

Recent Results on the Measurement of Fragmentation Functions in e^+e^- Annihilation

1

ANSELM VOSSEN

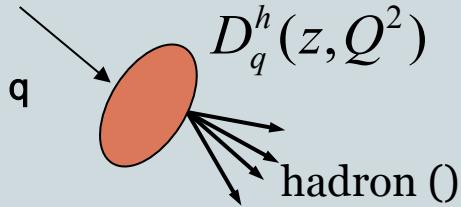
Ψ

INDIANA UNIVERSITY

- Motivation
- Belle (BaBar)
- Results
 - p/K Cross-sections
 - Kaon Collins Fragmentation Function
 - New Di-hadron asymmetries
- Outlook: SuperKEKB, Belle II

Why Study Fragmentation Functions?

2



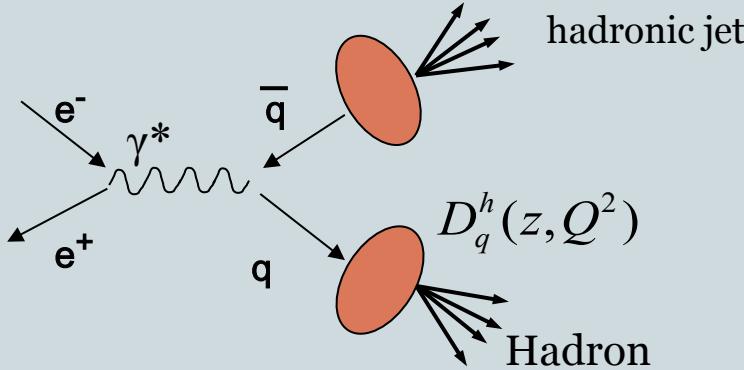
- FFs needed for Semi-inclusive measurements
 - Spin averaged for a_{LL} , x-sections etc
 - Transverse spin dependent for transverse spin structure
- FFs non-perturbative QCD objects
 - Confinement
 - Quarks with QCD vacuum
 - Compare to Nucleon Structure, study related issues like Evolution

$$\int \frac{d\xi}{2\pi} e^{ip\xi} \left\langle P \left| \bar{\psi}_i(0) a_h^+ a_h \psi_j(\xi) \right| P \right\rangle \quad \leftrightarrow \quad \int e^{ip\xi} \frac{d\xi}{2\pi} \left\langle 0 \left| \psi_i(\xi) a_h^+ a_h \bar{\psi}_j(0) \right| 0 \right\rangle$$

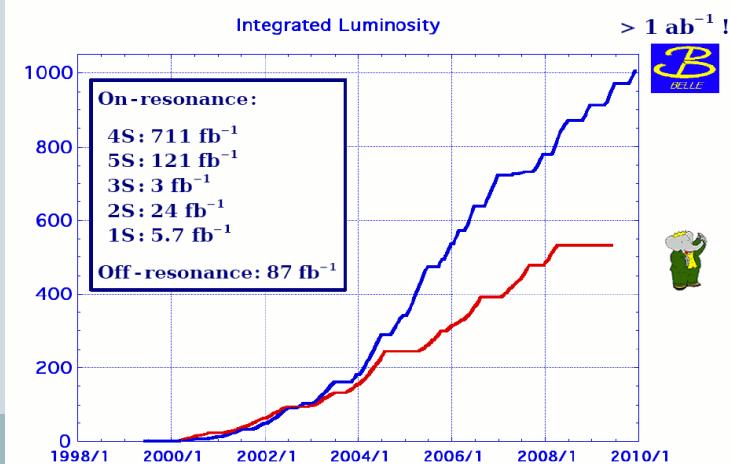
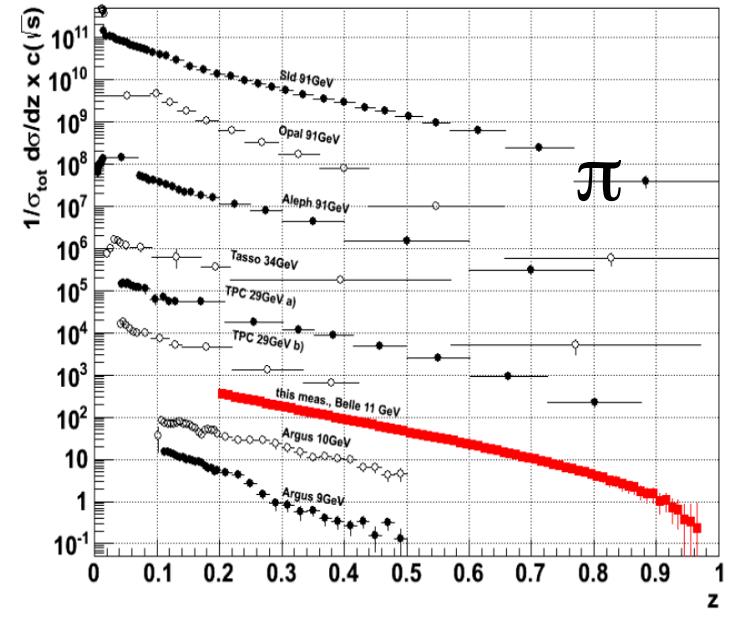
Where to Study?

3

- e^+e^- cleanest way to access FFs



- B factories
 - close in energy to SIDIS (100 GeV 2 vs 2-3 GeV 2)
 - Large integrated lumi!, high z reach

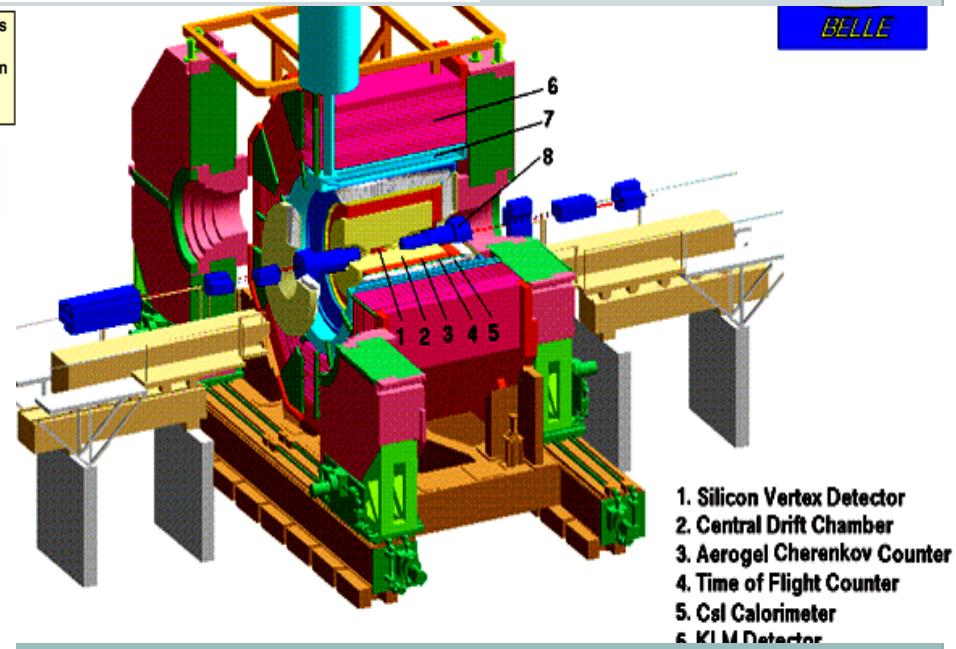
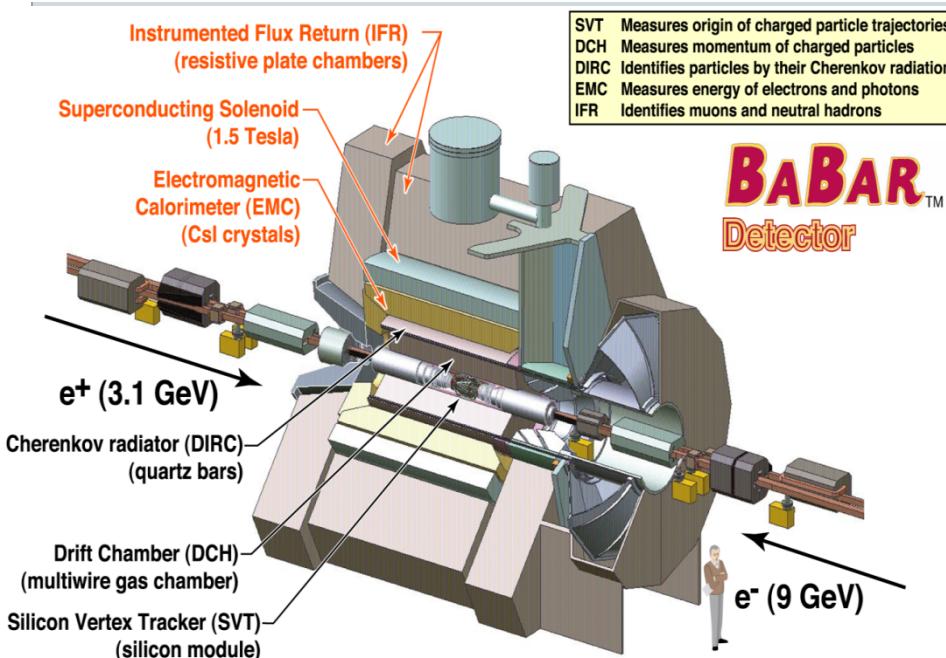
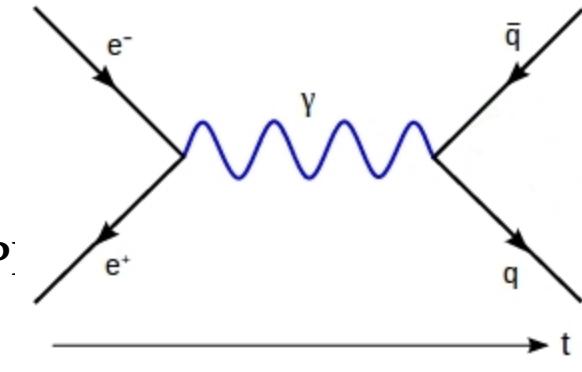


Measurements of Fragmentation Functions in e+e- at Belle and Babar

- B-Factories: asym. e⁺ (3.5/3.1 GeV) e⁻ (8/9 GeV) collider:
 - $\sqrt{s} = 10.58 \text{ GeV}$, $e^+e^- \rightarrow Y(4S) \rightarrow B \bar{B}$
 - $\sqrt{s} = 10.52 \text{ GeV}$, $e^+e^- \rightarrow q\bar{q}$ (u,d,s,c) ‘continuum’
- ideal detector for high precision measurements:
 - Azimuthally symmetric acceptance, high res. Tracking, P

Available data (Belle, Babar similar):

- ~ $1.8 * 10^9$ events at 10.58 GeV,
- ~ $220 * 10^6$ events at 10.52 GeV



Cross-Section for identified Pions and Kaons

- Initial State Radiation
- Exclude events where CME/2 changes by more than 0.5%
- Large at low z, correct based on MC

$$\frac{d\sigma_i}{dz} = \frac{1}{L_{tot}} \epsilon_{joint}^i(z) \epsilon_{ISR/FSR}^i(z) S_{zz_m}^{-1} \epsilon_{impu}^i(z_m) P_{ij}^{-1} N^{j,raw}(z_m)$$

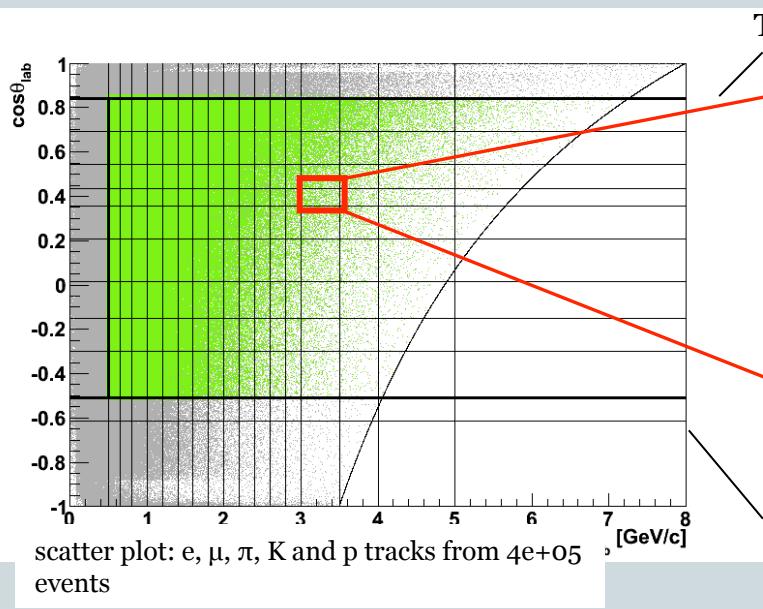
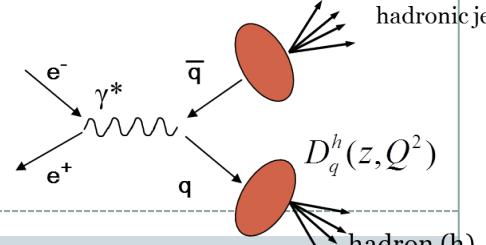
- Correct for acceptance,
- $\pi, 2\gamma$,
- decay in flight,

- Smearing Corrections

PID
 $i = \pi, K$

< 10%

PID Corrections from Data



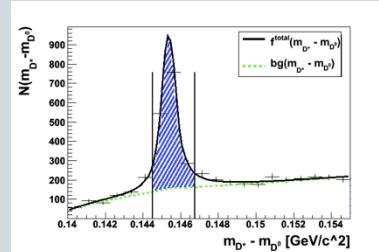
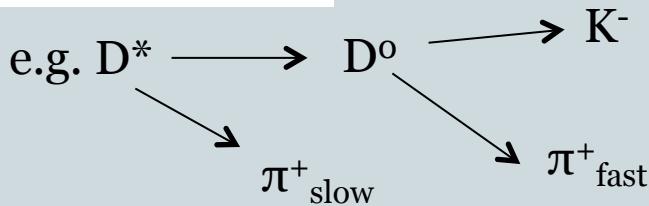
ToF forward geometry acceptance limit

fill matrix of PID probabilities for each single bin from real data calibration- need large statistics

$$[P]_{ij}$$

$$(p_{lab}, \cos\theta_{lab}) = \begin{pmatrix} p(e \rightarrow \tilde{e}) & p(\mu \rightarrow \tilde{e}) & p(\pi \rightarrow \tilde{e}) & p(K \rightarrow \tilde{e}) & p(p \rightarrow \tilde{e}) \\ p(e \rightarrow \tilde{\mu}) & p(\mu \rightarrow \tilde{\mu}) & p(\pi \rightarrow \tilde{\mu}) & p(K \rightarrow \tilde{\mu}) & p(p \rightarrow \tilde{\mu}) \\ p(e \rightarrow \tilde{\pi}) & p(\mu \rightarrow \tilde{\pi}) & p(\pi \rightarrow \tilde{\pi}) & p(K \rightarrow \tilde{\pi}) & p(p \rightarrow \tilde{\pi}) \\ p(e \rightarrow \tilde{K}) & p(\mu \rightarrow \tilde{K}) & p(\pi \rightarrow \tilde{K}) & p(K \rightarrow \tilde{K}) & p(p \rightarrow \tilde{K}) \\ p(e \rightarrow \tilde{p}) & p(\mu \rightarrow \tilde{p}) & p(\pi \rightarrow \tilde{p}) & p(K \rightarrow \tilde{p}) & p(p \rightarrow \tilde{p}) \end{pmatrix}$$

ToF backward geometry acceptance limit



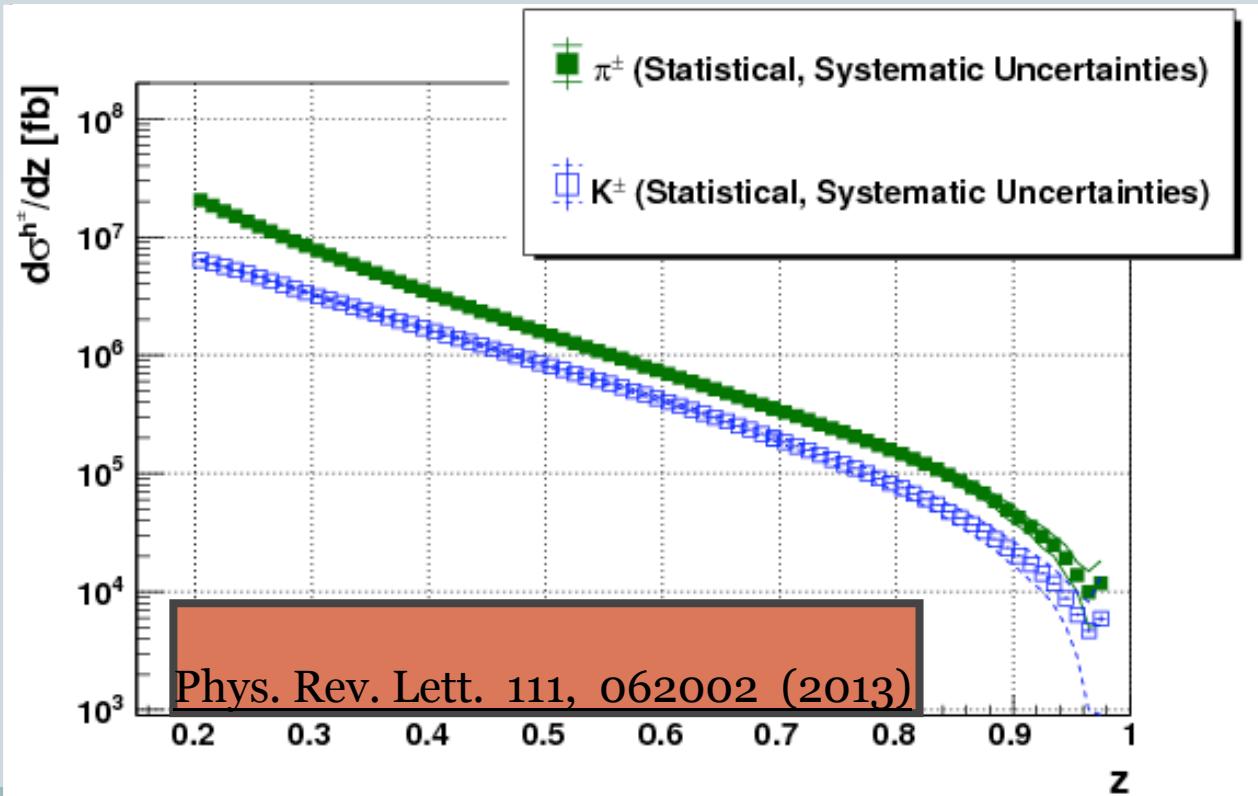
- Misidentification $\pi \rightarrow K$ up to 15%, $K \rightarrow \pi$ up to 20%

