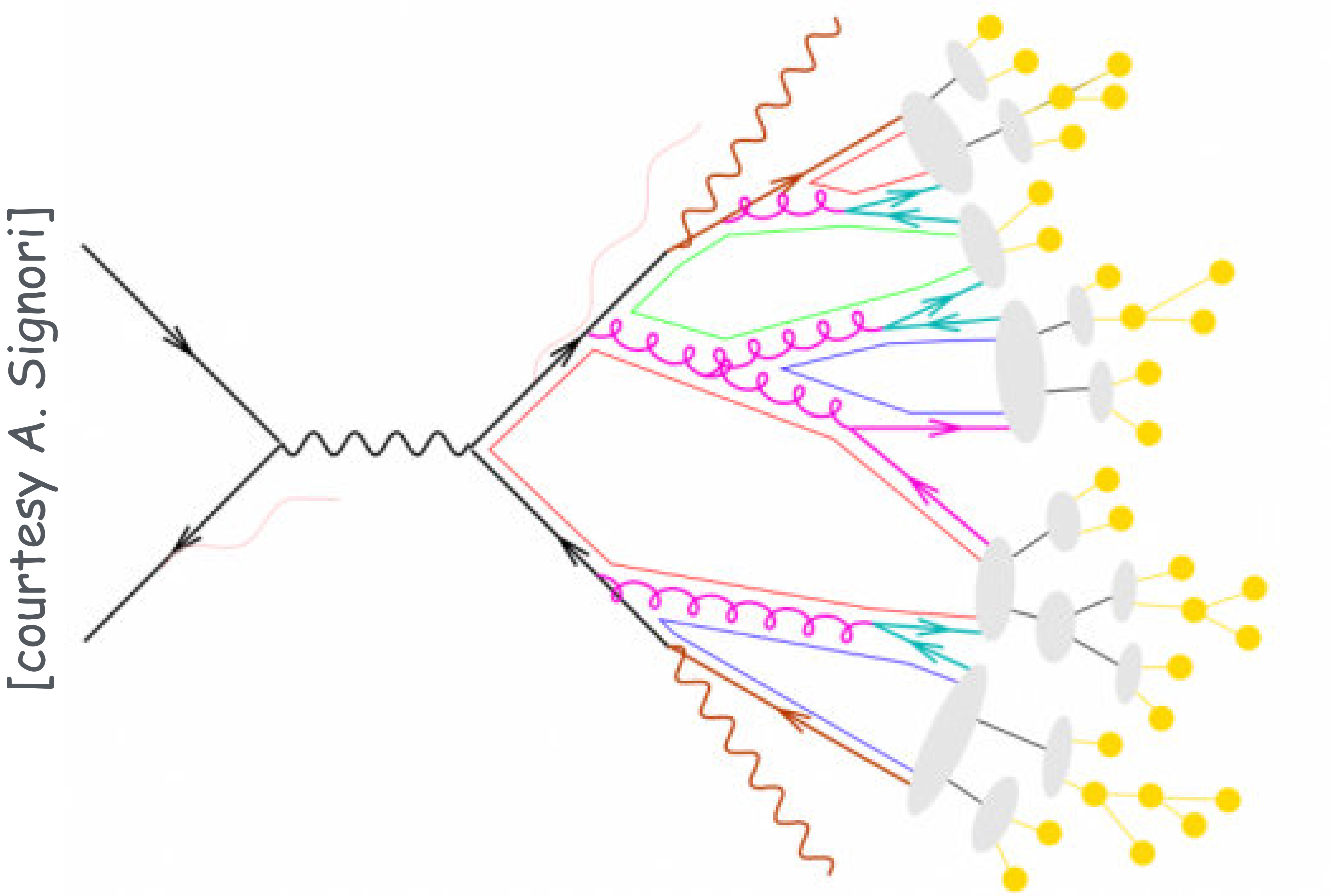
[courtesy A. Signori]

Fragmentation function measurements from

BELLE

Gunar.Schnell @ DESY.de

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

STRONG-2020

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Basque Foundation for Science

eman ta zabal zazu
Universidad del País Vasco
Euskal Herriko Unibertsitatea

single-hadron TMD*) fragmentation functions

*) TMD … transverse-momentum dependent

quark pol.

hadron pol.

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

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☚ relevant for unpolarized final state

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☚ relevant for unpolarized final state

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

ordinary FF: $D_1^{q\rightarrow h}$

FF … fragmentation function

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polarized final-state hadrons

polarizing FF

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☚ relevant for unpolarized final state

} polarized final-state hadrons

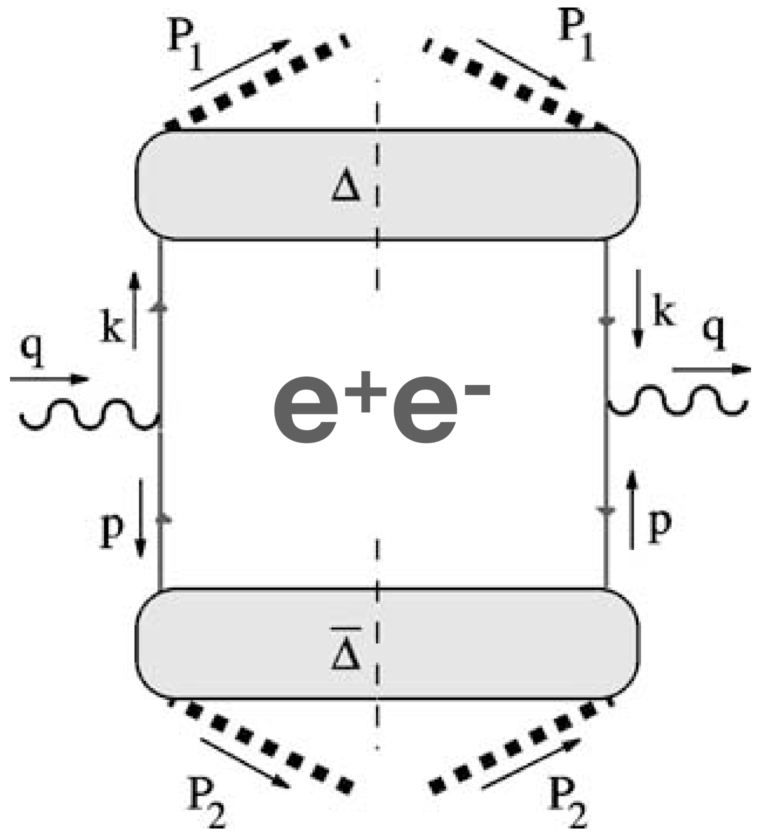
polarizing FF

➟ FFs act as quark flavor-tagger and polarimeter

FF … fragmentation function

fragmentation in e^+e^- annihilation

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



fragmentation in e^+e^- annihilation

- single-inclusive hadron production, **$e^+e^- \rightarrow hX$**
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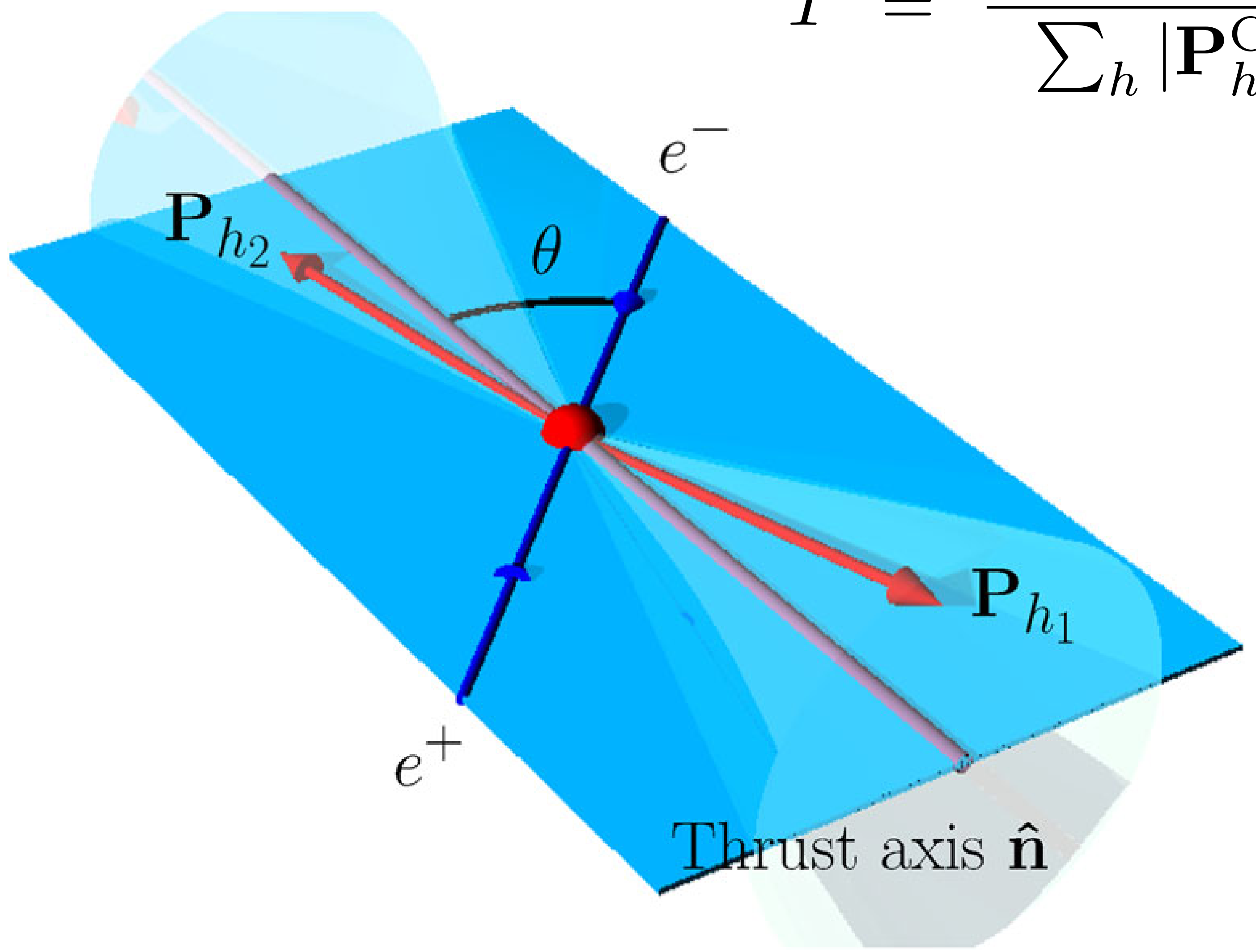
  - ($D_{1T}^{\perp}$ spontaneous transv. polarization)
- inclusive "back-to-back" hadron pairs, **$e^+e^- \rightarrow h_1h_2X$**
  - product of fragmentation functions
  - flavor, transverse-momentum, and/or polarization tagging

Thrust (axis):

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



fragmentation in e⁺e⁻ annihilation

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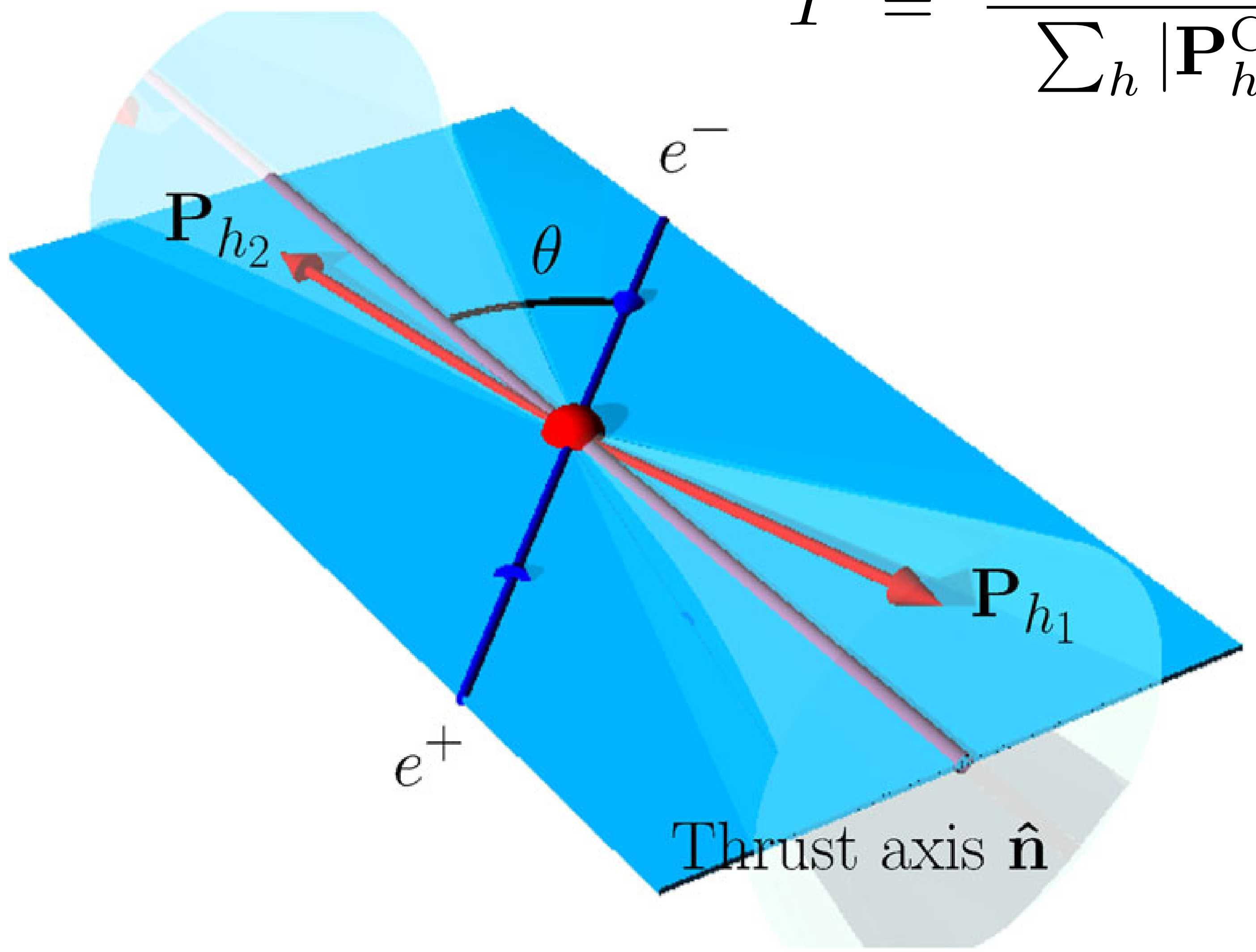
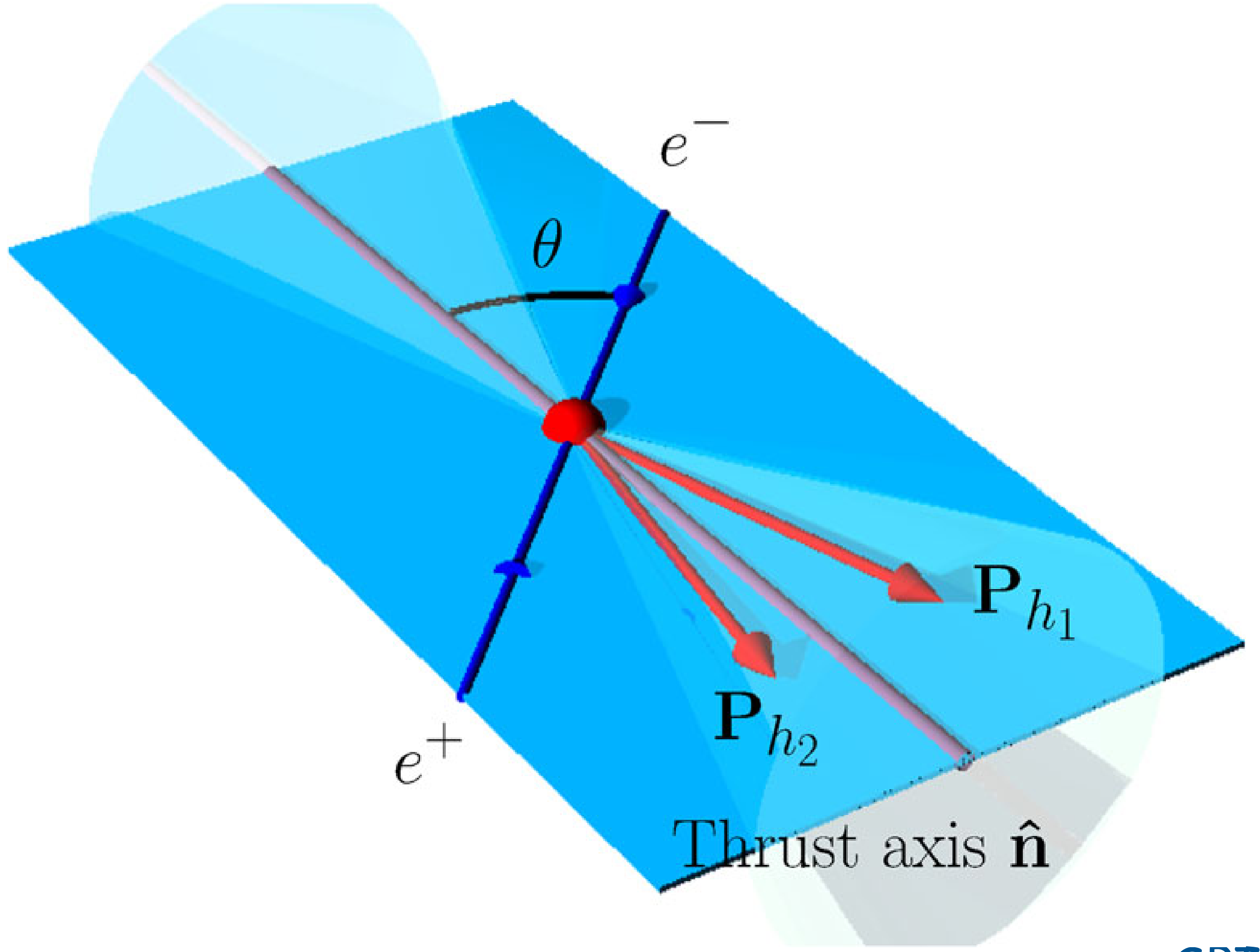
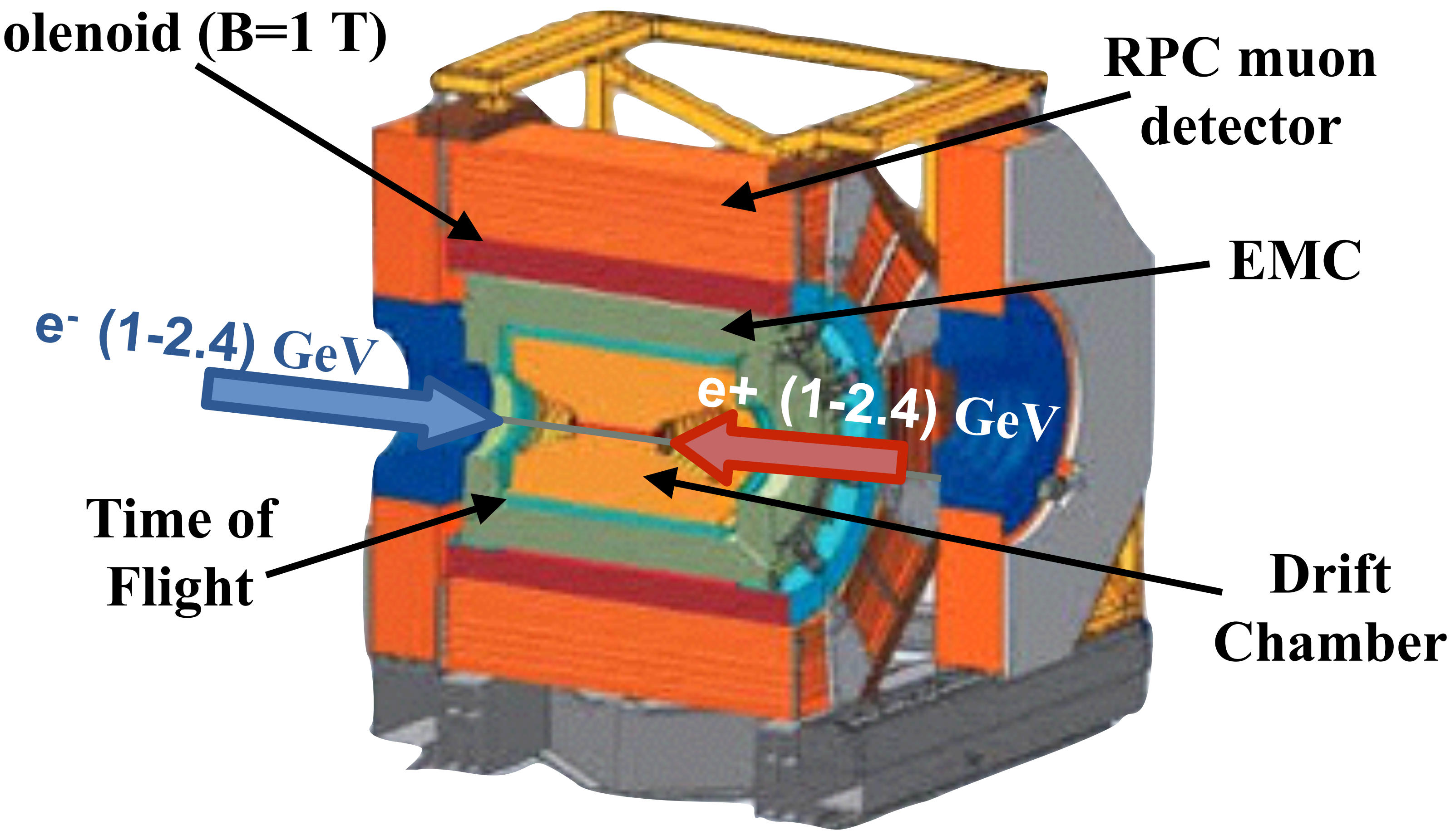
  - D_1 fragmentation function
  - ($D_{1T}^{\perp}$ spontaneous transv. polarization)
- inclusive “back-to-back” hadron pairs, **$e^+e^- \rightarrow h_1h_2X$**
  - product of fragmentation functions
  - flavor, transverse-momentum, and/or polarization tagging
- inclusive same-hemisphere hadron pairs, **$e^+e^- \rightarrow h_1h_2X$**
  - di-hadron fragmentation

