QCD EVOLUTION

Workshop

May 20 - 24, 2018
Santa Fe, NM,
Drury Plaza Hotel

TOPICS:

- Hadron structure: theory & experiment
- Transverse momentum dependent distributions
- Generalized parton distributions
- Effective theories, SCET
- Lattice QCD
- Multi-parton interactions
- Resummation techniques
- Nuclear effects, small-x

Organizing Committee

Ian Balitsky	Alexei Prokudin
Martha Constantinou	Anatoly Radyushkin
Leonard Gamberg	Matt Sievert
Chris Lee	Ivan Vitev (Chair)
Duff Neill	Shinsuke Yoshida

qcdevolution2018@lanl.gov
www.jlab.org/conferences/qcd-evolution2018

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Penn State University Berks

Measurements of light-quark fragmentation in e^+e^- annihilation

highlights from the past five years

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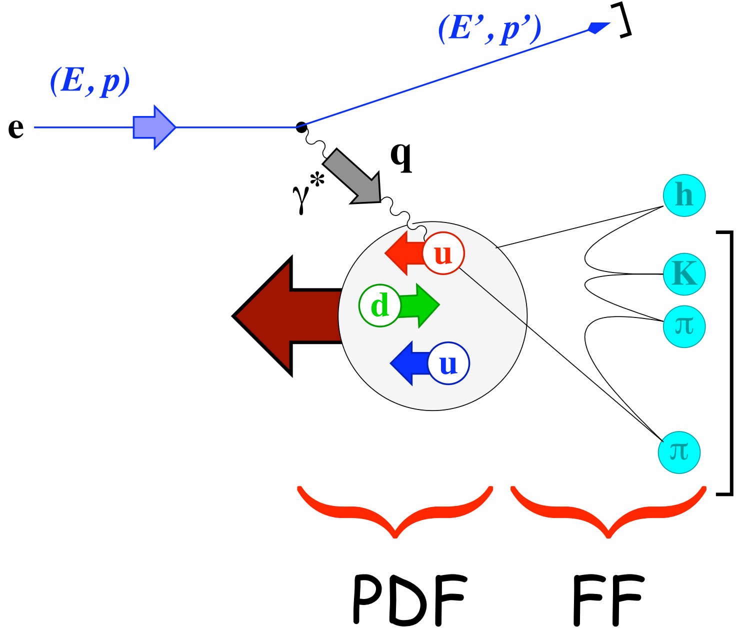
eman ta zabal zazu
Universidad del País Vasco
Euskal Herriko Unibertsitatea

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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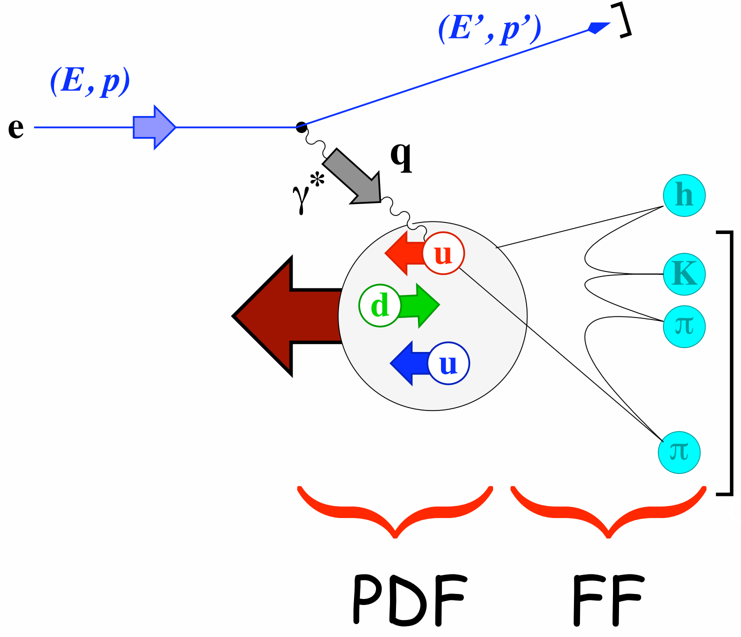

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DiFF: $H_1^{\angle,\,q\to h_1h_2}$

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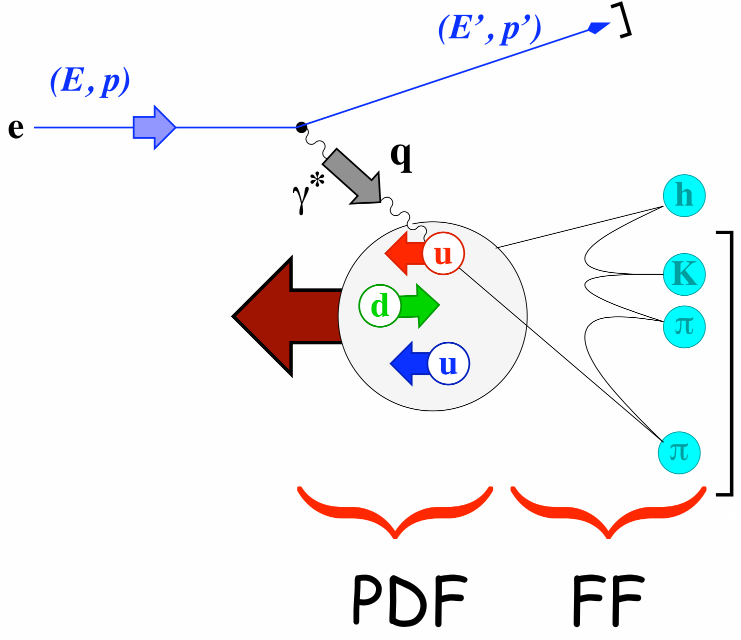

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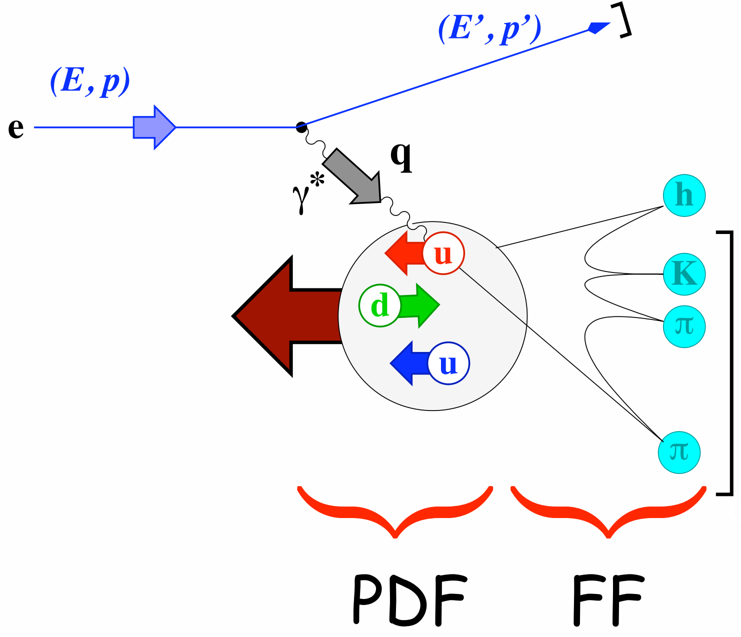

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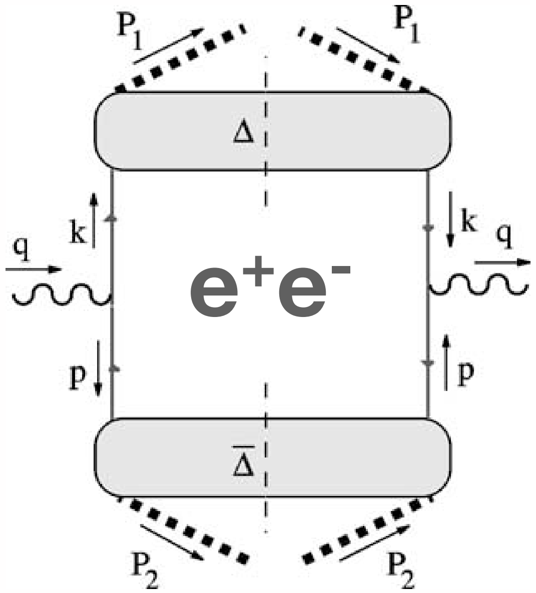
➟ FFs act as quark flavor-tagger and polarimeter

*) 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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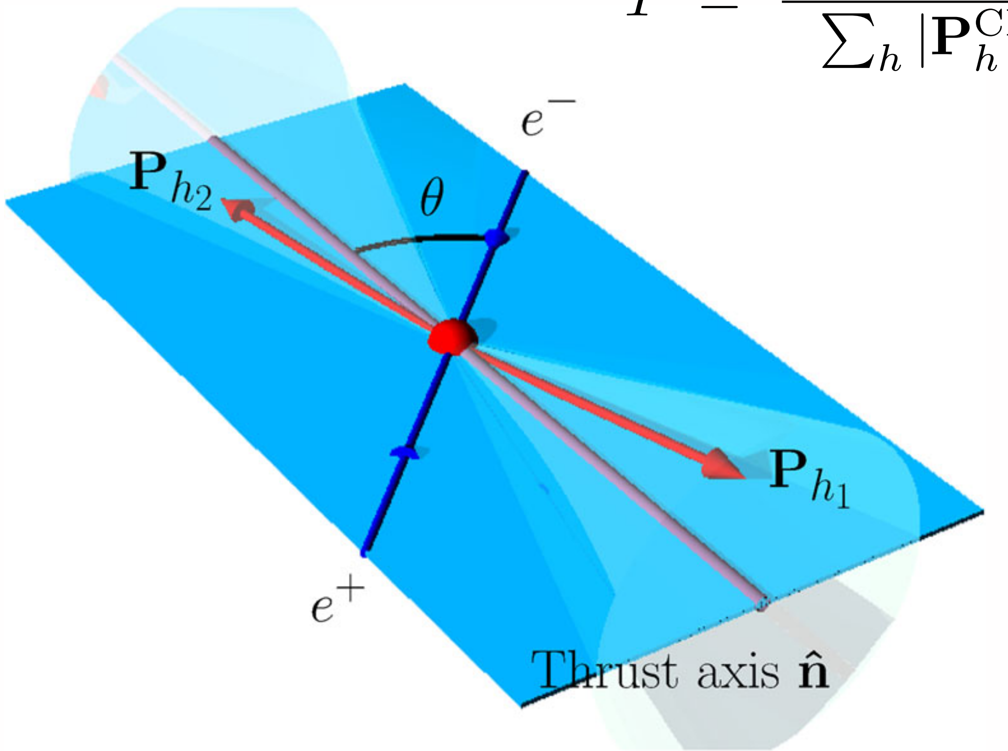
- inclusive "back-to-back" hadron pairs, **e^+e^- → h_1h_2X**
  - product of FFs
  - flavor, transverse-momentum, and/or polarization tagging

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

Thrust (axis):

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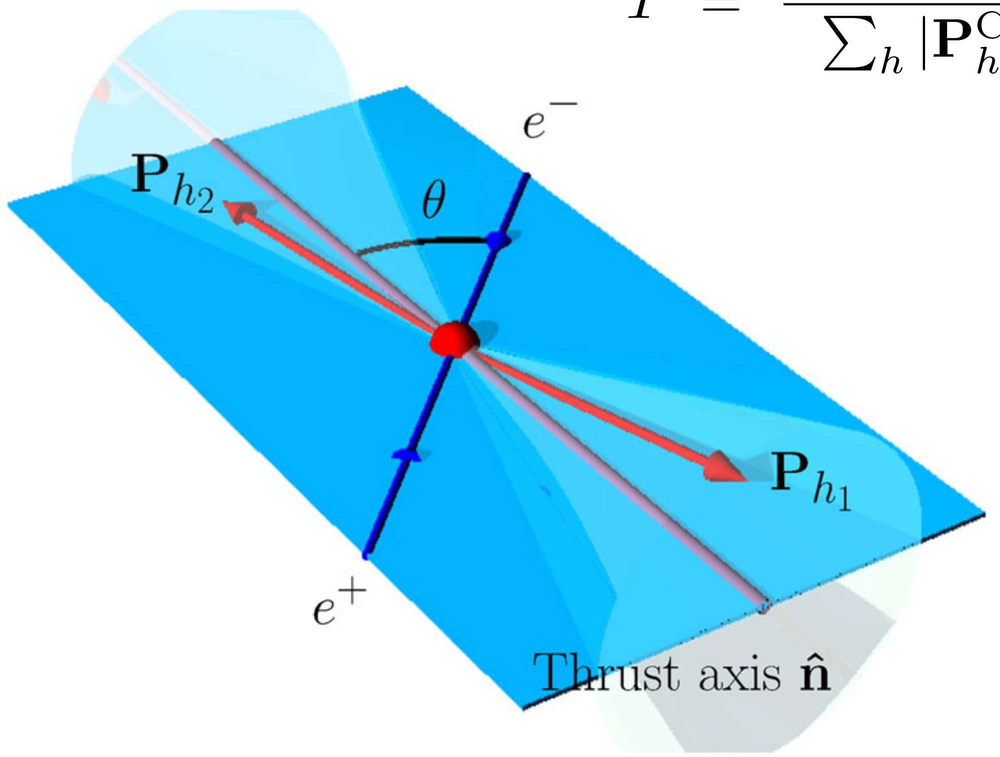
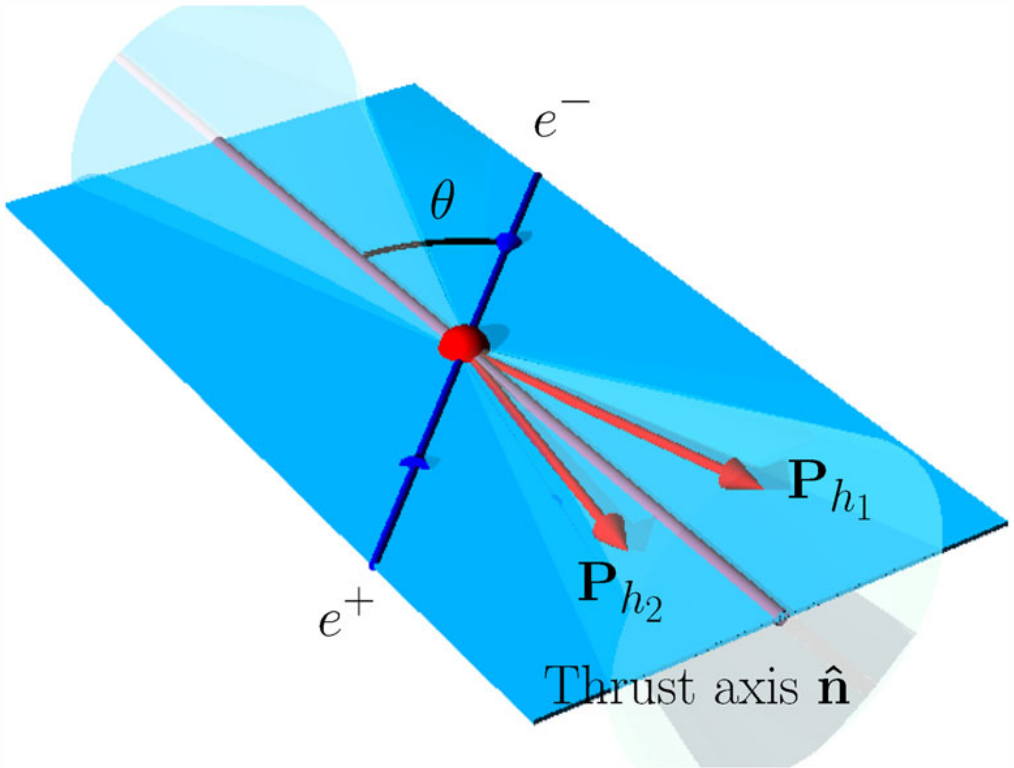


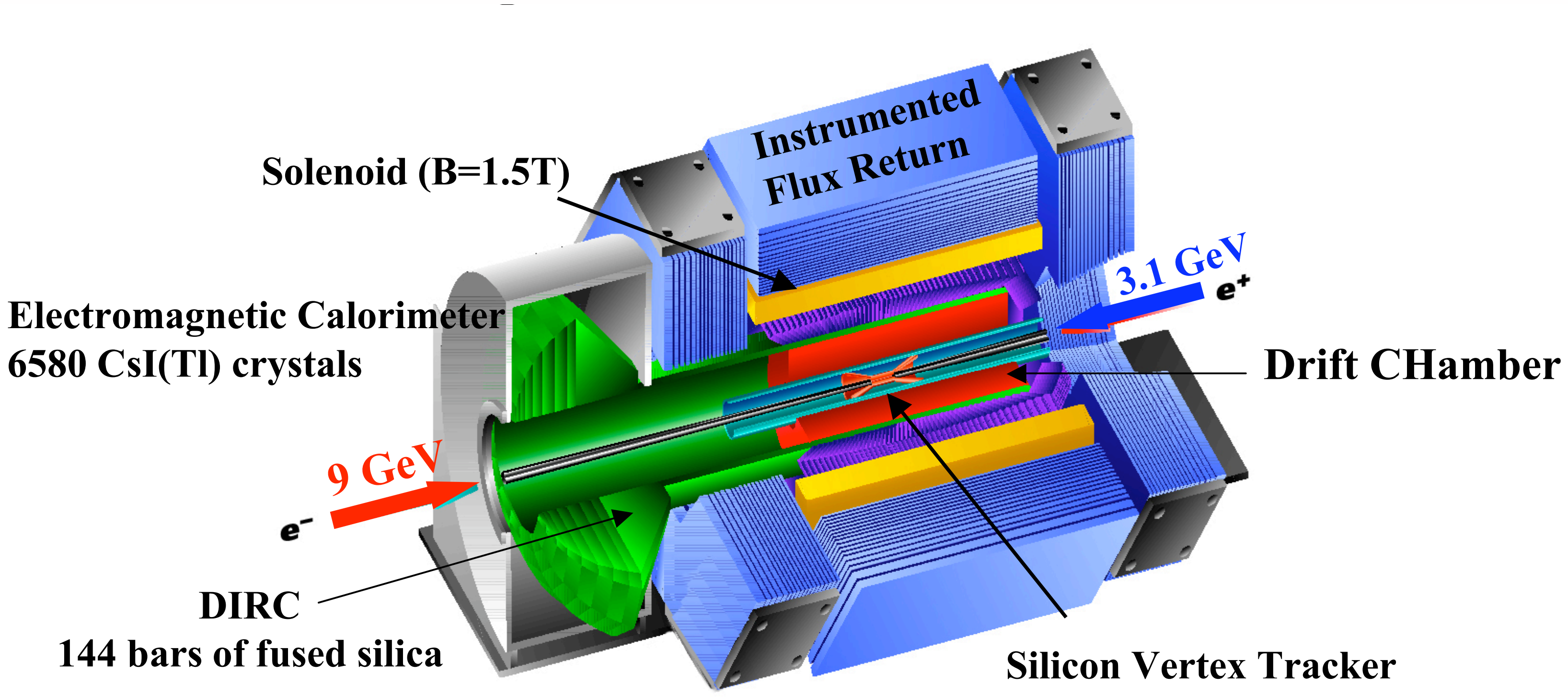


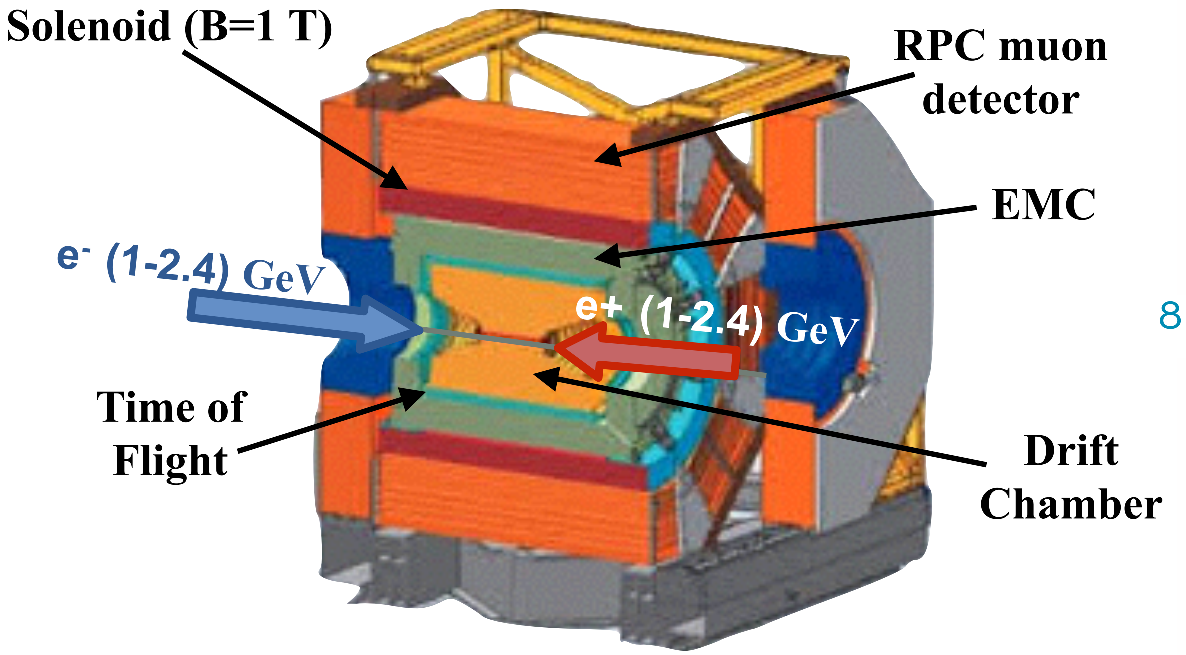
e^+e^- annihilation at BaBar, Belle, and BESIII

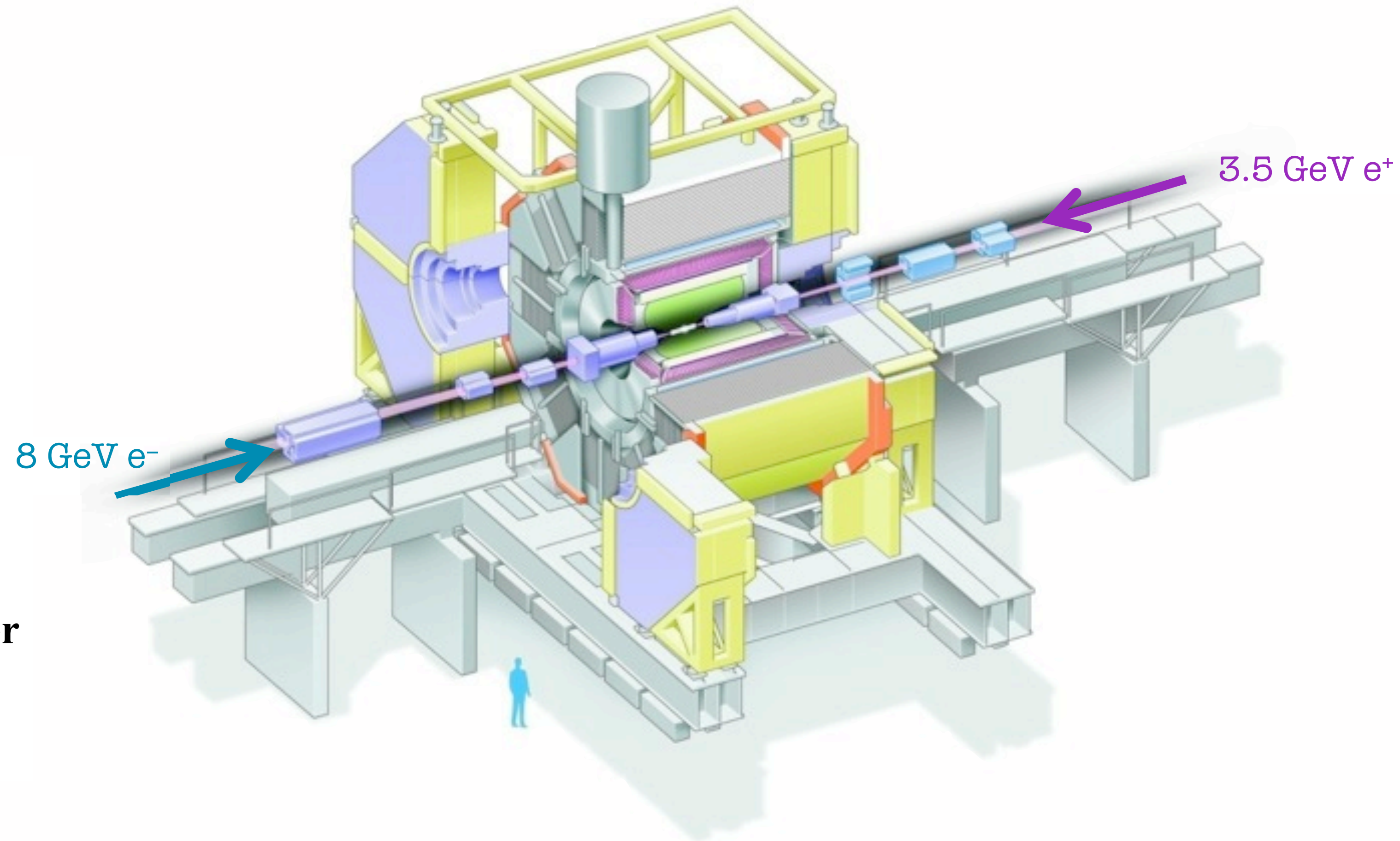
- BaBar/Belle: asymmetric beam-energy e+e- collider near/at ϒ(4S) resonance

  (10.58 GeV)

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







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

- BaBar/Belle: asymmetric beam-energy e+e- collider near/at Υ(4S) resonance

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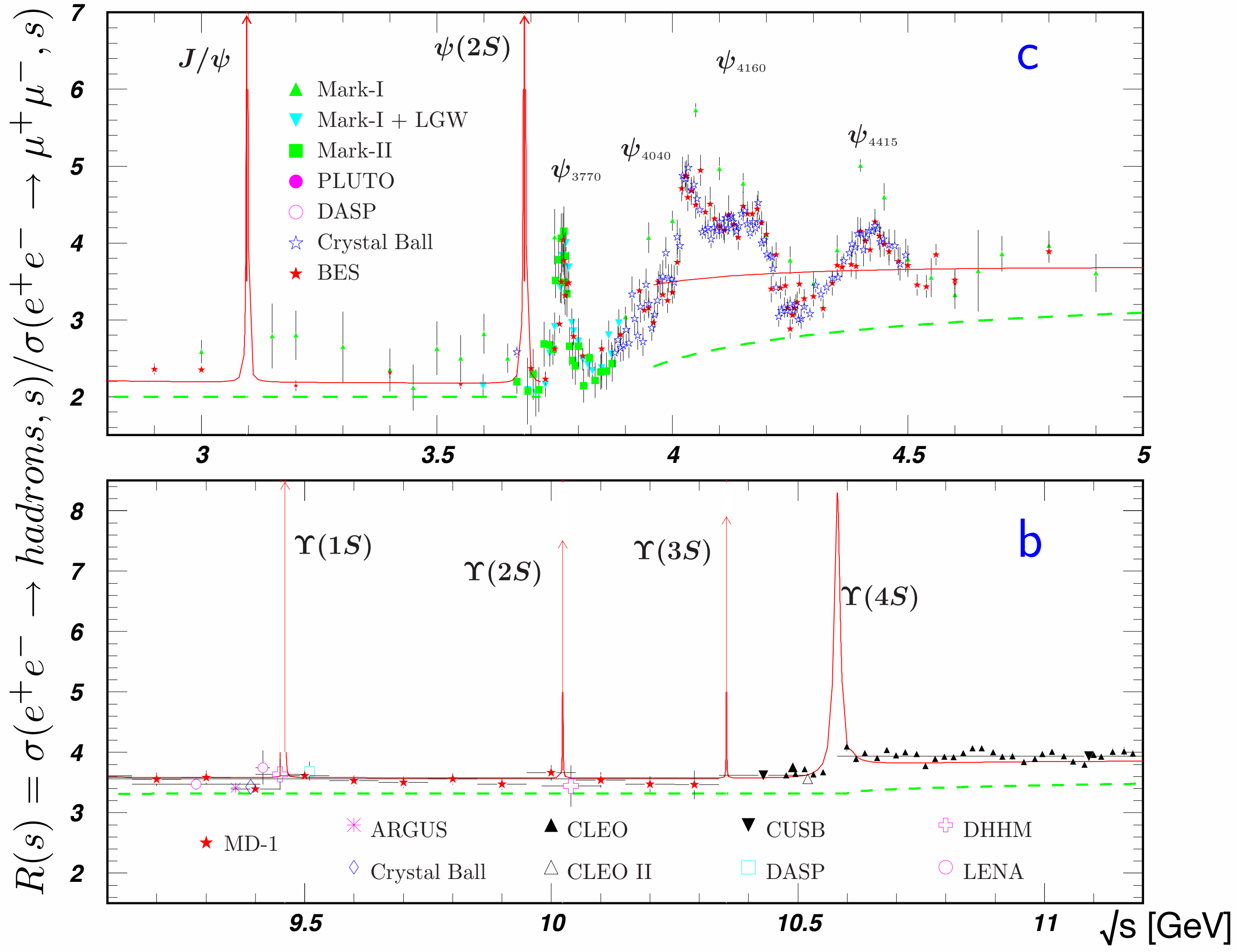
- BESIII: symmetric collider with E_e=1...2.4 GeV

- 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}	
BESIII			~62 pb^{-1} @3.65 GeV *)

*) used for the Collins analysis presented here

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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]
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- partially different approaches in different experiments/analyses

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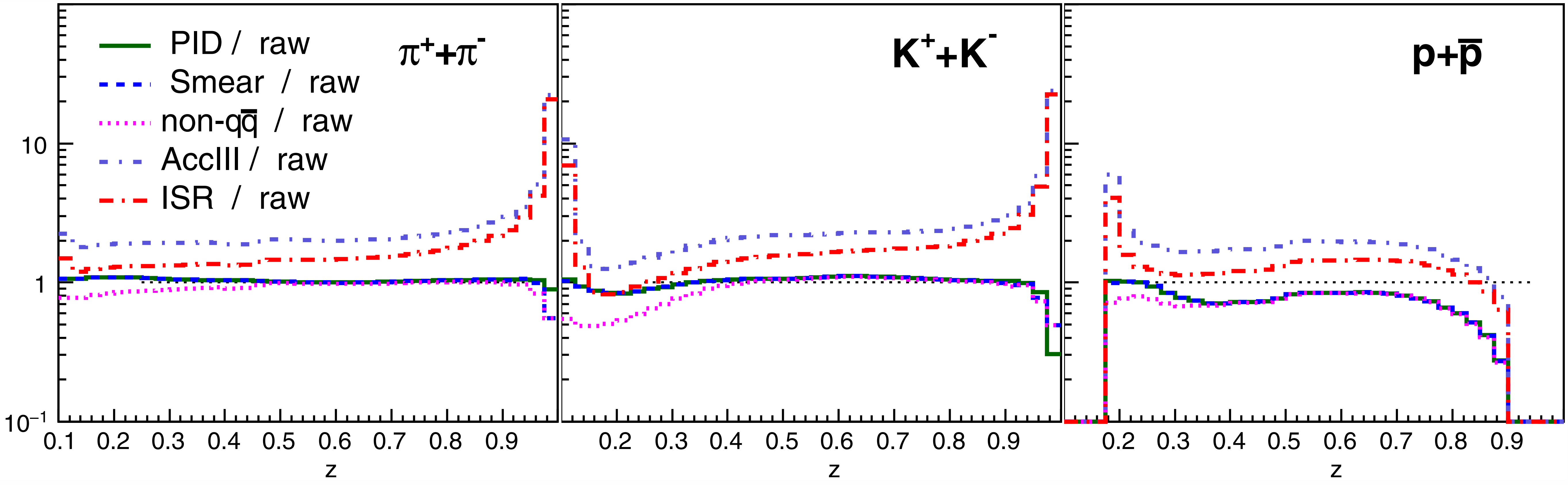
from hadron yields to cross sections

