TMD Fragmentation Functions

Transversity 2022

May 24, 2022

Ralf Seidl (RIKEN)

Single hadron FF

Unpolarized ingredients	Polarized ingredients	Flavor sensitivity
Single hadron cross sections: $e^+e^- \to hX$ $D_{1,q}^h(z, Q^2)$ **PRL111 (2013) 062002** **PRD101(2020) 092004**	Azimuthal asymmetries: $e^+e^- \to (h)(h)X$, $\cos(\phi_1 + \phi_2)$ $H_{1,q}^{\perp(1)h}(z, Q^2)$ **PRL 96 (2006) 232002** **PRD 78 (2008) 032011**	Unpol SIDIS, pp: $\frac{d\sigma}{dz}$ $e^+e^- \to (h)(h)X$ **PRD92 (2015) 092007** **PRD101(2020) 092004** and scale dependence
Transverse momentum dependent FFs: $e^+e^- \to (h)X$ $D_{1,q}^h(z, k_T, Q^2)$ **PRD 99 (2019) 112006**	Transverse momentum dependent asymmetries $e^+e^- \to (h)(h)X$, $\cos(\phi_1 + \phi_2), Q_t$ $H_{1,q}^{\perp h}(z, k_T, Q^2)$ **PRD100 (2019) 92008**	Polarizing Λ fragmentation **PRL 122 (2019), 042001** $D_{1,q}^{\perp h}(z, k_T, Q^2)$

Dihadron FF (IFF)

Unpolarized ingredients	Polarized ingredients	Flavor sensitivity
Dihadron cross sections $e^+e^- \to (hh)X$ $D_{1,q}^{h_1 h_2}(z, m, Q^2)$ **PRD96 (2017) 032005**	Azimuthal asymmetries: $e^+e^- \to (hh)(hh)X$, $\cos(\phi_1 + \phi_2)$, $H_{1,q}^{h_1,h_2,\sphericalangle}(z, Q^2, M_h)$ **PRL107 (2011) 072004**	Unpol SIDIS, pp: $\frac{d^2\sigma}{dzdm}$

Single hadron FF

Unpolarized ingredients	Polarized ingredients	Flavor sensitivity
Single hadron cross sections: $e^+e^- \to hX$ $D_{1,q}^h(z, Q^2)$ **PRD 88 (2013) 032011** (Babar)	Azimuthal asymmetries: $e^+e^- \to (h)(h)X$, $\cos(\phi_1 + \phi_2)$ $H_{1,q}^{\perp(1)h}(z, Q^2)$ **PRD 92 (2015) 111101** (Babar K) **PRL 116 (2016) 042001** (BESIII)	Unpol SIDIS, pp: $\frac{d\sigma}{dz}$ $e^+e^- \to (h)(h)X$ and scale dependence
Transverse momentum dependent FFs: $e^+e^- \to (h)X$ $D_{1,q}^h(z, k_T, Q^2)$	Transverse momentum dependent asymmetries $e^+e^- \to (h)(h)X$, $\cos(\phi_1 + \phi_2), Q_t$ $H_{1,q}^{\perp h}(z, k_T, Q^2)$ **PRD 90 (2014) 052003** (Babar)	 

Dihadron FF (IFF)

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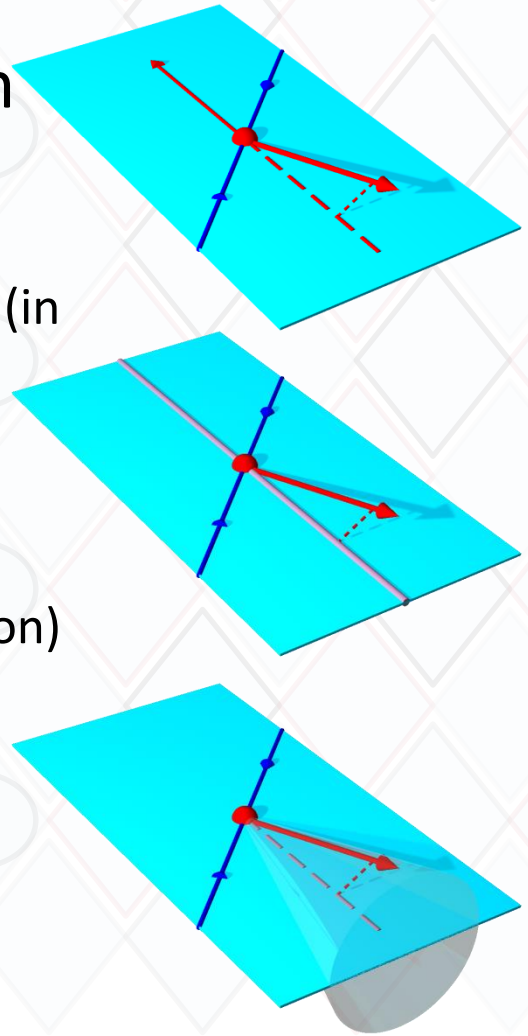
Dihadron cross sections $e^+e^- \to (hh)X$ $D_{1,q}^{h_1 h_2}(z, m, Q^2)$	Azimuthal asymmetries: $e^+e^- \to (hh)(hh)X$, $\cos(\phi_1 + \phi_2)$, $H_{1,q}^{h_1,h_2,\sphericalangle}(z, Q^2, M_h)$	Unpol SIDIS, pp: $\frac{d^2\sigma}{dzdm}$

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
    - →No convolution
    - →Need correction for $q\bar{q}$ axis (similar to a Jet function)
  - Single-hadron FF wrt jet axis
    - →No convolution
    - →Need Jet function



Ongoing (nearly finished)

Published

Ongoing (started)

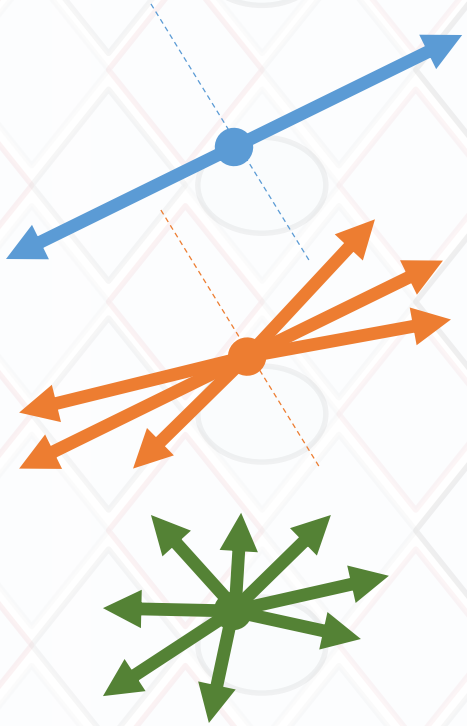
Thrust definition

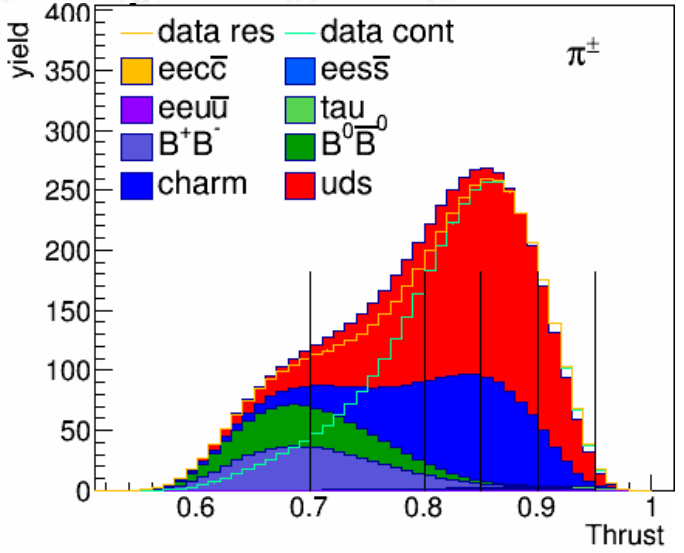
- Event shape variable thrust is defined as:

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

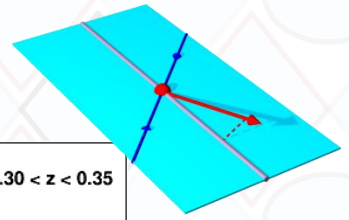
- All final-state particles are included in the sum (not on parton level!)
- A two-jet-like event has a high thrust value
- A completely spherical event has a thrust value of 0.5

