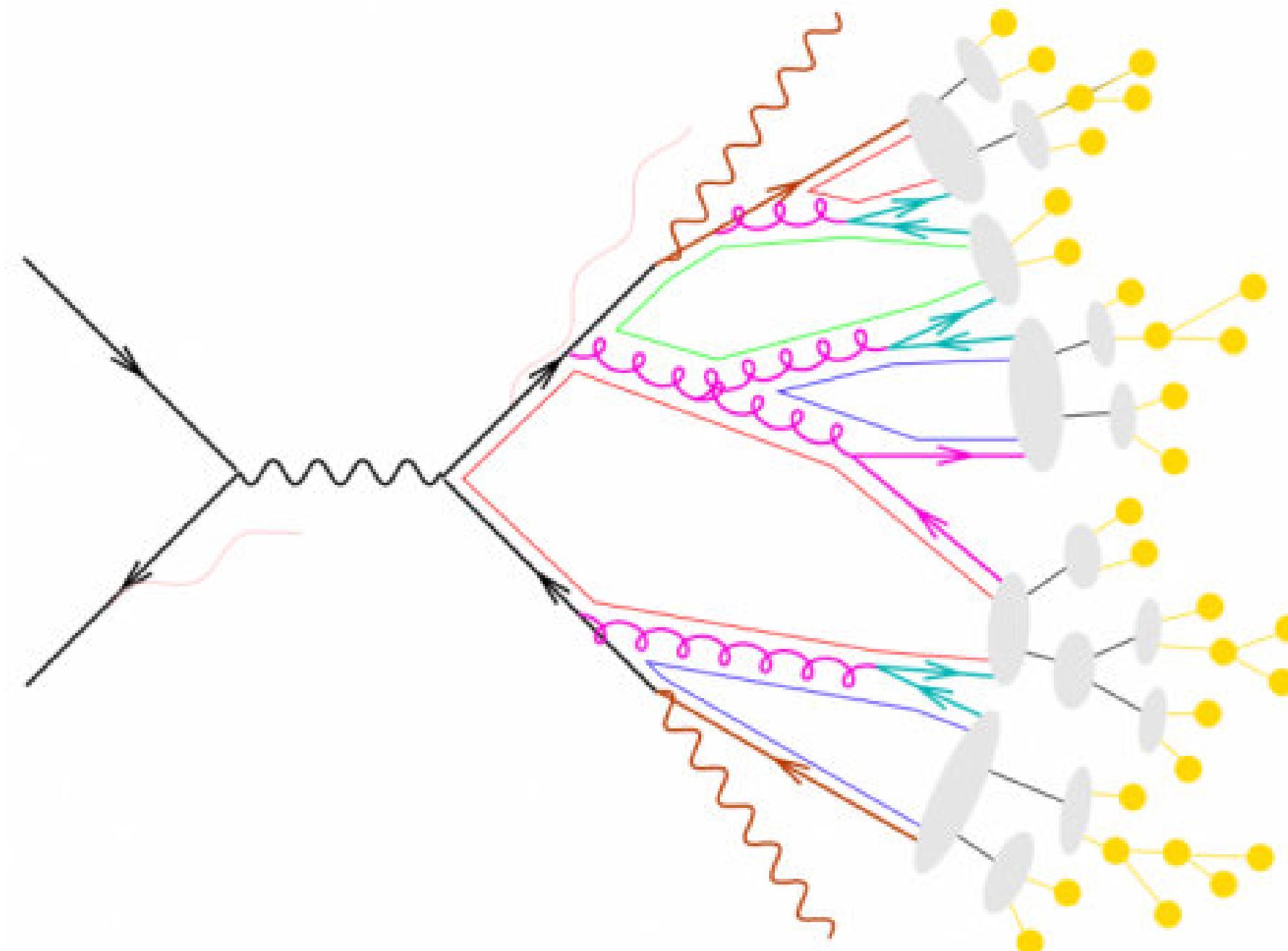


QCD Evolution Workshop 2023

22-26 May 2023
IJCLab, Orsay

[courtesy A. Signori]



*TMD-related fragmentation
function measurements from*



This work is part of a project that has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement STRONG-2020 - No 824093



Gunar.Schnell @ DESY.de



single-hadron TMD*) fragmentation functions

*) TMD ... transverse-momentum dependent

quark pol.

	U	L	T
U	D_1		H_1^\perp
L		G_1	H_{1L}^\perp
T	D_{1T}^\perp	G_{1T}^\perp	$H_1 H_{1T}^\perp$

single-hadron TMD*) fragmentation functions

*) TMD ... transverse-momentum dependent

quark pol.

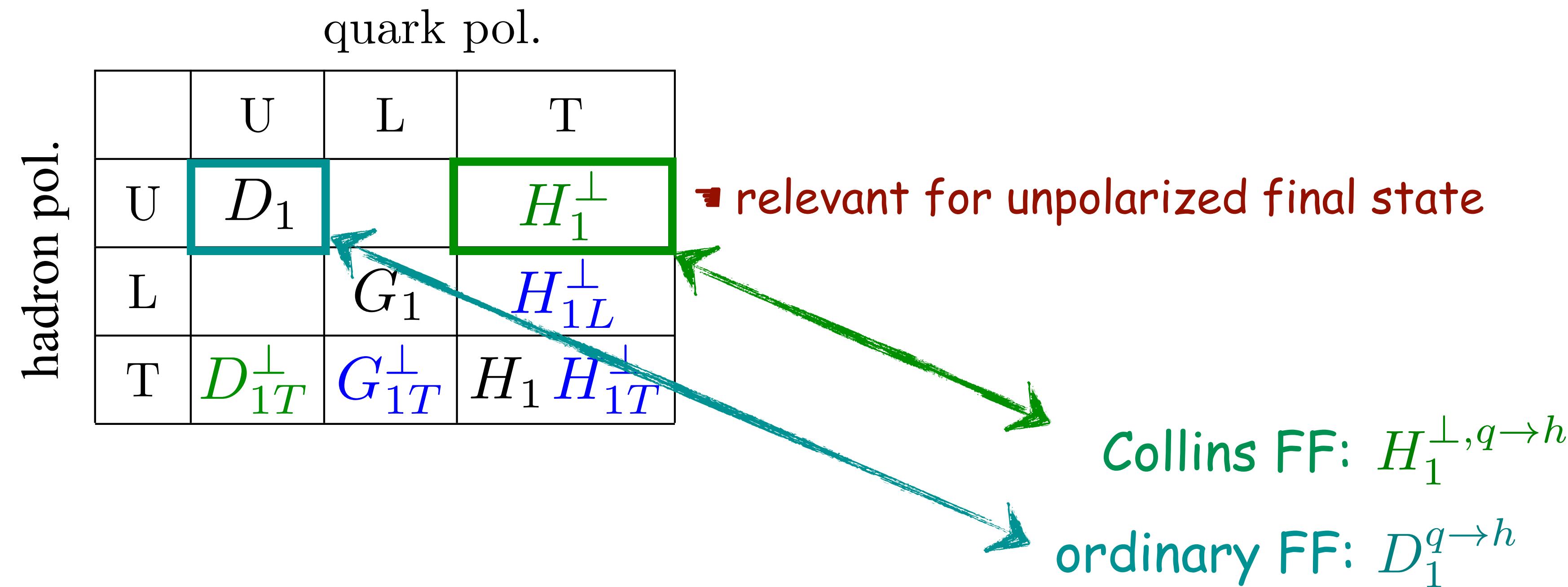
	U	L	T
U	D_1		H_1^\perp
L		G_1	H_{1L}^\perp
T	D_{1T}^\perp	G_{1T}^\perp	$H_1 H_{1T}^\perp$

hadron pol.

☞ relevant for unpolarized final state

single-hadron TMD*) fragmentation functions

*) TMD ... transverse-momentum dependent



FF ... fragmentation function

single-hadron TMD*) fragmentation functions

*) TMD ... transverse-momentum dependent

quark pol.

	U	L	T
U	D_1		H_1^\perp
L		G_1	H_{1L}^\perp
T	D_{1T}^\perp	G_{1T}^\perp	$H_1 H_{1T}^\perp$

hadron pol.

☞ relevant for unpolarized final state

} polarized final-state hadrons

polarizing FF

FF ... fragmentation function

single-hadron TMD*) fragmentation functions

*) TMD ... transverse-momentum dependent

quark pol.

	U	L	T
U	D_1		H_1^\perp
L		G_1	H_{1L}^\perp
T	D_{1T}^\perp	G_{1T}^\perp	$H_1 H_{1T}^\perp$

hadron pol.

☞ relevant for unpolarized final state

} polarized final-state hadrons

polarizing FF

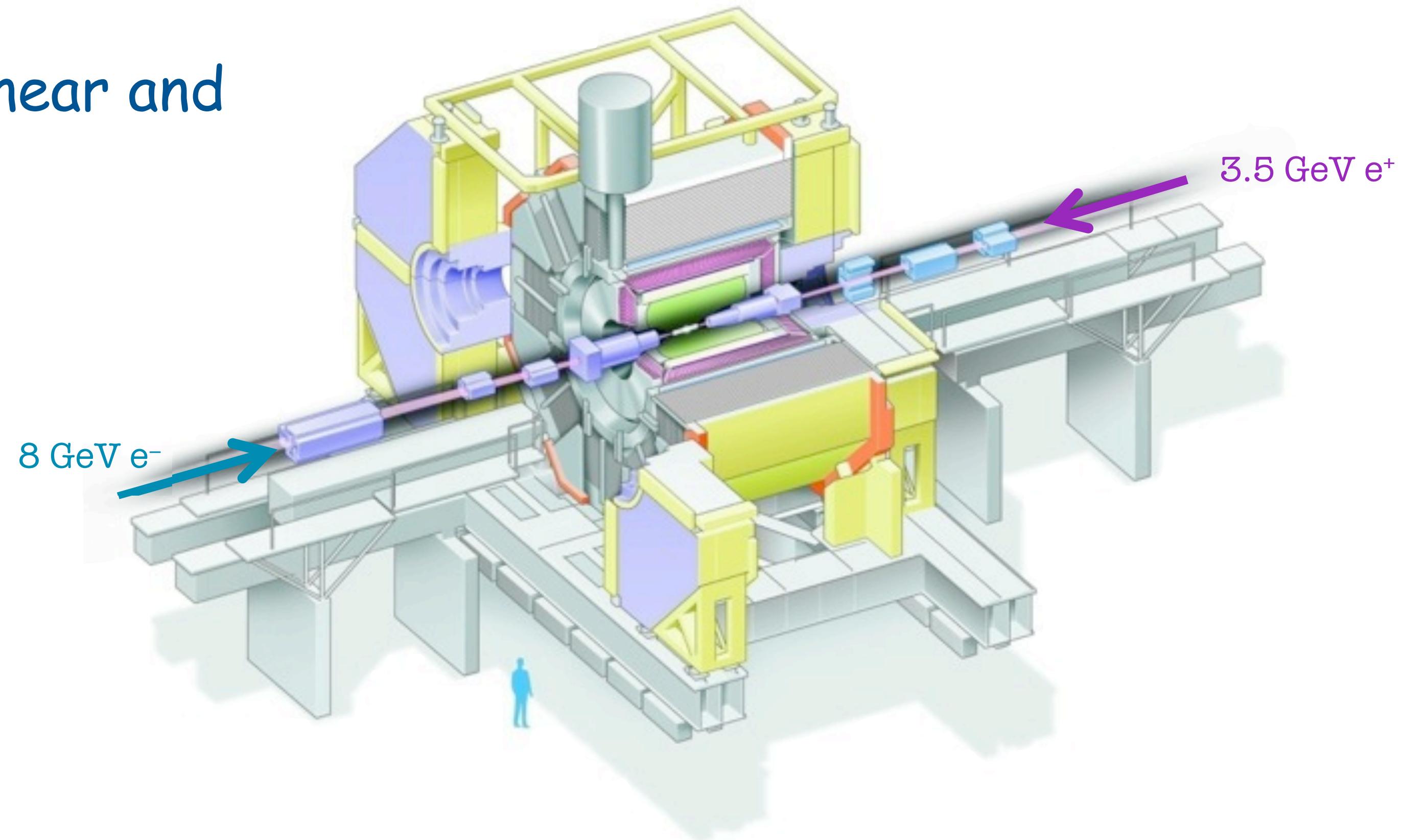
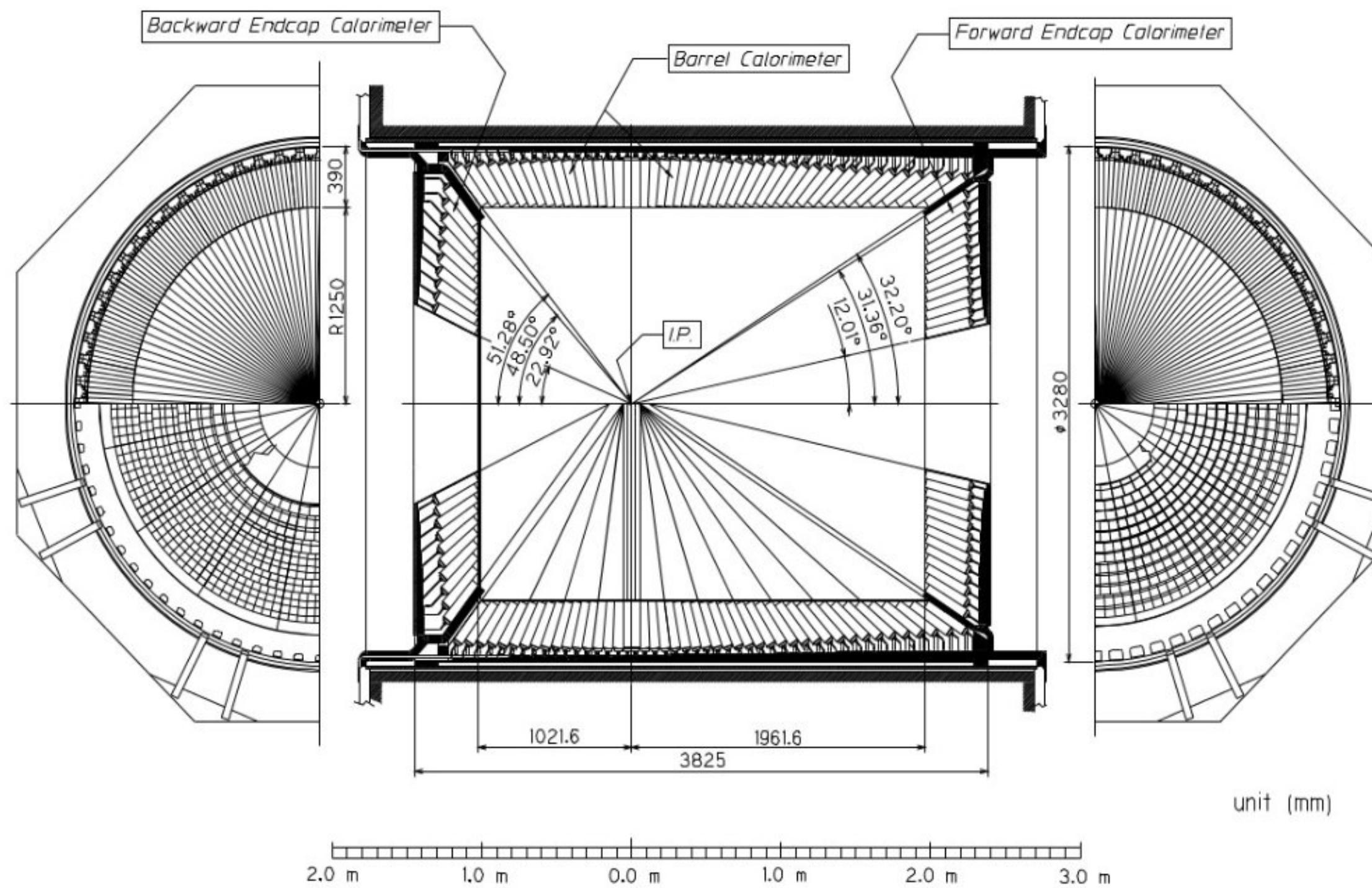
→ FFs act as quark flavor-tagger and polarimeter

FF ... fragmentation function

e^+e^- annihilation at Belle

- asymmetric beam-energy e^+e^- collider near and at $\Upsilon(4S)$ resonance (10.58 GeV)

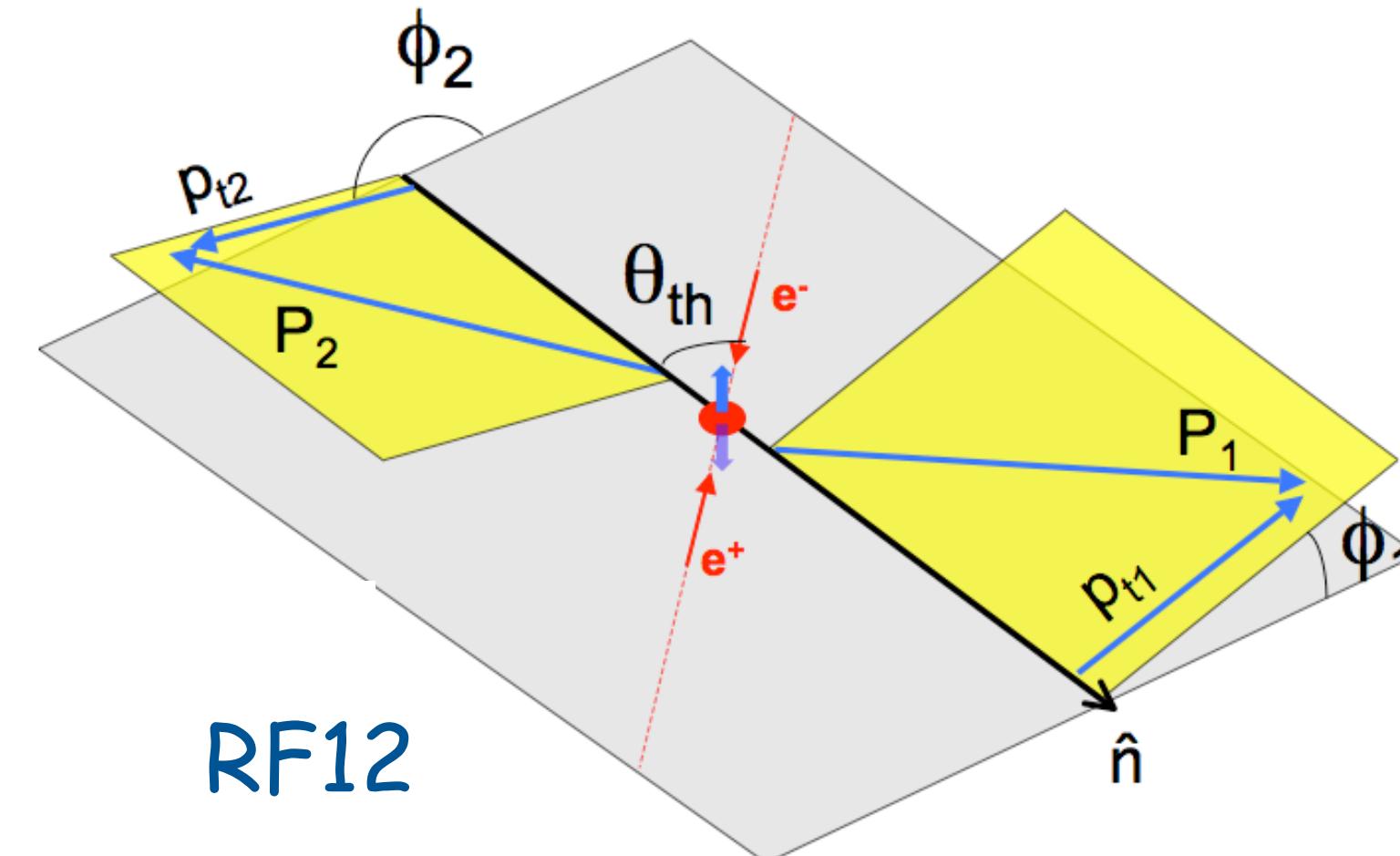
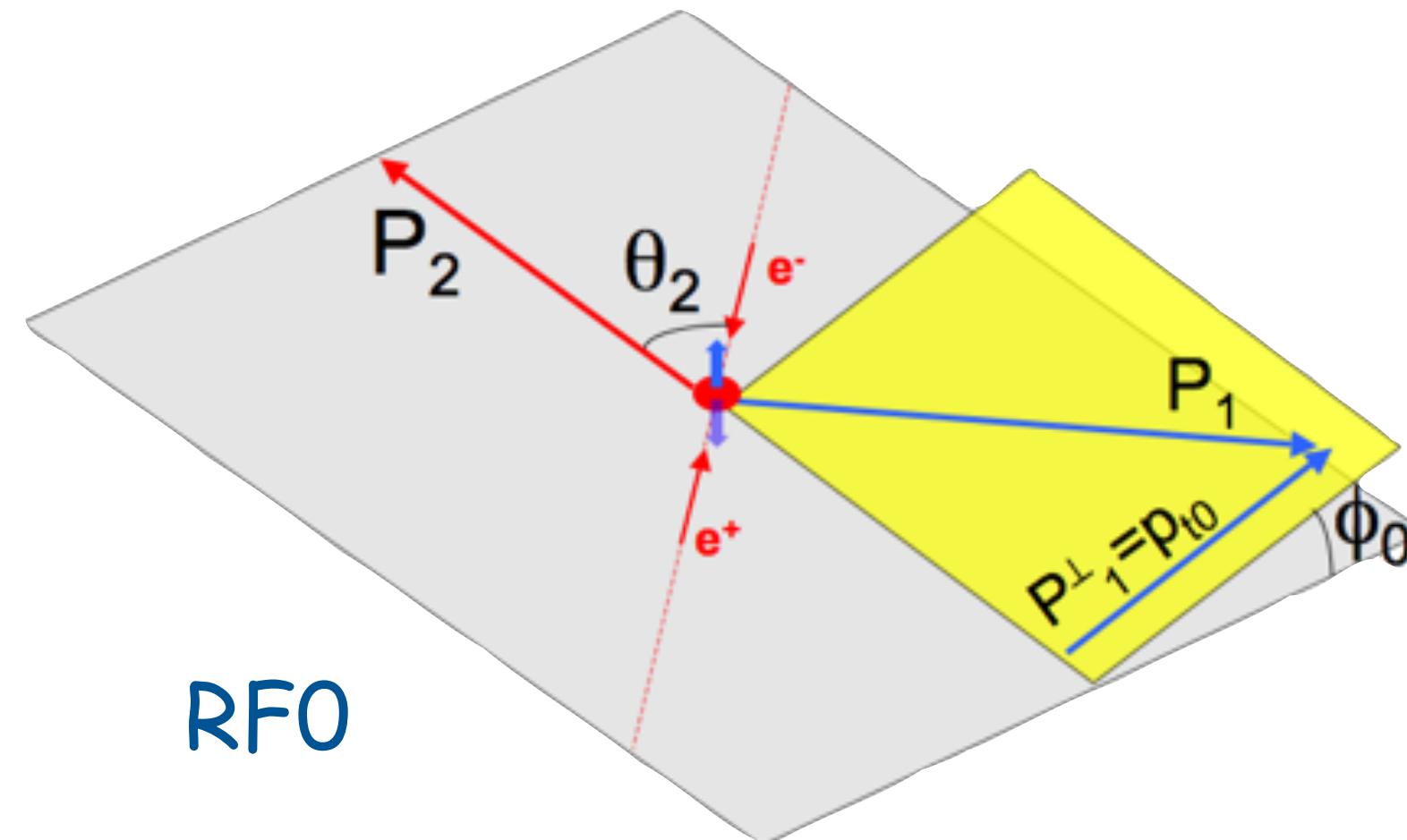
BELLE CsI ELECTROMAGNETIC CALORIMETER



polarization effects
despite unpolarized initial state

hadron pairs: angular correlations

- angular correlations between nearly back-to-back hadrons used to tag transverse quark polarization \rightarrow **Collins fragmentation functions**
- RFO: one hadron as reference axis $\rightarrow \cos(2\phi_0)$ modulation
- RF12: thrust (or similar) axis $\rightarrow \cos(\phi_1 + \phi_2)$ modulation



