TMDs and Fragmentation Functions in e^+e^-

and relation to EIC

INT EIC program 2018,
Washington University,
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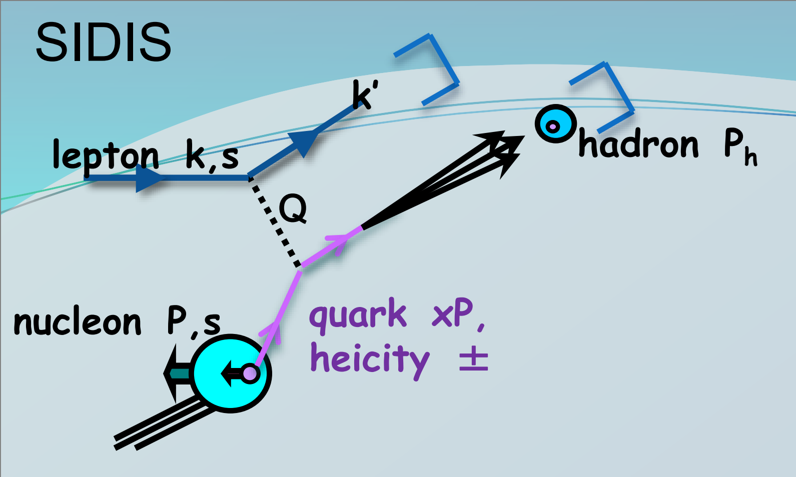
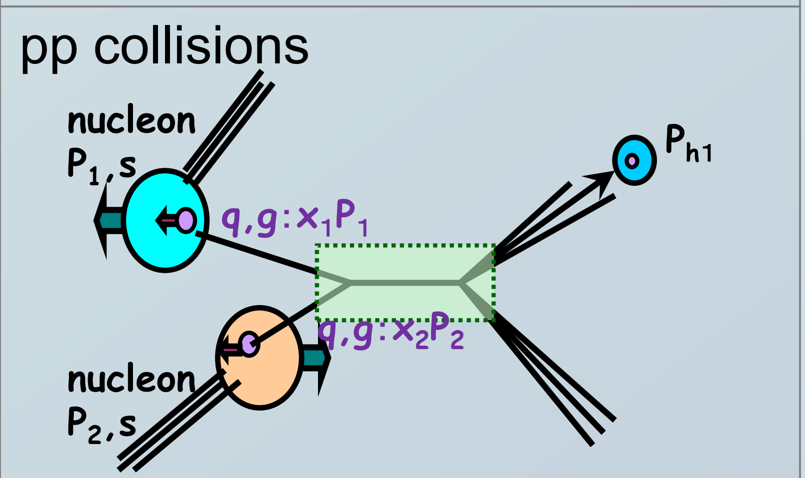
EIC without B factory input?
Very unlikely

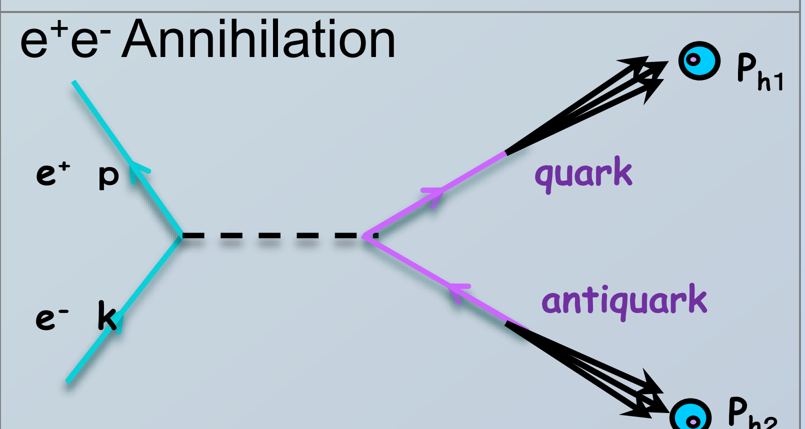
- Very limited helicity analysis possible (based on Kretzer or KKP)
- Only model dependent Tensor charge extraction
- Sivers and all TMDs just with naïve Gaussian dependence (no x or z dependence)

Outline

- Single hadron fragmentation
  - Light hadron, Hyperon and charmed Baryon fragmentation (not TMDs)
  - Collins measurements
  - Λ polarizing fragmentation → Anselms talk
- Di-hadron fragmentation
  - IFF measurements
  - Unpolarized mass, z dependence (for IFF)
- Other ongoing measurements (kt deptendence)
- Other possibilities







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-:

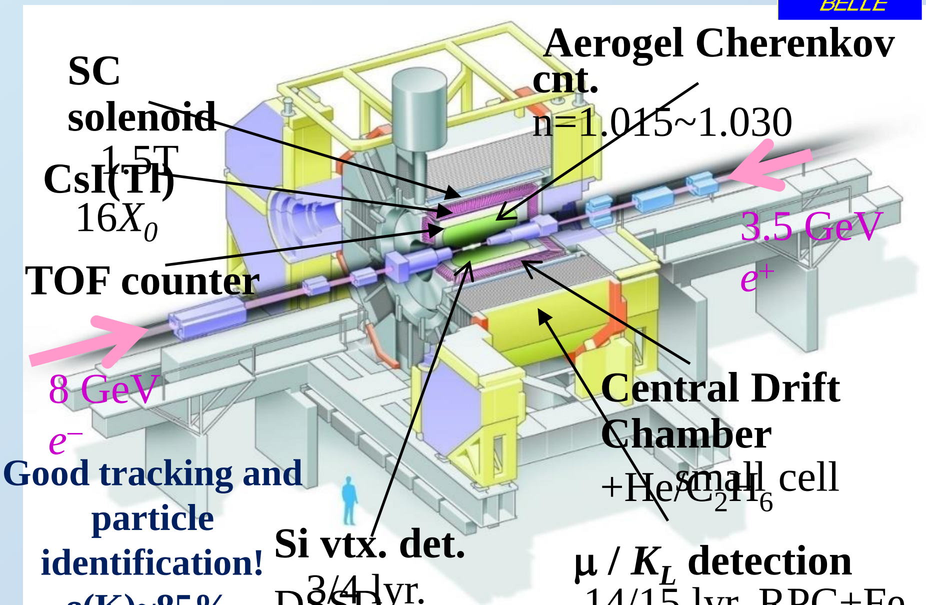
$$\sigma^h(z, Q^2, k_t) \propto \sum_q e_q^2 \left(D_{1,q}^h(z, k_t, Q^2) + D_{1,\bar{q}}^h(z, k_t, Q^2)\right)$$

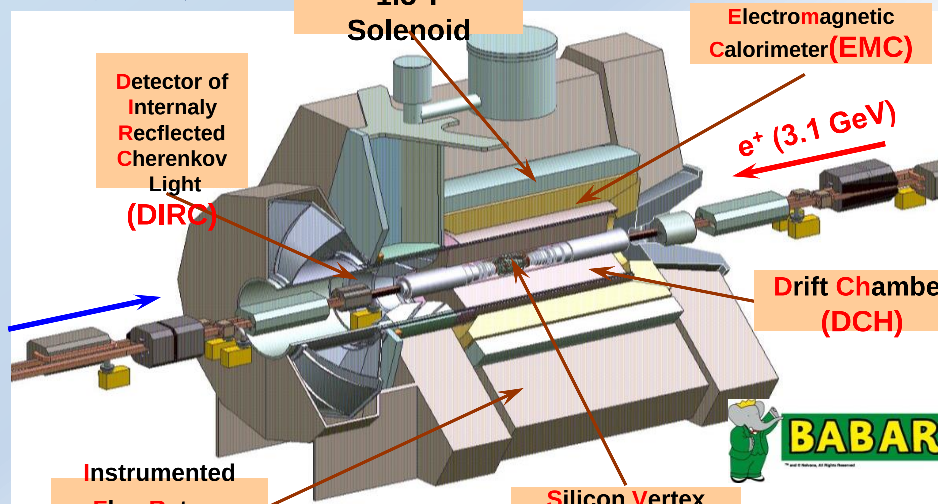
  - No PDFs necessary
  - Clean initial state, parton momentum known at LO
  - Flavor structure not directly accessible

B Factories: KEKB and PEPII

- Asymmetric colliders
  - 8GeV + 3.5GeV (Belle)
  - 9GeV + 3.1 GeV (BABAR)
- $\sqrt{s}$ = 10.58GeV (Y(4S))
- $e^+e^- \rightarrow Y(4S) \rightarrow B\ \bar{B}$
- Continuum production: 10.52 GeV
- $e^+e^- \rightarrow q\ \bar{q}$ (u,d,s,c) (75% of on resonance xsec)
- Integrated Luminosity: >1000 fb^{-1} (Belle) + 500 fb^{-1} (BABAR) on resonance
- >70fb^{-1} => continuum
- + various other energies

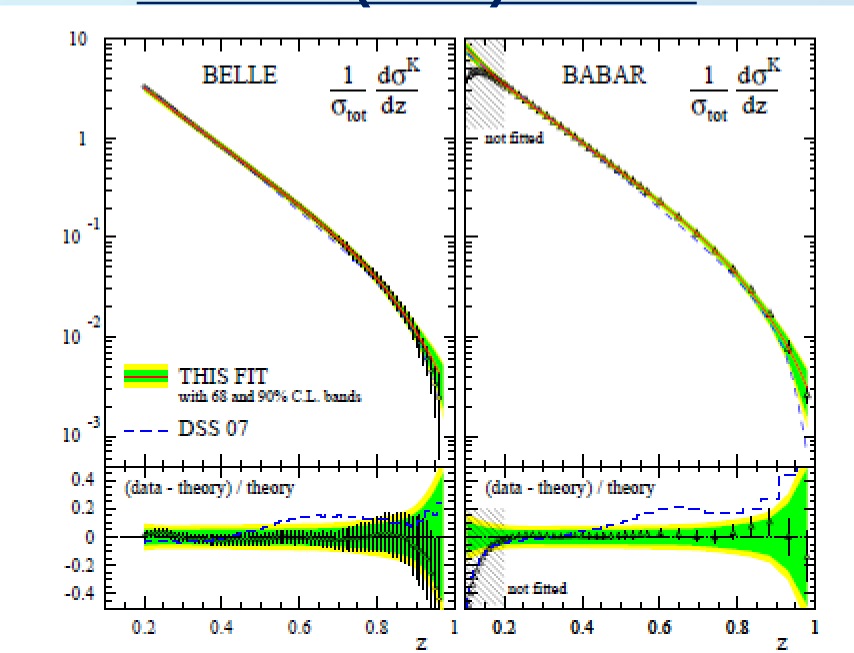
- Also BESIII as charm factory at various energies with fragmentation function input



