Asymmetry measurements in e^+e^-: methods, open points and perspectives

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INDIANA UNIVERSITY

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A PATH TOWARDS TMD EXTRACTION

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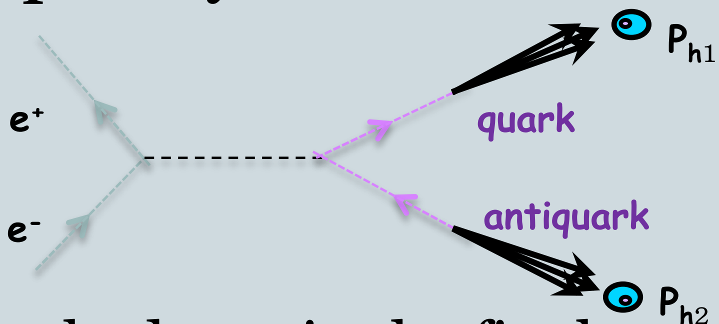
ECSAC

European Centre for Science Arts and Culture

Some Slides taken from R. Seidl, F. Giordano

Fragmentation Functions in e+e-

- Conceptually easiest access to Fragmentation functions



- Observe hadrons in the final state
- 1 hadron

$$\sigma^h(z,Q^2,p_T) \propto \sum_q e_q^2 \left(D_{1,q}^h(z,Q^2,p_T) + D_{1,\bar{q}}^h(z,Q^2,p_T)\right)$$

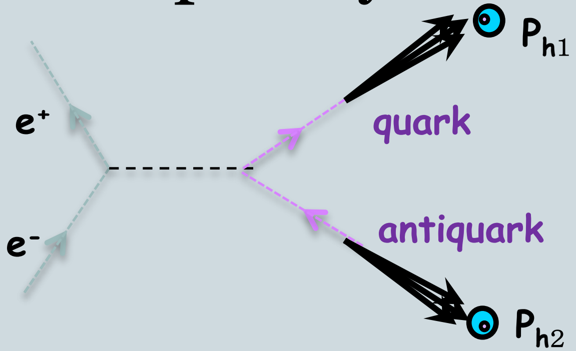
- 2 back-to-back hadrons

$$\sigma^{h_1,h_2}(z,Q^2,p_T) \propto \sum_q e_q^2 \left(D_{1,q}^h(z,Q^2,p_T) \otimes D_{1,\bar{q}}^h(z,Q^2,p_T)\right)$$

- 2 hadrons in the same hemisphere: Di-hadron FF + Single hadron FF at > LO

Fragmentation Functions in e+e-

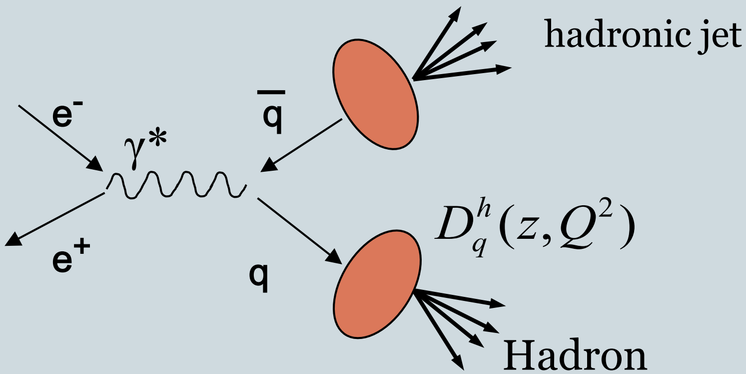
- Conceptually easiest access to Fragmentation functions

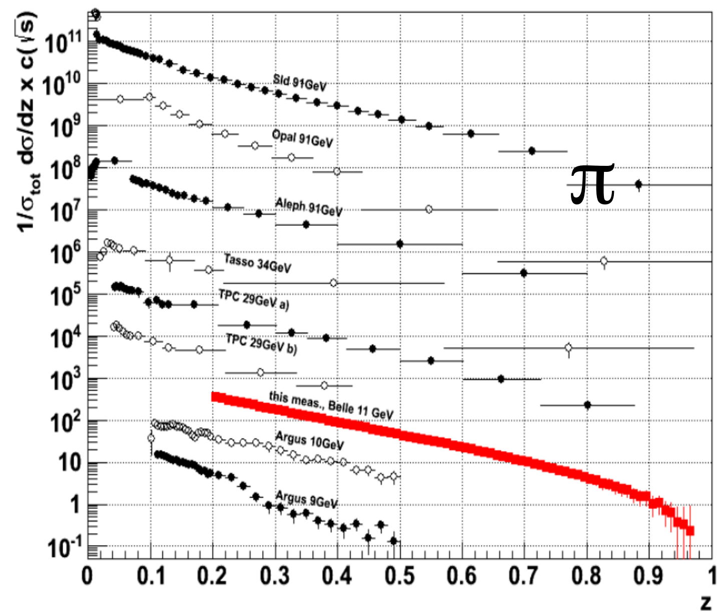


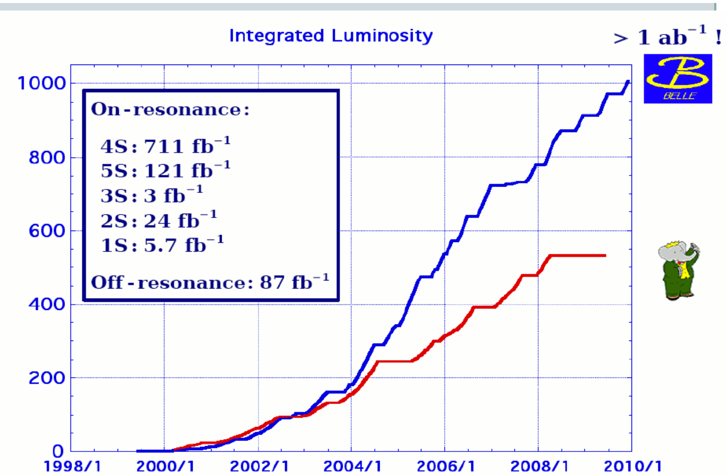
- Advantages:
  - Direct access to FFs (no contribution from unknown PDF)
  - Some initial state kinematics known ($\sqrt{s}$)
  - Experimentally clean environment (no underlying event, PID)
- Disadvantages
  - No Spin asymmetries
  - Limited access to initial partonic kinematics (quark direction)
  - Limited access to flavor information →charm contribution
  - Limited access to gluon FF

Where to Study?

- Long history of e+e- colliders
  - ~$\sqrt{s}=M_{Z0}$ (weak coupling instead of e_q)
  - ~30 GeV (PETRA, PEP), statistics?
  - Charm factories (CLEO-c, BES), no jets, thrust







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

Belle, a typical e+e- Experiment of generation 2000

•Asym. e^+ (3.5 GeV) e^- (8 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'

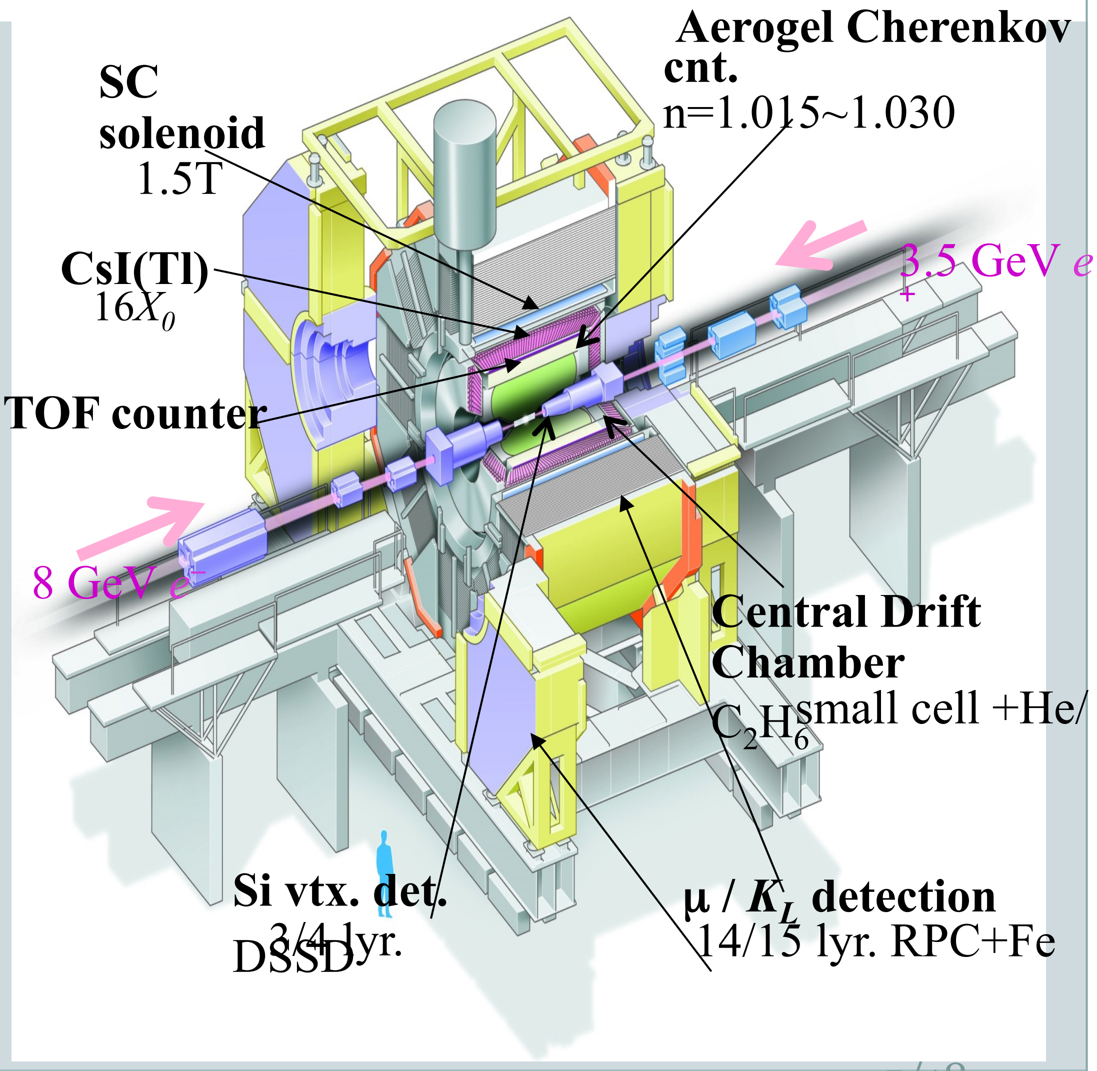
• ideal detector for high precision measurements:

- Azimuthally symmetric acceptance, high res. Tracking, PID: Kaon efficiency ~85%

Available data:

~1.8 *10^9 events at 10.58 GeV,

~220 *10^6 events at 10.52 GeV



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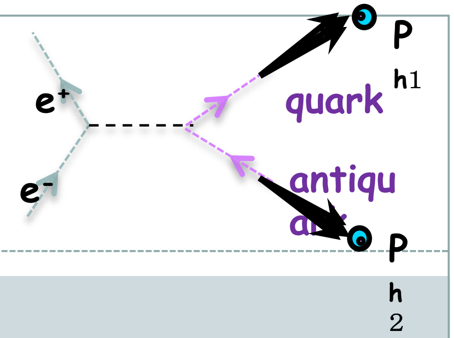
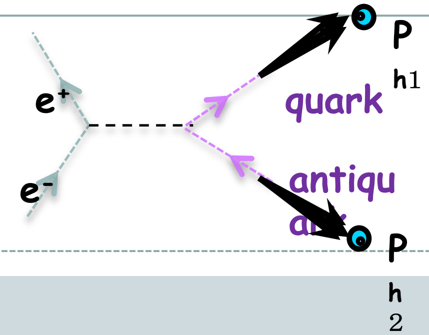
Baseline measurement D(z) from Cross-Section for identified Pions and Kaons



$$\sigma^h(z, Q^2, p_T) \propto \sum_q e_q^2 \left(D_{1,q}^h(z, Q^2, p_T) + D_{1,\bar{q}}^h(z, Q^2, p_T) \right)$$

$$\frac{d\sigma_i}{dz} = \frac{1}{L_{tot}} \qquad N^{j,raw}(z_m)$$

Baseline measurement D(z) from Cross-Section for identified Pions and Kaons



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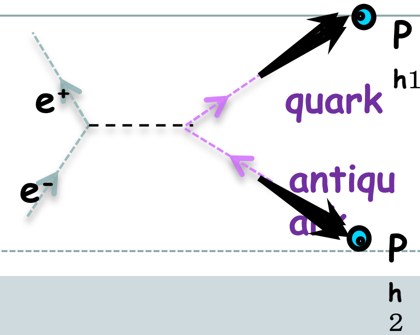
PID $i = \pi, K$

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

- Smearing Corrections

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

Baseline measurement D(z) from Cross-Section for identified Pions and Kaons



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PID $i = \pi, K$

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

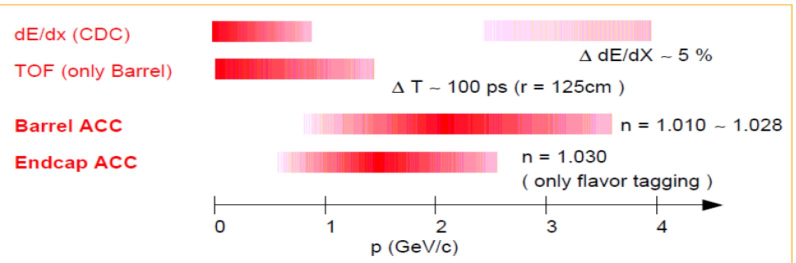
- Correct for acceptance,
- ττ, 2γ,
- decay in flight,

< 10%

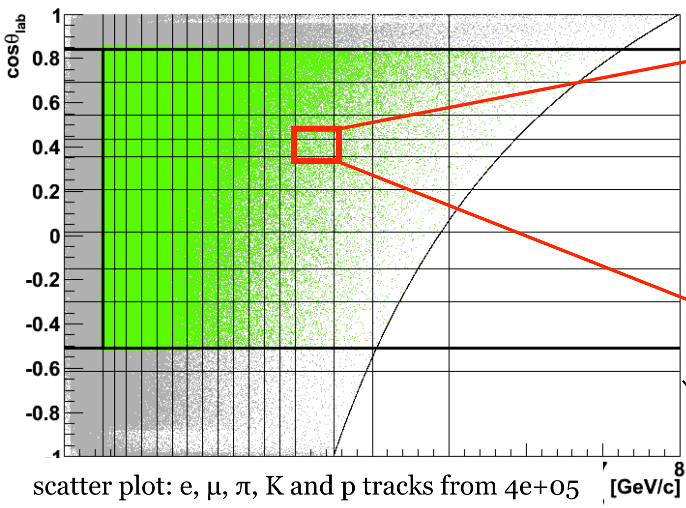
- Initial State Radiation
- Exclude events where CME/2 changes by more than 0.5%
- Large at low z, correct based on MC

- Smearing Corrections

PID Corrections from Data



ToF forward geometry acceptance limit



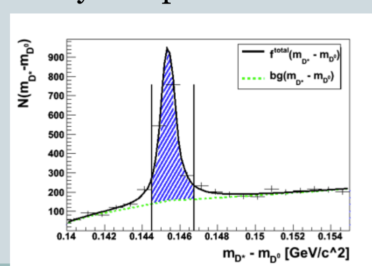
scatter plot: e, μ, π, K and p tracks from 4e+05 events

