

# TRANSVERSITY 2017

5<sup>th</sup> International Workshop on Transverse Polarization  
Phenomena in Hard Processes

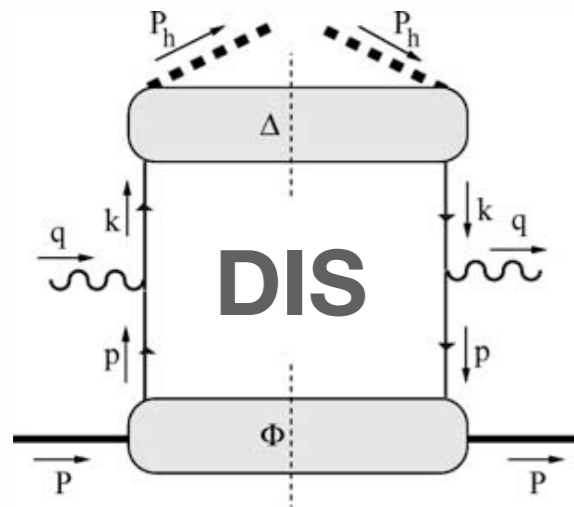
INFN - FRASCATI NATIONAL LABORATORIES

December 11-15, 2017

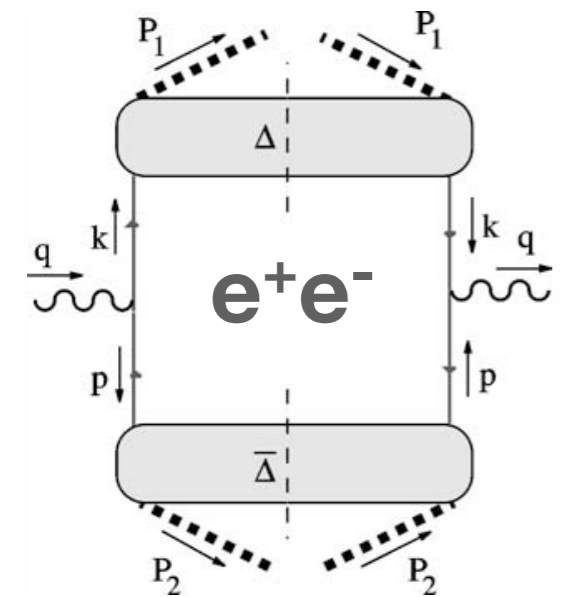


new results on  
fragmentation and  
perspectives

# a rich QCD laboratory

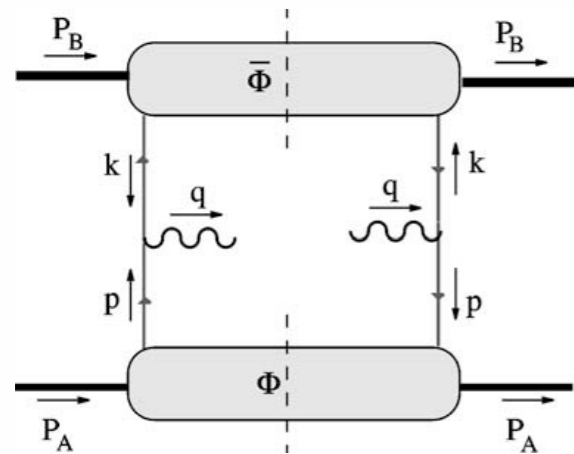


: PDF  $\otimes$  FF



: FF

FFs also needed/  
interesting for many  
other QCD studies



: PDF  $\otimes$  PDF

**Drell-Yan**



PDF|<sub>DIS</sub>



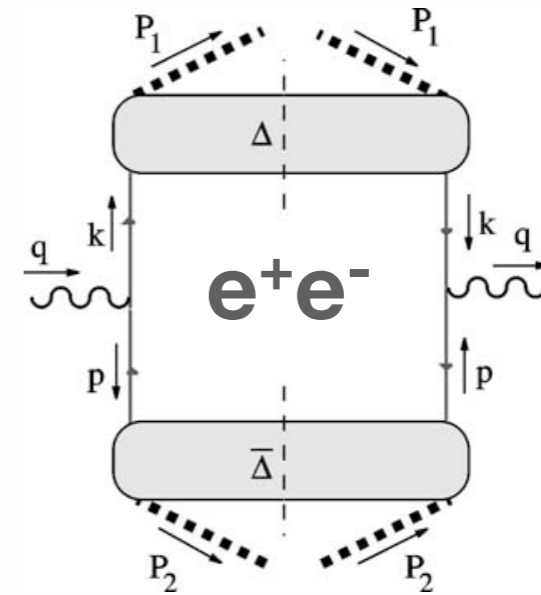
sign change?  
(where predicted)



PDF|<sub>DY</sub>

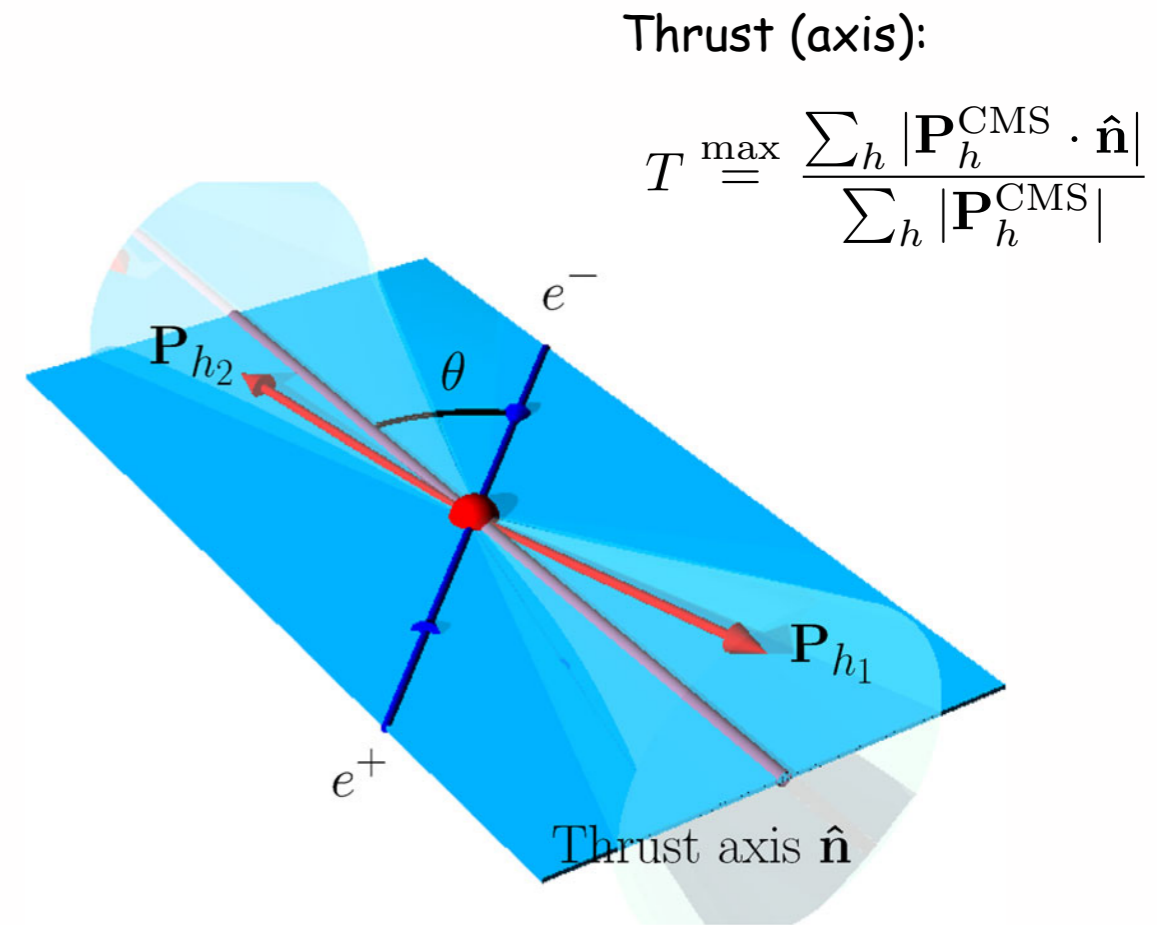
# fragmentation in $e^+e^-$ annihilation

- 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  $D_1$  or of Collins FFs
- flavor, transverse-momentum, and/or polarization tagging

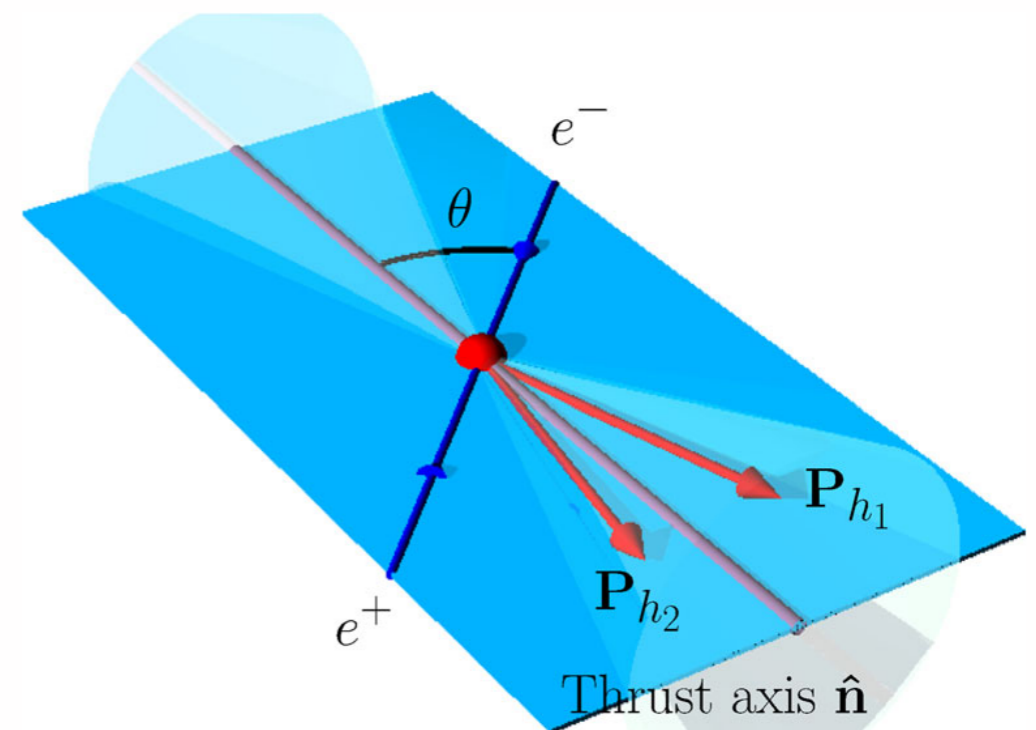
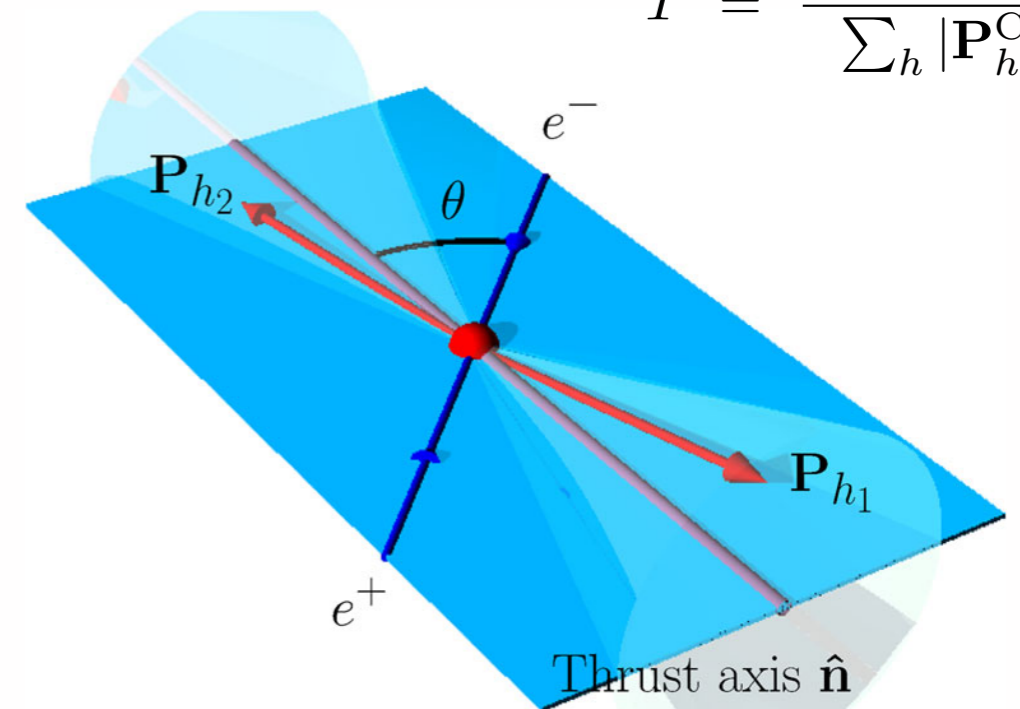


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  - flavor, transverse-momentum, and/or polarization tagging
- inclusive same-hemisphere hadron pairs,  $e^+e^- \rightarrow h_1h_2X$ 
  - dihadron fragmentation

Thrust (axis):

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

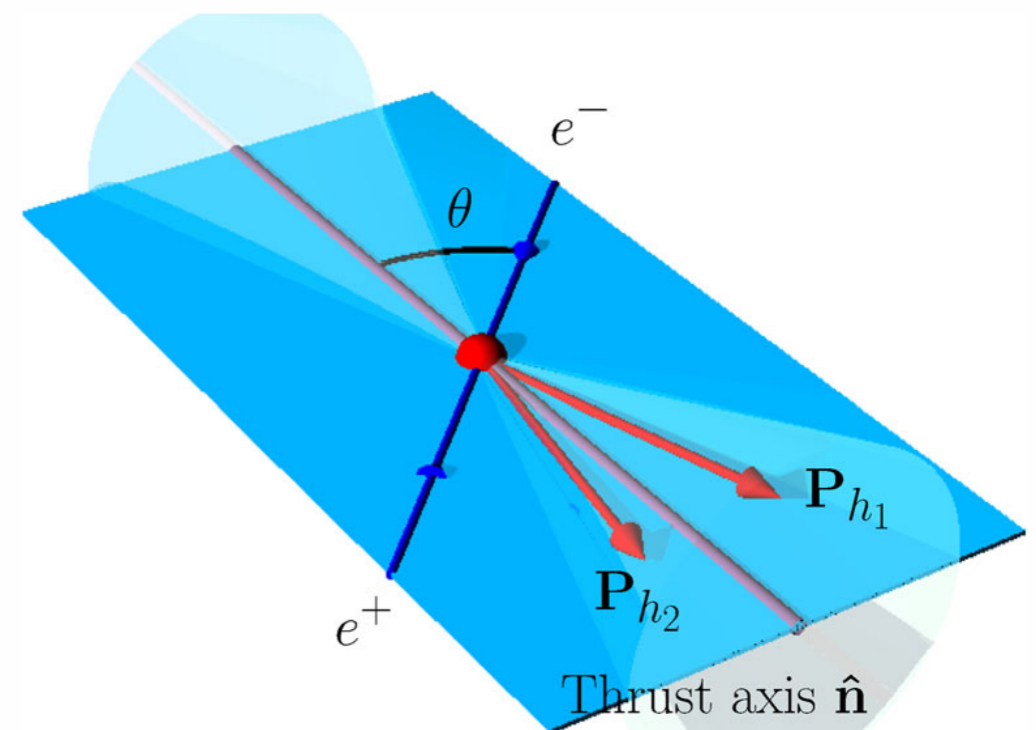
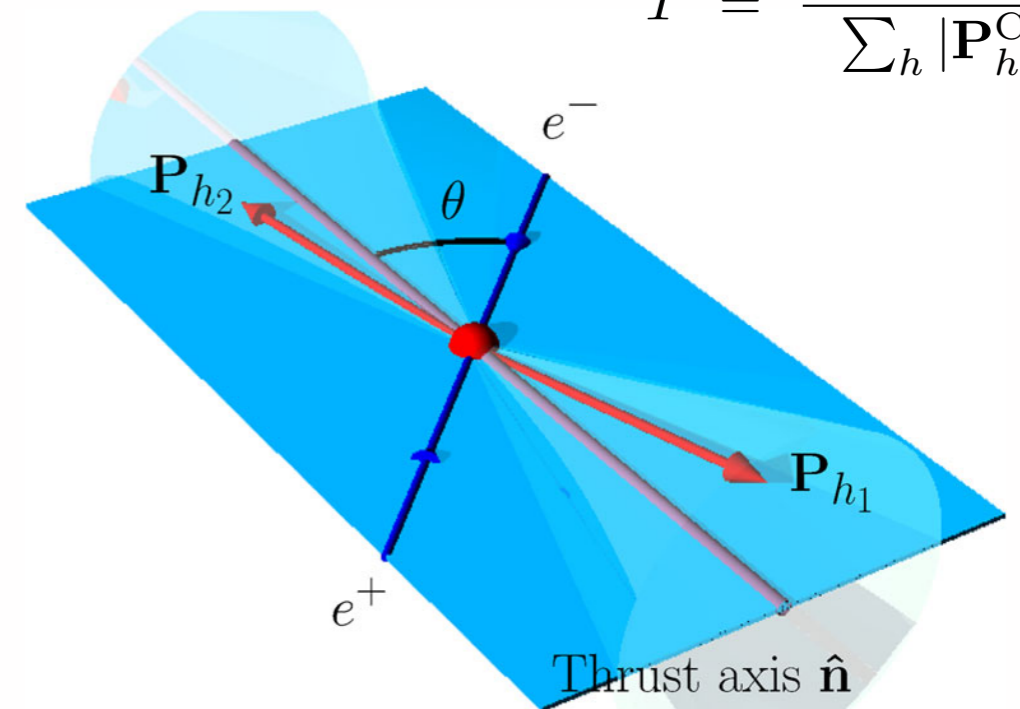


