The role of fragmentation measurements for TMD extractions

TMD/Lattice workshop
June 21

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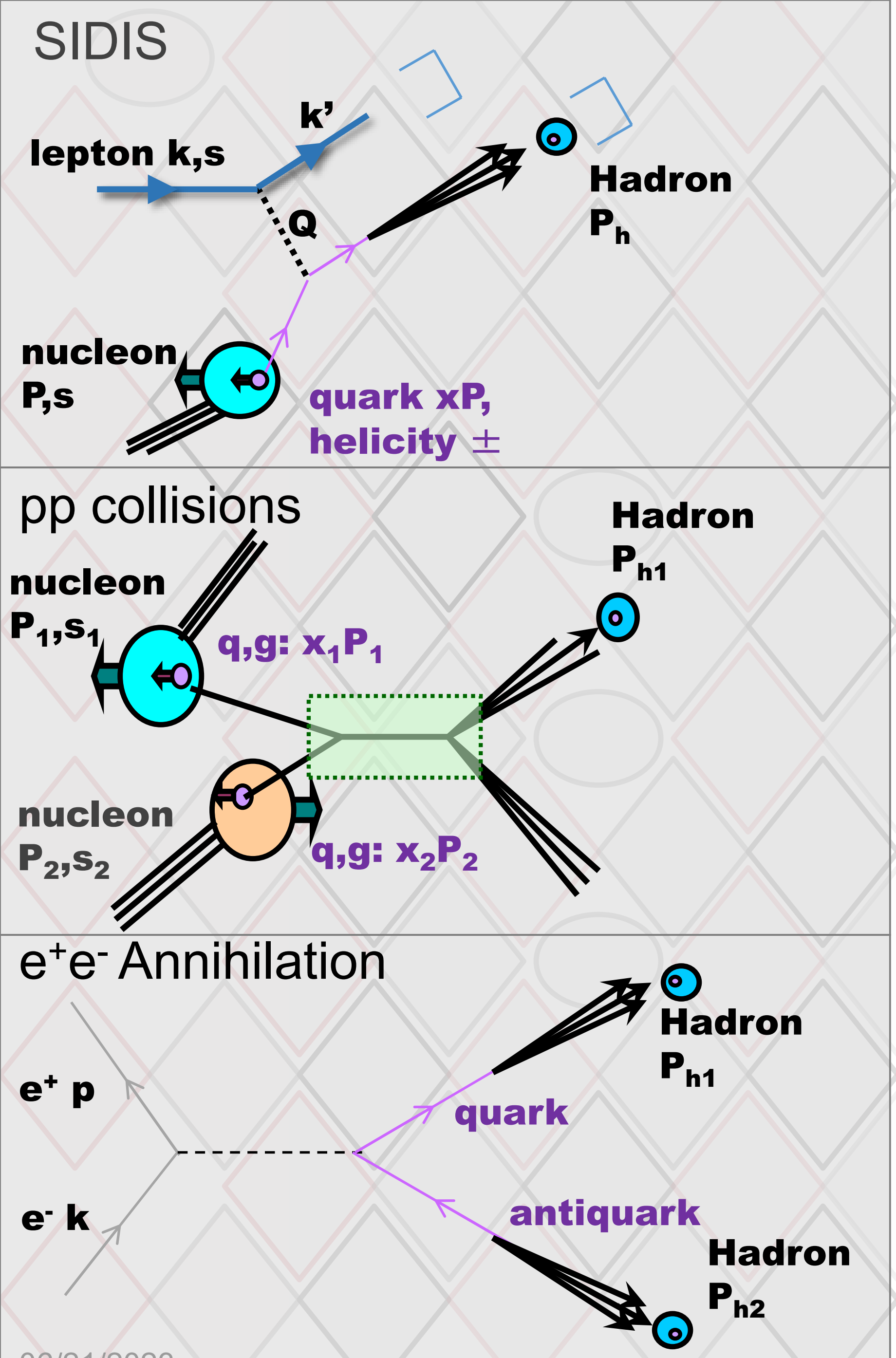
RIKEN



Access to Fragmentation functions

- 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*

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 measurements

Unpolarized ingredients	Polarized ingredients	Flavor sensitivity
Single hadron cross sections: $e^+e^- \to hX$ $D^h_{1,q}(z, Q^2)$ PRD 88 (2013) 032011 (Babar)	Azimuthal asymmetries: $e^+e^- \to (h)(h)X$, $\cos(\phi_1 + \phi_2)$ $H^{\perp(1)h}_{1,q}(z, Q^2)$ 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: $e^+e^- \to (h)X$ $D^h_{1,q}(z, k_T, Q^2)$	Transverse momentum dependent asymmetries $e^+e^- \to (h)(h)X$, $\cos(\phi_1 + \phi_2)$,Q_t $H^{\perp h}_{1,q}(z, k_T, Q^2)$ PRD 90 (2014) 052003 (Babar)	

Dihadron measurements

Unpolarized ingredients	Polarized ingredients	Flavor sensitivity
Dihadron cross sections $e^+e^- \to (hh)X$ $D^{h_1h_2}_{1,q}(z, m, Q^2)$	Azimuthal asymmetries: $e^+e^- \to (hh)(hh)X$, $\cos(\phi_1 + \phi_2)$, $H^{h_1,h_2,\sphericalangle}_{1,q}(z, Q^2, M_h)$	Unpol SIDIS, pp: $\frac{d^2\sigma}{dzdm}$

K_T Dependence of FFs in e+e-

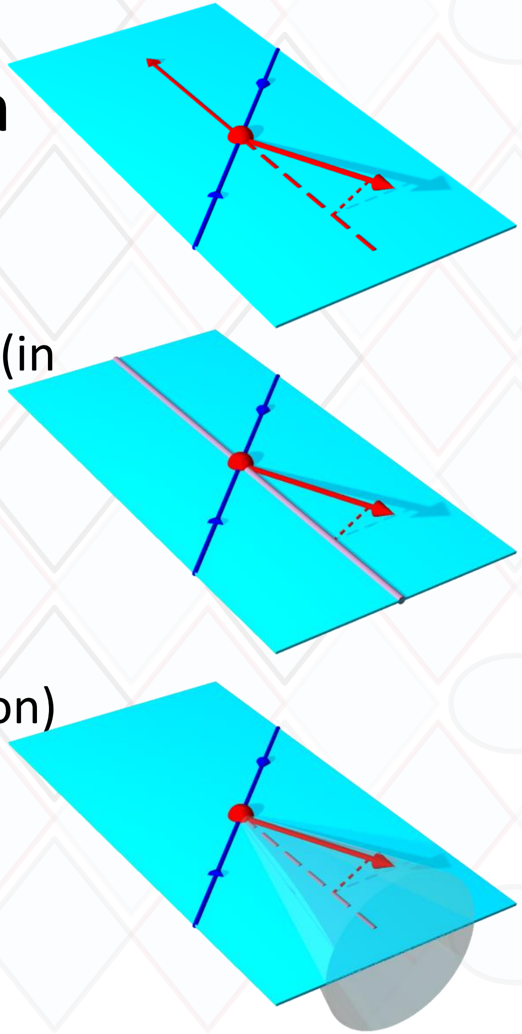
- Gain also sensitivity into transverse momentum generated in fragmentation
- Two ways to obtain transverse momentum dependence
  - Traditional 2-hadron FF

    →use transverse momentum between two hadrons (in opposite hemispheres)

    →Usual convolution of two transverse momenta
  - Single-hadron FF wrt to Thrust or jet axis

    →No convolution

    →Need correction for $q\bar{q}$ axis (similar to a Jet function)