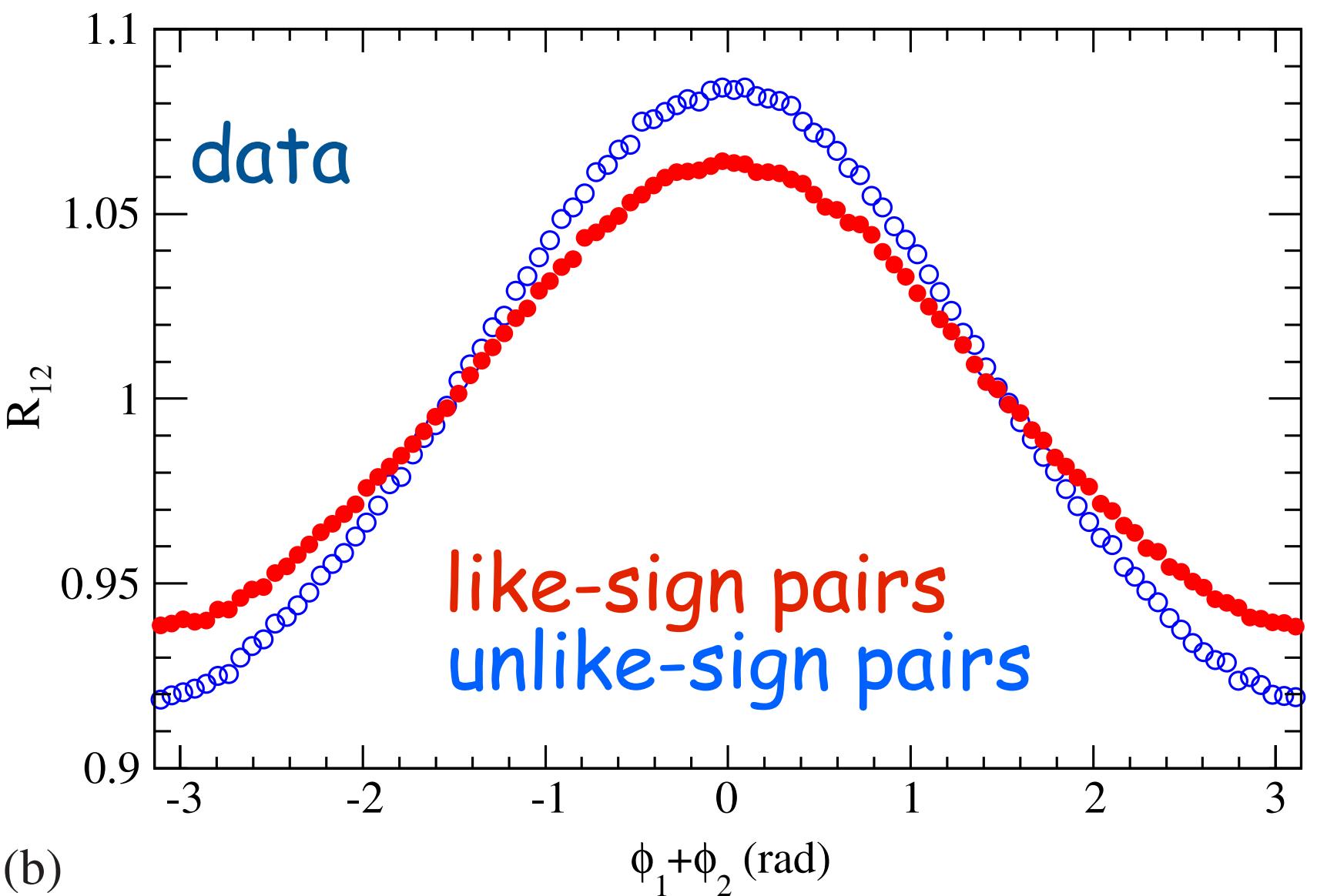
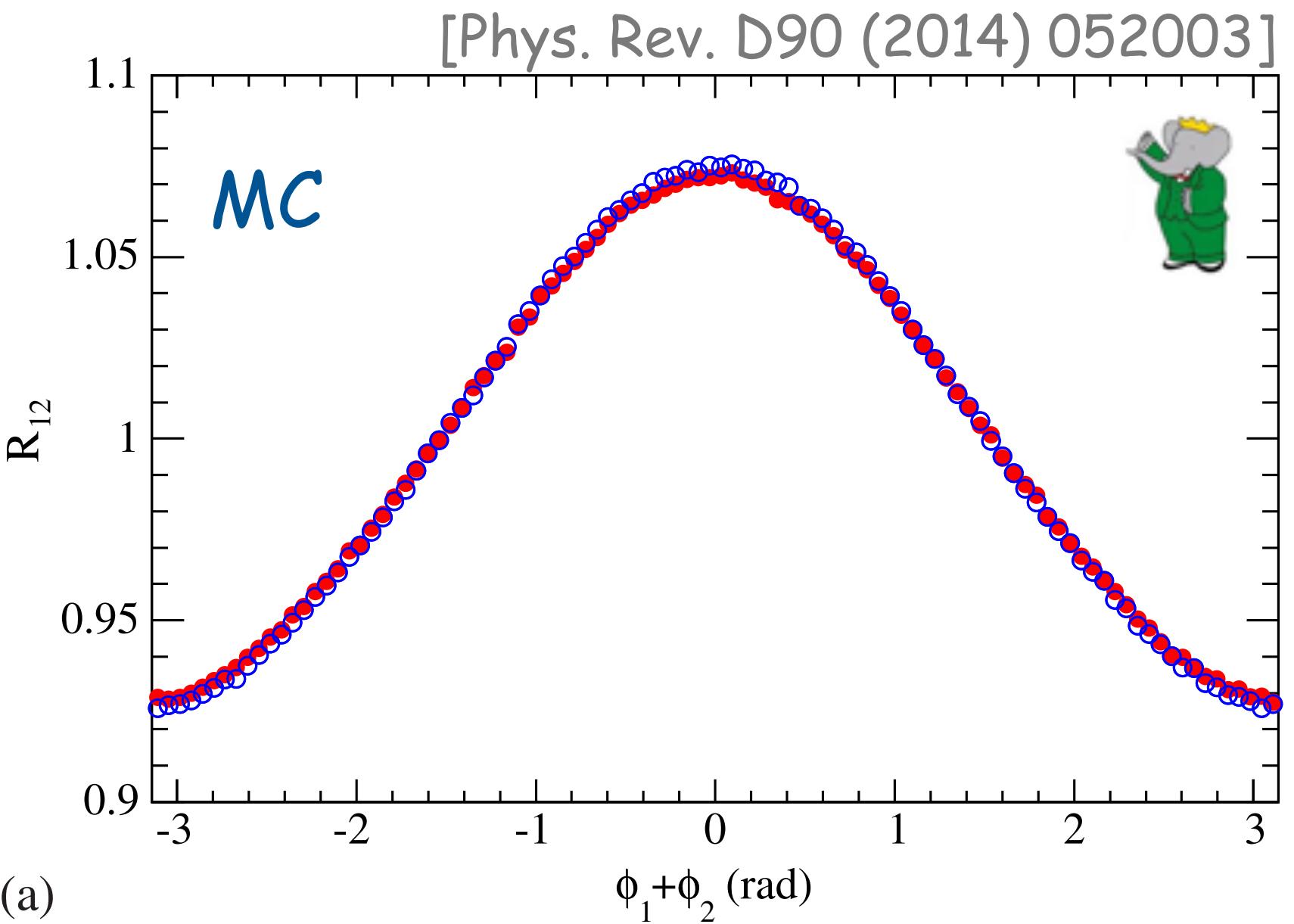
Thrust (axis):

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

- RFO and RF12: different convolutions over transverse momenta
- debatable: MC used to "correct" thrust axis to $q\bar{q}$ axis

hadron pairs: angular correlations

- challenge: large modulations even without Collins effect
(e.g., in PYTHIA MC)

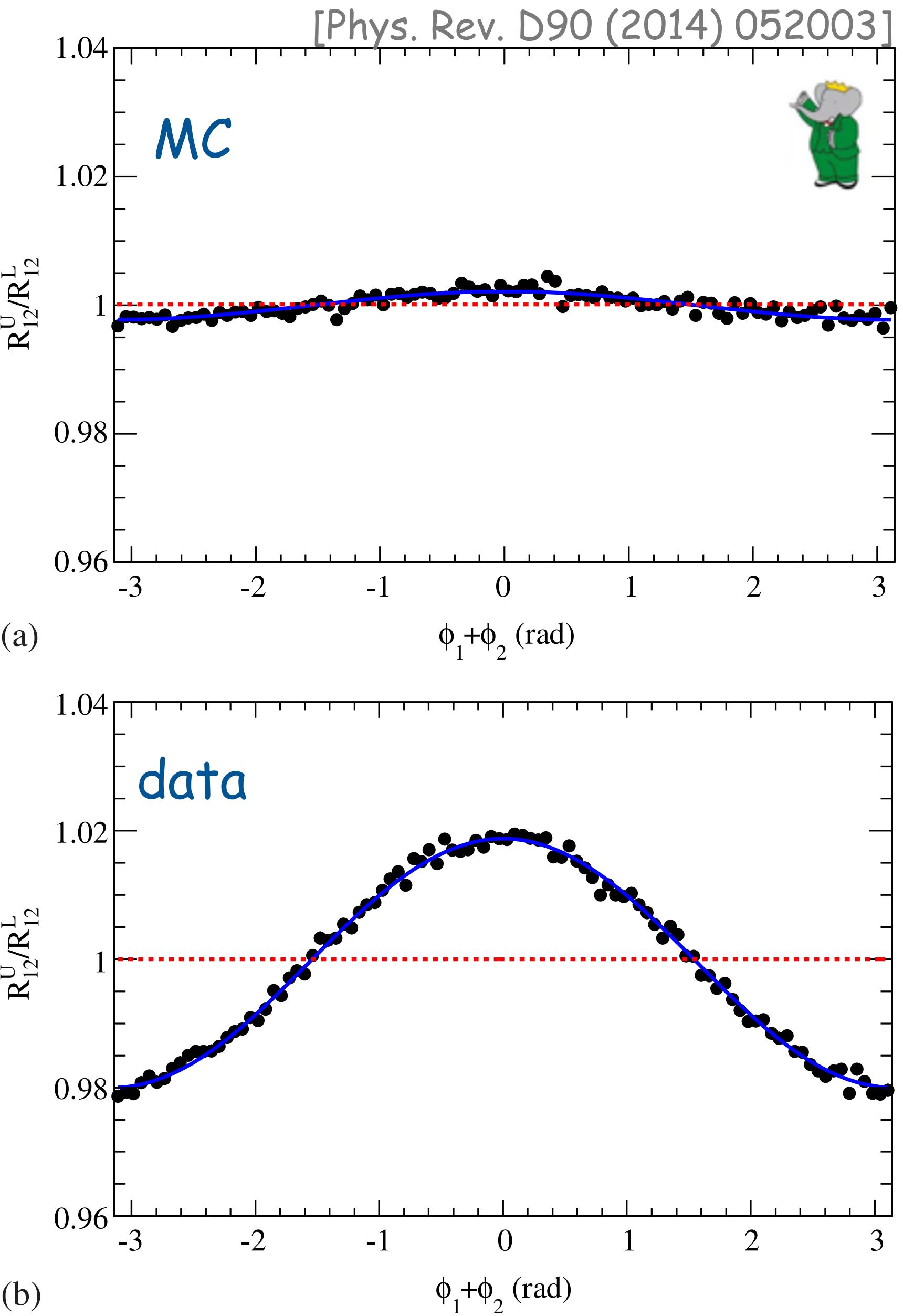


hadron pairs: angular correlations

- challenge: large modulations even without Collins effect (e.g., in PYTHIA MC)
- construct double ratio of normalized-yield distributions R_{12} , e.g. unlike-/like-sign:

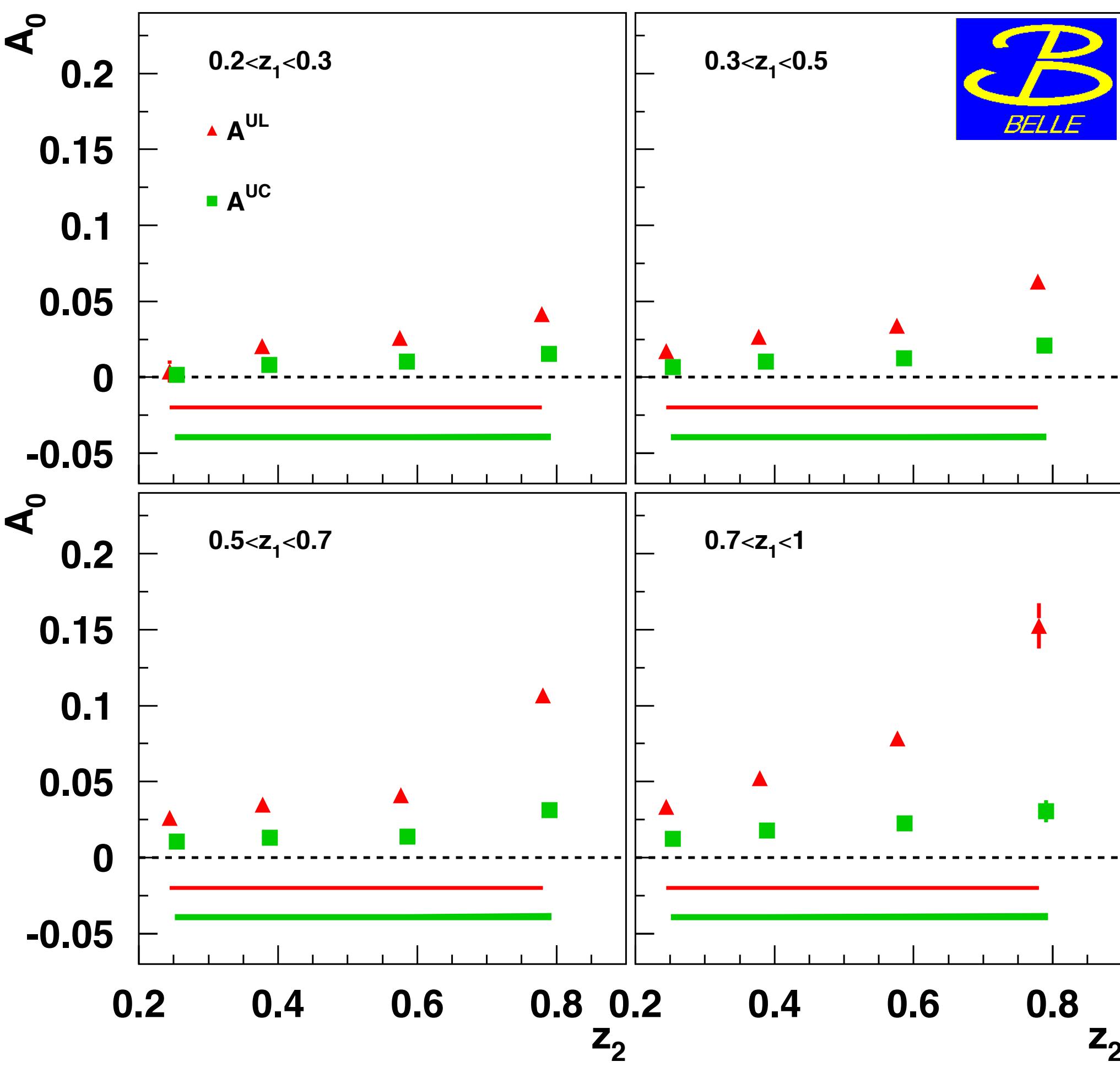
$$\begin{aligned} \frac{R_{12}^U}{R_{12}^L} &\simeq \frac{1 + \left\langle \frac{\sin^2 \theta_{\text{th}}}{1 + \cos^2 \theta_{\text{th}}} \right\rangle G^U \cos(\phi_1 + \phi_2)}{1 + \left\langle \frac{\sin^2 \theta_{\text{th}}}{1 + \cos^2 \theta_{\text{th}}} \right\rangle G^L \cos(\phi_1 + \phi_2)} \\ &\simeq 1 + \left\langle \frac{\sin^2 \theta_{\text{th}}}{1 + \cos^2 \theta_{\text{th}}} \right\rangle \{G^U - G^L\} \cos(\phi_1 + \phi_2) \end{aligned}$$

- suppresses flavor-independent sources of modulations
- G^U/L : specific combinations of FFs
- remaining MC asymmetries \rightarrow systematics



Collins asymmetries (RF0)

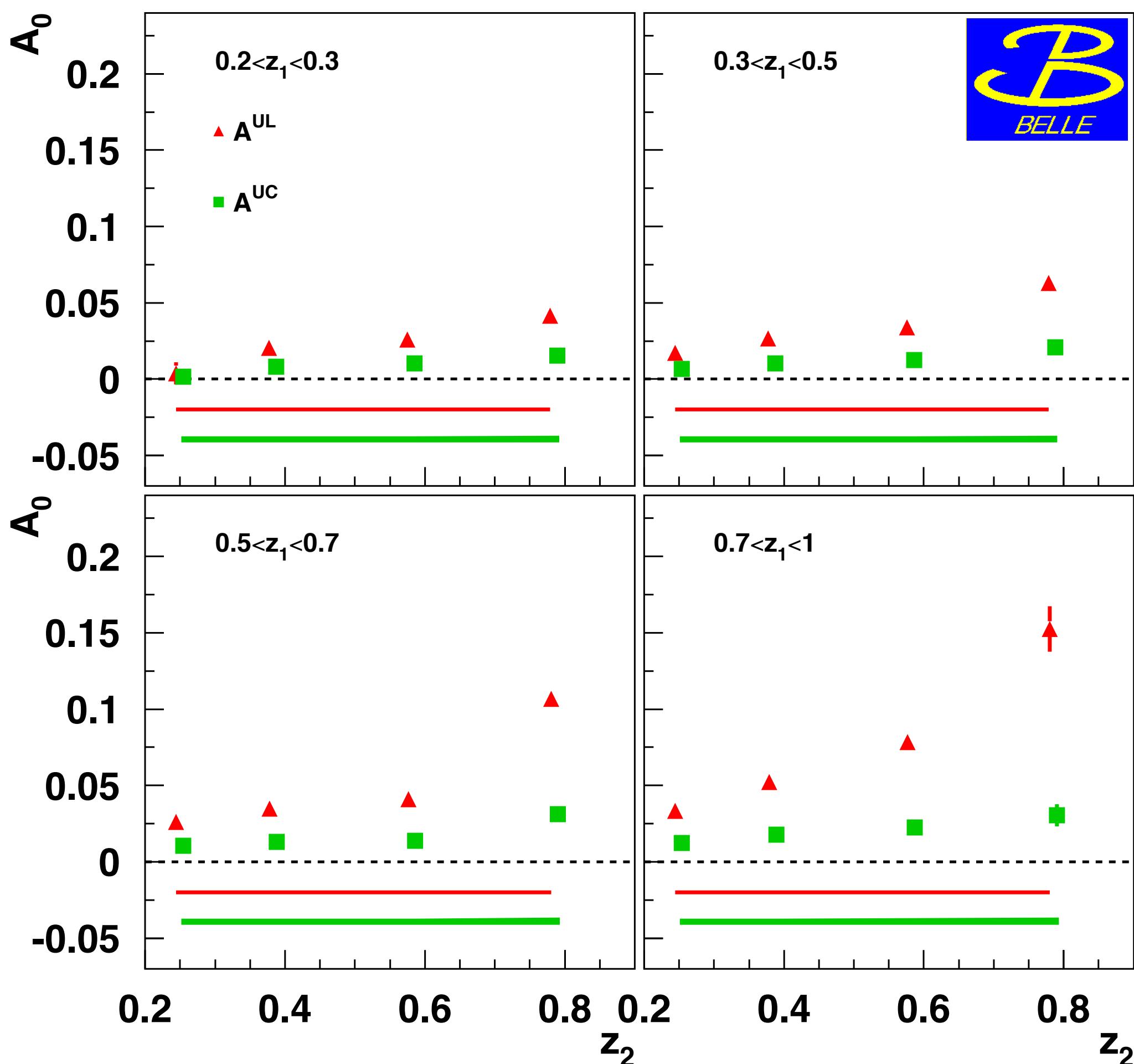
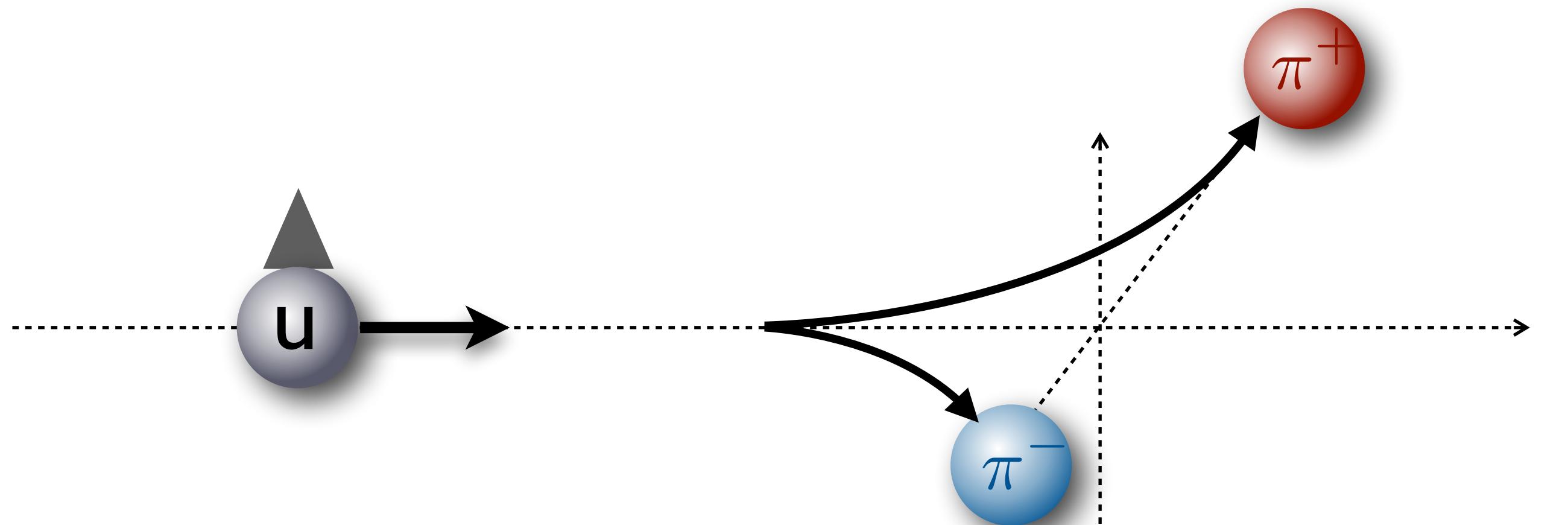
- first measurement of Collins asymmetries for charged pions by Belle [PRL 96 (2006) 232002, PRD 78 (2008) 032011, PRD 86 (2012) 039905(E)]
- significant asymmetries clearly rising with z
- used for first extractions of transversity parton distribution and Collins FF



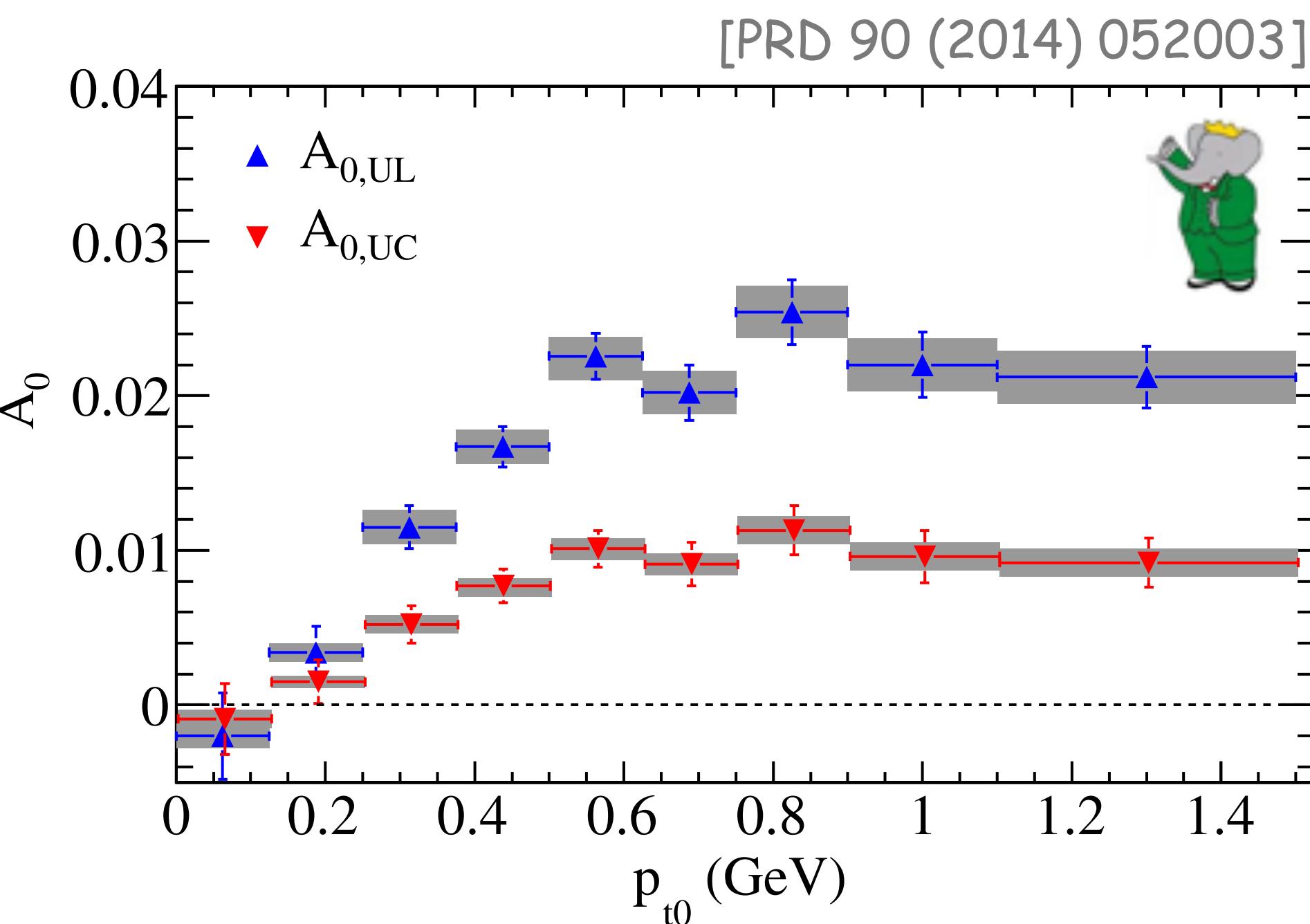
Collins asymmetries (RF0)

- first measurement of Collins asymmetries for charged pions by Belle [PRL 96 (2006) 232002, PRD 78 (2008) 032011, PRD 86 (2012) 039905(E)]

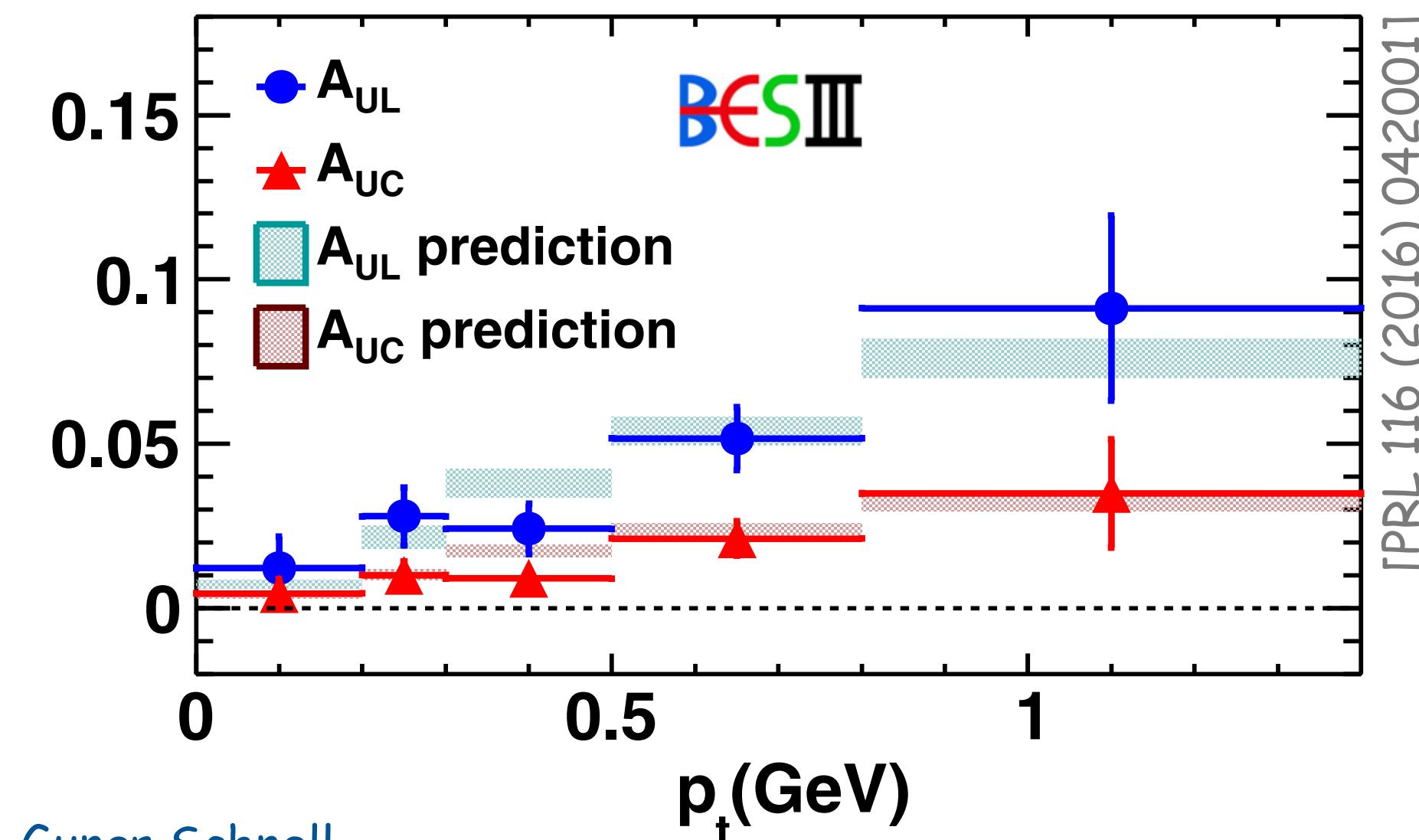
- significant asymmetries clearly rising with z
- used for first extractions of transversity parton distribution and Collins FF



