Measurement of Polarized Fragmentation Functions in e^+e^- at

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CEEM

Presenting work from
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Francesca Giordano
Martin Leitgab
Hairong Li
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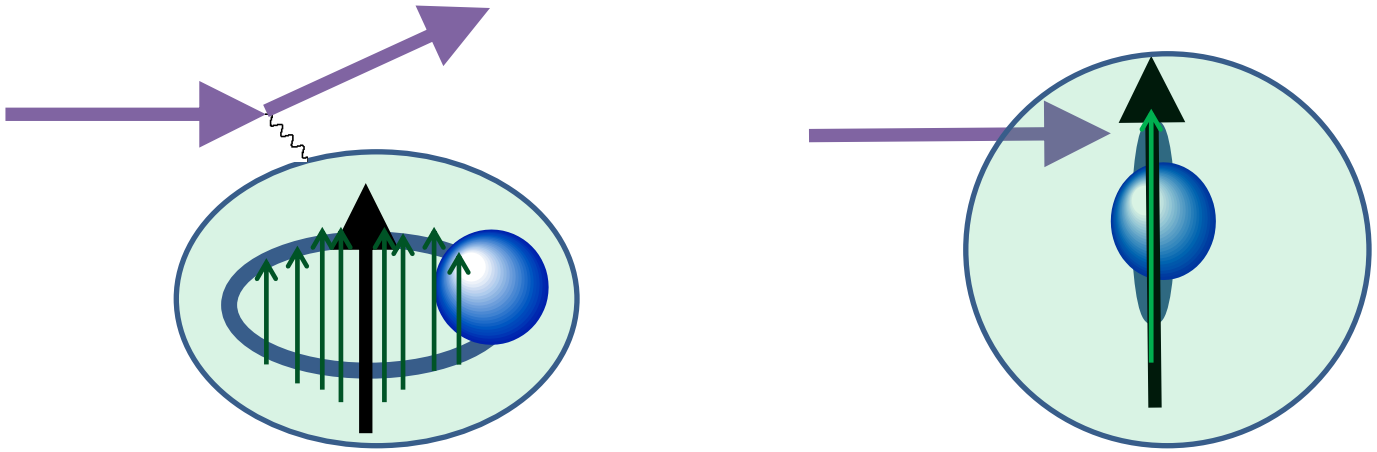
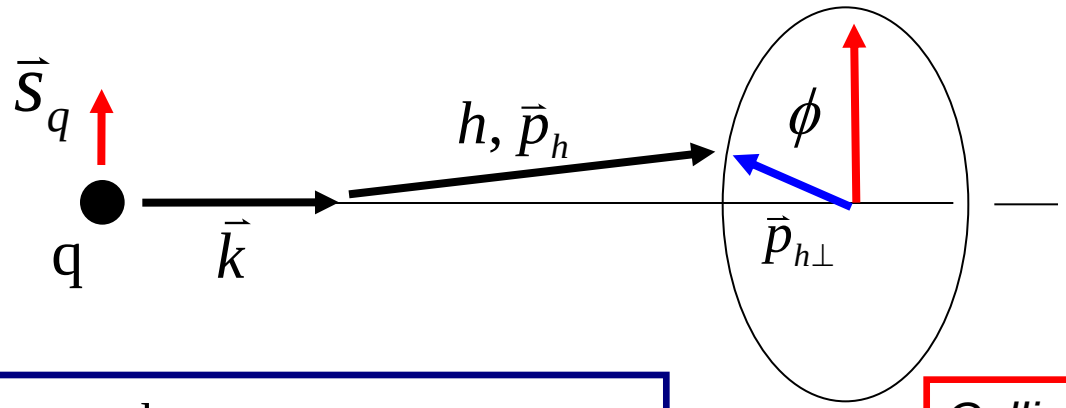
Transverse spin dependent FFs needed as quark polarimeters



- Relativistic Leptonic probe is ‘too fast’ to see transverse spin
- To probe: knock out quark and use effect generated by angular moment conservation

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

$z_h = E_h / E_q$

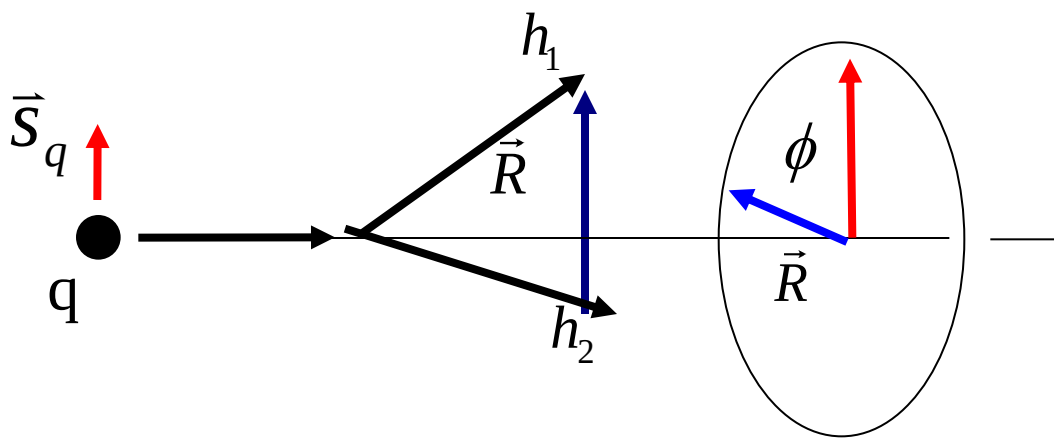
$= 2E_h / \sqrt{s}$: relative hadron momentum

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

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

$$\propto \sin\phi$$

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

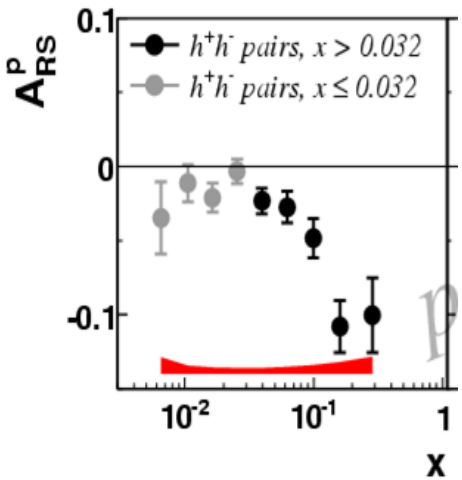
Interference Fragmentation Function:
Fragmentation of a transversely polarized quark *q* into two spin-less hadron *h1, h2* carries an azimuthal dependence:

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

$$\propto \sin\phi$$

Advantages of IFF over Collins route

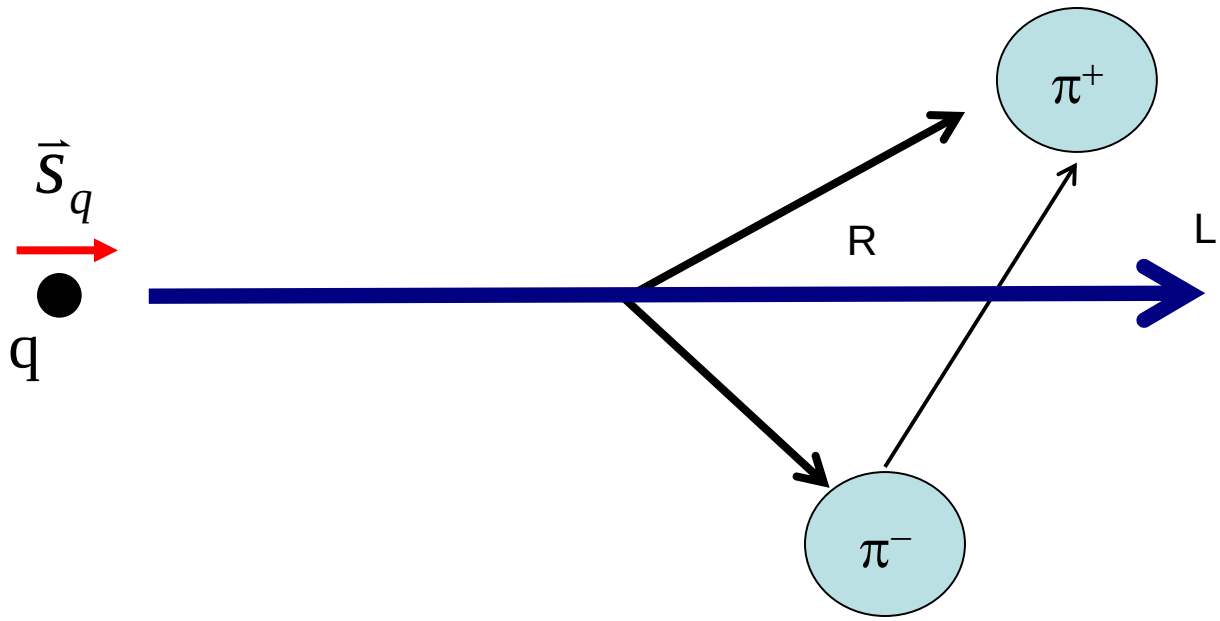
- Single Hadron asymmetries vanish integrated over transverse momentum: model dependency in global fit
- Di-hadron effect survives after integration over k_T: collinear factorization can be used
  - No Sudakov suppression
  - Known evolution
- Less background processes to consider (e.g. from gluon radiation, t-→$\pi^-\pi^+\pi^-\nu_\tau$)



- SIDIS experiment show that the effect is large

In p+p:
No jet reconstruction necessary,
better systematics: “Easier” measurement
Collider allows wide kinematic coverage!

Jet Handedness

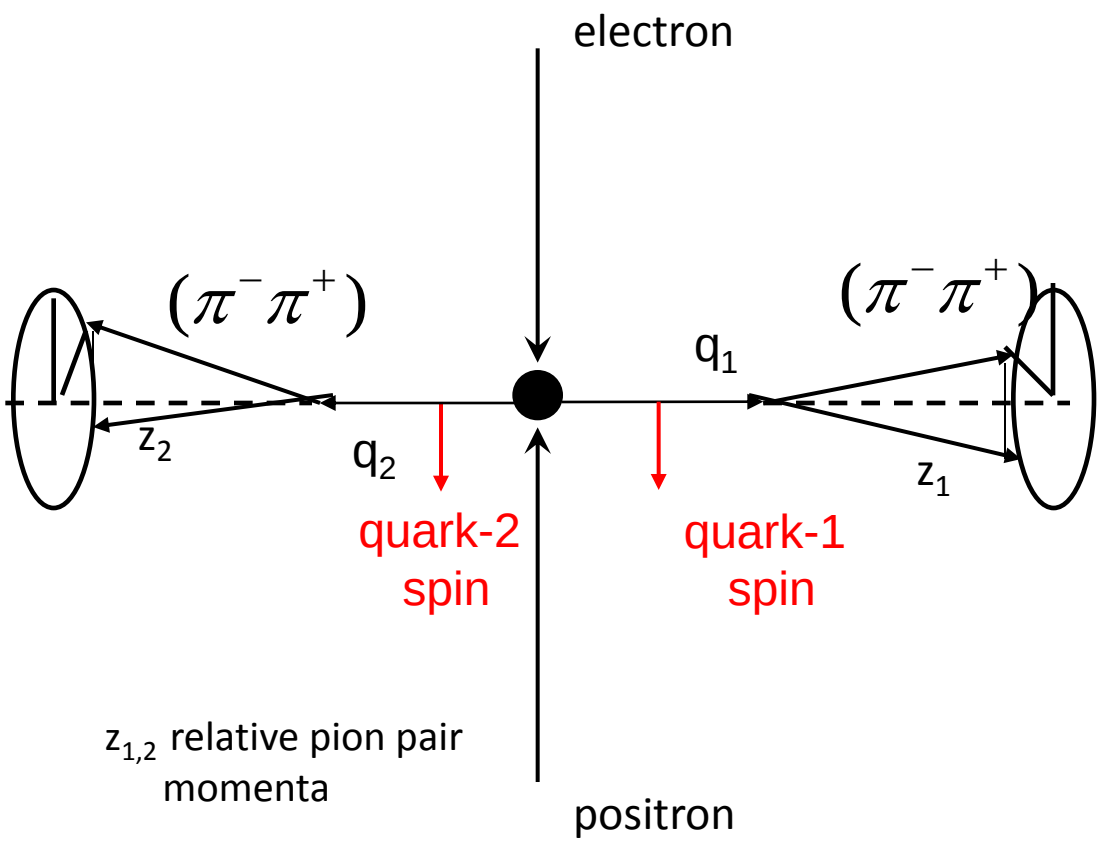


Handedness: $\frac{(\overrightarrow{k_+} \times \overrightarrow{k_-}) \cdot \vec{t}}{|\, k_+ \,||\, k_- \,|} = \sin\Phi \overset{?}{>} 0 \Rightarrow$ L/R

Jet *handedness:* $\frac{N_R - N_L}{N_R + N_L}$

Related to g_{1T}, T-odd, not chiral-odd. Effects for sphaleron coupling, or factorized TMD (different)
(D. Boer, Pavia DiFF minworkshop 2011)

Measuring spin dependent FFs in e^+e^- Annihilation into Quarks



Spin dependence in e^+e^- quark fragmentation will lead to (azimuthal) asymmetries in correlation measurements!

