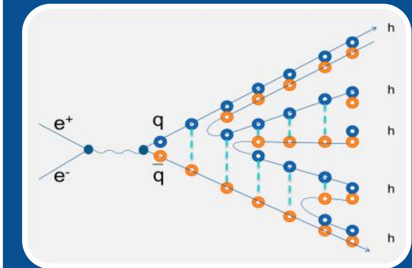
Fragmentation measurements in e^+e^- and relation to EIC

EIC User Group meeting, Trieste
July 18-22, 2017

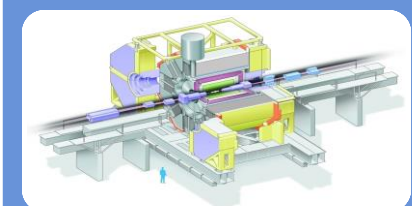
Ralf Seidl (RIKEN)

What are fragmentation functions?



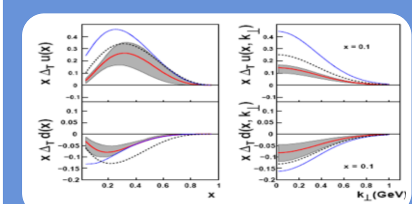
How do quasi-free partons fragment into confined hadrons？

- Does spin play a role？Flavor dependence?
- What about transverse momentum (and its Evolution)？



What experiments measure ：

- Normalized hadron momentum in CMS ： $e^+e^- \rightarrow h(z)\ X$; $z = 2E_h/\sqrt{s}$
- Hadron pairs' azimuthal distributions ： $e^+e^- \rightarrow h_1\ h_2\ X$; $\langle\cos(\phi_1+\phi_2)\rangle$; Collins FF、Interference （IFF）
- Cross sections or multiplicities differential in z: ep->hX, pp->hX



Additional benefits of the FF measurements ：

- Pol FFs necessary input to transverse spin SIDIS und pp measurements to extract Transversity distributions function
- Flavor separation of all Parton distribution functions (PDFs) via FFs (including unpolarized PDFs)
- Baseline for any Heavy Ion measurement
- Access to exotics?

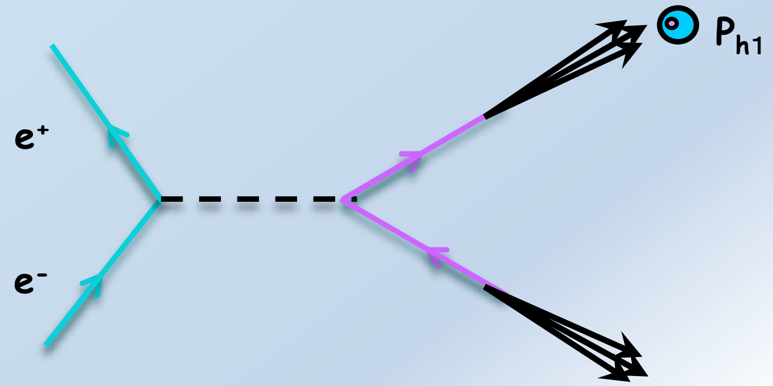
Fragmentation functions and spin structure of the nucleon

- Unpolarized fragmentation functions:
  - Provide flavor information in nucleon
  - Most apparent in SIDIS measurements related to $\Delta q(x)$
  - But also required for all RHIC hadron asymmetries (especially pion A_{LL} charge ordering)
  - Transverse momentum dependence needed for Sivers and other TMDs

- Polarized fragmentation functions:
  - For transverse spin almost unique access (require two chiral-odd functions):
    - DY: δq x δq or
    - SIDIS/RHIC: δq x Collins or δq x IFF
  - FFs from Belle/Babar

Unpolarized fragmentation functions

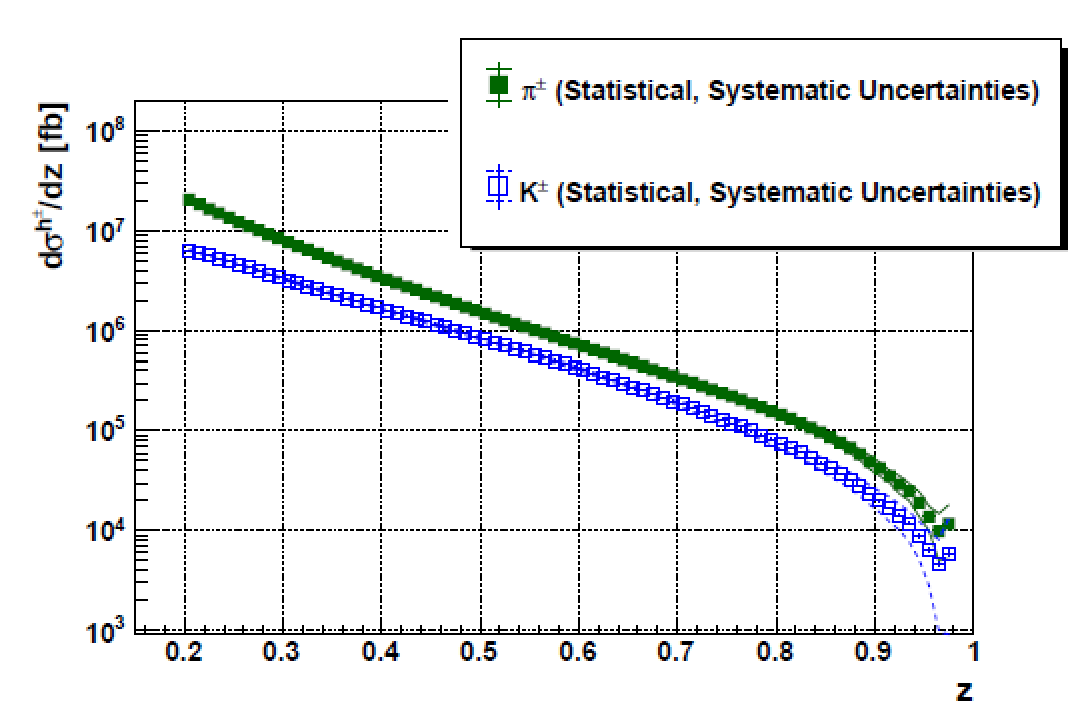
$$D^{h}_{1,q}(z, Q^2)$$



Unpolarized light hadron fragmentation

In e^+e^- annihilation:

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



BaBar: π,K,p - PRD 88 (2013) 032011
Belle : π,K - PRL 111 (2013) 062002
p - PRD92 (2015) 092007

B-factories: high precision at mid- to high-z, "low" Q^2 lever arm

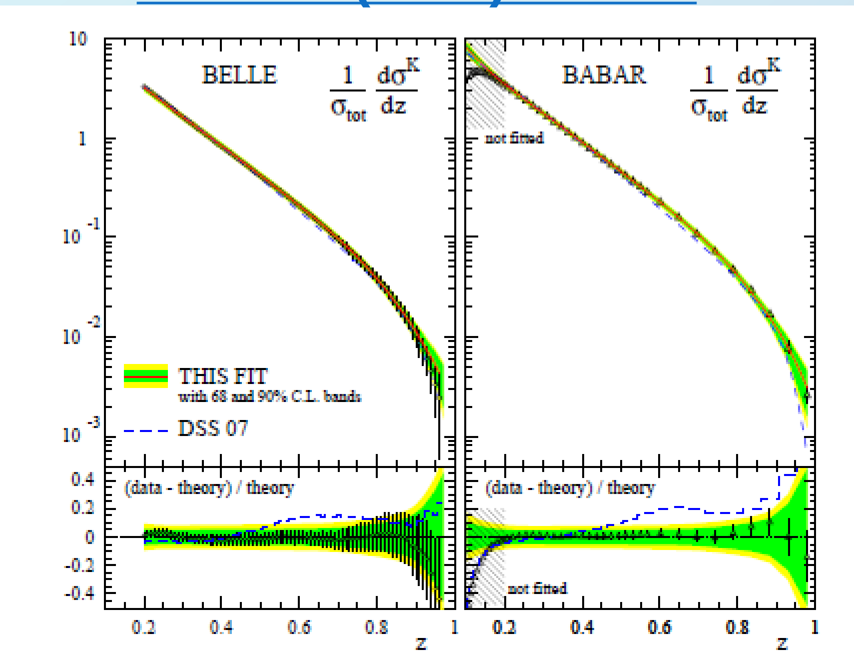
- Single-hadron cross sections at leading order in α_s related to fragmentation functions

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

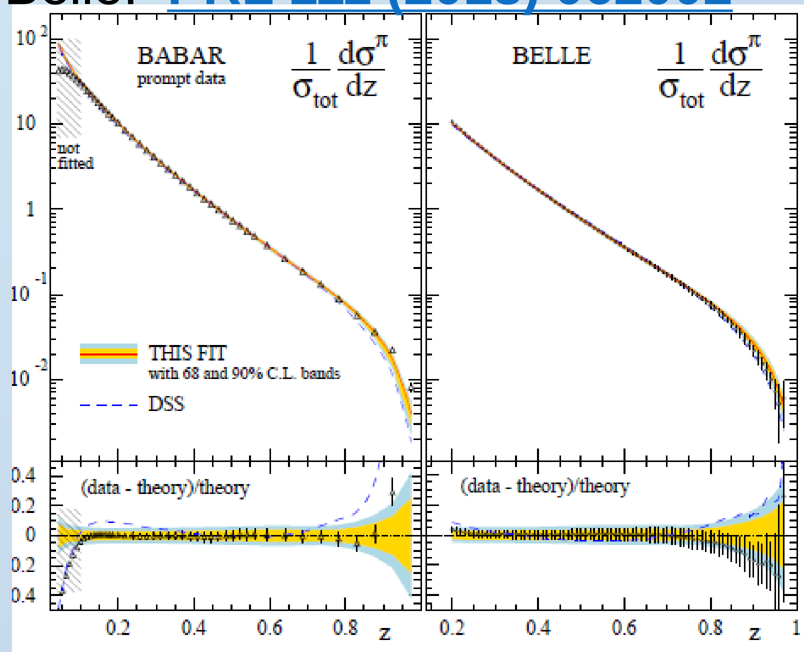
- Only at higher orders access to gluon FFs

B factory data (Q~10GeV)