Cross sections

7

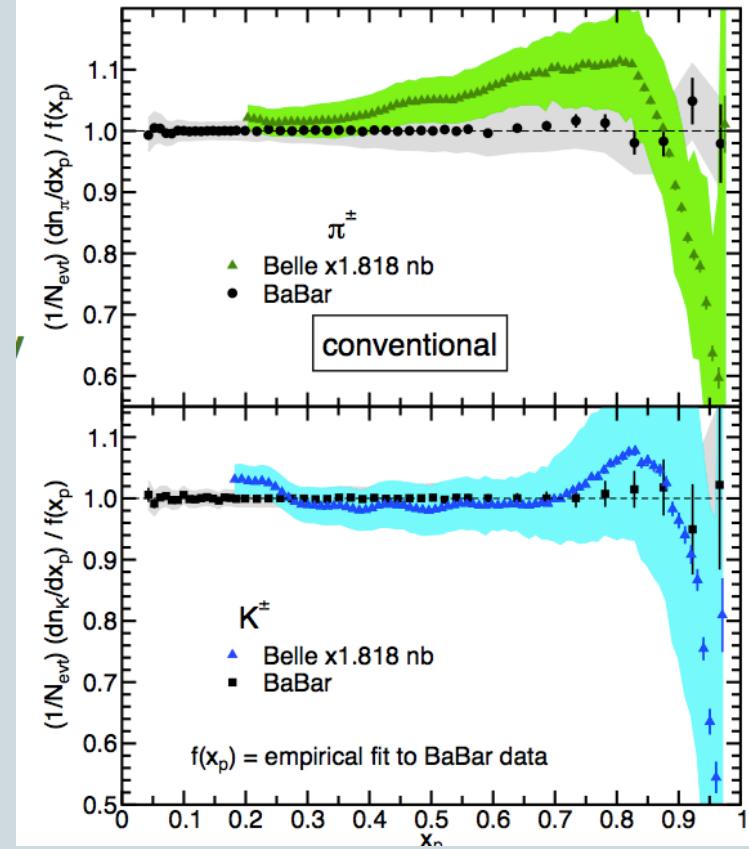
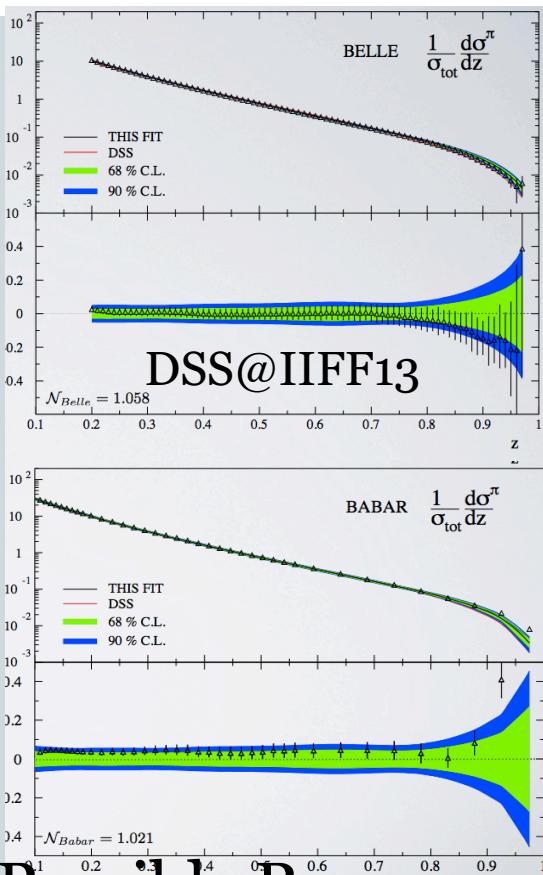
 $i = \pi, K$

$$\frac{d\sigma_i}{dz} = \frac{1}{L_{tot}} \epsilon_{joint}^i(z) \epsilon_{ISR/FSR}^i(z) S_{zz_m}^{-1} \epsilon_{impu}^i(z_m) P_{ij}^{-1} N^{j,raw}(z_m)$$



Some Tension between Belle/BaBar

8

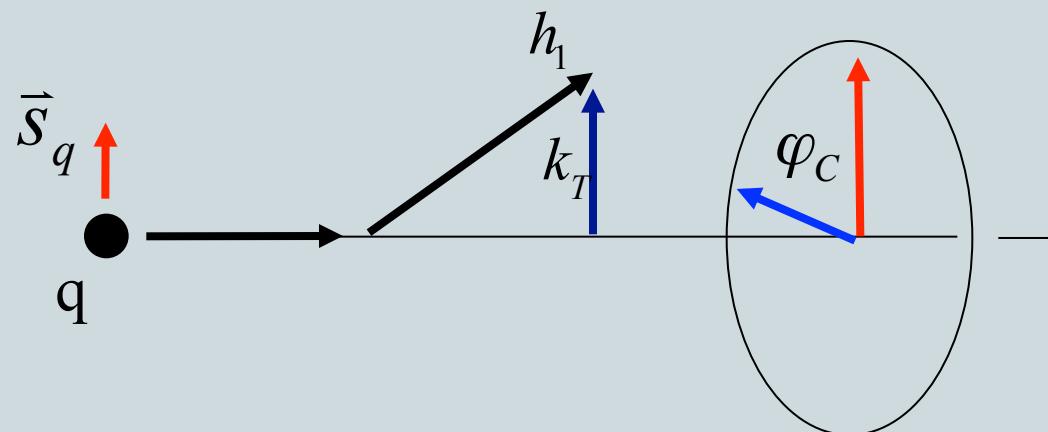


- Possible Reasons
 - ISR treatments
 - Decays (small contribution)

“Collins” Fragmentation Function for Kaons

9

- see F. Giordano @ DIS 14

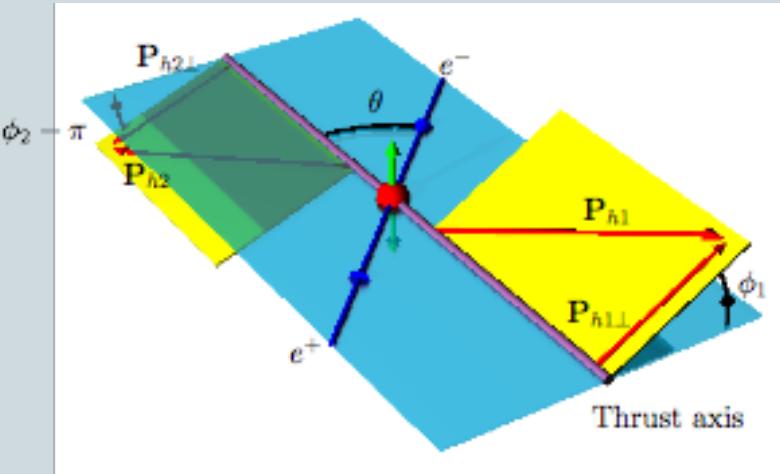


There are two methods with two or one soft scale

10

$\phi_1 + \phi_2$ method:

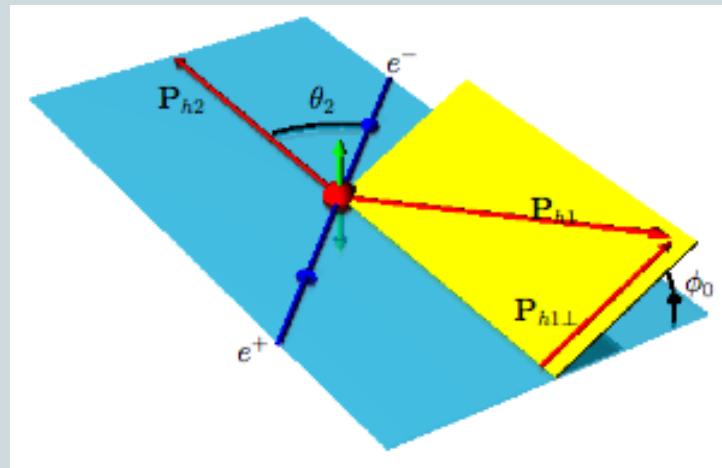
hadron azimuthal angles with respect to the $q\bar{q}$ axis proxy



ϕ_0 method:

hadron 1 azimuthal angle with respect to hadron 2

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



$$\sigma \sim \mathcal{M}_{12} \left(1 + \frac{\sin^2 \theta_T}{1 + \cos^2 \theta_T} \cos(\phi_1 + \phi_2) \frac{H_1^{\perp[1]}(z_1) \bar{H}_1^{\perp[1]}(z_2)}{D_1^{[0]}(z_1) \bar{D}_1^{[0]}(z_2)} \right)$$

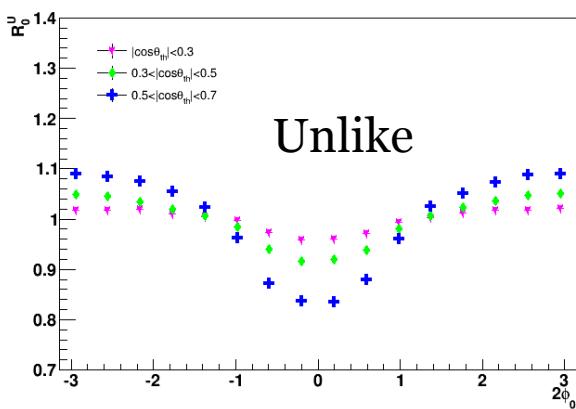
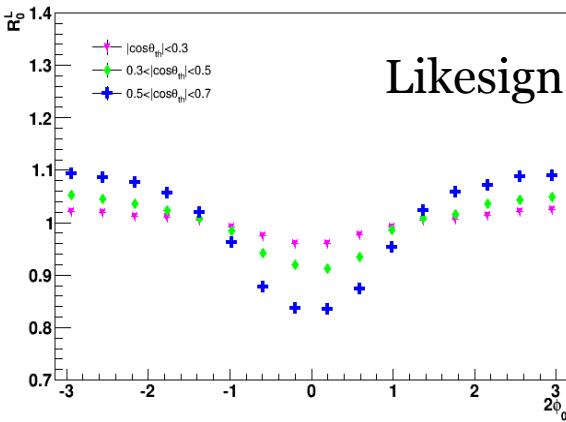
$$\sigma \sim \mathcal{M}_0 \left(1 + \frac{\sin^2 \theta_2}{1 + \cos^2 \theta_2} \cos(2\phi_0) \mathcal{F} \frac{H_1^{\perp}(z_1) \bar{H}_1^{\perp}(z_2)}{D_1^{\perp}(z_1) \bar{D}_1^{\perp}(z_2)} \right)$$

$$R_{12}^{U/L} = \frac{N(\varphi_1 + \varphi_2)}{\langle N_{12} \rangle}$$

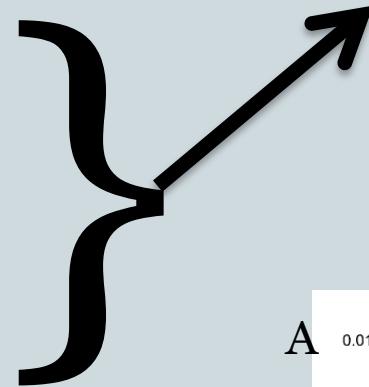
$$R_0^{U/L} = \frac{N(2\varphi_0)}{\langle N_0 \rangle}$$

Use of Double Ratios

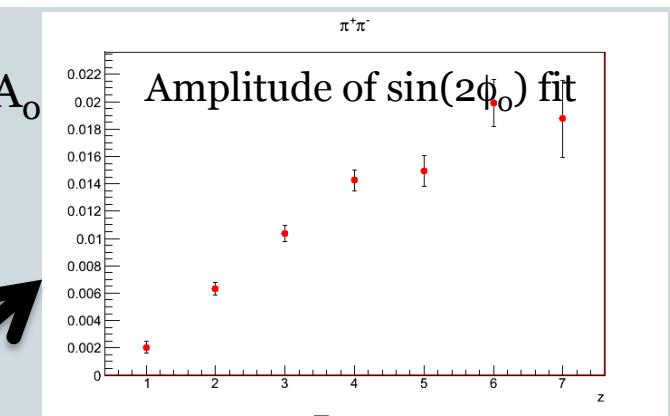
11



- False asymmetries due to Acceptance and QCD radiation
- Charge independent

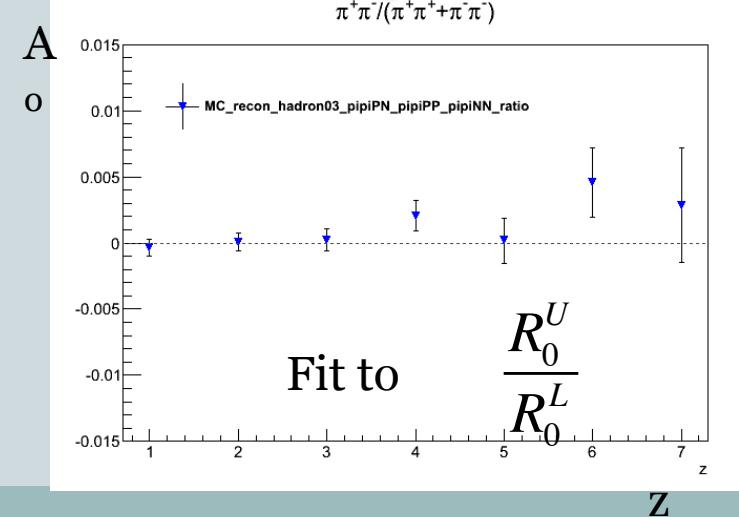


A_0



Z

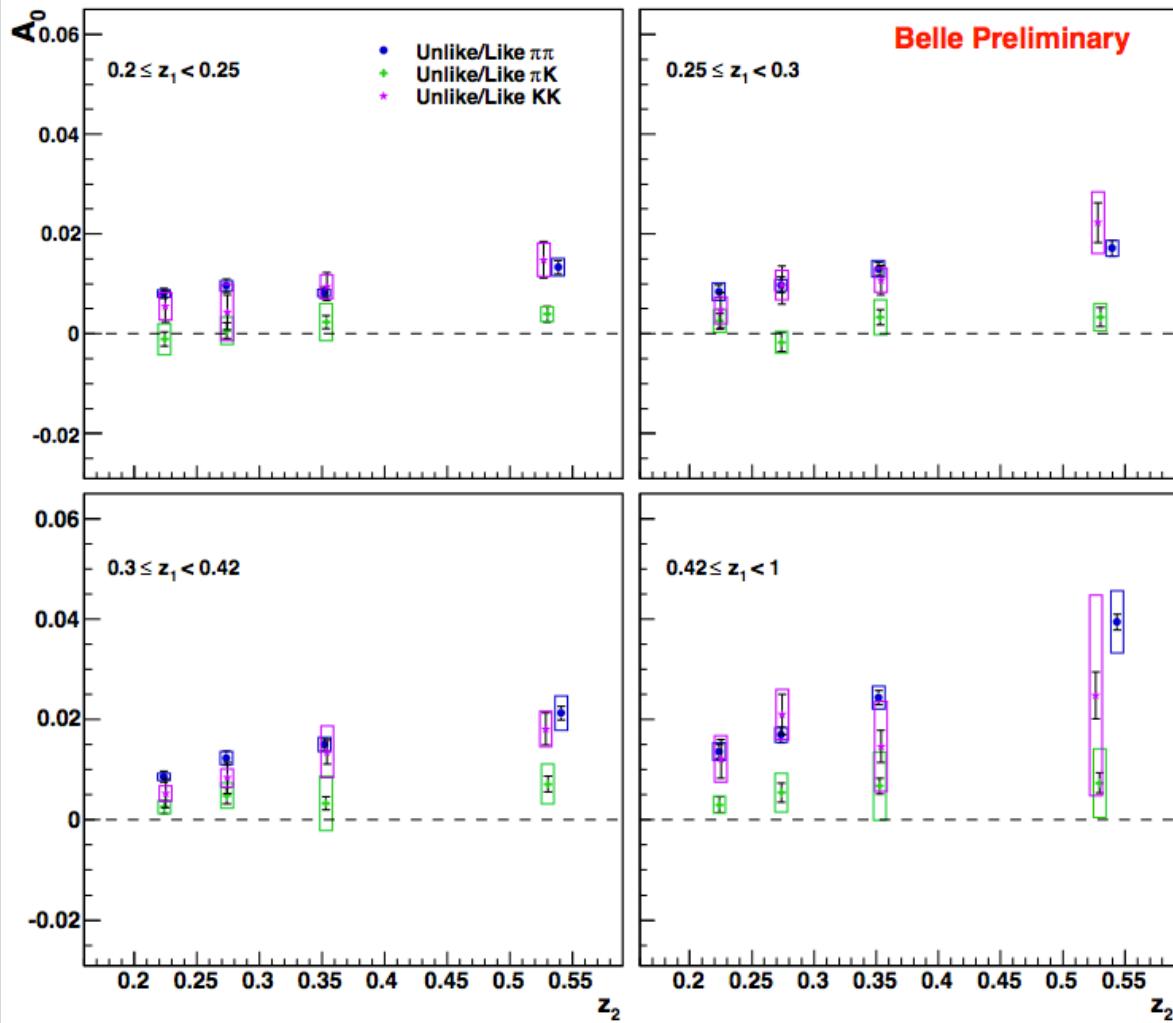
Use of "Double Ratios"



