Sardinian Workshop on Spin Studies - Cagliari, July 8-10, 2019

Hadron production in electron-positron annihilation

highlights from the past five years

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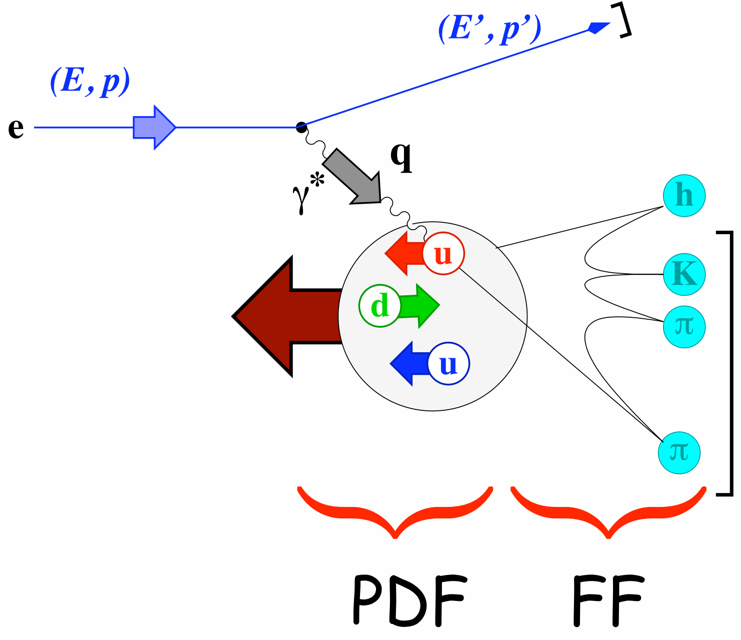
Probing parton dist's through fragmentation



quark pol.

nucleon pol.	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

in SIDIS*) couple PDFs to:

*) semi-inclusive DIS with unpolarized final state

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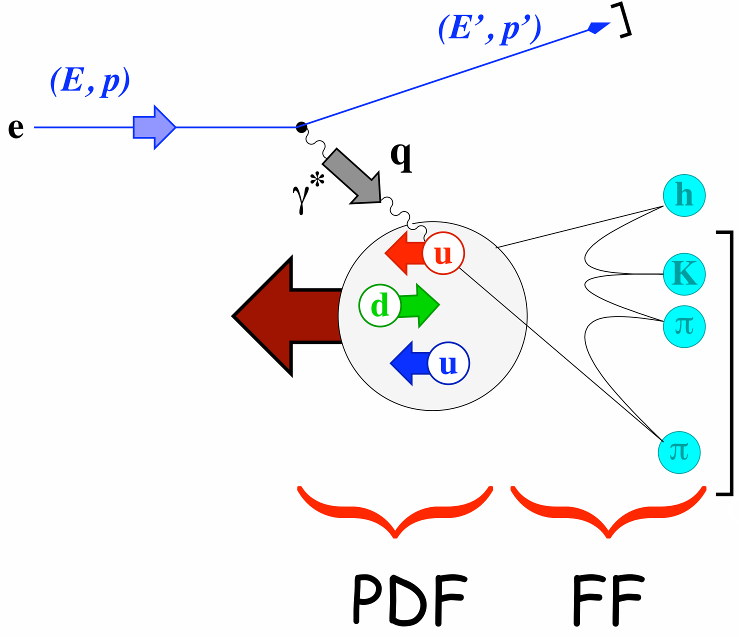

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in SIDIS*) couple PDFs to:

Collins FF: $H_1^{\perp,q\to h}$

DiFF: $H_1^{\angle,\,q\to h_1h_2}$

---

*) semi-inclusive DIS with unpolarized final state

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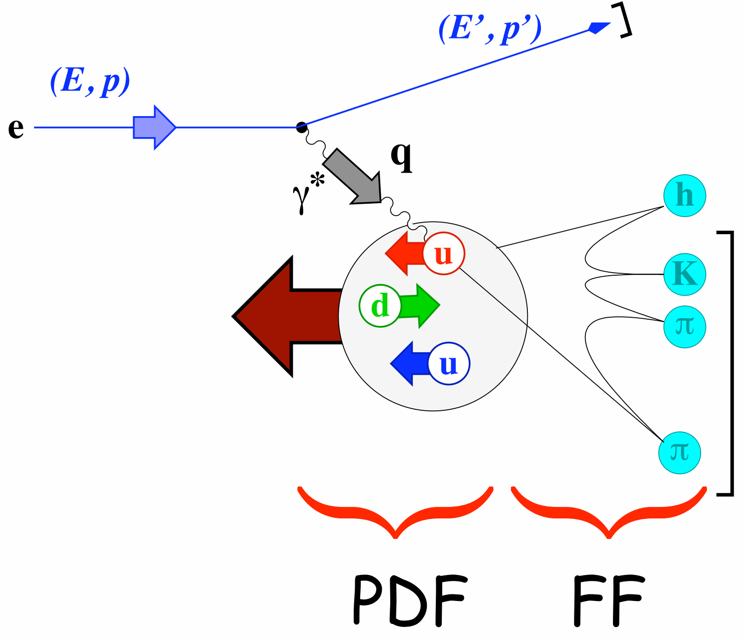

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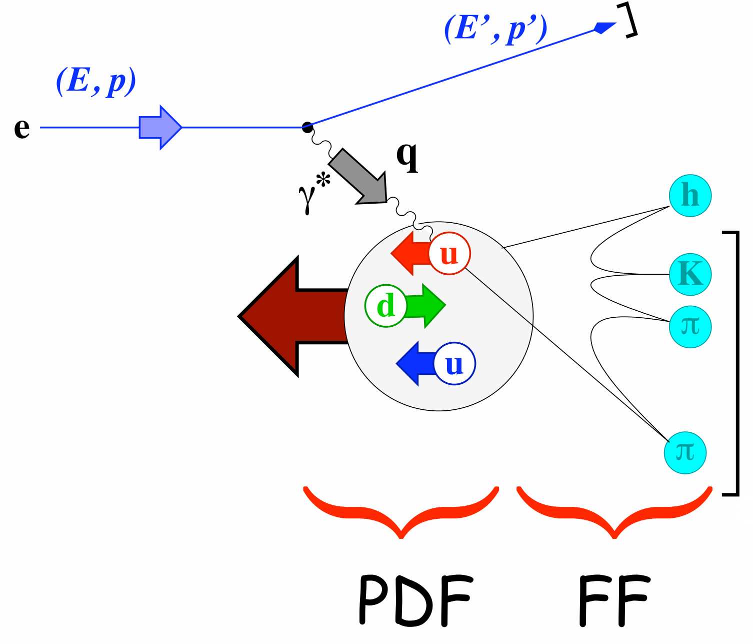

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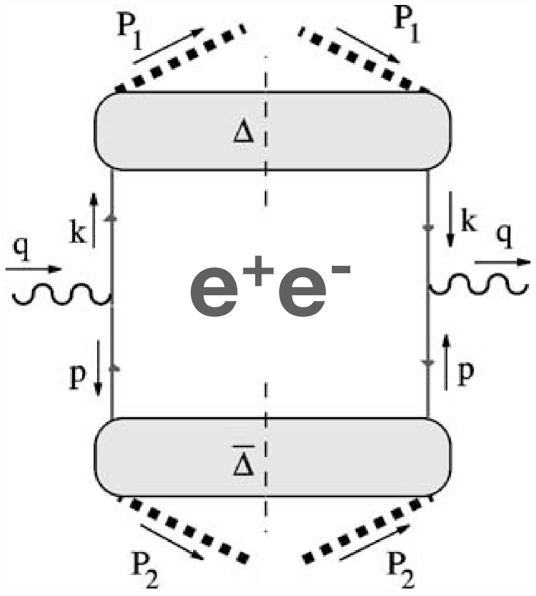
➟ FFs act as quark flavor-tagger and polarimeter

*) semi-inclusive DIS with unpolarized final state

fragmentation in e^+e^- annihilation

- single-inclusive hadron production, **$e^+e^- \rightarrow hX$**
  - D_1 fragmentation fctn.
  - $D_{1T}^{\perp}$ spontaneous transv. pol.



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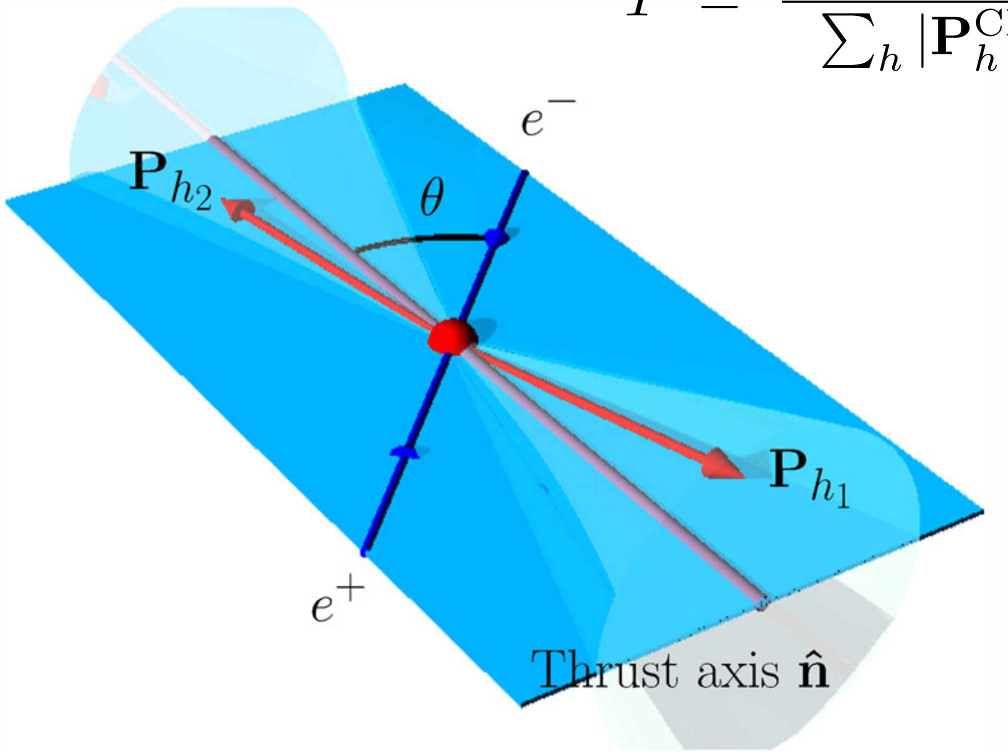
- inclusive “back-to-back” hadron pairs, **$e^+e^- \rightarrow h_1h_2X$**
  - product of FFs
  - flavor, transverse-momentum, and/or polarization tagging

Thrust (axis):

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



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- inclusive "back-to-back" hadron pairs, **$e^+e^- \rightarrow h_1h_2X$**
  - product of FFs
  - flavor, transverse-momentum, and/or polarization tagging
- inclusive same-hemisphere hadron pairs, **$e^+e^- \rightarrow h_1h_2X$**
  - dihadron fragmentation

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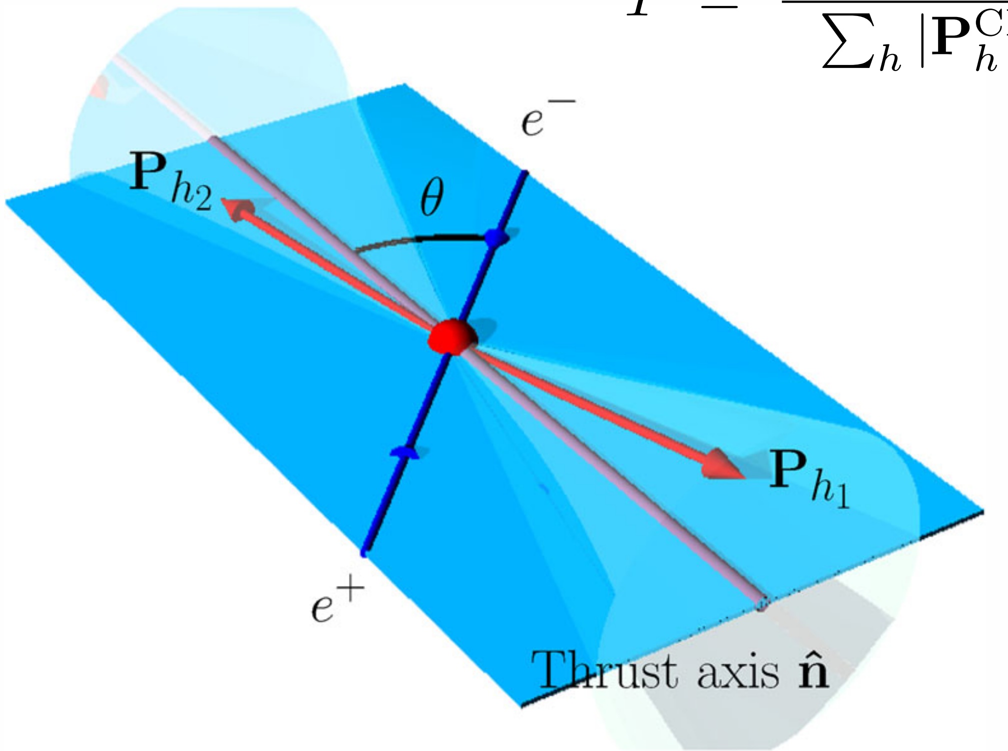
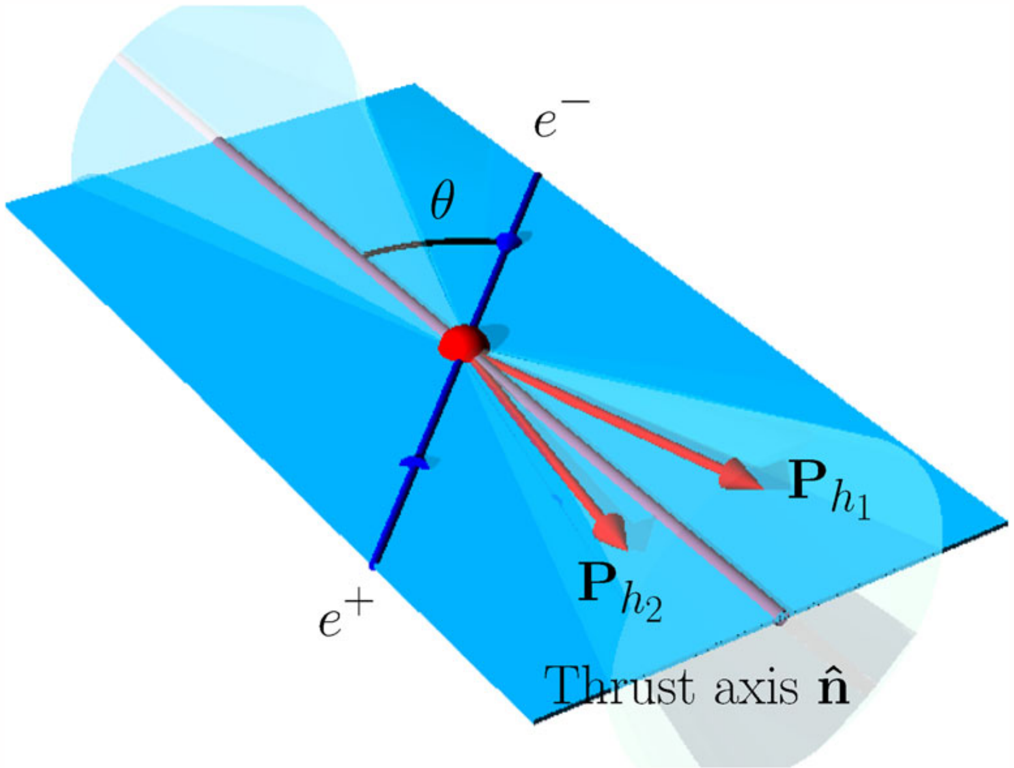


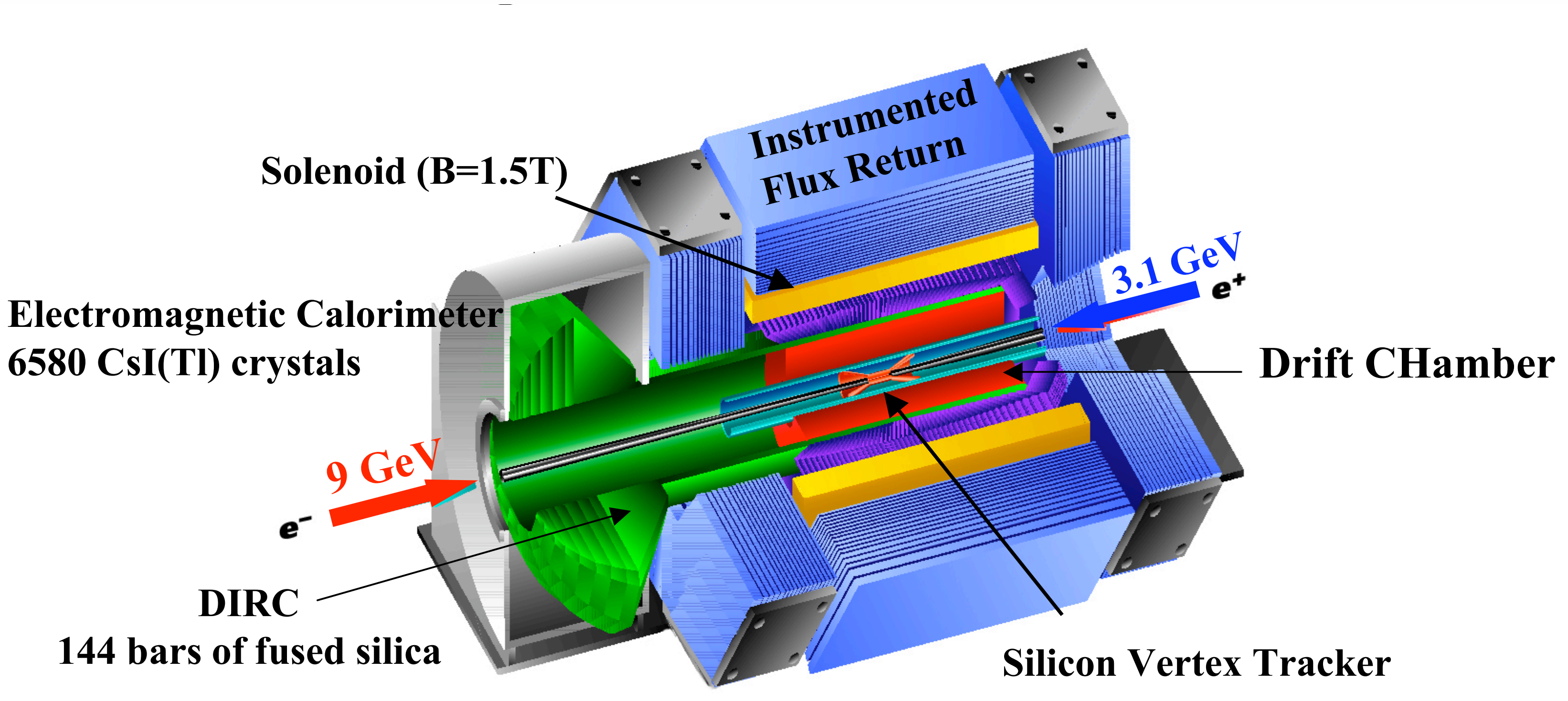


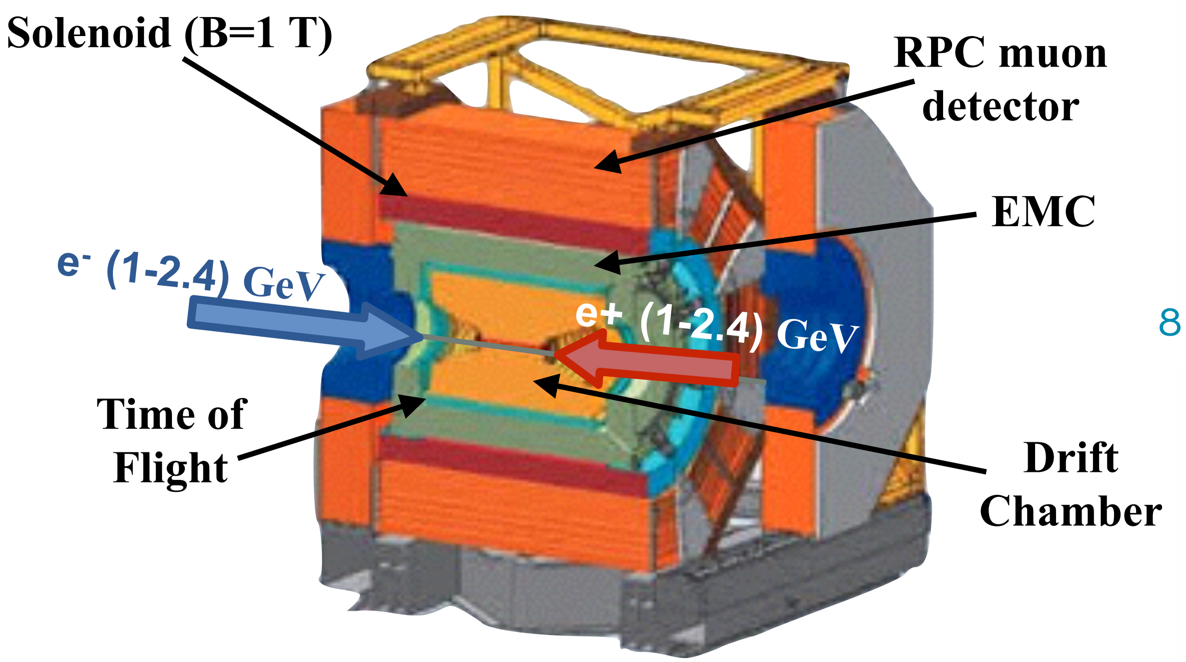
e^+e^- annihilation at BaBar, Belle, and BESIII

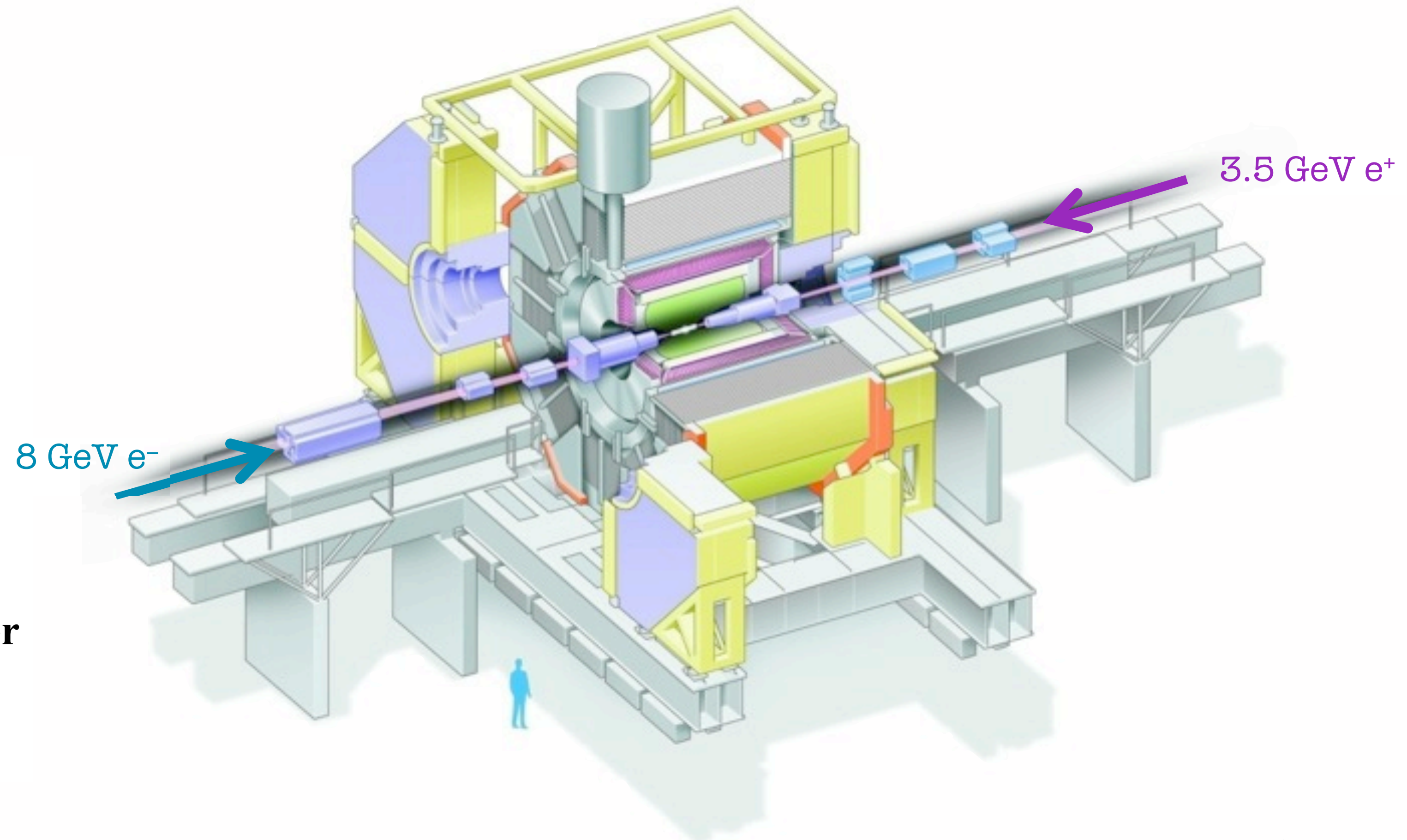
- BaBar/Belle: asymmetric beam-energy e^+e^- collider near/at $\Upsilon(4S)$ resonance

  (10.58 GeV)

- BESIII: symmetric collider with E_e=1...2.4 GeV







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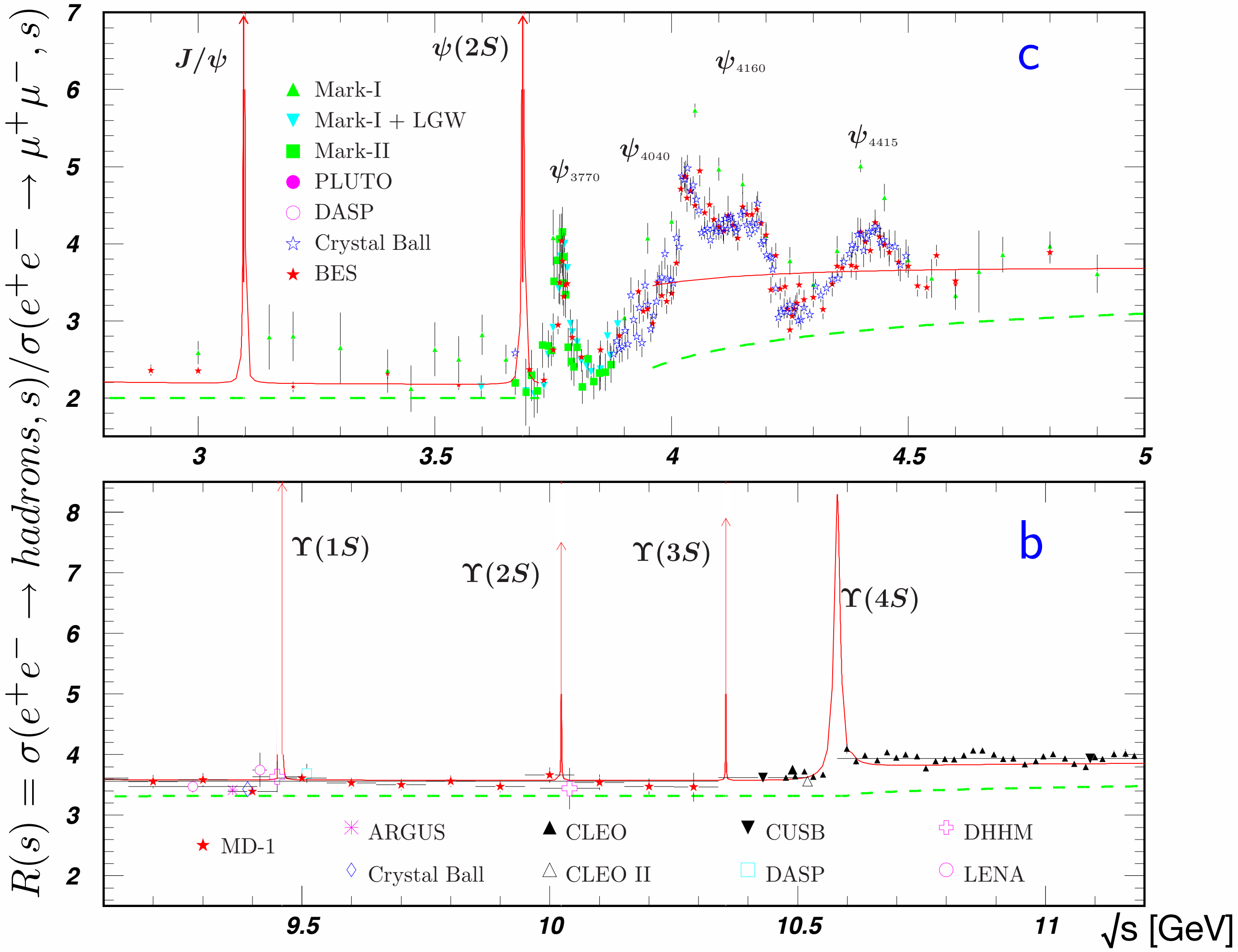
- integrated luminosities:



	ϒ(4S) on resonance	ϒ(4S) off resonance	other
BaBar	424.2 fb^{-1}	43.9 fb^{-1}	
Belle	(140+571) fb^{-1}	(15.6+73.8) fb^{-1}	~180 fb^{-1} @ϒ(nS)
BESIII			~62 pb^{-1} @3.65 GeV *)

*) used for the Collins analysis presented here

from hadron yields to cross sections

- hadron yields undergo series of corrections
  - particle (mis)identification [e.g., not every identified pion was a pion]
  - smearing unfolding [e.g., measured and true momentum might differ]
  - non-$q\bar{q}$ processes [e.g., two-photon processes, Υ -> BB, ...]
  - "4π" correction [selection criteria and limited geometric acceptance]
  - QED radiation [initial-state radiation (ISR)]
  - optional: weak-decay removal (e.g., "prompt fragmentation")

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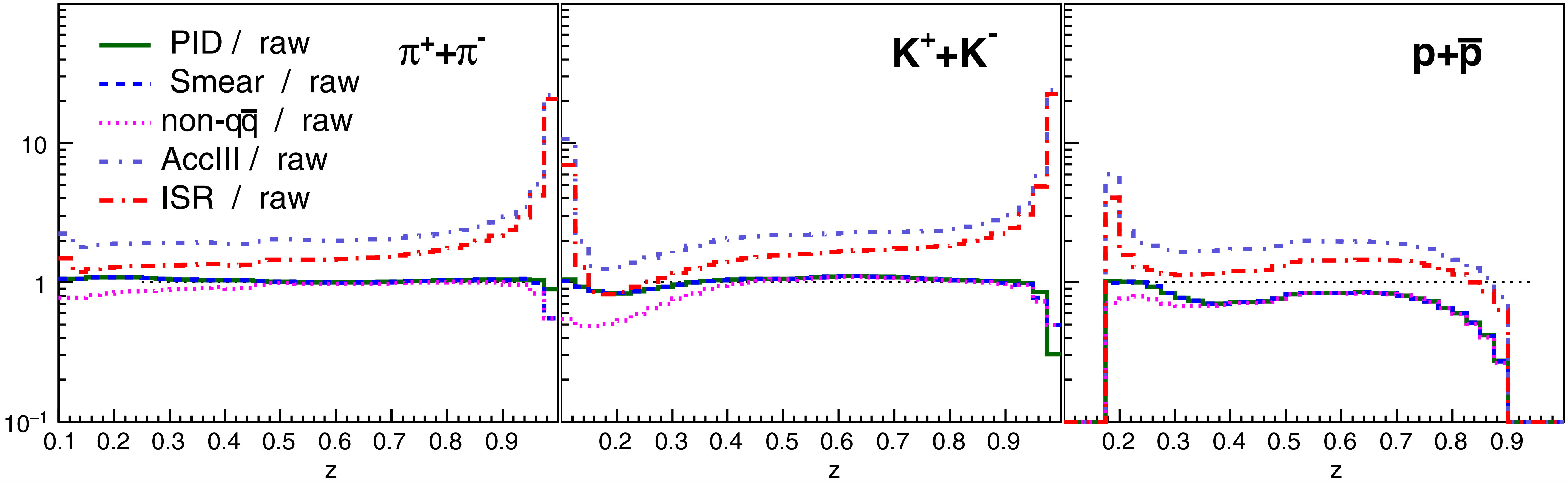
- Collins asymmetries also corrected for false asymmetries and maybe for $q\bar{q}$-axis (mis)reconstruction
- partially different approaches in different experiments/analyses

from hadron yields to cross sections

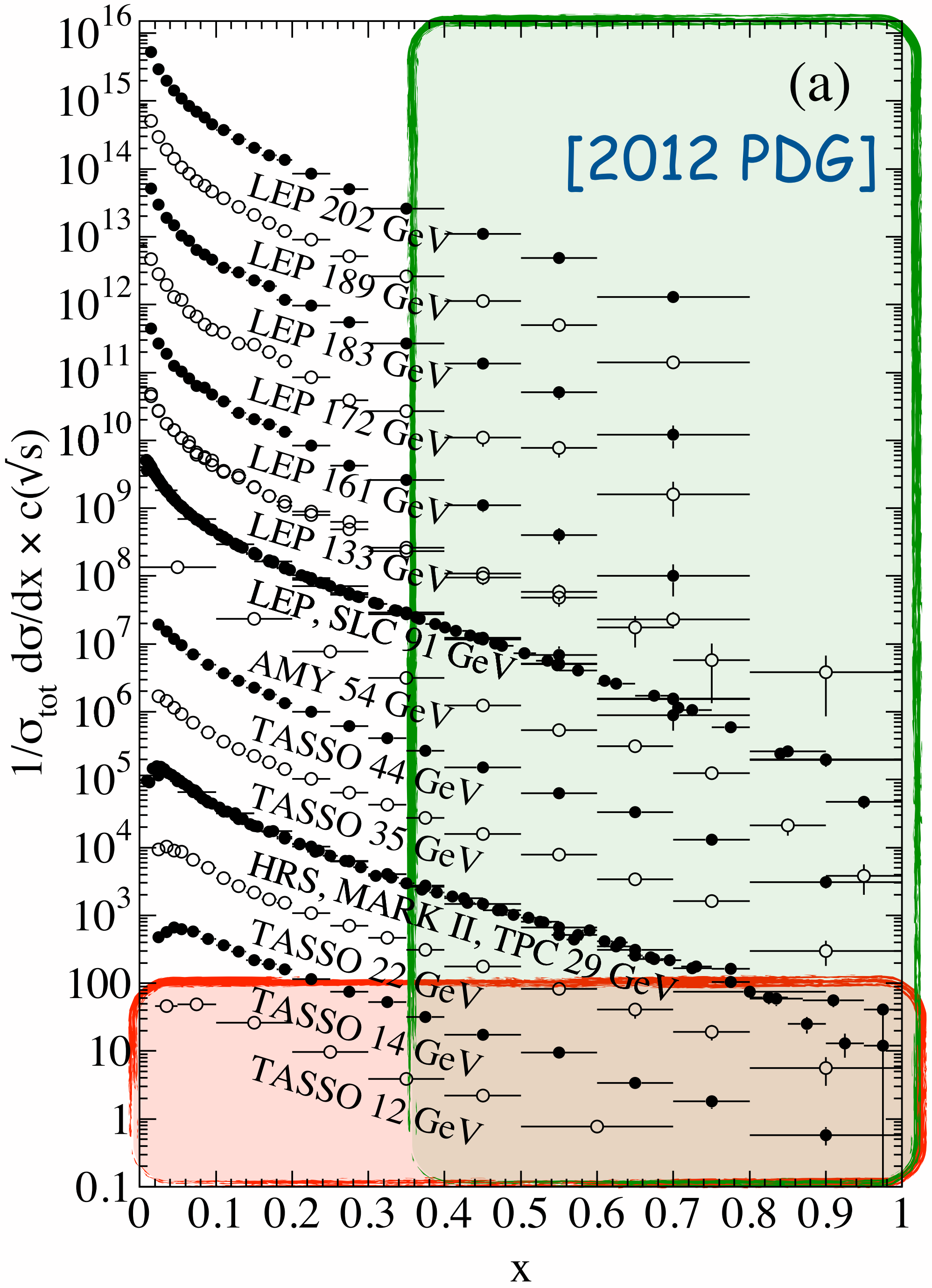
- **example**: single-hadron inclusive cross sections
  - cumulative effect of correction steps



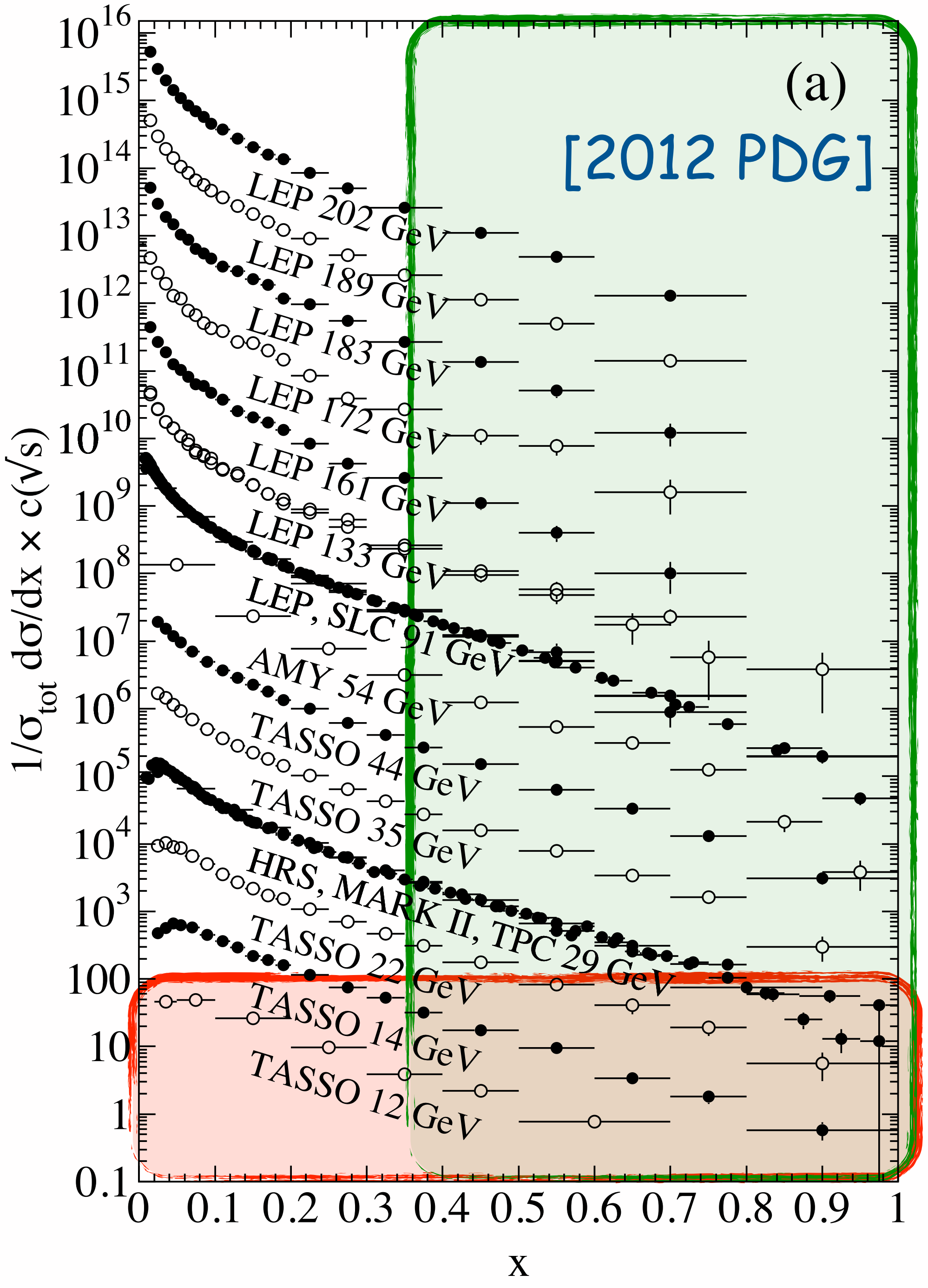
  - largest effect for mesons from acceptance and ISR correction
  - larger PID correction for protons than for mesons

single-hadron production

- before 2013: lack of precision data at (moderately) high z and at low √s
  - limits analysis of evolution and gluon fragmentation
  - limited information in kinematic region often used in semi-inclusive DIS