Babar: PRD 88 (2013) 032011



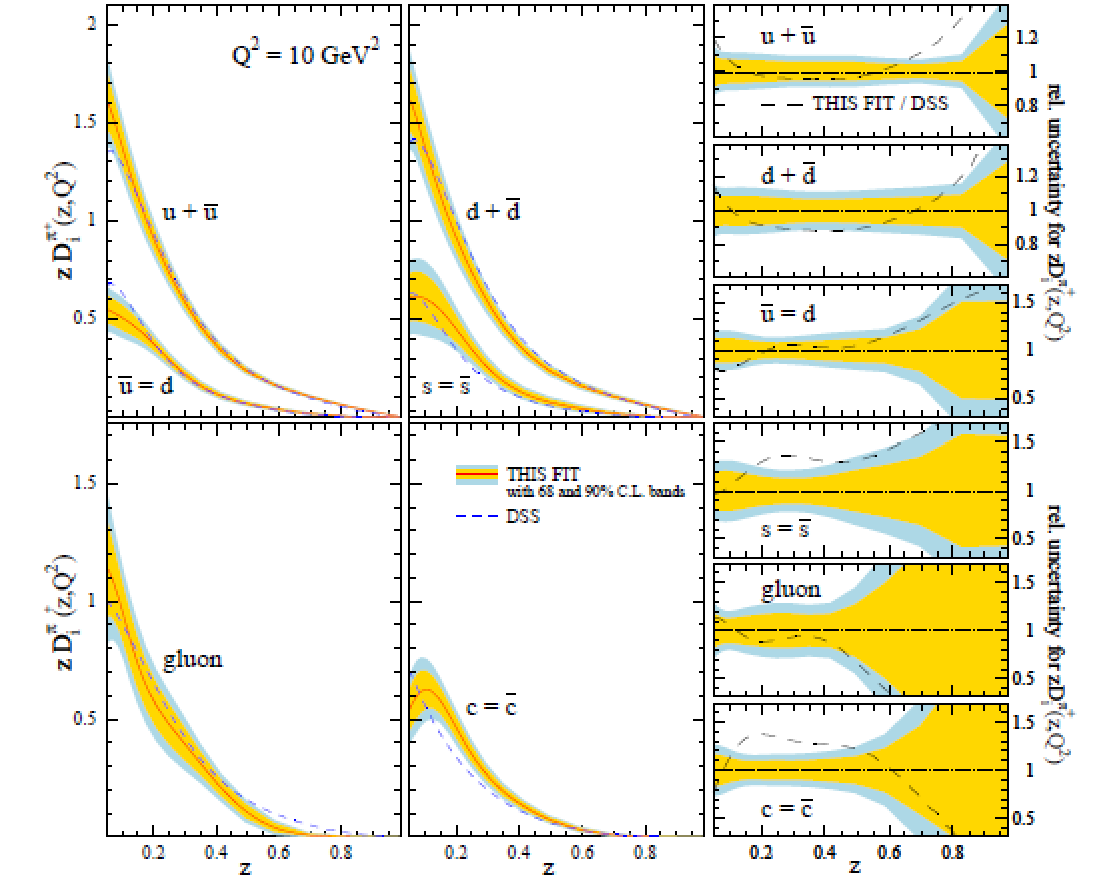
Belle: PRL 111 (2013) 062002



- High precision pion and kaon data from both B factory experiments
- Precision up to very high z
- Lever arm to much higher energy (Q~20 – 200GeV) data allows for determination of gluon fragmentation over evolution

Pion fragmentation

DSS15: [deFlorian et.al., Phys.Rev. D91 (2015) 014035]

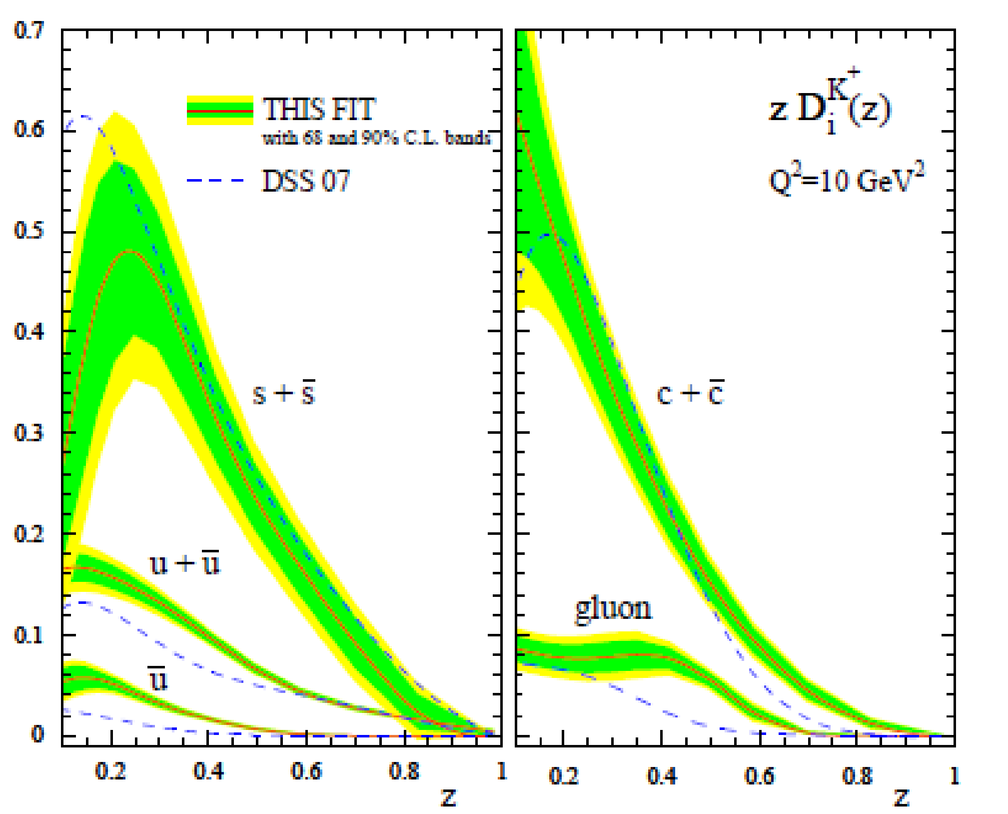


- Light quarks symmetric
- Dominated by favored fragmentation especially at high z
- Gluon substantial but falling off faster than quarks

Kaon fragmentation

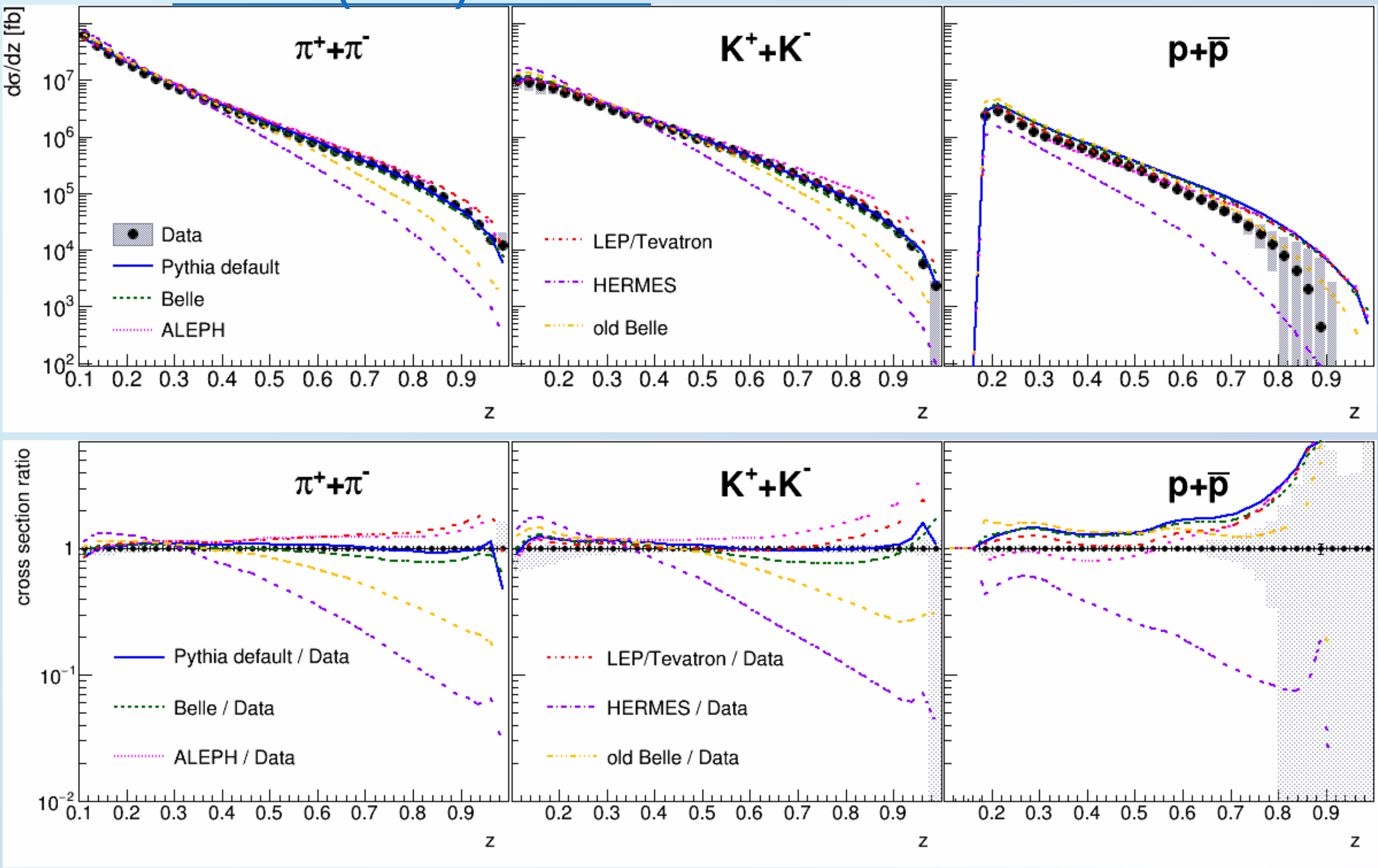
DHESS PRD 95 (2017) 094019

- Strange quarks are dominating kaon fragmentation
- Again likely dominated by favored fragmentation
- At lower z penalty for producing $s\bar{s}$ pair in fragmentation ($u+\bar{u} < s+\bar{s}$)
- Charm fragmentation comparable (what about weak decays?)