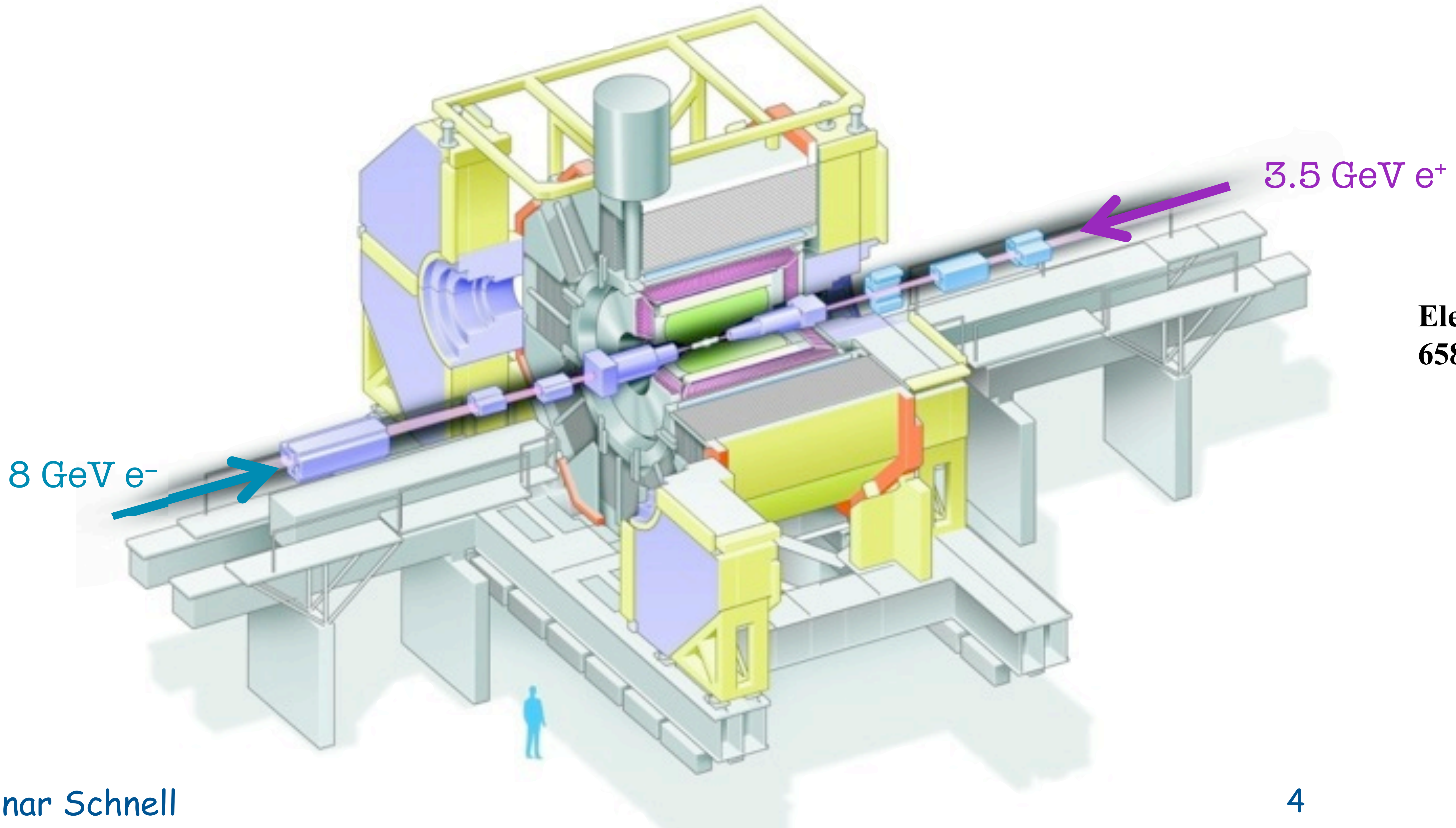


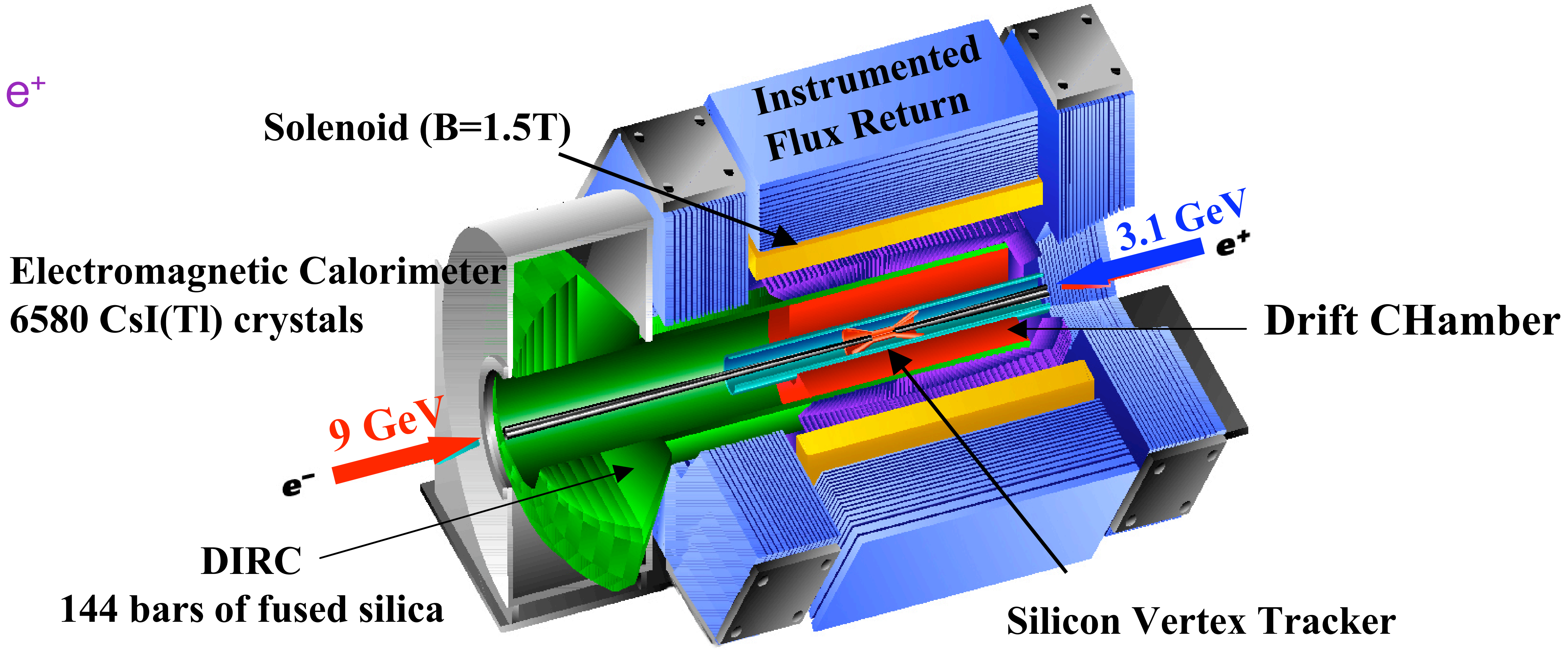


e^+e^- annihilation at BESIII, BaBar & Belle

- BESIII: symmetric collider (E_e=1…2.4 GeV)
- BaBar/Belle: asymmetric beam-energy e^+e^- collider near/at $\Upsilon(4S)$ resonance

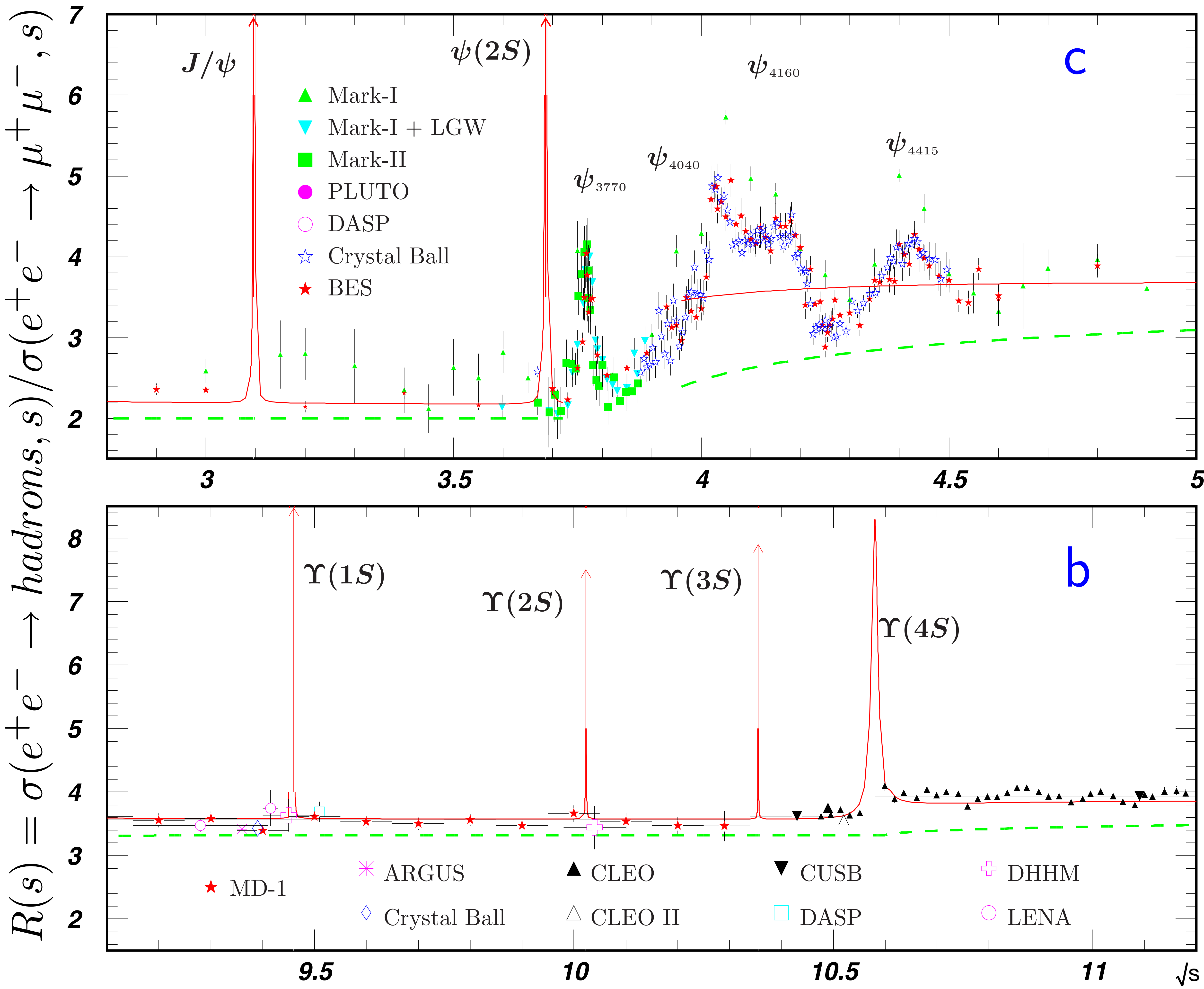






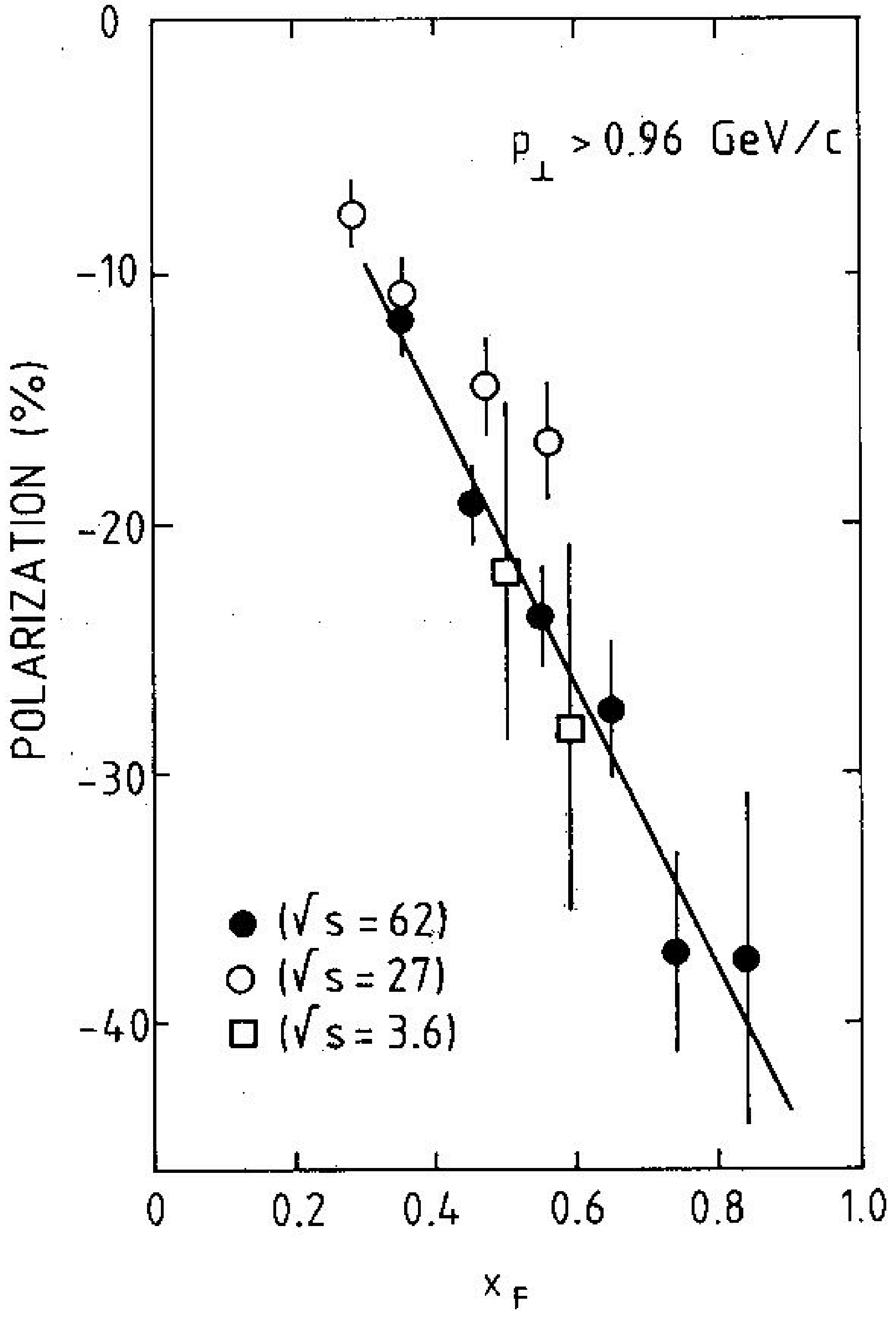
e^+e^- annihilation at BESIII, BaBar & Belle

- BESIII: symmetric collider (E_e=1...2.4 GeV)
- BaBar/Belle: asymmetric beam-energy e^+e^- collider near/at $\Upsilon(4S)$ resonance
- different scales (➠ QCD evolution)
- different quark-flavor sensitivities

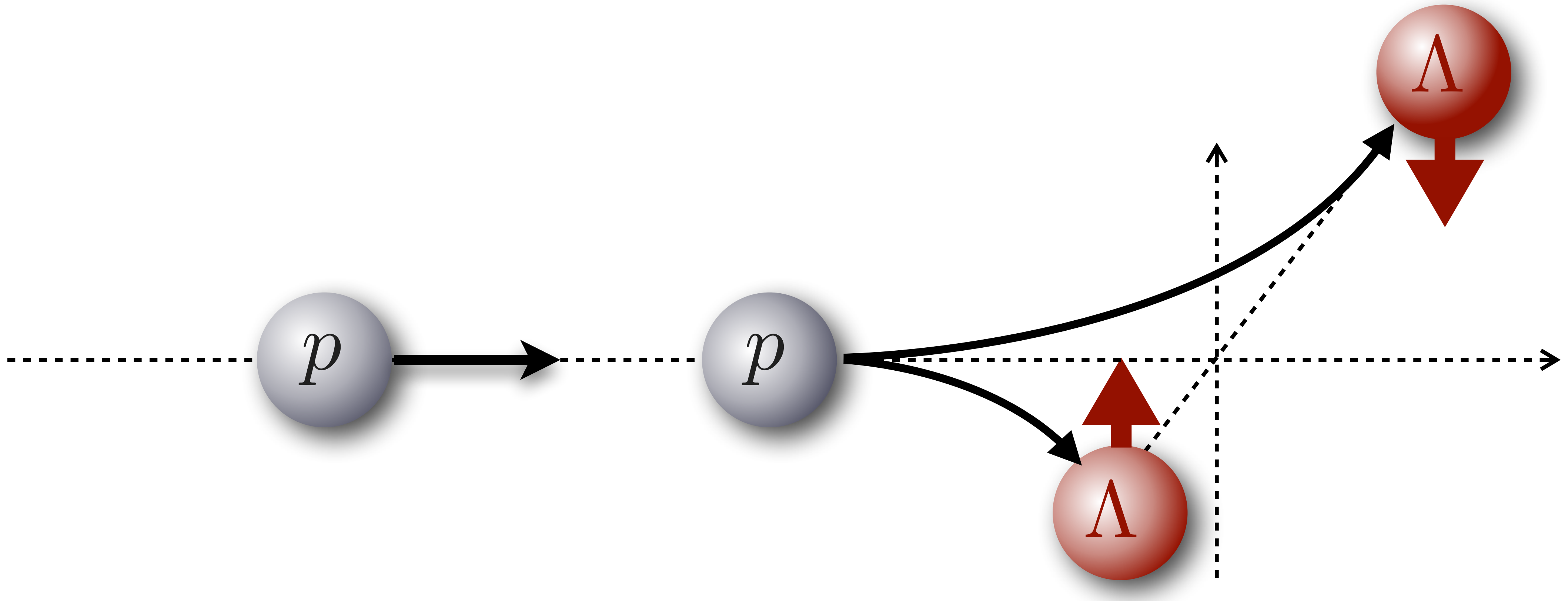


polarization

despite unpolarized initial state



polarizing fragmentation



- large hyperon polarization in unpolarized hadron collision observed

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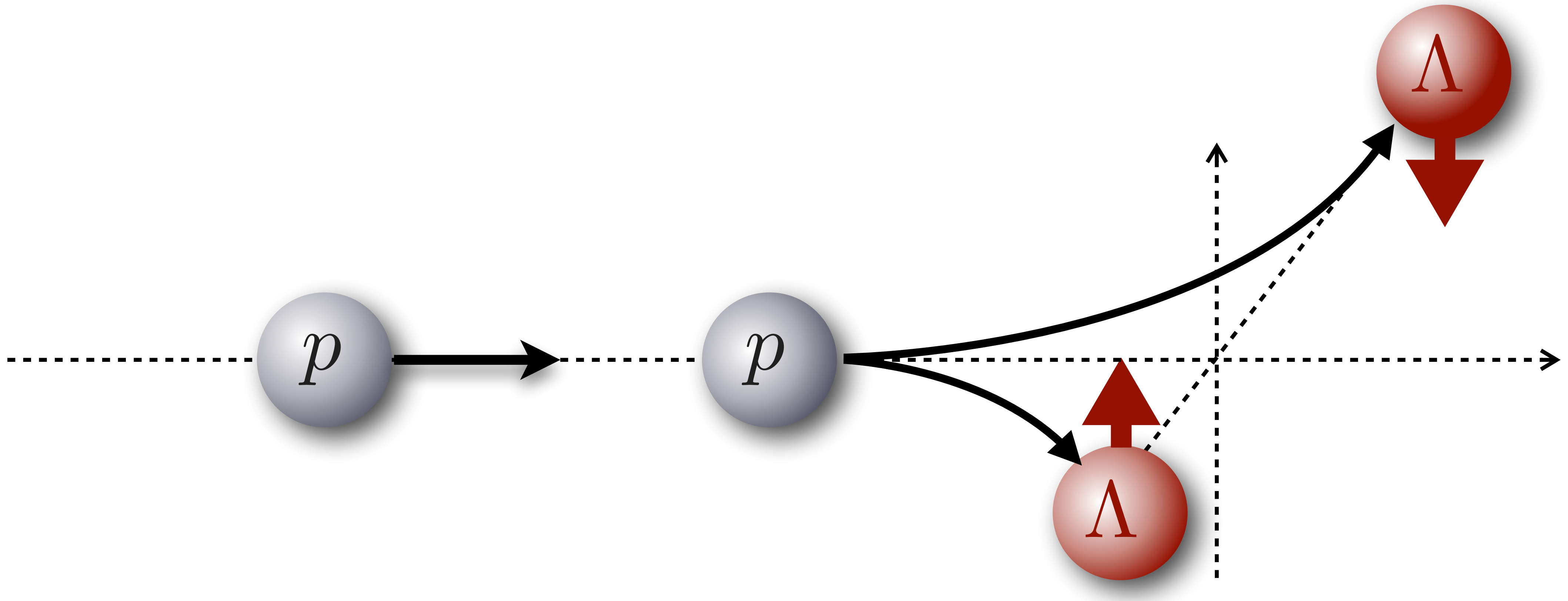
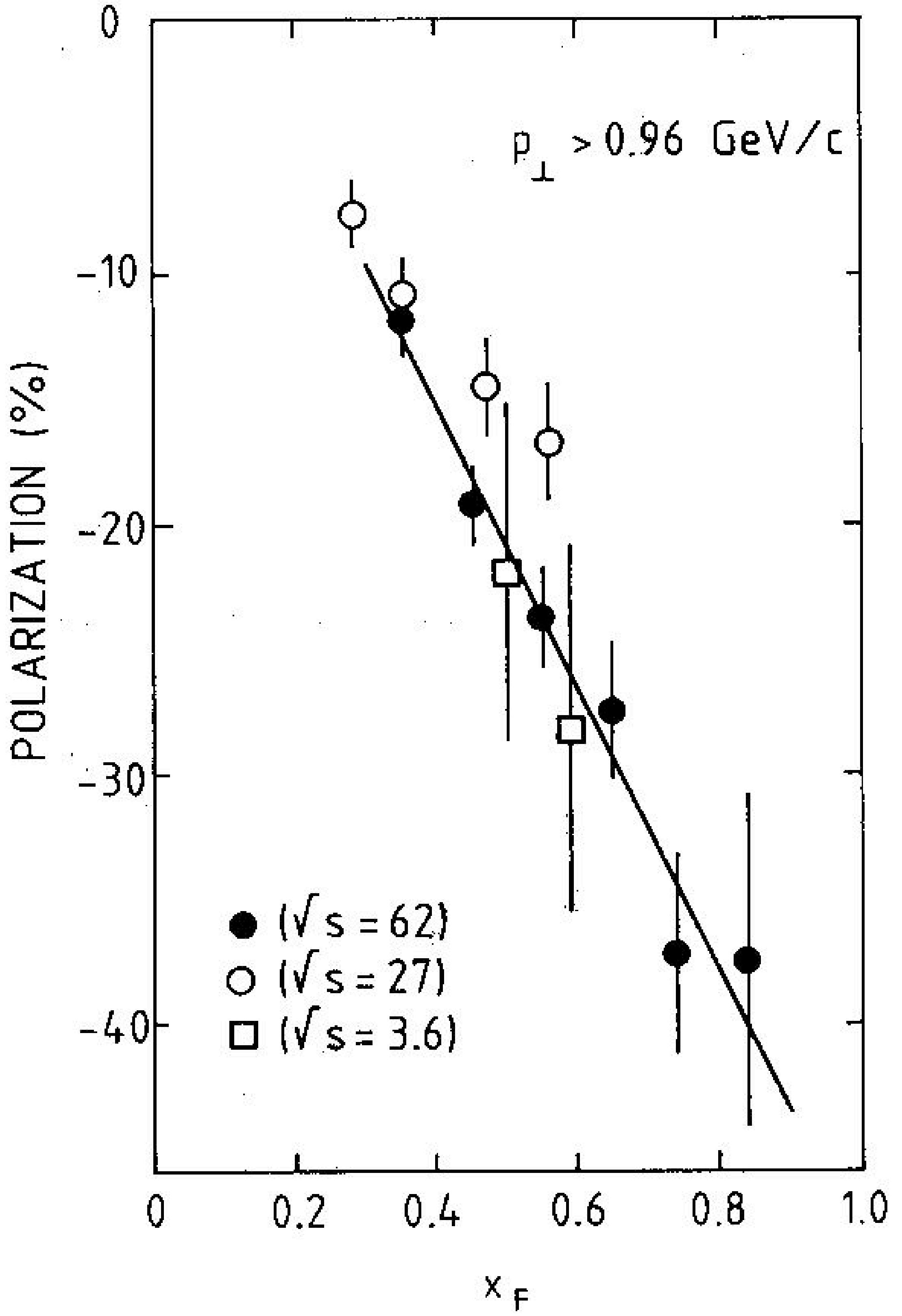
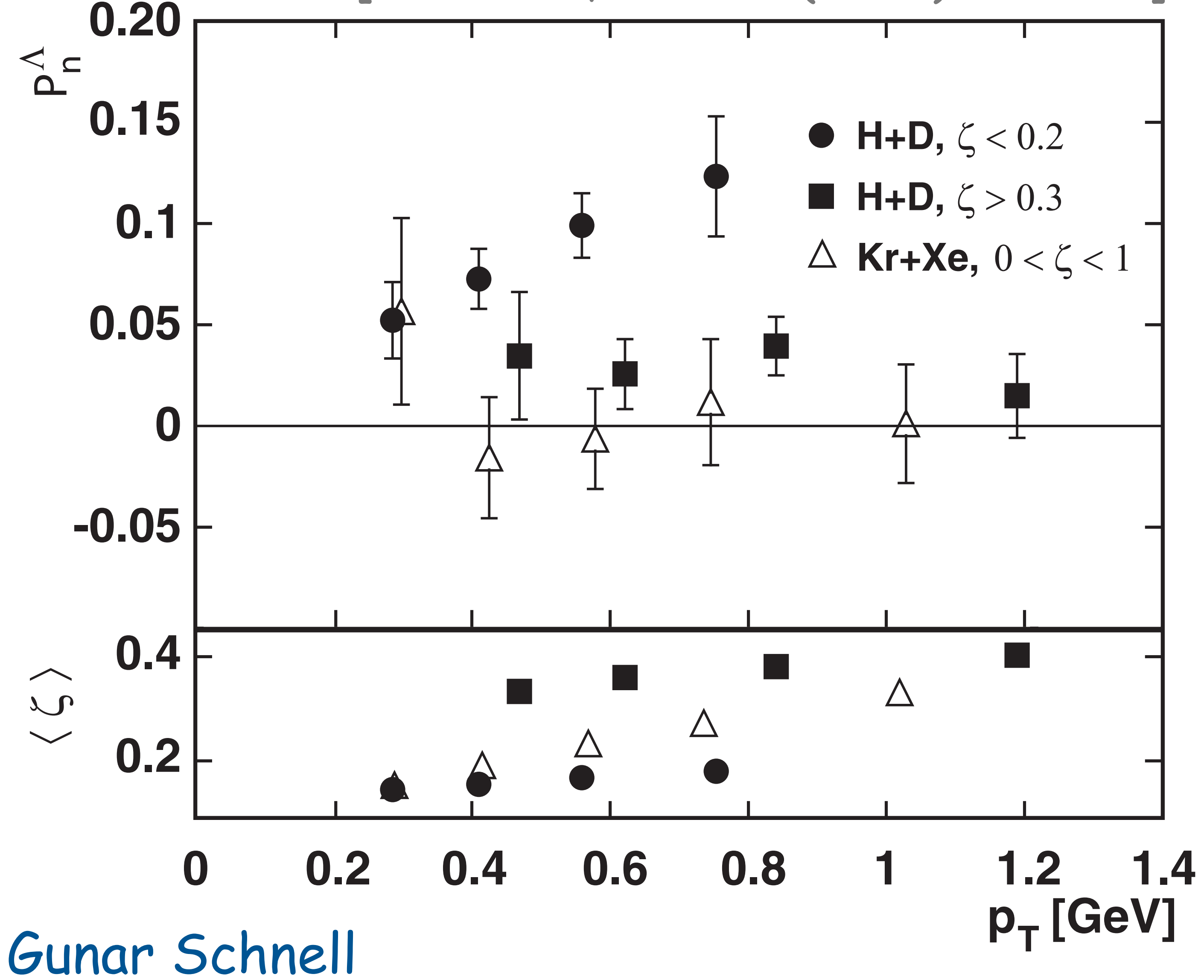