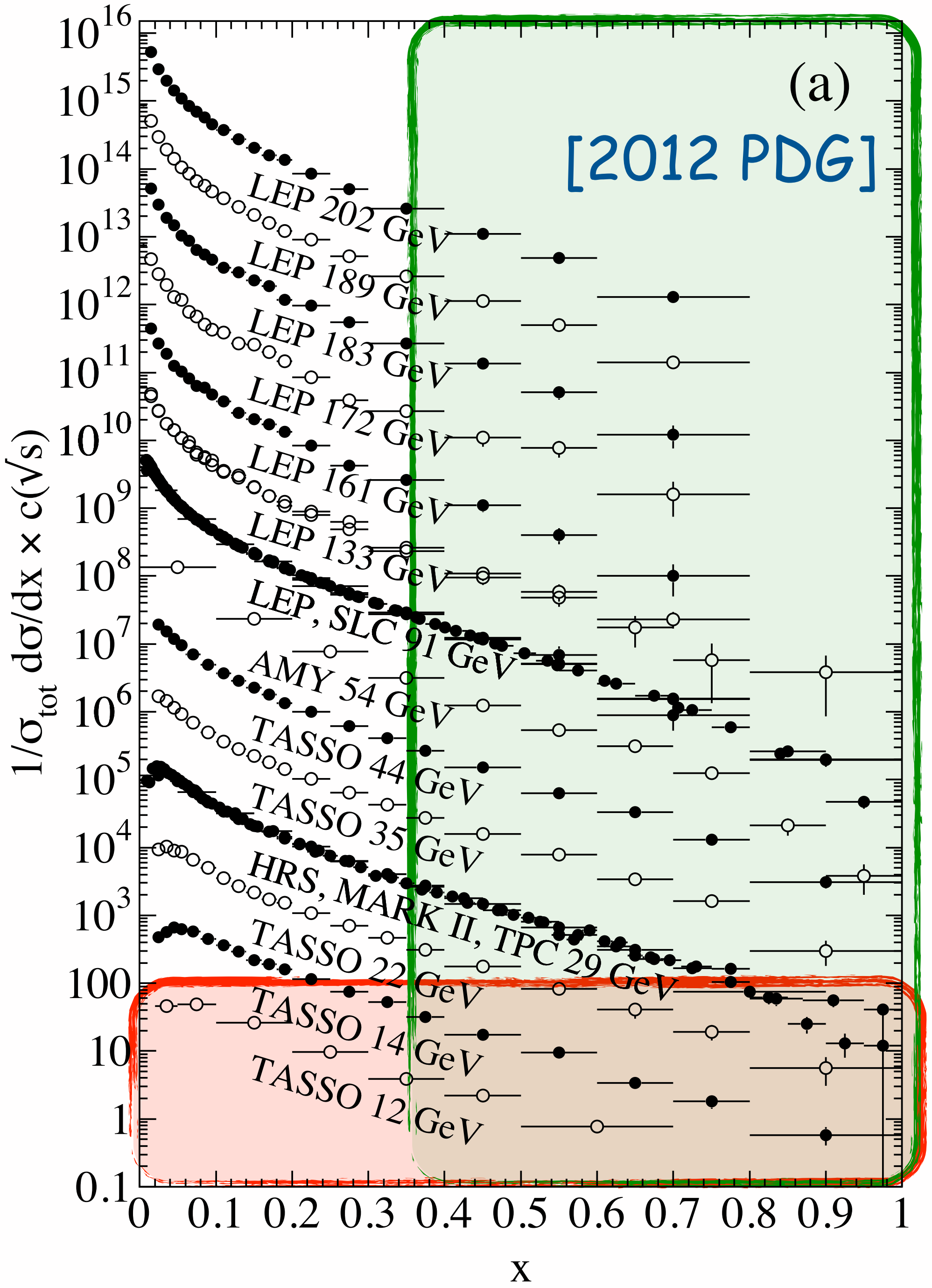
- **example**: single-hadron inclusive cross sections
  - cumulative effect of correction steps



  - 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



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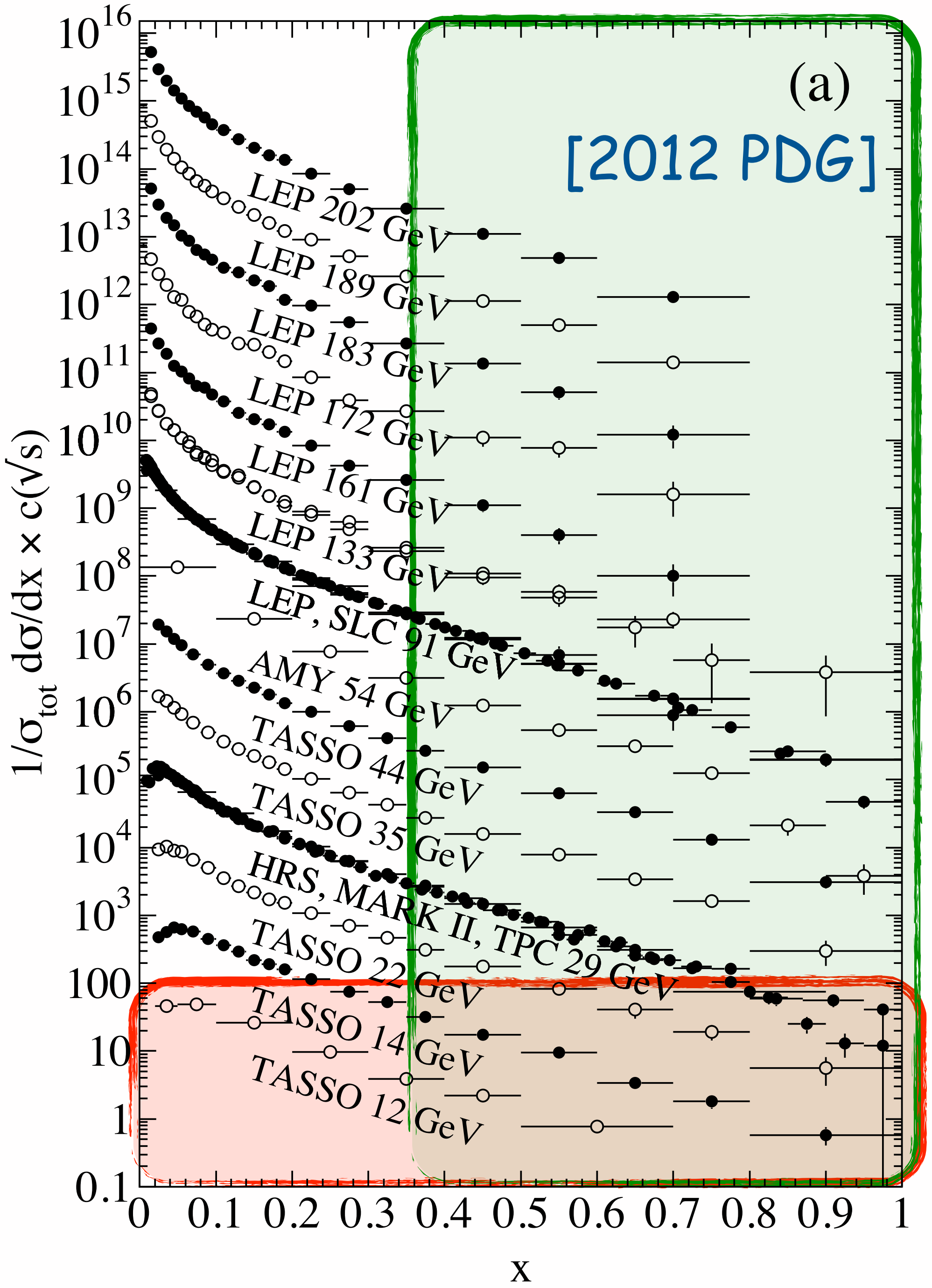

- before 2013: lack of precision data at (moderately) high z and at low √s
  - limits analysis of evolution and gluon fragmentation
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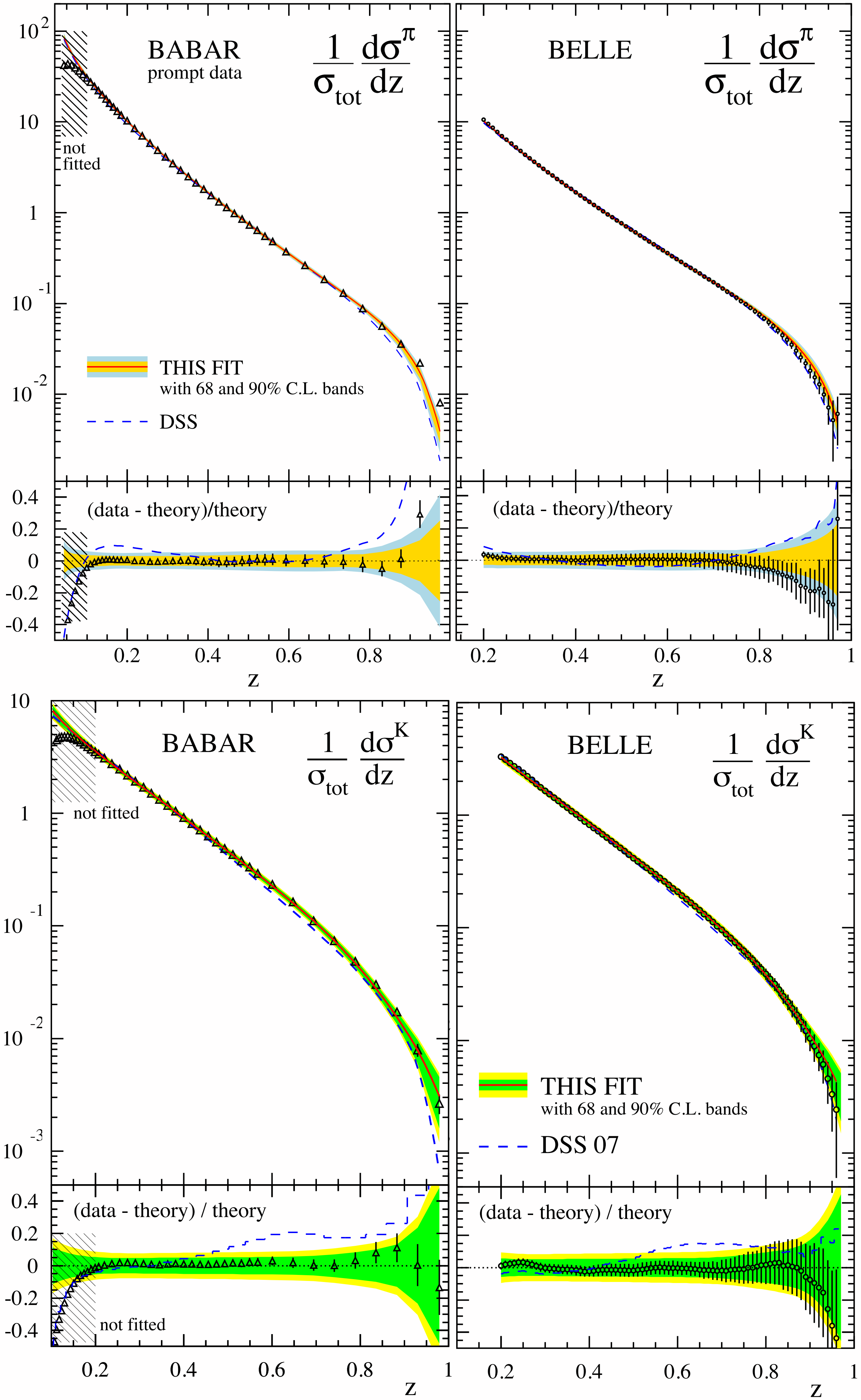
- now, results available from BaBar and Belle:
  - BaBar Collaboration, Phys. Rev. D88 (2013) 032011: **$\pi^\pm$, $K^\pm$, p+p̄**
  - Belle Collaboration, Phys. Rev. Lett. 111 (2013) 062002: **$\pi^\pm$, $K^\pm$**
  - Belle Collaboration, Phys. Rev. D92 (2015) 092007: **$\pi^\pm$, $K^\pm$, p+p̄**

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



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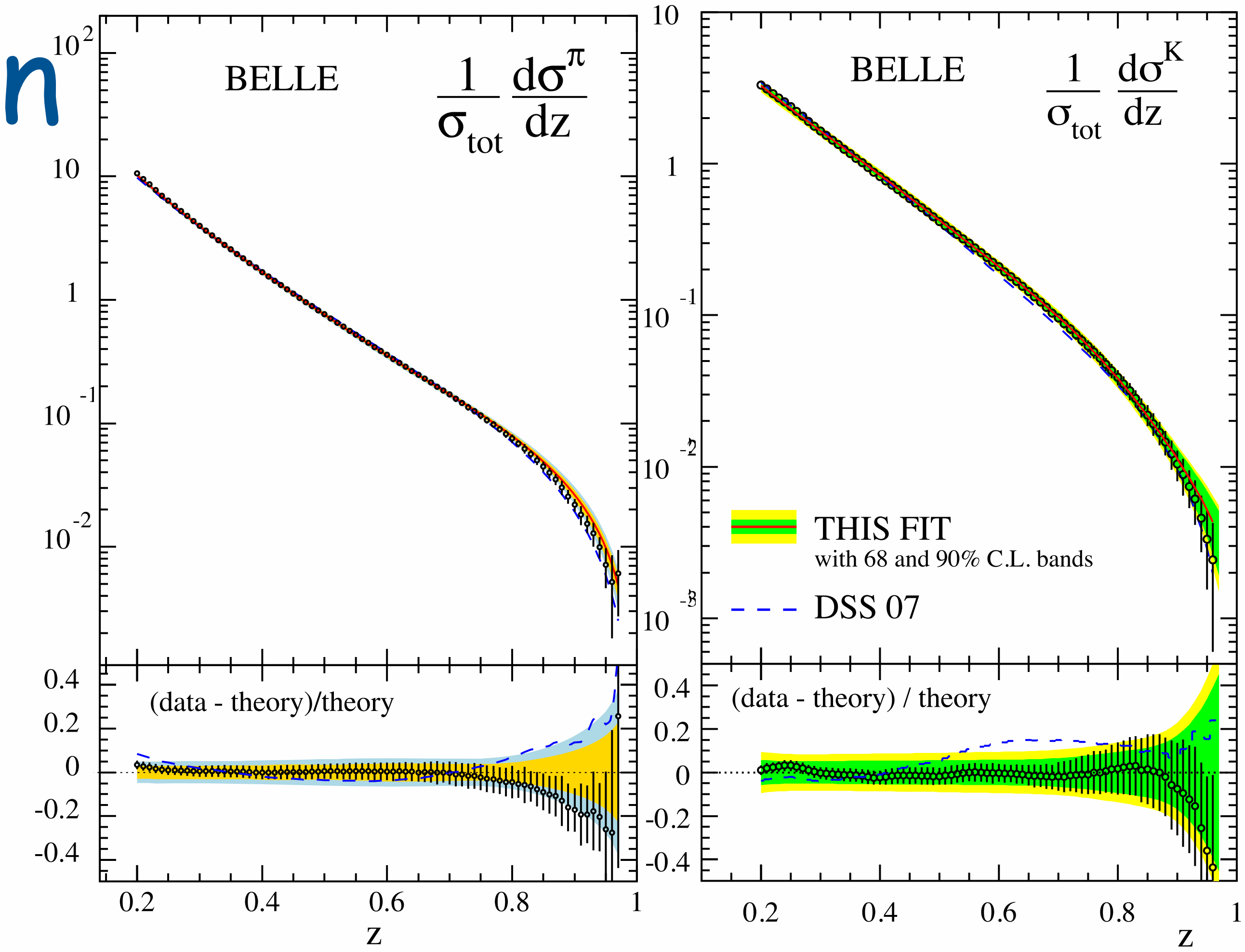

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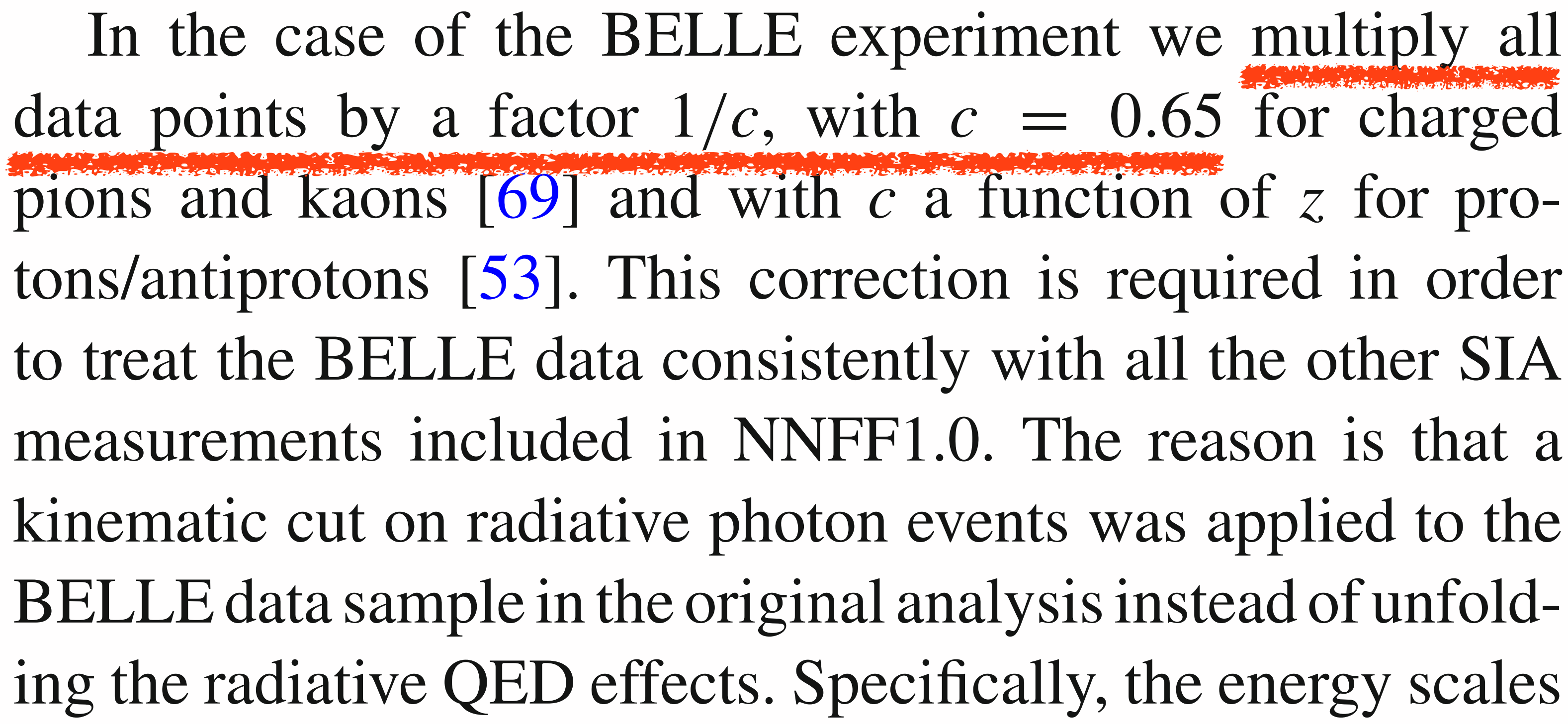
- included in recent DEHSS fits [e.g. PRD 91, 014035 (2015)]
- Belle radiative corrections **undone** in FF fits

[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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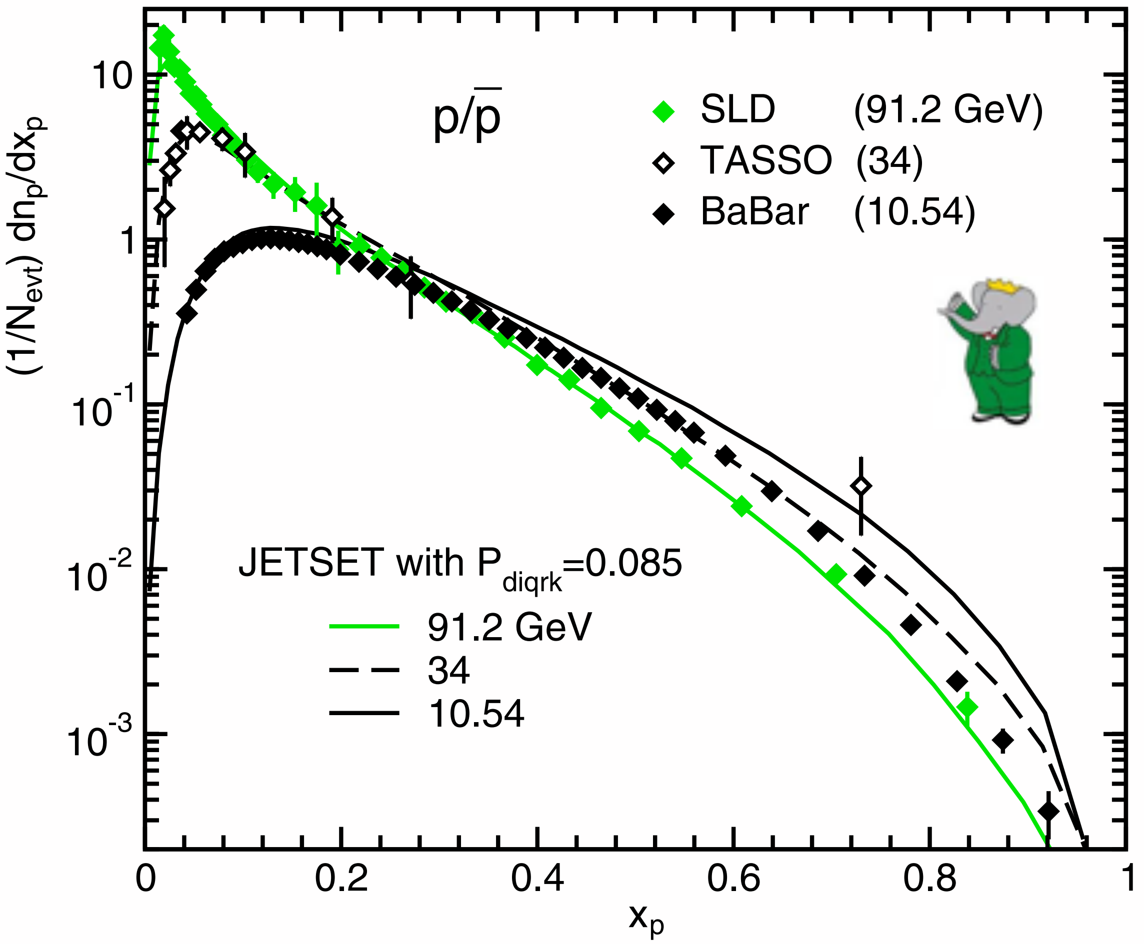
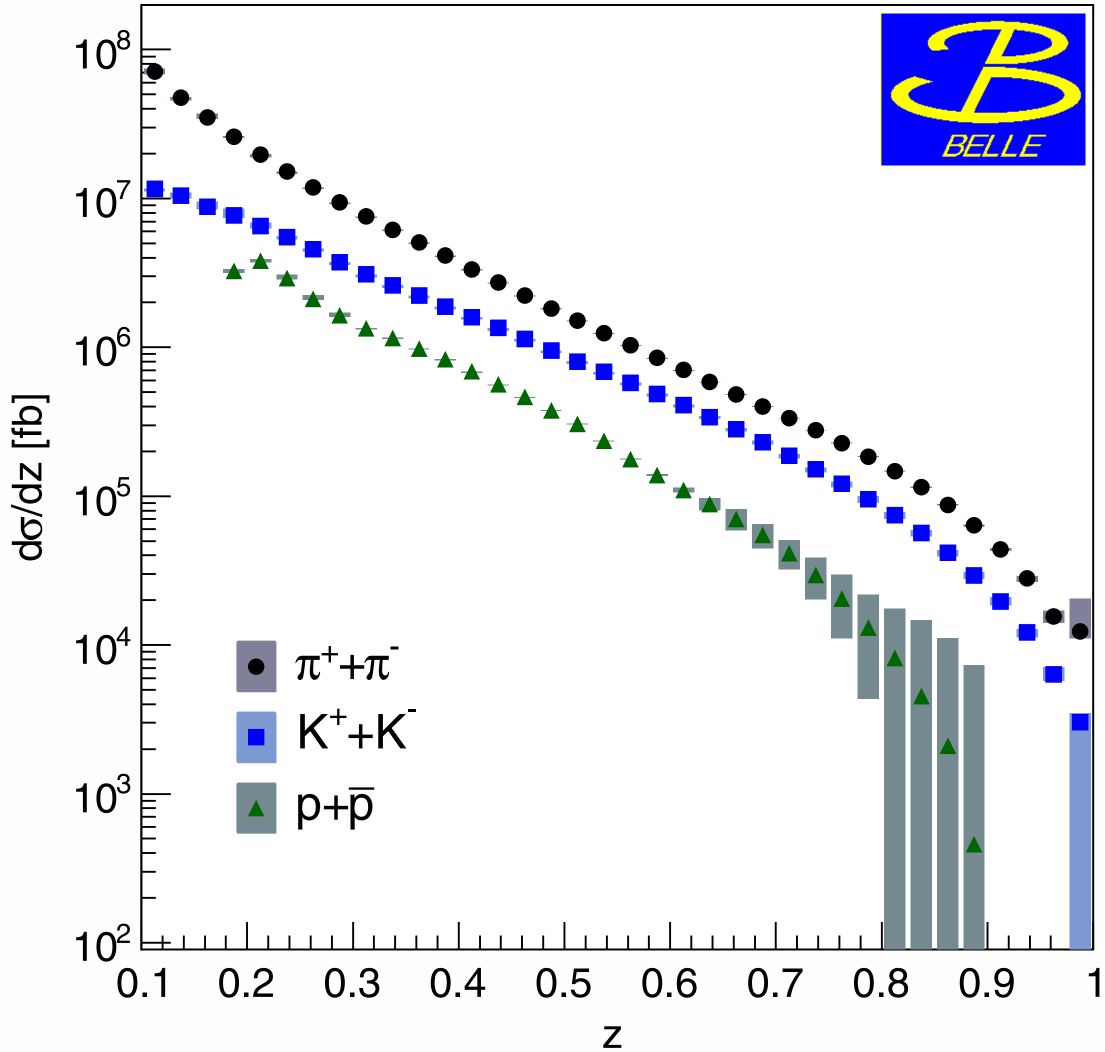
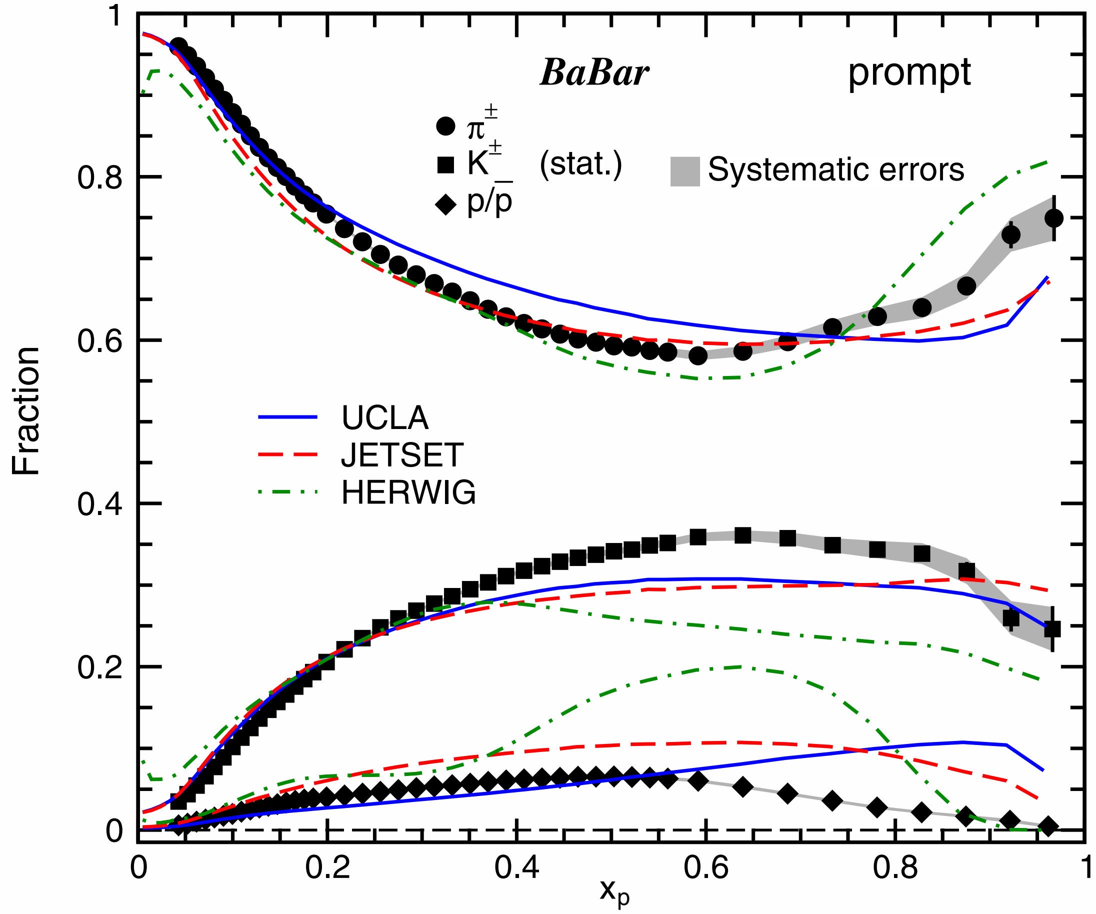
- Belle data available up to very large z (z<0.98)
- included in recent DEHSS fits [e.g. PRD 91, 014035 (2015)]
- Belle radiative corrections **undone** in FF fits
- **new**: data for protons and anti-protons
  - not (yet) included in DEHSS, but in NNFF 1.0 [EPJC 77 (2017) 516]
  - similar z dependence as pions
  - about ~⅕ of pion cross sections

