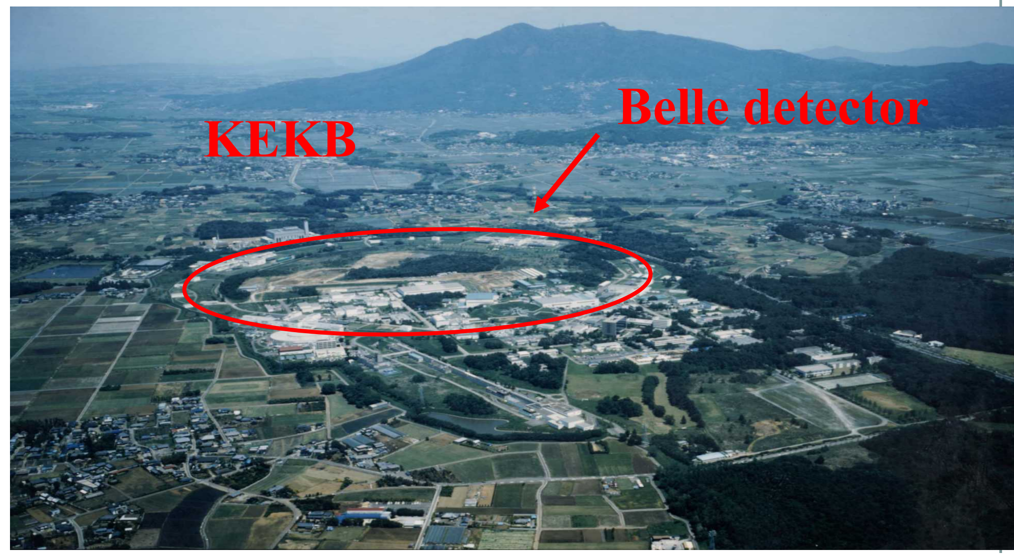
Fragmentation Functions at Belle

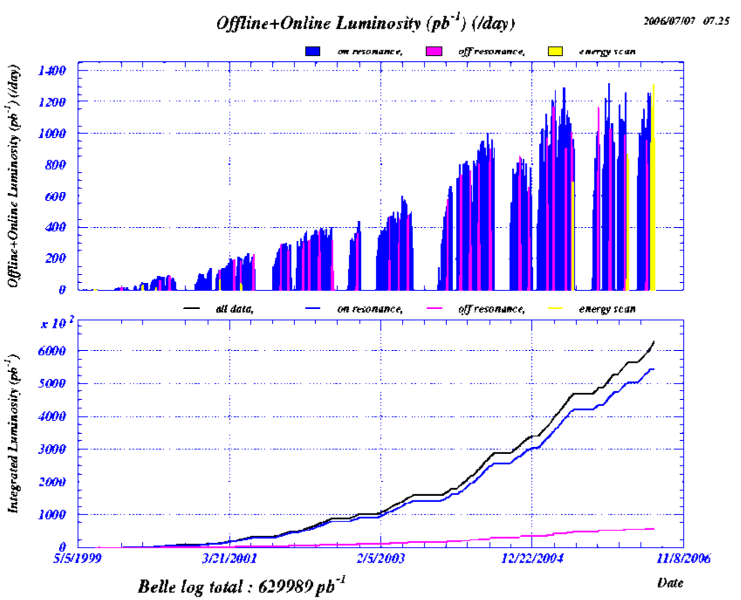
ANSELM VOSSEN

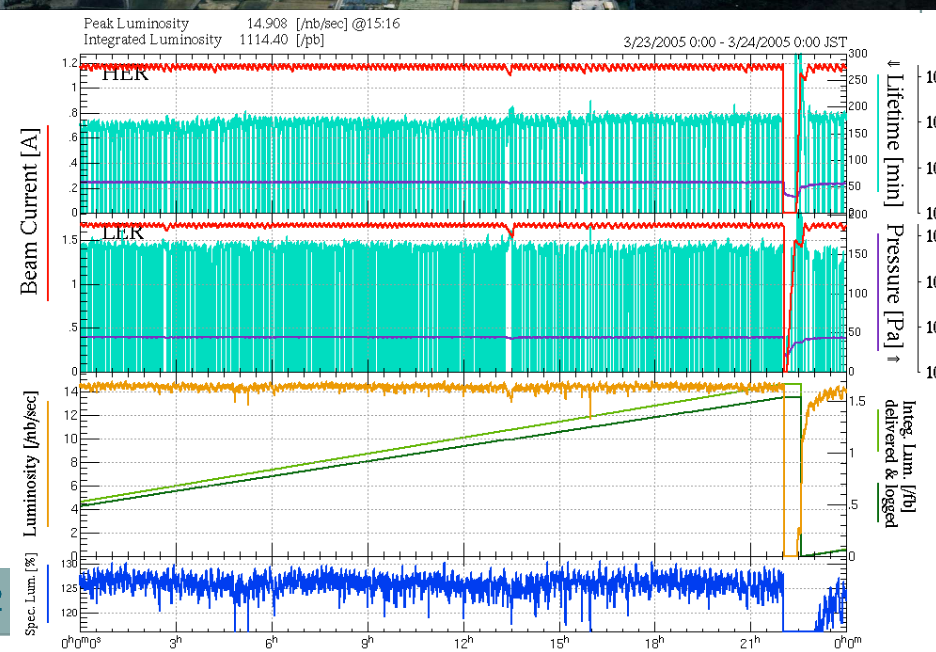
INDIANA UNIVERSITY

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

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







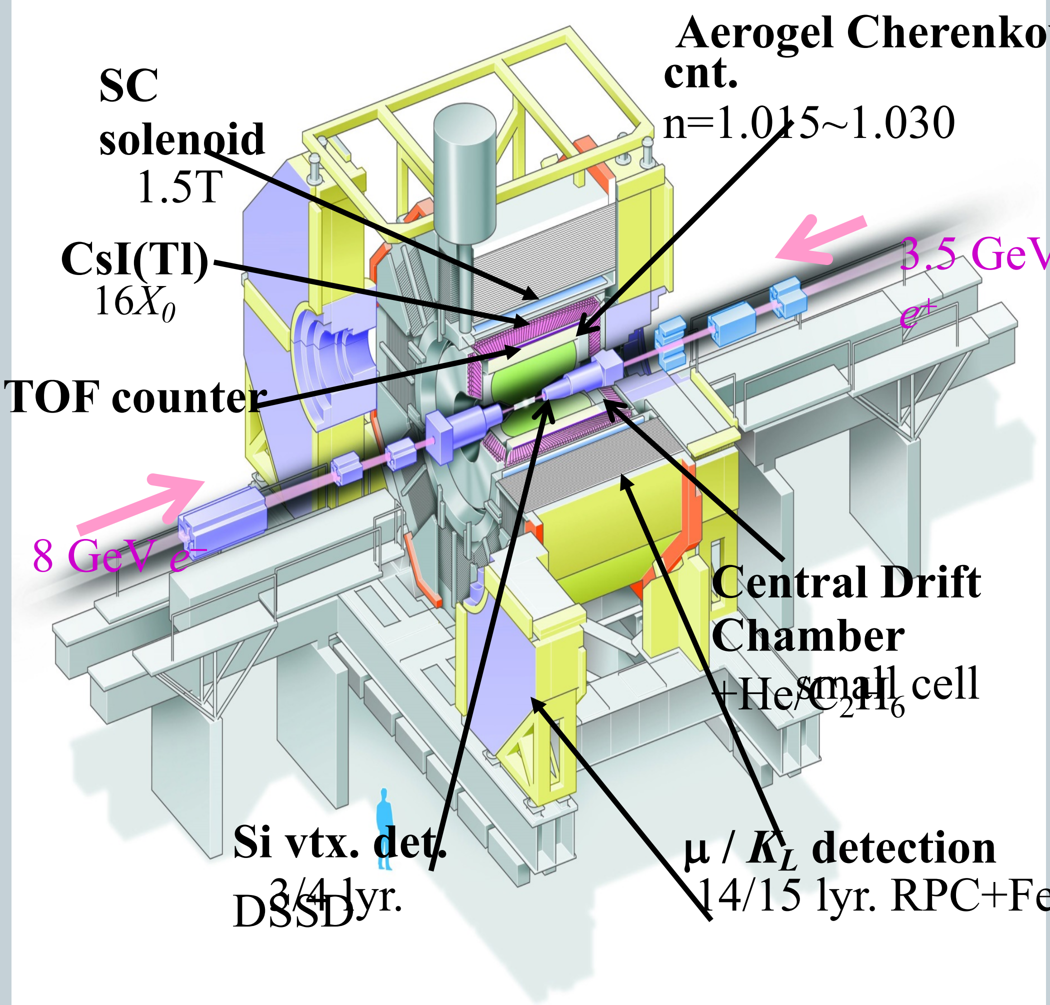
Belle, a typical e+e- Experiment of generation 2000

- Asym. e^+ (3.5 GeV) e^- (8 GeV) collider:
  - $\sqrt{s}$ = **10.58 GeV**, $e^+e^- \to Y(4S) \to B$ anti-B
  - $\sqrt{s}$ = 10.52 GeV, $e^+e^- \to$ 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,

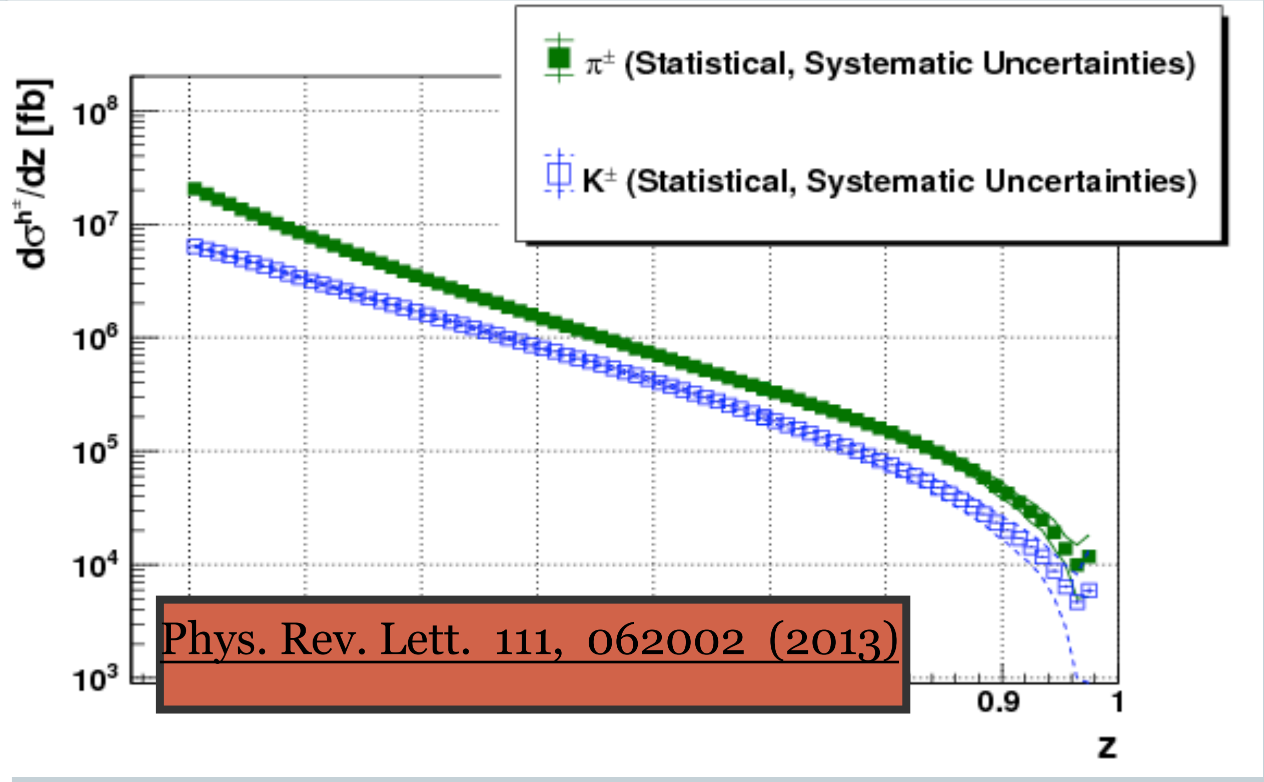
~220 $*10^6$ events at 10.52 GeV



Cross sections

$i = \pi, K$

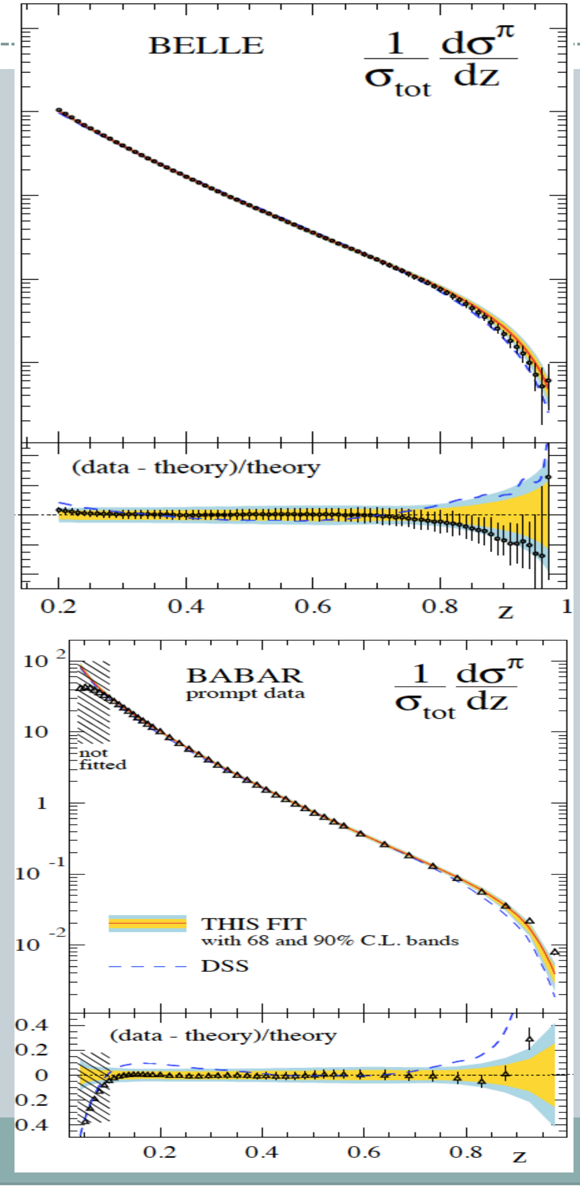
$$\frac{d\sigma_i}{dz} = \frac{1}{L_{tot}} \; \epsilon^i_{joint}(z)\, \epsilon^i_{ISR/FSR}(z)\, S^{-1}_{zz_m}\, \epsilon^i_{impu}(z_m)\, P^{-1}_{ij} N^{j,raw}(z_m)$$