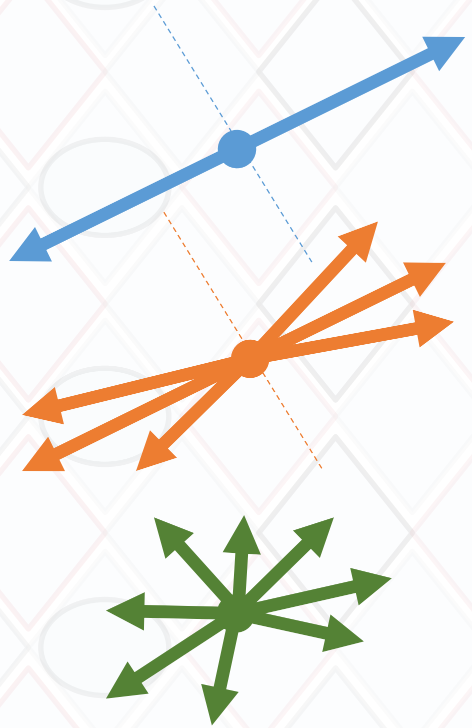
Thrust definition

- Event shape variable thrust is defined as:

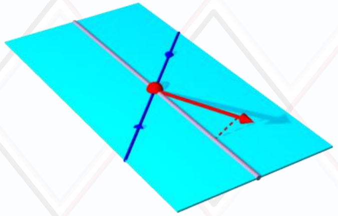
$$T \stackrel{max}{=} \frac{\sum_h |\mathbf{P}_h \cdot \hat{\mathbf{n}}|}{\sum_h |\mathbf{P}_h|}$$

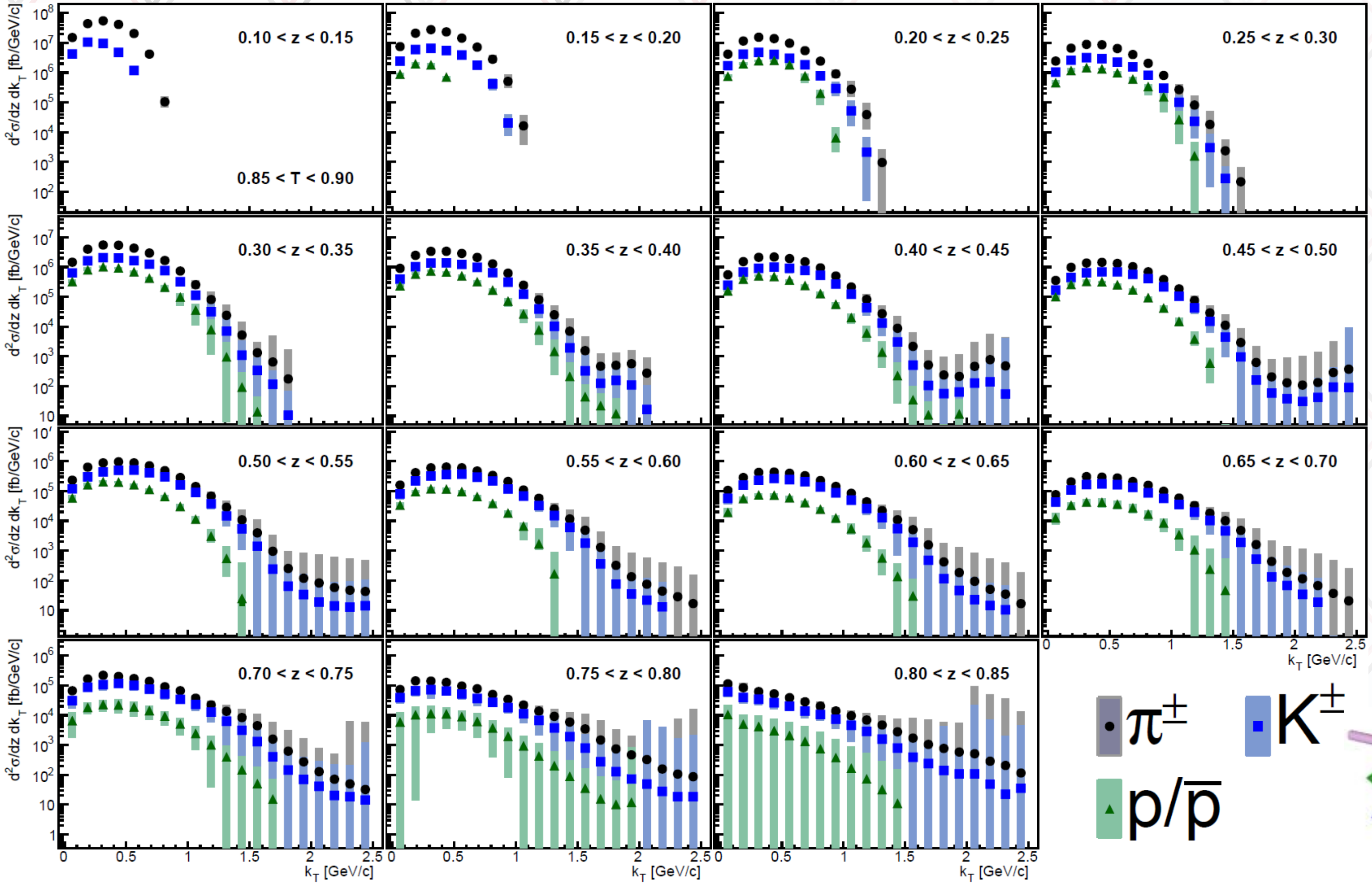
- All final-state particles are included in the sum
- A two-jet-like event has a high thrust value
- A completely spherical event has a thrust value of 0.5

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



Transverse momentum dependent cross sections for pions, kaons and protons



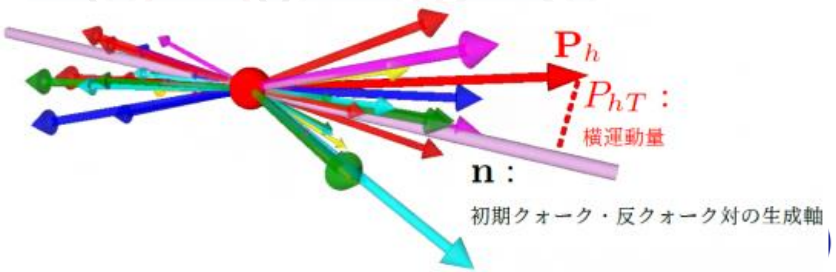


$$\frac{d^2\sigma}{dzdP_{hT}}$$

P_{hT}

Important baseline for most transverse momentum/spin dependent measurements at RHIC and EIC

