QCD evolution

May 22-26, 2017
Jefferson Lab
Newport News, VA

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Fragmentation functions and implications for semi-inclusive DIS

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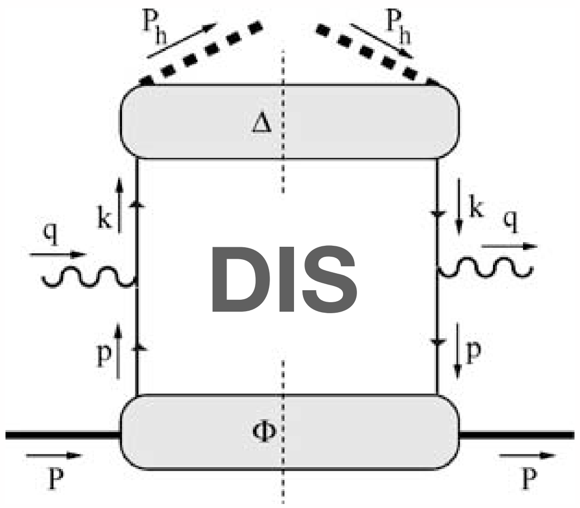
TMDs - a global approach



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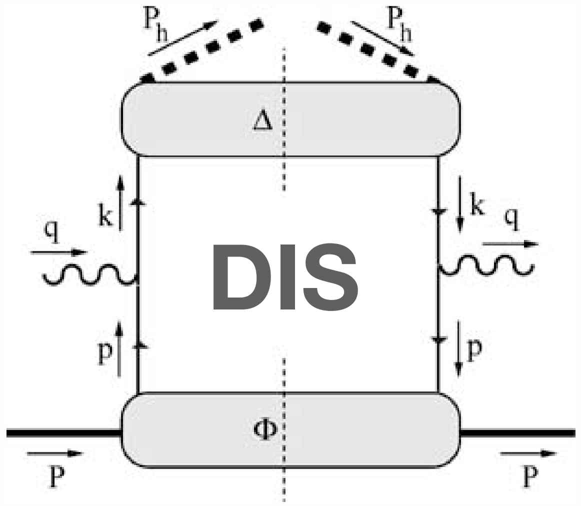

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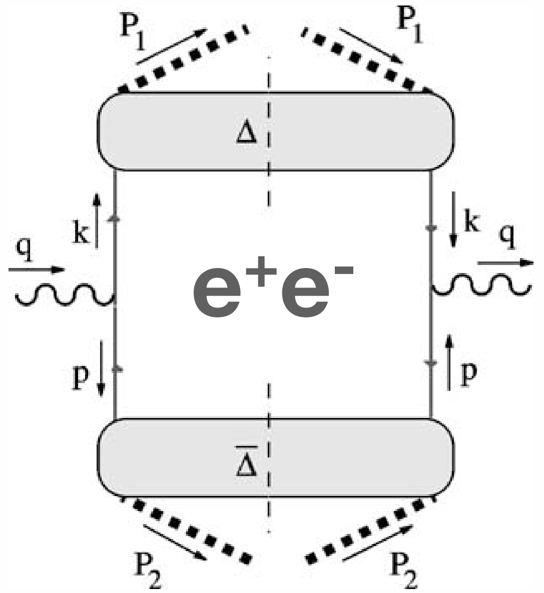

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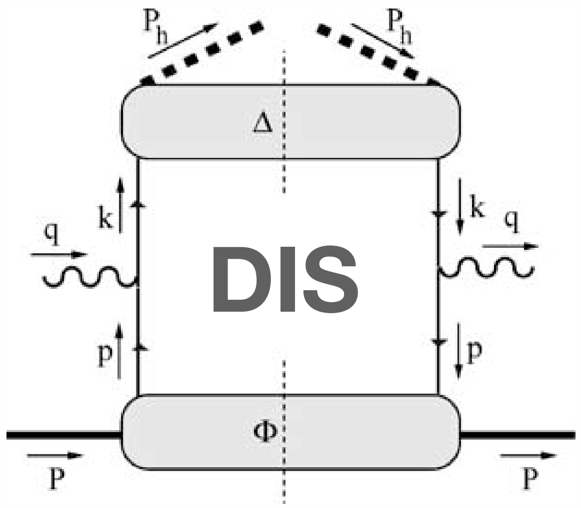

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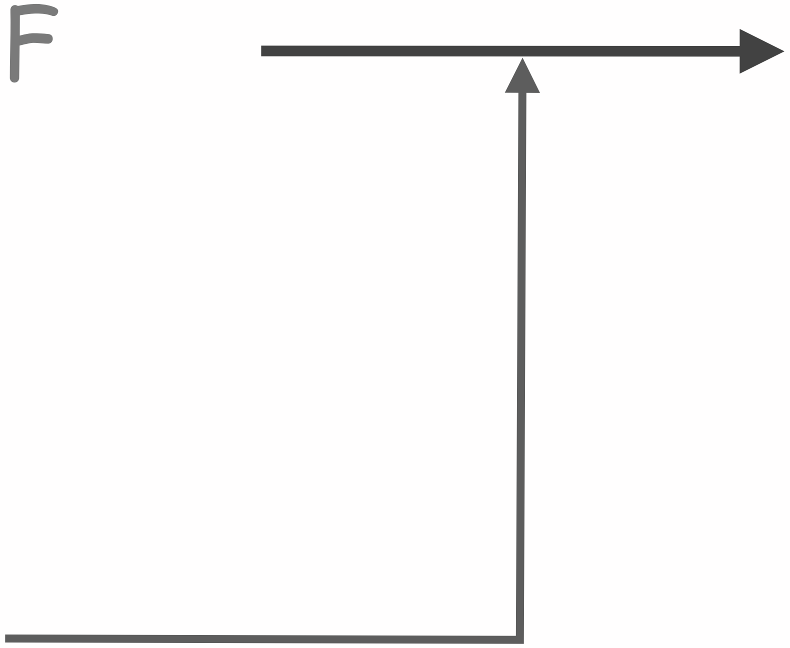
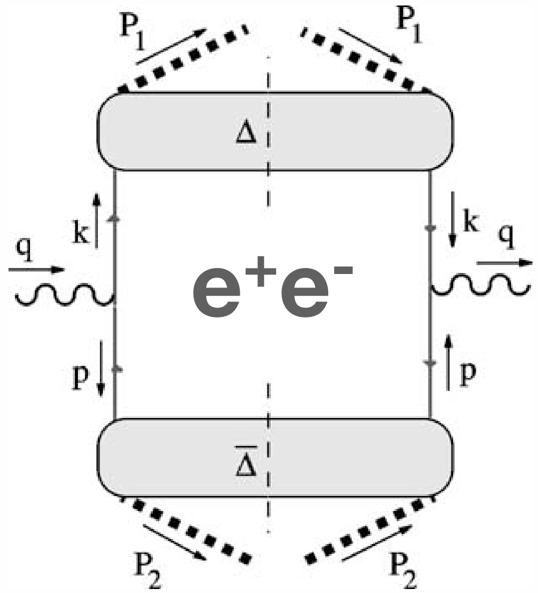


PDF|DIS



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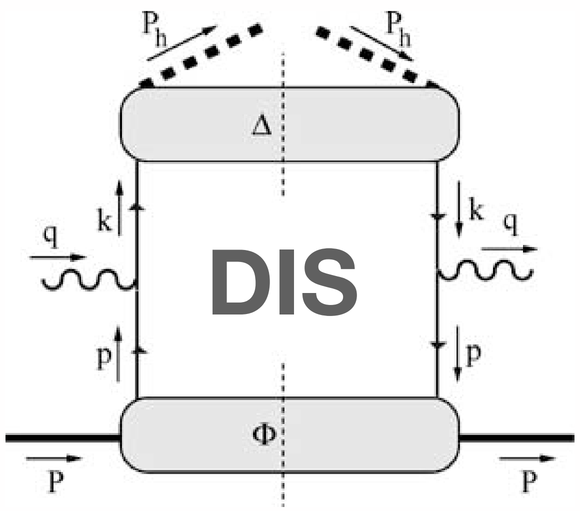

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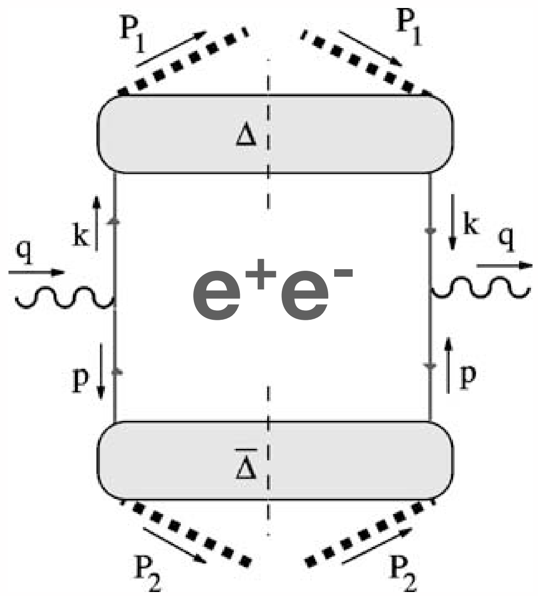

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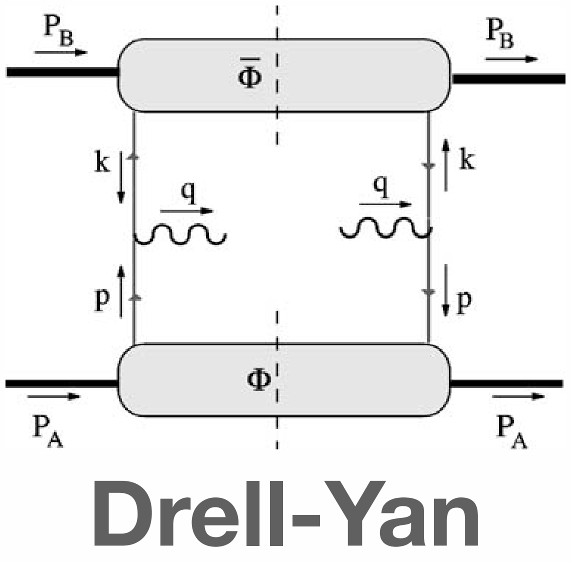

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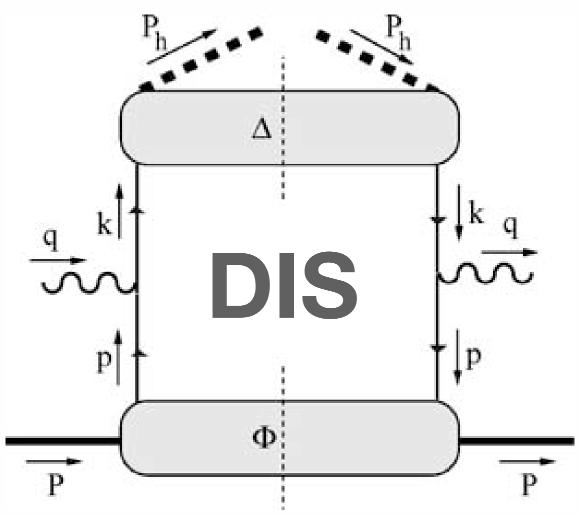

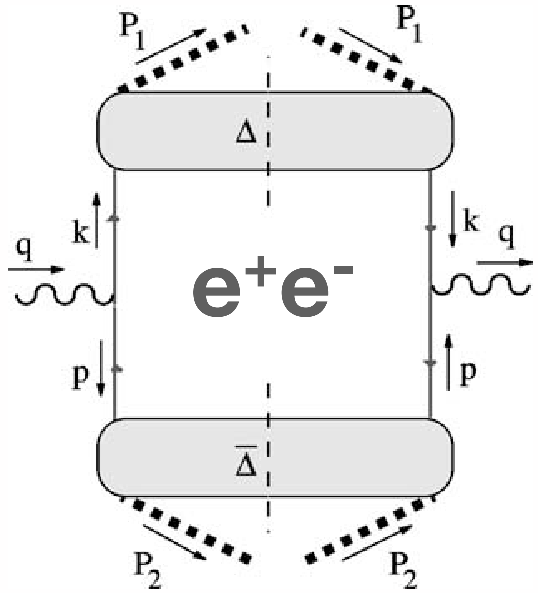

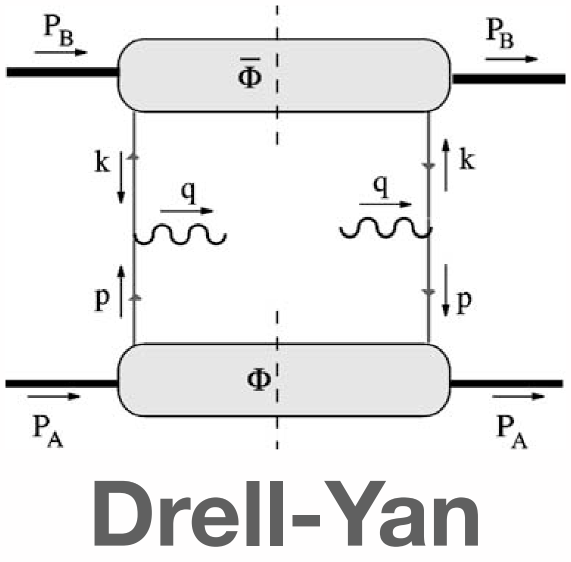

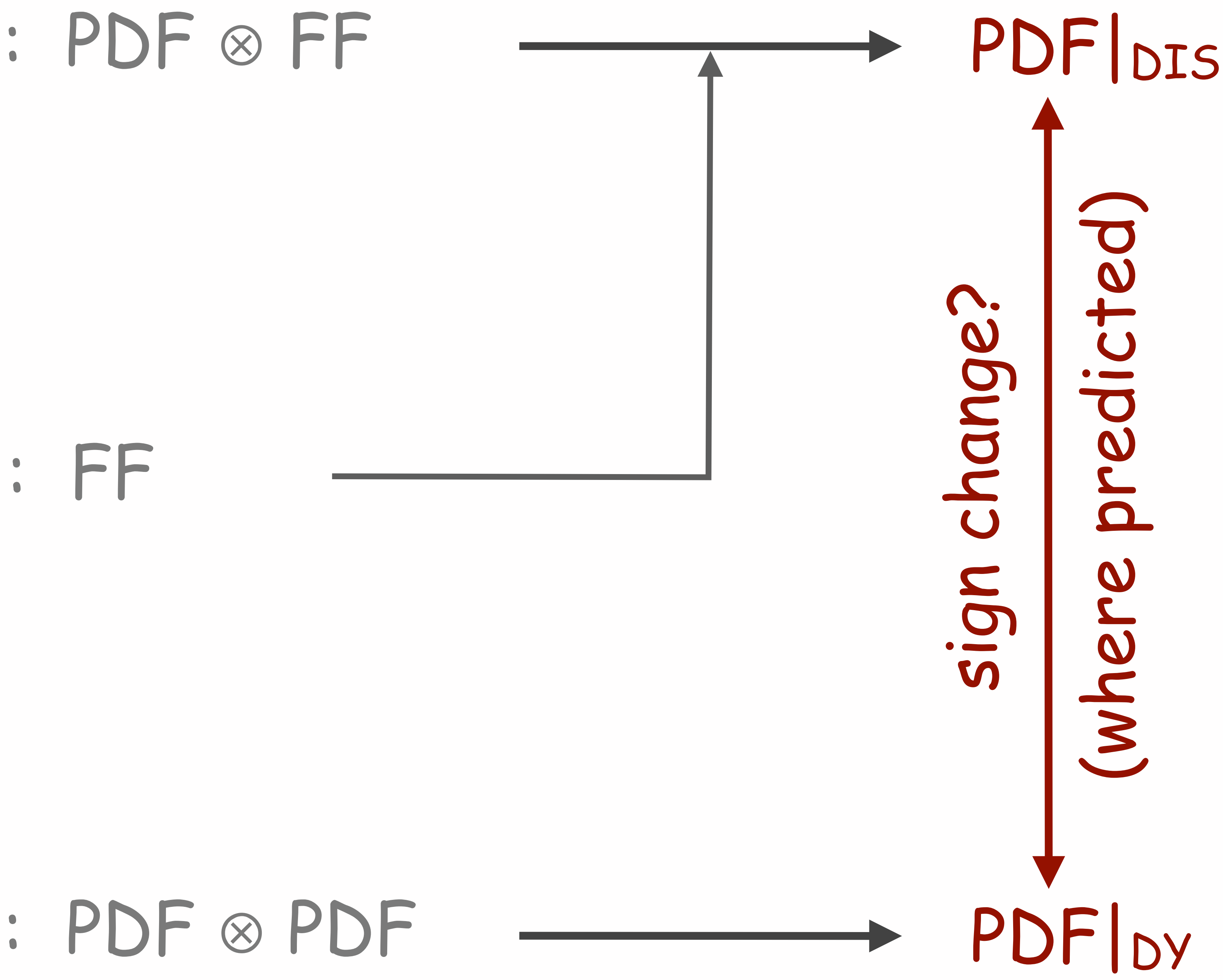

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sign change?
(where predicted)

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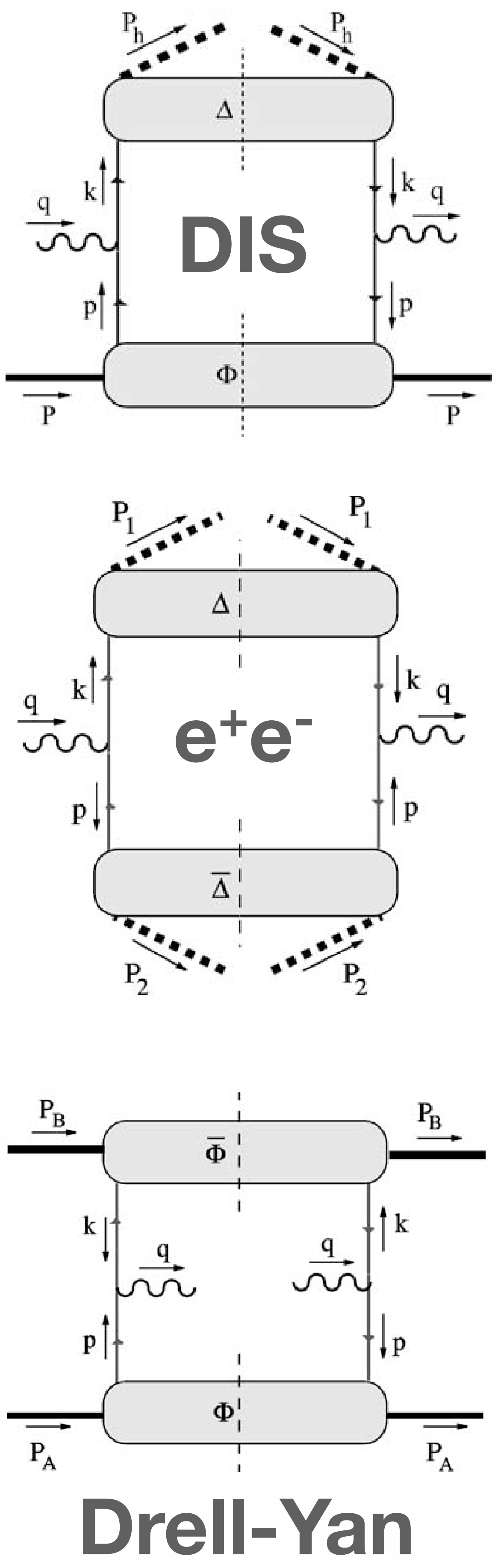

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: FF

FFs also needed/ interesting for many other studies!

