Measurement of Fragmentation Functions at

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Outline

- Motivation
  - Analysis of Transverse Spin Effects in SIDIS, proton-proton
  - Recent experimental results
  - Transversity extraction
- Measuring Fragmentation Functions at Belle
  - Experimental techniques
  - Interference Fragmentation Function Measurement
  - Comparison with theory
- Summary & Outlook

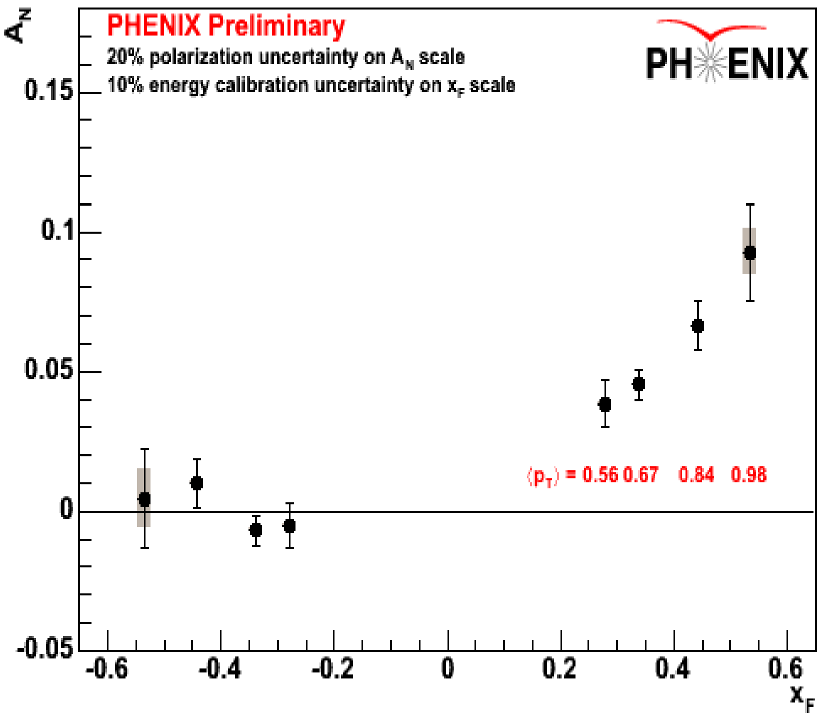
Transverse Spin Asymmetries

- Experimental results in SIDIS and pp

Transverse Spin Asymmetries - Single Hadrons

- Large transverse single spin effects persist at large scale
- Convolution of different effects

PHENIX, forward π^0 at s = 62 GeV, nucl-ex/0701031



$$x_F = \frac{2p_L}{\sqrt{s}} \overset{2->2}{=} x_1 - x_2$$

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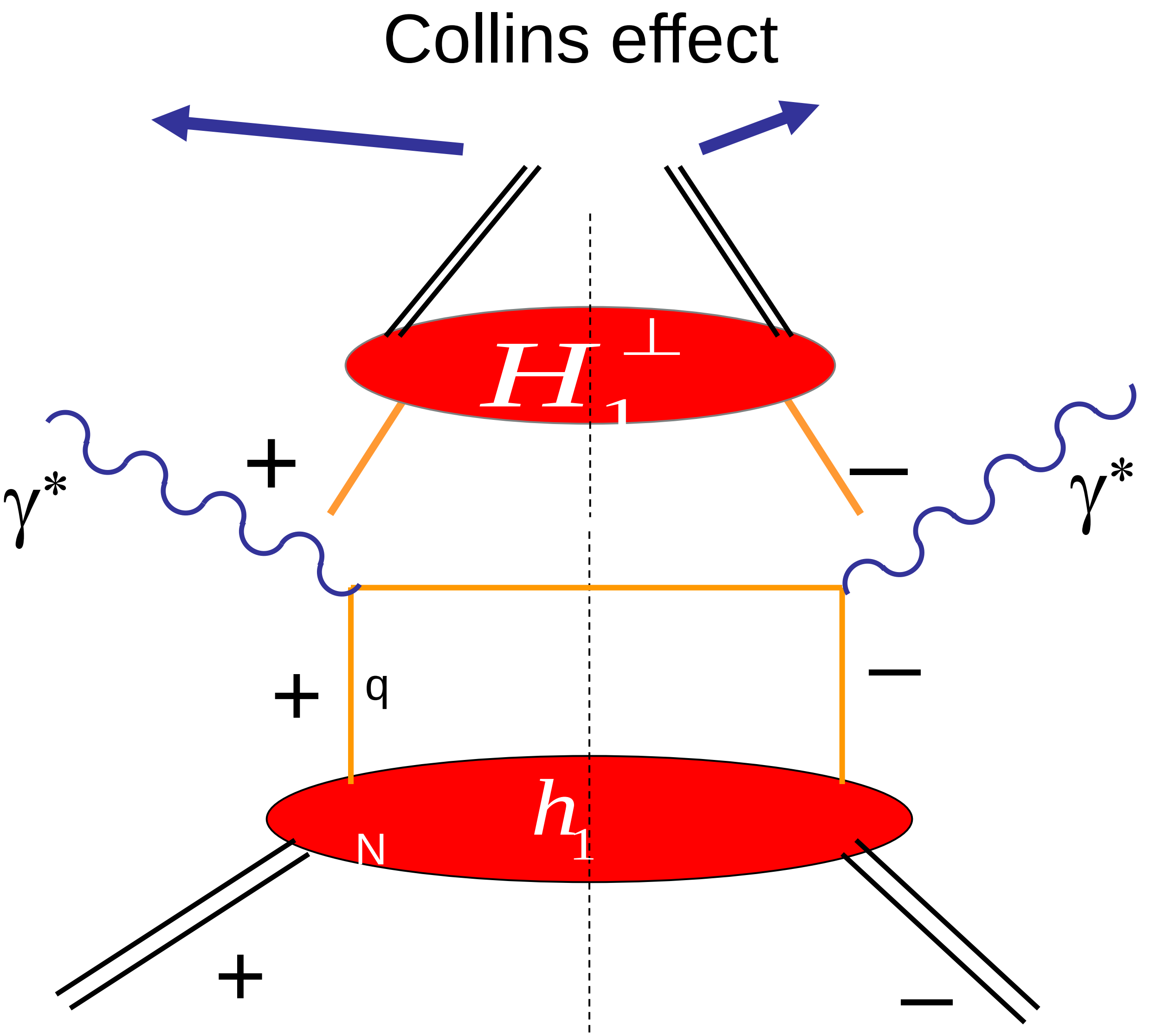
Transverse Spin Asymmetries

- Experimental results in SIDIS and pp
- Access to fundamental aspects of QCD and nucleon structure:
  - TMDs, orbital angular momentum
  - Initial, final state interactions
  - Gauge invariance of correlators
- Prominent effects:
  - Transversity * Collins
  - Sivers Effect
- Separation of different effects requires measurements at multiple experiments, channels -> pp, SIDIS, e^+e^-

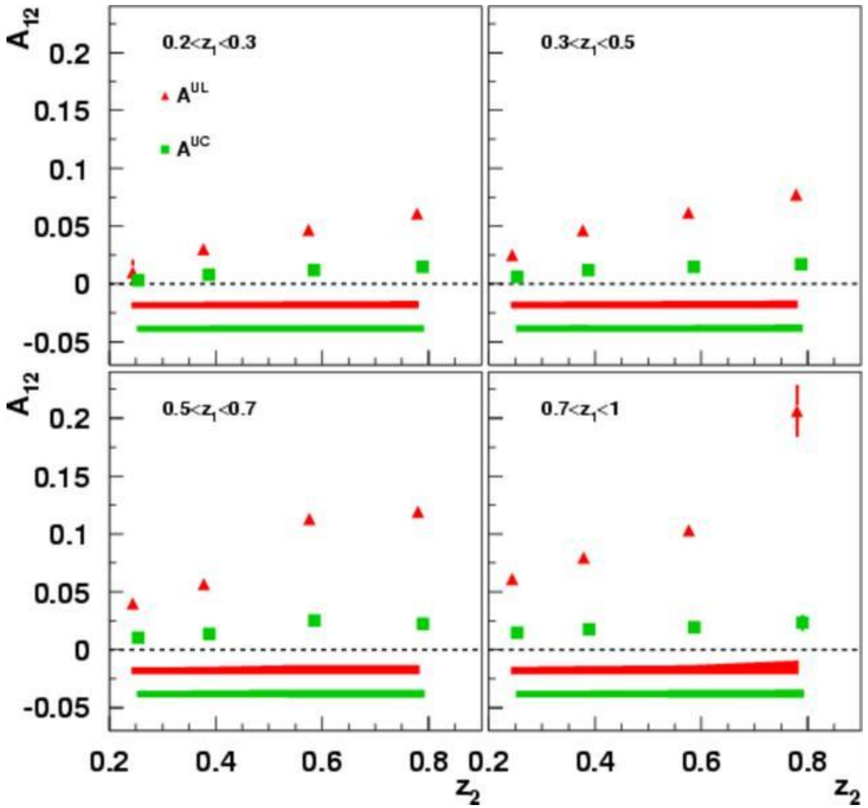
Chiral odd FFs



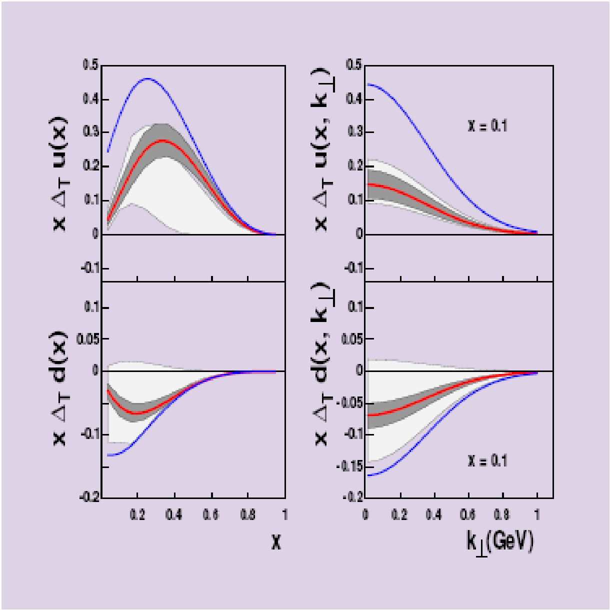
$H_1^{\perp}$: **Collins FF**

Collins Fragmentation at Belle

- First extraction of transversity quark



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



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

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

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

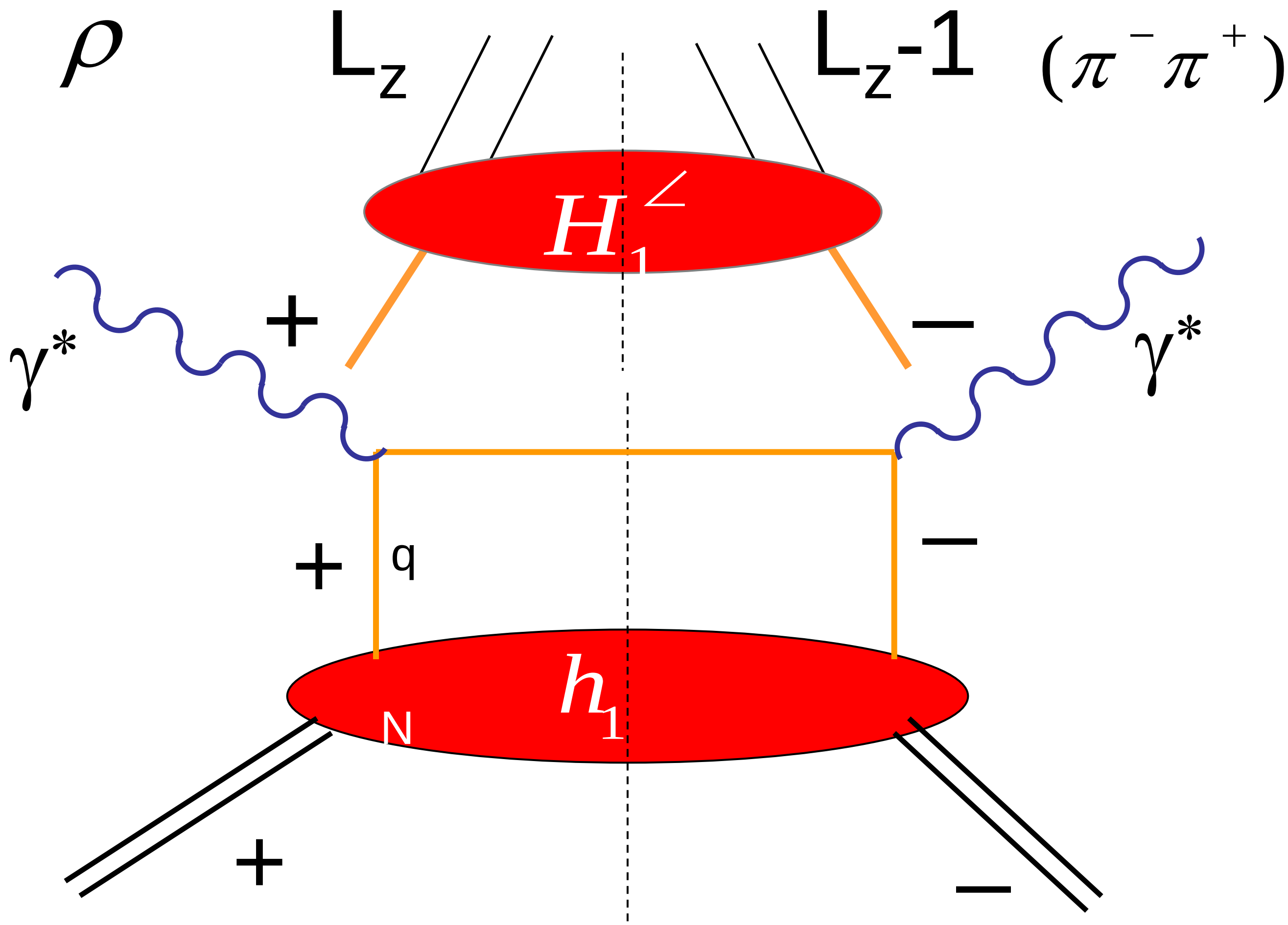
$p_\perp$ transverse hadron momentum in fragmentation

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

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

Chiral odd FFs

Interference Fragmentation Function

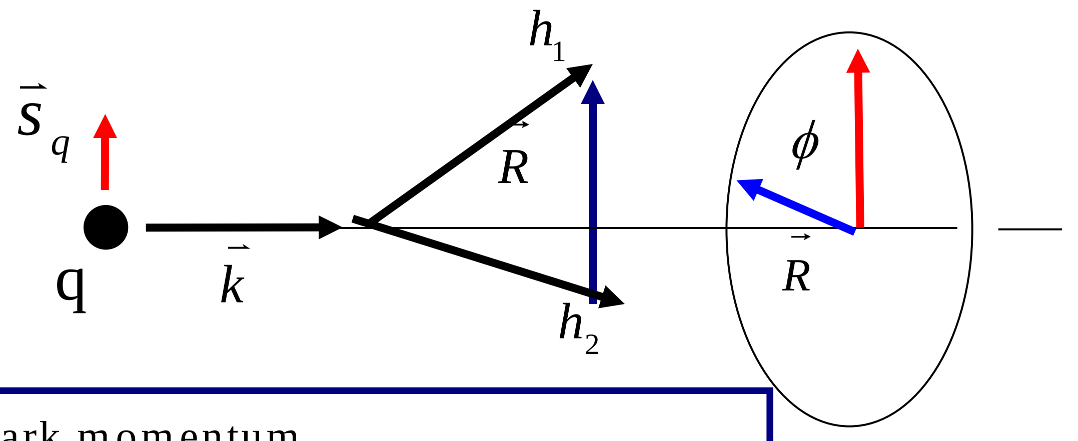


Advantages of IFF

- Independent Measurement
- Favourable in pp: no Sivers
- Transverse momentum is integrated
  - Collinear factorization
  - No assumption about k_t in evolution
  - Universal function
  - evolution known, collinear scheme can be used
  - directly applicable to semi-inclusive DIS and pp

- First experimental results from HERMES, COMPASS, PHENIX

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

$$z_{\text{pair}} = E_{pair} / E_q$$

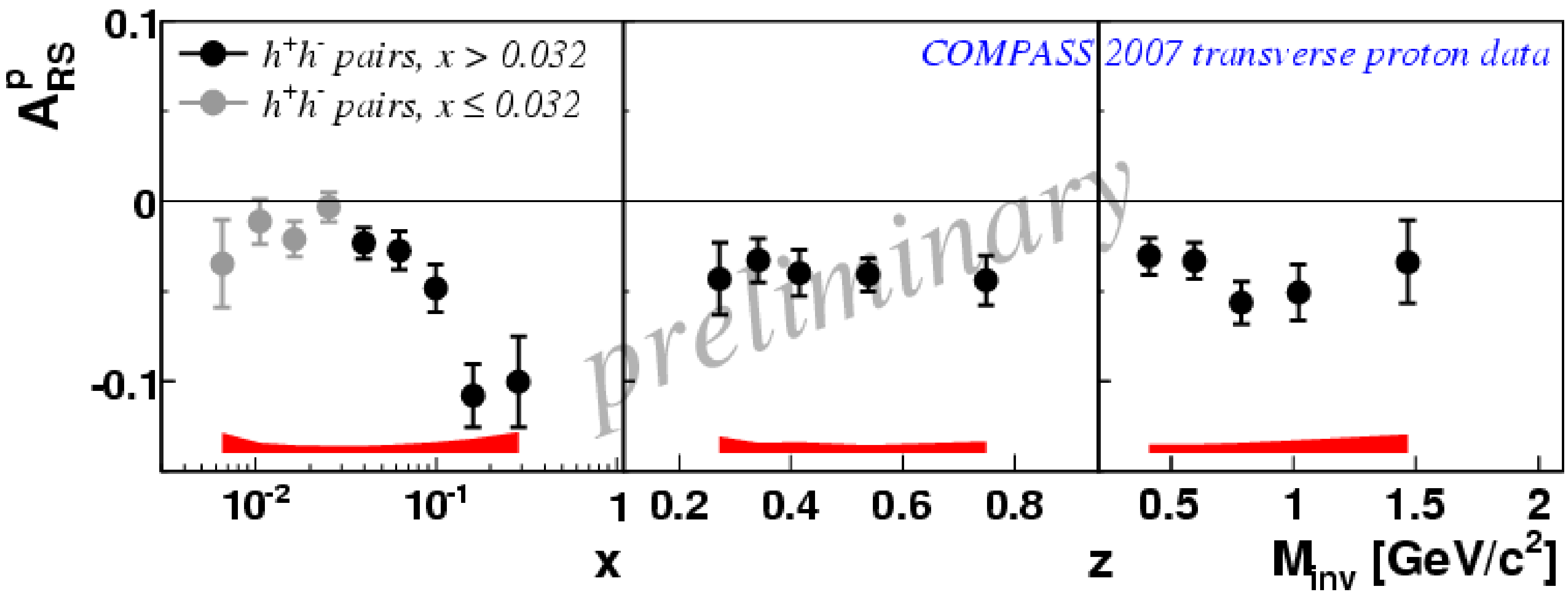
$$= 2 E_{pair} / \sqrt{s}$$: relative hadron pair momentum

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

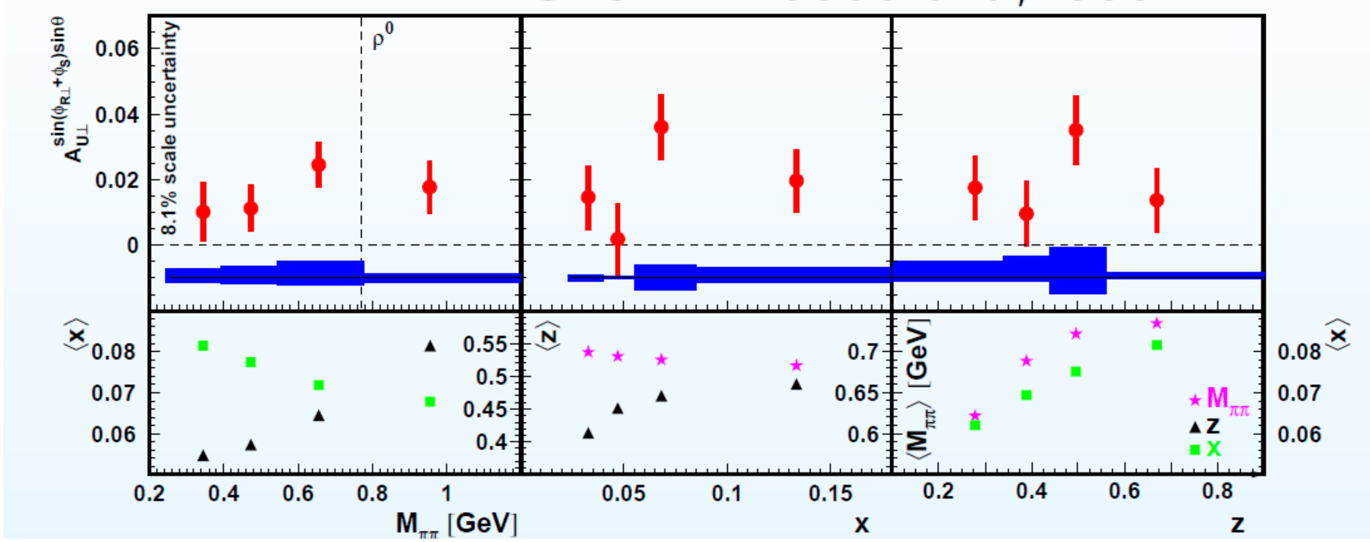
$$\propto \left(\vec{k} \times \vec{R}_T \right) \cdot \vec{s}_q$$

$$\propto \sin \phi$$

Di-Hadron SSA in SIDIS



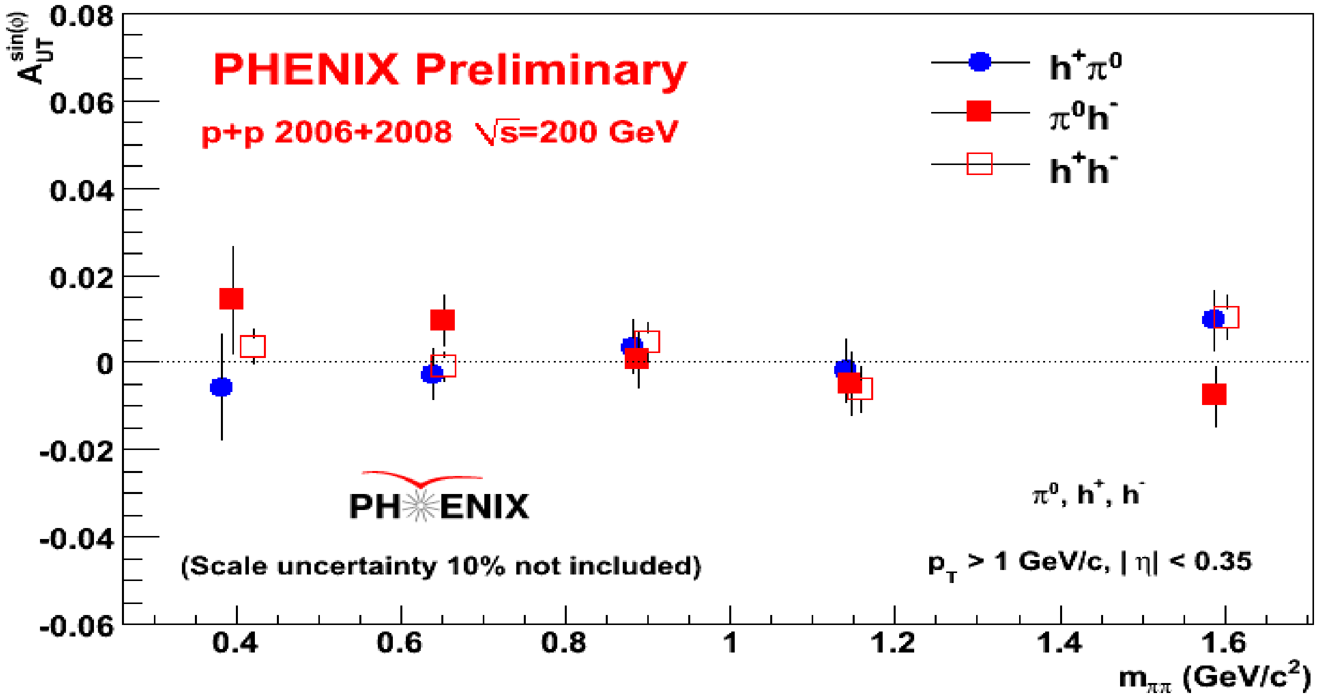
HERMES: JHEP 0806:017,2008



(both on proton target, sign convention different)

SSA from di-hadron production

Extended kinematic regime compared with SIDIS
Hard scale



Added statistics from 2008 running

As expected:

No significant asymmetries seen at central-rapidity.

