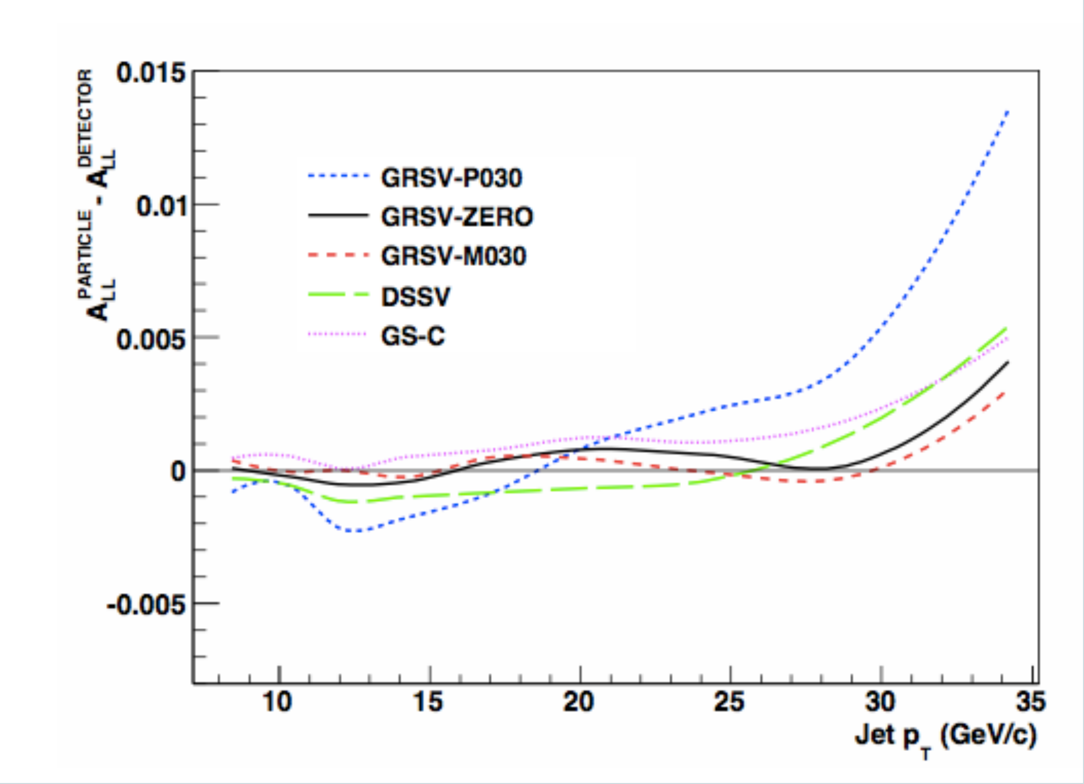


Use **PYTHIA + GEANT** to quantify detector response

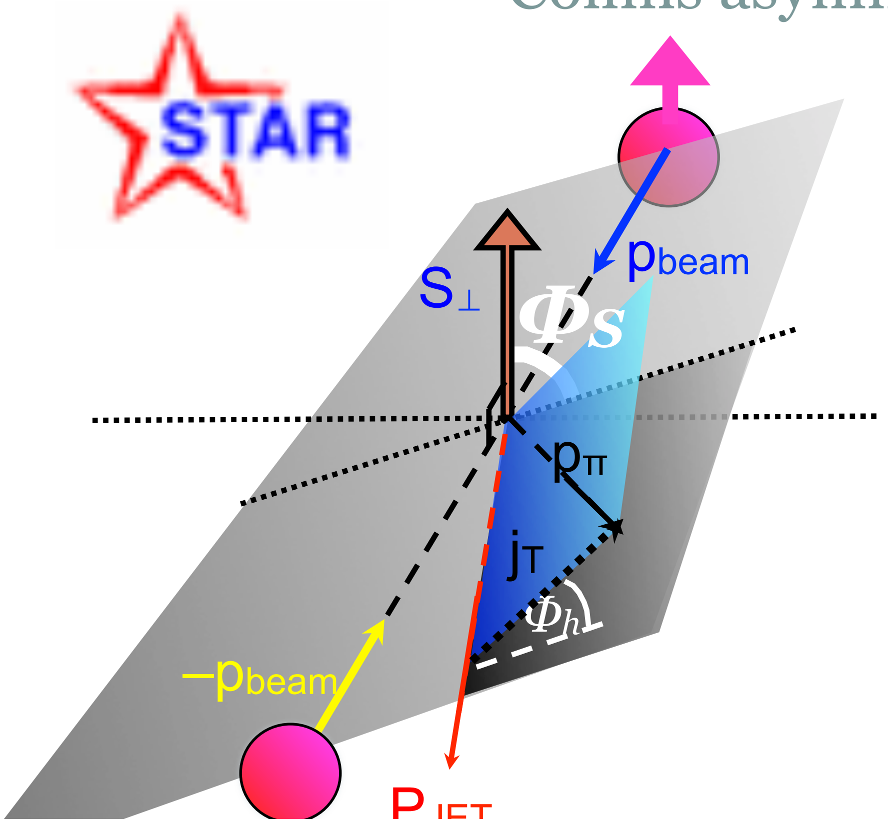
- Trigger Bias (bias for specific processes)
- Reconstruction smearing/bias (unfolding)
- Reconstruction of partonic variables, parton matching
- Underlying event/pileup effects

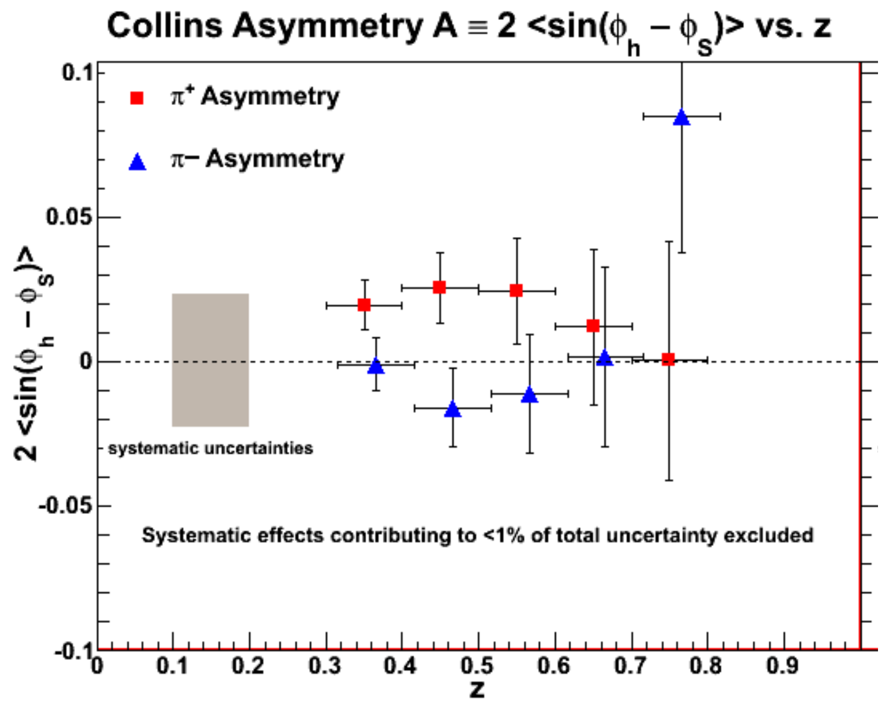
Estimating Trigger and Reconstruction bias

- **Example A_{LL}**
  - Trigger and reconstruction bias for different PDFs
  - Changing subprocesses and reconstruction efficiency



