Fragmentation function measurements at Belle

RIKEN high P_T Workshop,
BNL, March 17-19

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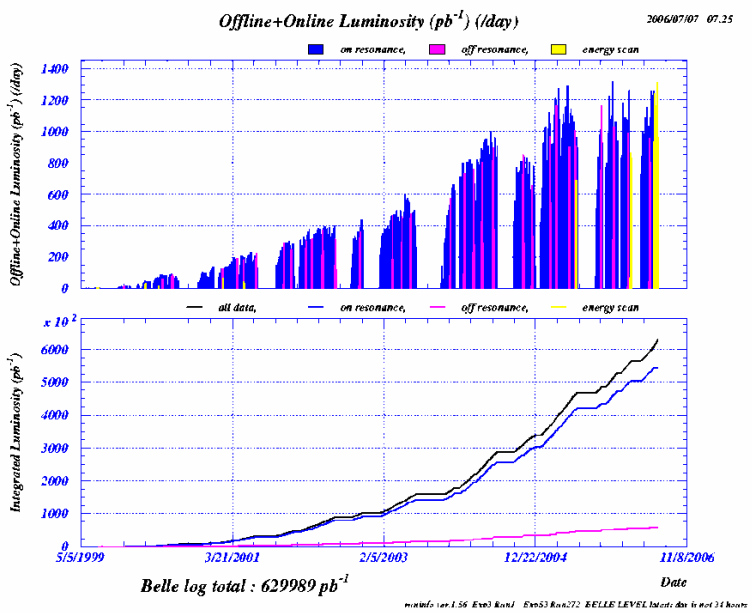
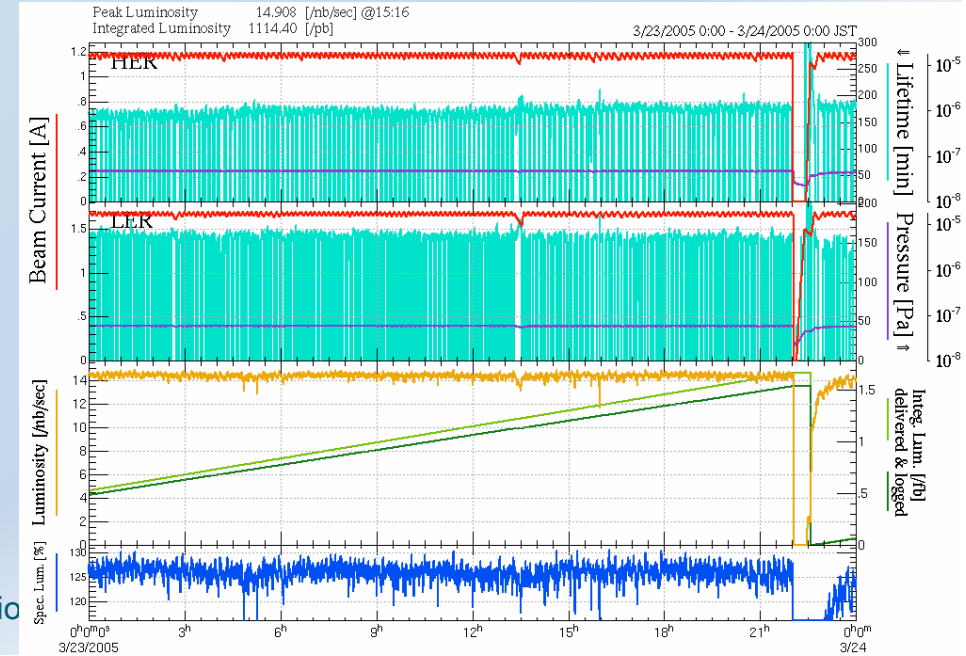
KEKB: $L>2.1\times10^{34}\,cm^{-2}s^{-1}$!!

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

Main research at Belle:
CP violation and determination of Cabbibo Kobayashi Maskawa (CKM) matrix





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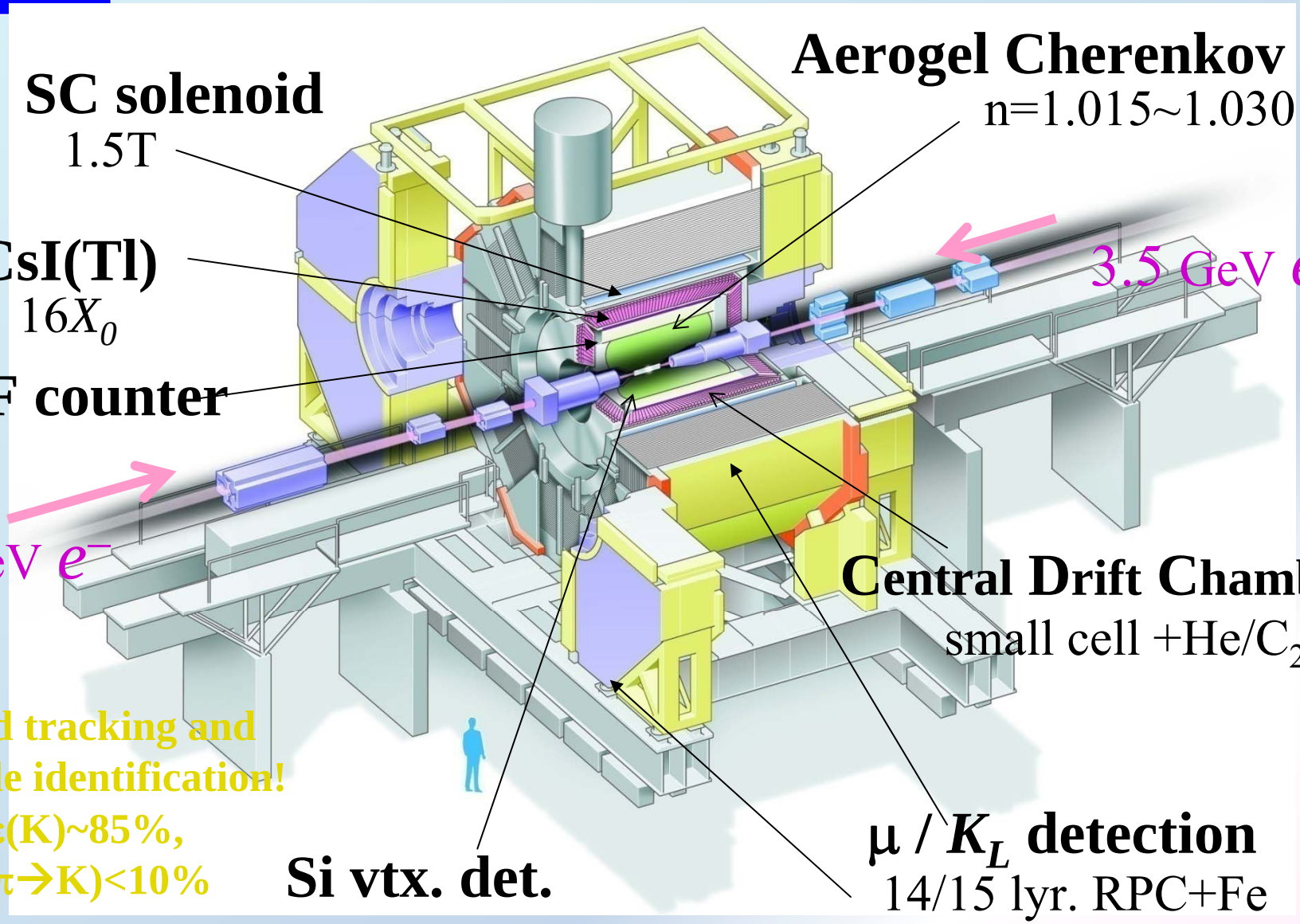
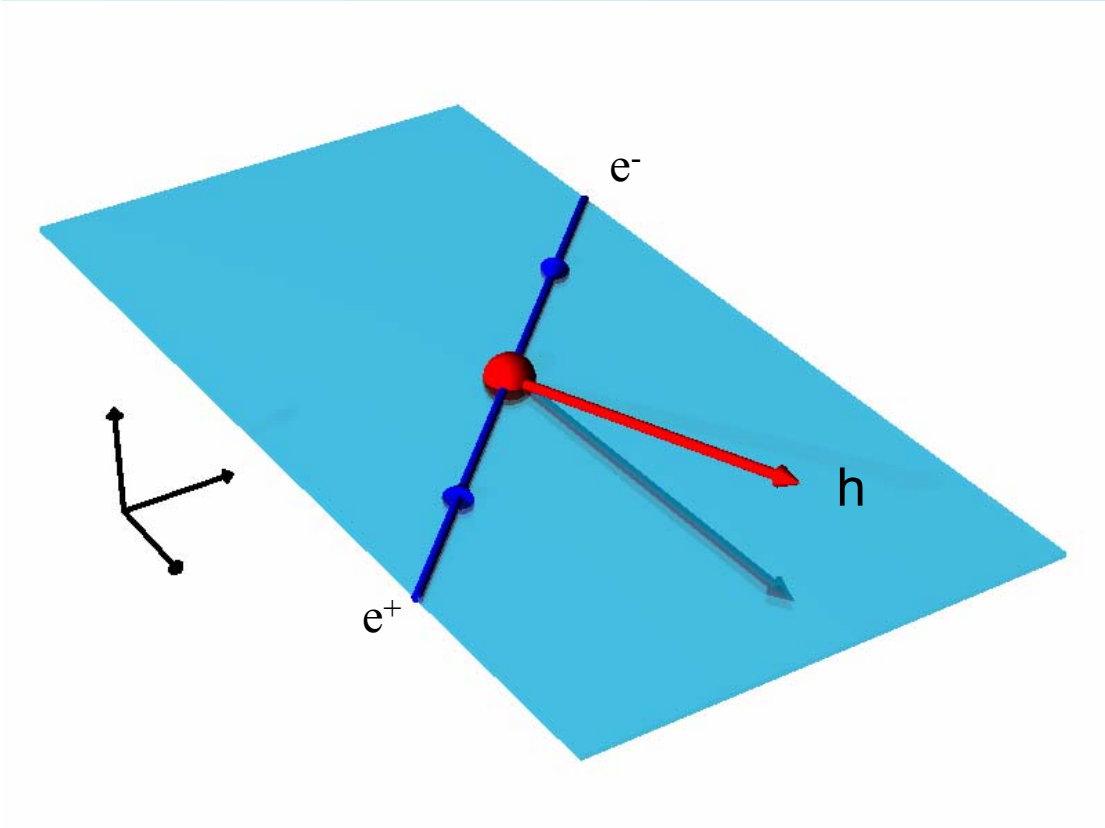
Belle Detector