Z

Double Ratios for π/K pairs

12



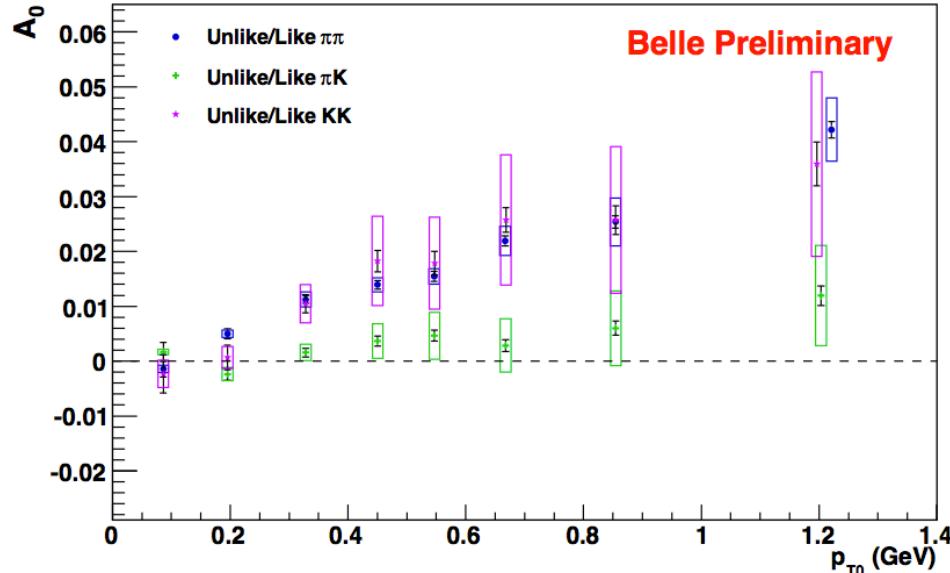
$\pi\pi \Rightarrow$ non-zero asymmetries,
increase with z_1, z_2

$\pi K \Rightarrow$ asymmetries
compatible with zero

$KK \Rightarrow$ non-zero asymmetries,
increase with z_1, z_2
similar size of pion-pion

P_{T0} Dependence

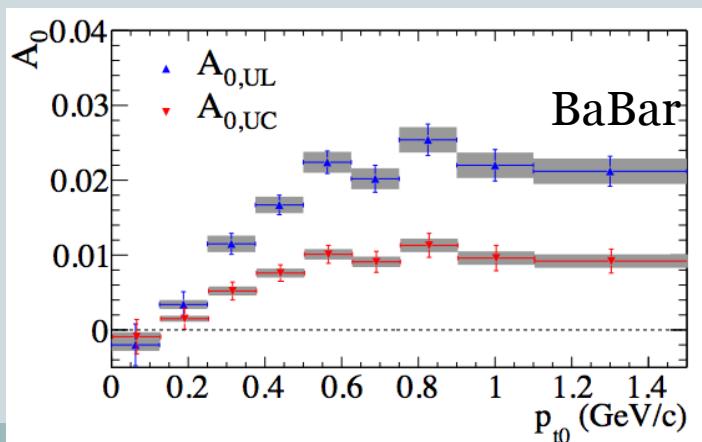
13



$\pi\pi \Rightarrow$ non-zero asymmetries,
increase with z_1, z_2

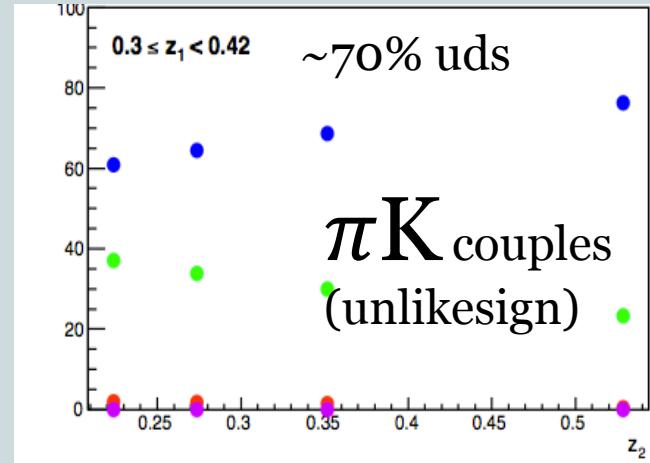
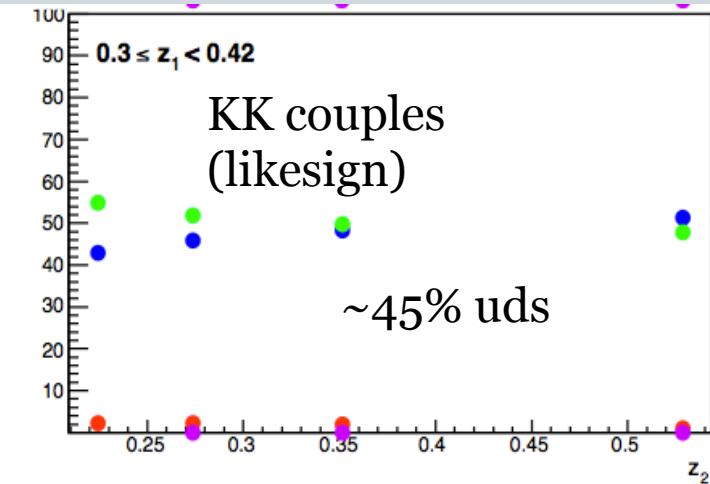
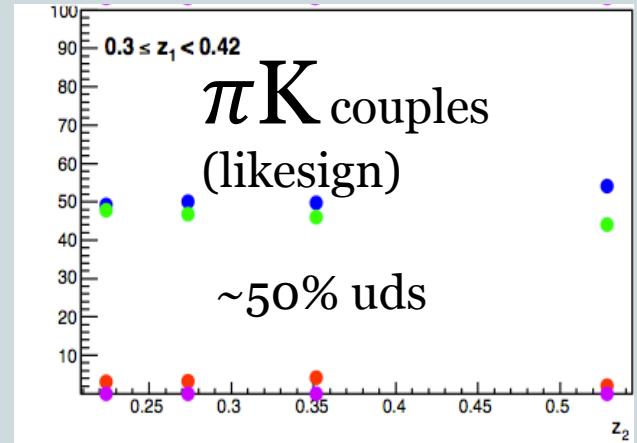
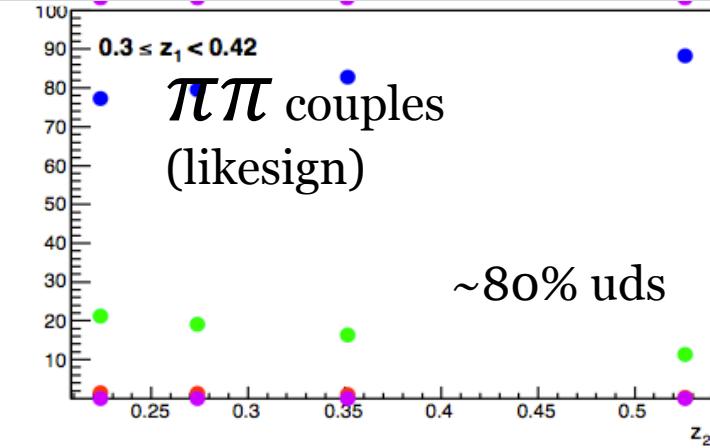
$\pi K \Rightarrow$ asymmetries
compatible with zero

$KK \Rightarrow$ non-zero asymmetries,
increase with z_1, z_2
similar size of pion-pion



Significant Charm to contribution to UDS

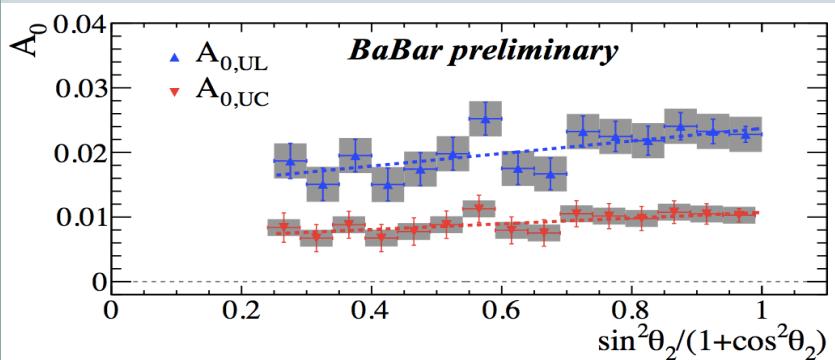
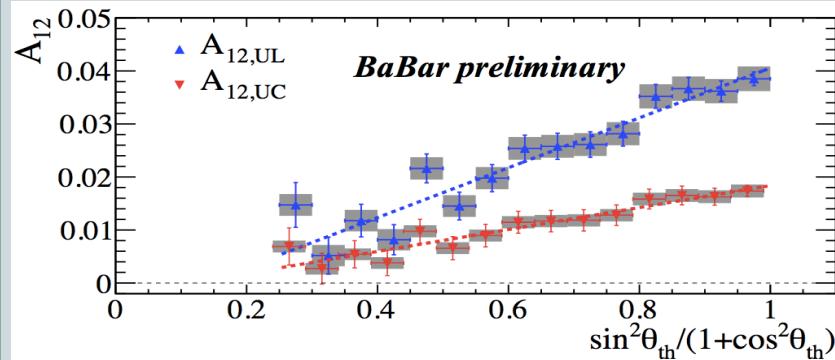
14



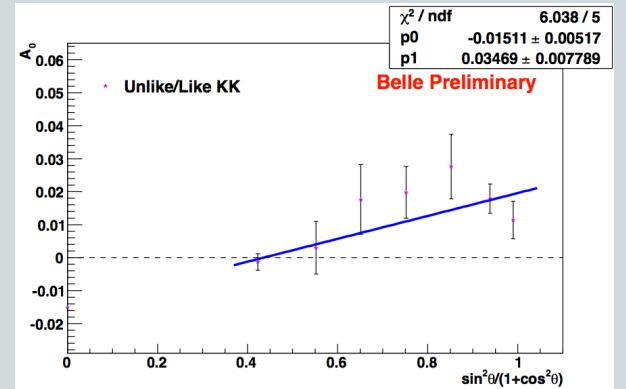
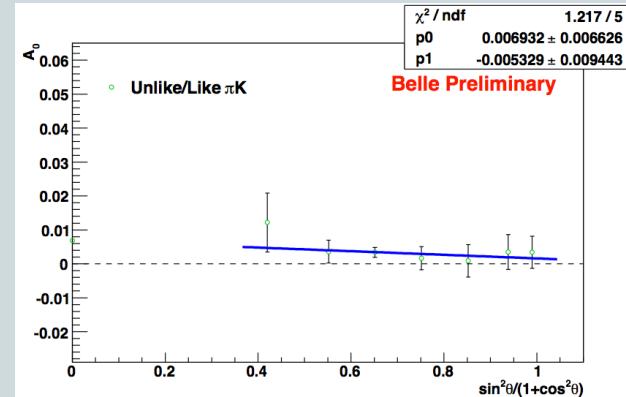
Test of Kinematic Dependence

15

$$A_0 = \frac{\sin^2 \theta}{1 + \cos^2 \theta} \mathcal{F} \left[\frac{H_1^\perp(z_1) \bar{H}_1^\perp(z_2)}{D_1^\perp(z_1) \bar{D}_1^\perp(z_2)} \right]$$



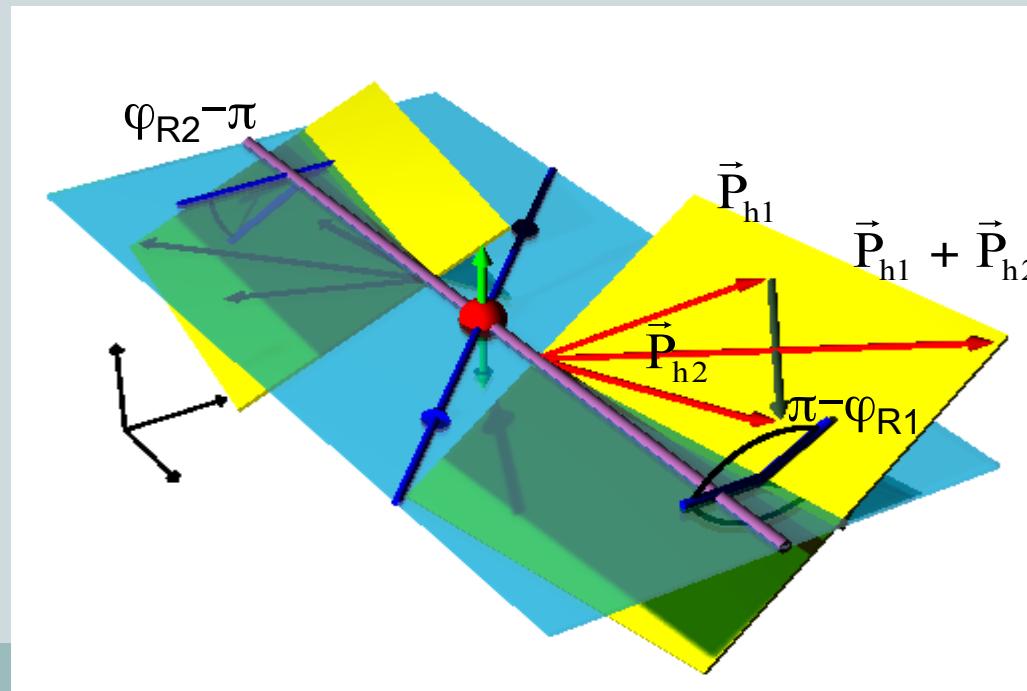
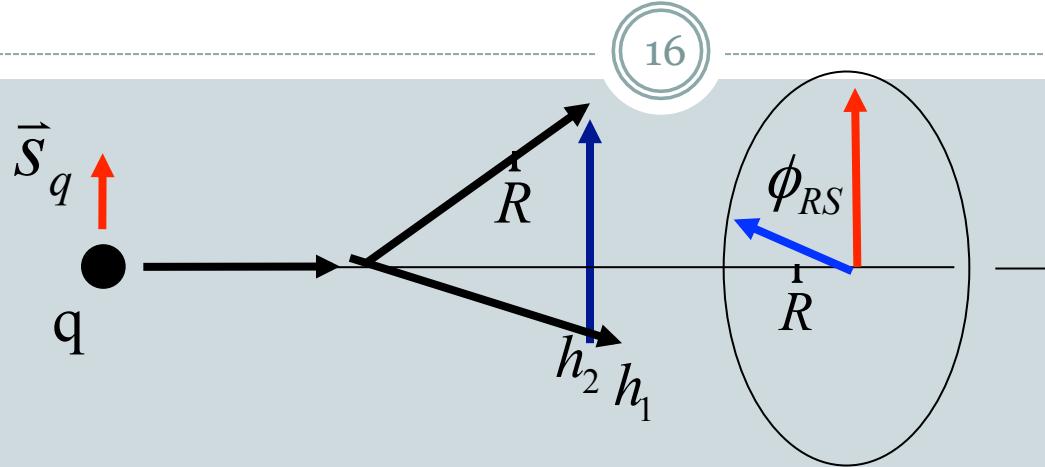
linear in $\sin^2 \theta / (1 + \cos^2 \theta)$,
go to 0 for $\sin^2 \theta / (1 + \cos^2 \theta) \rightarrow 0$



- A_0 dependence different from A_{12}
- No intersect with 0

Di-Hadron Fragmentation

16



Di-Hadron Asymmetries

17

- Di-hadron Cross Section from Boer,Jakob,Radici[PRD 67,(2003)]:
Expansion of Fragmentation Matrix Δ : encoding possible correlations in fragmentation ($k: P_{h1}+P_{h2}$)

$$\begin{aligned} & \frac{1}{32z} \int dk^+ \Delta(k; P_h, R) \Big|_{k^- = P_h^- / z, \mathbf{k}_T} \\ &= \frac{1}{4\pi} \frac{1}{4} \left\{ D_1^a(z, \xi, \mathbf{k}_T^2, \mathbf{R}_T^2, \mathbf{k}_T \cdot \mathbf{R}_T) \not{\epsilon}_- - G_1^{\perp a}(z, \xi, \mathbf{k}_T^2, \mathbf{R}_T^2, \mathbf{k}_T \cdot \mathbf{R}_T) \frac{\epsilon_{\mu\nu\rho\sigma} \gamma^\mu n_-^\nu k_T^\rho R_T^\sigma}{M_1 M_2} \gamma_5 \right. \\ & \quad \left. + H_1^{\triangleleft a}(z, \xi, \mathbf{k}_T^2, \mathbf{R}_T^2, \mathbf{k}_T \cdot \mathbf{R}_T) \frac{\sigma_{\mu\nu} R_T^\mu n_-^\nu}{M_1 + M_2} + H_1^{\perp a}(z, \xi, \mathbf{k}_T^2, \mathbf{R}_T^2, \mathbf{k}_T \cdot \mathbf{R}_T) \frac{\sigma_{\mu\nu} k_T^\mu n_-^\nu}{M_1 + M_2} \right\} . \end{aligned}$$

$$\langle \cos(2(\phi_R - \phi_{\bar{R}})) \rangle = \sum_{a,\bar{a}} e_a^2 \frac{3\alpha^2}{2Q^2} z^2 \bar{z}^2 A(y) \frac{1}{M_1 M_2 \bar{M}_1 \bar{M}_2} G_1^{\perp a}(z, M_h^2) \bar{G}_1^{\perp a}(\bar{z}, \bar{M}_h^2) .$$

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

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

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

18

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

Spin independent part

$$\frac{1}{32z} \int dk^+ \Delta(k; P_h, R) \Big|_{k^- = P_h^- / z, \mathbf{k}_T} = \frac{1}{4\pi} \frac{1}{4} \left\{ D_1^a(z, \xi, \mathbf{k}_T^2, \mathbf{R}_T^2, \mathbf{k}_T \cdot \mathbf{R}_T) \not{\eta}_- - G_1^{\perp a}(z, \xi, \mathbf{k}_T^2, \mathbf{R}_T^2, \mathbf{k}_T \cdot \mathbf{R}_T) \frac{\epsilon_{\mu\nu\rho\sigma} \gamma^\mu n_-^\nu k_T^\rho R_T^\sigma}{M_1 M_2} \gamma_5 \right. \\ \left. + H_1^{\triangleleft a}(z, \xi, \mathbf{k}_T^2, \mathbf{R}_T^2, \mathbf{k}_T \cdot \mathbf{R}_T) \frac{\sigma_{\mu\nu} R_T^\mu n_-^\nu}{M_1 + M_2} + H_1^{\perp a}(z, \xi, \mathbf{k}_T^2, \mathbf{R}_T^2, \mathbf{k}_T \cdot \mathbf{R}_T) \frac{\sigma_{\mu\nu} k_T^\mu n_-^\nu}{M_1 + M_2} \right\} .$$