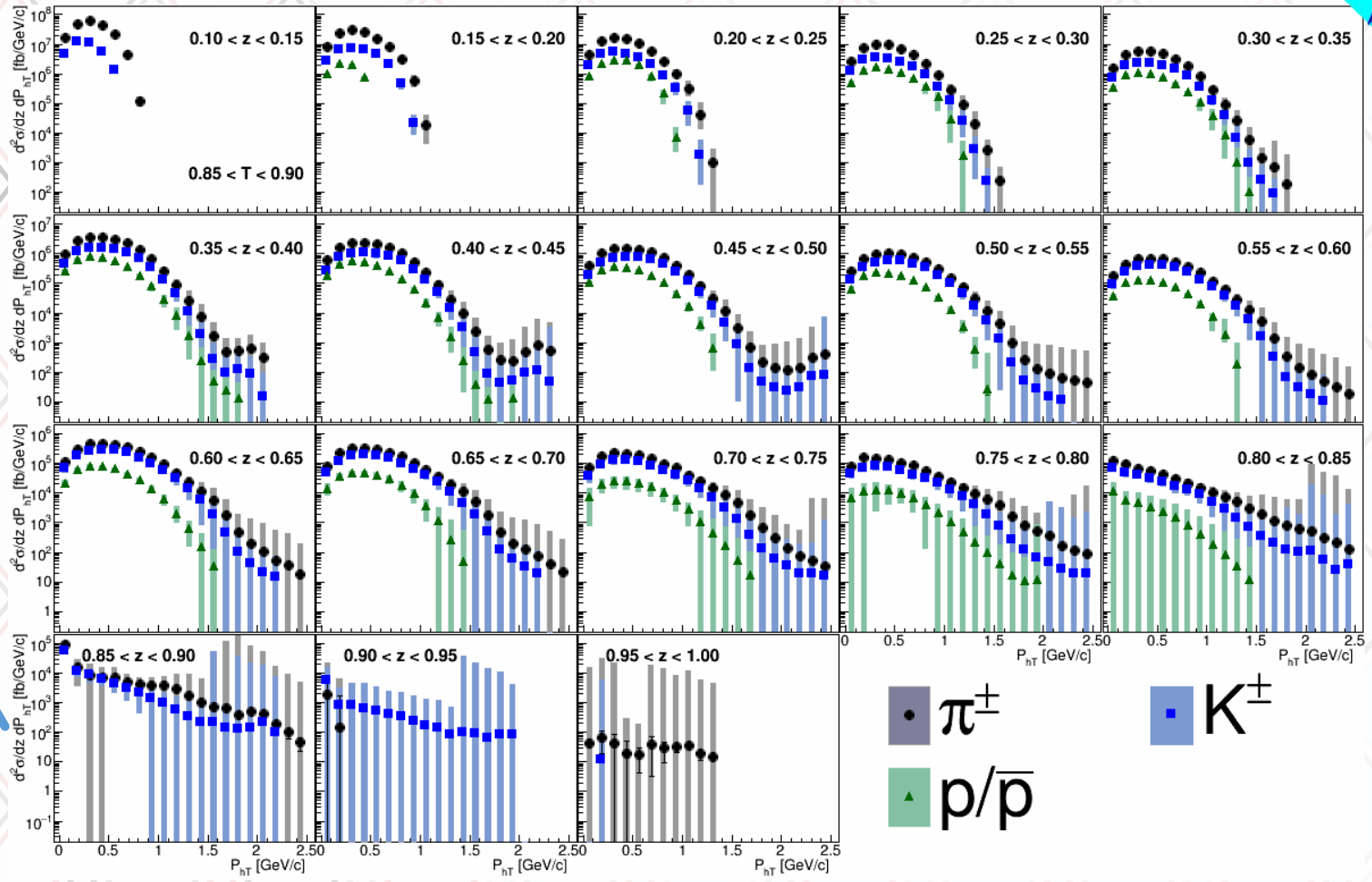
- Thrust axis **n** also defines the hemispheres