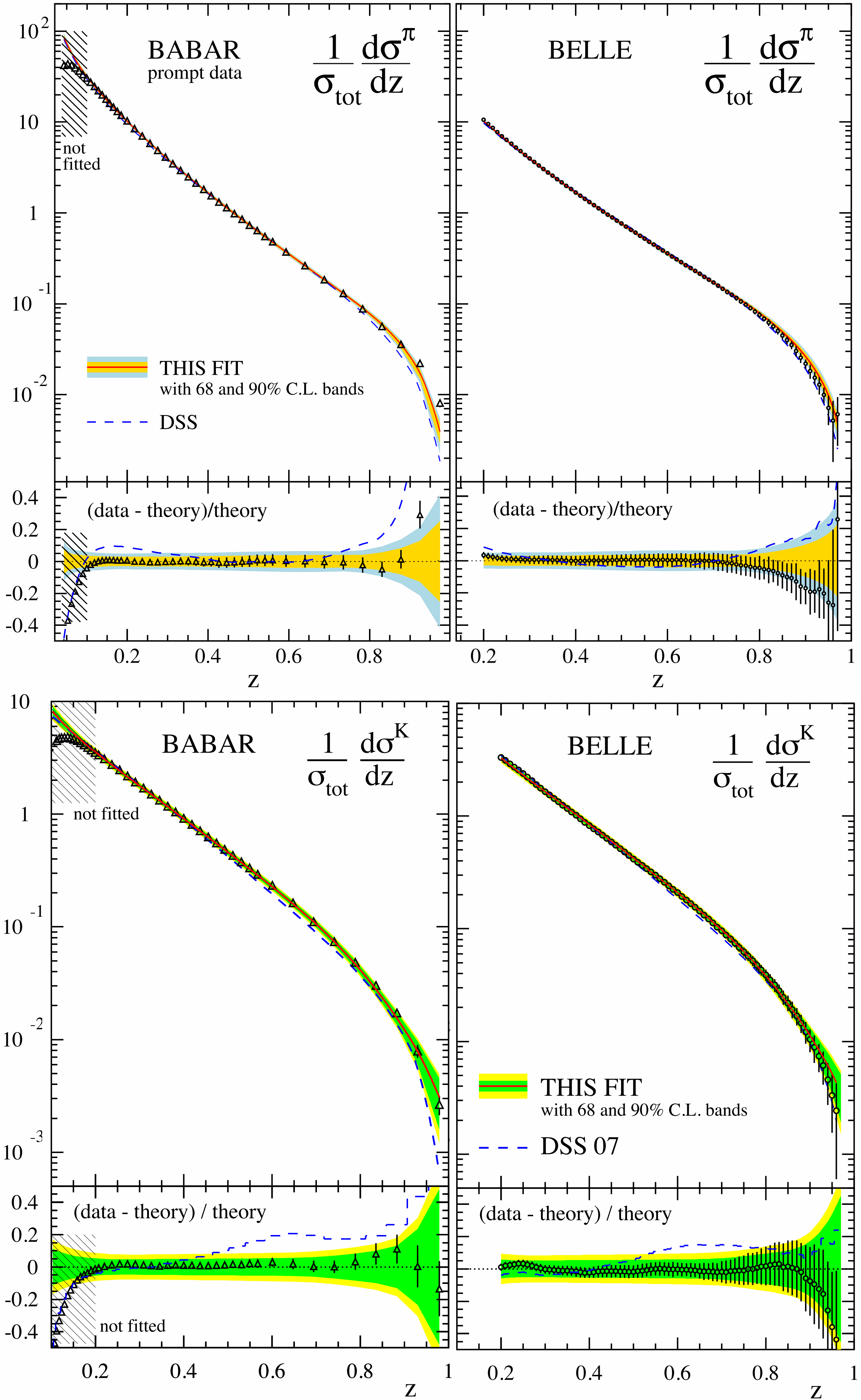
single-hadron production



- before 2013: lack of precision data at (moderately) high z and at low √s
  - limits analysis of evolution and gluon fragmentation
  - limited information in kinematic region often used in semi-inclusive DIS
- by now also results from BaBar and Belle:
  - BaBar Collaboration, Phys. Rev. D88 (2013) 032011: **π±, K±, p+p**
  - Belle Collaboration, Phys. Rev. Lett. 111 (2013) 062002: **π±, K±**
  - Belle Collaboration, Phys. Rev. D92 (2015) 092007: **π±, K±, p+p**

single-hadron production

- very precise data for charged pions and kaons
- Belle data available up to very large z (z<0.98)
- included in recent DEHSS fits
    - slight tension at low-z for BaBar and high-z for Belle



single-hadron production

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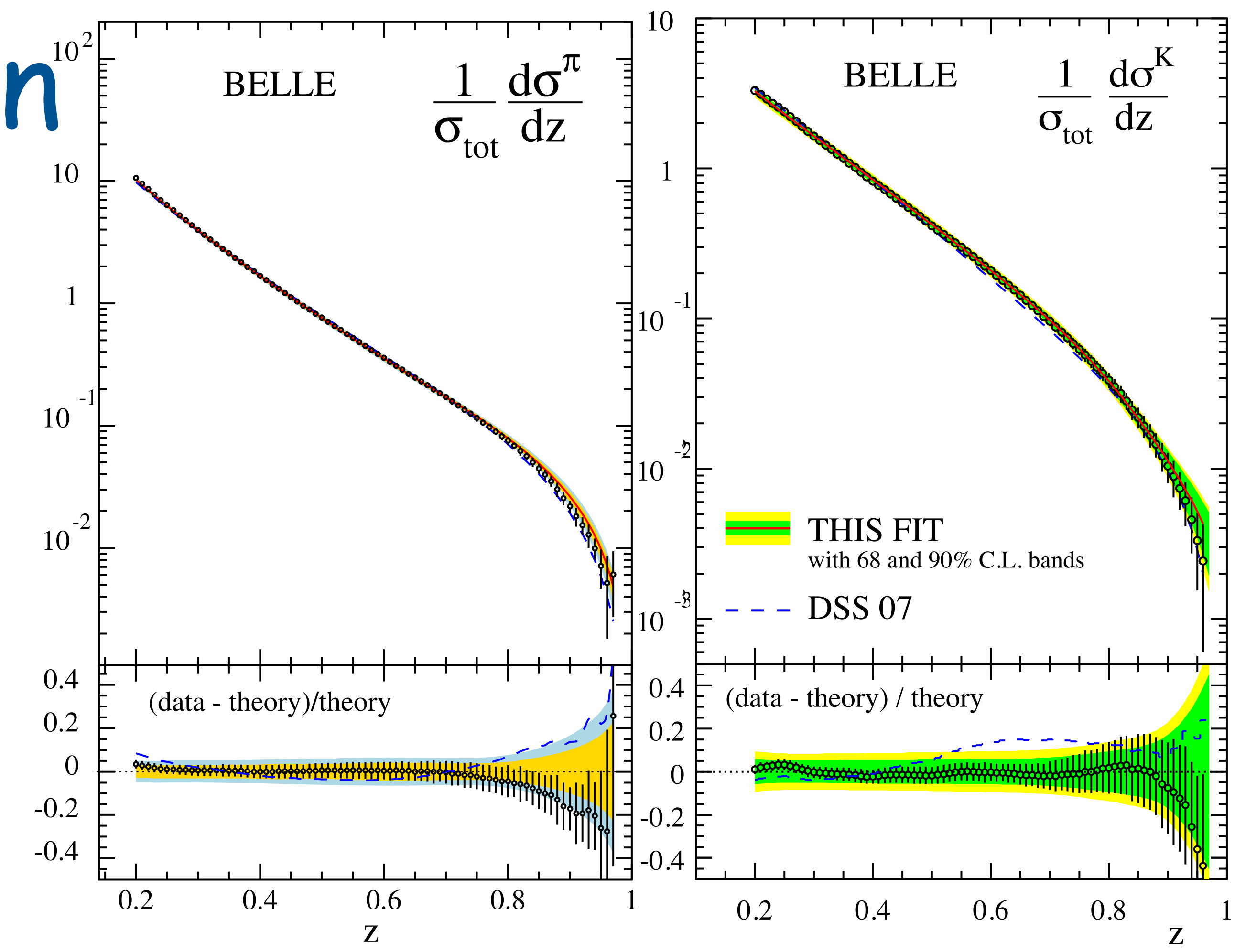
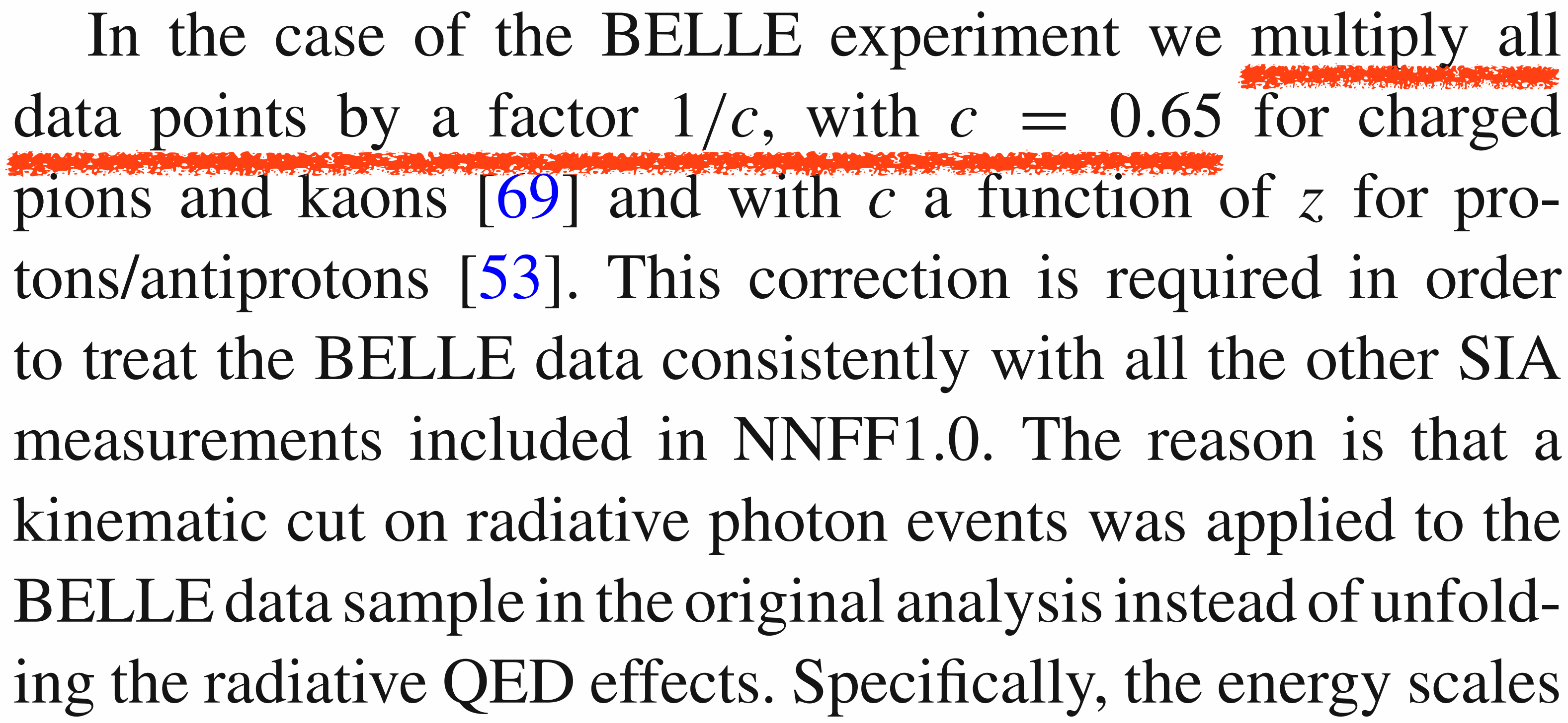
- included in recent DEHSS fits [e.g. PRD 91, 014035 (2015)]
- Belle radiative corrections “**undone**” in FF fits



[EPJC 77 (2017) 516, NNFF1.0]



In the case of the BELLE experiment we multiply all data points by a factor $1/c$, with $c = 0.65$ for charged pions and kaons [69] and with c a function of z for protons/antiprotons [53]. This correction is required in order to treat the BELLE data consistently with all the other SIA measurements included in NNFF1.0. The reason is that a kinematic cut on radiative photon events was applied to the BELLE data sample in the original analysis instead of unfolding the radiative QED effects. Specifically, the energy scales

single-hadron production

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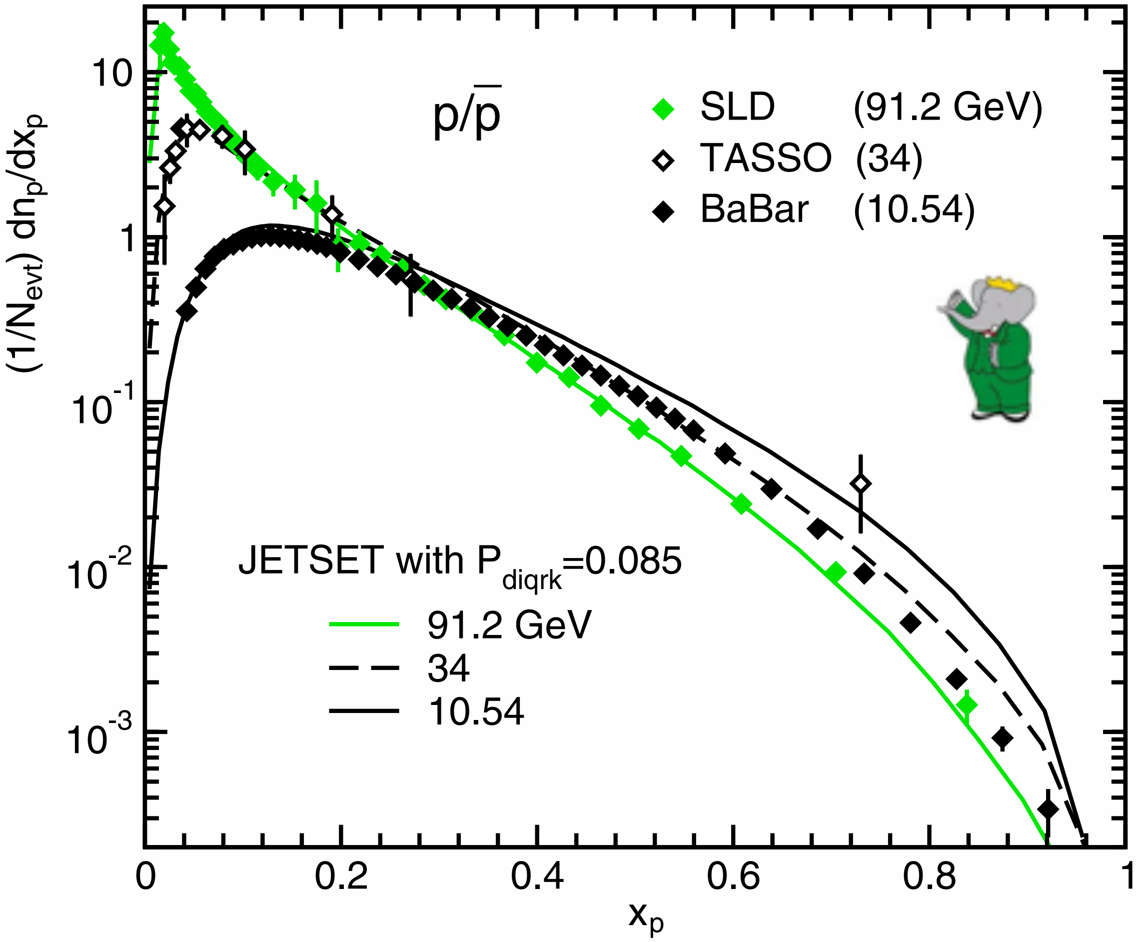
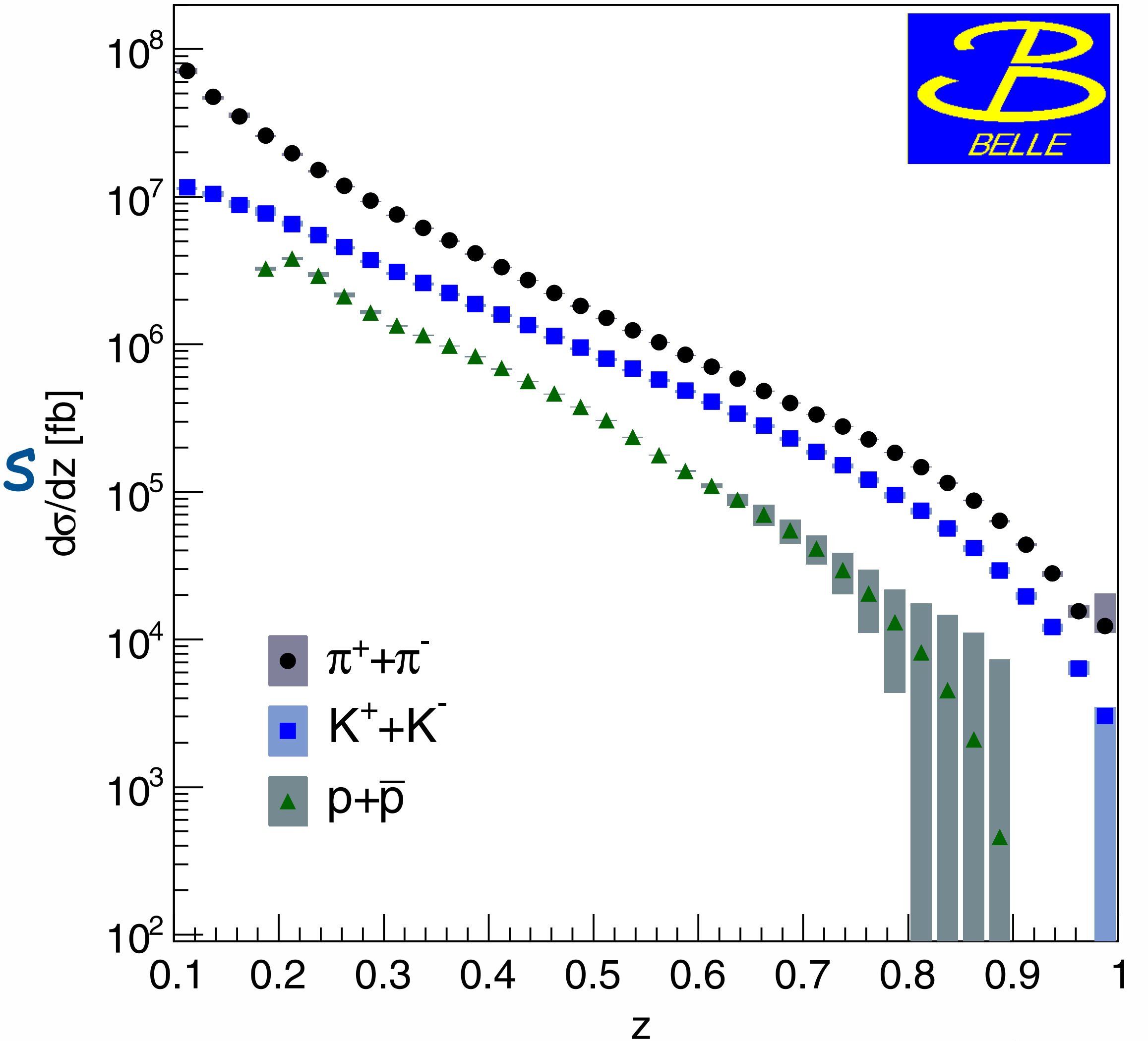
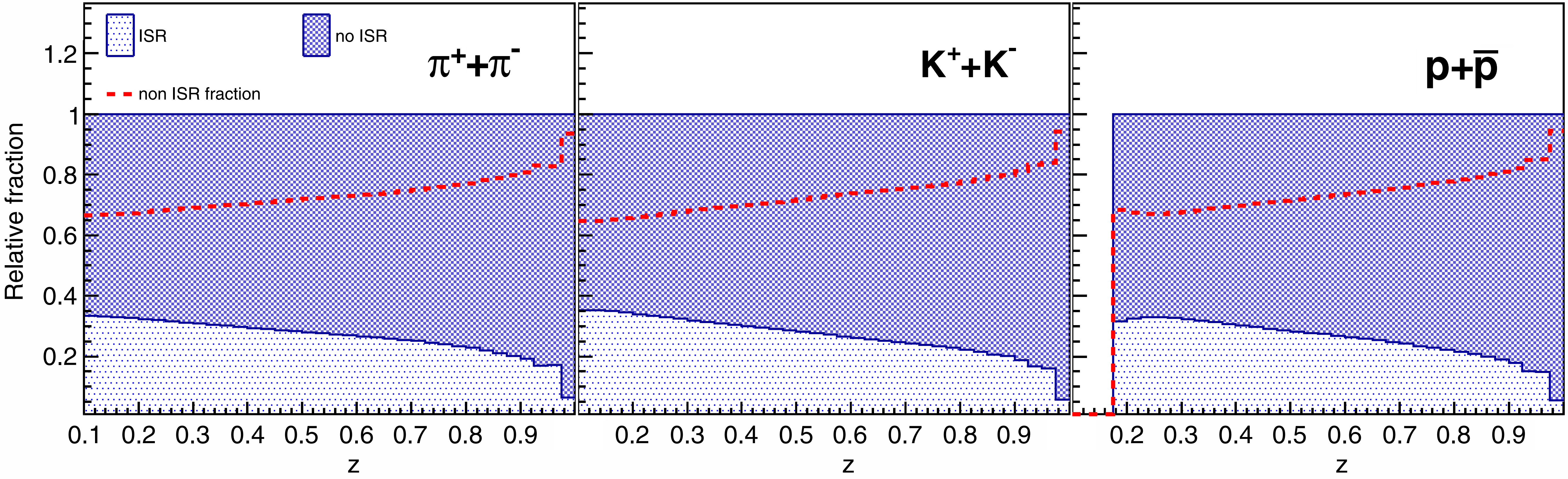
- included in recent DEHSS fits [e.g. PRD 91, 014035 (2015)]
- Belle radiative corrections "**undone**" in FF fits
- **Belle** data for protons and anti-protons
  - not (yet) included in DEHSS, but in NNFF 1.0 [EPJC 77 (2017) 516]
  - similar z dependence as pions
  - about ~⅕ of pion cross sections





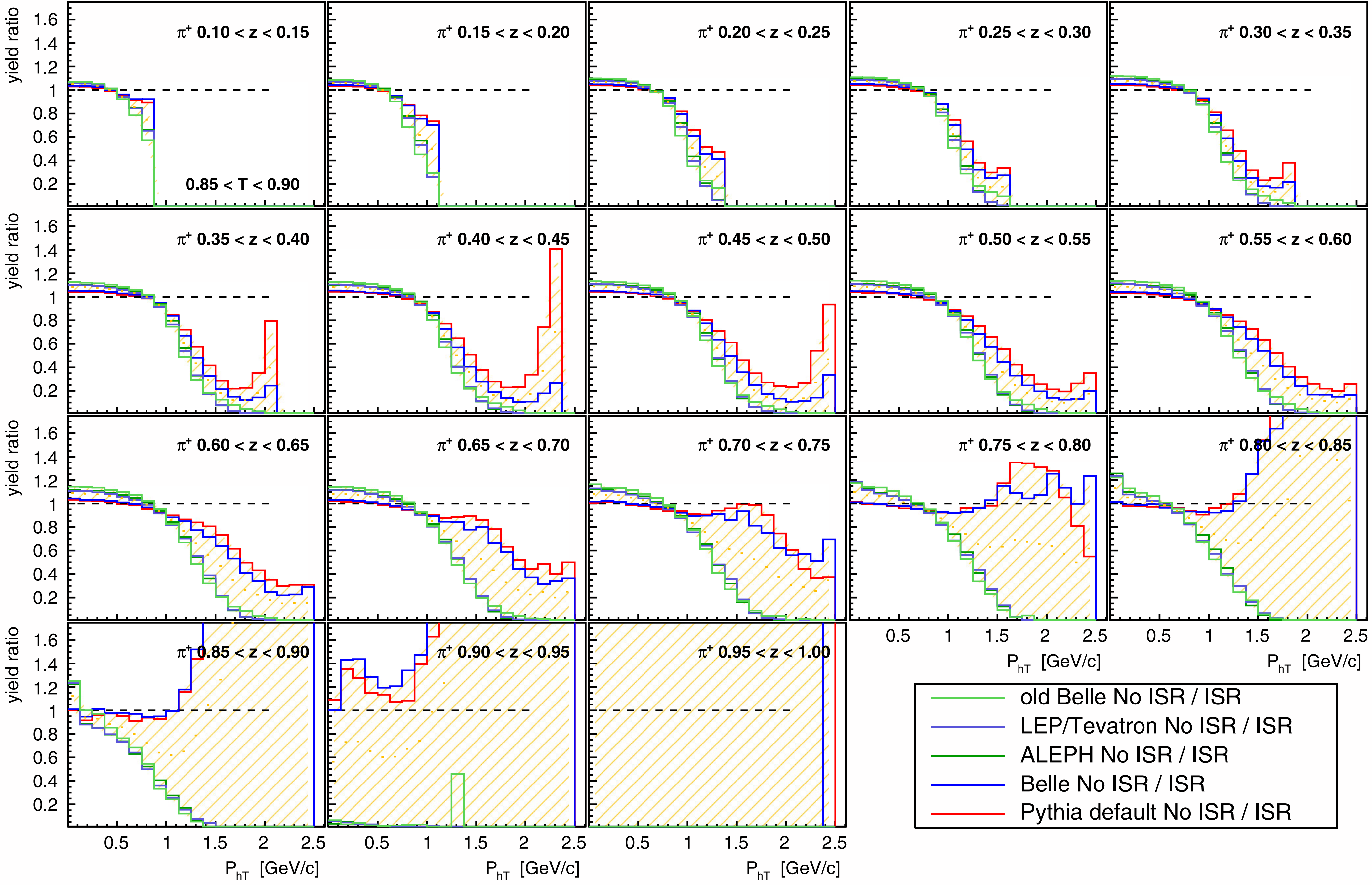
ISR corrections - PRD92 (2015) 092007



- relative fractions of hadrons as a function of z originating from ISR or non-ISR events (≡ energy loss less than 0.5%)
  - large non-ISR fraction at large z, as otherwise not kinematically reachable (remember $z = E_h / 0.5\sqrt{s_{nominal}}$)
  - keep only fraction of events w/o initial-state photon emission -> strictly speaking not single-inclusive annihilation

ISR corrections - PRD99 (2019) 112006

[PRD 99 (2019) 112006]

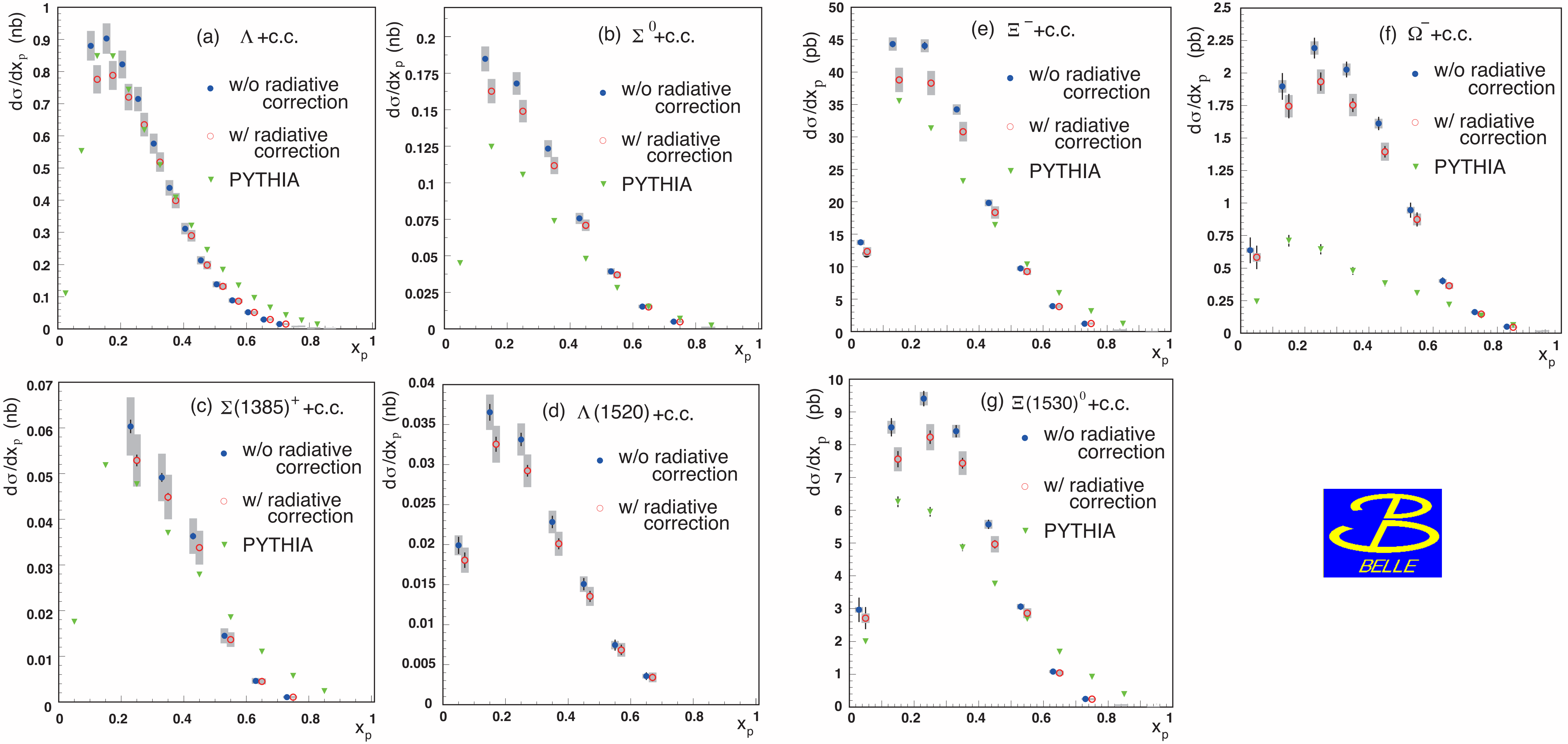


- non-ISR / ISR fractions based on PYTHIA switch MSTP(11)
  [e.g., for transverse-momentum dependence of incl. hadron production]

- PYTHIA model dependence; absorbed in systematics by variation of tunes

inclusive hyperon production

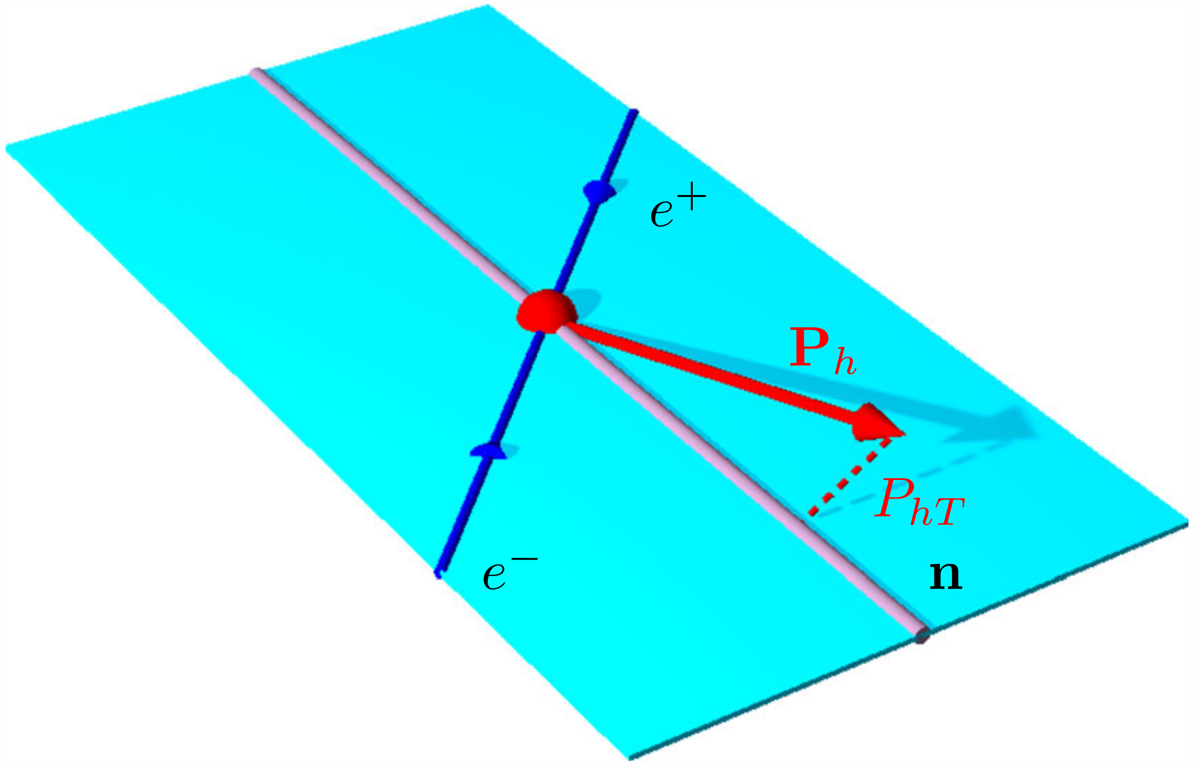
[PRD 97 (2018) 072005]



- Λ production reasonably well described by Pythia
- less satisfactory for heavier hyperons
- fails to describe Ω^- production

inclusive hadrons - transverse momentum

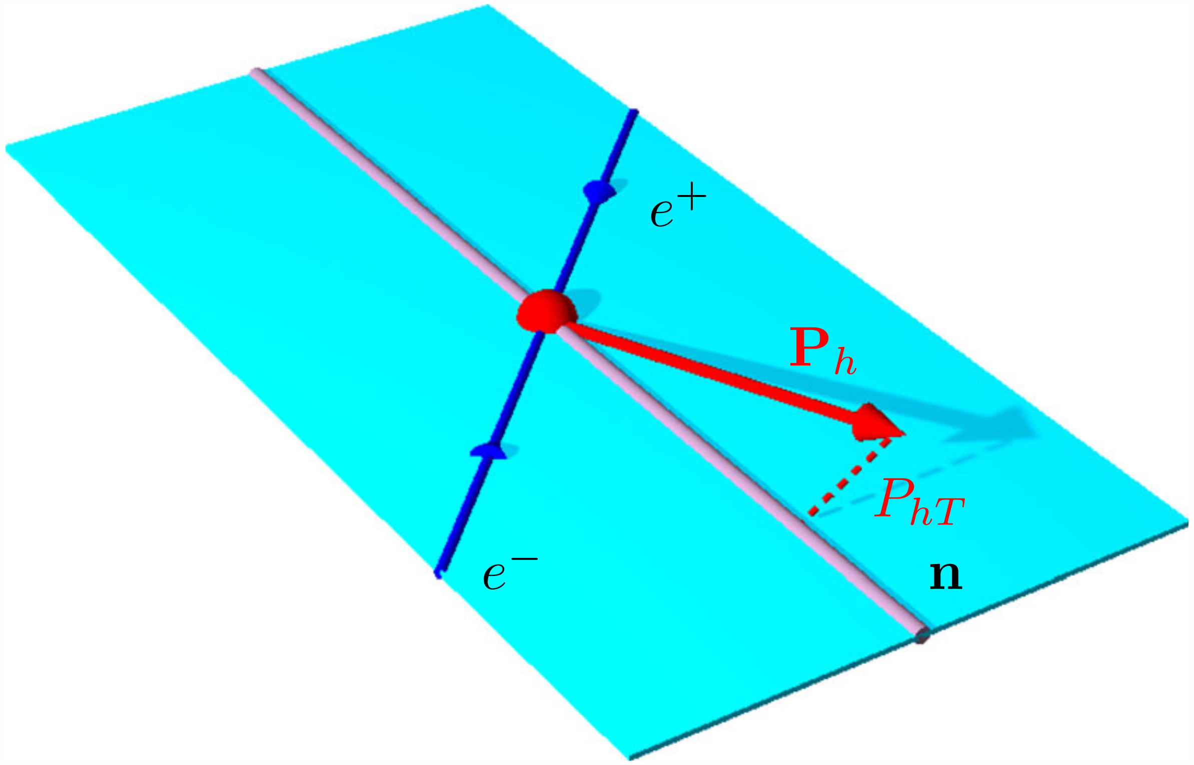
- quasi-inclusive hadron production gives access to transverse momentum in fragmentation
- transverse momentum measured with respect to thrust axis n
  - involves sum over all final-state particles in event
  - event selection and hadron distributions dependent on thrust value T required
    - low thrust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



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

inclusive hadrons - transverse momentum

- quasi-inclusive hadron production gives access to transverse momentum in fragmentation
- transverse momentum measured with respect to thrust axis n
- analysis performed differential in z and P_{hT} in various slices in T (18x20x6 bins)
- correction steps similar as for P_{hT}-integrated cross sections (using the "MSTP(11) radiative corrections")
- Gaussian fit to transverse-momentum distribution provided for all hadrons in (z,T)-bins



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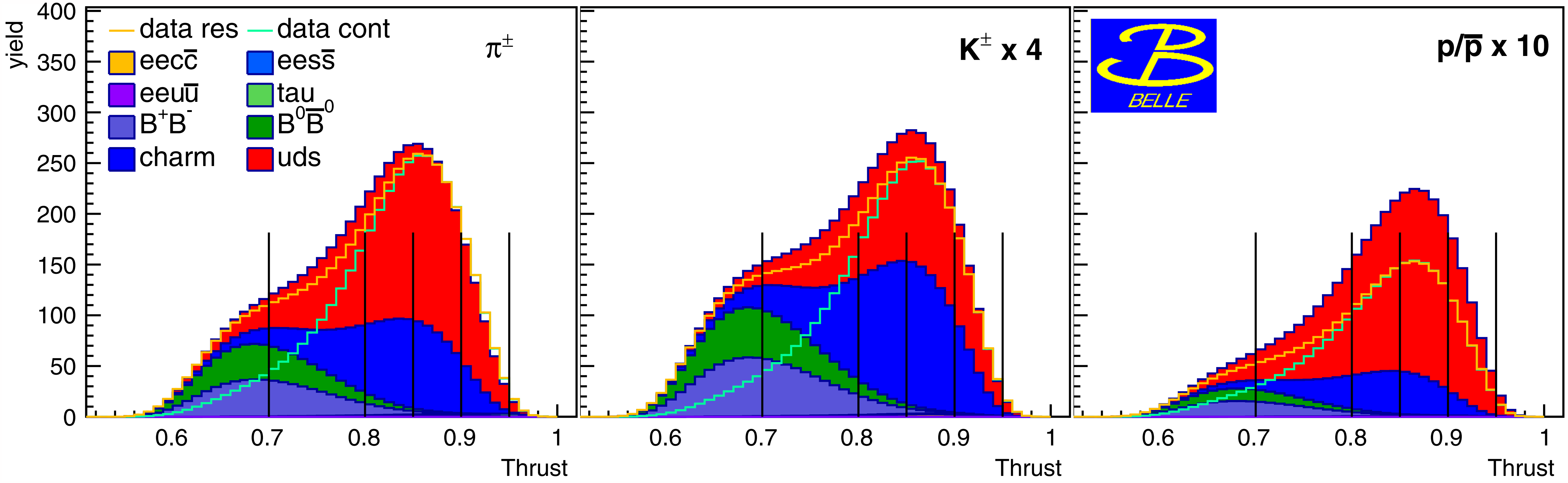
thrust distribution: process contributions

[Belle, PRD 99 (2019) 112006]

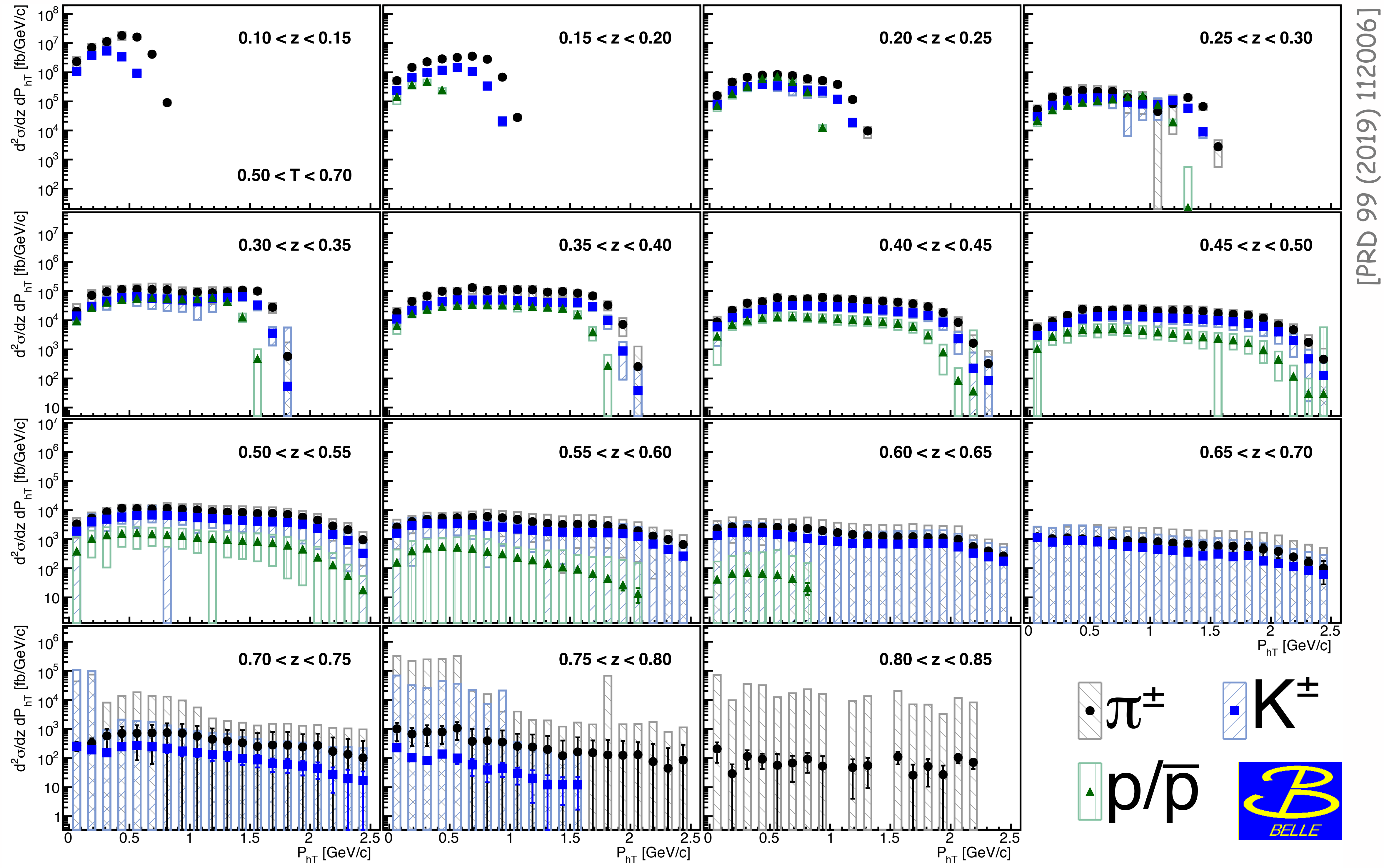


- large contribution from BB at lower thrust

- large thrust dominated by uds and charm fragmentation
  (at very large T significant τ contribution for pions, not visible here)

