Transverse momentum dependent Fragmentation Functions in Belle

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

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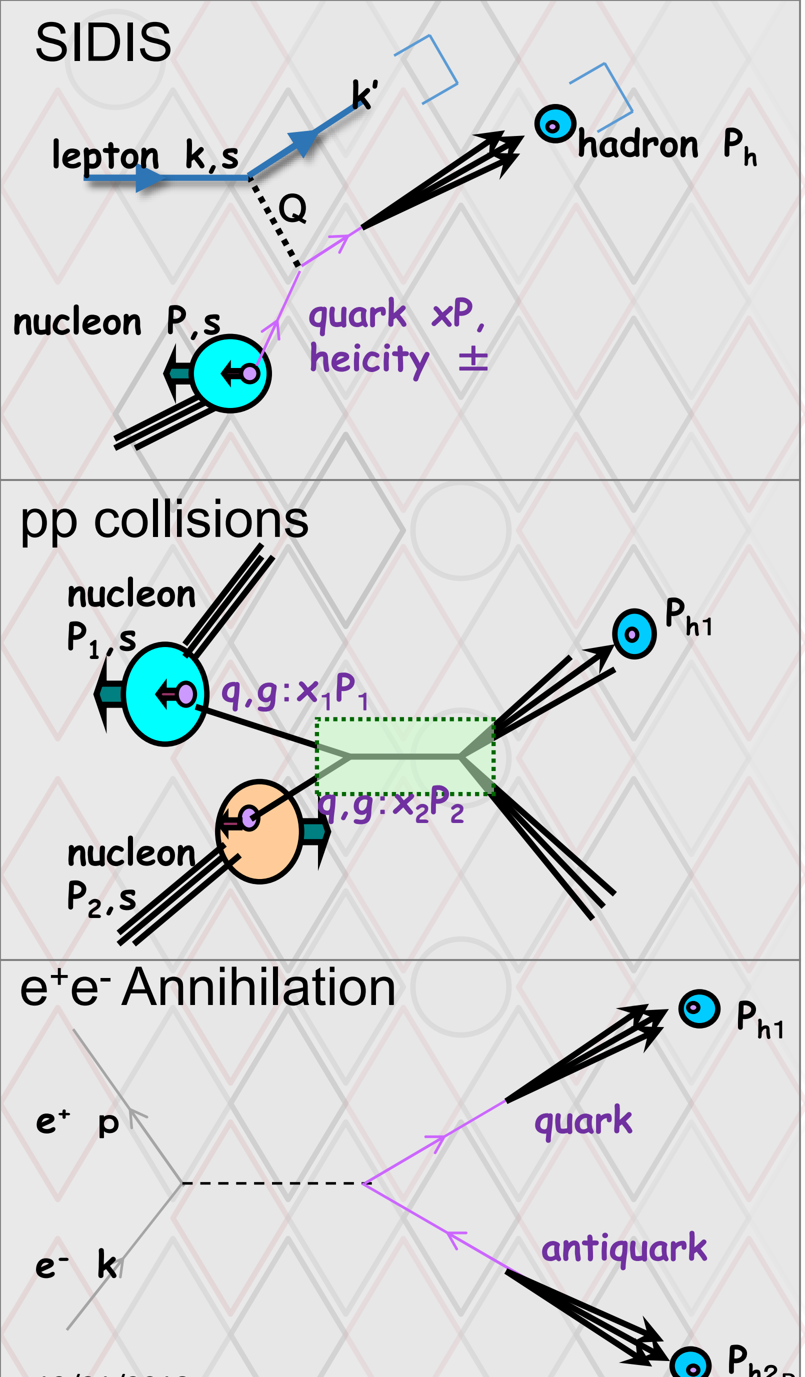
EIC without B factory input? Very unlikely

- 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)



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-:

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

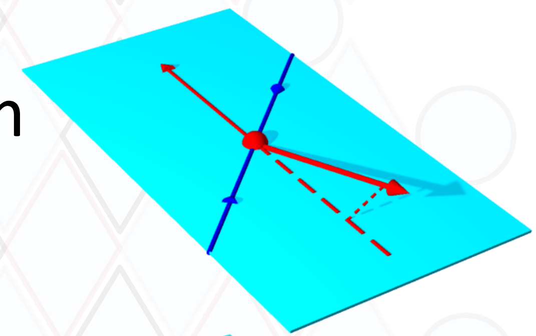
  - No PDFs necessary
  - Clean initial state, parton momentum known at LO
  - Flavor structure not directly accessible