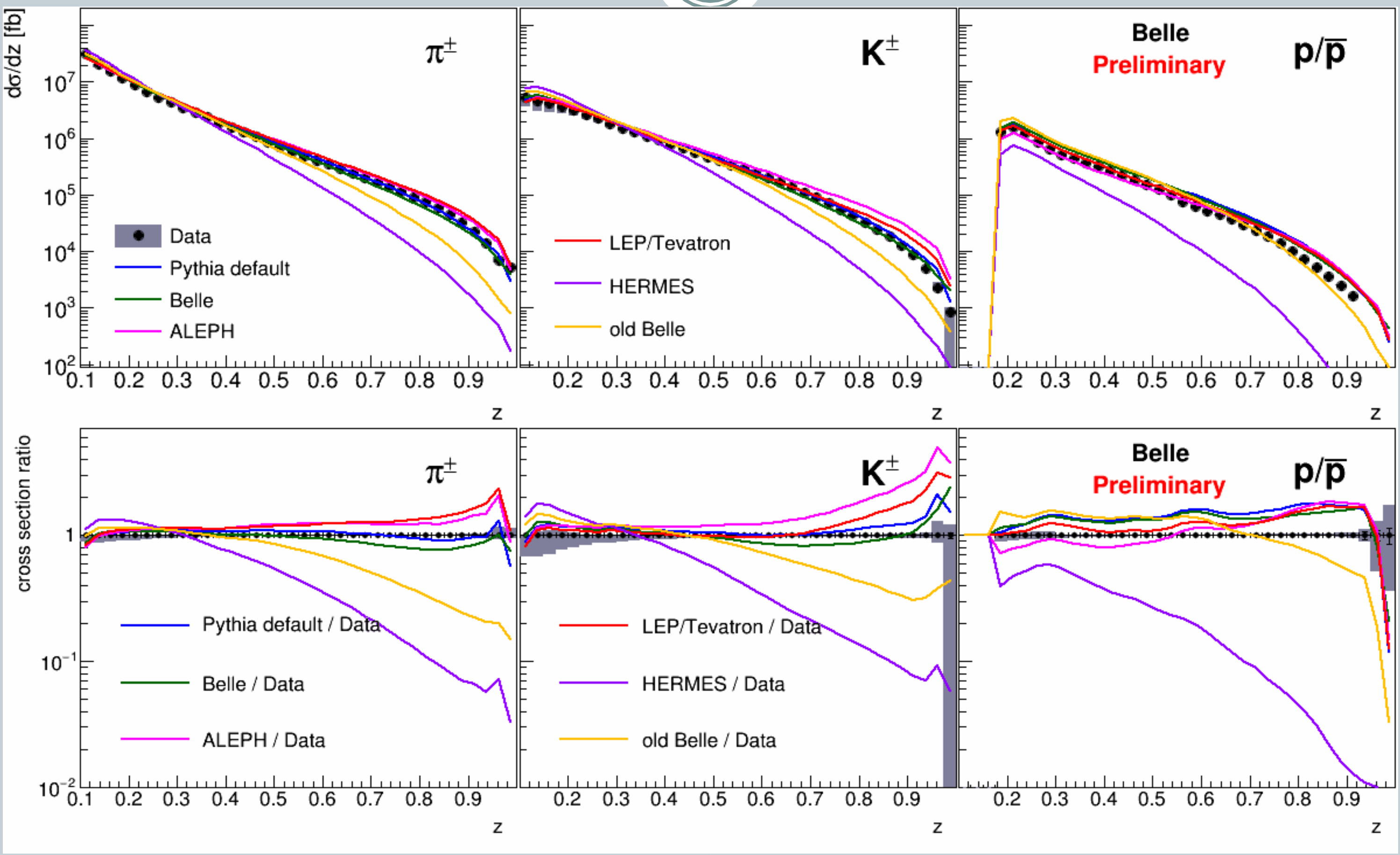
Phys. Rev. Lett. 111, 062002 (2013)

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



New addition: single protons



- Default Pythia and current Belle in good agreement with pions and kaons
- Protons not well described by any tune

Di-hadrons

In e^+e^- annihilation:

$$Q = \sqrt{s}$$
$$z = \frac{2E_h}{Q} \approx \frac{E_h}{E_q}$$

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

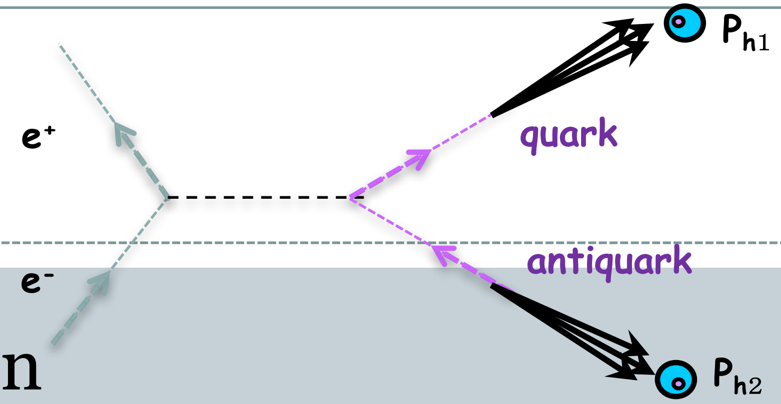
$$d\sigma(e^+e^- \to hX)/dz \propto \sum_q e_q^2 (D_{1,q}^h(z,Q^2) + D_{1,\overline{q}}^h(z,Q^2))$$

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

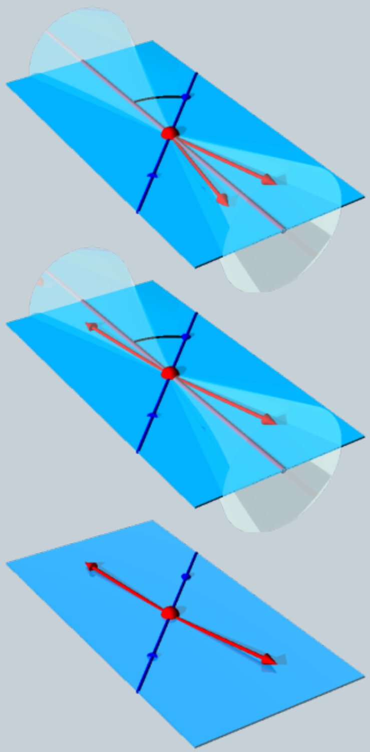
$$u\overline{u} \to \pi^+\pi^-X \quad \propto \quad D_{u,fav}^{\pi^+}(z_1,Q^2)\cdot D_{\overline{u},fav}^{\pi^-}(z_2,Q^2) + D_{\overline{u},dis}^{\pi^+}(z_1,Q^2)\cdot D_{u,dis}^{\pi^-}(z_2,Q^2)$$
$$u\overline{u} \to \pi^+\pi^+X \quad \propto \quad D_{u,fav}^{\pi^+}(z_1,Q^2)\cdot D_{\overline{u},dis}^{\pi^+}(z_2,Q^2)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

- Also: unpol baseline for interference fragmentation

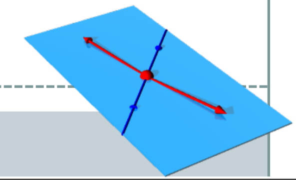
Setup



- 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



Results for diagonal z_1 z_2 bins

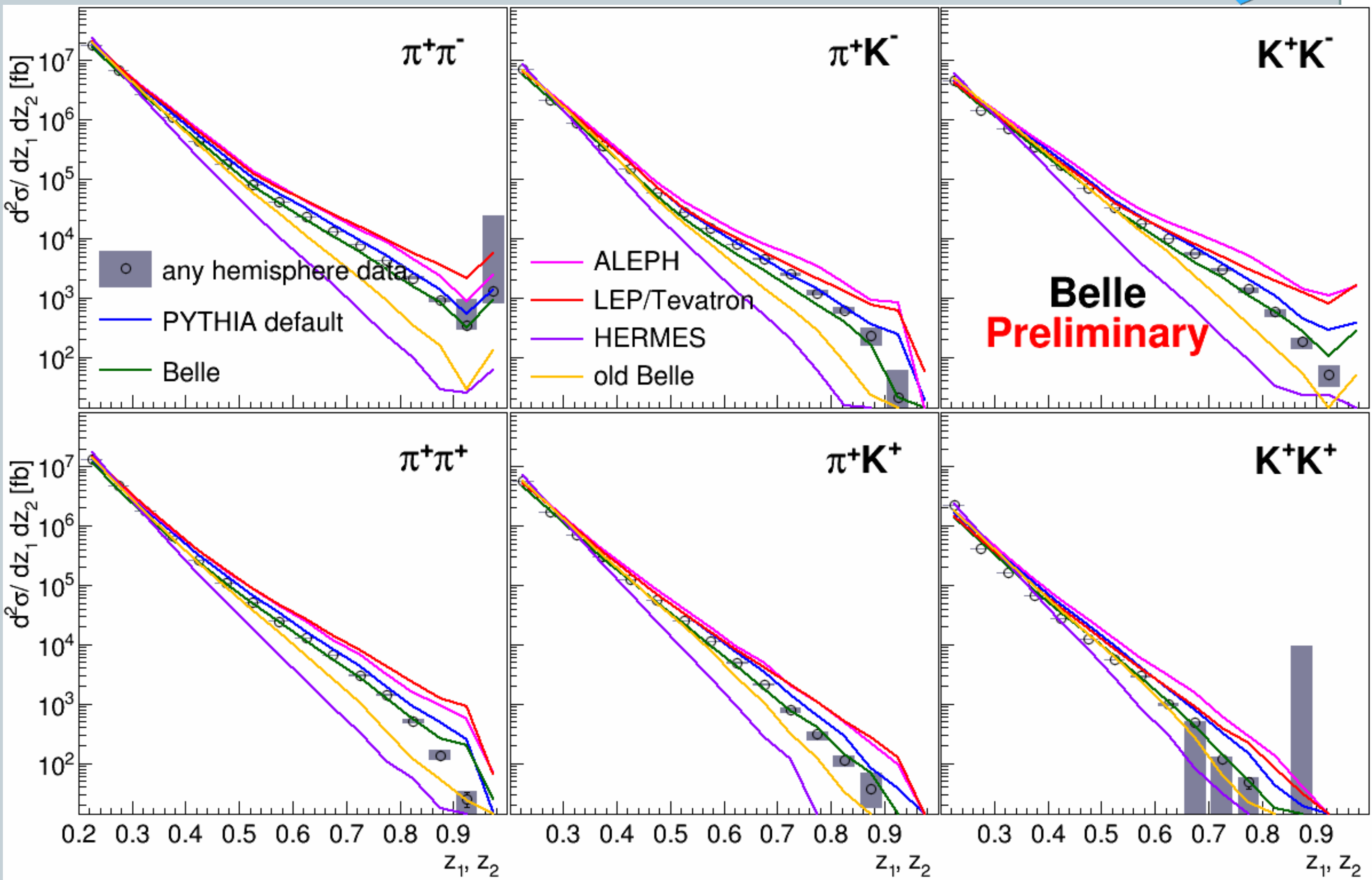


Diagonal z_1,z_2 bins

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



Pythia 6.2 embedded in EvtGen (see Phys.Rev. D92 (2015) no.9, 092007)

Spin dependent fragmentation

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

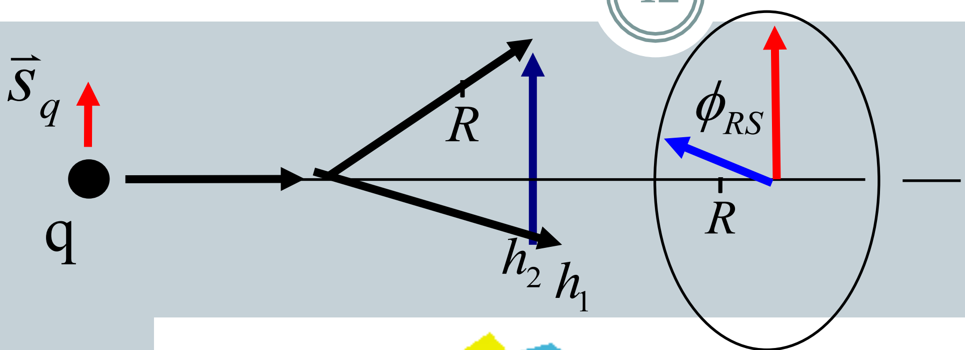
$$H_{1,q}^{h_1,h_2,\sphericalangle}(z, Q^2, M_h)$$

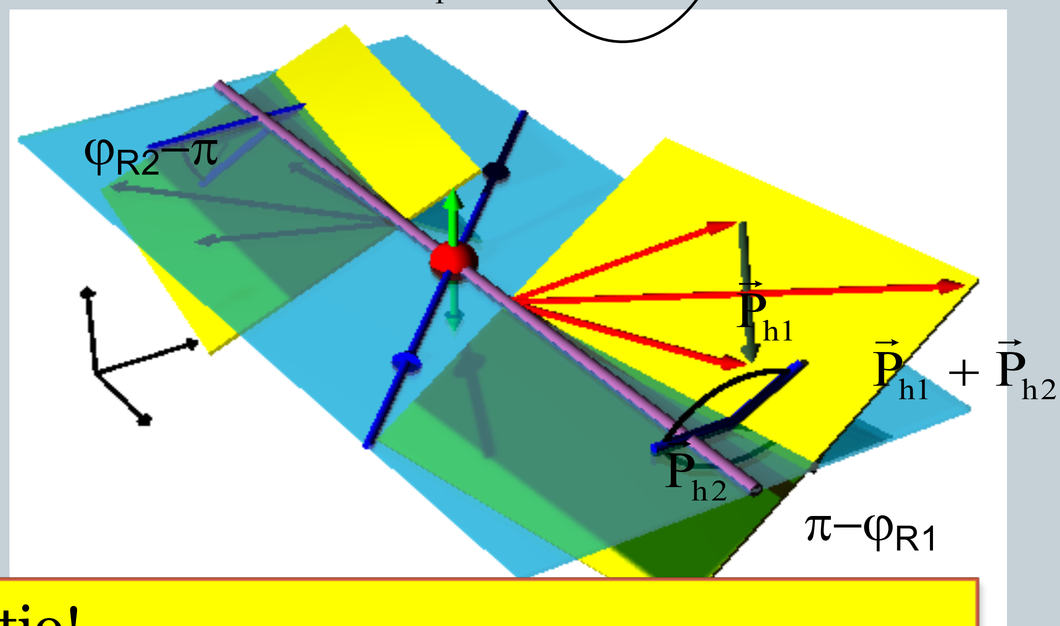
Spin dependent fragmentation

See Yesterday's Talk!

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

Di-Hadron Fragmentation

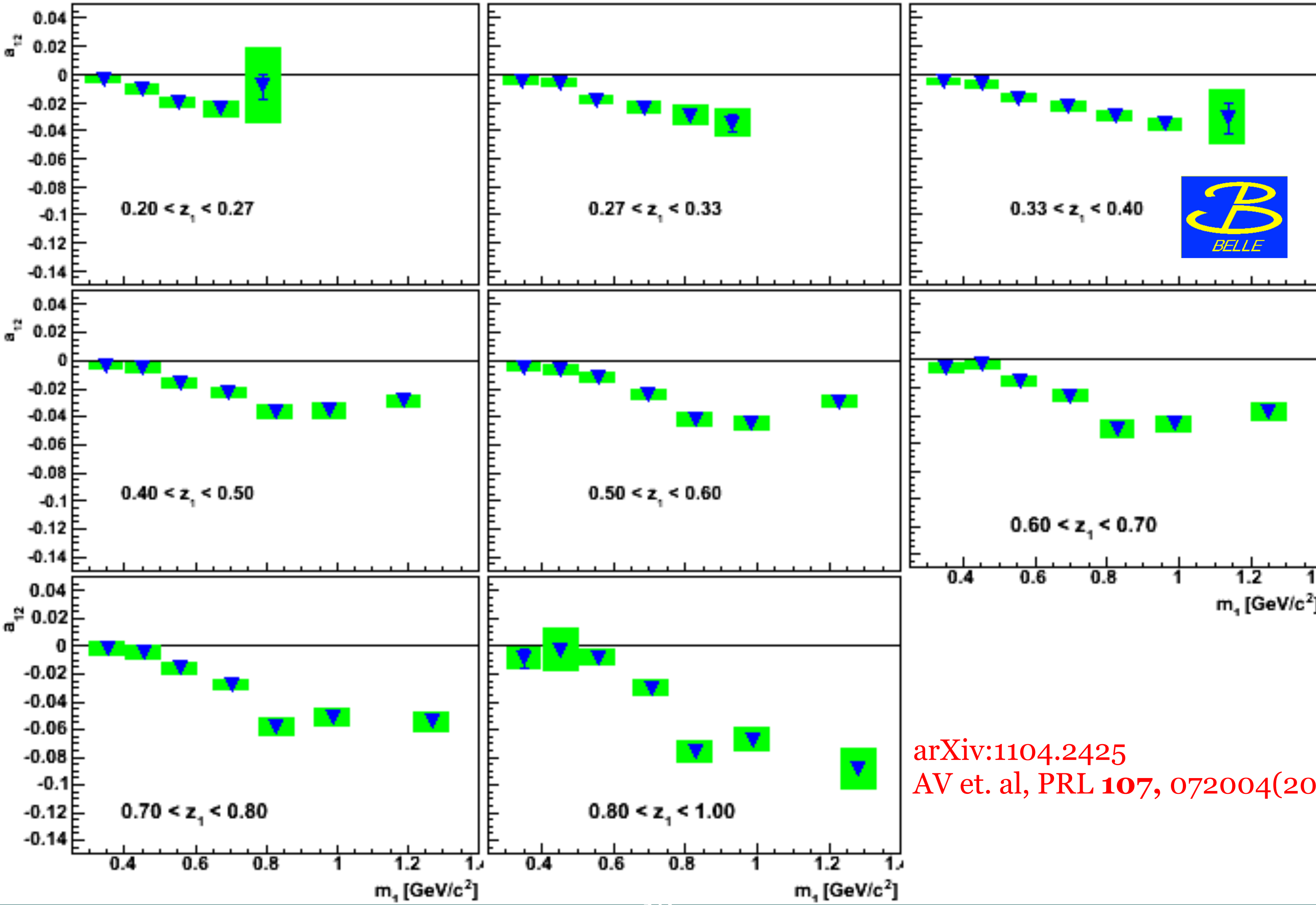




- No Double Ratio!
- Collinear: Theoretical advantages, e.g. evolution
- Experimentally easier in *pp* (no jet reconstruction)