Collins asymmetries, $A^{\sin(\phi_h-\phi_S)} \propto h_1 \otimes H_1$

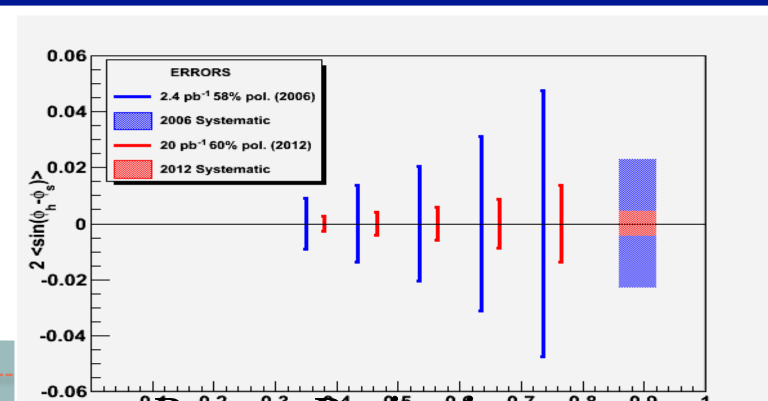




$$d\sigma \approx d\sigma^{UU}\left[1 + A_N \sin(\phi_h - \phi_s)\right]$$

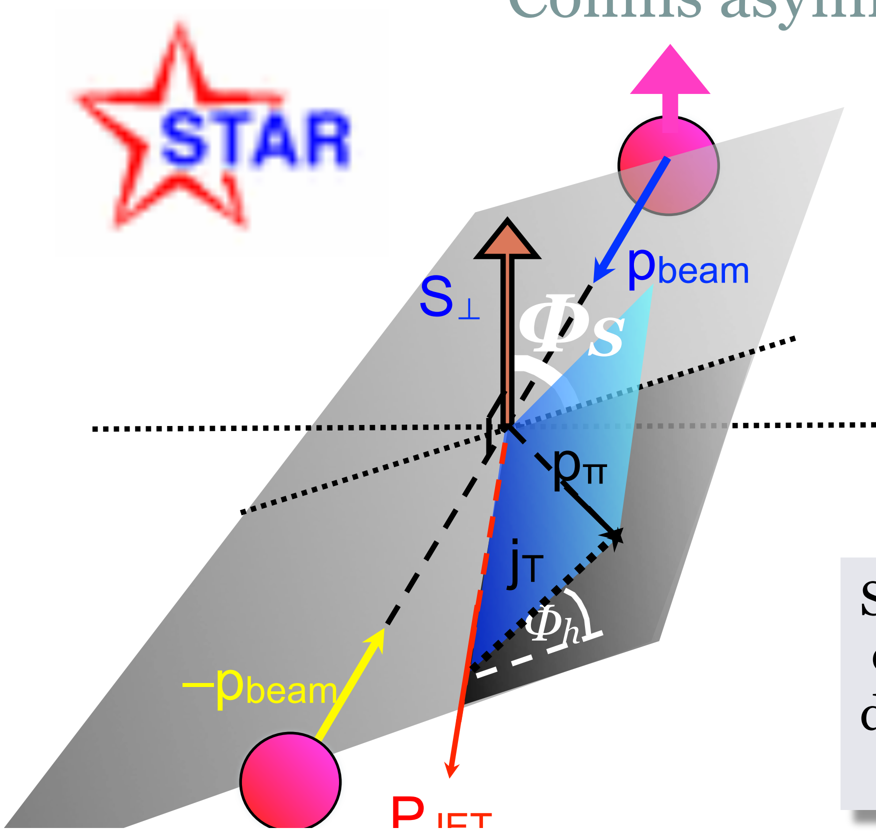
Terms in Numerator of TMD SSA for qq scattering	English Names	Modulate
$\Delta^N f_{a/A\uparrow} \bullet f_{b/B} \bullet D_{\pi/q}$	Sivers • PDF • FF	$\sin(\varphi_{S_A})$
$h_1^a \bullet \Delta^N f_{b\uparrow/B} \bullet D_{\pi/q}$	Transversity•Boer-Mulder•FF	$\sin(\varphi_{S_A})$
$h_{1T}^{\perp a} \bullet \Delta^N f_{b\uparrow/B} \bullet D_{\pi/q}$	Pretzelocity•Boer-Mulder•FF	$\sin(\varphi_{S_A})$
$h_1^a \bullet f_{b/B} \bullet \Delta D_{\pi/q\uparrow}$	Transversity•PDF •Collins	$\sin(\varphi_{S_A} - \varphi_\pi)$
$\Delta f_{a/A\uparrow}^N \bullet \Delta^N f_{b\uparrow/B} \bullet \Delta D_{\pi/q\uparrow}$	Sivers•Boer-Mulder•Collins	$\sin(\varphi_{S_A} - \varphi_\pi)$
$h_{1T}^{\perp a} \bullet f_{b/B} \bullet \Delta D_{\pi/q\uparrow}$	Pretzelocity•PDF•Collins	$\sin(\varphi_{S_A} + \varphi_\pi)$
$\Delta f_{a/A\uparrow}^N \bullet \Delta^N f_{b\uparrow/B} \bullet \Delta D_{\pi/q\uparrow}$	Sivers•Boer-Mulders•Collins	$\sin(\varphi_{S_A} + \varphi_\pi)$

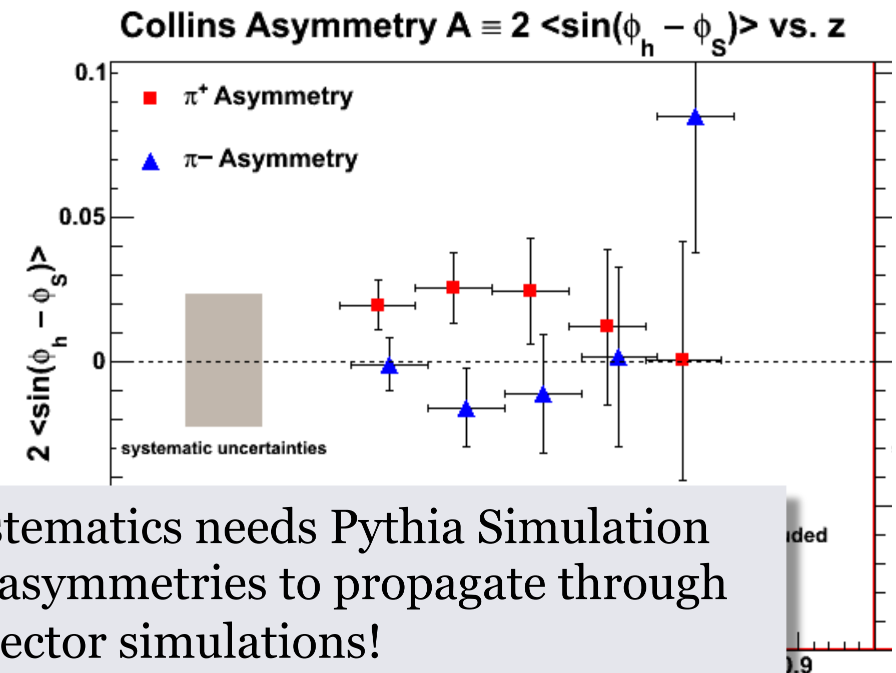
Based on work by F.Yuan (Phys.Rev.Lett.100:032003) and D'Alesio et al. (Phys.Rev. D83, 034021)



Run 12 Projection

Collins asymmetries, $A^{\sin(\phi h-\phi S)} \propto h_1 \otimes H_1$



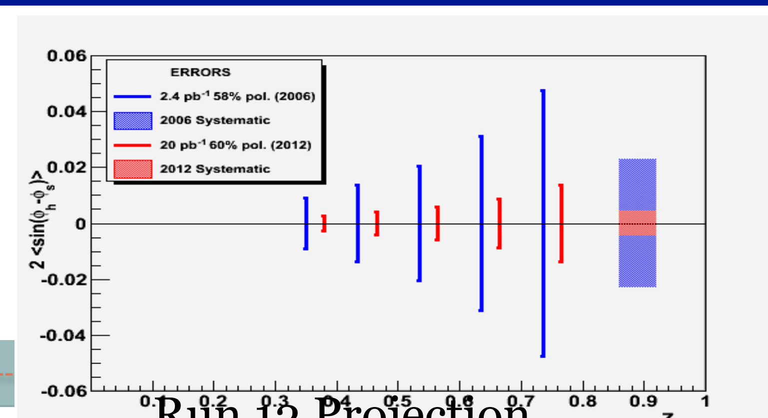


Systematics needs Pythia Simulation of asymmetries to propagate through detector simulations!

$$d\sigma \approx d\sigma^{UU}\left[1 + A_N \sin(\phi_h - \phi_s)\right]$$

Terms in Numerator of TMD SSA for qq scattering	English Names	Modulate
$\Delta^N f_{a/A\uparrow} \bullet f_{b/B} \bullet D_{\pi/q}$	Sivers • PDF • FF	$\sin(\varphi_{S_A})$
$h_1^a \bullet \Delta^N f_{b\uparrow/B} \bullet D_{\pi/q}$	Transversity•Boer-Mulder•FF	$\sin(\varphi_{S_A})$
$h_{1T}^{\perp a} \bullet \Delta^N f_{b\uparrow/B} \bullet D_{\pi/q}$	Pretzelocity•Boer-Mulder•FF	$\sin(\varphi_{S_A})$
$h_1^a \bullet f_{b/B} \bullet \Delta D_{\pi/q\uparrow}$	Transversity•PDF •Collins	$\sin(\varphi_{S_A} - \varphi_\pi)$
$\Delta f_{a/A\uparrow}^N \bullet \Delta^N f_{b\uparrow/B} \bullet \Delta D_{\pi/q\uparrow}$	Sivers•Boer-Mulder•Collins	$\sin(\varphi_{S_A} - \varphi_\pi)$
$h_{1T}^{\perp a} \bullet f_{b/B} \bullet \Delta D_{\pi/q\uparrow}$	Pretzelocity•PDF•Collins	$\sin(\varphi_{S_A} + \varphi_\pi)$
$\Delta f_{a/A\uparrow}^N \bullet \Delta^N f_{b\uparrow/B} \bullet \Delta D_{\pi/q\uparrow}$	Sivers•Boer-Mulders•Collins	$\sin(\varphi_{S_A} + \varphi_\pi)$

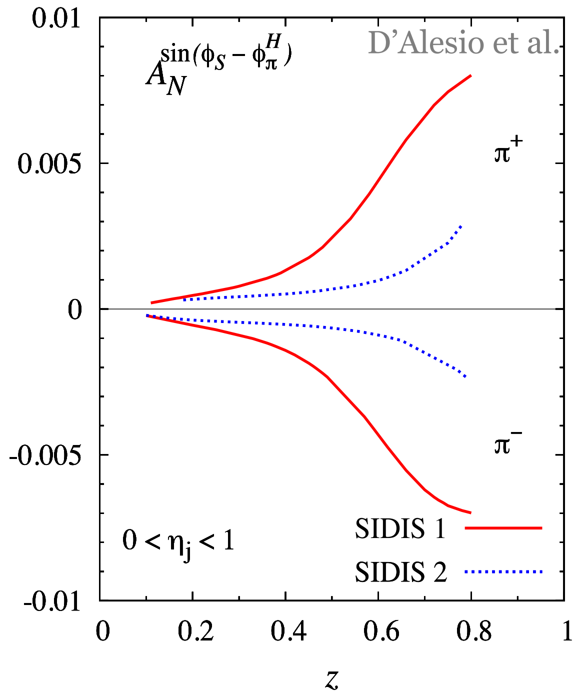
Based on work by F.Yuan (Phys.Rev.Lett.100:032003) and D'Alesio et al. (Phys.Rev. D83, 034021)

