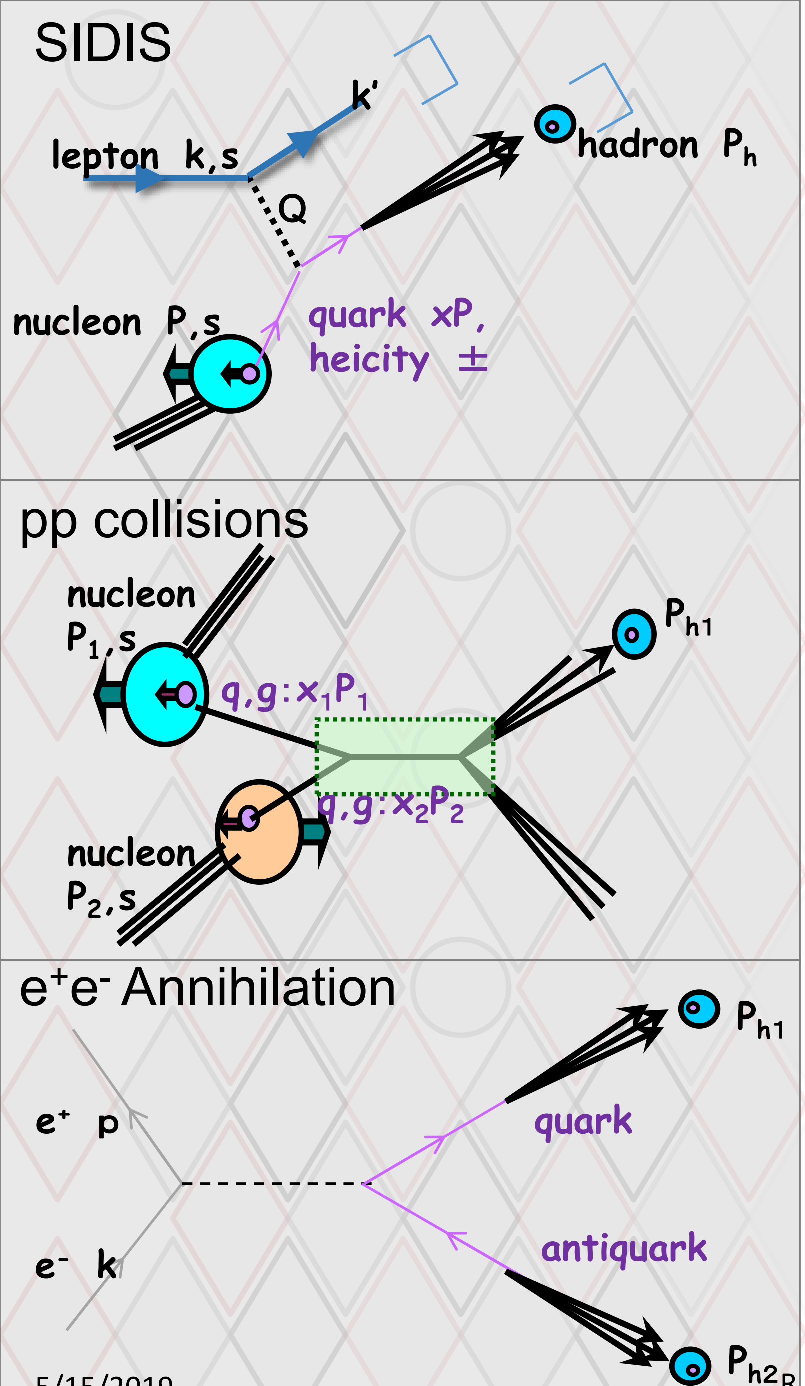
# Fragmentation Function measurements in Belle

**Evolution2019,**
**May 15, Argonne**

**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: $\delta q$ x $\delta q$ or
    - SIDIS/RHIC: $\delta q$ x Collins or $\delta q$ 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

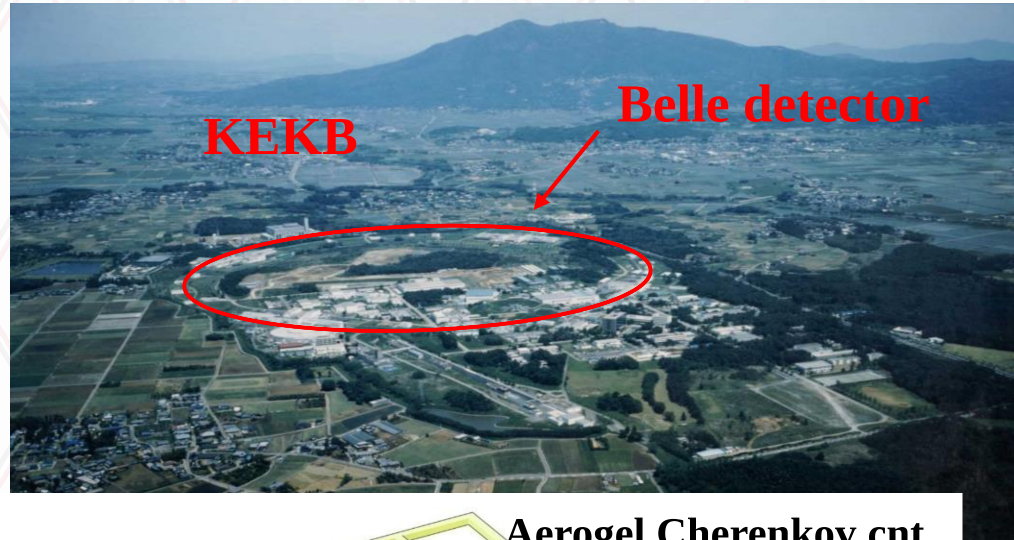
- e+e-:

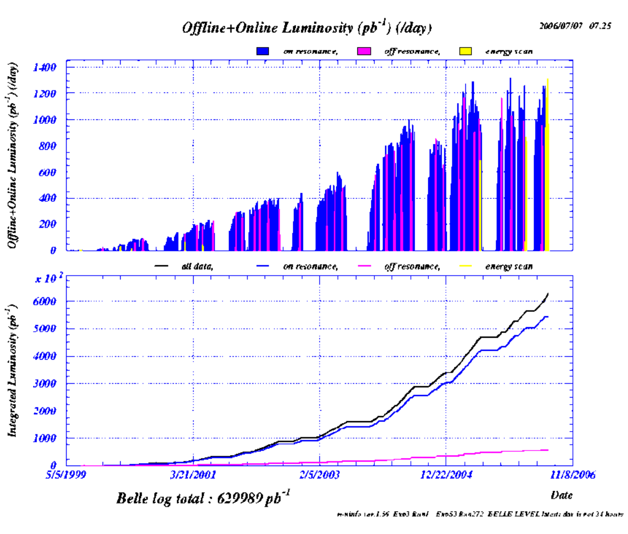
$$\sigma^h(z, Q^2, k_t) \propto \sum_q e_q^2 \left( D_{1,q}^h(z, k_t, Q^2) + D_{1,\bar{q}}^h(z, k_t, Q^2) \right)$$

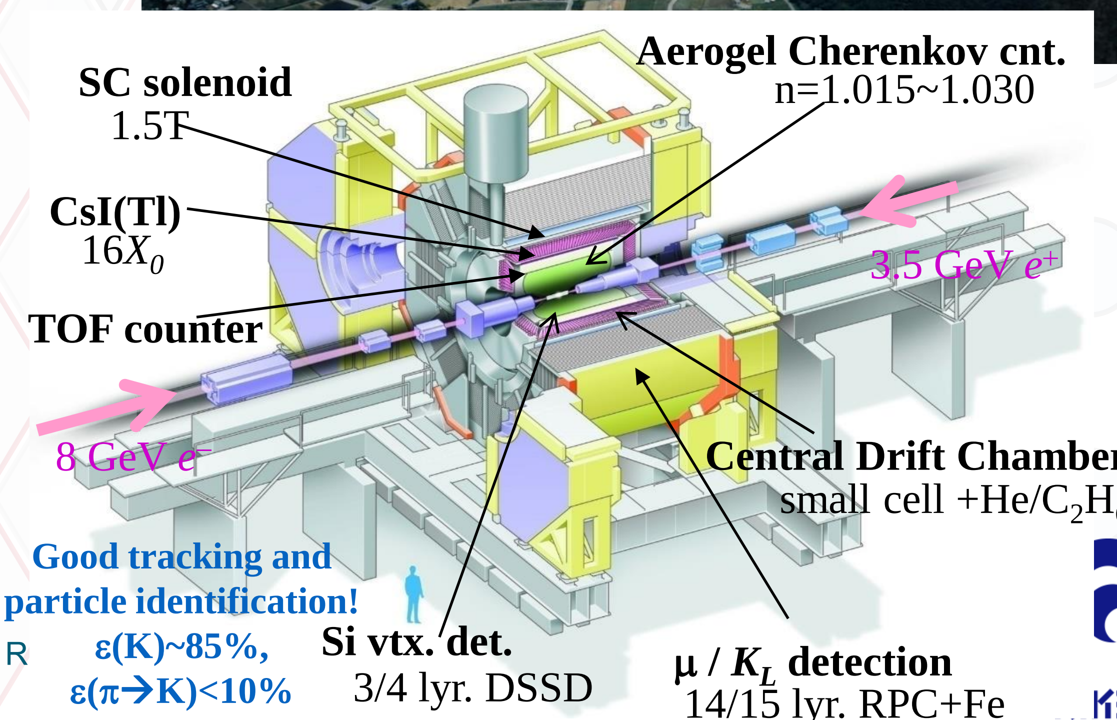
  - No PDFs necessary
  - Clean initial state, parton momentum known at LO
  - Flavor structure not directly accessible

# Belle Detector and KEKB

- Asymmetric collider
- 8GeV $e^-$ + 3.5GeV $e^+$
- $\sqrt{s}$ = 10.58GeV ($\Upsilon$(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 $fb^{-1}$
- >70$fb^{-1}$ => continuum

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# EIC without B factory input? Very unlikely

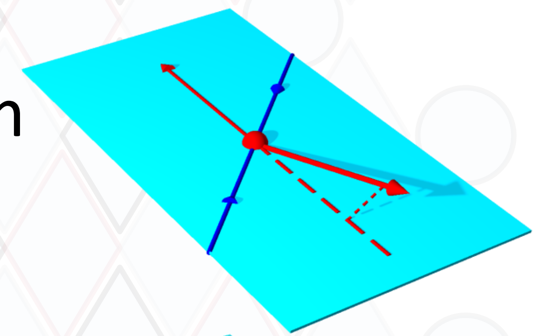
- Very limited helicity analysis possible (based on Kretzer or KKP)
- Only model dependent Tensor charge extraction
- Sivers and all TMDs just with naïve Gaussian dependence (no x or z dependence)

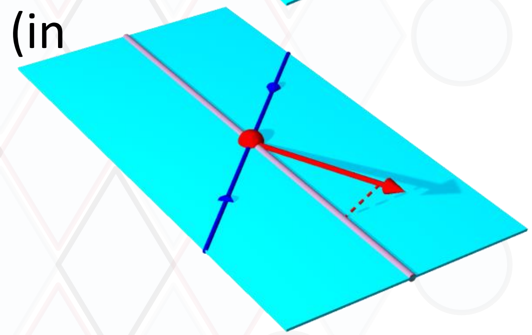
# Transverse momentum dependence

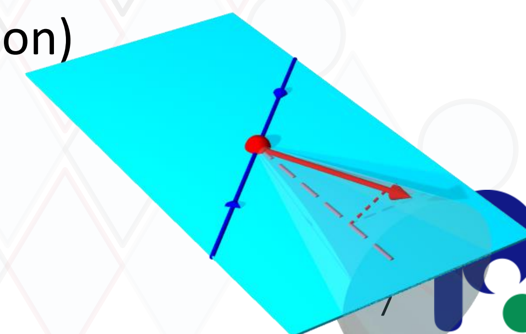
Aka un-integrated PDFs and FFs

# $K_T$ 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 $\boxed{\text{Thrust}}$ or jet axis
    - →No convolution
    - →Need correction for $q\bar{q}$ axis (similar to a Jet function)







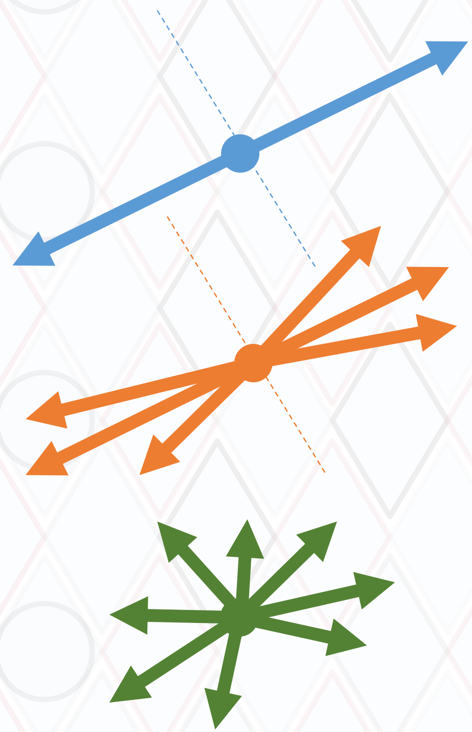
# Thrust definition

- Event shape variable thrust is defined as:

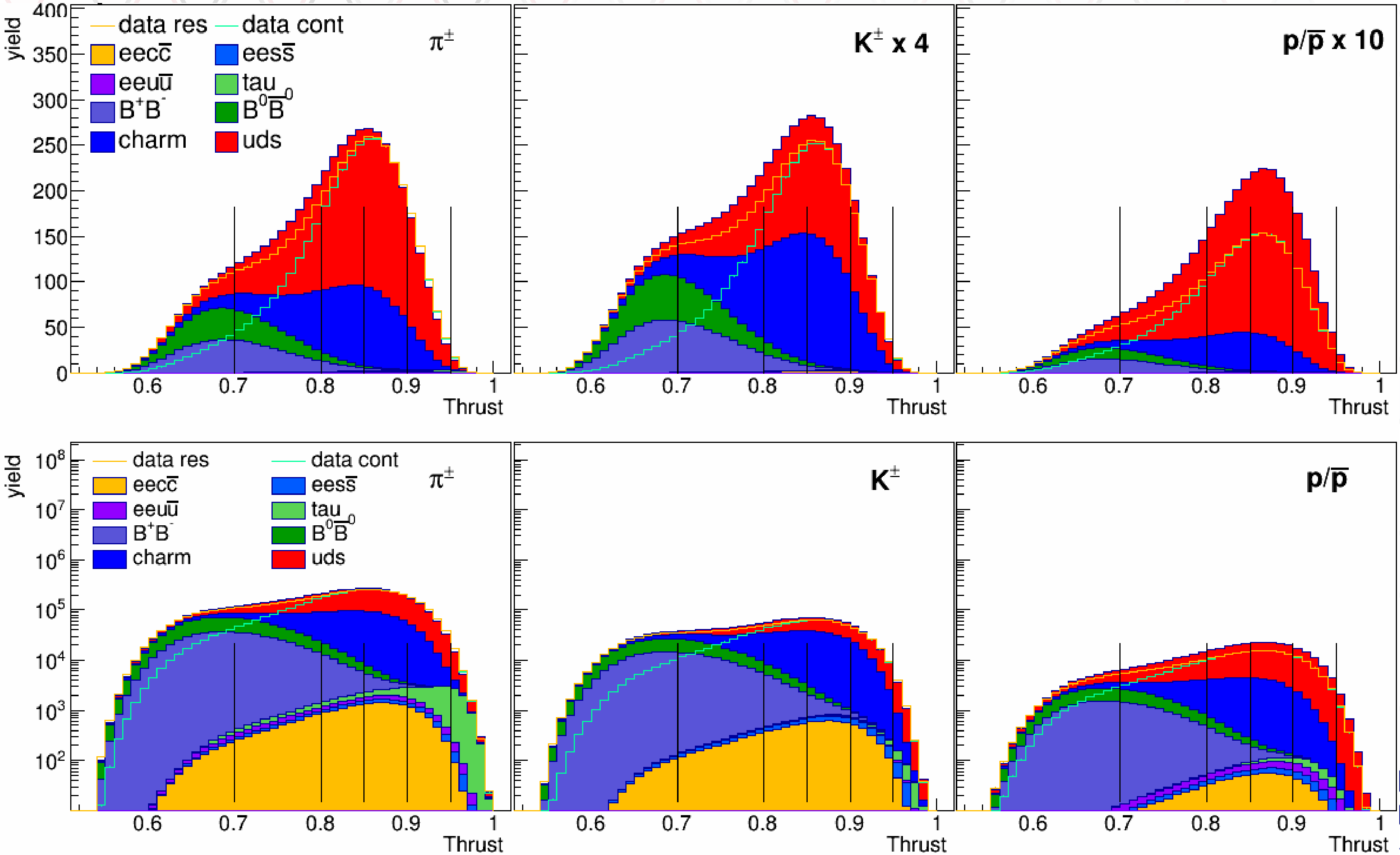
$$T \stackrel{max}{=} \frac{\sum_h |\mathbf{P}_h \cdot \hat{\mathbf{n}}|}{\sum_h |\mathbf{P}_h|}$$

