Fragmentation Function measurements in Belle

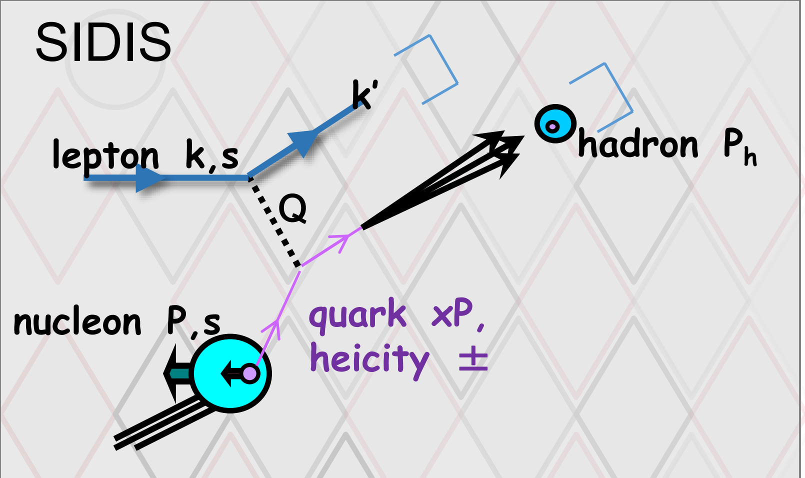
Pacific Spin 2019,
August 28, Miyazaki

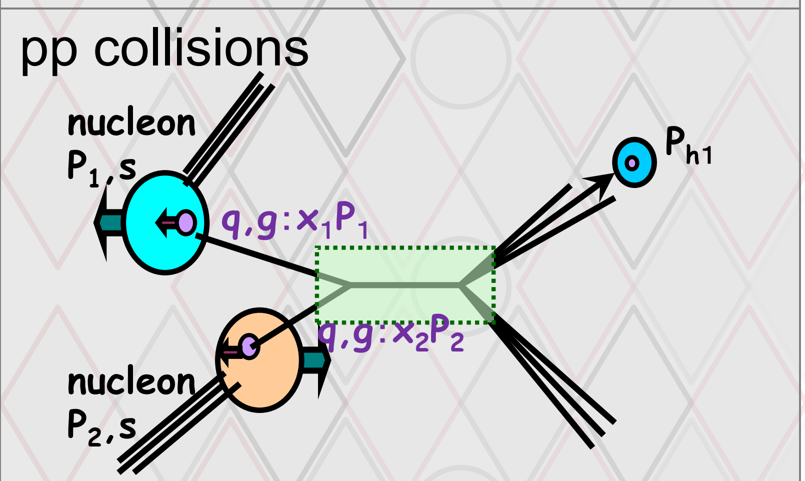
Ralf Seidl (RIKEN)

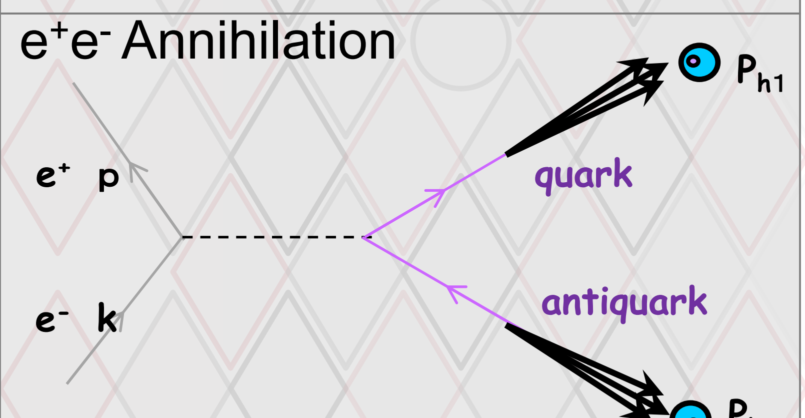
Fragmentation functions and spin structure of the nucleon

- 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

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

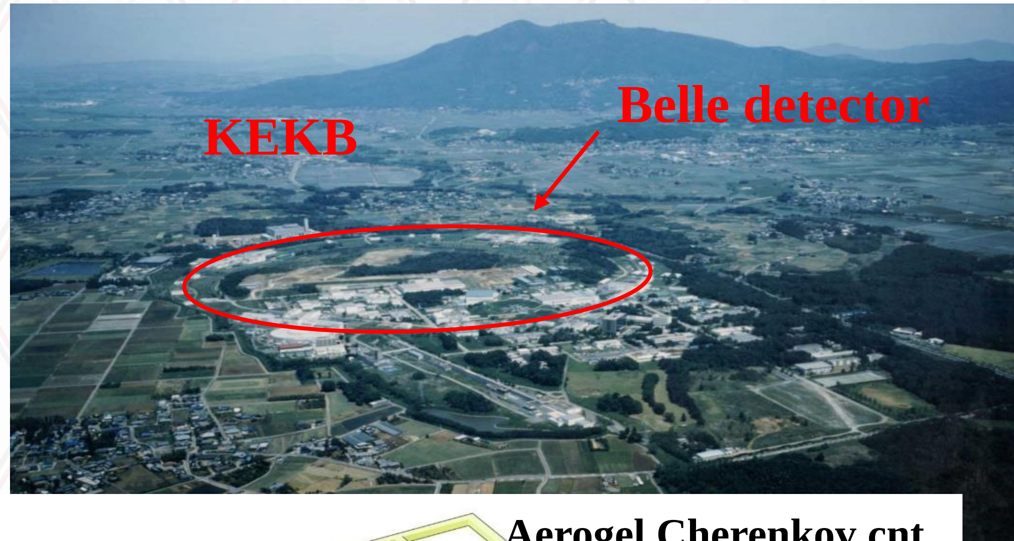
- e+e-:

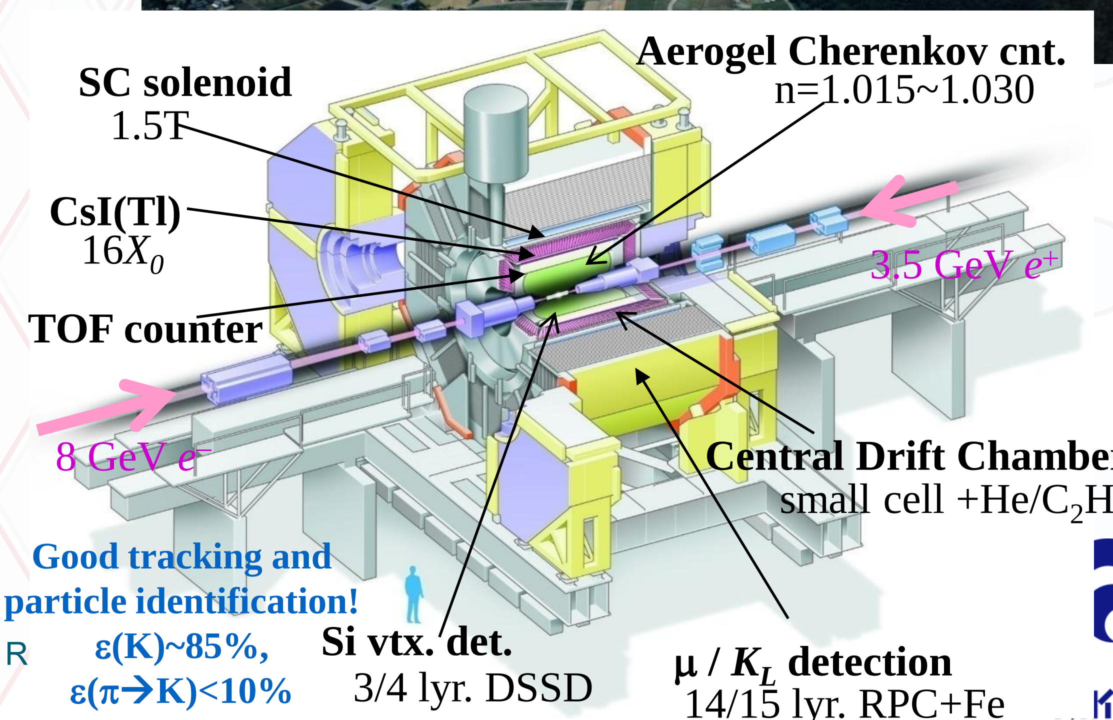
$$\sigma^h(z, Q^2, k_t) \propto \sum_q e_q^2 \left(D_{1,q}^h(z, k_t, Q^2) + D_{1,\bar{q}}^h(z, k_t, Q^2) \right)$$

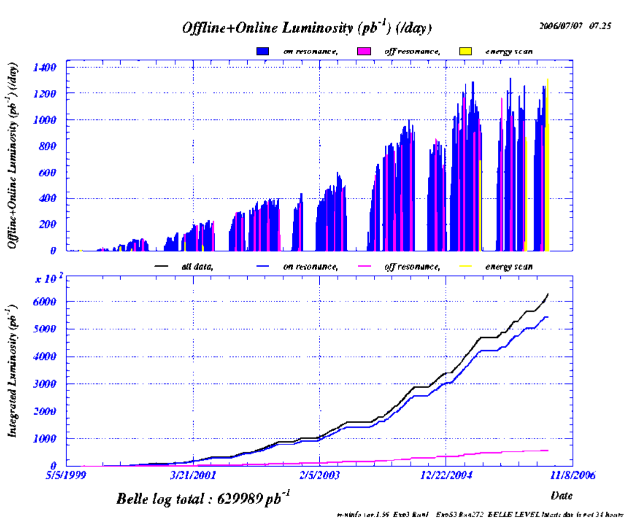
  - No PDFs necessary
  - Clean initial state, parton momentum known at LO
  - Flavor structure not directly accessible

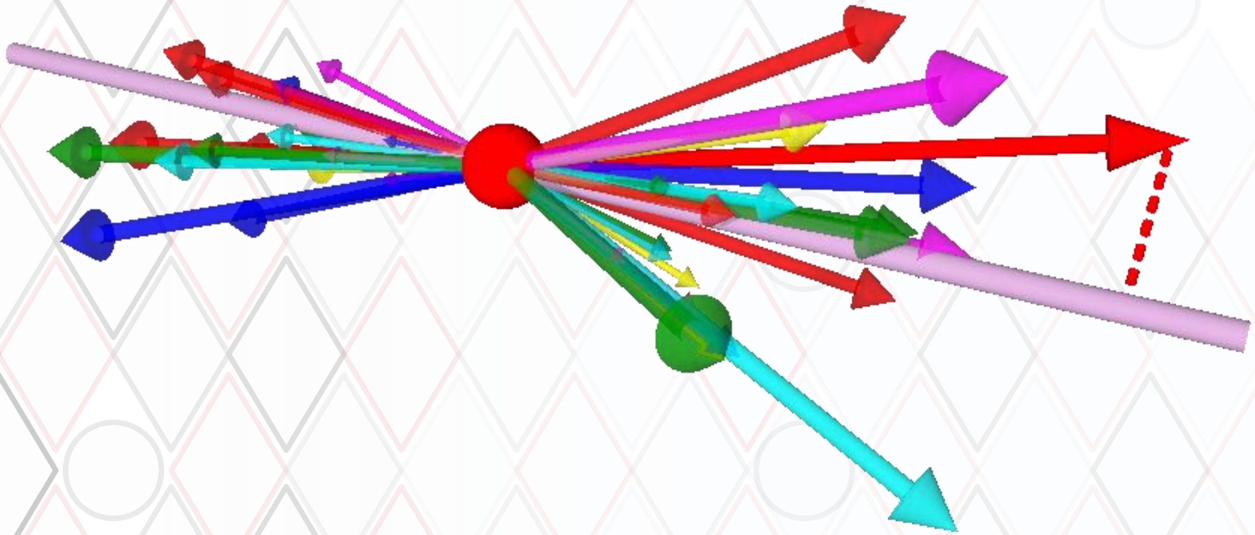
Belle Detector and KEKB

- Asymmetric collider
- 8GeV e^- + 3.5GeV e^+
- √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







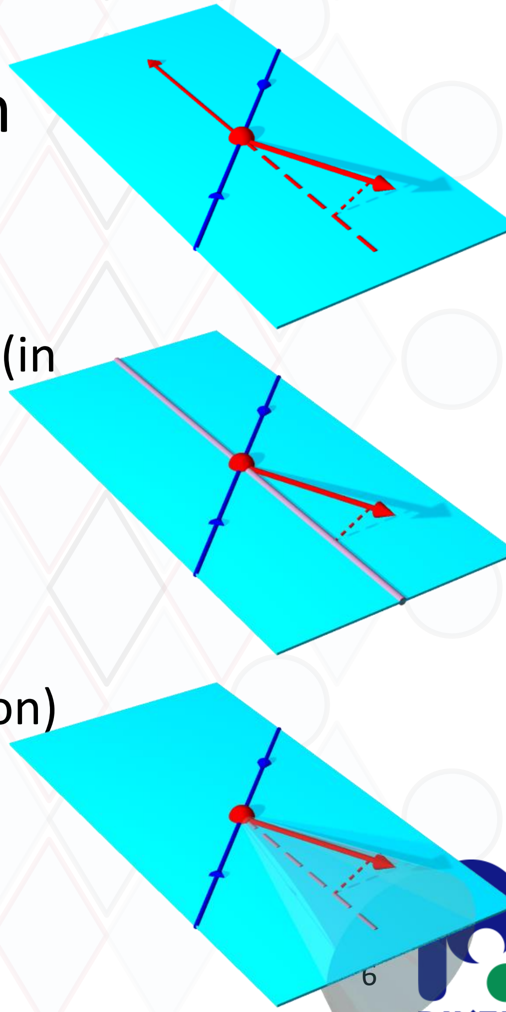


Transverse momentum dependence

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 (similar to a Jet function)



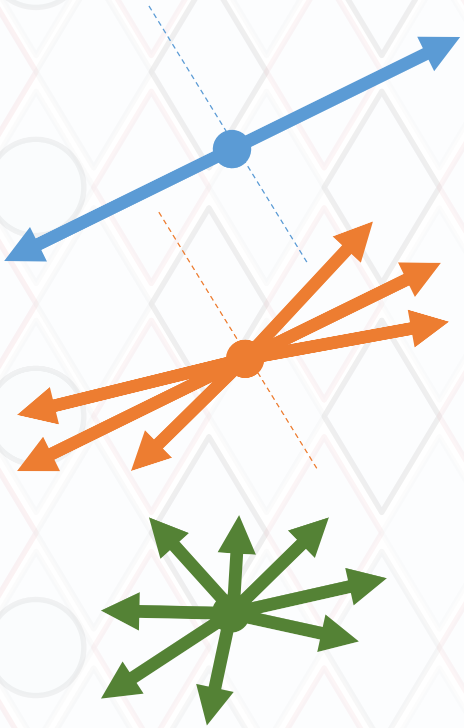
Thrust definition

- Event shape variable thrust is defined as:

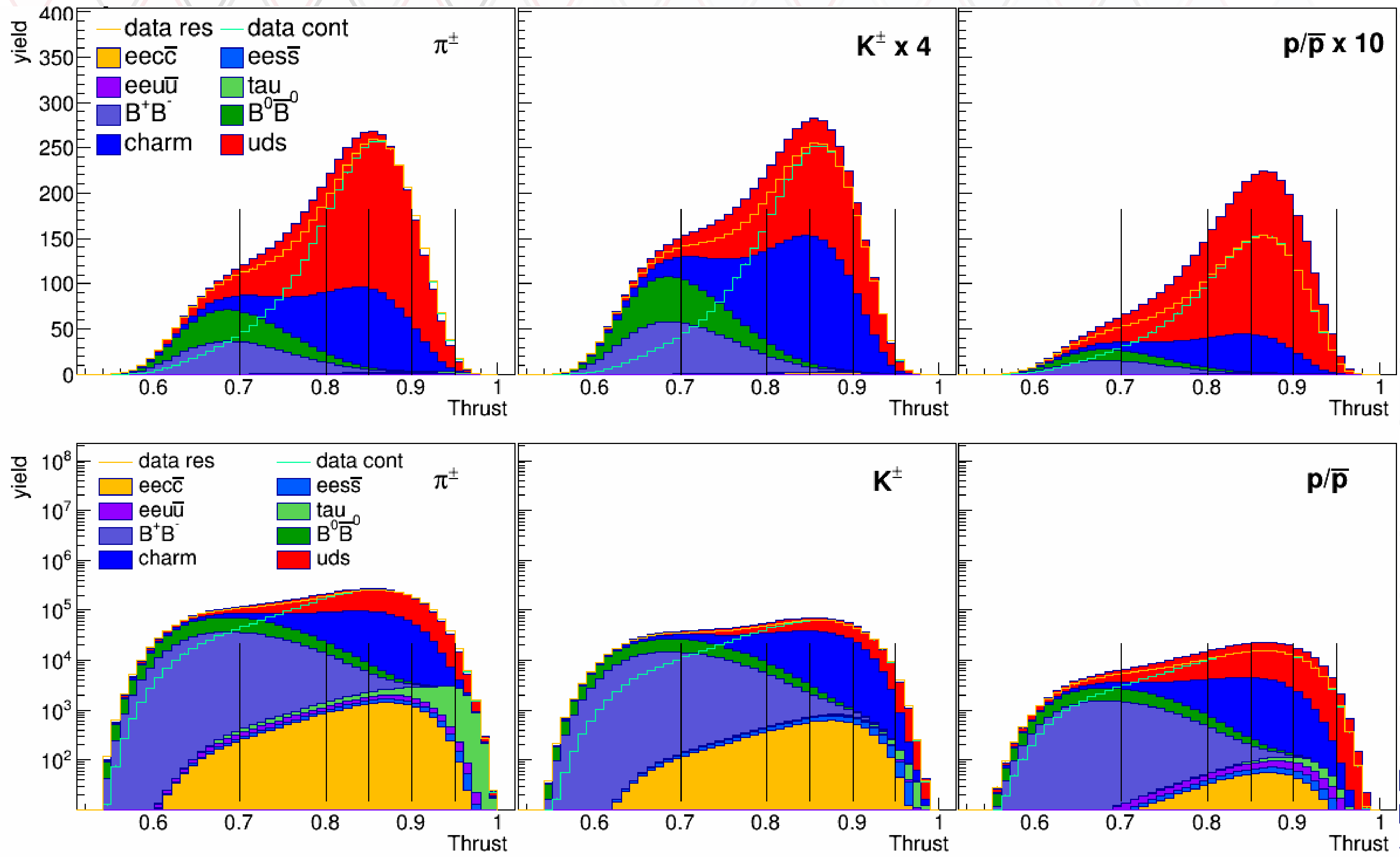
$$T \stackrel{max}{=} \frac{\sum_h |\mathbf{P}_h \cdot \hat{\mathbf{n}}|}{\sum_h |\mathbf{P}_h|}$$

- 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)



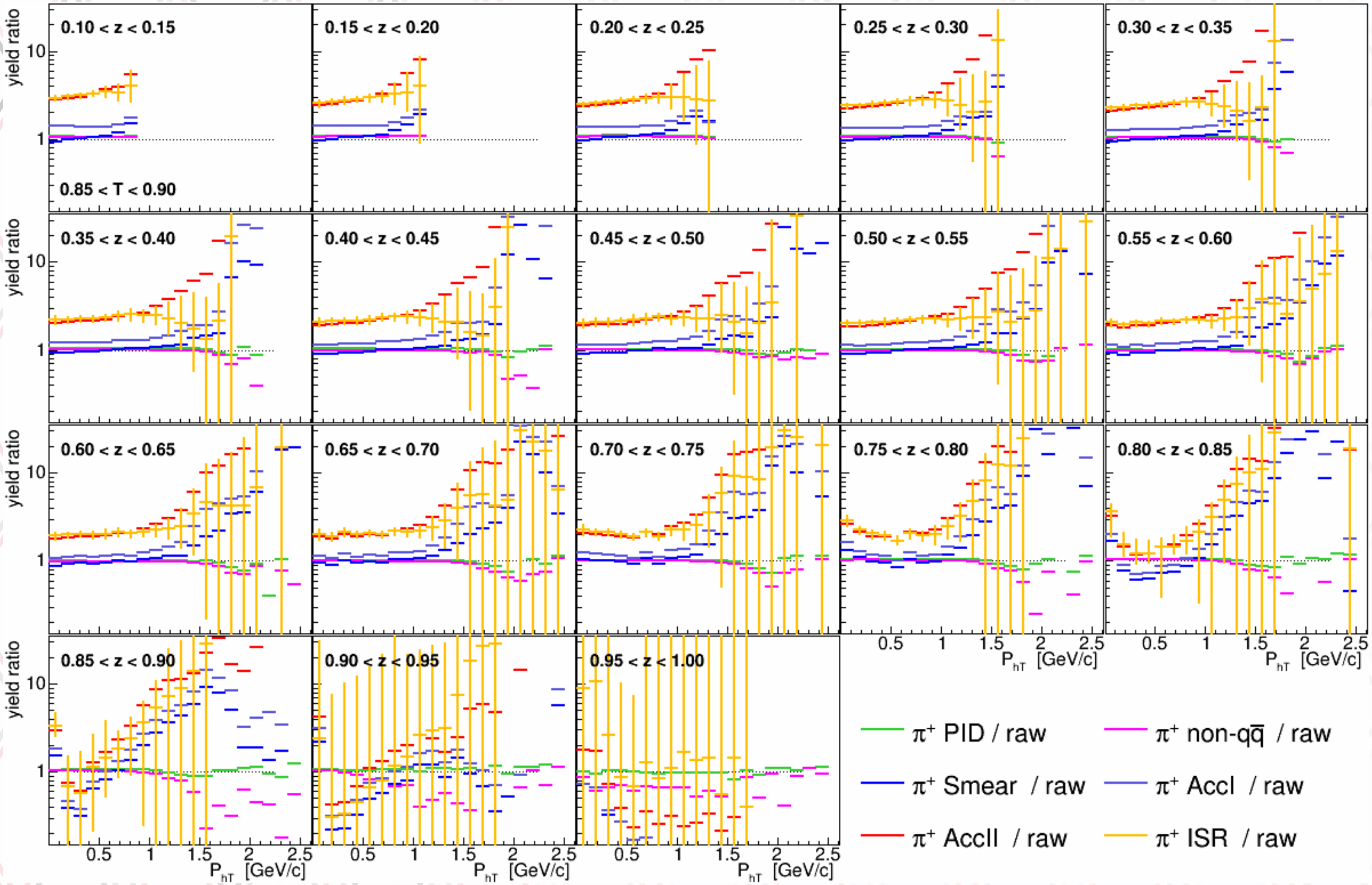
Correction chain

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

Total corrections impact

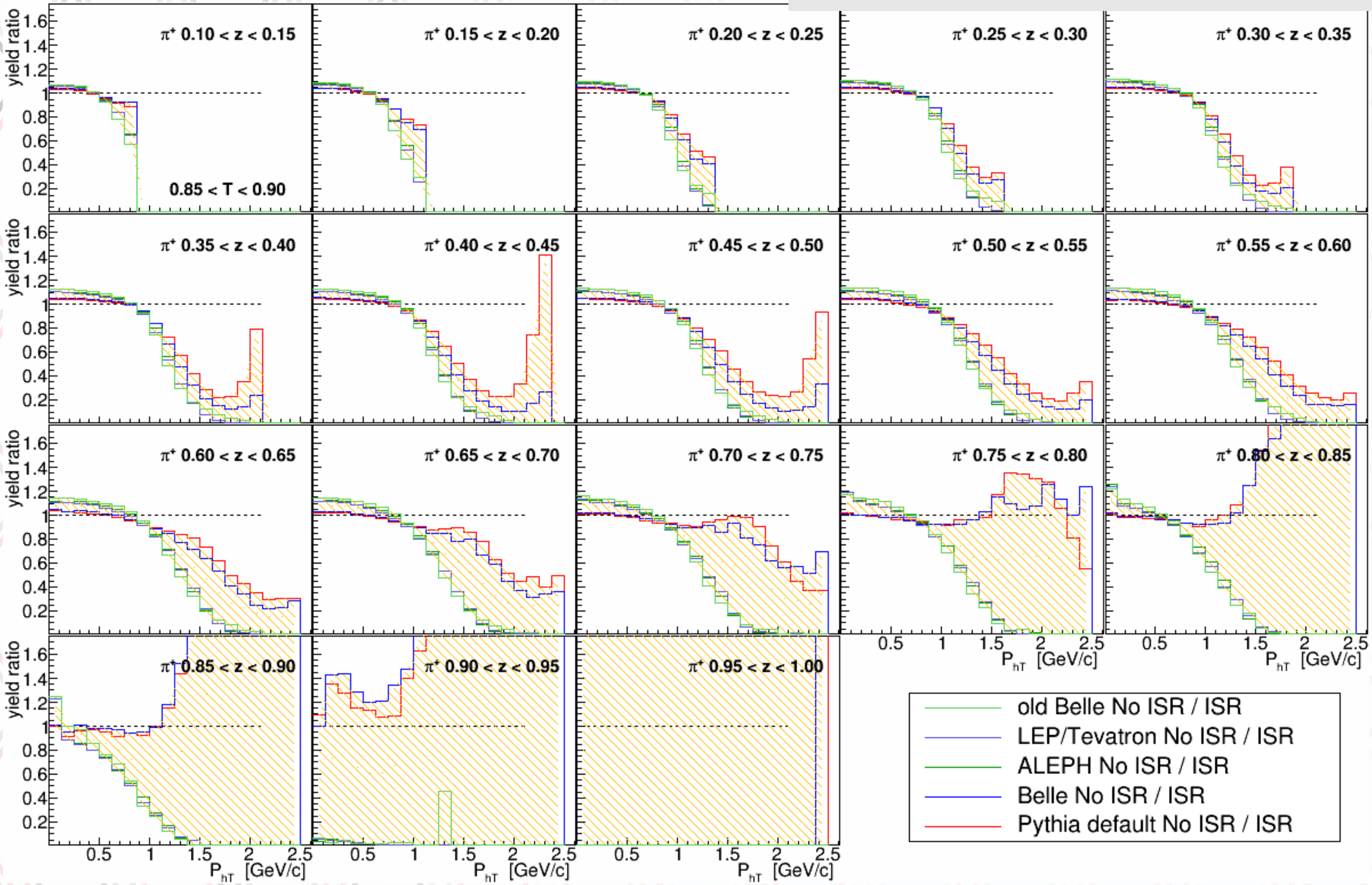
Most of the following slides display 0.85 < T< 0.9 Thrust bin