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

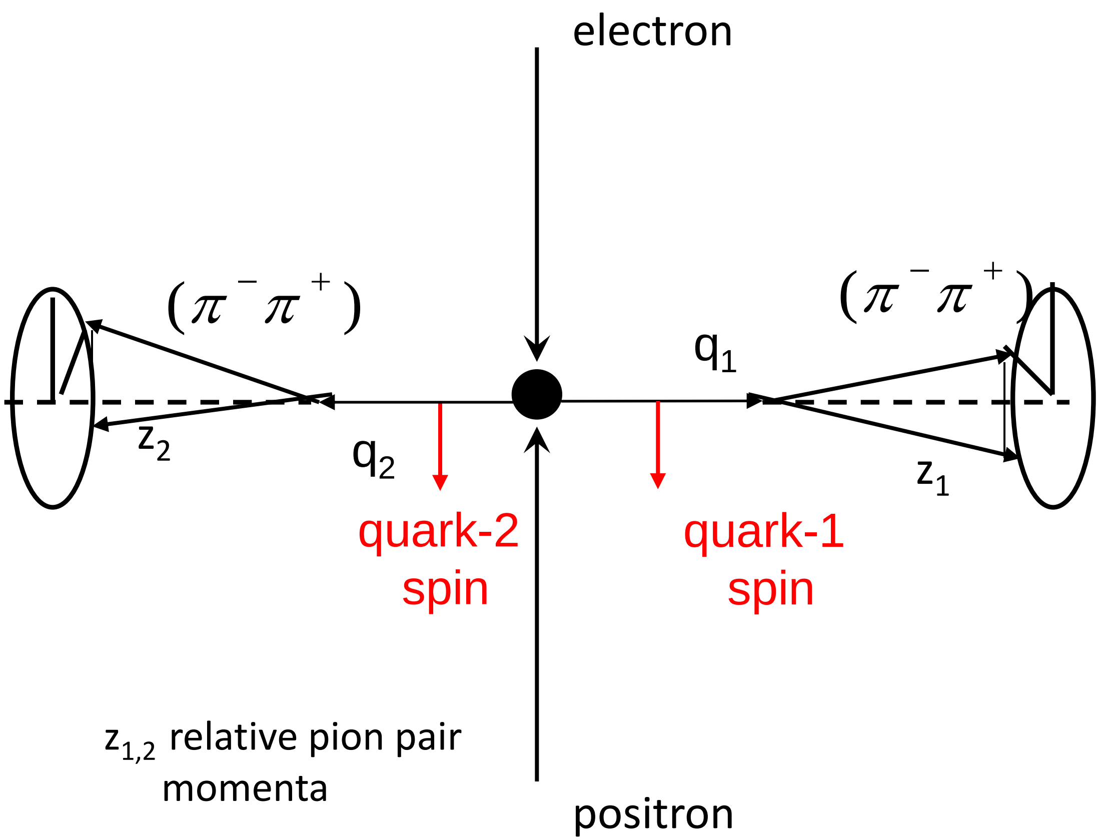
- Quark spin direction unknown: measurement of Interference Fragmentation function in one hemisphere is not possible

  sin φ modulation will average out.

- Correlation between two hemispheres with *sin* φ_{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



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

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

Experimental requirements:

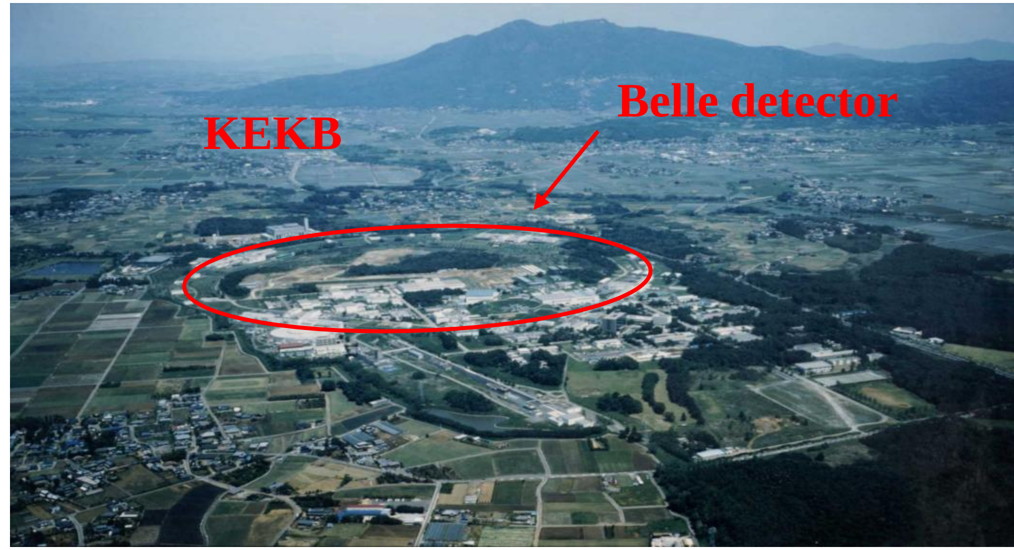
- Small asymmetries ➔ very large data sample!
- Good particle ID to high momenta.
- Hermetic detector
- Observable: $\cos(\varphi_{R1}+\varphi_{R2})$

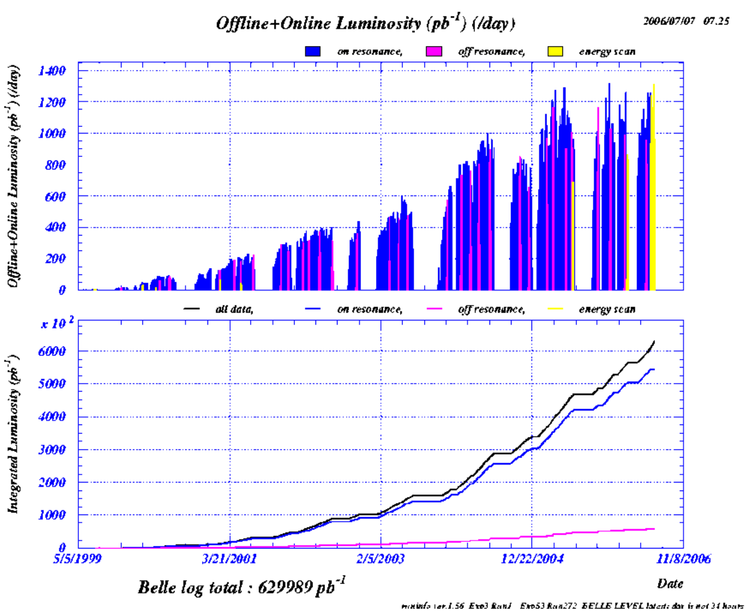
modulation measures $H_1^{\angle} \overline{H_1^{\angle}}$

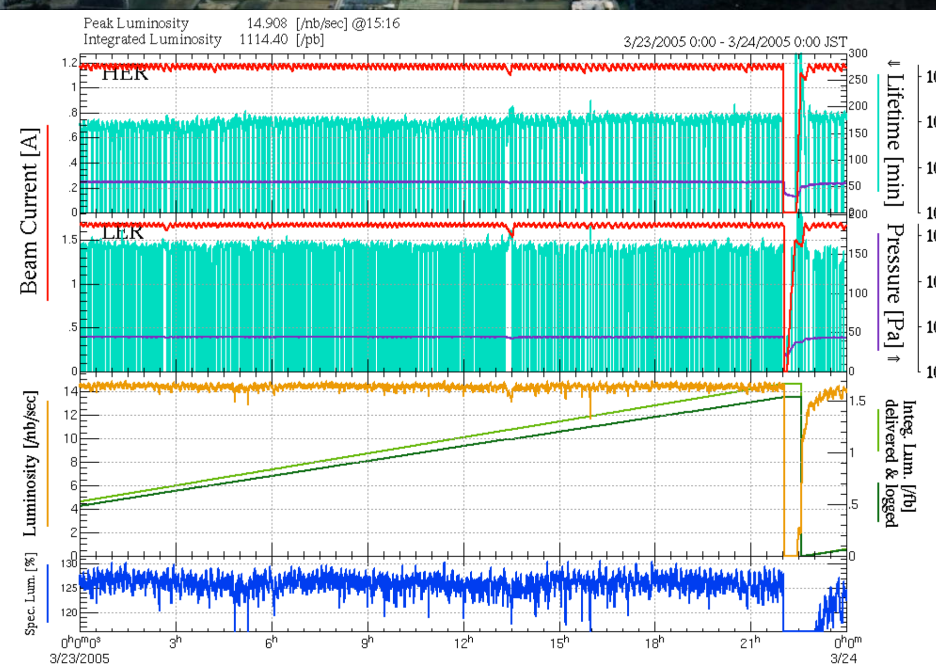
BELLE

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

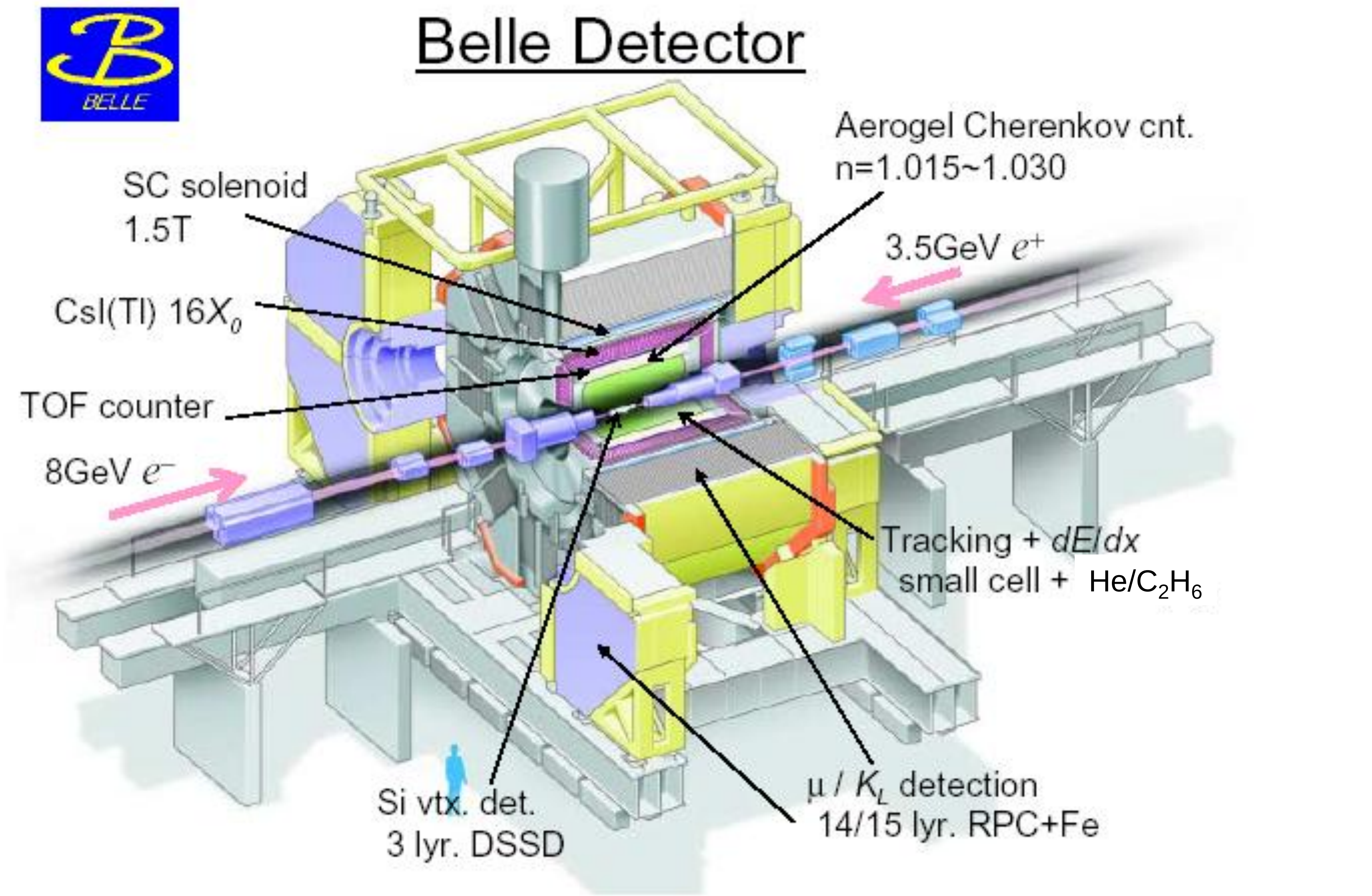
- Asymmetric collider
- 8GeV e^- + 3.5GeV e^+
- $\sqrt{s}$ = 10.58GeV (Υ(4S))
- $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\ \bar{B}$
- Continuum production:
  10.52 GeV
- $e^+e^- \rightarrow q\ \bar{q}$ (u,d,s,c)
- Integrated Luminosity: > 1000 fb^{-1}
- >70 fb^{-1} => continuum





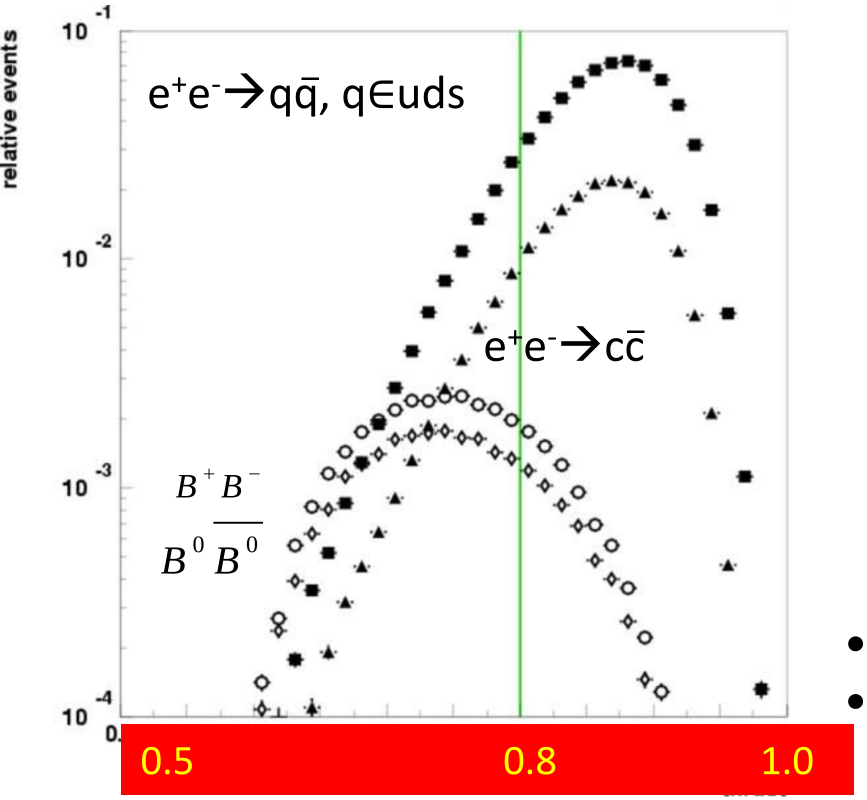


Belle Detector

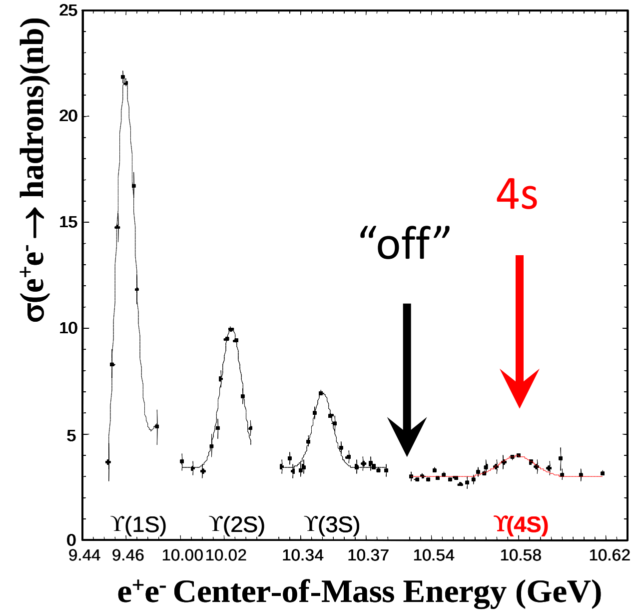


Large acceptance, good tracking and particle identification!

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}

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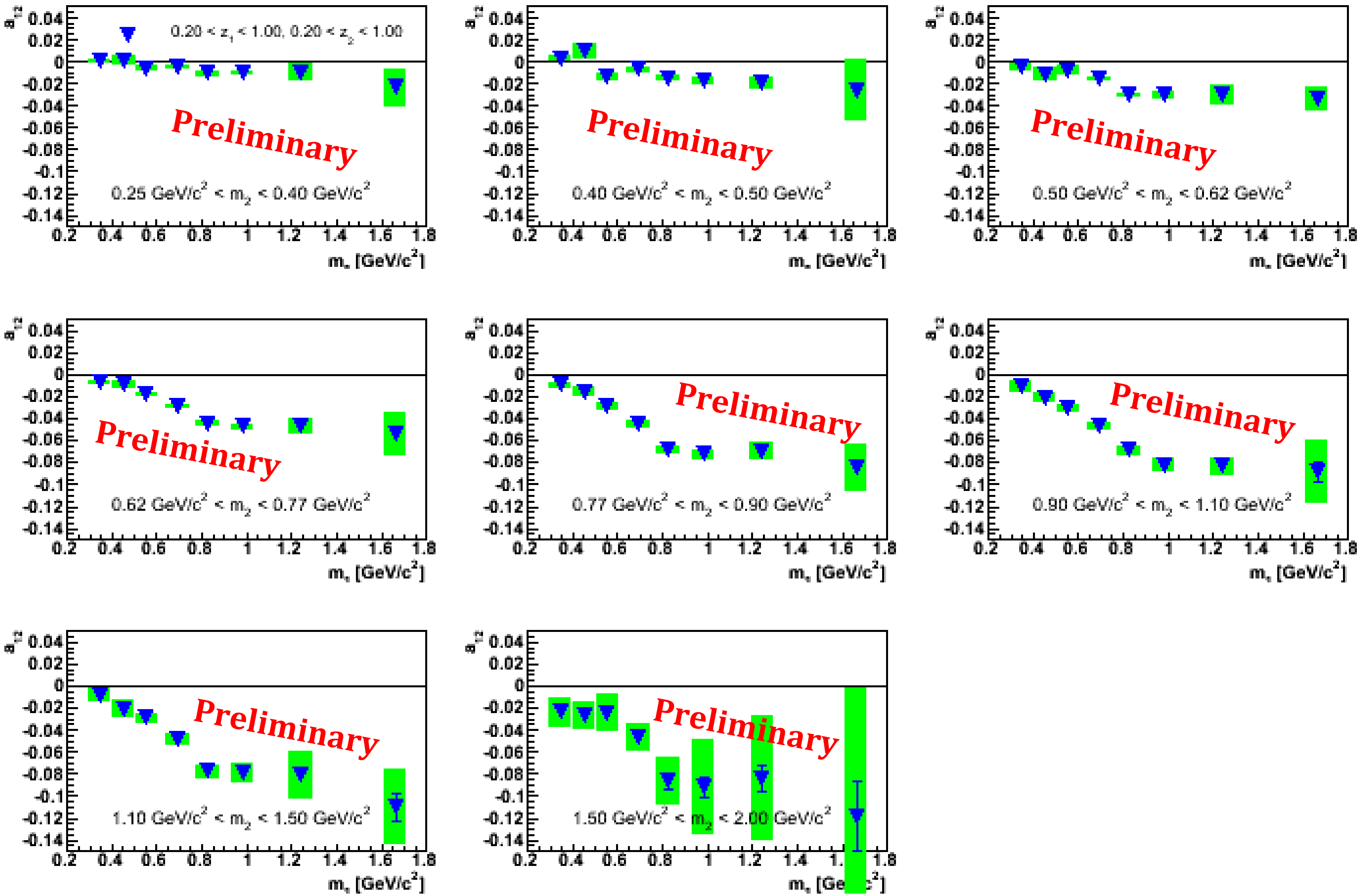
Cuts and Binning

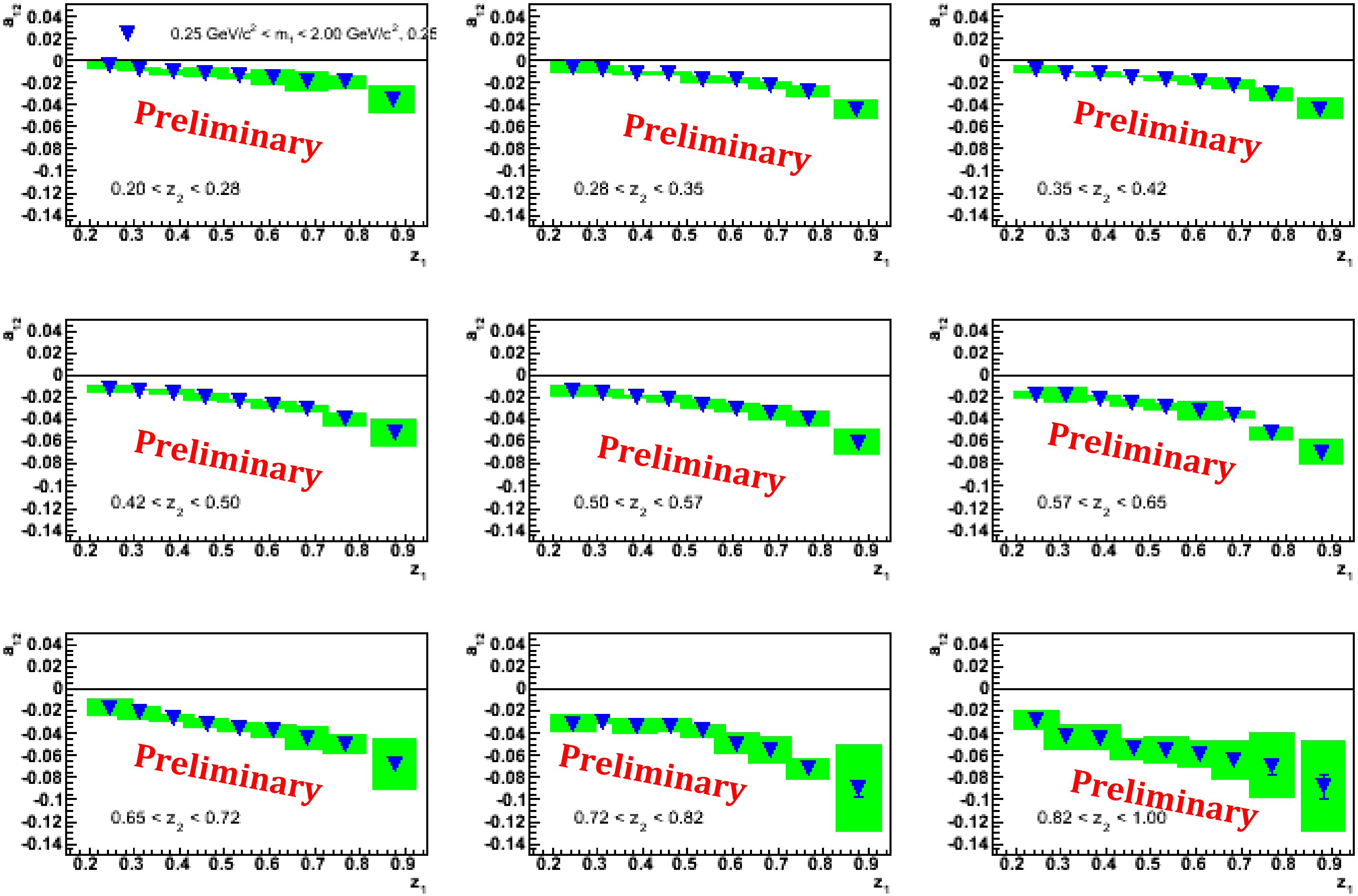
- Similar to Collins analysis, full off-resonance and on-resonance data

  (7-55): ~73 fb^{-1} + 588 fb^{-1}
- Visible energy >7GeV
- PID: Purities in Pion/Pion Sample > 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: abs(thrustz)<0.75
- Thrust > 0.8
- $z_{had1,had2}$>0.1
- $z_1 = z_{had1}+z_{had2}$ and z_2 in 9x9 bins
- $m_{\pi\pi1}$ and $m_{\pi\pi2}$ in 8x8 bins: [0.25 - 2.0] GeV