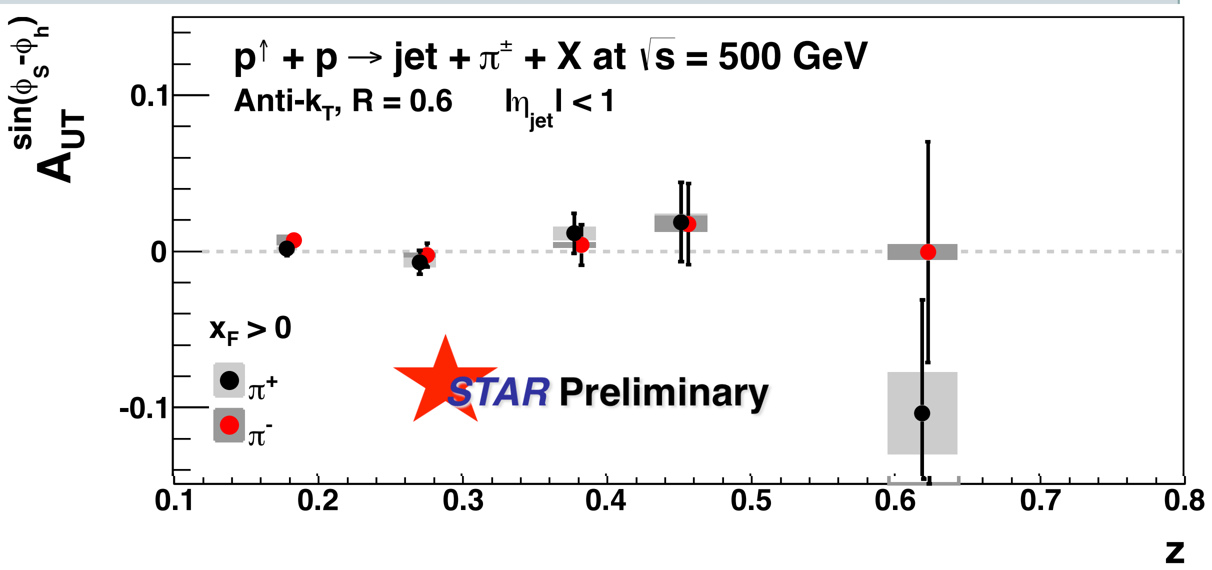


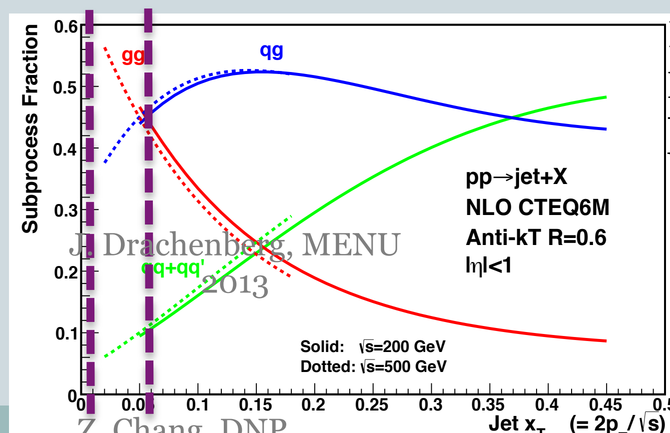
Run 12 Projection

Collins Asymmetry at 500 GeV

Increased gluonic subprocesses at $\sqrt{s}$ = 500 GeV lead to expectation of ***small Collins asymmetry*** until larger z



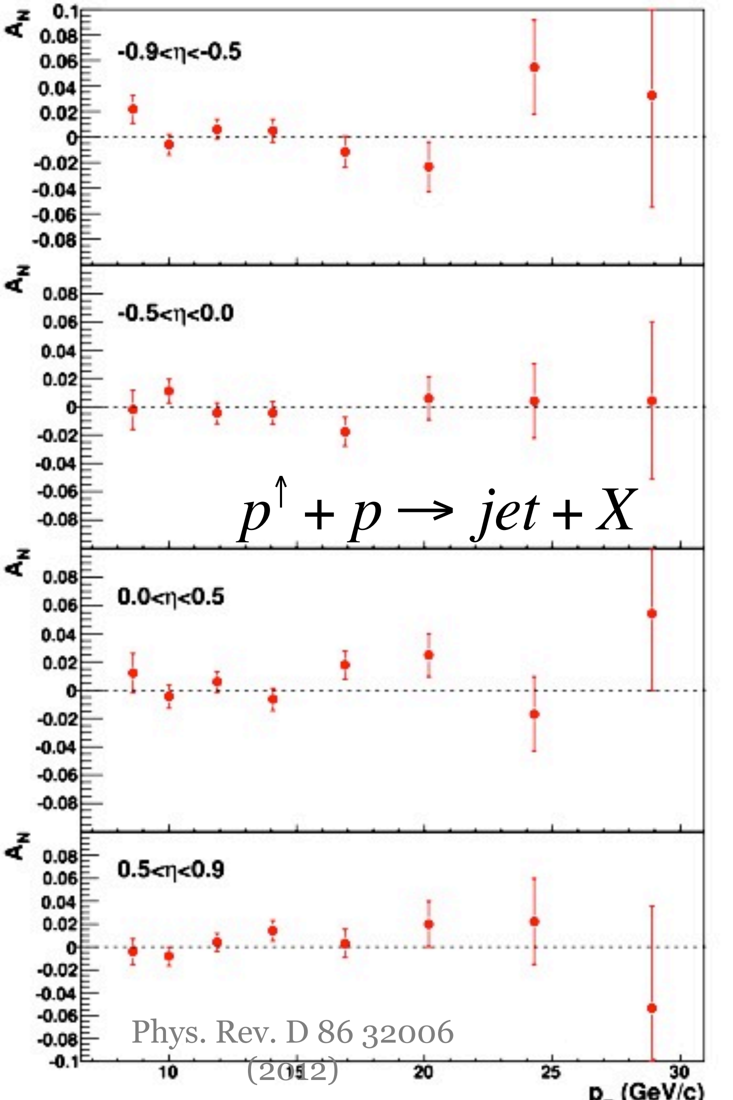




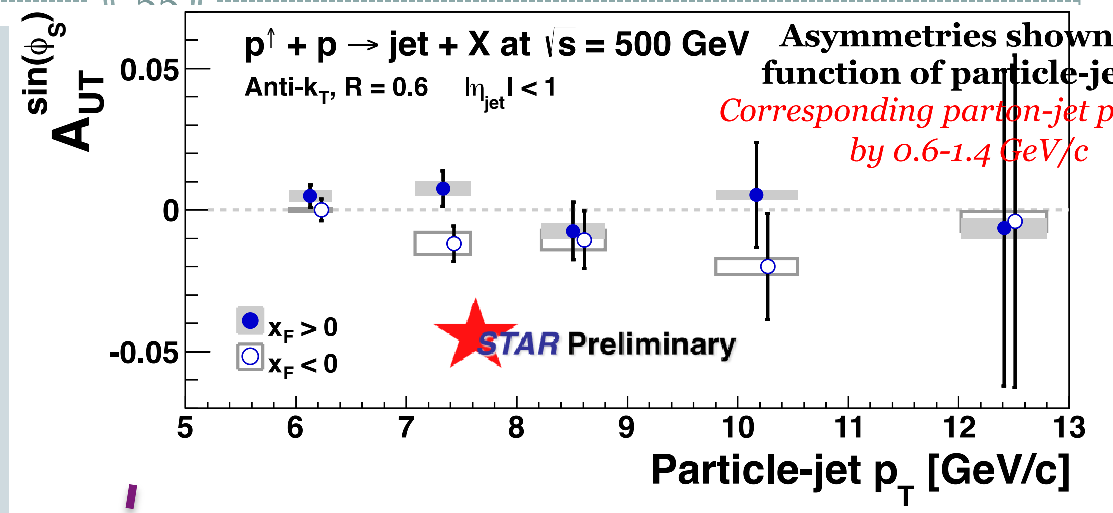
Z. Chang, DNP 2013

Leading sys.. Error from parton matchin, no sig. trigger bias due to min bias trigger

Star Jet A_N, $A^{\sin(\phi S)}$ related to $f_1^{\perp}$

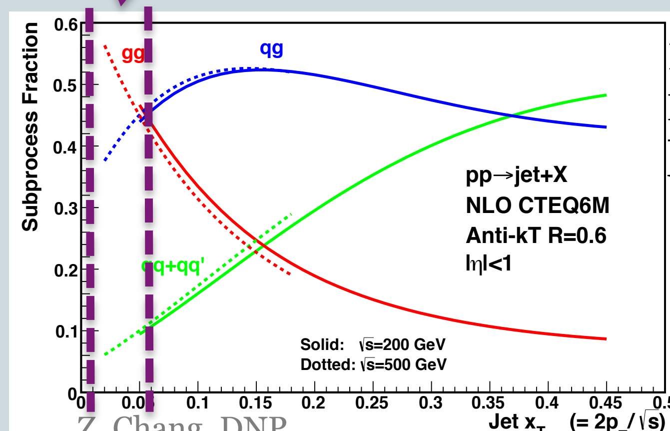


Phys. Rev. D 86 32006 (2012)



Asymmetries shown function of particle-je

Corresponding parton-jet p by 0.6-1.4 GeV/c



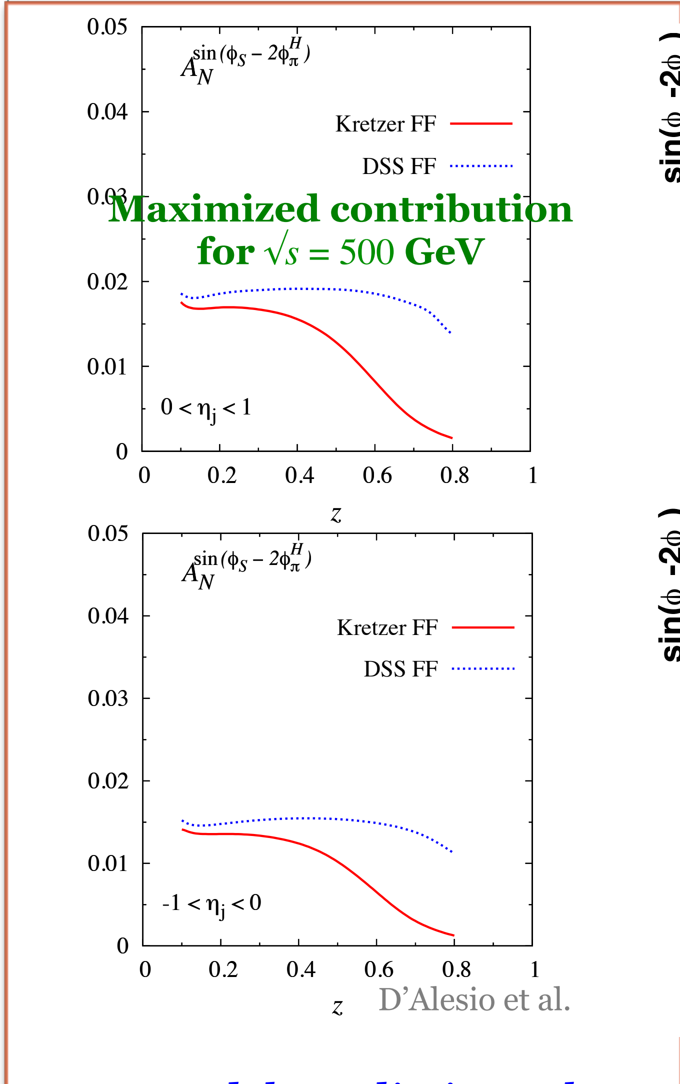
Leading sys.. Error from parton matchin, no sig. trigger bias due to min bias trigger