# fragmentation in $e^+e^-$ annihilation

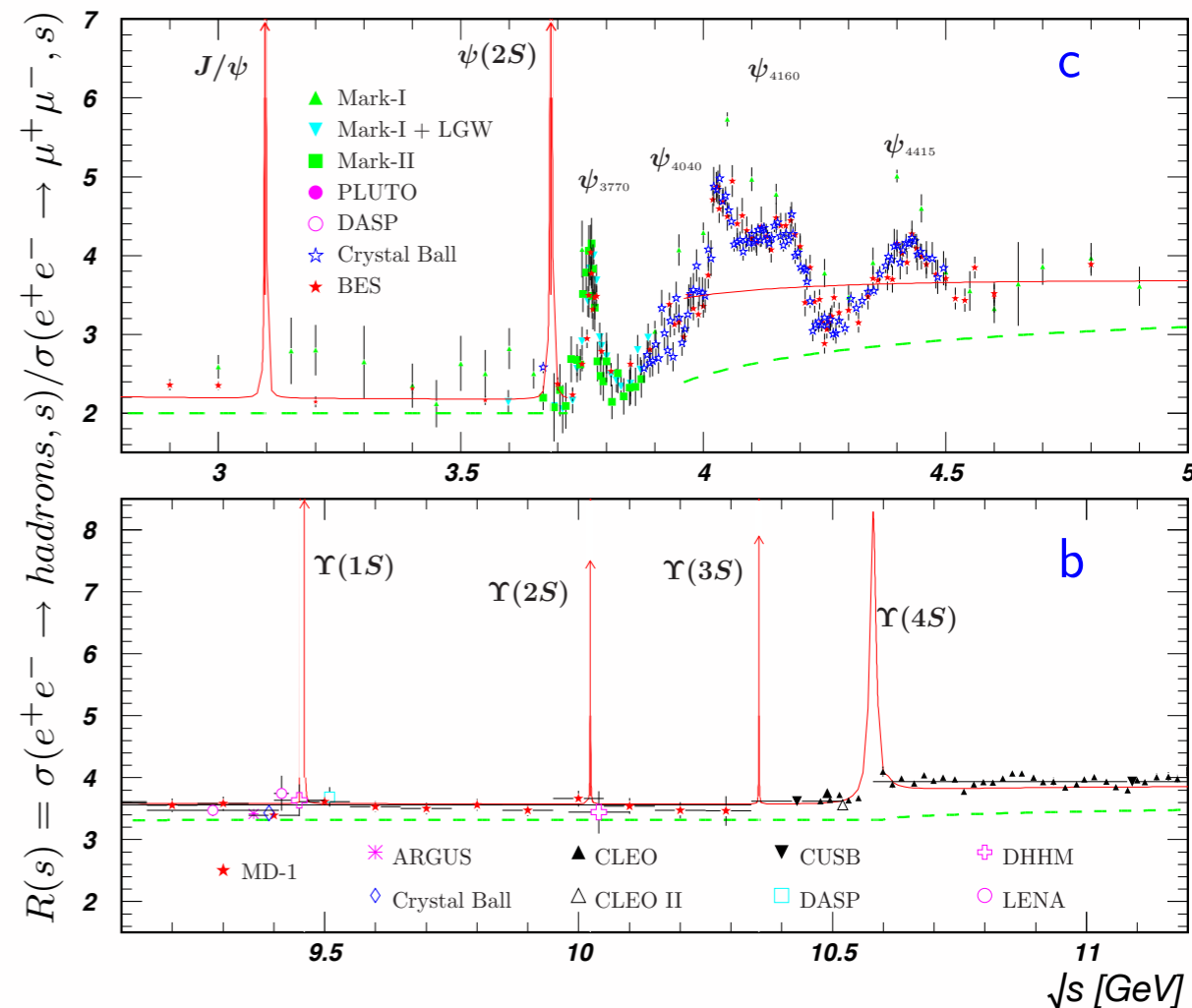
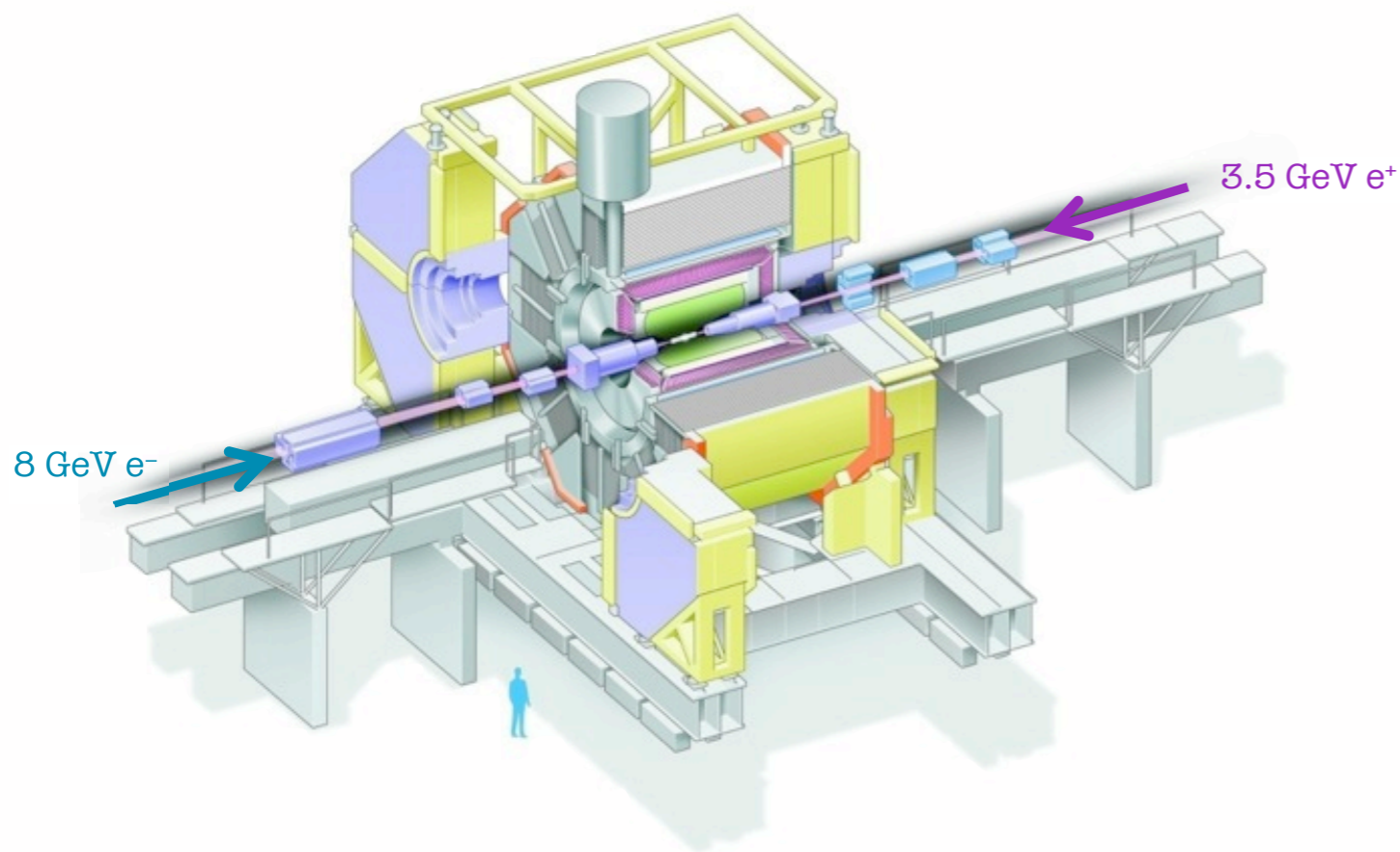
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# $e^+e^-$ annihilation at Belle



- KEKB: asymmetric beam-energy  $e^+e^-$  collider near/at  $\Upsilon(4S)$  resonance (10.58 GeV)
- large azimuthally symmetric geometric acceptance
- particle ID  $\rightarrow \pi, K, p$  results

$\Upsilon(4S)$ on resonance	$\Upsilon(4S)$ off resonance "udsc continuum"
655 fb <sup>-1</sup>	68 fb <sup>-1</sup>

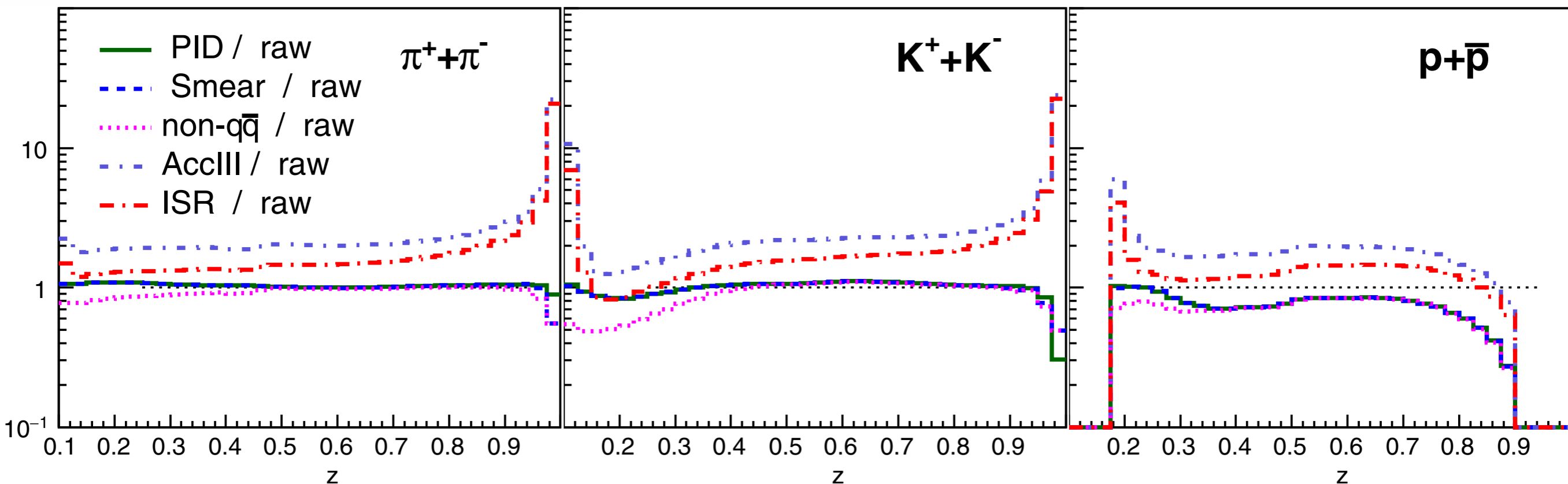
# from hadron yields to cross sections

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



# from hadron yields to cross sections

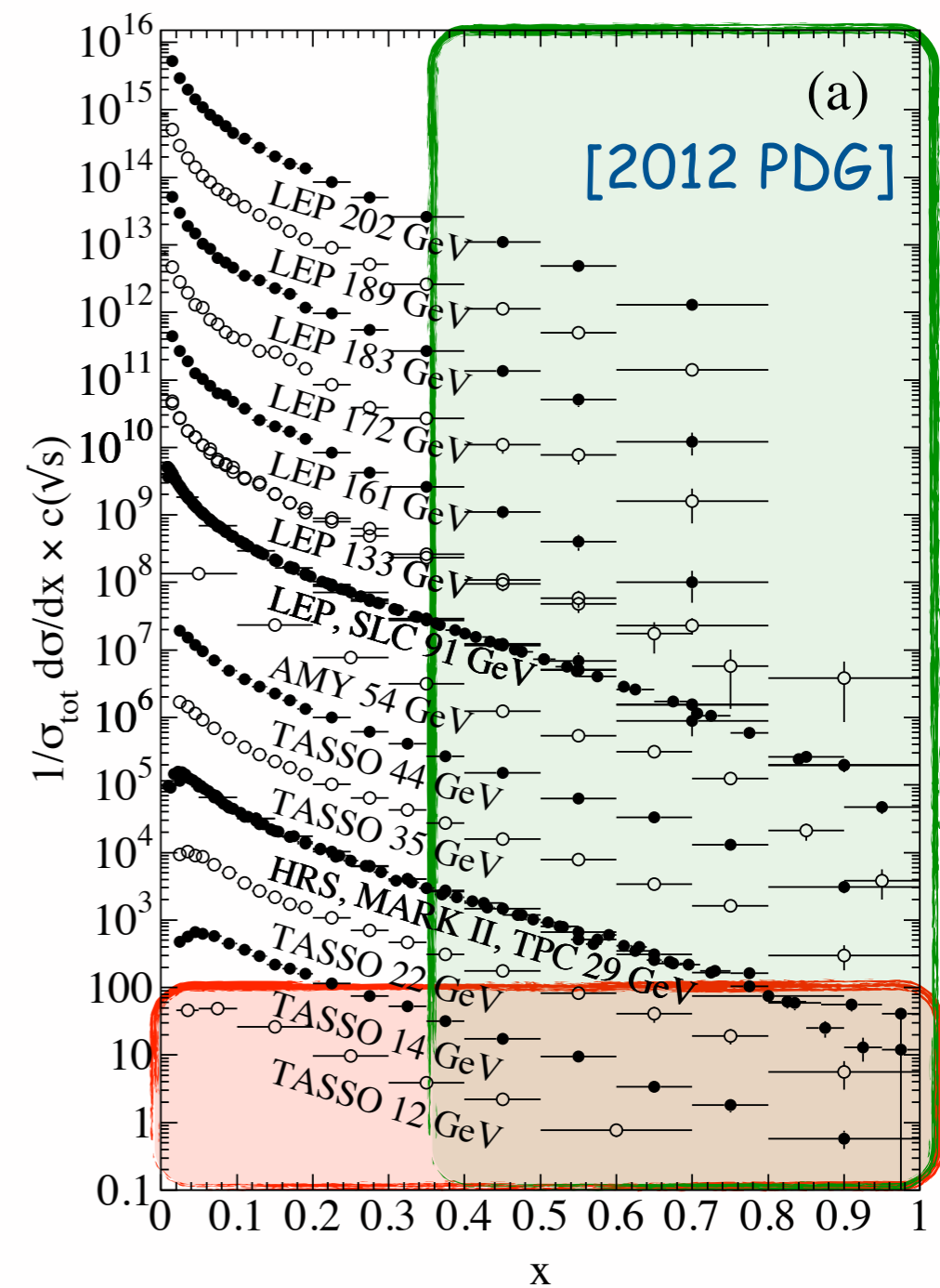
- example: single-hadron cross sections
- cumulative effect of correction steps