- 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)



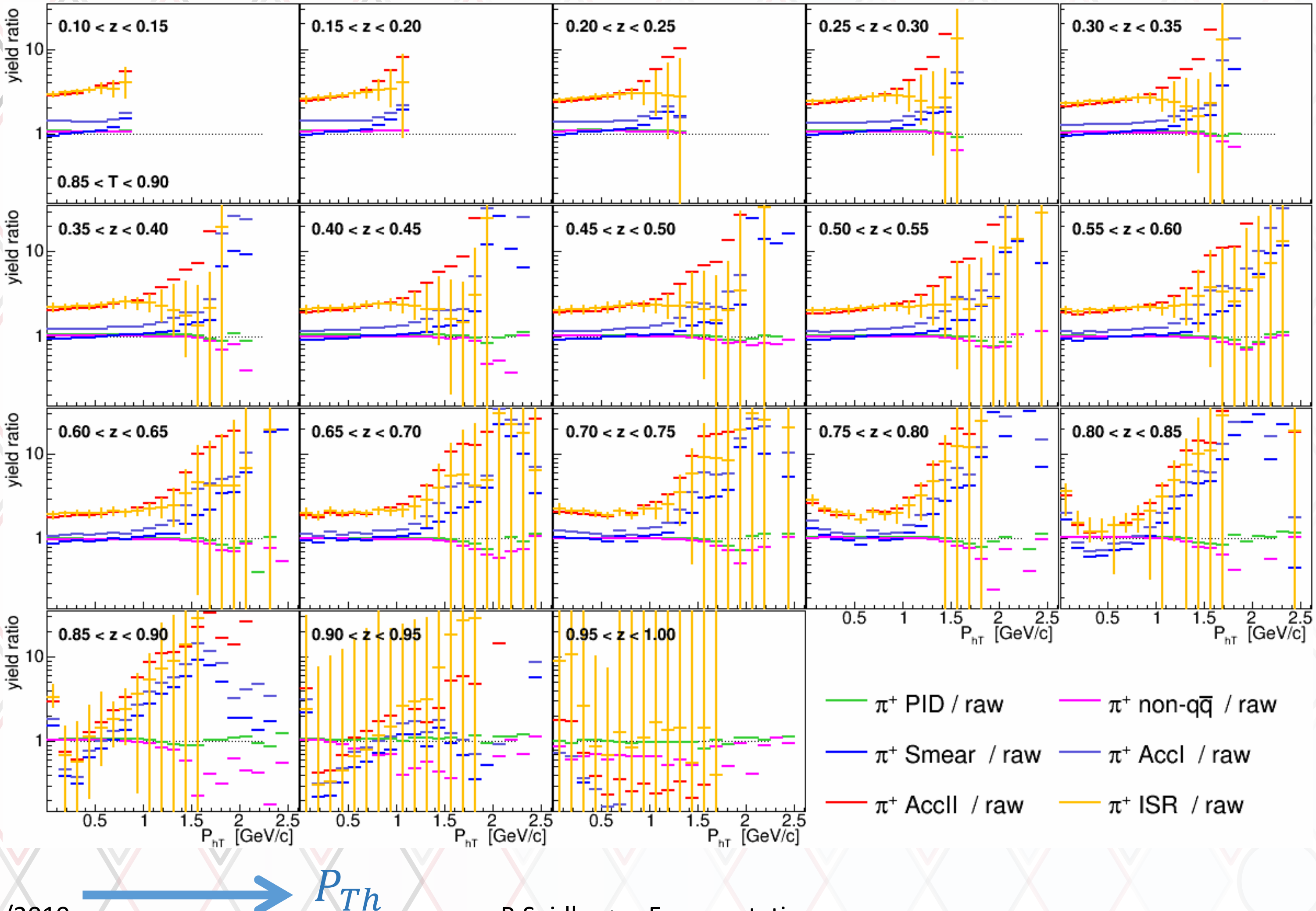
# Correction chain

| Correction | Method | Systematics |
|---|---|---|
| PID mis-id | PID matrices (5x5 for cos $\theta_{lab}$ 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 $4\pi$ | 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

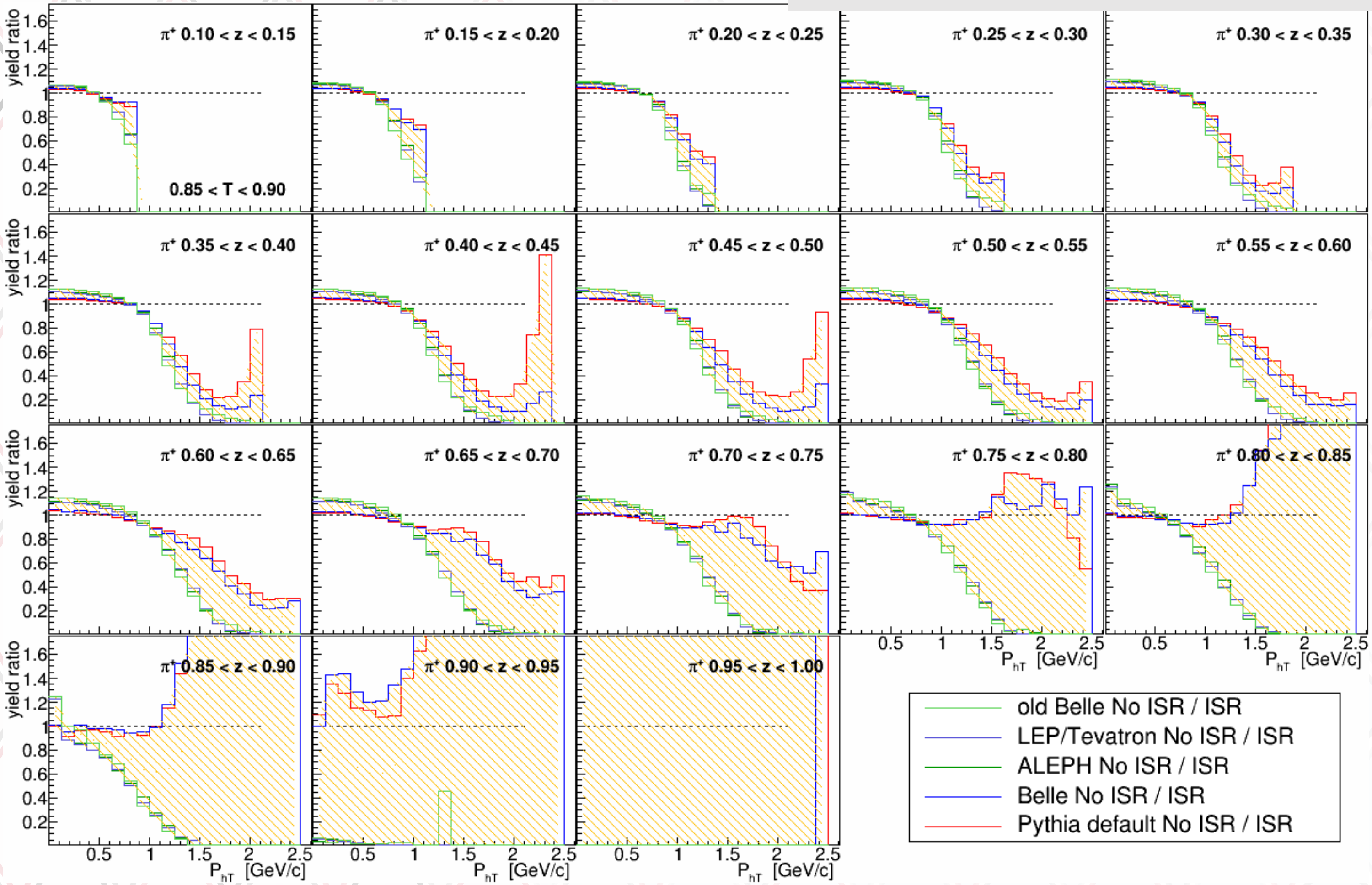
Most of the following slides display 0.85 < T< 0.9 Thrust bin



# ISR correction

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

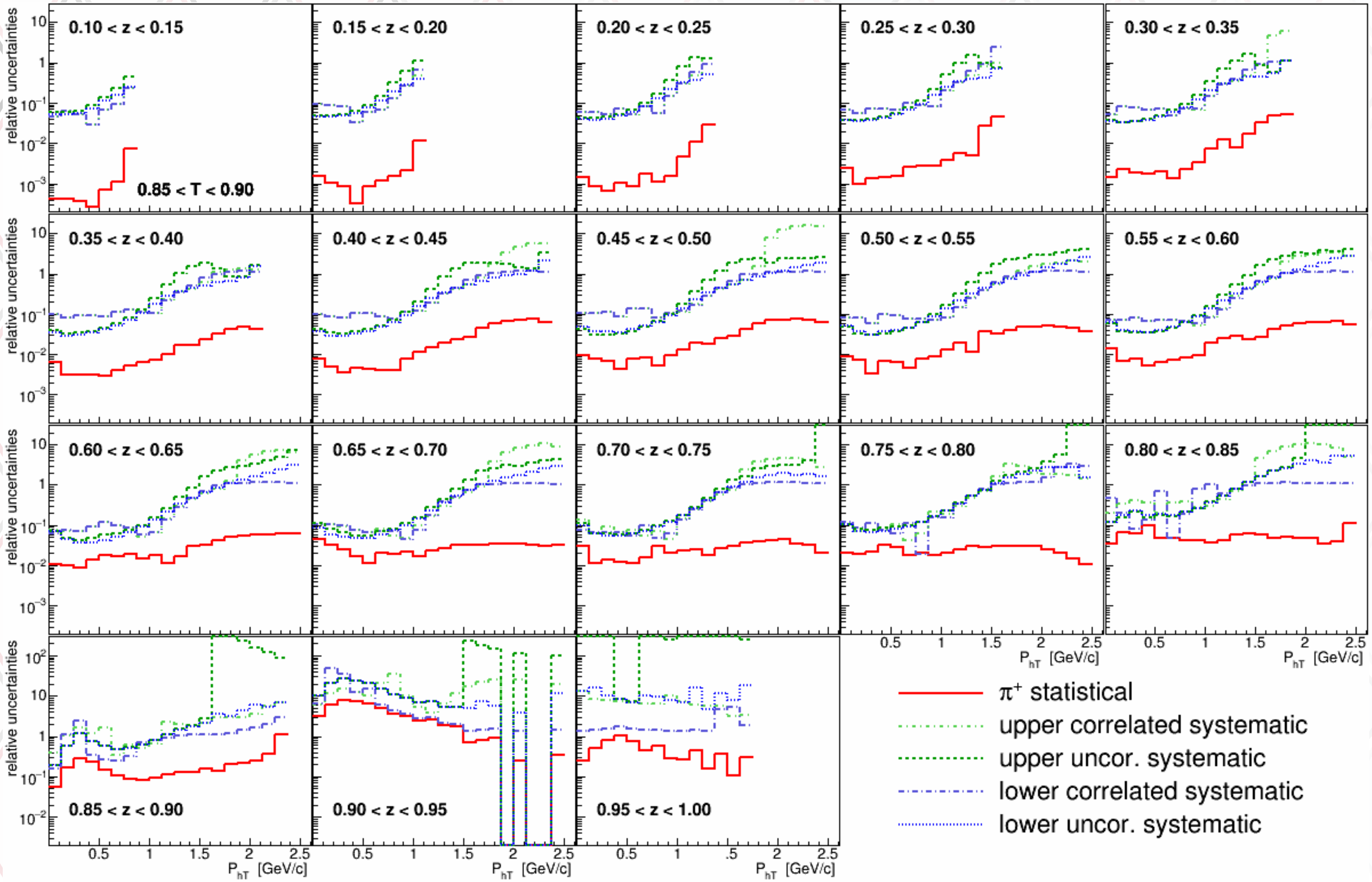
$$\frac{\sigma_{No\ ISR}}{\sigma_{ISR}}$$