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

$$\langle \cos(2(\phi_R - \phi_{\bar{R}})) \rangle = \sum_{a,\bar{a}} e_a^2 \frac{3\alpha^2}{2Q^2} z^2 \bar{z}^2 A(y) \frac{1}{M_1 M_2 \bar{M}_1 \bar{M}_2} G_1^{\perp a}(z, M_h^2) \bar{G}_1^{\perp a}(\bar{z}, \bar{M}_h^2) .$$

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

Cross Section

19

- Δ : Fragmentation Matrix, encoding possible correlations in fragmentation

Correlation of transverse spin with
Di-hadron plane

$$\begin{aligned} & \frac{1}{32z} \int dk^+ \Delta(k; P_h, R) \Big|_{k^- = P_h^- / z, \mathbf{k}_T} \\ &= \frac{1}{4\pi} \frac{1}{4} \left\{ D_1^a(z, \xi, \mathbf{k}_T^2, \mathbf{R}_T^2, \mathbf{k}_T \cdot \mathbf{R}_T) \not{\epsilon}_- - G_1^{\perp a}(z, \xi, \mathbf{k}_T^2, \mathbf{R}_T^2, \mathbf{k}_T \cdot \mathbf{R}_T) \frac{\epsilon_{\mu\nu\rho\sigma} \gamma^\mu n_-^\nu k_T^\rho R_T^\sigma}{M_1 M_2} \gamma_5 \right. \\ & \quad \left. + H_1^{\triangleleft a}(z, \xi, \mathbf{k}_T^2, \mathbf{R}_T^2, \mathbf{k}_T \cdot \mathbf{R}_T) \frac{\sigma_{\mu\nu} R_T^\mu n_-^\nu}{M_1 + M_2} + H_1^{\perp a}(z, \xi, \mathbf{k}_T^2, \mathbf{R}_T^2, \mathbf{k}_T \cdot \mathbf{R}_T) \frac{\sigma_{\mu\nu} k_T^\mu n_-^\nu}{M_1 + M_2} \right\}. \end{aligned}$$

$$\langle \cos(2(\phi_R - \phi_{\bar{R}})) \rangle = \sum_{a, \bar{a}} e_a^2 \frac{3\alpha^2}{2Q^2} z^2 \bar{z}^2 A(y) \frac{1}{M_1 M_2 \bar{M}_1 \bar{M}_2} G_1^{\perp a}(z, M_h^2) \bar{G}_1^{\perp a}(\bar{z}, \bar{M}_h^2).$$

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

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

20

- Δ : Fragmentation Matrix, encoding possible correlations in fragmentation
 - \mathbf{k} : $P_{h1} + P_{h2}$
- Helicity dependent correlation of Intrinsic transverse momentum with Di-hadron plane

$$\begin{aligned} \frac{1}{32z} \int dk^+ \Delta(k; P_h, R) \Big|_{k^- = P_h^- / z, \mathbf{k}_T} \\ = \frac{1}{4\pi} \frac{1}{4} \left\{ D_1^a(z, \xi, \mathbf{k}_T^2, \mathbf{R}_T^2, \mathbf{k}_T \cdot \mathbf{R}_T) \not{\epsilon}_- - G_1^{\perp a}(z, \xi, \mathbf{k}_T^2, \mathbf{R}_T^2, \mathbf{k}_T \cdot \mathbf{R}_T) \frac{\epsilon_{\mu\nu\rho\sigma} \gamma^\mu n_-^\nu k_T^\rho R_T^\sigma}{M_1 M_2} \gamma_5 \right. \\ \left. + H_1^{\triangleleft a}(z, \xi, \mathbf{k}_T^2, \mathbf{R}_T^2, \mathbf{k}_T \cdot \mathbf{R}_T) \frac{\sigma_{\mu\nu} R_T^\mu n_-^\nu}{M_1 + M_2} + H_1^{\perp a}(z, \xi, \mathbf{k}_T^2, \mathbf{R}_T^2, \mathbf{k}_T \cdot \mathbf{R}_T) \frac{\sigma_{\mu\nu} k_T^\mu n_-^\nu}{M_1 + M_2} \right\}. \end{aligned}$$

$$\langle \cos(2(\phi_R - \phi_{\bar{R}})) \rangle = \sum_{a, \bar{a}} e_a^2 \frac{3\alpha^2}{2Q^2} z^2 \bar{z}^2 A(y) \frac{1}{M_1 M_2 \bar{M}_1 \bar{M}_2} G_1^{\perp a}(z, M_h^2) \bar{G}_1^{\perp a}(\bar{z}, \bar{M}_h^2).$$

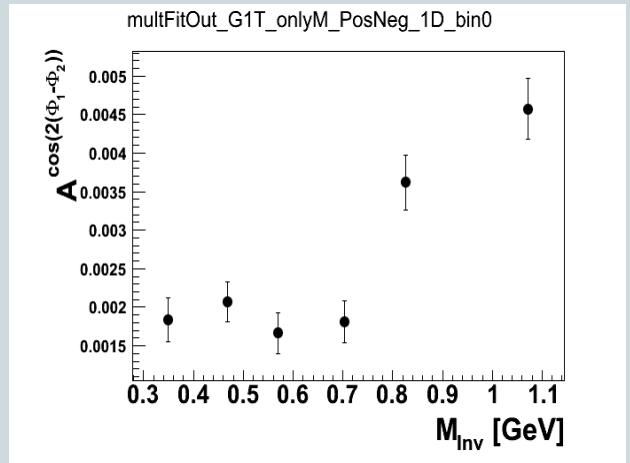
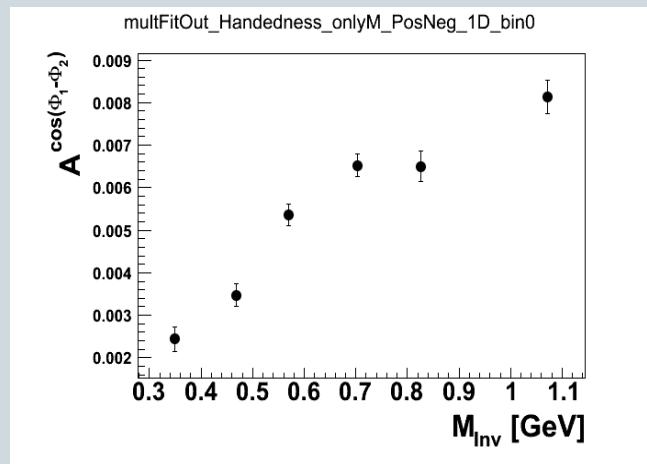
$$\langle \cos(\phi_R + \phi_{\bar{R}} - 2\phi^l) \rangle = \sum_{a, \bar{a}} e_a^2 \frac{3\alpha^2}{Q^2} \frac{z^2 \bar{z}^2 B(y)}{(M_1 + M_2)(\bar{M}_1 + \bar{M}_2)} H_{1(R)}^{\triangleleft a}(z, M_h^2) \bar{H}_{1(R)}^{\triangleleft a}(\bar{z}, \bar{M}_h^2).$$

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

Study of $A^{\cos(\varphi_1-\varphi_2)}$ and $A^{\cos(2(\varphi_1-\varphi_2))}$ Asymmetries in Belle MC

21

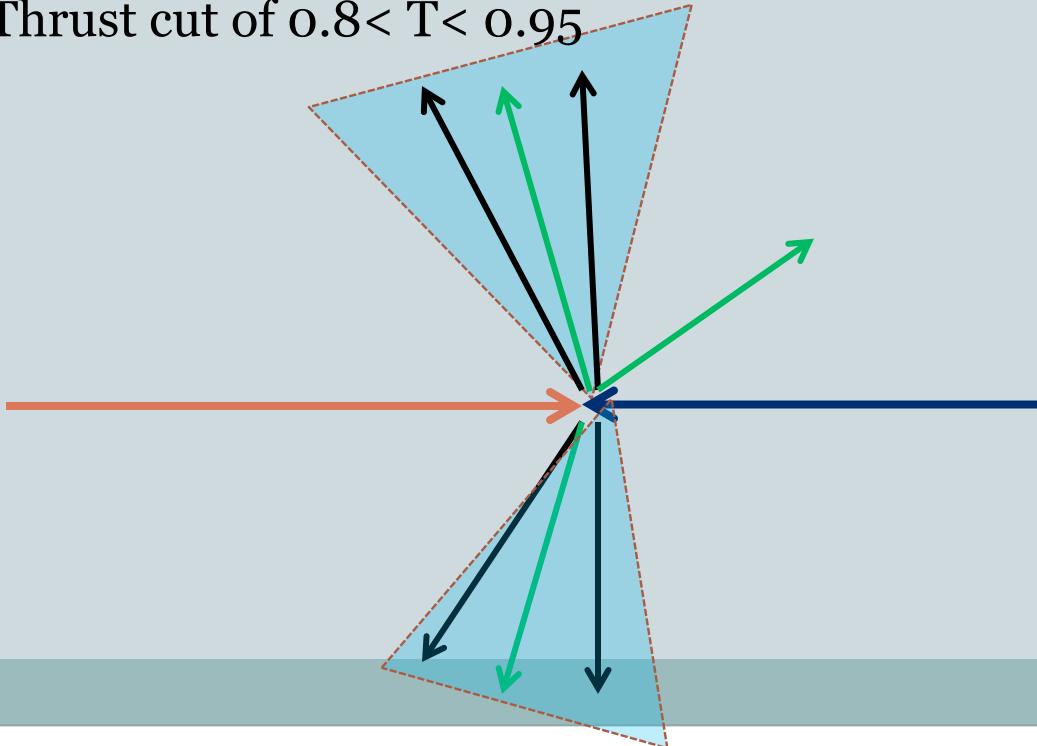
- Belle uses Pythia+Evtgen (implements decay tables)
- After detector asymmetries of the order of 1% (0.5%) are left.
- Pythia w/o detector is consistent with shows similar effect
- Possible culprits: gluon radiation, weak decays, detector effects



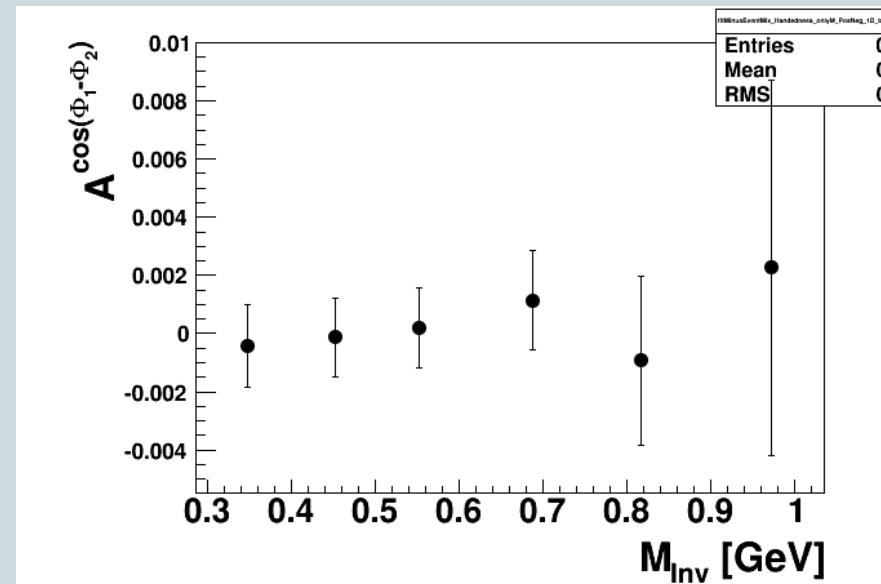
New: Use Jet Reconstruction at Belle

22

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

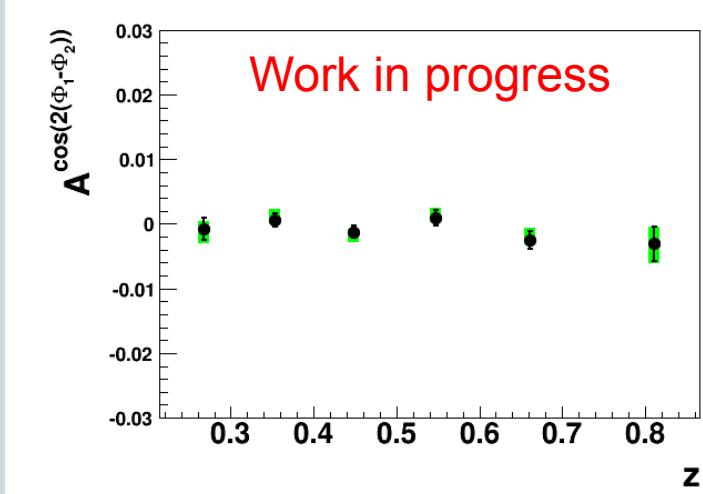
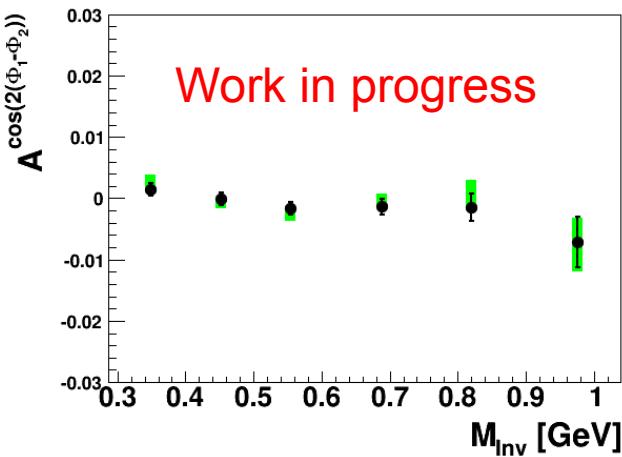


- Mixed event subtracted flattens acceptance related false asymmetries
- Remaining asymmetries in MC+their stat error used to estimate systematics



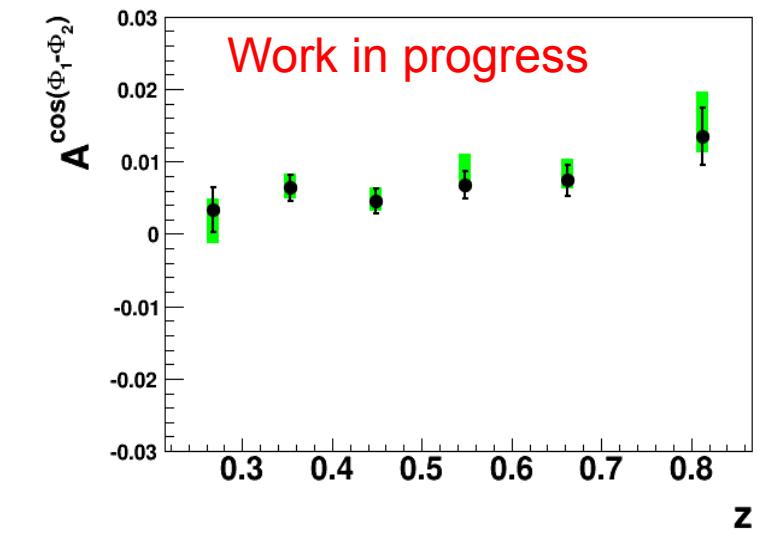
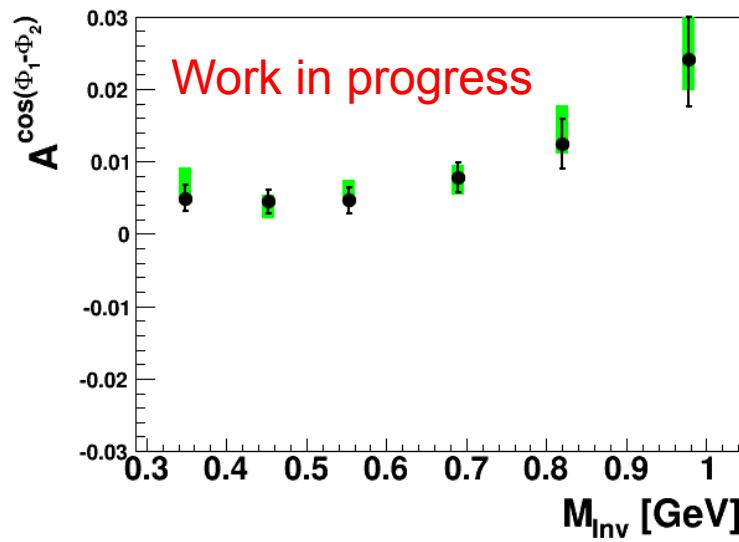
Asymmetries for $\text{Cos}(2(\phi_{R1}-\phi_{R2}))$ (G_1^\perp) small

24



Asymmetries in Data persists for $\text{Cos}(\phi_{R1}-\phi_{R2})$

25



- Systematics driven by MC...