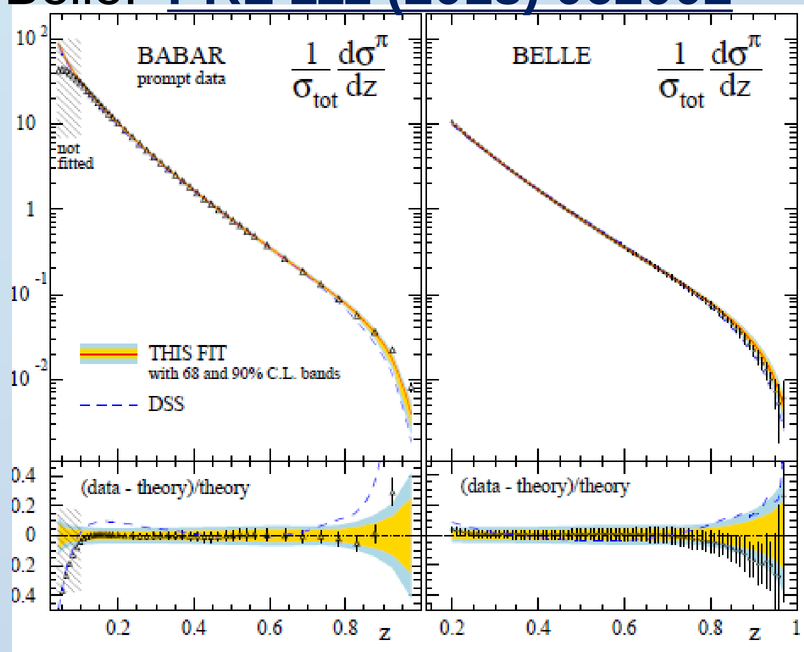


B factory data (Q~10GeV)

Babar: PRD 88 (2013) 032011



Belle: PRL 111 (2013) 062002

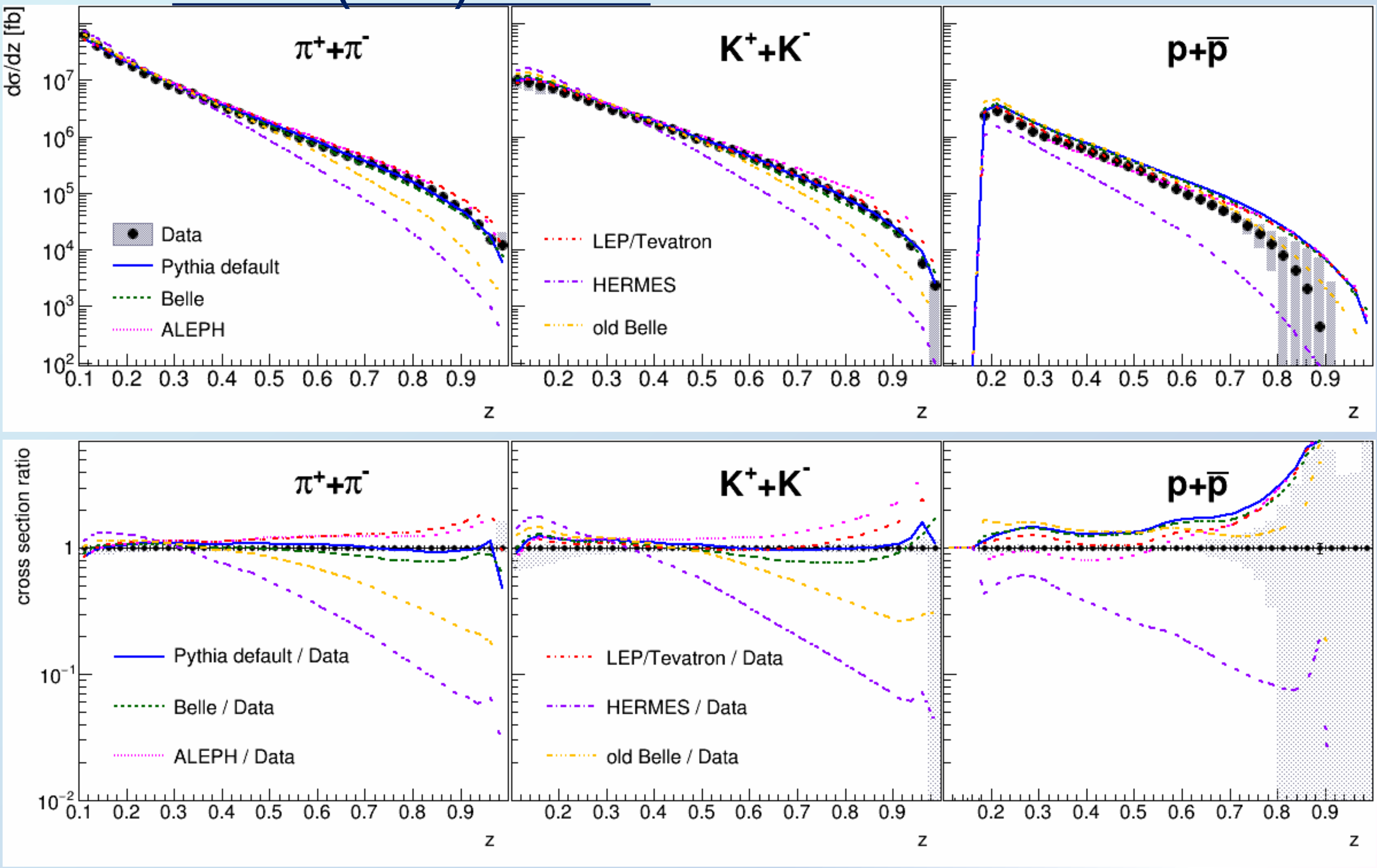


- High precision pion and kaon data from both B factory experiments
- Precision up to very high z
- Lever arm to much higher energy (Q~20 – 200GeV) data allows for determination of gluon fragmentation over evolution