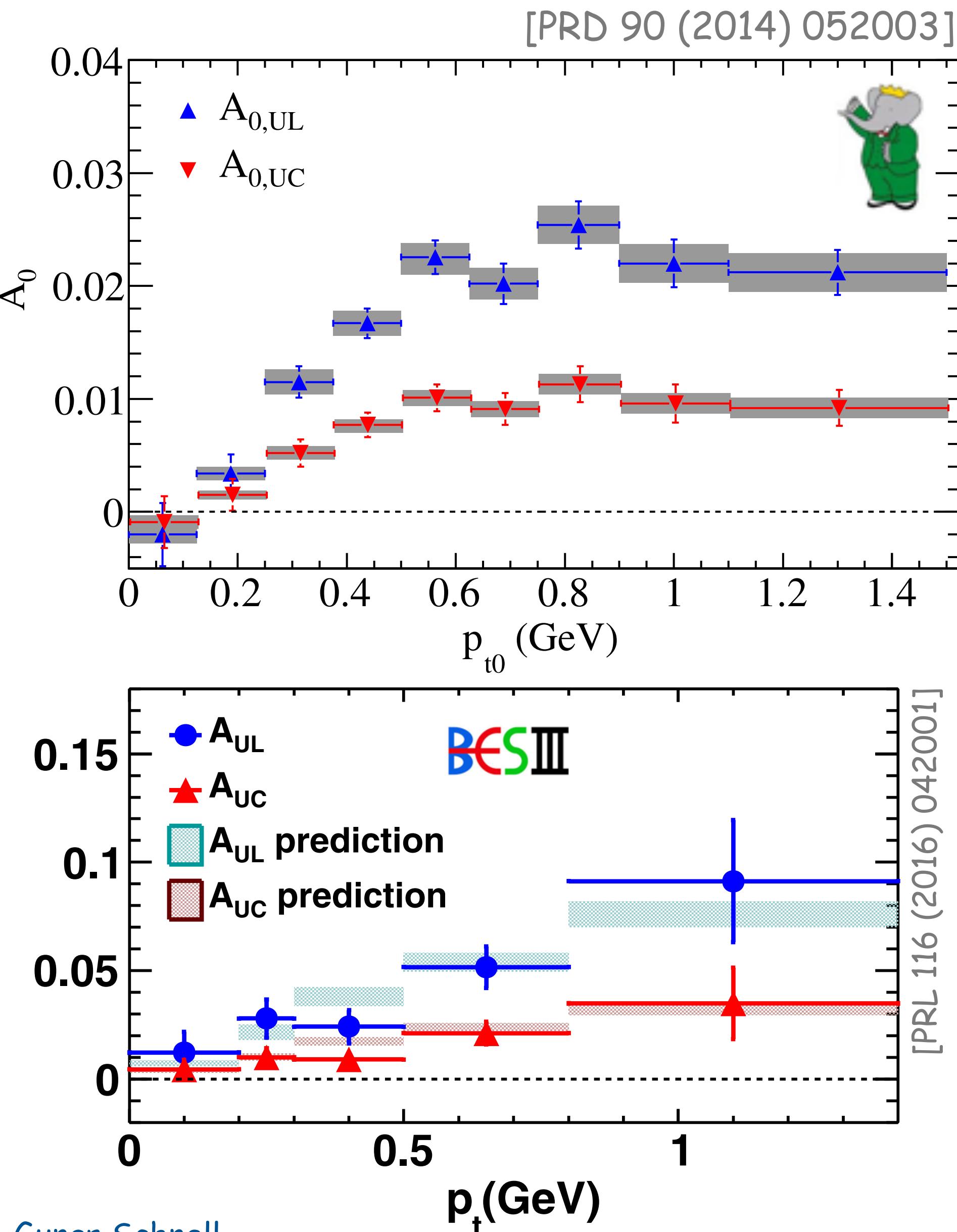
Collins asymmetries - going further



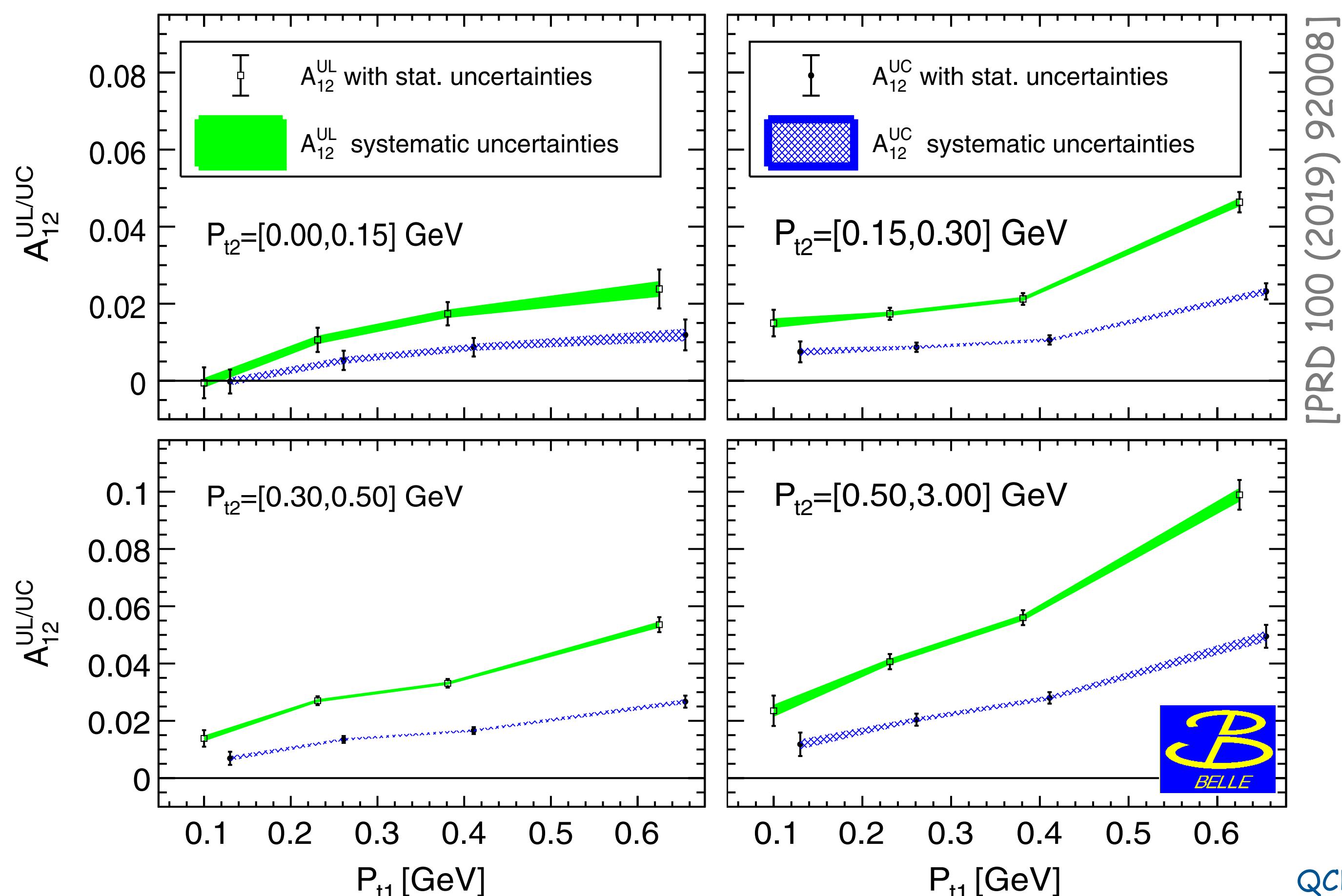
- p_T dependence for charged pions from BaBar & BESIII
- typical rise with p_T ; turnover around 0.8 GeV



Collins asymmetries - going further



- p_T dependence for charged pions from BaBar & BESIII
- typical rise with p_T ; turnover around 0.8 GeV
- ... now also from Belle in R12 frame:



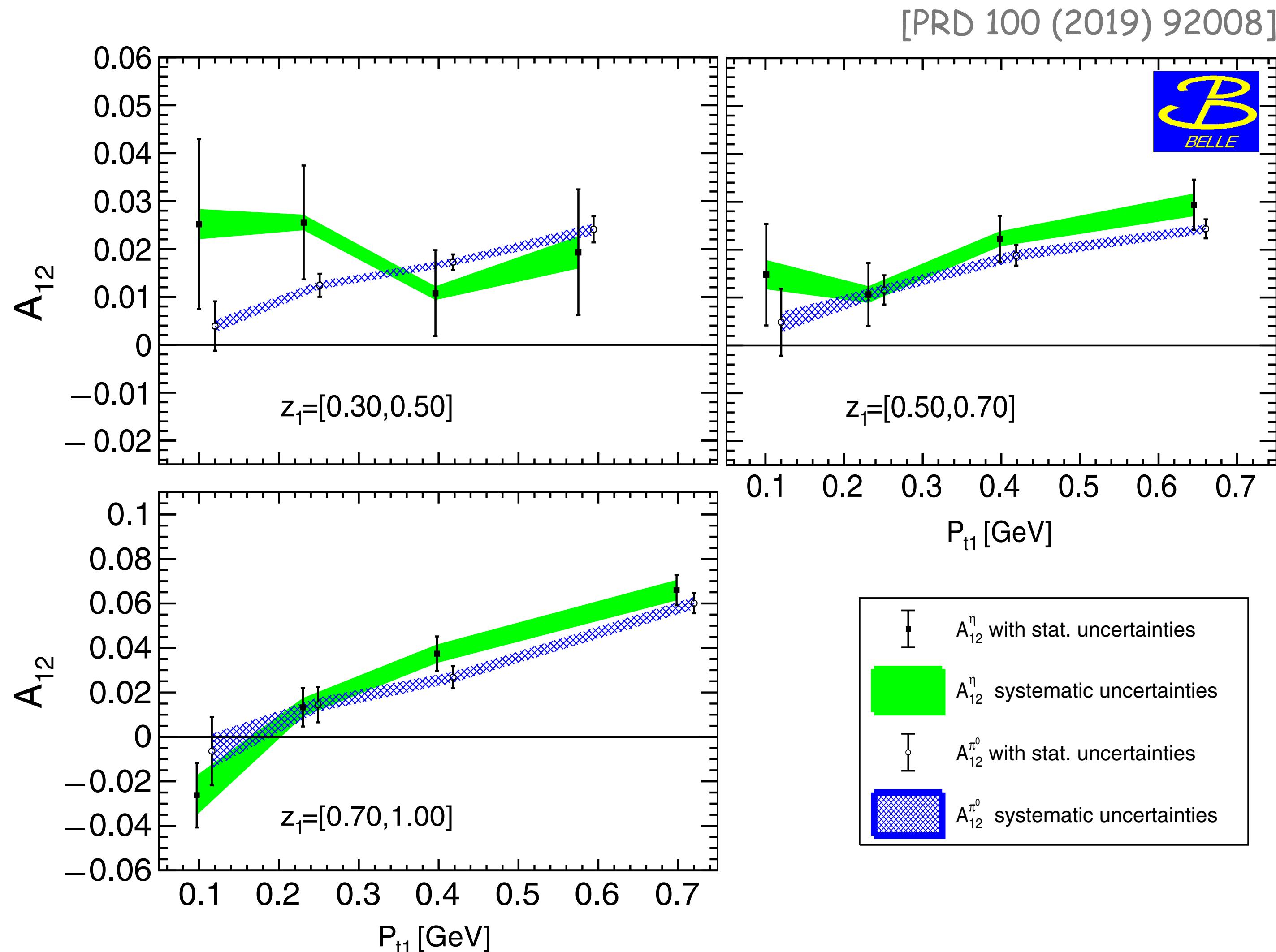
Collins asymmetries - going further

- ... as well as for neutral pion and eta

$$R_{12}^{\pi^0} = \frac{R_{12}^{0\pm}}{R_{12}^L} = \frac{\pi^0\pi^+ + \pi^0\pi^-}{\pi^+\pi^+ + \pi^-\pi^-}$$

$$R_{12}^\eta = \frac{R_{12}^{\eta\pm}}{R_{12}^L} = \frac{\eta\pi^+ + \eta\pi^-}{\pi^+\pi^+ + \pi^-\pi^-}$$

- no significant differences observed in this (z, P_t) -binning
- again, rise with P_t in particular for larger z



Collins asymmetries - going further

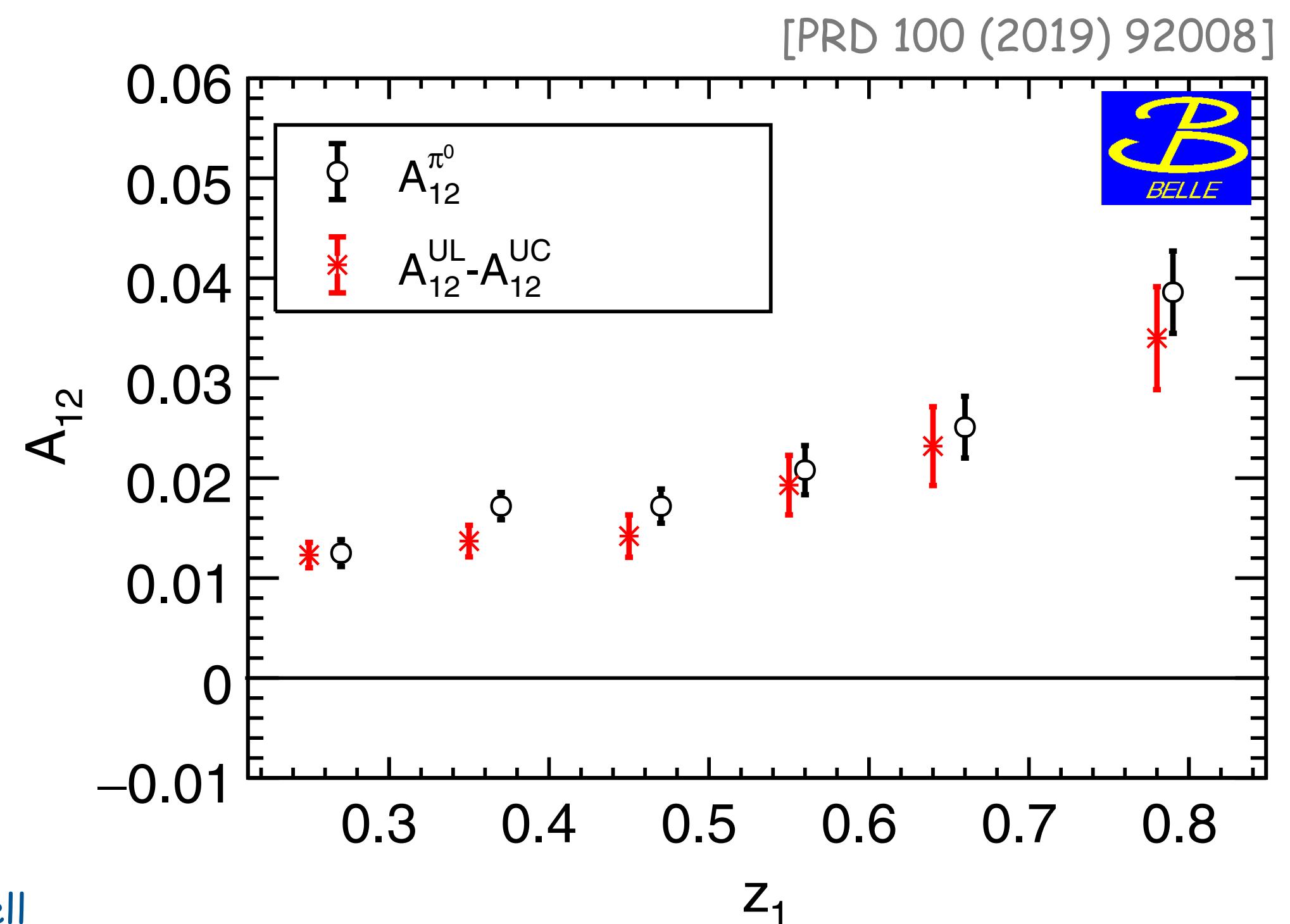
$$\begin{aligned}
R_{12}^{\pi^0} &= \frac{R_{12}^{0\pm}}{R_{12}^L} \approx 1 + \cos(\phi_{12}) \frac{\sin^2(\theta)}{1 + \cos^2(\theta)} \\
&\times \left\{ \frac{5(H_1^{\perp,fav} + H_1^{\perp,dis}) \otimes (H_1^{\perp,fav} + H_1^{\perp,dis}) + 4H_{1,s \rightarrow \pi}^{\perp,dis} \otimes H_{1,s \rightarrow \pi}^{\perp,dis}}{5(D_1^{fav} + D_1^{dis}) \otimes (D_1^{fav} + D_1^{dis}) + 4D_{1,s \rightarrow \pi}^{dis} \otimes D_{1,s \rightarrow \pi}^{dis}} \right. \\
&- \left. \frac{5(H_1^{\perp,fav} \otimes H_1^{\perp,dis} + H_1^{\perp,dis} \otimes H_1^{\perp,fav}) + 2H_{1,s \rightarrow \pi}^{\perp,dis} H_{1,s \rightarrow \pi}^{\perp,dis}}{5(D_1^{fav} \otimes D_1^{dis} + D_1^{dis} \otimes D_1^{fav}) + 2D_{1,s \rightarrow \pi}^{dis} \otimes D_{1,s \rightarrow \pi}^{dis}} \right\}.
\end{aligned}$$

isospin $\underline{\underline{A}}_{12}^{UL} - A_{12}^{UC}$

Collins asymmetries - going further

$$\begin{aligned}
 R_{12}^{\pi^0} &= \frac{R_{12}^{0\pm}}{R_{12}^L} \approx 1 + \cos(\phi_{12}) \frac{\sin^2(\theta)}{1 + \cos^2(\theta)} \\
 &\times \left\{ \frac{5(H_1^{\perp,fav} + H_1^{\perp,dis}) \otimes (H_1^{\perp,fav} + H_1^{\perp,dis}) + 4H_{1,s \rightarrow \pi}^{\perp,dis} \otimes H_{1,s \rightarrow \pi}^{\perp,dis}}{5(D_1^{fav} + D_1^{dis}) \otimes (D_1^{fav} + D_1^{dis}) + 4D_{1,s \rightarrow \pi}^{dis} \otimes D_{1,s \rightarrow \pi}^{dis}} \right. \\
 &- \left. \frac{5(H_1^{\perp,fav} \otimes H_1^{\perp,dis} + H_1^{\perp,dis} \otimes H_1^{\perp,fav}) + 2H_{1,s \rightarrow \pi}^{\perp,dis} H_{1,s \rightarrow \pi}^{\perp,dis}}{5(D_1^{fav} \otimes D_1^{dis} + D_1^{dis} \otimes D_1^{fav}) + 2D_{1,s \rightarrow \pi}^{dis} \otimes D_{1,s \rightarrow \pi}^{dis}} \right\}.
 \end{aligned}$$

isospin $\underline{\underline{A}}_{12}^{UL} - A_{12}^{UC}$

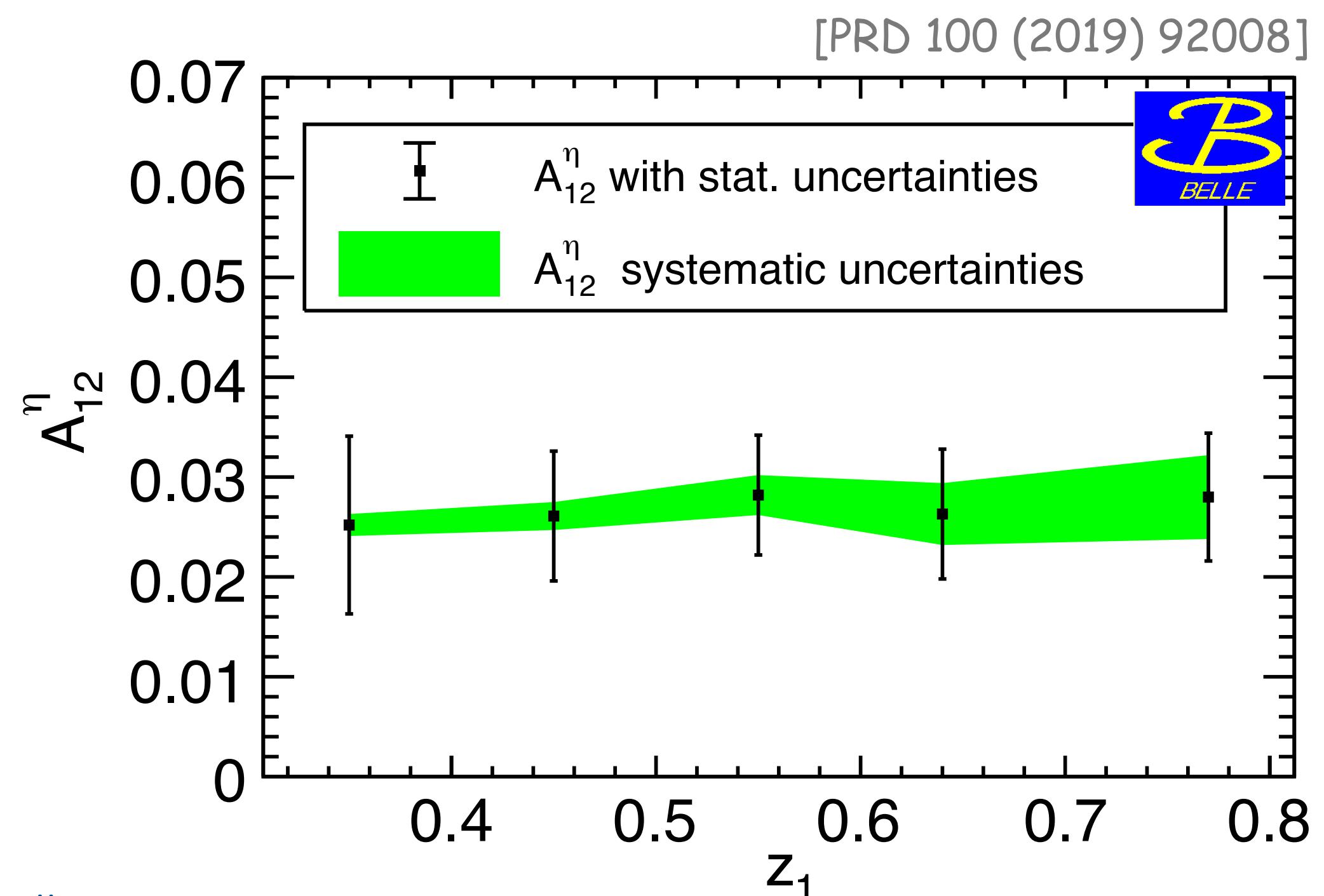


- consistency between neutral and charged pions
- typical rise with z also seen for neutral pions

Collins asymmetries - going further

$$\begin{aligned}
 R_{12}^{\pi^0} &= \frac{R_{12}^{0\pm}}{R_{12}^L} \approx 1 + \cos(\phi_{12}) \frac{\sin^2(\theta)}{1 + \cos^2(\theta)} \\
 &\times \left\{ \frac{5(H_1^{\perp,fav} + H_1^{\perp,dis}) \otimes (H_1^{\perp,fav} + H_1^{\perp,dis}) + 4H_{1,s \rightarrow \pi}^{\perp,dis} \otimes H_{1,s \rightarrow \pi}^{\perp,dis}}{5(D_1^{fav} + D_1^{dis}) \otimes (D_1^{fav} + D_1^{dis}) + 4D_{1,s \rightarrow \pi}^{dis} \otimes D_{1,s \rightarrow \pi}^{dis}} \right. \\
 &- \left. \frac{5(H_1^{\perp,fav} \otimes H_1^{\perp,dis} + H_1^{\perp,dis} \otimes H_1^{\perp,fav}) + 2H_{1,s \rightarrow \pi}^{\perp,dis} H_{1,s \rightarrow \pi}^{\perp,dis}}{5(D_1^{fav} \otimes D_1^{dis} + D_1^{dis} \otimes D_1^{fav}) + 2D_{1,s \rightarrow \pi}^{dis} \otimes D_{1,s \rightarrow \pi}^{dis}} \right\}.
 \end{aligned}$$