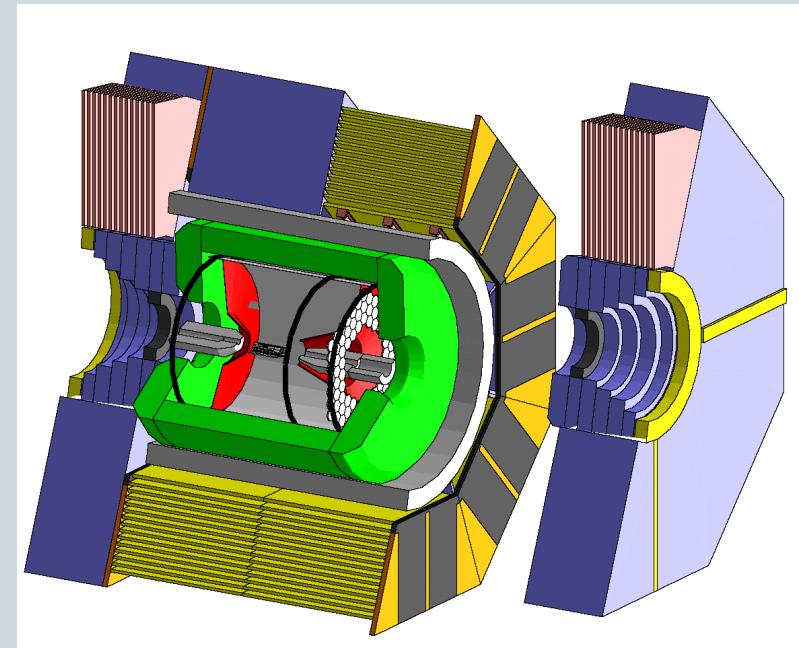
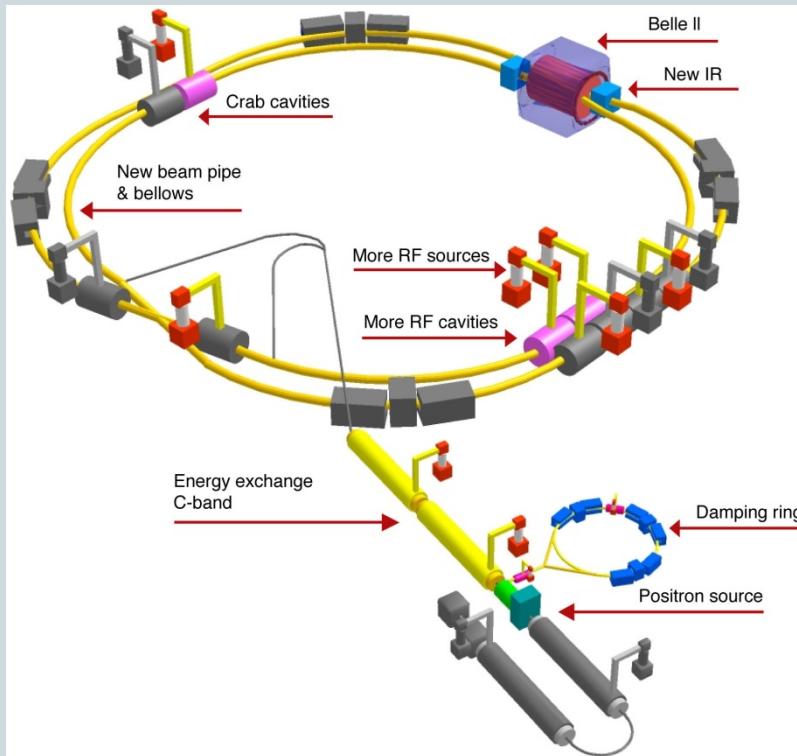
KEKB/Belle → SuperKEKB,

26



Upgrade

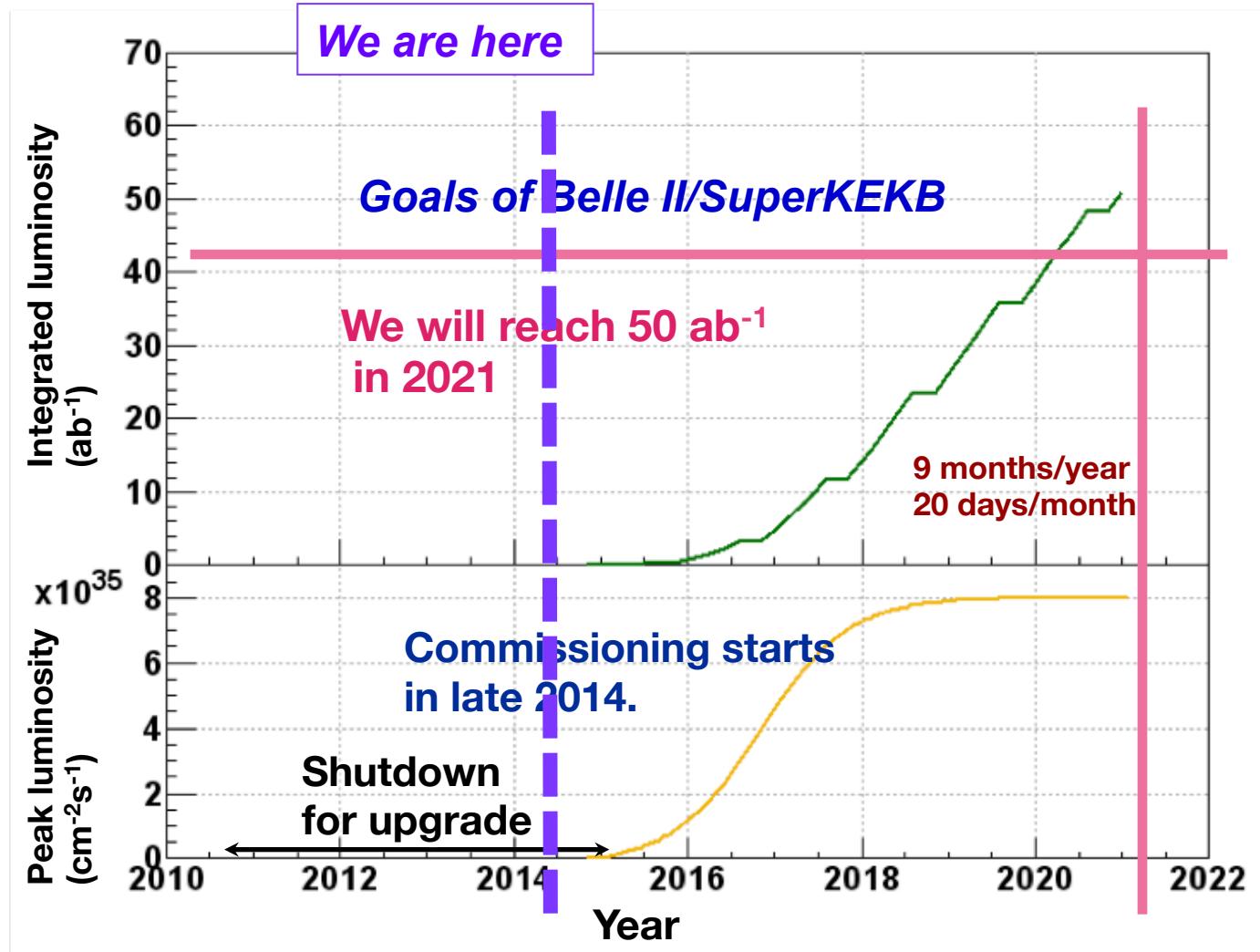
- Aim: super-high luminosity $\sim 10^{36} \text{ cm}^{-2}\text{s}^{-1}$ ($\sim 40x$ KEK/Belle)
- Upgrades of Accelerator (Microbeams + Higher Currents) and Detector (Vtx,PID, higher rates, modern DAQ)
- Significant US contribution



<http://belle2.kek.jp>

First data in 2016

SuperKEKB luminosity profile



The Belle II Detector

CsI(Tl) EM calorimeter:
waveform sampling
 electronics,
 pure CsI
 for end-caps

4 layers DSSD →
2 layers PXD
 (DEPFET) +
 4 layers DSSD

Central Drift Chamber:
smaller cell size,
long lever arm

7.4 m

3.3 m

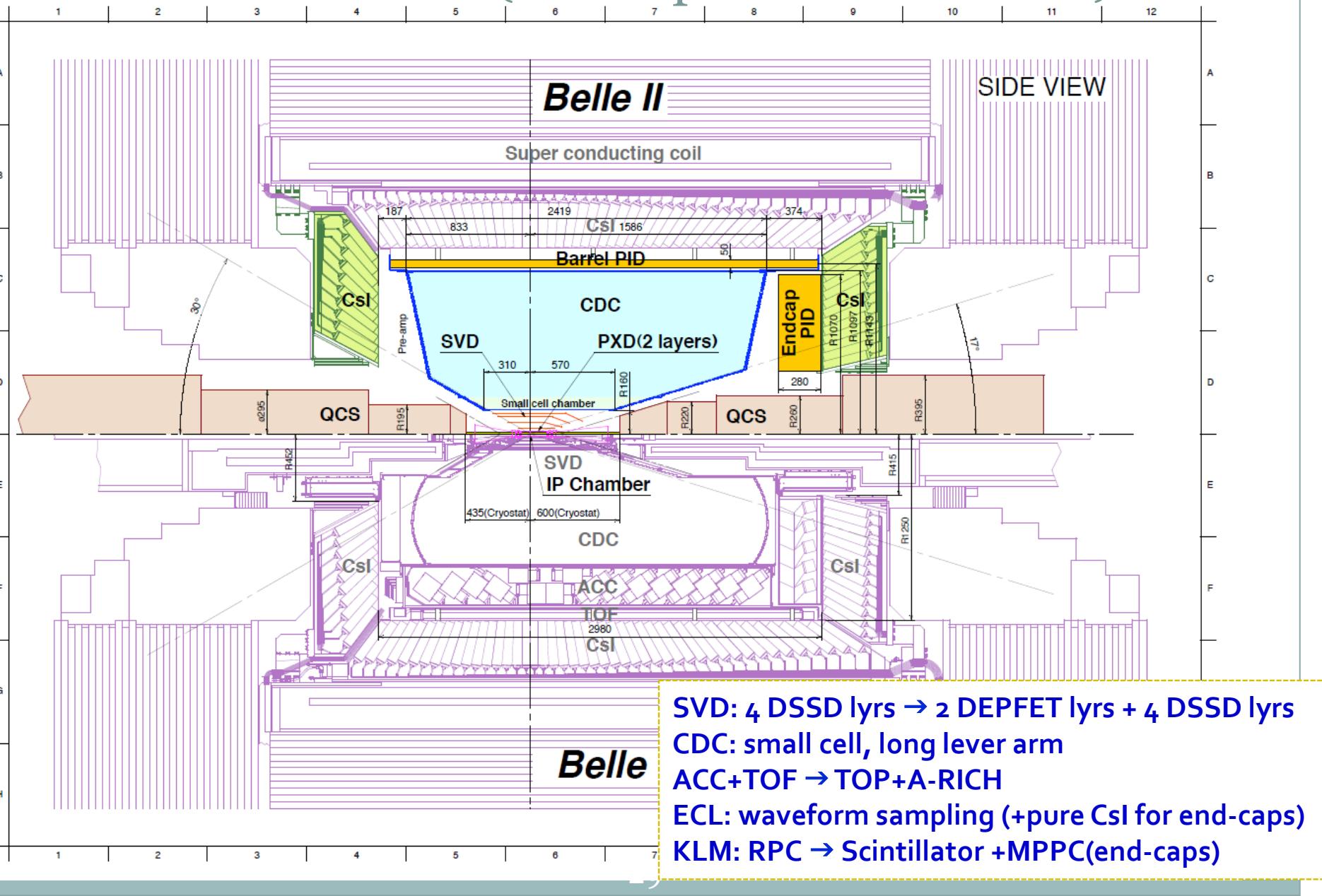
1.5 m

RPC μ & K_L counter:
scintillator + Si-PM
 for end-caps

7.1 m

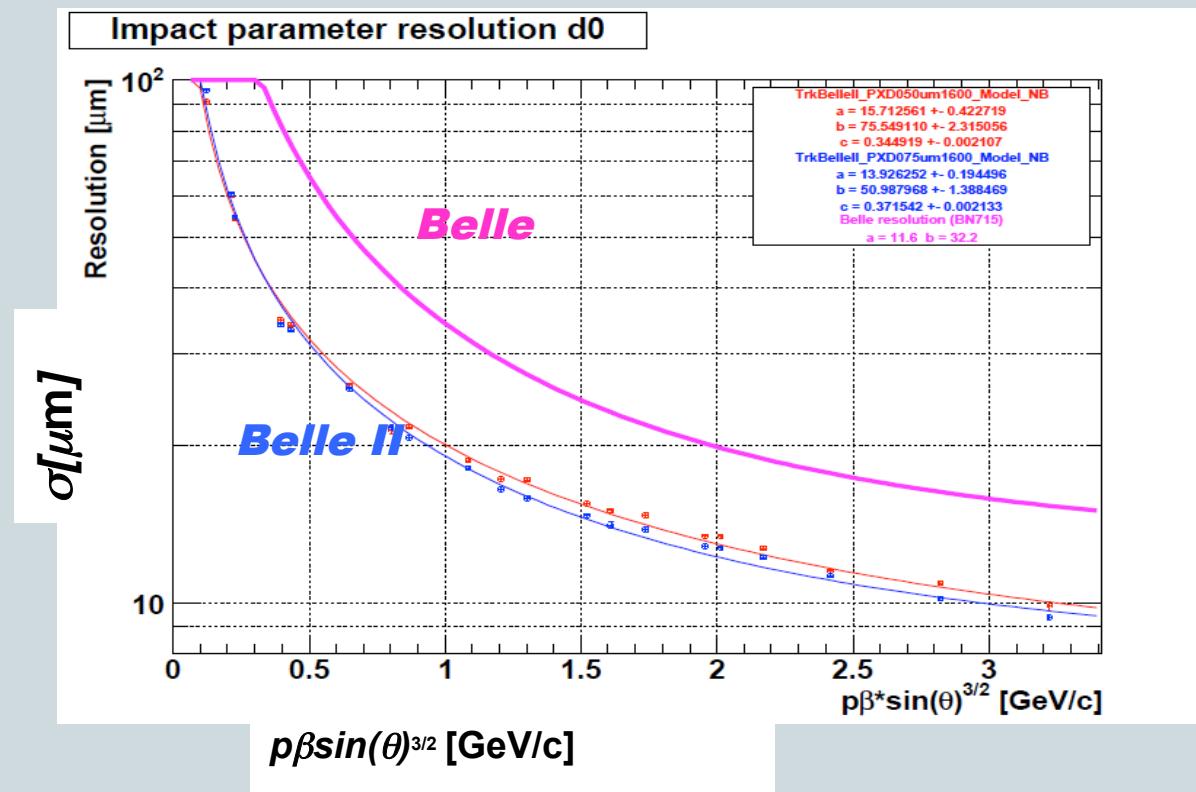
Time-of-Flight, Aerogel
 Cherenkov Counter →
Time-of-Propagation
 counter (barrel),
 proximity focusing Aerogel
 RICH (forward)

Belle II Detector (in comparison with Belle)



Improve Charm Discrimination with SVD&PXD

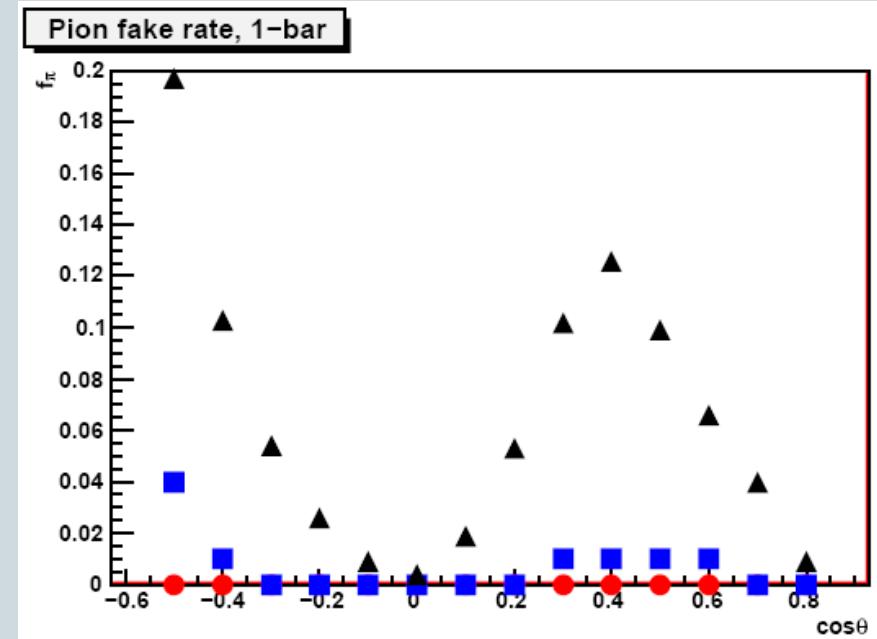
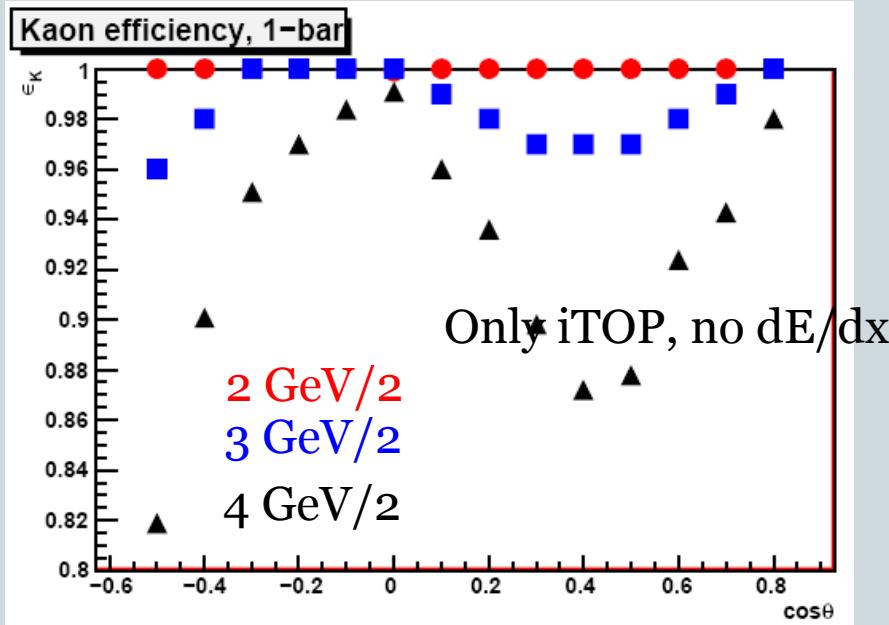
30