New addition: single protons

$\Delta g(x), \Delta q(x)$

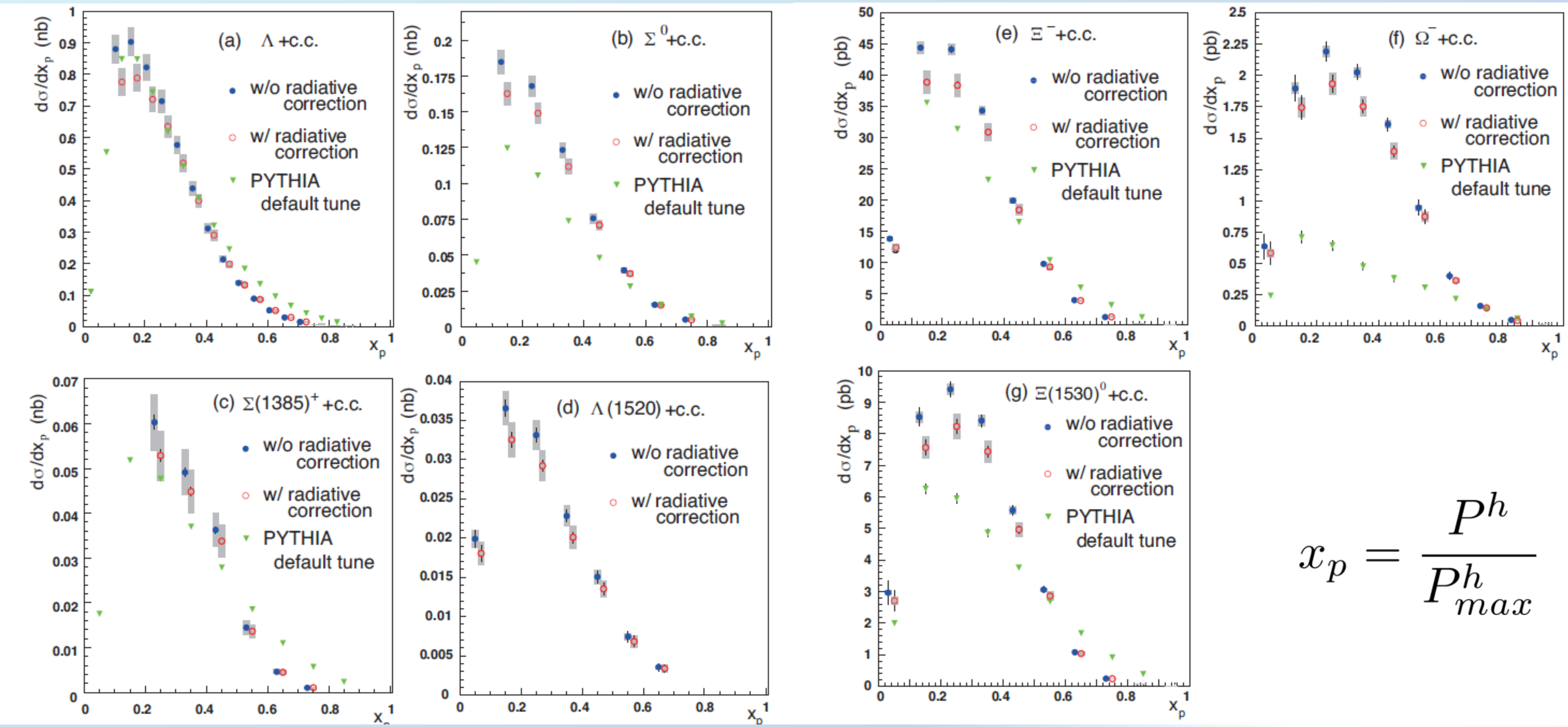
PRD92 (2015) 092007



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

Hyperon Fragmentation

Belle: Niiyama et. al. PRD 97 (2018), 072005

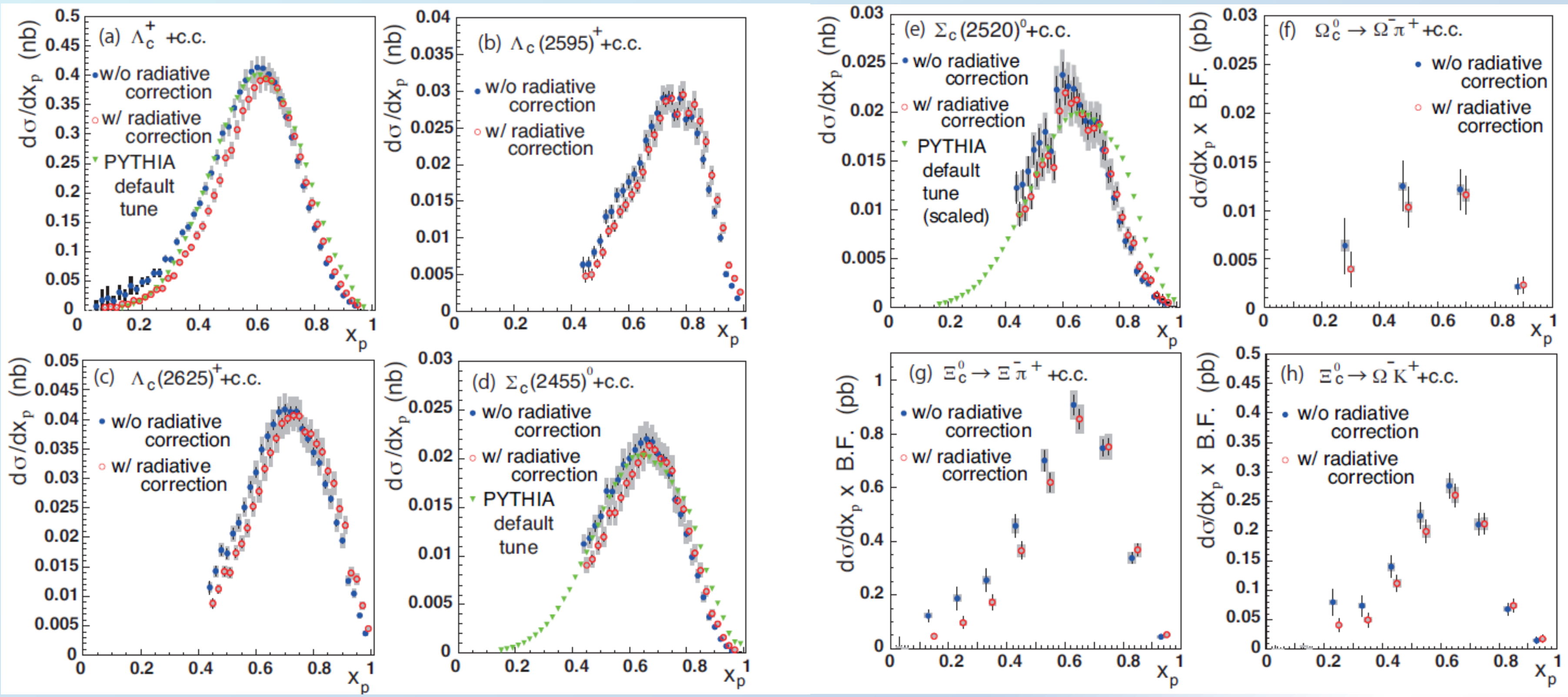


$$x_p = \frac{P^h}{P^h_{max}}$$

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

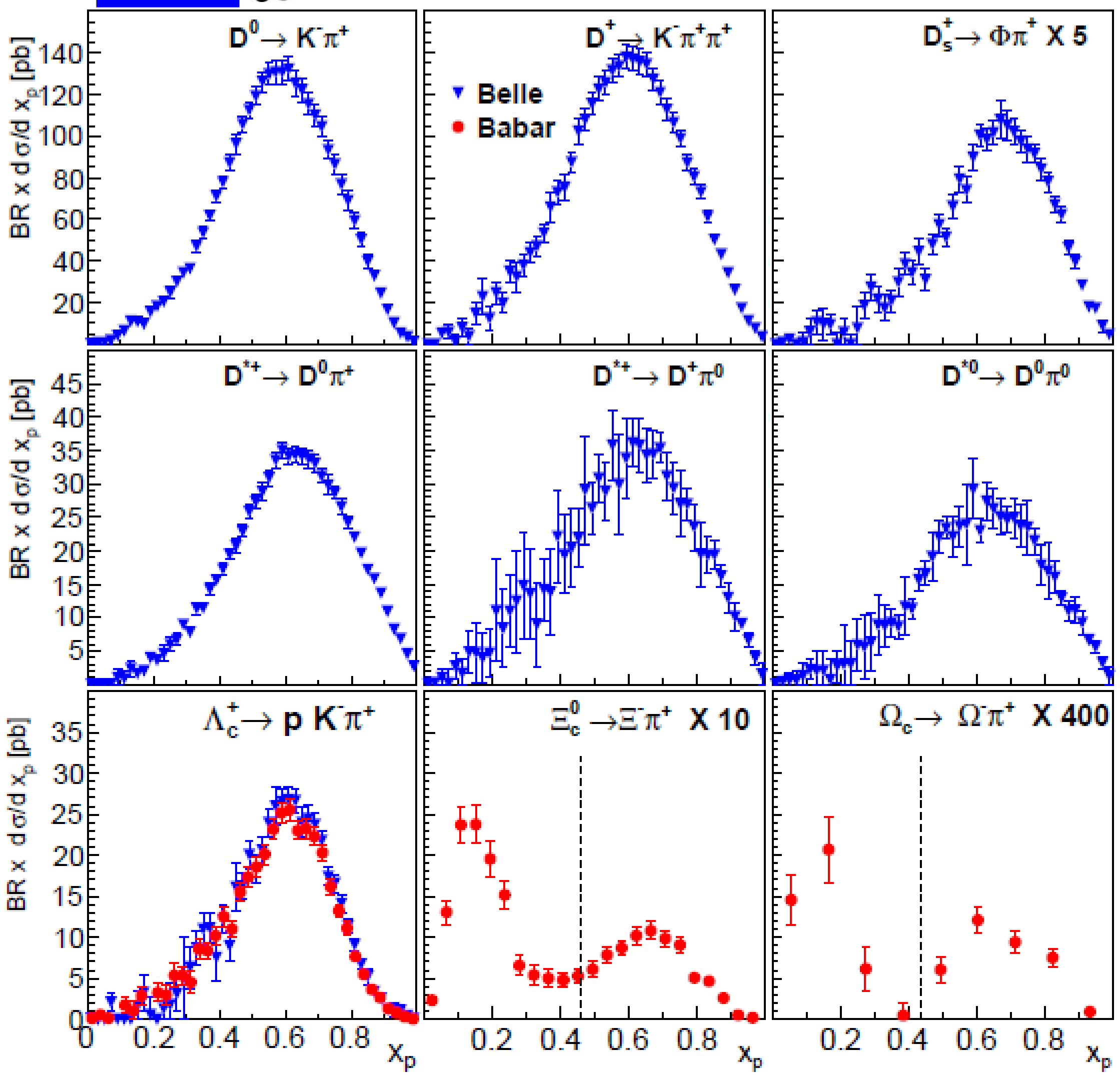
Charmed baryon Fragmentation

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

Charmed Fragmentation



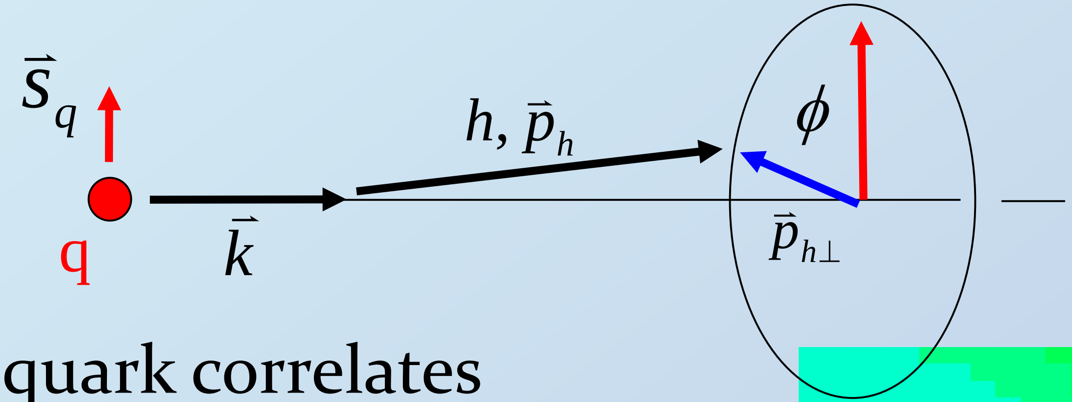
PRL.95, 142003 (2005)(Babar)
PRD73, 032002 (2006) (Belle)
PRD75, 012003 (2007)(Babar)
PRL 99, 062001 (2007)(Babar)