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

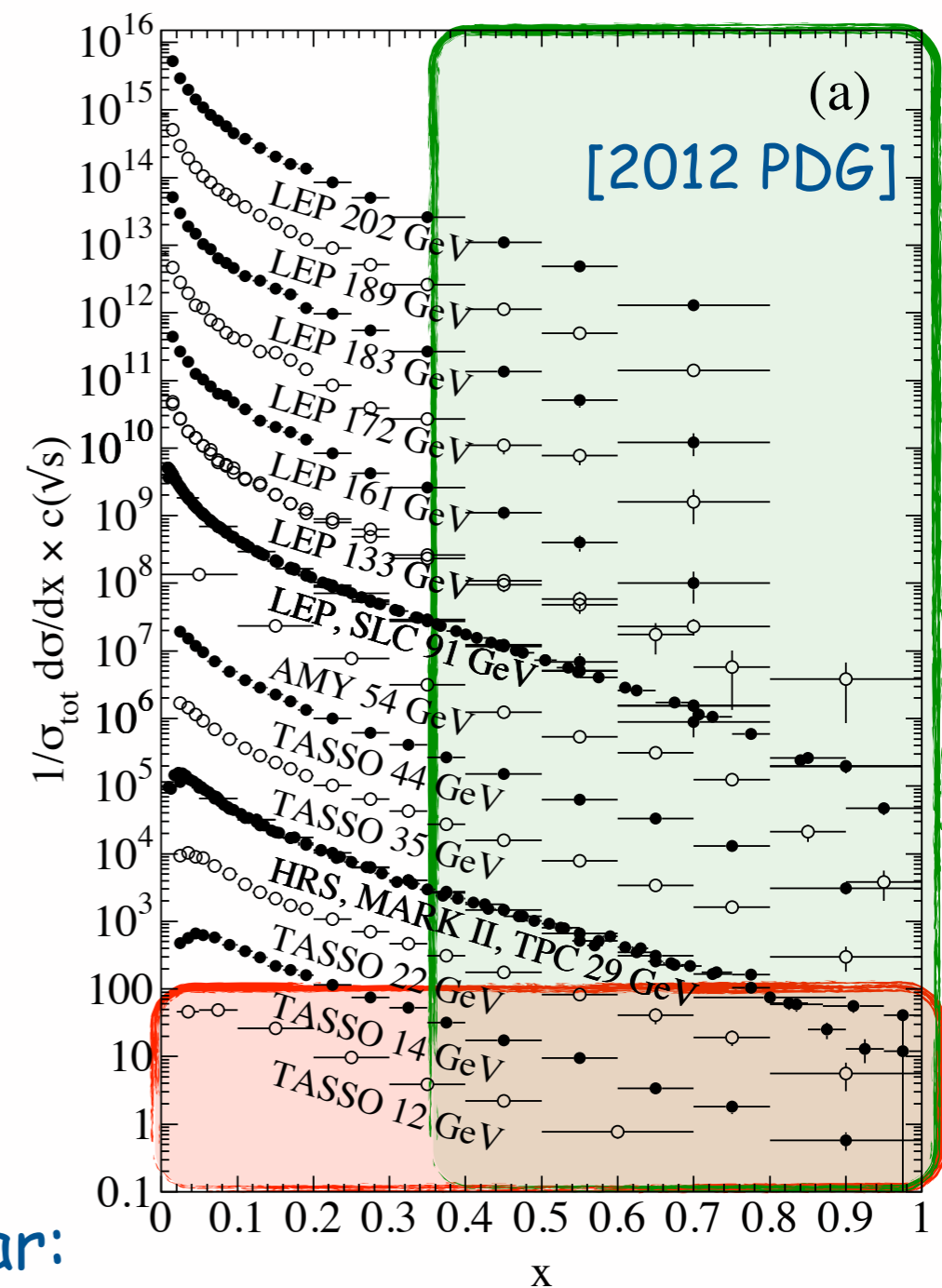
# single-hadron production

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



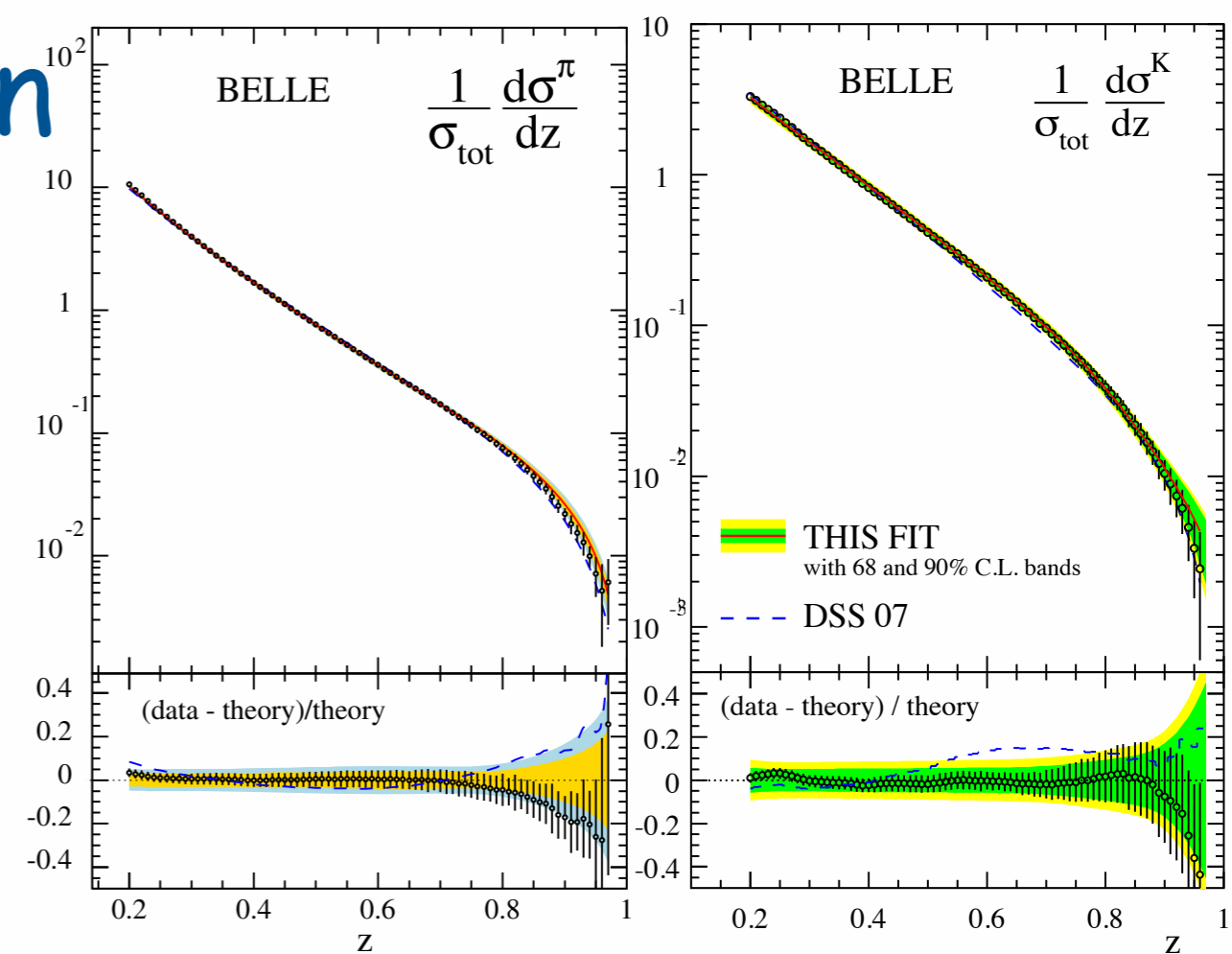
# single-hadron production

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  - limits analysis of evolution and gluon fragmentation
  - limited information in kinematic region often used in semi-inclusive DIS
- by now, results available from Belle and BaBar:
  - BaBar Collaboration, Phys. Rev. D88 (2013) 032011:  $\pi^\pm, K^\pm, p+p$
  - Belle Collaboration, Phys. Rev. Lett. 111 (2013) 062002:  $\pi^\pm, K^\pm$
  - Belle Collaboration, Phys. Rev. D92 (2015) 092007:  $\pi^\pm, K^\pm, p+\bar{p}$



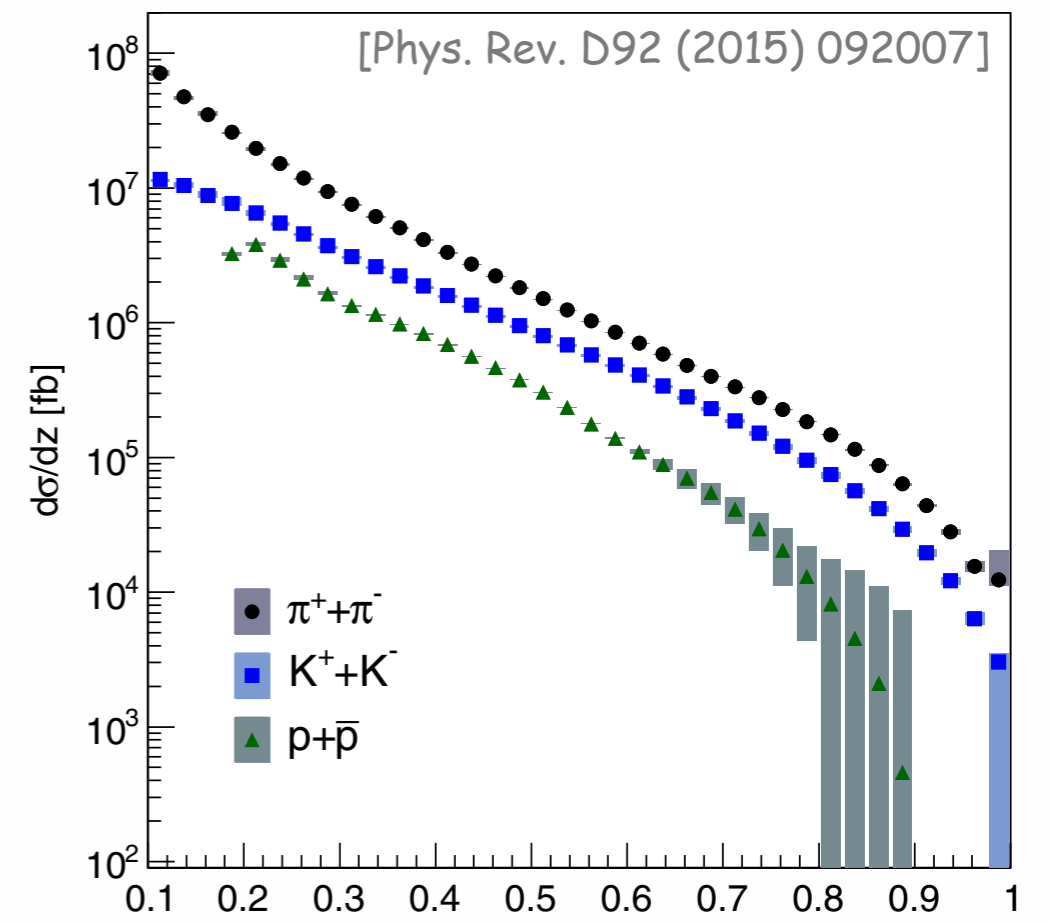
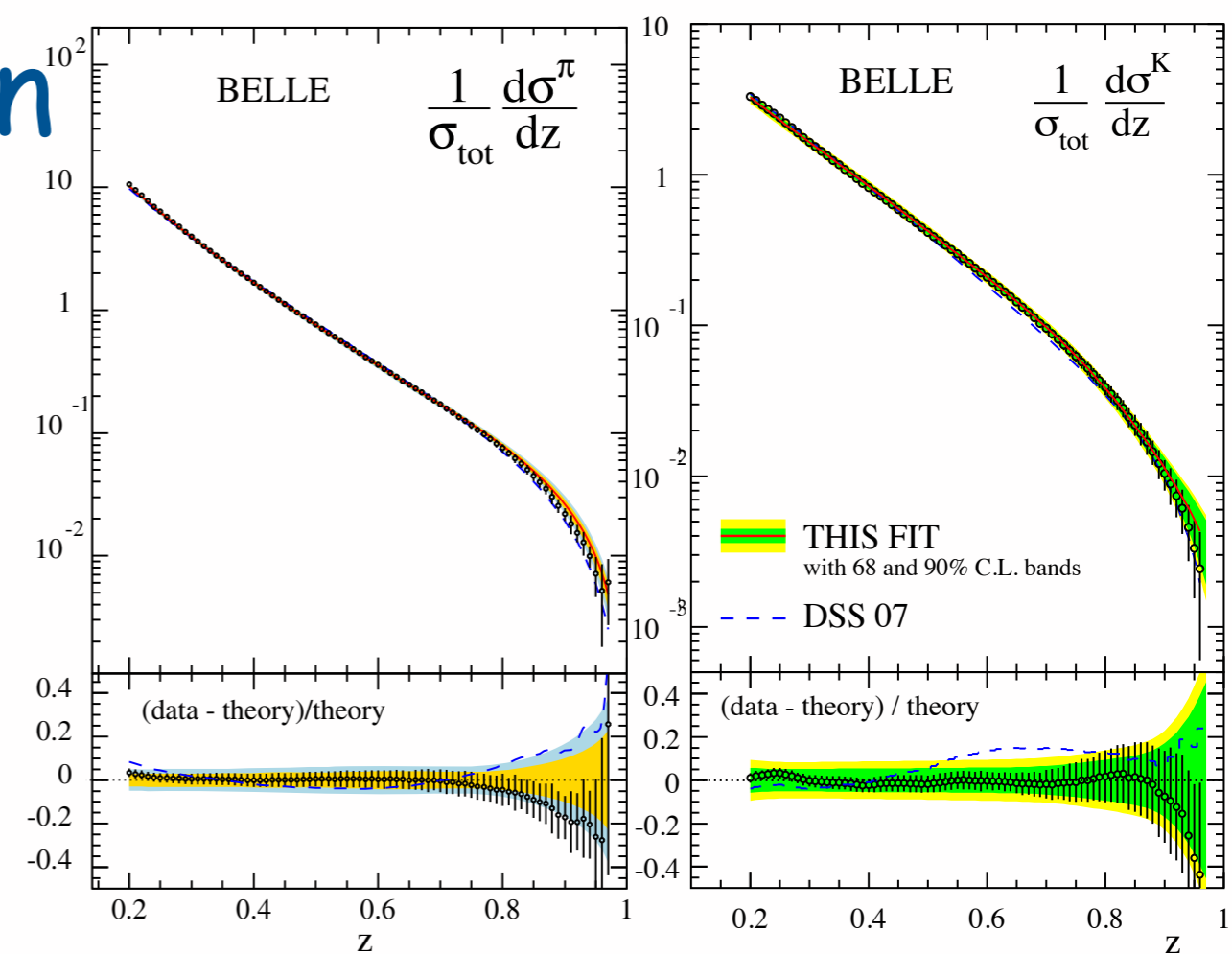
# single-hadron production

- very precise data for charged pions and kaons
- data available up to very large  $z$  ( $z < 0.98$ )
- included in recent DEHSS fits [e.g. PRD 91, 014035 (2015)]



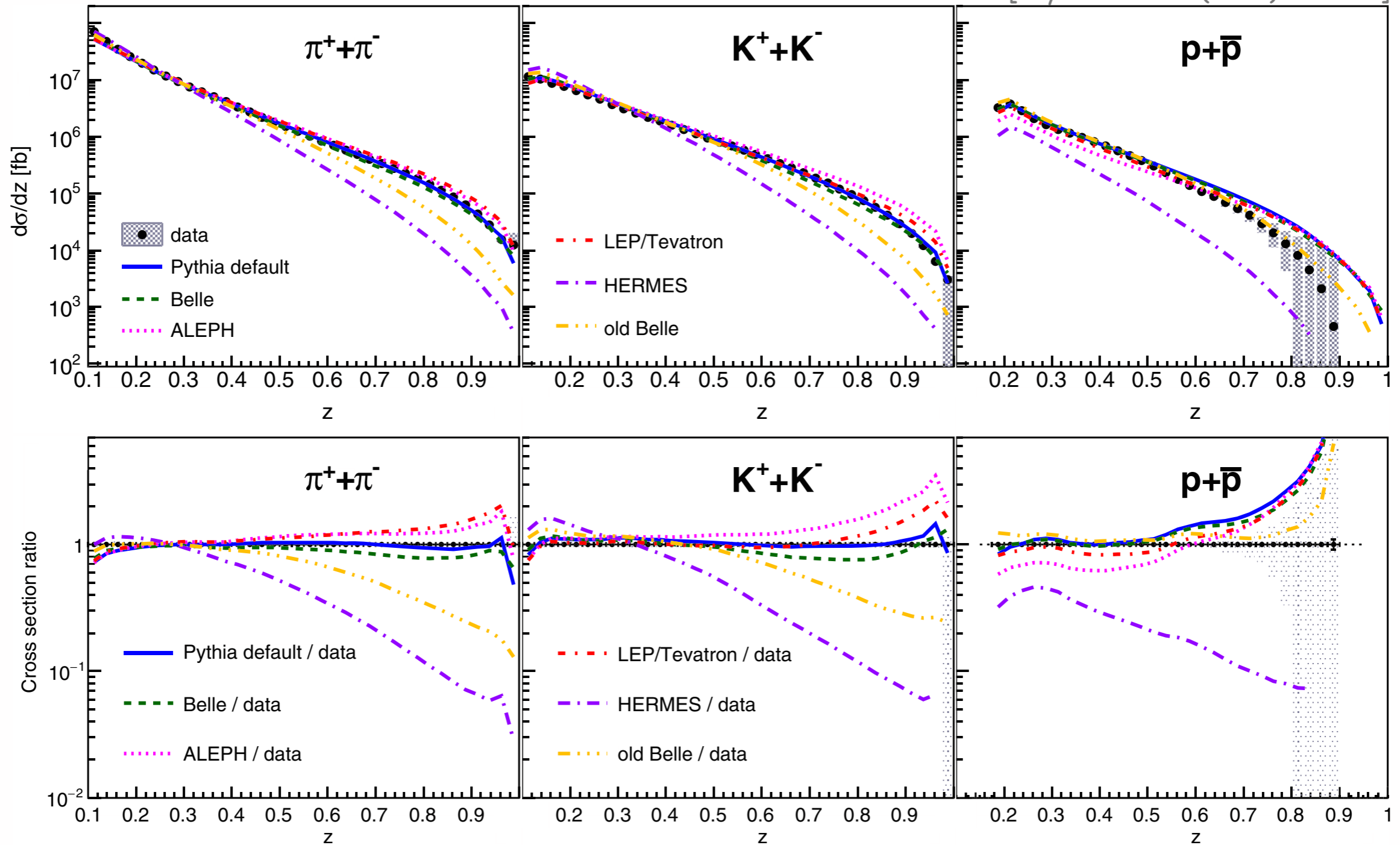
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- data available up to very large  $z$  ( $z < 0.98$ )
- included in recent DEHSS fits [e.g. PRD 91, 014035 (2015)]
- **new:** data for protons and anti-protons
- not (yet) included in DEHSS
- similar  $z$  dependence as pions
- about  $\sim 1/5$  of pion cross sections



