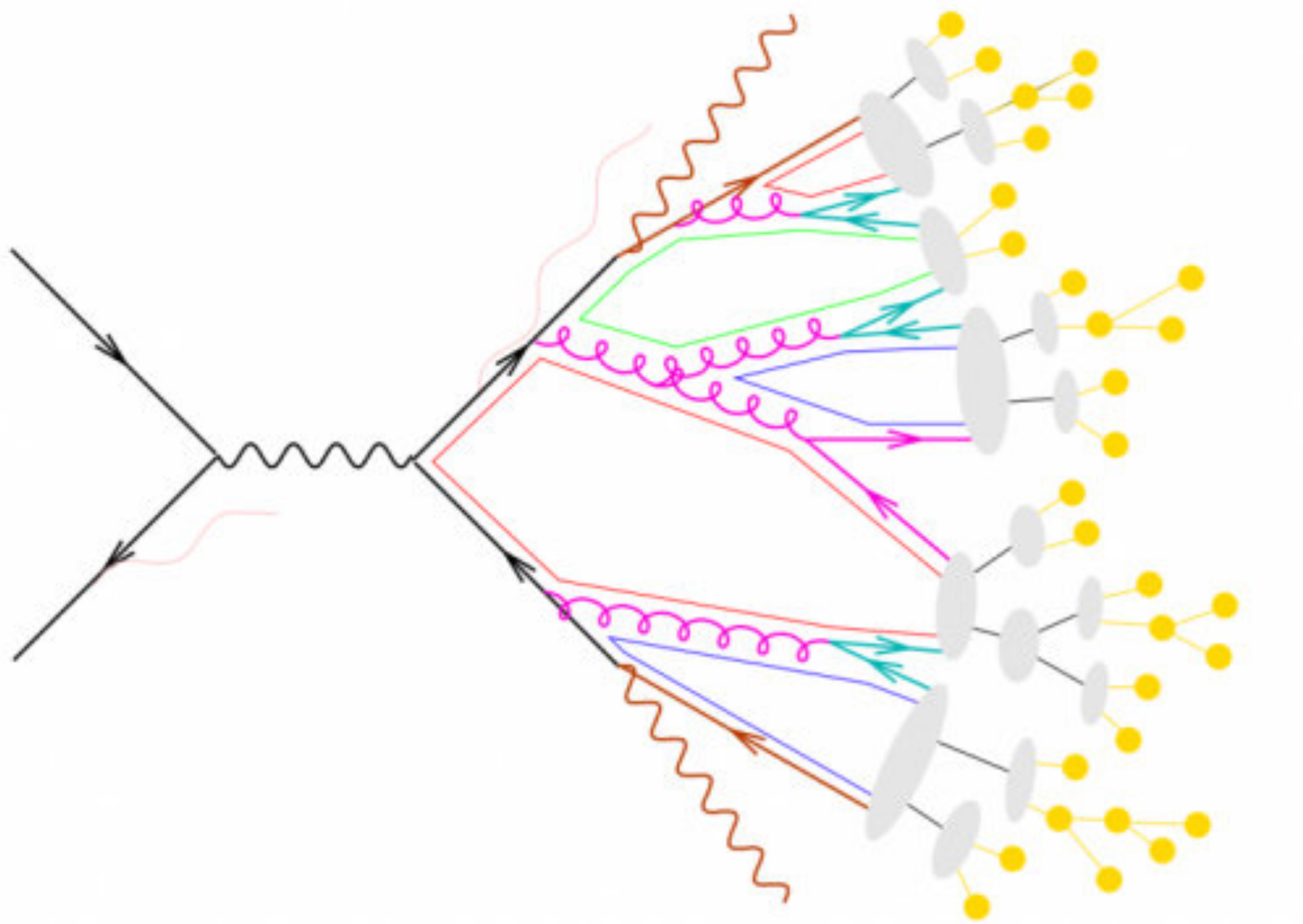
20th International Workshop on Hadron Structure and Spectroscopy & 5th Workshop on Correlations in Partonic and Hadronic Interactions

[courtesy A. Signori]



Hadronization in e^+e^- annihilation

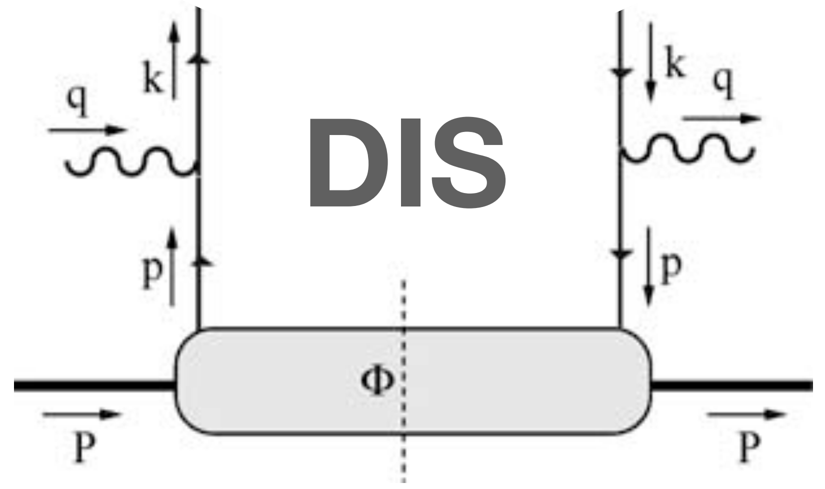
ikerbasque Basque Foundation for Science

Gunar.Schnell @ desy.de

eman ta zabal zazu
Universidad del País Vasco
Euskal Herriko Unibertsitatea

EHU QC
EHU Quantum Center

hadron structure - a global approach



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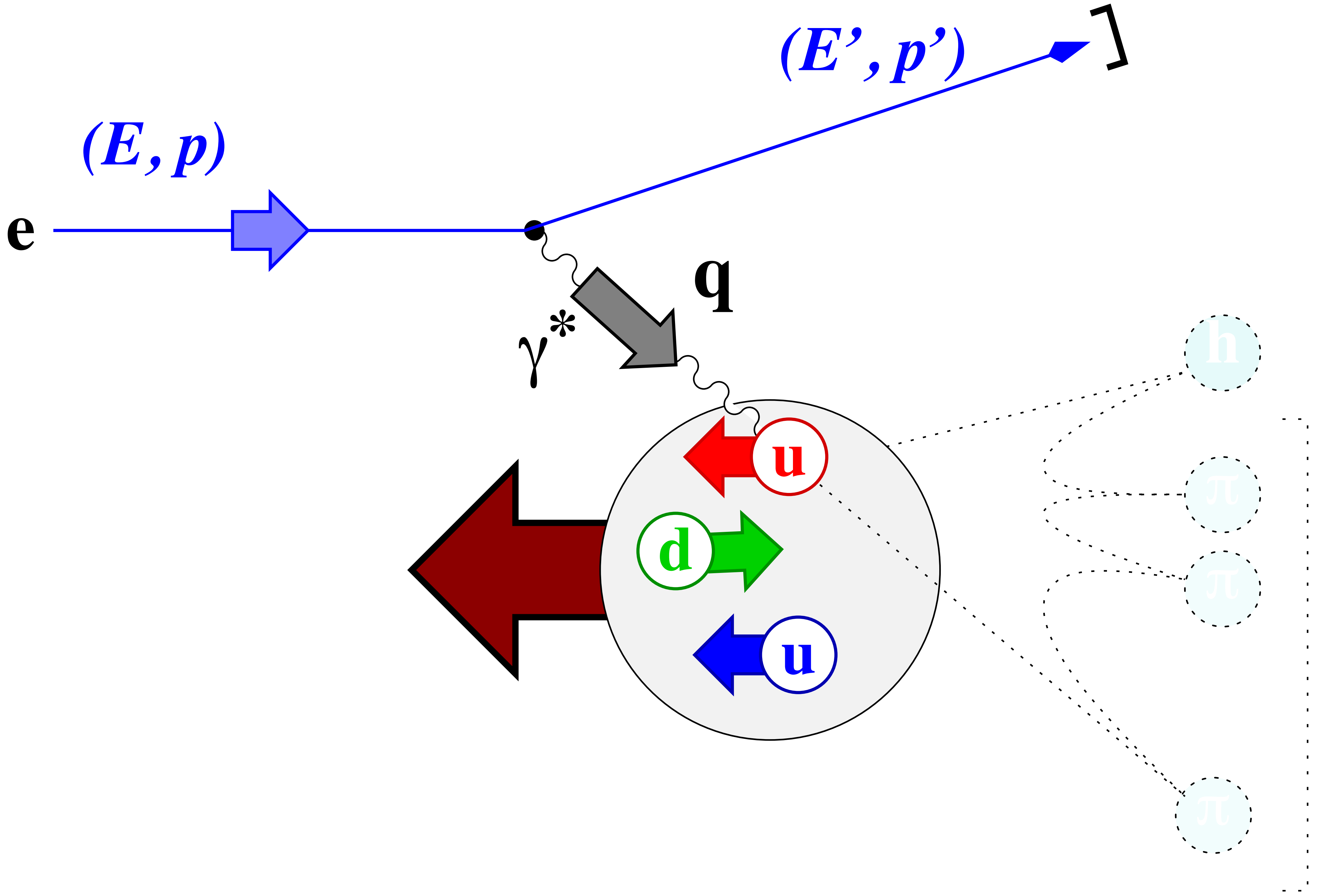
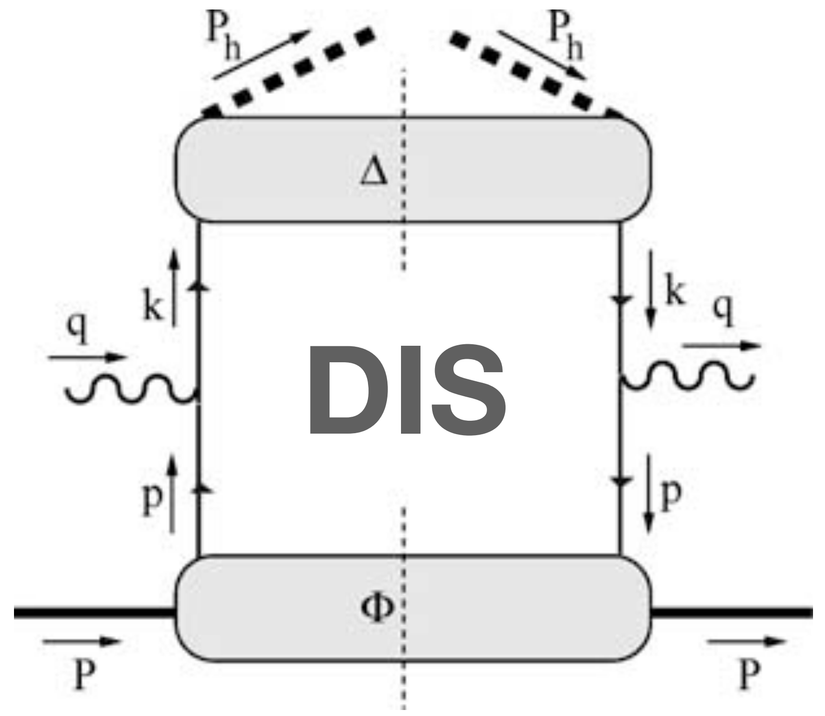


hadron structure - a global approach



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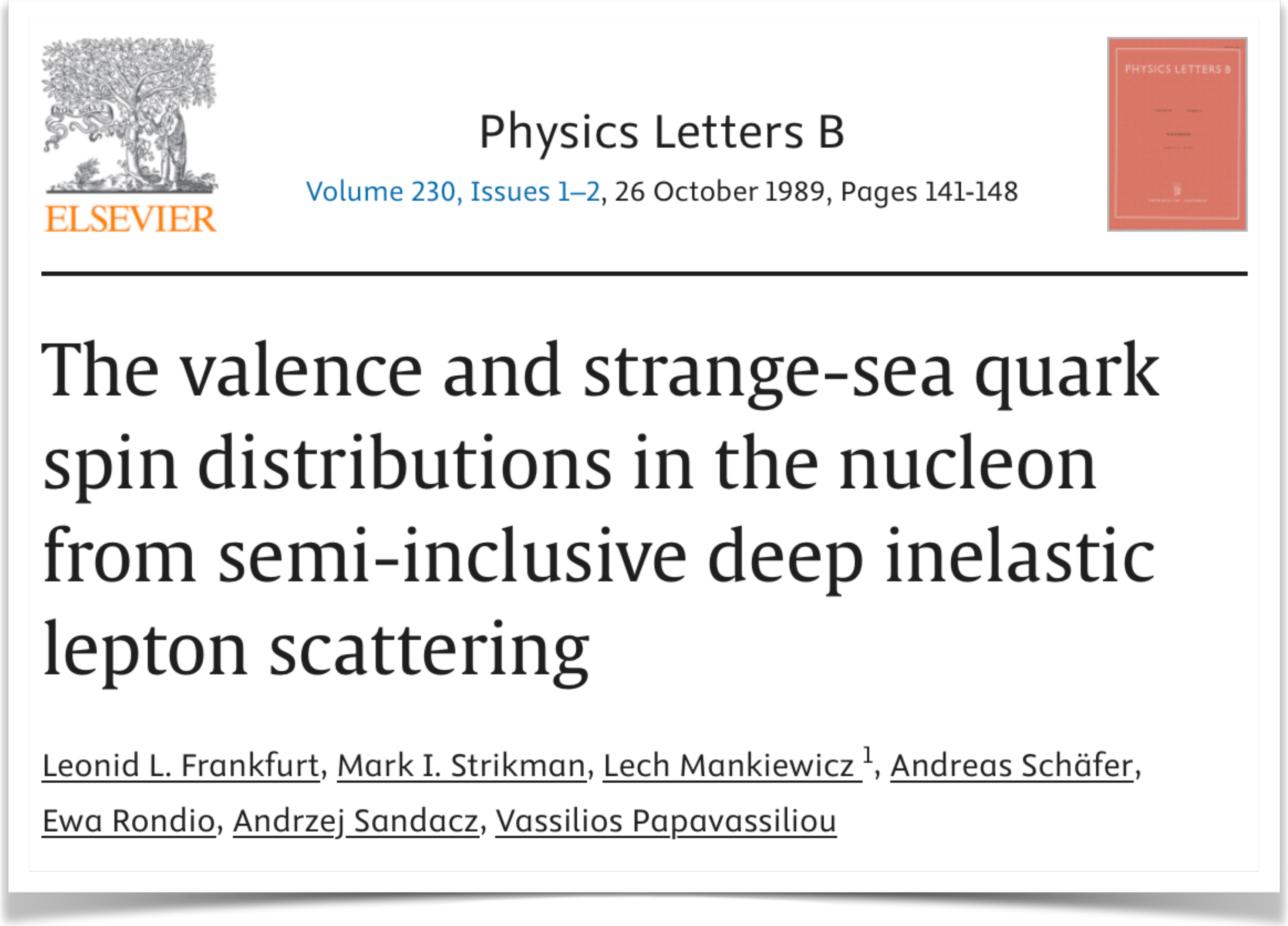


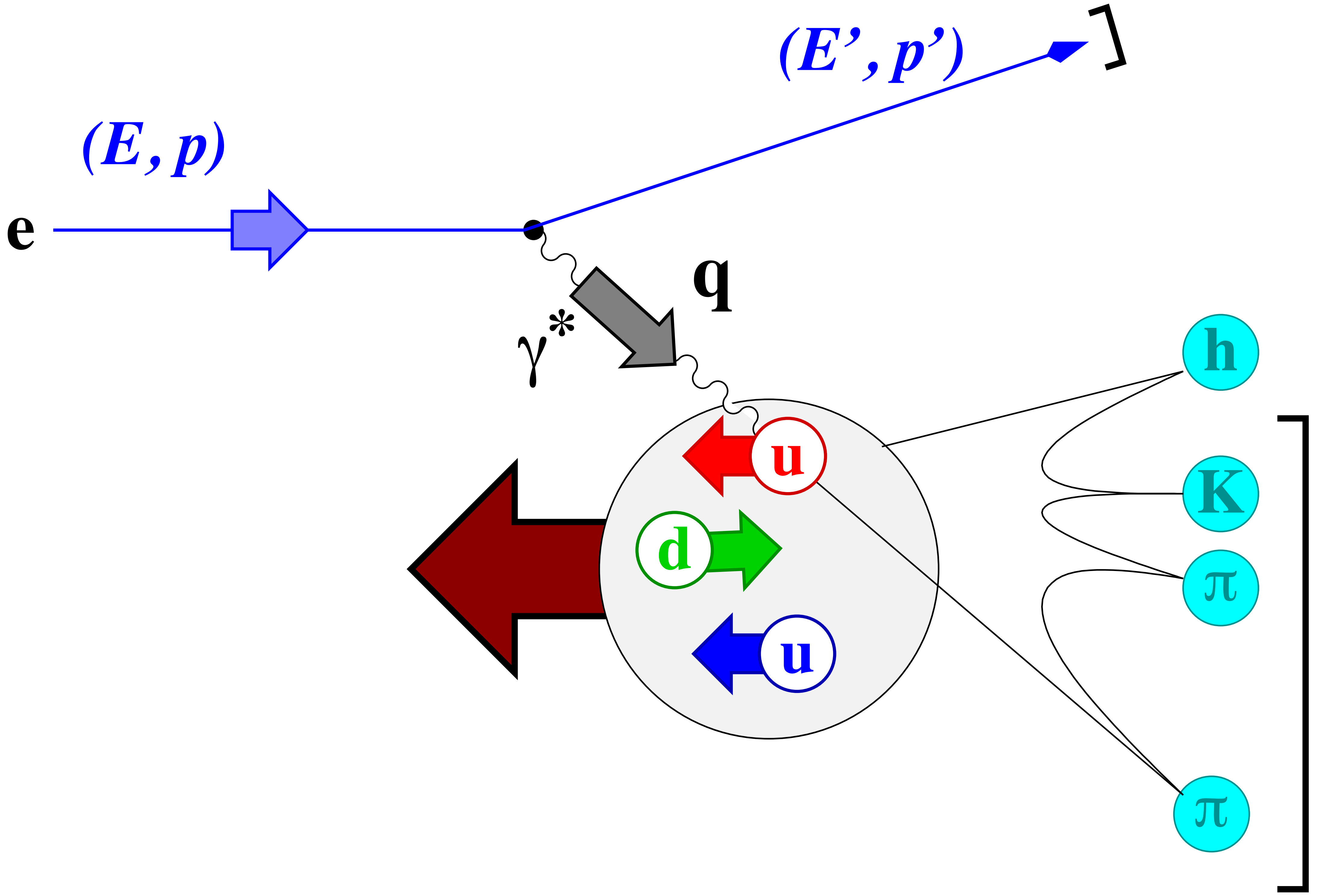
ELSEVIER

Physics Letters B

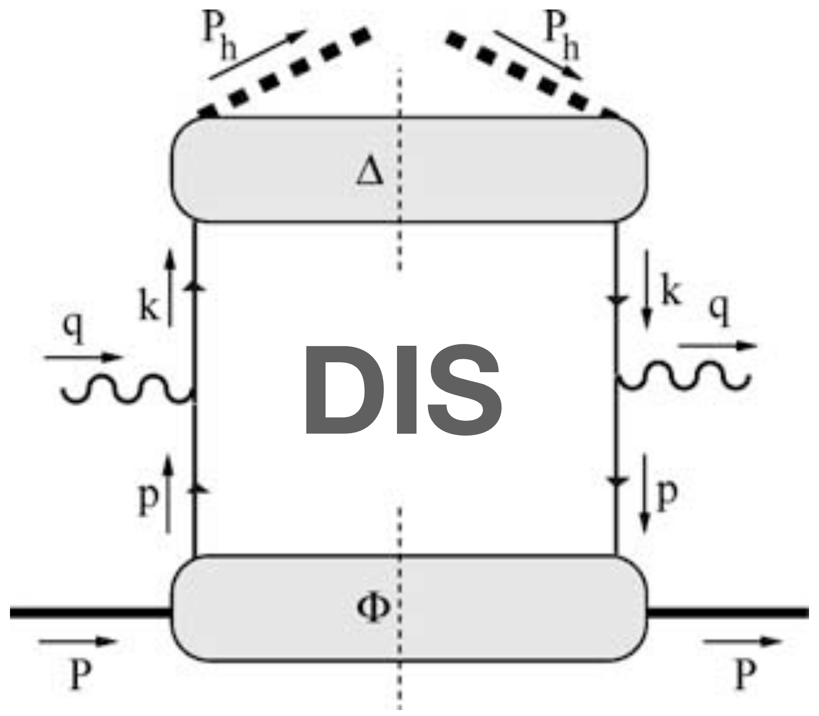
Volume 230, Issues 1–2, 26 October 1989, Pages 141-148

The valence and strange-sea quark spin distributions in the nucleon from semi-inclusive deep inelastic lepton scattering

Leonid L. Frankfurt, Mark I. Strikman, Lech Mankiewicz [1], Andreas Schäfer, Ewa Rondio, Andrzej Sandacz, Vassilios Papavassiliou



hadron structure - a global approach



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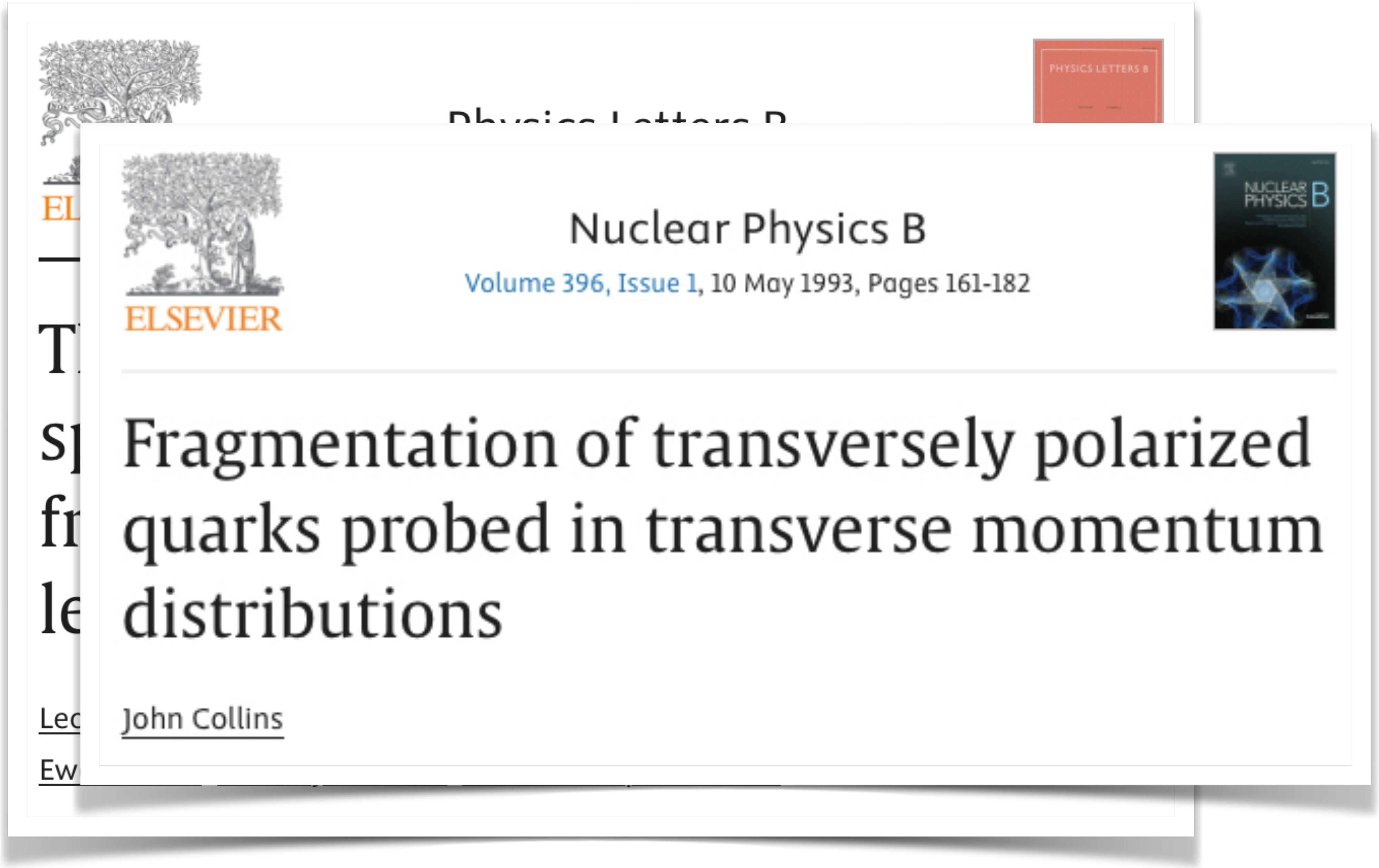
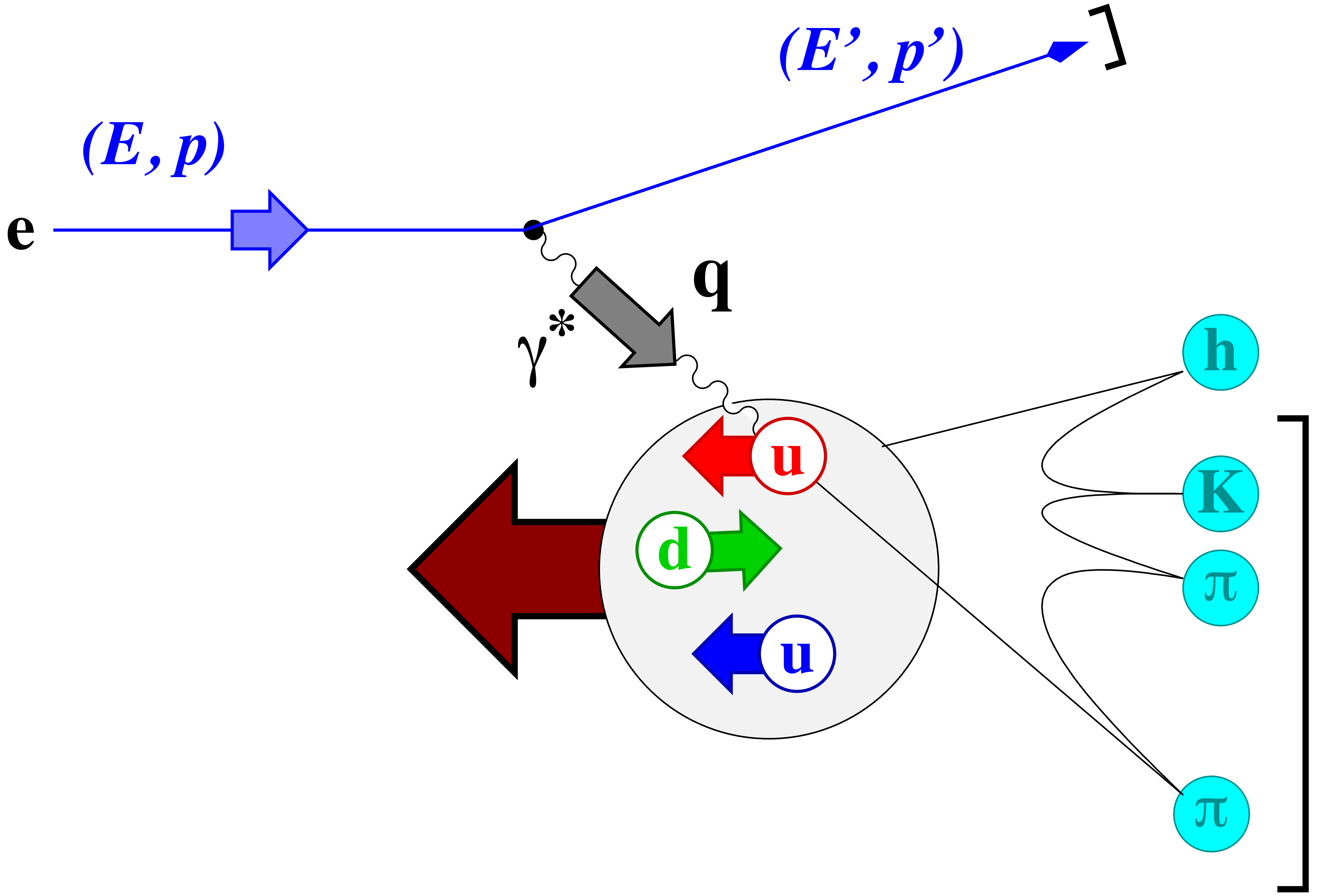
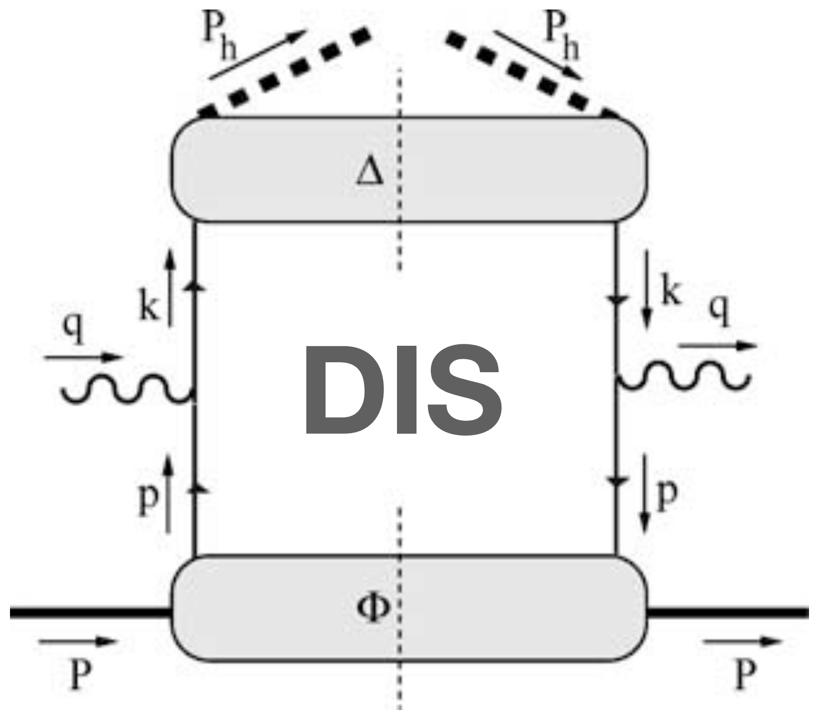