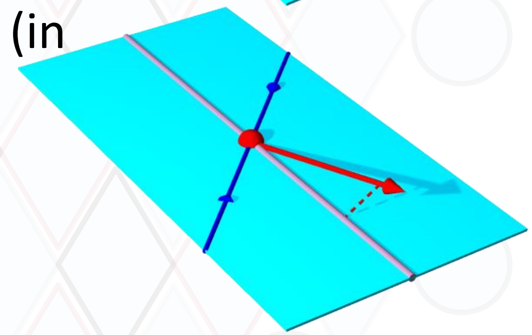
Transverse momentum dependence

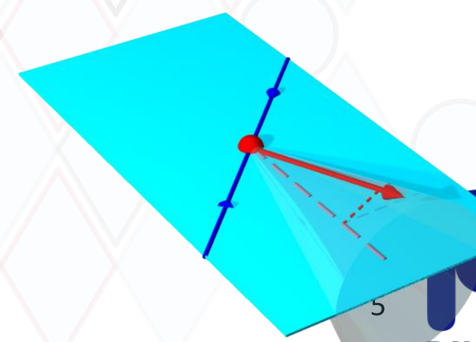
Aka un-integrated PDFs and FFs

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







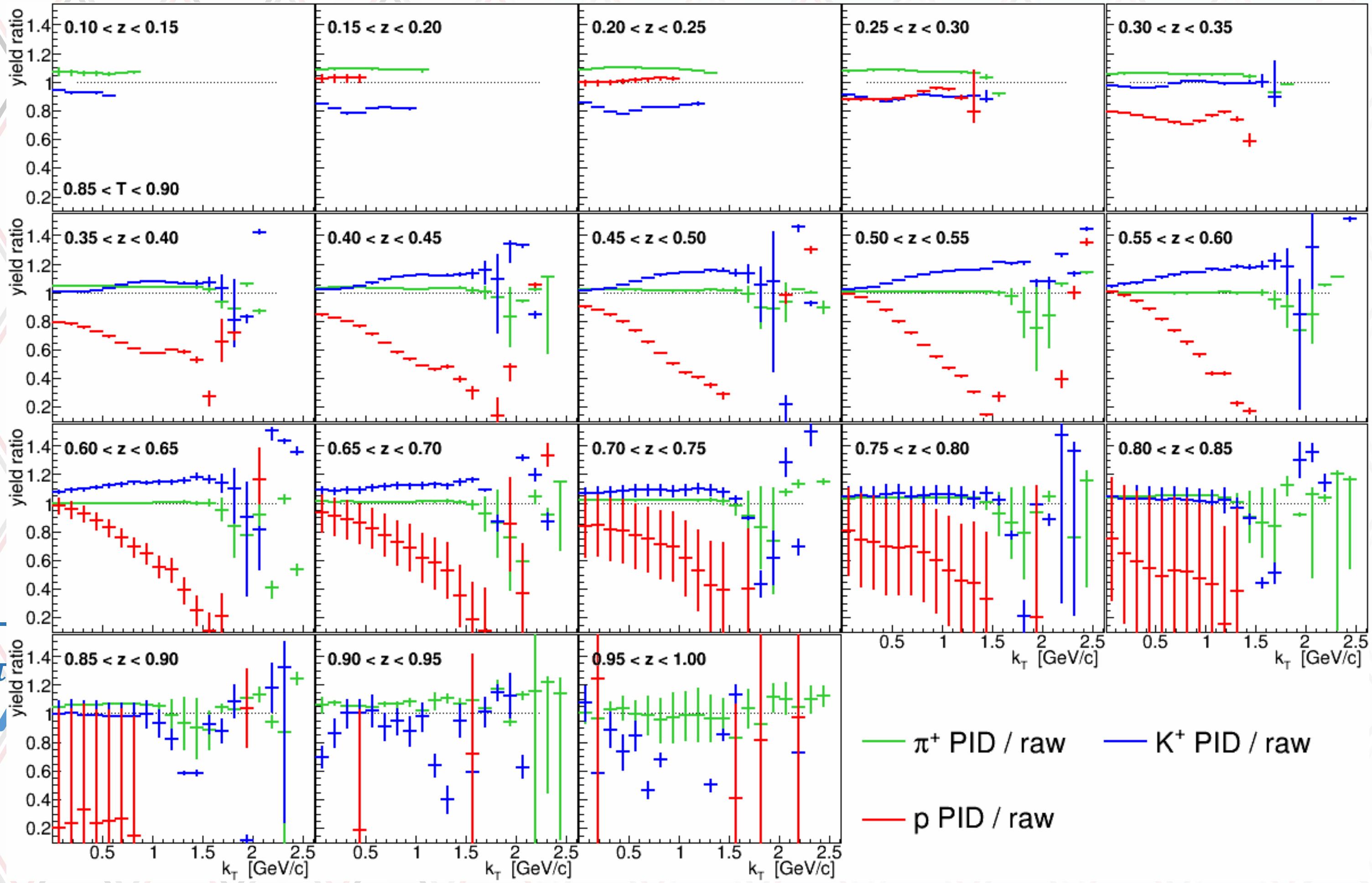
Correction chain

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

PID correction

Using Martin Leitgab's 5x5 PID matrices in fine 17 x 9 P_{lab} x $\cos\theta_{lab}$ binning