Results including systematic errors

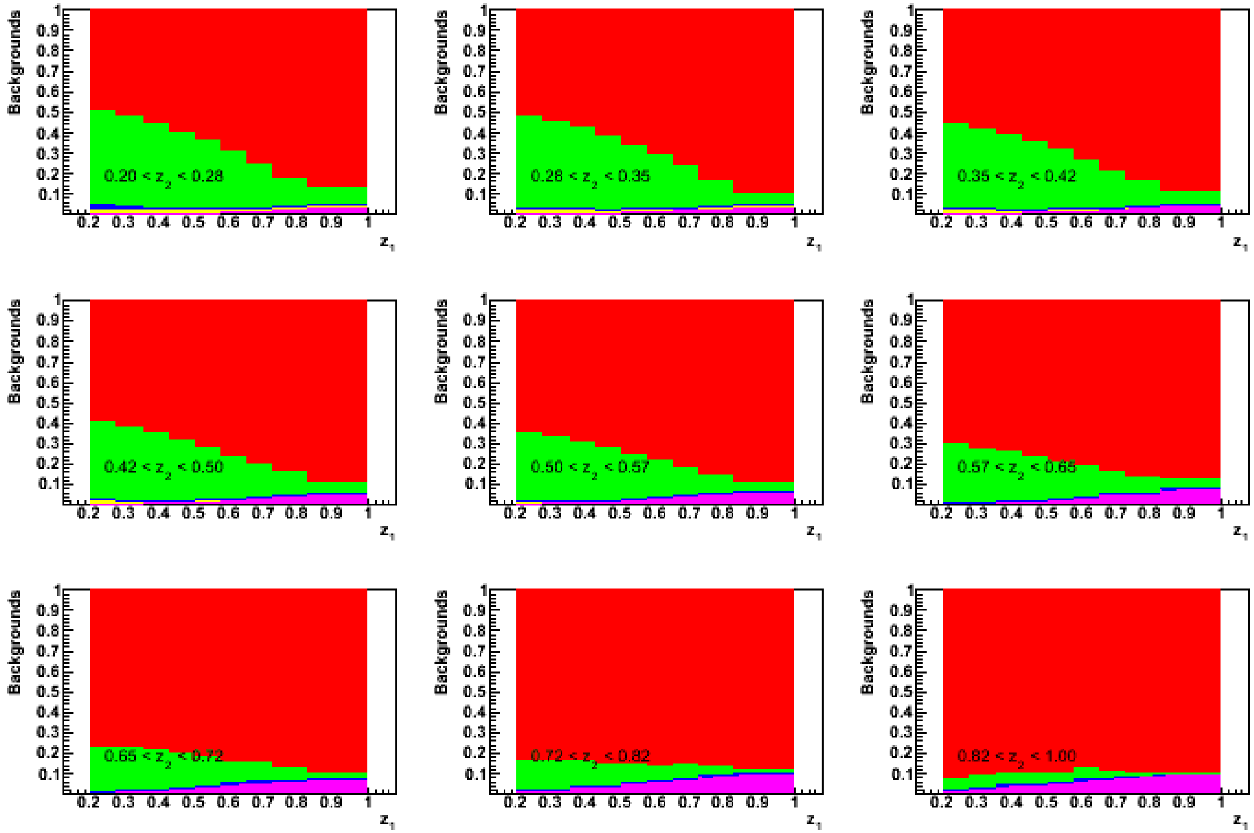


8x8 m_1 m_2 binning



9x9 z_1 z_2 binning

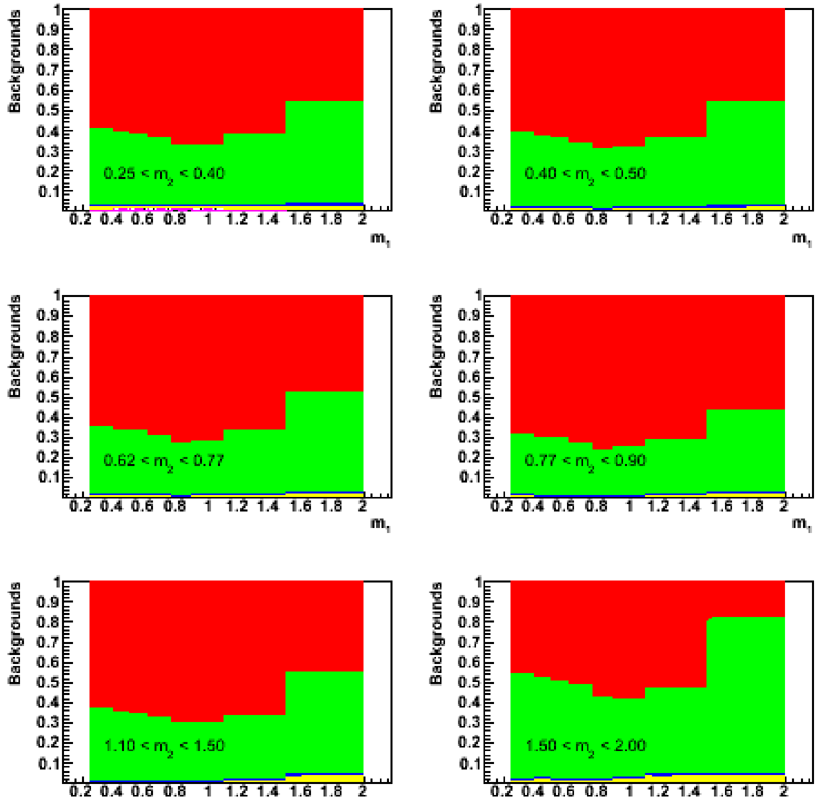
Subprocess contributions (MC)



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

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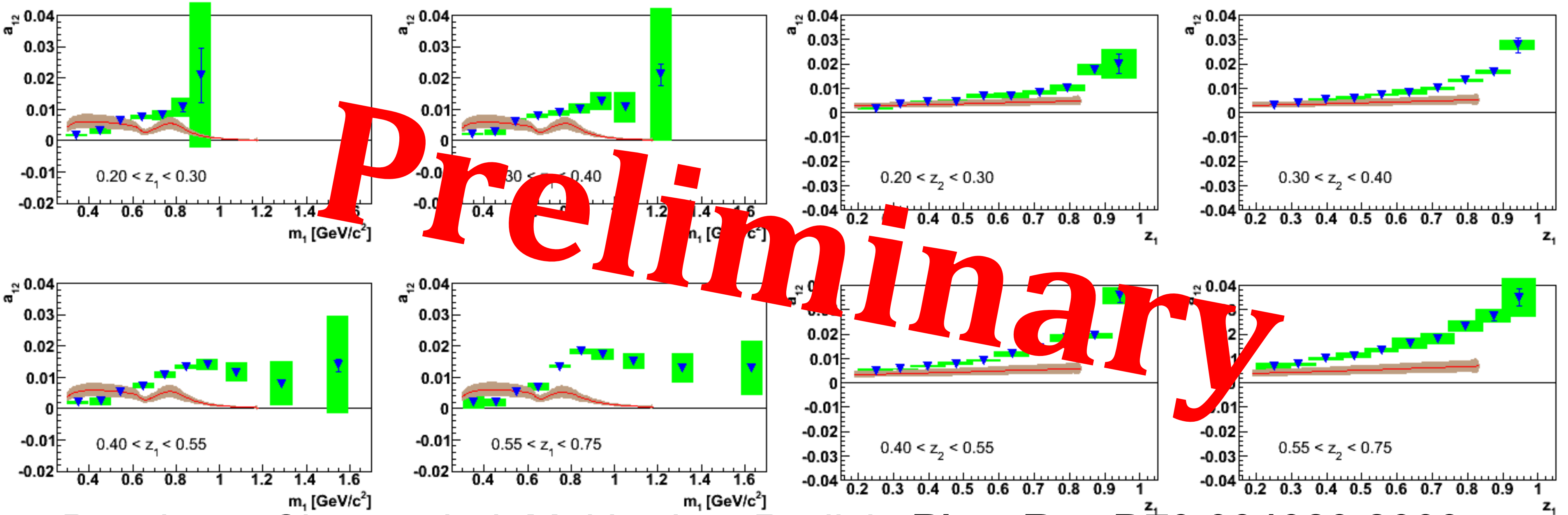
Comparison to theory predictions



Bacchetta,Checcopieri, Mukherjee, Radici : **Phys.Rev.D79:034029,2009**.

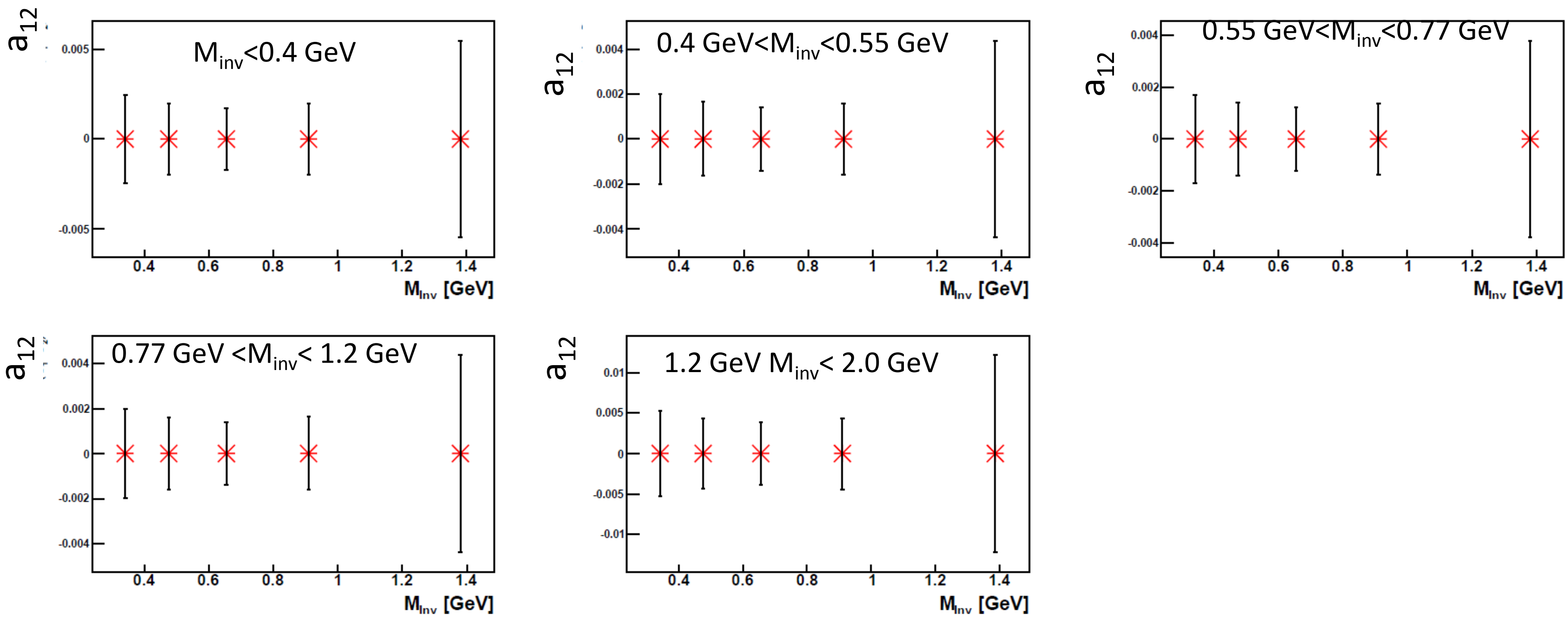
Leading order, experimental results might contain effects from gluon radiation not contained in the model

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

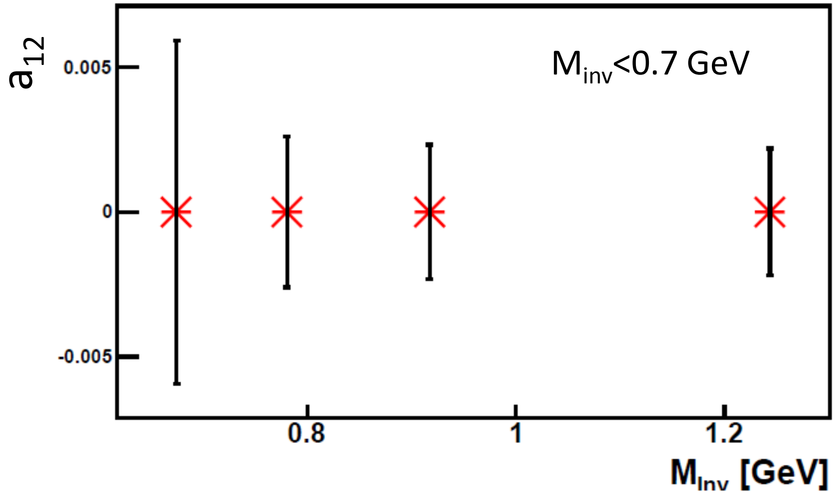
Z dependence : Rising behavior steeper

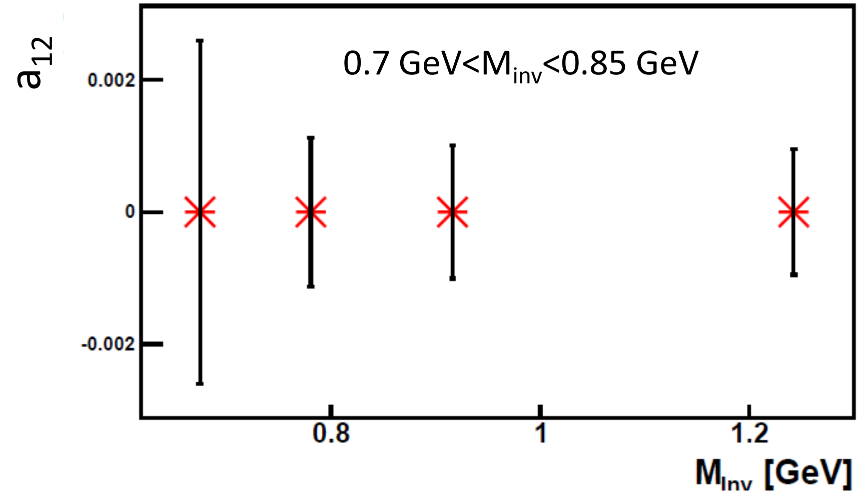
However: Theory contains parameters based on HERMES data which already fail to explain COMPASS well

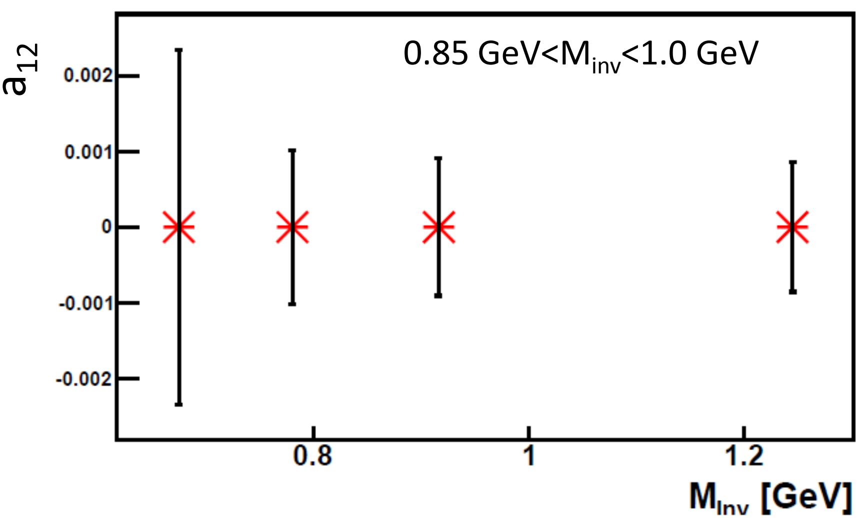
Projections for $(\pi^+\pi^0)$ $(\pi^+\pi^0)$ for 580 fb^{-1}

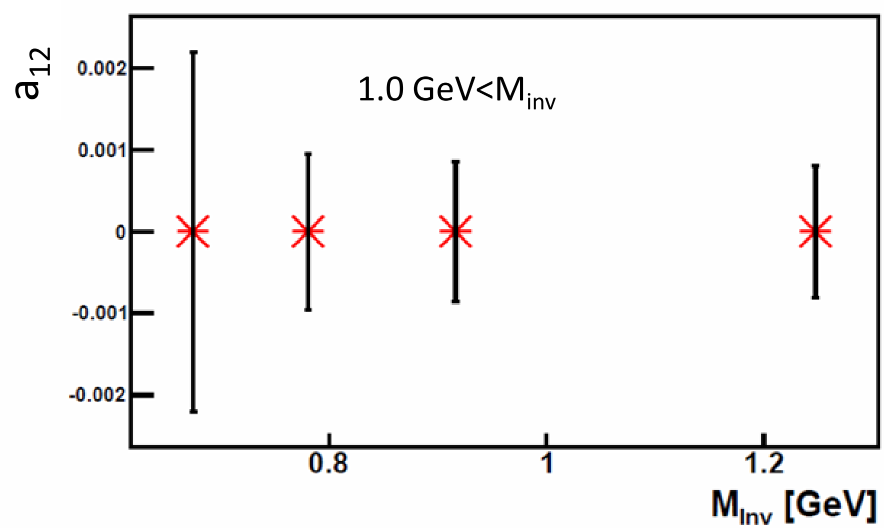


Projections for
(π^+K^-) $(K^+\pi^-)$ for 580 fb^{-1}









Summary

- First measurement of Interference Fragmentation Function!

- Asymmetry significant

- Combined Analysis of Di-hadron and single hadron measurements possible

- Systematic effects to be finalized
- Future goal: Combined analysis of SIDIS, pp, e^+e^- data
  - Extract transversity
  - Disentangle contributions to A_N

Outlook

- Near future
  - IFF/Collins for more flavors
  - A lot of effort on precise measurements of unpolarized identified fragmentation functions, first results soon!
  - Unpolarized two hadron fragmentation functions
- Far future
  - Continue to measure precise spin dependent fragmentation functions at Belle
    - kT dependence of Collins function
    - Artru model test with Vector meson Collins

Backup

Towards a global transversity analysis: Chiral –odd Fragmentation functions

RHIC and SIDIS experiments measure:

Transversity δq(x) X

Collins Fragmentation function $H_1^{\perp}(z)$

or Interference Fragmentation function (IFF)

2 Unknown Functions measured together

- Universality understood
- Evolution ?

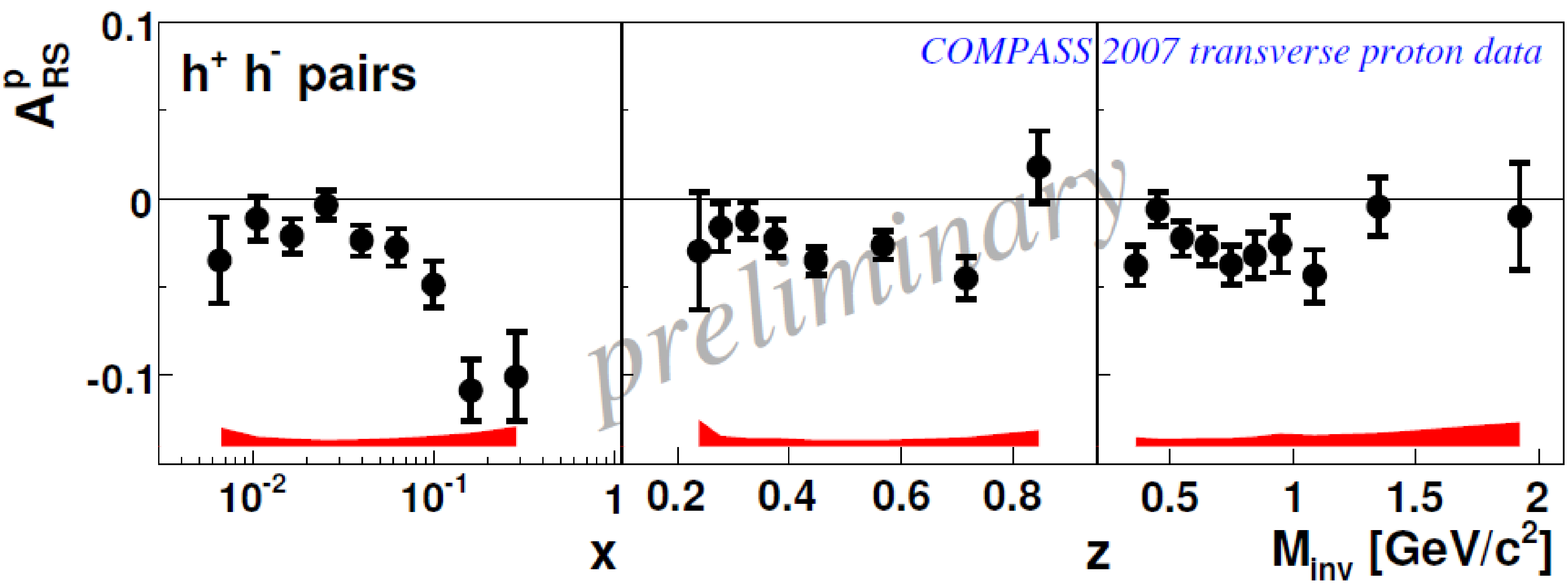
Belle measures:

Collins X Collins

or IFF X IFF

Transversity

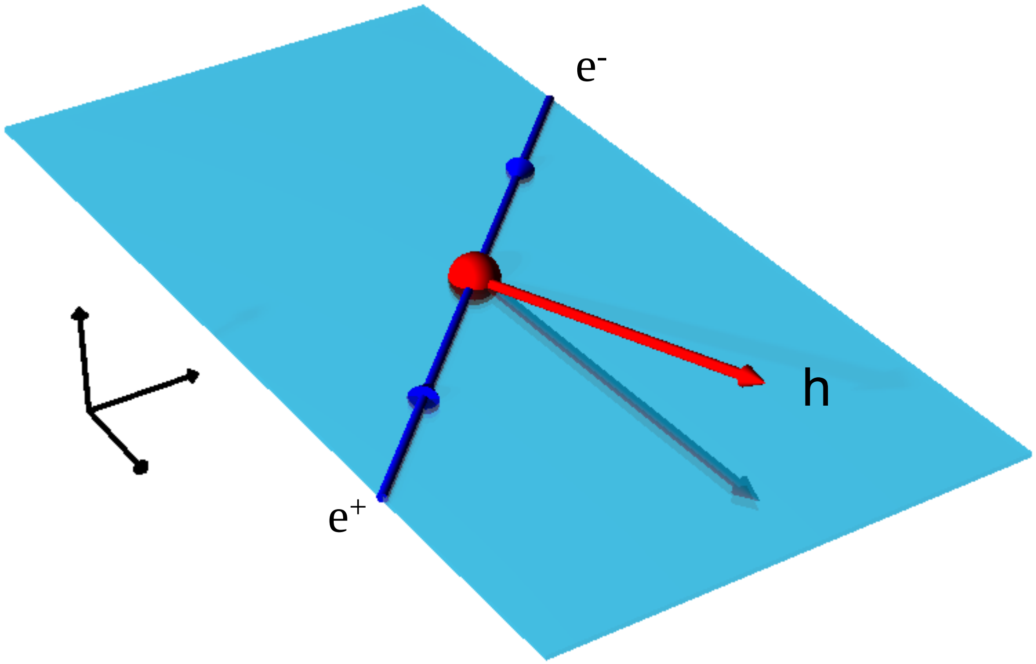
Motivation



A^{p}_{RS}
0.1
0
-0.1
h⁺ h⁻ pairs
COMPASS 2007 transverse proton data
preliminary
10^{-2}
10^{-1}
1
0.2
0.4
0.6
0.8
0.5
1
1.5
2
x
z
M_{inv} [GeV/c²]

Fragmentation functions in e^+e^- annihilation

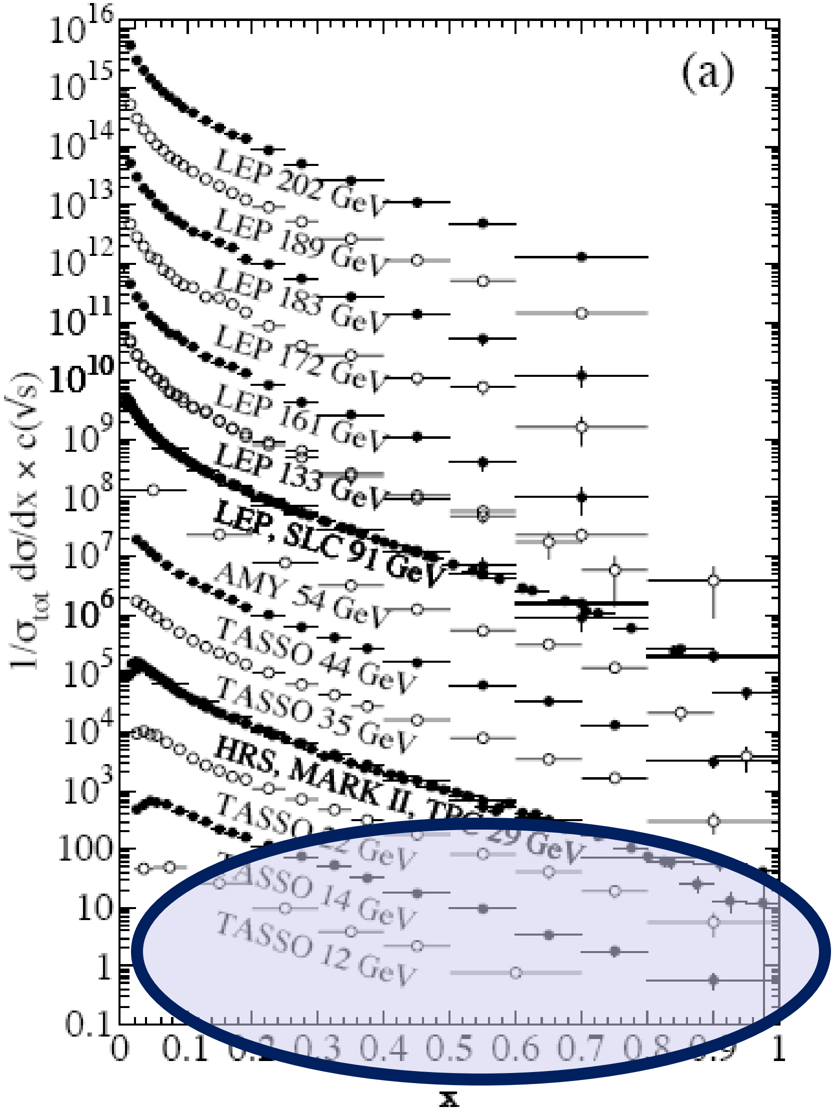
$$z = \frac{2E_h}{\sqrt{s}}, \quad \sqrt{s} = 10.52\ \mathbf{GeV}$$



