

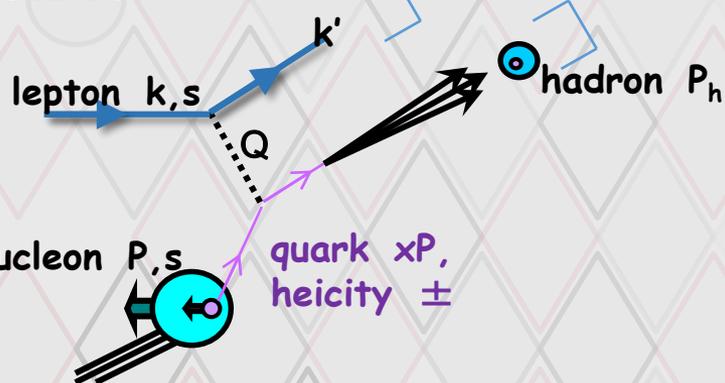


# unpolarized fragmentation related measurements at Belle

**Correlations in Partonic and  
Hadron Interactions 2020,  
February 3-7, CERN**

**Ralf Seidl (RIKEN)**

# SIDIS



# 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:

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

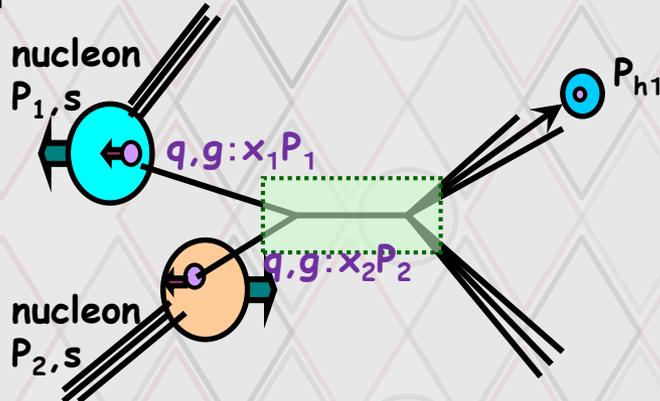
- Relies on unpol PDFs
- leading access to gluon FF
- Parton momenta not directly known

• e<sup>+</sup>e<sup>-</sup> annihilation:

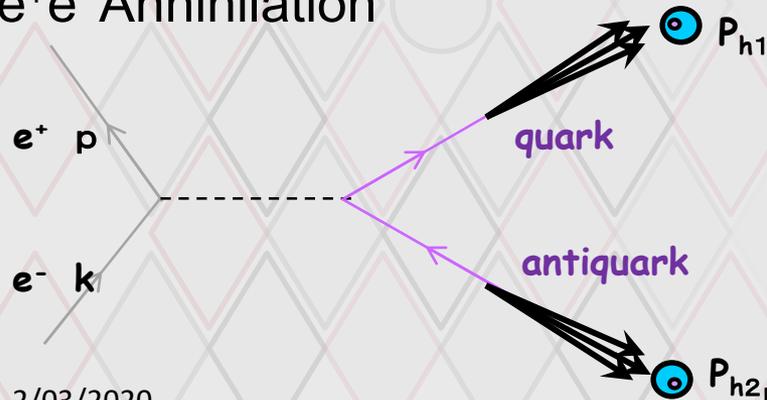
$$\sigma^h(z, Q^2, k_t) \propto \sum_q e_q^2 (D_{1,q}^h(z, k_t, Q^2) + D_{1,\bar{q}}^h(z, k_t, Q^2))$$

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

# pp collisions



# e<sup>+</sup>e<sup>-</sup> Annihilation



## Single hadron measurements

Unpolarized ingredients	Polarized ingredients	Flavor sensitivity
Single hadron cross sections: $e^+e^- \rightarrow hX$ $D_{1,q}^h(z, Q^2)$	Azimuthal asymmetries: $e^+e^- \rightarrow (h)(h)X,$ $\cos(\phi_1 + \phi_2)$ $H_{1,q}^{\perp(1)h}(z, Q^2)$	Unpol SIDIS, pp: $\frac{d\sigma}{dz}$ $e^+e^- \rightarrow (h)(h)X$  and scale dependence
Transverse momentum dependent FFs: $e^+e^- \rightarrow (h)X$ $D_{1,q}^h(z, k_T, Q^2)$	Transverse momentum dependent asymmetries $e^+e^- \rightarrow (h)(h)X,$ $\cos(\phi_1 + \phi_2), Q_t$ $H_{1,q}^{\perp h}(z, k_T, Q^2)$	Unpol SIDIS, pp: $\frac{d^2\sigma}{dzdP_{h\perp}}$

## Dihadron measurements

Unpolarized ingredients	Polarized ingredients	Flavor sensitivity
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## Single hadron measurements

Unpolarized ingredients	Polarized ingredients	Flavor sensitivity
Single hadron cross sections: $e^+e^- \rightarrow hX$ $D_{1,q}^h(z, Q^2)$  <a href="#">PRL111 (2013) 062002</a>	Azimuthal asymmetries: $e^+e^- \rightarrow (h)(h)X,$ $\cos(\phi_1 + \phi_2)$ $H_{1,q}^{\perp(1)h}(z, Q^2)$  <a href="#">PRL 96 (2006) 232002</a> <a href="#">PRD 78 (2008) 032011</a>	Unpol SIDIS, pp: $\frac{d\sigma}{dz}$ $e^+e^- \rightarrow (h)(h)X$ <a href="#">PRD92 (2015) 092007</a>  and scale dependence  
Transverse momentum dependent FFs: $e^+e^- \rightarrow (h)X$ $D_{1,q}^h(z, k_T, Q^2)$  <a href="#">PRD 99 (2019) 112006</a>	Transverse momentum dependent asymmetries $e^+e^- \rightarrow (h)(h)X,$ $\cos(\phi_1 + \phi_2), Q_t$ $H_{1,q}^{\perp h}(z, k_T, Q^2)$  <a href="#">PRD100 (2019) 92008</a>	

## Dihadron measurements

Unpolarized ingredients	Polarized ingredients	Flavor sensitivity
Dihadron cross sections  $e^+e^- \rightarrow (hh)X$ $D_{1,q}^{h_1 h_2}(z, m, Q^2)$ 2/03/2020 <a href="#">PRD96 (2017) 032005</a>	Azimuthal asymmetries: $e^+e^- \rightarrow (hh)(hh)X,$ $\cos(\phi_1 + \phi_2),$ $H_{1,q}^{h_1, h_2, \triangleleft}(z, Q^2, M_h)$ R.Seidl: e+e- Fragmentation <a href="#">PRL107 (2011) 072004</a>	Unpol SIDIS, pp:  $\frac{d^2\sigma}{dzdm}$

# Single hadron measurements

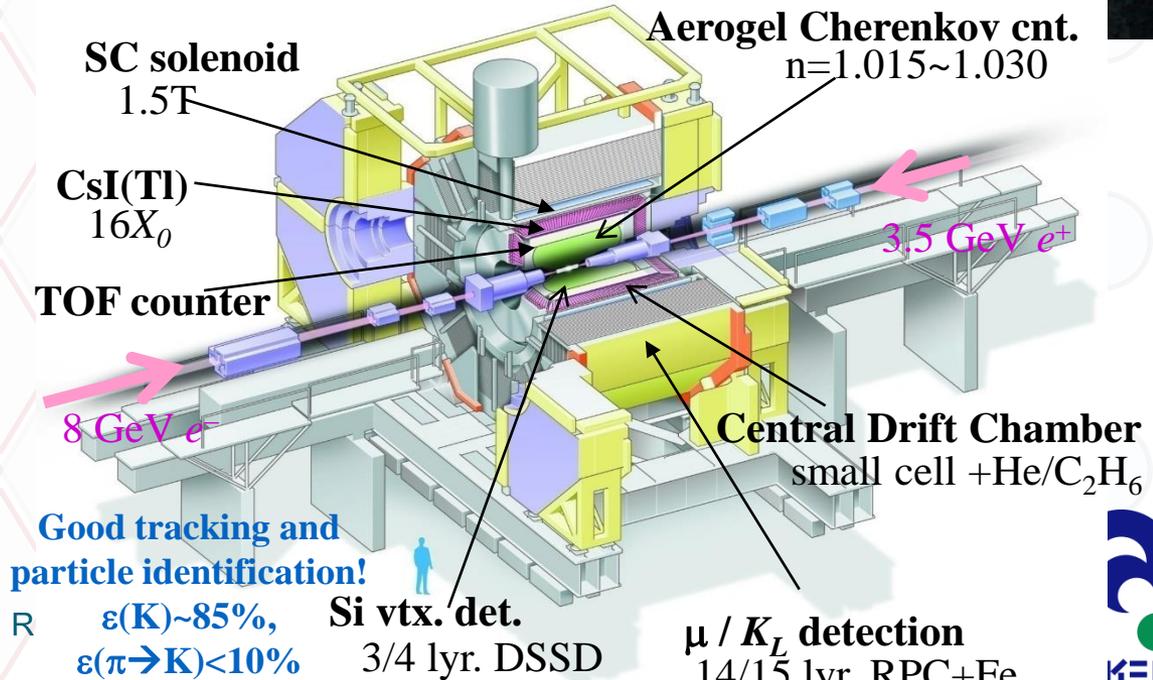
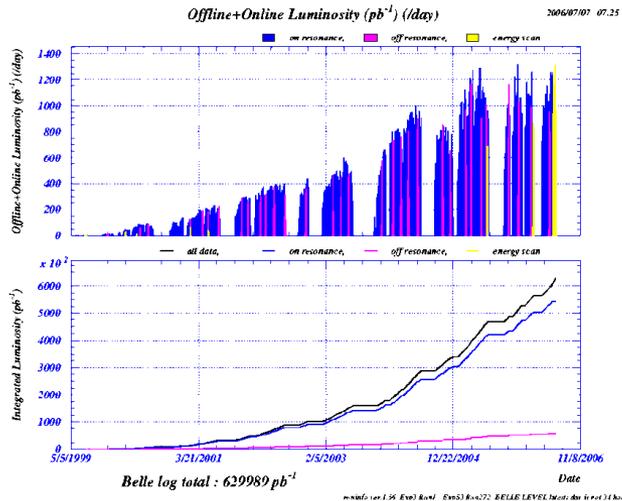
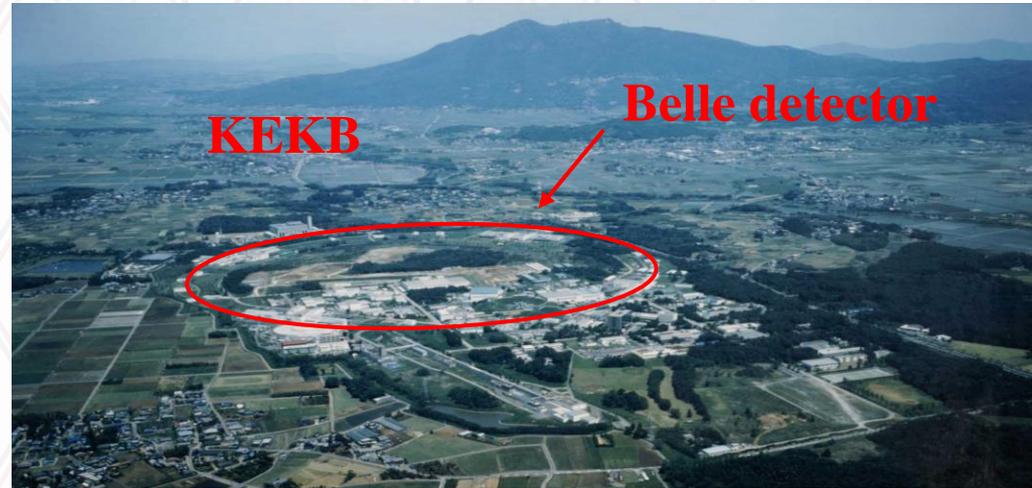
Unpolarized ingredients	Polarized ingredients	Flavor sensitivity
<p>Single hadron cross sections:</p> $e^+e^- \rightarrow hX$ $D_{1,q}^h(z, Q^2)$ <p><a href="#">PRL111 (2013) 062002</a></p>	<p>Azimuthal asymmetries:</p> $e^+e^- \rightarrow (h)(h)X,$ $\cos(\phi_1 + \phi_2)$ $H_{1,q}^{\perp(1)h}(z, Q^2)$ <p><a href="#">PRL 96 (2006) 232002</a> <a href="#">PRD 78 (2008) 032011</a></p>	<p>Unpol SIDIS, pp: <math>\frac{d\sigma}{dz}</math></p> $e^+e^- \rightarrow (h)(h)X$ <p><a href="#">PRD92 (2015) 092007</a></p> <p>and scale dependence</p>
<p>Transverse momentum dependent FFs:</p> $e^+e^- \rightarrow (h)X$ $D_{1,q}^h(z, k_T, Q^2)$ <p><a href="#">PRD 99 (2019) 112006</a></p>	<p>Transverse momentum dependent asymmetries</p> $e^+e^- \rightarrow (h)(h)X,$ $\cos(\phi_1 + \phi_2), Q_t$ $H_{1,q}^{\perp h}(z, k_T, Q^2)$ <p><a href="#">PRD100 (2019) 92008</a></p>	

