Measurement of Fragmentation Functions in e^+e^- Annihilation at Belle

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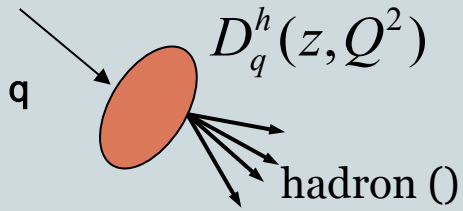
- Motivation
- Results
  - π/K Cross-sections
  - Pion/Kaon Collins Fragmentation Function
  - Di-hadron asymmetries
- Outlook: Analysis in progress, SuperKEKB, Belle II

Why Study Fragmentation Functions?



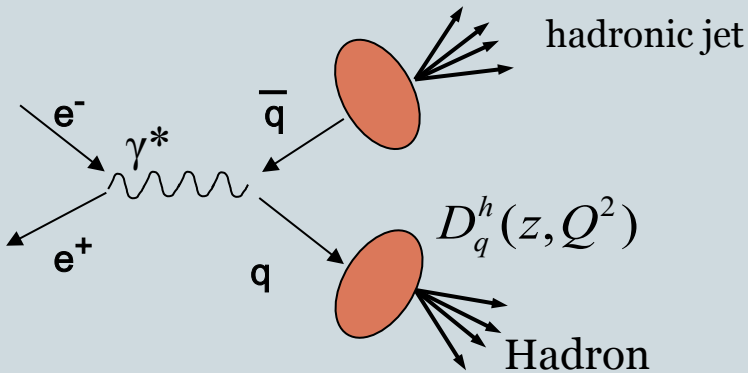
- FFs needed for Semi-inclusive measurements (Ingredient to extract nucleon structure)
  - Spin averaged for x-sections, long. spin asymmetries etc
  - Transverse spin dependent for chiral odd PDFs (quark polarimeters)
- FFs non-perturbative QCD objects
  - Compare to Nucleon Structure, study related issues like **Evolution** (CSS soft factor is universal)

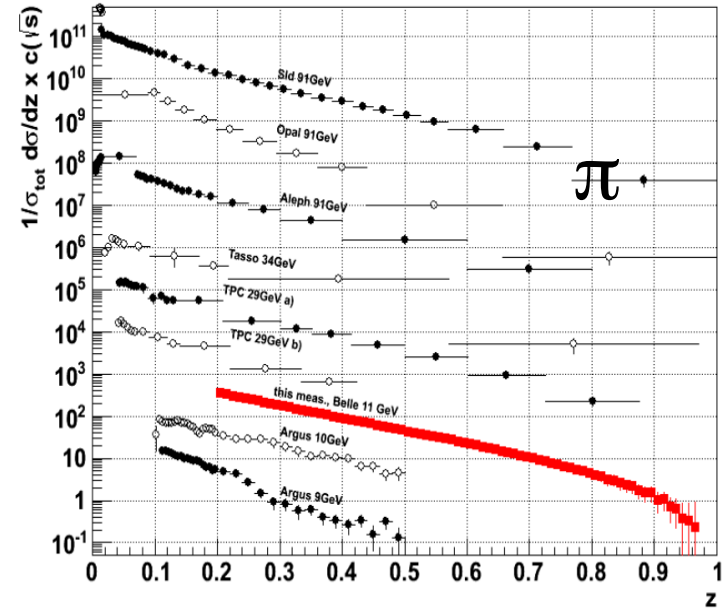
$$\int \frac{d\xi}{2\pi} e^{ip\xi} \left\langle P \middle| \overline{\psi_i}(0) a_h^+ a_h \psi_j(\xi) \middle| P \right\rangle \quad \longleftrightarrow \quad \int e^{ip\xi} \frac{d\xi}{2\pi} \left\langle 0 \middle| \psi_i(\xi) a_h^+ a_h \overline{\psi_j}(0) \middle| 0 \right\rangle$$

  - Cannot be computed on the lattice

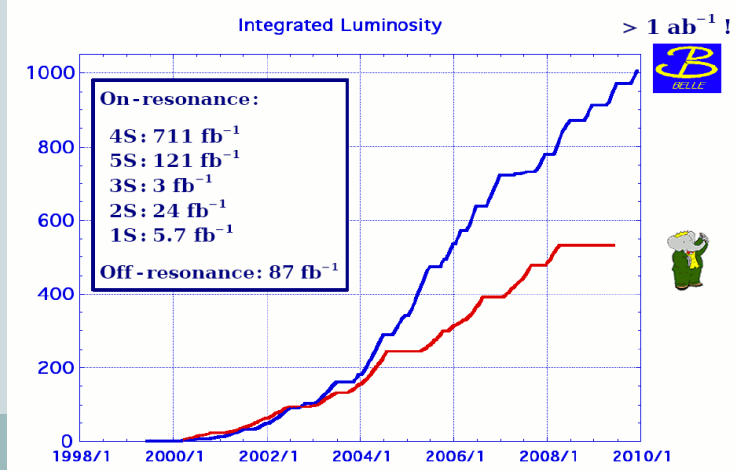
Where to Study?

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





- B factories
  - close in energy to SIDIS (100 GeV² vs 2-3 GeV²)
  - Large integrated lumi!, high z reach



Measurements of Fragmentation Functions in e+e- at Belle

•Asym. e^+ (3.5/3.1 GeV) e^- (8/9 GeV) collider:

-**$\sqrt{s}$ = 10.58 GeV,** e^+e^- →Y(4S)→B anti-B

-$\sqrt{s}$ = 10.52 GeV, e+e-→ qqbar (u,d,s,c) 'continuum'

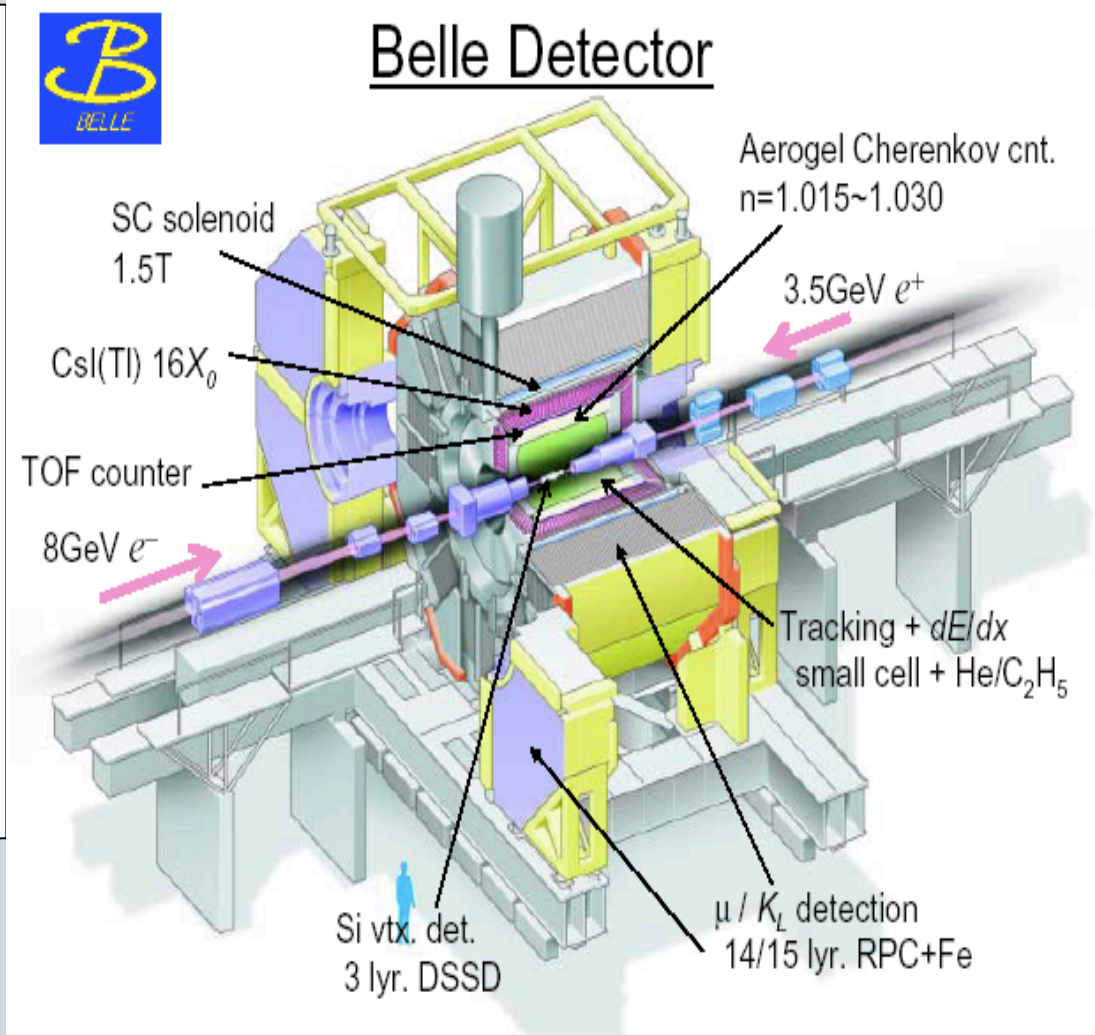
• ideal detector for high precision measurements:

- Azimuthally symmetric acceptance, high res. Tracking, PID

Available data:

~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

PID

$i = \pi, K$

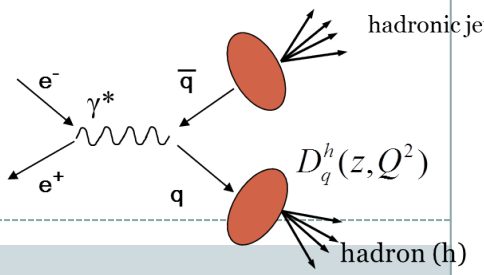
$$\frac{d\sigma_i}{dz} = \frac{1}{L_{tot}} \epsilon^i_{joint}(z)\, \epsilon^i_{ISR/FSR}(z)\, S^{-1}_{zz_m}\, \epsilon^i_{impu}(z_m)\, P^{-1}_{ij}\, N^{j,raw}(z_m)$$

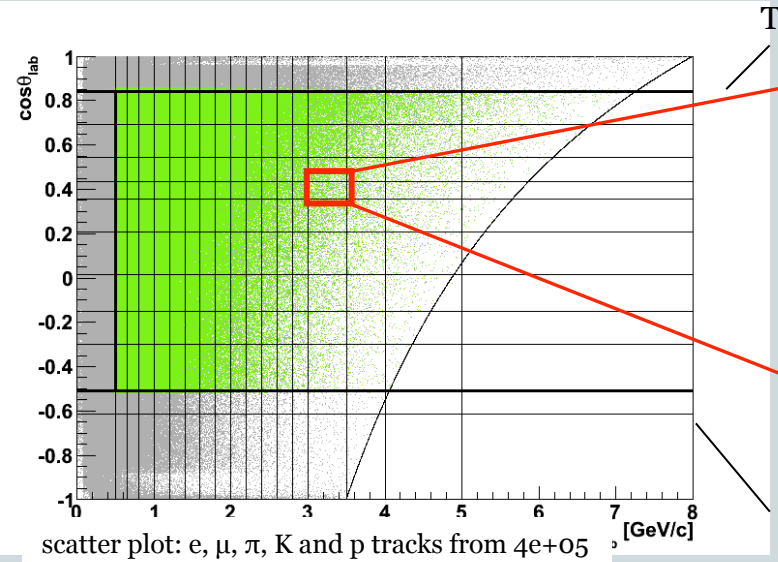
- Correct for acceptance,
- ττ, 2γ,
- decay in flight,

$< 10\%$

- Smearing Corrections

PID Corrections from Data





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

ToF forward geometry acceptance limit

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

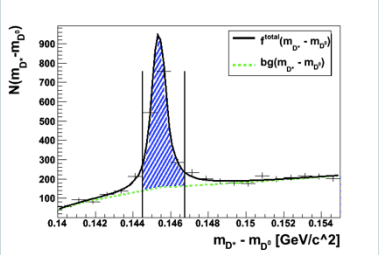
$$[P]_{ij\,(p_{lab},\,\cos\theta_{lab})} = \begin{pmatrix} p_{(e\to\tilde{e})} & p_{(\mu\to\tilde{e})} & p_{(\pi\to\tilde{e})} & p_{(K\to\tilde{e})} & p_{(p\to\tilde{e})} \\ p_{(e\to\tilde{\mu})} & p_{(\mu\to\tilde{\mu})} & p_{(\pi\to\tilde{\mu})} & p_{(K\to\tilde{\mu})} & p_{(p\to\tilde{\mu})} \\ p_{(e\to\tilde{\pi})}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

ToF backward geometry acceptance limit

e.g. $D^* \longrightarrow D^0 \longrightarrow K^-$

$D^* \longrightarrow \pi^+_{slow}$

$D^0 \longrightarrow \pi^+_{fast}$

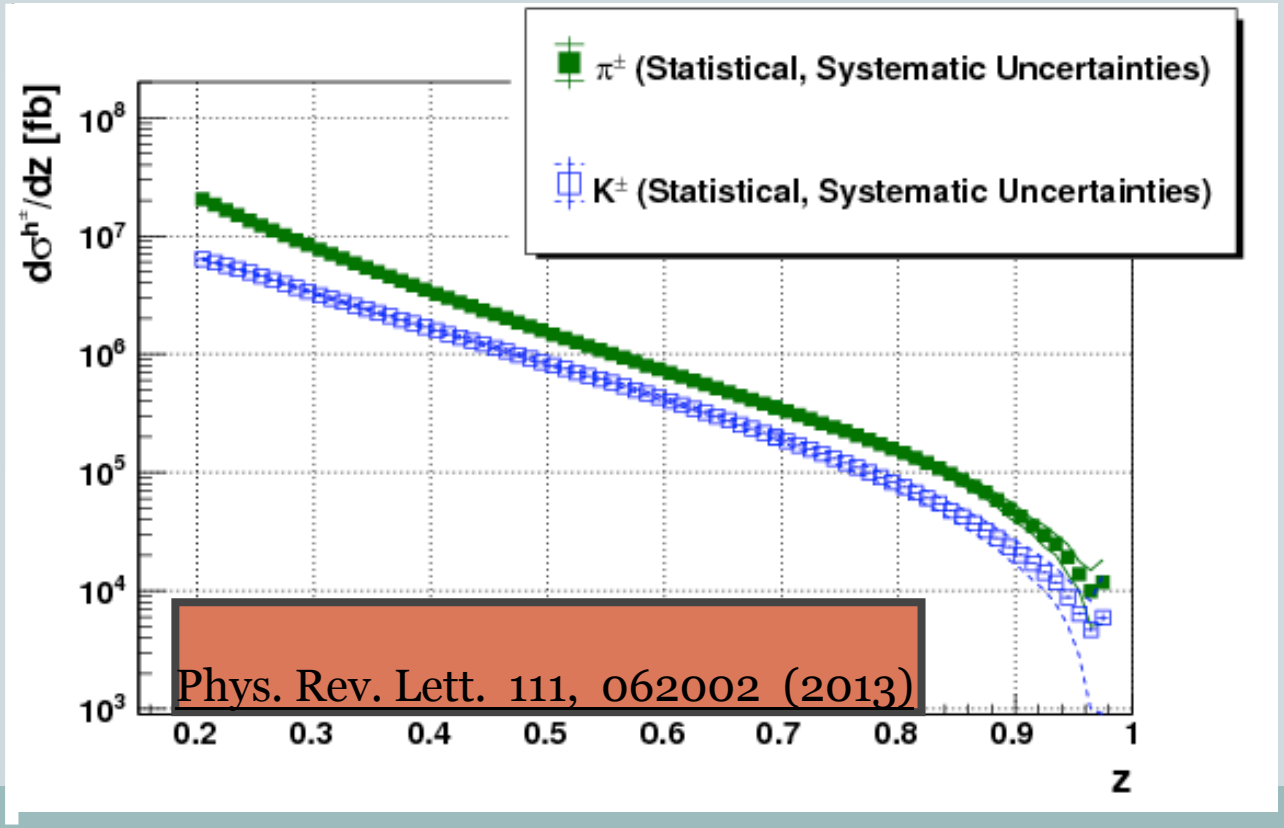


- Misidentification π→K up to 15%, K→π up to 20%

Cross sections

$i = \pi, K$

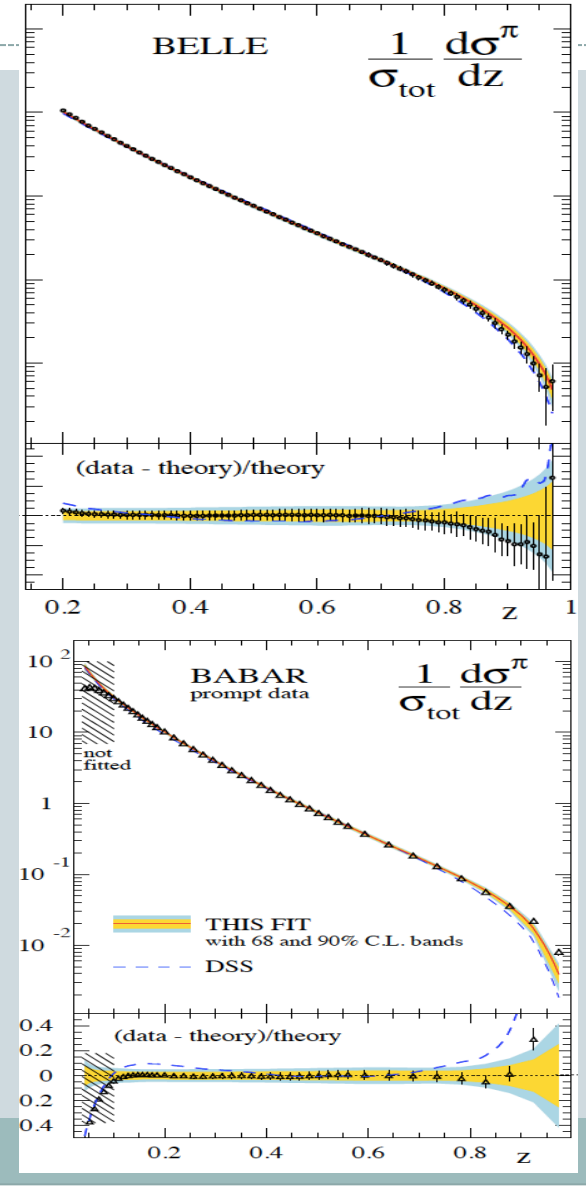
$$\frac{d\sigma_i}{dz} = \frac{1}{L_{tot}} \epsilon^i_{joint}(z)\, \epsilon^i_{ISR/FSR}(z)\, S^{-1}_{zz_m}\, \epsilon^i_{impu}(z_m)\, P^{-1}_{ij}\, N^{j,raw}(z_m)$$