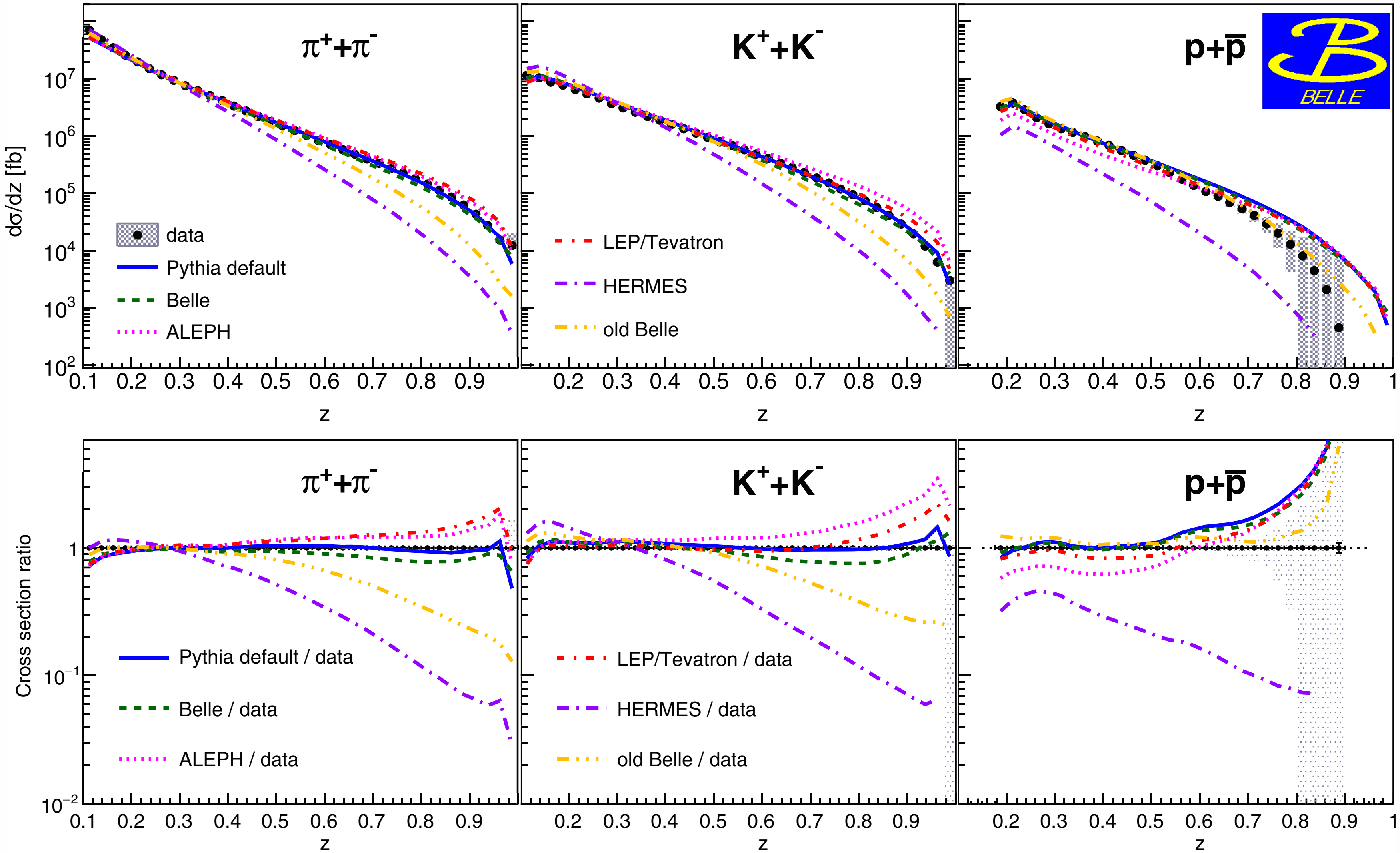




single-hadron production: data-MC comparison

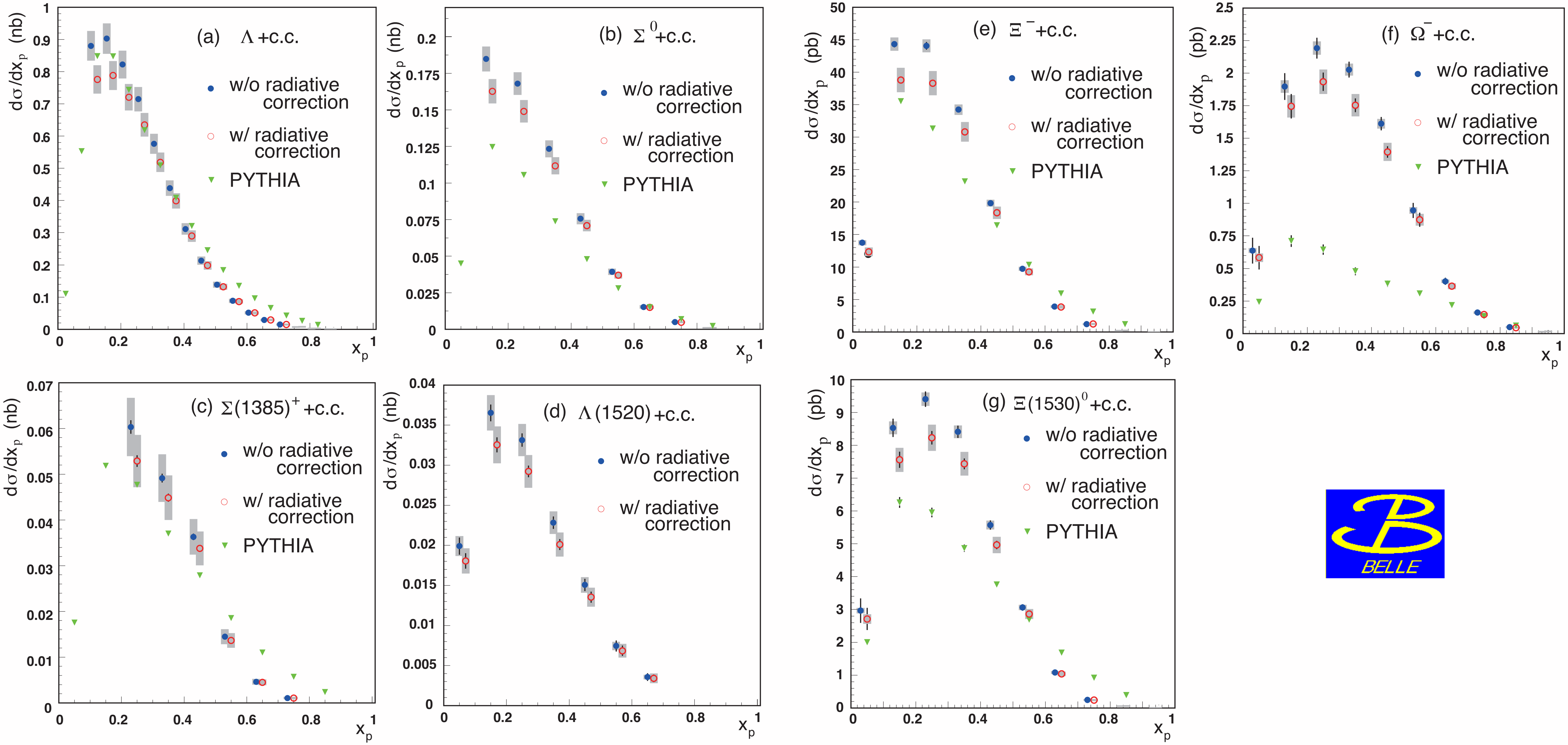


- pion and(?) kaon data reasonably well described by Jetset
- protons difficult to reproduce, especially at large z
  - MC overshoots data



inclusive hyperon production

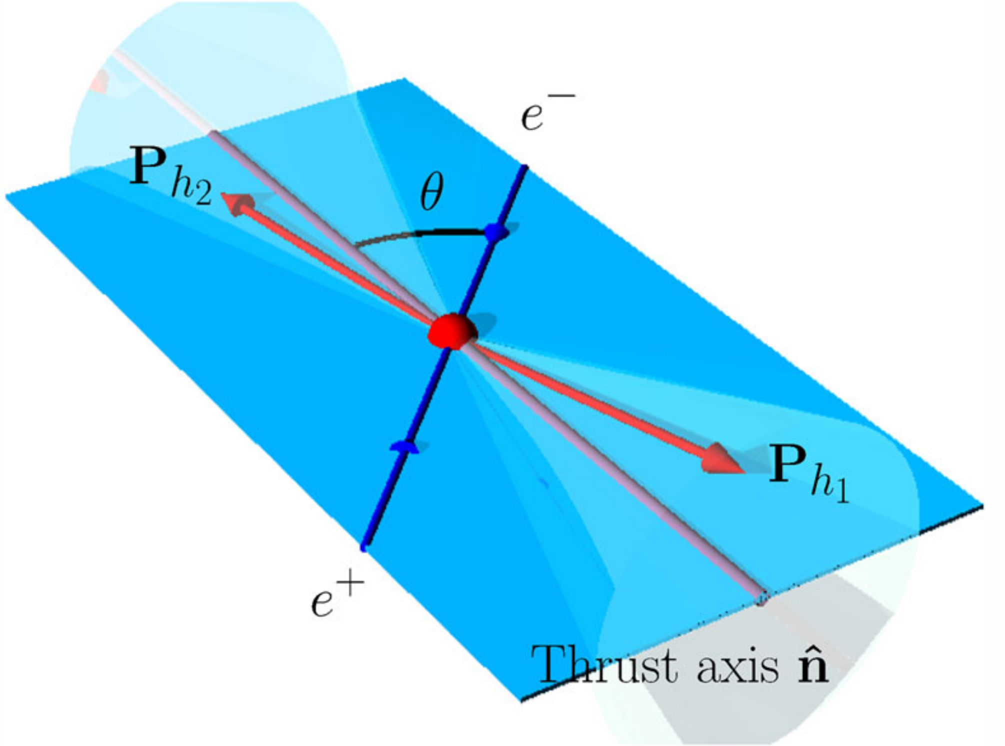
[M. Niiyama et al., PRD 97 (2018) 072005]

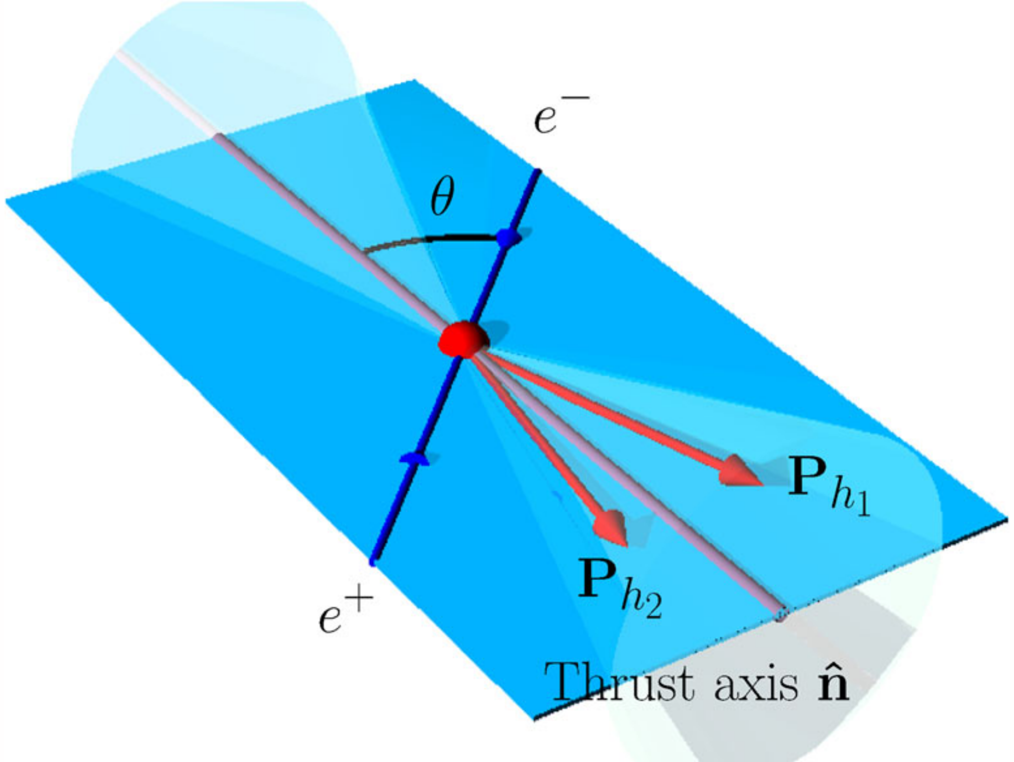


- Λ production reasonably well described by Pythia
- less satisfactory for heavier hyperons
- fails to describe Ω^- production

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]
- opens the question of defining hemispheres

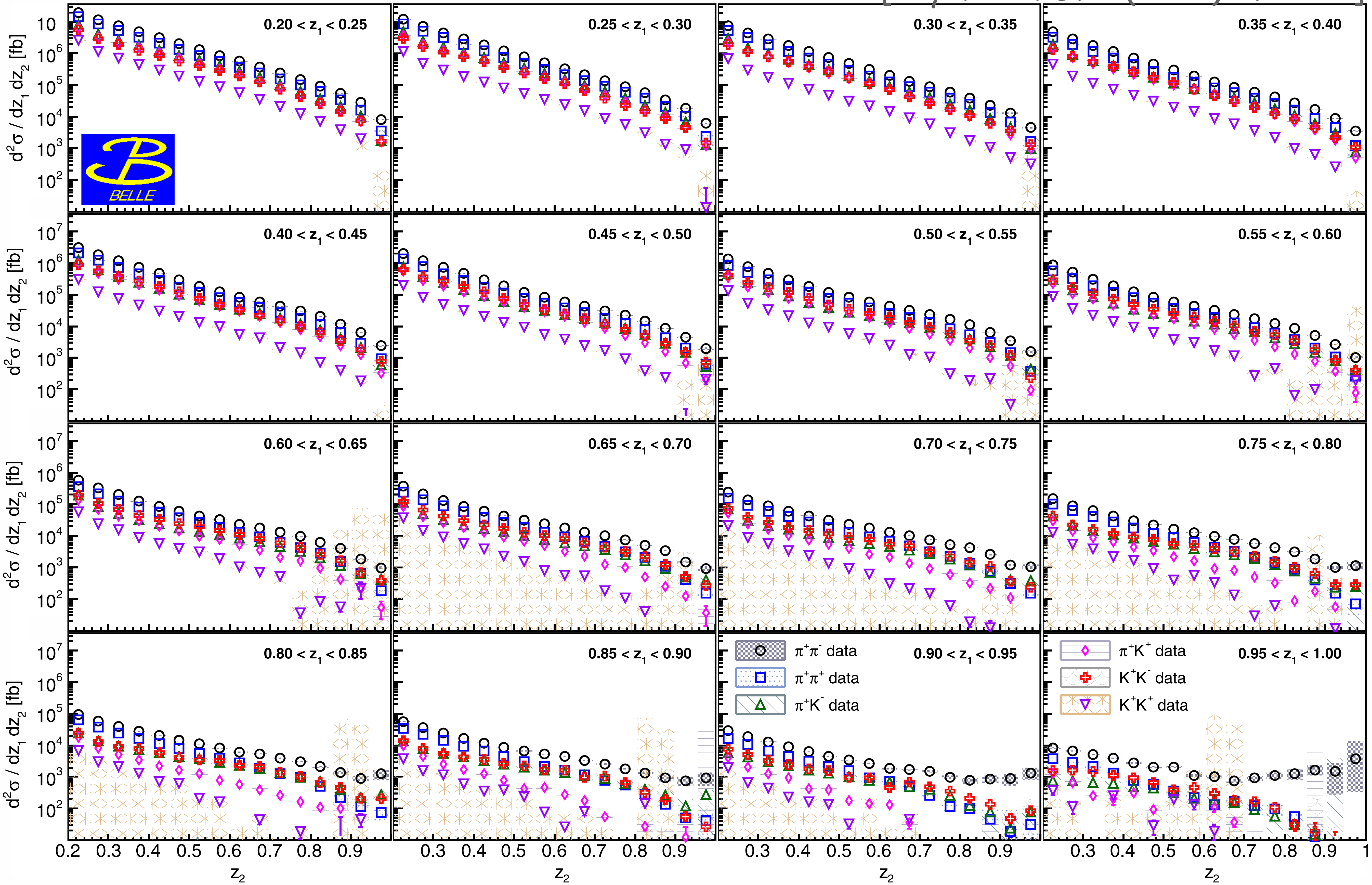




hadron-pair production

no hemisphere selection

[Phys. Rev. D92 (2015) 092007]



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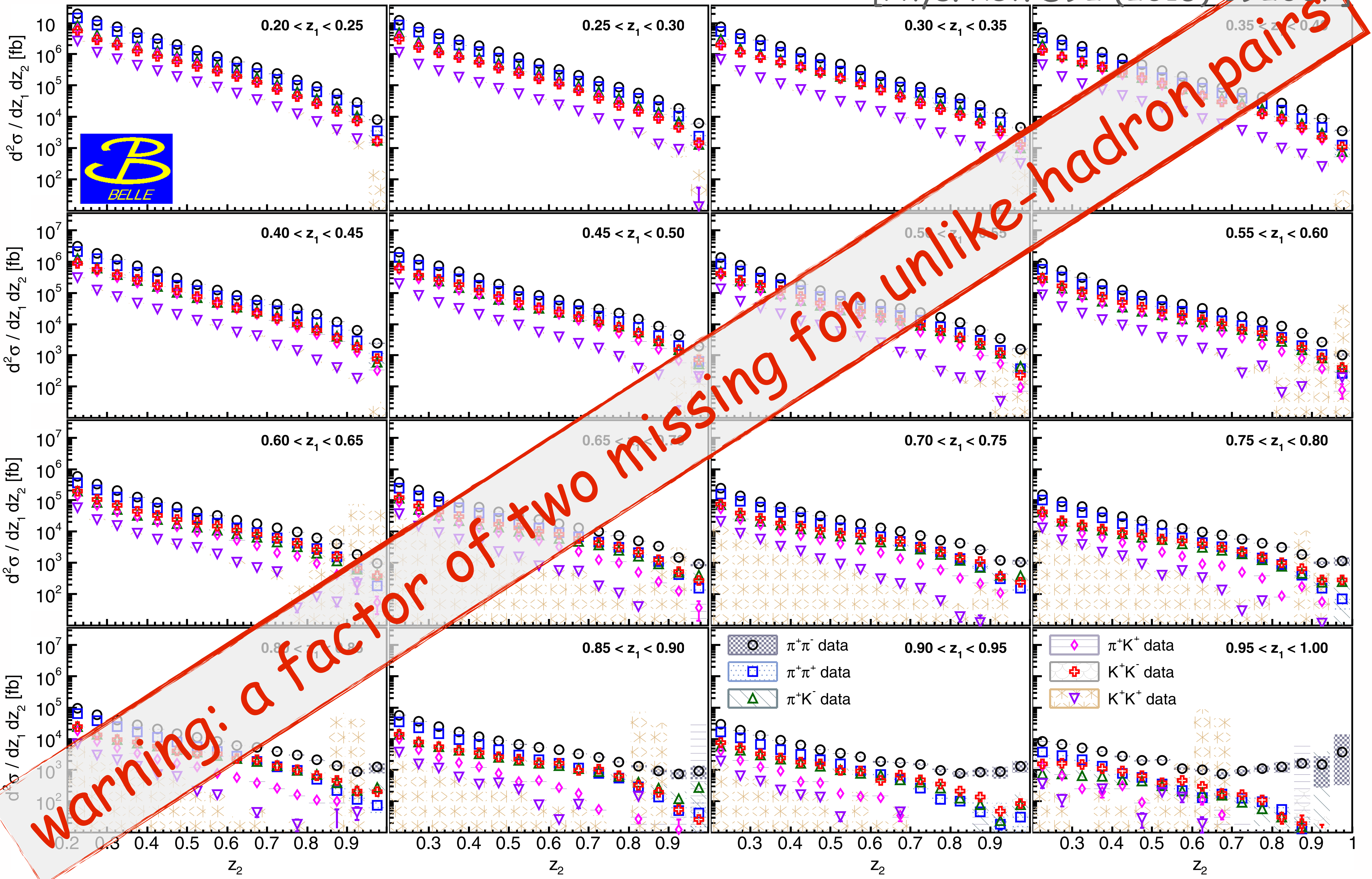
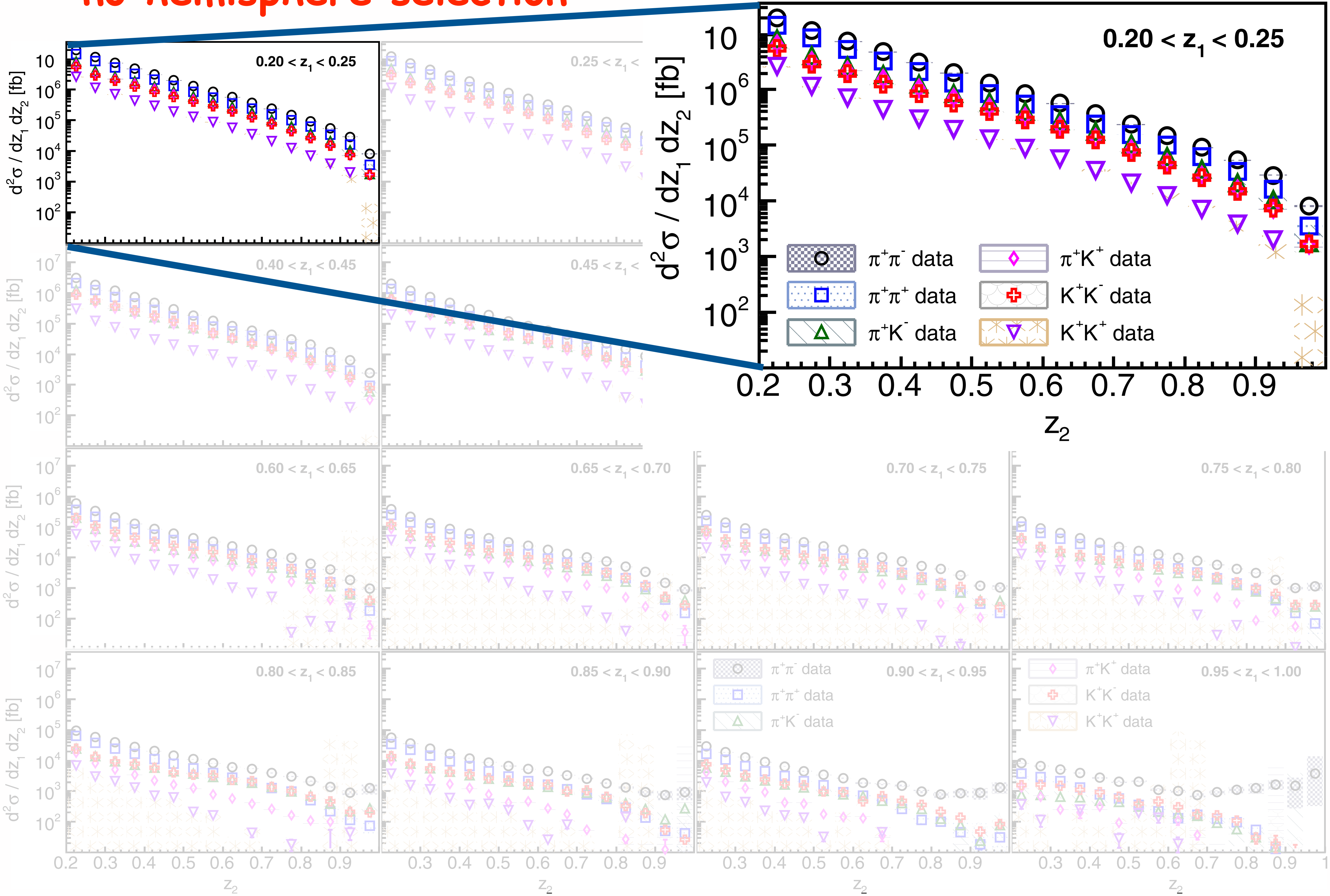


warning: a factor of two missing for unlike-hadron pairs

hadron-pair production

no hemisphere selection



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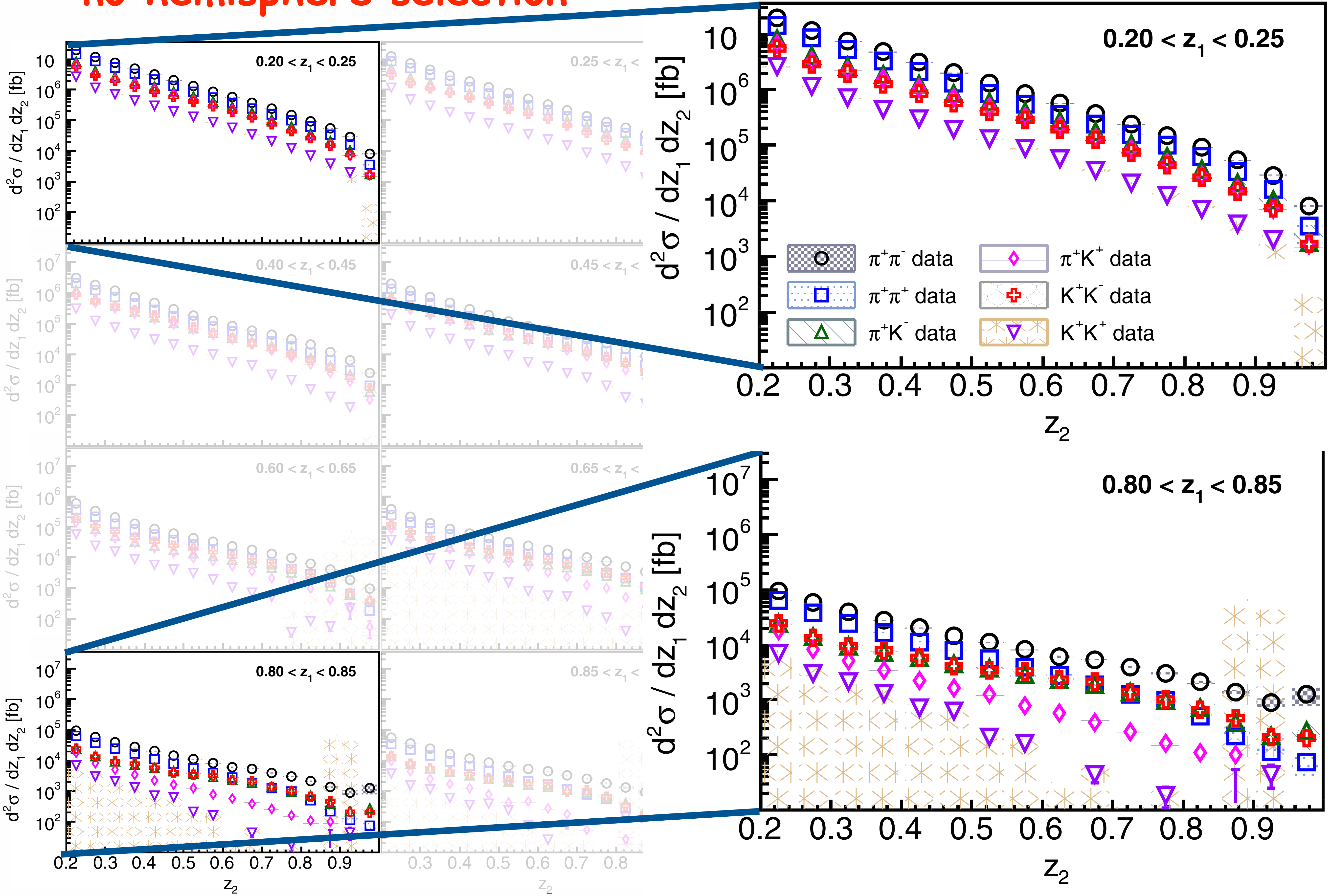
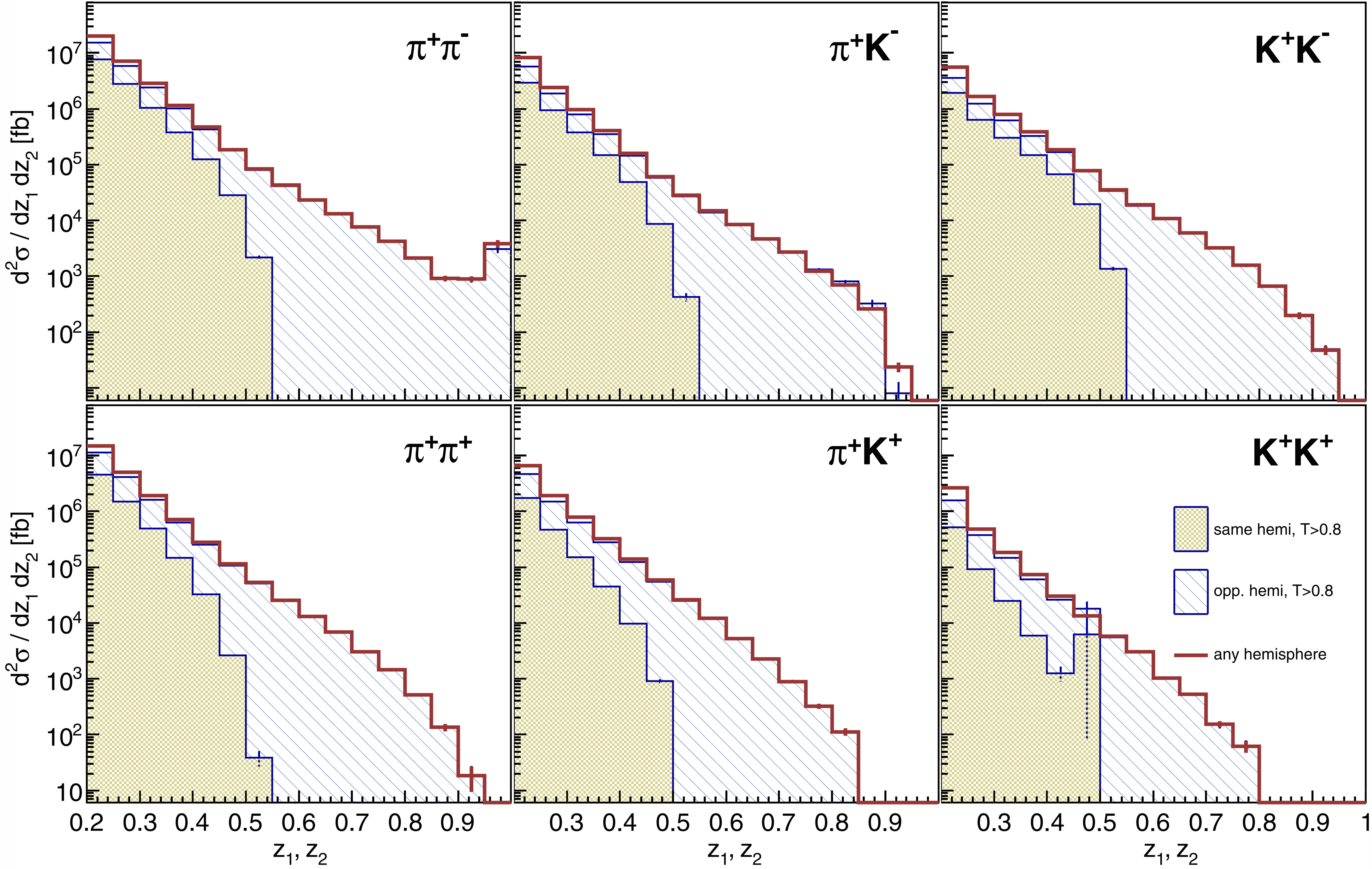


hadron-pairs: topology comparison

- 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]