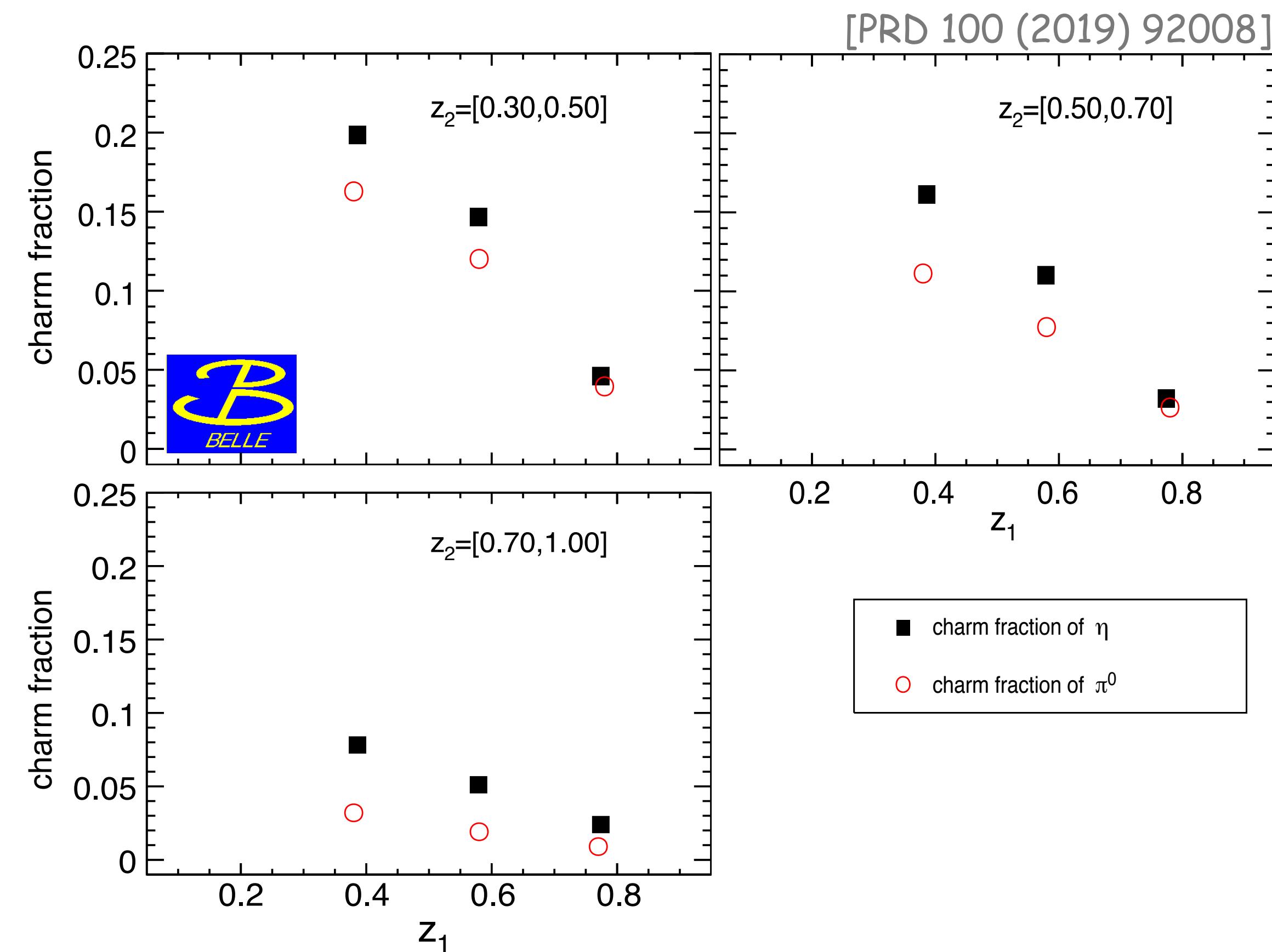
isospin $\underline{\underline{A}}_{12}^{UL} - A_{12}^{UC}$



- consistency between neutral and charged pions
- typical rise with z also seen for neutral pions
- ... while basically flat for eta

Collins asymmetries - going further

- qualitative changes in 2019 Belle analysis w.r.t. previous Belle analyses of Collins asymmetries:
- no correction to $q\bar{q}$ axis;
 - rather to thrust axis, which is observable
- upper limit on opening angle imposed
- no correction for charm contribution;
 - provide charm fraction



the unpolarized case
– baseline for asymmetries –

hadron-pair production

- single-hadron production has low discriminating power for parton flavor
- can use 2nd hadron in opposite hemisphere to "tag" flavor, transverse momentum, as well as polarization
- mainly sensitive to product of single-hadron FFs
- various definitions for scaling variable

- traditional z ("std"):

$$z_i = \frac{2P_i \cdot q}{q^2} \quad (i = 1, 2)$$

- Altarelli et al. ("AEMP"):

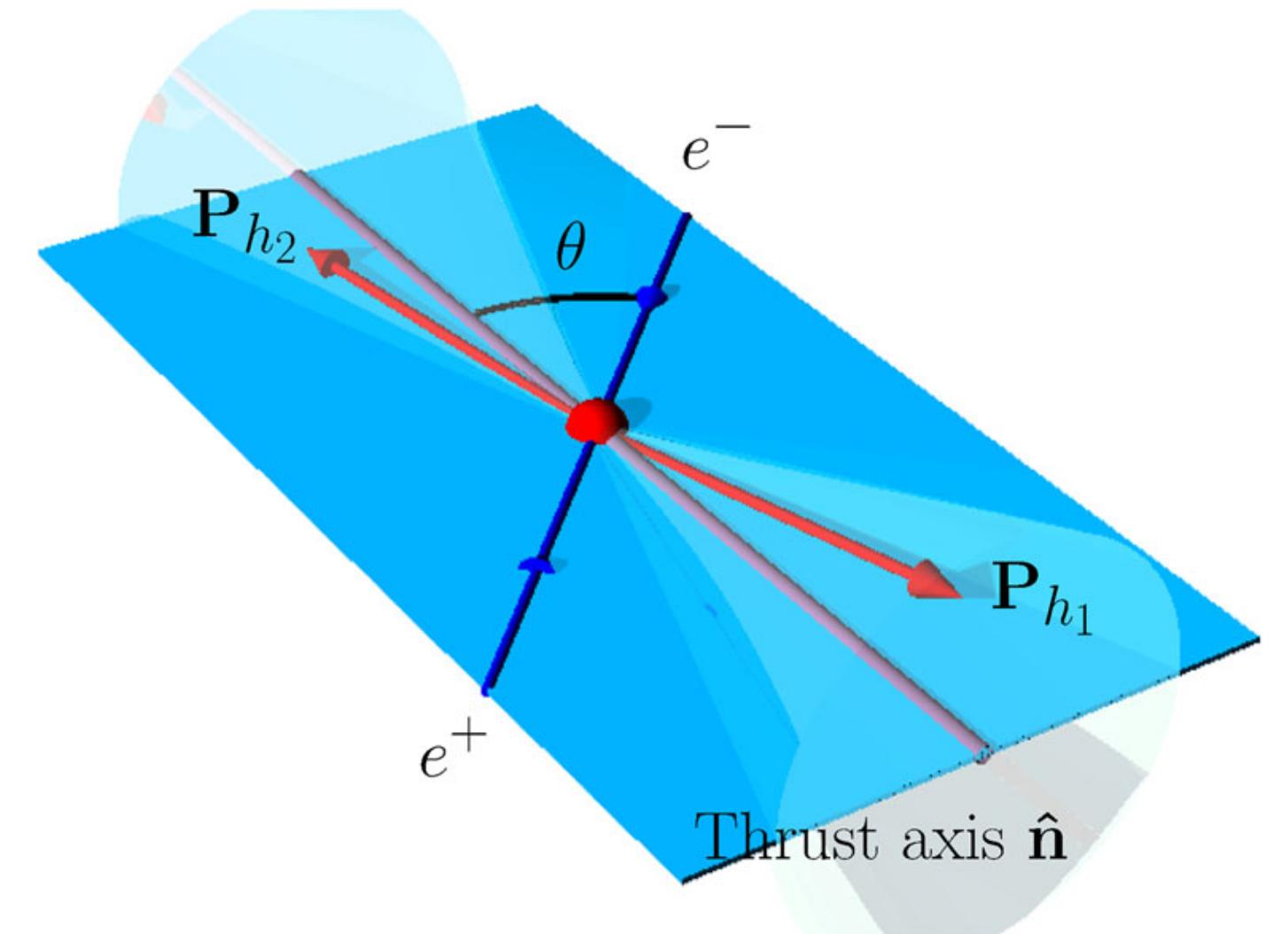
[Nucl. Phys. B160 (1979) 301]

- Mulders & van Hulse ("MVH"):

[PRD 100 (2019) 034011]

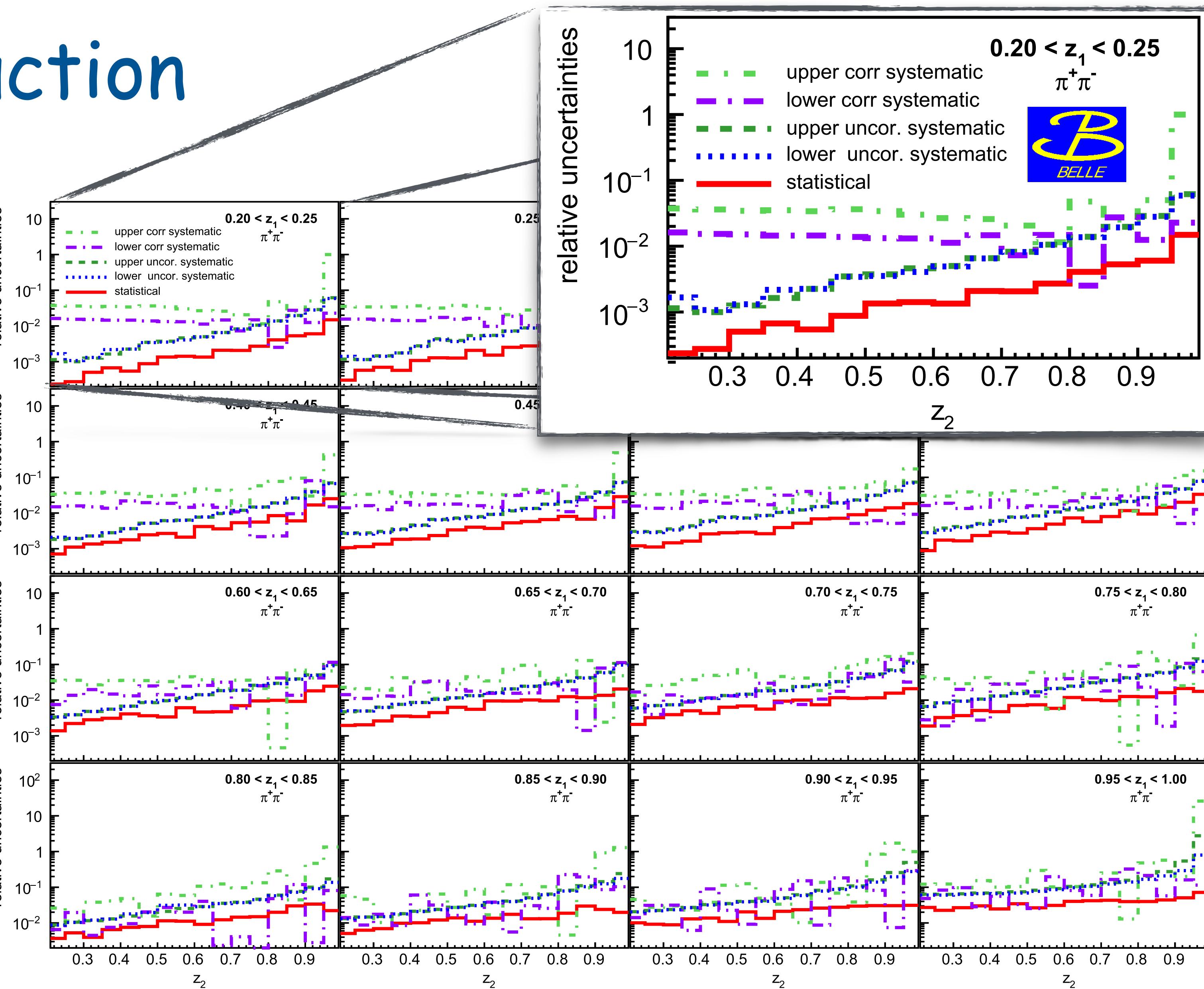
$$z_1 = \frac{2P_1 \cdot q}{q^2} \quad z_2 = \frac{P_1 \cdot P_2}{P_1 \cdot q}$$

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



light-meson pair production

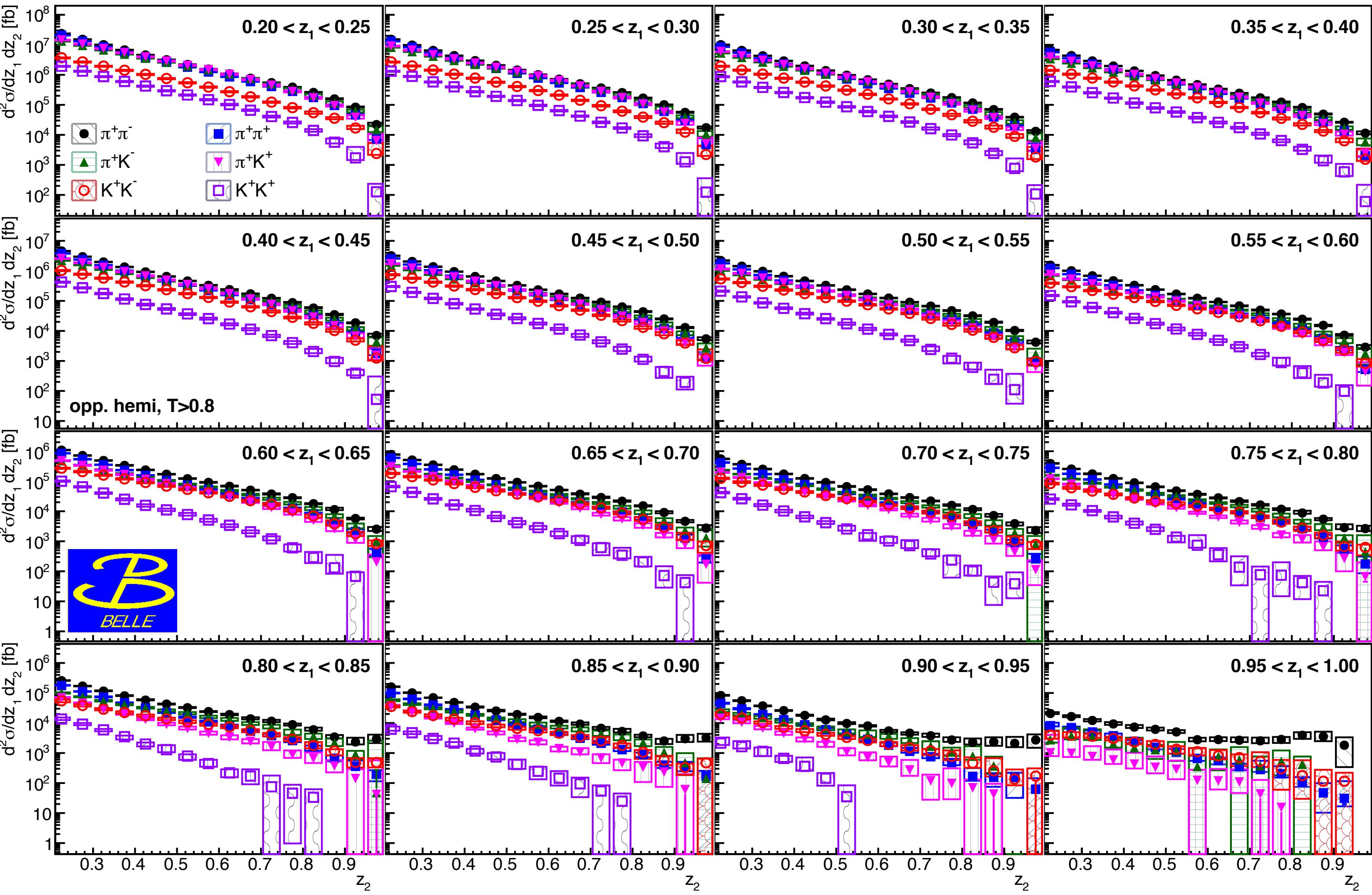
- systematics-dominated over entire kinematic range
- strongly asymmetric systematics
- main contribution from Monte Carlo tune dependence



light-meson pair production

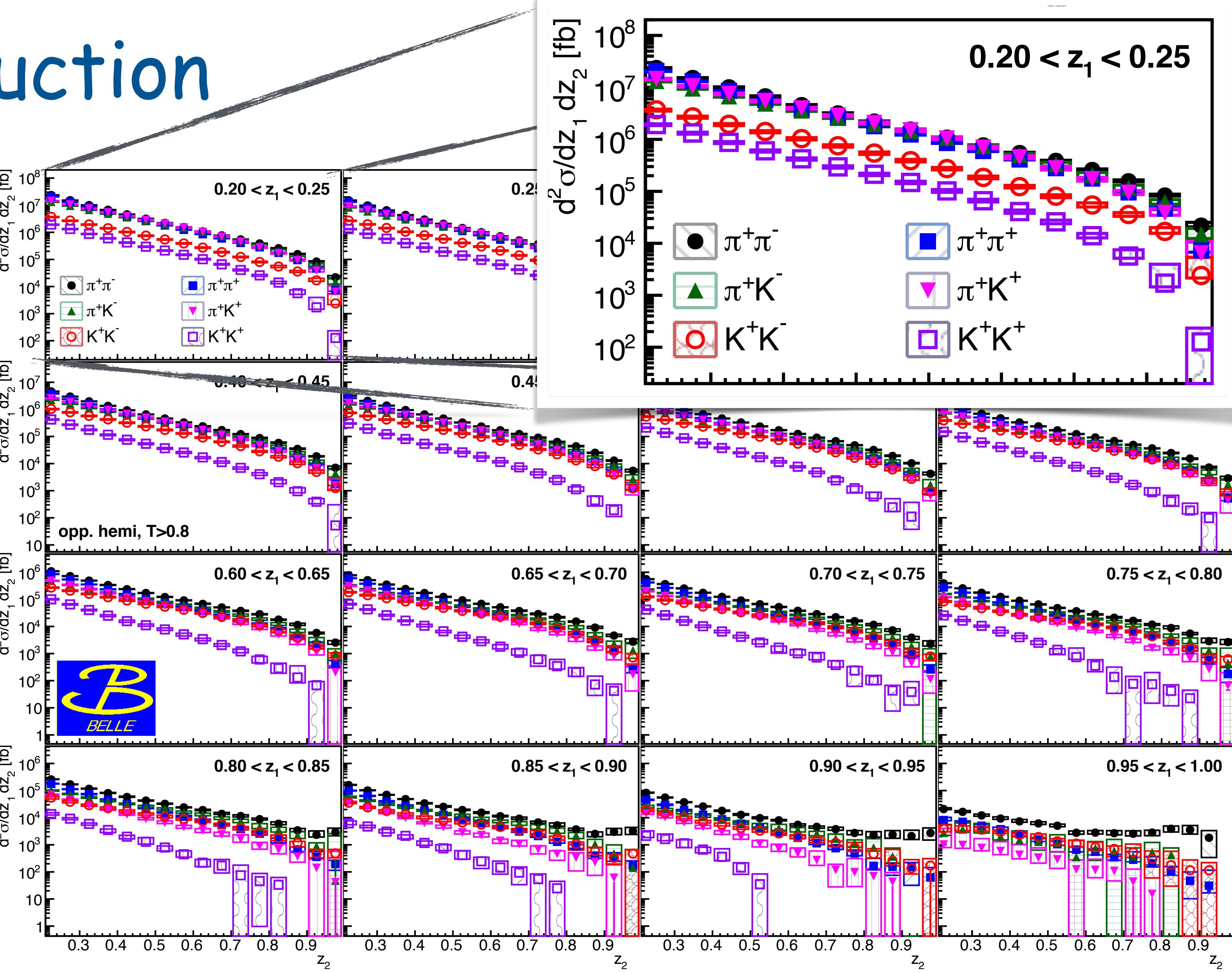
[PRD 101 (2020) 092004]

- systematics-dominated over entire kinematic range
- clear flavor dependence
 - suppression of kaons
 - suppression of like-sign pairs
- more pronounced at large z (stronger flavor sensitivity)



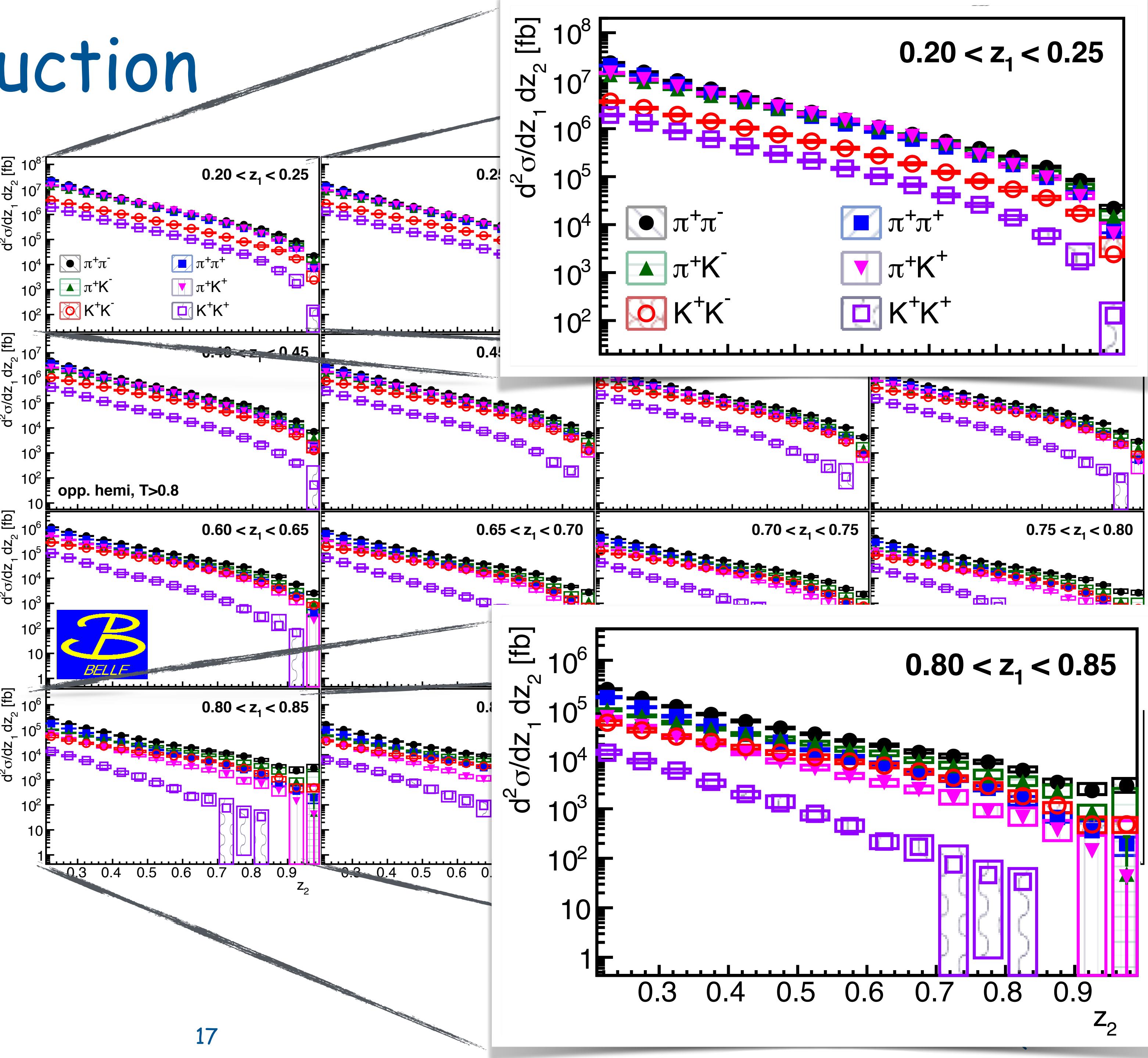
light-meson pair production

- systematics-dominated over entire kinematic range
- clear flavor dependence
 - suppression of kaons
 - suppression of like-sign pairs
- more pronounced at large z (stronger flavor sensitivity)



light-meson pair production

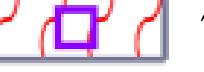
- systematics-dominated over entire kinematic range
- clear flavor dependence
 - suppression of kaons
 - suppression of like-sign pairs
- more pronounced at large z (stronger flavor sensitivity)

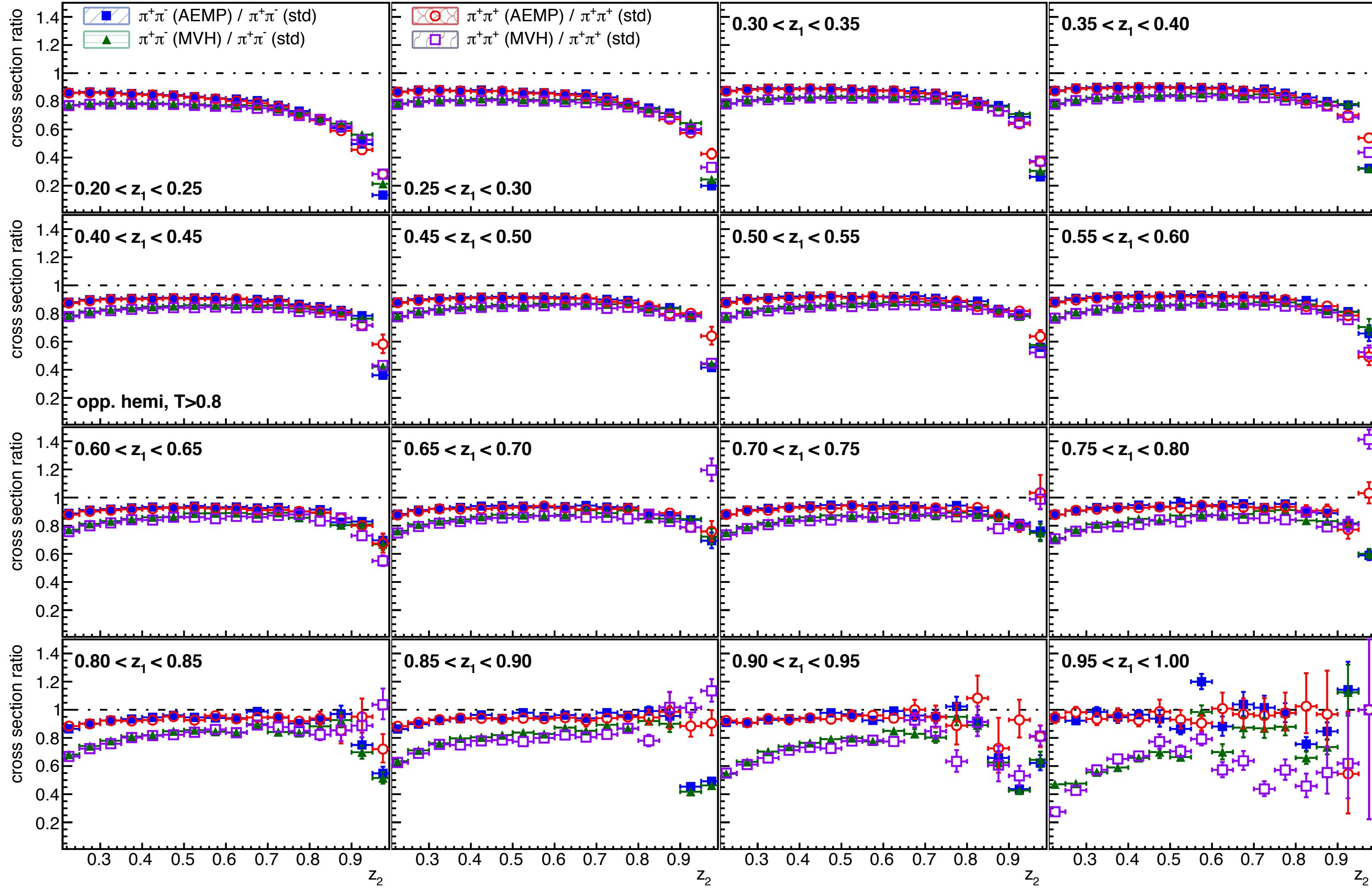


light-meson pair production

- systematics-dominated over entire kinematic range
- clear flavor dependence
 - suppression of kaons
 - suppression of like-sign pairs
 - more pronounced at large z (stronger flavor sensitivity)
- similar behavior for different z definitions when imposing $T>0.8$