# single-hadron production - MC comparison

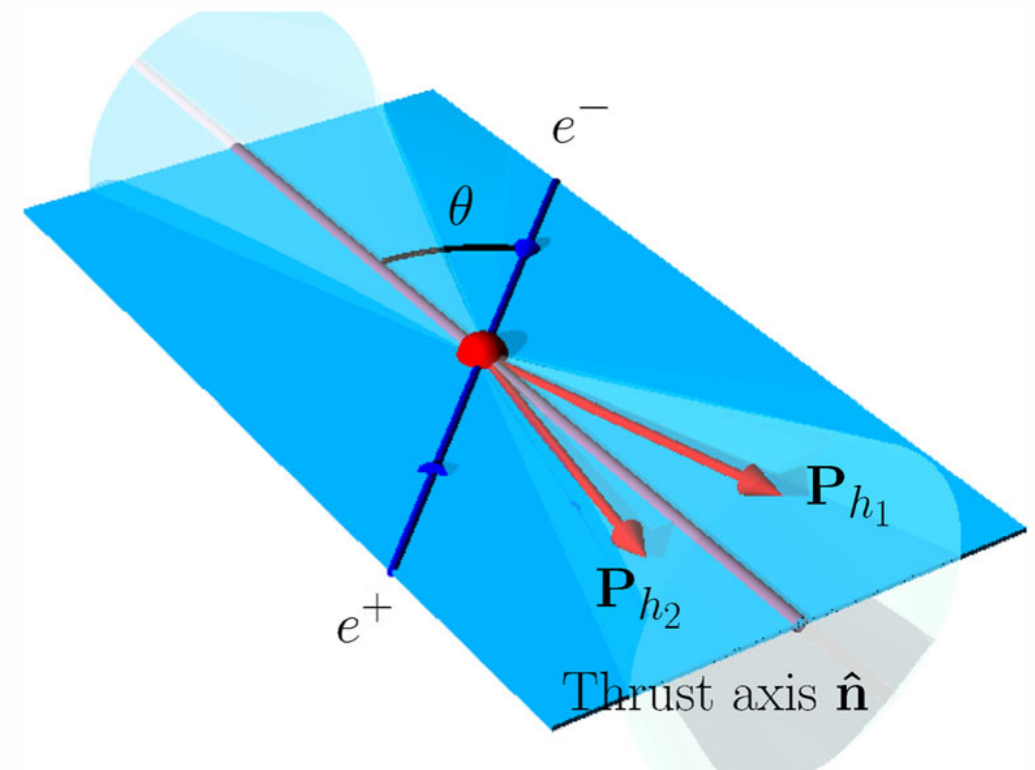
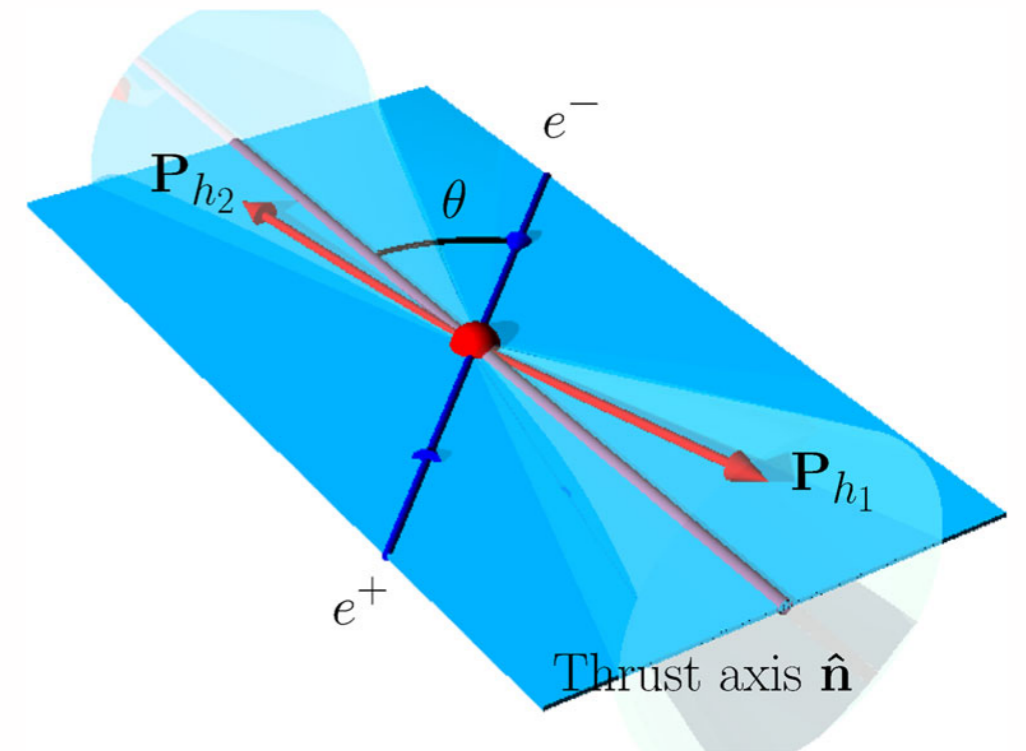
[Phys. Rev. D92 (2015) 092007]



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

# hadron-pair production

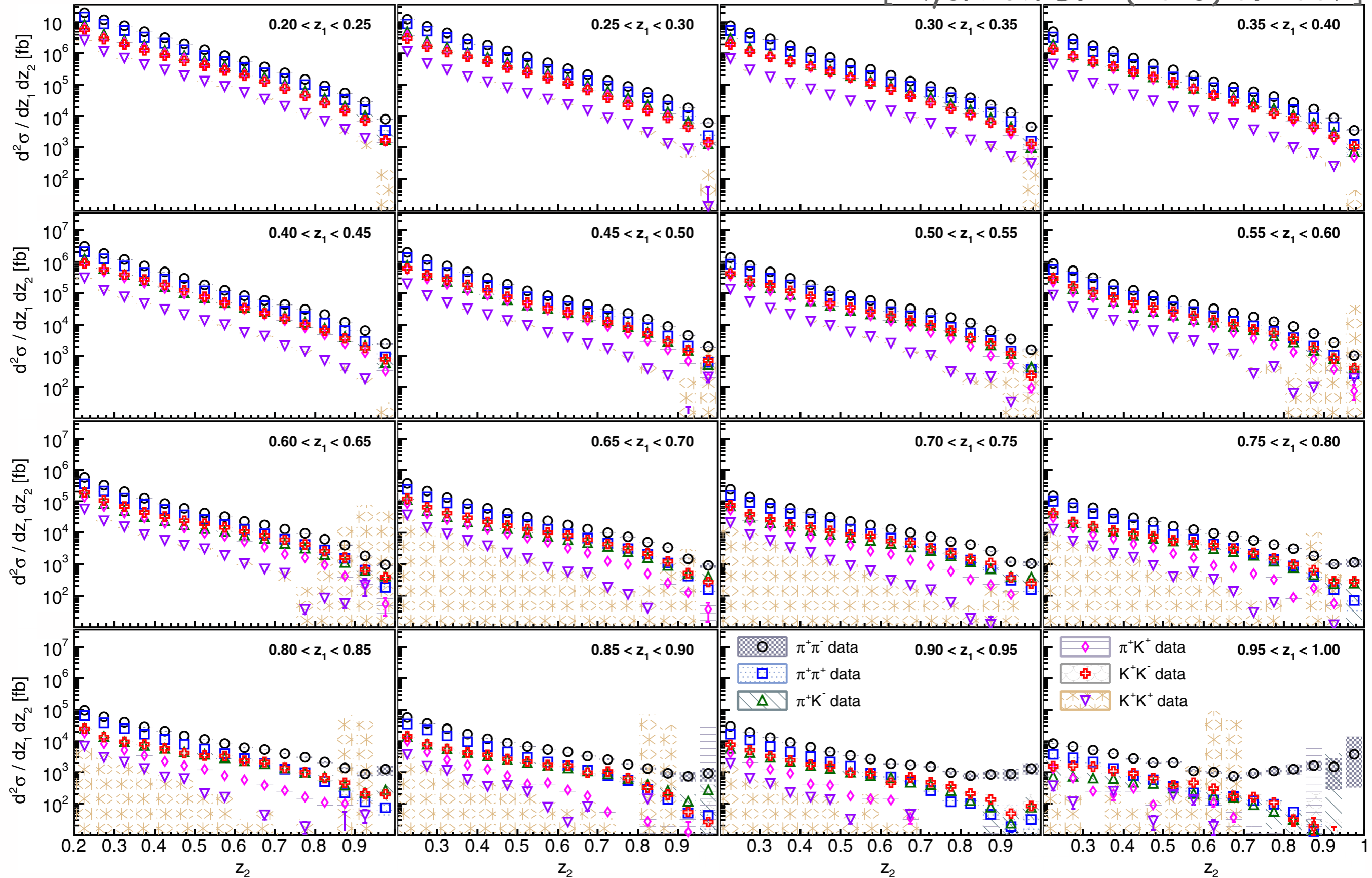
- single-hadron production has low discriminating power for parton flavor
- can use 2<sup>nd</sup> hadron in opposite hemisphere to "tag" flavor
- mainly sensitive to product of single-hadron FFs
- if hadrons in same hemisphere: **dihadron fragmentation**
  - a la de Florian & Vanni [Phys. Lett. B 578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



no hemisphere selection

# hadron-pair production

[Phys. Rev. D92 (2015) 092007]

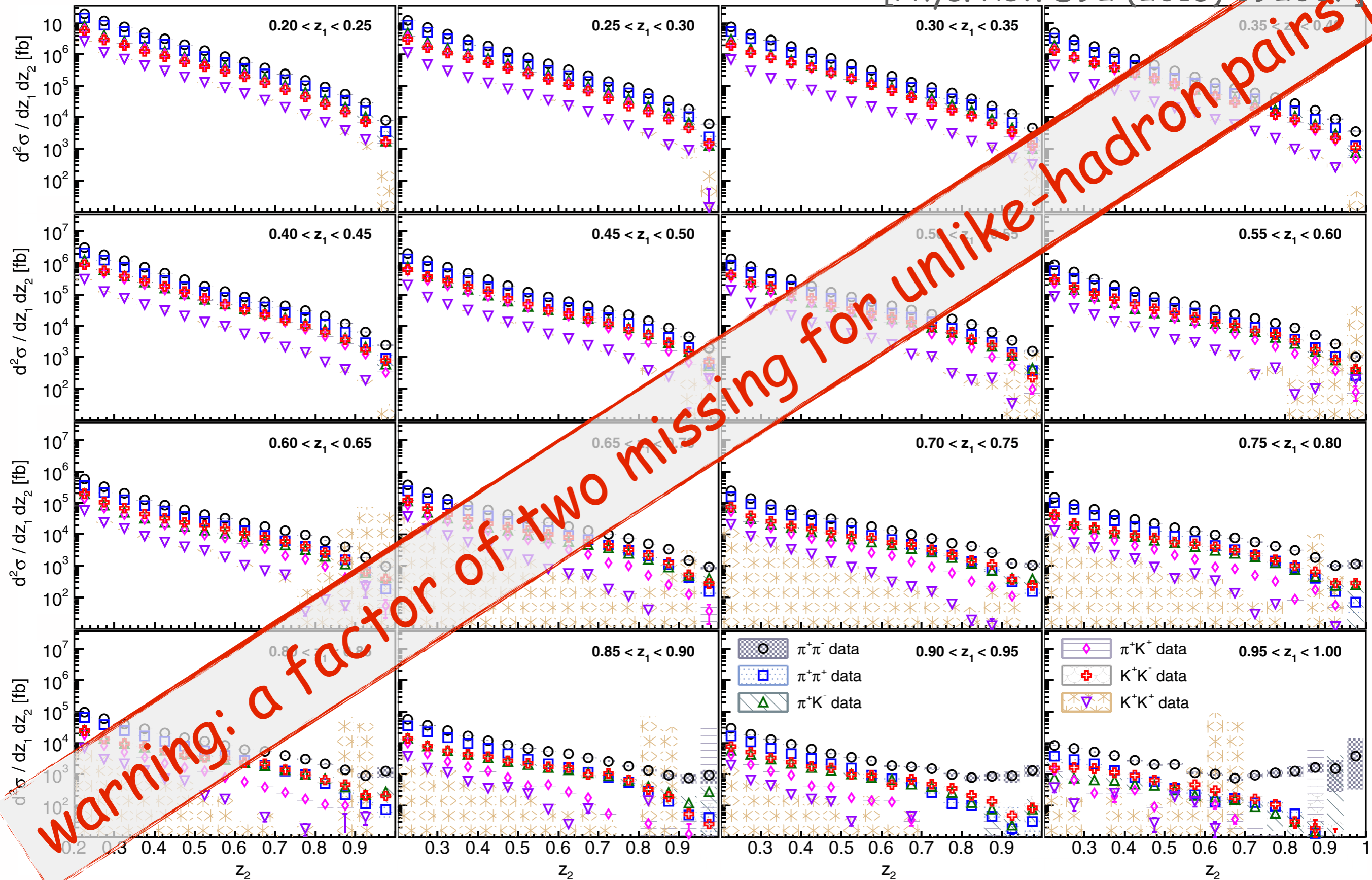




# hadron-pair production

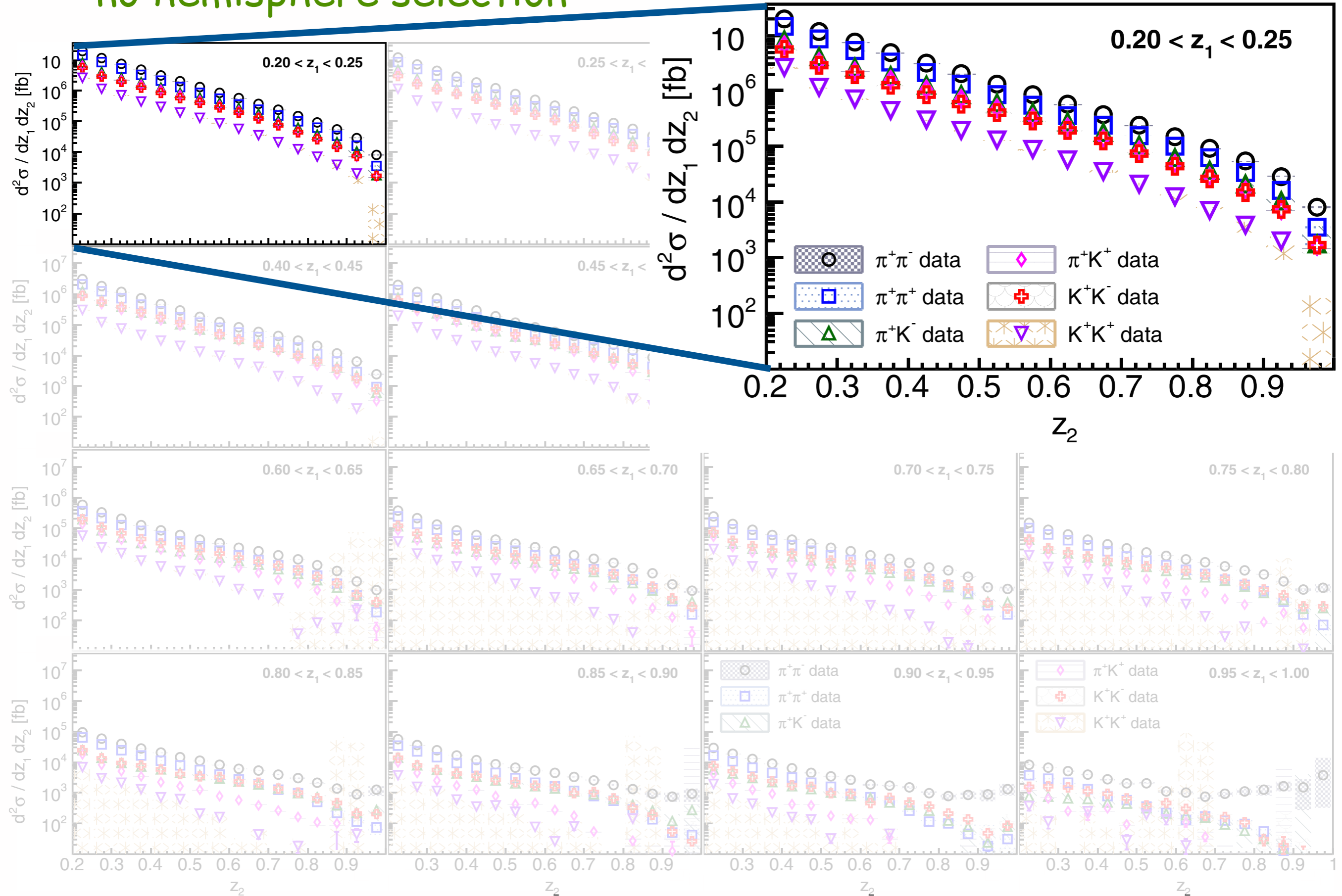
no hemisphere selection

[Phys. Rev. D92 (2015) 092007]



