Measurement of (Interference) Fragmentation Functions in e^+e^-

and Di-Hadron Correlations at SIDIS and p+p

Anselm Vossen

for the

BELLE

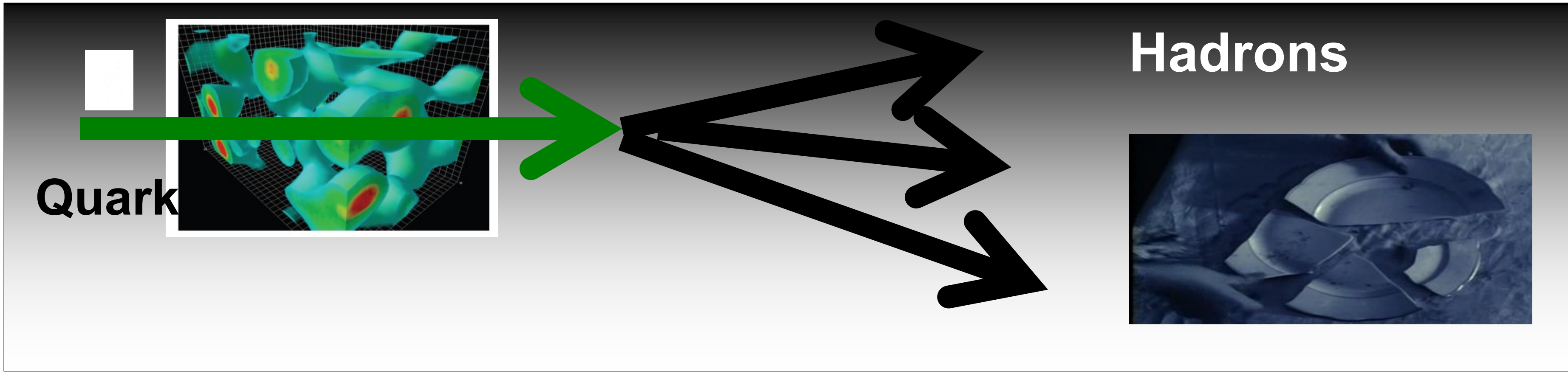
Collaboration

Transversity 2011
Veli Lošinj, Croatia, 29 August - 2 September 2011

arXiv:1104.2425
PRL **107,** 072004(2011)

INDIANA UNIVERSITY

Motivation & Outline



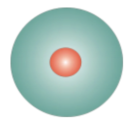
- Transverse spin dependent fragmentation functions are necessary to extract quark transversity
- Interference Fragmentation Function best way to extract transversity in p+p
  →Opens new kinematic domain of high x_{Bj} and z
- In SIDIS: Di-hadron Correlations provide independent approach to extract transversity with some theoretical advantages
- Measurement of Interference and Collins Fragmentation Functions at BELLE
- Results from di-hadron correlations at PHENIX, hermes, COMPASS
- Planned Measurements at STAR, BABAR
- Outlook: Unpolarized and more “exotic” Fragmentation functions

Parton Distribution Functions

The three leading order, collinear PDFs

$\mathbf{q(x)}$

$f_1^q\,(x)$



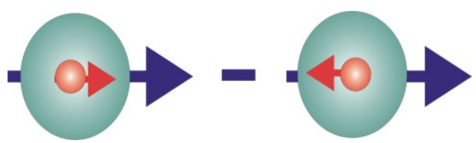
unpolarized PDF

quark with momentum $x = p_{quark}/p_{proton}$ in a nucleon

well known – unpolarized DIS

$\mathbf{\Delta q(x)}$

$g_1^q(x)$



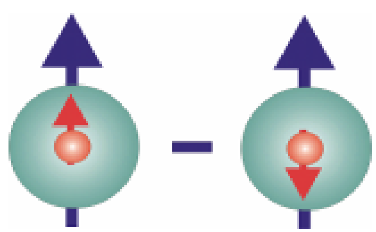
helicity PDF

quark with spin parallel to the nucleon spin in a longitudinally polarized nucleon

known – polarized DIS

$\mathbf{\Delta_T q(x)}$

$h_1^q(x)$



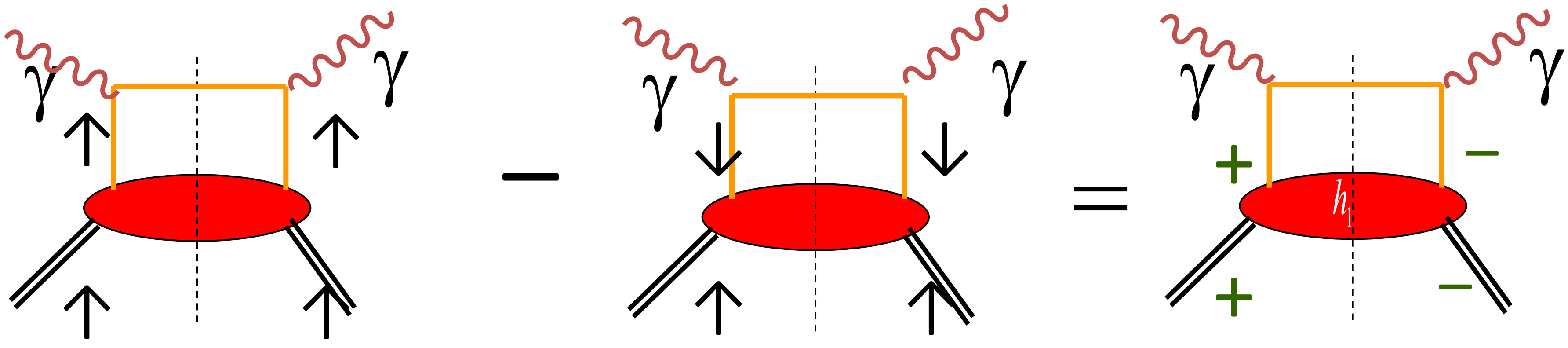
transversity PDF

quark with spin parallel to the nucleon spin in a transversely polarized nucleon

chiral odd, poorly known
Cannot be measured inclusively
Extract from semi-inclusive measurements

Transversity is Chiral Odd

- Transversity base:



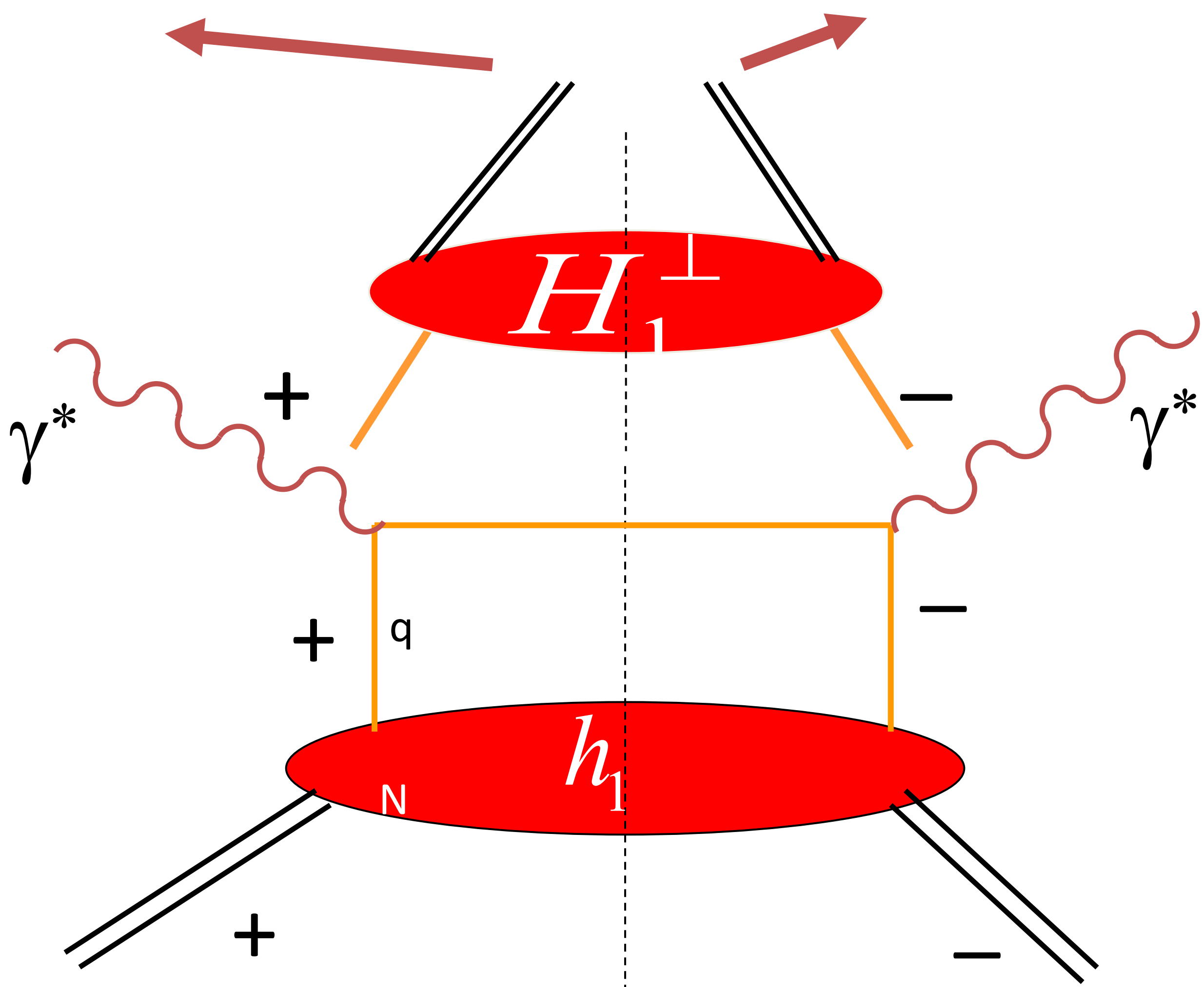
Difference in densities for ↑, ↓ quarks
in ↑ nucleon

- **Helicity base: chiral odd**
- **....see previous talks**
- **Does not couple to gluons ⇨different QCD evolution than $g_1(x)$**
- **Valence dominated⇨ Tensor charge comparable to Lattice calculations**

- **We want to extract tensor charge $g_T = \int_{-1}^{1} h_1(x)dx$**

Chiral odd Fragmentation Functions

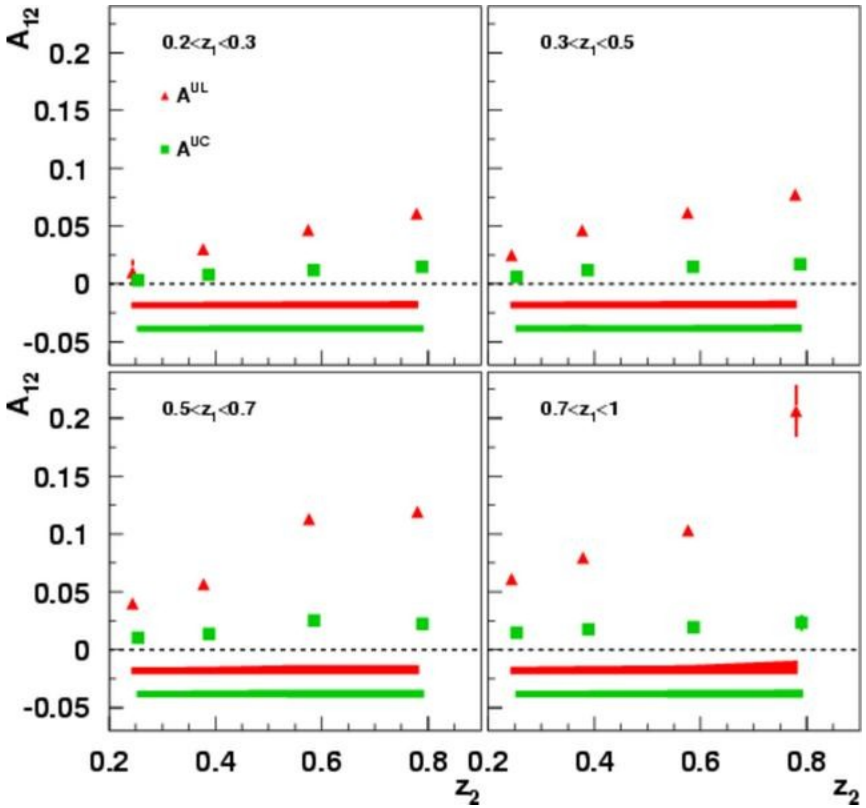
Collins effect



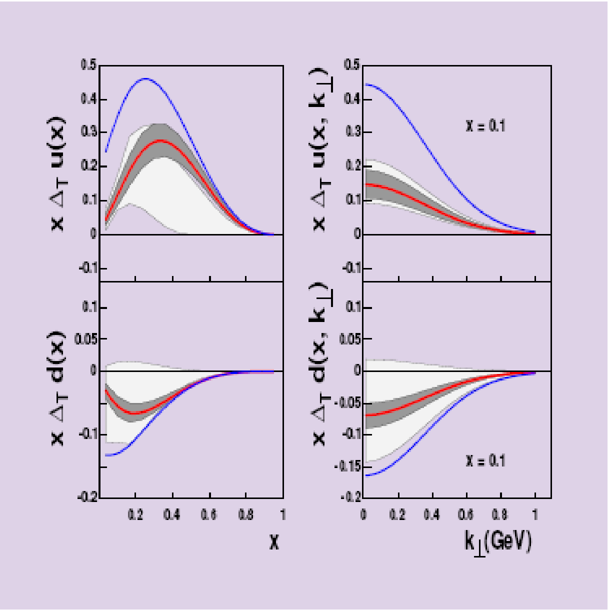
[redacted] **: Collins FF**

Belle Fragmentation Function Measurement makes first Extraction of Transversity possible!

Belle 547 fb^{-1} data set (Phys.Rev.D78:032011,2008.)



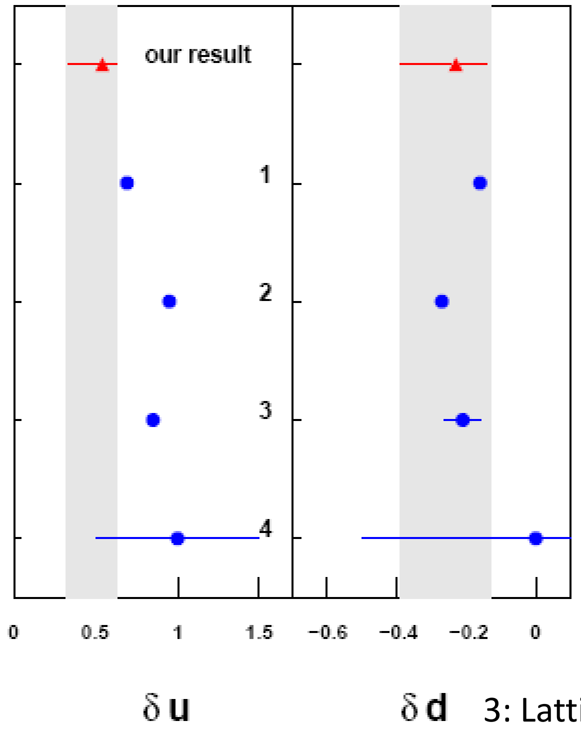
Together with HERMES, COMPASS First, still model dependent transversity Extraction :



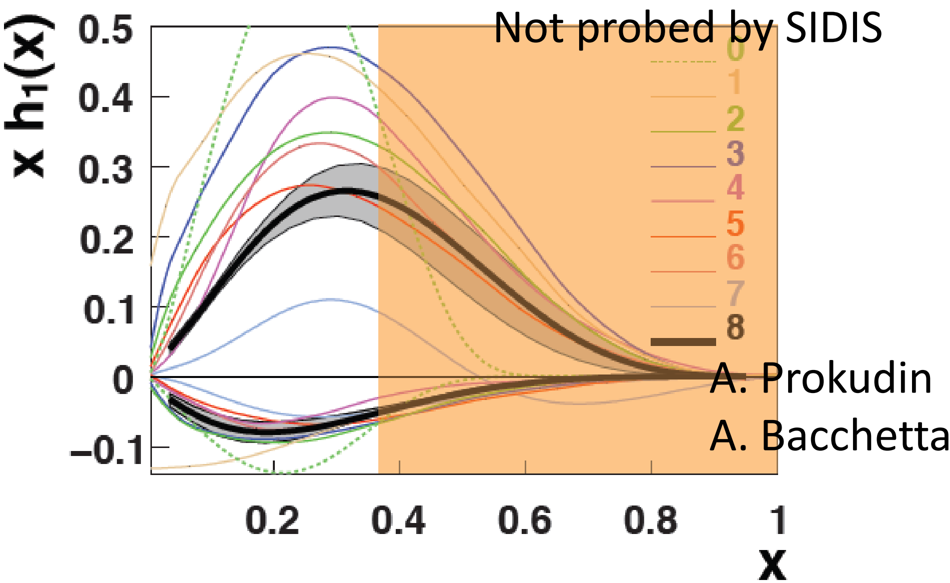
Alexei Prokudin, DIS2008, update of Anselmino et al: hep-ex 0701006

Extraction of double ratios unlike sign over like sign A^{UL} and unlike over all pairs A^{UC}
Gives different combinations of favored and unfavored fragmentation functions
Not direct extraction of Collins Fragmentation function : Only from global fit

First global analysis from Hermes proton-, Compass deuterium Collins asymmetries and Belle data



3: Lattice, Goekeler, PLB627 05



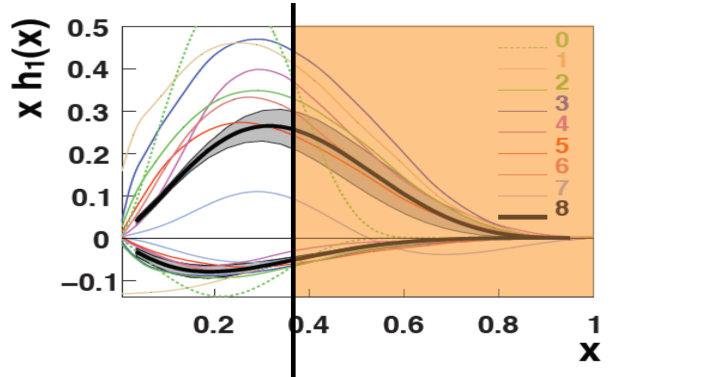
[1-7] models, [8] Anselmino et al., arXiv:0807.0173

Phys.Rev.D75:054032,2007, update in Nucl.Phys.Proc.Suppl.191:98-107,2009

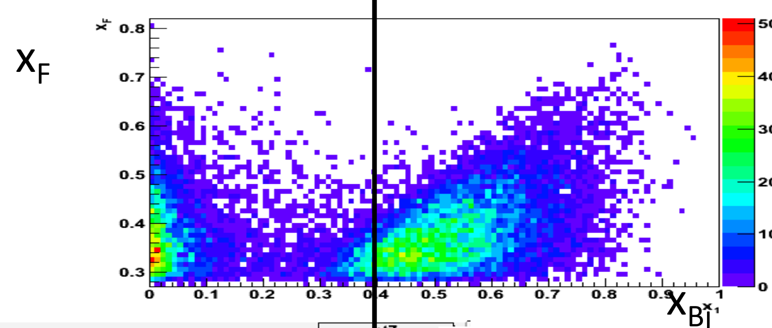
- First results available, still open questions from evolution of Collins FF and transverse momentum dependence
- More data available now
- Cross check using interference fragmentation functions needed
- Wider kinematic reach needed

p+p increased kinematic reach in x_{Bj}, z

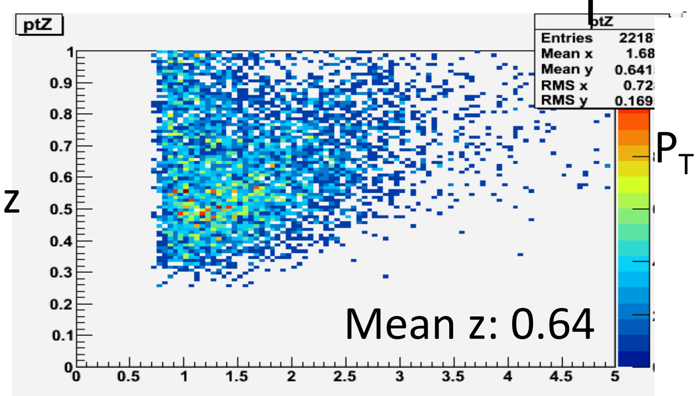
- Kinematic reach of SIDIS data

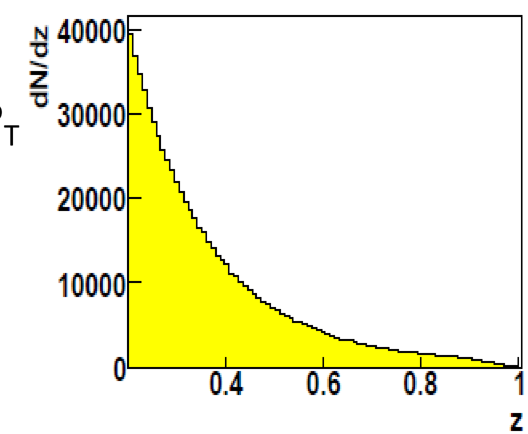


- Kinematic reach in p+p for single pions at 3<eta<4 (RHIC@200GeV)