ELSEVIER
Nuclear Physics B
Volume 396, Issue 1, 10 May 1993, Pages 161-182

Fragmentation of transversely polarized quarks probed in transverse momentum distributions

John Collins



hadron structure - a global approach



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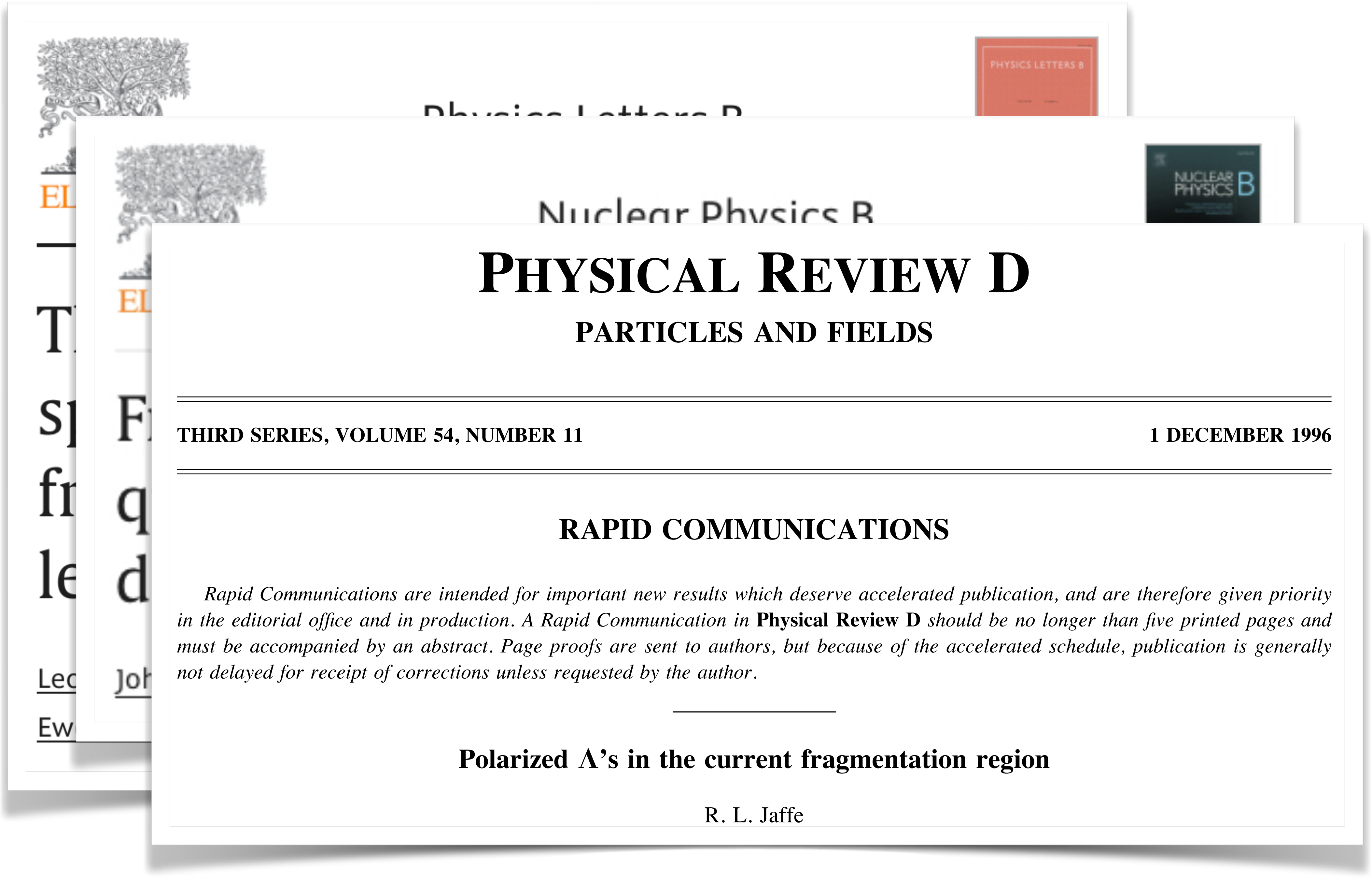
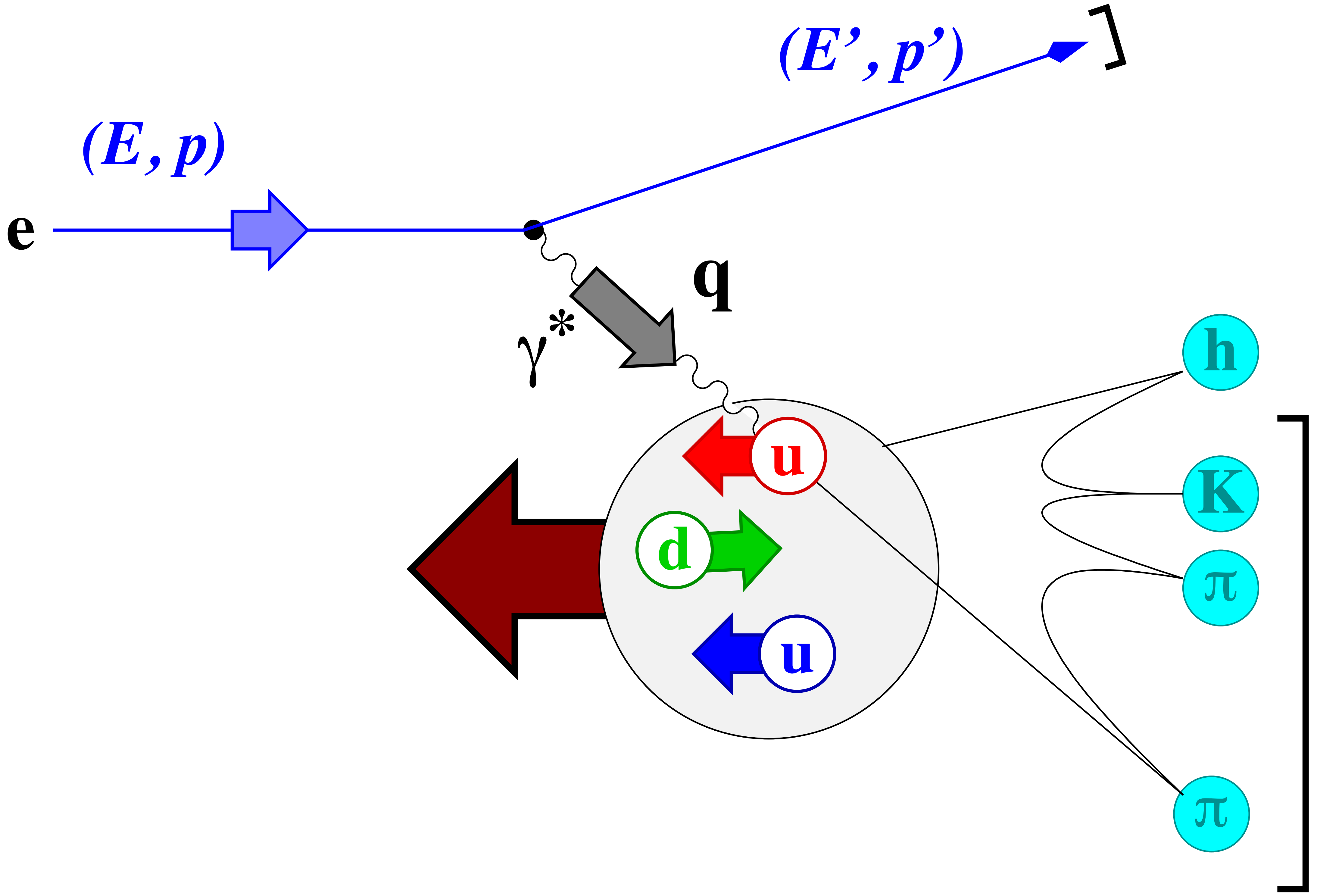
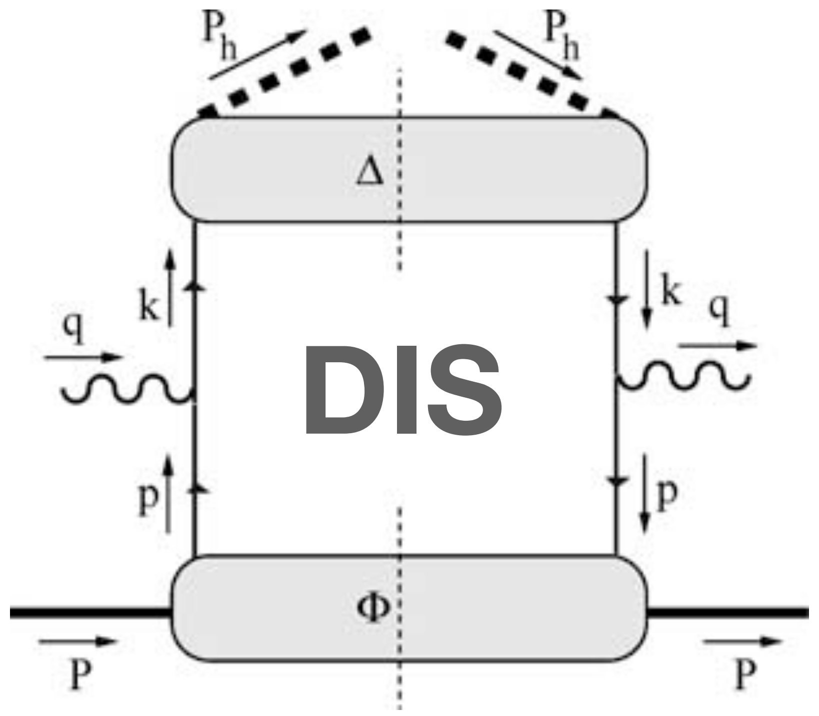

Physics Letters B
Nuclear Physics B
PHYSICAL REVIEW D
PARTICLES AND FIELDS
THIRD SERIES, VOLUME 54, NUMBER 11 1 DECEMBER 1996
RAPID COMMUNICATIONS
Rapid Communications are intended for important new results which deserve accelerated publication, and are therefore given priority in the editorial office and in production. A Rapid Communication in **Physical Review D** *should be no longer than five printed pages and must be accompanied by an abstract. Page proofs are sent to authors, but because of the accelerated schedule, publication is generally not delayed for receipt of corrections unless requested by the author.*

Polarized Λ's in the current fragmentation region

R. L. Jaffe



hadron structure - a global approach



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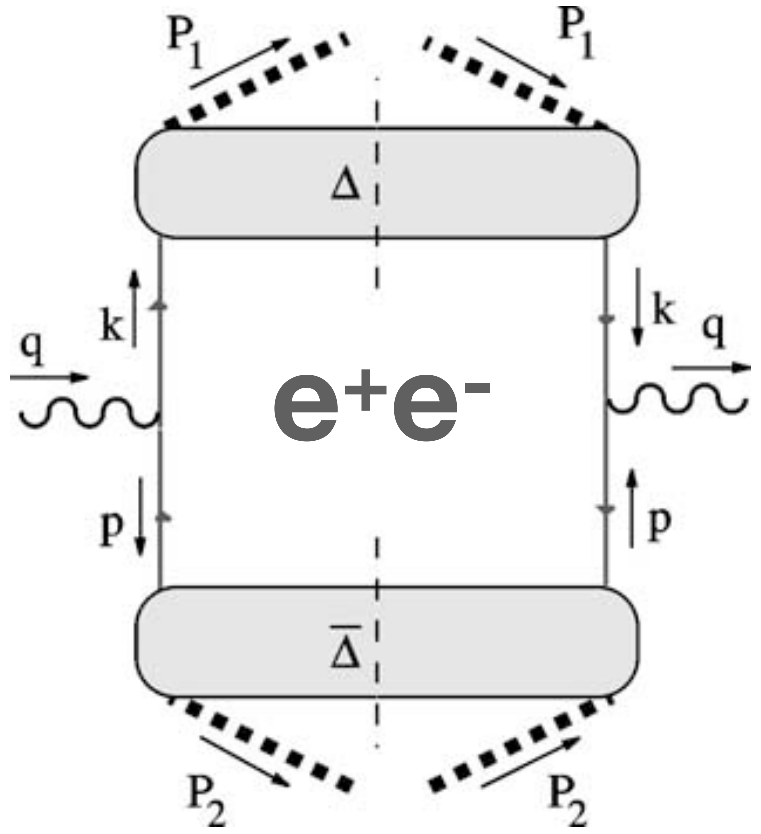

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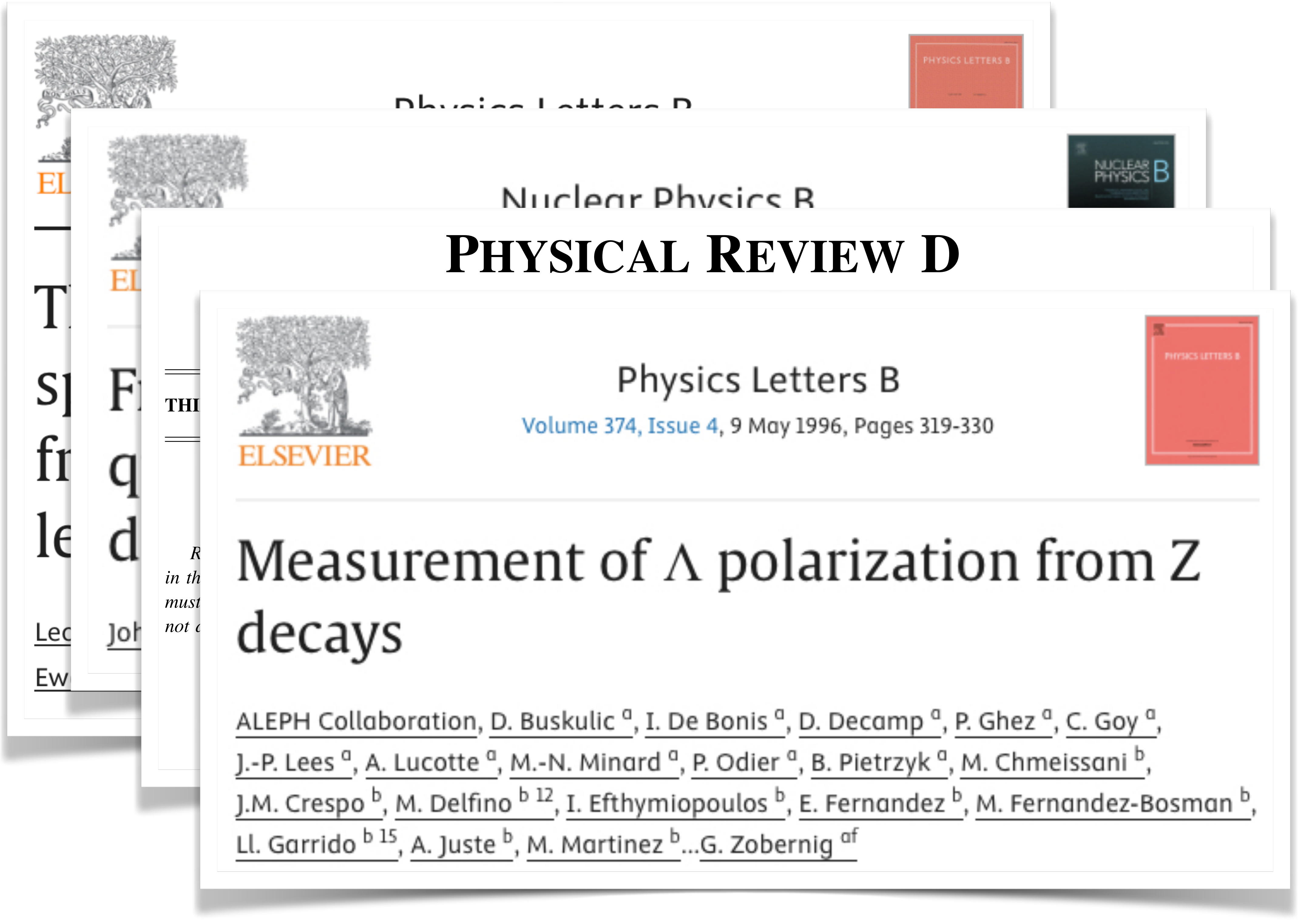

Physical Review D

Physics Letters B

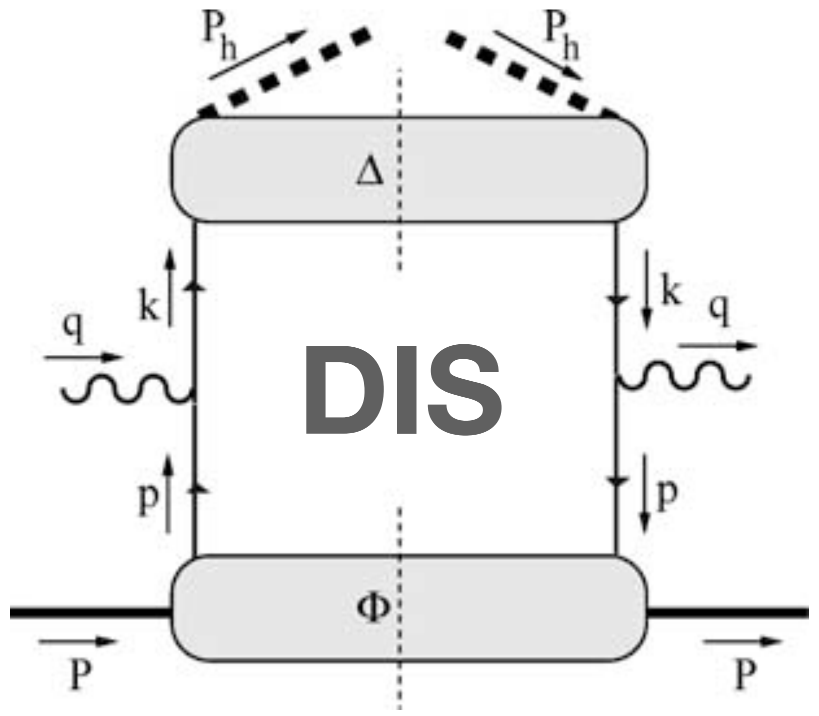
Volume 374, Issue 4, 9 May 1996, Pages 319-330

ELSEVIER

Measurement of Λ polarization from Z decays

ALEPH Collaboration, D. Buskulic [a], I. De Bonis [a], D. Decamp [a], P. Ghez [a], C. Goy [a], J.-P. Lees [a], A. Lucotte [a], M.-N. Minard [a], P. Odier [a], B. Pietrzyk [a], M. Chmeissani [b], J.M. Crespo [b], M. Delfino [b 12], I. Efthymiopoulos [b], E. Fernandez [b], M. Fernandez-Bosman [b], Ll. Garrido [b 15], A. Juste [b], M. Martinez [b]...G. Zobernig [af]

hadron structure - a global approach



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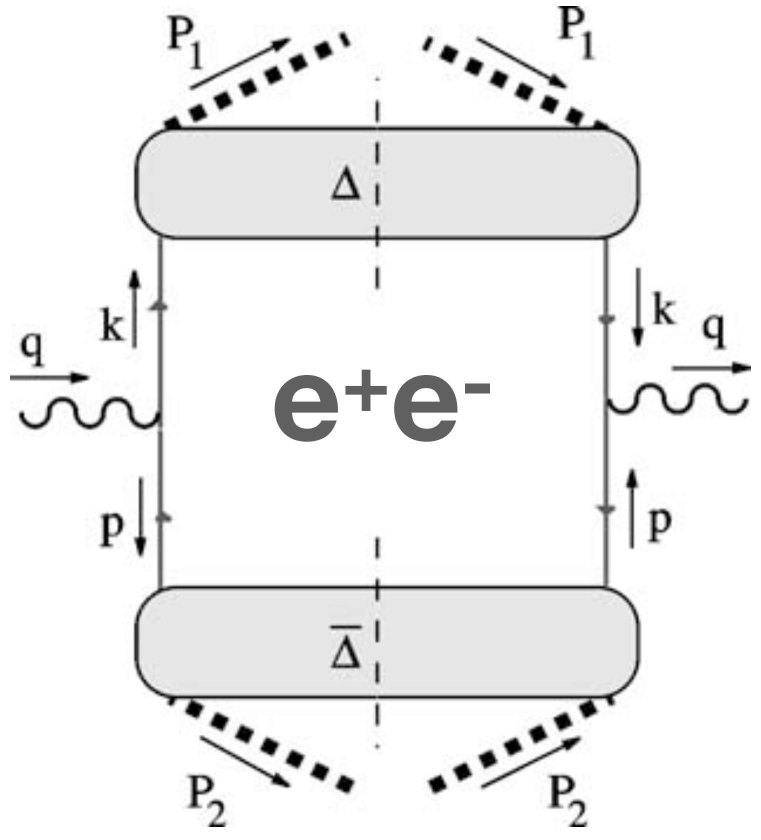

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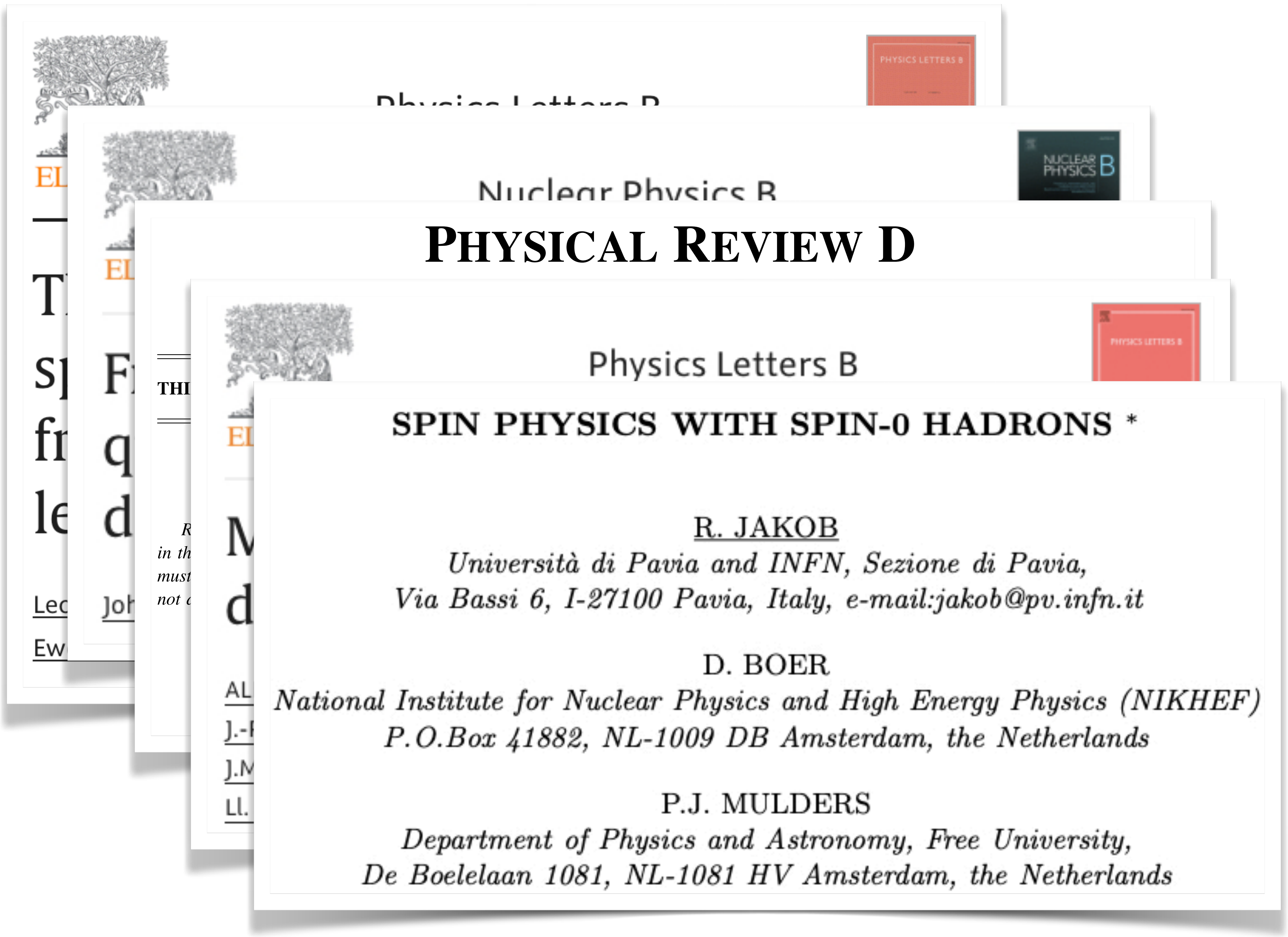

