transverse momentum dependent Fragmentation Functions

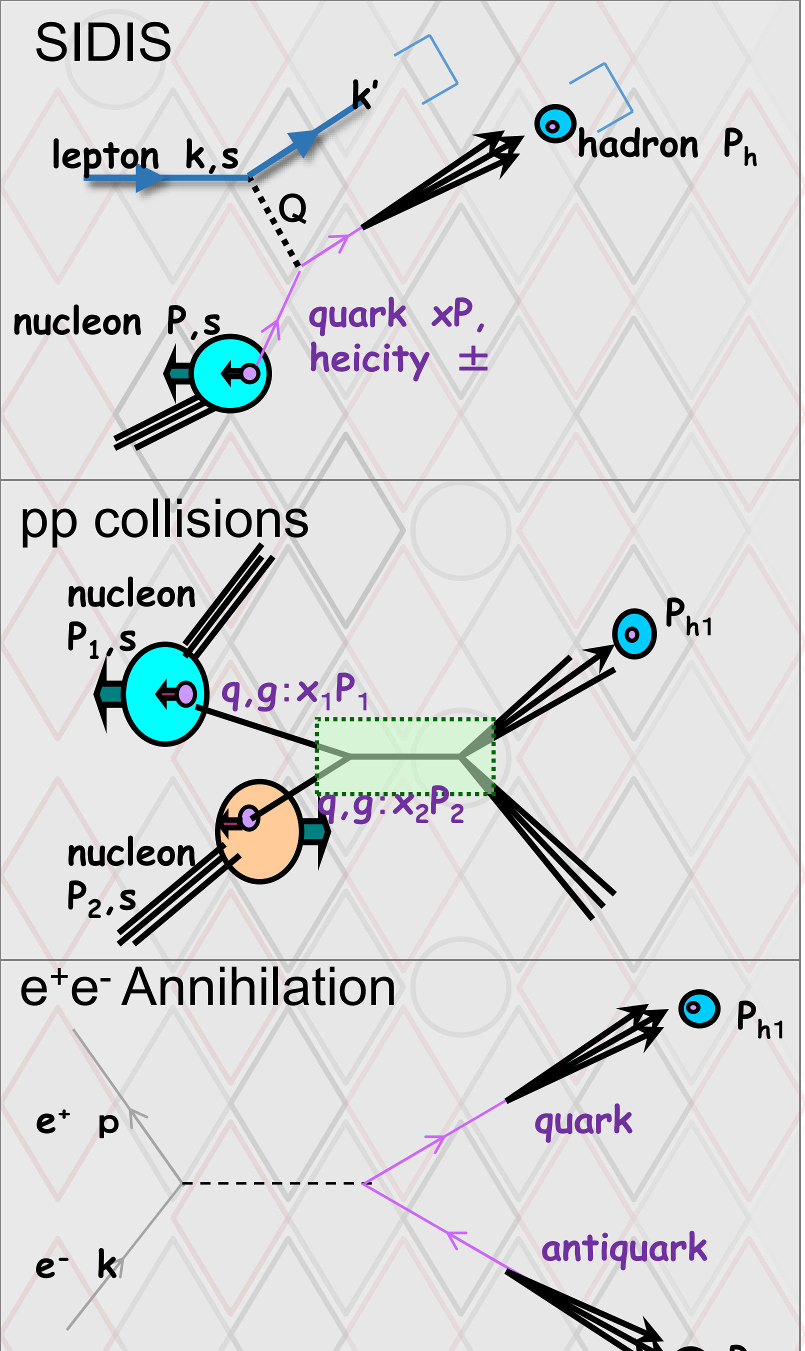
TMD Studies

May 6/7

Ralf Seidl (RIKEN)

Fragmentation

- Fragmentation functions (FF)s:
  - What particles (and how many) get created?
  - What fraction of the initial parton momentum (z) do they carry? Scaling variable of FFs (similar to x in PDFs)
  - Use this final state information to learn about fragmenting parton flavor, spin, momentum → nucleon structure at EIC



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

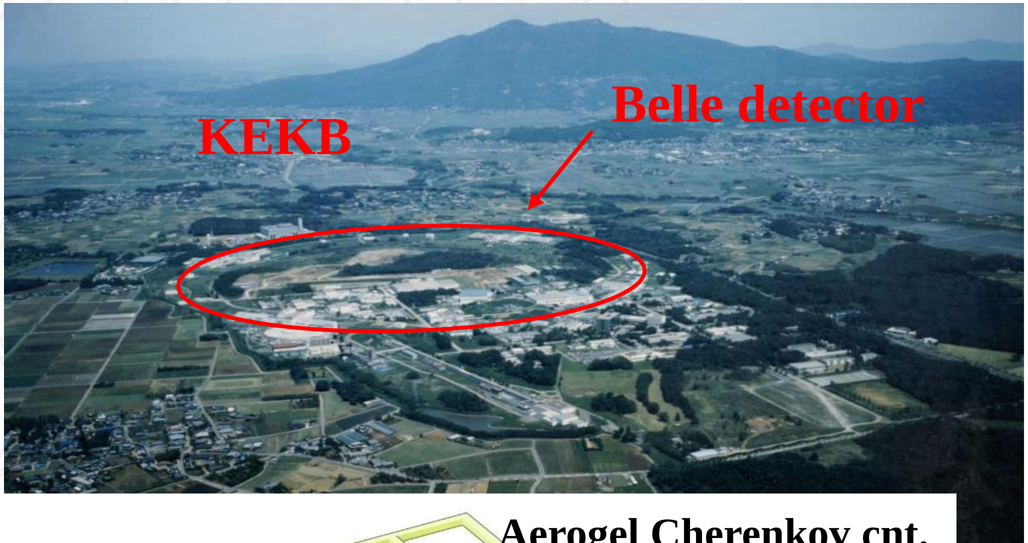
- e+e-:

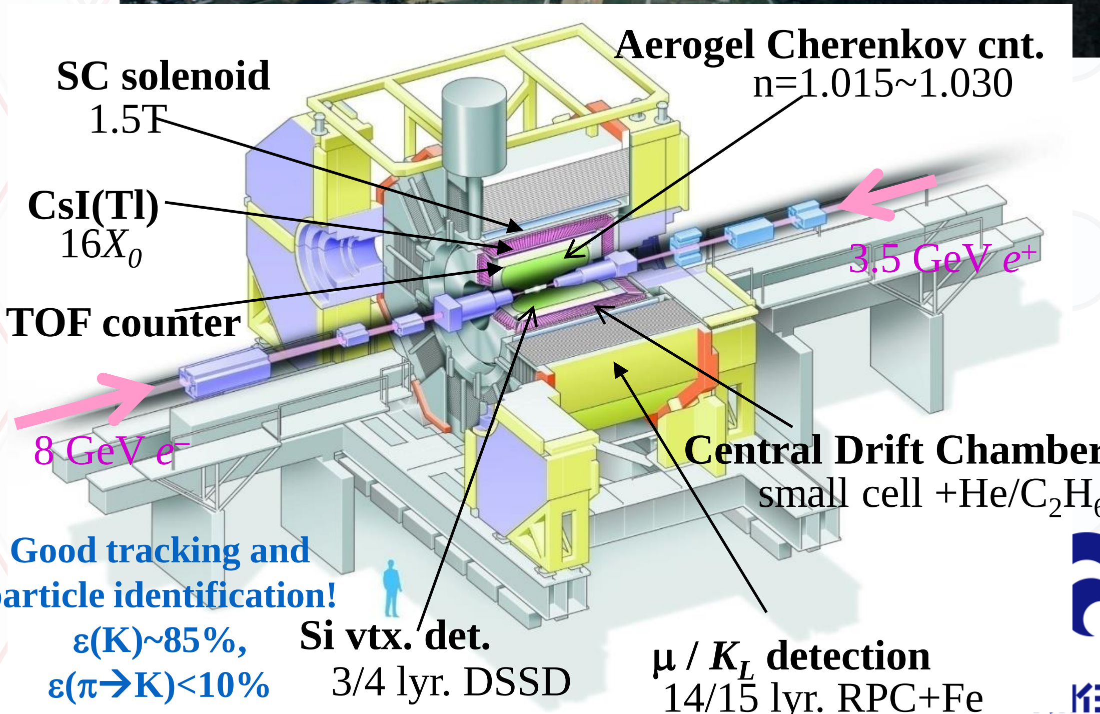
$$\sigma^h(z, Q^2, k_t) \propto \sum_q e_q^2 \left(D_{1,q}^h(z, k_t, Q^2) + D_{1,\bar{q}}^h(z, k_t, Q^2)\right)$$