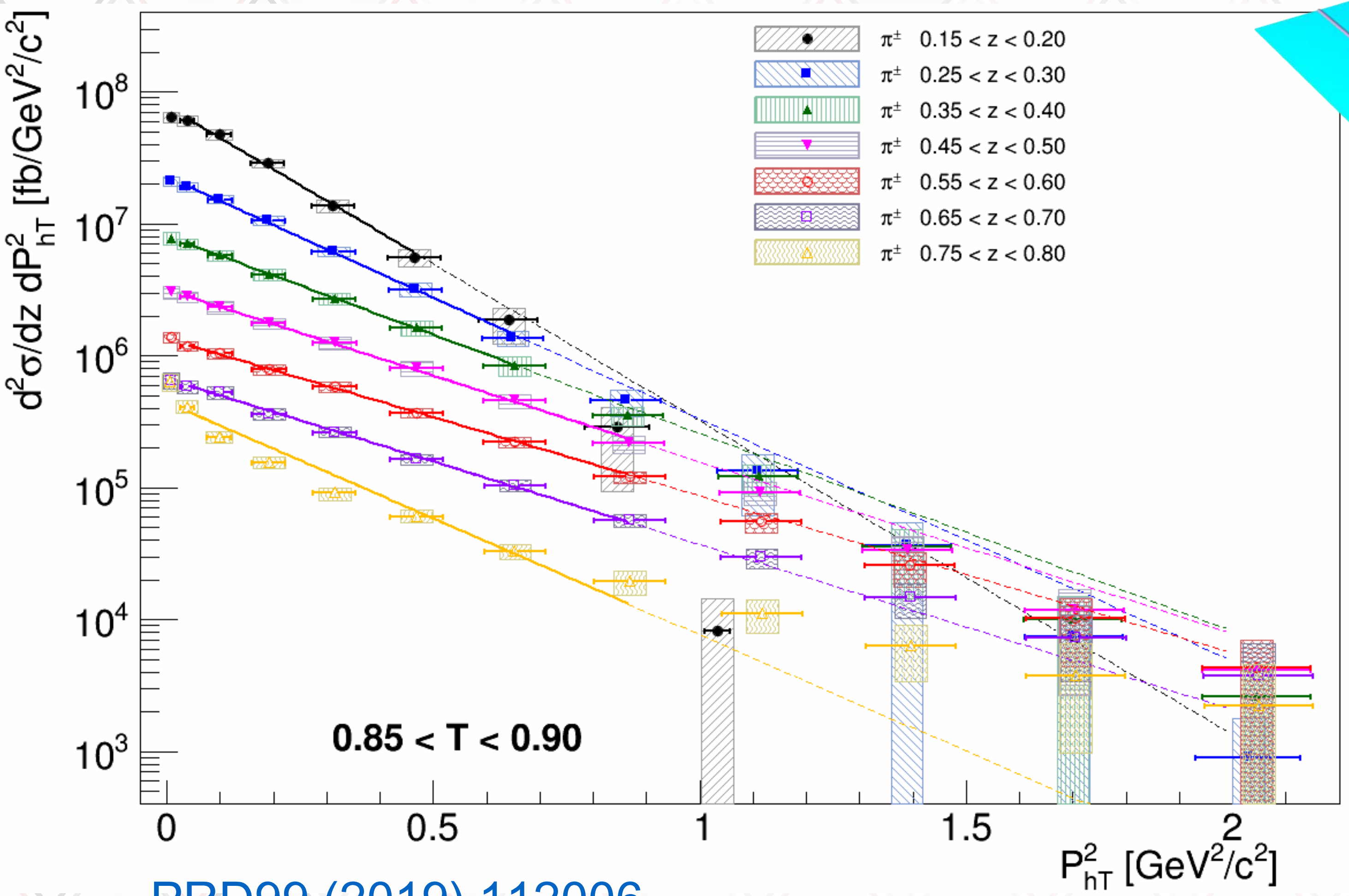
RIKEN Press release: https://www.riken.jp/press/2019/20190615_1/

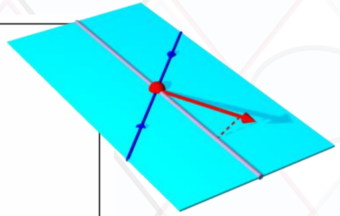


RS. et. al. [PRD99 (2019) 112006]

Fits vs P_{hT}^2

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



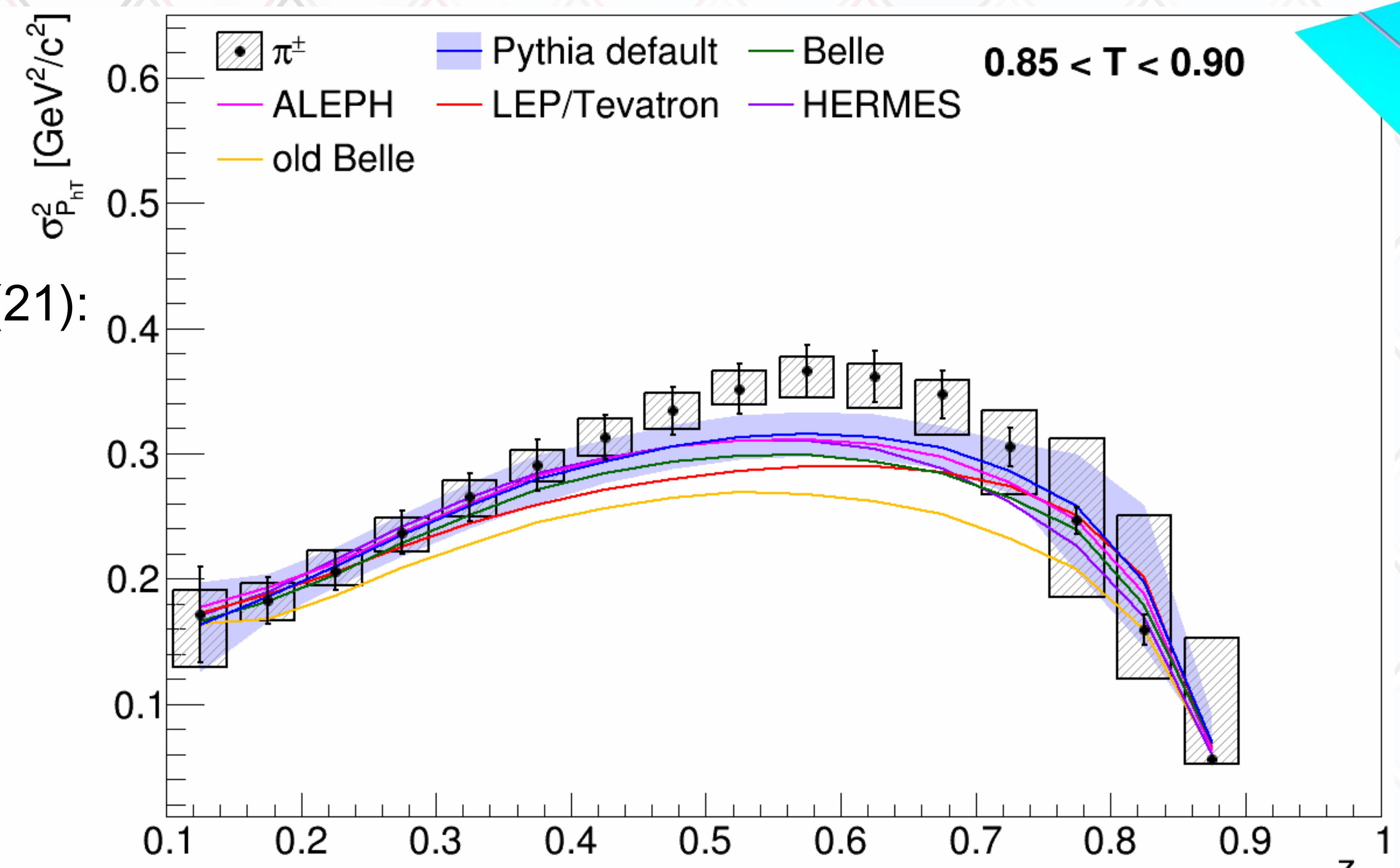


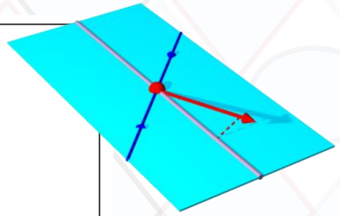
[PRD99 (2019) 112006](PRD99 (2019) 112006)