Experimental requirements:

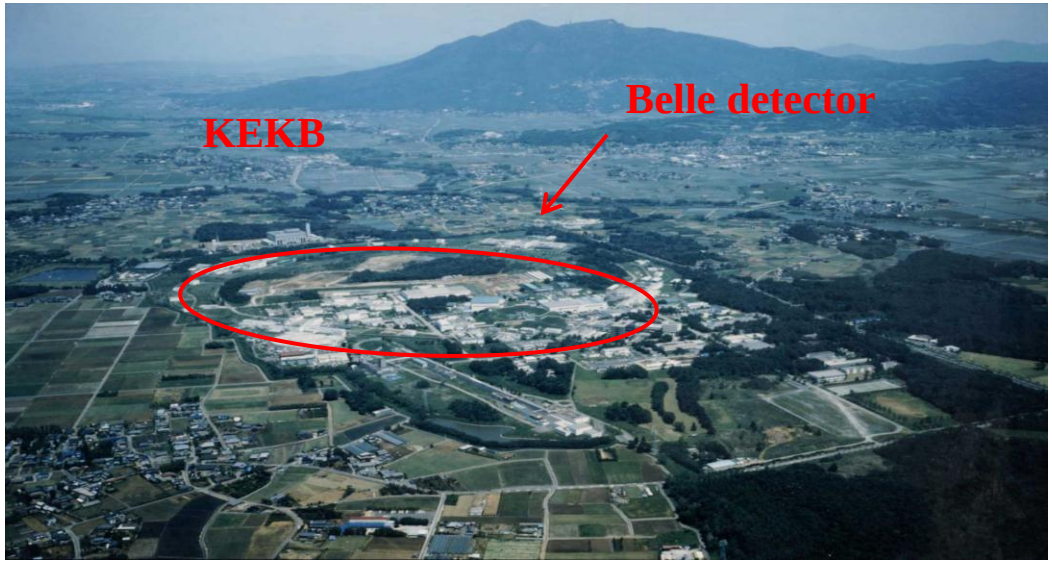
- Small asymmetries ➔ very large data sample!
- Good particle ID to high momenta.
- Hermetic detector

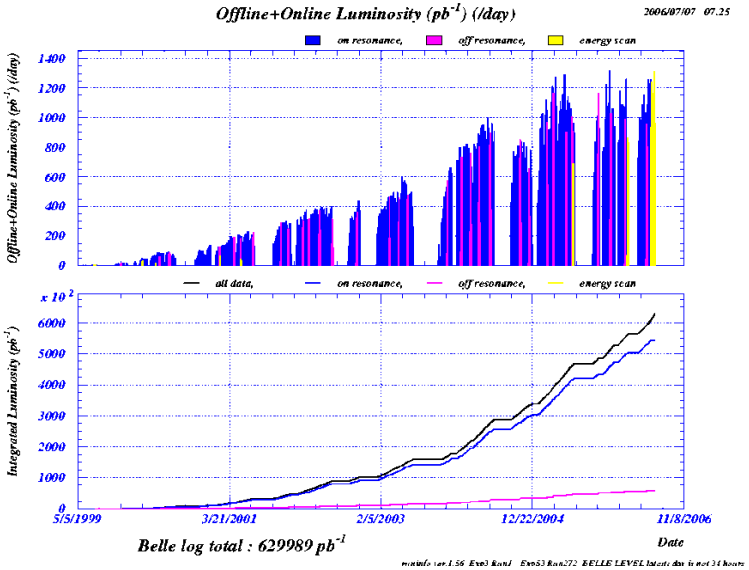
Here for di-hadron correlations:

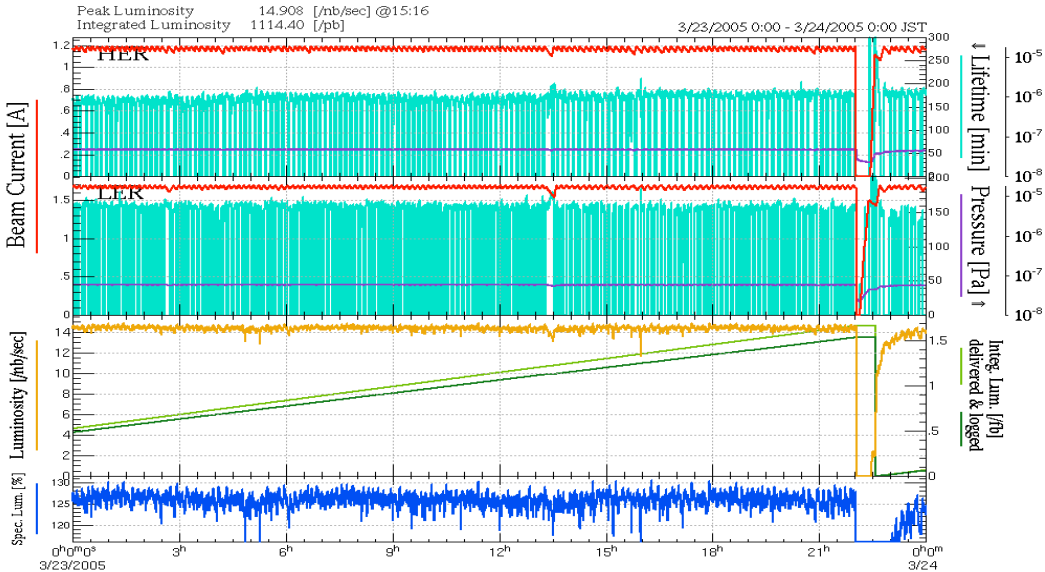
$$A \propto H_1^{\angle}(z_1, m_1)\overline{H}_1^{\angle}(z_2, m_2)\cos(\varphi_1 + \varphi_2)$$

Measurement of Fragmentation Functions @

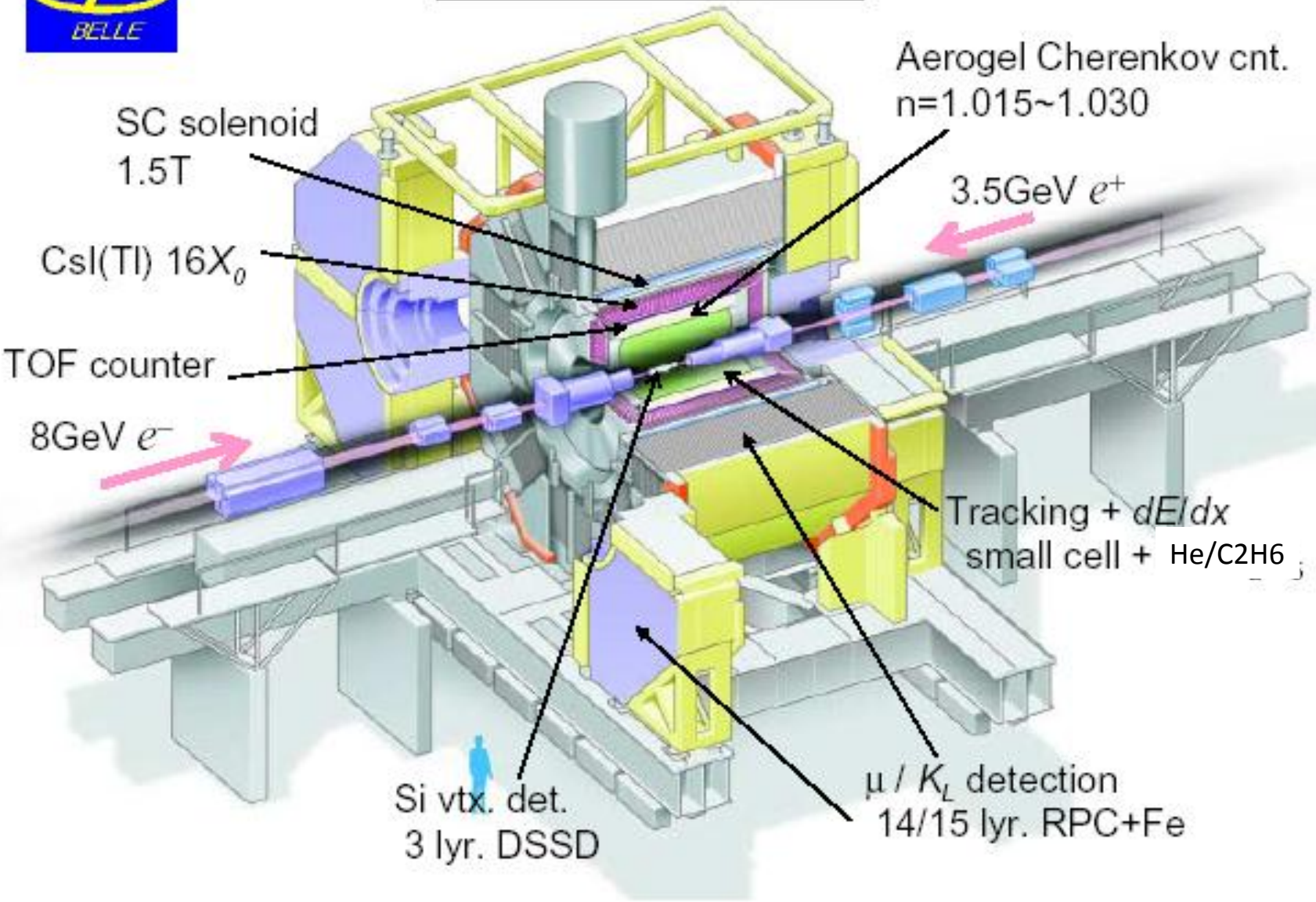
- KEKB: L>2.11 x 10^{34}cm^{-2}s^{-1}
- Asymmetric collider:
- 8GeV e^- + 3.5 GeV e^+
- $\sqrt{s}$=10.58 GeV (▪(4S))
- e^+e^-▪▪(4S)▪BB
- Integrated Luminosity: > 1000 fb^{-1}
- Continuum production: 10.52 GeV
- e^+e^-▪(u, d, s, c)
- >70 fb^{-1} => continuum