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) 094003]: 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

- 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

from Boer,Jakob,Radici[PRD 67,(2003) 094003]

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

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

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

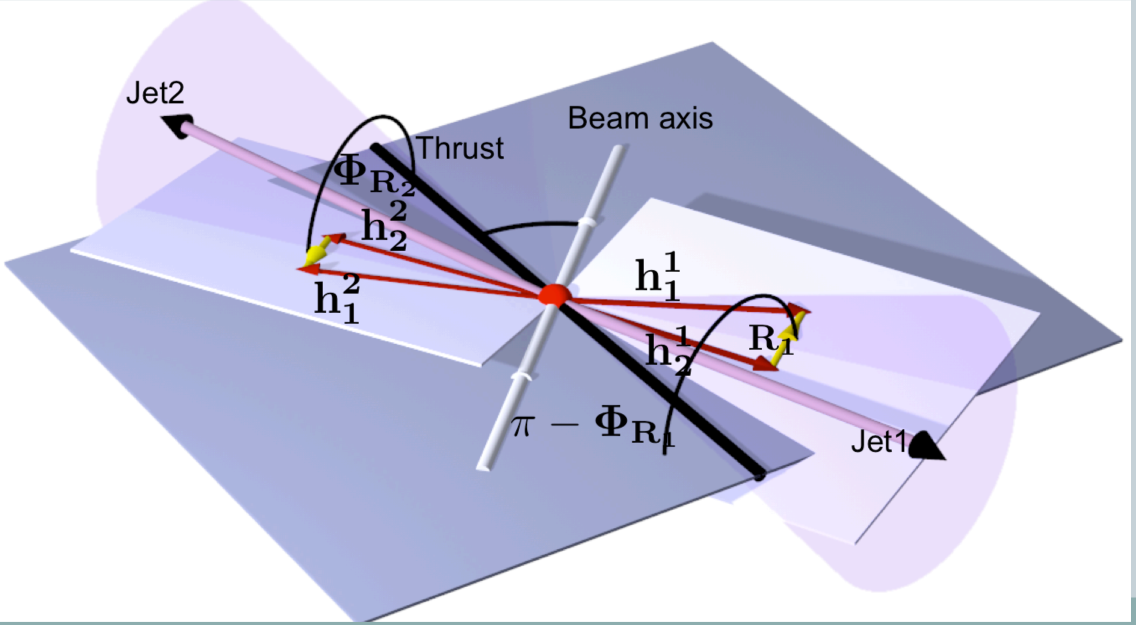
$$\langle\cos(2(\phi_R-\phi_{\overline{R}}))\rangle = \sum_{a,\overline{a}} e_a^2\,\frac{3\,\alpha^2}{2Q^2}\,z^2\overline{z}^2\,A(y)\,\frac{1}{M_1M_2\overline{M}_1\overline{M}_2}\,G_1^{\perp a}(z,M_h^2)\,\overline{G}_1^{\perp a}(\overline{z},\overline{M}_h^2)\,.$$

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

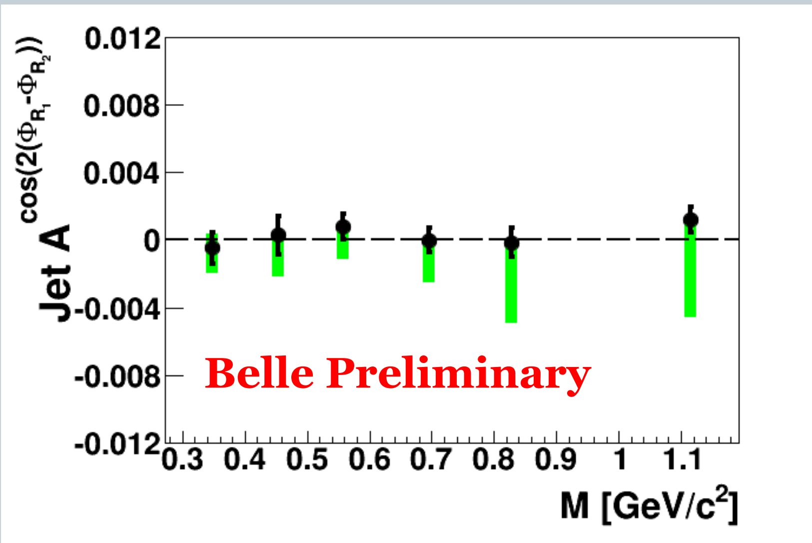
Measure $\cos(\phi_{R1}+\phi_{R2})$, $\cos(2(\phi_{R1}-\phi_{R2}))$ Modulations

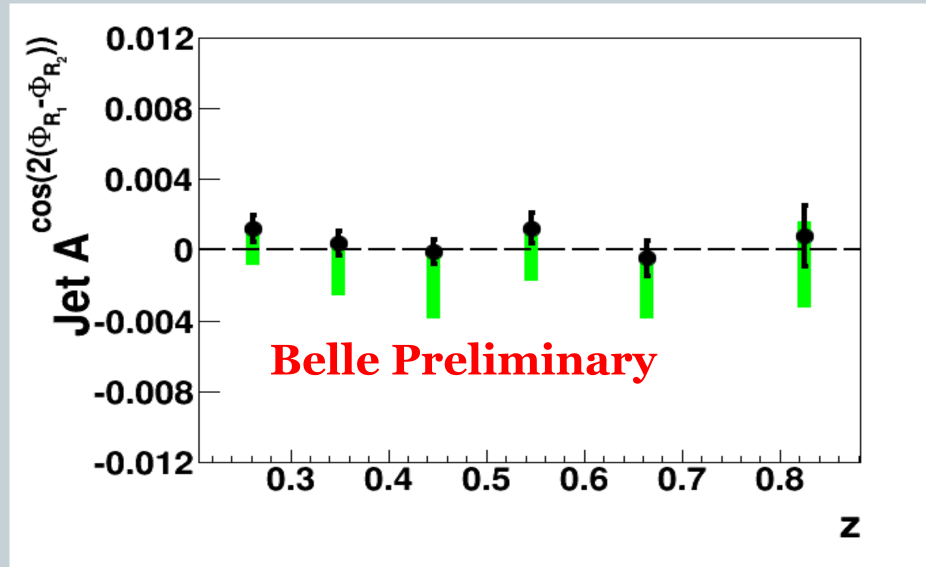
New: Use Jet Reconstruction at Belle

- 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



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

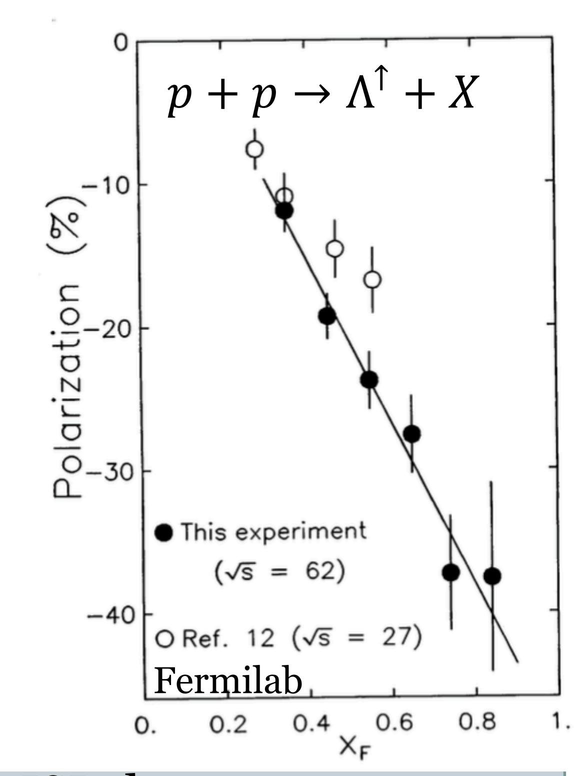




- No evidence of local p-odd effects yet
- Next step: partial wave analysis

Polarized Hyperon Production (see Y. Guan @ SPIN2016 & arXiv:1611.06648)

- Large Λ transverse polarization in unploarized pp collision **PRL36, 1113 (1976); PRL41, 607 (1978)**
- Caused by polarizing FF $D_{1T}^{\perp}(z, p_{\perp}^2)$?
- Polarizing FF is chiral-even, has been proposed as a test of universality. **PRL105,202001（2010）**
- OPAL experiment at LEP has been looking at transverse Λ polarization, no significant signal was observed. **Eur. Phys. J. C2, 49 (1998)**

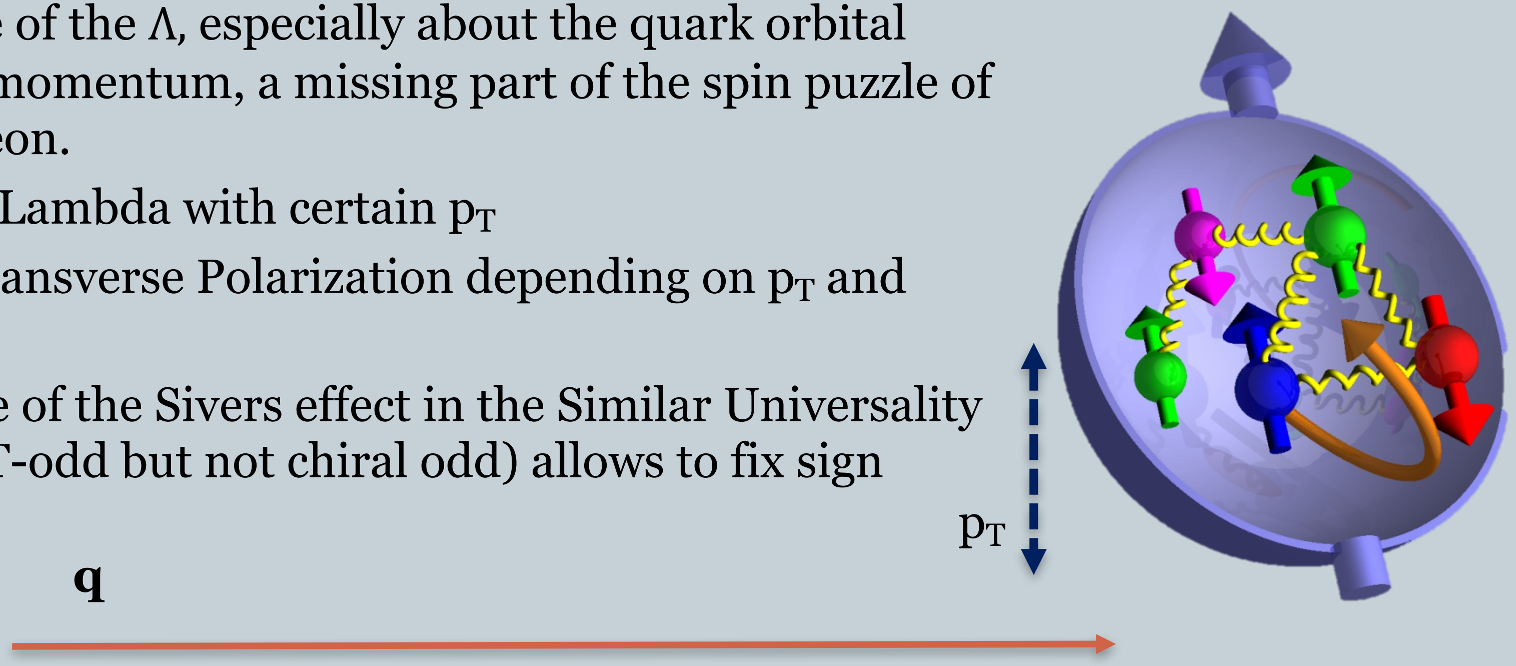


ISR data
(Phys.Lett. B185 (1987) 209)

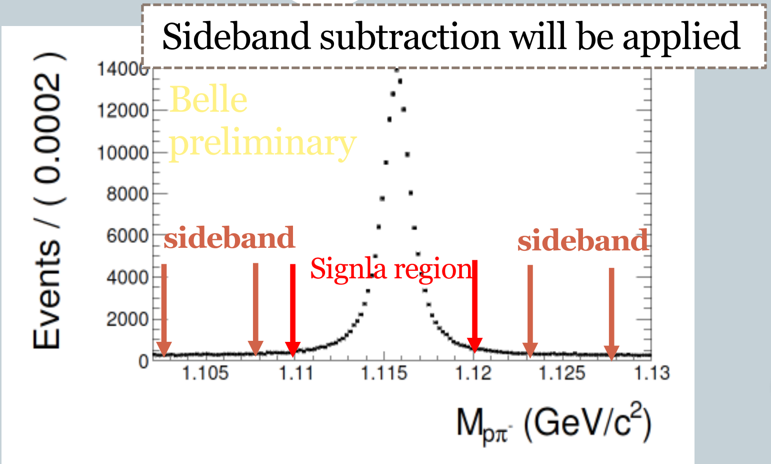
$x_F = p_L / \max p_L \sim_{LO} x_1 - x_2 \sim_{forward} x_1$

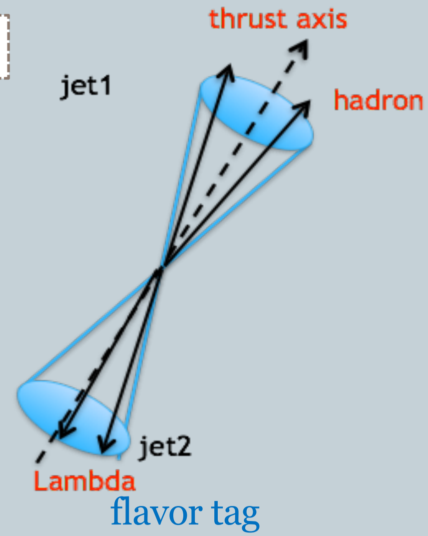
Hyperon Production as a tool to study baryon spin structure

- Lambda polarization allows to study spin-orbit correlation of quarks inside Baryon → counterpart of the Sivers parton distribution function (k_T dependence of quark distributions in transversely polarized proton)
- A non-vanishing $D_{1T}^{\perp}$ could help to shed light on the spin structure of the Λ, especially about the quark orbital angular momentum, a missing part of the spin puzzle of the nucleon.
- Produce Lambda with certain p_T
- Check Transverse Polarization depending on p_T and flavor
- Analogue of the Sivers effect in the Similar Universality checks (T-odd but not chiral odd) allows to fix sign



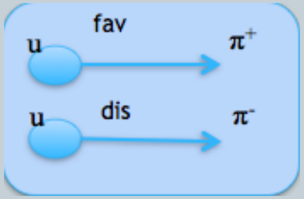
Lambda Reconstruction





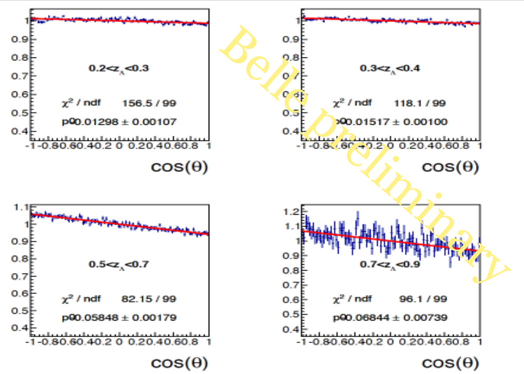
- Signal process $\Lambda \to p\pi^-(\bar{\Lambda} \to \bar{p}\,\pi^+)$. Clear Λ peak.
- Detect light hadron $(K^{\pm}, \pi^{\pm})$ in the opposite hemisphere→ enhance or suppress different flavors fragmenting in $\Lambda(\bar{\Lambda})$.