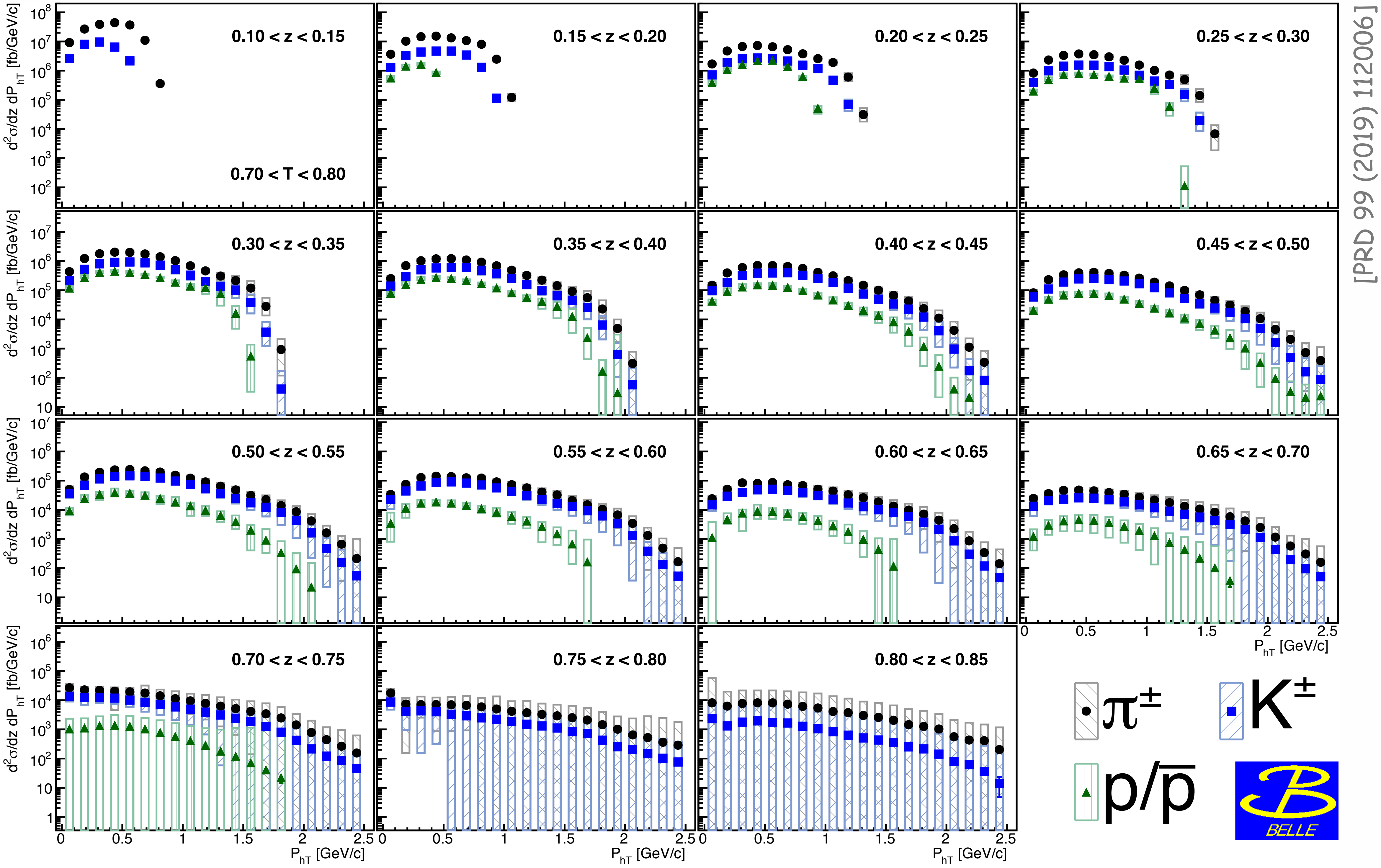
  - concentrate mainly on 0.85<T<0.9 bin, though others available as well

transverse-momentum distributions



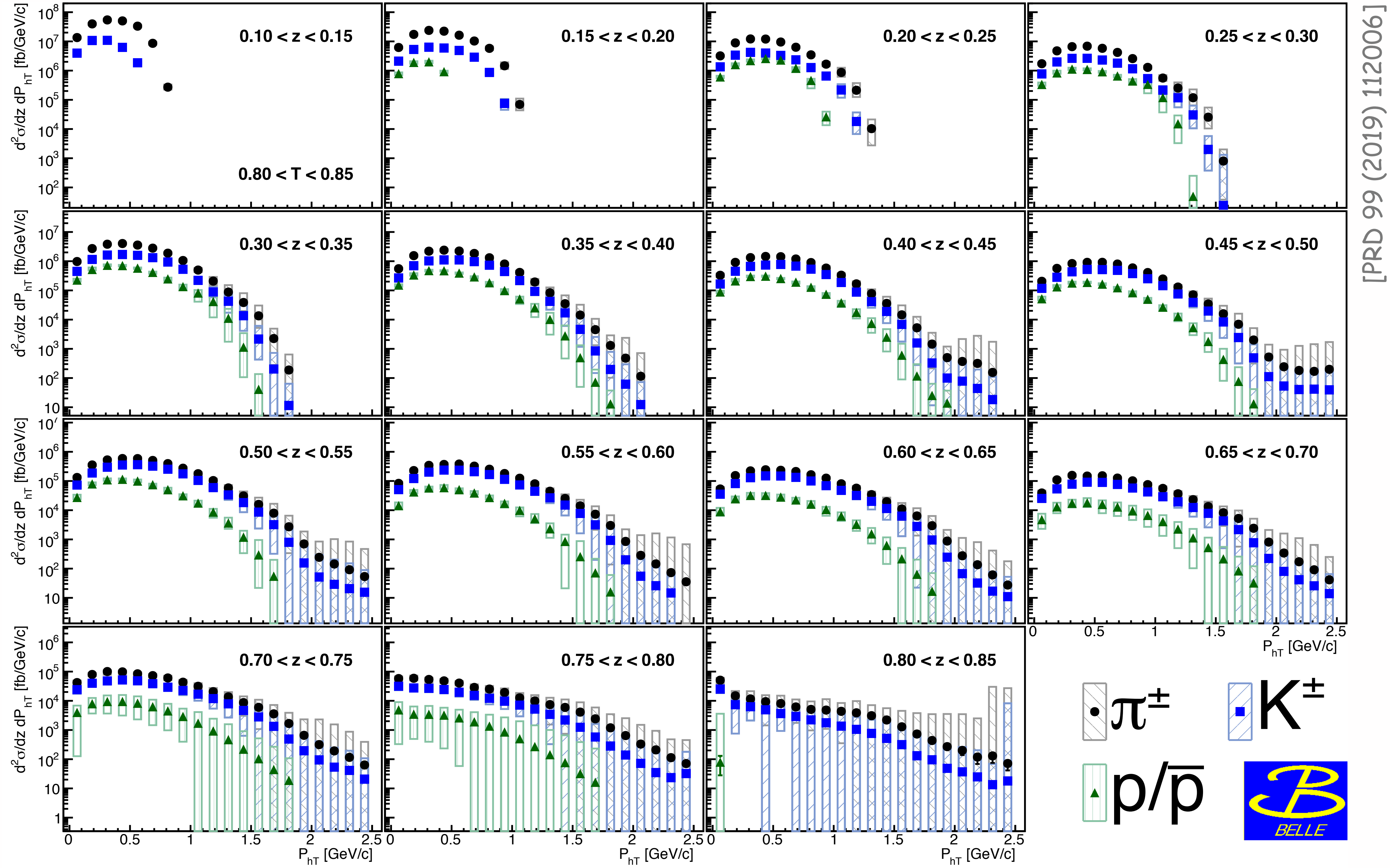
- lowest T bin -> rather spherical events
  - transverse momenta almost uniformly distributed in medium-z bins
  - faster drop for heavier hadrons

transverse-momentum distributions



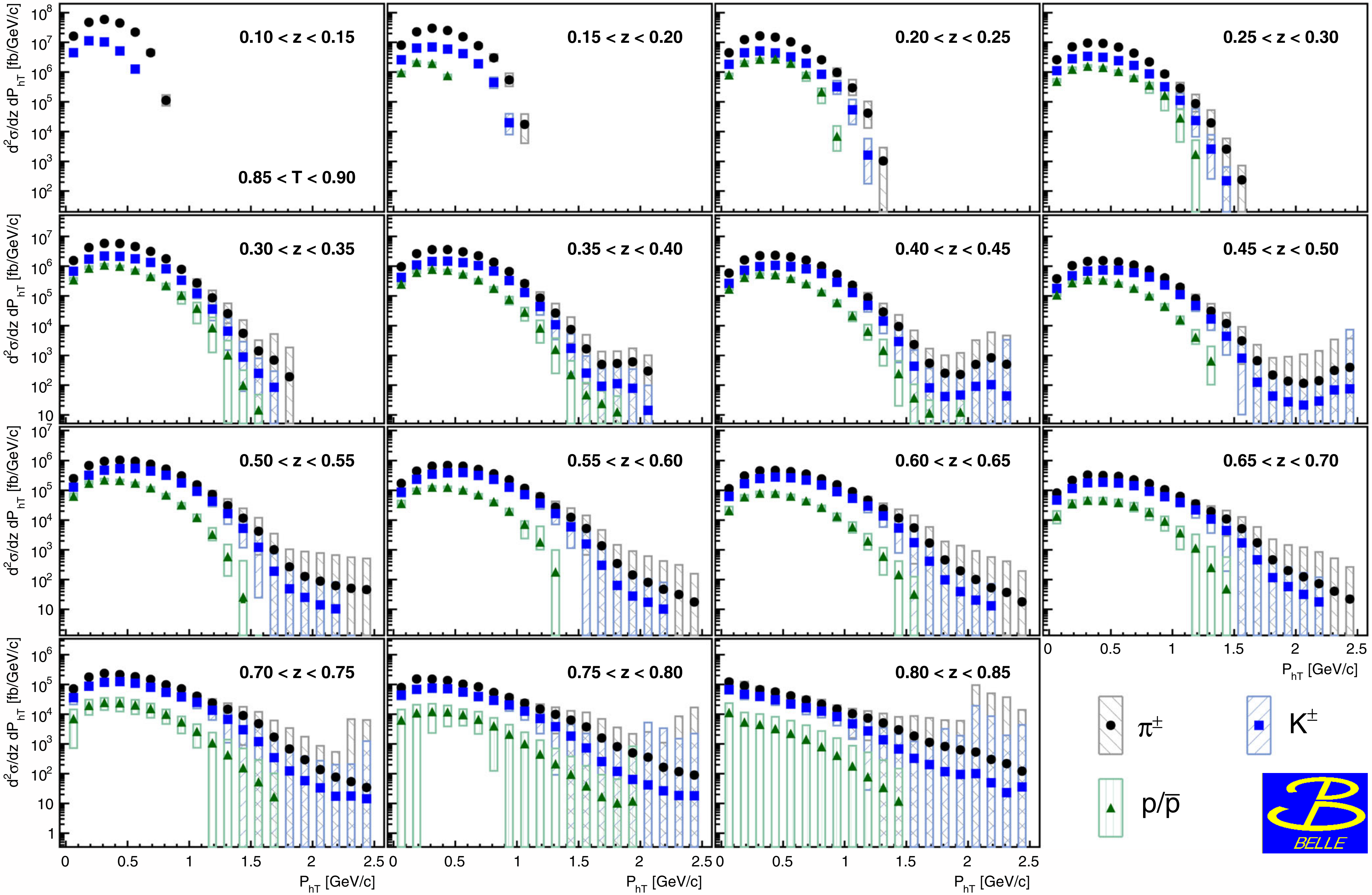
- 0.7 < T < 0.8 -> particles already more collimated
  - transverse momenta already more Gaussian distributed
- large-z region with large uncertainties

transverse-momentum distributions



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

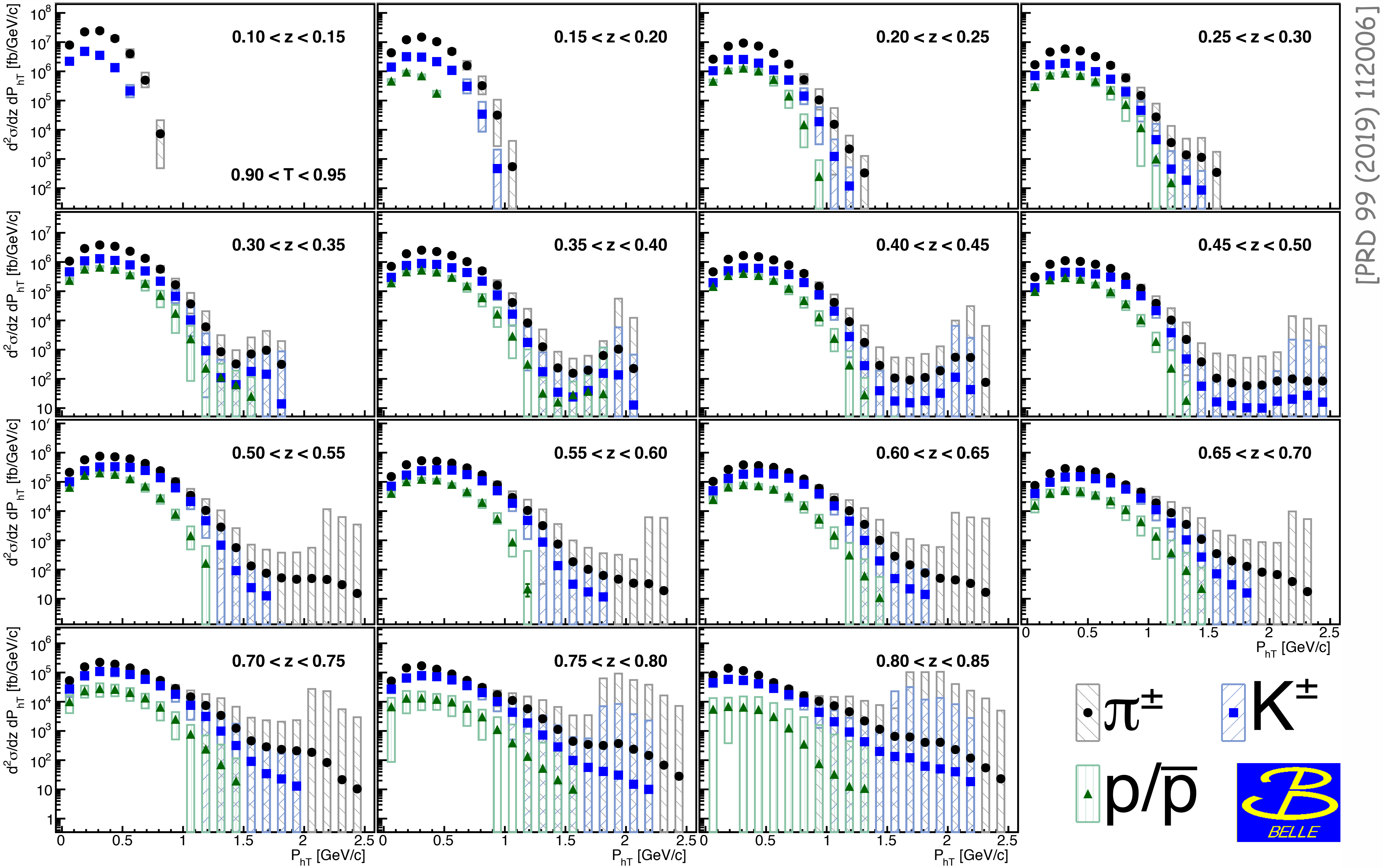
transverse-momentum distributions



[PRD 99 (2019) 112006]

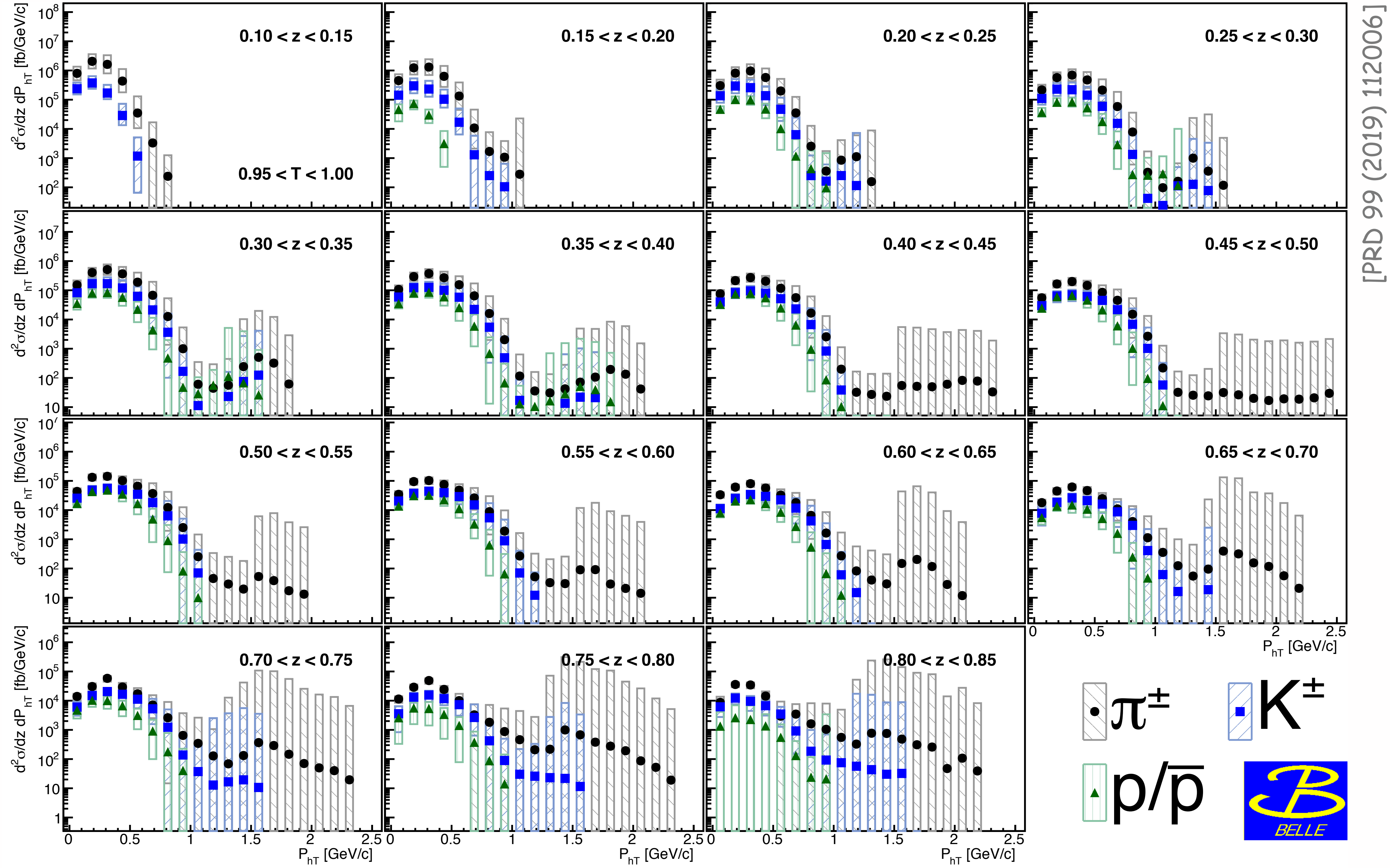
- 0.85 < T < 0.9
  - transverse momenta mostly Gaussian distributed; widths narrowing
  - possible deviations for large-P_{hT} tails [but also larger uncertainties]

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]

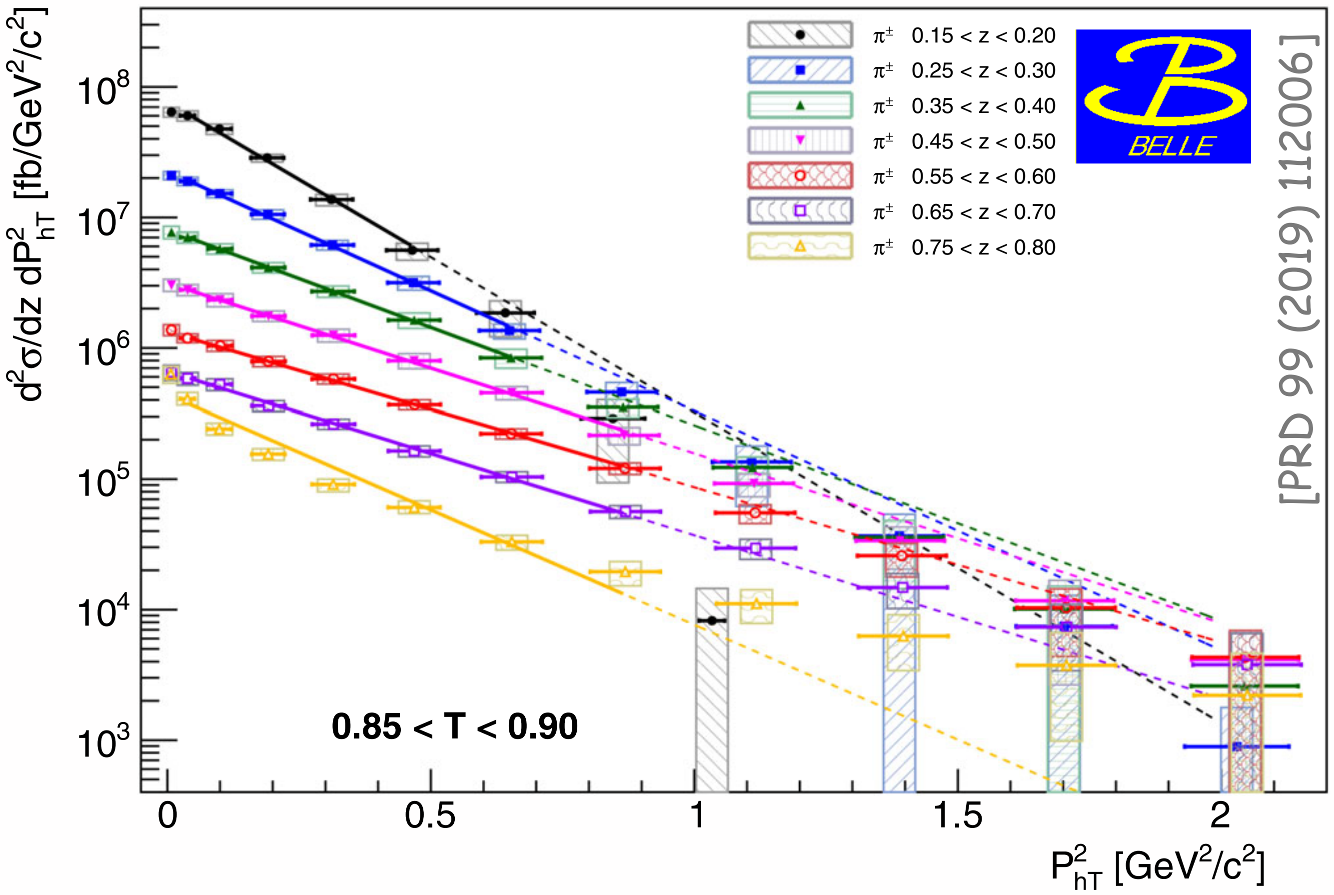
transverse-momentum distributions



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

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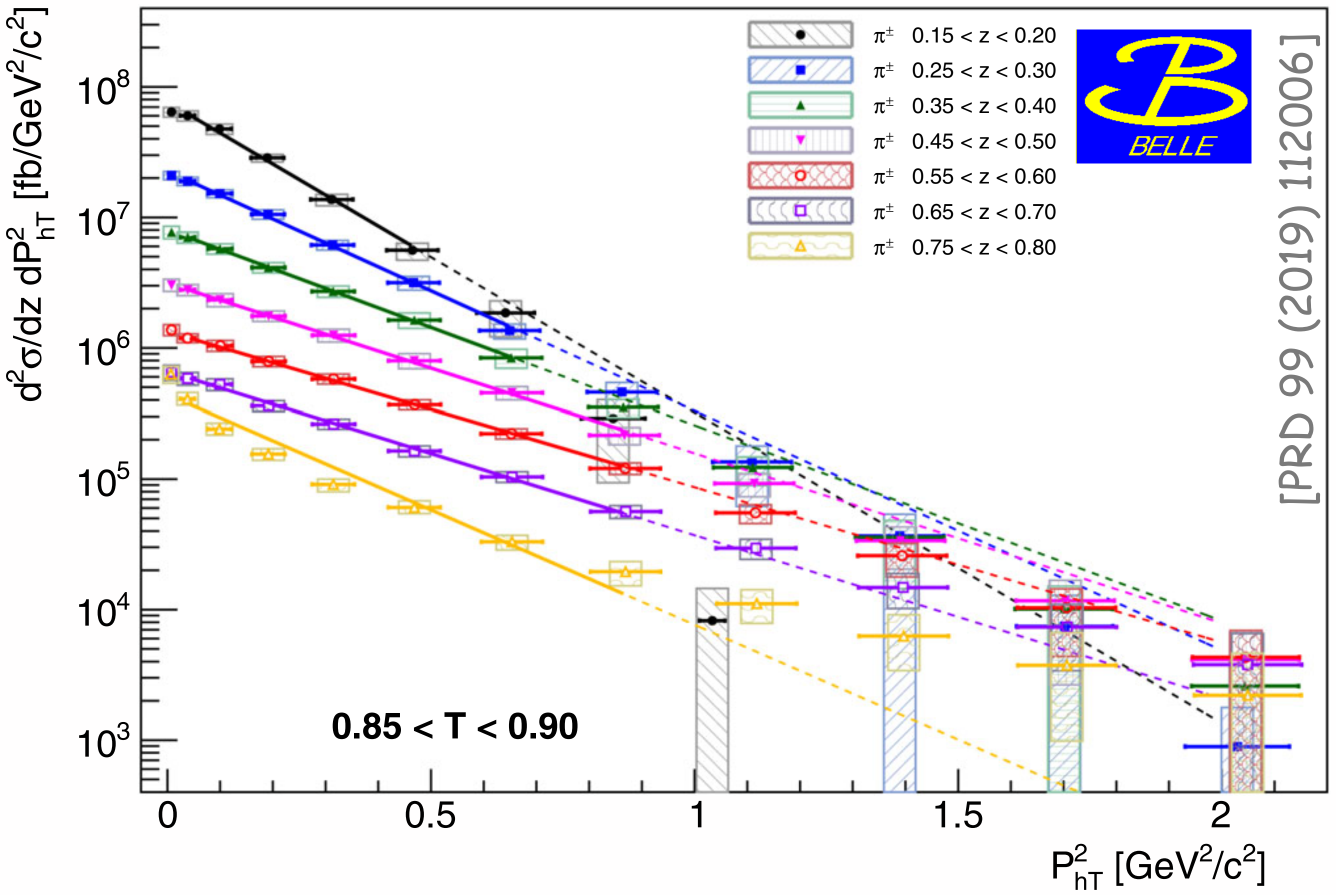
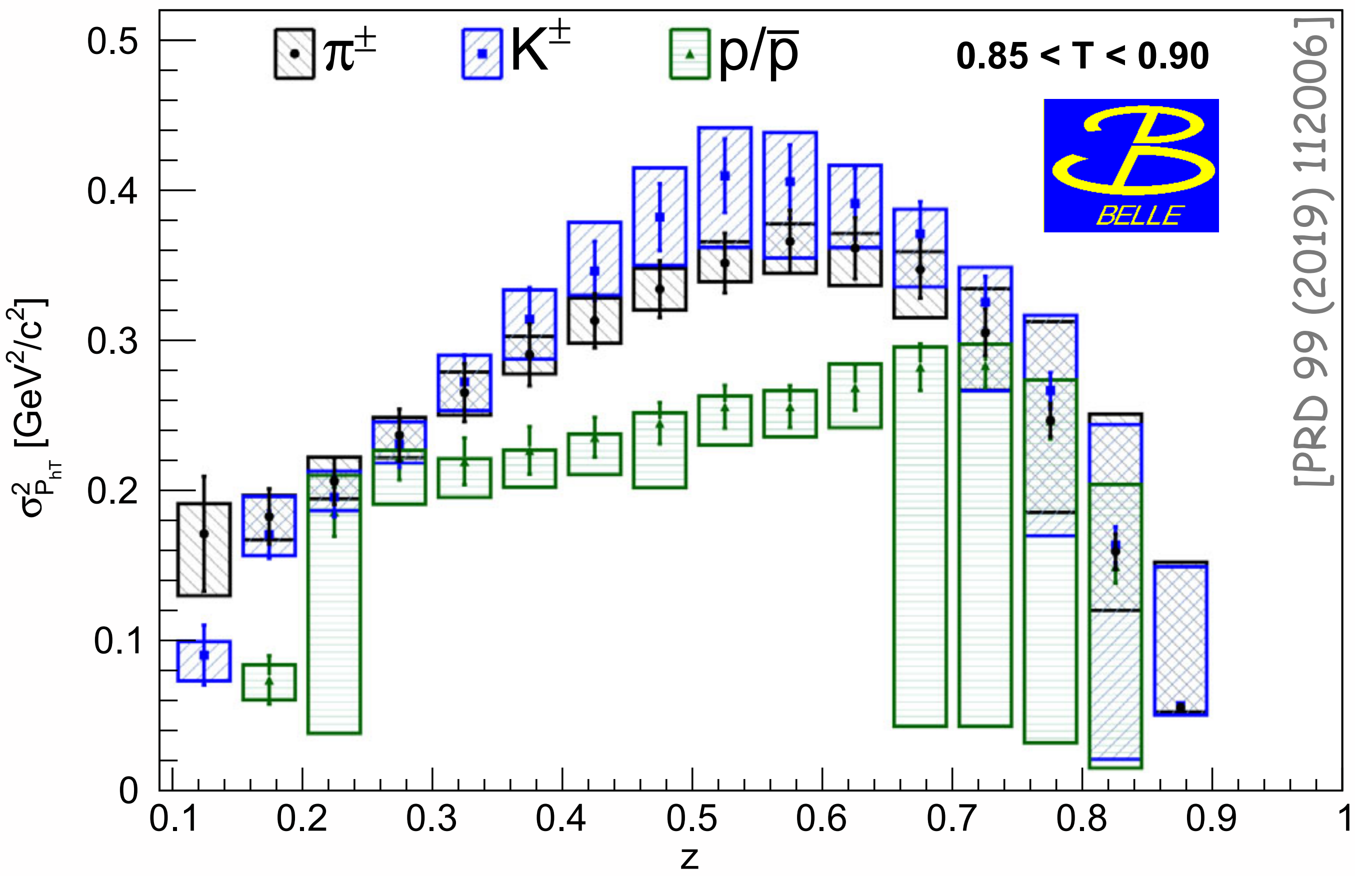
    - deviation from Gauss at large P_{hT}
    - clear increase of width with z for low values of z
- Gaussian widths as function of z
    - general increase with z with turnover at larger values of z for mesons
    - protons with smaller width and more linear rise with z



[PRD 99 (2019) 112006]



[PRD 99 (2019) 112006]

transverse-momentum: Gaussian widths

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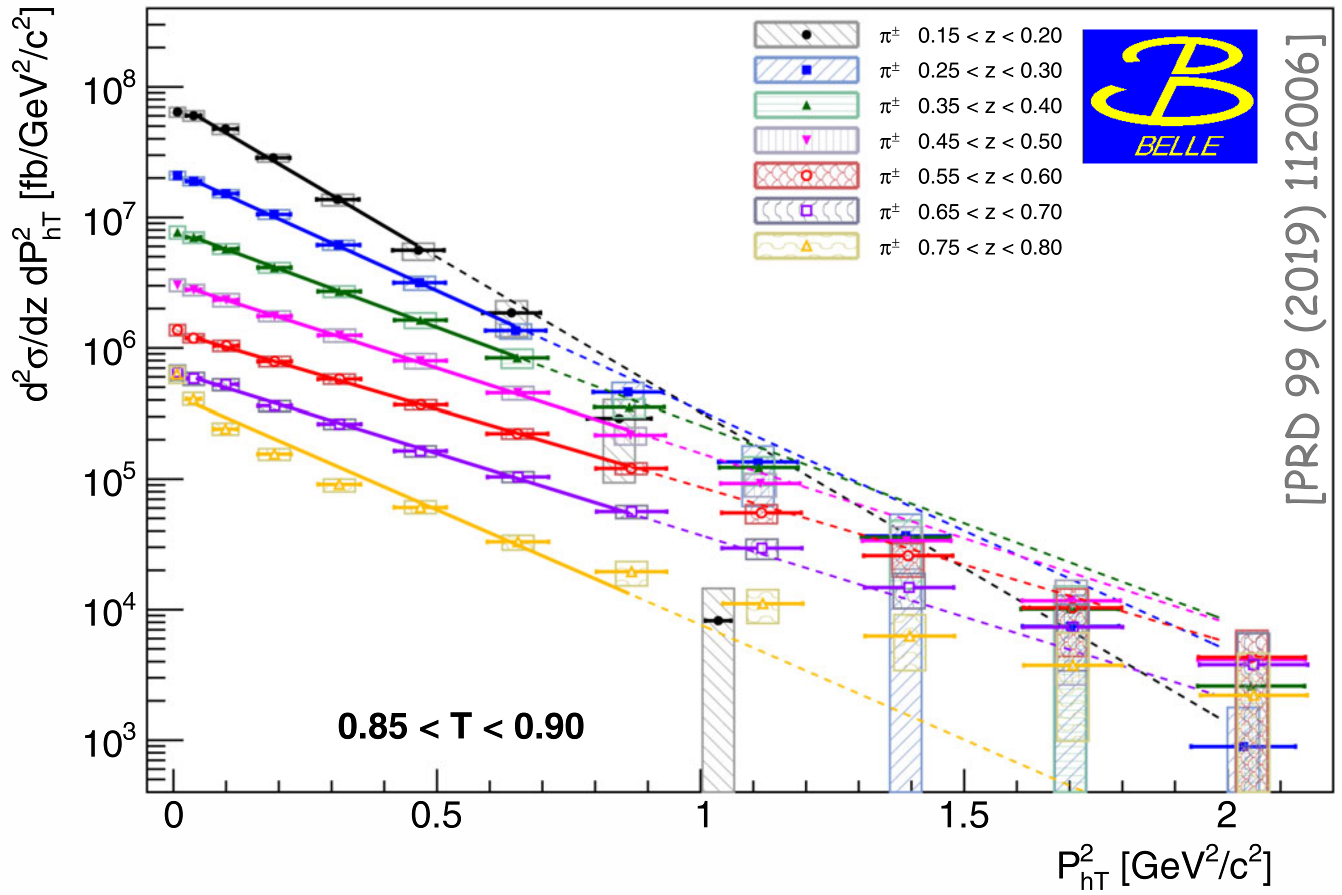
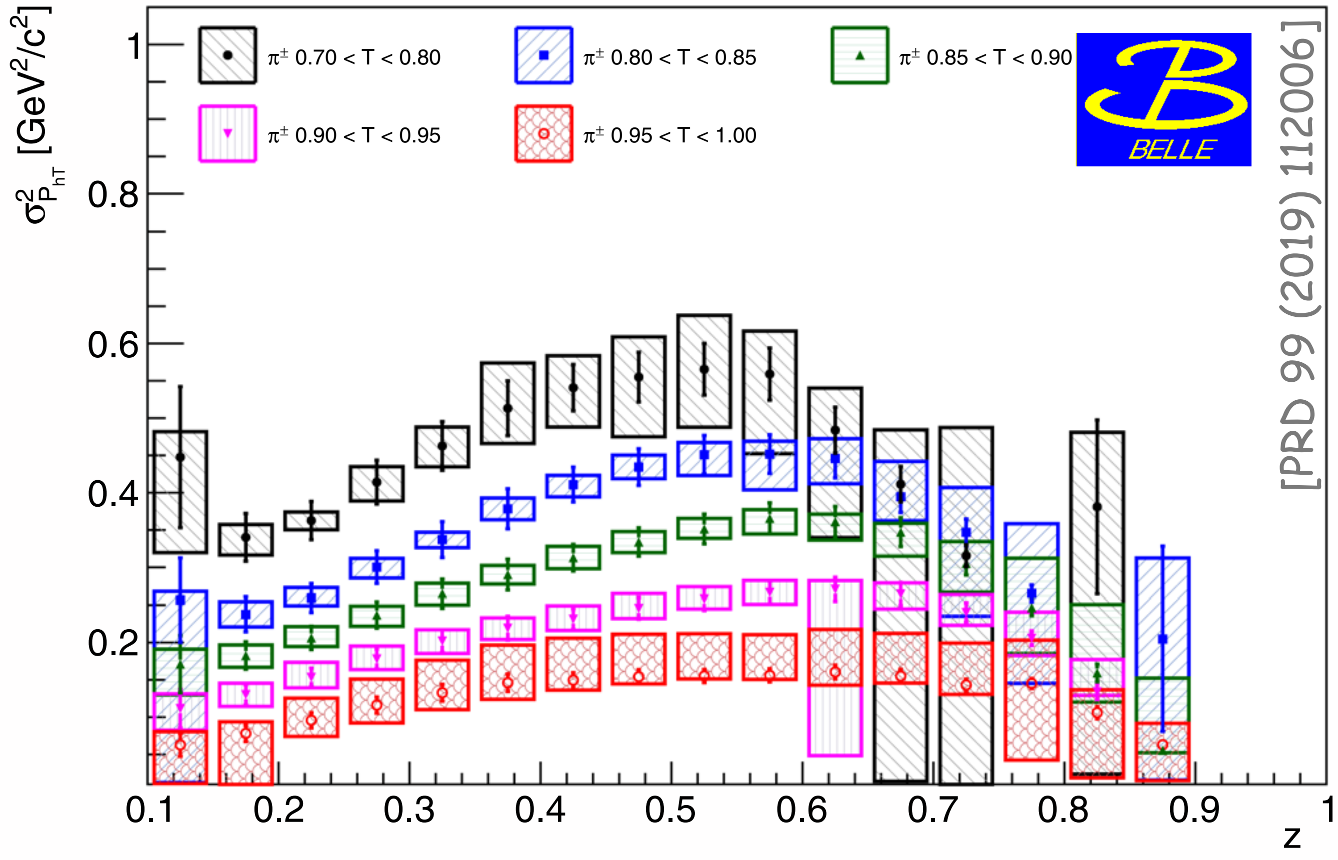
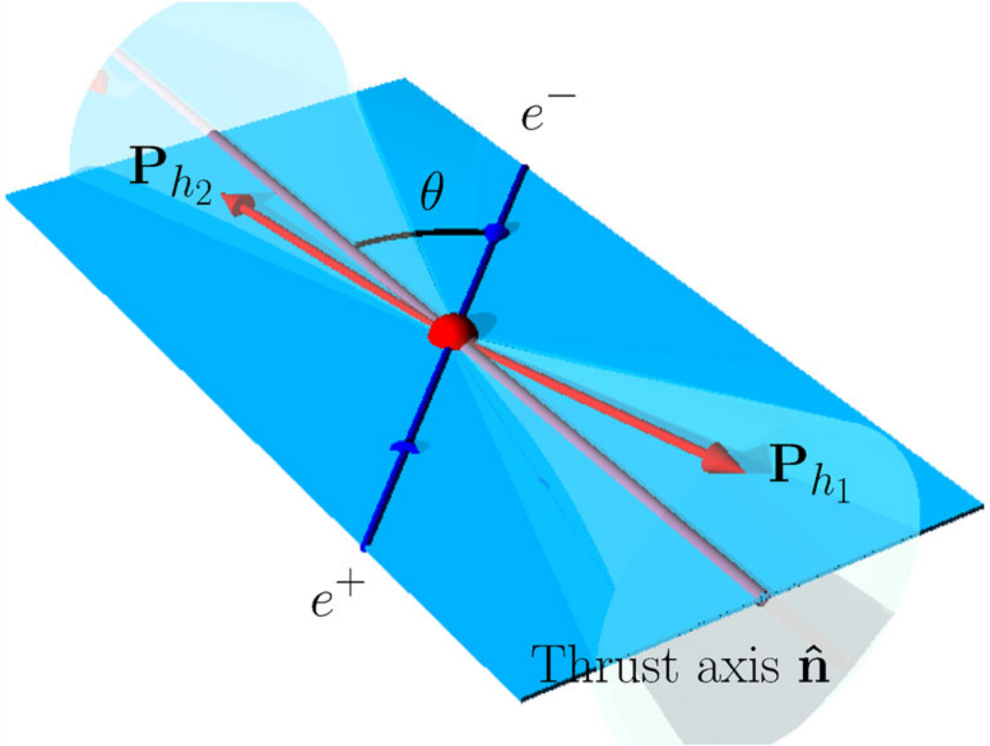
  - fit Gauss to low-P_{hT} data
  - mostly well described with possible exception at high z
  - deviation from Gauss at large P_{hT}
  - clear increase of width with z for low values of z
- Gaussian widths depend on z and T
  - general increase with z with turnover at larger values of z
  - clear decrease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

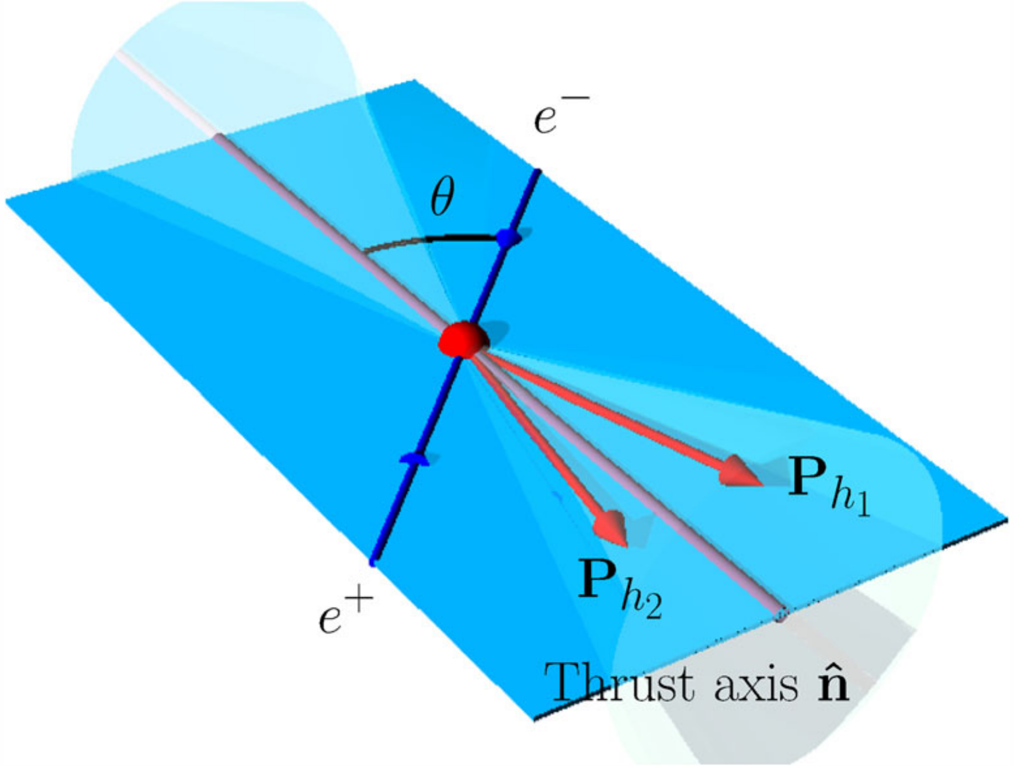




hadron-pair production

- single-hadron production has low discriminating power for parton flavor
- can use 2nd hadron in opposite hemisphere to "tag" flavor
  - mainly sensitive to product of single-hadron FFs
- if hadrons in same hemisphere: **dihadron fragmentation**
  - a la de Florian & Vanni [Phys. Lett. B 578 (2004) 139]
  - a la Collins, Heppelmann & Ladinsky [Nucl. Phys. B 420 (1994) 565]; Boer, Jacobs & Radici [Phys. Rev. D 67 (2003) 094003]
- raises question of defining hemispheres