Cross sections various hadrons





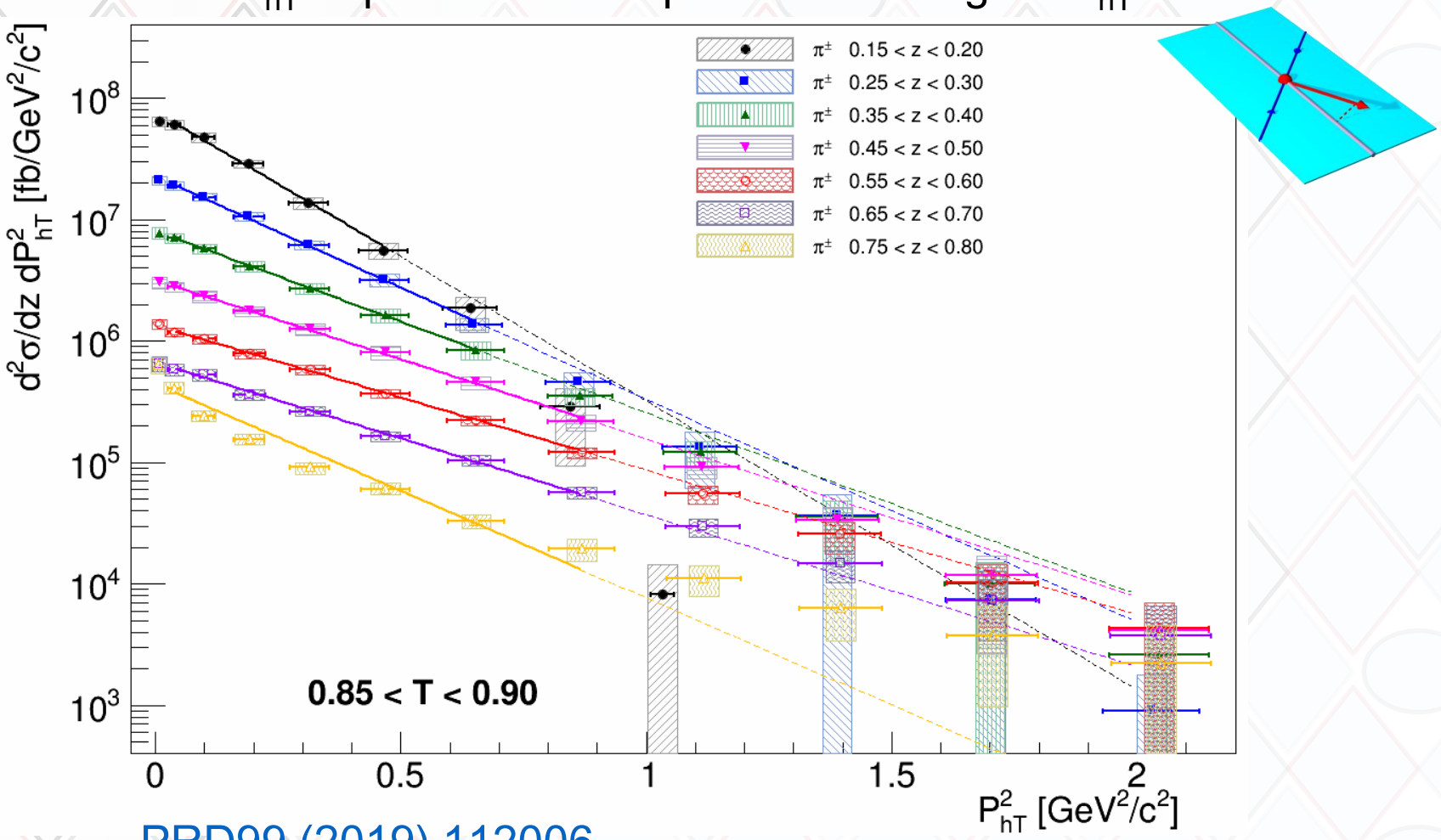
$\frac{d^2\sigma}{dzdP_{hT}}$

P_{hT}

RS. et. al. PRD99 (2019) 112006

Fits vs P_{hT}^2

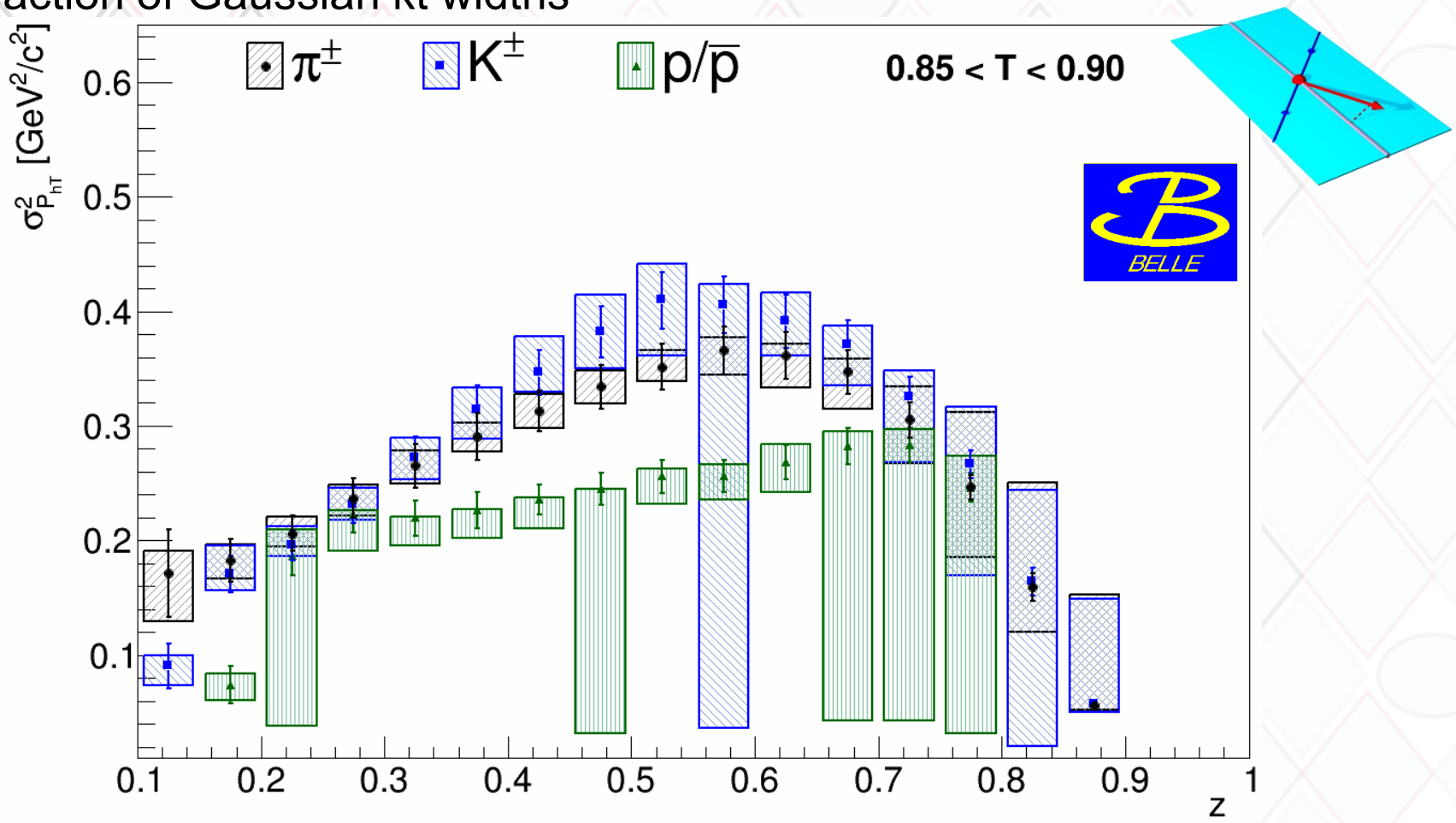
Fit exponential to smaller transverse momenta for Gaussian P_{hT} dependence and power low at higher P_{hT}



[PRD99 (2019) 112006]

Transverse momentum dependent unpol FFs:

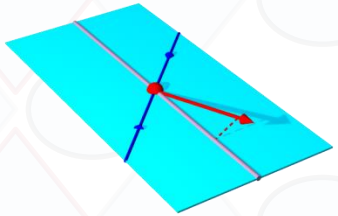
- First direct (no convolutions) measurement of z and kt dependence
- Extraction of Gaussian kt widths



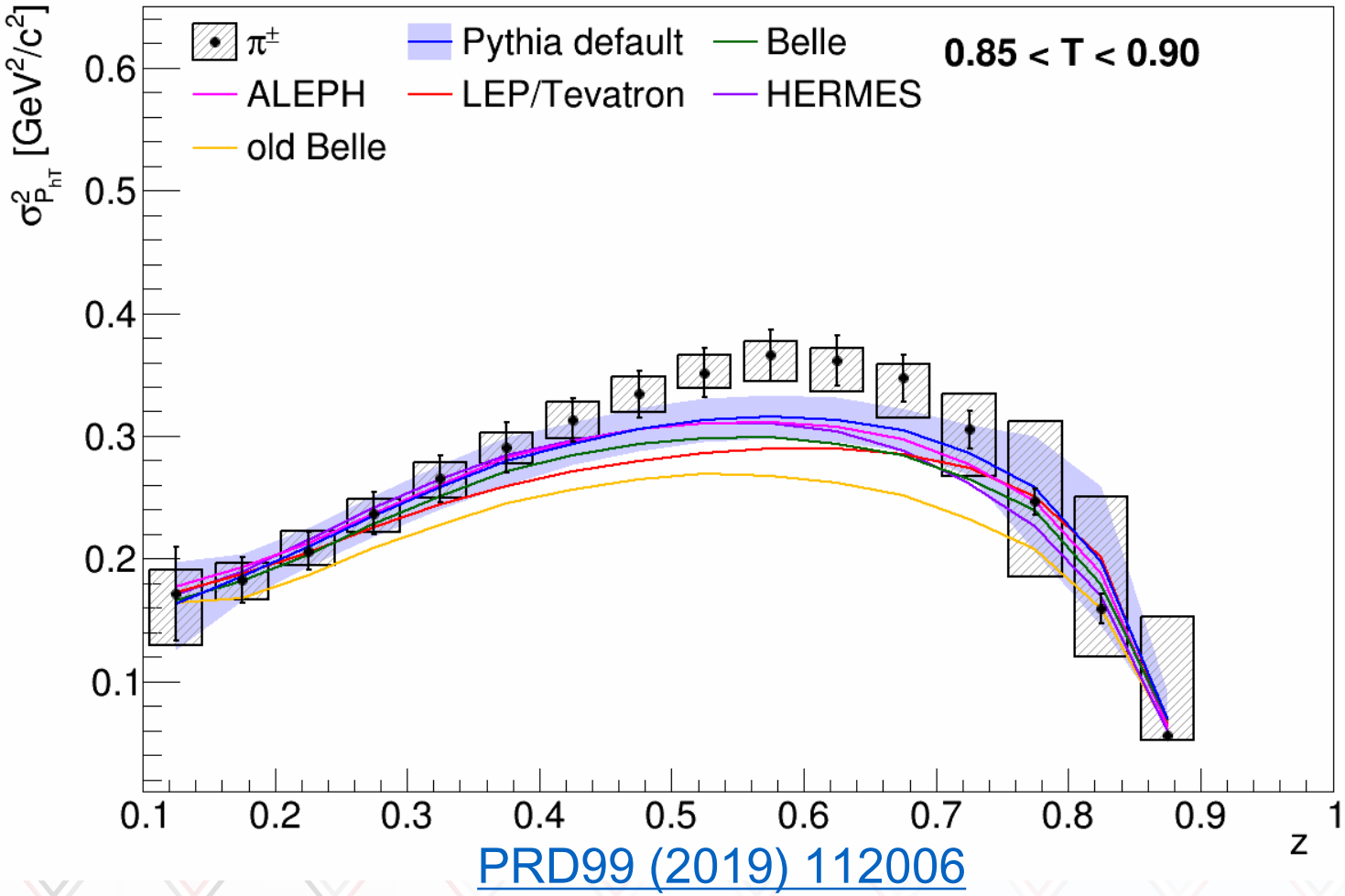
PRD99 (2019) 112006

Gaussian widths comparison to MC

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



Pythia6
MSTP(21):
0.28
0.325
0.36
0.36
0.37
0.40

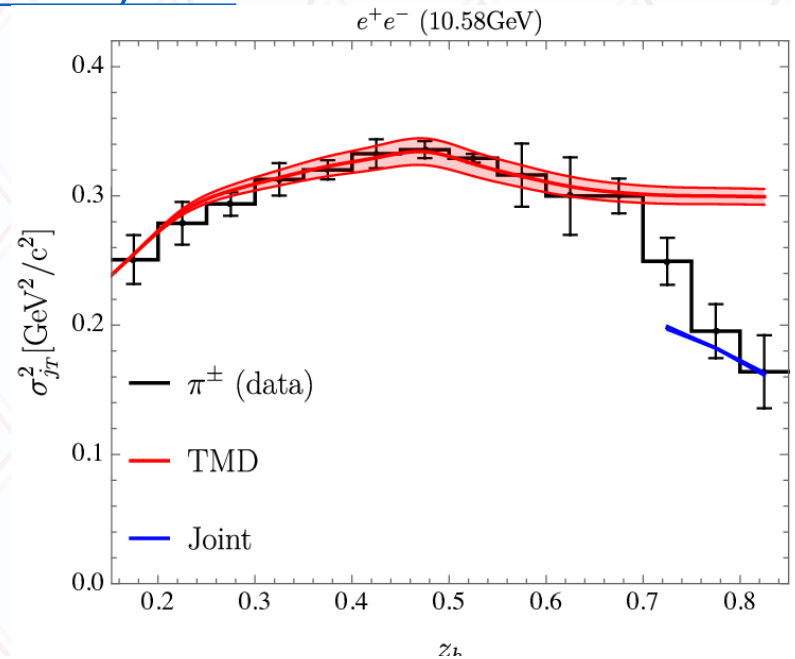


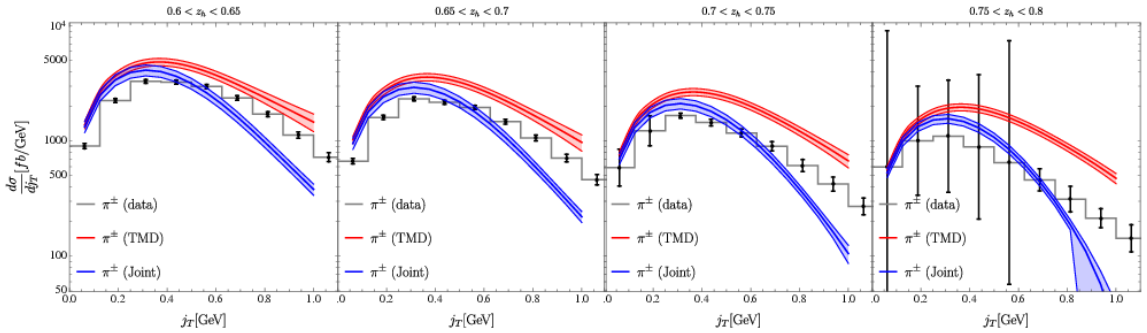
PRD99 (2019) 112006

Phenomenological Fits of cross sections I

Kang, et. al. JHEP 12 (2020) 127

- SCET formalism
- Inclusion of Thrust axis possible in similar way to Jet functions TMD and threshold resummation needed
- TMD region of $j_T << Q$
- Additional description for high-z region