$P_{Th}$

# Overall systematic uncertainties

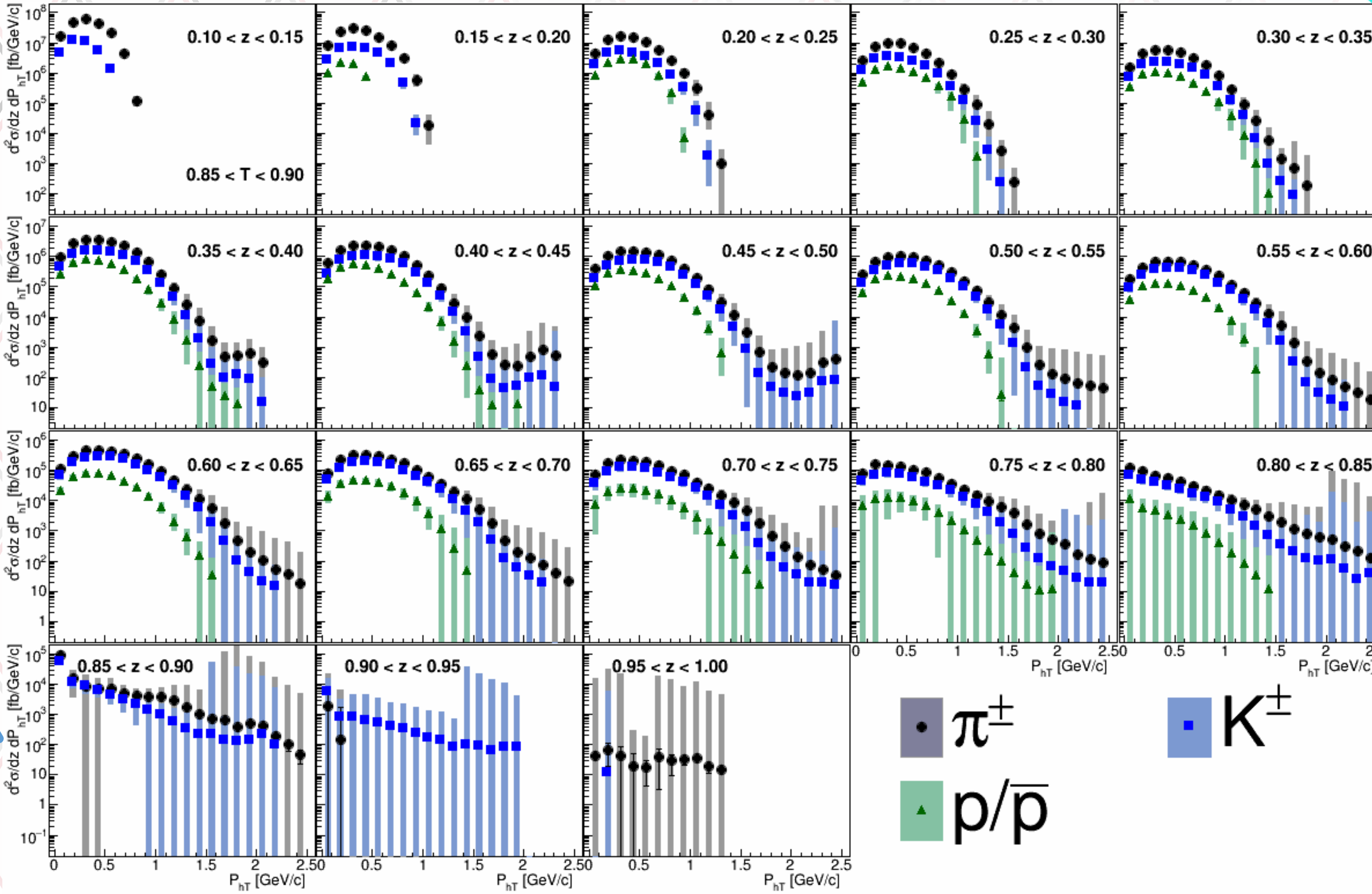
Systematic uncertainties dominated by acceptance correction (for different tunes), PID uncertainties and ISR correction