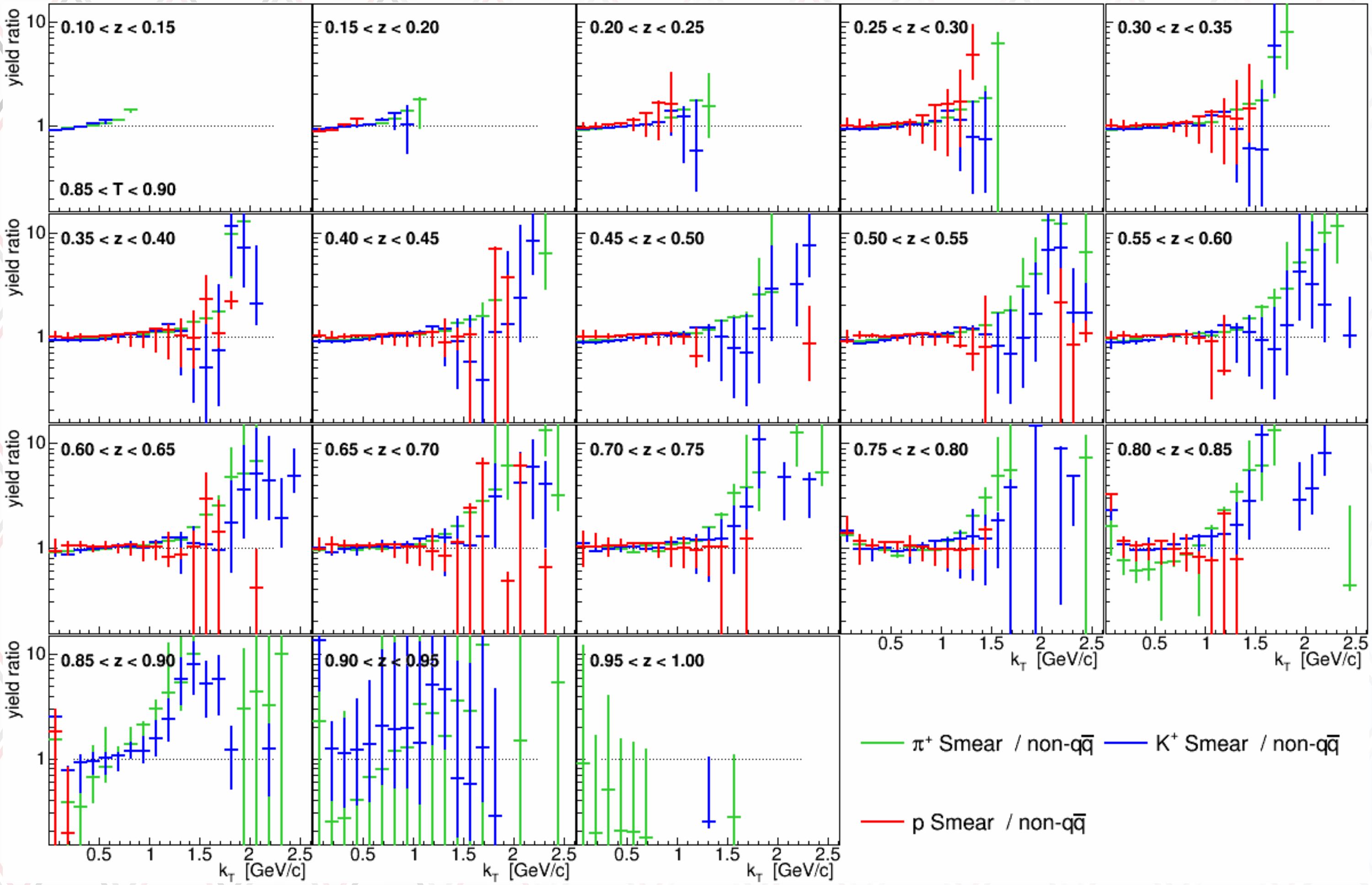


$$\frac{d^2\sigma}{dz dm_{\pi\pi}}$$

$m_{\pi\pi}$

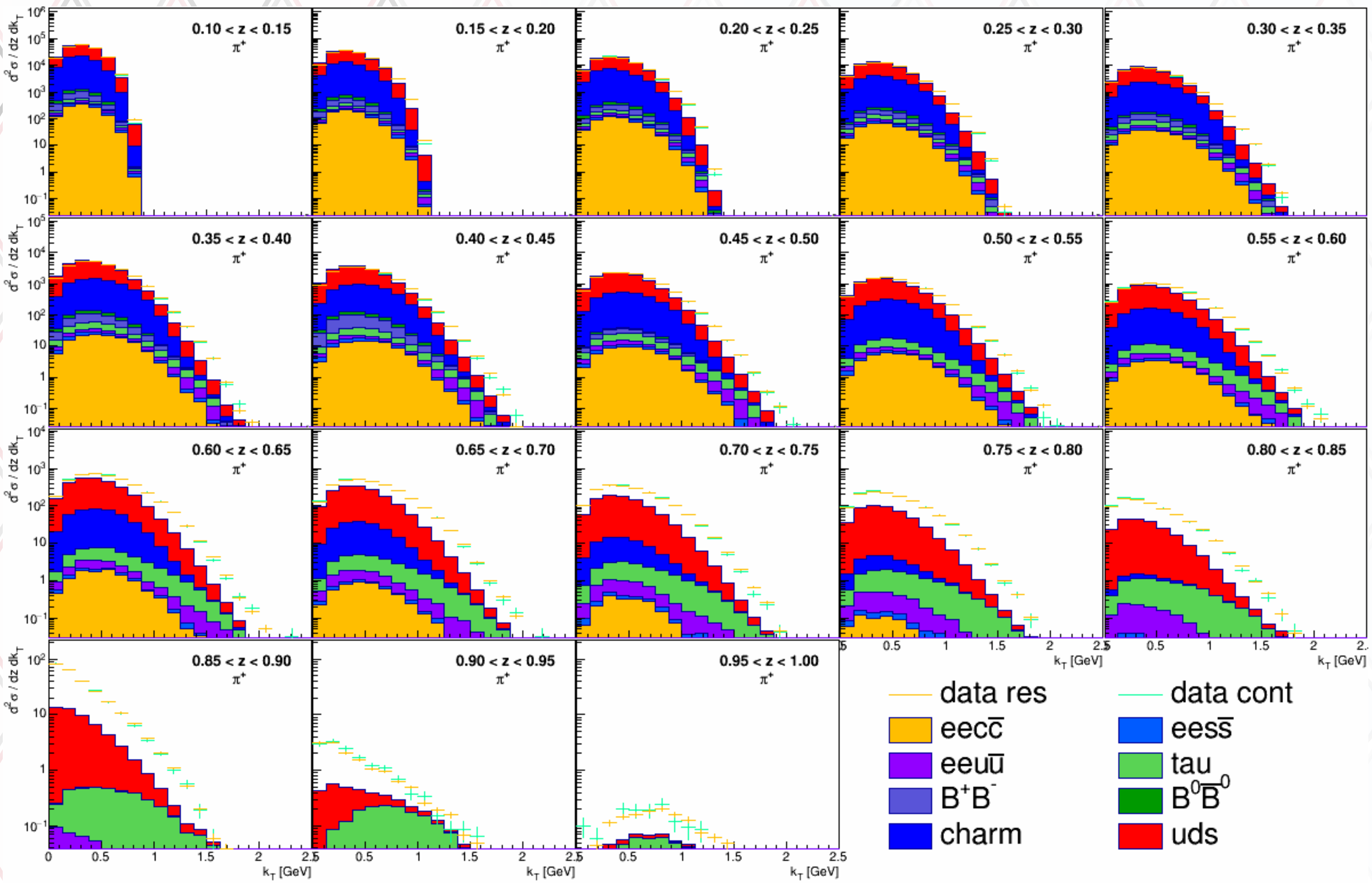
Smearing

- Reduced smearing matrices from 2160 x 2160 to filled (ie kinematically reachable bins)
- Using SVDUnfold Method in Root

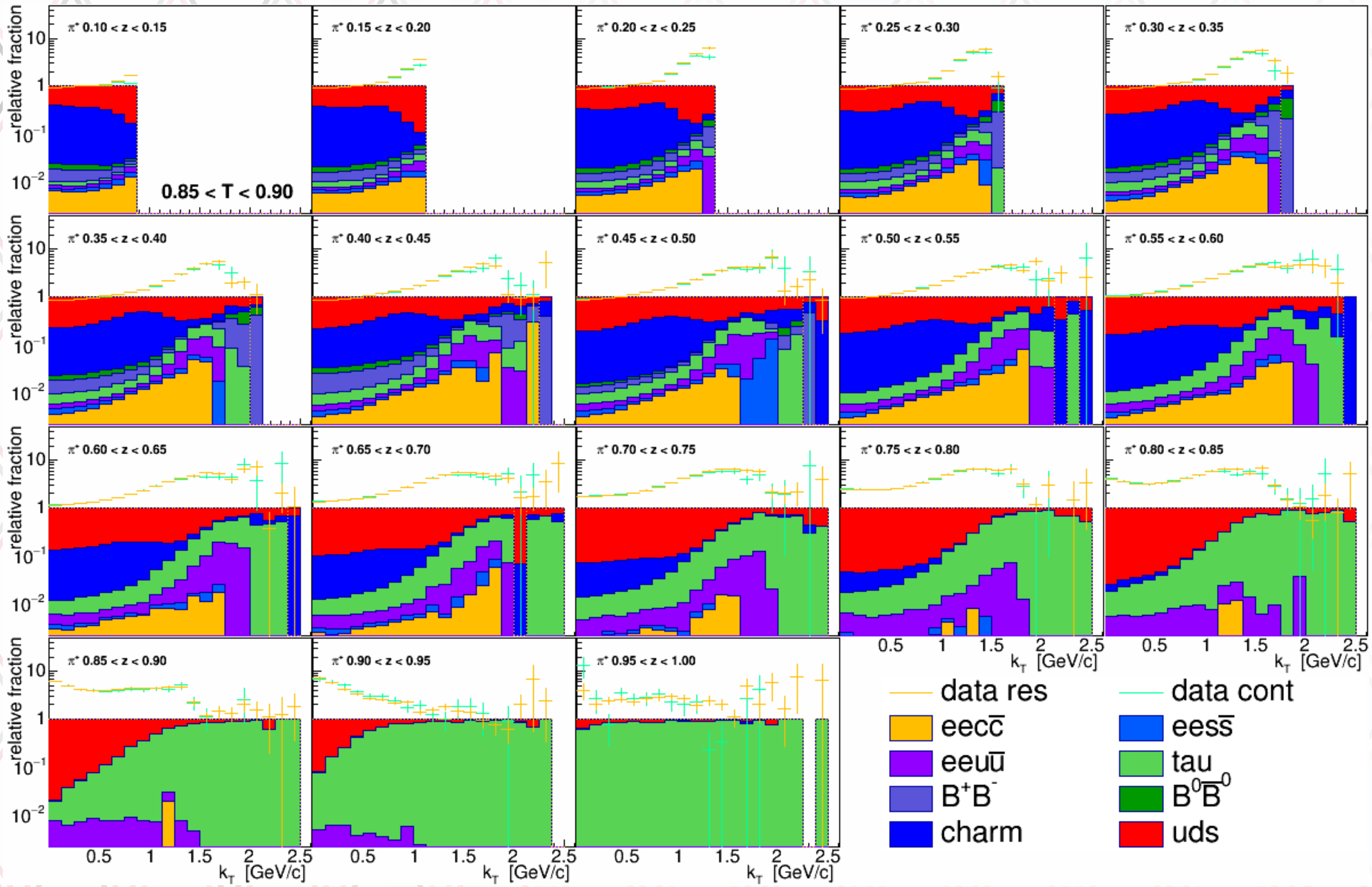


Non-qqbar removal:

Remove all two-photon and tau events from yields, contributions generally up to several %, slightly higher for kaons rand low thrust