- Process:
  $e^+ e^- \rightarrow hX$
- At leading order sum of unpolarized fragmentation f… ions from … k and anti- … k side

LO $F^h(z,s) = \frac{\sum_q e_q^2 [D_q^h(z) + D_{\bar{q}}^h(z)]}{\sum_q e_q^2}$ NLO $F^h(z,s) = \sum_i \int_z^1 \frac{dz'}{z'} C_i(s; z' \alpha_s) D_q^h(z)$

World data and motivation for precise FFs

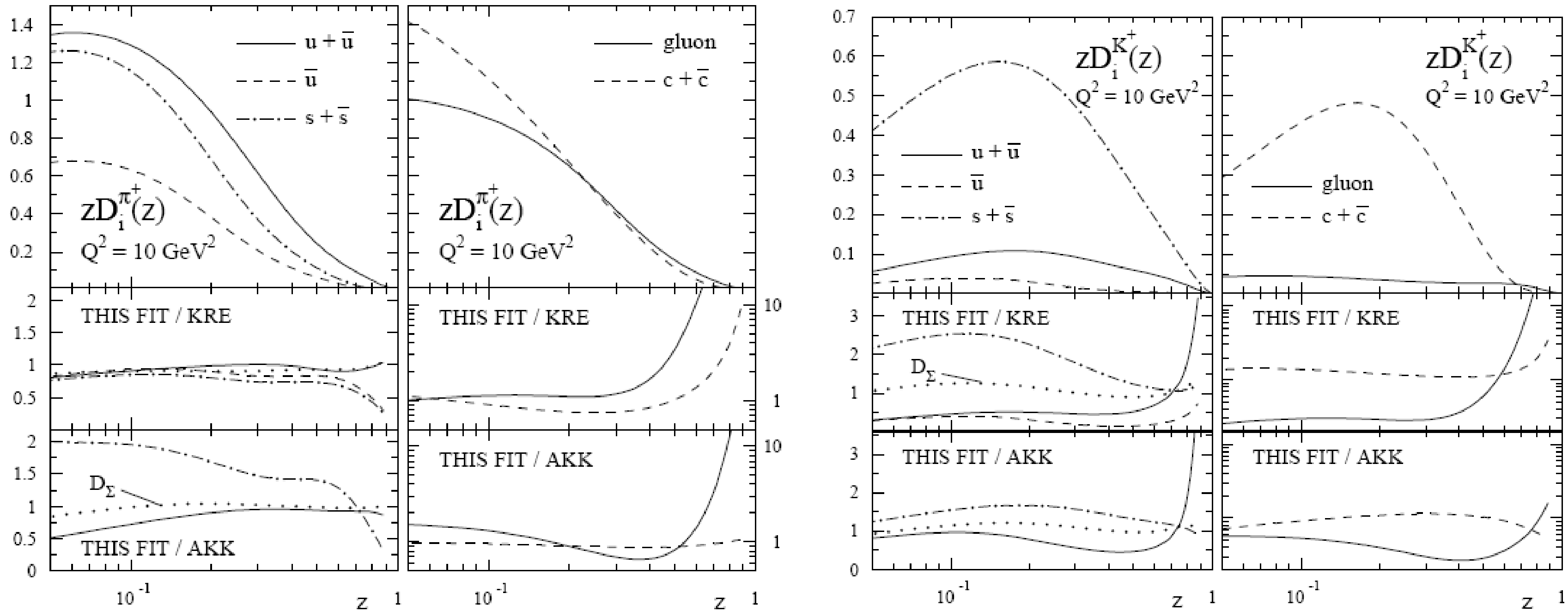


- Most data obtained at LEP energies,
- At lower CMS energies very little data available
- 3-jet fragmentation to access gluon FF theoretically difficult

➔Gluon fragmentation from evolution not yet well

Current knowledge on fragmentation functions - DSS

DeFlorian, Sassot, Stratmann, PRD hep-ph/0703242



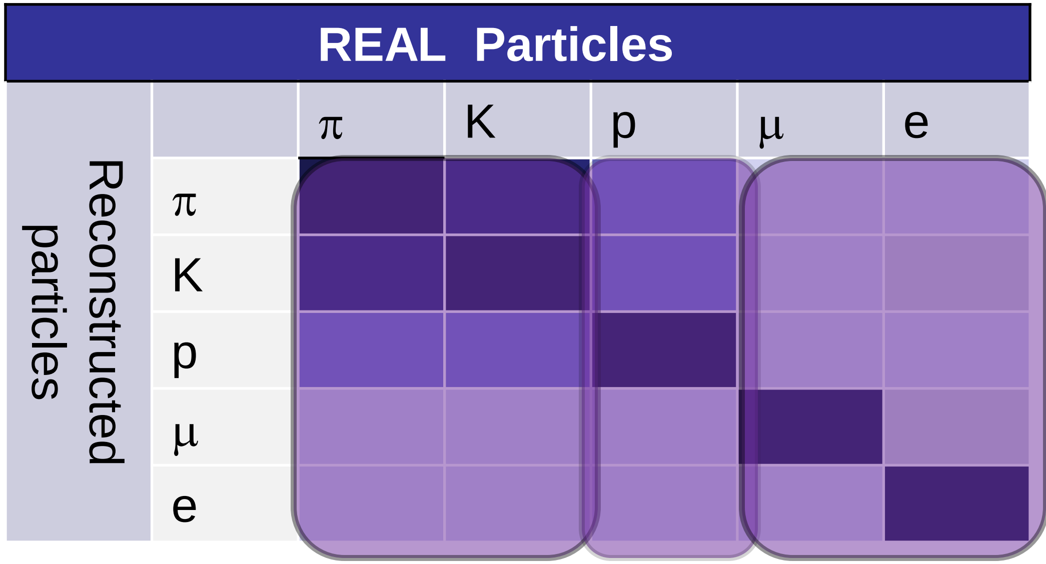
Differences between different global fits still large for high-z gluon contributions and kaons

Systematic studies: Particle identification

- Particle identification:

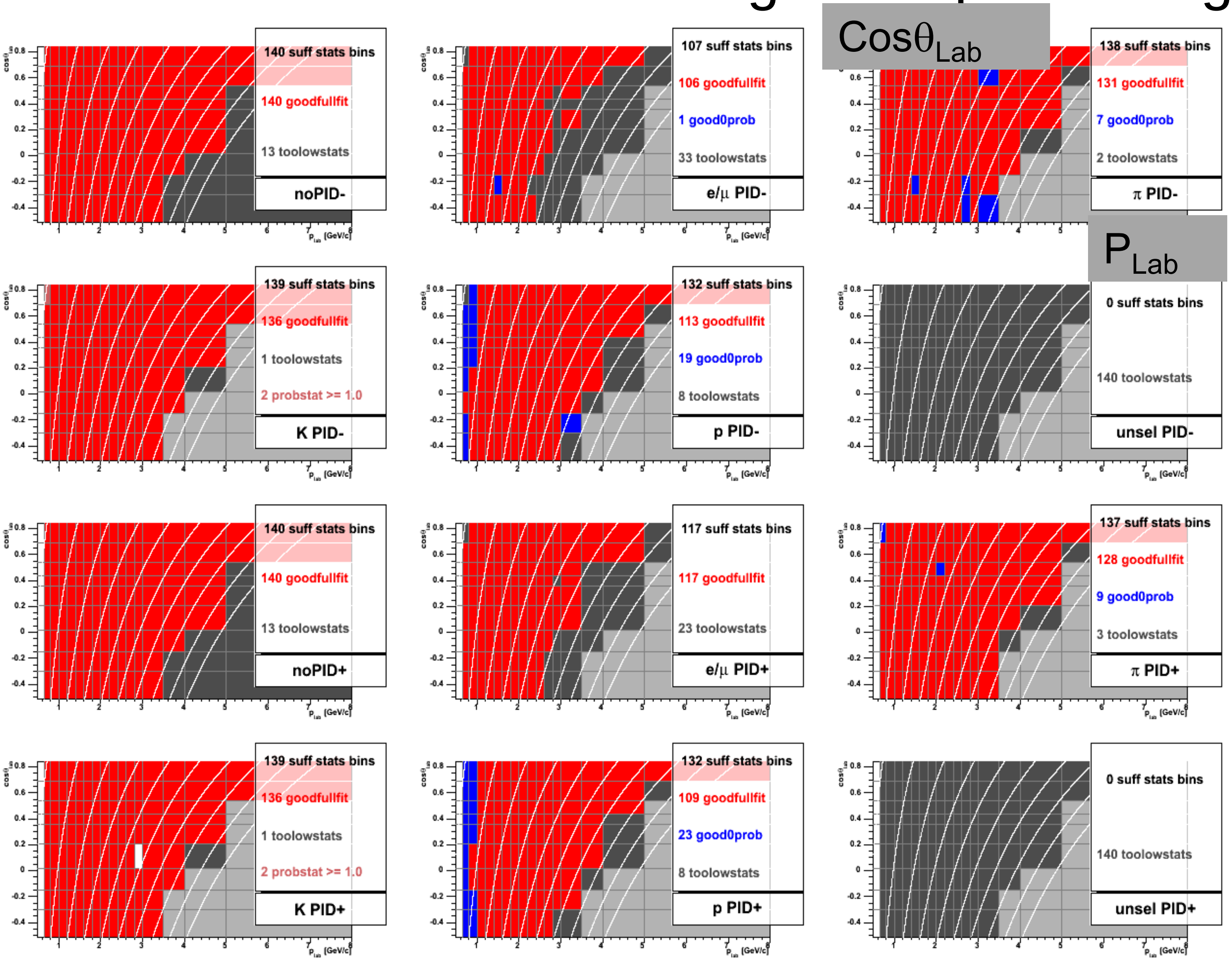
  create PID efficiency matrix for K,π,p,e,μ
- PID responses from MC not reliable, use well identified decays from data:
  - Use $D^{*} \rightarrow \pi_{slow} D^{0} \rightarrow \pi_{slow}\pi_{fast}K$ for K,π identification
  - Use $\Lambda \rightarrow \pi p$ for p,π identification
  - $J/\psi \rightarrow \mu^{+}\mu^{-}$, $e^{+}e^{-}$ for leptons

$$\begin{pmatrix} N_e^{likelihood-cut} \\ N_\mu^{likelihood-cut} \\ N_\pi^{likelihood-cut} \\ N_K^{likelihood-cut} \\ N_P^{likelihood-cut} \end{pmatrix} = \begin{pmatrix} \epsilon_{e\rightarrow e} & \epsilon_{e\rightarrow\mu} & \epsilon_{e\rightarrow\pi} & \epsilon_{e\rightarrow K} & \epsilon_{e\rightarrow P} \\ \epsilon_{\mu\rightarrow e} & \epsilon_{\mu\rightarrow\mu} & \epsilon_{\mu\rightarrow\pi} & \epsilon_{\mu\rightarrow K} & \epsilon_{\mu\rightarrow P} \\ \epsilon_{\pi\rightarrow e} & \epsilon_{\pi\rightarrow\mu} & \epsilon_{\pi\rightarrow\pi} & \epsilon_{\pi\rightarrow K} & \epsilon_{\pi\rightarrow P} \\ \epsilon_{K\rightarrow e} & \epsilon_{K\rightarrow\mu} & \epsilon_{K\rightarrow\pi} & \epsilon_{K\rightarrow K} & \epsilon_{K\rightarrow P} \\ \epsilon_{P\rightarrow e} & \epsilon_{P\rightarrow\mu} & \epsilon_{P\rightarrow\pi} & \epsilon_{P\rightarrow K} & \epsilon_{P\rightarrow P} \end{pmatrix} \begin{pmatrix} N_e^{real} \\ N_\mu^{real} \\ N_\pi^{real} \\ N_K^{real} \\ N_P^{real} \end{pmatrix}$$



D* Extraction

final extraction: large acceptance region covere



K^-

K^+

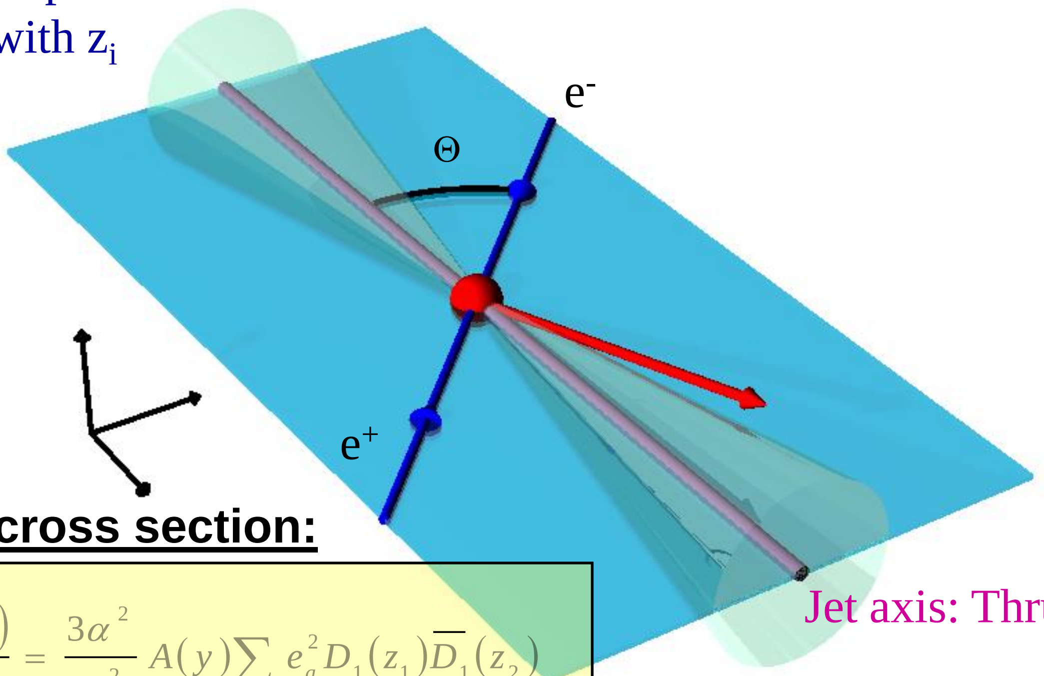
Event Structure for hadron pairs in e^+e^- annihilation

<u>e^+e^- CMS frame:</u>

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

Near-side Hemisphere:
h_i, $i=1,N_n$ with z_i

$\langle N_{h+,-} \rangle = 6.4$



<u>Spin averaged cross section:</u>

$$\frac{d\sigma\left(e^+e^- \rightarrow h_1 h_2 X\right)}{d\Omega\, dz_1 dz_2} = \frac{3\alpha^2}{Q^2} A(y) \sum_{a,\bar{a}} e_a^2 D_1(z_1) \overline{D_1}(z_2)$$

$$A(y) = \left(\frac{1}{2} - y + y^2\right) \stackrel{(cm)}{=} \frac{1}{4}\left(1 + \cos^2\Theta\right)$$

Unpolarized 2-hadron fragmentation

Favored	= u→π^+,d→π^-,cc.
Unfavored	= d→π^+,u→π^-,cc.

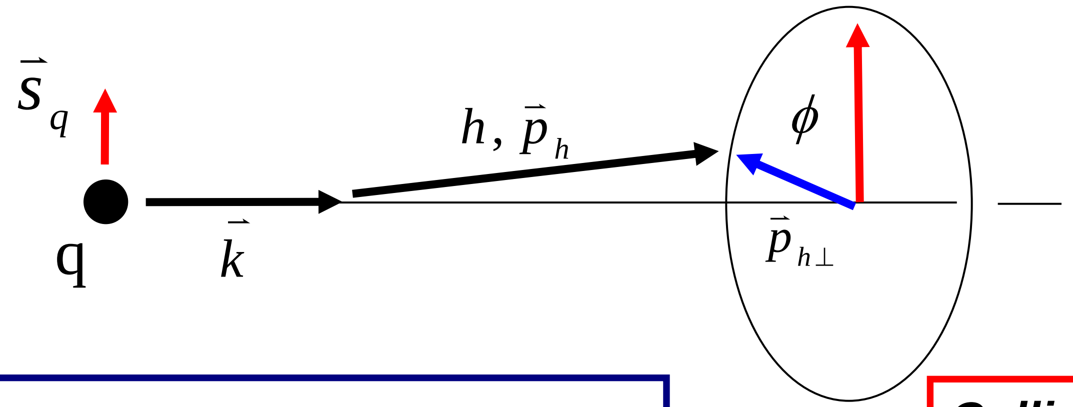
- Detect two hadrons simultaneously
- If two hadrons in opposite hemispheres one obtains sensitivity

- Problems:
  - Either need to ensure two-jet topology (thrust cut)

- Unlike-sign pion pairs (U):
  (favored x favored + unfavored x unfavored)
- Like-sign pion pairs (L):
  (favored x unfavored + unfavored x favored)
- $\pi^\pm\pi^0$ or any charge hadron pairs (C):
  (favored + unfavored) x (favored + unfavored)

Collins effect in quark fragmentation

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



$\vec{k}$: quark momentum

$\vec{s}_q$: quark spin

$\vec{p}_h$: hadron momentum

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

$z_h = E_h / E_q$

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

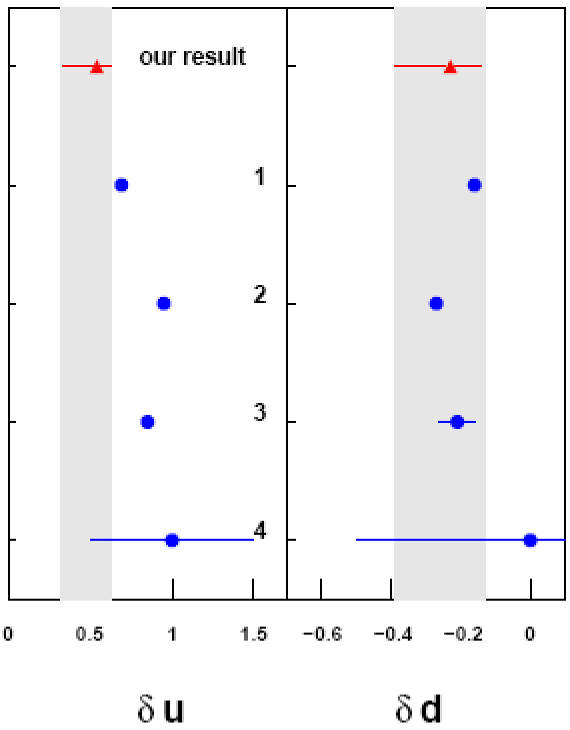
Collins Effect:

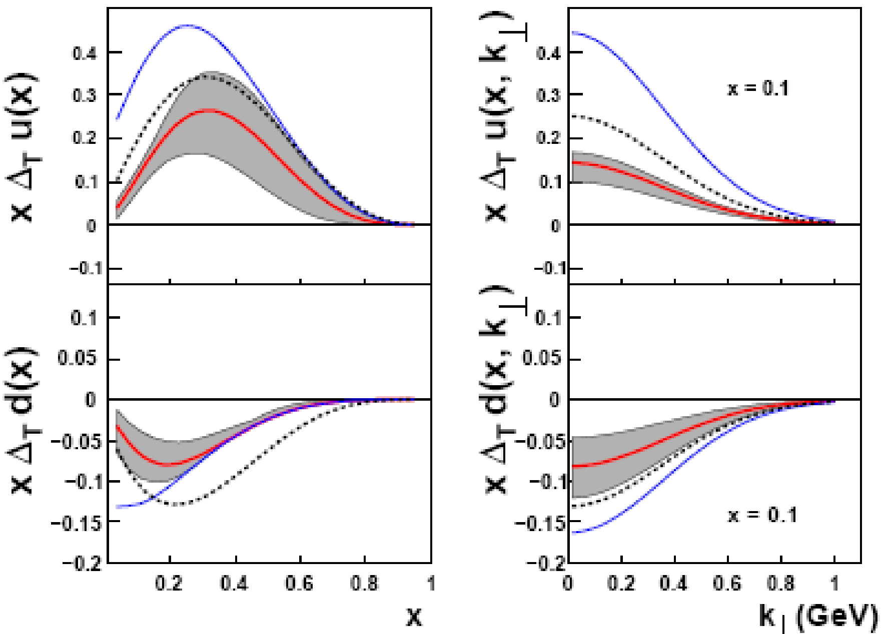
Fragmentation with of a quark *q* with spin s_q into a spinless hadron *h* carries an azimuthal dependence:

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

$$\propto \sin\phi$$

First global analysis from Collins Hermes, Compass d and Belle data

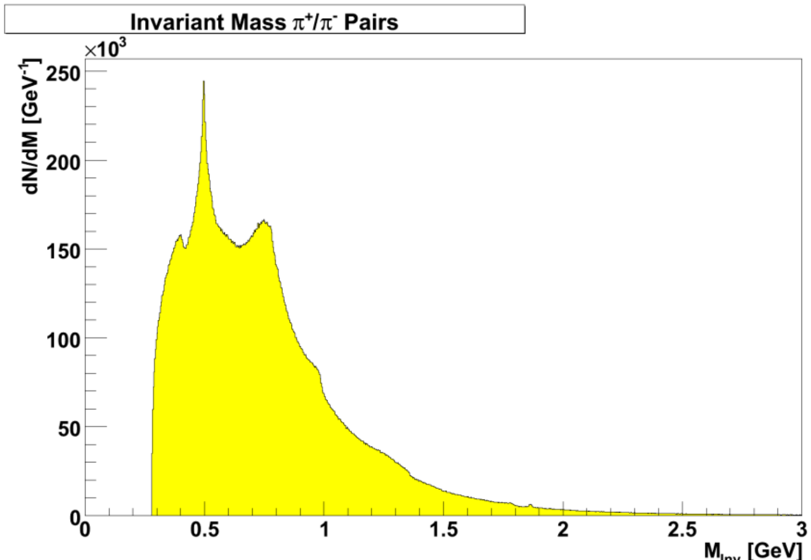


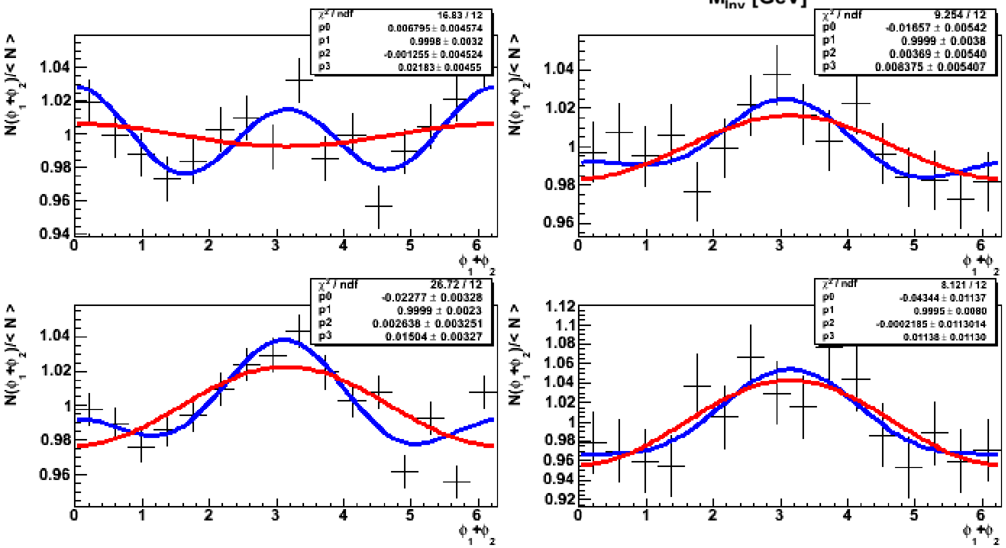


Phys.Rev.D75:054032,2007, update in Nucl.Phys.Proc.Suppl.1 91:98-107,2009

- First results available, still open questions from evolution of Collins FF and transverse momentum dependence