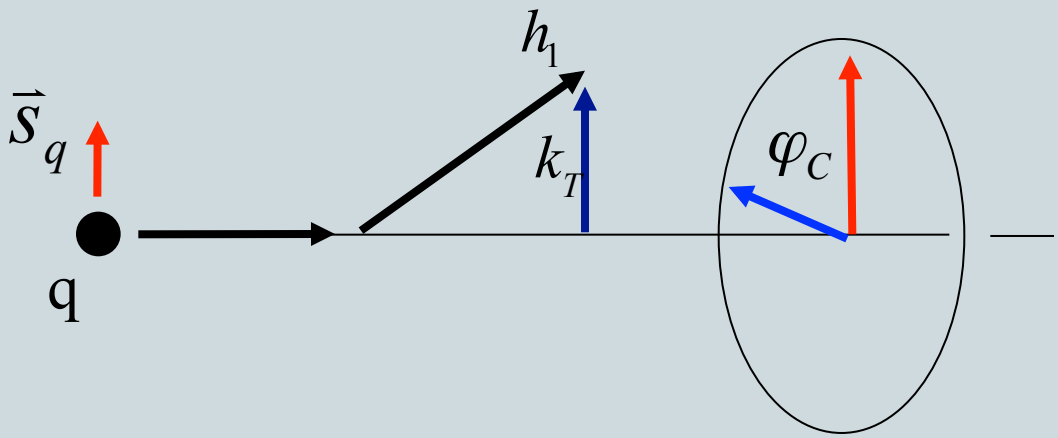
Phys. Rev. Lett. 111, 062002 (2013)

New DSS(E,H-P) Fit

- Good agreement, however, there seems to be a trend away from the fit for the Belle data at high z
- Babar low z data needs resummation
- From DSS:
  - Precise data at high z
  - Some info from scaling violations (Belle vs experiments at M_Z)
  - Some info on flavor due to charge weighting



“Collins” Fragmentation Function for Identified Pions and Kaons

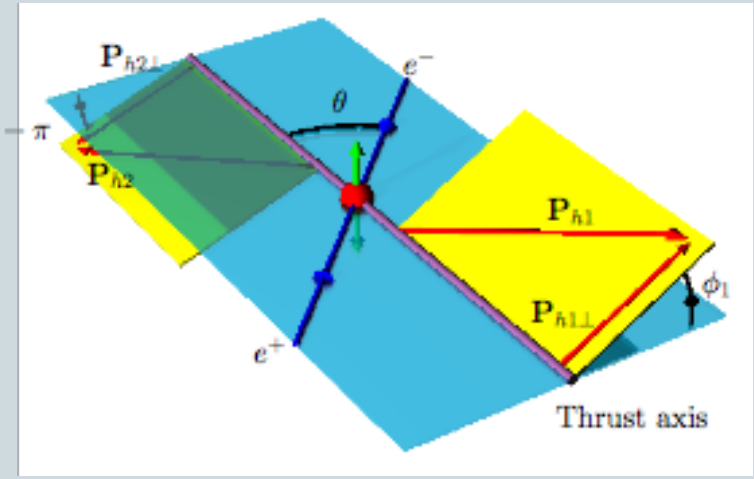


There are two methods with two or one soft scale

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

$\phi_1+\phi_2$ method:

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

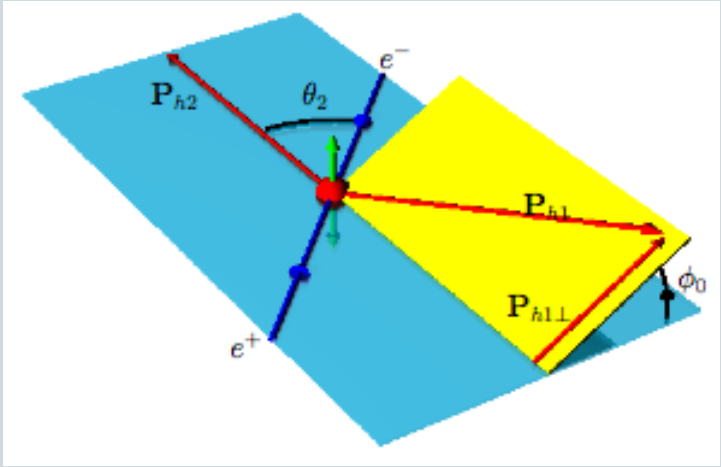


$$\sigma \sim \mathcal{M}_{12}\left(1+\frac{\sin^2\theta_T}{1+\cos^2\theta_T}\,cos(\phi_1+\phi_2)\boxed{\frac{H_1^{\perp[1]}(z_1)\bar{H}_1^{\perp[1]}(z_2)}{D_1^{[0]}(z_1)\bar{D}_1^{[0]}(z_2)}}\right)$$

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

ϕ_0 method:

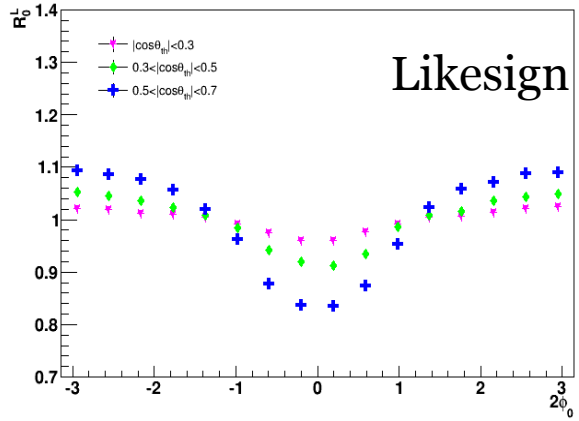
hadron 1 azimuthal angle with respect to hadron 2

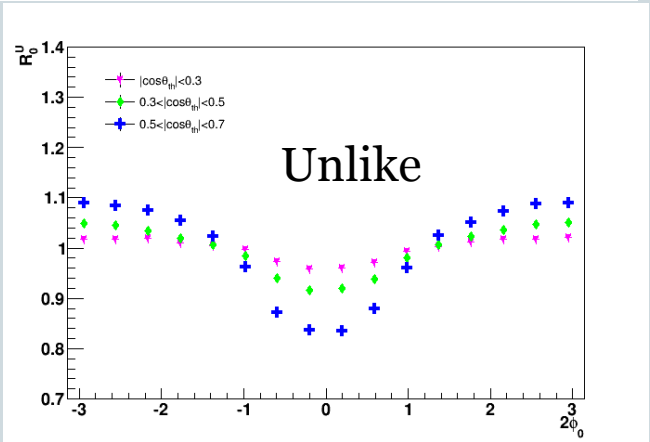


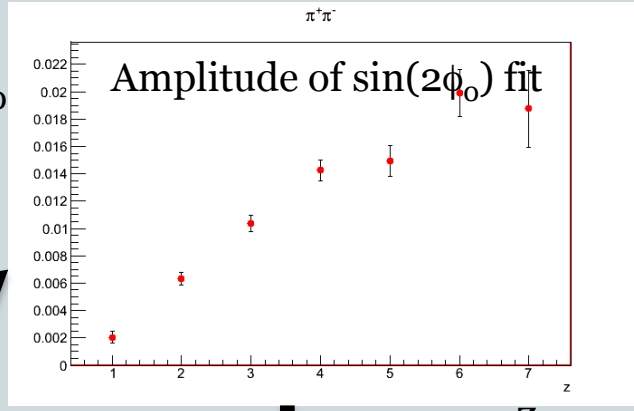
$$\sigma \sim \mathcal{M}_0\left(1+\frac{\sin^2\theta_2}{1+\cos^2\theta_2}\,cos(2\phi_0)\mathcal{F}\boxed{\frac{H_1^{\perp}(z_1)\bar{H}_1^{\perp}(z_2)}{D_1^{\perp}(z_1)\bar{D}_1^{\perp}(z_2)}}\right)$$

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

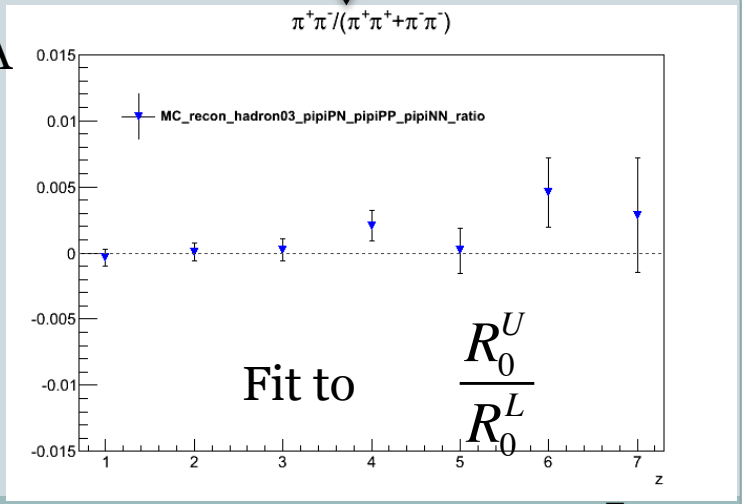
Use of Double Ratios





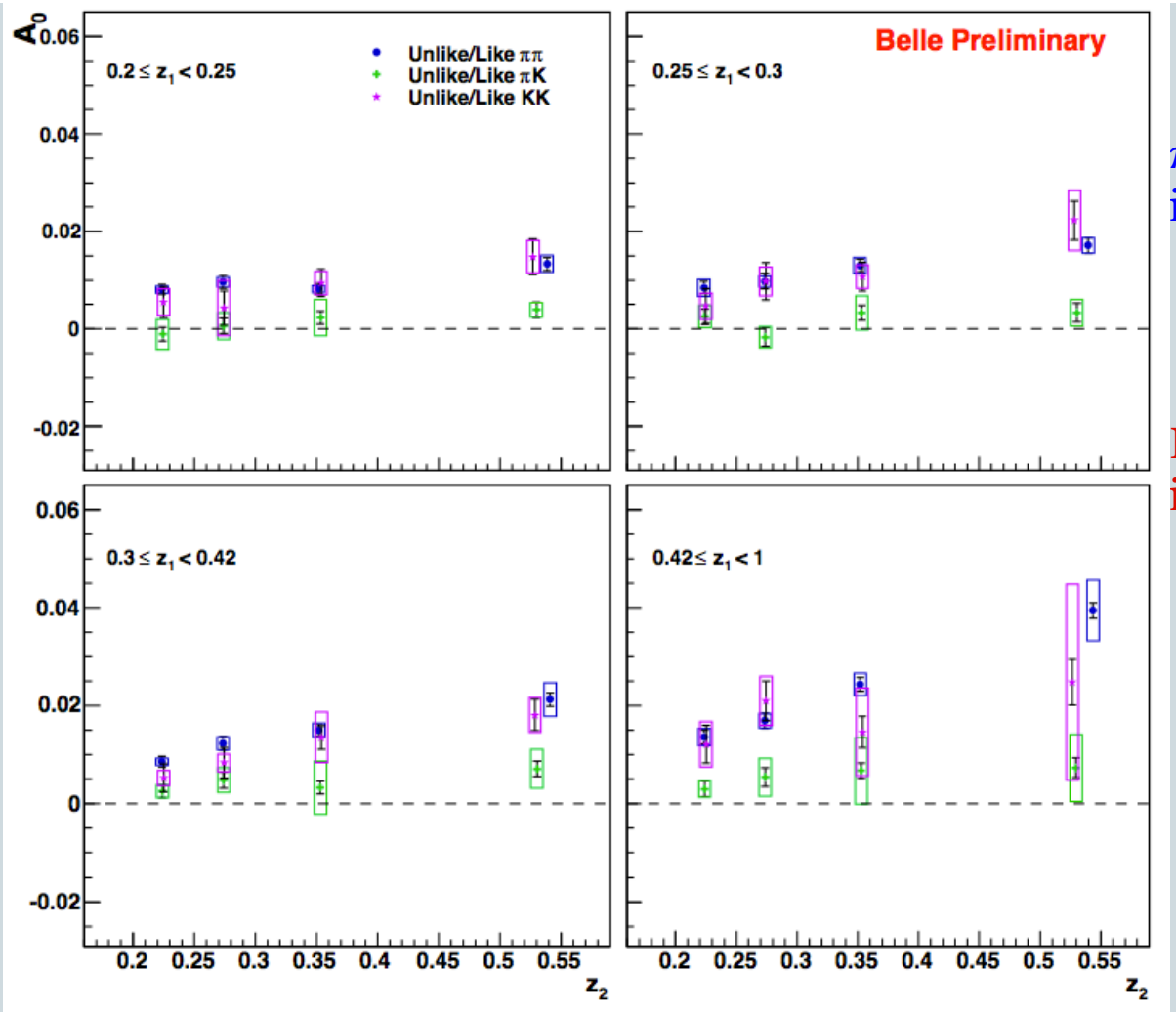


Use of "Double Ratios"



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

Double Ratios for π/K pairs

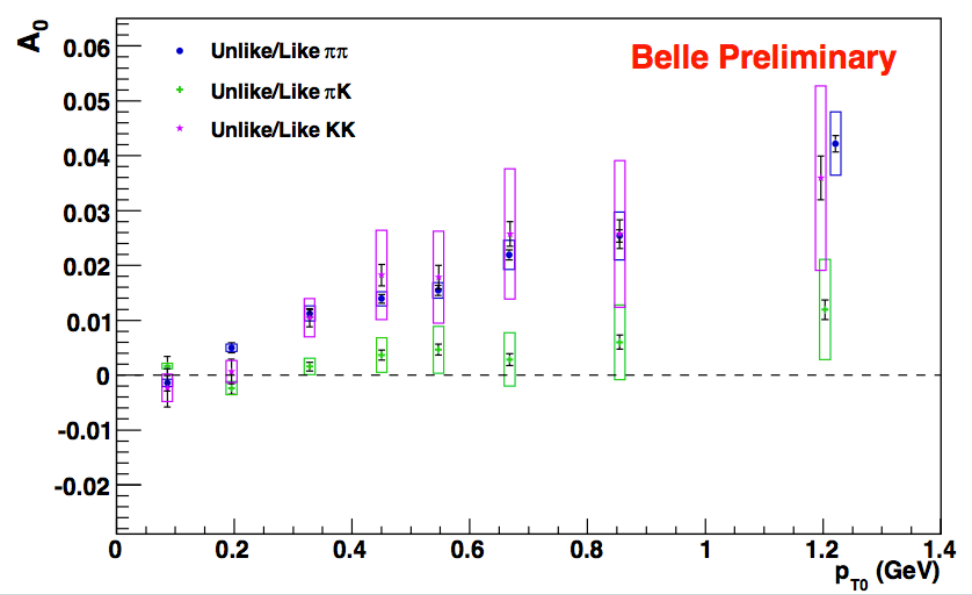


ππ => non-zero asymmetries, increase with z_1, z_2

πK => asymmetries compatible with zero

KK => non-zero asymmetries, increase with z_1,z_2
similar size of pion-pion

P_{T0} Dependence

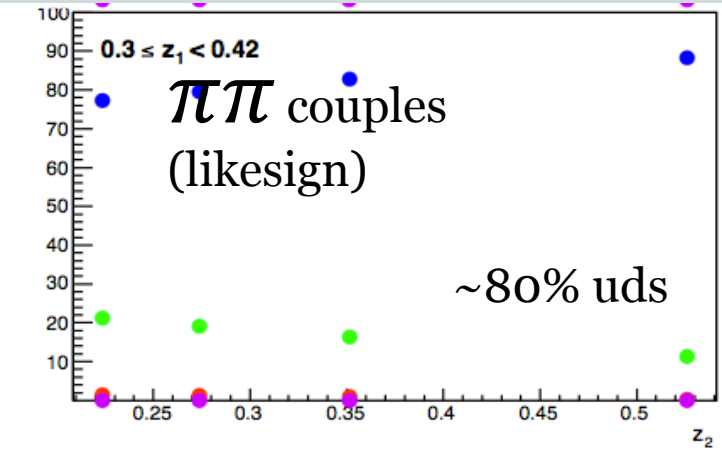


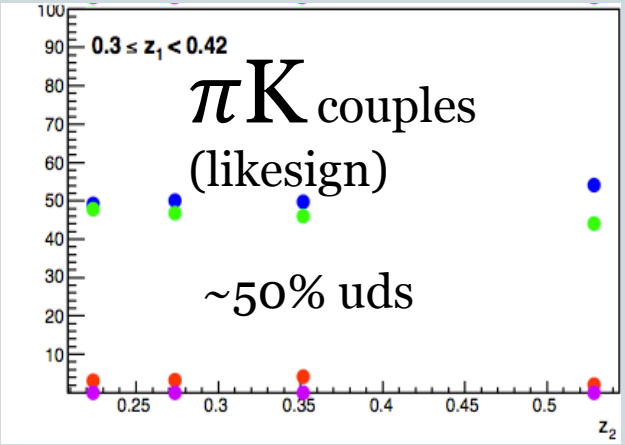
$\pi\pi$ => non-zero asymmetries, increase with z_1, z_2

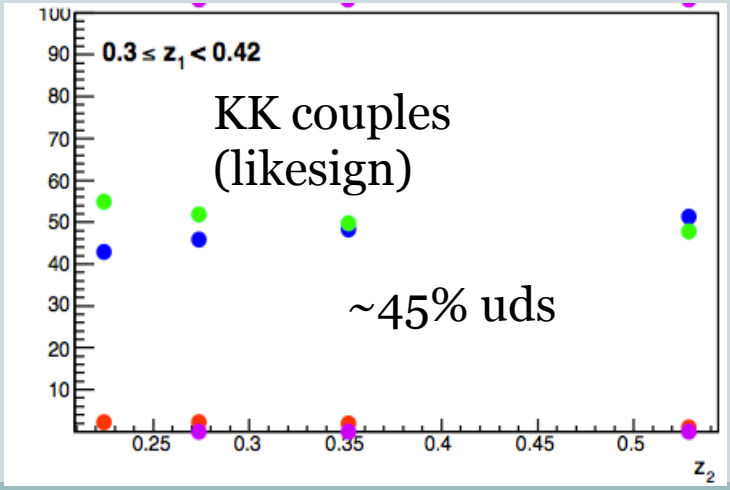
πK => asymmetries compatible with zero

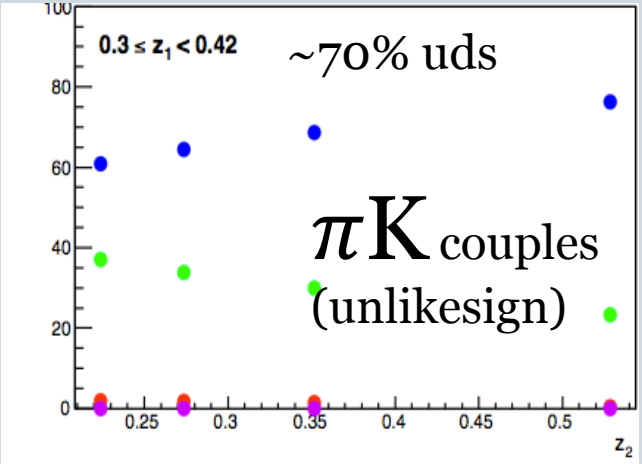
KK => non-zero asymmetries, increase with z_1,z_2
similar size of pion-pion