- Relative hadron momentum z for p+p (3<eta<4) collisions and SIDIS (COMPASS), only single hadron, di-hadron z_1+z_2 ‘less different,

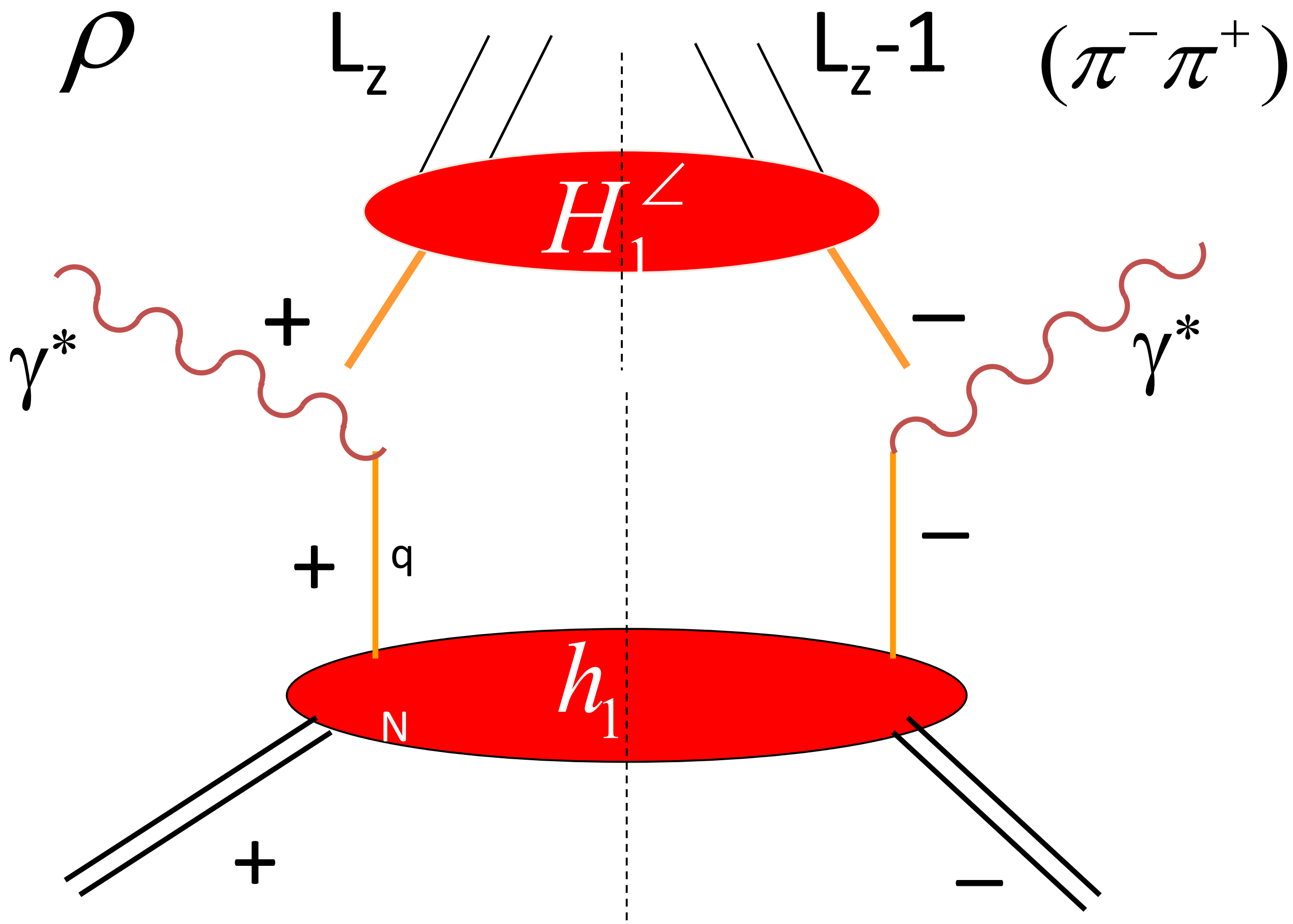




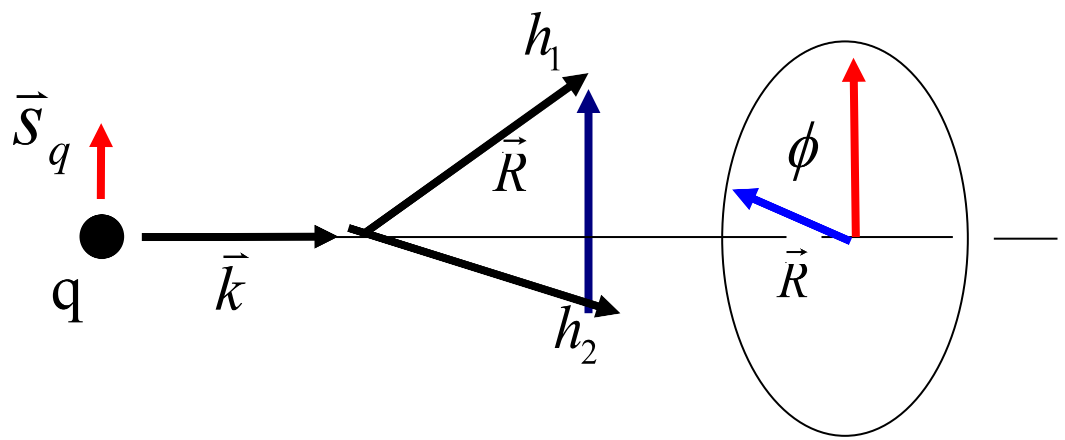
But Collins measurement hard (see STAR Talk Nikola Poljak) and theoretically hard to interpret (fact. Breaking)

Chiral odd Fragmentation Functions

Interference Fragmentation Function



Interference FF in Quark Fragmentation



$\vec{k}$	: quark momentum
$\vec{s}_q$	:quark spin
$\vec{R}$	: momentum difference $\vec{p}_{h1} - \vec{p}_{h2}$
$\vec{R}_T$	transverse hadron momentum difference
z_{pair}	$= E_{pair}/E_q$
$=2E_{pair}/\sqrt{s}$	: relative hadron pair momentum
m	: hadron pair invariant mass

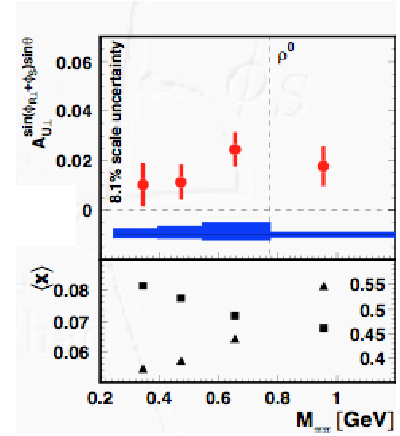
Interference Fragmentation Function:
Fragmentation of a transversely polarized quark *q* into two spin-less hadron *h1, h2* carries an azimuthal dependence:

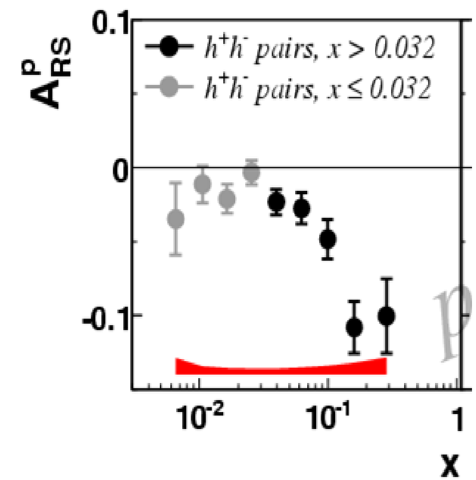
$$\propto \left(\vec{k} \times R_T \right) \cdot \vec{s}_q$$

$$\propto \sin \phi$$

Interference FF vs. Collins Effect

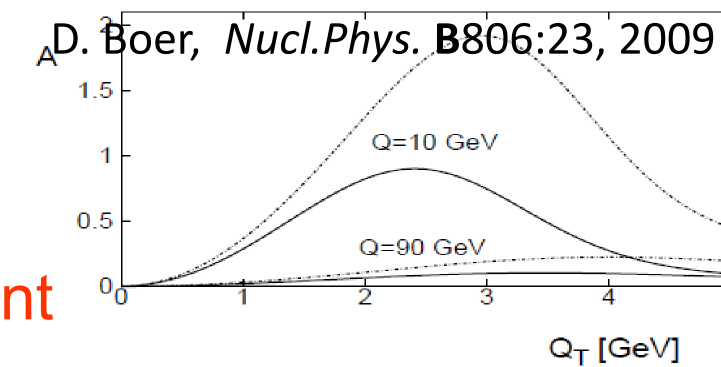
- Independent Measurement
- Effect persists with transverse momentum integrated
  – Collinear factorization
- No assumption about k_t in evolution
- evolution known, collinear scheme can be used
- Universal function: directly applicable to semi-inclusive DIS and pp
- First experimental results from HERMES, COMPASS, PHENIX and now Belle
- Sudakov suppression in Collins case
- Favorable in proton-proton collisions: no other contributions (no Sivers): Disentangle sources of large transverse spin asymmetries





In p+p:
No jet reconstruction necessary,
better systematics: “Easier” measurement

D. Boer, *Nucl.Phys.* B806:23, 2009



Spin Dependent FF in e^+e^- : Need Correlation between Hemispheres !

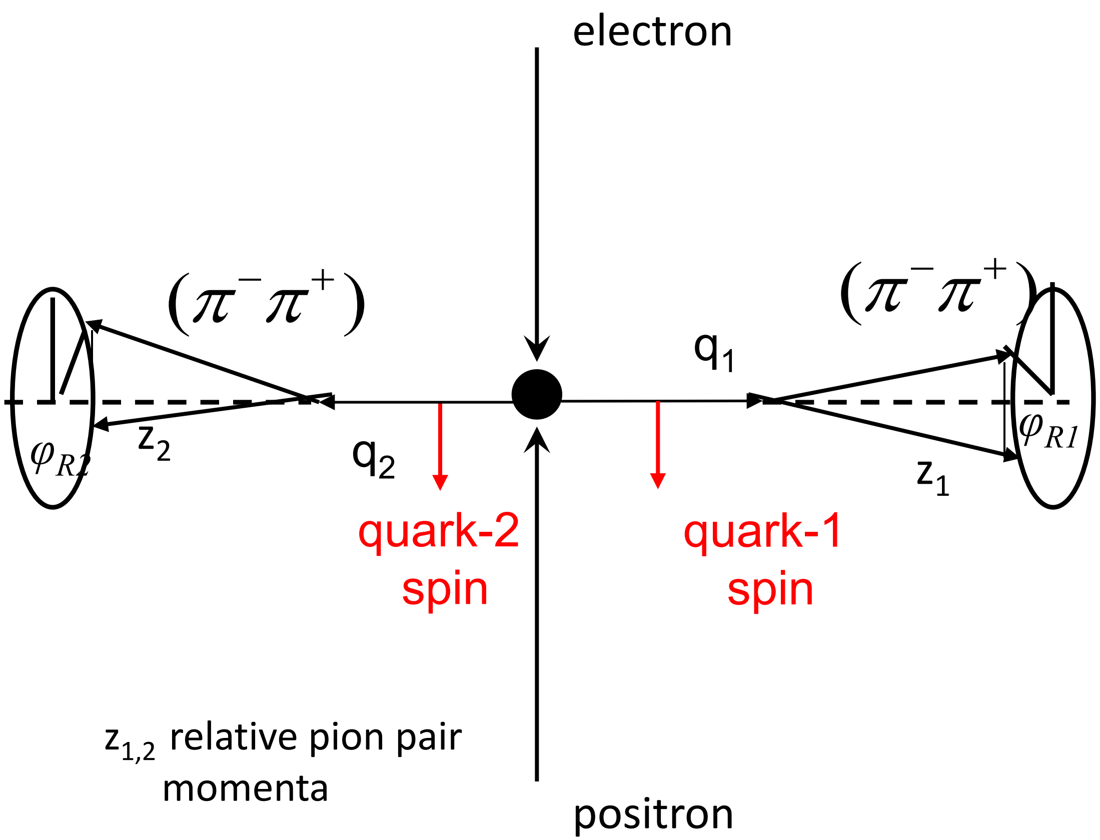
- Quark spin direction unknown: measurement of Interference Fragmentation function in one hemisphere is not possible

  $\sin \varphi$ modulation will average out.

- Correlation between two hemispheres with $\sin \varphi_{Ri}$ single spin asymmetries results in $\cos(\varphi_{R1}+\varphi_{R2})$ modulation of the observed di-hadron yield.

→ Measurement of azimuthal correlations for di-pion pairs around the jet axis in two-jet events!

Measuring di-Hadron Correlations In e^+e^- Annihilation into Quarks



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

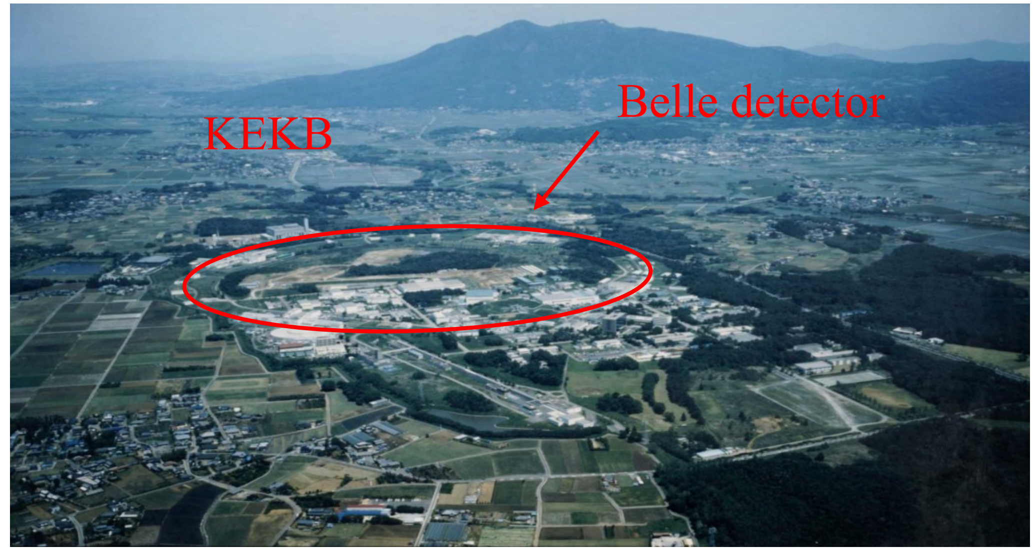
<u>Experimental requirements:</u>

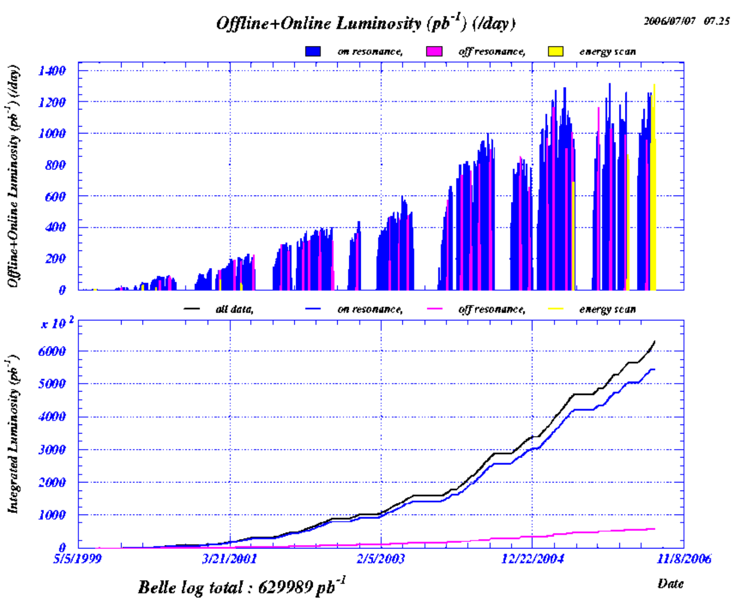
- Small asymmetries ➔ very large data sample!
- Good particle ID to high momenta.
- Hermetic detector
- Observable: $\cos(\varphi_{R1}+\varphi_{R2})$

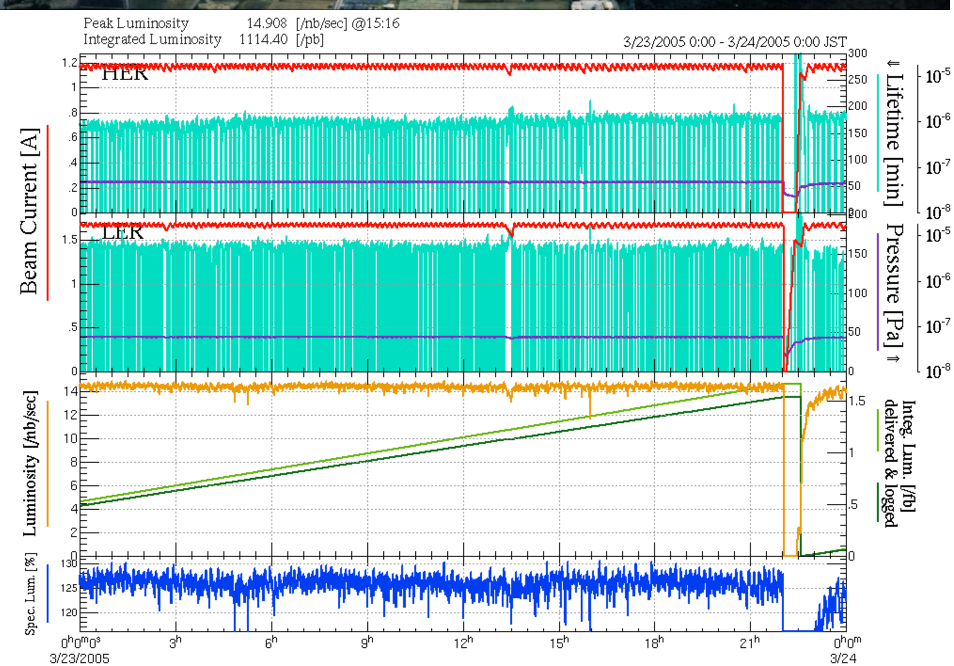
modulation measures $H_1^{\angle}\overline{H_1^{\angle}}$

KEKB: $L>2.11 \times 10^{34} cm^{-2}s^{-1}$!!