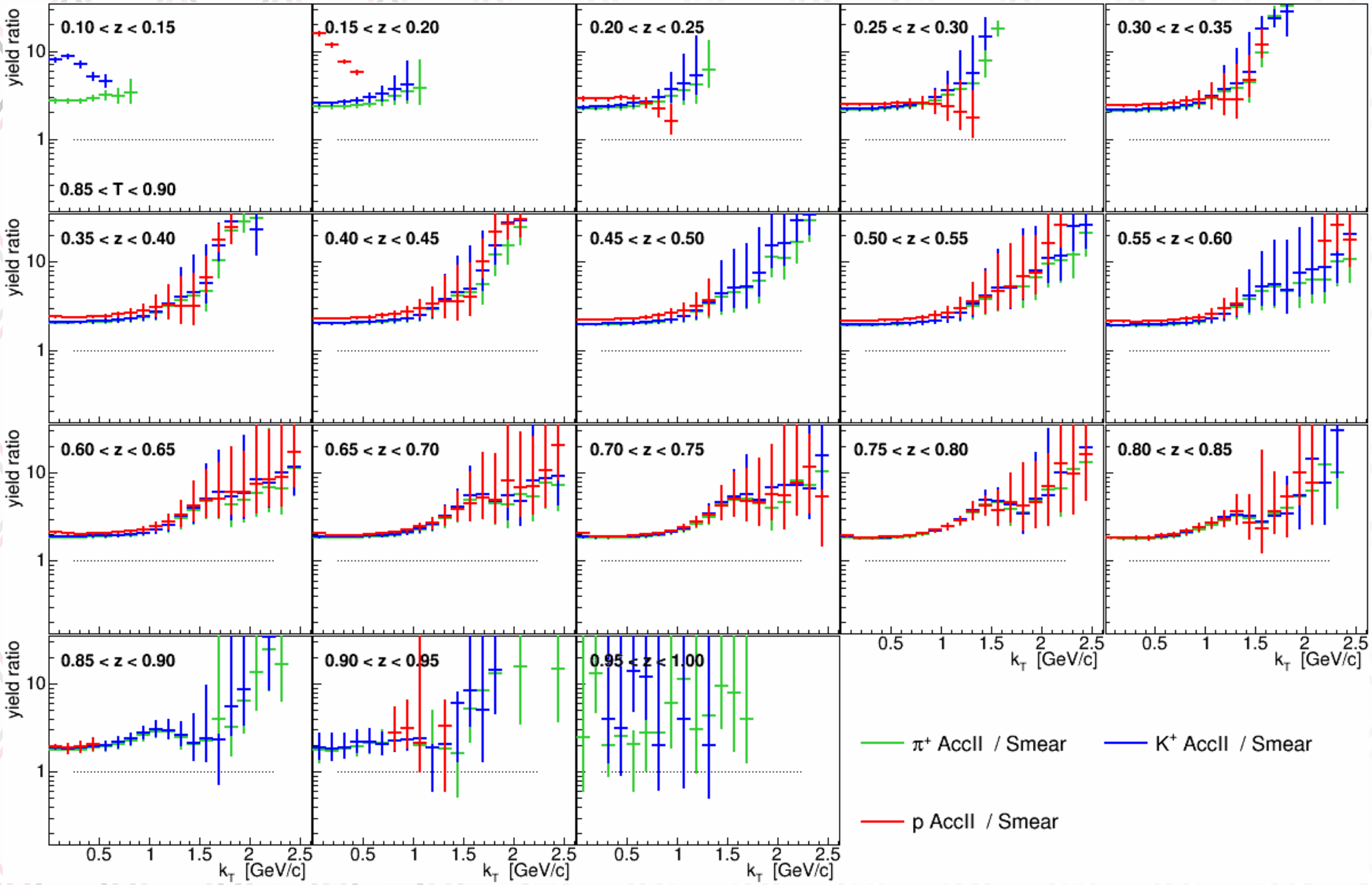
Stacked, relative contributions



Acceptance correction

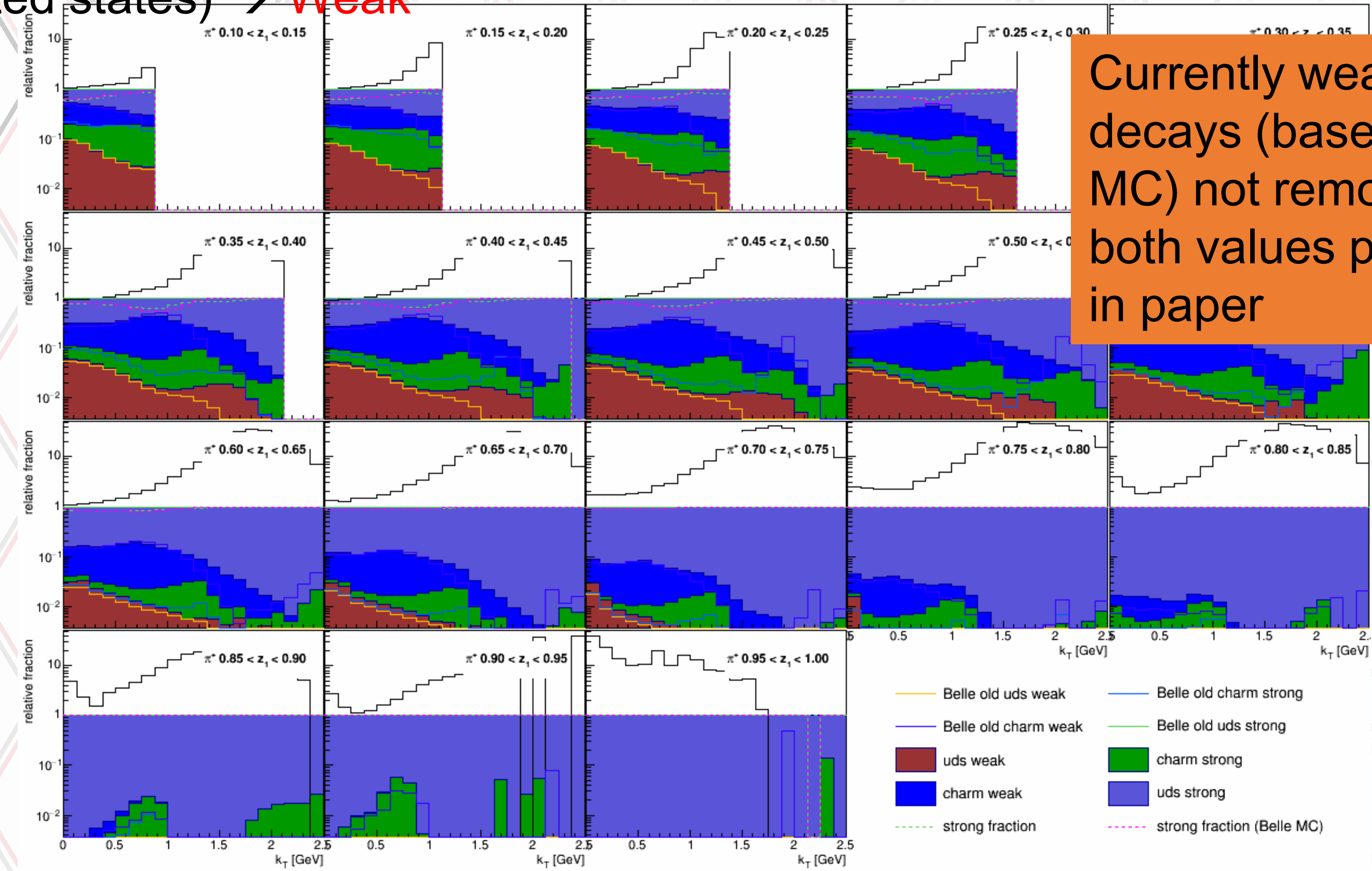
ACCI:Reconstruction and efficiency correction in Barrel acceptance

ACCII: Barrel to 4π correction



Weak correction(optional)

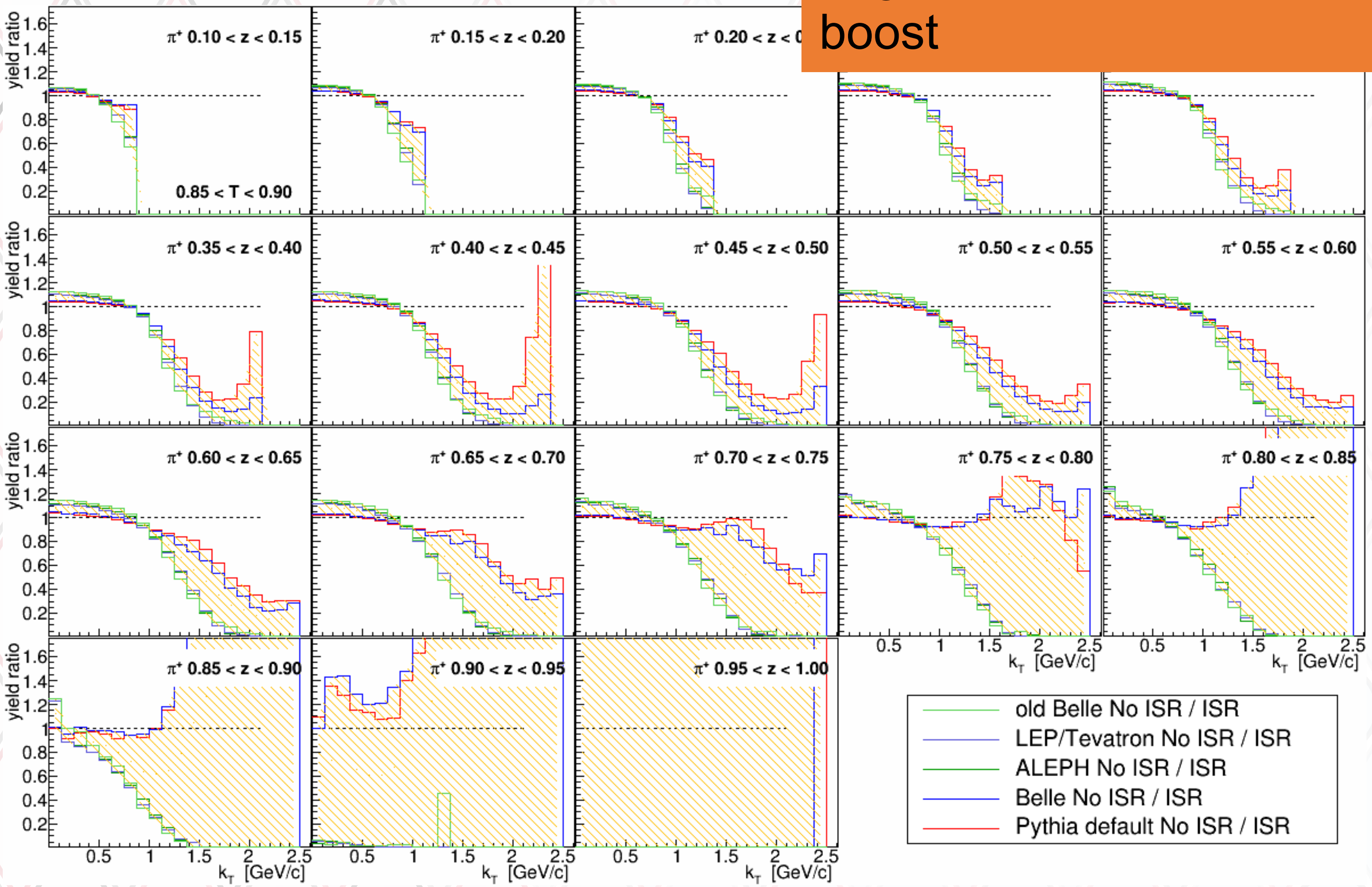
Traced in gen MC hadrons back to mothers with non ud content → if not vetoed (K*, ssbar, ccbar resonances, some hyperons and excited states) → Weak