Significant Charm to contribution to UDS

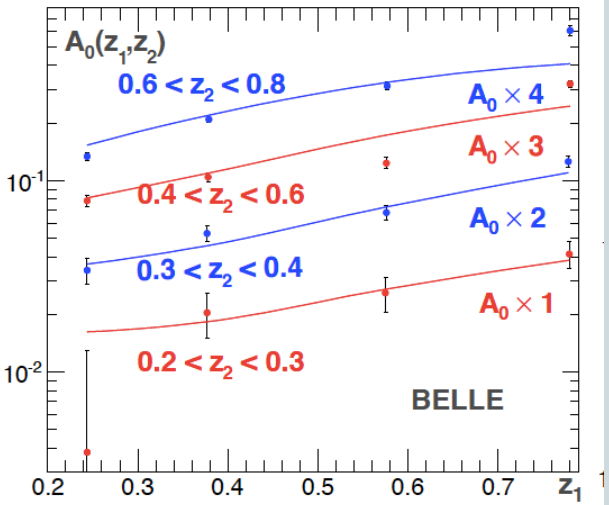


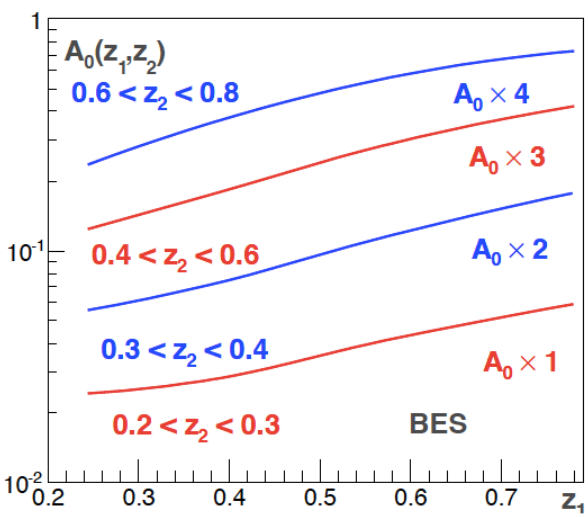


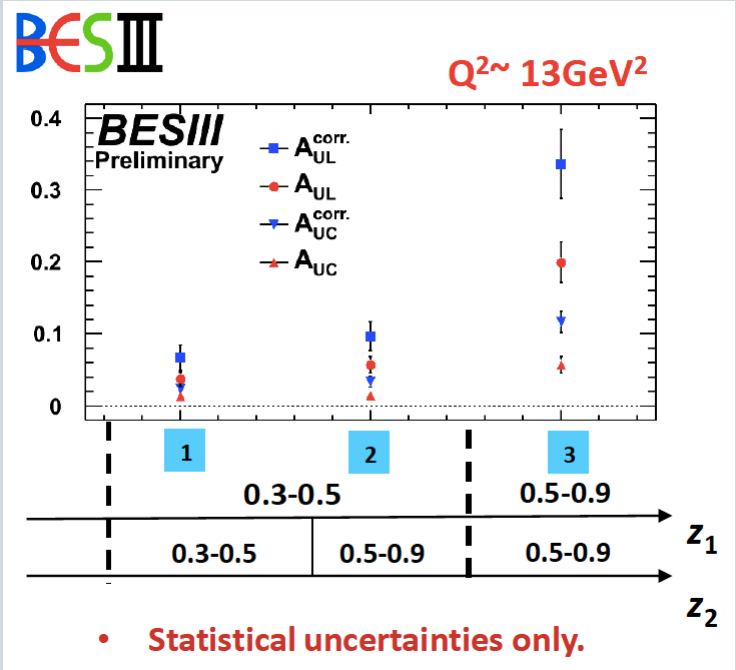




Test of Evolution from FFs



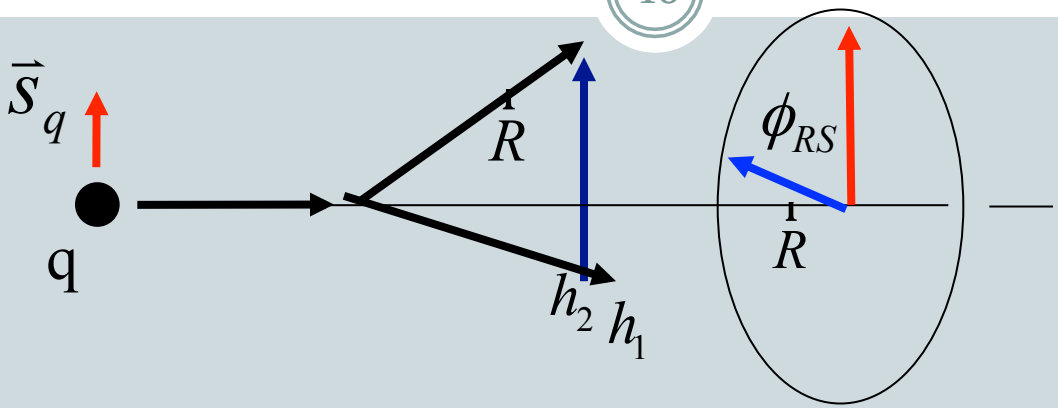


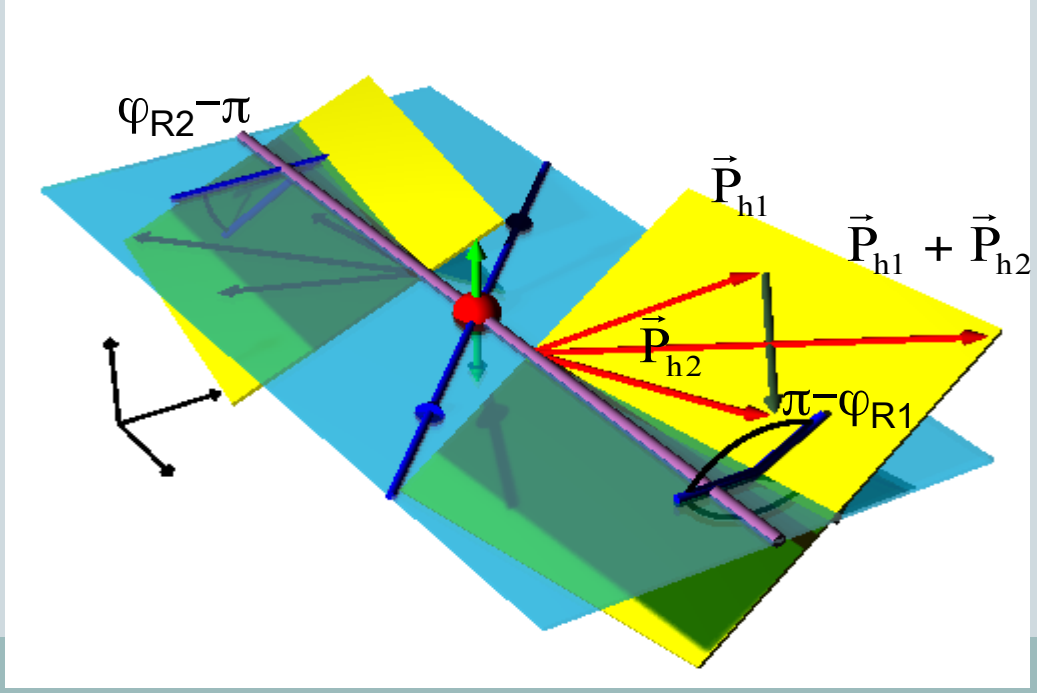


Yinghui Guan At Spin 2014

PRD 88. 034016 (2013)
(approximation to CSS,
predictions based on fits to Belle data**)**

Di-Hadron Fragmentation





Di-Hadron Asymmetries

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

$$\frac{1}{32z}\int dk^+ \Delta(k;P_h,R)\Big|_{k^-=P_h^-/z,\mathbf{k}_T}$$

$$= \frac{1}{4\pi}\frac{1}{4}\Big\{ D_1^a(z,\xi,\boldsymbol{k}_T^2,\boldsymbol{R}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{R}_T)\,\not{n}_- - G_1^{\perp\,a}(z,\xi,\boldsymbol{k}_T^2,\boldsymbol{R}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{R}_T)\,\frac{\epsilon_{\mu\nu\rho\sigma}\,\gamma^\mu\,n_-^\nu\,k_T^\rho\,R_T^\sigma}{M_1M_2}\,\gamma_5$$

$$+ H_1^{\sphericalangle\,a}(z,\xi,\boldsymbol{k}_T^2,\boldsymbol{R}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{R}_T)\,\frac{\sigma_{\mu\nu}\,R_T^\mu\,n_-^\nu}{M_1+M_2} + H_1^{\perp\,a}(z,\xi,\boldsymbol{k}_T^2,\boldsymbol{R}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{R}_T)\,\frac{\sigma_{\mu\nu}\,k_T^\mu\,n_-^\nu}{M_1+M_2}\Big\}\,.$$

$$\langle\cos(2(\phi_R-\phi_{\overline{R}}))\rangle = \sum_{a,\overline{a}} e_a^2\,\frac{3\,\alpha^2}{2Q^2}\,z^2\overline{z}^2\,A(y)\,\frac{1}{M_1M_2\overline{M}_1\overline{M}_2}\,G_1^{\perp a}(z,M_h^2)\,\overline{G}_1^{\perp a}(\overline{z},\overline{M}_h^2)\,.$$

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

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

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

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

Spin independent part

$$\frac{1}{32z}\int dk^+ \Delta(k;P_h,R)\Big|_{k^-=P_h^-/z,\mathbf{k}_T}$$

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

$$= \frac{1}{4\pi}\frac{1}{4}\Big\{ D_1^a(z,\xi,\boldsymbol{k}_T^2,\boldsymbol{R}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{R}_T)\,\not{n}_- - G_1^{\perp\,a}(z,\xi,\boldsymbol{k}_T^2,\boldsymbol{R}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{R}_T)\,\frac{\epsilon_{\mu\nu\rho\sigma}\,\gamma^\mu\,n_-^\nu\,k_T^\rho\,R_T^\sigma}{M_1M_2}\,\gamma_5$$

$$+ H_1^{\sphericalangle\,a}(z,\xi,\boldsymbol{k}_T^2,\boldsymbol{R}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{R}_T)\,\frac{\sigma_{\mu\nu}\,R_T^\mu\,n_-^\nu}{M_1+M_2} + H_1^{\perp\,a}(z,\xi,\boldsymbol{k}_T^2,\boldsymbol{R}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{R}_T)\,\frac{\sigma_{\mu\nu}\,k_T^\mu\,n_-^\nu}{M_1+M_2}\Big\}\,.$$

$$\langle\cos(2(\phi_R-\phi_{\overline{R}}))\rangle = \sum_{a,\overline{a}} e_a^2\,\frac{3\,\alpha^2}{2Q^2}\,z^2\overline{z}^2\,A(y)\,\frac{1}{M_1M_2\overline{M}_1\overline{M}_2}\,G_1^{\perp a}(z,M_h^2)\,\overline{G}_1^{\perp a}(\overline{z},\overline{M}_h^2)\,.$$

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

Cross Section

- Δ: Fragmentation Matrix, encoding possible correlations in fragmentation

Correlation of transverse spin with Di-hadron plane

$$\frac{1}{32z}\int dk^+ \Delta(k;P_h,R)\Big|_{k^-=P_h^-/z,\mathbf{k}_T}$$

$$= \frac{1}{4\pi}\frac{1}{4}\Big\{ D_1^a(z,\xi,\boldsymbol{k}_T^2,\boldsymbol{R}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{R}_T)\,\not{n}_- - G_1^{\perp\,a}(z,\xi,\boldsymbol{k}_T^2,\boldsymbol{R}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{R}_T)\,\frac{\epsilon_{\mu\nu\rho\sigma}\,\gamma^\mu\,n_-^\nu\,k_T^\rho\,R_T^\sigma}{M_1M_2}\,\gamma_5$$

$$+ H_1^{\sphericalangle\,a}(z,\xi,\boldsymbol{k}_T^2,\boldsymbol{R}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{R}_T)\,\frac{\sigma_{\mu\nu}\,R_T^\mu\,n_-^\nu}{M_1+M_2} + H_1^{\perp\,a}(z,\xi,\boldsymbol{k}_T^2,\boldsymbol{R}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{R}_T)\,\frac{\sigma_{\mu\nu}\,k_T^\mu\,n_-^\nu}{M_1+M_2}\Big\}\,.$$

$$\langle\cos(2(\phi_R-\phi_{\overline{R}}))\rangle = \sum_{a,\overline{a}} e_a^2\,\frac{3\,\alpha^2}{2Q^2}\,z^2\overline{z}^2\,A(y)\,\frac{1}{M_1M_2\overline{M}_1\overline{M}_2}\,G_1^{\perp a}(z,M_h^2)\,\overline{G}_1^{\perp a}(\overline{z},\overline{M}_h^2)\,.$$

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

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

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

Helicity dependent correlation of Intrinsic transverse momentum with Di-hadron plane→Test of TMD framework

$$\frac{1}{32z}\int dk^+ \Delta(k;P_h,R)\Big|_{k^-=P_h^-/z,\mathbf{k}_T}$$

$$= \frac{1}{4\pi}\frac{1}{4}\Big\{ D_1^a(z,\xi,\boldsymbol{k}_T^2,\boldsymbol{R}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{R}_T)\,\not{n}_- + G_1^{\perp a}(z,\xi,\boldsymbol{k}_T^2,\boldsymbol{R}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{R}_T)\,\frac{\epsilon_{\mu\nu\rho\sigma}\,\gamma^\mu n_-^\nu\, k_T^\rho R_T^\sigma}{M_1 M_2}\,\gamma_5$$

$$+ H_1^{\sphericalangle a}(z,\xi,\boldsymbol{k}_T^2,\boldsymbol{R}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{R}_T)\,\frac{\sigma_{\mu\nu}\,R_T^\mu n_-^\nu}{M_1+M_2} + H_1^{\perp a}(z,\xi,\boldsymbol{k}_T^2,\boldsymbol{R}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{R}_T)\,\frac{\sigma_{\mu\nu}\,k_T^\mu n_-^\nu}{M_1+M_2}\Big\}\,.$$

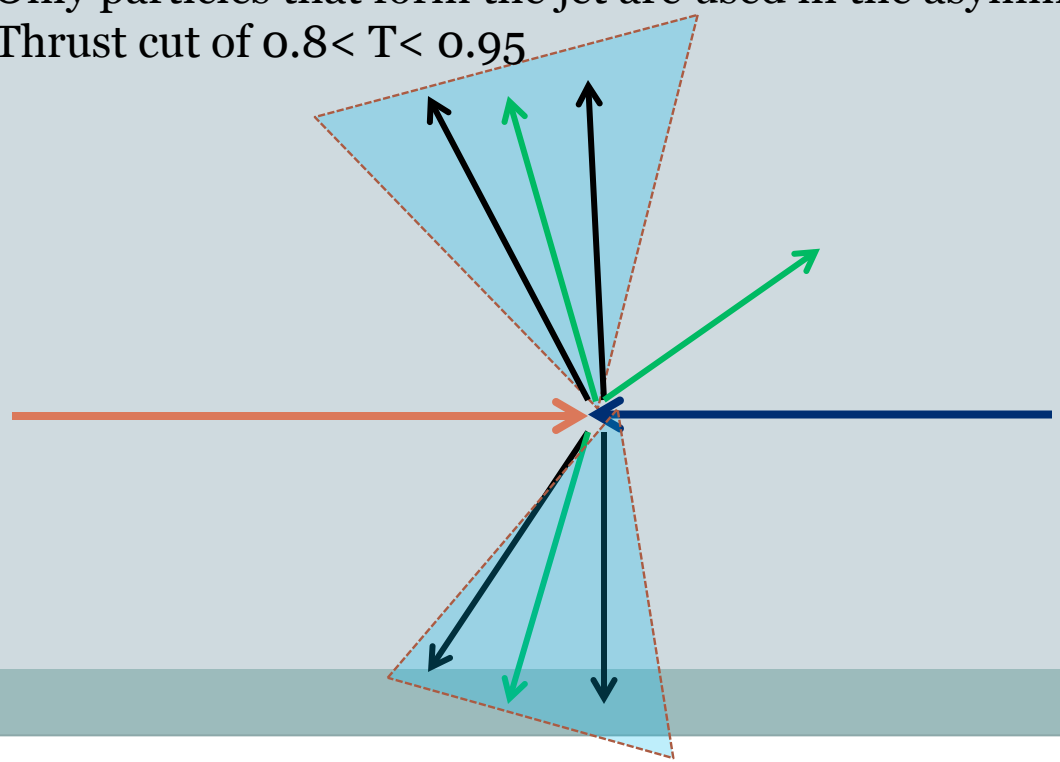
$$\langle\cos(2(\phi_R-\phi_{\overline{R}}))\rangle = \sum_{a,\overline{a}} e_a^2\,\frac{3\,\alpha^2}{2Q^2}\,z^2\overline{z}^2\,A(y)\,\frac{1}{M_1M_2\overline{M}_1\overline{M}_2}\,G_1^{\perp a}(z,M_h^2)\,\overline{G}_1^{\perp a}(\overline{z},\overline{M}_h^2)\,.$$

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

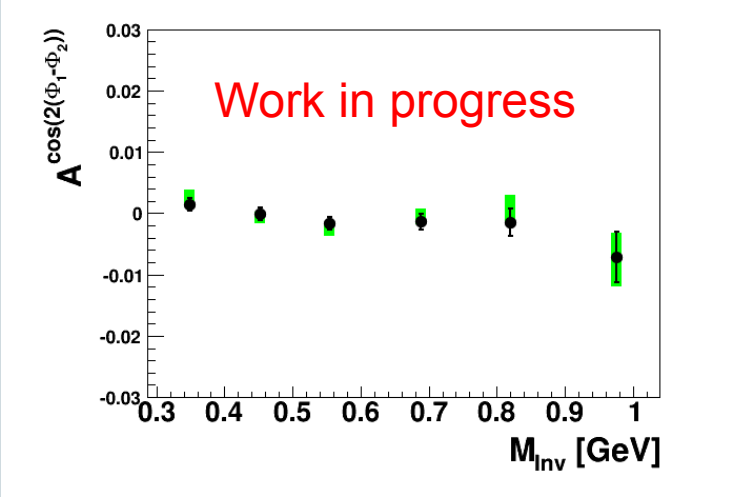
Measure $\cos(\phi_{R1}+\phi_{R2})$, $\cos(2(\phi_{R1}-\phi_{R2}))$ Modulations and additional $\cos(\phi_{R1}-\phi_{R2})$ (handedness, non pQCD related)