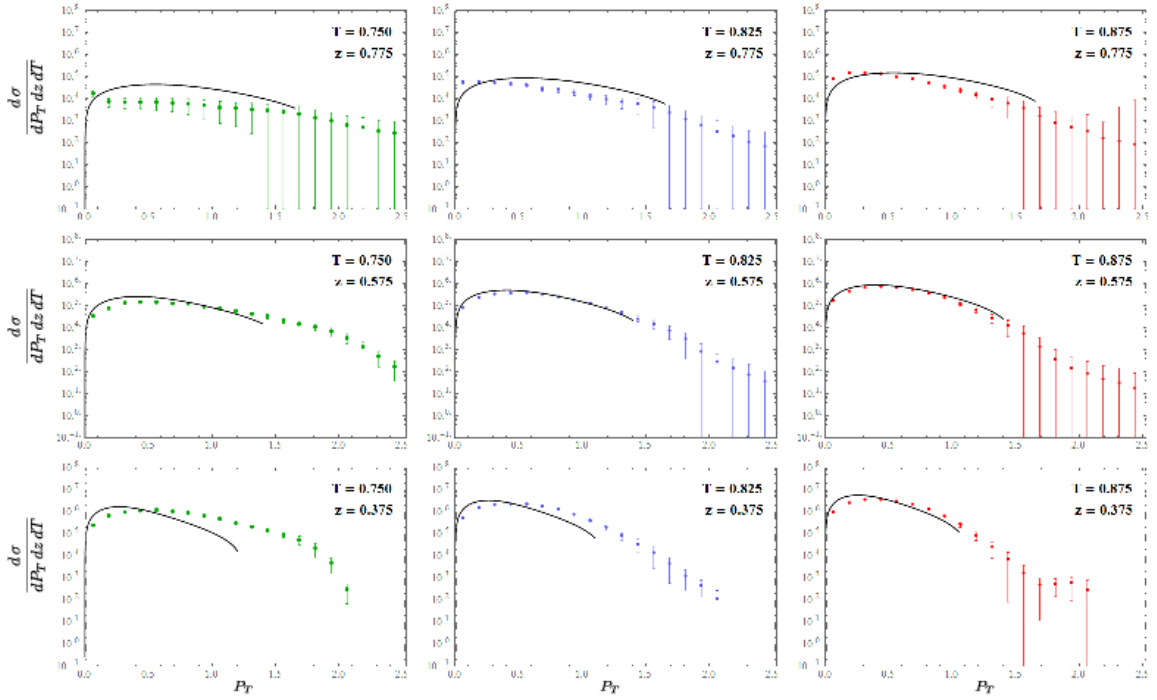




Phenomenological Fits of cross sections II

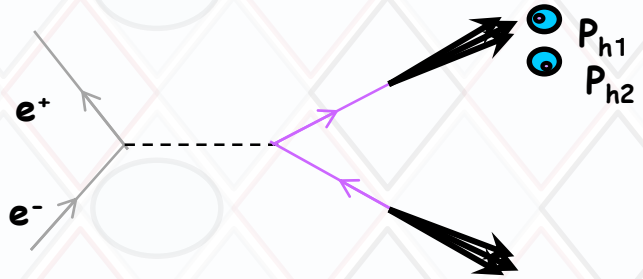
Boglione, Simonelli JHEP 02 (2021) 076

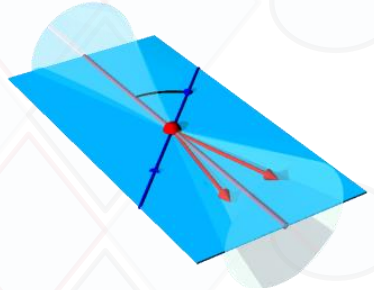
- NLO and NLL description of cross sections, based on NNFF1.0_NLO
- Collinear parts of phase space need to be cut out (esp. high P_T)
- Intermediate Thrust range can be described well
- High thrust and high z range would need different pheno treatment



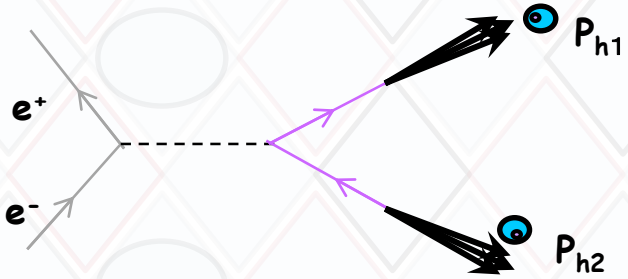
Di-hadron fragmentation functions

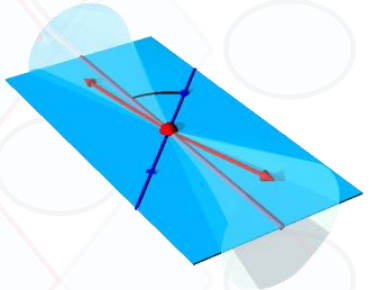
$$D_{1,q}^{h_1 h_2}(z, m, Q^2)$$





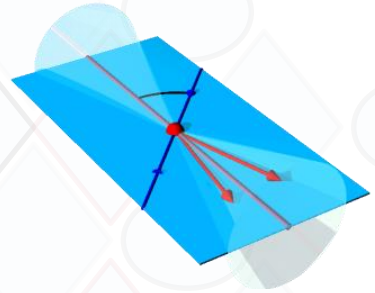
$$D_{1,q}^{h}(z_1, Q^2) D_{1,q}^{h}(z_2, Q^2)$$