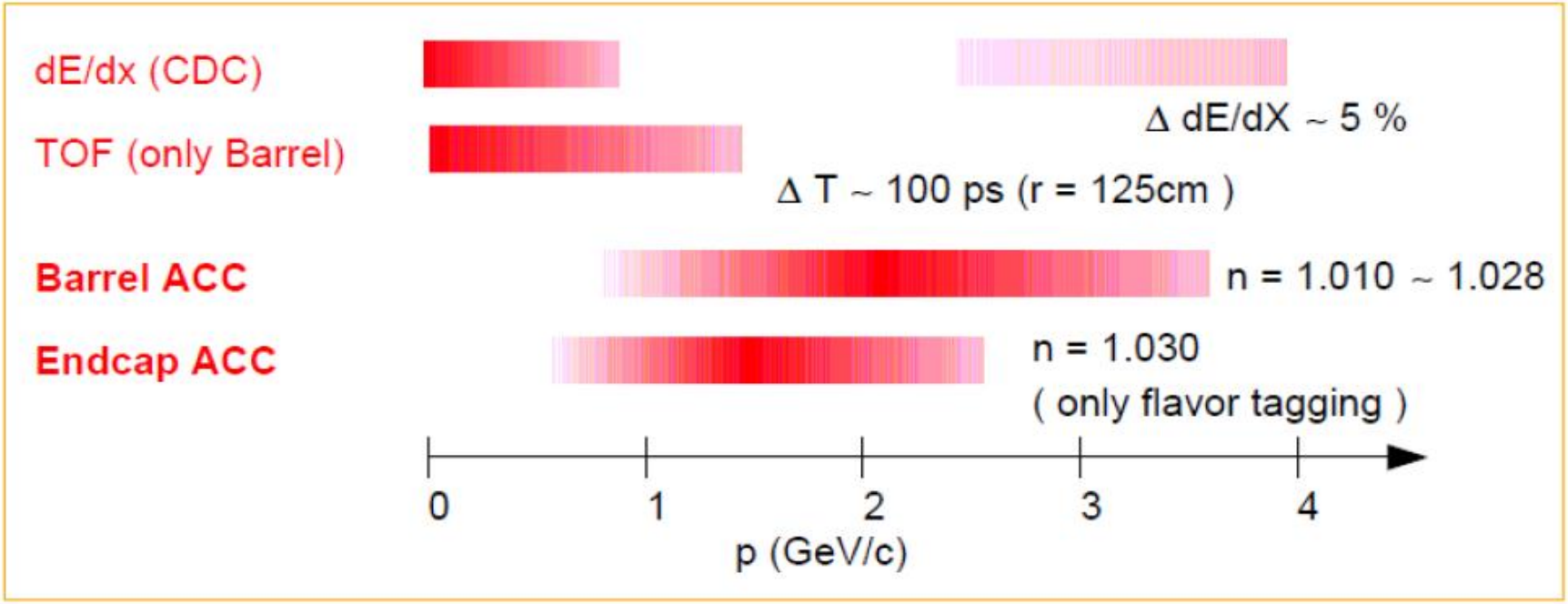


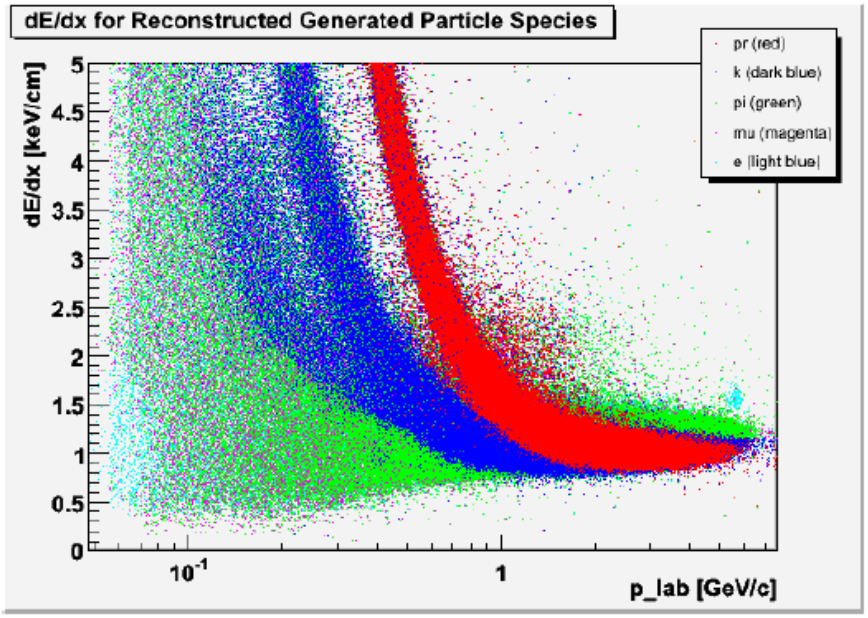


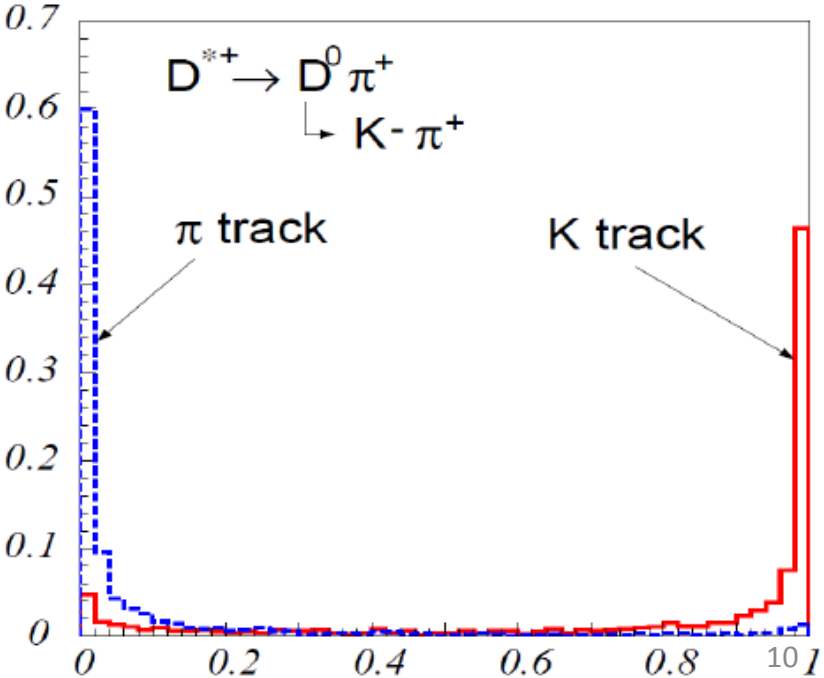
Belle Detector



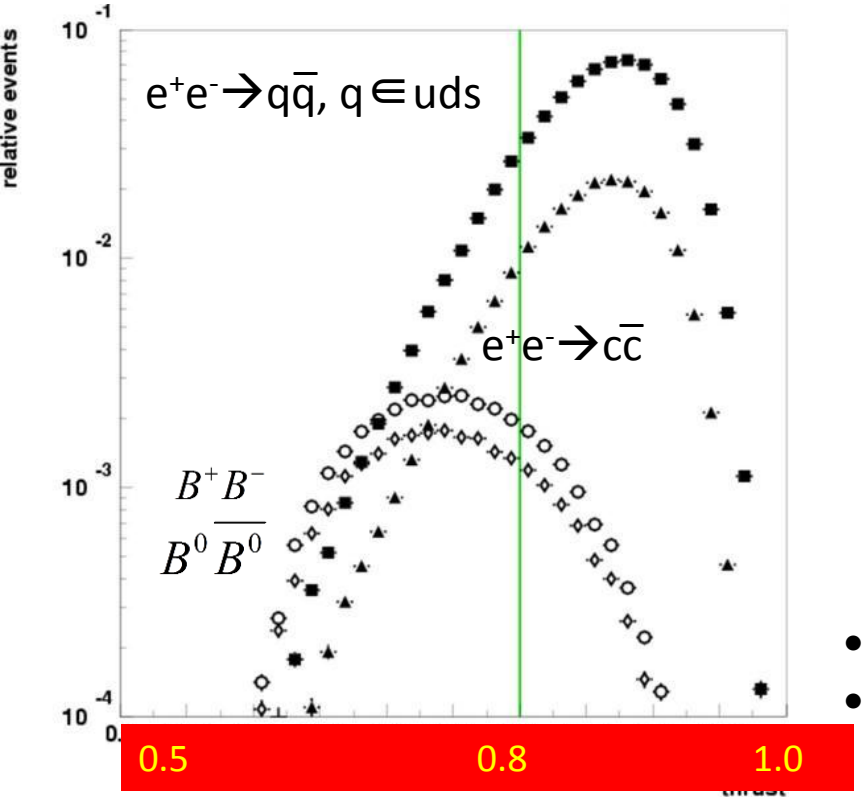
Large acceptance, good tracking and particle identification!


dE/dx (CDC)
Δ dE/dX ~ 5 %
TOF (only Barrel)
Δ T ~ 100 ps (r = 125cm)
Barrel ACC
n = 1.010 ~ 1.028
Endcap ACC
n = 1.030
(only flavor tagging)
0
1
2
3
4
p (GeV/c)

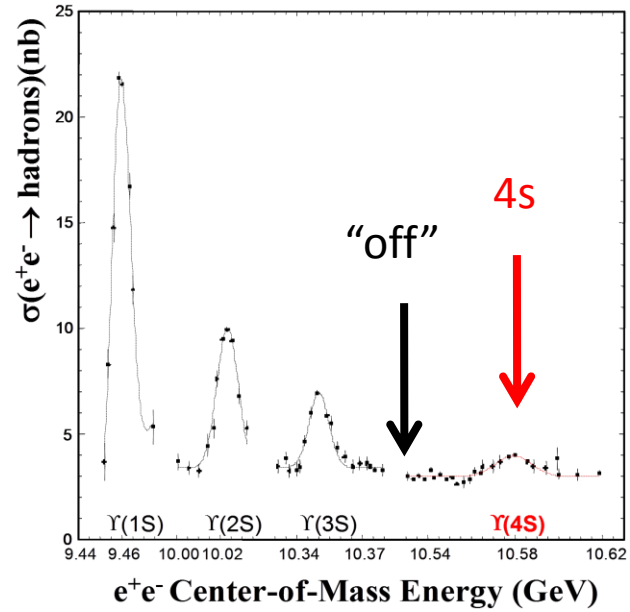

dE/dx for Reconstructed Generated Particle Species
pr (red)
k (dark blue)
pi (green)
mu (magenta)
e (light blue)
dE/dx [keV/cm]
p_lab [GeV/c]


$D^{*+} \rightarrow D^0 \pi^+$
$\hookrightarrow K^- \pi^+$
π track
K track

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



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

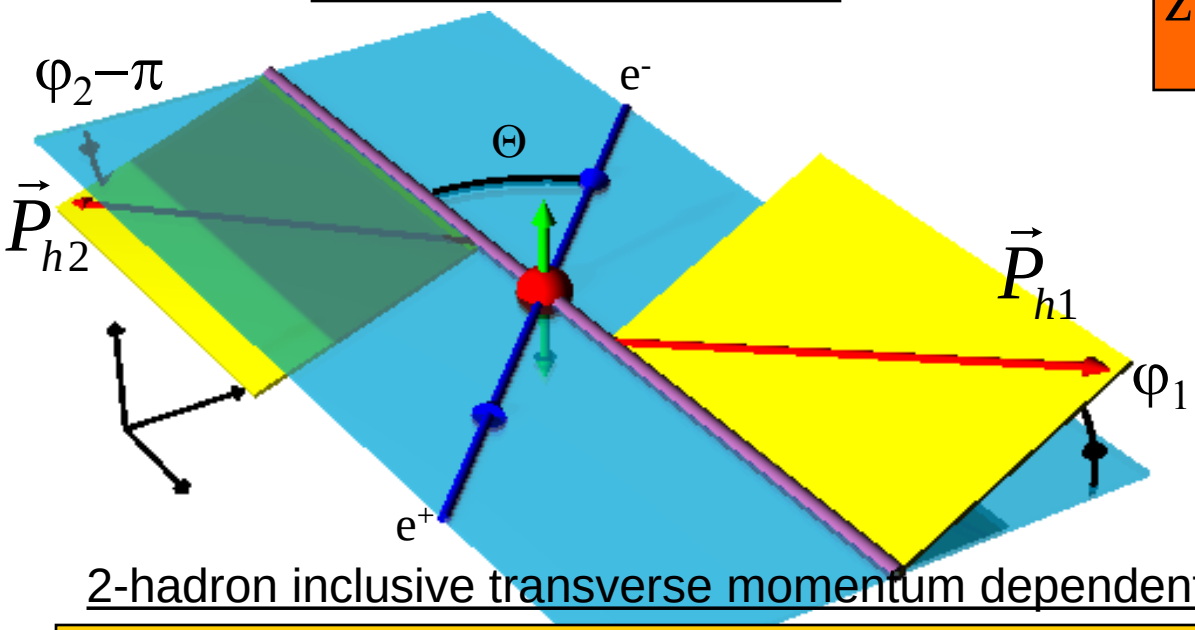


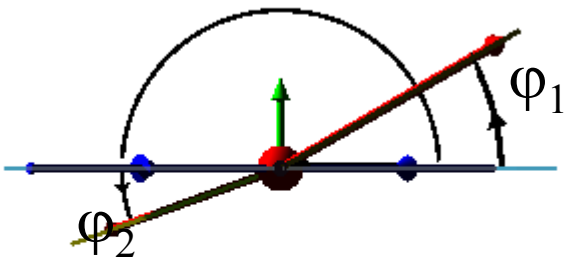
- small B contribution (<1%) in high thrust sample
- >75% of X-section continuum under ϒ (4S) resonance
- ~100 fb^{-1} ➔ ~1000 fb^{-1}

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

e^+e^- CMS frame:

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





[D.Boer: **PhD thesis(1998)**]

2-hadron inclusive transverse momentum dependent cross section:

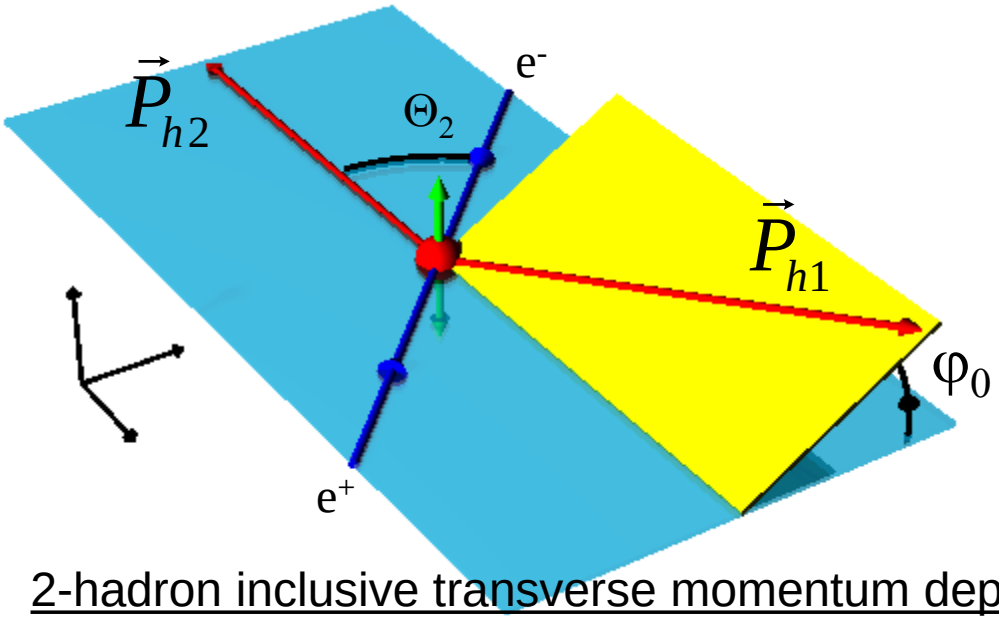
$$\frac{d\sigma(e^+e^- \to h_1h_2X)}{d\Omega dz_1 dz_2 d^2\boldsymbol{q}_T} = \cdots B(y)\cos(\varphi_1+\varphi_2)H_1^{\perp[1]}(z_1)\overline{H}_1^{\perp[1]}(z_2)$$