- 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

Collins fragmentation function

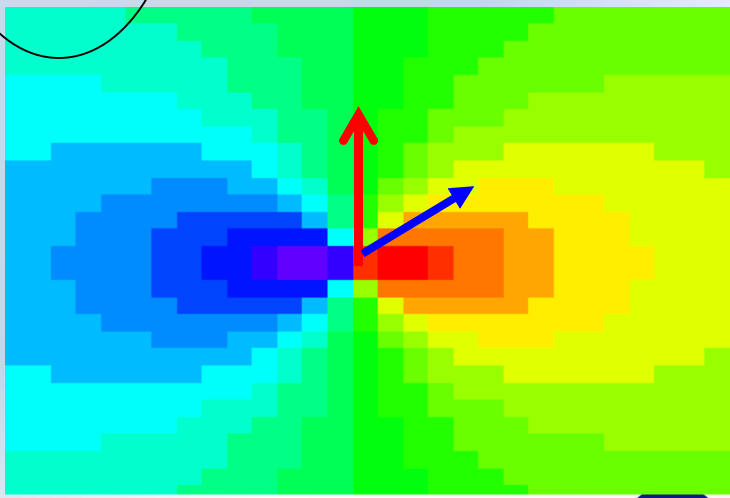
J. Collins, Nucl. Phys. B396, (1993) 161

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



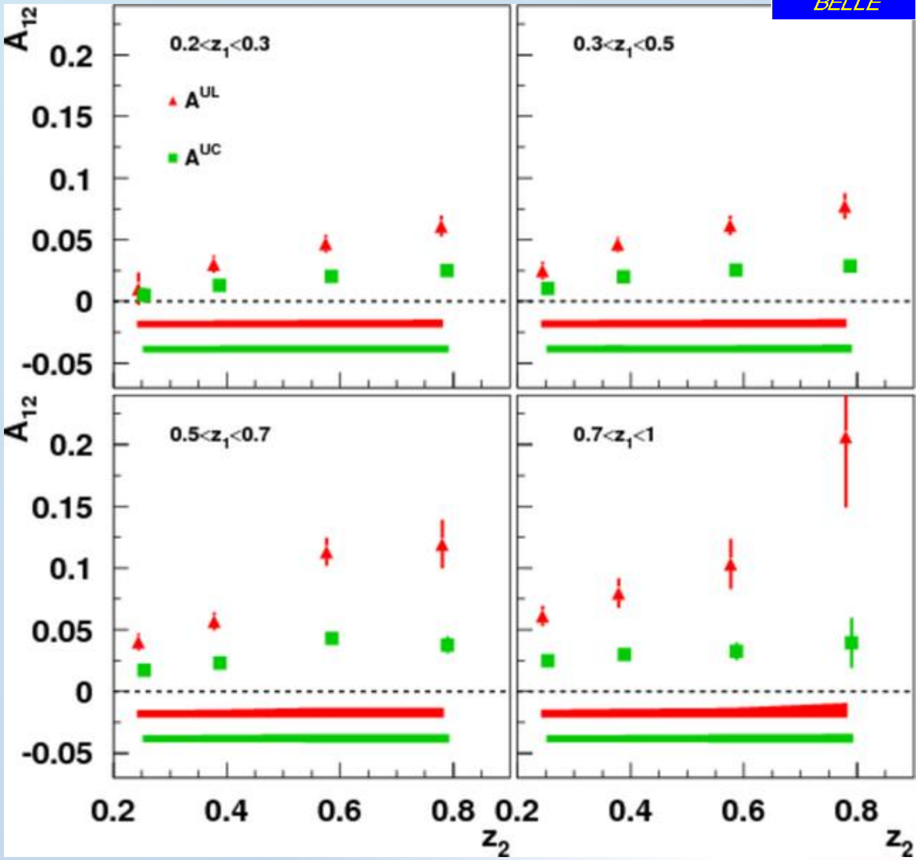
- Spin of quark correlates with hadron transverse momentum

➔translates into azimuthal anisotropy of final state hadrons



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

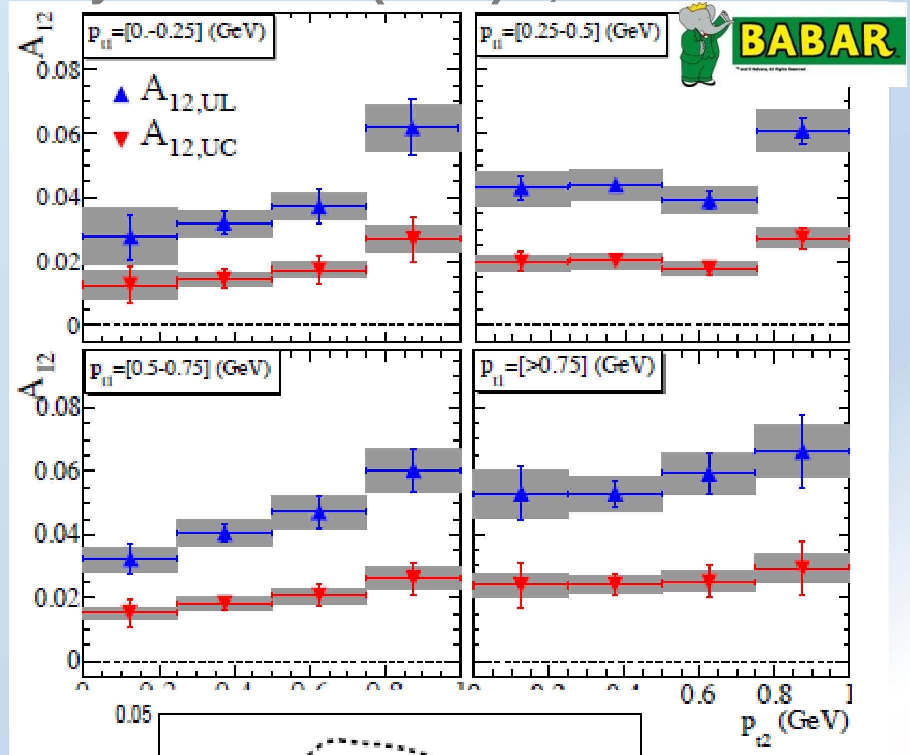


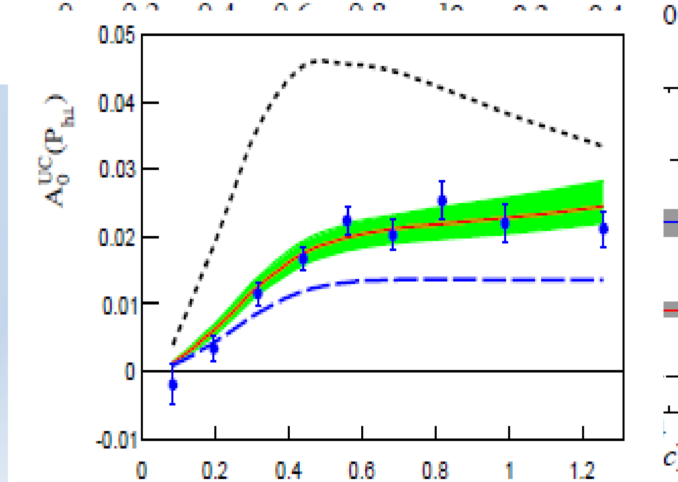
RS et al (Belle), PRL96: 232002
PRD 78:032011, D86:039905

Explicit transverse momentum dependence

- First explicit transverse momentum dependent extraction for Collins asymmetries (relative to thrust axis* or second hadron)
- Global Transversity and Collins fit (PRD93 (2016) 014009)able to reproduce the dependence

Phys.Rev. D90 (2014) 5, 052003



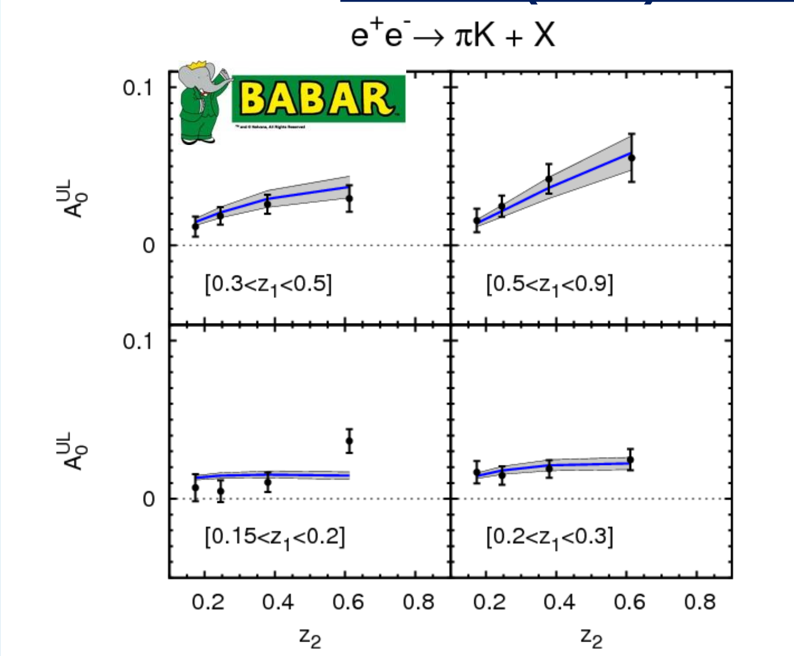


$\delta q(x)$ BSM

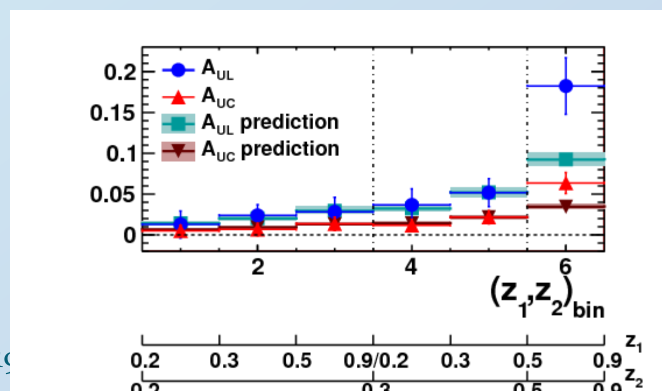
Quark transversity via Collins: Kaons

BABAR: PRD 92 (2015) 111101

Anselmino et al: PRD 93 (2016) 034025



BESIII: PRL 116 (2016) 042001

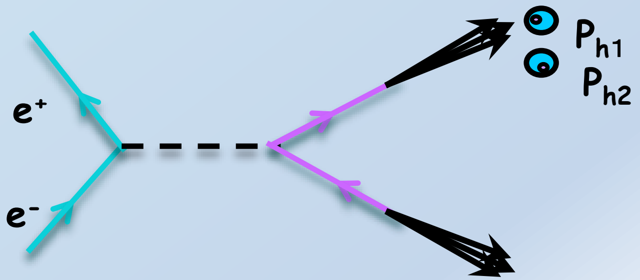


- Addition of kaon Collins fragmentation strongly needed for flavor decomposition of quark transversity
- Large amount of potentially participating FFs well described by light and "heavy" favored and disfavored FFs
- Allows inclusion of HERMES and COMPASS kaon asymmetries (+eventually EIC) in fits
- Also: pion Collins at lower scale(BESIII) consistent with TMD evolution
- Soon also π^0 and η results
- Belle update from with kaons and kt dependence (multi-dimensional) planned