Λ(uds); $\pi^+(\mathrm{u}\bar{d})$; K^+ $(\mathrm{u}\bar{s})$

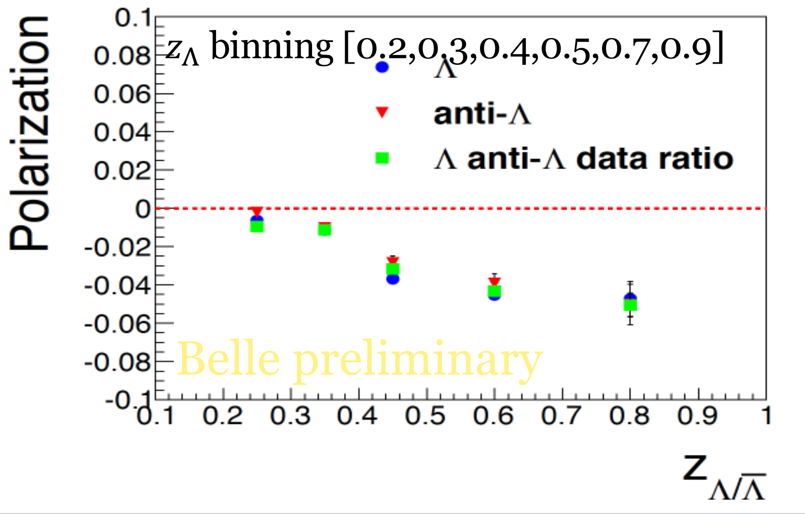


Fits and Extract polarization

- Fit to the cosθ distributions with $1 + p_0 cos\theta$.
- The polarization of interest: p_0/α.
- In the data ratio, polarization is obtained via $p_0/(\alpha_+ - \alpha_-)$.
- In data ratios, the slope on the cosθ distributions are about two times larger than that in MC-corrected ratios, the $(\alpha_+ - \alpha_-)$ is also about times larger than $\alpha_+(\alpha_-)$.
- Results from MC-corrected ratio and data ratio are consistent with each other.
- Nonzero polarization, magnitude rises to about ~5% with $z_\Lambda = 2E_\Lambda/\sqrt{s}$.

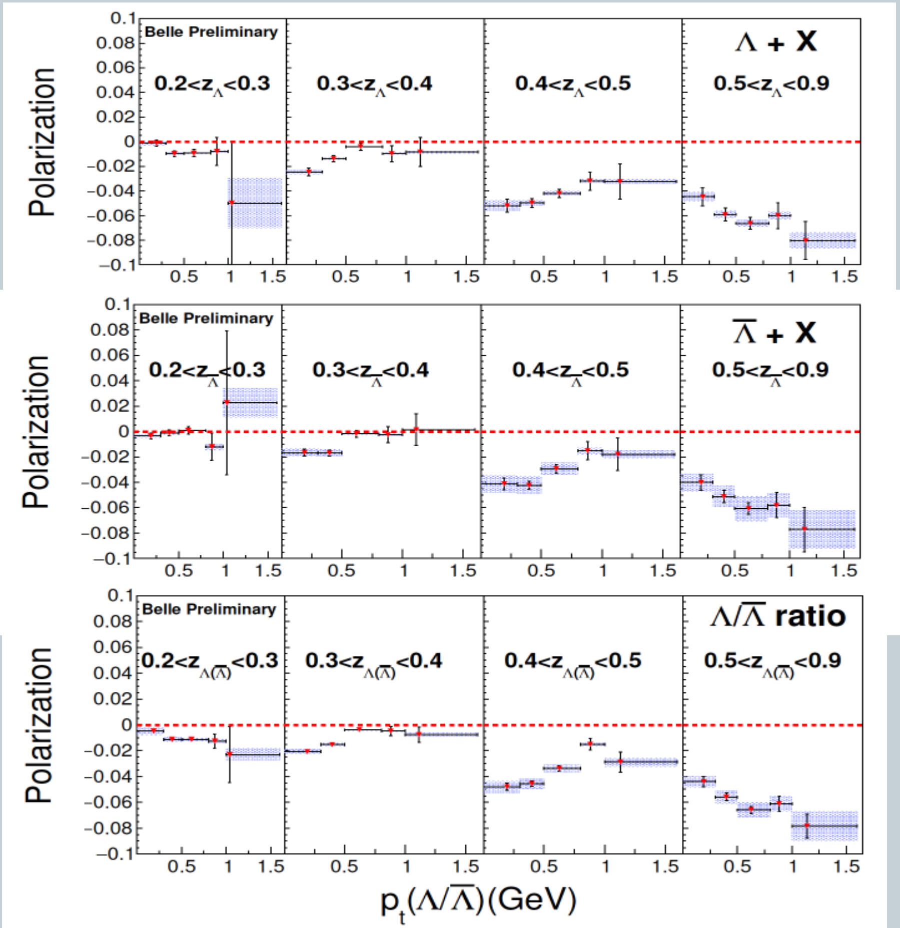


Fit plots for Λ -($\bar{\Lambda}$) data ratio.



Results in thrust frame

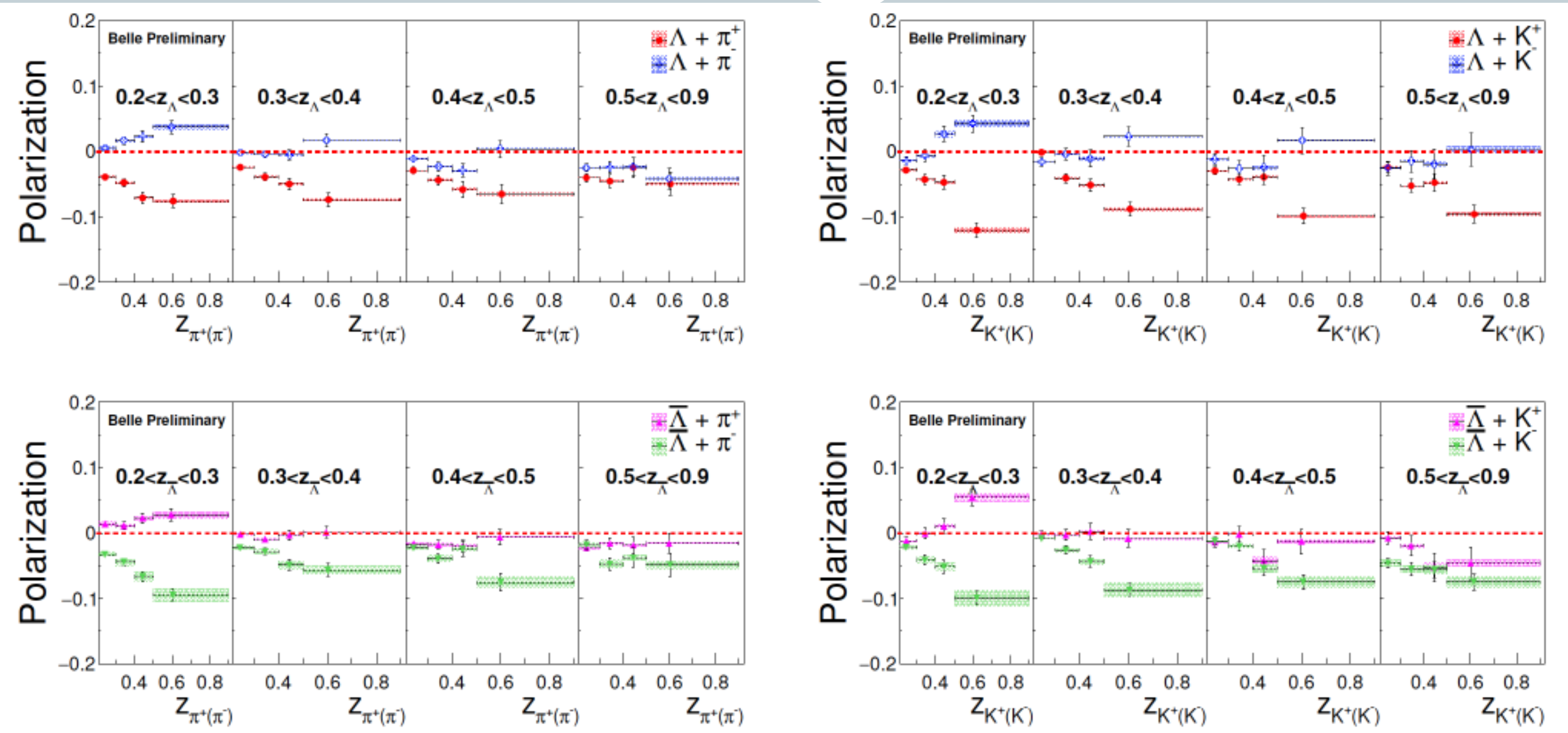
vs. (z,p_t)



- Four z bins and five p_t bins are used: z_Λ=[0.2,0.3,0.4,0.5,0.9]; p_t=[0.0,0.3,0.5,0.8,1.0,1.6] GeV
- Nonzero polarization was observed. Interesting shape as a function of (z_Λ, p_t).
- The polarization rise with higher p_t in the lowest z_Λ and highest z_Λ bin. But the dependence reverses around 1 GeV in the intermediate z_Λ bins.
- Results are consistent between Λ and $(\bar\Lambda)$ and Λ -$(\bar\Lambda)$ data ratio.
- Error bars are statistical uncertainties and shaded areas show the systematic uncertainties.

Results in hadron frame

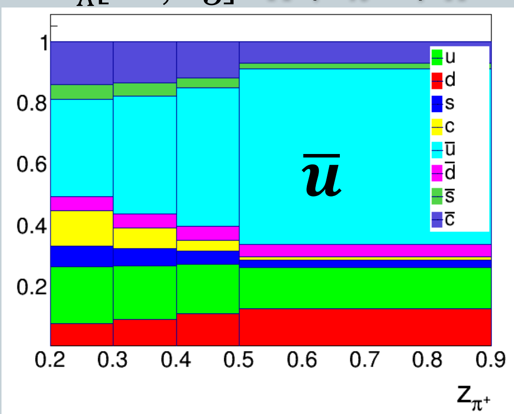
vs. (z_Λ, z_h)



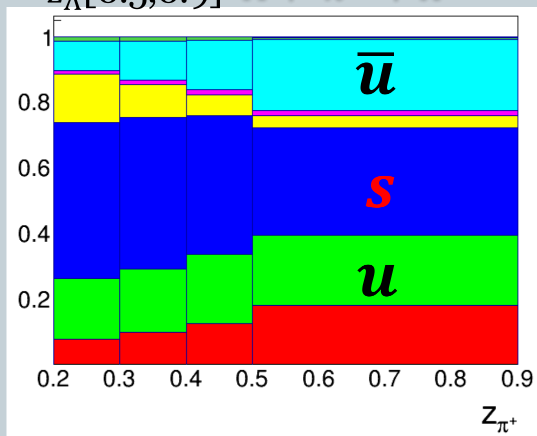
- Similar results with that in the thrust frame.
- Results from charge-conjugate modes are consistent with each other.

Quark flavor tag by the light hadron

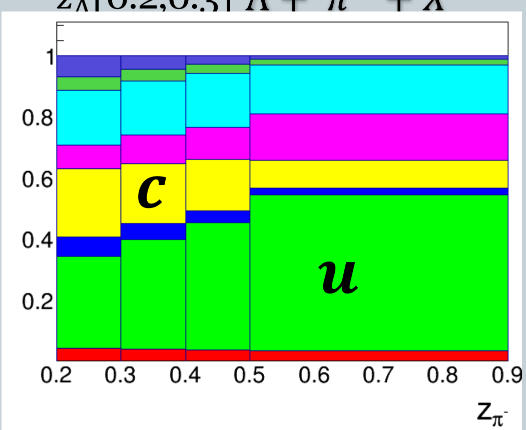
$z_\Lambda[0.2,0.3]$ $\Lambda + \pi^+ + X$



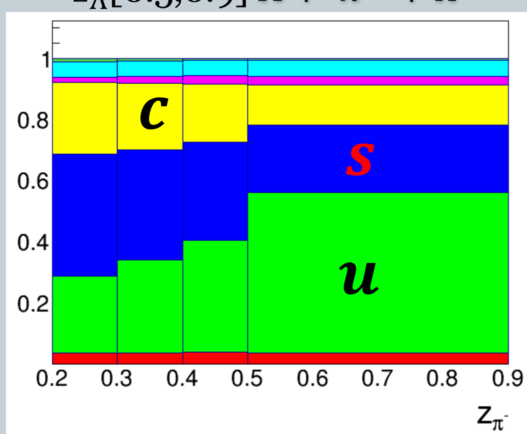
$z_\Lambda[0.5,0.9]$ $\Lambda + \pi^+ + X$



$z_\Lambda[0.2,0.3]$ $\Lambda + \pi^- + X$



$z_\Lambda[0.5,0.9]$ $\Lambda + \pi^- + X$



- An attempt to look at the flavor tag effect of the light hadron, based on MC. (Pythia6.2)
- The fractions of various quark flavors going to the Λ's hemisphere are shown in different $[z_\Lambda\ z_\mathrm{h}]$ region.
- MC indicates that the tag of the quark flavors is more effective at low z_Λ and high z_h. It explains why at low z_Λ and high z_h, polarization in $\Lambda + h^+$ and $\Lambda + h^-$ have opposite sign.

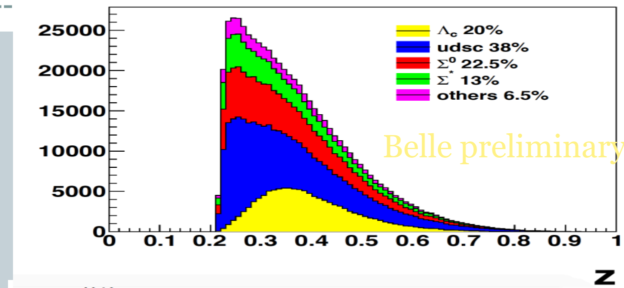
Background unfolding

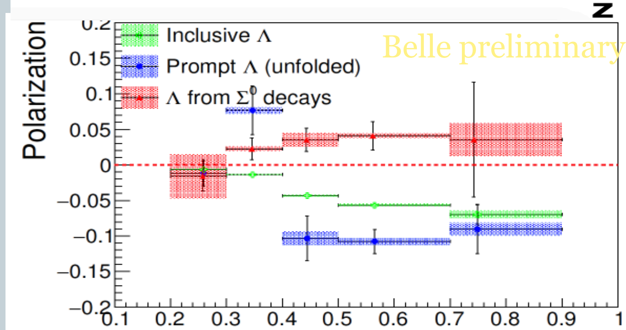
- Non-Λ backgrounds are excluded out in the sideband subtraction.
- Σ^* decays to Λ strongly, is included in the signal.
- Feed-down from Σ^0(22.5%), Λ_c(20%) decays need to be understood.
- The Σ^0-enhanced ($\Sigma^0 \to \Lambda + \gamma$) (Br~100%). and Λ_c-enhanced($\Lambda_c \to \Lambda + \pi^+$)(Br~1.07%) data sets are selected and studied.

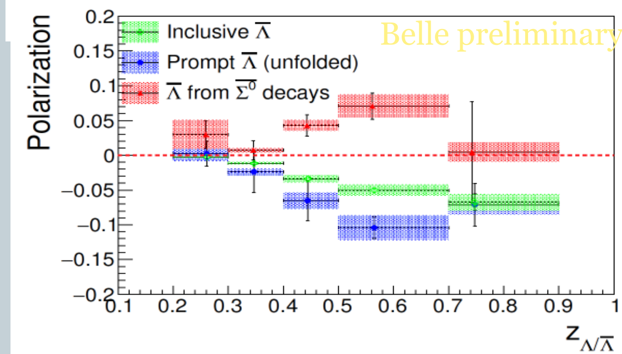
○ The measured polarization can be expressed as:

$$P^{mea.} = (1 - \sum_i \boxed{F_i}) P^{true} + \sum_i \boxed{F_i} P_i,$$

- F_i is the fraction of feed-down component i, estimated from MC. P_i is polarization of component i.
- Polarization of Λ from Σ^0 decays is found has opposite sign with that of inclusive Λ.