Fragmentation functions in e^+e^- annihilation



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

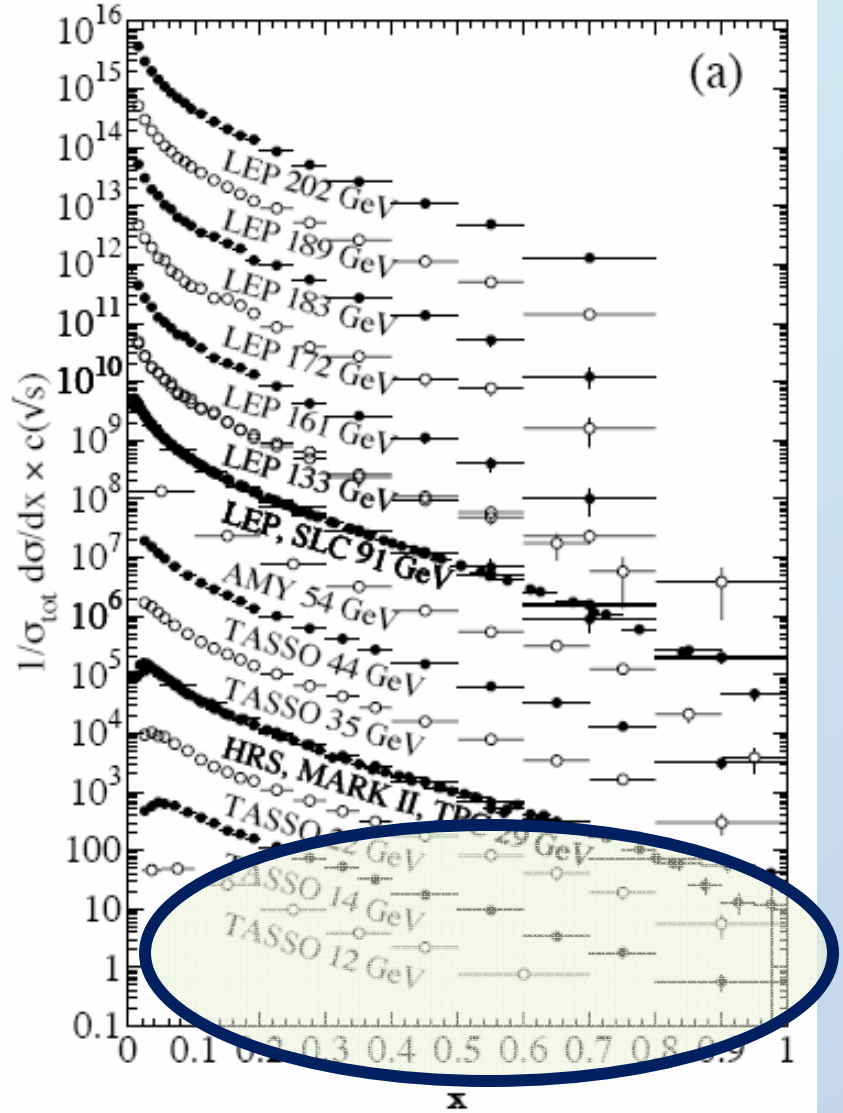
- Process:

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



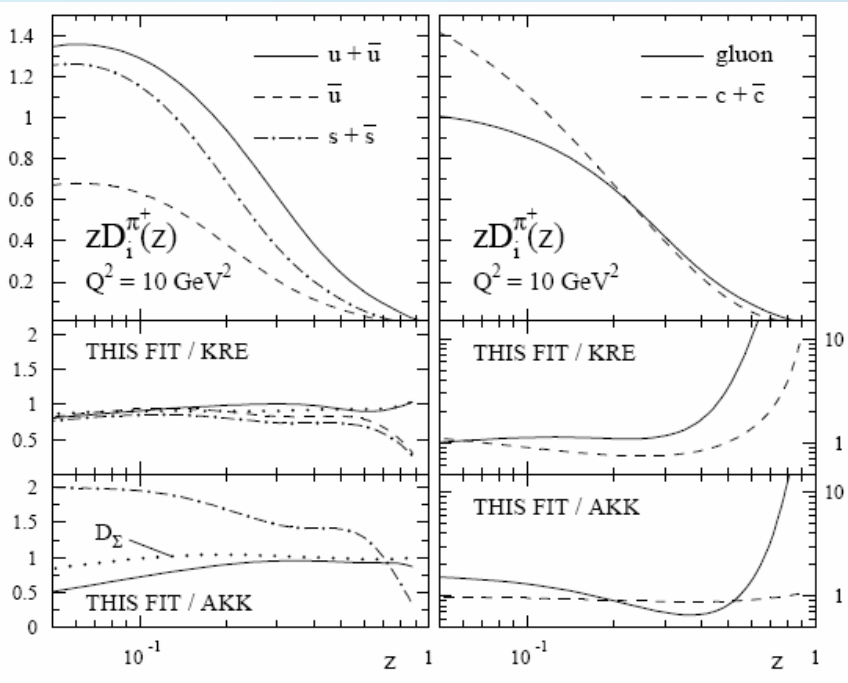
- Most data obtained at LEP energies,
- At lower CMS energies very little data available
- 3-jet fragmentation to access gluon FF theoretically difficult

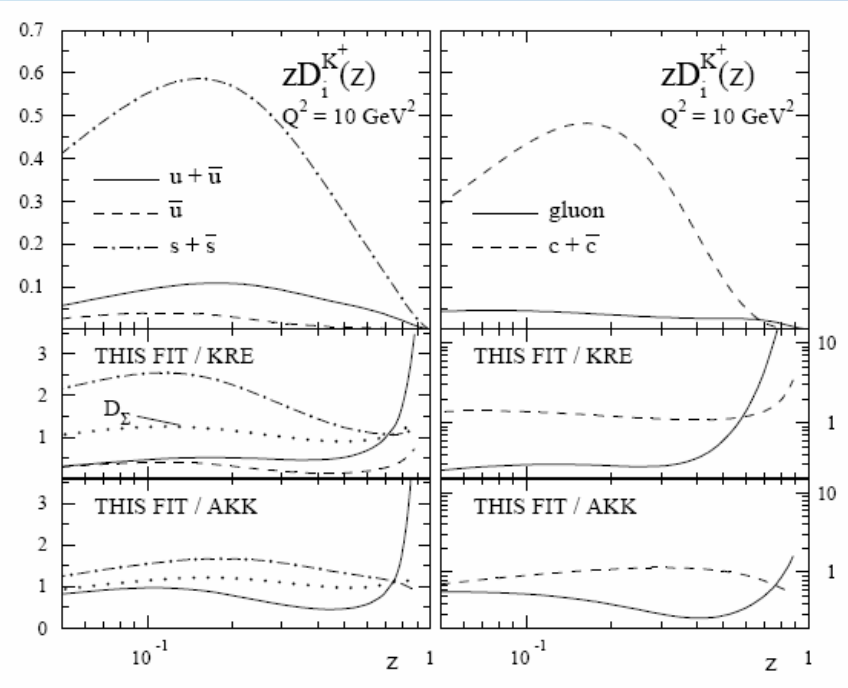
➔ Gluon fragmentation from evolution not yet well constrained

➔ Higher z FFs (>0.7) hardly available

Current knowledge on fragmentation functions - DSS

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





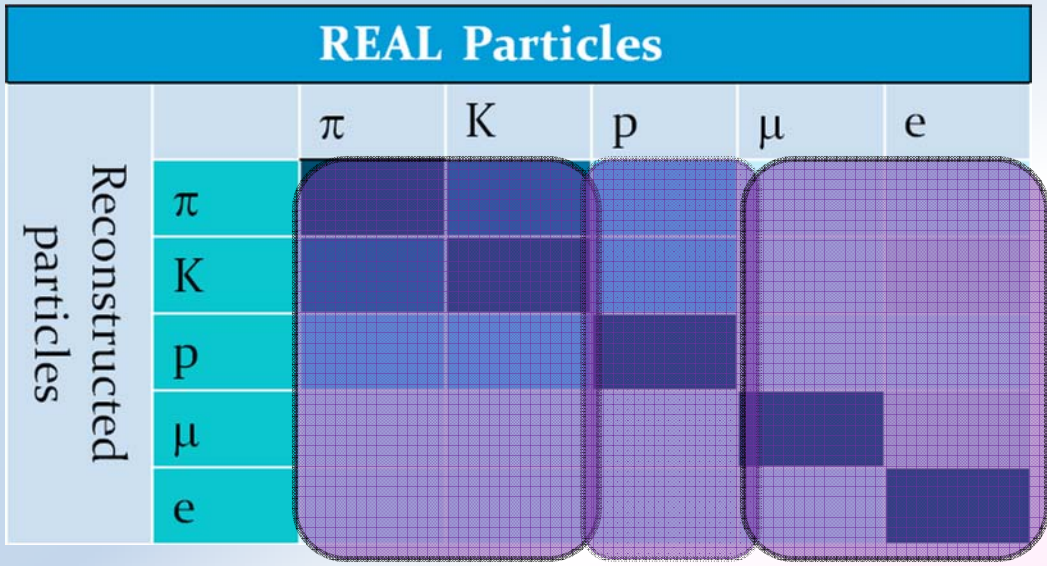
Differences between different global fits still large for high-z gluon contributions and kaons