Di-hadron fragmentation functions

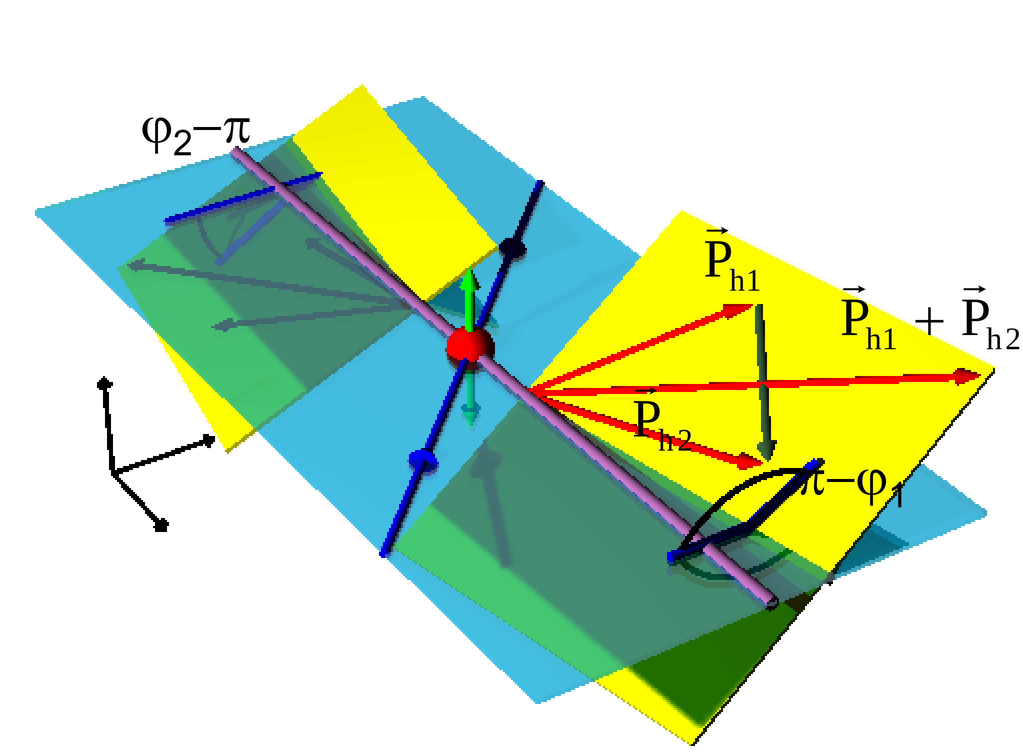
$$D_{1,q}^{h_1 h_2}(z, m, Q^2)$$

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



Interference Fragmentation (IFF) in e^+e^-

- $e^+e^- \rightarrow (\pi^+\pi^-)_{jet1}(\pi^+\pi^-)_{jet2}X$
- Theoretical guidance by papers of Boer,Jakob,Radici[PRD 67,(2003)] and Artru,Collins[ZPhysC69(1996)]
- Early work by Collins, Heppelmann, Ladinsky [NPB420(1994)]



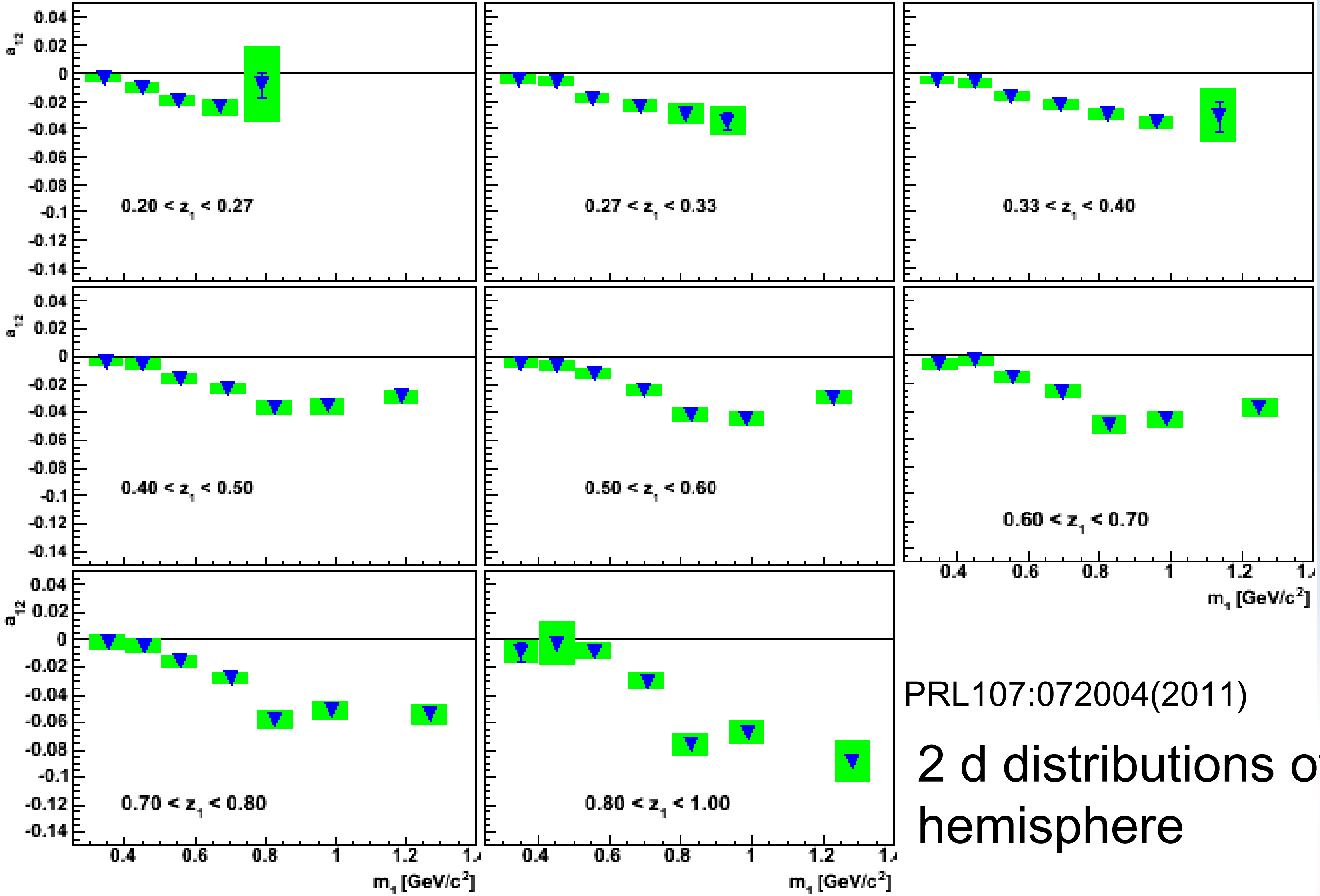
Model predictions by:

•Jaffe et al. [PRL **80,**(1998)]

•Radici et al. [PRD **65,**(2002)]

$$A \propto H_1^{\angle}(z_1, m_1)\overline{H}_1^{\angle}(z_2, m_2)\cos(\varphi_1 + \varphi_2)$$

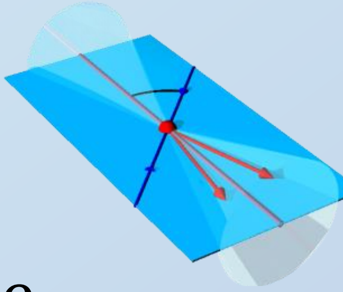
Belle IFF asymmetries: $(z_1 x\ m_1)$ Binning



PRL107:072004(2011)

2 d distributions of one hemisphere

Explicit di-hadron mass dependence

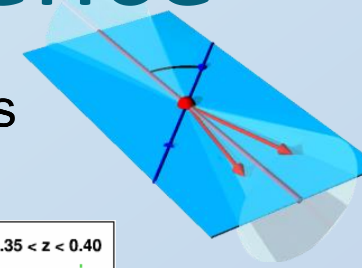


- IFF related asymmetries extracted by Belle in 2011 (PRL107:072004(2011))
- SIDIS (JHEP 0806 (2008),PLB713 (2012)) and RHIC ([PRL 115 (2015) 242501](#)) IFF asymmetries published
- Global fits currently missing unpolarized di-hadron FF baseline