SPIN PHYSICS WITH SPIN-0 HADRONS *

R. JAKOB
Università di Pavia and INFN, Sezione di Pavia,
Via Bassi 6, I-27100 Pavia, Italy, e-mail:jakob@pv.infn.it

D. BOER
National Institute for Nuclear Physics and High Energy Physics (NIKHEF)
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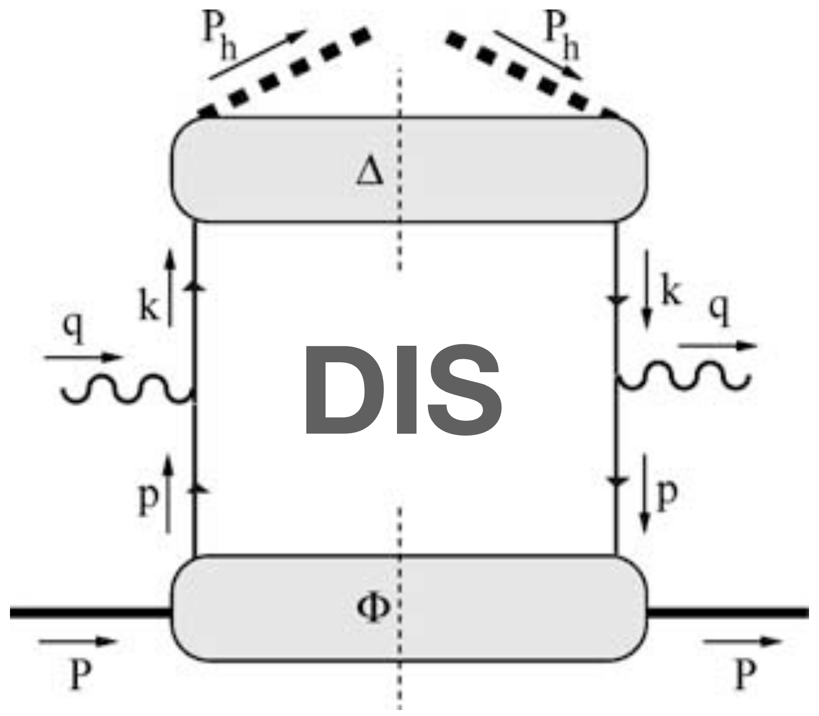
P.J. MULDERS
Department of Physics and Astronomy, Free University,
De Boelelaan 1081, NL-1081 HV Amsterdam, the Netherlands

hadron structure - a global approach



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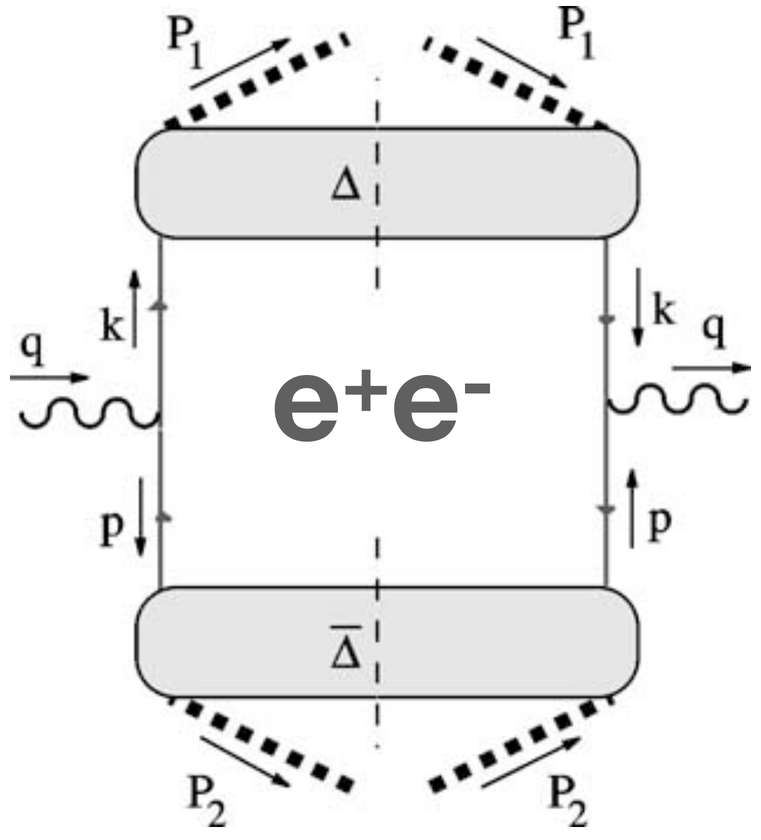

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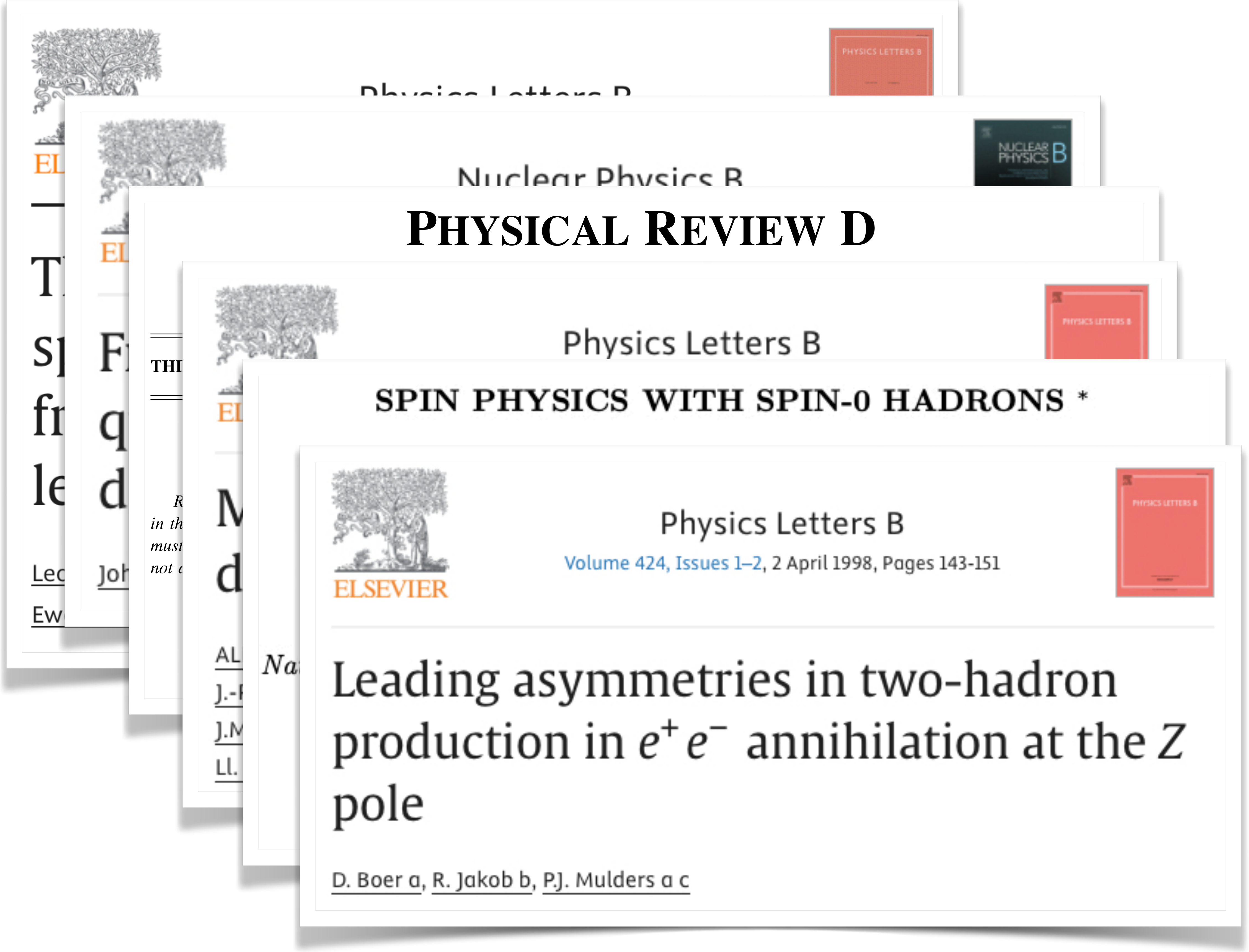

Nuclear Physics B

PHYSICAL REVIEW D

Physics Letters B

SPIN PHYSICS WITH SPIN-0 HADRONS *

Physics Letters B

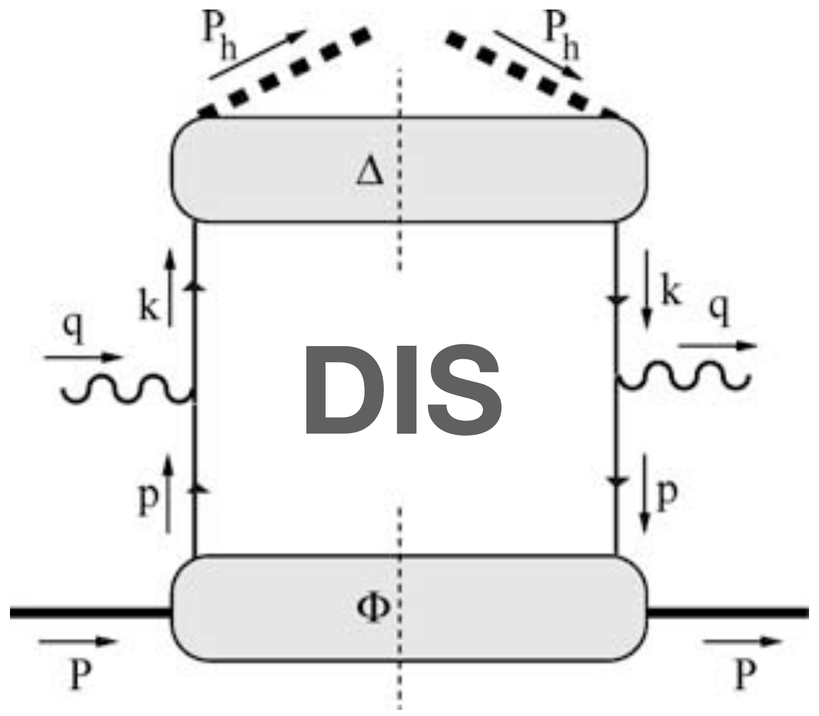
Volume 424, Issues 1–2, 2 April 1998, Pages 143-151

ELSEVIER

Leading asymmetries in two-hadron production in e^+e^- annihilation at the Z pole

D. Boer a, R. Jakob b, P.J. Mulders a c

hadron structure - a global approach



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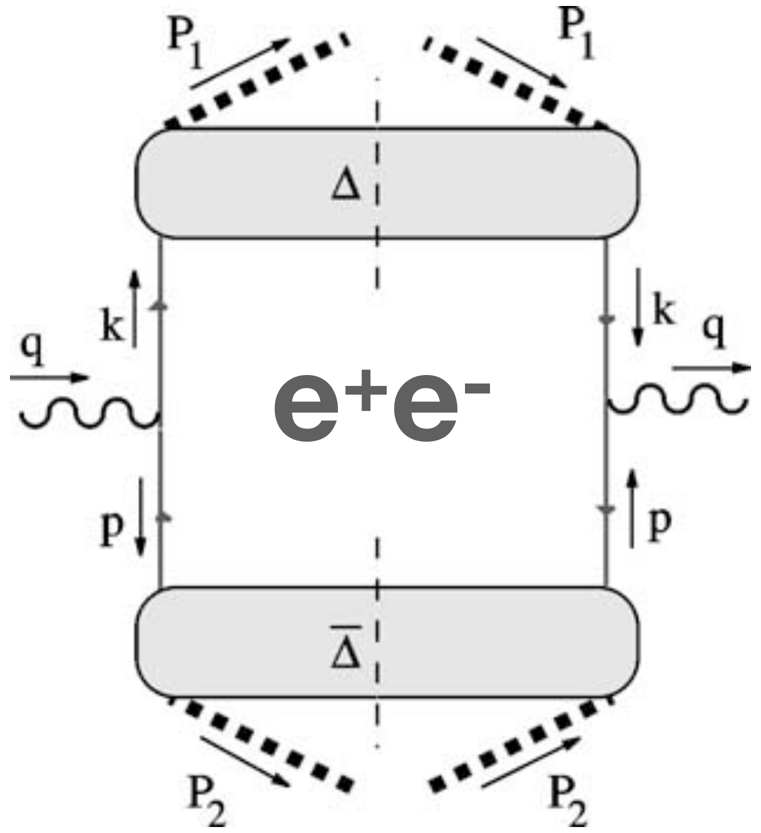

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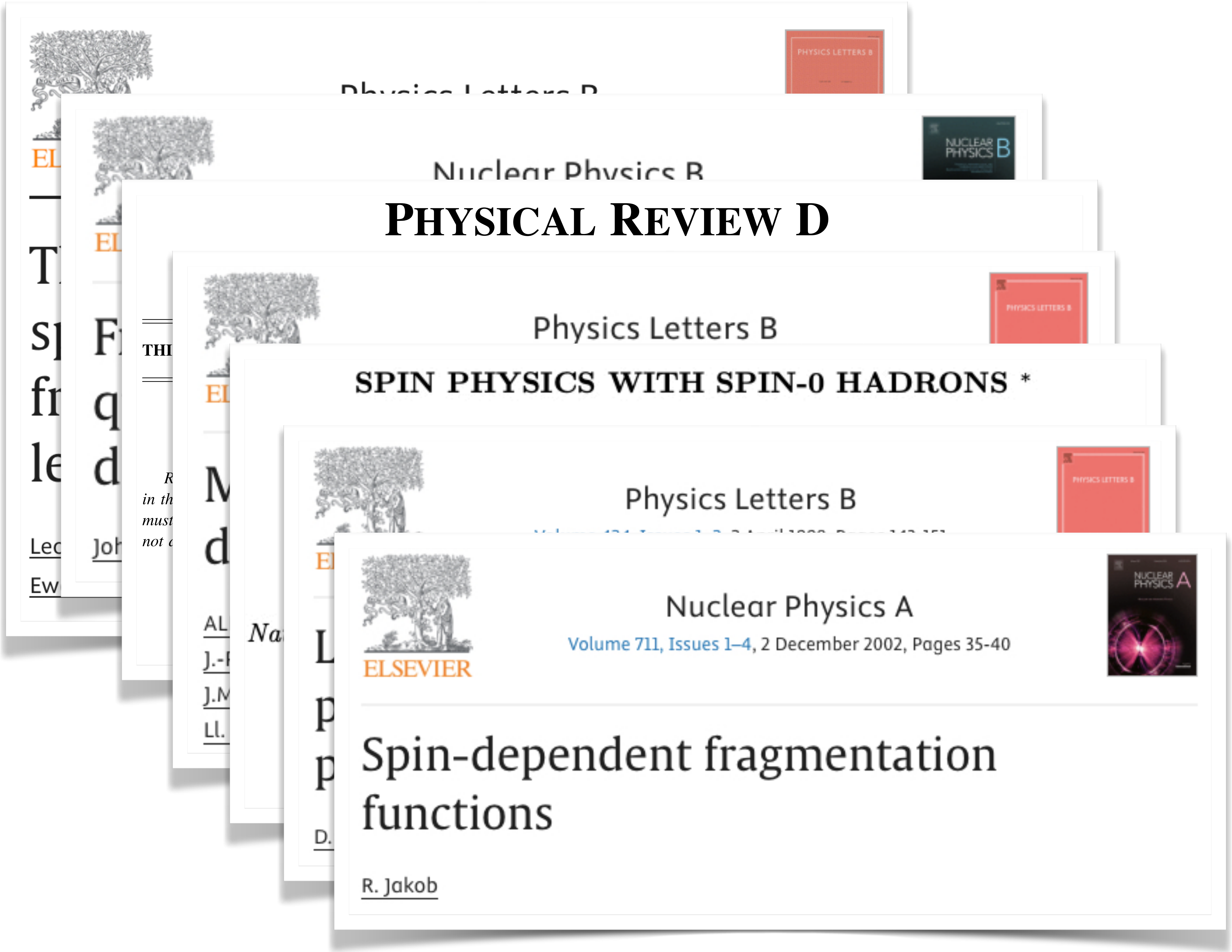
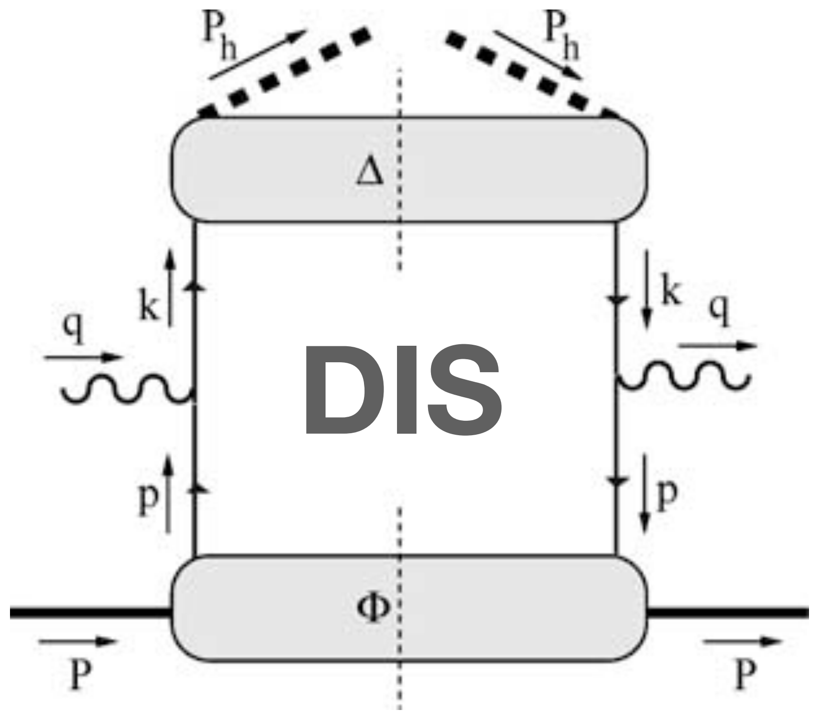


hadron structure - a global approach



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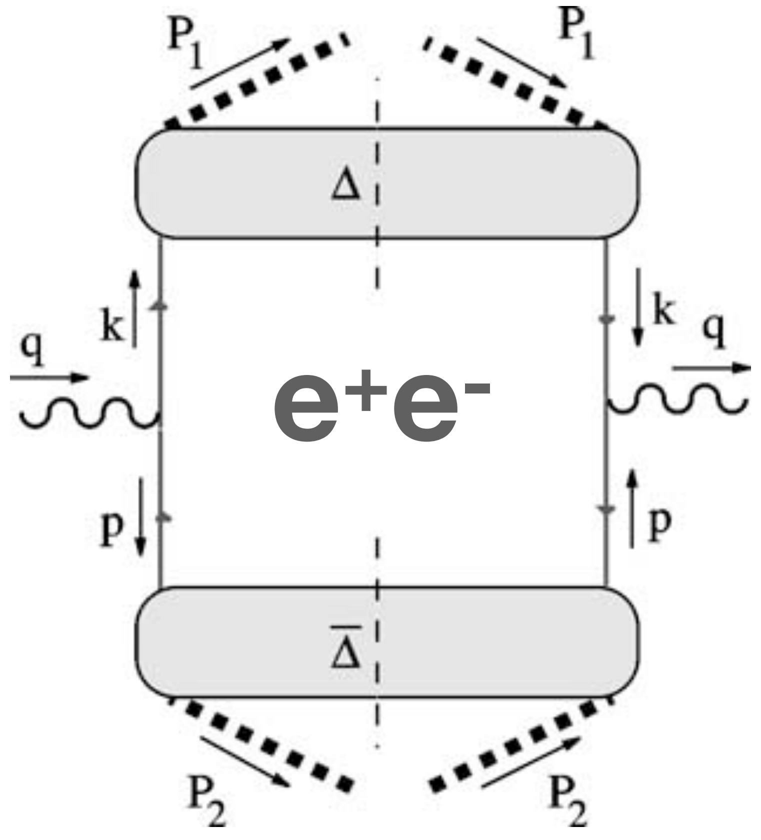

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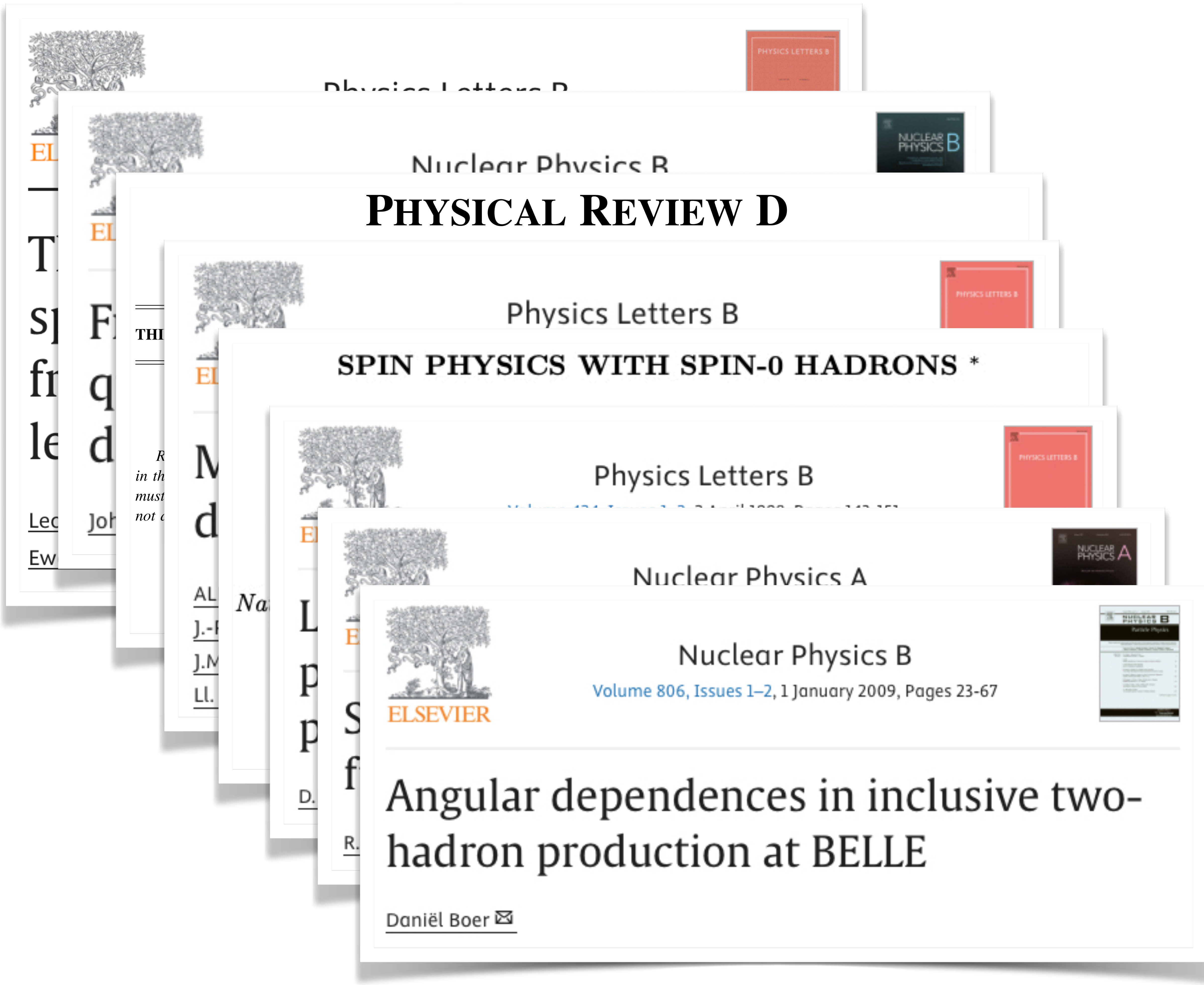
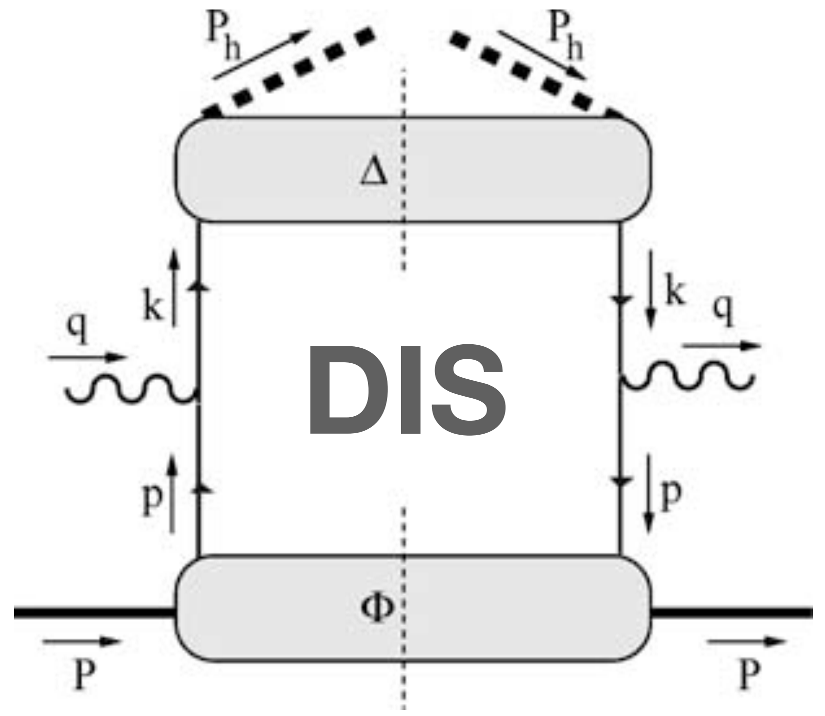


hadron structure - a global approach



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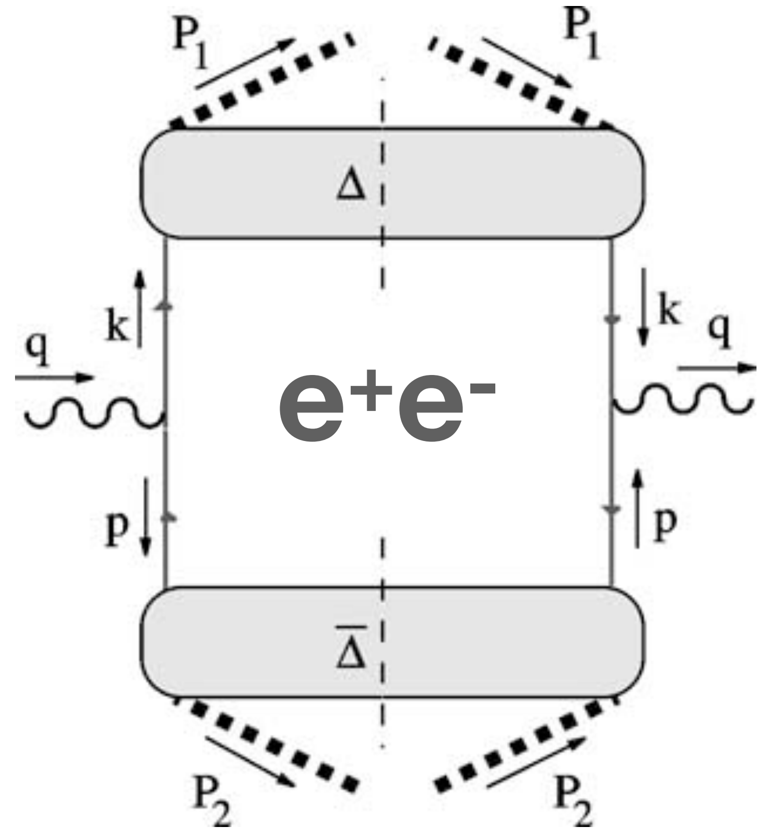

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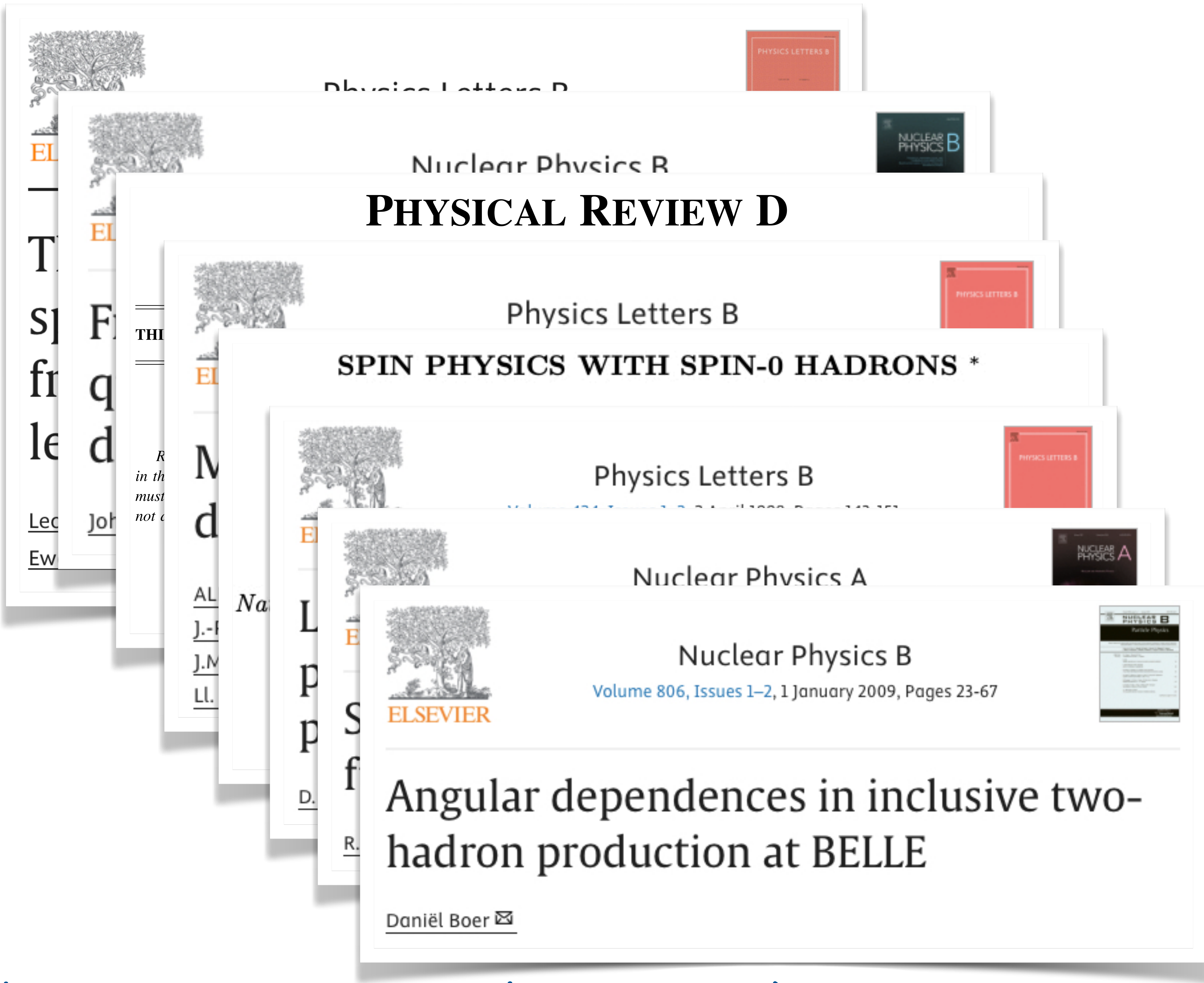

- FFs needed/interesting for many other studies! (confinement, heavy-ion physics, etc.)
- FFs **not calculable** from first principles
- hadronization very active field (Monte Carlo, hadrons in jets, event shapes, etc.)