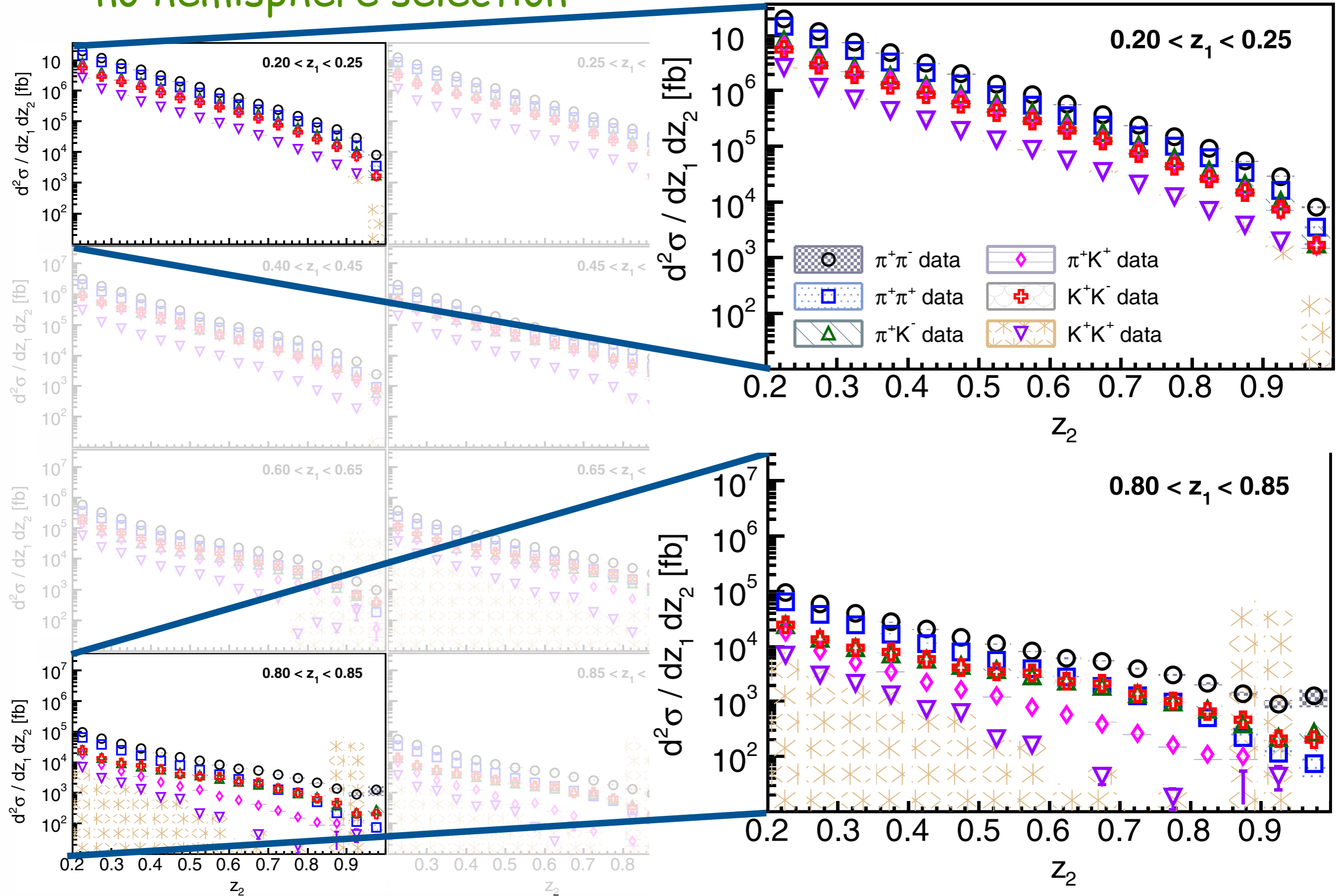
# hadron-pair production

no hemisphere selection



# hadron-pair production

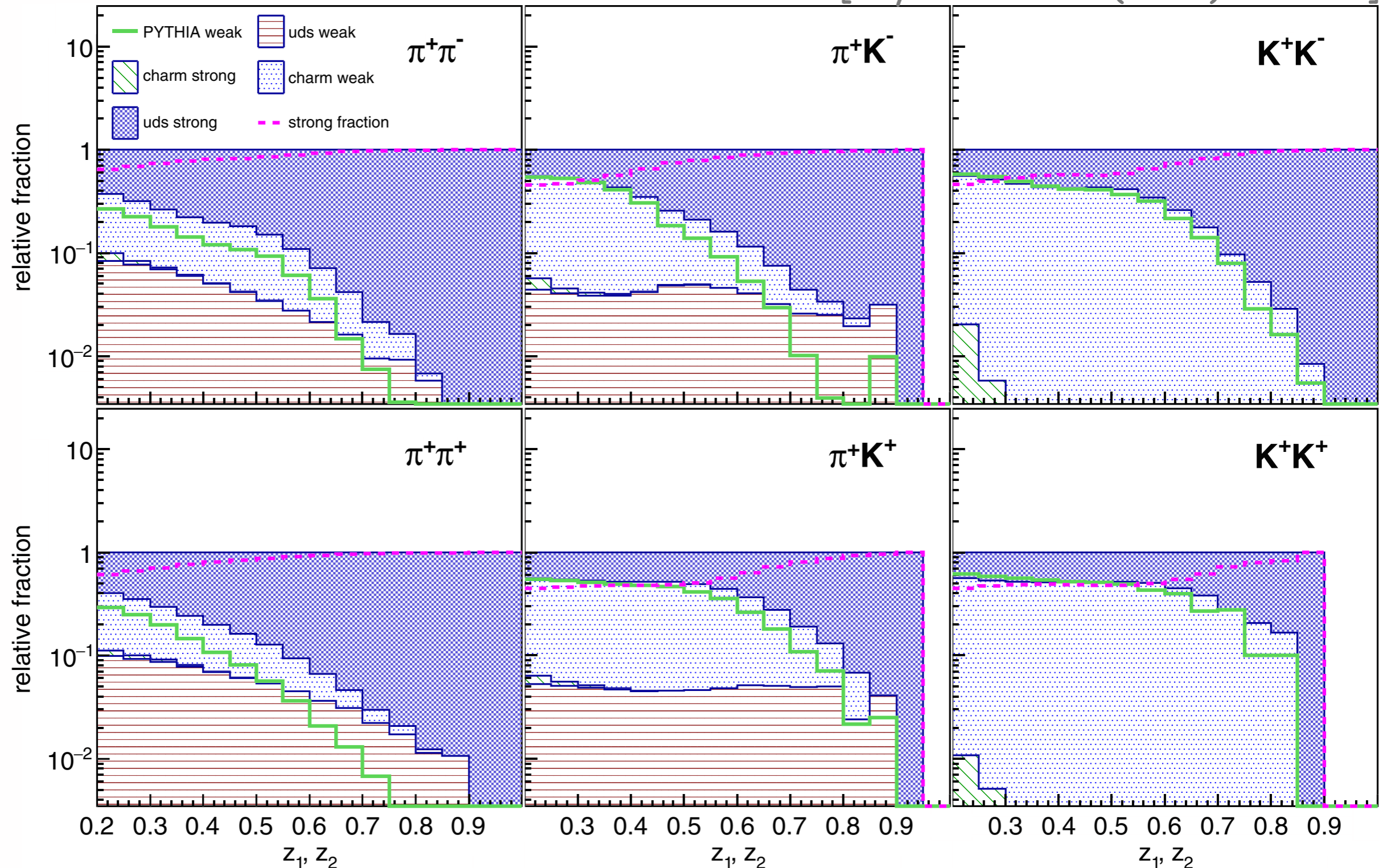
no hemisphere selection



# 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

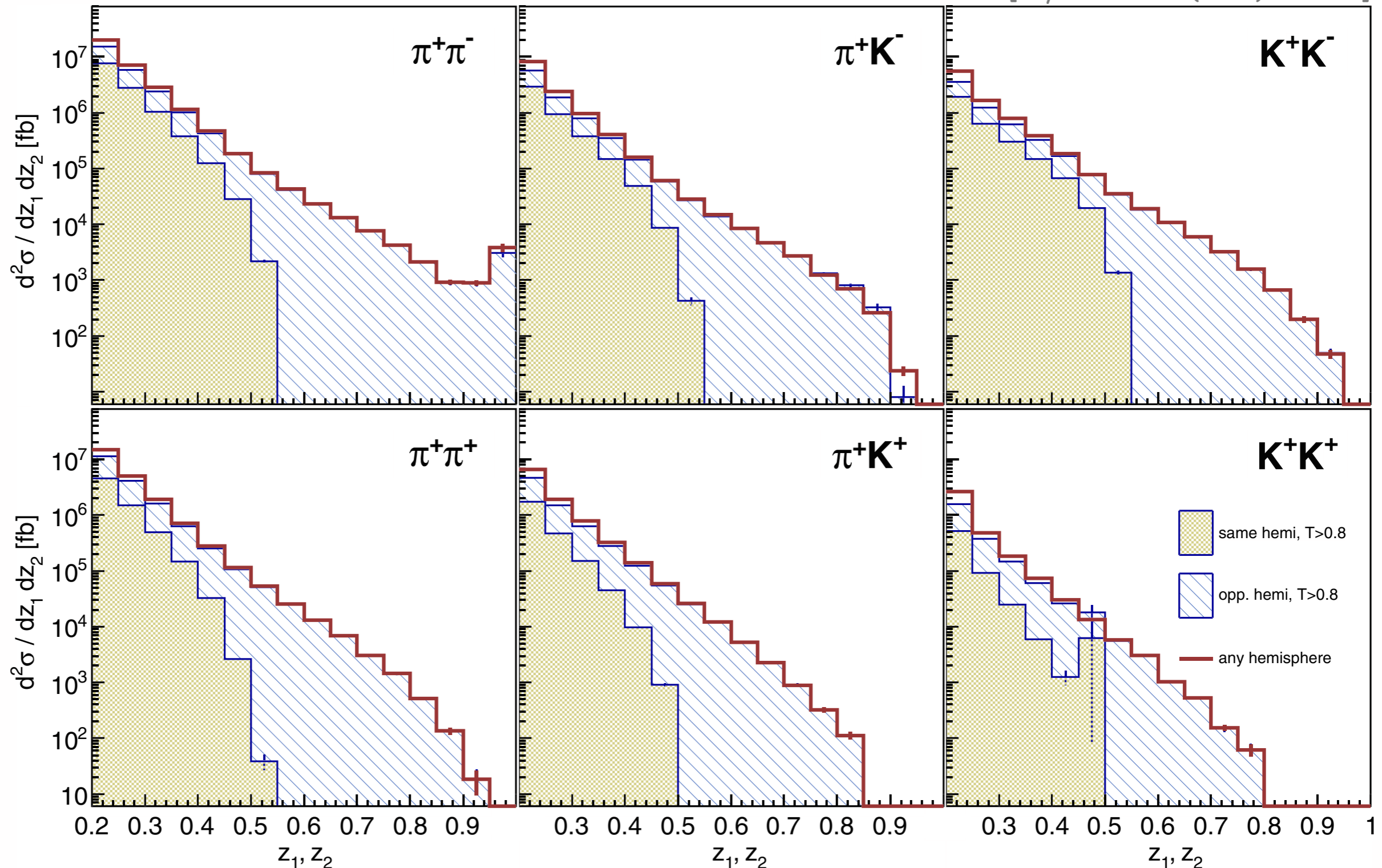
[Phys. Rev. D92 (2015) 092007]



# hadron-pairs: topology comparison

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

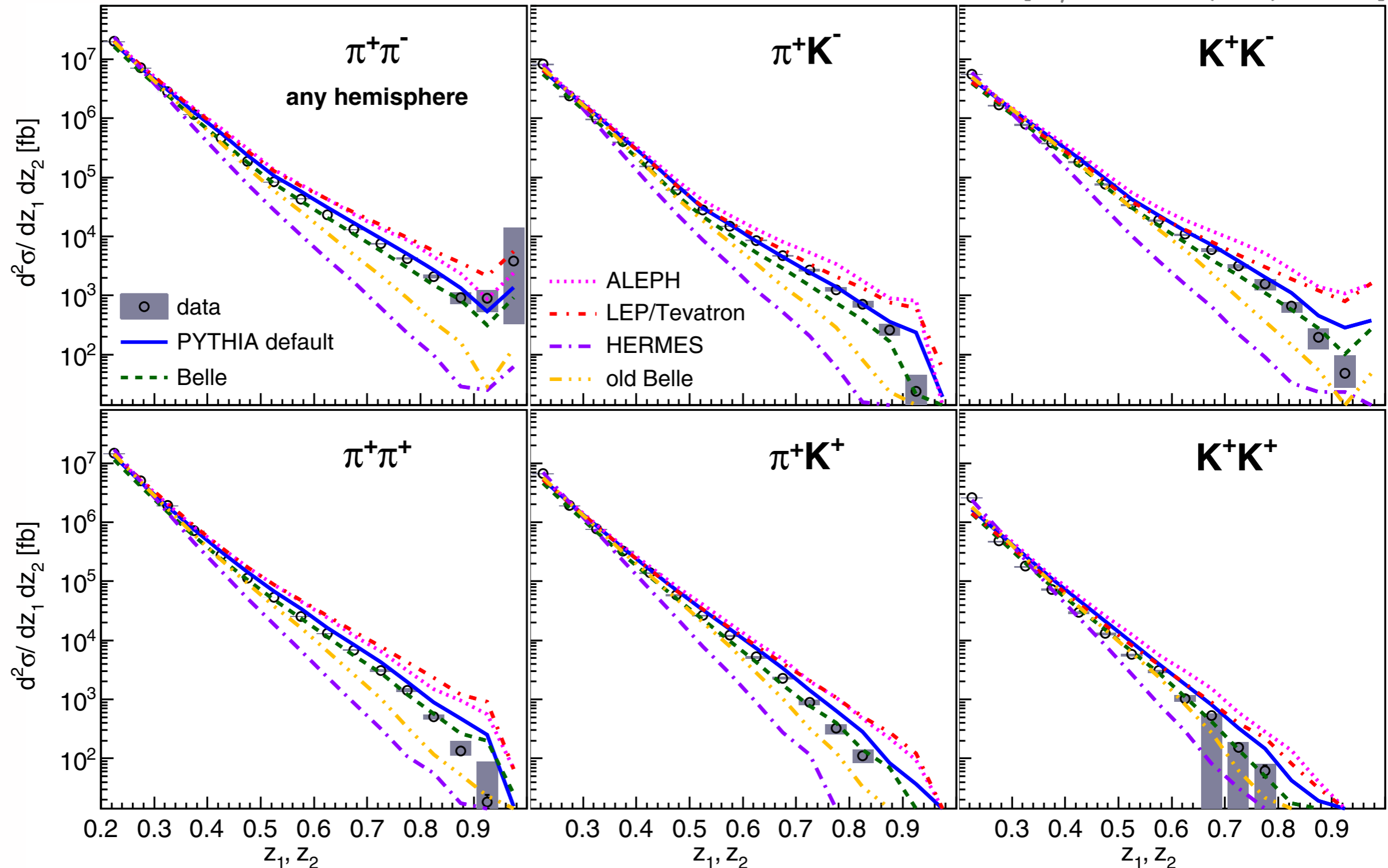
[Phys. Rev. D92 (2015) 092007]



# 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]

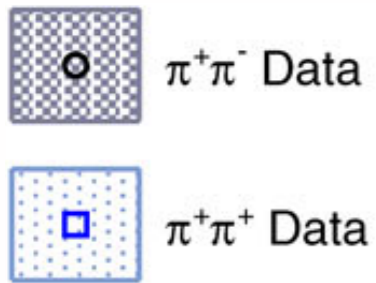


# same-hemisphere data: $M_{h_1 h_2}$ dependence

[Phys. Rev. D96 (2017) 032005]

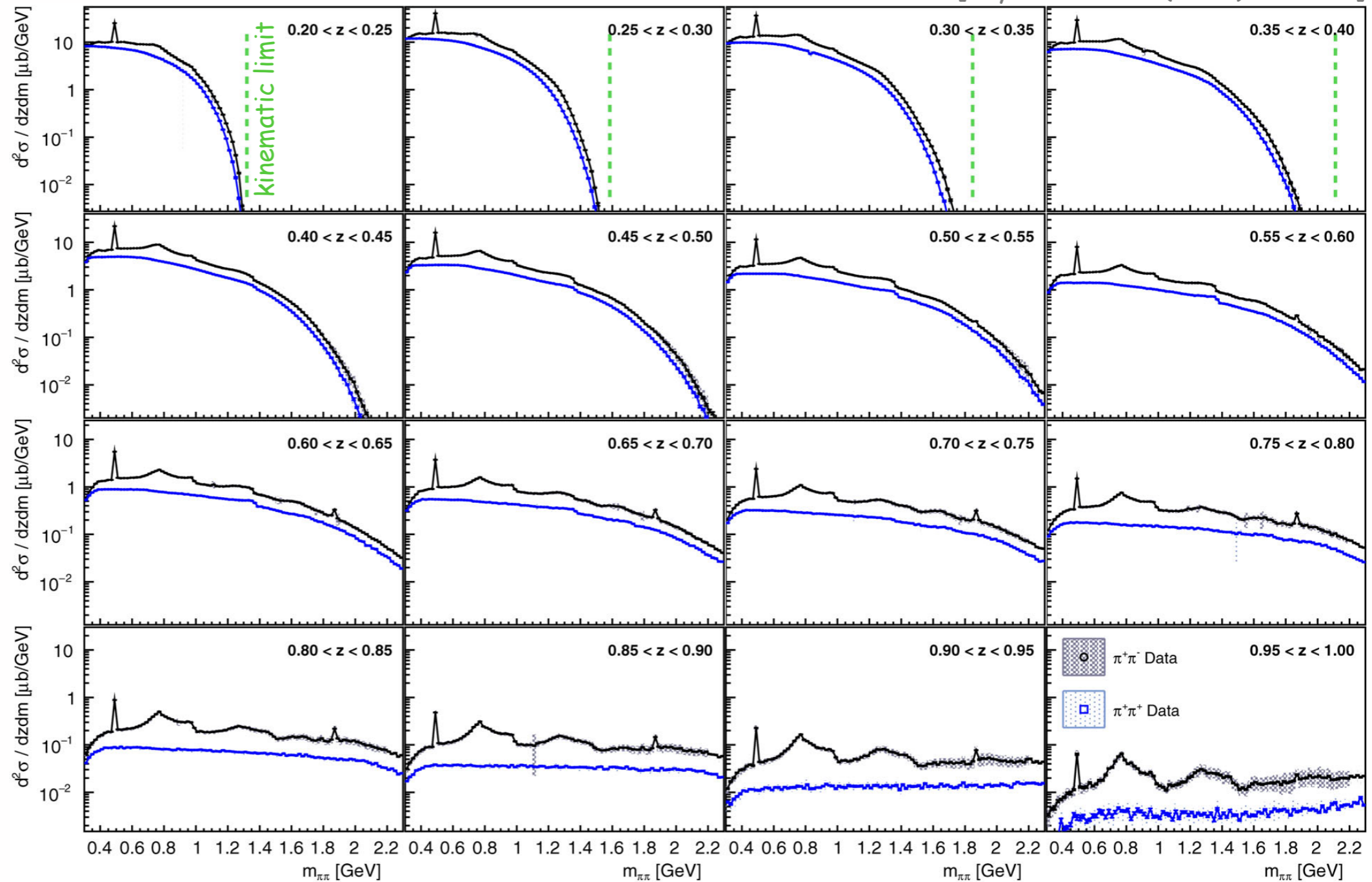
unlike-sign  
hadron pairs

like-sign  
hadron pairs



$T > 0.8$

$z_{1,2} > 0.1$



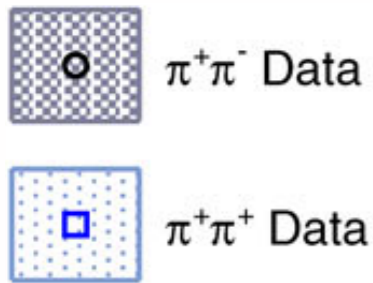
- unlike-sign pairs with clear decay and resonance structure:  $K_s$ ,  $\rho^0$  ...
- like-sign pairs with much smoother and smaller cross sections

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[Phys. Rev. D96 (2017) 032005]

