



Fragmentation Function

measurements at Belle

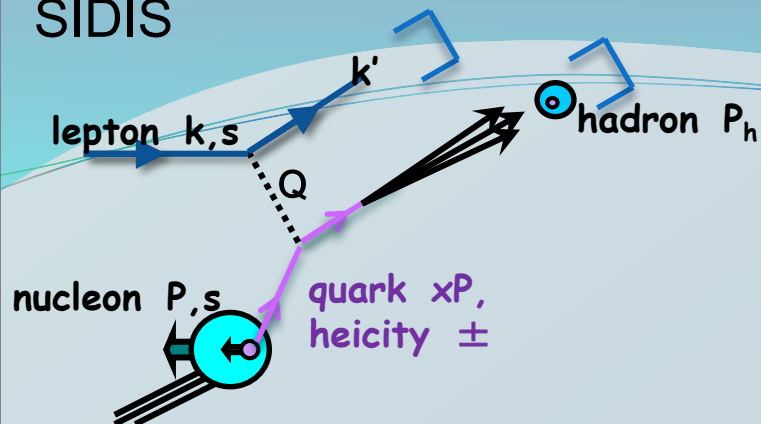
**ICHEP 2018, Seoul,
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Ralf Seidl (RIKEN)

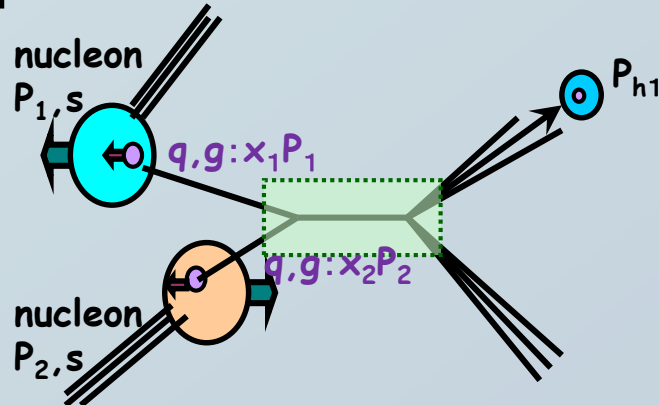
Outline

- Single hadron fragmentation
 - Hyperon and charmed Baryon fragmentation
 - Λ polarizing fragmentation
- Di-hadron fragmentation
 - Unpolarized mass, z dependence
- Other ongoing measurements (k_T dependence)

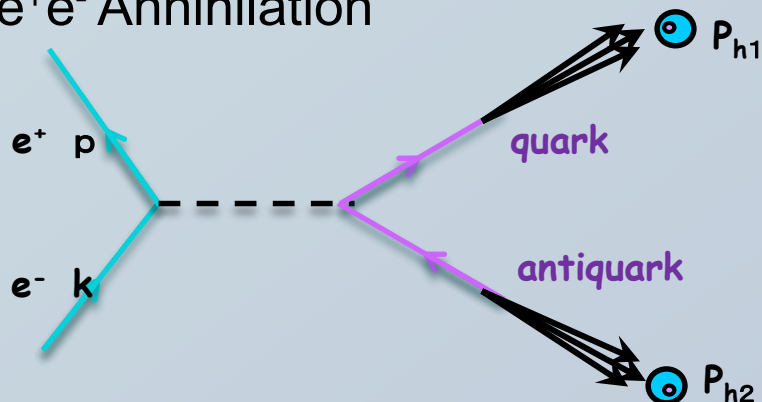
SIDIS



pp collisions



e⁺e⁻ Annihilation



Access to FFs

• SIDIS:

$$\sigma^h(x, z, Q^2, P_{h\perp}) \propto \sum_q e_q^2 q(x, p_t, Q^2) D_{1,q}^h(z, k_t, Q^2)$$

- Relies on unpol PDFs
- Parton momentum known at LO
- Flavor structure directly accessible
- Transverse momenta convoluted between FF and PDF

• pp:

$$\sigma^h(P_T) \propto \int_{x_1, x_2, z} \sum_{a, a' \in q, g} f_a(x_1) \otimes f_{a'}(x_2) \otimes \sigma_{aa'} \otimes D_{1,q}^h(z)$$

- Relies on unpol PDFs
- leading access to gluon FF
- Parton momenta not directly known