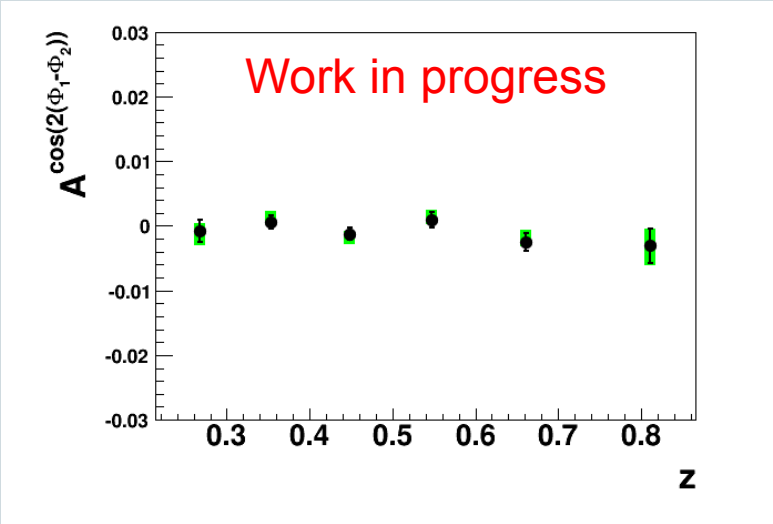
New: Use Jet Reconstruction at Belle

- Robust vs. final state radiation
- **De-correlate axis between hemispheres**
- We use anti-kT 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



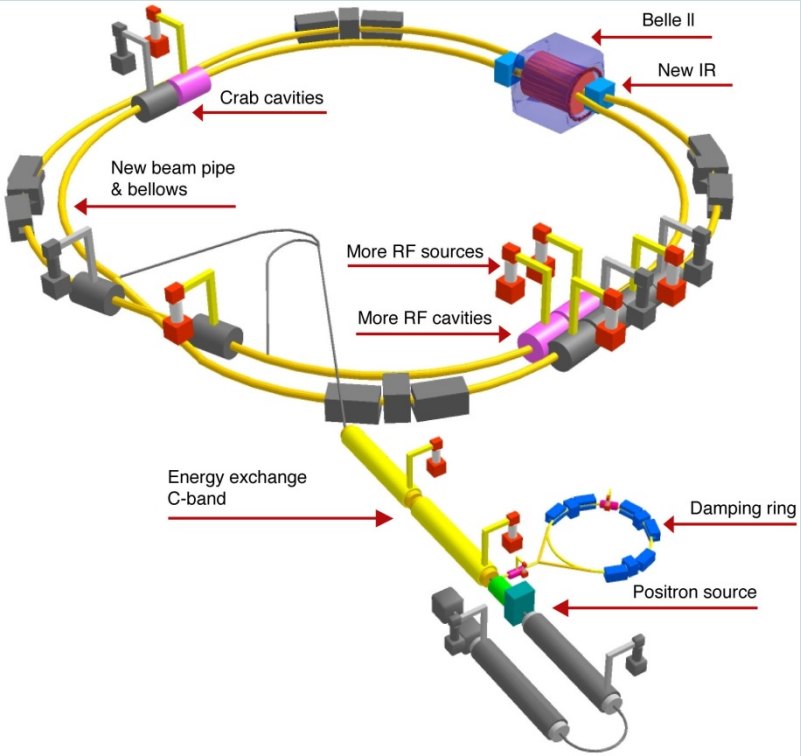
Asymmetries for Cos(2(ϕ_{R1}-ϕ_{R2})) ($G_1^{\perp}$) small

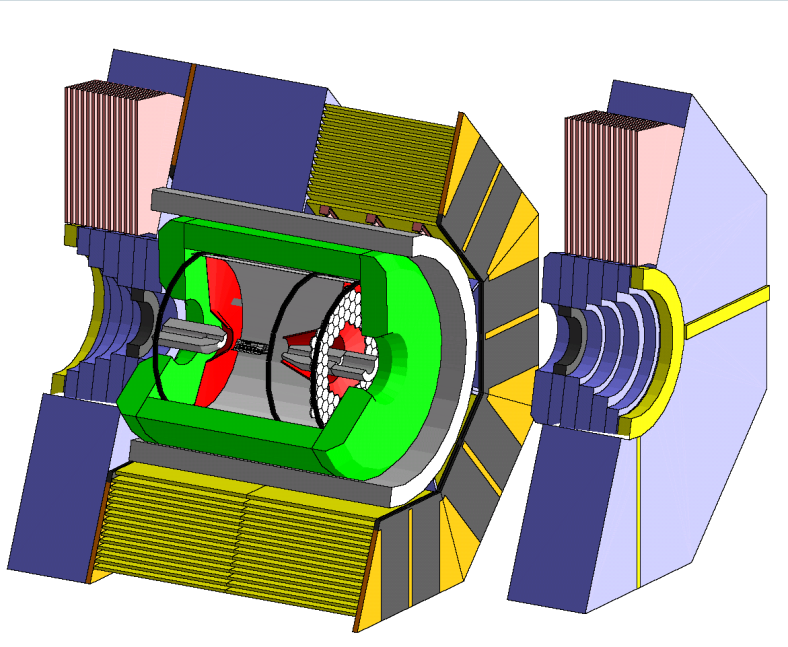




KEKB/Belle→SuperKEKB, Upgrade

- 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/European contribution (e.g. LNF Frascati)

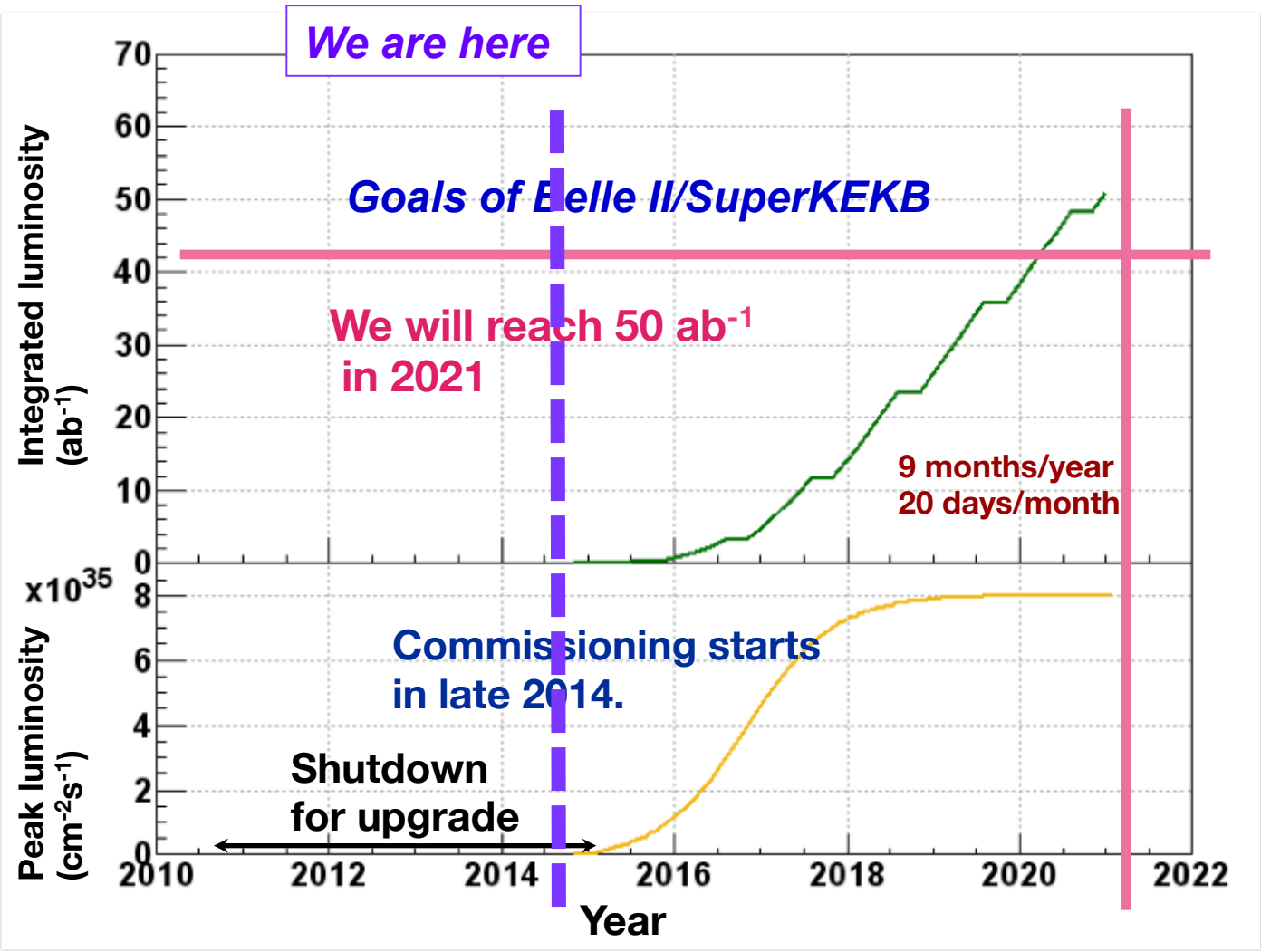




http://belle2.kek.jp

First data in 2016

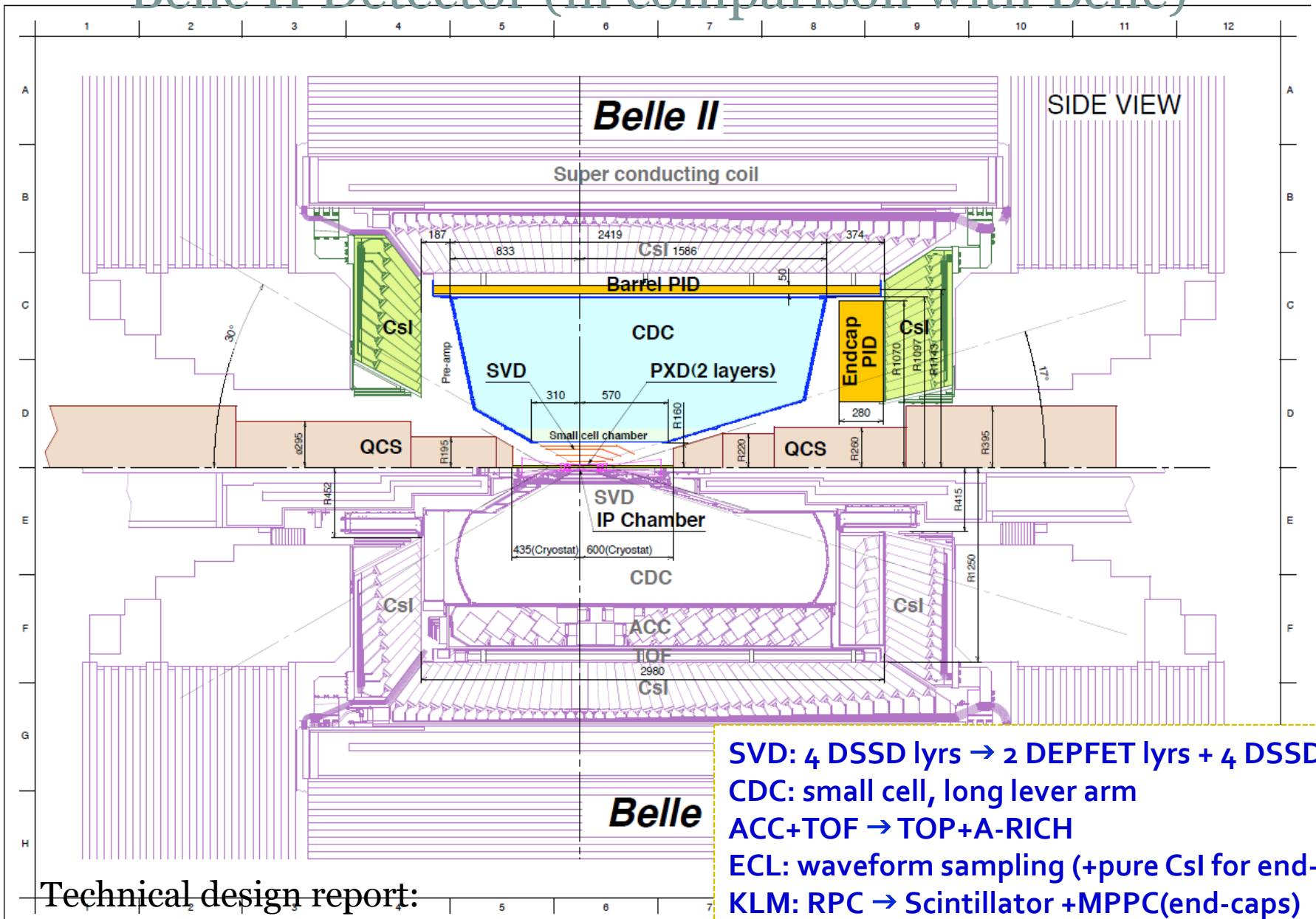
SuperKEKB luminosity profile
50 ab^{-1} over ~7 years



N.B. Schedule not up to date

Y. Ohnishi

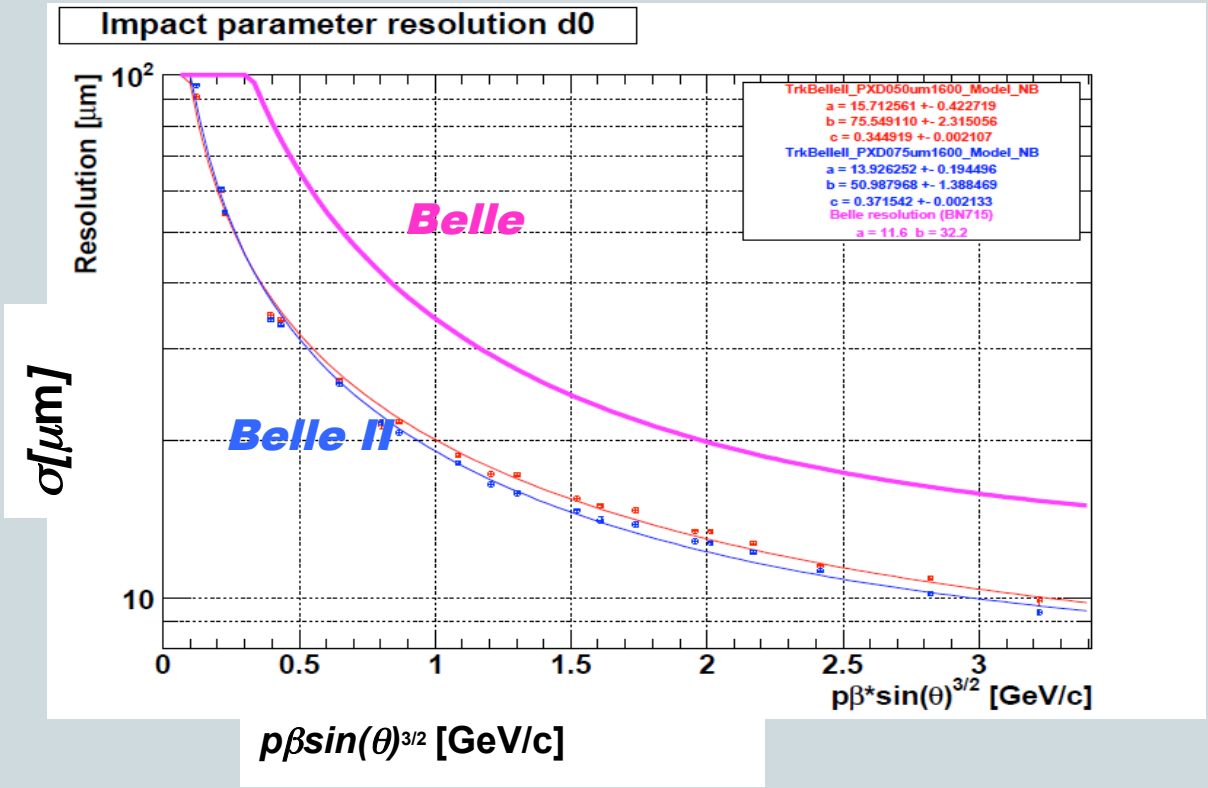
Belle II Detector (in comparison with Belle)



SVD: 4 DSSD lyrs → 2 DEPFET lyrs + 4 DSSD lyrs
CDC: small cell, long lever arm
ACC+TOF → TOP+A-RICH
ECL: waveform sampling (+pure CsI for end-caps)
KLM: RPC → Scintillator +MPPC(end-caps)

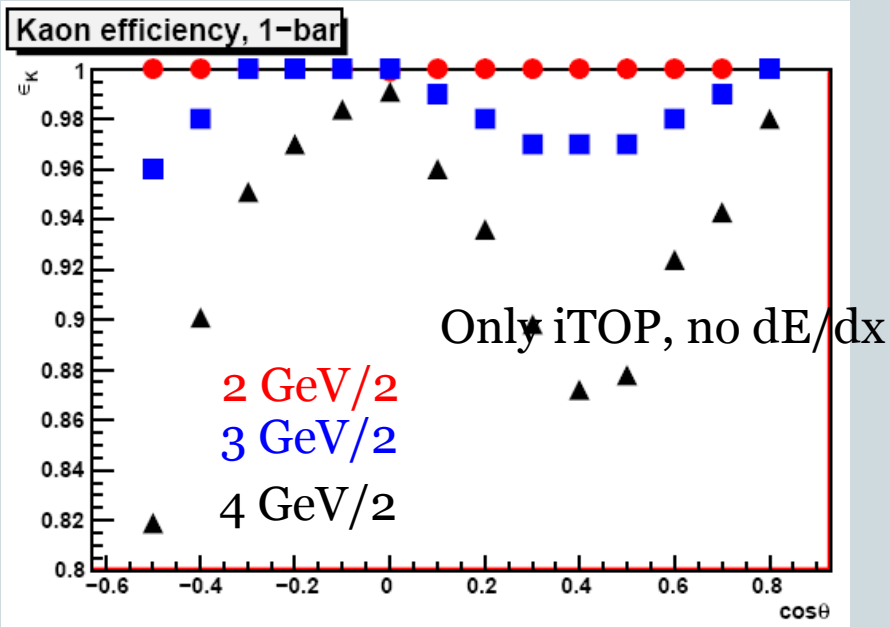
Technical design report: arXiv:1011.0352