# Dihadron measurements

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# 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:  $10.52\text{ GeV}$
- $e^+e^- \rightarrow q \bar{q}$  (u,d,s,c)
- Integrated Luminosity:  $>1000\text{ fb}^{-1}$
- $>70\text{fb}^{-1} \Rightarrow$  continuum

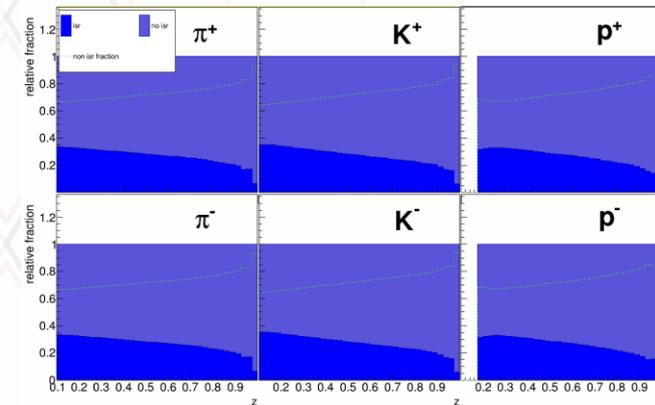
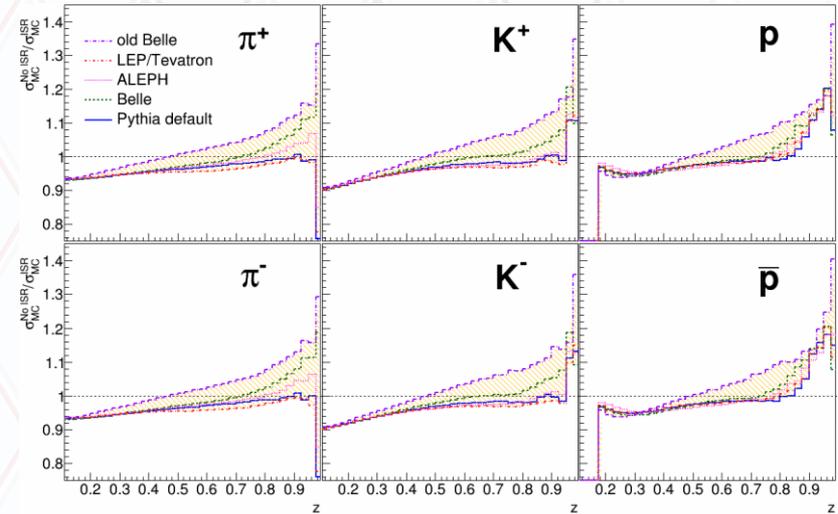


# Updates to single and di-hadron measurements

- Recently submitted update to  $\pi/K$  pair cross sections as a function of fractional energies and single  $\pi/K/p$ 
  - Updated ISR correction based on ratios of ISR on (MSTP11) to ISR off MC – consistent with recent Belle publications
  - Explicit separation of all correlated and uncorrelated systematic uncertainties  $\rightarrow$  improve impact in global fits
  - Additional fractional energy/momentum definitions and their comparisons for di-hadrons

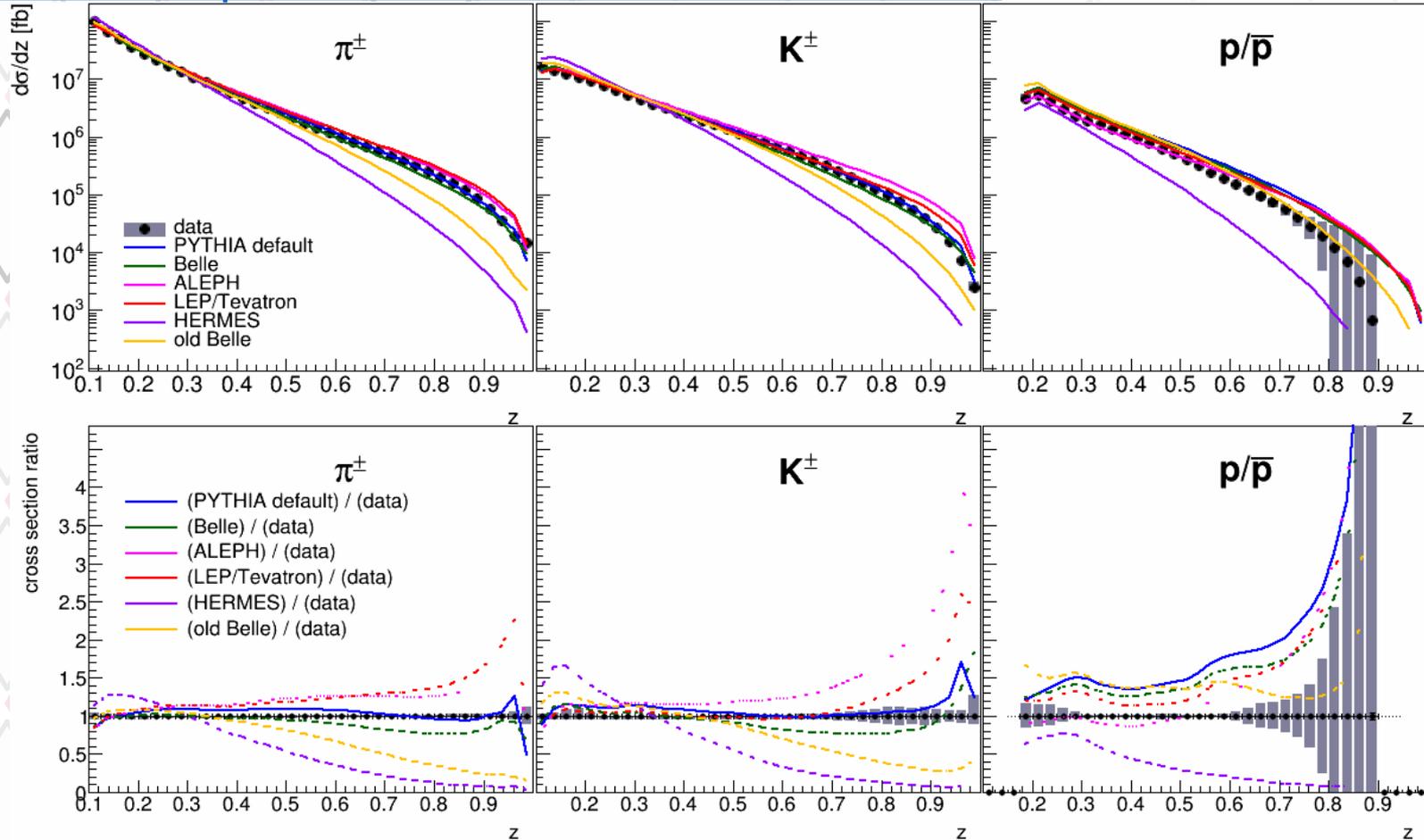
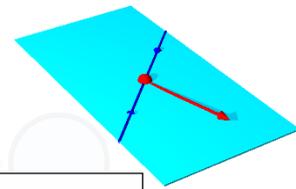
# ISR correction update

- Previously used fraction of events with actual qqbar CMS energy 99.5% larger than nominal CMS energy, leaving only 60-70 % of events
- Now use fractions of ISR on/off, take various tunes as systematic uncertainties (as performed in dihedron mass dep xsecs and kt dependent single hadron publications)



# Unpolarized single hadrons

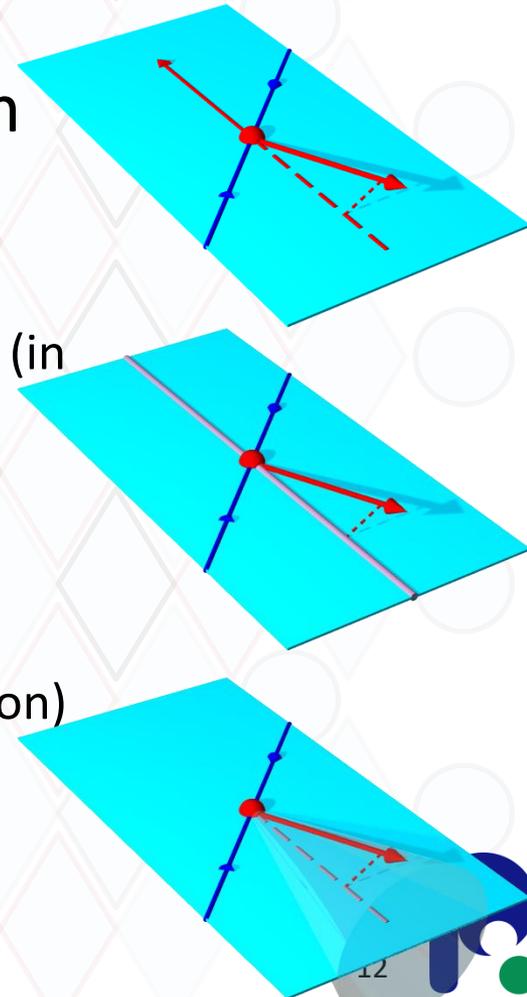
RS et al, hep-ex 2001.10194, Submitted to PRD



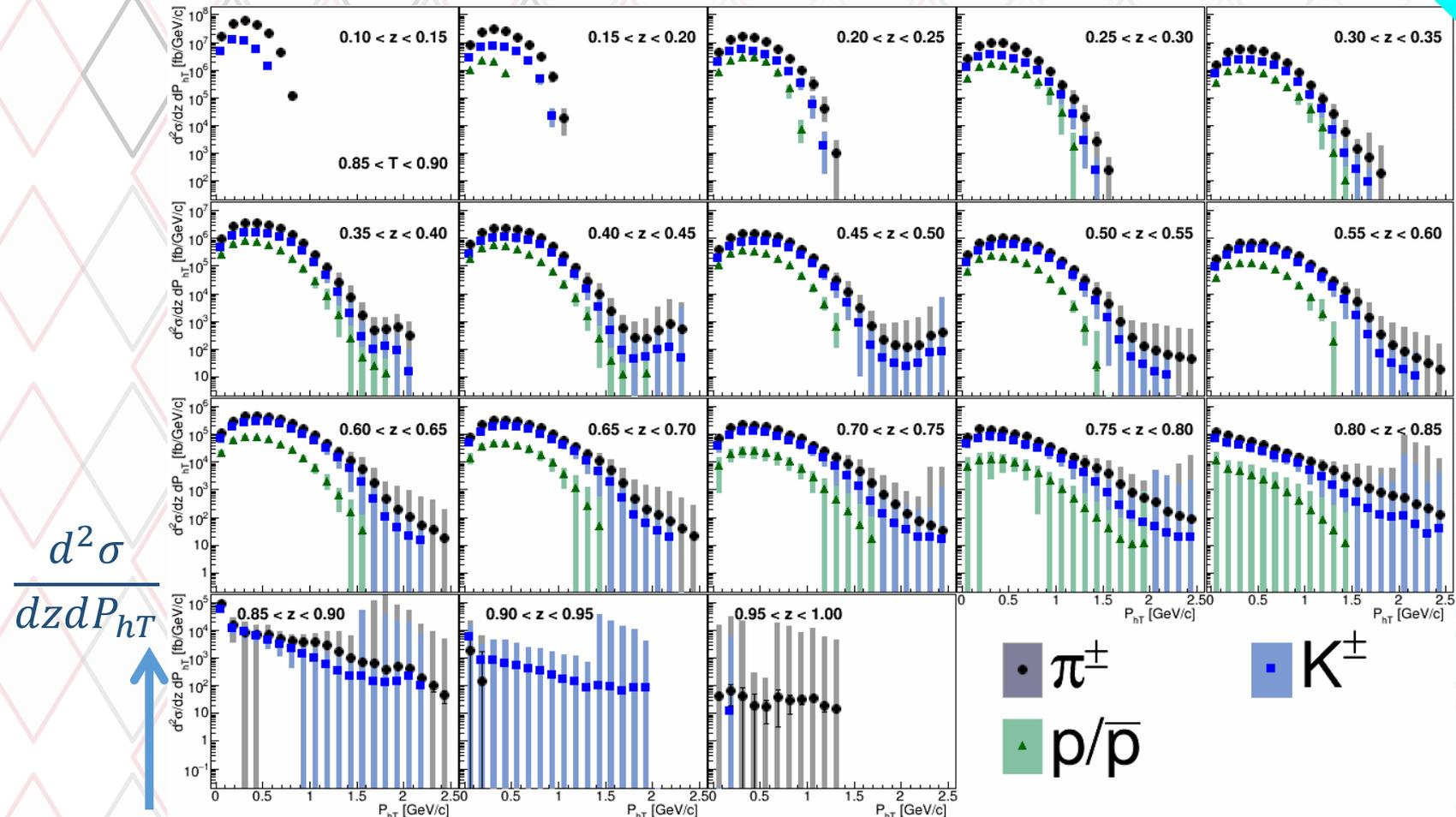
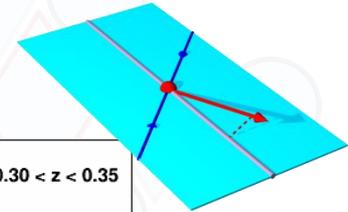
- Update with better ISR correction submitted to PRD
- Correlated and uncorrelated uncertainties separated  $\rightarrow$  improve global unpolarized FF fits