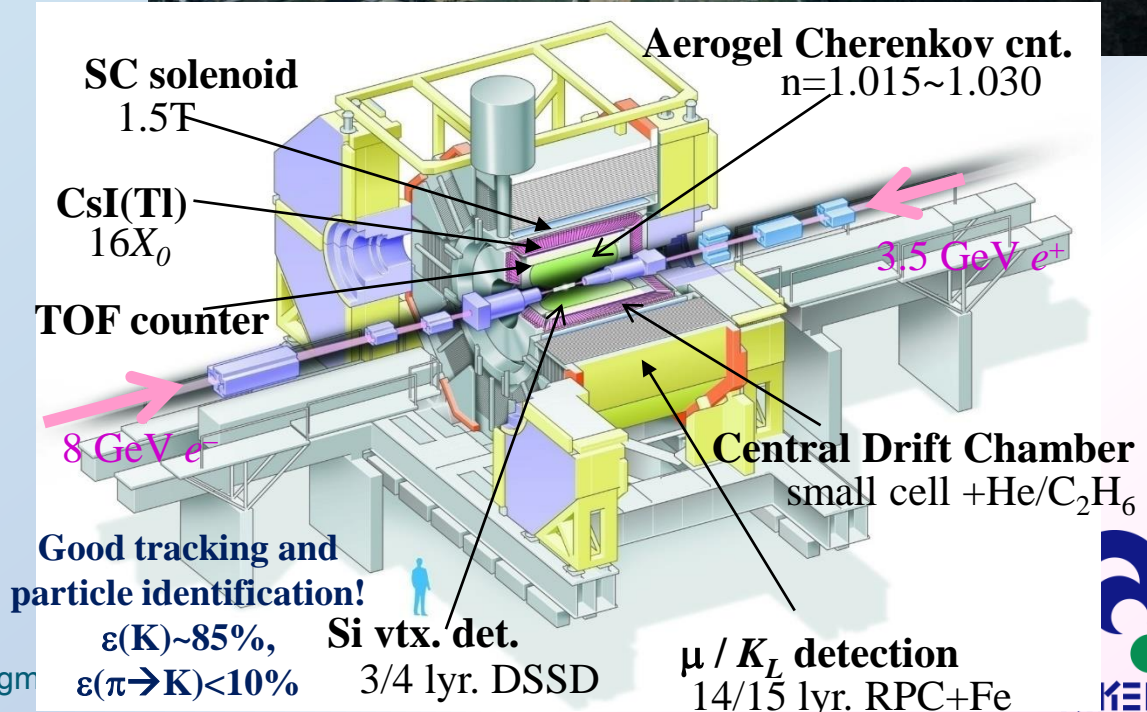
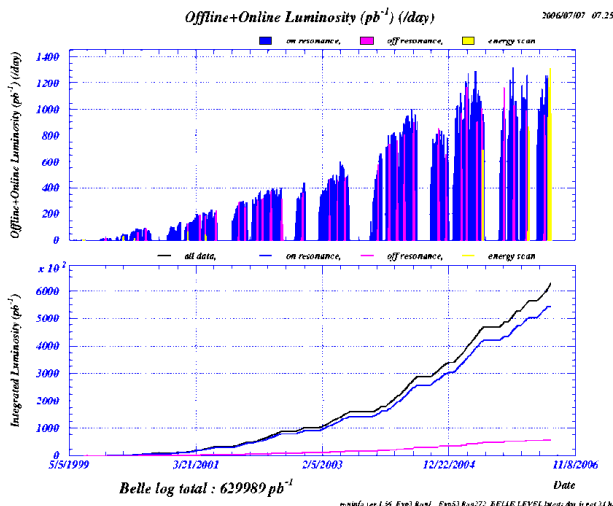
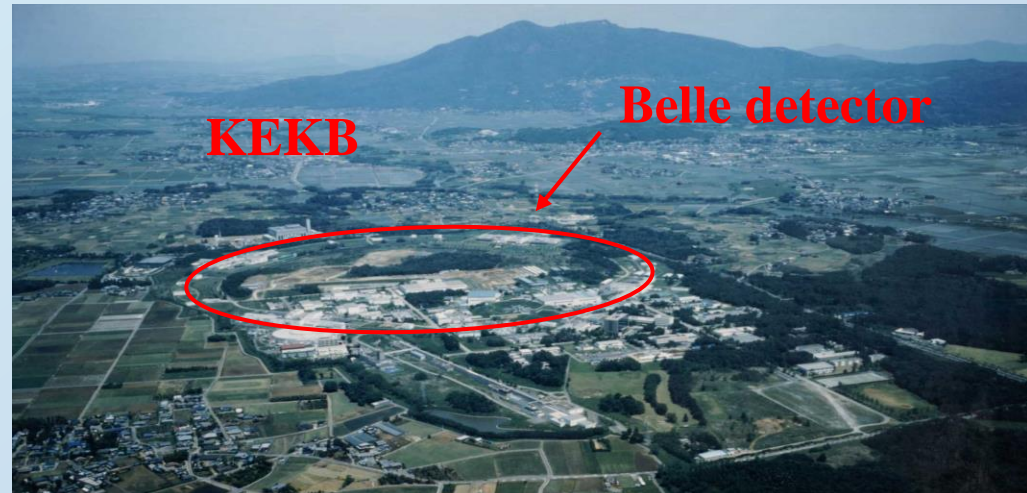
• e⁺e⁻:

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

- No PDFs necessary
- Clean initial state, parton momentum known at LO
- Flavor structure not directly accessible

Belle Detector and KEKB

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



Single hadron fragmentation

In e^+e^- annihilation:

$$Q = \sqrt{s}$$

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

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

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

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

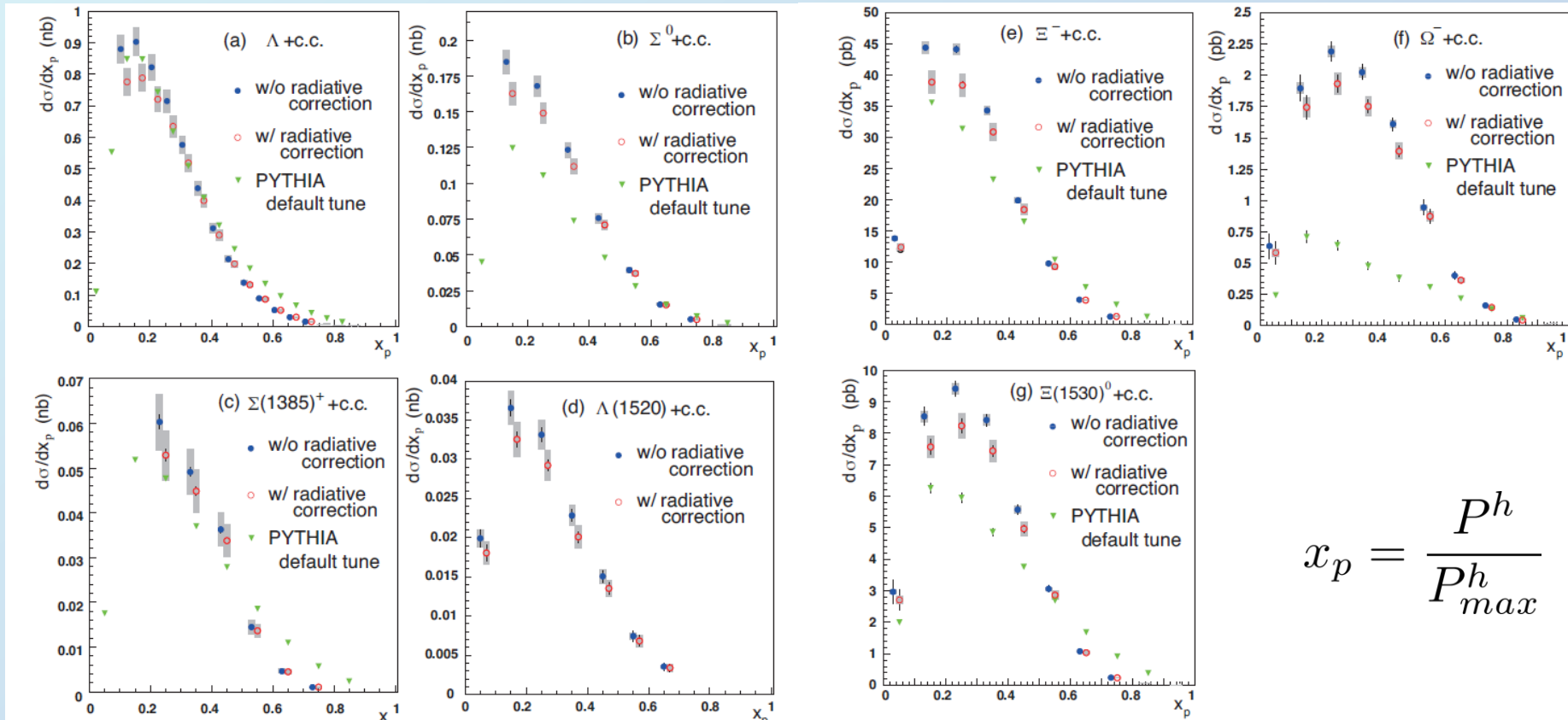
$$D_{1,q}^{\perp h}(z, k_T, Q^2)$$

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

$$\mathcal{G}_q^h(z, z_h, \omega_J R, j_{\perp}, Q^2)$$

Hyperon Fragmentation

Belle: Niiyama et. al. [PRD 97 \(2018\), 072005](#)