New addition: single protons

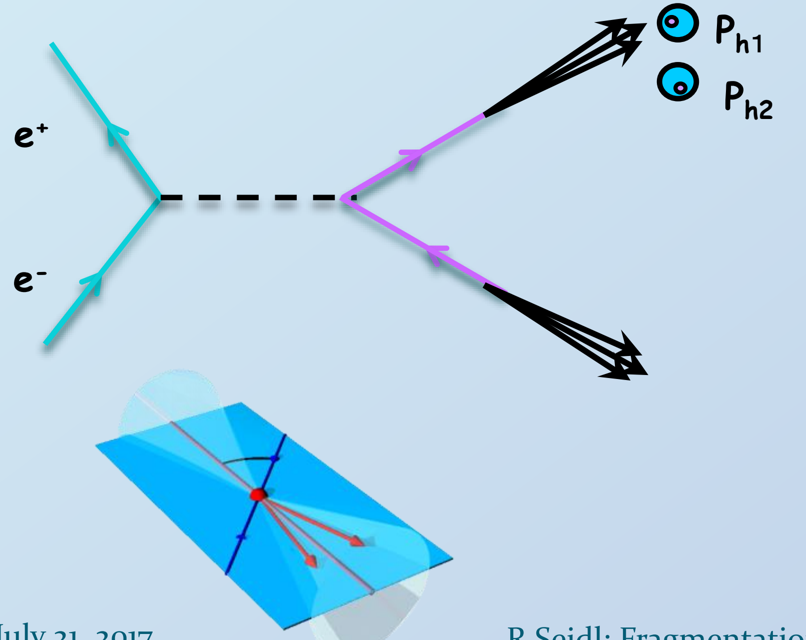
PRD92 (2015) 092007



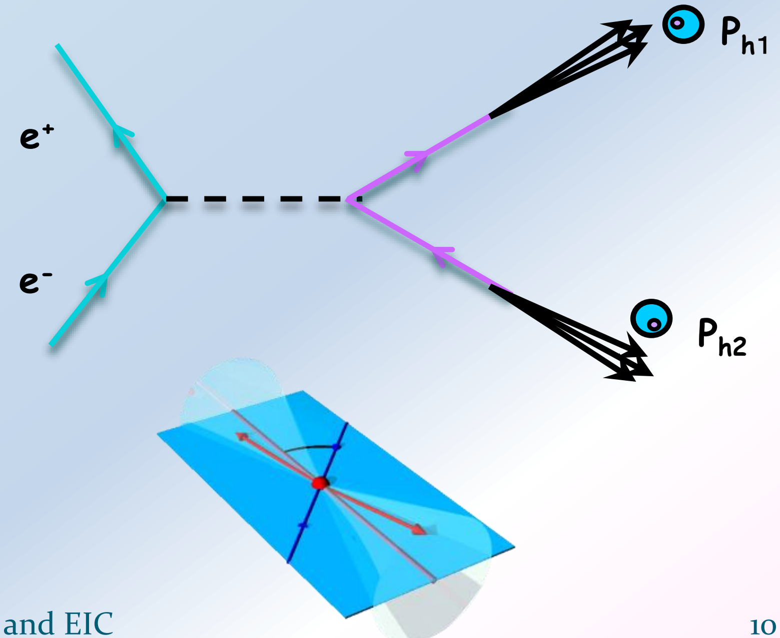
- Default Pythia and current Belle in good agreement with pions and kaons
- Protons not well described by any tune

Di-hadron fragmentation functions

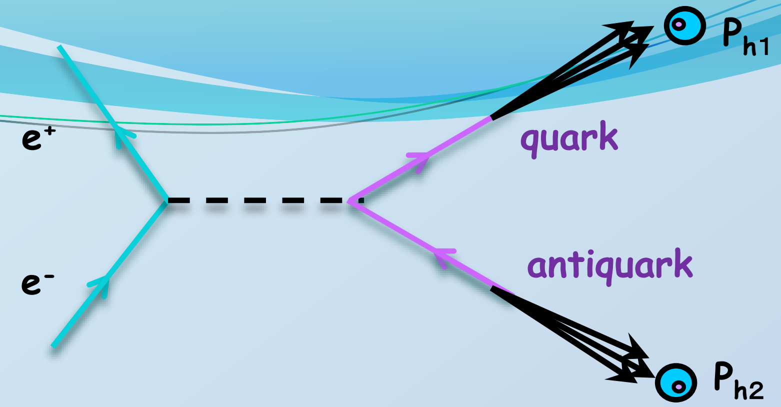
$$D_{1,q}^{h_1 h_2}(z, m, Q^2)$$



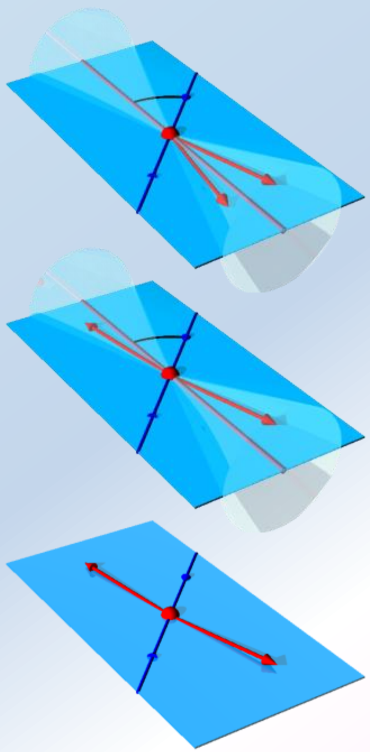
$$D_{1,q}^{h}(z_1, Q^2) D_{1,q}^{h}(z_2, Q^2)$$