# $K_T$ 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 (similar to a Jet function)



# Cross sections various hadrons



2/03/2020

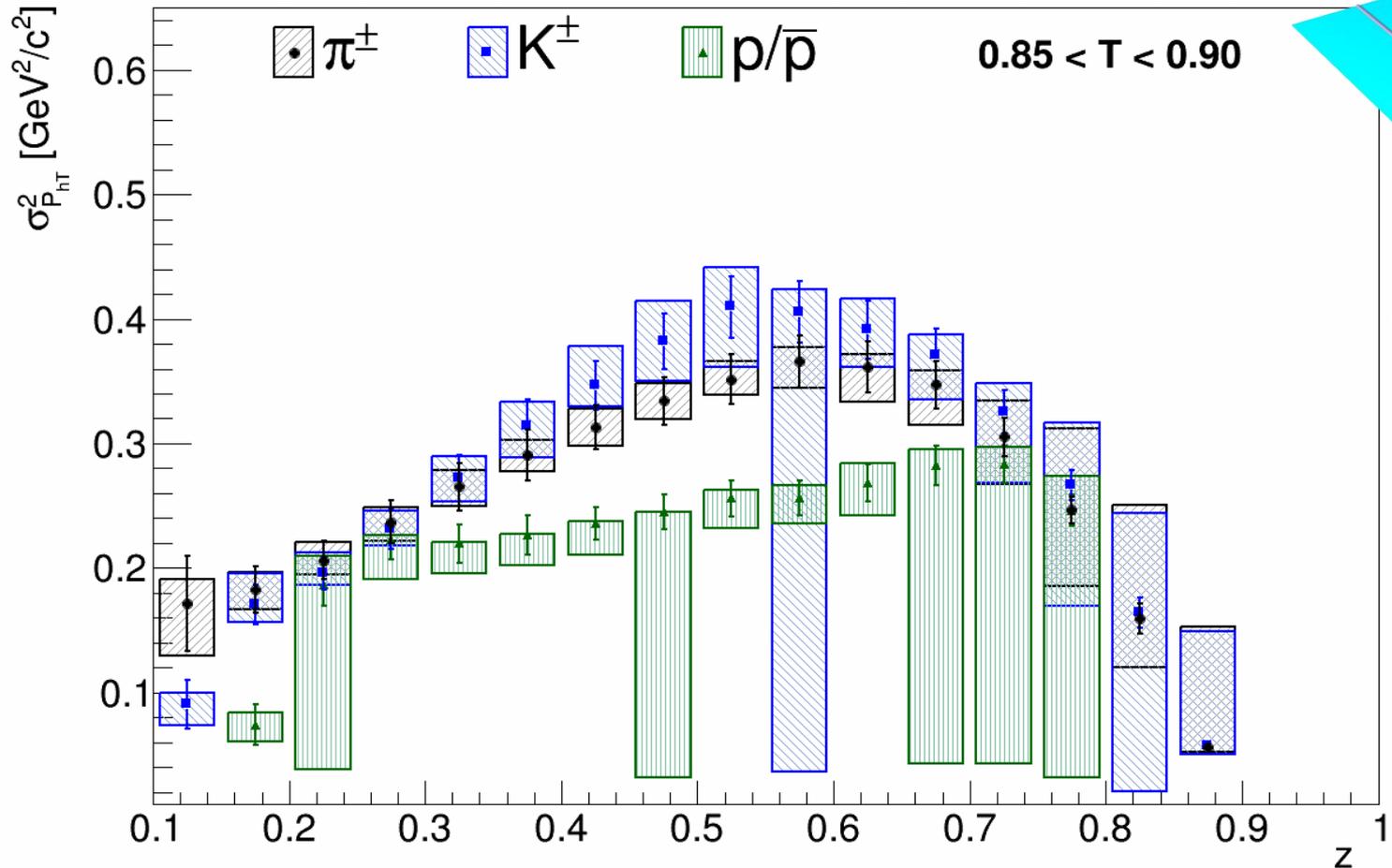
$\longrightarrow P_{hT}$

RS. et. al. [PRD99 \(2019\) 112006](#)

R.Seidl: e+e- Fragmentation

# Transverse momentum dependent unpol FFs:

- First direct (no convolutions) measurement of  $z$  and  $k_t$  dependence
- Extraction of Gaussian  $k_t$  widths



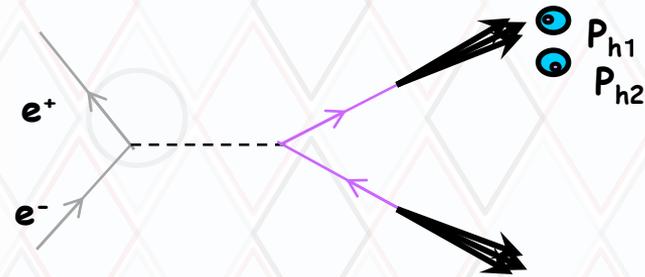
[PRD99 \(2019\) 112006](#)

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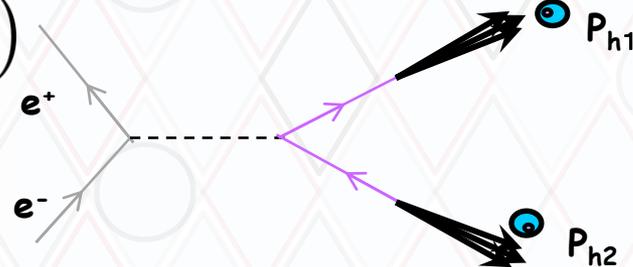
Current phenomenological models: no or linear  $z$  dependence only

# Di-hadron fragmentation functions

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



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



# Additional fractional energy definitions

- Traditional definition as:
- “New” definition based on 4-momentum dot products (Altarelli et al NPB160 (1979) , 301): automatic stress on nearly back-to-back pairs, better applicability for NLO analysis
- Also new definition interested in transverse momentum in pair (Mulders/vanHulse: [PRD 20100 \(2019\), 034011](#)):

$$z_{1,2} = \frac{2E_{1,2}}{q^2}$$

$$z_1 = \frac{2P_1 \cdot q}{q^2}$$

$$z_2 = u = \frac{P_1 \cdot P_2}{P_1 \cdot q}$$

$$z_1 = \left( P_1 \cdot P_2 - \frac{M_{h1}^2 M_{h2}^2}{P_1 \cdot P_2} \right) \frac{1}{P_2 \cdot q - M_{h2}^2 \frac{P_1 \cdot q}{P_1 \cdot P_2}}$$

$$1 \leftrightarrow 2$$

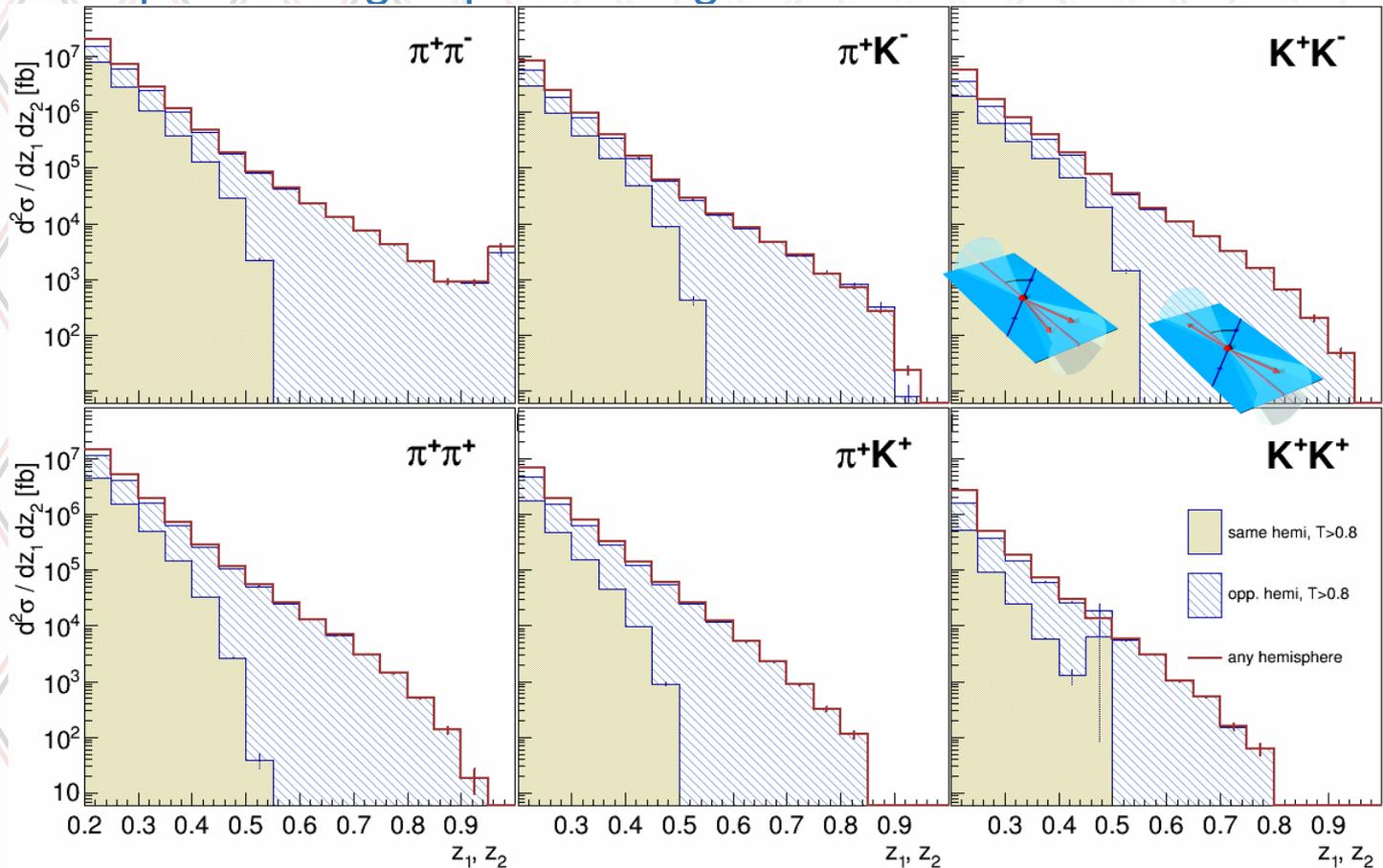
# Hemisphere composition

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](#)