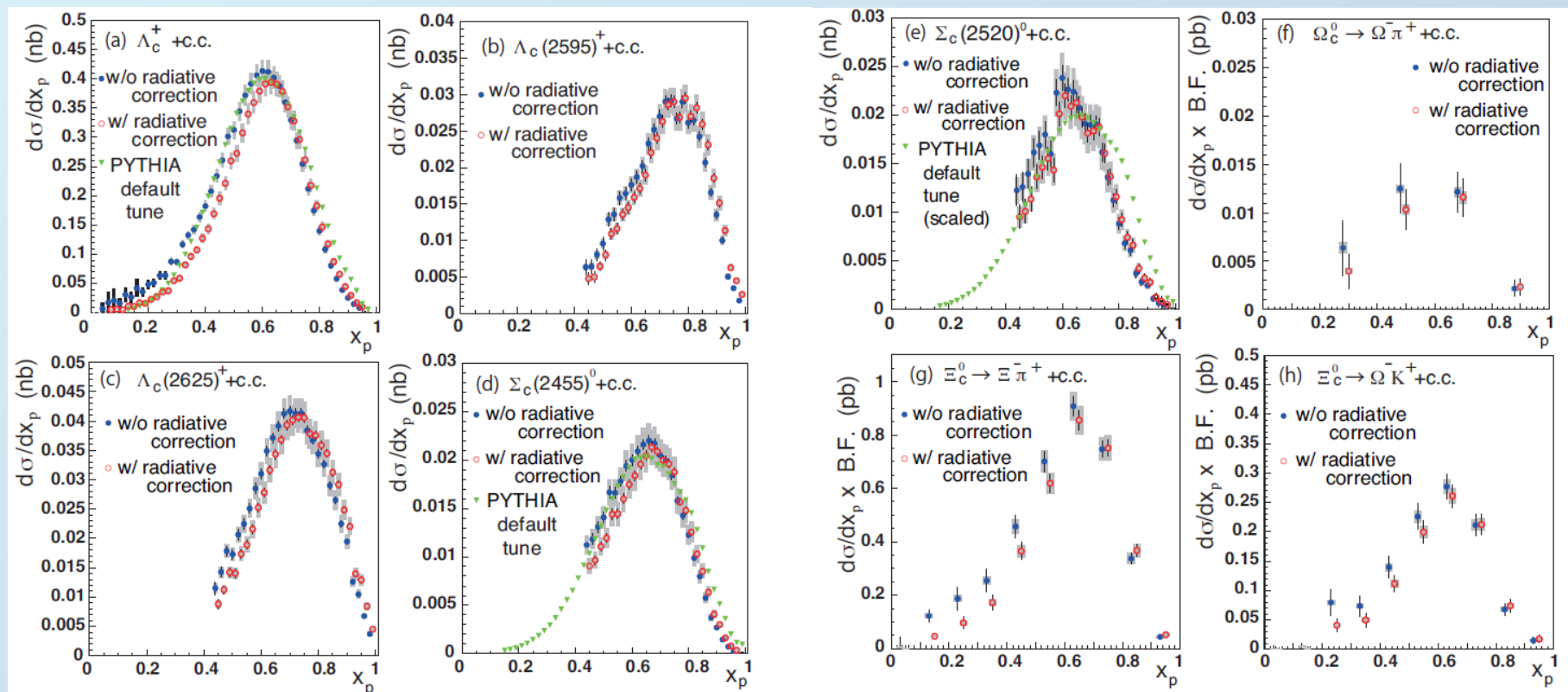


$$x_p = \frac{P^h}{P_{max}^h}$$

- Hyperons similar to light hadron fragmentation \rightarrow peaking at low z (x_p)
- Baryon production not too well described by Pythia 6 default settings

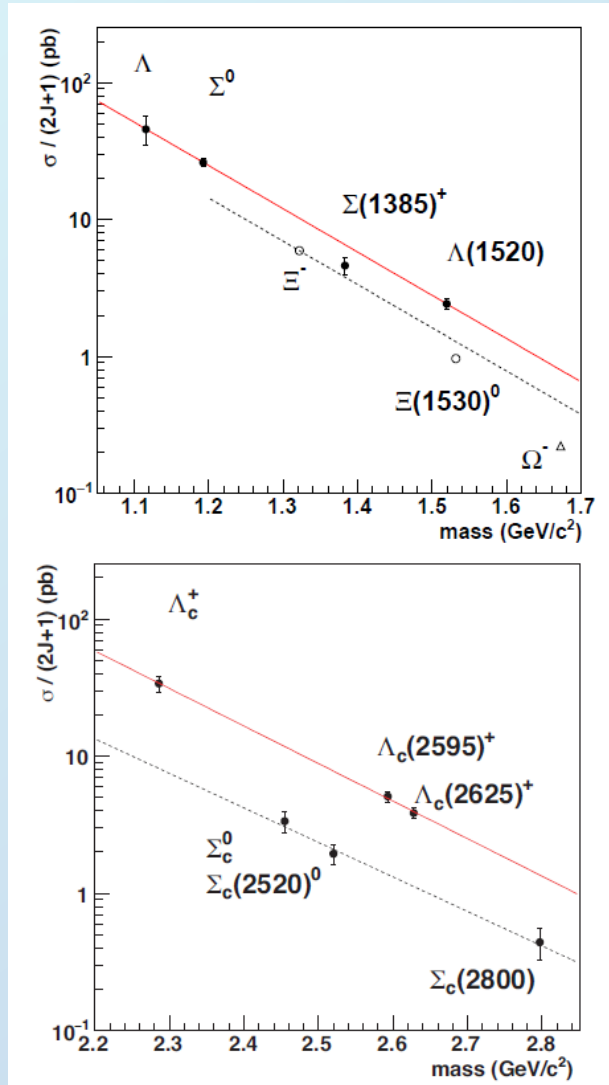
Charmed baryon Fragmentation

Belle: Niiyama et. al. [PRD 97 \(2018\), 072005](#)