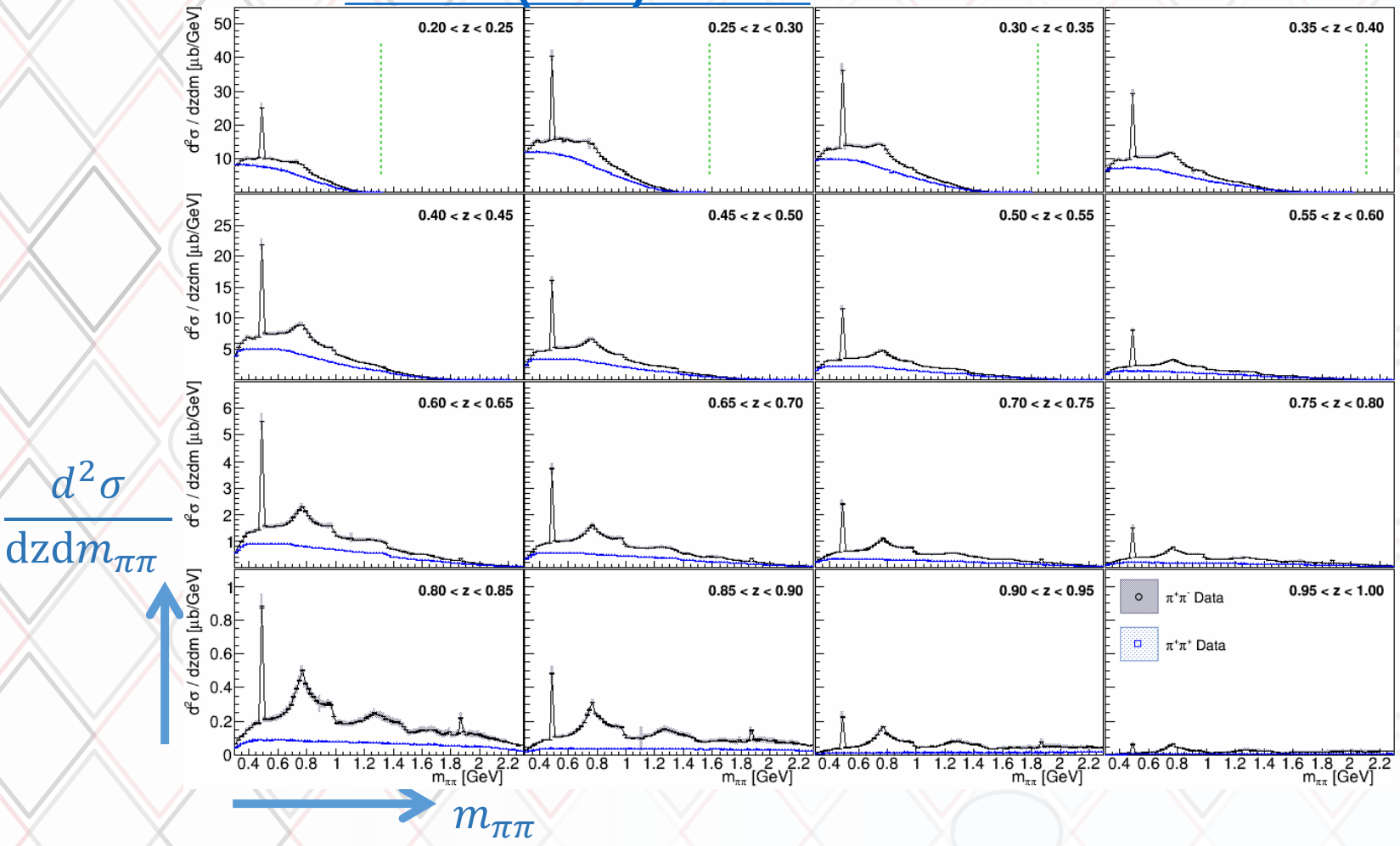




Di-hadron mass dependence

Belle: RS et.al. **PRD96 (2017) 032005**

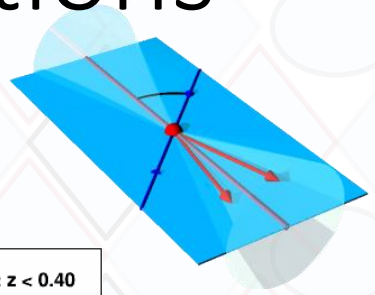




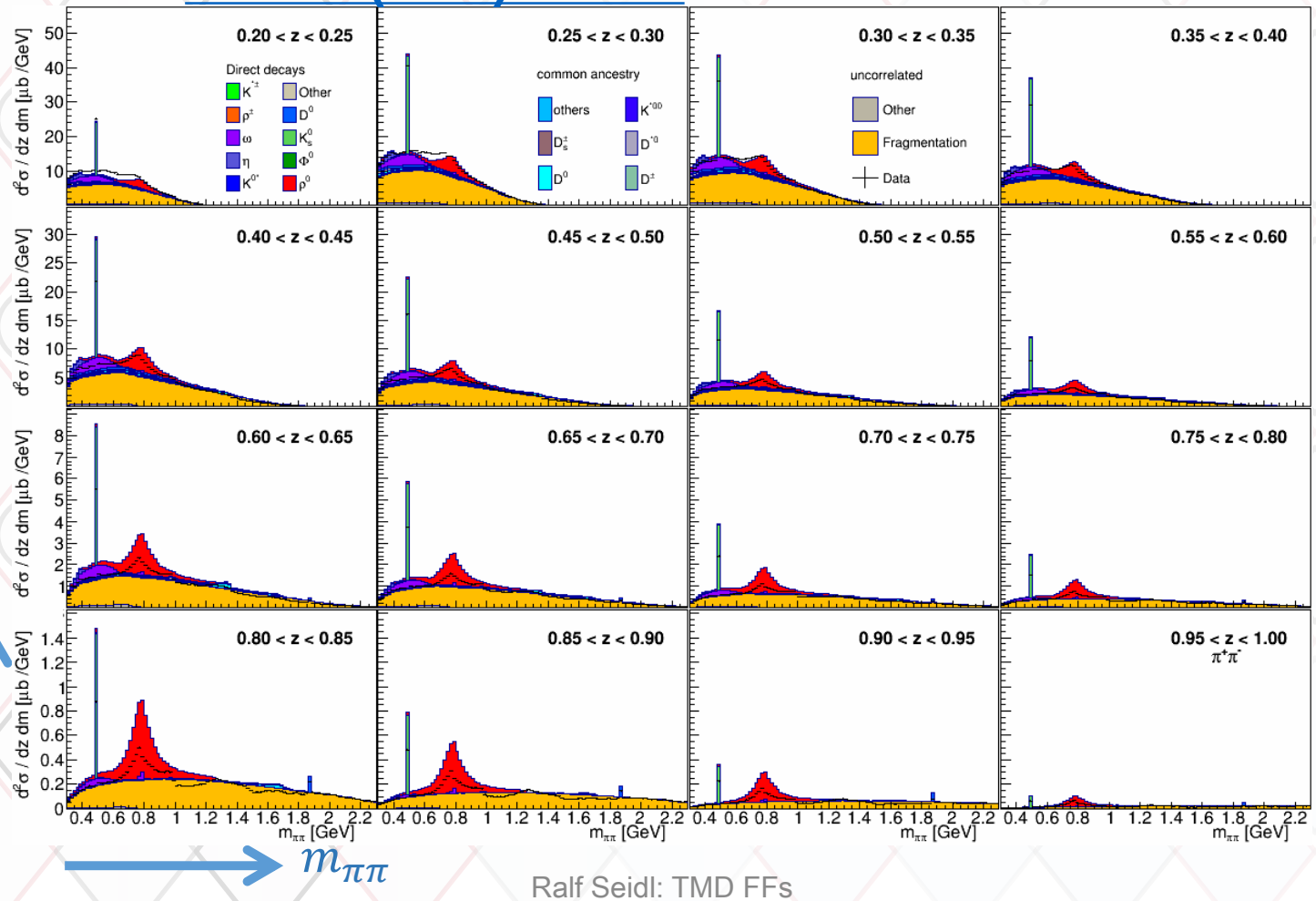
- Important input for IFF based transversity global analysis
- Individual resonances, etc quite visible; interesting for FF in itself

Di-pion individual contributions

Contributions from various resonances and direct fragmentation



Belle: RS et.al. **PRD96 (2017) 032005**

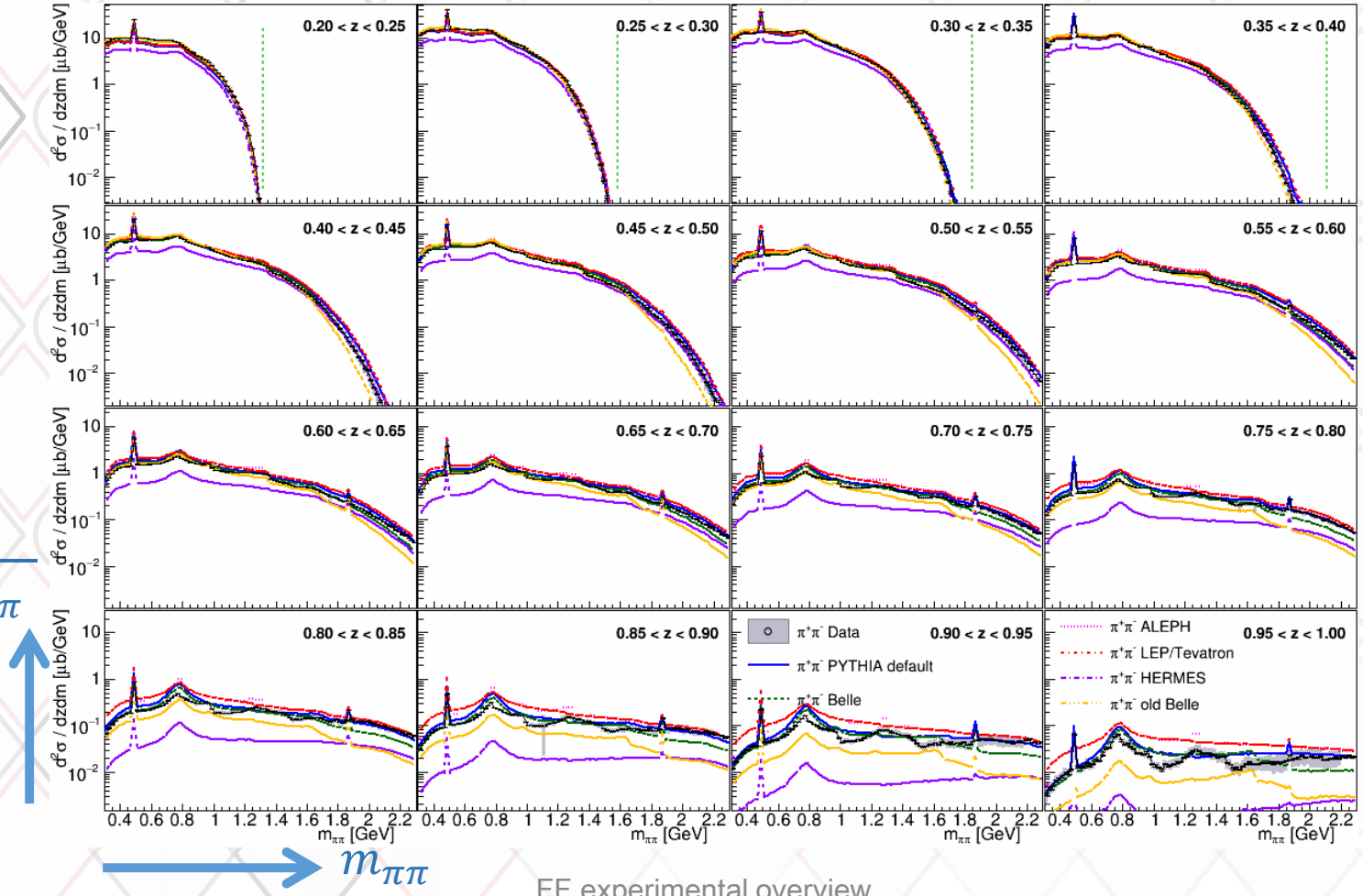


$$\frac{d^2\sigma}{\mathrm{dz}\mathrm{d}m_{\pi\pi}}$$

$m_{\pi\pi}$

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)