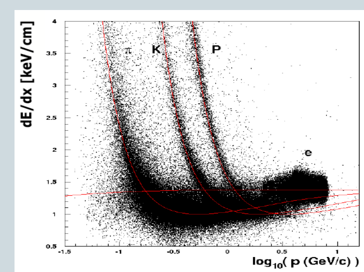
ToF backward geometry acceptance limit

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

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

e.g. $D^* \to D^0 \pi^+_{slow}$, $D^0 \to K^- \pi^+_{fast}$



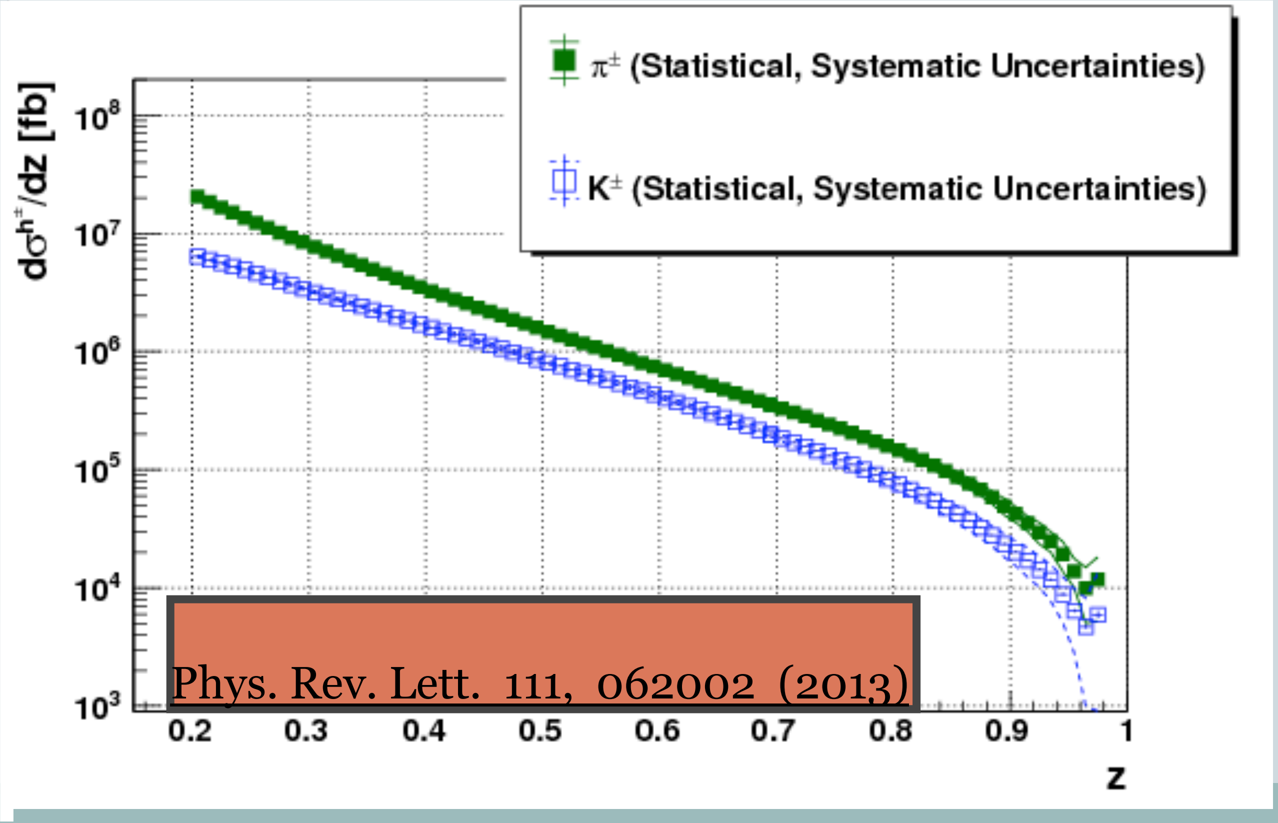


- Misidentification π→K up to 15%, K→π up to 20%

Cross sections

$i = \pi, K$

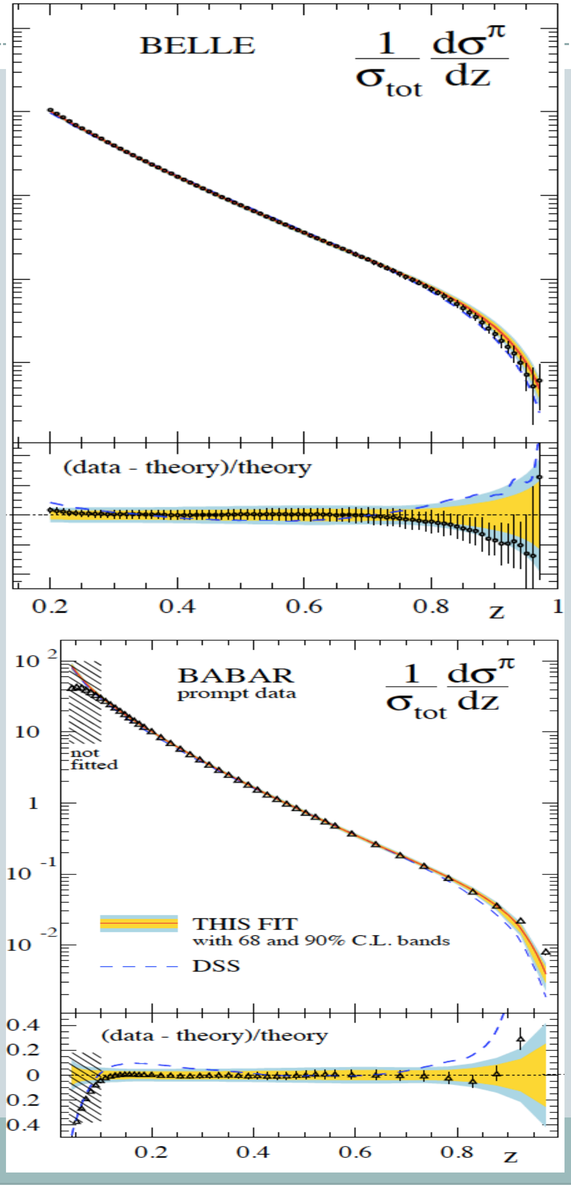
$$\frac{d\sigma_i}{dz} = \frac{1}{L_{tot}} \; \epsilon^i_{joint}(z)\, \epsilon^i_{ISR/FSR}(z)\, S^{-1}_{zz_m}\, \epsilon^i_{impu}(z_m)\, P^{-1}_{ij} N^{j,raw}(z_m)$$



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

New DSS(E,H-P) Fit

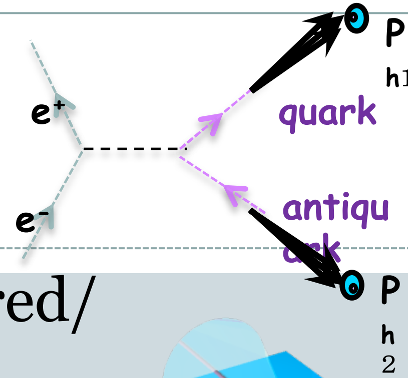
- Good agreement, however, there seems to be a trend away from the fit for the Belle data at high z
- From DSS:
  - Precise data at high z
  - Some info from scaling violations (Belle vs experiments at M_Z)
  - Some info on flavor due to charge weighting



Open Questions

- Most straightforward measurement, still some questions
- Experimental
  - Decay in flight treatment (weak decays?)
  - Initial state radiation correction?
  - Subtract charm w/o impacting phase space? (this will be even more important later-on), there is charm tagged data from LEP and SLAC for D
- Theory:
  - low/high z treatment →Similar to techniques needed for JLAB Data? (see CJ fits)
  - x-section vs multiplicities

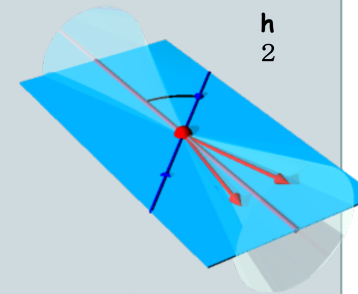
Di-Hadrons access flavor structure

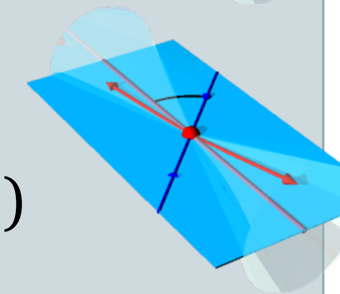


- Opposite Hemispheres: separation between favored/ unfavored

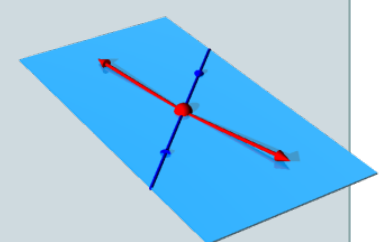
$$\sigma(u\bar{u} \to \pi^+\pi^- + X) \propto D_{u,\mathrm{fav}} \cdot D_{\bar{u},\mathrm{fav}} + D_{u,\mathrm{disfav}} \cdot D_{\bar{u},\mathrm{disfav}}$$

$$\sigma(u\bar{u} \to \pi^+\pi^+ + X) \propto D_{u,\mathrm{fav}} \cdot D_{\bar{u},\mathrm{disfav}} + D_{u,\mathrm{disfav}} \cdot D_{\bar{u},\mathrm{fav}}$$





- Same Hemisphere: Di-Hadron FF (mixed with single hadron at NLO?)
- Generally look at 4 x 4 hadron combinations (π, K, +,-)
  - Keep separate until end: only 6 independent yields
- 3 hemisphere combinations:
  - same hemisphere (thrust >0.8)
  - opposite hemisphere (thrust >0.8)
  - any combination (no thrust selection)
- 16 x 16 z_1 z_2 binning between 0.2 - 1

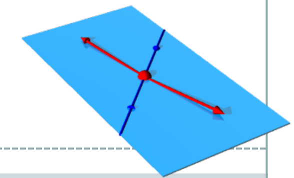


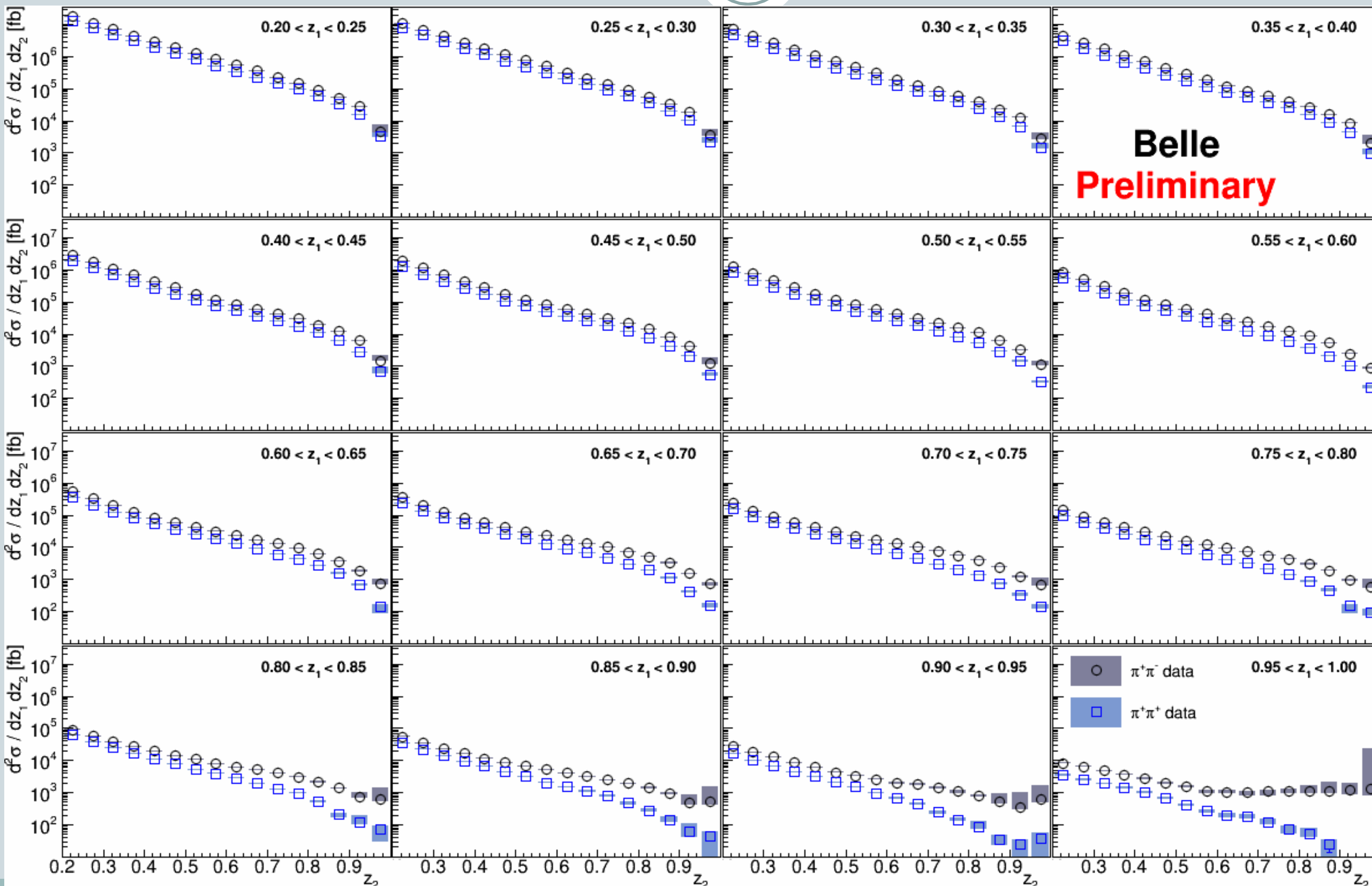
N.B. Favored/Unfavored separation can also be done with polarized beam a
At $\sqrt{S}=M_{Z_0}$ (see SLD analysis)

Correction chain similar to 1D case

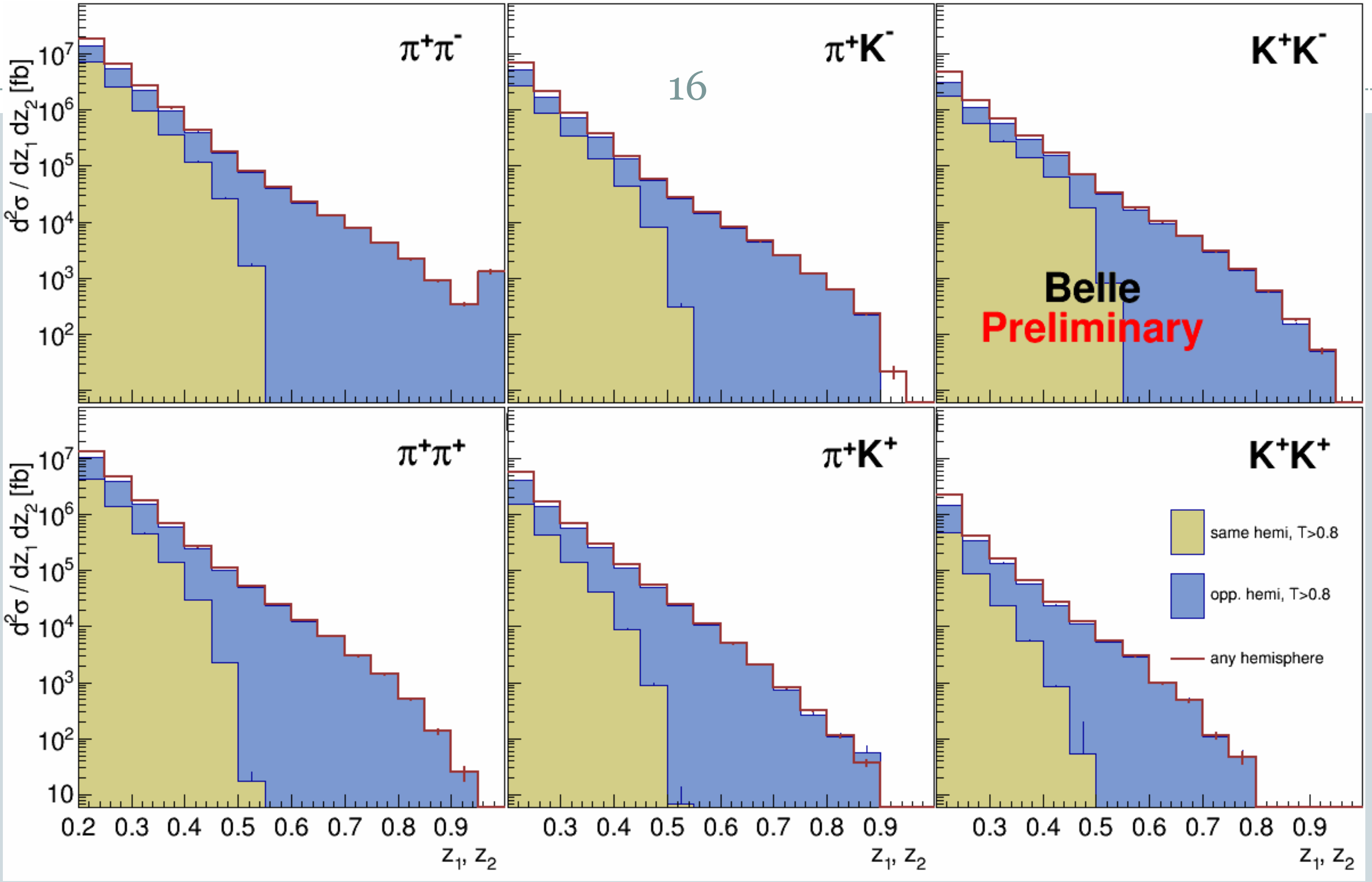
Correction	Method	Systematics
PID mis-id	PID matrices (5x5 for cos θ_{lab} and p_{lab})	MC sampling of inverted matric element uncertainties
Momentum smearing	MC based smearing matrices (256x256), SVD unfold	SVD unfolding vs analytically inverted matrix, reorganized binning, MC statistics
Non-qqbar BG removal	eeuu, eess, eecc, tau MC subtraction	Variation of size, MC statistics
Acceptance I (cut efficiency)	In barrel reconstucted vs udsc generated in barrel	MC statistics
Acceptance II	udsc Gen MC barrel to 4pi	MC statistics
Weak decay removal (optional)	udcs check evt record for weak decays	Compare to other Pythia settings
Acceptance III	Extrapolation to $\|\cos\theta\| \rightarrow 1$ in (Fit to MC)	Fit uncertainties
ISR	Keep event fraction with E> 0.995 E_{cms}	

Full results for pion pairs



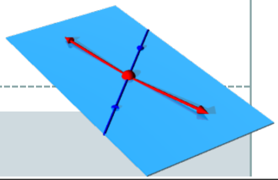


Hemisphere composition



Same hemisphere contribution drops rapidly
Consistent with LO assumption of
Same hemisphere: single quark → di-hadron FF: ($z_1+z_2<1$)
Opposite hemisphere: single quark→single hadron FF