☛ talks by Albi, Gevorg, Valerio, Xiao-Rui, Xuanbo, ...

single-hadron*) (TMD**)) fragmentation functions

*) complemented by rich world of di-hadrons
**) 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: $H_1^{\perp,q\to h}$

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

FF … fragmentation function

single-hadron*) (TMD**)) fragmentation functions

*) complemented by rich world of di-hadrons
**) transverse-momentum dependent

quark pol. (columns) / hadron pol. (rows)

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

☚ relevant for unpolarized final state

polarized final-state hadrons

polarizing FF

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☚ relevant for unpolarized final state

polarized final-state hadrons

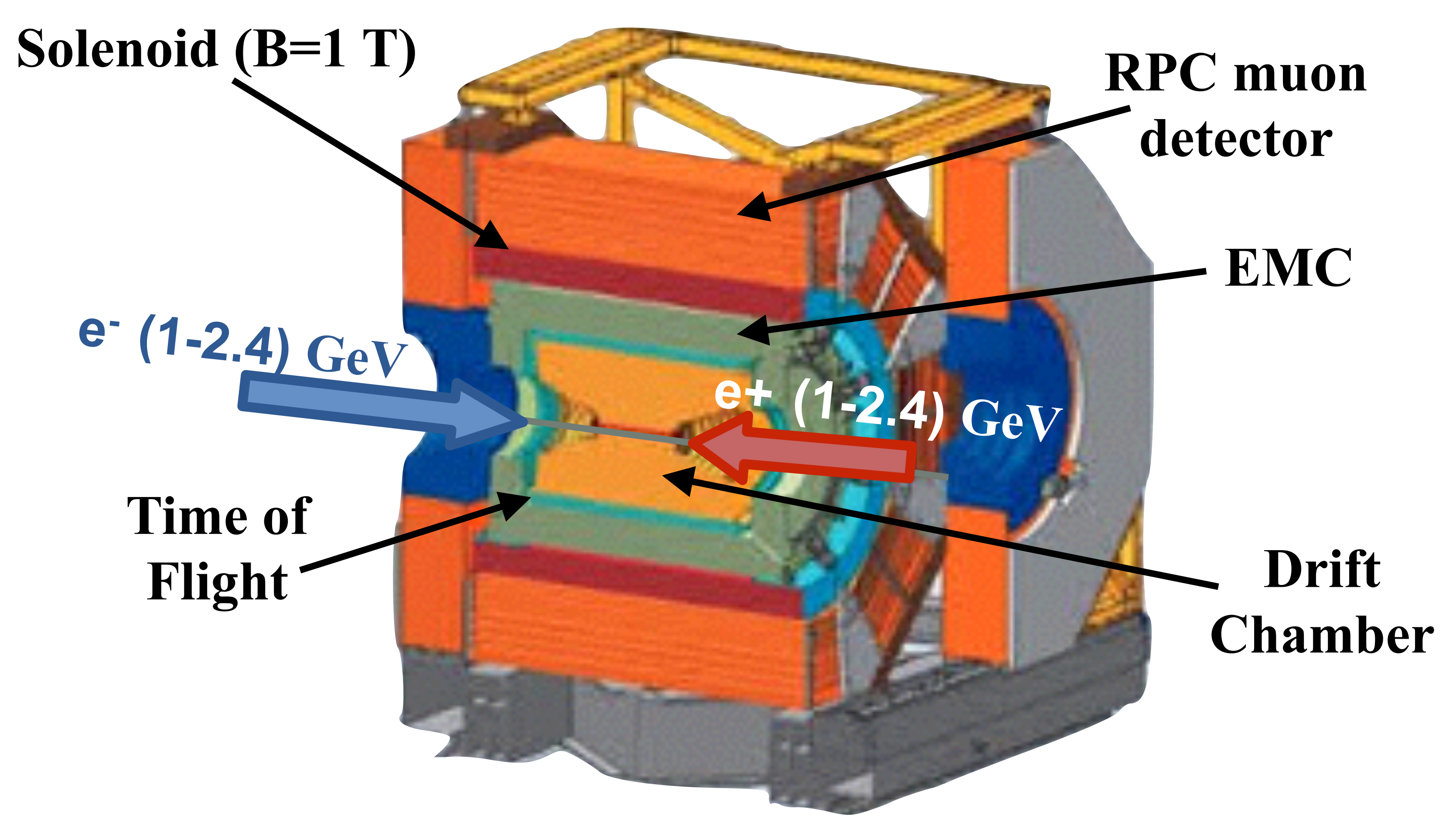
polarizing FF

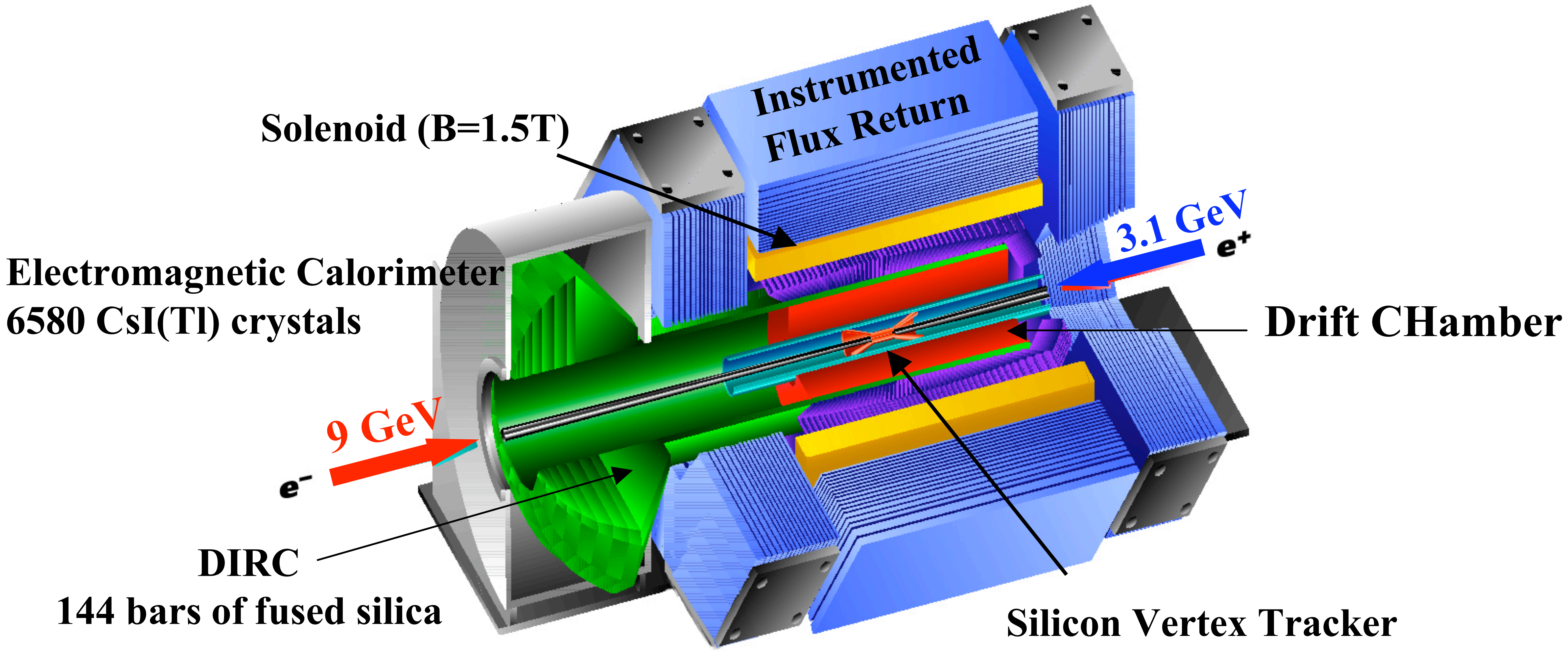
➟ FFs act as quark flavor-tagger and polarimeter

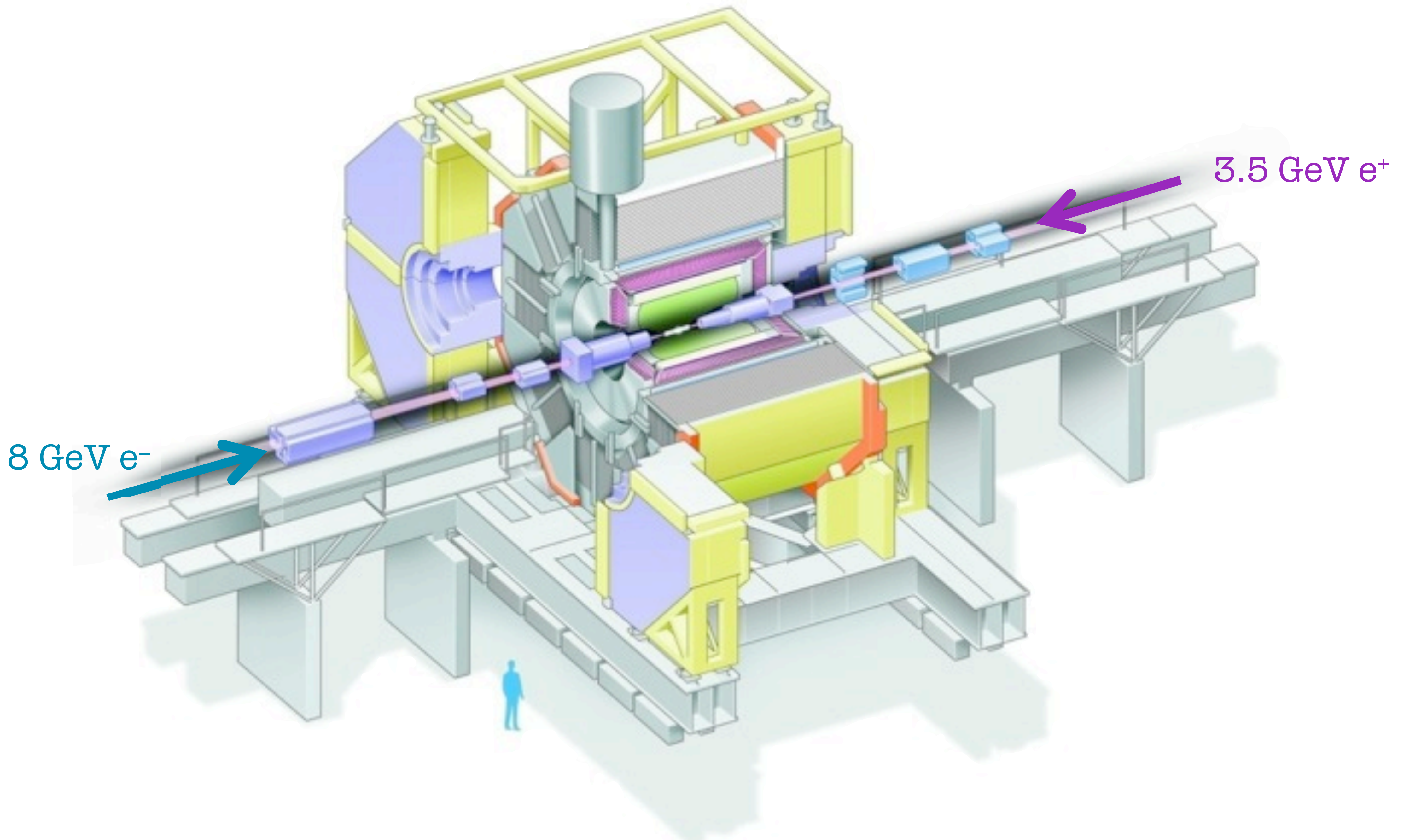
FF … fragmentation function

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

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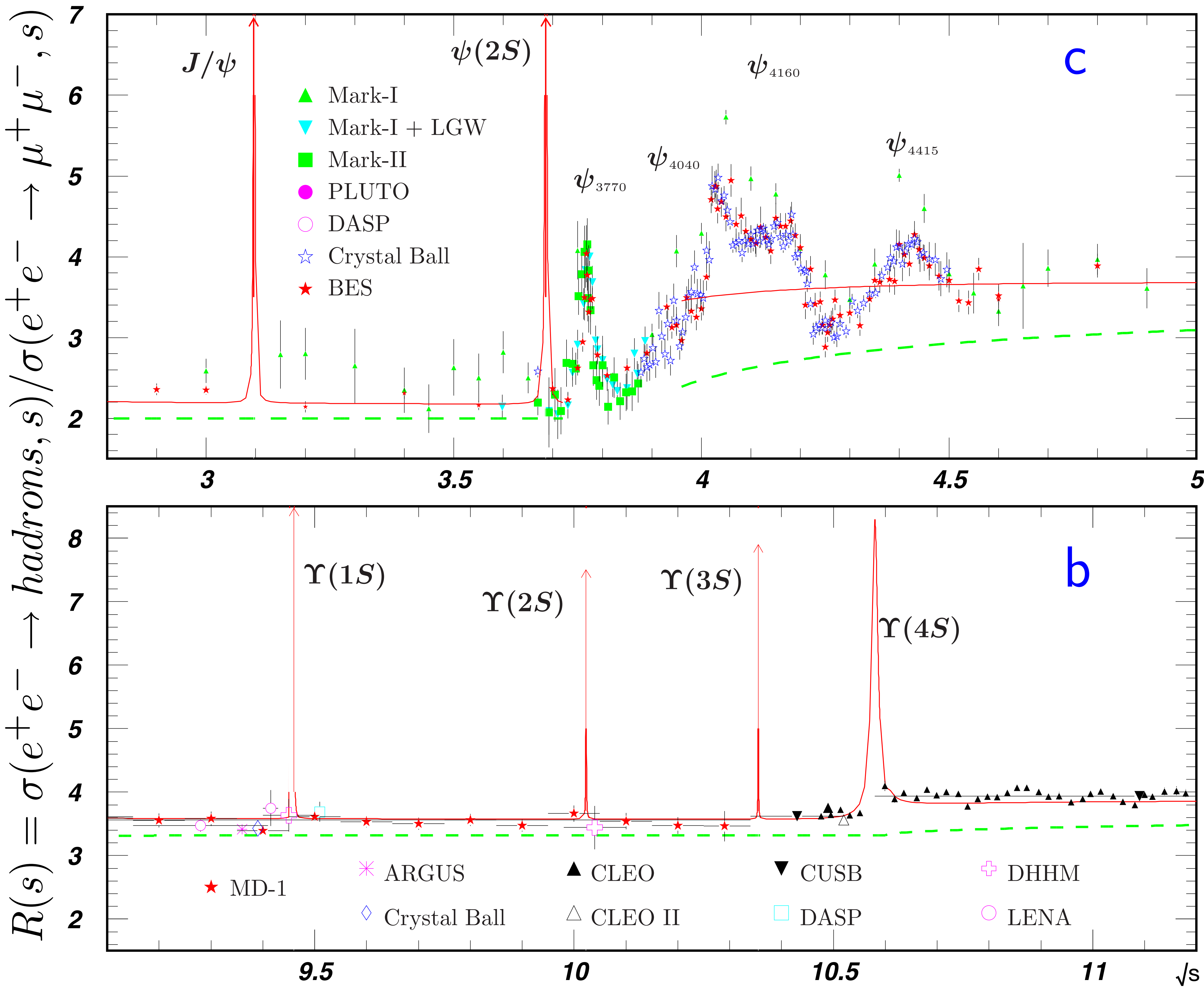
- different scales (➠ QCD evolution) and sensitivities to quark flavor
  - BESIII below charm threshold closer to typical SIDIS case



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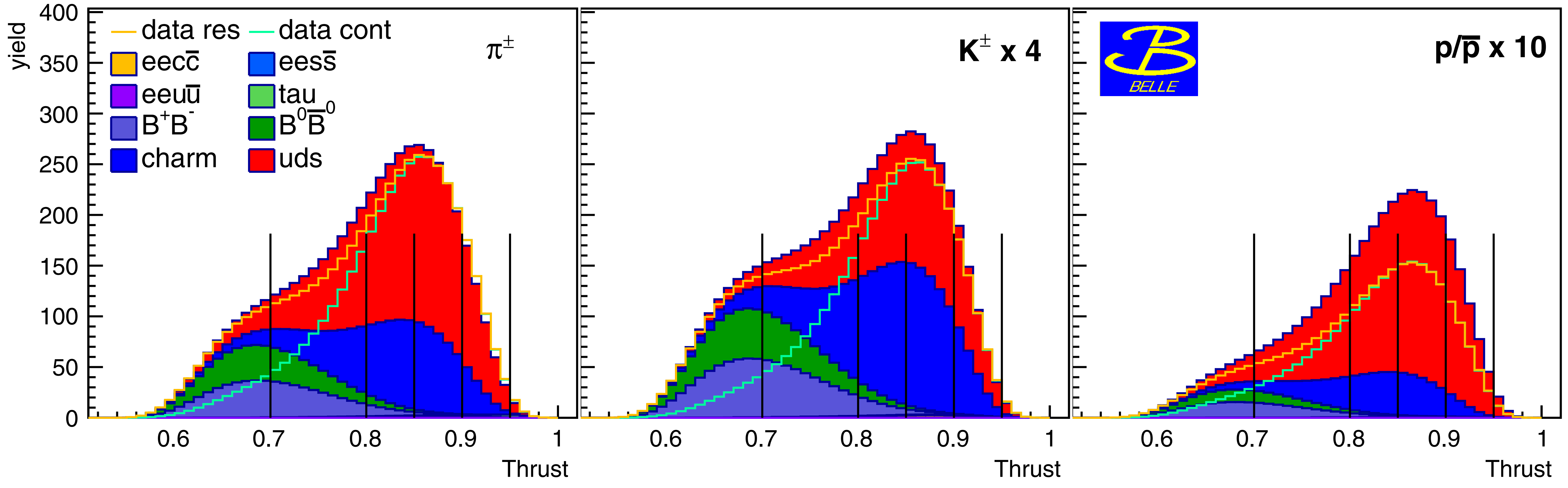
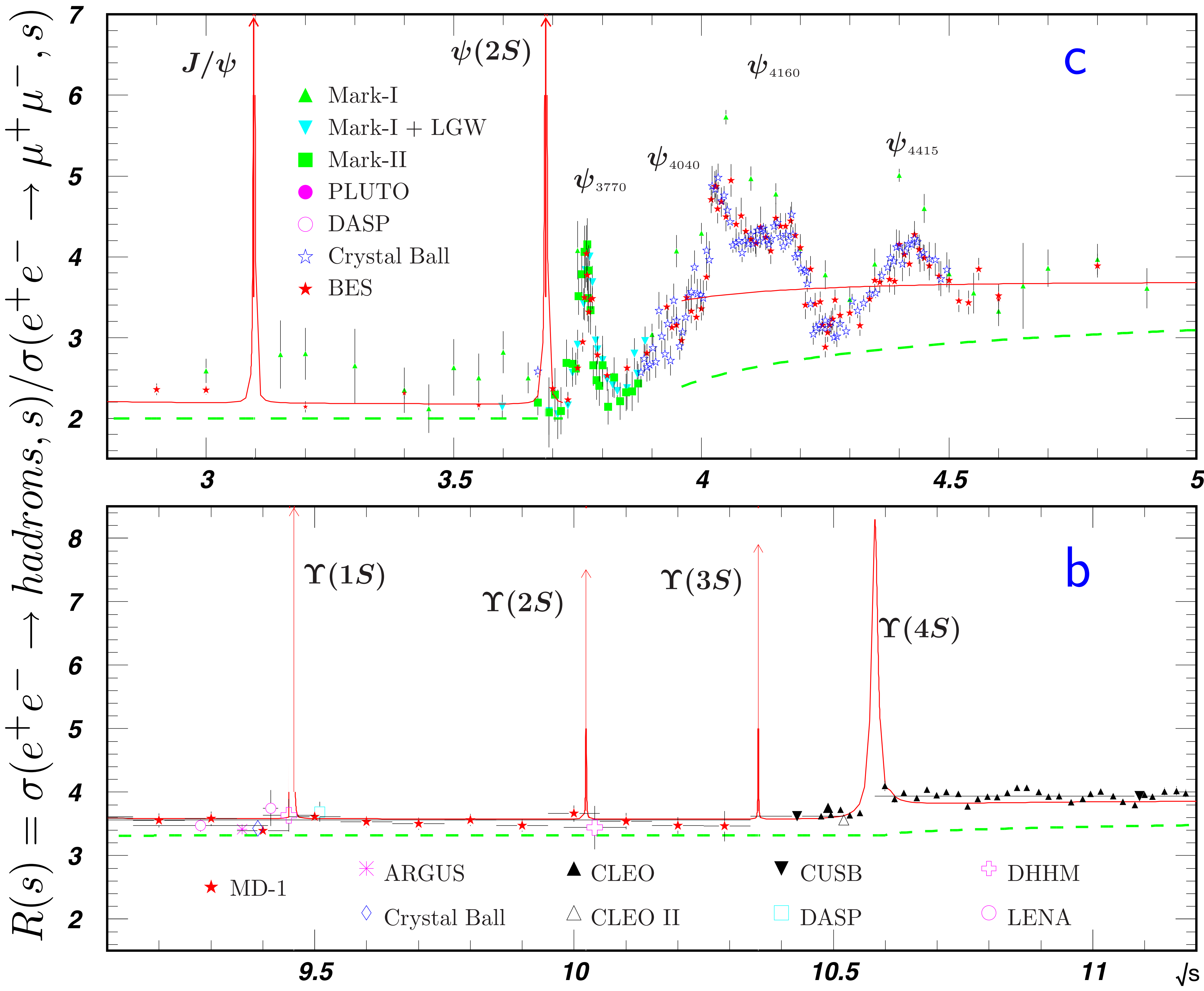
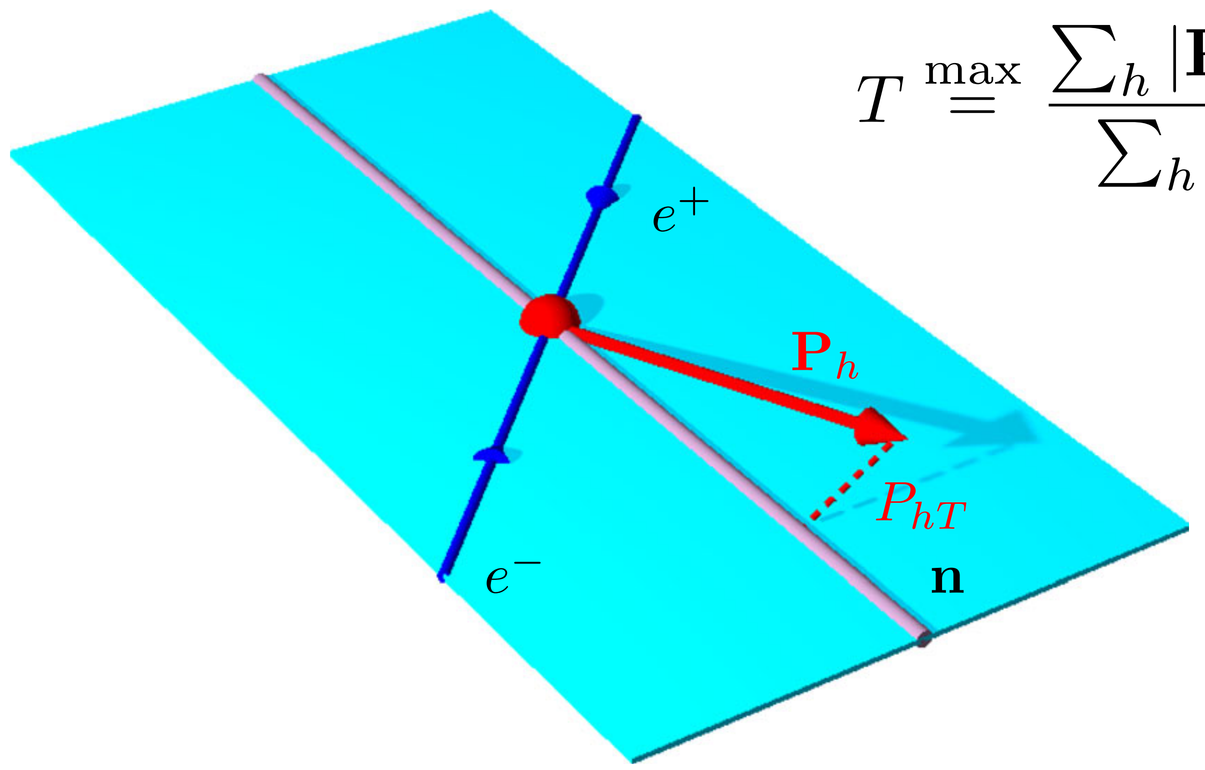