➔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

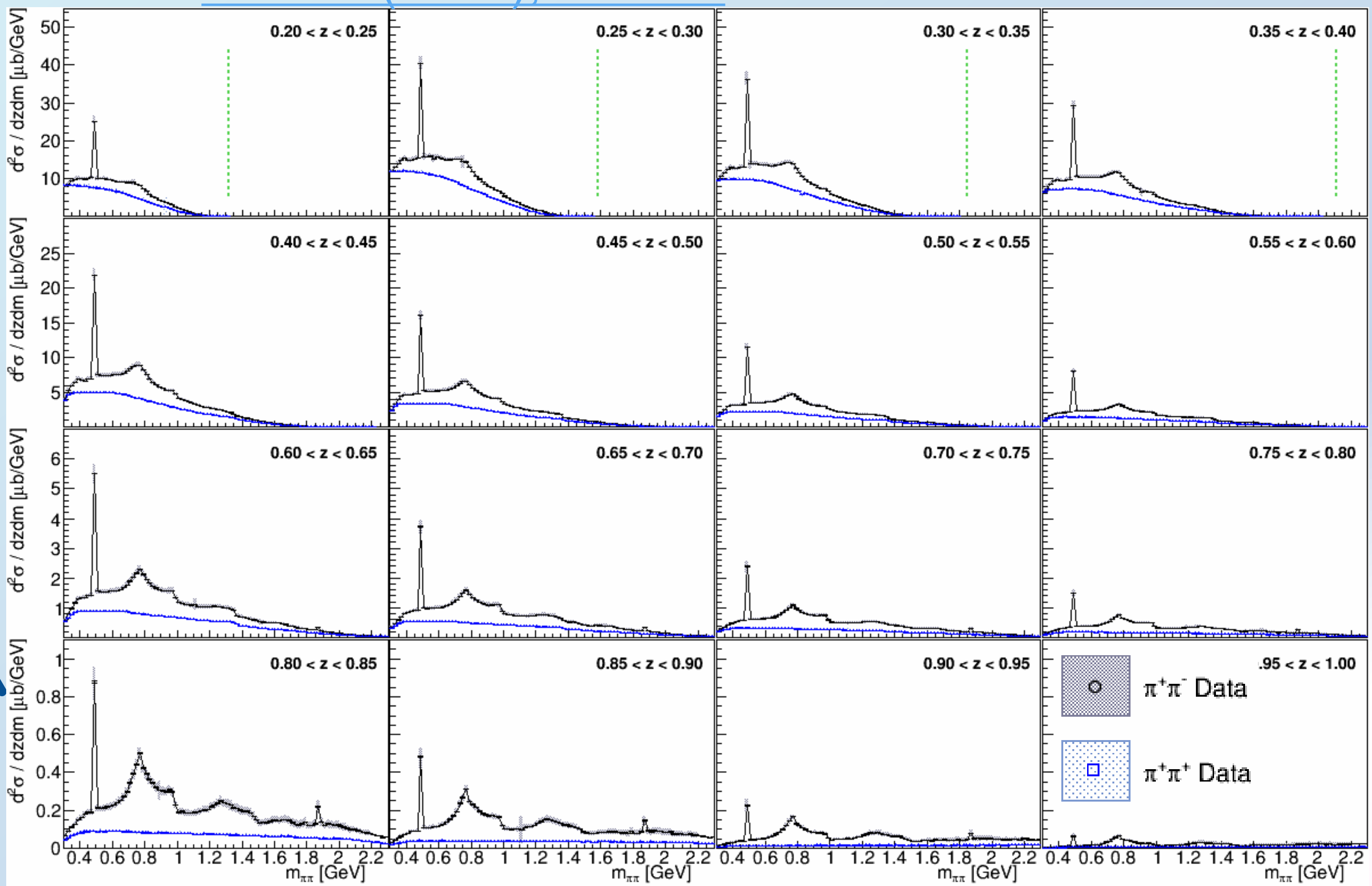
Di-hadron mass dependence



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

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

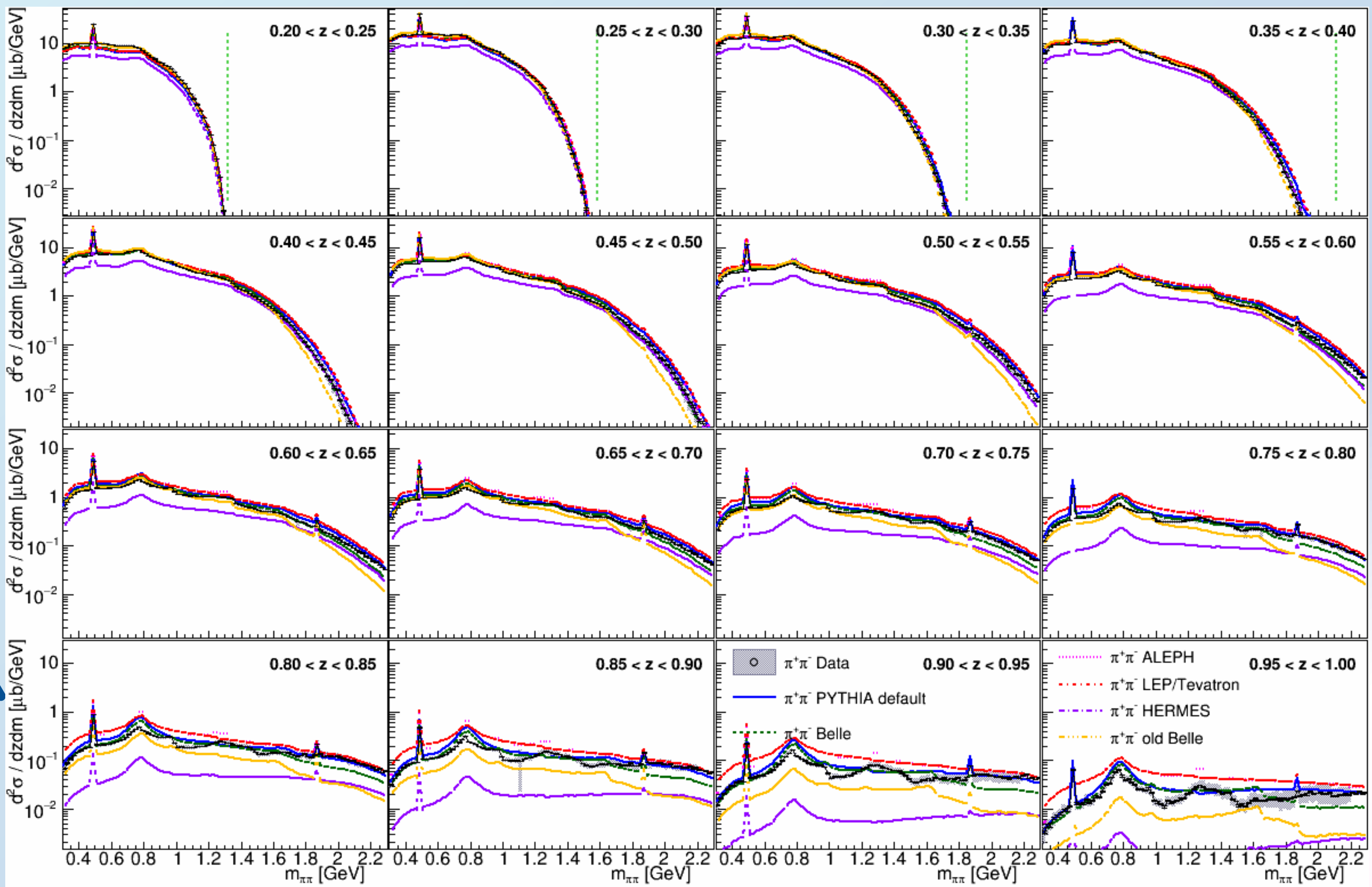


$m_{\pi\pi}$

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)