: PDF $\otimes$ PDF → PDF|DY

sign change?
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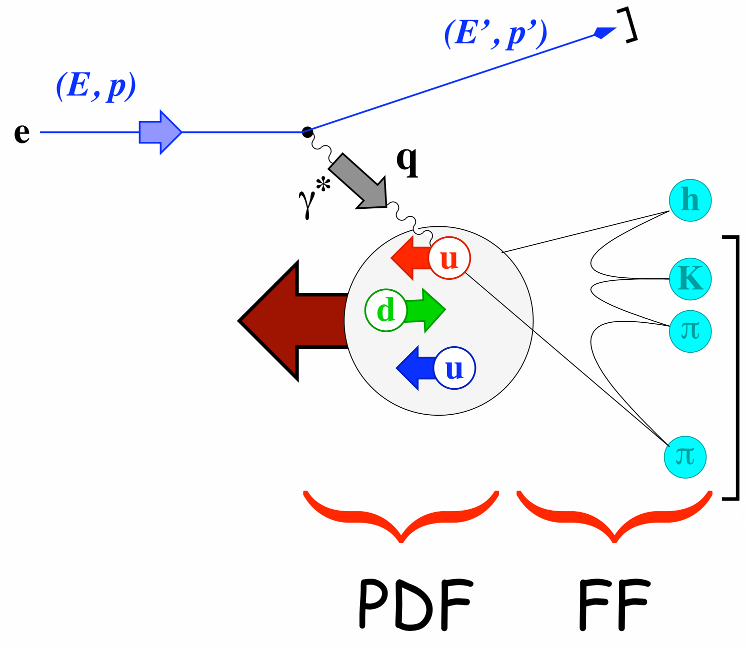
Probing TMDs through fragmentation



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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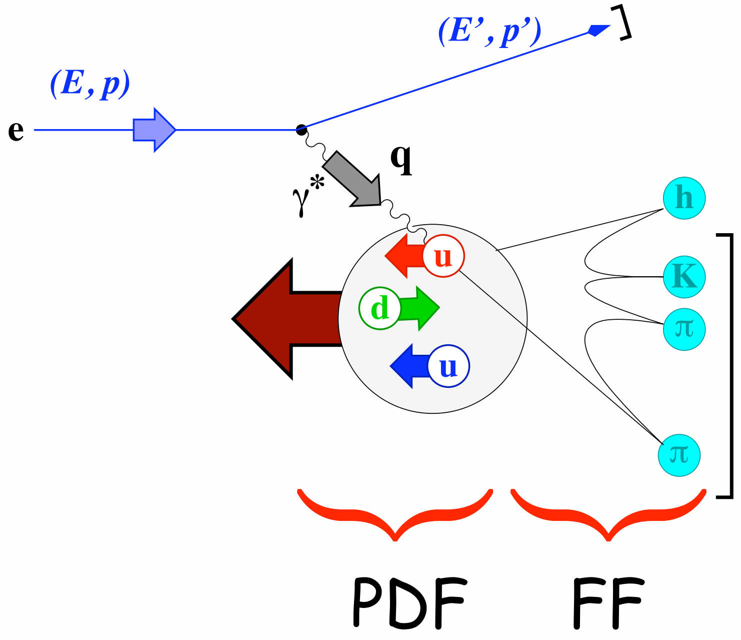

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DiFF: $H_1^{\angle,\,q\to h_1h_2}$

---

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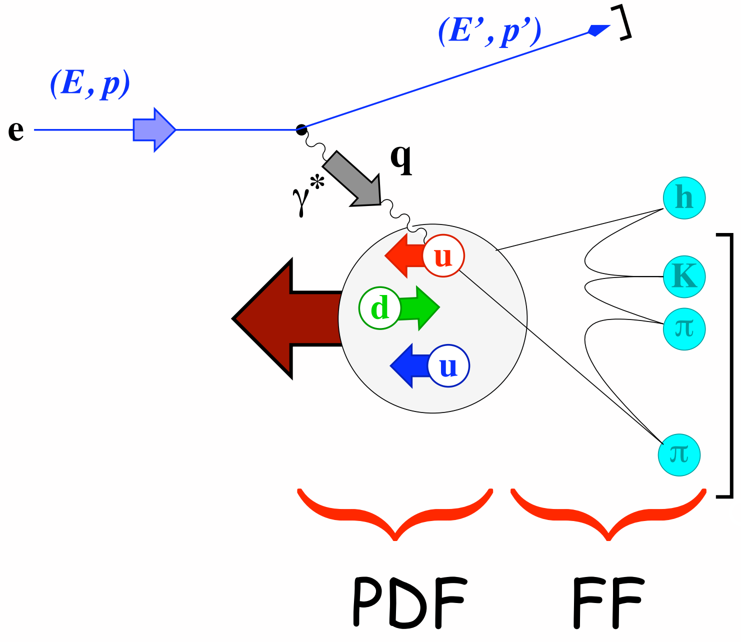
Probing TMDs through fragmentation



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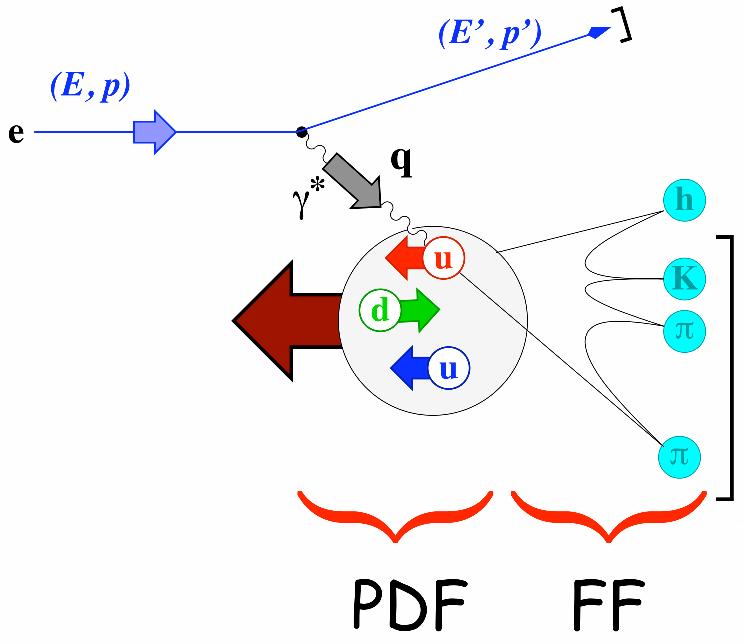

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➟ FFs act as quark flavor-tagger and polarimeter

*) semi-inclusive DIS with unpolarized final state

fragmentation in e^+e^- annihilation

- single-inclusive hadron production,
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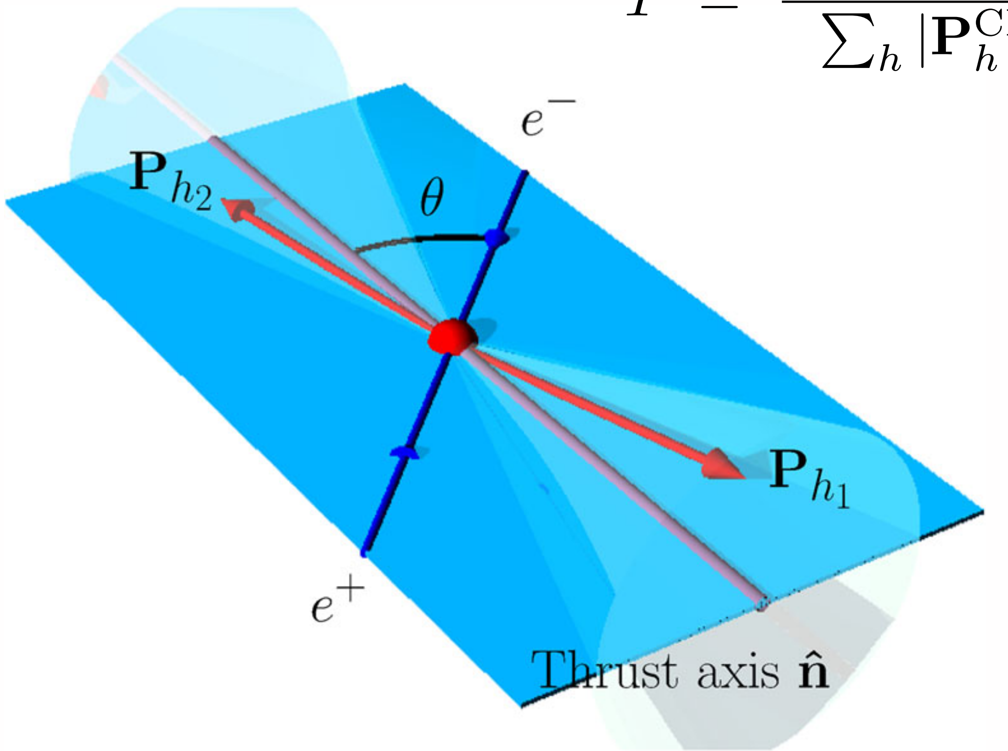
Thrust (axis):

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



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- inclusive “back-to-back” hadron pairs, **$e^+e^- \rightarrow h_1h_2X$**
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- inclusive same-hemisphere hadron pairs, **$e^+e^- \rightarrow h_1h_2X$**
    - dihadron fragmentation

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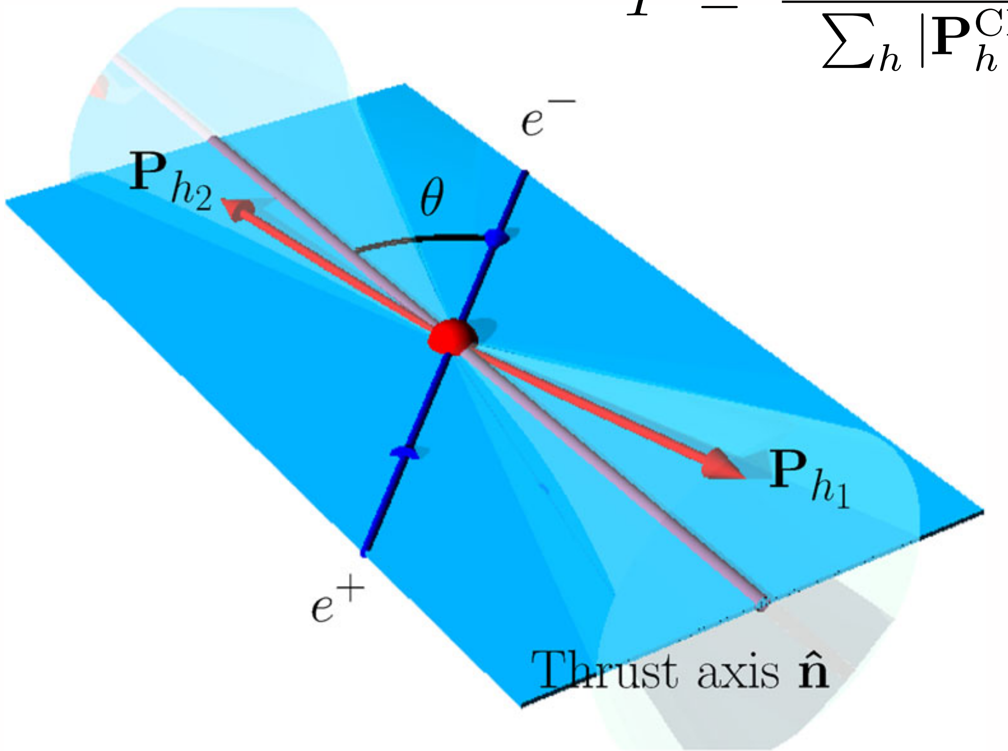
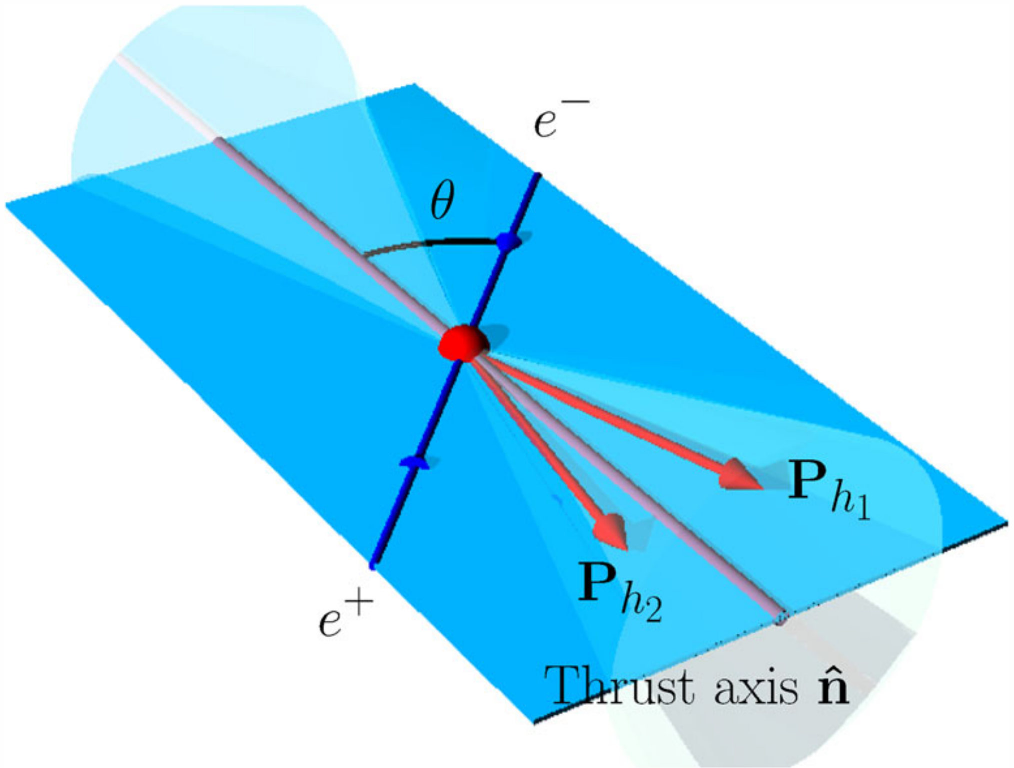


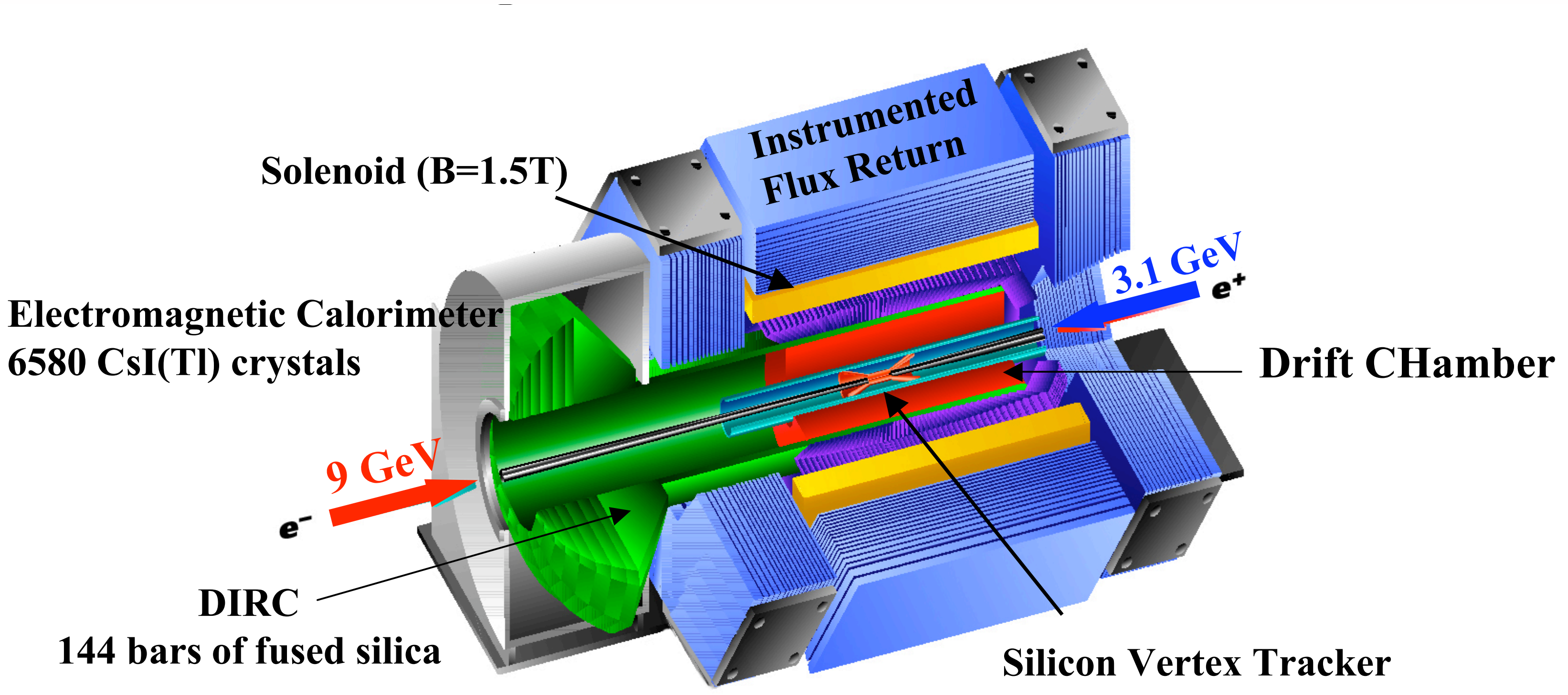


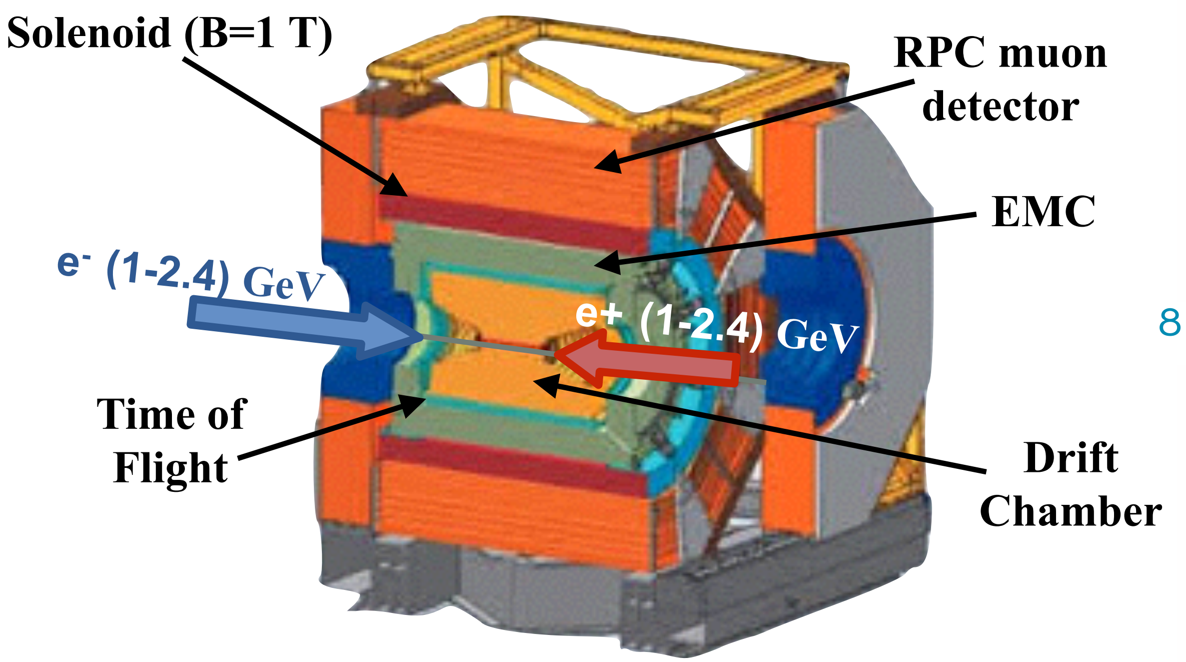
e^+e^- annihilation at BaBar, Belle, and BESIII