P_{Th}

ISR correction

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

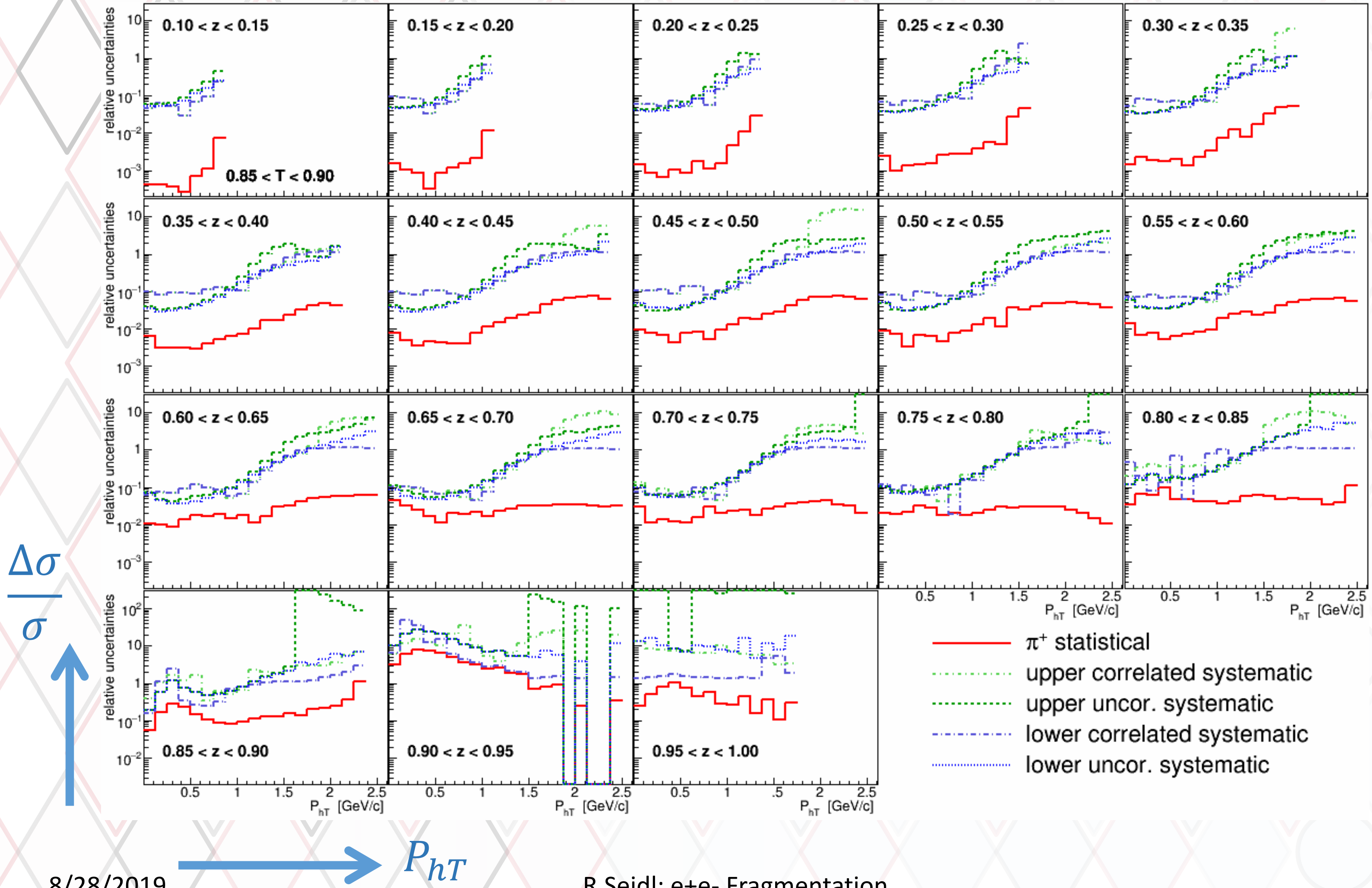


$\frac{\sigma_{No\ ISR}}{\sigma_{ISR}}$ ↑

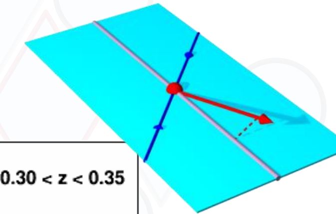
→ P_{Th}

Overall systematic uncertainties

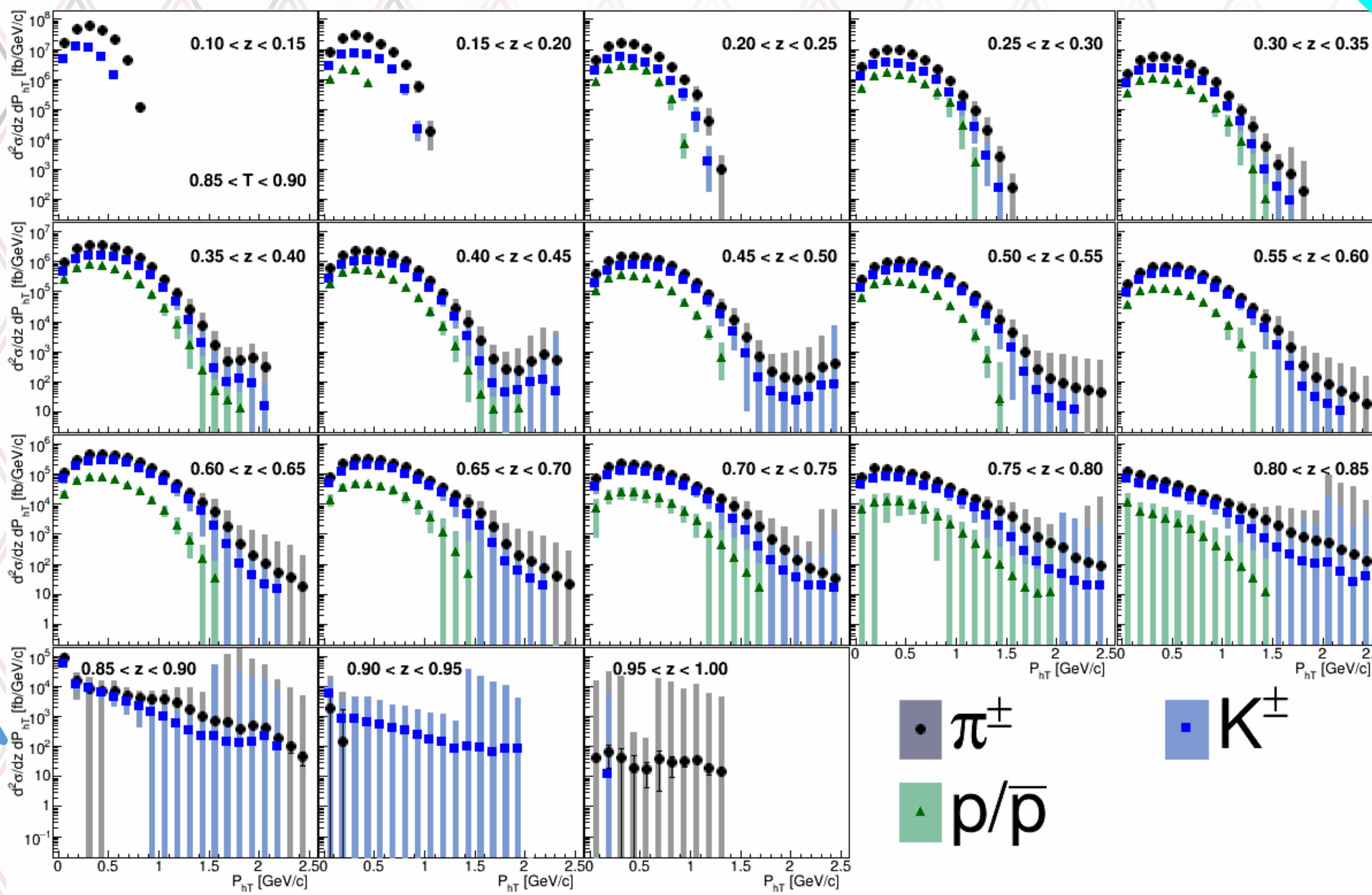
Systematic uncertainties dominated by acceptance correction (for different tunes), PID uncertainties and ISR correction



Cross sections various hadrons



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

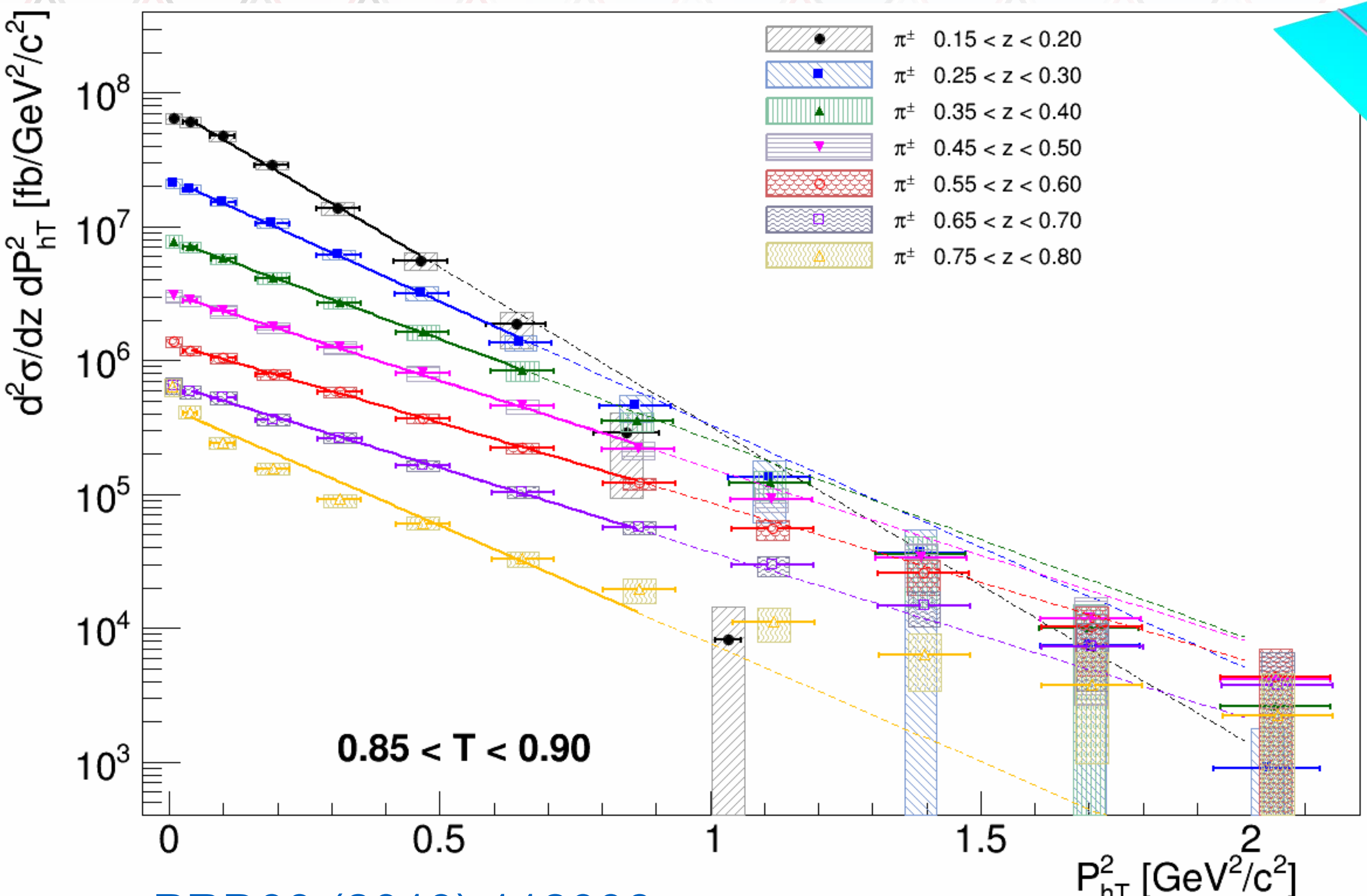


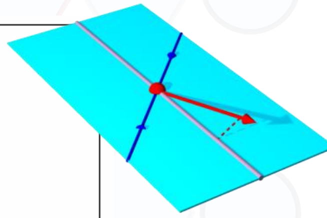
P_{hT}

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}





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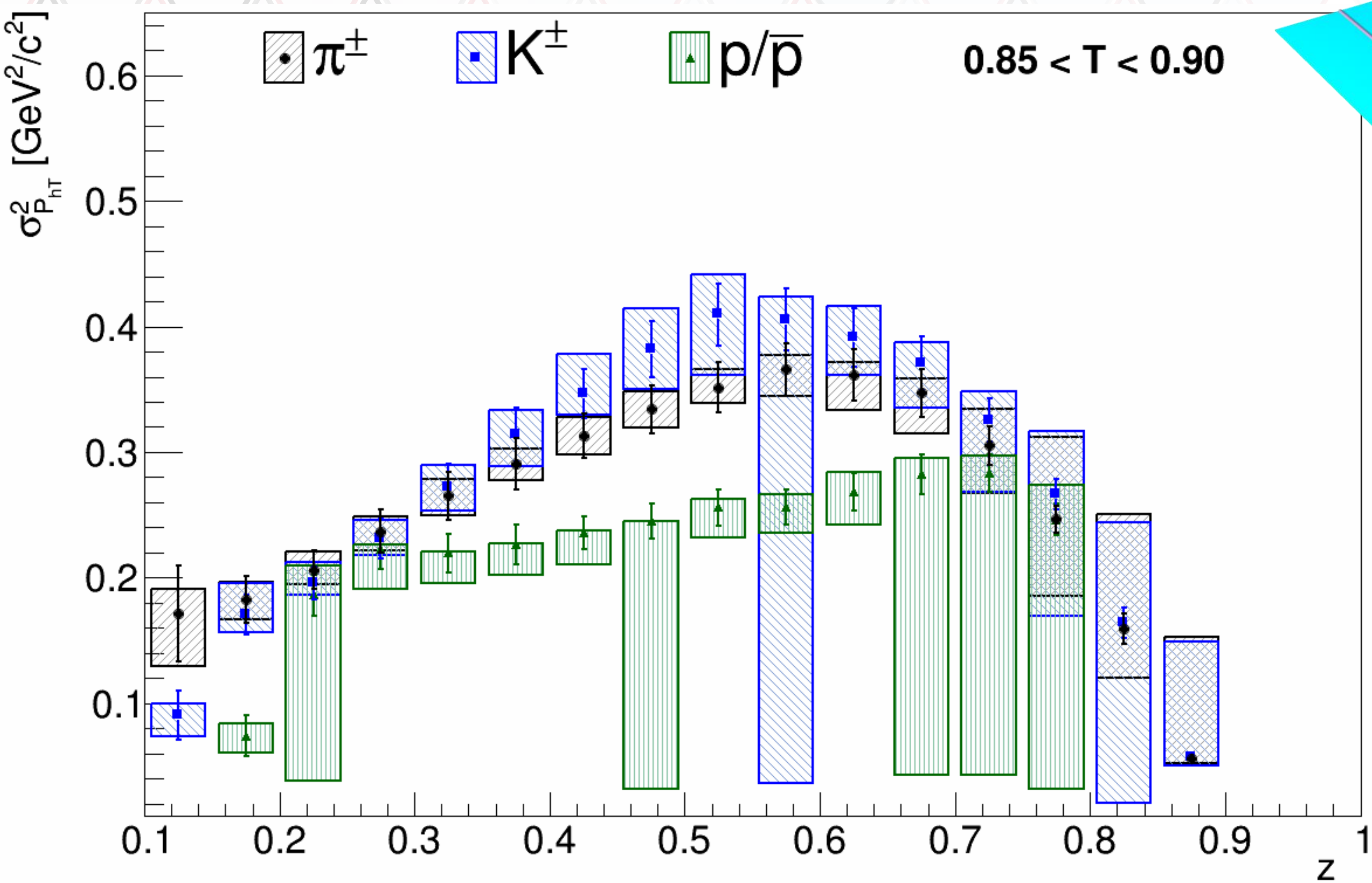
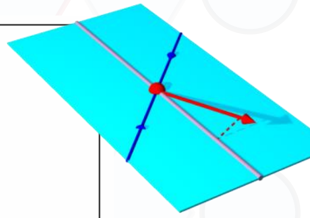
Gaussian widths

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



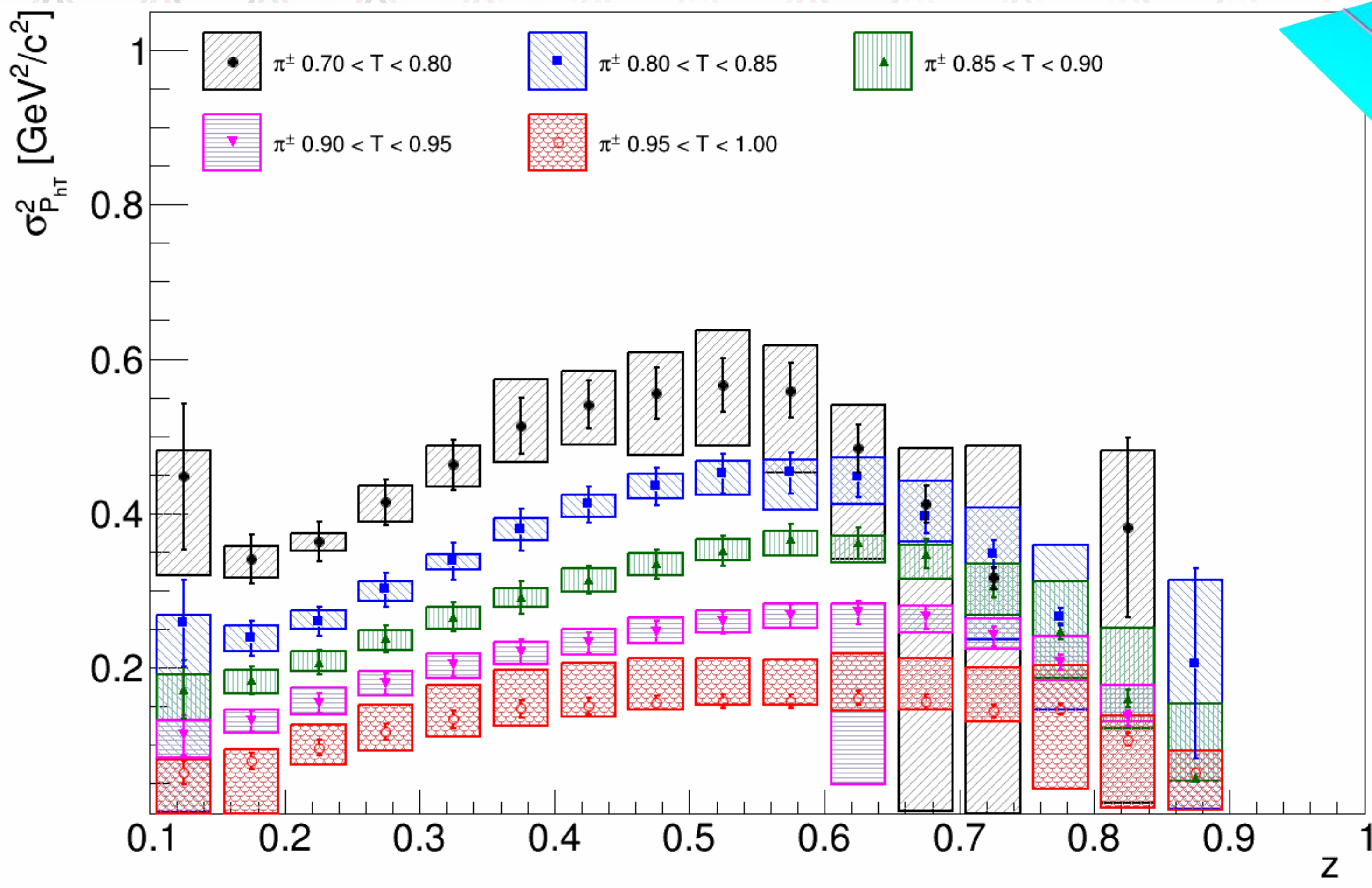


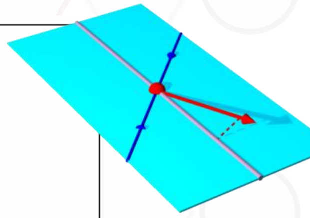
[PRD99 (2019) 112006](https://doi.org/10.1103/PhysRevD.99.112006)