Asymmetry extraction





- Build normalized yields: $\frac{N(\phi_1+\phi_2)}{\langle N \rangle}$,

- Fit with:

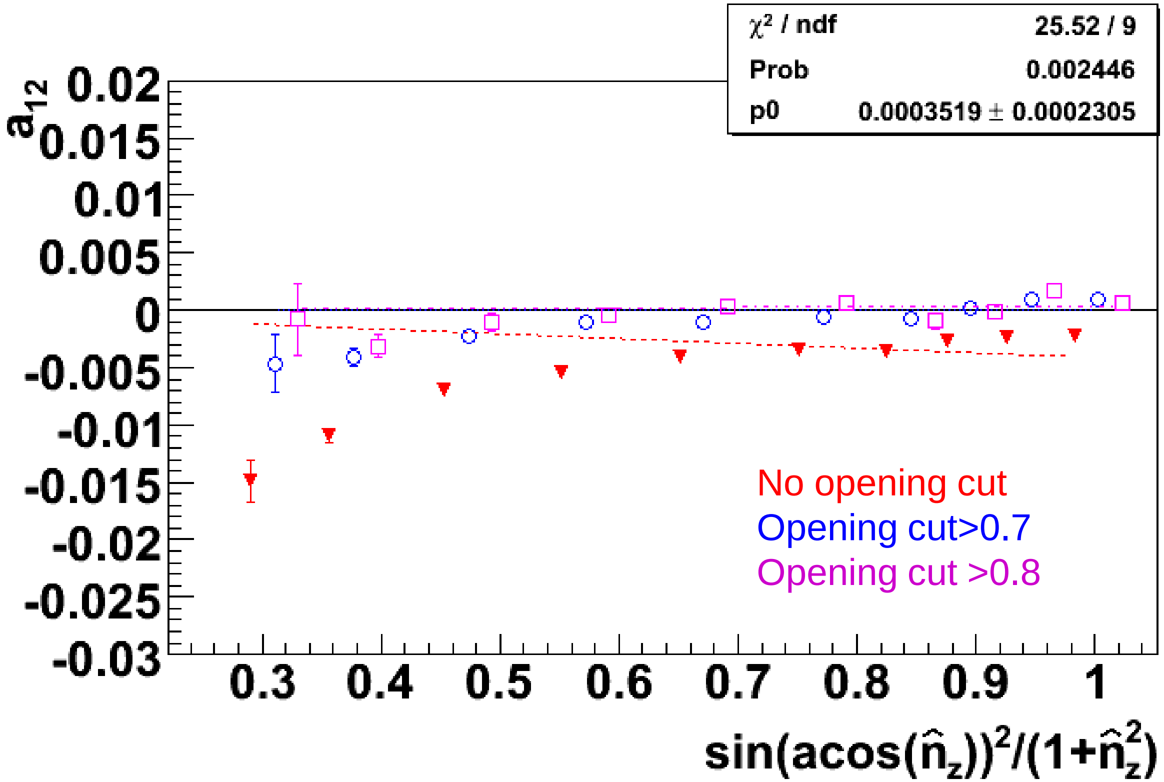
$$a_{12}\cos(\phi_1+\phi_2)+b_{12}$$

or

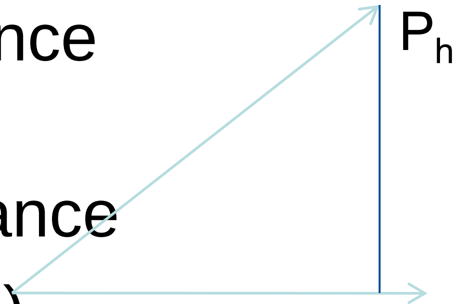
$$a_{12}\cos(\phi_1+\phi_2)+b_{12}+ c_{12}\cos 2(\phi_1+\phi_2)+d_{12}\sin(\phi_1+\phi_2)$$

Amplitude a_{12} directly measures IFF!
(squared, no double ratios)

Zero tests: MC

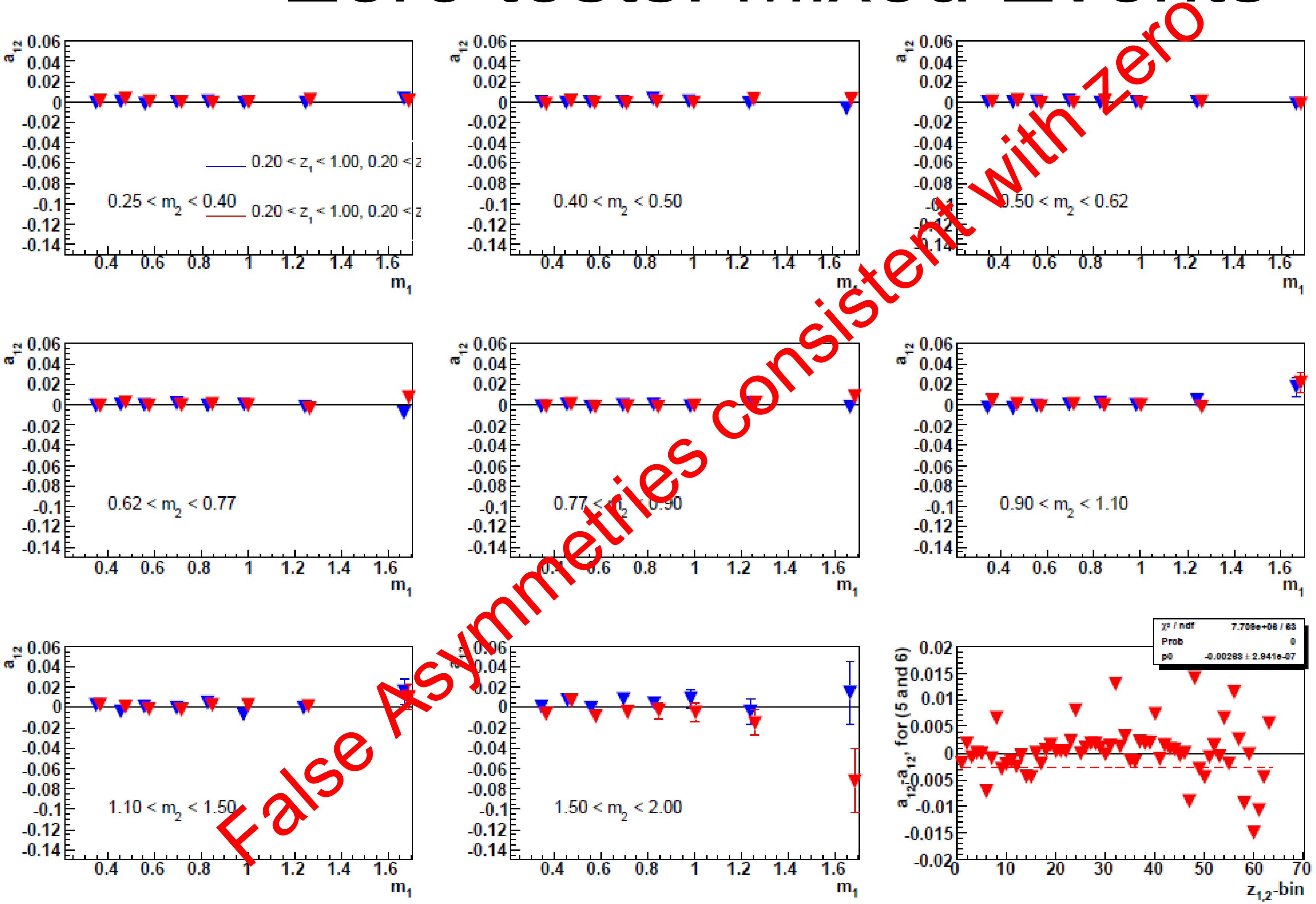


- A small asymmetry seen due to acceptance effect
- Mostly appearing at boundary of acceptance
- Opening cut in CMS of 0.8 (~37 degrees) reduces acceptance effect to the sub-per-mille level



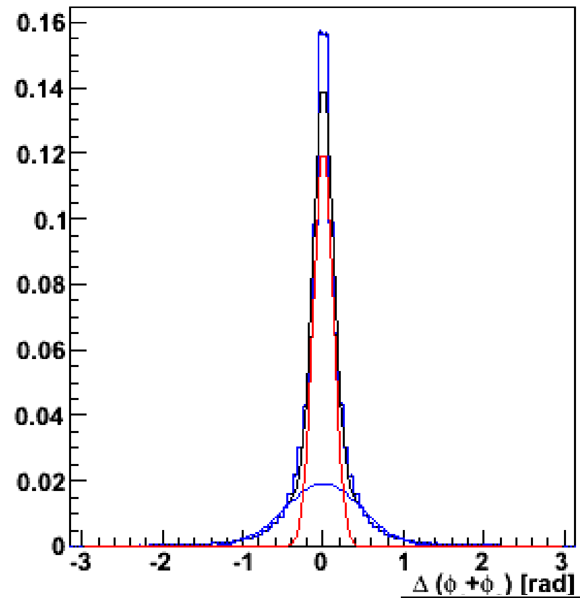
$$\frac{P_h \bullet \hat{n}}{|P_h|} = \cos(P, n)$$ 43

Zero tests: Mixed Events

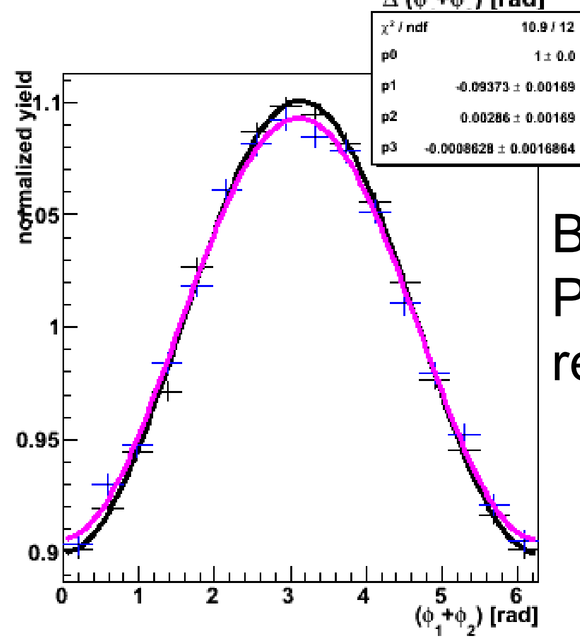


Weighted MC asymmetries

- Inject asymmetries in Monte Carlo
- Reconstruction smears thrust axis,
- ~94% of input asymmetry is reconstructed
- (Integrated over thrust axis: 98%)
- Effect is understood, can be reproduced in Toy MC
- Asymmetries



Smearing
In azimuthal
Angle of
thrust
Axis in CMS



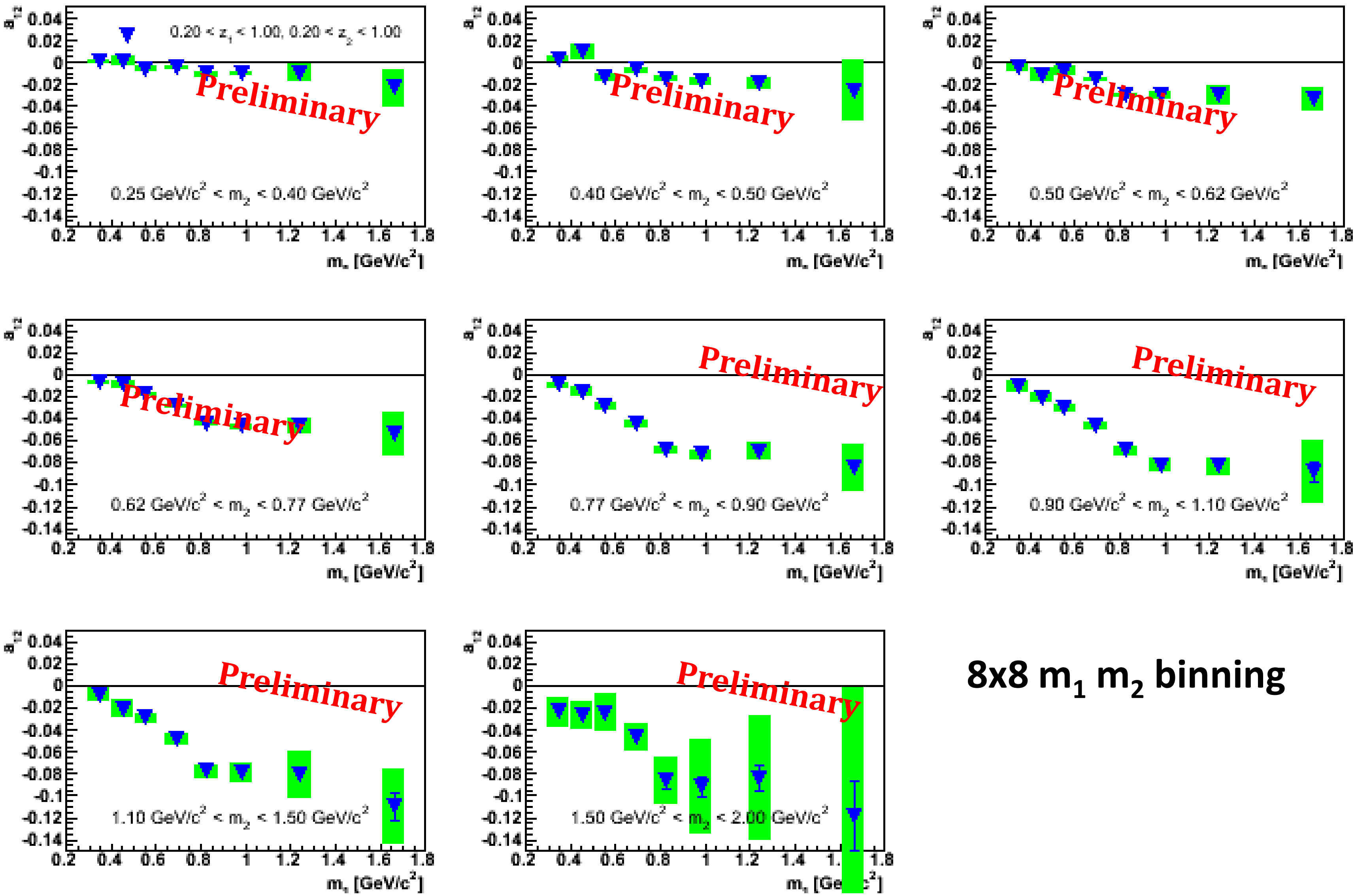
Black: injected
Purple
reconstructed

Cuts and Binning

- Similar to Collins analysis, full off-resonance and on-resonance data

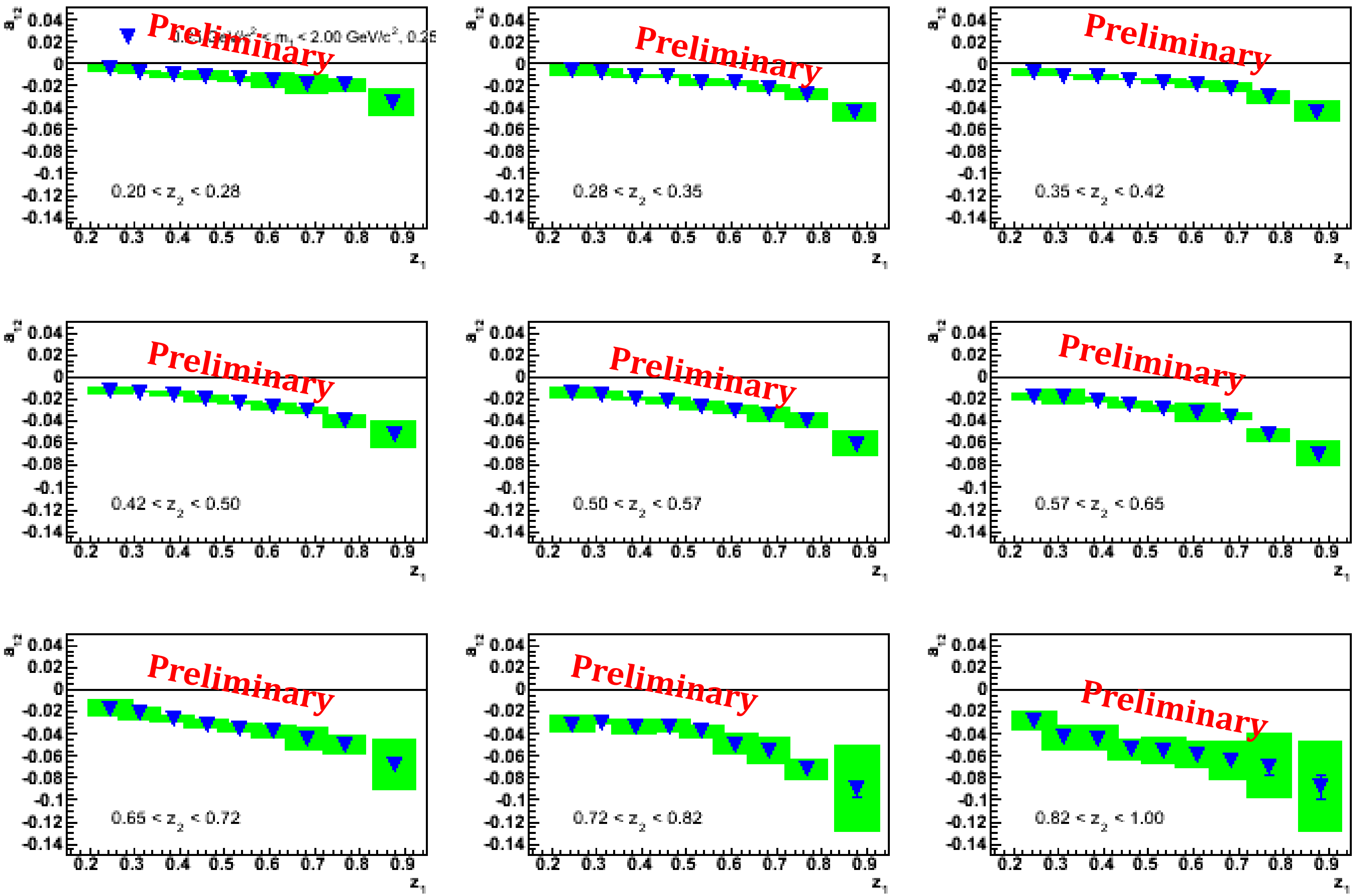
  (7-55): ~73 fb^{-1} + 588 fb^{-1}
- Visible energy >7GeV
- PID: Purities in Pion/Pion Sample > 90%
- Same Hemisphere cut within pair ($\pi^+\pi^-$), opposite hemisphere between pairs
- All 4 hadrons in barrel region: $-0.6 < \cos(\theta) < 0.9$
- Thrust axis in central area: abs(thrustz)<0.75
- Thrust > 0.8
- $z_{had1,had2} > 0.1$

Results including systematic errors



8x8 m_1 m_2 binning

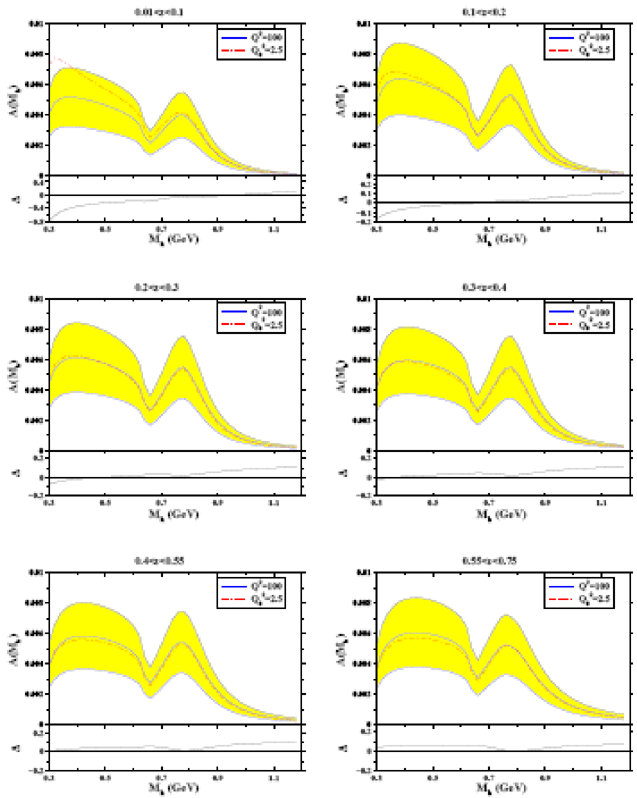
Results for 9x9 z_1 z_2 binning



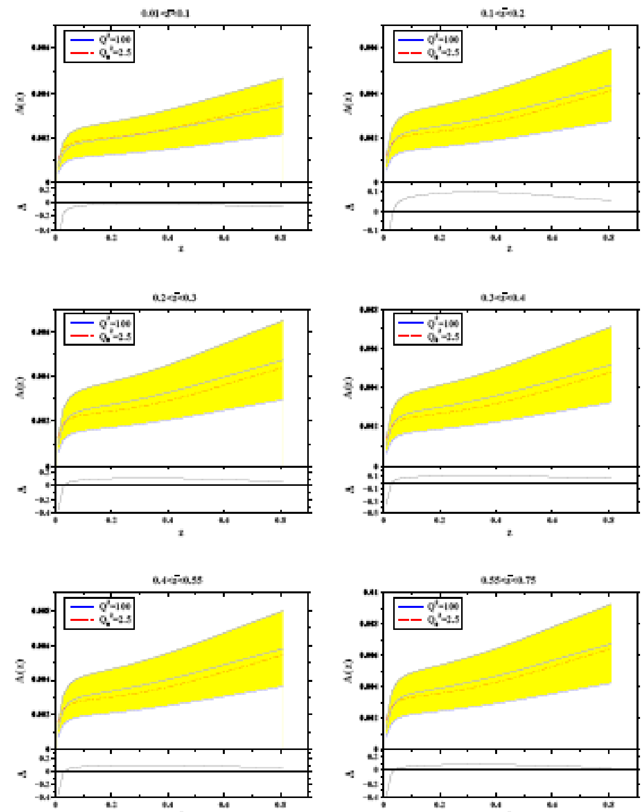
Model predictions for e^+e^-

Bacchetta,Checcopieri, Mukherjee, Radici : **Phys.Rev.D79:034029,2009**.