PID improvement with iTOP

31

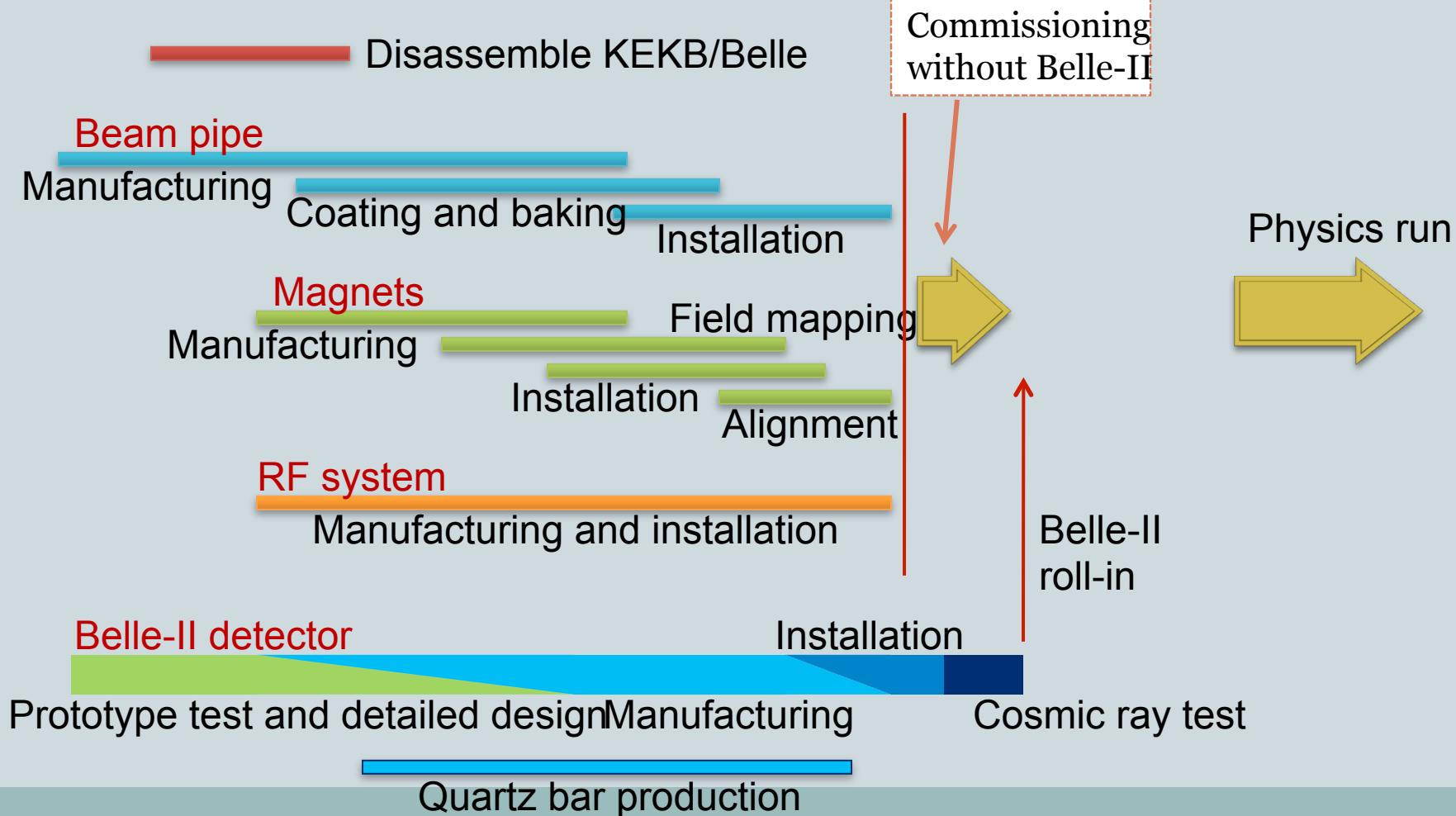
- Compare with ~85% efficiency for Belle



SuperKEKB Schedule

CY2010 CY2011 CY2012 CY2013 CY2014 CY2015 CY2016

US-FY2010 US-FY2011 US-FY2012 US-FY2013 US-FY2014 US-FY2015 US-FY2016



Outlook

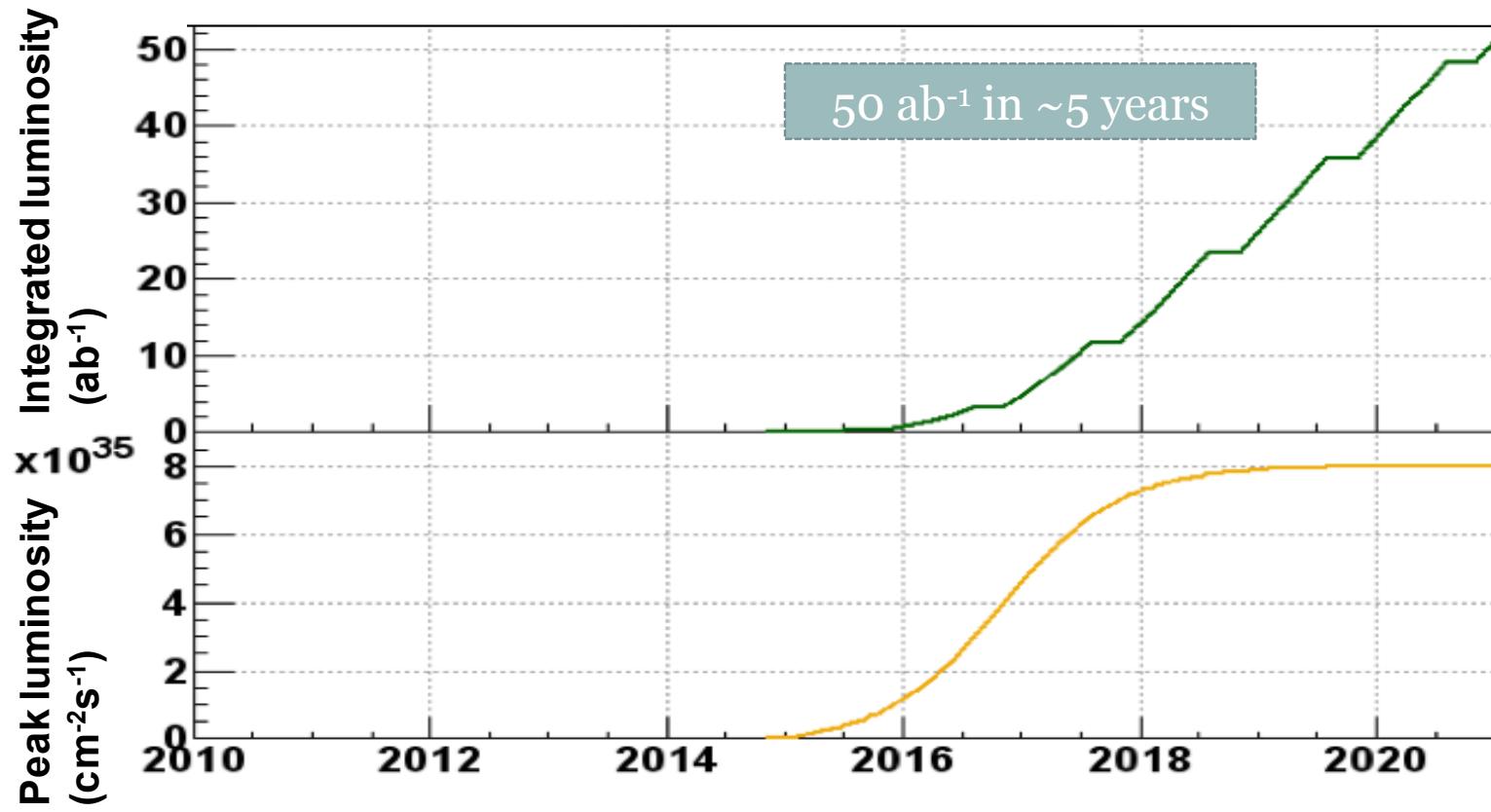
33

- Analysis Underway
 - Di-Hadron Asymmetries
 - Neutral Meson Collins Fragmentation Function
 - Jet-Jet asymmetries from gluon radiation
- Analysis started
 - Di-Hadron Cross-sections
- Belle II

Backup

34

35



$u, d \rightarrow \pi$ ($u\bar{d}, \bar{u}d$)

$$D^{fav} = D_u^{\pi^+} = D_d^{\pi^-} = D_{\bar{u}}^{\pi^-} = D_{\bar{d}}^{\pi^+}$$

$$D^{dis} = D_u^{\pi^-} = D_d^{\pi^-} = D_{\bar{u}}^{\pi^+} = D_{\bar{d}}^{\pi^-}$$

$s \rightarrow \pi$ ($u\bar{d}, \bar{u}d$)

$$D_{s \rightarrow \pi}^{dis} = D_s^{\pi^+} = D_s^{\pi^-} = D_{\bar{s}}^{\pi^+} = D_{\bar{s}}^{\pi^-}$$

$u, d \rightarrow K$ ($u\bar{s}, \bar{u}s$)

$$D_{u \rightarrow K}^{fav} = D_u^{K^+} = D_{\bar{u}}^{K^-}$$

$$D_{u,d \rightarrow K}^{dis} = D_u^{K^-} = D_{\bar{u}}^{K^-} = D_d^{K^+} = D_{\bar{d}}^{K^-} = D_d^{K^-} = D_{\bar{d}}^{K^-}$$

$s \rightarrow K$ ($u\bar{s}, \bar{u}s$)

$$D_{s \rightarrow K}^{fav} = D_s^{K^-} = D_{\bar{s}}^{K^+}$$

$$D_{s \rightarrow K}^{dis} = D_s^{K^+} = D_{\bar{s}}^{K^-}$$

In the end we are left with 7 possible fragmentation functions:

$$D^{fav}, D^{dis}, D_{s \rightarrow \pi}^{dis}, D_{u \rightarrow K}^{fav}, D_{u,d \rightarrow K}^{dis}, D_{s \rightarrow K}^{fav}, D_{s \rightarrow K}^{dis}$$

Assuming charm contribute
only as a dilution

For pion-pion couples:

$$D \frac{U_{\pi\pi}}{L_{\pi\pi}} \propto 1 + \cos 2\phi_0 \frac{\sin^2 \theta}{1+\cos^2 \theta} \left(\frac{5H_1^{fav} H_2^{fav} + 5H_1^{dis} H_2^{dis} + 2H_{1s \rightarrow \pi}^{dis} H_{2s \rightarrow \pi}^{dis}}{5D_1^{fav} D_2^{fav} + 5D_1^{dis} D_2^{dis} + 2D_{1s \rightarrow \pi}^{dis} D_{2s \rightarrow \pi}^{dis}} \right. \\ \left. - \frac{5H_1^{fav} H_2^{dis} + 5H_1^{dis} H_2^{fav} + 2H_{1s \rightarrow \pi}^{dis} H_{2s \rightarrow \pi}^{dis}}{5D_1^{fav} D_2^{dis} + 5D_1^{dis} D_2^{fav} + 2D_{1s \rightarrow \pi}^{dis} D_{2s \rightarrow \pi}^{dis}} \right)$$

For pion-Kaon couples:

$$D \frac{U_{\pi K}}{L_{\pi K}} \propto 1 + \cos 2\phi_0 \frac{\sin^2 \theta}{1+\cos^2 \theta} \times \\ \left(\frac{4H_1^{fav} H_{2K}^{fav} + H_{1K}^{dis} (5H_2^{dis} + H_2^{fav}) + H_{2K}^{dis} (5H_1^{dis} + H_1^{fav}) + 4H_{1K}^{fav} H_2^{fav} + H_{1s \rightarrow \pi}^{dis} (H_{2s \rightarrow K}^{dis} + H_{2s \rightarrow K}^{fav}) + H_{2s \rightarrow \pi}^{dis} (H_{1s \rightarrow K}^{fav} + H_{1s \rightarrow K}^{dis})}{4D_1^{fav} D_{2K}^{fav} + D_{1K}^{dis} (5D_2^{dis} + D_2^{fav}) + D_{2K}^{dis} (5D_1^{dis} + D_1^{fav}) + 4D_{1K}^{fav} D_2^{fav} + D_{1s \rightarrow \pi}^{dis} (D_{2s \rightarrow K}^{dis} + D_{2s \rightarrow K}^{fav}) + D_{2s \rightarrow \pi}^{dis} (D_{1s \rightarrow K}^{fav} + D_{1s \rightarrow K}^{dis})} \right. \\ \left. + H_{2K}^{dis} (5H_1^{fav} + H_1^{dis}) + 4H_{1K}^{fav} H_2^{dis} + 4H_1^{dis} H_{2K}^{fav} + H_{1K}^{dis} (5H_2^{fav} + H_2^{dis}) + H_{1s \rightarrow \pi}^{dis} (H_{2s \rightarrow K}^{fav} + H_{2s \rightarrow K}^{dis}) + (H_{1s \rightarrow K}^{dis} + H_{1s \rightarrow K}^{fav}) H_{2s \rightarrow \pi}^{dis} \right) \\ \left. + D_{2K}^{dis} (5D_1^{fav} + D_1^{dis}) + 4D_{1K}^{fav} D_2^{dis} + 4D_1^{dis} D_{2K}^{fav} + D_{1K}^{dis} (5D_2^{fav} + D_2^{dis}) + D_{1s \rightarrow \pi}^{dis} (D_{2s \rightarrow K}^{fav} + D_{2s \rightarrow K}^{dis}) + (D_{1s \rightarrow K}^{dis} + D_{1s \rightarrow K}^{fav}) D_{2s \rightarrow \pi}^{dis} \right)$$

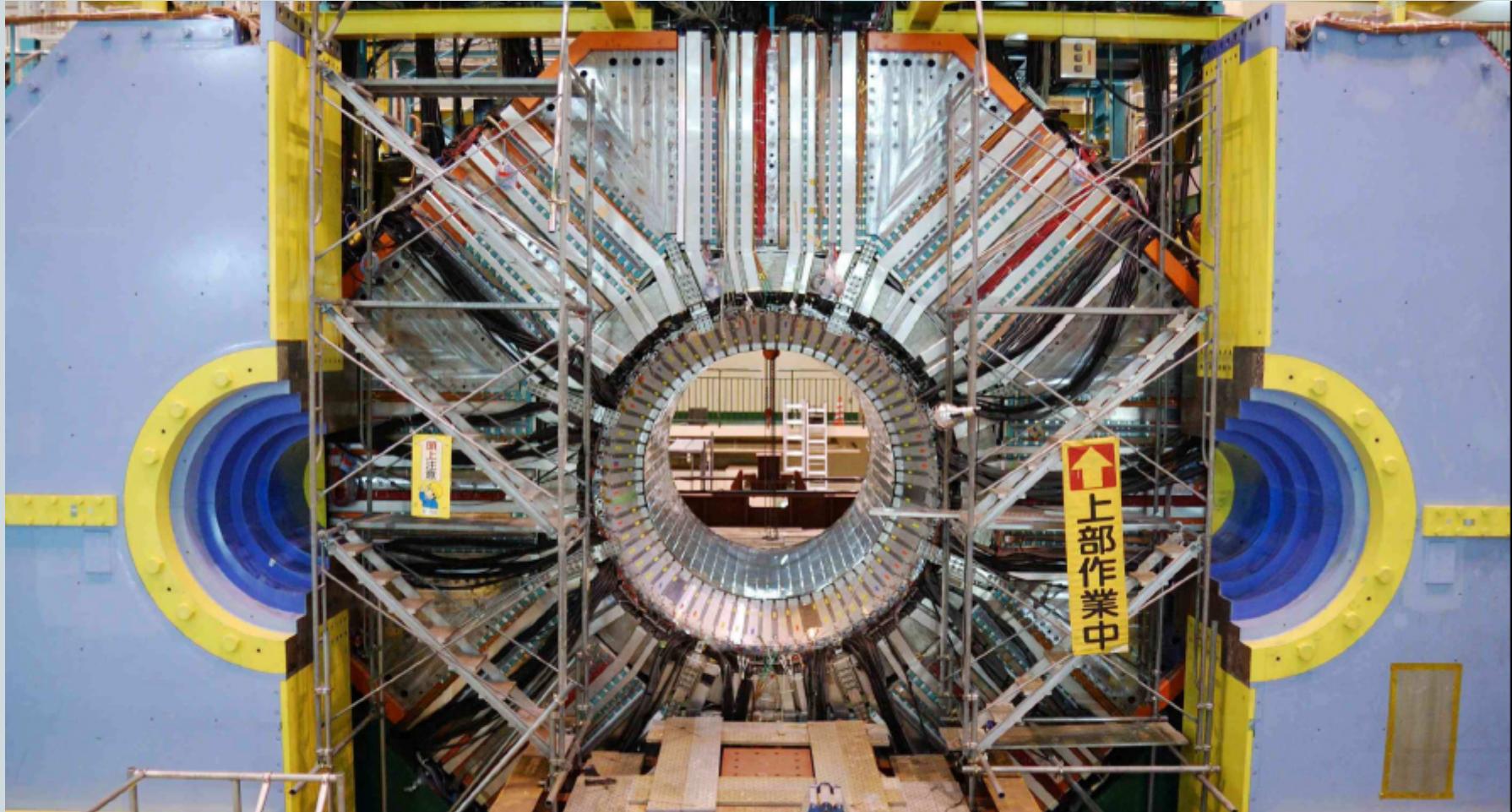
For Kaon-Kaon couples:

$$D \frac{U_{KK}}{L_{KK}} \propto 1 + \cos 2\phi_0 \frac{\sin^2 \theta}{1+\cos^2 \theta} \left(\frac{4H_{1K}^{fav} H_{2K}^{fav} + 6H_{1K}^{dis} H_{2K}^{dis} + H_{1s \rightarrow K}^{dis} H_{2s \rightarrow K}^{dis} + H_{1s \rightarrow K}^{fav} H_{2s \rightarrow K}^{fav}}{4D_{1K}^{fav} D_{2K}^{fav} + 6D_{1K}^{dis} D_{2K}^{dis} + D_{1s \rightarrow K}^{dis} D_{2s \rightarrow K}^{dis} + D_{1s \rightarrow K}^{fav} D_{2s \rightarrow K}^{fav}} \right. \\ \left. - \frac{4H_{1K}^{fav} H_{2K}^{dis} + 4H_{1K}^{dis} H_{2K}^{fav} + 2H_{1K}^{dis} H_{2K}^{dis} + H_{1s \rightarrow K}^{dis} H_{2s \rightarrow K}^{fav} + H_{1s \rightarrow K}^{fav} H_{2s \rightarrow K}^{dis}}{4D_{1K}^{fav} D_{2K}^{dis} + 4D_{1K}^{dis} D_{2K}^{fav} + 2D_{1K}^{dis} D_{2K}^{dis} + D_{1s \rightarrow K}^{dis} D_{2s \rightarrow K}^{fav} + D_{1s \rightarrow K}^{fav} D_{2s \rightarrow K}^{dis}} \right)$$