- large hyperon polarization in unpolarized hadron collision observed
- … as well as in inclusive lepto-production



[HERMES, PRD 90 (2014) 072007]



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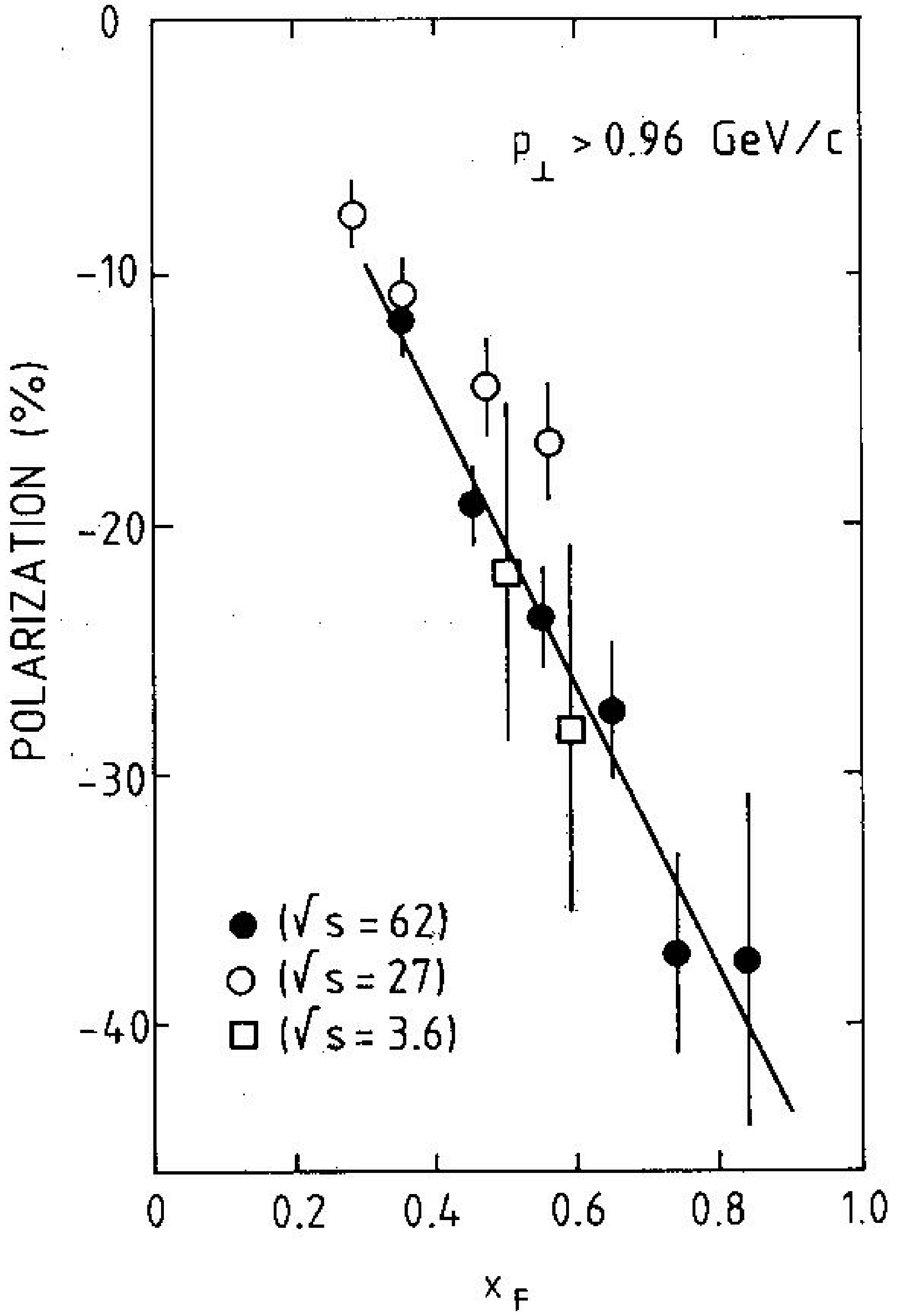

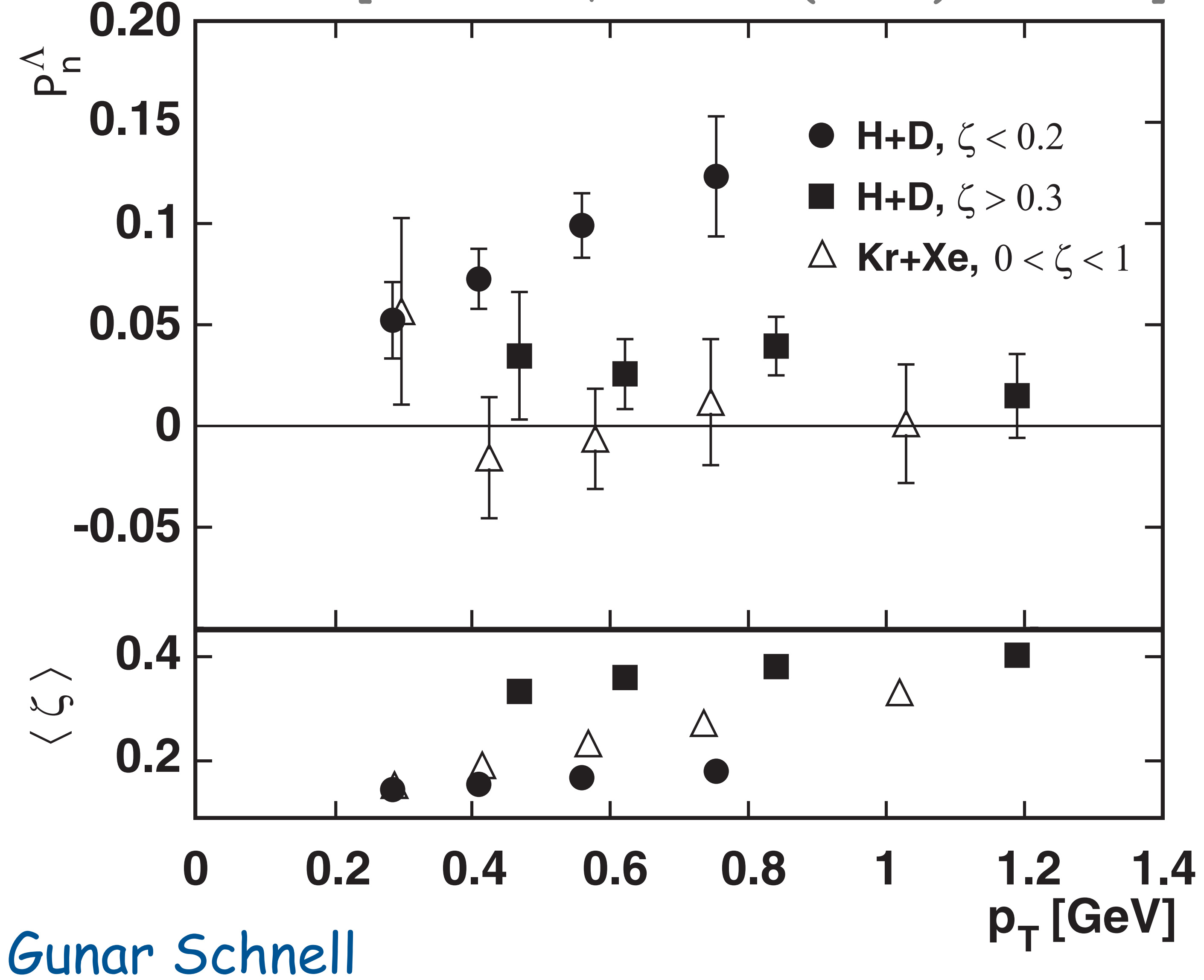

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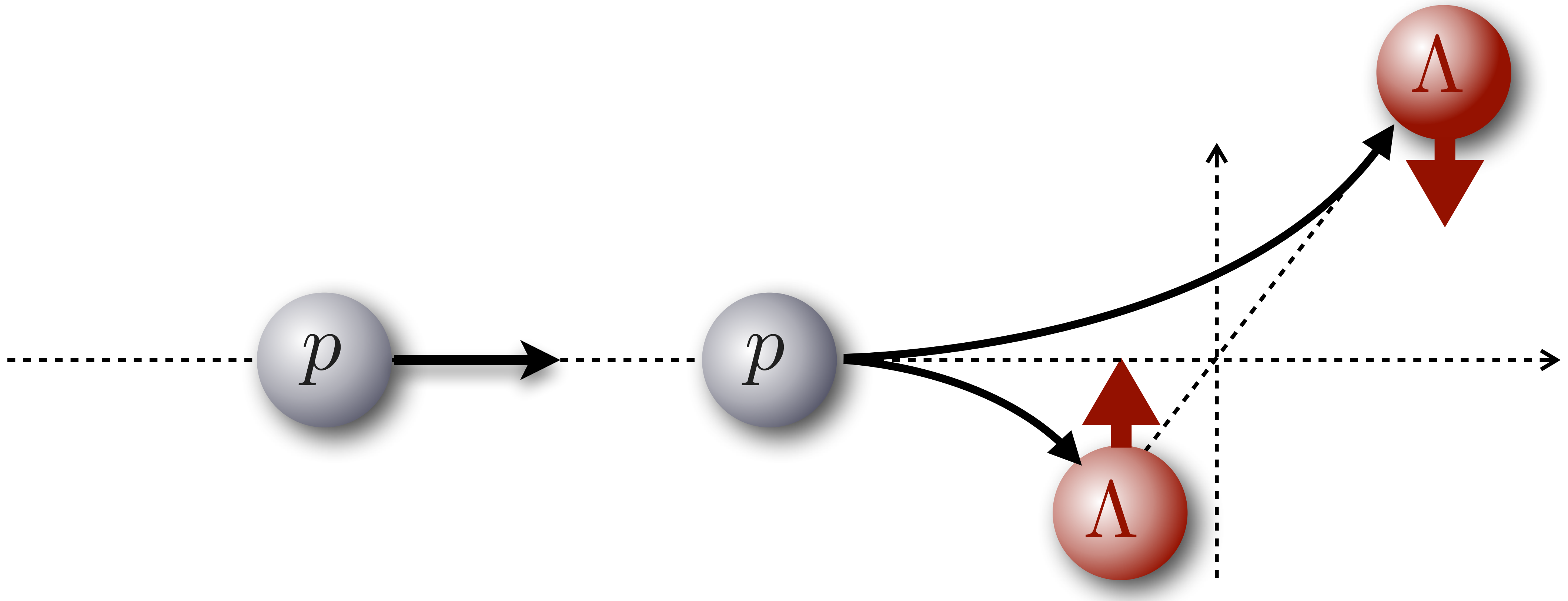
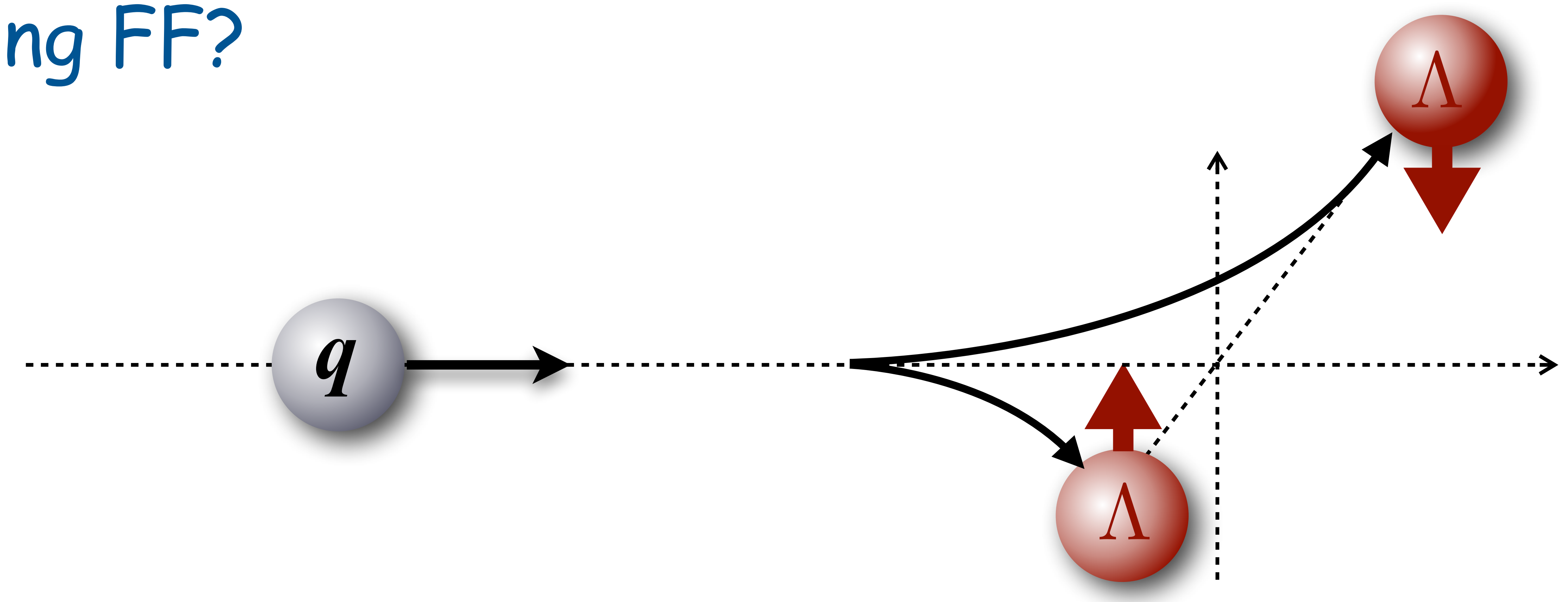
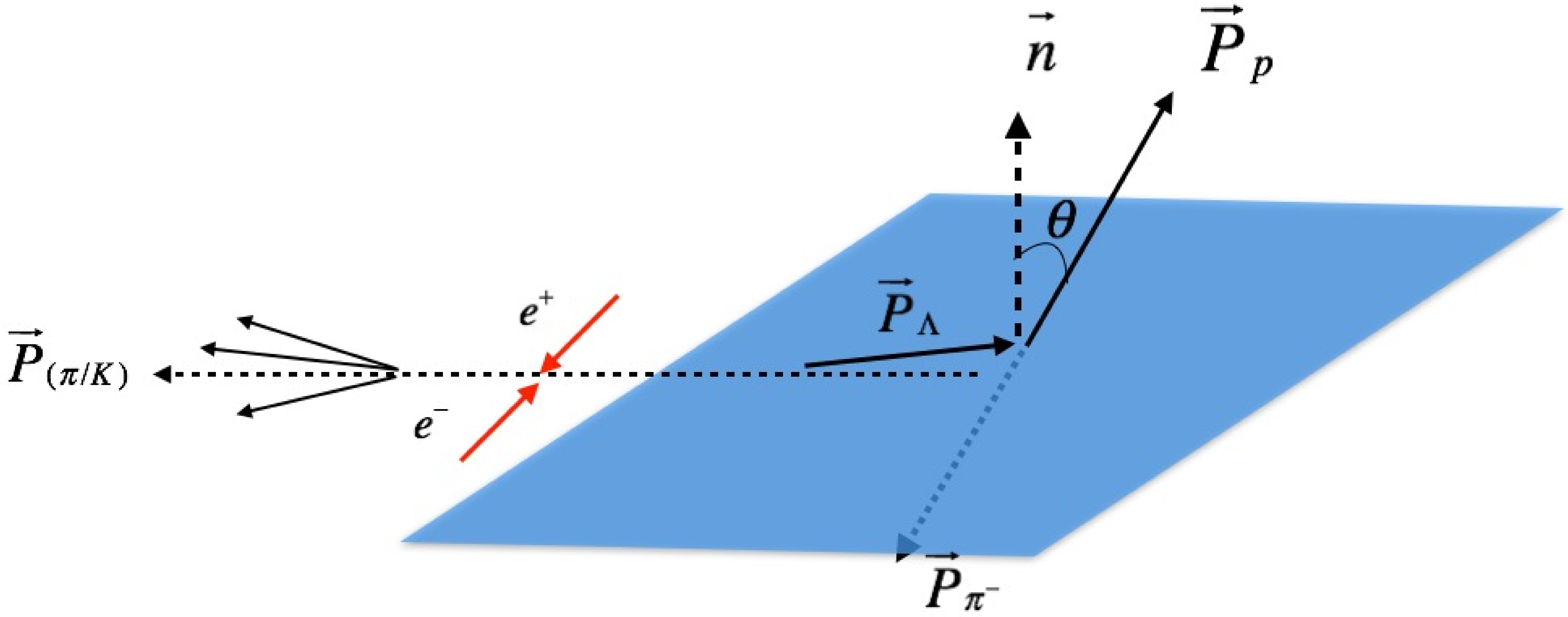


- large hyperon polarization in unpolarized hadron collision observed
- … as well as in inclusive lepto-production
- caused by polarizing FF?



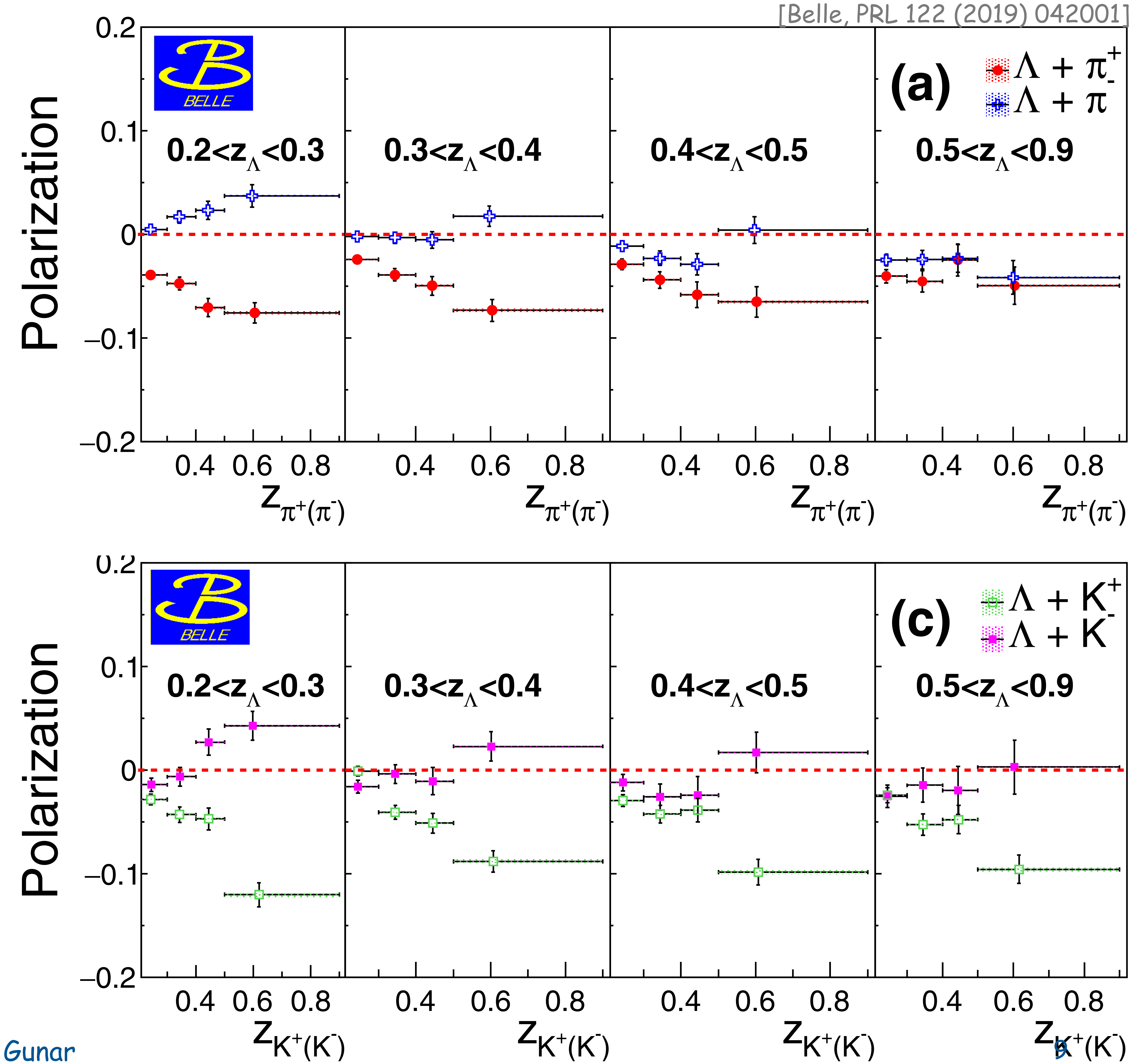
polarizing fragmentation function

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



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

polarizing fragmentation function



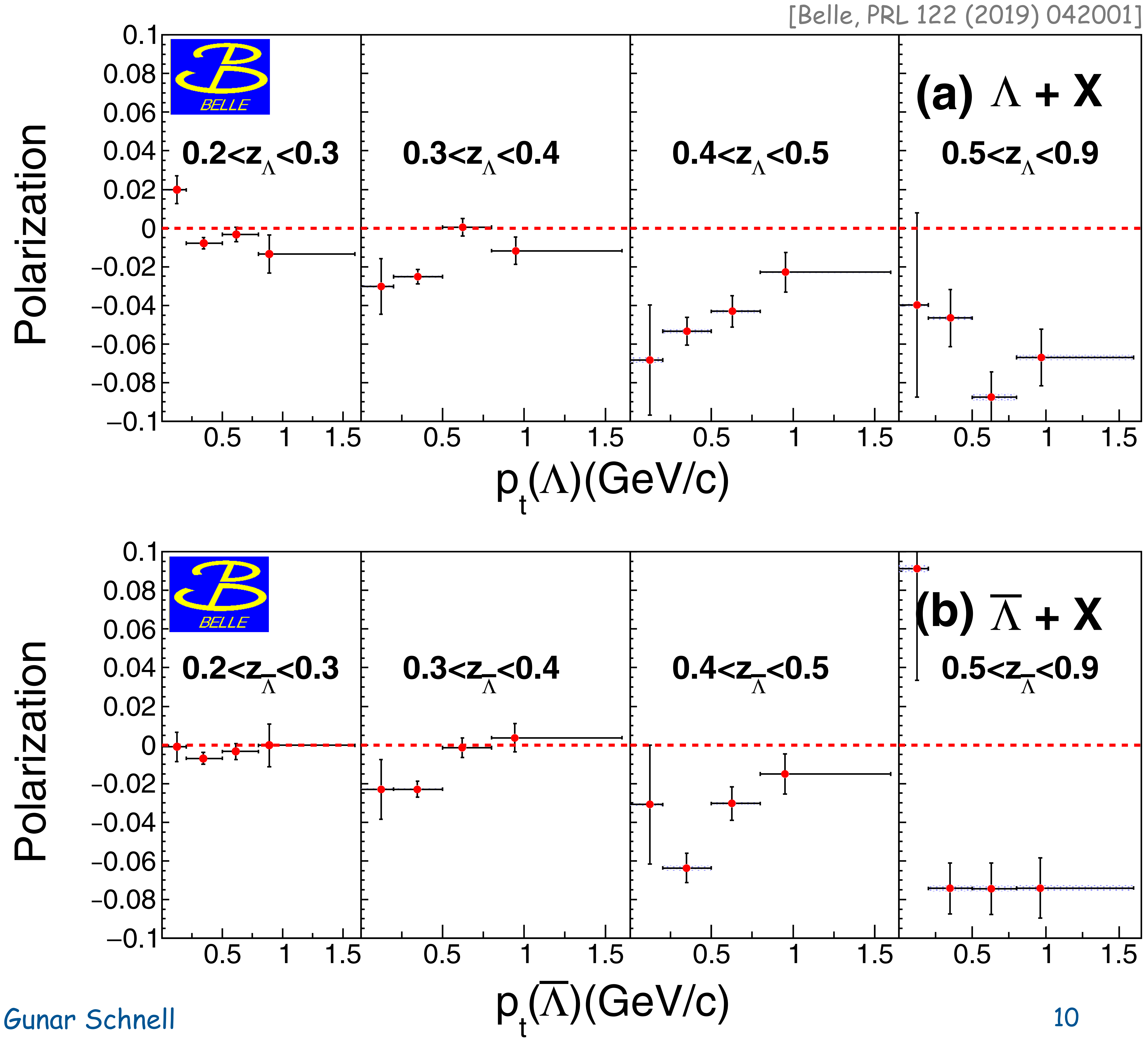
- flavor tagging through hadrons in opposite hemisphere:
  - large-z_h hadrons tag quark flavor more efficiently