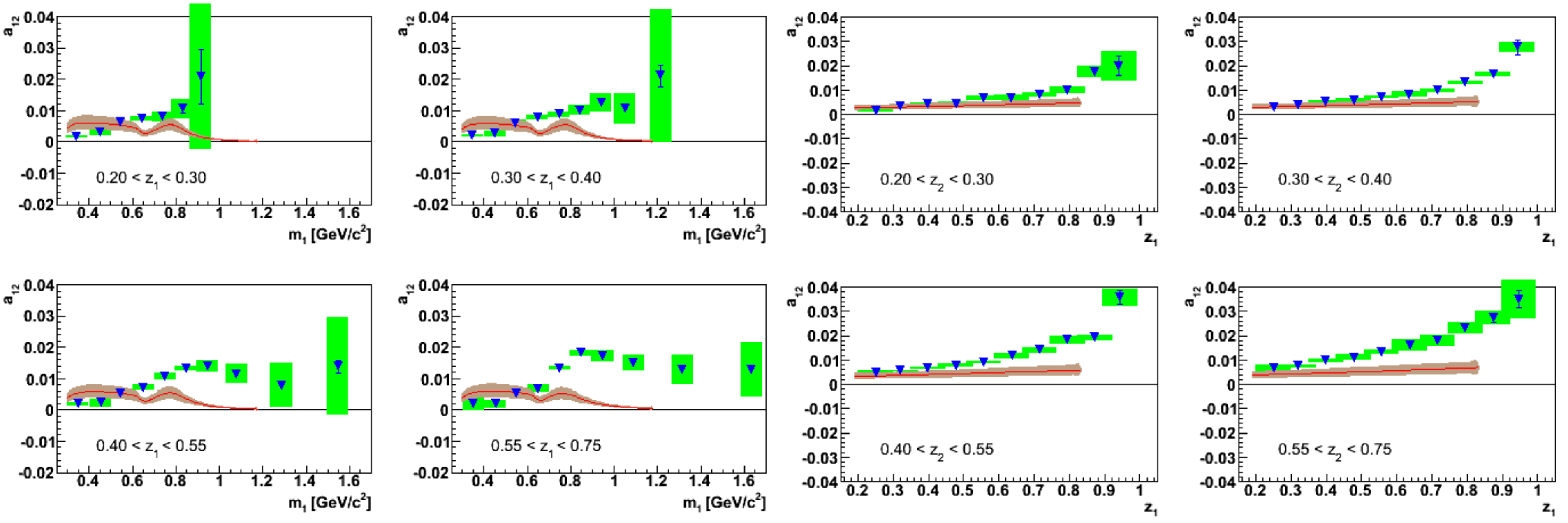
Invariant mass$_1$ dependence for increasing z



z_1 dependence for increasing z_2



Comparison to theory predictions



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

Applied cuts, binning

- Off-resonance data
  - 60 MeV below Υ(4S) resonance
  - 29.1 fb^{-1}

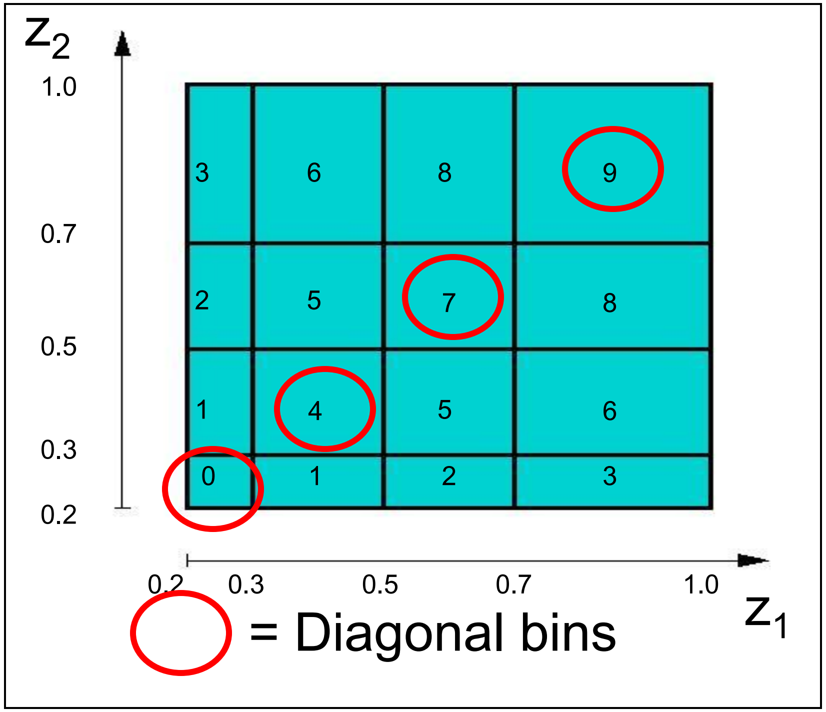
→ Later also on-resonance data: 547 fb^{-1}

- Track selection:
  - pT > 0.1GeV
  - vertex cut: dr<2cm, |dz|<4cm
- Acceptance cut
  - $-0.6 < \cos\theta_i < 0.9$
- Event selection:
  - Ntrack ≥ 3
  - Thrust > 0.8
  - $Z_1, Z_2 > 0.2$

- Hemisphere cut

$$(P_{h2}\cdot\hat{n})\hat{n}\cdot(P_{h1}\cdot\hat{n})\hat{n} < 0$$

- $Q_T < 3.5$ GeV



Other Favored/Unfavored Combinations →charged pions or π^0

Challenge: current double ratios not very sensitive to favored to disfavored Collins function ratio ➔ Examine other combinations:

- Unlike-sign pion pairs (U):
  (favored x favored + unfavored x unfavored)
- Like-sign pion pairs (L):
  (favored x unfavored + unfavored x favored)
- $\pi^{\pm}\pi^0$ pairs
  (favored + unfavored) x (favored + unfavored)
- P.Schweitzer(**[hep-ph/0603054]**): charged ππ pairs are similar

UL

UC

(and easier to handle) (C):

➔Build new double ratios

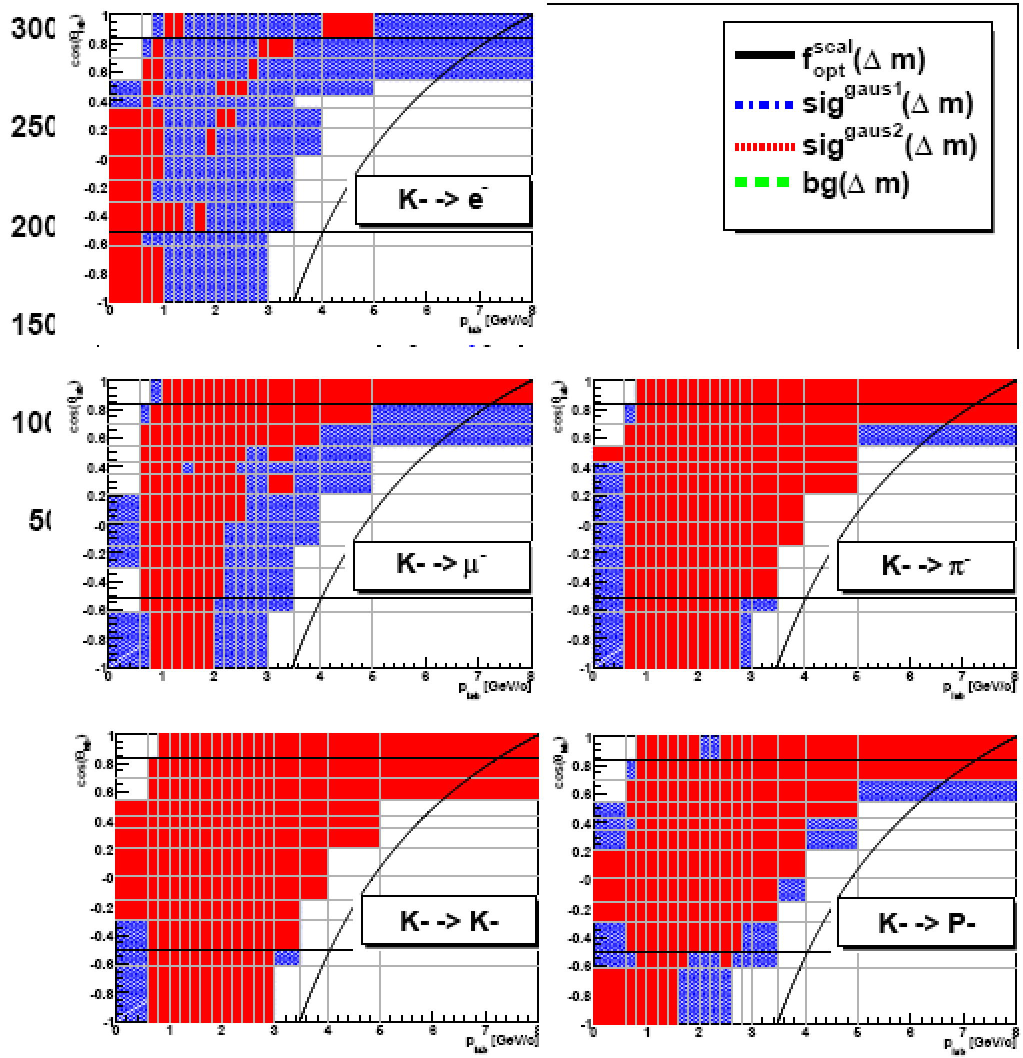
(favored + unfavored) x (f

➔Unlike-sign/charged ππ pairs (UC)

Favored	= u→π^+,d→π^-,cc.
Unfavored	= d→π^+,u→π^-,cc.

D^* analysis

- Measure signal N^i and yield contributions in Fit of $\Delta m(D^*\text{-}m(K,\pi_{fast}))$ distribution to obtain real K, π yields
- Repeat Fits for particular particle likelihood selection

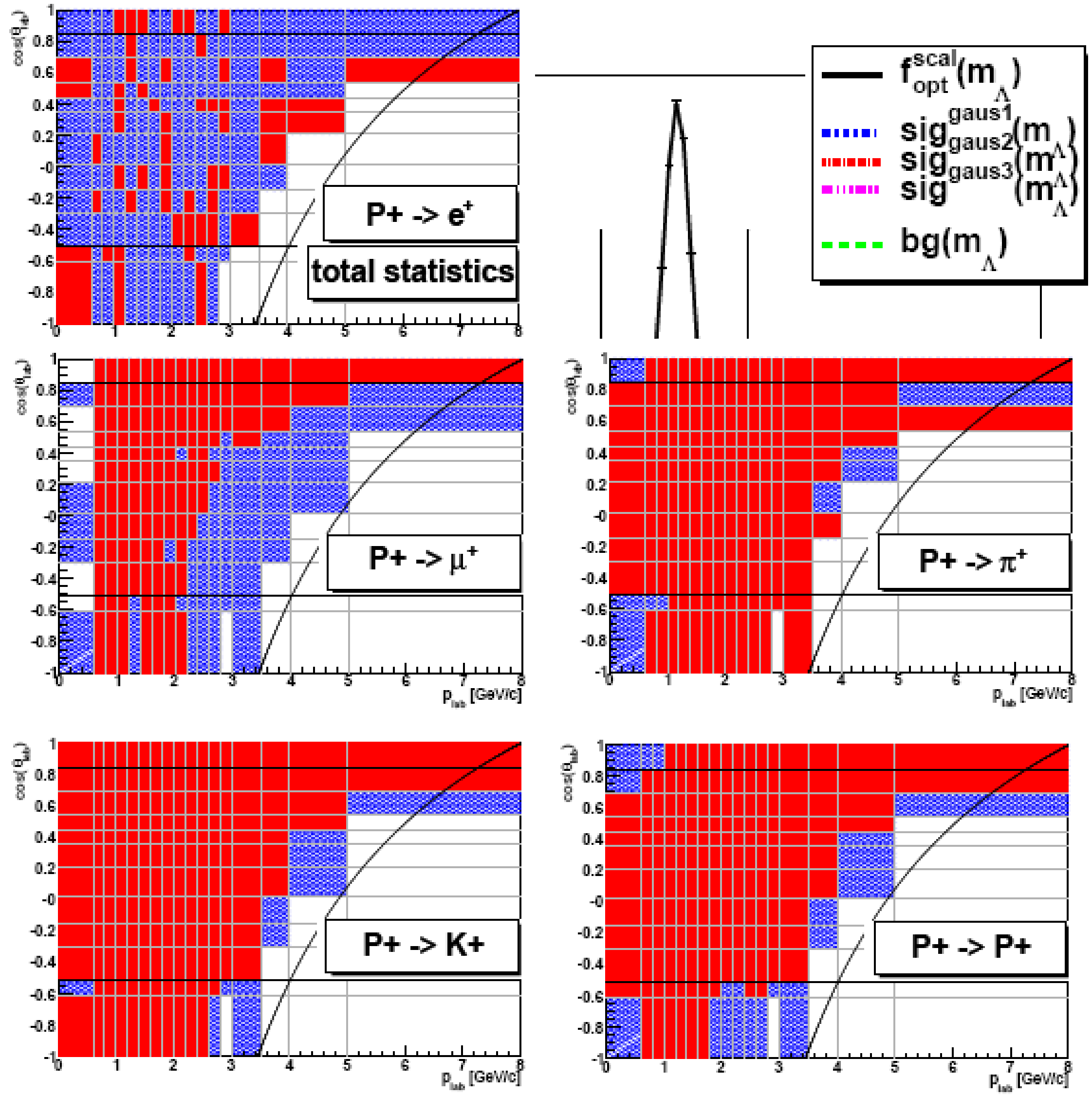


Further FF measurements

- Additional FF measurements planned:
  - π^0 (cross check with completely different systematics)
  - η (PHENIX A_{LL} measurement available, higher strange content??)
  - Other decaying particles (K_S,f^0,γ…?)
  - $\mathbf{k_t}$ dependent FFs

Λ analysis, leptons

- Similarly calculate efficiencies from m(Pπ) distribution
- Most kinematic regions well covered
- So far: lepton efficiencies from MC,
  in the future: extract

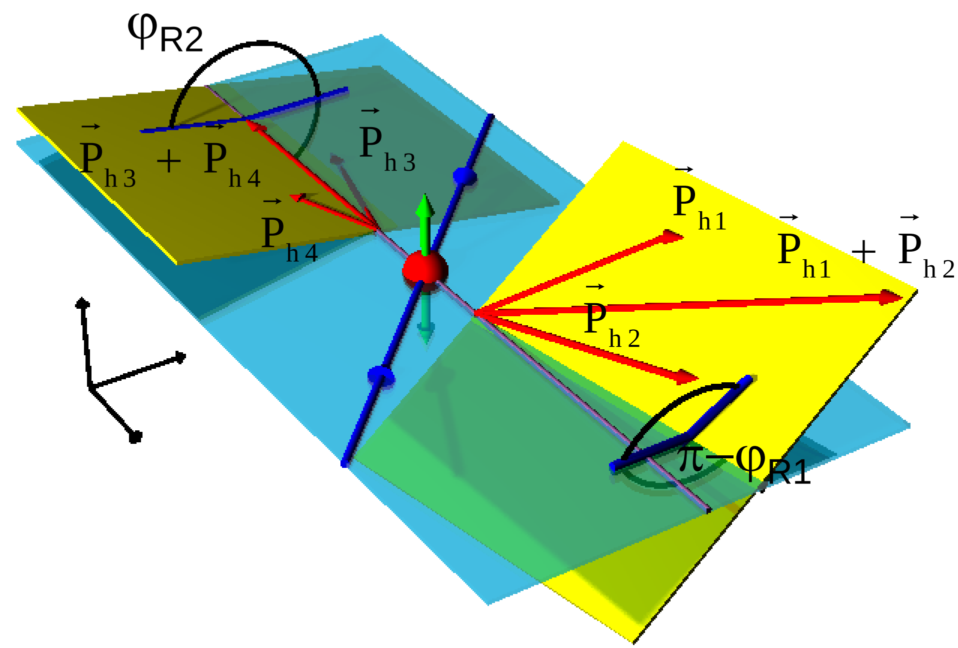


Interference Fragmentation – "ϕ_0 " method

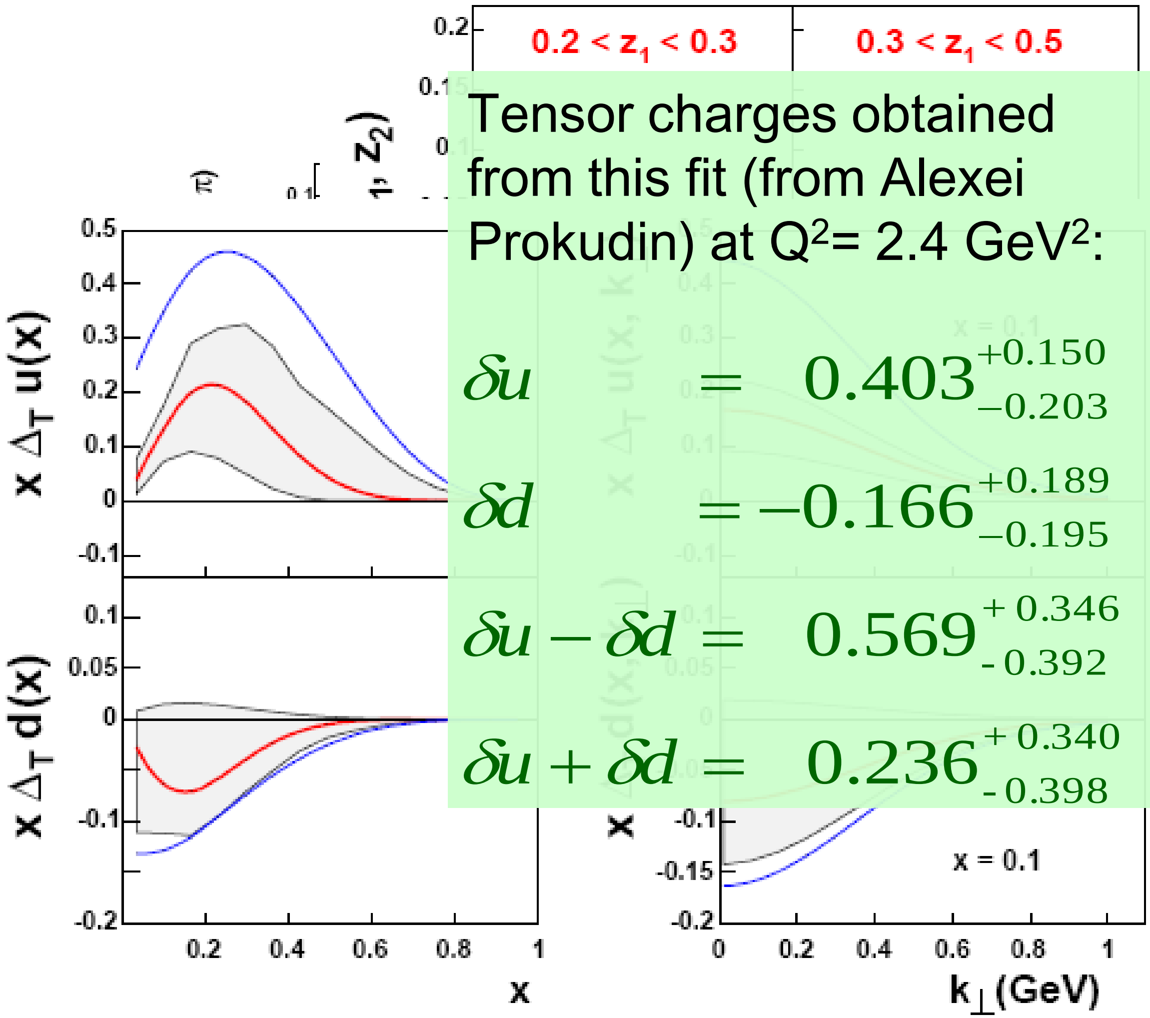
- Similar to previous method
- Observe angles $\varphi_{1R}+\varphi_{2R}$ between the event-plane (beam, two-pion-axis) and the two two-pion planes.

$$A \propto H_1^{\angle}(z_1, m_1)\overline{H}_1^{\angle}(z_2, m_2)\, cos\,(\varphi_{1R} + \varphi_{2R})$$

- Theoretical guidance by Boer, Jakob, Radici



First successful attempt at a global analysis for the transverse SIDIS and the BELLE Collins data



Tensor charges obtained from this fit (from Alexei Prokudin) at Q^2= 2.4 GeV^2:

$$\delta u = 0.403^{+0.150}_{-0.203}$$

$$\delta d = -0.166^{+0.189}_{-0.195}$$

$$\delta u - \delta d = 0.569^{+0.346}_{-0.392}$$

$$\delta u + \delta d = 0.236^{+0.340}_{-0.398}$$

- HERMES A_{UT} p data
- COMPASS A_{UT} d data
- Belle $e^+ e^-$ Collins data
- Kretzer FF

➔ First extraction of transversity (up to a

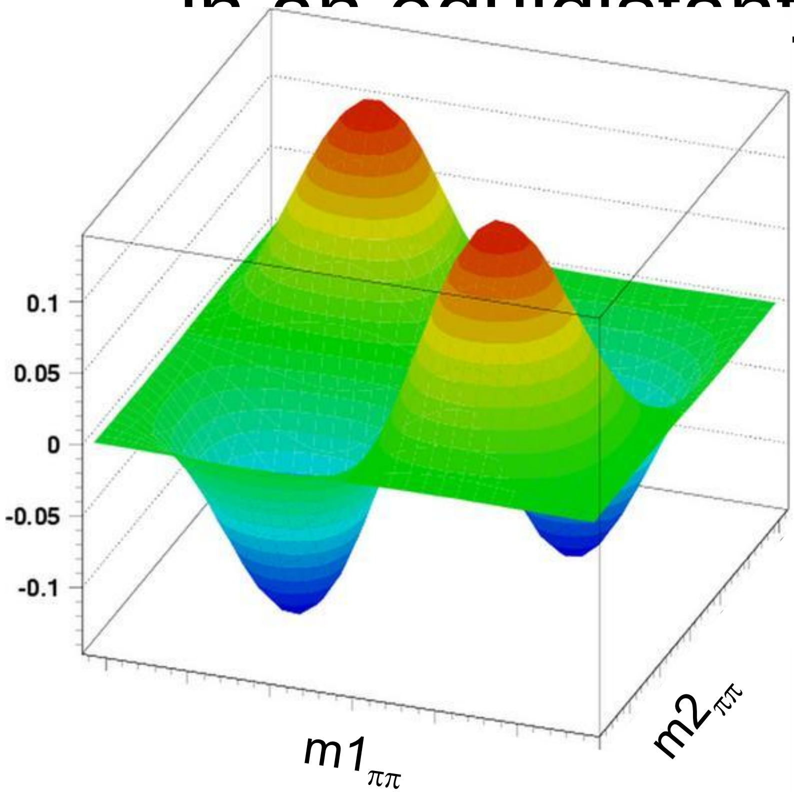
Anselmino et al: hep-ex 0701006

Cuts and Binning

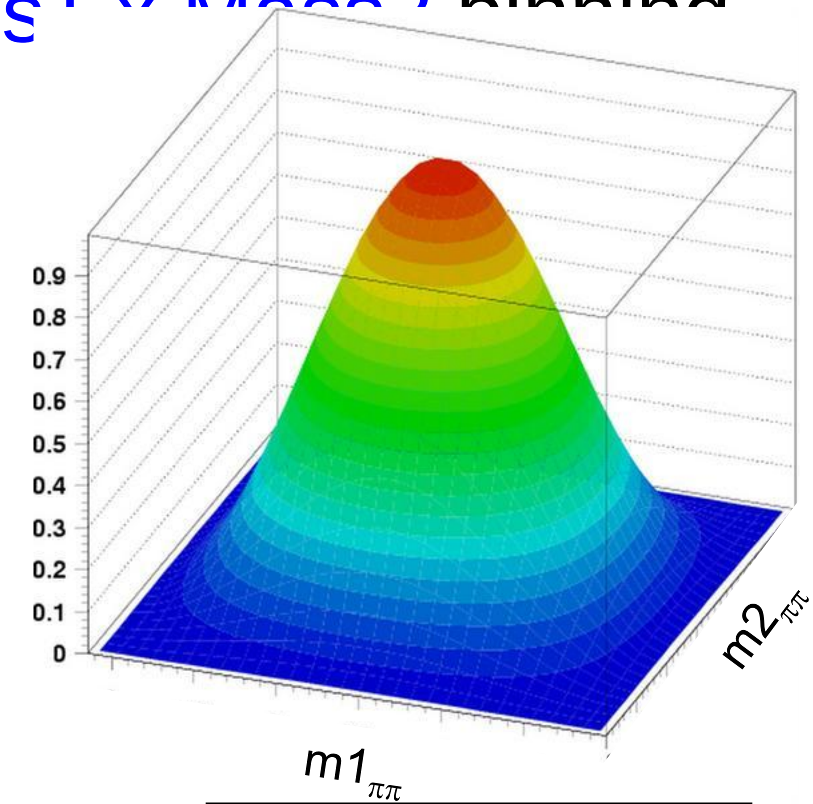
- Similar to Collins analysis, full off-resnanance data(7-55): ~60 fb^{-1}
- HadronB(J) skim
- visible energy >7GeV
- PID:
  - e veto:eid>0.8
  - μ veto:mu_like>0.9&&mu_chi2!=0.
  - p veto:kpr<0.2
  - π: kpi<0.3
  - K: kpi>0.6
- Hemisphere cut between pairs
- $z_1 = z_{had1}+z_{had2}$ and z_2 in 5 bins: [0.2 , 0.3 , 0.4 , 0.55 ,0.75, 1]
- $m_{\pi\pi 1}$ and $m_{\pi\pi 2}$ in 5 bins: [0.25 , 0.40 , 0.55 , 0.77 ,1.2,
- $m_{K\pi 1}$ and $m_{\pi K2}$ in 5 bins: [0.5 , 0.7 , 0.9 , 1.2 ,1.6, 2]
- m_{KK1} and m_{KK2} in 5 bins: [0.9 , 1.1 ,1.4, 1.8, 2.2, 3]
- For pairs with charge sum=0 first hadron is positive, second negative, angle and plane defined by $\mathbf{R}=(\mathbf{P}_1-\mathbf{P}_2)/2$
- Same sign pion pairs ordered according to z
- All 4 hadrons in barrel region: $-0.6 < \cos(\theta) < 0.9$
- Trust axis in central area: abs(thrustz)<0.75
- Thrust > 0.8
- $z_{1,2}>0.1$

What would we see in e^+e^-?