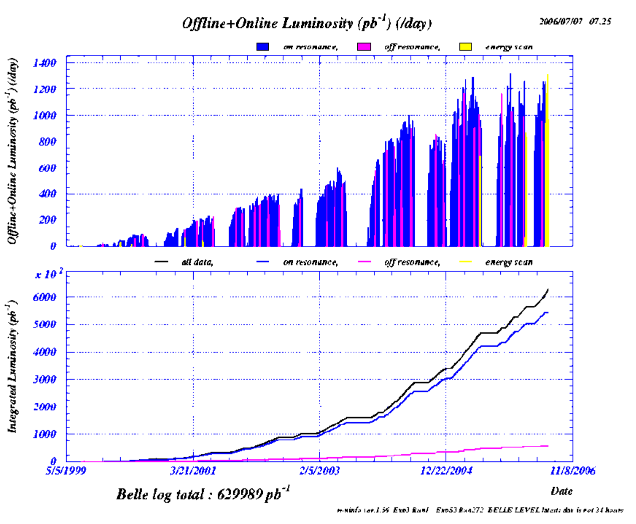
  - No PDFs necessary
  - Clean initial state, parton momentum known at LO
  - Flavor structure not directly accessible

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

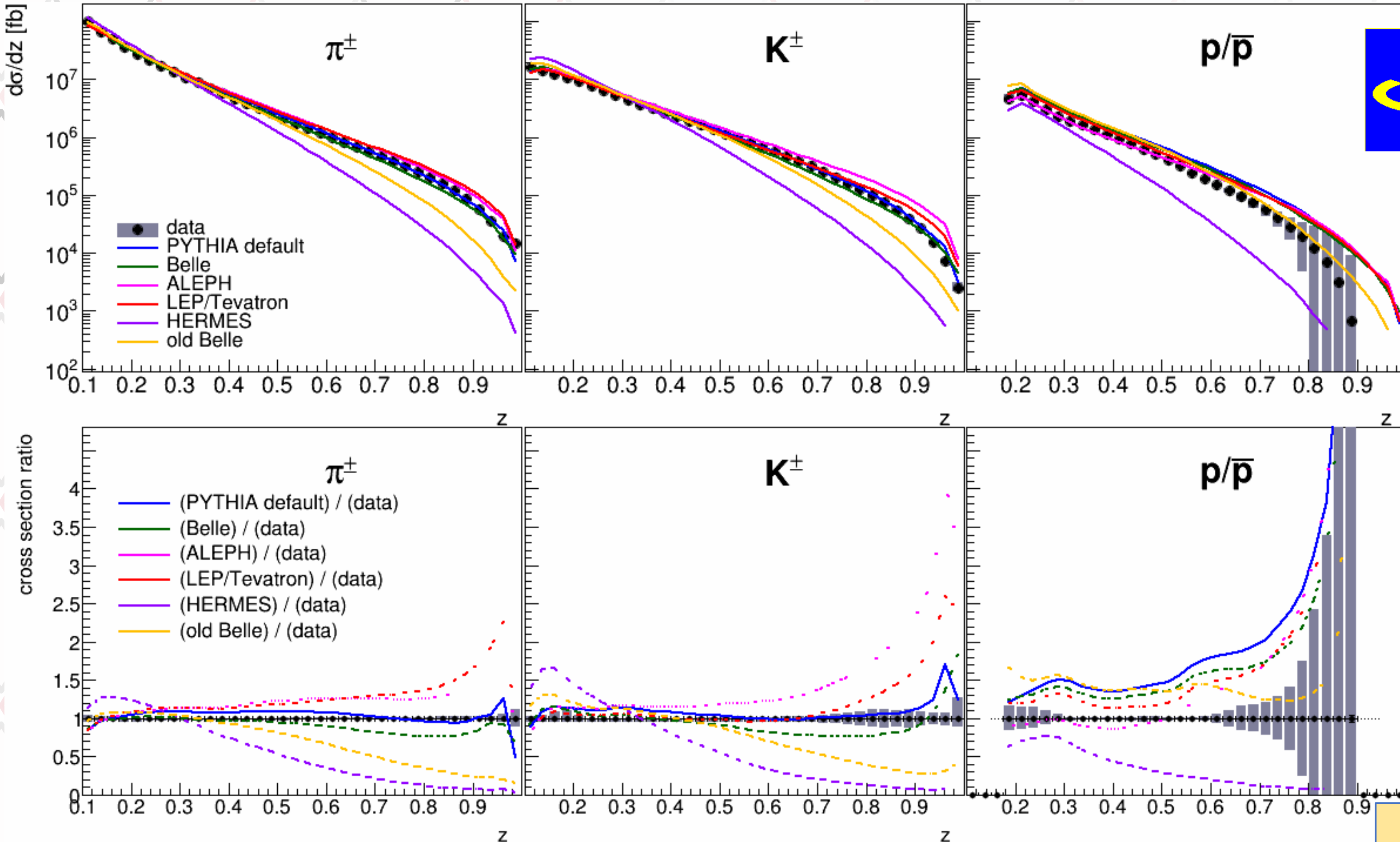






Single hadrons cross sections

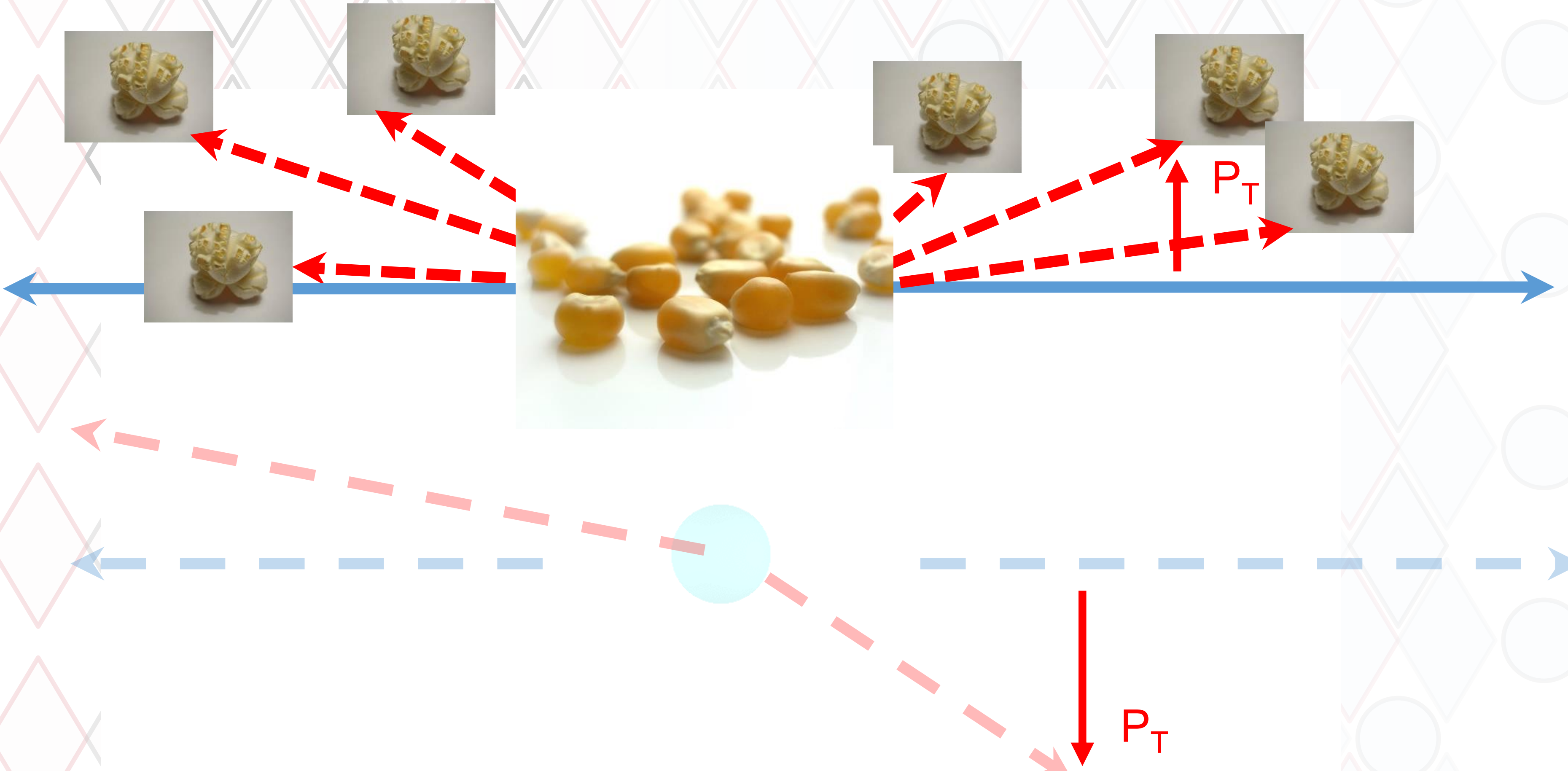
PRD 101 (2020) 092004



$$z = \frac{2E_h}{\sqrt{s}}$$

- Update with better ISR correction
- Correlated and uncorrelated uncertainties separated → improve global unpolarized FF fits