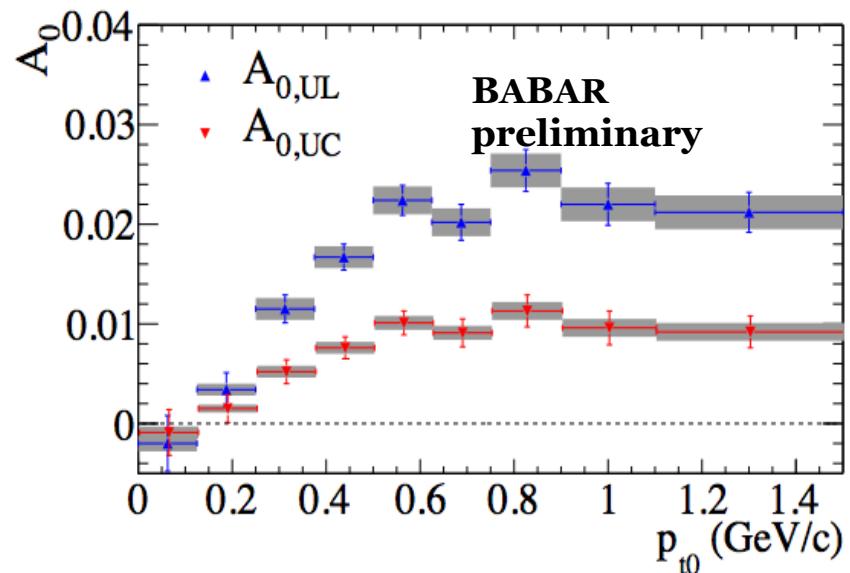
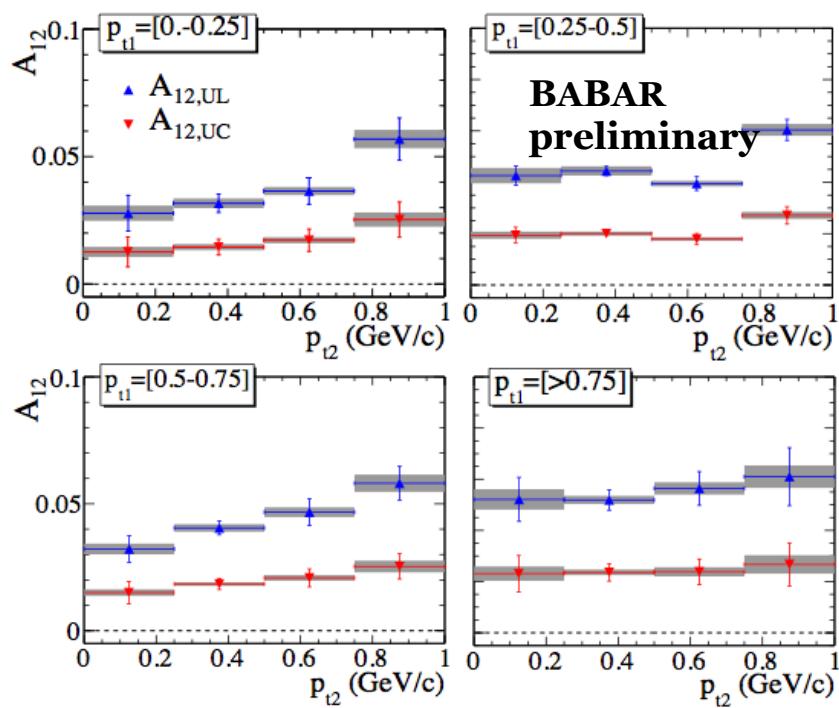
Not so easy! A full phenomenological study needed!

Belle detector today – ready for upgrade

38



Results: A_{12} vs. (p_{t1}, p_{t2}) ; A_0 vs. p_{t0}



**FIRST MEASUREMENT of
Collins asymmetries *vs.* p_t in e^+e^- annihilation at $Q^2 \sim 110$ (GeV/c) 2**

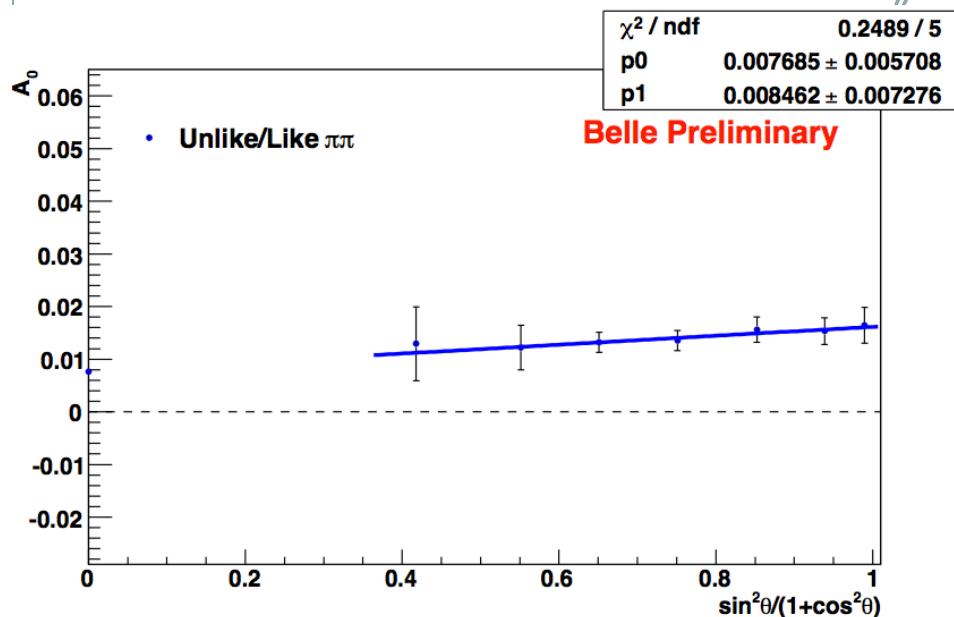
- nonzero A_{12}^{UL} and A_{12}^{UC}

⇒ only modest dependence on (p_{t1}, p_{t2}) ;

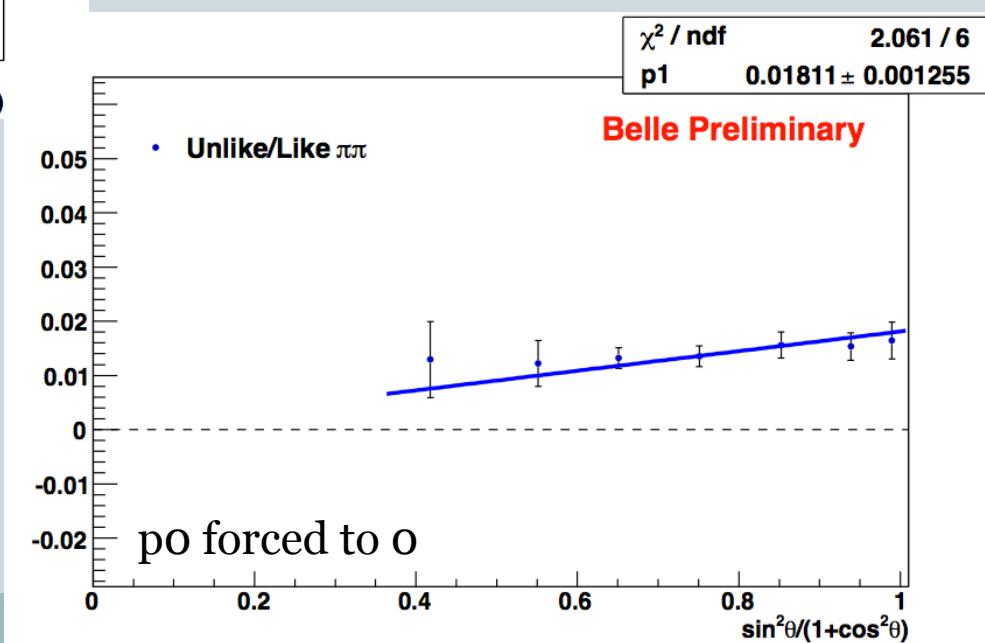
⇒ $A_{12}^{\text{UC}} < A_{12}^{\text{UL}}$; complementary information on $H_1^{\perp, \text{fav}}$ and $H_1^{\perp, \text{dis}}$

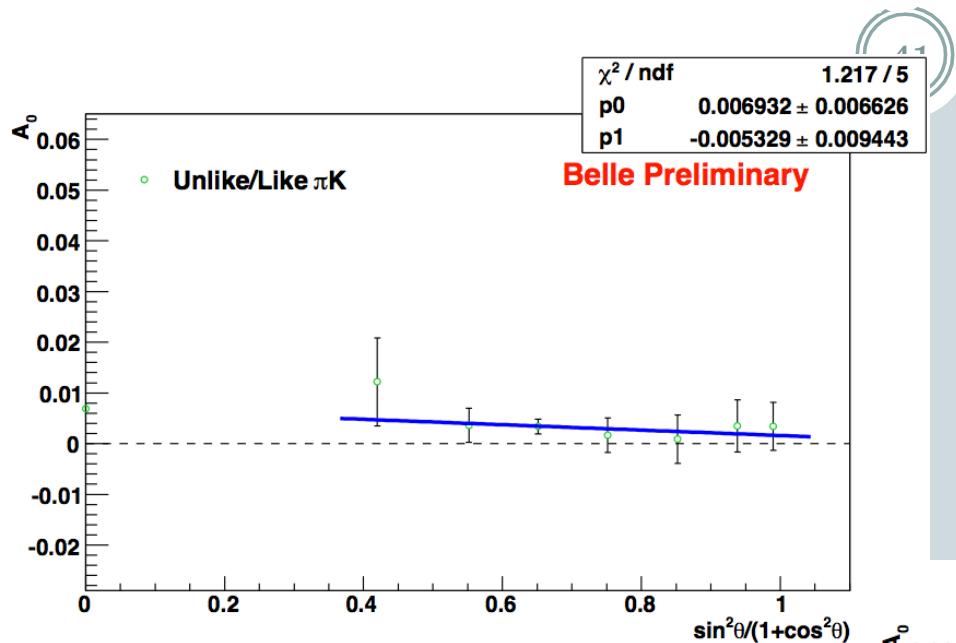
⇒ $A_0 < A_{12}$, but interesting structure in p_t

versus $\sin^2\theta/(1+\cos^2\theta)$



fit form: $p_0 + p_1 \sin^2\theta/(1+\cos^2\theta)$

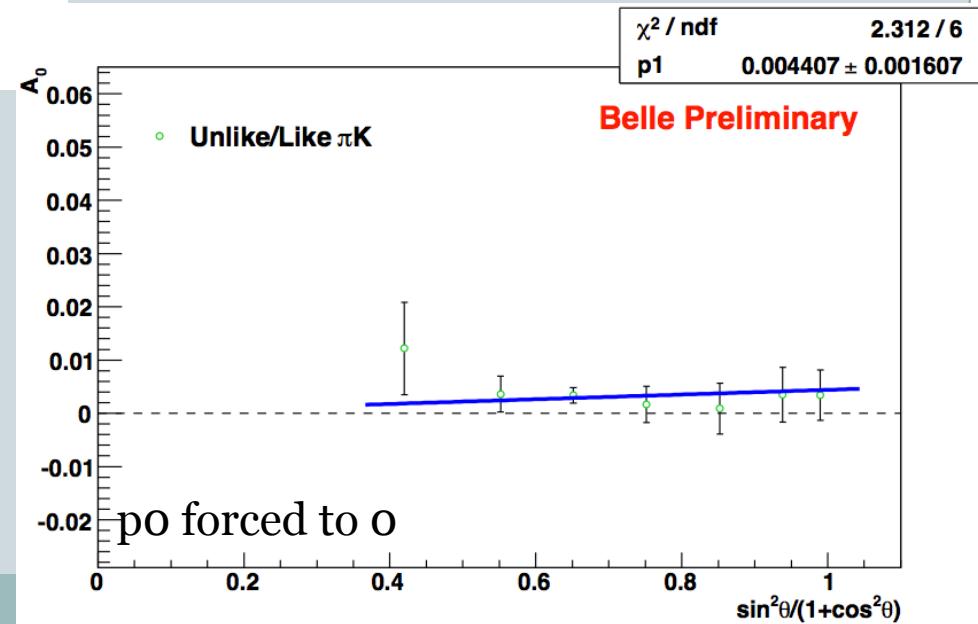


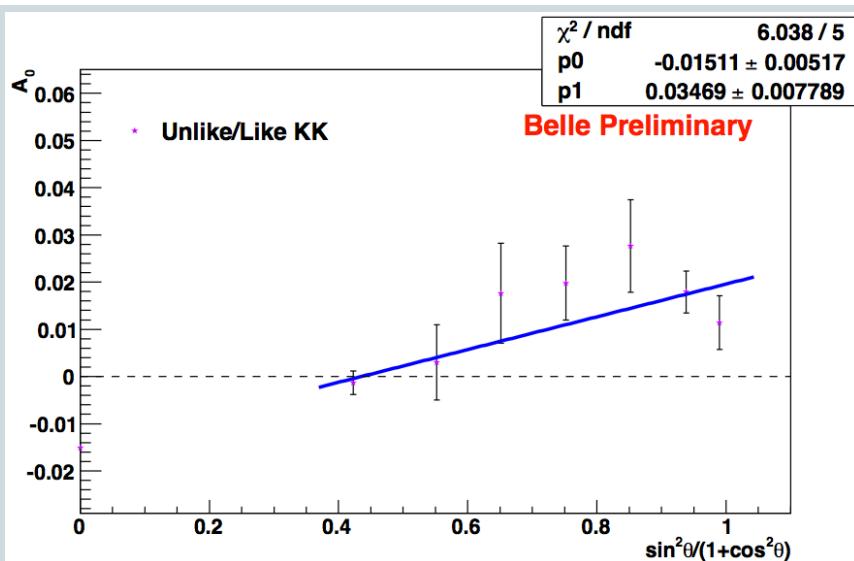


fit form: $p_0 + p_1 \sin^2 \theta / (1+\cos^2 \theta)$

$$A_0 = \frac{\sin^2 \theta}{1 + \cos^2 \theta} \mathcal{F} \left[\frac{H_1^\perp(z_1) \bar{H}_1^\perp(z_2)}{D_1^\perp(z_1) \bar{D}_1^\perp(z_2)} \right]$$

linear in $\sin^2 \theta / (1+\cos^2 \theta)$,
go to 0 for $\sin^2 \theta / (1+\cos^2 \theta) \rightarrow 0$

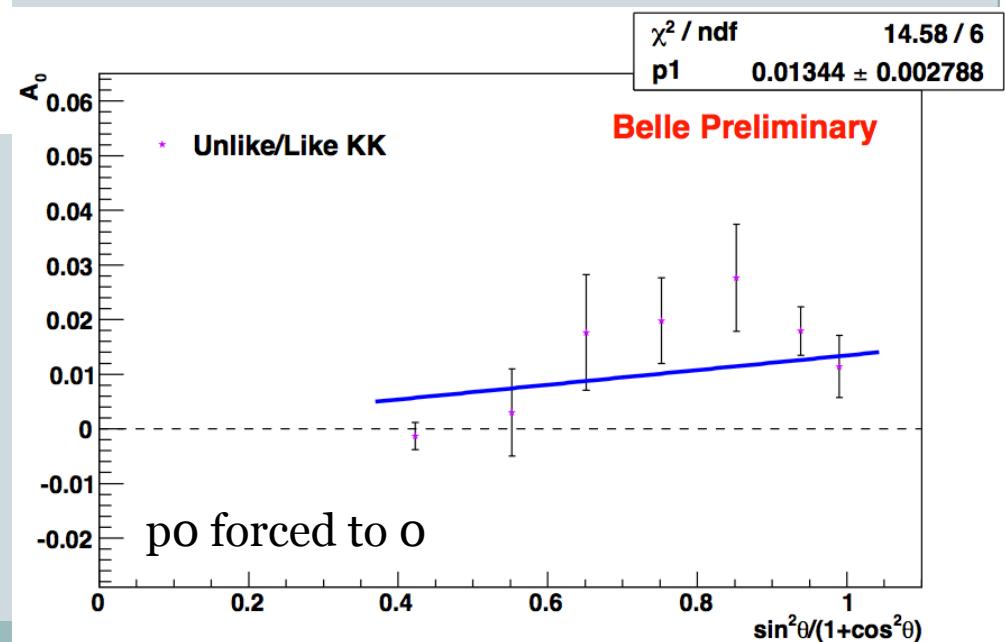




fit form: $p_0 + p_1 \sin^2 \theta / (1 + \cos^2 \theta)$

$$A_0 = \frac{\sin^2 \theta}{1 + \cos^2 \theta} \mathcal{F} \left[\frac{H_1^\perp(z_1) \bar{H}_1^\perp(z_2)}{D_1^\perp(z_1) \bar{D}_1^\perp(z_2)} \right]$$

linear in $\sin^2 \theta / (1 + \cos^2 \theta)$,
go to 0 for $\sin^2 \theta / (1 + \cos^2 \theta) \rightarrow 0$