Current phenomenological models: no or linear z dependence only

Gaussian widths, thrust dependence

Gaussian widths get narrower with higher Thrust

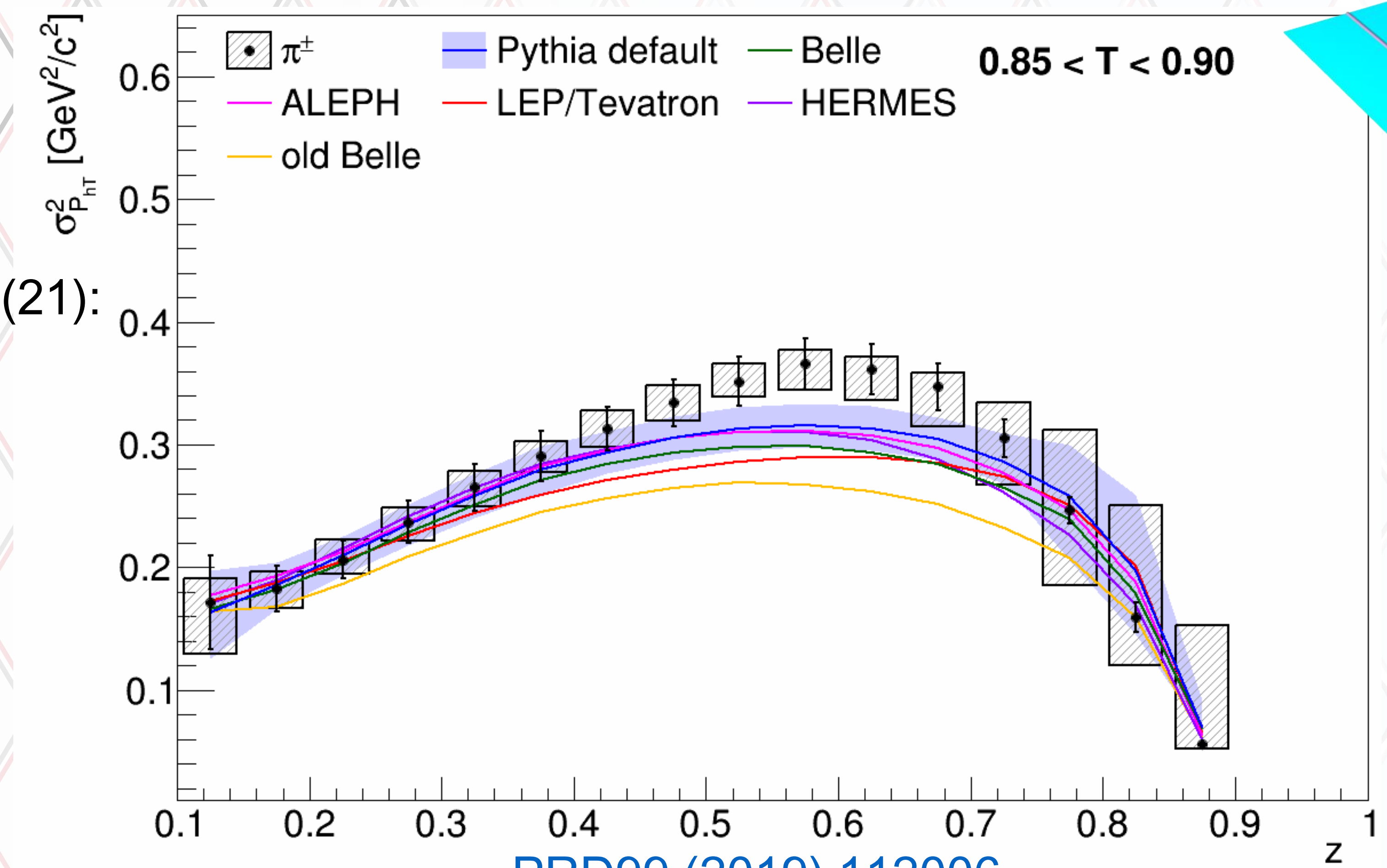


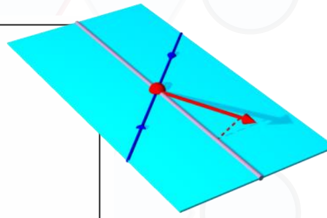


[PRD99 (2019) 112006](https://doi.org/10.1103/PhysRevD.99.112006)

Gaussian widths comparison to MC

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



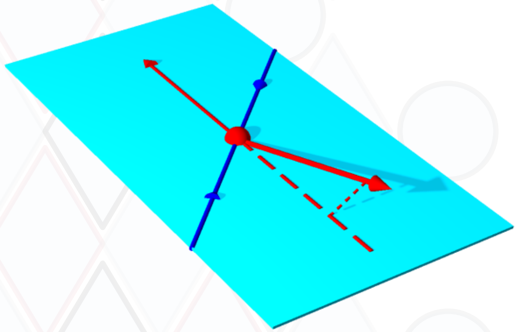


MSTP(21):
0.28
0.325
0.36
0.36
0.37
0.40

PRD99 (2019) 112006

Ongoing work: two-hadron transverse momentum

- Analysis ongoing (Anselm/Charlotte)
  - Differential in z_1,z_2 and q_t for pion and kaon combinations
  - All the correction steps (PID, smearing, non-qqbar,acceptance, ISR) similar to recent Belle FF analyses



Single Λ polarization measurements

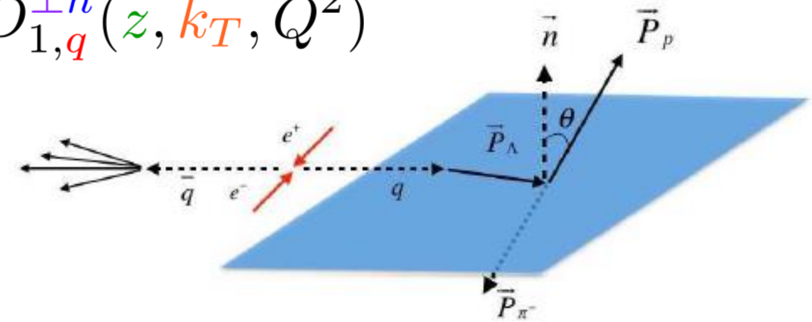
- Related to open question about Λ polarization in hadron collisions from 40 years ago!
- Fragmentation counterpart to the Sivers Function:

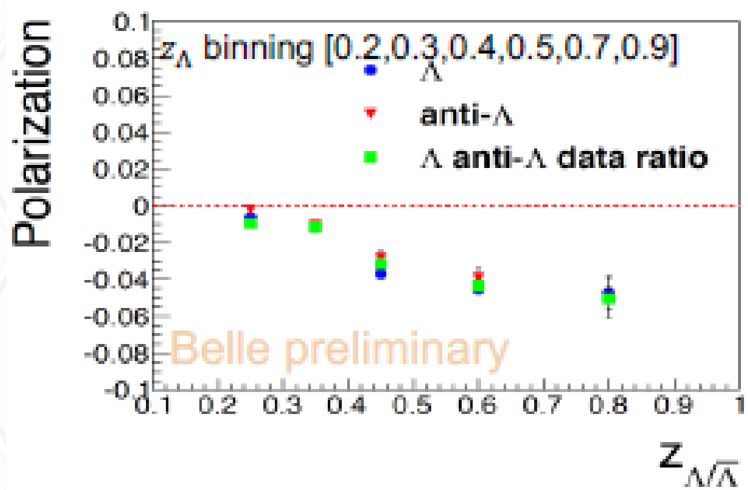
  unpolarized parton fragments into transversely polarized baryon with transverse momentum wrt to parton direction

- Reconstruct Λ, its transverse momentum and polarization

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

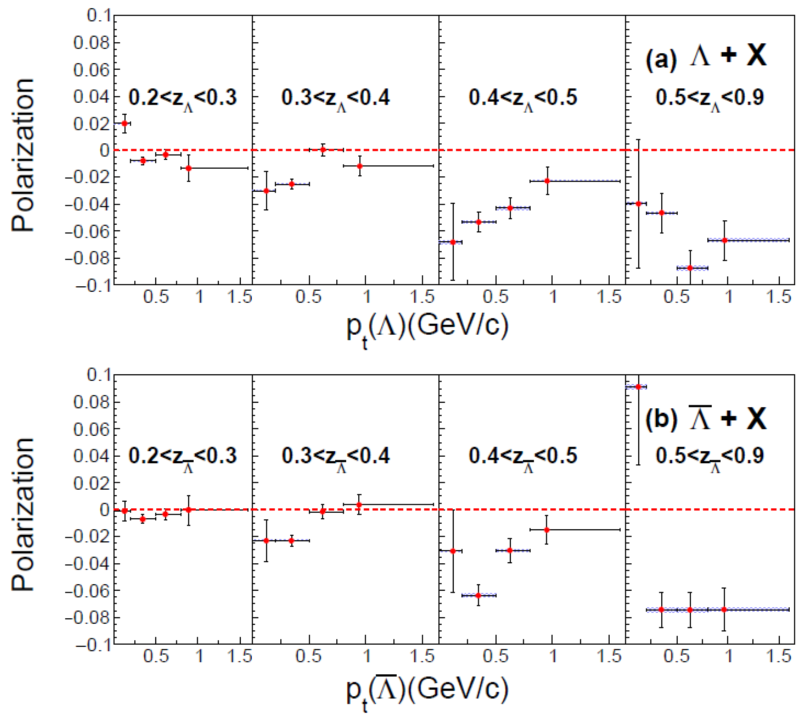
$D_{1,q}^{\perp h}(z, k_T, Q^2)$





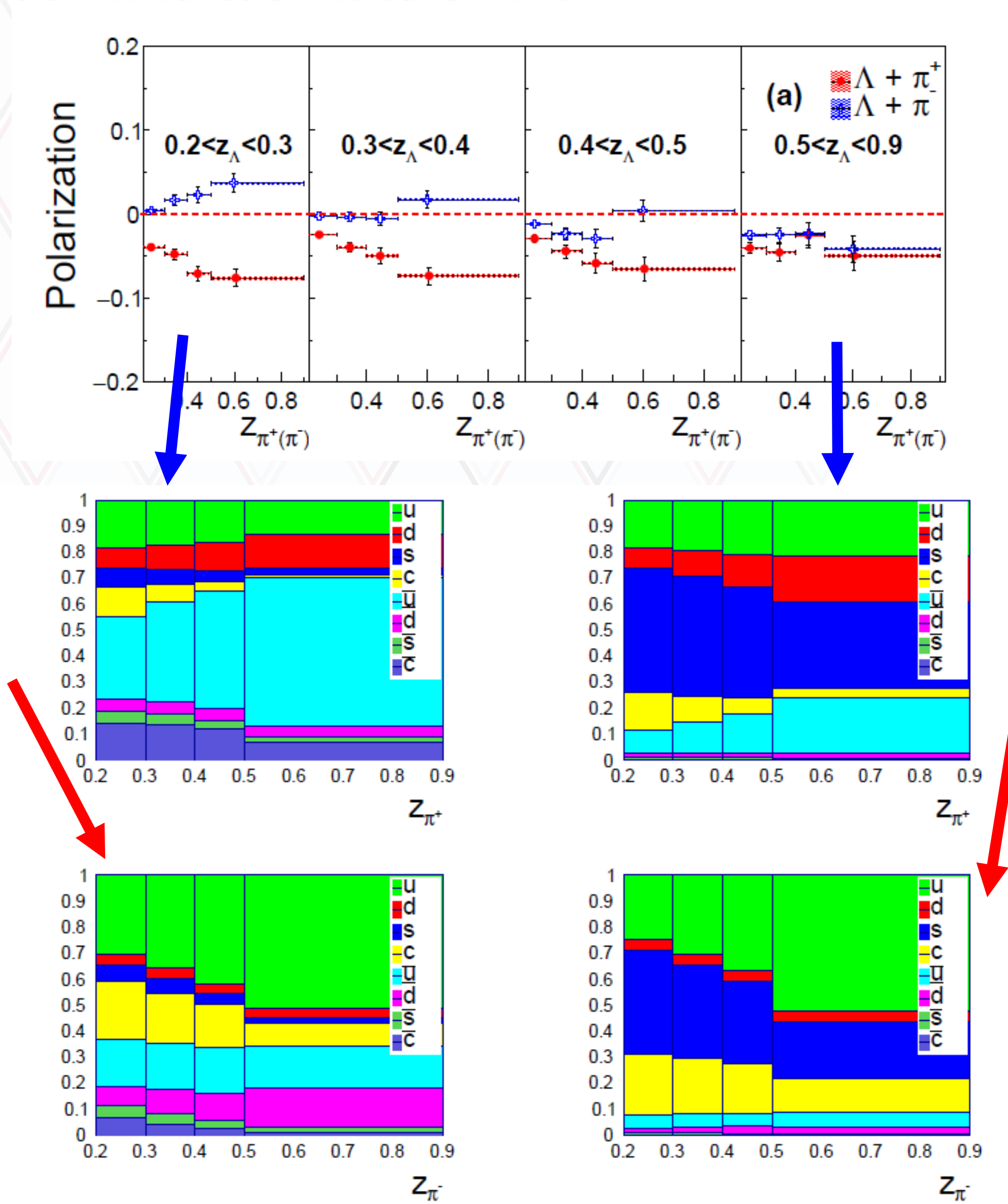
Transverse momentum dependence

- 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



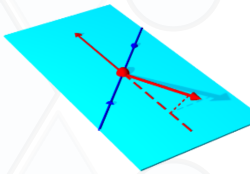
Opposite hemisphere pion correlation

- 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



Other ongoing work

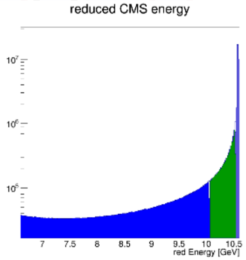
- Neutral pion and eta Collins (finalized - to be submitted in the next week or so)



- Di-hadron transverse momentum dependent fragmentation
- Update of z_1 z_2 dependent di-hadron fragmentation (PRD) using additional z definitions and better ISR correction
- Multi-dimensional analysis of Collins asymmetries for pion and kaon combinations
- Other exploratory work (FFs using ISR, hadron in jets, etc)

New possibilities: other final state FFs needed?