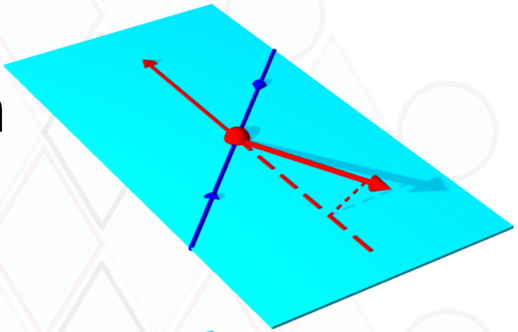
Transverse momentum generation (Popcorn)

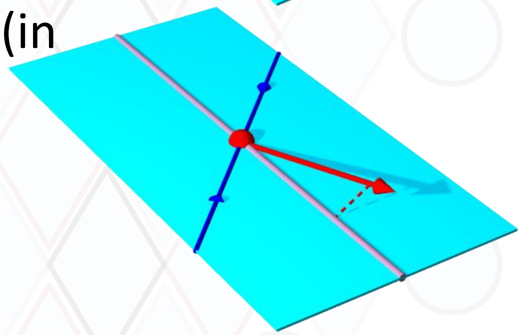


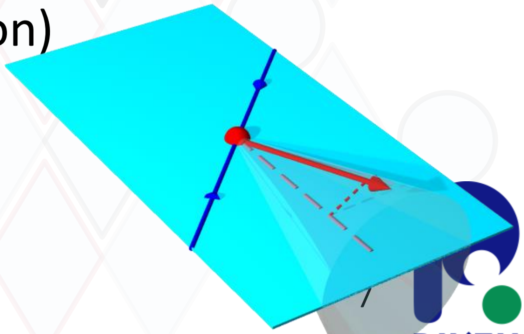
- Transverse momentum gets generated relative to the fragmenting parton
- What is its distribution?
- What is its angular distribution and relation to initial spin?

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)







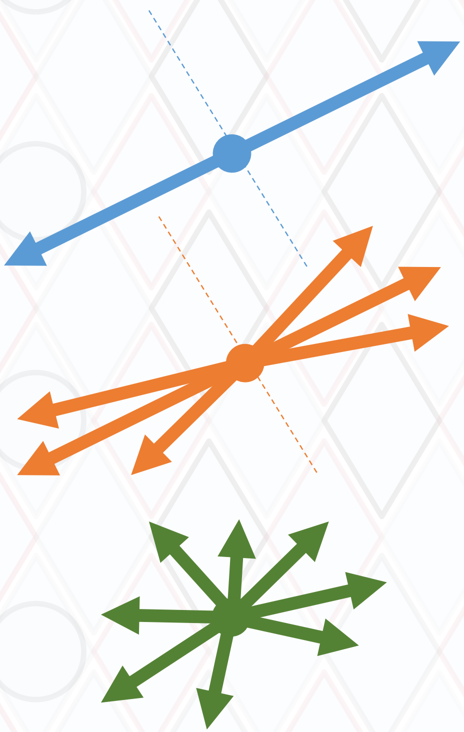
Thrust definition

- Event shape variable thrust is defined as:

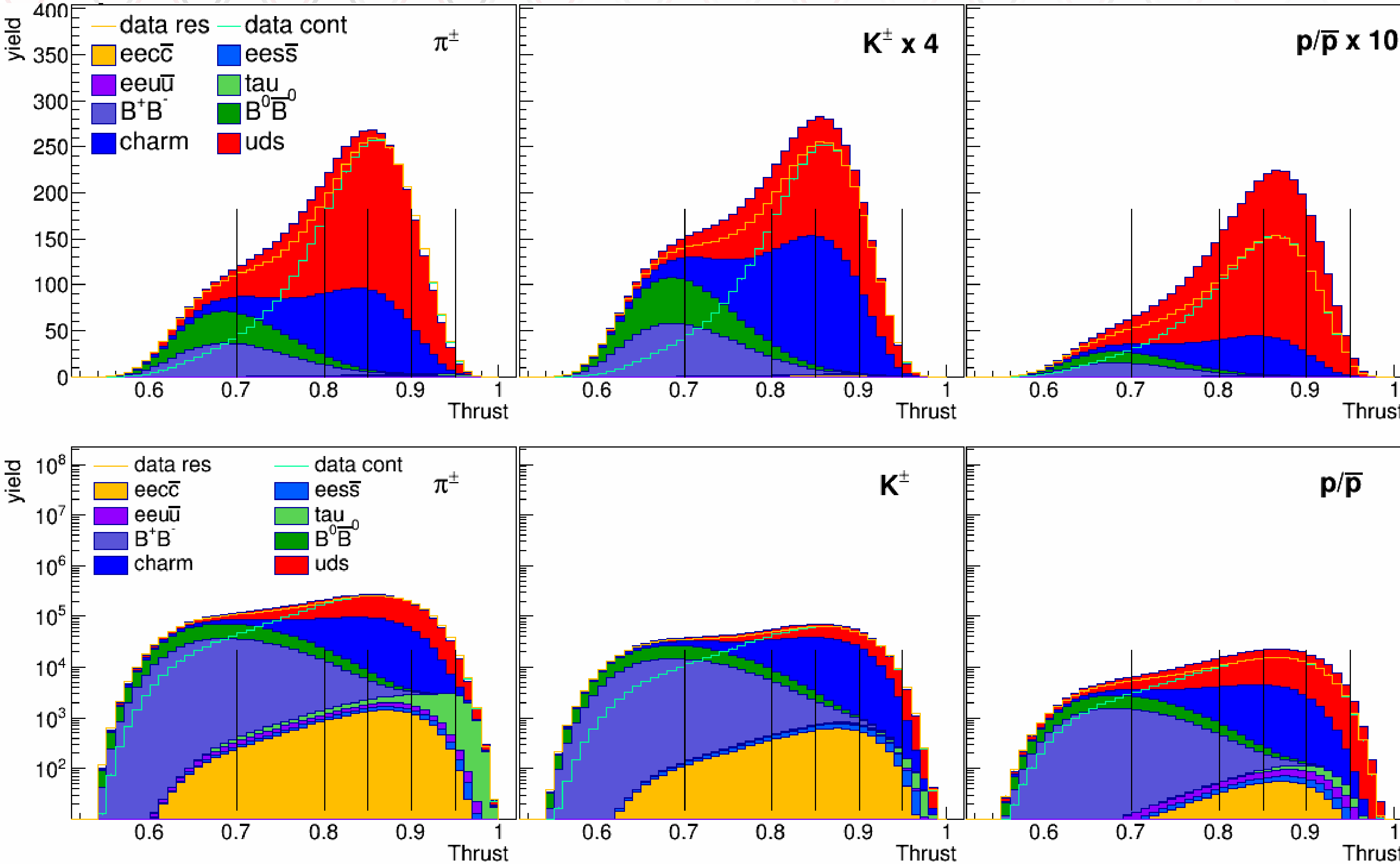
$$T \stackrel{max}{=} \frac{\sum_h |\mathbf{P}_h \cdot \hat{\mathbf{n}}|}{\sum_h |\mathbf{P}_h|}$$

- 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



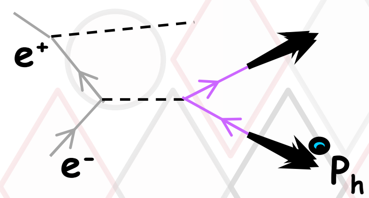
Thrust distributions (lin and log)



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 (2160x2160), 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