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 $D^* \rightarrow \pi_{slow}$ $D^o \rightarrow \pi_{slow}\pi_{fast}K$ for K,π identification
  - Use $\Lambda \rightarrow \pi p$ for p,π identification
  - $J/\psi \rightarrow \mu^+ \mu^-$, $e^+ e^-$ for leptons (if needed also Υ(1S))

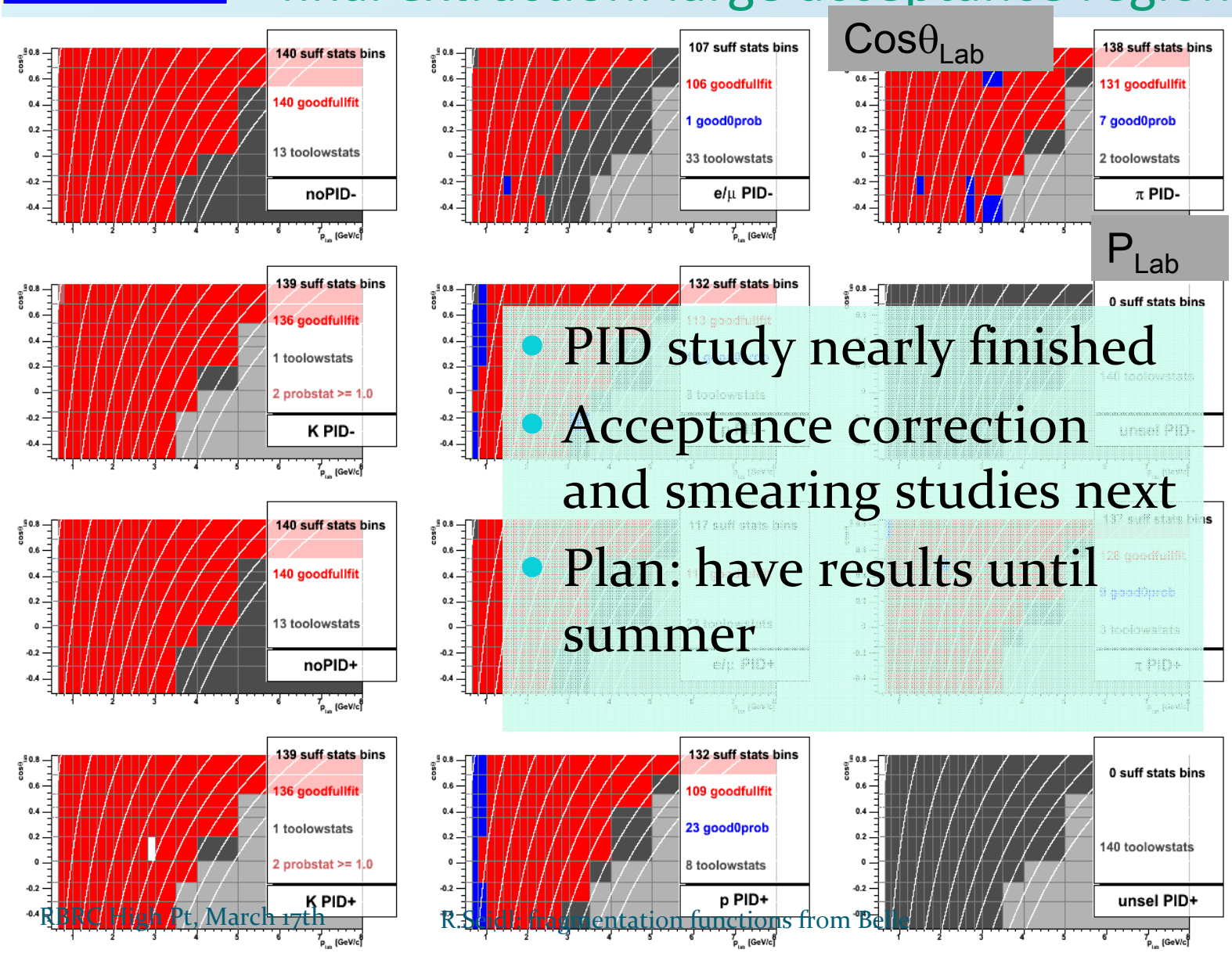
→ Unfolding

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



D* Extraction

final extraction: large acceptance region covered



K-

K+

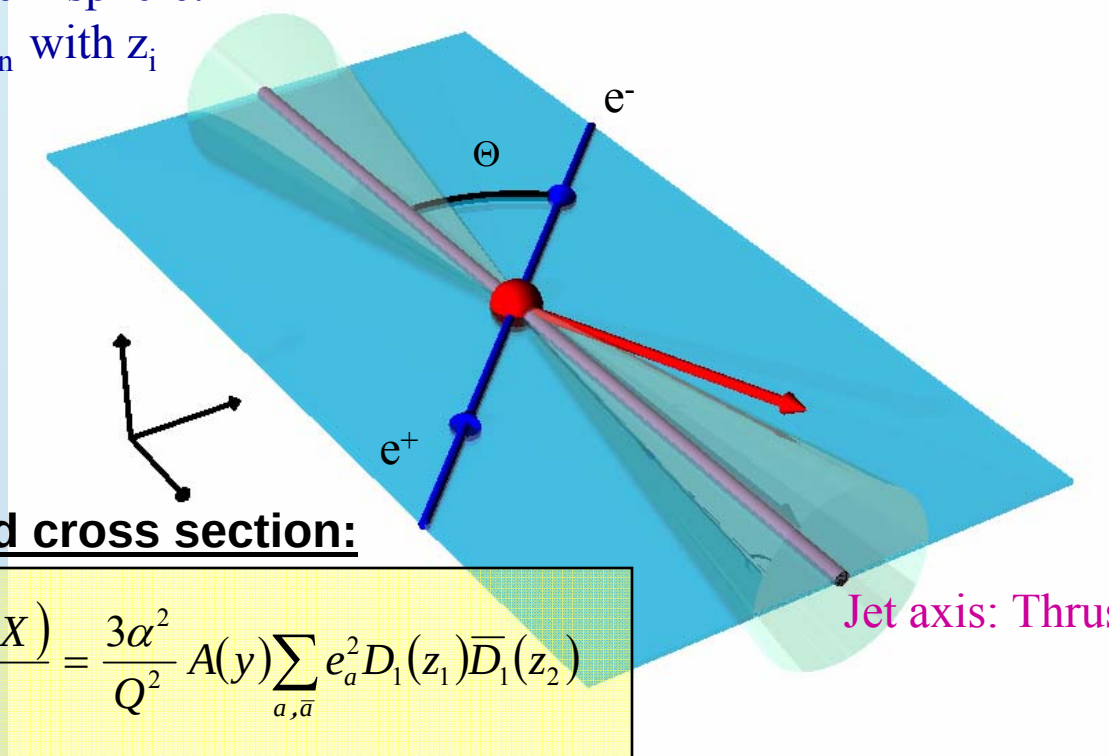
- PID study nearly finished
- Acceptance correction and smearing studies next
- Plan: have results until summer

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

e^+e^- CMS frame:

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

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



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

Jet axis: Thrust

Spin averaged cross section:

$$\frac{d\sigma(e^+e^- \to h_1 h_2 X)}{d\Omega dz_1 dz_2} = \frac{3\alpha^2}{Q^2} A(y) \sum_{a,\bar{a}} e_a^2 D_1(z_1) \bar{D}_1(z_2)$$

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

Unpolarized 2-hadron fragmentation

Favored	= $u \rightarrow \pi^+, d \rightarrow \pi^-$, cc.
Unfavored	= $d \rightarrow \pi^+, u \rightarrow \pi^-$, cc.

- Detect two hadrons simultaneously
- If two hadrons in opposite hemispheres one obtains sensitivity to favored/disfavored fragmentation:
- Problems:
  - Either need to ensure two-jet topology (thrust cut)
  - Or contribution from one quark fragmentation $q \rightarrow hhX$

- 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)

Towards a global transversity analysis: Chiral –odd Fragmentation functions

RHIC and SIDIS experiments measure:

Transversity $\delta q(x)$ X

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

or Interference Fragmentation function (IFF)

2 Unknown Functions measured together

•Universality understood
•Evolution ?