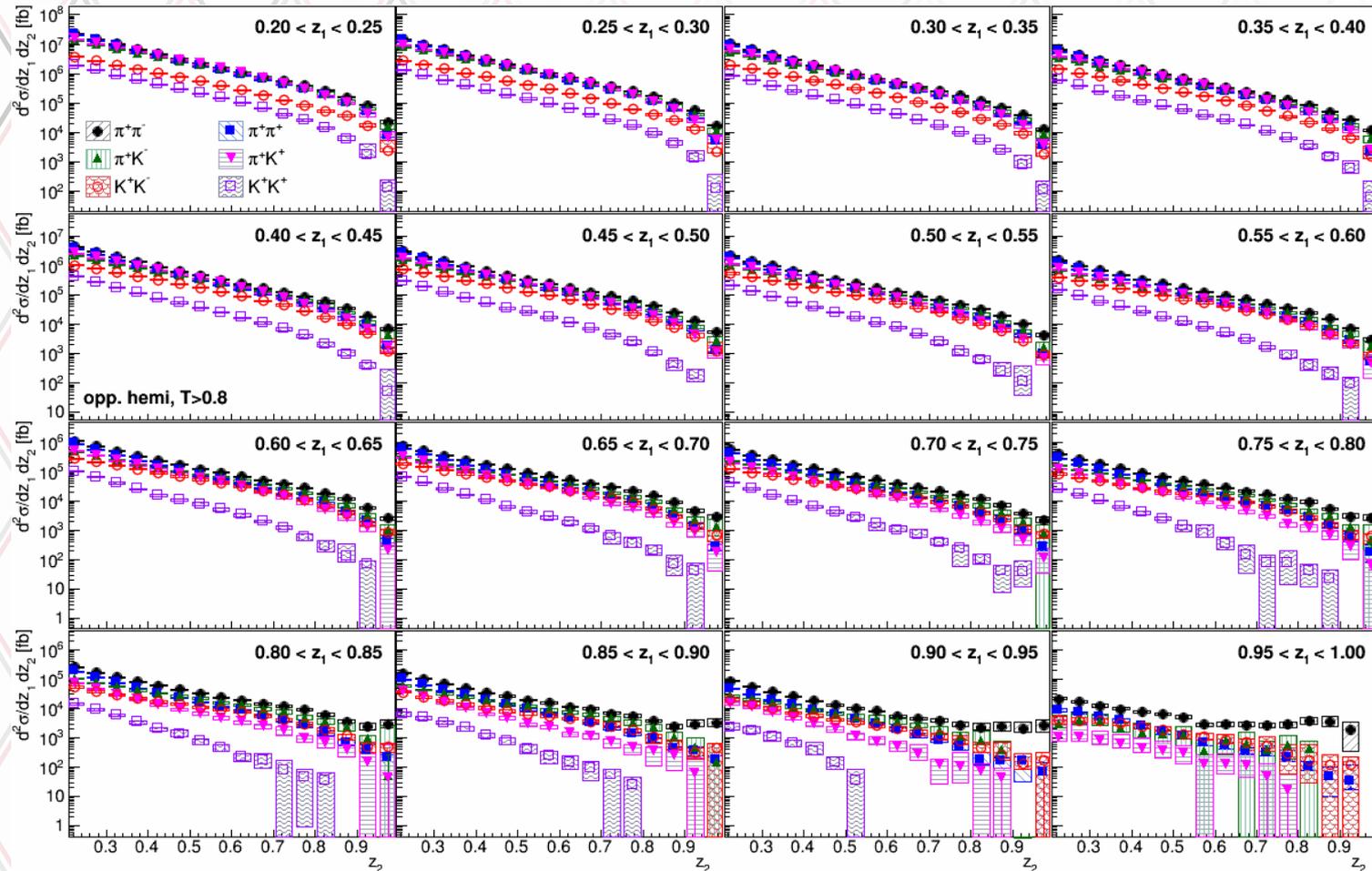
2/03/2020

Systematic uncertainties not displayed

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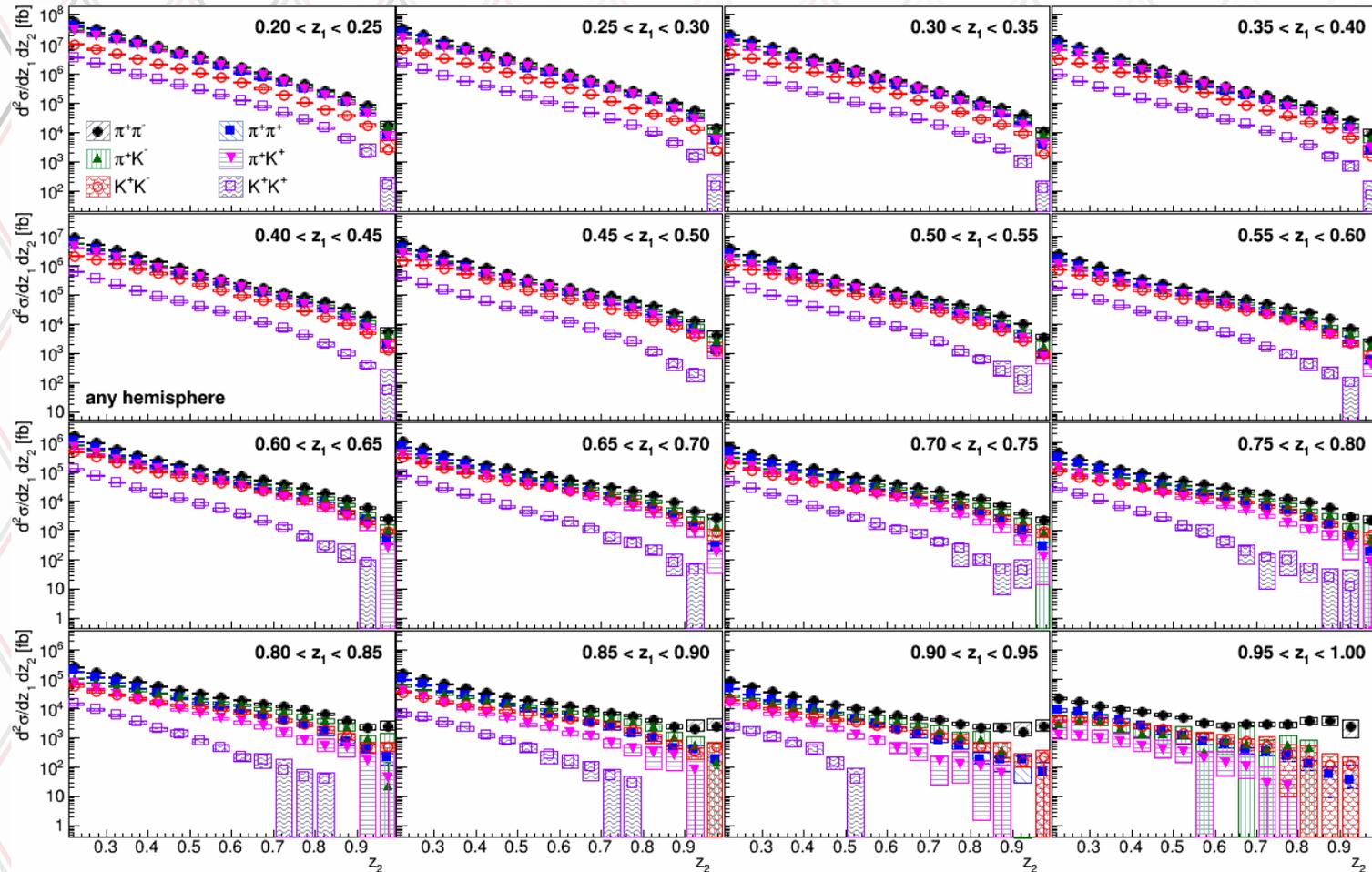
# Conventional $z$ definitions: opposite hemisphere