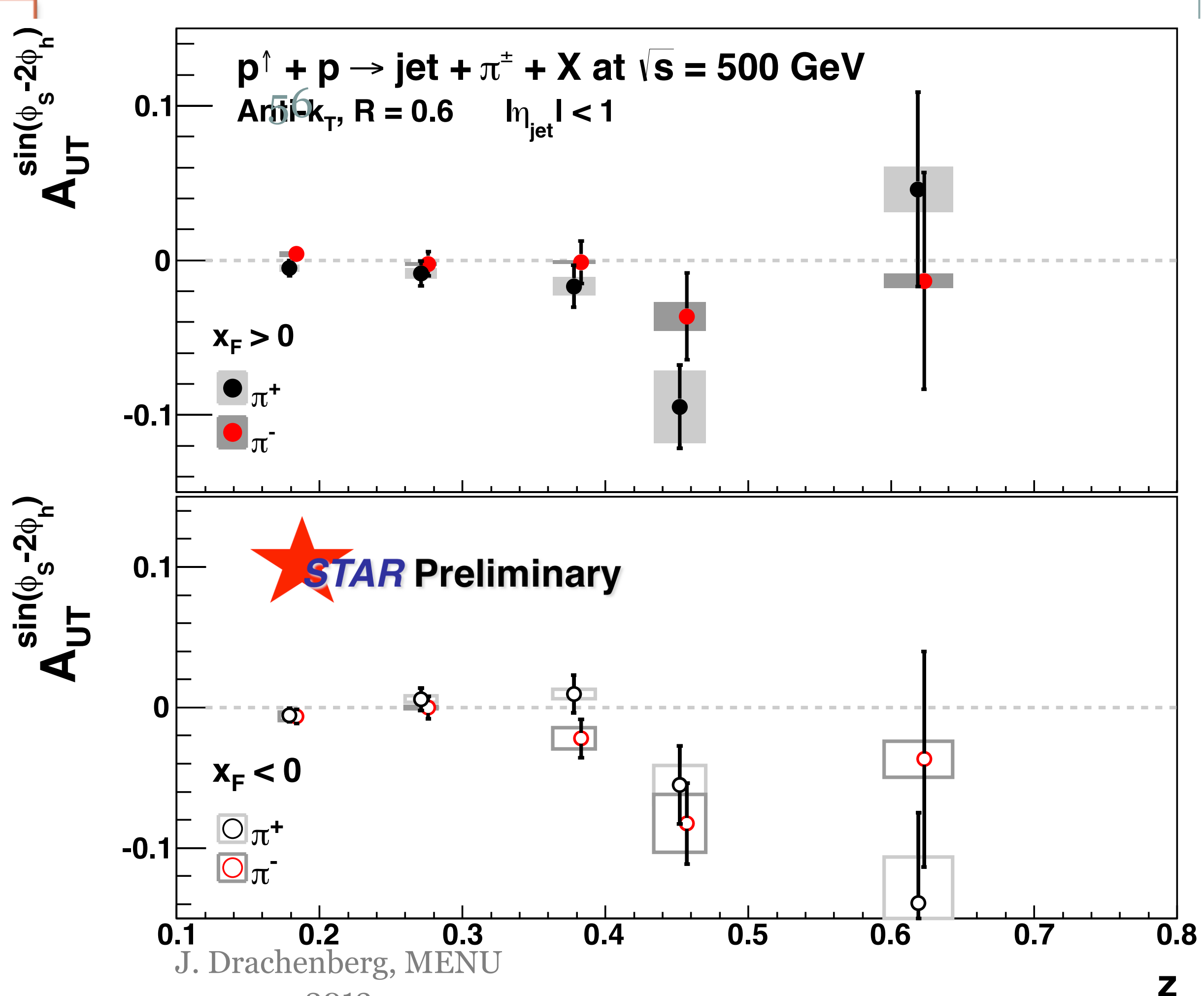
Z. Chang, DNP 2013

Similarly, di-jet at central psuedorapidity and 200 GeV consistent with zero

PRL 99, 142003

"Collins Like": $A^{\cos(3\phi h-\phi S)} \propto h_1^{\perp,g} \otimes H_1$





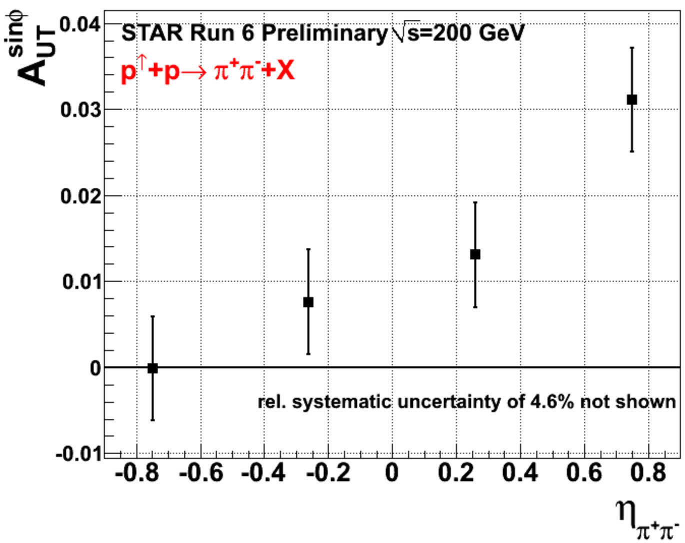
J. Drachenberg, MENU 2013

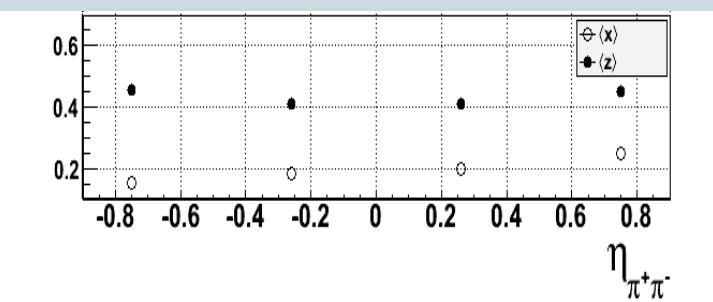
Model predictions shown for "maximized" effect, saturated to positivity bound

Until now, Collins-like asymmetries completely unconstrained

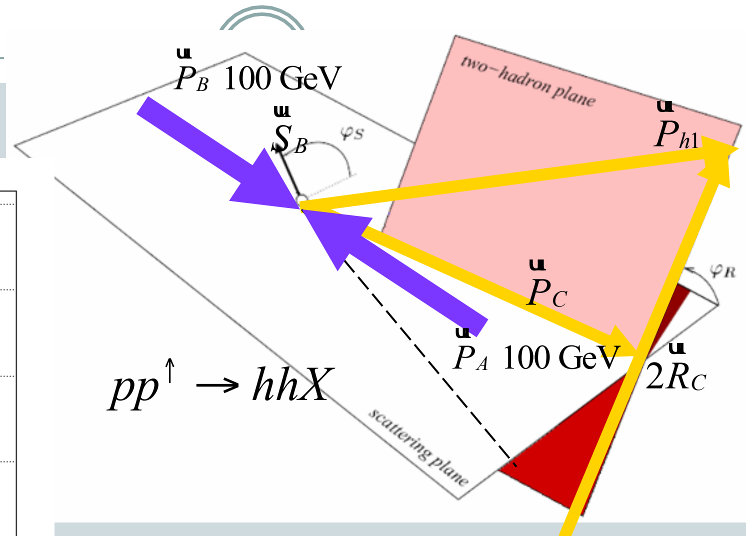
→ Sensitive to linearly polarized gluons

Transversity from di-Hadron SSA





Trigger bias/partonic variables estimated
From Pythia+GEANT simulations
(gluon,quarks averaged…)



p+p c.m.s. = lab frame

$\vec{P}_A, \vec{P}_B$: momenta of protons

$\vec{P}_{h1}, \vec{P}_{h2}$: momenta of hadrons

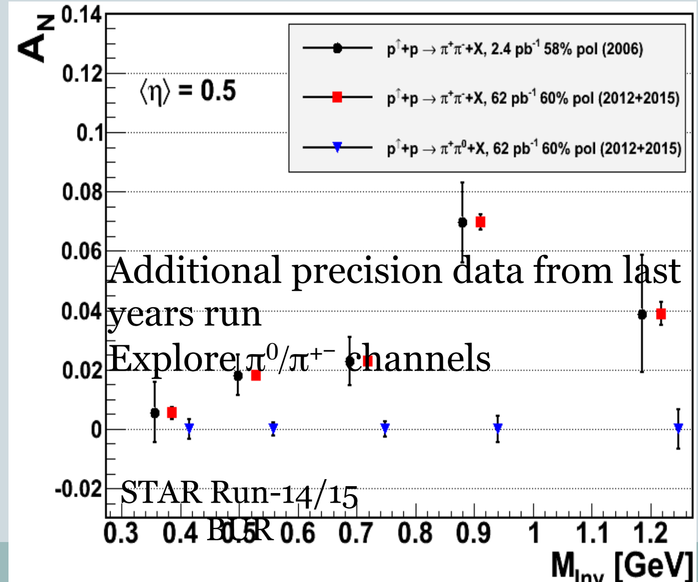
$\vec{P}_C = \vec{P}_{h1} + \vec{P}_{h2}$

$\vec{R}_C = (\vec{P}_{h1} - \vec{P}_{h2})/2$

$\vec{S}_B$: proton spin orientation

ϕ_R : from scattering plane to hadron plane

ϕ_S : from polarization vector to scattering plane



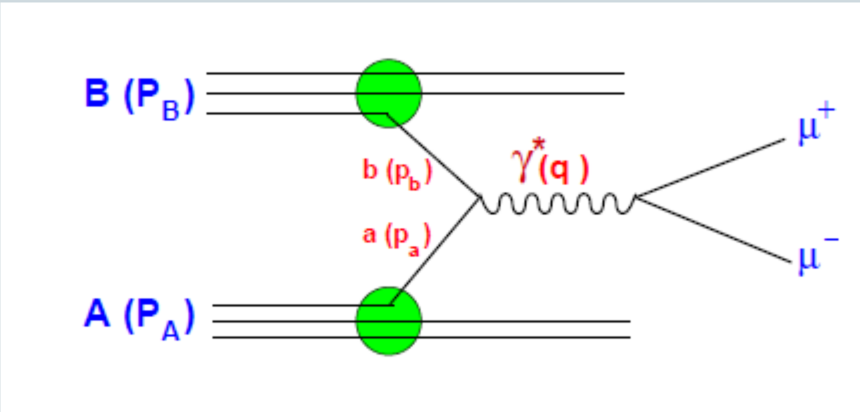
Additional precision data from last years run