Transversity

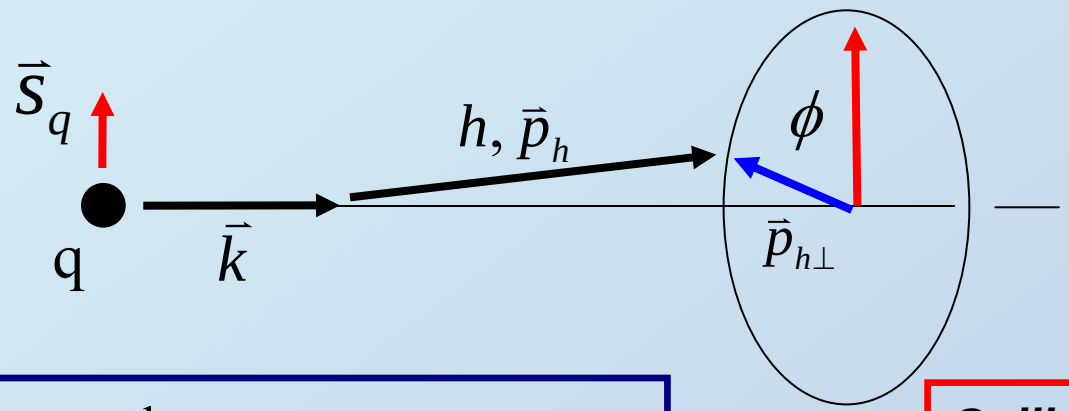
Belle measures:

Collins X Collins

or IFF X IFF

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

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

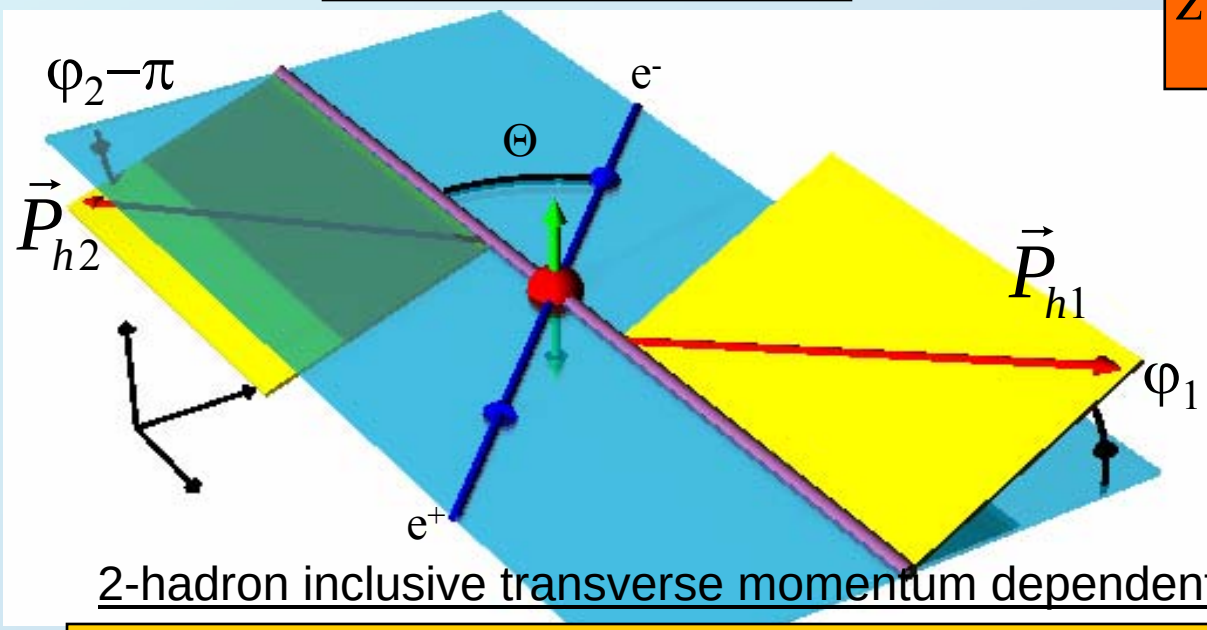
$$\propto \left(\vec{k} \times \vec{p}_{h\perp}\right) \cdot \vec{s}_q$$

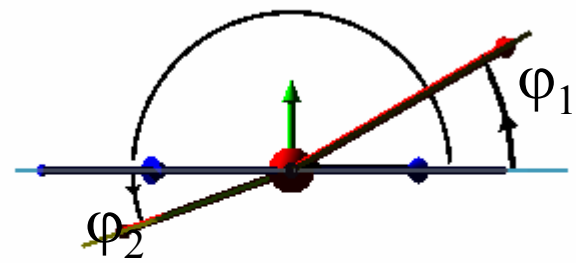
$$\propto \sin\phi$$

Collins fragmentation in e^+e^- : Angles and Cross section $\cos(\phi_1+\phi_2)$ method

e^+e^- CMS frame:

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





[D.Boer: PhD thesis(1998)]

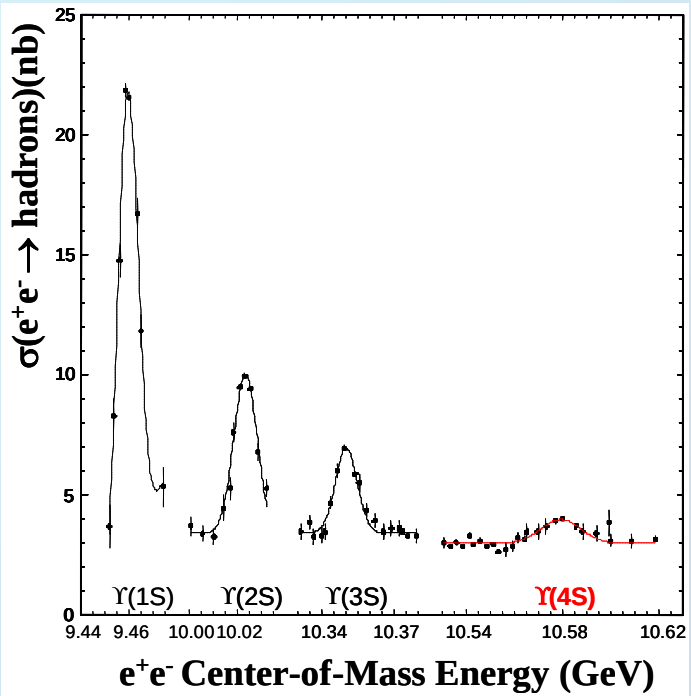
2-hadron inclusive transverse momentum dependent cross section:

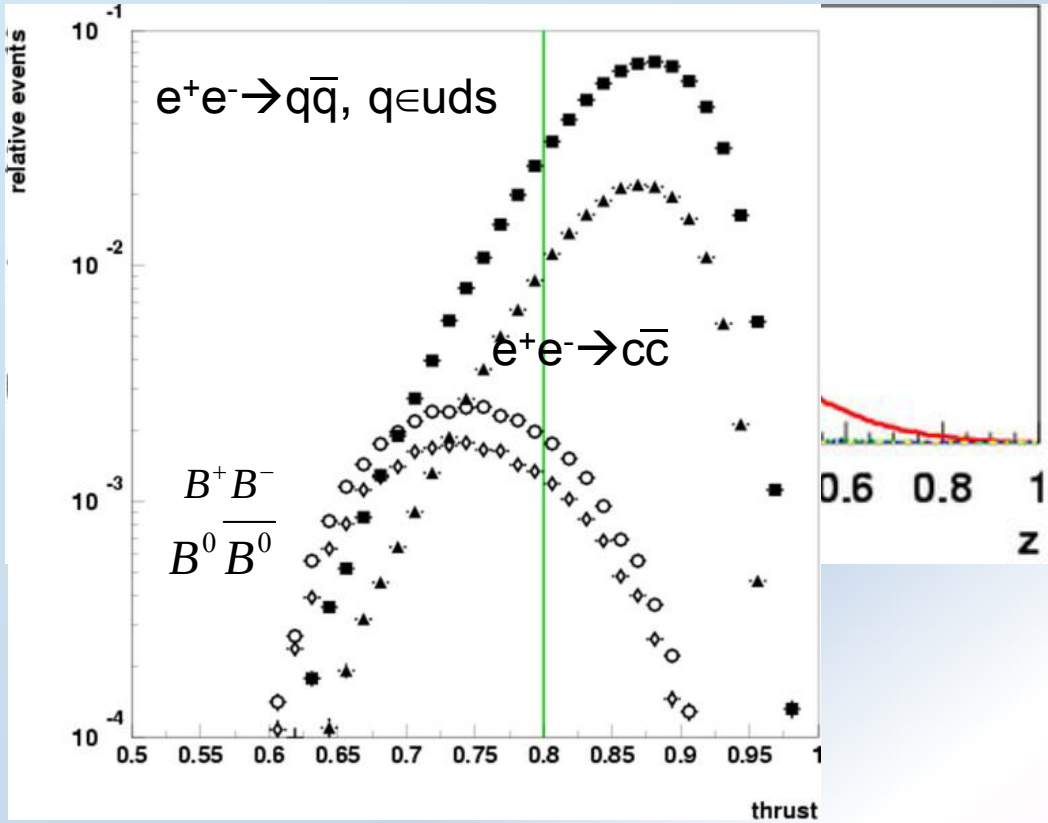
$$\frac{d\sigma(e^+e^- \to h_1 h_2 X)}{d\Omega dz_1 dz_2 d^2\boldsymbol{q}_T} = \cdots B(y)\cos(\varphi_1+\varphi_2) H_1^{\perp[1]}(z_1)\overline{H}_1^{\perp[1]}(z_2)$$