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



$m_{\pi\pi}$

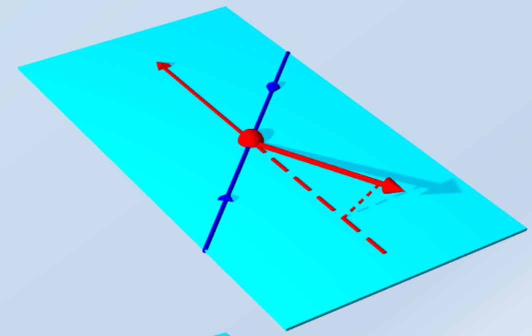
Transverse momentum dependence

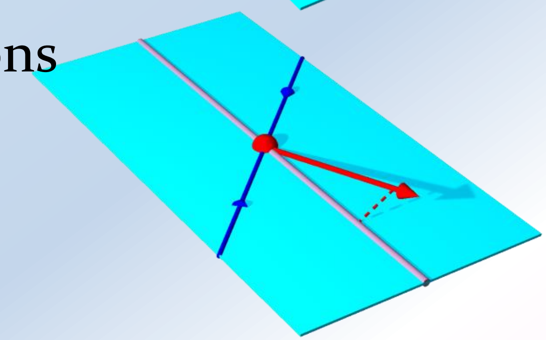
Aka un-integrated PDFs and FFs

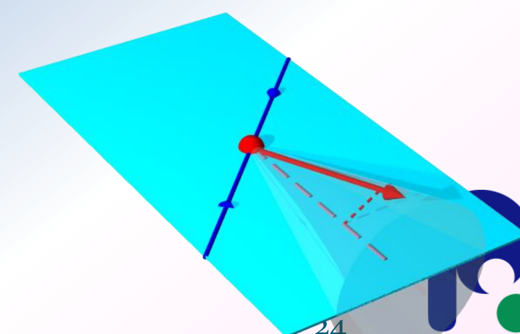
$$D^{h}_{1,q}(z, Q^2, k_t)$$

K_T Dependence of FFs in e+e-

- 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

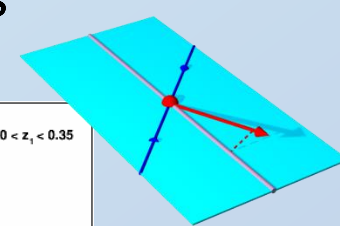




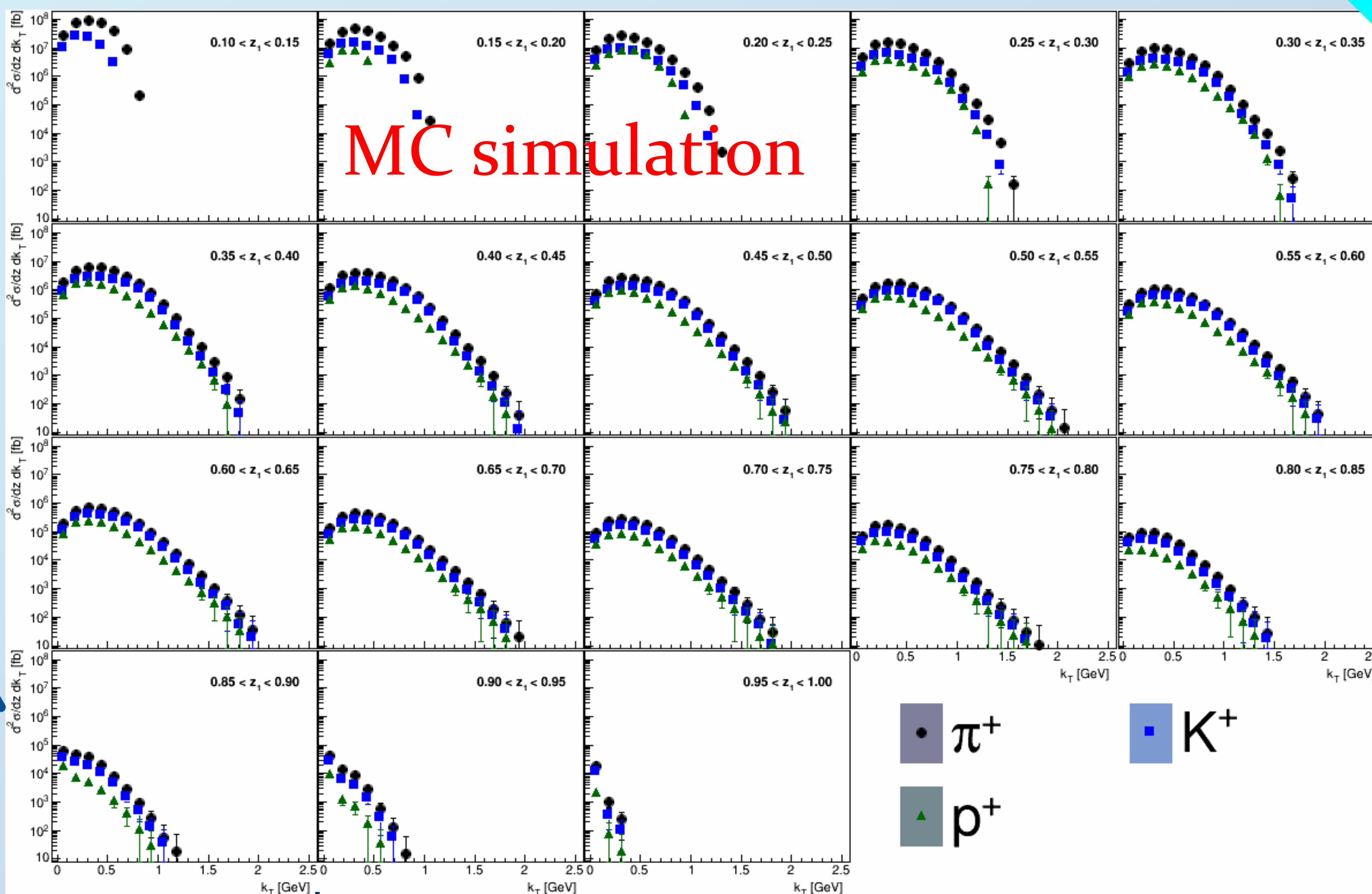


MC sample for various hadrons

6 thrust bins [0.5,0.7,0.8,0.85,0.9,0.95,1.0] x 18 z bins x 20 kt bins



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

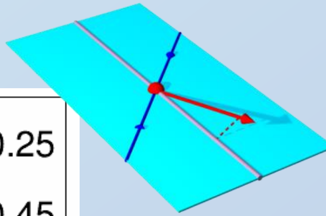


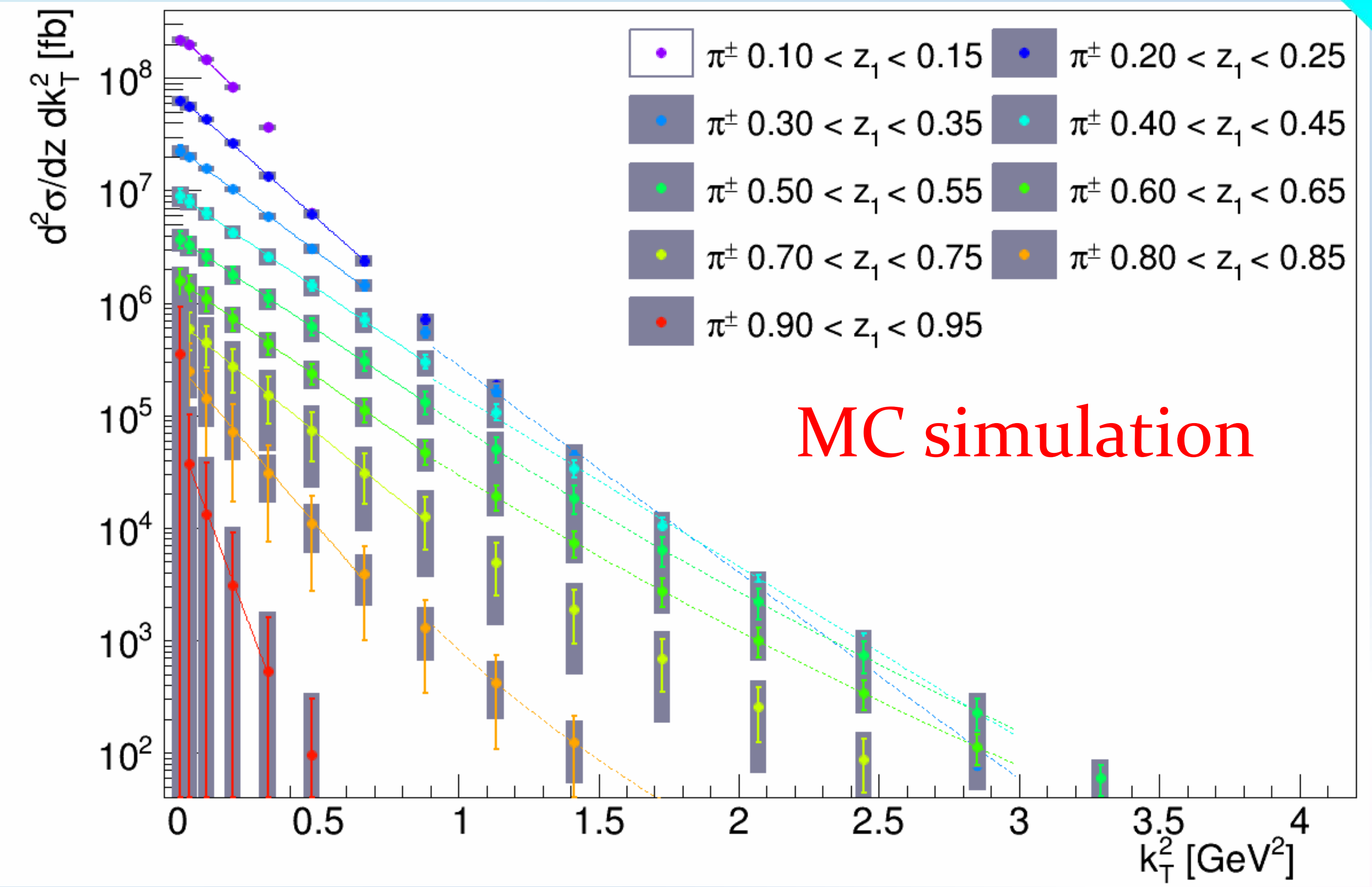
k_T

$\delta q(x), f_{1T}^{\perp}(x, k_t), H_1^{\perp}(z, k_T)$

MC examples vs k_T^2

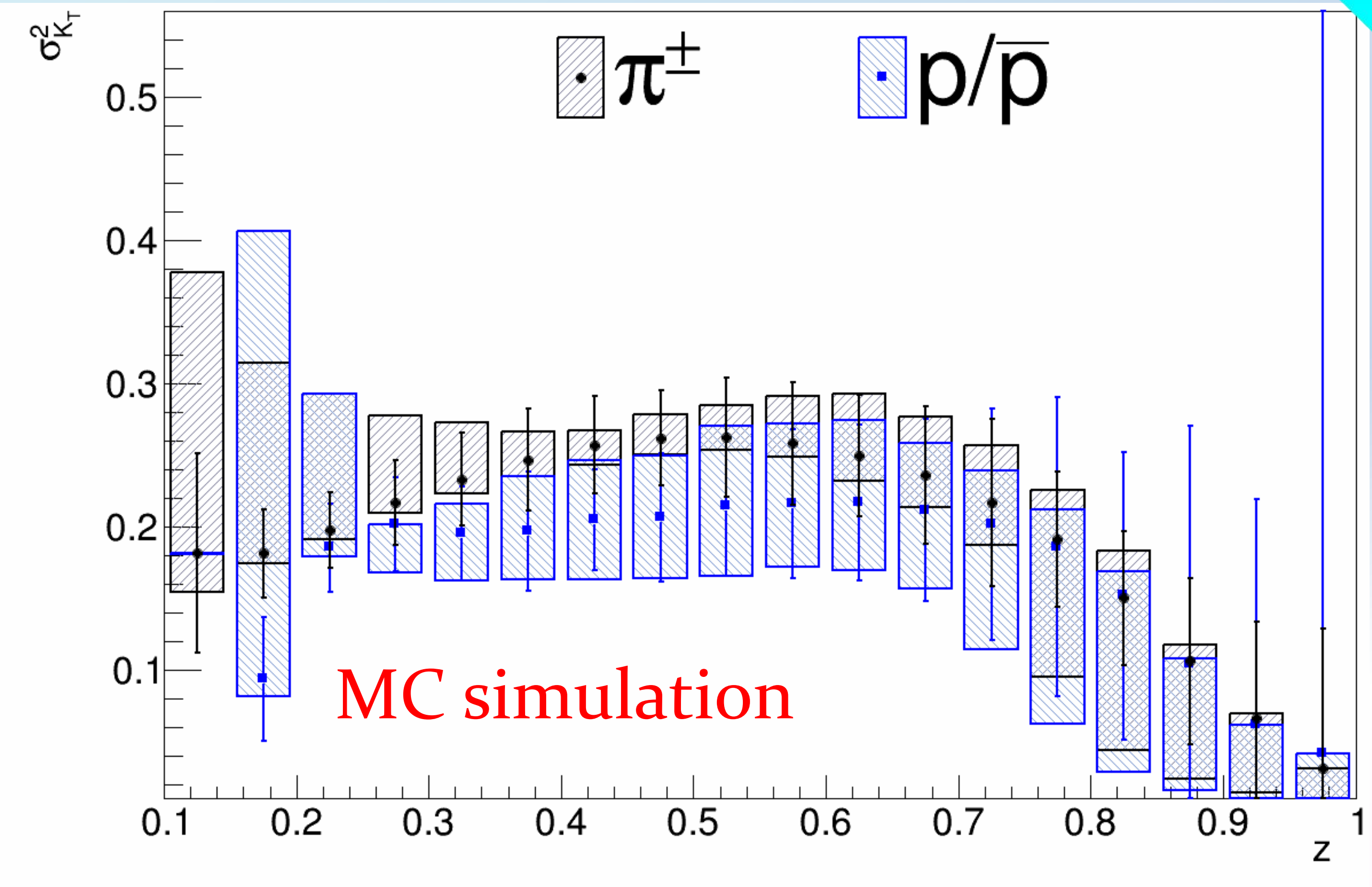
Fit exponential to smaller transverse momenta for Gaussian k_T dependence and power low at higher k_T