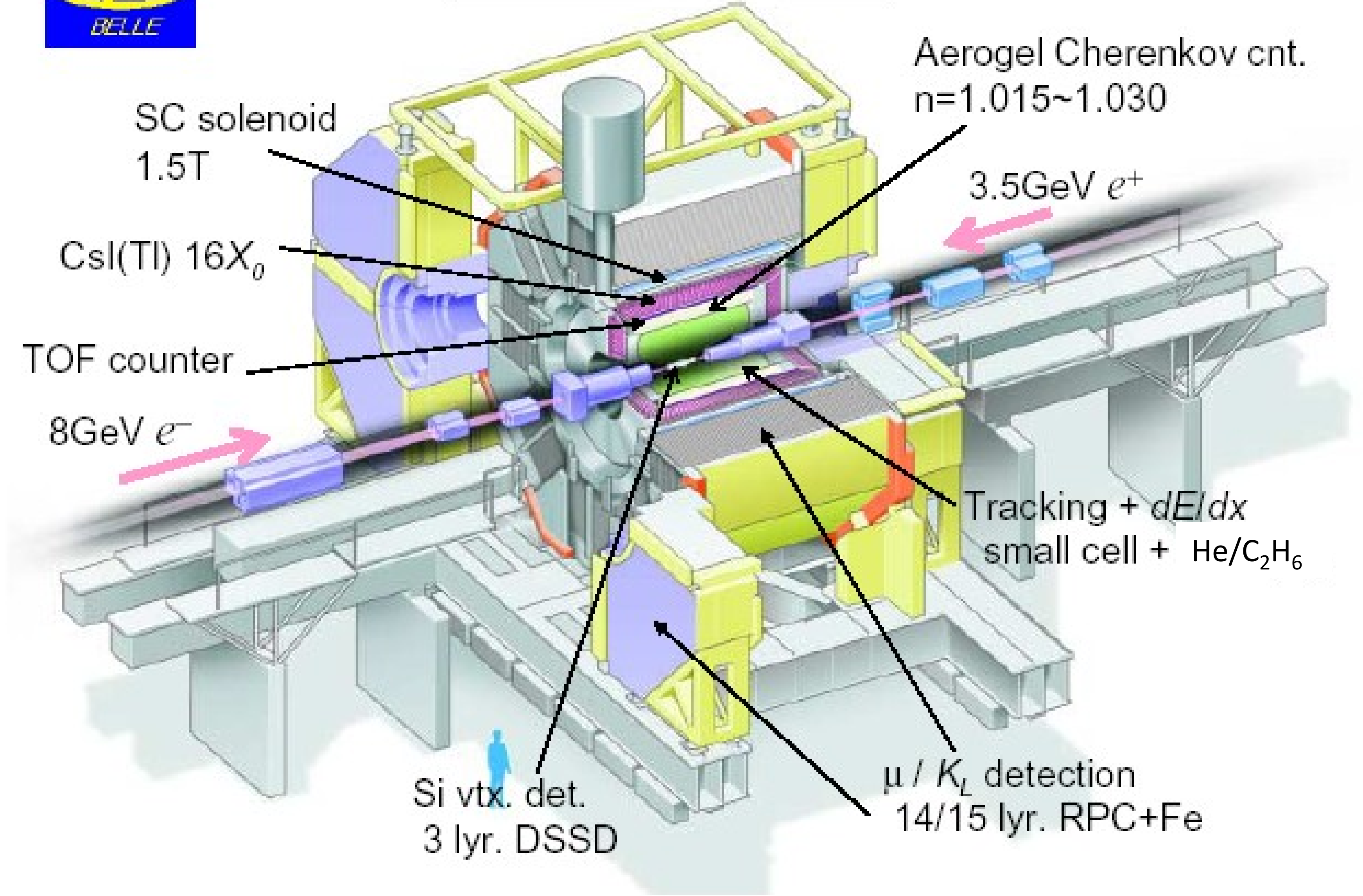
- Asymmetric collider
- 8GeV e^- + 3.5GeV e^+
- $\sqrt{s}$ = 10.58GeV ($\Upsilon(4S)$)
- $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\ \bar{B}$
- Off-resonance production: 10.52 GeV
- $e^+e^- \rightarrow q\ \bar{q}$ (u,d,s,c)
- Integrated Luminosity: > 1000 fb^{-1}
- >70 fb^{-1} => continuum







Belle Detector



Large acceptance, good tracking and particle identification!

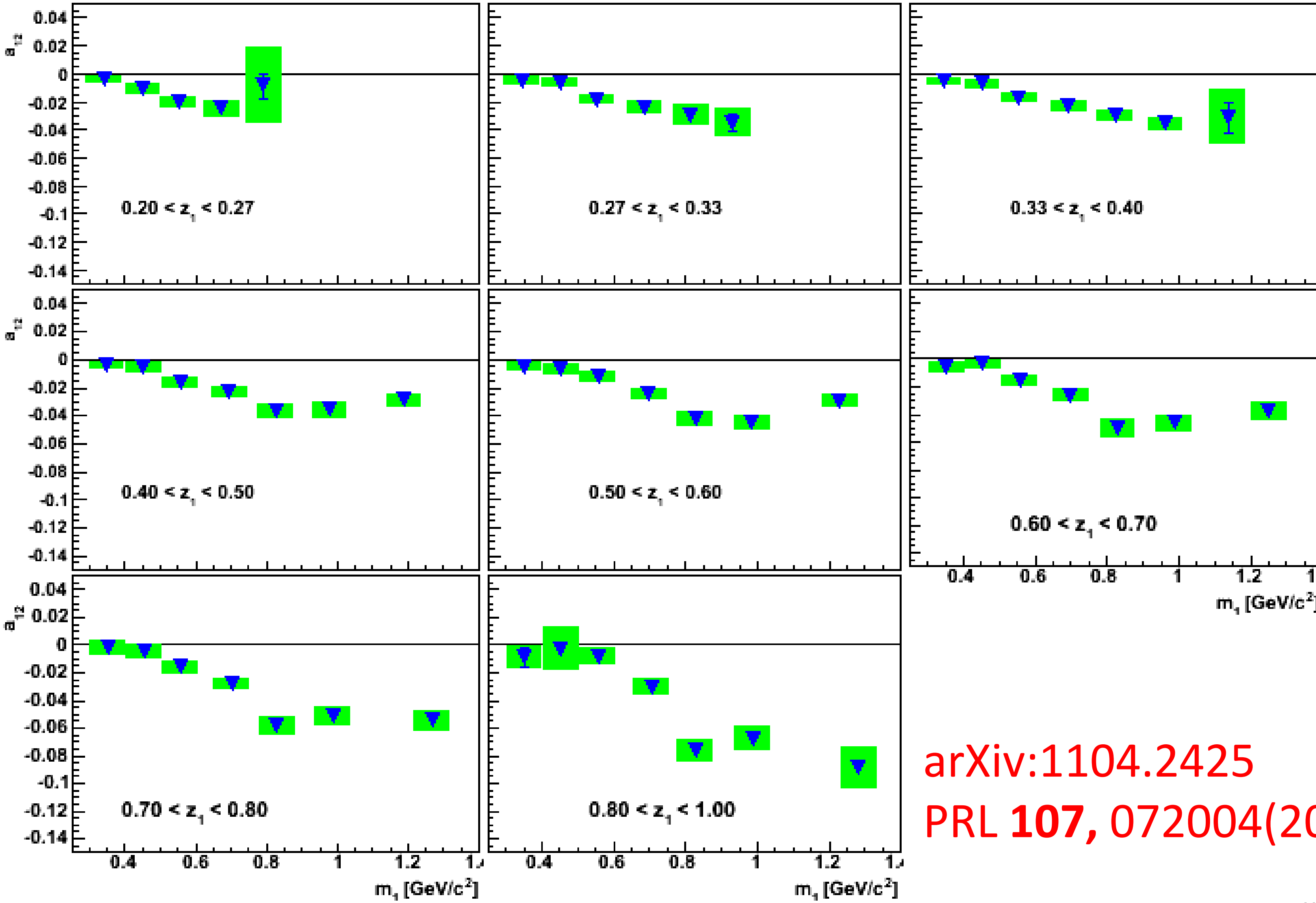
Cuts and Binning

- Similar to Collins analysis, full off-resonance and on-resonance data (7-55): ~73 fb^{-1} + 588 fb^{-1}
- Visible energy >7GeV
- PID: Purities in for di-pion pairs > 90%
- Same Hemisphere cut within pair ($\pi^+\pi^-$), opposite hemisphere between pairs
- All 4 hadrons in barrel region: -0.6 < cos (θ) <0.9
- Thrust axis in central area: cosine of thrust axis around beam <0.75
- Thrust > 0.8 to remove B-events → < 1% B events in sample
- $z_{had1,had2}$>0.1
- $z_1 = z_{had1}+z_{had2}$ and z_2 in 9x9 bins
- $m_{\pi\pi 1}$ and $m_{\pi\pi 2}$ in 8x8 bins: [0.25 - 2.0] GeV
- New: Mixed binning

Systematic Errors

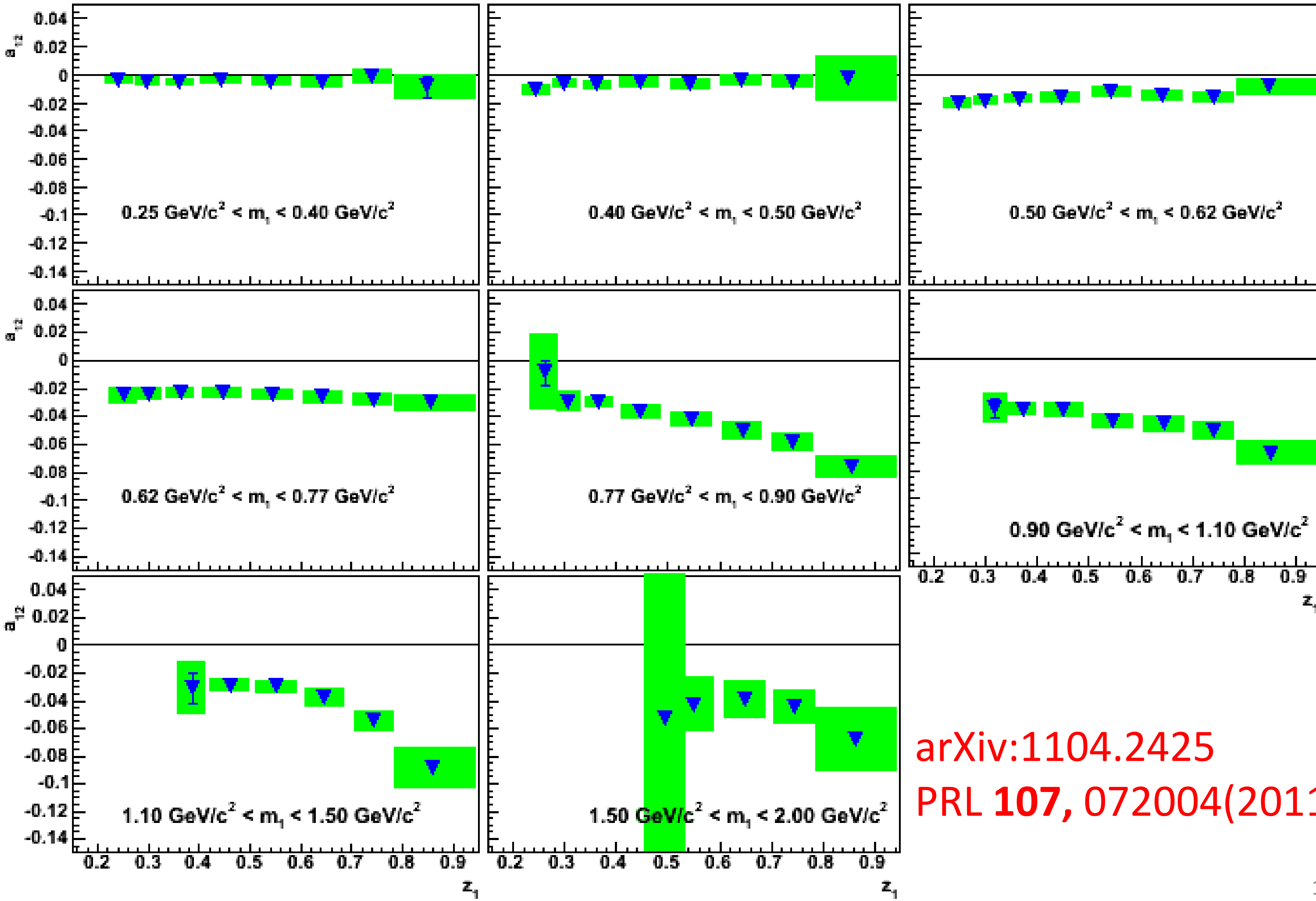
- Dominant:
  - MC asymmetry + its statistical error (up to % level)
- Smaller contributions:
  - PID: per mille level
  - higher moments: sub per mille level
  - axis smearing
  - mixed asymmetries: per mille level

(z_1x m_1) Binning



arXiv:1104.2425
PRL **107,** 072004(2011)

(m_1x z_1) Binning



arXiv:1104.2425
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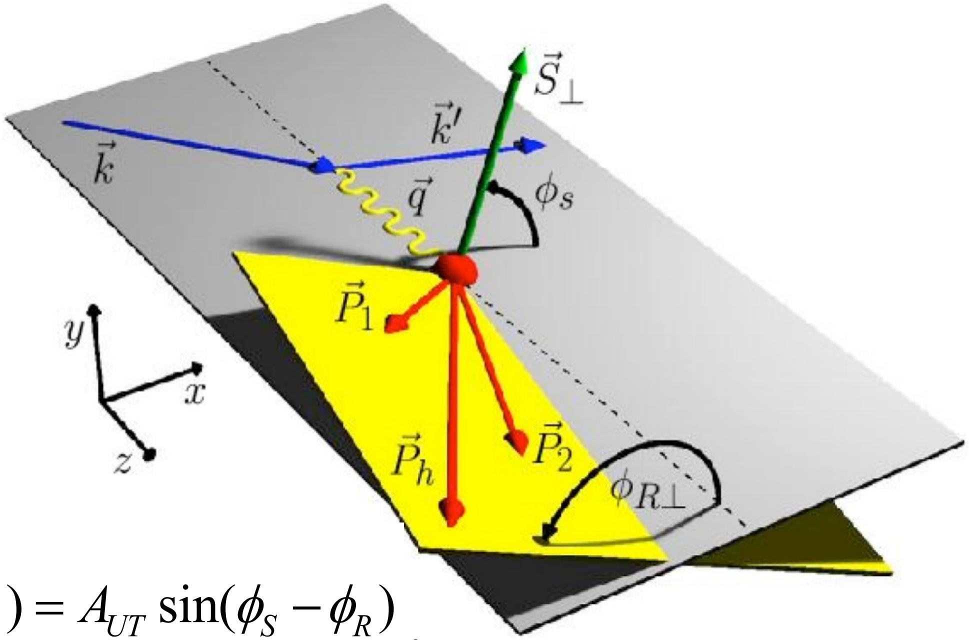
Di-Hadron Correlations in DIS



$$\frac{\sigma^{\uparrow}-\sigma^{\downarrow}}{\sigma^{\uparrow}+\sigma^{\downarrow}}(\phi_S-\phi_R)=A_{UT}\sin(\phi_S-\phi_R)$$

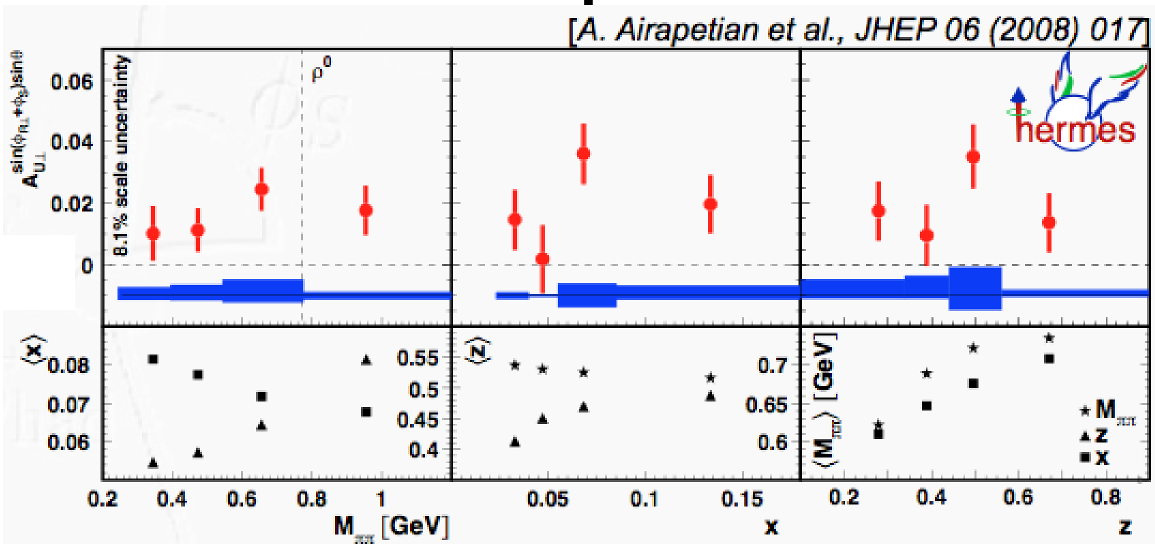
$$A_{UT}\propto h_1\otimes H_1^{<}$$

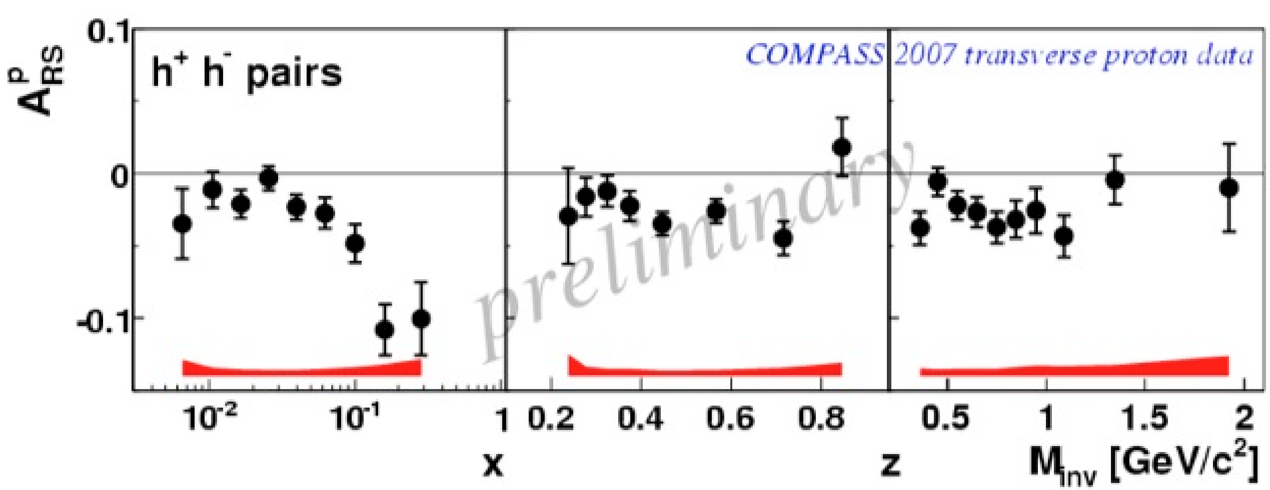
Armine Rostomyan, Tue 10:15,

Christopher Braun, Tue 11:35, 9:40,

Plans at Jlab @ 12GeV: Volker Burkert Fr. 11:05

Hermes and Compass results on the proton

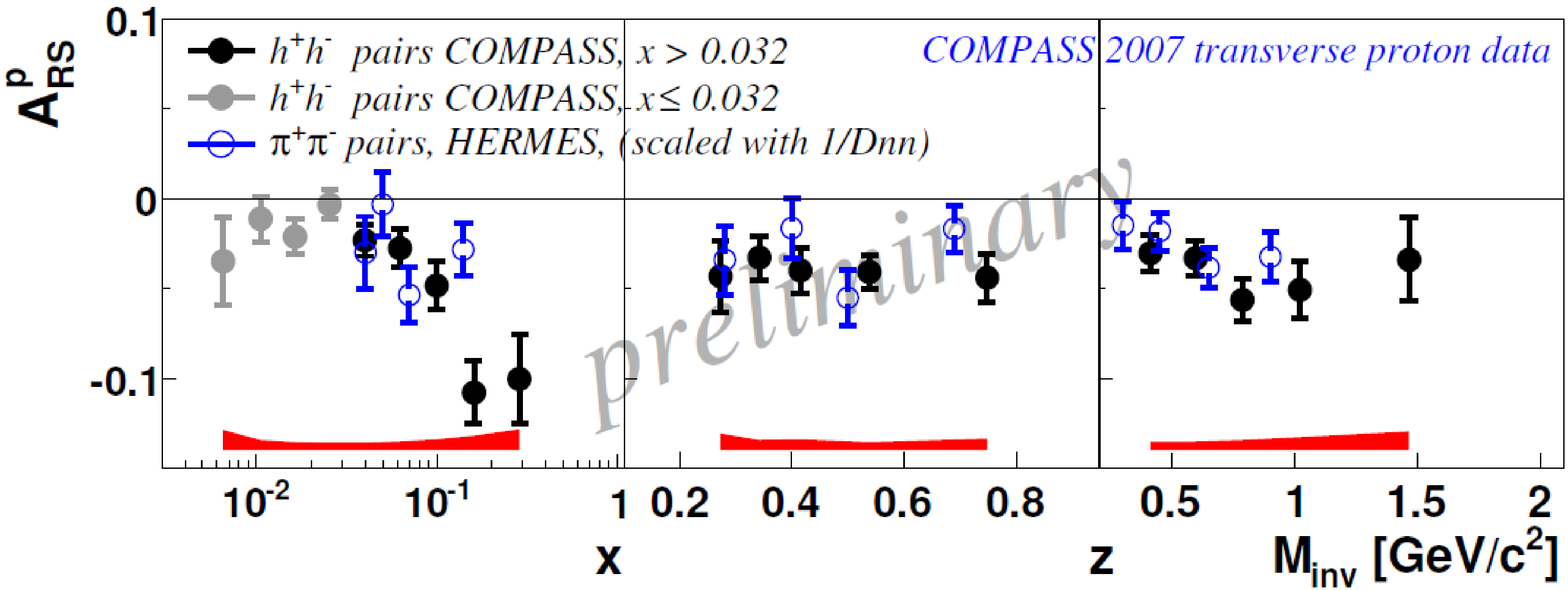




... look different still, but ...