Results for diagonal z_1 z_2 bins

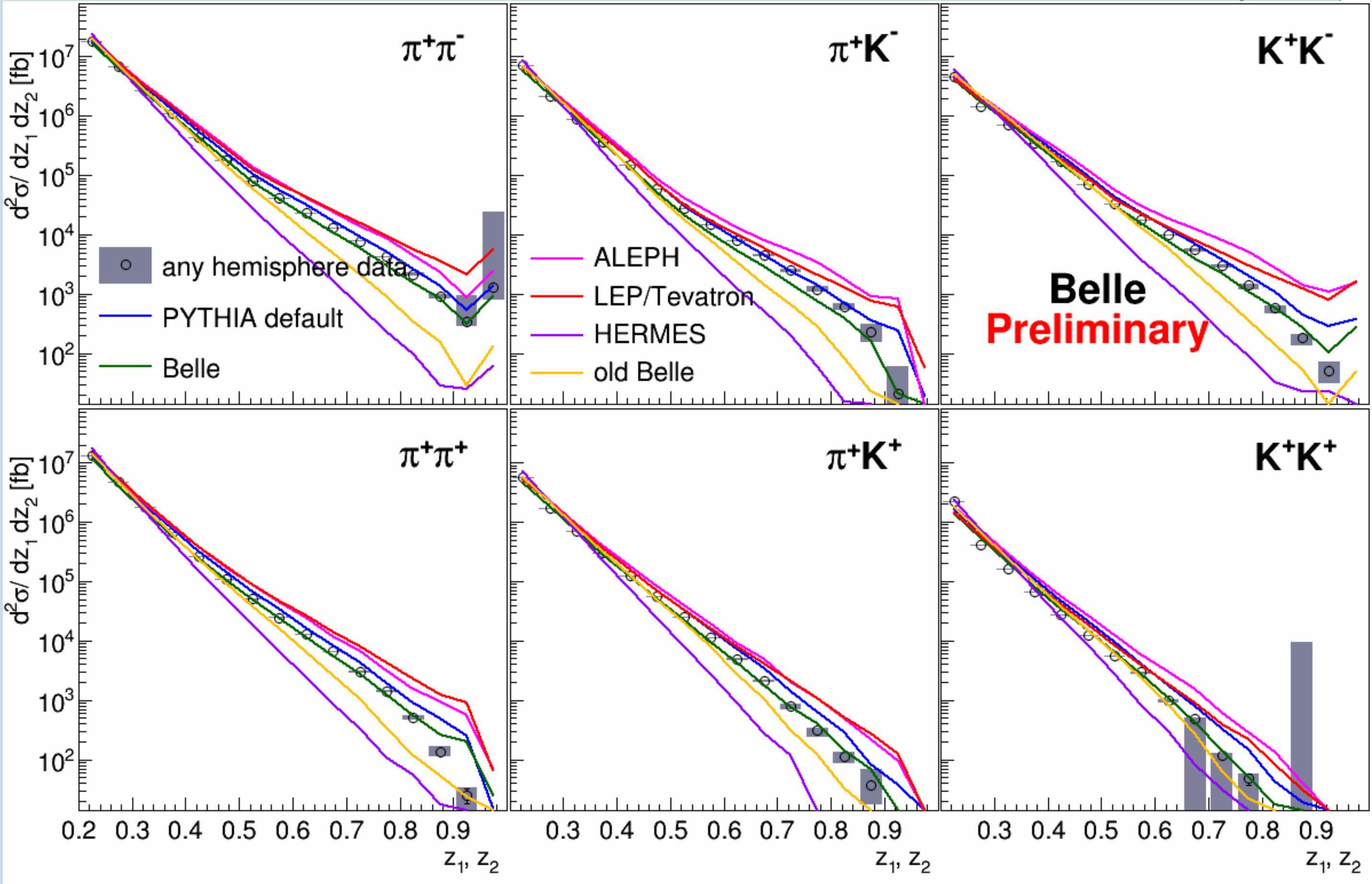


Low z dominates integral:
→Well defined, all tunes agree

High z not well measured, especially at Belle energies:
→large spread in tunes

Default Pythia settings and current Belle setting with good agreement

Diagonal z_1,z_2 bins



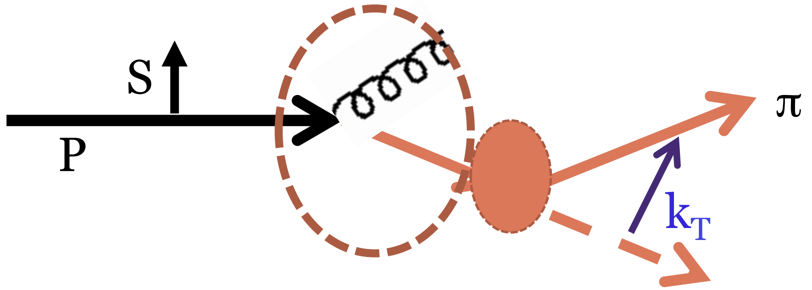
Open Issues

- Similar to Single Hadron (e.g. ISR)
- Corrections from MC (e.g. weak)
  - →more difficult for multi-dimensional analysis (M dependence etc)

Transverse momentum dependence

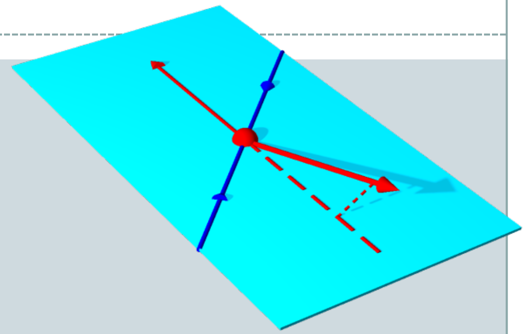
AKA UN-INTEGRATED FFS

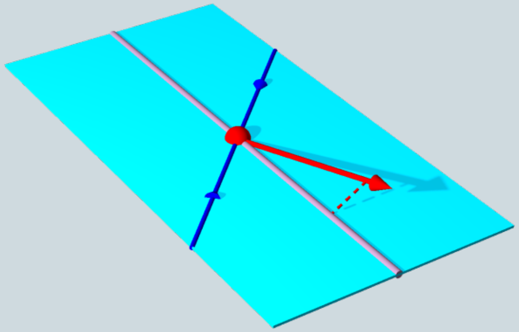
$$D_{1,q}^{h}(z, Q^2, k_t)$$

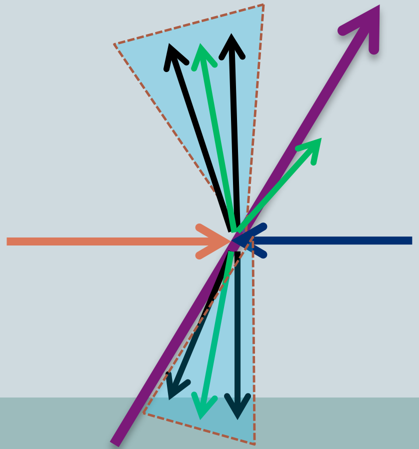


k_T Dependence of FFs

- Gain sensitivity into transverse momentum generated in fragmentation
- Two ways to obtain transverse momentum dependence
  - Traditional 2-hadron FF
    - → use transverse momentum between two hadrons (in opposite hemispheres)
    - → Usual convolution of two transverse momenta
    - → Analysis well underway: First step **shapes** for unidentified charged back-to-back pi+K
  - Single-hadron FF wrt to Thrust or jet axis
    - → No convolution
    - → Need correction for $q\bar{q}$ axis
    - → Deconvolution of $q\bar{q}$ axis resolution in kT needed

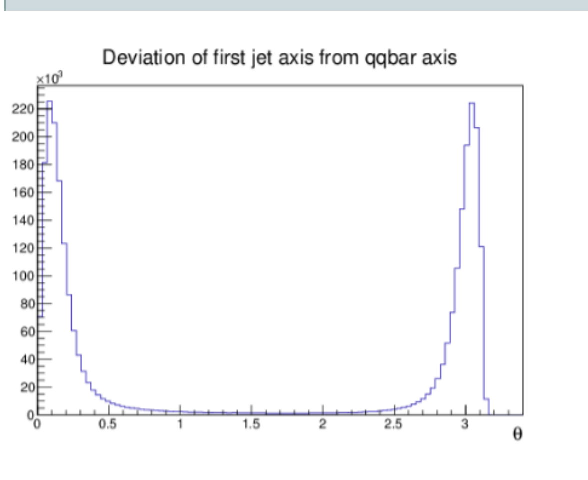


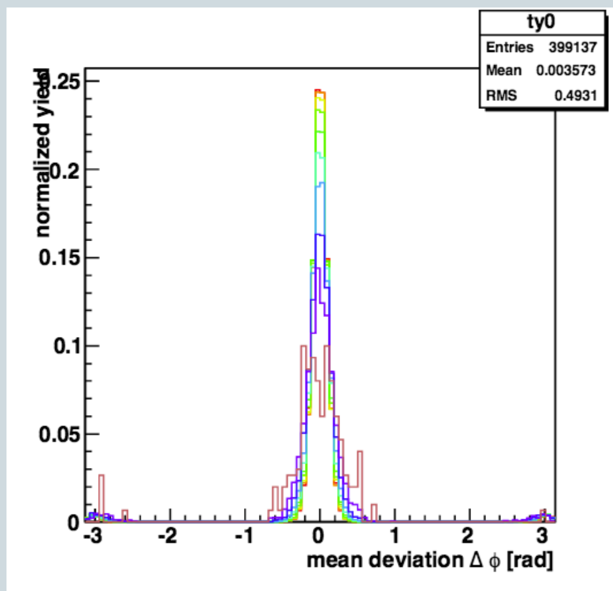


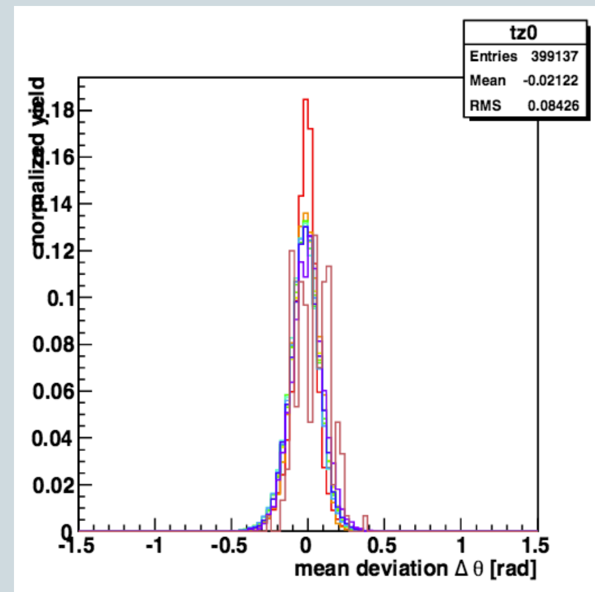


Jet vs Thrust vs q-q bar axis

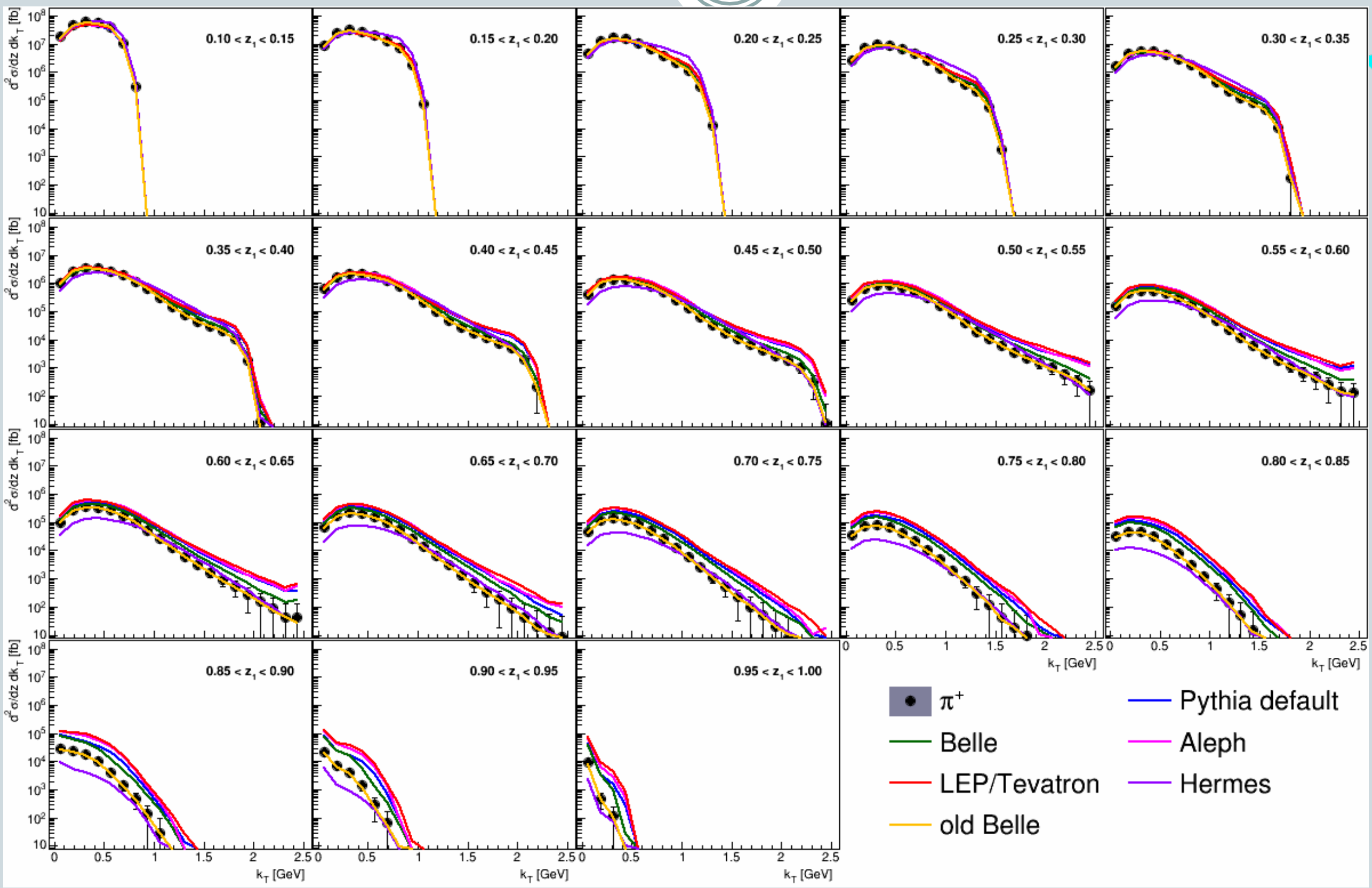
- Non-negligible resolution effects
- In terms of k_T multiply by ~z*0.5√s, e.g. for typical RMS of 0.1 rad RMS ~100 MeV RMS for p_T (Similar as BaBar)

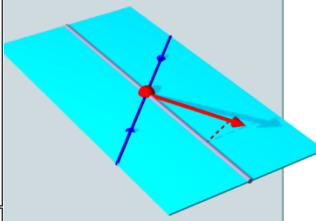






MC example of k_T sensitivities





- Jet/Thrust smearing unfolding needs multidimensional unfolding
- Additional Uncertainties due to kT description in MC

Open Issues

- Theory
  - Definition of transverse momentum
    - Back-to-back (easiest for Theory)
    - Jets? (easiest for experiment)→Also useful for p+p
    - Thrust (introduce correlations between hemispheres (problem e.g. for Collins like analysis)
    - Cuts on thrust in calculations?
  - Jet size
    - Interplay with evolution
    - Large closer to quark direction, small better for comparison e.g. with LHC where small cone approximation is used
- Experimental
  - Back-to-back, unidentified, analysis well underway
  - Acceptance effects on k_T distributions →Restrict Thrust to have flat k_T acceptance?
  - Charm treatment/Weak decays
  - ISR Treatment
  - Jet/Thrust smearing unfolding needs multidimensional unfolding

Spin dependent fragmentation

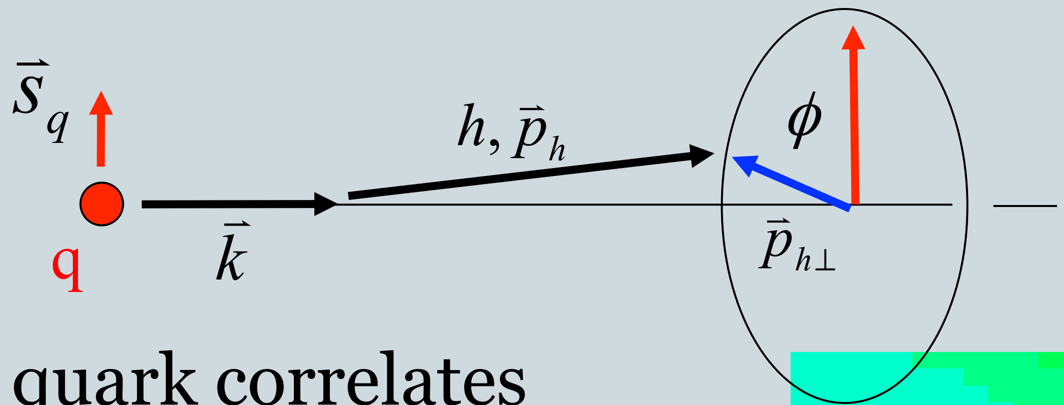
$$H_{1,q}^{h,\perp}(z, Q^2, k_t)$$

$$H_{1,q}^{h_1,h_2,\sphericalangle}(z, Q^2, M_h)$$

Collins fragmentation function

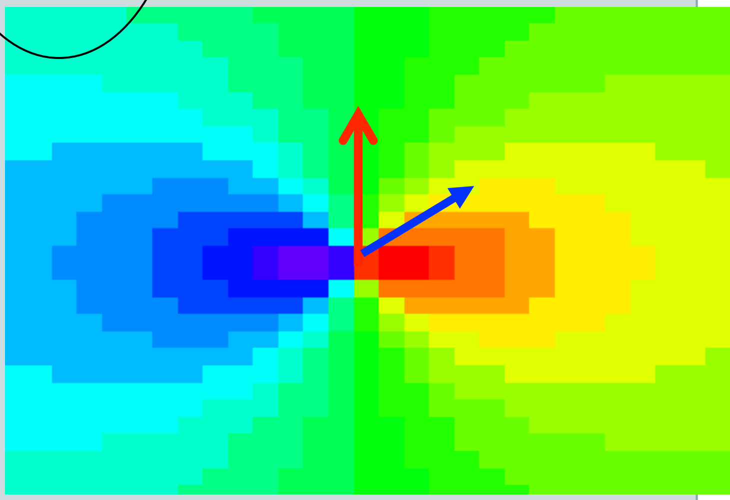
J. Collins, Nucl. Phys. B396, (1993) 161

$$D^{h}_{q\uparrow}(z, P_{h\perp}) = D^{h}_{1,q}(z, P^2_{h\perp}) + H^{\perp h}_{1,q}(z, P^2_{h\perp}) \frac{(\hat{\mathbf{k}} \times \mathbf{P}_{h\perp}) \cdot \mathbf{S}_q}{z M_h}$$