RS et al, hep-ex 2001.10194, Submitted to PRD



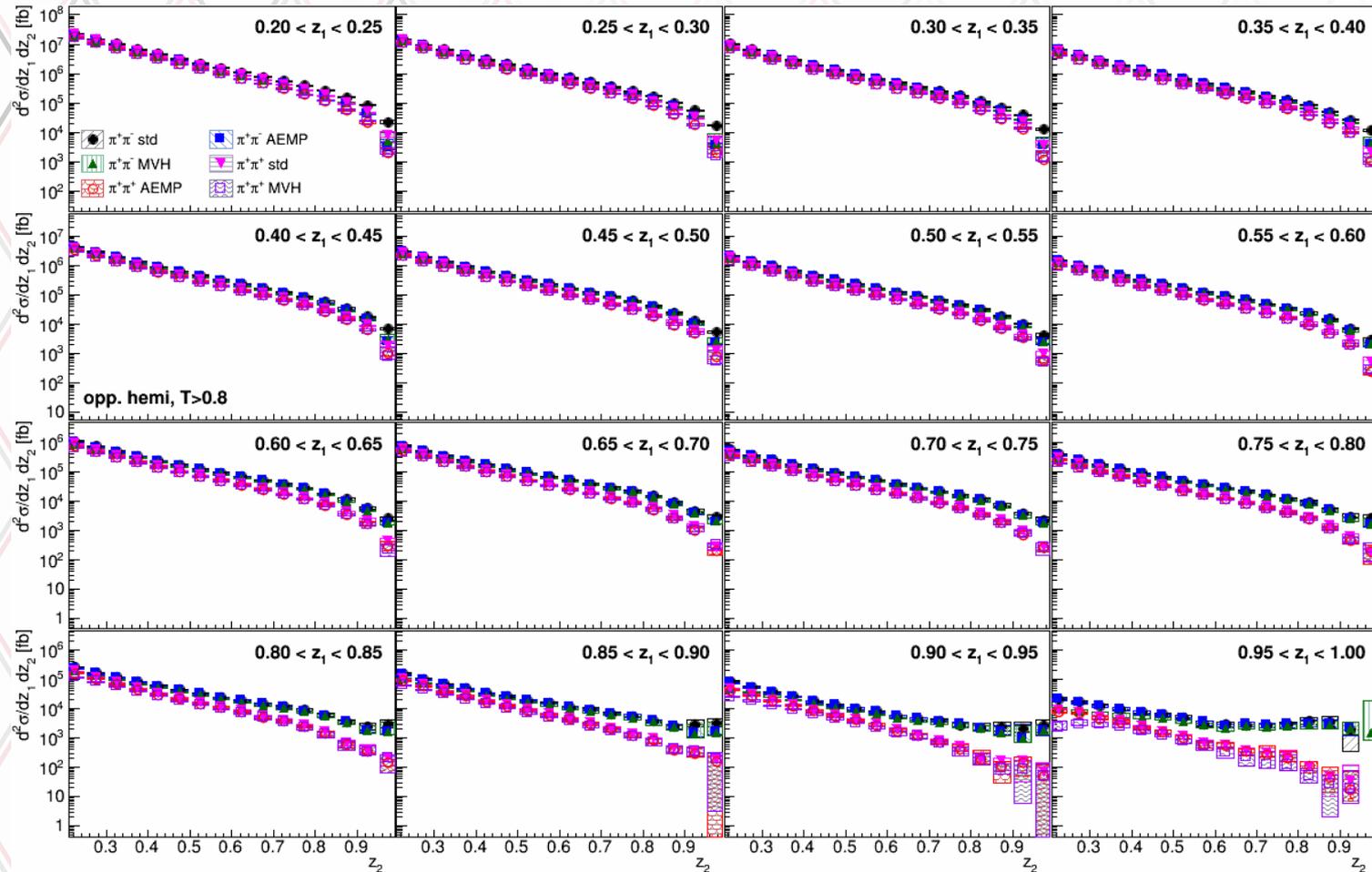
# Any hemisphere

RS et al, hep-ex 2001.10194, Submitted to PRD



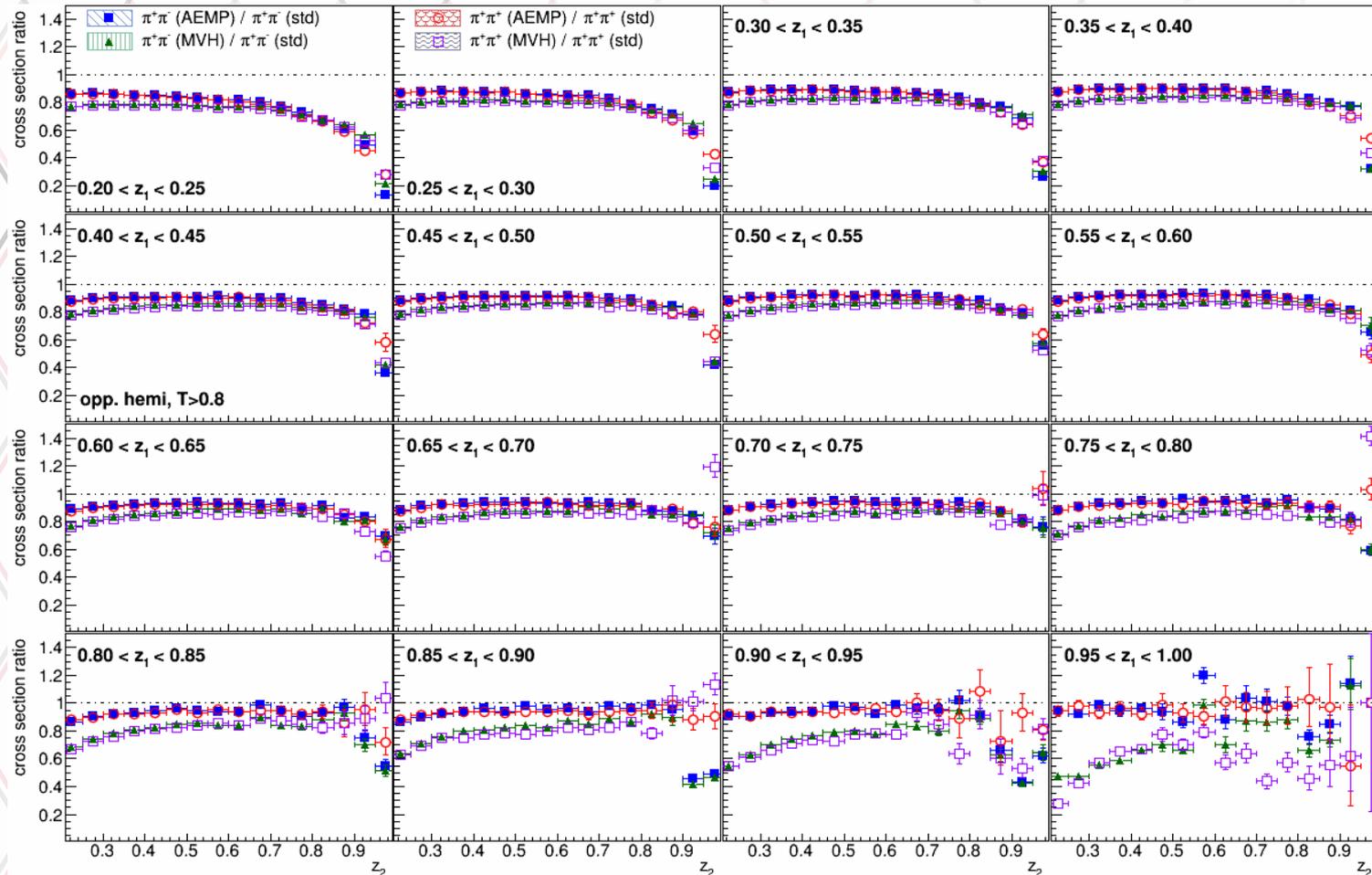
# Comparison of definitions I: pions

RS et al, hep-ex 2001.10194, Submitted to PRD



# Ratios to standard definitions: opposite hemisphere

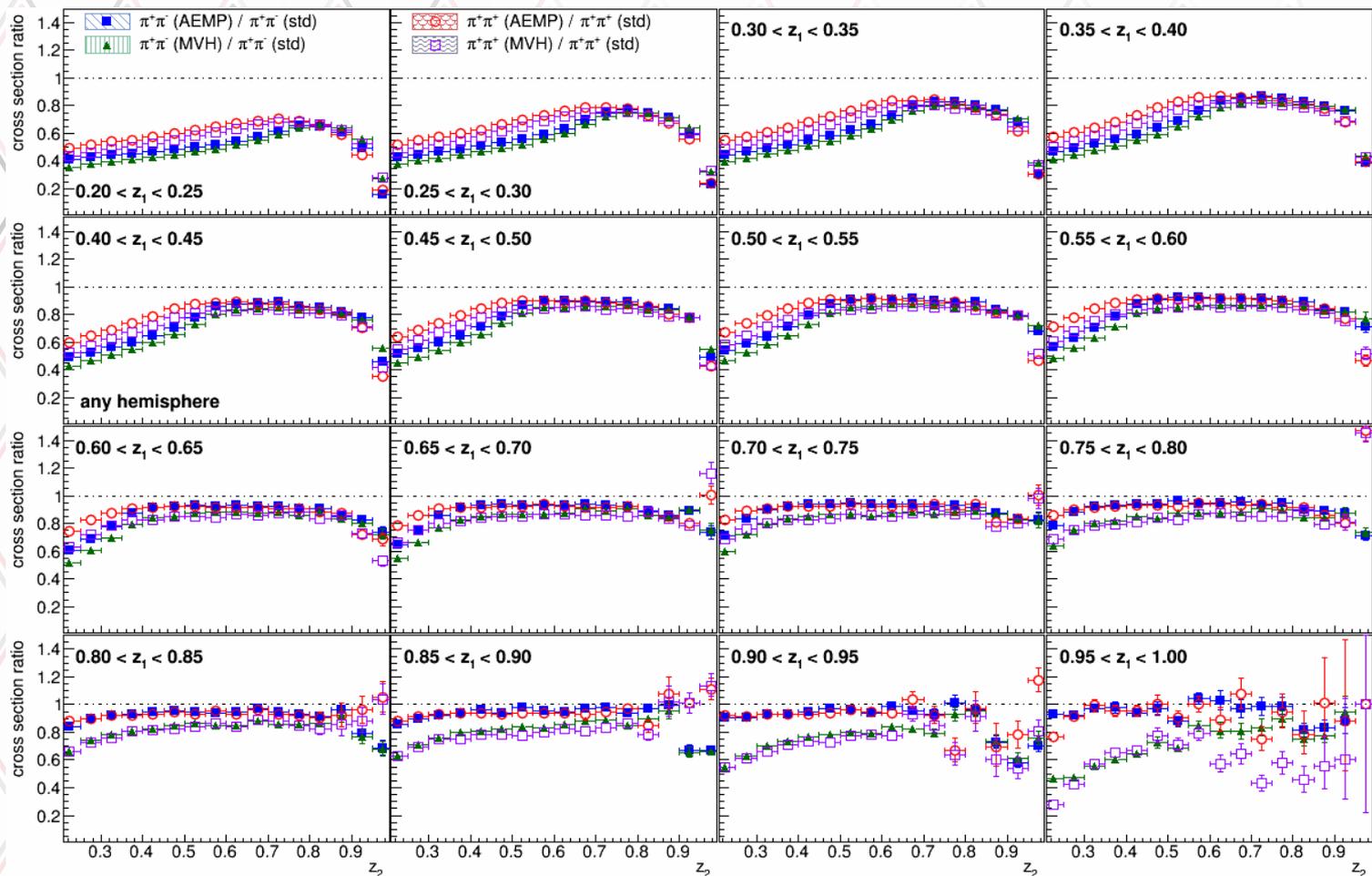
RS et al, hep-ex 2001.10194, Submitted to PRD



AEMP : suppressed at small fractional energies, at high  $z$  close to unity  
MvH : further suppressed due to transverse momentum

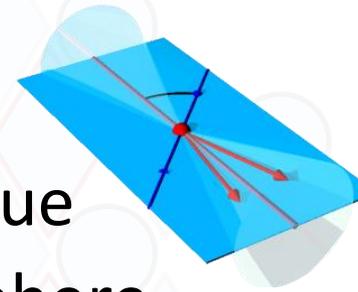
# Ratios for any hemisphere

RS et al, hep-ex 2001.10194, Submitted to PRD



AEMP+MvH : both further suppressed at smaller z due same hemisphere contributions shifter to much lower values

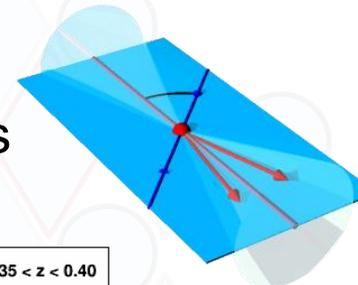
# Explicit di-hadron mass dependence



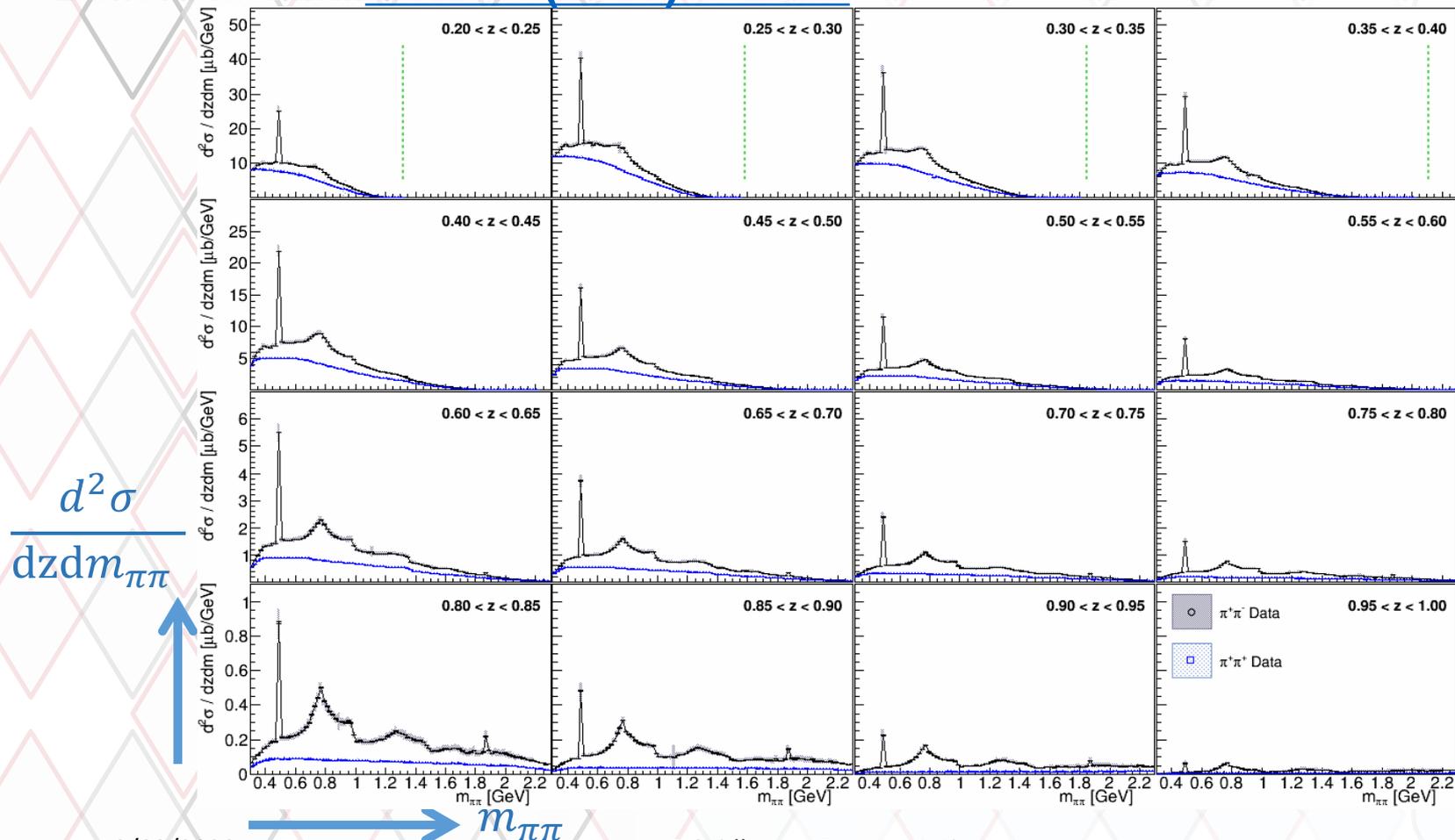
- IFF related asymmetries extracted by Belle in 2011 (PRL107:072004(2011))
  - SIDIS (JHEP 0806 (2008), PLB713 (2012)) and RHIC ([PRL 115 \(2015\) 242501](#)) IFF asymmetries published
  - Global fits currently missing unpolarized di-hadron FF baseline
- Belle to the rescue
- Use same hemisphere di-hadrons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

# 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](#)



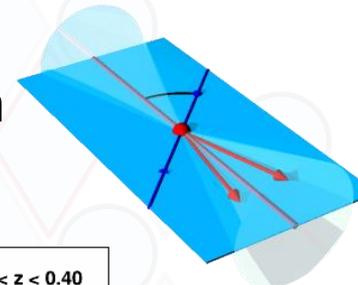
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R.Seidl: e+e- Fragmentation

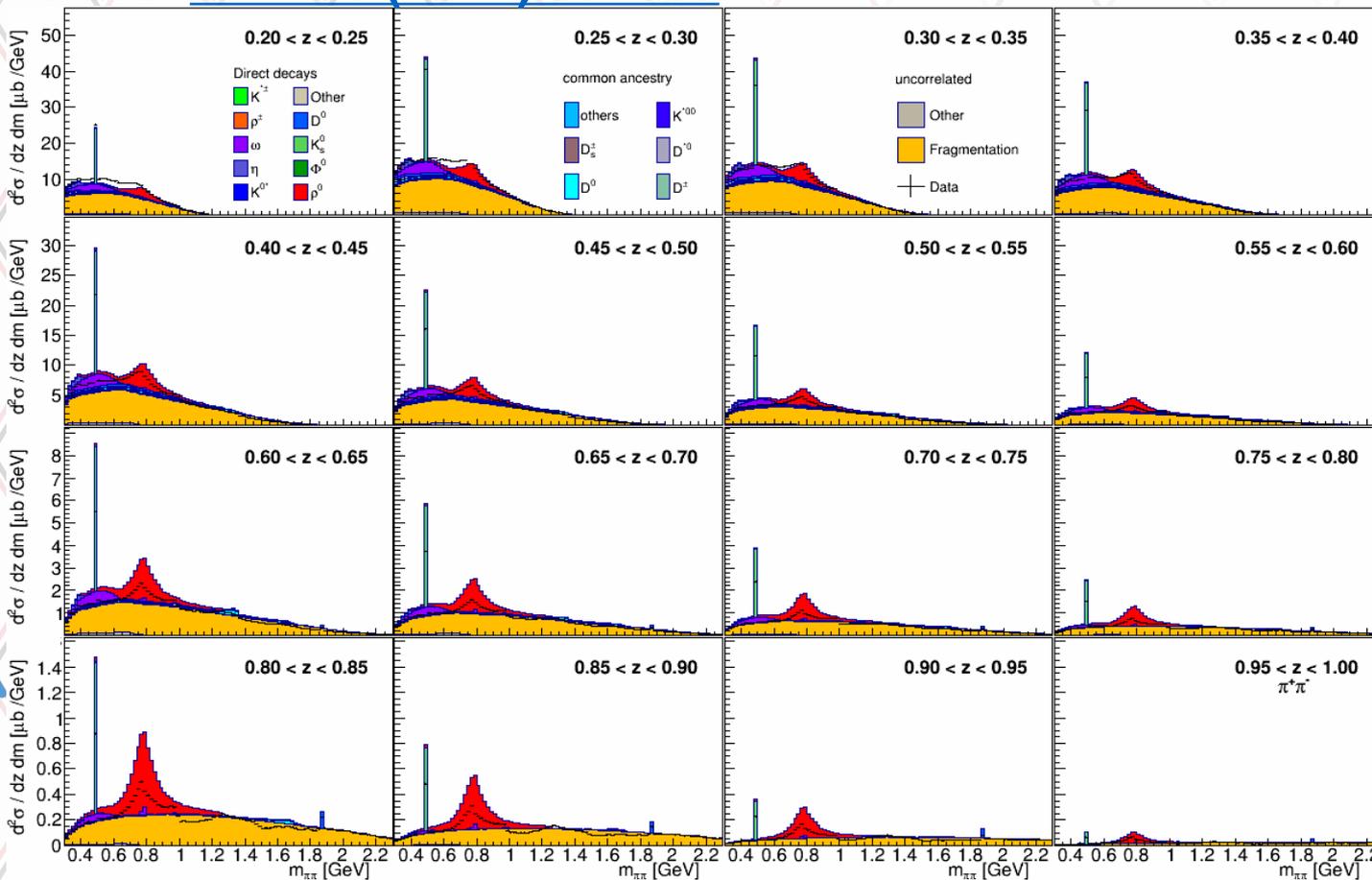
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# Di-pion individual contributions