  ➡ enlarges differences between oppositely charged hadrons

  - MC-based quark-flavor decomposition in backup

$$z_h = \frac{E_h}{\sqrt{s}/2}$$

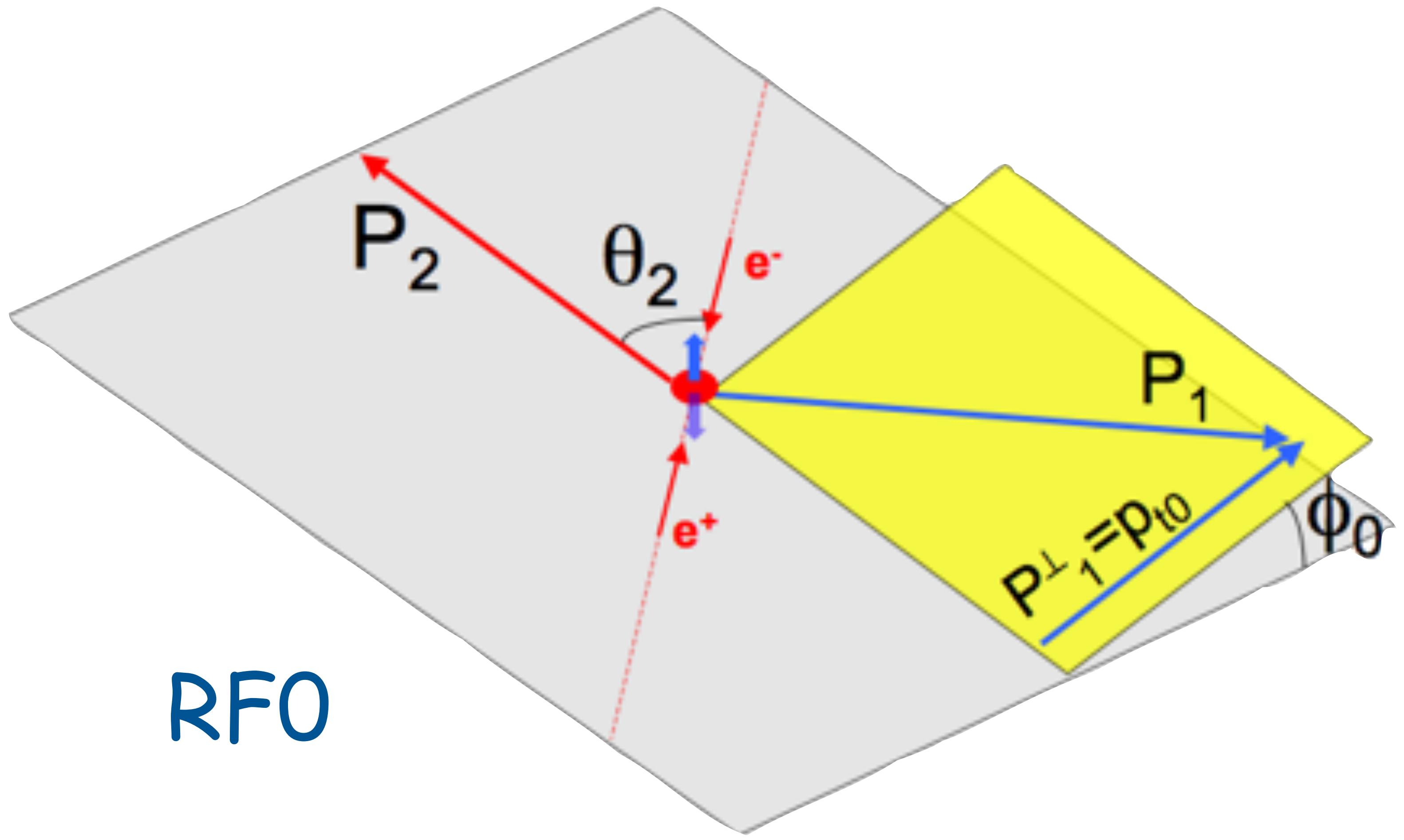
polarizing fragmentation function


[Belle, PRL 122 (2019) 042001]

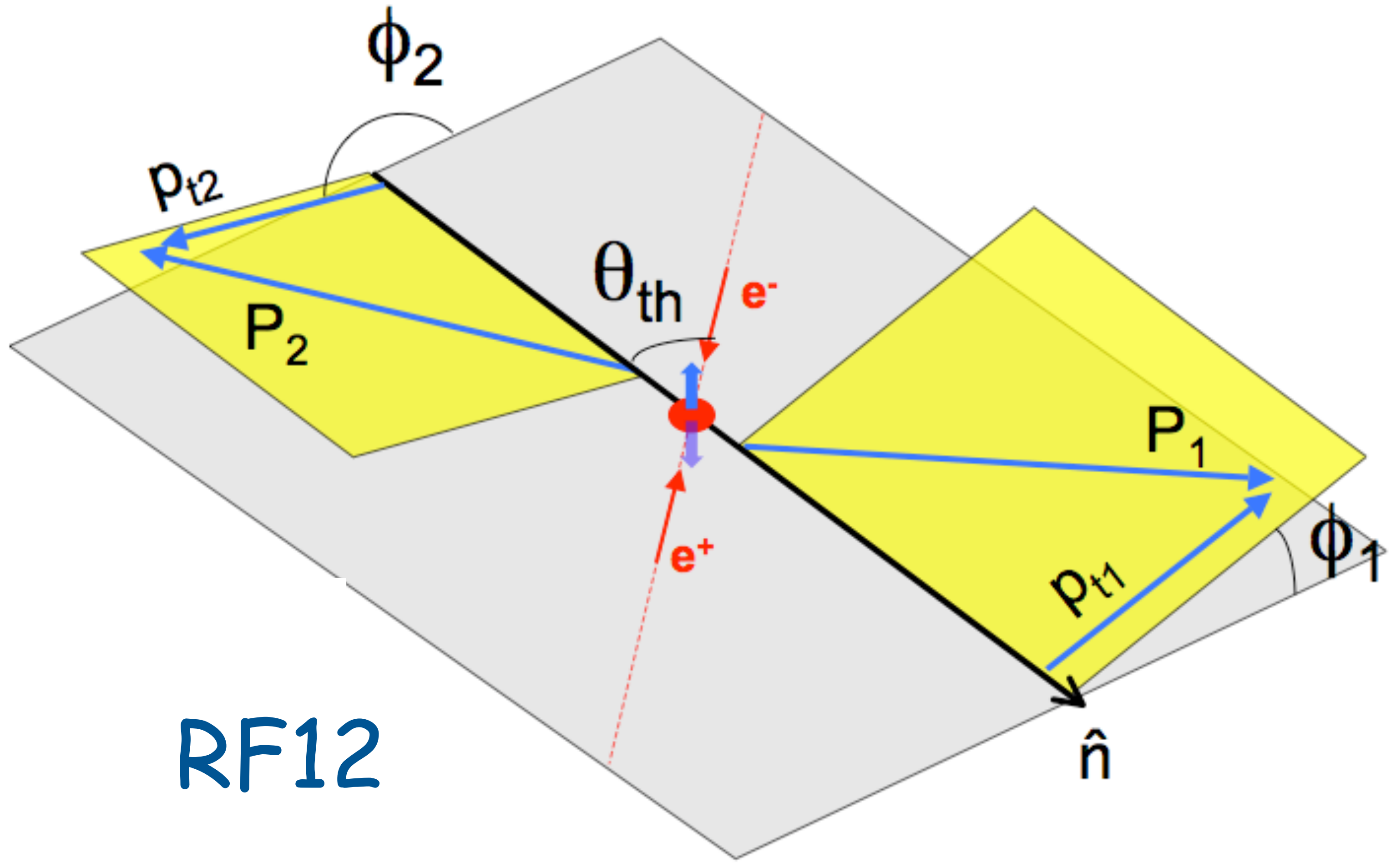
- polarization measured as function of z and p_T (p_T ... transverse momentum with respect to reference axis)
- strong dependence on both kinematics somewhat unexpected behavior for p_T -> 0
  - e.g., transverse-momentum dependence different for different quark flavors?

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



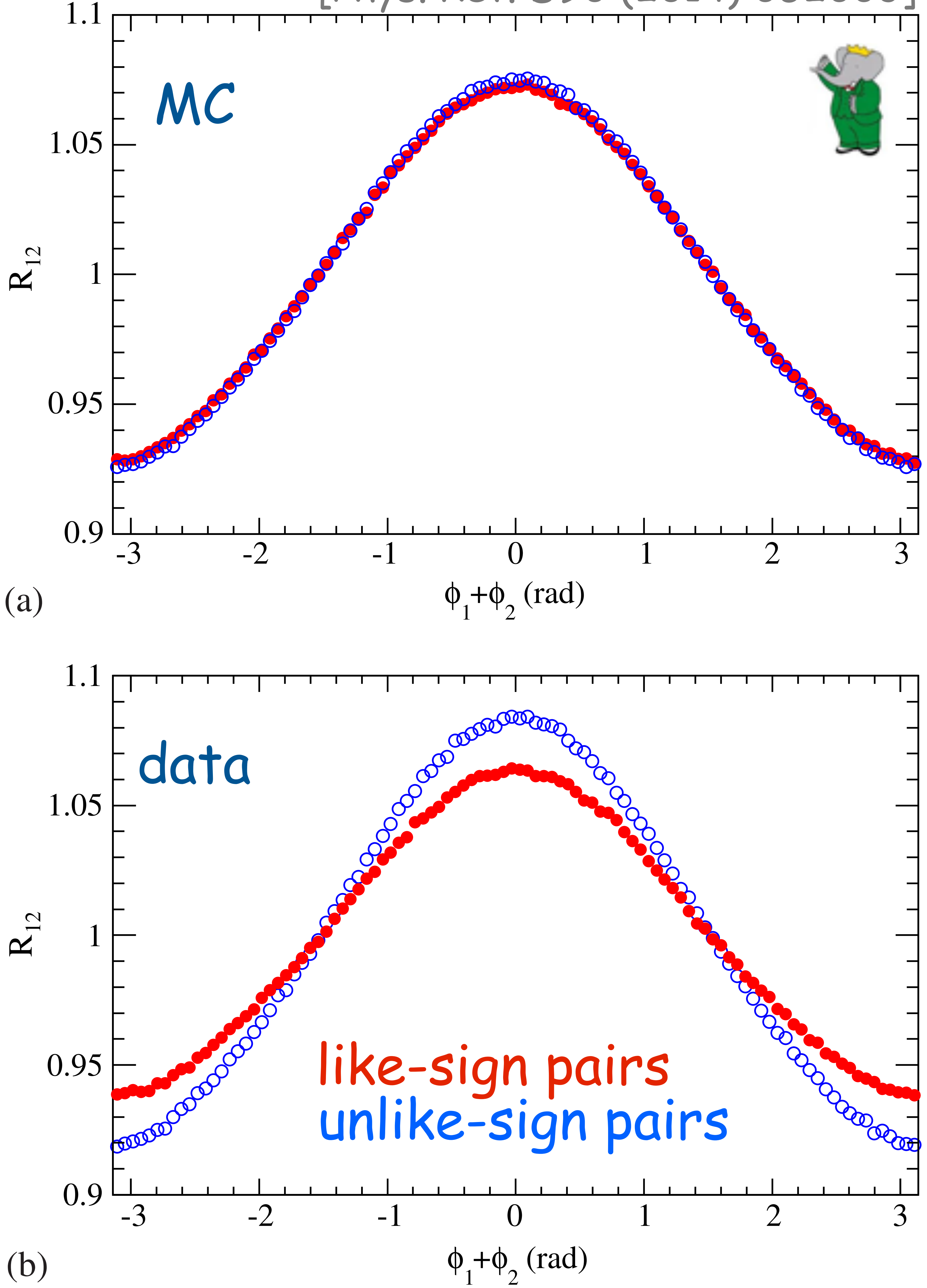
RF12

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

hadron pairs: angular correlations

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

[Phys. Rev. D90 (2014) 052003]



hadron pairs: angular correlations

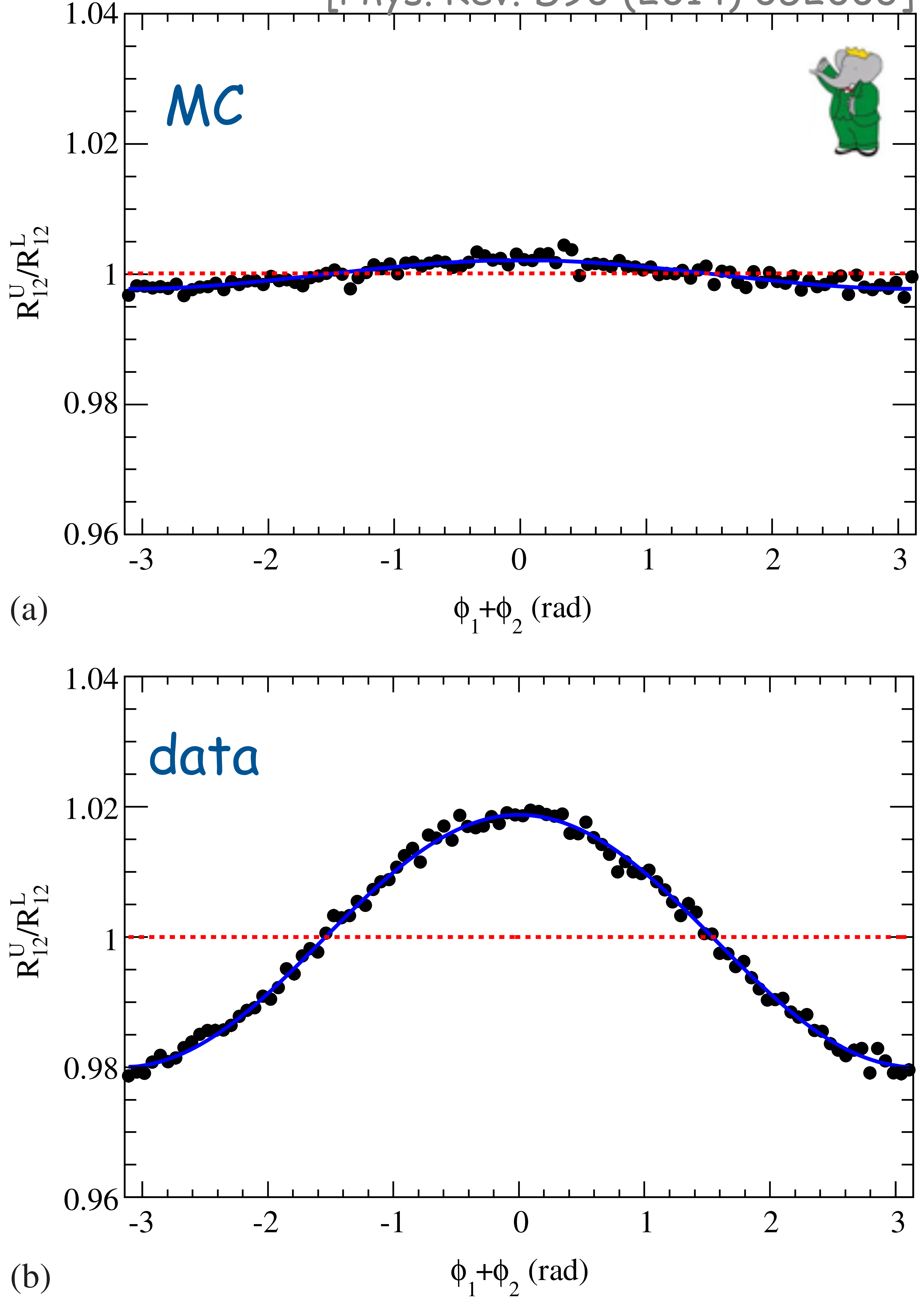
- challenge: large modulations even without Collins effect (e.g., in PYTHIA MC)
- construct double ratio of normalized-yield distributions R_{12}, e.g. unlike-/like-sign:

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

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

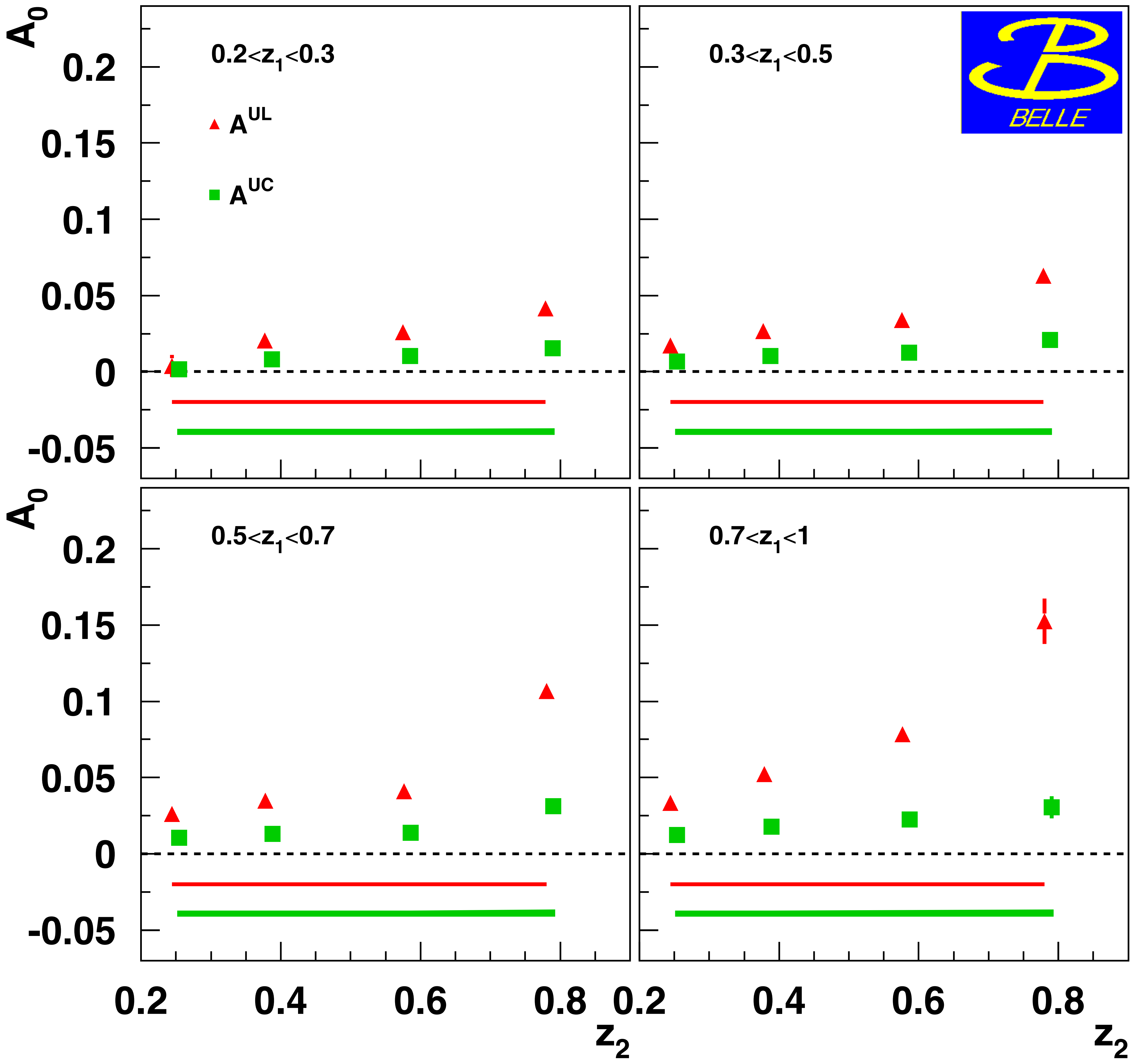
  - suppresses flavor-independent sources of modulations
  - $G^{U/L}$: specific combinations of FFs
  - remaining MC asymmetries ➠ systematics