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



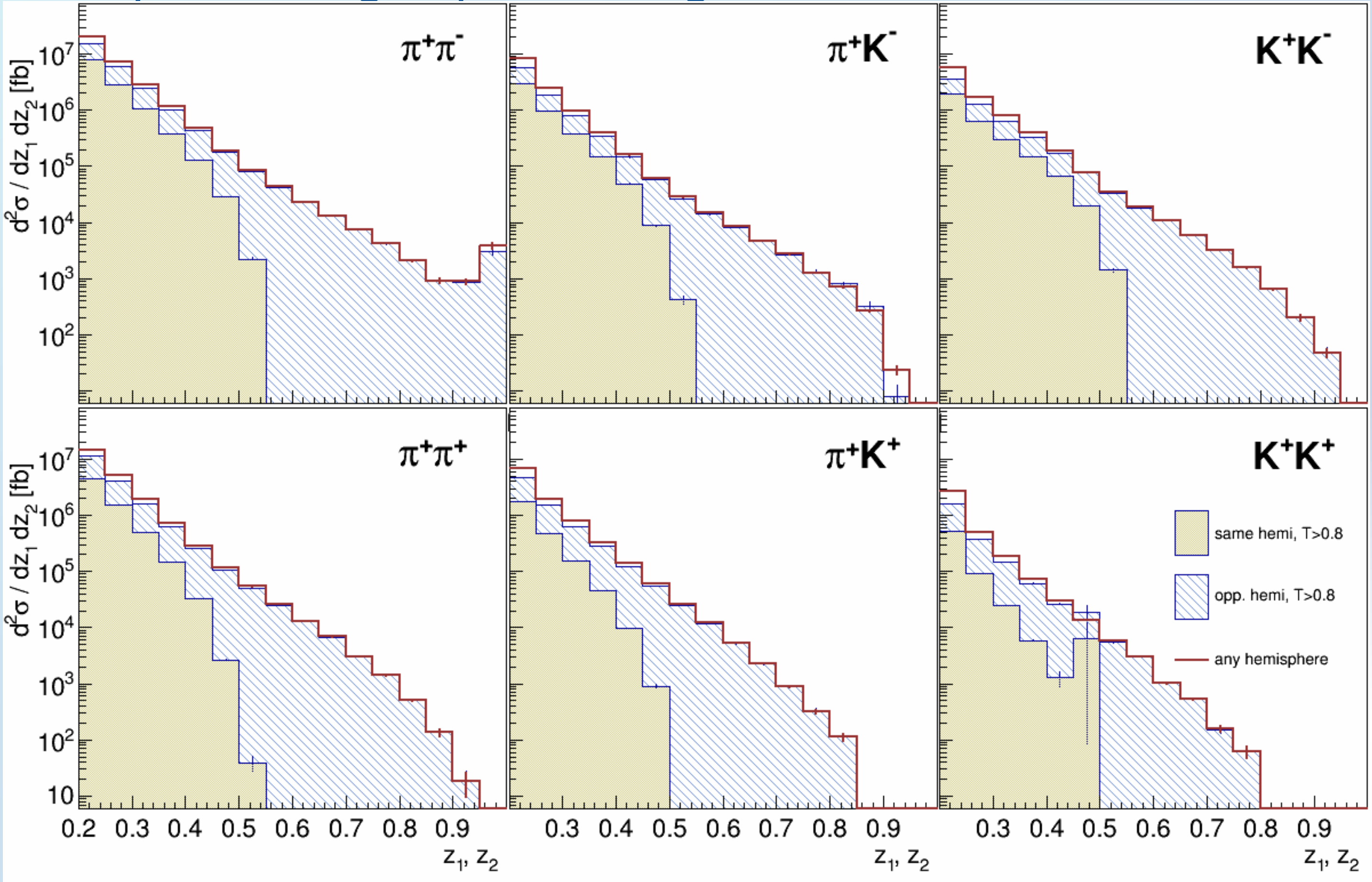
Hemisphere composition

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

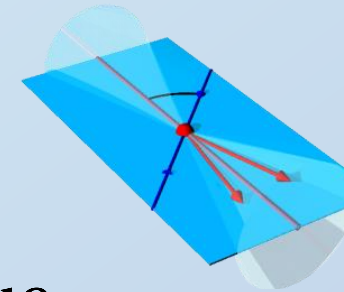
Diagonal z_1,z_2 bins



Belle: RS et.al., PRD92 (2015) 092007

Systematic uncertainties not displayed

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

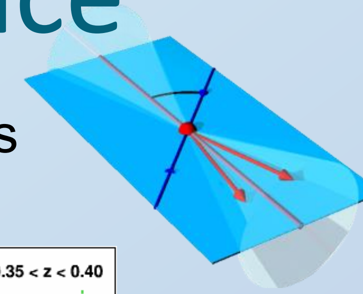
Correction chain

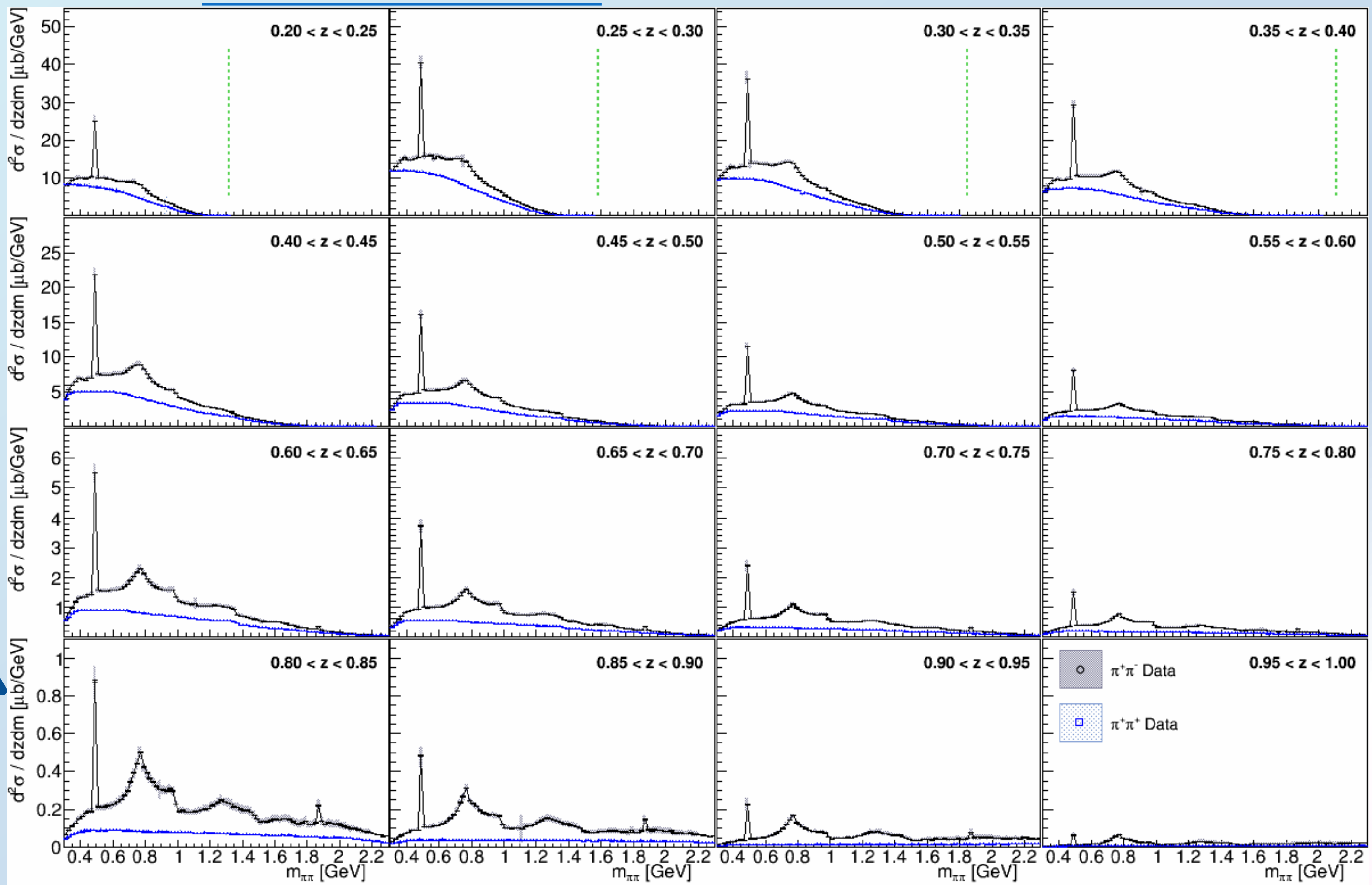
Correction	Method	Systematics
PID mis-id	PID matrices (5x5 for cos θ_{lab} and p_{lab})	MC sampling of inverted matric element uncertainties, variation of PID correction method
Momentum smearing	MC based smearing matrices (1600x1600), SVD unfold	SVD unfolding vs analytically inverted matrix, reorganized 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 4π	MC statistics, variation in tunes
Weak decay removal (optional)	udcs check evt record for weak decays	Compare to other Pythia settings
ISR	ISR on vs ISR off in Pythia	Variatons in tunes

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. arXiv:1706.08348

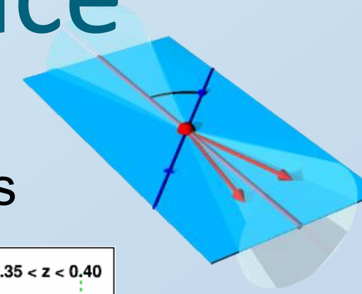




$$\frac{d^2\sigma}{\mathrm{dzd}m_{\pi\pi}}$$

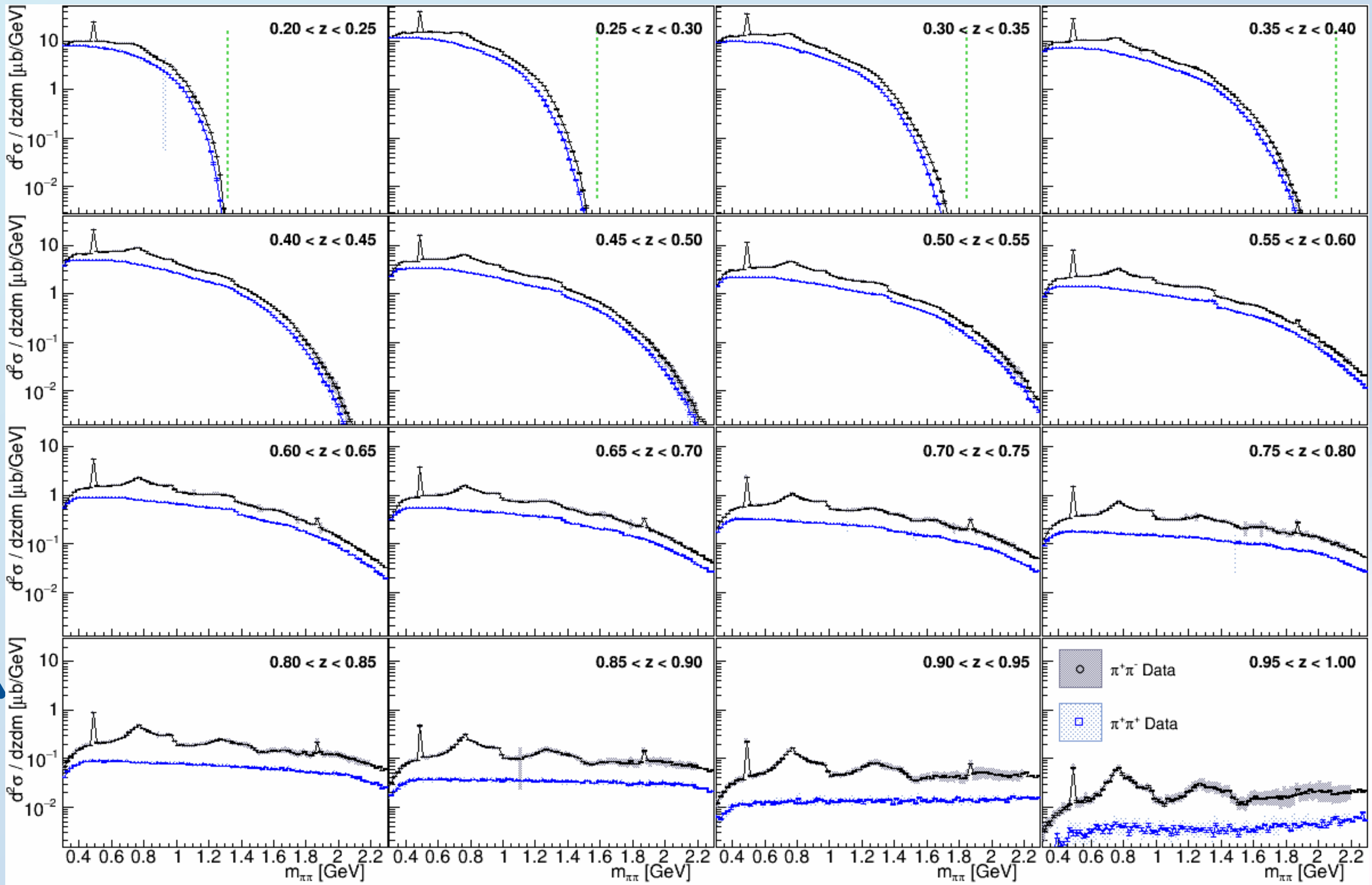
$m_{\pi\pi}$

Di-hadron mass dependence



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

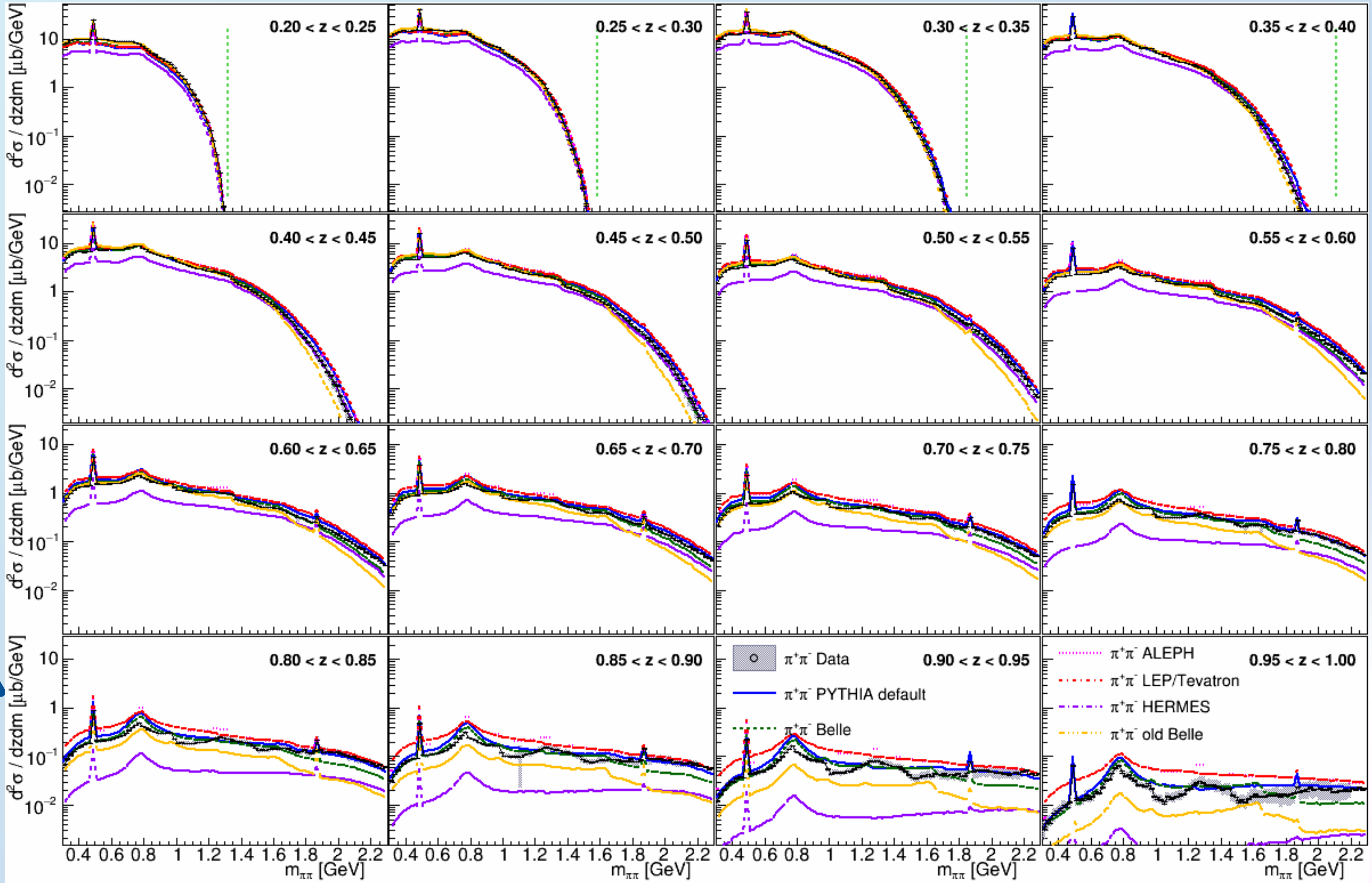
$$\frac{d^2\sigma}{\mathrm{dz}dm_{\pi\pi}}$$