$\frac{\Delta\sigma}{\sigma}$

$P_{hT}$

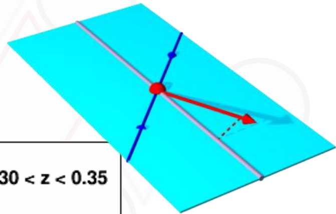
# Cross sections various hadrons




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

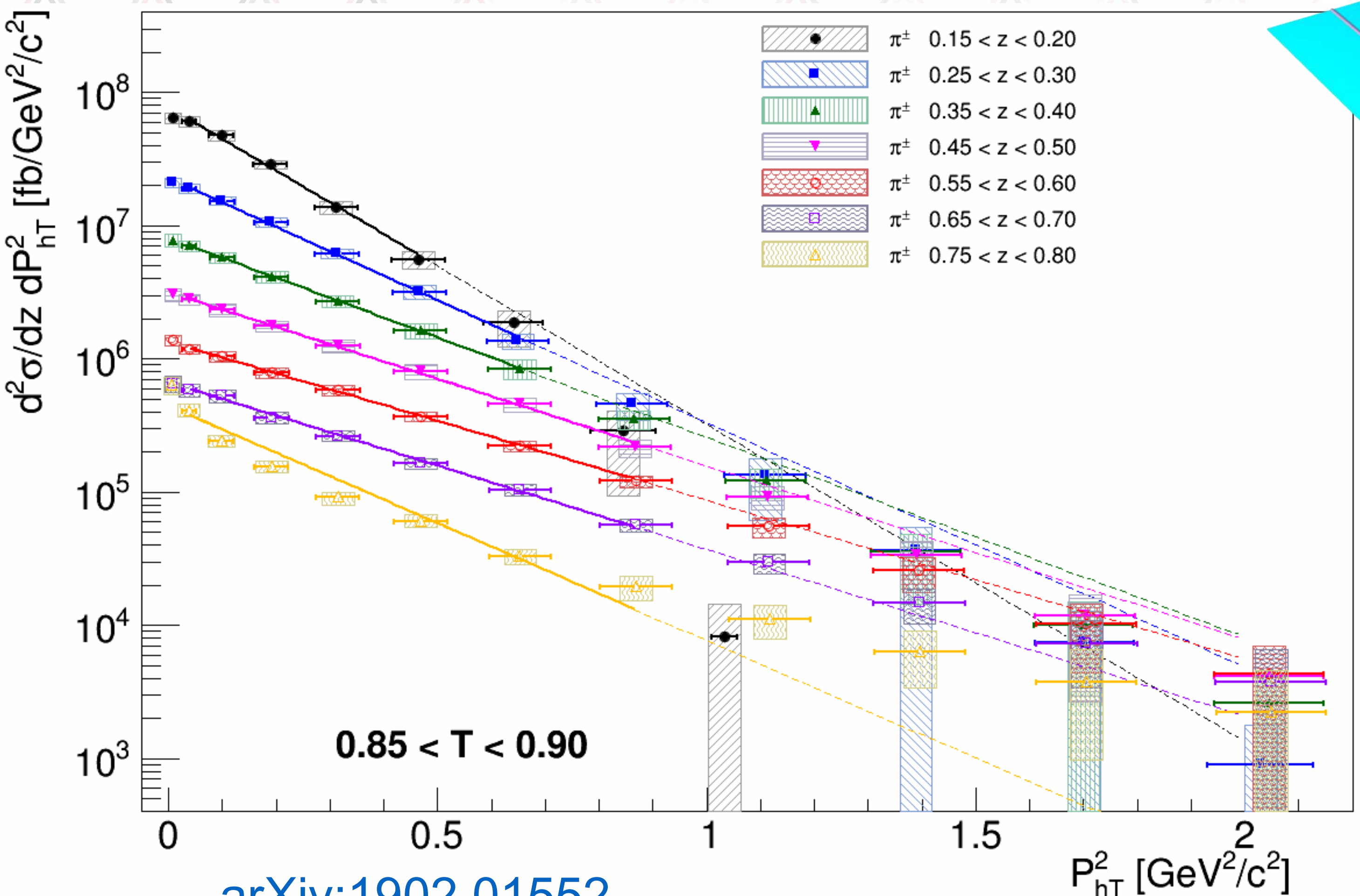
$P_{hT}$

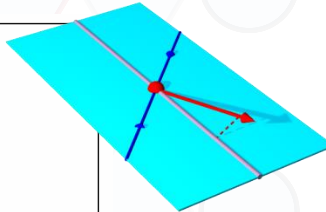
RS. et. al. arXiv:1902.01552



# Fits vs $P_{hT}^2$

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

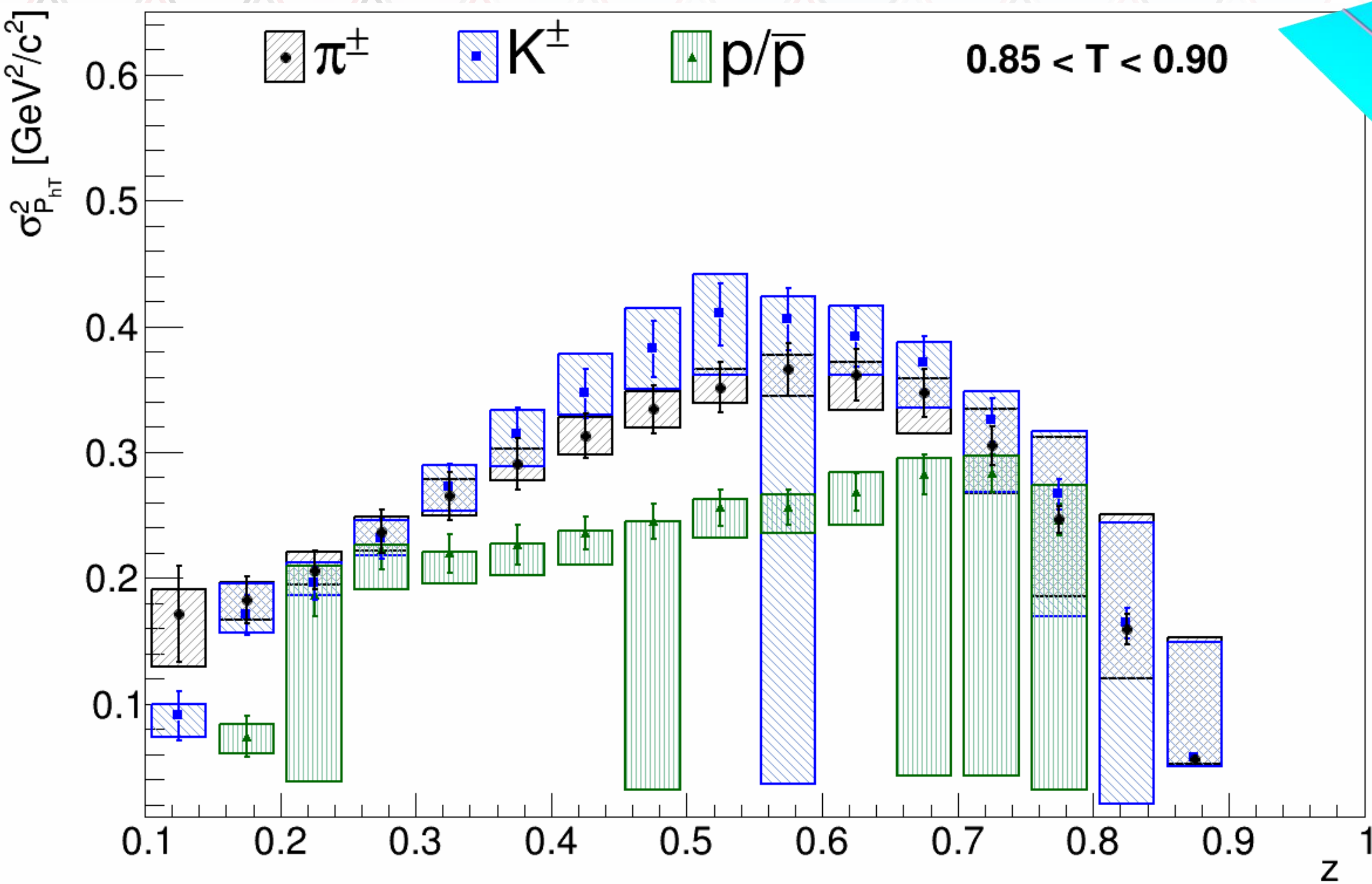


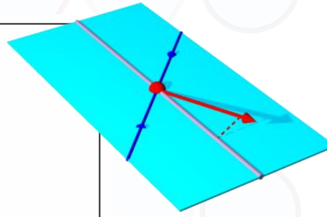



arXiv:1902.01552

# Gaussian widths

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



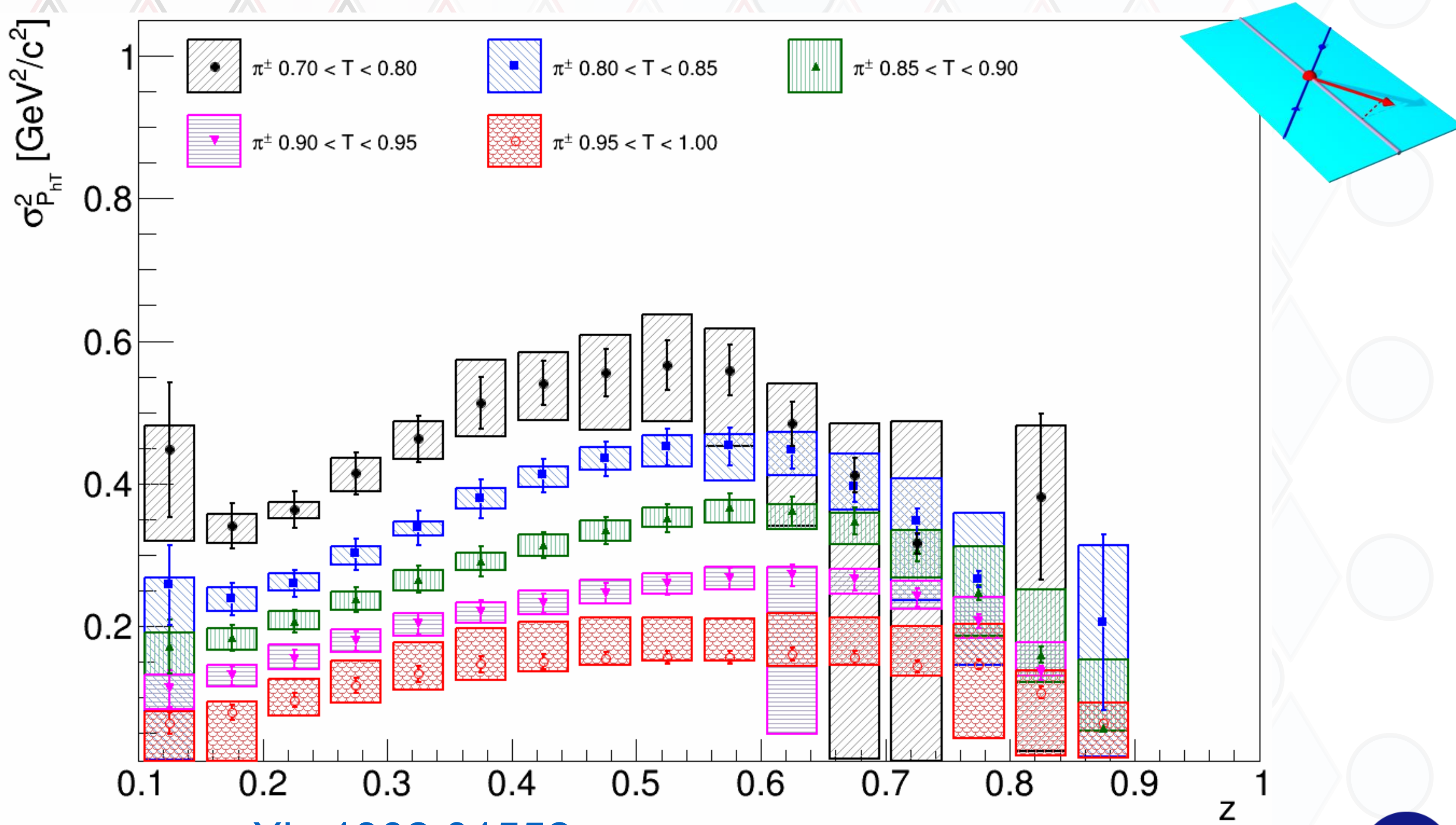



arXiv:1902.01552

Current phenomenological models: no or linear z dependence only

# Gaussian widths, thrust dependence

Gaussian widths get narrower with higher Thrust

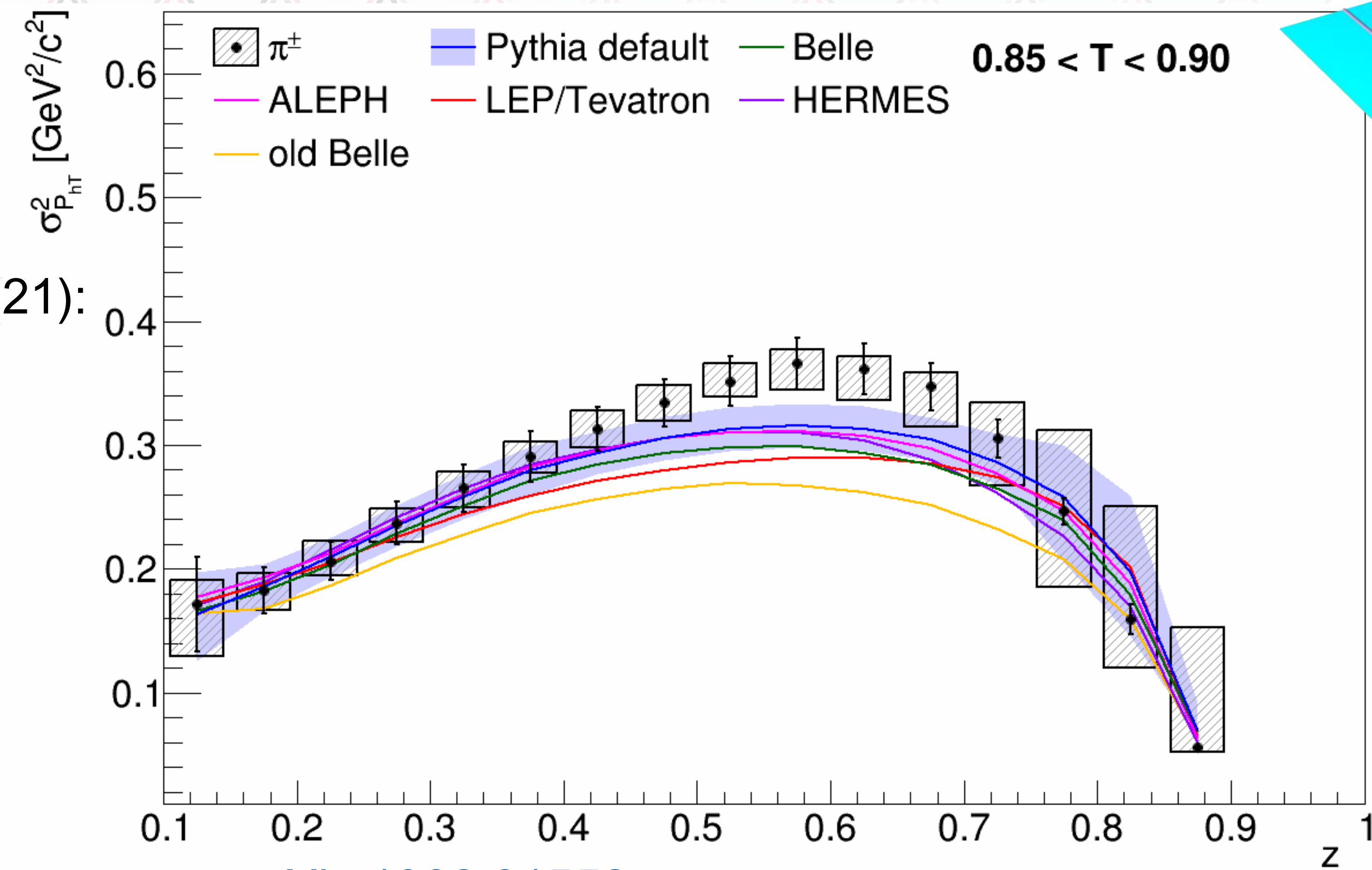


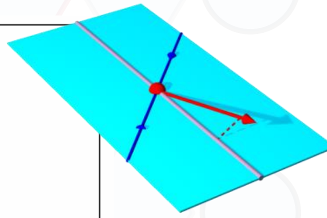

arXiv:1902.01552

# 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

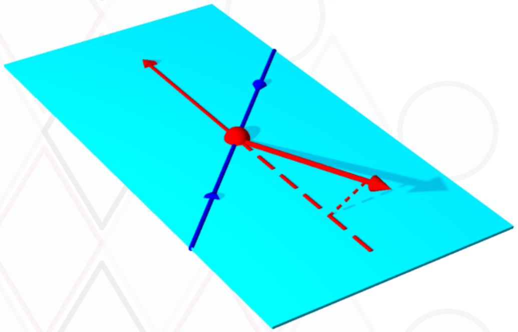


arXiv:1902.01552

# 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



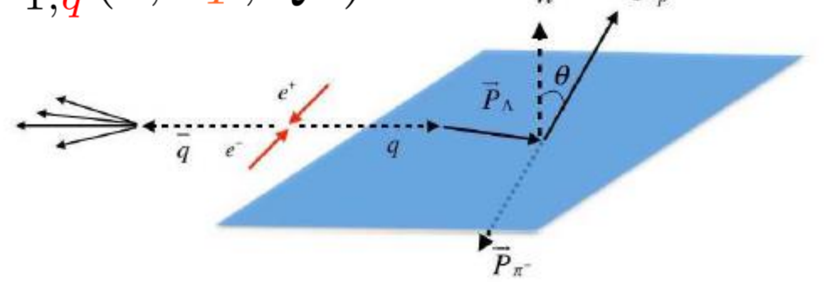
# Single $\Lambda$ polarization measurements

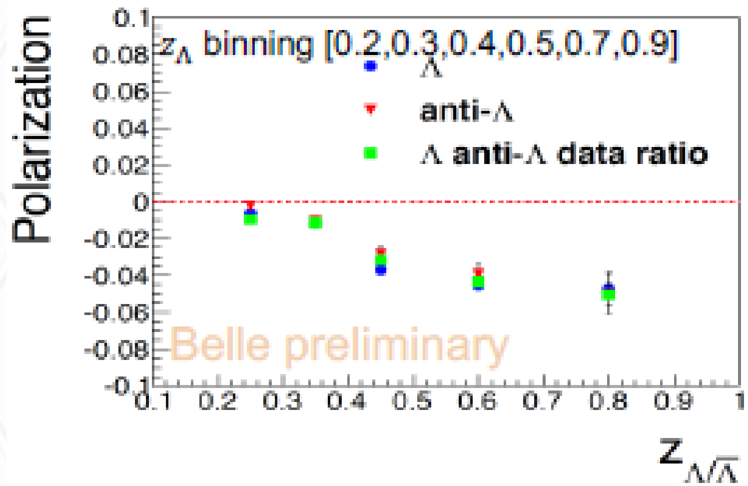
- Related to open question about $\Lambda$ polarization in hadron collisions from 40 years ago!
- Fragmentation counterpart to the Sivers Function:

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

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

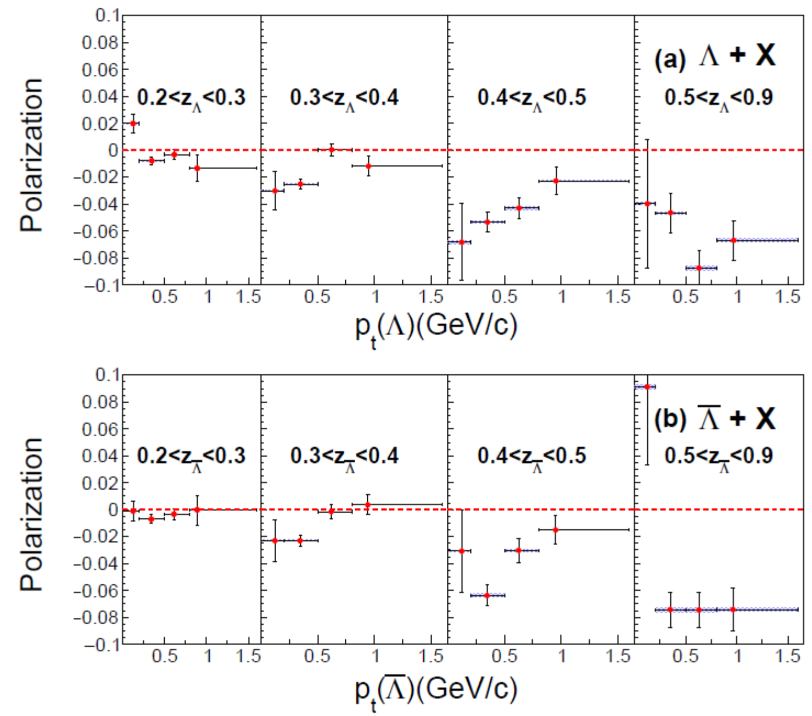
$D_{1,q}^{\perp h}(z, k_T, Q^2)$



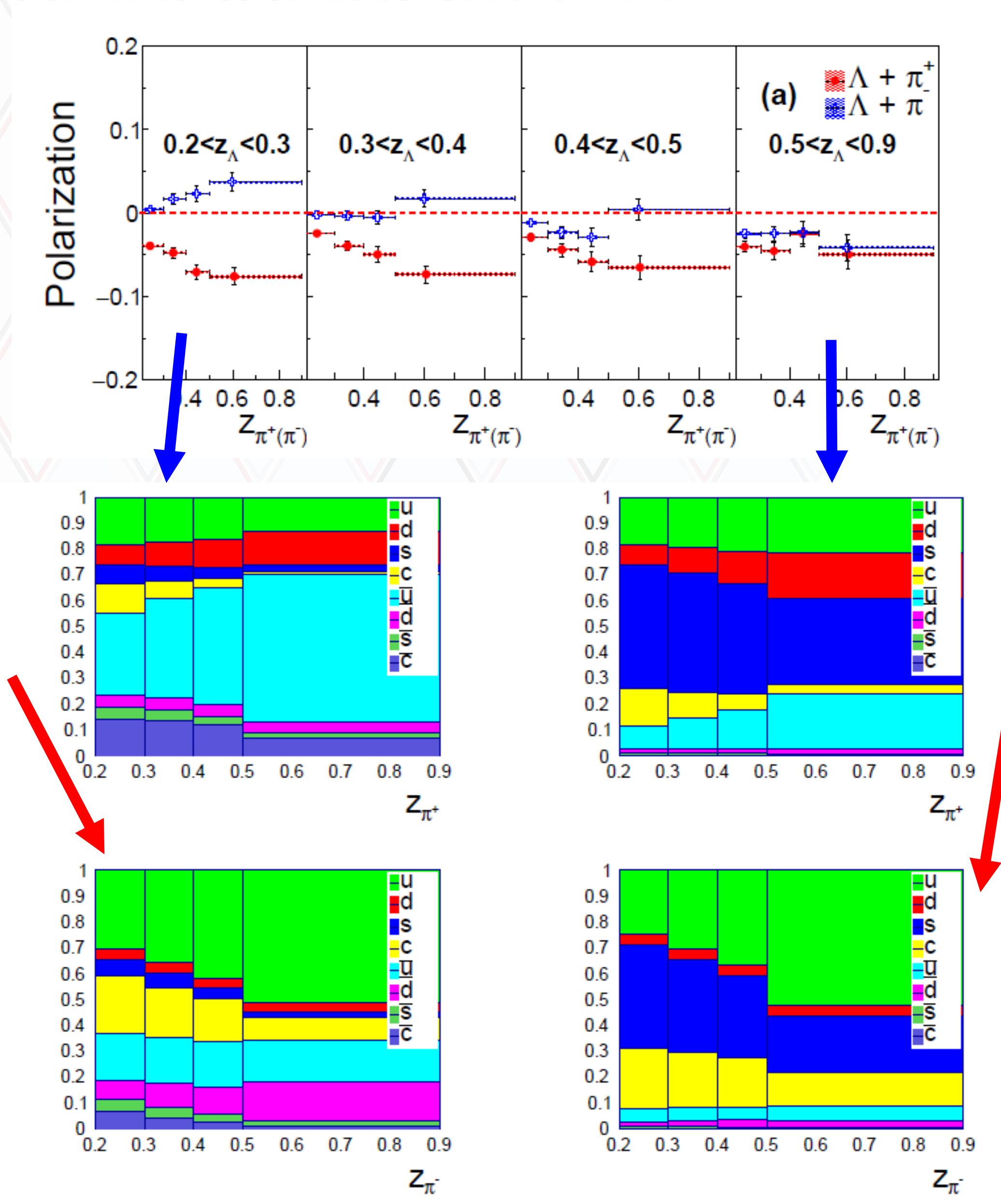
# Transverse momentum dependence

- 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

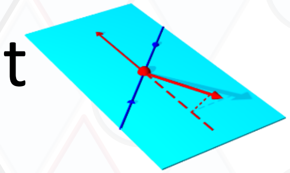
- Interesting $z_\pi$ and $z_\Lambda$ dependence :
- At low $z_\Lambda$ light quark fragmentation dominant, some charm in $\pi^-$ → different signs
- At high $z_\Lambda$ strange + charm fragmentation more relevant → same signs



# 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 ($z_1$) x 6 ($z_2$) x 4($k_{t1}$) x 4($k_{t2}$) x 1 (costheta) x 8 (phi)
  - 6 ($z_1$) x 6 ($z_2$) x 10($q_t$) x 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)

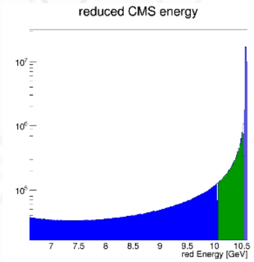
# Other ongoing work



- 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
- Neutral pion and eta Collins
- 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:
  - $K_s$, $K^*$, $\phi$, $\rho$, etc
- $\pi$K 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