$$B(y) = y(1-y) \overset{cm}{=} \frac{1}{4}\sin^2\Theta$$

Net (anti-)alignment of transverse quark spins

Why is it possible to include resonance data? Different Thrust distributions

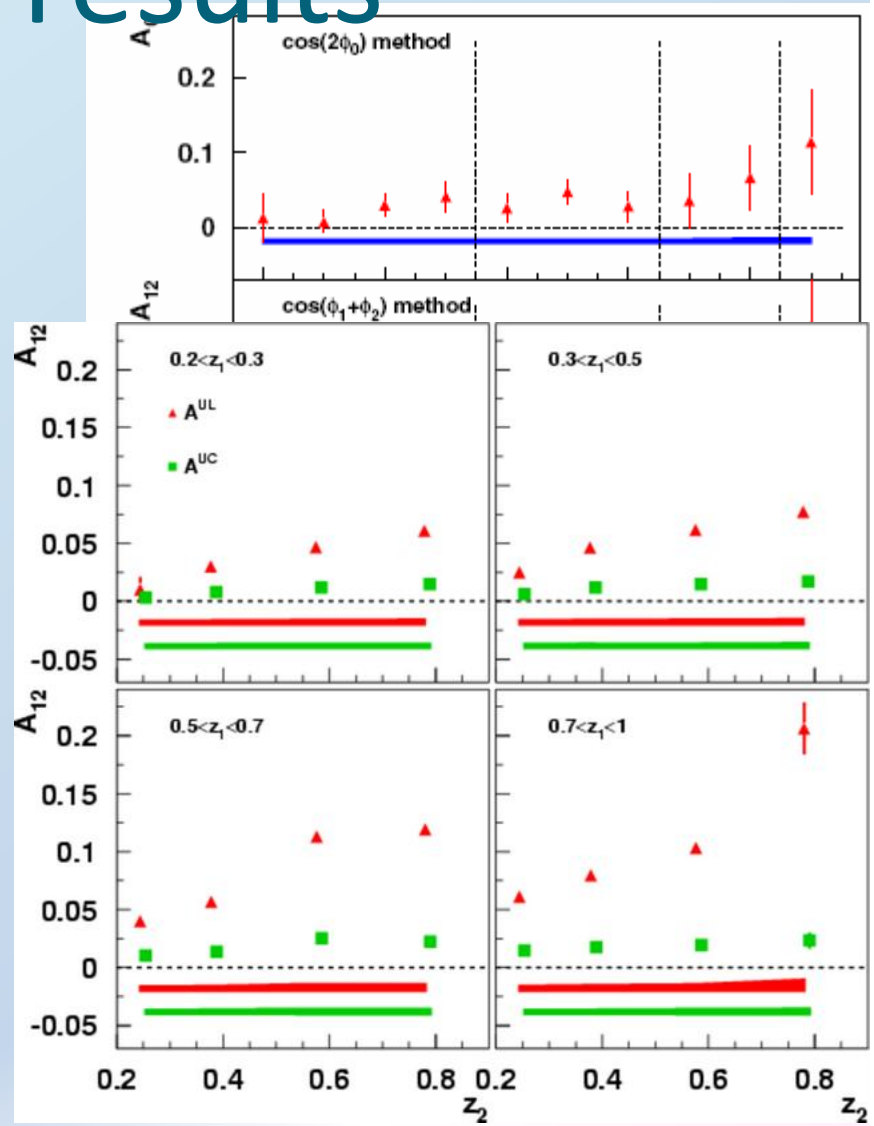




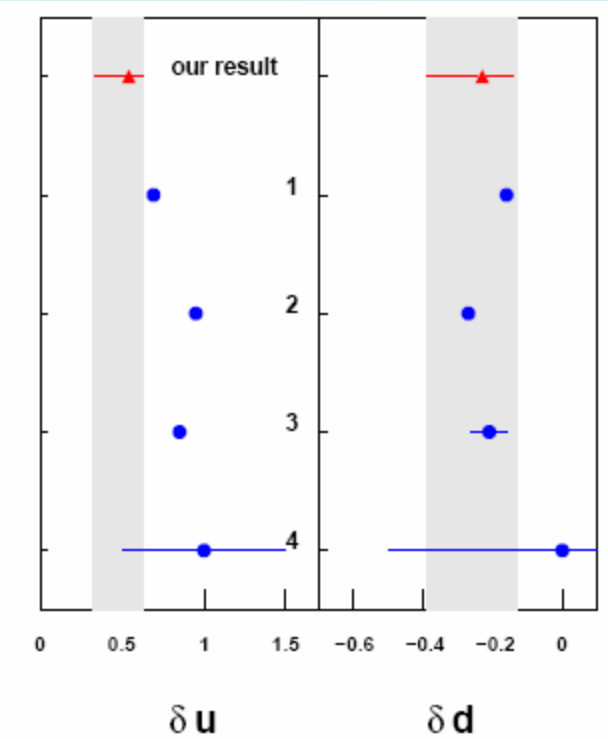
- Charm-tagged Data sample (used for charm correction) also increases with statistics
- Largest systematic errors reduce with more statistics

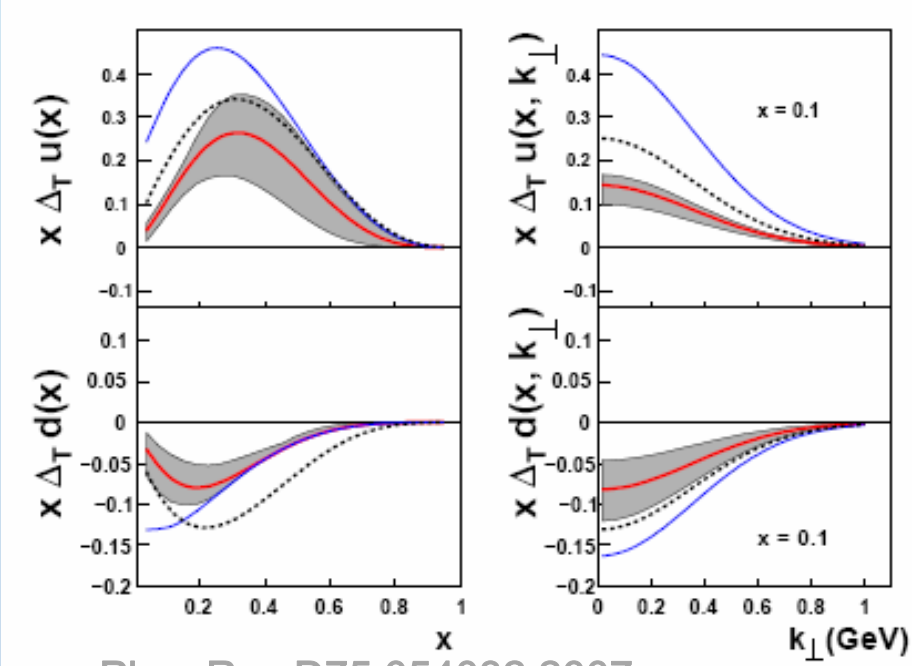
Final Collins results

- First direct measurement of the Collins effect: (PRL96: 232002)
- Nonzero asymmetries
- Belle 547 fb^{-1} data set (PRD78:032011)



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





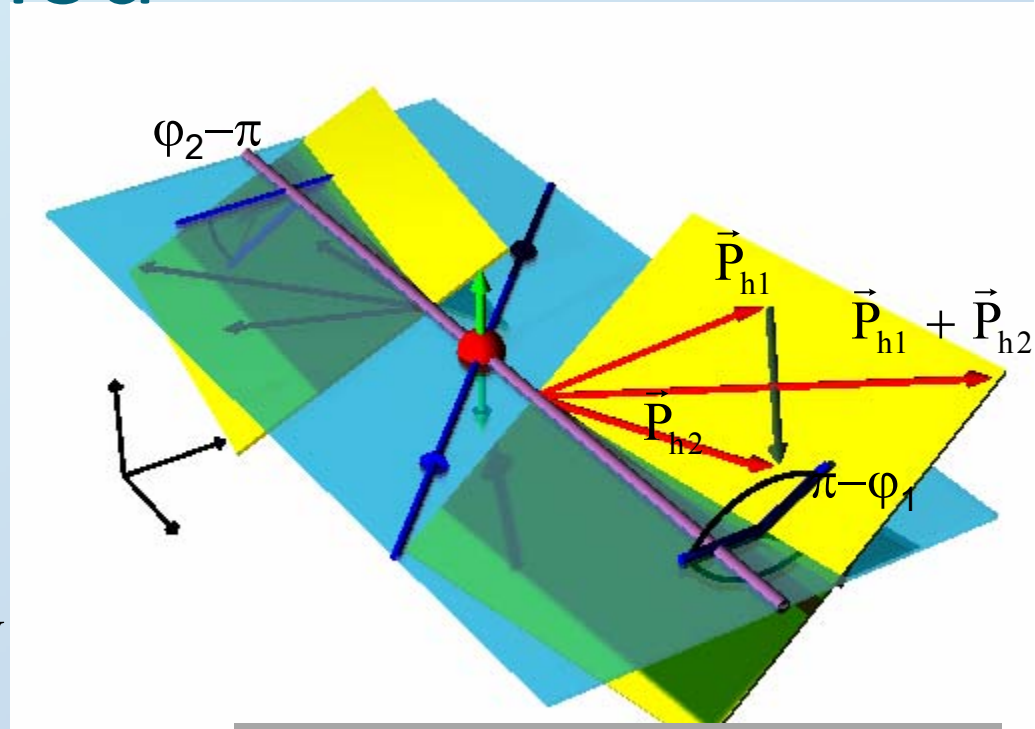
Phys.Rev.D75:054032,2007, update in Nucl.Phys.Proc.Suppl.1 91:98-107,2009

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

Interference Fragmentation – thrust method

- $e^+e^- \rightarrow (\pi^+\pi^-)_{jet1}(\pi^+\pi^-)_{jet2}X$
- Stay in the mass region around ρ-mass
- Find pion pairs in opposite hemispheres
- Observe angles $\varphi_1+\varphi_2$ between the event-plane (beam, jet-axis) and the two two-pion planes.
- Transverse momentum is integrated (universal function, evolution easy → directly applicable to semi-inclusive DIS and pp)
- Theoretical guidance by papers of Boer,Jakob,Radici[PRD 67,(2003)] and Artru,Collins[ZPhysC69(1996)]
- Early work by Collins, Heppelmann, Ladinsky [NPB420(1994)]

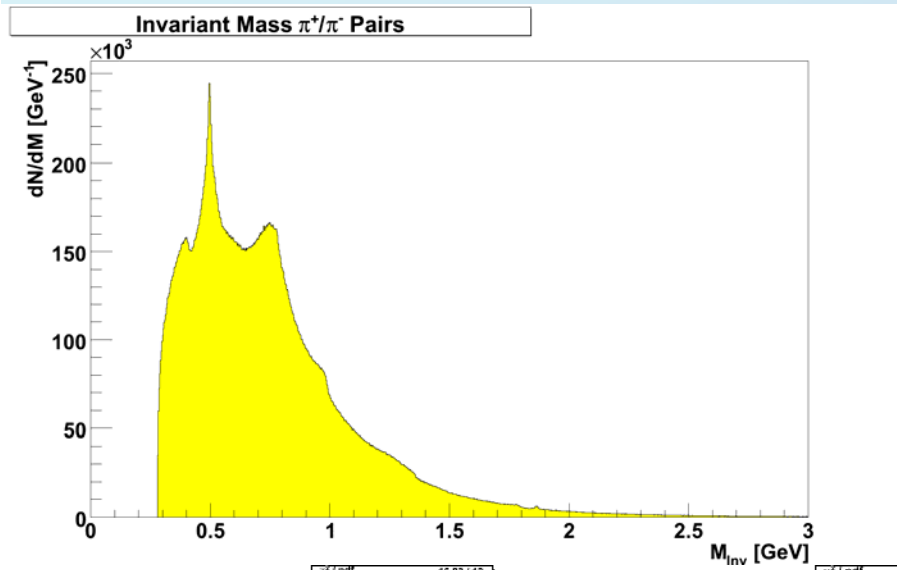
$$A \propto H_1^{\angle}(z_1, m_1) H_1^{\angle}(z_2, m_2) \cos(\varphi_1 + \varphi_2)$$