 $\pi^+\pi^-$ (AEMP) / $\pi^+\pi^-$ (std)
 $\pi^+\pi^-$ (MVH) / $\pi^+\pi^-$ (std)

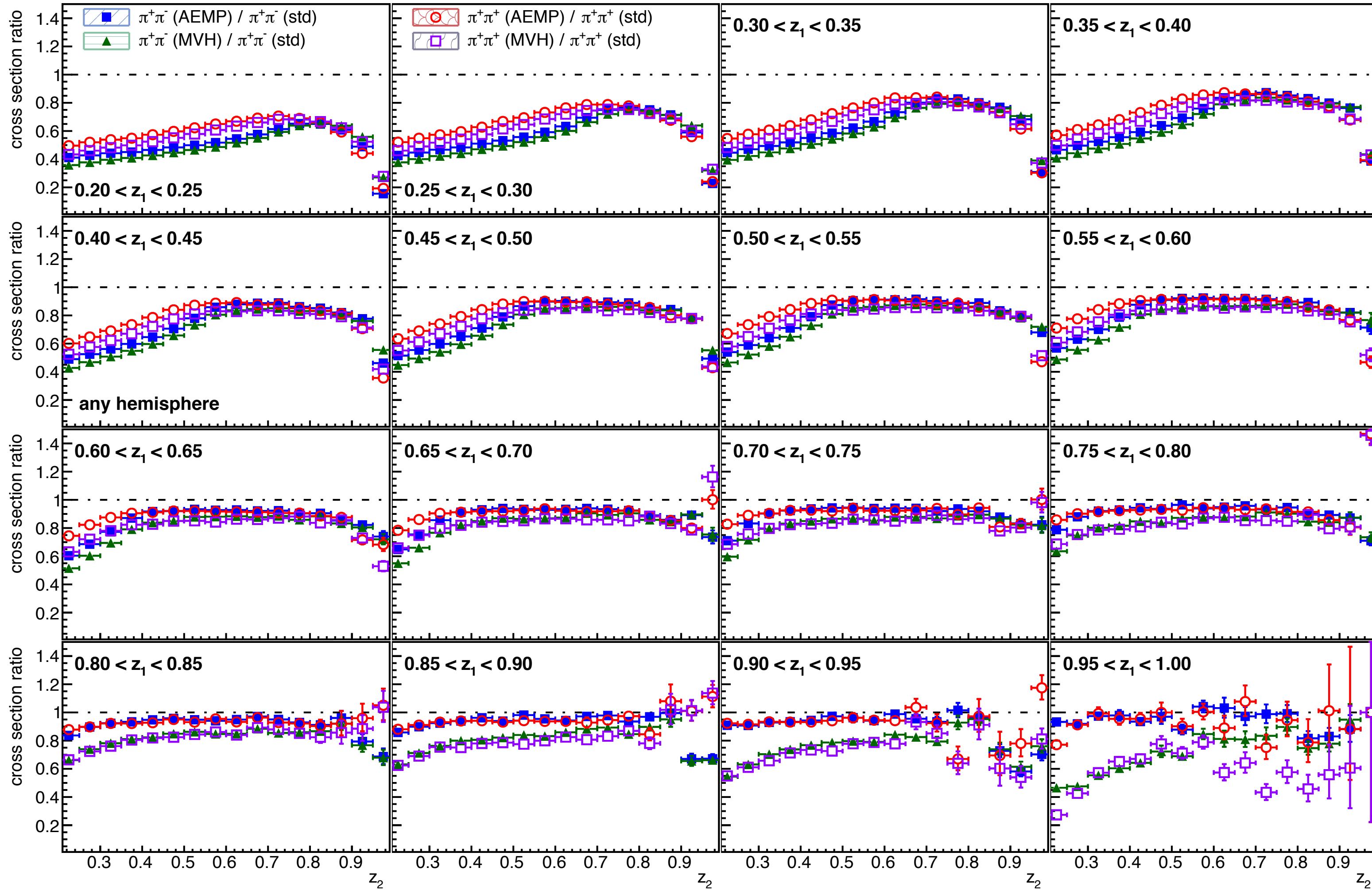
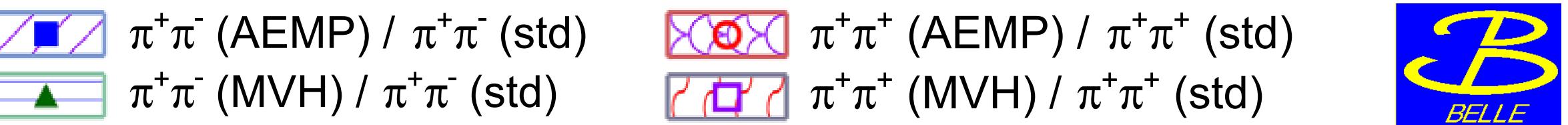
 $\pi^+\pi^+$ (AEMP) / $\pi^+\pi^+$ (std)
 $\pi^+\pi^+$ (MVH) / $\pi^+\pi^+$ (std)



[PRD 101 (2020) 092004]

light-meson pair production

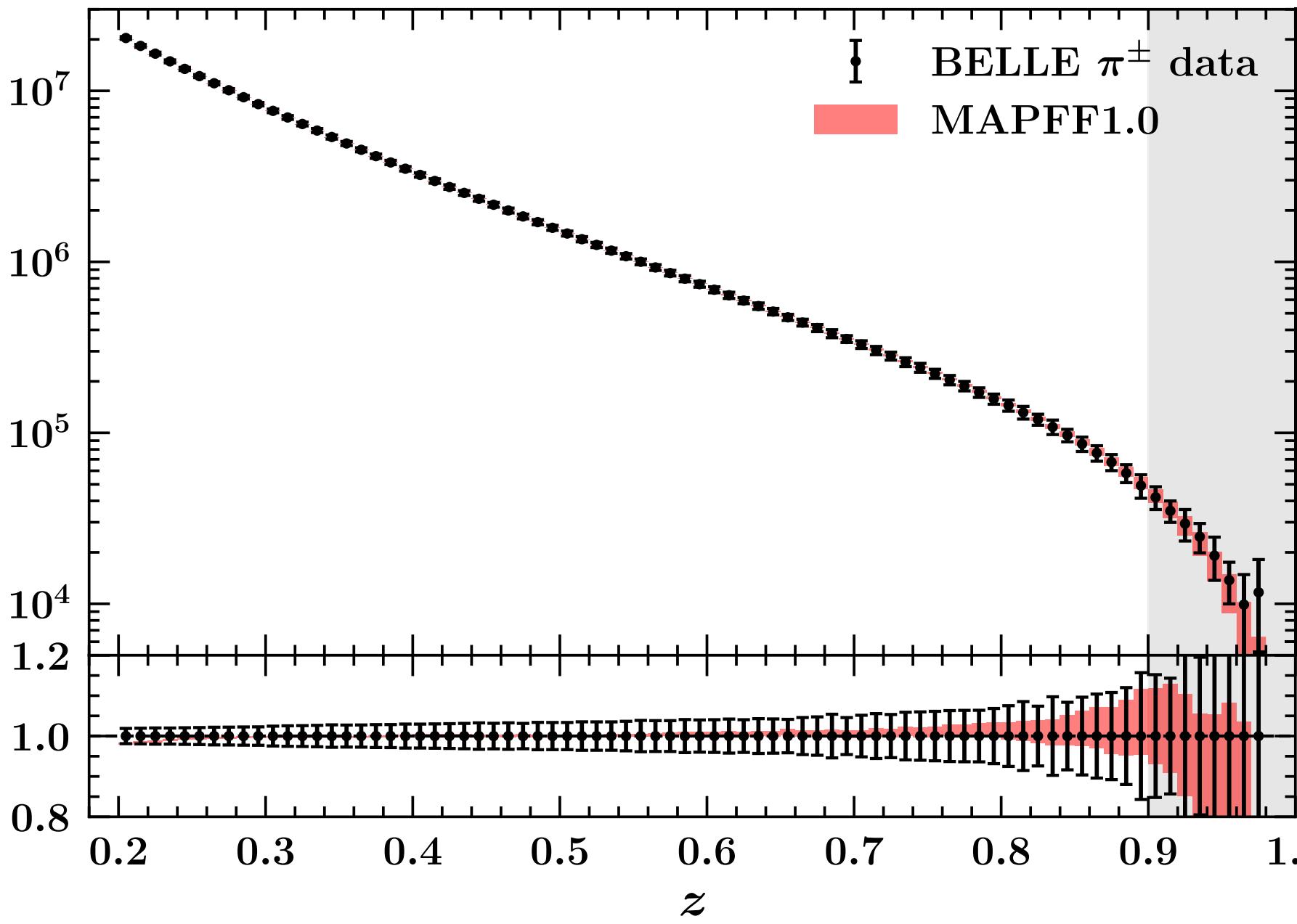
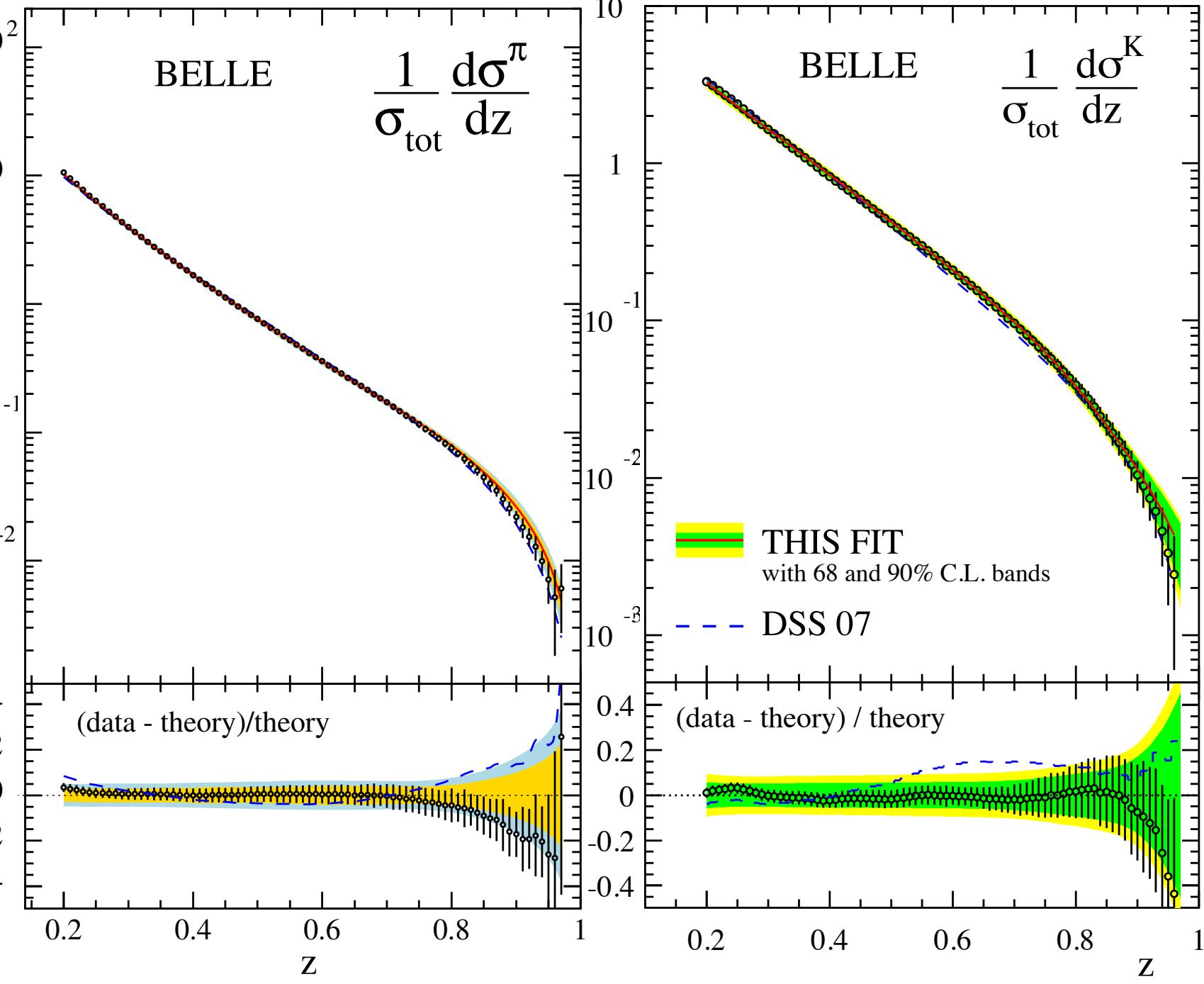
- systematics-dominated over entire kinematic range
- clear flavor dependence
 - suppression of kaons
 - suppression of like-sign pairs
 - more pronounced at large z (stronger flavor sensitivity)
- similar behavior for different z definitions when imposing $T > 0.8$
- larger suppression (low z) for fully inclusive pairs ("any hemisphere")



[PRD 101 (2020) 092004]

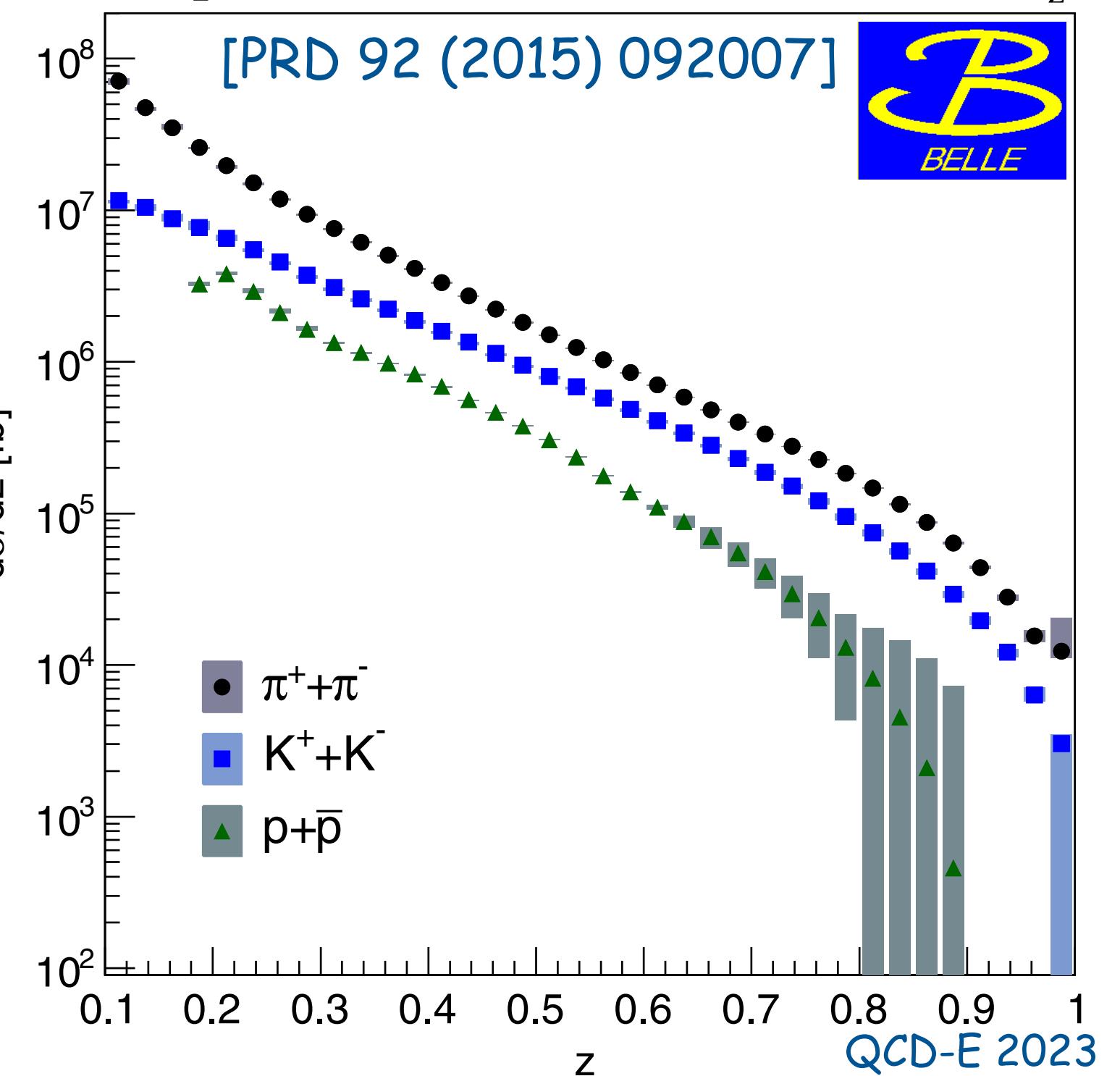
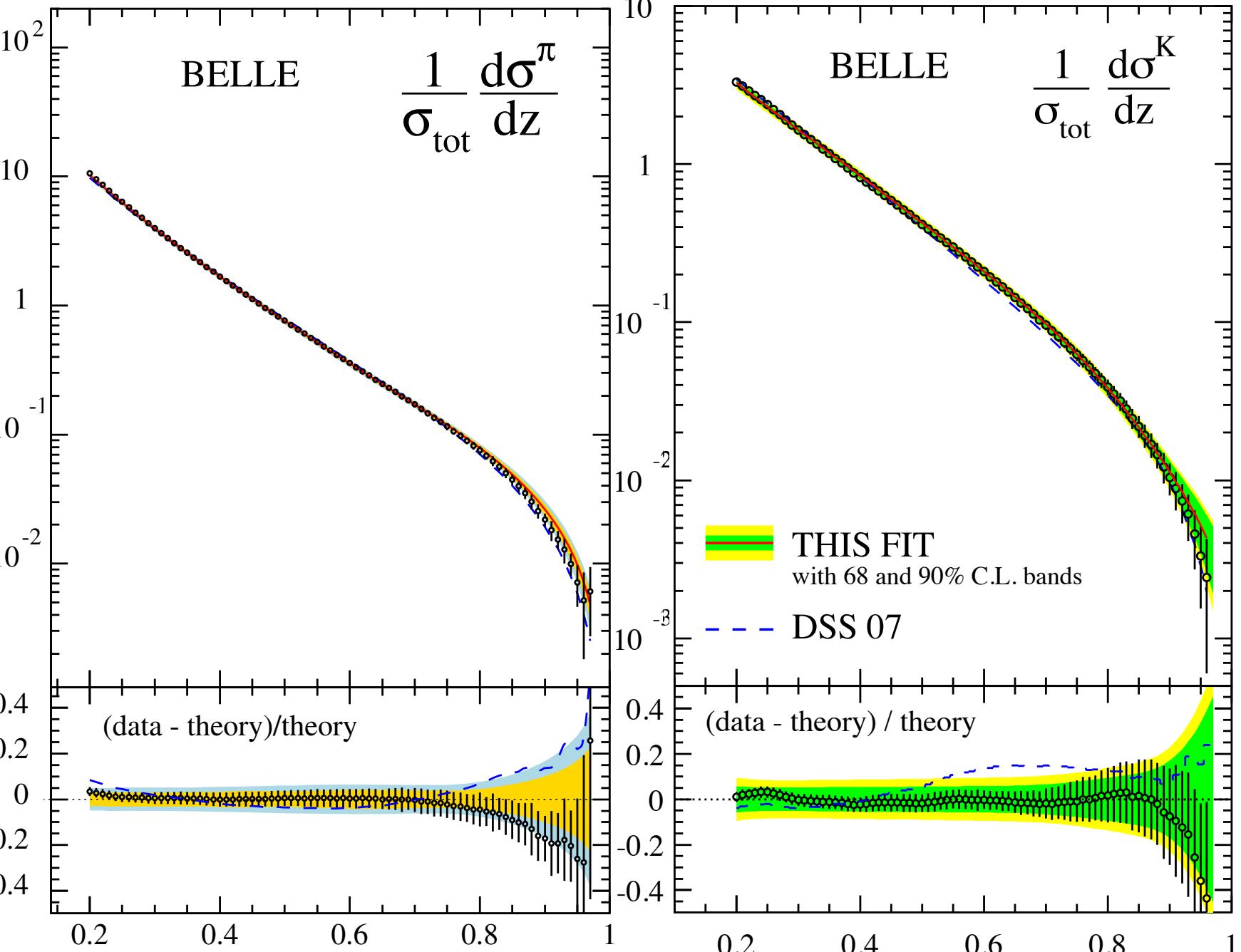
single-hadron production

- very precise data for charged pions and kaons
- Belle data available up to very large z ($z < 0.98$)
- included in several FF fits (e.g. DEHSS or MAPFF)
[cf. talk by Emanuele on Wed.]
- Belle radiative corrections “undone” in FF fits



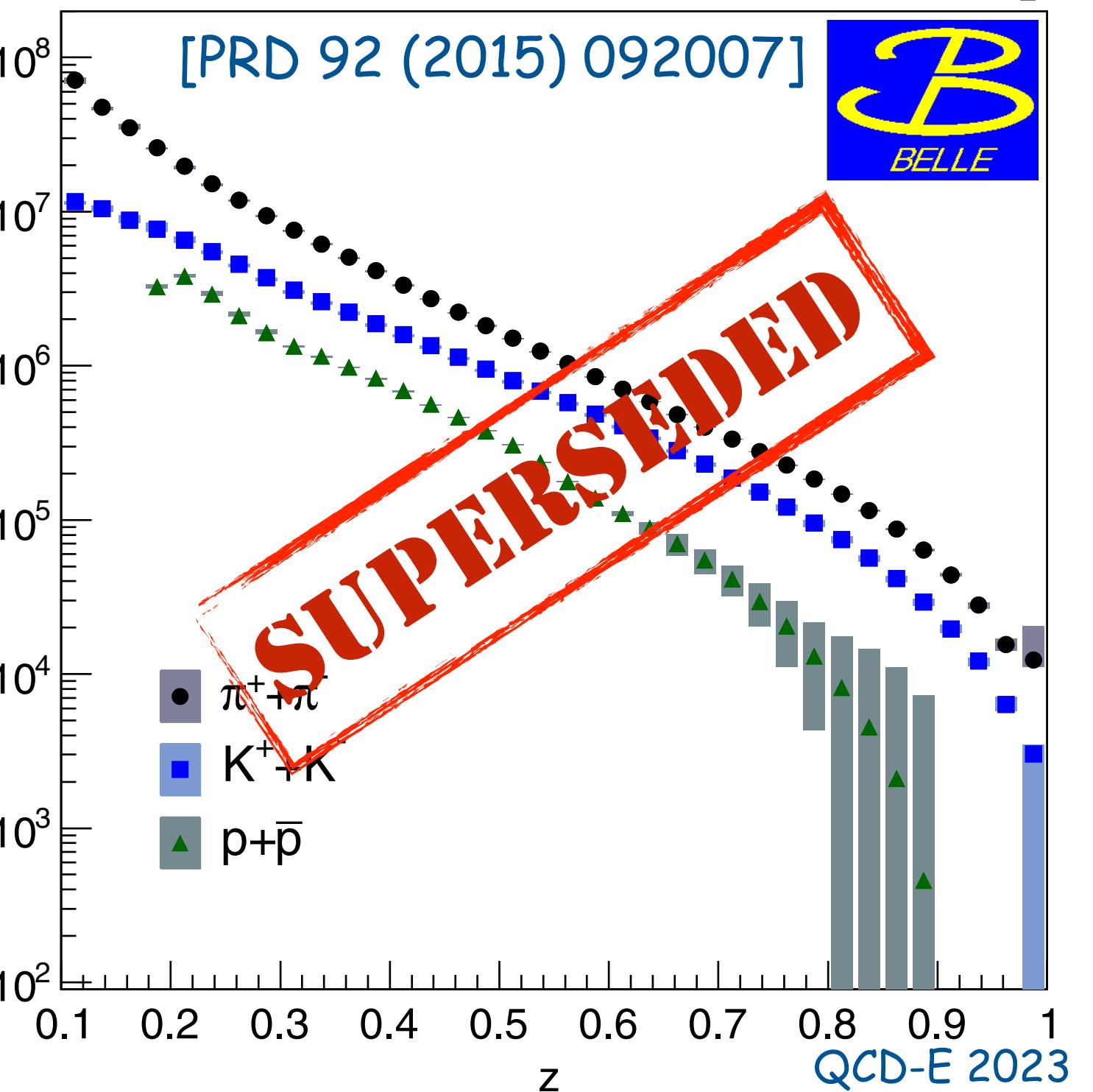
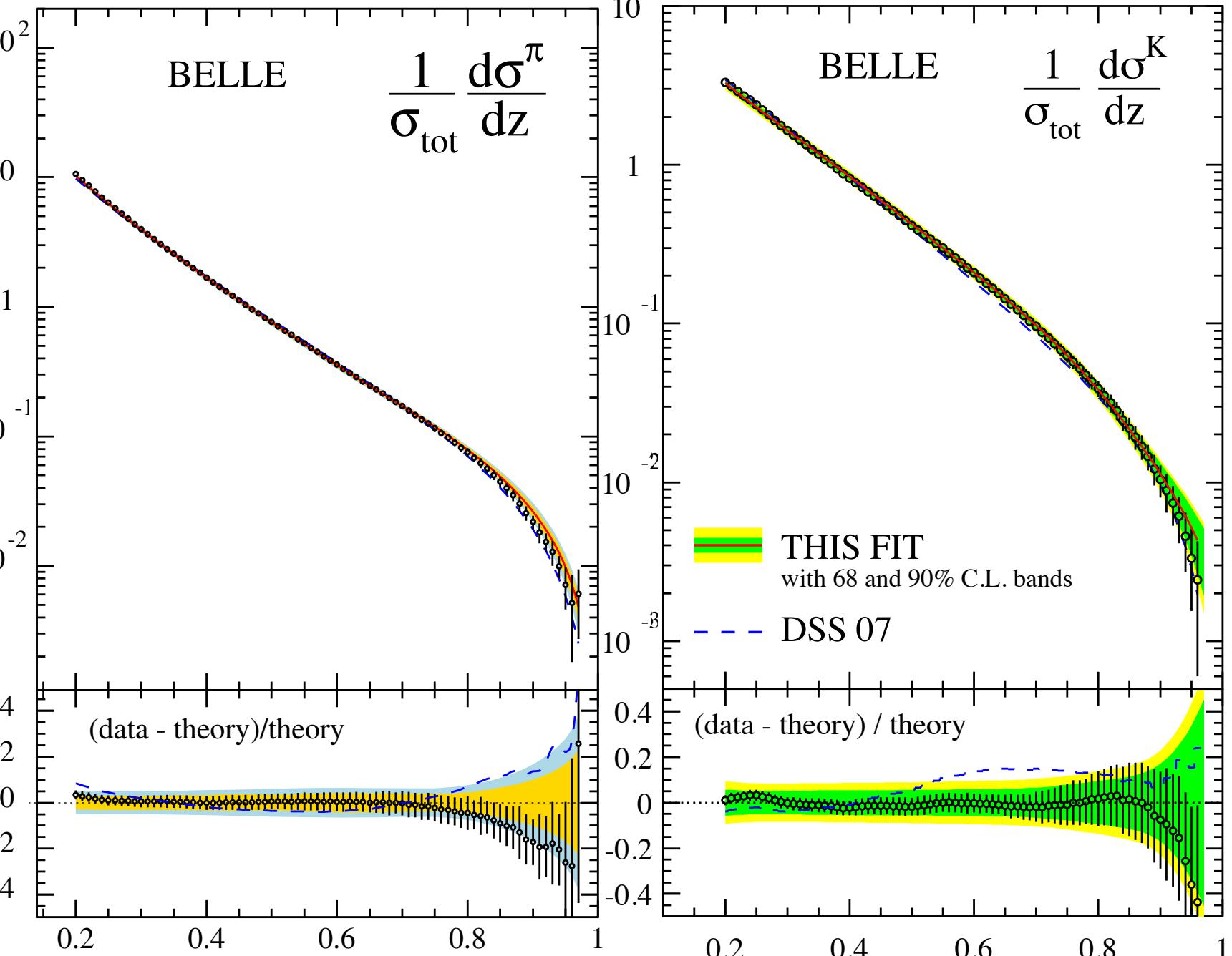
single-hadron production