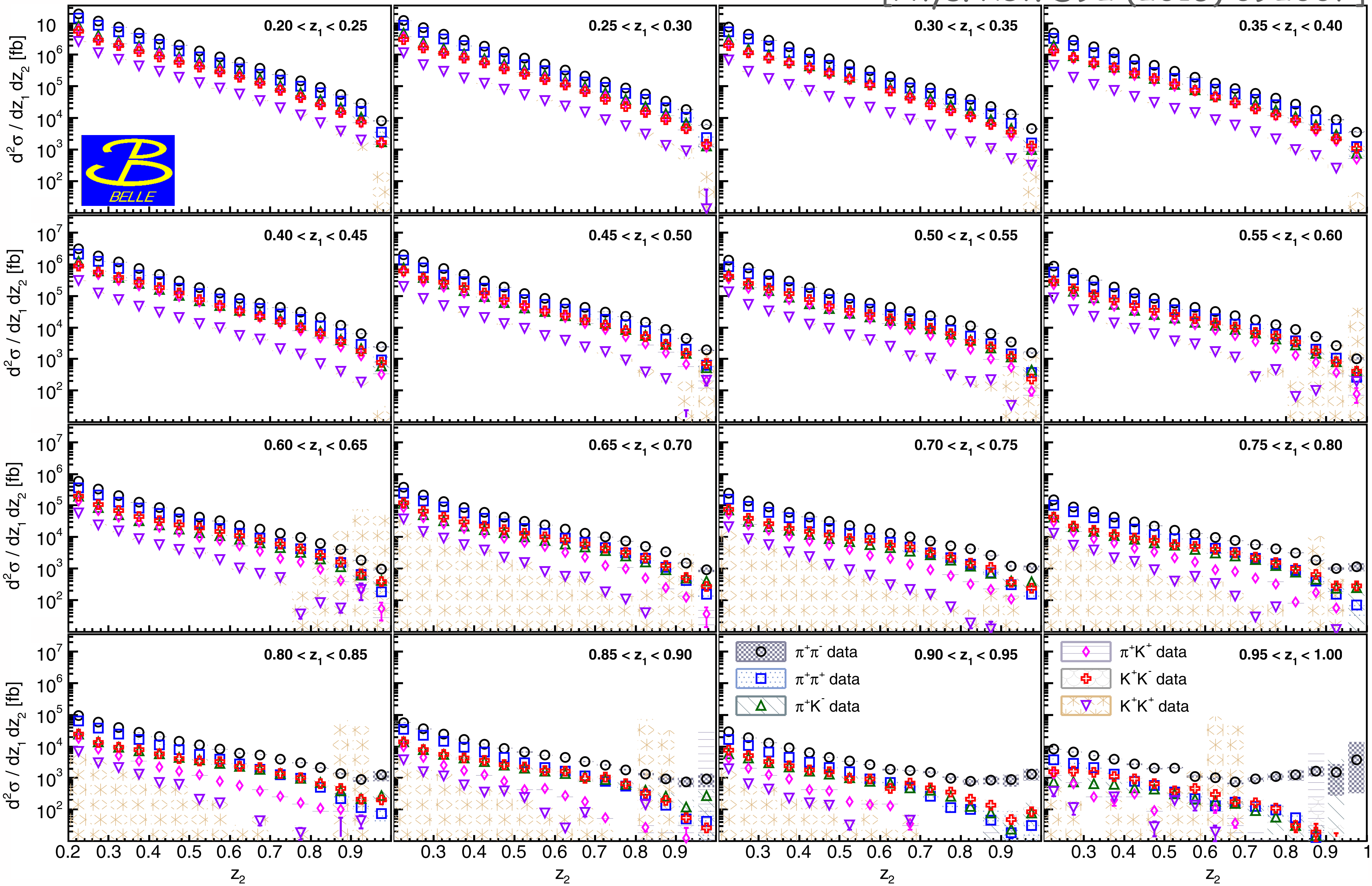




hadron-pair production

no hemisphere selection

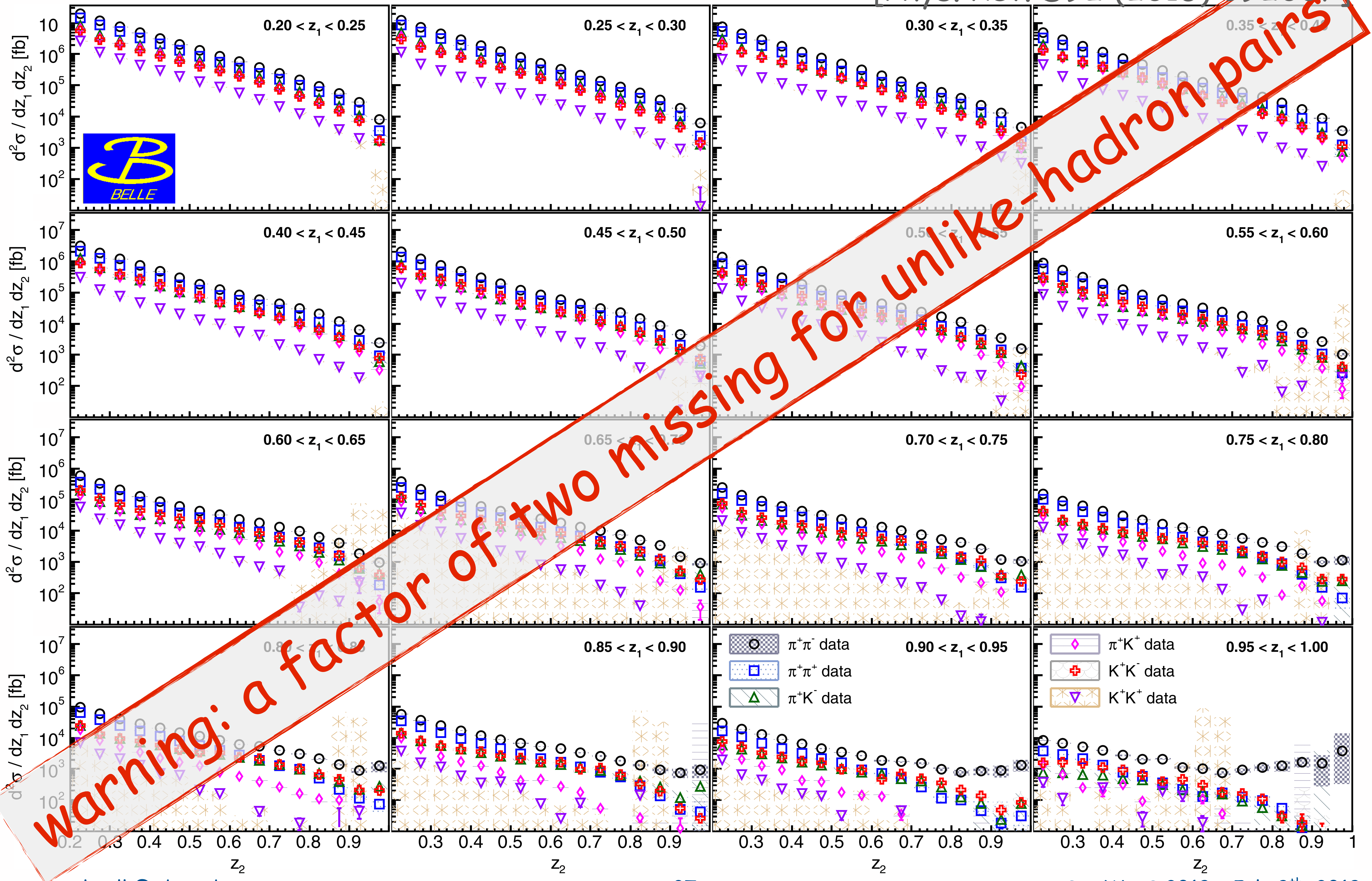
[Phys. Rev. D92 (2015) 092007]



hadron-pair production

no hemisphere selection

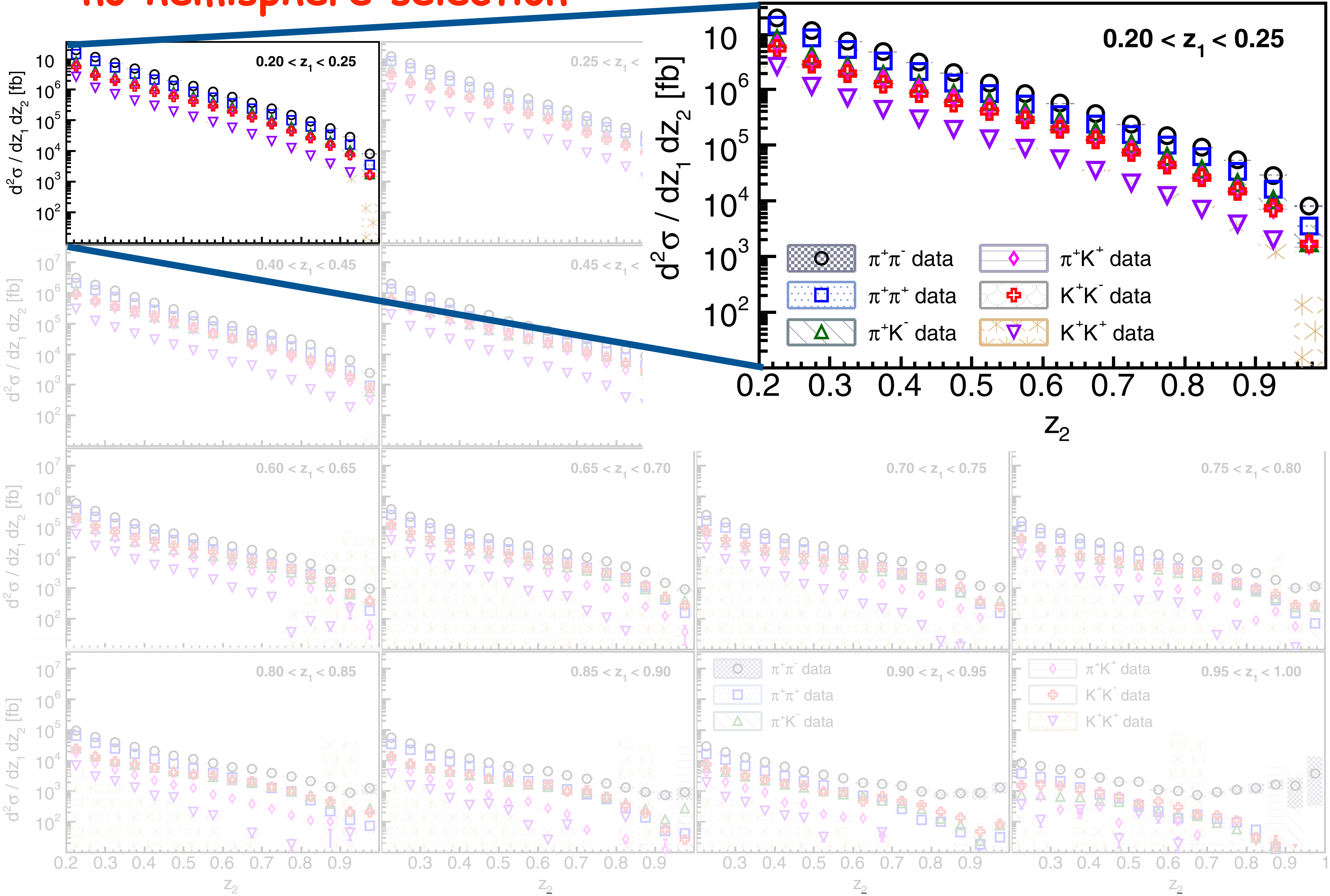
[Phys. Rev. D92 (2015) 092007]



warning: a factor of two missing for unlike-hadron pairs

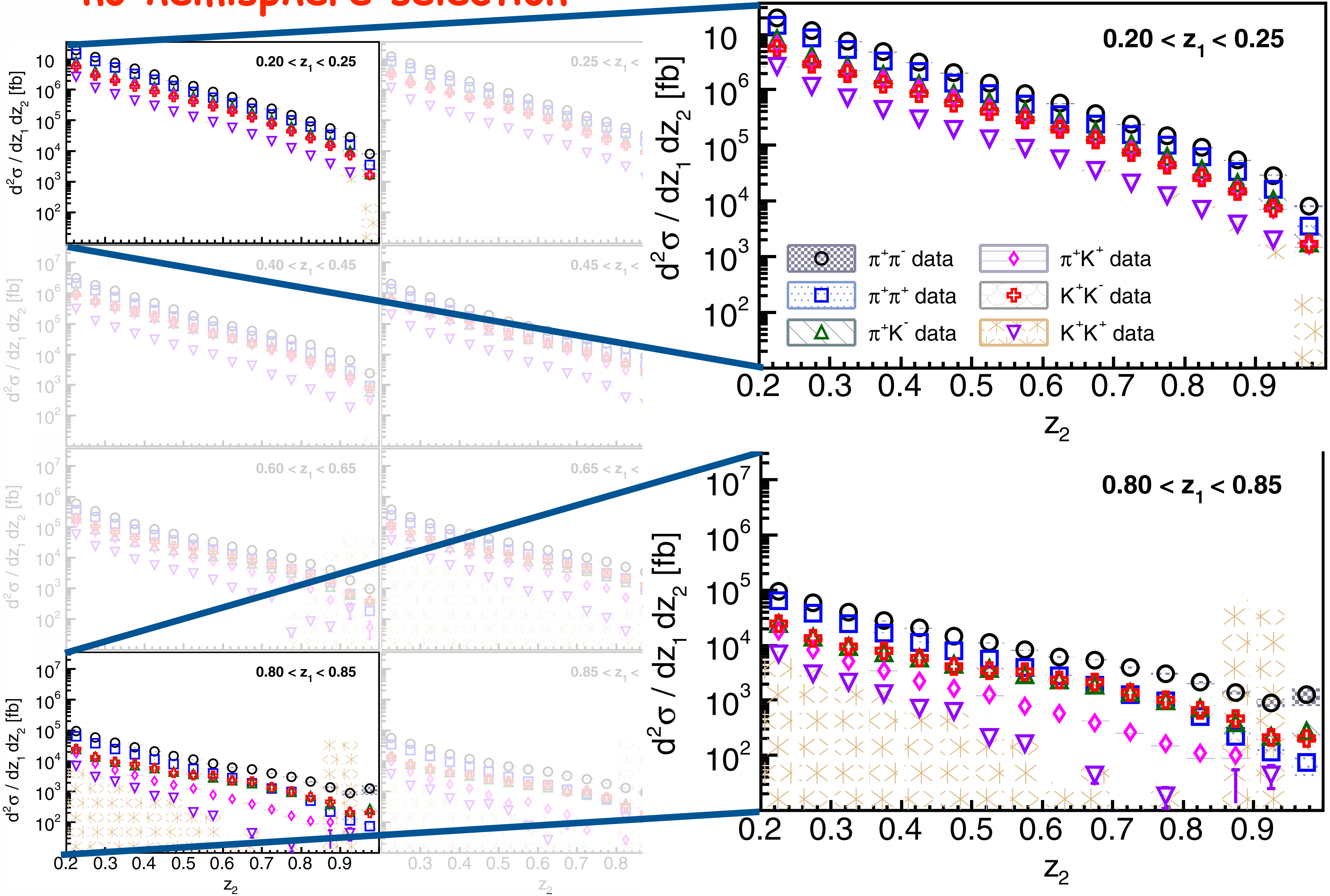
hadron-pair production

no hemisphere selection



hadron-pair production

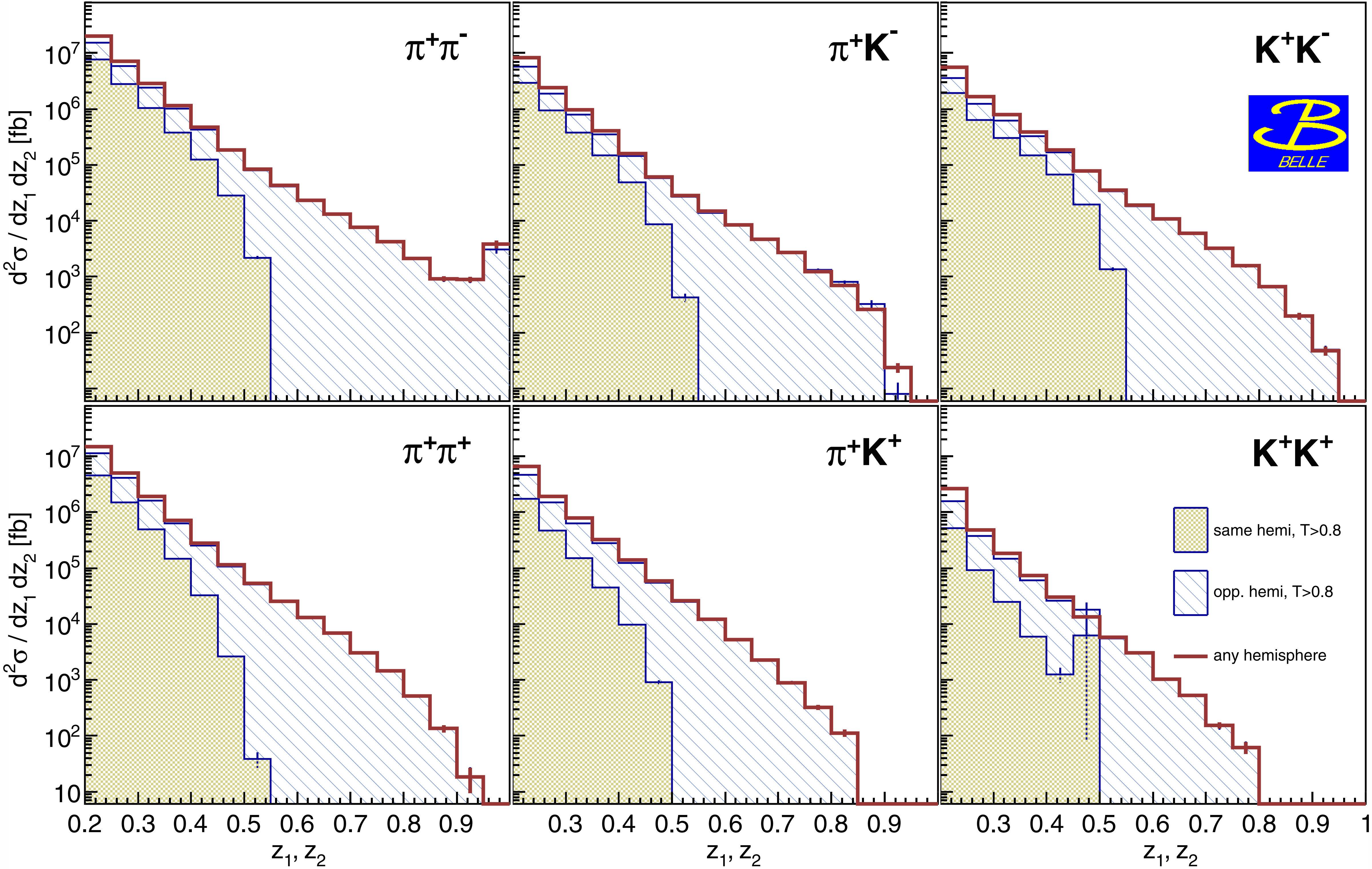
no hemisphere selection



hadron-pairs: topology comparison

- any hemisphere vs. opposite- & same-hemisphere pairs
  - same-hemisphere pairs with kinematic limit at $z_1=z_2=0.5$

[Phys. Rev. D92 (2015) 092007]



same-hemisphere data: M_{h1h2} dependence

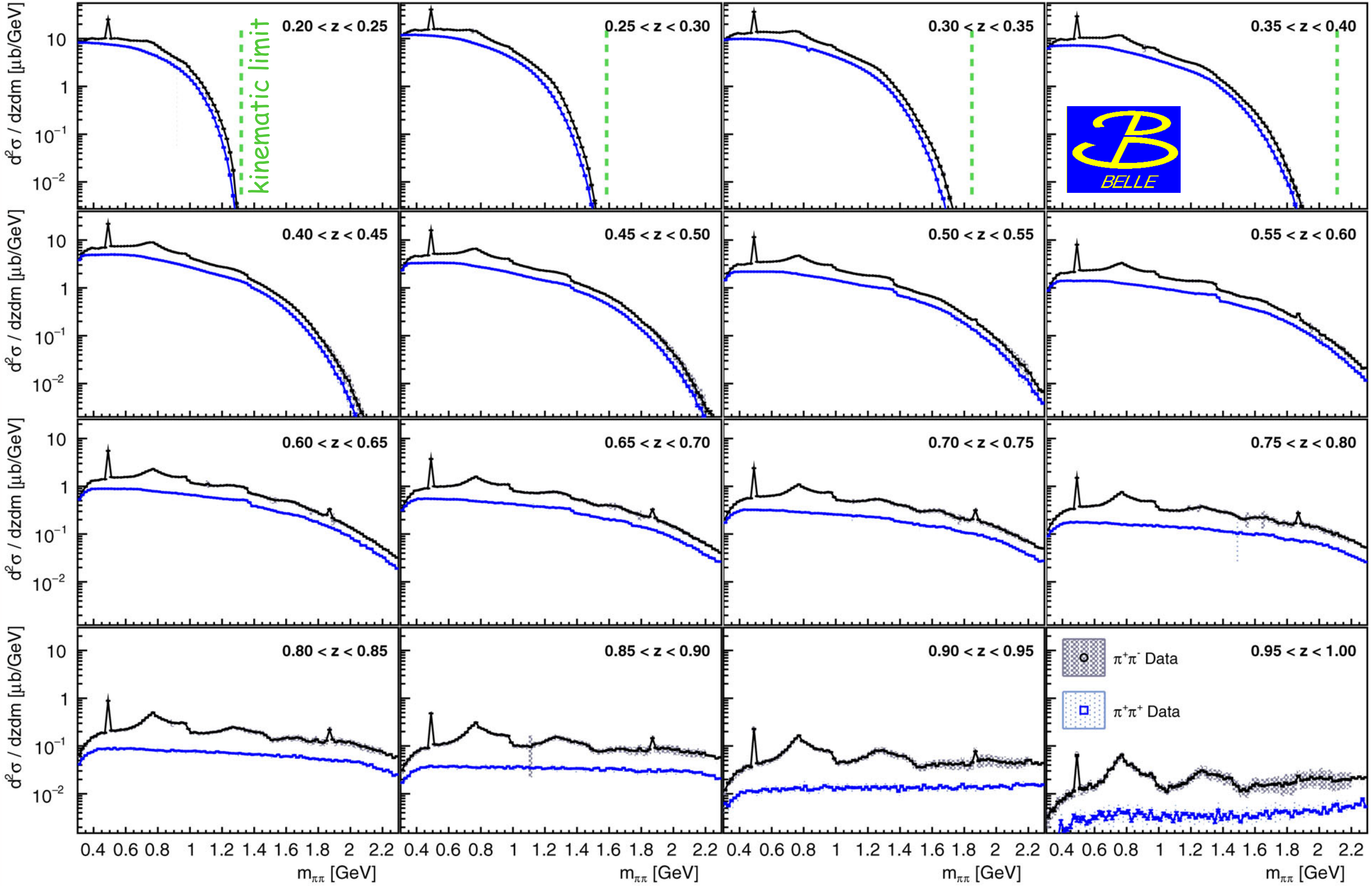
[Phys. Rev. D96 (2017) 032005]

unlike-sign
hadron pairs

like-sign
hadron pairs

▨ $\pi^+\pi^-$ Data

▨ $\pi^+\pi^+$ Data



same-hemisphere data: M_{h1h2} dependence

[Phys. Rev. D96 (2017) 032005]

unlike-sign
hadron pairs

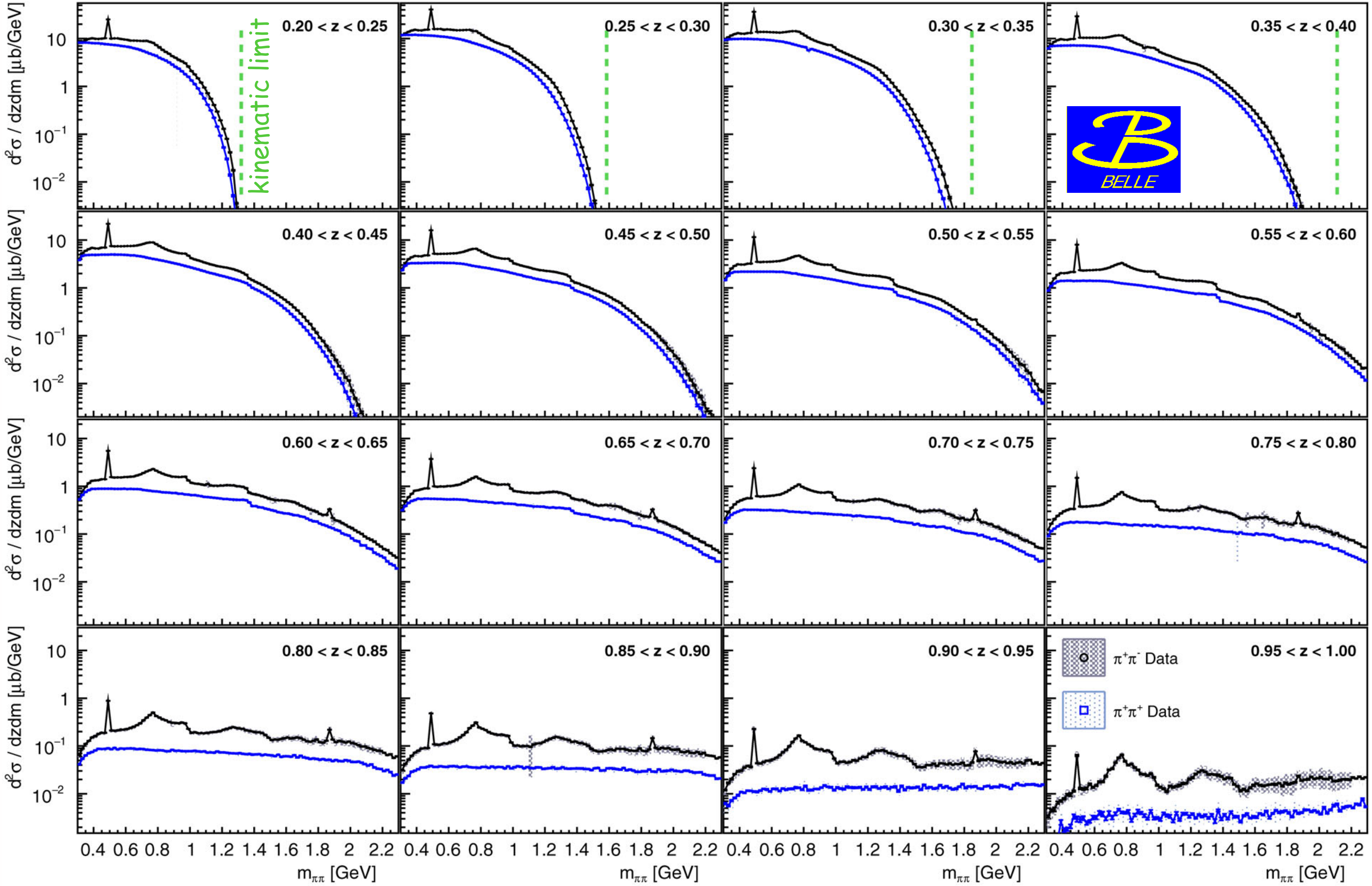
like-sign
hadron pairs

○ $\pi^+\pi^-$ Data

□ $\pi^+\pi^+$ Data

$T > 0.8$

$z_{1,2} > 0.1$



same-hemisphere data: M_{h1h2} dependence

[Phys. Rev. D96 (2017) 032005]

unlike-sign
hadron pairs

like-sign
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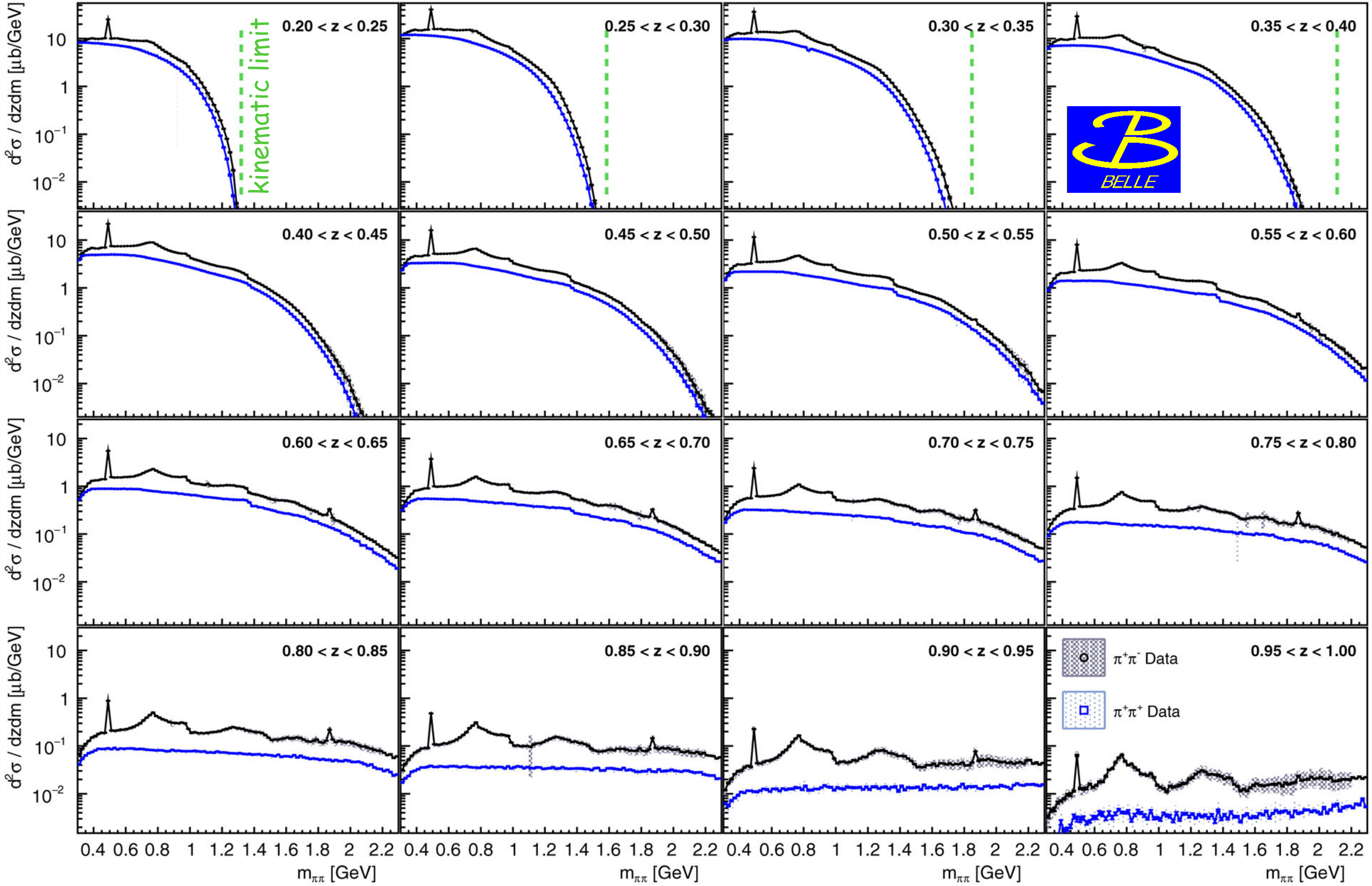


$T > 0.8$

$z_{1,2} > 0.1$

- unlike-sign pairs with clear decay and resonance structure: K_s, ρ^0 ...
- like-sign pairs with much smoother and smaller cross sections

same-hemisphere data: M_{h1h2} dependence

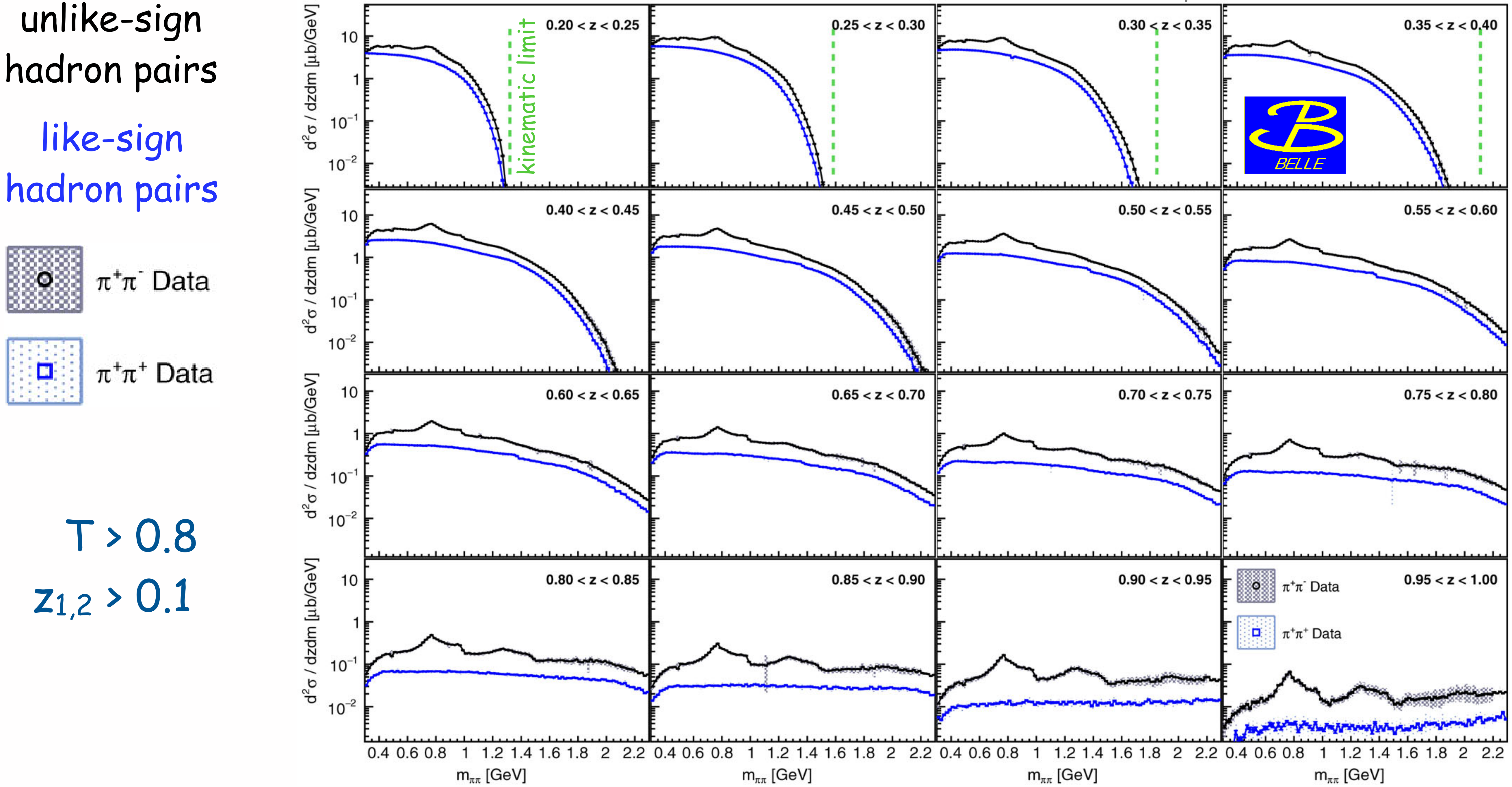
unlike-sign hadron pairs

like-sign hadron pairs

$T > 0.8$

$z_{1,2} > 0.1$

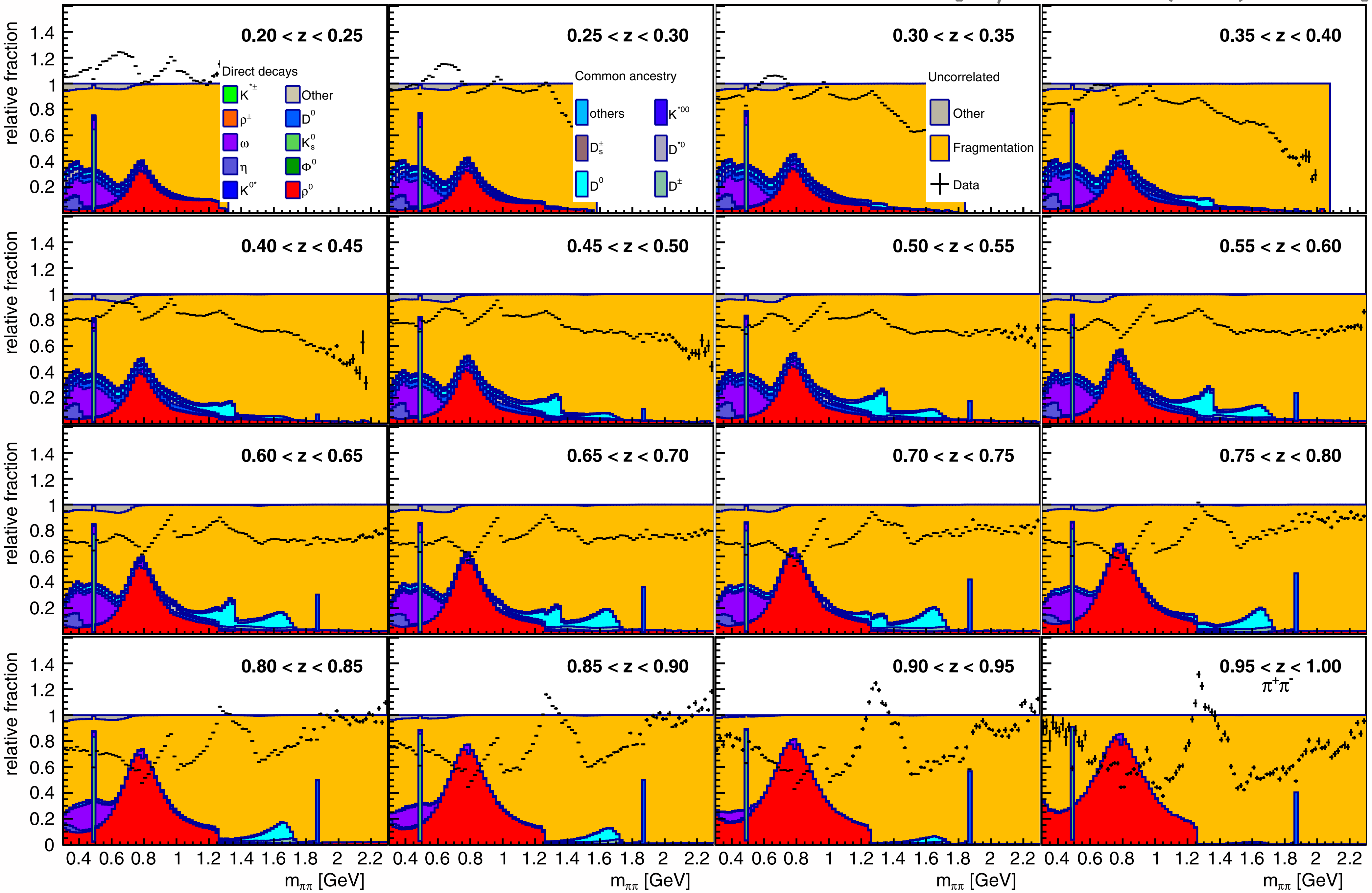
[Phys. Rev. D96 (2017) 032005]



- cross sections after (MC-based) **removal of weak-decay contributions**
  - relies on good description of those channels in PYTHIA

same-hemisphere data: M_{h1h2} dependence

unlike-sign
pion pairs



$T > 0.8$

$z_{1,2} > 0.1$

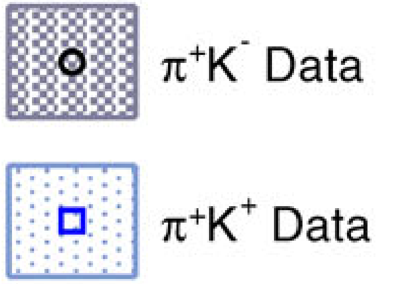
- decomposition based on PYTHIA simulation
- clear differences in invariant-mass dependence between MC and data

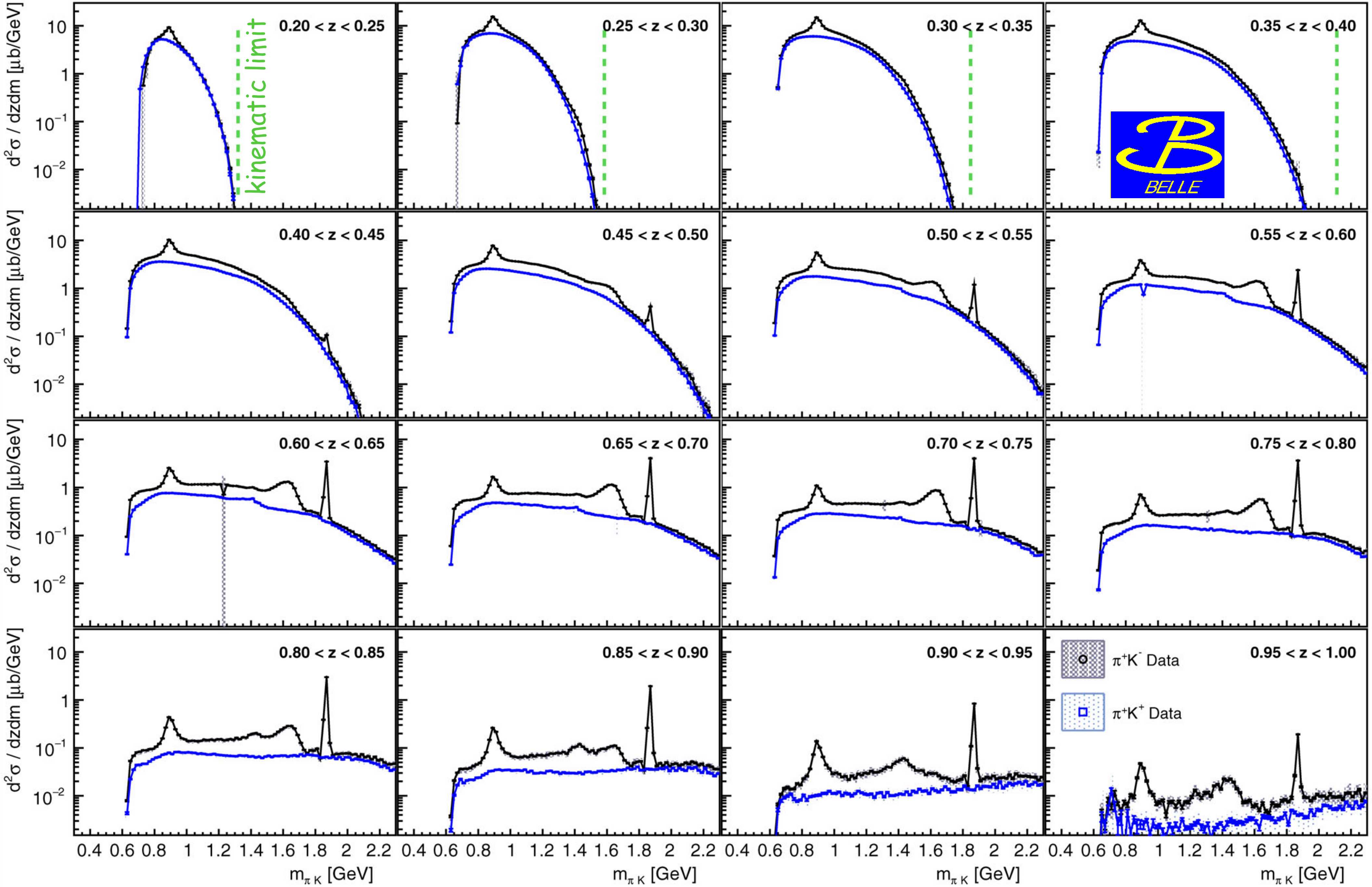
same-hemisphere data: M_{h1h2} dependence