- Extension of di-hadron analysis to any resonant hadron possible:
  - K_s, K^*, ϕ, ρ, etc
- πK and KK IFF measurements
- Other Collins measurements?
- 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

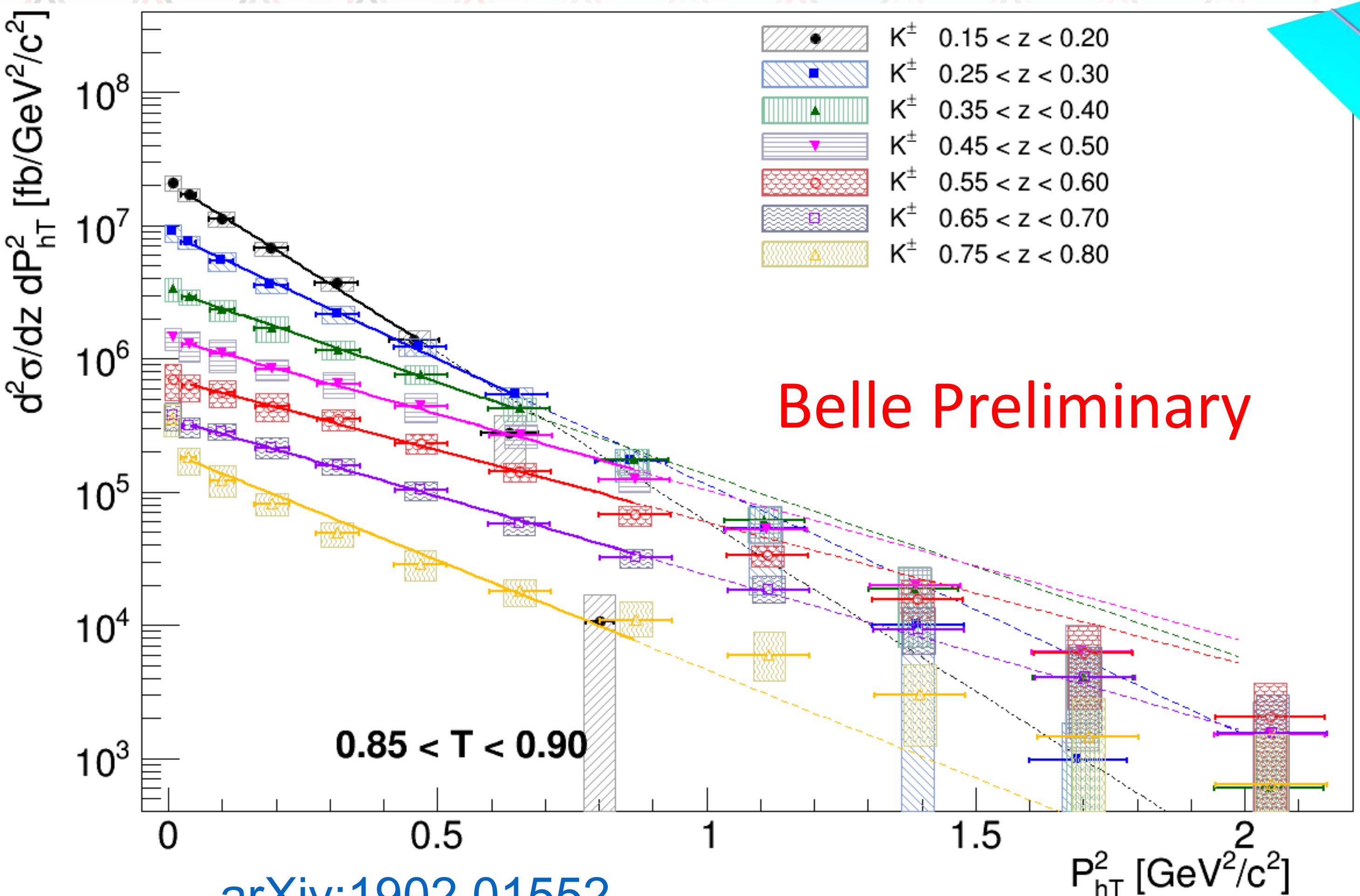
- P_{hT} dependent cross sections and Gaussian widths extracted
  - Very clear z dependence of widths, not as assumed by phenomenologists
  - Pions and kaons similar, protons narrower (diquarks?)
- Lambda polarization paper finally published
- More Belle measurements ongoing (di-hadron kt, Collins)

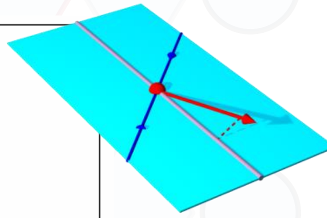
Ongoing work: Collins multidimensional analysis and Kaon combinations

- Currently revisiting kaon combinations of the Collins asymmetries previously done by Francesca
- While doing so, try to perform a full multi-dimensional analysis:
  - Currently (for testing):
  - $6\,(z_1) \times 6\,(z_2) \times 4(k_{t1}) \times 4(k_{t2}) \times 1$ (costheta) x 8 (phi)
  - $6\,(z_1) \times 6\,(z_2) \times 10(q_t) \times 1$ (costheta) x 8 (phi)
  - Consider 5 k_t bins and several costheta bins after successful test (ongoing)
- Use most correction steps similar to recent analyses (PID, smearing, non-qqbar removal, acceptance?, ISR?)
- To simplify smearing unfold each z_1-z_2 bin separately (z smearing almost nonexistent)