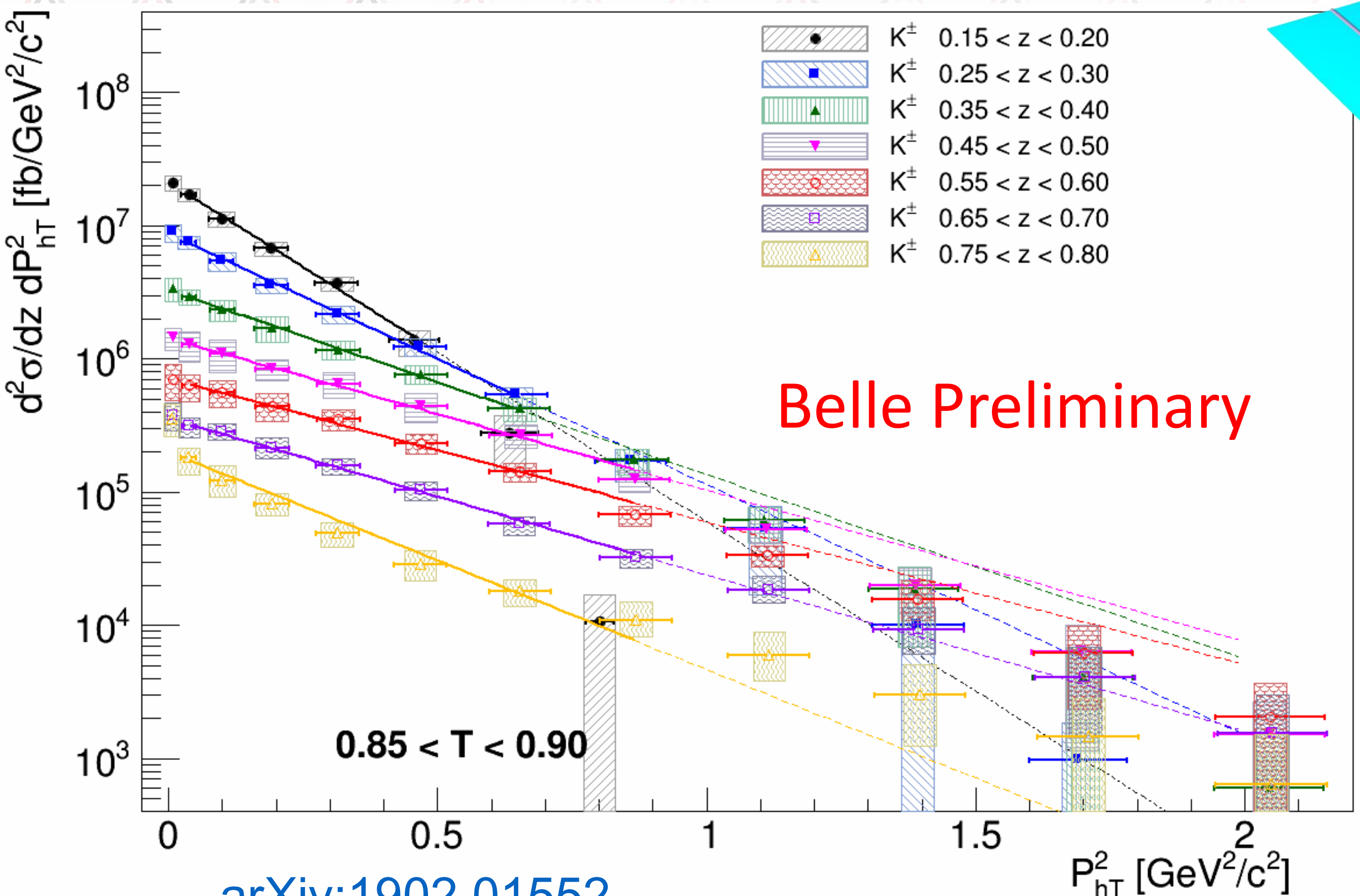


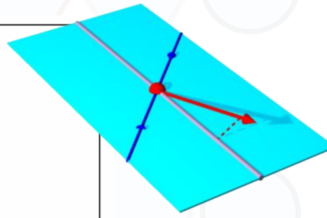
# Summary

- $P_{hT}$ 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)