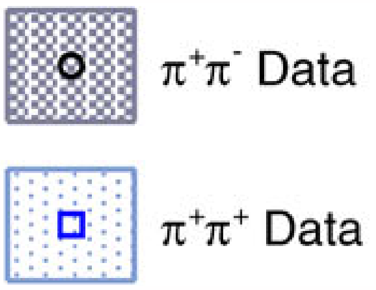


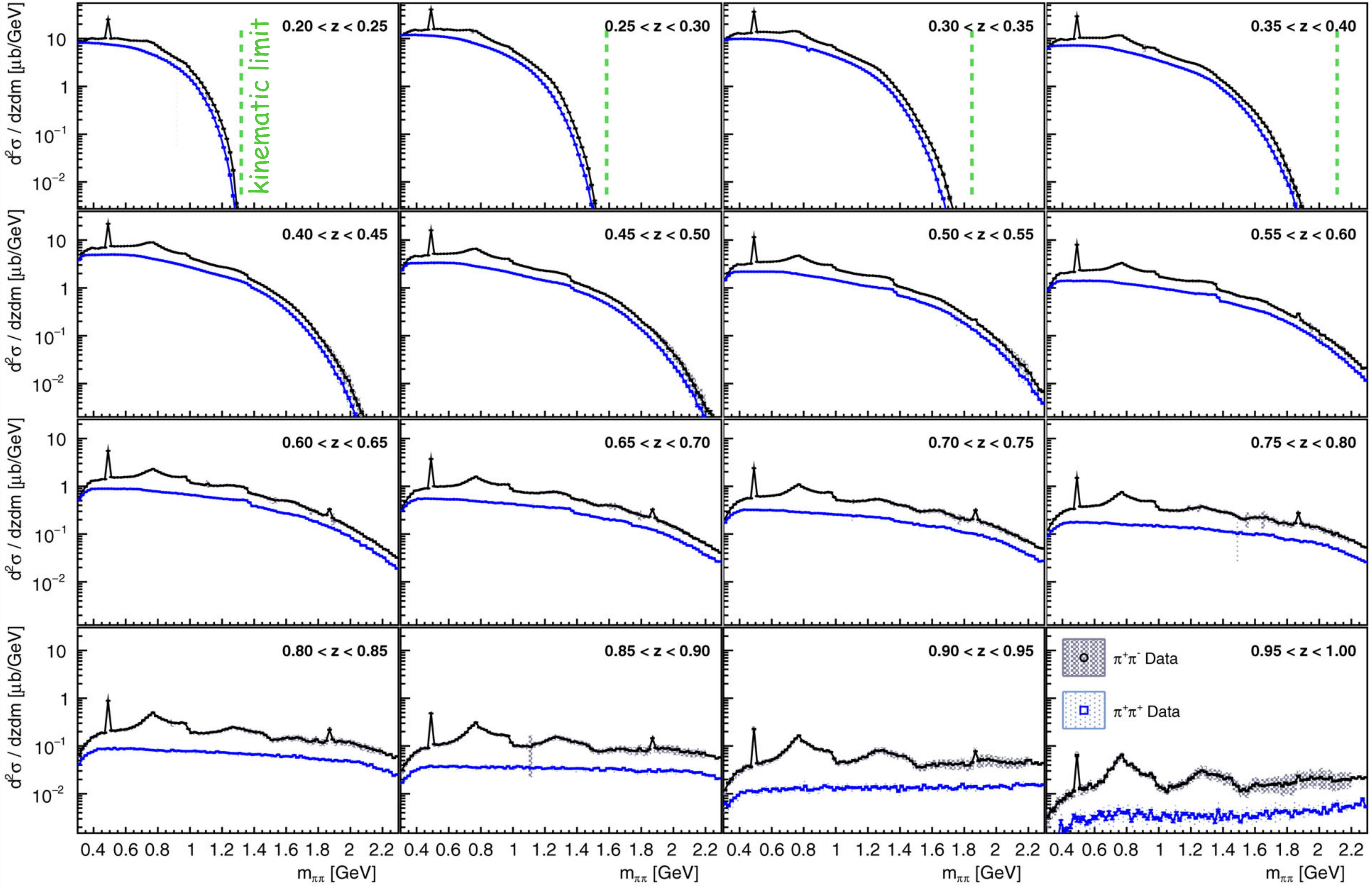
same-hemisphere data: M_{h1h2} dependence

[Phys. Rev. D96 (2017) 032005]

unlike-sign
hadron pairs

like-sign
hadron pairs





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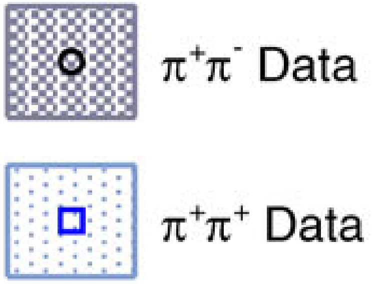

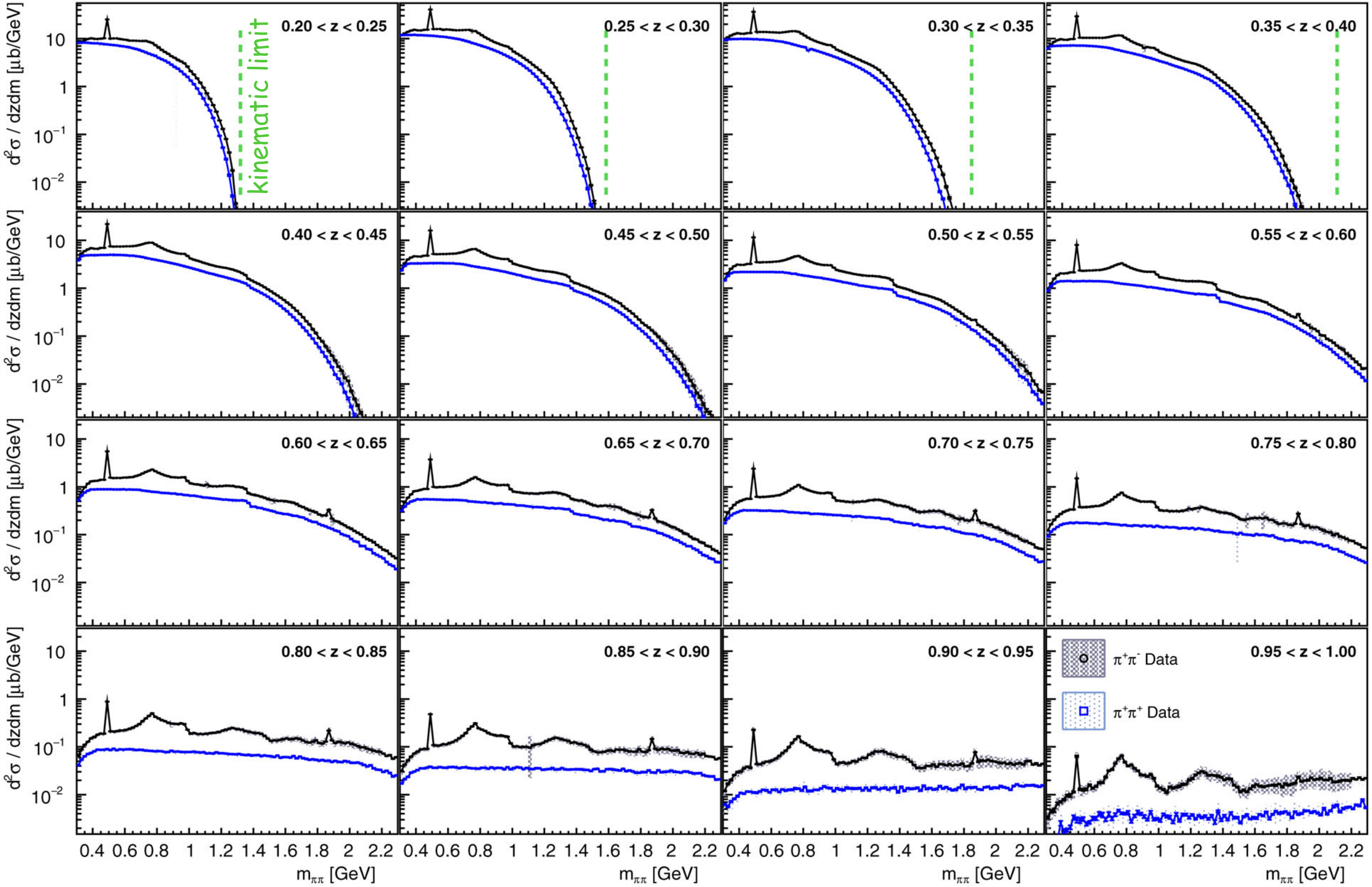

$T > 0.8$

$z_{1,2} > 0.1$

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[Phys. Rev. D96 (2017) 032005]

unlike-sign
hadron pairs

like-sign
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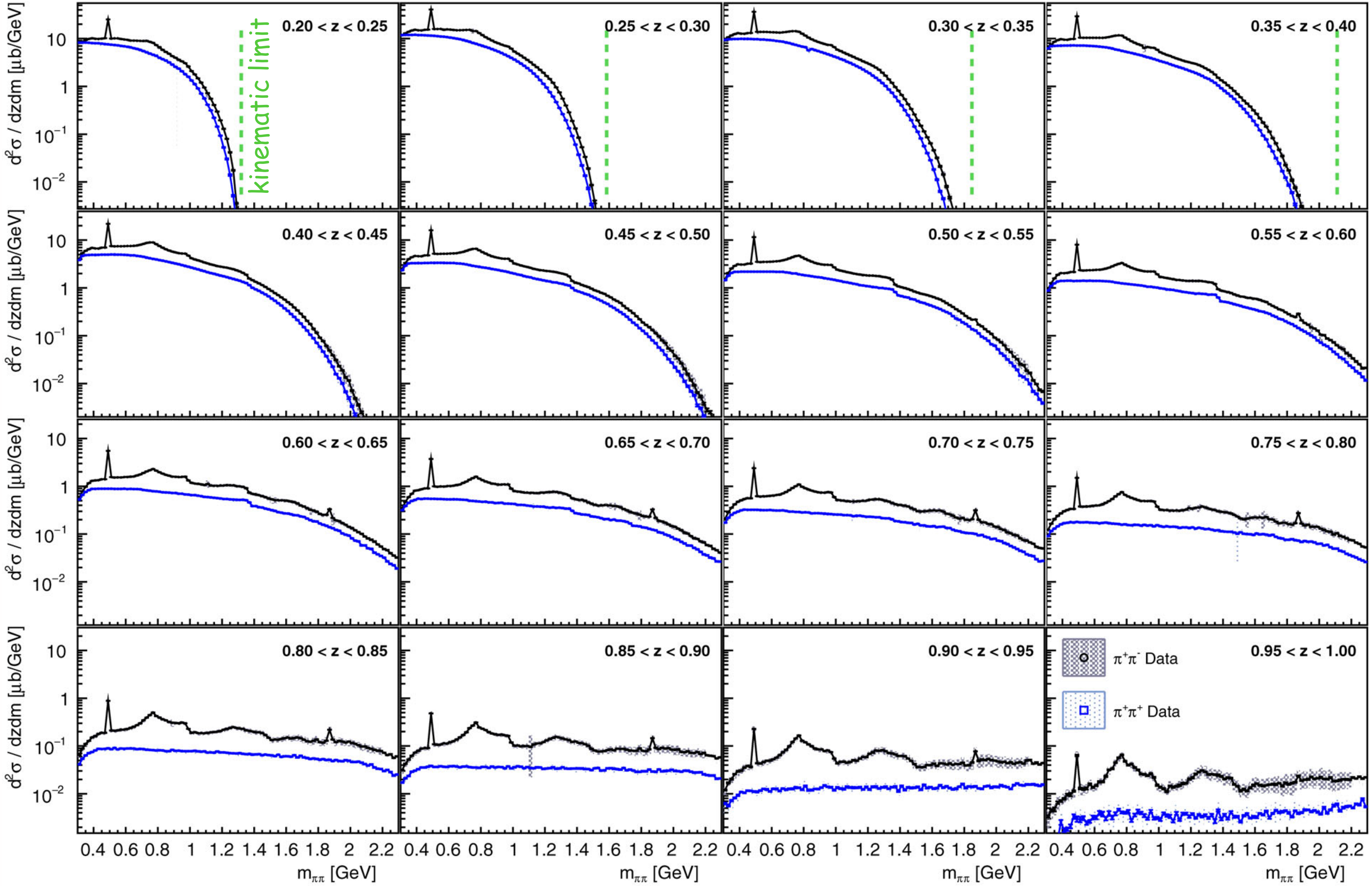
○ $\pi^+\pi^-$ Data

□ $\pi^+\pi^+$ Data



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

- 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

[Phys. Rev. D96 (2017) 032005]

unlike-sign hadron pairs

like-sign hadron pairs

▨ ○ $\pi^+\pi^-$ Data

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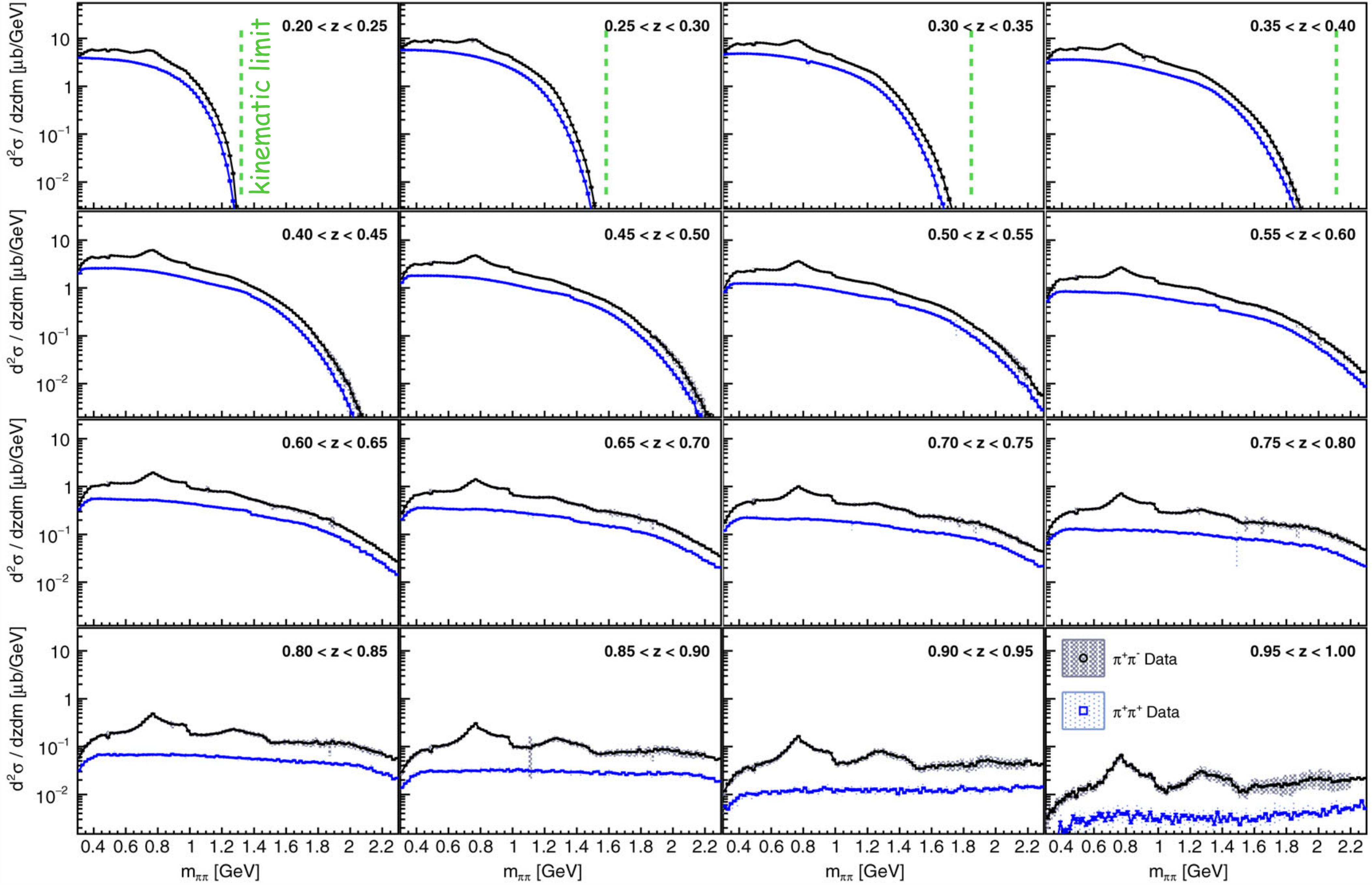
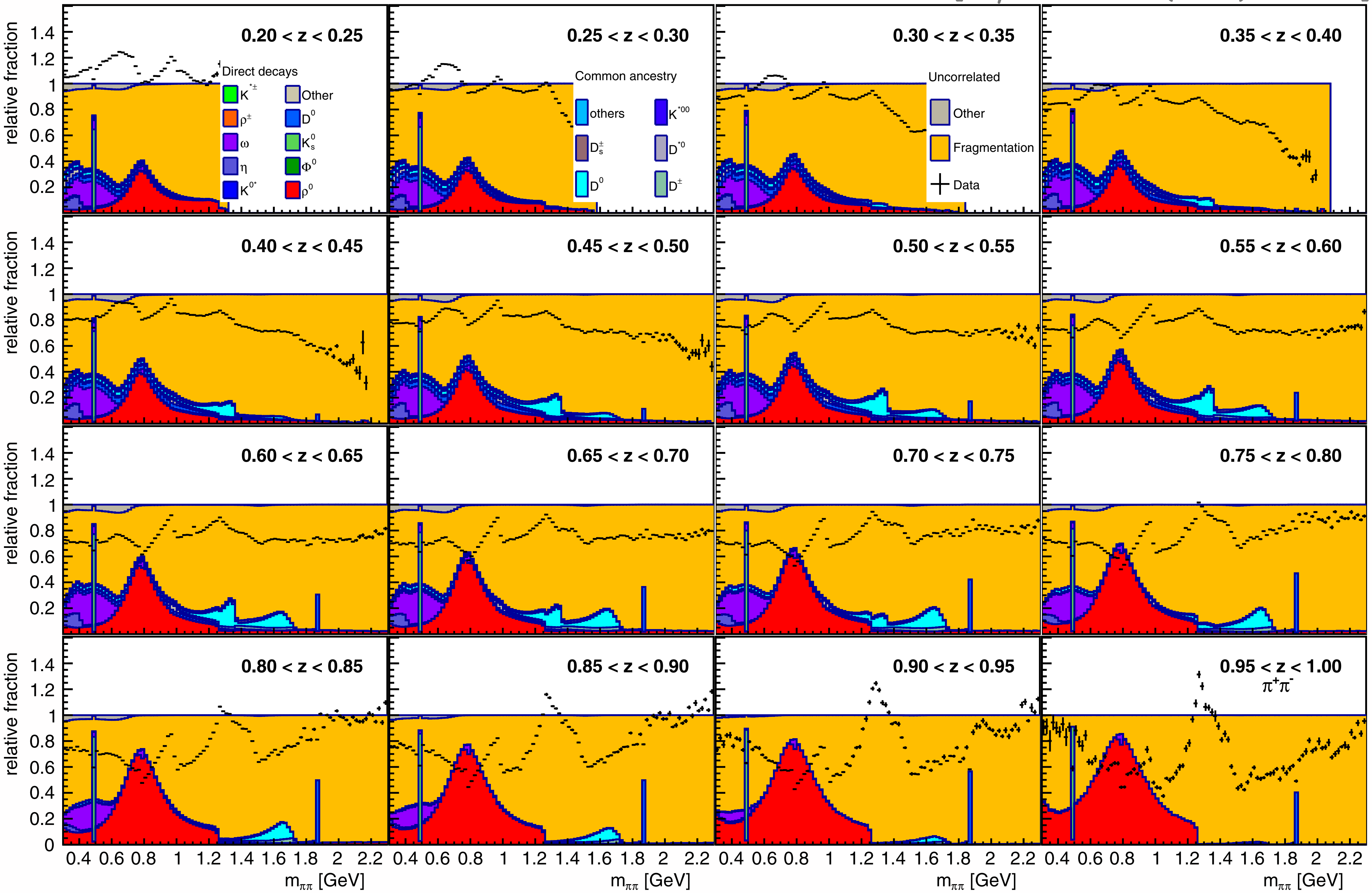


- cross sections after (MC-based) **removal of weak-decay contributions**
  - relies on good description of those channels in PYTHIA

same-hemisphere data: M_{h1h2} dependence

[Phys. Rev. D96 (2017) 032005]

unlike-sign
pion pairs



T > 0.8

$z_{1,2}$ > 0.1

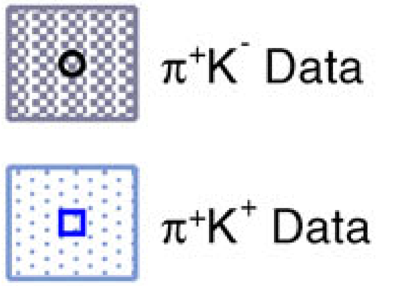
- decomposition based on PYTHIA simulation
- clear differences in invariant-mass dependence between MC and data

same-hemisphere data: M_{h1h2} dependence

[Phys. Rev. D96 (2017) 032005]

unlike-sign
hadron pairs

like-sign
hadron pairs



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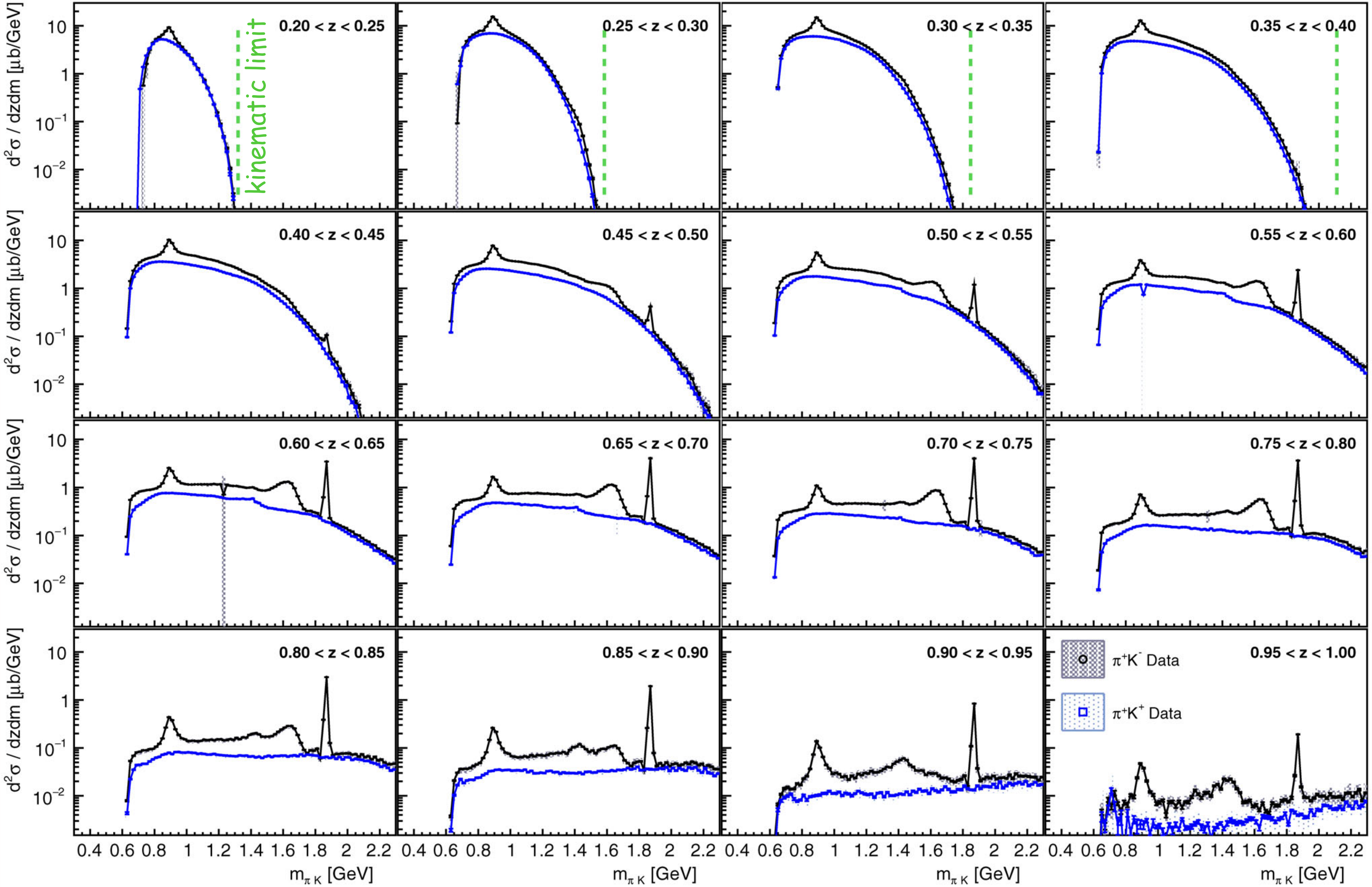

- unlike-sign πK pairs with clear K* and increased D-decay contributions

same-hemisphere data: M_{h1h2} dependence

unlike-sign
hadron pairs

like-sign
hadron pairs

○ K^+K^- Data

□ K^+K^+ Data

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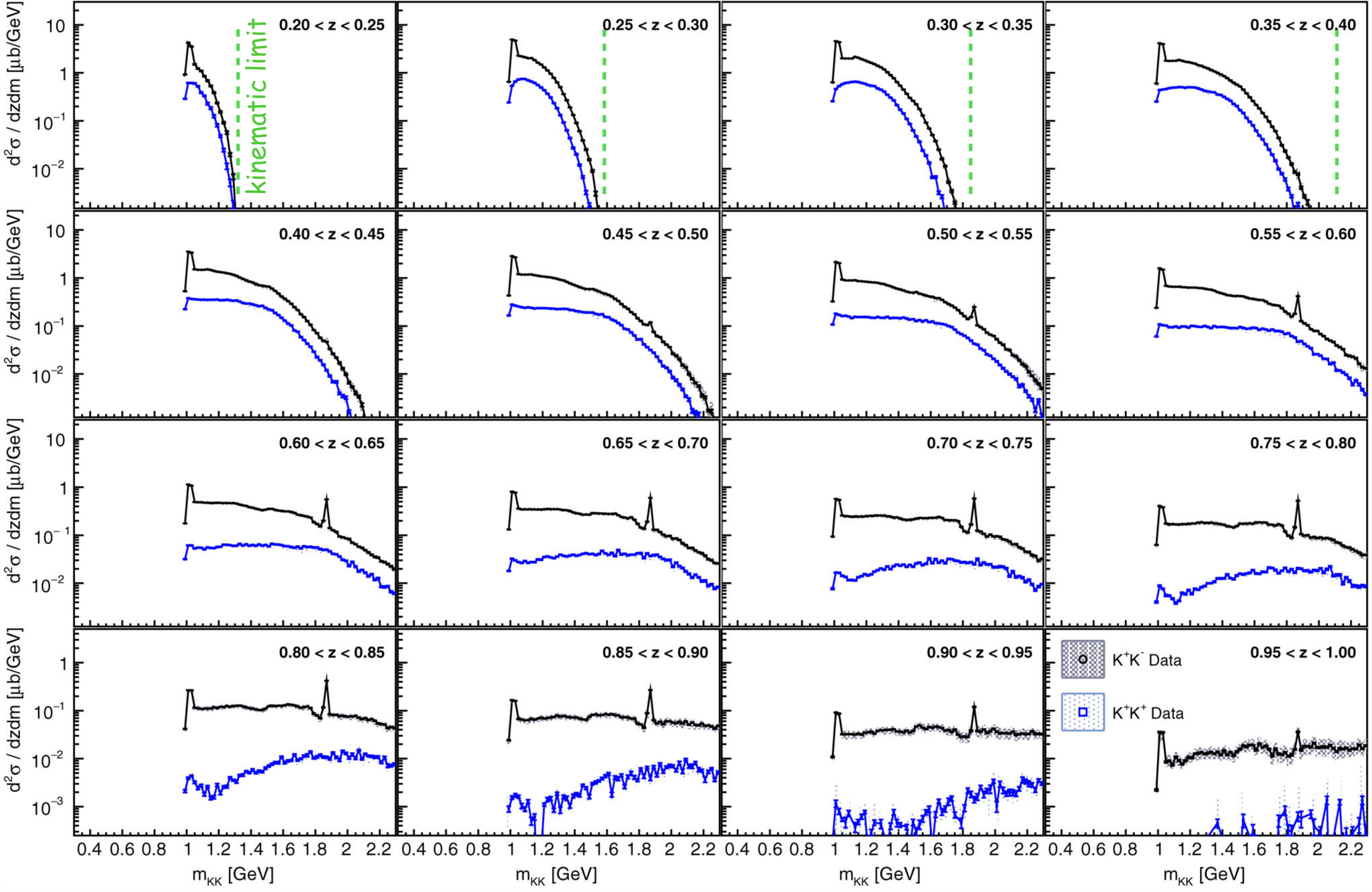
$z_{1,2} > 0.1$

[Phys. Rev. D96 (2017) 032005]