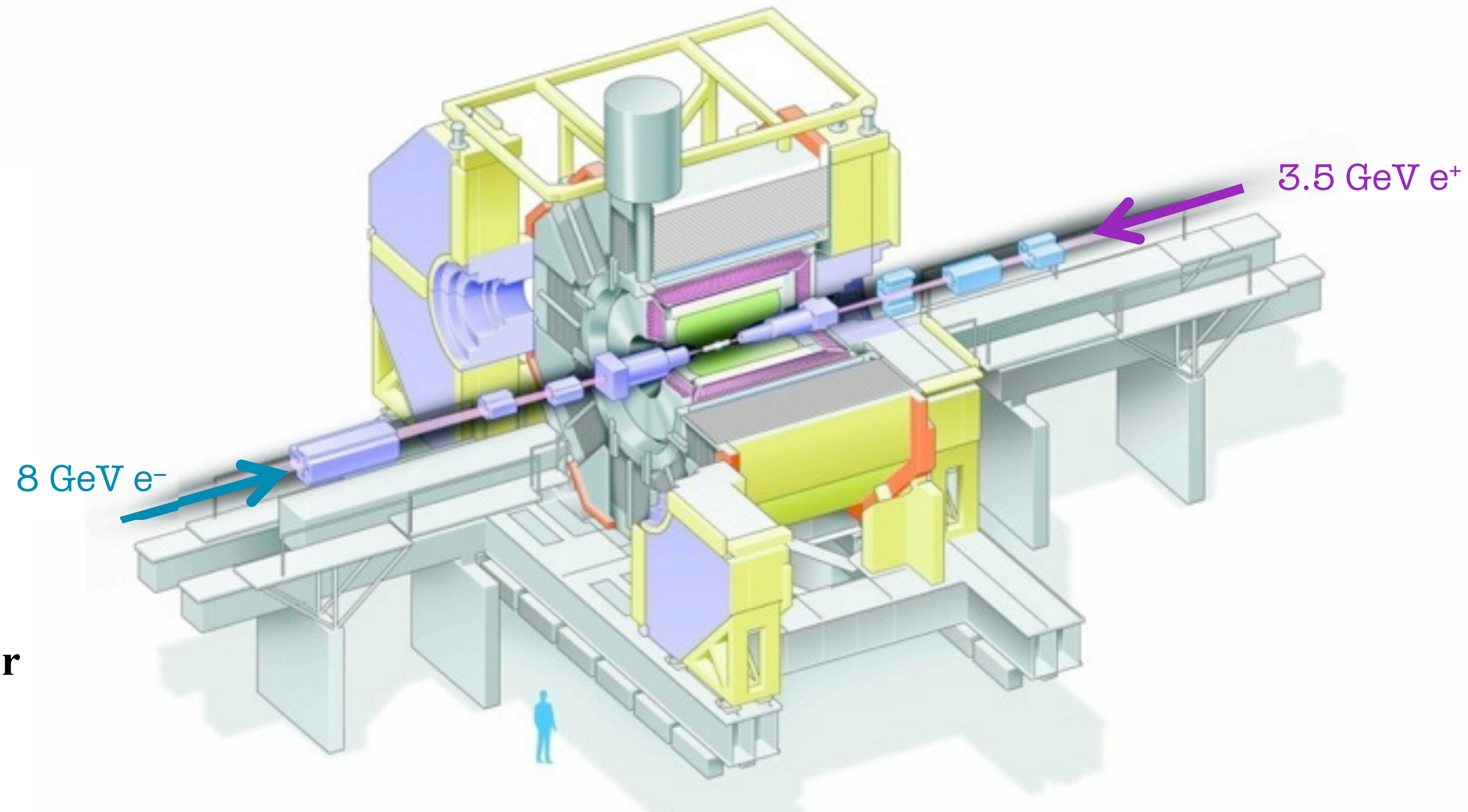
- BaBar/Belle: asymmetric beam-energy e+e- collider near/at Υ(4S) resonance

  (10.58 GeV)

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







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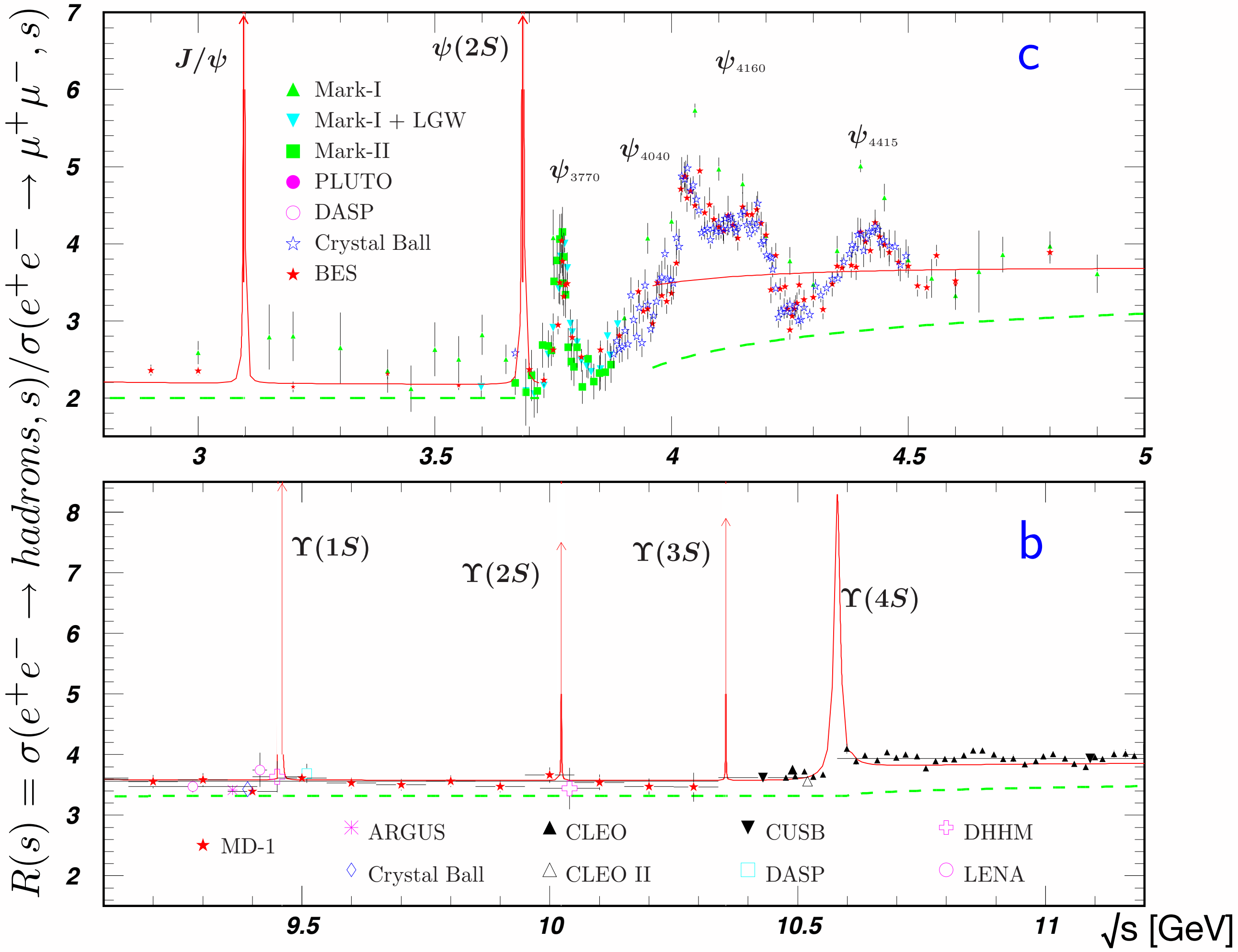
- integrated luminosities:



	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}	
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
  - 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, Υ -> BB, ...]
  - "4π" correction [limited geometric acceptance and selection criteria]
  - QED radiation [initial-state radiation (ISR)]
  - optional: weak-decay removal (e.g., "prompt fragmentation")

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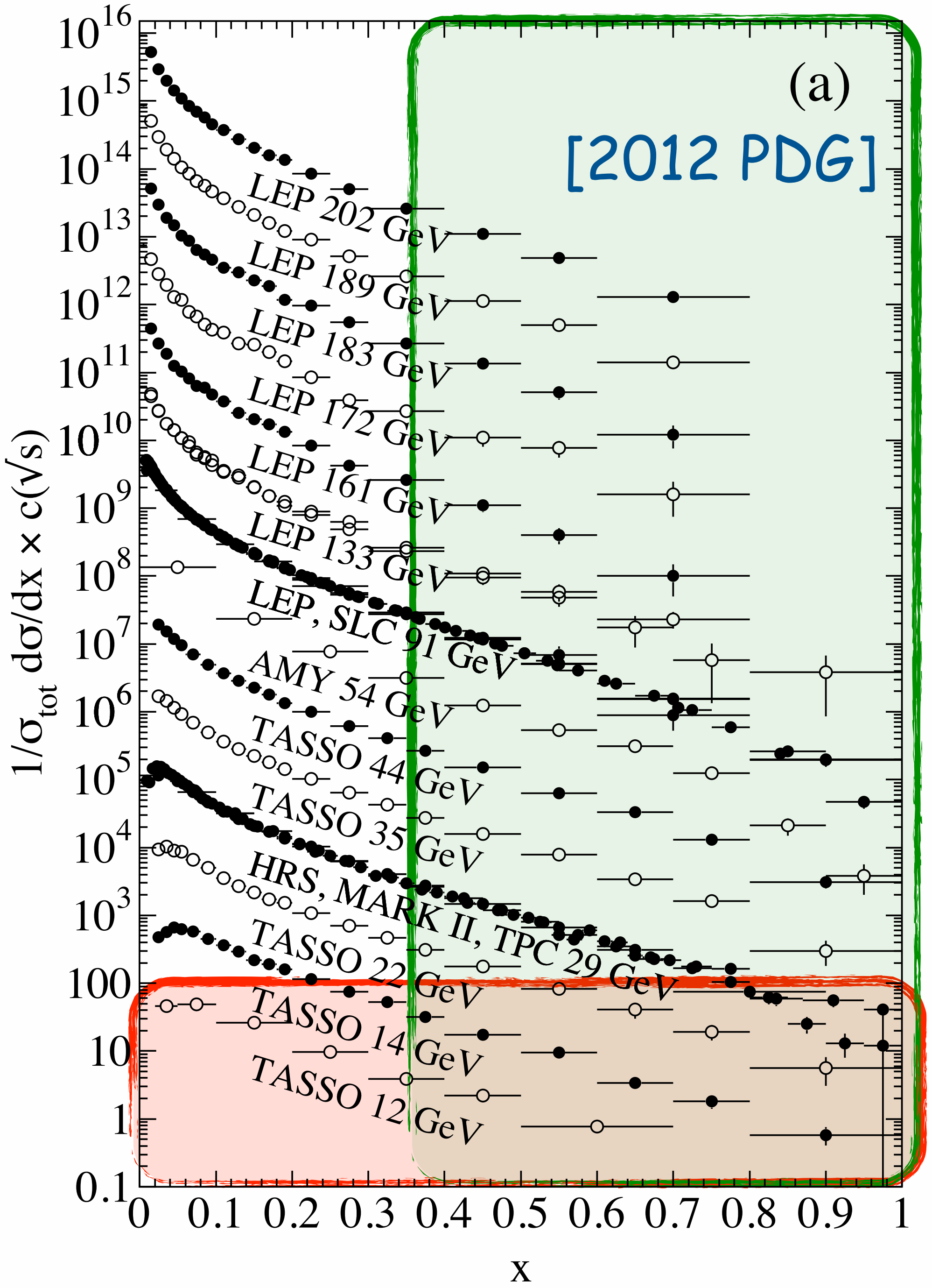
- partially different approaches in different experiments/analyses

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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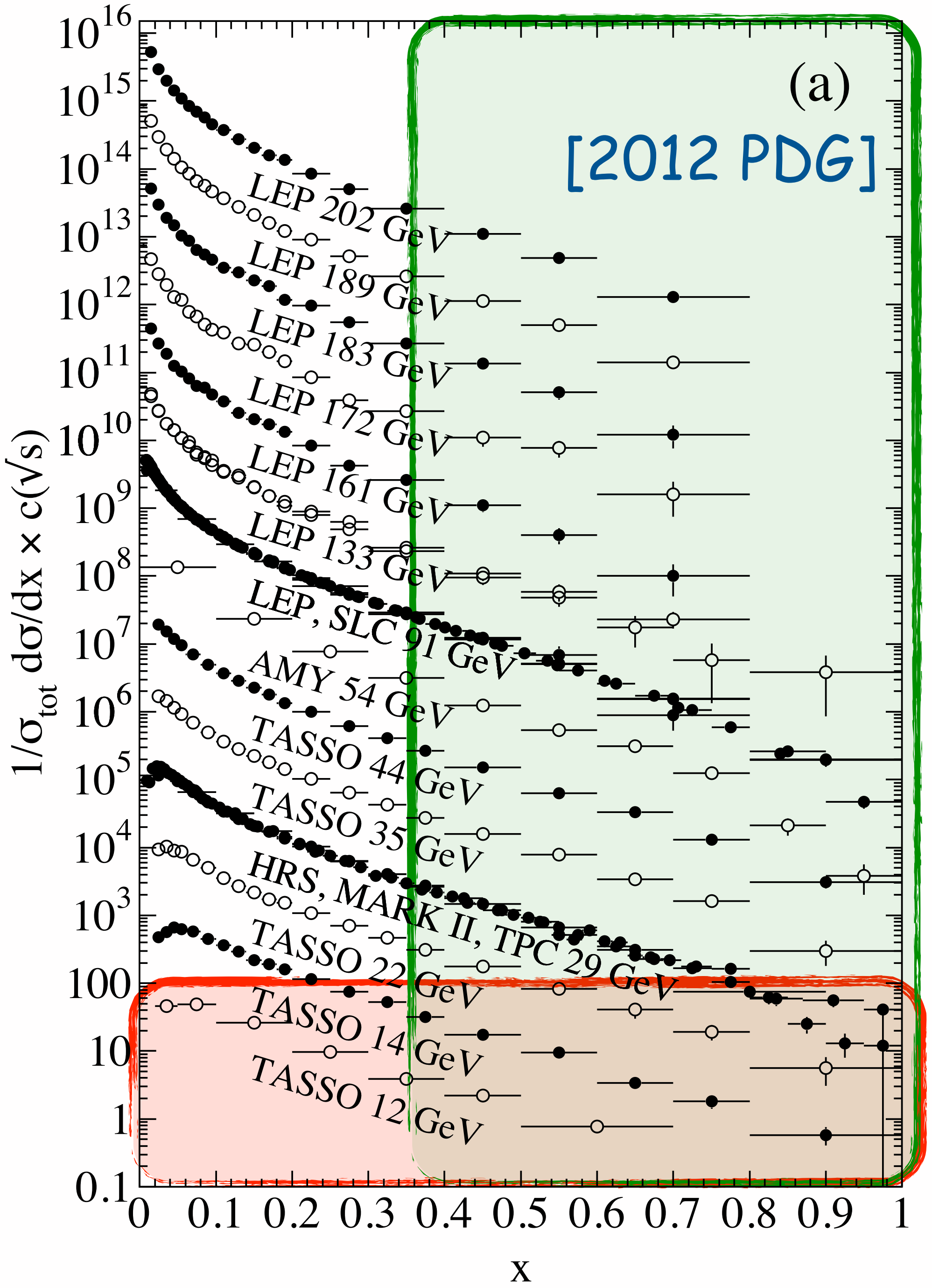

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  - limits analysis of evolution and gluon fragmentation
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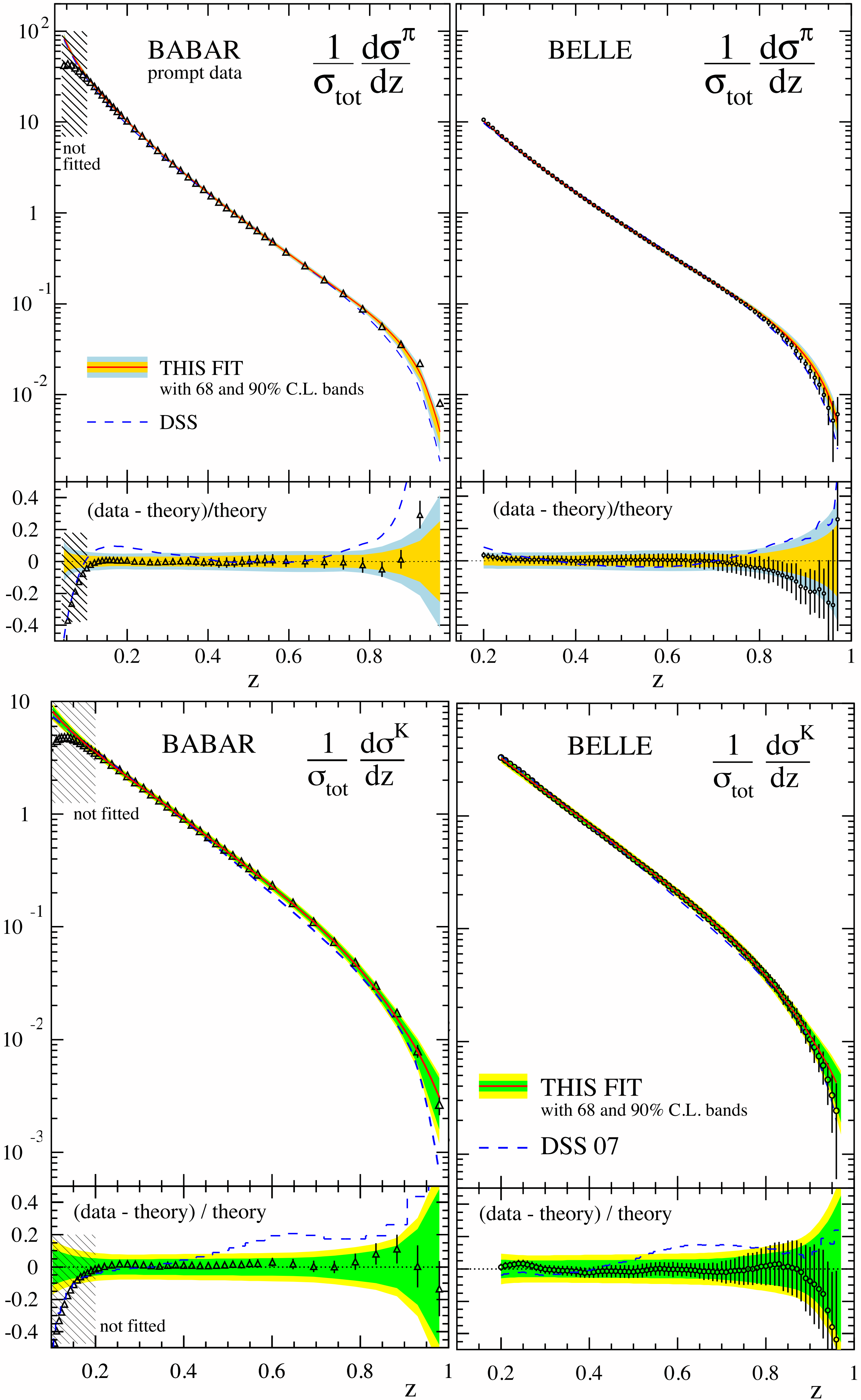
- now, results available from BaBar and Belle:
  - BaBar Collaboration, Phys. Rev. D88 (2013) 032011: **$\pi^\pm$, $K^\pm$, p+p**
  - Belle Collaboration, Phys. Rev. Lett. 111 (2013) 062002: **$\pi^\pm$, $K^\pm$**
  - Belle Collaboration, Phys. Rev. D92 (2015) 092007: **$\pi^\pm$, $K^\pm$, p+p**