# Fits vs $P_{hT}{}^2$

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

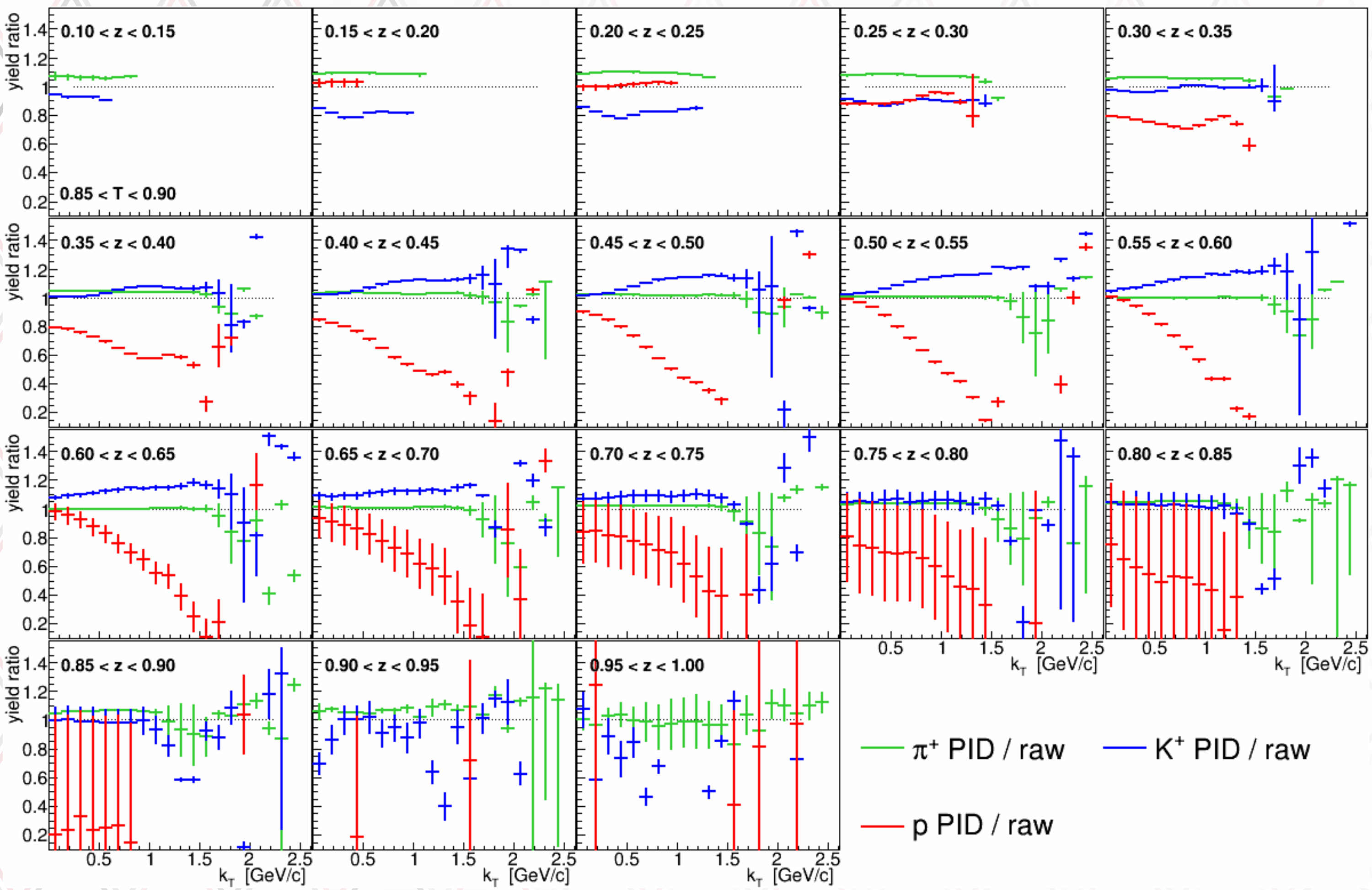


arXiv:1902.01552

# PID correction

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

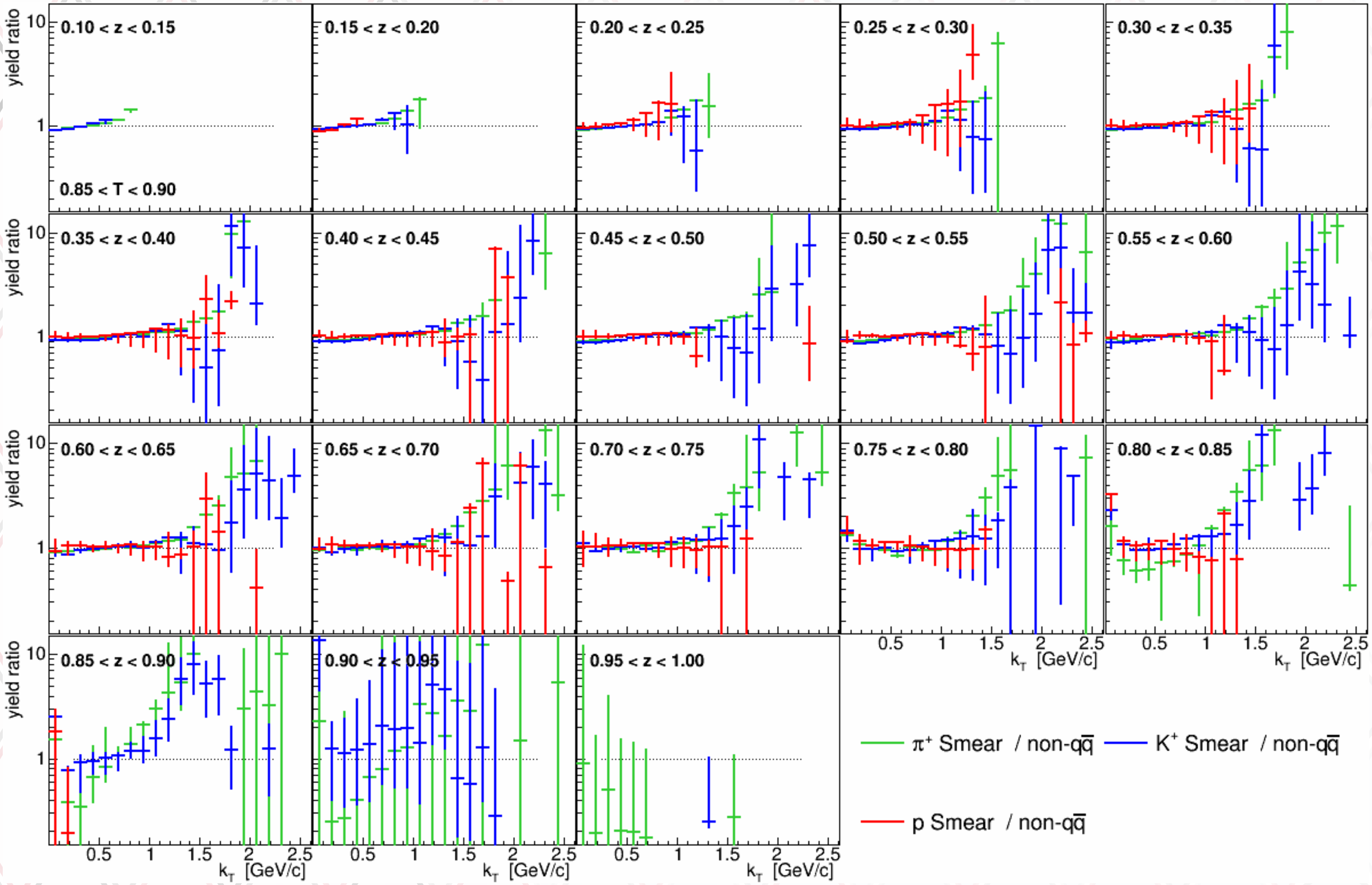



$$\frac{d^2\sigma}{dz\,dk_{T,h}}$$

$k_{Th}$

# Smearing

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

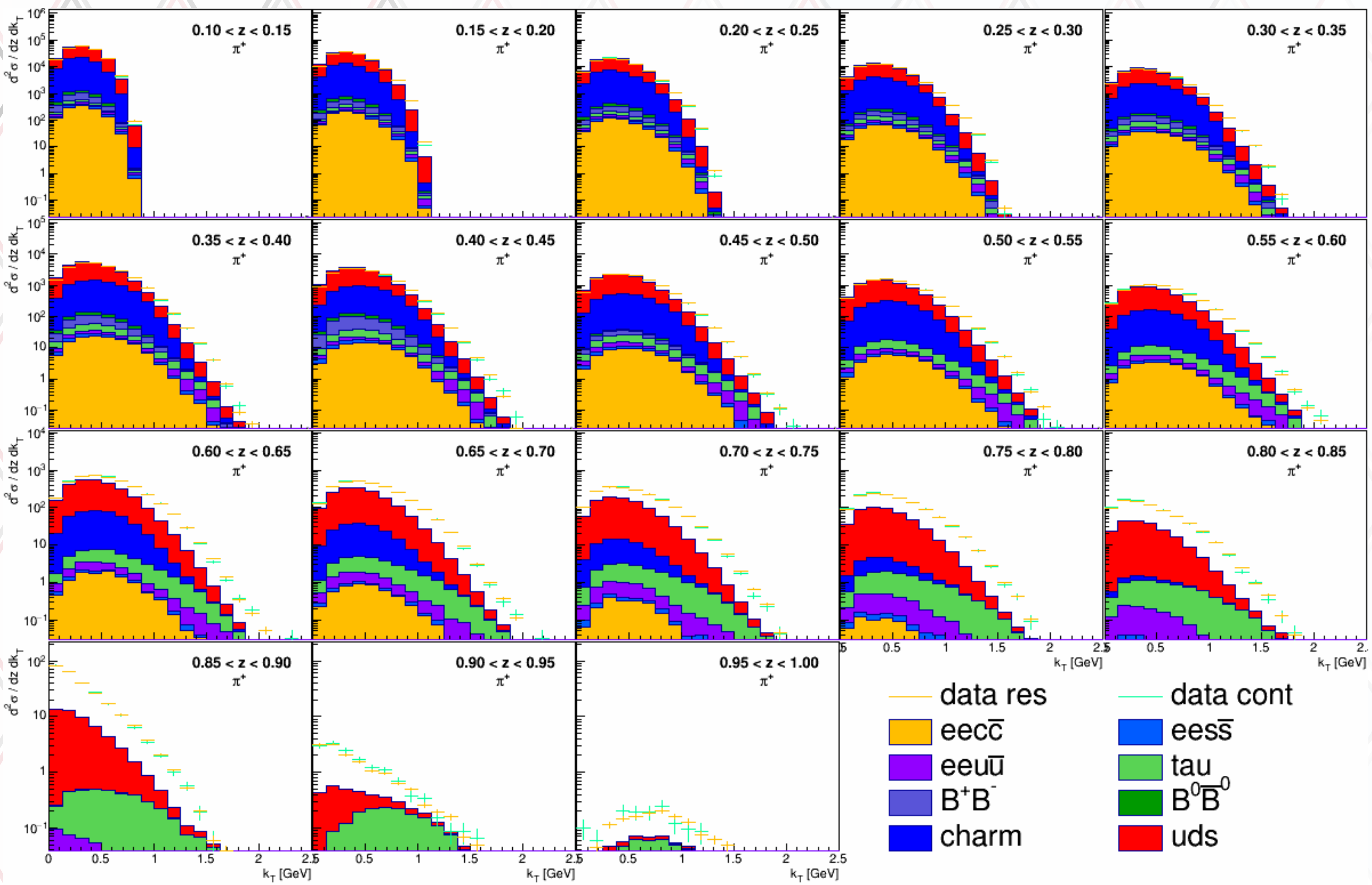



$$\frac{d^2\sigma}{dzdk_{T,h}}$$

$k_{Th}$

# Non-qqbar removal:

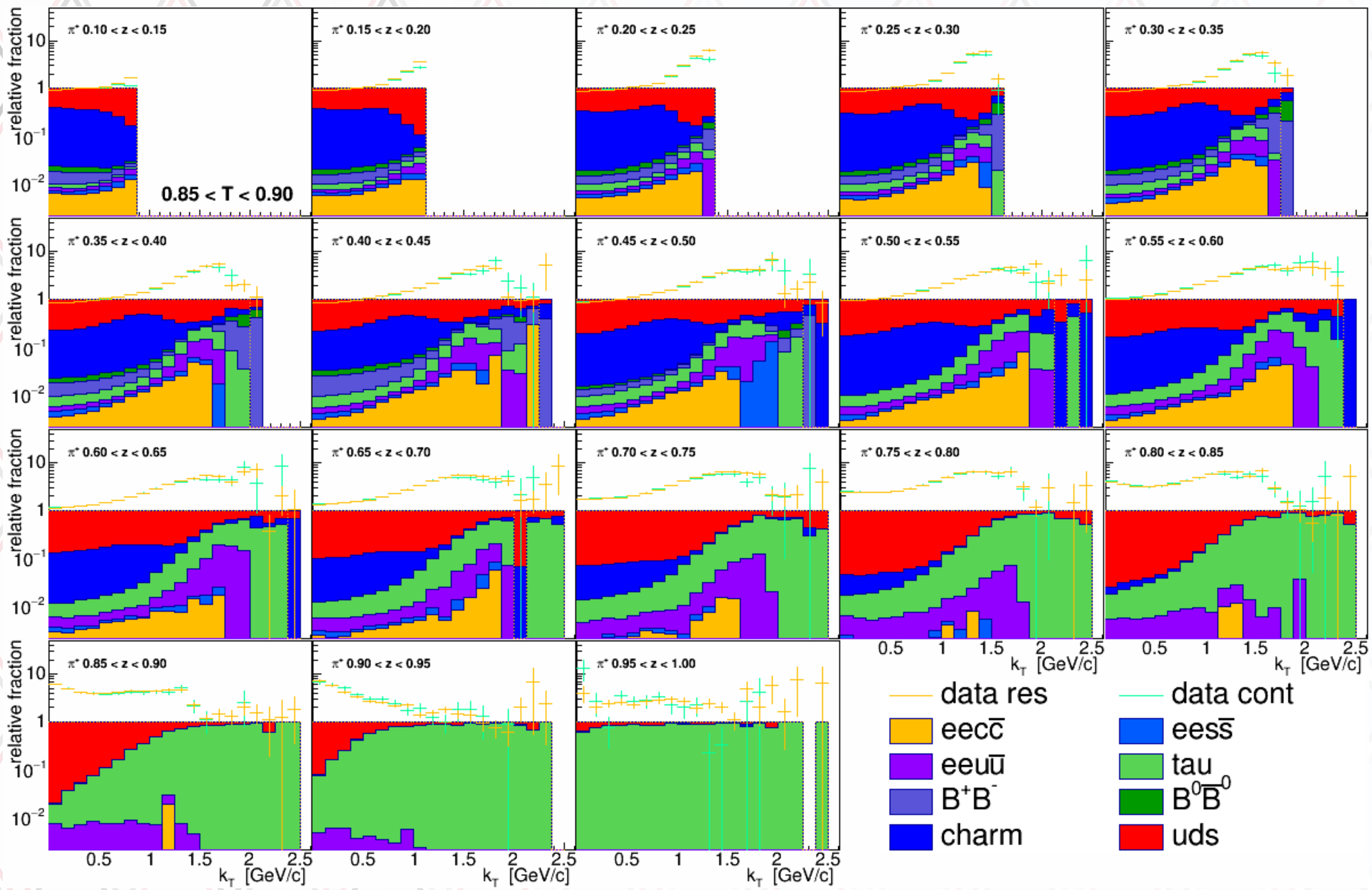
Remove all two-photon and tau events from yields, contributions generally up to several %, slightly higher for kaons rand low thrust