$m_{\pi\pi}$

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)

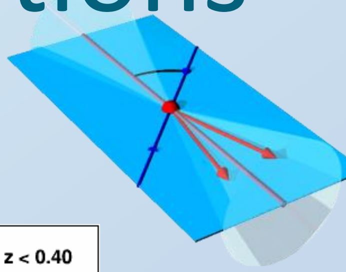


$$\frac{d^2\sigma}{dzdm_{\pi\pi}}$$

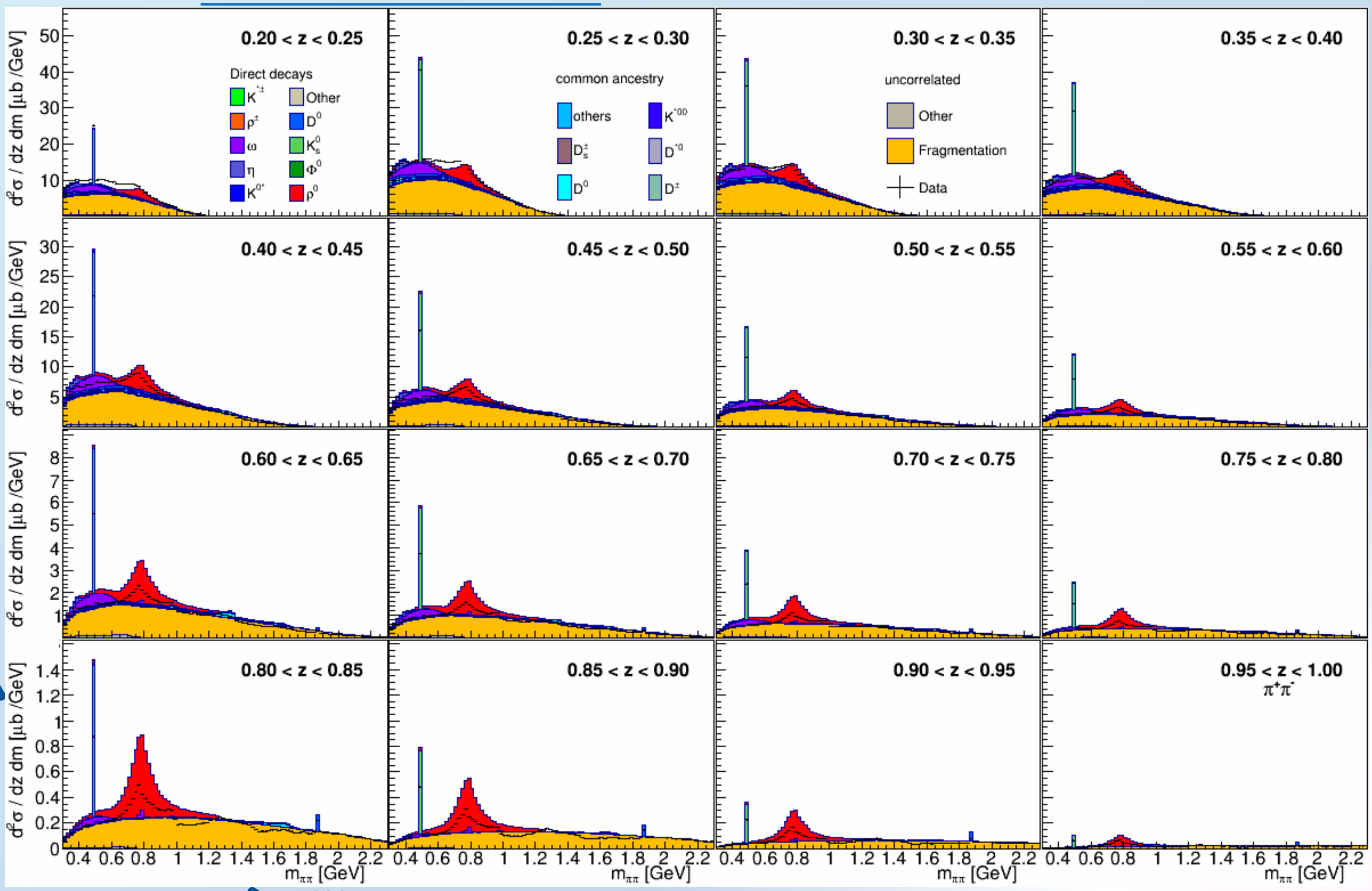
$m_{\pi\pi}$

Di-pion individual contributions

Contributions from various resonances and direct fragmentation



Belle: RS et.al. arXiv:1706.08348

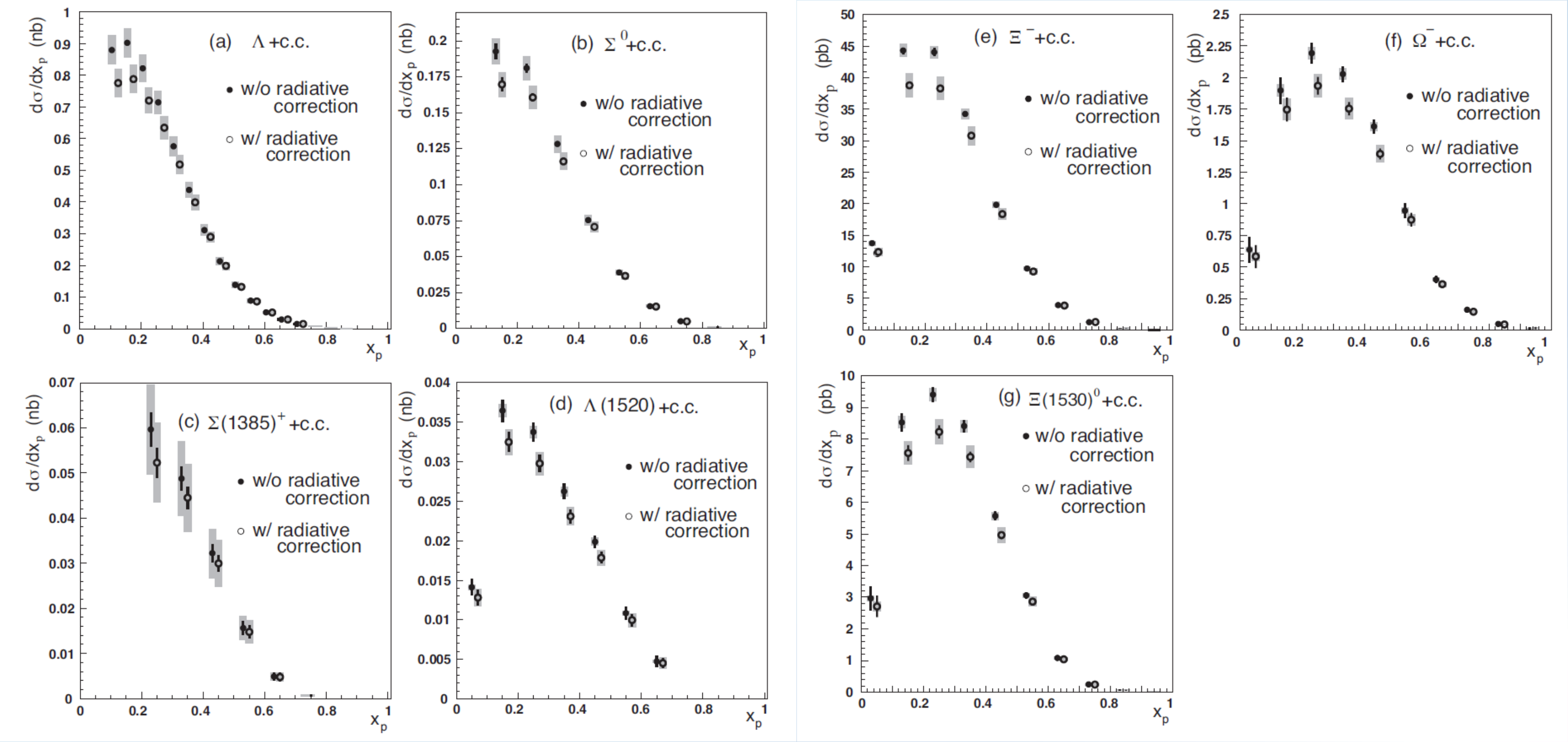


$$\frac{d^2\sigma}{dzdm_{\pi\pi}}$$

$m_{\pi\pi}$

Hyperon Fragmentation

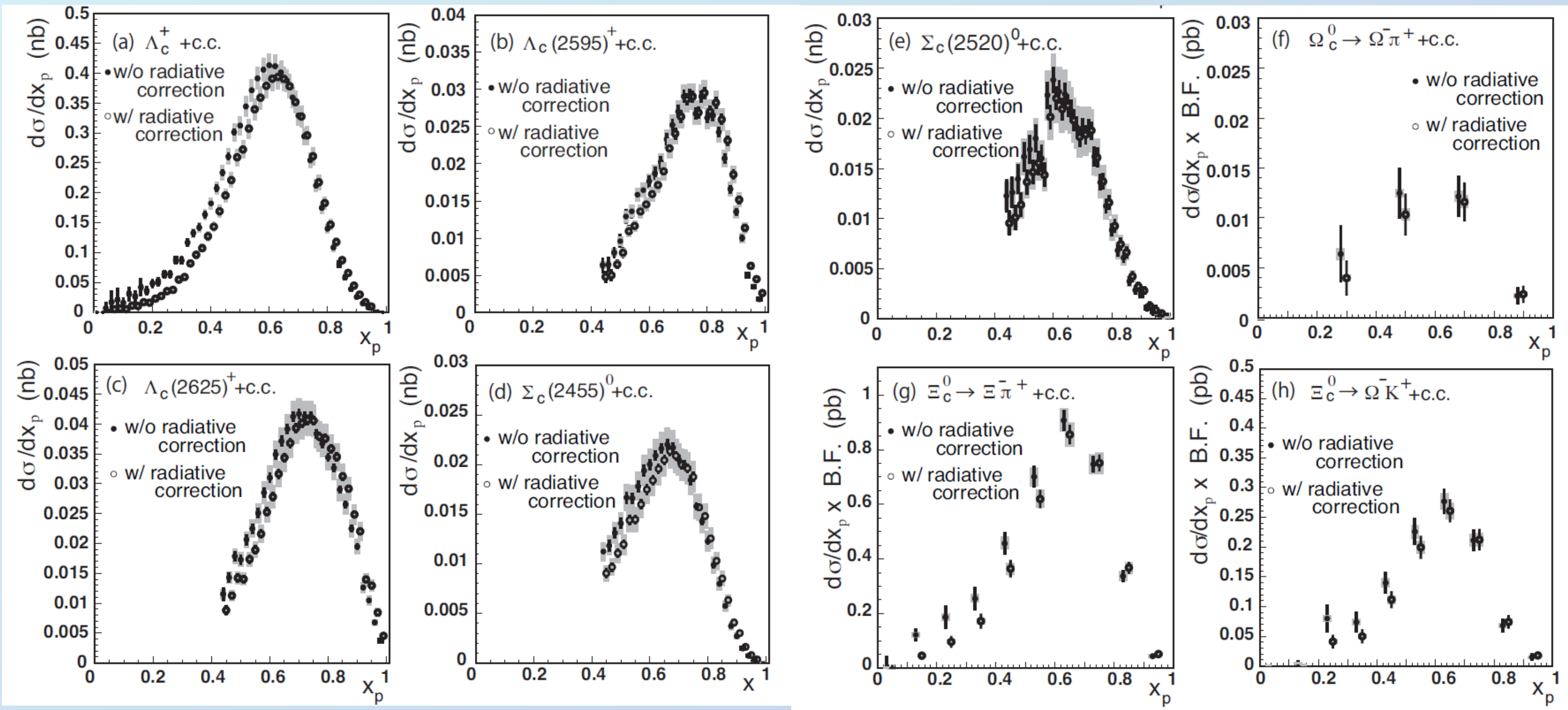
Belle: Niiyama et. al. arXiv:1706.06791



Hyperons similar to light hadron fragmentation → peaking at low z (x_p)

Charmed baryon Fragmentation

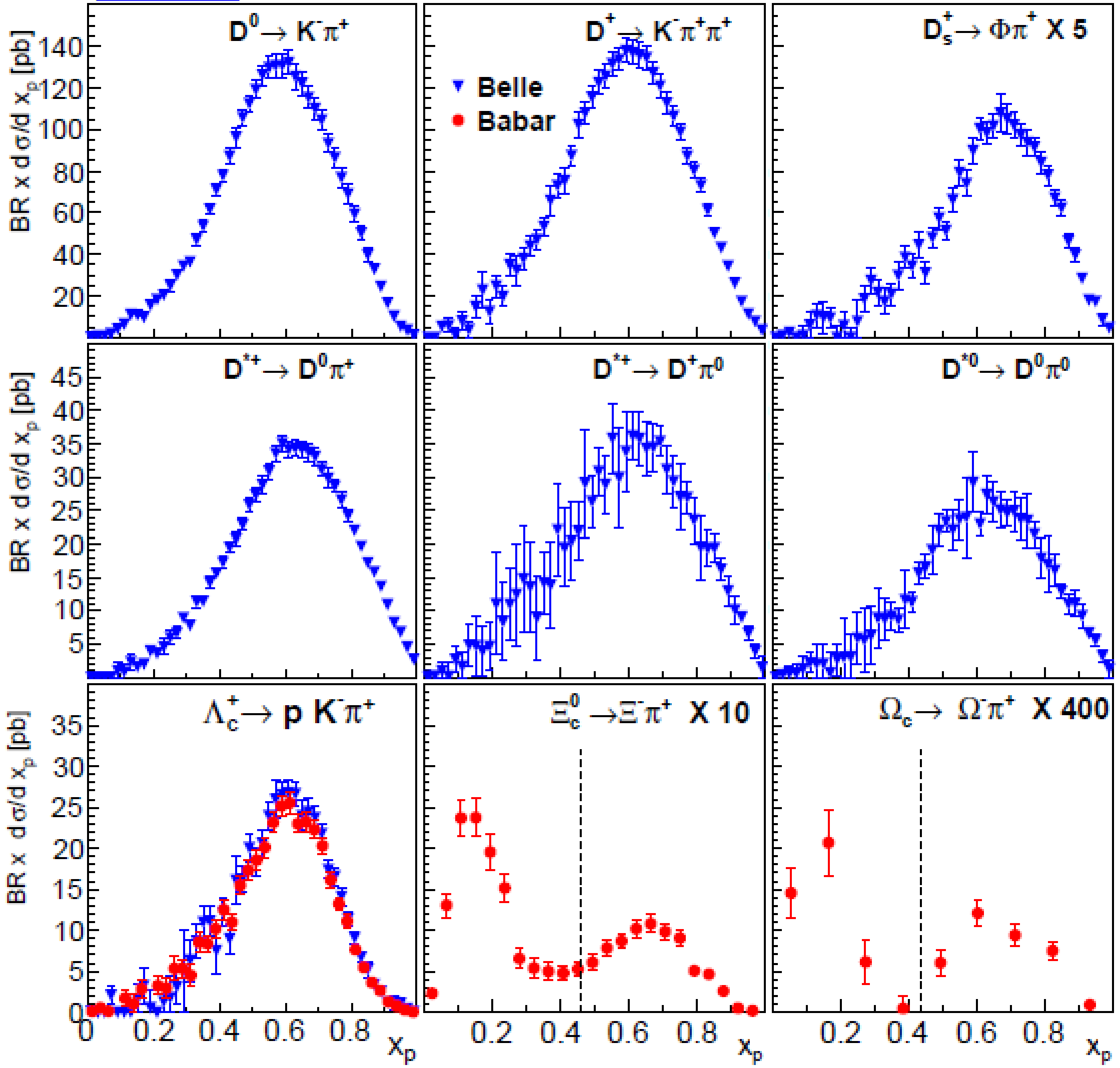
Belle: Niiyama et. Al. [arXiv:1706.06791](https://arxiv.org/abs/1706.06791)



Also Λ_c measurements by:
BaBar: PRD 75,012003 (2007)
and Cleo

Charmed hadrons carry large fraction of parton momentum

Charmed Fragmentation



PRL.95, 142003 (2005)(Babar)
PRD73, 032002 (2006) (Belle)