[Phys. Rev. D96 (2017) 032005]

unlike-sign
hadron pairs

like-sign
hadron pairs





$T > 0.8$

$z_{1,2} > 0.1$

- unlike-sign πK pairs with clear K* and increased D-decay contributions

same-hemisphere data: M_{h1h2} dependence

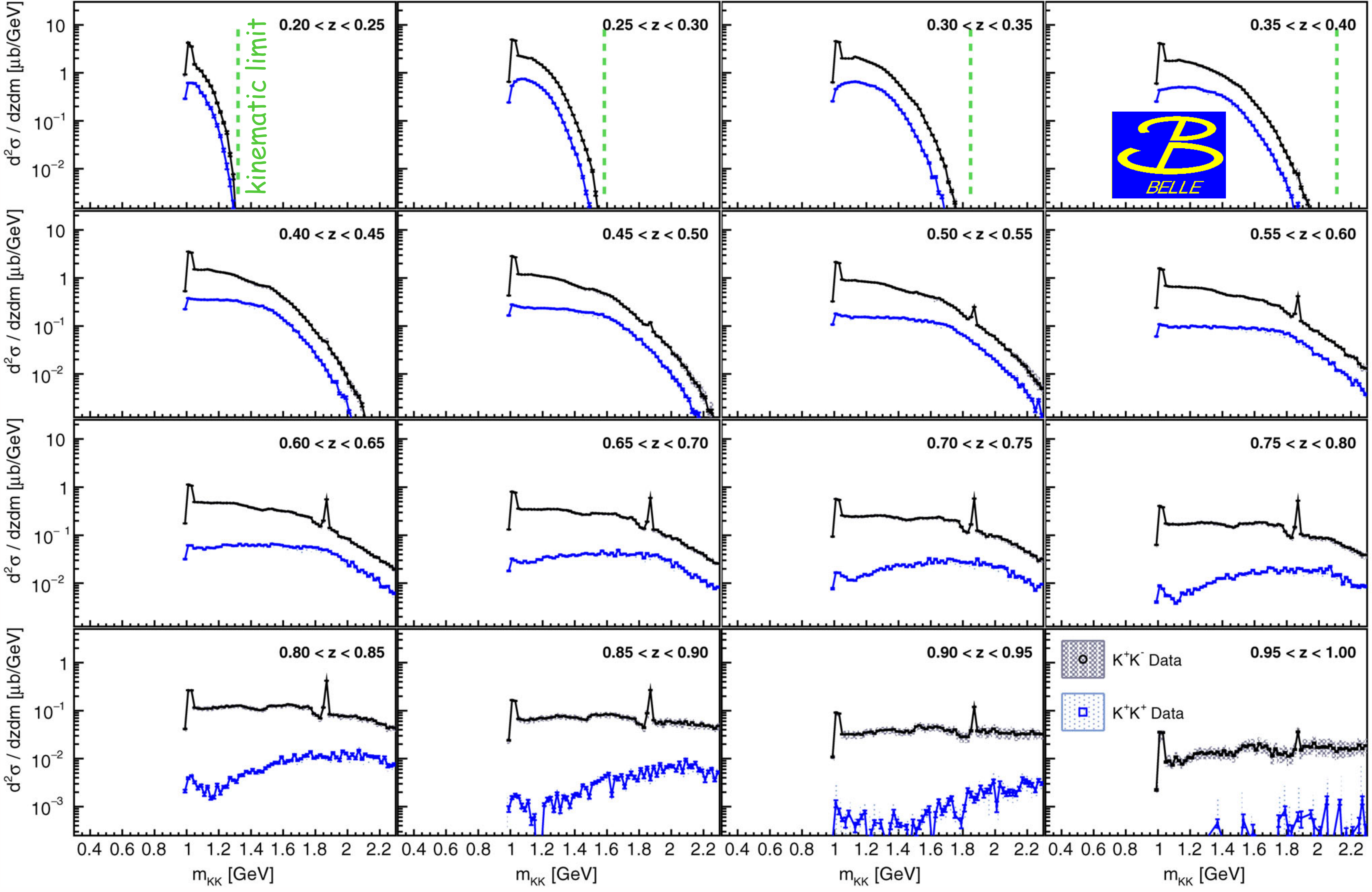
[Phys. Rev. D96 (2017) 032005]

unlike-sign
hadron pairs

like-sign
hadron pairs

○ K^+K^- Data

□ K^+K^+ Data



T > 0.8
$z_{1,2}$ > 0.1

- unlike-sign kaon pairs with (again) a decay structure (e.g. ϕ and D)
- like-sign kaon pairs strongly suppressed at larger z

some more details

same-hemisphere data: M_{h1h2} dependence

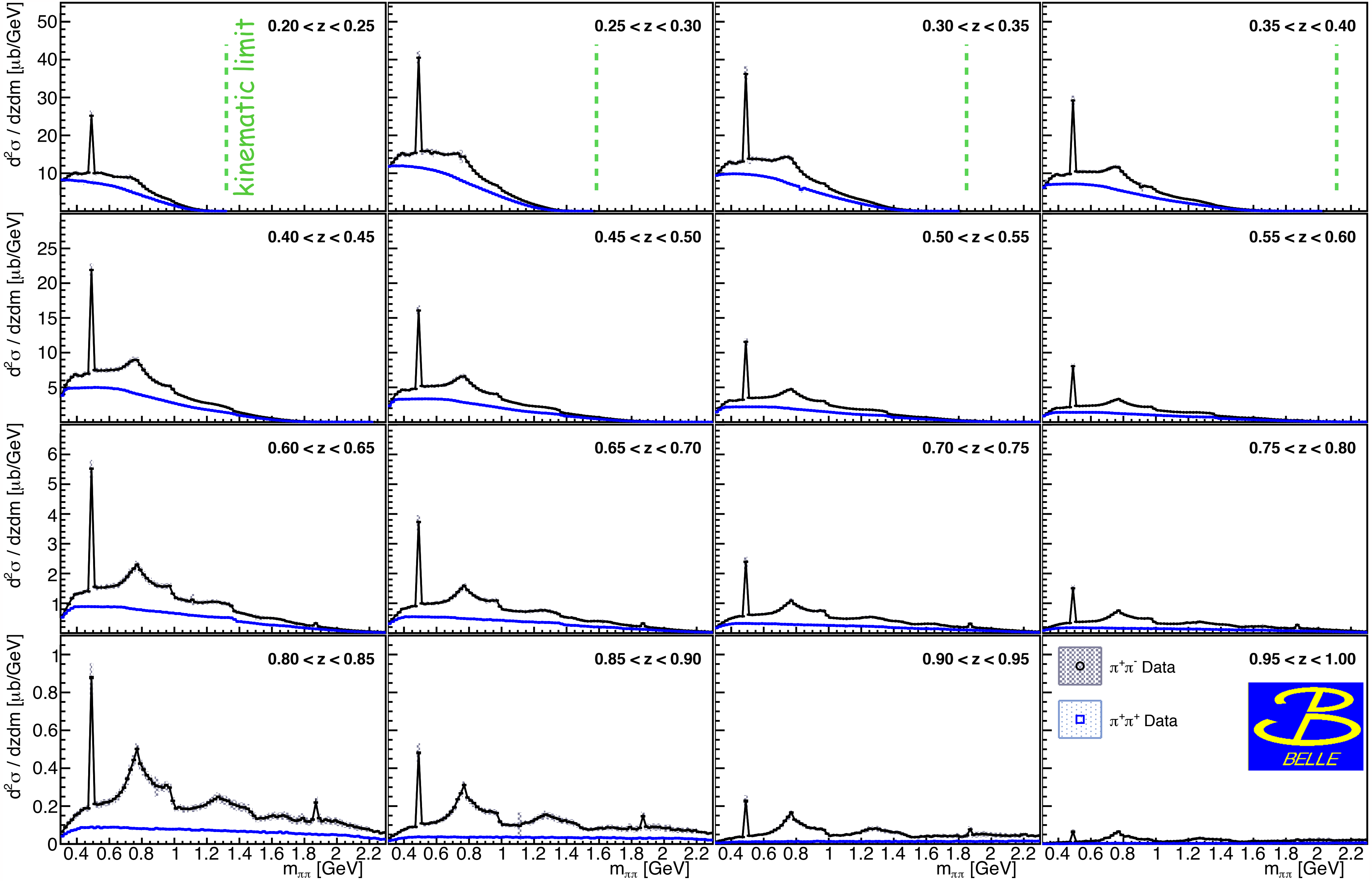
[Phys. Rev. D96 (2017) 032005]

unlike-sign
hadron pairs

like-sign
hadron pairs

▨ $\pi^+\pi^-$ Data

▨ $\pi^+\pi^+$ Data



$T > 0.8$

$z_{1,2} > 0.1$

same-hemisphere data: M_{h1h2} dependence

[Phys. Rev. D96 (2017) 032005]

unlike-sign
hadron pairs

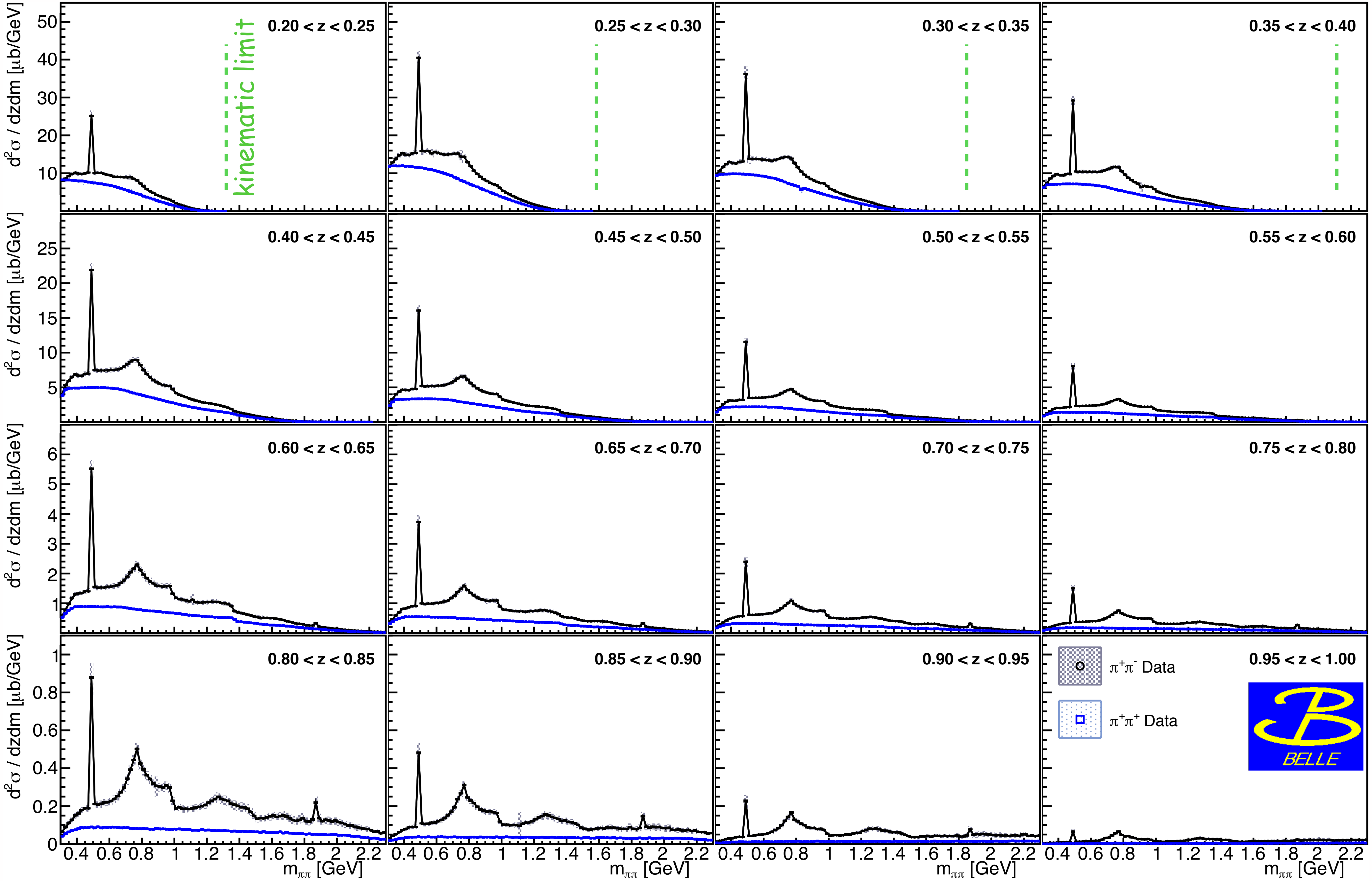
like-sign
hadron pairs

○ $\pi^+\pi^-$ Data

□ $\pi^+\pi^+$ Data

T > 0.8

$z_{1,2} > 0.1$



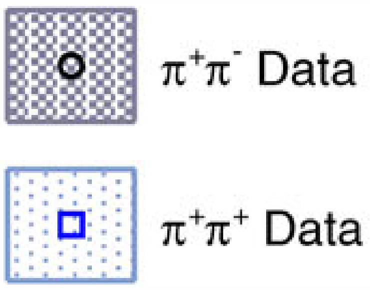
- **thrust** very useful experimentally to suppress BG and to define hemispheres
- potentially difficult to incorporate in phenomenology (unlike thrust axis?)

same-hemisphere data: M_{h1h2} dependence

[Phys. Rev. D96 (2017) 032005]

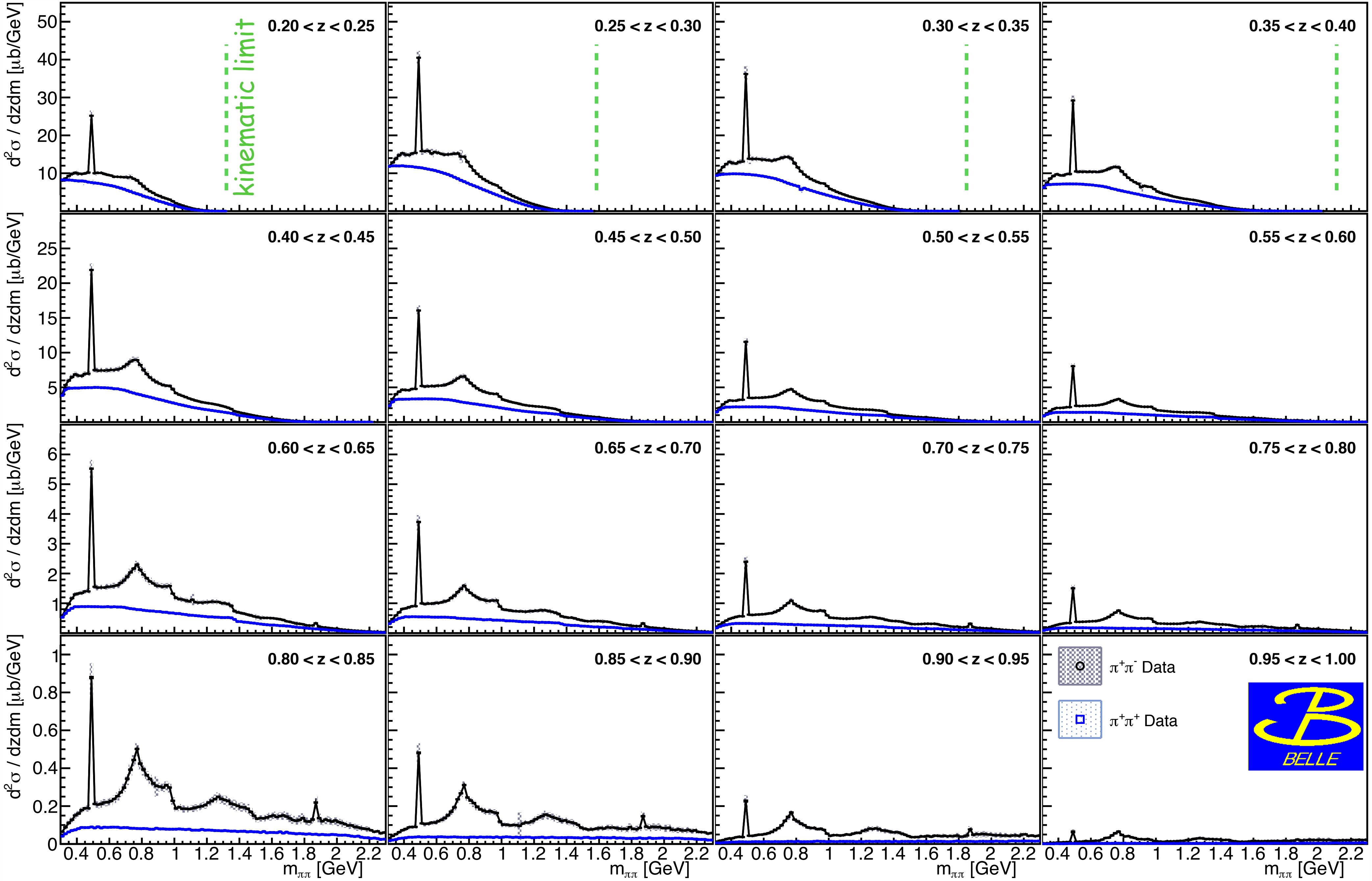
unlike-sign
hadron pairs

like-sign
hadron pairs



T > 0.8

$z_{1,2} > 0.1$

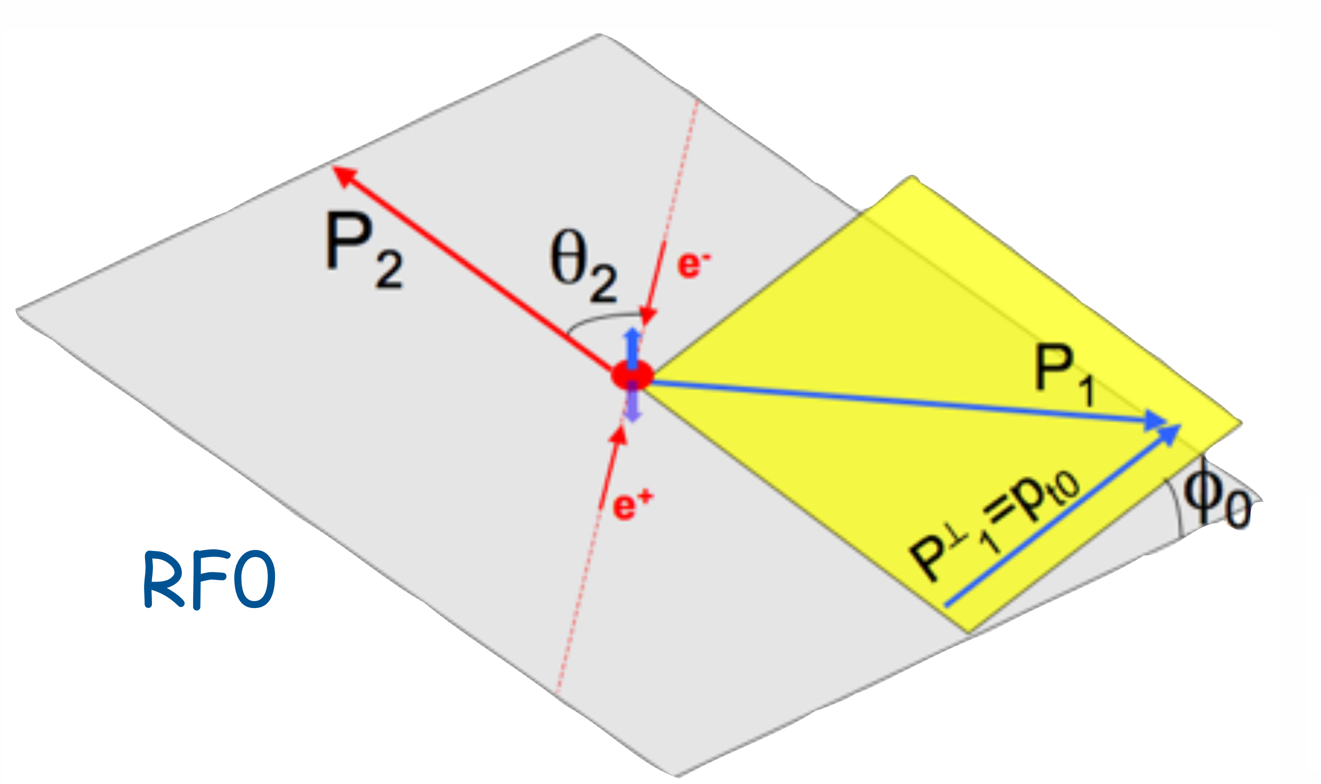


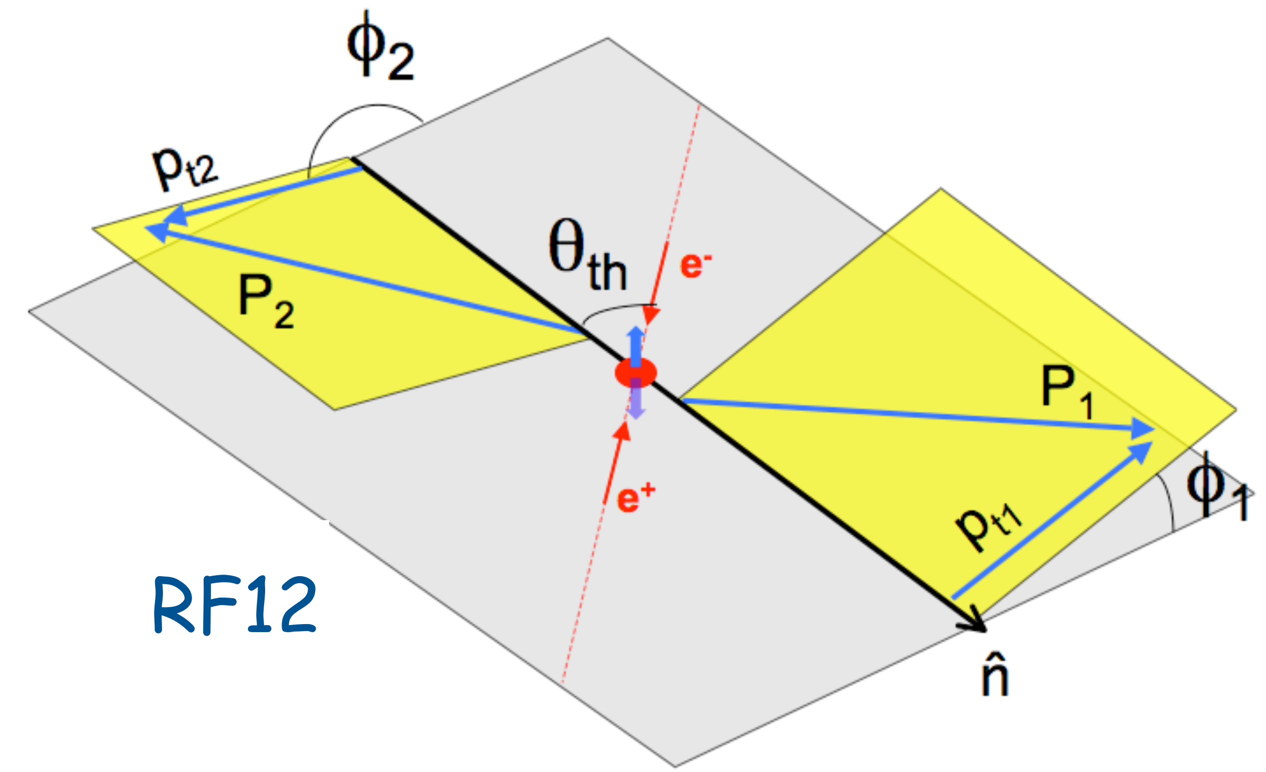
- experimental constraints on individual z restricts phase space of hadron pairs, however, not easy to avoid (detection requirements!)
- among others leads to mixing of partial-wave contributions [GS, QCDE'17]

polarization

hadron pairs: angular correlations

- angular correlations between nearly back-to-back hadrons used to tag transverse quark polarization -> Collins fragmentation functions
  - RF0: one hadron as reference axis -> $\cos(2\phi_0)$ modulation
  - RF12: thrust (or similar) axis -> $\cos(\phi_1+\phi_2)$ modulation

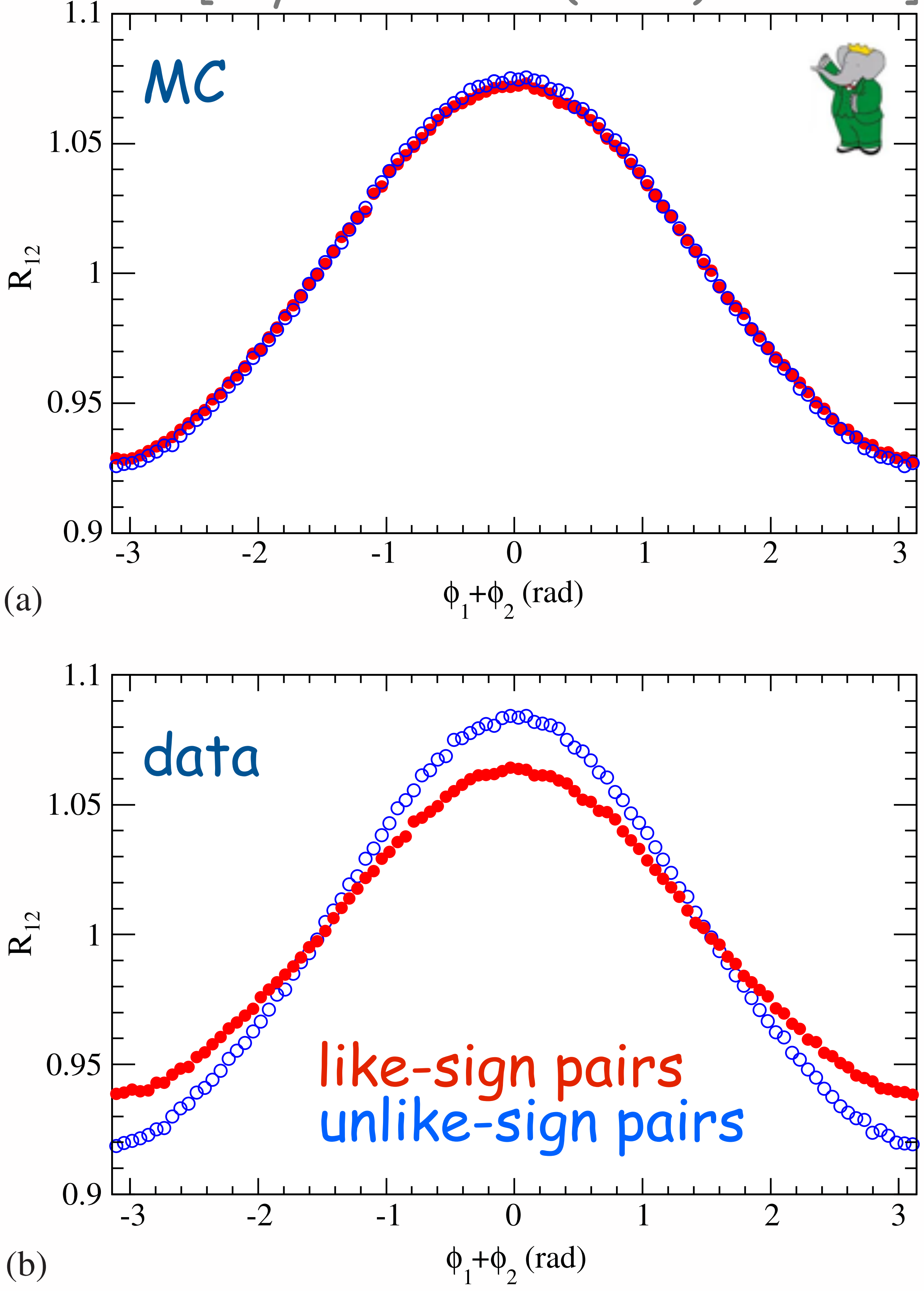




- RF0 and RF12: different convolutions over transverse momenta
- debatable: MC used to "correct" thrust axis to $q\bar{q}$ axis

hadron pairs: angular correlations

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



[Phys. Rev. D90 (2014) 052003]

hadron pairs: angular correlations

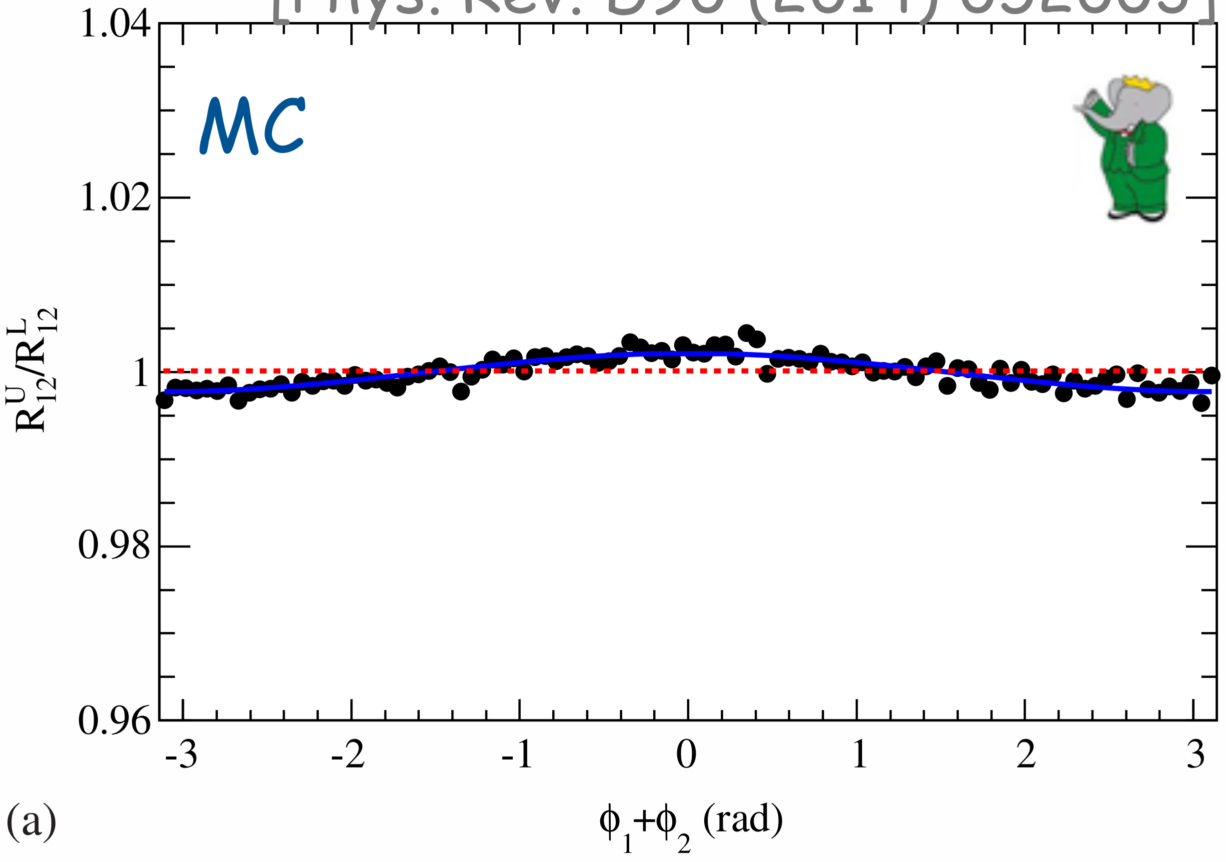
- challenge: large modulations even without Collins effect (e.g., MC)
- construct double ratio of normalized-yield distributions R_{12}, e.g. unlike-/like-sign:

$$\frac{R^U_{12}}{R^L_{12}} \simeq \frac{1+\langle\frac{\sin^2\theta_{\mathrm{th}}}{1+\cos^2\theta_{\mathrm{th}}}\rangle G^U\cos(\phi_1+\phi_2)}{1+\langle\frac{\sin^2\theta_{\mathrm{th}}}{1+\cos^2\theta_{\mathrm{th}}}\rangle G^L\cos(\phi_1+\phi_2)}$$

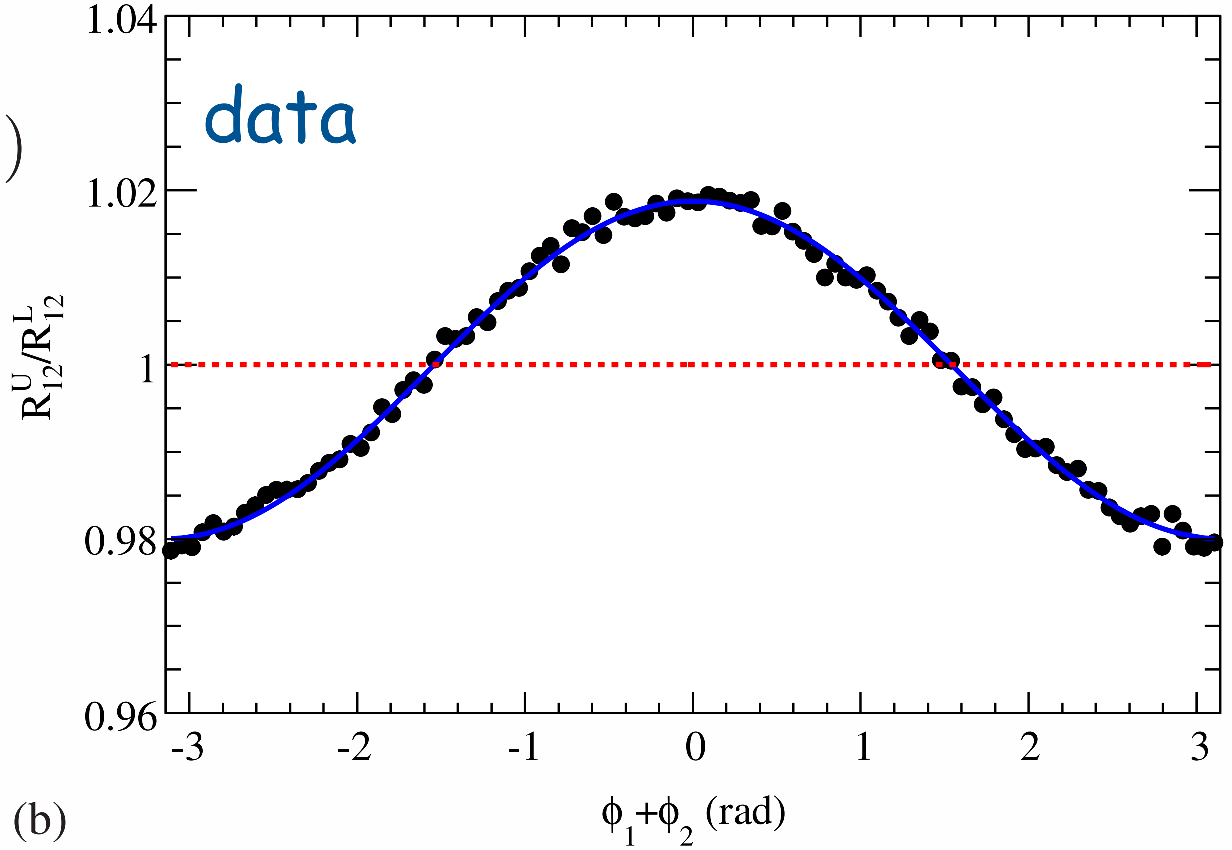
$$\simeq 1+\left\langle\frac{\sin^2\theta_{\mathrm{th}}}{1+\cos^2\theta_{\mathrm{th}}}\right\rangle\{G^U - G^L\}\cos(\phi_1+\phi_2)$$

  - suppresses flavor-independent sources of modulations
  - $G^{U/L}$ specific combinations of FFs
  - remaining MC asym.'s: systematics

[Phys. Rev. D90 (2014) 052003]



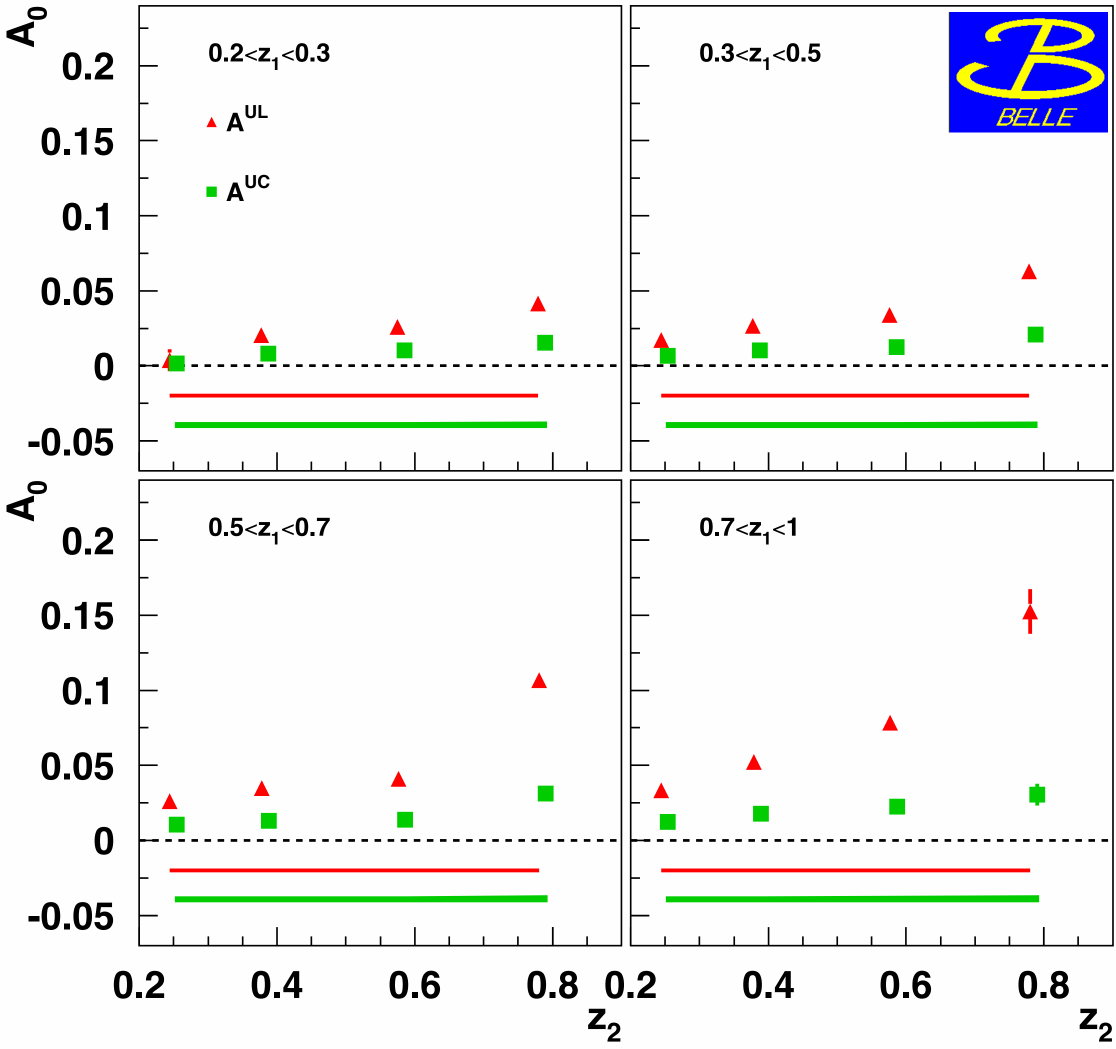
(a)



(b)

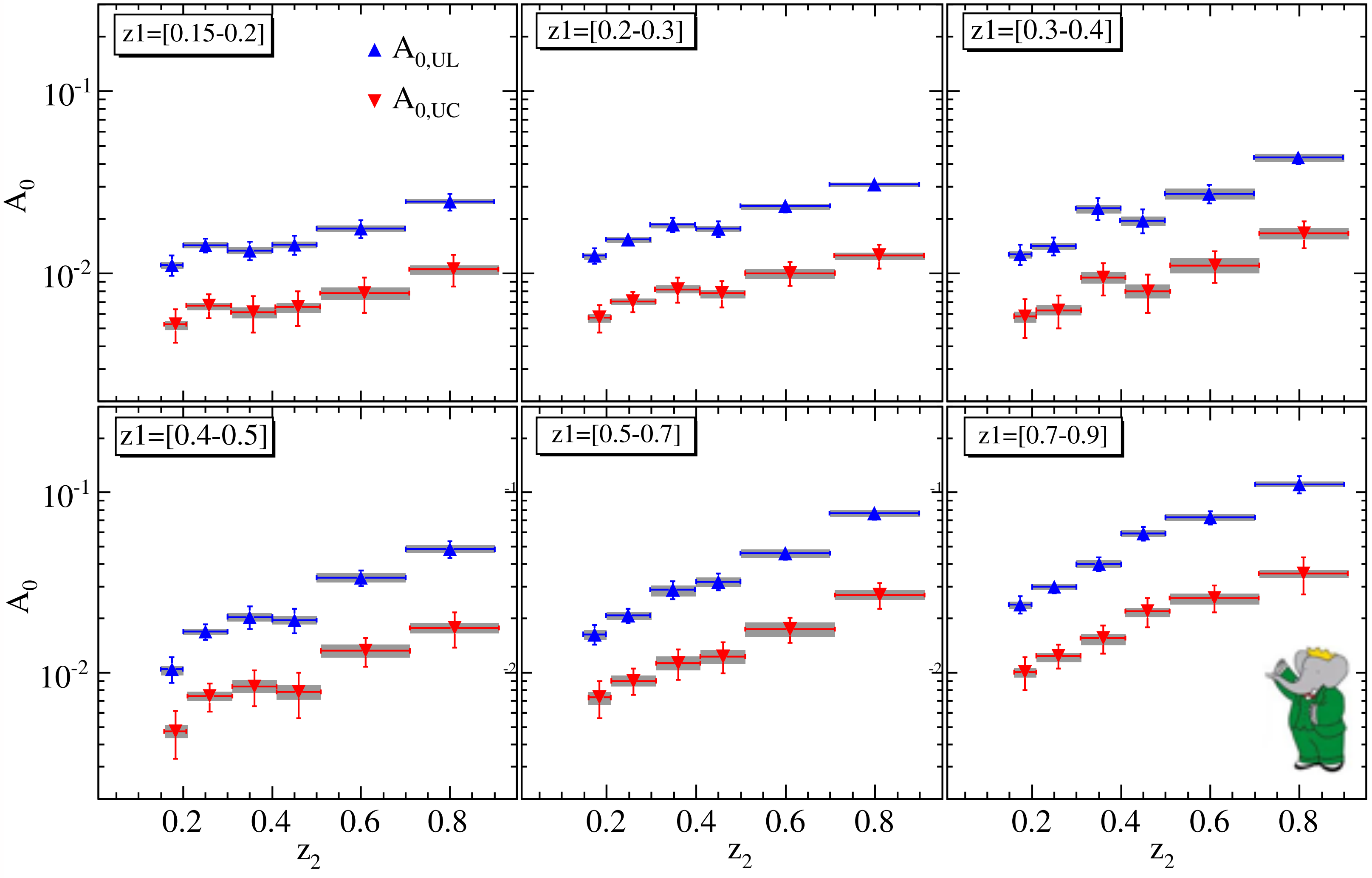
Collins asymmetries (RF0)