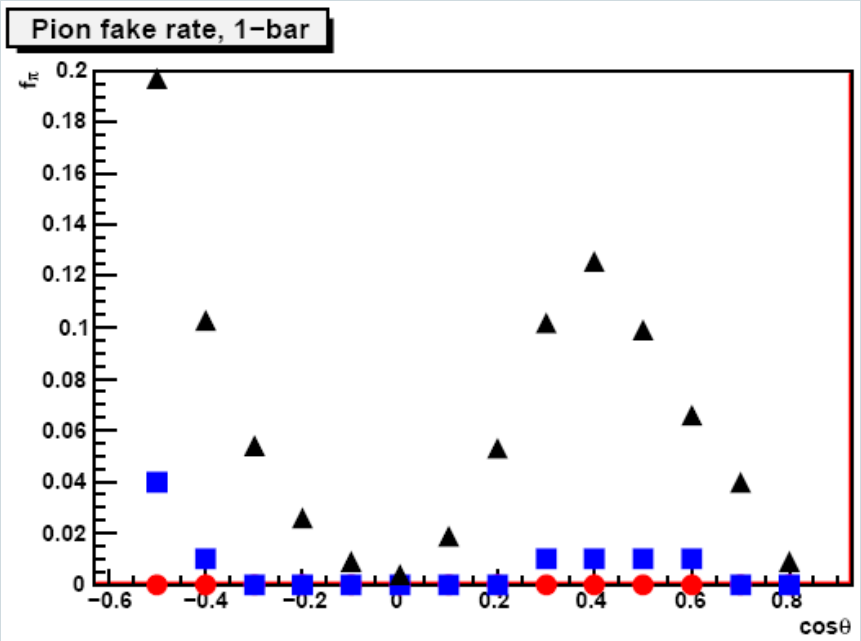
Improve Charm Discrimination with SVD&PXD



PID improvement with iTOP

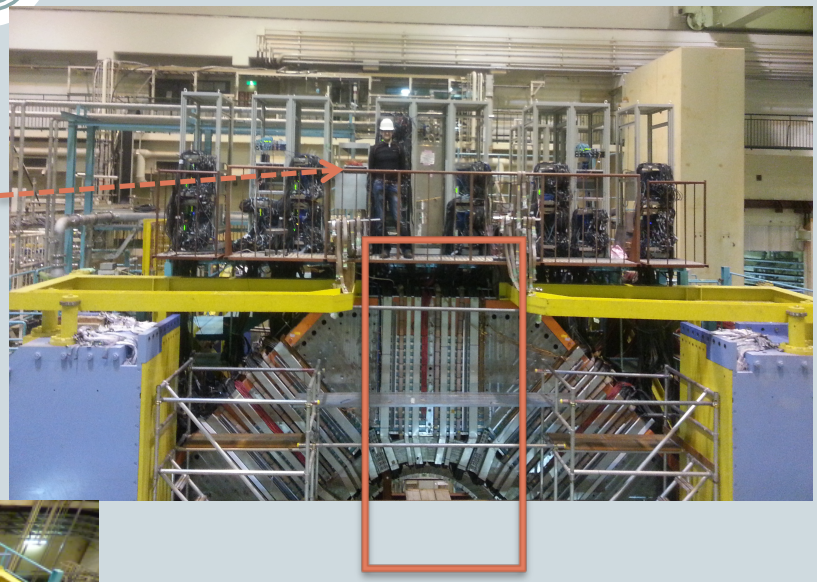
- Compare with ~85% efficiency for Belle

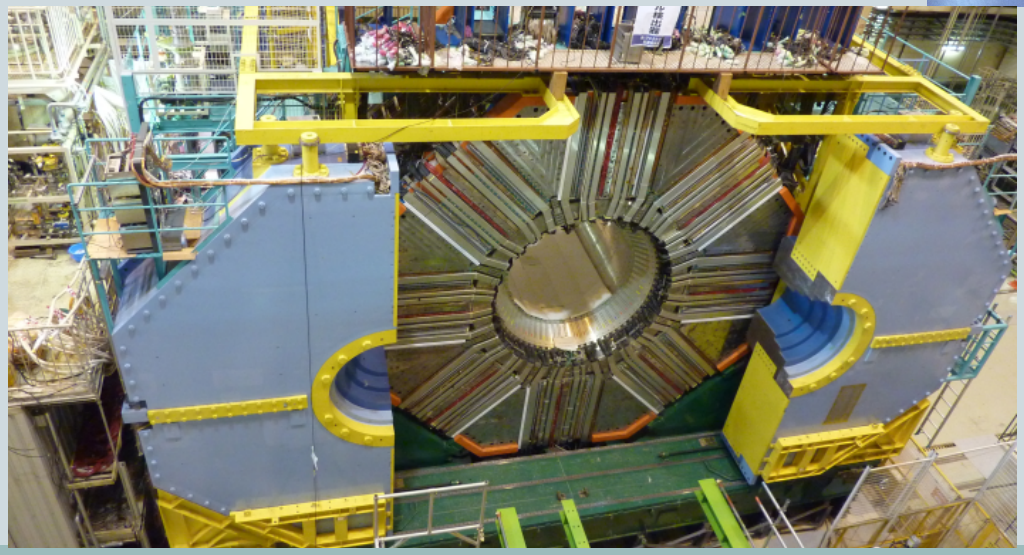




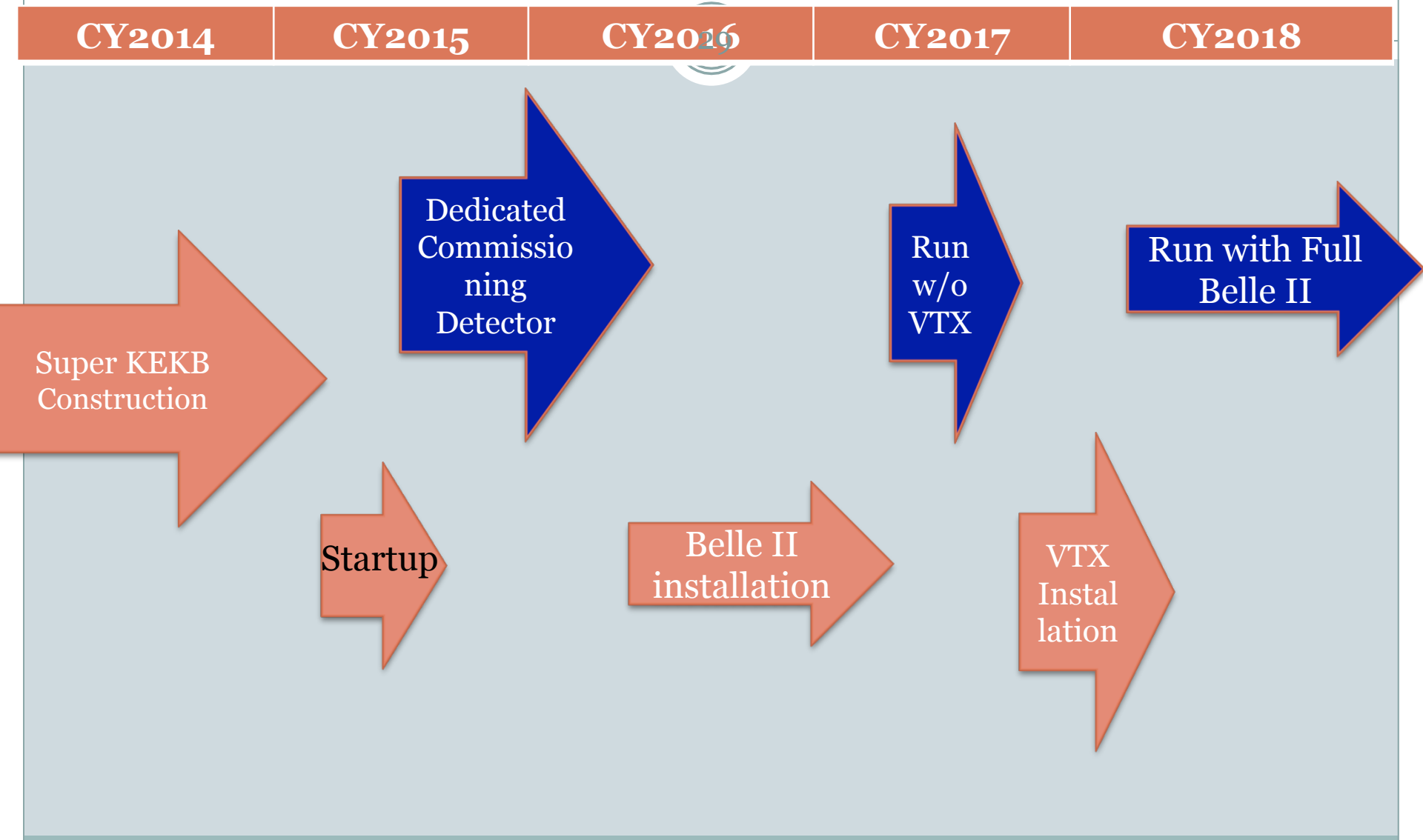
Last week at KEK….

Sector Test of KLM
(B Kunkler from IU)



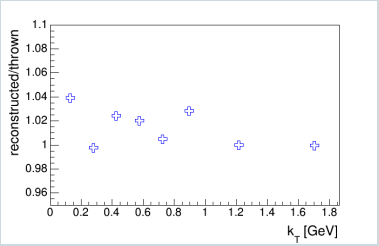


One Possible SuperKEKB/Belle II Schedule



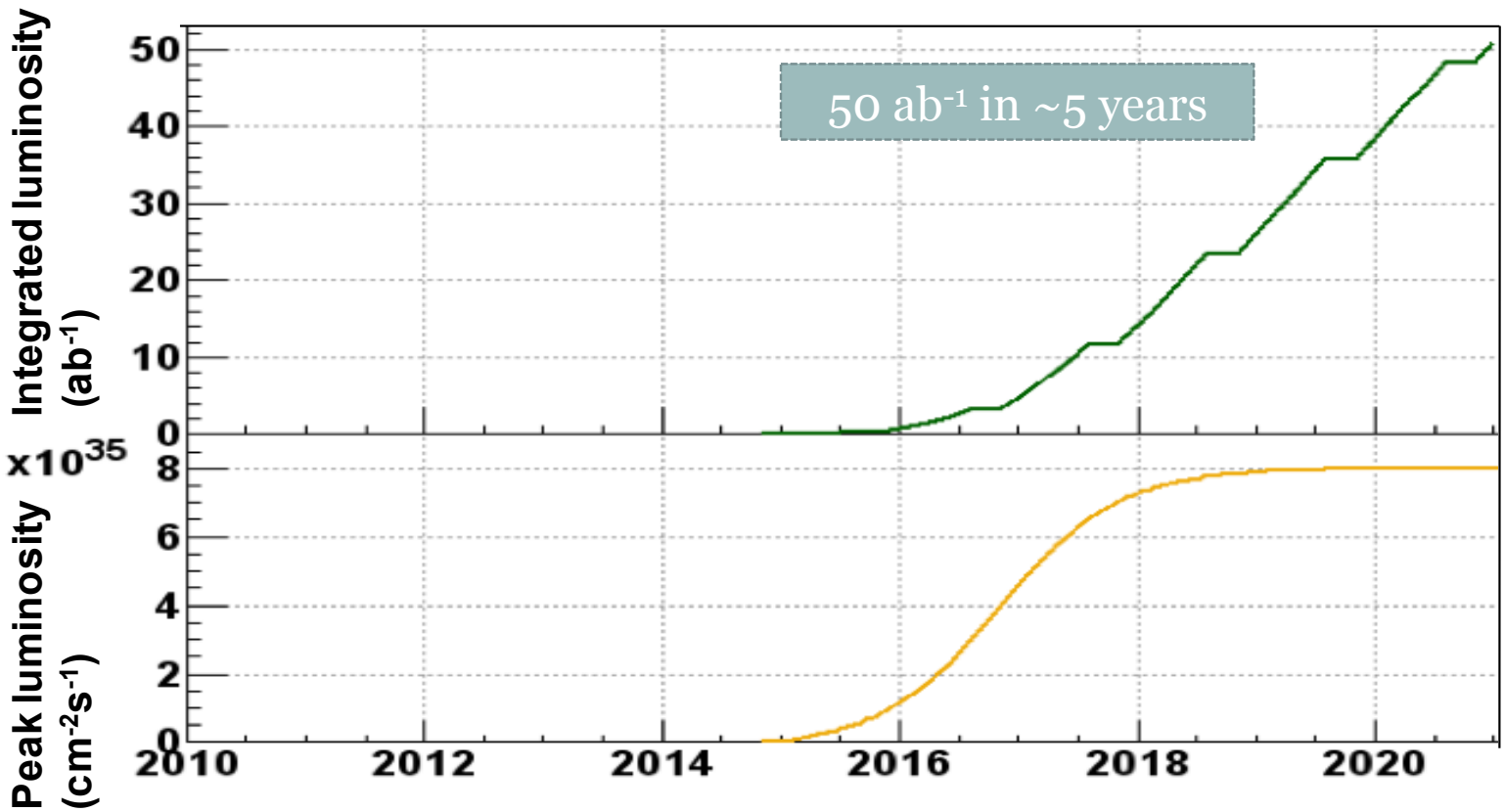
Outlook

- Analysis Underway
  - Di-Hadron Asymmetries (+Rho FF)
  - Neutral Meson Collins Fragmentation Function
    - Use Combinations $\frac{\pi^+\pi^0+\pi^0\pi^-}{\pi^+\pi^++\pi^-\pi^-}$ and $\frac{\pi^+\eta+\eta\pi^-}{\pi^+\pi^++\pi^-\pi^-}$
  - Di-Hadron Pair Cross Section
  - Pt dependence of charged hadron Multiplicities
    - Aim for first measurement with systematic effct O(10%)
    - ISR/FSR & charm tagging seems to be under control



- Belle II
  - Lots of statistics, state of the art detector

Backup


50 ab-1 in ~5 years
Integrated luminosity (ab-1)
50
40
30
20
10
0
x10^35
Peak luminosity (cm-2s-1)
8
6
4
2
0
2010
2012
2014
2016
2018
2020

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

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

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

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

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

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

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

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

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

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

Assuming charm contribute only as a dilution

For pion-pion couples:

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

For pion-Kaon couples:

$$D^{\frac{U_{\pi K}}{L_{\pi K}}} \propto 1 + \cos 2\phi_0 \frac{\sin^2\theta}{1+cos^2\theta} \times$$

$$\left(\frac{4H_1^{fav}H_{2\,K}^{fav}+H_{1K}^{dis}(5H_2^{dis}+H_2^{fav})+H_{2K}^{dis}(5H_1^{dis}+H_1^{fav})+4H_{1K}^{fav}H_2^{fav}+H_{1s\to\pi}^{dis}(H_{2s\to K}^{dis}+H_{2s\to K}^{fav})+H_{2s\to\pi}^{dis}(H_{1s\to K}^{fav}+H_{1s\to K}^{dis})}{4D_1^{fav}D_{2\,K}^{fav}+D_{1K}^{dis}(5D_2^{dis}+D_2^{fav})+D_{2K}^{dis}(5D_1^{dis}+D_1^{fav})+4D_{1K}^{fav}D_2^{fav}+D_{1s\to\pi}^{dis}(D_{2s\to K}^{dis}+D_{2s\to K}^{fav})+D_{2s\to\pi}^{dis}(D_{1s\to K}^{fav}+D_{1s\to K}^{dis})}\right.$$

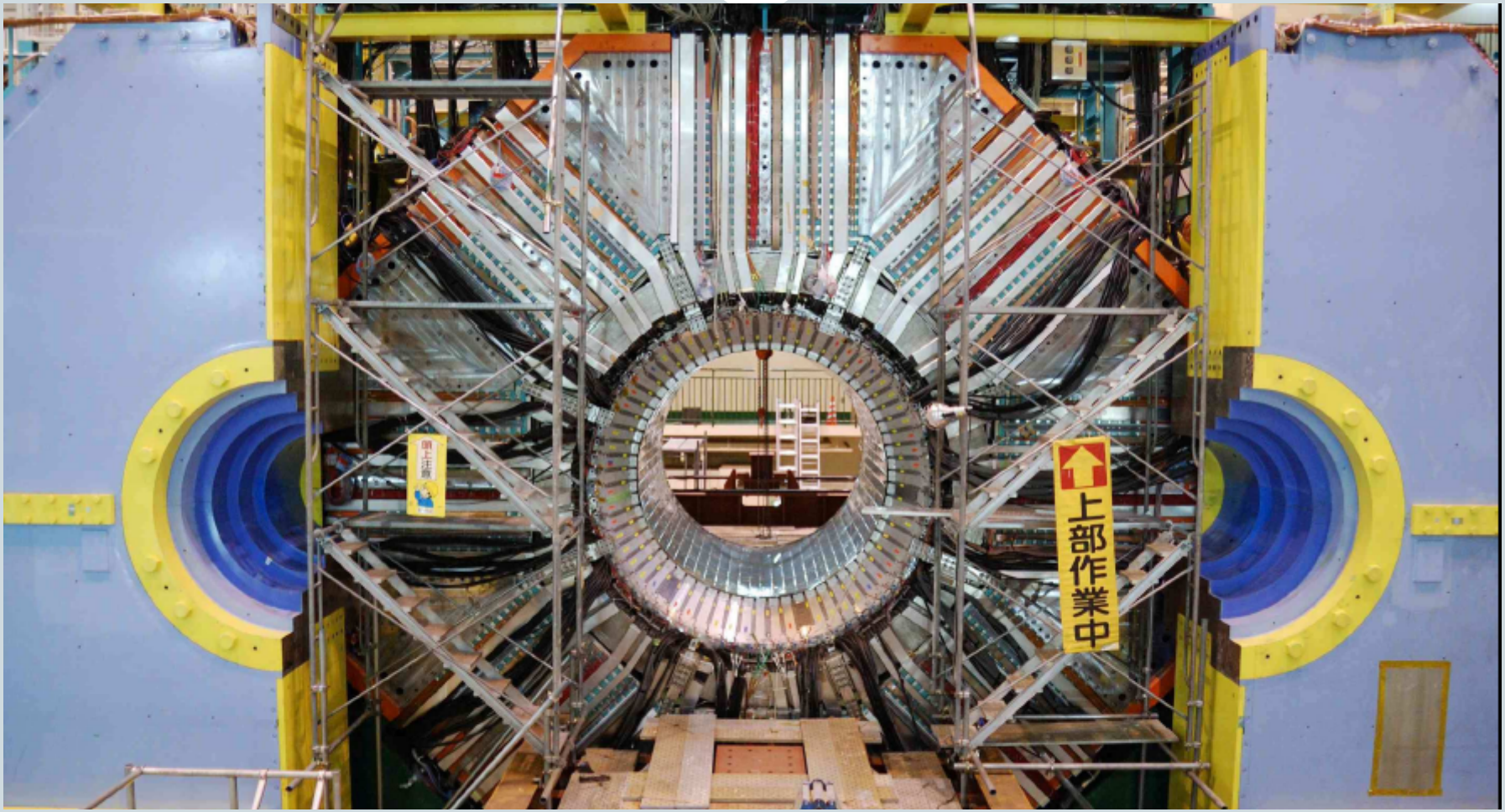
$$\left.\frac{H_{2\,K}^{dis}(5H_1^{fav}+H_1^{dis})+4H_{1\,K}^{fav}H_2^{dis}+4H_1^{dis}H_{2K}^{fav}+H_{1K}^{dis}(5H_2^{fav}+H_2^{dis})+H_{1s\to\pi}^{dis}(H_{2s\to K}^{fav}+H_{2s\to K}^{dis})+(H_{1s\to K}^{dis}+H_{1s\to K}^{fav})H_{2s\to\pi}^{dis}}{D_{2\,K}^{dis}(5D_1^{fav}+D_1^{dis})+4D_{1\,K}^{fav}D_2^{dis}+4D_1^{dis}D_{2K}^{fav}+D_{1K}^{dis}(5D_2^{fav}+D_2^{dis})+D_{1s\to\pi}^{dis}(D_{2s\to K}^{fav}+D_{2s\to K}^{dis})+(D_{1s\to K}^{dis}+D_{1s\to K}^{fav})D_{2s\to\pi}^{dis}}\right)$$