fragmentation in e^+e^- annihilation

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



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

fragmentation in e⁺e⁻ annihilation

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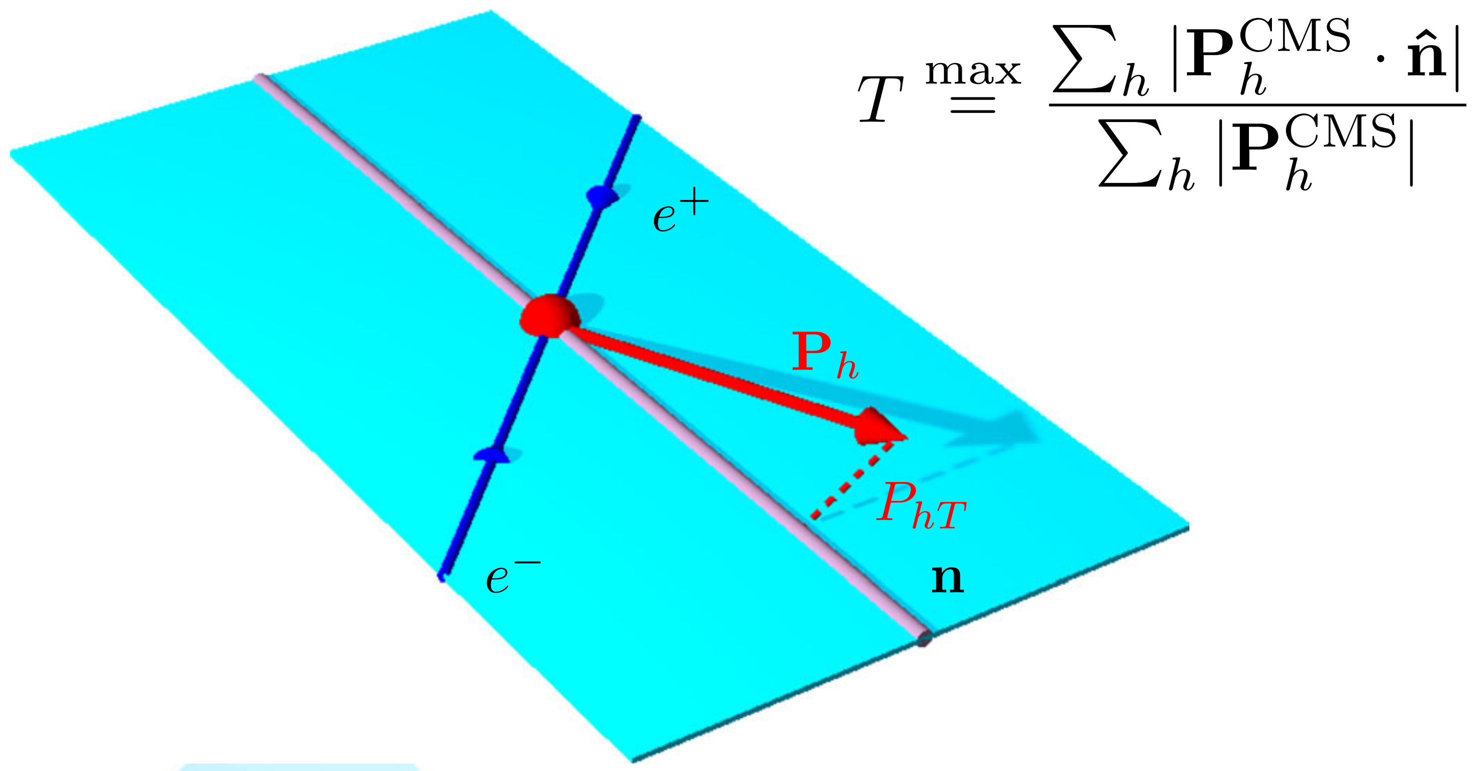
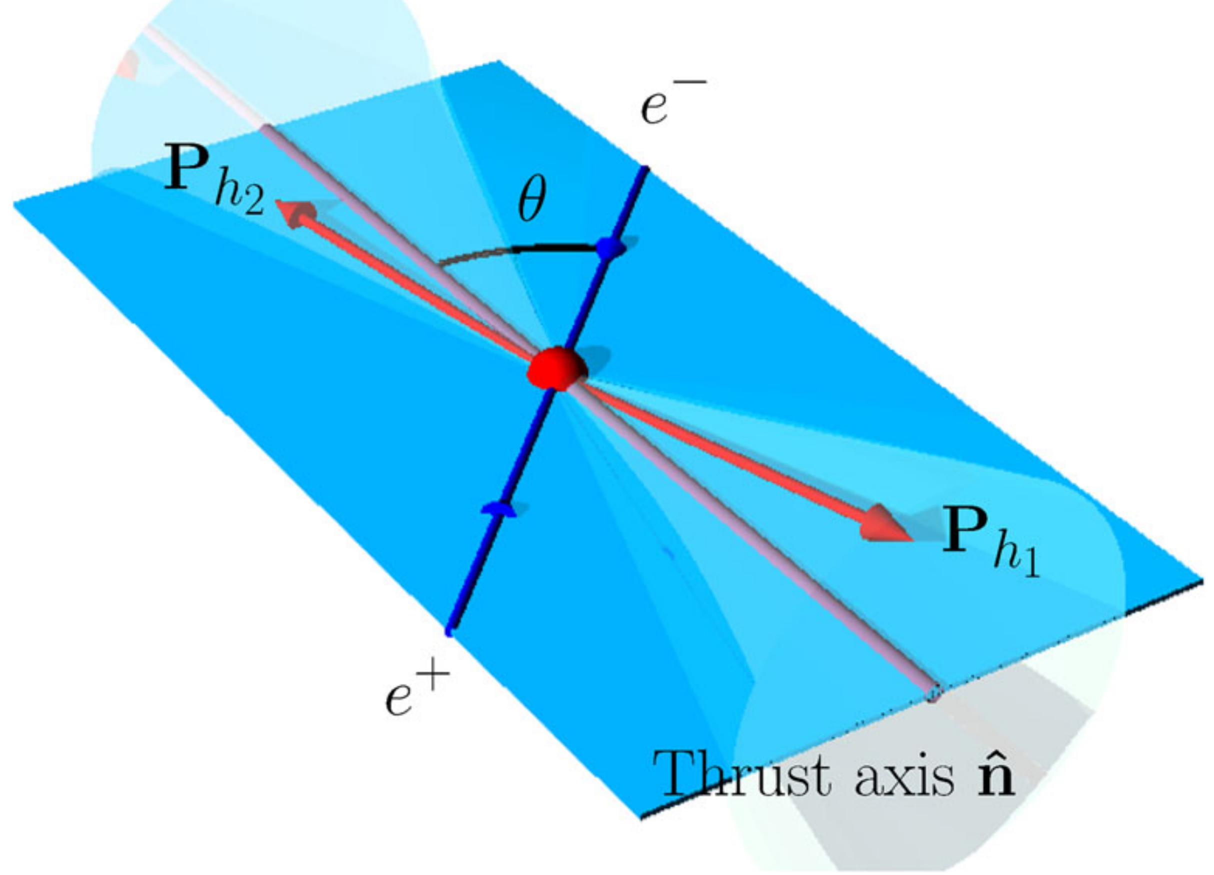
  - D_1 fragmentation function
  - ($D_{1T}^{\perp}$ spontaneous transv. polarization)

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





fragmentation in e⁺e⁻ annihilation

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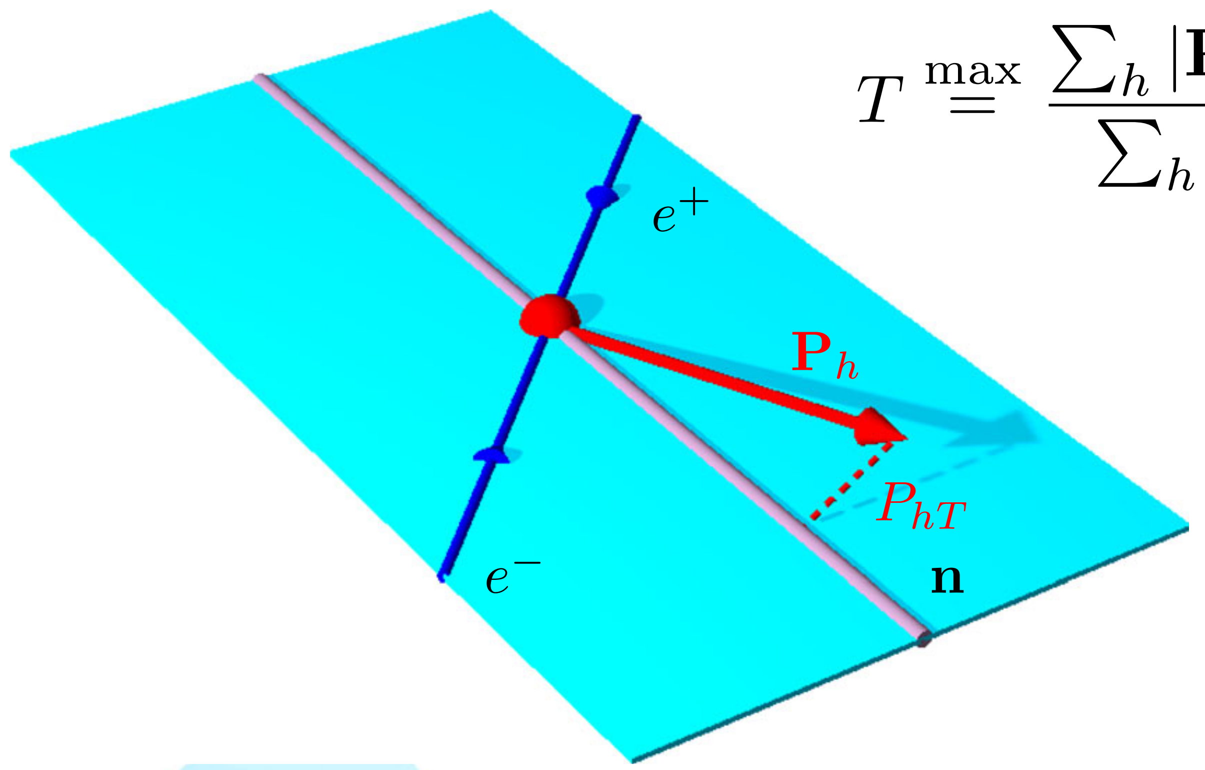
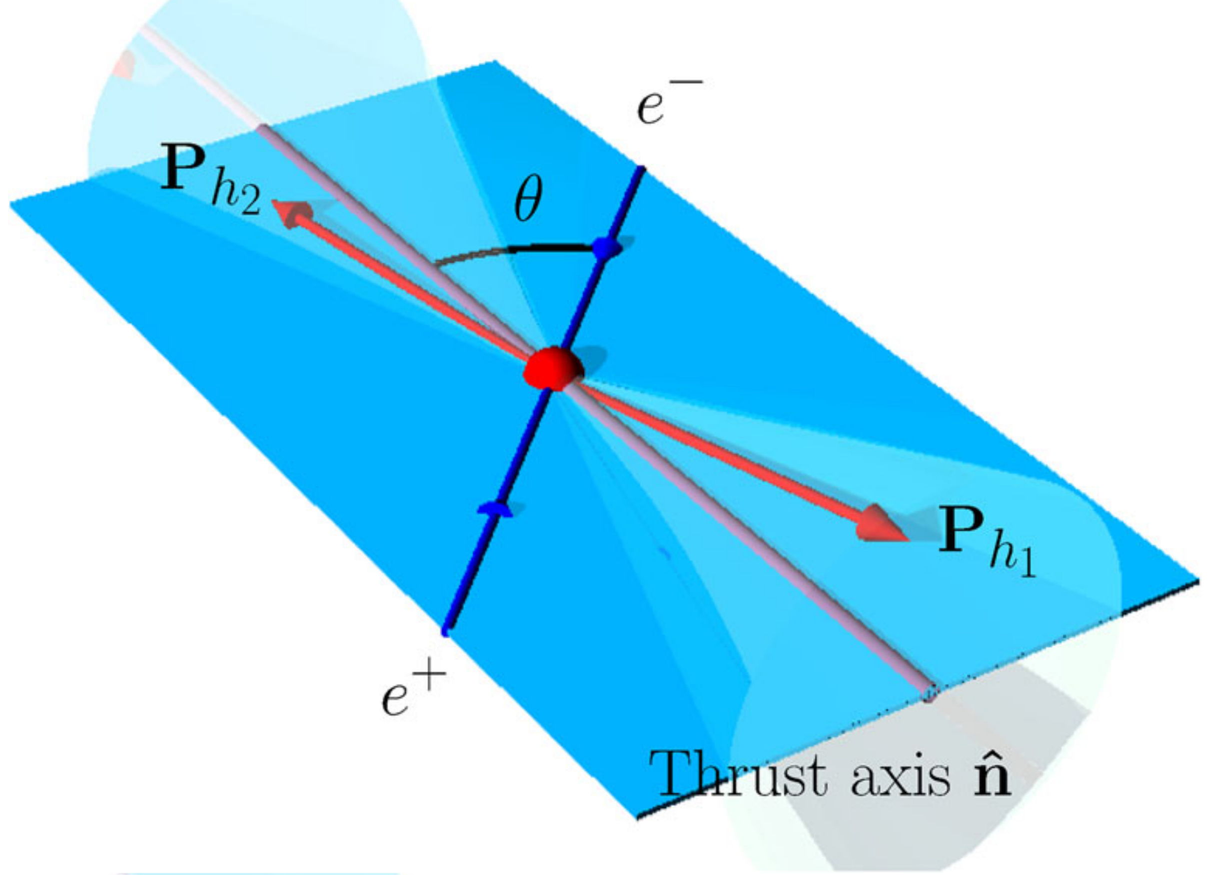
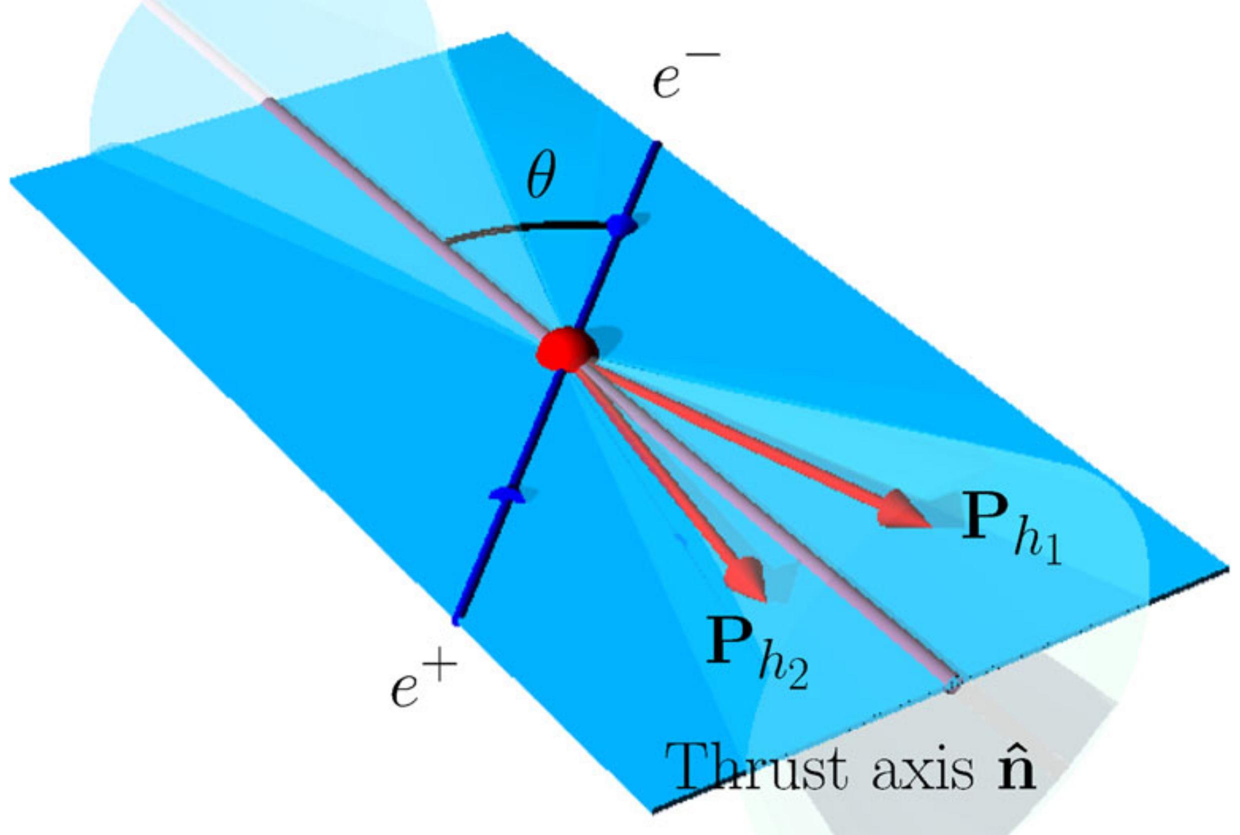
- inclusive "back-to-back" hadron pairs, **$e^+e^- \rightarrow h_1h_2X$**
  - product of fragmentation functions
  - allows for **tagging** of flavor, transverse-momentum, and/or polarization
- inclusive same-hemisphere hadron pairs, **$e^+e^- \rightarrow h_1h_2X$**
  - di-hadron fragmentation

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



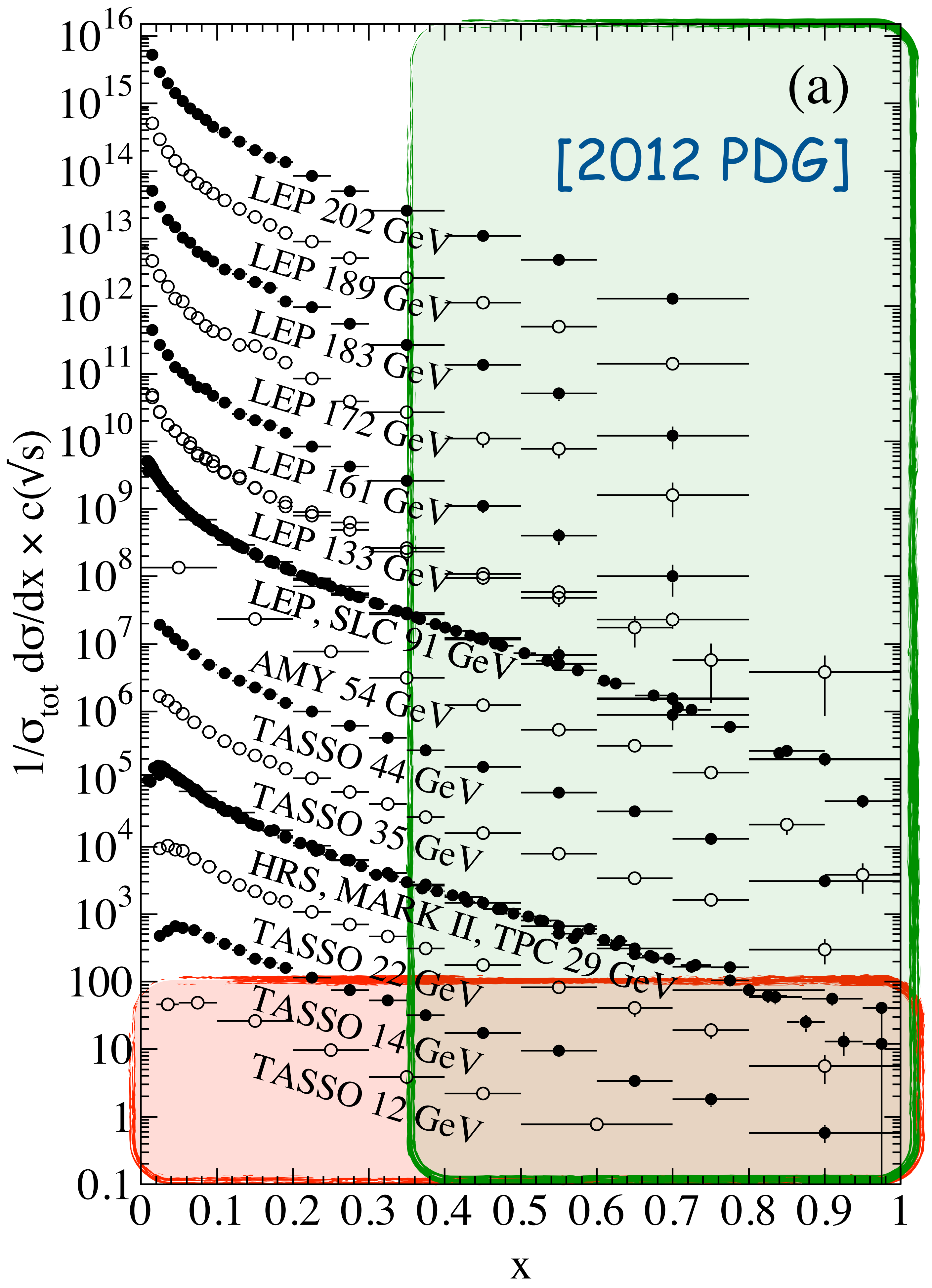




the collinear case

single-hadron production

- before 2013: lack of precision data at (moderately) high z and low √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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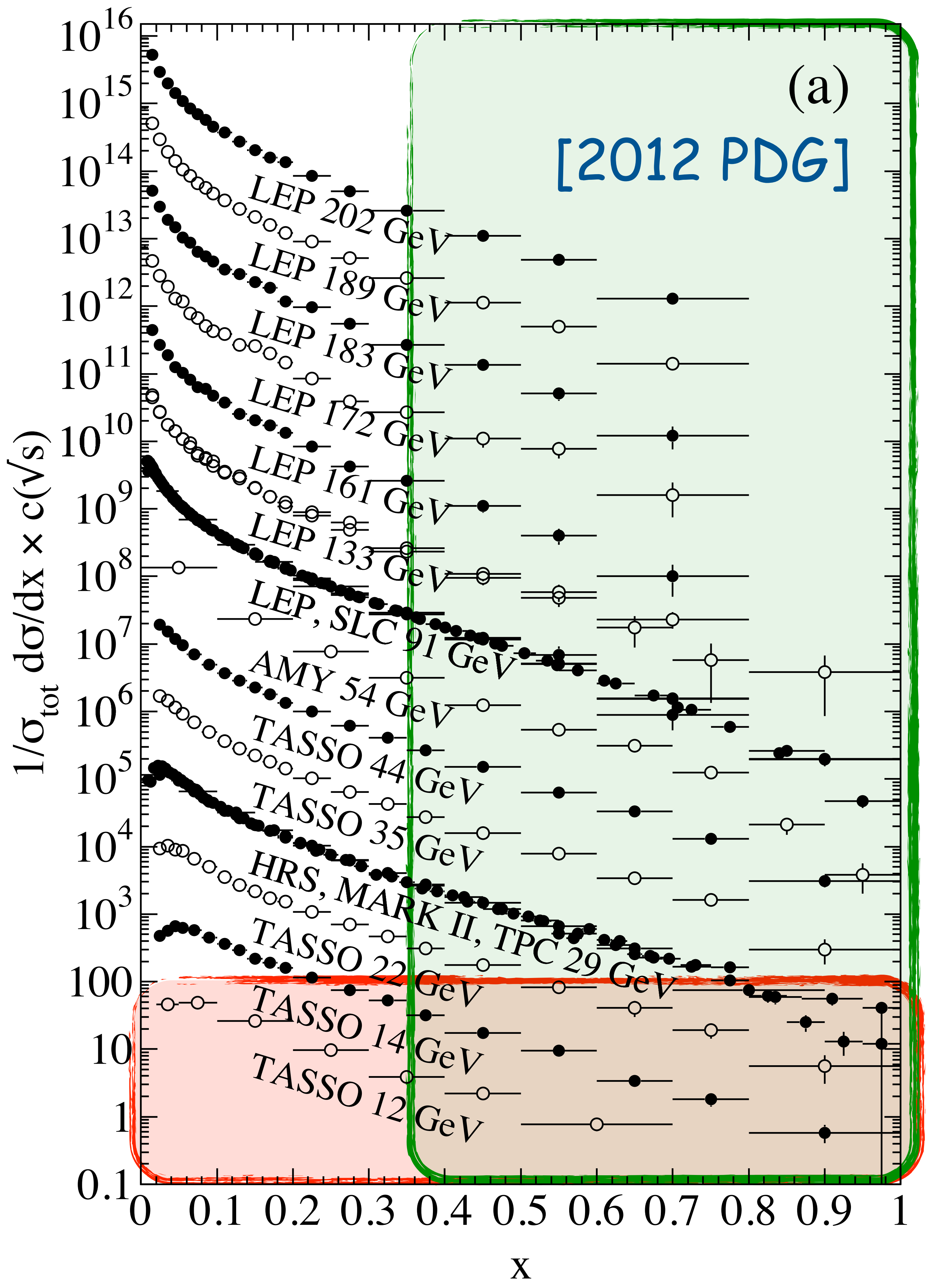
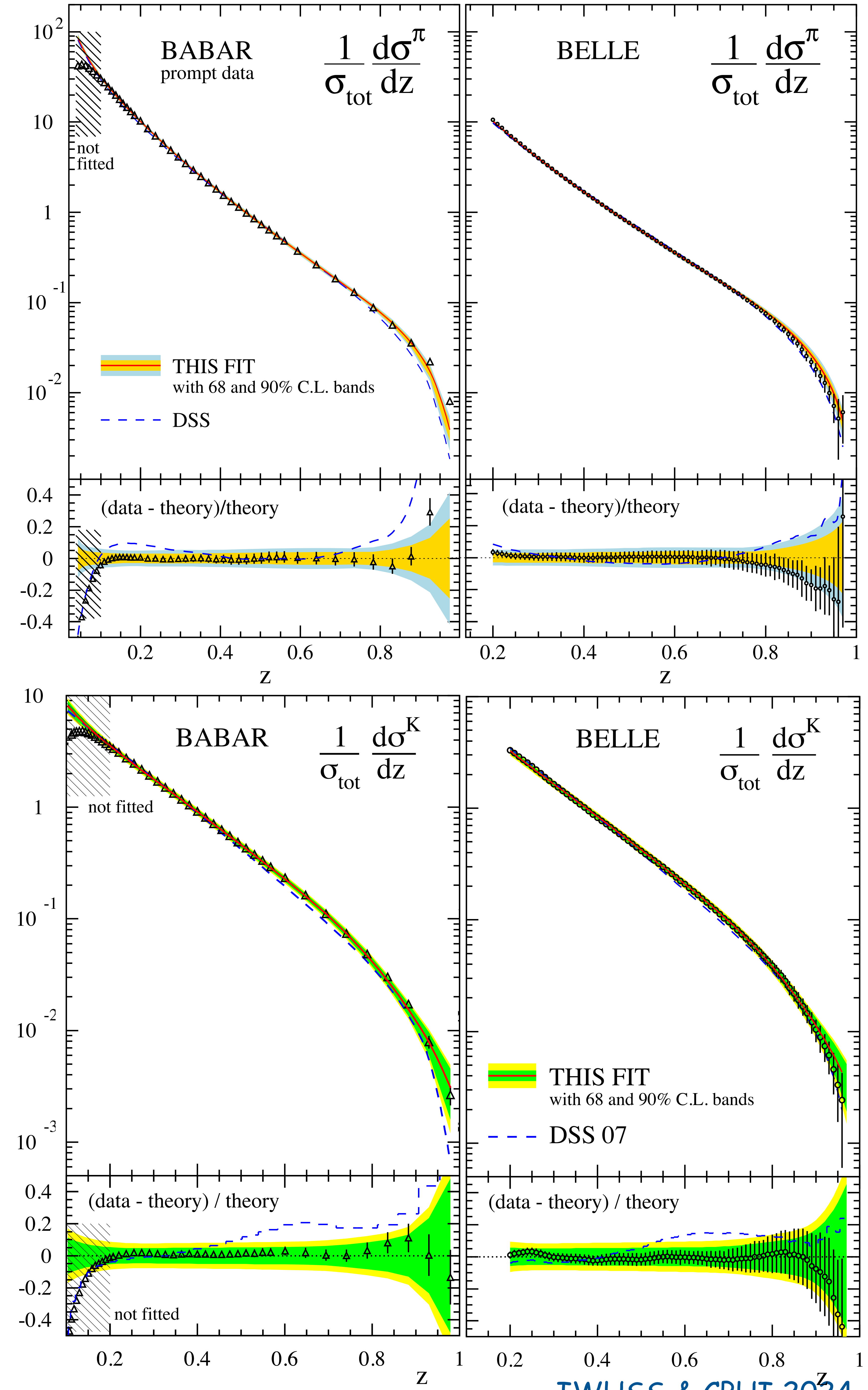
  - limits analysis of evolution and gluon fragmentation
  - limited information in kinematic region often used in semi-inclusive DIS
- by now also results from BaBar, Belle, and BESIII:
  - BaBar Collaboration, PRD 88 (2013) 032011: **$\pi^\pm$, $K^\pm$, $p+\bar{p}$**
  - Belle Collaboration, PRL 111 (2013) 062002: **$\pi^\pm$, $K^\pm$**
  - Belle Collaboration, PRD 92 (2015) 092007 & 101 (2020) 092004: **$\pi^\pm$, $K^\pm$, $p+\bar{p}$**
  - **NEW:** BESIII Collaboration, PRL 130 (2023) 231901 & 133 (2024) 021901 : π^0, K^0_S & η



single-hadron production

- very precise data for charged pions and kaons
- Belle data available up to very large z (z<0.98)
- DEHSS fits [e.g., PRD91 (2015) 014035]
  - slight tension at low-z for BaBar and high-z for Belle