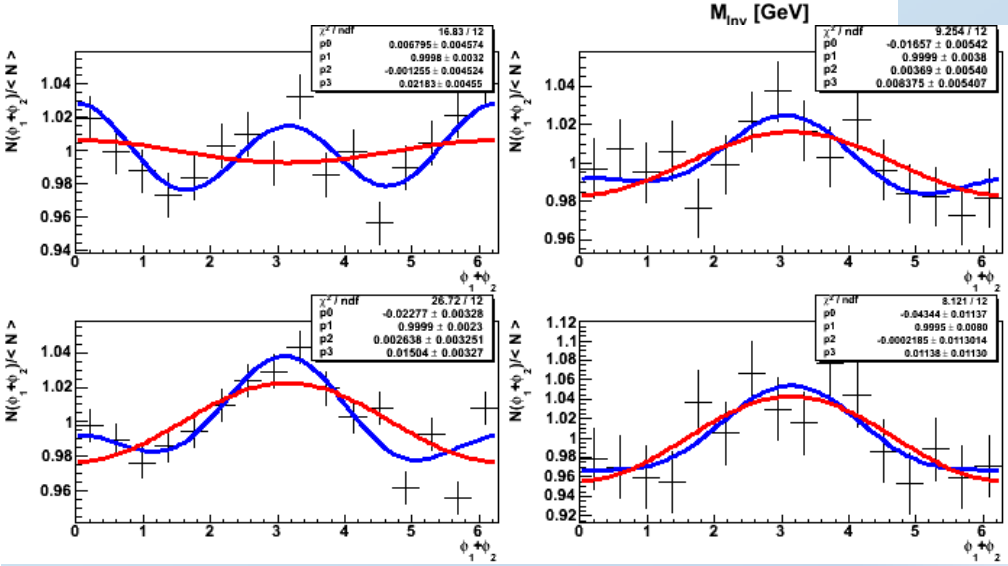


Model predictions by:

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

Asymmetry extraction





- Build normalized yields:

$$\frac{N(\phi_1+\phi_2)}{\langle N\rangle},$$

- Fit with:

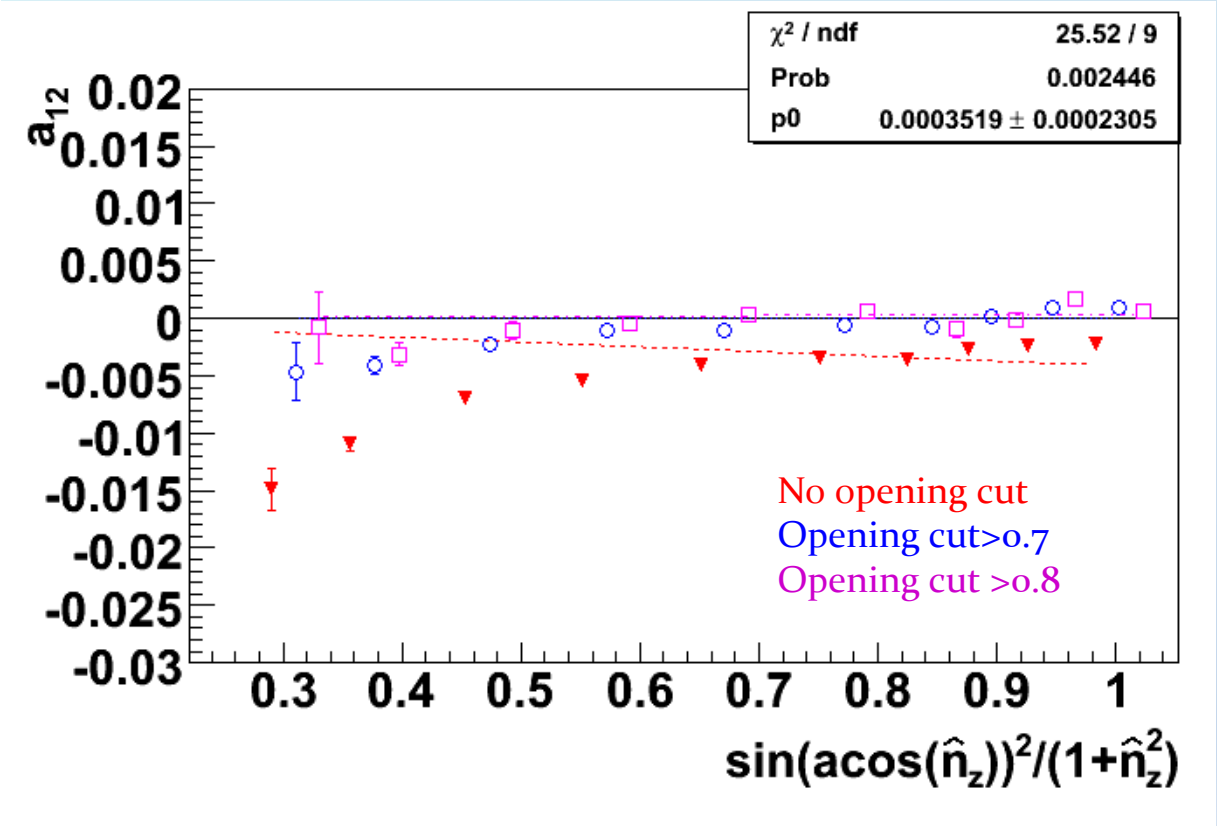
$$a_{12}\cos(\phi_1+\phi_2)+b_{12}$$

or

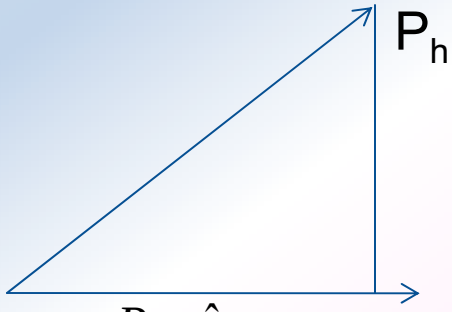
$$a_{12}\cos(\phi_1+\phi_2)+b_{12}+$$
$$c_{12}\cos 2(\phi_1+\phi_2)+d_{12}\sin(\phi_1+\phi_2)$$

Amplitude a_{12} directly measures (IFF) x (-IFF) (no double ratios)

Zero tests: MC

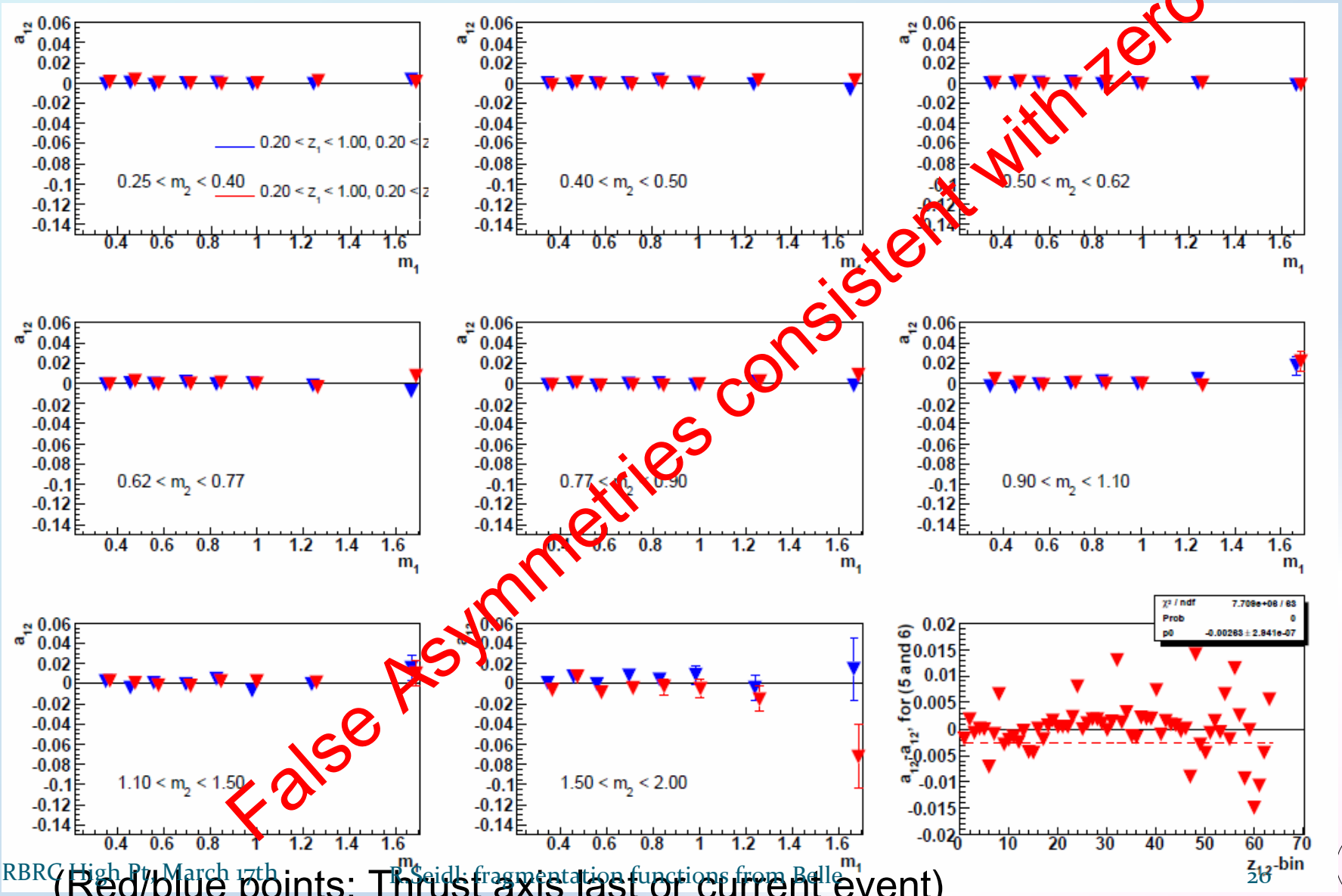


- A small asymmetry seen due to acceptance effect
- Mostly appearing at boundary of acceptance
- Opening cut in CMS of 0.8 (~37 degrees) reduces acceptance effect to the sub-per-mille level