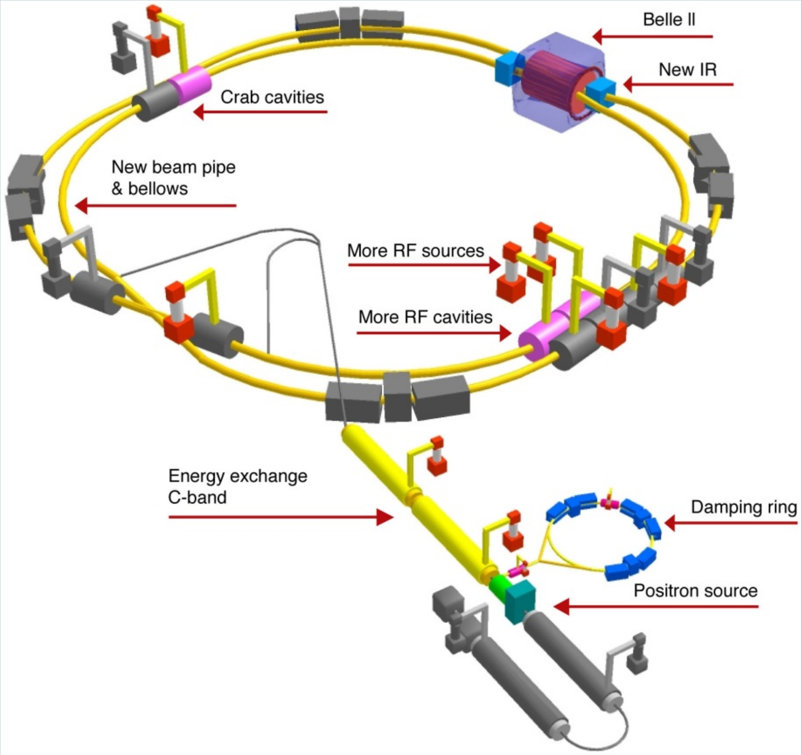


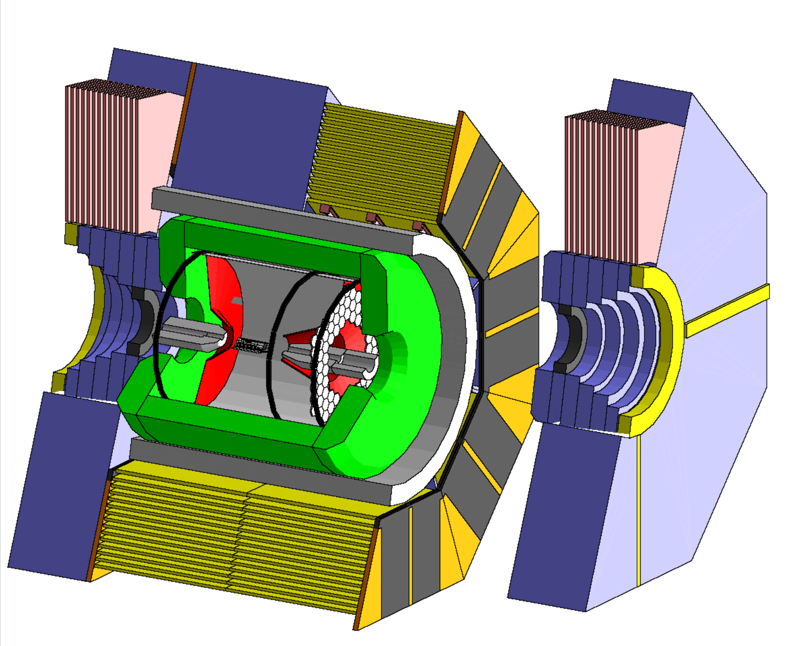


R. Gatto, Phys. Rev. 109, 610 (1958); Phys.Lett.B303,350(1993)

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

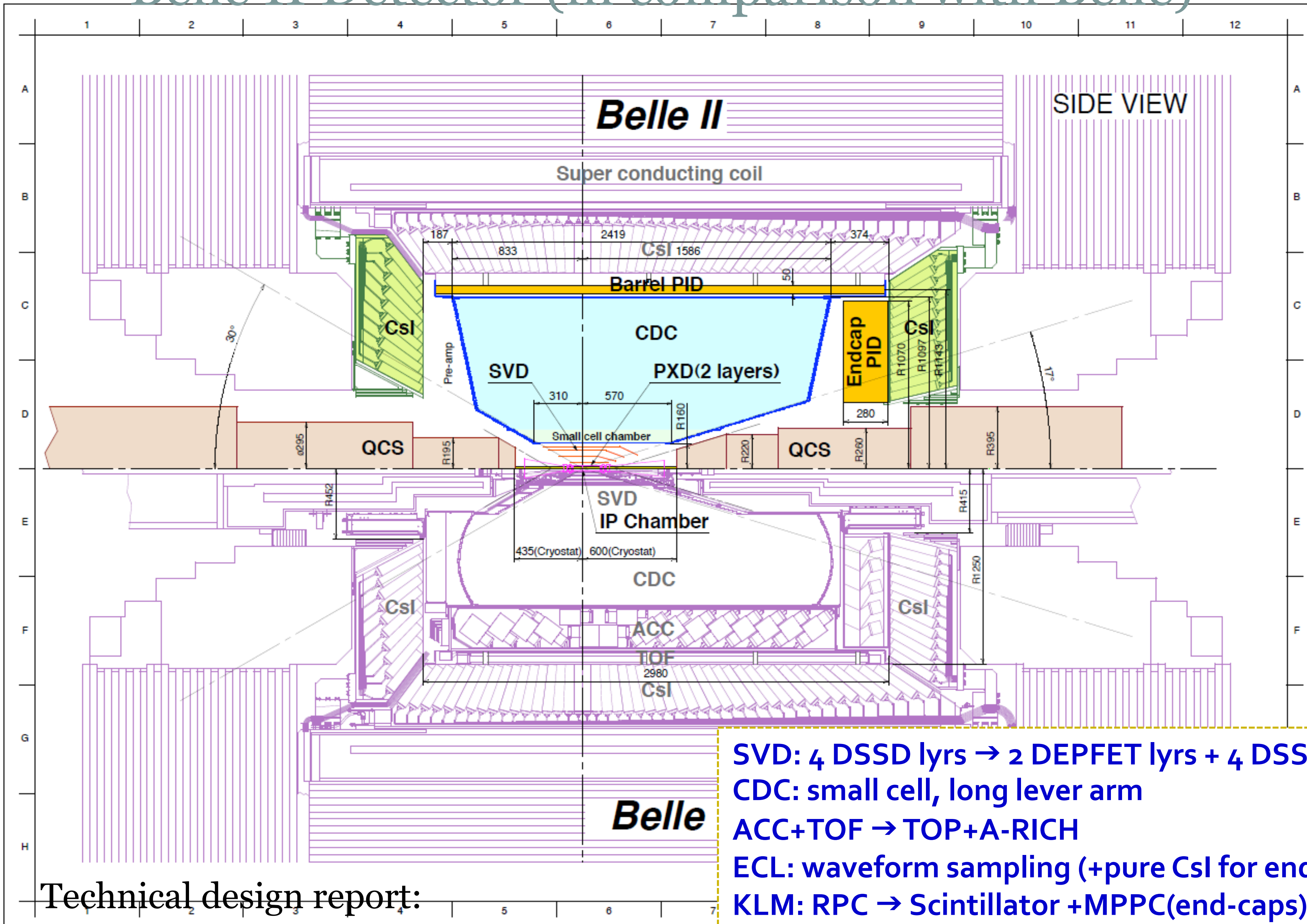




http://belle2.kek.jp

Start of comissioning in 2016

Belle II Detector (in comparison with Belle)

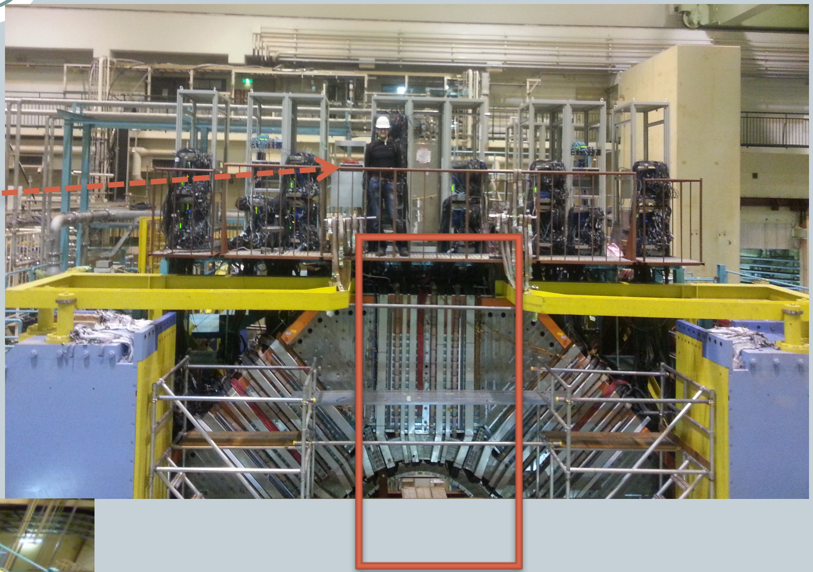


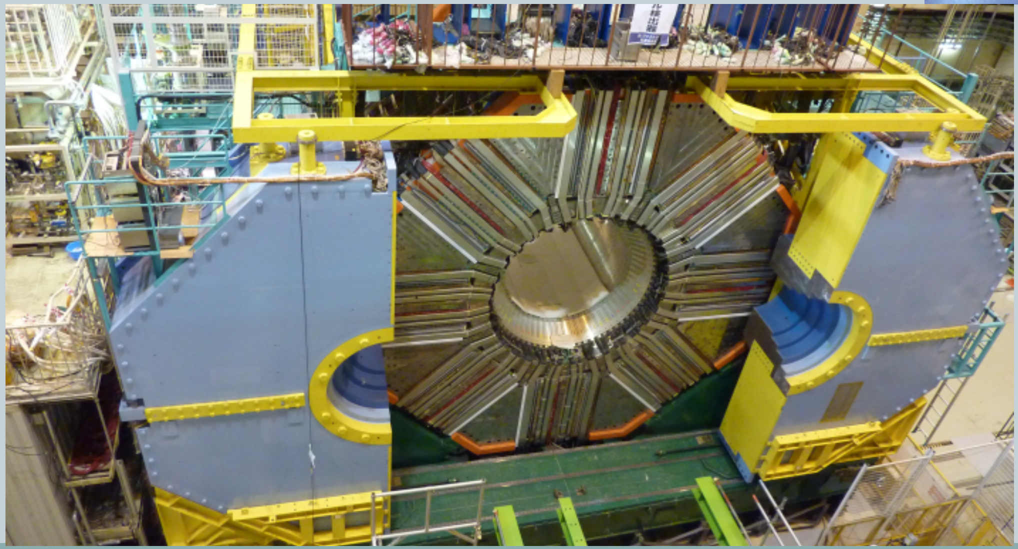
- SVD: 4 DSSD lyrs → 2 DEPFET lyrs + 4 DSSD lyrs
- CDC: small cell, long lever arm
- ACC+TOF → TOP+A-RICH
- ECL: waveform sampling (+pure CsI for end-caps)
- KLM: RPC → Scintillator +MPPC(end-caps)

Technical design report: arXiv:1011.0352

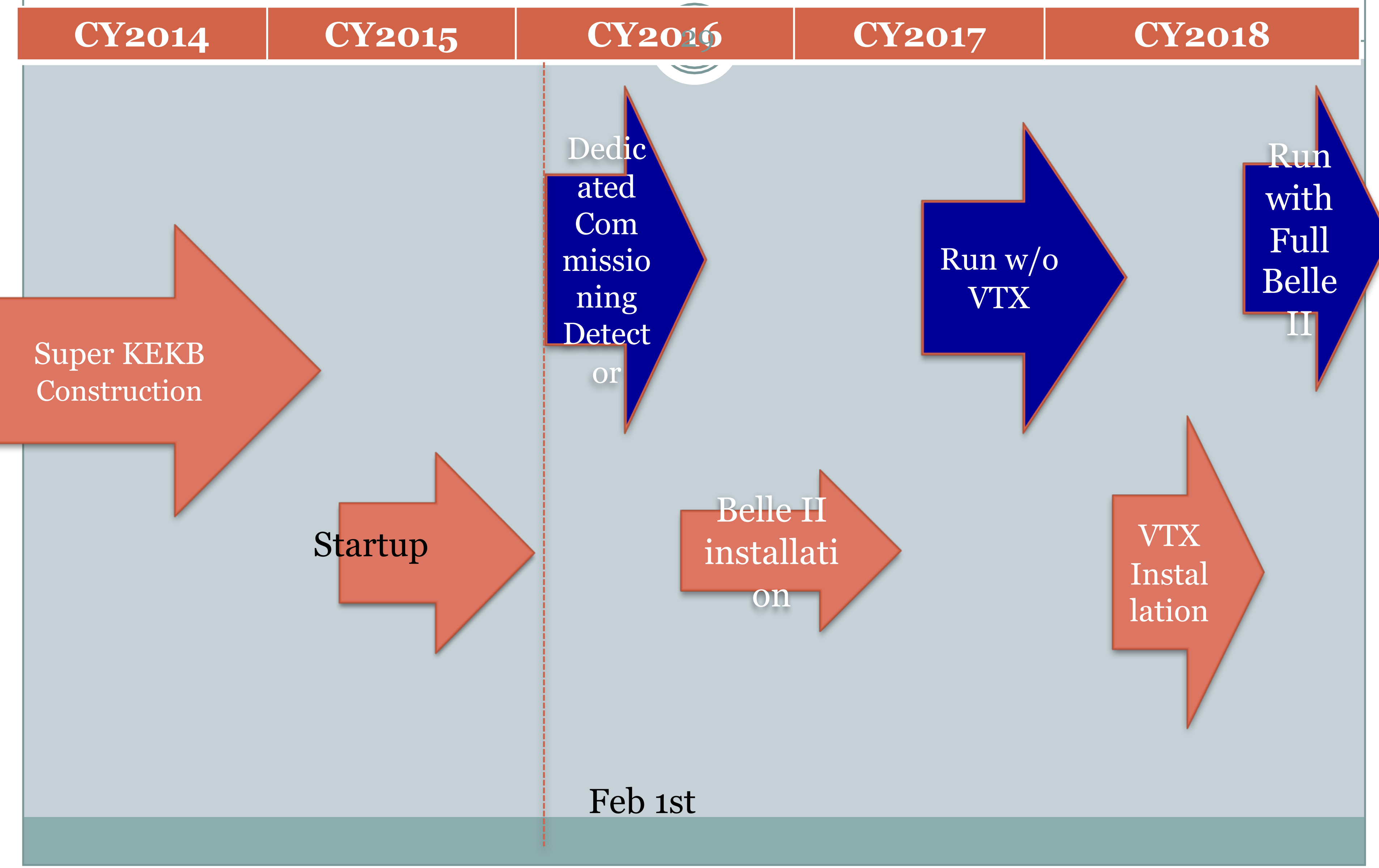
Status of Belle II Installation

Sector Test of KLM
(B Kunkler from IU)