Currently weak decays (based on MC) not removed: both values provided in paper

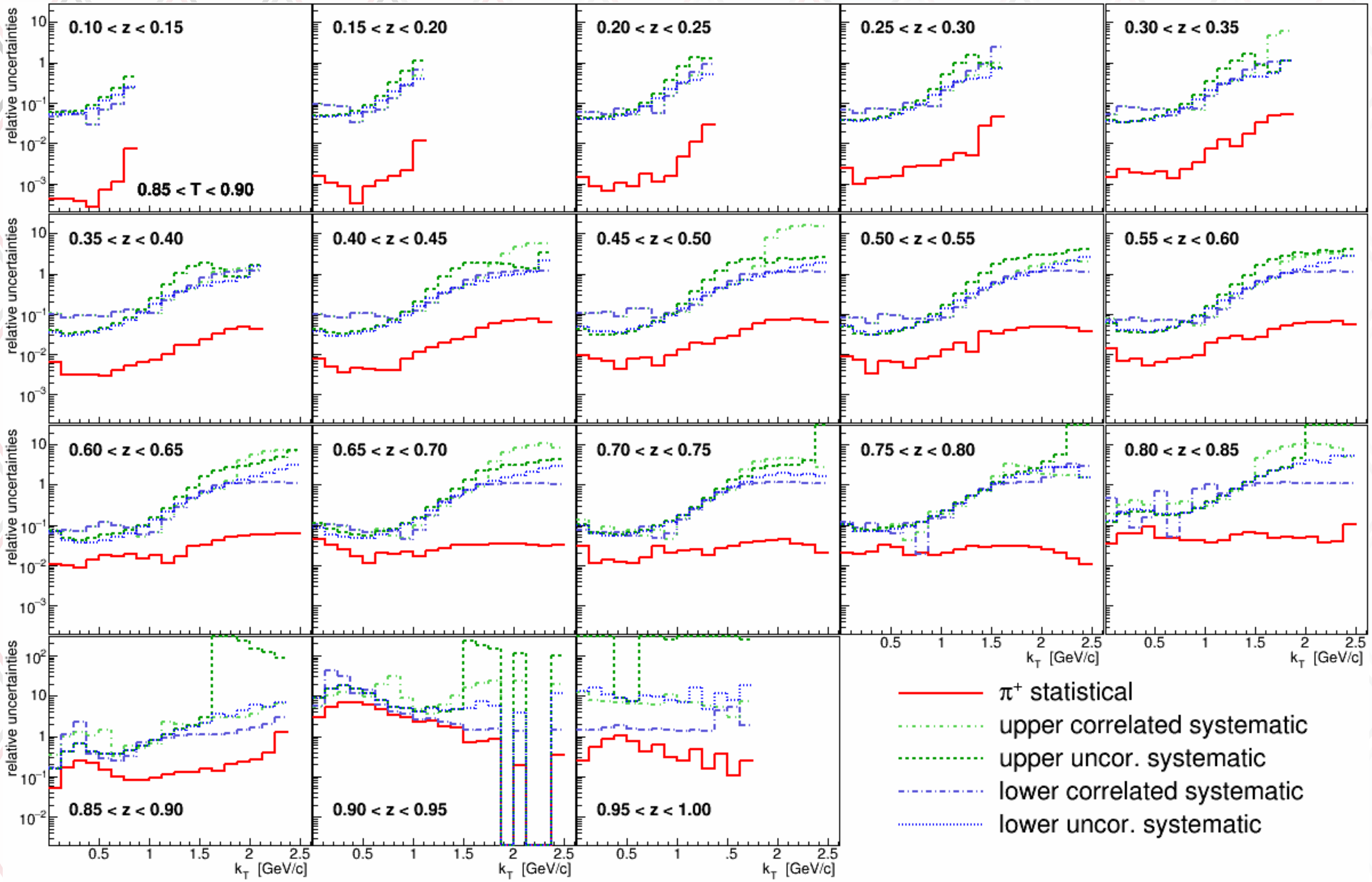
ISR correction

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

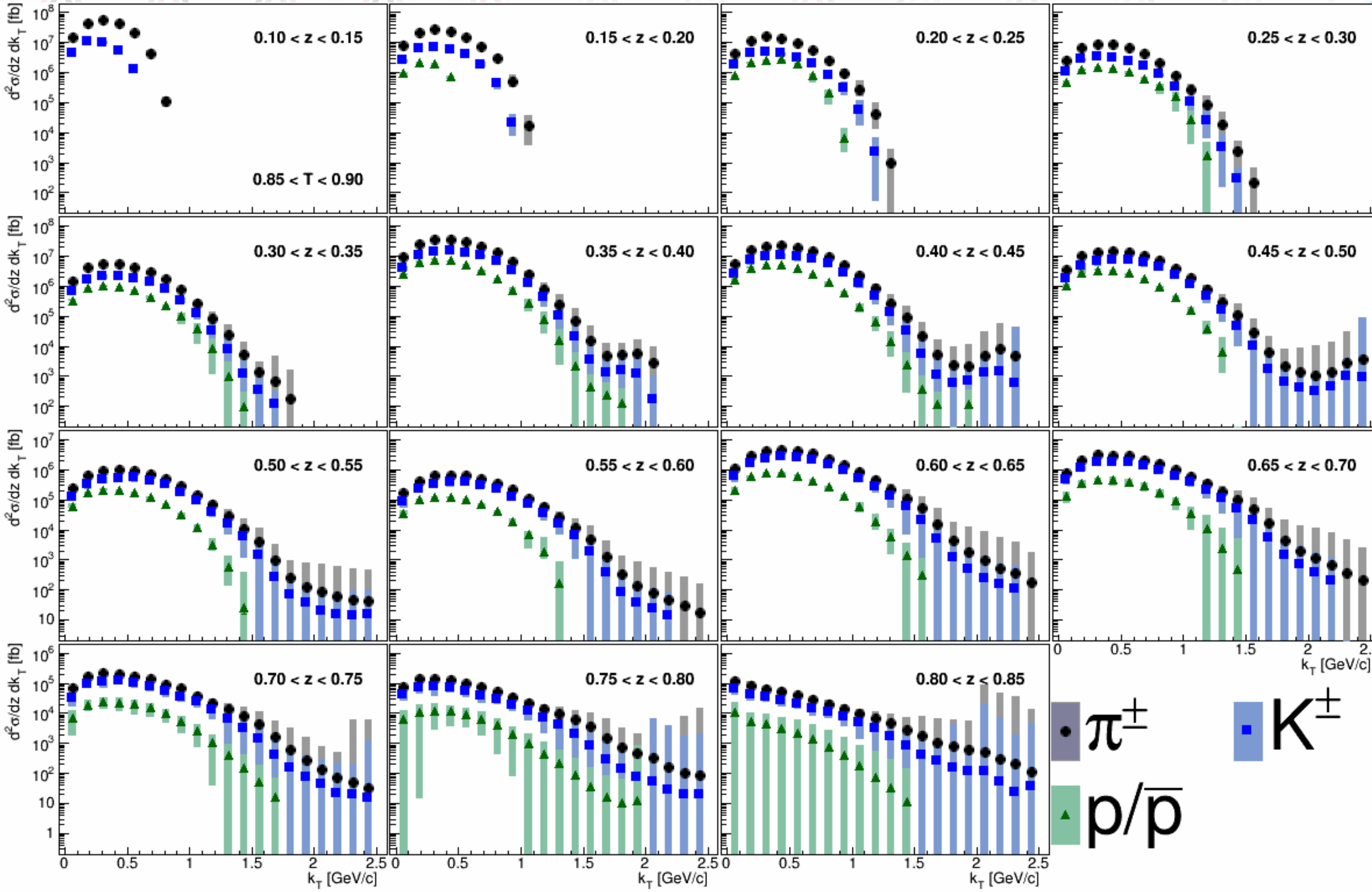


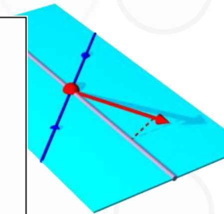
Overall systematic uncertainties

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