For Kaon-Kaon couples:

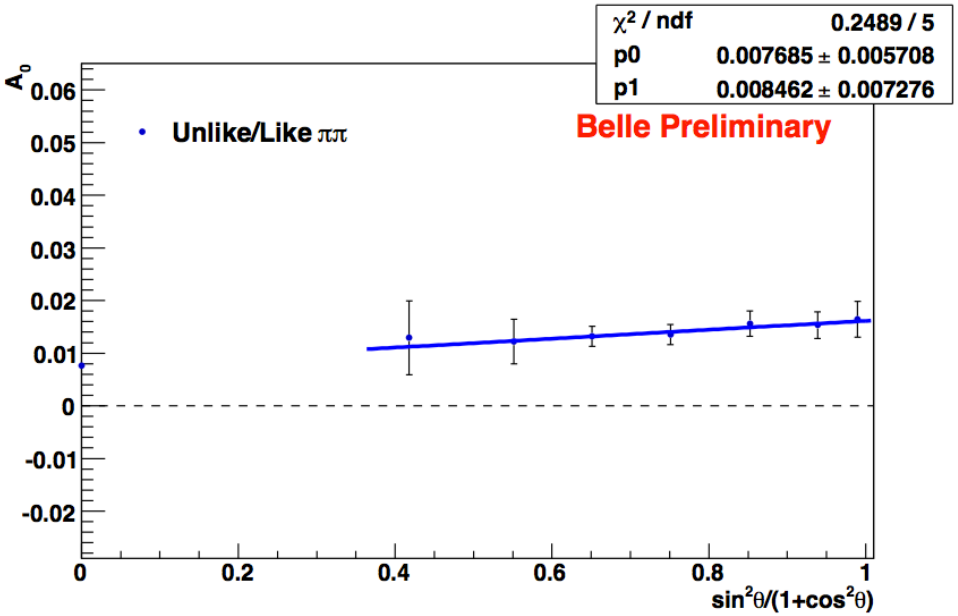
$$D^{\frac{U_{KK}}{L_{KK}}} \propto 1 \quad + \cos 2\phi_0 \frac{\sin^2\theta}{1+cos^2\theta}\left(\frac{4H_{1K}^{fav}H_{2\,K}^{fav}+6H_{1\,K}^{dis}H_{2K}^{dis}+H_{1s\to K}^{dis}H_{2s\to K}^{dis}+H_{1s\to K}^{fav}H_{2s\to K}^{fav}}{4D_{1K}^{fav}D_{2\,K}^{fav}+6D_{1\,K}^{dis}D_{2K}^{dis}+D_{1s\to K}^{dis}D_{2s\to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

Not so easy! A full phenomenological study needed!

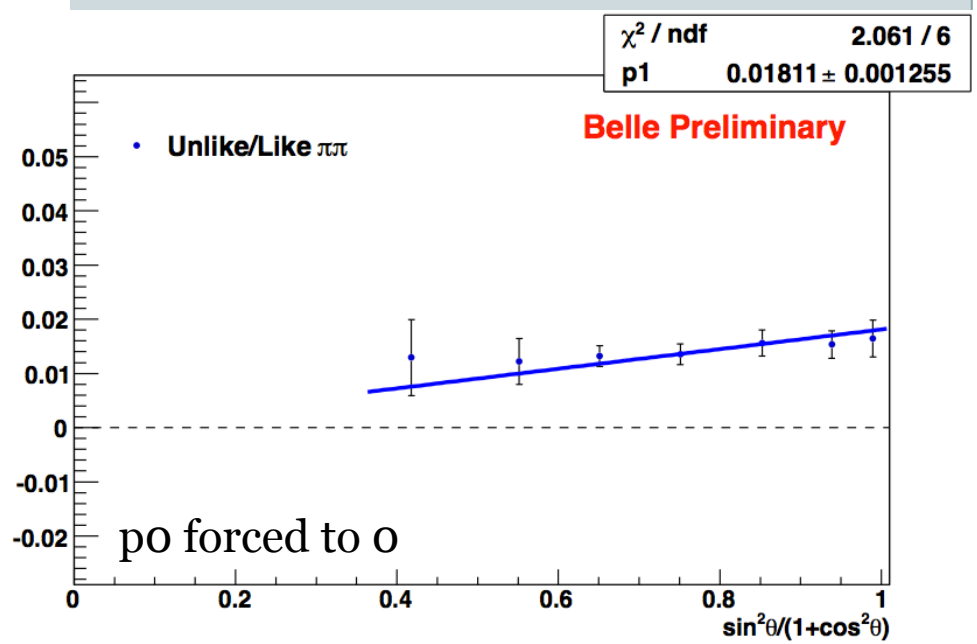
Belle detector today – ready for upgrade

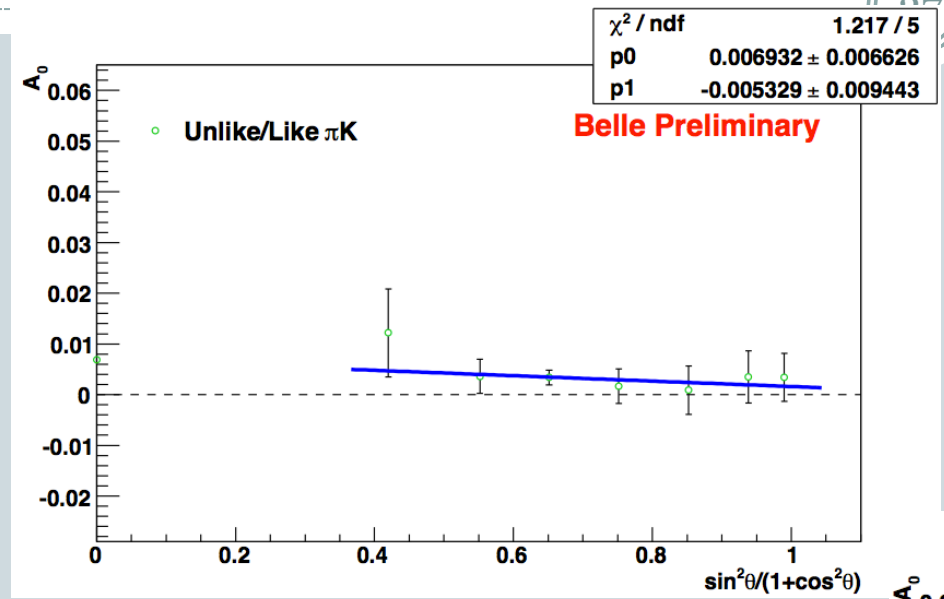


versus $\sin^2\theta/(1+\cos^2\theta)$



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

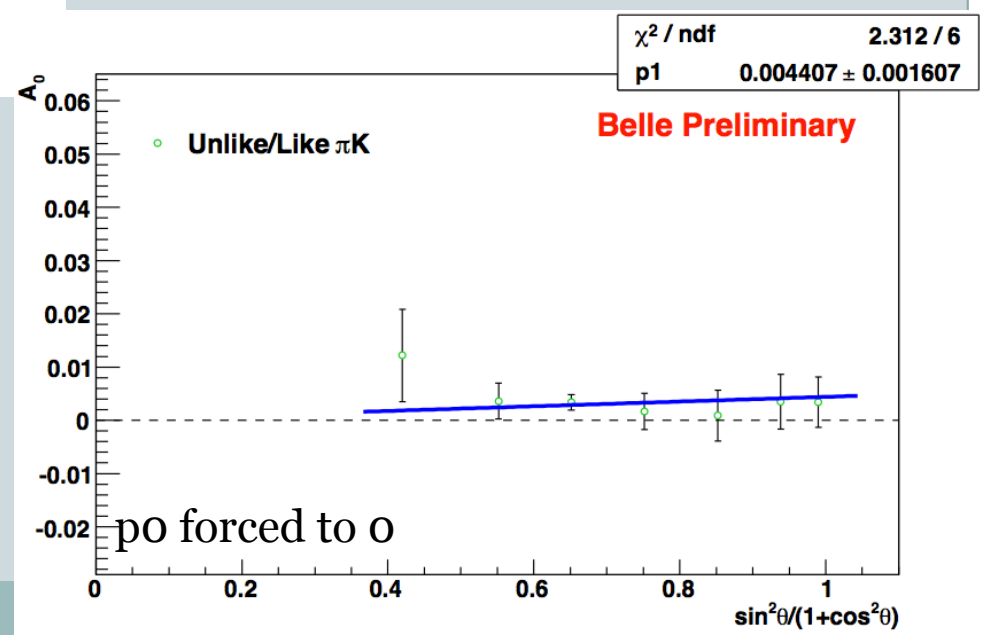


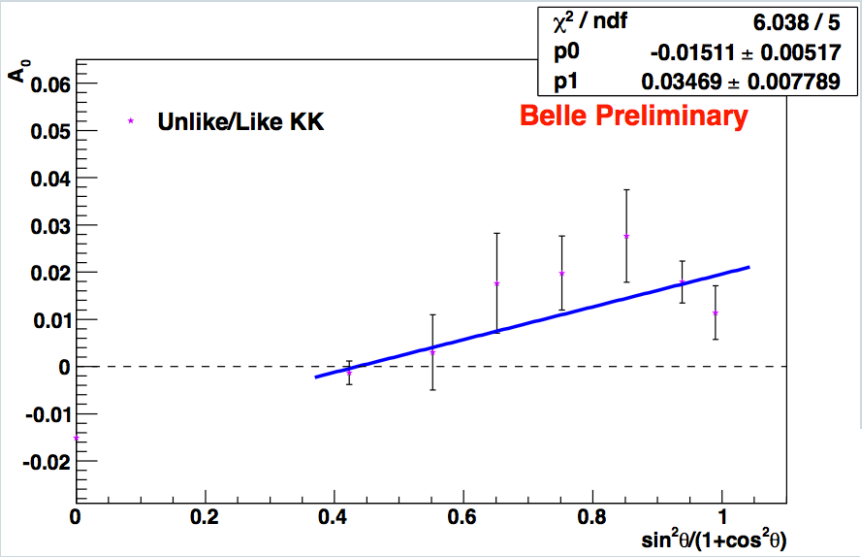


$$A_0 = \frac{\sin^2\theta}{1+\cos^2\theta}\,\mathcal{F}\left[\frac{H_1^\perp(z_1)\bar{H}_1^\perp(z_2)}{D_1^\perp(z_1)\bar{D}_1^\perp(z_2)}\right]$$

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

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

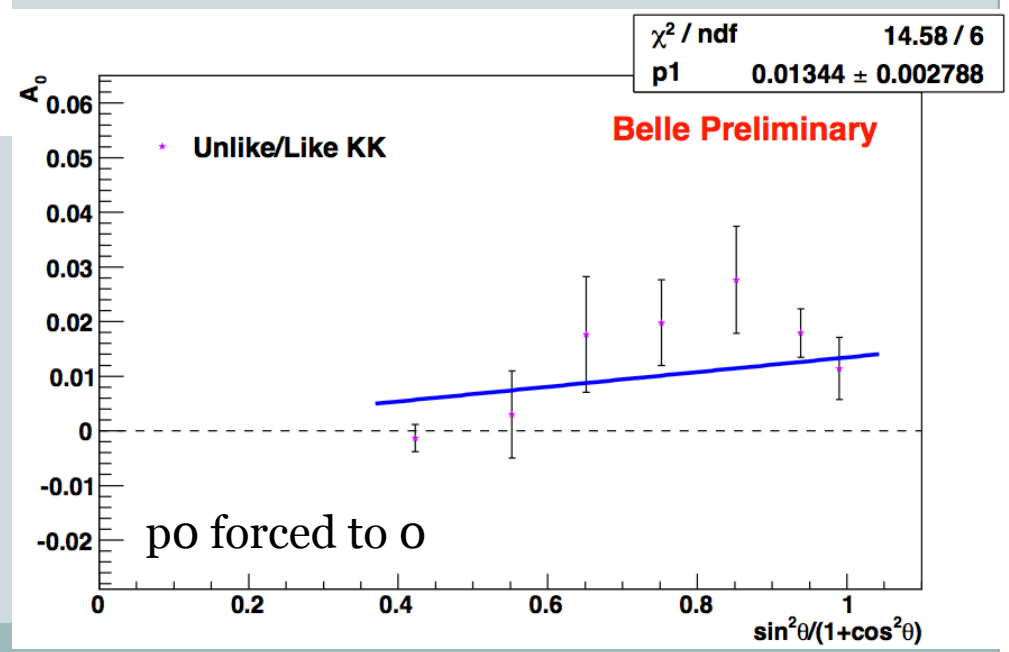




$$A_0 = \frac{\sin^2\theta}{1+\cos^2\theta}\,\mathcal{F}\left[\frac{H_1^\perp(z_1)\bar{H}_1^\perp(z_2)}{D_1^\perp(z_1)\bar{D}_1^\perp(z_2)}\right]$$

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

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



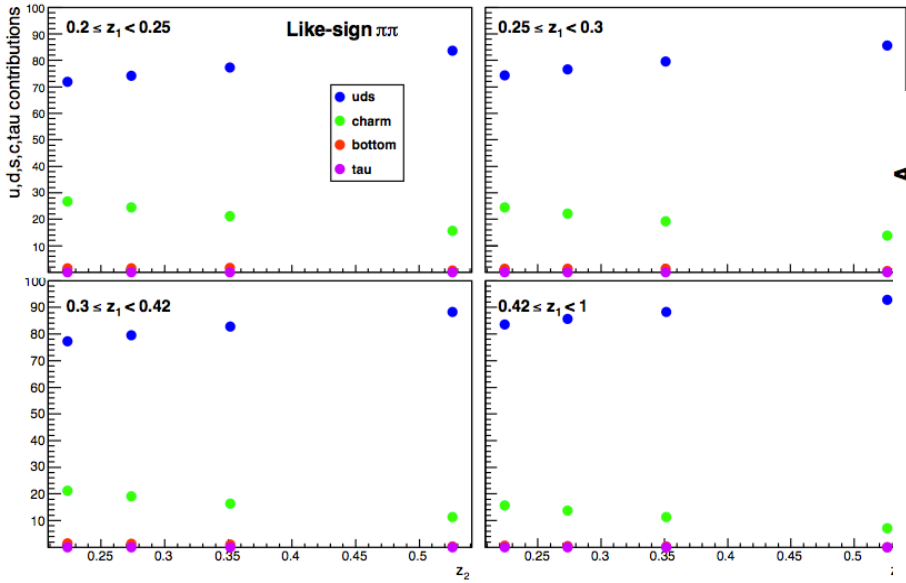
$$F^{[n]}(z_i) \equiv \int d|k_T|^2 \left[\frac{|k_T|}{M_i}\right]^{[n]} F(z_i, |k_T|^2)$$

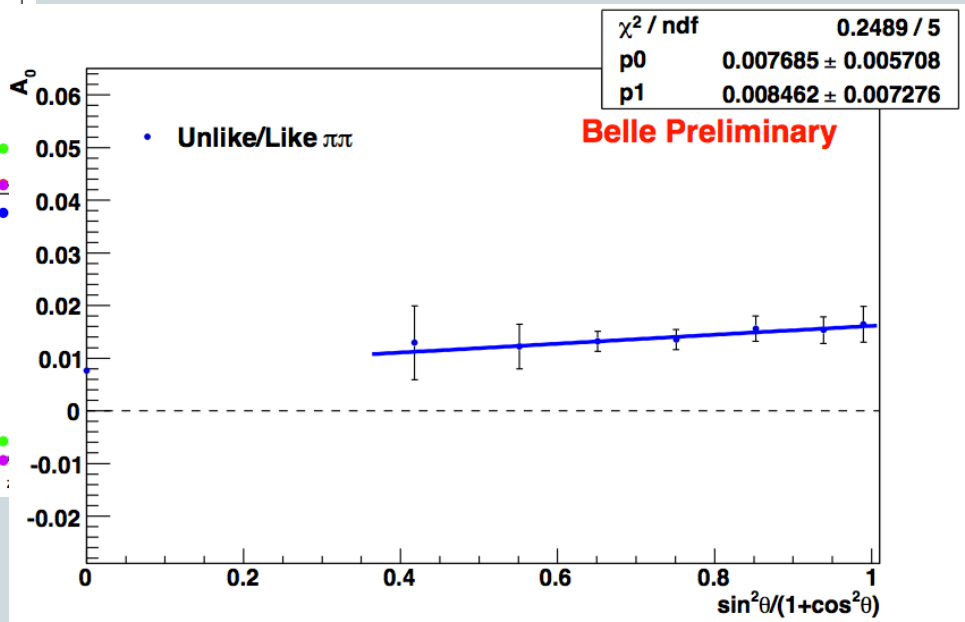
$$\mathcal{F}[X] = \sum_{q\bar{q}} \int [2\hat{\mathbf{h}} \cdot \mathbf{k_{T1}} \hat{\mathbf{h}} \cdot \mathbf{k_{T2}} - \mathbf{k_{T1}} \cdot \mathbf{k_{T2}}]$$