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

Net (anti-)alignment of transverse quark spins

Collins fragmentation in e^+e^- : Angles and Cross section $\cos(2\phi_0)$ method

e^+e^- CMS frame:



- Independent of thrust-axis
- Convolution integral $\mathcal{I}$ over transverse momenta involved

[Boer,Jakob,Mulders: **NPB504(1997)345**]

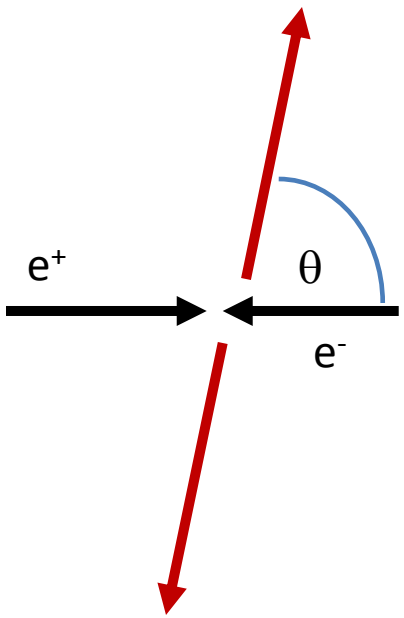
2-hadron inclusive transverse momentum dependent cross section:

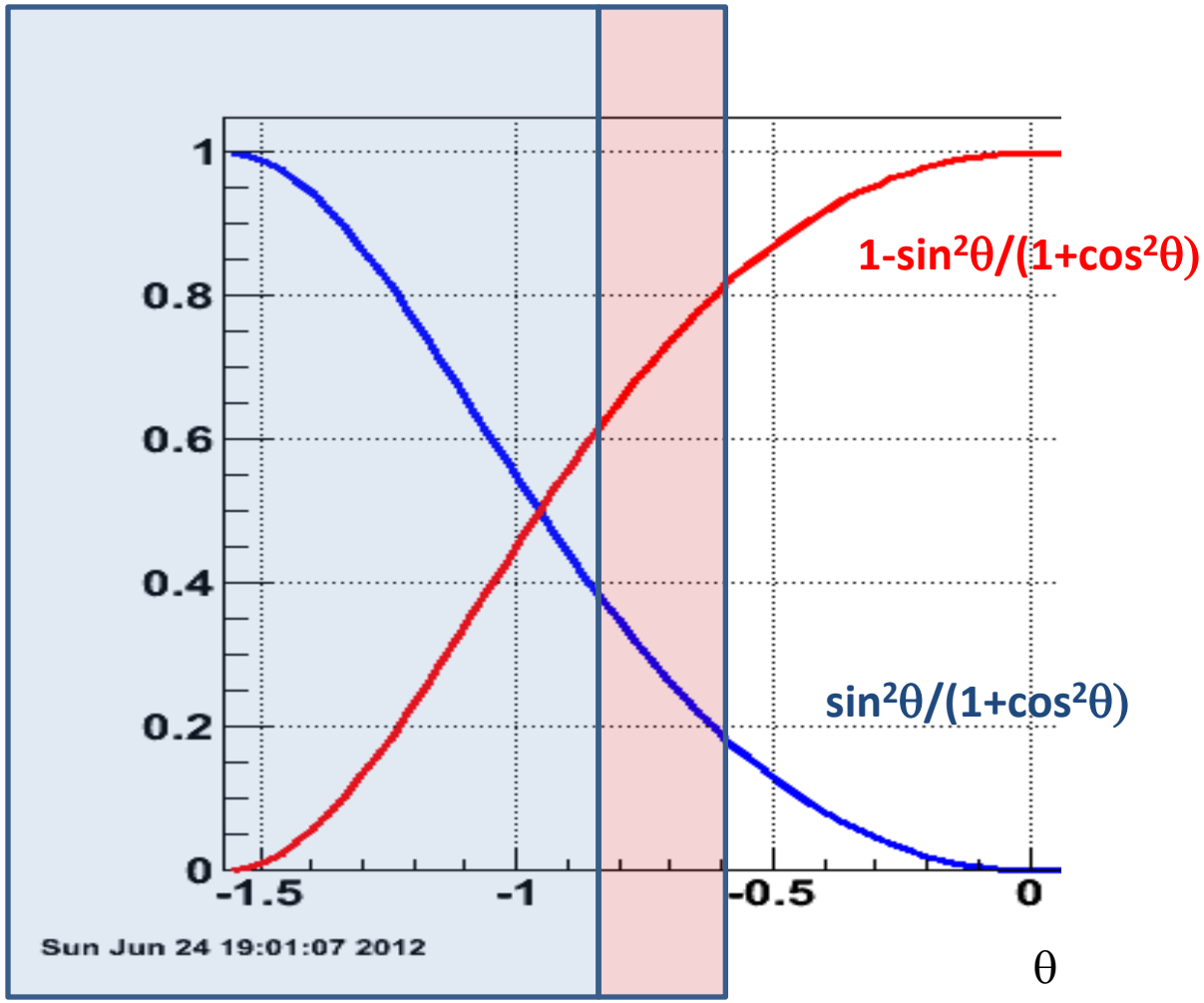
$$\frac{d\sigma\left(e^+e^- \to h_1 h_2 X\right)}{d\Omega dz_1 dz_2 d^2 q_T} = \cdots B(\Theta)\cos(2\varphi_0)\mathrm{I}\left[\left(2\hat{h}\cdot k_T \hat{h}\cdot p_T - k_T \cdot p_T\right)\frac{H_1^\perp \bar{H}_1^\perp}{M_1 M_2}\right]$$

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

Net (anti-)alignment of transverse quark spins

Spin Projection in Barrel and Endcap



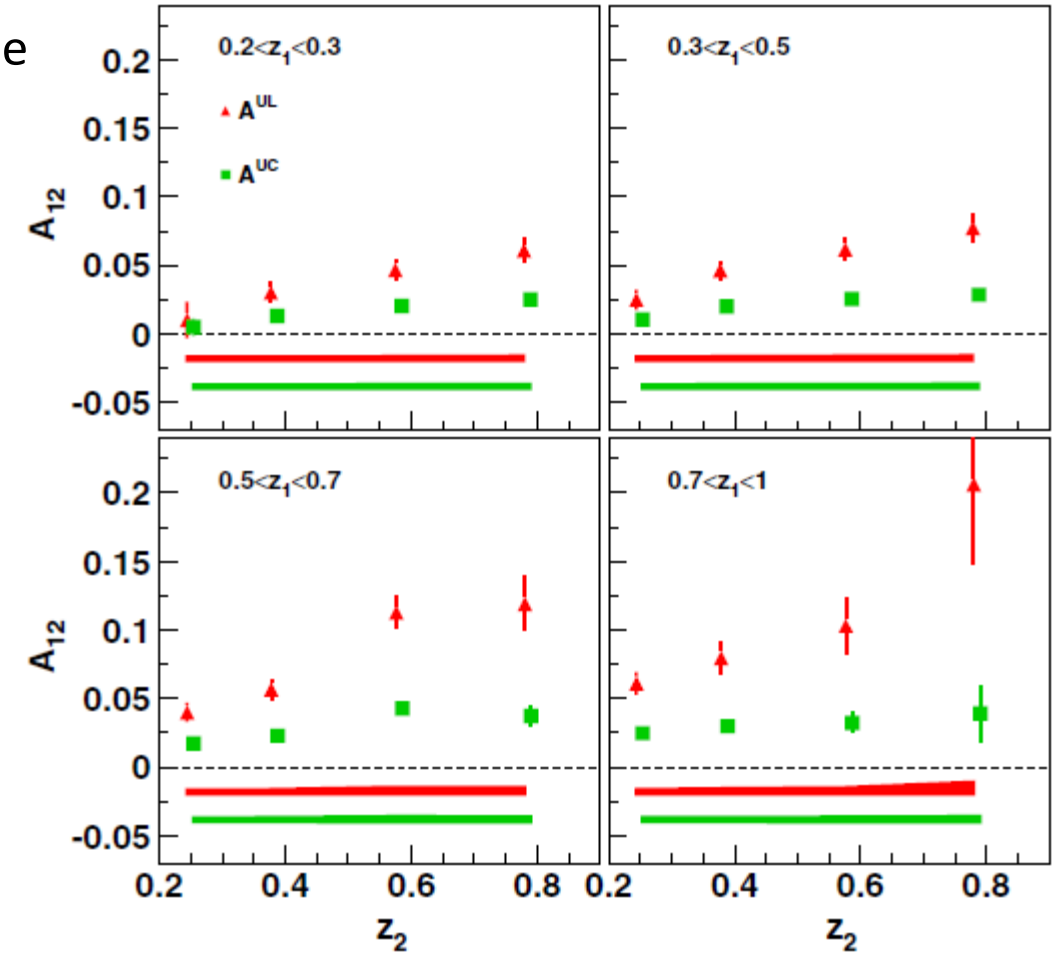


Transverse Spin Dependent FFs: Cuts and Binning

- Full off-resonance and on-resonance data (7-55): ~73 fb^{-1} + 588 fb^{-1}
- Visible energy >7GeV
- PID: Purities in for pion pairs > 90%
- Opposite hemisphere between pairs pions
- All hadrons in barrel region: $-0.6 < \cos(\theta) < 0.9$
- 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} >0.2

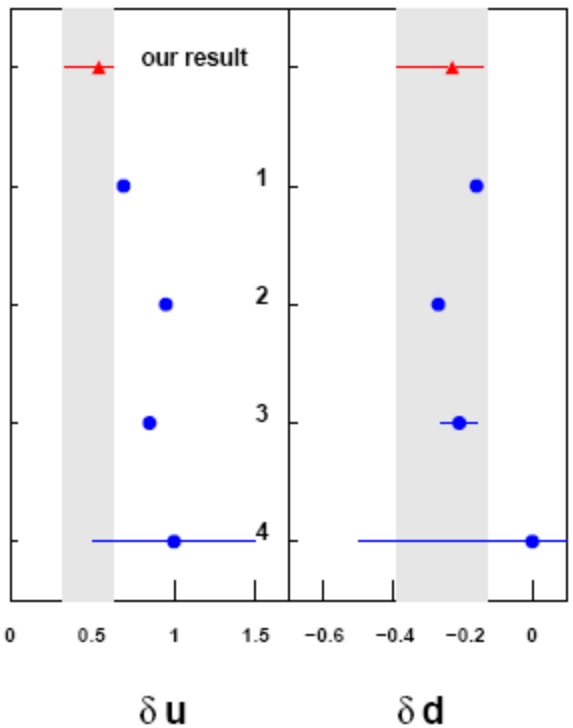
Final Collins results

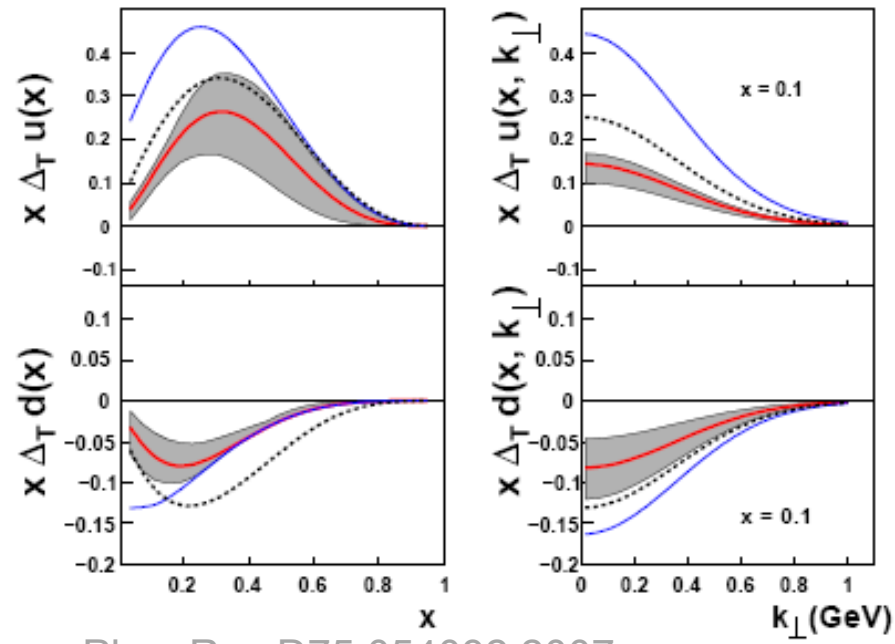
- First direct measurement of the Collins effect: (PRL96: 232002)
- Nonzero asymmetries
- Consistent with BaBar measurement (see talk by David Muller)
- Belle 547 fb^{-1} data set (PRD78:032011)