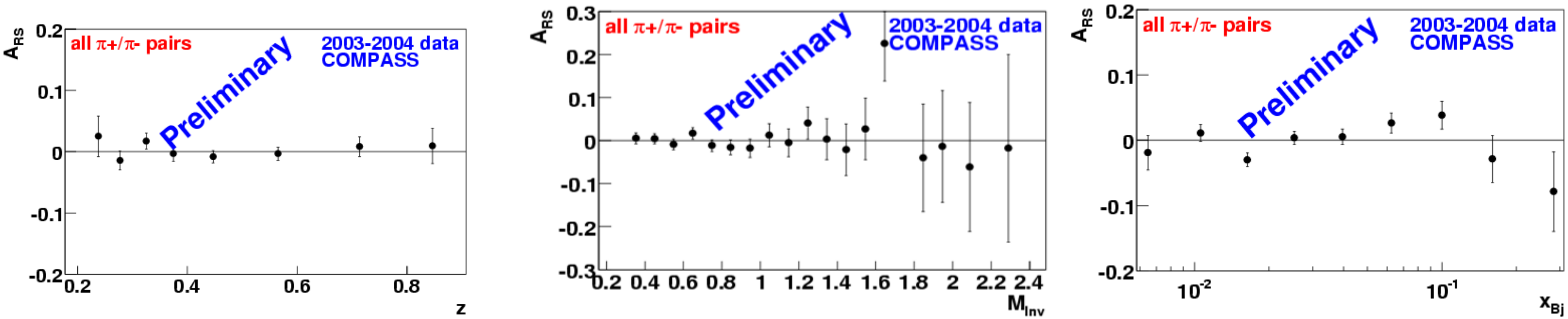
Good agreement after correction for experiments conventions

Proton



HERMES values scaled with $1/D_{nn}$

Compass measured also (very small) asymmetries from Deuterium



Direct product!
No assumption needed!

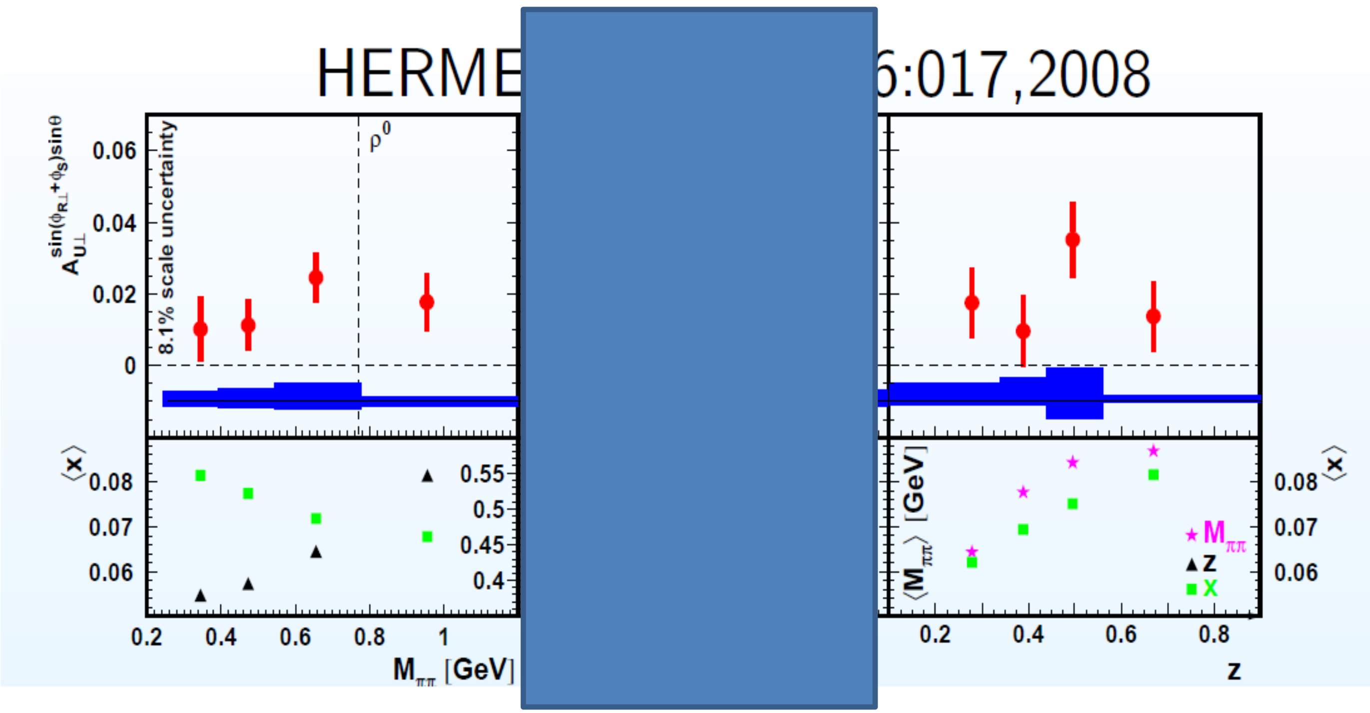
$$A_{UT} \propto h_1 \otimes H_1^{<}$$

First transversity extraction from HERMES and Belle IFF data

Alessandro Bacchetta at RHIC DY workshop May 2011:

First glimpses at transversity

Collinear Framework: Point by Point extraction possible!



Bacchetta, Radici, Courtoy, arXiv:1104.3855

- **SIDIS asymmetries A_{UT} are $\propto H^{\perp} \cdot h_1$**

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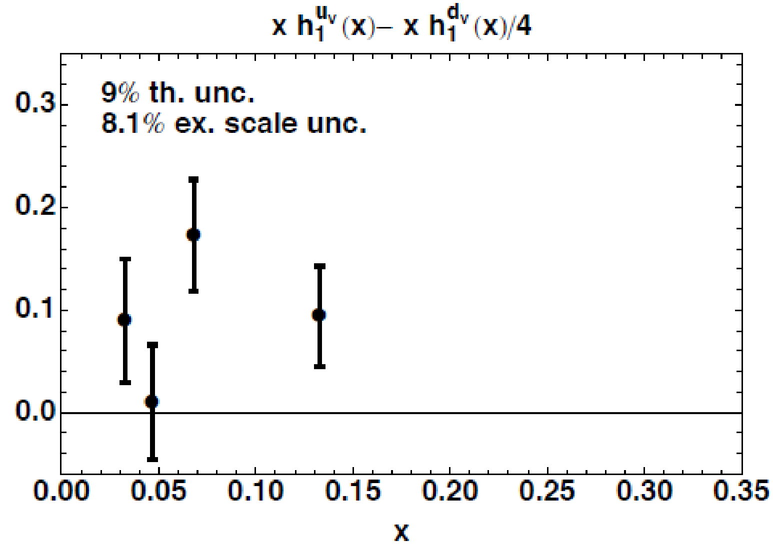

New result

Bacchetta, Radici, Courtoy, arXiv:1104.3855

- Early studies indicate little effect of evolution in Collins function,
- Preliminary data by Compass and PHENIX not used

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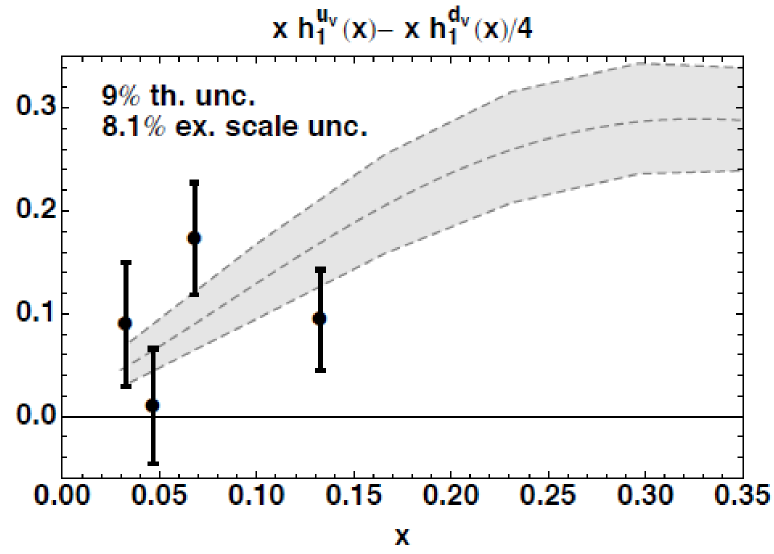
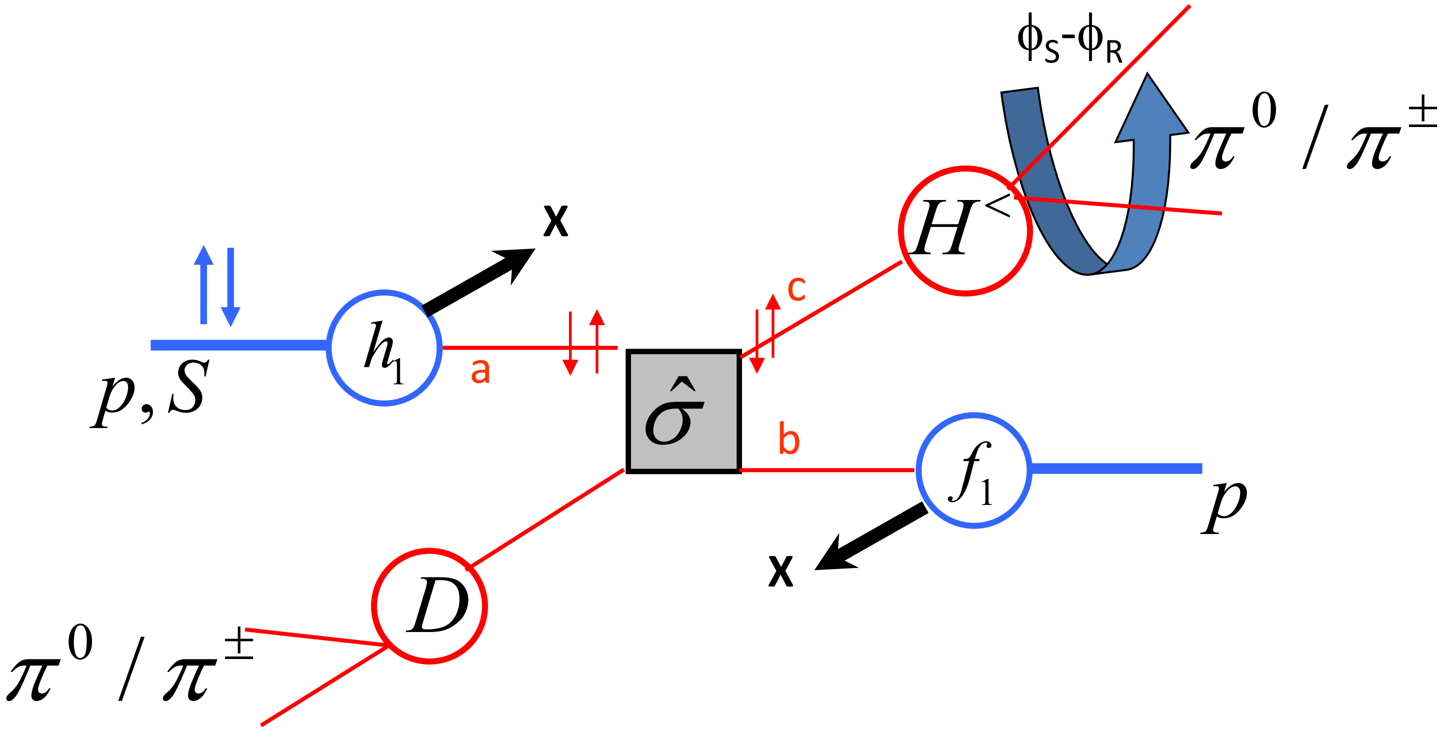


New result

Bacchetta, Radici, Courtoy, arXiv:1104.3855

- Consistent with Extraction by Anselmino et.al.

Interference Fragmentation Function in p-p

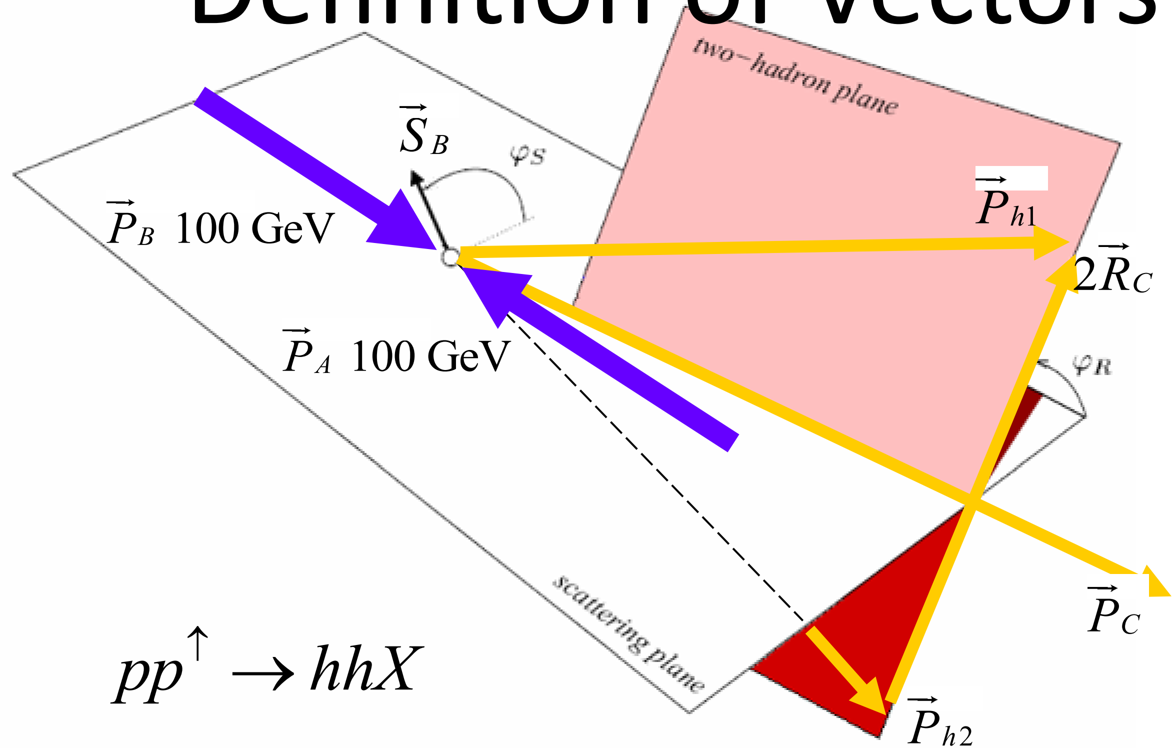


$$\frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow}(\phi_S - \phi_R) = A_{UT} \sin(\phi_S - \phi_R) \qquad A_{UT} \propto h_1 \otimes H_1^<$$

ϕ_S: Angle between polarisation vector and event plane

ϕ_R: Angle between two hadron plane and event plane

Definition of Vectors and Angles



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

hadron plane: $\vec{P}_{h1}, \vec{P}_{h2}$

scattering plane: $\vec{P}_C, \vec{P}_B$

ϕ_R : from scattering plane to hadron plane

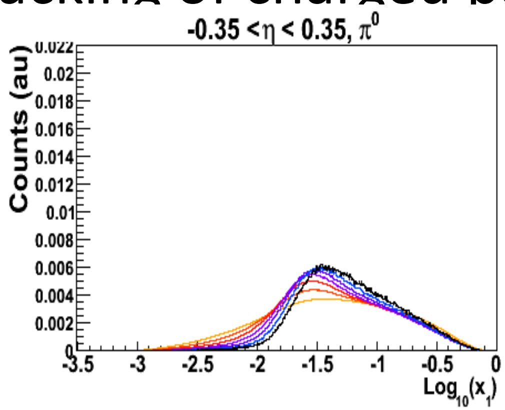
ϕ_S : from polarization vector to scattering plane

Bacchetta and Radici, PRD70, 094032 (2004)

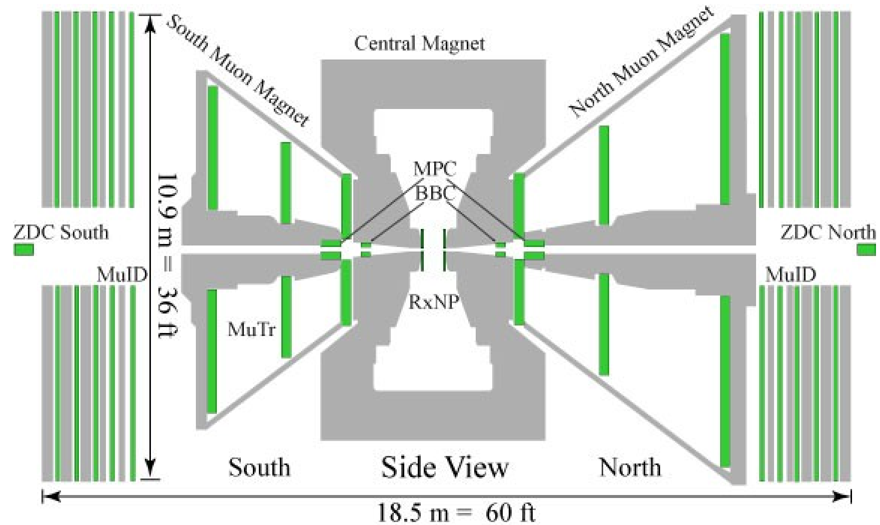
PHENIX Detectors used for IFF Analysis

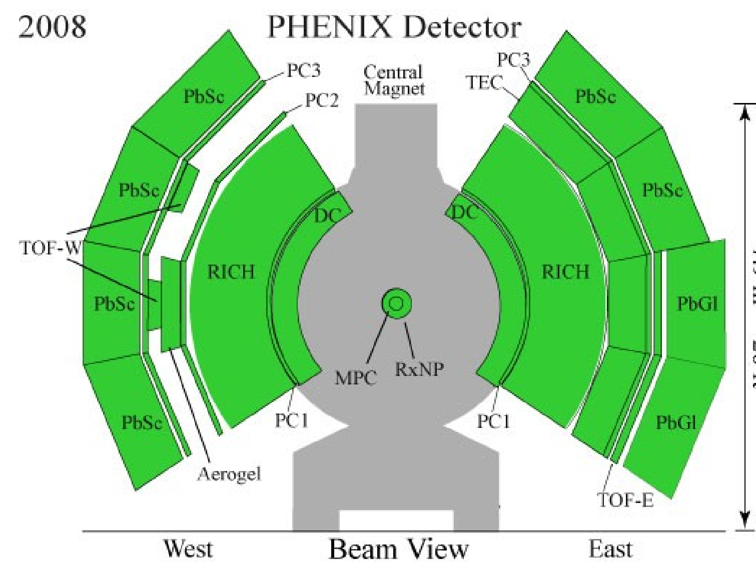
- @RHIC, 200 GeV p+p
- Use 2 separate spectrometer arms at central rapidity, $|\eta| < 0.35$
- Azimuthal coverage: 90° + 90°
- Electromagnetic Calorimeters
  - PbSC + PbGl
  - High granularity $\Delta\eta\times\Delta\phi=0.01\times0.01$
- Tracking of charged particles