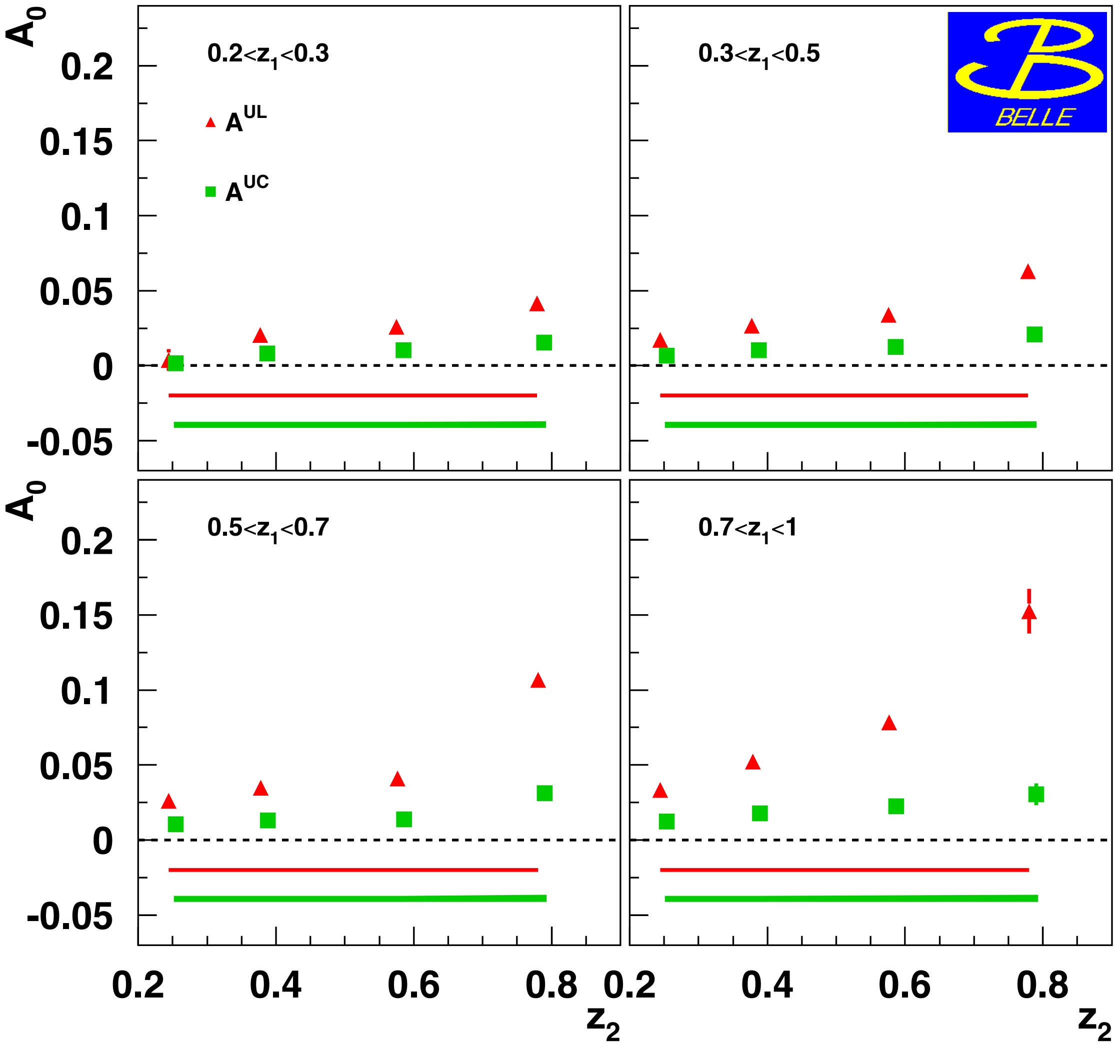
- first measurement of Collins asymmetries by Belle [PRL 96 (2006) 232002, PRD 78 (2008) 032011, PRD 86 (2012) 039905(E)]
    - significant asymmetries rising with z
    - used for first transversity and Collins FF extractions



Collins asymmetries (RF0)

[Phys. Rev. D90 (2014) 052003]

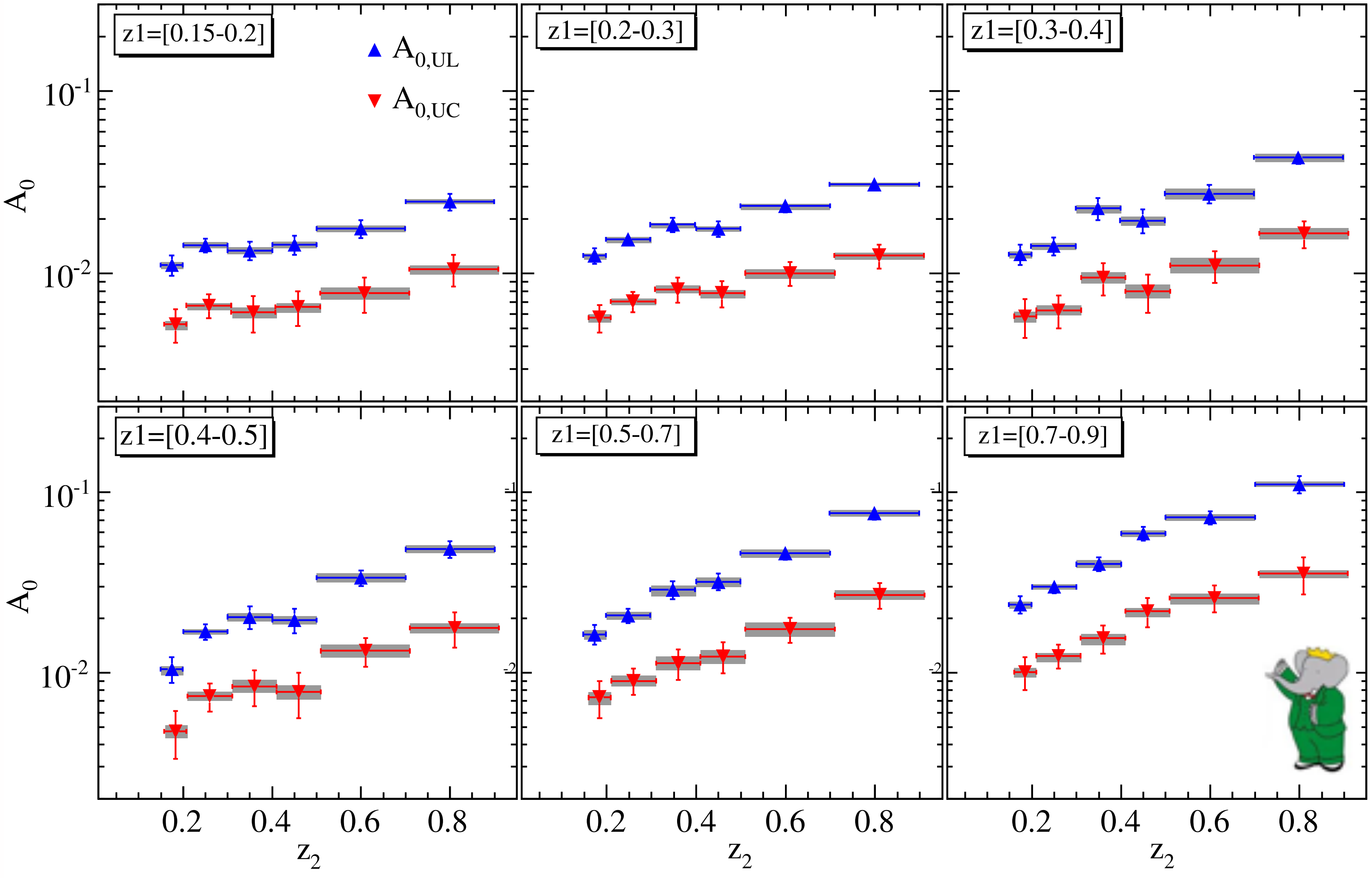


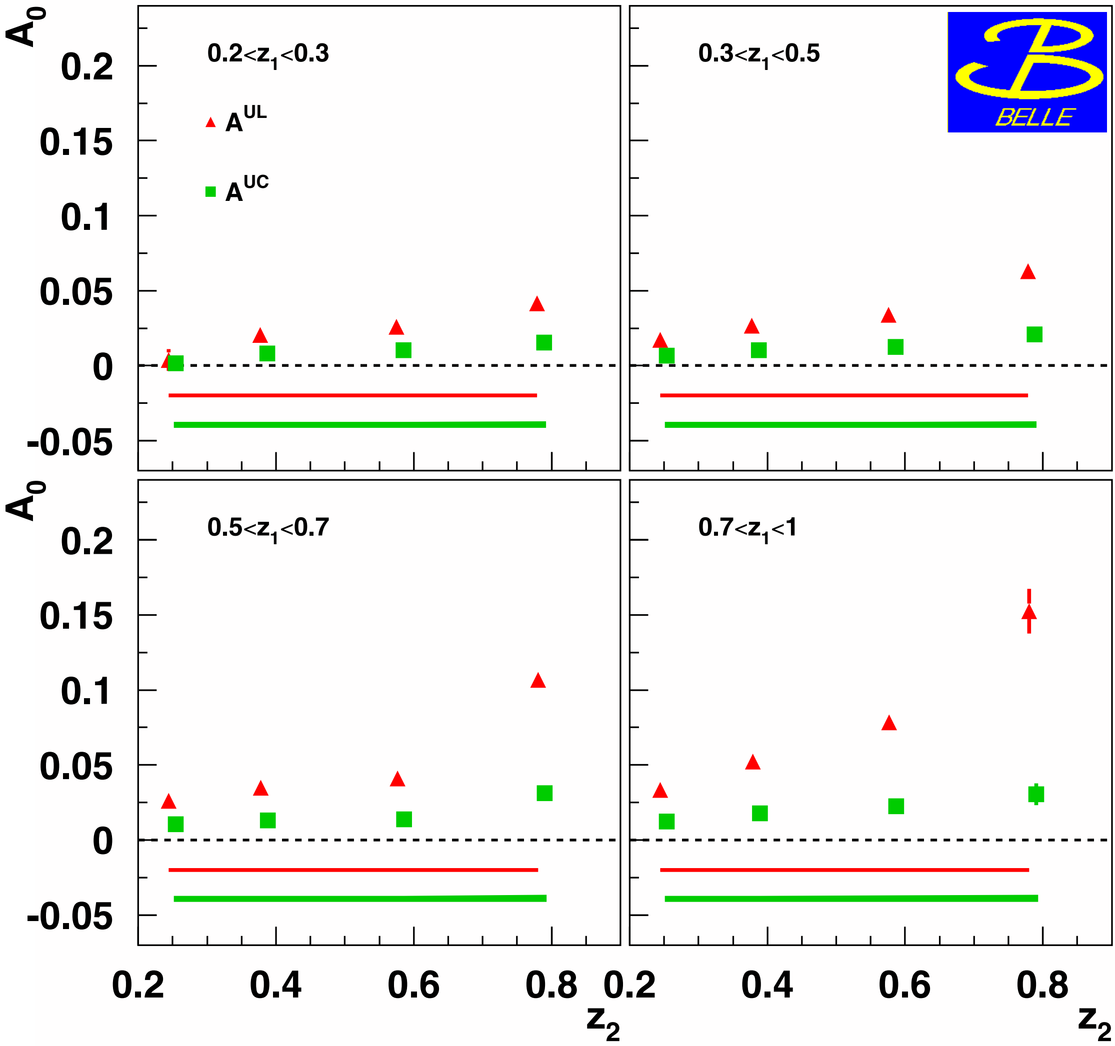


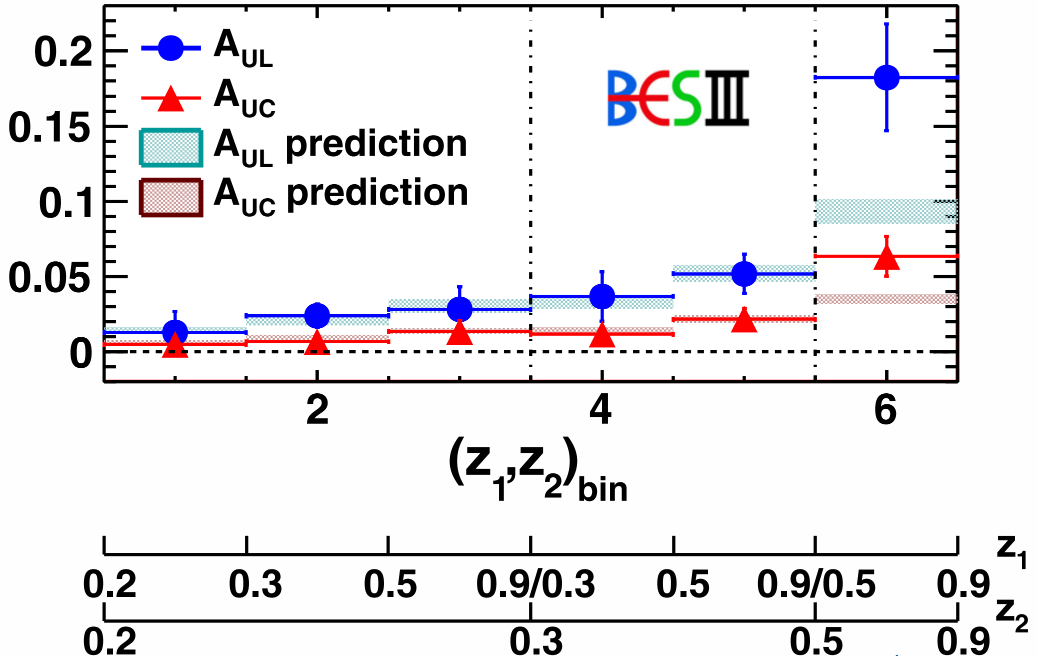
- BaBar results [PRD 90 (2014) 052003] consistent with Belle

Collins asymmetries (RF0)

[Phys. Rev. D90 (2014) 052003]

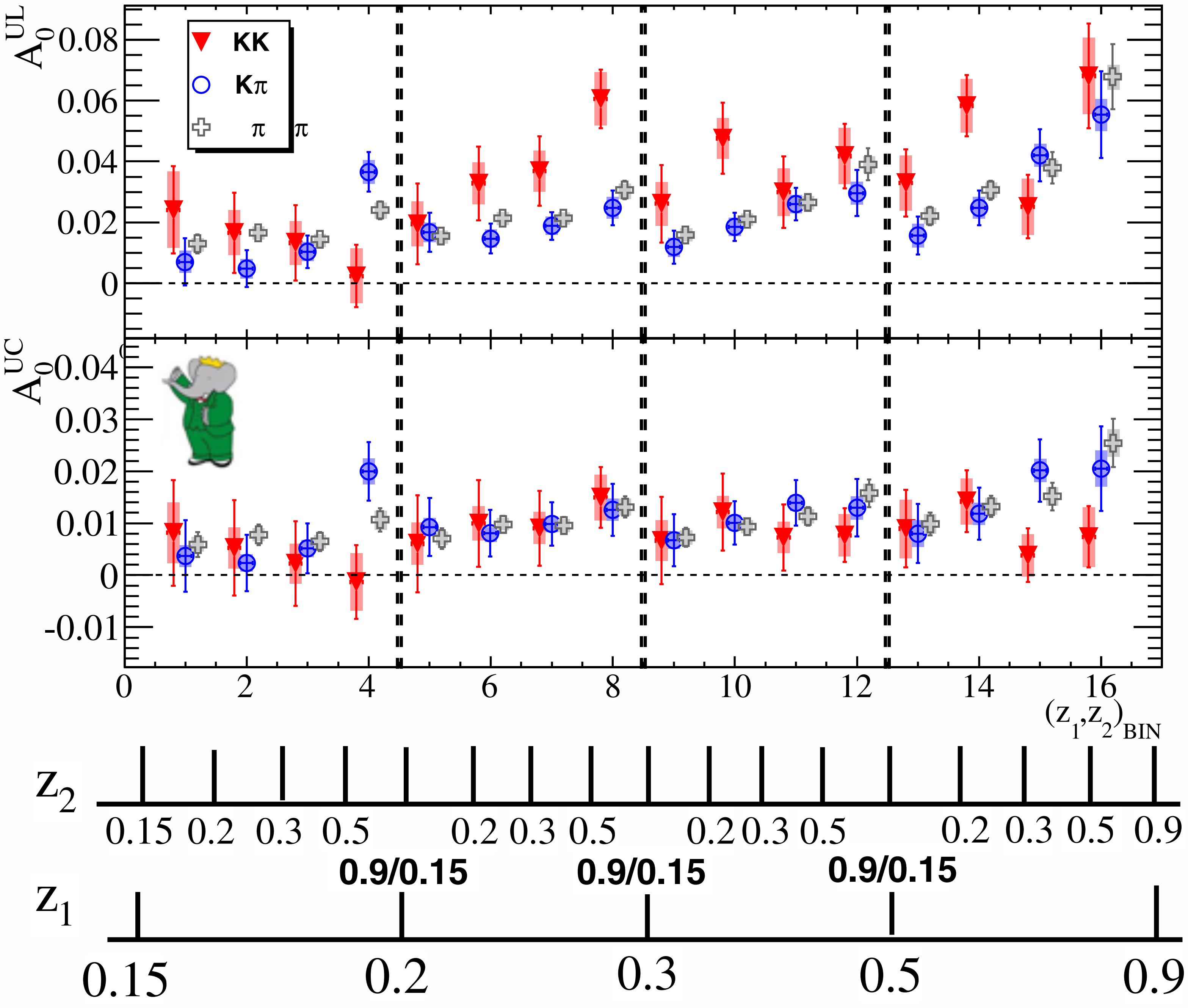






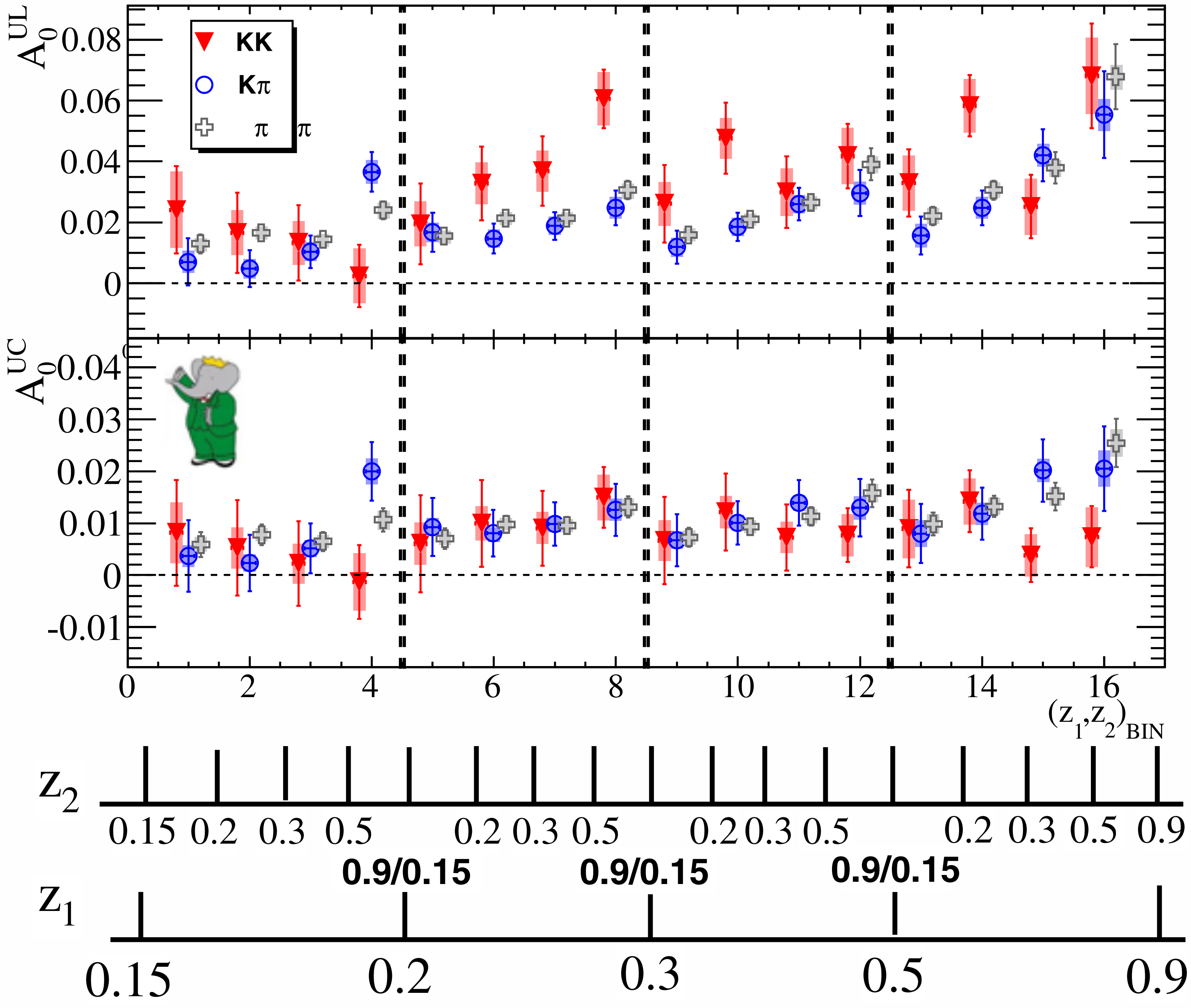
- BaBar results [PRD 90 (2014) 052003] consistent with Belle
- BESIII [PRL 116 (2016) 042001] (at smaller s) consistent with TMD evolution [Z.-B. Kang et al., PRD 93 (2016) 014009]

Collins asymmetries - going further

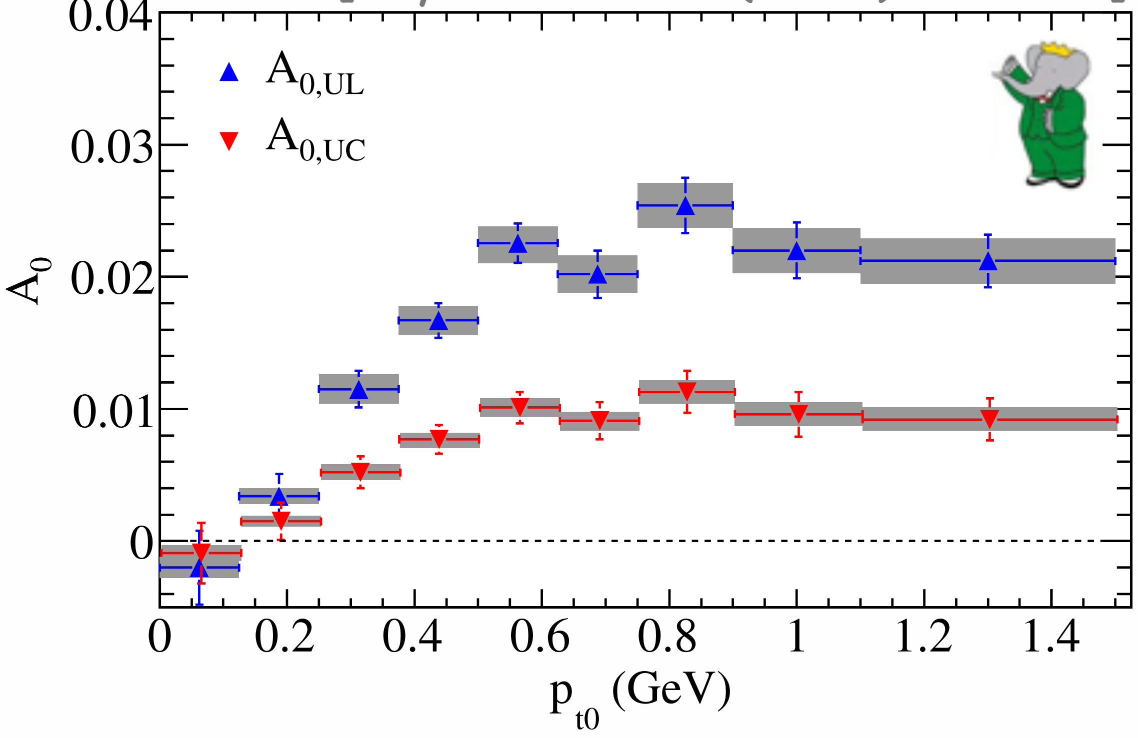


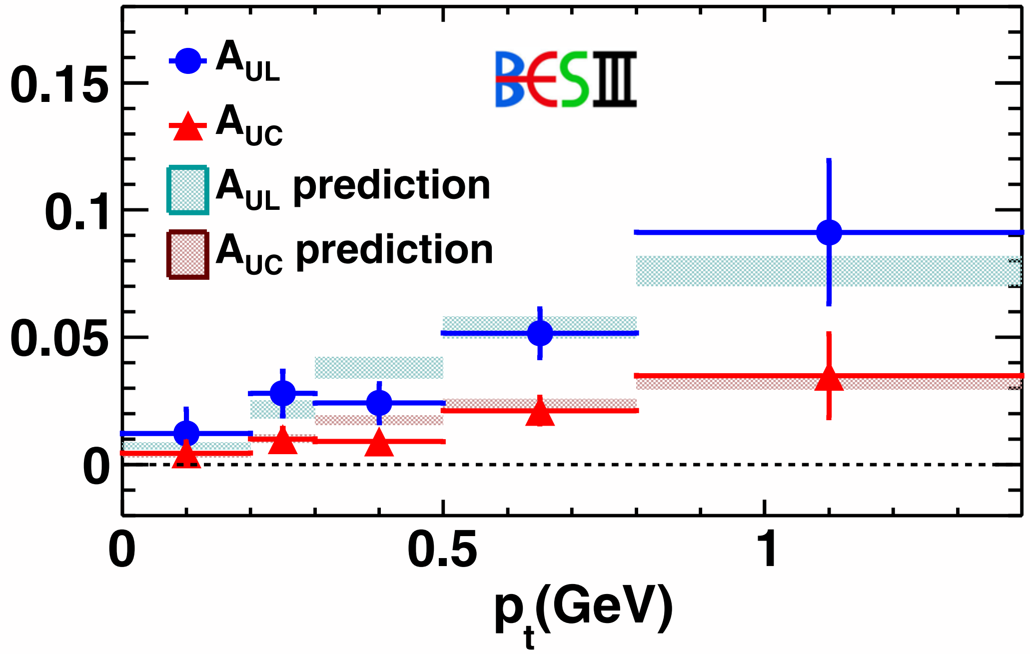
- even larger effects seen for kaon pairs

Collins asymmetries - going further



[Phys. Rev. D90 (2014) 052003]

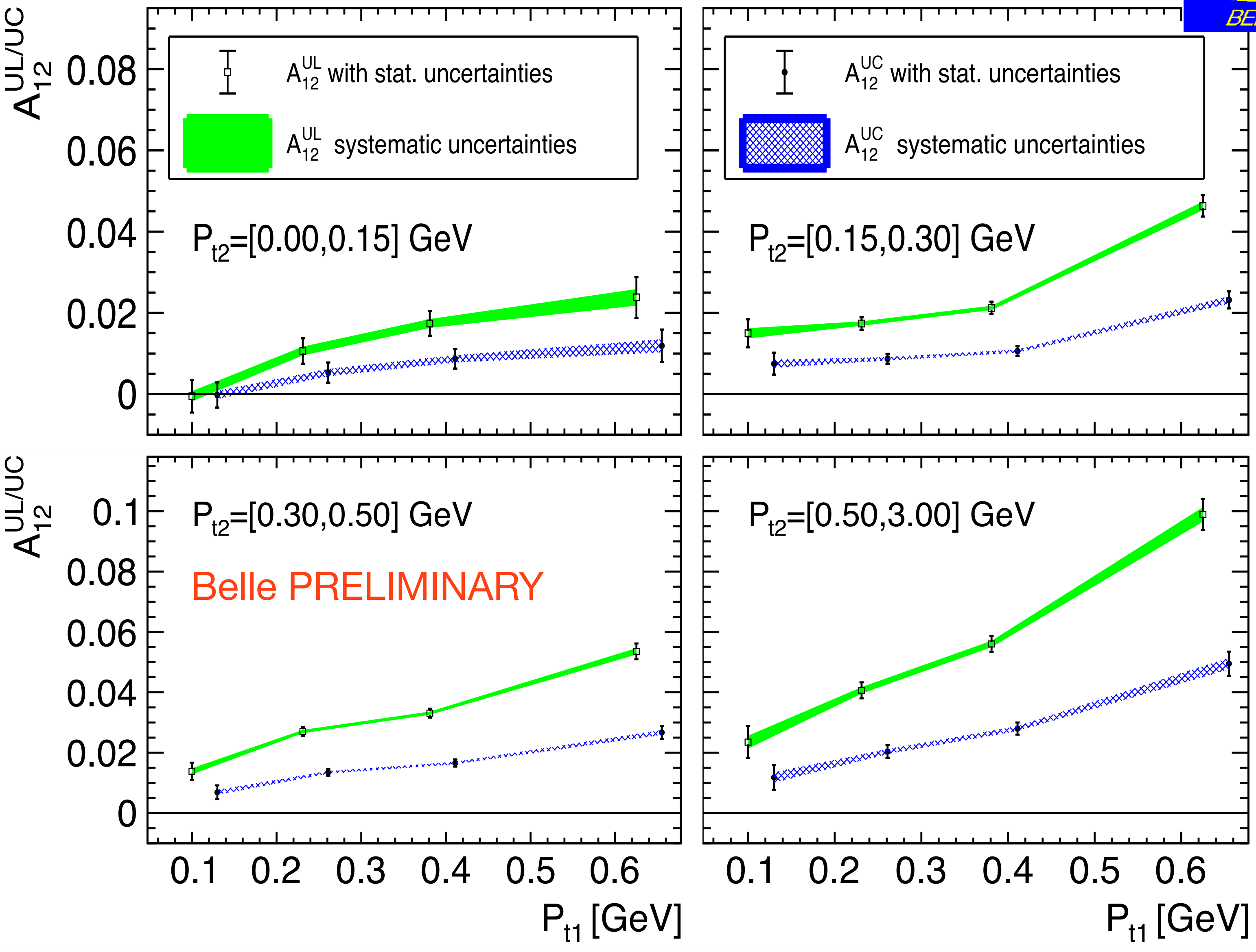




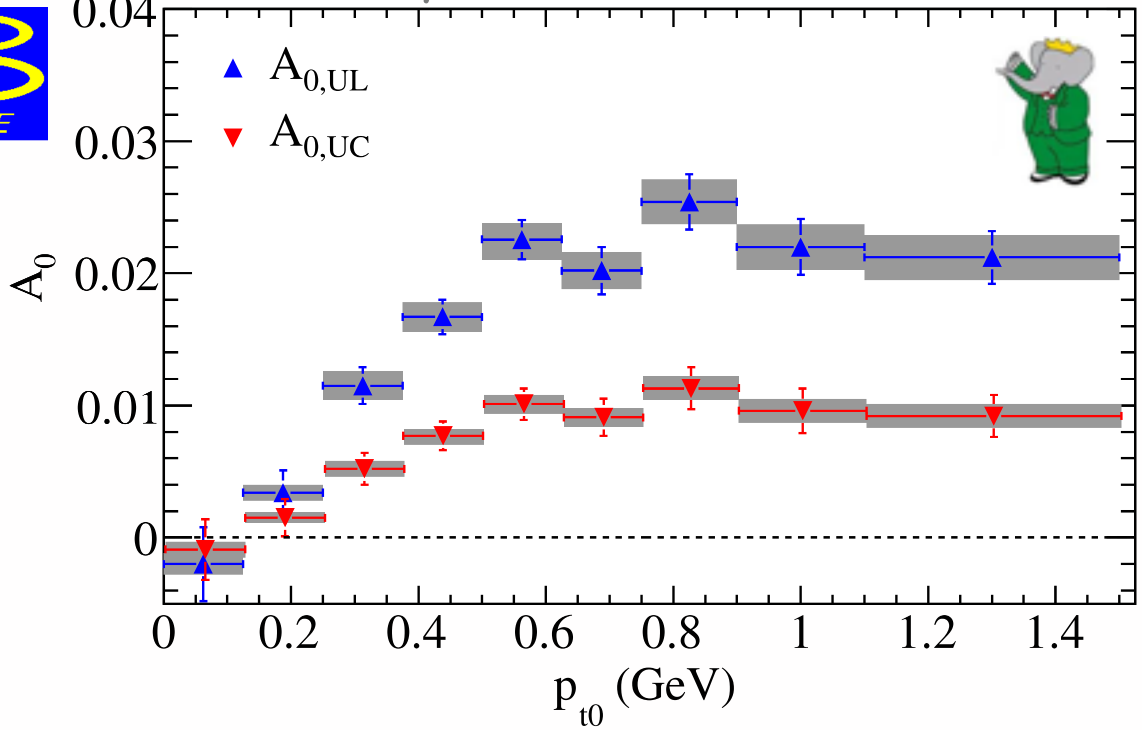
[PRL 116 (2016) 042001]

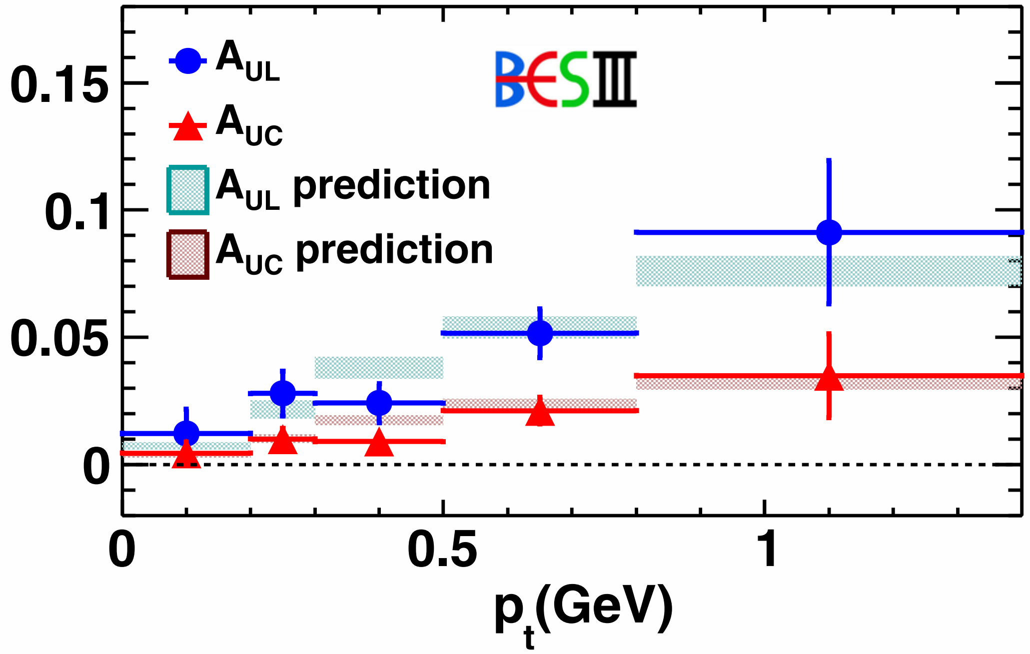
- even larger effects seen for kaon pairs
- p_T dependence for pions

Collins asymmetries - going further



[Phys. Rev. D90 (2014) 052003]

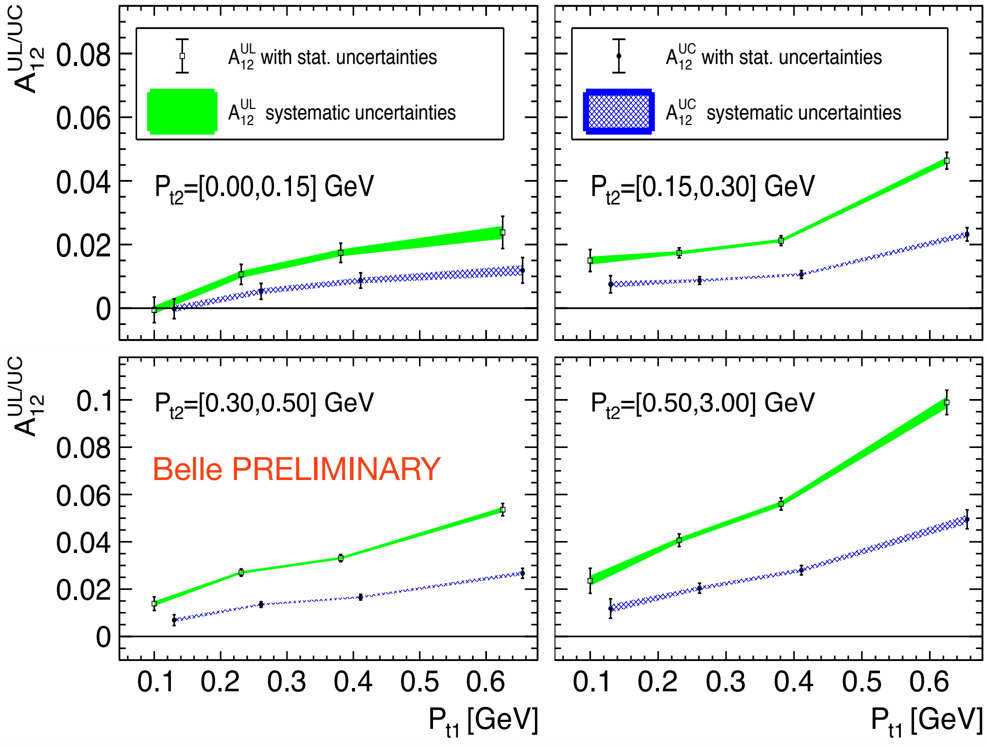


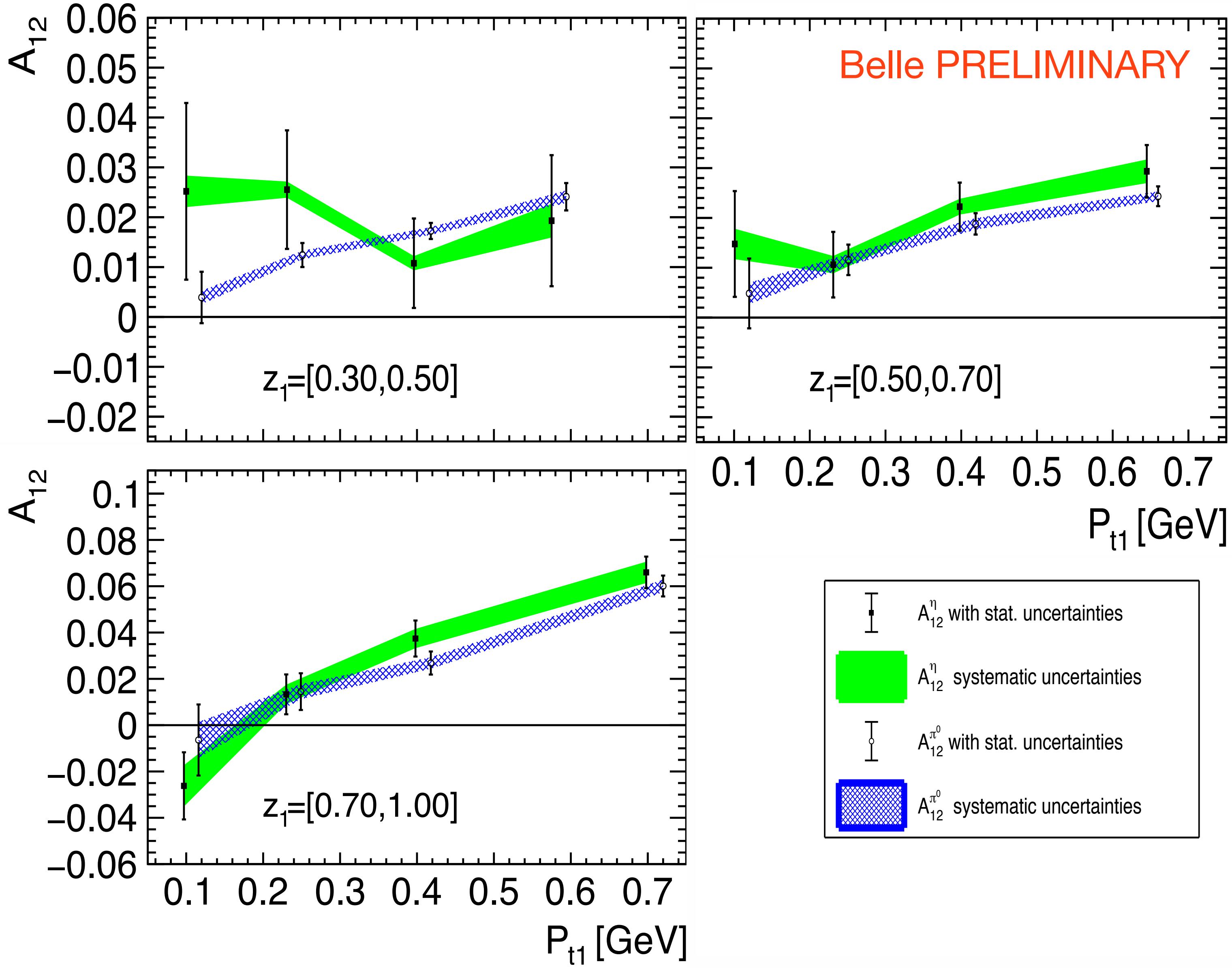


[PRL 116 (2016) 042001]