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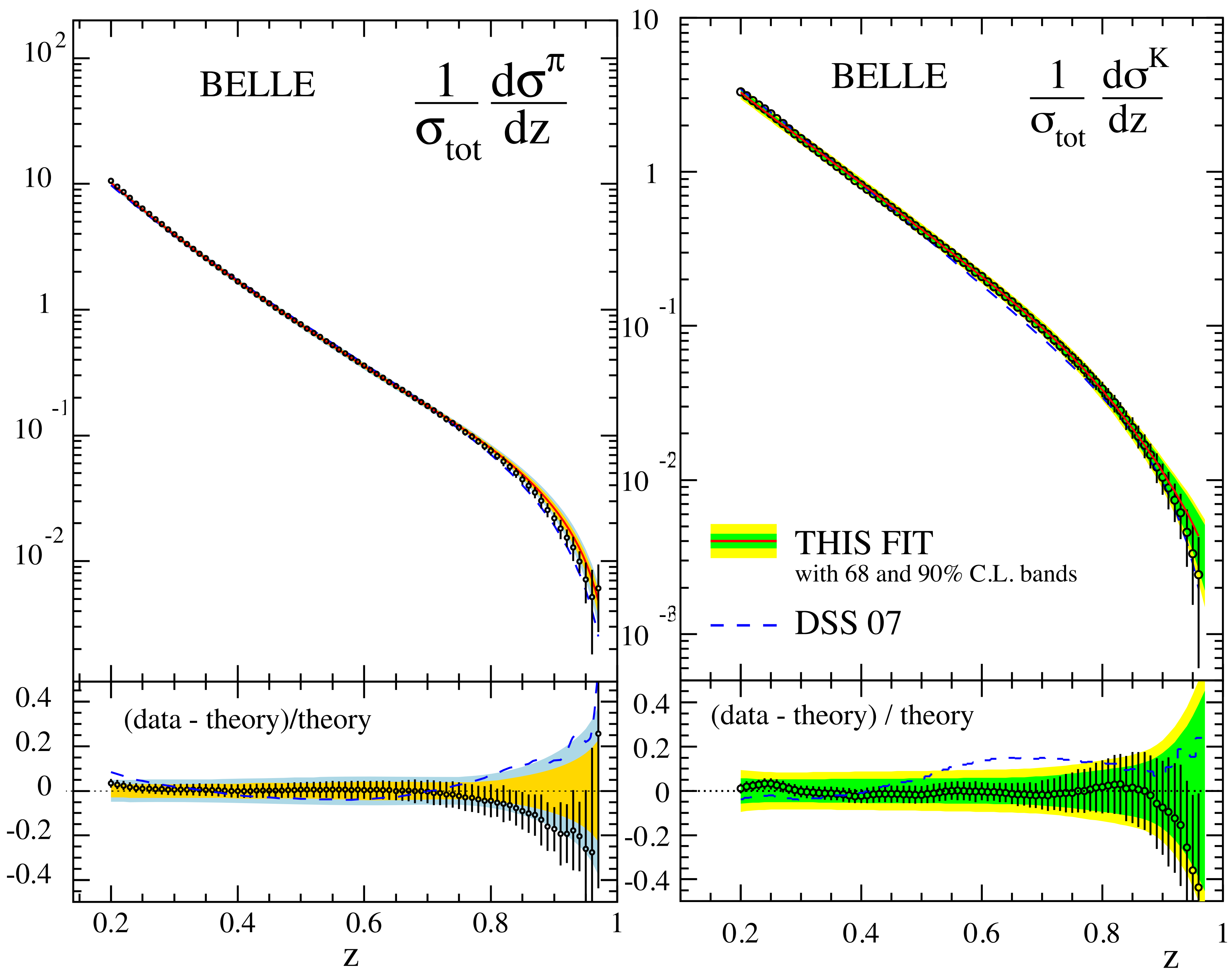

[EPJC 77 (2017) 516, NNFF1.0]

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

single-hadron production

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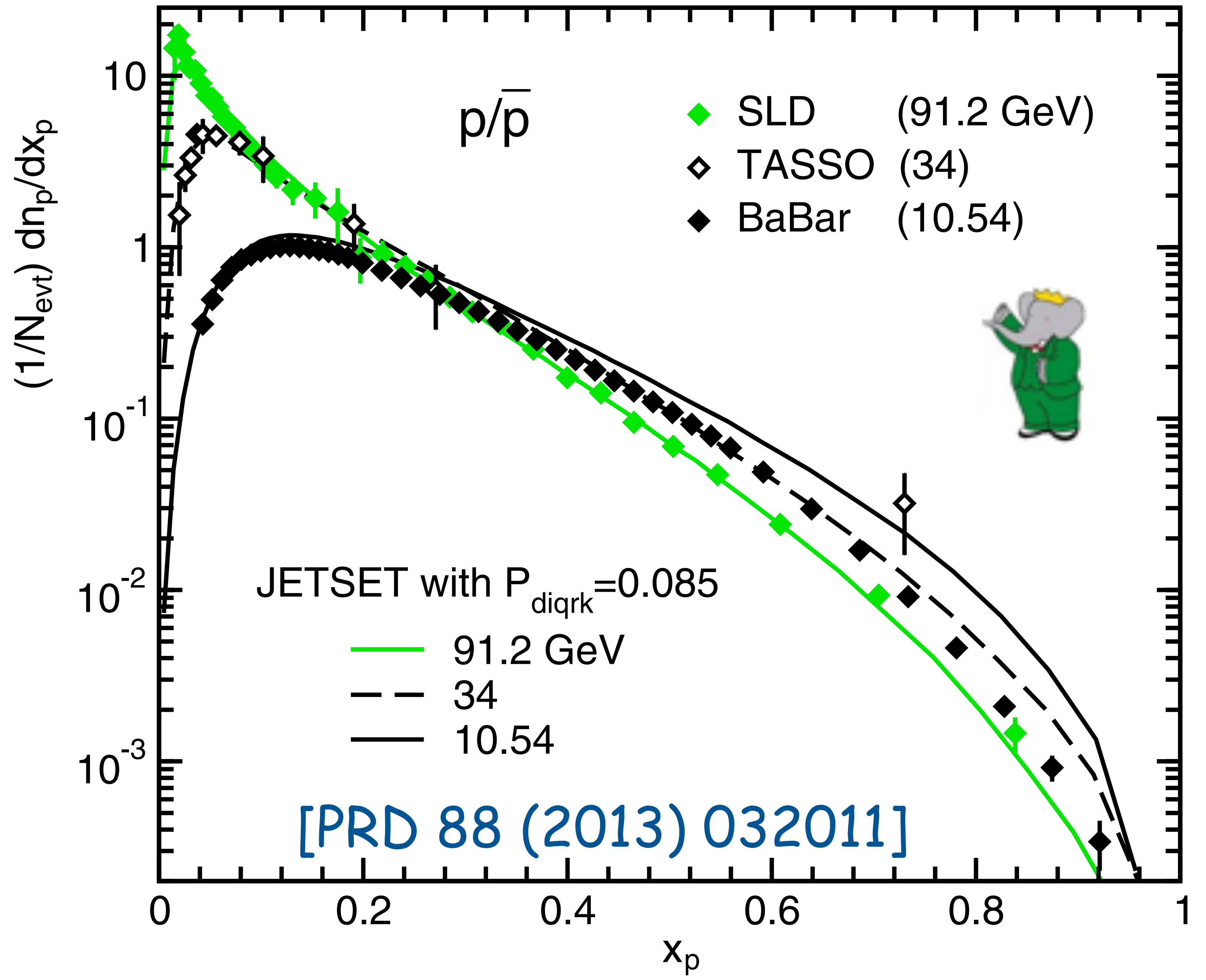
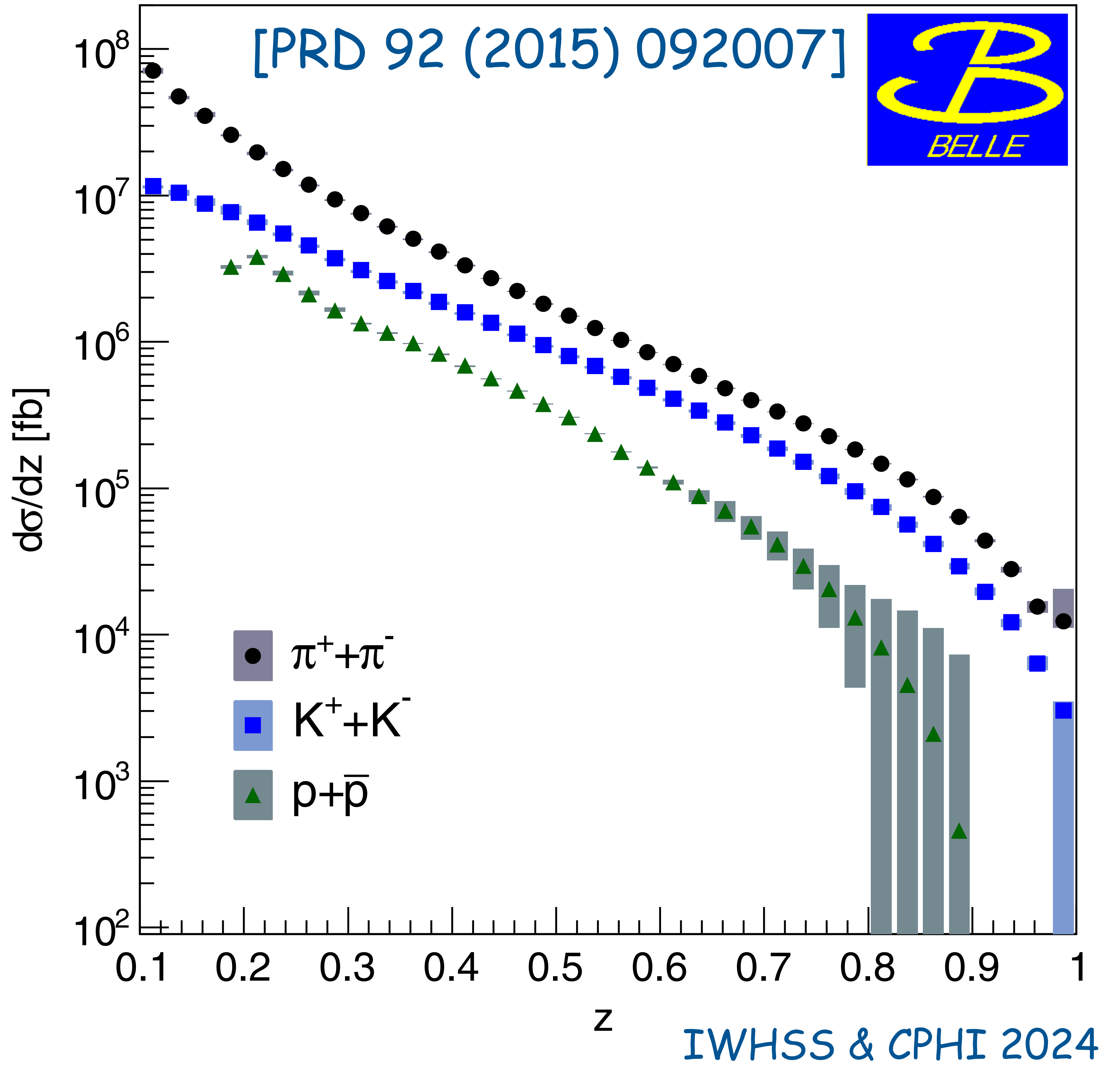
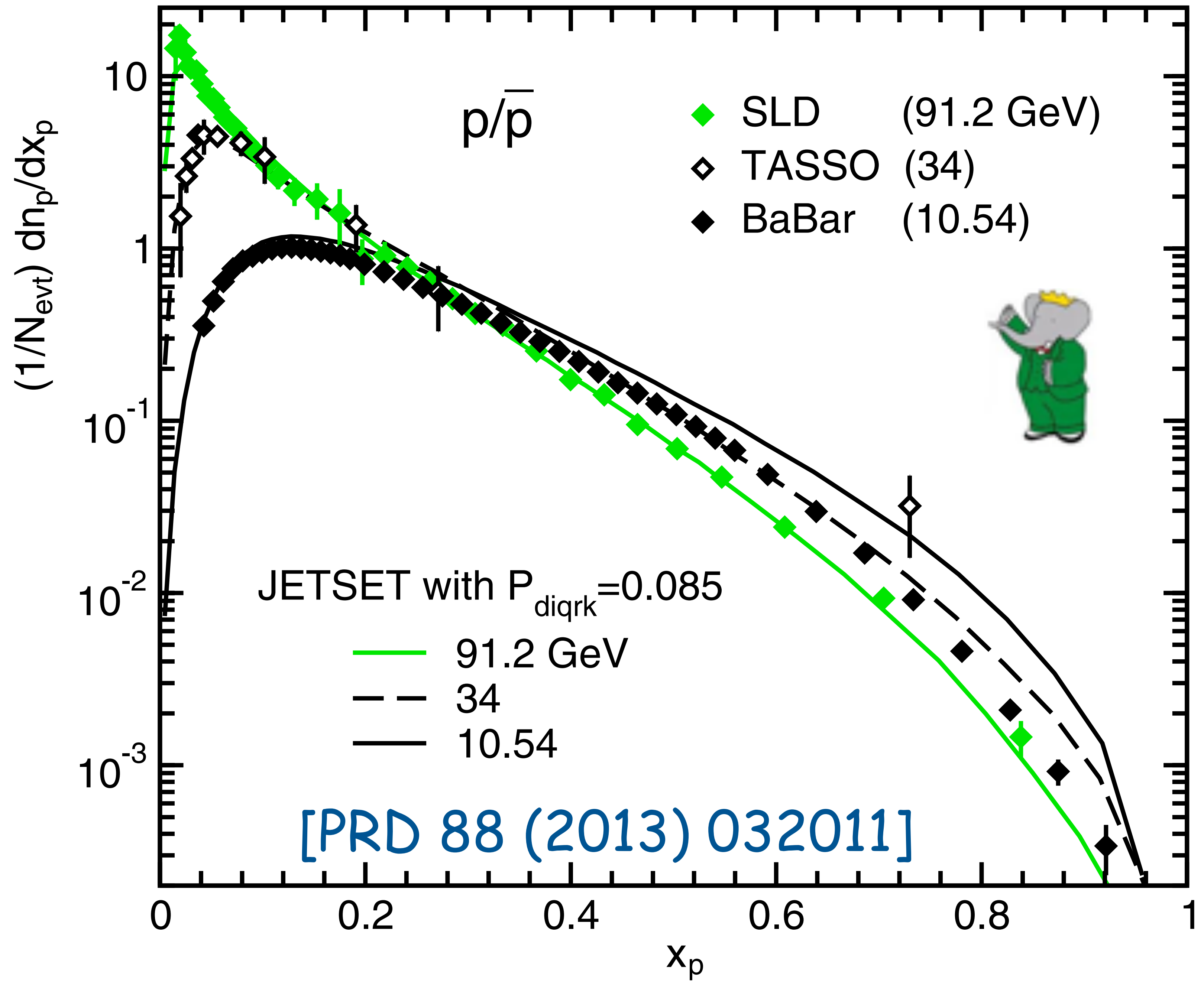
- 2015 DEHSS fits [e.g., PRD91 (2015) 014035]
  - slight tension at low-z for BaBar and high-z for Belle
- Belle radiative corrections generally "**undone**" in FF fits
- data available for (anti)protons
  - similar z dependence as pions
  - about ~⅕ of pion cross sections

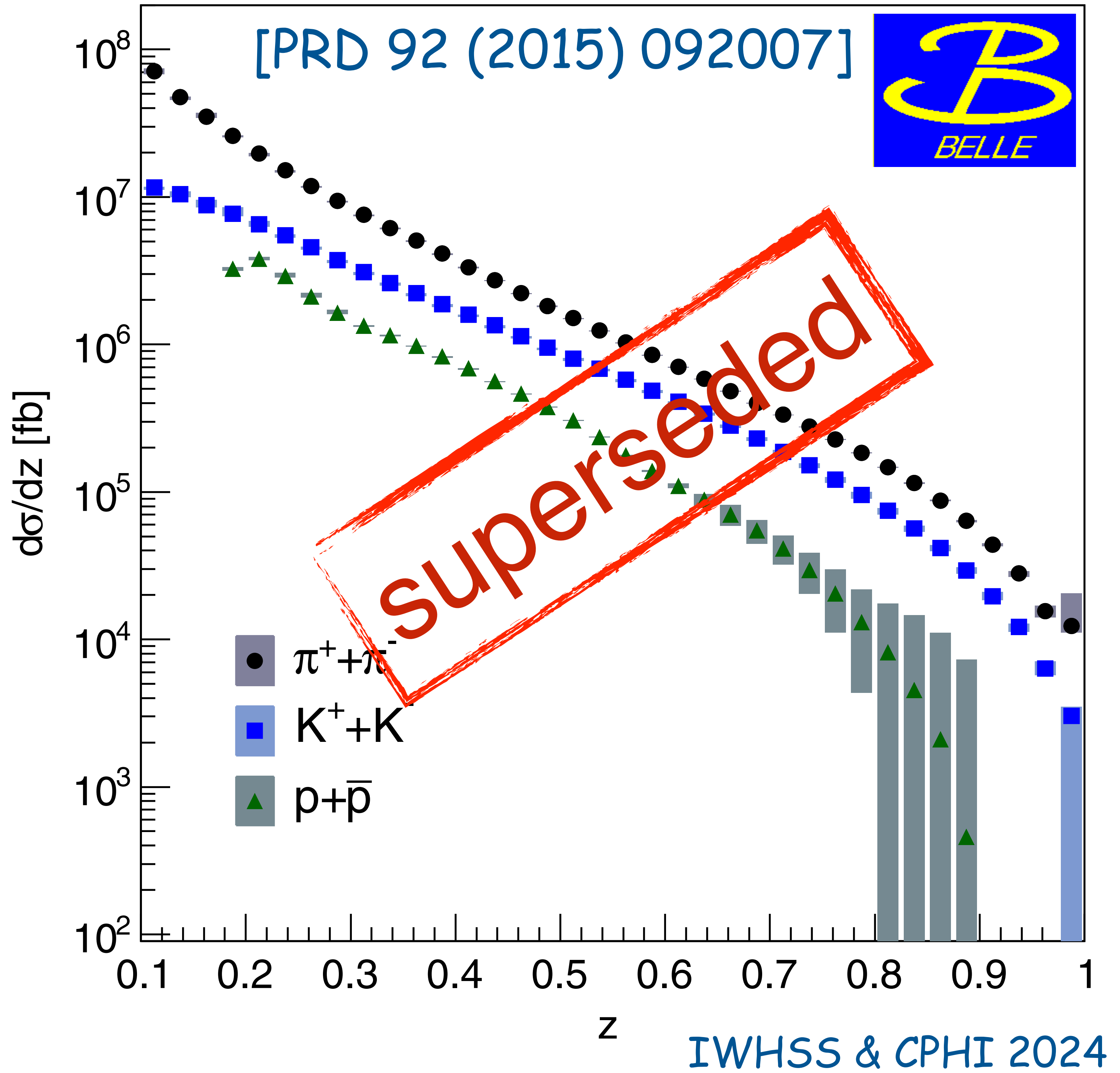




single-hadron production

- very precise data for charged pions and kaons
- Belle data available up to very large z (z<0.98)
- 2015 DEHSS fits [e.g., PRD91 (2015) 014035]
  - slight tension at low-z for BaBar and high-z for Belle
- Belle radiative corrections generally "**undone**" in FF fits
- data available for (anti)protons
  - similar z dependence as pions
  - about ~⅕ of pion cross sections
- Belle **re-analysis** presented in **PRD 101 (2020) 092004**





interlude

about counting

- cross sections are basically count rates
- "how to count?" sounds like a simple question, but the devil is in the details
  - what to do with hadrons that have (somewhere!) an ISR photon
  - in general, how to deal with events that are assigned to "wrong" kinematic bin due to instrumental effects [e.g., measured and true momentum might differ]
  - book-keeping of assigning event's contribution to bin's statistical uncertainty

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  - book-keeping of assigning event's contribution to bin's statistical uncertainty
- hadron yields also undergo series of other corrections:
  - particle (mis)identification [e.g., not every identified pion was a pion]
  - non-qq processes [e.g., two-photon processes, Υ -> BB, ...]
  - "4π" correction [e.g., selection criteria and limited geometric acceptance]
  - "optional": weak-decay removal [e.g., "prompt fragmentation"]

ISR

- what to do with hadrons that have (somewhere) an ISR photon
  - nothing! — leave it to phenomenology to deal with QED corrections
    - however, (uncorrected/corrected) yields are ISR & detector dependent
  - reject all events that have an isolated photon?
    - detectors almost never fully hermetic, many ISR photons travel down the beam pipe
    - still fully inclusive reaction?
  - use some Monte Carlo to estimate event fraction with an ISR photon that carries away more than x% of total available energy (e.g., 0.5% as in earlier Belle analyses)
    - what is a reasonable choice for x?
    - ISR treatment model dependent, indeed depends on annihilation cross section
  - use some Monte Carlo to estimate ratio of hadrons produced in absence of ISR vs. full QED+QCD simulation
    - again model dependent: number of hadrons produced at given z for different s depends on differential cross section (e.g., from evolution)

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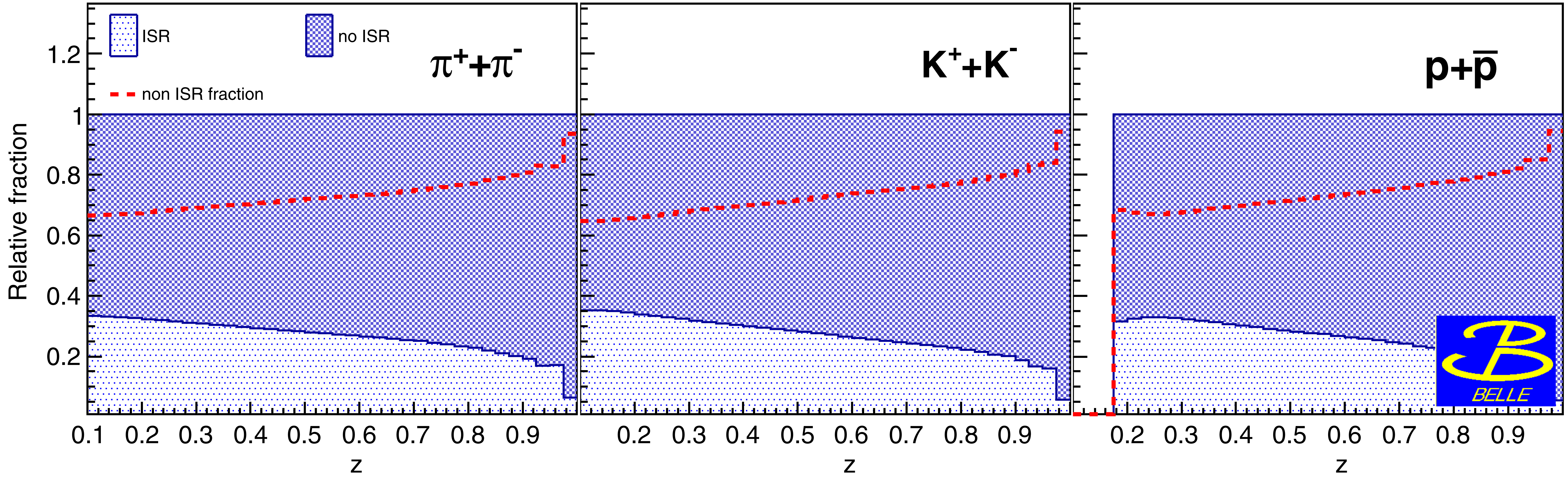
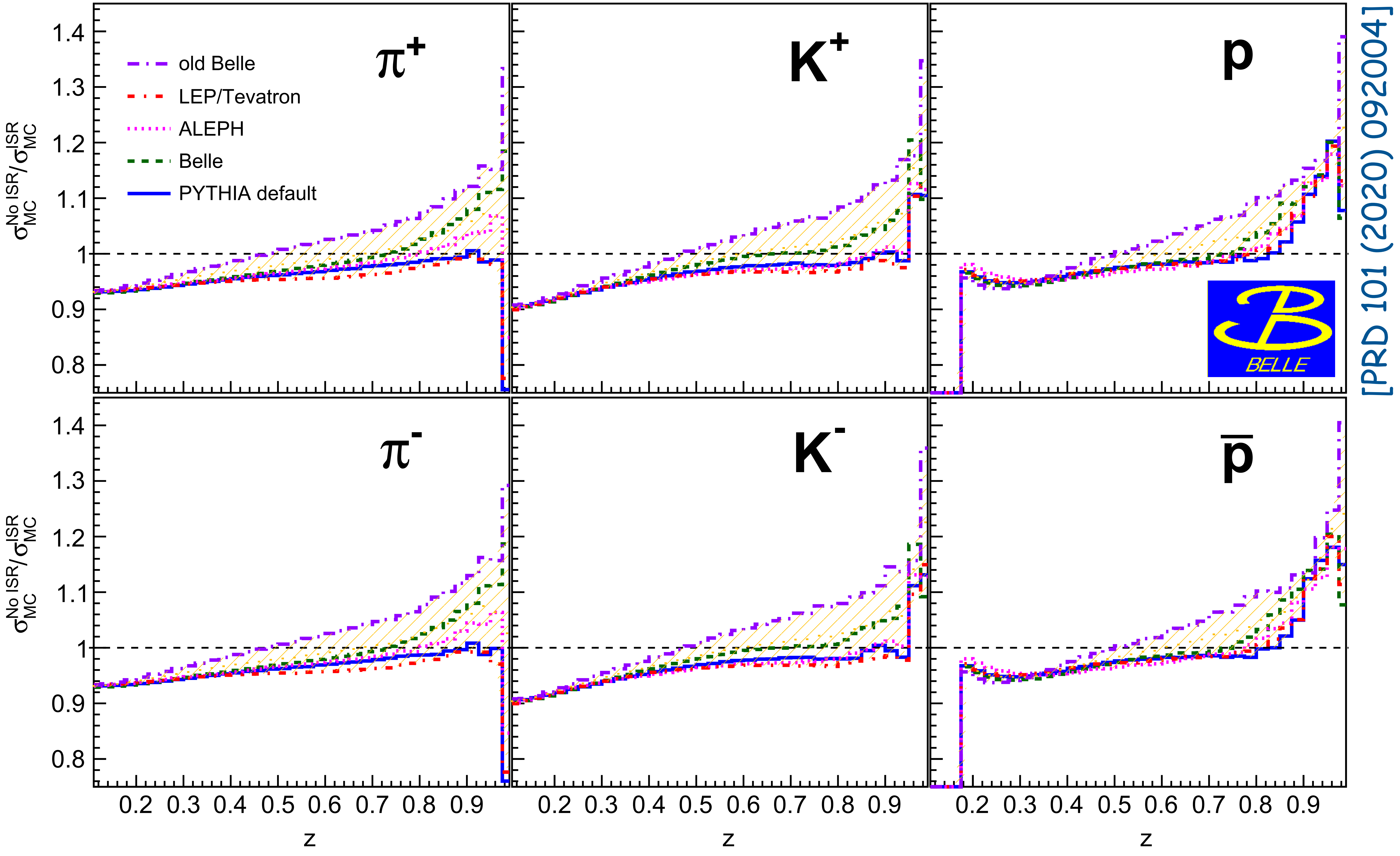
ISR corrections - PRD 92 (2015) 092007



- 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
  - currently used constant 0.65 correction to undo ISR correction is not a constant vs. z