Fits vs P_{hT}^2

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

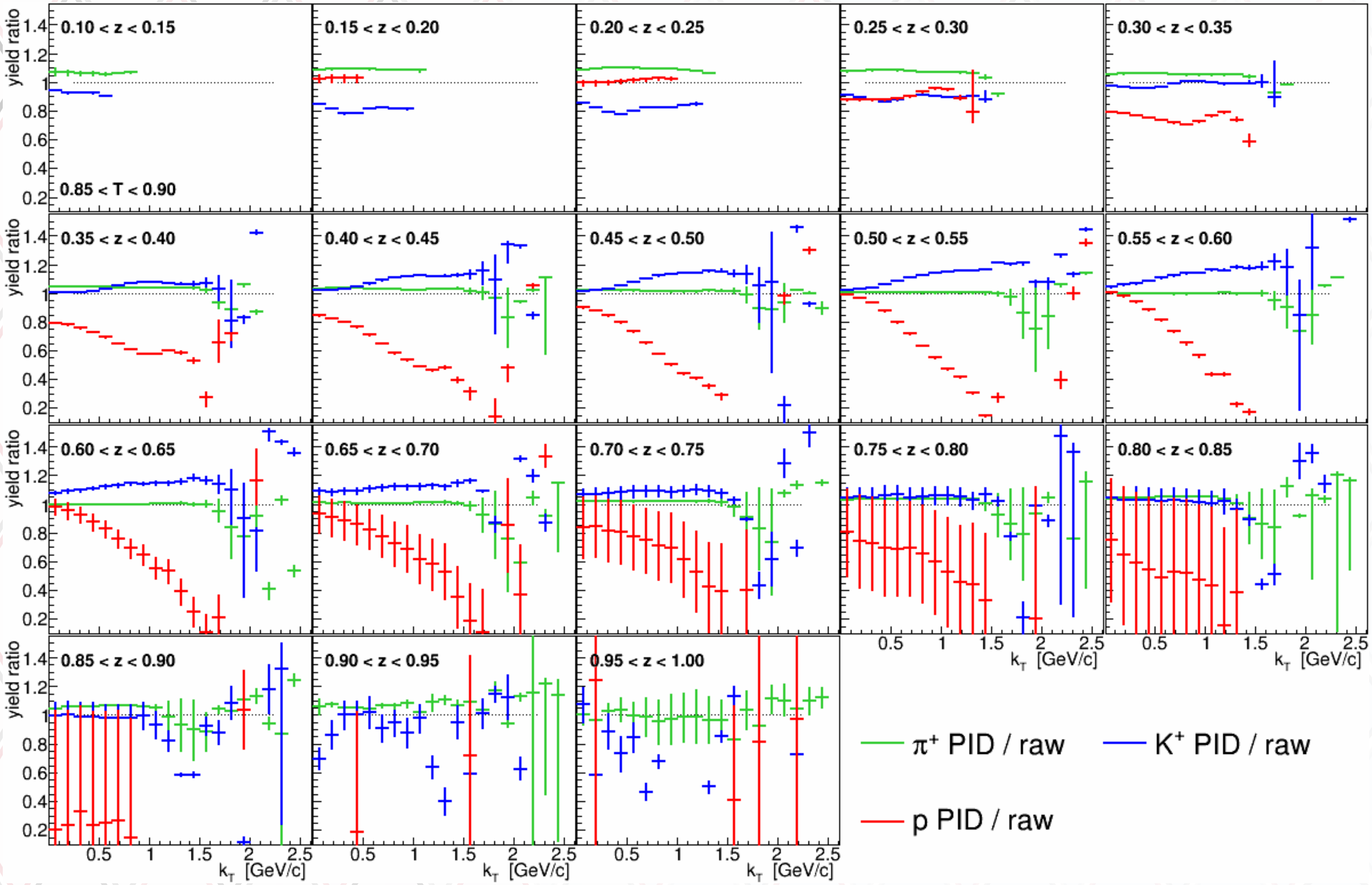




arXiv:1902.01552

PID correction

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

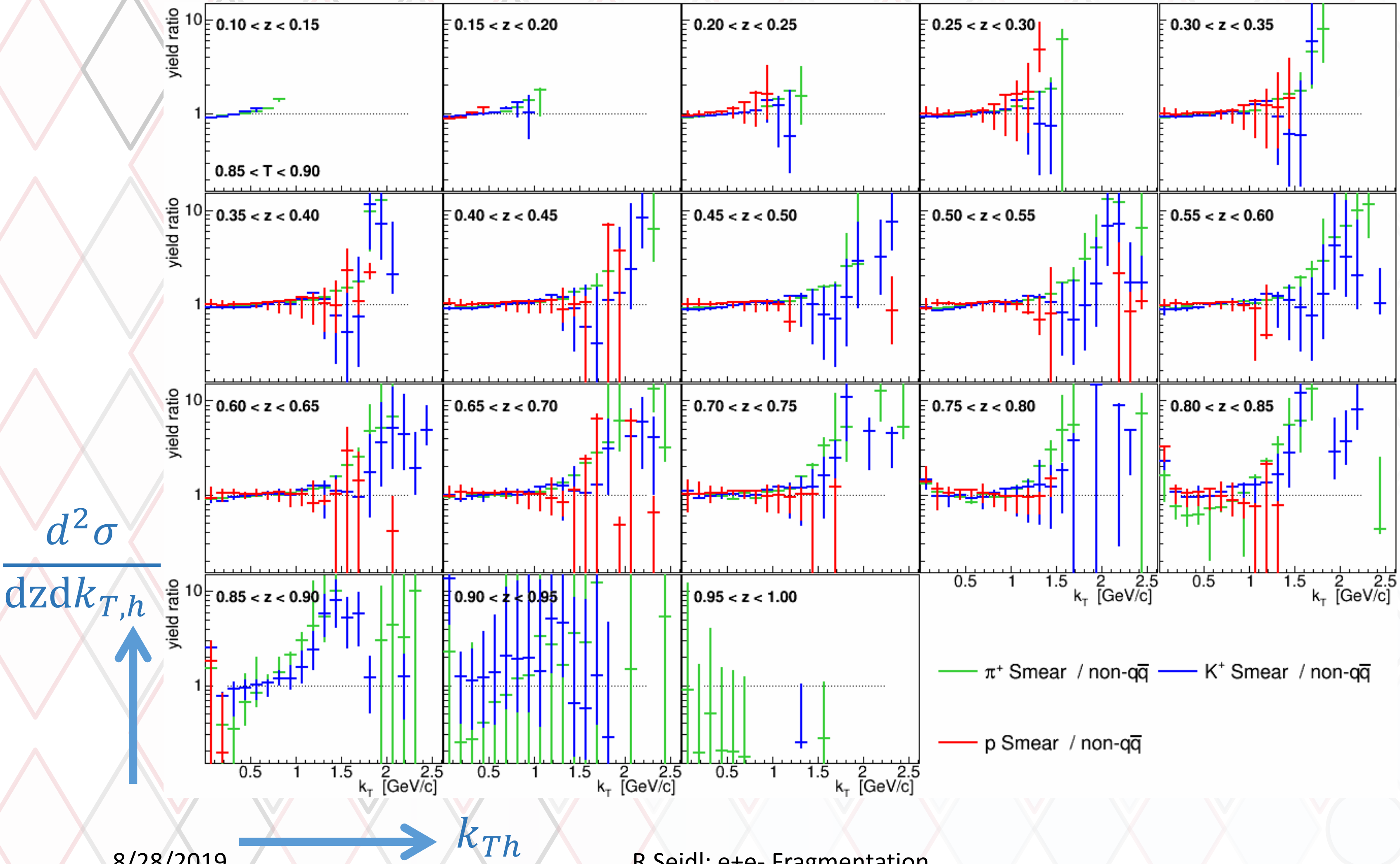


$\frac{d^2\sigma}{dz dk_{T,h}}$

k_{Th}

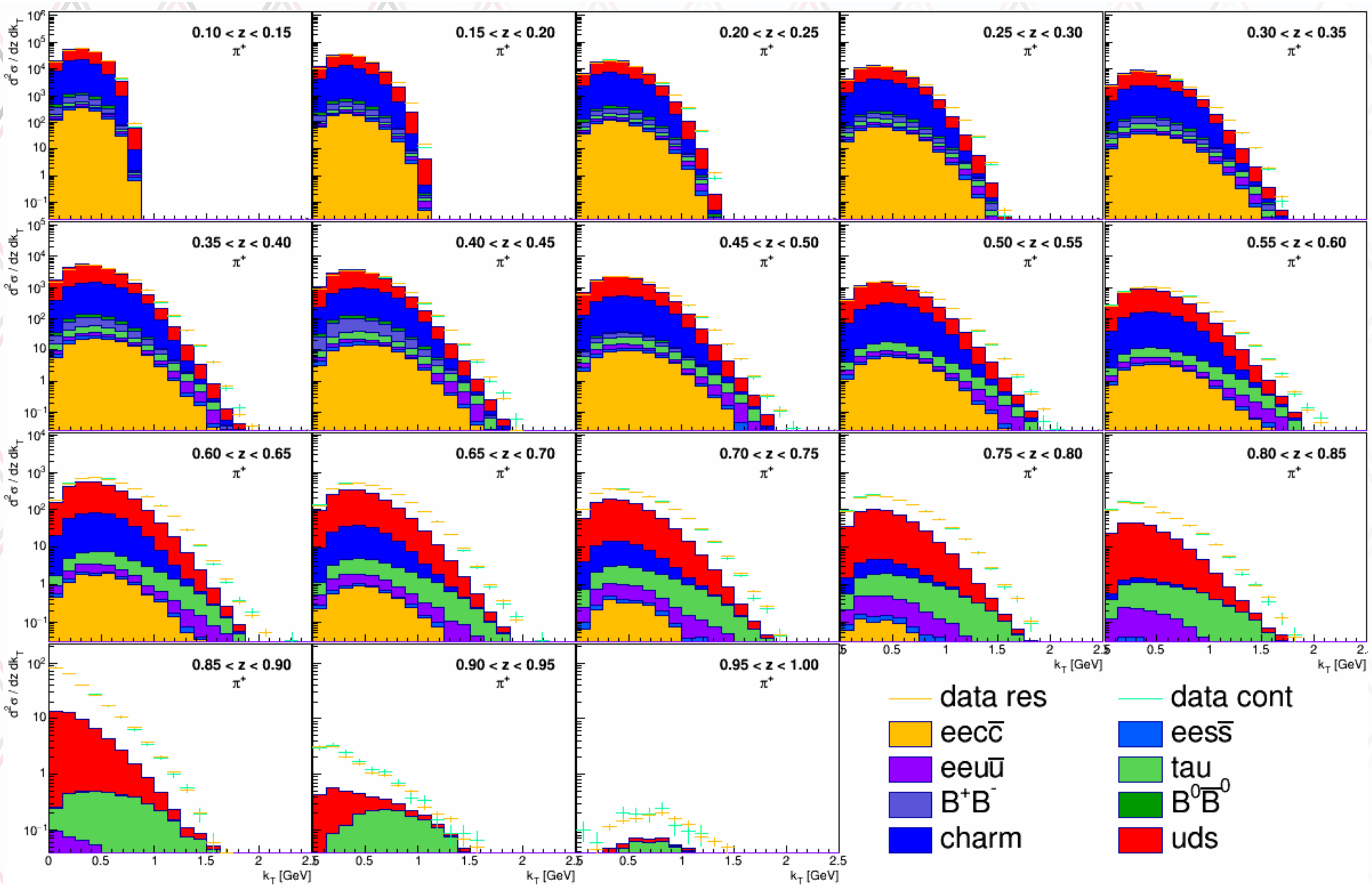
Smearing

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



Non-qqbar removal:

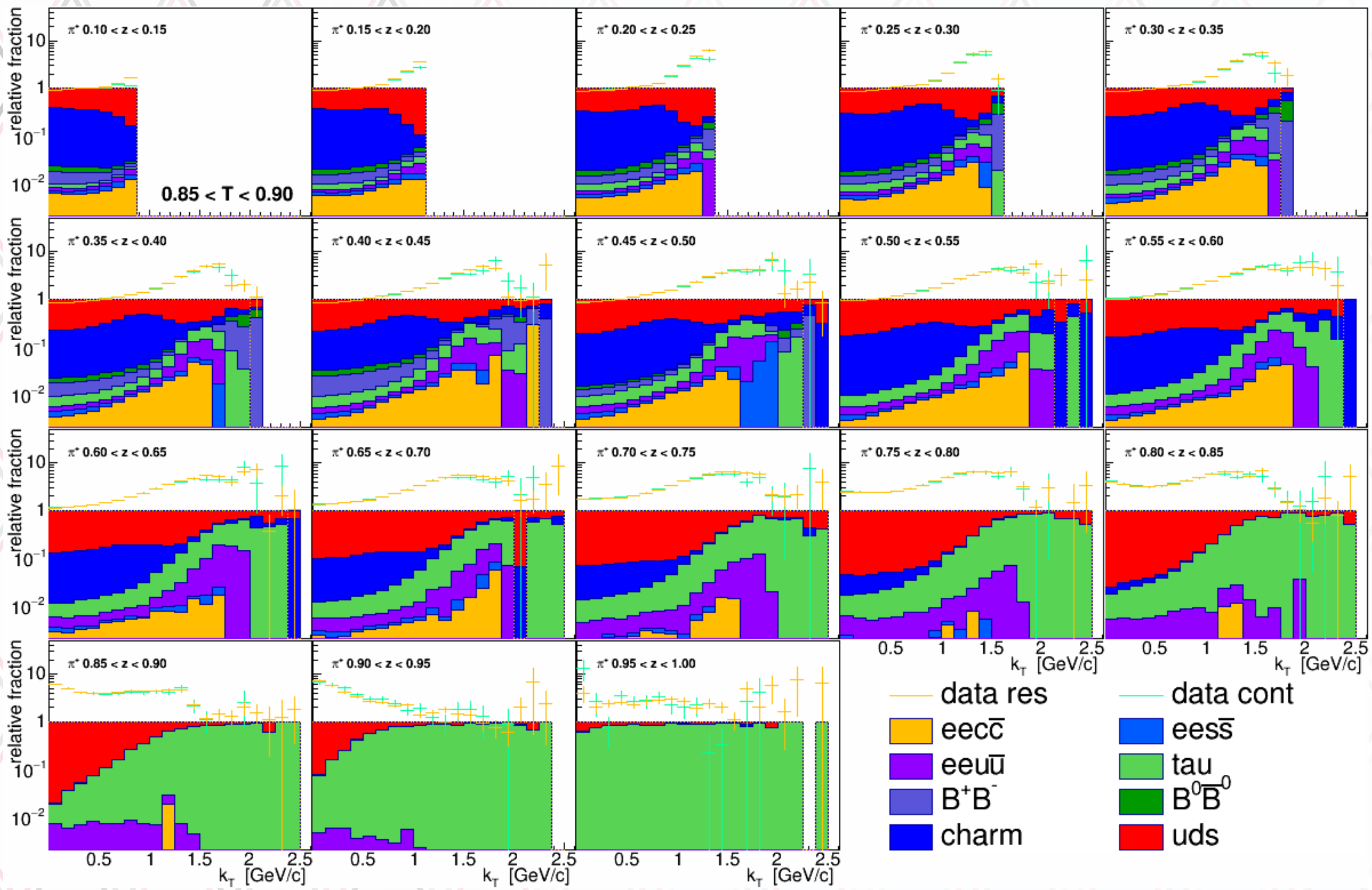
Remove all two-photon and tau events from yields, contributions generally up to several %, slightly higher for kaons rand low thrust