- now also from Belle for charged pions
- p_T dependence for pions

Collins asymmetries - going further





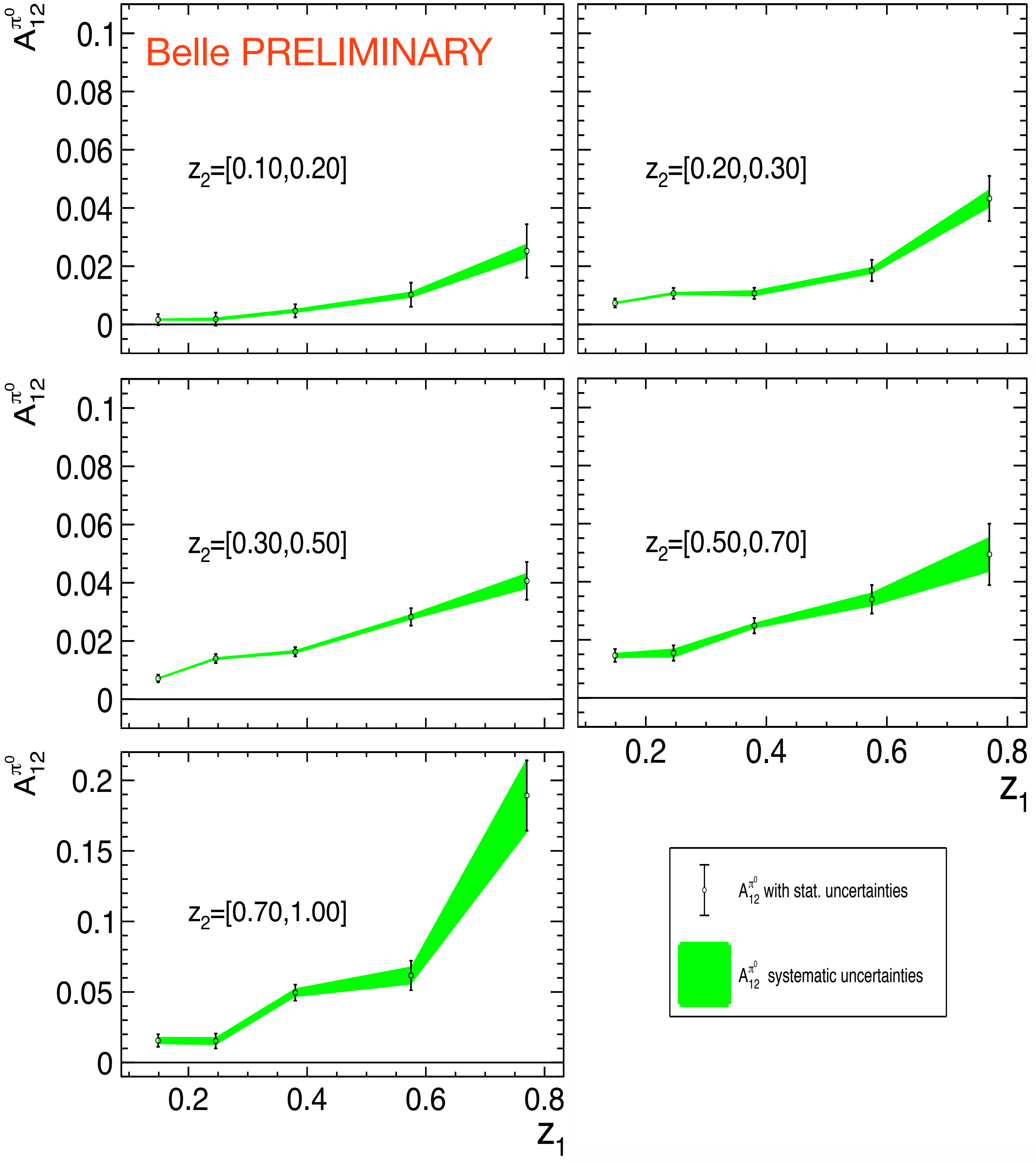
$$R_{12}^{\pi^0} = \frac{R_{12}^{0\pm}}{R_{12}^{L}} = \frac{\pi^0\pi^+ + \pi^0\pi^-}{\pi^+\pi^+ + \pi^-\pi^-};$$

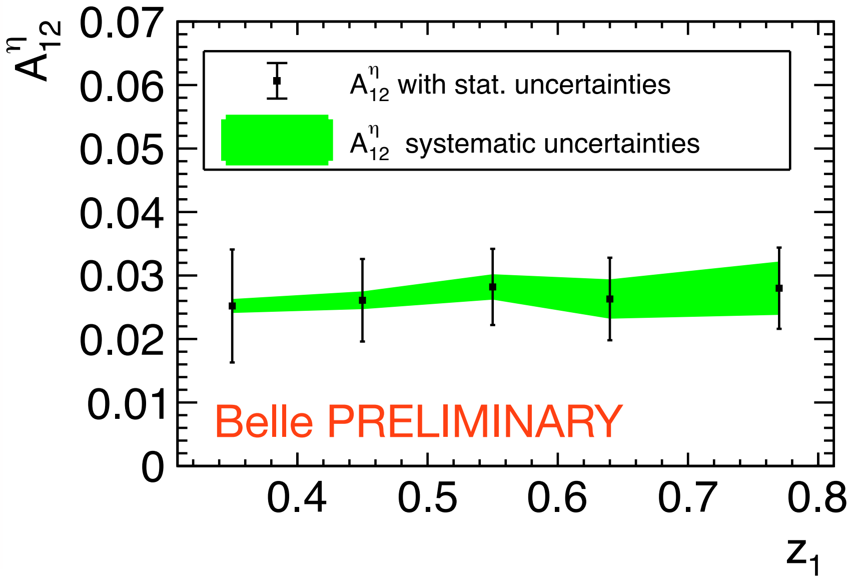
$$R_{12}^{\eta} = \frac{R_{12}^{\eta\pm}}{R_{12}^{L}} = \frac{\eta\pi^+ + \eta\pi^-}{\pi^+\pi^+ + \pi^-\pi^-}.$$

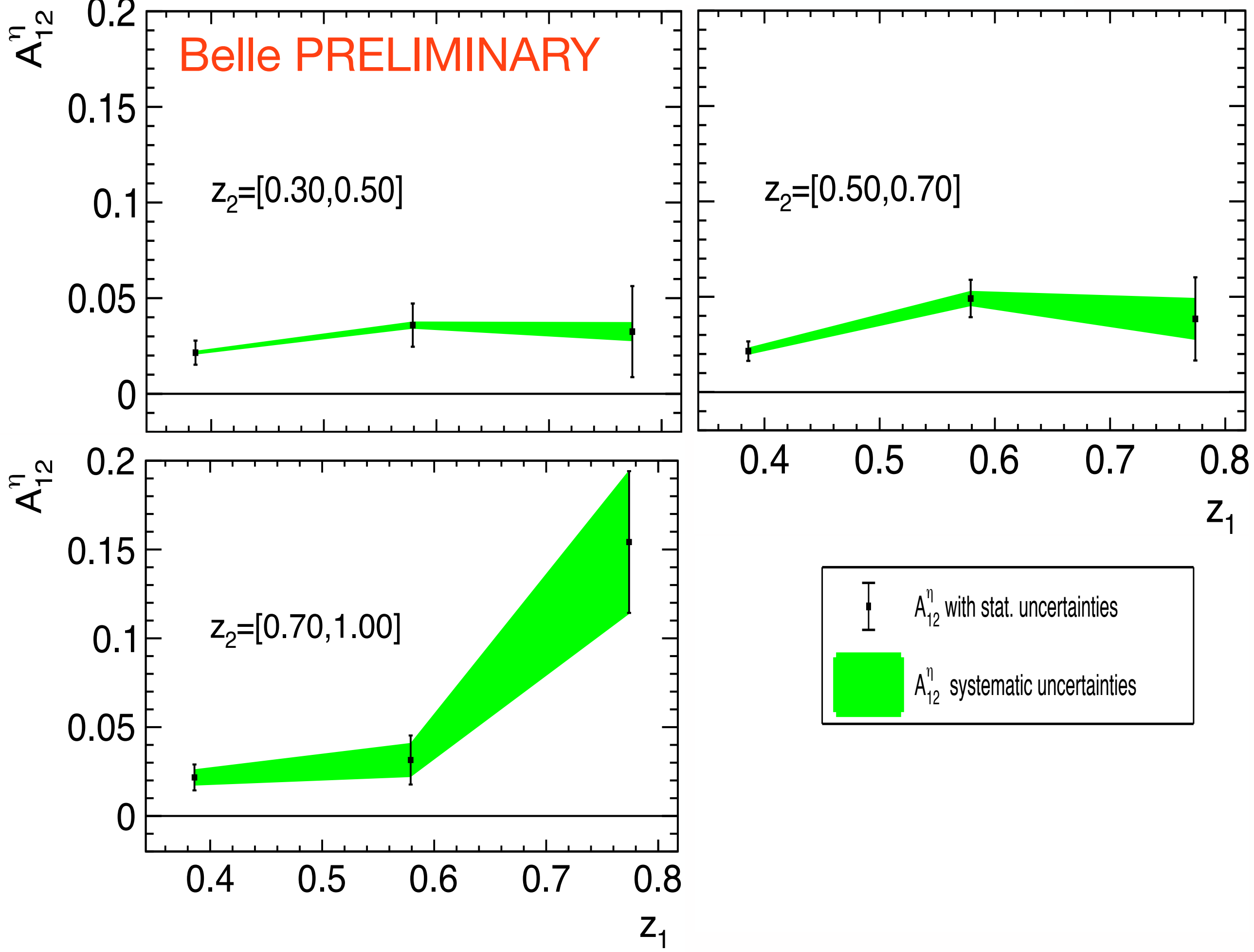
- now also from Belle for charged pions

- ... and neutral pion and eta

Collins asymmetries - going further







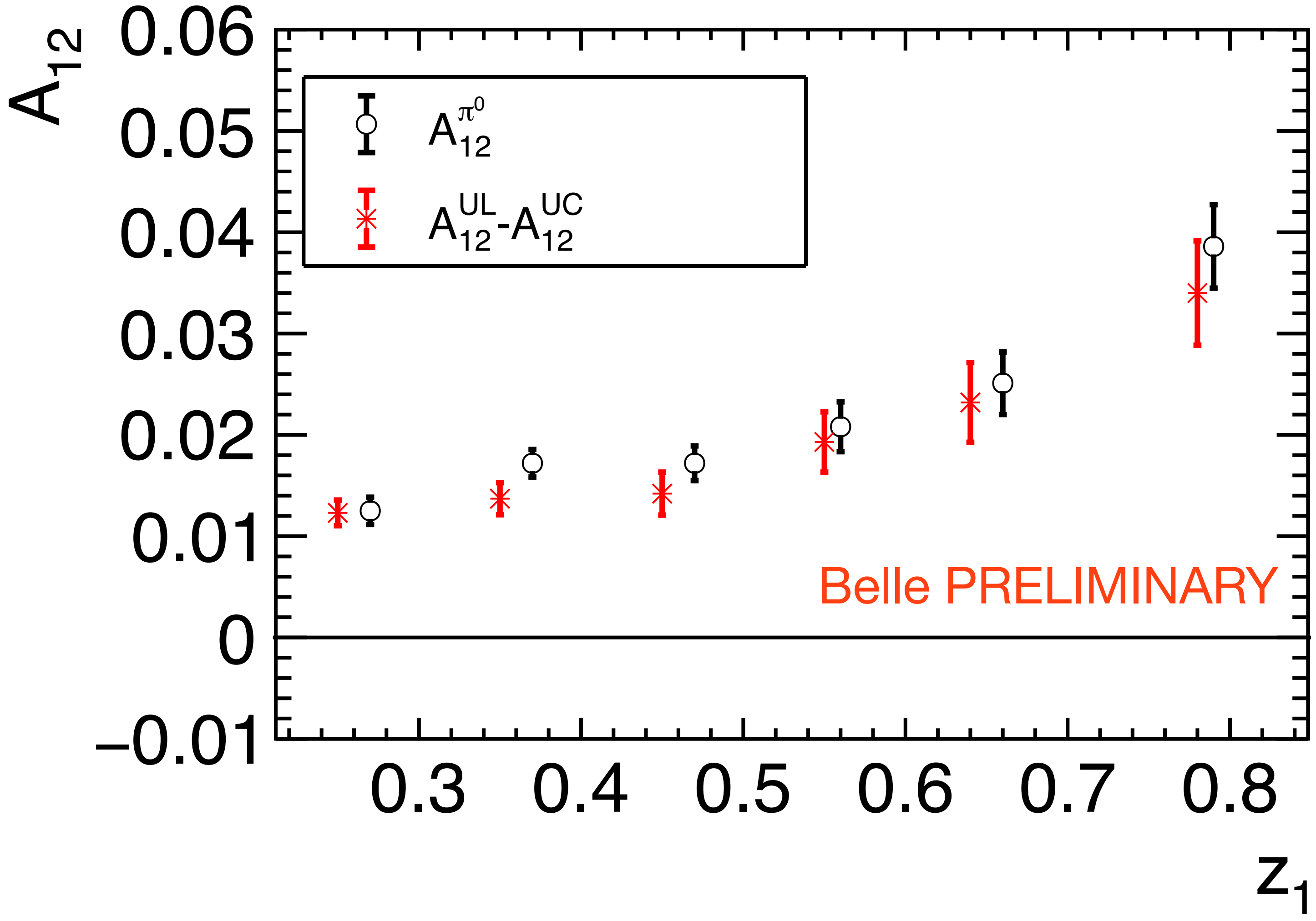
- typical rise with z seen for neutral pion
- eta almost flat except for large-z region

Collins asymmetries - going further

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

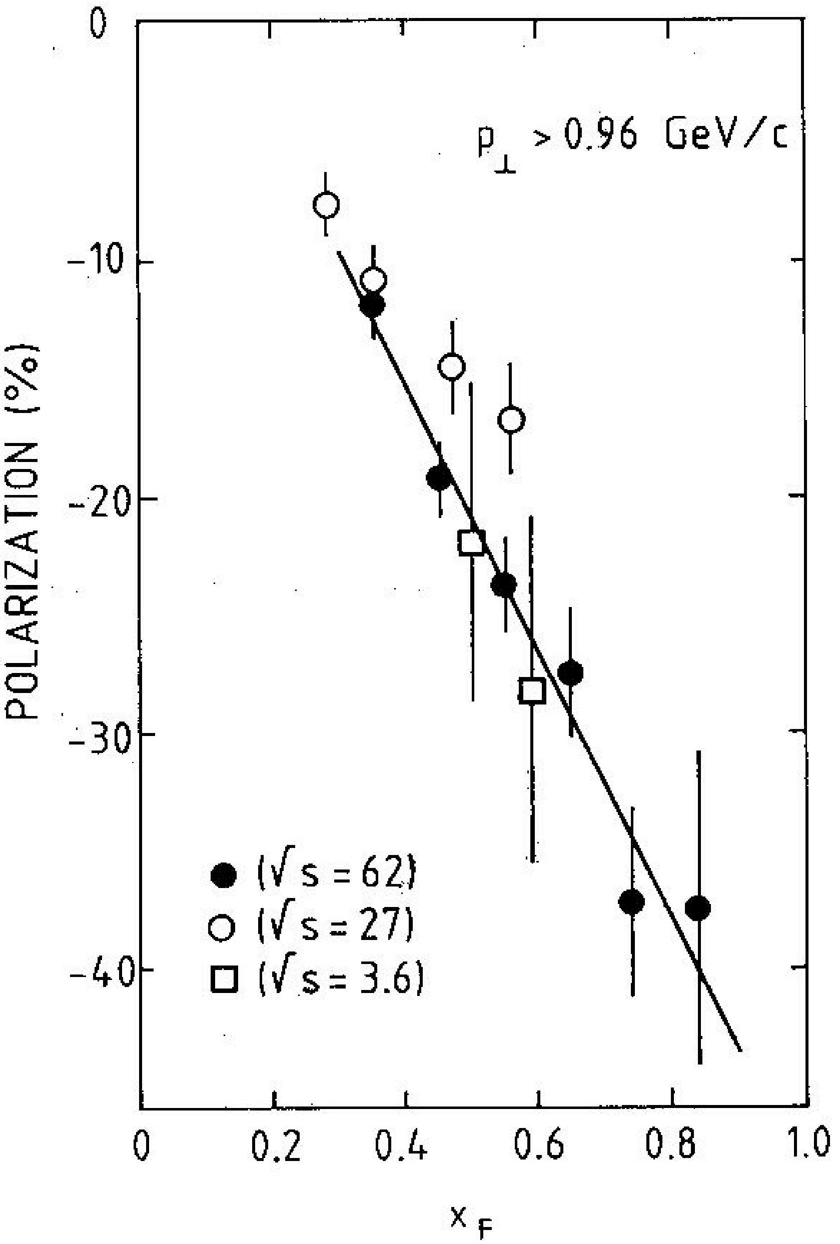
Collins asymmetries - going further

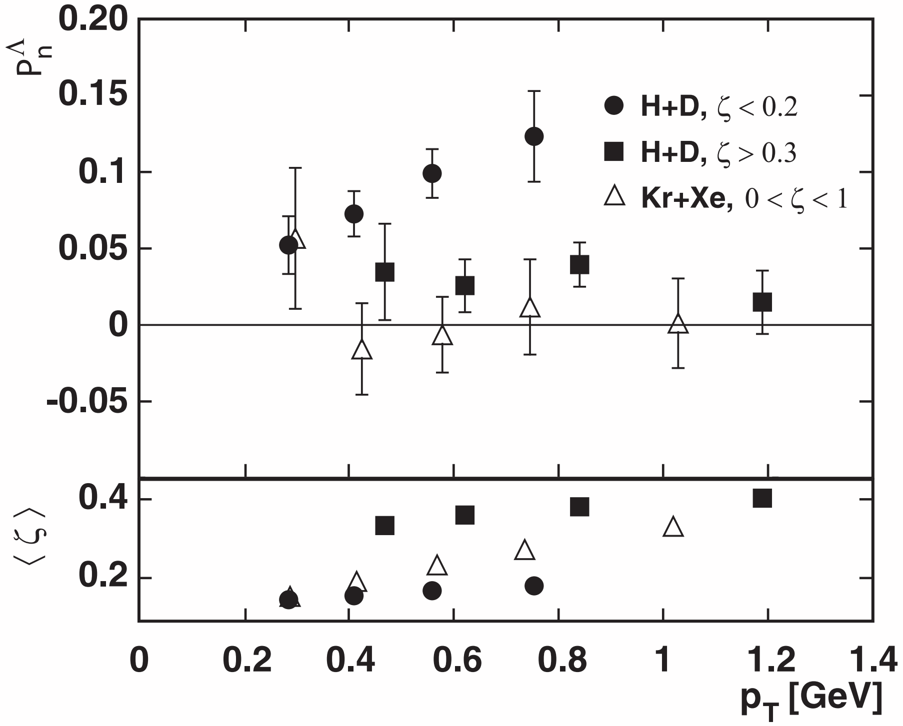
$$\left.\begin{array}{l} R_{12}^{\pi^0} = \dfrac{R_{12}^{0\pm}}{R_{12}^{L}} \approx 1+\cos(\phi_{12})\dfrac{\sin^2(\theta)}{1+\cos^2(\theta)} \\ \quad \times \left\{ \dfrac{5(H_1^{\perp,fav}+H_1^{\perp,dis})\otimes(H_1^{\perp,fav}+H_1^{\perp,dis})+4H_{1,s\to\pi}^{\perp,dis}\otimes H_{1,s\to\pi}^{\perp,dis}}{5(D_1^{fav}+D_1^{dis})\otimes(D_1^{fav}+D_1^{dis})+4D_{1,s\to\pi}^{dis}\otimes D_{1,s\to\pi}^{dis})} \right. \\ \quad \left. - \dfrac{5(H_1^{\perp,fav}\otimes H_1^{\perp,dis}+H_1^{\perp,dis}\otimes H_1^{\perp,fav})+2H_{1,s\to\pi}^{\perp,dis}H_{1,s\to\pi}^{\perp,dis}}{5(D_1^{fav}\otimes D_1^{dis}+D_1^{dis}\otimes D_1^{fav})+2D_{1,s\to\pi}^{dis}\otimes D_{1,s\to\pi}^{dis}} \right\}. \end{array}\right\} \overset{\text{isospin}}{=} A_{12}^{UL} - A_{12}^{UC}$$



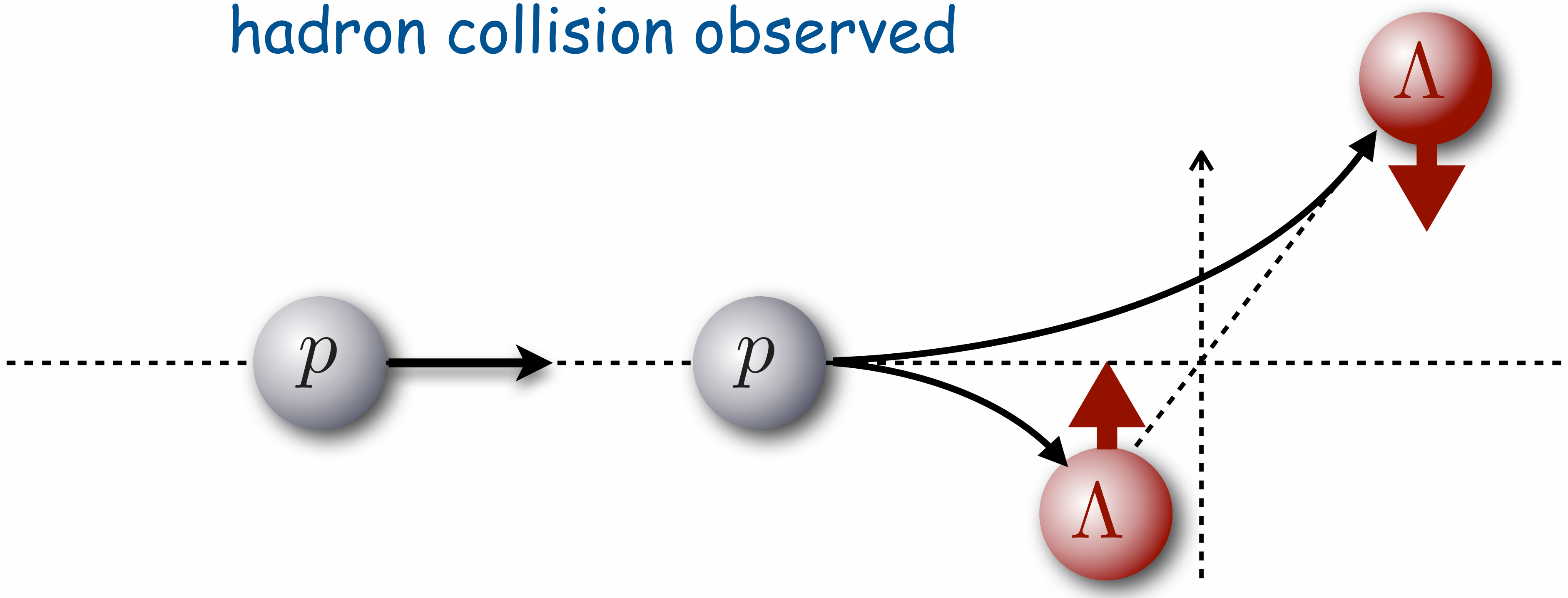
- consistency between neutral and charged pions

polarizing fragmentation



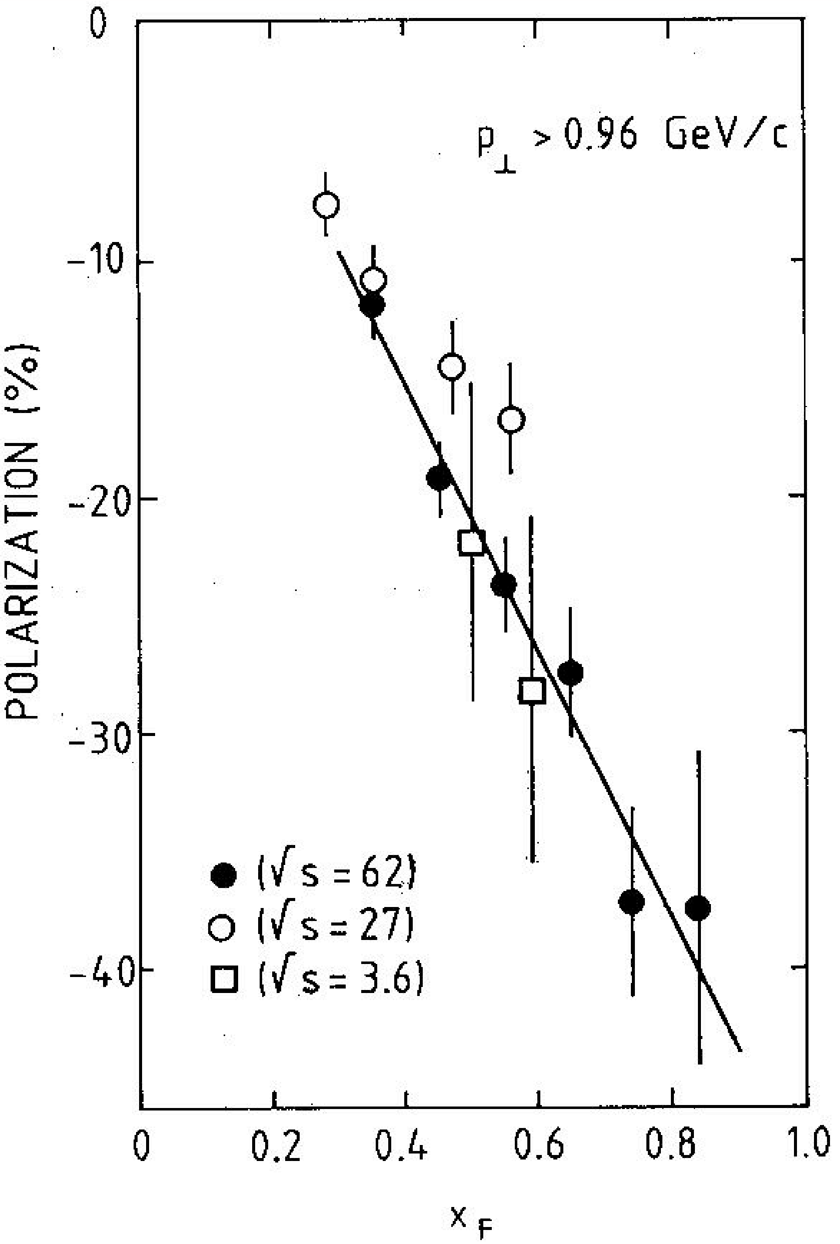


- large hyperon polarization in unpolarized hadron collision observed

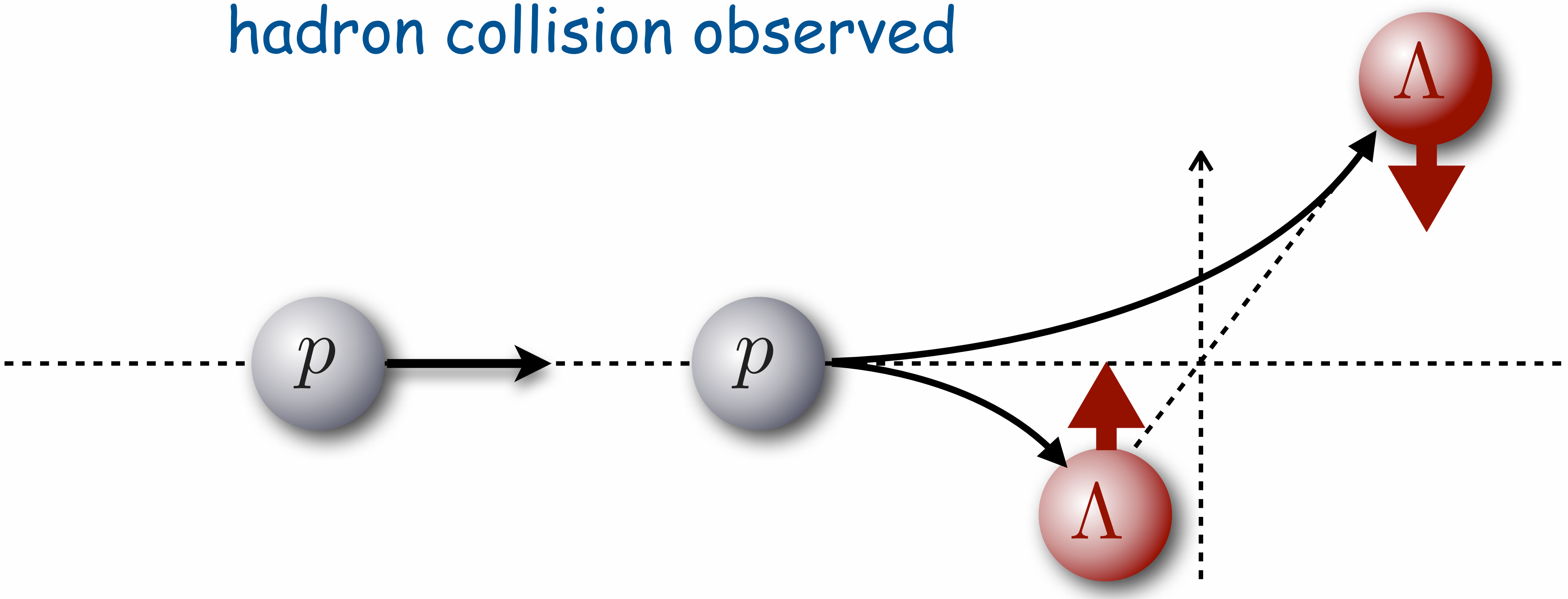


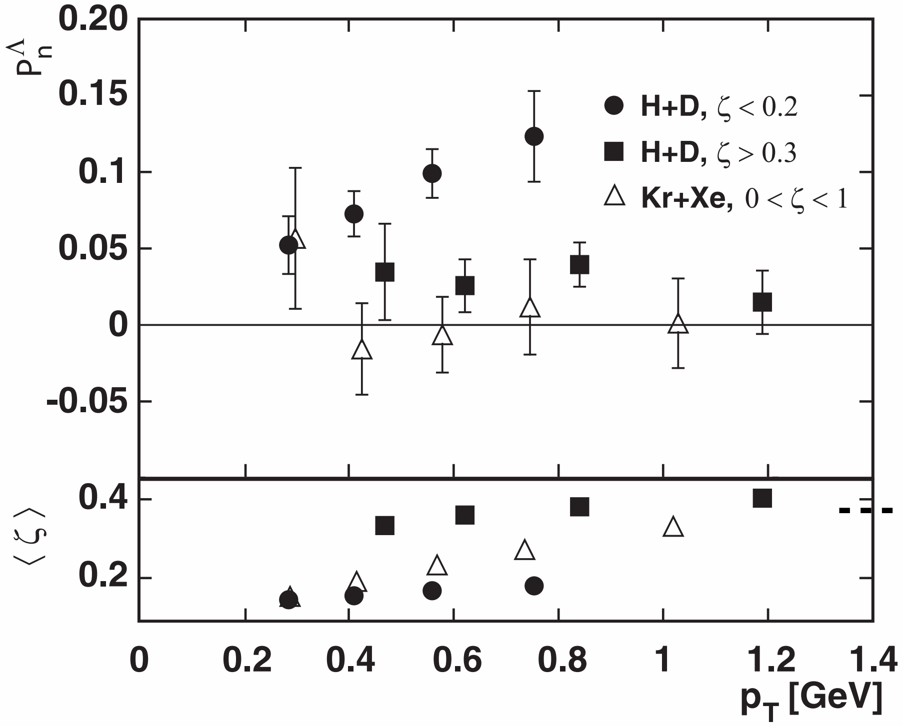
- … as well as in inclusive lepto-production

polarizing fragmentation

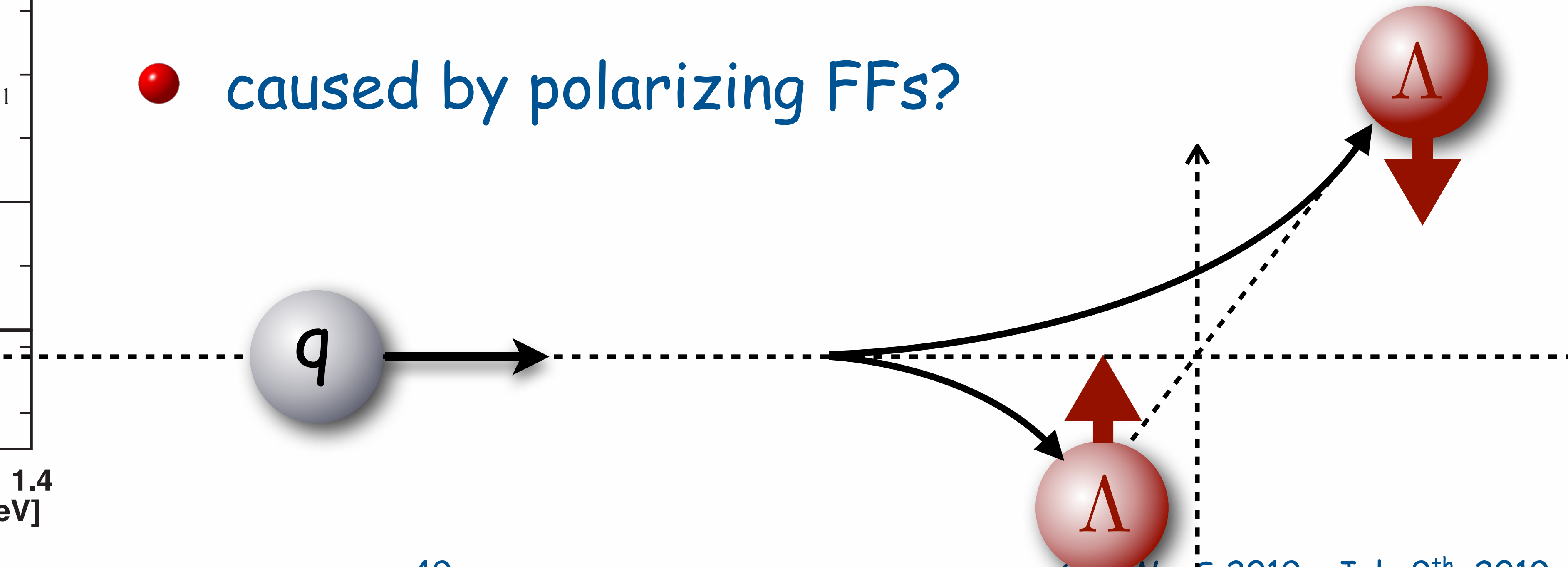


- large hyperon polarization in unpolarized hadron collision observed





- … as well as in inclusive lepto-production
- caused by polarizing FFs?



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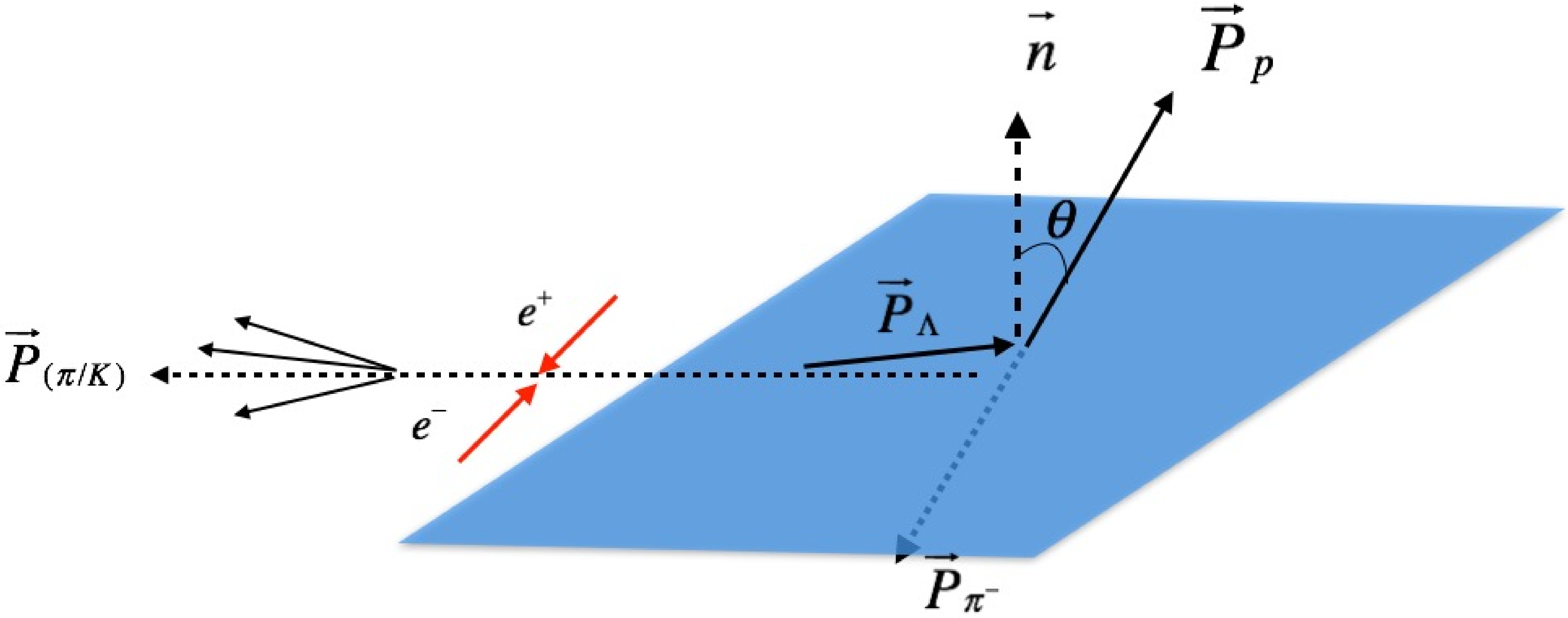
polarizing fragmentation function

- polarization measured normal to production plane, i.e. ∝("P_q" × P_Λ)

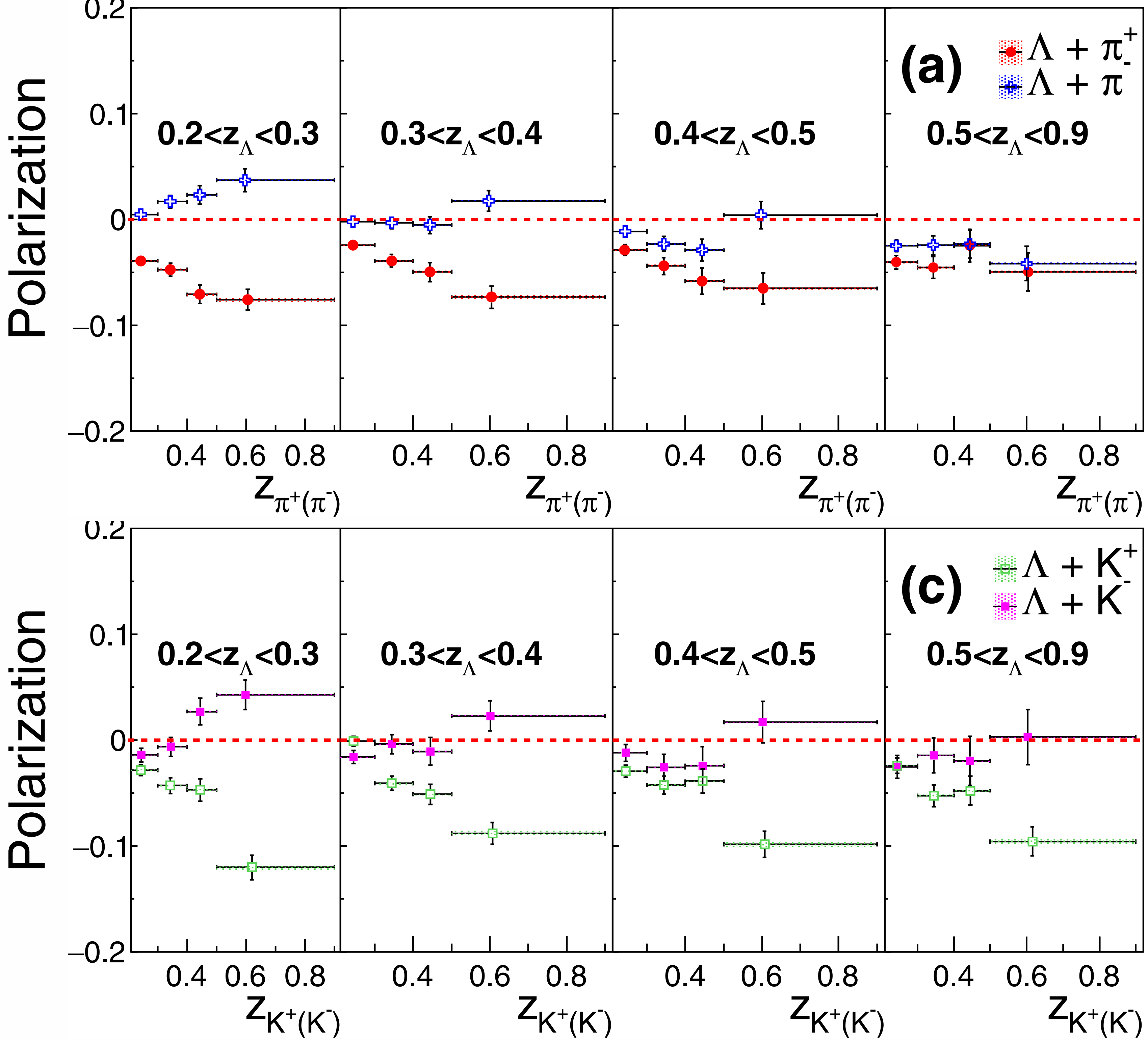


- reference axis to define transverse momentum:
  - "hadron frame" - use momentum direction of "back-to-back" hadron
  - "thrust frame" - use thrust axis
- use self-analyzing weak decay of Λ to determine polarization

polarizing fragmentation function

- flavor tagging through hadrons in opposite hemisphere:

[Belle, PRL 122 (2019) 042001]