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

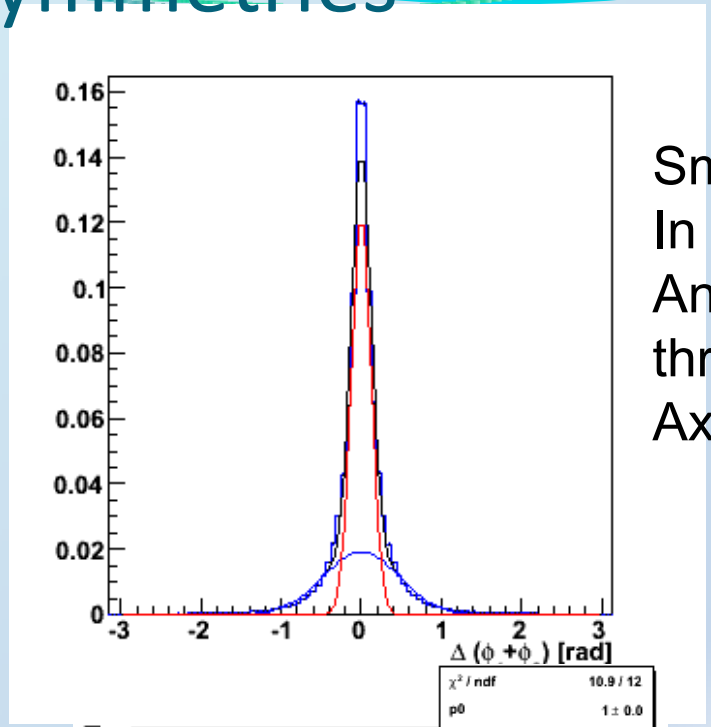
Zero tests: Mixed Events



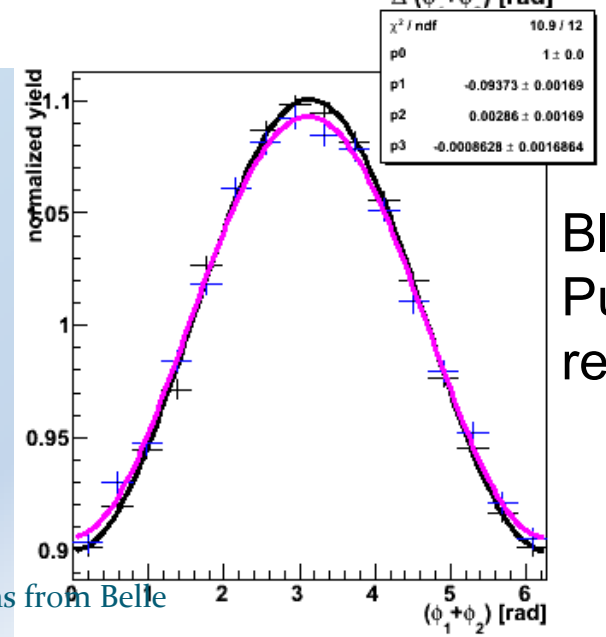
(Red/blue points: Thrust axis last or current event)