single-hadron production

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



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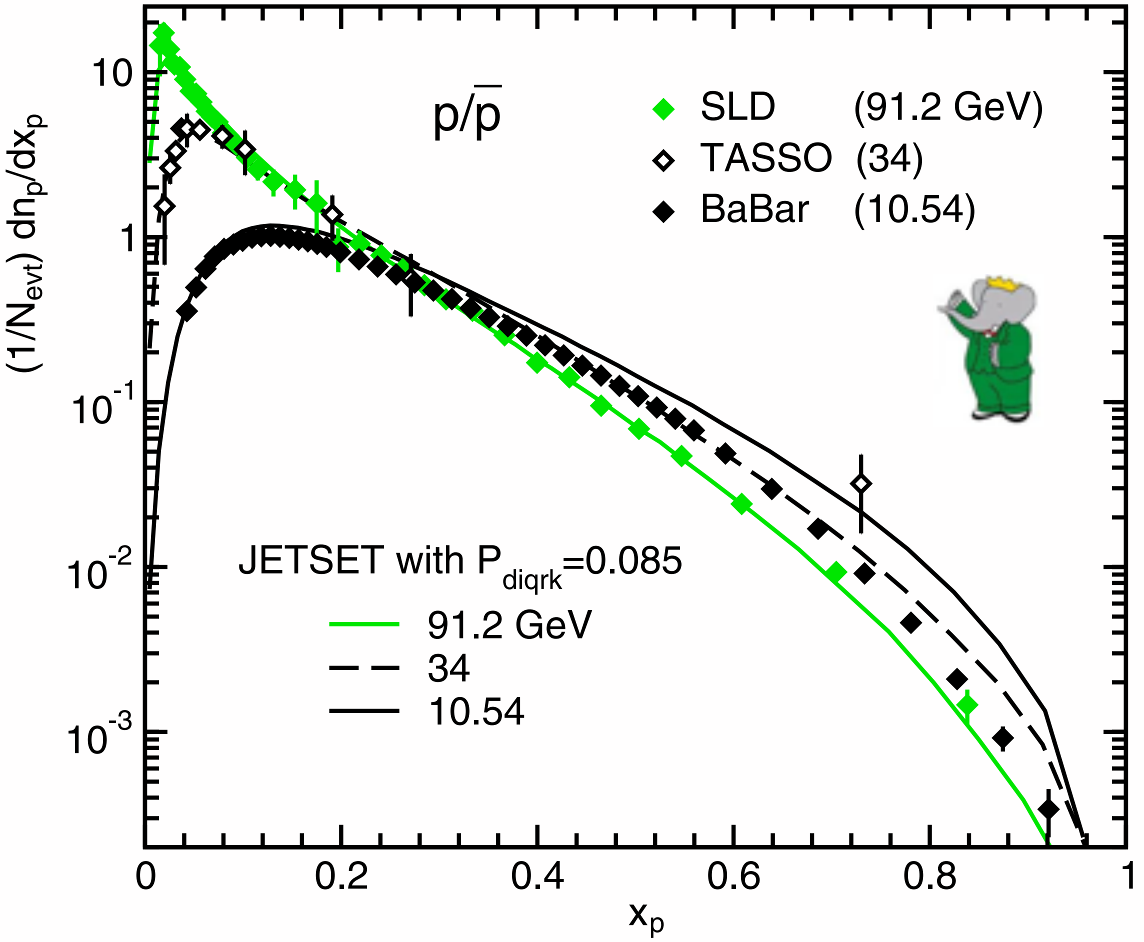
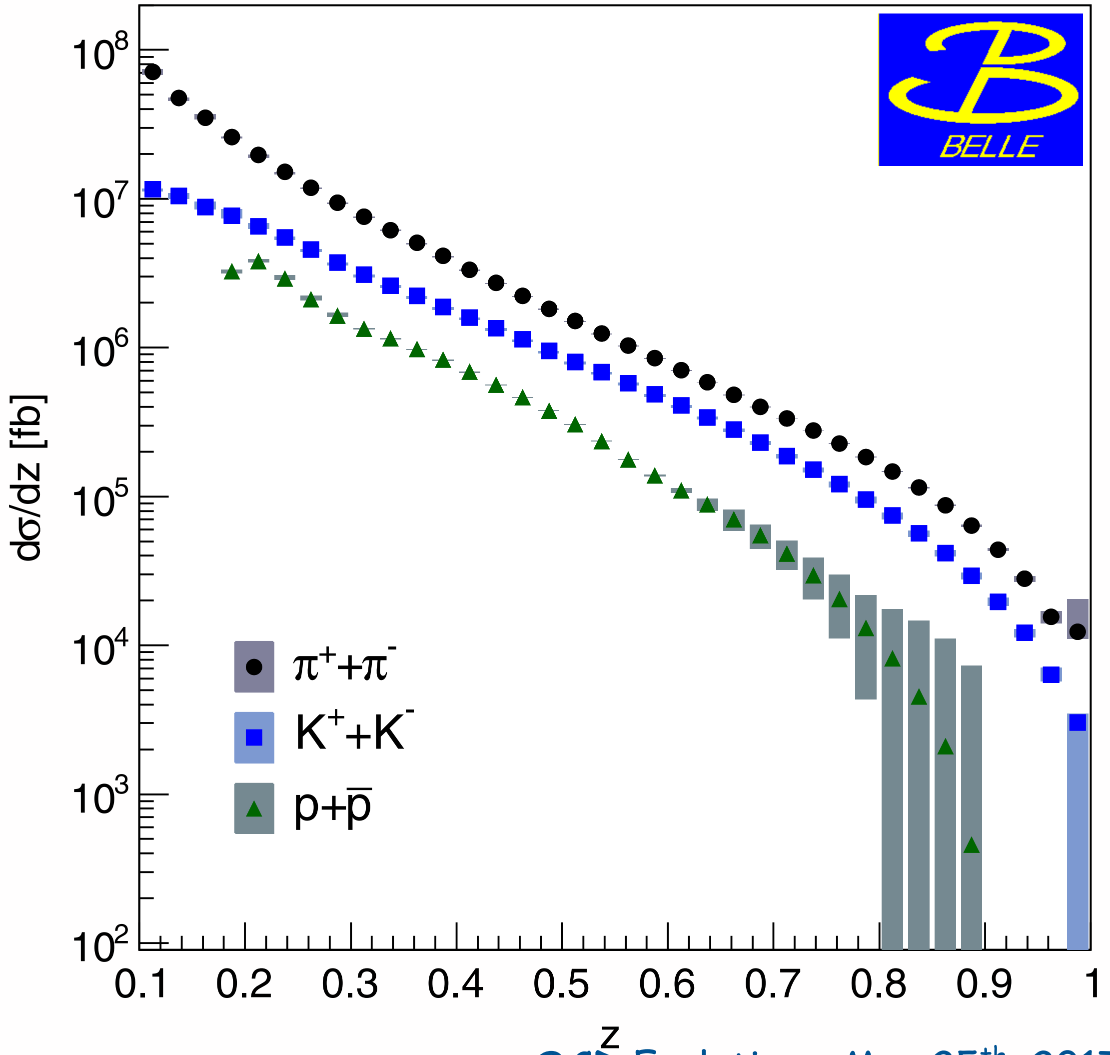
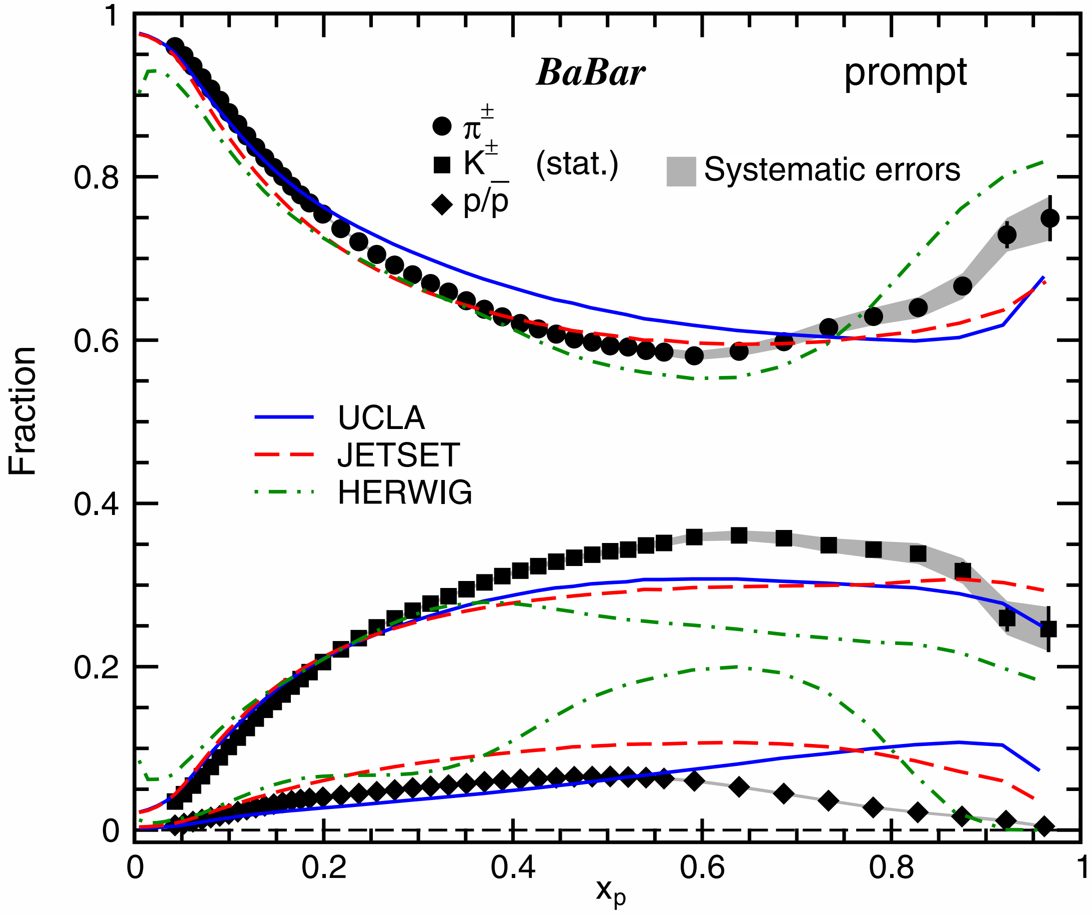
  - slight tension at low-z for BaBar and high-z for Belle
- also available: data for protons and anti-protons
  - not (yet) included in DSS++
  - similar z dependence as pions
  - about ~⅕ of pion cross sections

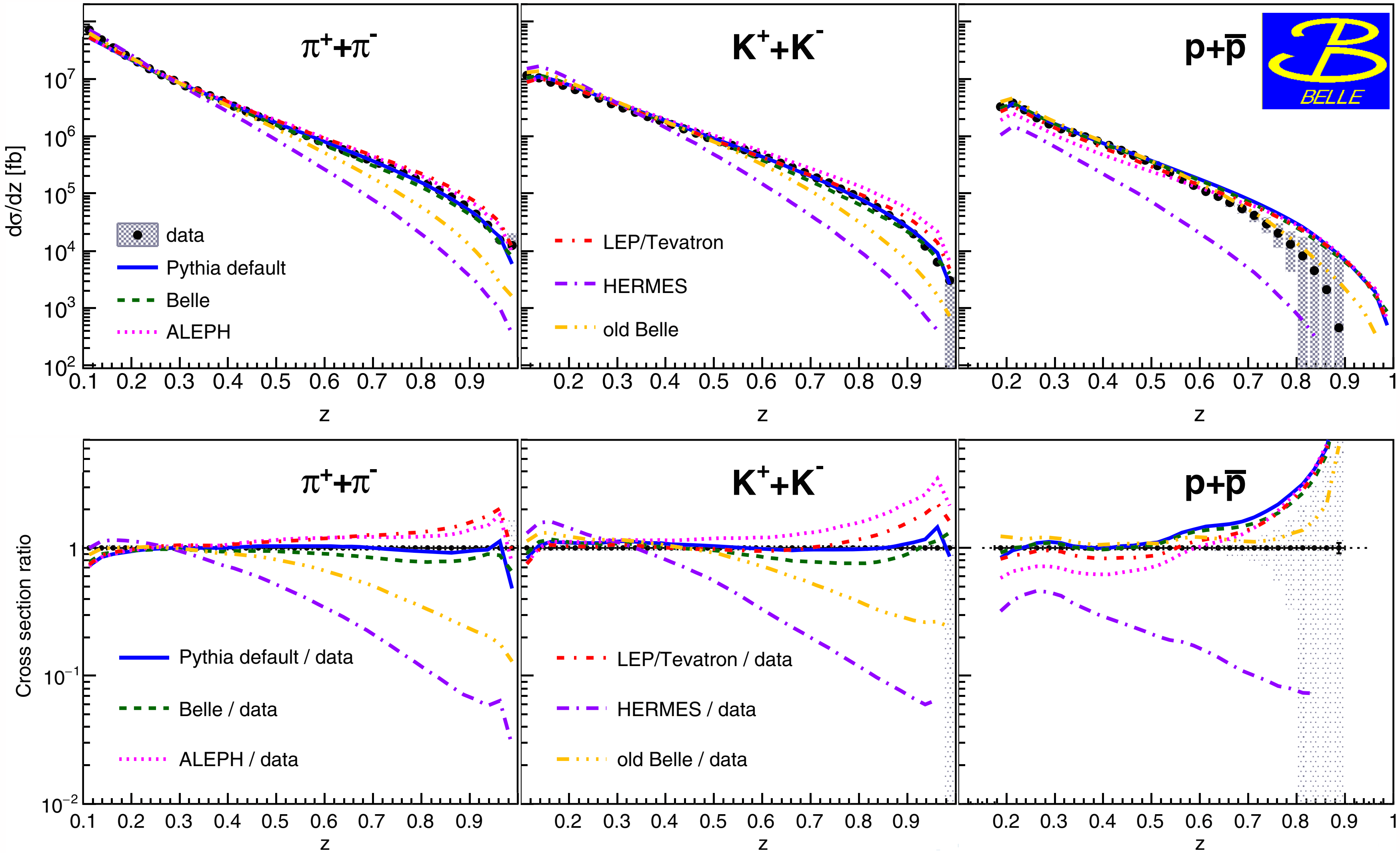




single-hadron production

- 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 2nd hadron in opposite hemisphere to “tag” flavor (& polarization)
  - 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]
  - dihadron fragmentation a la Collins, Heppelmann & Ladinsky [Nucl. Phys. B 420 (1994) 565]; Boer, Jacobs & Radici [Phys. Rev. D 67 (2003) 094003]

Thrust (axis):

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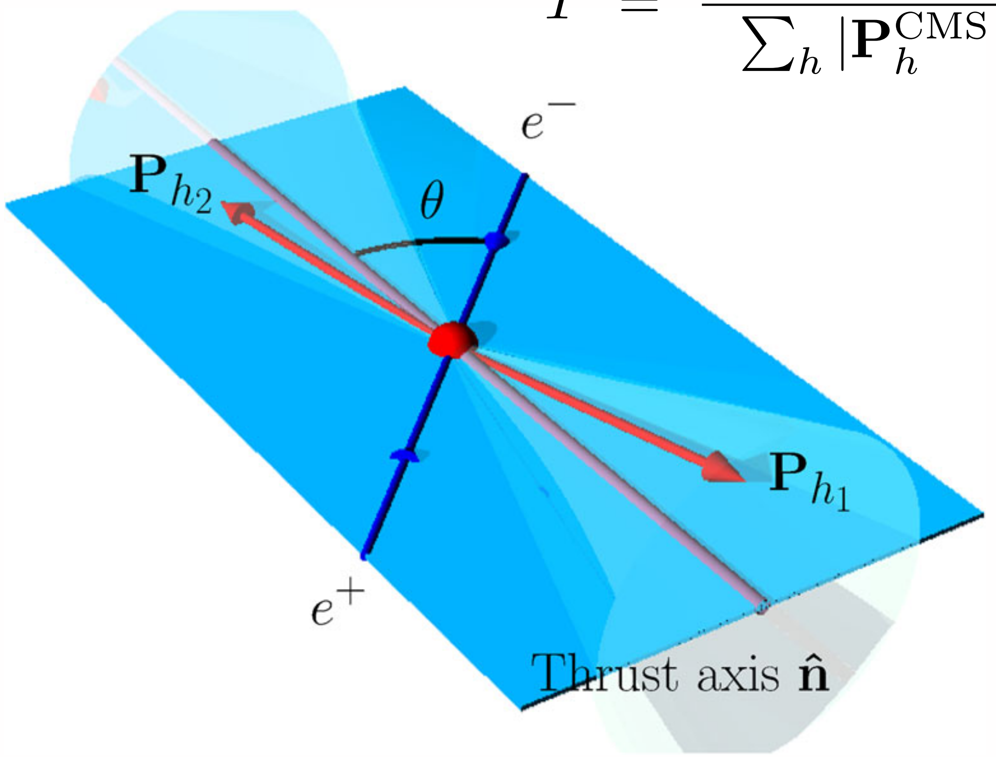
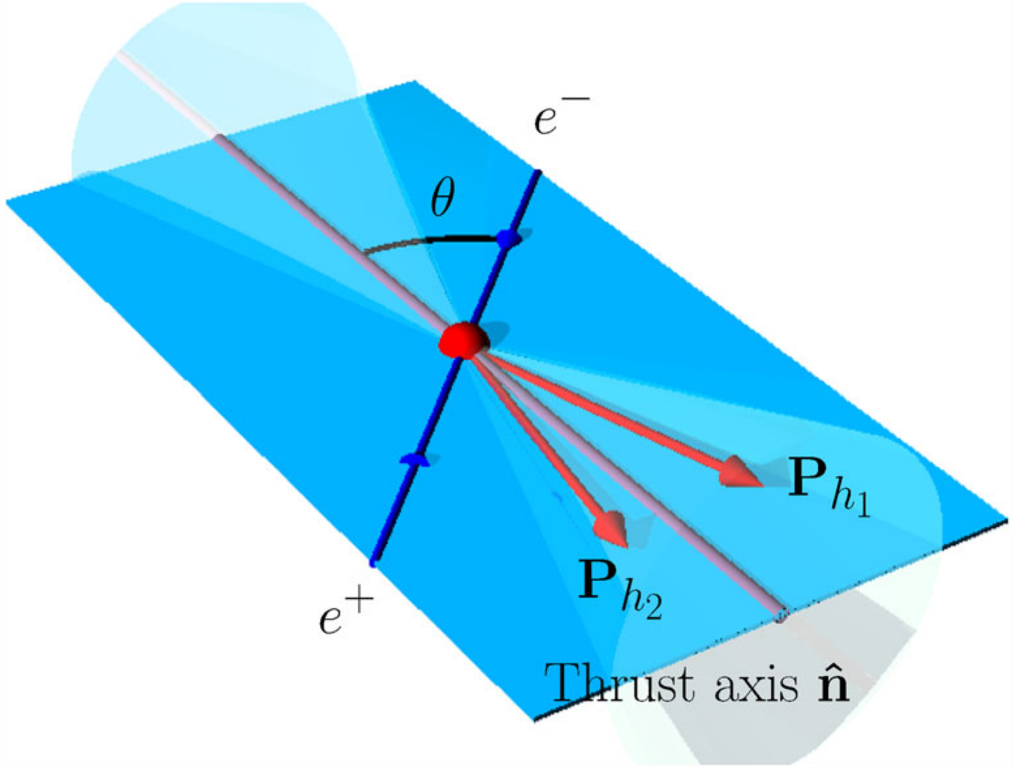
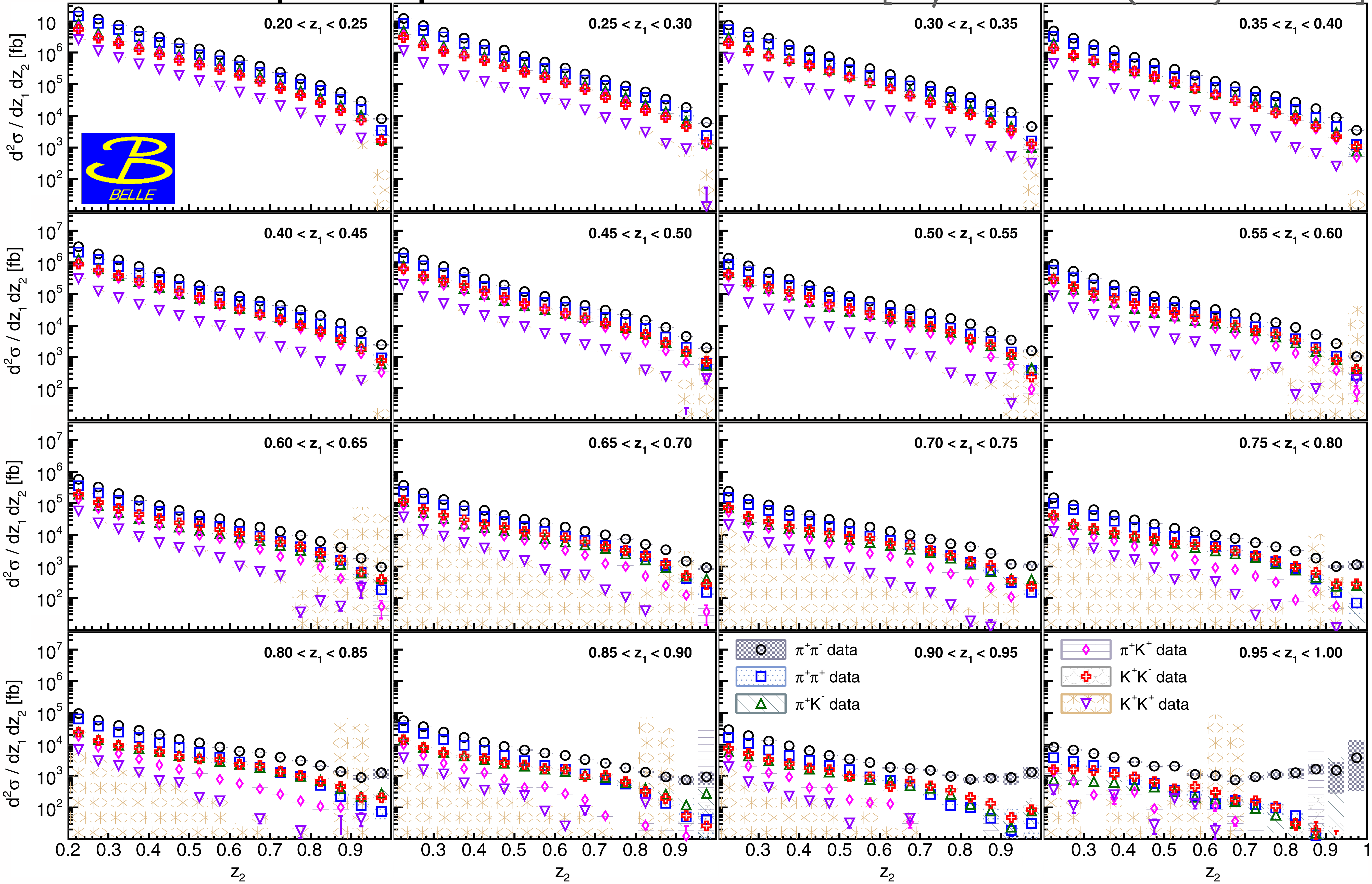