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

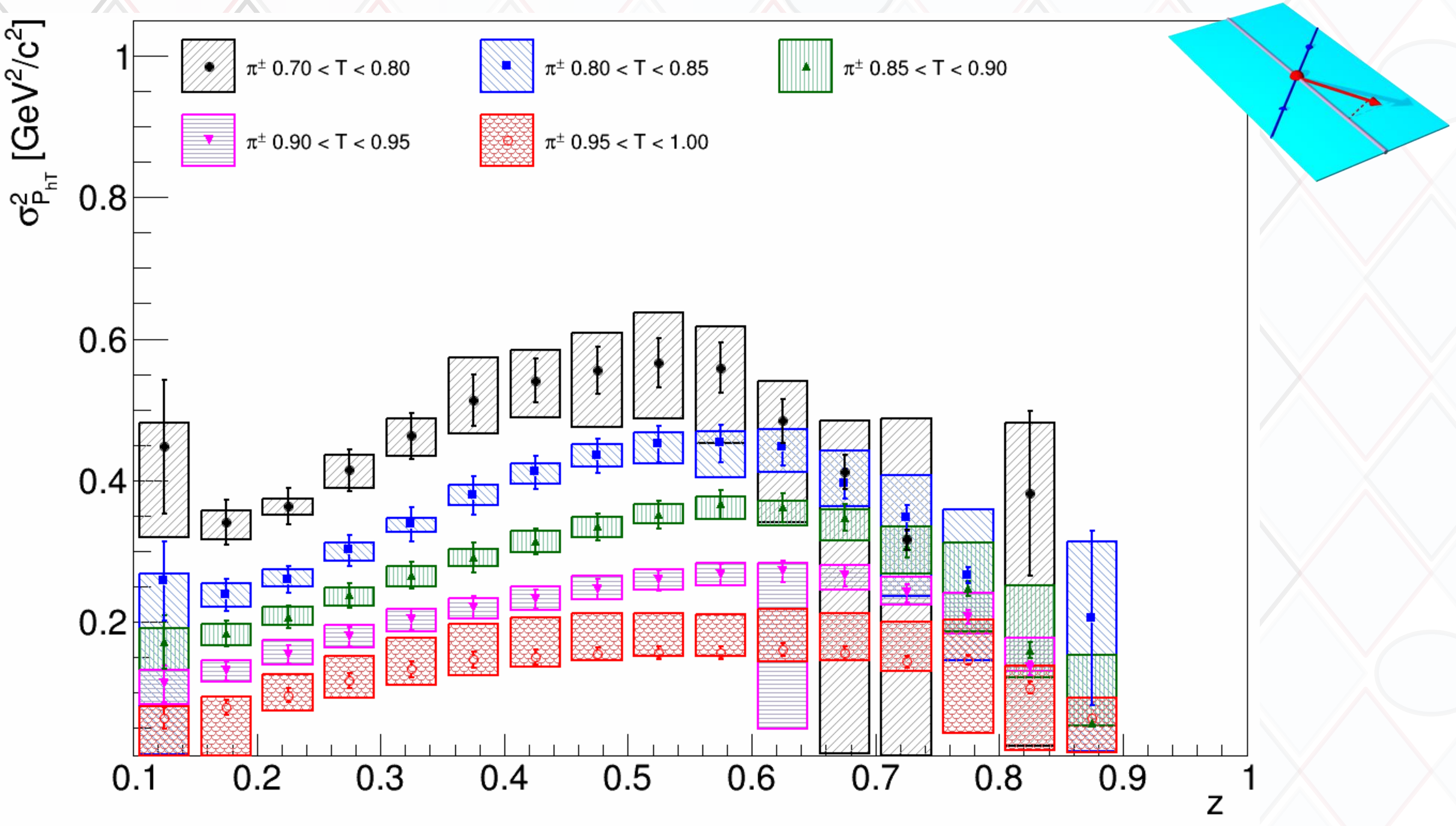




PRD99 (2019) 112006

Gaussian widths, thrust dependence

Gaussian widths get narrower with higher Thrust

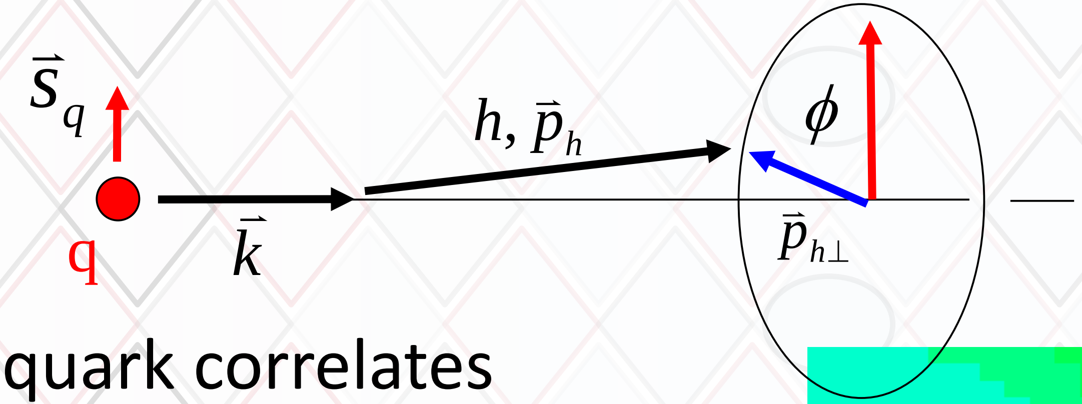


PRD99 (2019) 112006

Collins fragmentation function

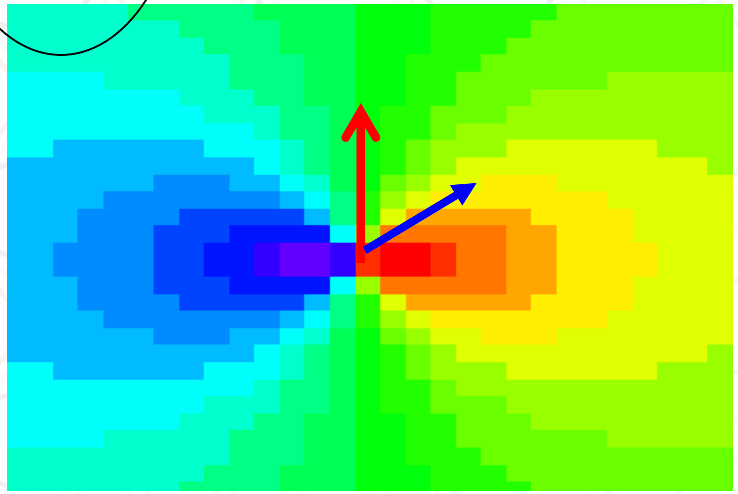
J. Collins, Nucl. Phys. B396, (1993) 161