Contributions from various resonances and direct fragmentation



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



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



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# Ongoing work

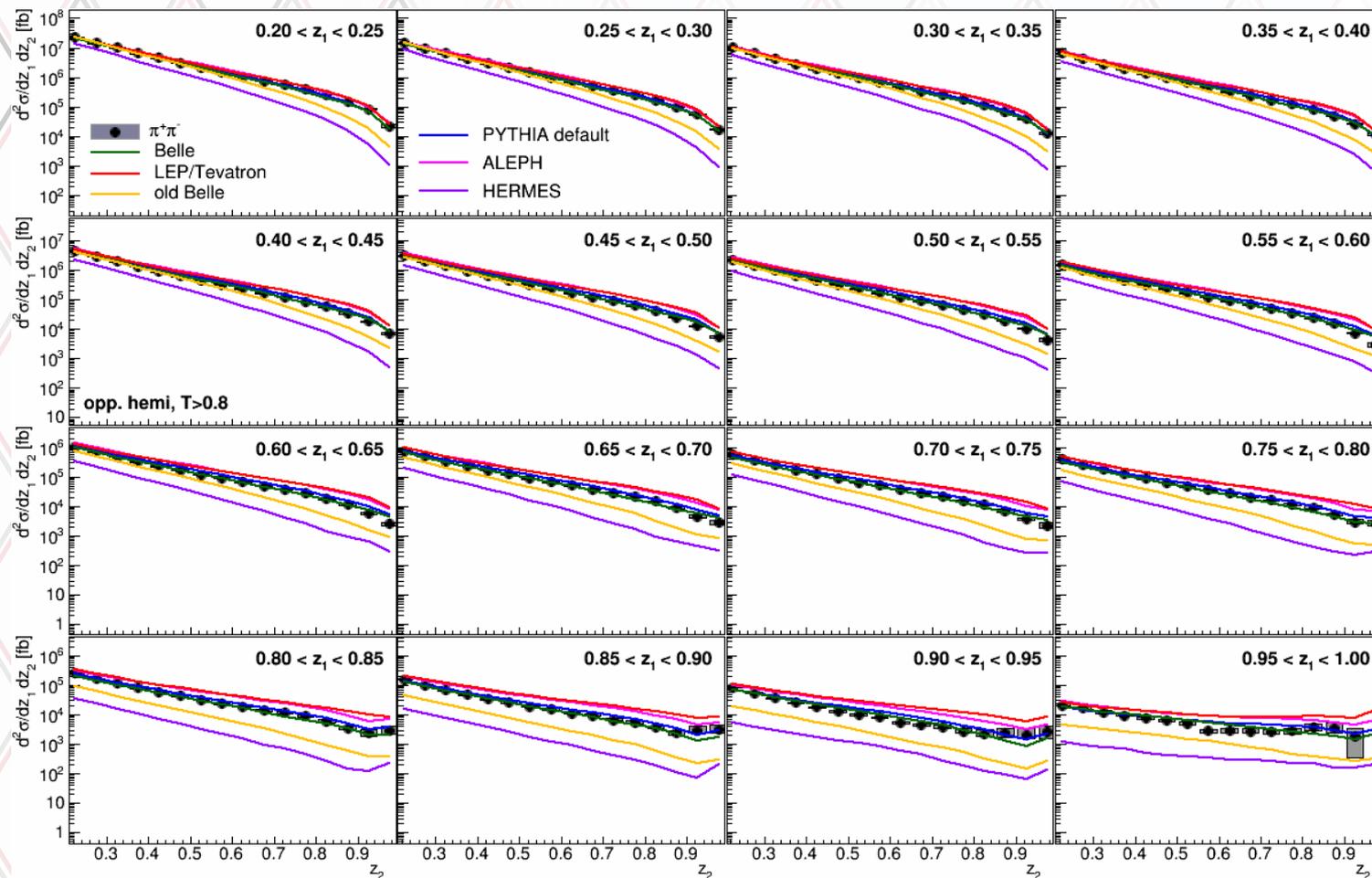
- Back-to-back di-hadron relative transverse momentum  $/Q_t$  measurements (Anselm/Charlotte) progressing
- Extraction of production cross sections for  $K_s, \rho, \omega, K^*, \phi$ , cross check of  $D_0$ s and potentially  $f_0(980)$  and further study of decay contributions to light hadrons
- Jets(+shape) and fragmentation?

# Summary

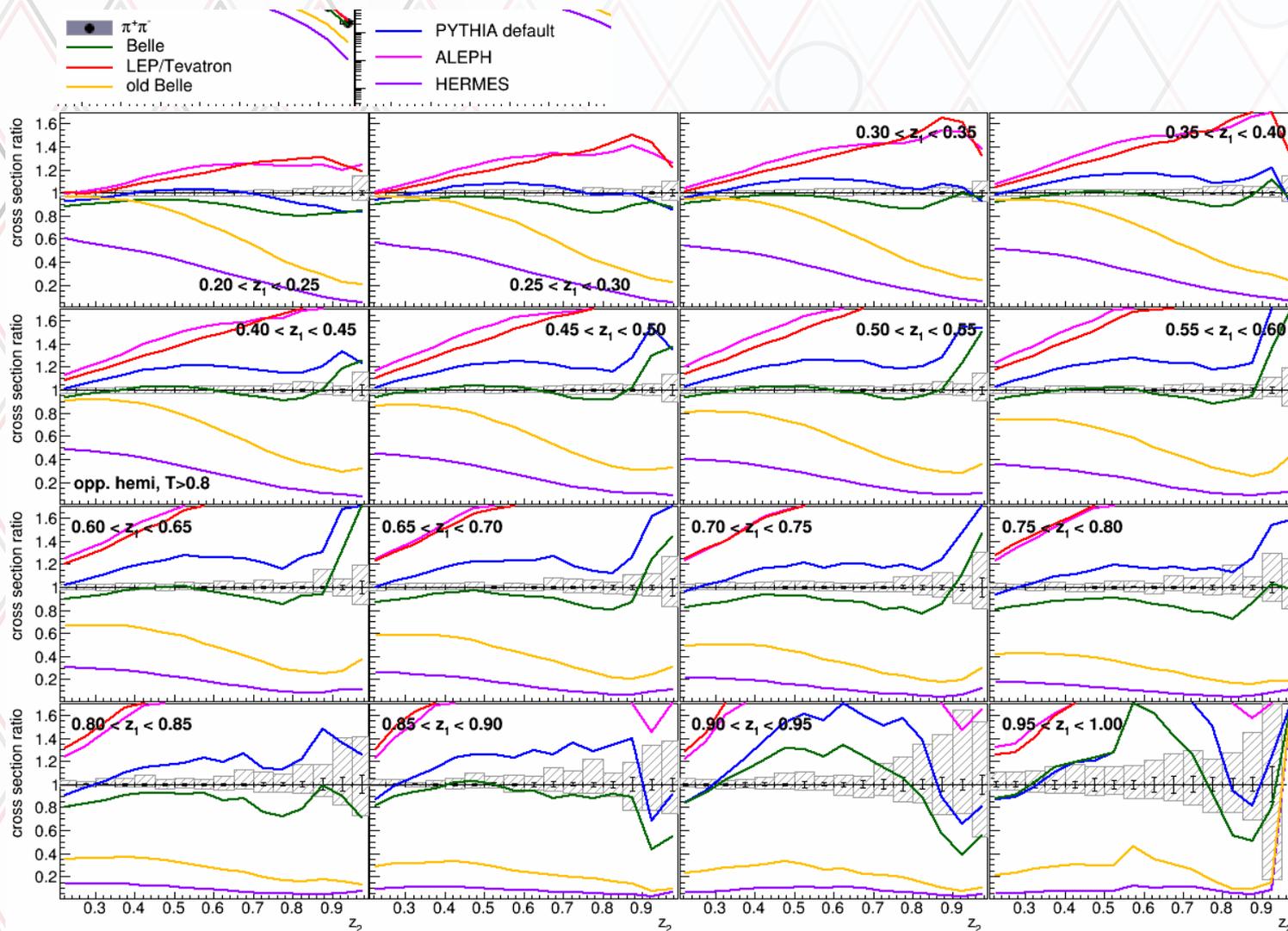
- New updates on the single and di-hadron cross sections for unpolarized fragmentation functions
- The  $e^+e^-$  annihilation experiments, in particular Belle, have provided nearly all relevant measurements needed for the EIC:
  - Single and dihadron cross sections
  - Collins and Interference FF asymmetries
  - Transverse momentum dependence
- Baseline for successful Tensor charge/TMD/helicity extractions from EIC



# Data-MC comparisons, opposite pion pairs

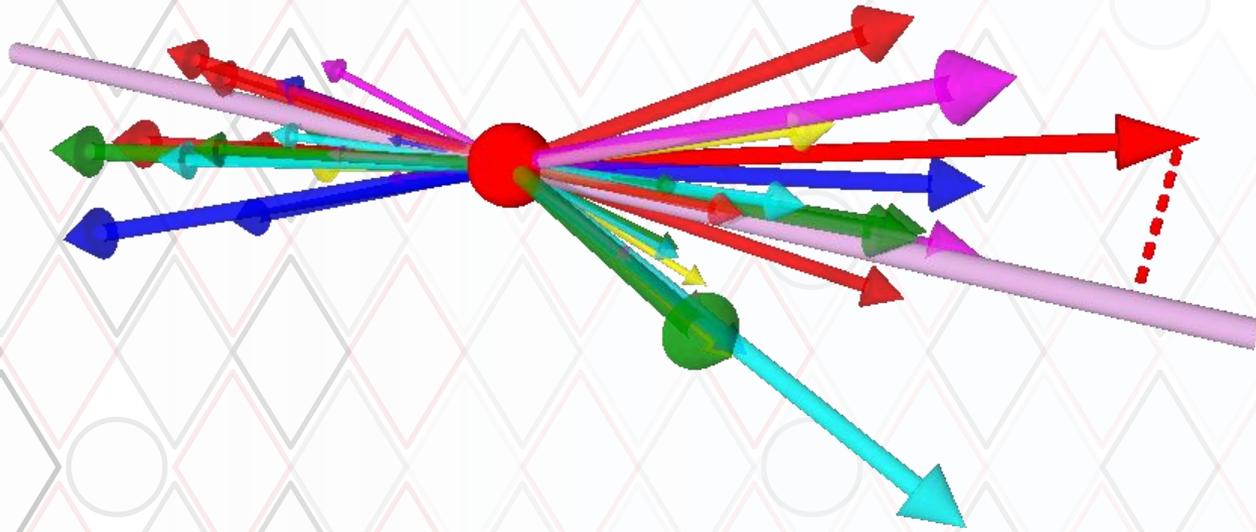


# Data-MC comparisons, opposite pion pairs



# 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:  $\delta q \times \delta q$  or
    - SIDIS/RHIC:  $\delta q \times$  Collins or  $\delta q \times$  IFF
  - FFs from Belle/Babar



# Transverse momentum dependence

Aka un-integrated PDFs and FFs

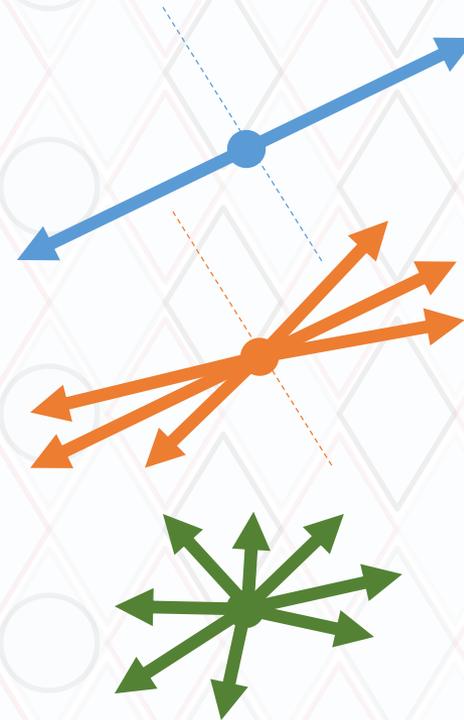
# Thrust definition

- Event shape variable thrust is defined as:

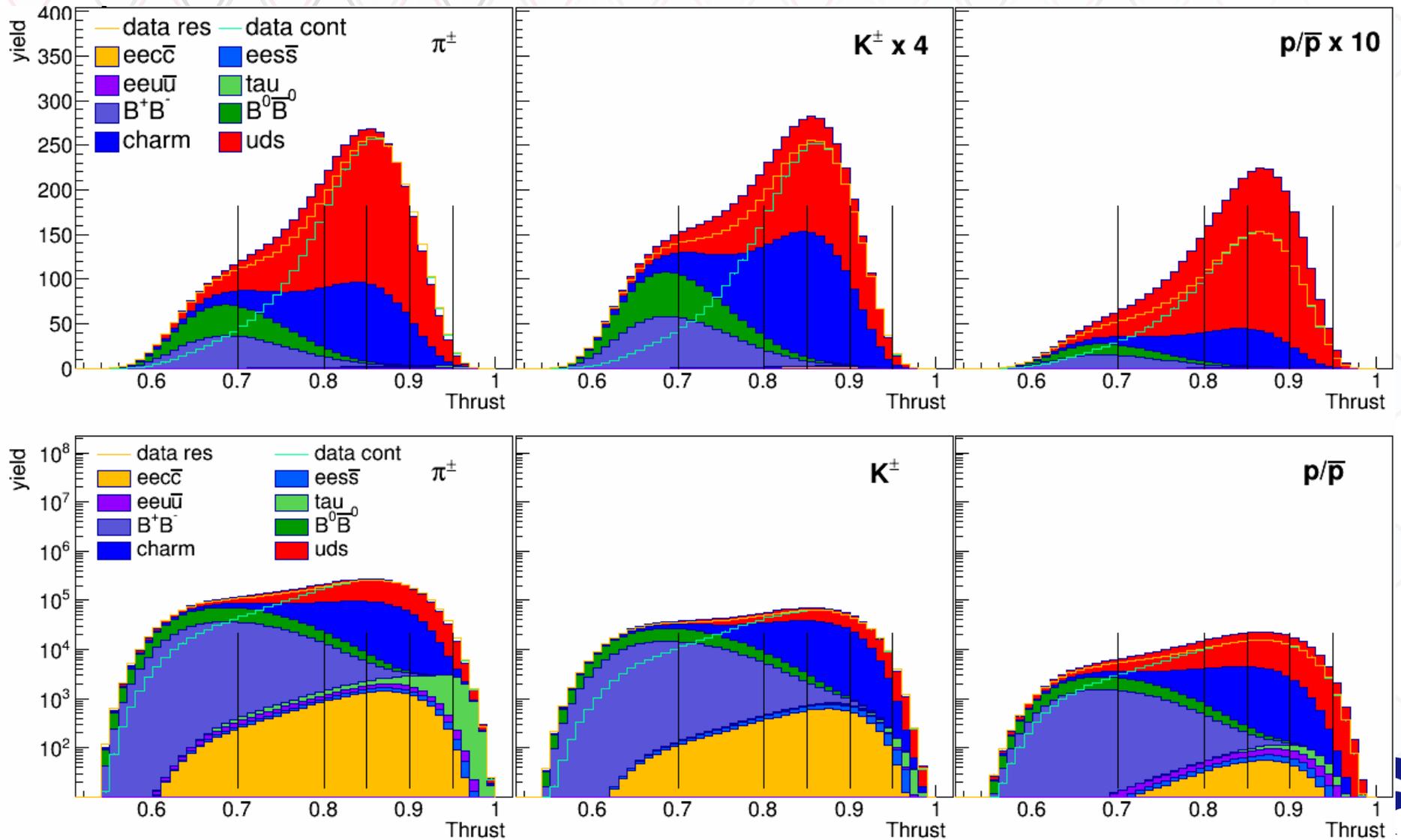
$$T \stackrel{\text{max}}{=} \frac{\sum_h |\mathbf{P}_h \cdot \hat{\mathbf{n}}|}{\sum_h |\mathbf{P}_h|}$$

- All final-state particles are included in the sum
- A **two-jet-like** event has a high thrust value
- A completely **spherical** event has a thrust value of 0.5

- Thrust axis  $\mathbf{n}$  also defines the hemispheres

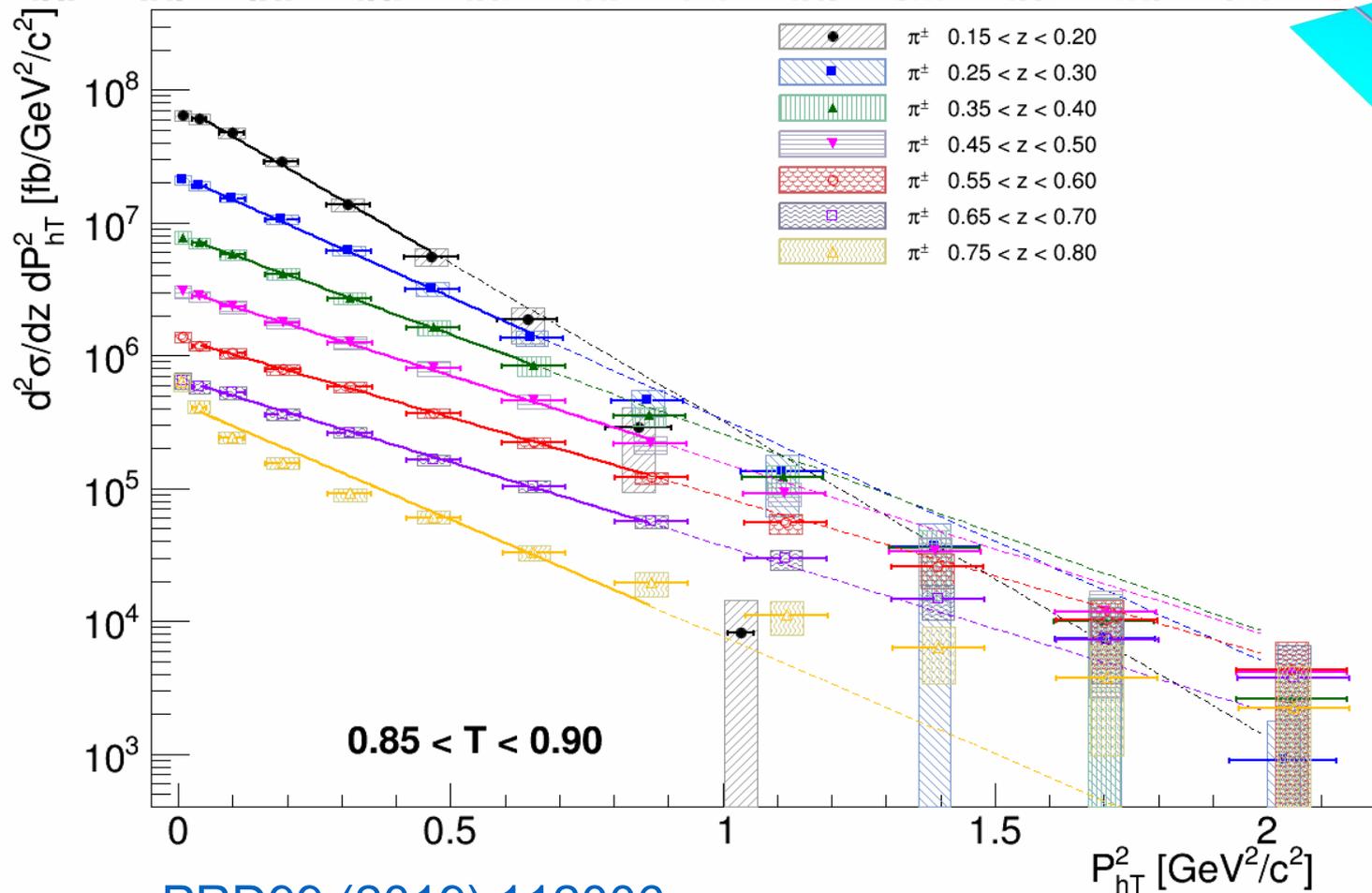


# Thrust distributions (lin and log)



# Fits vs $P_{hT}^2$

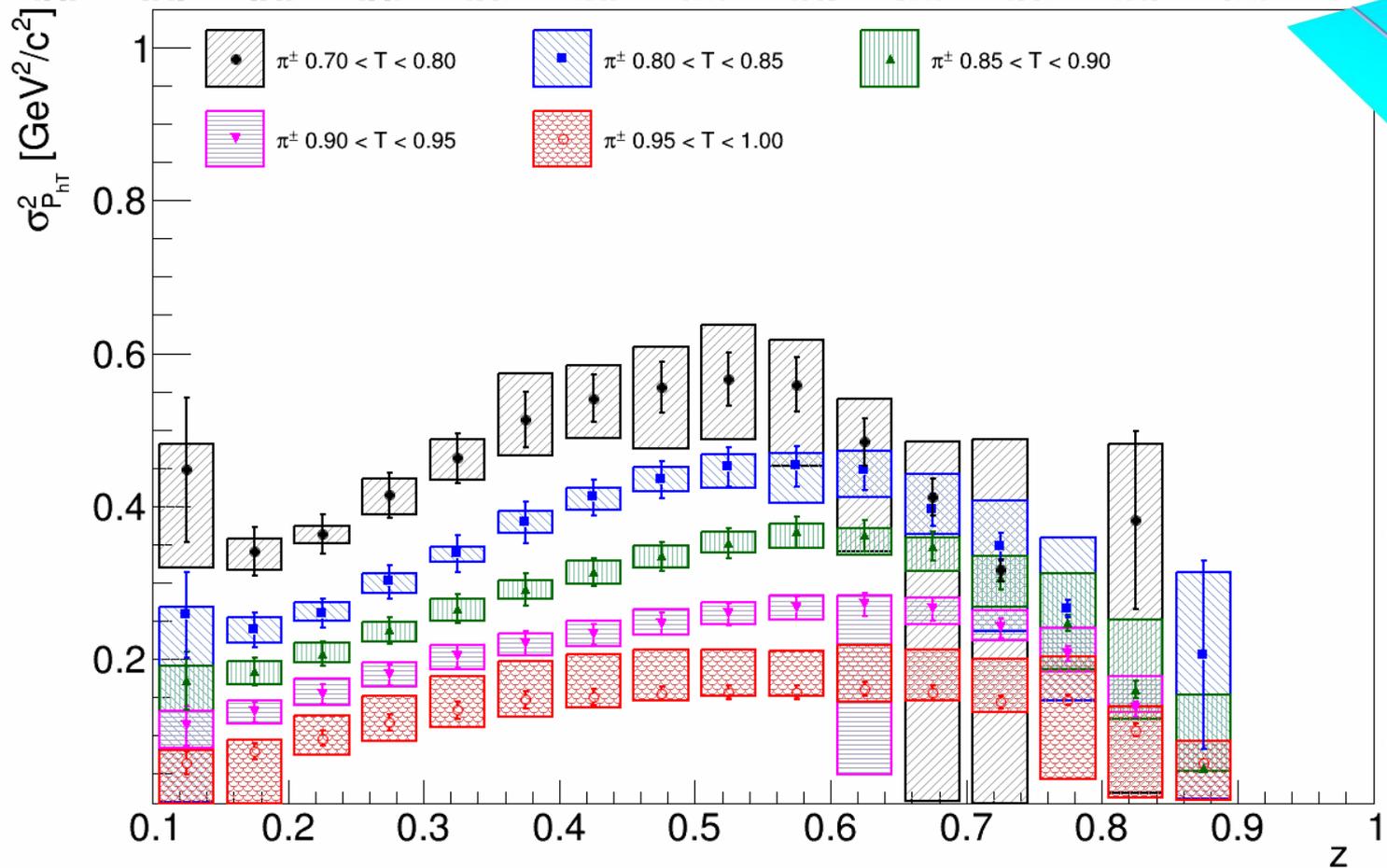
Fit exponential to smaller transverse momenta for  
Gaussian  $P_{hT}$  dependence and power law at higher  $P_{hT}$



[PRD99 \(2019\) 112006](#)