- 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

unlike-sign hadron pairs

like-sign hadron pairs

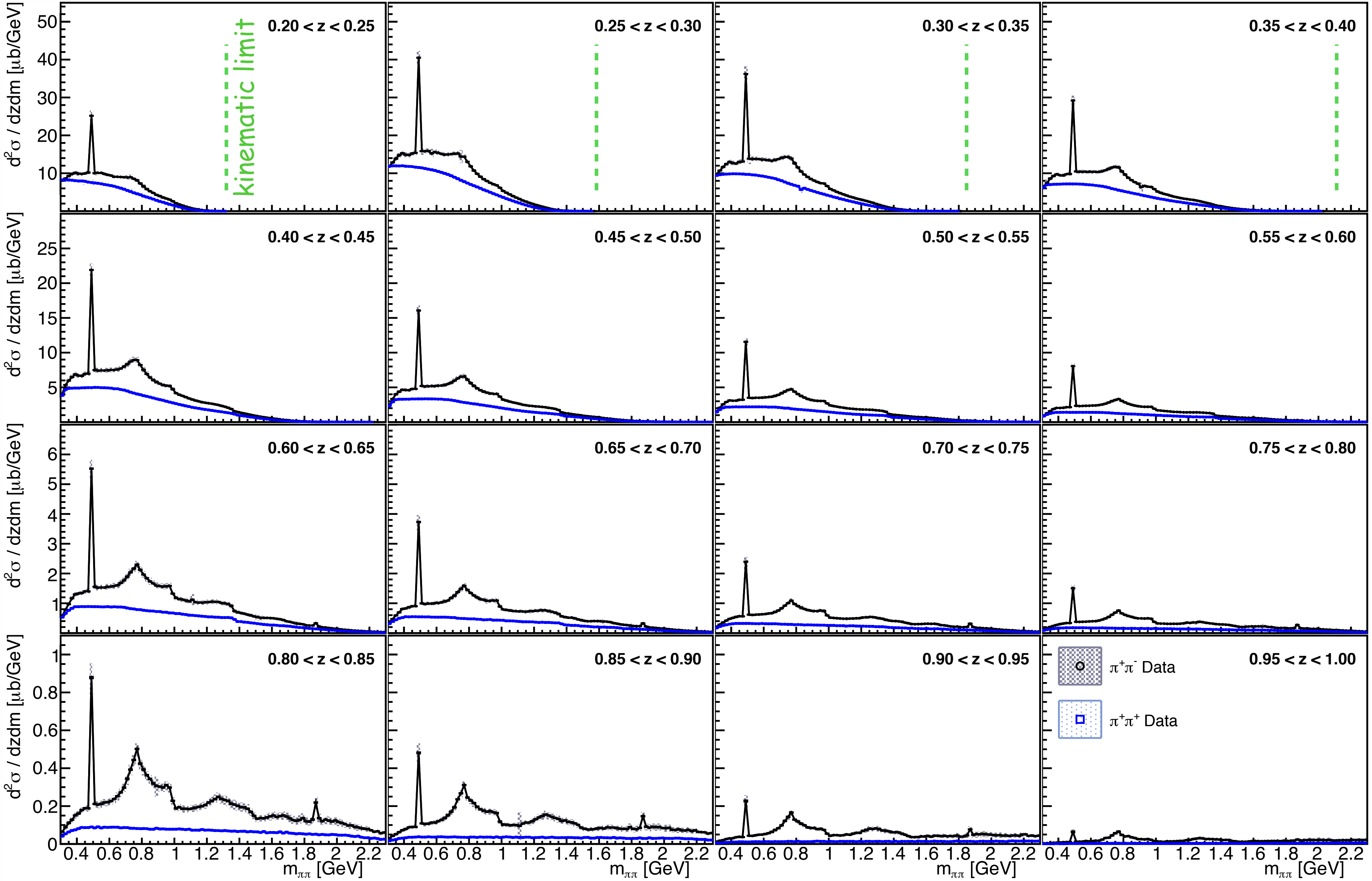
▨ $\pi^+\pi^-$ Data

▨ $\pi^+\pi^+$ Data

T > 0.8

$z_{1,2}$ > 0.1

[Phys. Rev. D96 (2017) 032005]



same-hemisphere data: M_{h1h2} dependence

[Phys. Rev. D96 (2017) 032005]

unlike-sign
hadron pairs

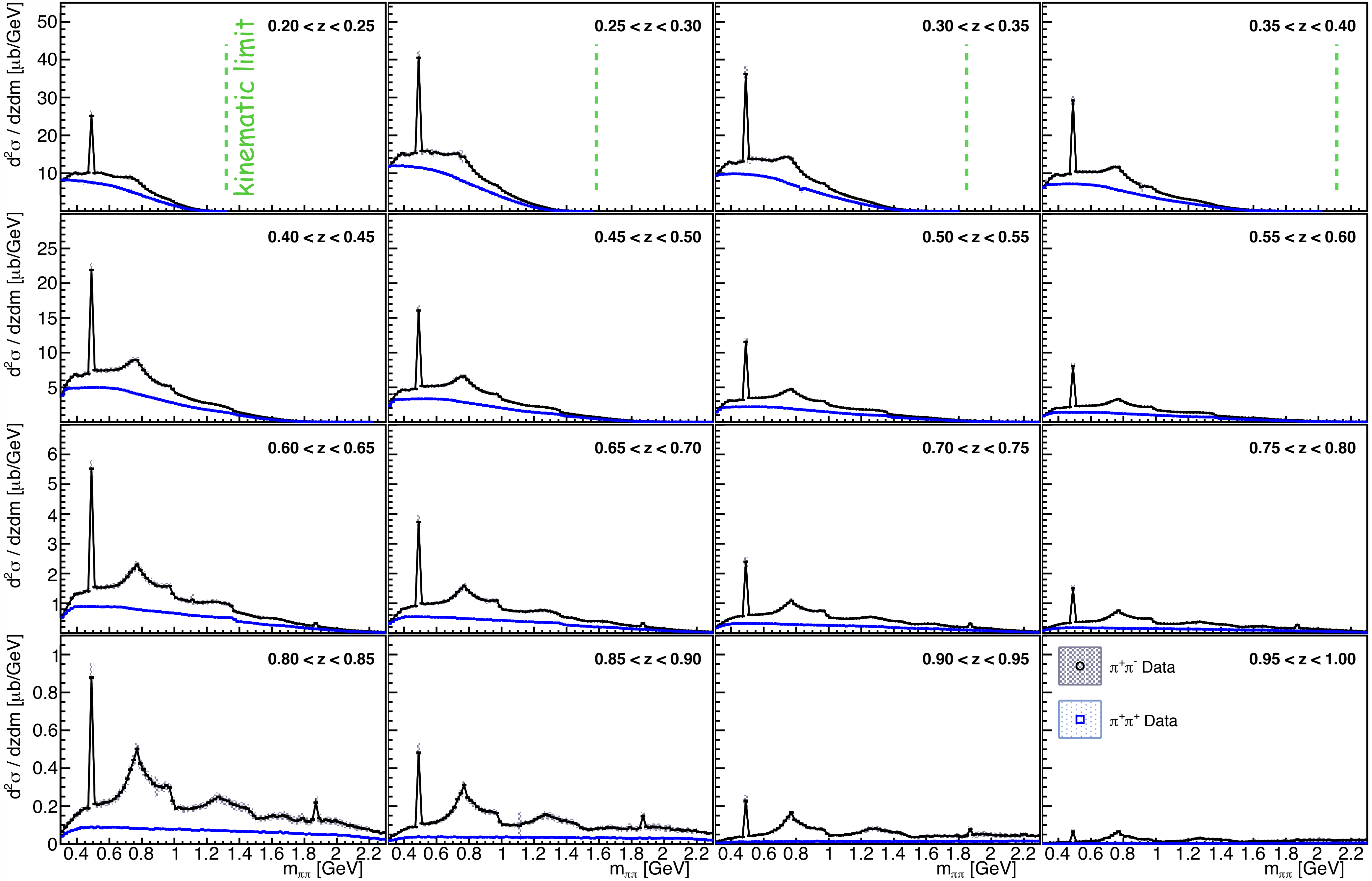
like-sign
hadron pairs

▨ $\pi^+\pi^-$ Data

▨ $\pi^+\pi^+$ Data

T > 0.8

$z_{1,2} > 0.1$



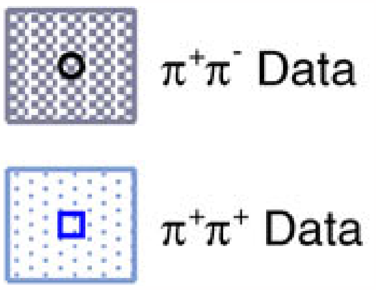
- **thrust** very useful experimentally to suppress BG and to define hemispheres
- potentially difficult to incorporate in phenomenology (unlike thrust axis?)

same-hemisphere data: M_{h1h2} dependence

[Phys. Rev. D96 (2017) 032005]

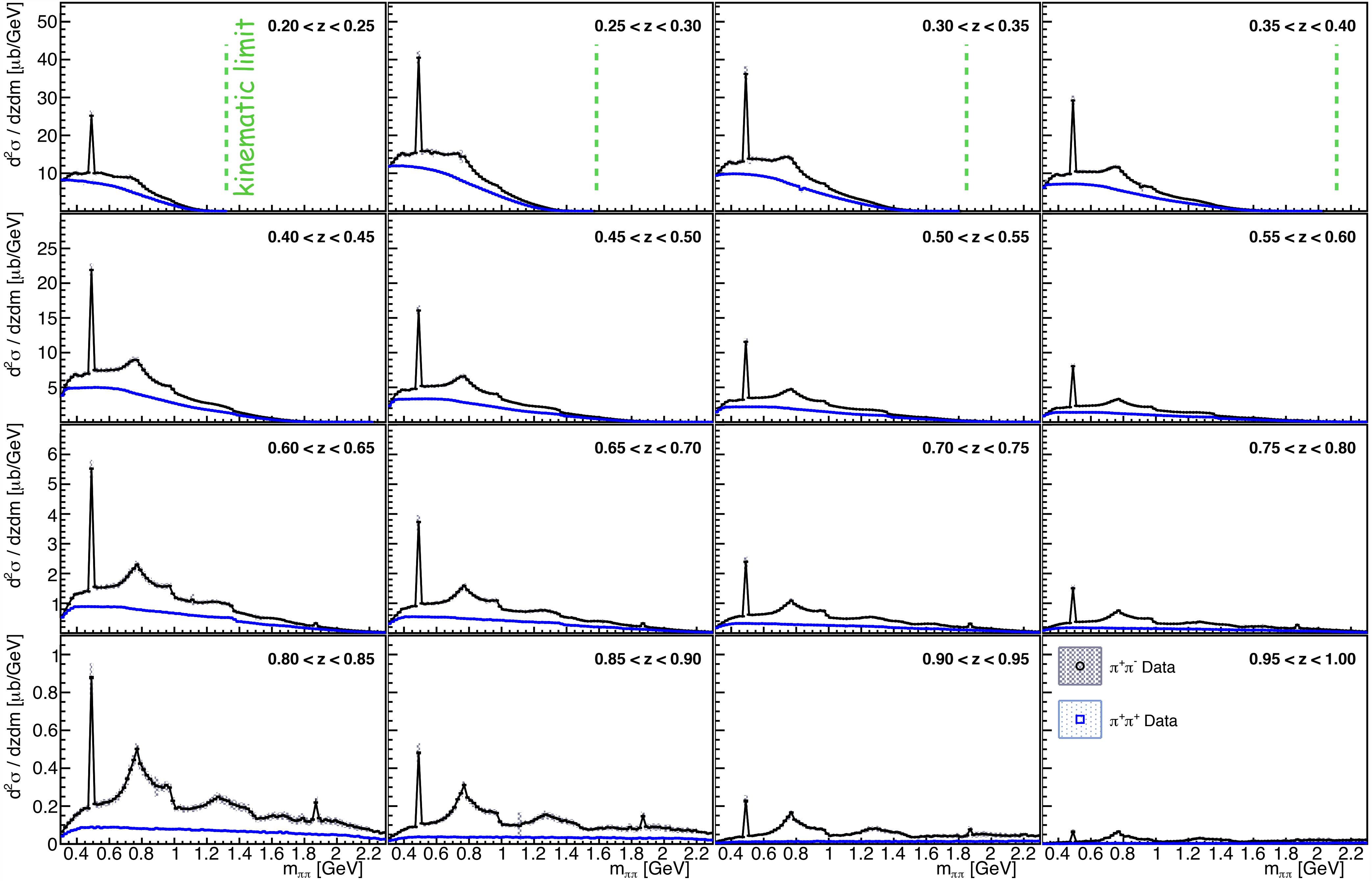
unlike-sign
hadron pairs

like-sign
hadron pairs



$T > 0.8$

$z_{1,2} > 0.1$

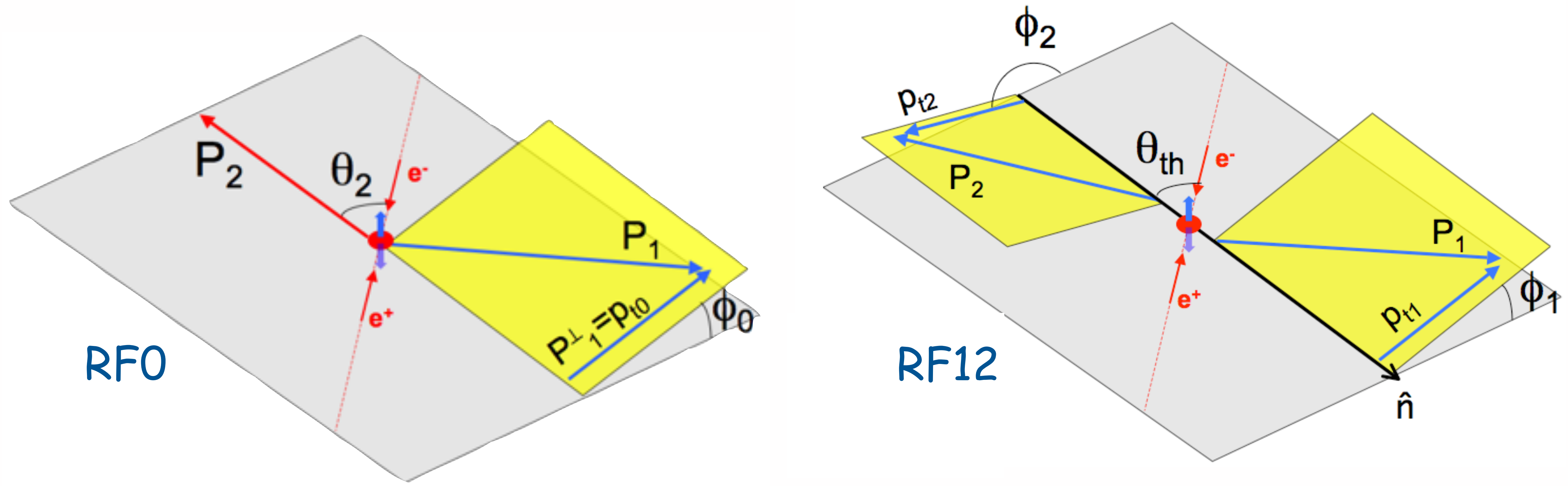


- experimental constraints on individual z restricts phase space of hadron pairs, however, not easy to avoid (detection requirements!)
- among others leads to mixing of partial-wave contributions [GS, QCDE'17]

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

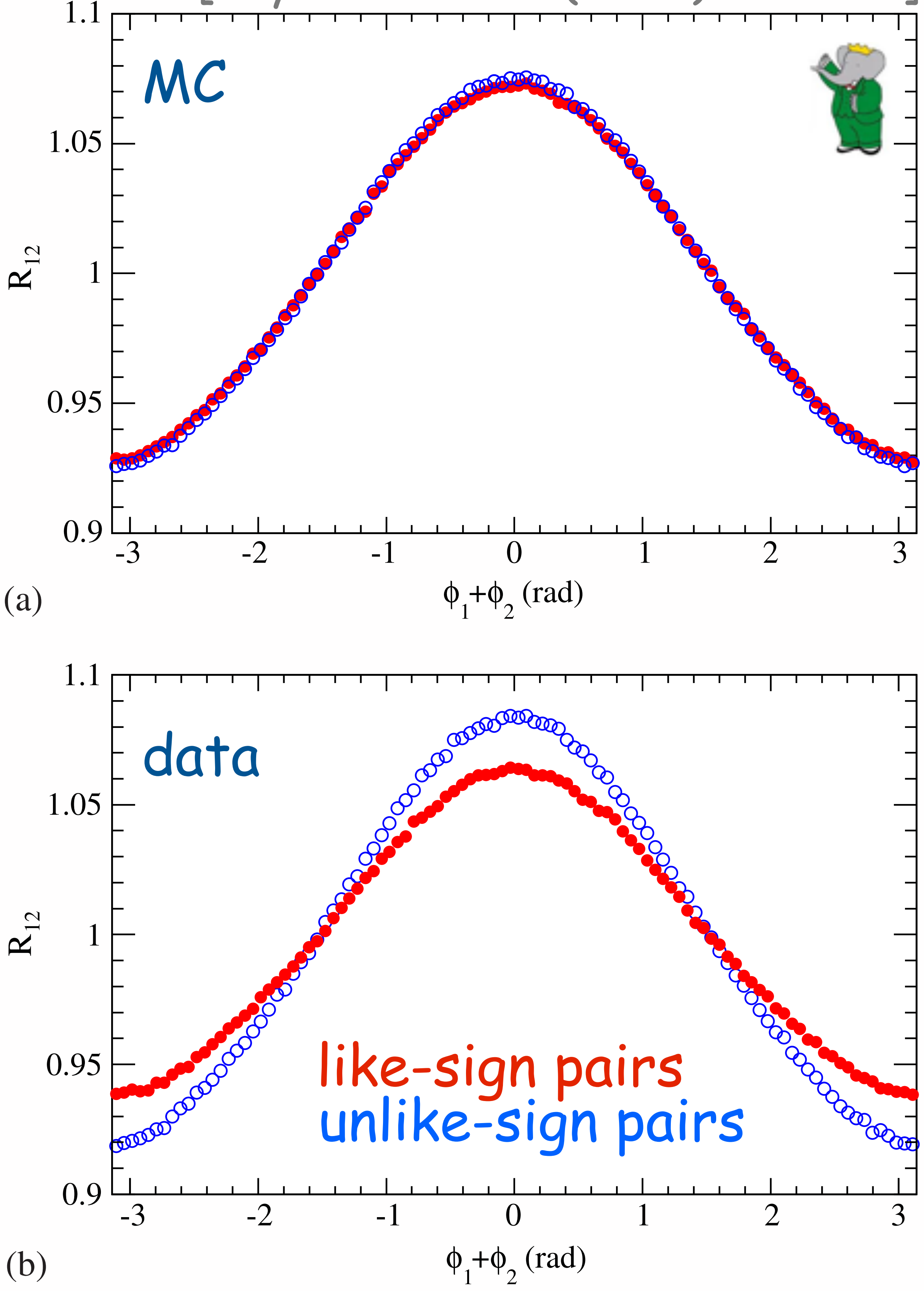


- RF0 and RF12: different convolutions over transverse momenta
- debatable: MC used to “correct” thrust axis to $q\bar{q}$ axis

hadron pairs: angular correlations

[Phys. Rev. D90 (2014) 052003]

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



hadron pairs: angular correlations

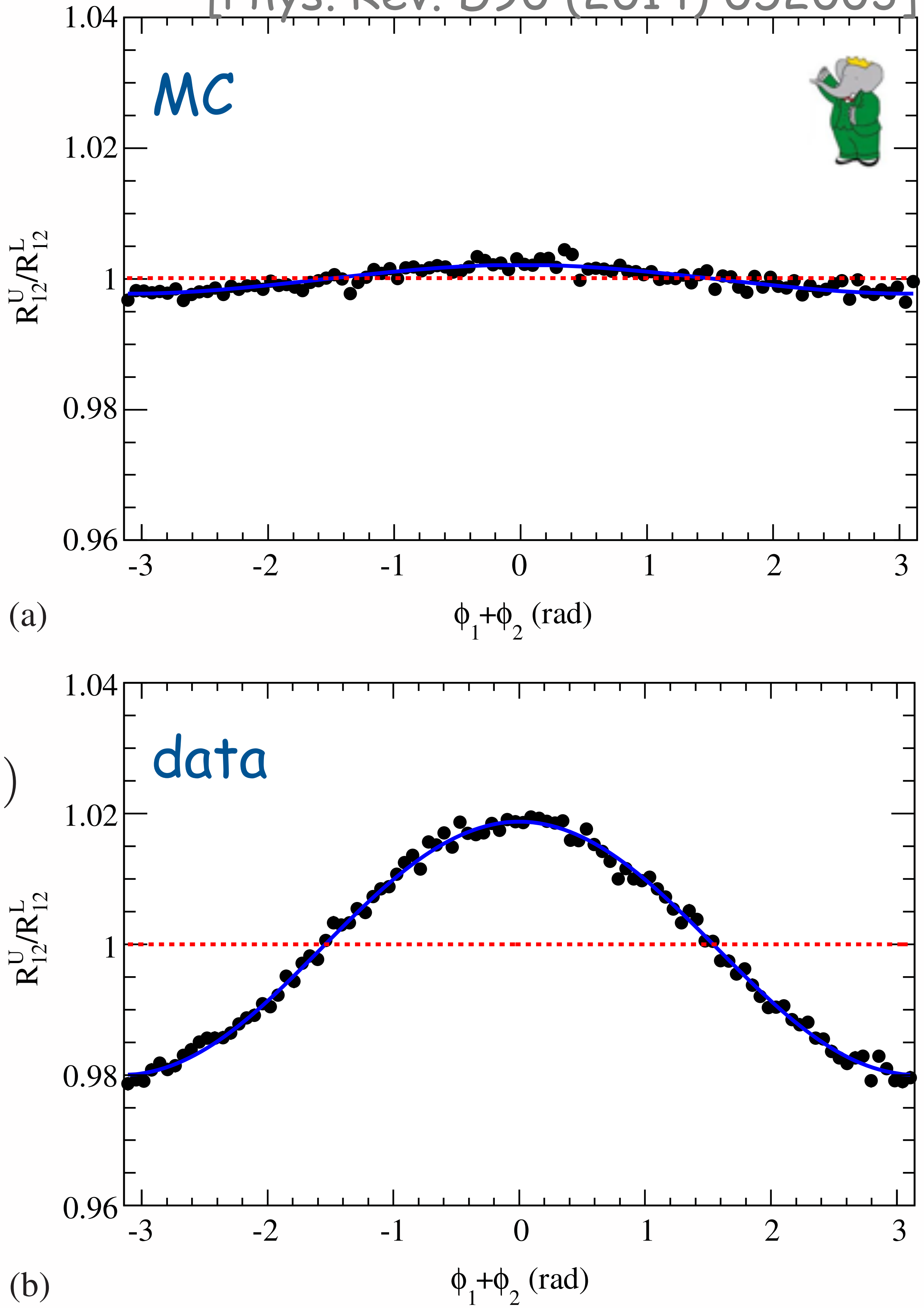
- challenge: large modulations even without Collins effect (e.g., MC)
- construct double ratio of normalized-yield distributions R12, e.g. unlike-/like-sign:

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

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

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

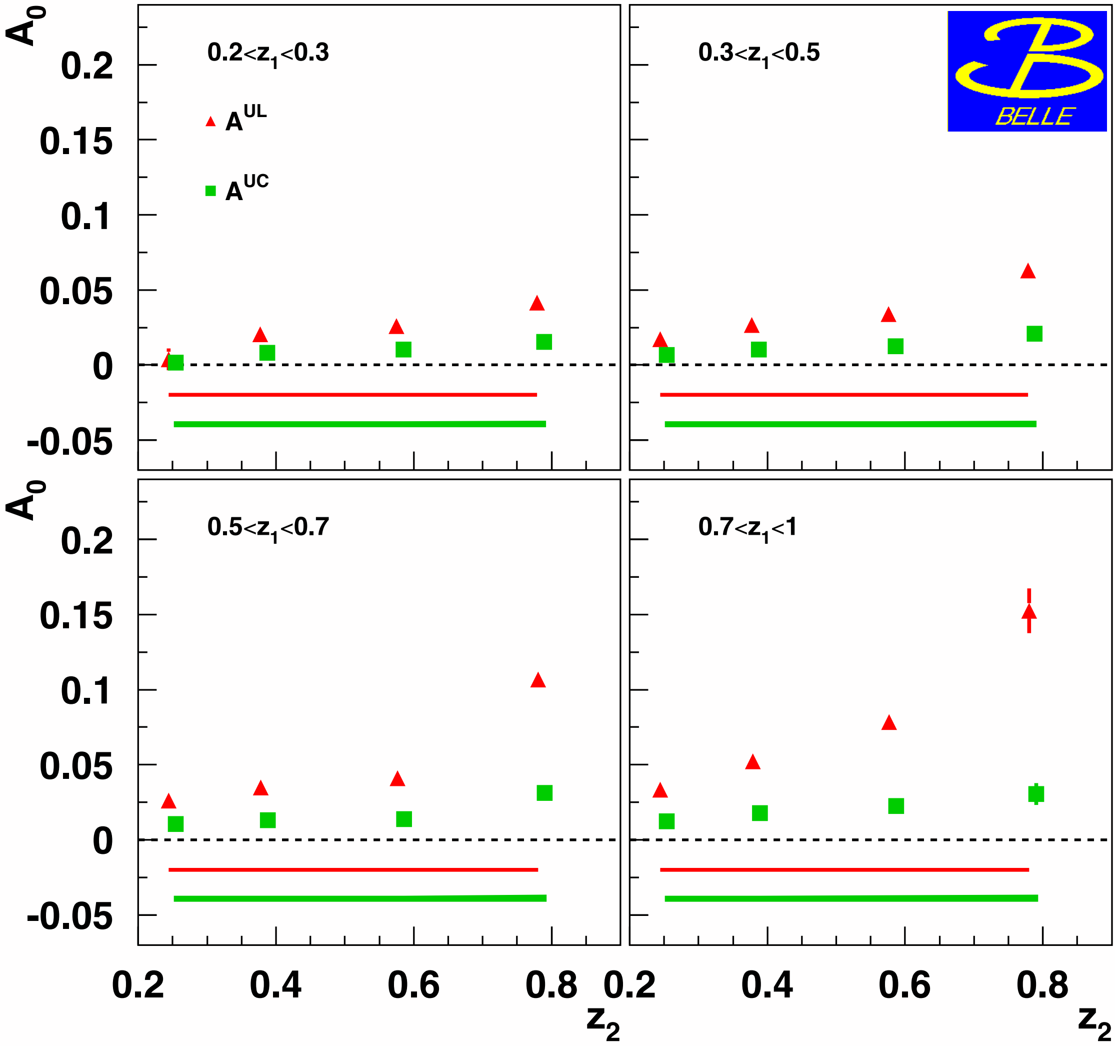
[Phys. Rev. D90 (2014) 052003]



Collins asymmetries (RF0)

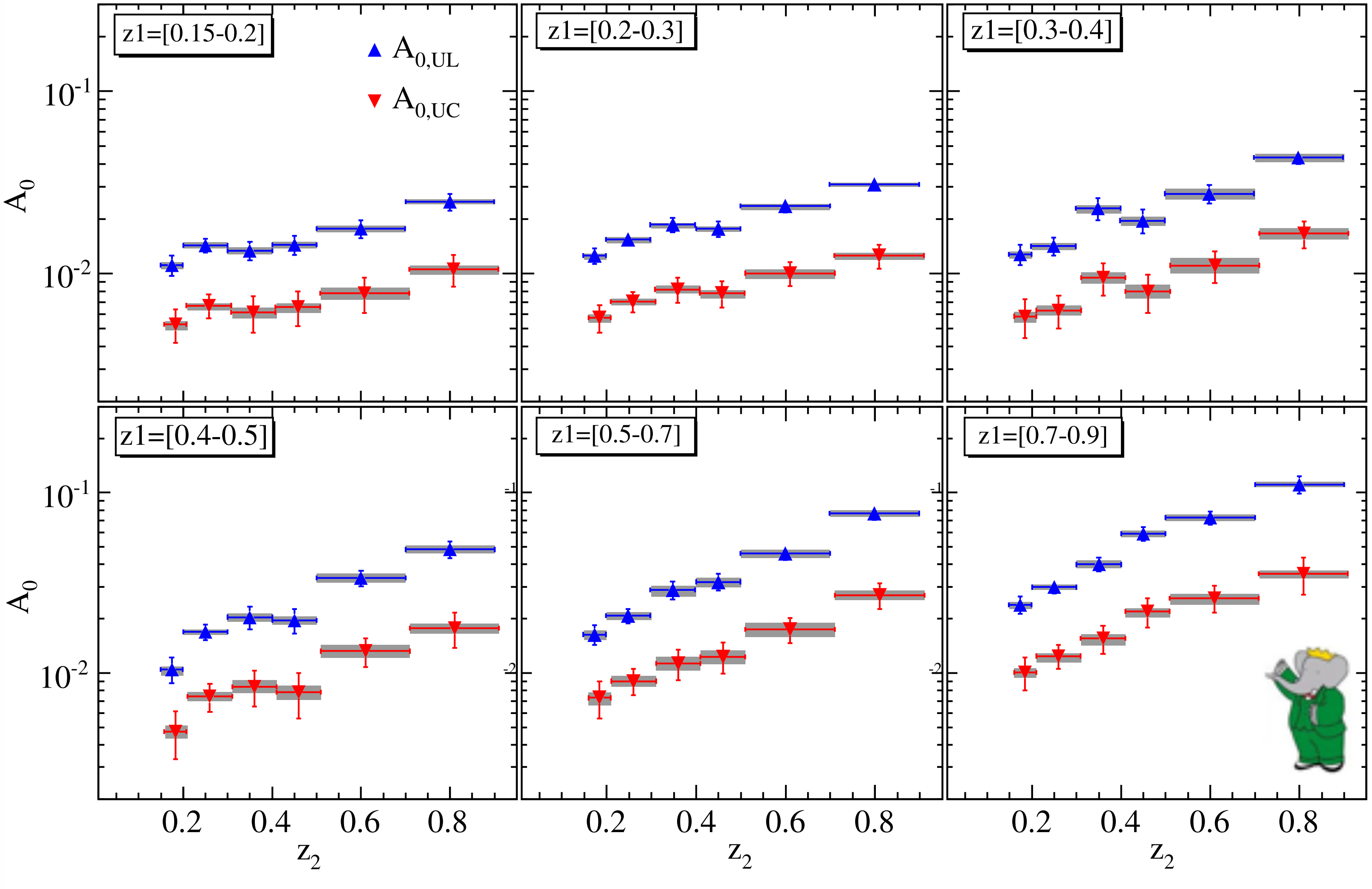
- first measurement of Collins asymmetries by Belle [PRL 96 (2006) 232002, PRD 78 (2008) 032011, PRD 86 (2012) 039905(E)]