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



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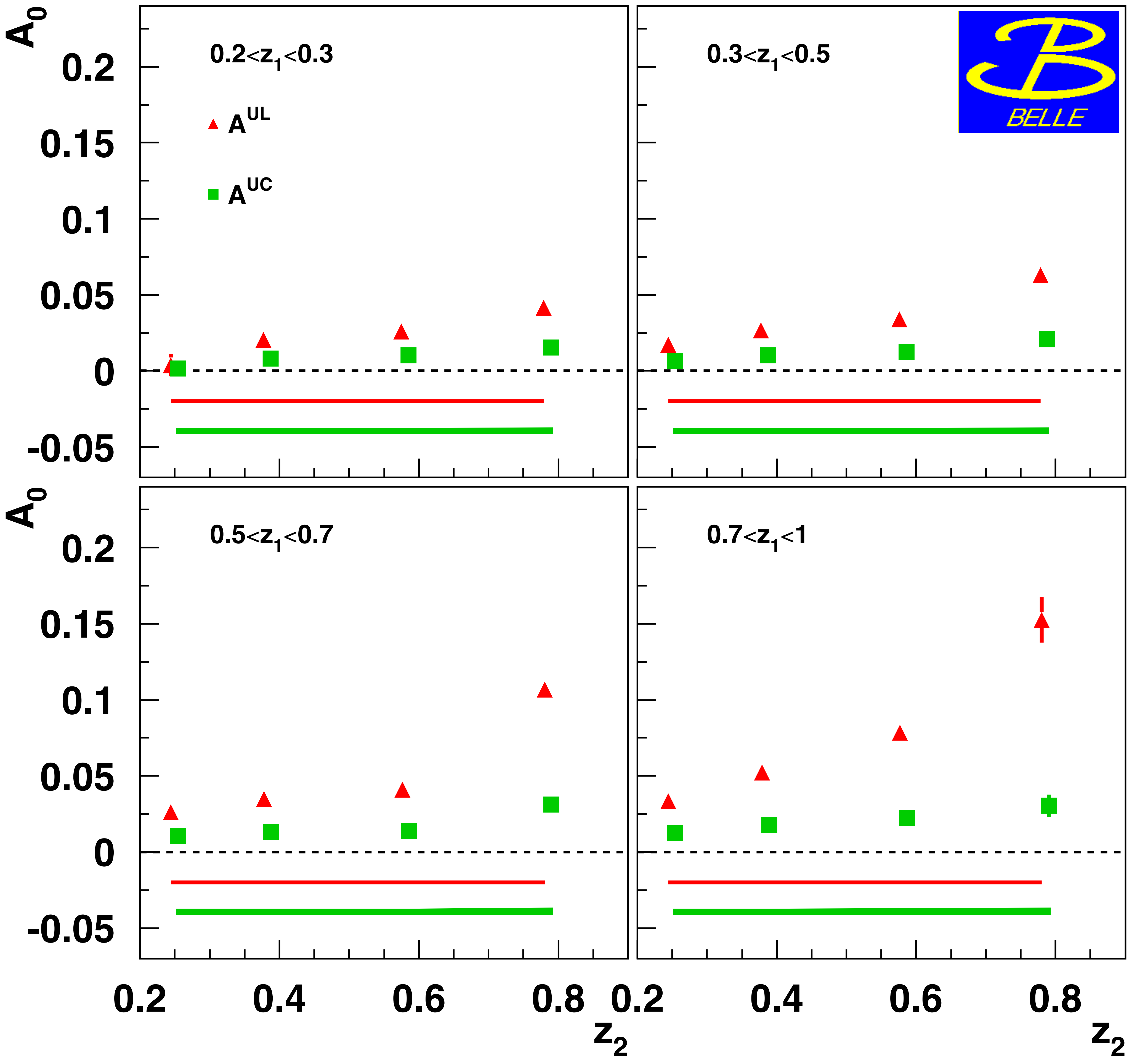
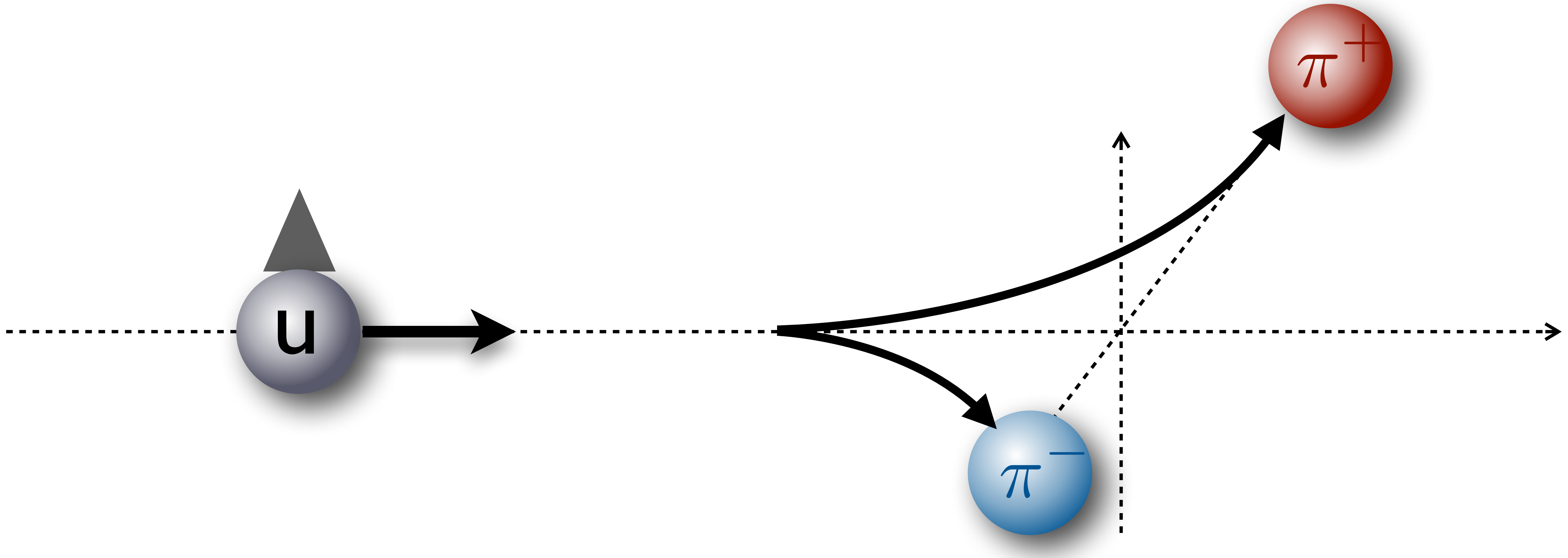
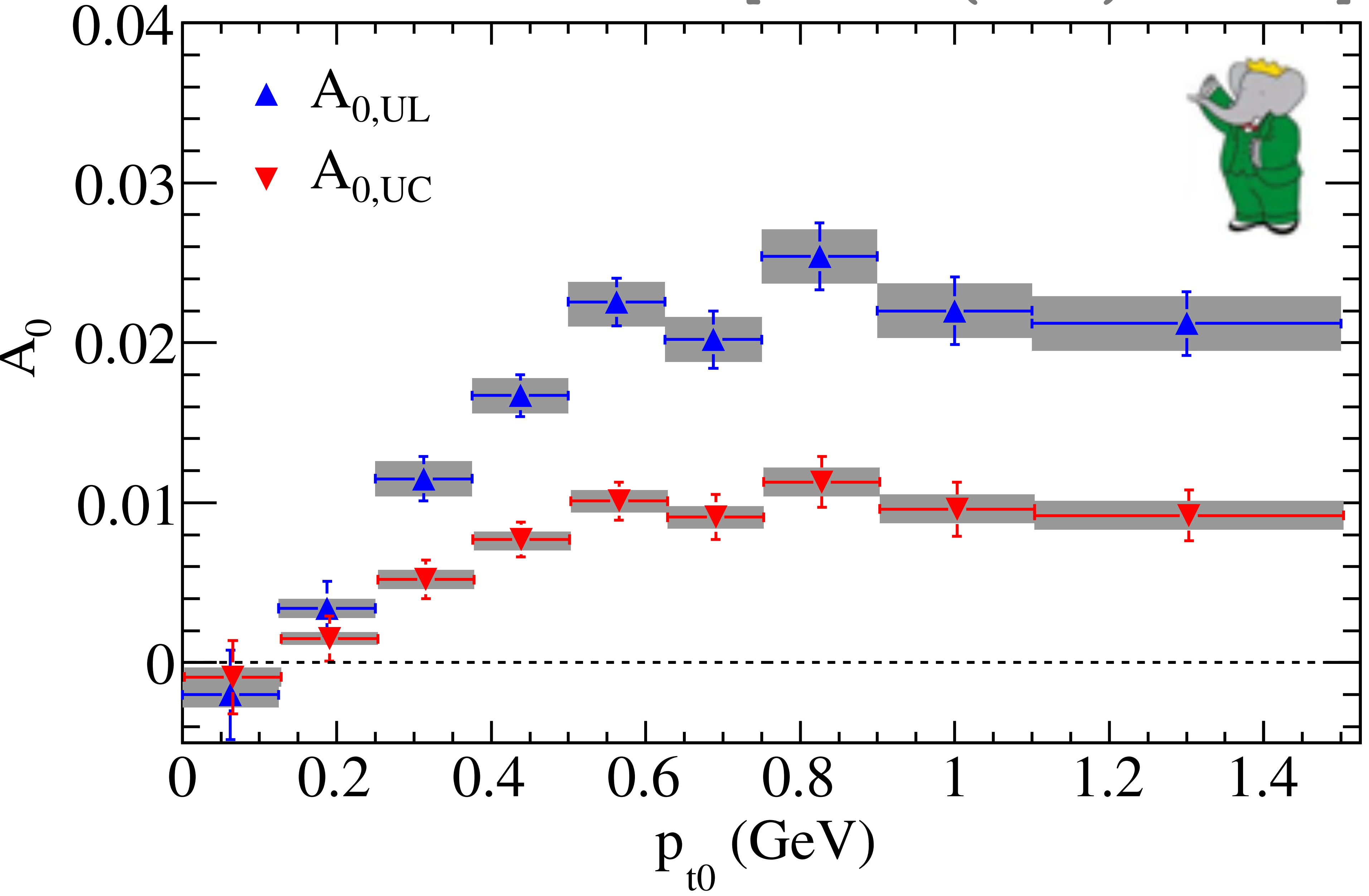
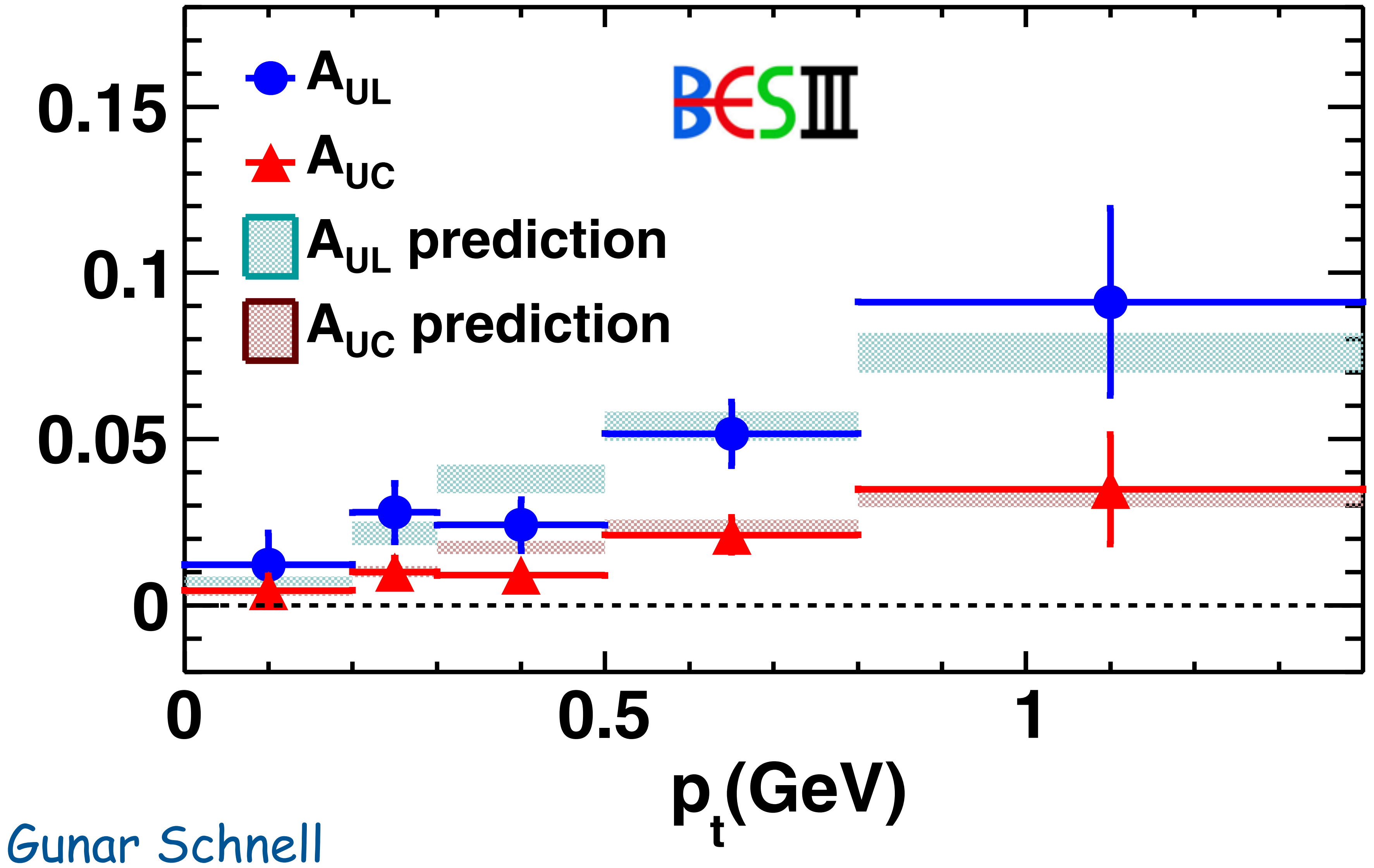




Collins asymmetries - going further

[PRD 90 (2014) 052003]

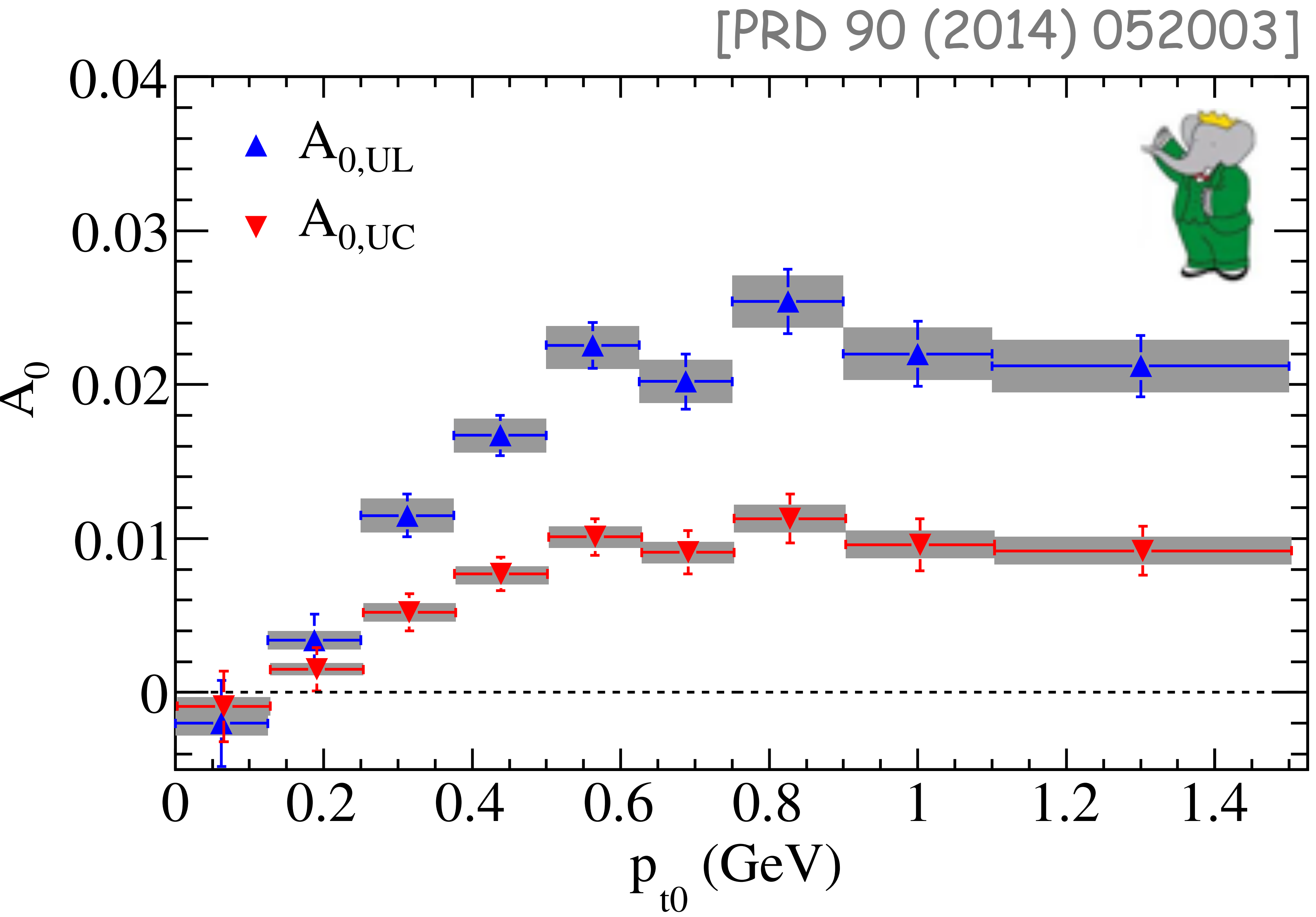


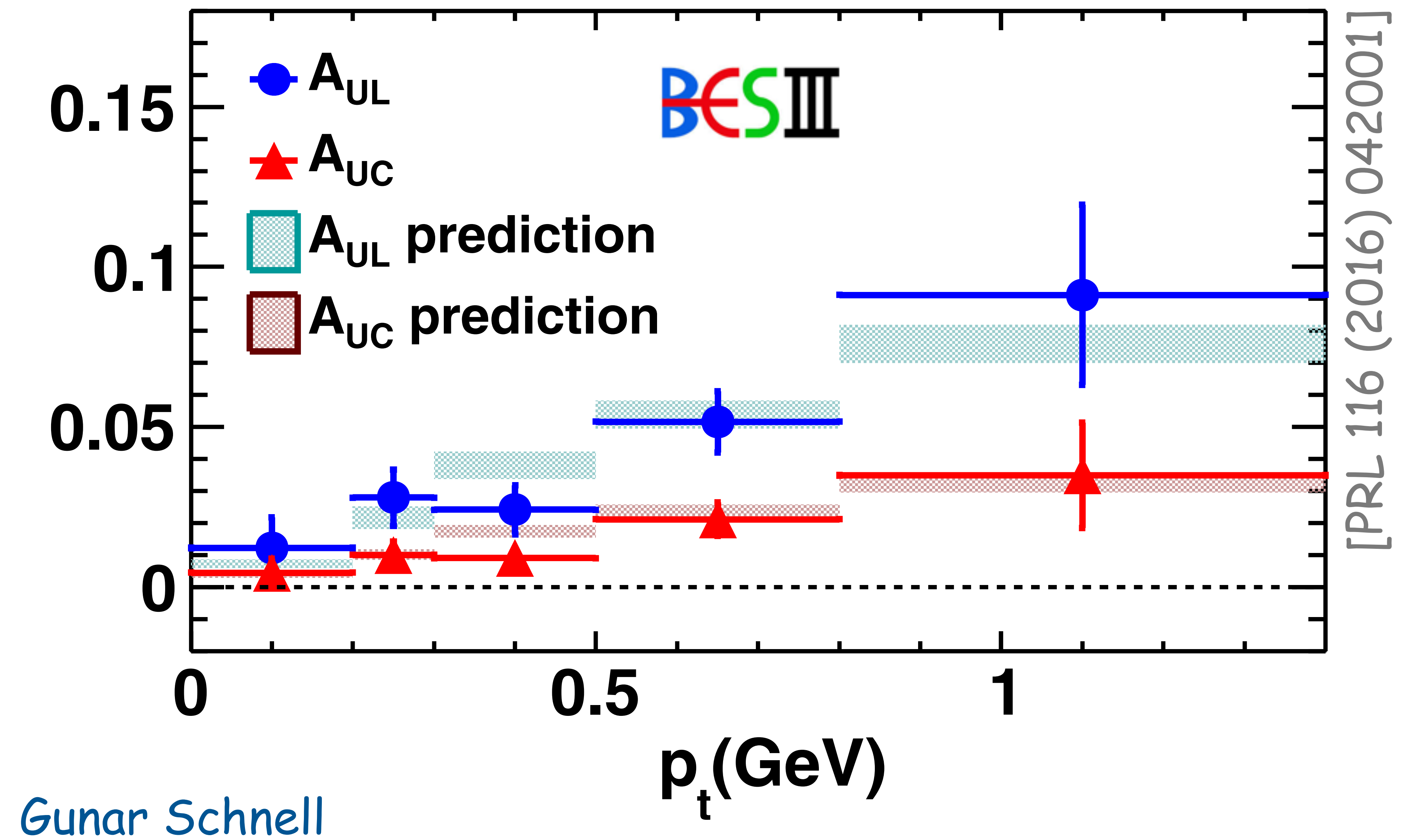


[PRL 116 (2016) 042001]

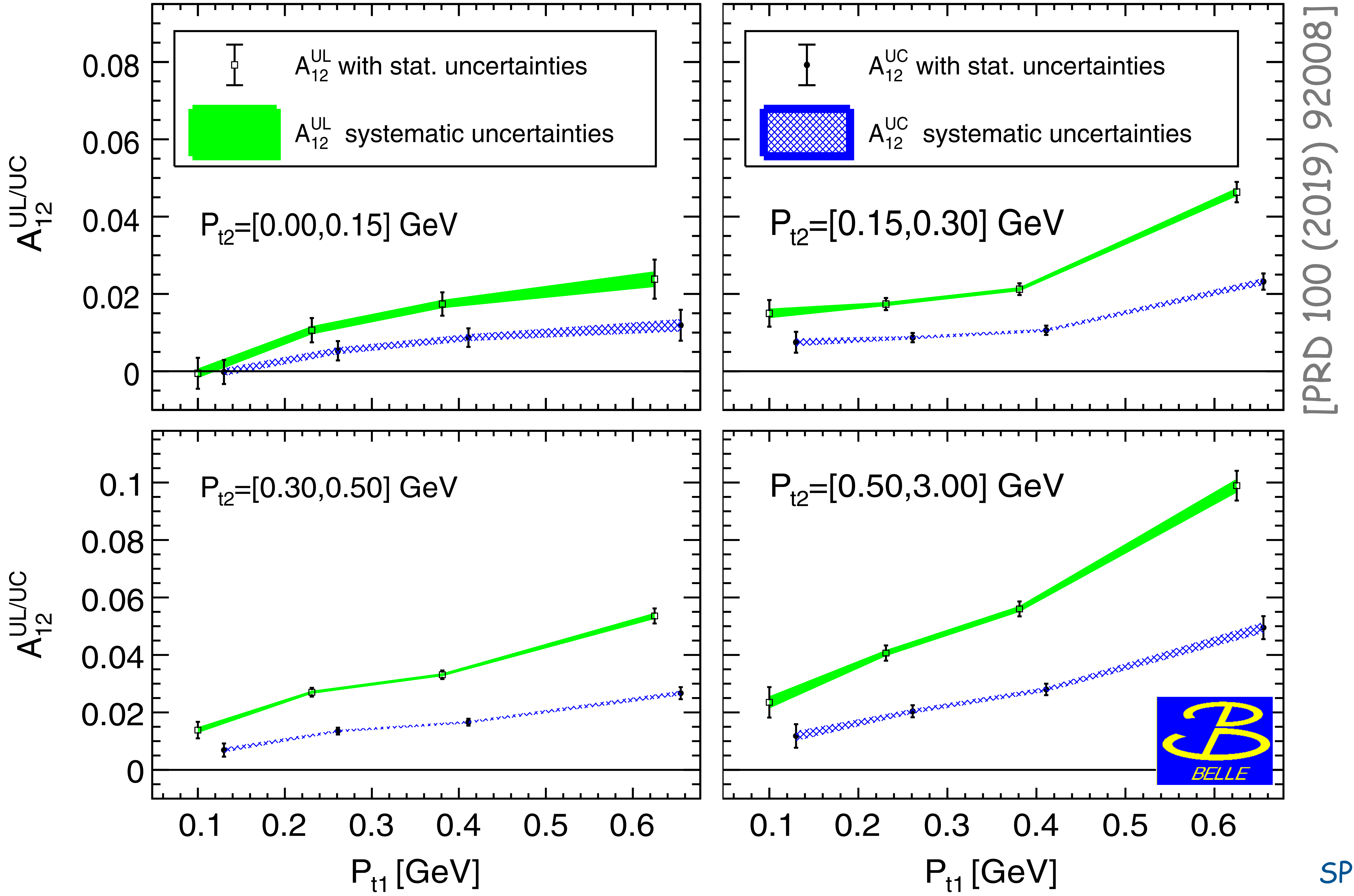
- p_T dependence for charged pions from BaBar & BESIII
  - typical rise with p_T; turnover around 0.8 GeV

Collins asymmetries - going further





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



Collins asymmetries - going further

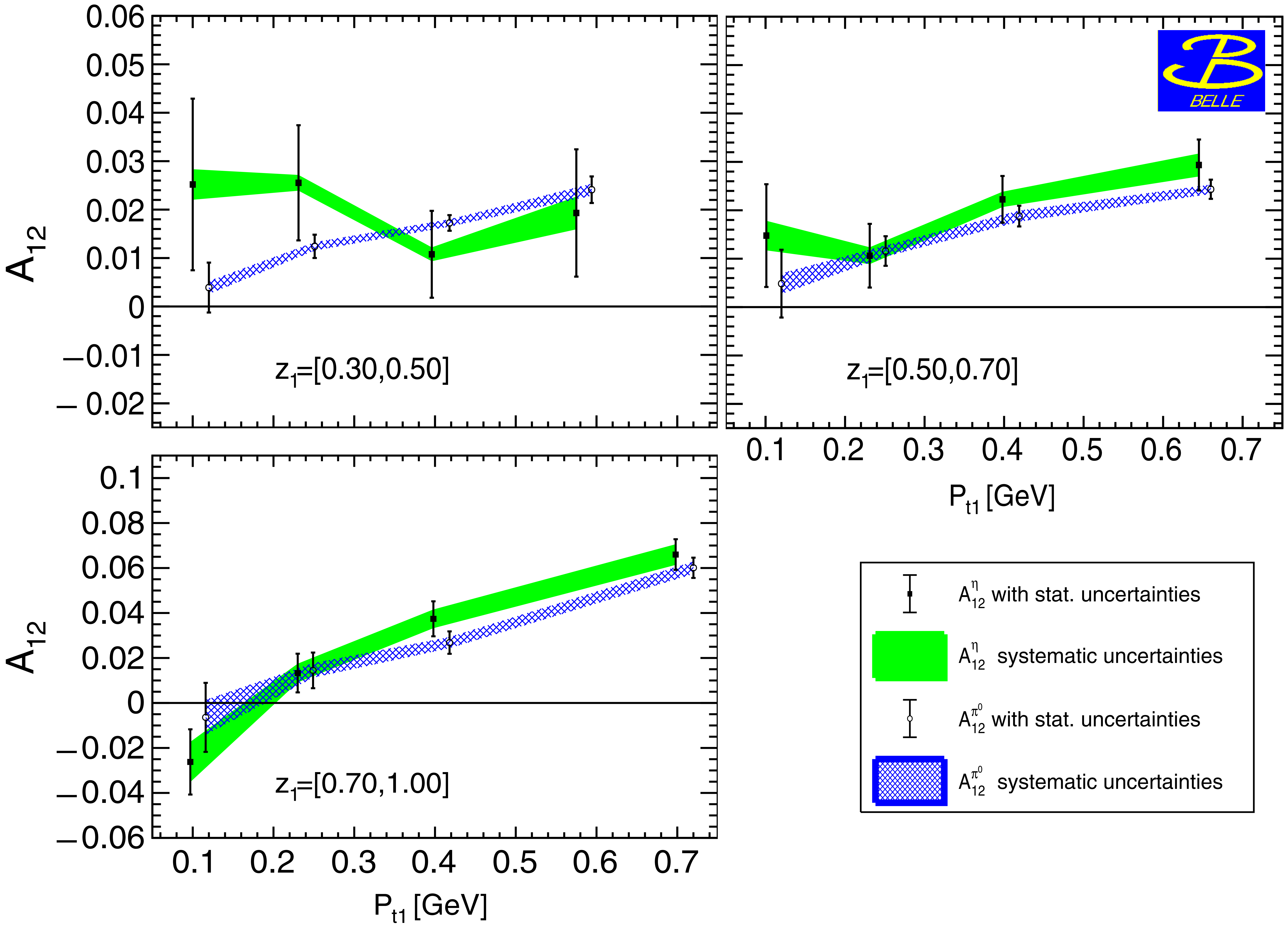
- … as well as for neutral pion and eta

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

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

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

[PRD 100 (2019) 92008]