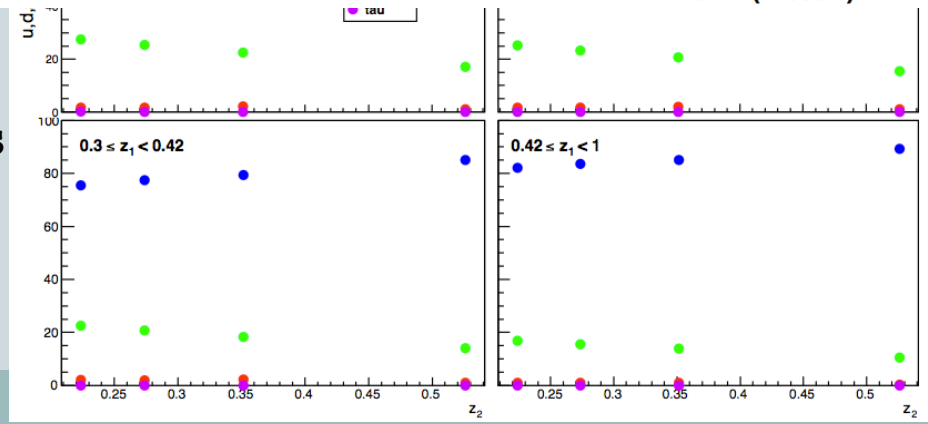
$$d^2\mathbf{k_{T1}} d^2\mathbf{k_{T2}}\, \delta^2(\mathbf{k_{T1}} + \mathbf{k_{T2}} - \mathbf{q_T}) X$$

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

uds-charm-bottom-tau contributions







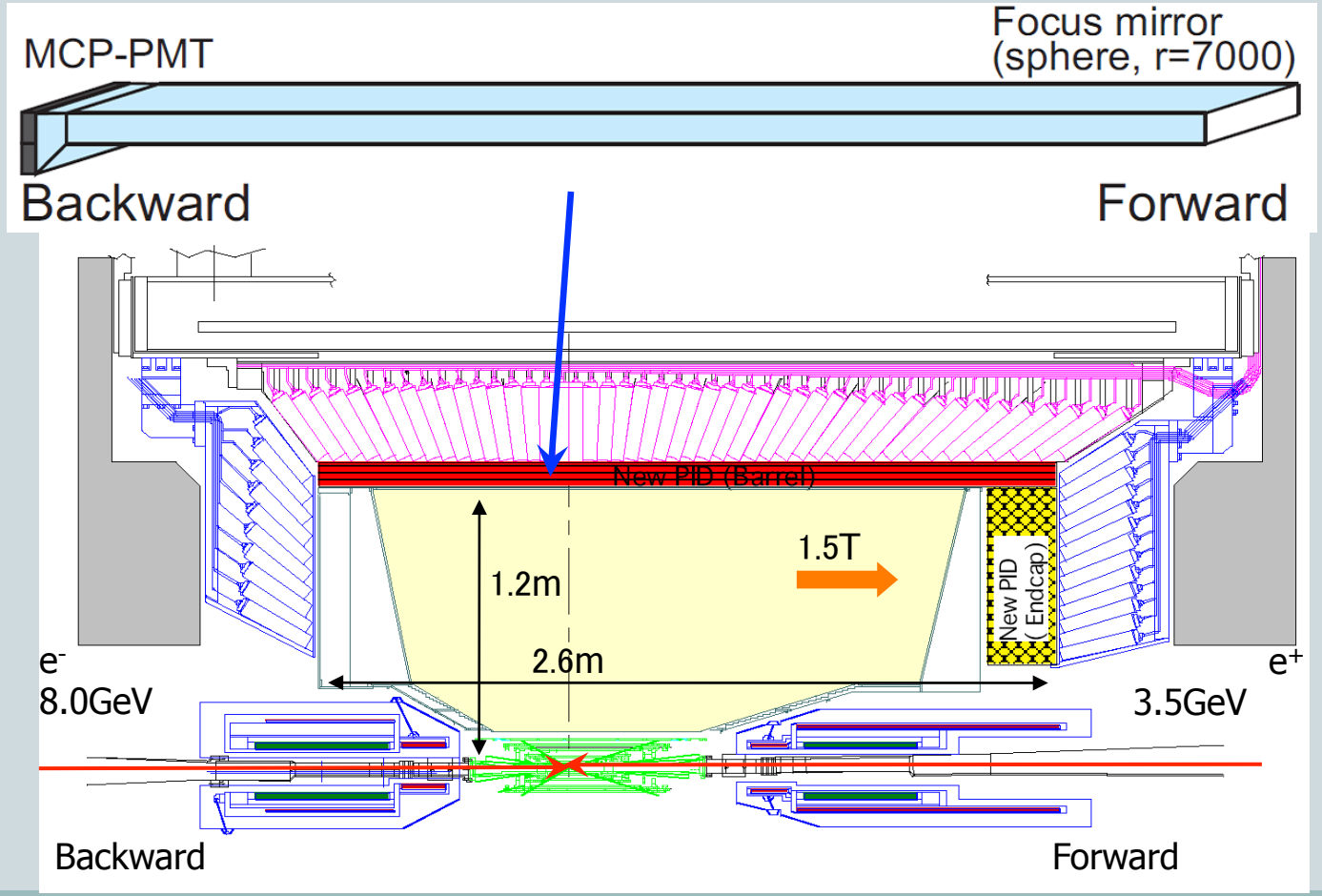
Published $\pi\pi$ studied a charm enhanced data and found charm contribute only as dilution

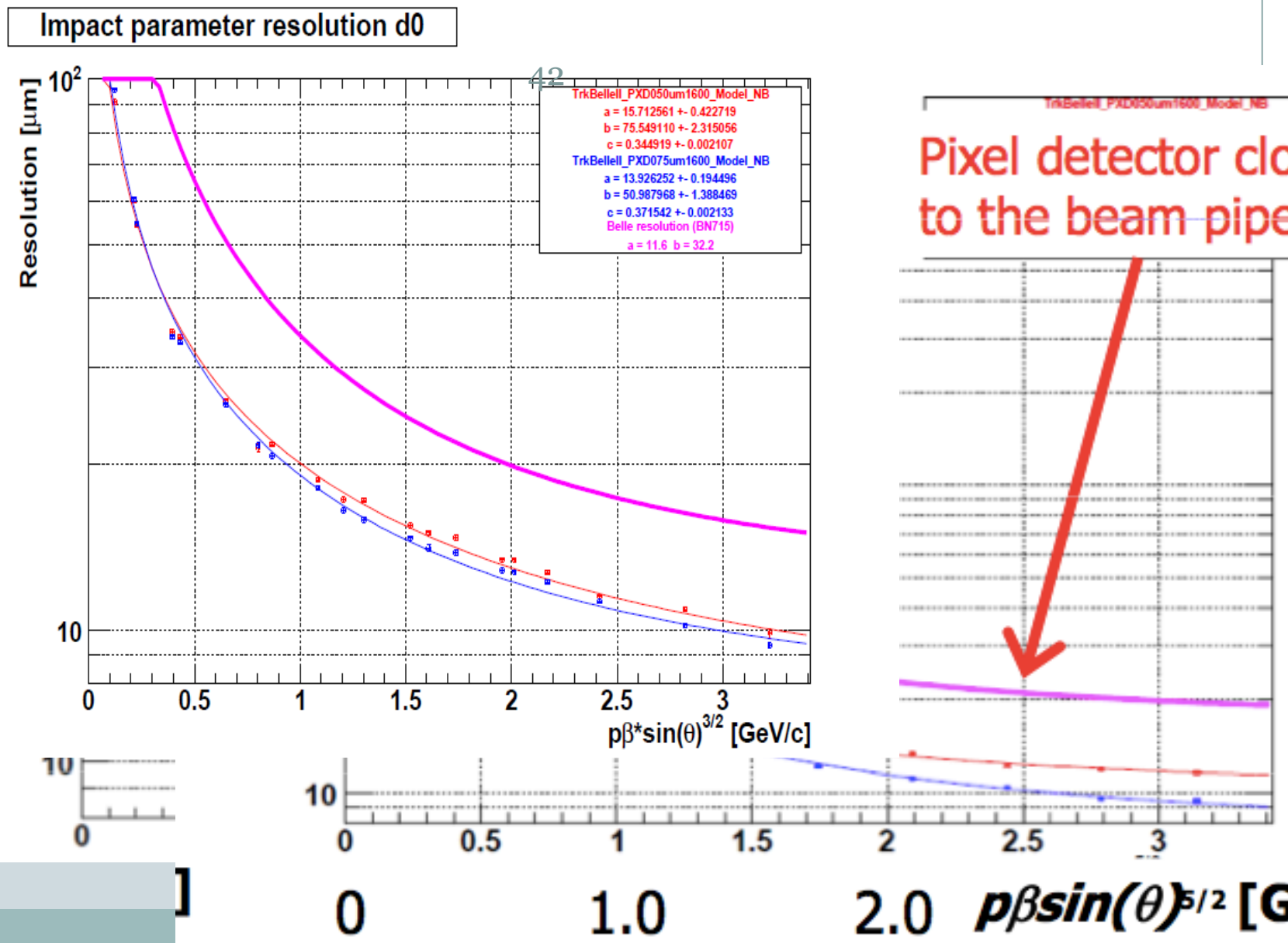
=> charm contribution corrected out

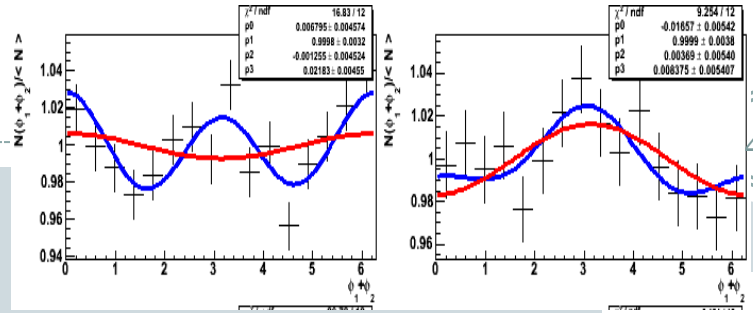
iTOP: an imaging time-of-propagation detector

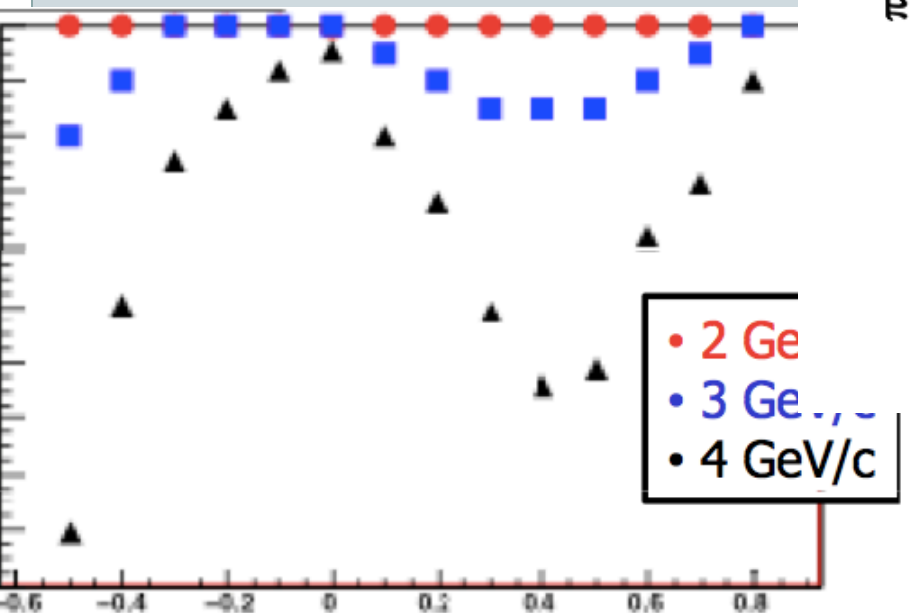
Space constrained by existing calorimeters

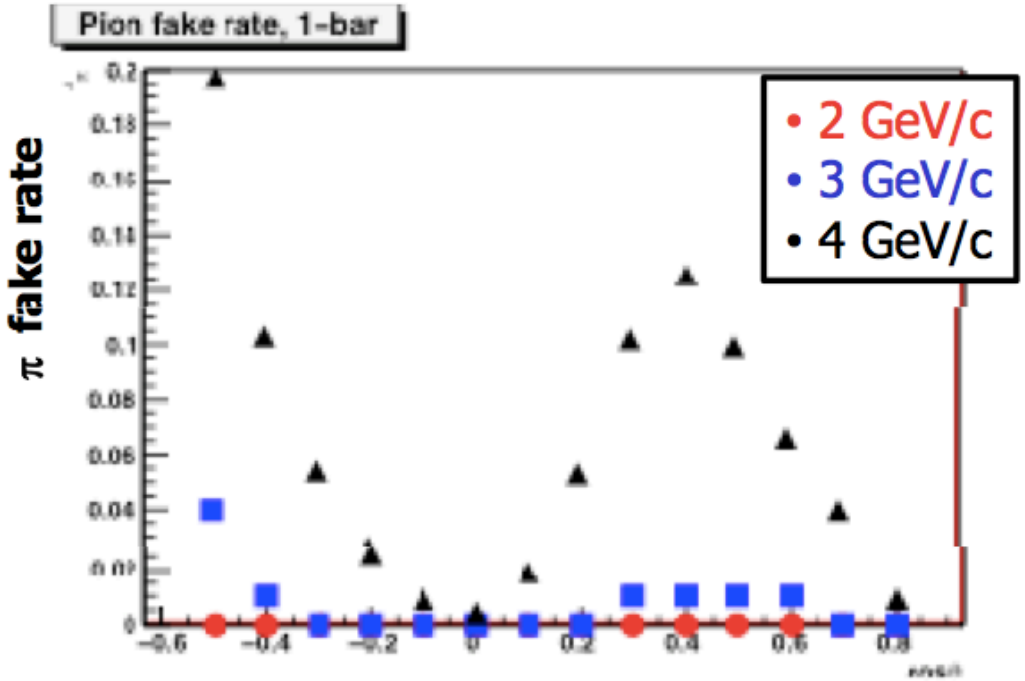
Quartz radiator + mirror + expansion block + MCP-PMT




Impact parameter resolution d0
Resolution [μm]
TrkBelleII_PXD050um1600_Model_NB
a = 15.712561 +- 0.422719
b = 75.549110 +- 2.315056
c = 0.344919 +- 0.002107
TrkBelleII_PXD075um1600_Model_NB
a = 13.926252 +- 0.194496
b = 50.987968 +- 1.388469
c = 0.371542 +- 0.002133
Belle resolution (BN715)
a = 11.6 b = 32.2
pβ*sin(θ)^3/2 [GeV/c]
Pixel detector clo
to the beam pipe
σ[μm]
pβsin(θ)^5/2 [G

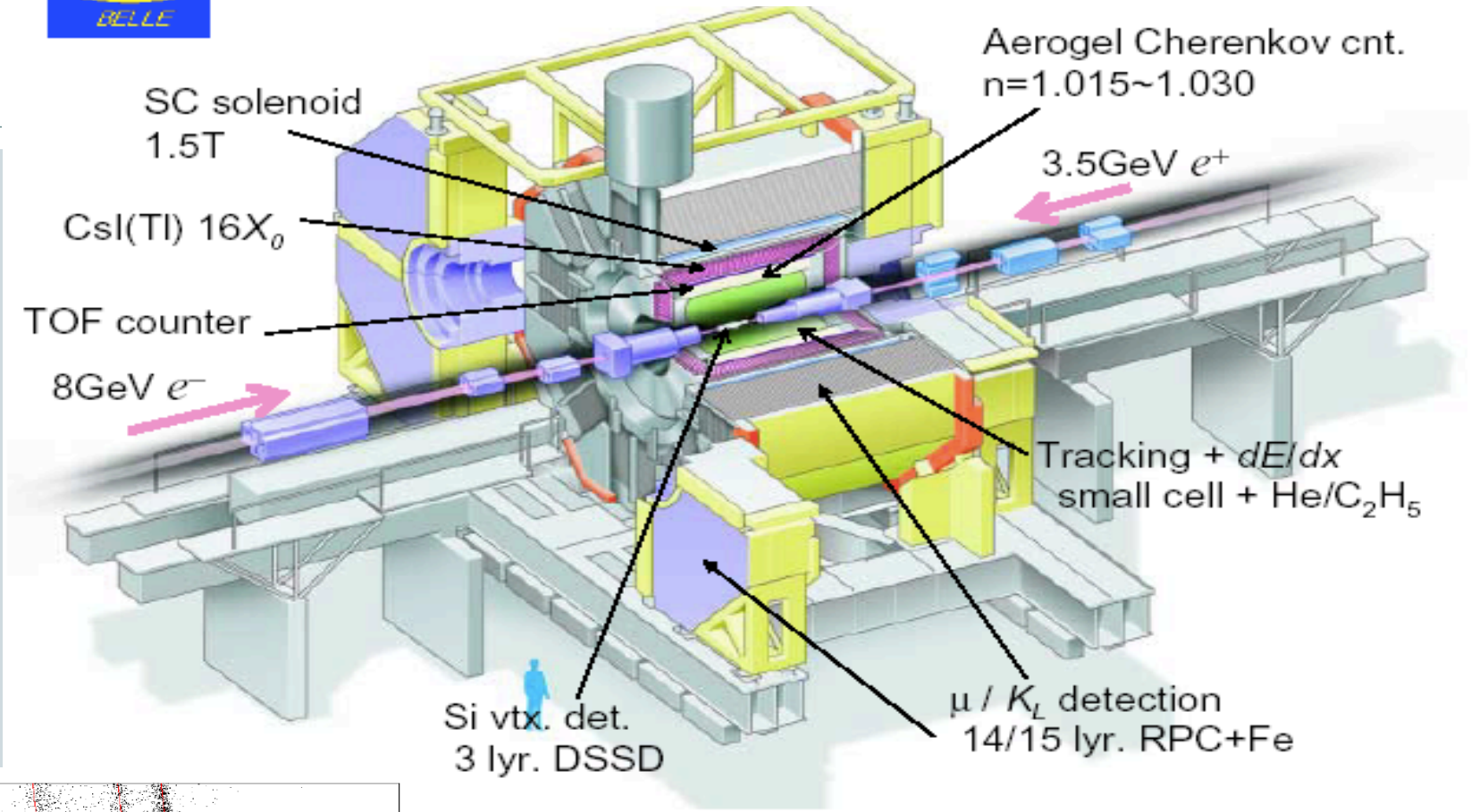


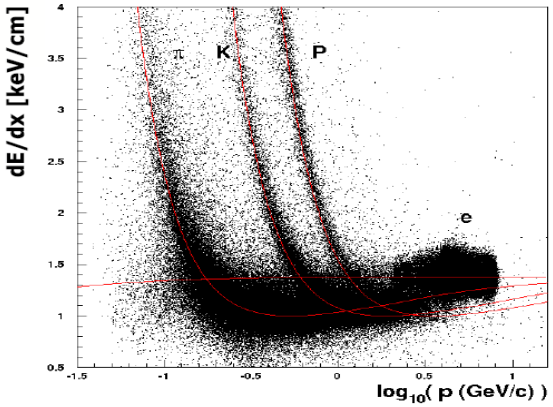


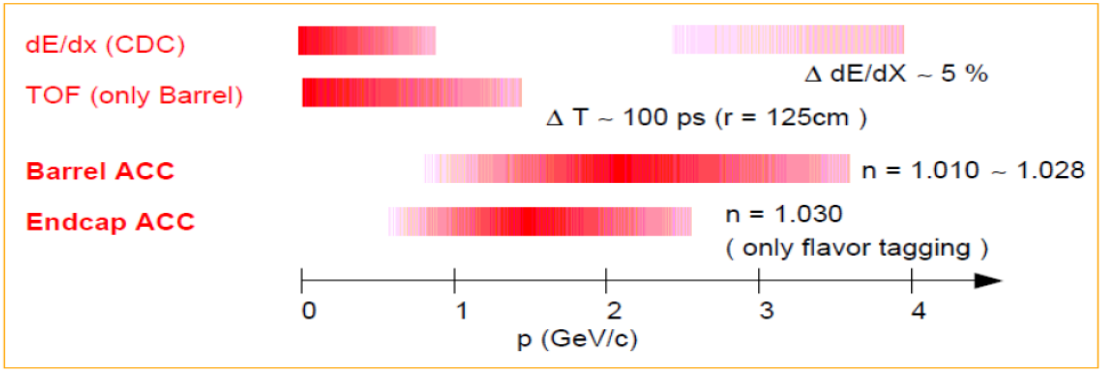


iTOP only (no dE/dx)