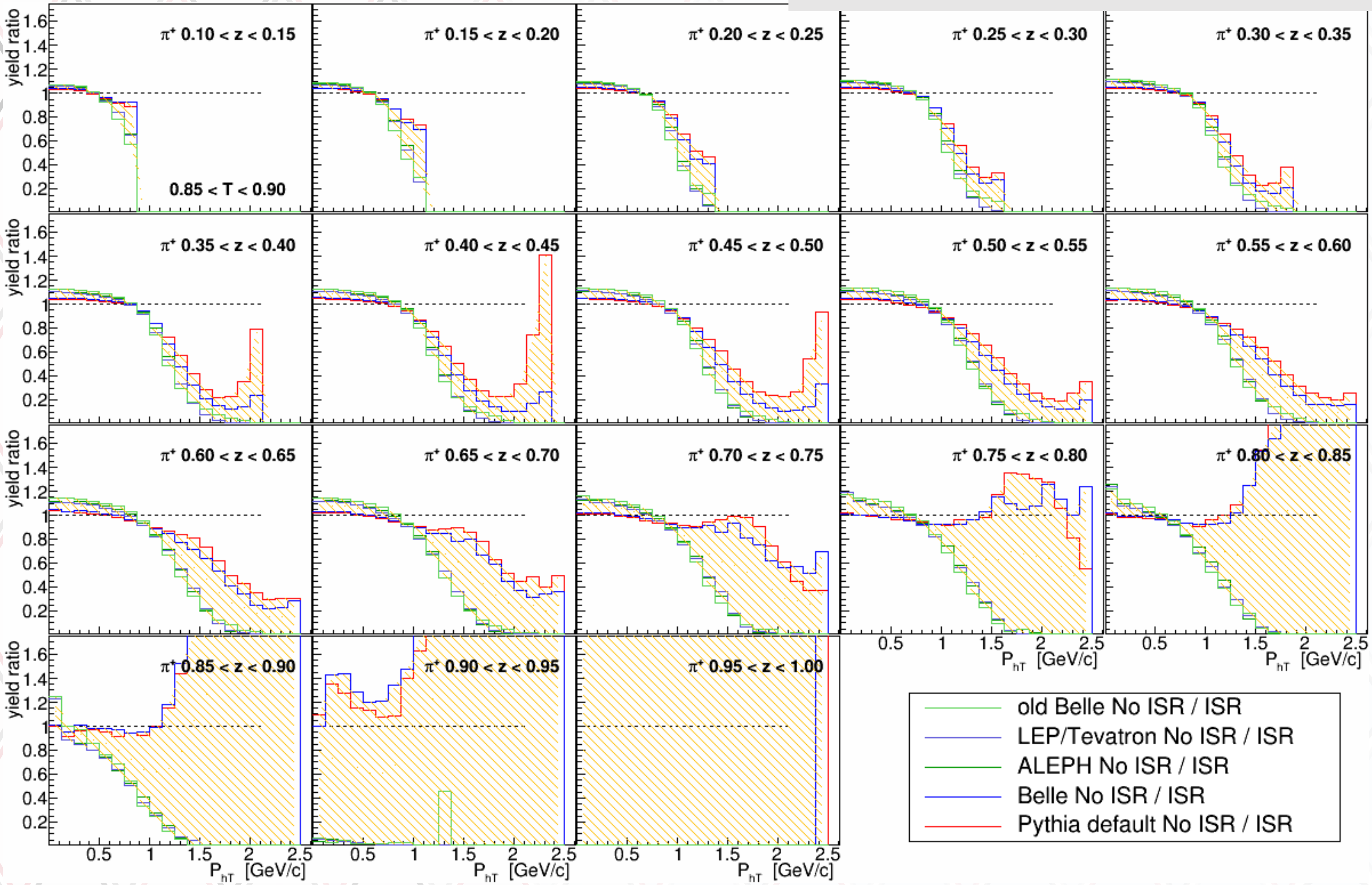
6 thrust bins [0.5,0.7,0.8,0.85,0.9,0.95,1.0] x 18 z bins x 20 kt bins



ISR correction

Different boost of qqbar system due to ISR photon taking away energy

All different tunes very similar except old Belle tune
→ assigned as systematics
-high P_{hT} drop of ratio due to ISR boost