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



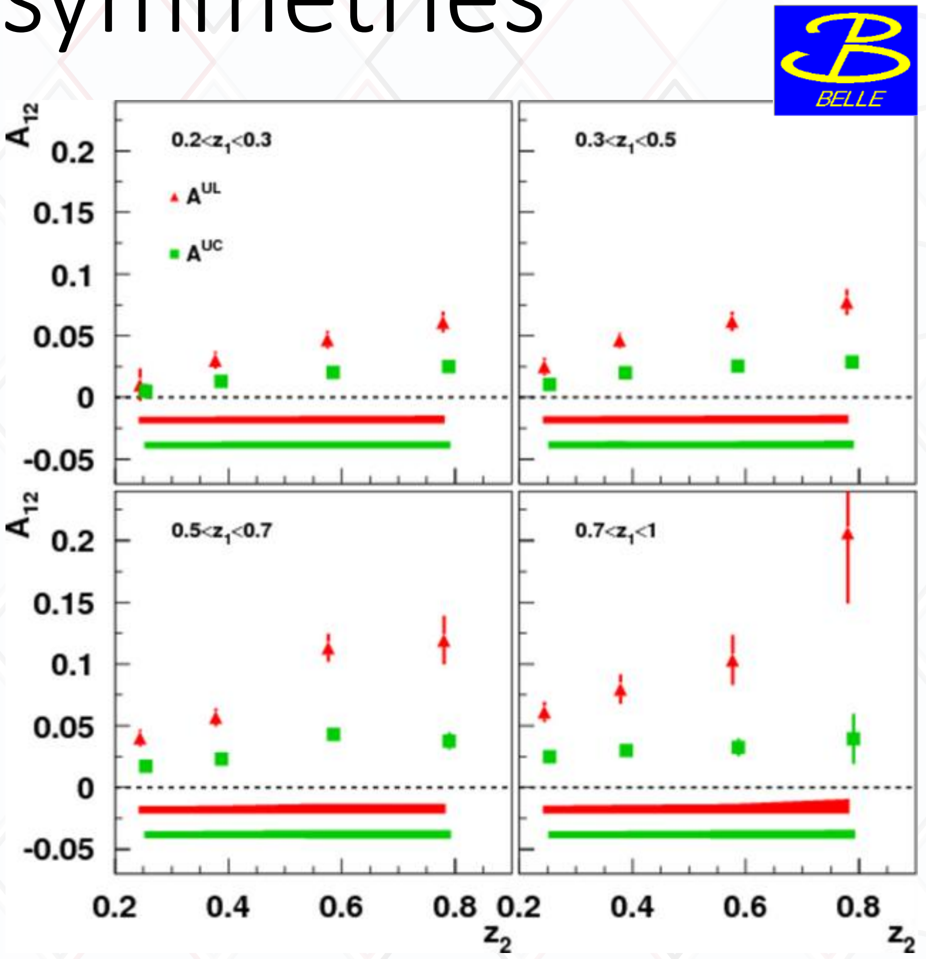
- Spin of quark correlates with hadron transverse momentum

➔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

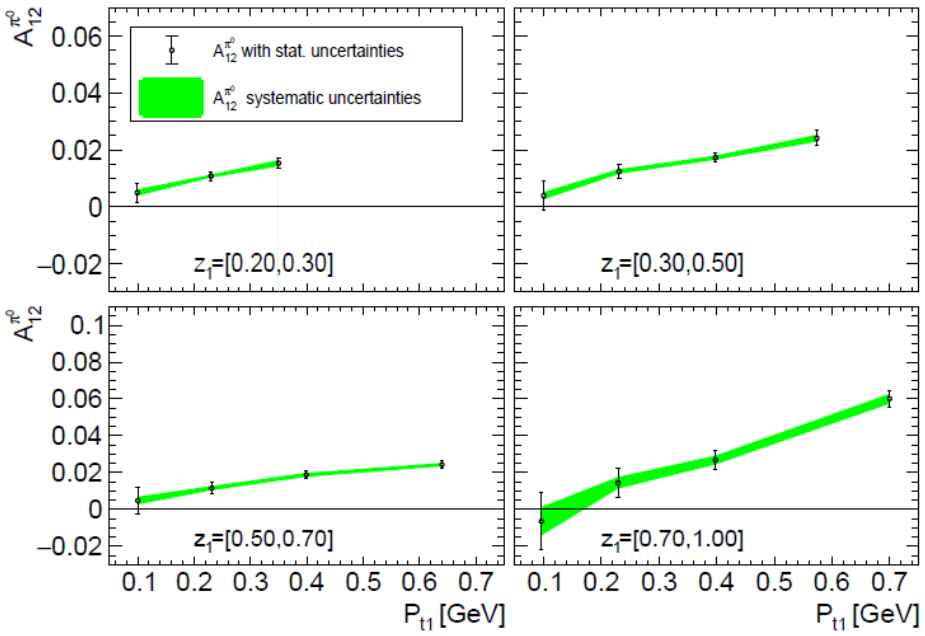


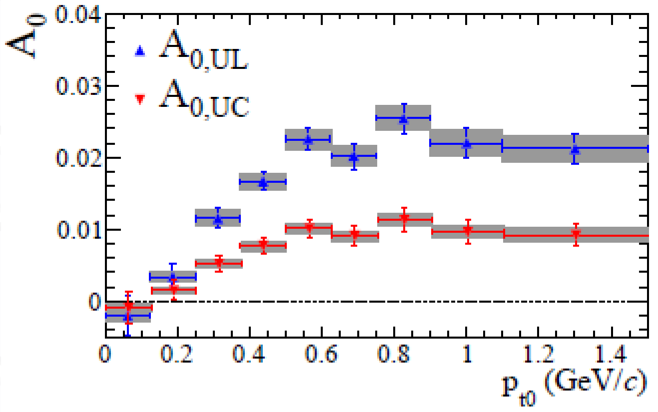
RS et al (Belle), PRL96: 232002
PRD 78:032011, Erratum D86:039905

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



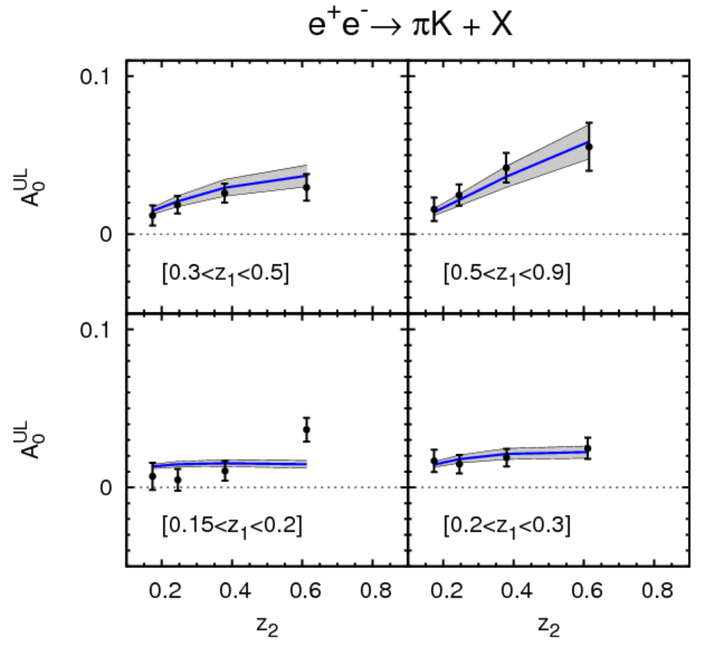


PRD 90 (2014) 052003 (Babar)

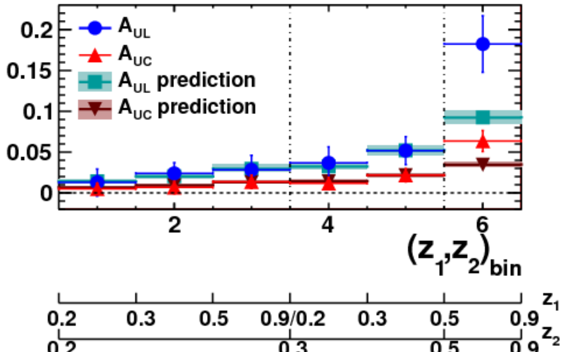
Quark transversity via Collins: Kaons

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 :
  - $6 (z_1) \times 6 (z_2) \times 5(k_{t1}) \times 5(k_{t2}) \times 1$ (costheta) x 8 (phi) for A_{12} method
  - $6 (z_1) \times 6 (z_2) \times 10(q_t) \times 1$ (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