- Charmed baryons carry large fraction of parton momentum, similar to charmed mesons
- Charmed fragmentation reasonably described in Pythia for main states

Baryon production rates



- First feed-down corrected production rates extracted
- No $\Lambda(1520)$ enhancement seen
- Strangeness suppression seen for hyperons:

$$\frac{\sigma(S = -1)}{(2J + 1)} > \frac{\sigma(S = -2, -3)}{(2J + 1)}$$

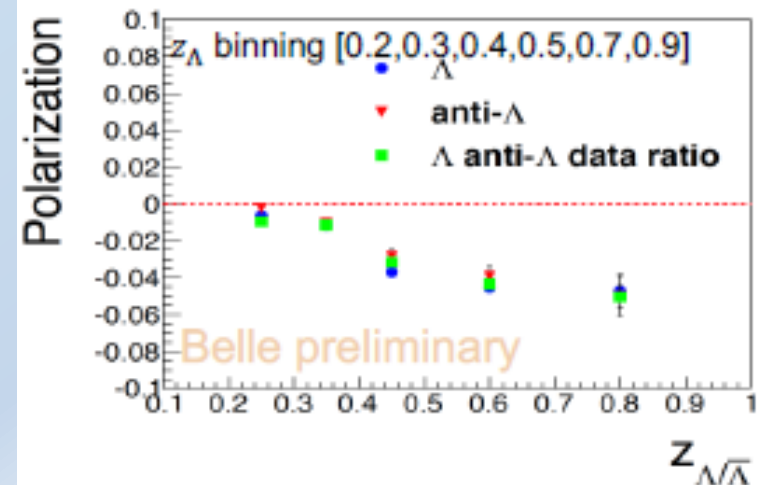
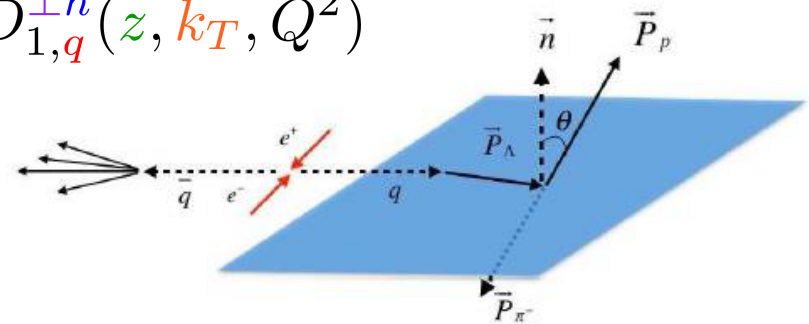
- Difference in slopes for Λ_c and Σ_c in support of diquark production picture (spin 1 diquarks suppressed)

Single Λ polarization measurements

YingHui Guan (Indiana/KEK):
[arXiv:1611.06648](https://arxiv.org/abs/1611.06648)

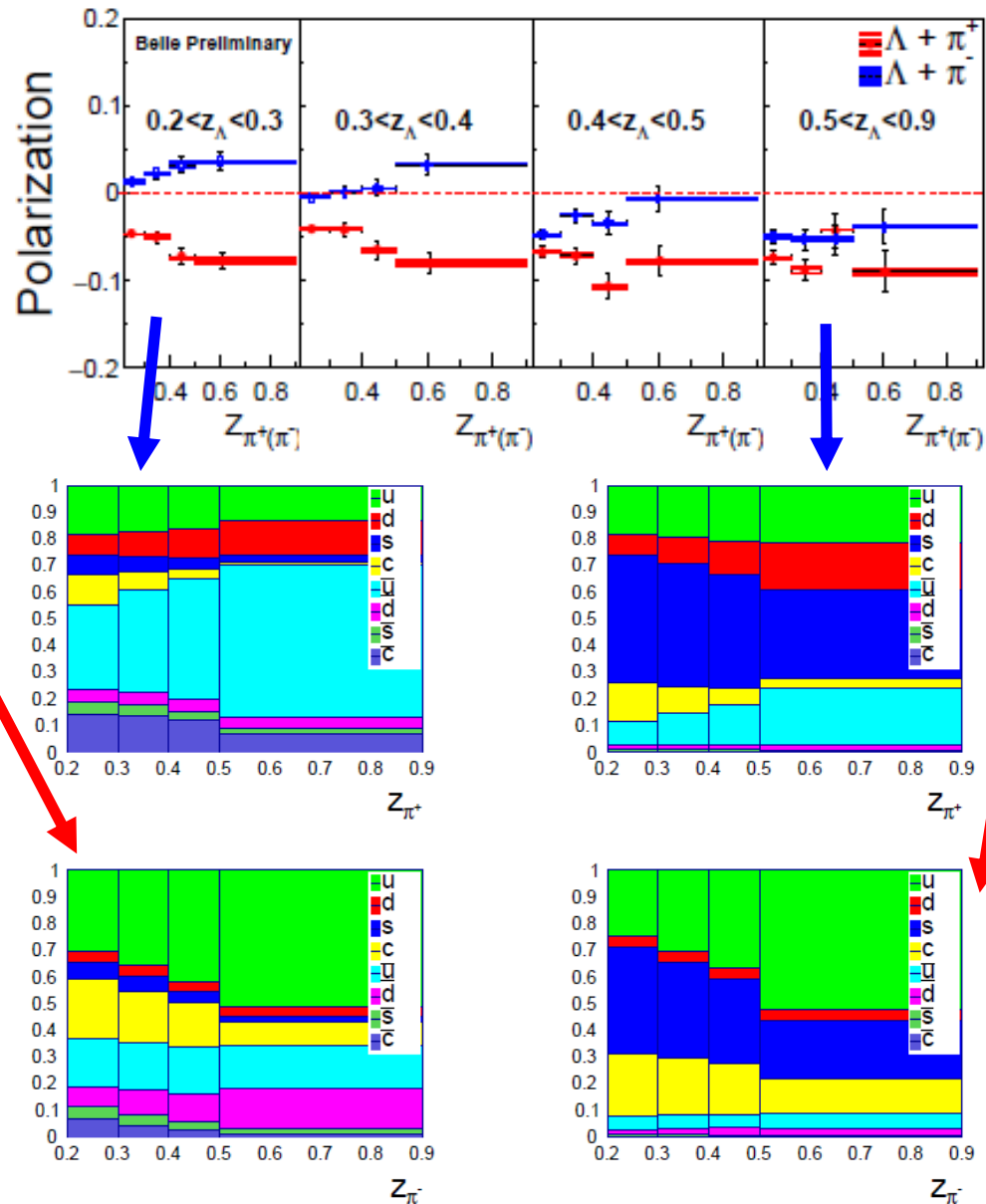
- Related to open question about Λ polarization in hadron collisions from 40 years ago!
- Fragmentation counterpart to the Sivers Function:
 unpolarized parton fragments into transversely polarized baryon with transverse momentum wrt to parton direction
- Reconstruct Λ , its transverse momentum and polarization