Collins asymmetries - going further

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

Collins asymmetries - going further

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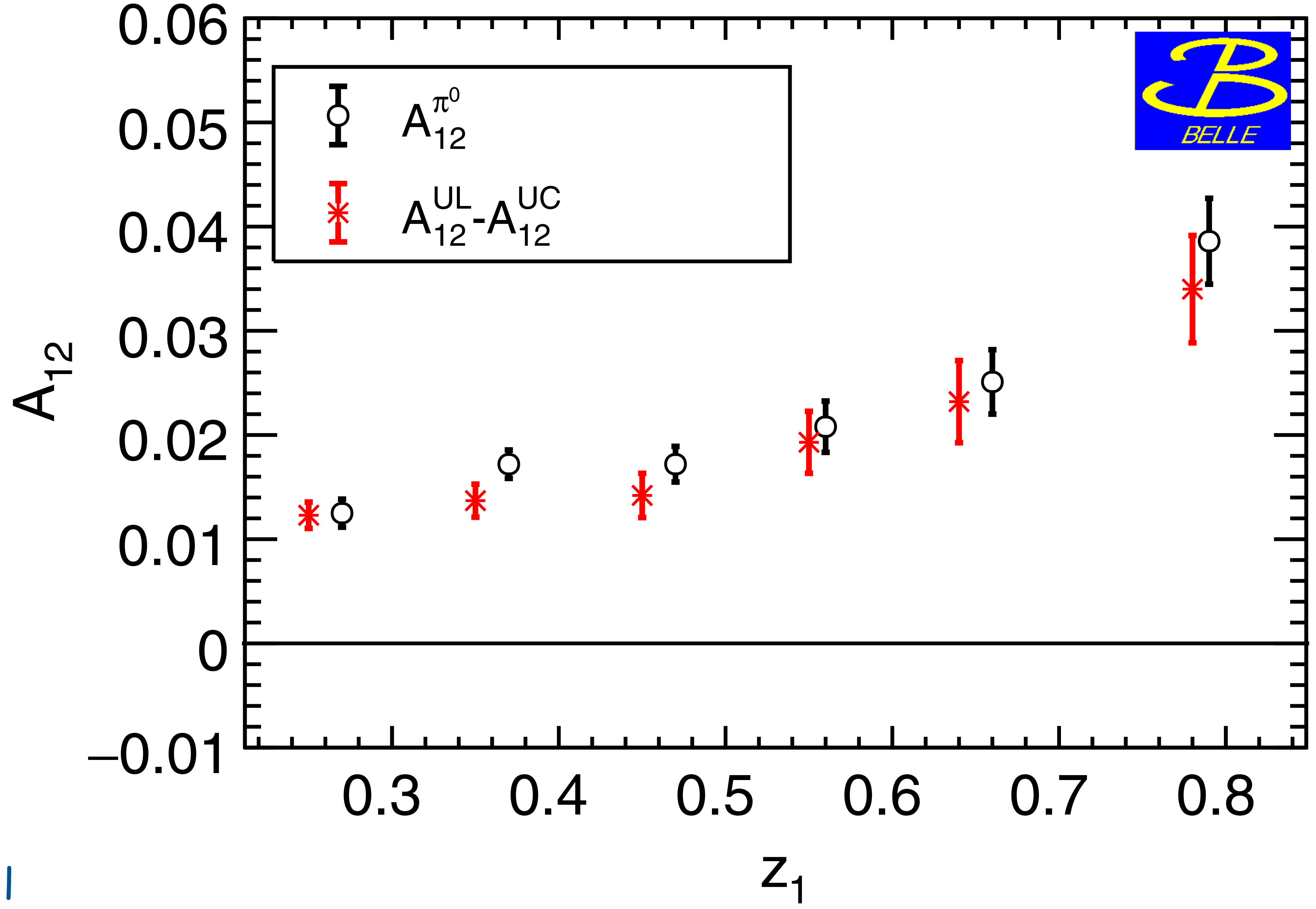

[PRD 100 (2019) 92008]

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

Collins asymmetries - going further

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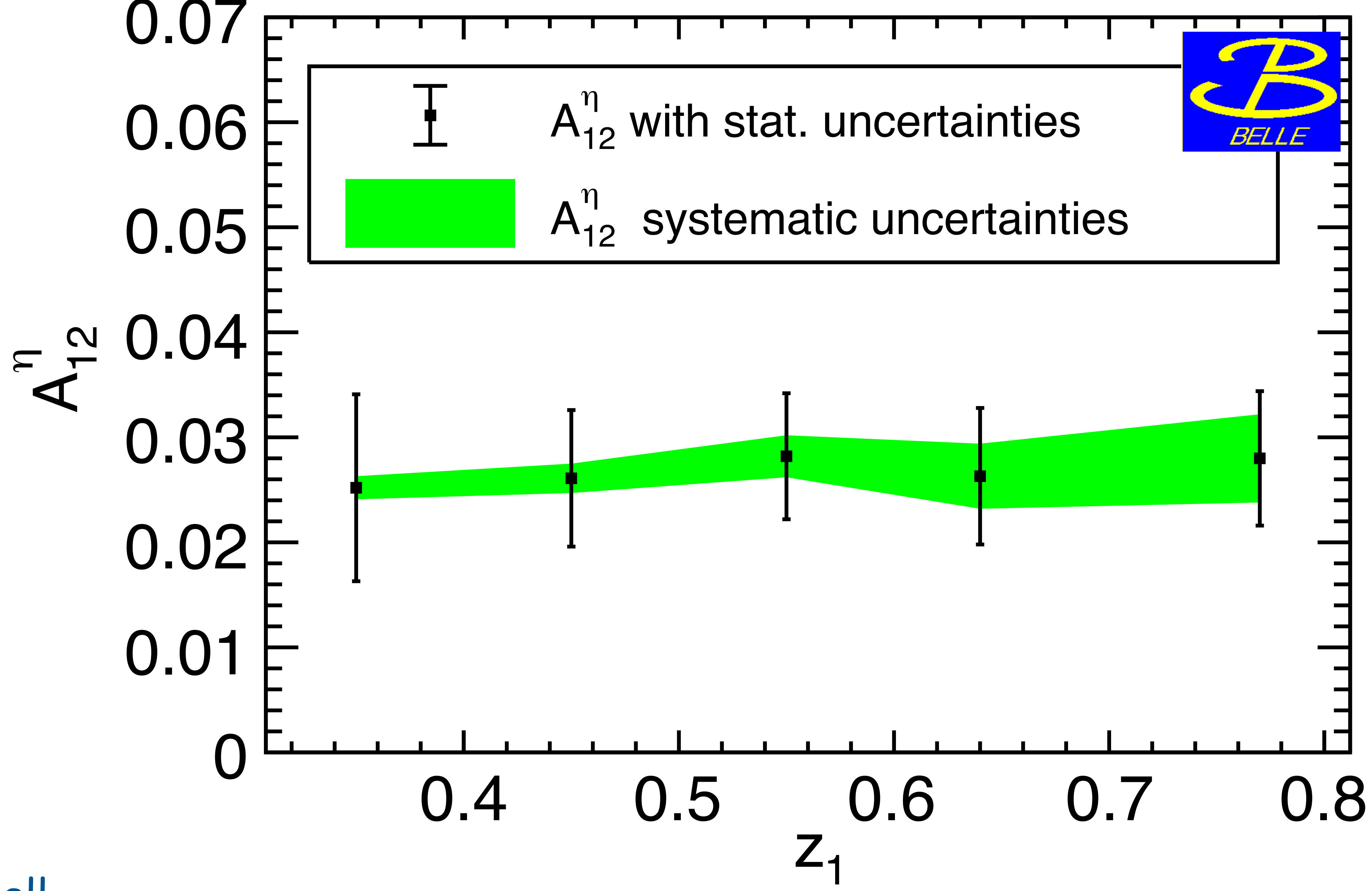
[PRD 100 (2019) 92008]

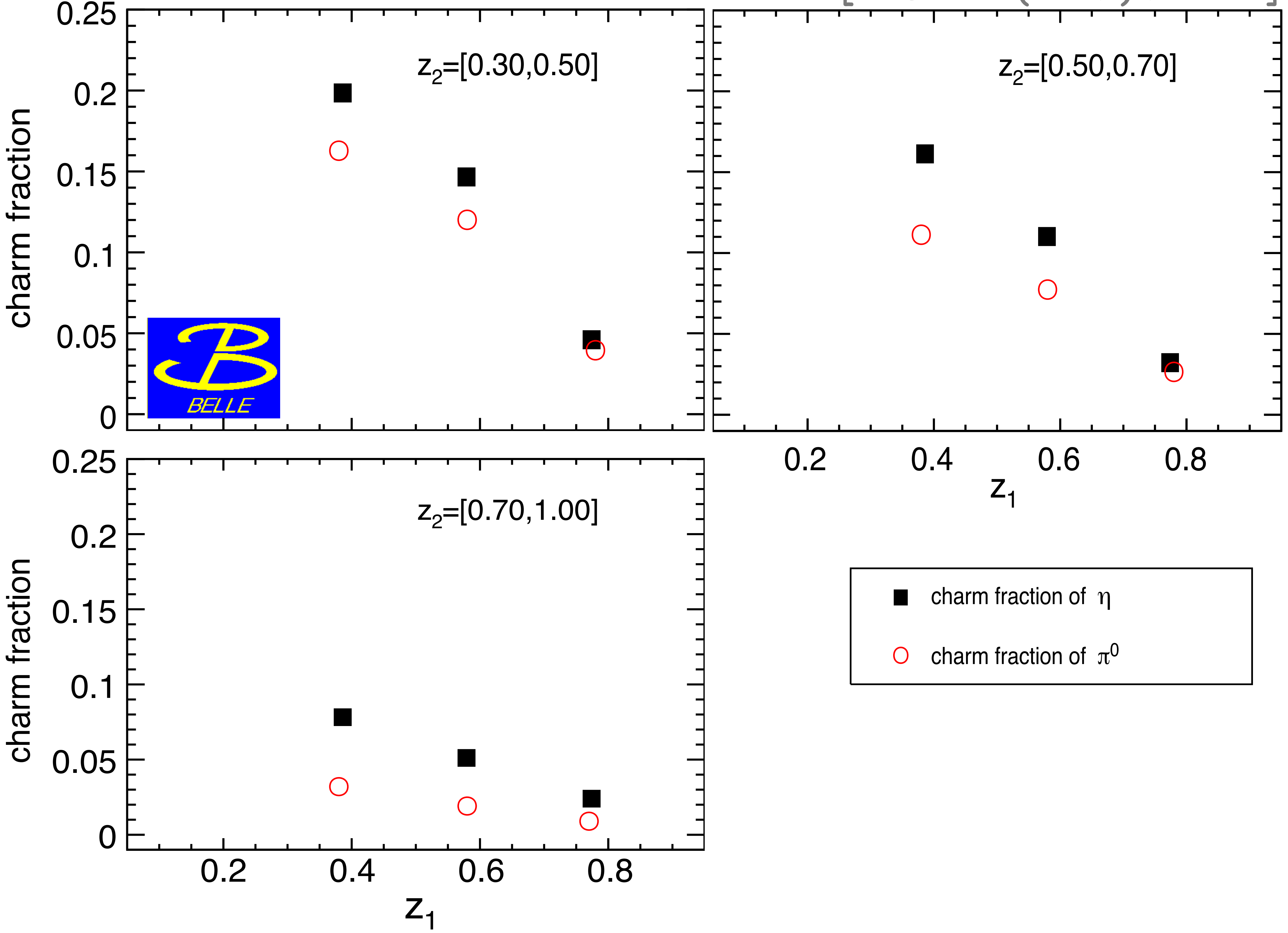


- consistency between neutral and charged pions
  - typical rise with z also seen for neutral pions
  - … while basically flat for eta

Collins asymmetries - going further

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

[PRD 100 (2019) 92008]



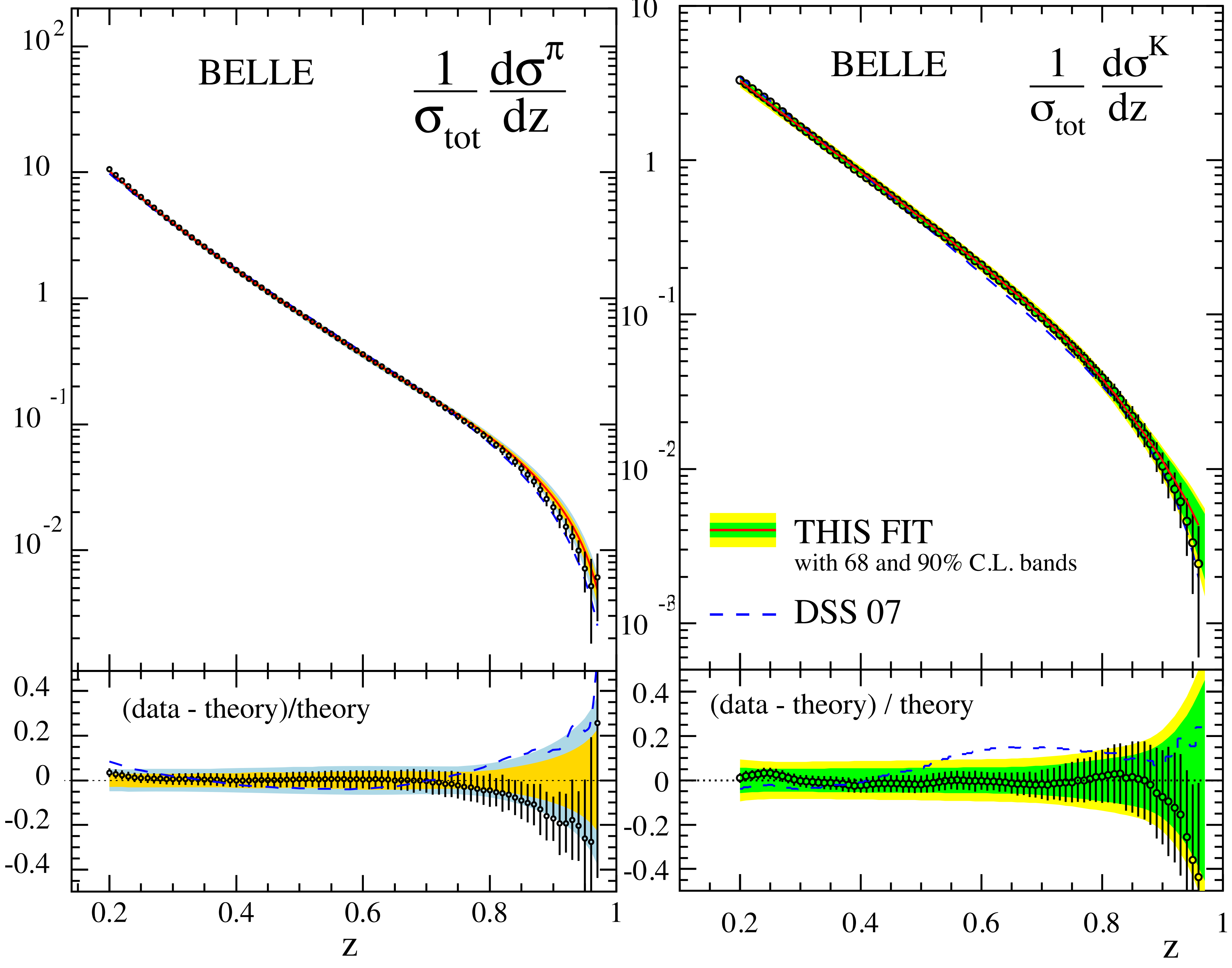
the unpolarized case

— baseline for asymmetries —

(if time permits)

single-hadron production

- very precise data for charged pions and kaons
- Belle data available up to very large z (z<0.98)
- included in 2015 DEHSS fits [e.g., PRD91 (2015) 014035]



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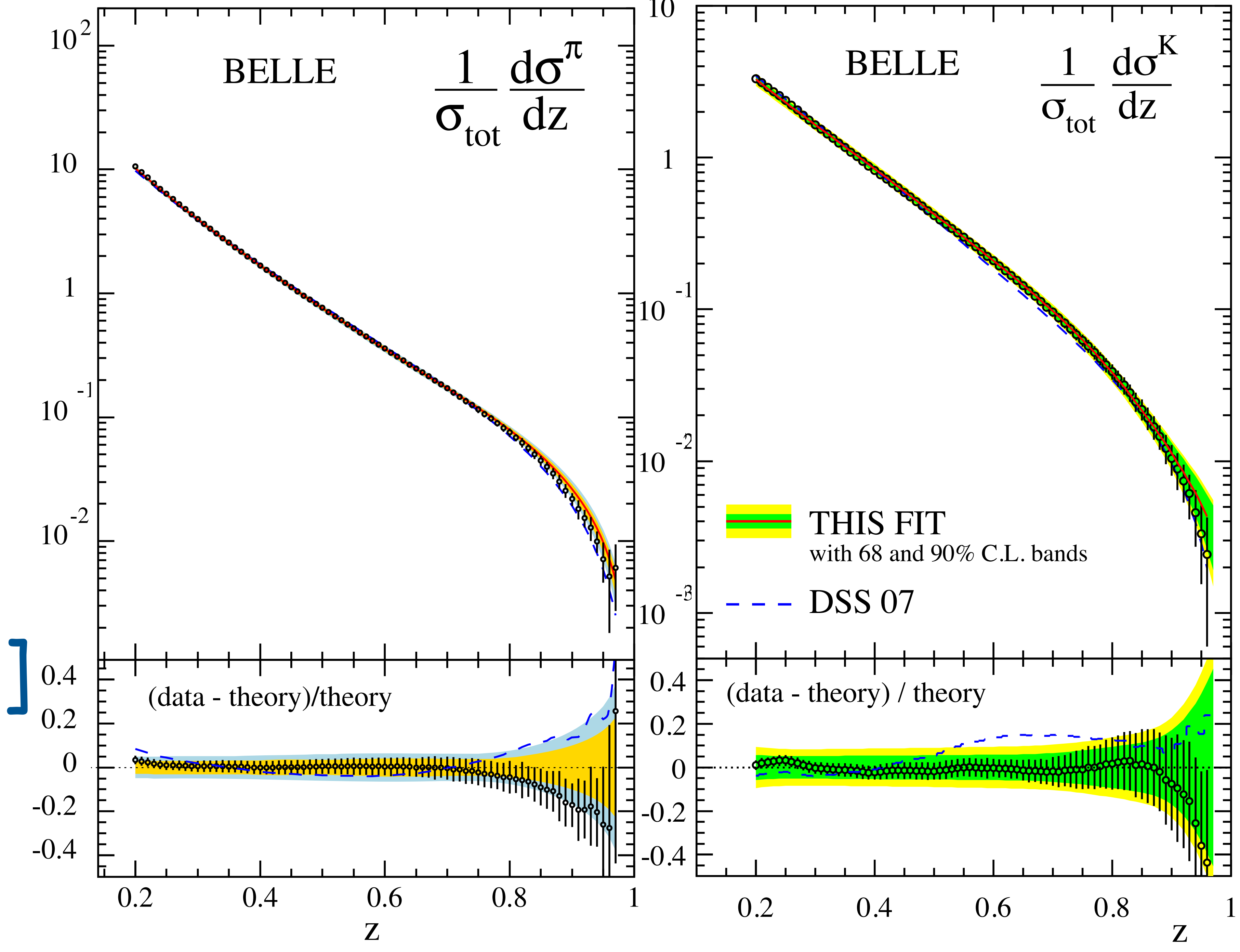
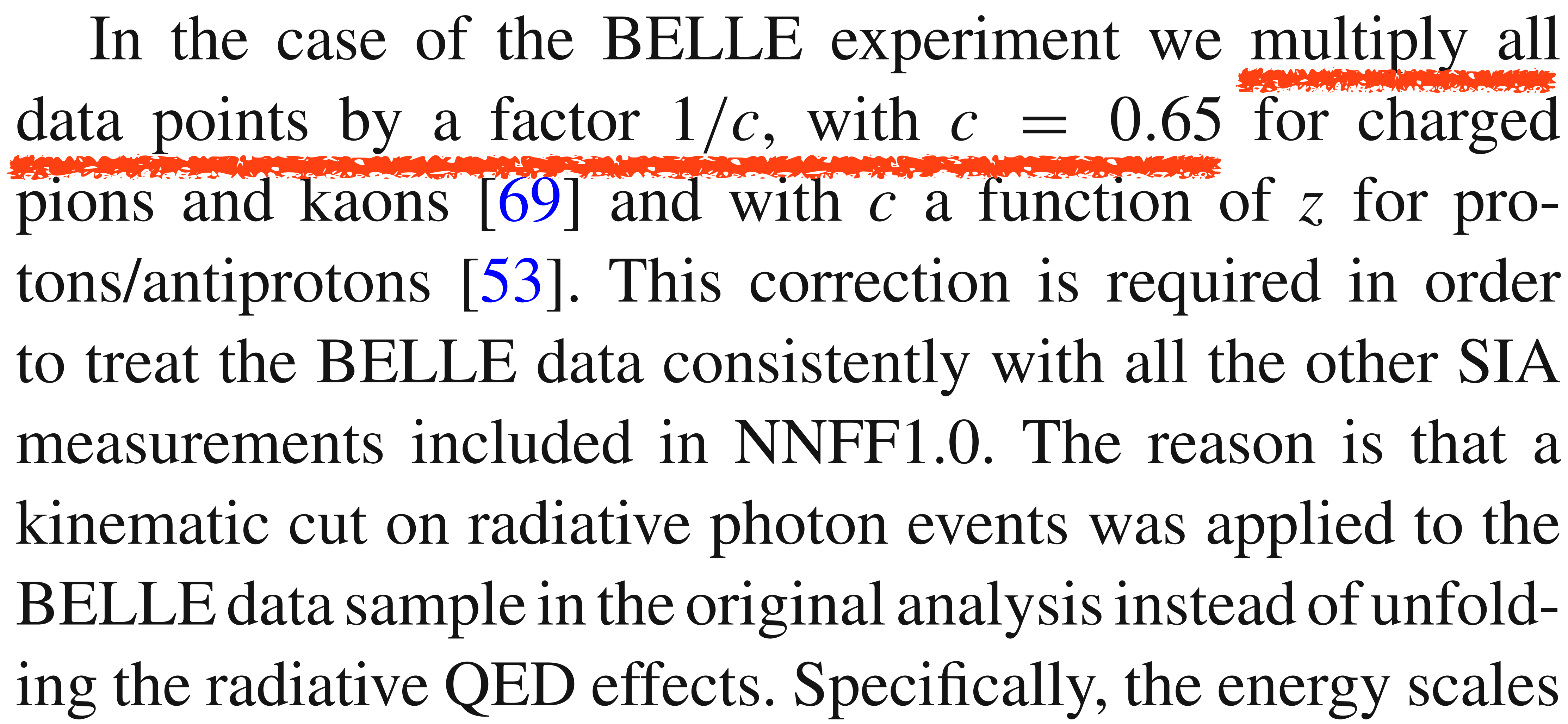


[EPJC 77 (2017) 516, NNFF1.0]