ıbers



Little p_t dependence of x at mid rapidity, low x

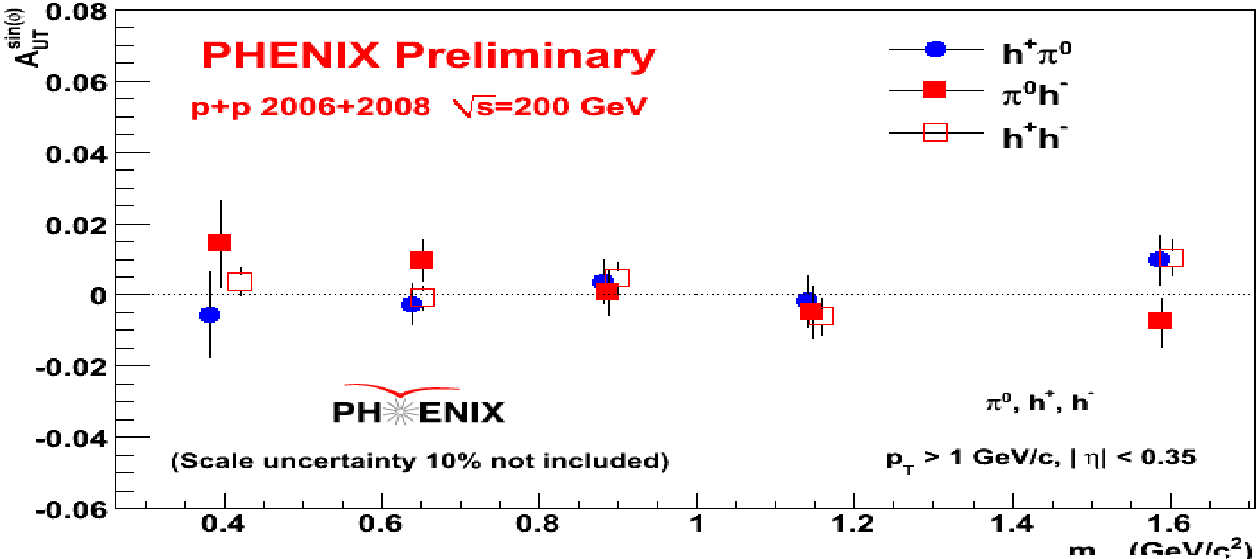




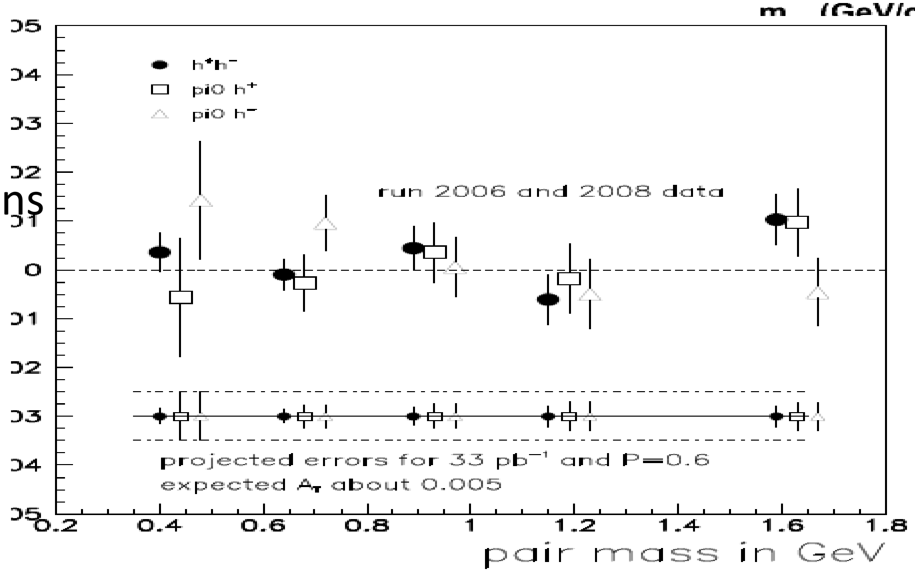
Results: John Koster, Wed. 9:40

$A_{UT}^{\sin\phi}$ vs Invariant Mass of the Pair

First measurement of IFF in pp



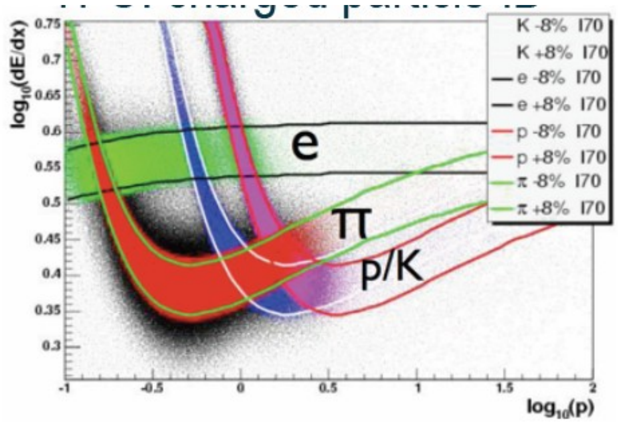
Results and Projections
From run 12+13

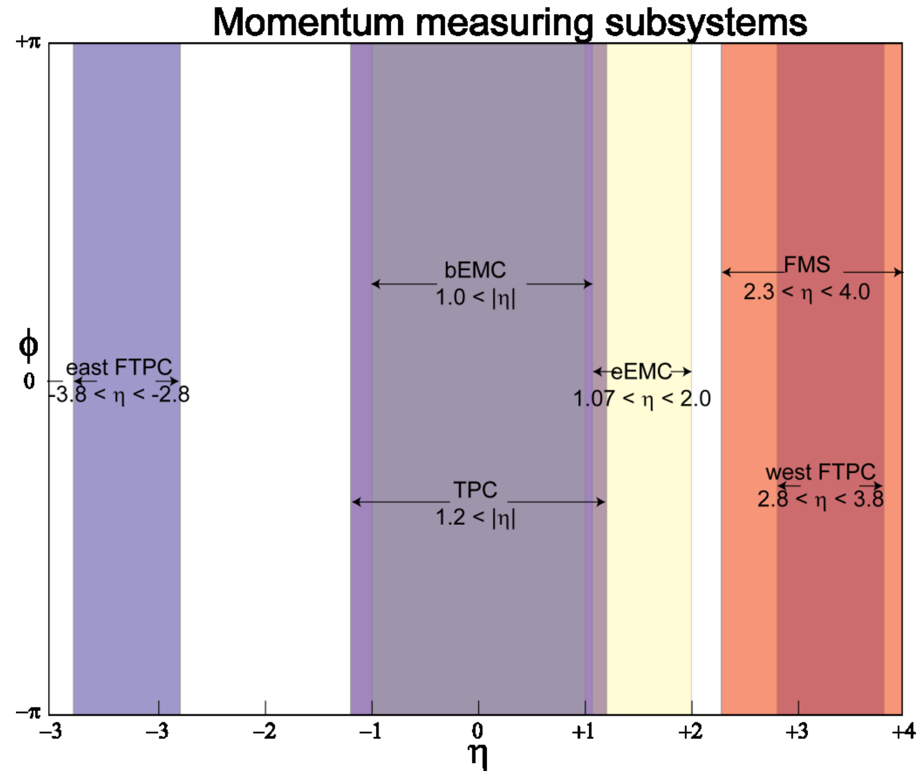


PHENIX

Di-Hadron correlations measurements at STAR

- **Di-Hadron correlations measurements with current detector**
  - Need different charged hadrons
  - π^0 in Barrel and Endcap, π^+ /π^- inTPC



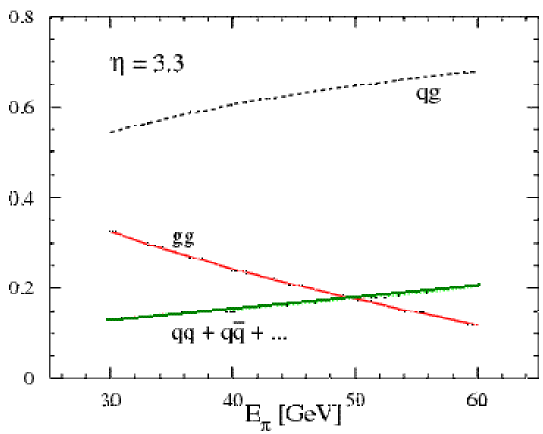


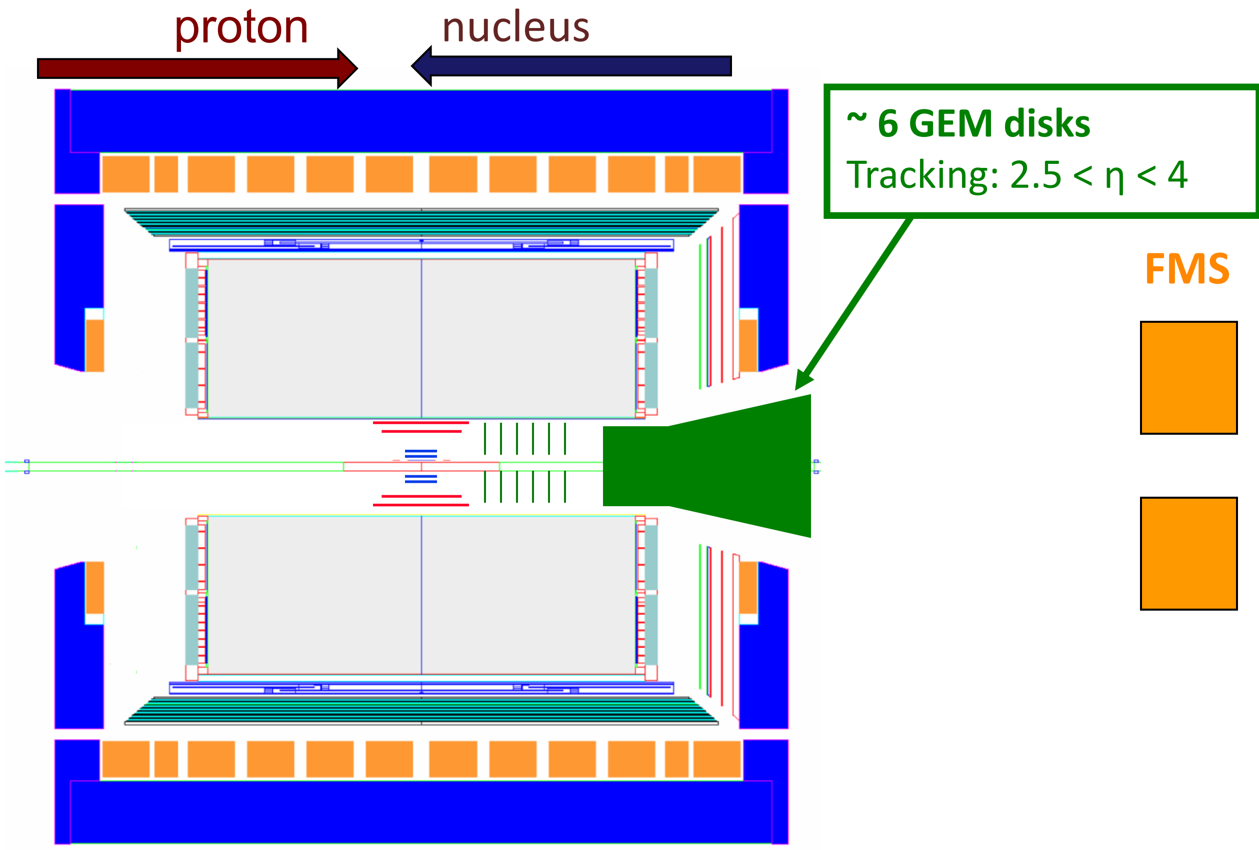
Full azimuth spanned with nearly contiguous electromagnetic calorimetry from -1<η<4

⇒ approaching full acceptance detector

PID (Barrel) with dE/dx, in the future: ToF pi/K separation up to 1.9 GeV

One Scenario for a STAR forward upgrade





- Transverse spin effect dominated by valence quarks accessed in forward direction

- Forward instrumentation optimized for **p+A** and **transverse spin** physics
  - Charged Tracking upgrade covering FMS will enable di-hadron measurements and jet measurements
  - Star decadal plans calls additionally for PID (e.g. RICH) and pi0/gamma separation (preshower)

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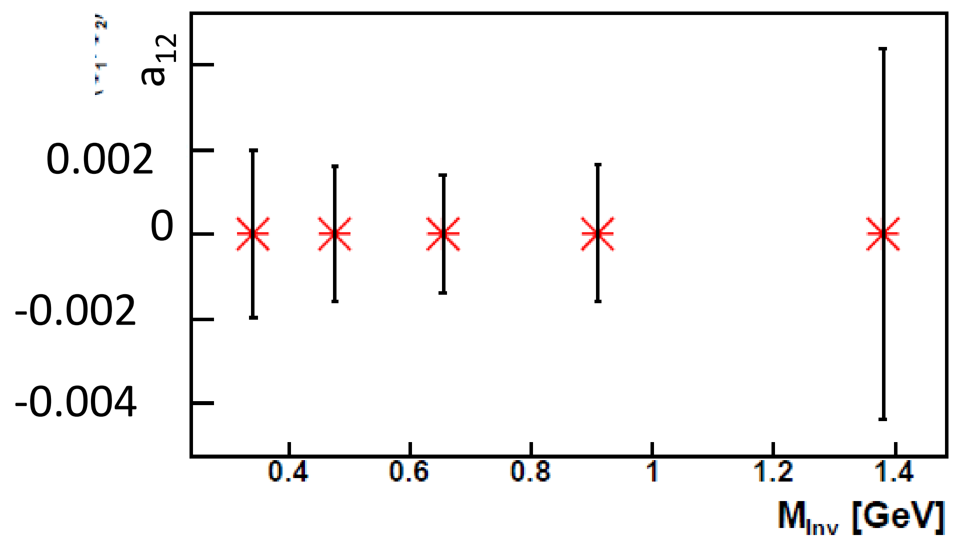
Projections for Belle Measurements of IFF Channel: $(\pi^+\pi^0)$ $(\pi^+\pi^0)$ relevant for p+p

- Errors one order of magnitude smaller than average asymmetry in $(\pi^+\pi^-)$

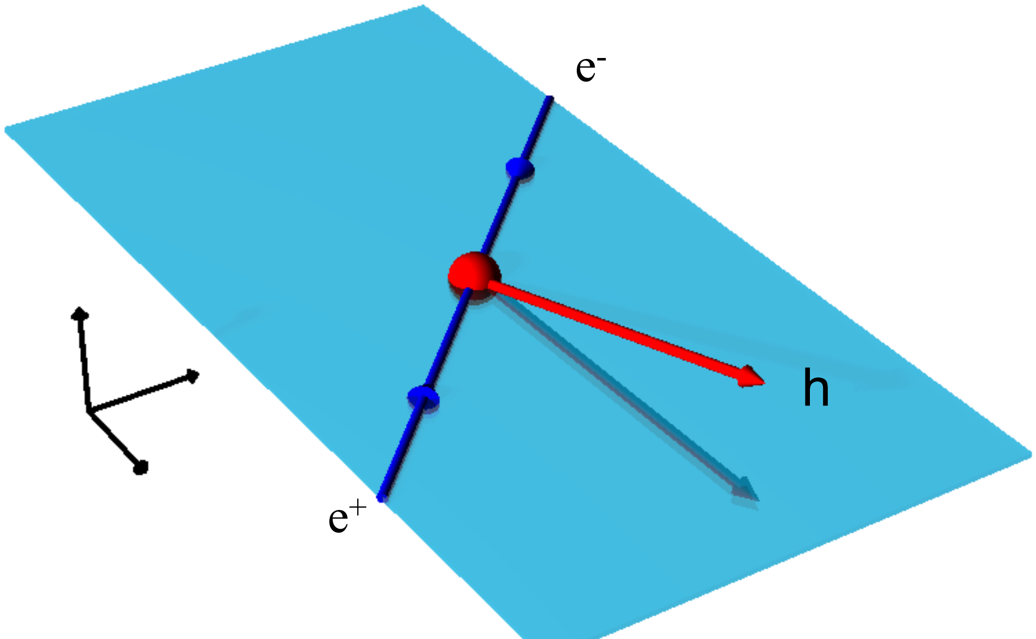
Hadron pair in second hemisphere:
0.77 GeV $< M_{inv} <$ 1.2 GeV



(580 fb^{-1} integrated luminosity)

Unpolarized Fragmentation functions

- Process:
  $e^+ e^- \rightarrow hX$
- At leading order sum of unpolarized fragmentation functions from quark and anti-quark side



$$z = \frac{2E_h}{\sqrt{s}}, \quad \sqrt{s} = 10.52\ GeV$$

LO $$F^h(z,s)=\frac{\sum_q e_q^2[D_q^h(z)+D_q^h(z)]}{\sum_q e_q^2}$$

NLO $$F^h(z,s)=\sum_i \int_z^1 \frac{dz'}{z'} C_i(s;z'\alpha_s) D_q^h(z)$$

Unpolarized Fragmentation Functions at BELLE

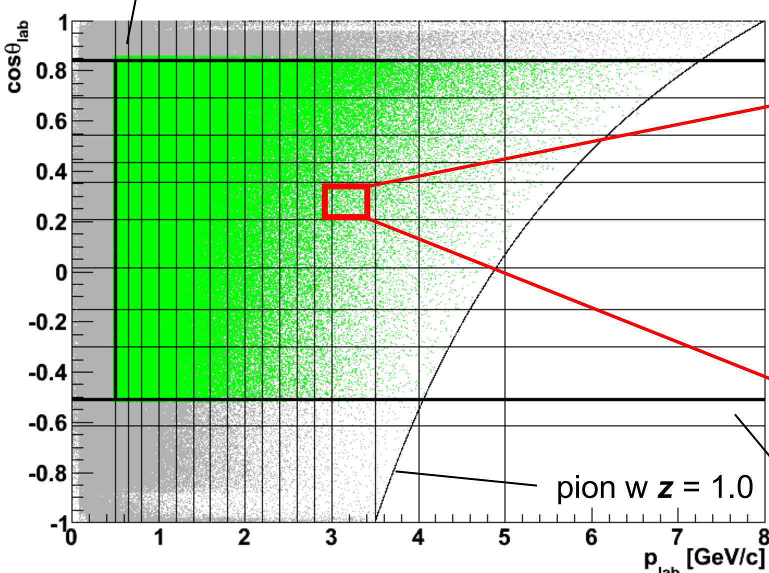
- Precision Measurement of unpolarized FFs important for almost all extractions of PDFs
- But this is a hard measurement, at Belle
  - Extensive systematic studies for PID effects: calibration & deconvolution/ correction
  - further corrections for momentum smearing, acceptance effects, ….

PID correction:

$$\vec{\tilde{N}}_j = \hat{P}\,\vec{N}_i \;\Rightarrow\; \vec{N}_i = \hat{P}^{-1}\,\vec{\tilde{N}}_j :$$

PID correction by inversion of PID probability matrix.

p_{lab} > 0.5 GeV/c



ToF forward geometry acceptance limit

ToF backward geometry acceptance limit

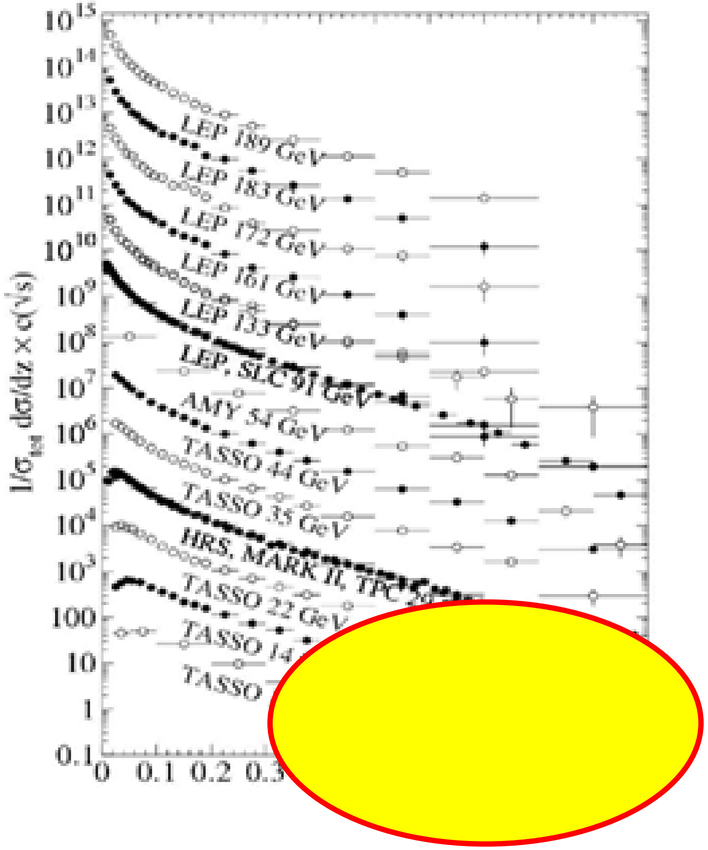
scatter plot: e, μ, π, K and p tracks from 4e+05 events

filling matrix of PID probabilities for each single bin from real data calibration

$$[P]_{ij\,(p_{lab},\,\cos\theta_{lab})} = \begin{pmatrix} p_{(e\to\tilde{e})} & p_{(\mu\to\tilde{e})} & p_{(\pi\to\tilde{e})} & p_{(K\to\tilde{e})} & p_{(p\to\tilde{e})} \\ p_{(e\to\tilde{\mu})} & p_{(\mu\to\tilde{\mu})} & p_{(\pi\to\tilde{\mu})} & p_{(K\to\tilde{\mu})} & p_{(p\to\tilde{\mu})} \\ p_{(e\to\tilde{\pi})} & p_{(\mu\to\tilde{\pi})} & p_{(\pi\to\tilde{\pi})} & p_{(K\to\tilde{\pi})} & p_{(p\to\tilde{\pi})} \\ p_{(e\to\tilde{K})} & p_{(\mu\to\tilde{K})} & p_{(\pi\to\tilde{K})} & p_{(K\to\tilde{K})} & p_{(p\to\tilde{K})} \\ p_{(e\to\tilde{p})} & p_{(\mu\to\tilde{p})} & p_{(\pi\to\tilde{p})} & p_{(K\to\tilde{p})} & p_{(p\to\tilde{p})} \end{pmatrix}$$