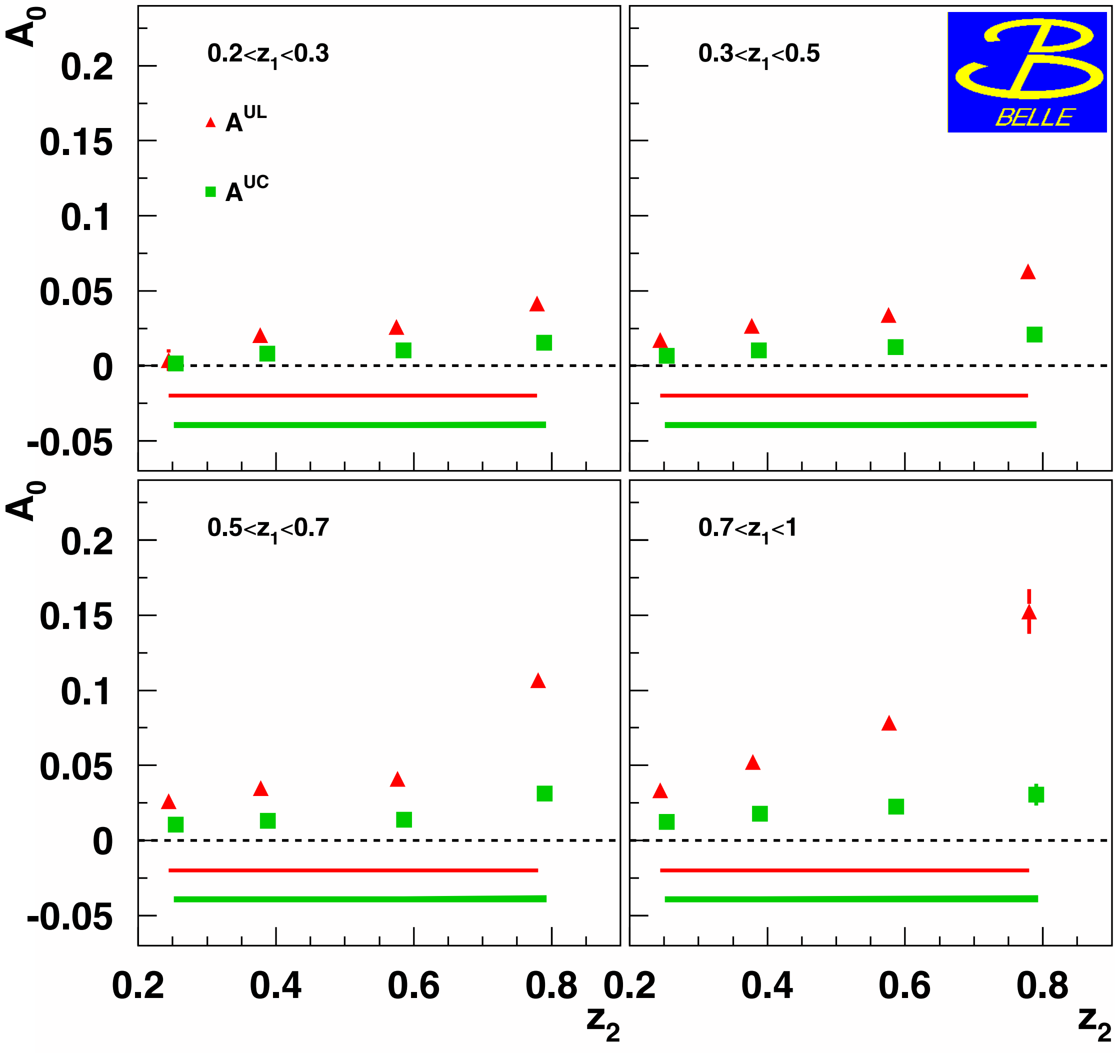
  - significant asymmetries rising with z
  - used for first transversity and Collins FF extractions



Collins asymmetries (RF0)

[Phys. Rev. D90 (2014) 052003]

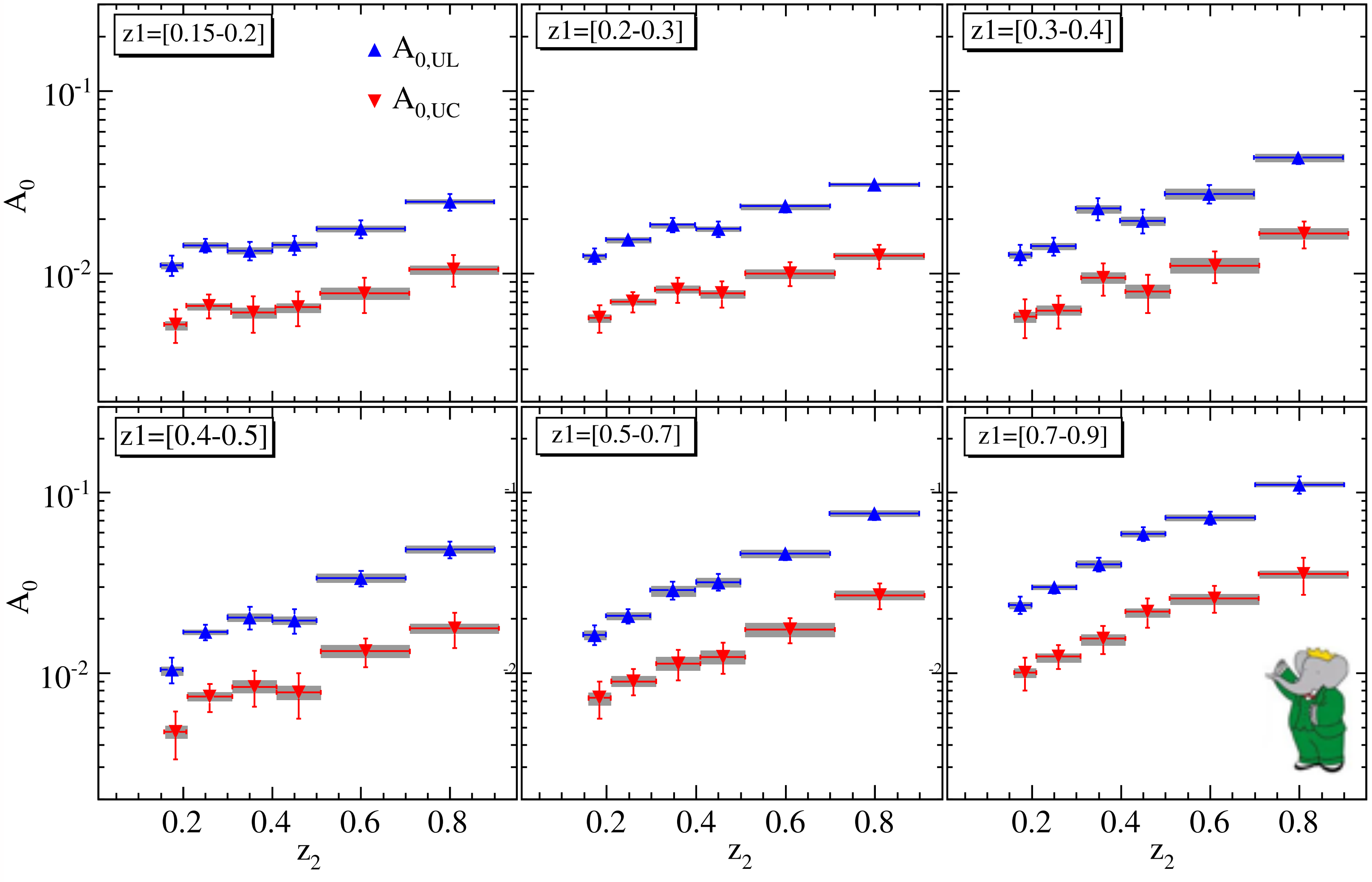


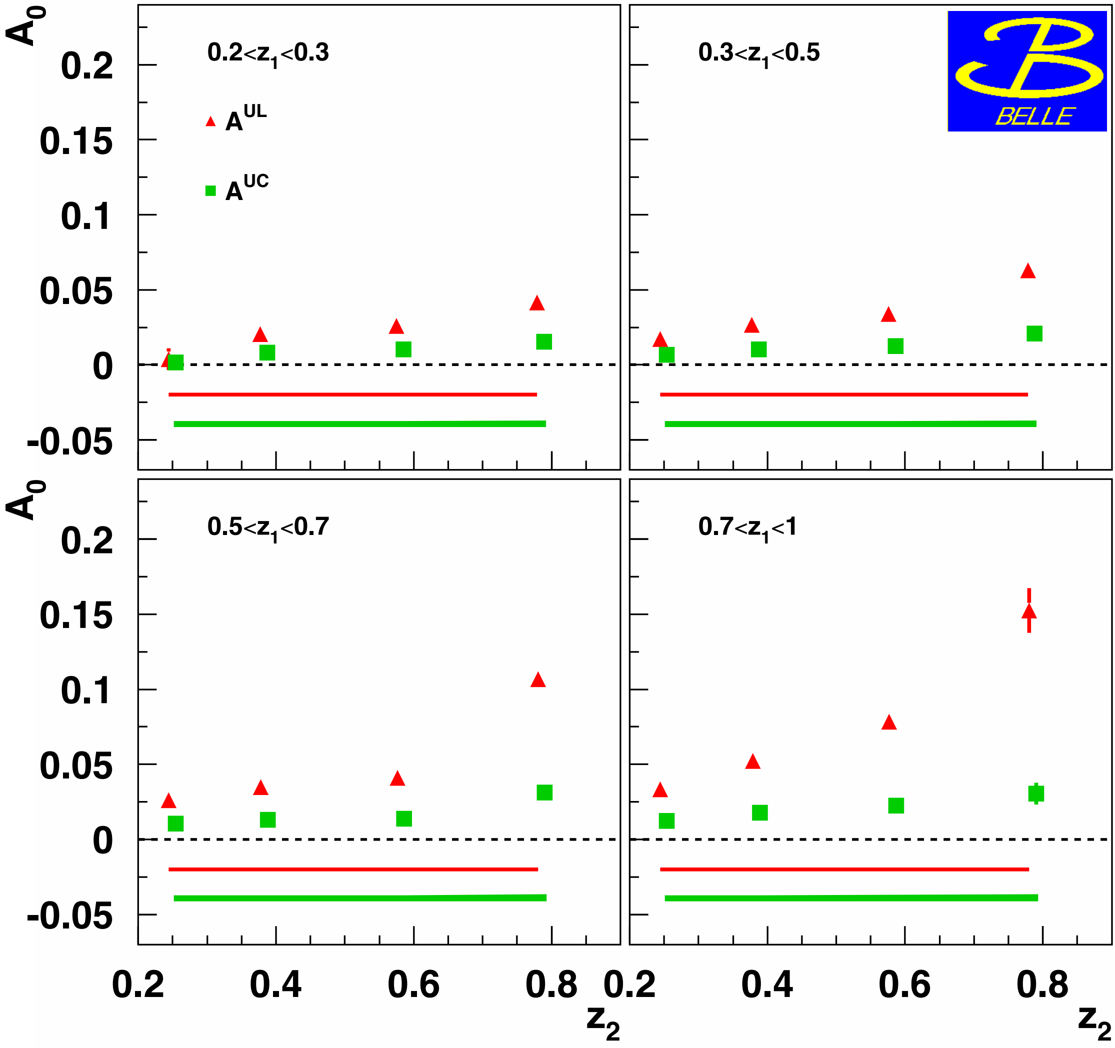


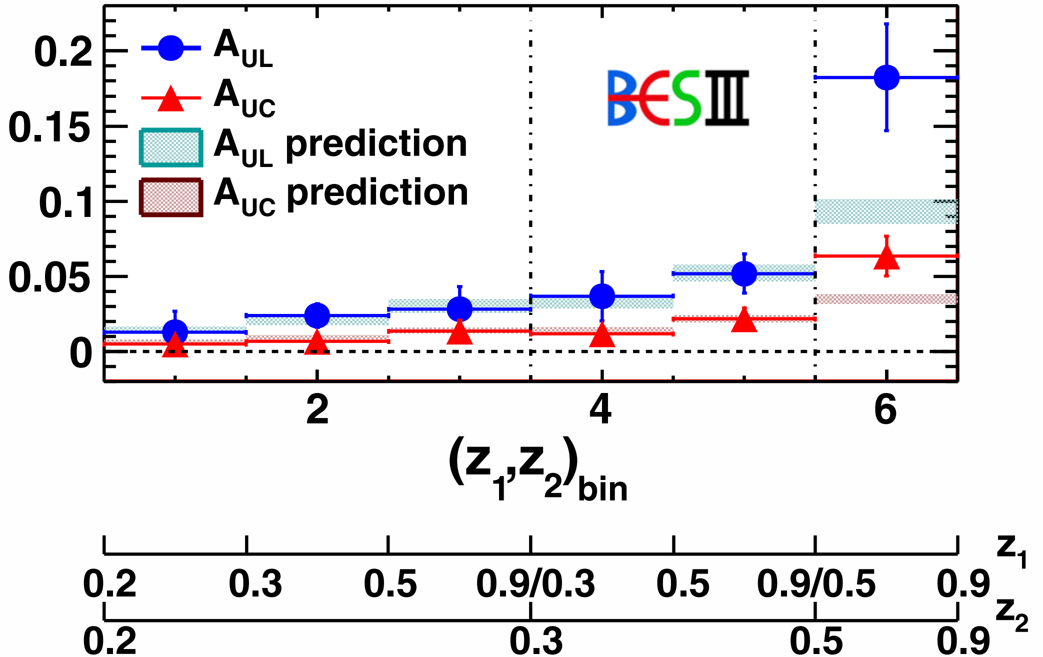
- BaBar results [PRD 90 (2014) 052003] consistent with Belle

Collins asymmetries (RF0)

[Phys. Rev. D90 (2014) 052003]

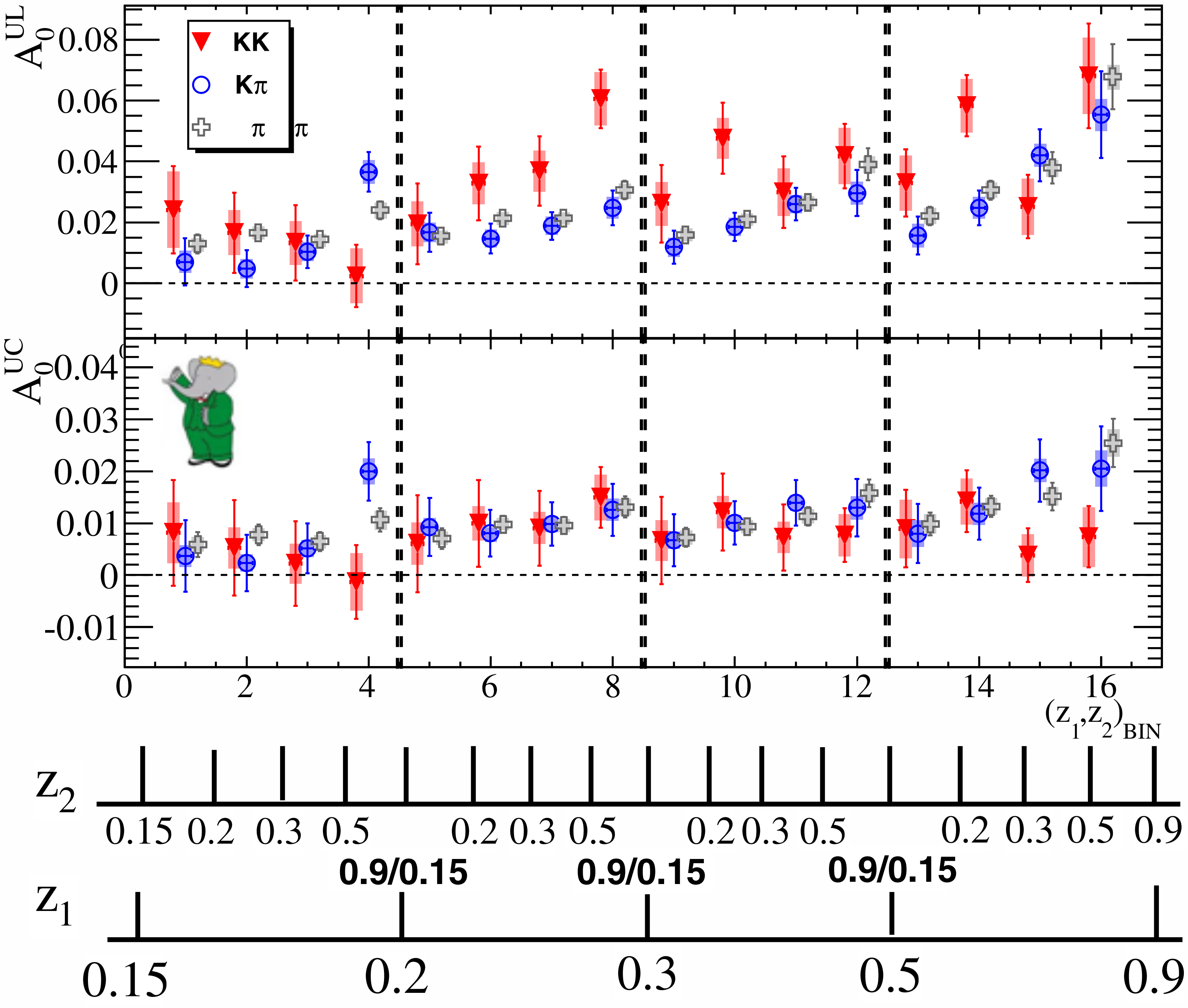






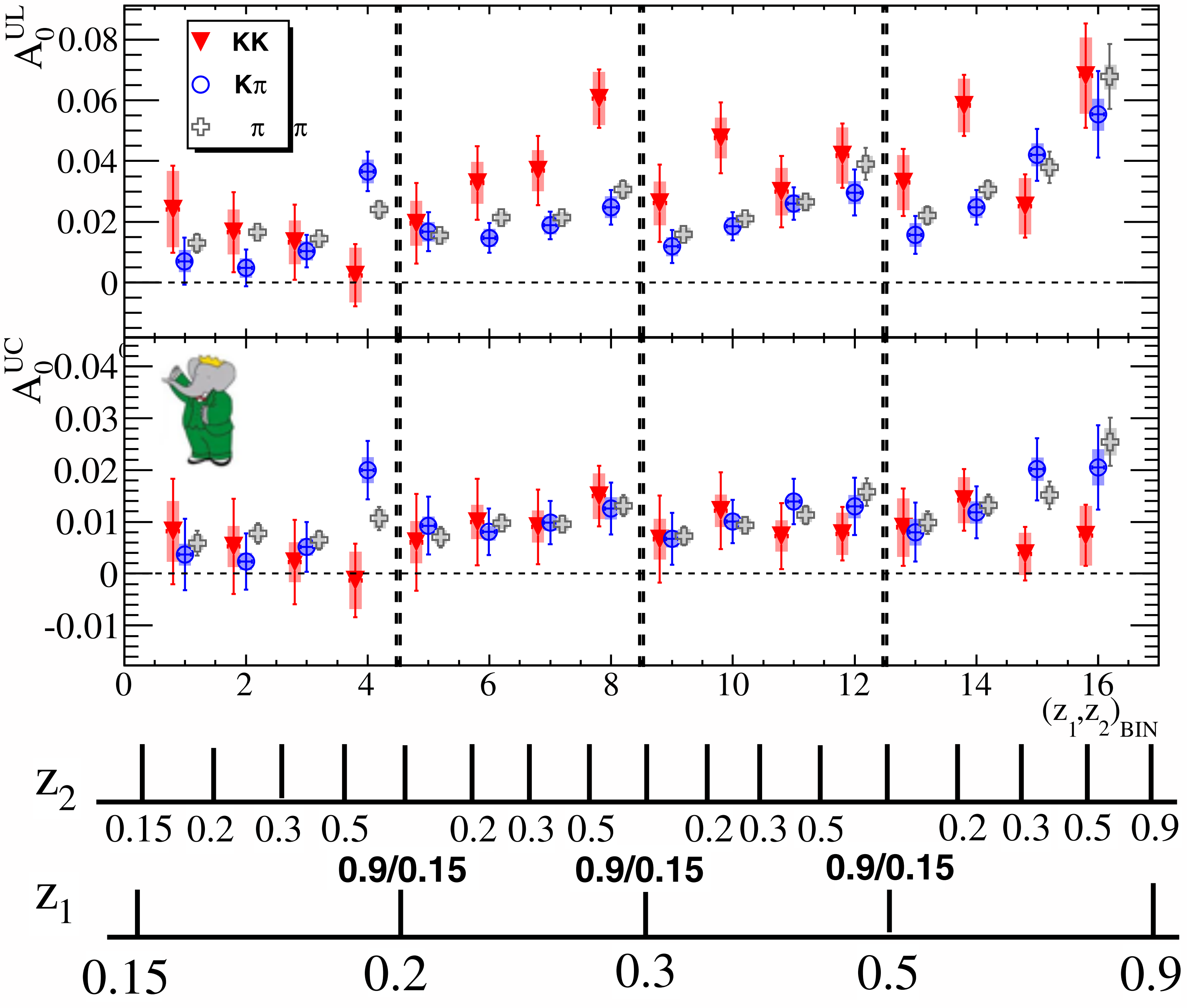
- BaBar results [PRD 90 (2014) 052003] consistent with Belle
- BESIII [PRL 116 (2016) 042001] (at smaller s) consistent with TMD evolution [Z.-B. Kang et al., PRD 93 (2016) 014009]

Collins asymmetries - going further

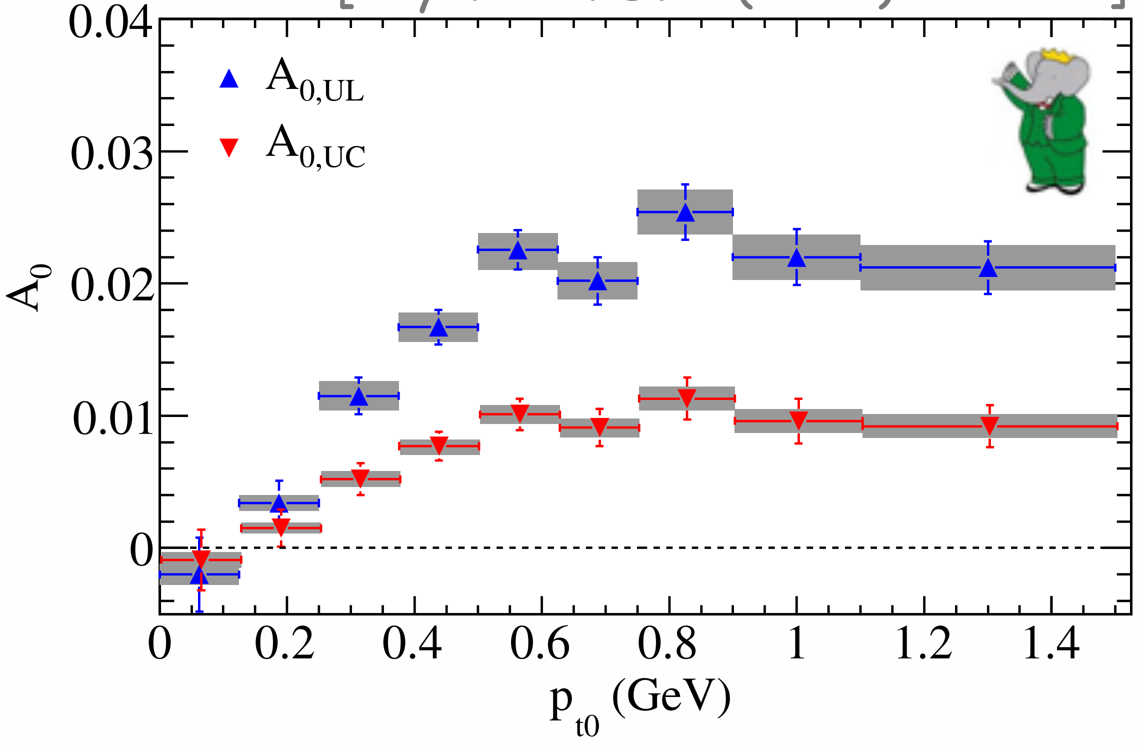


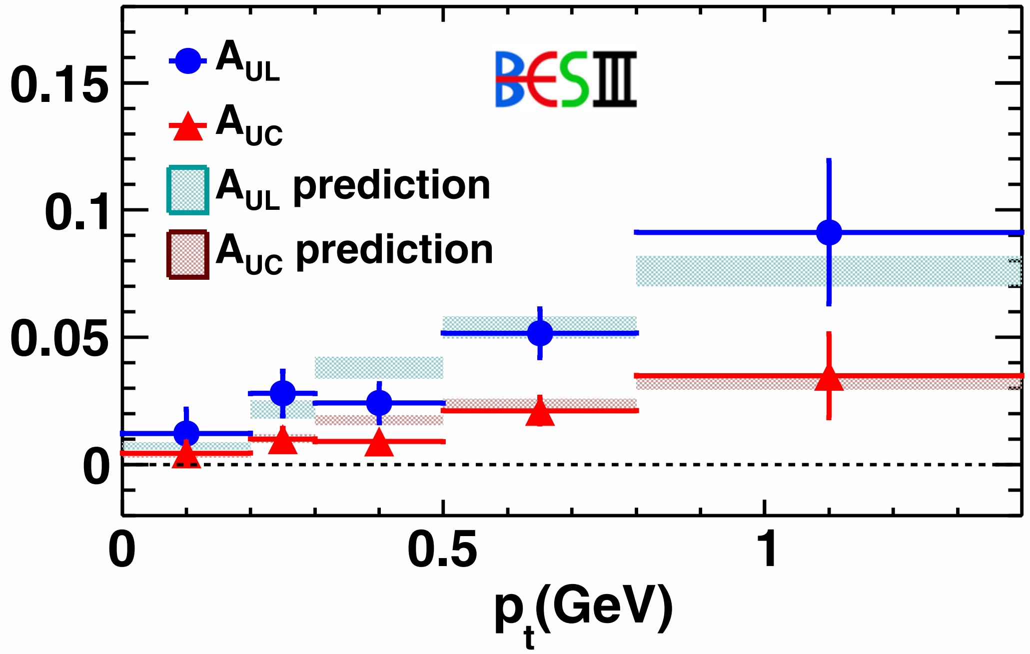
- even larger effects seen for kaon pairs

Collins asymmetries - going further



[Phys. Rev. D90 (2014) 052003]

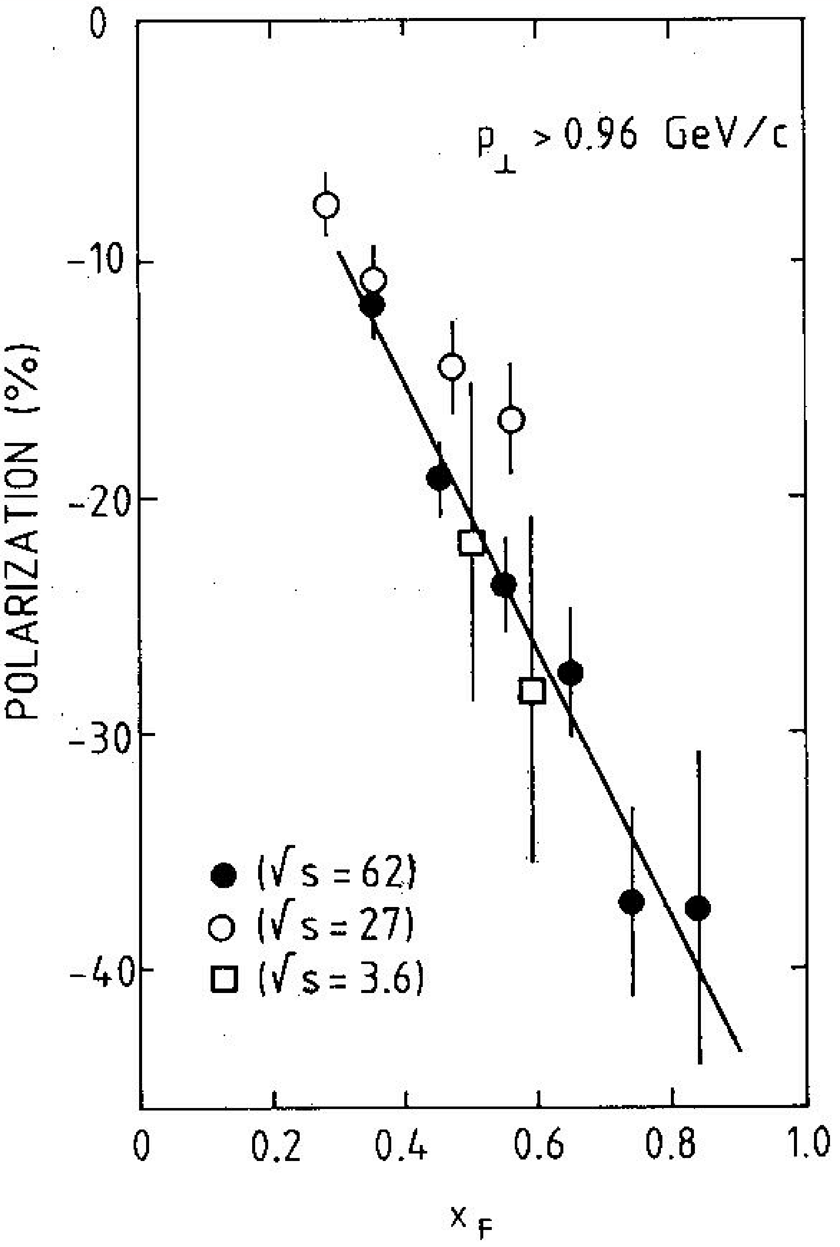




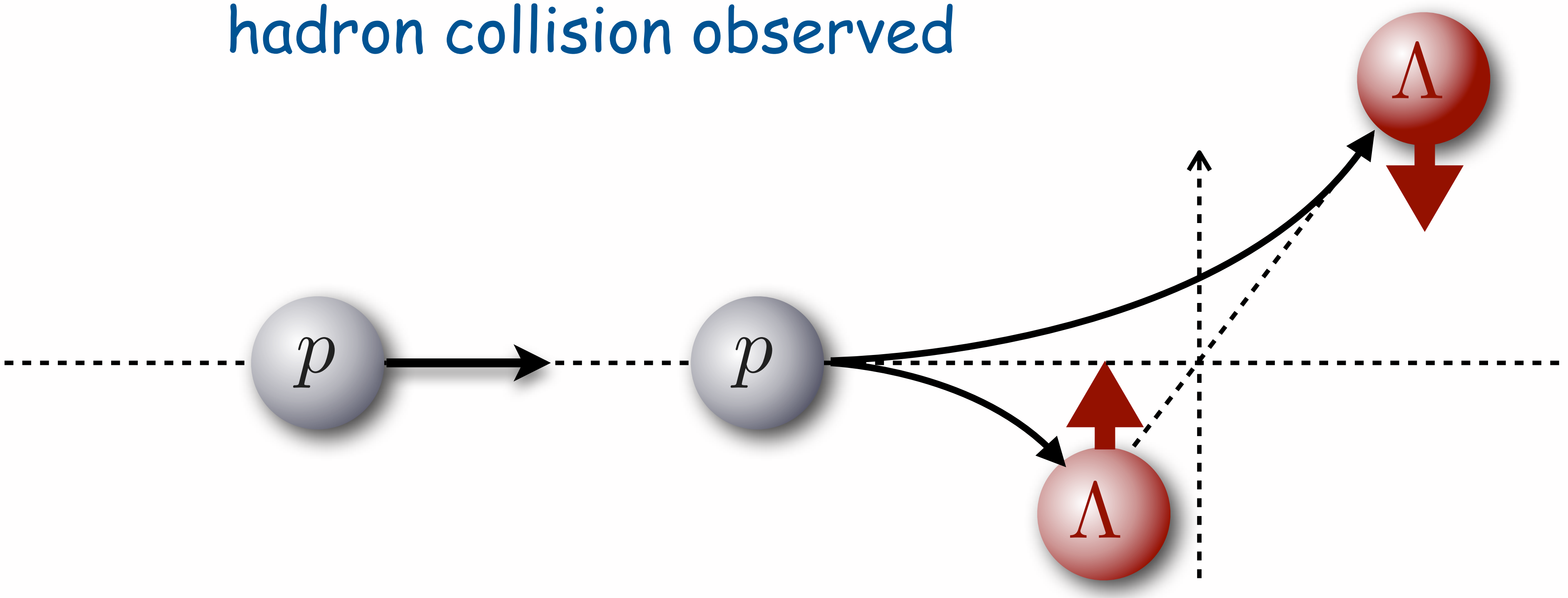
[PRL 116 (2016) 042001]