- Spin of quark correlates with hadron transverse momentum

➔translates into azimuthal anisotropy of final state hadrons

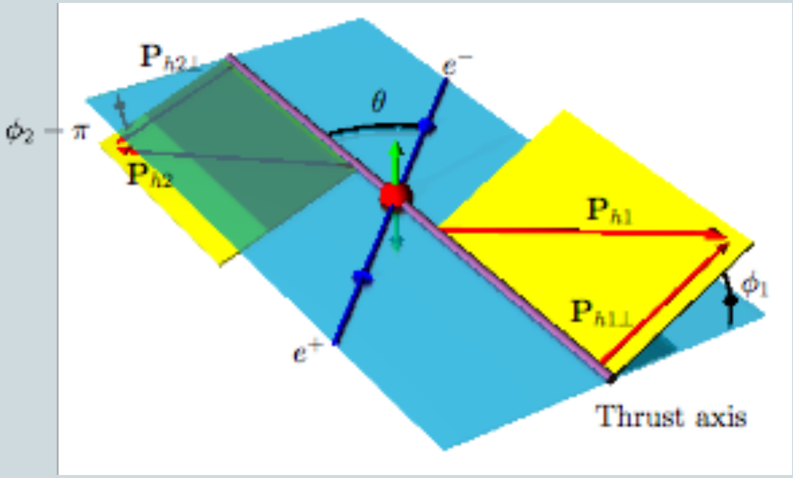


There are two methods with two or one soft scale

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

$\phi_1+\phi_2$ method:

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

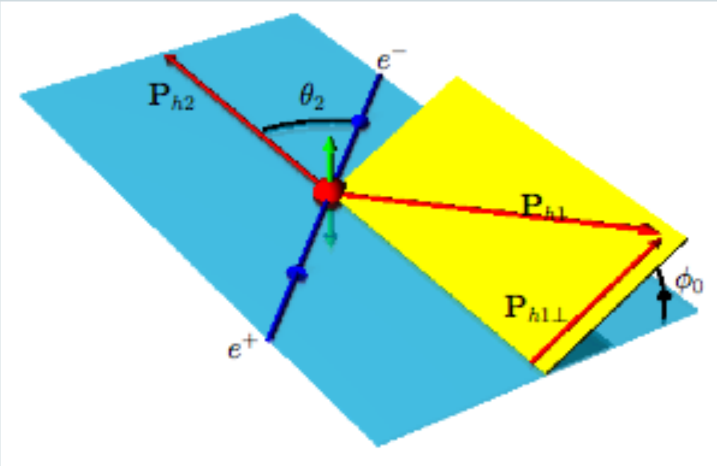


$$\sigma \sim \mathcal{M}_{12}\left(1+\frac{\sin^2\theta_T}{1+\cos^2\theta_T}\,cos(\phi_1+\phi_2)\frac{H_1^{\perp[1]}(z_1)\bar{H}_1^{\perp[1]}(z_2)}{D_1^{[0]}(z_1)\bar{D}_1^{[0]}(z_2)}\right)$$

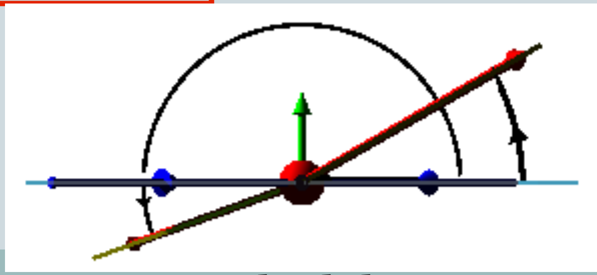
$$R_{12}^{U/L}=\frac{N(\varphi_1+\varphi_2)}{\langle N_{12}\rangle}$$

ϕ_0 method:

hadron 1 azimuthal angle with respect to hadron 2



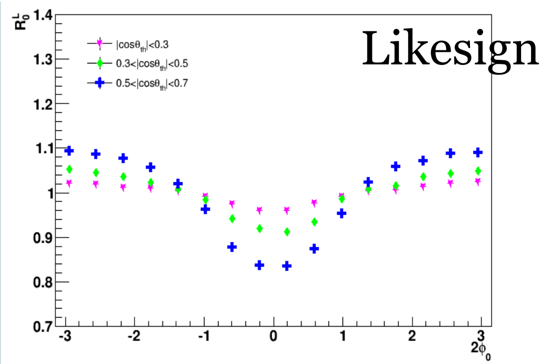
$$\sigma \sim \mathcal{M}_0\left(1+\frac{\sin^2\theta_2}{1+\cos^2\theta_2}\,cos(2\phi_0)\mathcal{F}\left[\frac{H_1^{\perp}(z_1)\bar{H}_1^{\perp}(z_2)}{D_1^{\perp}(z_1)\bar{D}_1^{\perp}(z_2)}\right]\right)$$

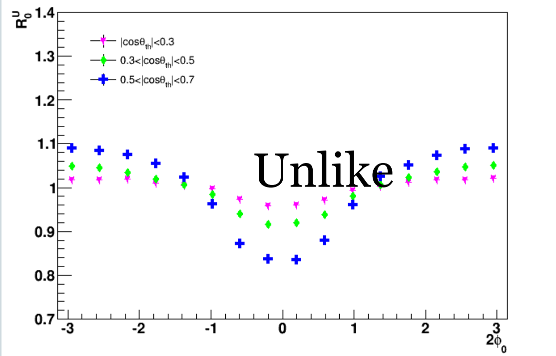


$$R_0^{U/L}=\frac{N(2\varphi_0)}{\langle N_0\rangle}$$

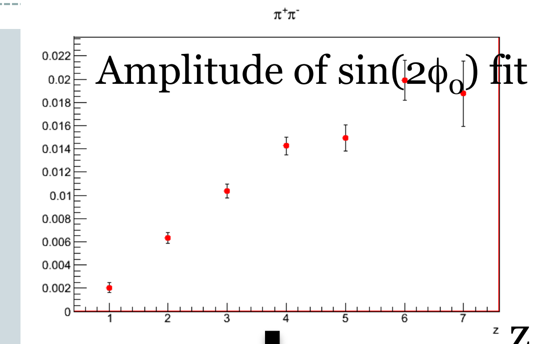
kT moment or convolution: Important which kT region is sampled

Use of Double Ratios



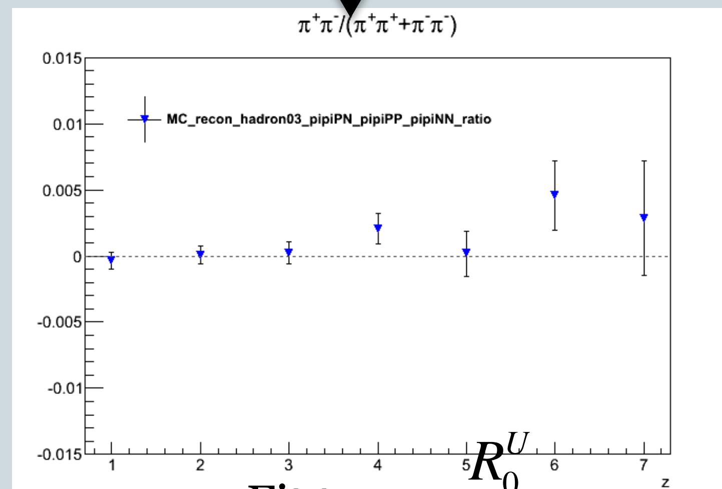


A_0



Use of "Double Ratios"

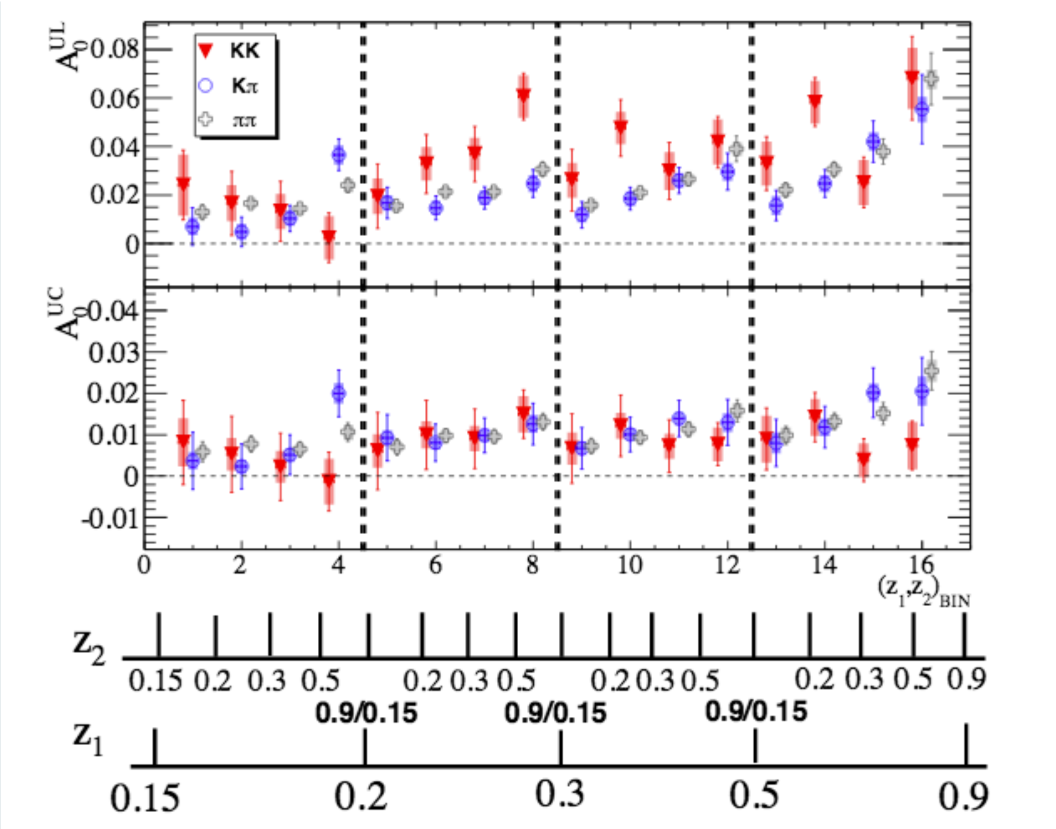
A_0

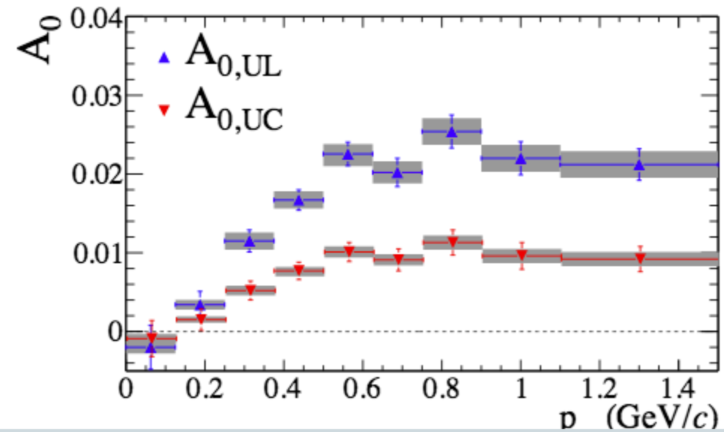


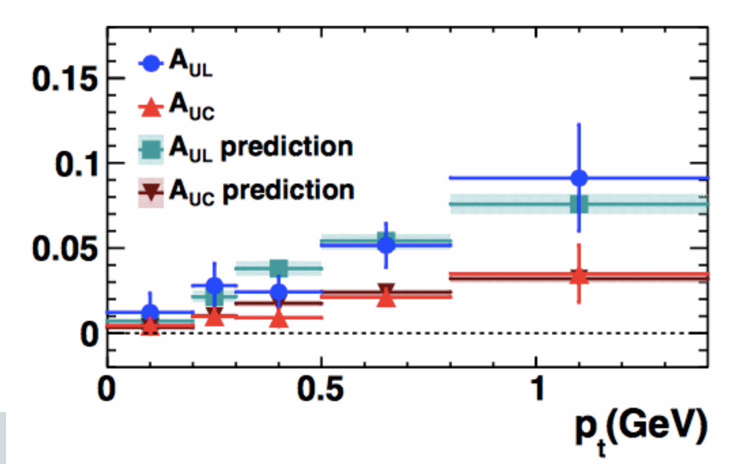
Fit to $\frac{R_0^U}{R_0^L}$ z

- False asymmetries due to Acceptance and QCD radiation
- Charge independent
- **Open question: Smearing correction/ Unfolding in Thrust/Jet method non-trivial in ratio**

Recent Results (BaBar): p_T dependence, Kaons, BES III @ $\sqrt{S}$=3.65 GeV







BES-II (arXiv:1507.06824)

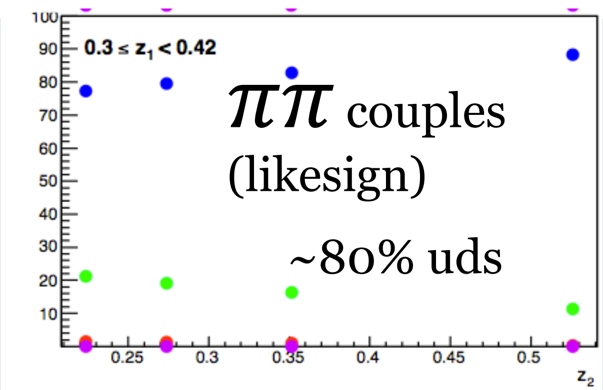
Babar: Phys.Rev. D90 (2014) 5, 052003

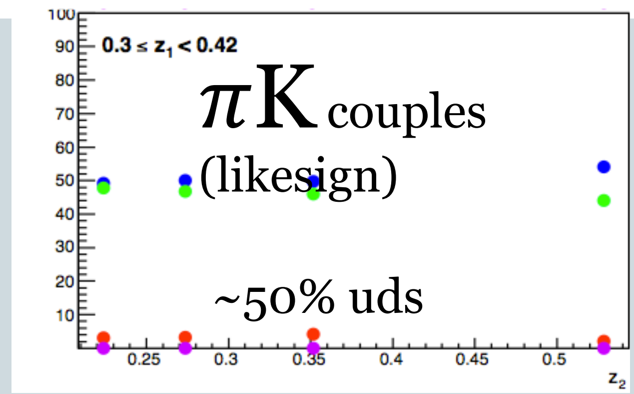
- **Inflation of FF functions:**

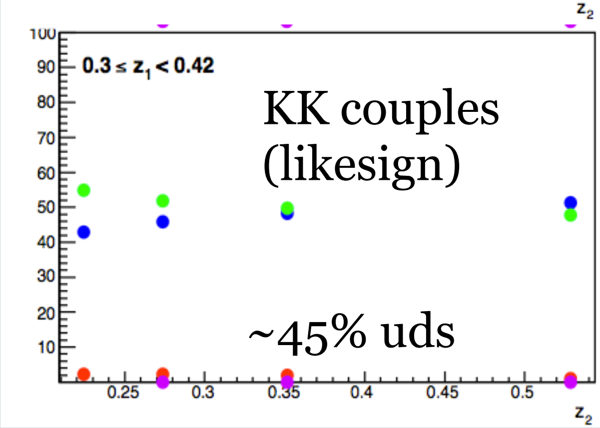
  u,d →p: 2

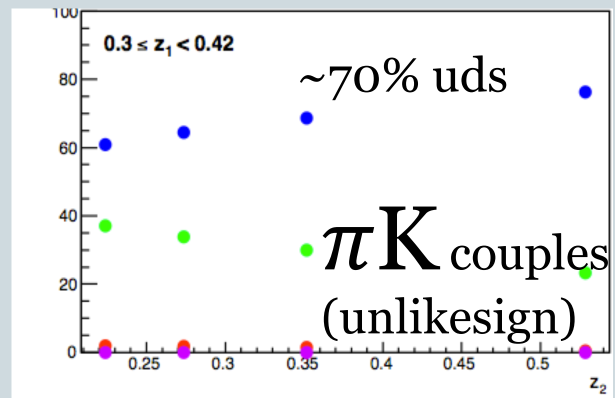
  u,d,s →p,K: 6+

Significant Charm to contribution to UDS









- Current Charm correction methods not satisfying
  - MC (unclear uncertainties)
  - From Data (D-tagged samples): Bias phase space (e.g. selection of decay modes with low momentum pions)
- Need state-of-the-art vertex detection→ Belle II