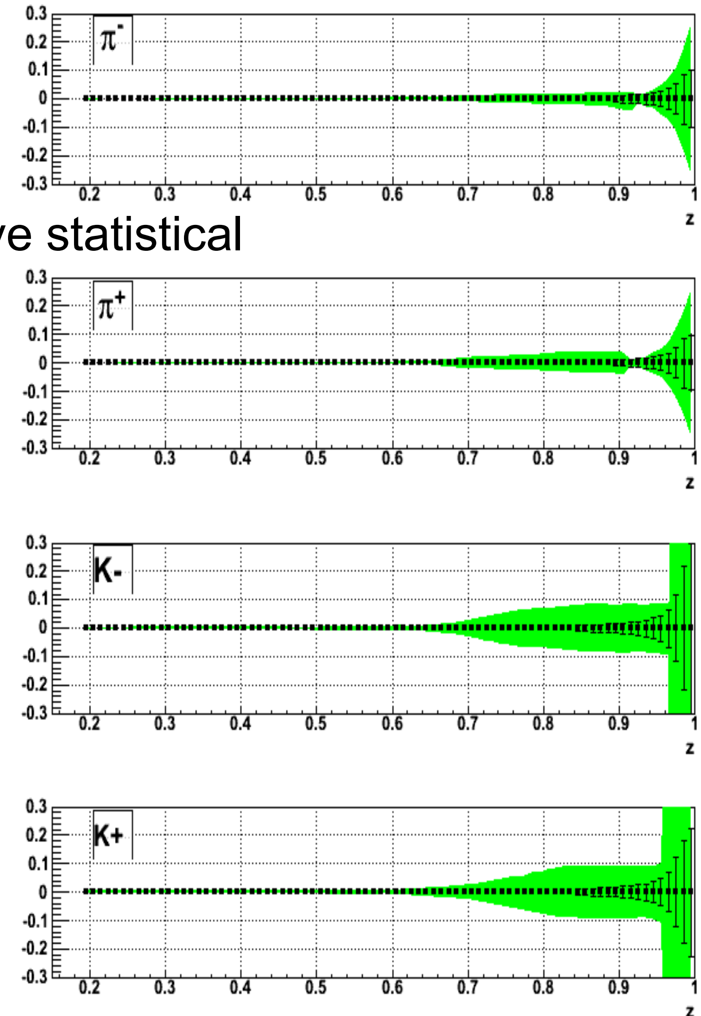
Projections: Unpolarized Fragmentation Functions-

- Measurement will give precision data set for low Q^2 and high z:



e+e- -> h+- X data

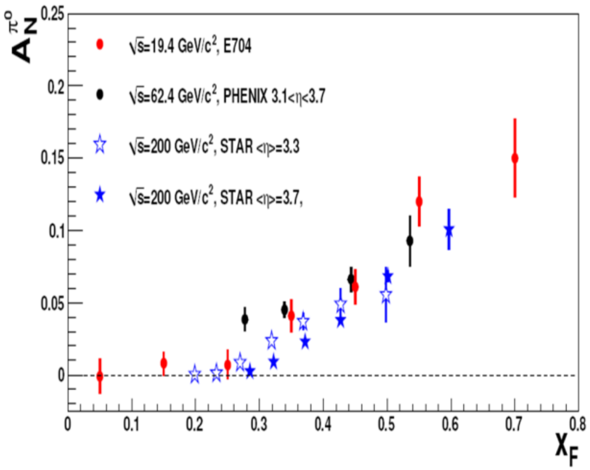
Projected relative statistical and systematic uncertainties



In the future: include k_t dependence and measure di-hadron FFs needed for transversity extraction from di-hadron correlations

Summary and Outlook

- Interference Fragmentation can be used to measure transversity in di-hadron correlations in p+p
  - First Belle and PHENIX results
  - More measurements at STAR, Belle and PHENIX planned
  - Relatively easy measurement in proton-proton collisions
  - Access high x, z necessary to extract tensor charge
- In SIDIS transversity can be accessed in an independent way and in the collinear framework
  - COMPASS and HERMES results
  - First extraction of transversity in collinear framework
- Theory Calculations for $pi^0/pi^{+/-}$ and p+p underway
- Measurement of $pi^0/pi^{+/-}$ at Belle and Phenix/STAR
- Jlab with 12 GeV upgrade plans to measure IFF
- Belle plans to measure related quantities:
  - Collins Asymmetries for vector mesons
  - Collins Asymmetries for Kaons
  - di-hadron unpolarized FF: e.g. needed for denominator
  - P-odd fragmentation functions
  - Lambda FFs
  - …
- Unpolarized Fragmentation Function Measurement at Belle near completion
- Unpolarized and Collins FF measurements at BaBar: Isabella Garzia (next talk)



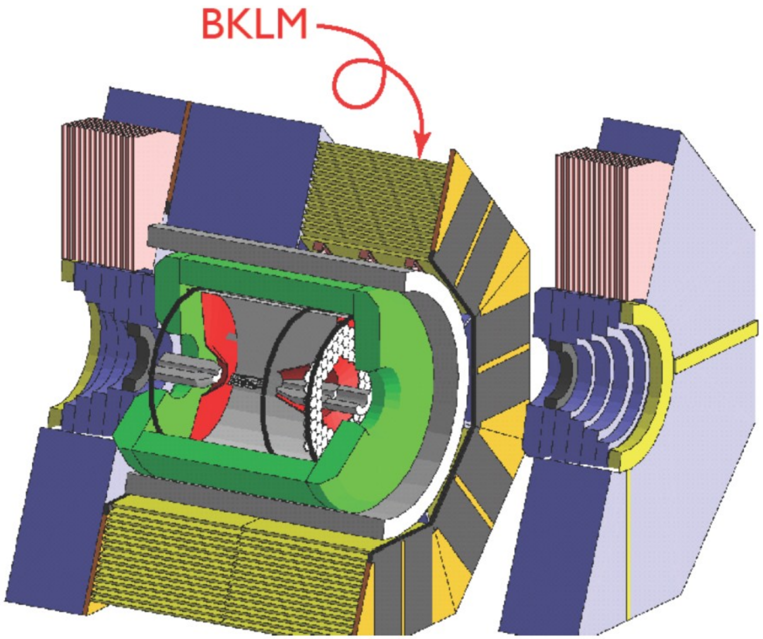
Belle Fragmentation activity

	RIKEN/RBRC	Illinois	Indiana	Titech
Unpol FFs $e^+e^- \rightarrow hX$: $e^+e^- \rightarrow (hh)X$, $(h)(h)X, hhX$: Unpol k_T dependence:	Neutral hadrons: (π^0, η^0) John Koster Charged di-hadrons: Ralf Seidl	Charged hadrons (π, K, P): Martin Leitgab Martin Leitgab		
Collins FFs $e^+e^- \rightarrow (h)(h)X$: k_T dependence:	$\pi\pi^0$: John Koster $\pi\rho^0$: Ralf Seidl $\pi\pi$: Ralf Seidl $\pi\pi^0$: John Koster	$\pi K, KK$: Francesca Giordano Francesca Giordano	$\pi\rho^{\pm}$: ?	
Interference FF: $e^+e^- \rightarrow (hh)(hh)X$	Charged $\pi\pi$: Ralf Seidl		Charged $\pi\pi$: Anselm Vossen $\pi\pi^0$: Anselm Vossen	Charged πK, KK: Nori-aki Kobayas
Local Ᵽ : Λ(polFF,SSA) : Jet-jet asy:			Anselm Vossen	

Black: about to start
Green: ongoing
Grey: finished

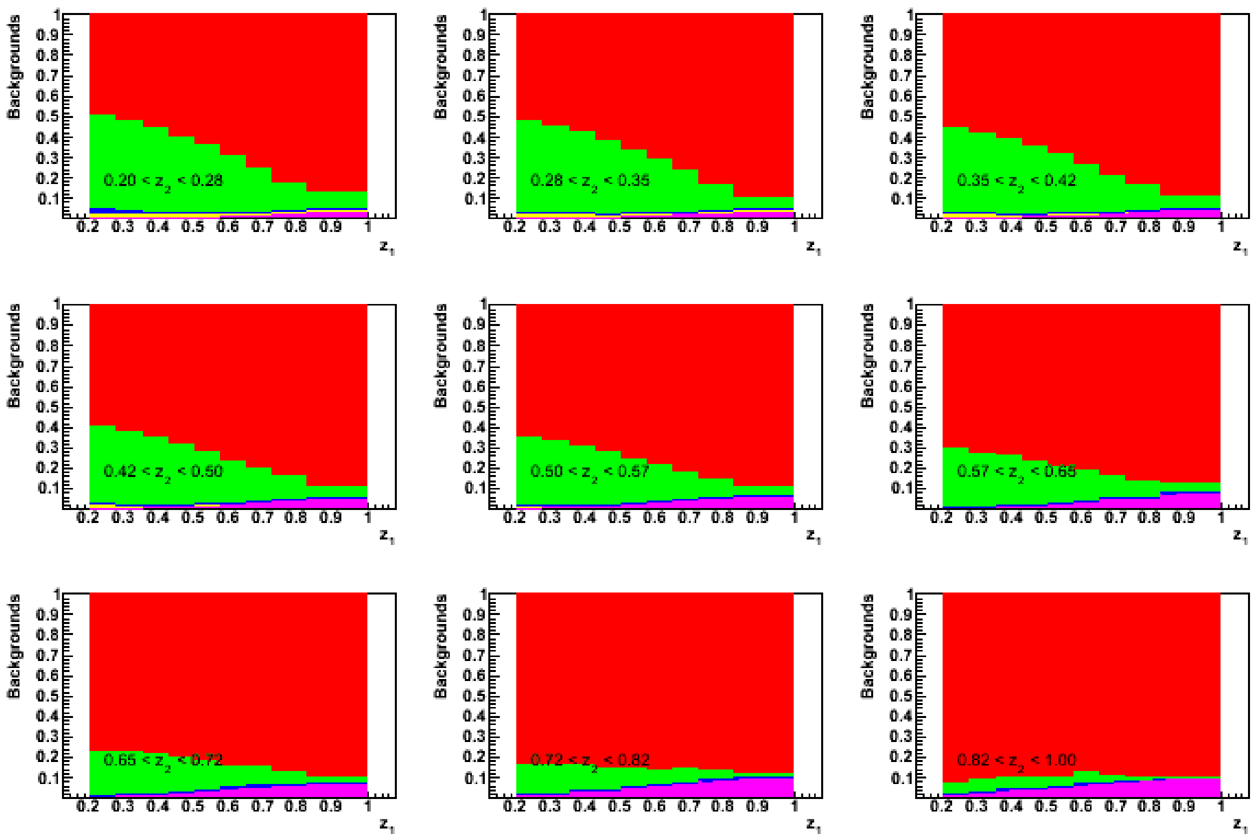
Upgrade to

- Belle II is a significant upgrade to Belle and will sample 2 orders of magnitude higher luminosity
- High precision data will enable measurement of
  - P-odd FFs
  - Transverse momentum dependent FFs
  - Charm suppression possible
- IU develops FEE for Barrel KLM detector crucial for high precision FF measurement of identified particles




THANK
YOU
THANK

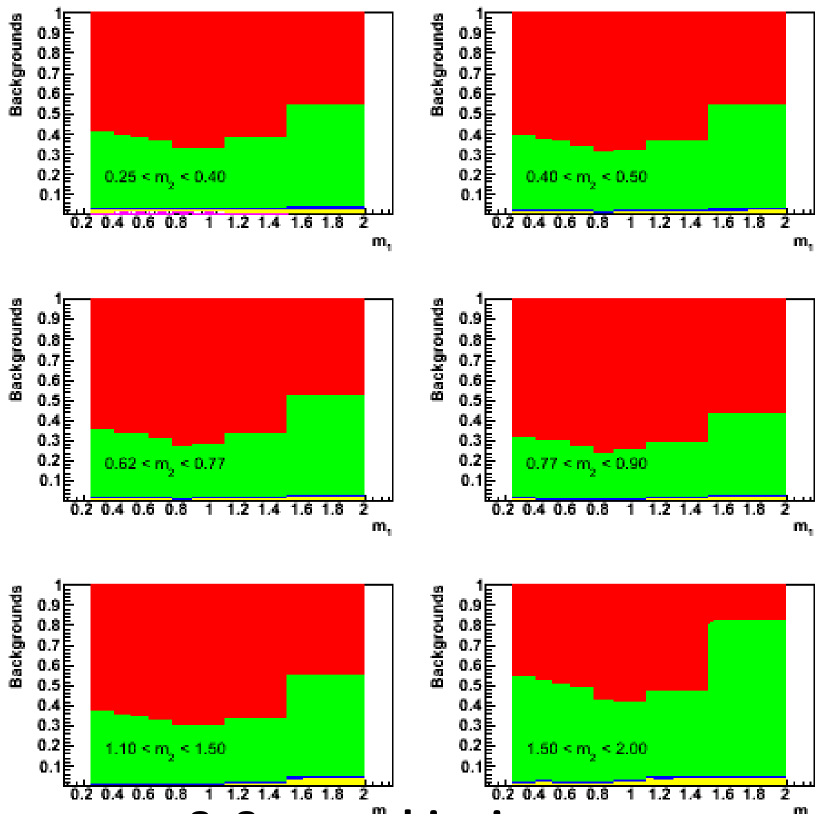
Subprocess contributions (MC)



9x9 z_1 z_2 binning

tau contribution (only significant at high z)
charged B(<5%, mostly at higher mass)
Neutral B (<2%)
charm(20-60%, mostly at lower z)
uds (main contribution)

Subprocess contributions (MC)



8x8 m_1 m_2 binning

Data not corrected for Charm contributions

charged B(<5%, mostly at higher mass)
Neutral B (<2%)
charm(20-60%, mostly at highest masses)
uds (main contribution)

Charm Asymmetries in simulated data consistent with zero!
To be checked with charm enhanced sample

Combined Analysis:
Extract Transversity Distributions

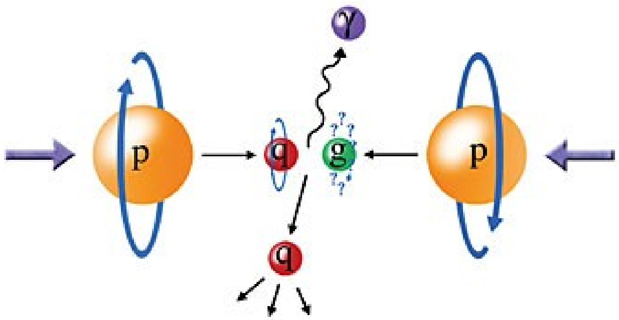
SIDIS

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

Factorization ?
+
Evolution

e^+e^-

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



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

Theory

pp → jets

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

pp → $h^+ + h^- + X$
~ $G(x_1)$ x $\delta q(x_2)$ x $IFF(z)$

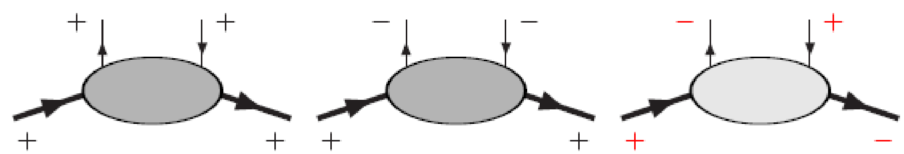
pp → $l^+ + l^- + X$
~ $\delta q(x_1)$ x $\delta q(x_2)$

Lattice QCD: Tensor Charge

Transversity properties

- Helicity flip amplitude
- Chiral odd
- Since all interactions conserve chirality one needs another chiral odd object
- Does not couple to gluons ⇨different QCD evolution than $\Delta q(x)$
- Valence dominated⇨ Comparable to Lattice calculations, especially tensor charge

$$q(x) = q_+(x) + q_-(x) \sim Im(\mathcal{A}_{++,++} + \mathcal{A}_{+-,+-})$$
$$\Delta q(x) = q_+(x) - q_-(x) \sim Im(\mathcal{A}_{++,++} - \mathcal{A}_{+-,+-})$$
$$\delta q(x) = q_\uparrow(x) - q_\downarrow(x) \sim Im\mathcal{A}_{+-,-+}$$



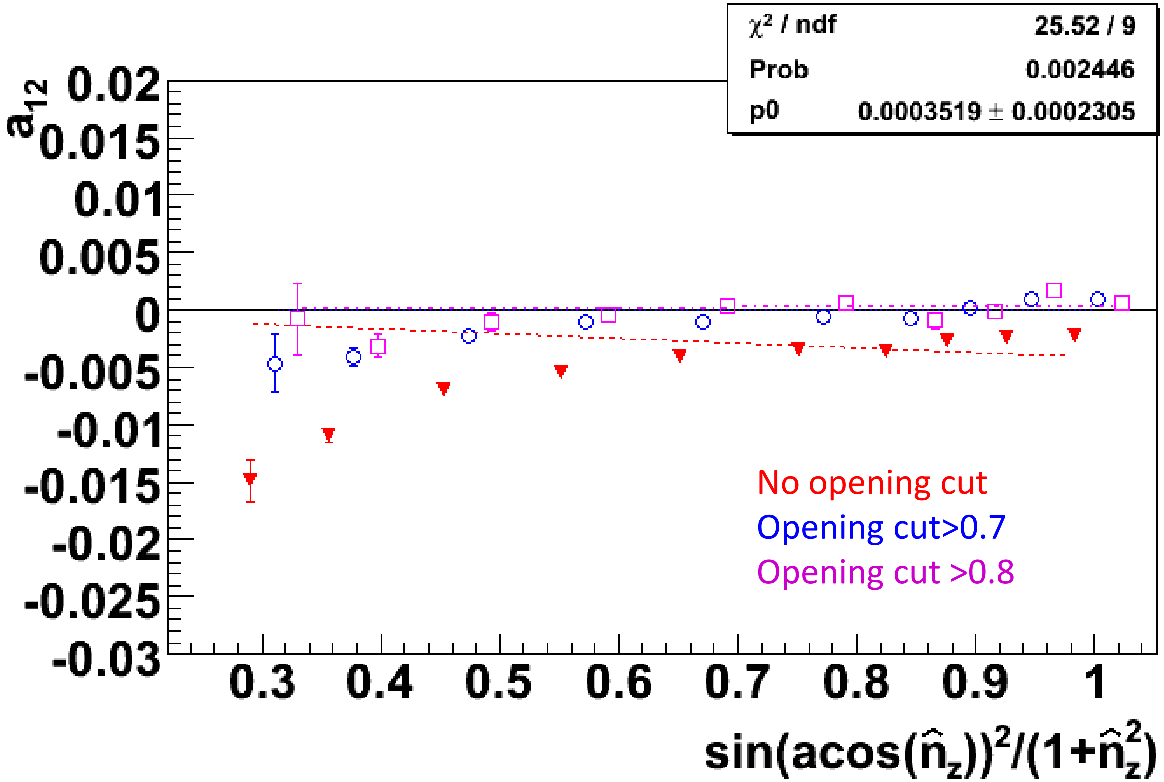
Positivity bound:

$$|\delta q(x)| \leq q(x)$$

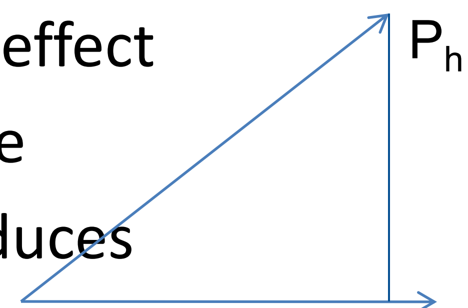
Soffer bound:

$$|\delta q(x)| \leq \tfrac{1}{2}\left(q(x) + \Delta q(x)\right)$$

Zero tests: MC

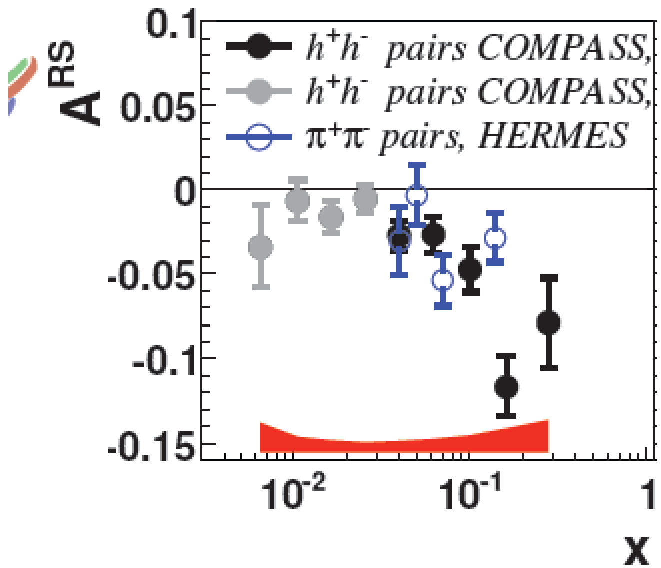


- A small asymmetry seen due to acceptance effect
- Mostly appearing at boundary of acceptance
- Opening cut in CMS of 0.8 (~37 degrees) reduces acceptance effect to the sub-per-mille level