Use of double ratios to cancel gluon radiation effects

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



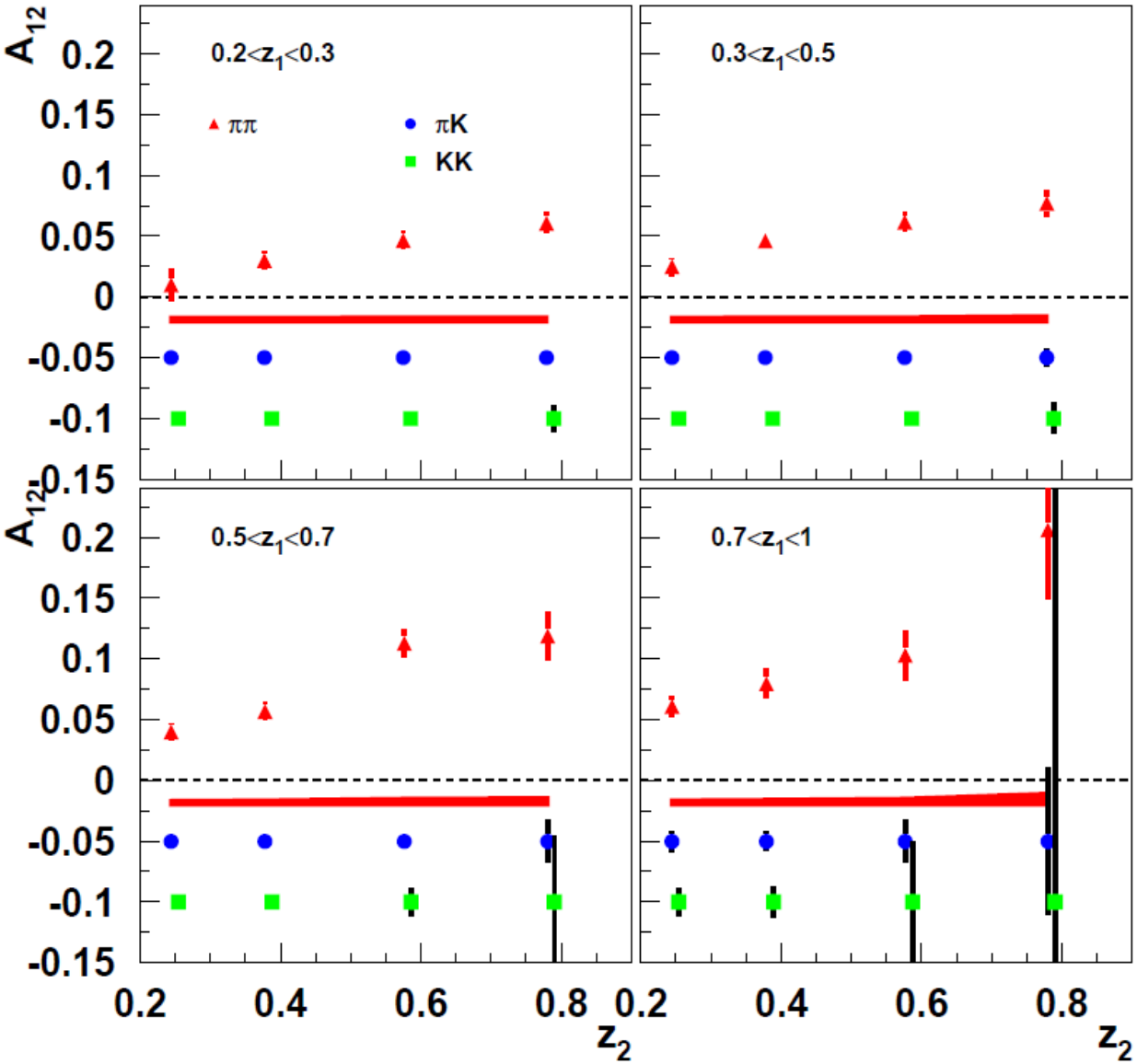


Phys.Rev.D75:054032,2007, update in Nucl.Phys.Proc.Suppl.1 91:98-107,2009

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

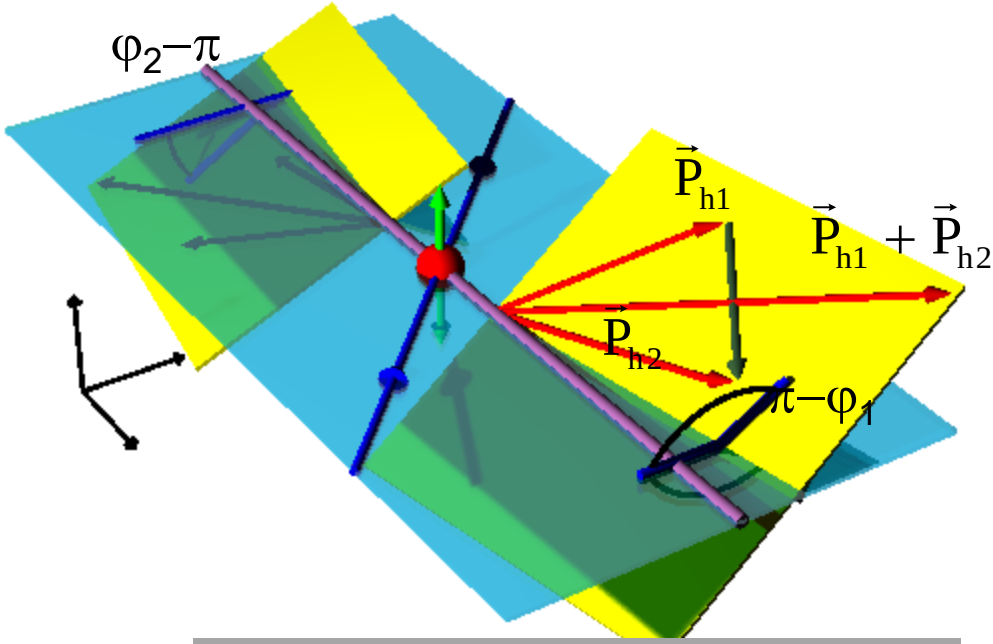
Projections for Kaon Collins

- Using same PID matrices as recent K/π yield extraction (see Martin Leitgab's talk)
- Error bars statistical, Charm correction, smearing uncertainties not yet included



Interference Fragmentation – thrust method

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



Model predictions by:

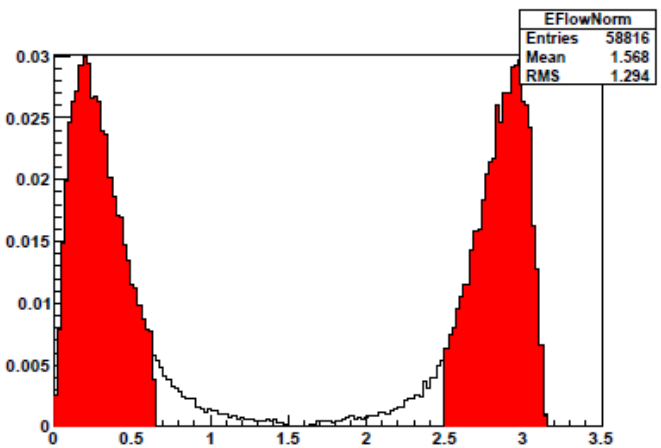
- Jaffe et al. [PRL **80,**(1998)]
- Radici et al. [PR**D 65,**(2002)]

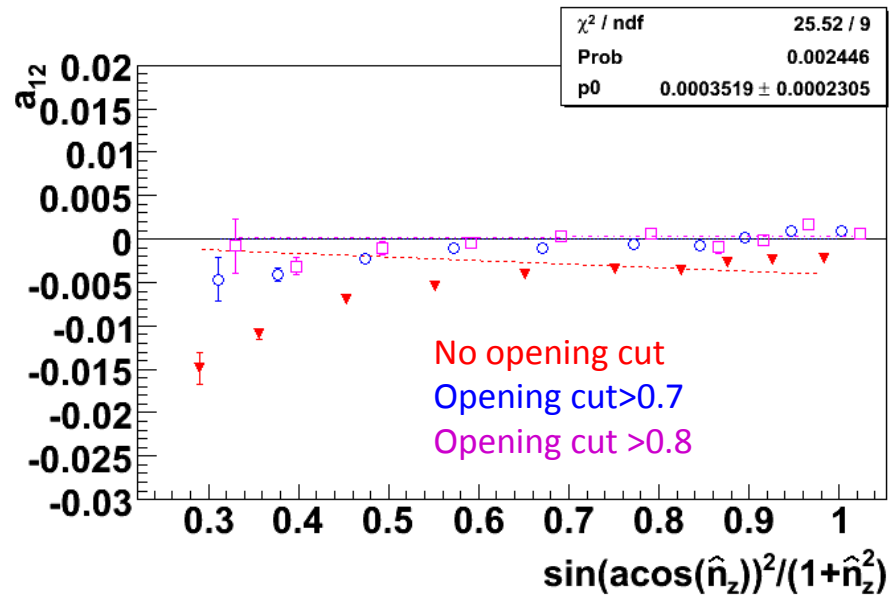
$$A \propto H_1^{\angle}(z_1, m_1)\overline{H}_1^{\angle}(z_2, m_2)\cos(\varphi_1 + \varphi_2)$$

Transverse Spin Dependent FFs: Cuts and Binning

- 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: $-0.6 < \cos(\theta) < 0.9$
- 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 binning
- $m_{\pi\pi 1}$ and $m_{\pi\pi 2}$ binning
- Here: Mixed binning

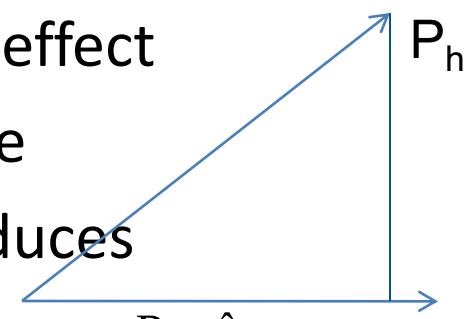
Zero tests: MC





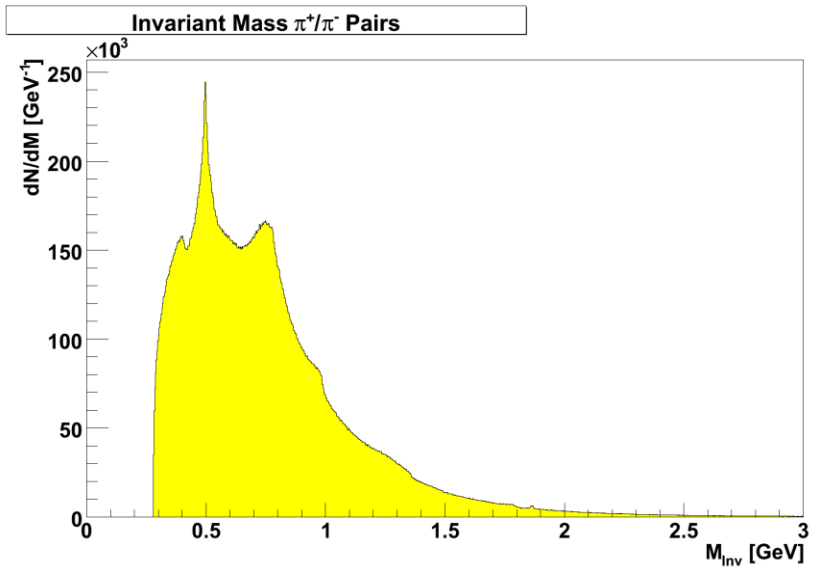
Energy flow with opening cut of 0.8

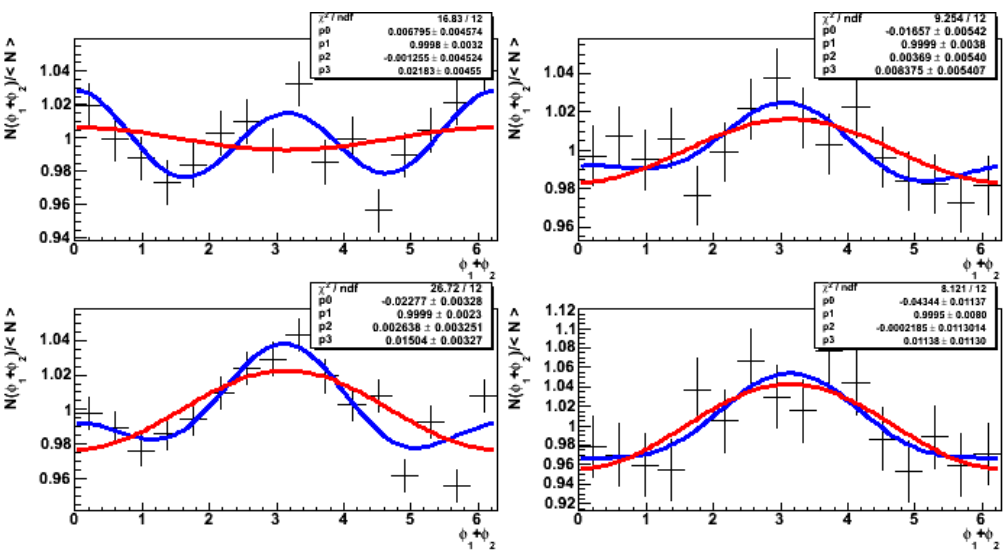
- A small asymmetry seen due to acceptance effect
- Mostly appearing at boundary of acceptance
- Opening cut in CMS of 0.8 (~37 degrees) reduces acceptance effect to the sub-per-mille level