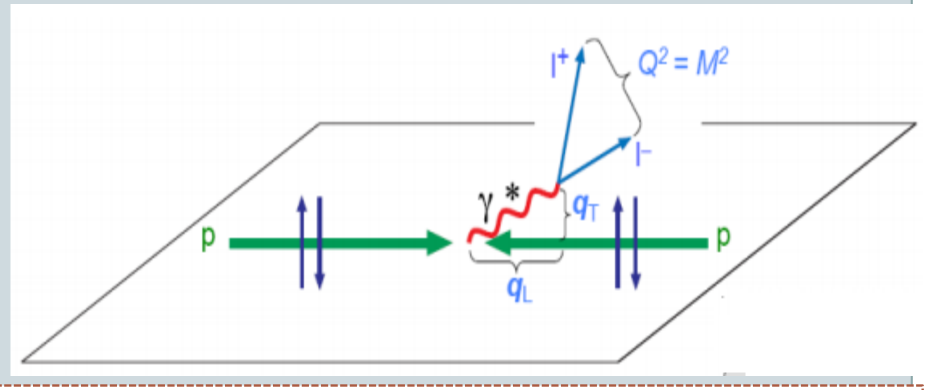
Explore π^0/π^{+-} channels

STAR Run-14/15

BUR

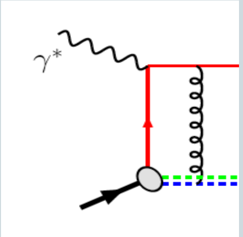
Outlook: Sivers Asymmetries in Polarized Drell Yan at COMPASS



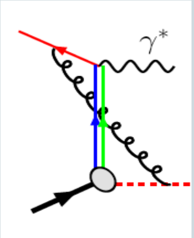


$$A^{\sin\phi} \propto f_1(\text{beam}) \otimes f_{1T}^{\perp}(\text{target})$$

DIS: attractive

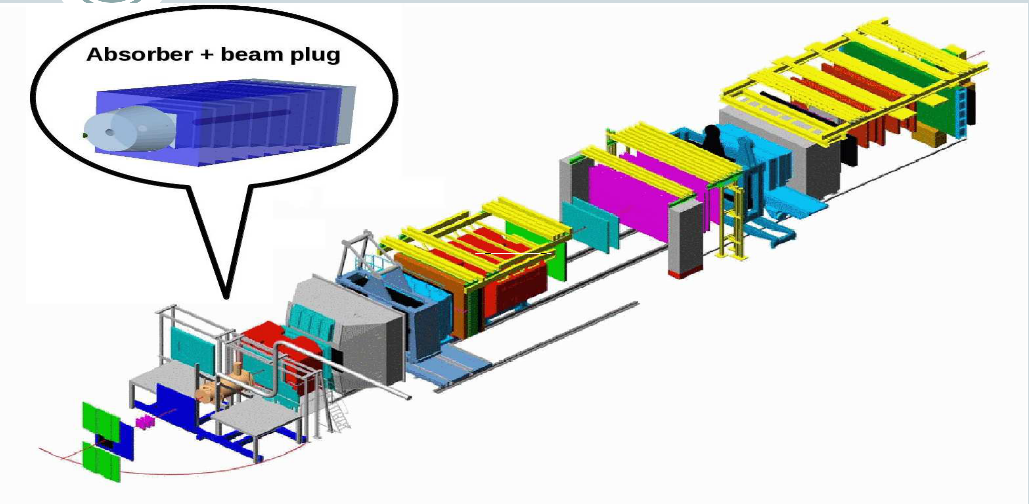


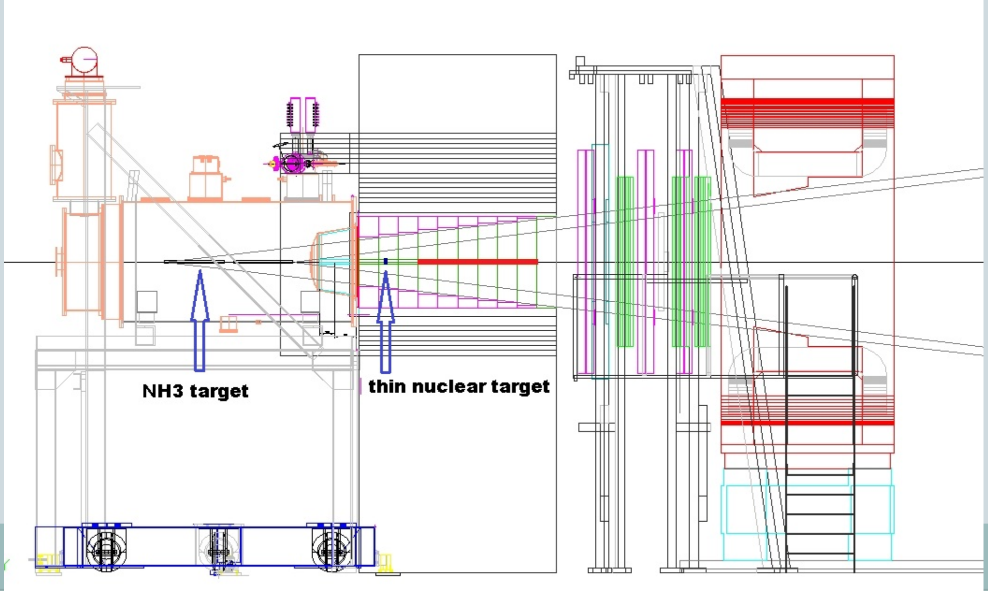
Drell-Yan: repulsive



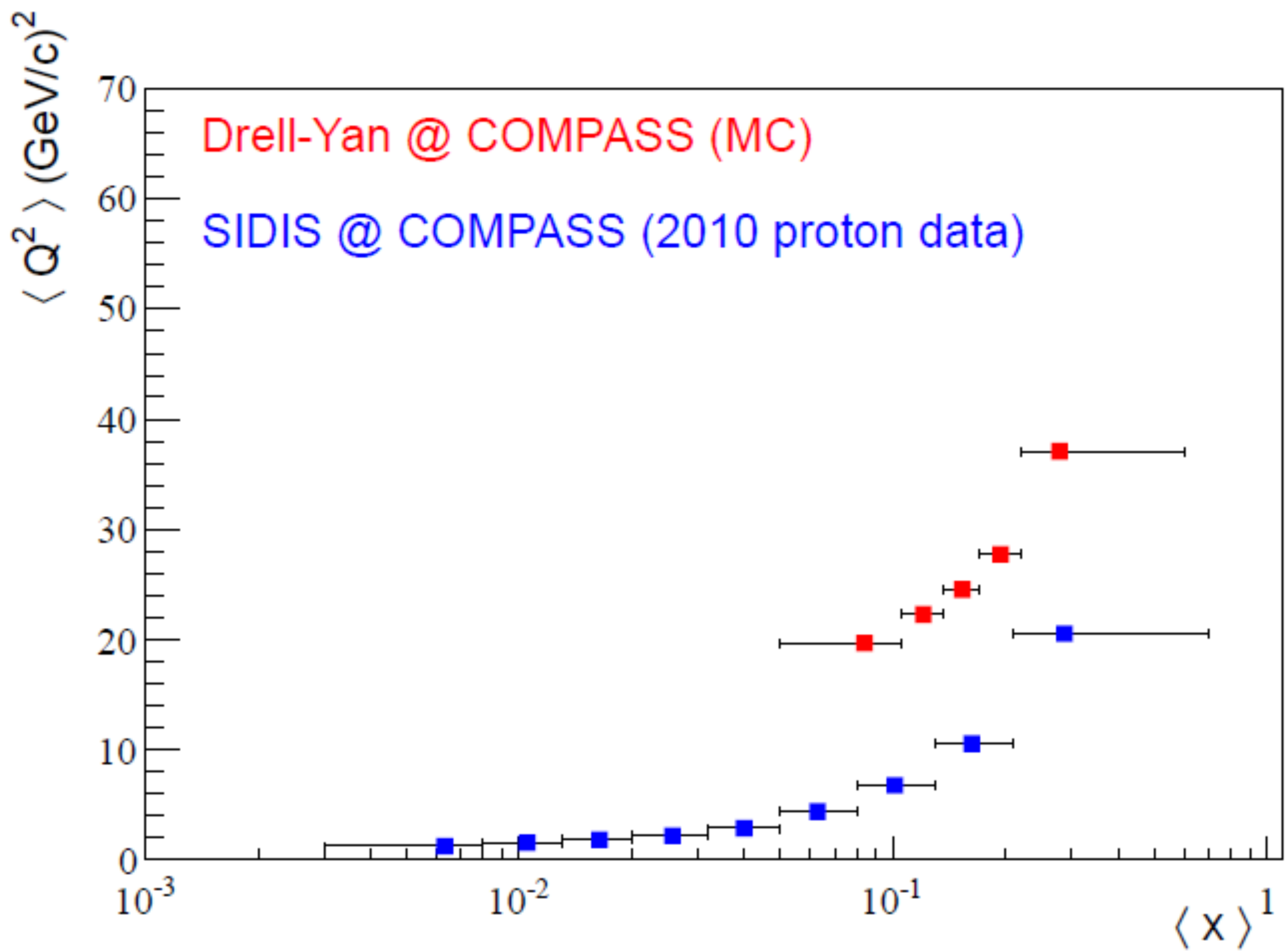
Fundamental QCD Predictions, e.g. sign change Sivers –DY (later), Nuclear physics milestone!