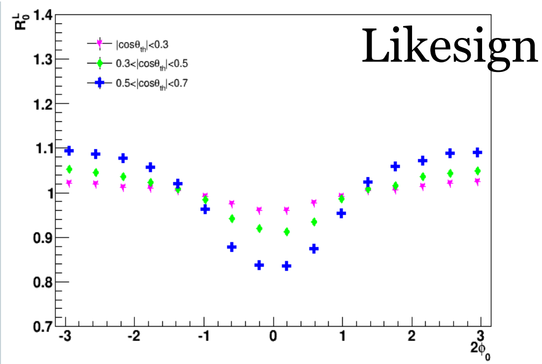
Current SuperKEKB/Belle II Schedule

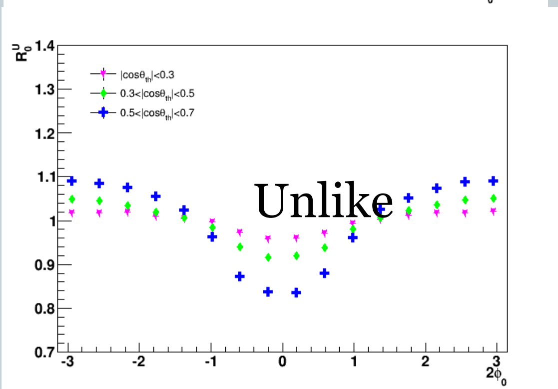


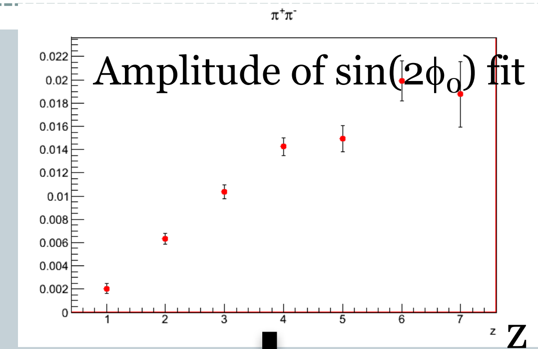
Conclusion/Outlook

- Hadronization Studies in e+e- provide a complimentary access to non-perturbative QCD
- Exciting new results with respect to polarized and polarizing FFs
- k_T dependent FFs on the horizon
- Belle II will provide ample new opportunities
- Analysis underway
  - Back-to-back hadrons to extract p_T dependence of D_1
  - p_T dependence with respect to thrust axis
  - Di-hadron FFs with mass dependence
  - Di-hadron Collins and di-hadron modulations including kaons

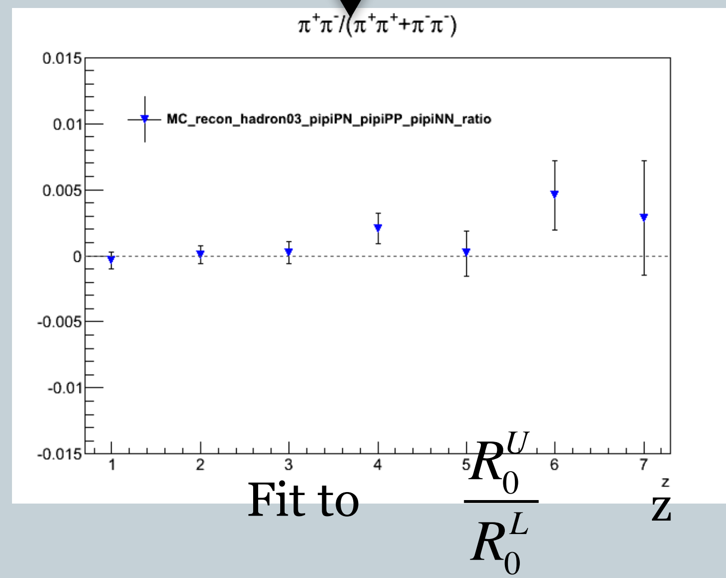
Use of Double Ratios





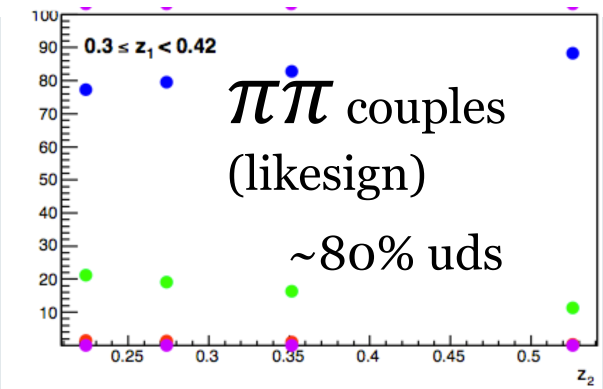


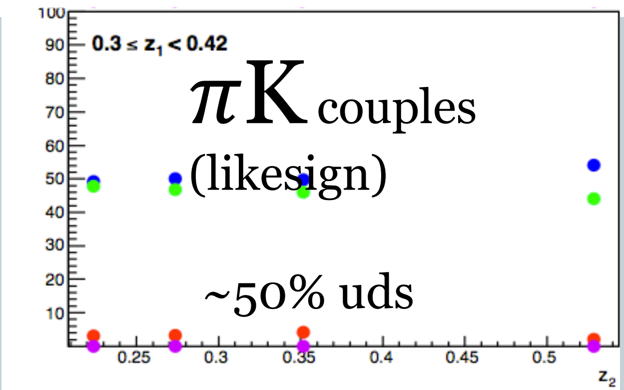
Use of "Double Ratios"

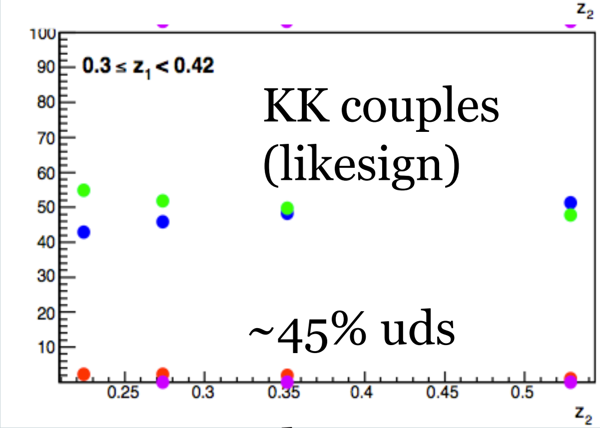


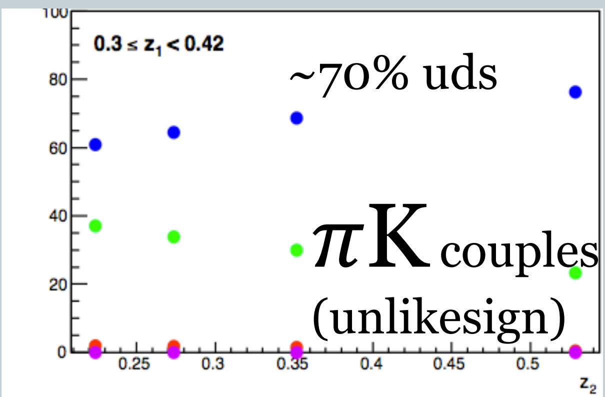
- False asymmetries due to Acceptance and QCD radiation
- Charge independent
- **Open question: Smearing correction/Unfolding in Thrust/Jet method non-trivial in ratio**

Significant Charm to contribution to UDS







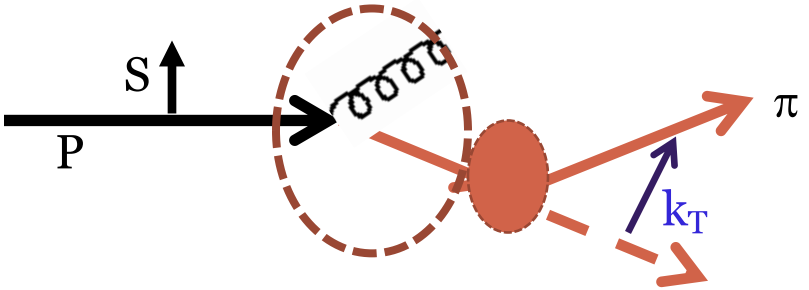


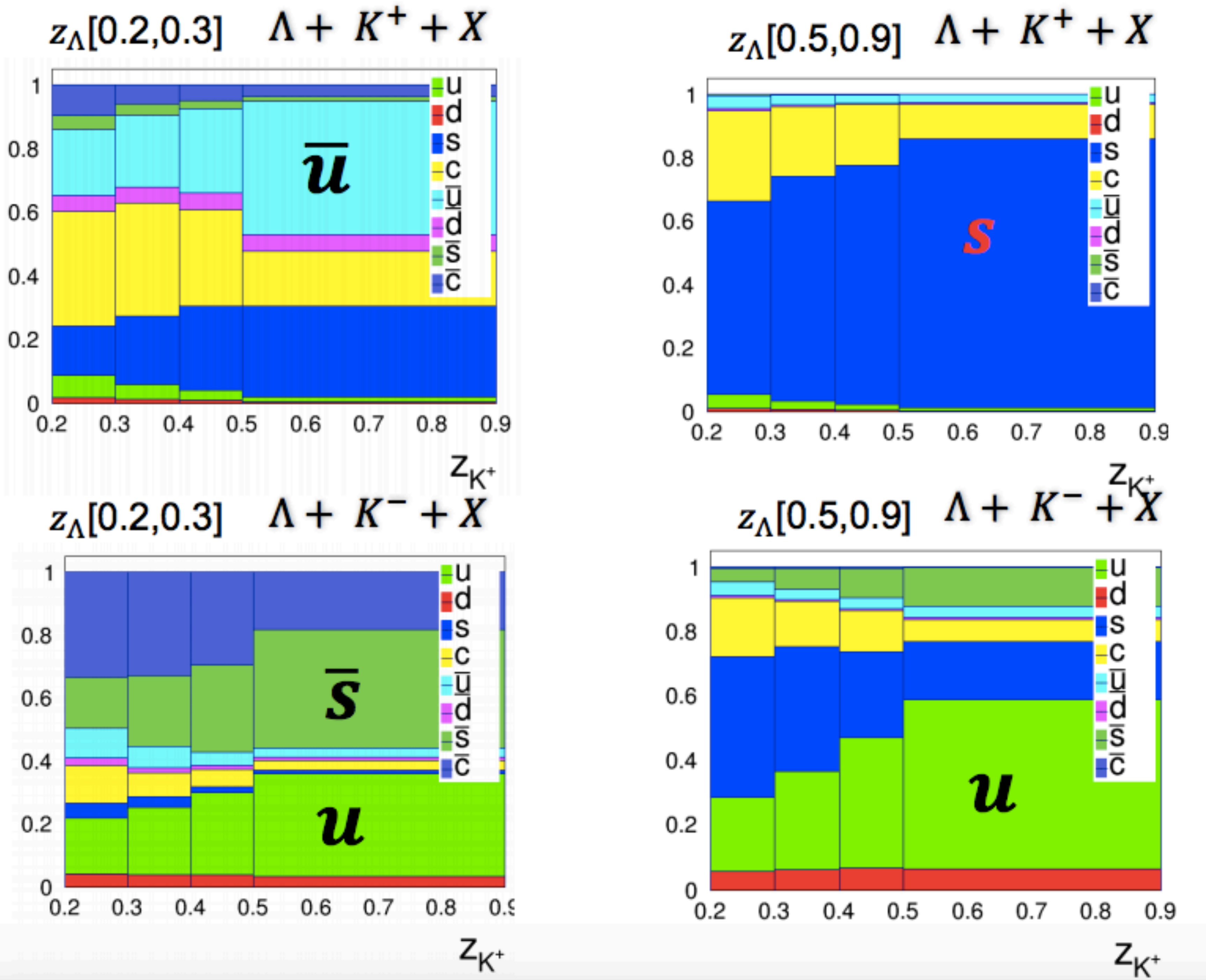
- Current Charm correction methods not satisfying
  - MC (unclear uncertainties)
  - From Data (D-tagged samples): Bias phase space (e.g. selection of decay modes with low momentum pions)
- Need state-of-the-art vertex detection→ Belle II

Transverse momentum dependence

AKA UN-INTEGRATED FFS

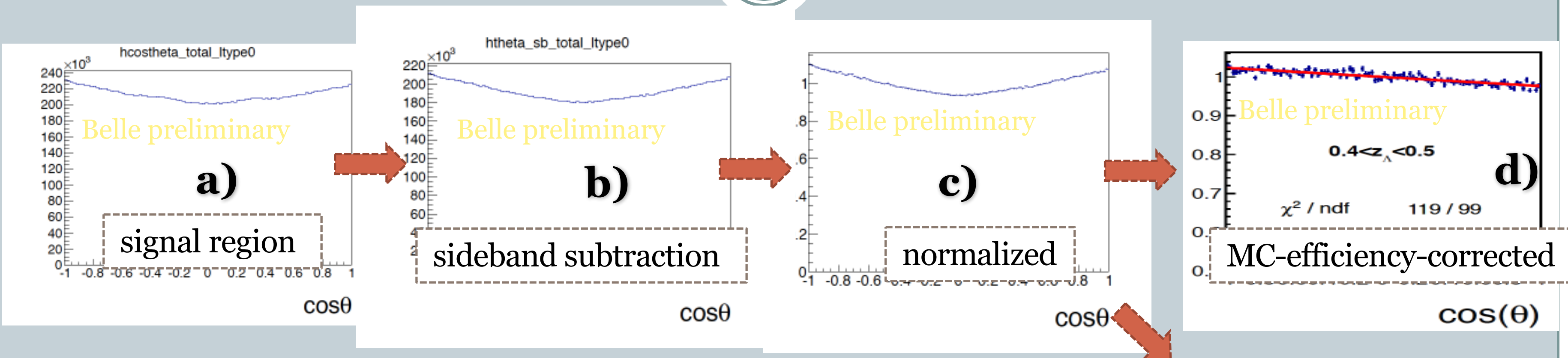
$$D^{h}_{1,q}(z, Q^2, k_t)$$



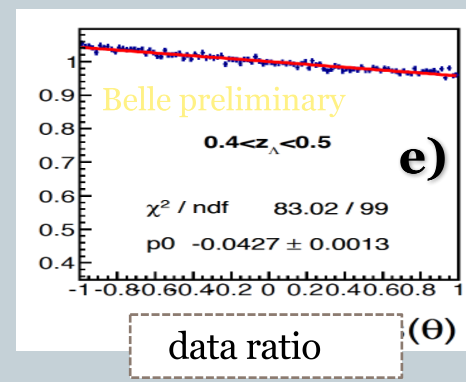


$z_\Lambda[0.2,0.3]$ $\Lambda + K^+ + X$
$z_\Lambda[0.5,0.9]$ $\Lambda + K^+ + X$
$z_\Lambda[0.2,0.3]$ $\Lambda + K^- + X$
$z_\Lambda[0.5,0.9]$ $\Lambda + K^- + X$
u
d
s
c
$\bar{u}$
$\bar{d}$
$\bar{s}$
$\bar{c}$
$\bar{u}$
s
$\bar{s}$
u
u
z_{K^+}

Analysis flow

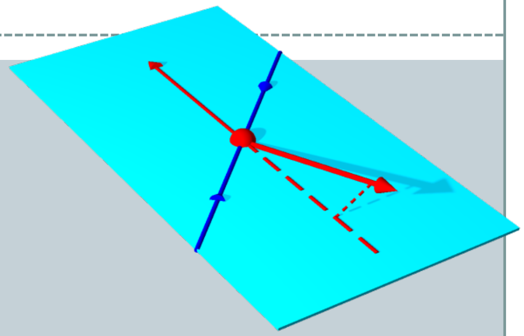


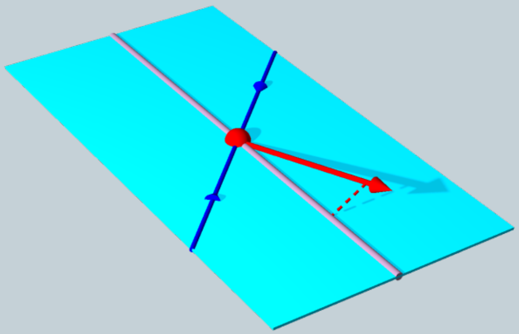
- Cosθ distribution in Λ signal region **a)** is corrected by sideband subtraction→ **b)**
- Normalized by itself, as shown in **c).**
- The shape **c)** is divided by the corresponding shape from MC, so that we obtain the efficiency-corrected curve **d).**
- Or **c)** shape of Λ events is divided by that from anti-Λ events if we assume efficiency is independent on charge, that is **e),** this is called data ratios.
- We fit **d)** and **e)** to get the polarization of interest.