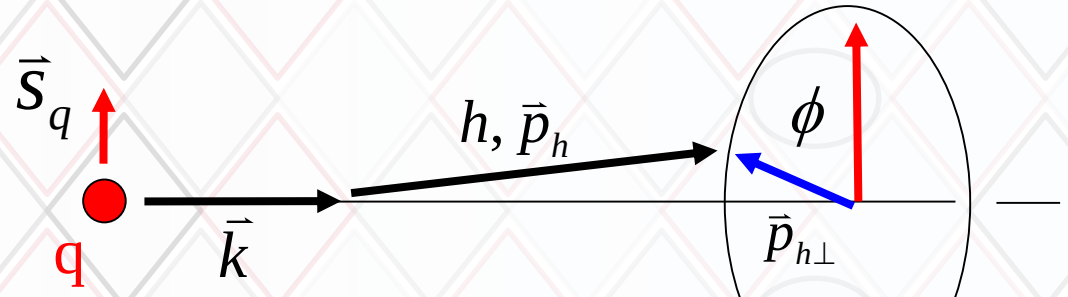
$$\frac{d^2\sigma}{\mathrm{dz}\mathrm{d}m_{\pi\pi}}$$

$m_{\pi\pi}$

Collins fragmentation function

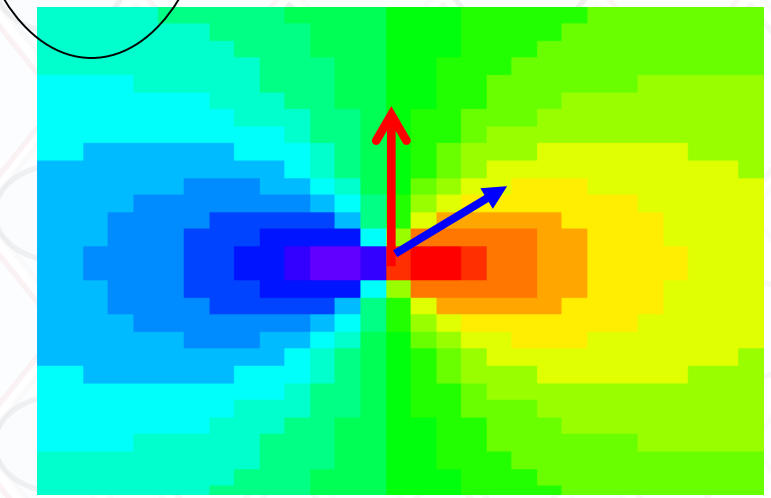
J. Collins, Nucl. Phys. B396, (1993) 161

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



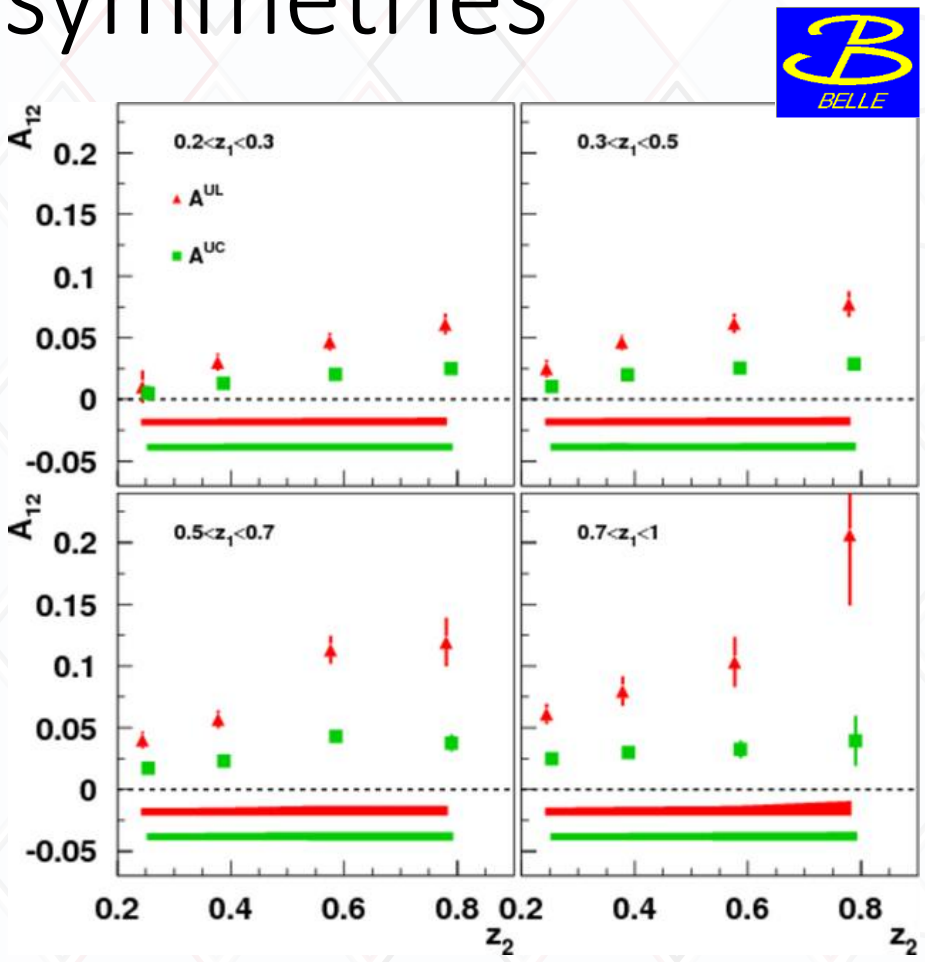
- Spin of quark correlates with hadron transverse momentum

➔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, Erratum D86:039905

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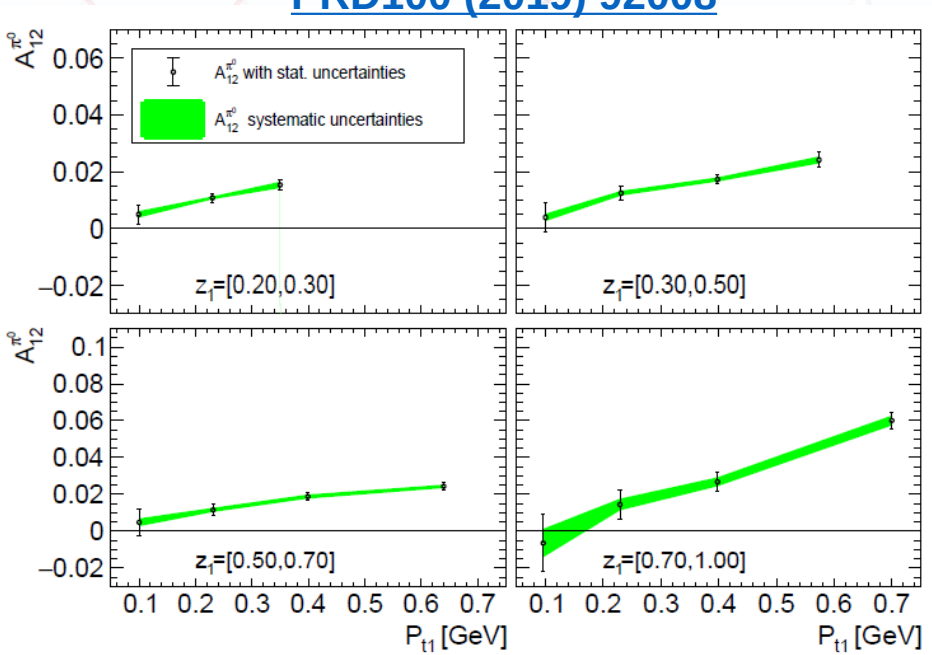
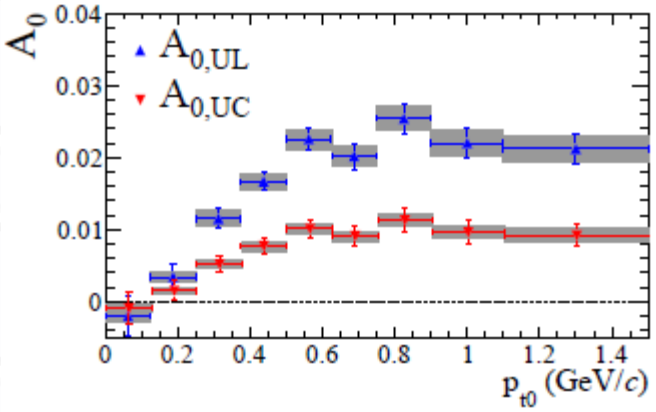
Transverse momentum

- Add transverse momentum to Collins asymmetries' z dependence
- Currently only 1 or 2-dimensional extractions available (q_t, z_1x z_2, p_{t1}x p_{t2},z_1xp_{t1})
- Increasing asymmetries with both z and pt, but pt reach limited
- Multidimensional extractions needed