- very precise data for charged pions and kaons
- Belle data available up to very large z ($z < 0.98$)
- included in several FF fits (e.g. DEHSS or MAPFF)
[cf. talk by Emanuele on Wed.]
- Belle radiative corrections “undone” in FF fits
- data available also for (anti)protons
 - not (yet) included in DEHSS or MAPFF, but, e.g., in NNFF [EPJC 77 (2017) 516]
 - similar z dependence as pions
 - about $\sim \frac{1}{5}$ of pion cross sections

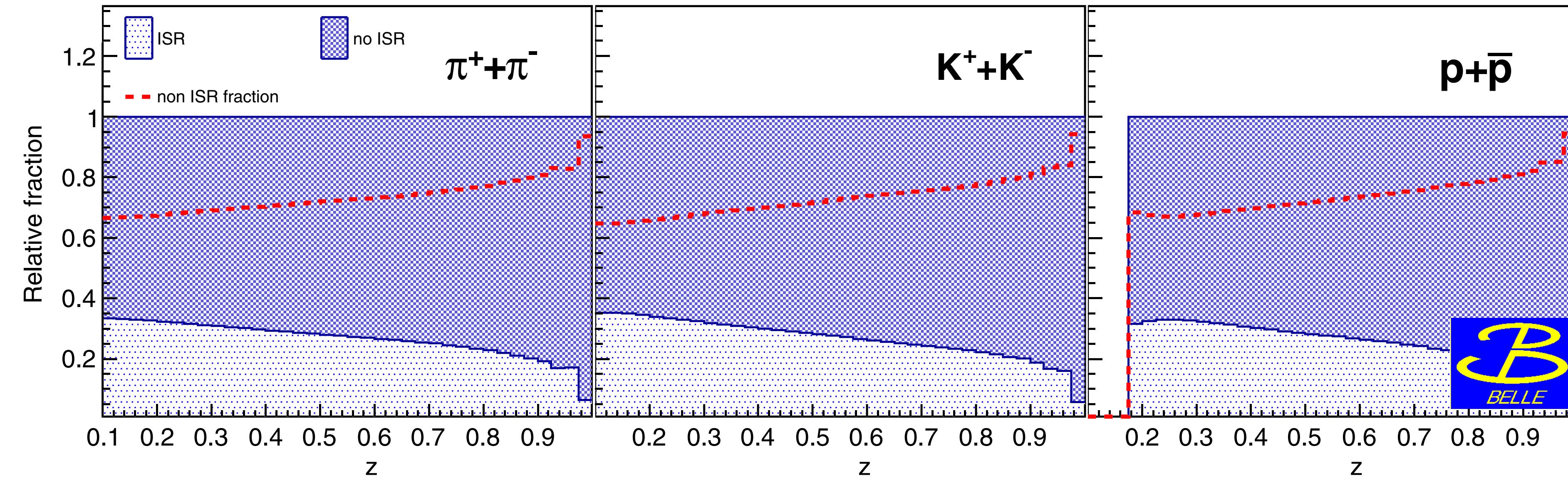


single-hadron production

- very precise data for charged pions and kaons
- Belle data available up to very large z ($z < 0.98$)
- included in several FF fits (e.g. DEHSS or MAPFF)
[cf. talk by Emanuele on Wed.]
- Belle radiative corrections “undone” in FF fits
- data available also for (anti)protons
 - not (yet) included in DEHSS or MAPFF, but, e.g., in NNFF [EPJC 77 (2017) 516]
 - similar z dependence as pions
 - about $\sim \frac{1}{5}$ of pion cross sections
- Belle re-analysis presented in PRD 101 (2020) 092004

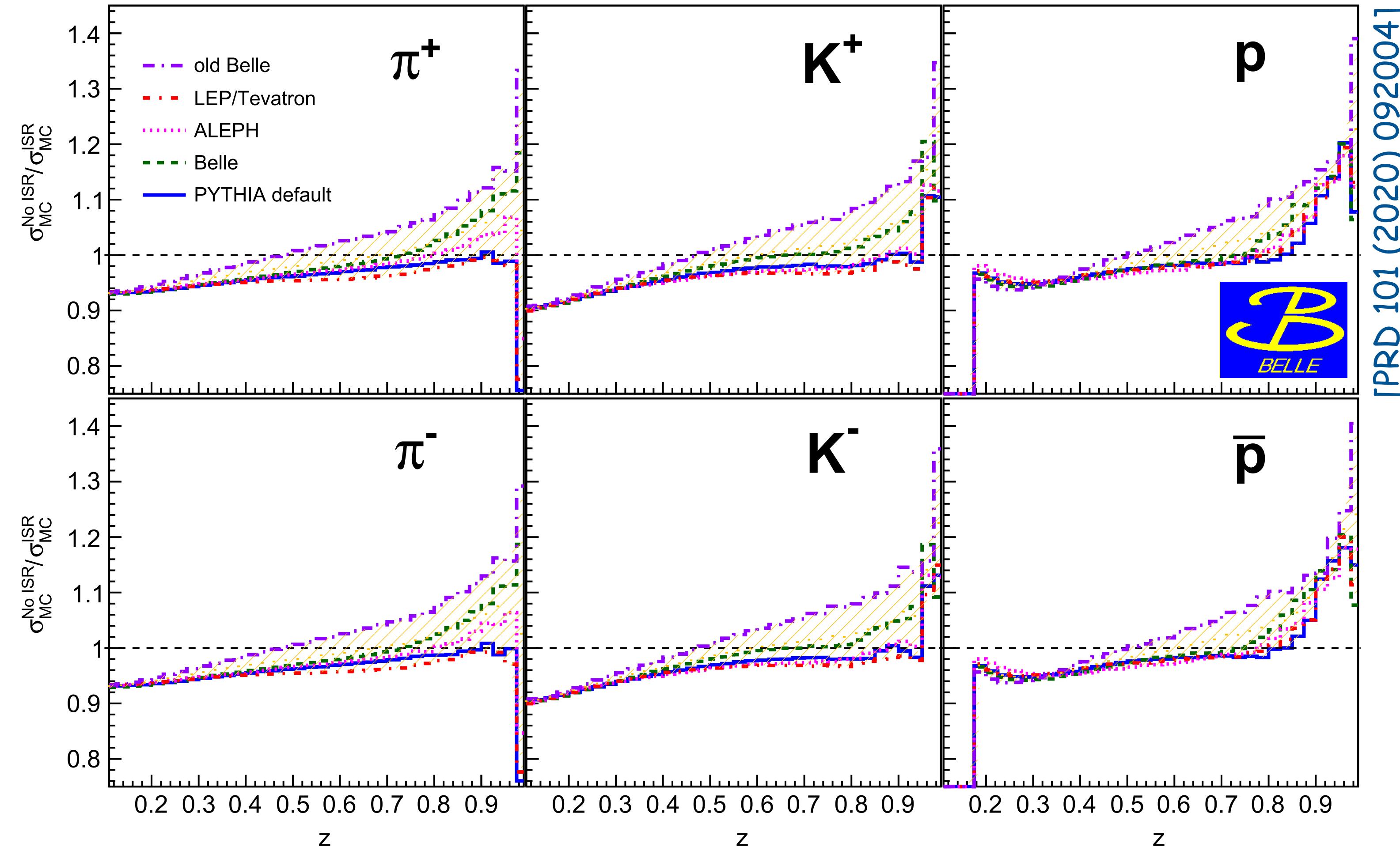


ISR corrections - PRD 92 (2015) 092007



- relative fractions of hadrons as a function of z originating from ISR or non-ISR events (\equiv energy loss less than 0.5%)
- large non-ISR fraction at large z , as otherwise not kinematically reachable
(remember: $z = E_h / 0.5\sqrt{s}_{\text{nominal}}$)
- keep only fraction of the events \rightarrow strictly speaking not single-inclusive annihilation

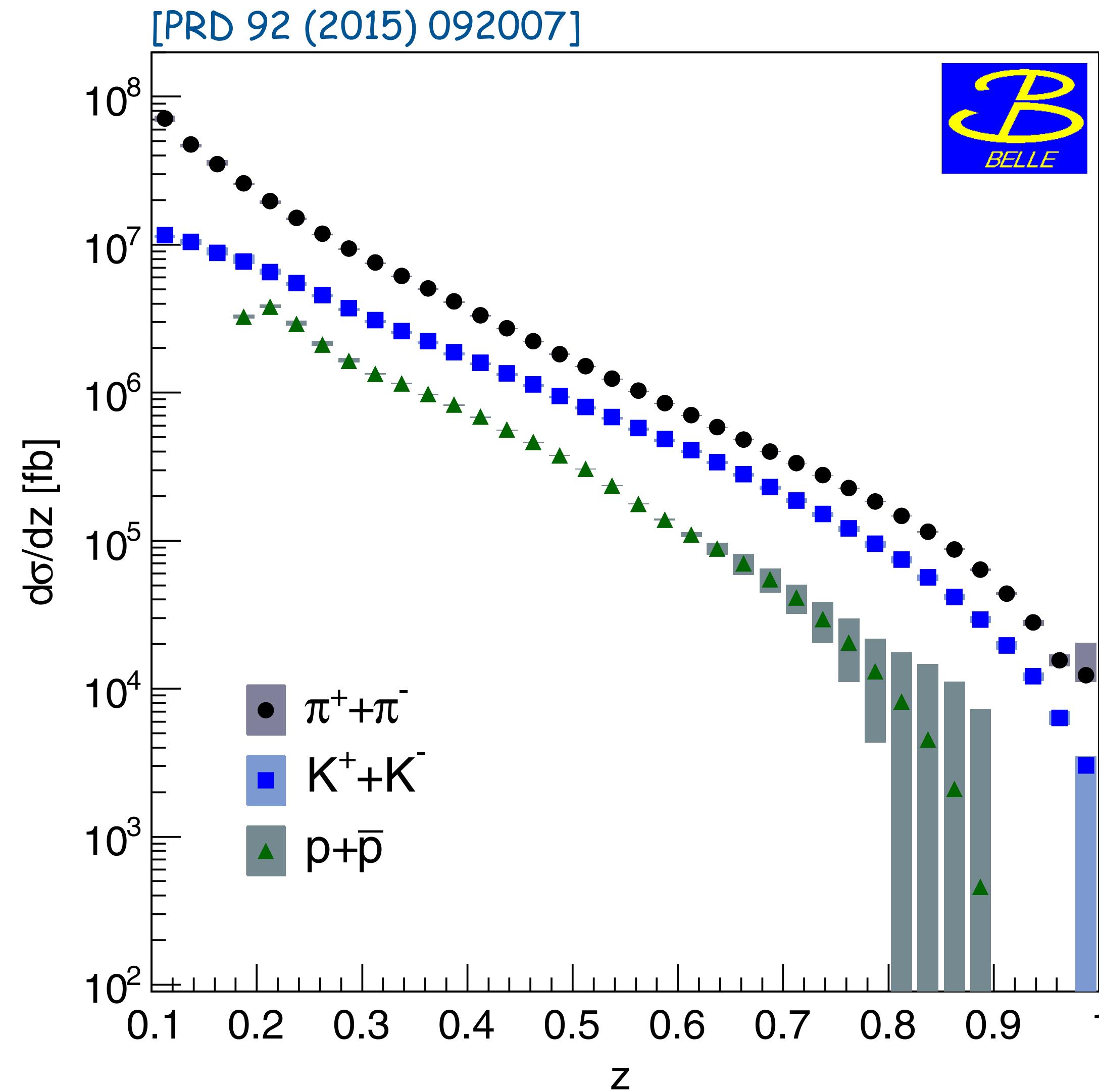
ISR corrections - PRD 101 (2020) 092004



- non-ISR / ISR fractions based on PYTHIA switch MSTP(11)
- PYTHIA model dependence; absorbed in systematics by variation of tunes

comparison old&new Belle single-hadron cross sections

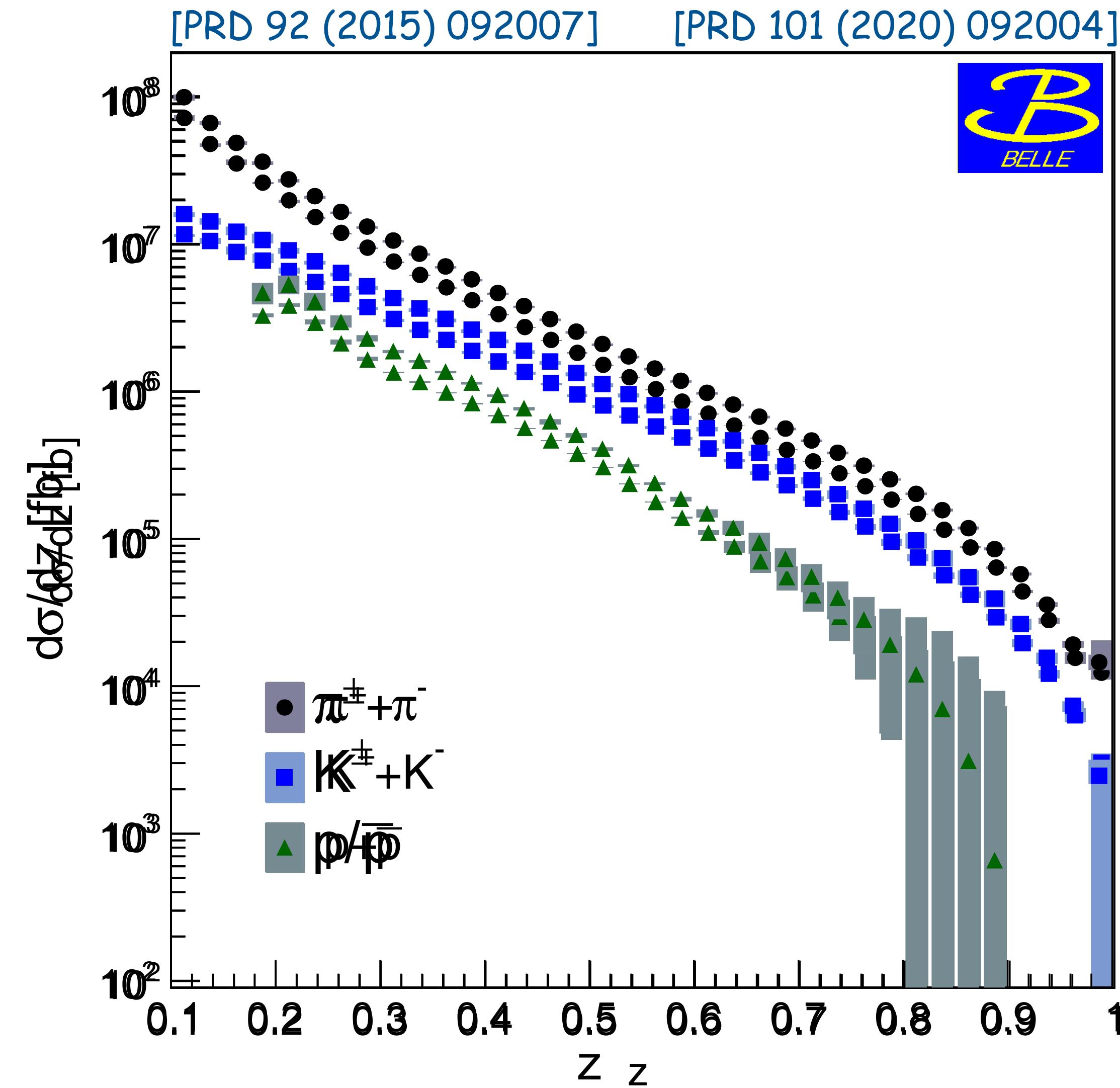
● previous analysis



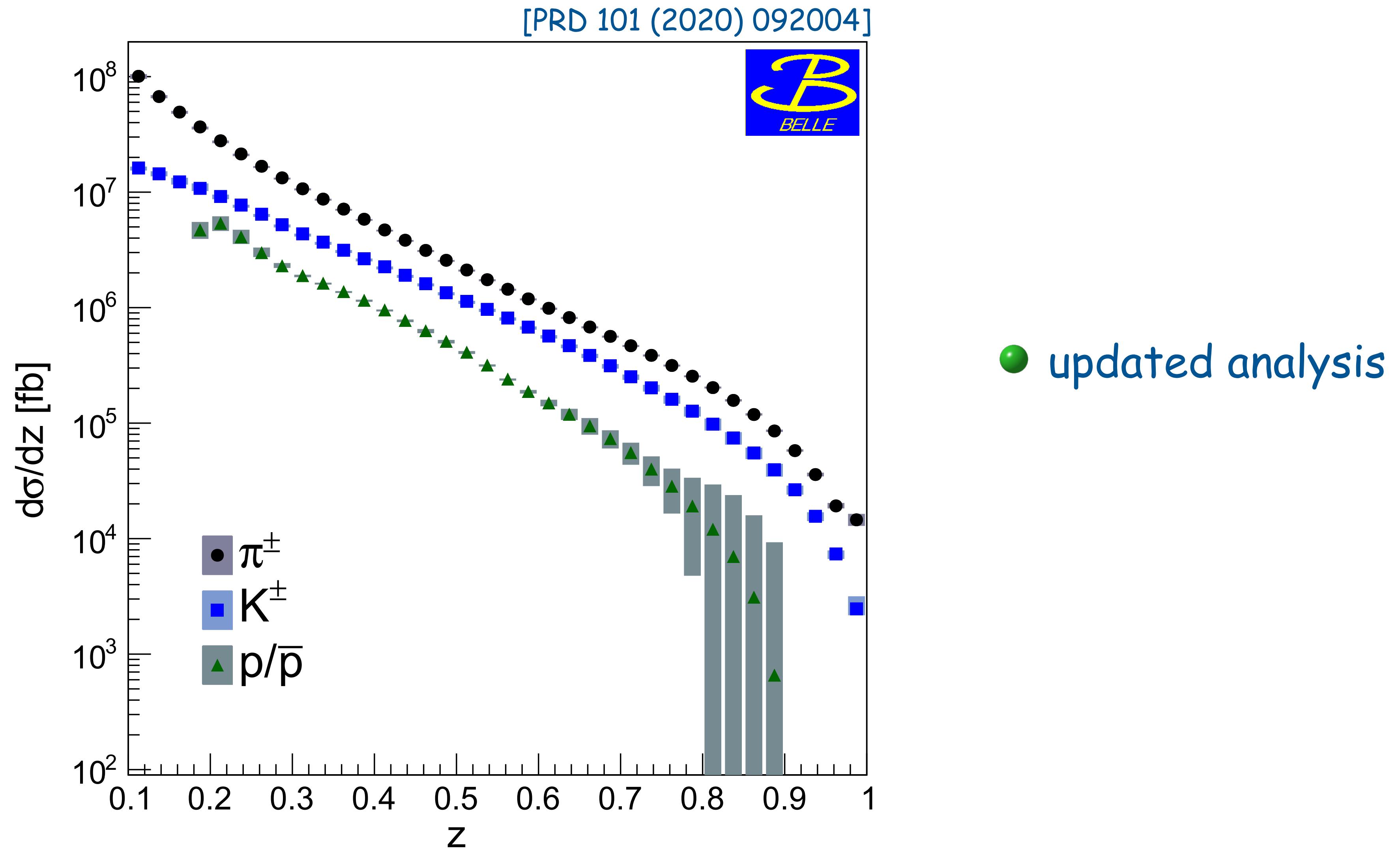
comparison old&new Belle single-hadron cross sections

● previous analysis

● updated analysis

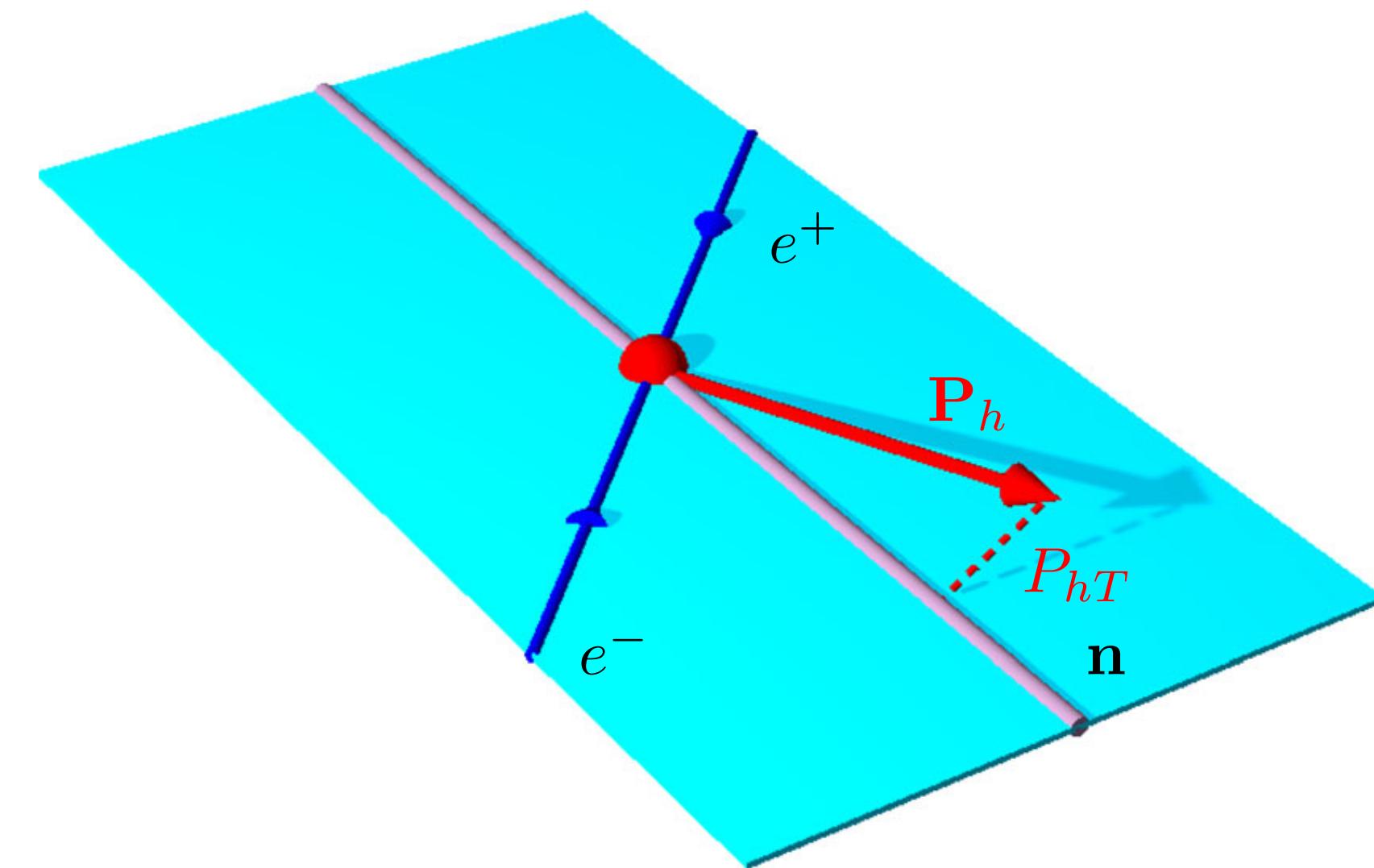


comparison old&new Belle single-hadron cross sections



inclusive hadrons - transverse momentum

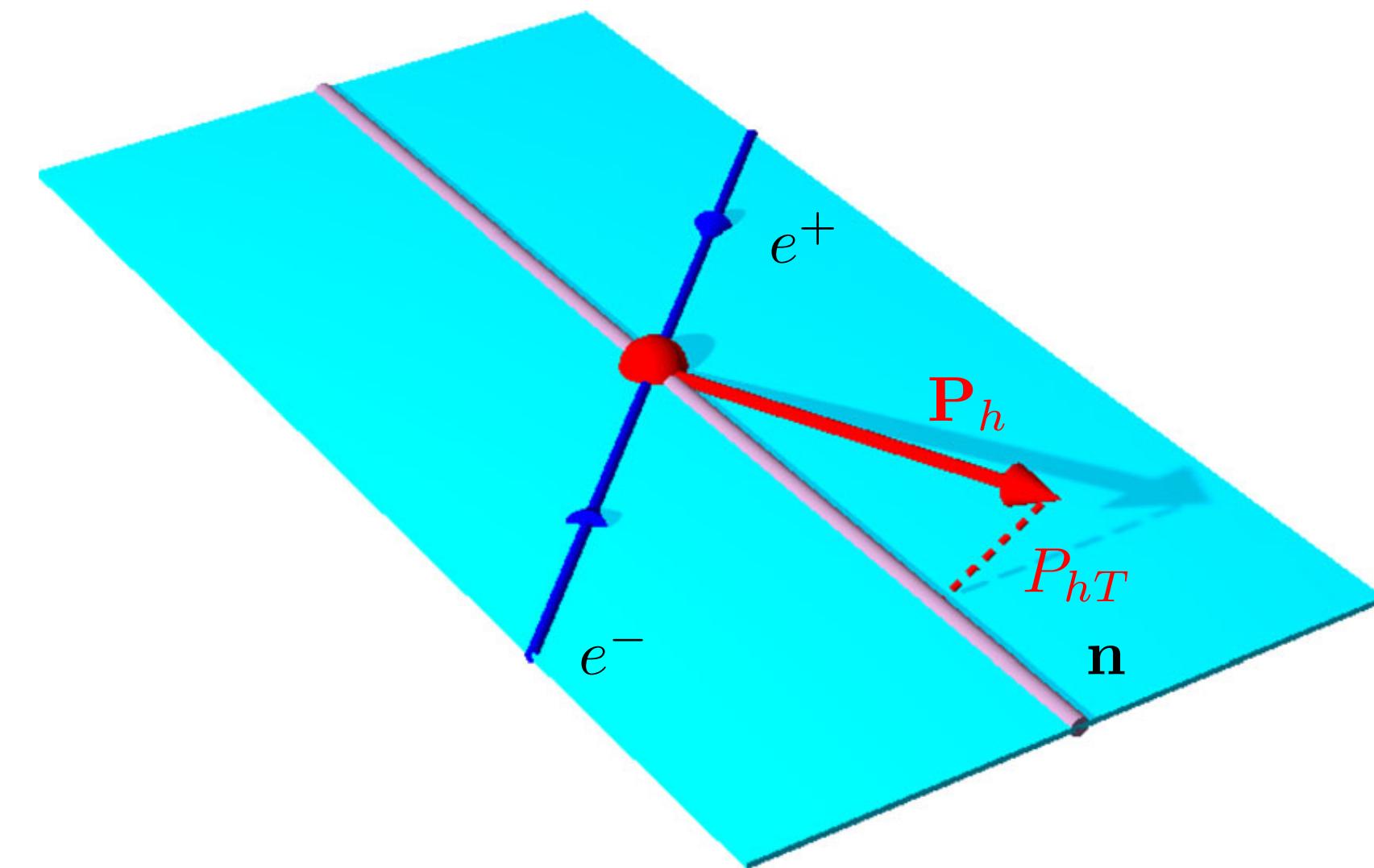
- quasi-inclusive hadron production gives access to transverse momentum in fragmentation
- transverse momentum measured with respect to thrust axis \mathbf{n}
- involves sum over all final-state particles in event
- event selection and hadron distributions dependent on thrust value T required
 - low thrust \rightarrow more spherical
 - high thrust \rightarrow highly collimated