MC sample for various hadrons



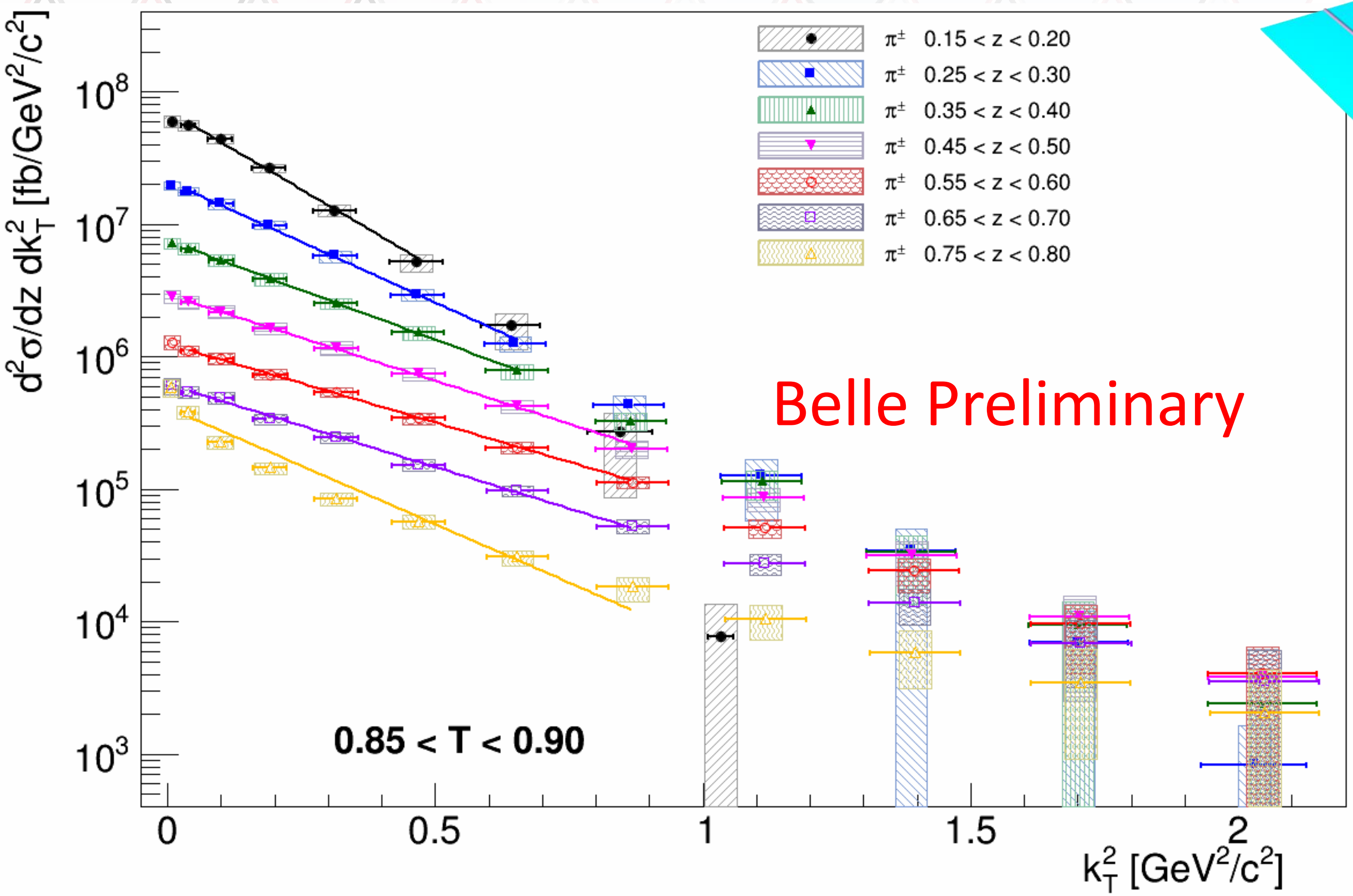


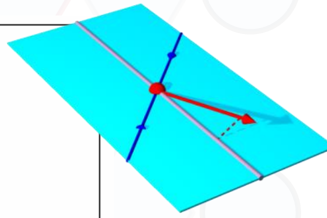
$\frac{d^2\sigma}{dzdk_T}$

$\rightarrow k_T$

Fits vs k_T^2

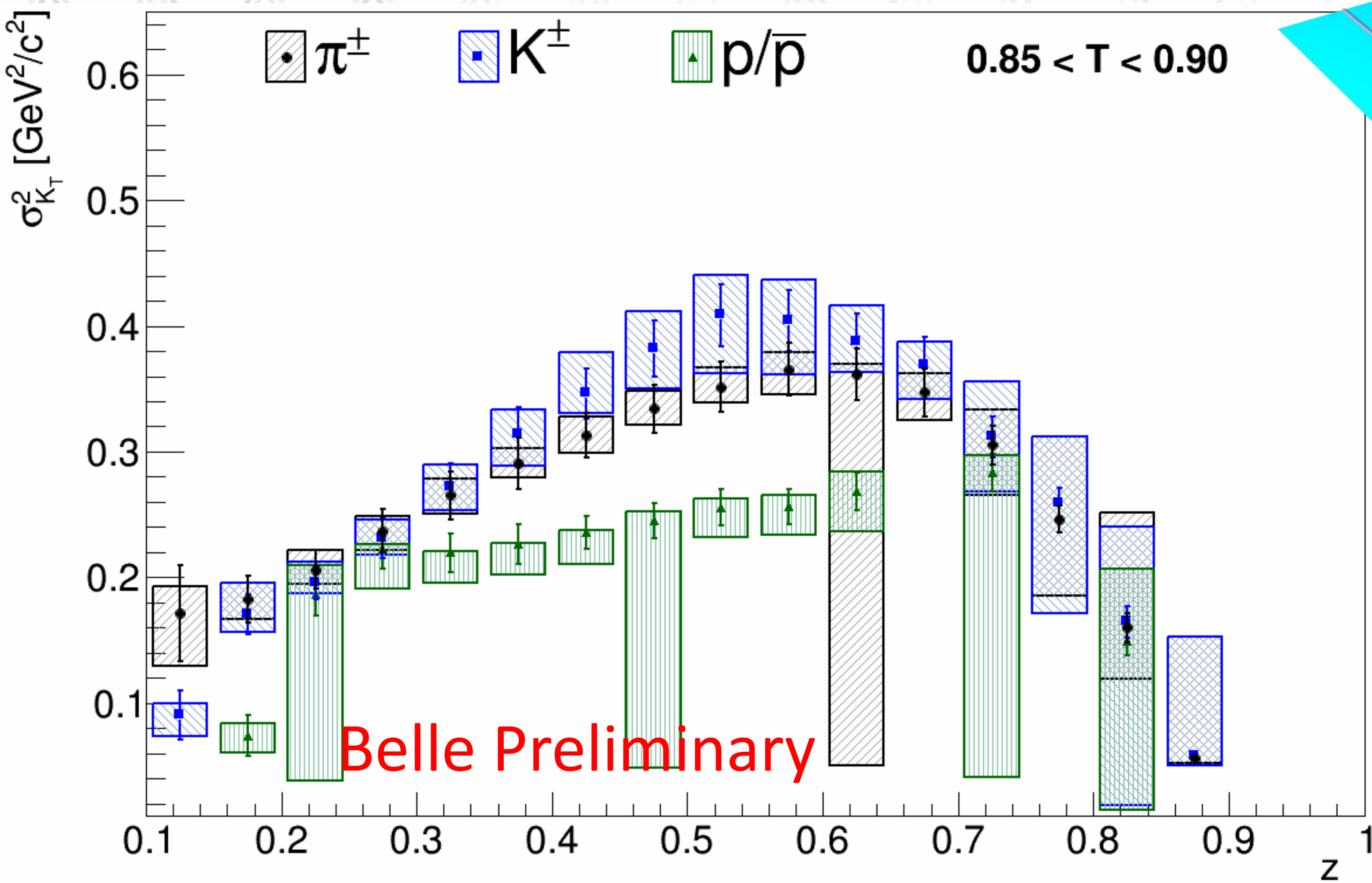
Fit exponential to smaller transverse momenta for Gaussian k_T dependence and power low at higher k_T