$$\frac{d^2\sigma}{\mathrm{d}z\mathrm{d}k_{T,h}}$$

$k_{Th}$

# Stacked, relative contributions




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

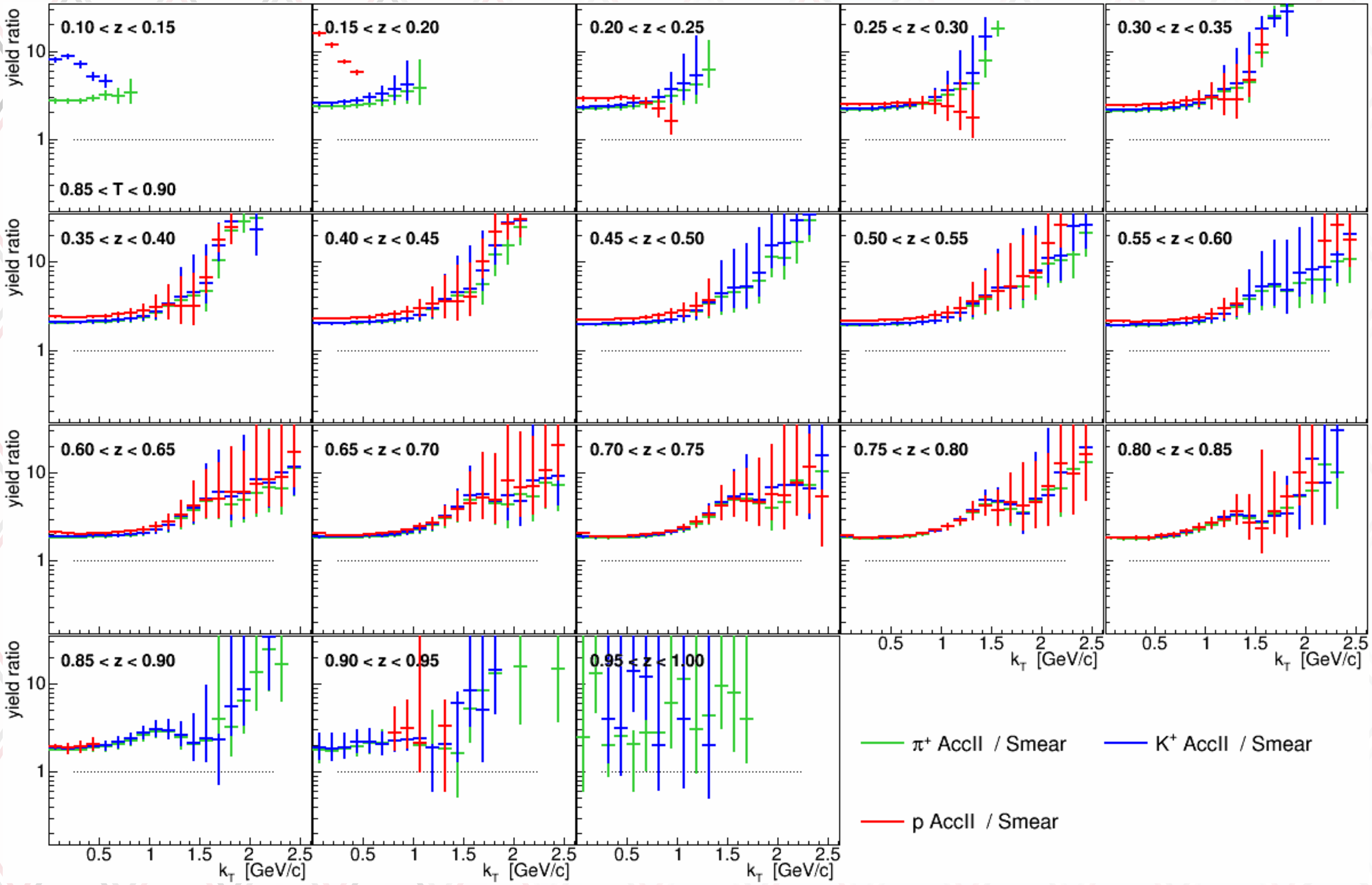
$k_{Th}$

# Acceptance correction

ACCI:Reconstruction and efficiency correction in Barrel acceptance

ACCII: Barrel to 4π correction

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

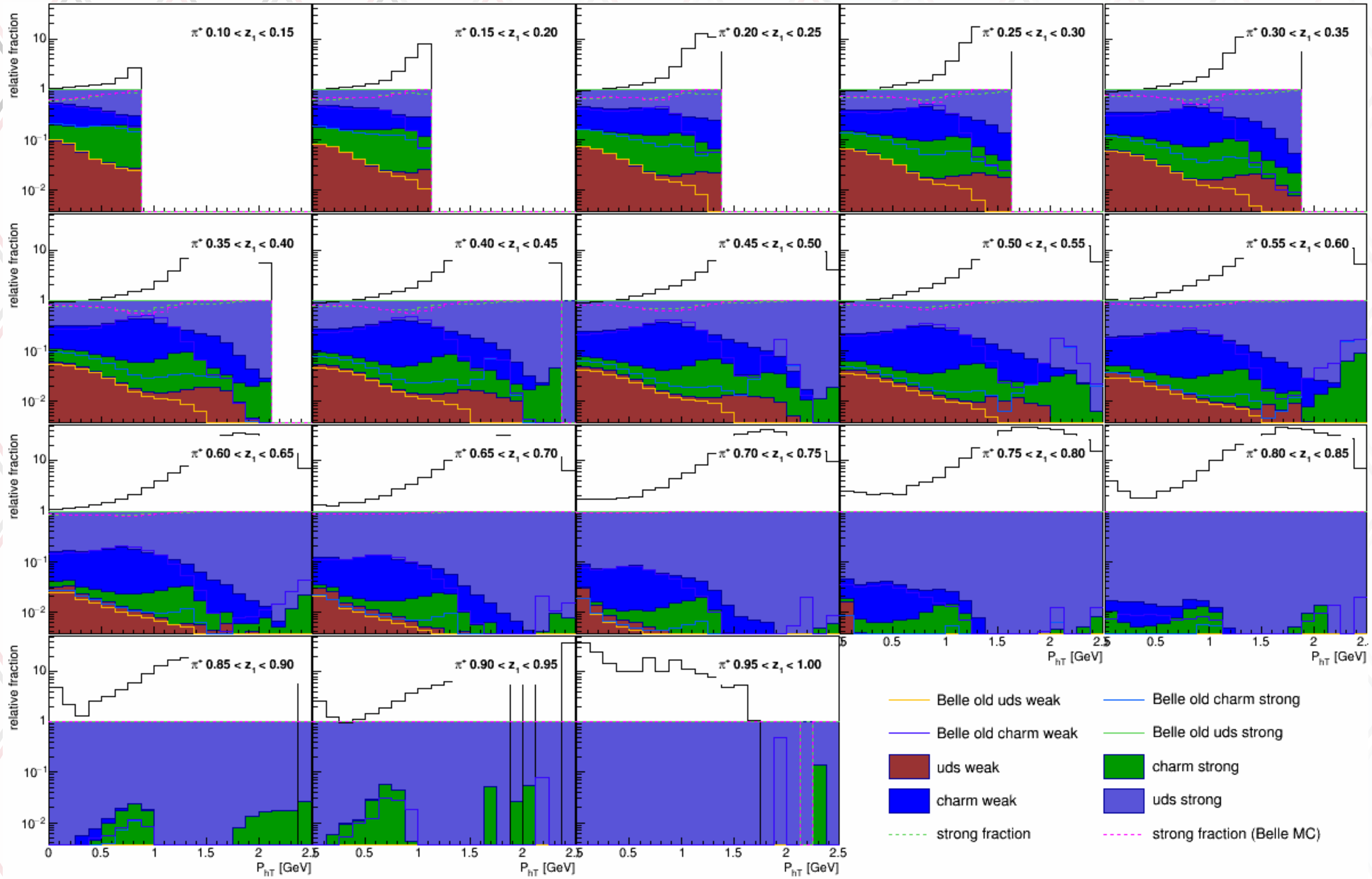



$k_{Th}$

# 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

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




$k_{Th}$

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

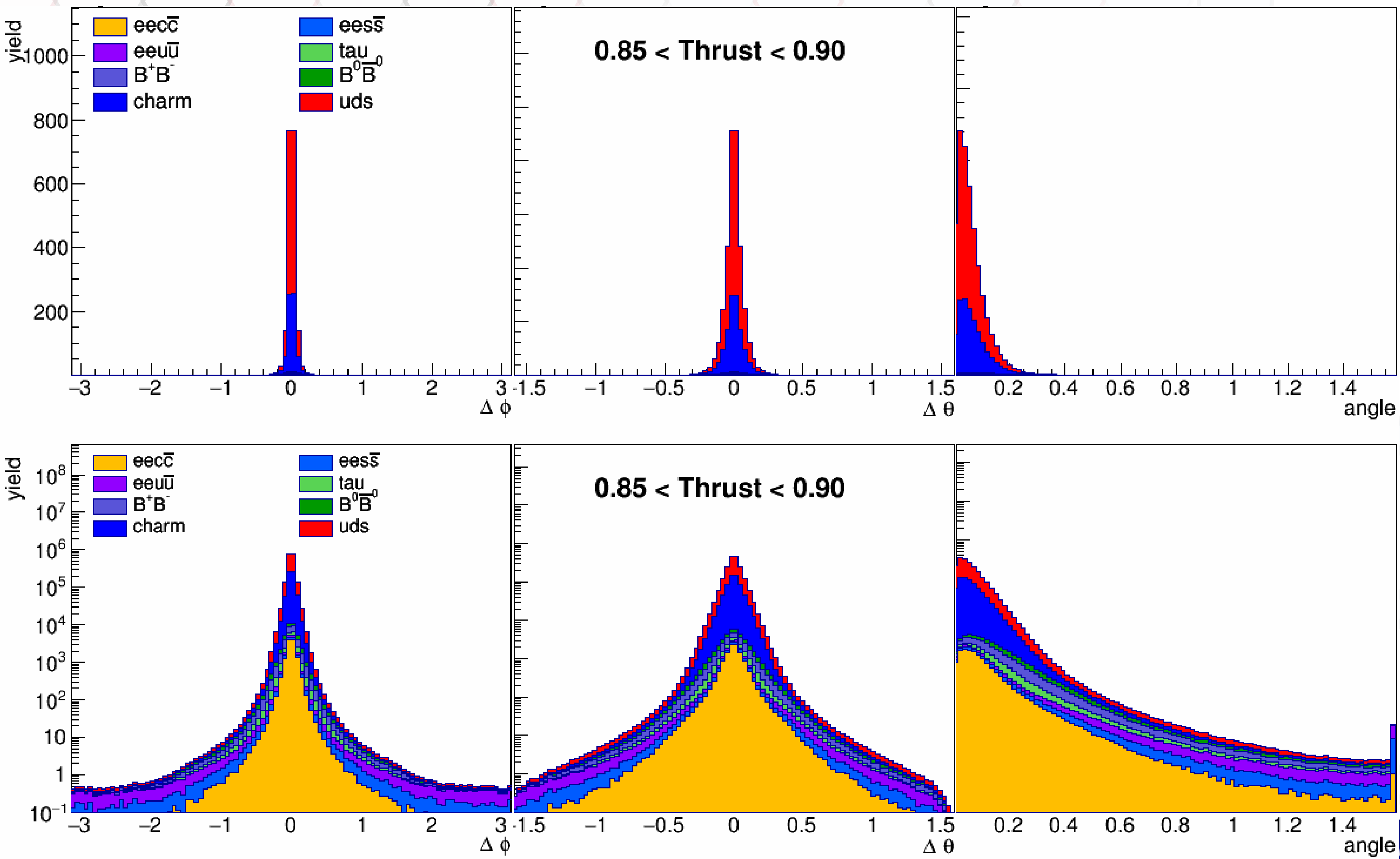
$P_x$,$P_y$ Gauss width

Lund params

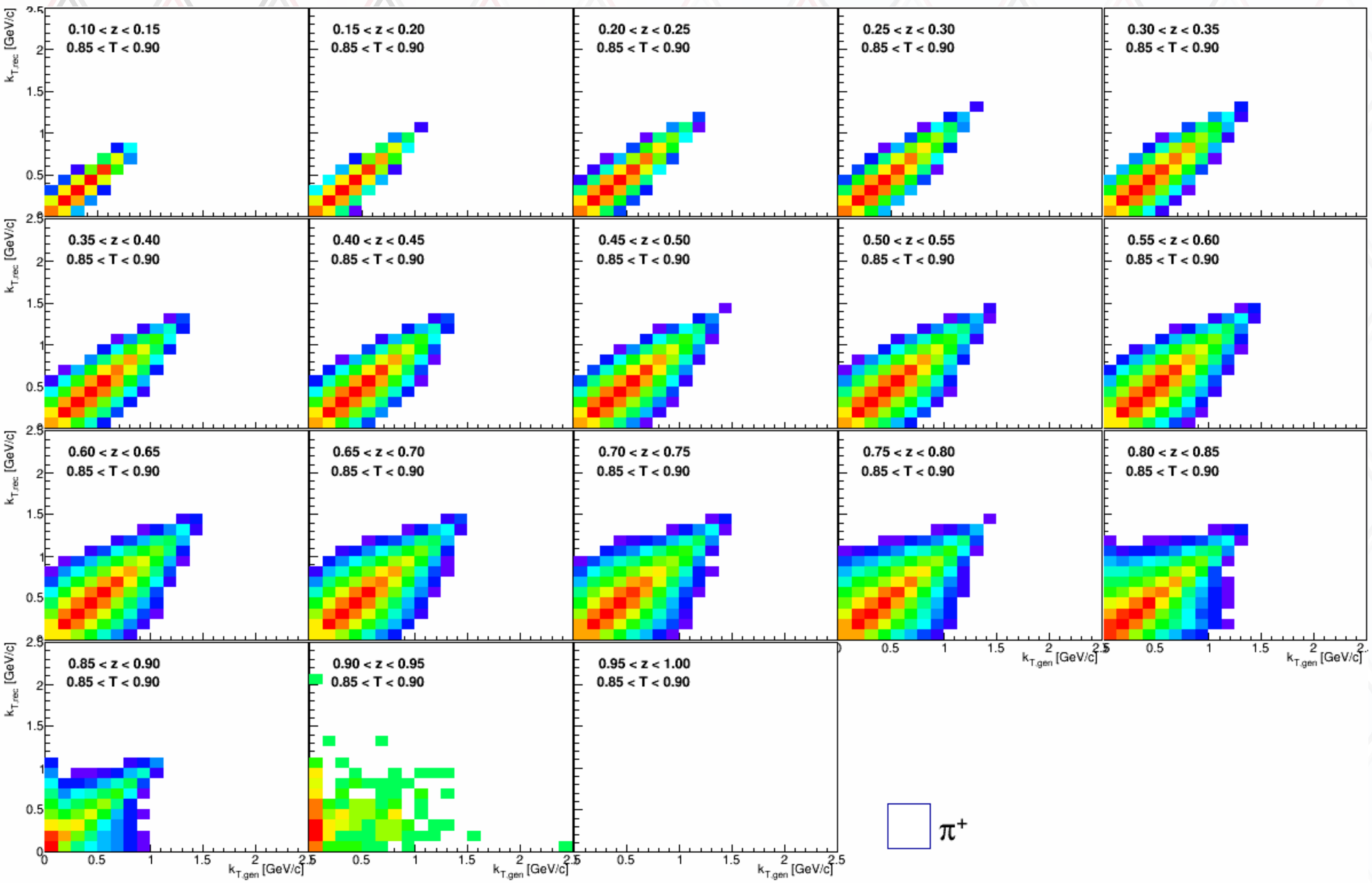
$\Lambda_{QCD}$ and E cutoff

# Pythia/Jetset parameters

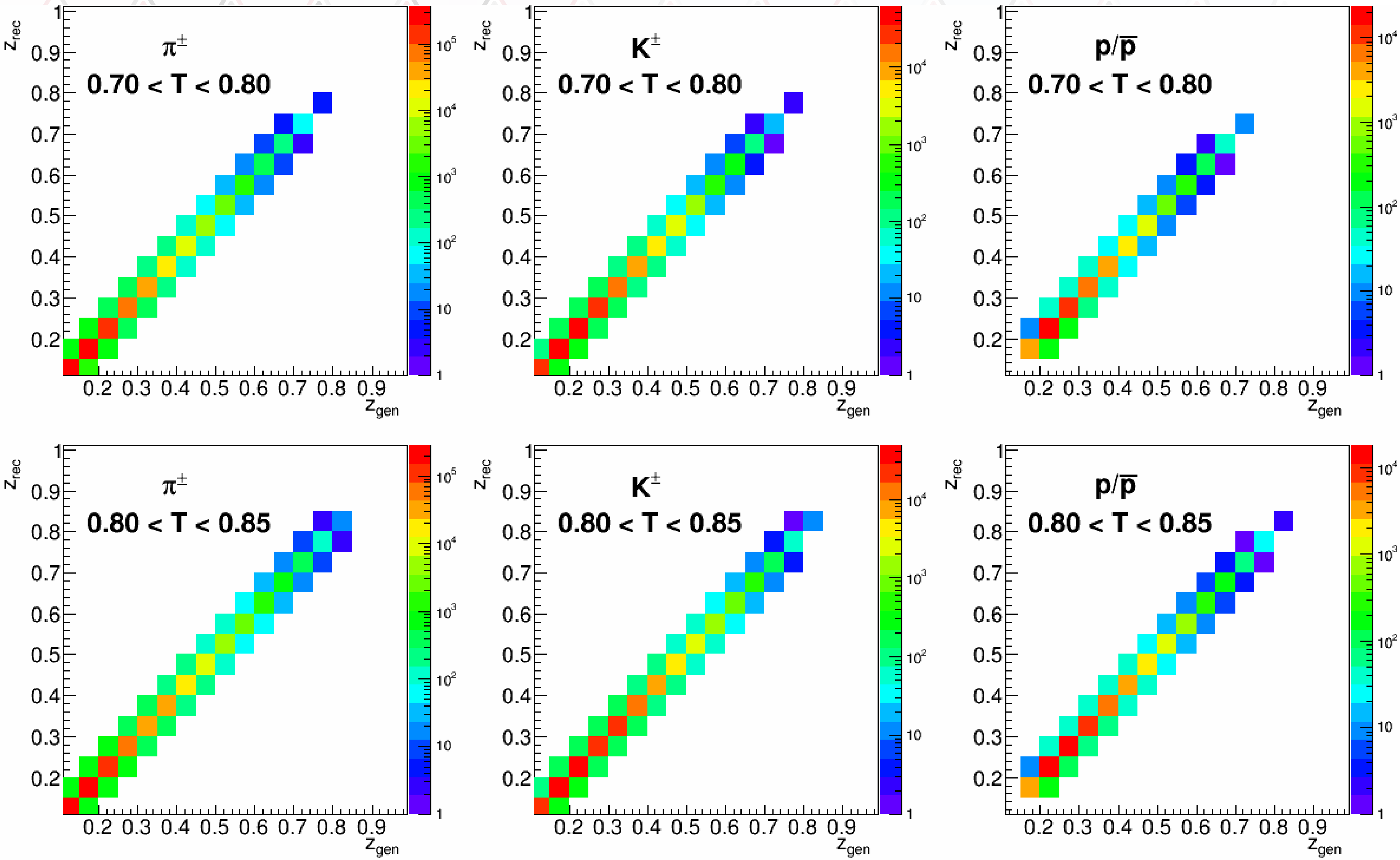
| | | |
|---|---|---|
| PARJ(1) | : | Diquark suppression relative to quark antiquark production |
| PARJ(2) | : | Strangeness suppression relative to u or d pair production |
| PARJ(3) | : | Extra suppression of strange diqurks relative to strange quark production |
| PARJ(4) | : | Axial ($ud_1$) vs 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) | : | $\eta$ production suppression factor |
| PARJ(26) | : | $\eta'$ 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) | : | $\Lambda_{QCD}$ for parton showers |
| PARJ(82) | : | invariant mass cut-off for parton showers |



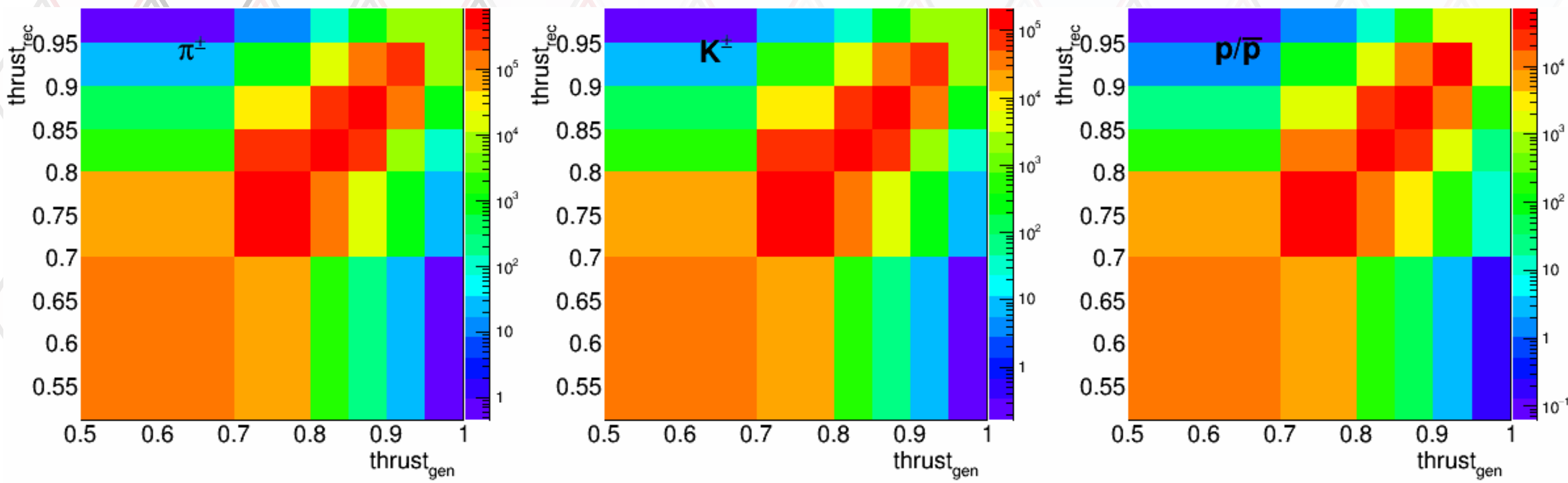
0.85 < Thrust < 0.90
yield
$ee c\bar{c}$
$ee u\bar{u}$
$B^+B^-$
charm
$ee s\bar{s}$
tau
$B^0\bar{B}^0$
uds
Δ φ
Δ θ
angle
0.85 < Thrust < 0.90