PRD100 (2019) 92008



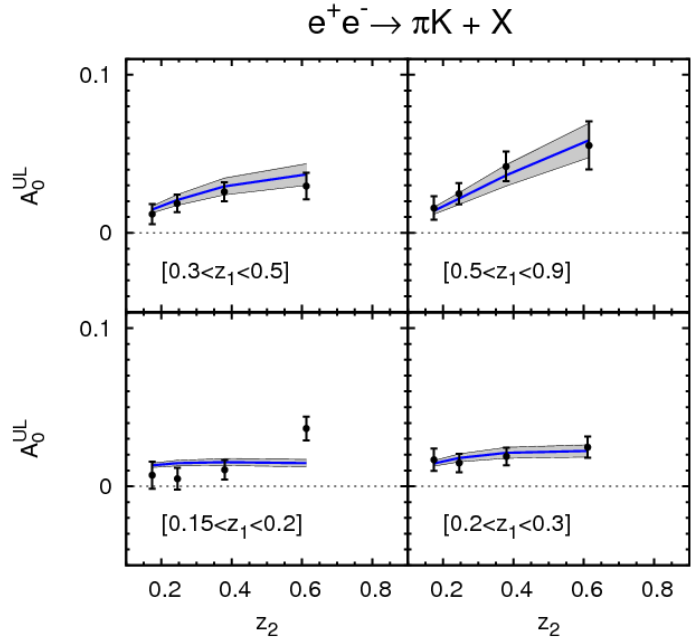


PRD 90 (2014) 052003 (Babar)

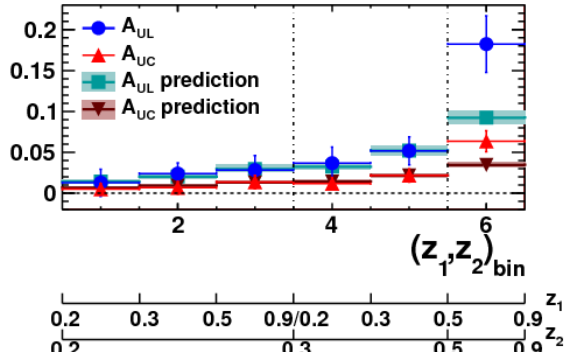
Quark transversity via Collins: Kaons

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

Ongoing work: Collins multidimensional analysis and Kaon combinations

- Currently revisiting kaon combinations of the Collins asymmetries
- While doing so, try to perform a full multi-dimensional analysis:
  - Consider :
  - 6 (z_1) x 6 (z_2) x 5(k_{t1}) x 5(k_{t2}) x 1 (costheta) x 8 (phi) for A_{12} method
  - 6 (z_1) x 6 (z_2) x 10(q_t) x 1 (costheta) x 8 (phi) for A_0 method
- Perform most correction steps similar to recent analyses (PID, smearing)
  - Possibly simplified smearing unfolding as each z_1-z_2 bin separately (z smearing almost nonexistent in such a binning)
  - non-qqbar removal, charm removal, ISR correction and acceptance might require introduction of nonzero MC asymmetries

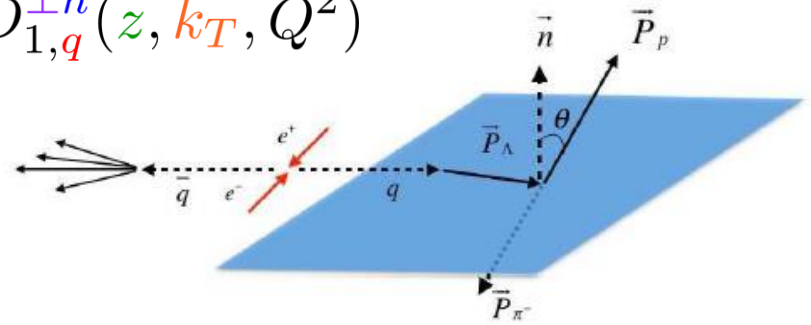
Single Λ polarization measurements

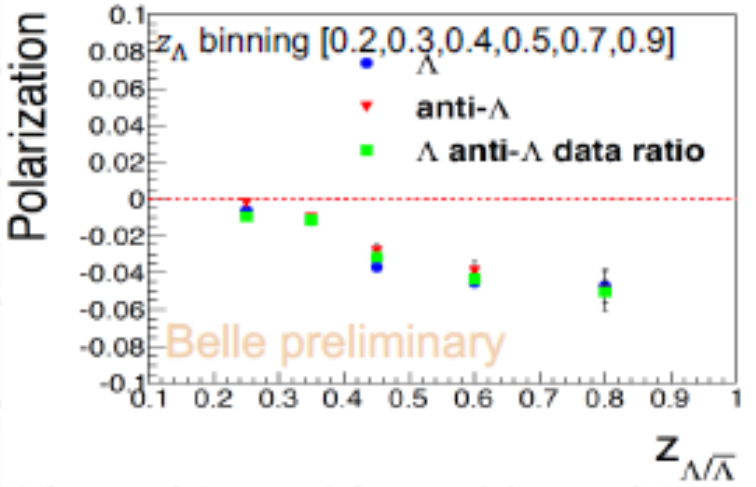
- Related to open question about Λ polarization in hadron collisions from 40 years ago!
- Fragmentation counterpart to the Sivers Function:

  unpolarized parton fragments into transversely polarized baryon with transverse momentum wrt to parton direction
- Reconstruct Λ, its transverse momentum and polarization