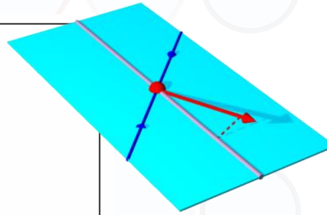




Gaussian widths

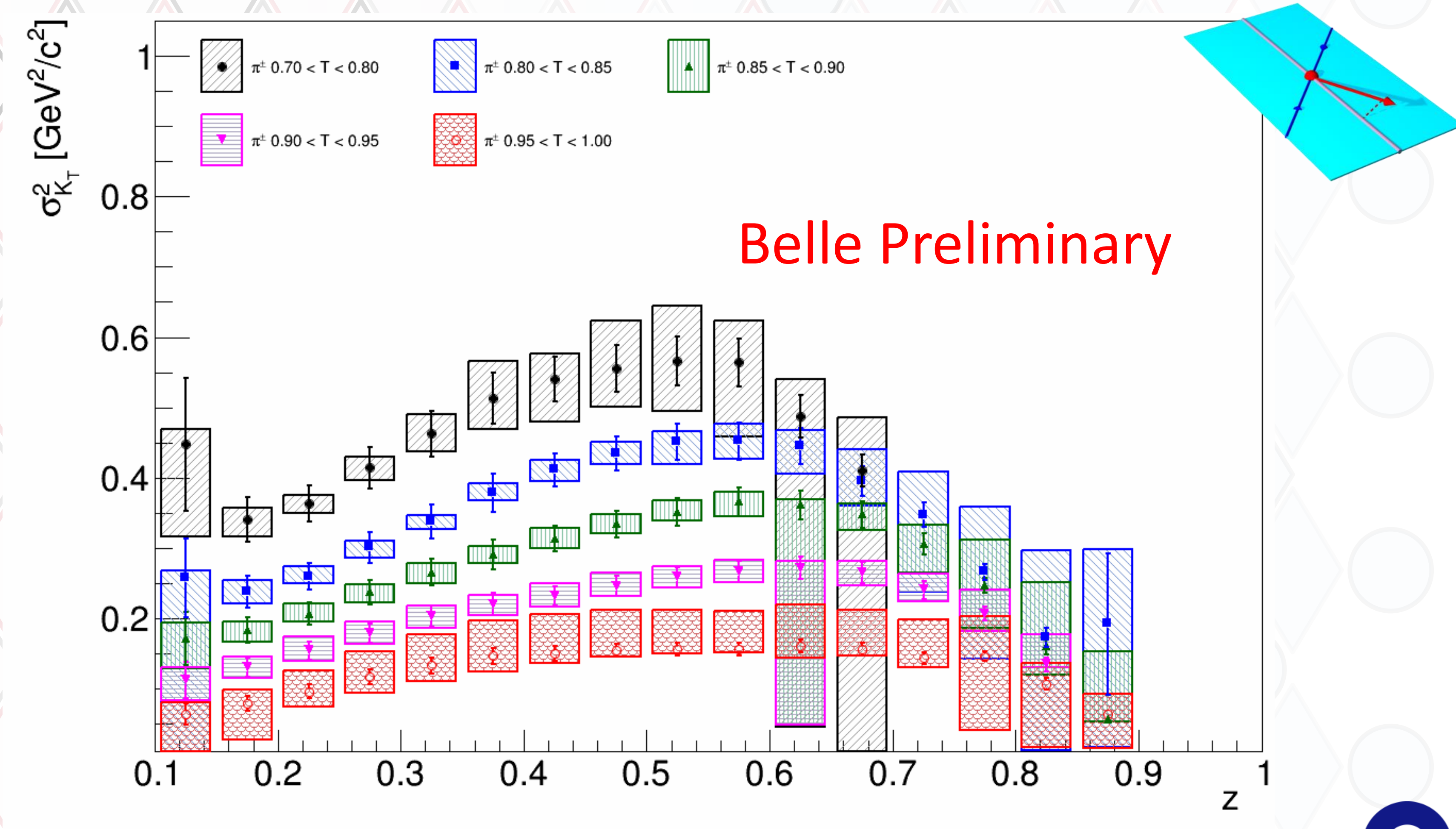
first direct (no convolutions) measurement of z dependence of Gaussian widths