PRD75, 012003 (2007)(Babar)
PRL 99, 062001 (2007)(Babar)

- Heavier particles generally plotted vs normalized momentum $x_p = \frac{P^h}{P^h_{max}}$
- Unlike light hadrons charmed hadrons contain large fraction of charm quark momentum

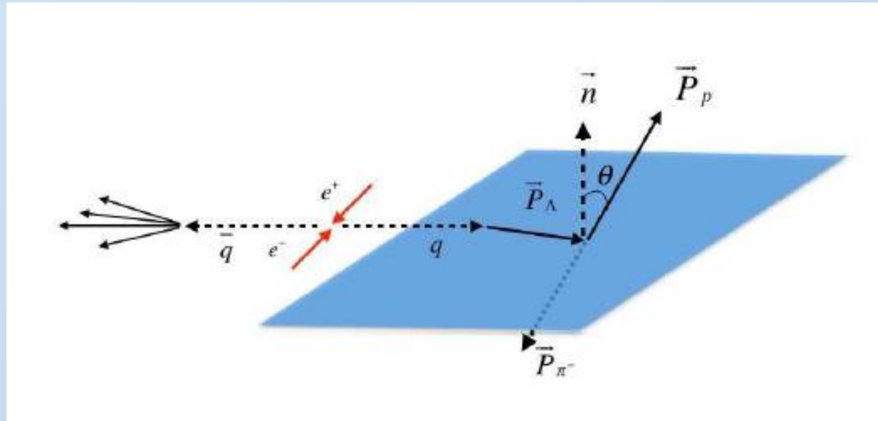
Single Λ polarization measurements

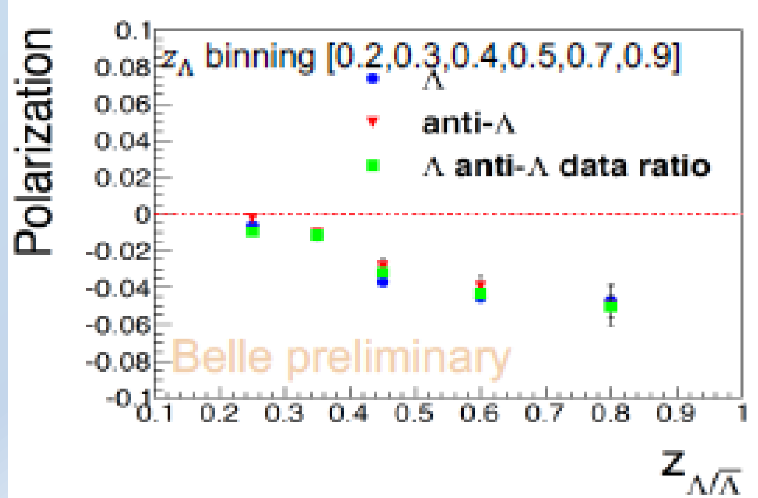
YingHui Guan (Indiana/KEK):
arXiv:1611.06648

- Fragmentation counterpart to the Sivers Function:

  unpolarized parton fragments into transversely polarized baryon with transverse momentum wrt to parton direction

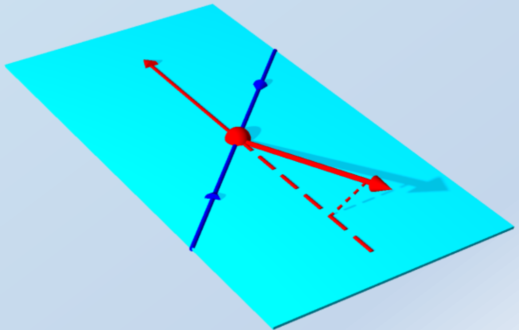
- Reconstruct Λ, its transverse momentum and polarization

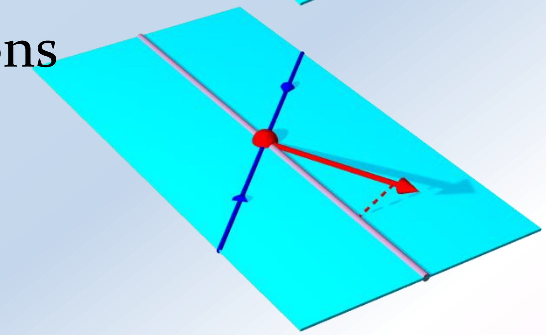


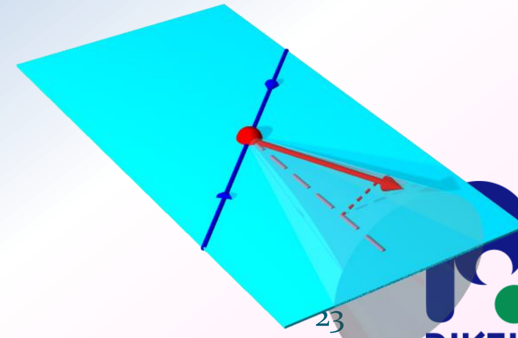


K_T Dependence of FFs

- Gain also 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
  - Single-hadron FF wrt to Thrust or jet axis
    - → No convolution
    - → Need correction for $q\bar{q}$ axis