$$D_{1,q}^{\perp h}(z, k_T, Q^2)$$



Opposite hemisphere pion correlation

- Interesting z_π and z_Λ dependence :
- At low z_Λ light quark fragmentation dominant, some charm in $\pi^- \rightarrow$ different signs
- At high z_Λ strange + charm fragmentation more relevant \rightarrow same signs

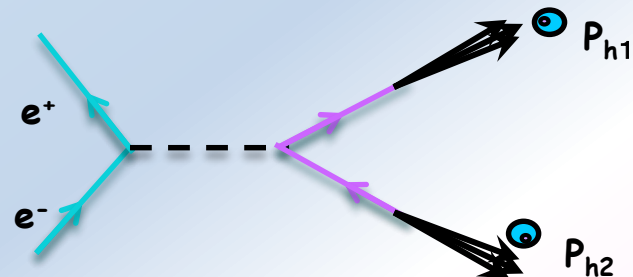
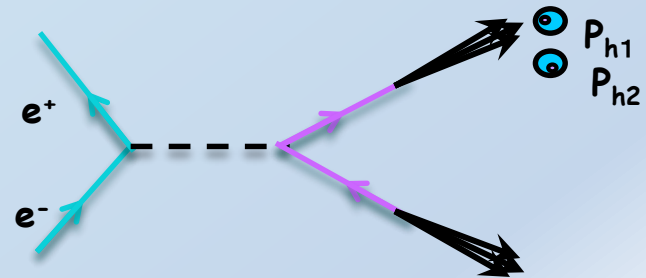


Di-hadron fragmentation functions

$$D_{1,q}^{h_1 h_2}(z, m, Q^2)$$

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

$$D_{1,q}^h(z_1, Q^2) D_{1,q}^h(z_2, Q^2)$$



Di-hadrons

In e^+e^- annihilation:

$$Q = \sqrt{s}$$

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

- Single inclusive hadron multiplicities ($e^+e^- \rightarrow hX$) sum over all available flavors and quarks and antiquarks:

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

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

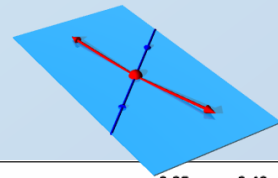
$$u\bar{u} \rightarrow \pi^+ \pi^- X \propto D_{u,fav}^{\pi^+}(z_1, Q^2) \cdot D_{\bar{u},fav}^{\pi^-}(z_2, Q^2) + D_{\bar{u},dis}^{\pi^+}(z_1, Q^2) \cdot D_{u,dis}^{\pi^-}(z_2, Q^2)$$

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

- Also: unpol baseline for interference fragmentation

Ratios to opposite charge pion pairs

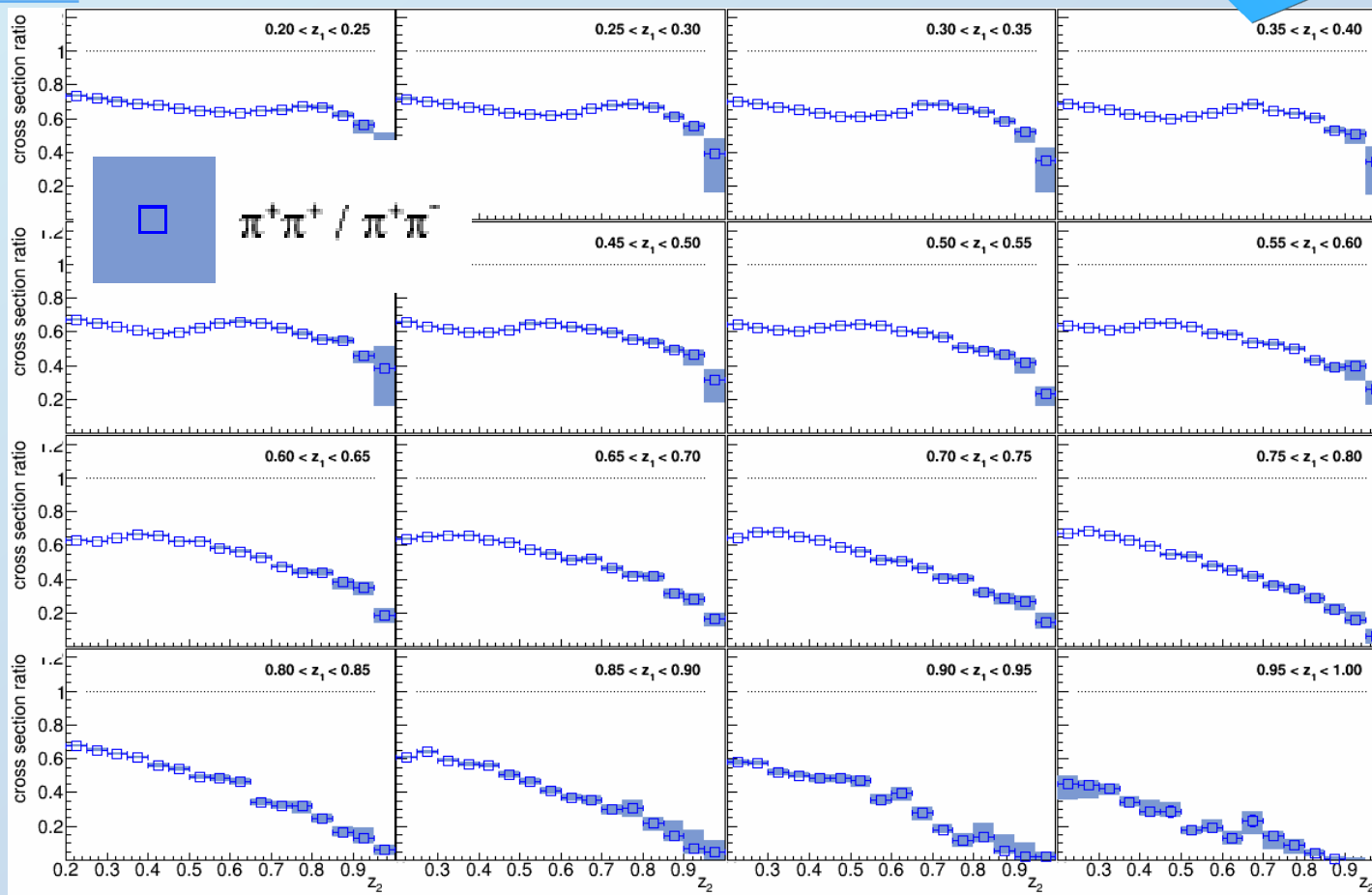
$$R \approx \frac{D_{dis}(z_1)D_{fav}(z_2) + D_{fav}(z_1)D_{dis}(z_2)}{D_{fav}(z_1)D_{fav}(z_2) + D_{dis}(z_1)D_{dis}(z_2)}$$