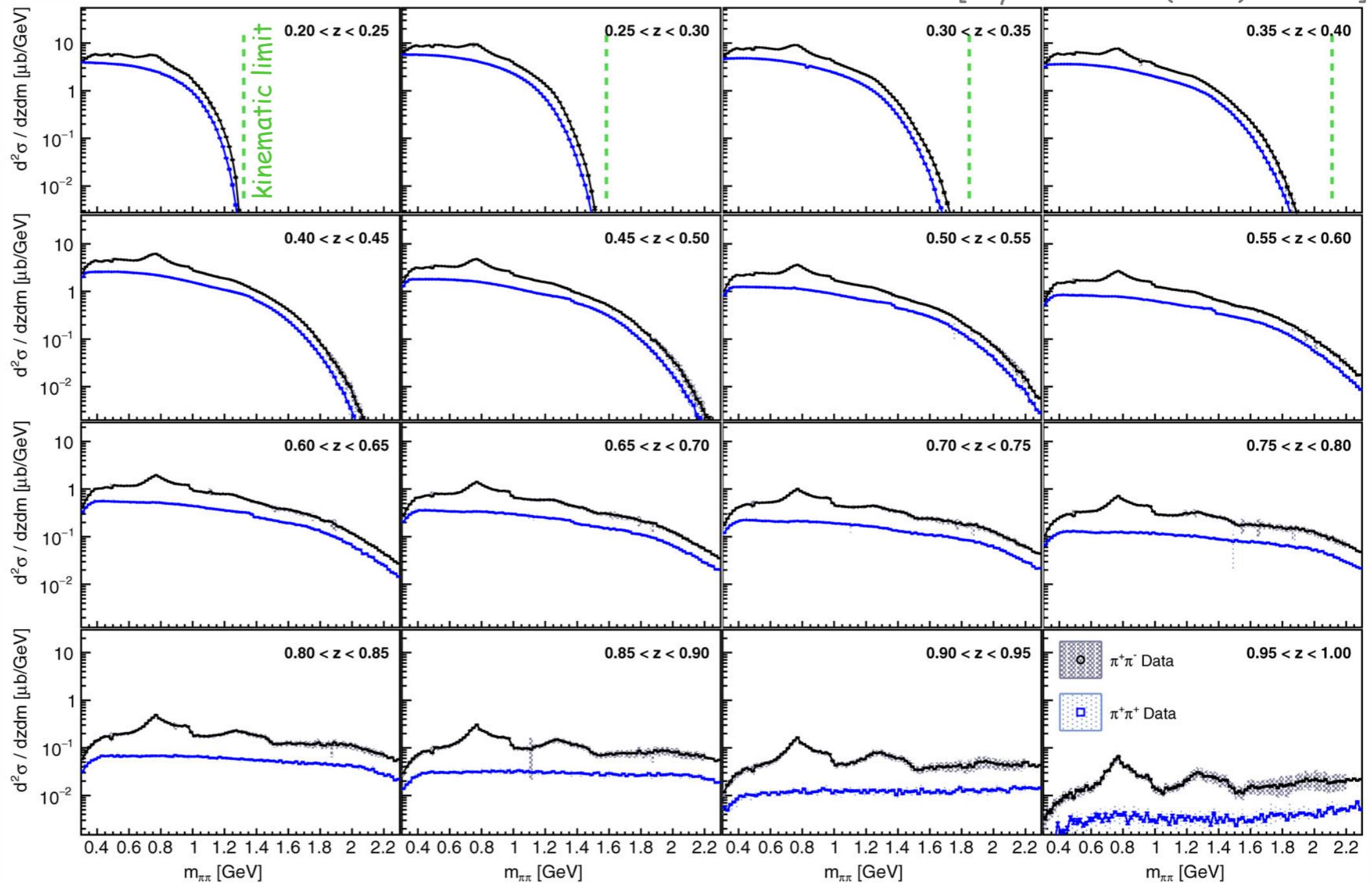
unlike-sign  
hadron pairs

like-sign  
hadron pairs



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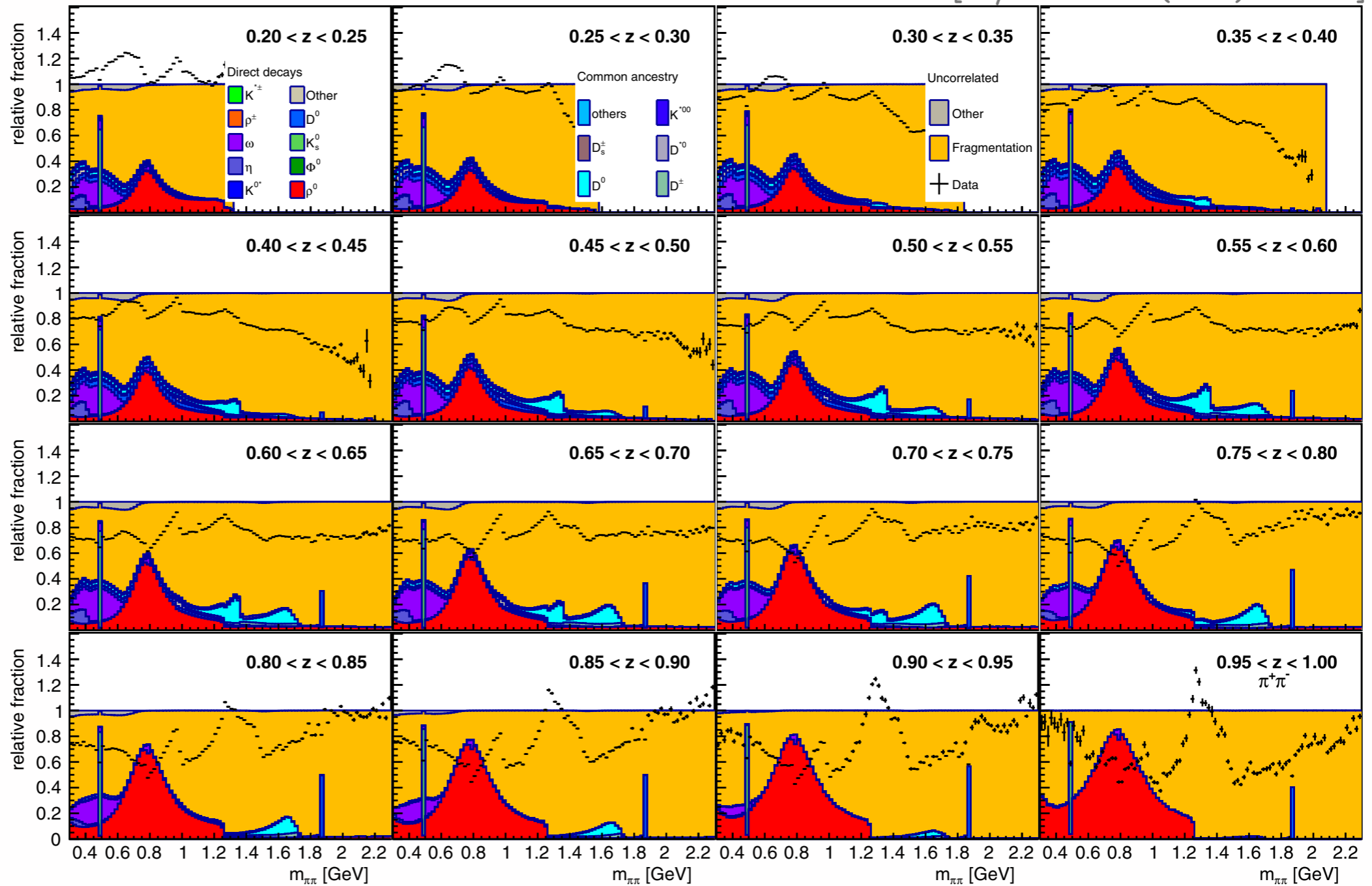
● cross sections after (MC-based) removal of weak-decay contributions



# same-hemisphere data: $M_{h_1 h_2}$ dependence

[Phys. Rev. D96 (2017) 032005]

unlike-sign  
pion pairs



$T > 0.8$

$z_{1,2} > 0.1$

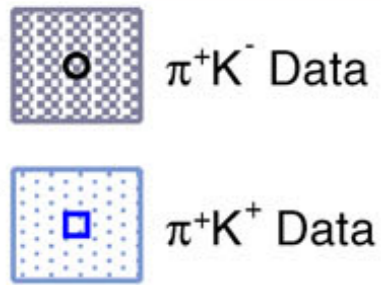
- decomposition based on PYTHIA simulation
- clear differences in invariant-mass dependence between MC and data

# same-hemisphere data: $M_{h_1 h_2}$ dependence

[Phys. Rev. D96 (2017) 032005]

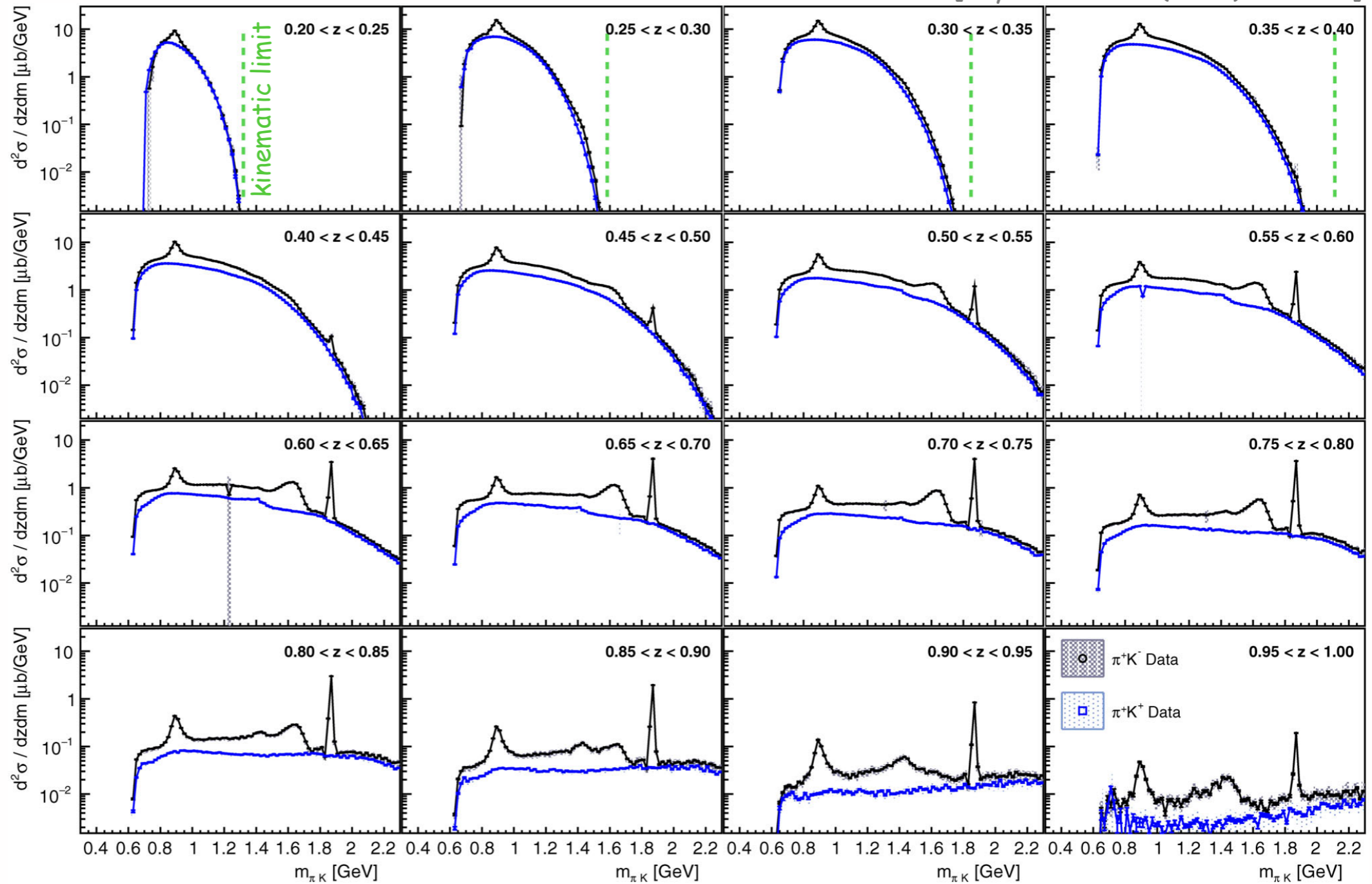
unlike-sign  
hadron pairs

like-sign  
hadron pairs



$\tau > 0.8$

$z_{1,2} > 0.1$



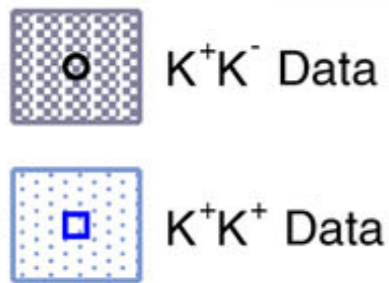
● unlike-sign  $\pi K$  pairs with clear  $K^*$  and increased D-decay contributions

# same-hemisphere data: $M_{h_1 h_2}$ dependence

[Phys. Rev. D96 (2017) 032005]

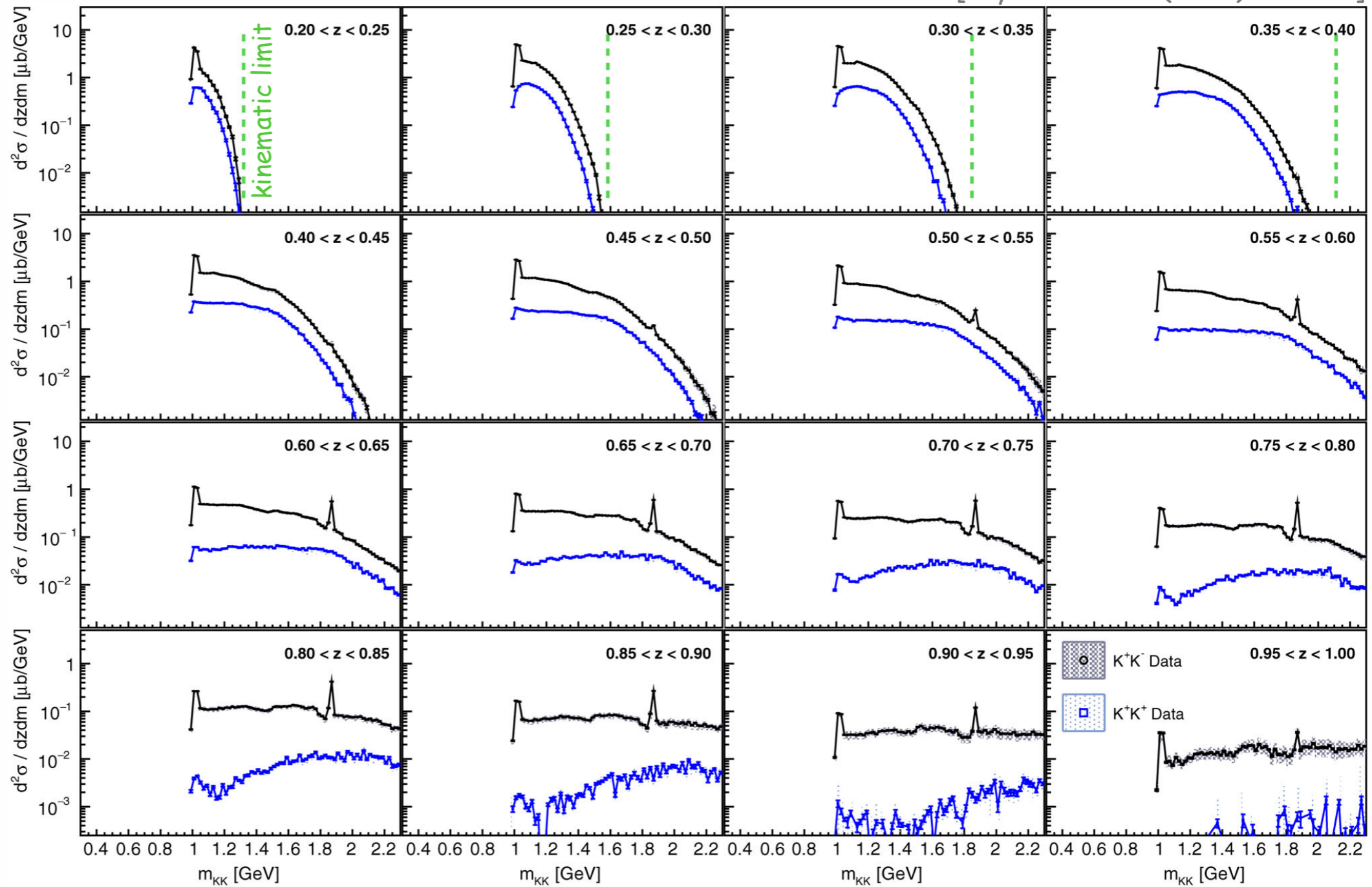
unlike-sign  
hadron pairs

like-sign  
hadron pairs



$T > 0.8$

$z_{1,2} > 0.1$



- unlike-sign kaon pairs with (again) a decay structure from  $\phi$  and  $D$
- like-sign kaon pairs strongly suppressed at larger  $z$

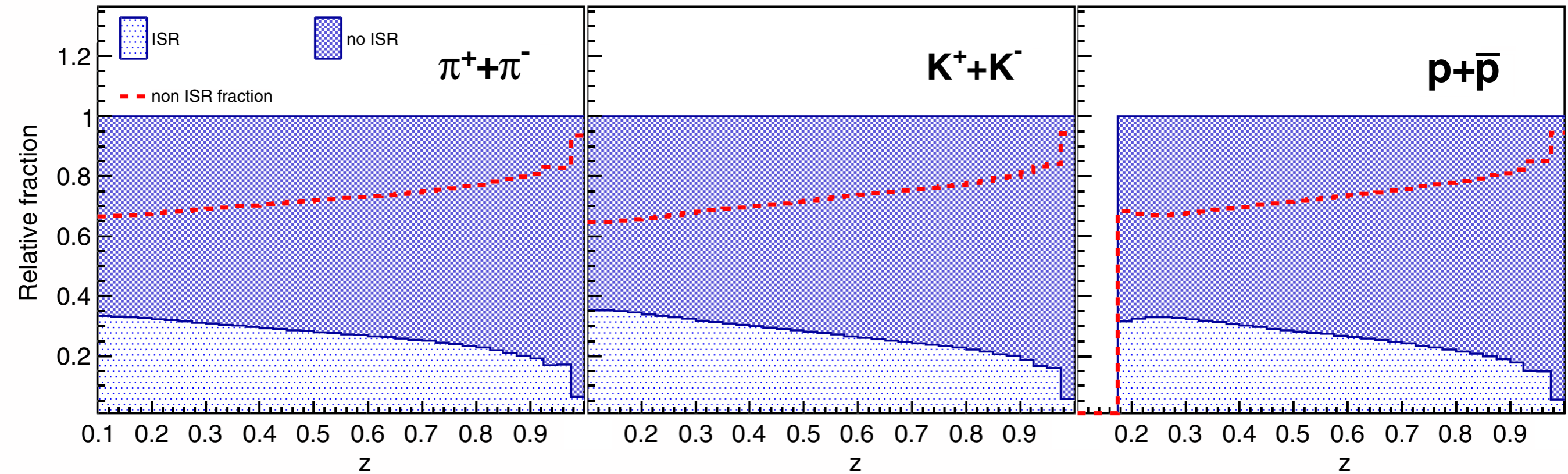
# what to further expect from Belle

- production cross sections of hyperons and charmed baryons  
(submitted to Phys. Rev. D, arXiv:1706.06791)
- transverse polarization of inclusively produced  $\Lambda^0$  hyperons  
(arXiv:1611.06648)
- $\pi^0$  and  $\eta$  Collins asymmetries
- $k_T$ -dependent  $D_1$  FFs
  - hadron-to-thrust
  - nearly back-to-back hadrons
- hadron-pair cross sections revisited: fully differential and/or differential in other variables
- helicity-dependent dihadron fragmentation:  $G_1^\perp$  ("jet handedness")