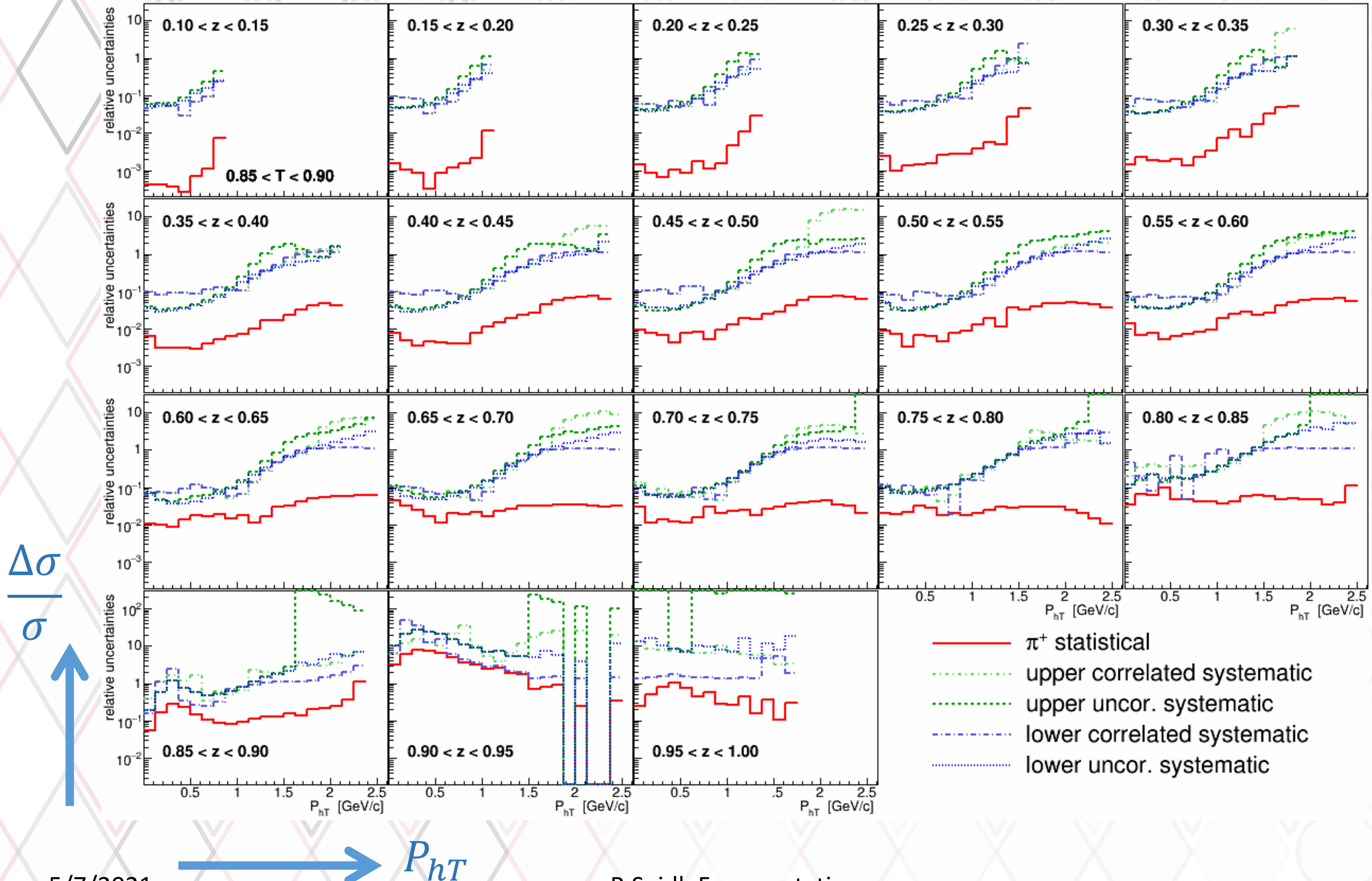


$$\frac{\sigma_{No\ ISR}}{\sigma_{ISR}}$$

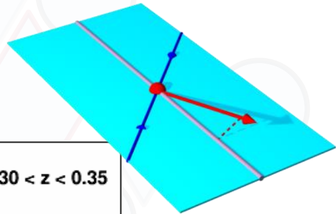
P_{Th}

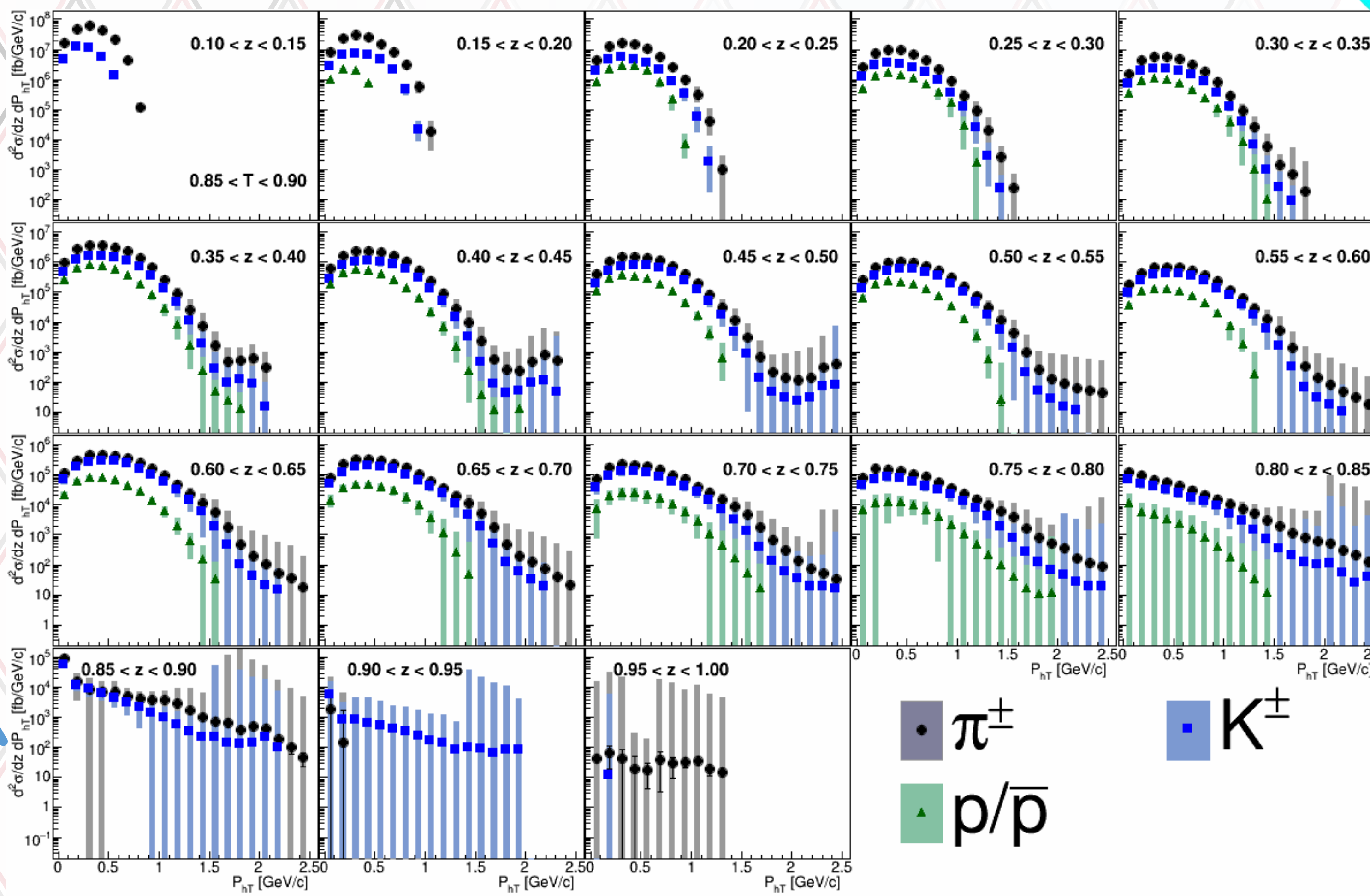
Overall systematic uncertainties

Systematic uncertainties dominated by acceptance correction (for different tunes), PID uncertainties and ISR correction