ISR corrections - PRD 101 (2020) 092004

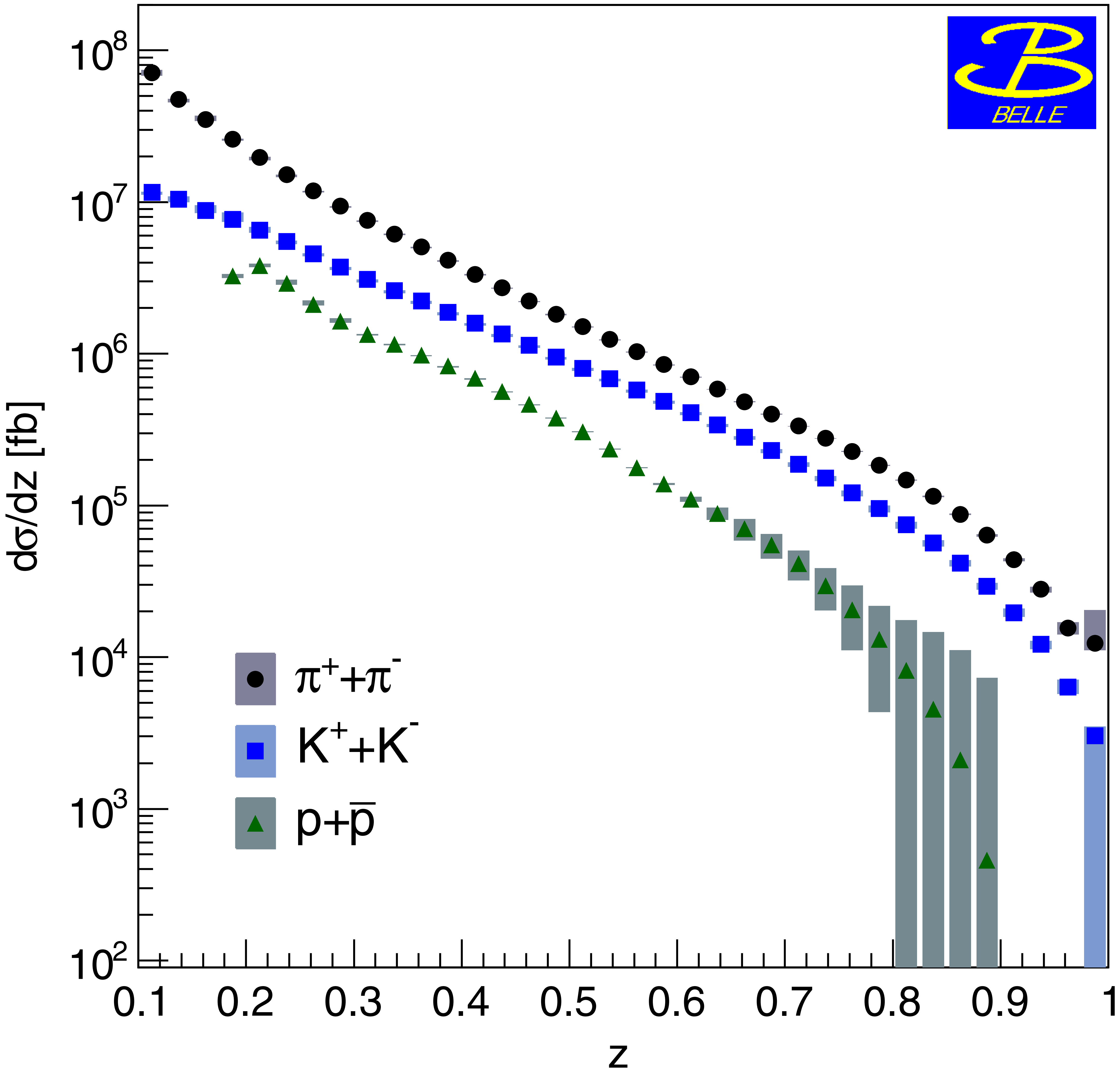


- non-ISR / ISR fractions based on PYTHIA switch MSTP(11)
- PYTHIA model dependence; absorbed in systematics by variation of tunes

comparison old&new Belle single-hadron cross sections

- previous analysis

[PRD 92 (2015) 092007]



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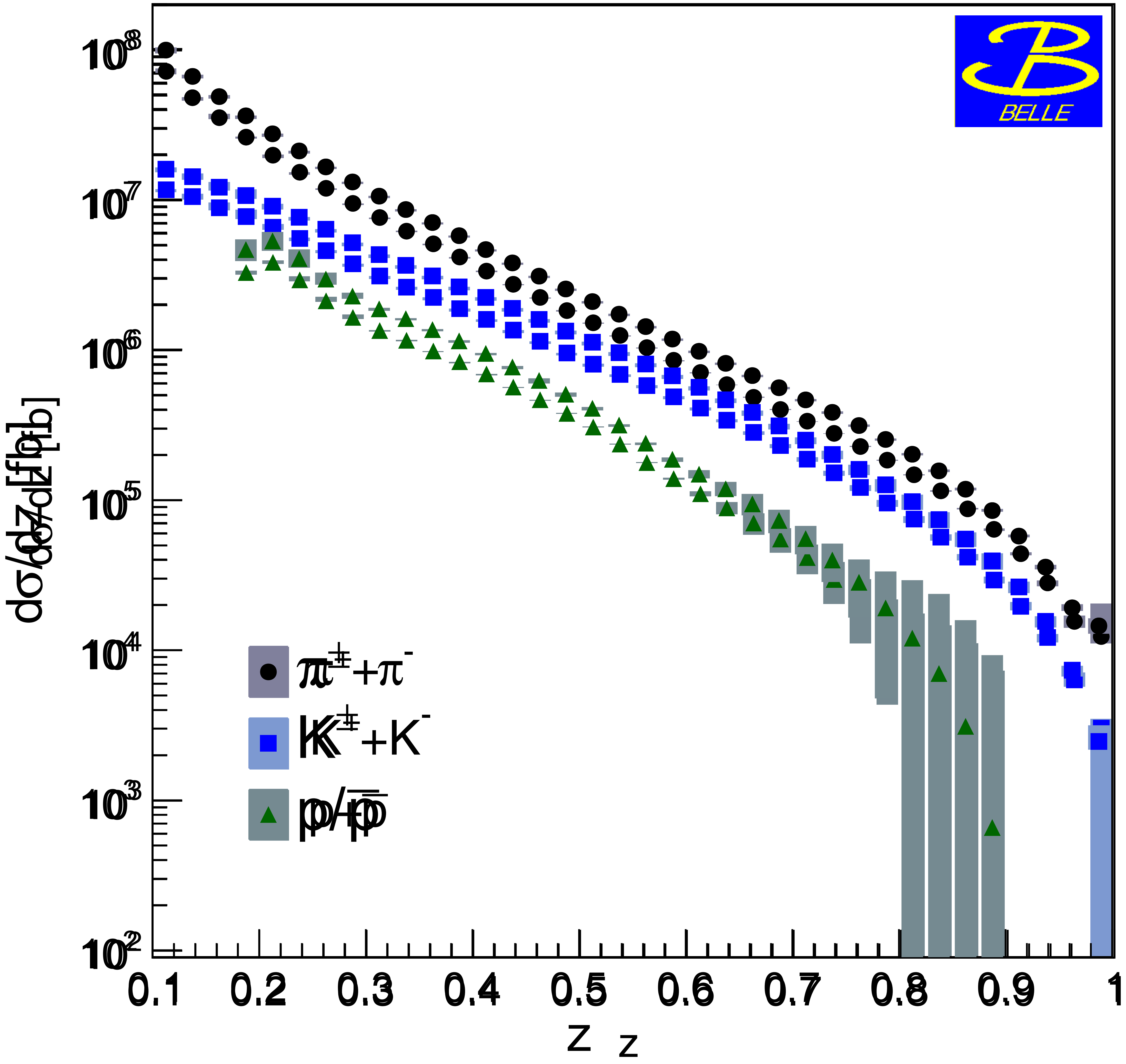
[PRD 92 (2015) 092007] [PRD 101 (2020) 092004]



- updated analysis

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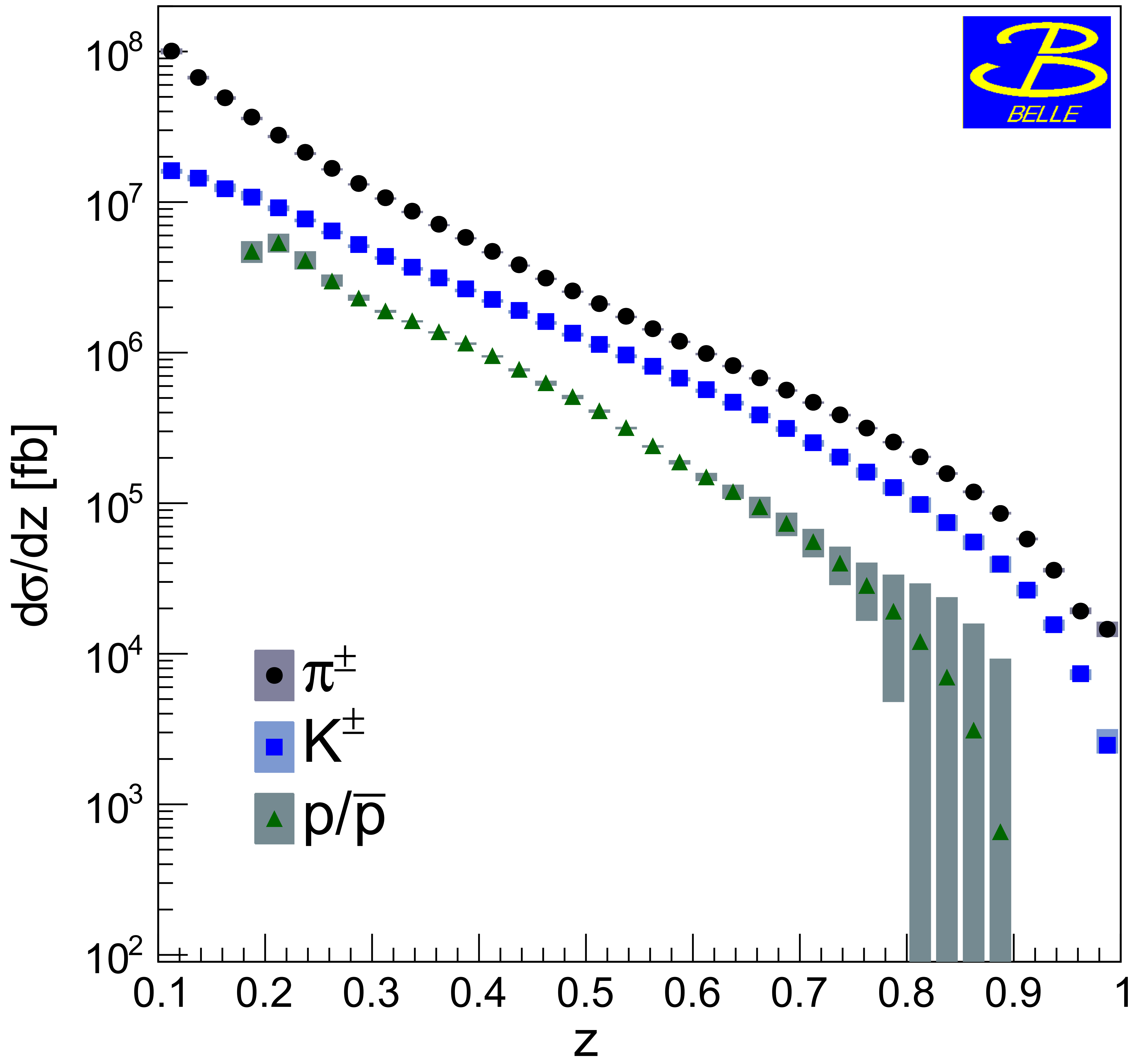
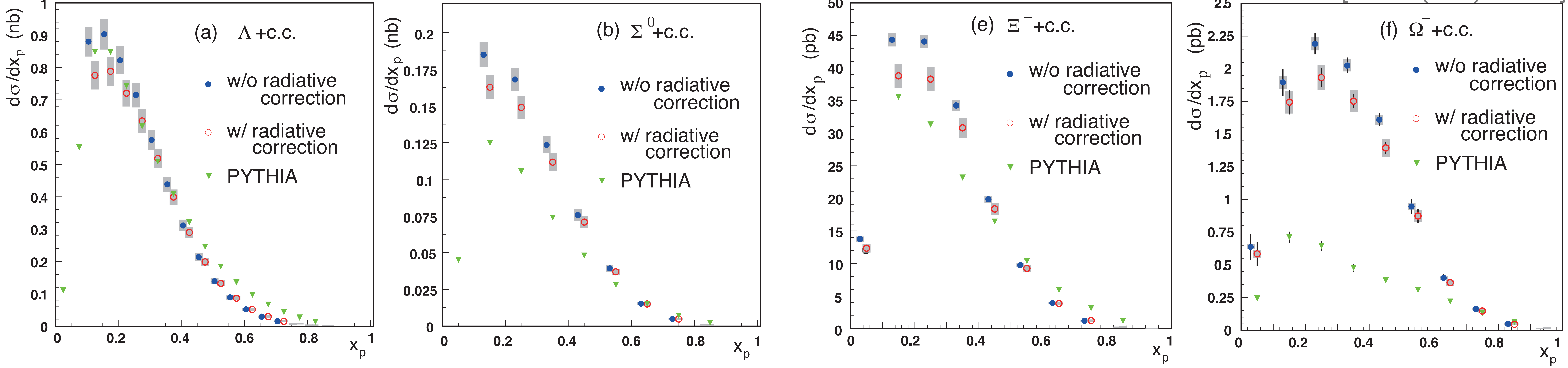
[PRD 101 (2020) 092004]

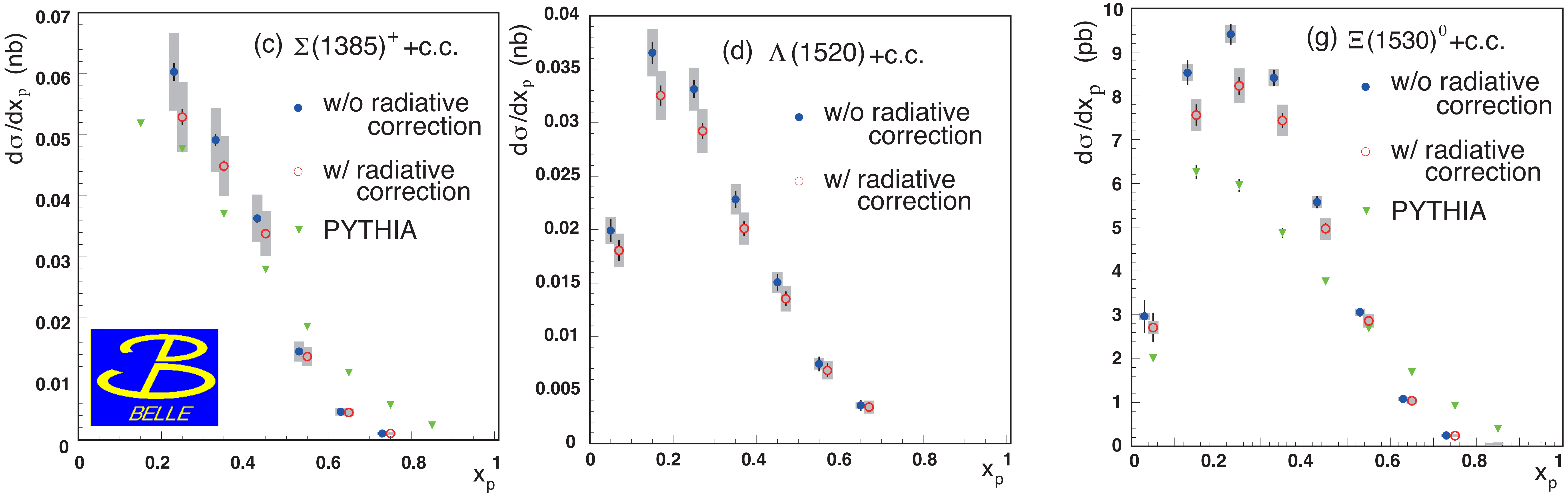


- updated analysis

single-hadron production: **hyperons**

[PRD 97 (2018) 072005]



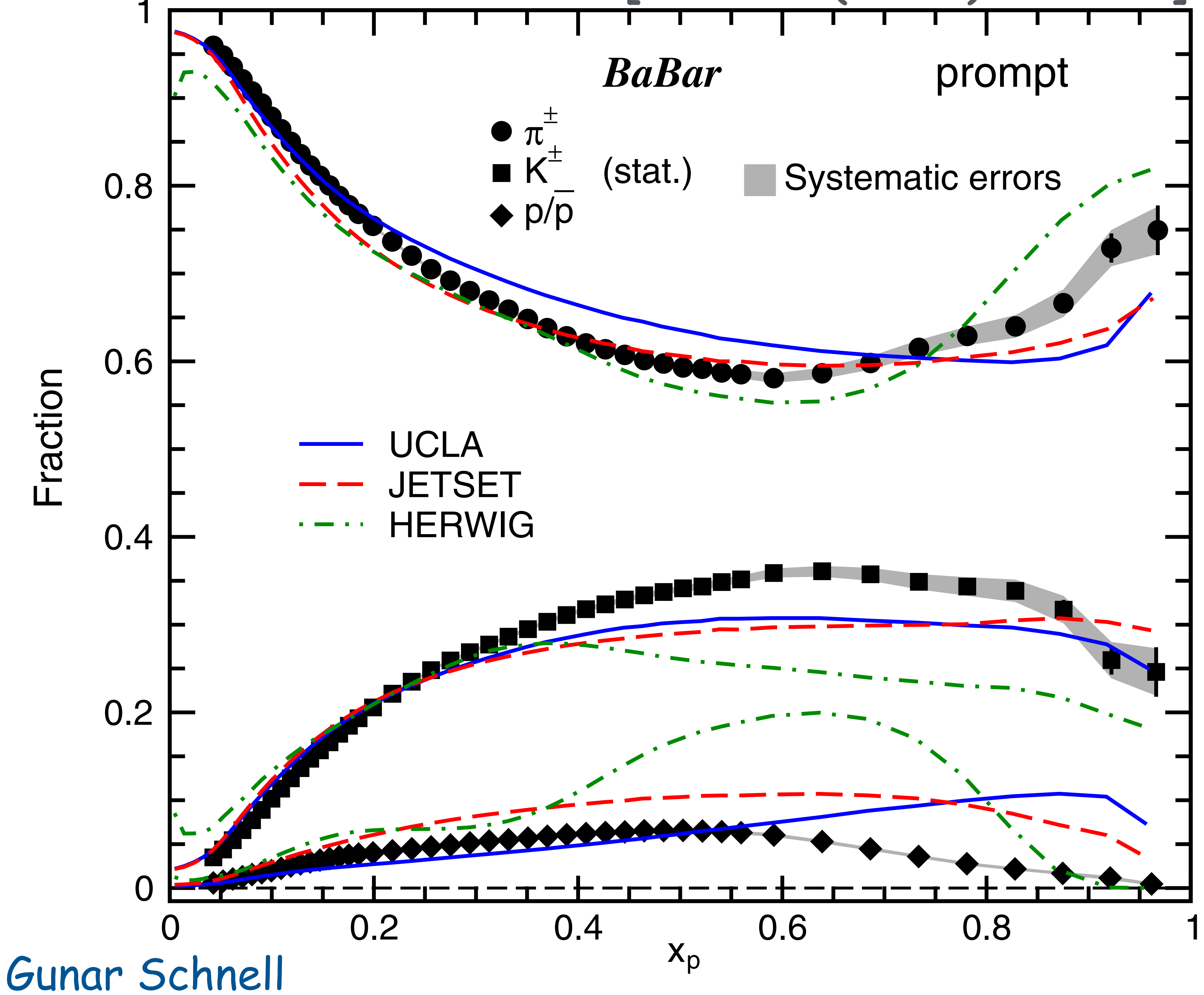


- Λ production reasonably well described by PYTHIA
- less satisfactory for heavier hyperons (a quite common problem)
- basically fails to describe Ω^- production

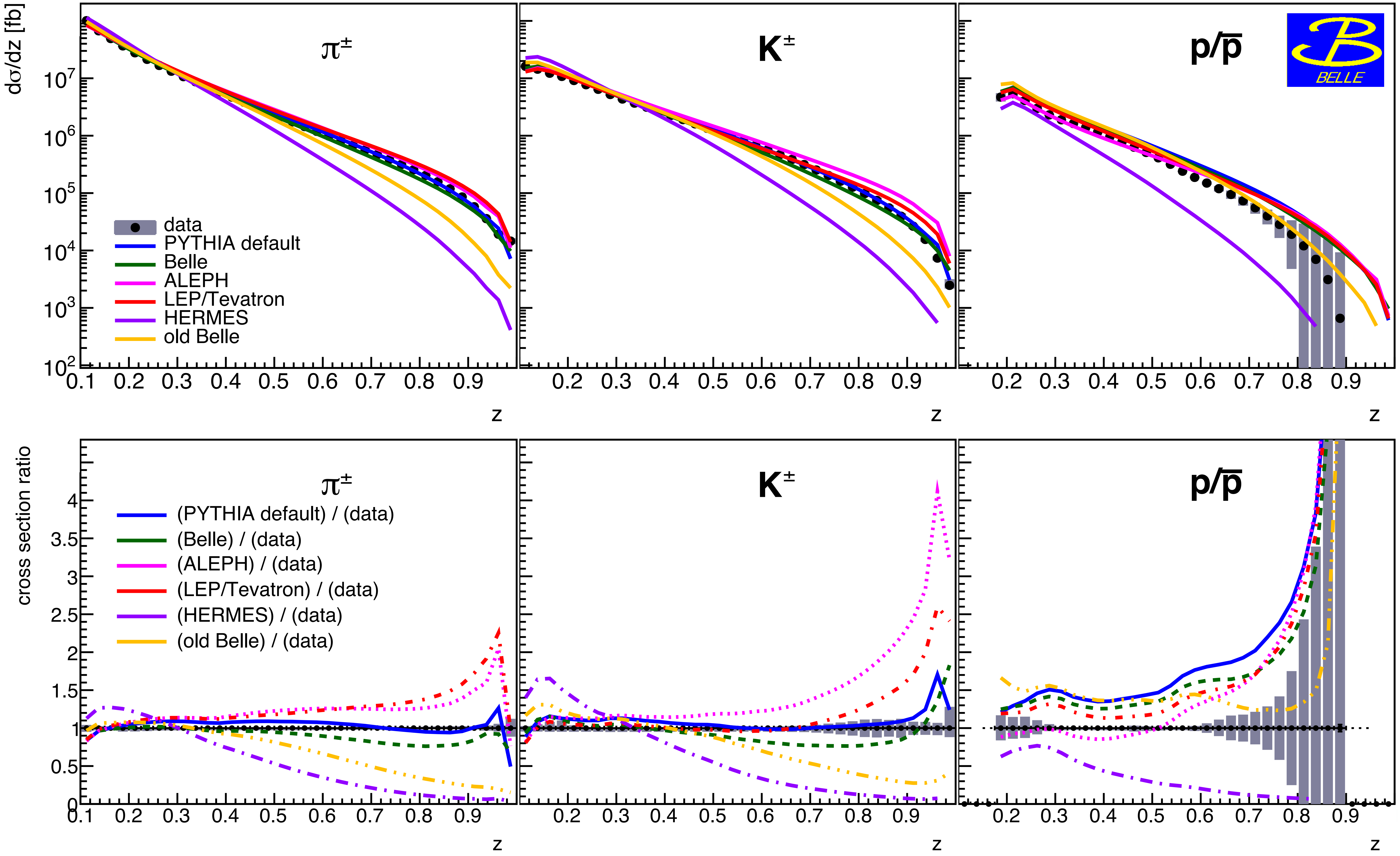
single-hadron production: data-MC comparison

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

[PRD 88 (2013) 032011]



[PRD 101 (2020) 092004]

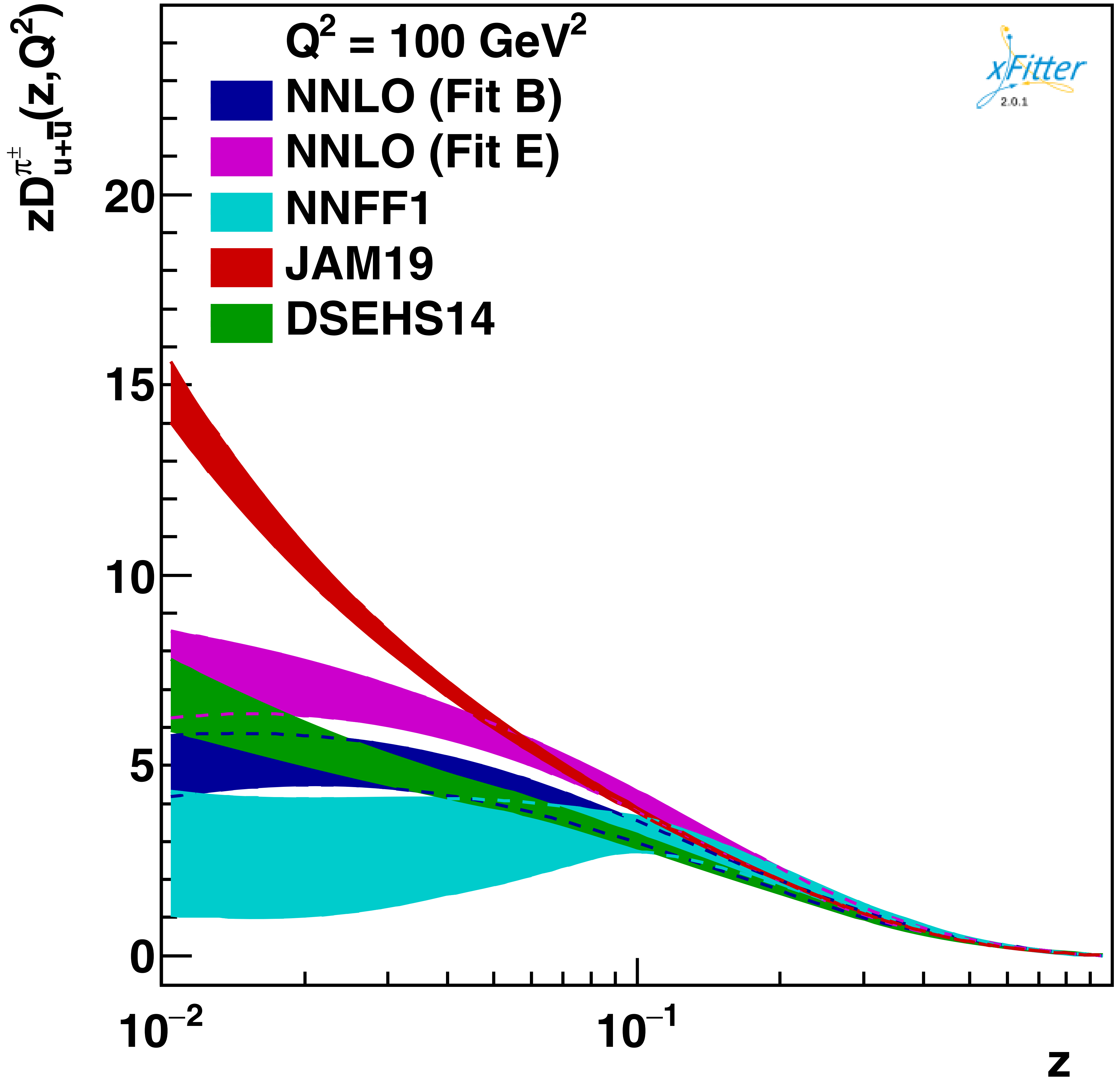


pion fragmentation functions: fit comparisons

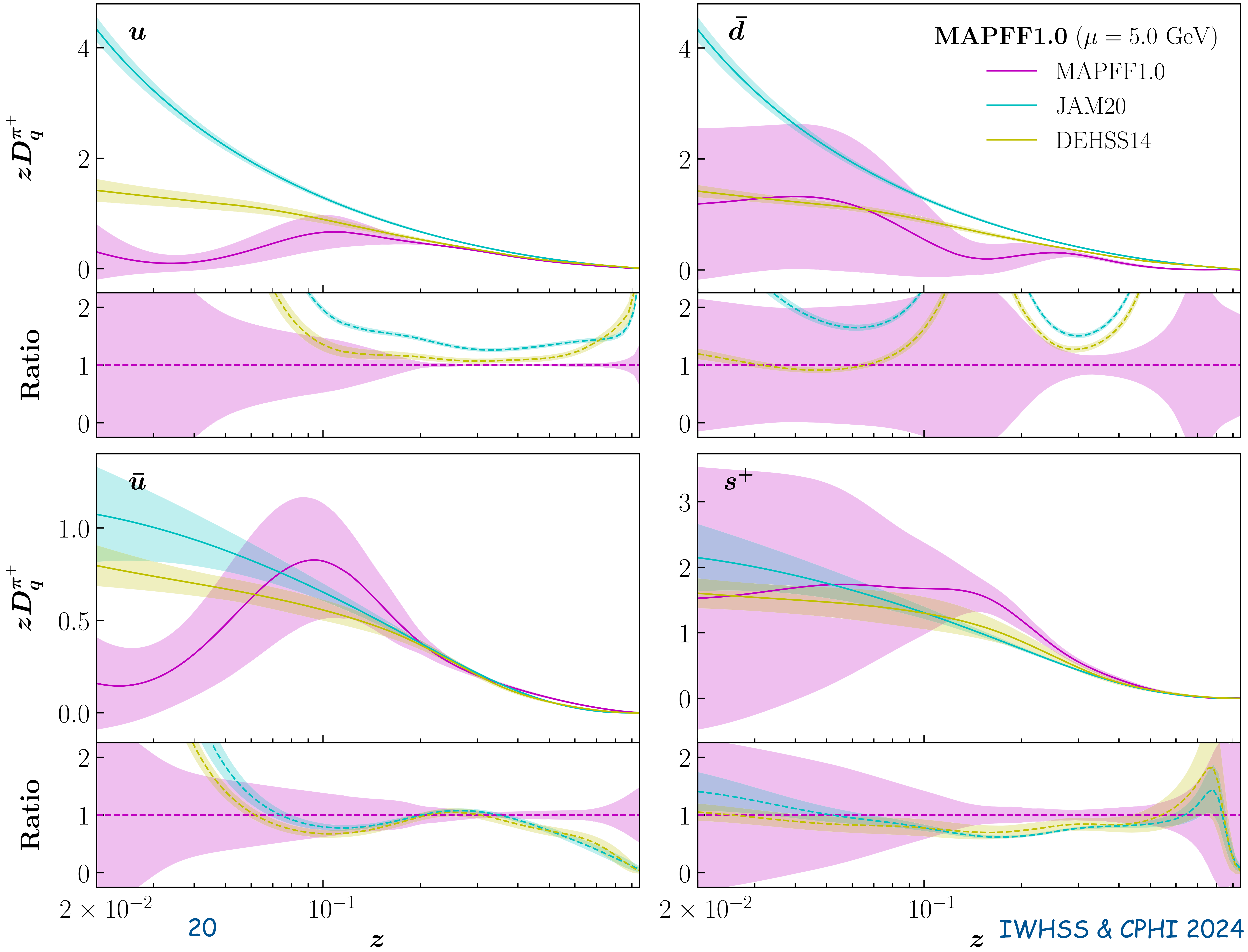
- still large differences in FF fits

☛ talk by Valerio

[PRD 104 (2021) 056019]