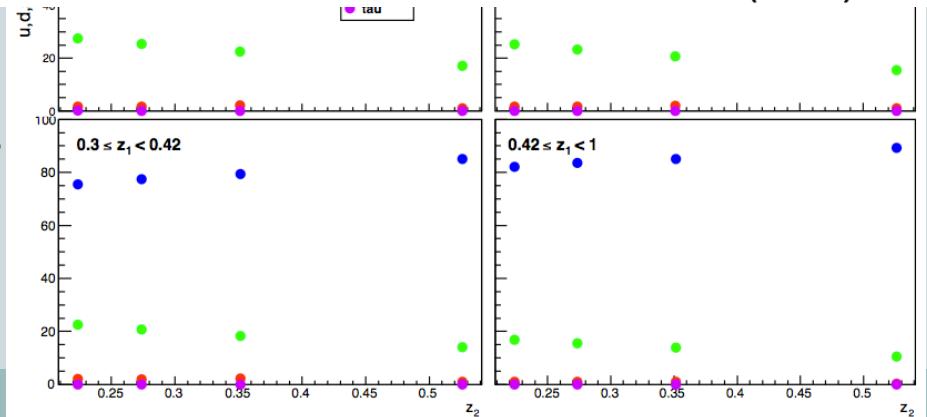
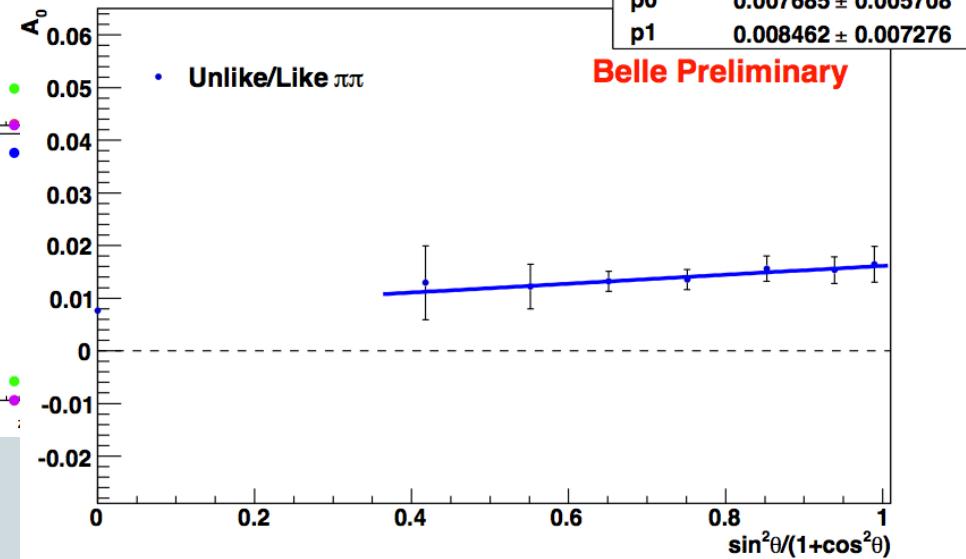
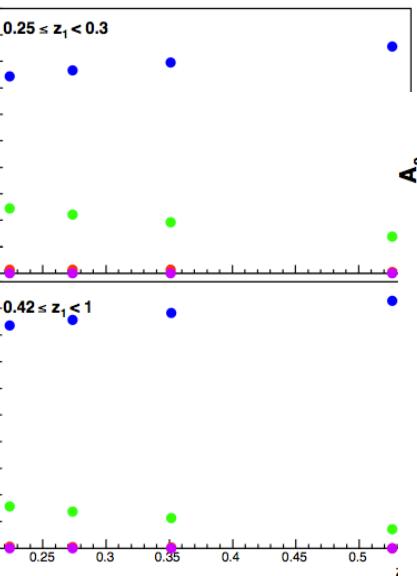
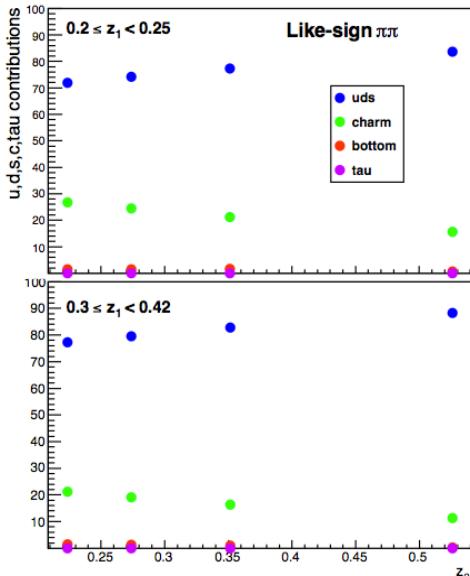
$$F^{[n]}(z_i) \equiv \int d|k_T|^2 \left[\frac{|k_T|}{M_i} \right]^{[n]} F(z_i, |k_T|^2)$$

$$\begin{aligned} \mathcal{F}[X] = & \sum_{q\bar{q}} \int [2\hat{\mathbf{h}} \cdot \mathbf{k}_{\mathbf{T1}} \hat{\mathbf{h}} \cdot \mathbf{k}_{\mathbf{T2}} - \mathbf{k}_{\mathbf{T1}} \cdot \mathbf{k}_{\mathbf{T2}}] \\ & d^2\mathbf{k}_{\mathbf{T1}} d^2\mathbf{k}_{\mathbf{T2}} \delta^2(\mathbf{k}_{\mathbf{T1}} + \mathbf{k}_{\mathbf{T2}} - \mathbf{q}_T) X \end{aligned}$$

$$k_{Ti} = z_i p_{Ti}$$

uds-charm-bottom-tau contributions

44

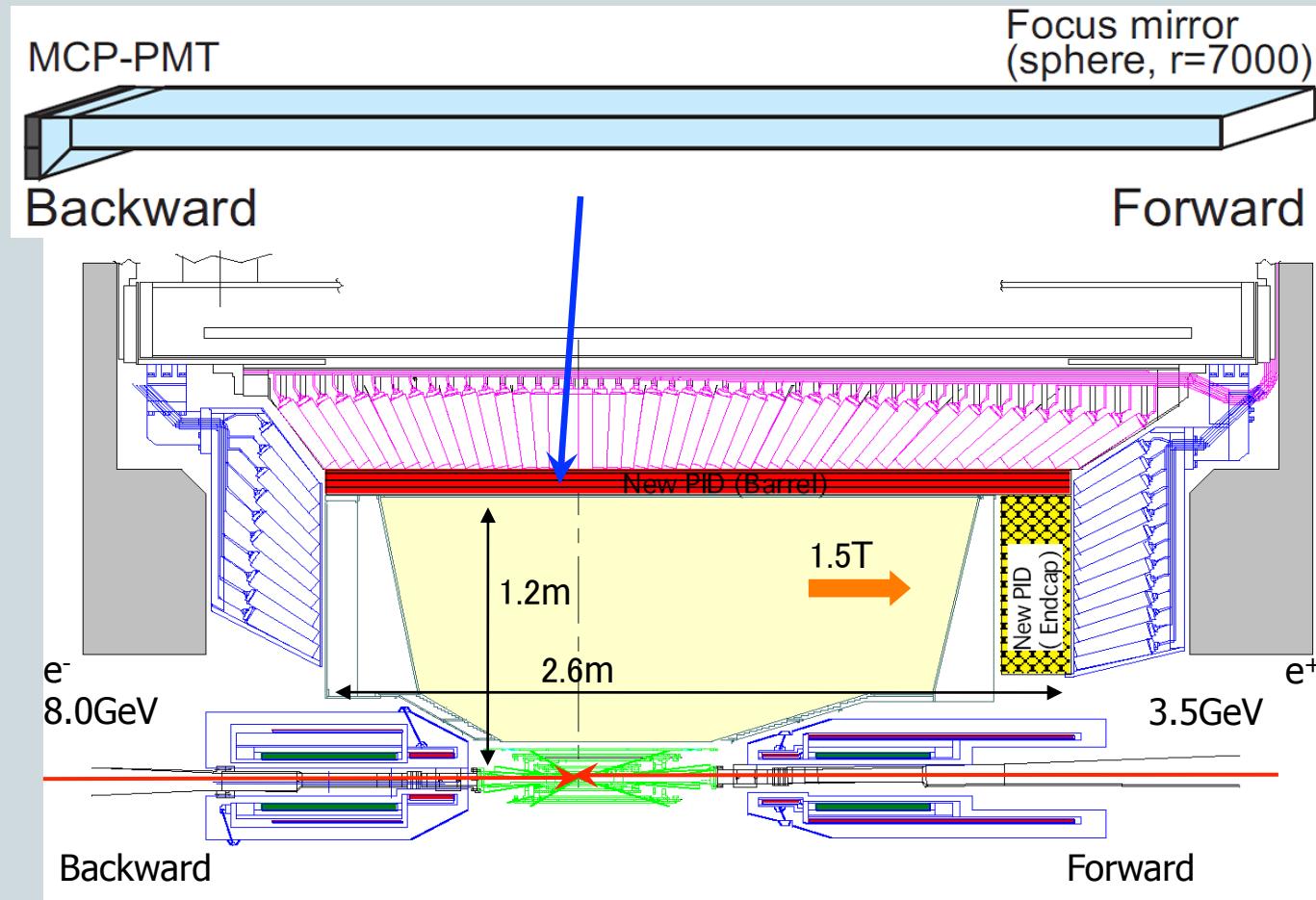


Published $\pi\pi$ studied a charm enhanced data and found charm contribute only as dilution
 => charm contribution corrected out

iTOP: an imaging time-of-propagation detector

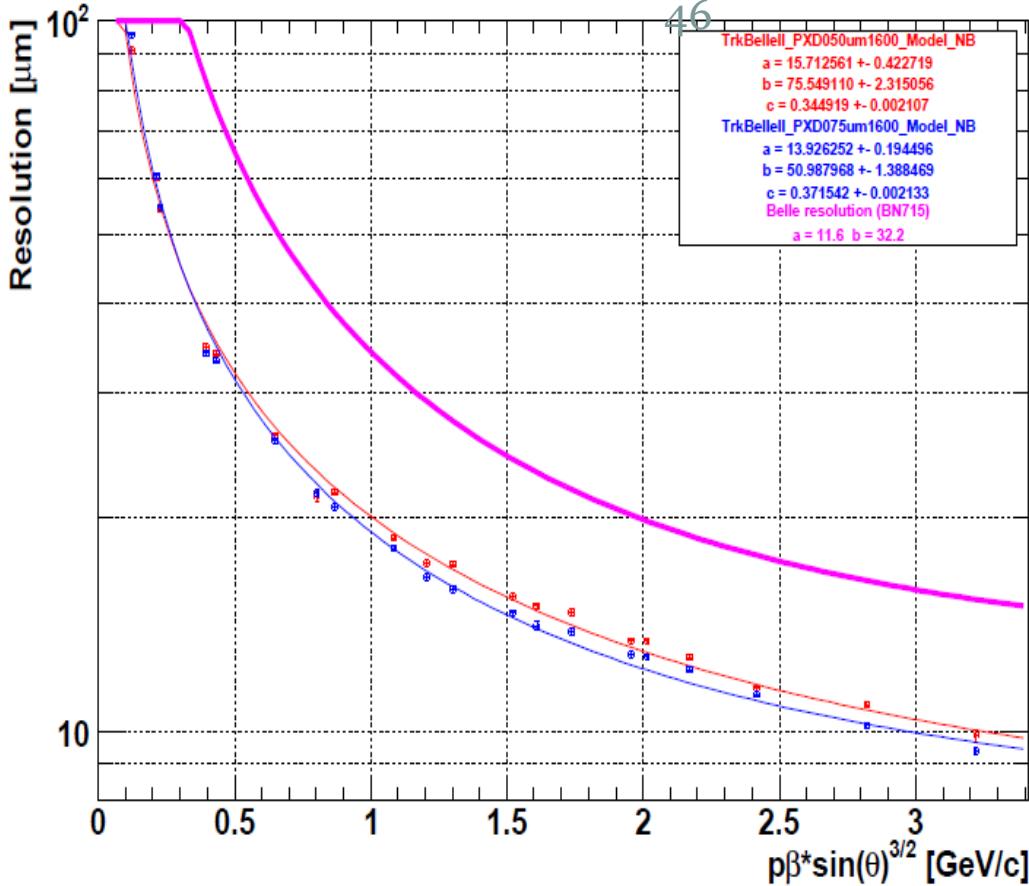
Space constrained by existing calorimeters

Quartz radiator + mirror + expansion block + MCP-PMT

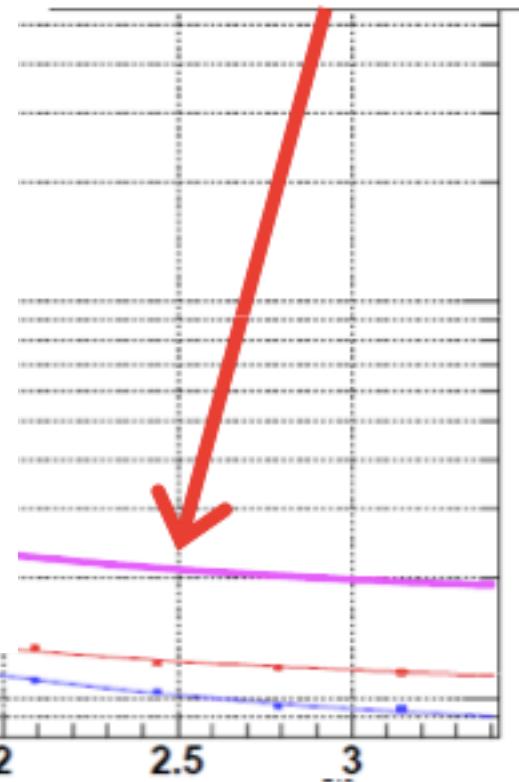


$\sigma[\mu\text{m}]$

Impact parameter resolution d0

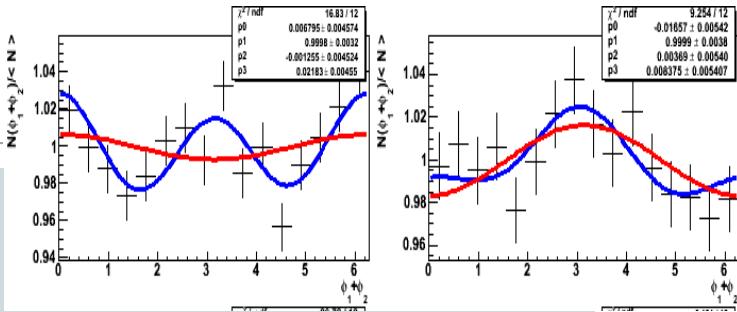


Pixel detector close to the beam pipe



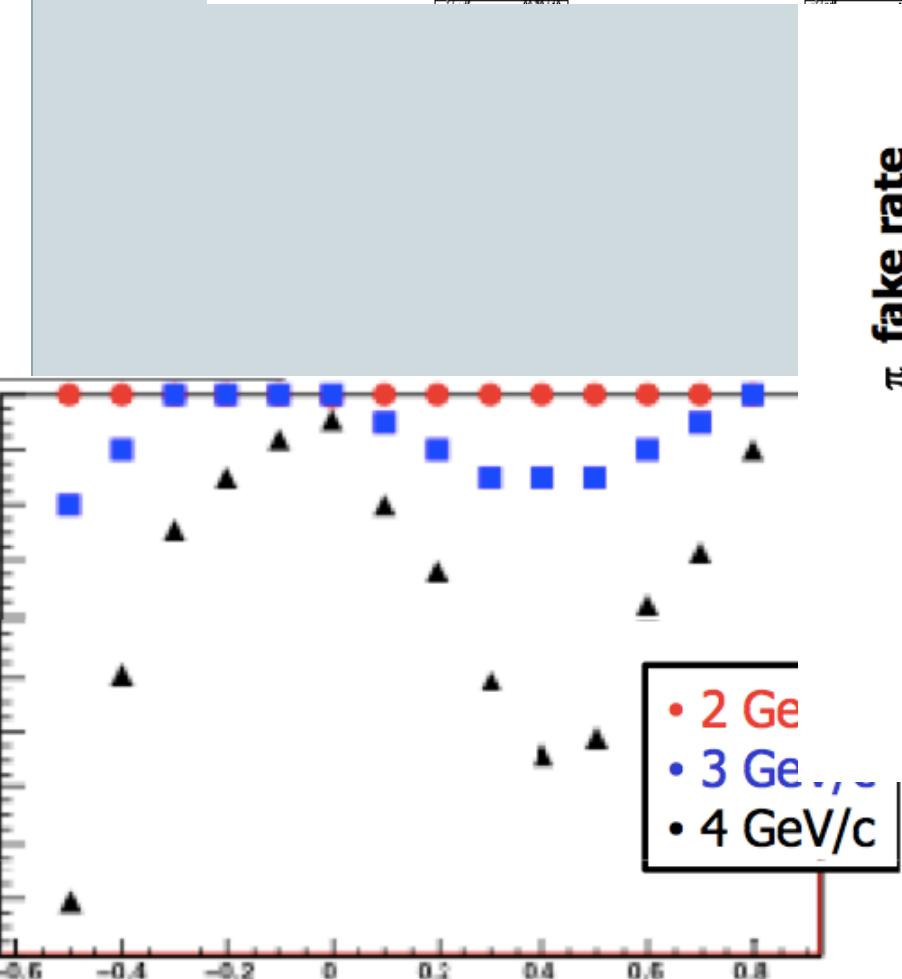
1.0

2.0 $p\beta\sin(\theta)^{5/2}$ [GeV/c]

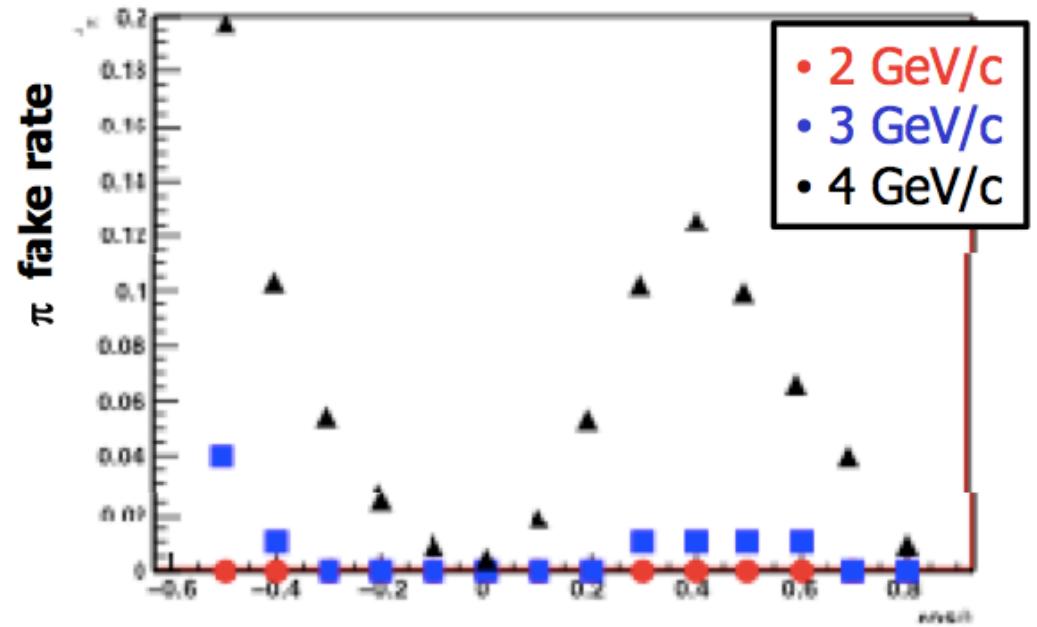


47

cos i



Pion fake rate, 1-bar



iTOP only (no dE/dx)

21



Belle at KEKB