hadron-pair production

no hemisphere preference

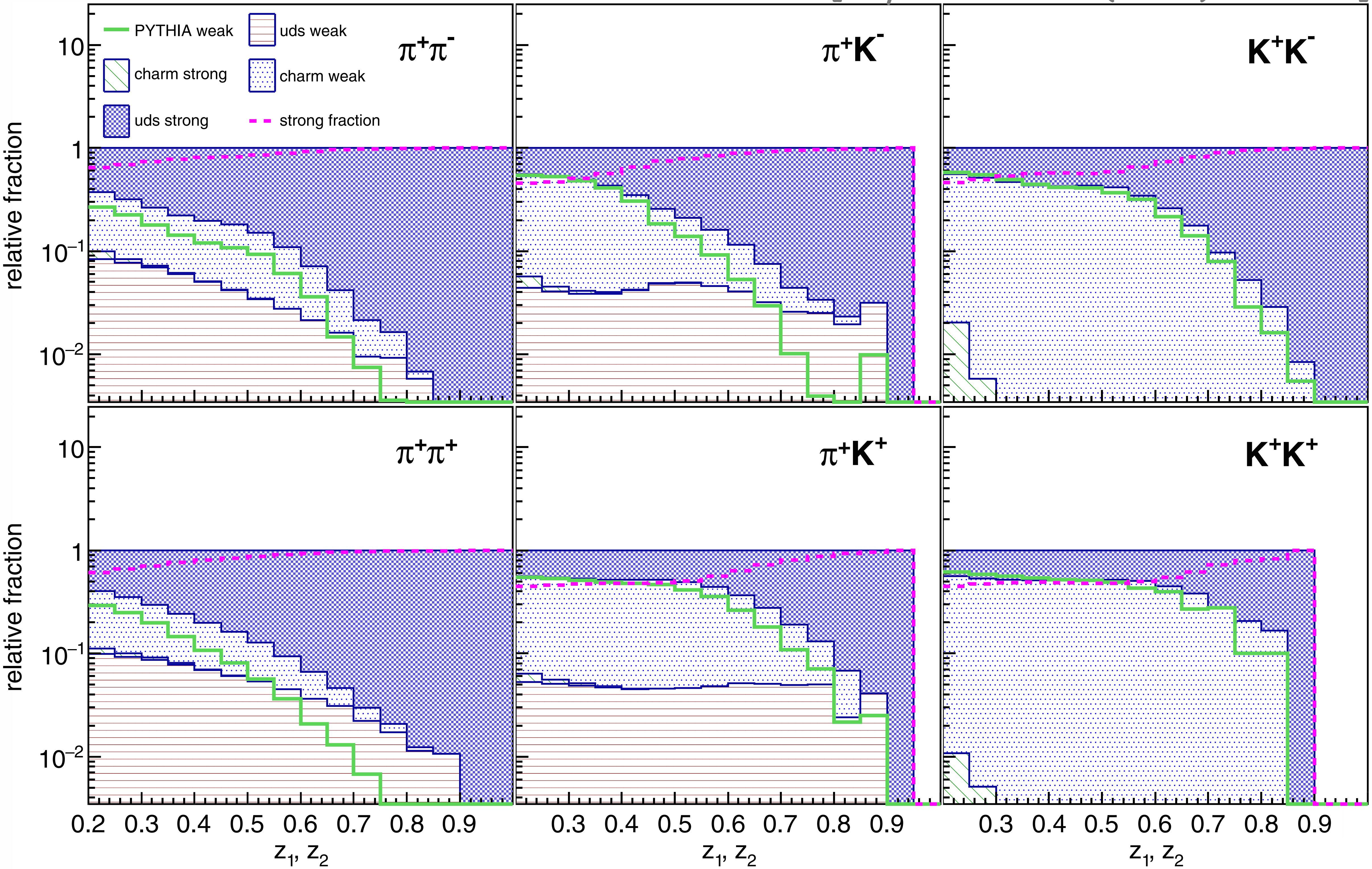
[Phys. Rev. D92 (2015) 092007]



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

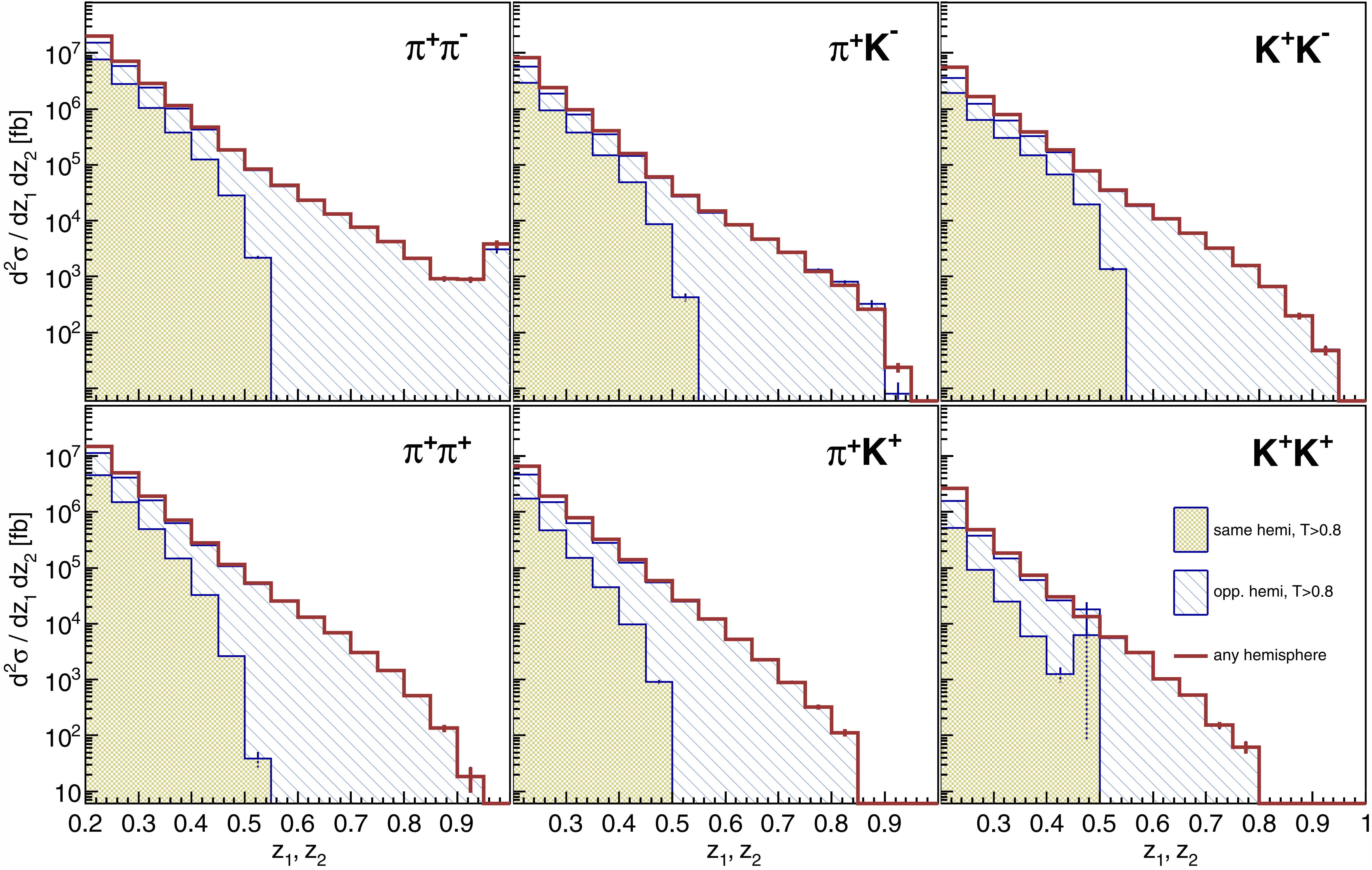
[Phys. Rev. D92 (2015) 092007]



hadron-pairs: topology comparison

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

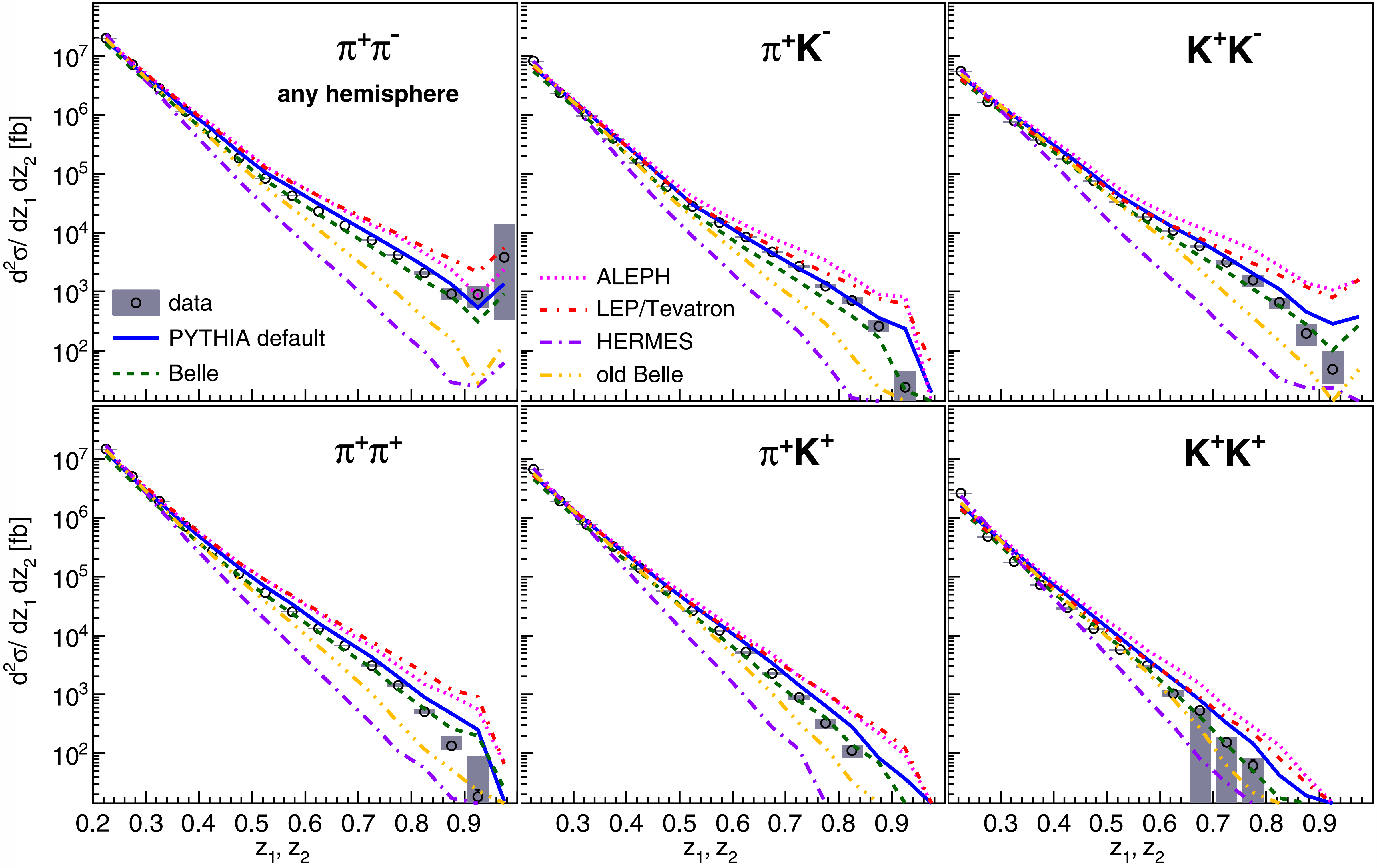
[Phys. Rev. D92 (2015) 092007]



hadron-pairs: comparison with PYTHIA

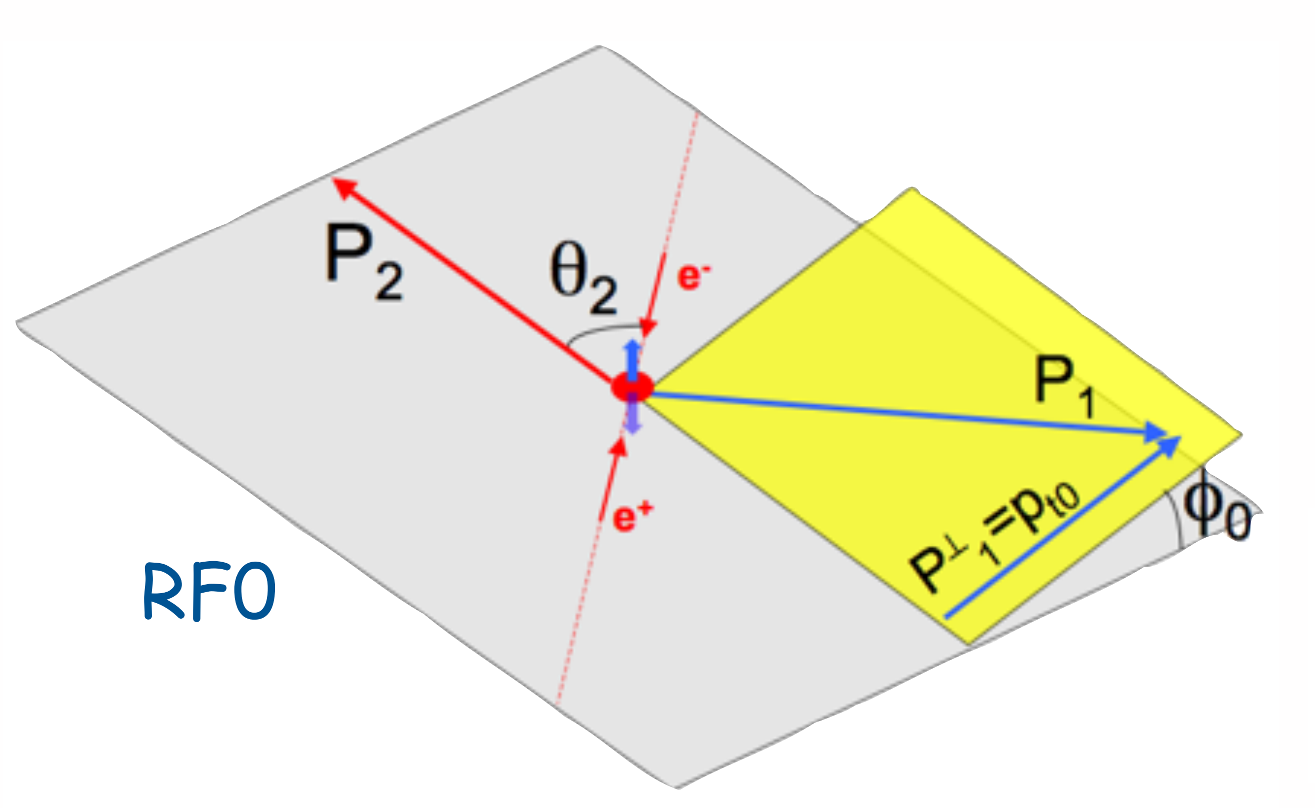
- generally good agreement at low z
  - at large z only present Belle and PYTHIA default tunes satisfactory

[Phys. Rev. D92 (2015) 092007]