$\frac{d^2\sigma}{dzdk_{T,h}}$

k_{Th}

Stacked, relative contributions



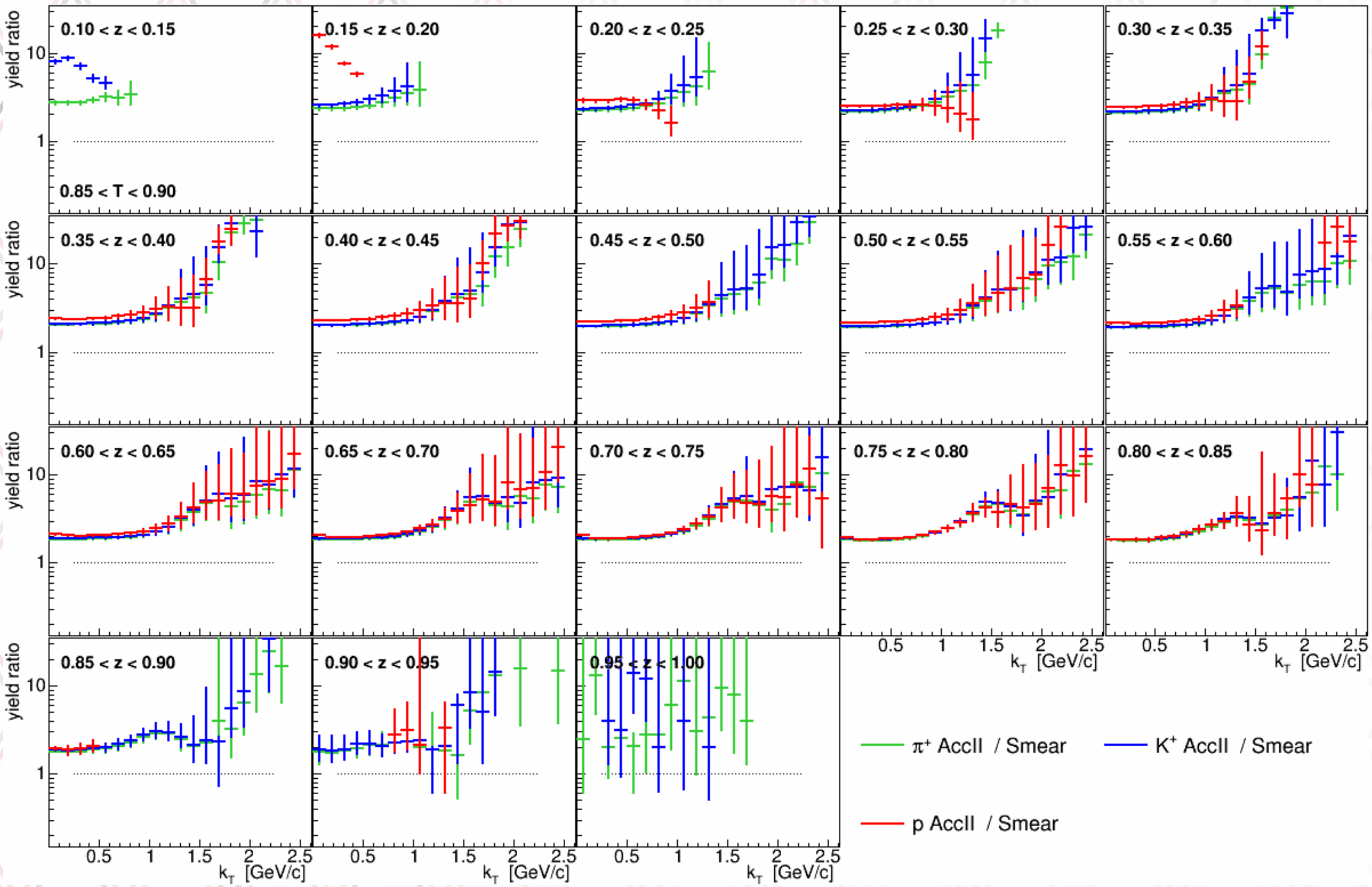
$\frac{d^2\sigma}{dzdk_{T,h}}$

k_{Th}

Acceptance correction

ACCI:Reconstruction and efficiency correction in Barrel acceptance

ACCII: Barrel to 4π correction

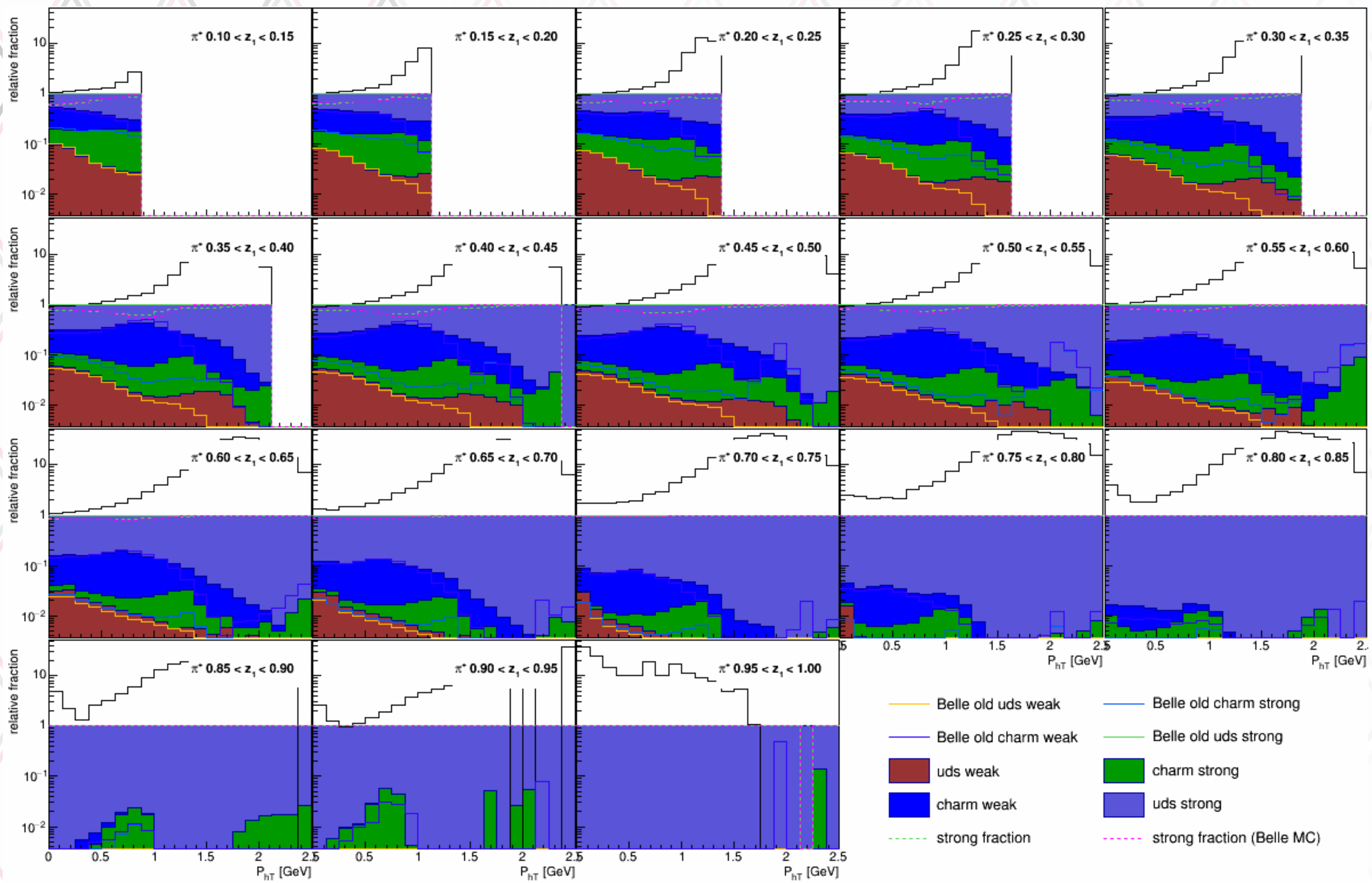


$$\frac{d^2\sigma}{dzdk_{T,h}}$$

k_{Th}

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



$$\frac{d^2\sigma}{dz dk_{T,h}}$$

k_{Th}

both cross sections provided in paper

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

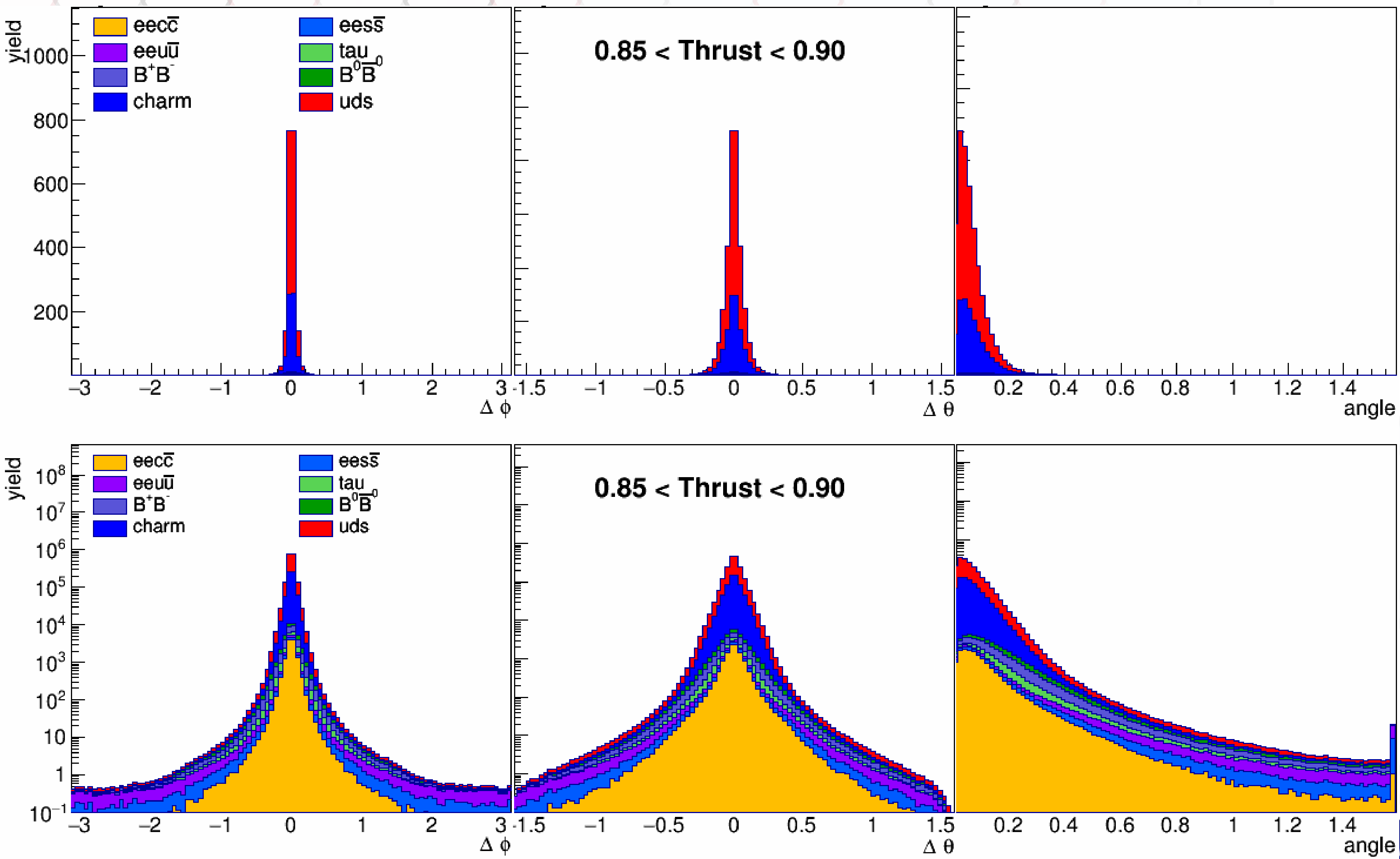
P_x,P_y Gauss width

Lund params

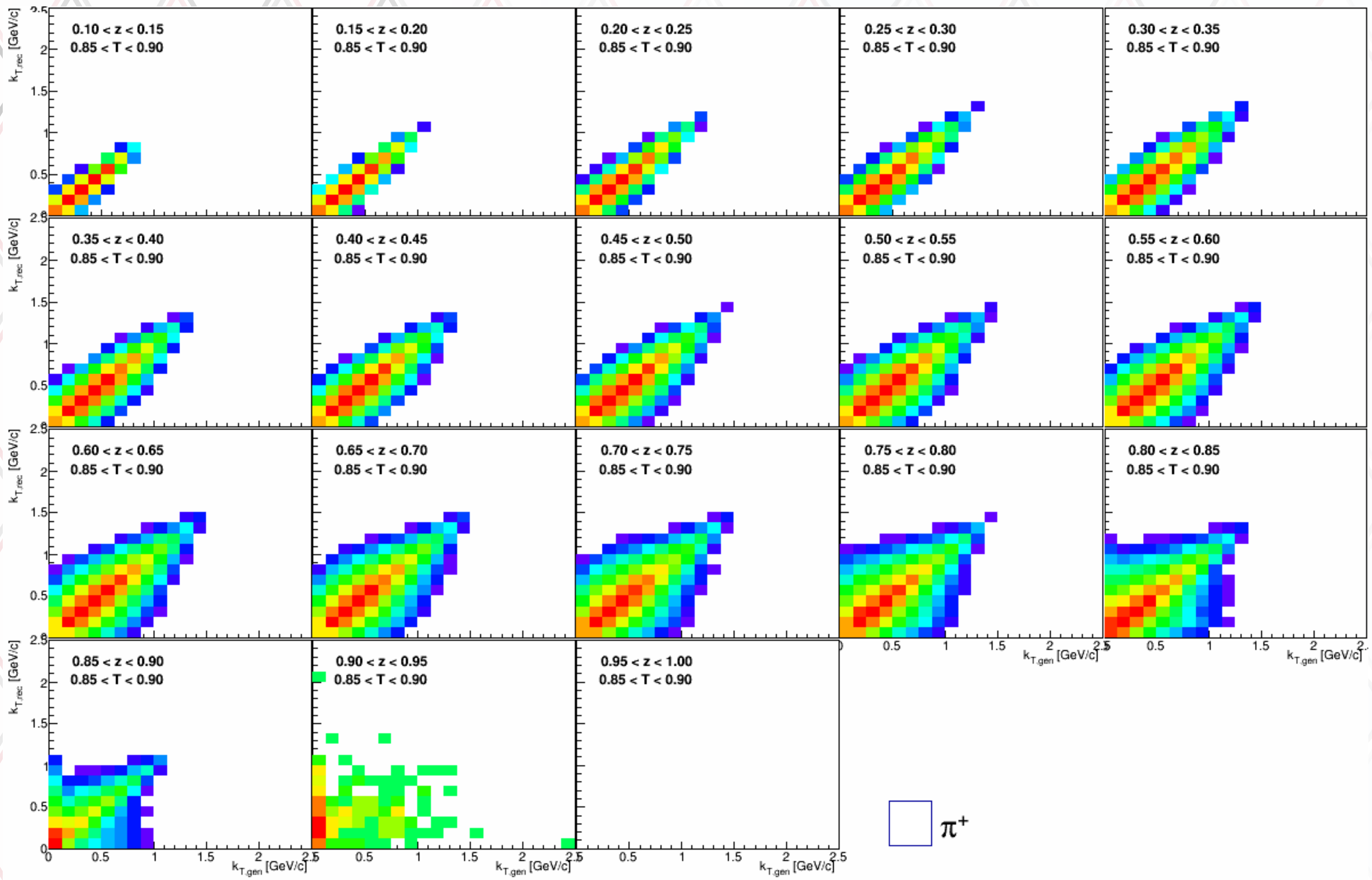
Λ_{QCD} and E cutoff

Pythia/Jetset parameters

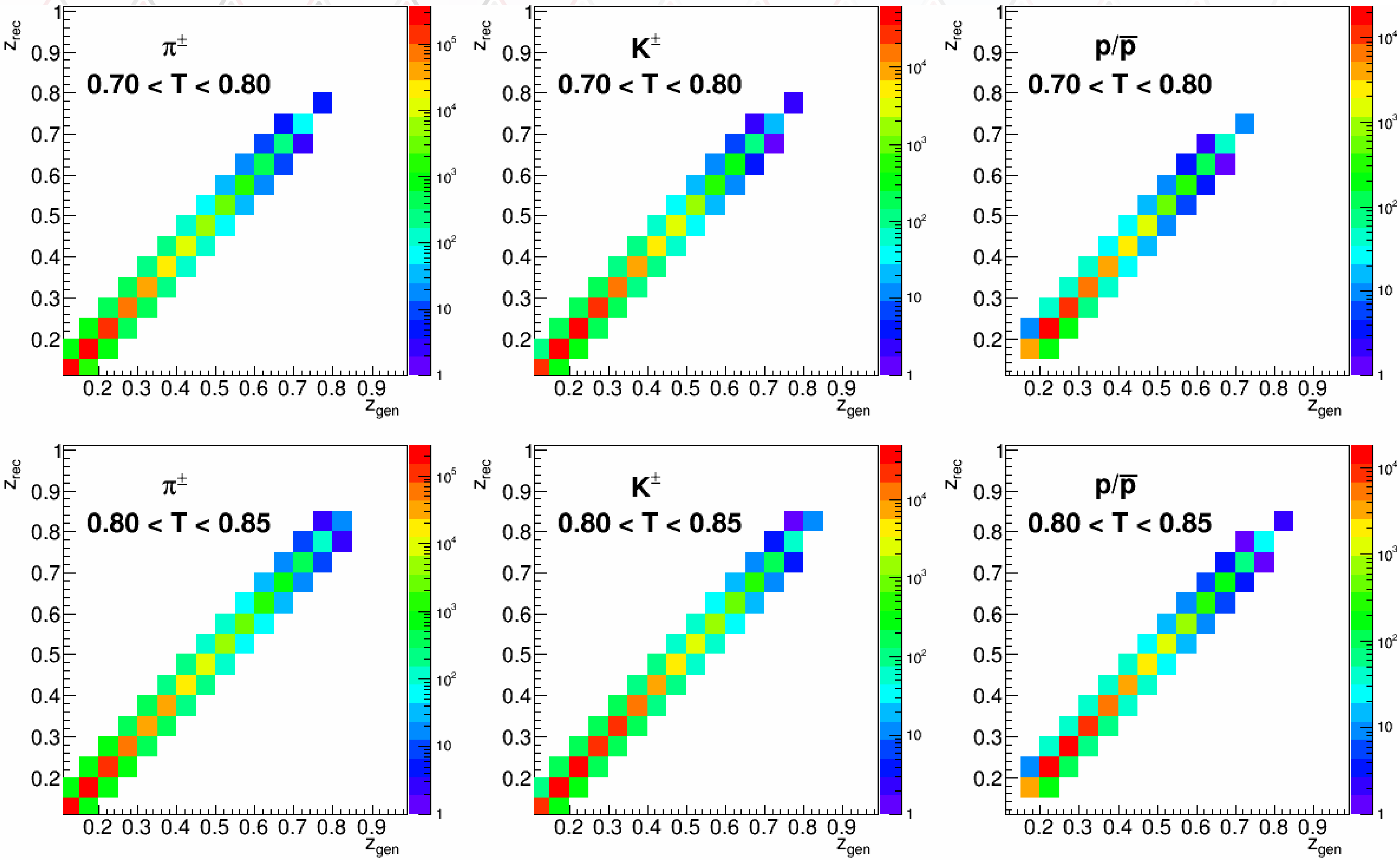
PARJ(1)	:	Diquark suppression relative to quark antiquark production
PARJ(2)	:	Strangeness suppression relative to u or d pair production
PARJ(3)	:	Extra suppression of strange diqurks relative to strange quark production
PARJ(4)	:	Axial (ud_1) vs scalar (ud_0) diquark suppression
PARJ(11)	:	Light meson 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



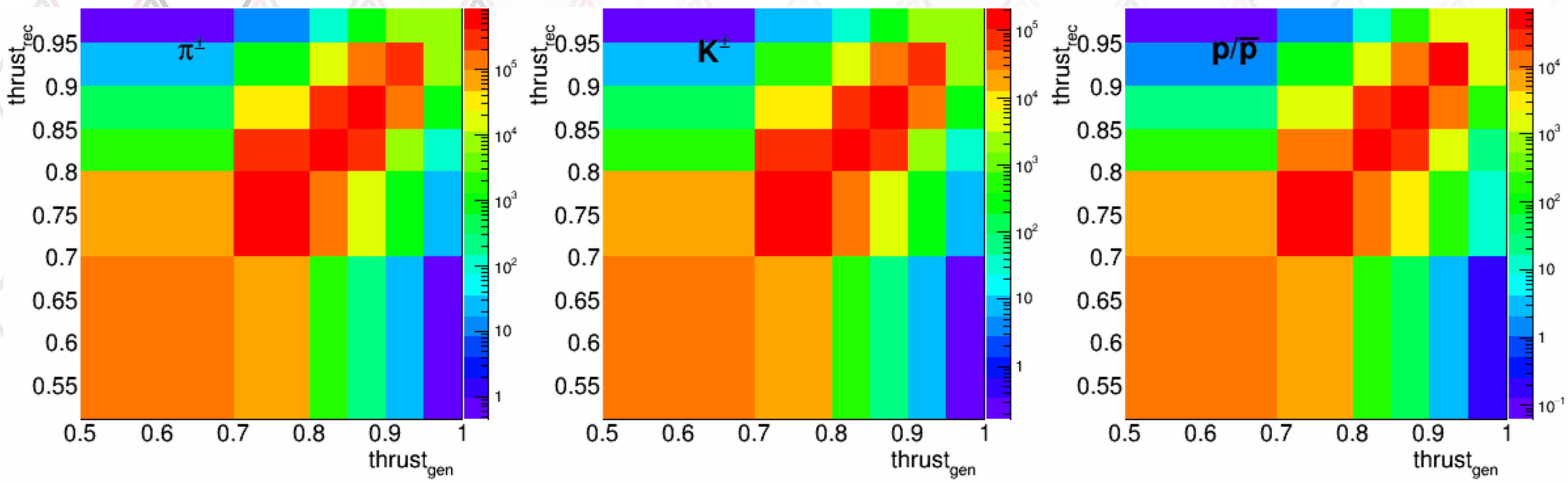
yield
eec$\bar{c}$
eeu$\bar{u}$
B^+B^-
charm
ees$\bar{s}$
tau
$B^0\bar{B}^0$
uds
0.85 < Thrust < 0.90
Δ φ
Δ θ
angle