2014/2015 COMPASS DY with π beam

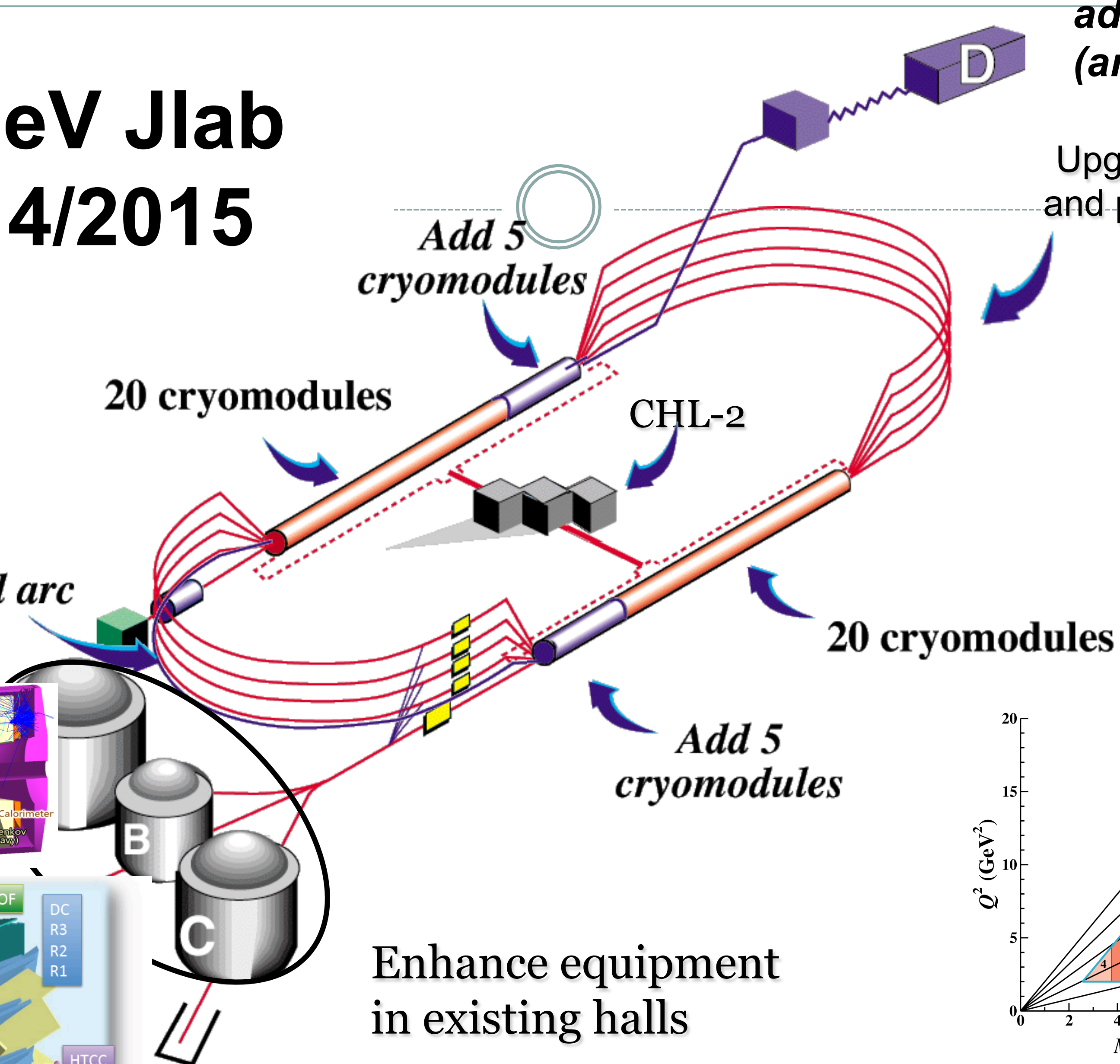


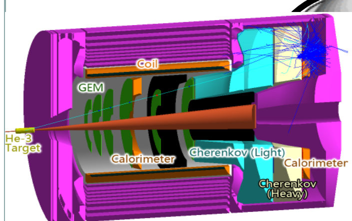


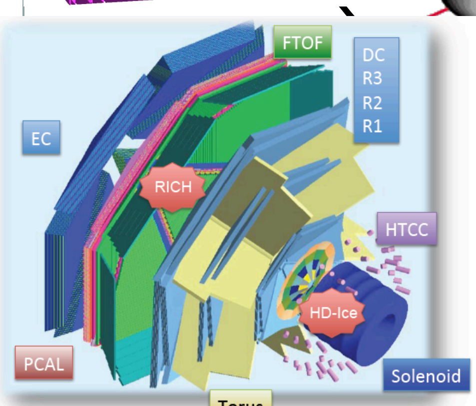
4M events in 2 years of Compass running – Overlapping kinematics



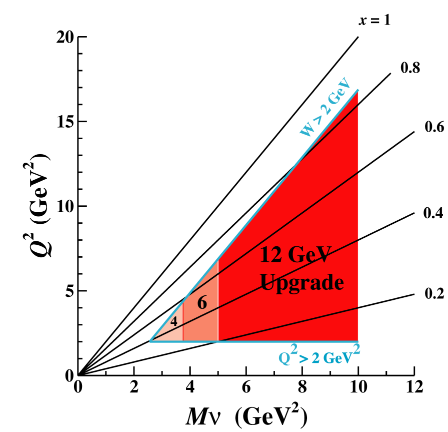
12 GeV Jlab 2014/2015







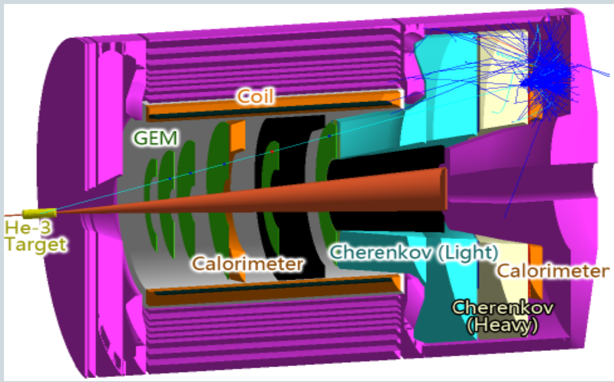
Enhance equipment
in existing halls

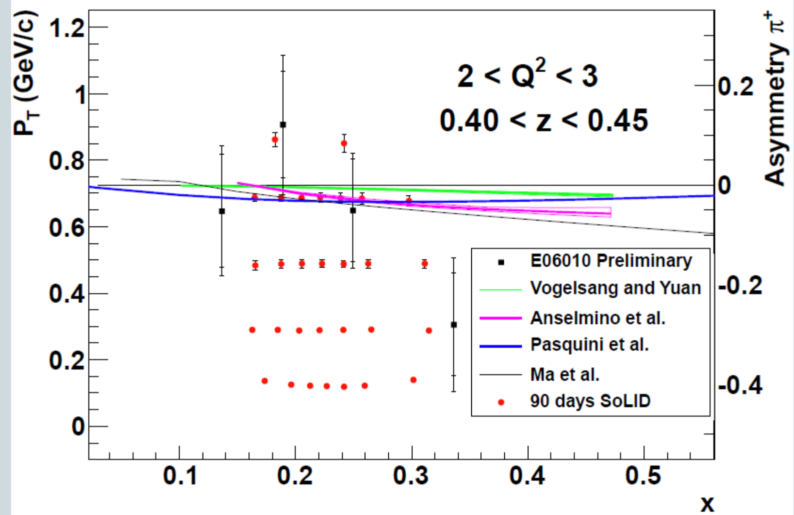


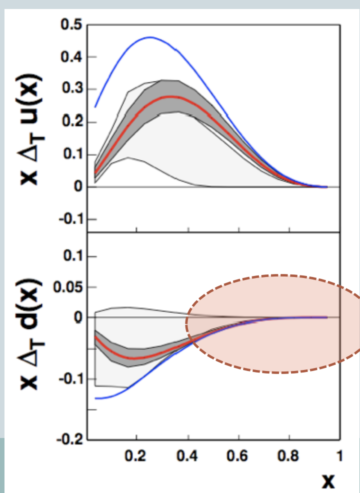
High Luminosity
Access to valence quarks

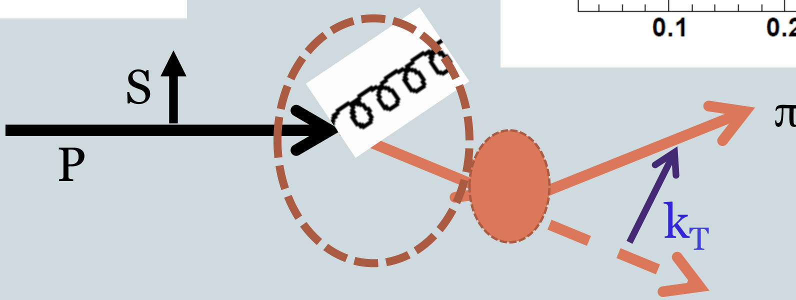
DIS up to x~0.8
SIDIS, x~0.55

Transversity at high x from polarized He3 at SoLID with 12 GeV Upgrade at JLab









- Precise measurement of p_T dependent Collins effect
  - Needs precise measurement of Collins and spin averaged p_T dependent fragmentation functions

Belle II Detector at SuperKEKB (L x 40)

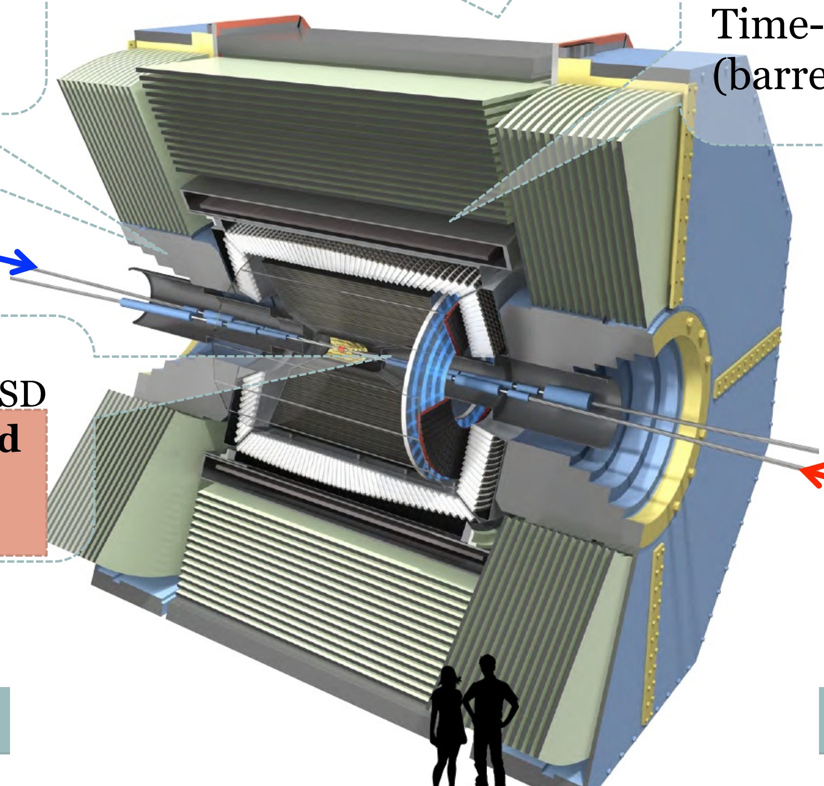
- Barrel PID instrumental for fragmentation function measurements

K_L and muon detector:
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)
RPC Front End Electronics, Concentrator boards for barrel and endcap scintillator layers