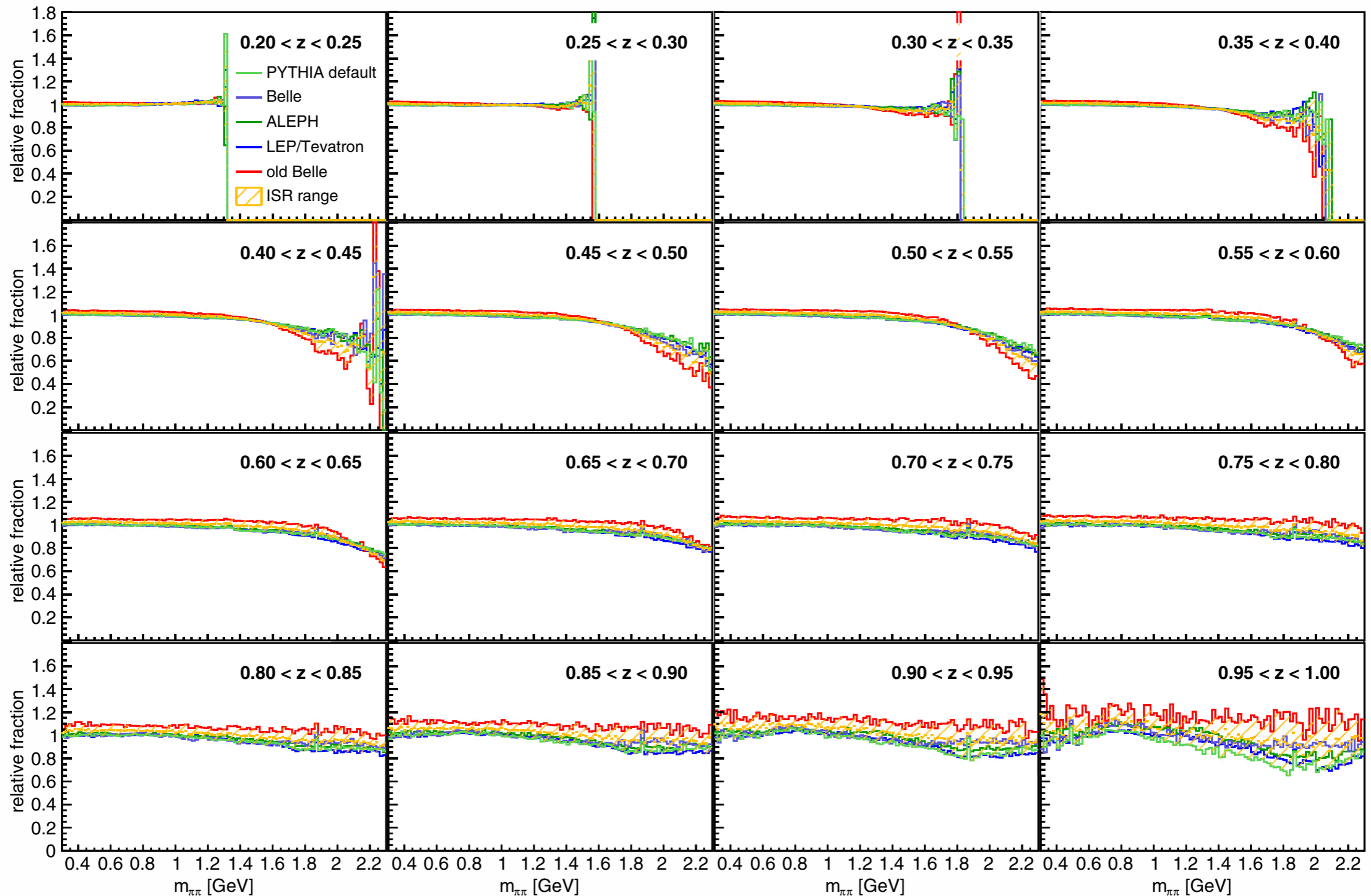
backup slides

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

# ISR corrections - PRD96 (2017) 032005

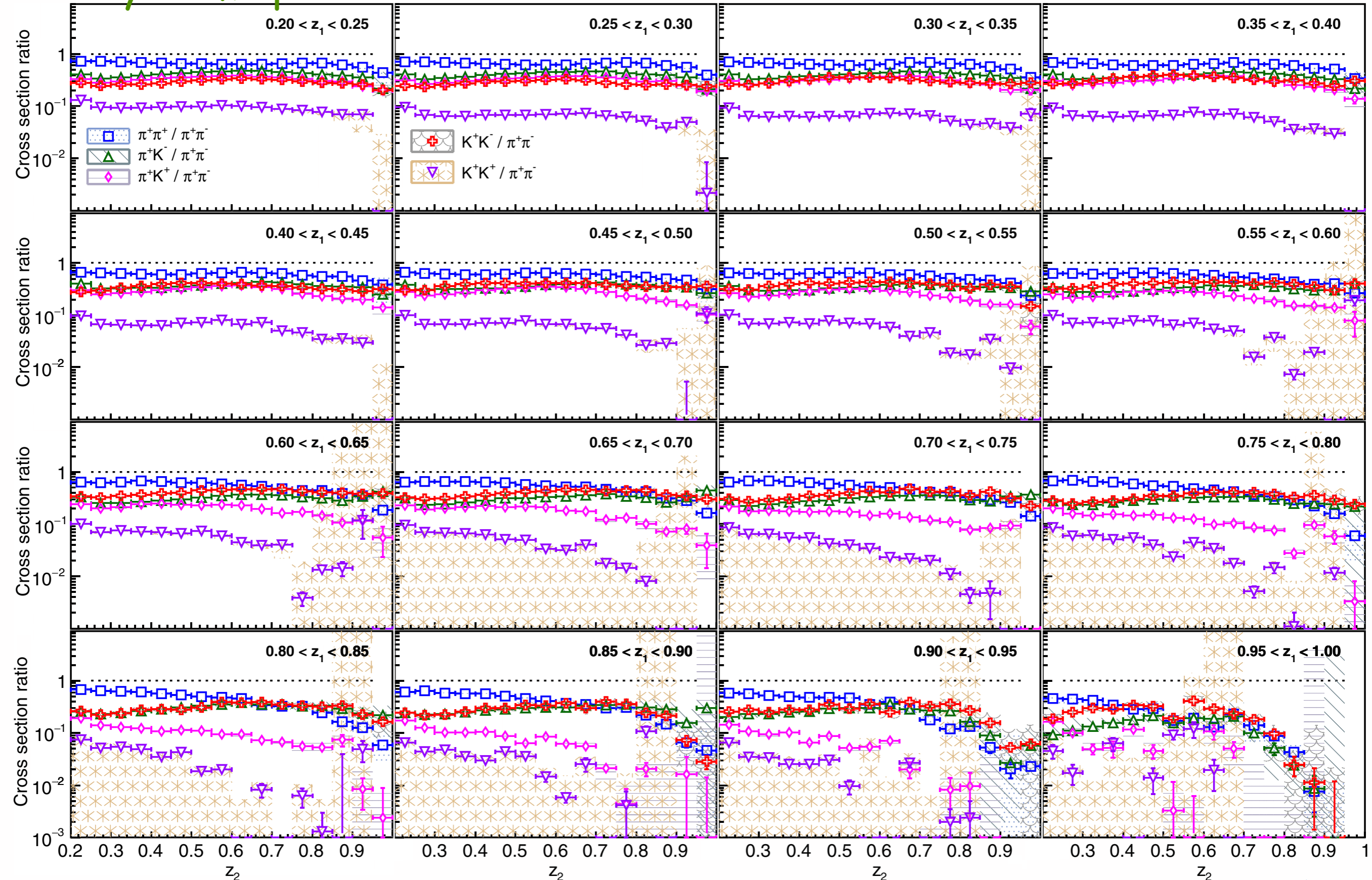


● non-ISR / ISR fractions based on PYTHIA switch MSTP(11)

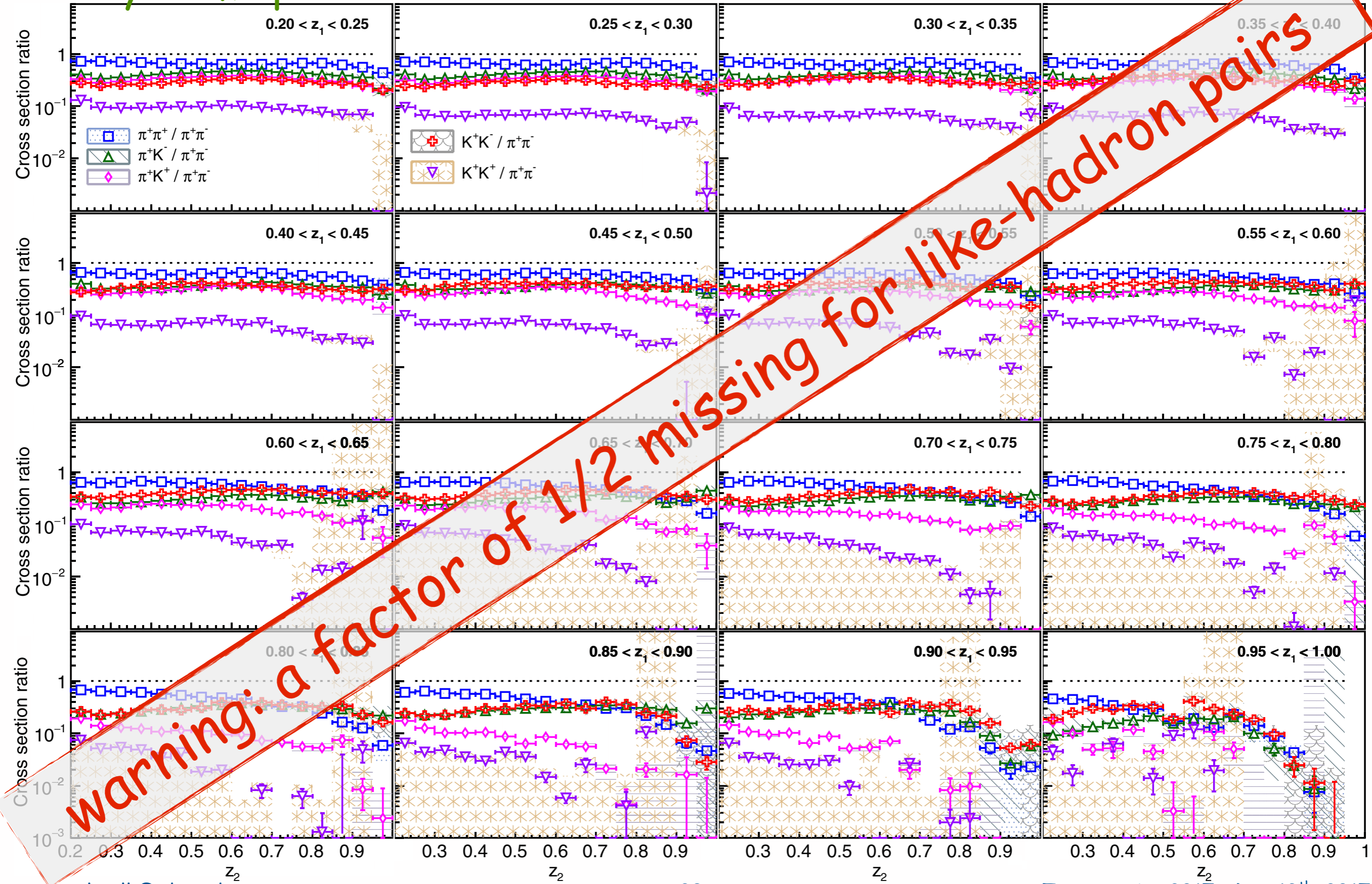
● several PYTHIA tunes used for estimate of systematic uncertainty



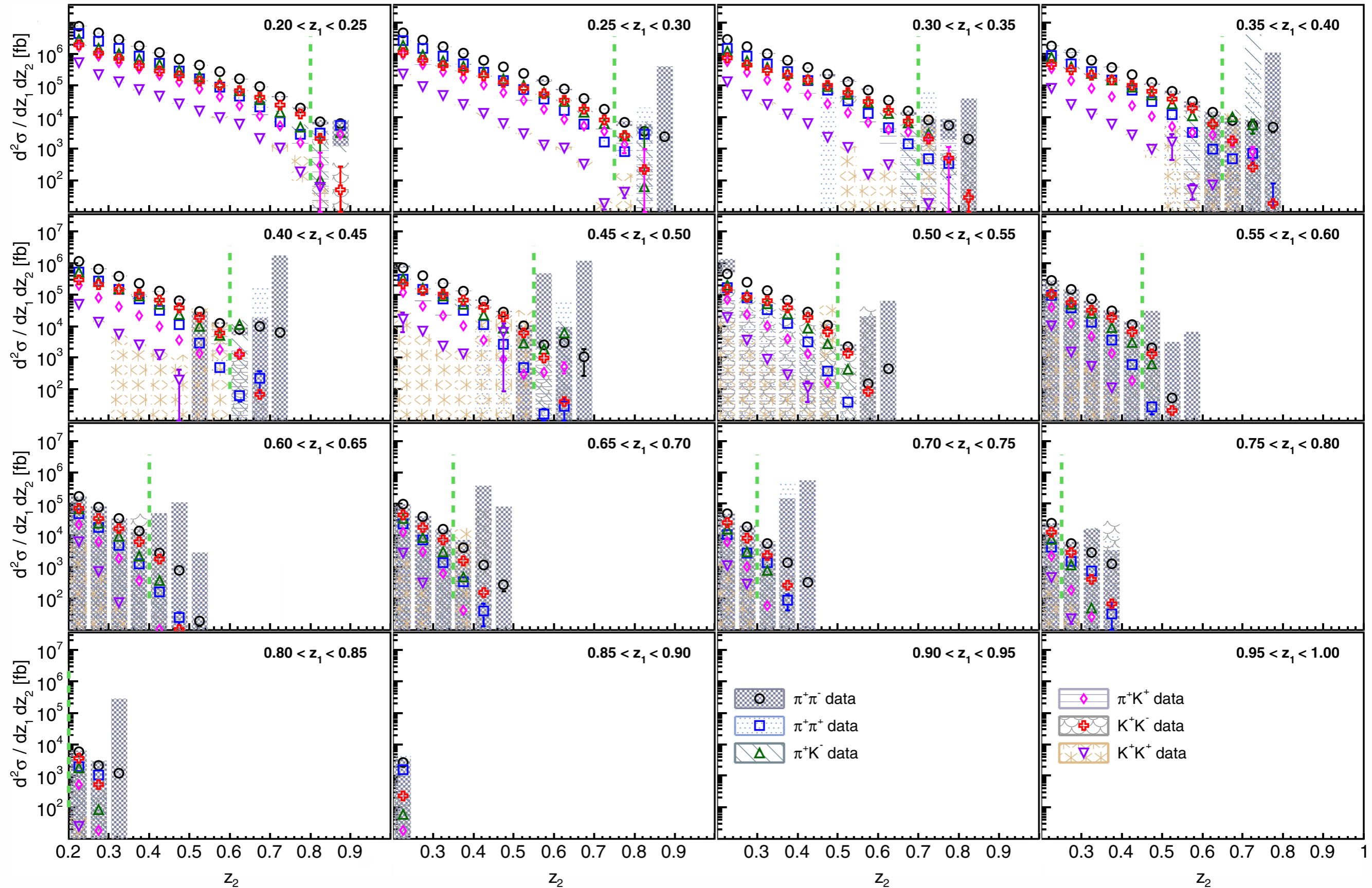
# hadron-pair cross sections relative to $\pi^+\pi^-$ any hemisphere