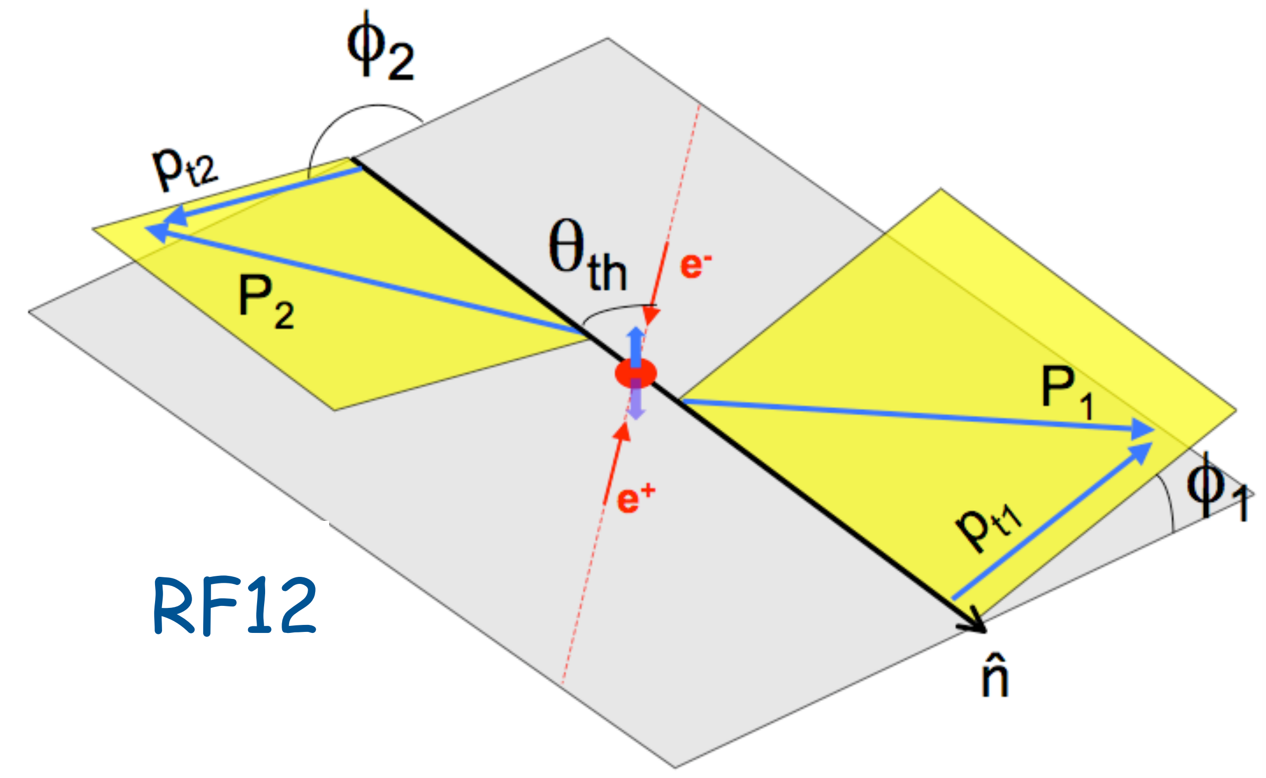


hadron-pairs: angular correlations

- 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



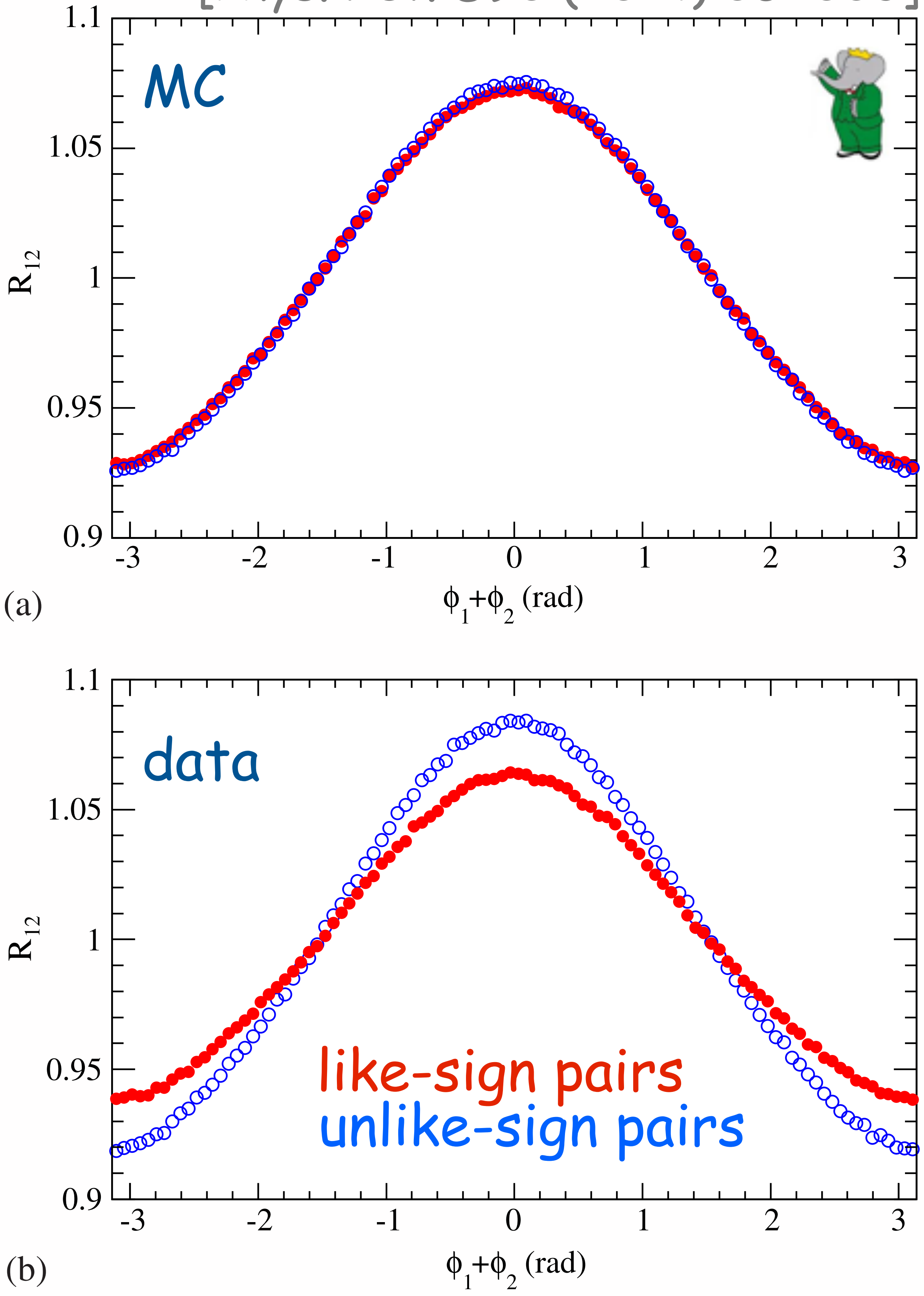
RF12

- 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

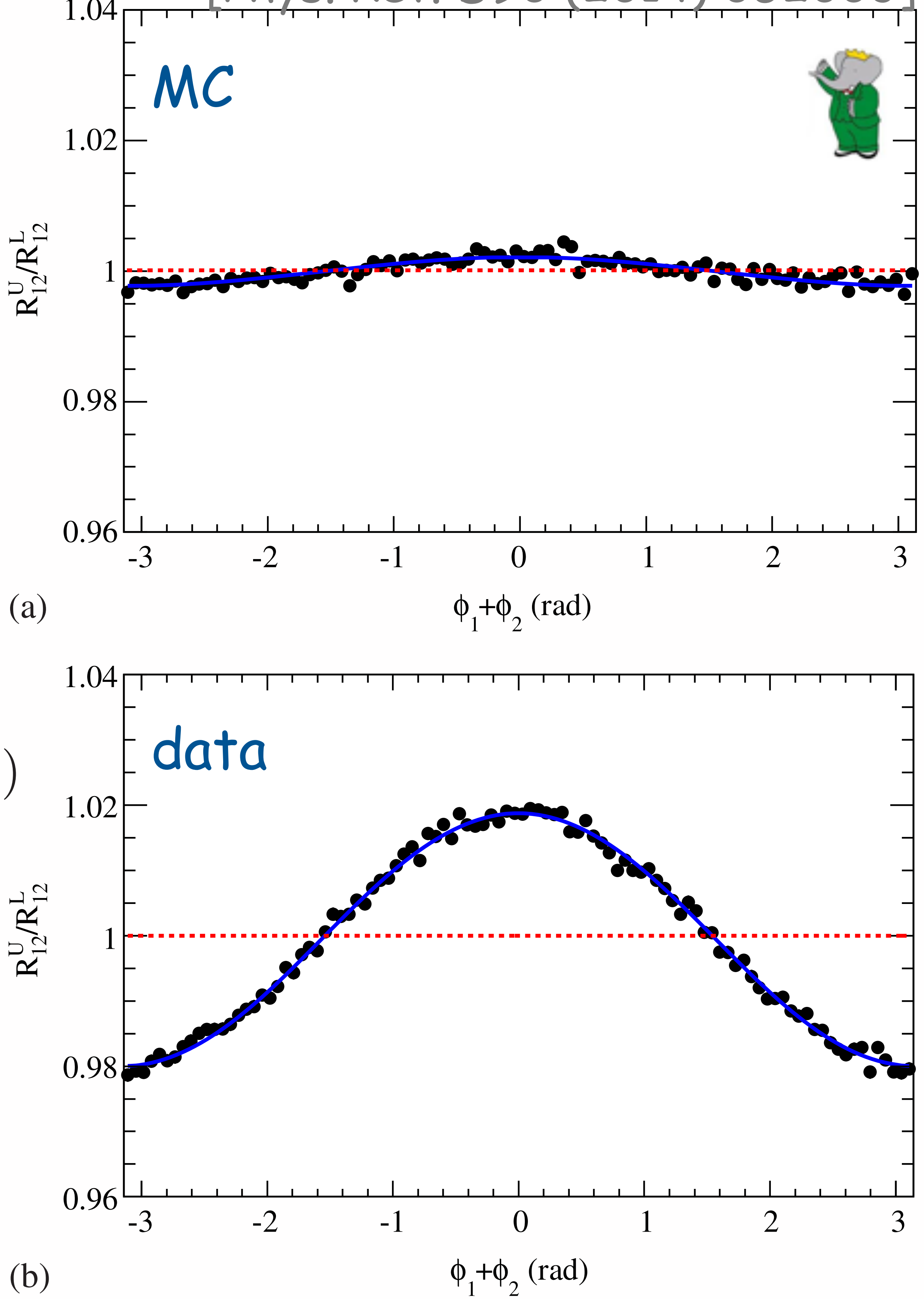
- challenge: large modulations even without Collins effect (e.g., MC)
- construct double ratio of normalized-yield distributions R_{12}, e.g. unlike-/like-sign:

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

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

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

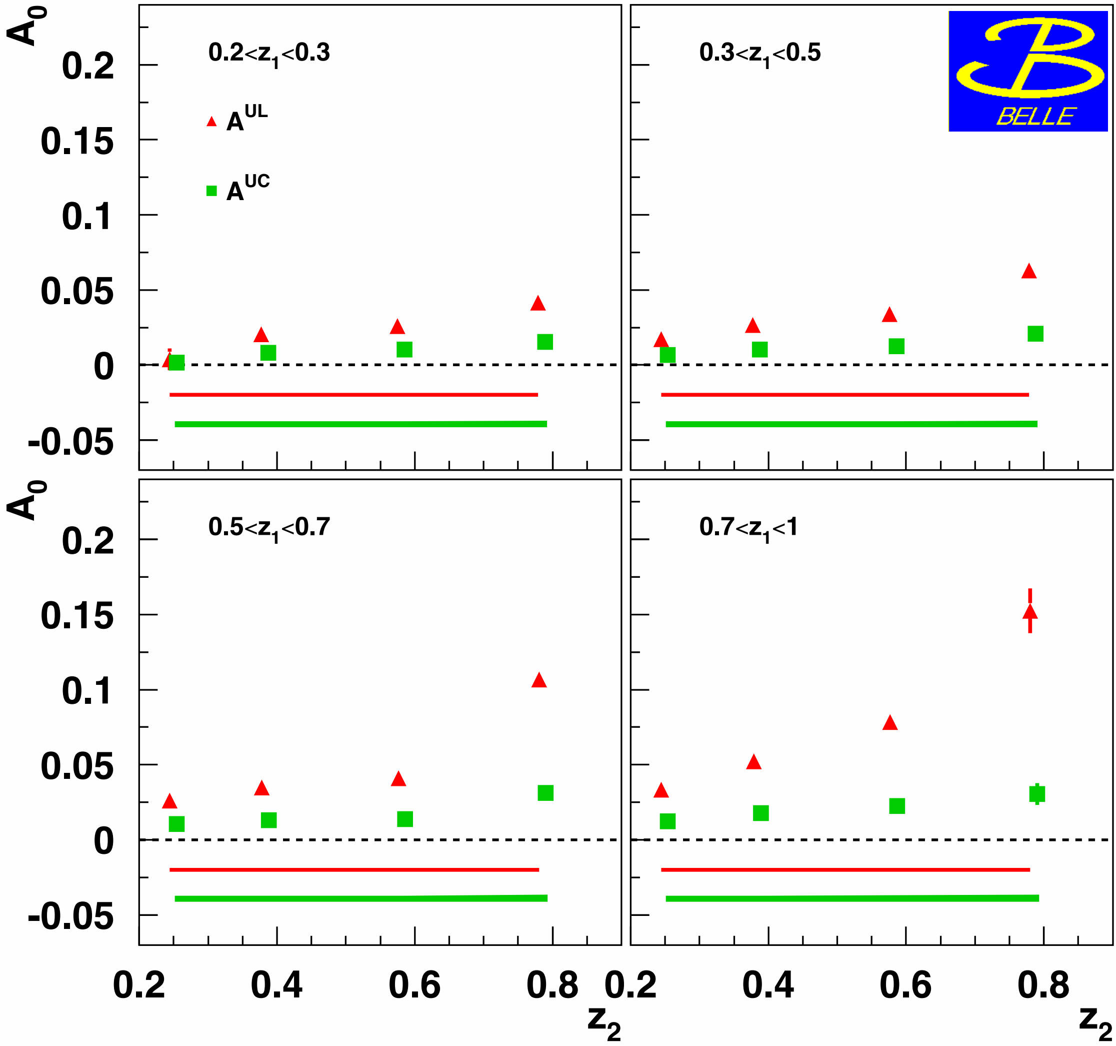
[Phys. Rev. D90 (2014) 052003]



Collins asymmetries (RF0)

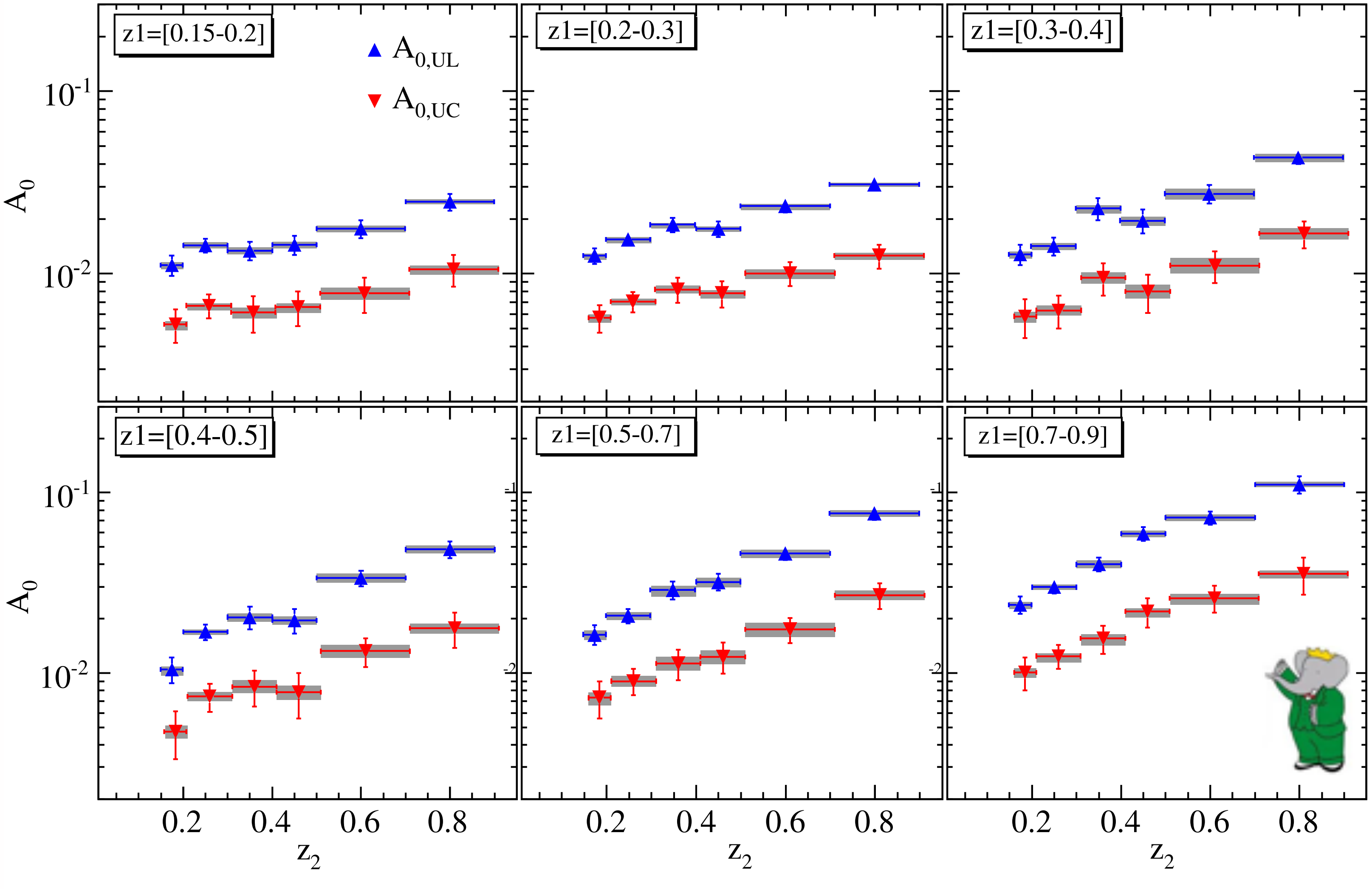
- first measurement of Collins asymmetries by Belle [PRL 96 (2006) 232002, PRD 78 (2008) 032011, PRD 86 (2012) 039905(E)]

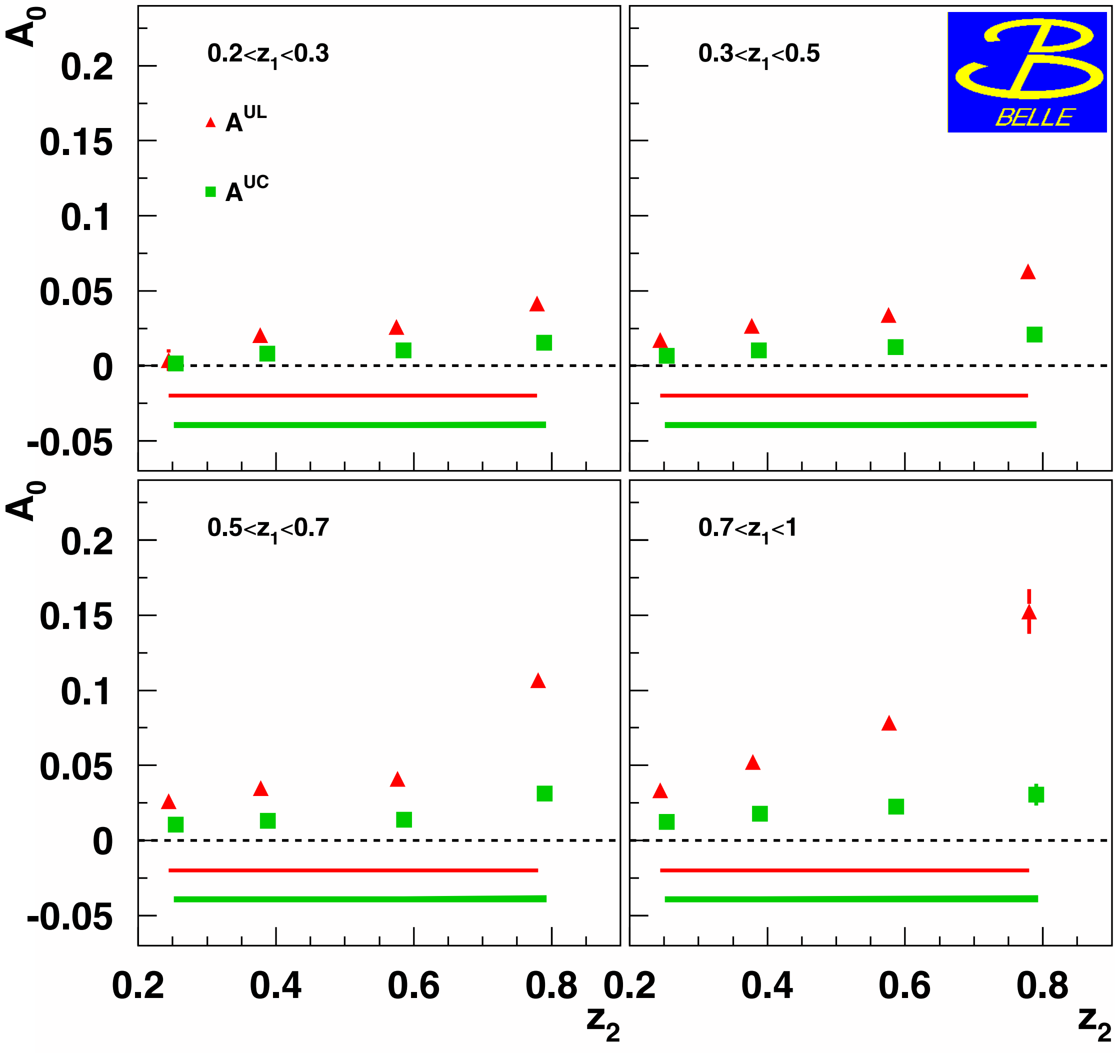
  - significant asymmetries rising with z
  - used for first transversity and Collins FF extractions



Collins asymmetries (RF0)

[Phys. Rev. D90 (2014) 052003]