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



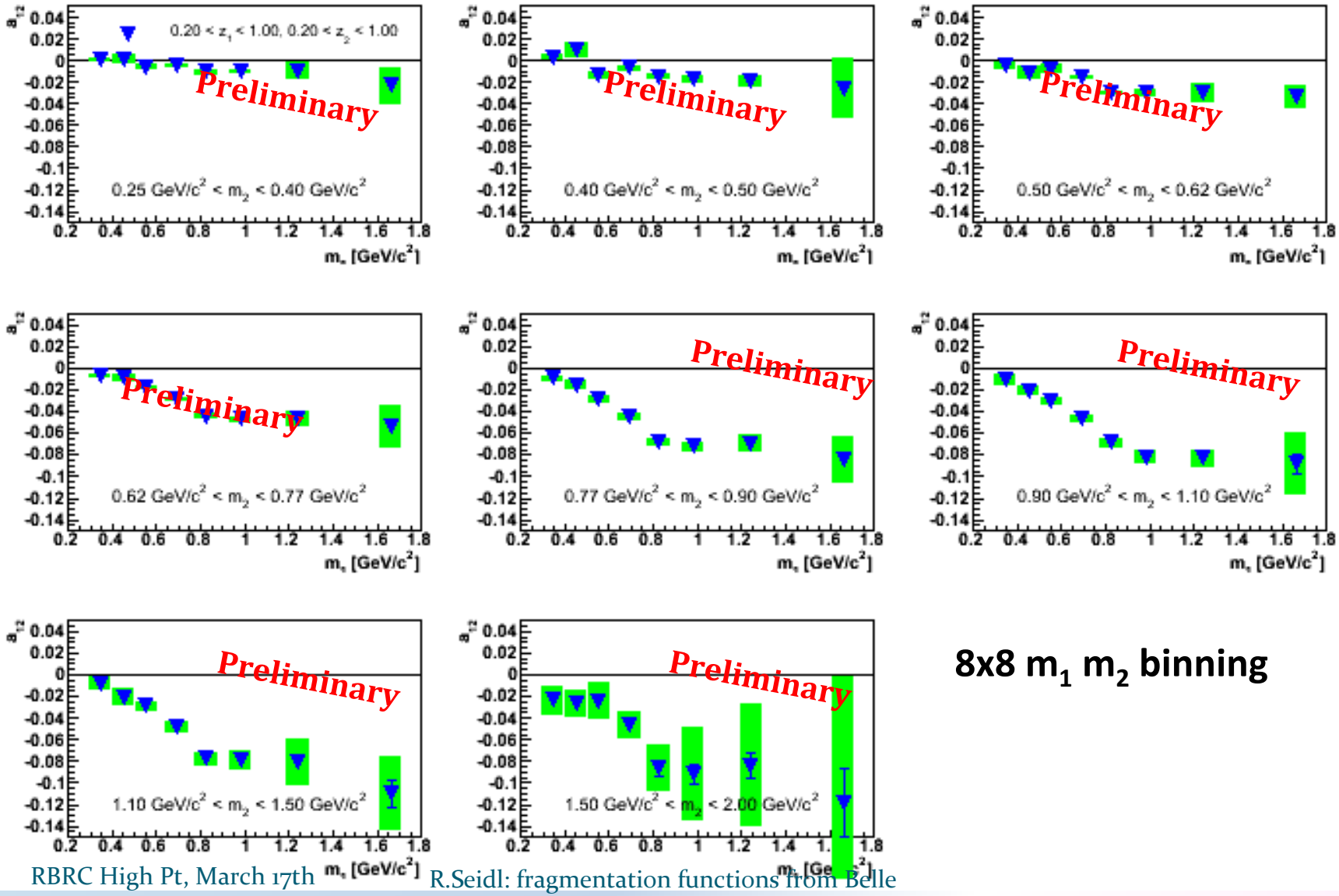
Black: injected
Purple
reconstructed

Cuts and Binning

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

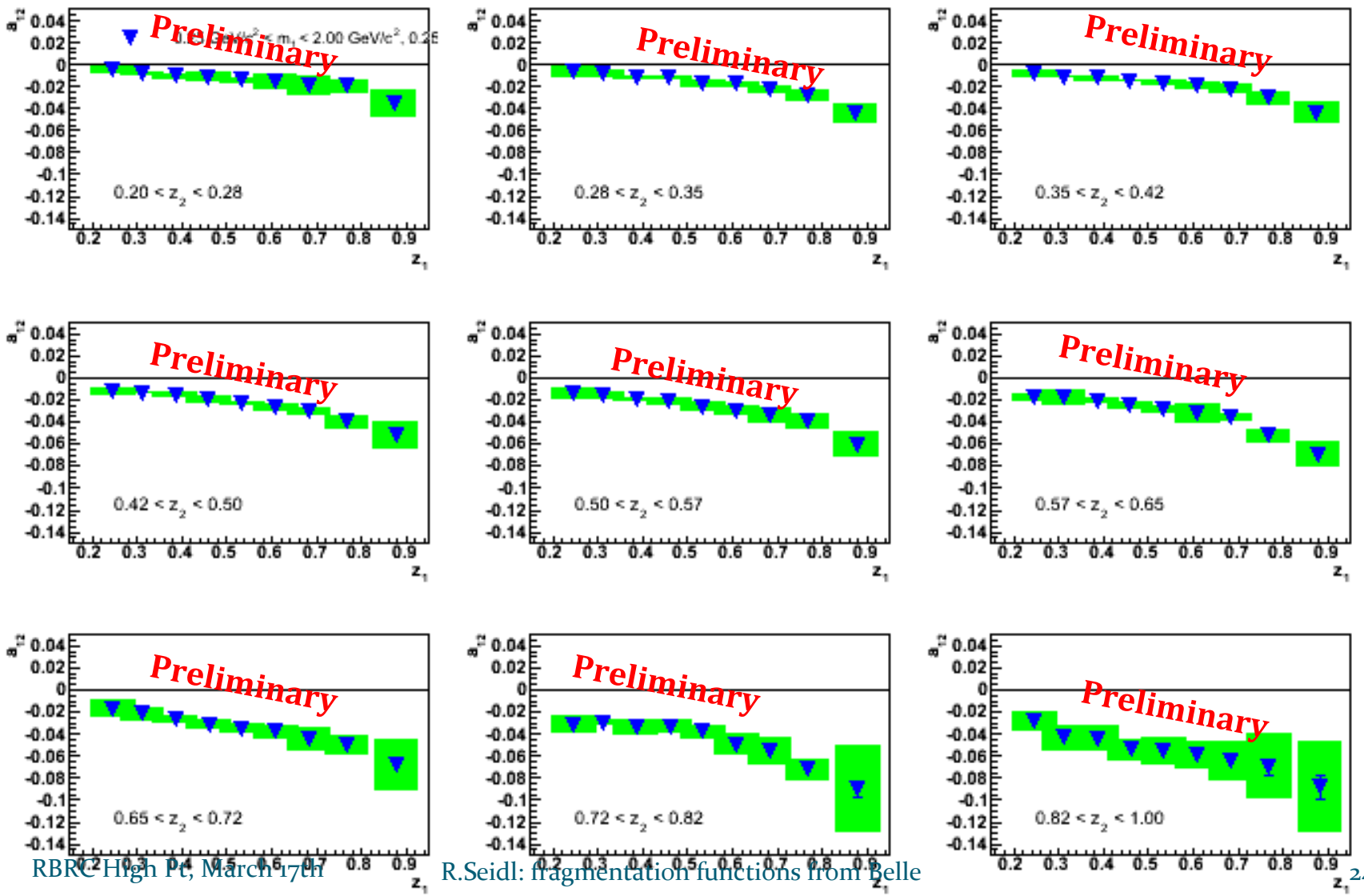
  (7-55): ~73 fb^{-1} + 588 fb^{-1}
- Visible energy >7GeV
- PID: Purities in Pion/Pion Sample > 90%
- Same Hemisphere cut within pair ($\pi^+\pi^-$), opposite hemisphere between pairs
- All 4 hadrons in barrel region: $-0.6 < \cos(\theta) < 0.9$
- Thrust axis in central area: abs(thrustz)<0.75
- Thrust > 0.8
- $z_{had1,had2} > 0.1$
- $z_1 = z_{had1} + z_{had2}$ and z_2 in 9x9 bins
- $m_{\pi\pi 1}$ and $m_{\pi\pi 2}$ in 8x8 bins: [0.25 - 2.0] GeV

Results including systematic errors



8x8 m_1 m_2 binning

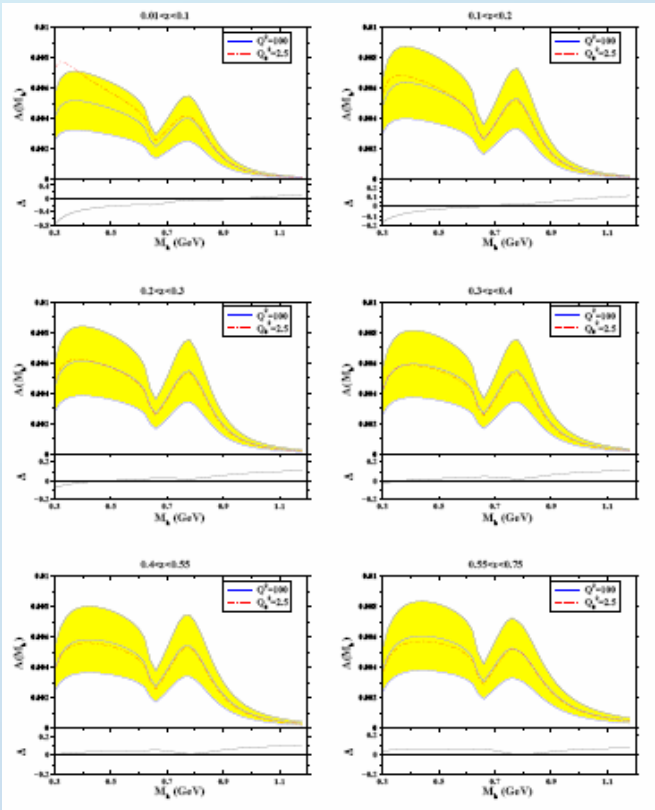
Results for 9x9 z_1 z_2 binning



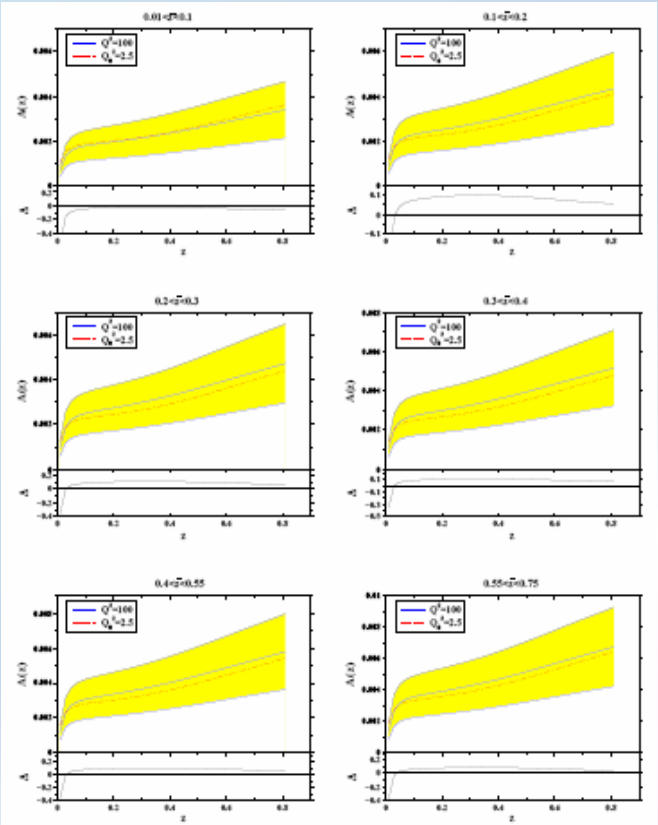
Model predictions for e^+e^-

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

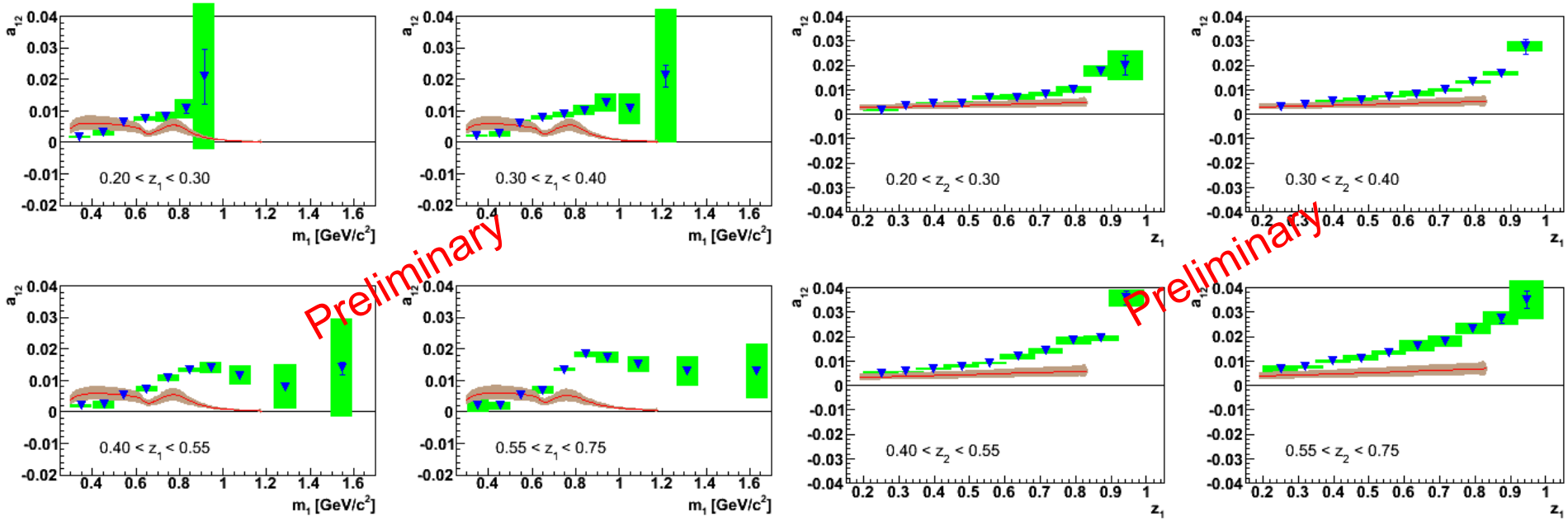
Invariant mass$_1$ dependence for increasing z_1



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

Summary and outlook

- First direct measurement of the interference fragmentation function
  - Large asymmetries seen, rising with z and invariant mass
  - No sign change at ρ mass
  - No double reatios make interpretation simple
- Significant, nonzero Collins asymmetries, long paper published
- Data used already in Global analysis
- Measure precise unpolarized fragmentation functions of many final states

→ Important input for general QCD physics and helicity structure measurements

- Analysis progressing:
  - PID studies finished
  - Acceptance correction
- Continue to measure precise spin dependent fragmentation functions at Belle
  - kT dependence of Collins function
  - Artru model test with Vector meson Collins
- Measure other interesting QCD-related quantities at Belle:
  - Chiral-odd Λ-fragmentation function
  - Λ single spin asymmetry
  - Event shapes
  - R-ratio with ISR