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

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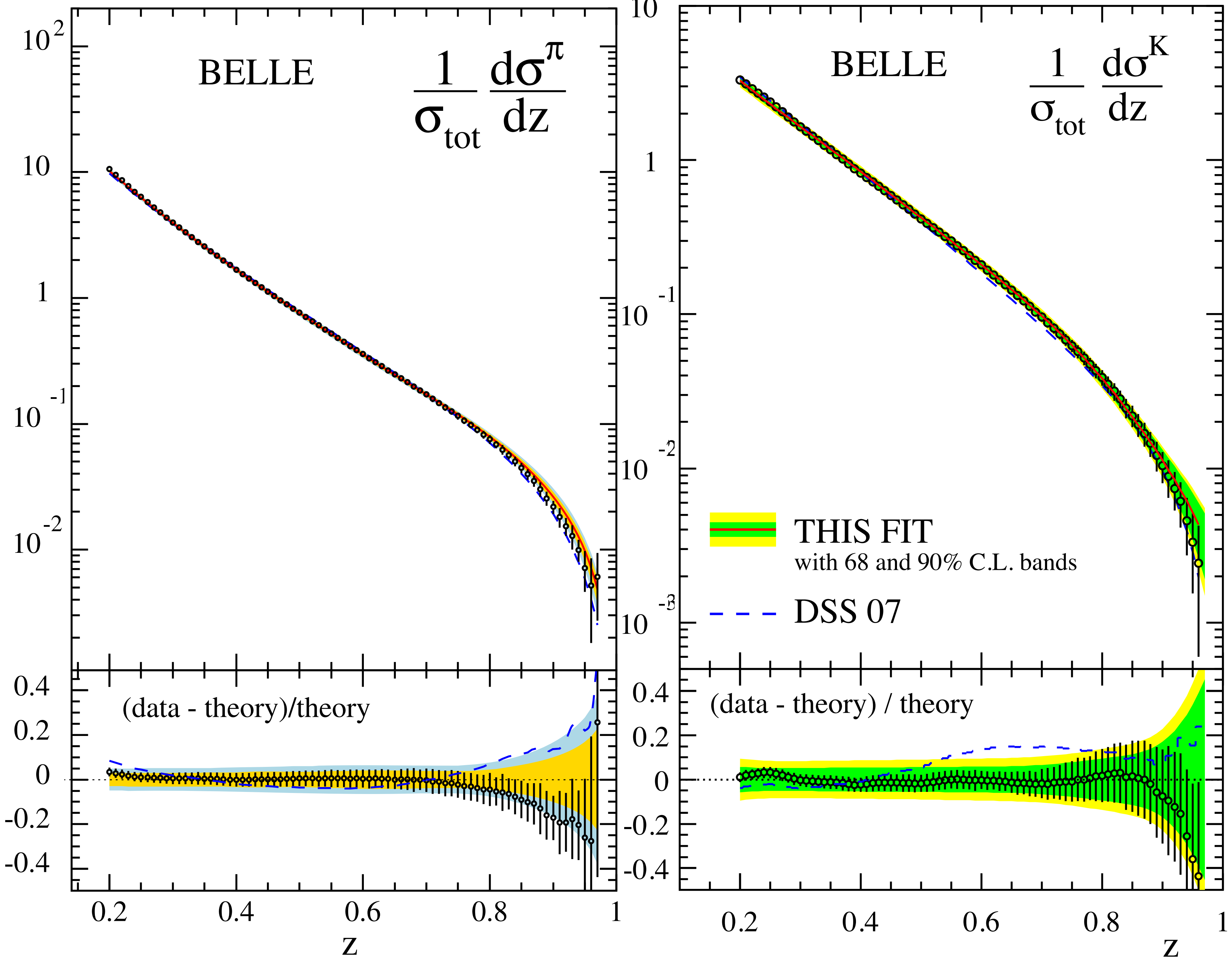
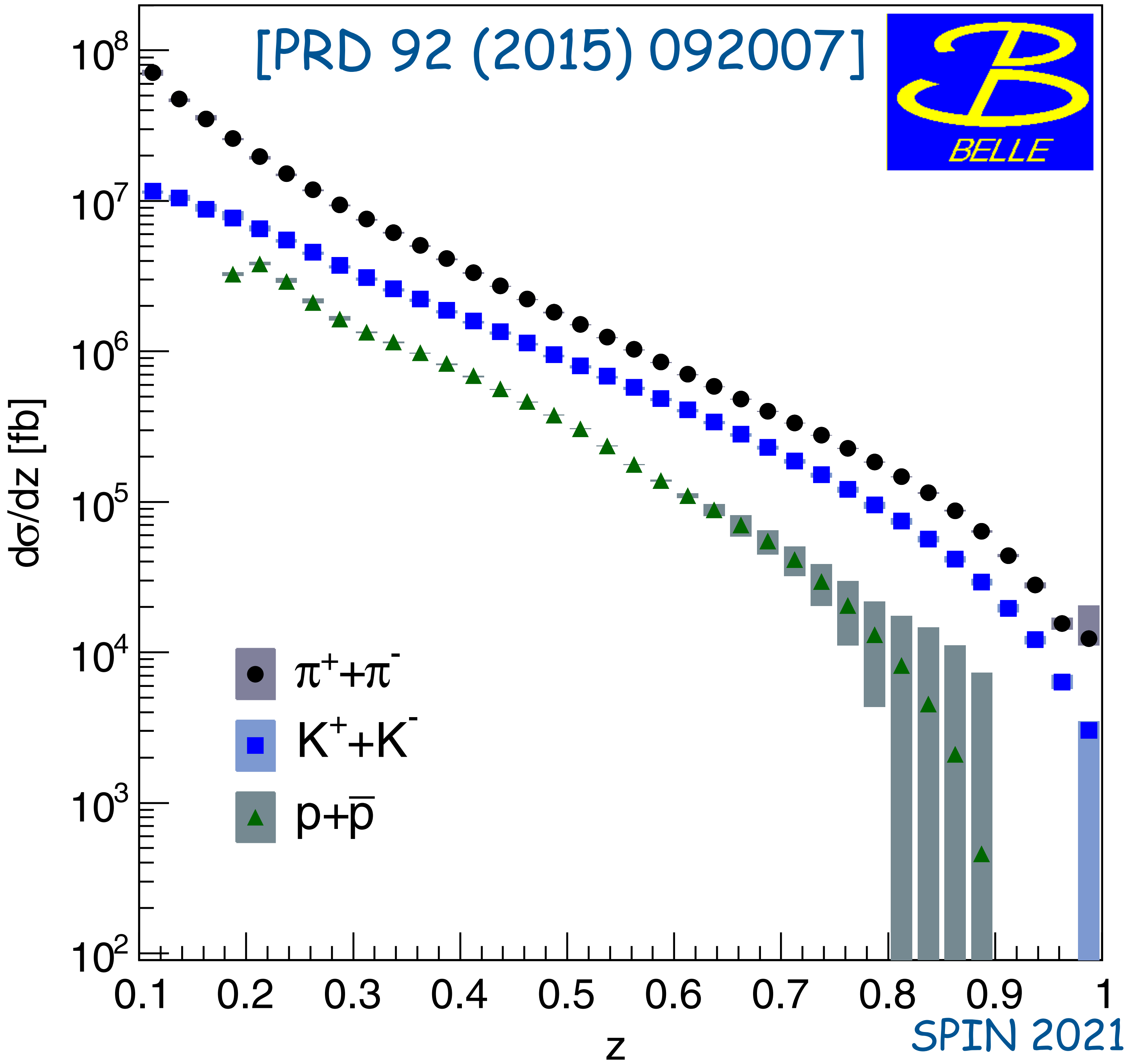
    - similar z dependence as pions
    - about ~⅕ of pion cross sections




[PRD 92 (2015) 092007]

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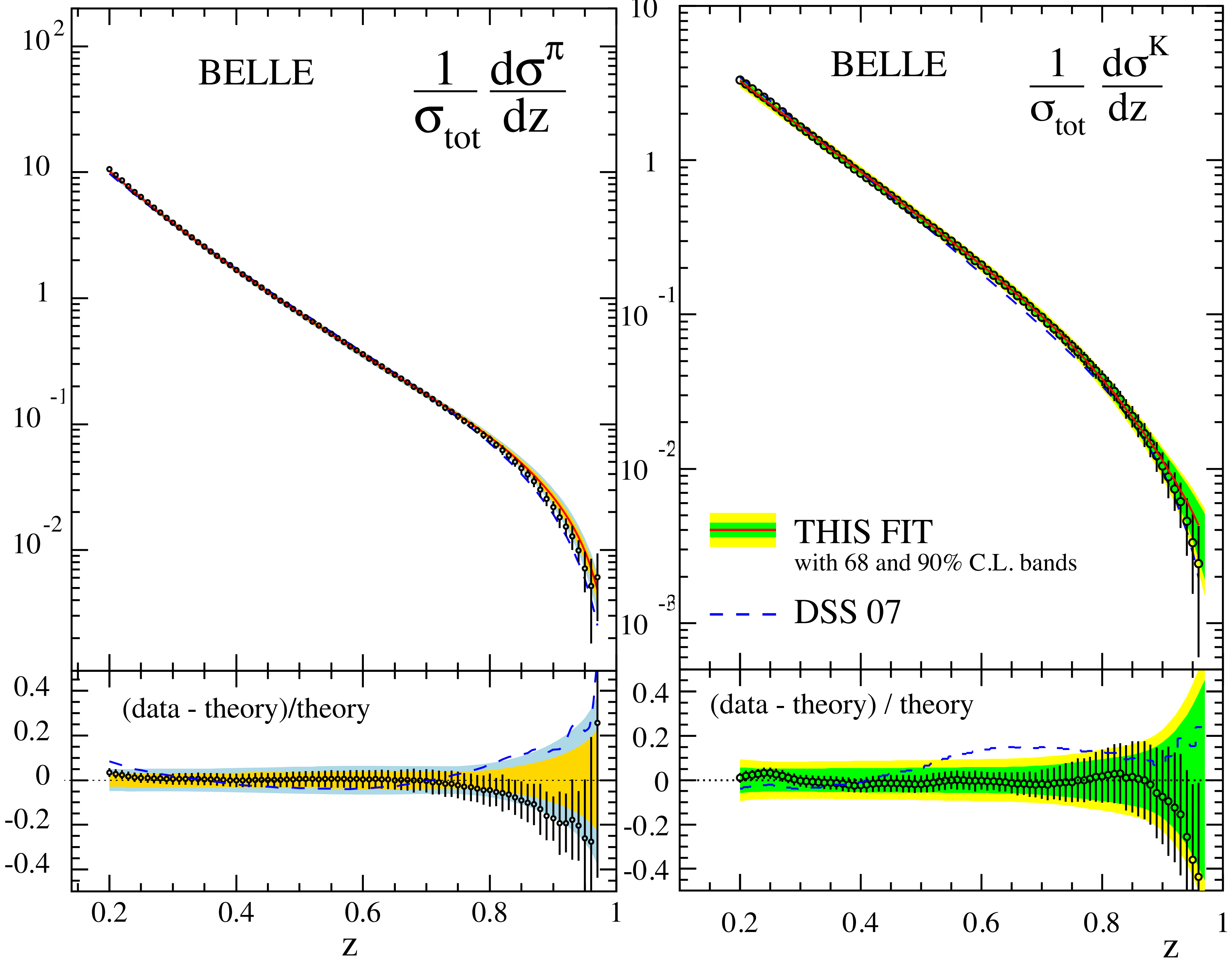
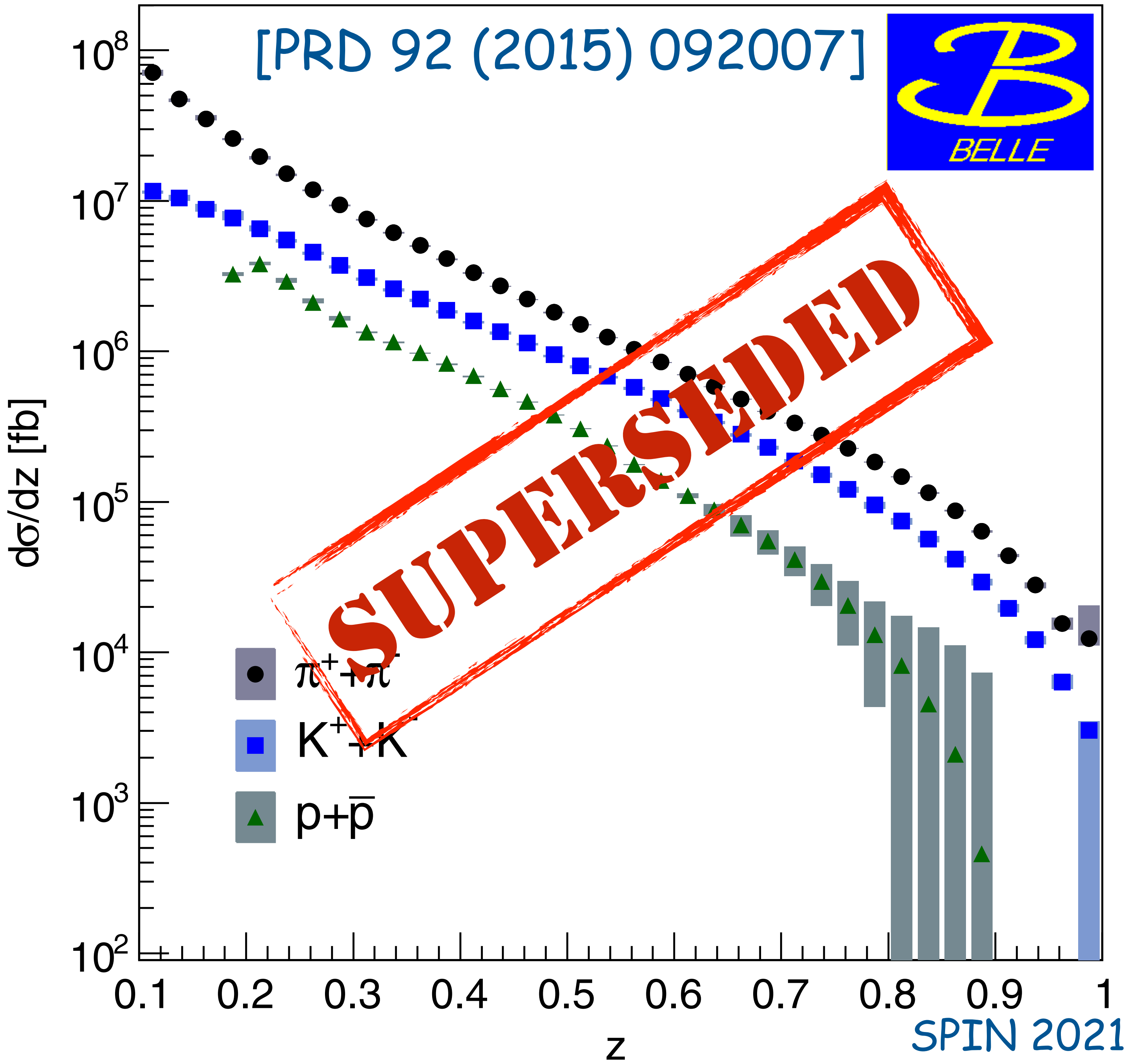
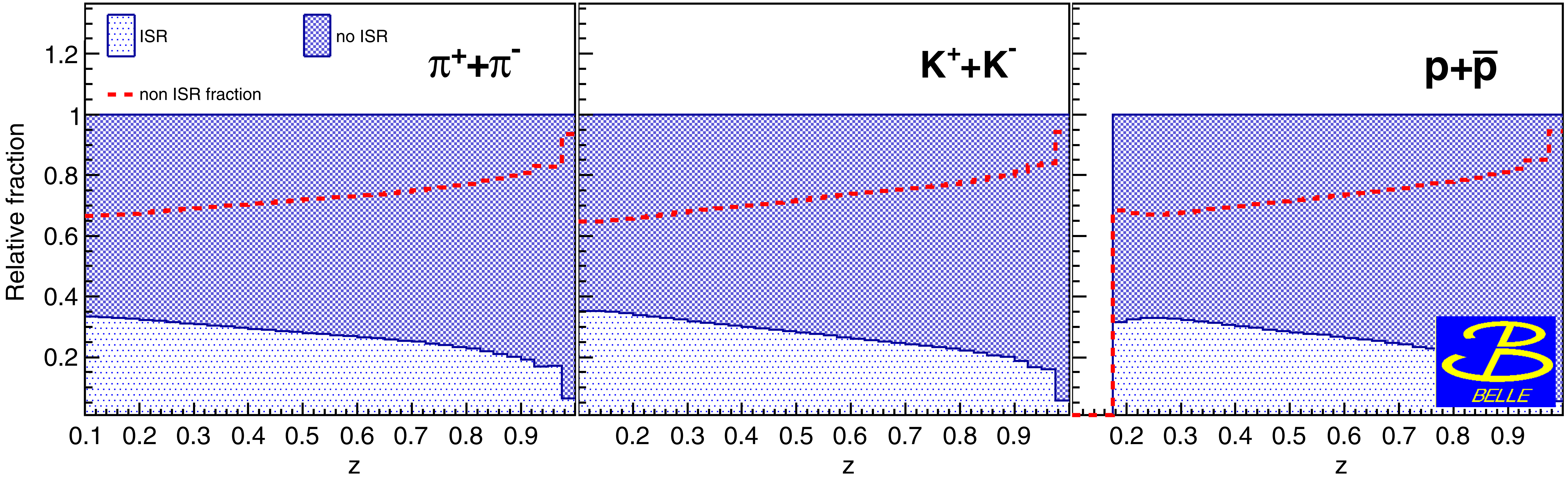
- Belle **re-analysis** presented in **PRD 101 (2020) 092004**



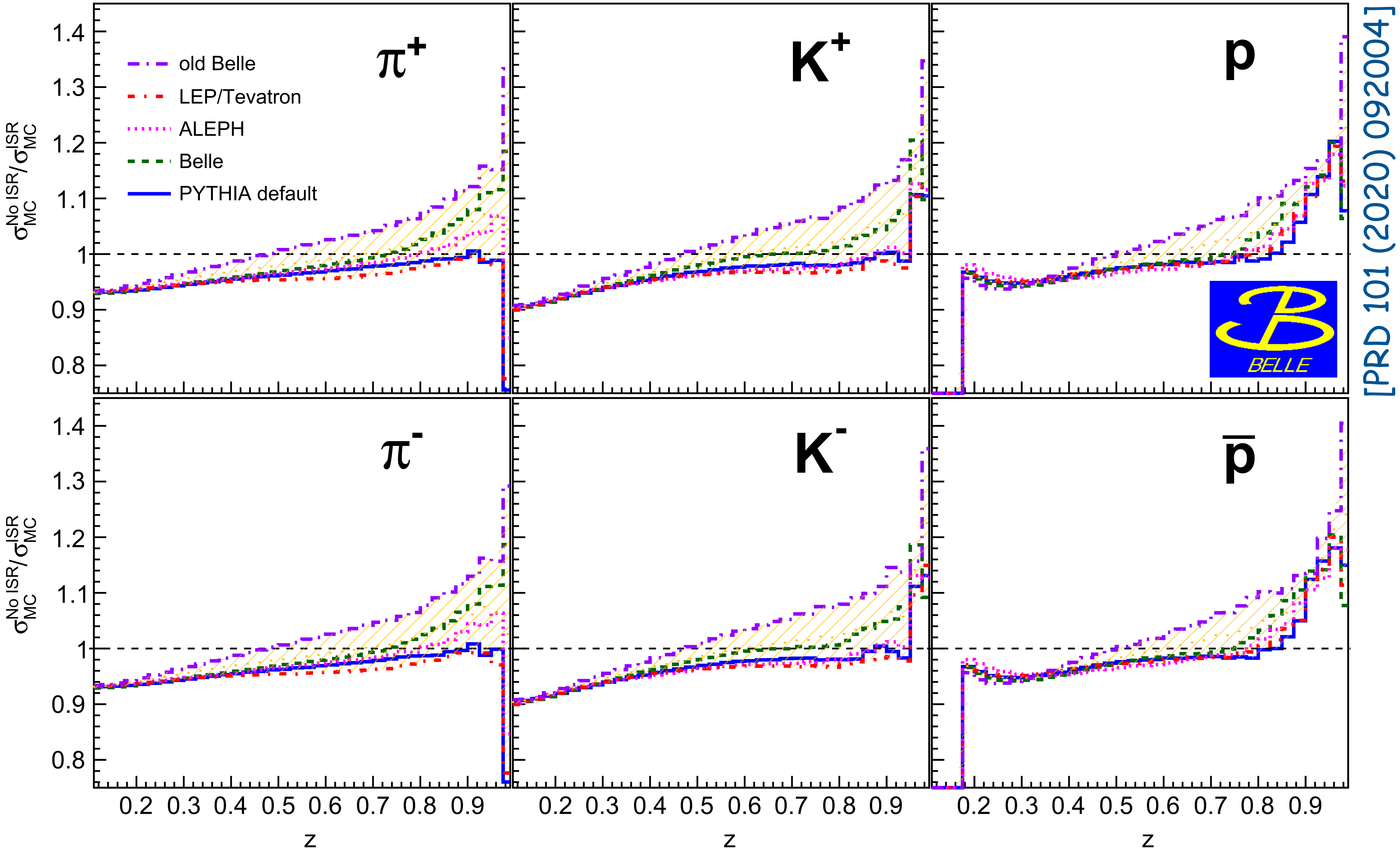


ISR corrections - PRD 92 (2015) 092007



- relative fractions of hadrons as a function of z originating from ISR or non-ISR events (≡ 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 the events -> strictly speaking not single-inclusive annihilation

ISR corrections - PRD 101 (2020) 092004

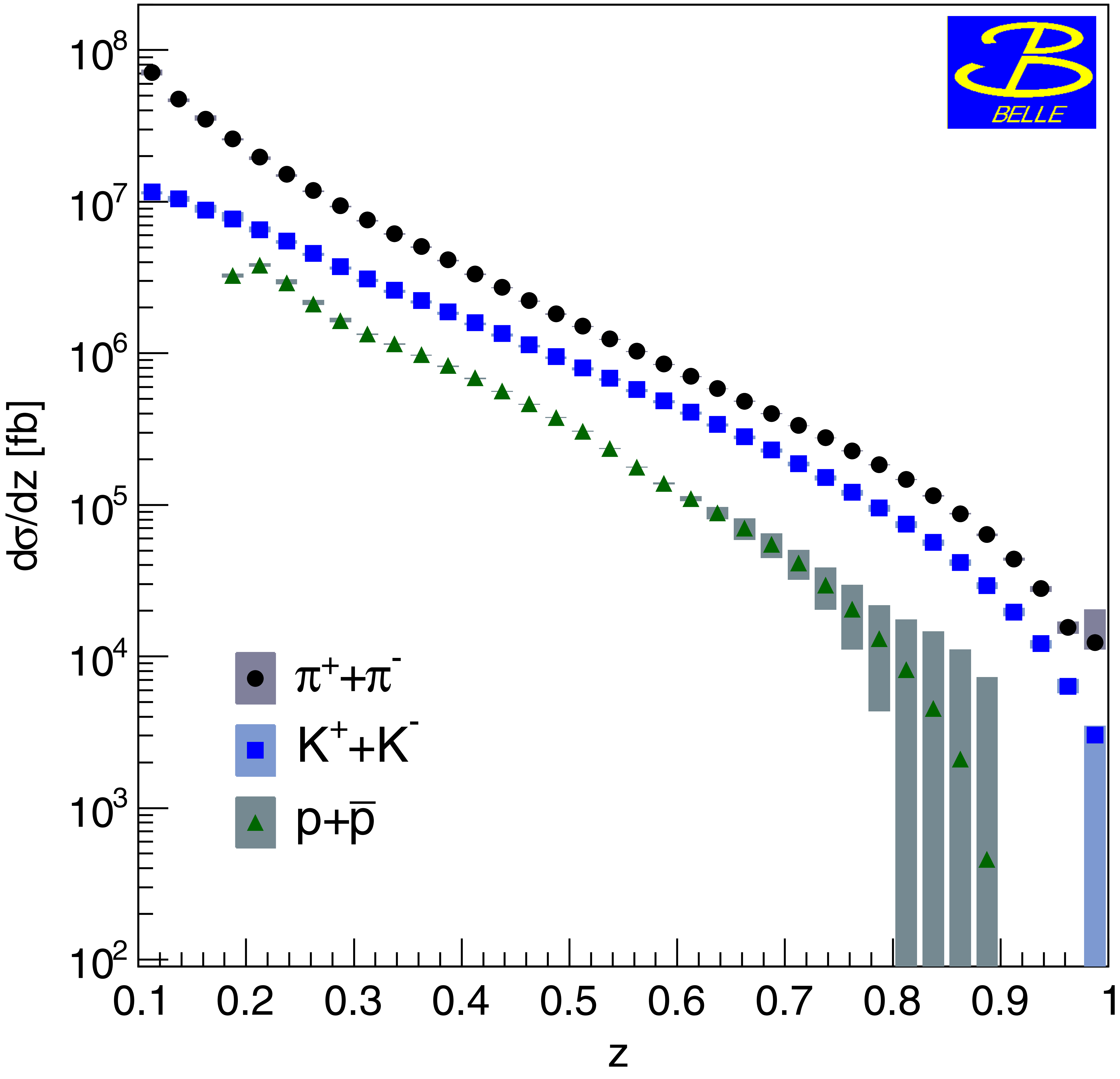


- non-ISR / ISR fractions based on PYTHIA switch MSTP(11)
- PYTHIA model dependence; absorbed in systematics by variation of tunes

comparison old&new Belle single-hadron cross sections

- previous analysis

[PRD 92 (2015) 092007]