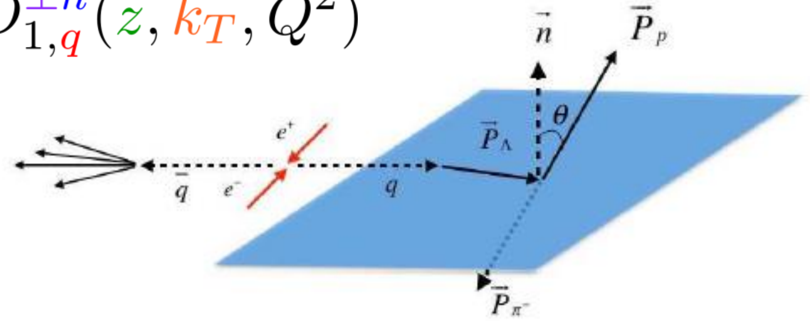
- Related to open question about Λ polarization in hadron collisions from 40 years ago!
- Fragmentation counterpart to the Sivers Function:

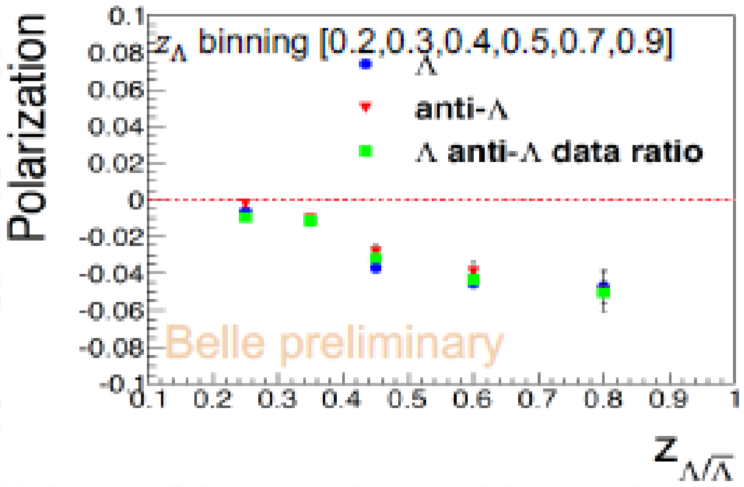
  unpolarized parton fragments into transversely polarized baryon with transverse momentum wrt to parton direction