Simply modeled the shapes of these predictions in an equidistant Mass1 x Mass2 binning



“Jaffe”

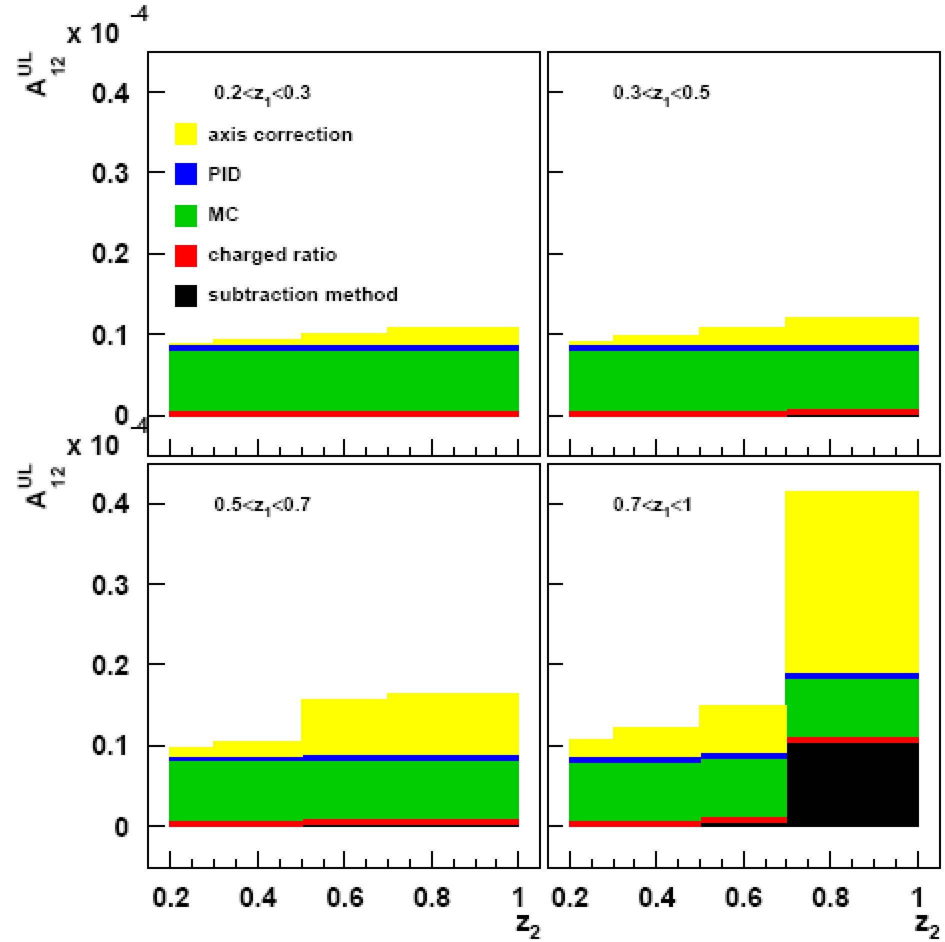


“Radici”

Improved systematic errors

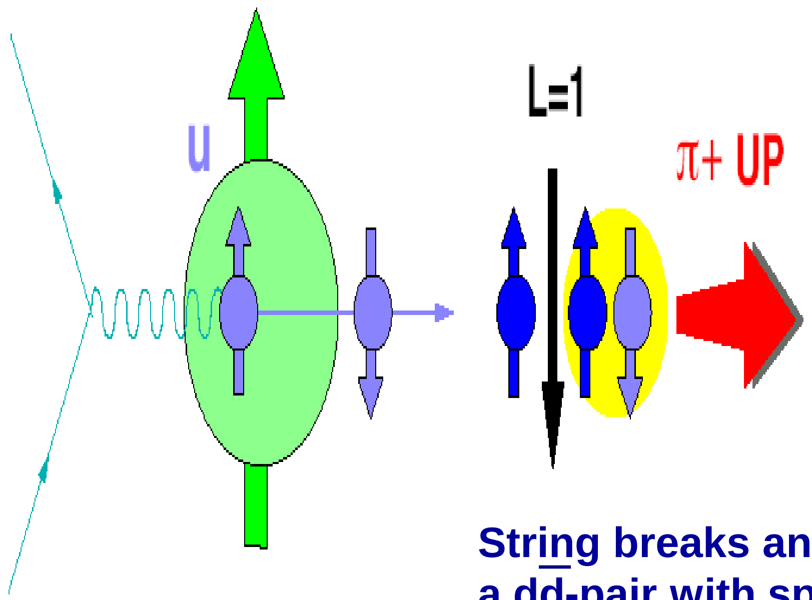
- Tau contribution (not shown)
- Quark axis correction
- PID systematics
- MC uncertainties
- Charged ratios ($\pi^+\pi^+ / \pi^-\pi^-$)
- higher moments in Fit (not

•Beam polarization studies
→consistent with zero
•Correction for charm events



The Collins effect in the Artru fragmentation model

A simple model to illustrate that spin-orbital angular momentum coupling can lead to left right asymmetries in spin-dependent fragmentation:

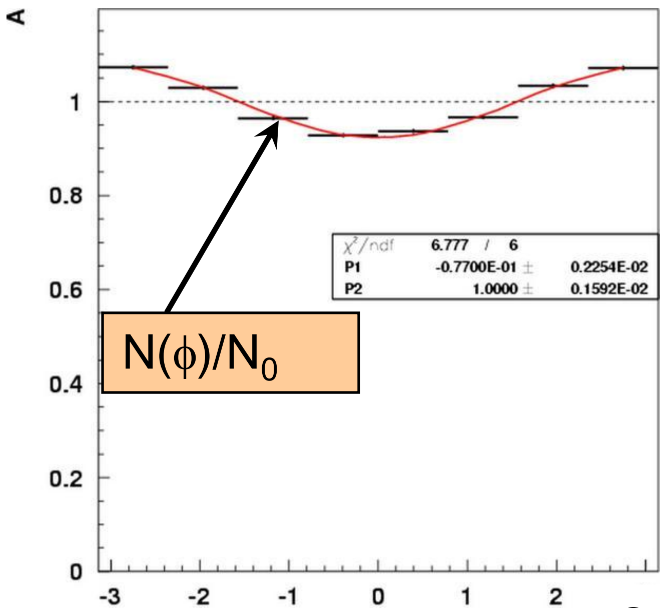


String breaks and a d$\bar{d}$-pair with spin -1 is inserted.

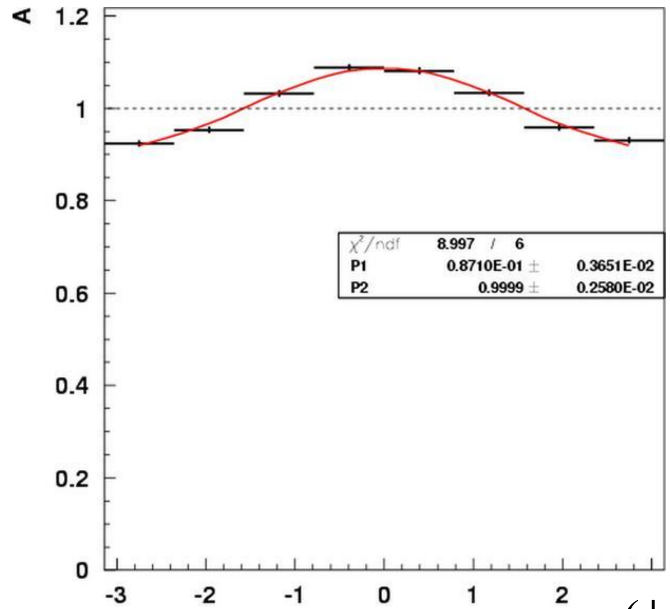
π^+ picks up L=1 to compensate for the pair S=1 and is emitted to the right.

In Artru Model: favored (ie u→π^+) and disfavored (ie u→π^-) Collins function naturally of opposite sign

Examples of fits to azimuthal asymmetries



$2\phi_0$



$(\phi_1+\phi_2)$

- Cosine modulations
- clearly visible
- P1 contains … on on Collins

$$\frac{N(\phi)}{N_0} = \frac{aD_1\overline{D_1} + cos(2\phi)\left(bH_1\overline{H_1} + cD_1\overline{D_1}\right)}{aD_1\overline{D_1}} = P2 + P1\cos(2\phi)$$

D_1: spin averaged fragmentation function,

H_1: Collins fragmentation function

No change in cosine moments when including sine and higher harmonics

Methods to eliminate gluon contributions: Double ratios and subtractions

Double ratio method:

$$R := \frac{\frac{N^{Unlike}(\phi)}{N_0^{Unlike}}}{\frac{N^{Like}(\phi)}{N_0^{Like}}} \approx 1 + F\left(\frac{H_1^{\perp,fav}(z)}{D_1^{fav}(z)}, \frac{H_1^{\perp,unfav}(z)}{D_1^{unfav}(z)}\right) + \mathcal{O}\left(F(Q_T)^2)\right)$$

Pros: Acceptance cancels out

Cons: Works only if effects are small (both gluon radiation and signal)

Subtraction method:

$$S := \frac{N^{Unlike}(\phi)}{N_0^{Unlike}} - \frac{N^{Like}(\phi)}{N_0^{Like}} = F\left(\frac{H_1^{\perp,fav}(z)}{D_1^{fav}(z)}, \frac{H_1^{\perp,unfav}(z)}{D_1^{unfav}(z)}\right)$$

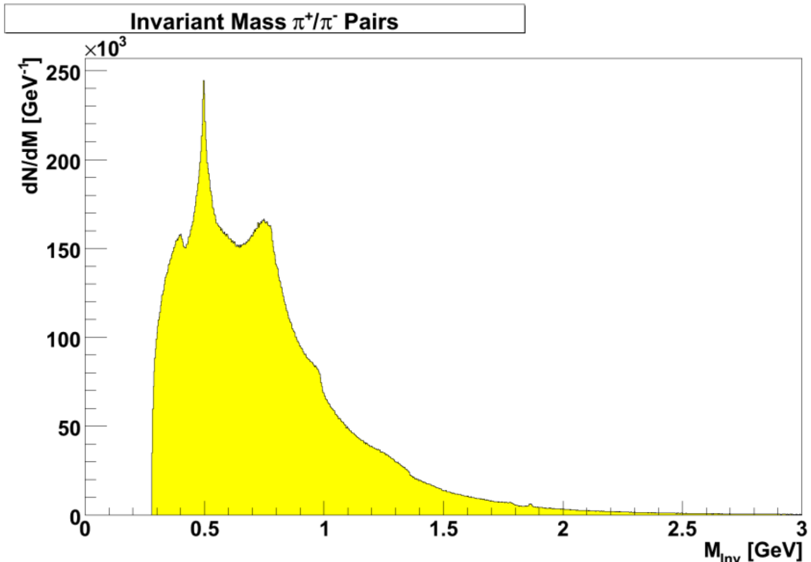
Pros: Gluon radiation cancels out exactly

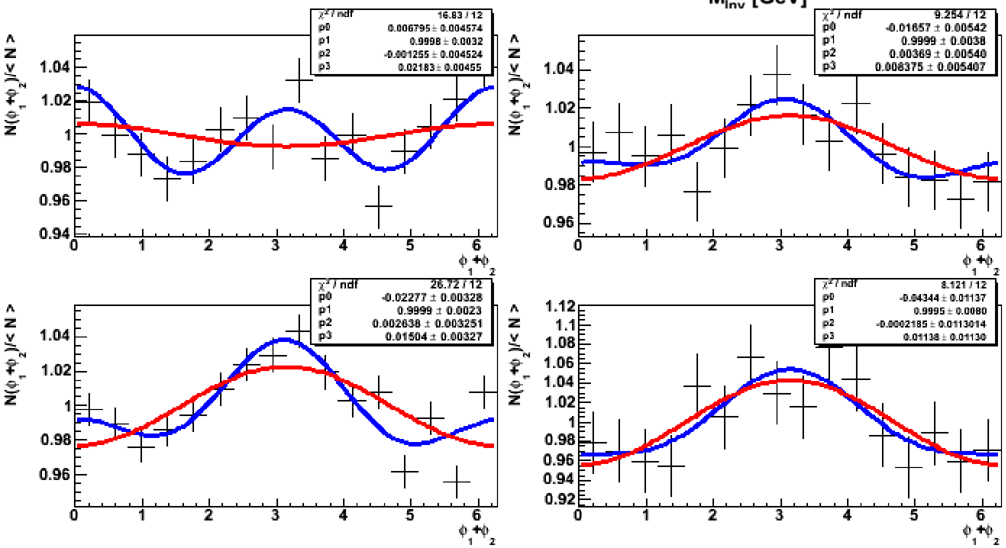
Cons: Acceptance effects remain

2 methods give very small difference in the result

$$A := F = \cos(2\varphi_0)\frac{\sin^2(\theta)}{1+\cos^2(\theta)}\left[\frac{\sum_q e^2(H^{Fav}\cdot\overline{H}^{Fav} + H^{Unf}\cdot\overline{H}^{Unf})}{\sum_q e^2(D^{Fav}\cdot\overline{D}^{Fav} + D^{Unf}\cdot\overline{D}^{Unf})} - \frac{\sum_q e^2(H^{Fav}\cdot\overline{H}^{Unf} + H^{Unf}\cdot\overline{H}^{Fav})}{\sum_q e^2(D^{Fav}\cdot\overline{D}^{Unf} + D^{Unf}\cdot\overline{D}^{Fav})}\right]$$

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:

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

or

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

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

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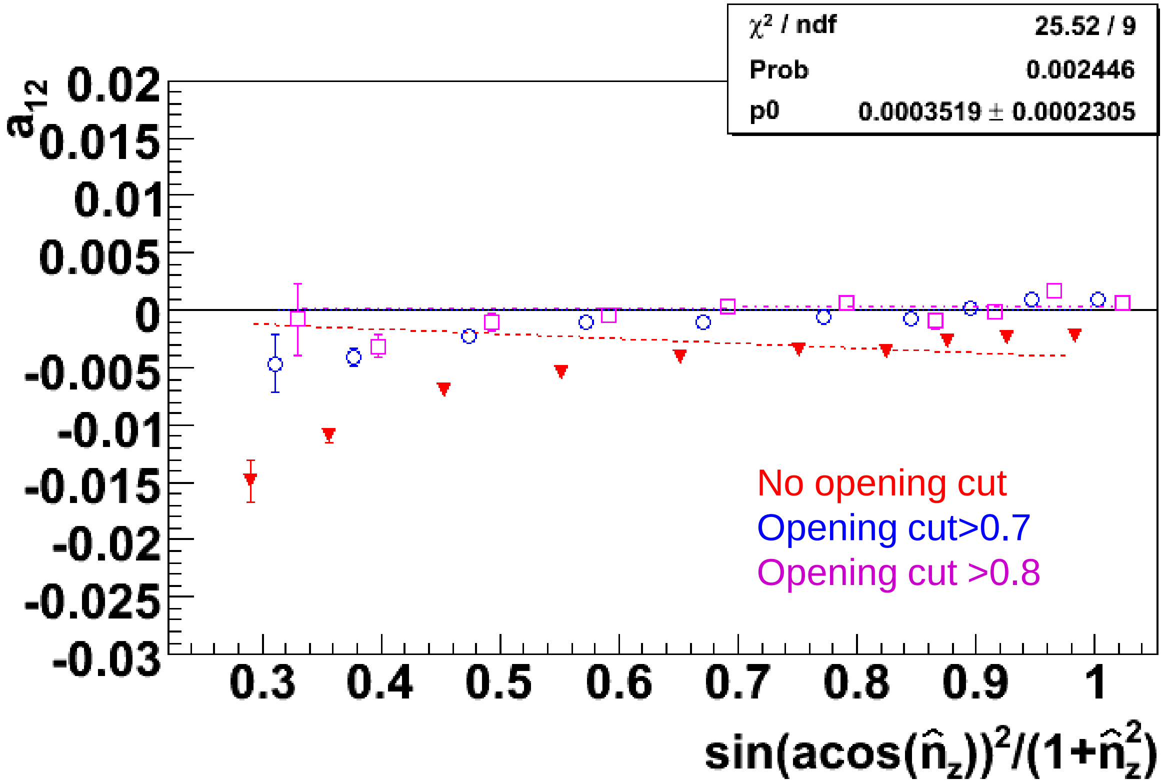
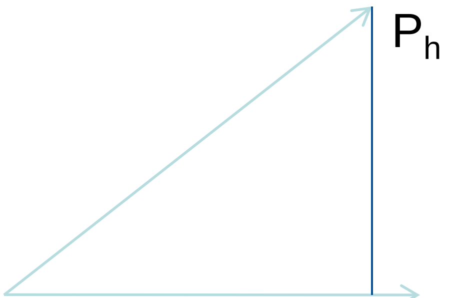
Zero tests: MC

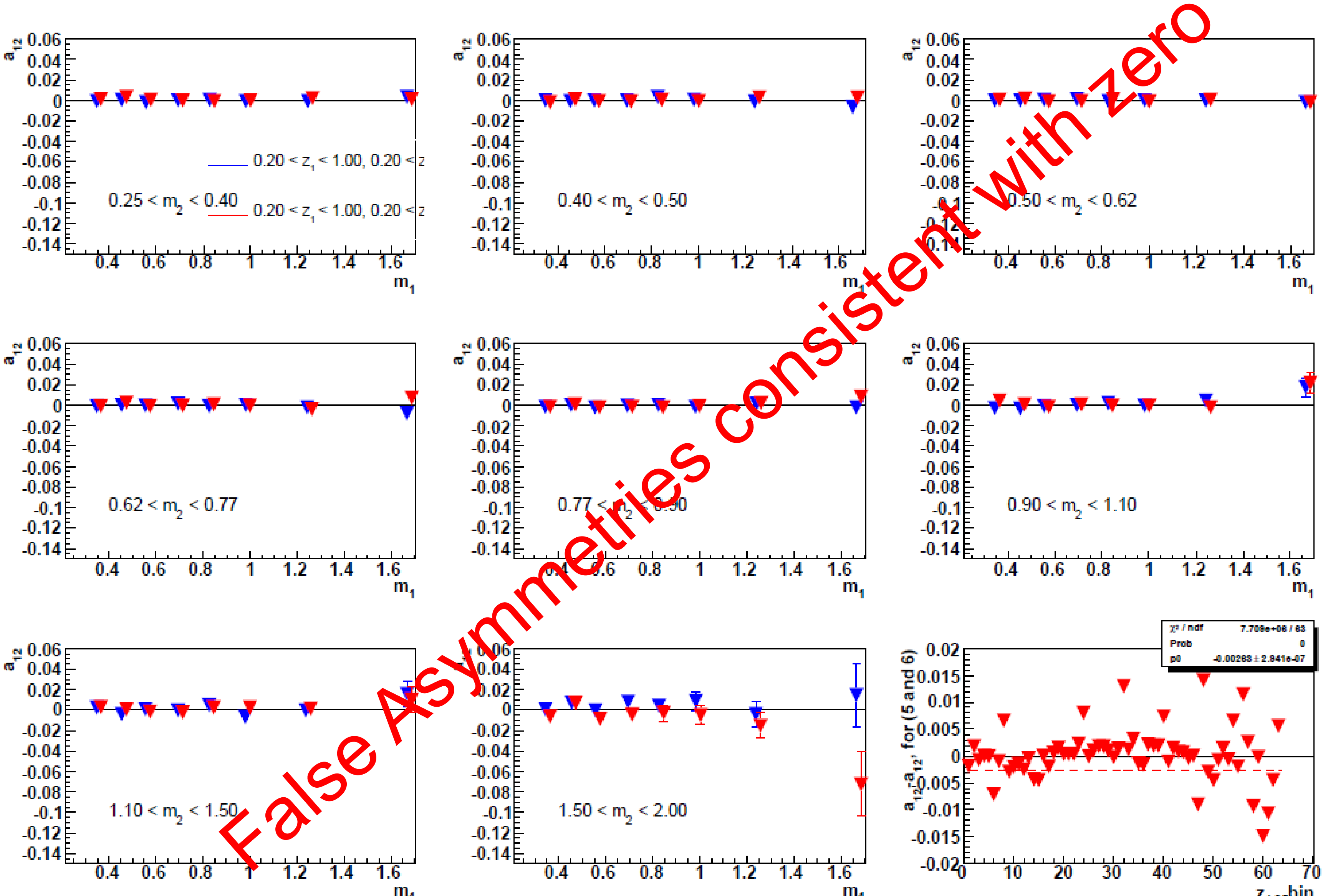


- A small asymmetry seen due to acceptance effect
- Mostly appearing at boundary of acceptance
- Opening cut in CMS of 0.8 (~37 degrees) reduces acceptance effect to the sub-per-mille level
- $\sin^2\theta/(1+\cos^2\theta) > 0.5$



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

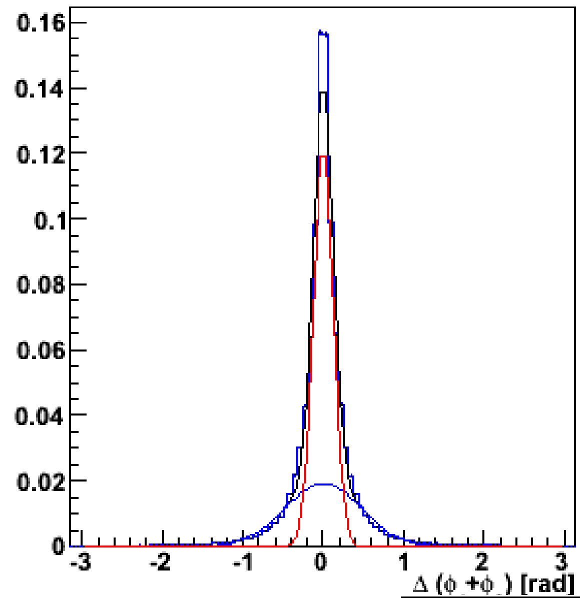
Zero tests: Mixed Events



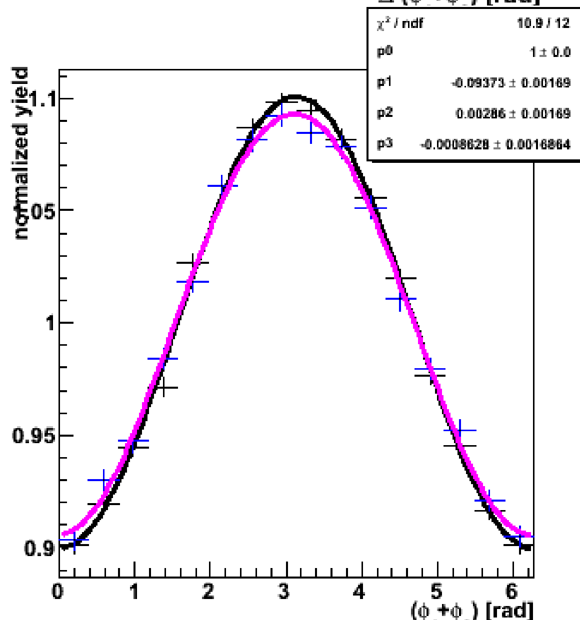
(Red/blue points: Thrust axis last or current event)

Weighted MC asymmetries

- Inject asymmetries in Monte Carlo
- Reconstruction smears thrust axis,
- ~94% of input asymmetry is reconstructed
- (Integrated over thrust axis: 98%)
- Effect is understood, can be reproduced in Toy MC
- Asymmetries corrected



Smearing
In azimuthal
Angle of thrust
Axis in CMS



Black: injected
Purple reconstructed

$(\phi_{1R} + \phi_{2R})$

67

Cuts and Binning

- Similar to Collins analysis, full off-resonance and on-resonance data

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- Visible energy >7GeV
- PID: Purities in Pion/Pion Sample > 90%
- Same Hemisphere cut within pair ($\pi^+\pi^-$), opposite hemisphere between pairs
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- Thrust > 0.8
- $z_{had1,had2}>0.1$
- $z_1 = z_{had1}+z_{had2}$ and z_2 in 9x9 bins
- $m_{\pi\pi 1}$ and $m_{\pi\pi 2}$ in 8x8 bins: [0.25 - 2.0] GeV

Comparison with Collins FF extraction

- a_{12} Asymmetries directly measure IFF squared
- IFF asymmetries can be integrated over k_t
  - No double ratios necessary to cancel gluon radiation effects

Systematic Errors

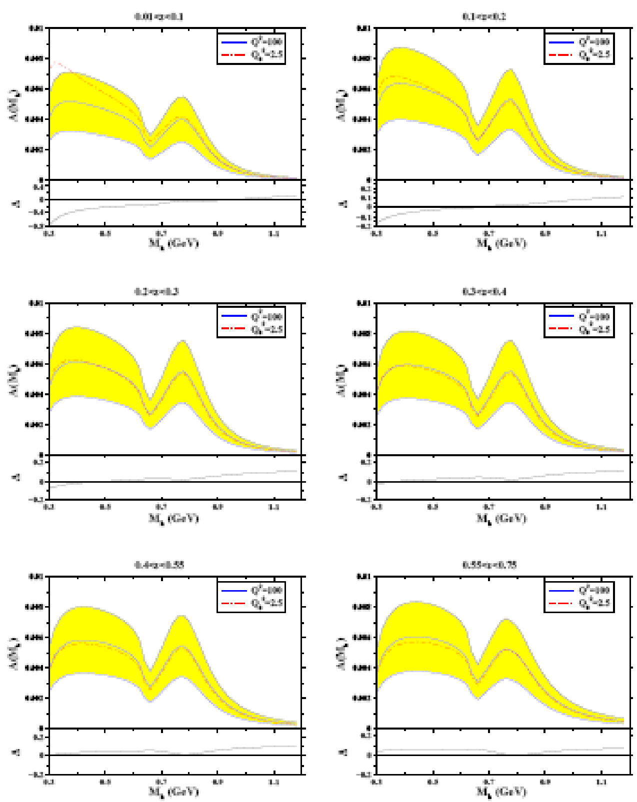
- Dominant:
  - MC asymmetry + its statistical error (up to % level)
- Smaller contributions:
  - mixed asymmetries: per mille level
  - higher moments: sub per mille level
  - axis smearing,
  - tau contribution
  - Charm contributions

- Possible Gluon radiation not accounted for

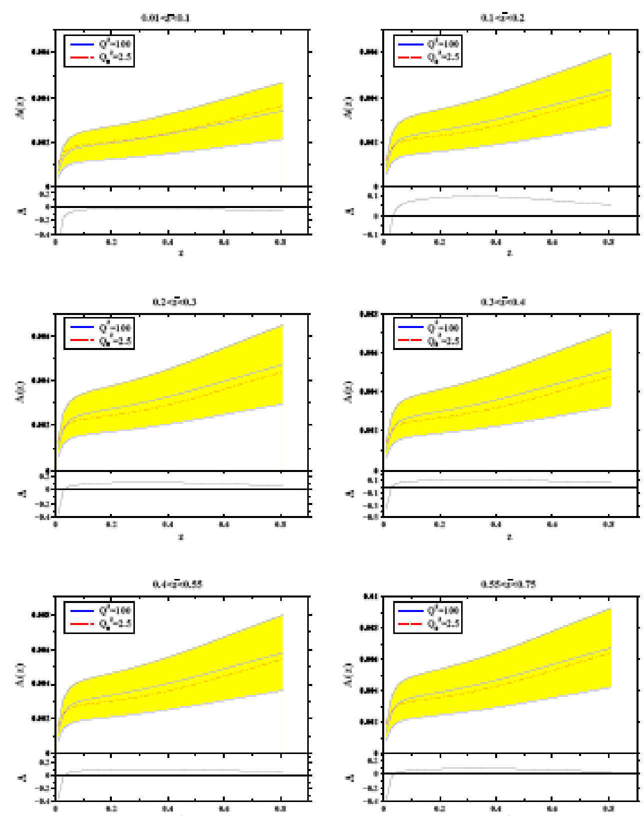
Model predictions for e^+e^-

Bacchetta,Checcopieri, Mukherjee, Radici : **Phys.Rev.D79:034029,2009**.