0.10 < z < 0.15
0.85 < T < 0.90
0.15 < z < 0.20
0.85 < T < 0.90
0.20 < z < 0.25
0.85 < T < 0.90
0.25 < z < 0.30
0.85 < T < 0.90
0.30 < z < 0.35
0.85 < T < 0.90
0.35 < z < 0.40
0.85 < T < 0.90
0.40 < z < 0.45
0.85 < T < 0.90
0.45 < z < 0.50
0.85 < T < 0.90
0.50 < z < 0.55
0.85 < T < 0.90
0.55 < z < 0.60
0.85 < T < 0.90
0.60 < z < 0.65
0.85 < T < 0.90
0.65 < z < 0.70
0.85 < T < 0.90
0.70 < z < 0.75
0.85 < T < 0.90
0.75 < z < 0.80
0.85 < T < 0.90
0.80 < z < 0.85
0.85 < T < 0.90
0.85 < z < 0.90
0.85 < T < 0.90
0.90 < z < 0.95
0.85 < T < 0.90
0.95 < z < 1.00
0.85 < T < 0.90
$k_{T,rec}$ [GeV/c]
$k_{T,gen}$ [GeV/c]
π^+

Z smearing (integrating over ktbins)

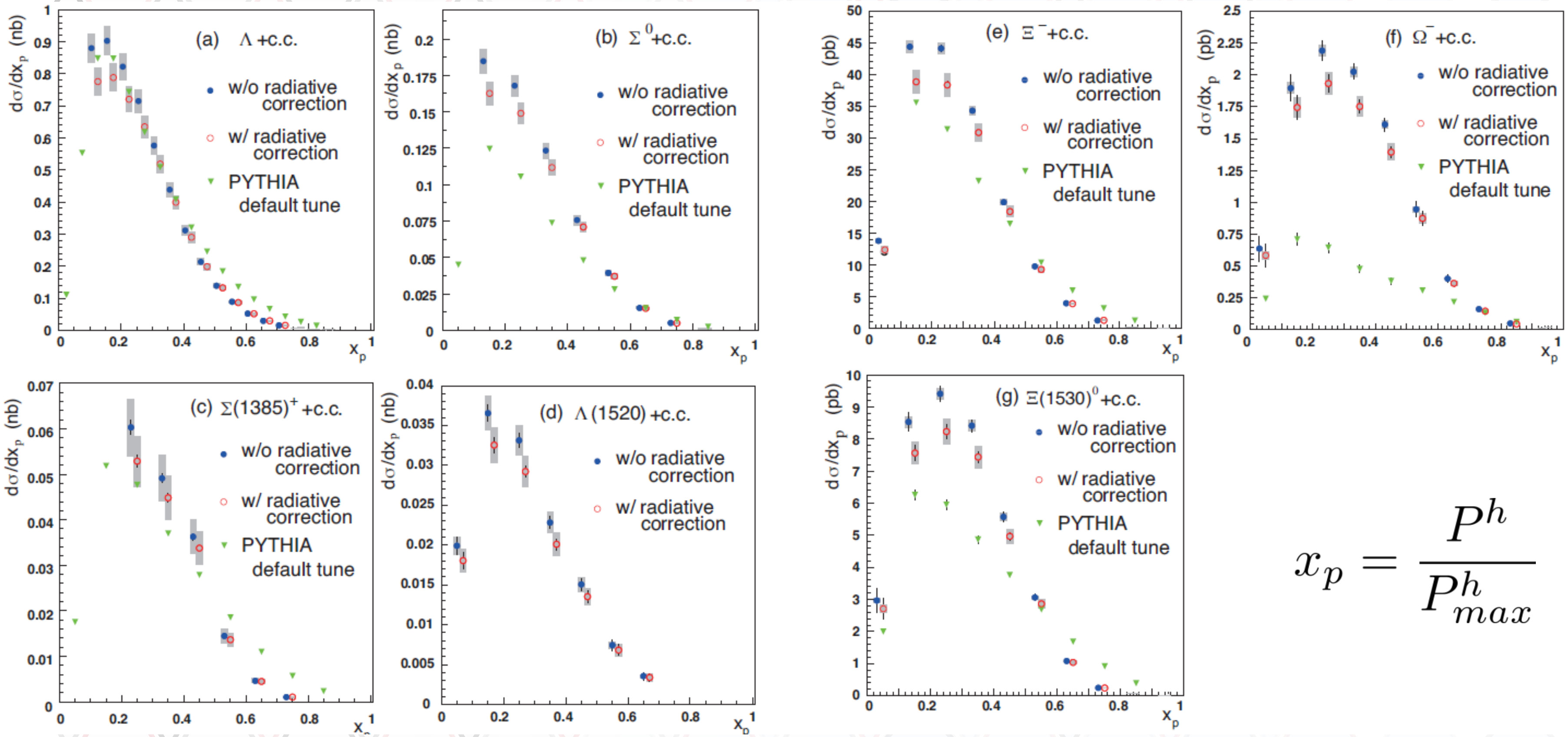


Thrust smearing (integrating over z and kt bins)



Hyperon Fragmentation

Belle: Niiyama et. al. [PRD 97 (2018), 072005]

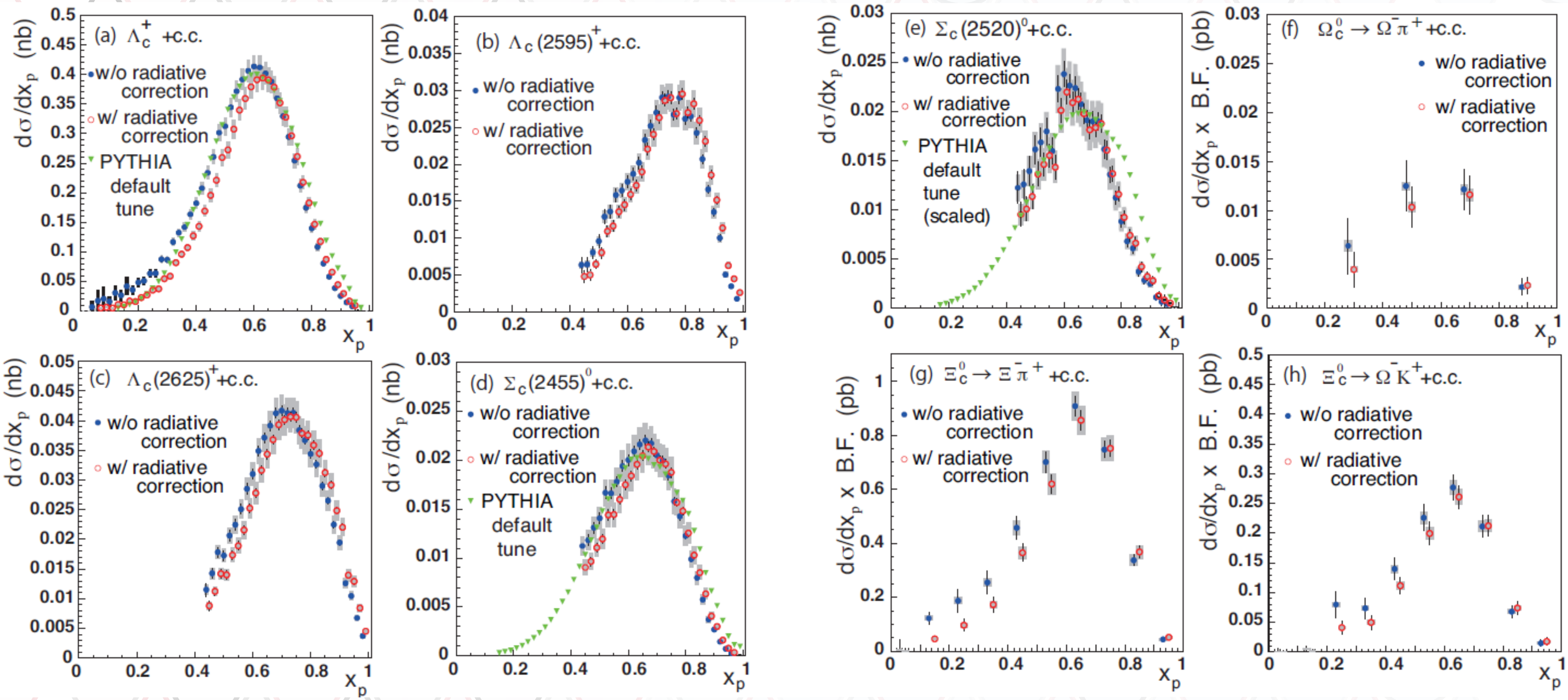


$$x_p = \frac{P^h}{P^h_{max}}$$

- Hyperons similar to light hadron fragmentation → peaking at low z (x_p)
- Baryon production not too well described by Pythia 6 default settings

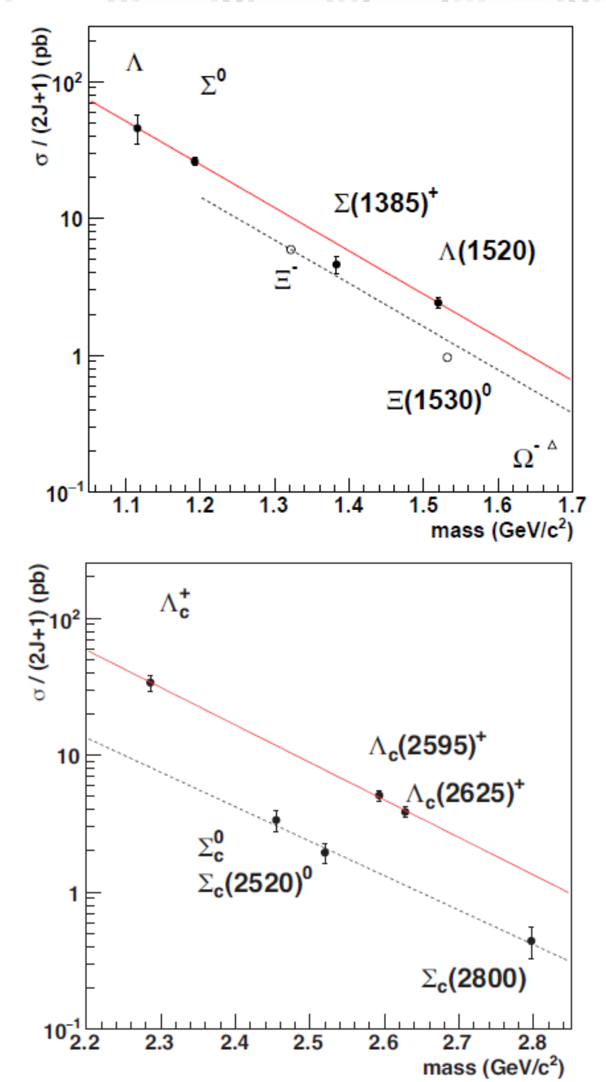
Charmed baryon Fragmentation

Belle: Niiyama et. al. PRD 97 (2018), 072005



- Charmed baryons carry large fraction of parton momentum, similar to charmed mesons
- Charmed fragmentation reasonably described in Pythia for main states

Baryon production rates

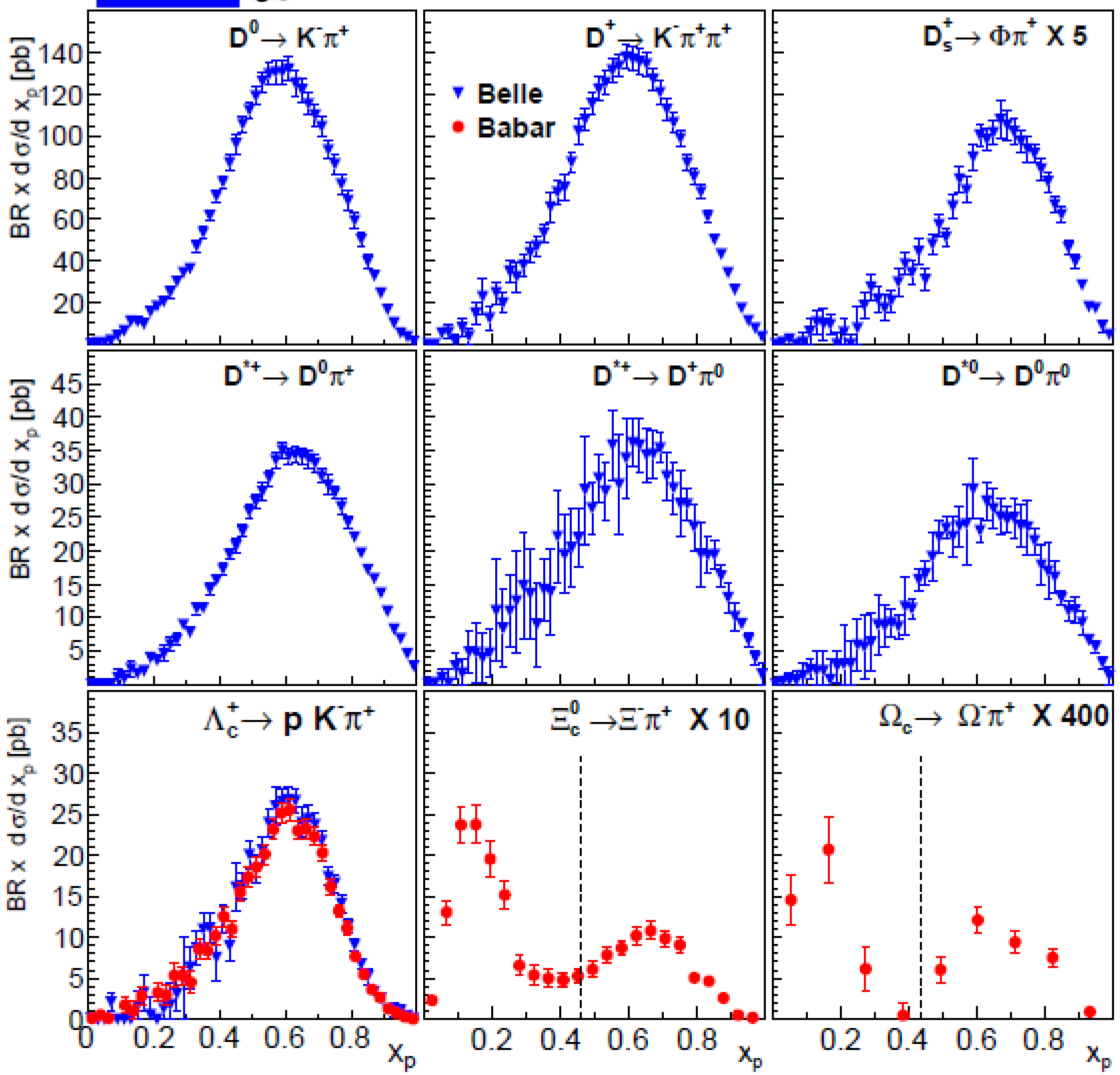


- First feed-down corrected production rates extracted
- No $\Lambda(1520)$ enhancement seen
- Strangeness suppression seen for hyperons:

$$\frac{\sigma(S=-1)}{(2J+1)} > \frac{\sigma(S=-2,-3)}{(2J+1)}$$

- Difference in slopes for Λ_c and Σ_c in support of diquark production picture (spin 1 diquarks suppressed)

Charmed Fragmentation



PRL.95, 142003 (2005)(Babar)
PRD73, 032002 (2006) (Belle)
PRD75, 012003 (2007)(Babar)
PRL 99, 062001 (2007)(Babar)

- Heavier particles generally plotted vs normalized momentum $x_p = \frac{P^h}{P^h_{max}}$
- Unlike light hadrons charmed hadrons contain large fraction of charm quark momentum