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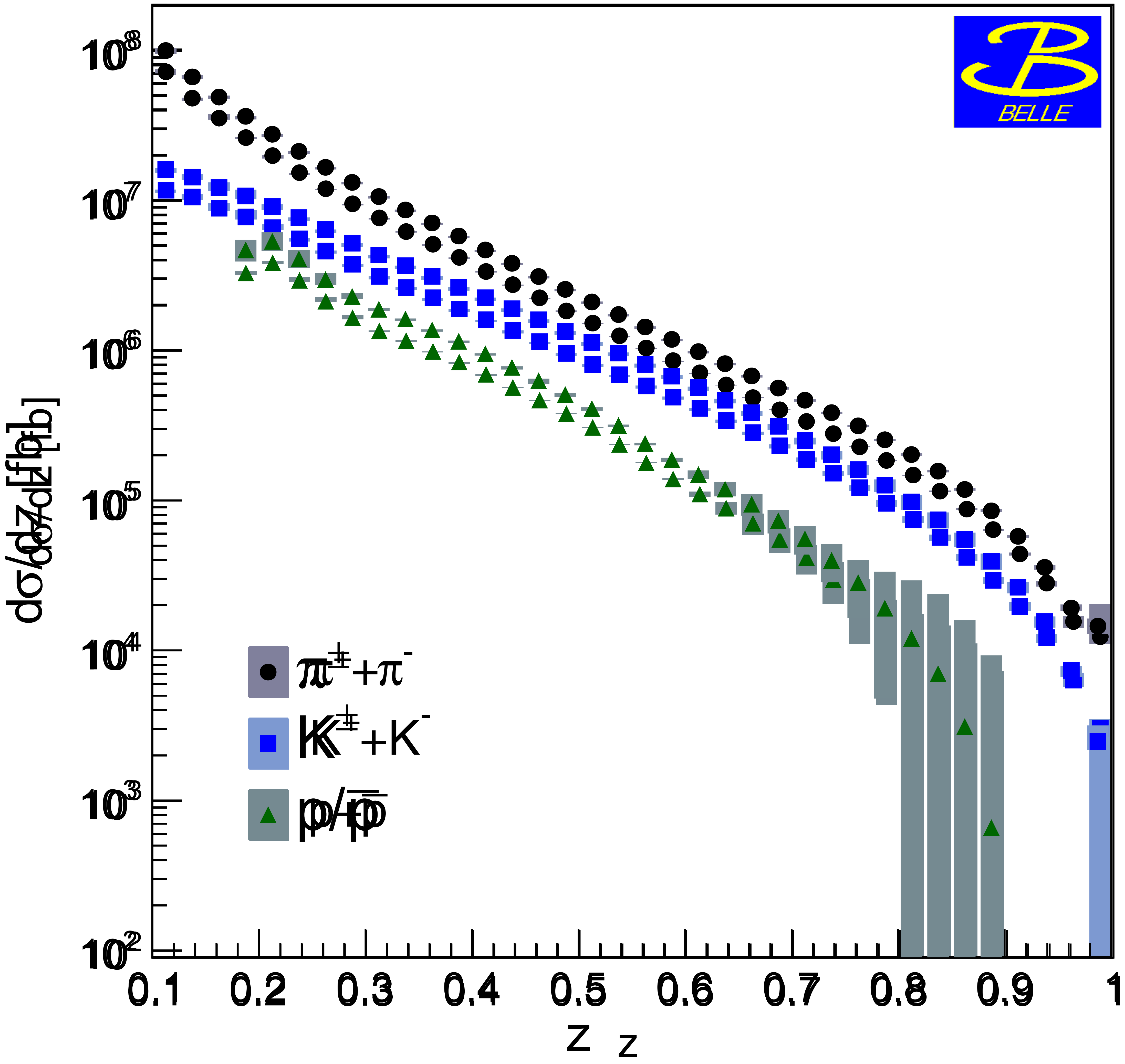
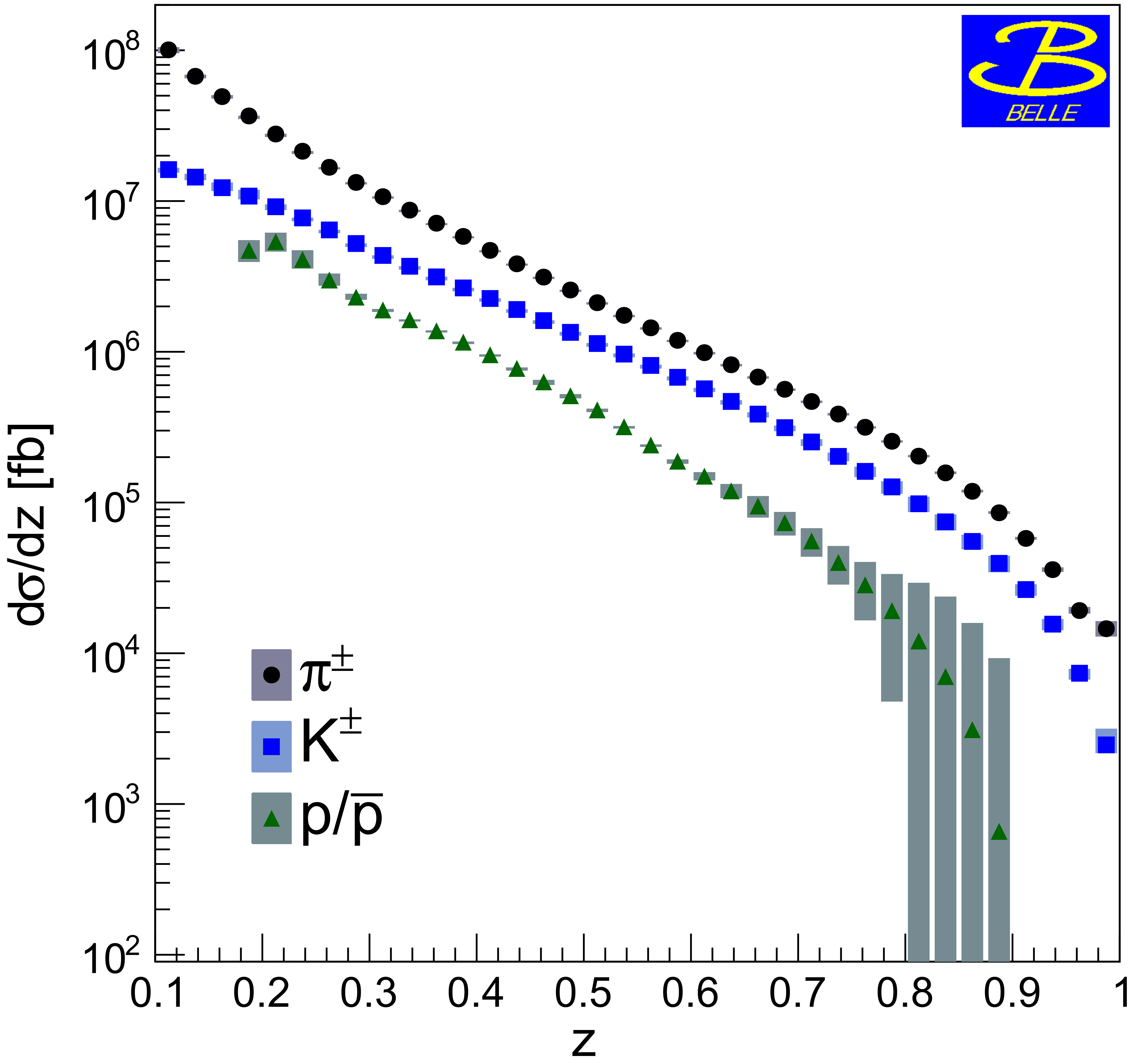
[PRD 92 (2015) 092007]　　[PRD 101 (2020) 092004]



- updated analysis

comparison old&new Belle single-hadron cross sections

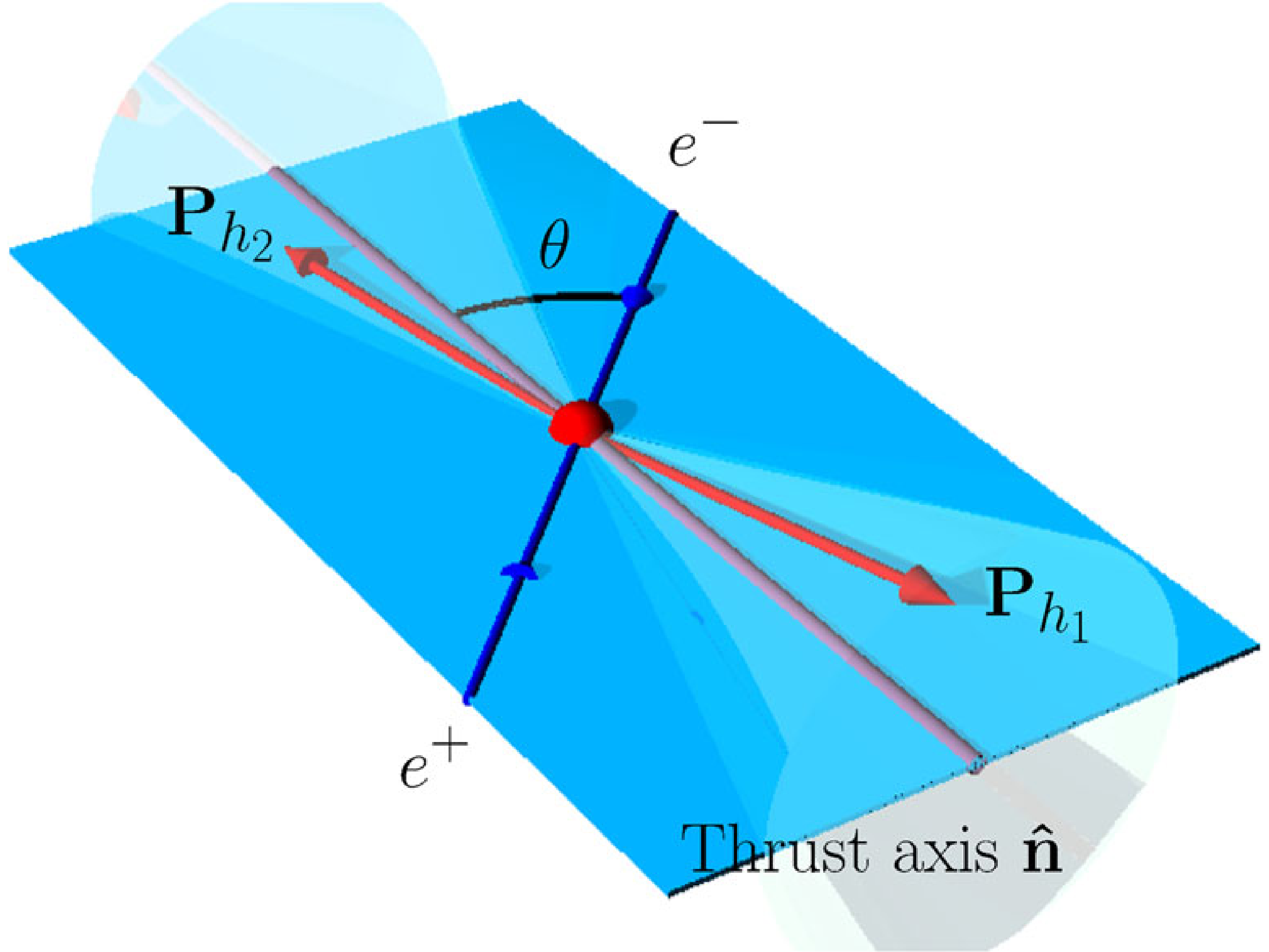
[PRD 101 (2020) 092004]



- updated analysis

hadron-pair production

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

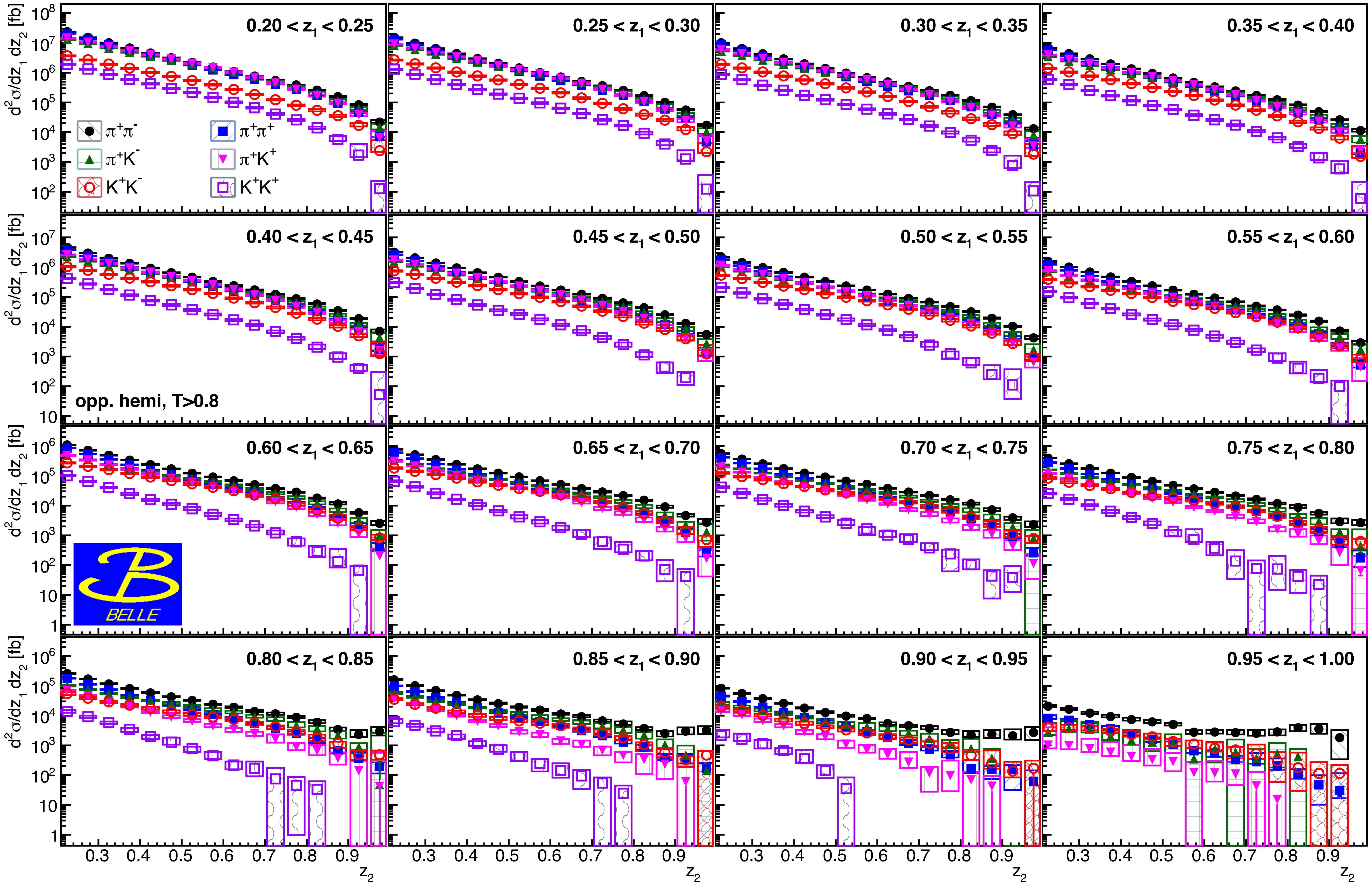


- various definitions for scaling variable
  - traditional z (“std”): $$z_i = \frac{2P_i \cdot q}{q^2} \qquad (i = 1, 2)$$
  - Altarelli et al. (“AEMP”): [Nucl. Phys. B160 (1979) 301] $$z_1 = \frac{2P_1 \cdot q}{q^2} \qquad z_2 = \frac{P_1 \cdot P_2}{P_1 \cdot q}$$
  - Mulders & van Hulse (“MVH”): [PRD 100 (2019) 034011] $$z_1 = \left(P_1 \cdot P_2 - \frac{M_{h1}^2 M_{h2}^2}{P_1 \cdot P_2} \right) \frac{1}{P_2 \cdot q - M_{h2}^2 \frac{P_1 \cdot q}{P_1 \cdot P_2}}$$

light-meson pair production

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

[PRD 101 (2020) 092004]



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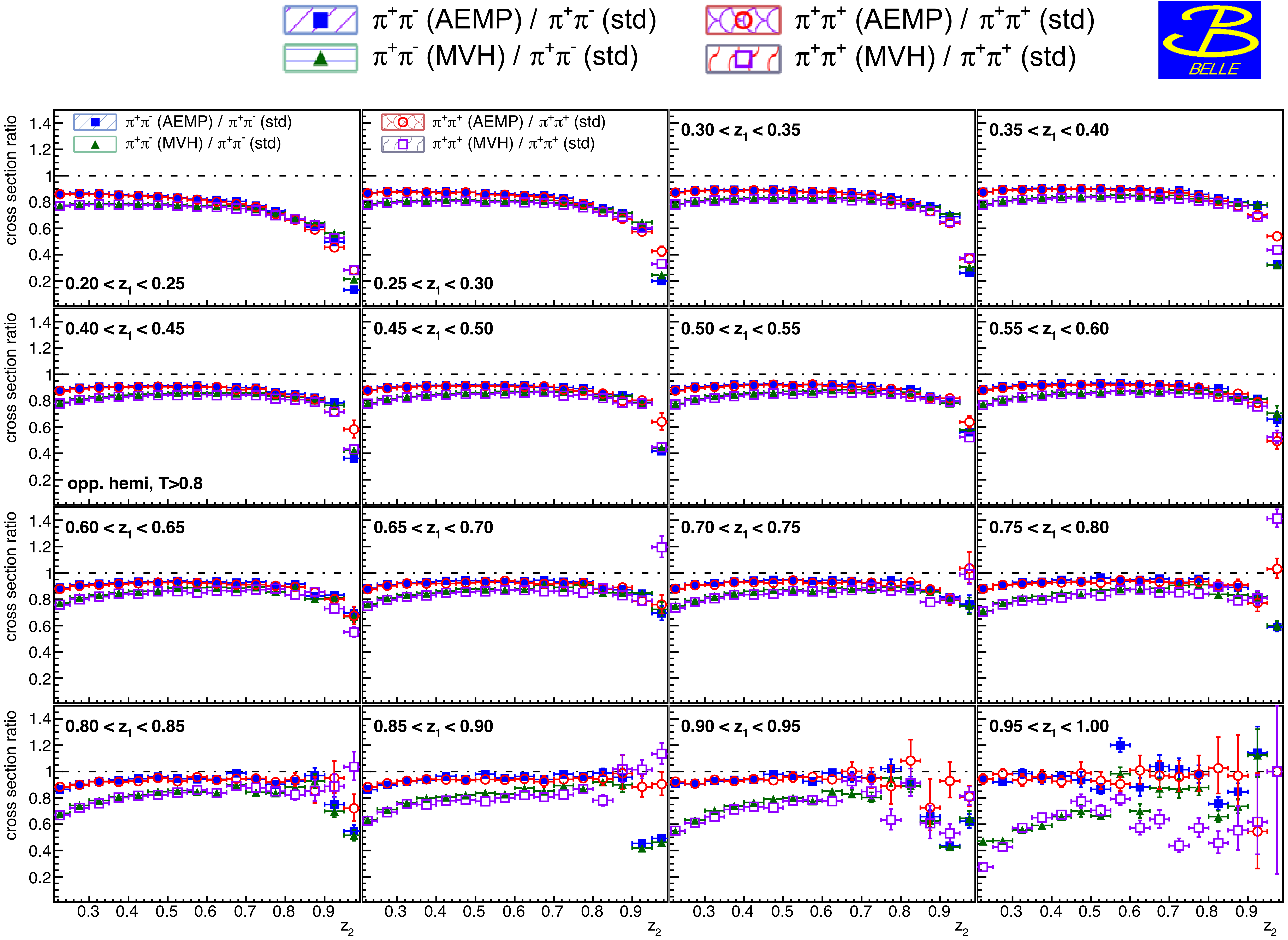

[PRD 101 (2020) 092004]

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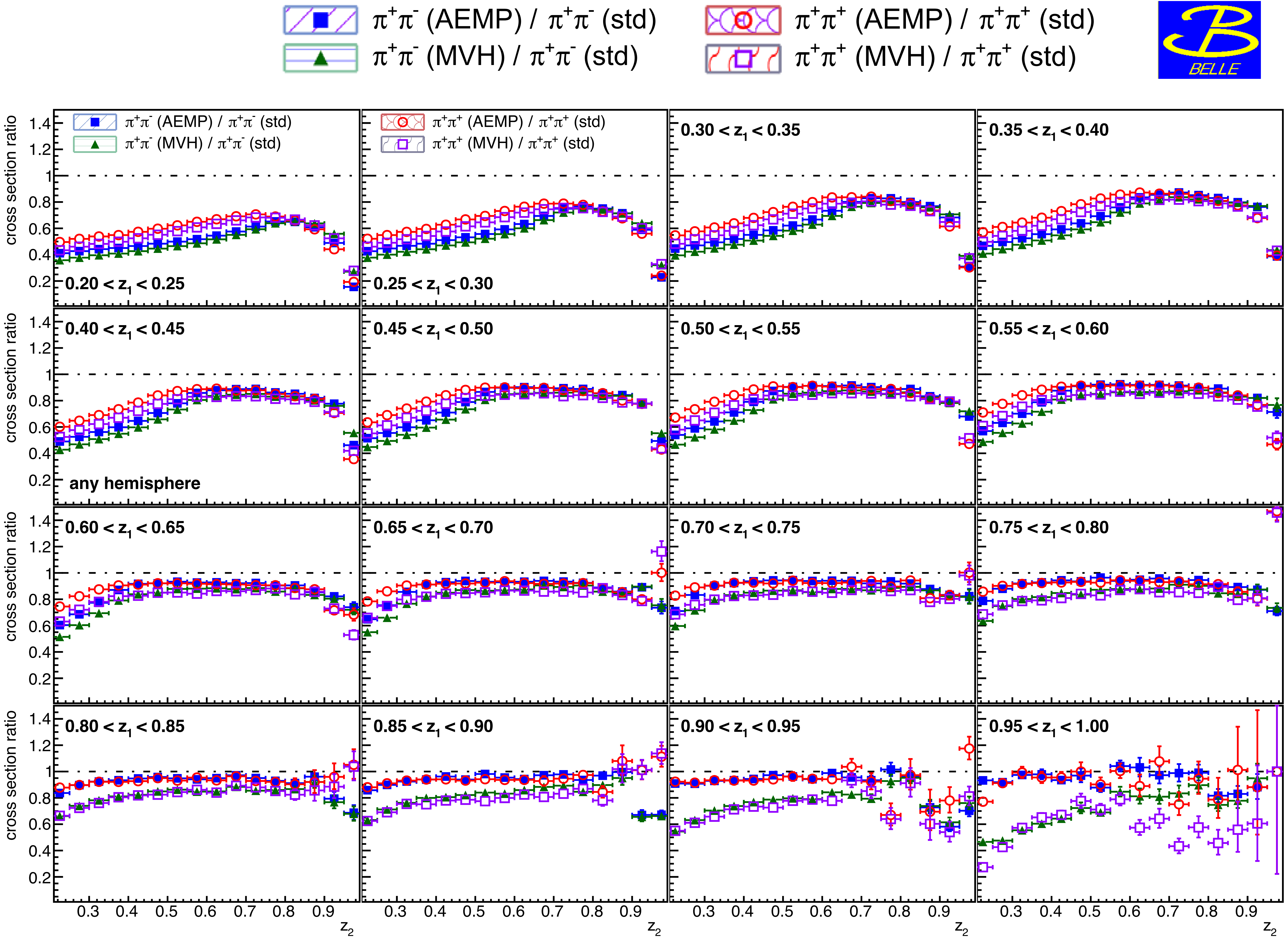
- larger suppression (low z) for fully inclusive pairs ("any hemisphere")



[PRD 101 (2020) 092004]

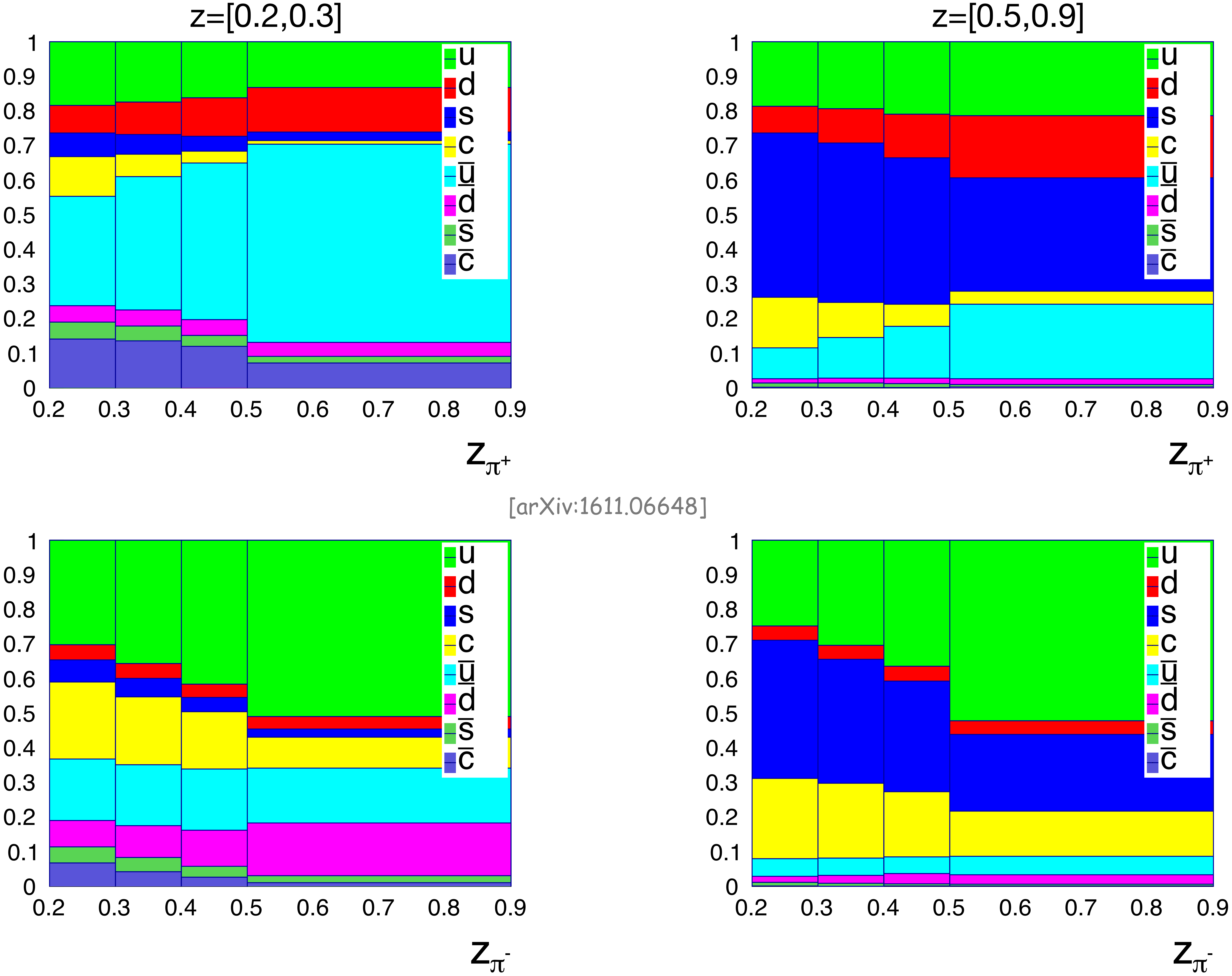
summary

- e^+e^- annihilation is powerful laboratory for hadronization studies
  - in two-hadron production, observing a "back-to-back" hadron allows for tagging transverse momenta, quark flavor as well as polarization
- clearly non-zero transverse Λ-hyperon self-polarization at Belle
- Collins effect allows for the study of quark-polarisation dependence of hadronization
  - previous charged-pion analyses supplemented with transverse-momentum dependence and analysis of neutral-pion and eta mesons in latest Belle Collins analysis
    - results for neutral & charged pions consistent
    - no significant difference between neutral pions and eta seen
- re-analysis of unpolarized fragmentation
  - updated ISR correction; now consistent ISR treatment in all Belle unpolarized Xsec's
  - inclusion of alternative variable choices for two-hadron cross sections

backup

quark-flavor contributions to Lambda prod.

- flavor tagging through opposite-hemisphere hadrons



[arXiv:1611.06648]