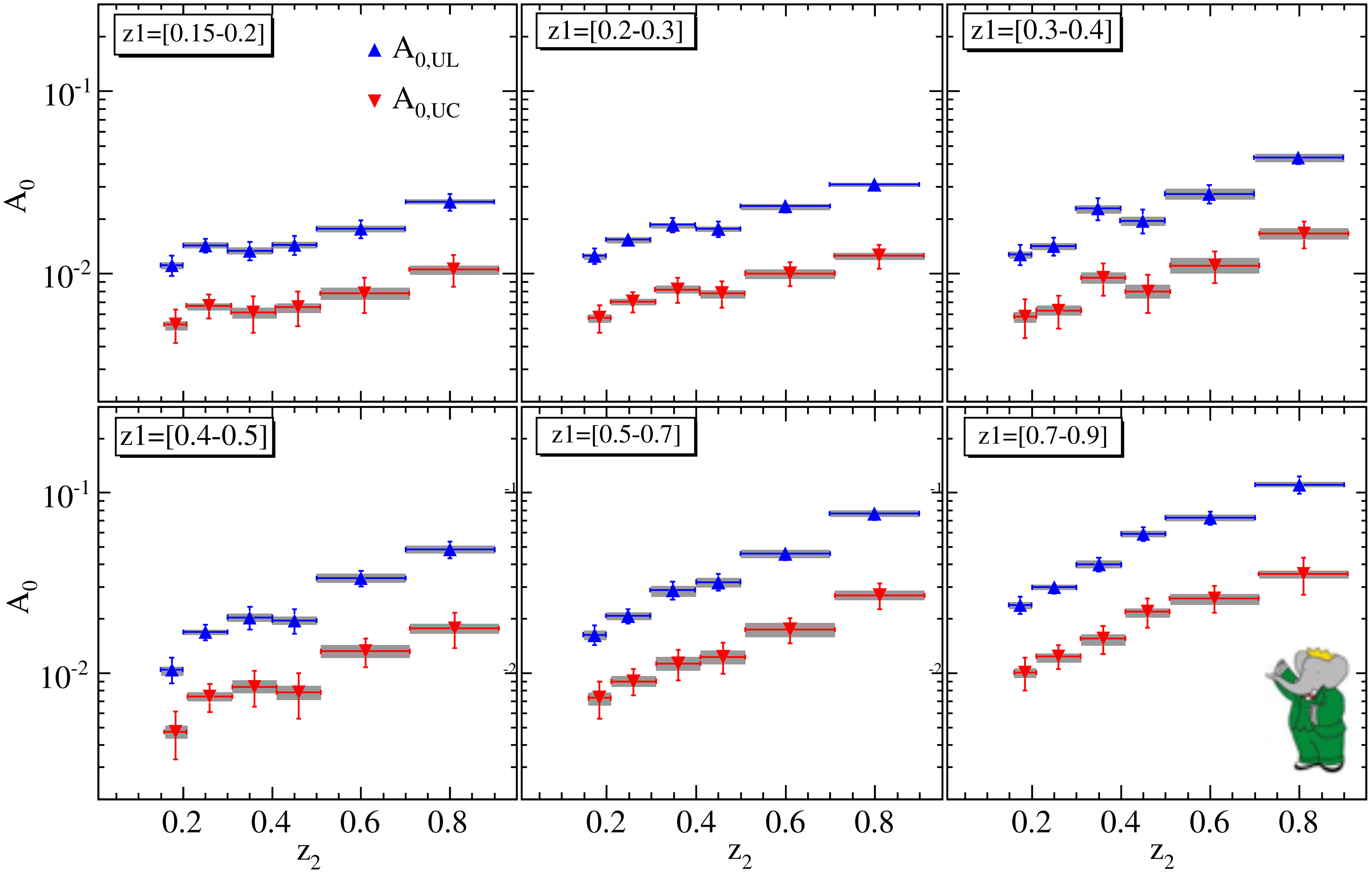


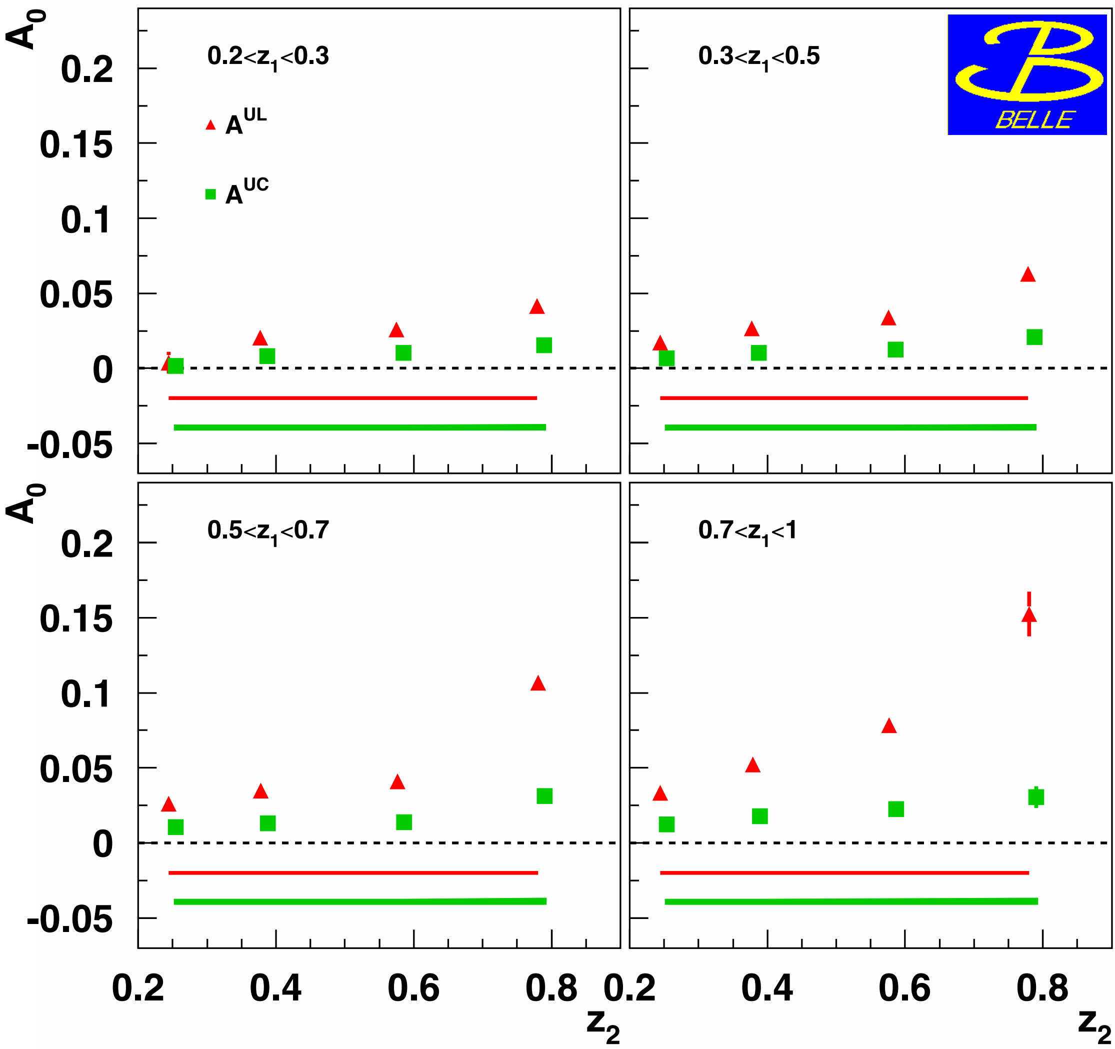


- BaBar results [PRD 90 (2014) 052003] consistent with Belle

Collins asymmetries (RF0)

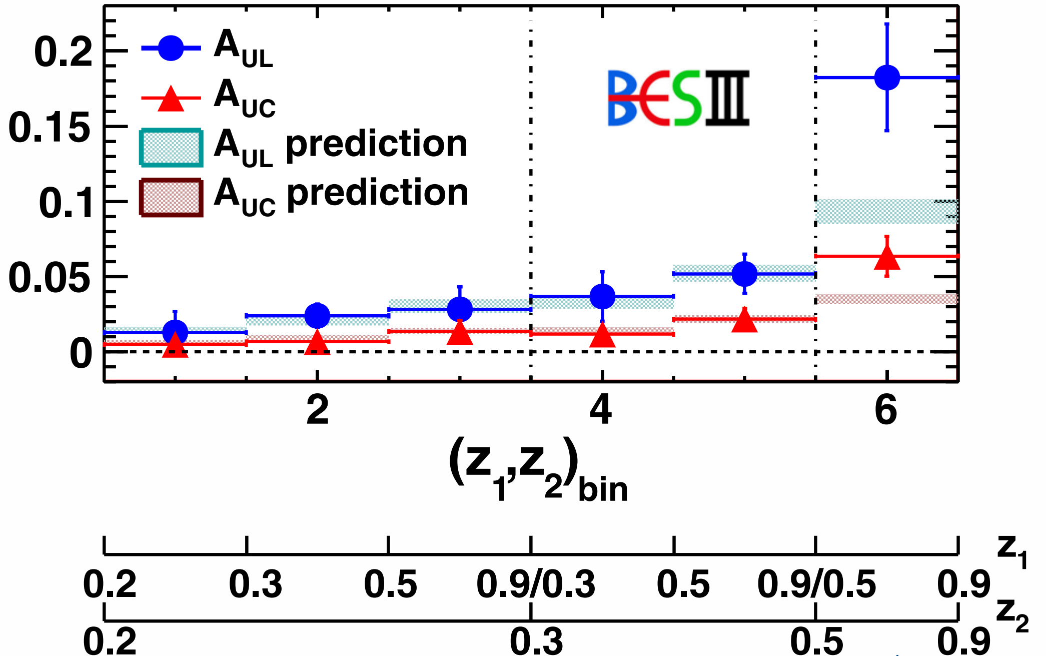
[Phys. Rev. D90 (2014) 052003]



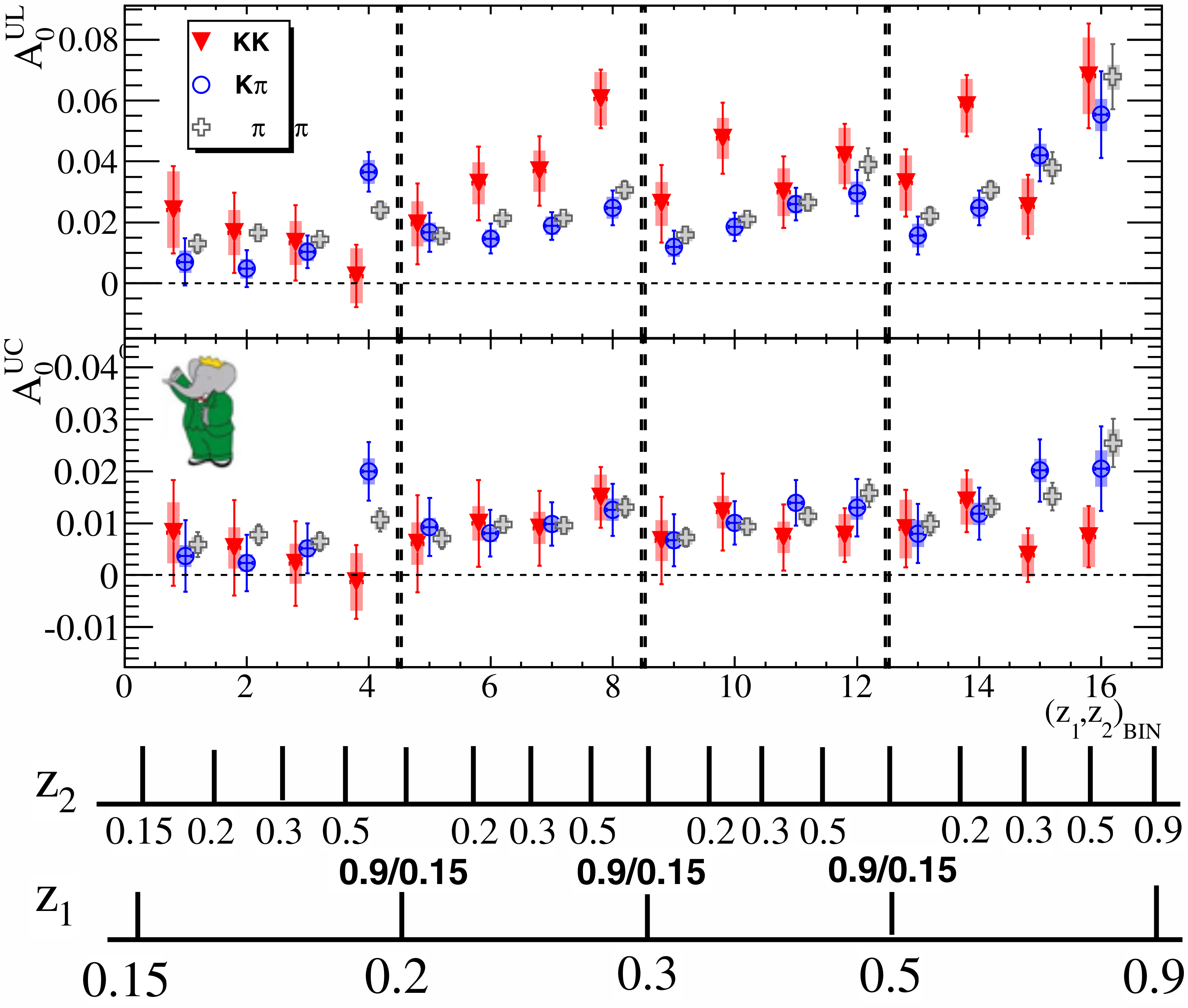


- **BaBar results** [PRD 90 (2014) 052003] consistent with Belle

- **BESIII** [PRL 116 (2016) 042001] (at smaller s) consistent with TMD evolution [Z.-B. Kang et al., PRD 93 (2016) 014009]

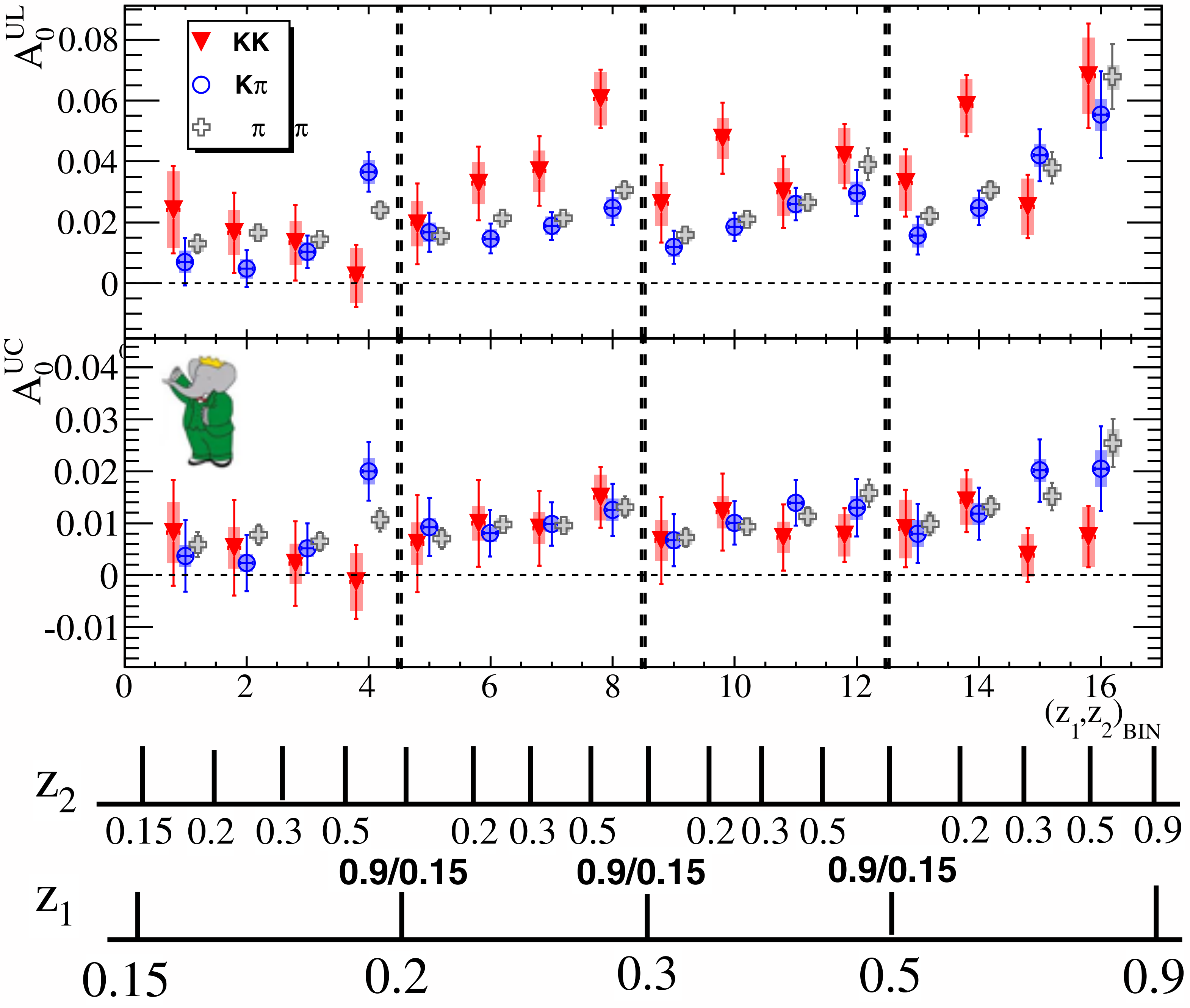


Collins asymmetries - going further

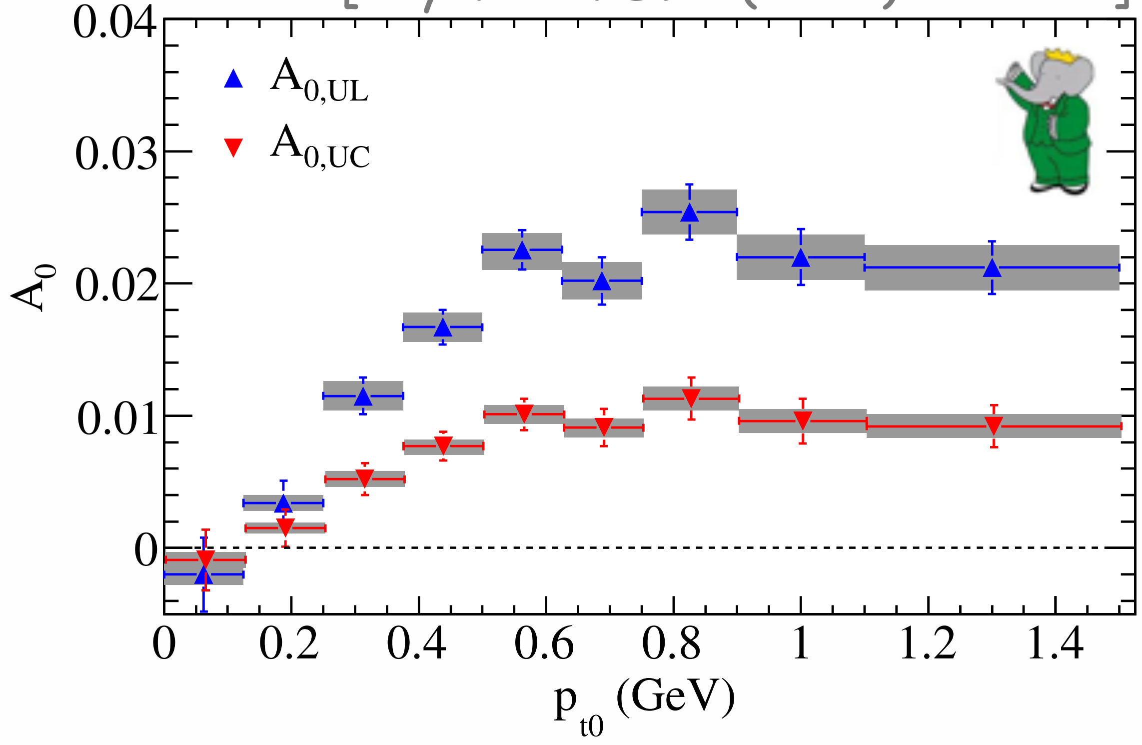


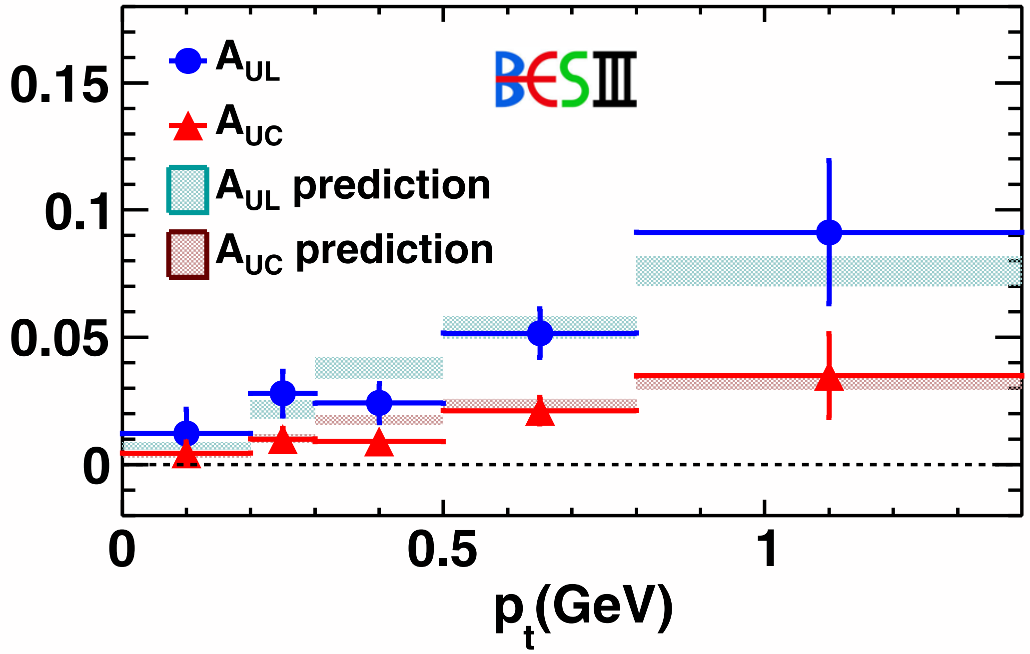
- even larger effects seen for kaon pairs

Collins asymmetries - going further



[Phys. Rev. D90 (2014) 052003]





[PRL 116 (2016) 042001]