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

inclusive hadrons - transverse momentum

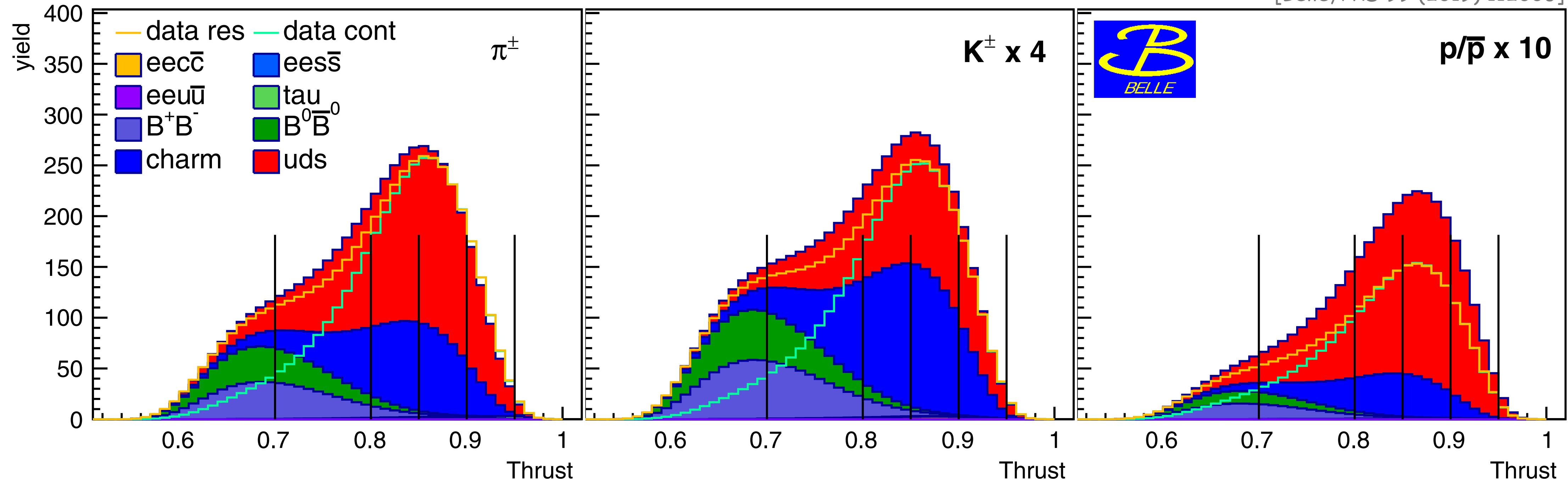
- quasi-inclusive hadron production gives access to transverse momentum in fragmentation
- transverse momentum measured with respect to thrust axis \mathbf{n}
- analysis performed differential in z & P_{hT} , in various slices in thrust T ($\Rightarrow 18 \times 20 \times 6$ bins)
- correction steps similar as for P_{hT} -integrated cross sections
- Gaussian fits to transverse-momentum distribution provided for all hadrons in (z, T) -bins



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

thrust distribution: process contributions

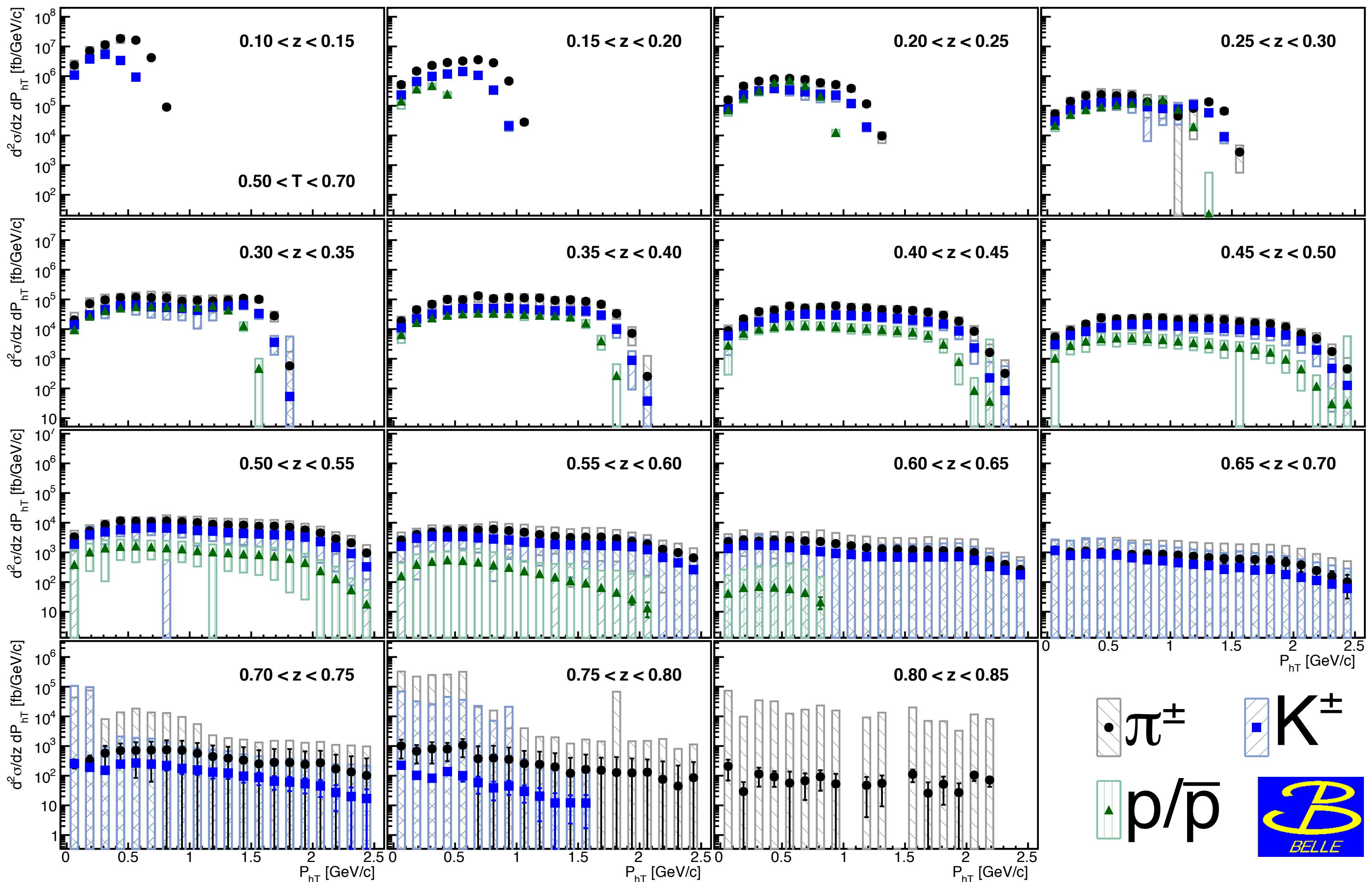
[Belle, PRD 99 (2019) 112006]



- large contribution from BB at lower thrust
- large thrust dominated by uds and $charm$ fragmentation
(at very large T significant τ contribution for pions, not visible here)
- will concentrate mainly on $0.85 < T < 0.9$ bin, though others available as well

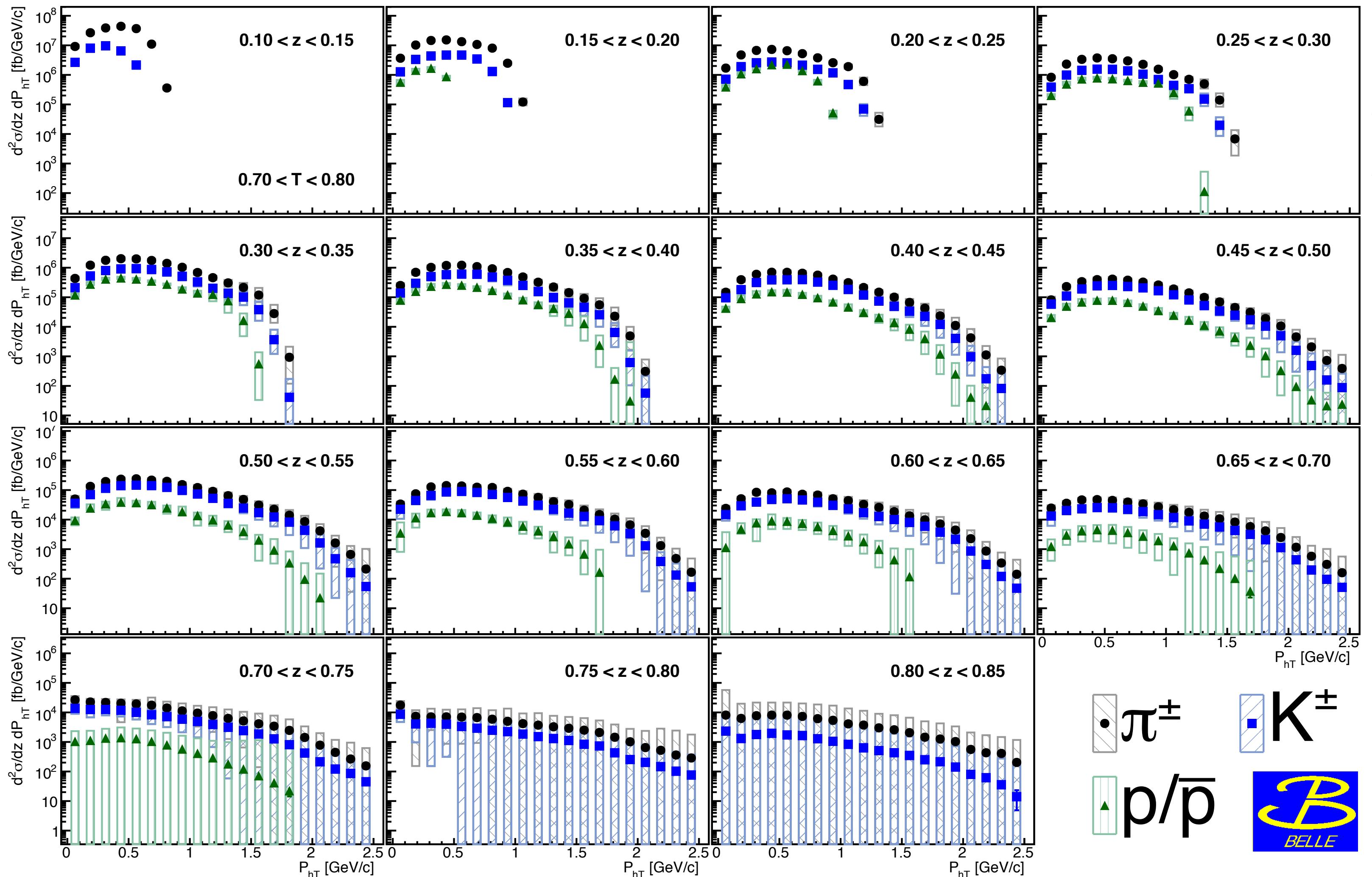
transverse-momentum distributions

- lowest T bin → rather spherical events
- transverse momenta almost uniformly distributed in medium-z bins
- faster drop for heavier hadrons



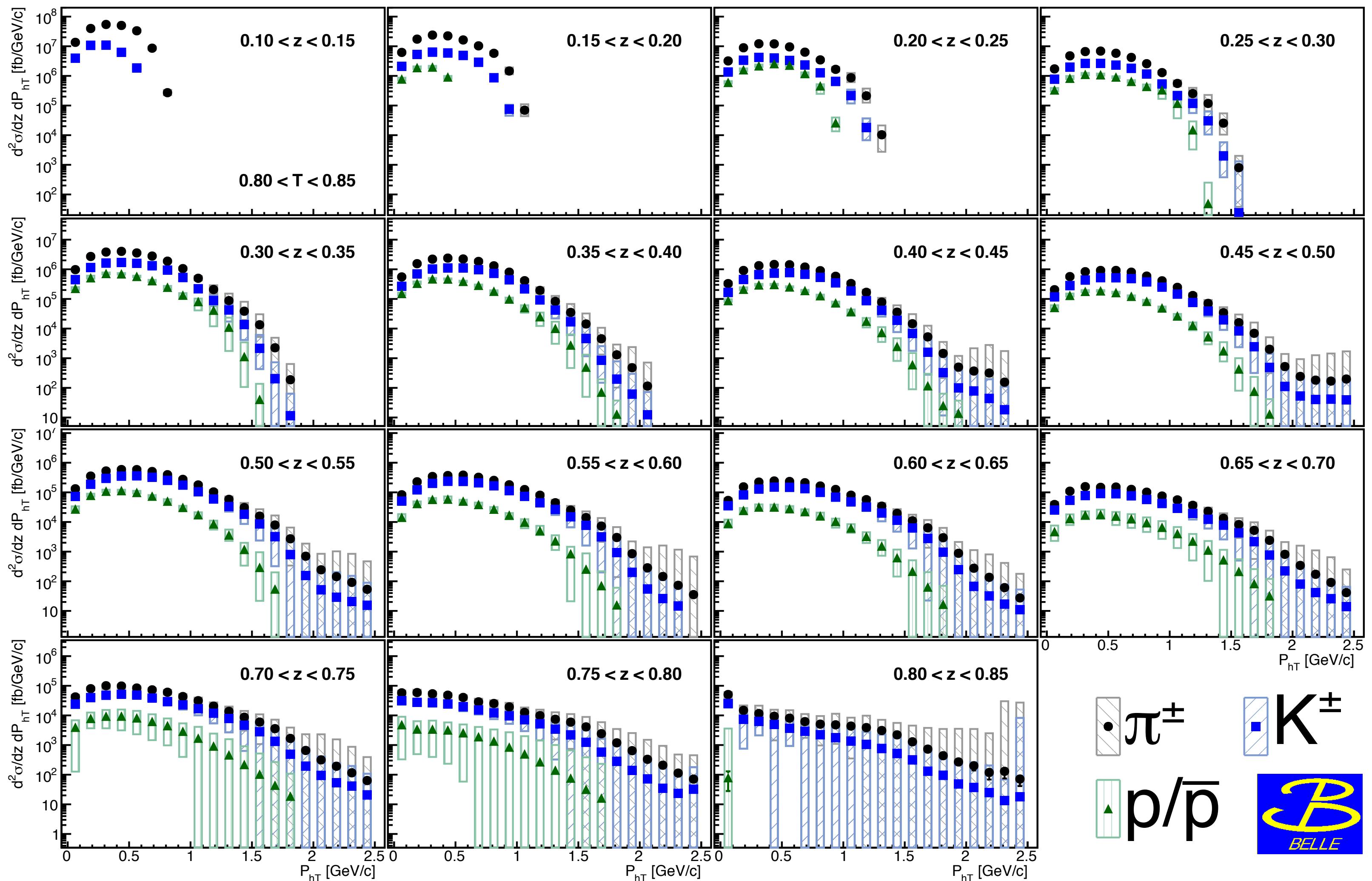
transverse-momentum distributions

- $0.7 < T < 0.8 \rightarrow$ particles already more collimated
- transverse momenta more Gaussian distributed
- large- z region with large uncertainties



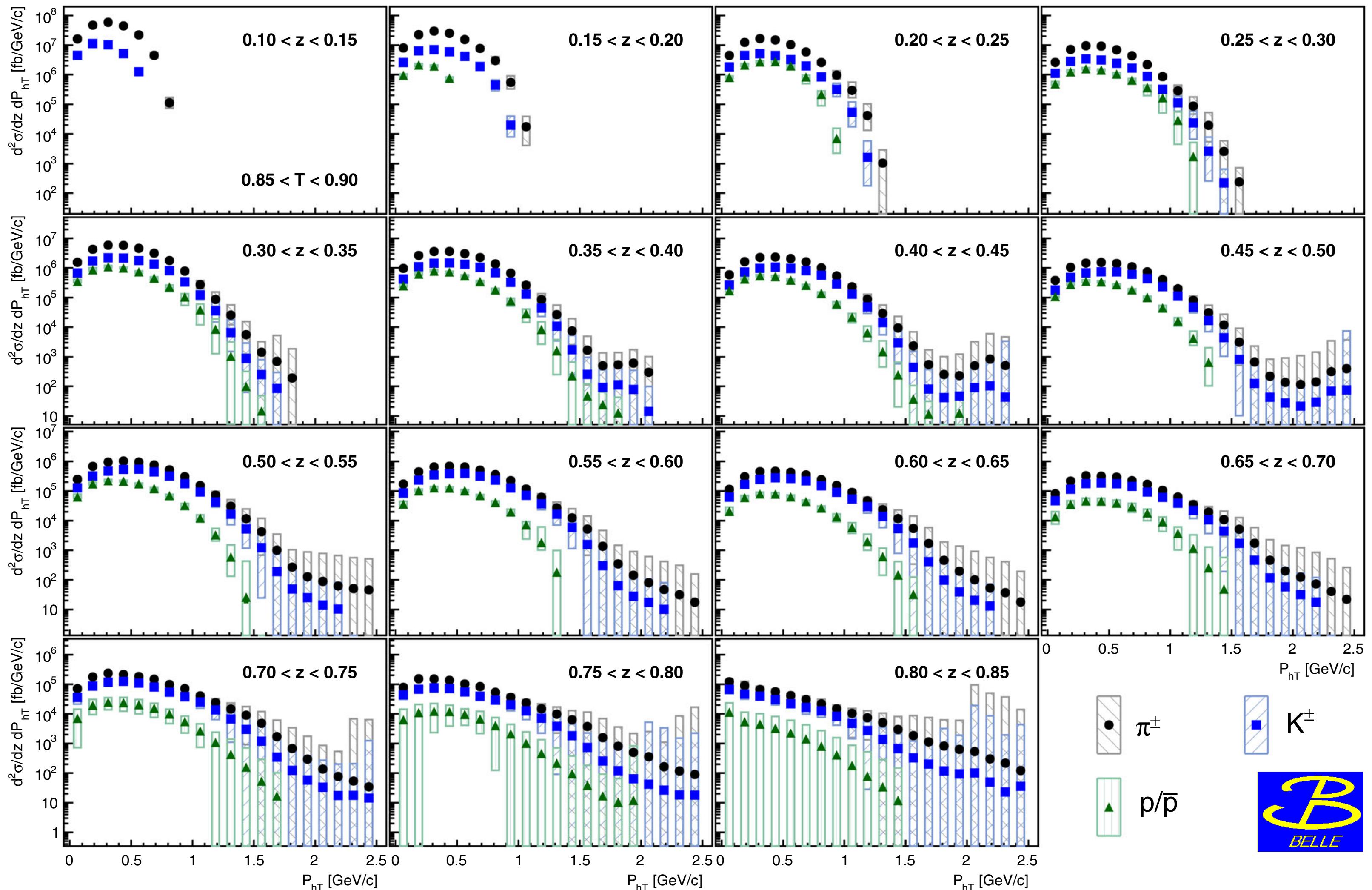
transverse-momentum distributions

- $0.8 < T < 0.85$
- transverse momenta mostly Gaussian distributed
- possible deviations for large- P_{hT} tails [but also larger uncertainties]



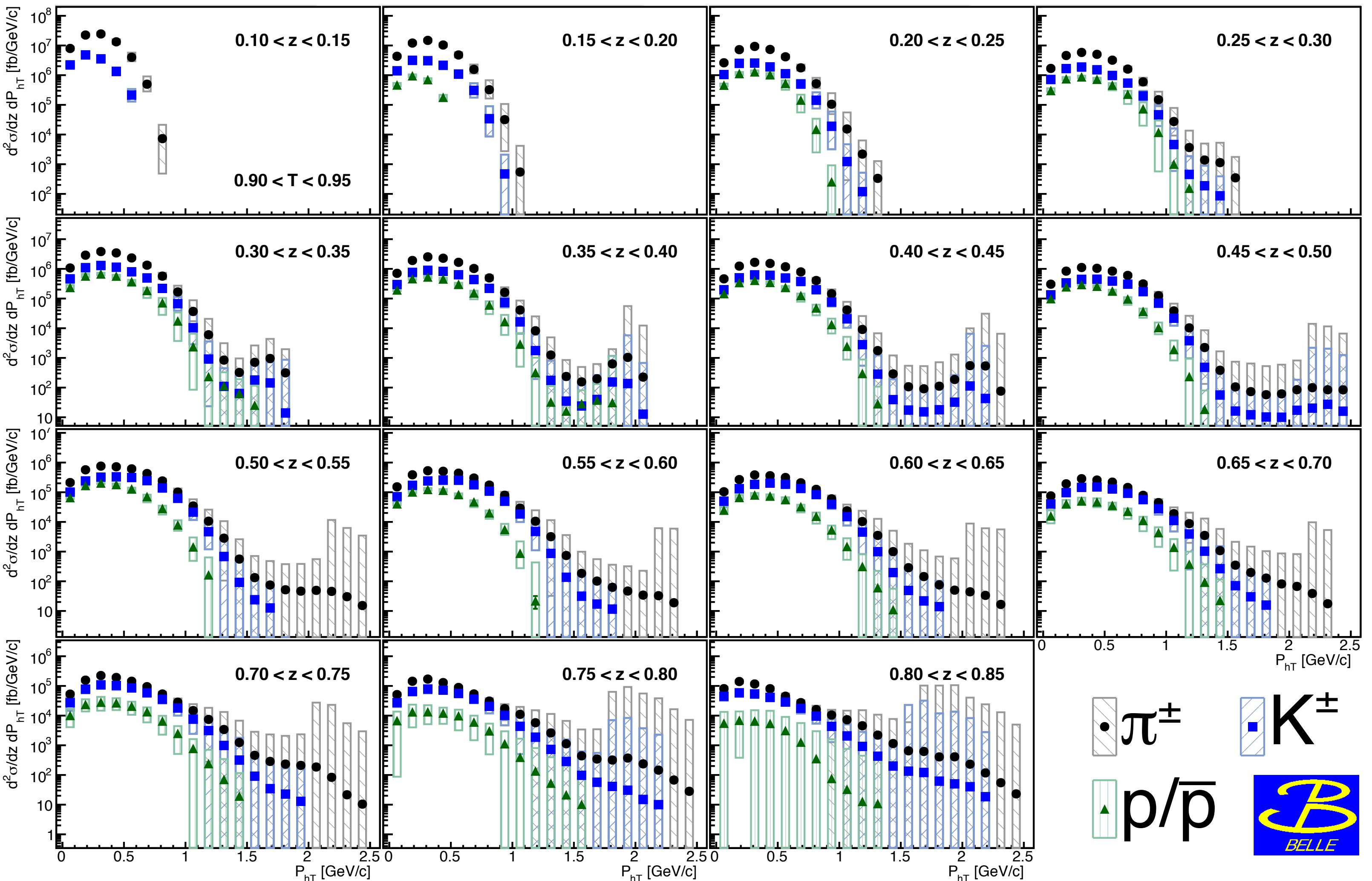
transverse-momentum distributions

- $0.85 < T < 0.9$
- transverse momenta mostly Gaussian distributed; widths narrowing
- possible deviations for large- P_{hT} tails [but also larger uncertainties]