Belle at KEKB

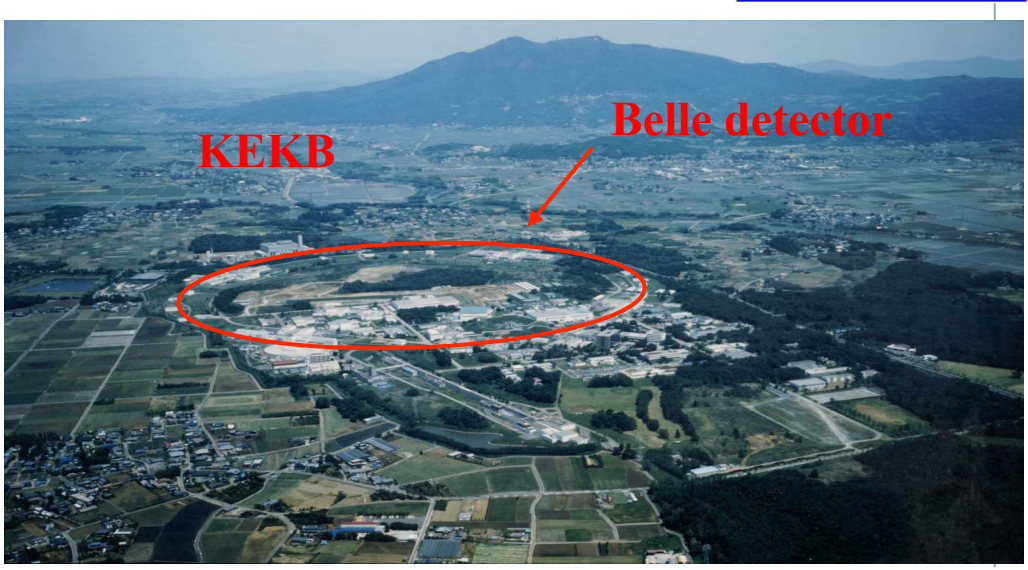


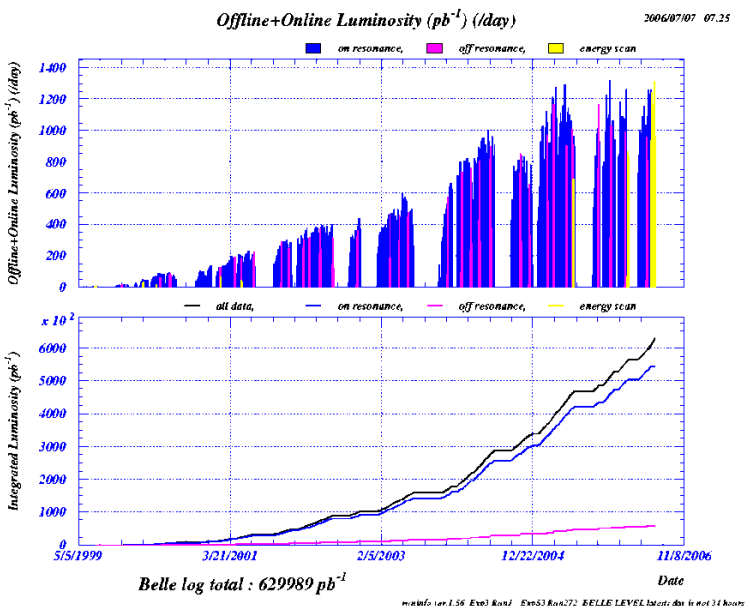


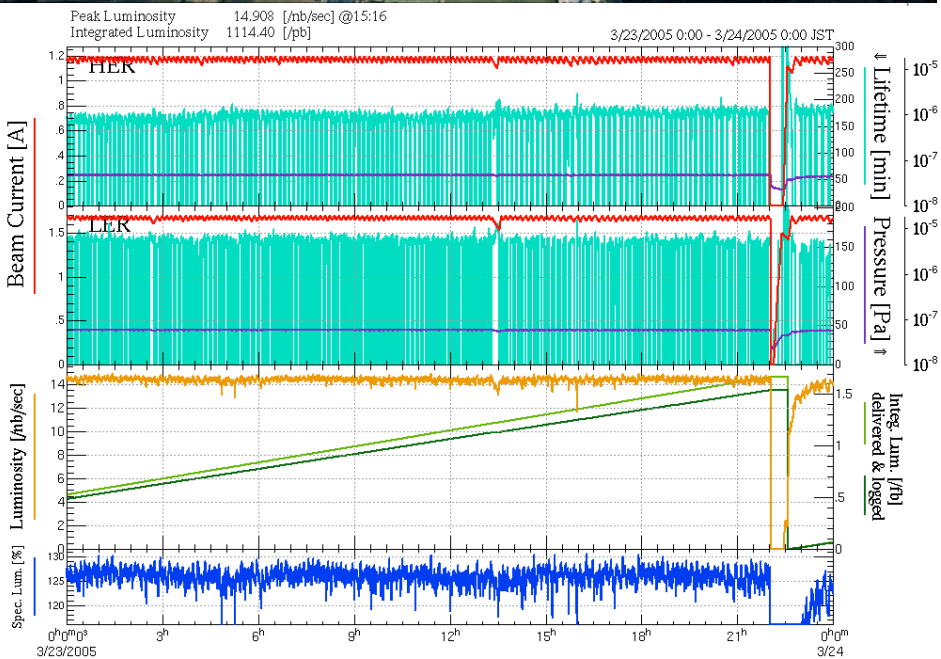


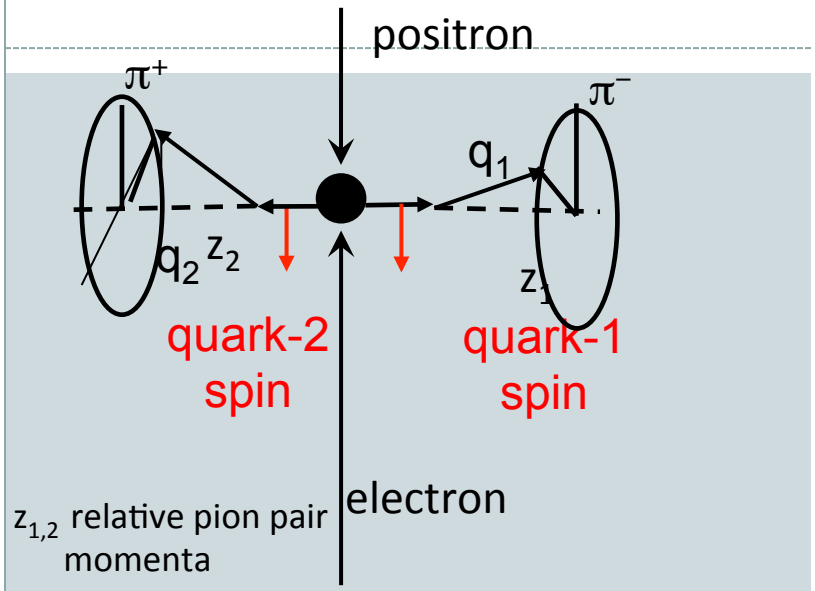
Measurement of Fragmentation Functions @

- KEKB: $L > 2.11 \times 10^{34} cm^{-2} s^{-1}$!!
- Asymmetric collider
- 8GeV e^- + 3.5GeV e^+
- $\sqrt{s}$ = 10.58GeV (Y(4S))
- Continuum production: @$\sqrt{s}$ =10.52 GeV
- $e^+e^- \rightarrow q/anti\text{-}q$ (u,d,s,c)
- Integrated Luminosity: > 1000 fb^{-1}
- ~100 fb^{-1} → continuum

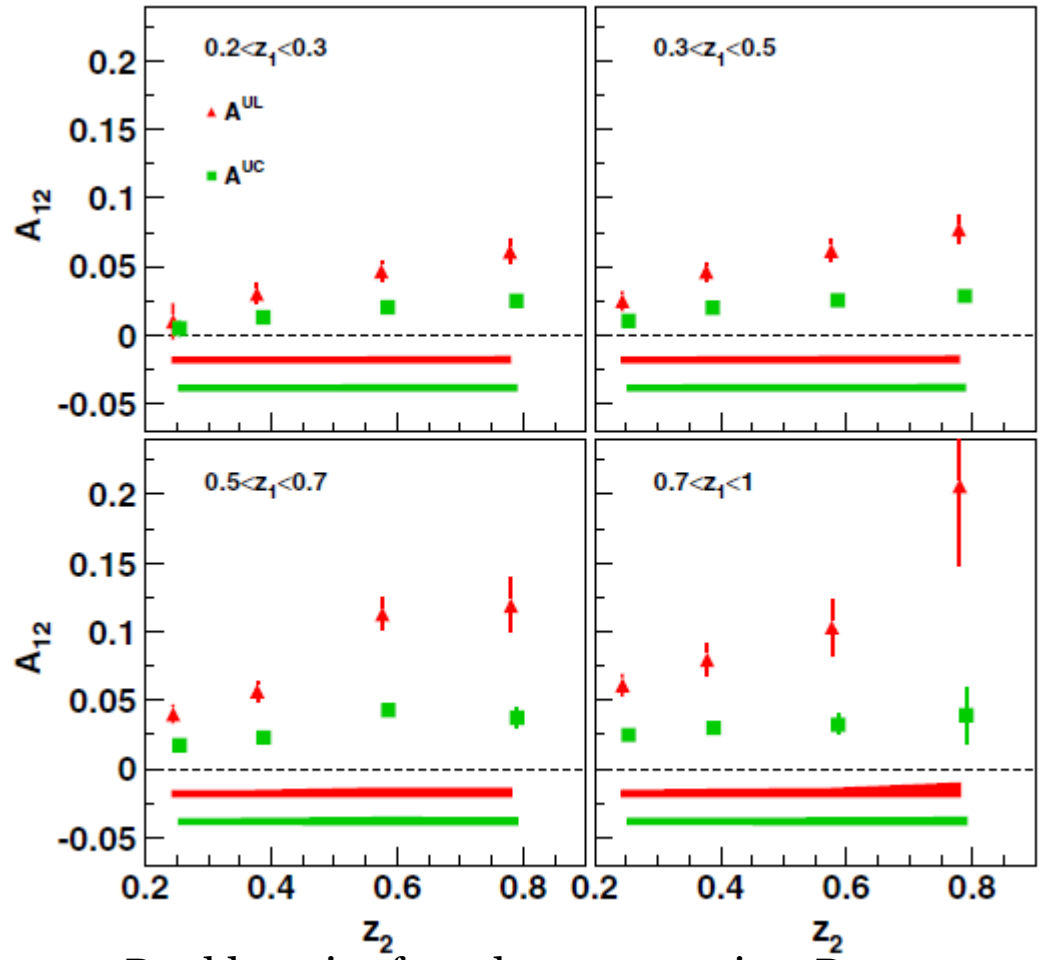








$$A_{12} \propto H_1(z_1)H_1(z_2)\cos(\phi_1+\phi_2)+....$$



Double ratios for robustness against Detector Effects:

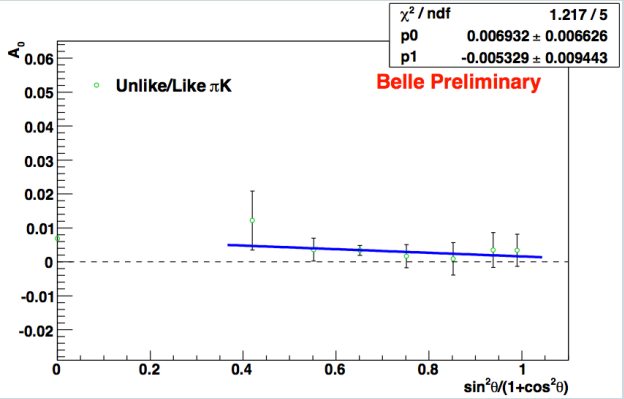
A_{UL}: unlike over like sign pions

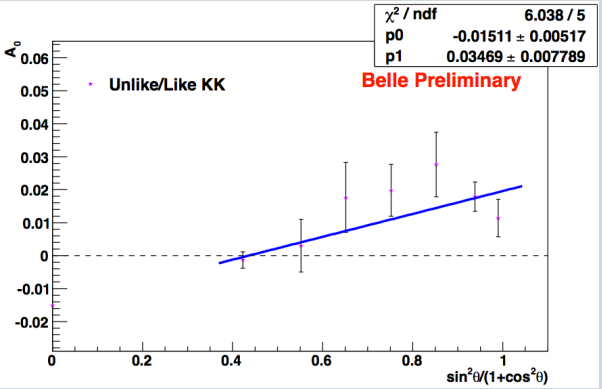
A_{UC}: unlike over charge integrated pions

Test of Kinematic Dependence

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

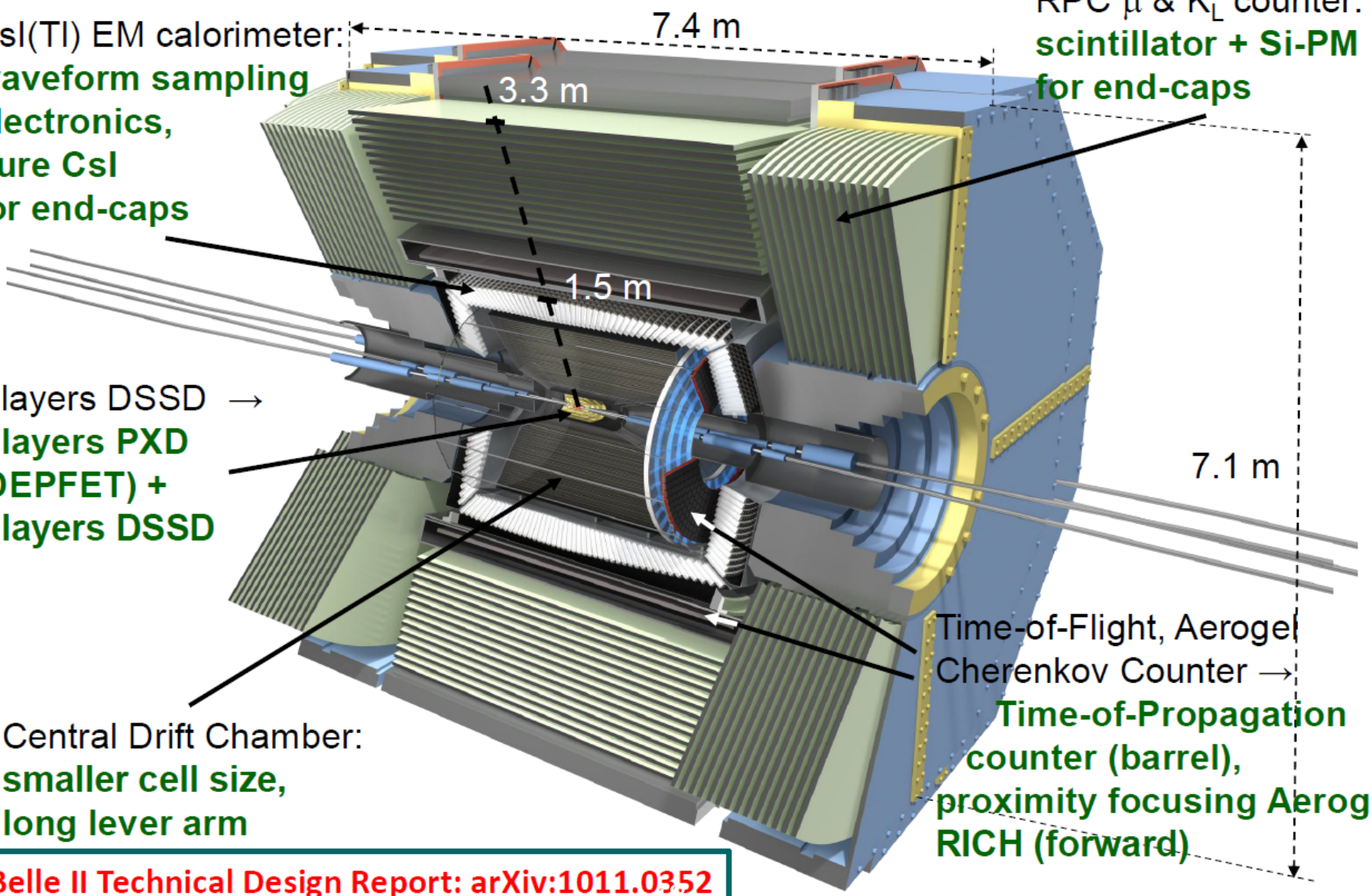
linear in $\sin^2\boldsymbol{\theta}/(1+\cos^2\boldsymbol{\theta})$,
go to 0 for $\sin^2\boldsymbol{\theta}/(1+\cos^2\boldsymbol{\theta}) \rightarrow 0$





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

The Belle II Detector



Belle II Technical Design Report: arXiv:1011.0352

$\sim D^0\ c\tau$