PRD92 (2015) 092007

$\pi^+\pi^+$ 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



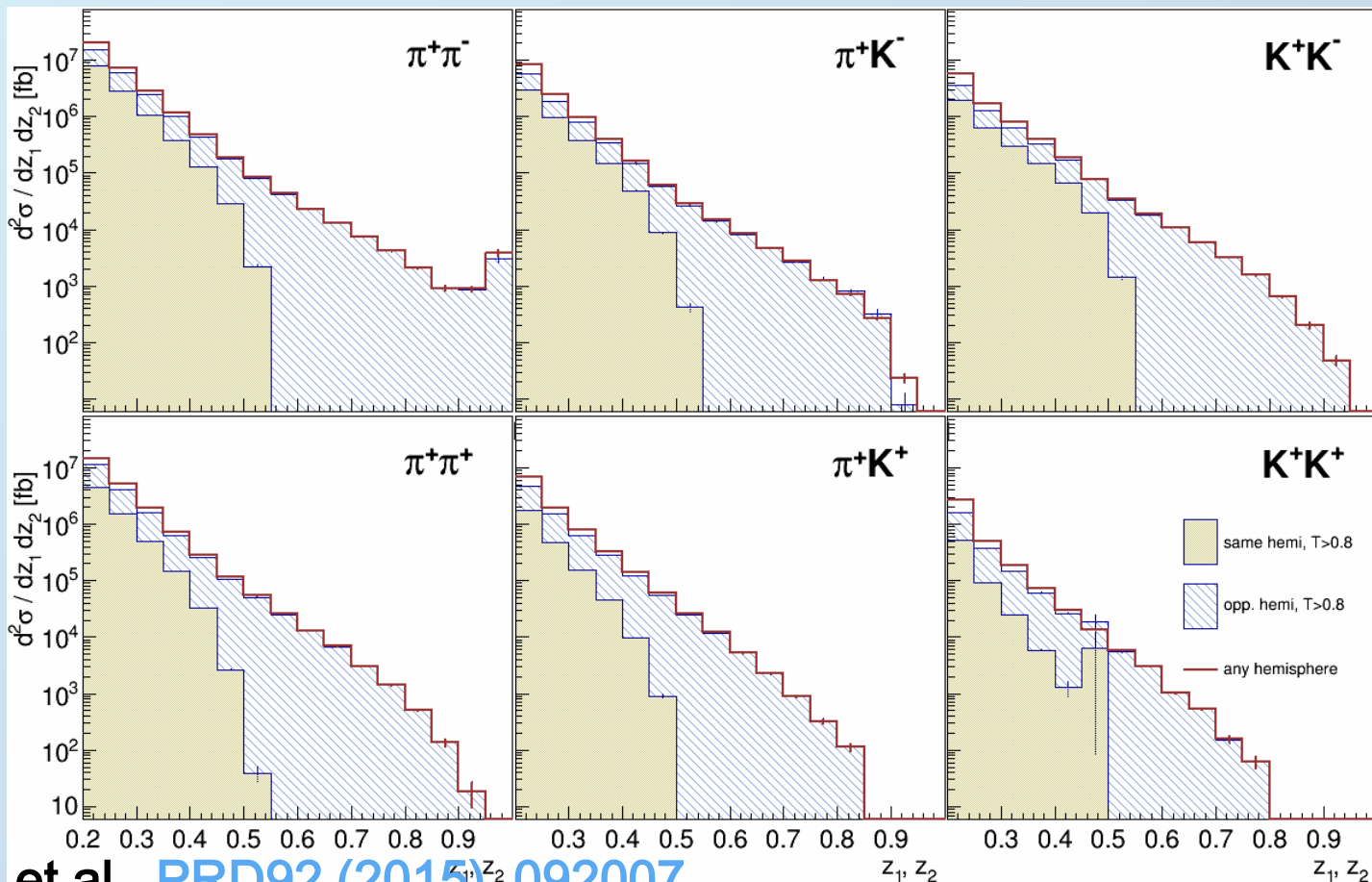
Hemisphere composition

Same hemisphere contribution drops rapidly: Consistent with LO assumption of

Same hemisphere: single quark \rightarrow di-hadron FF: ($z_1 + z_2 < 1$)

Opposite hemisphere: single quark \rightarrow single hadron FF

Diagonal
 z_1, z_2
bins

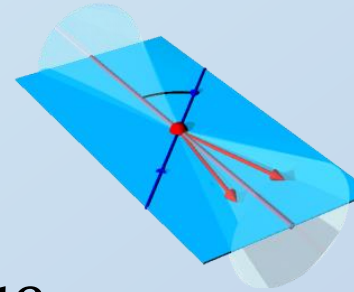


Belle: RS et.al., [PRD92 \(2015\) 092007](#)