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]
$\pi^+$

# Z smearing (integrating over ktbins)

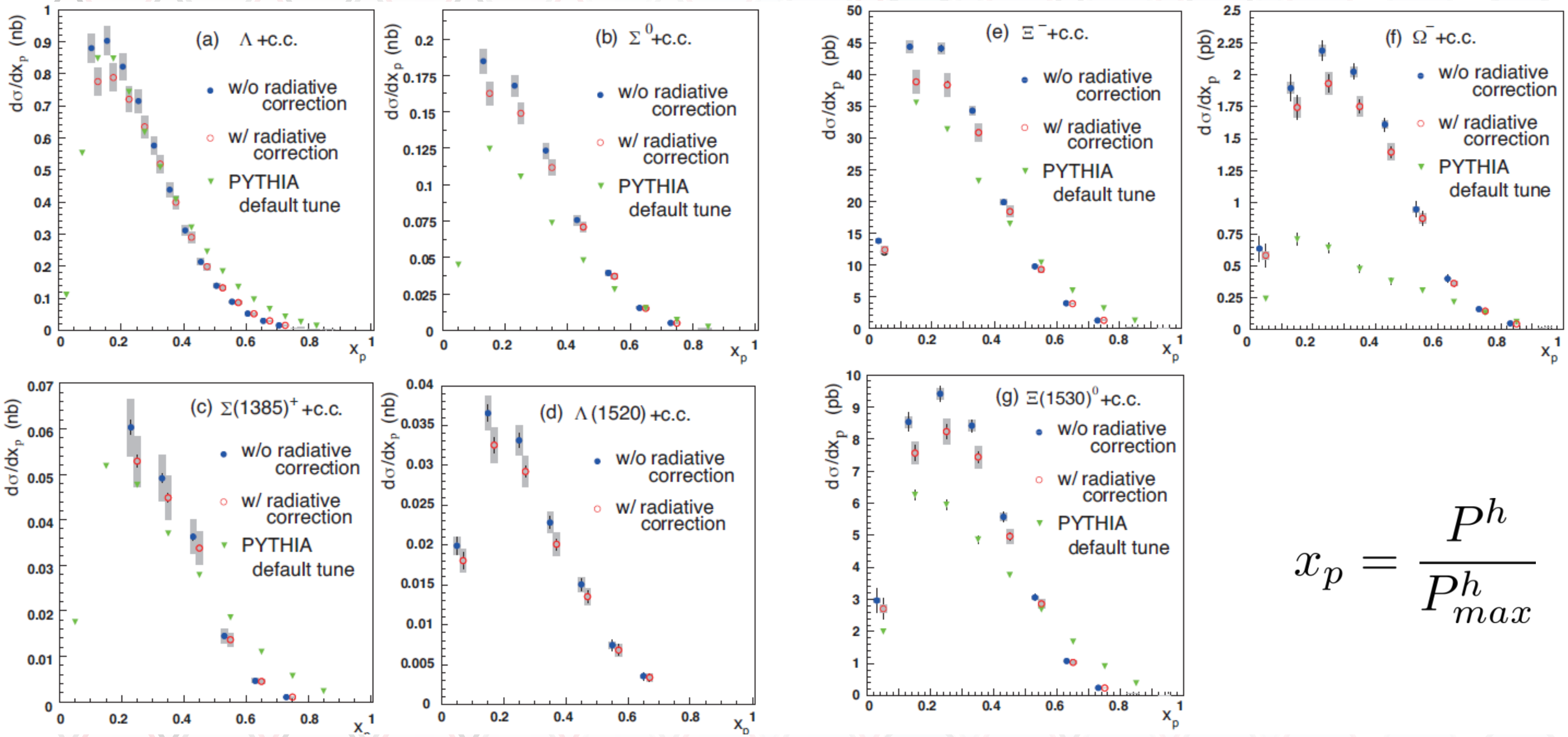


# Thrust smearing (integrating over z and kt bins)



# Hyperon Fragmentation

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

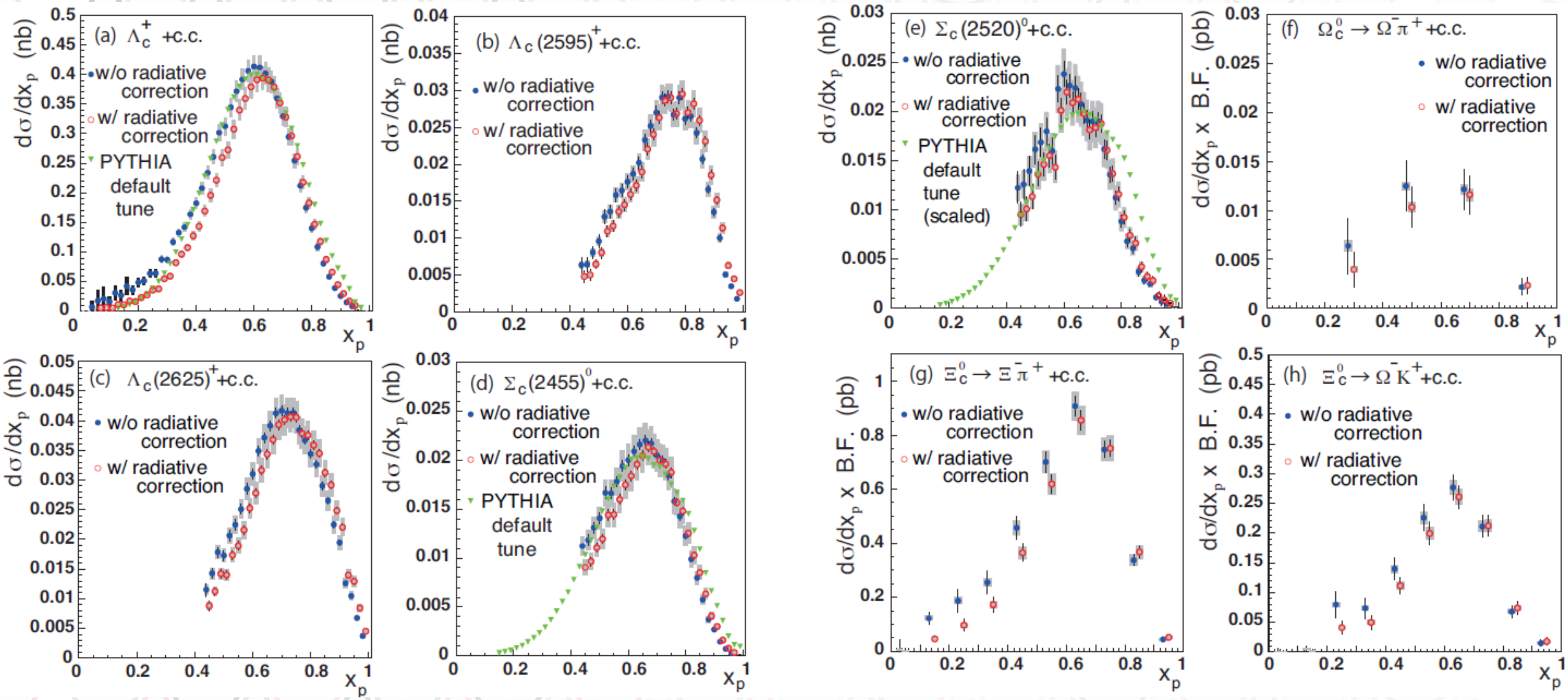



$$x_p = \frac{P^h}{P^h_{max}}$$

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

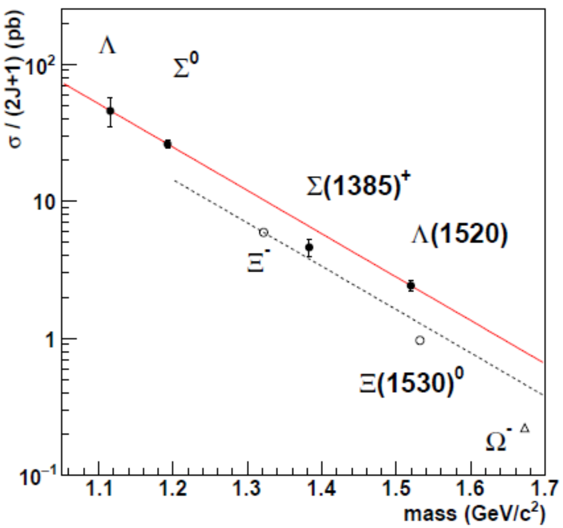
# Charmed baryon Fragmentation

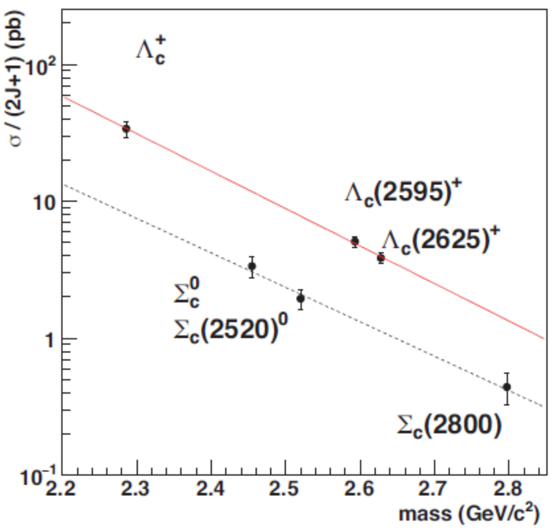
Belle: Niiyama et. al. [PRD 97 (2018), 072005]




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

# Baryon production rates



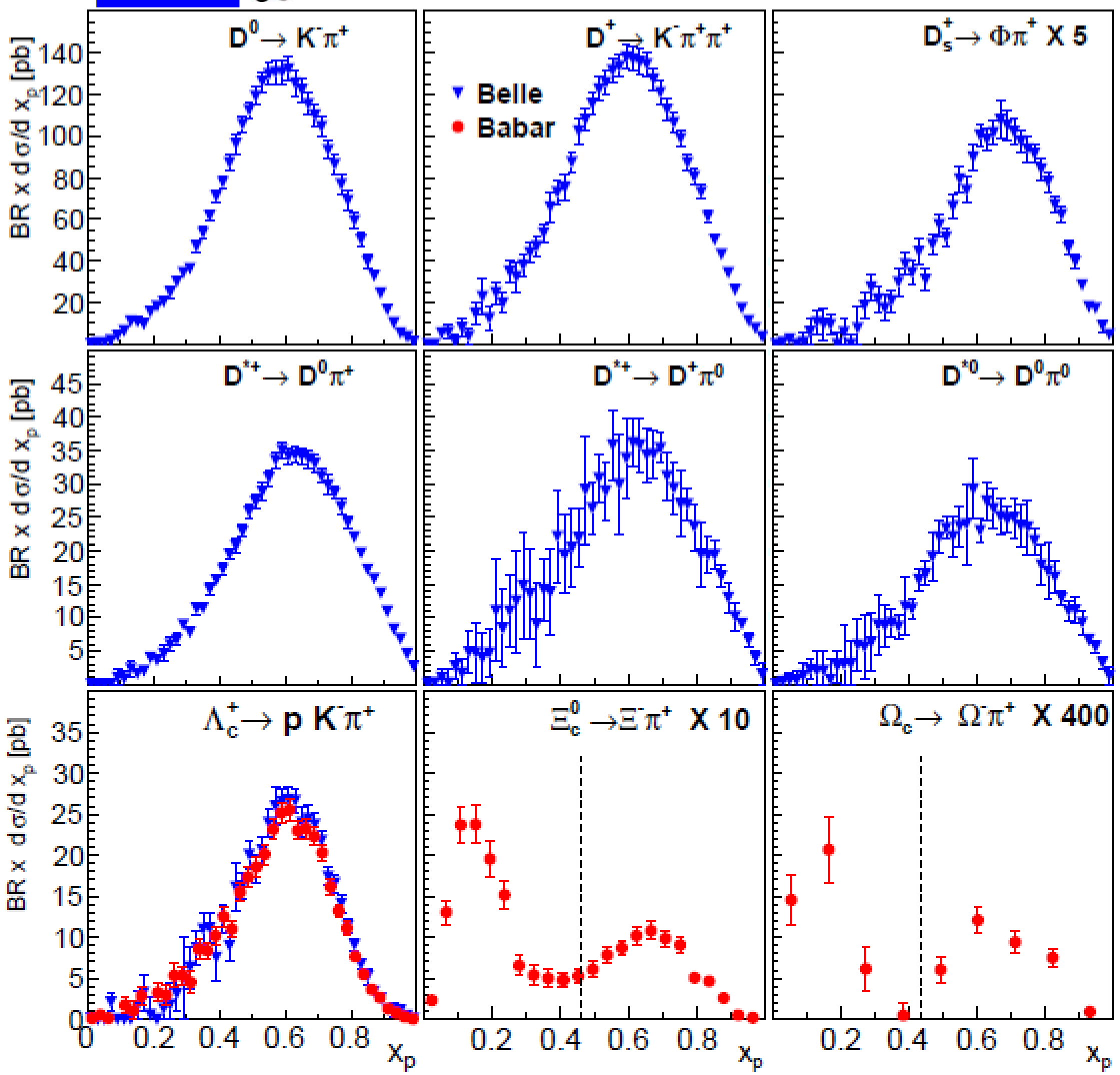




- First feed-down corrected production rates extracted
- No $\Lambda(1520)$ enhancement seen
- Strangeness suppression seen for hyperons:

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

- Difference in slopes for $\Lambda_c$ and $\Sigma_c$ in support of diquark production picture (spin 1 diquarks suppressed)

# Charmed Fragmentation

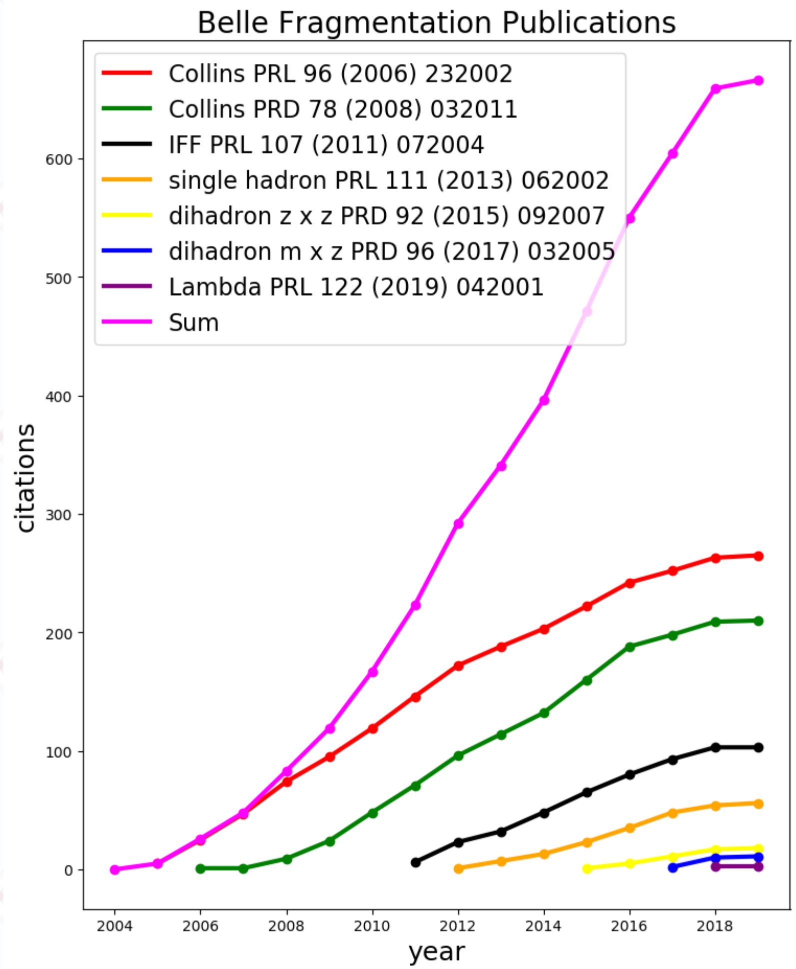



PRL.95, 142003 (2005)(Babar)
PRD73, 032002 (2006) (Belle)
PRD75, 012003 (2007)(Babar)
PRL 99, 062001 (2007)(Babar)

- 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

# Belle fragmentation

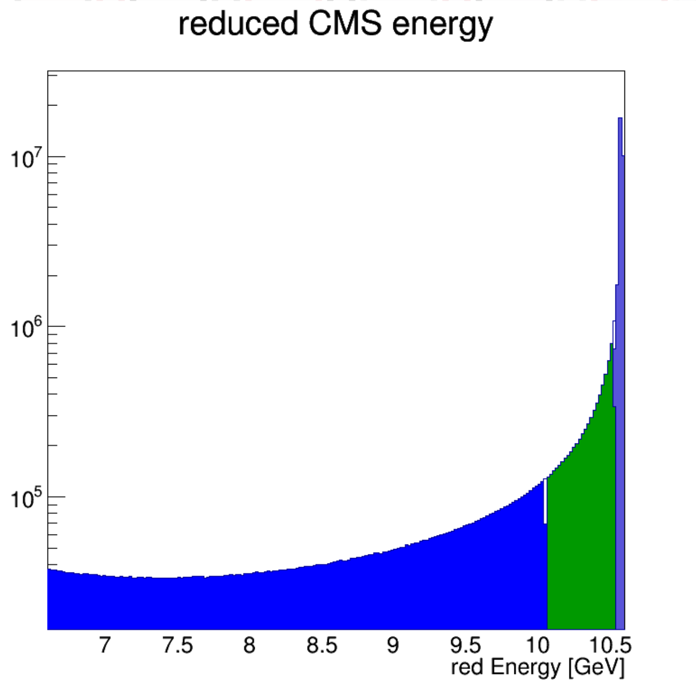
- Initially started by RBRC fellow M. Perdekamp (now UIUC), A. Ogawa (BNL) and S. Lange (now U Giessen)
- Continued by RCS with additional help from UIUC (Matthias) and IU/Duke (A. Vossen) and JSPS



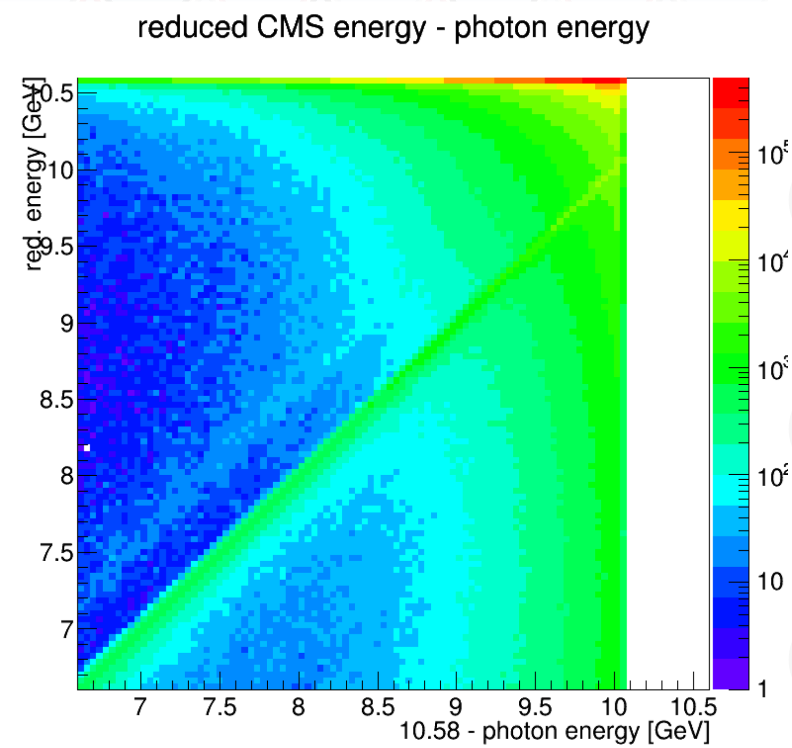
# New possibilities: From Correcting ISR to using it as a tool

- During di-hadron analysis and kt analysis successfully checked actual boost of qqbar pair in ISR events
- General Idea: Use photons reconstructed in Belle(2) to tune the reduced sqrt(s) and scale of the fragmenting qqbar system
- Belle(2) acceptance covers a larger range with EM Calorimetry than for tracking→ good at catching not too soft photons
- First test: use all photons that cannot be combined with another photon to be close to the $\pi^0$ (0.1-0.17) or $\eta$ (0.5-0.6) mass range

# CMS energy of the qqbar system




- Remove detected photon(s), E>0.5GeV from system
- Correlation to true CMS energy seen




- Possible improvements:
  - Correlation w/ angle to the thrust axis
  - Small angles to the beam directions
  - Mostly from the higher energy beam
  - Total reconstructed energy