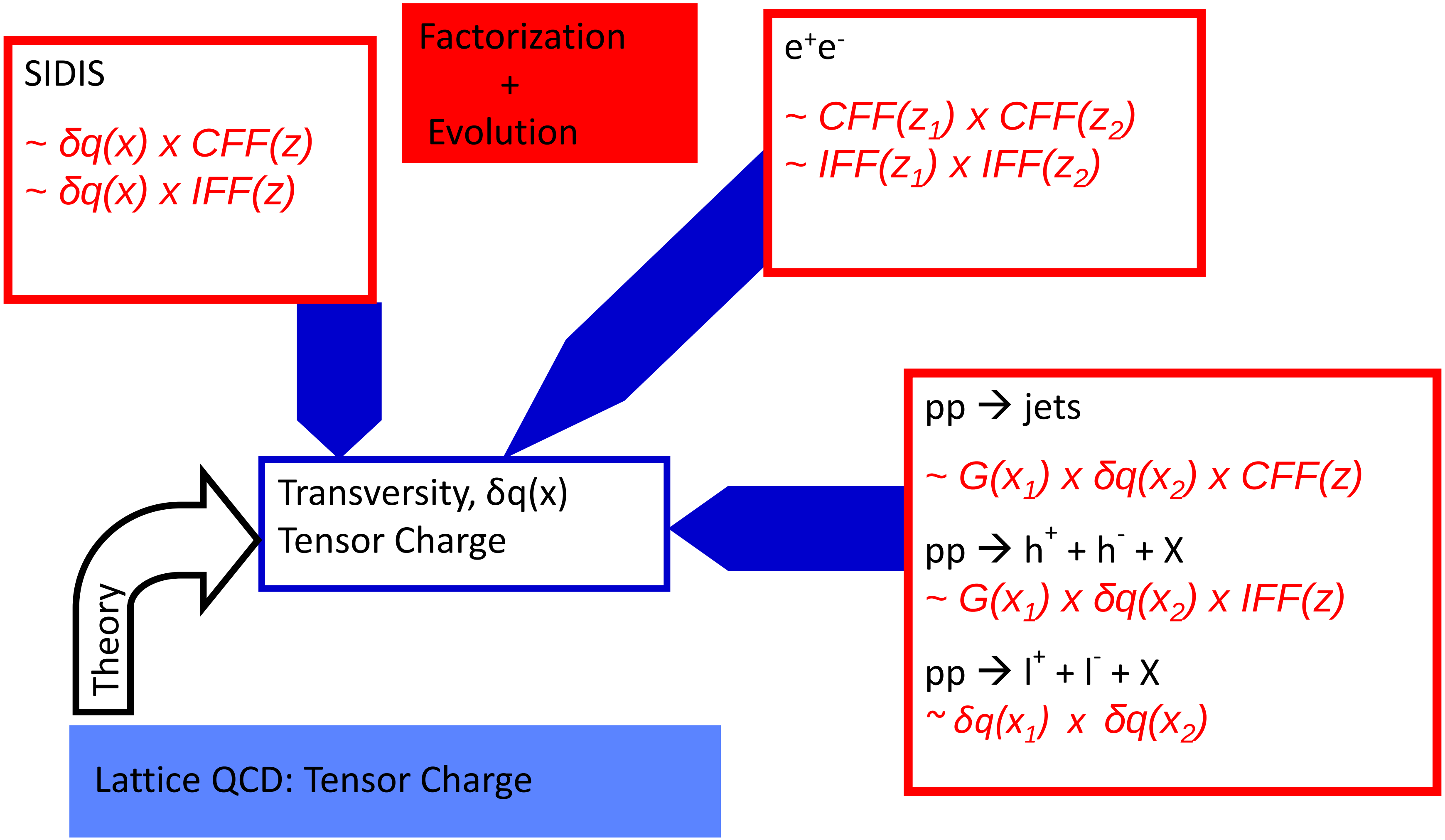
Invariant mass$_1$ dependence for increasing z_1



z_1 dependence for increasing z_2



Combined Analysis:
Extract Transversity Distributions



Measurements of quark transversity

	1991	2005	Underway	Future
p+p	E704, 1991 Large forward SSA	STAR, PHENIX, BRAHMS, 2004~2005 Inclusive A_N	RHIC IFF asym.	RHIC Collins asym. JParc, RHIC, FAIR Drell-Yan
SIDIS		HERMES 2005, COMPASS 2006 A_{UT}	COMPASS p target	JLab ^{3}He and 12 GeV
$e^+ + e^-$		BELLE 2006 Collins FF	BELLE IFF	BELLE k_T dep. Pol. & upol FF, pol. Lambda FF

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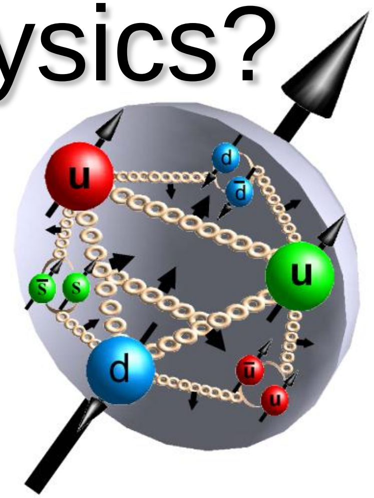
Motivation for QCD Spin Physics?



- What contributes most of the visible mass in the universe?
  - ***Not Higgs: The QCD interaction!***
- Proton mass is dominated by it
- Proton momentum is half carried by quarks, half by gluons
- SPIN is fundamental quantity: What role does it play in strong interactions?

➔ Spin crisis: EMC - Quarks contribute only ~30% to nucleon spin

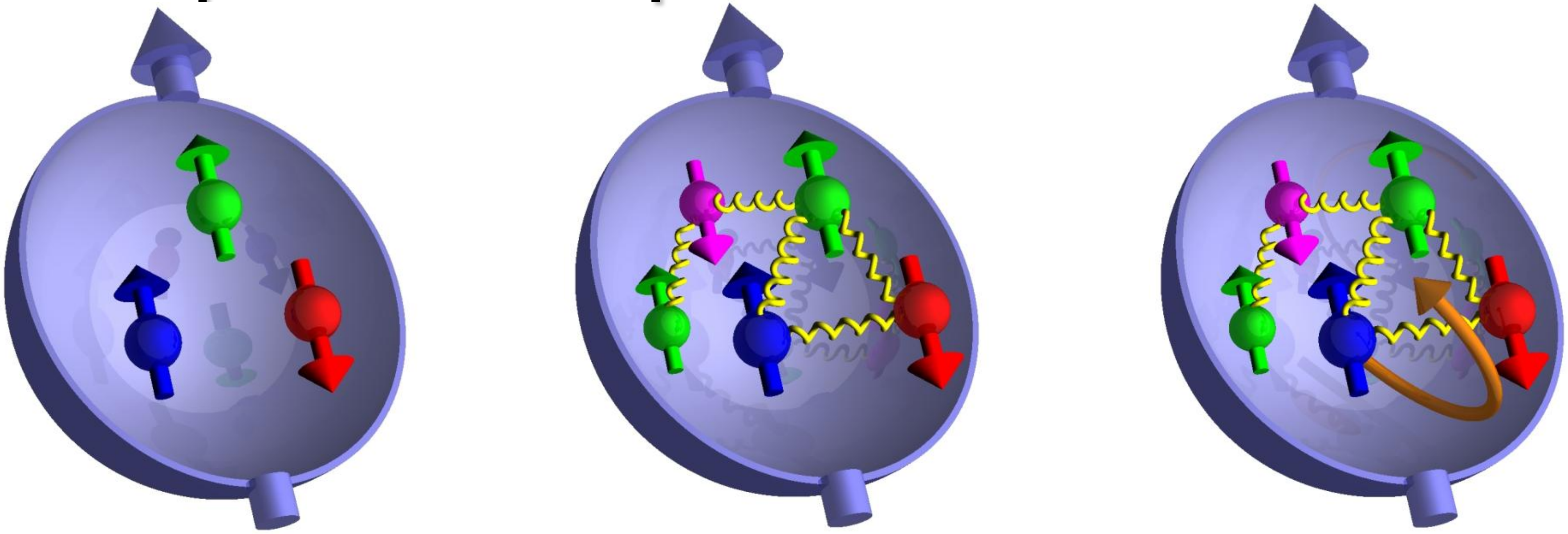
➔ Nucleon spin still not understood

➔ Confinement

➔ Large transverse single spin asymmetries

➔ Interesting transverse spin effects help us understand QCD

Spin Decomposition of the Proton



Naïve quark model – 3 valence quark

$$\frac{1}{2} = \frac{1}{2}\underbrace{\left(\Delta u_v + \Delta d_v + \Delta q_s\right)}$$

$$\Delta\Sigma = 1\ ???$$

CERN, SLAC, DESY, JLAB:

$\Delta\Sigma \sim 0.30$

QCD:
..additional contributions from gluons and gluon splitting, sea quarks…

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G$$

$\Delta G = ?$

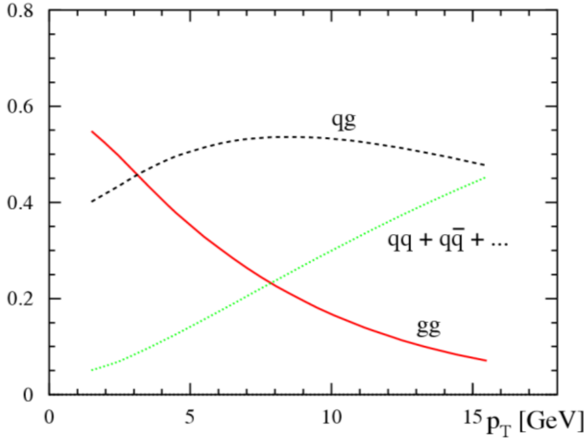
…and orbital angular momentum…

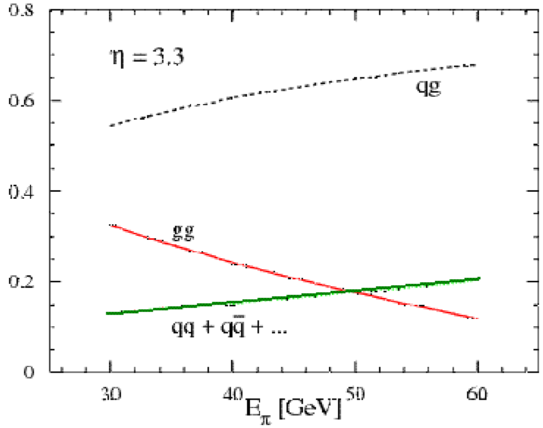
$$\frac{1}{2} = J_q + J_g$$

$$= \frac{1}{2}\Delta\Sigma + L_q$$

$$+ \quad \Delta G + L_g$$

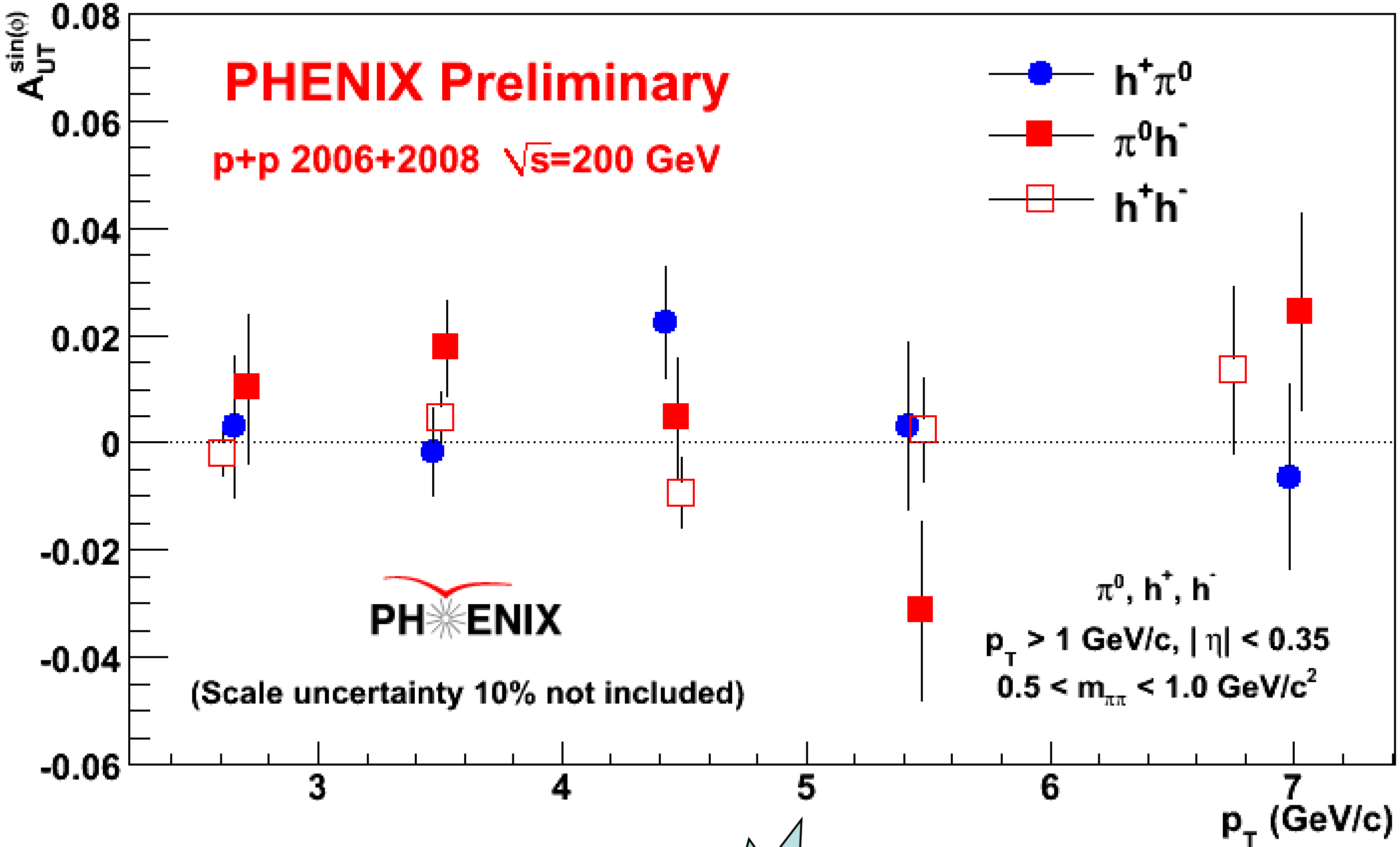
Kinematics





Central arms

$A_{UT}^{\sin\phi}$ vs invariant mass of the pair

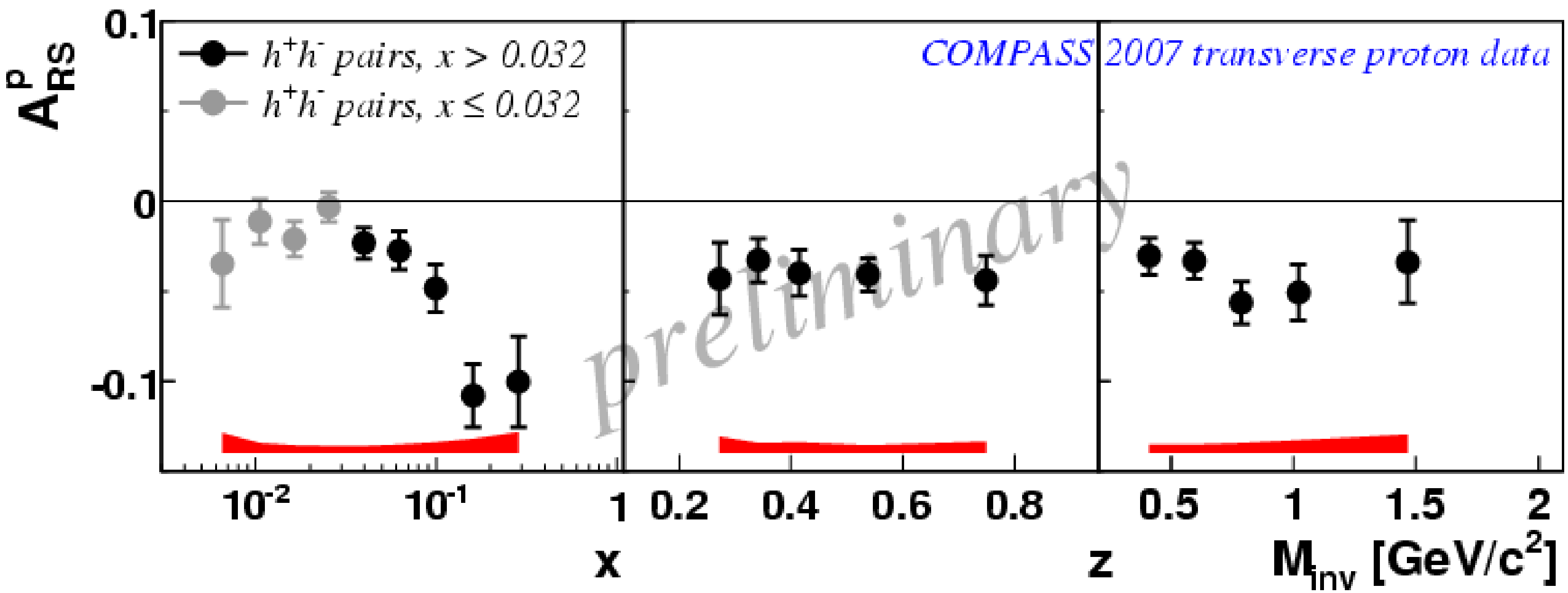


Added statistics from 2008 running

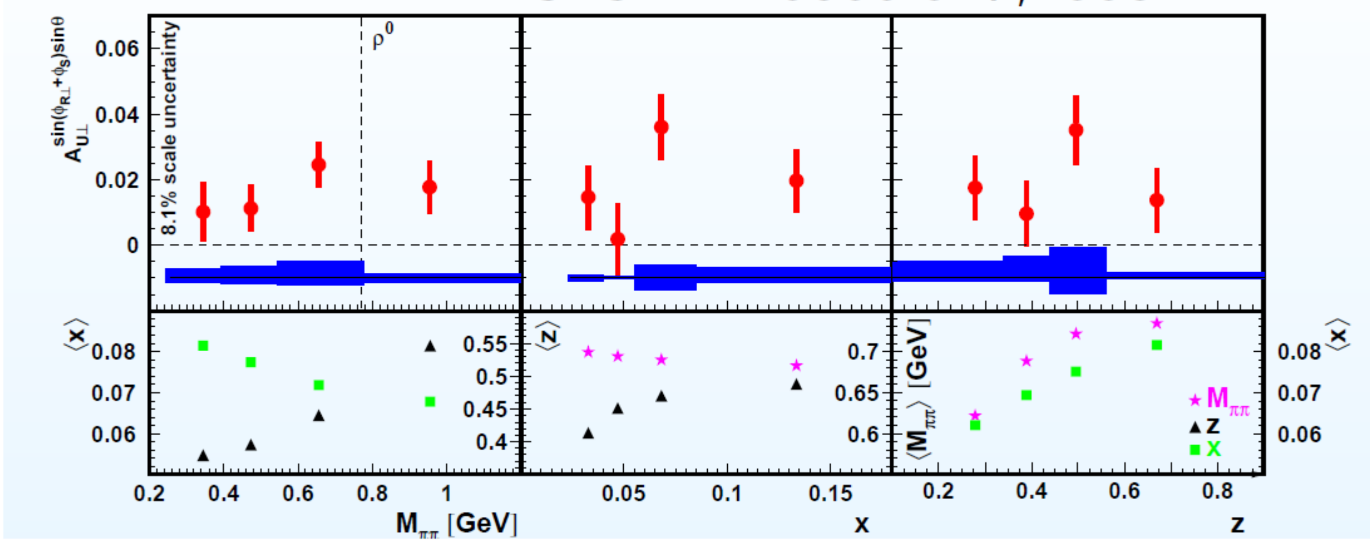
NEW

No significant asymmetries seen at mid-rapidity.

Di-Hadron SSA in SIDIS

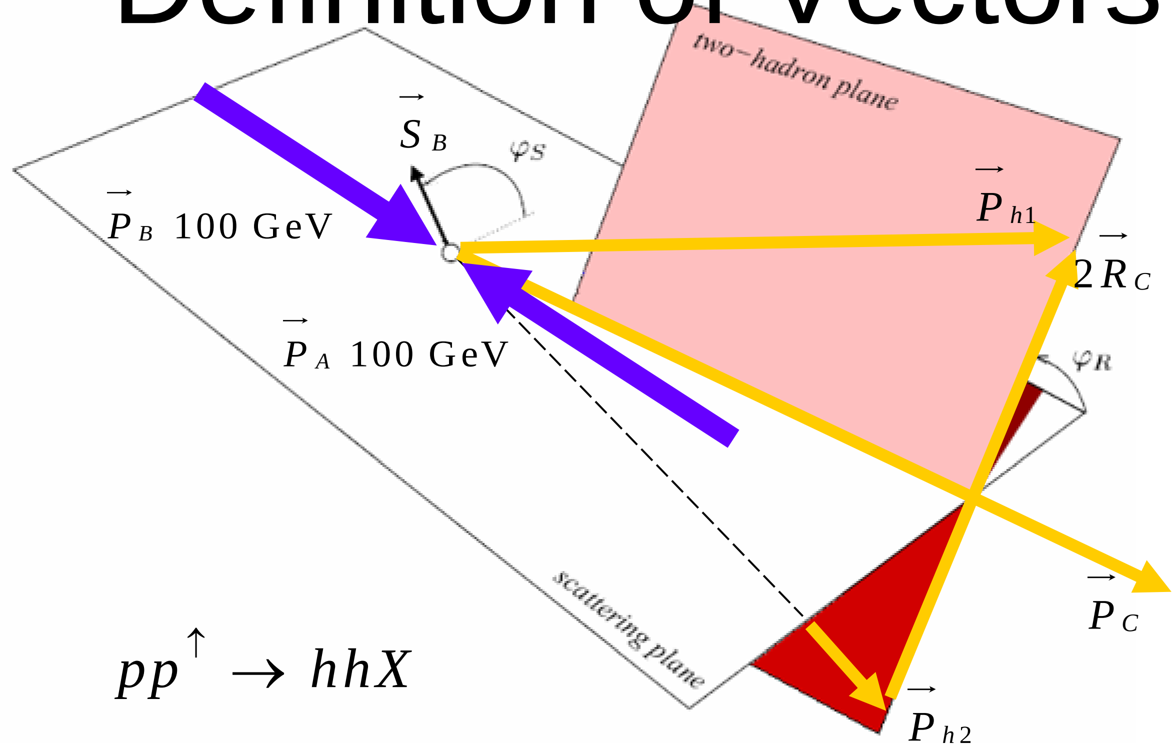


HERMES: JHEP 0806:017,2008



(both on proton target, sign convention different)

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)