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

Asymmetry extraction





- Build normalized yields:

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

- Fit with:

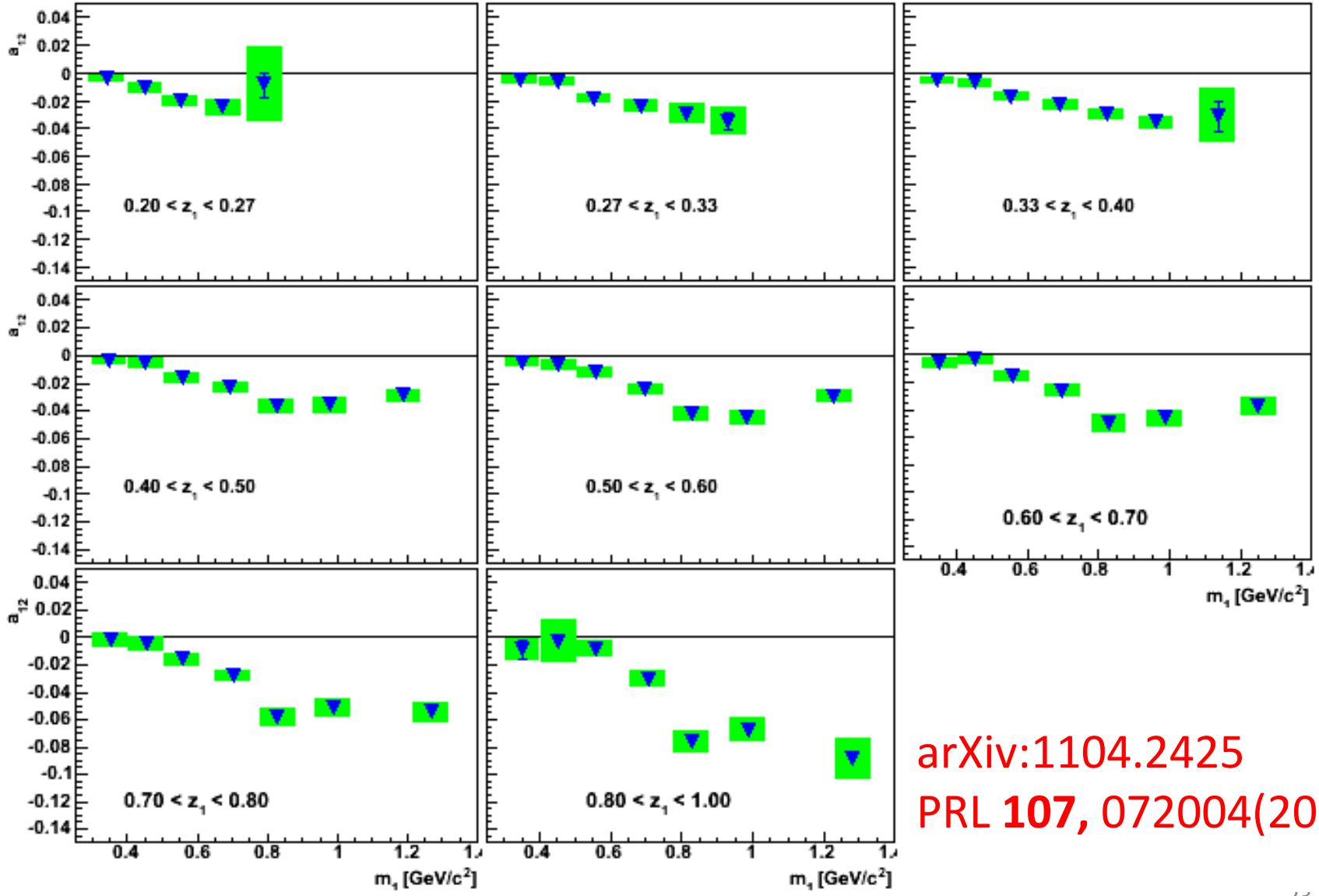
$$a_{12}\cos(\phi_1+\phi_2)+b_{12}$$

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)

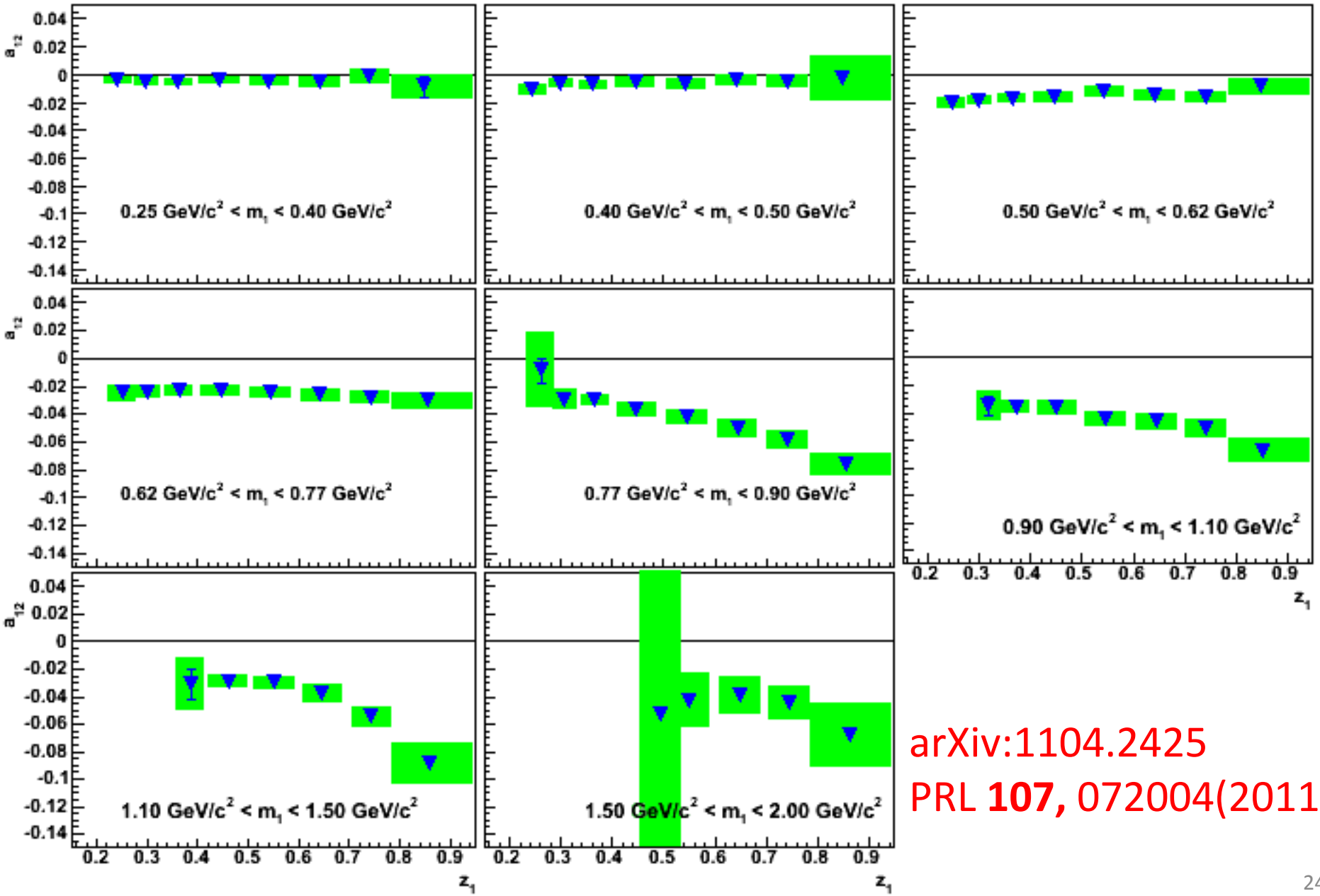
(z_1x m_1) Binning



arXiv:1104.2425

PRL **107,** 072004(2011)

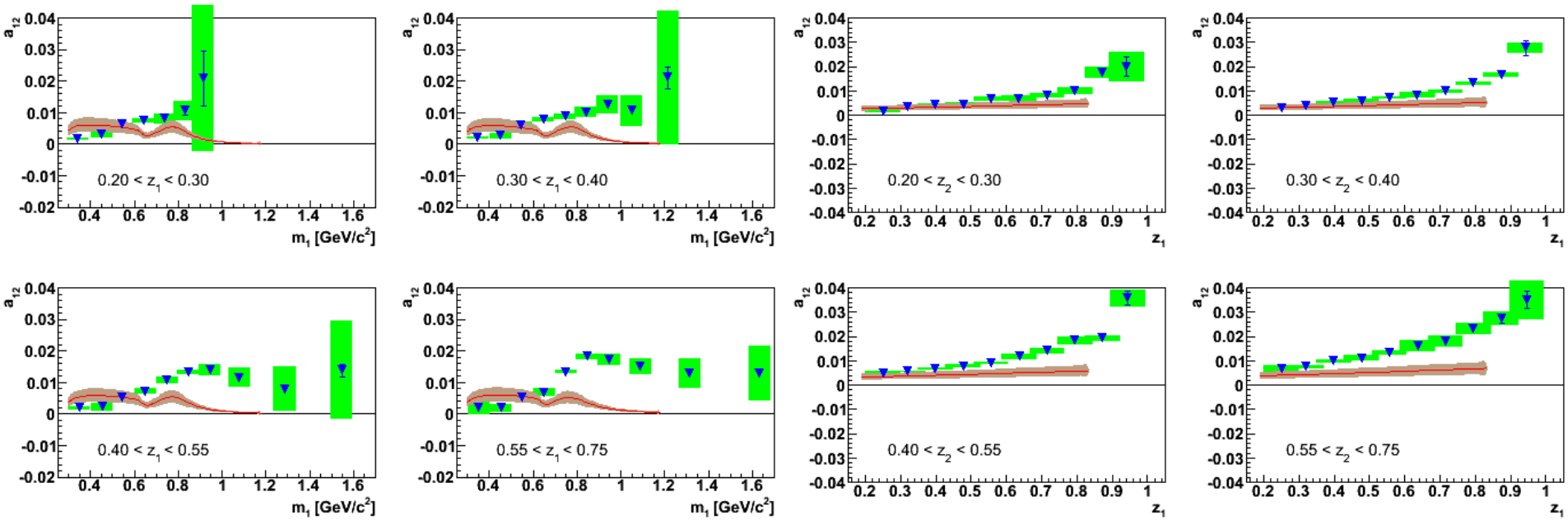
(m_1x z_1) Binning



arXiv:1104.2425

PRL **107,** 072004(2011)