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

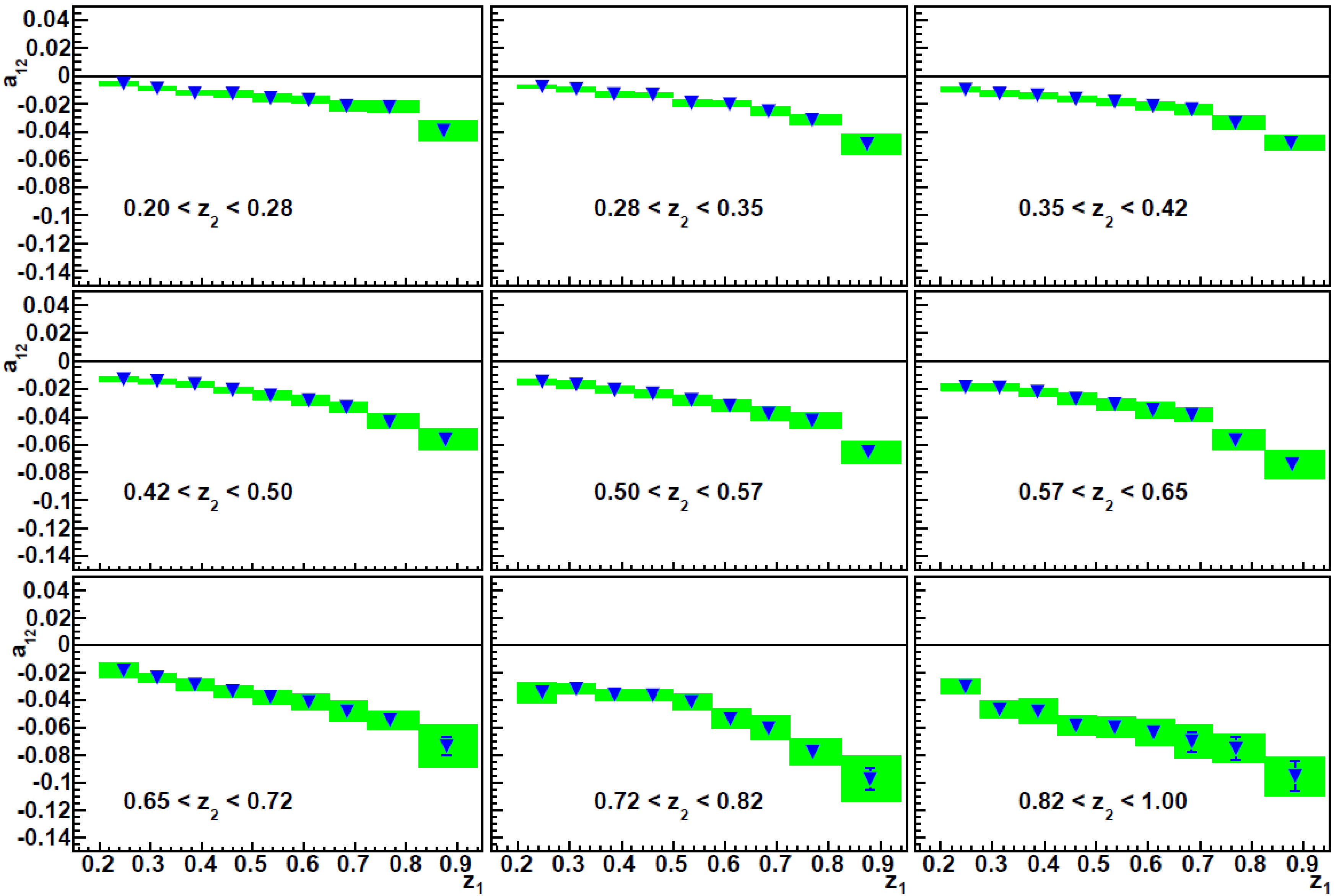
45



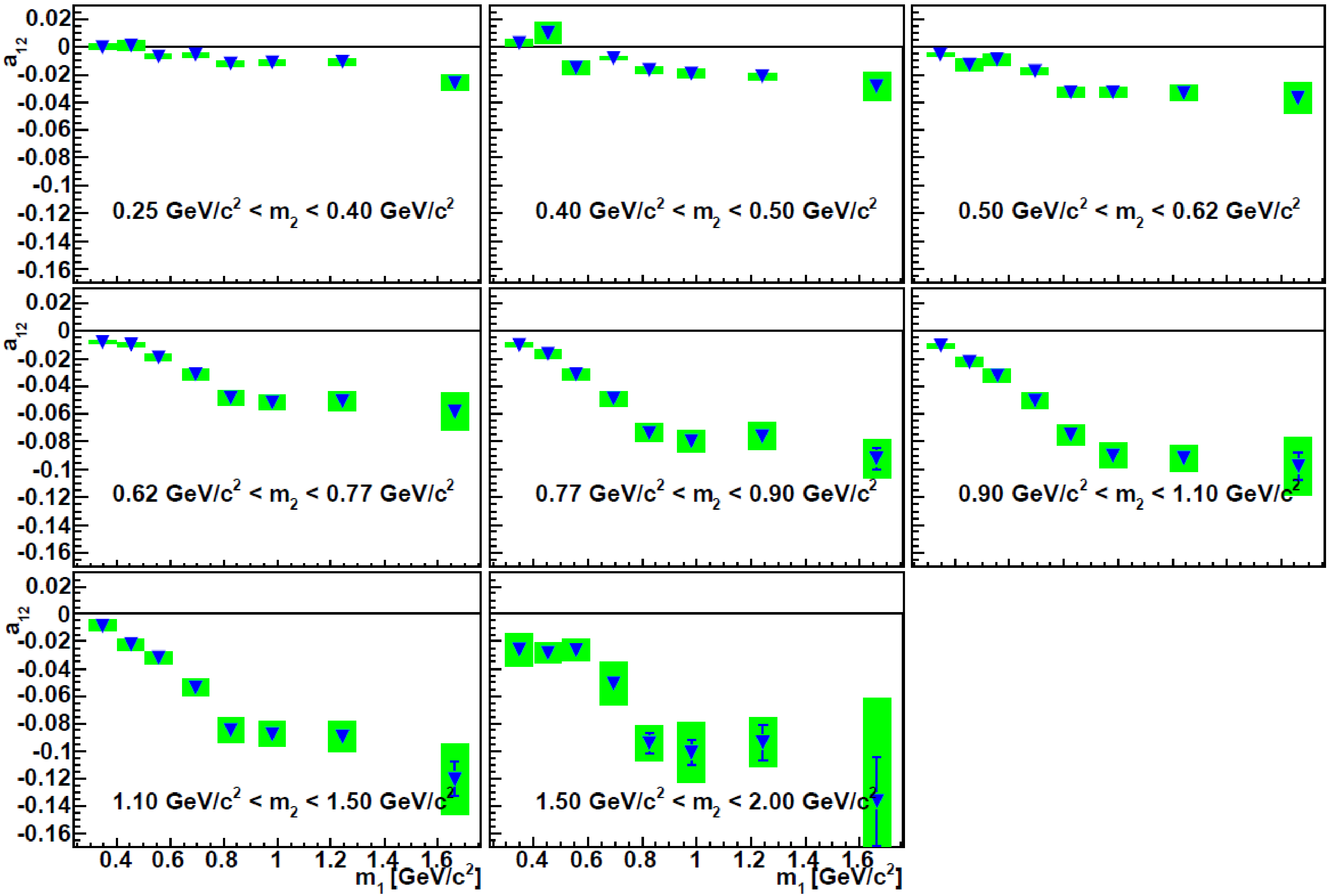
Preliminary

H. Wollny, CERN-THESIS-2010-108

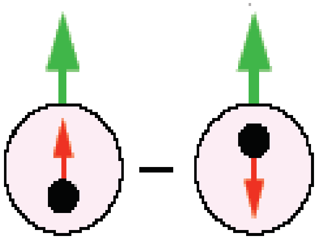
Results incl. sys. errors: (z_1x z_2) Binning



(m_1x m_2) Binning



Transversity d*q*(x)

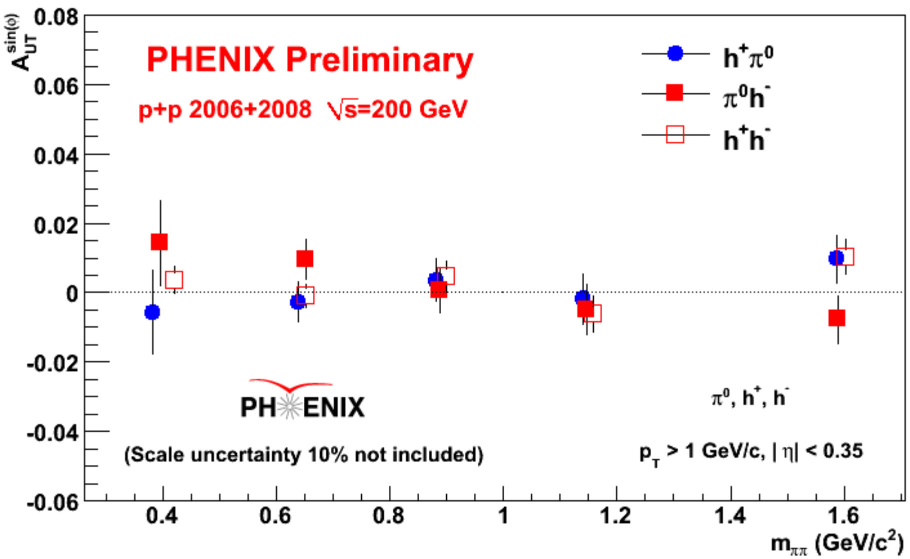


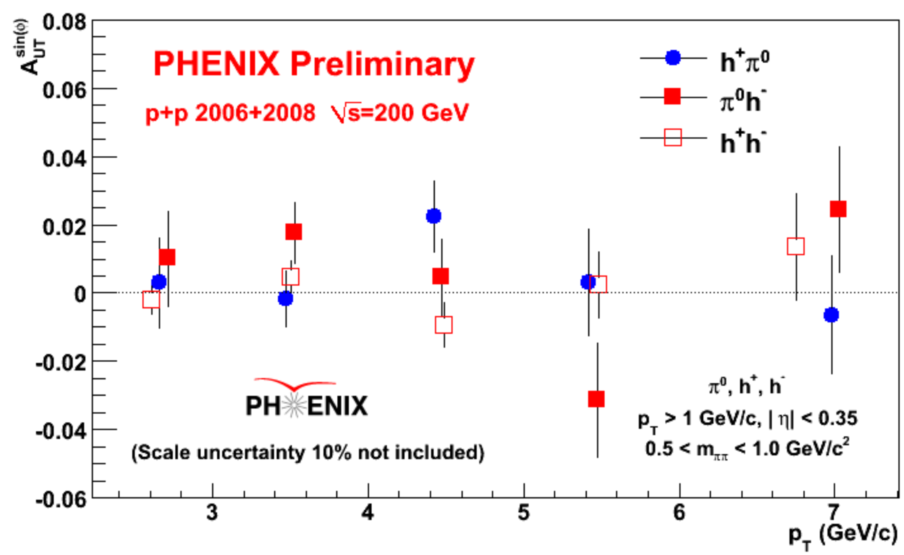
Transverse spin information at leading twist

$$A^{h_1,h_2}_{UT,\phi} = \frac{\sigma^{\uparrow}_{\phi} - \sigma^{\downarrow}_{\phi}}{\sigma^{\uparrow}_{\phi} + \sigma^{\downarrow}_{\phi}}$$

Measure d*q* X Interference Fragmentation functions

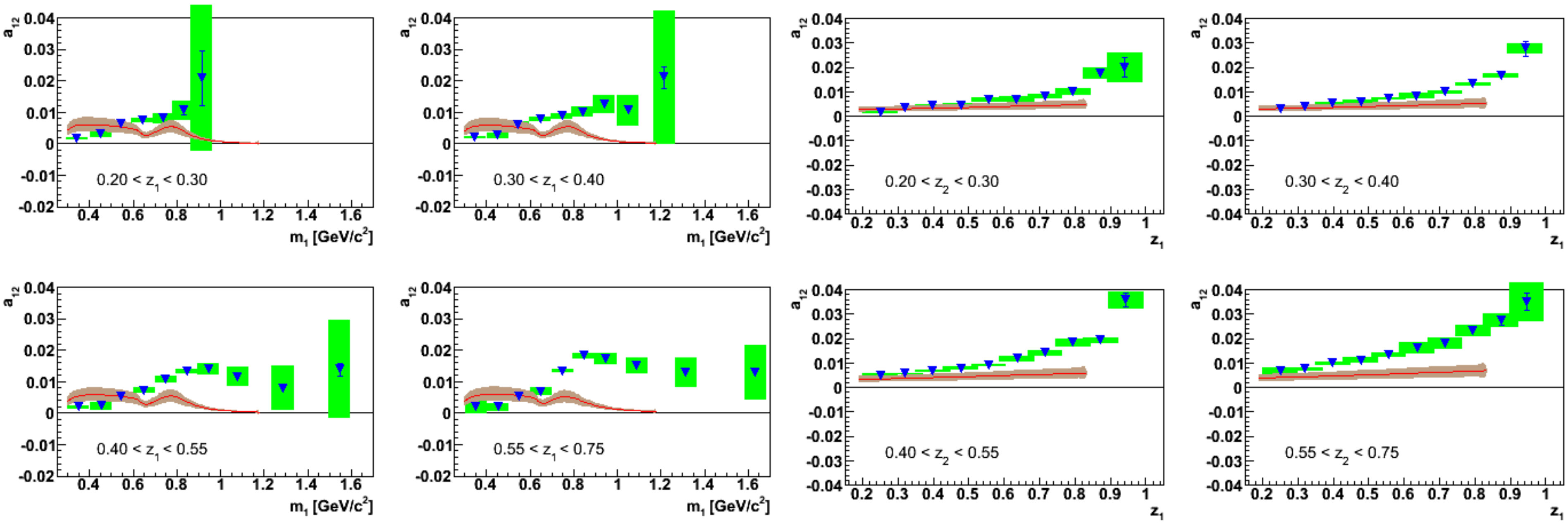
Transversity extraction will become possible with Interference Fragmentation Function - BELLE has shown first observation of IFF asymmetries





Exploring analysis with hadrons in forward region

Comparison to Theory Predictions



Initial model description by Bacchetta,Checcopieri, Mukherjee, Radici : **Phys.Rev.D79:034029,2009**.

Leading order,

Mass dependence : Magnitude at low masses comparable, high masses significantly larger (some contribution possibly from charm)

Z dependence : Rising behavior steeper

However: Theory contains parameters based on HERMES data which already fail to explain COMPASS well

Transversity from di-Hadron SSA

Physics asymmetry $A_{UT} = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} = \frac{\sigma_{UT}}{\sigma_{UU}}$

$$d\sigma_{UU} = 2\,|\mathbf{P}_{C\perp}| \sum_{a,b,c,d} \int \frac{dx_a dx_b}{4\pi^2 z_c} f_1^a(x_a)\, f_1^b(x_b) \frac{d\hat{\sigma}_{ab\to cd}}{d\hat{t}} D_{1,oo}(\bar{z}_c, M_C^2)$$

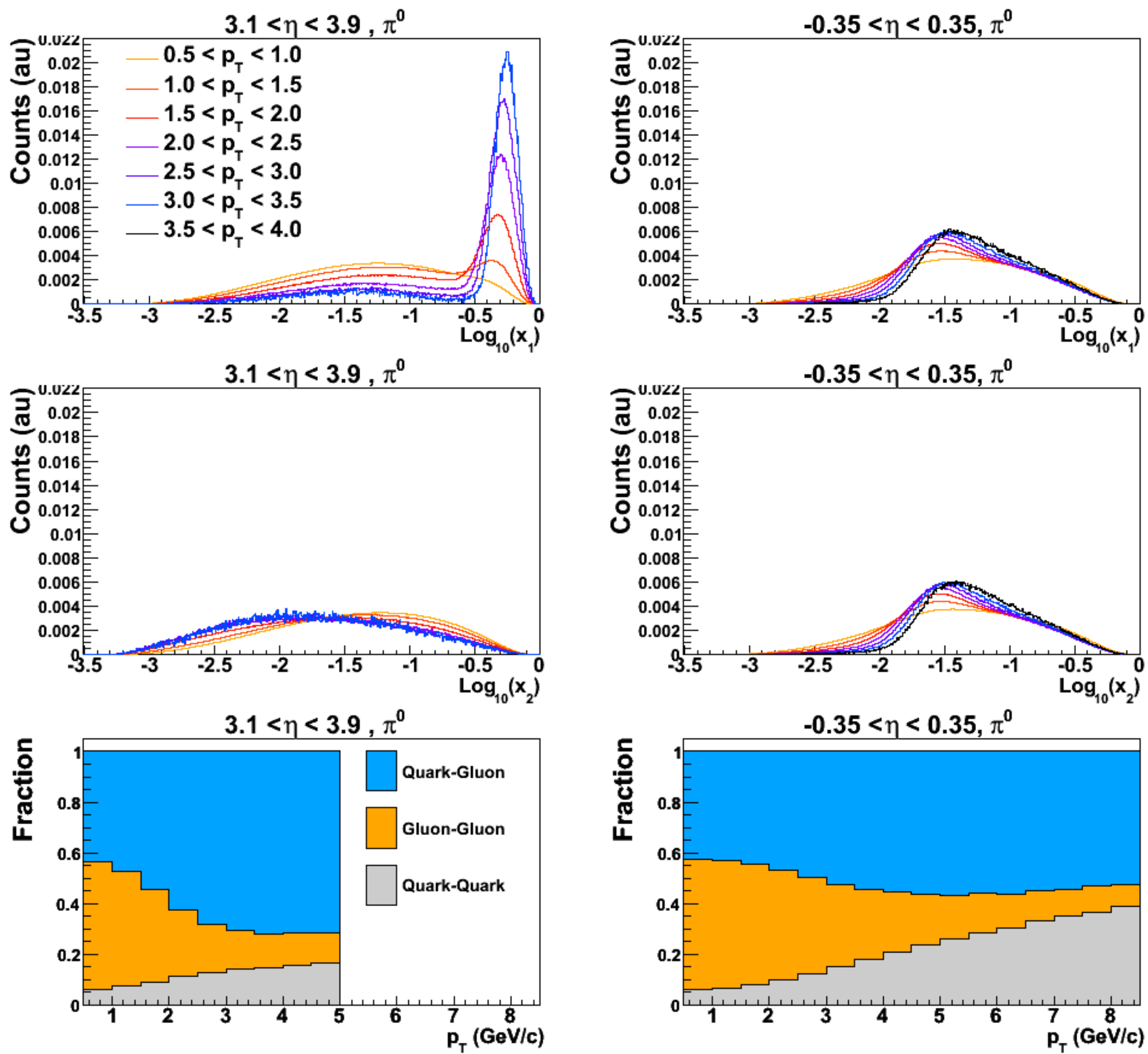
Unpolarized quark distribution
Known from DIS

Transversity
to be extracted

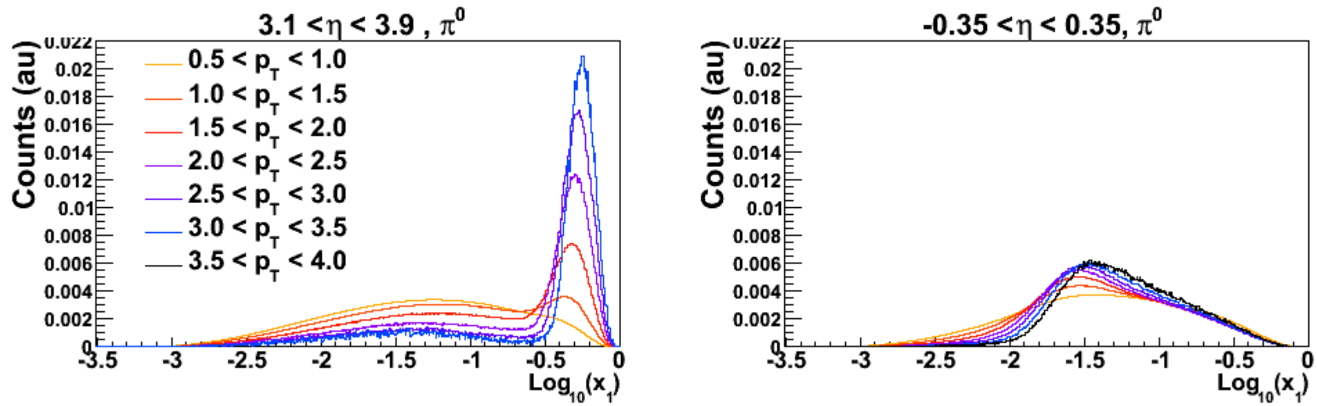
Hard scattering cross section
from pQCD

IFF + Di-hadron FF
measured in e+e-

$$d\sigma_{UT} = 2\,|\mathbf{P}_{C\perp}| \sum_{a,b,c,d} \frac{|\mathbf{R}_C|}{M_C} |\mathbf{S}_{BT}| \sin(\phi_{S_B} - \phi_{R_C}) \int \frac{dx_a dx_b}{16\pi z_c} f_1^a(x_a)\, h_1^b(x_b) \frac{d\Delta\hat{\sigma}_{ab^\uparrow\to c^\uparrow d}}{d\hat{t}} H_{1,ot}^{\sphericalangle c}(\bar{z}_c, M_C^2)$$