YingHui Guan (Indiana/KEK):
PRL 122 (2019), 042001

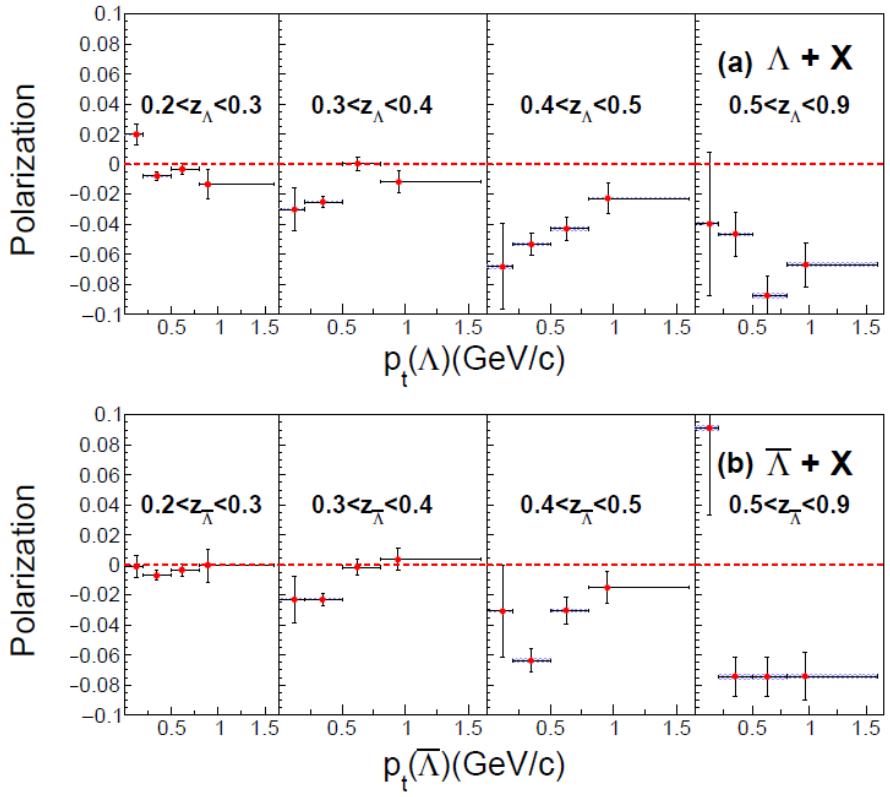
$D_{1,q}^{\perp h}(z, k_T, Q^2)$





Transverse momentum dependence

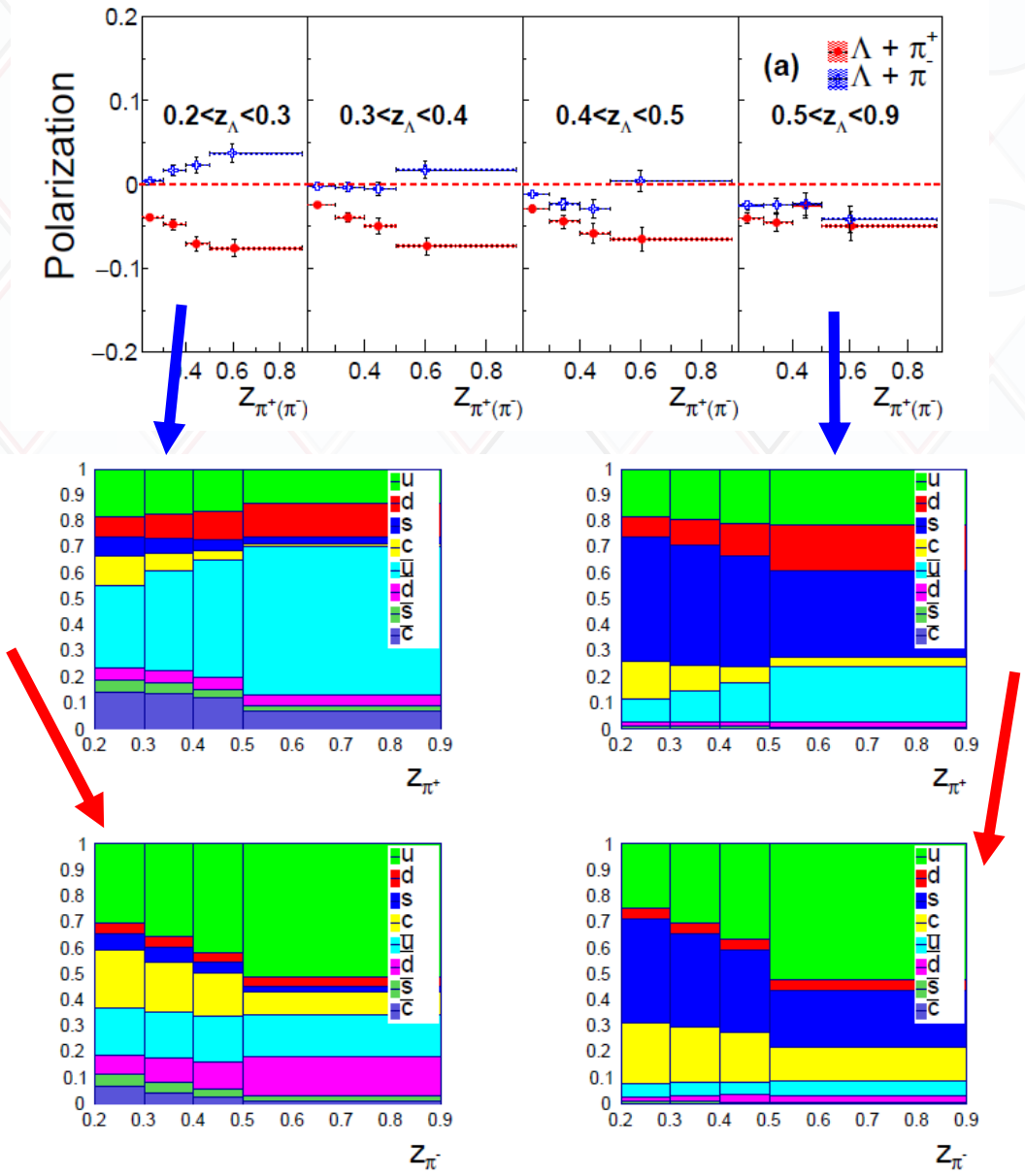
- Different behavior for low and high-z :
- At low z small
- At intermediate z falling Polarization with P_t
- At high z increasing polarization with P_t



Opposite hemisphere pion correlation

- Interesting z_π and z_Λ dependence :

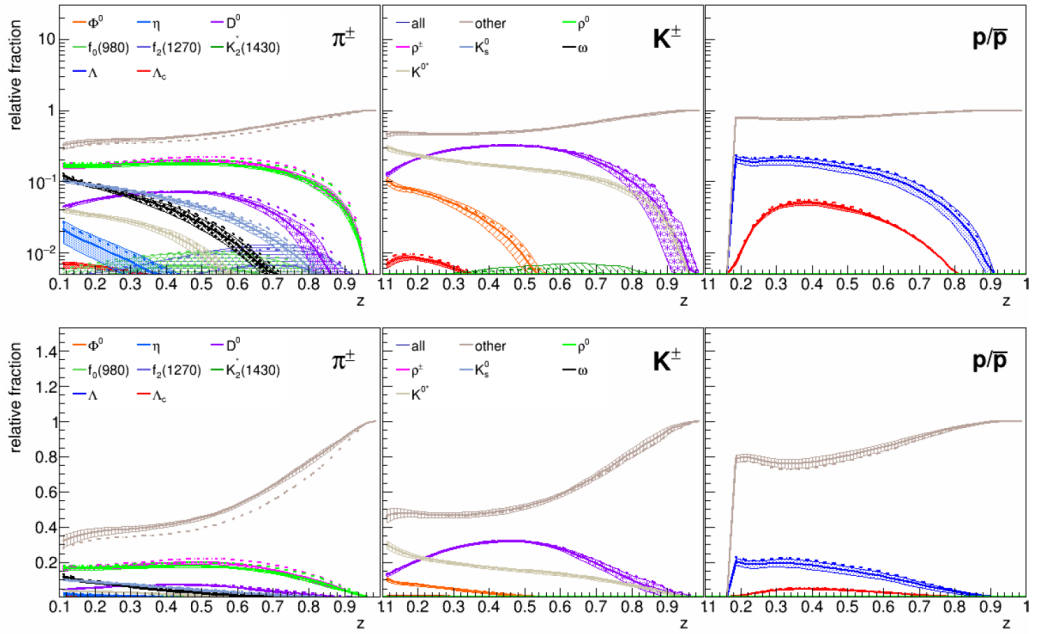
- At low z_Λ light quark fragmentation dominant, some charm in π^- → different signs
- At high z_Λ strange + charm fragmentation more relevant → same signs
- Several fits to data with slightly different results



Not TMD(yet) but indirectly related: Weak and strong decay feed-down

- Hadrons from Weak decays technically not part of FF definition, but often included
- Strong decays part of total sum over hadronic final state
- Both can affect the z (and transverse momentum) dependence of the detected hadrons:
  - naturally included in unpolarized MC,
  - in part added to polarized generators (→Albi)
  - How does PHENO handle this (additional parameters?)

Decaying hadron fractions in light hadrons at $\sqrt{s}$ = 10.58 GeV (PYTHIA6):

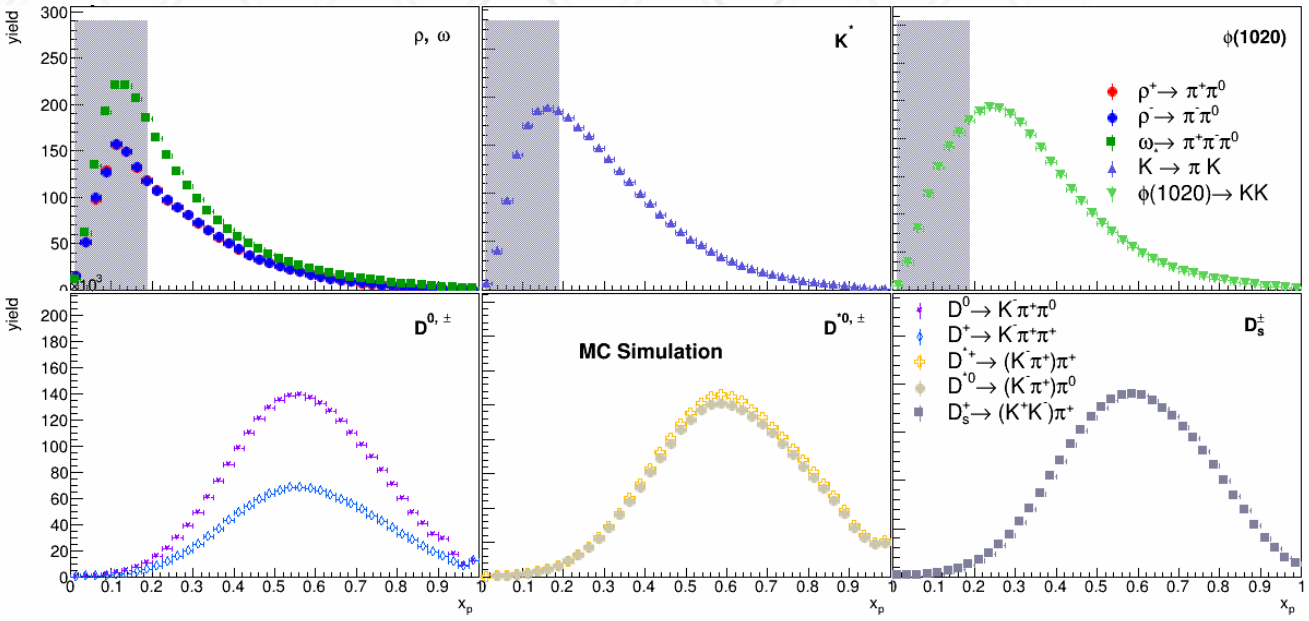


Bands: various Pythia tunes, including PARJ(11 VM to PS ratio) range from 0.3-0.55
Dashed lines: default, but PARJ(11) =0.6

Ongoing: Decaying particle FFs

- Study the explicit differential cross sections for VMs, D mesons as a function of x_p
- Mostly mass distributions and fits well-behaved, except for ρ–ω (interference) and more exotic resonances
- Also of interest for ultra high-energetic cosmic ray air shower research (muon problem)

- Example from MC at Belle energies (for 4π acceptance):



Summary

- Many Belle/Babar/BES3 TMD fragmentation related measurements available:
  - Unpolarized single hadrons wrt thrust axis
  - Collins asymmetries (k_t dependent, kaons)
  - Polarizing Λ fragmentation
- Detailed di-hadron cross section and asymmetry measurements
- More measurements on going for:
  - Other venues for unpolarized TMDs (opposite hemisphere dihadrons, hadron in jet)
  - Multi-dimensional extractions of Collins asymmetries
  - Other studies ongoing on the fragmentation of VMs and Ds
  - More to come from Belle and BelleII

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