Open Issues

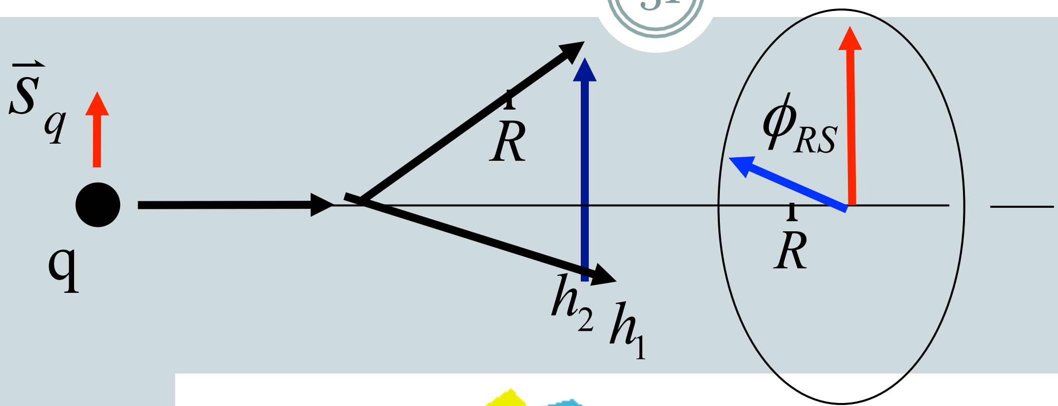
- Charm Contributions
- Thrust/Jet vs di-hadron?
  - Experimentally Jets have advantages→ Decorrelated between hemispheres
  - Correction back to q-q bar axis for thrust/jet ~factor 2
- Jet radius
  - Narrow (to compare with narrow cone approximation) or wide to be closer to quark axis?
  - Interplay with evolution effects?
- Collins FF depends on kT
  - Thrust/jet smearing might need unfolding in k_T (z is pretty well under control)
  - Analysis should ideally be differential in kT,z_1,z_2 to account for correlation and match to SIDIS, p+p →BaBar already has z, kT

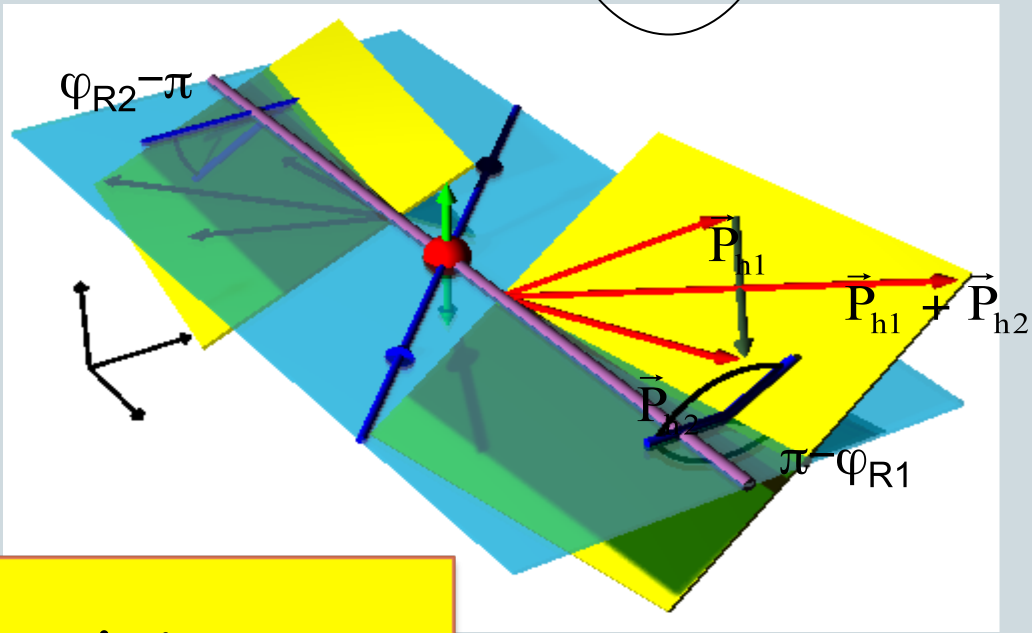
- Revisit double ratios?
  - Very indirect access to physics quantities, e.g. pi0/eta analysis:

$$\frac{\pi^+\eta + \eta\pi^-}{\pi^+ + \pi^+ + \pi^-\pi^-}$$

  - Corrections from MC with DR as validation?

Di-Hadron Fragmentation

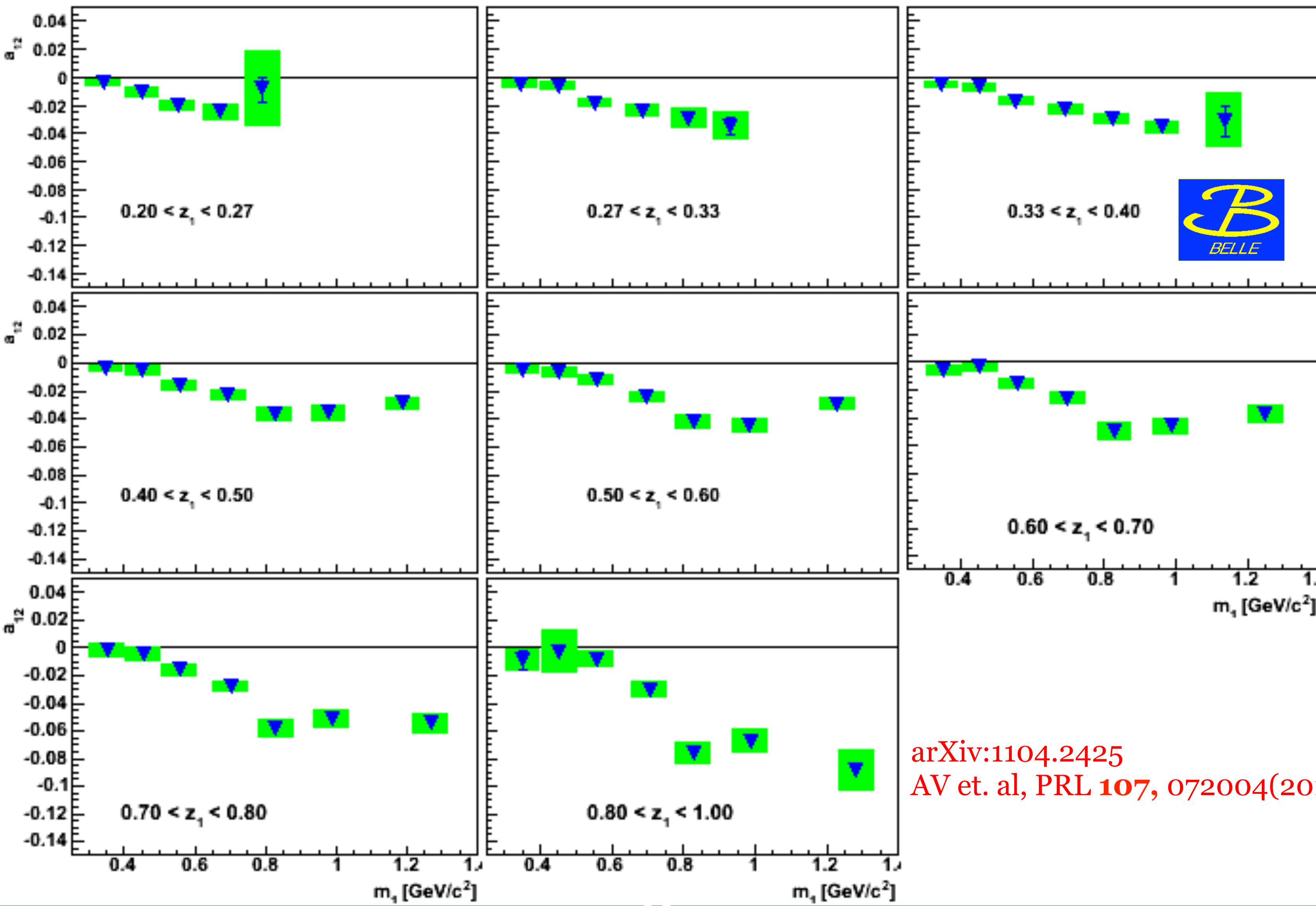




- No Double Ratio!

First measurement of Interference Fragmentation Function

$a_{12} \propto H_1^{<} * H_1^{<}$



arXiv:1104.2425
AV et. al, PRL **107**, 072004(2011)

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: $P_{h1}+P_{h2}$)

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

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

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

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

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

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

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

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

Spin independent part

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

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

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

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

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

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

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

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

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

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

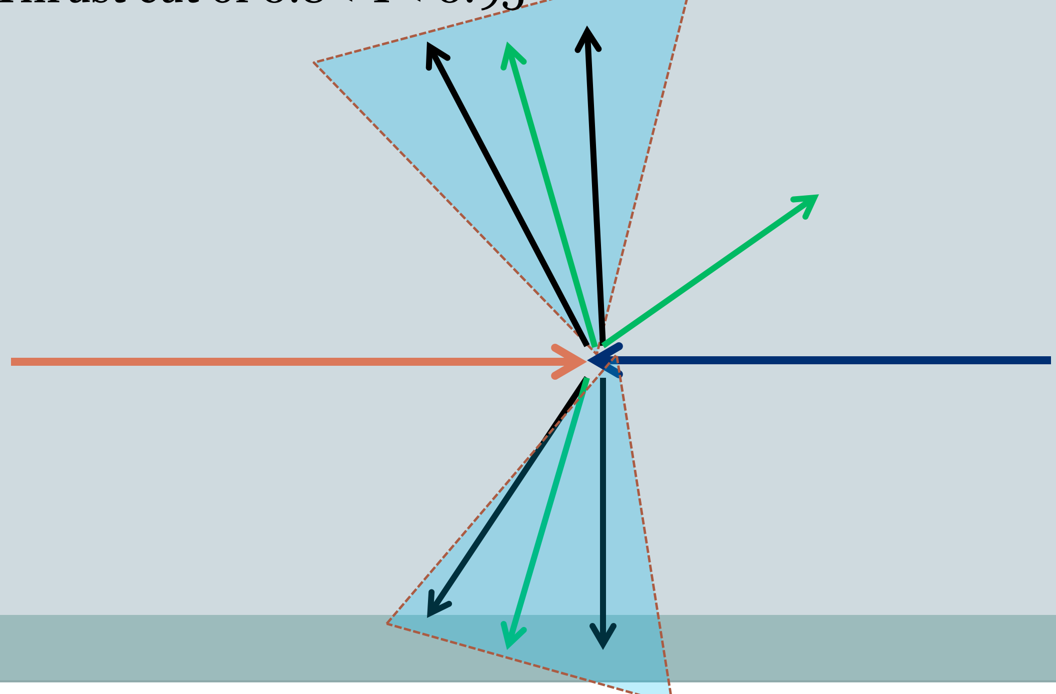
$$\langle\cos(2(\phi_R-\phi_{\overline{R}}))\rangle = \sum_{a,\bar a} e_a^2\,\frac{3\,\alpha^2}{2Q^2}\,z^2\bar z^2\,A(y)\,\frac{1}{M_1M_2\overline{M}_1\overline{M}_2}\,G_1^{\perp a}(z,M_h^2)\,\overline{G}_1^{\perp a}(\bar z,\overline{M}_h^2)\,.$$

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

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=1.0
- 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



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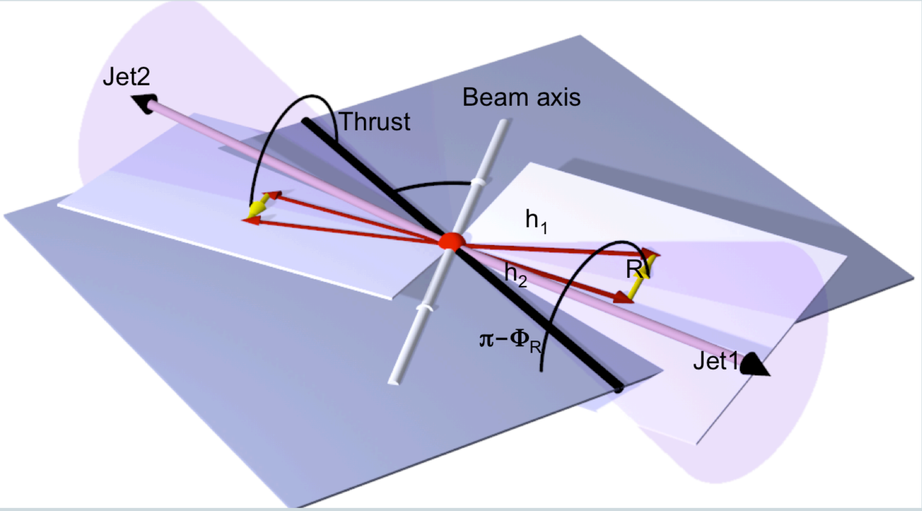
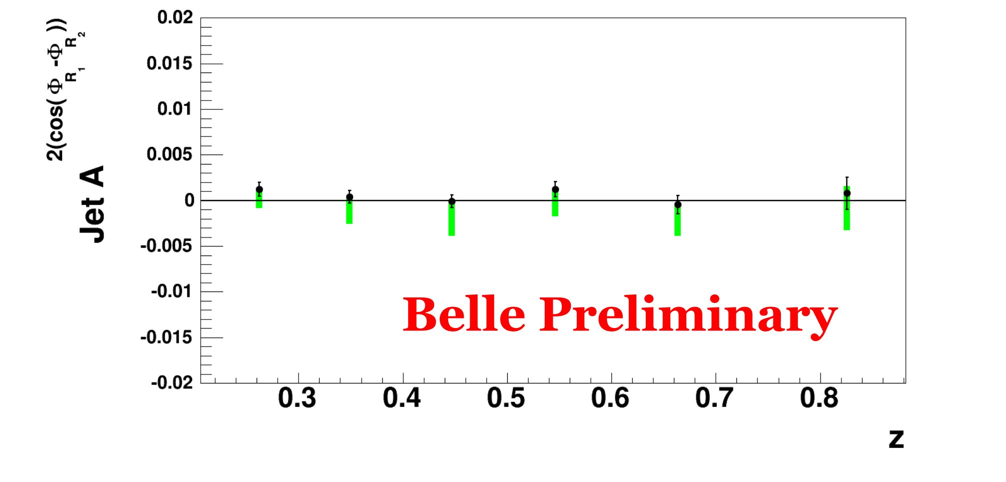
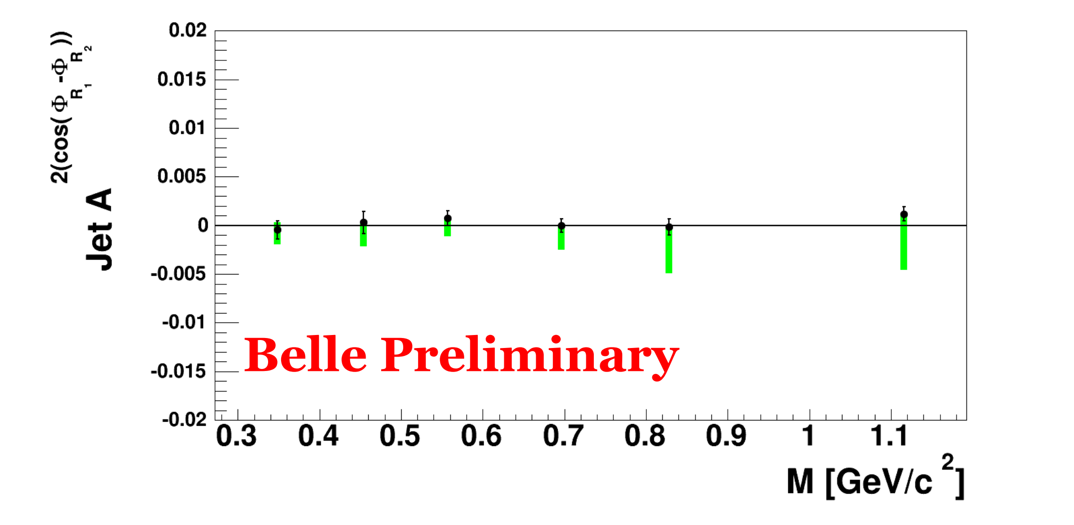


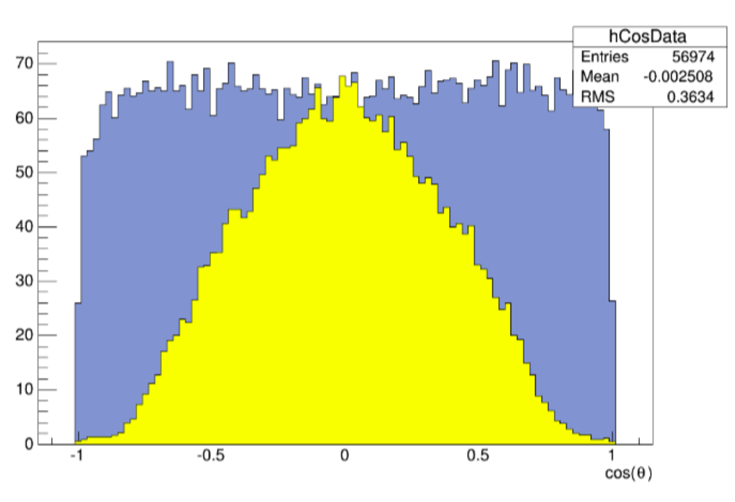
Asymmetries for Cos(2(ϕ_{R1}-ϕ_{R2})) ($G_1^{\perp}$) small