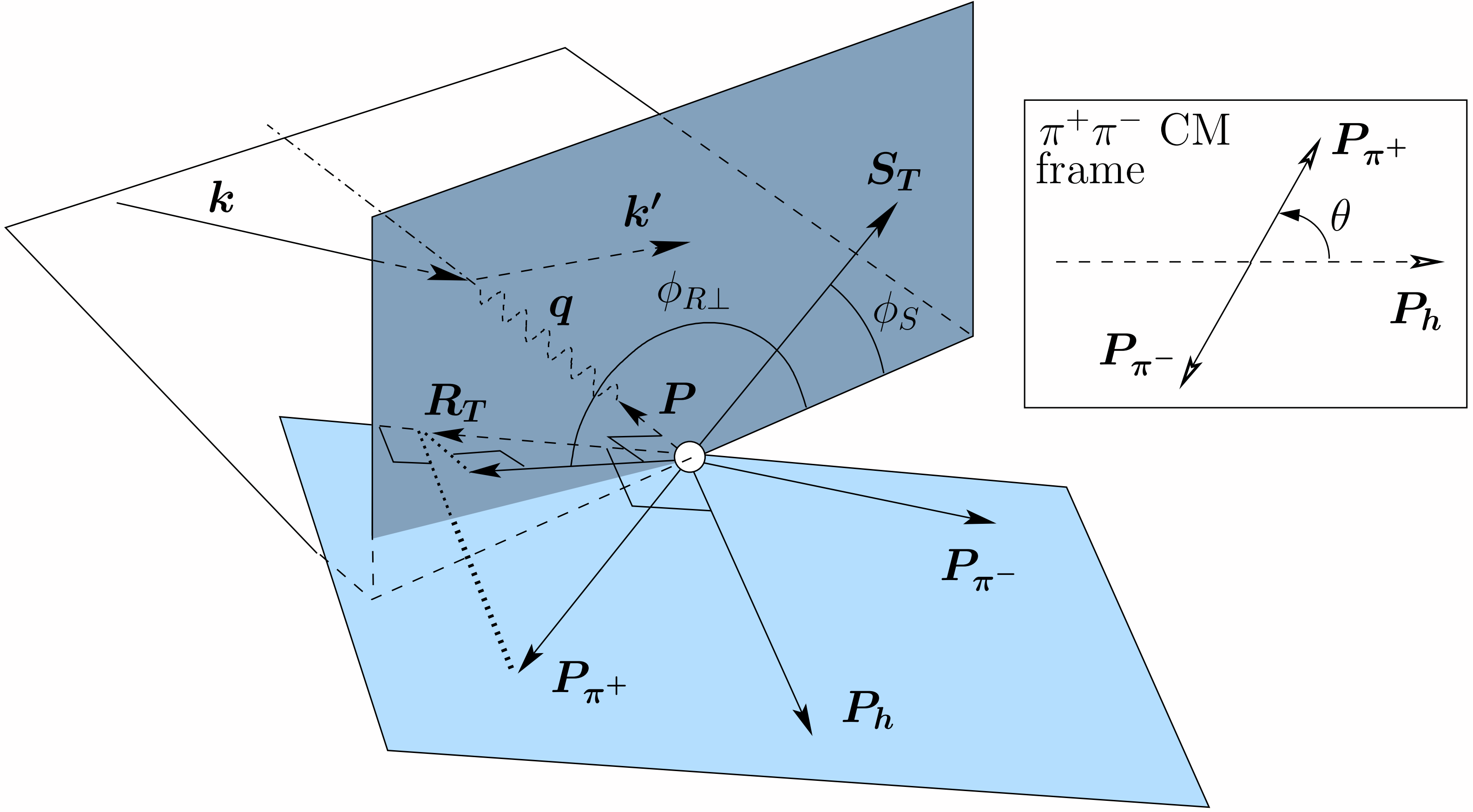
- even larger effects seen for kaon pairs
- p_t dependence for pions

what to further expect from e^+e^-

- dihadron fragmentation function: M_{h1h2} dependence (Belle)
- helicity-dependent dihadron fragmentation $G_1^\perp$ (“jet handedness”) (Belle)
- kaon and pion-kaon pairs as well as p_t dependence of Collins asymmetries (Belle, BESIII)
- Collins asymmetries without double ratios (BaBar, BESIII)
- k_T-dependent D_1 FFs (Belle)
  - nearly back-to-back hadrons
  - hadron-to-thrust
- transverse polarization of inclusively produced Λ^0 hyperons (Belle)

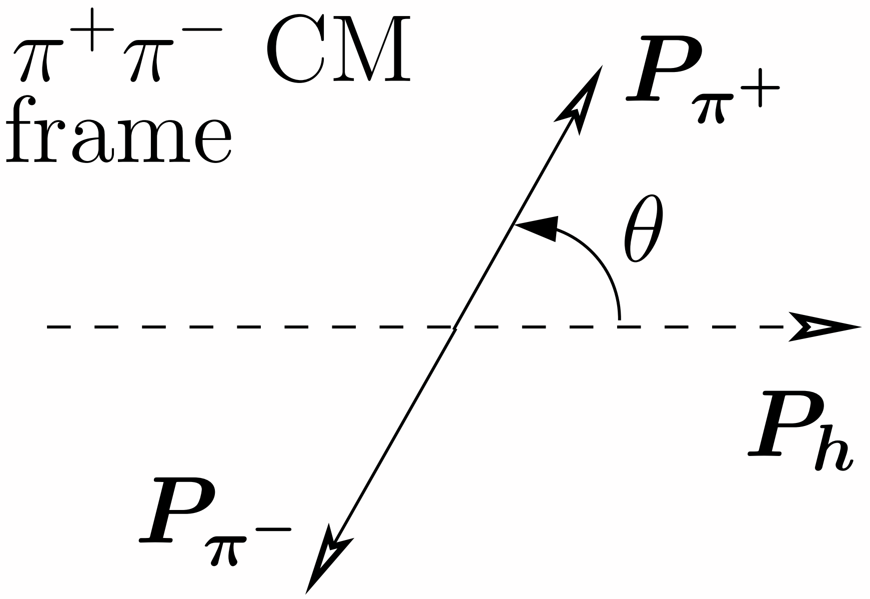
“pitfalls” in dihadron fragmentation

“appetizer”



- dihadron FFs: alternative path to extract (collinear) transversity
  - exploit orientation of hadron’s relative momentum, correlate with target polarization
- complication: SIDIS cross section now differential in 9(!) variables
- integration over polar angle eliminates, in theory, a number of contributing FFs (partial waves)
- experimental constraints limit acceptance in polar angle, most prominently the minimum-momentum requirements

simple case study



basic assumptions:

- dihadron pair with equal-mass hadrons; here: pions
- e^+e^- annihilation, thus energy fractions z translates directly to energy/momentum of particles/system as primary energy is "fixed" (-> simplifies Lorentz boost)
- without loss of generality, focus on B factory and use primary quark energy E_0 = 5.79GeV
- minimum energy of each pion in lab frame: 0.1 E_0 (i.e., z_{min} = 0.1)

application of Lorentz boost

- can easily apply Lorentz boost using the invariant mass of the dihadron M and its energy zE$_0$ to arrive at condition on θ, e.g., polar angle of pions in center-of-mass frame:

$$\cos\theta \leq \frac{z - 2z_{\min}}{\sqrt{[(zE_0)^2 - M^2)(M^2 - 4m_\pi^2)]}} E_0 M$$

- as both pions have to fulfill the constraint on the minimum energy:

$$\cos(\pi - \theta) = -\cos\theta \leq \frac{z - 2z_{\min}}{\sqrt{[(zE_0)^2 - M^2)(M^2 - 4m_\pi^2)]}} E_0 M$$

thus:

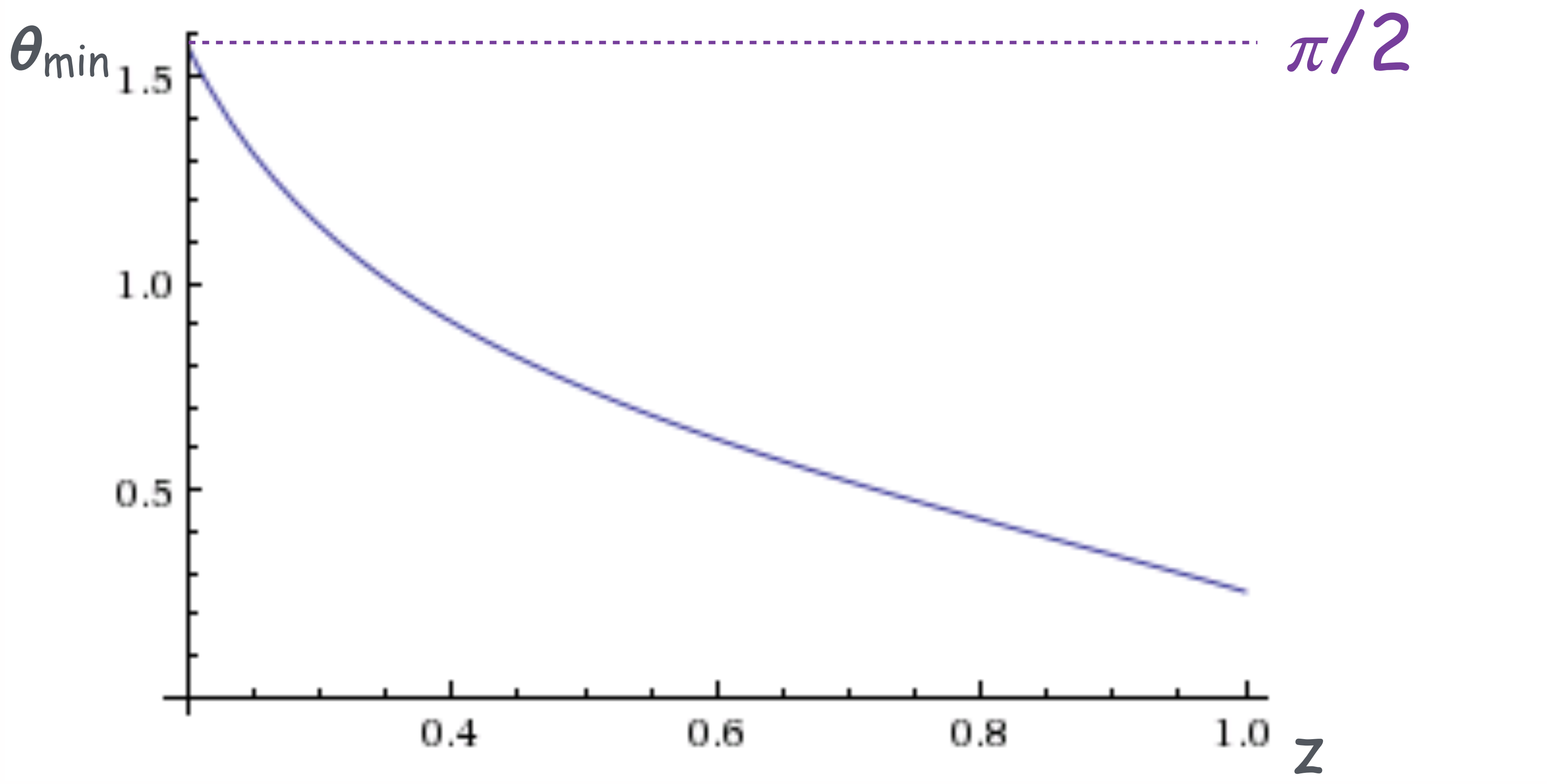
$$|\cos\theta| \leq \frac{z - 2z_{\min}}{\sqrt{[(zE_0)^2 - M^2)(M^2 - 4m_\pi^2)]}} E_0 M$$

- translates to a symmetric range around $\pi/2$

  (can be easily understood because at $\pi/2$ the pions will have both the same energy in the lab and easily pass the z$_{\min}$ requirement, while in the case of one pion going backward in the CMS, that pion will have less energy in the lab frame … and maybe too little)

impact of z_{min}=0.1 on accepted polar range

- (again without loss of generality) let's assume M=0.5 GeV :



- all theta below curve (and above its mirror curve relative to dashed line) are excluded
- clearly limited, especially at low z

partial-wave expansion of dihadron FF

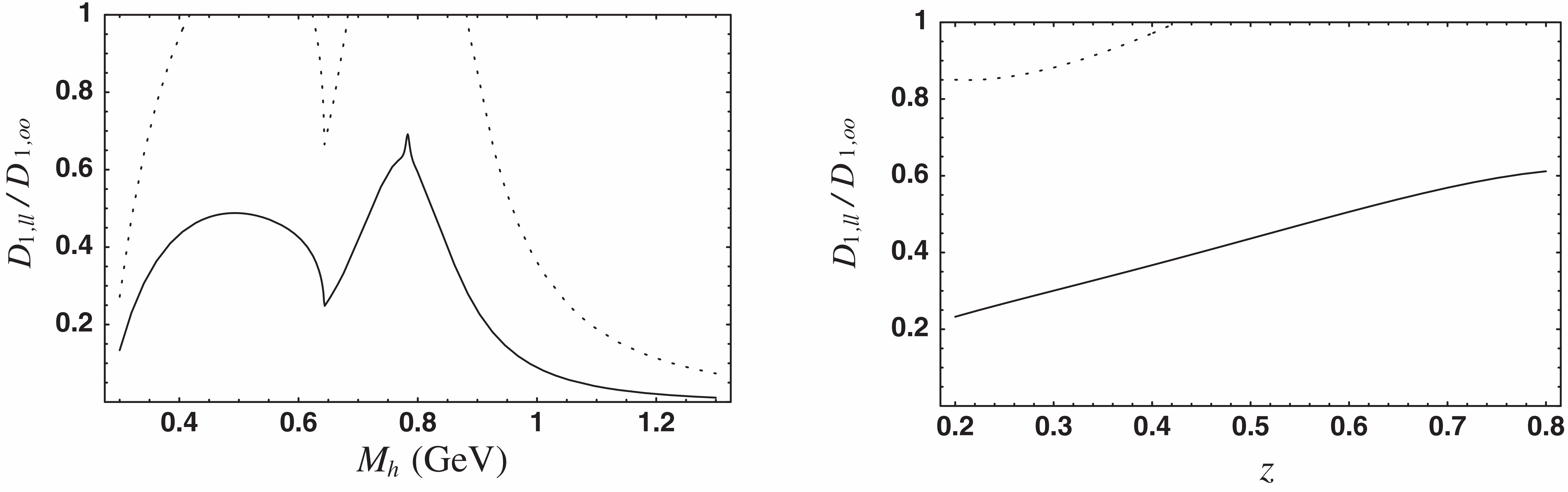
- partial-wave expansion worked out in Phys. Rev. D67 (2003) 094002
- for the particular case here, use Phys. Rev. D74 (2006) 114007, in particular Eq. (12), and (later on) Figure 5:

$$D_1^q(z, \cos\theta, M_h^2) \approx D_{1,oo}^q(z, M_h^2) + D_{1,ol}^q(z, M_h^2)\cos\theta + D_{1,ll}^q(z, M_h^2)\tfrac{1}{4}(3\cos^2\theta - 1), \qquad (12)$$

- it is the first contribution ($D_{1,oo}$) that is used in “collinear extraction” of transversity (and subject of a current Belle analysis)
  - it is also the only one surviving the integration over θ
- the $D_{1,ol}$ contribution vanishes upon integration over θ as long as the theta range is symmetric around $\pi/2$ (as it is the case here)
- the $D_{1,ll}$ term, however, will in general contribute in case of only partial integration over θ — the question is how much?

$D_{1,ll}$ contribution to dihadron fragmentation

- $D_{1,ll}$ is unknown and can't be calculated using first principles
- it can not be extracted from cross sections integrated over θ
- upon (partial) integration there is no way to disentangle the two contributions
- in PRD74 (2006) 114007, a model for dihadron fragmentation was tuned to PYTHIA and used to estimate the various partial-wave contributions
- its Figure 5 gives an indication about the relative size of $D_{1,ll}$ vs. $D_{1,oo}$:



effect of partial integration

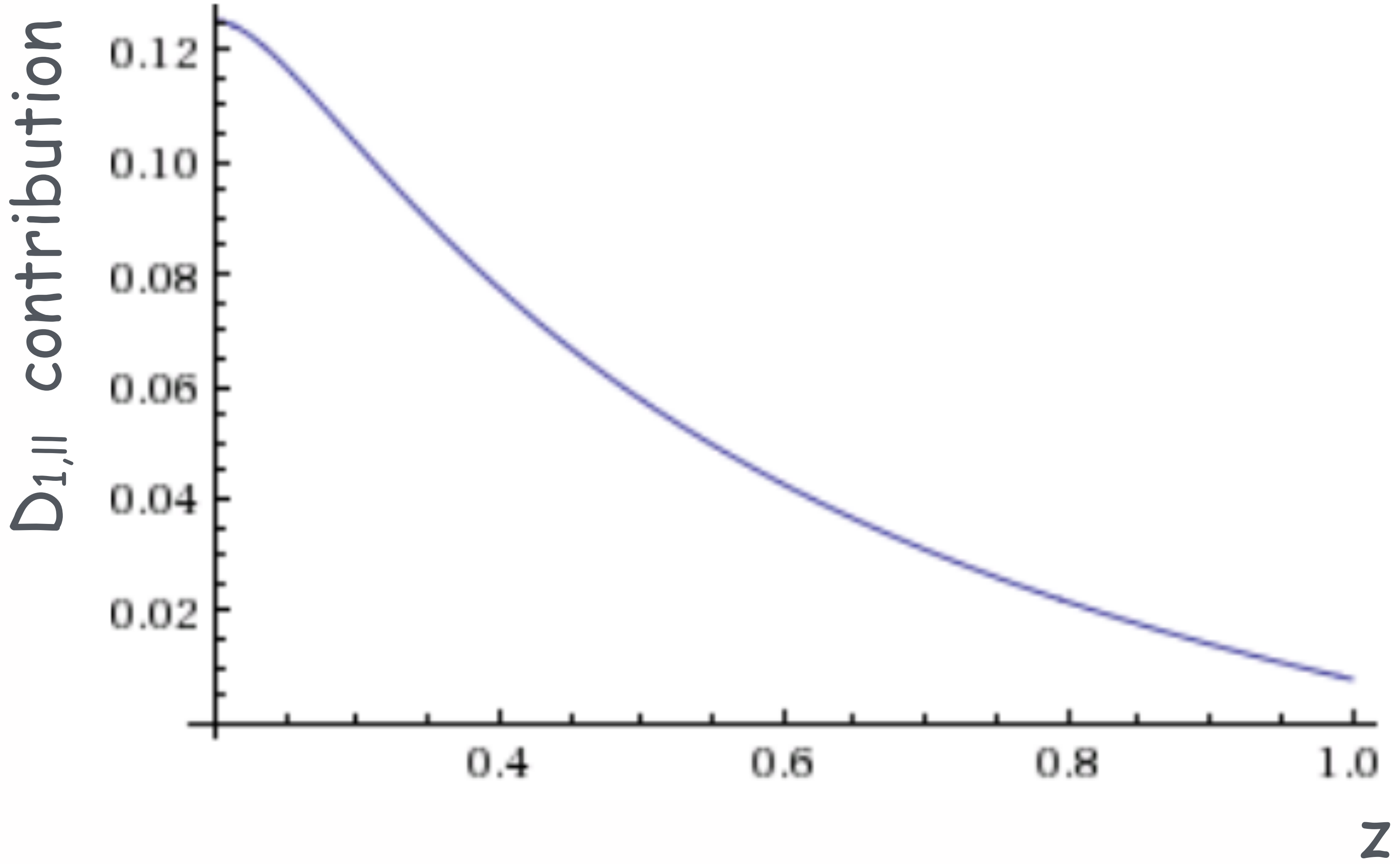
- as both contributions — $D_{1,ll}$ and $D_{1,oo}$ — will be affected by the partial integration, look at relative size of the $D_{1,ll}$ to $D_{1,oo}$ modulations when subjected to integration:

$$\frac{D_{1,ll}}{D_{1,oo}} \frac{\int_{\cos(\pi-\theta_0)}^{\cos\theta_0} \mathrm{d}\cos\theta \, \frac{1}{4}(3\cos^2\theta - 1)}{\int_{\cos(\pi-\theta_0)}^{\cos\theta_0} \mathrm{d}\cos\theta} = -\frac{1}{4}(1-\cos^2\theta_0) \, \frac{D_{1,ll}}{D_{1,oo}}$$

- without limit in the polar-angular range (θ_0 =0) -> no contribution from $D_{1,ll}$ (sanity check!)
- the relative size of the partial integrals reaches a maximum of 25% for z=0.2 (i.e., pions at 90 degrees in center-of-mass system)
- in order to estimate the $D_{1,ll}$ contribution, one "just" needs the relative size of $D_{1,ll}$ vs. $D_{1,oo}$, e.g., Figure 5 of PRD74 (2006) 114007
    - let's take for that size 0.5 (rough value for M=0.5 GeV)

effect of partial integration

- … $D_{1,ll}$ / $D_{1,oo}$ ~0.5 results in an up to O(10%) effect on the measured cross section:



- depending on the sign of $D_{1,ll}$, the partial integration thus leads to a systematic **underestimation** (positive $D_{1,ll}$) or **overestimation** (negative $D_{1,ll}$) **of the "integrated" dihadron cross section**

  - **leads to overestimate/underestimate of extracted transversity**

conclusions

- e^+e^- data has provided a rich precision data set for fragmentation studies
  - input to D_1 FF phenomenology
  - hadron-pair data could further constrain flavor dependence
  - transverse-momentum dependence on the horizon
  - Collins asymmetries available for pions and kaons, at different s and by now also p_T dependent
  - dihadron fragmentation for, e.g., collinear extraction of transversity

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- e^+e^- data has provided a rich precision data set for fragmentation studies
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  - Collins asymmetries available for pions and kaons, at different s and by now also p_T dependent
  - dihadron fragmentation for, e.g., collinear extraction of transversity
- however, precision =/= accuracy (at least not always)
  - e.g., partial-wave contributions can survive due to experimental constraints
  - discussed for e^+e^-, but even more so for SIDIS or pp->h_1h_2X
  - important to keep in mind when aiming for precision measurements

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