Systematic uncertainties not displayed

R.Seidl: Belle Fragmentation

Explicit di-hadron mass dependence

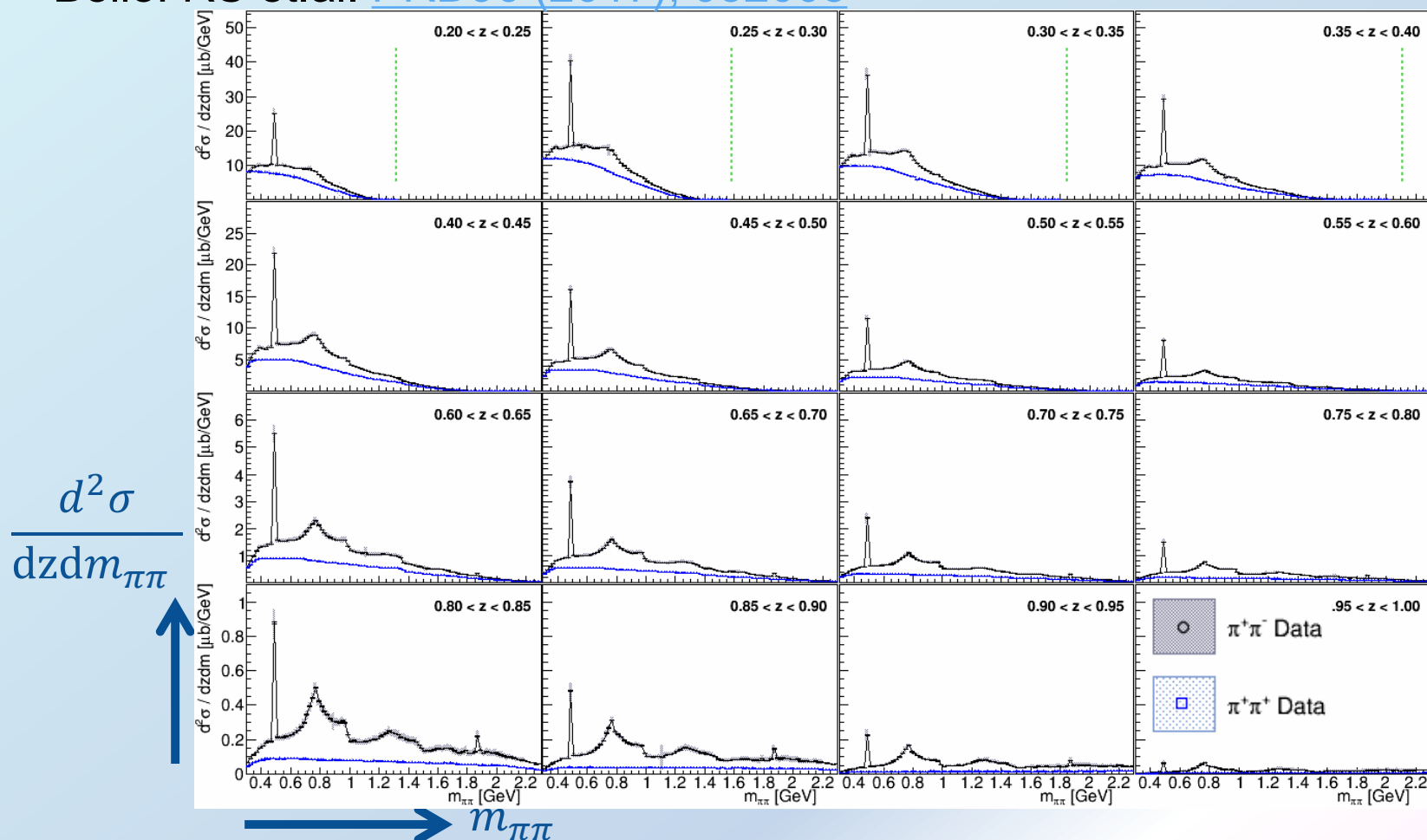


- IFF related asymmetries extracted by Belle in 2011 (PRL107:072004(2011))
 - SIDIS (JHEP 0806 (2008), PLB713 (2012)) and RHIC ([PRL 115 \(2015\) 242501](#)) IFF asymmetries published
 - Global fits currently missing unpolarized di-hadron FF baseline
- ➔ Belle to the rescue
- Use same hemisphere di-hadrons for this analysis
 - 16 z bins between 0.2 – 1
 - 100 mass bins between 0.3 – 2.3 GeV
 - Data analysis and correction steps same as previous di-hadron analysis, except for ISR treatment

Di-hadron mass dependence

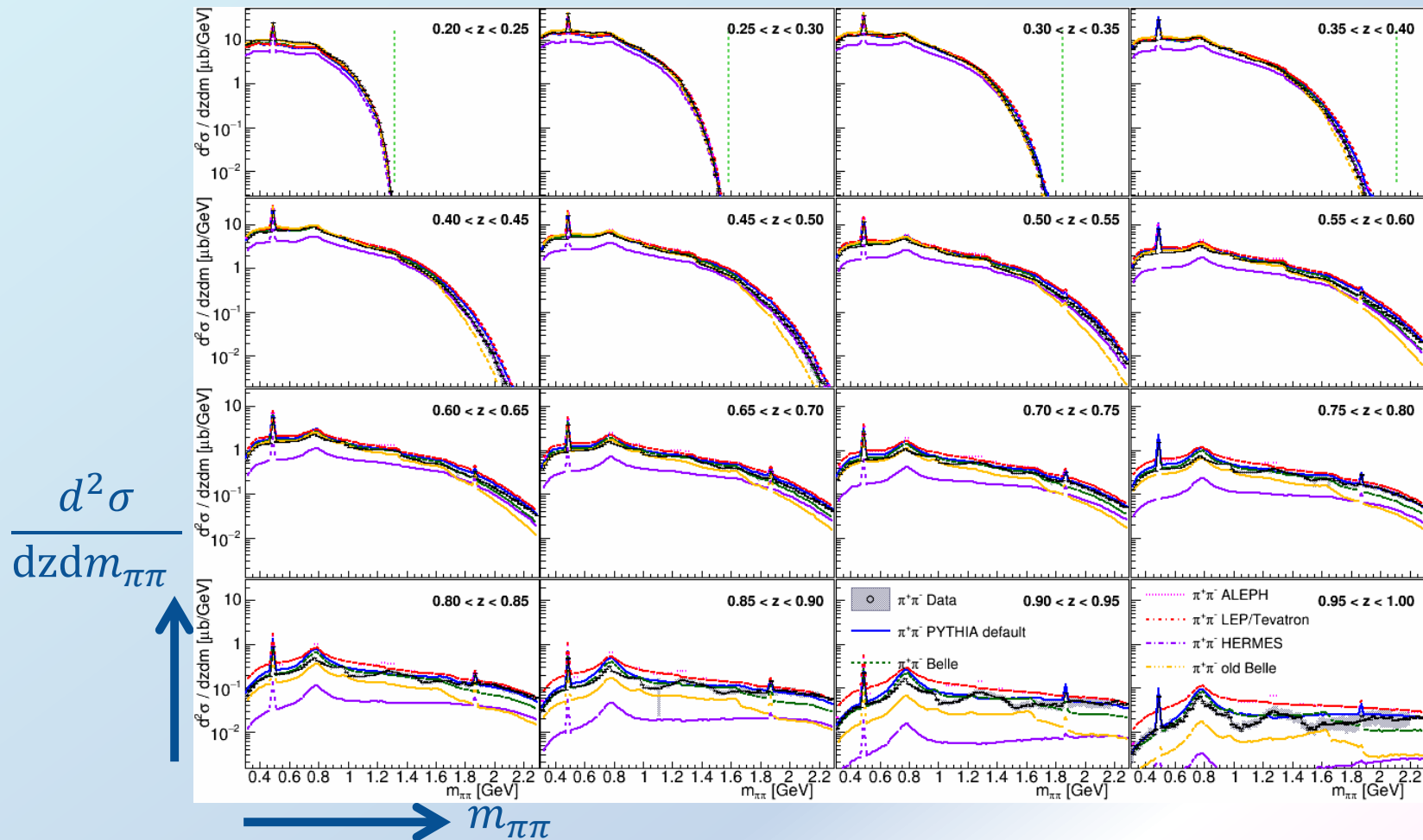
Similar analysis in same hemisphere and mass – combined z binning. Important input for IFF based transversity global analysis