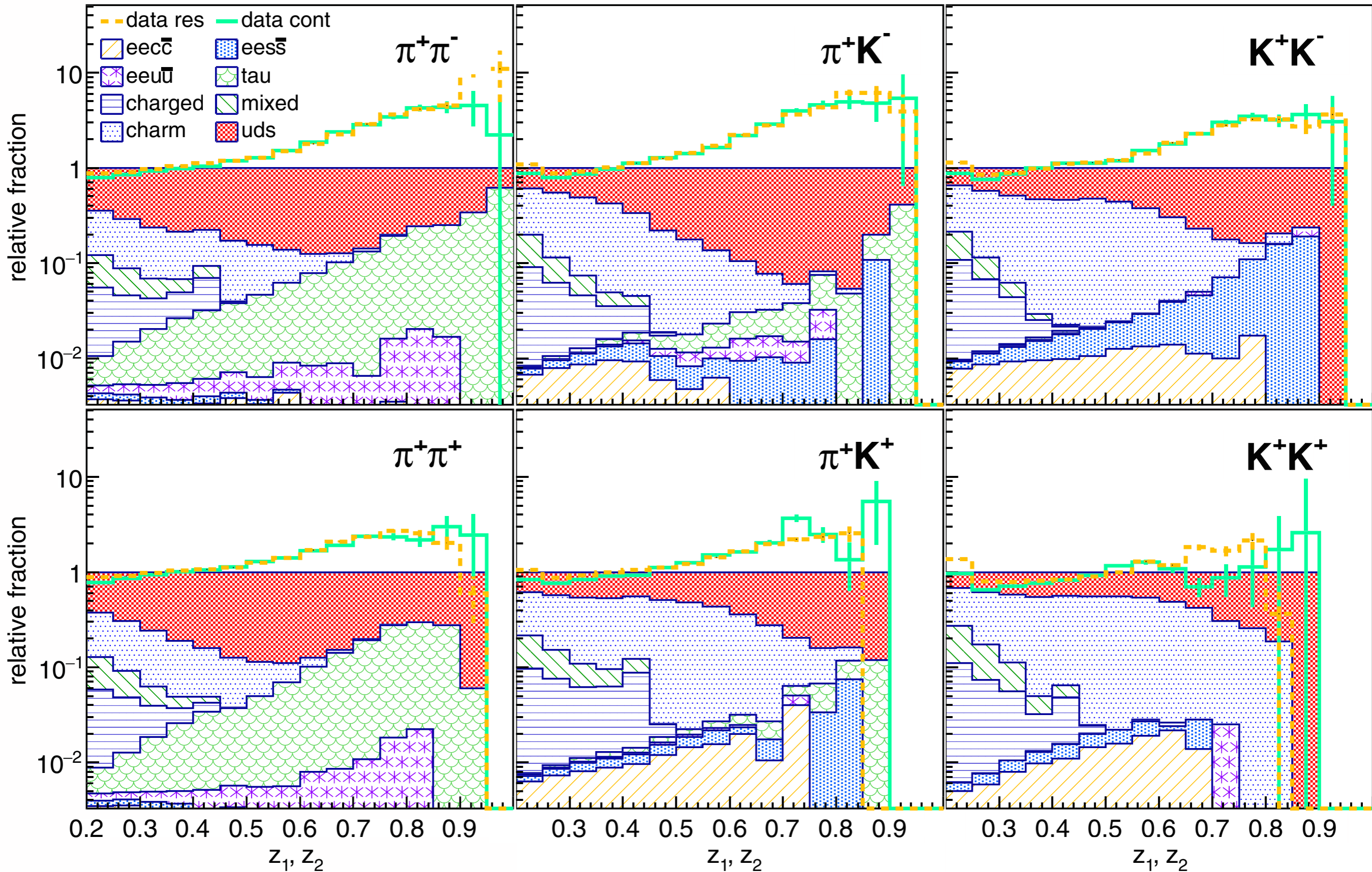
# hadron-pair cross sections relative to $\pi^+\pi^-$ any hemisphere



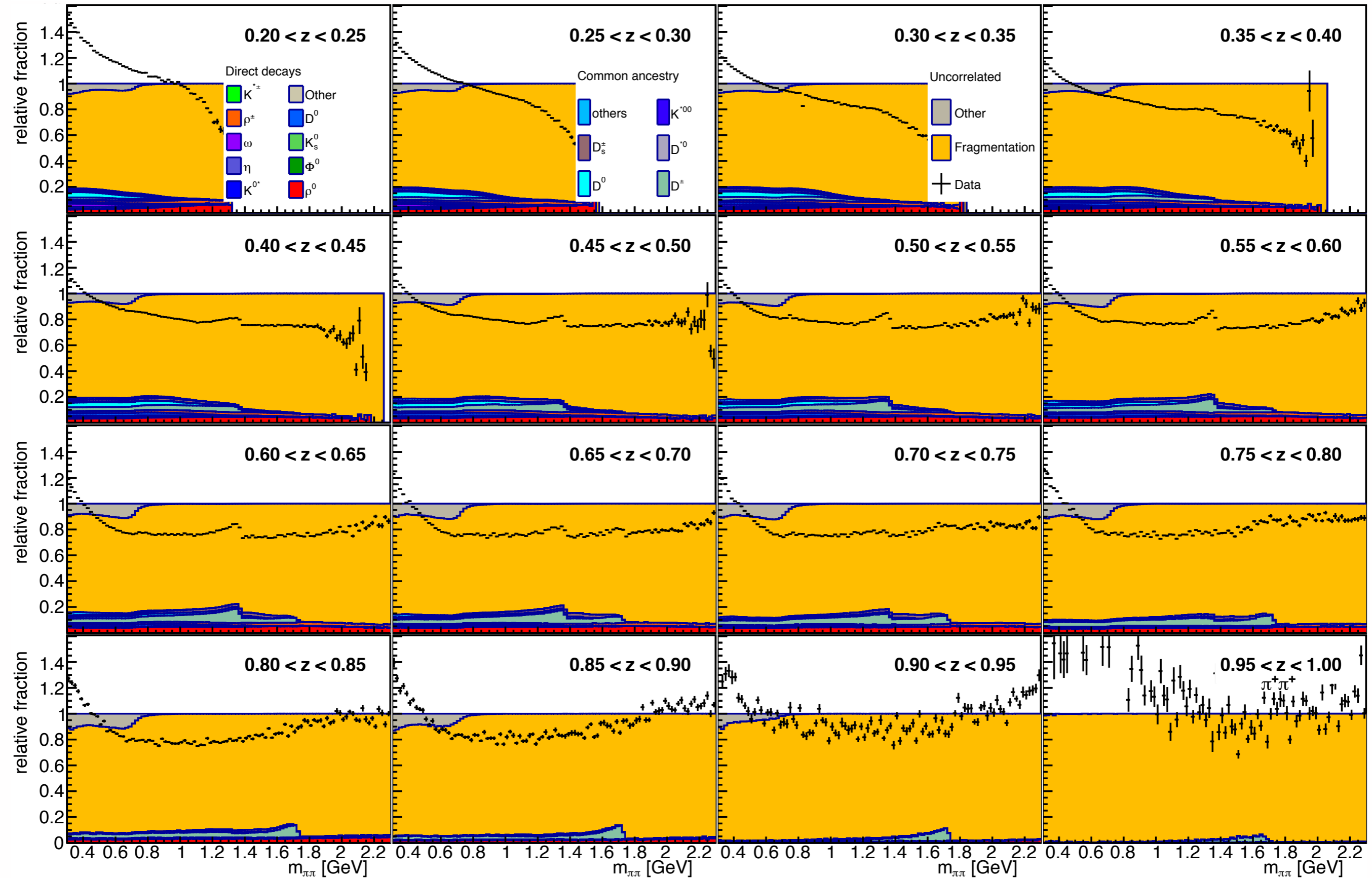
# same-hemisphere hadron pairs



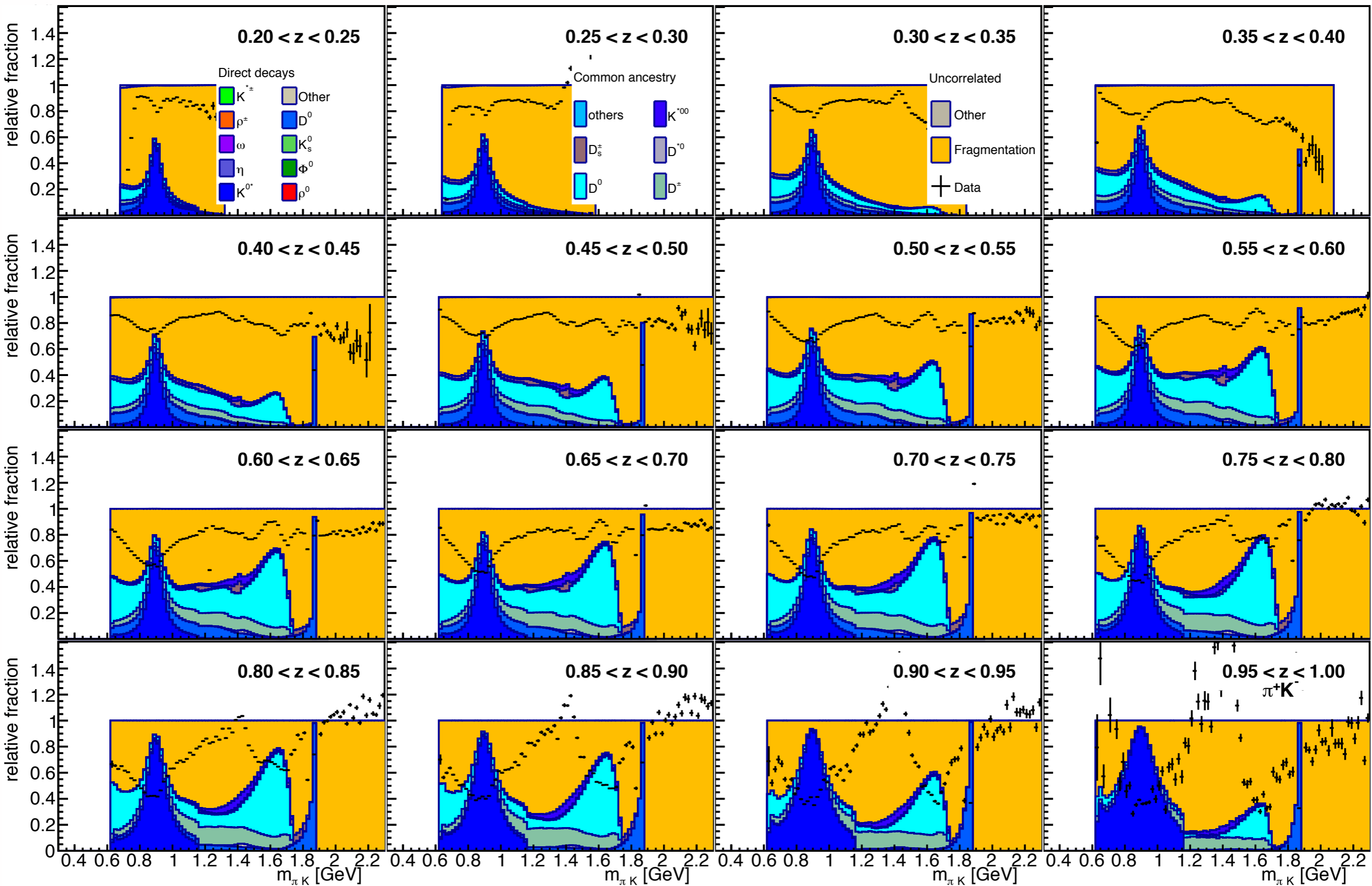
# subprocess contributions



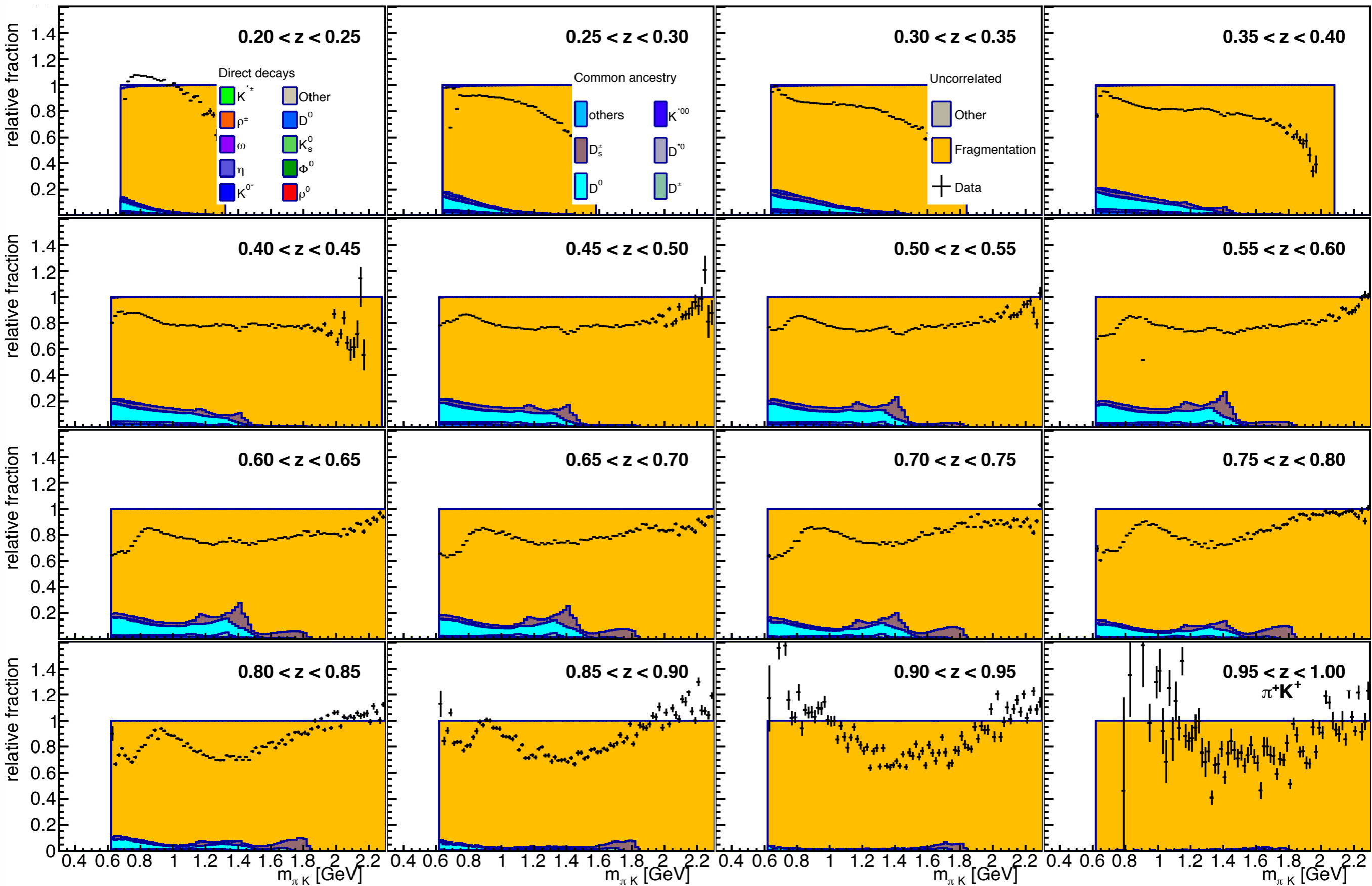
# like-sign di-pion cross sections



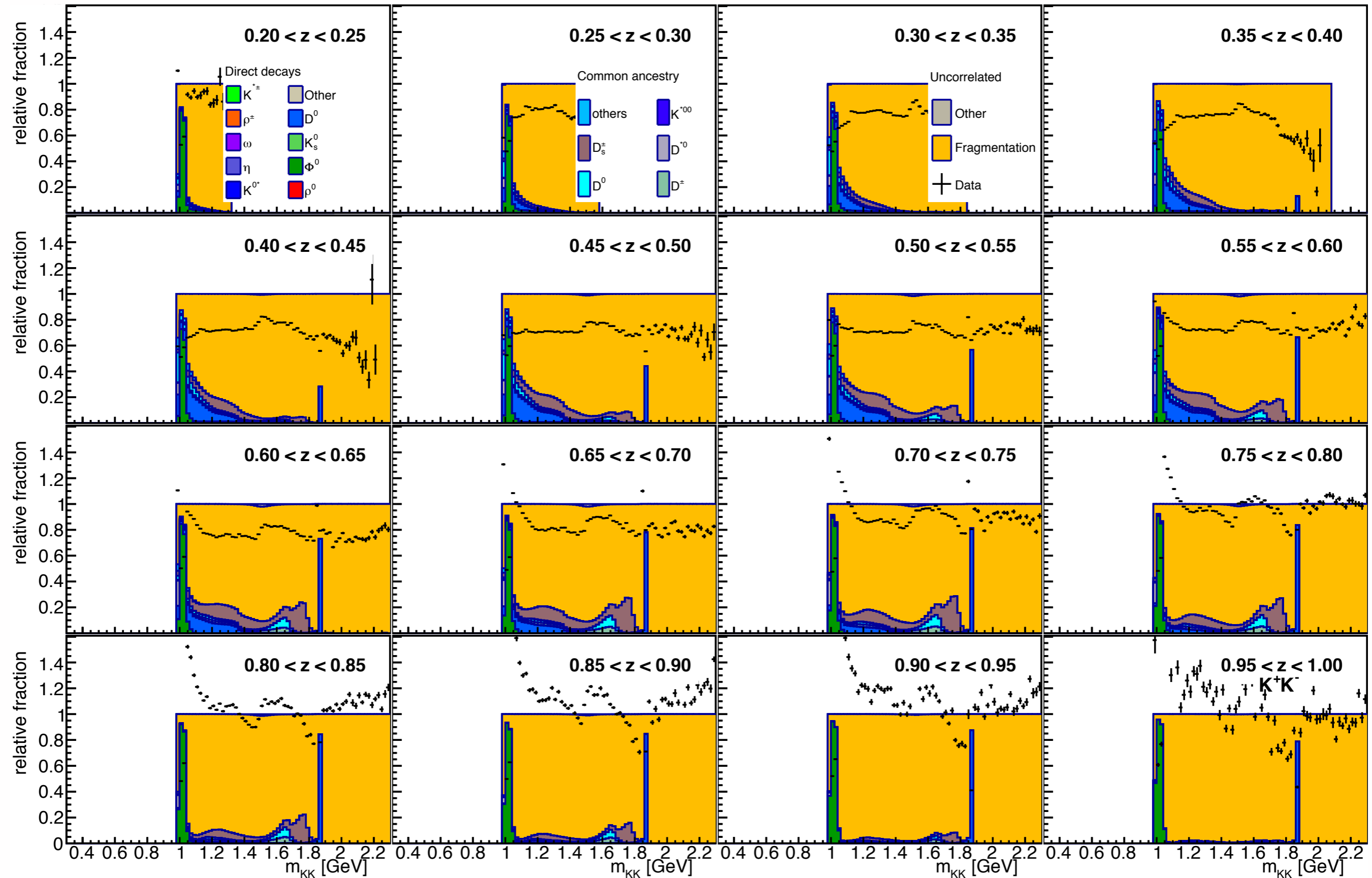
# unlike-sign pi-K cross sections



# like-sign pi-K cross sections



# unlike-sign di-kaon cross sections





# like-sign di-kaon cross sections