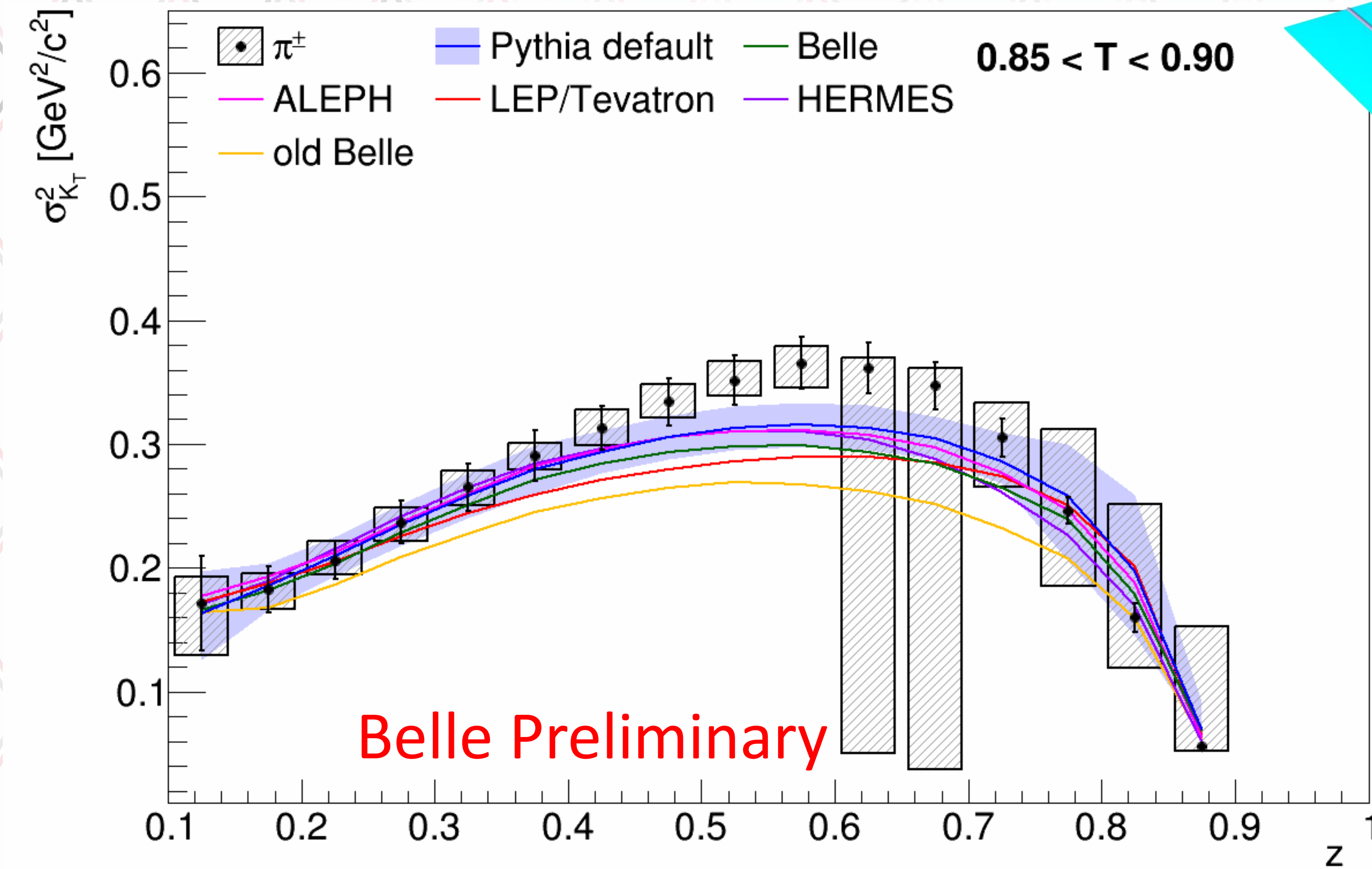
Gaussian widths, thrust dependence

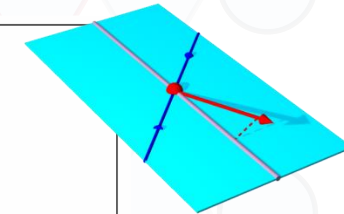
Gaussian widths get narrower with higher Thrust



Gaussian widths comparison to MC

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





Summary

- Kt 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?)
- Final 1-week internal review before submission to PRD
- Upon acceptance consider media announcement

Differences in Pythia/JetSet settings

Par	0	1	9	10	11	12	13	udscatlas	udschermes
	Pythia def.	belle	Atlas	Aleph	LEP/tev.	Hermes	gen Belle		
PARJ(1)	0.1			0.106	0.073	0.029			0.029
PARJ(2)	0.3			0.285	0.2	0.283			0.283
PARJ(3)	0.4			0.71	0.94	1.2			1.2
PARJ(4)	0.05			0.05	0.032				
PARJ(11)	0.5			0.55	0.31				
PARJ(12)	0.6			0.47	0.4				
PARJ(13)	0.75			0.65	0.54				
PARJ(14)	0.0	0.0	0.0	0.02	0.0	0.0	0.05	0.0	0.0
PARJ(15)	0.0	0.0	0.0	0.04	0.0	0.0	0.05	0.0	0.0
PARJ(16)	0.0		0.0	0.02	0.0	0.0	0.05	0.0	0.0
PARJ(17)	0.0	0.0	0.0	0.2	0.0	0.0	0.05	0.0	0.0
PARJ(19)	1			0.57					
PARJ(21)	0.36			0.37	0.325	0.400	0.28	0.28	0.400
PARJ(25)	1				0.63		0.27	0.27	
PARJ(26)	0.4			0.27	0.12		0	0	
PARJ(33)	0.8		0.8	0.8	0.8	0.3		0.8	0.8
PARJ(41)	0.3			0.4	0.5	1.94	0.32	0.32	1.94
PARJ(42)	0.58			0.796	0.6	0.544	0.62	0.62	0.544
PARJ(45)	0.5					1.05			1.05
PARJ(46)	1.						1.0	1.0	
PARJ(47)	1.				0.67				
PARJ(54)	-0.050	-0.040	-0.050	-0.04	-0.050	-0.050		-0.050	-0.050
PARJ(55)	-0.005	-0.004	-0.005	-0.0035	-0.005	-0.005		-0.005	-0.005
PARJ(81)	0.29			0.292	0.29		0.38	0.38	
PARJ(82)	1.0			1.57	1.65		0.5	0.5	
MSTJ(11)	4			3	5		4	4	
MSTJ(12)	2			3		1			1
MSTJ(26)	2	0	2	2	2	2	0	2	2
MSTJ(45)	5					4			4
MSTJ(107)	0	1	0	0	0	0	1	0	0

VM suppression

P_x, P_y Gauss width

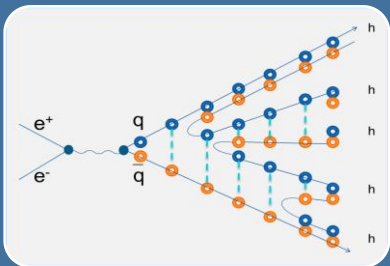
Lund params

Λ_{QCD} and E cutoff

Pythia/Jetset parameters

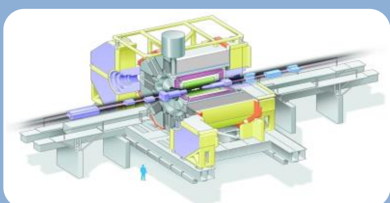
PARJ(1)	:	Diquark suppression relative to quark antiquark production
PARJ(2)	:	Strangeness suppression relative to u or d pair production
PARJ(3)	:	Extra suppression of strange diqurks relative to strange quark production
PARJ(4)	:	Axial (ud_1) vs scalar (ud_0) diquark suppression
PARJ(11)	:	Light meson with spin 1 probability
PARJ(12)	:	Strange meson with spin 1 probability
PARJ(13)	:	Charm meson with spin 1 probability
PARJ(14)	:	Spin 0 meson with L = 1 and J = 1 probability
PARJ(15)	:	Spin 1 meson with L = 1 and J = 0 probability
PARJ(16)	:	Spin 1 meson with L = 1 and J = 1 probability
PARJ(17)	:	Spin 1 meson with L = 1 and J = 2 probability
PARJ(19)	:	Extra baryon suppression relative to regular diquark suppression (if MSTJ(12) = 3)
PARJ(21)	:	Gaussian Width of p_x and p_y for primary hadrons
PARJ(25)	:	η production suppression factor
PARJ(26)	:	η' production suppression factor
PARJ(33)	:	Energy cutoff of fragmentation process
PARJ(41)	:	Lund a parameter: $(1-z)^a$
PARJ(42)	:	Lund b parameter: $exp(-bm_\perp^2/z)$
PARJ(45)	:	addition to a parameter for diquarks
PARJ(46)	:	modification of Lund fragmentation for heavy quarks with Bowler, charm, bottom
PARJ(47)	:	modification of Lund fragmentation for heavy quarks with Bowler, bottom
PARJ(54)	:	charm fragmentation functional form and value if MSTJ(11) = 2 or 3
PARJ(55)	:	bottom fragmentation functional form and value if MSTJ(11) = 2 or 3
PARJ(81)	:	Λ_{QCD} for parton showers
PARJ(82)	:	invariant mass cut-off for parton showers

What are fragmentation functions?



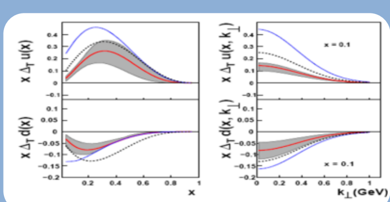
How do quasi-free partons fragment into confined hadrons？

- Does spin play a role？Flavor dependence?
- What about transverse momentum (and its Evolution)？



What experiments measure：

- Normalized hadron momentum in CMS： $e^+e^- \rightarrow h(z)\ X$; $z = 2E_h/\sqrt{s}$
- Hadron pairs' azimuthal distributions： $e^+e^- \rightarrow h_1\ h_2\ X$; $\langle\cos(\phi_1+\phi_2)\rangle$; Collins FF、Interference（IFF）
- Cross sections or multiplicities differential in z: ep->hX, pp->hX



Additional benefits of the FF measurements：

- Pol FFs necessary input to transverse spin SIDIS und pp measurements to extract Transversity distributions function
- Flavor separation of all Parton distribution functions (PDFs) via FFs (including unpolarized PDFs)
- Baseline for any Heavy Ion measurement
- Access to exotics?

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: δq x δq or
    - SIDIS/RHIC: δq x Collins or δq x IFF
  - FFs from Belle/Babar