Belle: RS et.al. [PRD96 \(2017\), 032005](#)



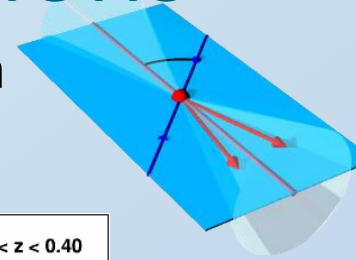
Mass dependence comparisons to Pythia tunes

Magnitude and z dependence reasonable in Pythia 6.4 default,
Intermediate mass structure better described by LEP tunes (higher spin mesons)

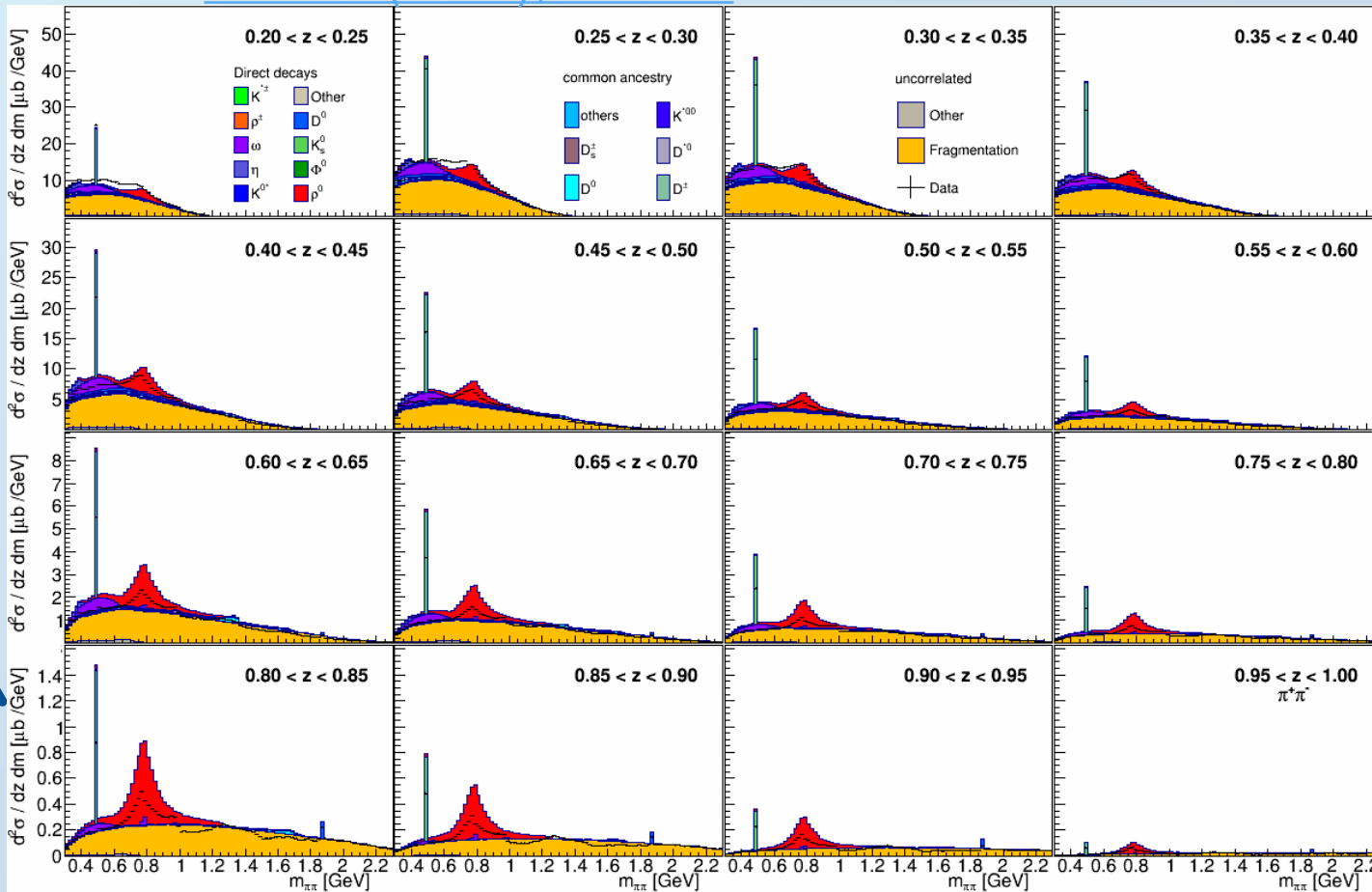


Di-pion individual contributions

Contributions from various resonances and direct fragmentation



Belle: RS et.al. [PRD96 \(2017\), 032005](#)



$\frac{d^2\sigma}{dz dm_{\pi\pi}}$

$m_{\pi\pi}$

R.Seidl: Belle Fragmentation

Summary and outlook

- Hyperon and charmed baryon fragmentation measurements just published, support for diquark picture in charm FF
- Nonzero Lambda polarization measured, interesting flavor dependence
- Di-hadron fragmentation functions measured, important input for di-hadron related Transversity/Tensor charge extractions
- Transverse momentum dependent fragmentation analysis ongoing
- Other results being finalized as well (η, π^0 Collins)