- Reconstruct Λ, its transverse momentum and polarization

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

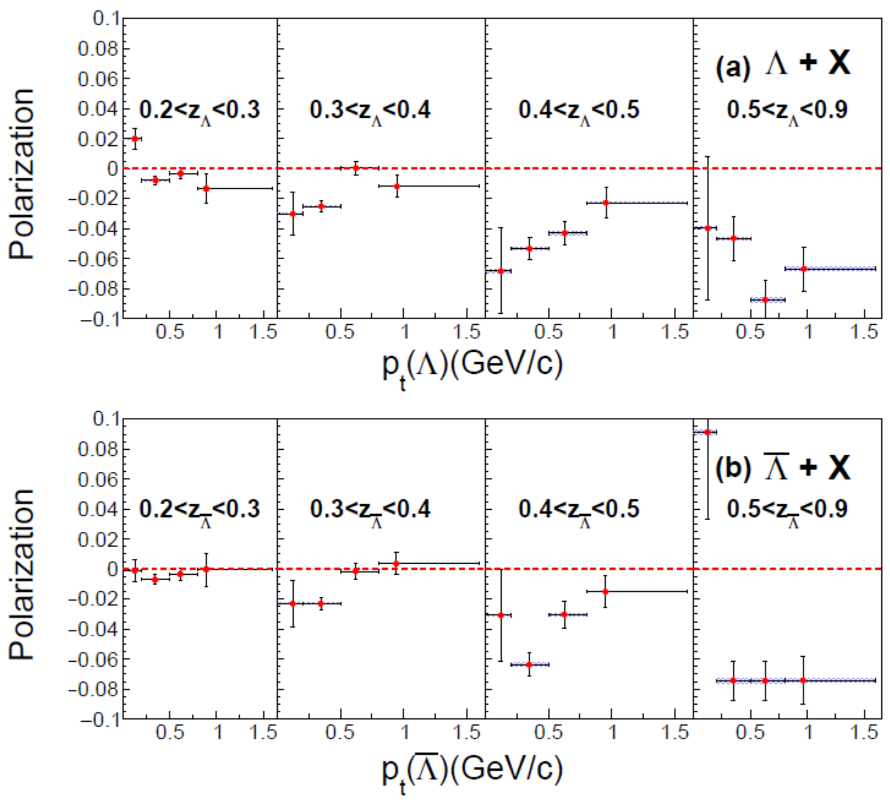
$D_{1,q}^{\perp h}(z, k_T, Q^2)$





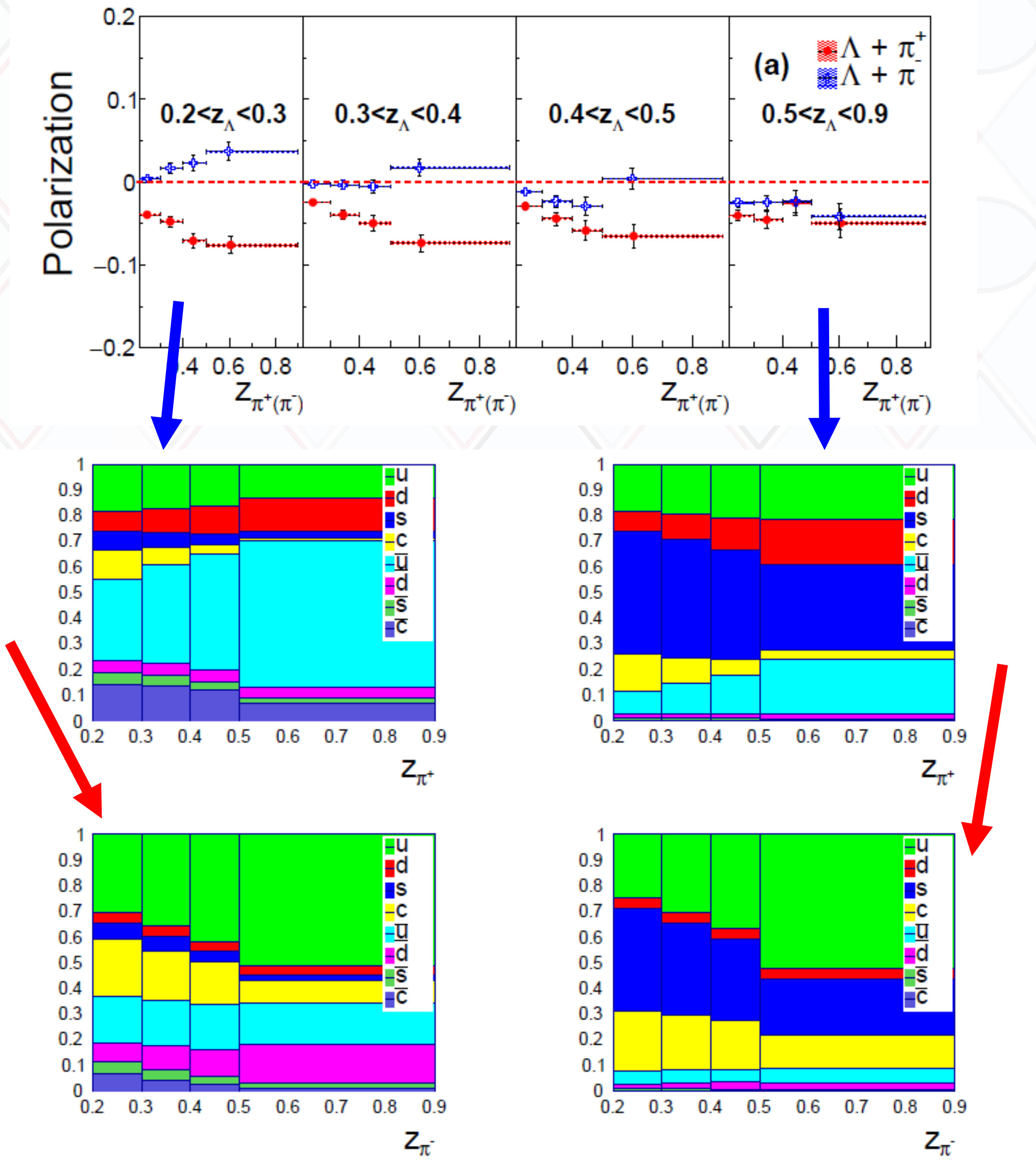
Transverse momentum dependence

- 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



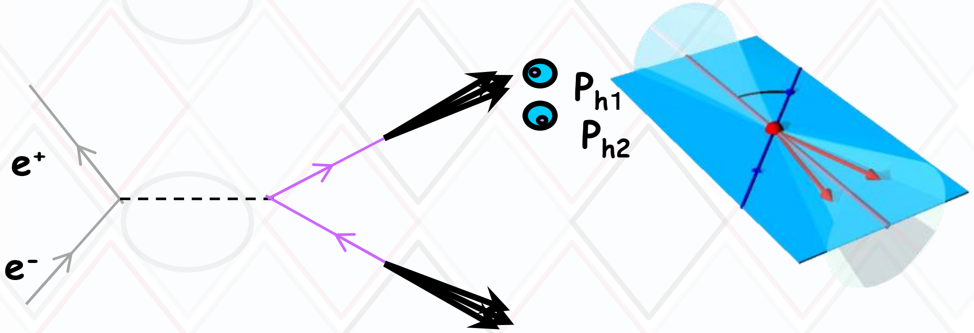
Opposite hemisphere pion correlation

- 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

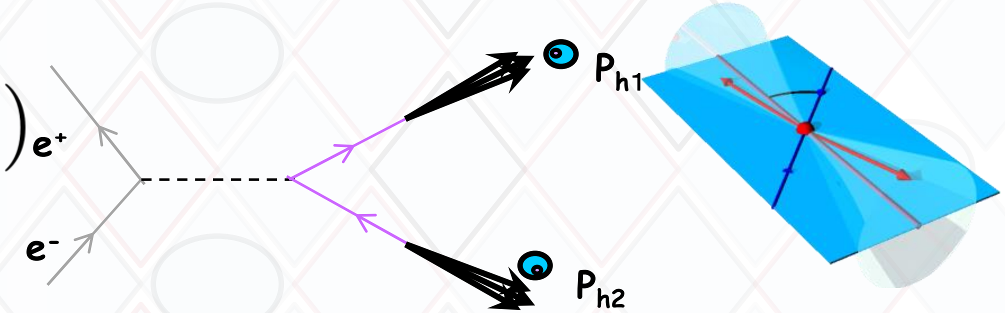


Di-hadron fragmentation functions

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



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



Additional fractional energy definitions

- Traditional definition as:

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

- "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

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

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

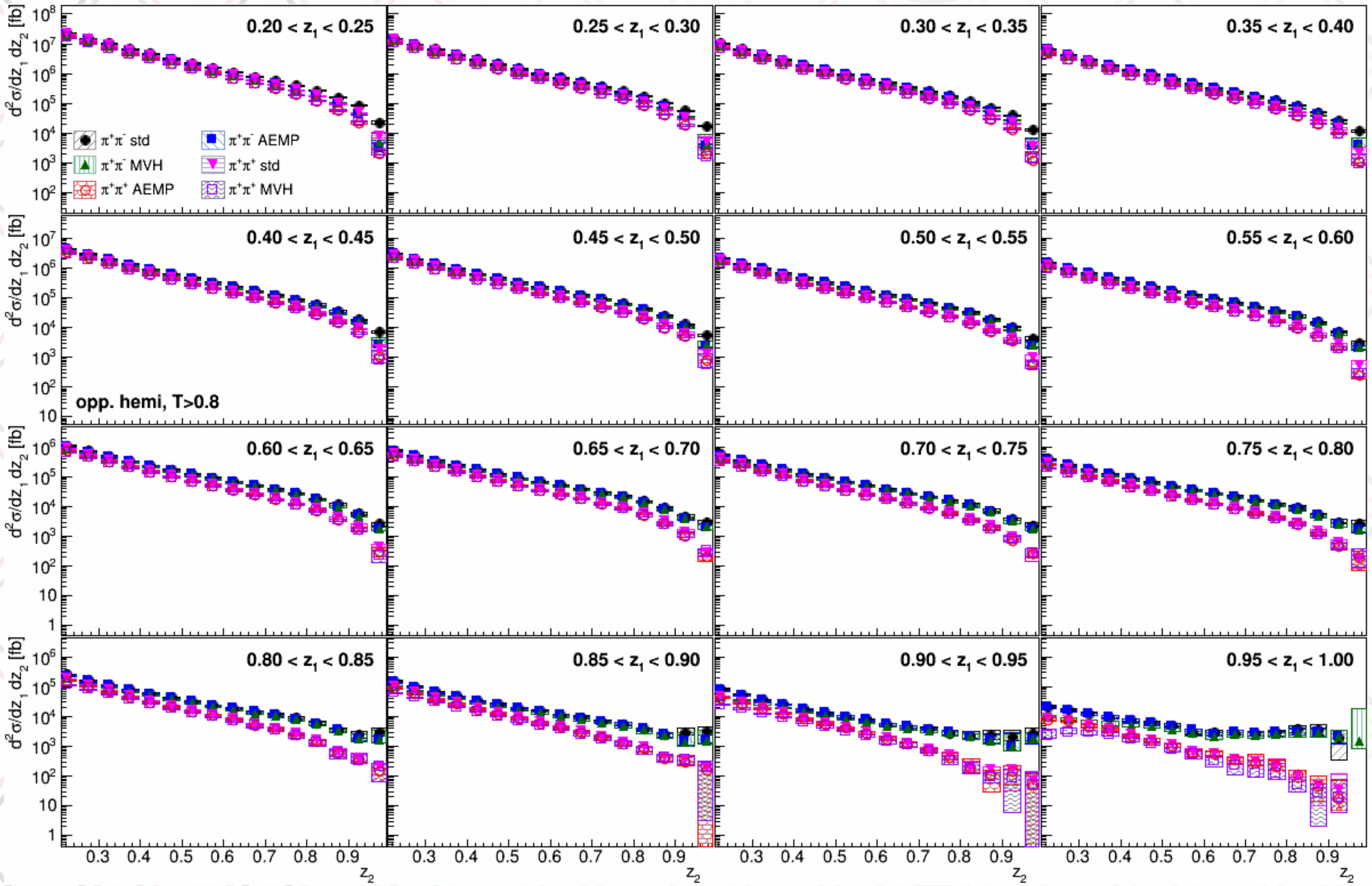
- Also new definition interested in transverse momentum in pair (Mulders/vanHulse:PRD 20100 (2019), 034011):