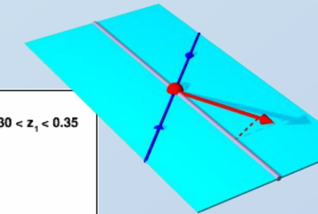


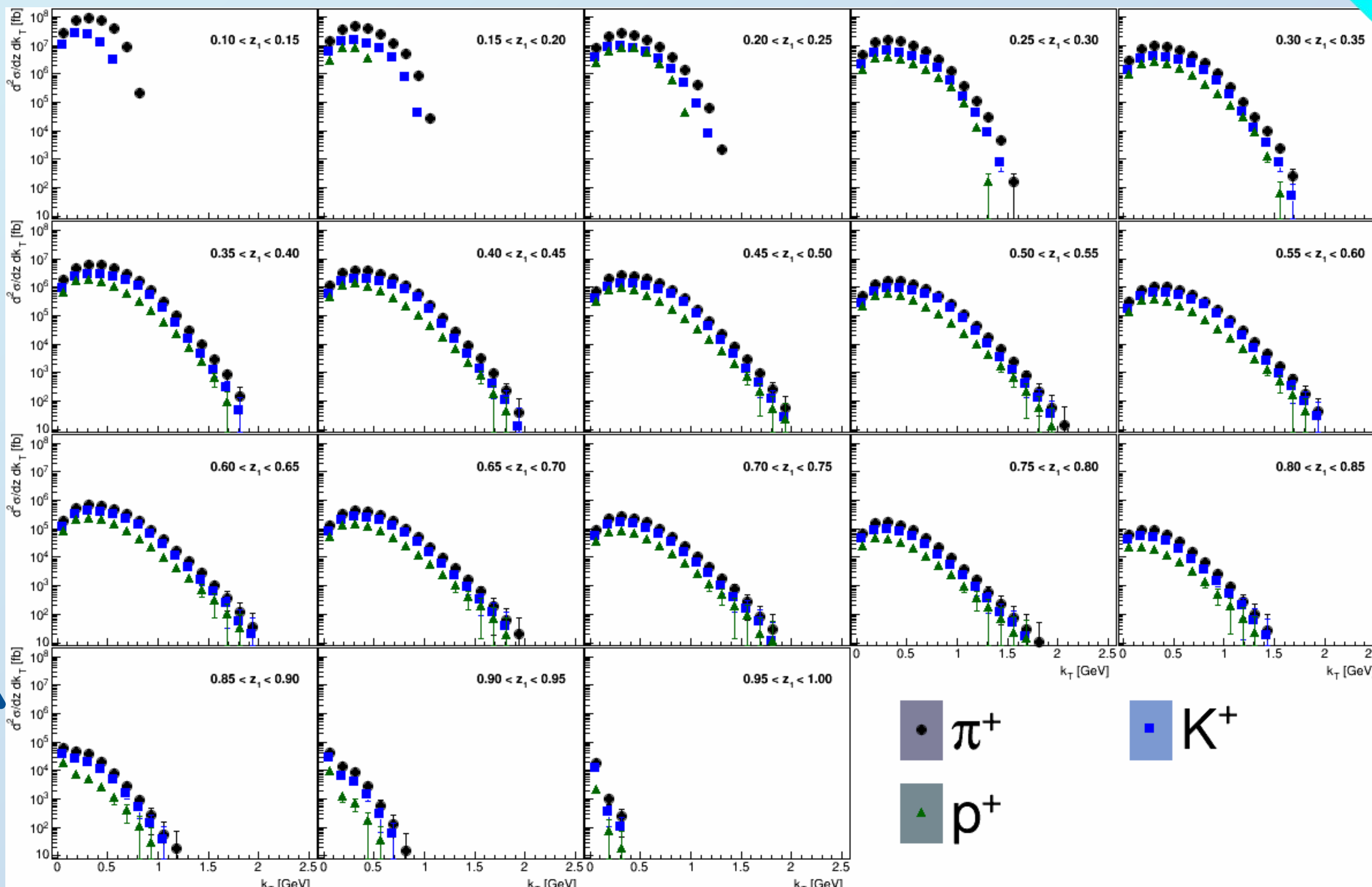




MC sample for various hadrons

MC simulation





$$\frac{d^2\sigma}{dz dk_T}$$

k_T

Spin dependent fragmentation

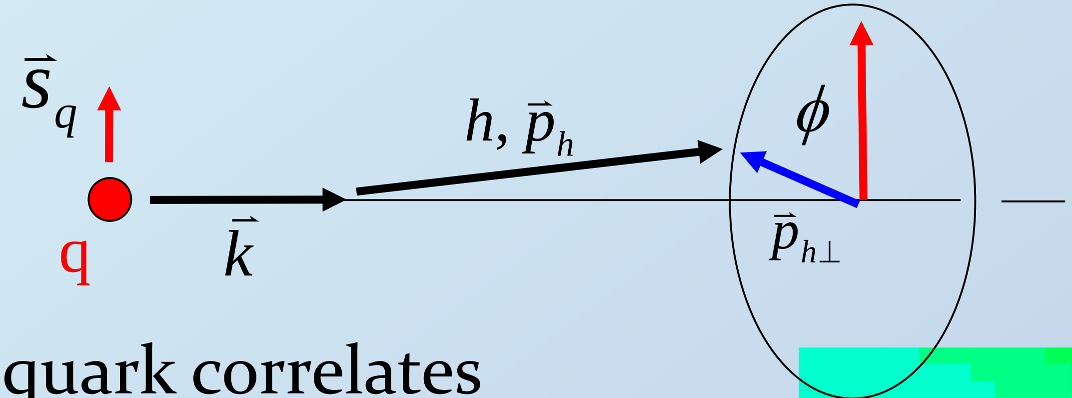
$$H_{1,q}^{h,\perp}(z, Q^2, k_t)$$

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

Collins fragmentation function

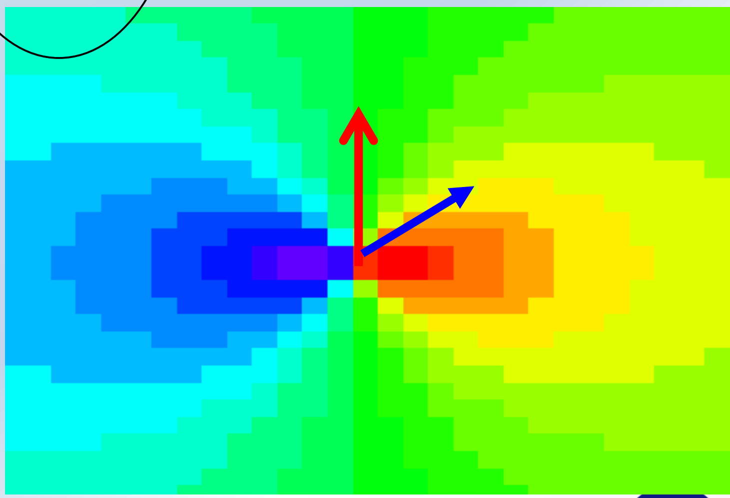
J. Collins, Nucl. Phys. B396, (1993) 161

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



- Spin of quark correlates with hadron transverse momentum

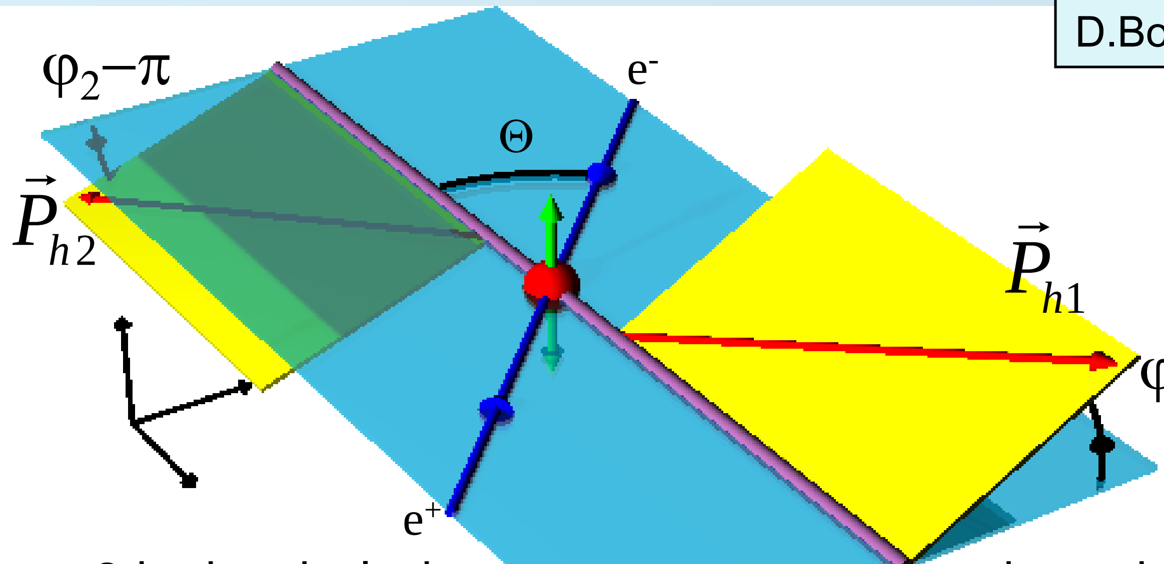
➔translates into azimuthal anisotropy of final state hadrons

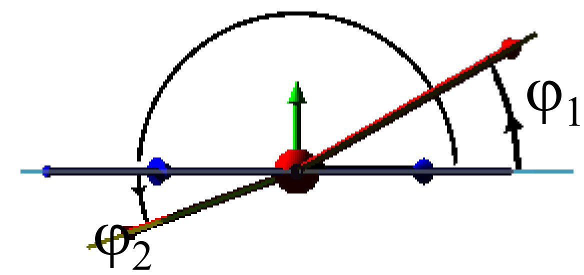


Collins fragmentation in e^+e^- : Angles and Cross section $\cos(\phi_1+\phi_2)$ method

e^+e^- CMS frame:

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





2-hadron inclusive transverse momentum dependent cross section:

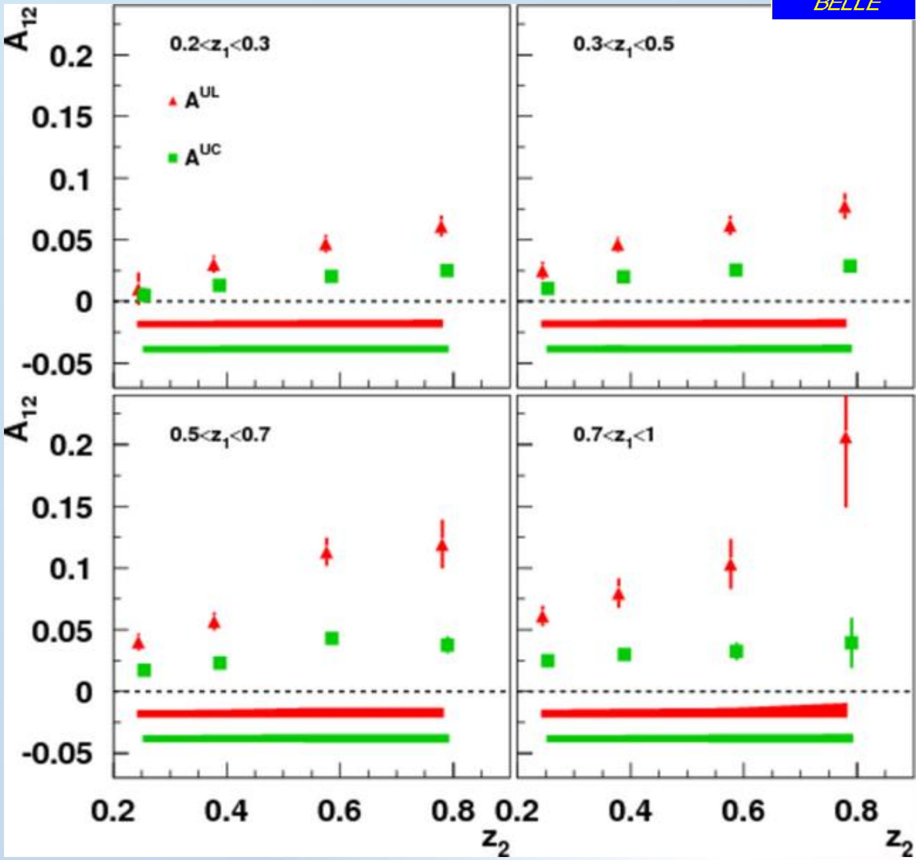
$$\frac{d\sigma\left(e^+e^- \to h_1 h_2 X\right)}{d\Omega dz_1 dz_2 d^2\boldsymbol{q}_T} = \cdots B(y)\, cos(\varphi_1+\varphi_2) H_1^{\perp[1]}(z_1) \overline{H}_1^{\perp[1]}(z_2)$$

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

Net (anti-)alignment of transverse quark spins

Belle Collins asymmetries

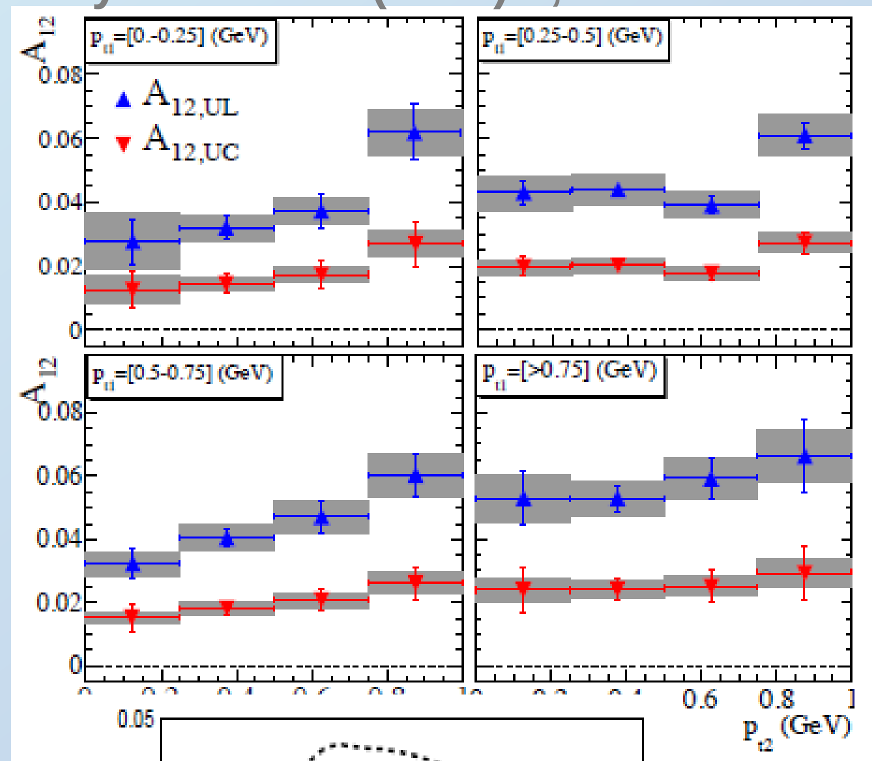
- Red points : $\cos(\phi_1 + \phi_2)$ moment of Unlike sign pion pairs over like sign pion pair ratio : A^{UL}
- Green points : $\cos(\phi_1 + \phi_2)$ moment of Unlike sign pion pairs over any charged pion pair ratio : A^{UC}
- Collins fragmentation is large effect
- Consistent with SIDIS indication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

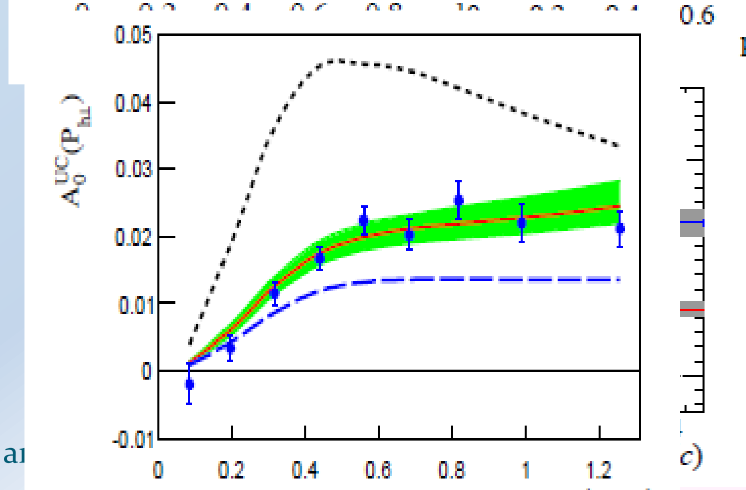


RS et al (Belle), PRL96: 232002
PRD 78:032011, Erratum D86:039905

Explicit transverse momentum dependence

Phys.Rev. D90 (2014) 5, 052003



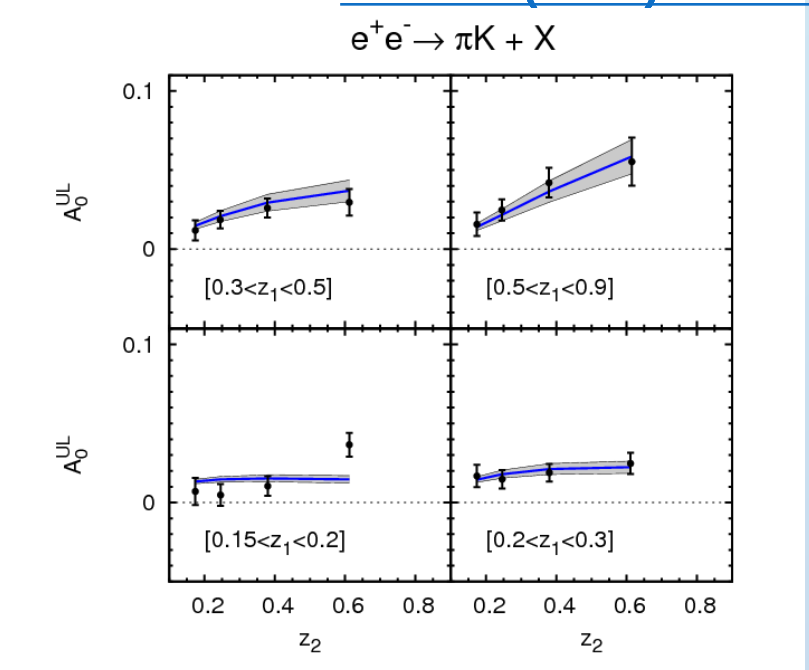


- First explicit transverse momentum dependent extraction for Collins asymmetries (relative to thrust axis* or second hadron)
- Global Transversity and Collins fit (arXiv:1505.05589)able to reproduce the dependence

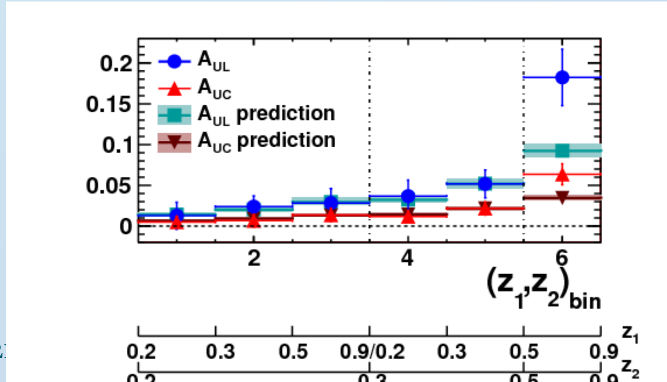
Quark transversity via Collins: Kaons

BABAR: [PRD 92 (2015) 111101]

Anselmino et al: [PRD 93 (2016) 034025]



BESIII:[PRL 116 (2016) 042001]



- Addition of kaon Collins fragmentation strongly needed for flavor decomposition of quark transversity
- Large amount of potentially participating FFs well described by light and “heavy” favored and disfavored FFs
- Allows inclusion of HERMES and COMPASS kaon asymmetries (+eventually EIC) in fits
- Also: pion Collins at lower scale(BESIII) consistent with TMD evolution
- Also: unpolarized kaon multiplicities from COMPASS

Summary and outlook

- Unpol FFs are the main access to the flavor information in SIDIS/pp:
  - quark helicities, unpol PDFs
- Polarized FF as nearly unique way to access Transversity and tensor charge
- Kt dpendent FFs (pol/unpol) needed for deconvolution of TMDs in SIDIS

➔Cleanest access to these FFs in e+e- with the wealth of B factory data

- Recently:
  - Di-hadron fragmentation submitted; needed for IFF based Transversity extractions
  - Hyperon and charmed baryon FFs
  - Λ polarization
  - Two types of unpol. Transverse momentum dependent cross sections ongoing

RIKEN