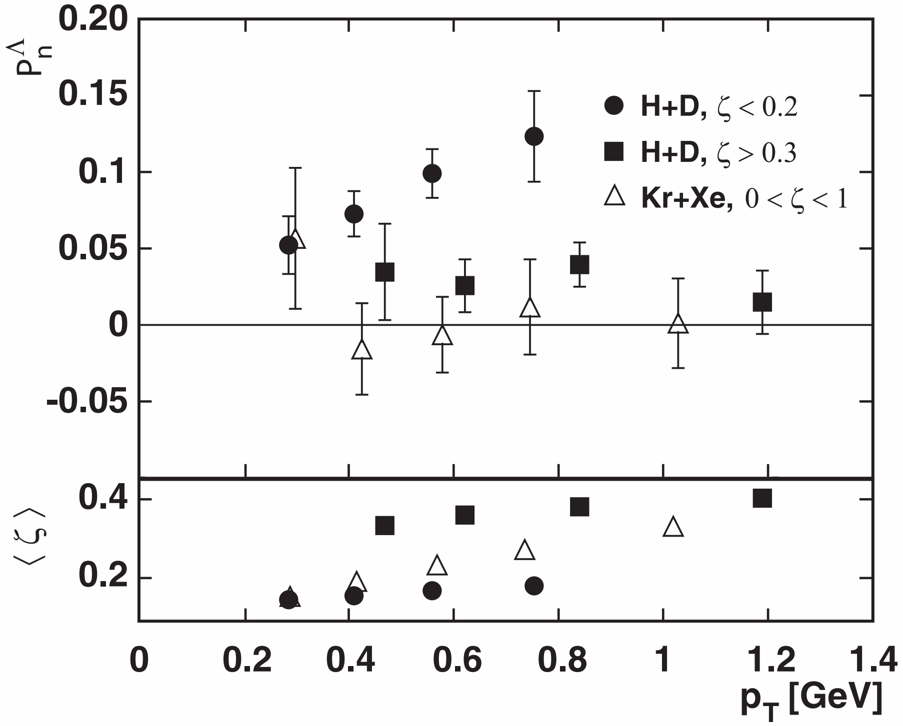
- even larger effects seen for kaon pairs
- p_T dependence for pions

polarizing fragmentation



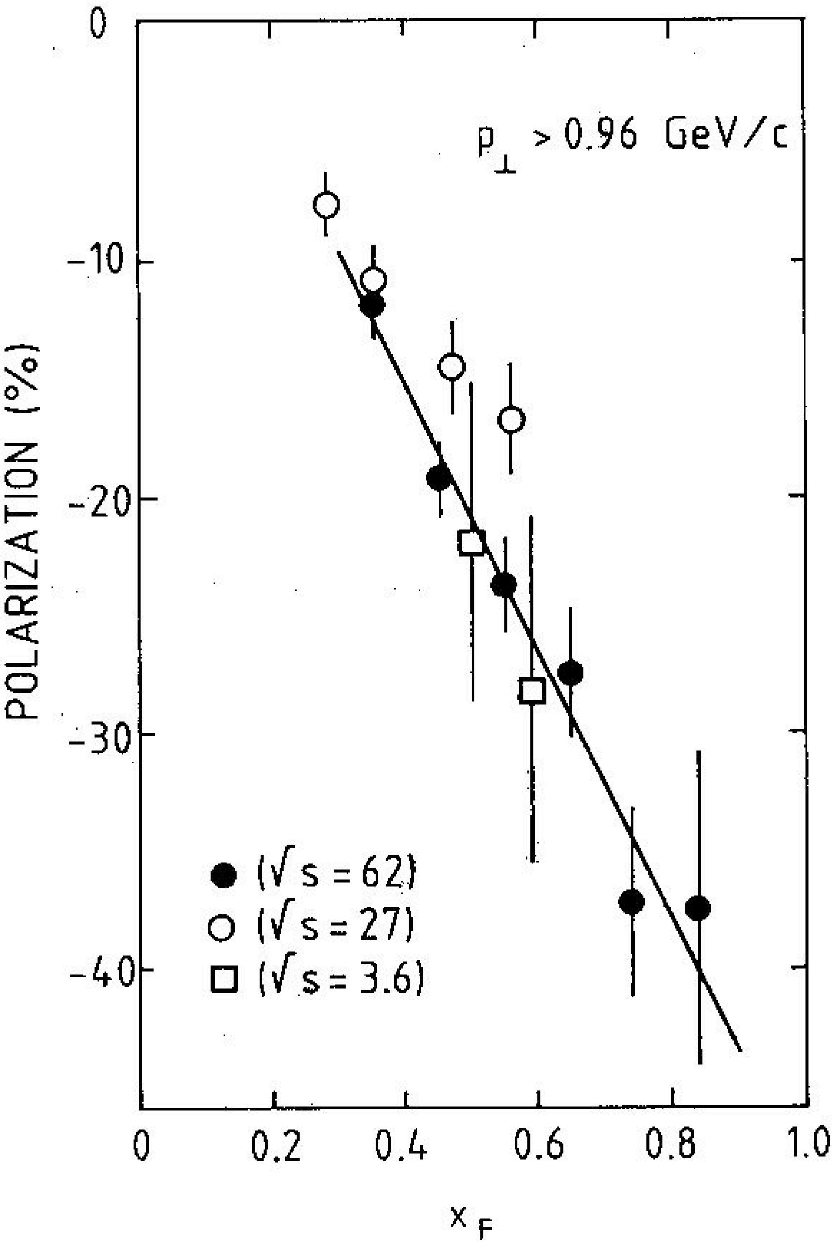
- large hyperon polarization in unpolarized hadron collision observed

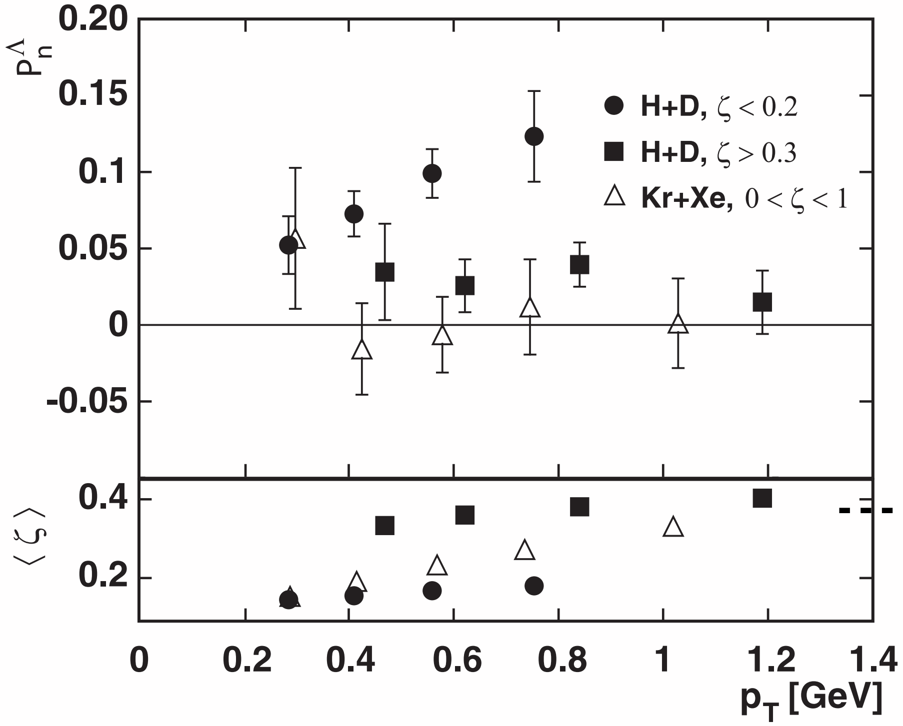




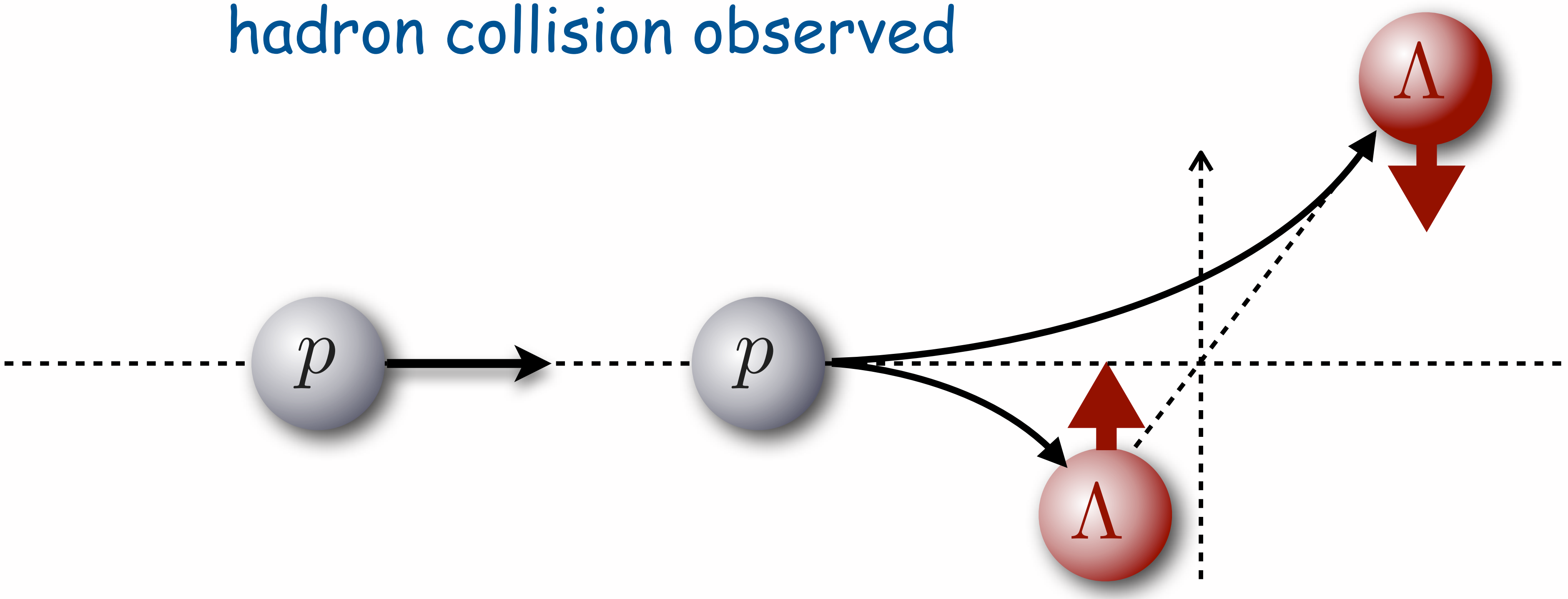
- … as well as in inclusive lepto-production

polarizing fragmentation

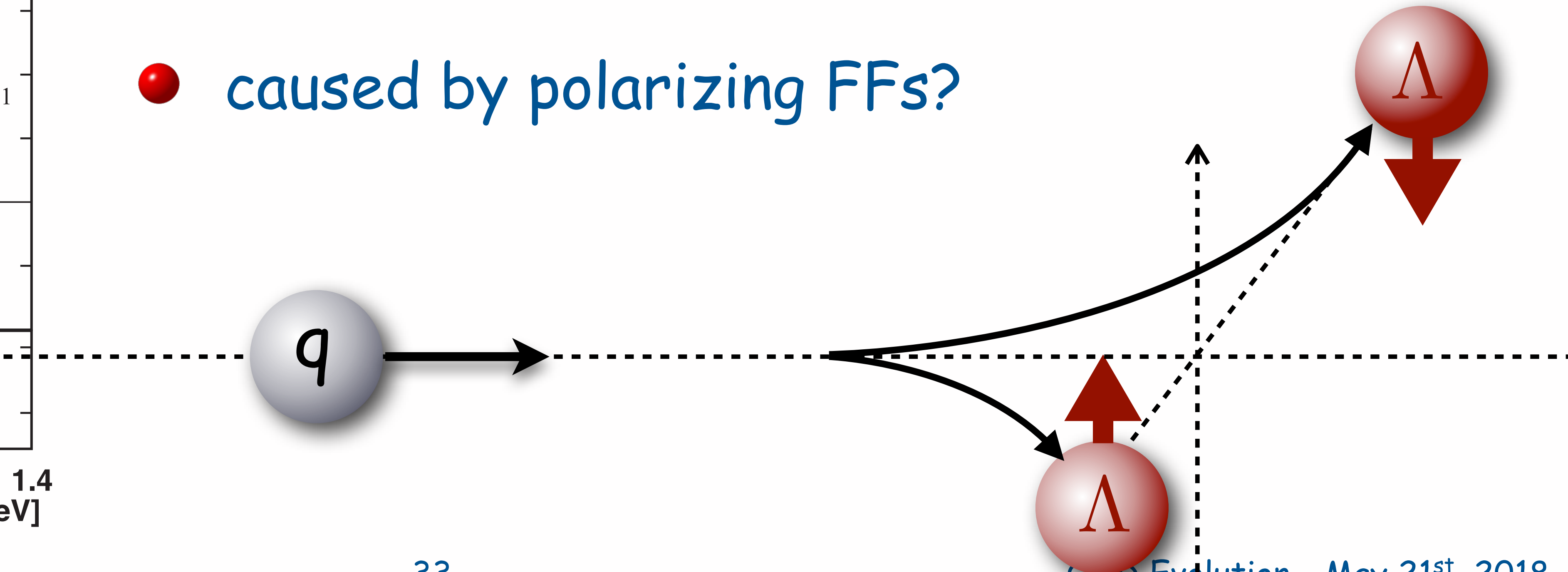




- large hyperon polarization in unpolarized hadron collision observed



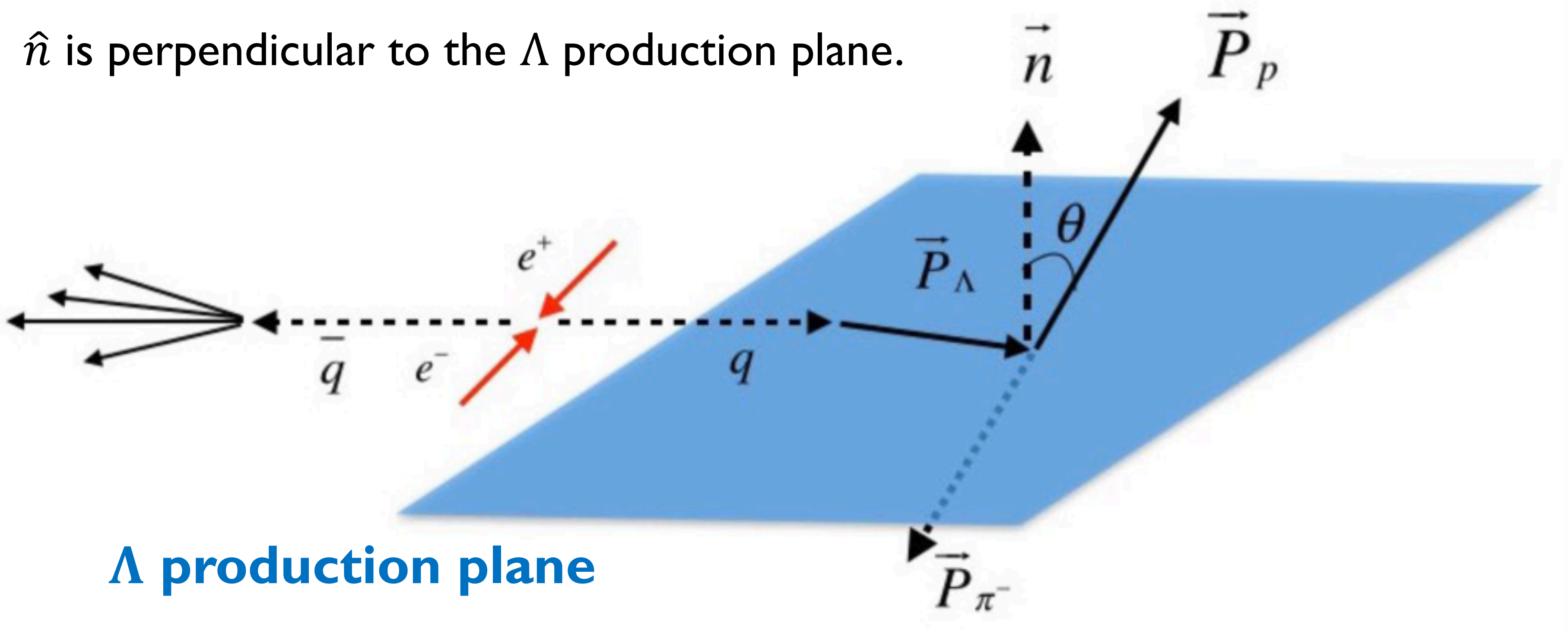
- … as well as in inclusive lepto-production
- caused by polarizing FFs?



polarizing fragmentation function

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

  (note that sign got reversed in the drawing)

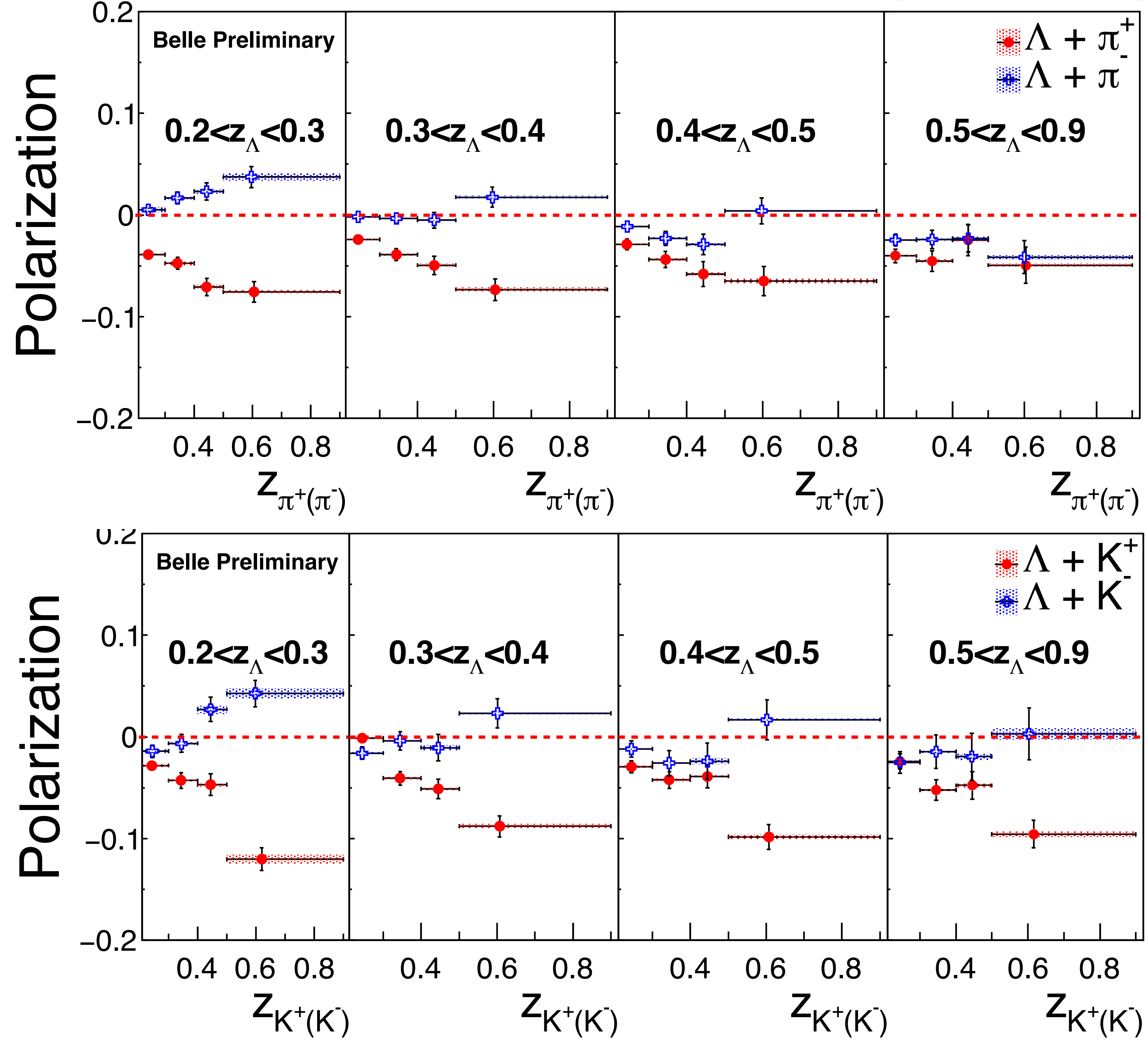


- reference axis to define transverse momentum:
  - "thrust frame" - use thrust axis
  - "hadron frame" - use momentum direction of "back-to-back" hadron

polarizing fragmentation function

- flavor tagging through hadrons in opposite hemisphere:

[arXiv:1611.06648]



- large-z_h hadrons tag quark flavor more efficiently

➡ enlarges differences between oppositely charged hadrons

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

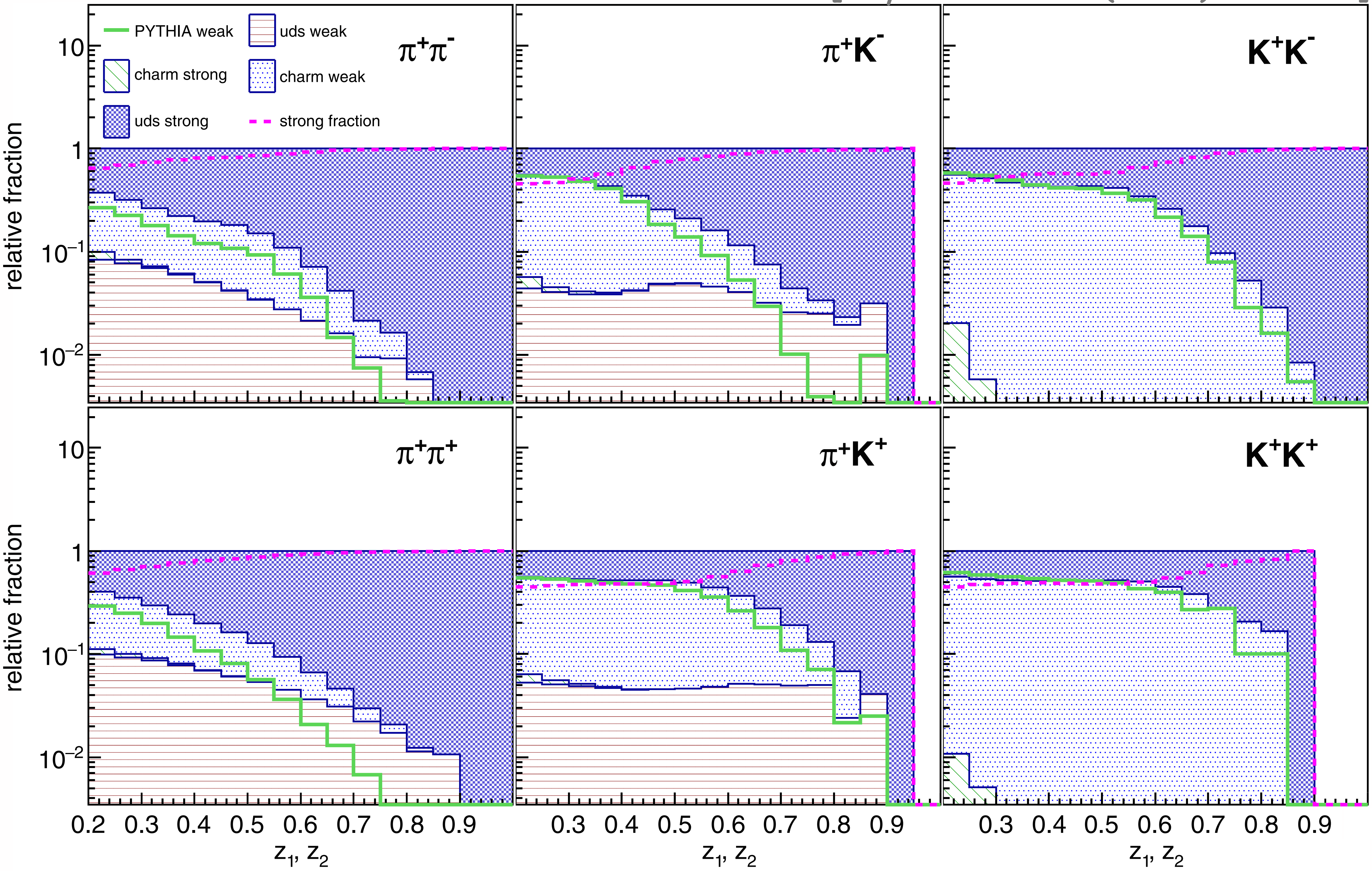
- **transverse polarization of inclusively produced Λ^0 hyperons** (Belle)
- Collins asymmetries:
  - **neutral meson (pion and eta) incl. k_T dependence** (Belle)
  - kaon and pion-kaon pairs as well as k_T dependence of Collins asymmetries (BaBar, Belle, BESIII)
  - Collins asymmetries without double ratios (BaBar)
- k_T-dependent D_1 FFs (Belle)
  - **hadron-to-thrust**
  - nearly back-to-back hadrons
- helicity-dependent dihadron fragmentation function $G_1^\perp$ ("jet handedness") (Belle)

backup

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

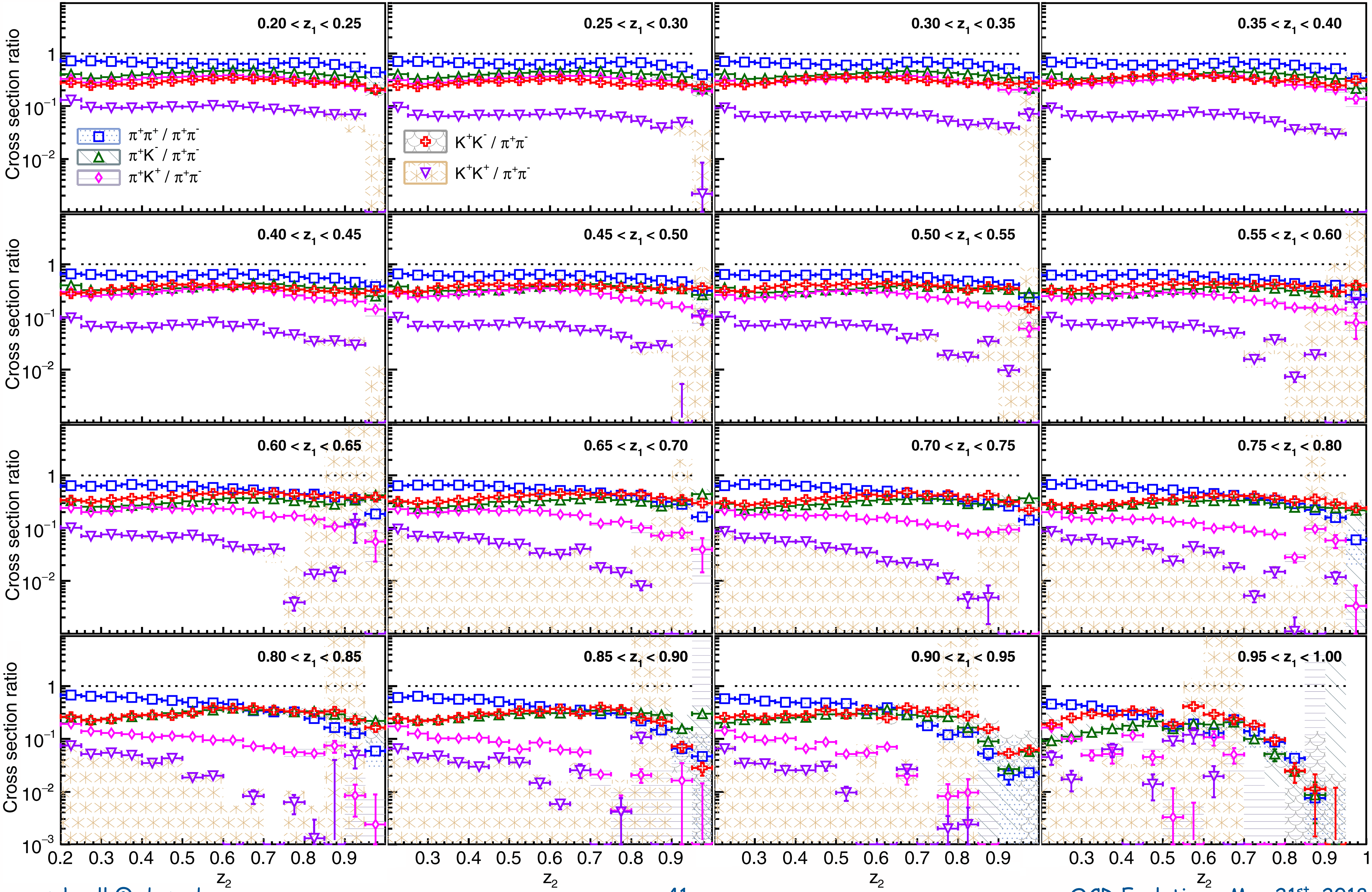
[Phys. Rev. D92 (2015) 092007]



hadron-pair production

no hemisphere selection

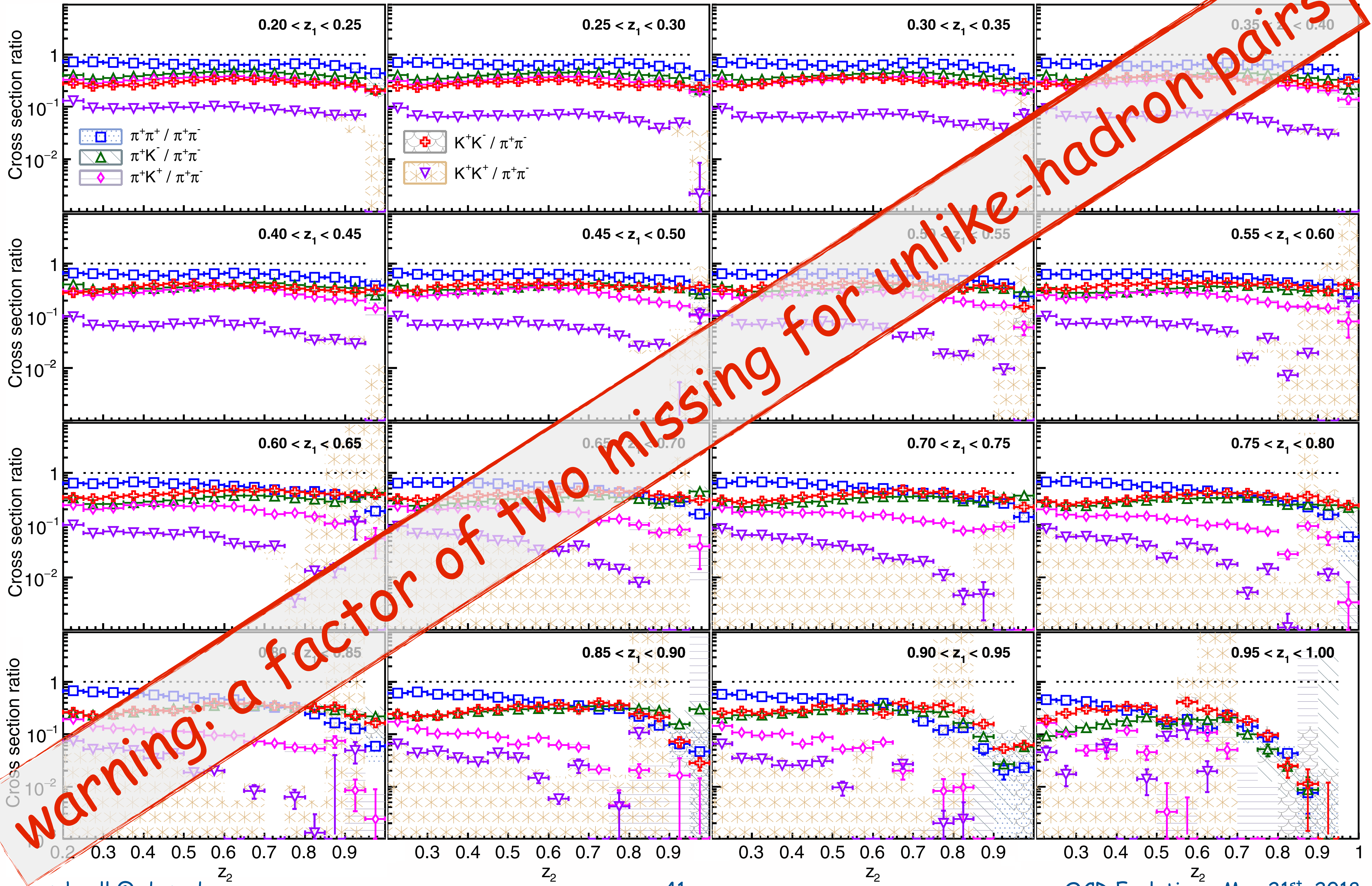
[Phys. Rev. D92 (2015) 092007]