- large-z_h hadrons tag quark flavor more efficiently

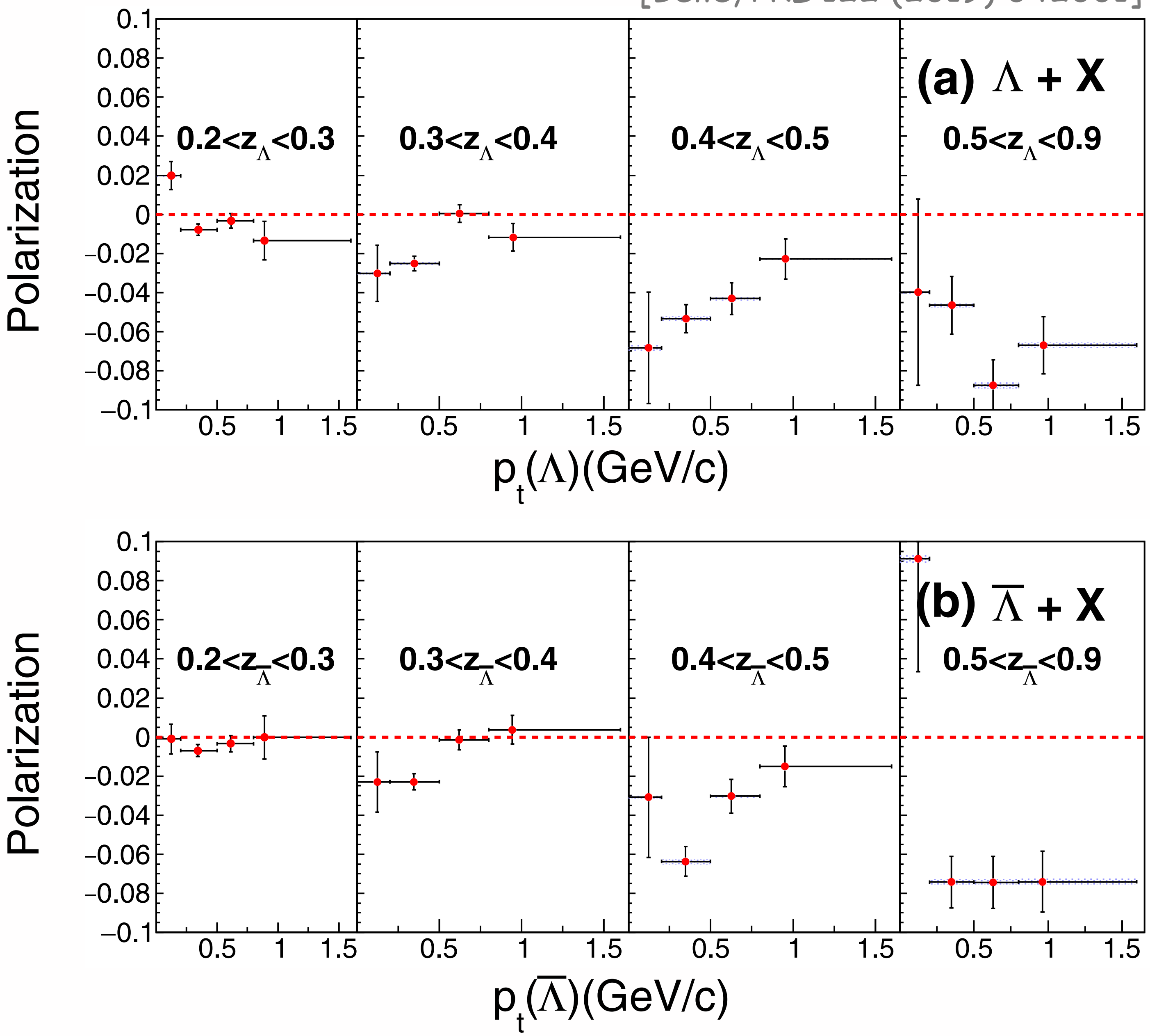
➡ enlarges differences between oppositely charged hadrons

- MC-based quark-flavor decomposition in backup

polarizing fragmentation function

- polarization measured as function of z and p_t

[Belle, PRL 122 (2019) 042001]

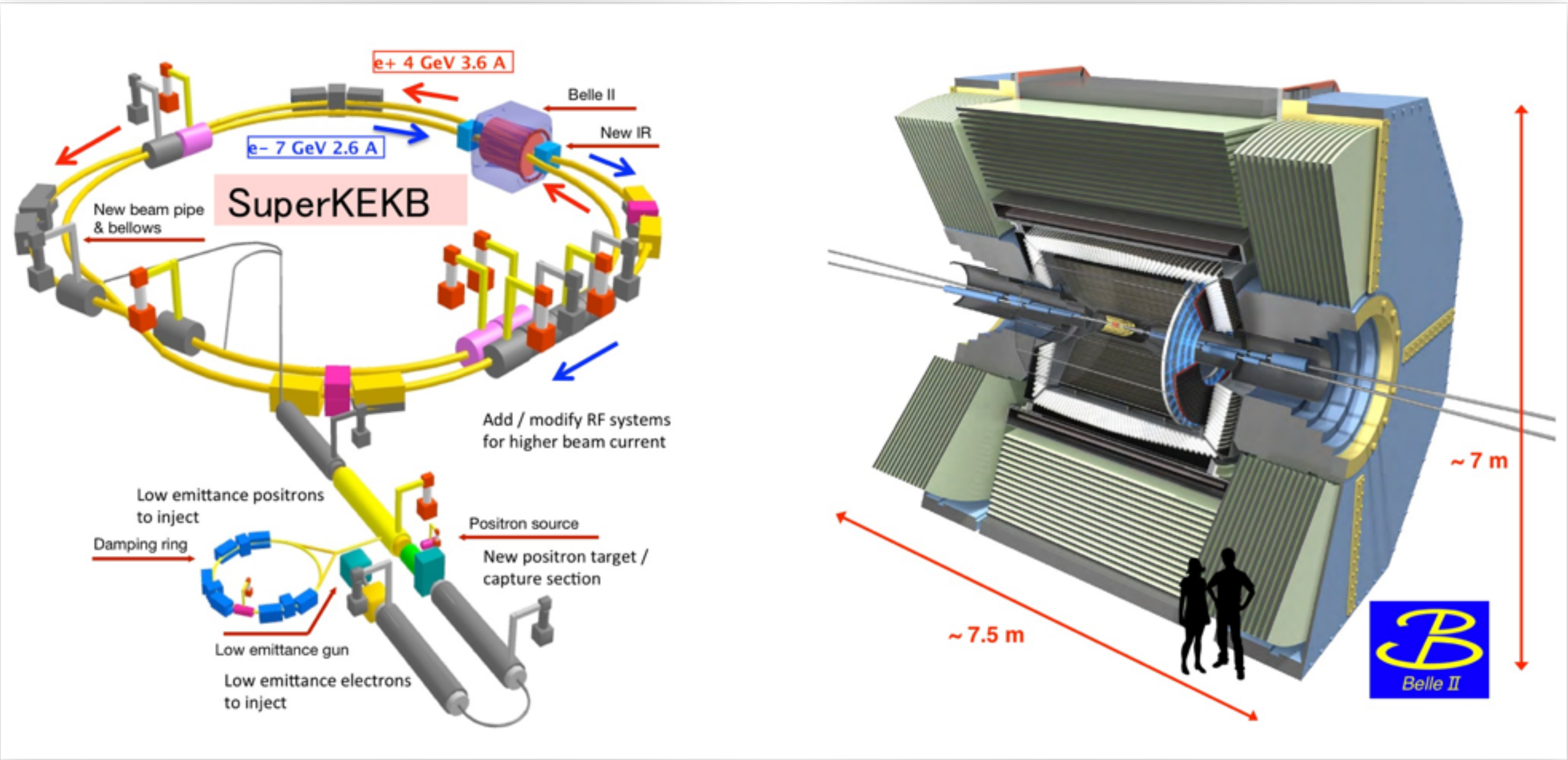


- strong dependence on both kinematics
  - unexpected/surprising behavior for p_t -> 0

what to further expect (**soon**) from e^+e^-

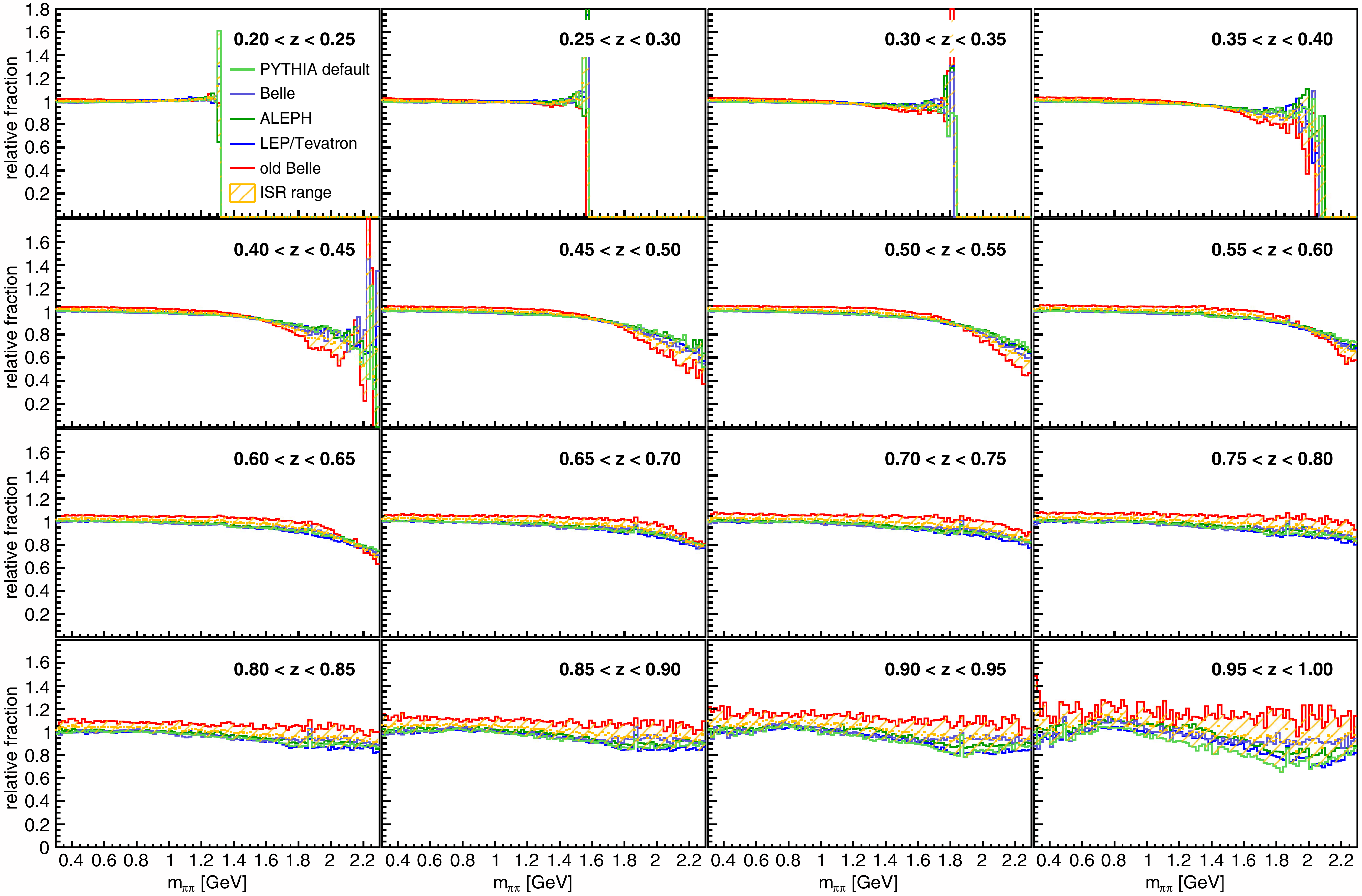
- single-hadron production
  - **re-analysis with new ISR (Belle)**
  - lower-s data (BESIII; Belle via ISR)
- k_T-dependent D_1 FFs (Belle, possibly BESIII)
  - nearly back-to-back hadrons
- Collins asymmetries:
  - **neutral meson (pion and eta) incl. k_T dependence** (Belle)
  - kaon and pion-kaon pairs as well as k_T dependence of Collins asymmetries (Belle, BESIII)
  - Collins asymmetries without double ratios (BaBar)
- di-hadron production (Belle)
  - **collinear FF with new ISR and different momentum-fraction variable choice (Altarelli et al, NPB160 (1979) 301 & Mulders and Van Hulse)**
  - helicity-dependent dihadron fragmentation function $G_1^\perp$ ("jet handedness")

the future starts now



backup

ISR corrections - PRD96 (2017) 032005

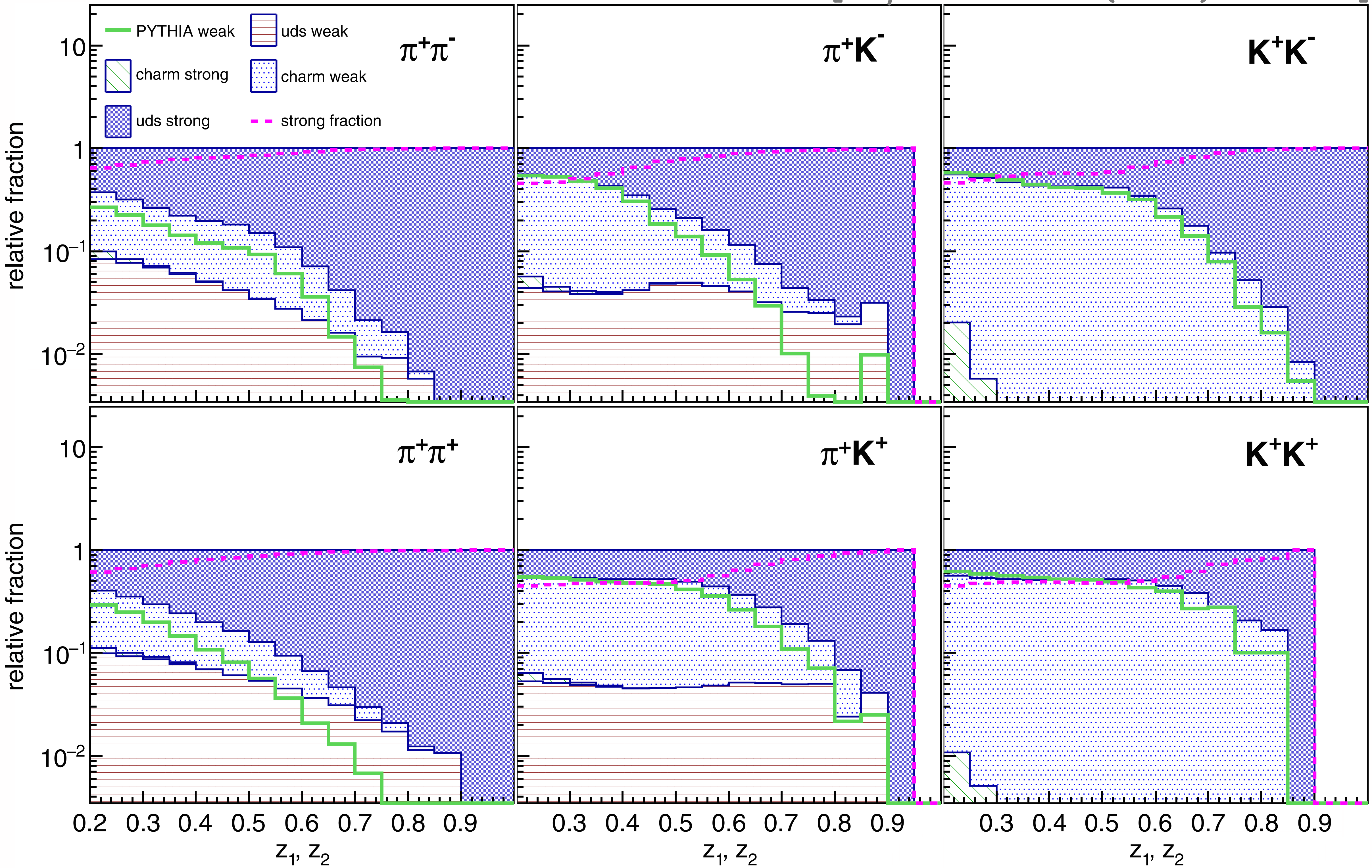


- non-ISR / ISR fractions based on PYTHIA switch MSTP(11)
  [e.g., for dihadron invariant-mass analysis shown here, but discussed later]
- model dependence absorbed in variation of PYTHIA tunes in estimate of systematic uncertainty

hadron-pairs: weak-decay contributions

- not all hadrons originate from uds quarks but e.g., from D decay
  - here only z_1=z_2 diagonal bins

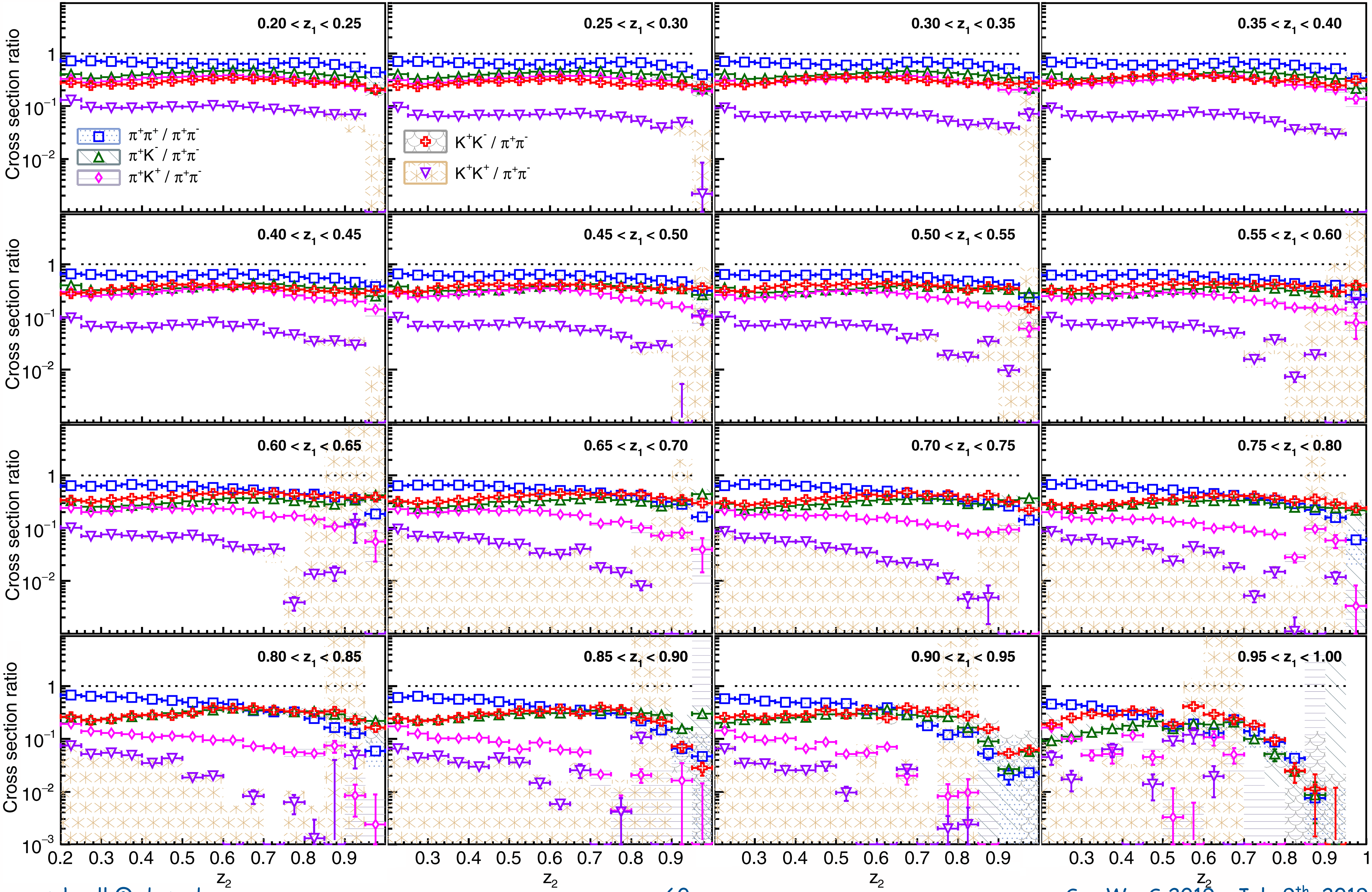
[Phys. Rev. D92 (2015) 092007]



hadron-pair production

no hemisphere selection

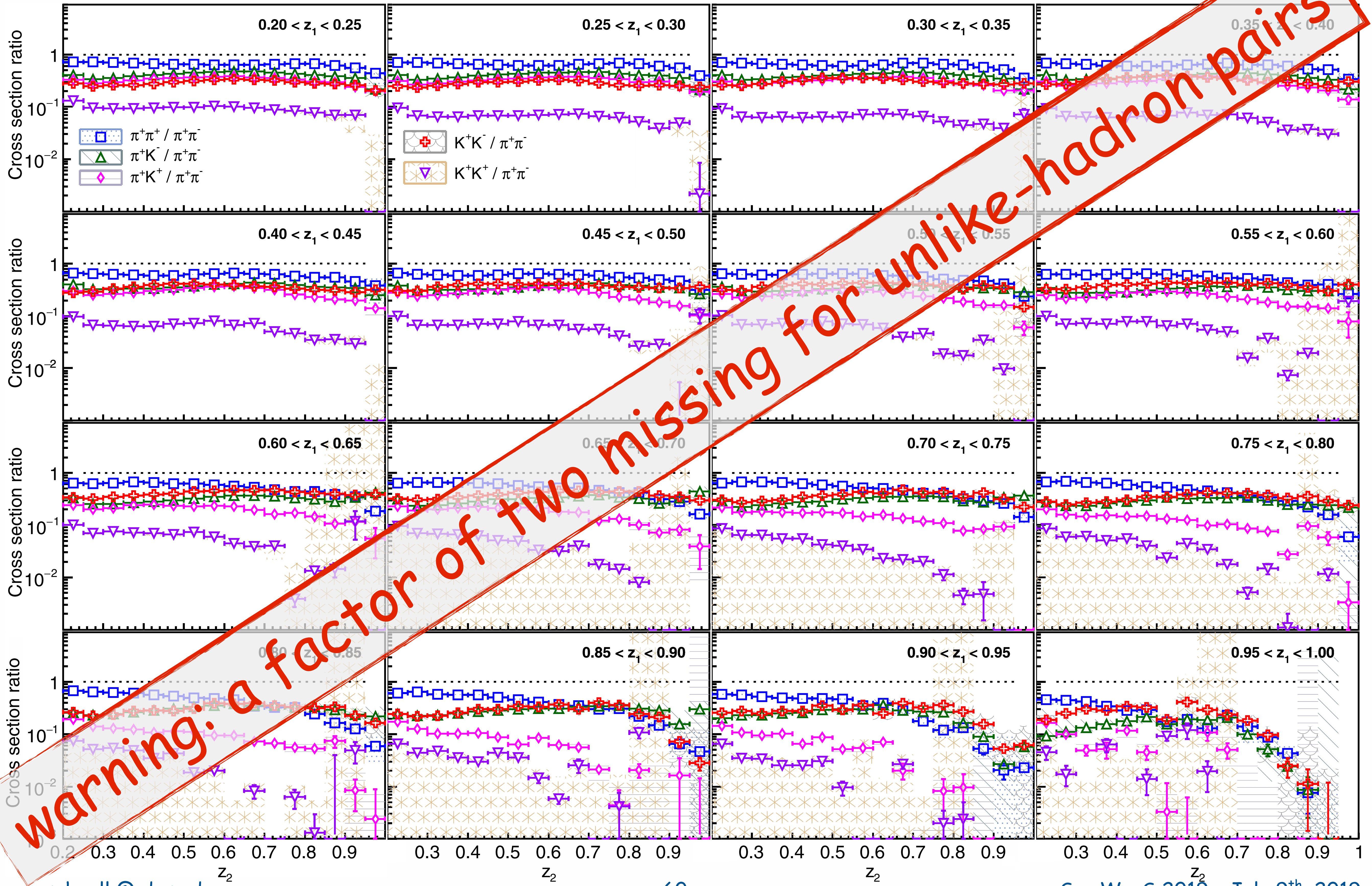
[Phys. Rev. D92 (2015) 092007]



hadron-pair production

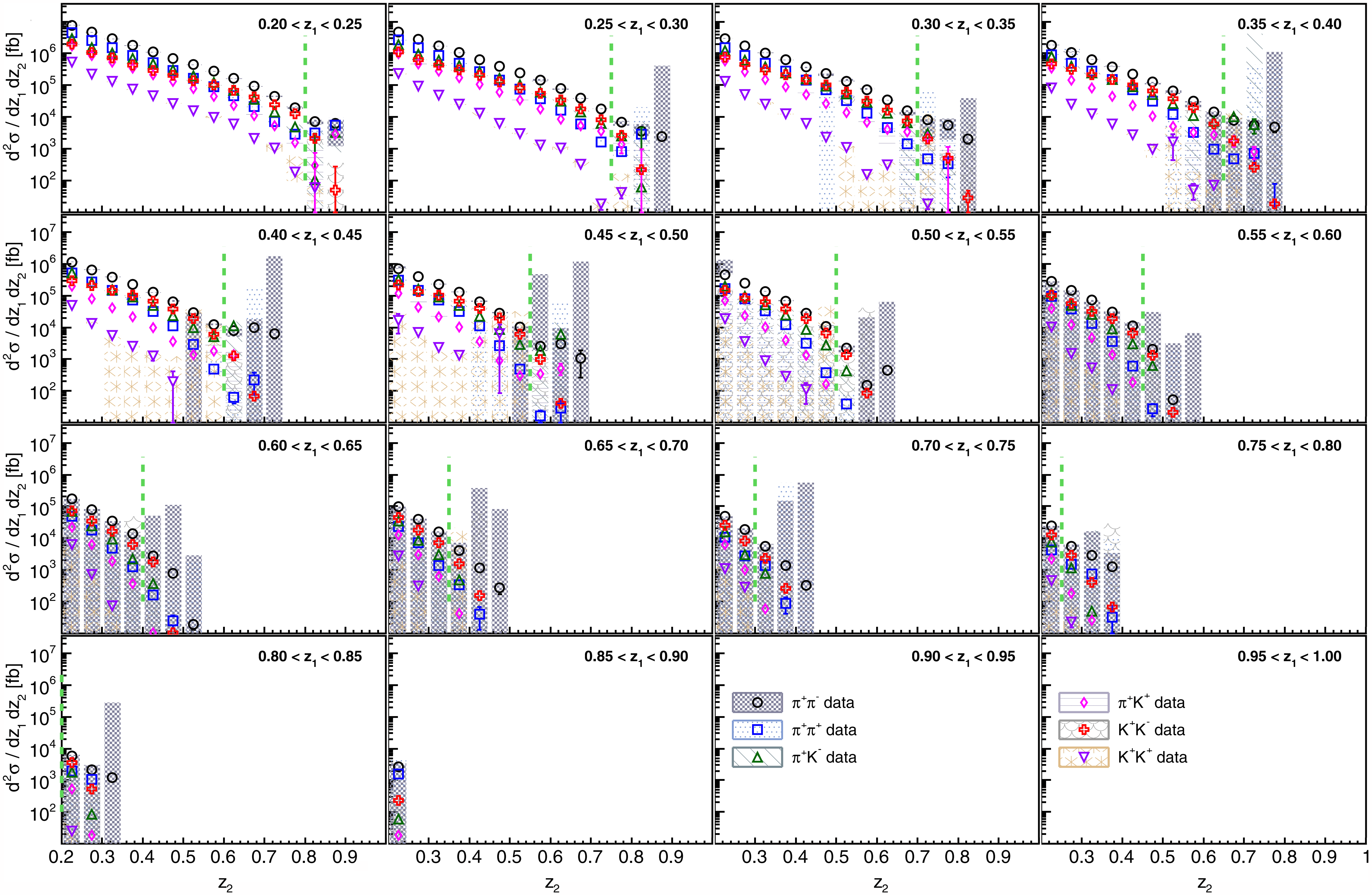
no hemisphere selection

[Phys. Rev. D92 (2015) 092007]



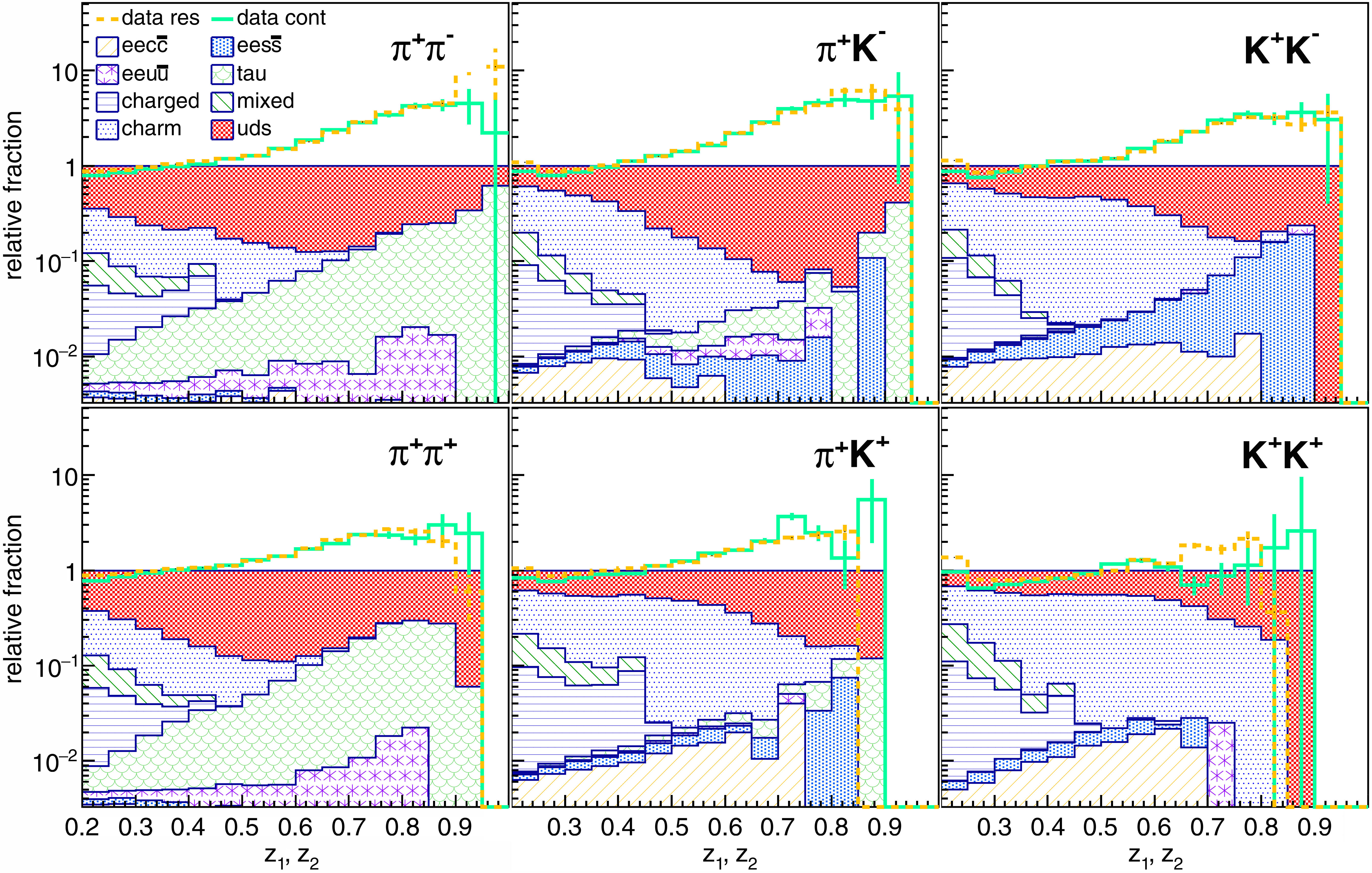
warning: a factor of two missing for unlike-hadron pairs

same-hemisphere hadron pairs



hadron-pairs: subprocess contributions

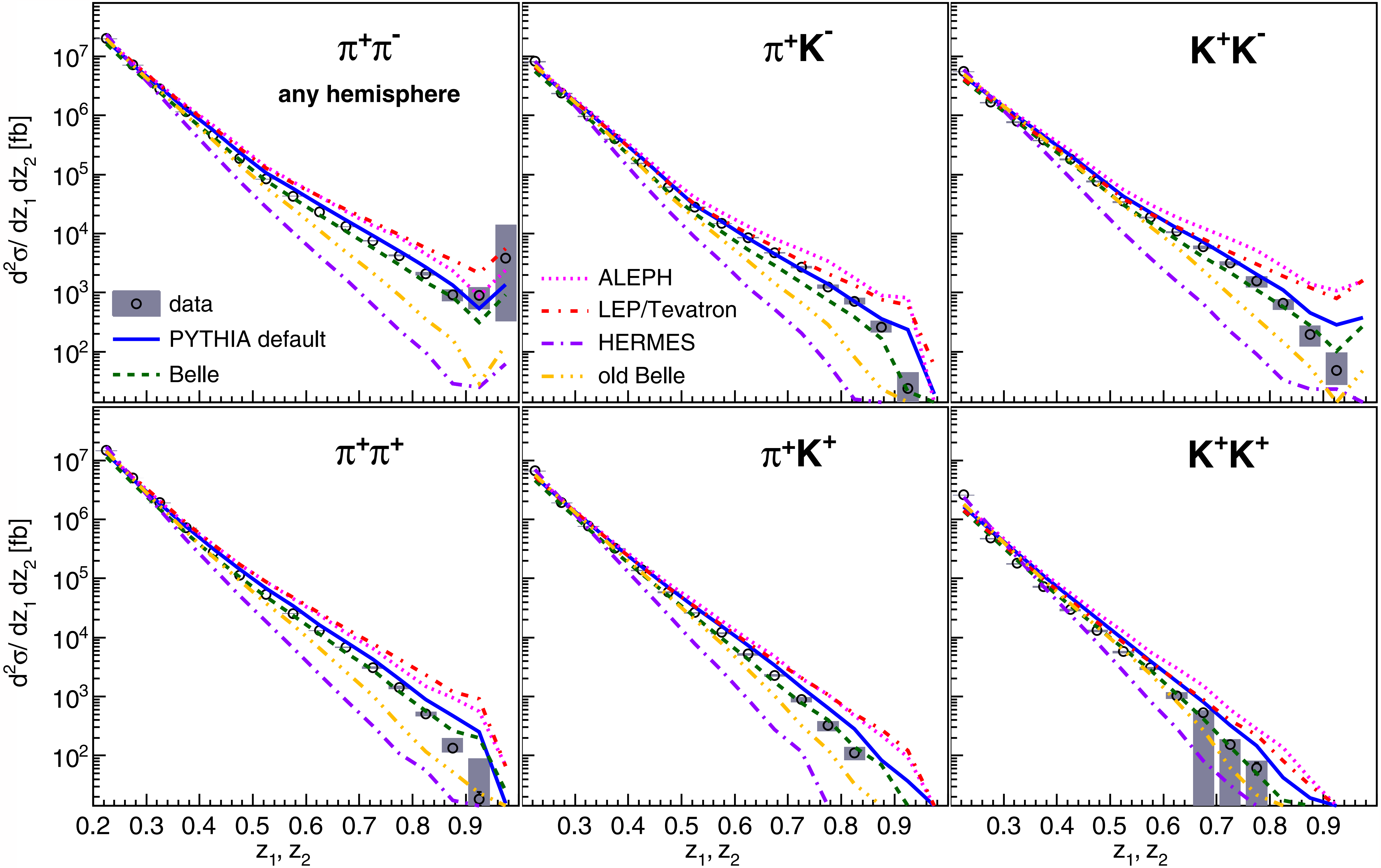
[Phys. Rev. D92 (2015) 092007]



hadron-pairs: comparison with PYTHIA

- generally good agreement at low z
  - at large z only present Belle and PYTHIA default tunes satisfactory

[Phys. Rev. D92 (2015) 092007]

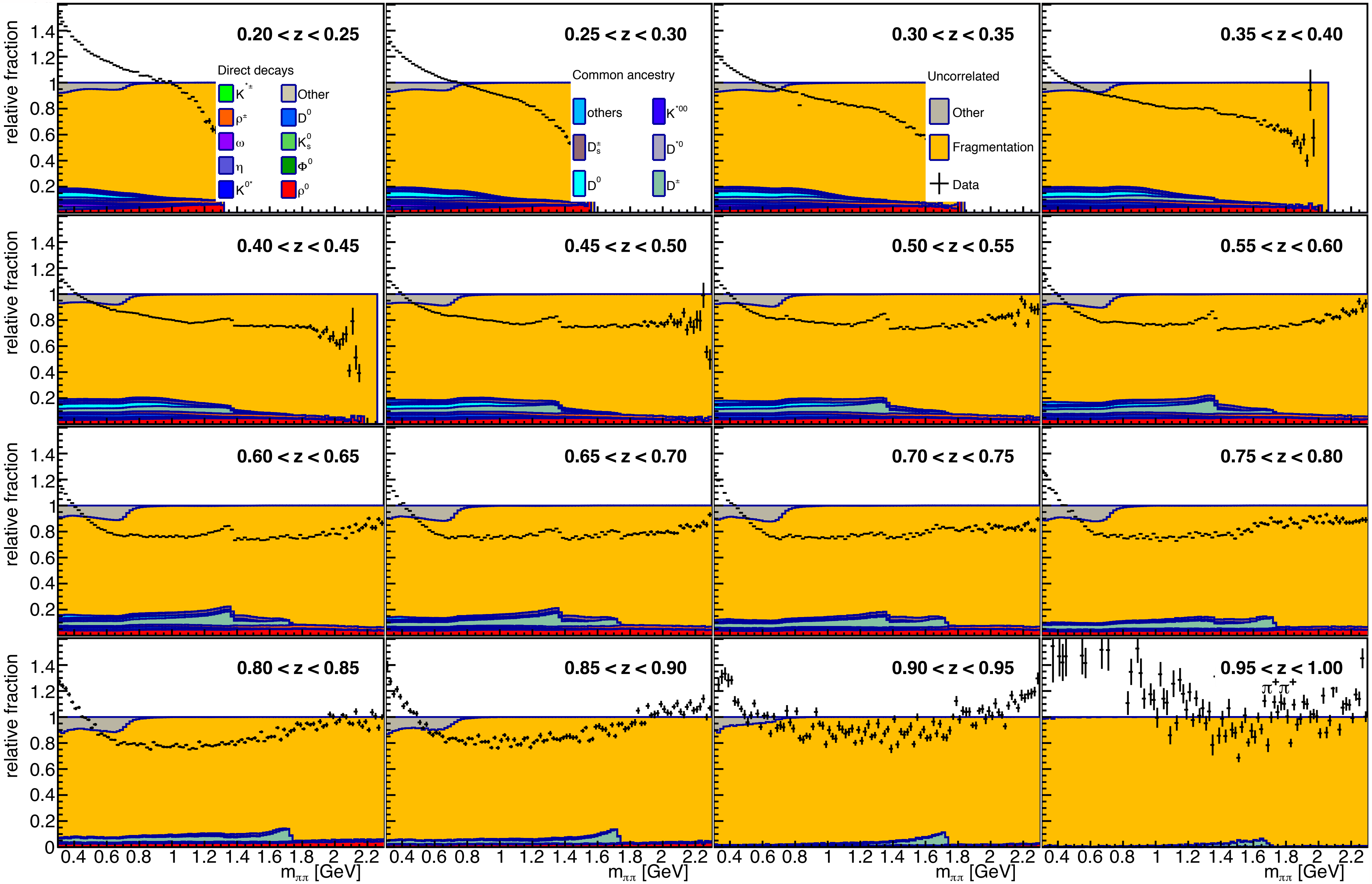


same-hemisphere data: M_{h1h2} dependence

[Phys. Rev. D96 (2017) 032005]

like-sign
pioin pairs

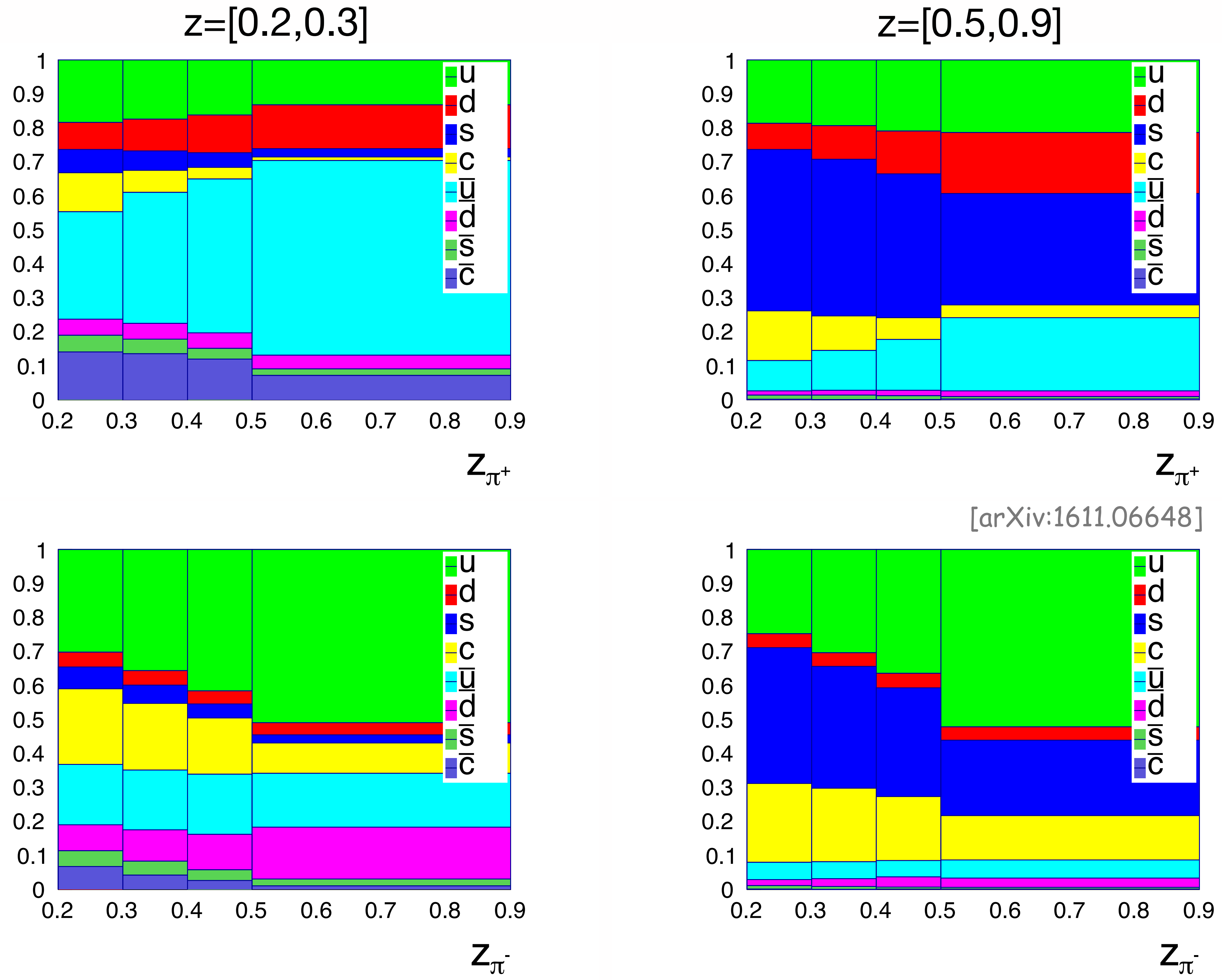
$T > 0.8$
$z_{1,2} > 0.1$



- decomposition based on PYTHIA simulation
- though no strong resonance structure still clear MC/data discrepancy

quark-flavor contributions to Lambda prod.

- flavor tagging through opposite-hemisphere hadrons



[arXiv:1611.06648]