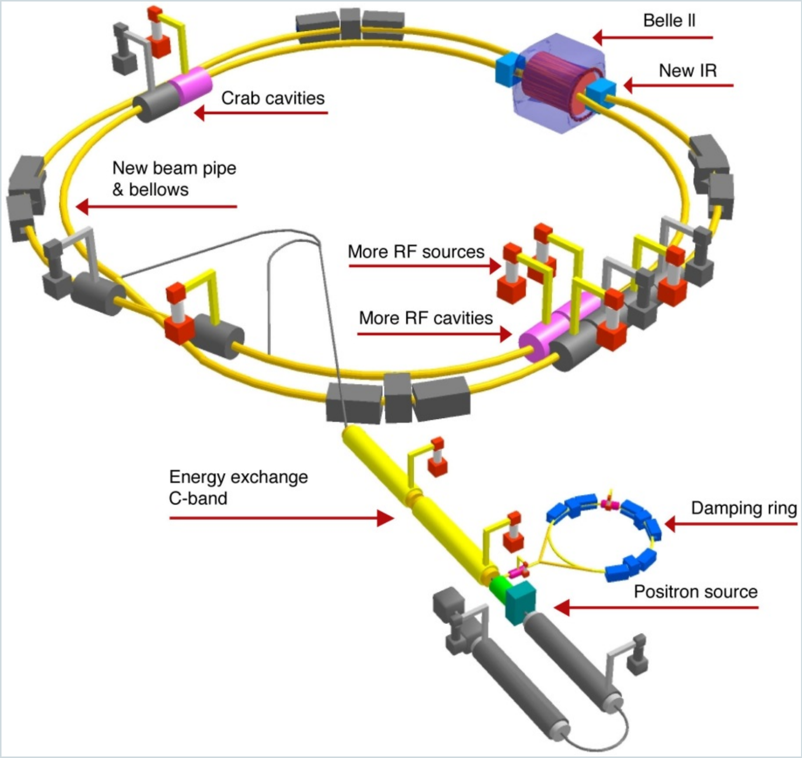
Open Issues

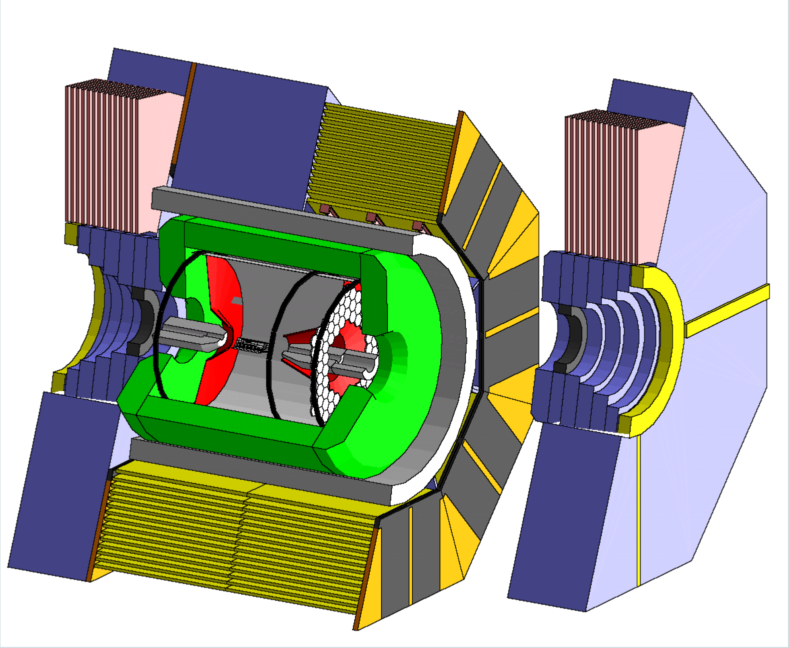
- Experimental
  - Need Acceptance correction to compare Jet with Thrust Method (and with SIDIS and p+p?)
  - (Also plan on Di-hadron Collins)
  - E.g. θ acceptance (z dependent)
- Theory
  - Thrust/Jet vs back-to back
  - Need theory for jets! (or thrust)
  - Global fit including p+p
  - Partial wave expansion important?



KEKB/Belle→SuperKEKB, Belle II Upgrade

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

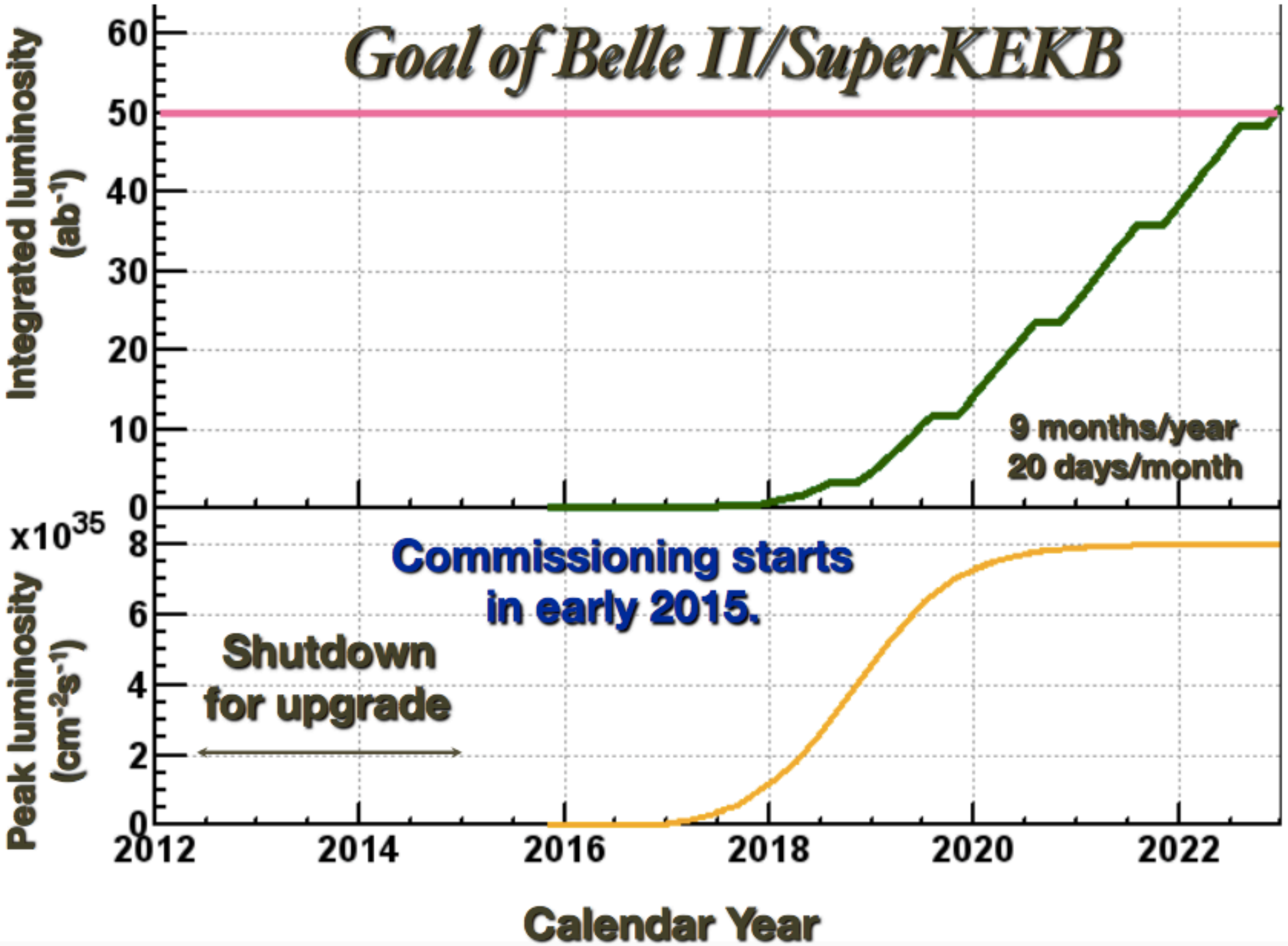




http://belle2.kek.jp

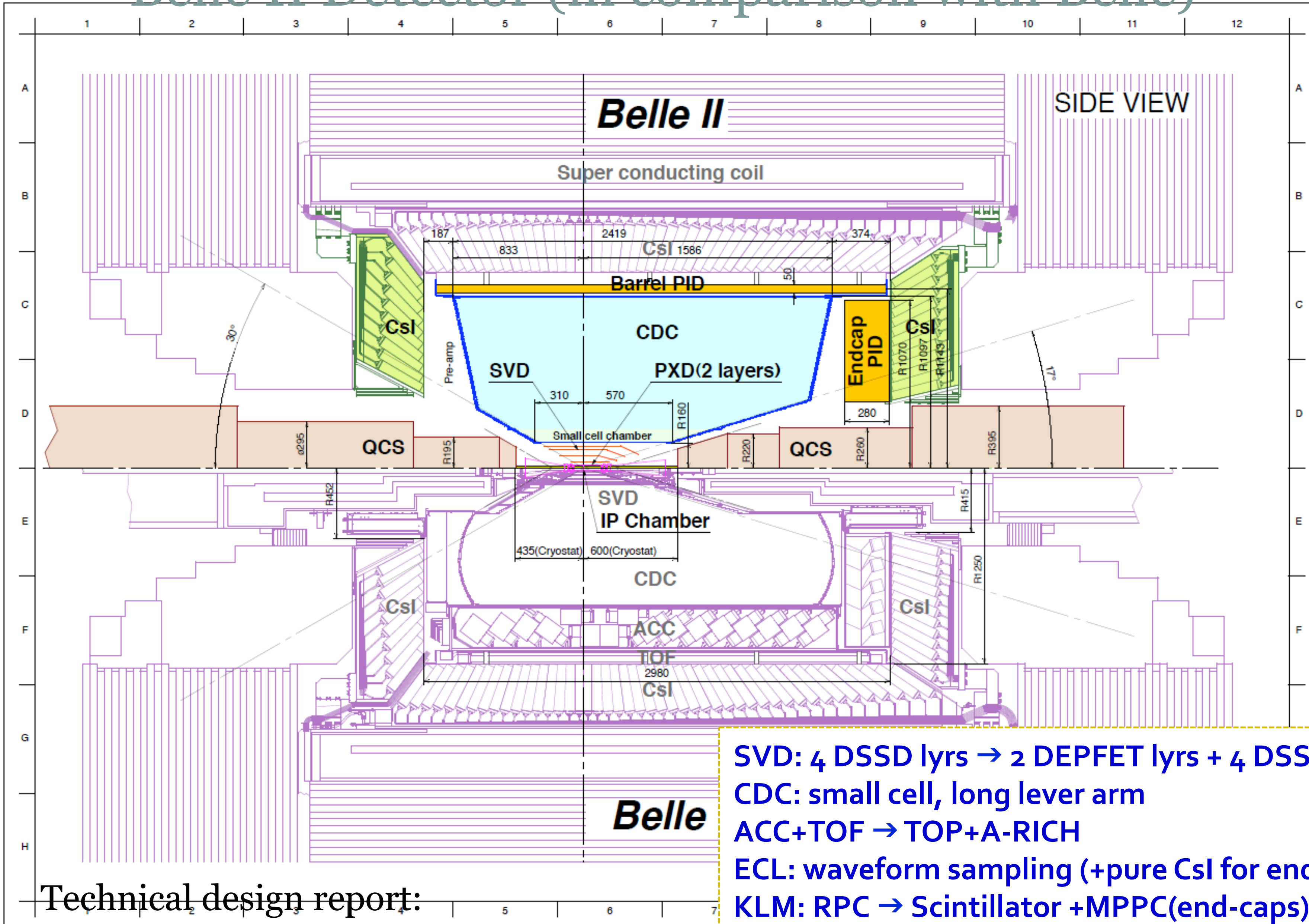
Start of comissioning in 2016

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



N.B. Schedule not up to date

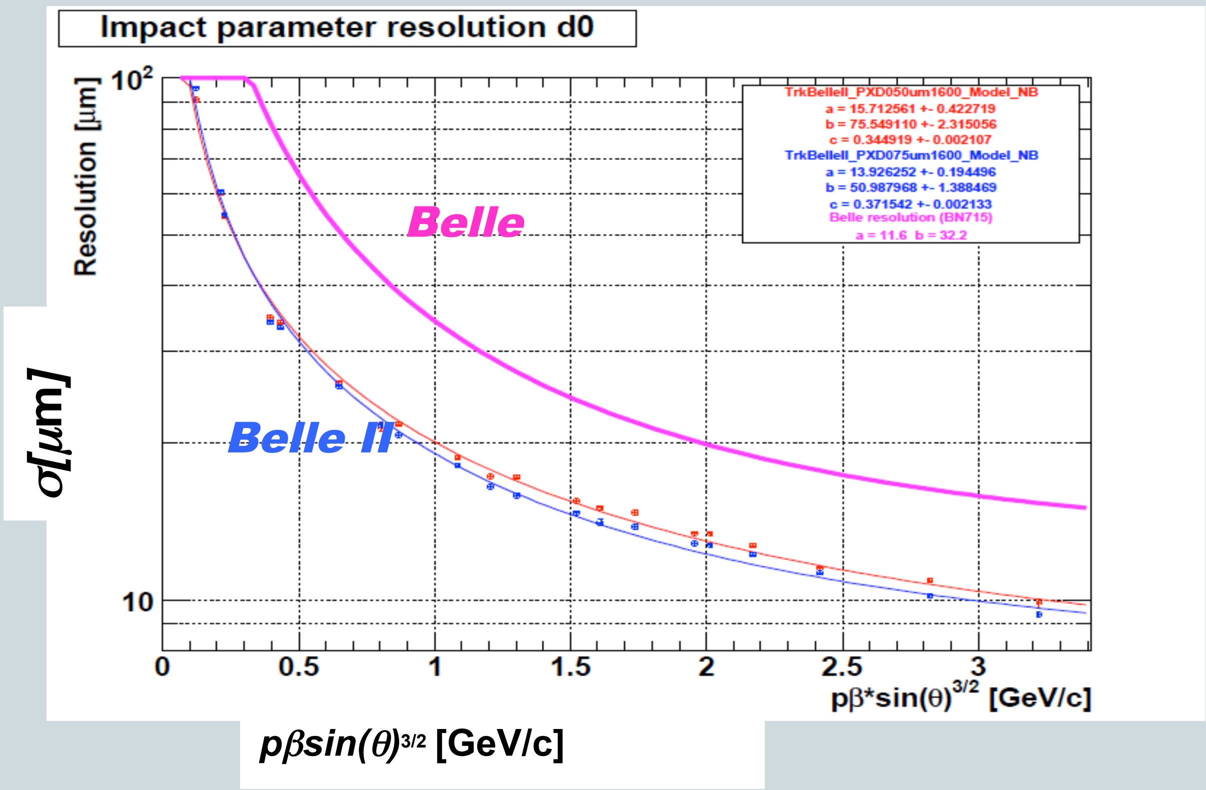
Belle II Detector (in comparison with Belle)



- 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)

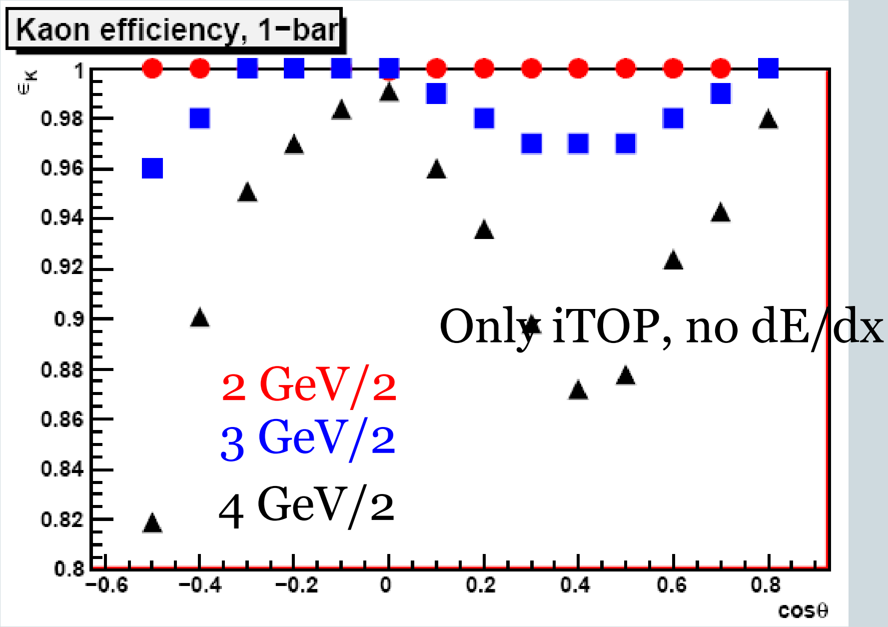
Technical design report: arXiv:1011.0352