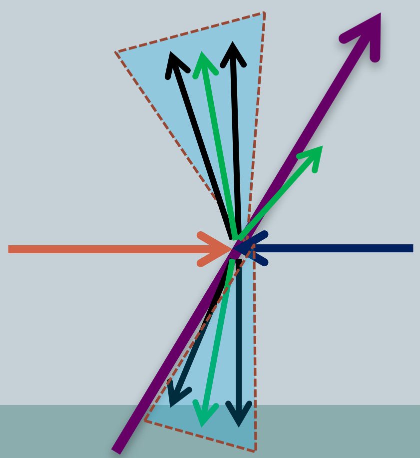


k_T Dependence of FFs

- 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





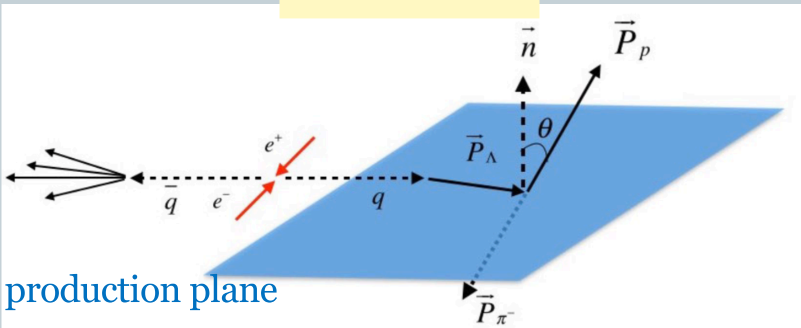


QCD studies at Belle II

- Precision study of local strong parity violation to probe the QCD vacuum
- Hadronization studies in transverse momentum-spin correlations (Λ)/Fragmentation function
- Precision studies of fragmentation functions needed for JLab12 program
  - Precision
  - Charm suppresion
  - Kaon ID

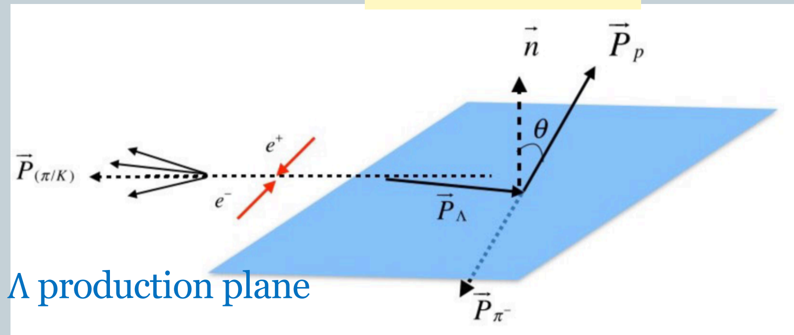
Reference frames

Thrust Frame



Λ production plane

Hadron Frame



Λ production plane

- The reference vector $\hat{n}$ is perpendicular to the Λ production plane.
- The p_t is defined as the transverse momentum of Λ relative to thrust axis in thrust frame and to hadron axis in hadron frame.
- Give a polarization of P, the yield of the events follow:

$$\frac{1}{N}\frac{dN}{d\cos\theta} = 1 + \alpha P\cos\theta$$

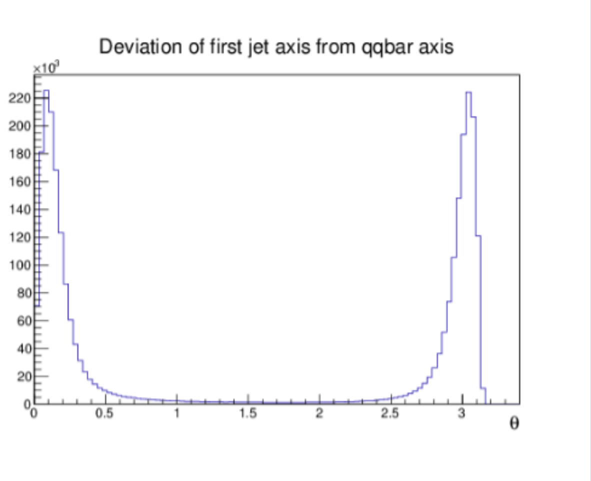
- where α is the decay parameter: α_+=0.642 ± 0.013 for Λ and α_-=-0.71 ± 0.08 for $\bar{\Lambda}$ (PDG).

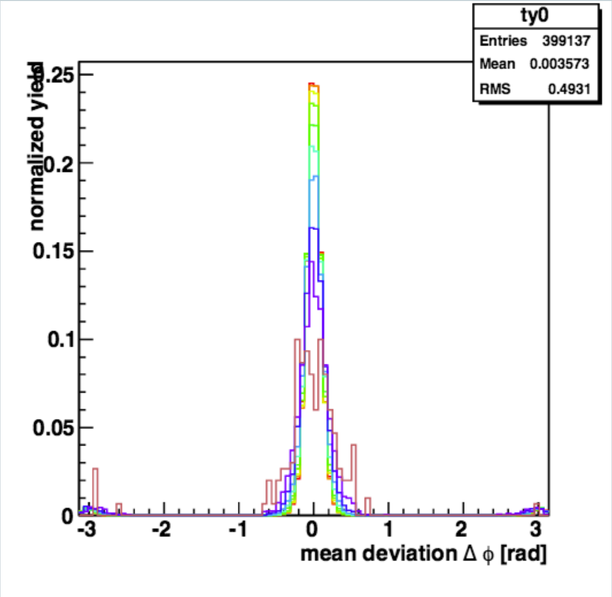
kinematic variables

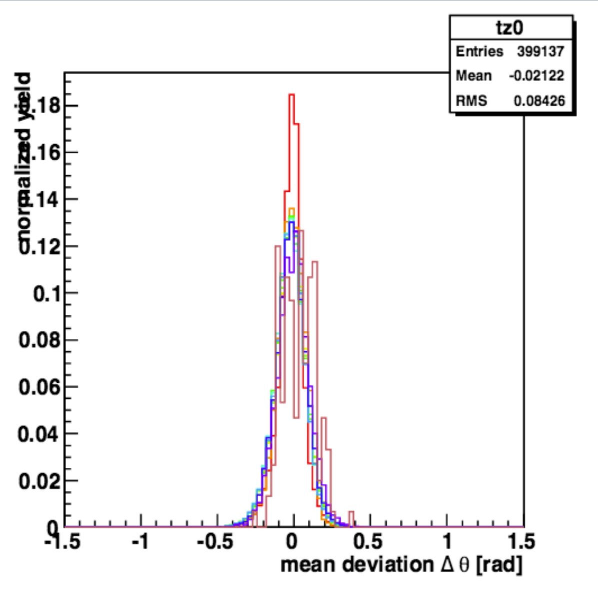
$\Lambda + X$	thrust frame	
variables	z_Λ , p_t	
$\Lambda + h + X$	thrust frame	hadron frame
variables	z_Λ, z_h, p_t	z_Λ, z_h, p_t

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)

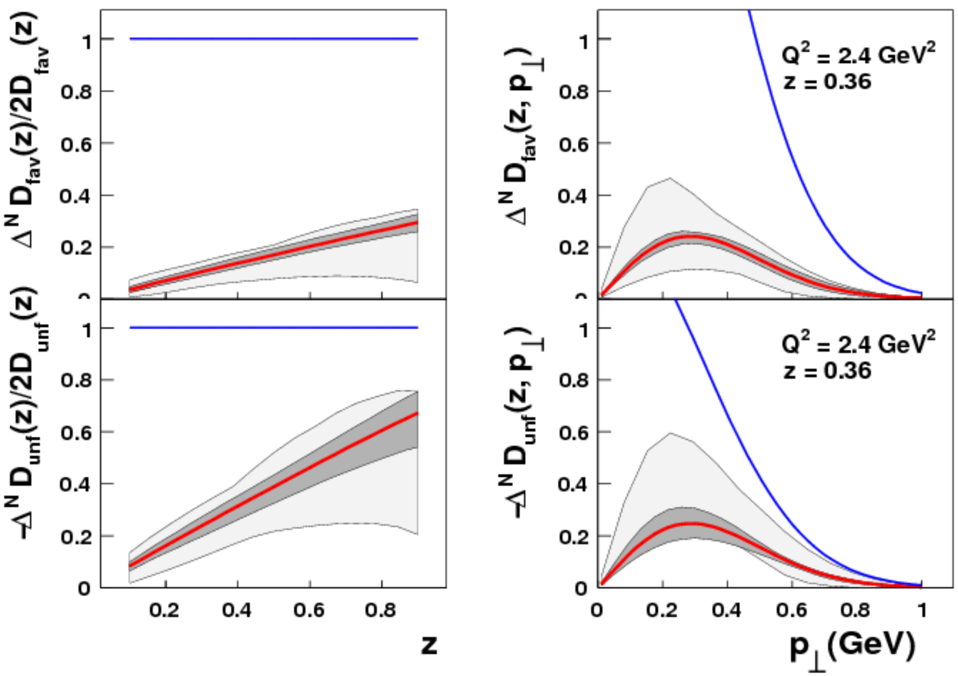




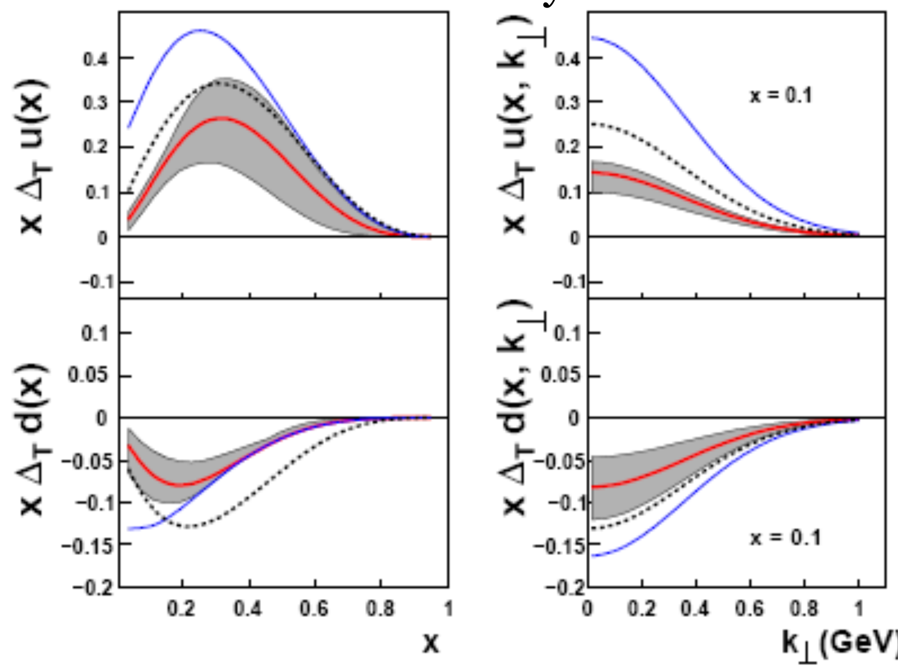


Global Fit of Collins FF and Transversity (HERMES, COMPASS d, Belle)

Collins function



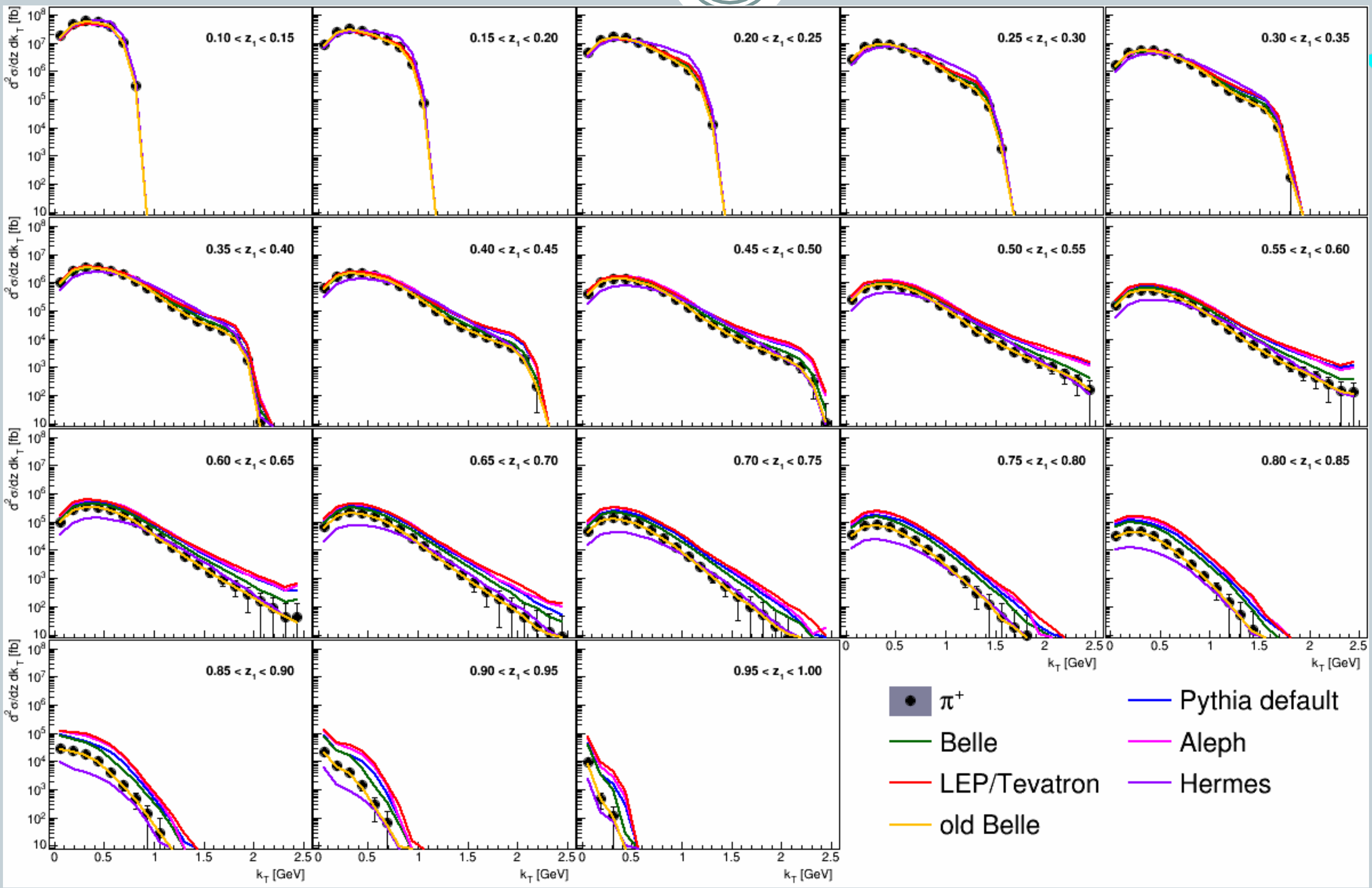
Transversity

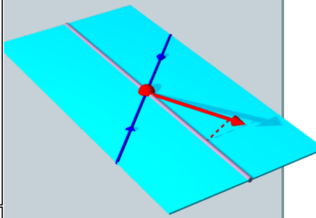


Phys.Rev.D75:054032,2007, update in Nucl.Phys.Proc.Suppl.191:98-107,2009

- Latest SIDIS data not included inFIT
- Open questions：
  - TMD evolution unknown（however from Belle to HERMES no large differences seen）
  - Kt dependence from Assumption（Belle measurements planned）
- Interference FF（IFF) as independent Cross check