EM Calorimeter:
CsI(Tl), waveform sampling (barrel)
Pure CsI + waveform sampling (end-caps)

Particle Identification
Time-of-Propagation counter (barrel)

e- (7GeV)



e+ (4GeV)

Vertex Detector
2 layers DEPFET + 4 layers DSSD
Vertex resolution improved by order of magnitude: Separate charm/uds

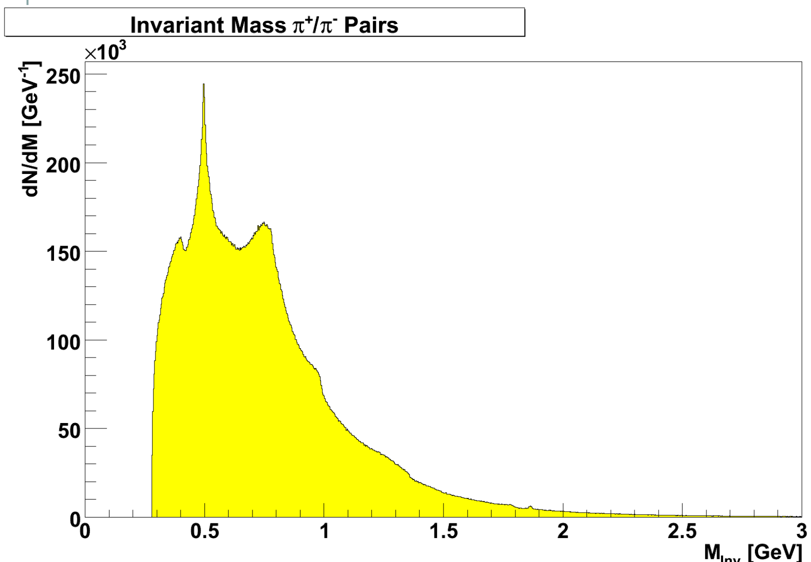
Summary

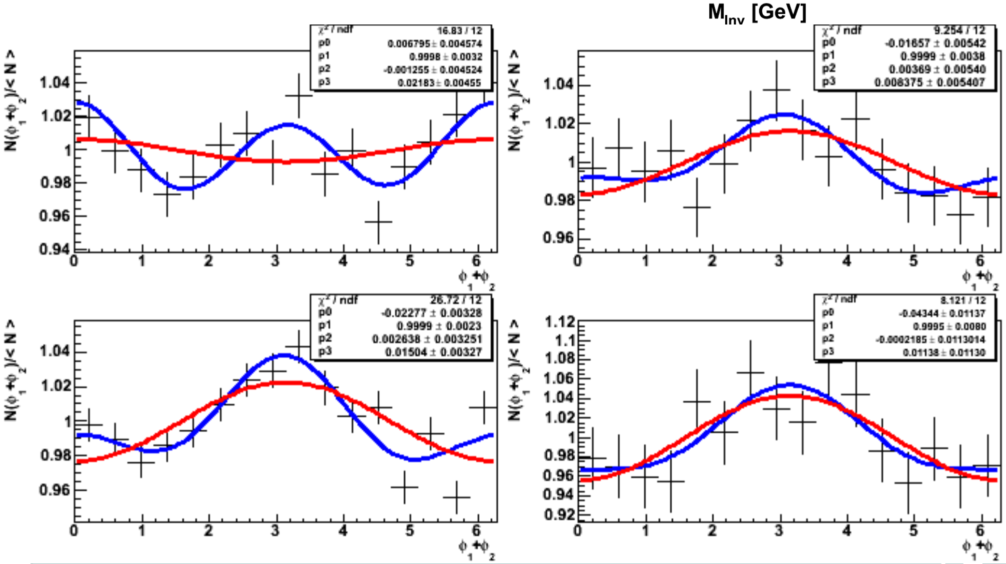
- Pioneering TMD measurements
  - In SIDIS: HERMES and COMPASS, Jlab
  - In p+p: STAR, PHENIX, AnDY
- Significant Sivers, Collins, Boer-Mulders effects
- Hints of pretzelosity, worm-gear
- Simulation crucial for unpolarized measurements (SIDIS and e+e-), e+e- depends on correct simulations, p+p jets
- Not mentioned: Jet A_N @ AnDY, charged pion/kaon A_N @ Brahms, η-π^0 differences at Phenix, Star, Compass, Hermes Kaon results

- Outlook
  - CLAS, SoLID @JLab: TMD x-section, map out in k_T
  - Belle II: Continuation of FF measurements with improved Kaon ID and vertex reconstruction
  - Test TMD framework
  - COMPASS: Test fundamental prediction of sign change in Sivers function

Backup

Asymmetry extraction





- Build normalized yields:

$$\frac{N(\phi_1+\phi_2)}{\langle N\rangle}, \qquad \frac{N(\phi_{1R}+\phi_{2R})}{\langle N\rangle}$$

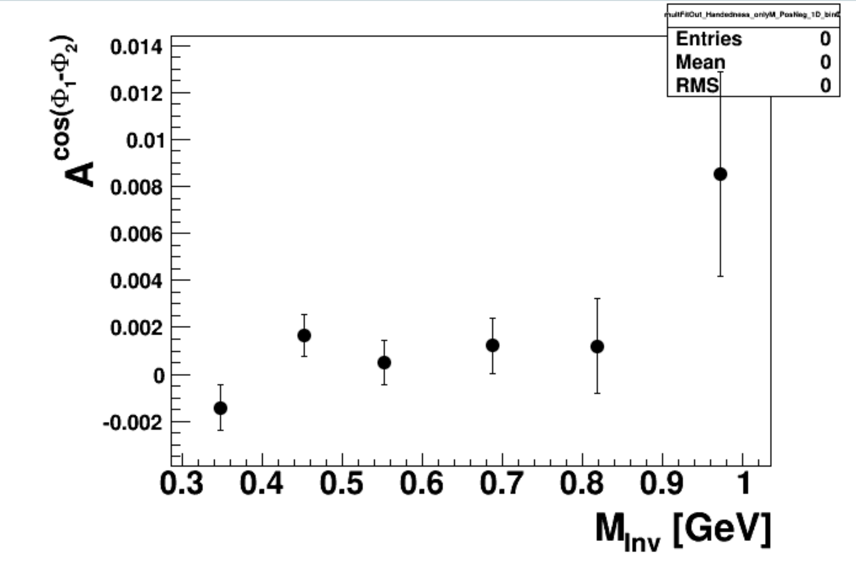
- Fit with:

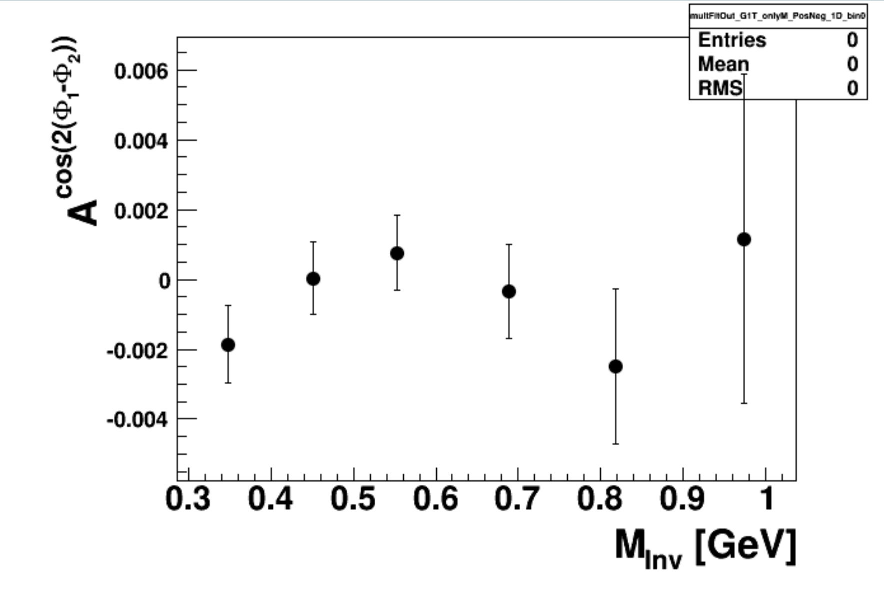
or $a_{12}\cos(\phi_1+\phi_2)+b_{12}$

$$a_{12}\cos(\phi_1+\phi_2)+b_{12}+ c_{12}\cos 2(\phi_1+\phi_2)+d_{12}\sin(\phi_1+\phi_2)$$

Amplitude a_{12} directly measures IFF! (squared)

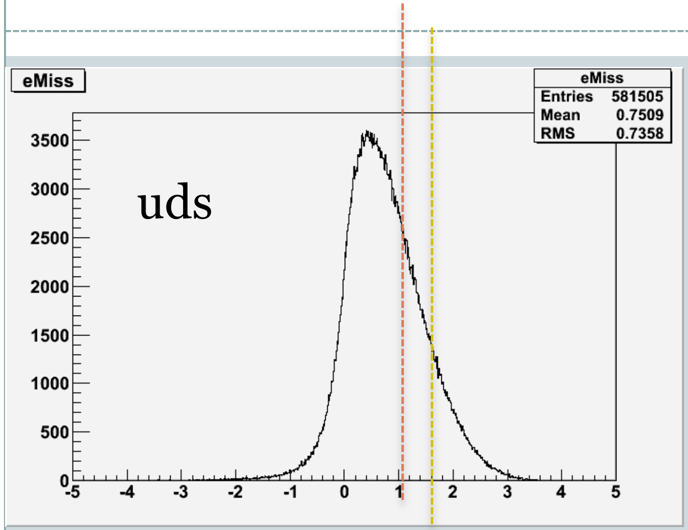
Mixed event subtraction

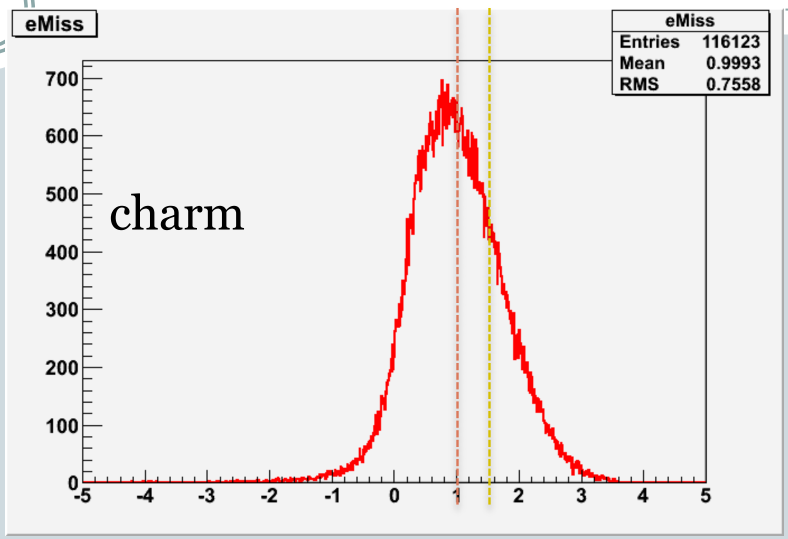




- $A^{\cos(\phi 1-\phi 1)}$ exhibits some acceptance effects → subtract mixed events sorted by jet topology