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

$$1 \leftrightarrow 2$$

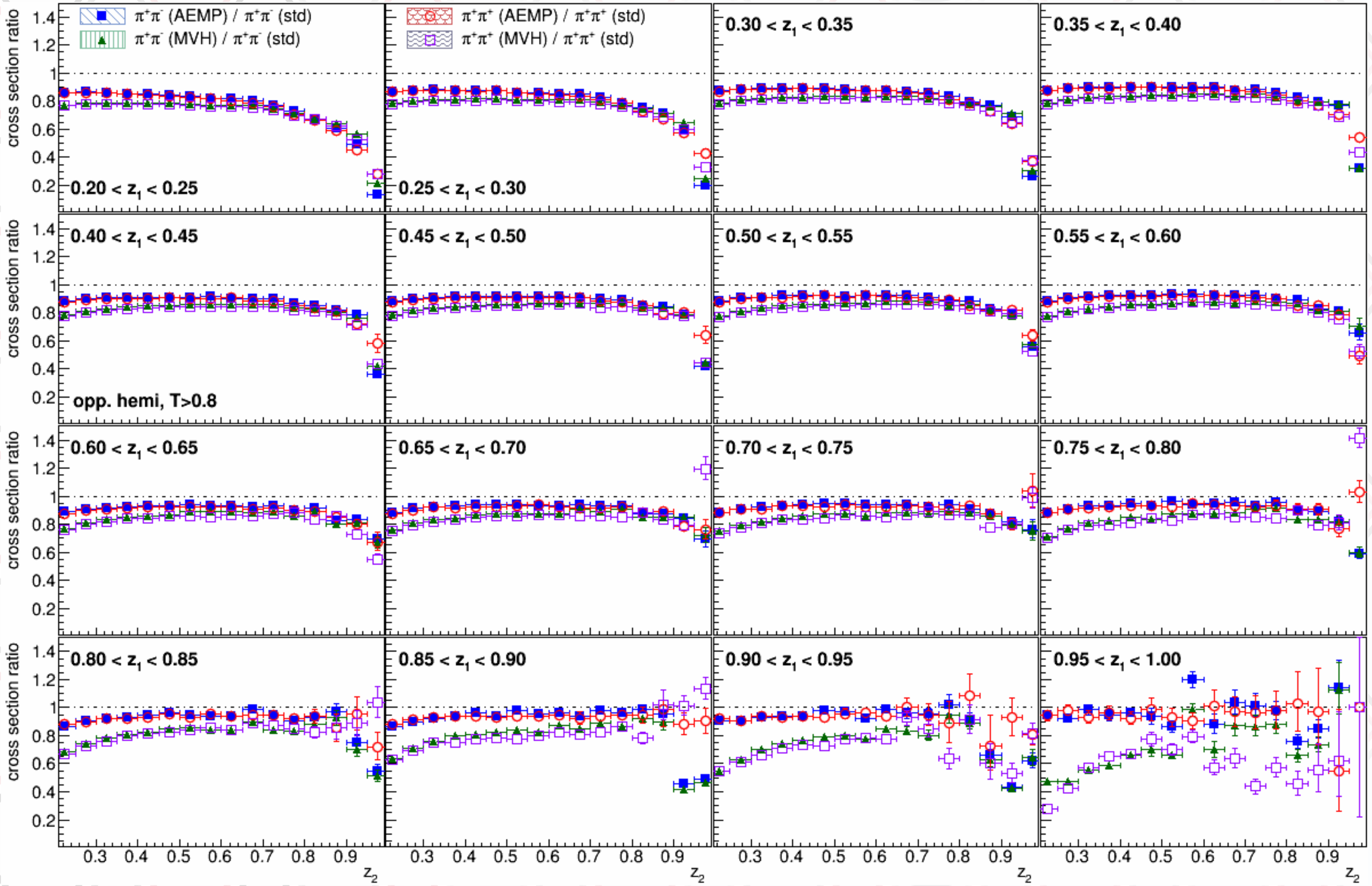
Comparison of definitions: pion pairs in opposite hemispheres

RS et al, PRD 101 (2020) 092004



Ratios to standard definitions: pion pairs in opposite hemisphere

RS et al, PRD 101 (2020) 092004



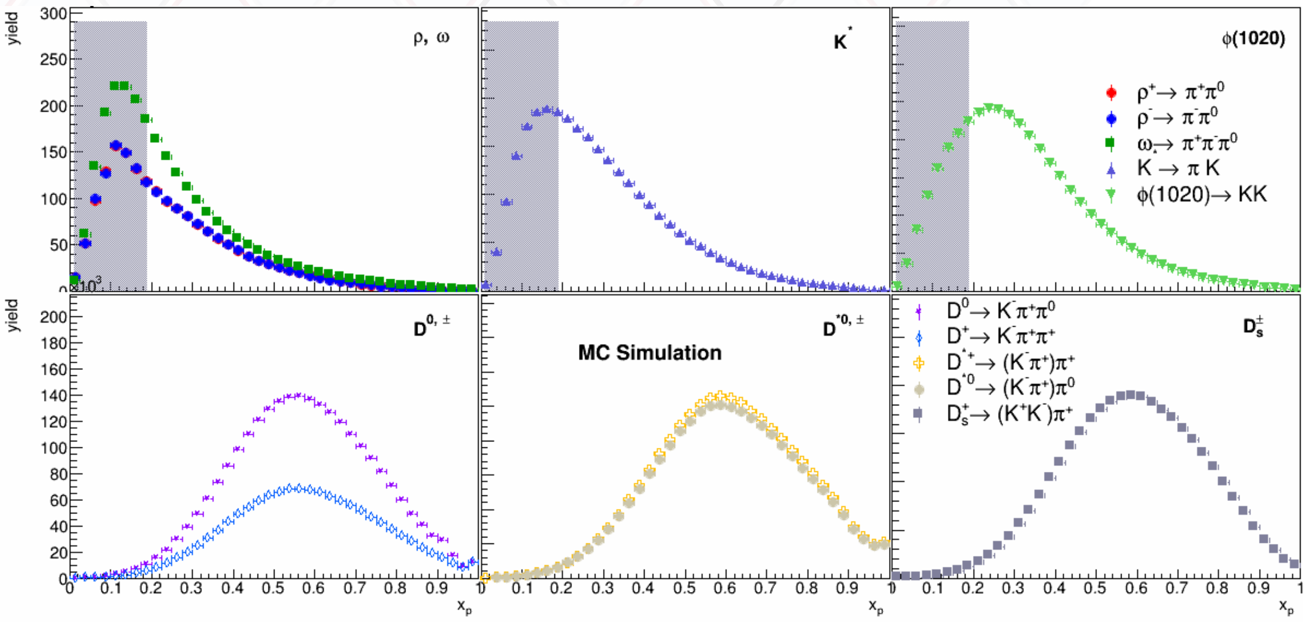
AEMP : suppressed at small factional energies, at high z close to unity

MvH : further suppressed due to transverse momentum

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):



Important resource for EIC, RHIC and HI physics

Summary

- e^+e^- is an excellent source to study fragmentation
- Crucial information for any SIDIS/pp measurements to access PDFs
- Sensitivity not only to collinear FFs but also TMD FFs:
  - Explicitly kt dependent unpol FFs
  - Collins asymmetries
  - Polarizing L fragmentation
  - Nearly back-to-back di-hadron measurements
  - Role of D and Vector Meson fragmentation and its impact on light hadrons
- More to come

Belle Detector and KEKB

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