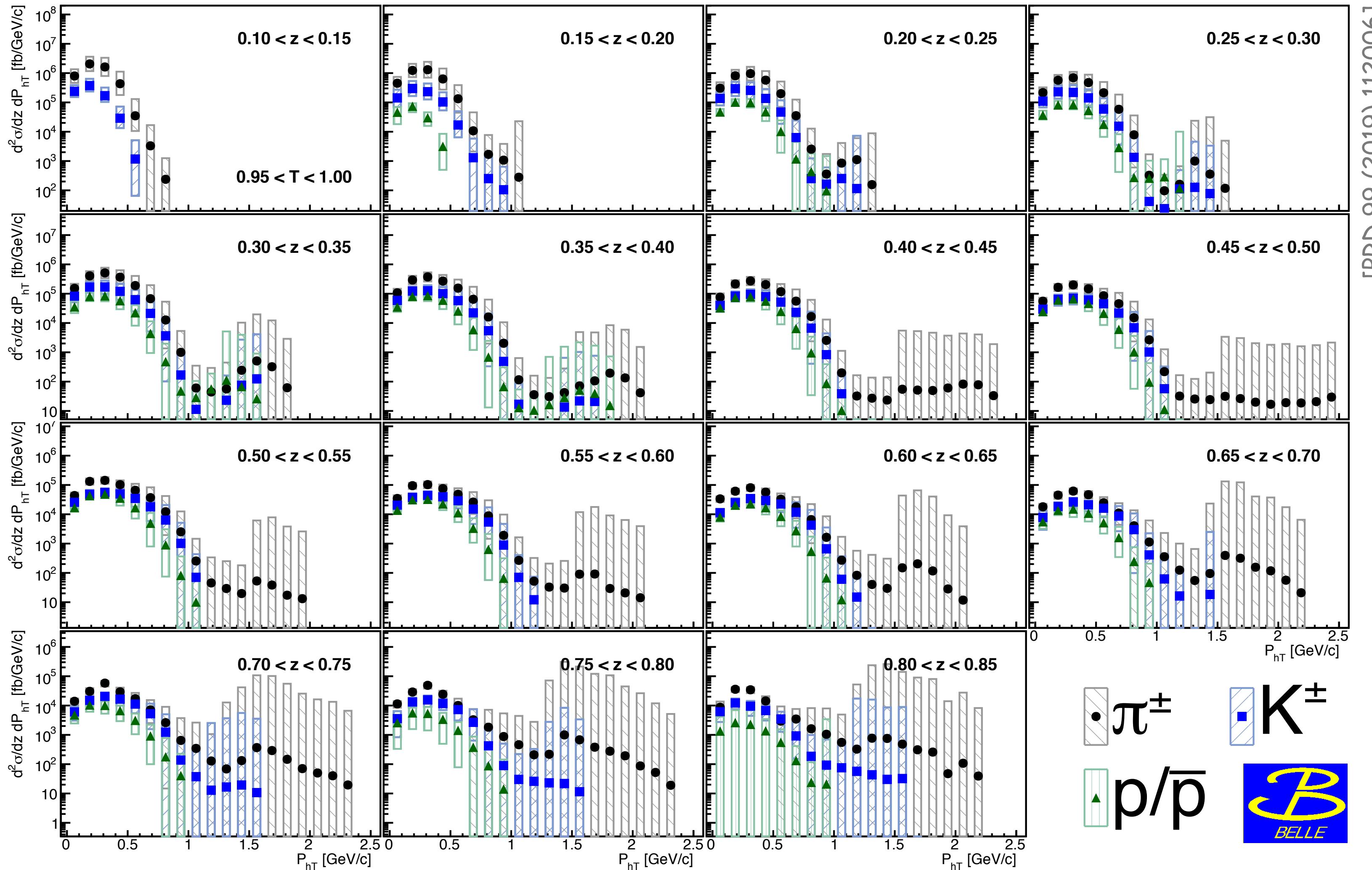
transverse-momentum distributions

- $0.9 < T < 0.95$
- transverse momenta mostly Gaussian distributed; widths even narrower
- possible deviations for large- P_{hT} tails [but also larger uncertainties]



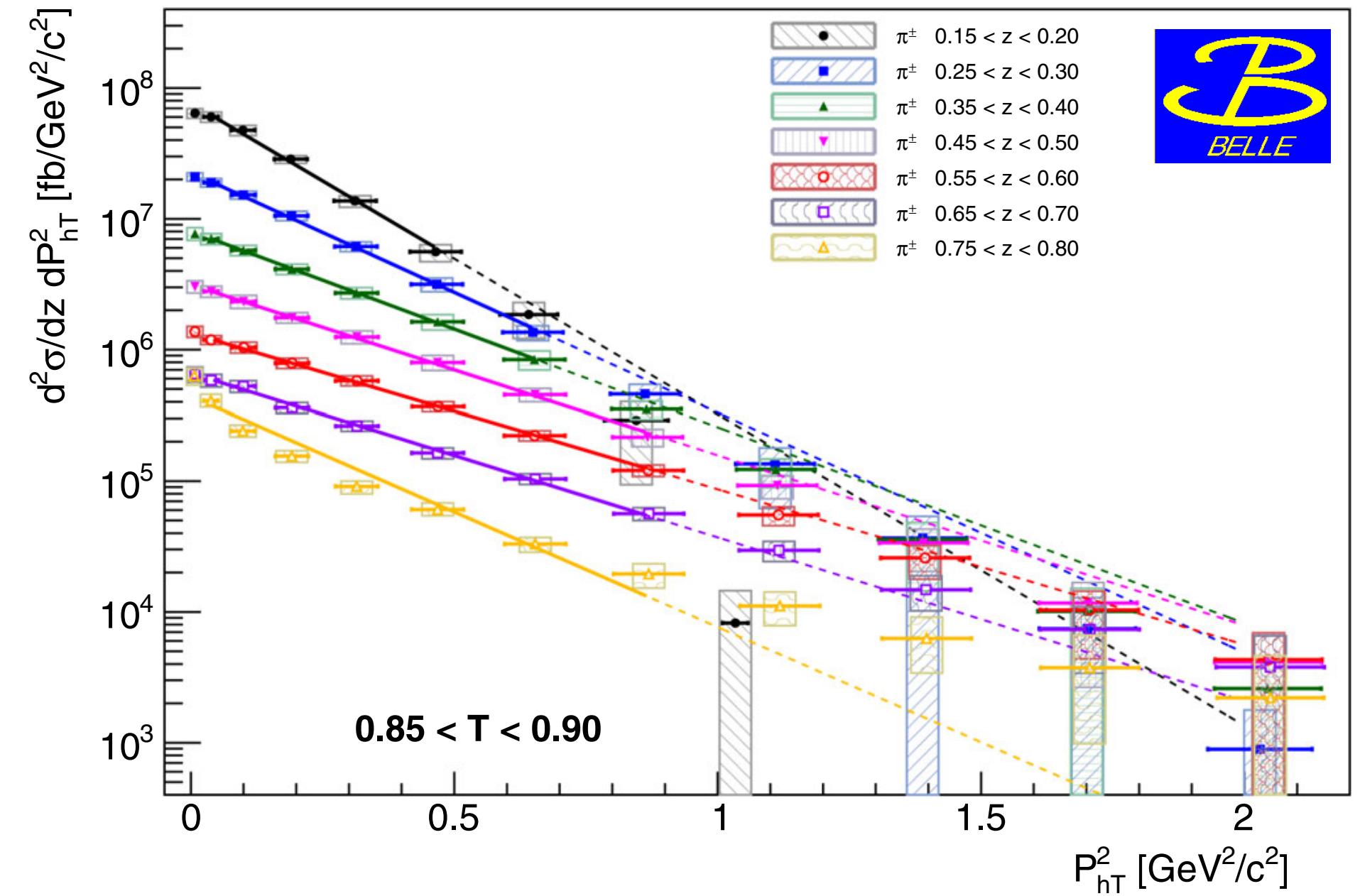
transverse-momentum distributions

- $0.95 < T < 1.0$
- transverse momenta mostly Gaussian distributed
- widths very narrow as particles now very collimated

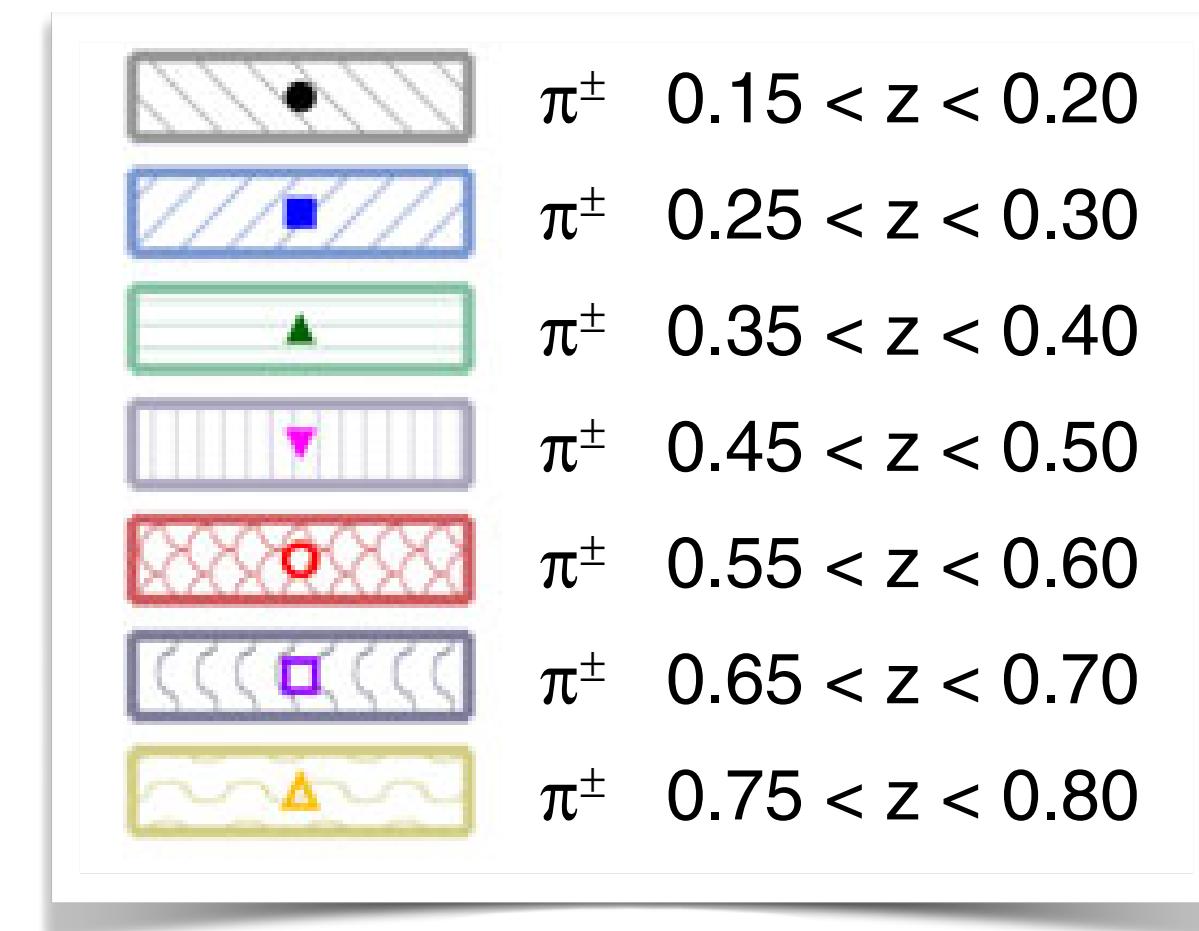


transverse-momentum: Gaussian widths

- $0.85 < T < 0.90$
- fit Gauss to low- P_{hT} data
- mostly well described with possible exception at high z
- deviation from Gauss at large P_{hT}
- clear increase of width with z for low values of z

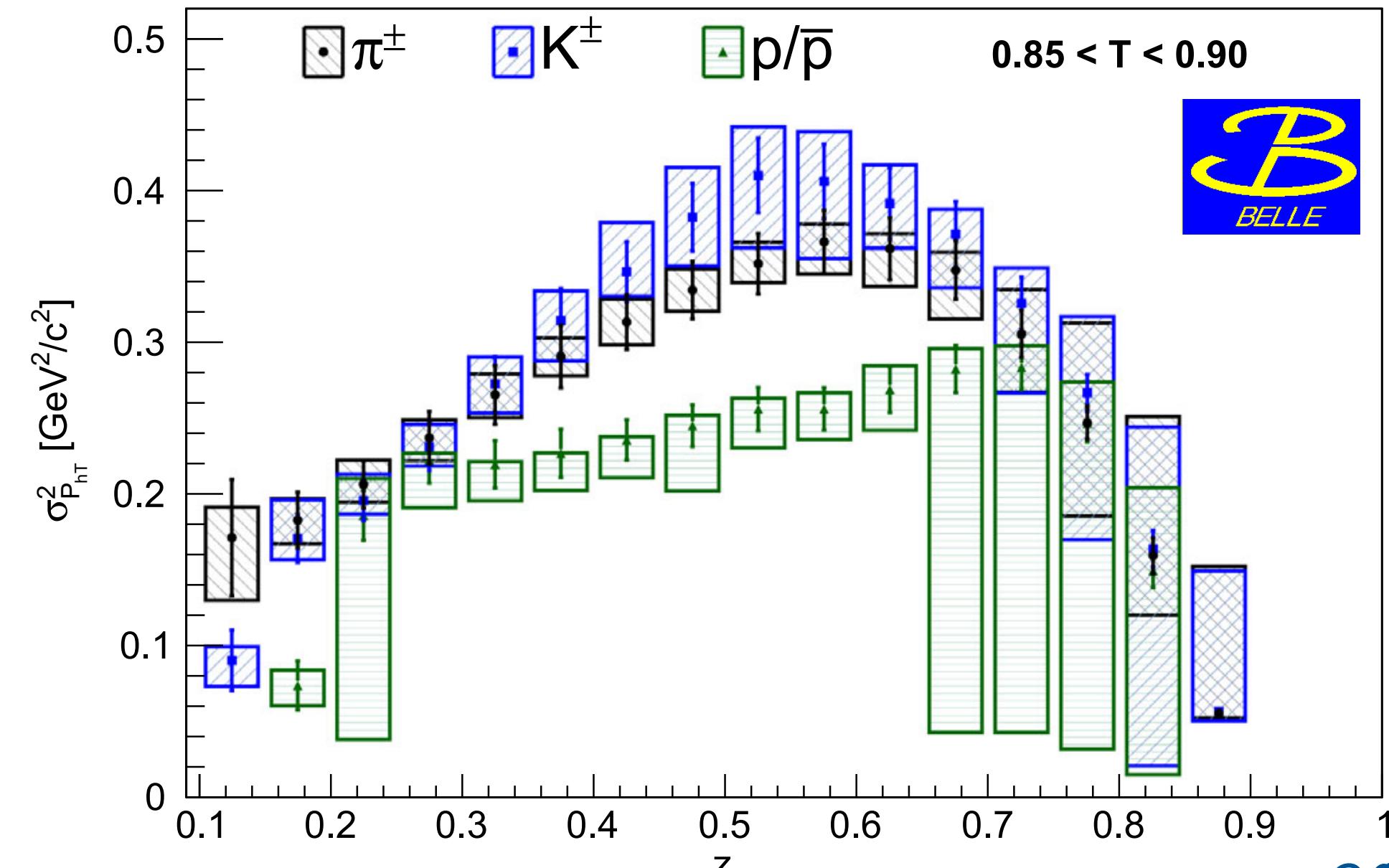
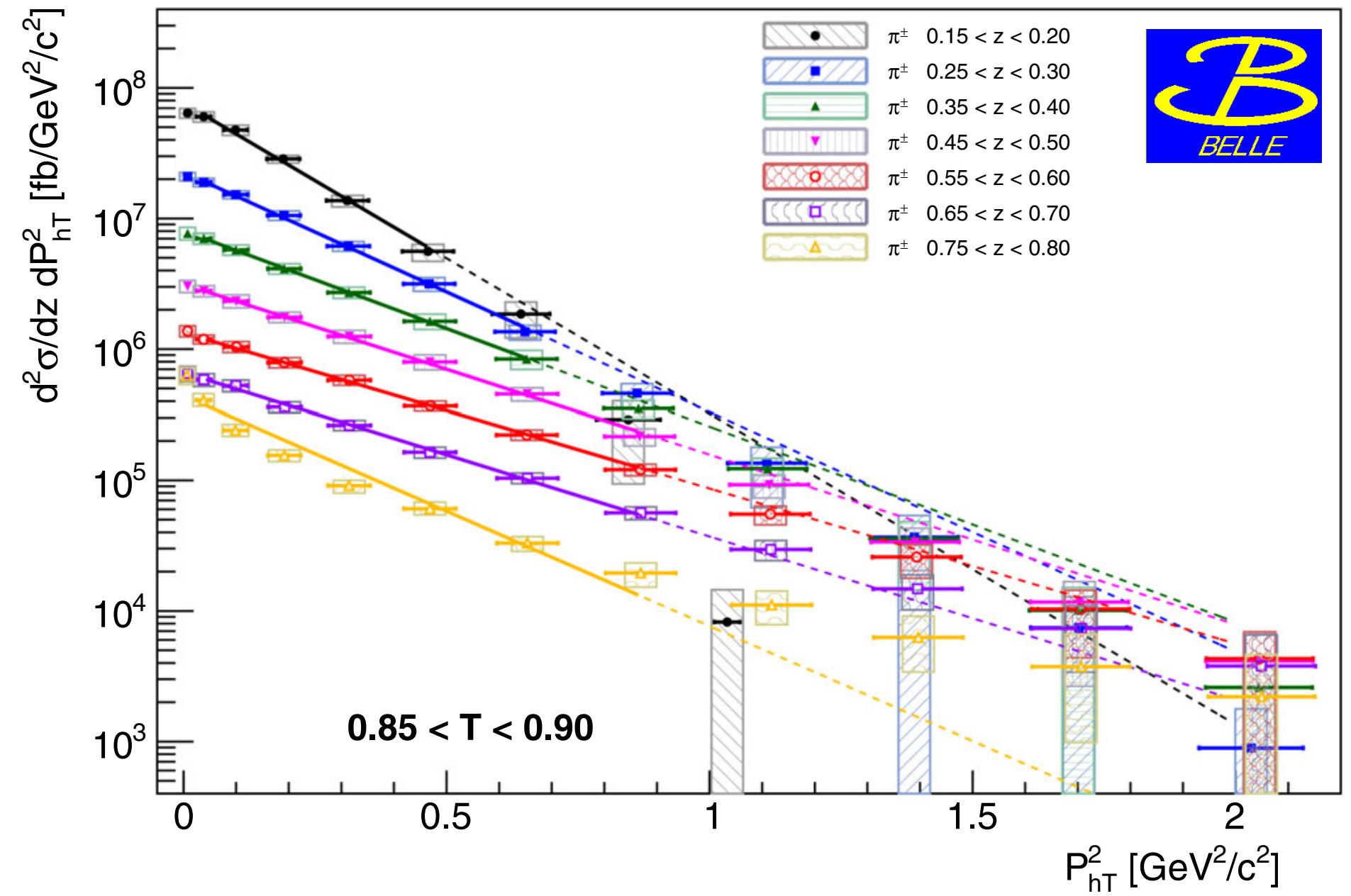


[PRD 99 (2019) 112006]



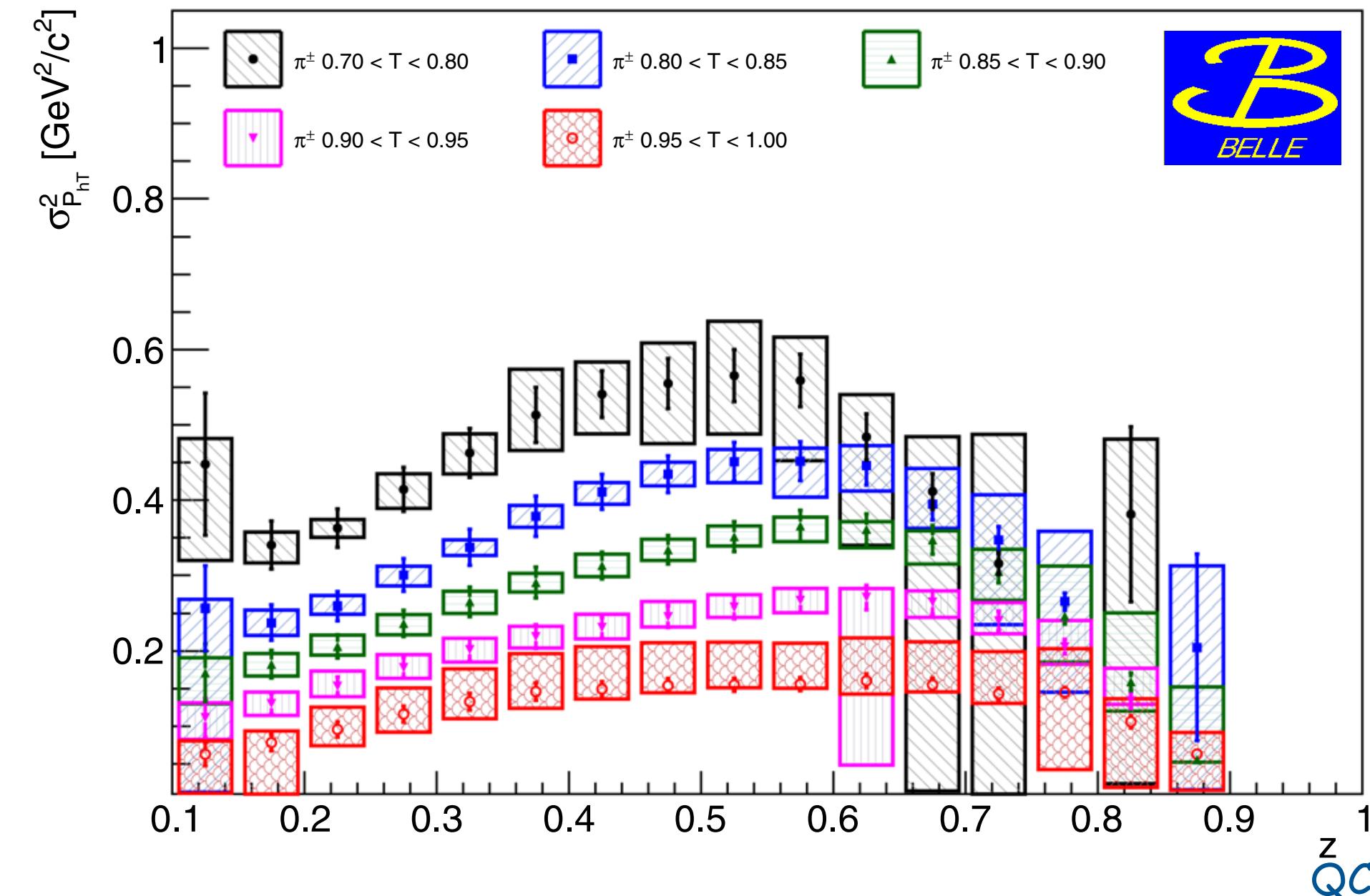
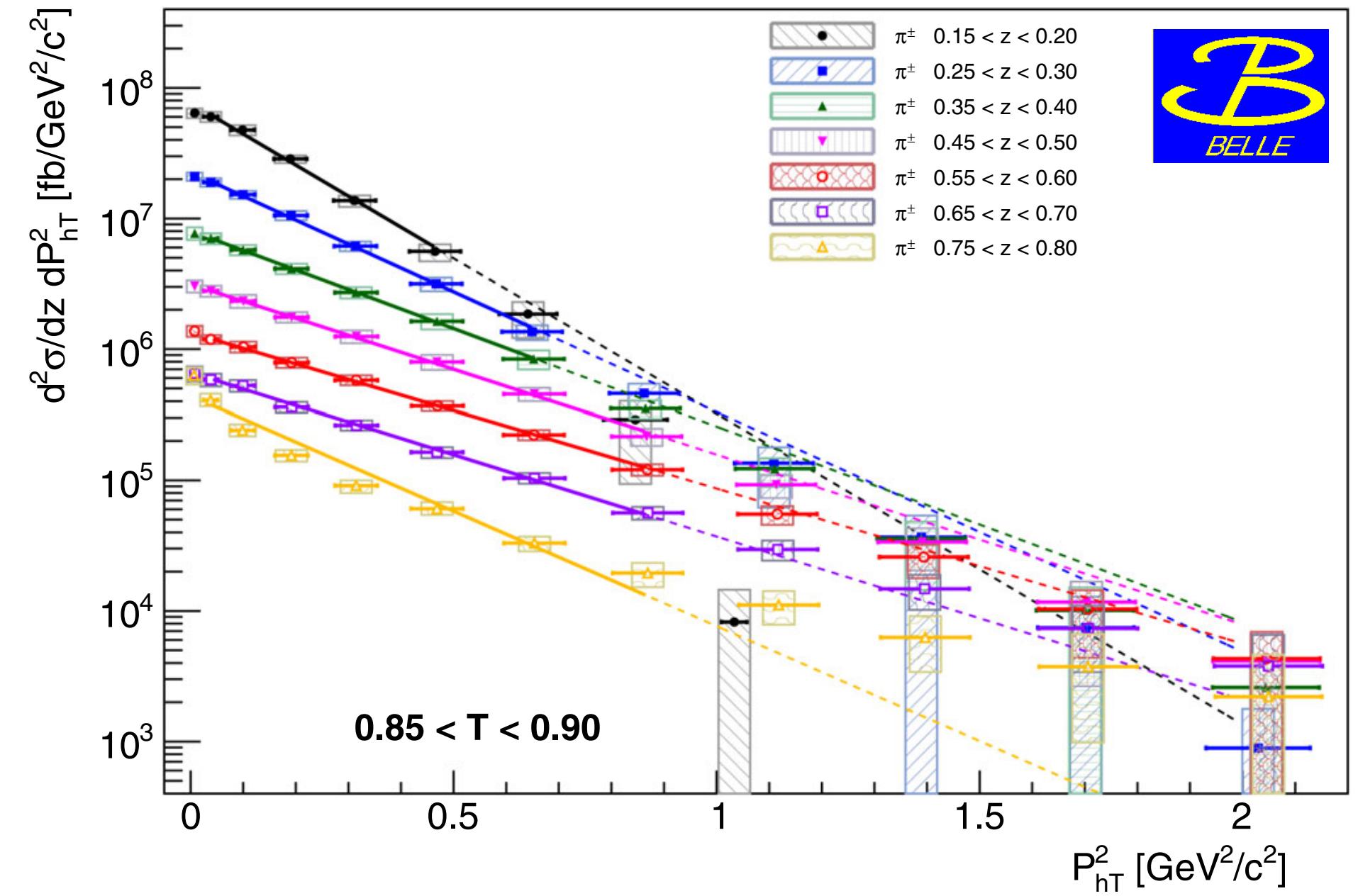
transverse-momentum: Gaussian widths

- $0.85 < T < 0.90$
- fit Gauss to low- P_{hT} data
- mostly well described with possible exception at high z
- deviation from Gauss at large P_{hT}
- clear increase of width with z for low values of z
- Gaussian widths as function of z
- general increase with z with turnover at larger values of z for mesons
- protons with smaller width and a more linear rise with z



transverse-momentum: Gaussian widths

- $0.85 < T < 0.90$
- fit Gauss to low- P_{hT} data
- mostly well described with possible exception at high z
- deviation from Gauss at large P_{hT}
- clear increase of width with z for low values of z
- Gaussian widths depend on z and T
- general increase with z with turnover at larger values of z
- clear decrease of widths with increase of T
- particles more and more collimated



Summary

- e^+e^- annihilation is powerful laboratory for hadronization studies
 - in two-hadron production, observing a “back-to-back” hadron allows for tagging transverse momenta, quark flavor as well as polarization
 - Collins effect allows for the study of quark-polarisation dependence of hadronization
 - previous charged-pion analyses supplemented with transverse-momentum dependence and analysis of neutral-pion and eta mesons in latest Belle Collins analysis
 - results for neutral & charged pions consistent
 - no significant difference between neutral pions and eta seen
 - re-analysis of unpolarized fragmentation
 - inclusion of alternative variable choices for two-hadron cross sections
 - updated ISR correction; now consistent ISR treatment in all Belle unpolarized Xsec's
 - non-trivial hadron and thrust dependent transverse momentum distributions
 - clearly non-zero transverse Λ -hyperon self-polarization at Belle [not shown here; cf. talk by Marco on Monday]