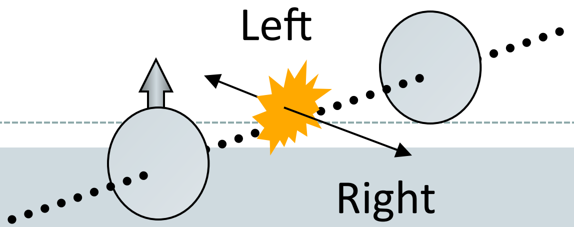
Missing Energy cut to remove possible contributions from weak decays





- Indicated the cuts at 1GeV and 1.5 GeV in missing CMS energy. Effect on uds is 32/14%, charm is cut by48/24% respectively

Simple: Forward ~3<η<4 Left-Right Asymmetries (π^o)



$$pp^{\uparrow} \rightarrow \pi + X$$

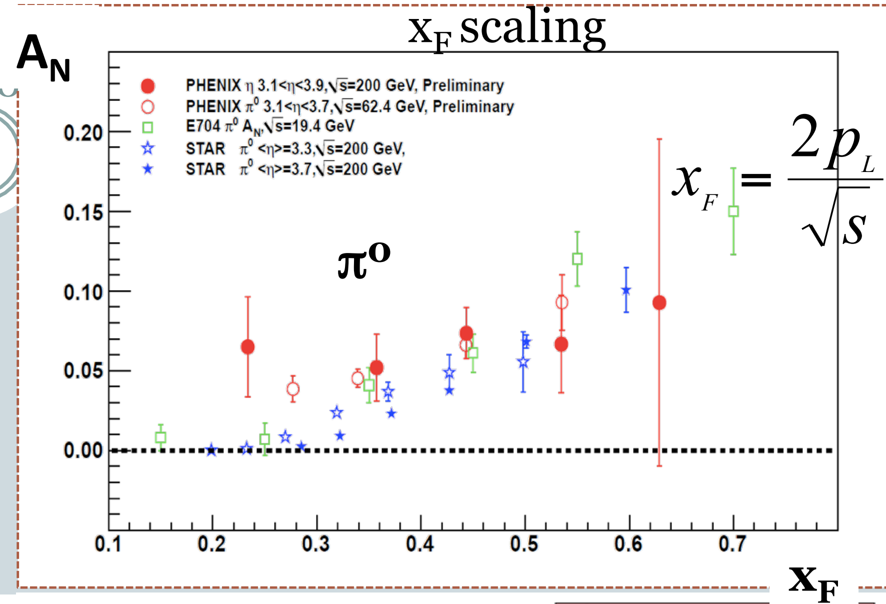
$$A_N = \frac{1}{P}\frac{\sigma_L^{\pi} - \sigma_R^{\pi}}{\sigma_L^{\pi} + \sigma_R^{\pi}}$$

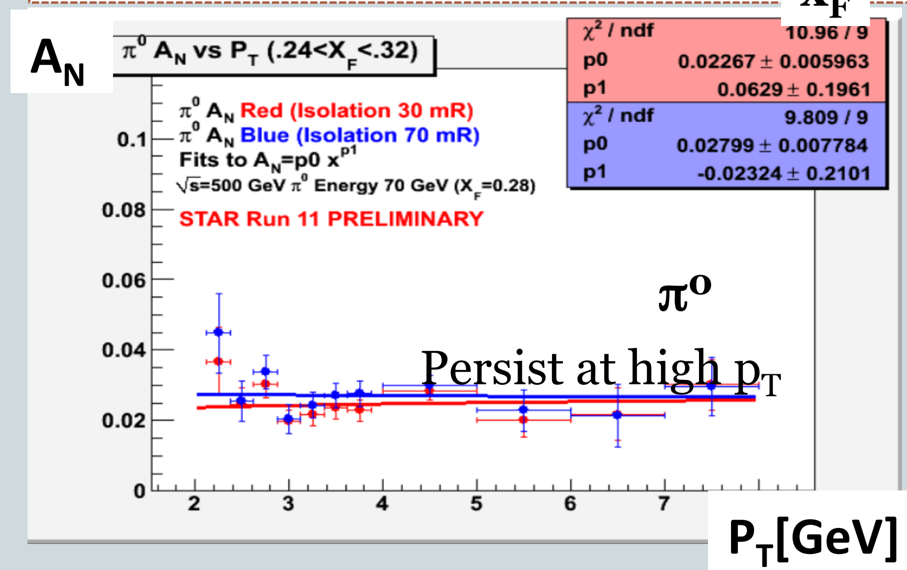
A_N difference in cross-section between particles produced to the left and right

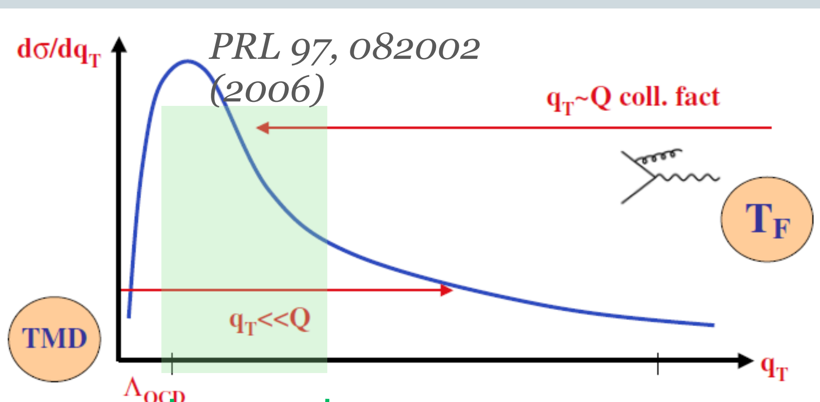
RHIC first time in perturbative regime

Initial parton kinematics unknown, cannot disentangle Sivers/Twist3, Collins effects

No Jets → One scale: p_T



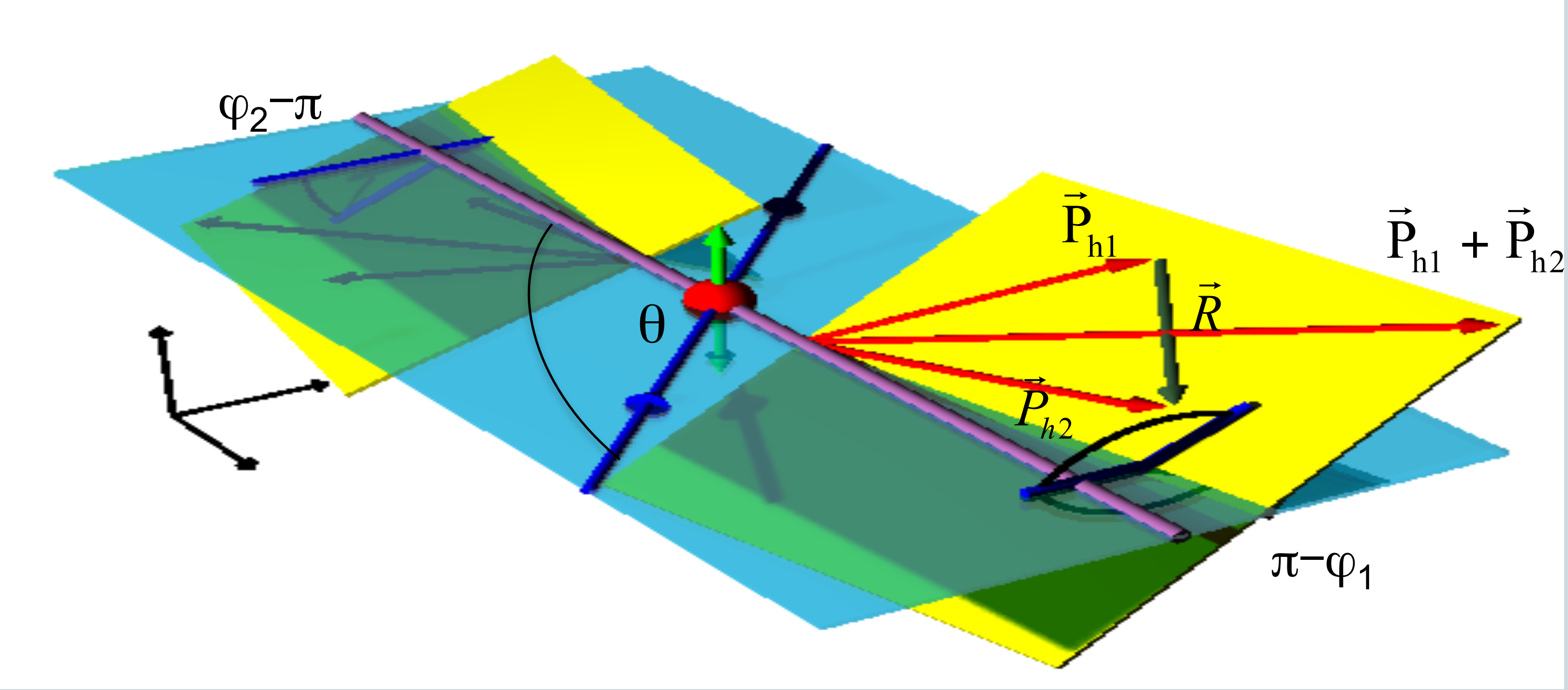




What about (Boer, Mulders, Pijlman, 2003, Ji, Qiu, Vogelsang, Yuan, 2006)

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

Azimuthal angles in the Di-Pion Pair x-section



- $e^+e^- \rightarrow (\pi^+\pi^-)_{jet1}(\pi^+\pi^-)_{jet2}X$
- Find pion pairs in opposite hemispheres
- Observe angles φ_1, φ_2 between the event-plane (beam, jet-axis) and the two two-pion planes.
- Kinematic factor $\sin\varphi^2/(1+\cos\varphi^2)$ gives transverse spin projection