Comparison to theory predictions



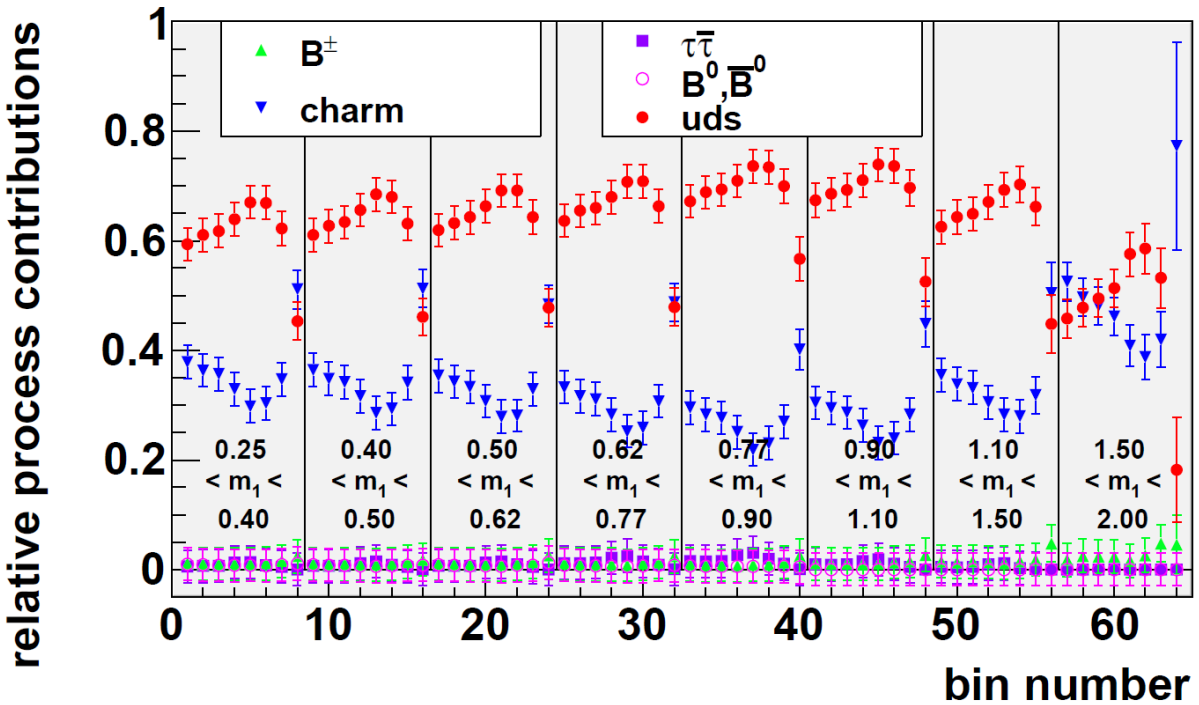
Red line: theory prediction + uncertainties

Blue points: data

- Mass dependence : Magnitude at low masses comparable, high masses significantly larger (some contribution possibly from charm)
- Z dependence : Rising behavior steeper

Subprocess contributions (MC)

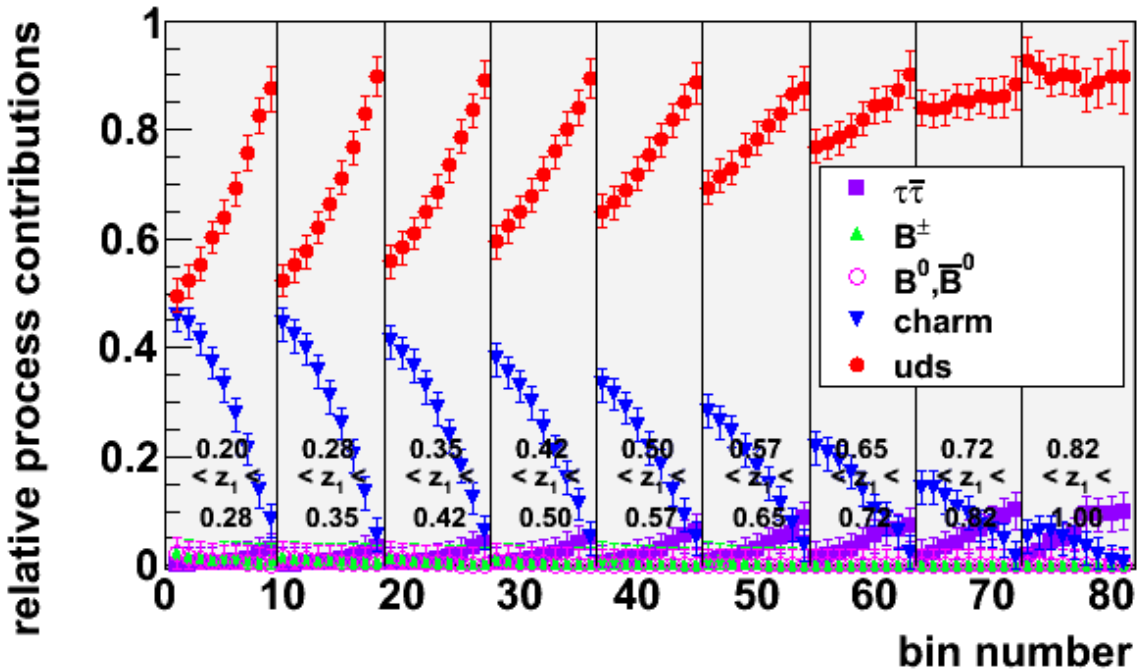
8x8 m_1 m_2 binning



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)

9x9 z_1 z_2 binning



tau contribution (only significant at high z)
charged B(<5%, mostly at higher mass)
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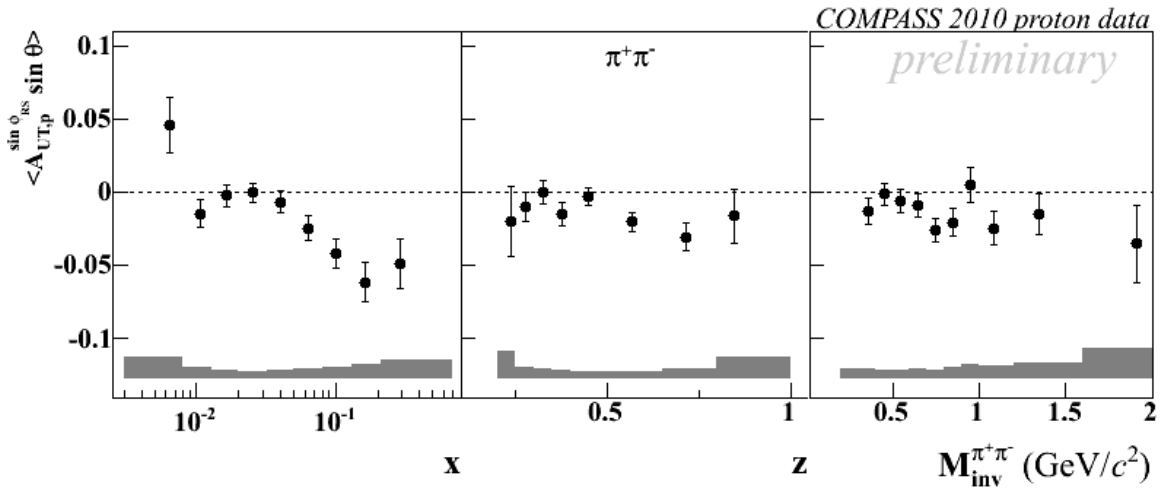
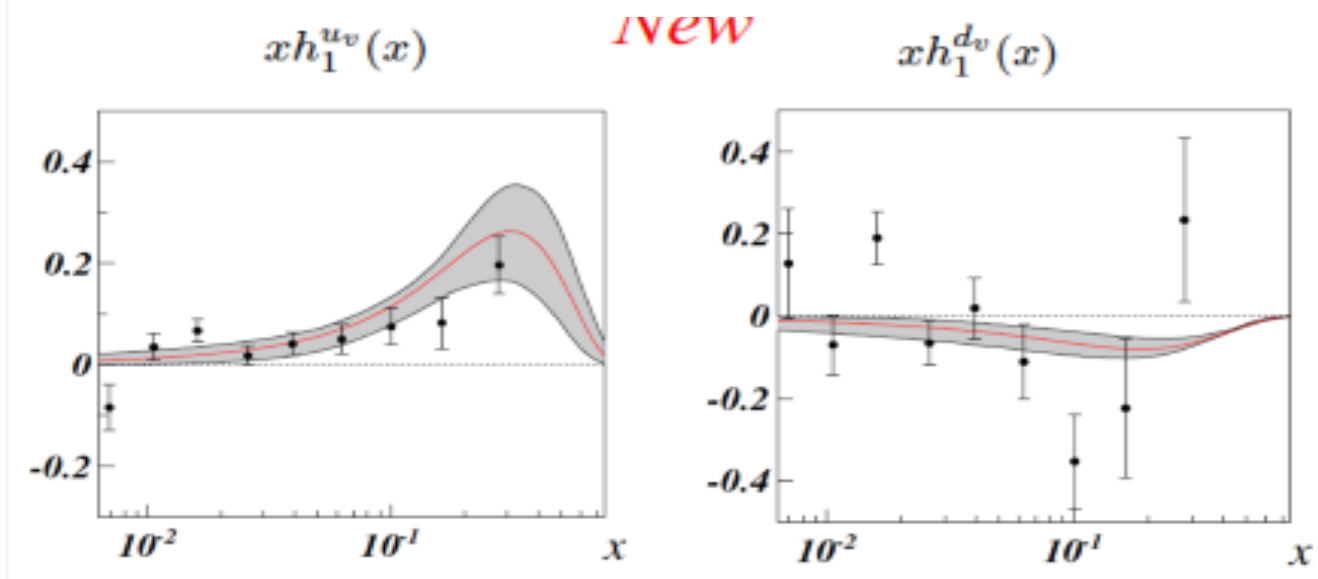
uds (main contribution)

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

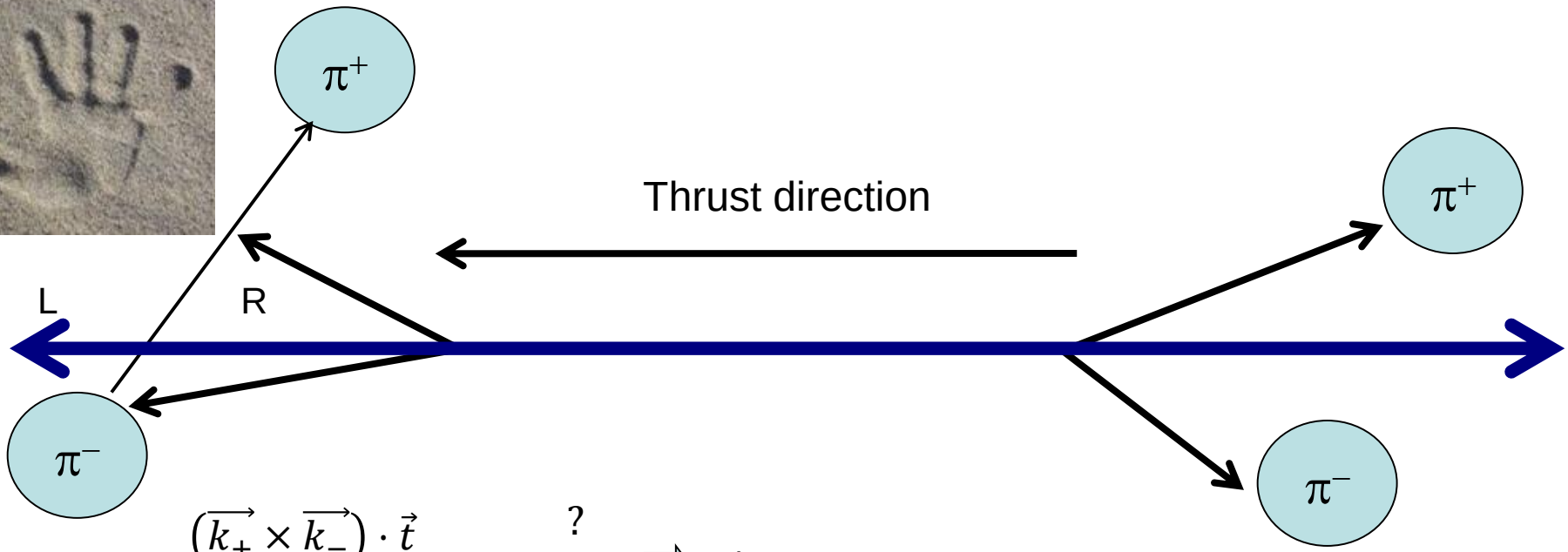




A.Martin, Qcd Evolution 2012, Using A. Bacchetta, M.Radici and A. Courtoy: Phys. Rev. Lett. 107:012001,2011

See Marco Radici's talk

Handedness



Handedness: $\frac{(\overrightarrow{k_+} \times \overrightarrow{k_-}) \cdot \vec{t}}{|\, k_+ \,||\, k_- \,|} = \sin\Phi \overset{?}{>} 0$ ⇨ L/R

Jet *handedness:* $\frac{N_R - N_L}{N_R + N_L}$

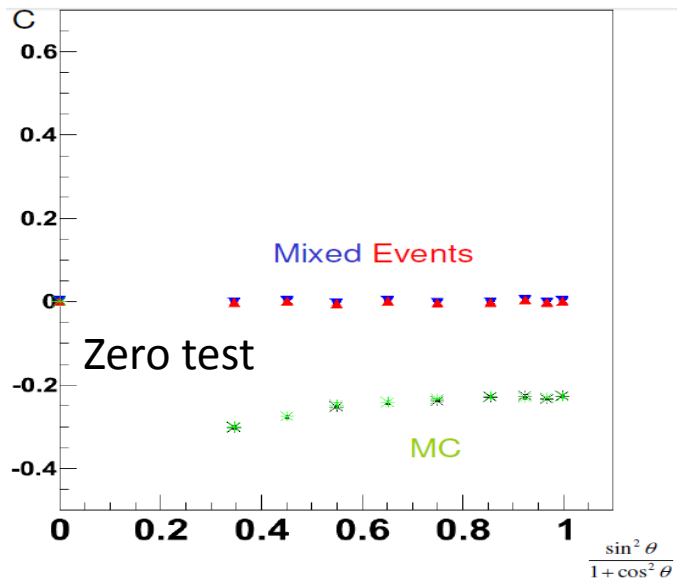
C: $\frac{N_{RL} + N_{LR} - N_{RR} - N_{LL}}{N_{RL} + N_{LR} + N_{RR} + N_{LL}}$