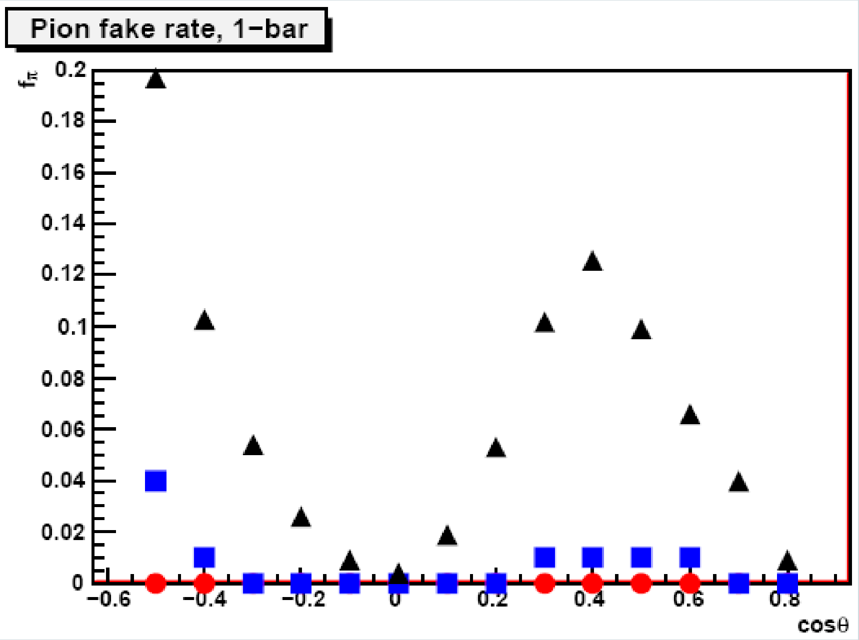
Improve Charm Discrimination with SVD&PXD



PID improvement with iTOP

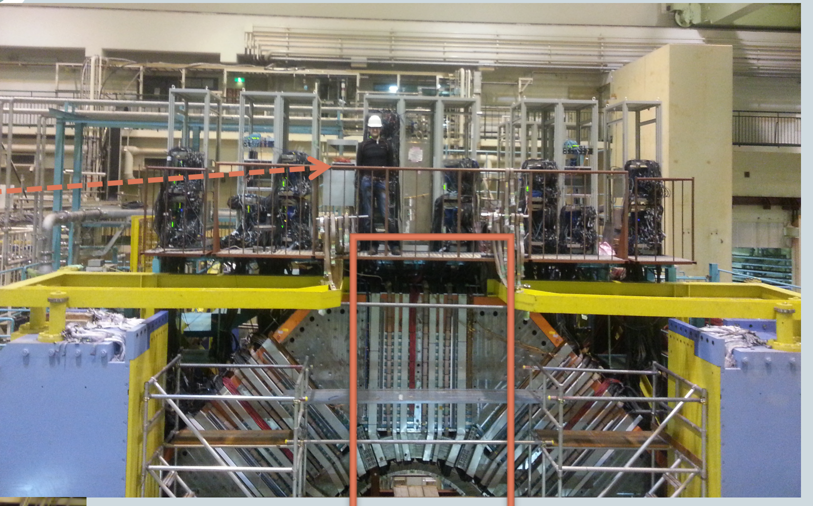
- Compare with ~85% efficiency for Belle

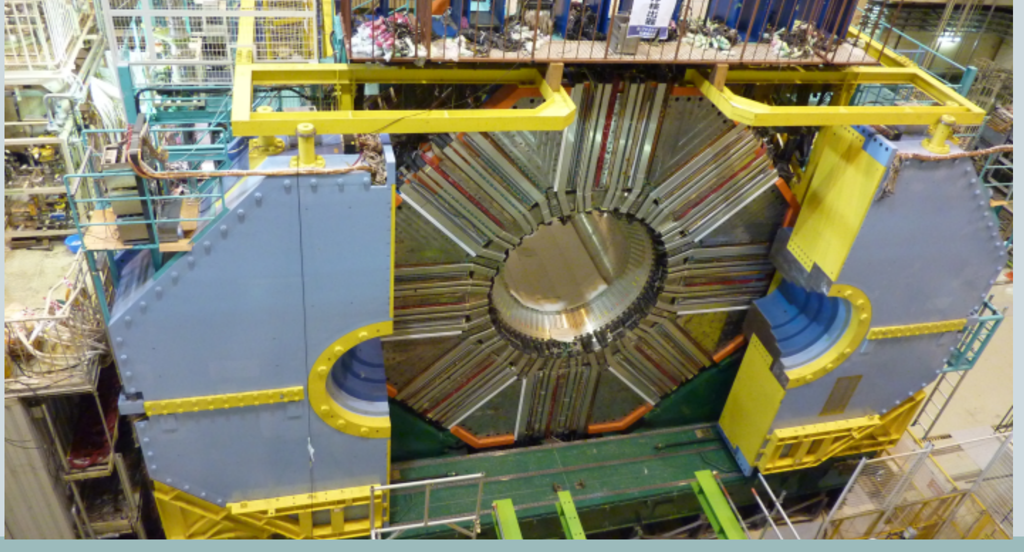




Last November at KEK….

Sector Test of KLM
(B Kunkler from IU)





Summary/Open Issues/Perspectives

- Experiments
  - **Multidimensional analysis** to account for phase space cut due to fiducial volume, e.g. differential in kT/θ
  - Differential kT/θ also needed for comparison between methods and experiments, e.g. match to kinematic phase space of SIDIS
  - Non-correlation measurements (kT spectra) have no zero tests
  - Do we need Double Ratios? (are physics background e.g. from gluon radiation neglígle?)
  - **Charm Correction**
- Theory
  - Jet/Thrust vs back-to-back
    - two scale vs one scale process
    - Evolution, gluon radiation different?
    - Jet radius (NCA or ~1.0)?
    - **Need to work out theory for jet/thrust method!**
  - Twist3 observables?
  - p+p Information
  - Kinematic "matching" between SIDIS, pp
  - Double ratio for $\pi/K\ \pi^0, \eta$?
- Outlook
  - Belle II will provide better PID, unbiased charm discrimination and boatloads of statistics

Di-hadrons

- Single inclusive hadron multiplicities (e+e-→hX) sum over all available flavors and quarks and antiquarks:

$$d\sigma(e^+e^- \to hX)/dz \propto \sum_q e_q^2 (D_{1,q}^h(z,Q^2) + D_{1,\bar{q}}^h(z,Q^2))$$

- Especially distinction between favored (ie u→π⁺) and disfavored (ū →π⁺) fragmentation would be important
- Idea: Use di-hadron fragmentation, preferably from opposite hemispheres and access favored and disfavored combinations:

$$u\bar{u} \to \pi^+\pi^- X \quad \propto \quad D_{u,fav}^{\pi^+}(z_1,Q^2)\cdot D_{\bar{u},fav}^{\pi^-}(z_2,Q^2) + D_{\bar{u},dis}^{\pi^+}(z_1,Q^2)\cdot D_{u,dis}^{\pi^-}(z_2,Q^2)$$

$$u\bar{u} \to \pi^+\pi^+ X \quad \propto \quad D_{u,fav}^{\pi^+}(z_1,Q^2)\cdot D_{\bar{u},dis}^{\pi^+}(z_2,Q^2) + D_{\bar{u},dis}^{\pi^+}(z_1,Q^2)\cdot D_{u,fav}^{\pi^+}(z_2,Q^2)$$

- Also: unpol baseline for interference fragmentation

N.B. Favored/Unfavored separation can also be done with polarized beam a
At sqrtS=M_Z0 (see SLD analysis)

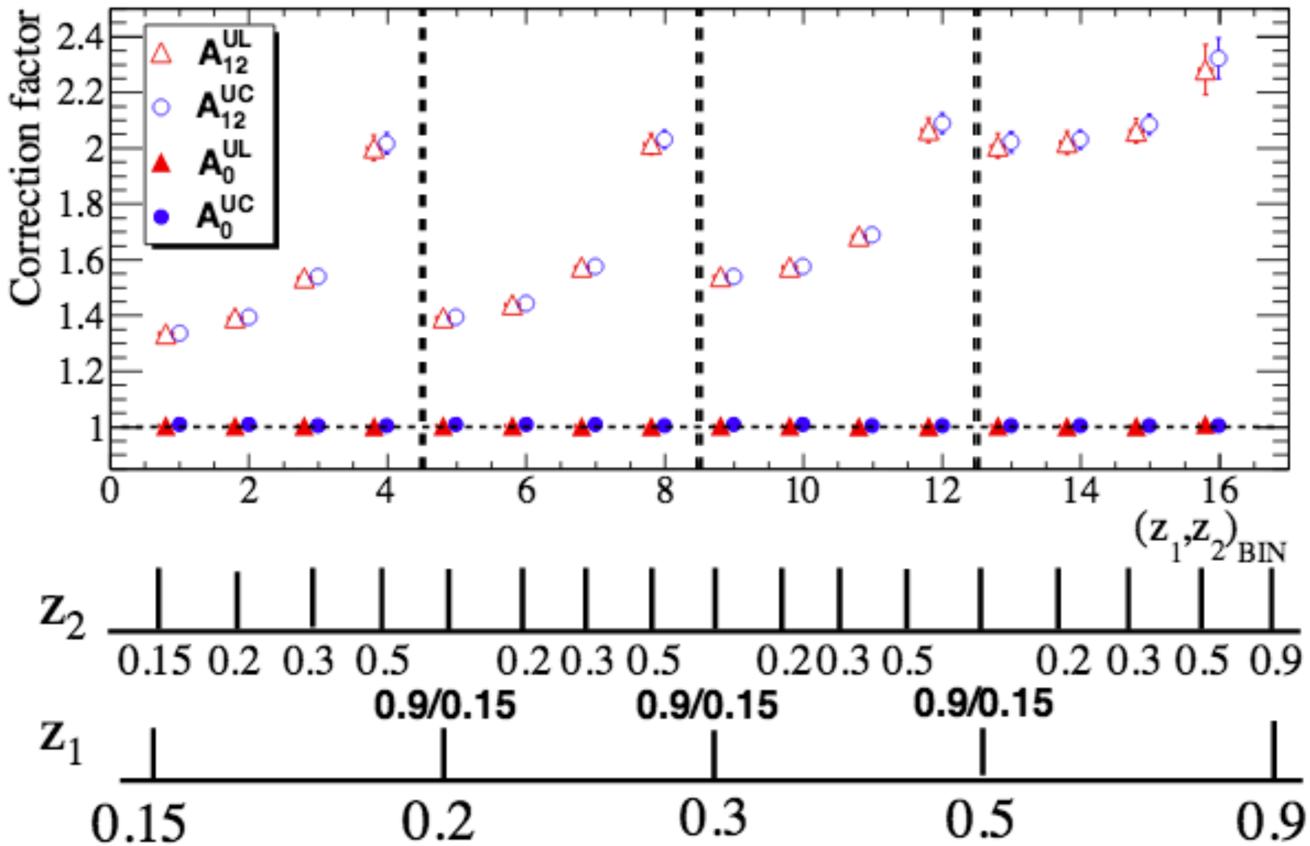
- e+e- needed for FF (precision) measurements
  - Backdraw →gluon, flavor (Z0 different from Y(4S))
  - Most data from Belle/Babar →udsc (ratios)
  - In particular important for FFs which couple at functions that are also unknown (transversity)
  - Or kT dependency (unknown in PDF)

  - FFs also basic QCD objects
    - E.g. universality tests, QCD vacuum structure, MLLA

- Experimental overview
- →Acceptance, kinematics? (jets ..?)
  - Do we have jet plots? Jet size.. →larger closer to quark, smaller better for narrow jet approximation (not important at Belle because partons do not overlap, but other experiments?)
- In principle unfolding? E.g. kT dependence not taken into account. Smearing is kT dependent z,kT correlation for smearing unfolding in principle…

- Measurements
  - Collins
  - IFF
  - Jet correlations
- Acceptance contributions?
- (unfolding etc? (look at hermes stuff…))

- Remember Belle II MC/Data plots.
- Point out importance of MC
  - (how used?) Comp plots by Ralf?



Correction factor
A_{12}^{UL}
A_{12}^{UC}
A_{0}^{UL}
A_{0}^{UC}
$(z_1,z_2)_{BIN}$
z_2
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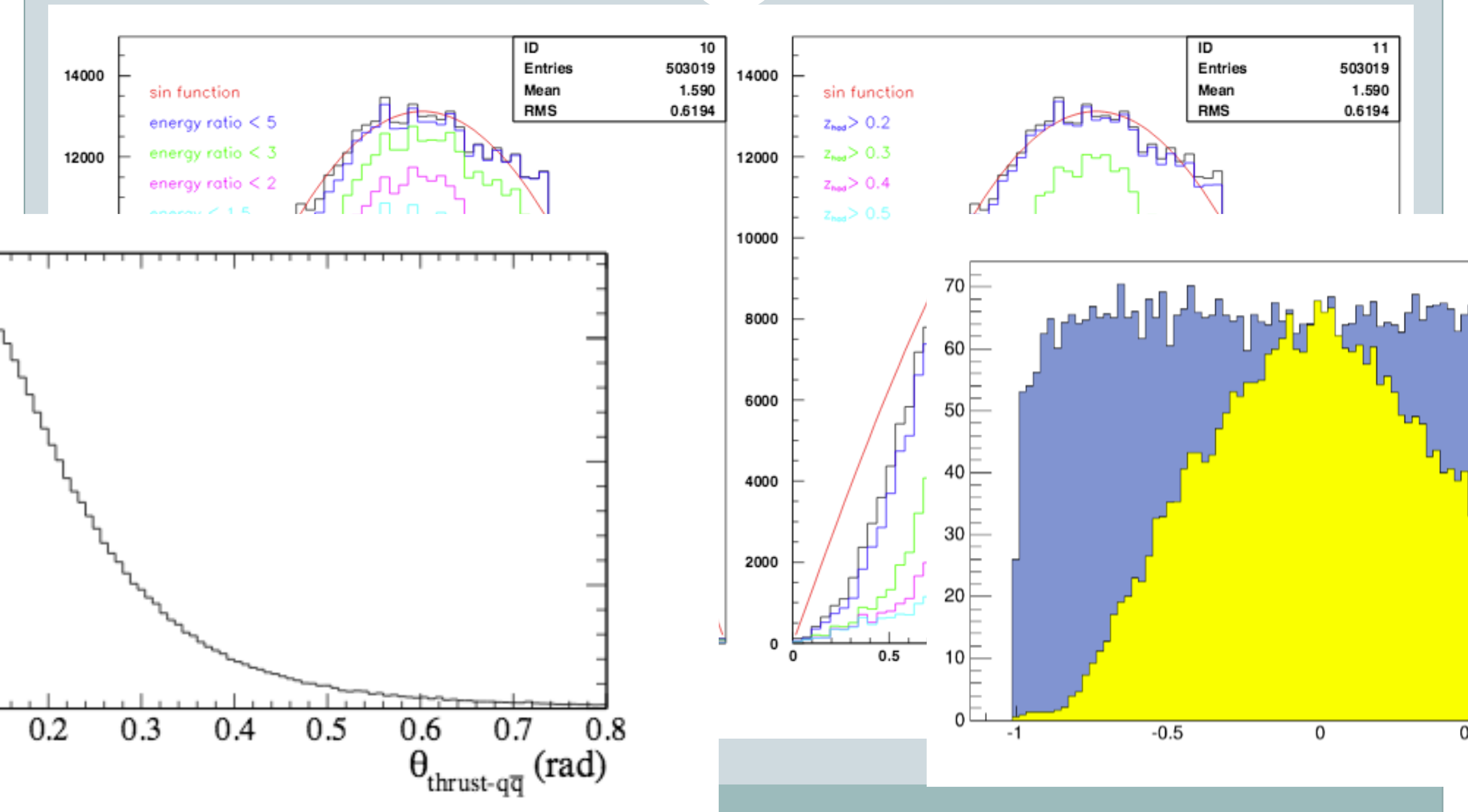
0.9/0.15 0.9/0.15 0.9/0.15
z_1
0.15 0.2 0.3 0.5 0.9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sin function
z_{had}> 0.2
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z_{had}> 0.5
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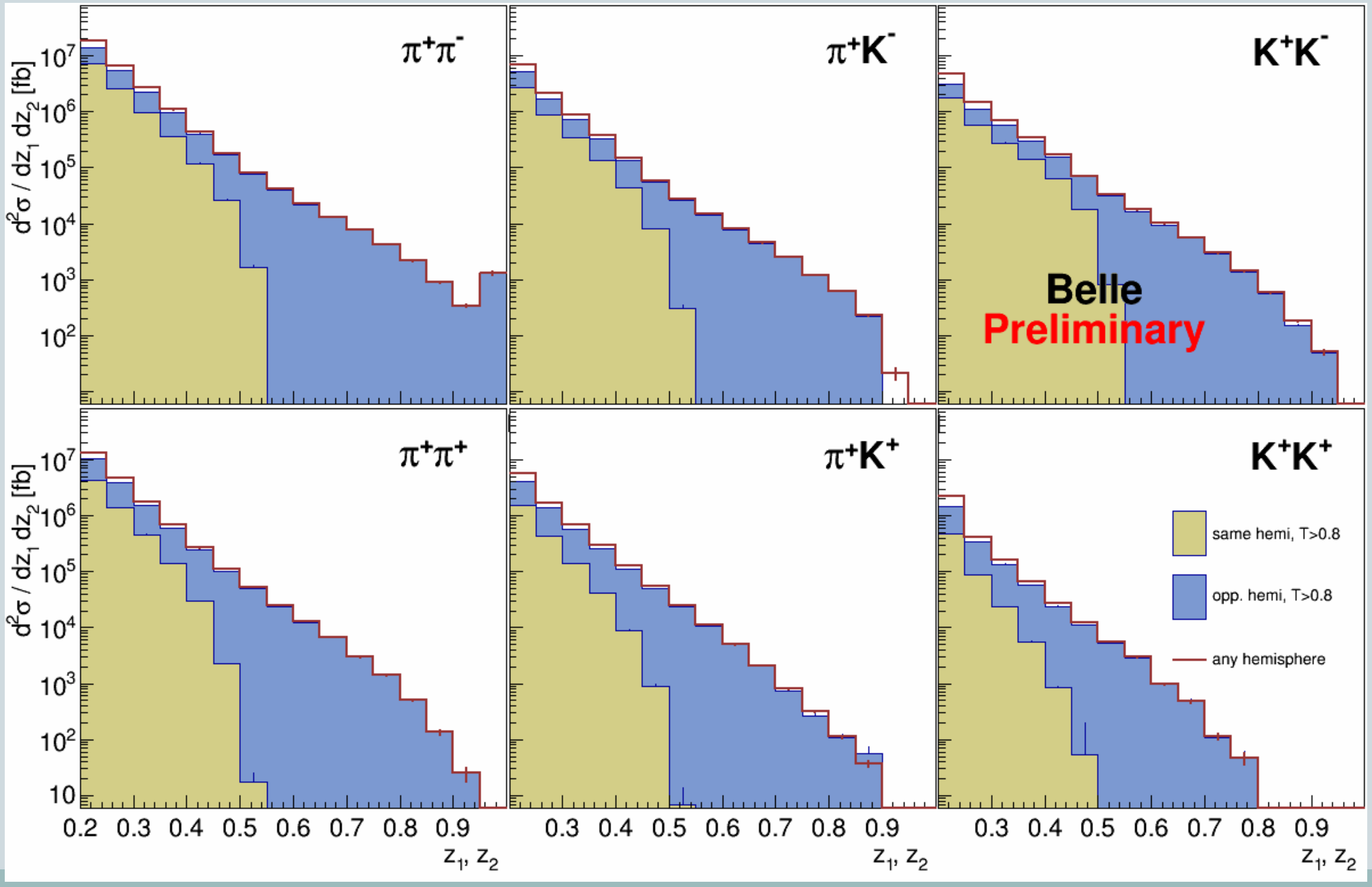
12000
10000
8000
6000
4000
2000
0
0
0.5
0.2 0.3 0.4 0.5 0.6 0.7 0.8
$\theta_{thrust\text{-}q\overline{q}}$ (rad)
70
60
50
40
30
20
10
0
-1
-0.5
0