Cross sections various hadrons





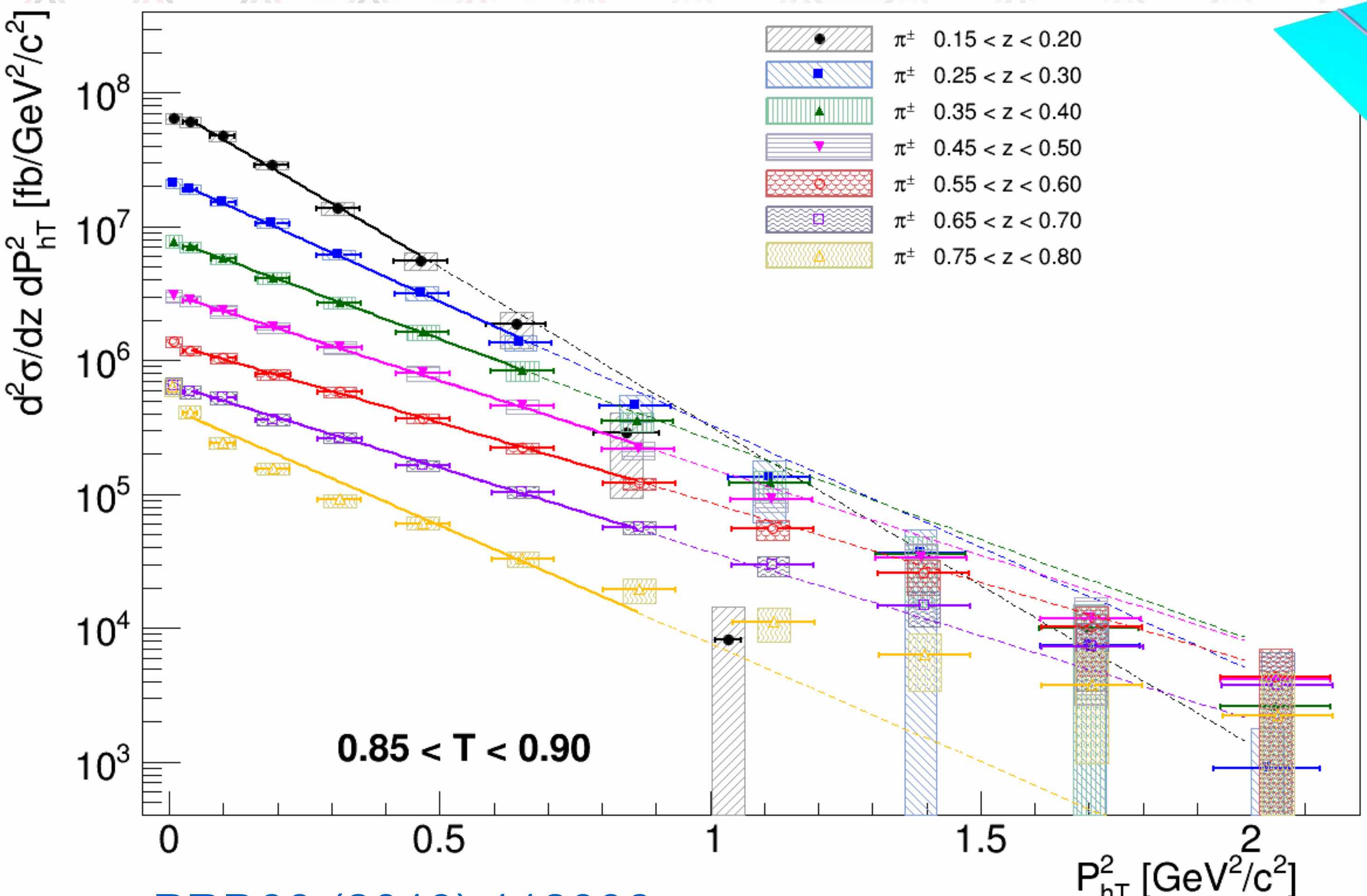
$$\frac{d^2\sigma}{dz dP_{hT}}$$

P_{hT}

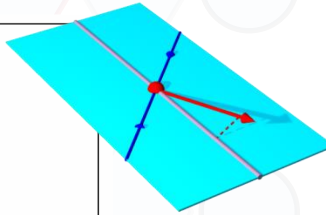
RS. et. al. PRD99 (2019) 112006

Fits vs P_{hT}^2

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

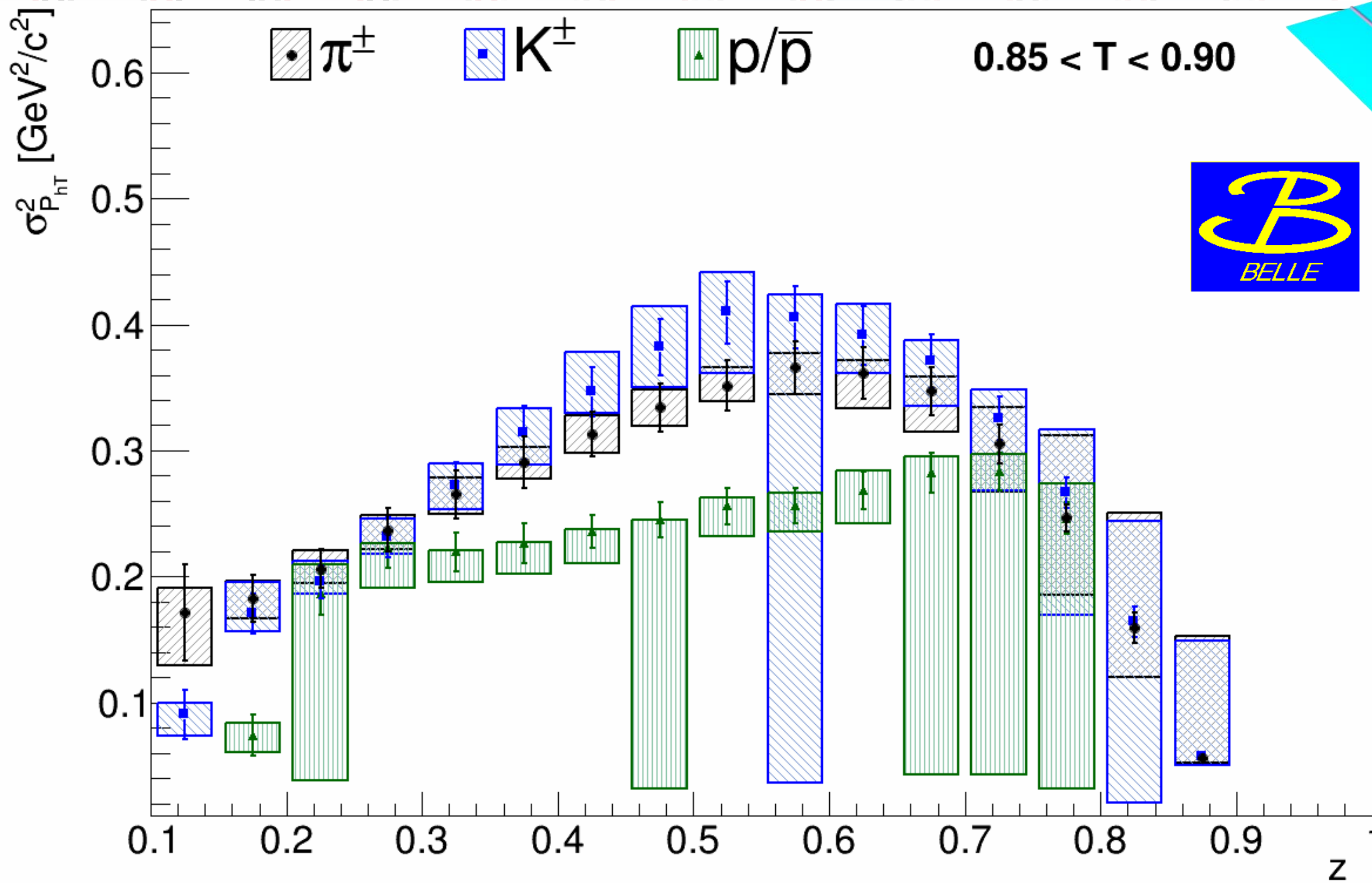


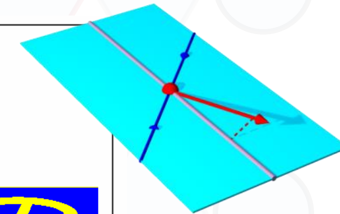
PRD99 (2019) 112006



Transverse momentum dependent unpol FFs:

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



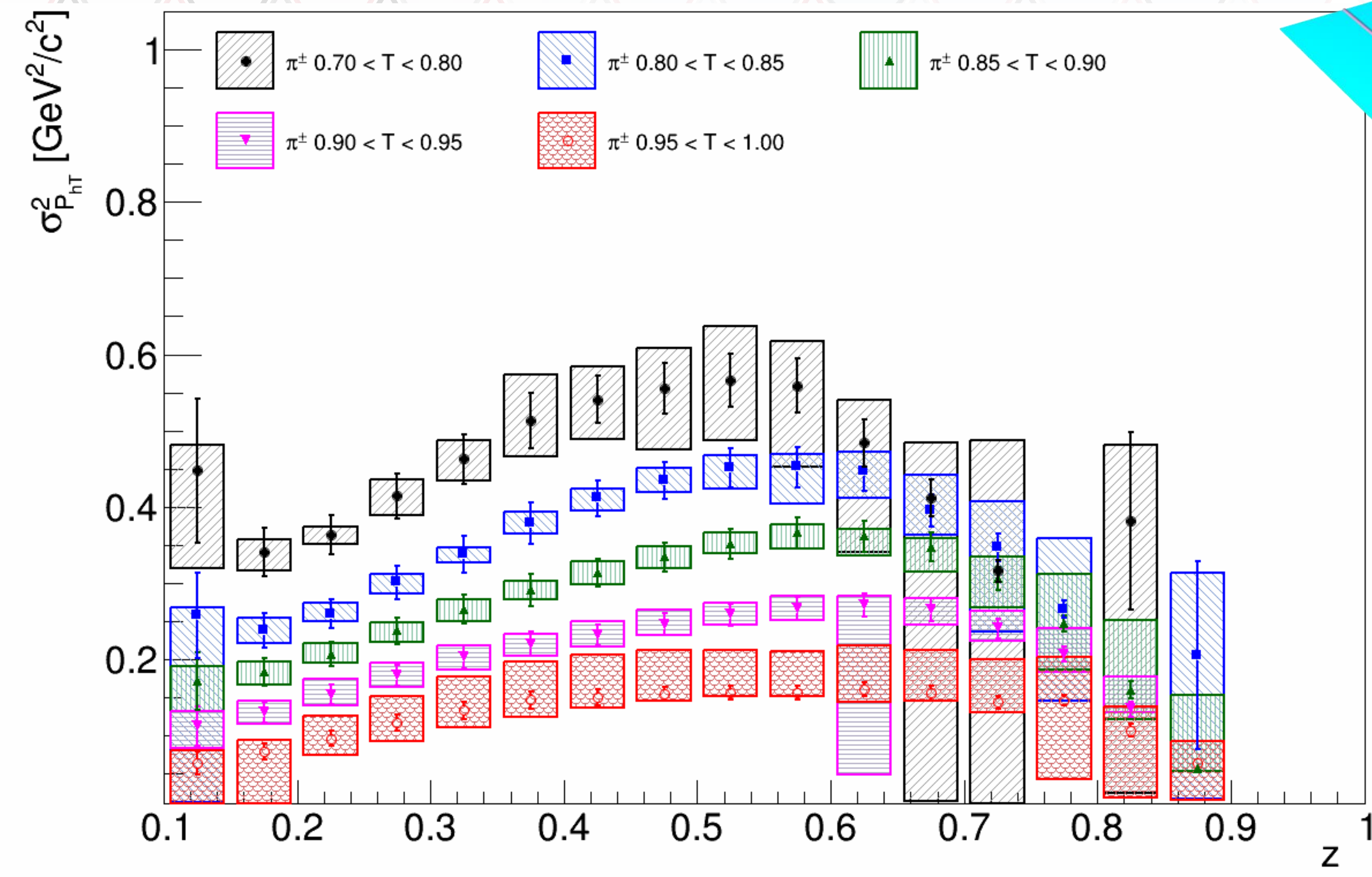


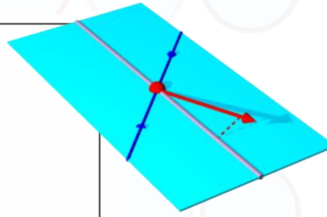
PRD99 (2019) 112006

Current phenomenological models: no or linear z dependence only

Gaussian widths, thrust dependence

Gaussian widths get narrower with higher Thrust



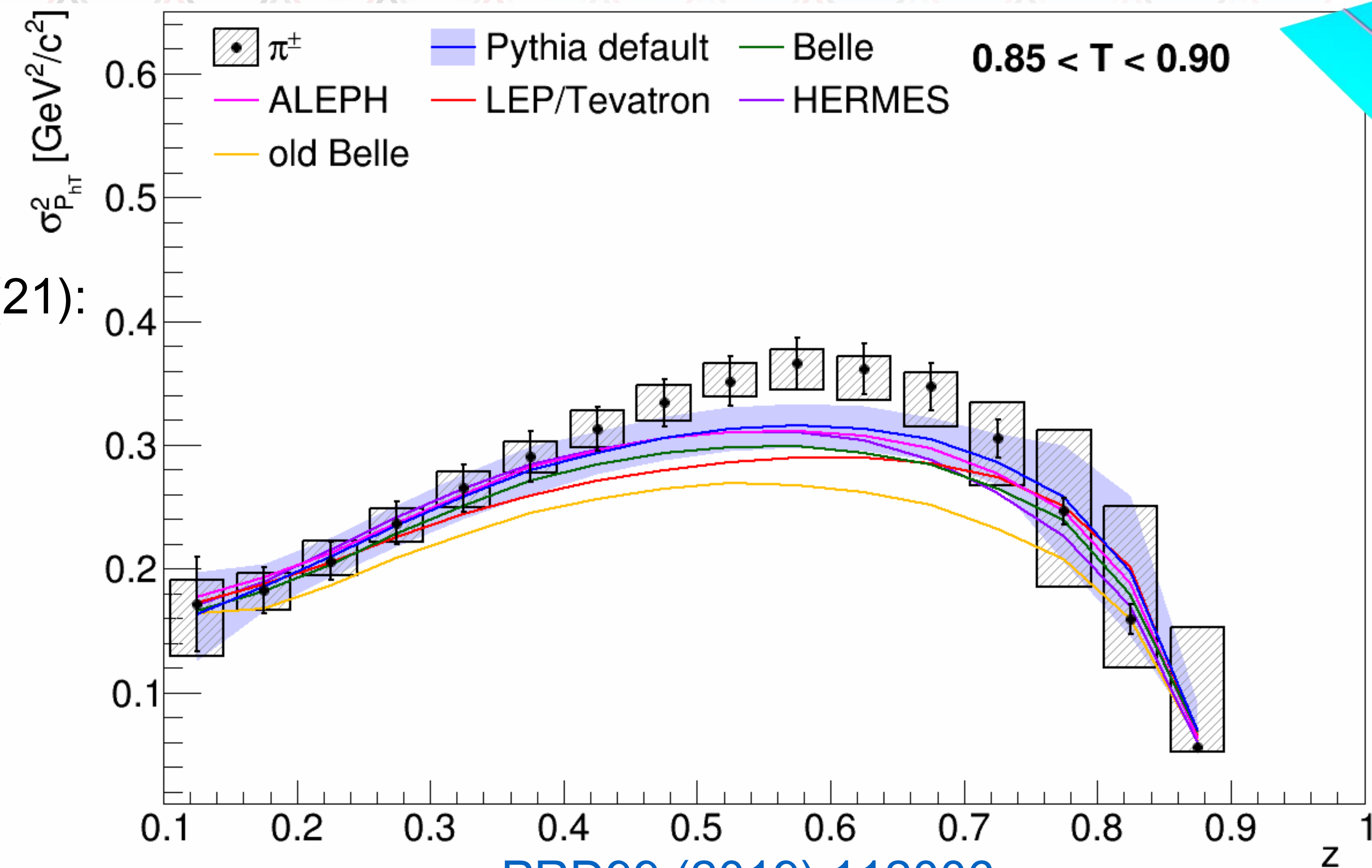


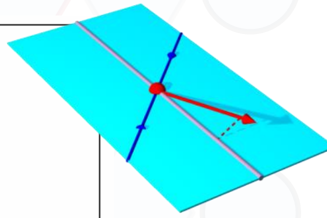
[PRD99 (2019) 112006](PRD99 (2019) 112006)

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



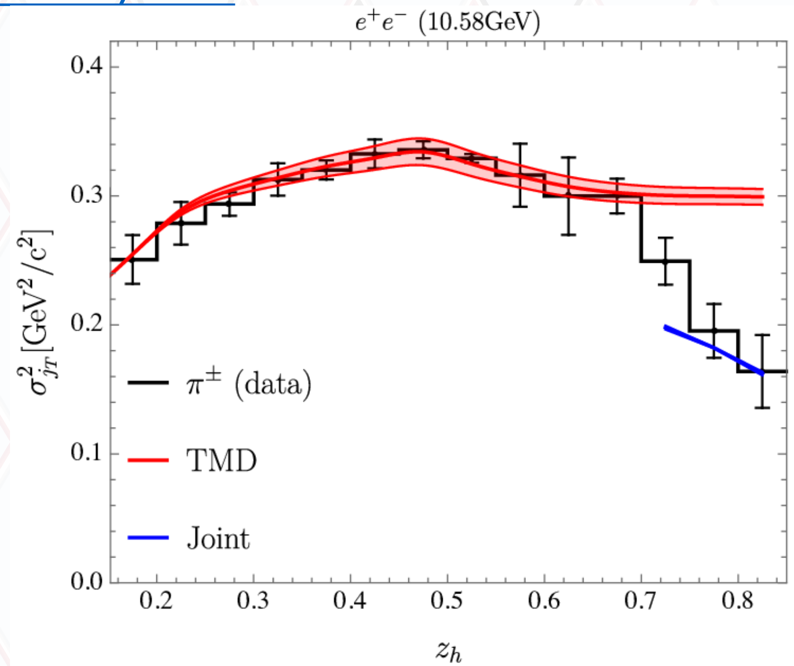


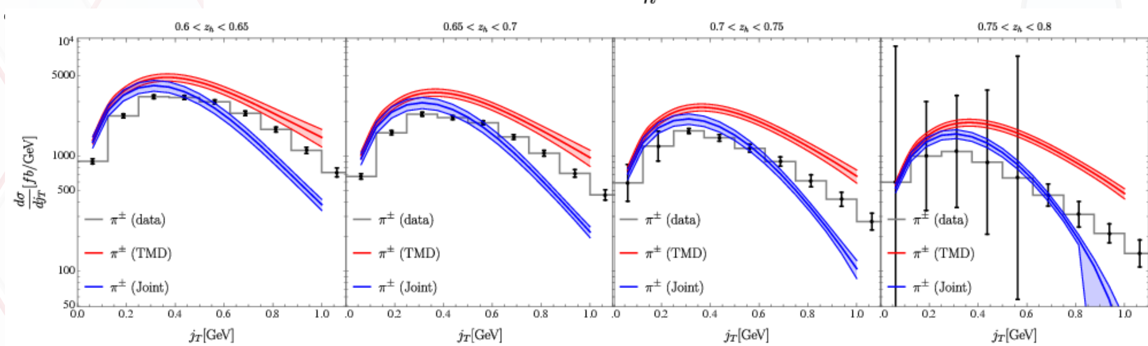
[PRD99 (2019) 112006]

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 descript for high-z region

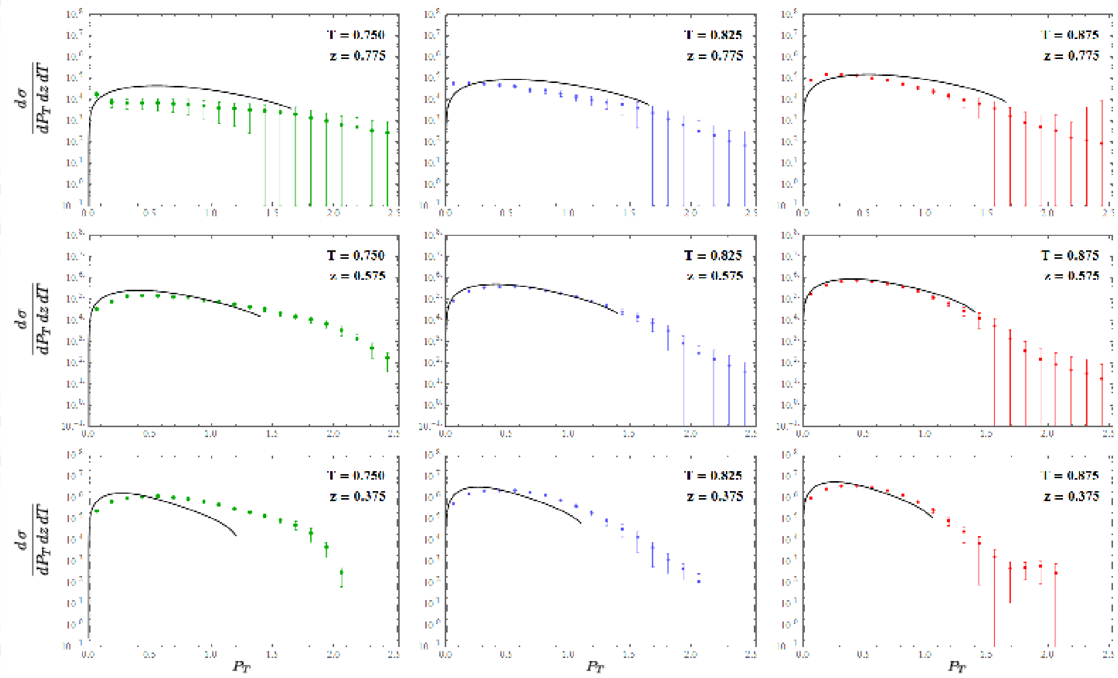




Phenomenological Fits of cross sections II

[*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



Other Belle fragmentation measurements

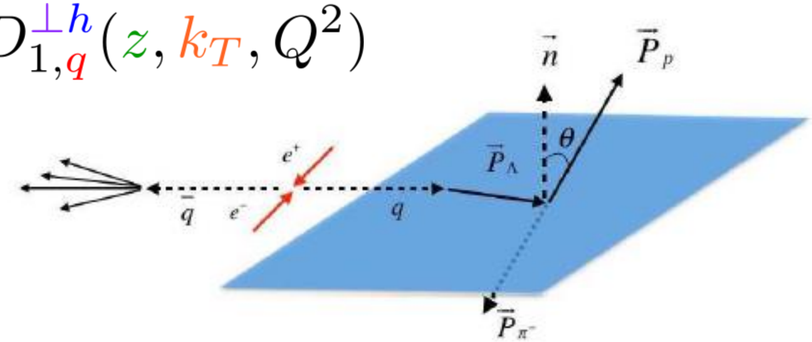
Single Λ polarization measurements

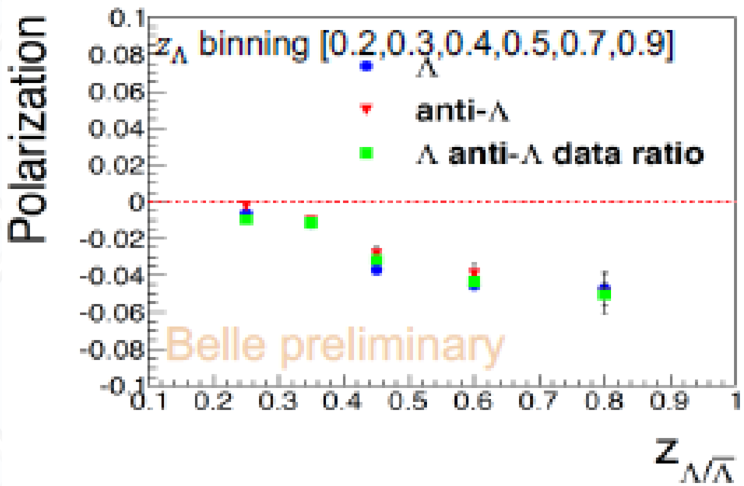
- Related to open question about Λ polarization in hadron collisions from 40 years ago!
- Fragmentation counterpart to the Sivers Function:

  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

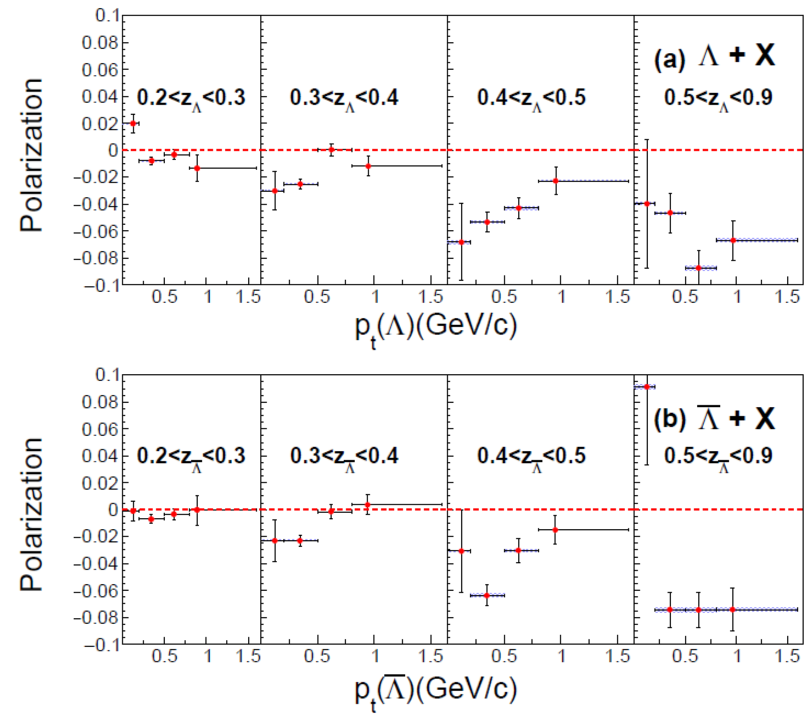
$D_{1,q}^{\perp h}(z, k_T, Q^2)$





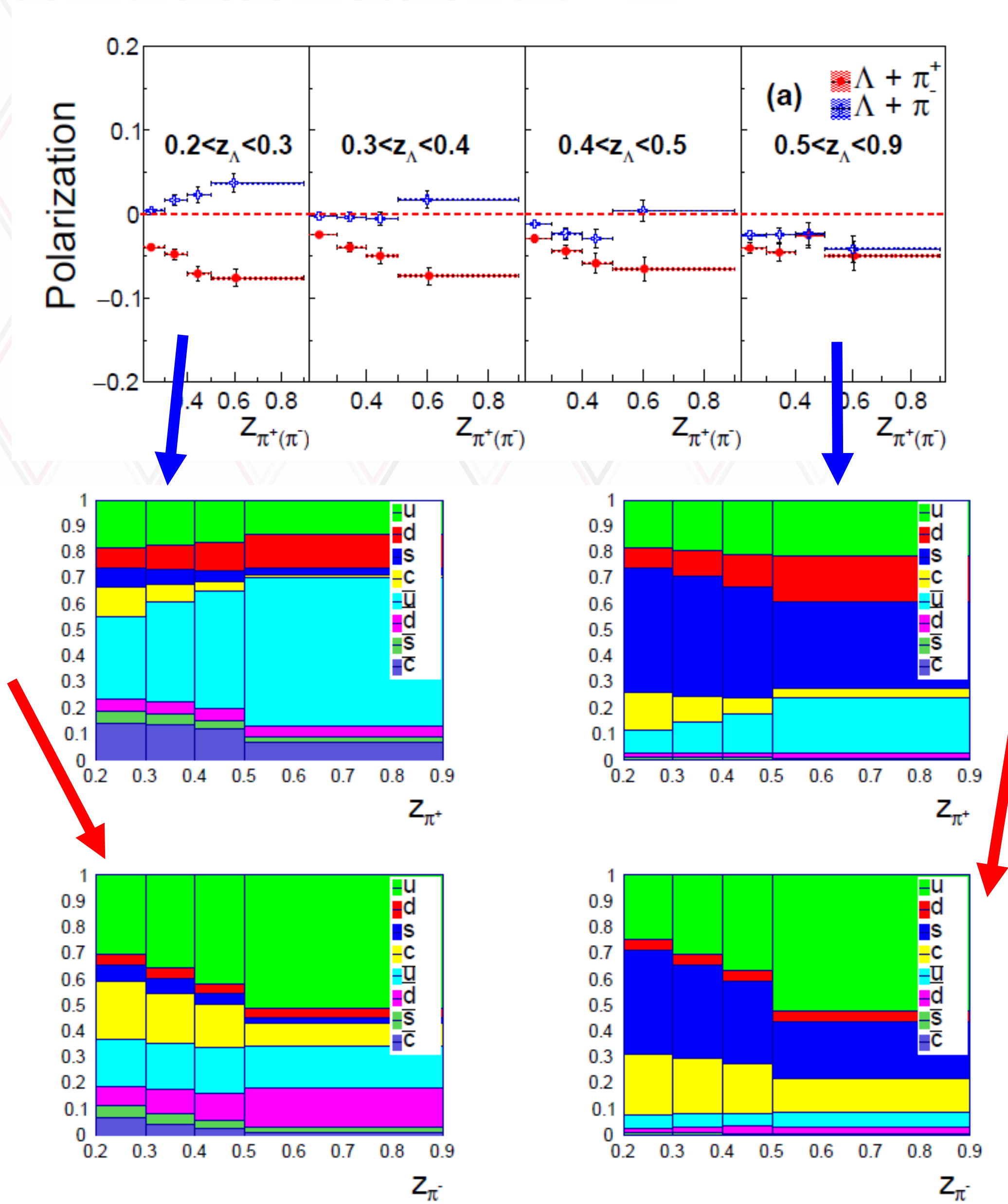
Transverse momentum dependence

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



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



Single hadron measurements

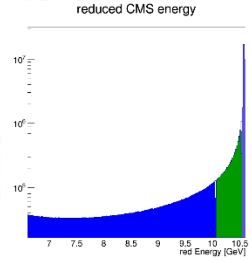
Unpolarized ingredients	Polarized ingredients	Flavor sensitivity
Single hadron cross sections: $e^+e^- \to hX$ $D_{1,q}^{h}(z, Q^2)$ **PRL111 (2013) 062002** **PRD101(2020) 092004**	Azimuthal asymmetries: $e^+e^- \to (h)(h)X$, $\cos(\phi_1+\phi_2)$ $H_{1,q}^{\perp(1)h}(z, Q^2)$ **PRL 96 (2006) 232002** **PRD 78 (2008) 032011**	Unpol SIDIS, pp: $\frac{d\sigma}{dz}$ $e^+e^- \to (h)(h)X$ **PRD92 (2015) 092007** 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**	):

Dihadron measurements

Unpolarized ingredients	Polarized ingredients	Flavor sensitivity
Dihadron cross sections $e^+e^- \to (hh)X$ $D_{1,q}^{h_1h_2}(z, m, Q^2)$ **PRD96 (2017) 032005** **PRD101(2020) 092004**	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: $\frac{d^2\sigma}{dzdm}$

other FF related measurements (ongoing or planned)

- Extension of di-hadron measurements to any resonant hadron possible:
  - K_s, K^*,ϕ, ρ, etc
- πK and KK IFF measurements
- Multidimensional Collins analysis for pions and kaons
- Especially rho mesons might be of interest for explaining the muon discrepancy in cosmic air shower models
- Explicitly study scale dependence of kt dependent FFs using ISR photons



Summary

- Fragmentation functions provide important input for the understanding of QCD as well as the nucleon structure
- The e^+e^- annihilation experiments, in particular Belle, have provided nearly all relevant measurements:
  - Single and dihadron cross sections
  - Collins and Interference FF asymmetries
  - Transverse momentum dependence
- Baseline for all semi-inclusive EIC measurements
- P_{hT} dependent cross sections and Gaussian widths extracted
  - Very clear z dependence of widths, not as assumed by phenomenologists
  - Pions and kaons similar, protons narrower (diquarks?)
- Polarizing Lambda fragmentation measured
- Various cross sections for light hadrons, heavy baryons, di-hadrons, etc available
- More Belle measurements ongoing (di-hadron kt, Collins)