Expect negative correlation for local p-odd effect

Zero if factorized TMD picture holds

First Look at Handedness Correlation

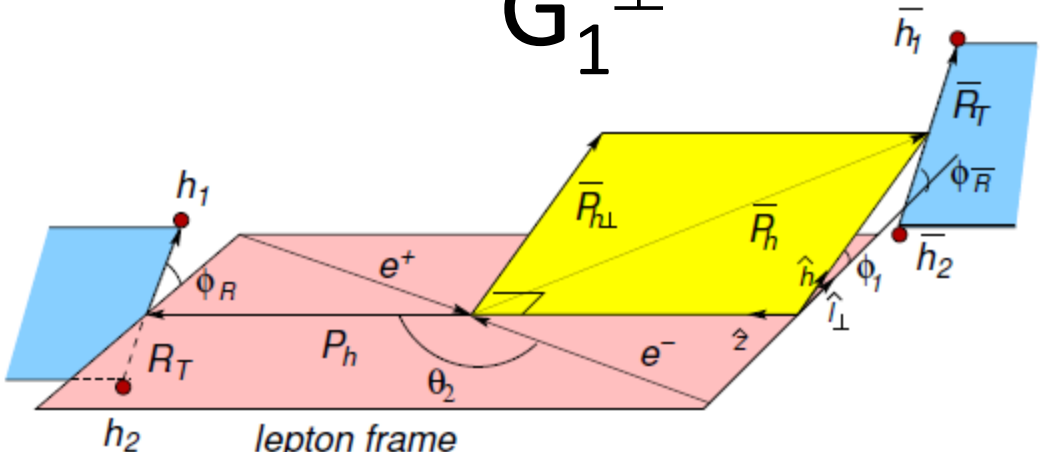
- Test of TMD picture (C=0)
- Sphaleron interaction would lead to C<0



Should be zero. Effect probably due to insufficient separation of hemispheres

Work in Progress….

$G_1^{\perp}$



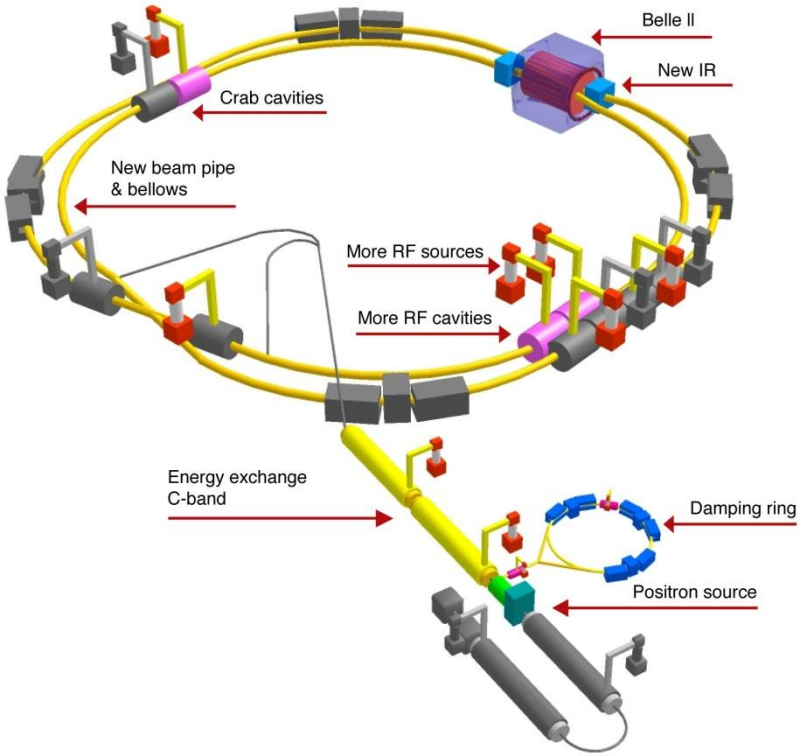
$$\langle \cos 2(\phi_R - \phi_{\overline{R}}) \rangle \propto \frac{\sum_{a,\bar{a}} e_a^2 \, z^2 \bar{z}^2 \, G_1^{\perp\, a}(z, M_h^2) \, \overline{G}_1^{\perp\, a}(\bar{z}, \overline{M}_h^2)}{\sum_{a,\bar{a}} e_a^2 \, z^2 \, \bar{z}^2 \, D_1^a(z, M_h^2) \, \overline{D}_1^a(\bar{z}, \overline{M}_h^2)}$$

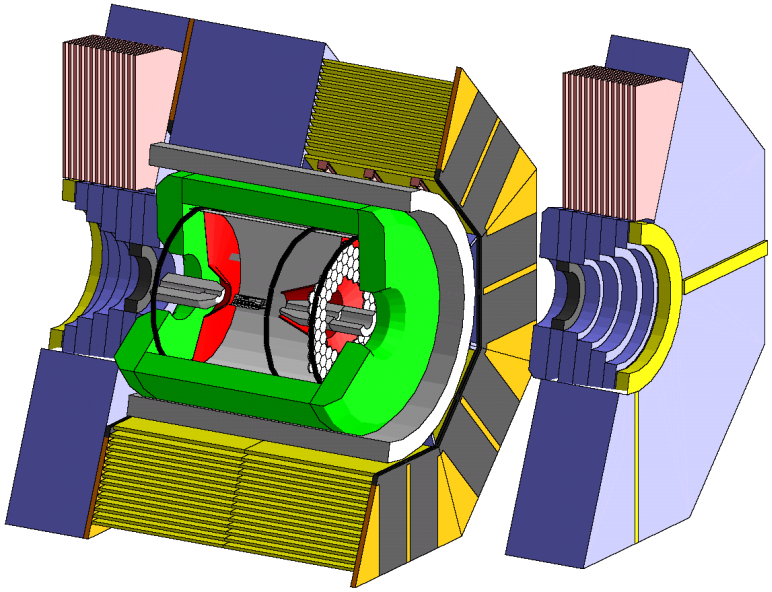
From:
D. Boer,
DiFF Miniworkshop,
Pavia,2011

- Measurements of $G_1^{\perp}$ will test TMD framework
- Together with handedness correlations will give insights into mechanisms behind transverse spin effects

KEKB/Belle→SuperKEKB, Belle II upgrade (2010–2015)

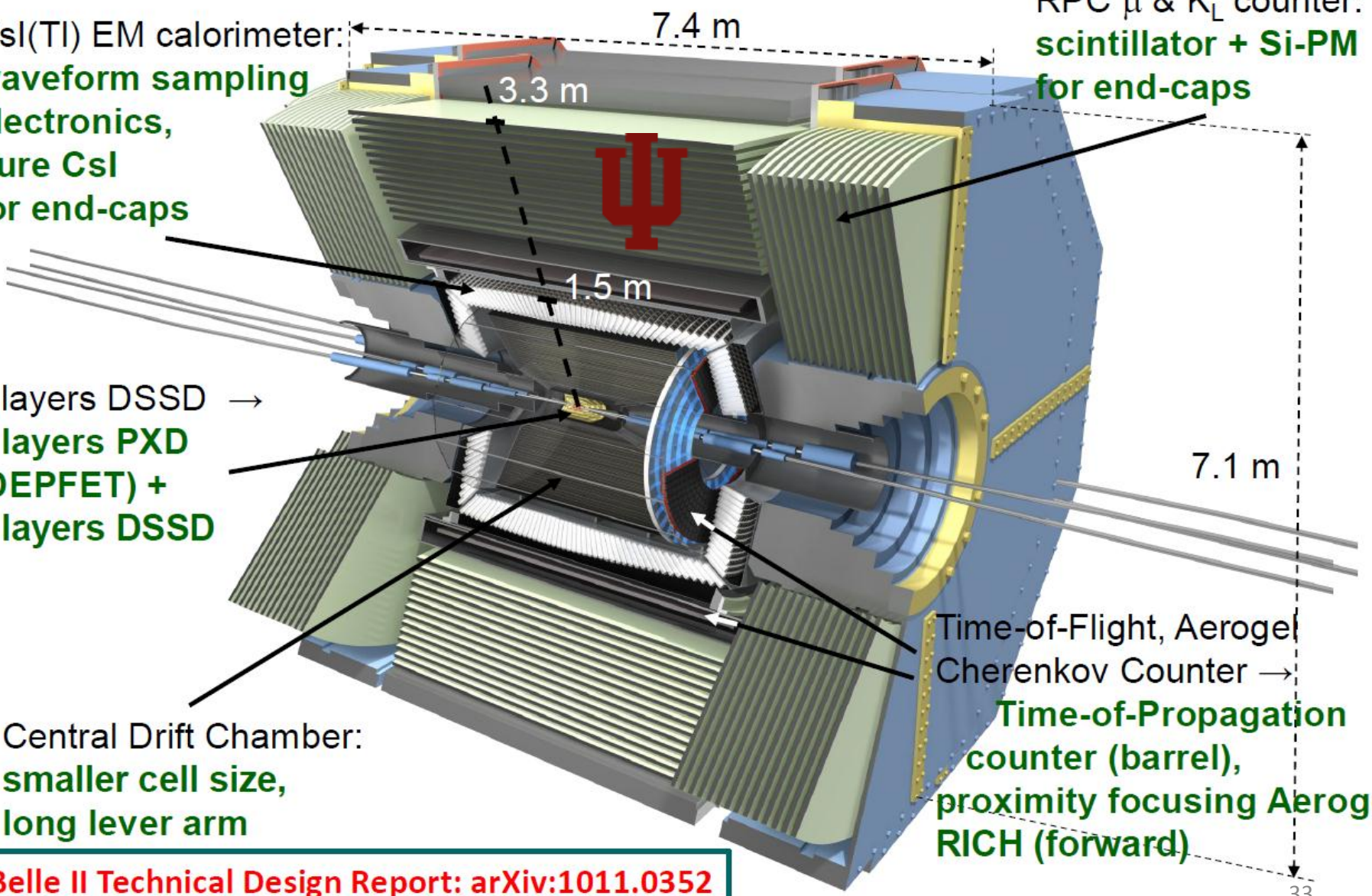
- Aim: super-high luminosity ~10^{36} $cm^{-2}s^{-1}$ (~40x KEK/Belle)
- Upgrades of Accelerator (Microbeams + Higher Currents) and Detector (Vtx,PID, higher rates, modern DAQ)
- Significant US contribution





http://belle2.kek.jp

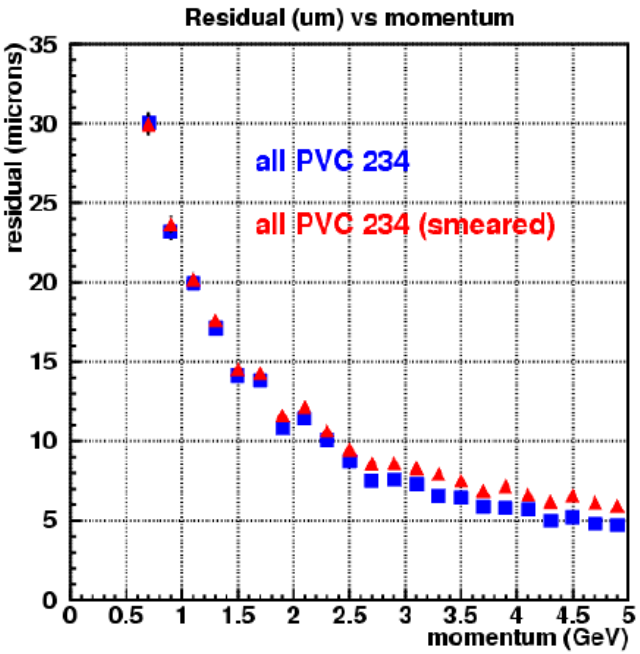
The Belle II Detector



Belle II Technical Design Report: arXiv:1011.0352

Highlights (for FF measurements) Of Belle II

- Kaon efficiency > 95% over relevant kinematics, fake rate < 5%
- Vertex resolution improved by order of magnitude
- Obviously more statistics



Conclusion and Outlook

- Belle measurements played a crucial role in the first extractions of transversity from single and di-hadron asymmetries
- Current plans include
  - Pi0/eta Collins FF
  - VM Collins FF
  - IFF with π^{+-}/π^0 in final state
  - Handedness and $G_1^{\perp}$ correlations
- Belle II will add better vertexing and PID capabilities (and much more statistics)

Backup