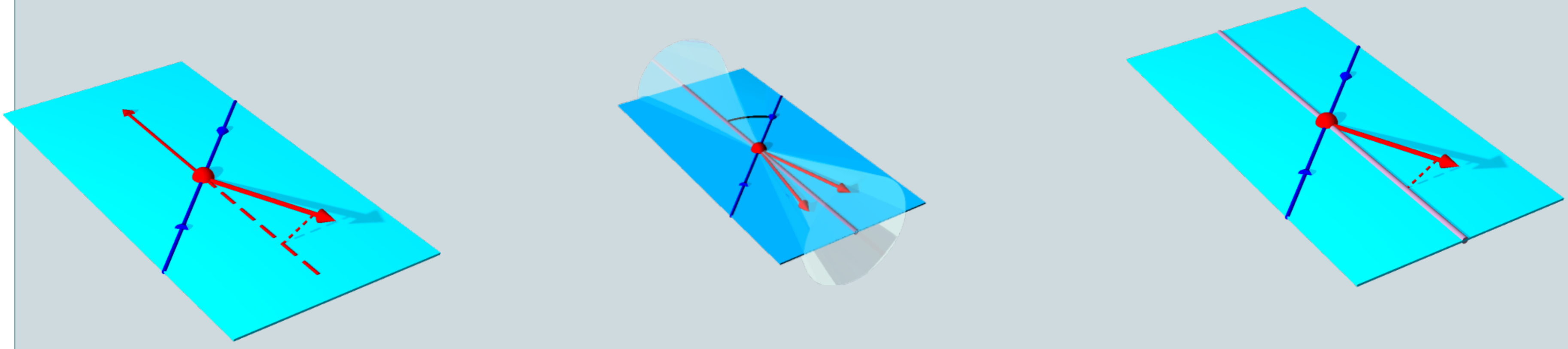
Hemisphere composition

Same hemisphere contribution drops rapidly
Consistent with LO assumption of
Same hemisphere: single quark → di-hadron FF: (z_1+z_2 <1)
Opposite hemisphere: single quark→single hadron FF

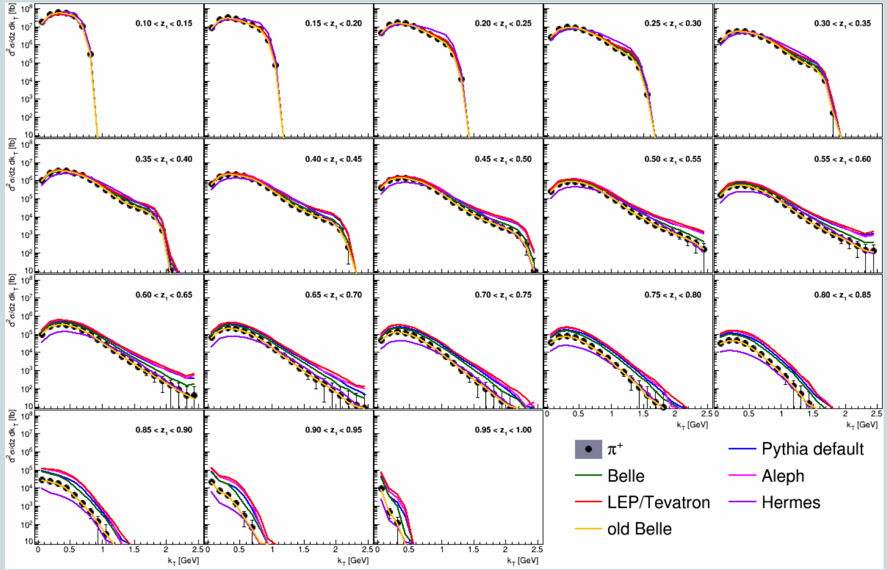


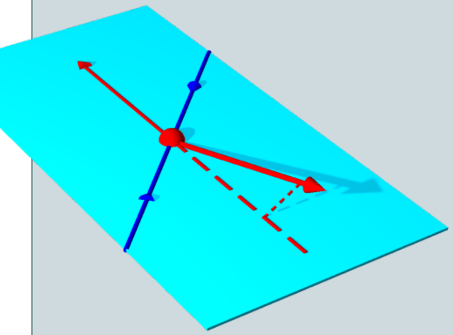
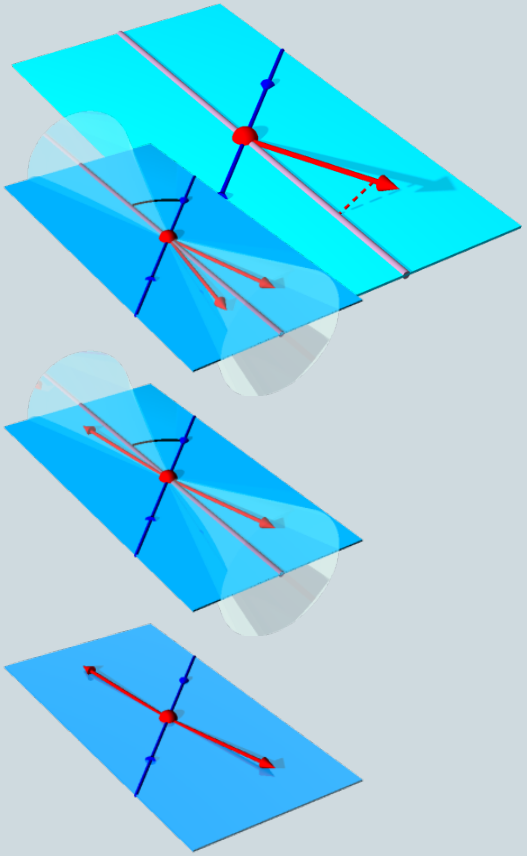
TMDs – Unpolarized D(z,kT)

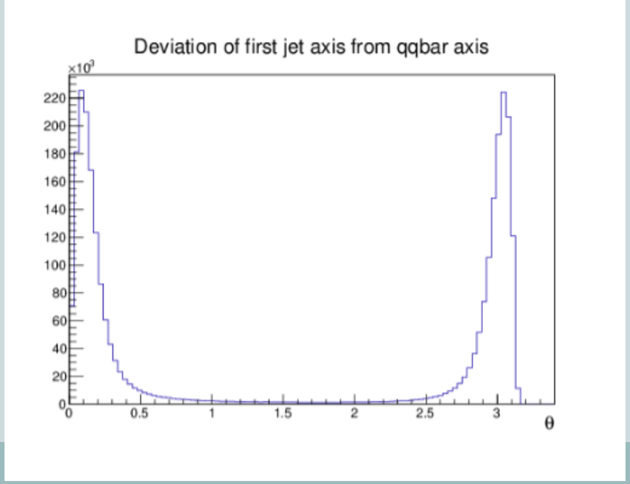
- Observables
  - Back-to-back Hadrons (relative kT) measures D(z,kT)xD(z,kT)
  - kT of one hadron relative to the quark axis (more indirect)
    - Relative to thrust? Jet?
    - Experimental issues (resolution)

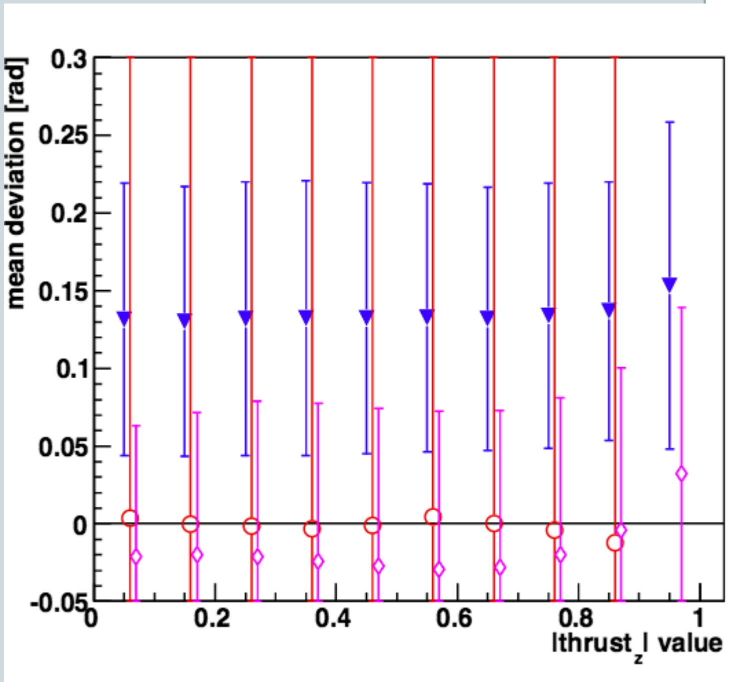


- Issues
  - Charm correction?
  - ISR correction?
  - If thrust or jet axis: z, kT unfolding

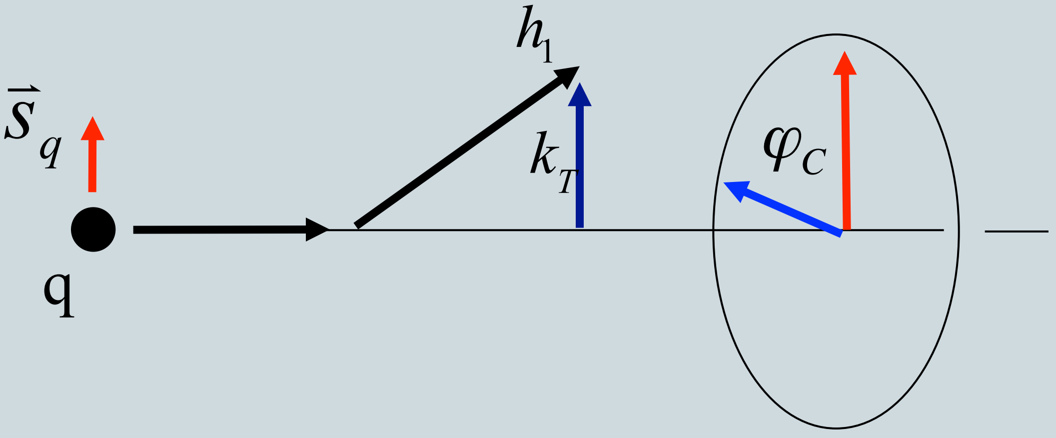


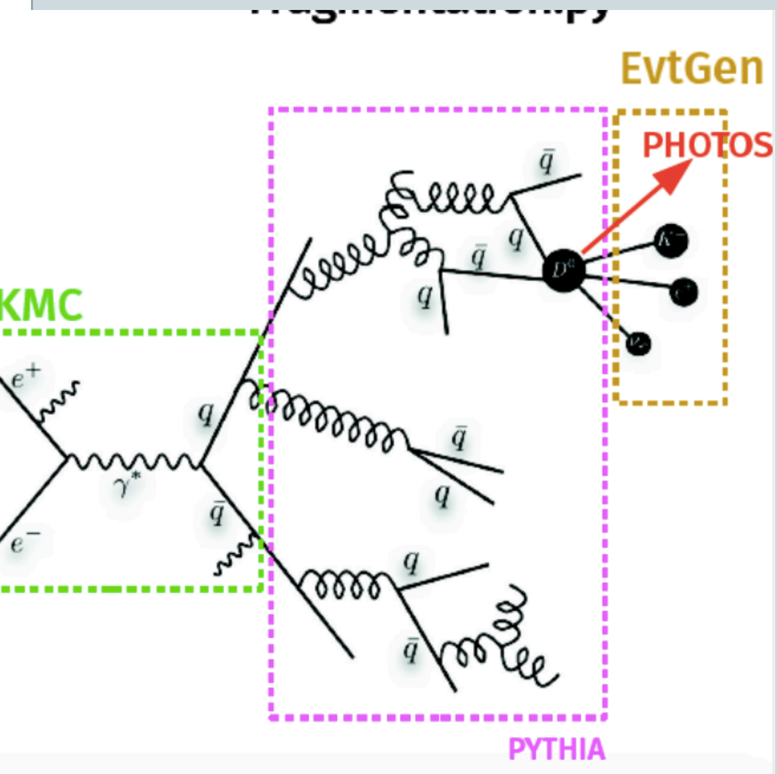



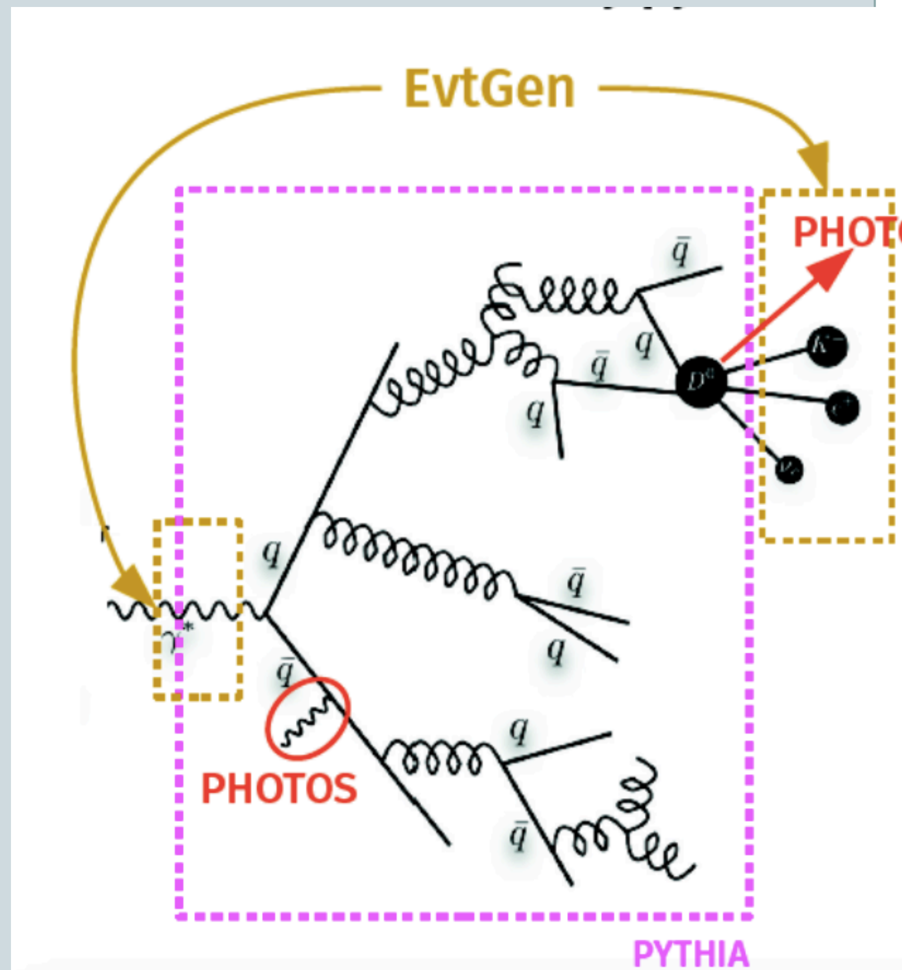

Deviation of first jet axis from qqbar axis
×10³
θ


mean deviation [rad]
|thrust_z| value

"Collins" Fragmentation Function for Identified Pions and Kaons




EvtGen
PHOTOS
KMC
PYTHIA


EvtGen
PHOTOS
PYTHIA

contributions

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

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

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

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

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

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

$$D^{fav}_{u\to K} = D_u^{K^+} = D_{\bar{u}}^{K^-}$$

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

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

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

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

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

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

Assuming charm contribute only as a dilution