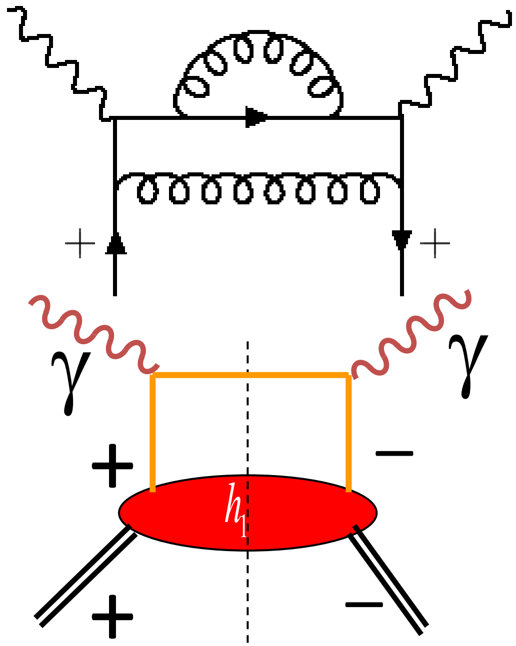


3.1 <η < 3.9 , π⁰
-0.35 <η < 0.35, π⁰
Counts (au)
0.5 < p_T < 1.0
1.0 < p_T < 1.5
1.5 < p_T < 2.0
2.0 < p_T < 2.5
2.5 < p_T < 3.0
3.0 < p_T < 3.5
3.5 < p_T < 4.0
Log10(x1)
Log10(x2)
Fraction
Quark-Gluon
Gluon-Gluon
Quark-Quark
p_T (GeV/c)



3.1 <η < 3.9 , π0
Counts (au)
0.5 < pT < 1.0
1.0 < pT < 1.5
1.5 < pT < 2.0
2.0 < pT < 2.5
2.5 < pT < 3.0
3.0 < pT < 3.5
3.5 < pT < 4.0
Log10(x1)
-0.35 <η < 0.35, π0
Counts (au)
Log10(x1)

QED, QCD Preserve Helicity



QED and QCD interactions (and SM weak interactions) conserve helicity:

Cannot measure h_1 inclusively

- Helicity base: chiral odd

Need chiral odd partner => Fragmentation function

Collins Extraction of Transversity: model dependence from Transverse Momentum Dependences!

$$A_{UT}^{Collins} = \frac{\sum_q e_q^2 \int d\phi_S d\phi_h d^2k_\perp \delta q(x,k_\perp) \frac{d(\Delta\sigma)}{dy} H_{1,q}^{\perp}(z,p_\perp) \sin(\phi_S + \phi + \phi_q^h) \sin(\phi_S + \phi_h)}{\sum_q e_q^2 \int d\phi_S d\phi_h d^2k_\perp q(x,k_\perp) \frac{d(\Delta\sigma)}{dy} D_q^h(z,p_\perp)}$$

transversity

Collins FF

quark pdf

hadron FF

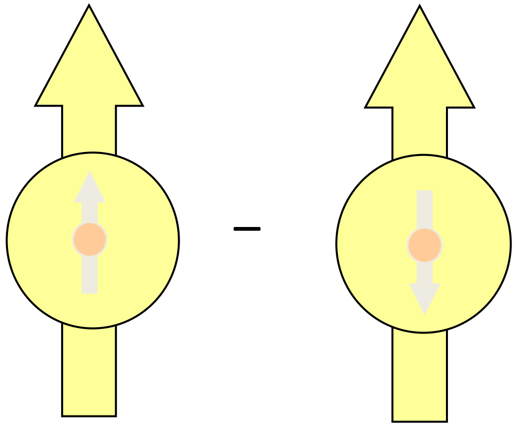
$k_\perp$ transverse quark momentum in nucleon

$p_\perp$ transverse hadron momentum in fragmentation

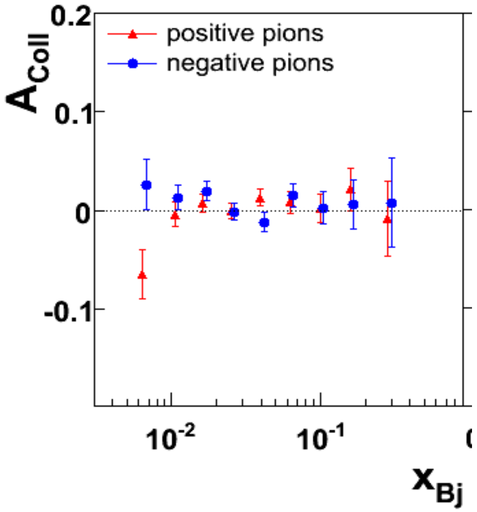
Anselmino, Boglione, D'Alesio, Kotzinian, Murgia, Prokudin, Turk Phys. Rev. D75:05032,2007

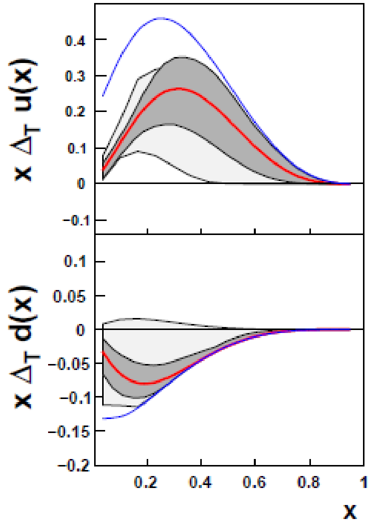
The transversse momentum dependencies are unknown and difficult to obtain experimentally!

Why is transversity so difficult to measure?



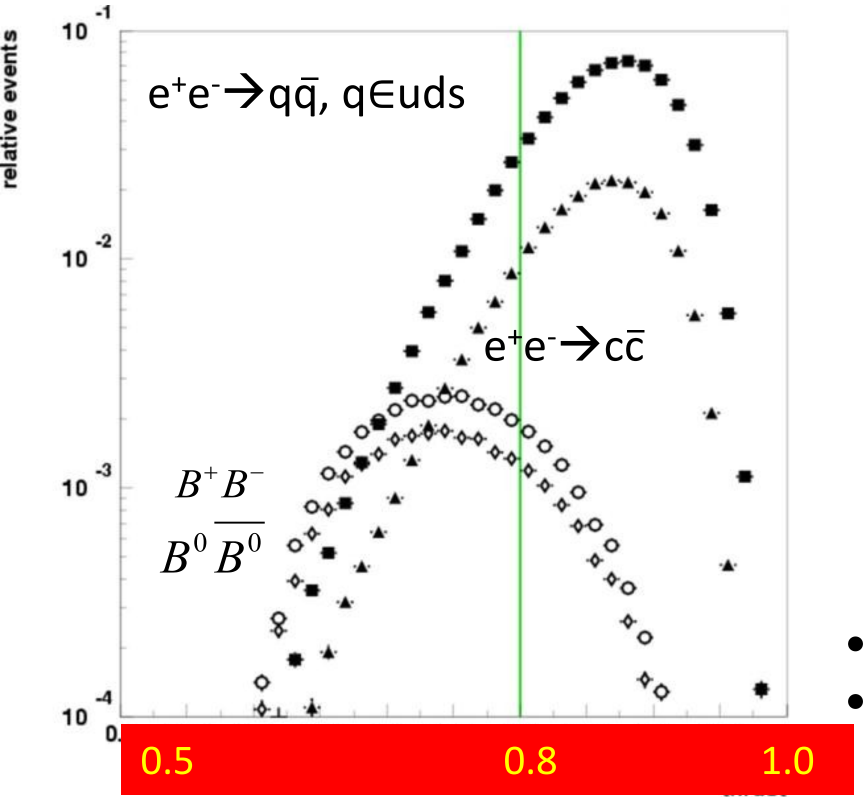
- Chiral odd: Inclusive asymmetries suppressed
  - Cannot be measured inclusively
  - Instead: Use semi inclusive asymmetries
  - Measure transverse polarisation of fragmenting quarks



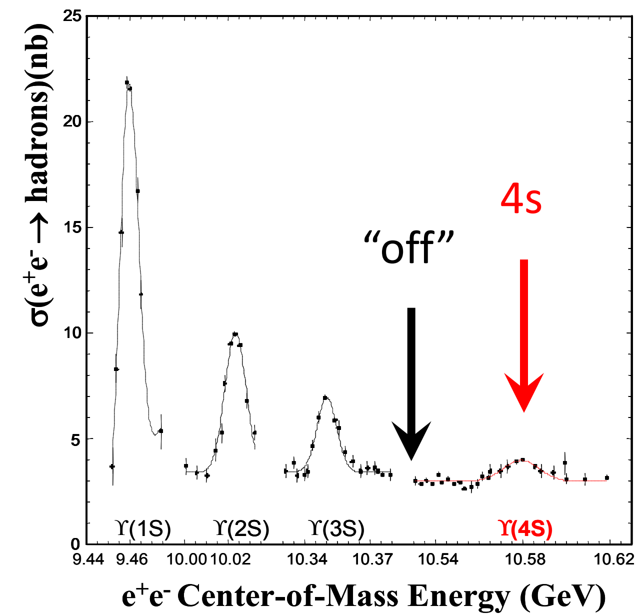


Alexei Prokudin, DIS2008, update of Anselmino et al: hep-ex 0701006

Measuring Light Quark Fragmentation Functions on the ϒ(4S) Resonance



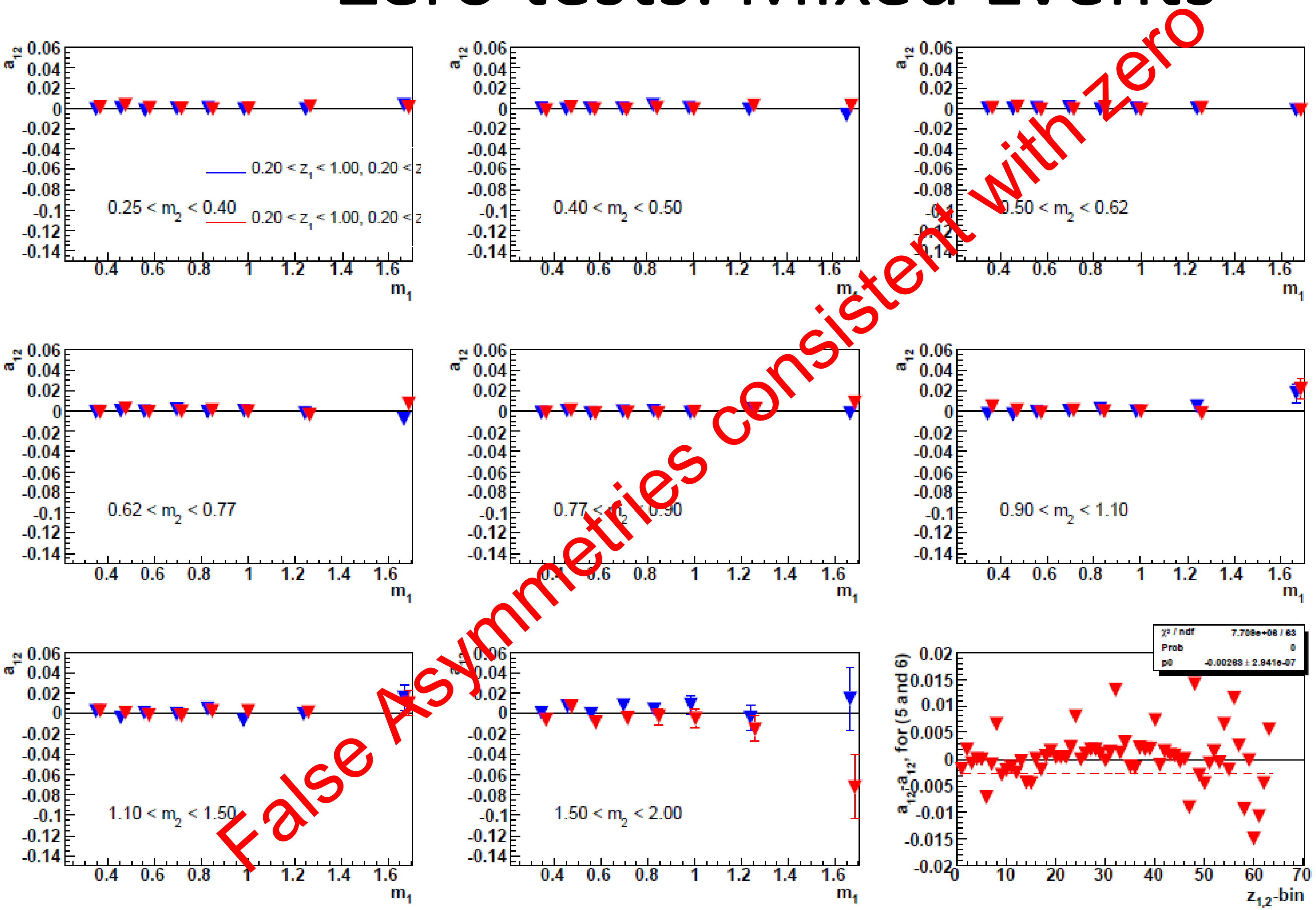
$$Thrust: T = \frac{\sum_i |p_i \cdot \hat{n}|}{\sum_i |p_i|}$$



- small B contribution (<1%) in high thrust sample
- >75% of X-section continuum under ϒ (4S) resonance
- 73 fb^{-1} ➔ 662 fb^{-1}

57

Zero tests: Mixed Events



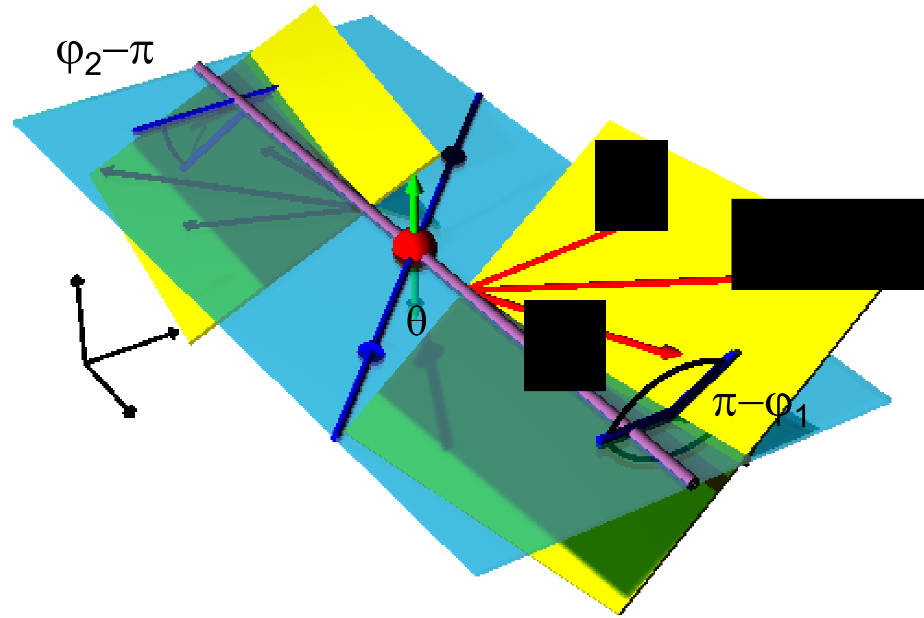
Positivity and soffer bound

$$|h_1(x)| \leq f_1(x)$$

$$|h_1(x)| \leq \tfrac{1}{2}\left(f_1(x) + g_1(x)\right)$$

Interference Fragmentation–thrust method

- $e^+e^- \rightarrow (\pi^+\pi^-)_{jet1}(\pi^-\pi^+)_{jet2}X$
- Find pion pairs in opposite hemispheres
- Theoretical guidance by papers of Boer,Jakob,Radici[PRD 67,(2003)] and Artru,Collins[ZPhysC69(1996)]
- Early work by Collins, Heppelmann, Ladinsky [NPB420(1994)]



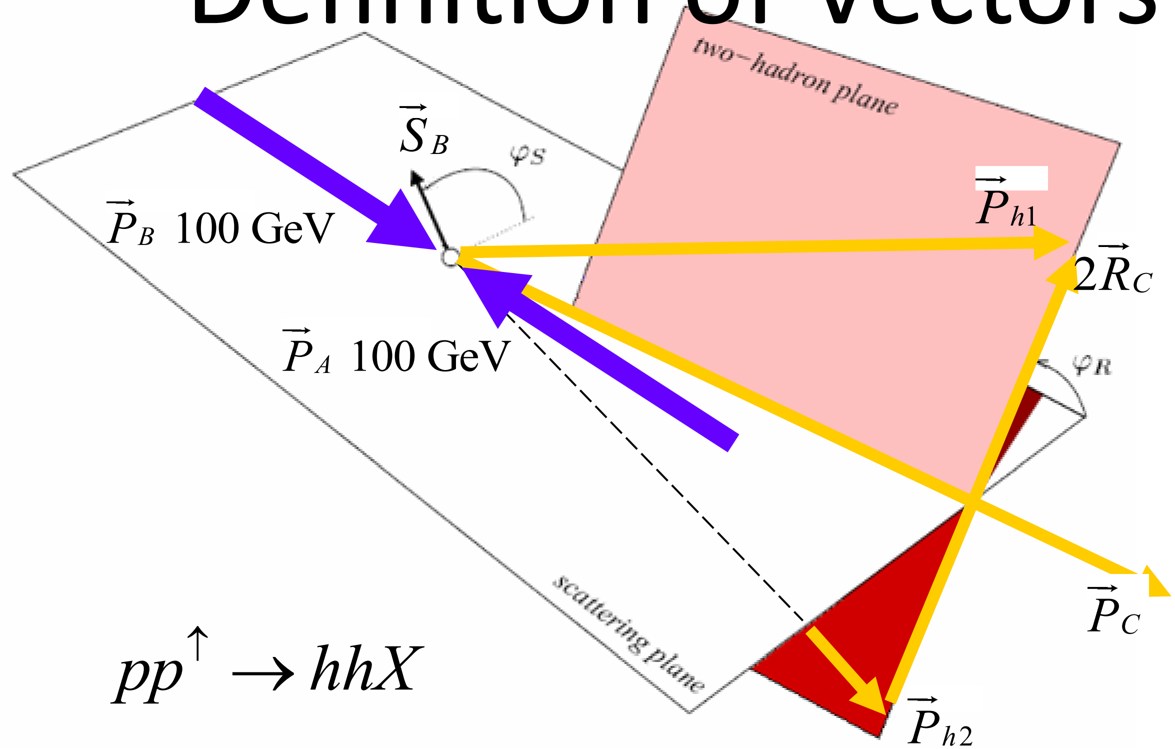
- $\frac{\sin^2\theta}{1+\cos^2\theta}$ transverse spin projection

Model predictions by:

- Jaffe et al. [PRL **80,**(1998)]
- Radici et al. [PR**D 65,** (2002)]

$$A \propto H_1^{\angle}(z_1, m_1)\overline{H}_1^{\angle}(z_2, m_2)\,cos(\varphi_1 + \varphi_2)$$

Definition of Vectors and Angles



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

hadron plane: $\vec{P}_{h1}, \vec{P}_{h2}$

scattering plane: $\vec{P}_C, \vec{P}_B$

ϕ_R : from scattering plane to hadron plane

ϕ_S : from polarization vector to scattering plane

Bacchetta and Radici, PRD70, 094032 (2004)

2. Unpolarized Fragmentation Functions- Current Extractions

- NLO pQCD fits of **e⁺e⁻** annihilation, **SIDIS** and **pp** data with uncertainties (**global analysis**): de Florian, Sassot, Stratmann (**DSS**), Phys. Rev. D **75**,114010 (2007)
- Little constraint on gluon fragmentation functions- remedied by **precision measurement at low Q^2**