hadron-pair production

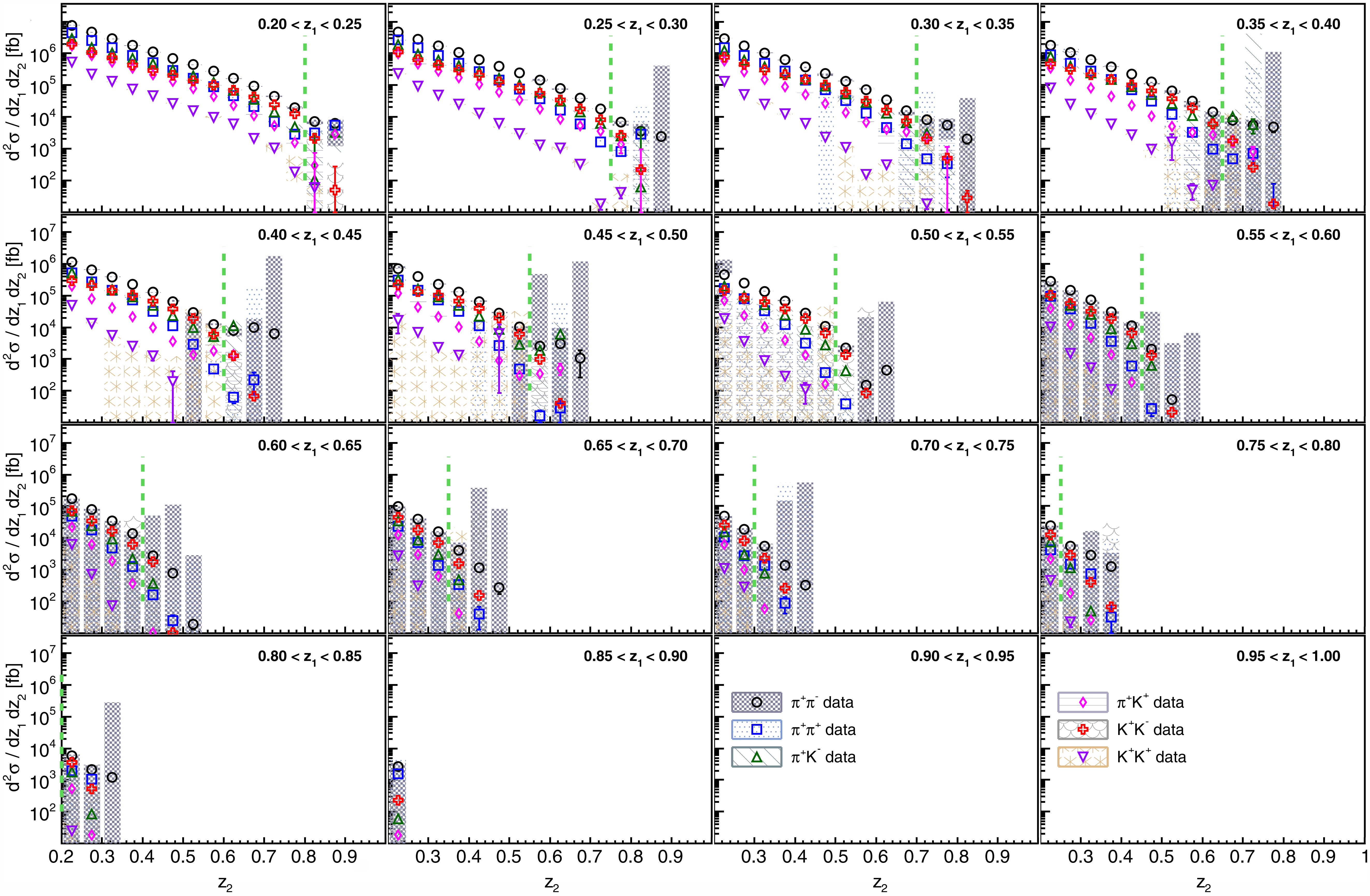
no hemisphere selection

[Phys. Rev. D92 (2015) 092007]



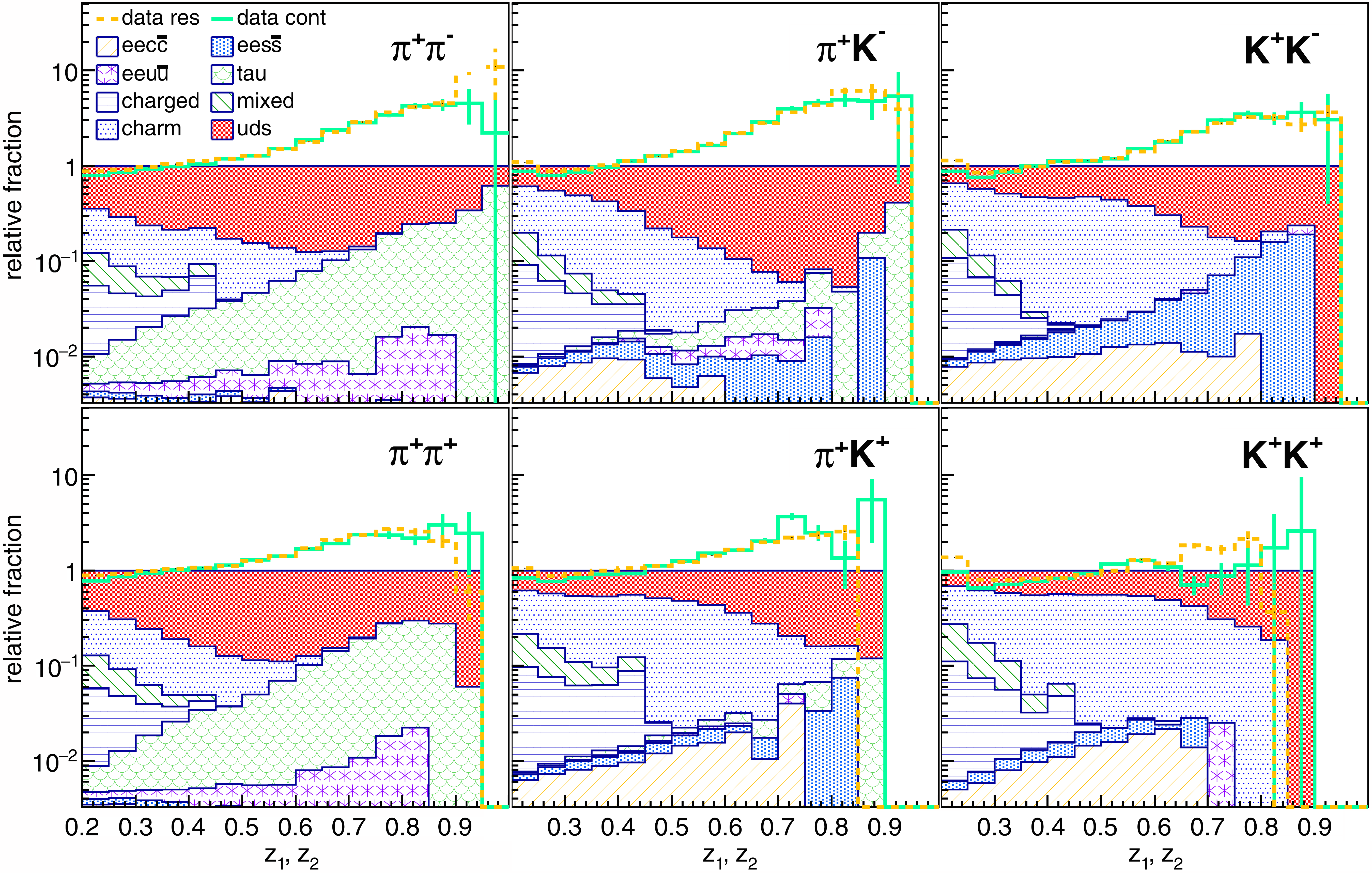
warning: a factor of two missing for unlike-hadron pairs

same-hemisphere hadron pairs



hadron-pairs: subprocess contributions

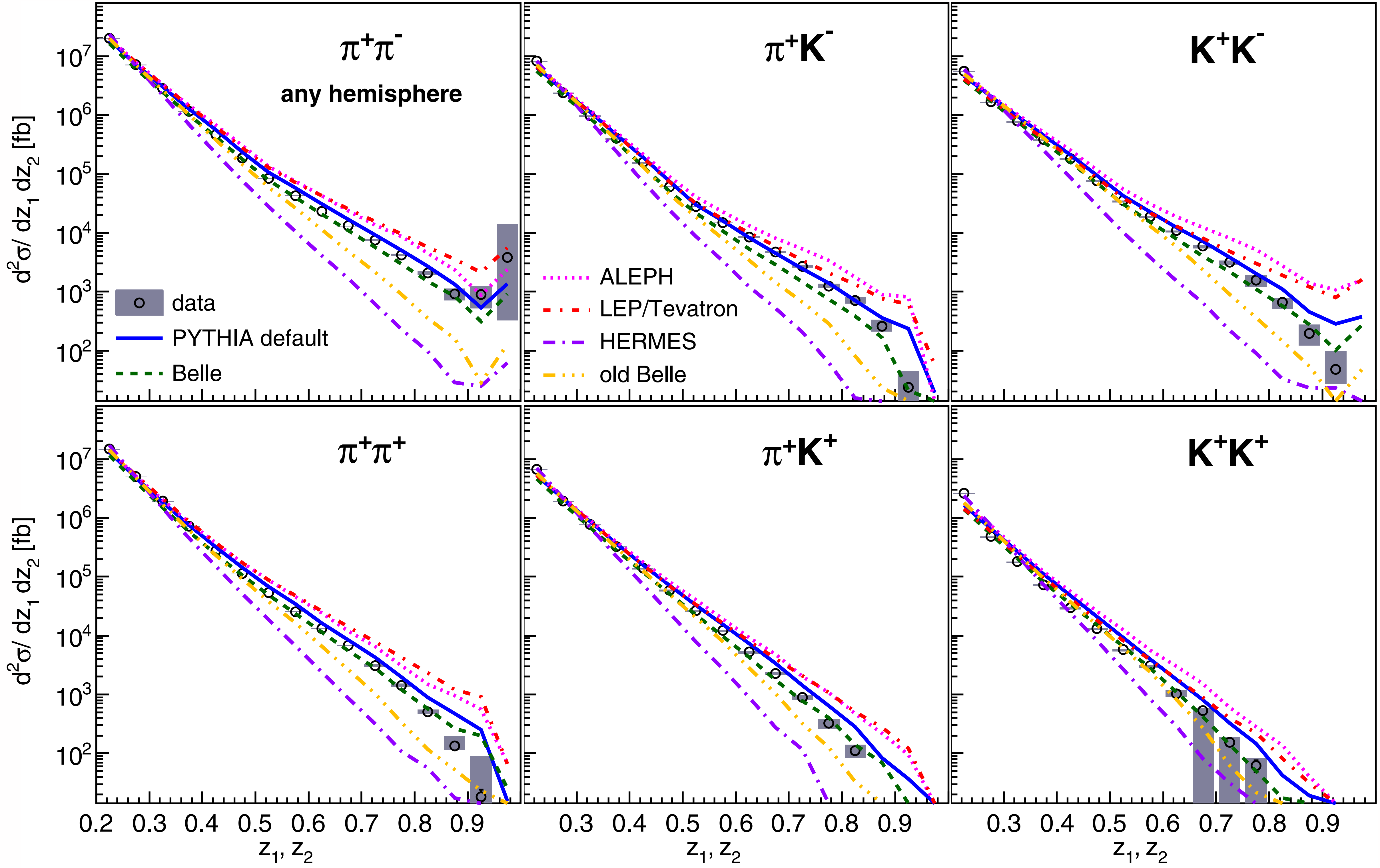
[Phys. Rev. D92 (2015) 092007]



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]

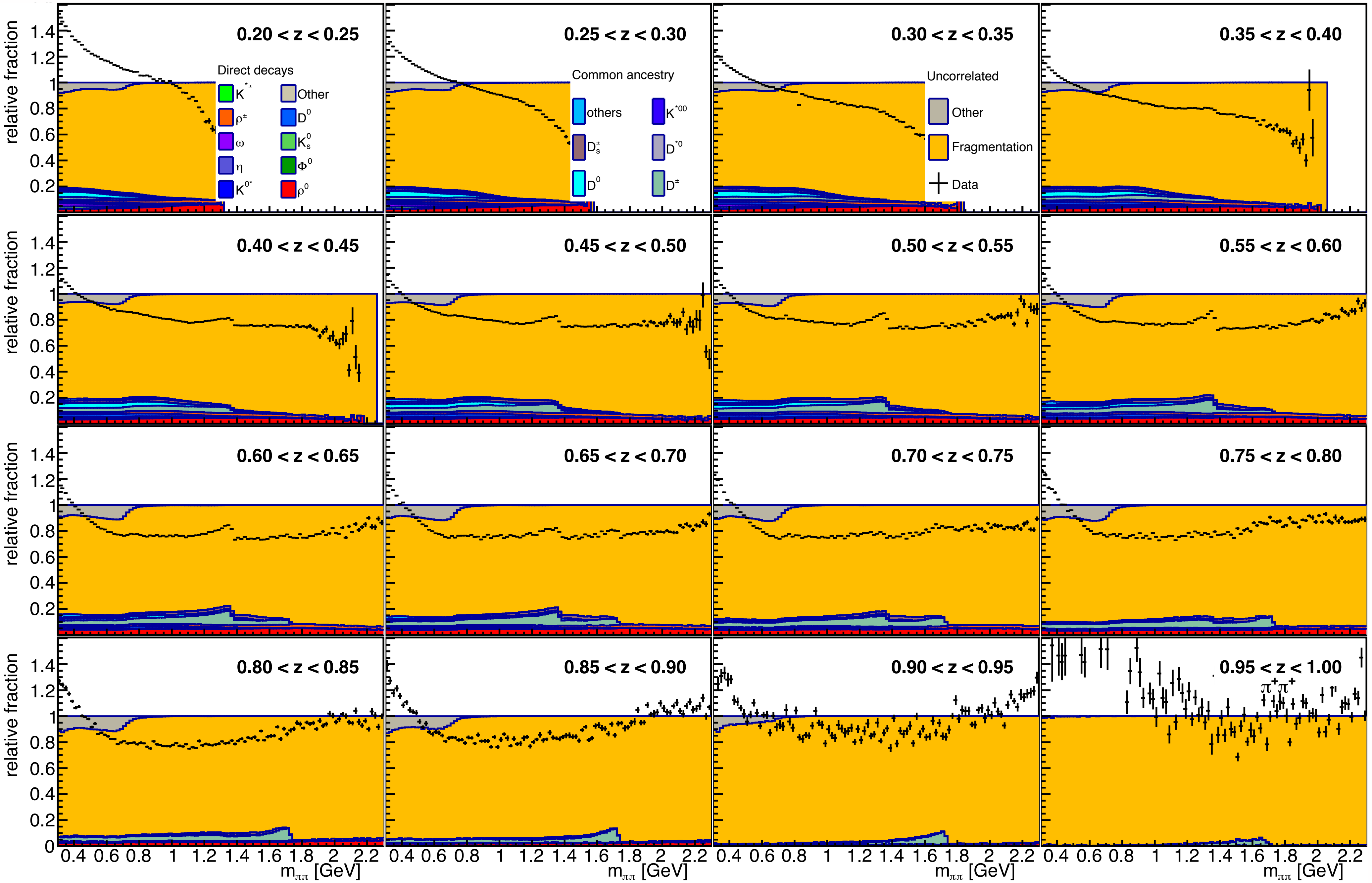


same-hemisphere data: M_{h1h2} dependence

[Phys. Rev. D96 (2017) 032005]

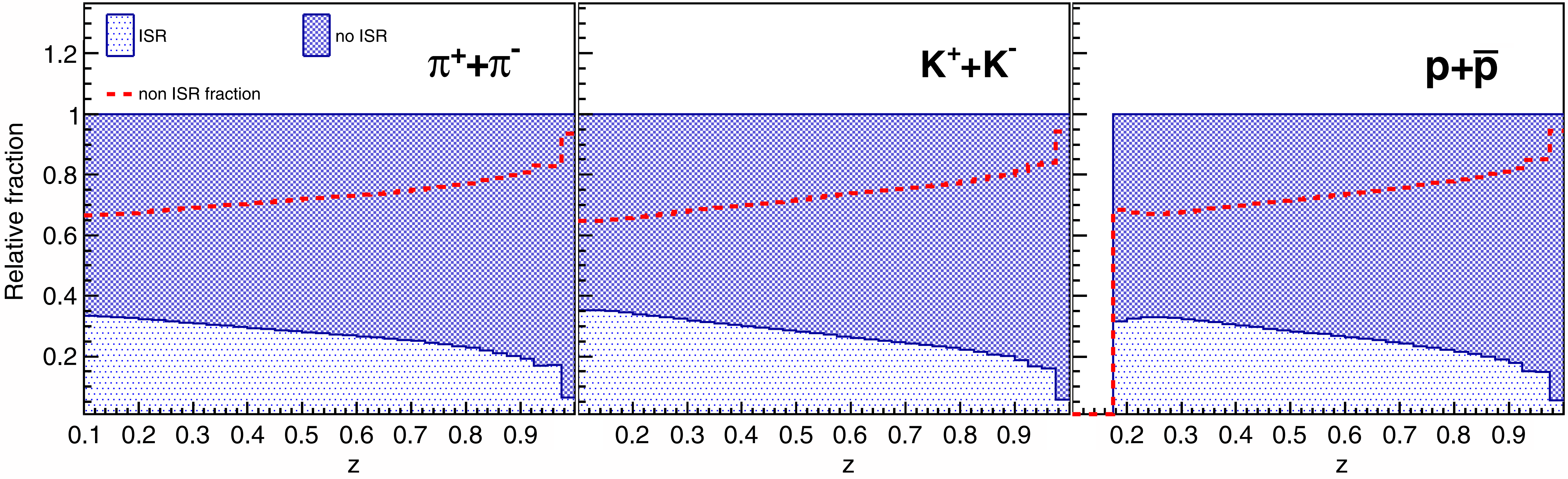
like-sign
pioin pairs

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



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

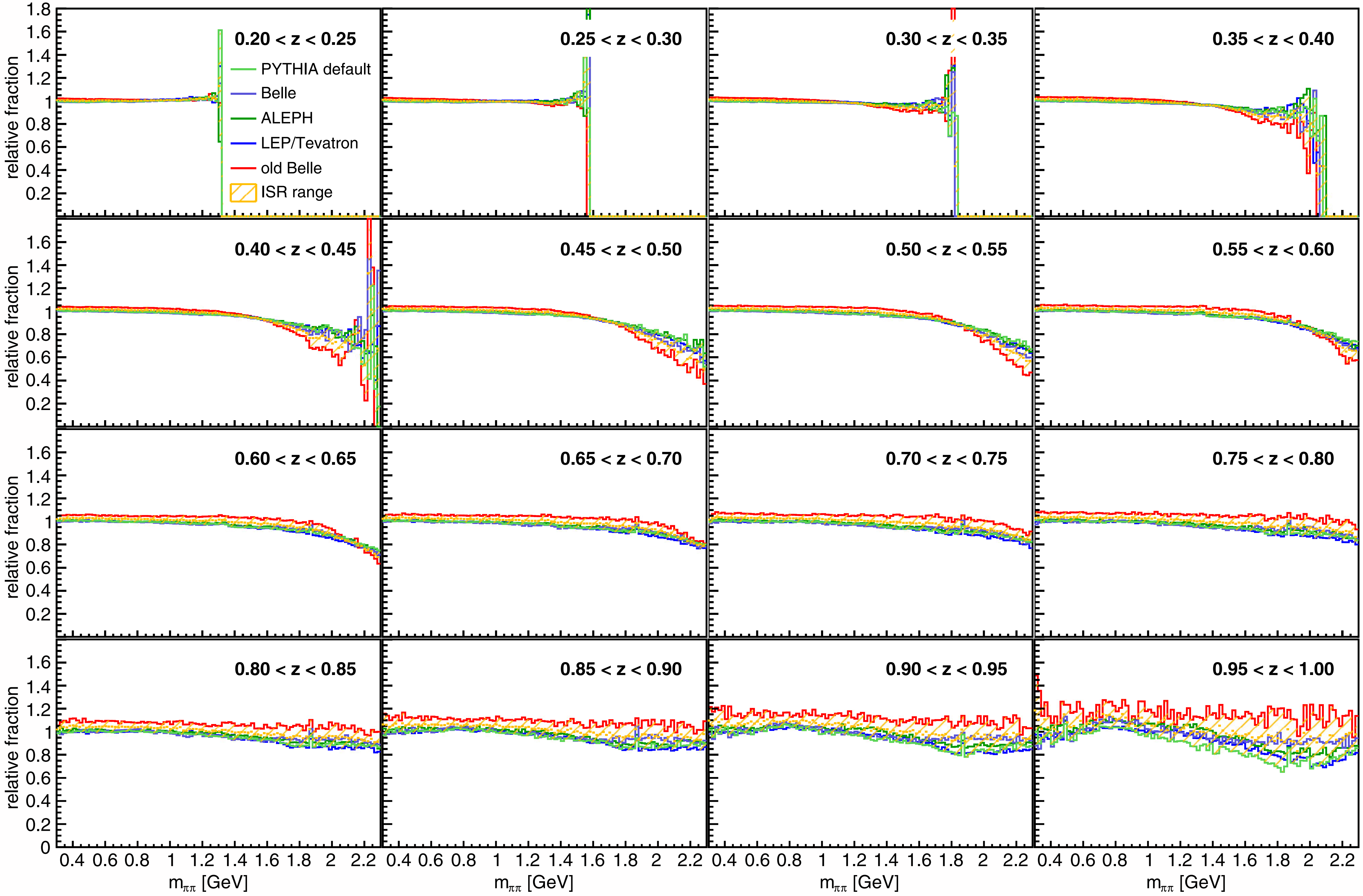
ISR corrections - PRD92 (2015) 092007



- 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 $z = E_h / 0.5\sqrt{s_{nominal}}$)

☛ Ralf

ISR corrections - PRD96 (2017) 032005

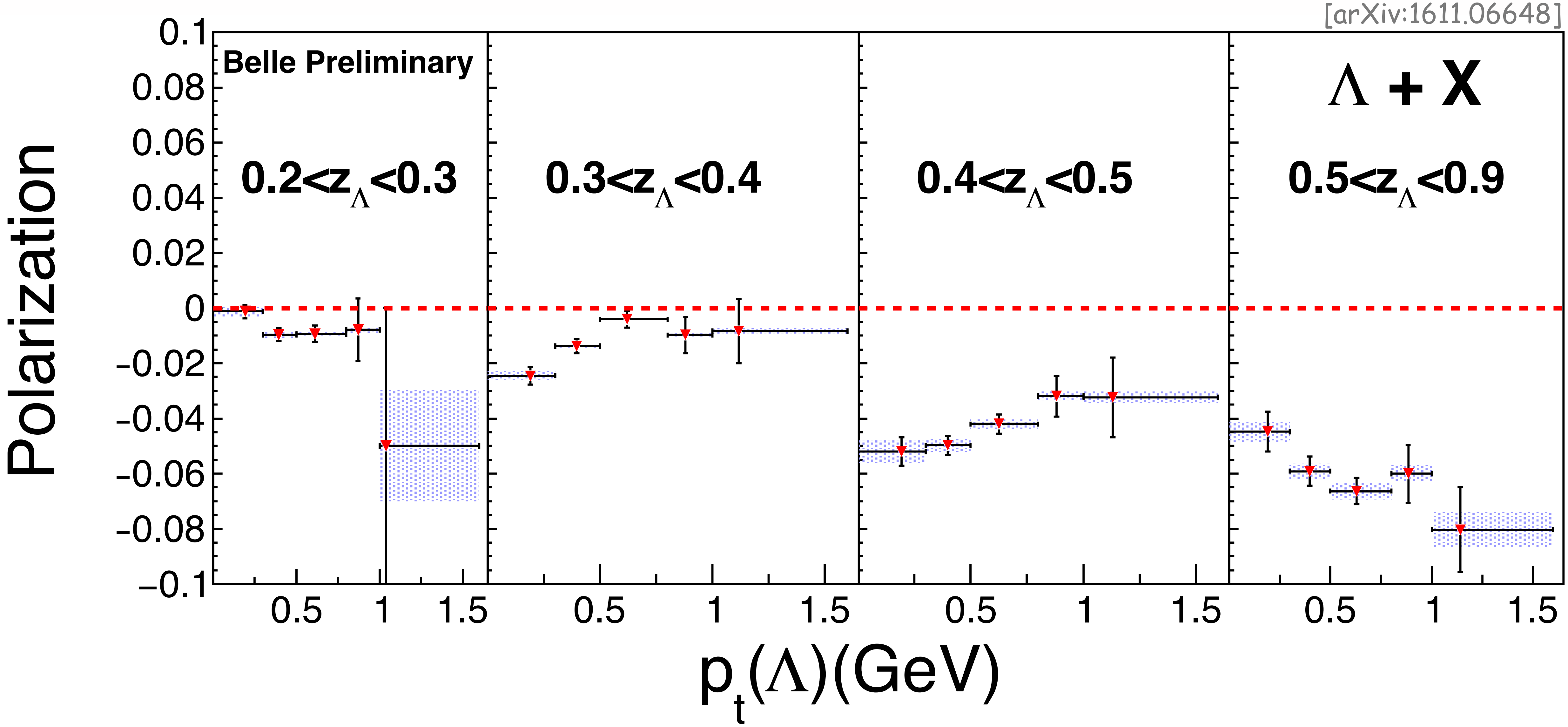


- non-ISR / ISR fractions based on PYTHIA switch MSTP(11)
  - several PYTHIA tunes used for estimate of systematic uncertainty

polarizing fragmentation function

- polarization measured as function of z and p_t

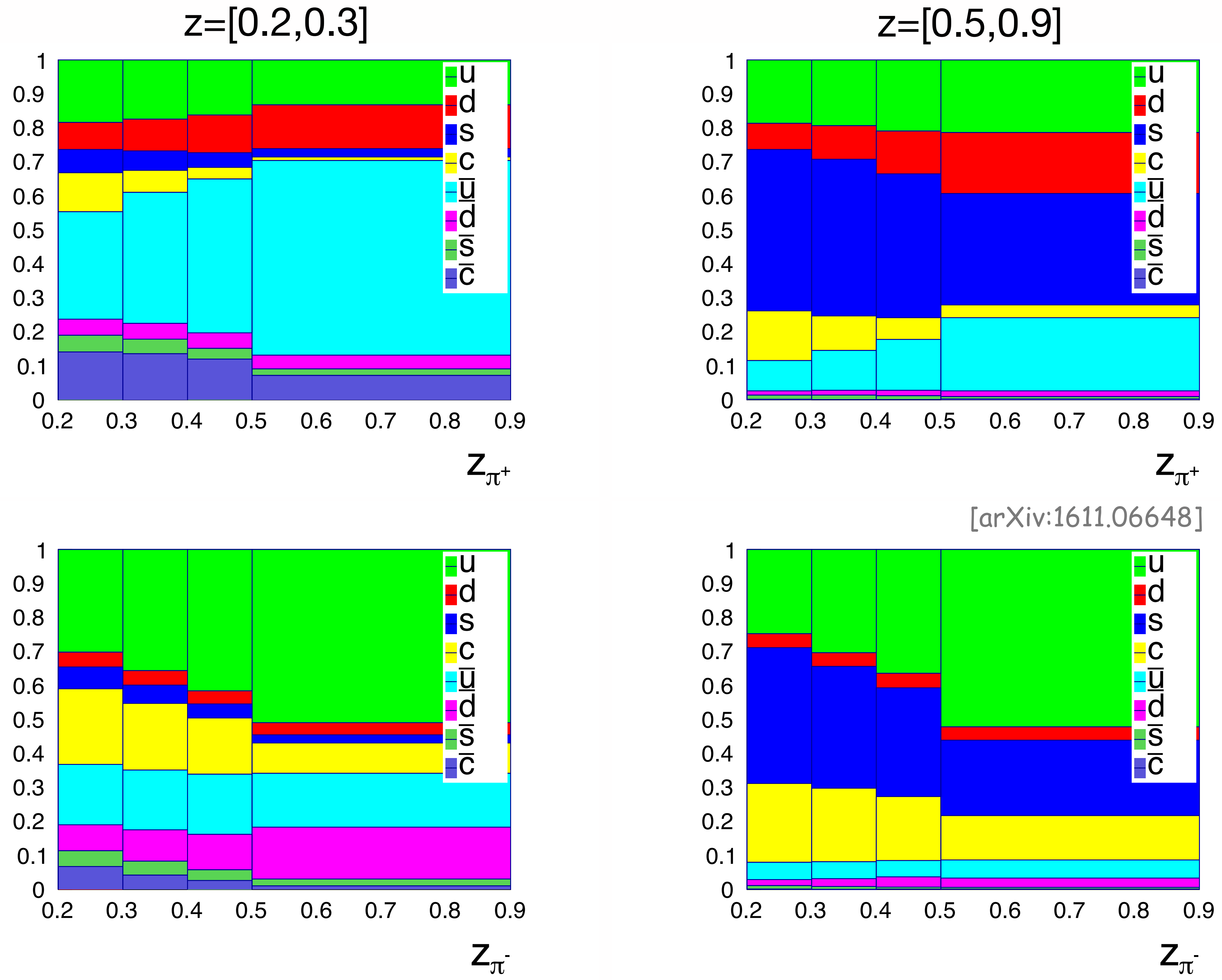
[arXiv:1611.06648]



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

quark-flavor contributions to Lambda prod.

- flavor tagging through opposite-hemisphere hadrons



[arXiv:1611.06648]