# Gaussian widths, thrust dependence

Gaussian widths get narrower with higher Thrust

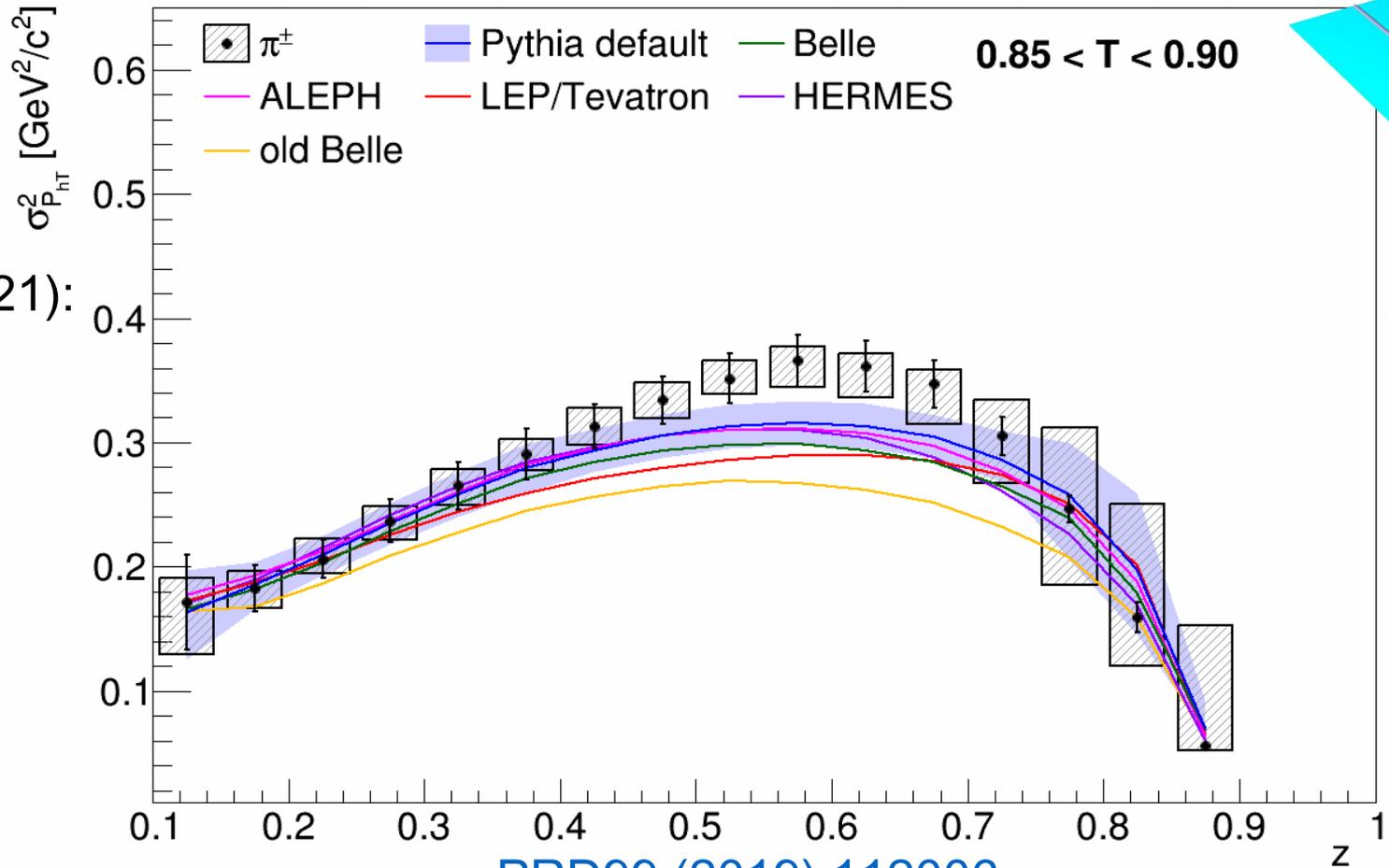


[PRD99 \(2019\) 112006](#)

R.Seidl: e+e- Fragmentation

# Gaussian widths comparison to MC

first direct (no convolutions) measurement of z dependence of Gaussian widths



MSTP(21):

0.28

0.325

0.36

0.36

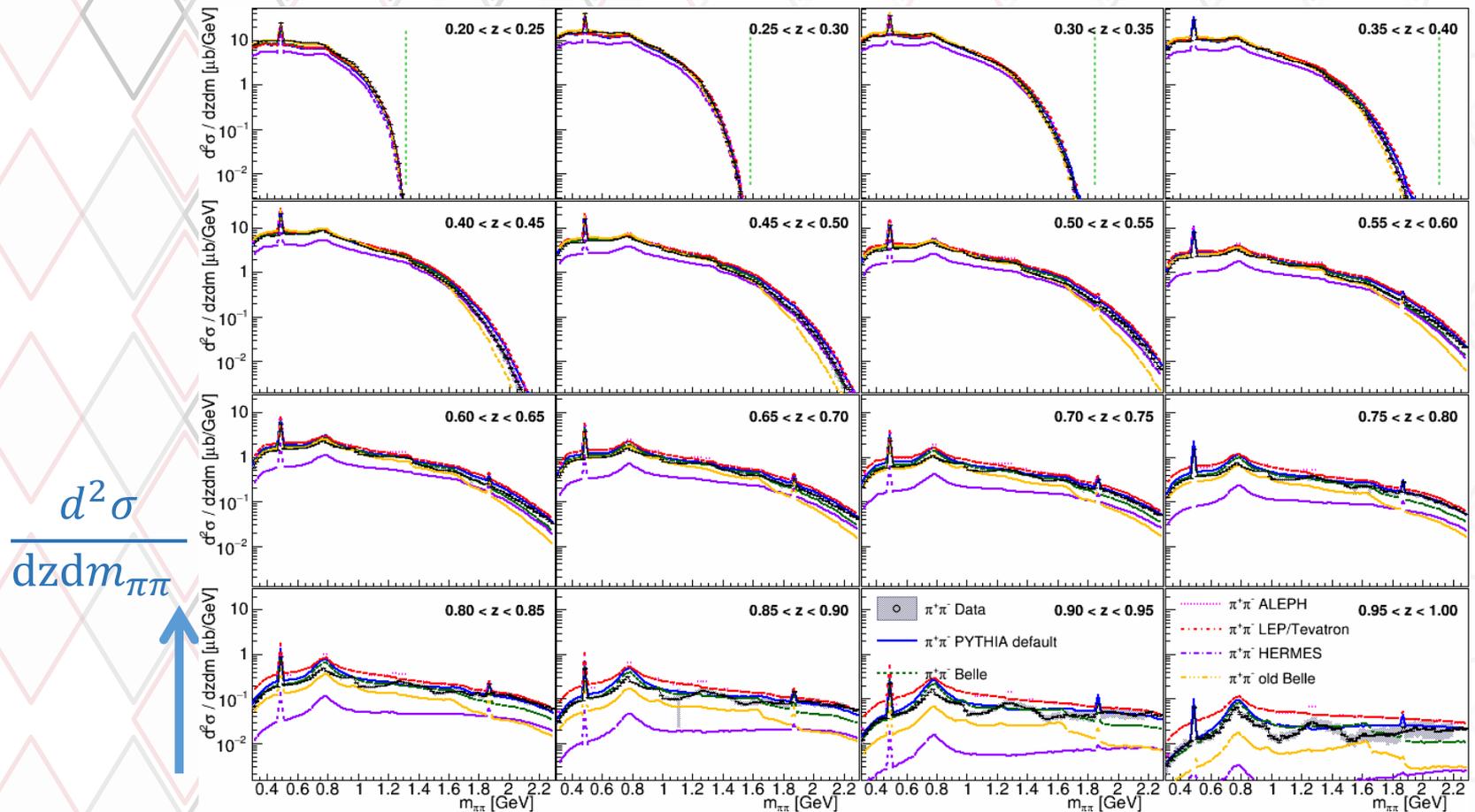
0.37

0.40

[PRD99 \(2019\) 112006](#)

# 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)



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

↑

2/03/2020

→  $m_{\pi\pi}$

R.Seidl: e+e- Fragmentation

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# Access to Transversity/Tensor charge

- Chiral-odd object needs to be coupled with second chiral-odd object to be experimentally accessible
- (anti)quark Transversity/BoerMulders : Drell Yan  $A_{TT}$

$$A_{TT} \propto \delta q \delta \bar{q} / q \bar{q}$$

- chiral-odd fragmentation function:

$$A_{UT} \propto \delta q(x) H_{1,q}^h(z) / q(x) D_1^h(z)$$

- Collins FF (single hadron, TMD function)

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

- Interference FF (dihadron, collinear function)

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

- Polarized  $\Lambda$  fragmentation function

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

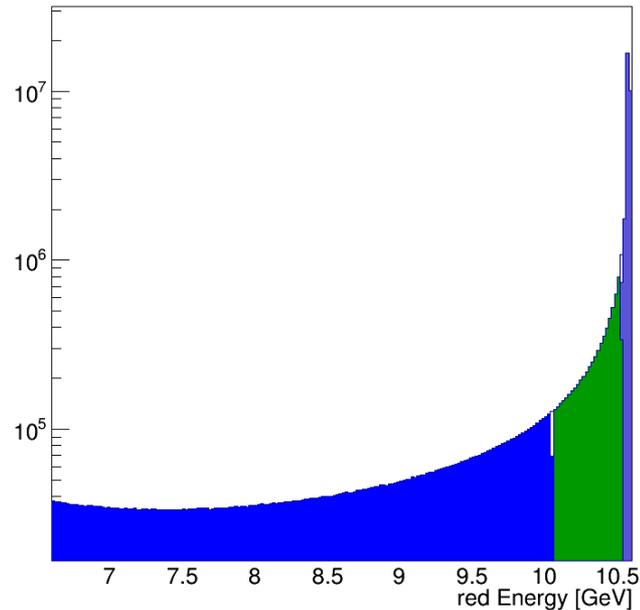
# New possibilities:

## 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  $\pi^0$  (0.1-0.17) or  $\eta$  (0.5-0.6) mass range

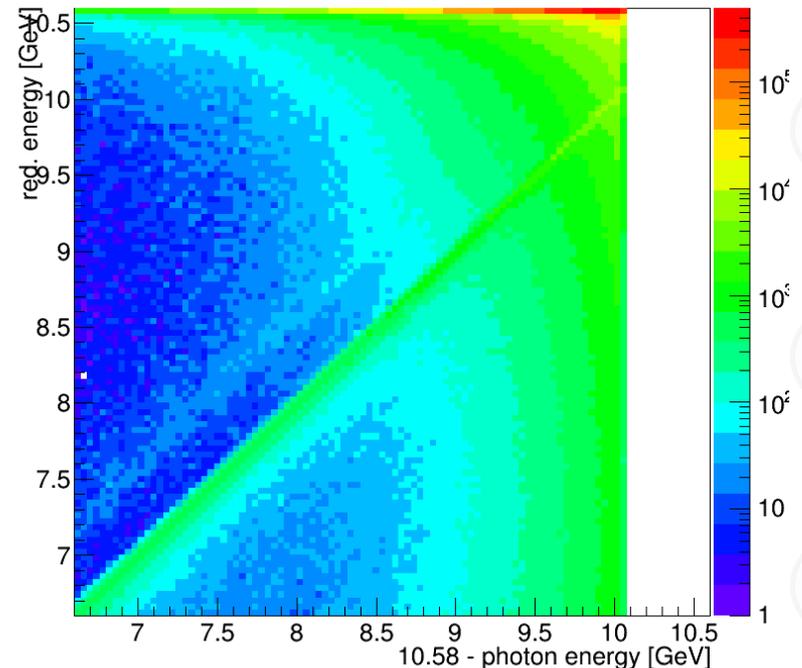
# CMS energy of the qqbar system

reduced CMS energy



- Remove detected photon(s),  $E > 0.5 \text{ GeV}$  from system
- Correlation to true CMS energy seen

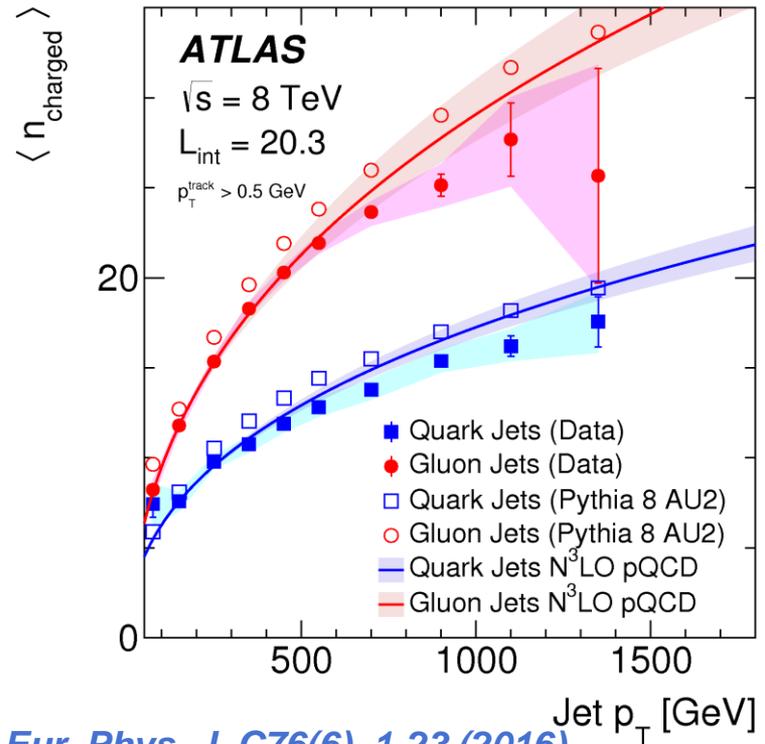
reduced CMS energy - photon energy



- 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?



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

# Belle fragmentation

- Initially started by RBRC fellow M. Perdekamp (now UIUC), A. Ogawa (BNL) and S. Lange (now U Giessen)
- Continued by RCS with additional help from UIUC (Matthias) and IU/Duke (A. Vossen) and JSPS