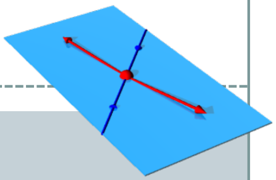
MC example of k_T sensitivities





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

Ratios to opposite charge pion pairs

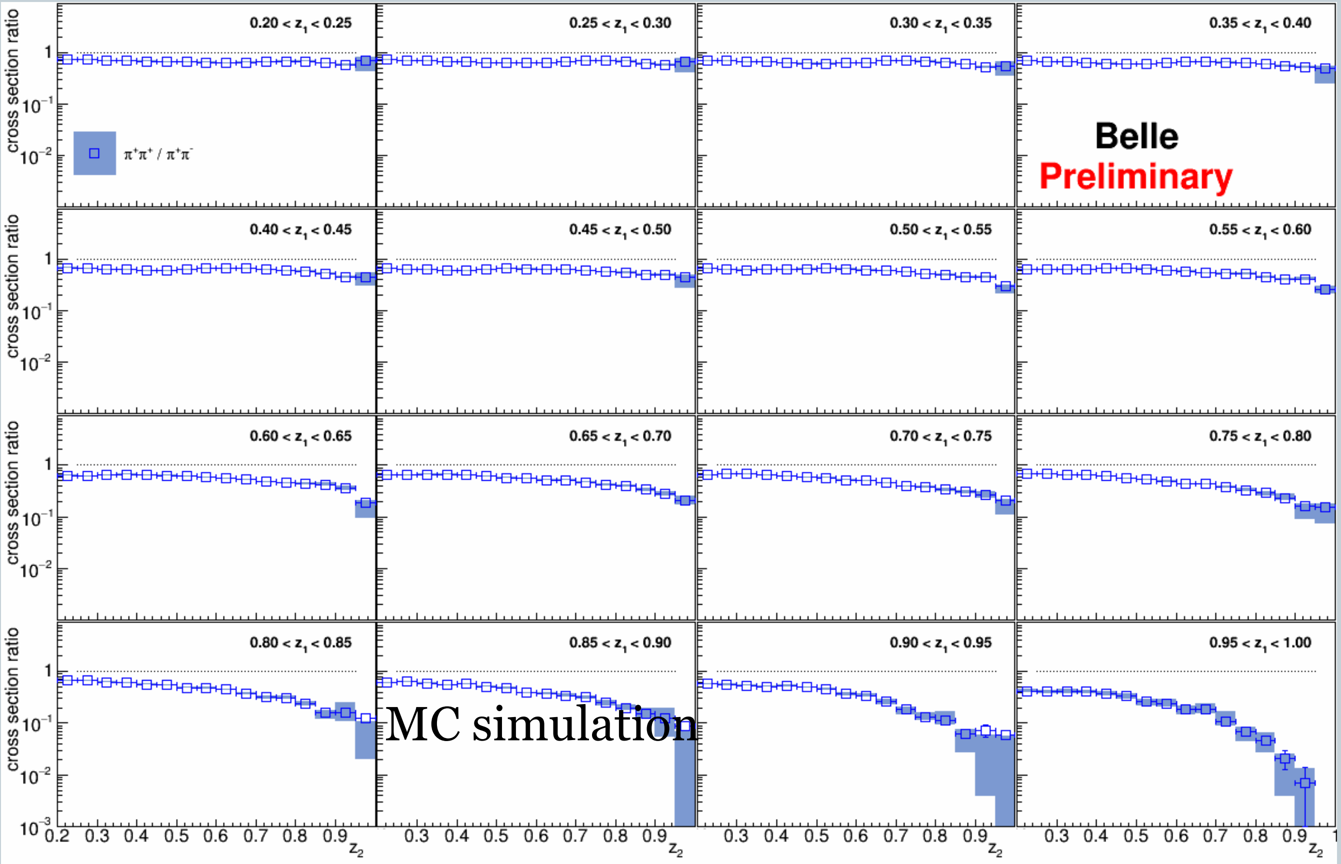


$$R \approx \frac{D_{fav}(z_1)D_{fav}(z_2) + D_{dis}(z_1)D_{dis}(z_2)}{D_{dis}(z_1)D_{fav}(z_2) + D_{fav}(z_1)D_{dis}(z_2)}$$

$\pi^+\pi^+$ comparable to $\pi^+\pi^-$ at low z, decreasing towards high z:

→ Favored and disfavored fragmentation similar at low z

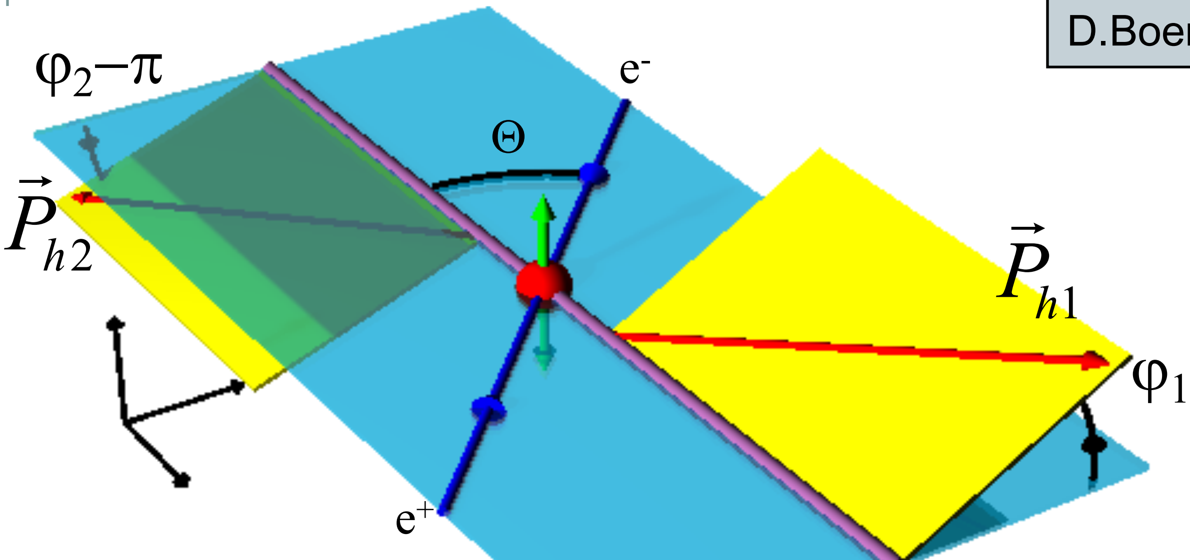
→ Disfavored much smaller at high z

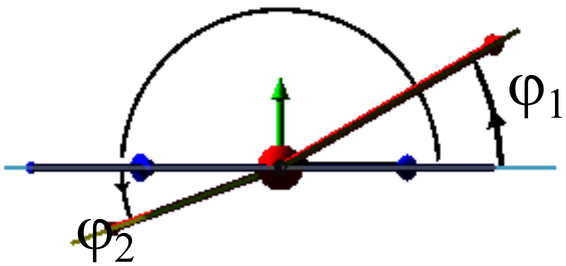


Collins fragmentation in e^+e^- : Angles and Cross section $\cos(\phi_1+\phi_2)$ method

<u>e^+e^- CMS frame:</u>

D.Boer: **Nucl.Phys. B806 (2009) 23-6**





<u>2-hadron inclusive transverse momentum dependent cross section:</u>

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

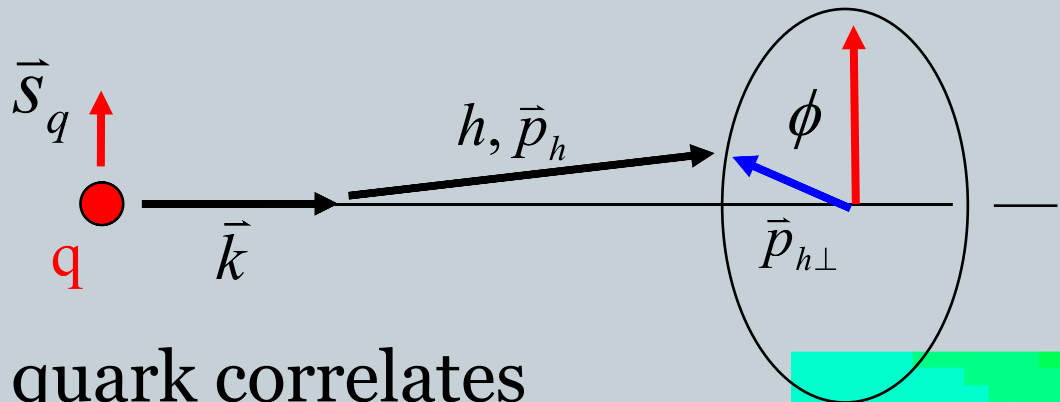
$$B(y) = y(1-y) \overset{cm}{=} \frac{1}{4}\sin^2\Theta$$

Net (anti-)alignment of transverse quark spins

Collins fragmentation function

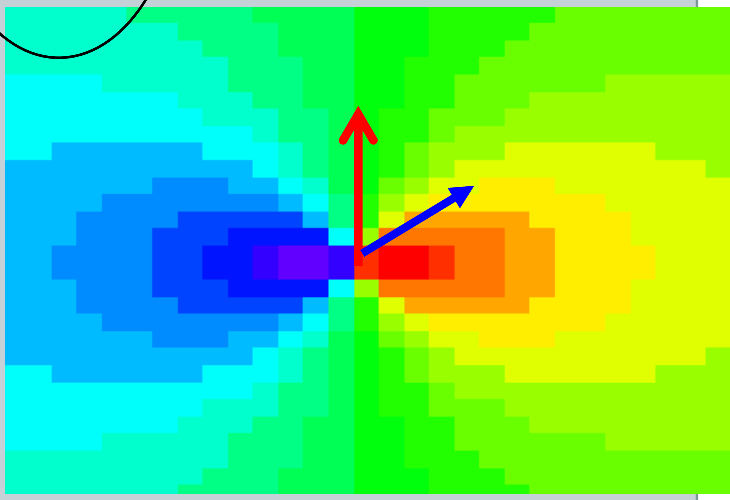
J. Collins, Nucl. Phys. B396, (1993) 161

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



- Spin of quark correlates with hadron transverse momentum

➔translates into azimuthal anisotropy of final state hadrons

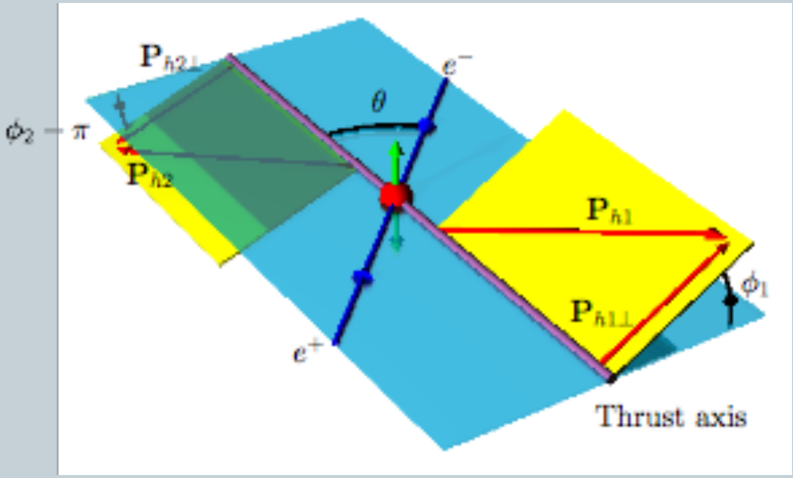


There are two methods with two or one soft scale

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

$\phi_1+\phi_2$ method:

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

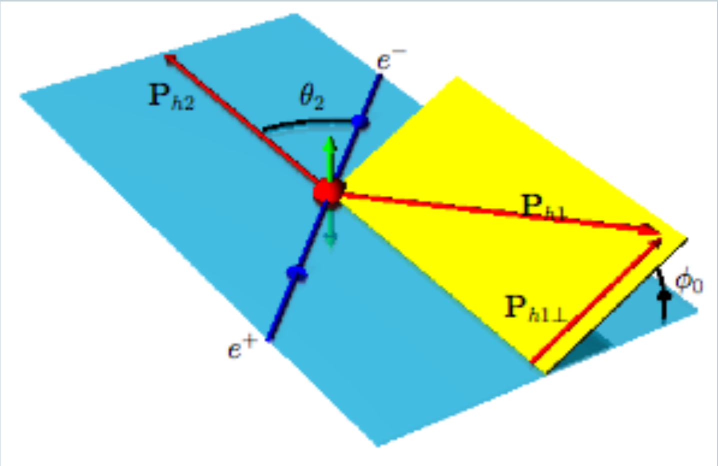


$$\sigma \sim \mathcal{M}_{12}\left(1+\frac{\sin^2\theta_T}{1+\cos^2\theta_T}\, cos(\phi_1+\phi_2)\boxed{\frac{H_1^{\perp[1]}(z_1)\bar{H}_1^{\perp[1]}(z_2)}{D_1^{[0]}(z_1)\bar{D}_1^{[0]}(z_2)}}\right)$$

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

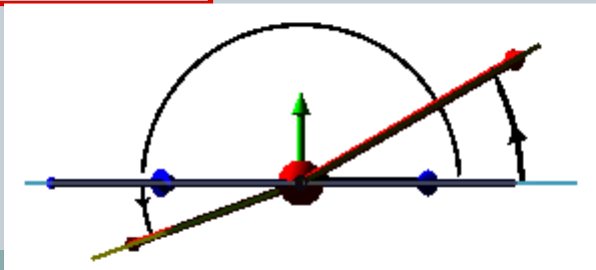
ϕ_0 method:

hadron 1 azimuthal angle with respect to hadron 2



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

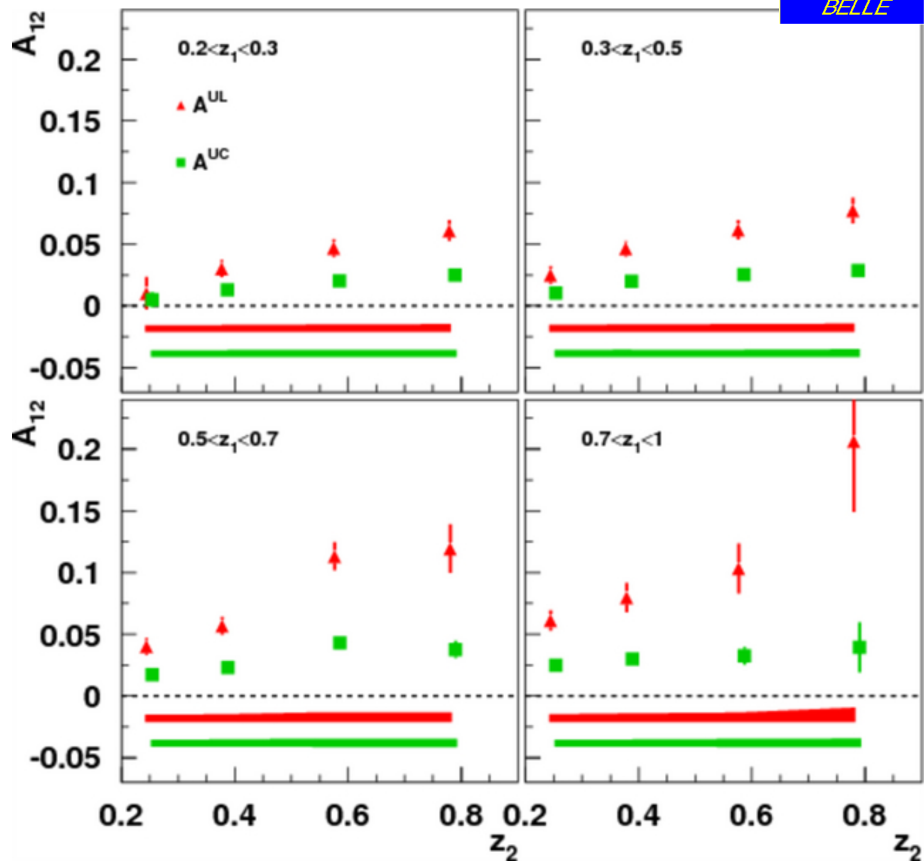
$$R_{0}^{U/L} = \frac{N(2\varphi_0)}{\langle N_0\rangle}$$



kT moment or convolution: Important which kT region is sampled

Belle Collins asymmetries

- Red points : $\cos(\phi_1 + \phi_2)$ moment of Unlike sign pion pairs over like sign pion pair ratio : A^{UL}
- Green points : $\cos(\phi_1 + \phi_2)$ moment of Unlike sign pion pairs over any charged pion pair ratio : A^{UC}
- Collins fragmentation is large effect
- Consistent with SIDIS indication of sign change between favored and disfavored Collins FF



RS et al (Belle), PRL96: 232002
PRD 78:032011, Erratum D86:039905