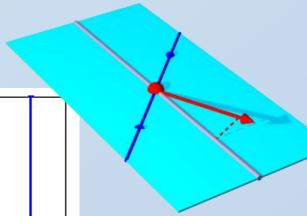




MC Gaussian widths

Once available for data this will be the first direct (no convolutions) measurement of z dependence of Gaussian widths





$\delta q(x), f_{1T}^{\perp}(x, k_t), H_1^{\perp}(z, k_T)$

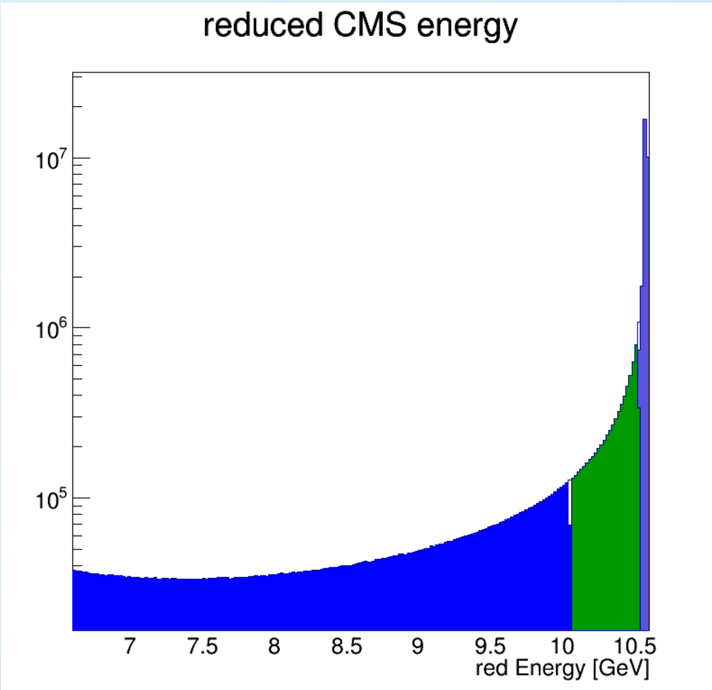
K_T analysis status

- Single hadron analysis:
  - Analysis finished, Last stages of Belle internal review, paper draft written
  - Will include fits of Gaussian widths as a function of x and thrust for each particle
- Two-hadron k_T-analysis:
  - Finalizing analysis and cross checks

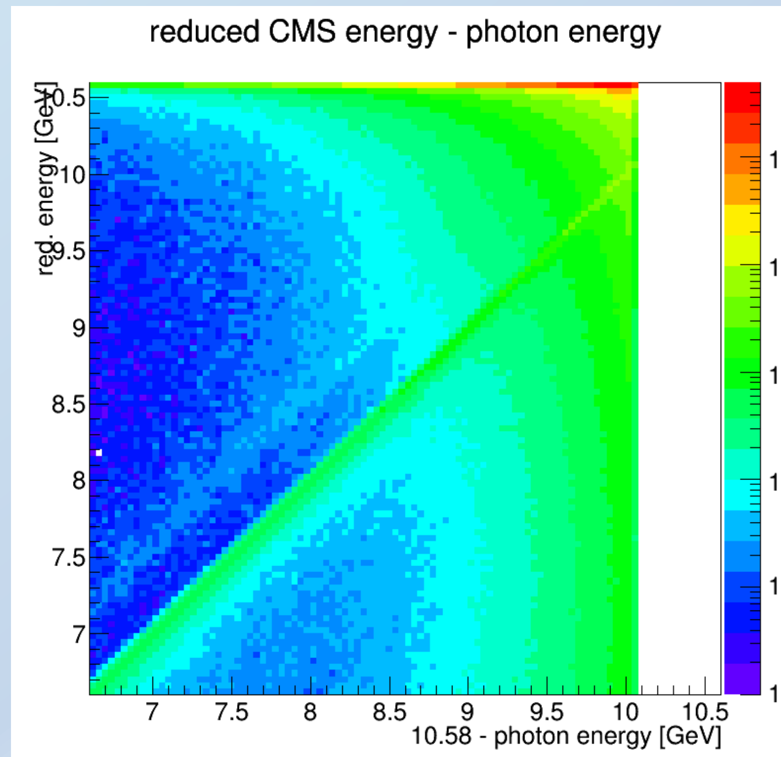
New possibilities: From Correcting ISR to using it as a tool

- During di-hadron analysis and kt analysis successfully checked actual boost of qqbar pair in ISR events
- General Idea: Use photons reconstructed in Belle(2) to tune the reduced sqrt(s) and scale of the fragmenting qqbar system
- Belle(2) acceptance covers a larger range with EM Calorimetry than for tracking→ good at catching not too soft photons
- First test: use all photons that cannot be combined with another photon to be close to the π^0 (0.1-0.17) or η (0.5-0.6) mass range

CMS energy of the qqbar system



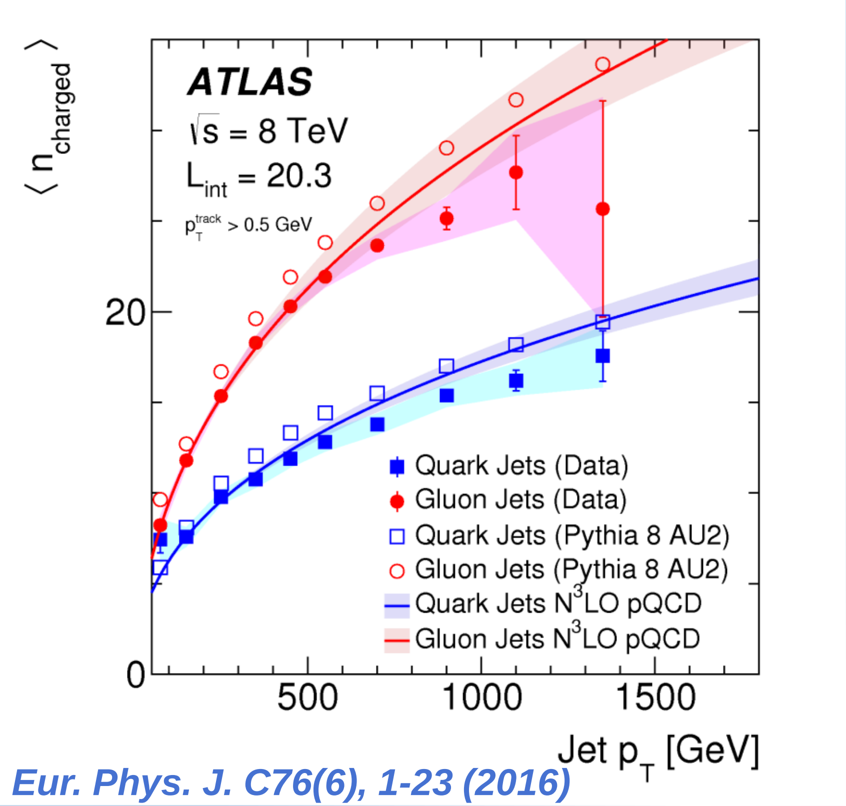
- Remove detected photon(s), E>0.5GeV from system
- Correlation to tru CMS energy seen



- Possible improvements:
  - Correlation w/ angle to the thrust axis
  - Small angles to the beam directions
  - Mostly from the higher energy beam
  - Total reconstructed energy

New possibilities: jet-substructure+fragmentation

- Could jet-substructure work from HEP be used at EIC (and e+e-/pp/pA)?
  - Possibility to use jet charge and mass to distinguish quark and gluon jets might be very useful
  - → even better flavor separation
  - → Gluon background removal for chiral-odd measurements?
  - Up-down separation also possible? Sufficient discriminators available in e+e- or ep?



Eur. Phys. J. C76(6), 1-23 (2016)

➔Plan to study this in the next years (if JSPS has mercy)

New possibilities: other final state FFs needed?

- Extension of di-hadron analysis to any resonant hadron possible:
  - K_s, K^*,ϕ, ρ, etc
- πK and KK IFF measurements
- Other Collins measurements?

EIC input

- Tensor charge: Flavor separation (π,K Collins, IFF), reduced model dependence (k_T dependence, unpol di-hadron FFs)
- Sivers, Boer-Mulders, etc: Flavor separation (unpol FFs), reduced model dependence (k_T dependence)
- Helicity global analysis (unpol FFs)
- Heavy flavor access (clean charm FFs)
- Explicit TMD evolution input? (explicit ISR)
- Quark and gluon separated jet input? (jet-shape + FF)