[PRD 104 (2021) 034007]

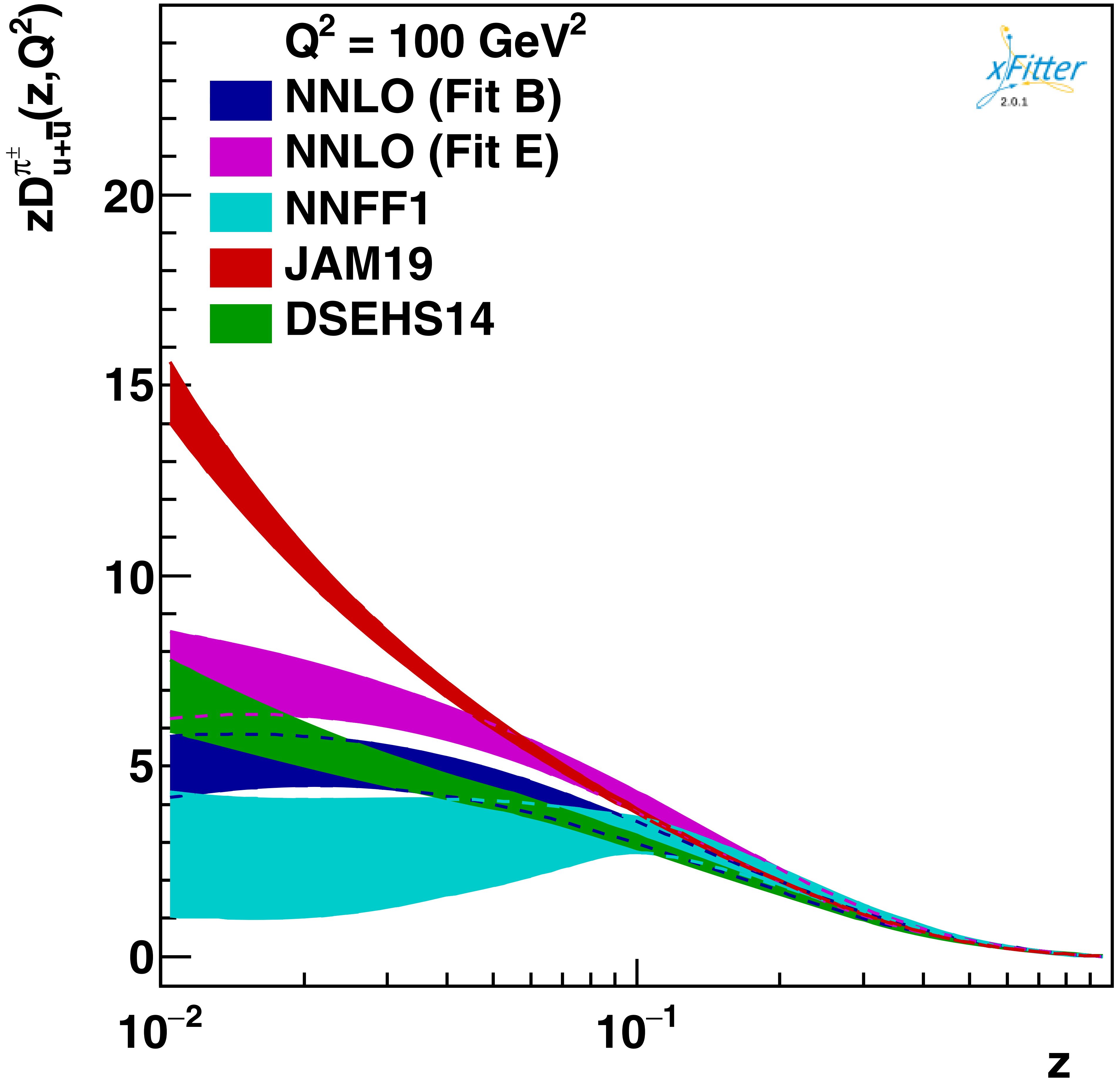


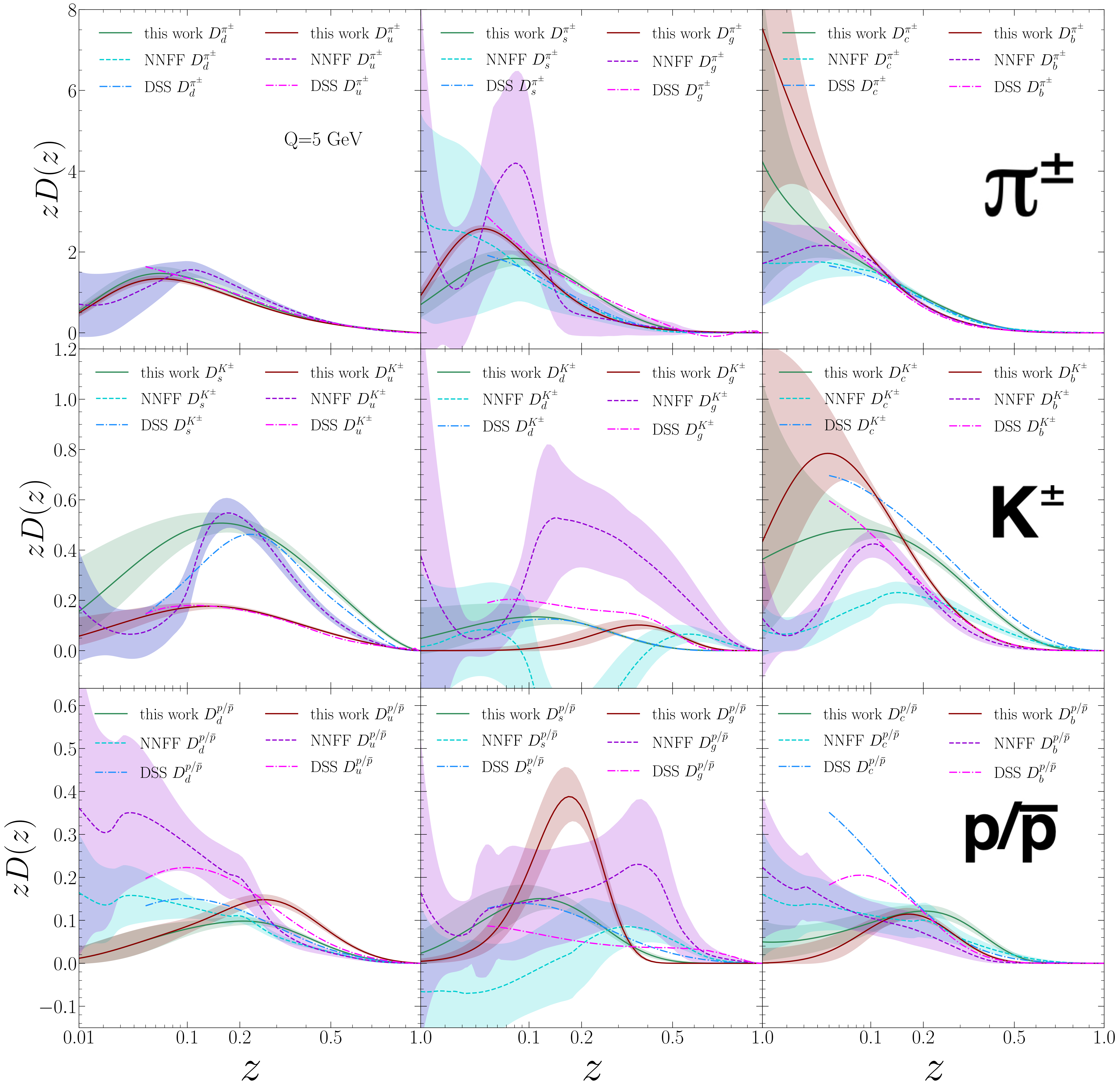
pion fragmentation functions: fit comparisons

[arXiv:2407.04422]

- still large differences in FF fits
  - also in "SIDIS" region, where needed as flavor tagger

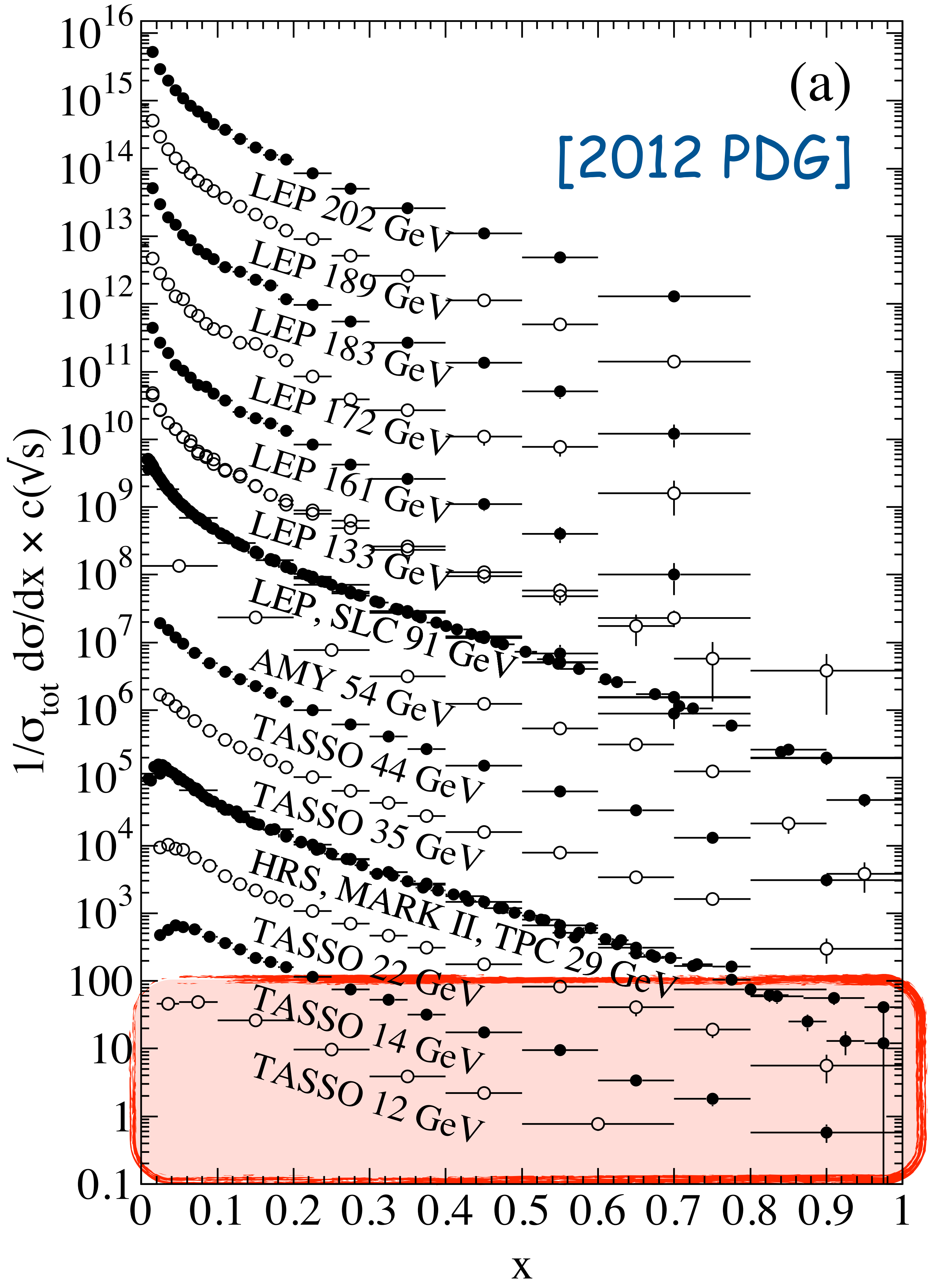
[PRD 104 (2021) 056019]





single-hadron production

- **before 2022**: lack of precision data at low √s
  - even B factories somewhat troublesome due to large charm contribution



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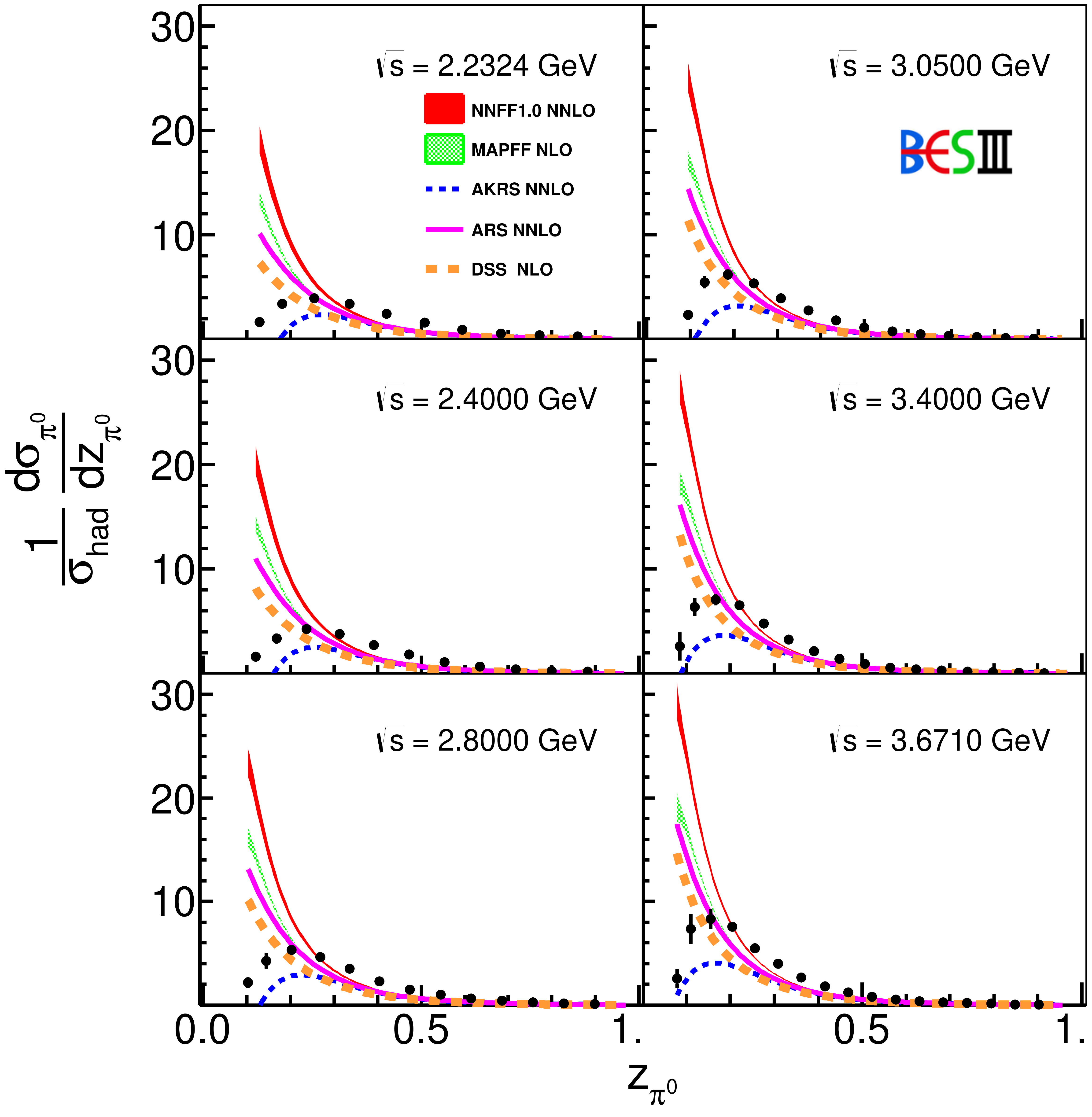
- by now also results from BESIII
  - PRL 130 (2023) 231901 & 133 (2024) 021901
- "challenge" to current FF parametrizations
  - somewhat surprising for neutral **pions** as easily related to charge-pion FFs

[PRL 130 (2023) 231901]



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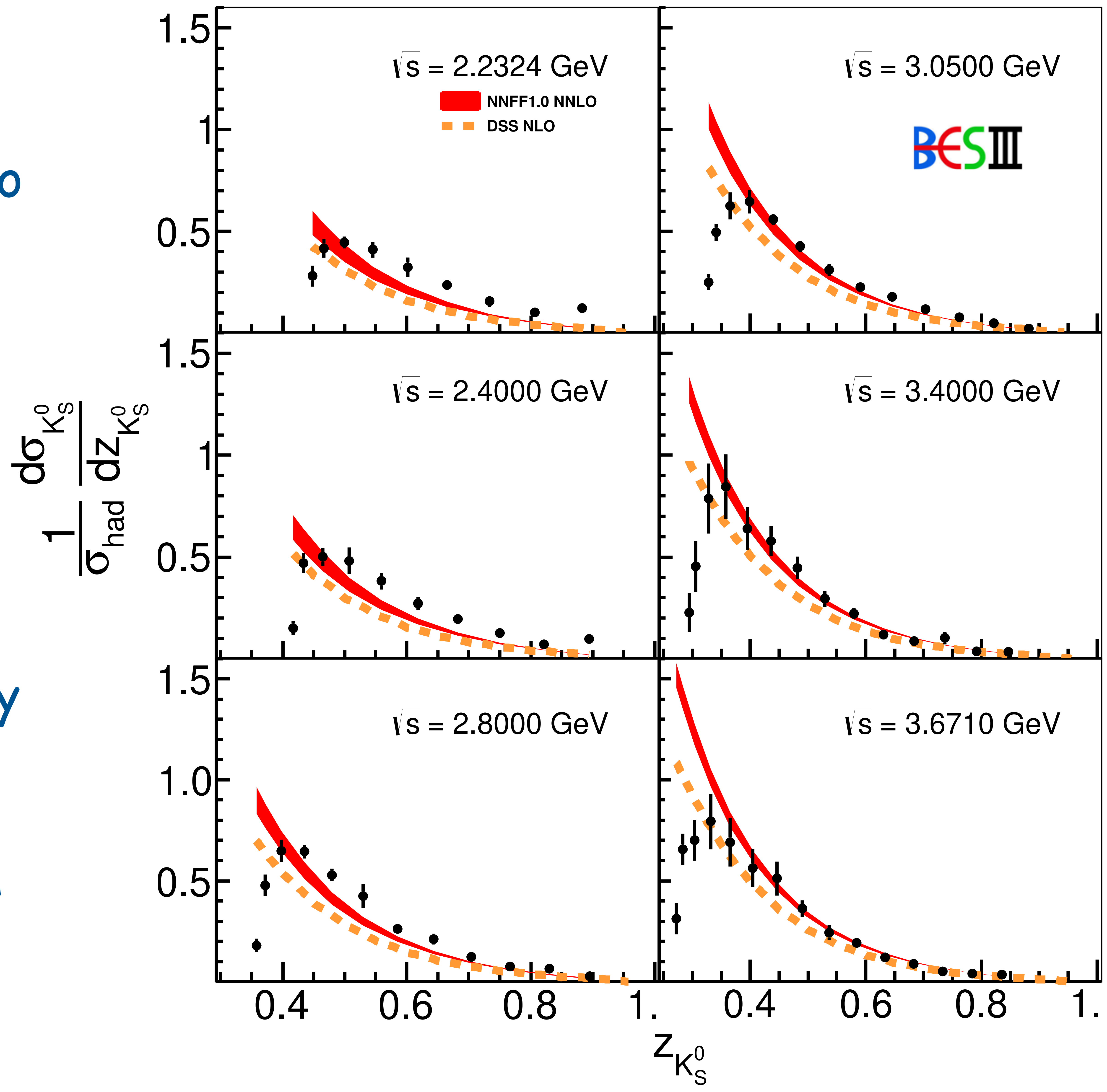
[PRL 130 (2023) 231901]



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- "challenge" to current FF parametrizations
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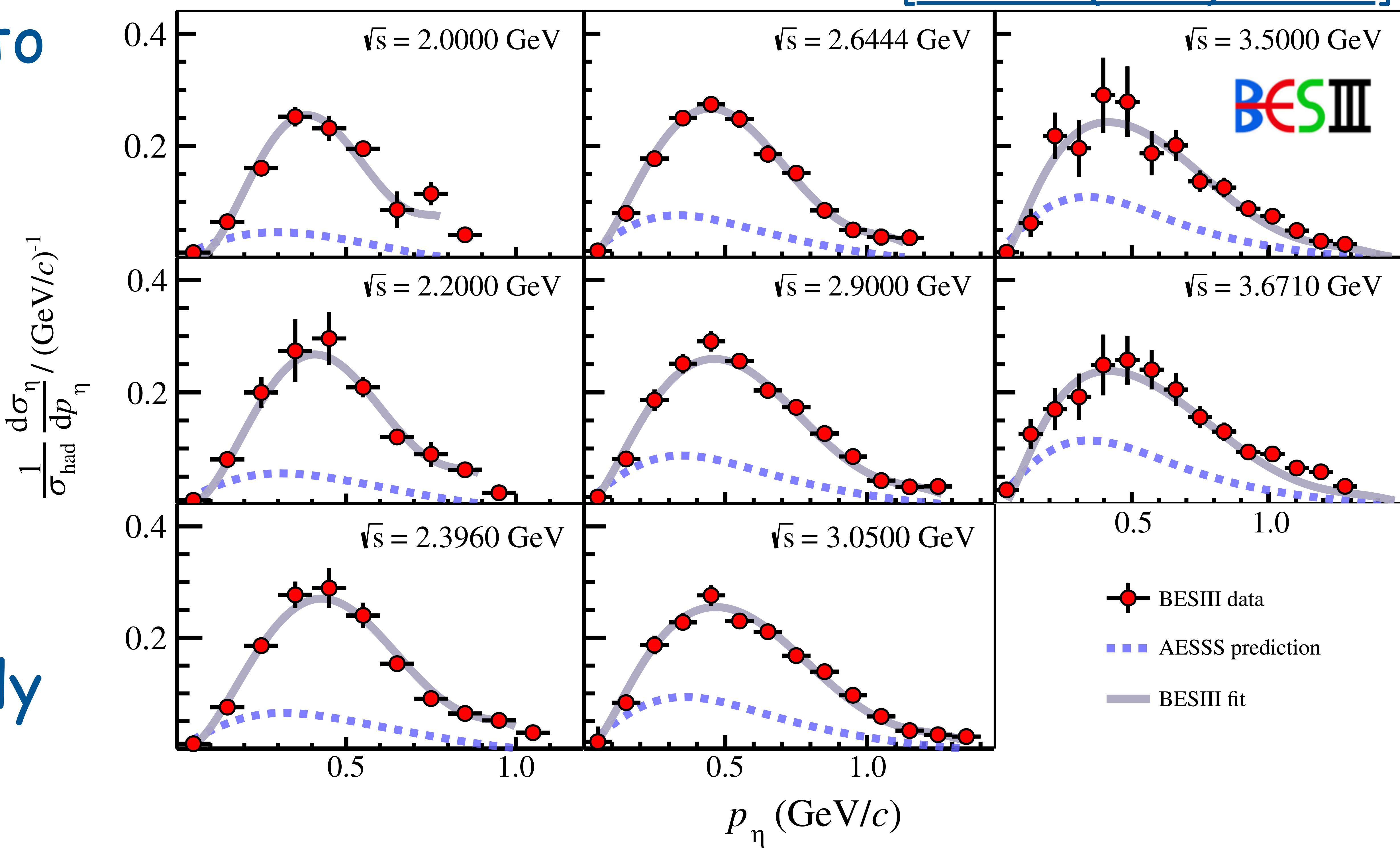
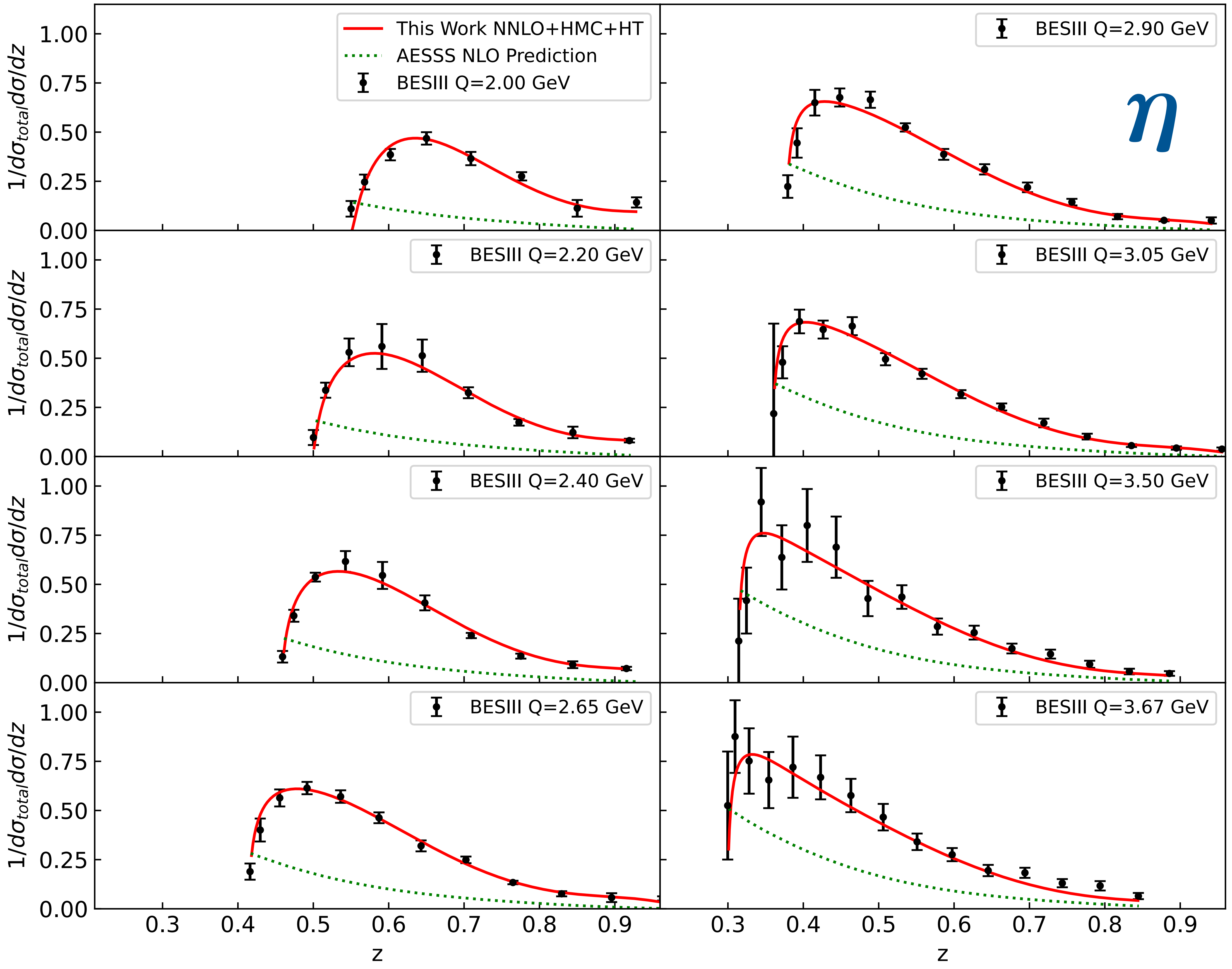
  - neutral-kaon FF related here to charged-kaon FFs as charge average
  - previous **eta** FF fit severely below BESIII data

[PRL 133 (2024) 021901]

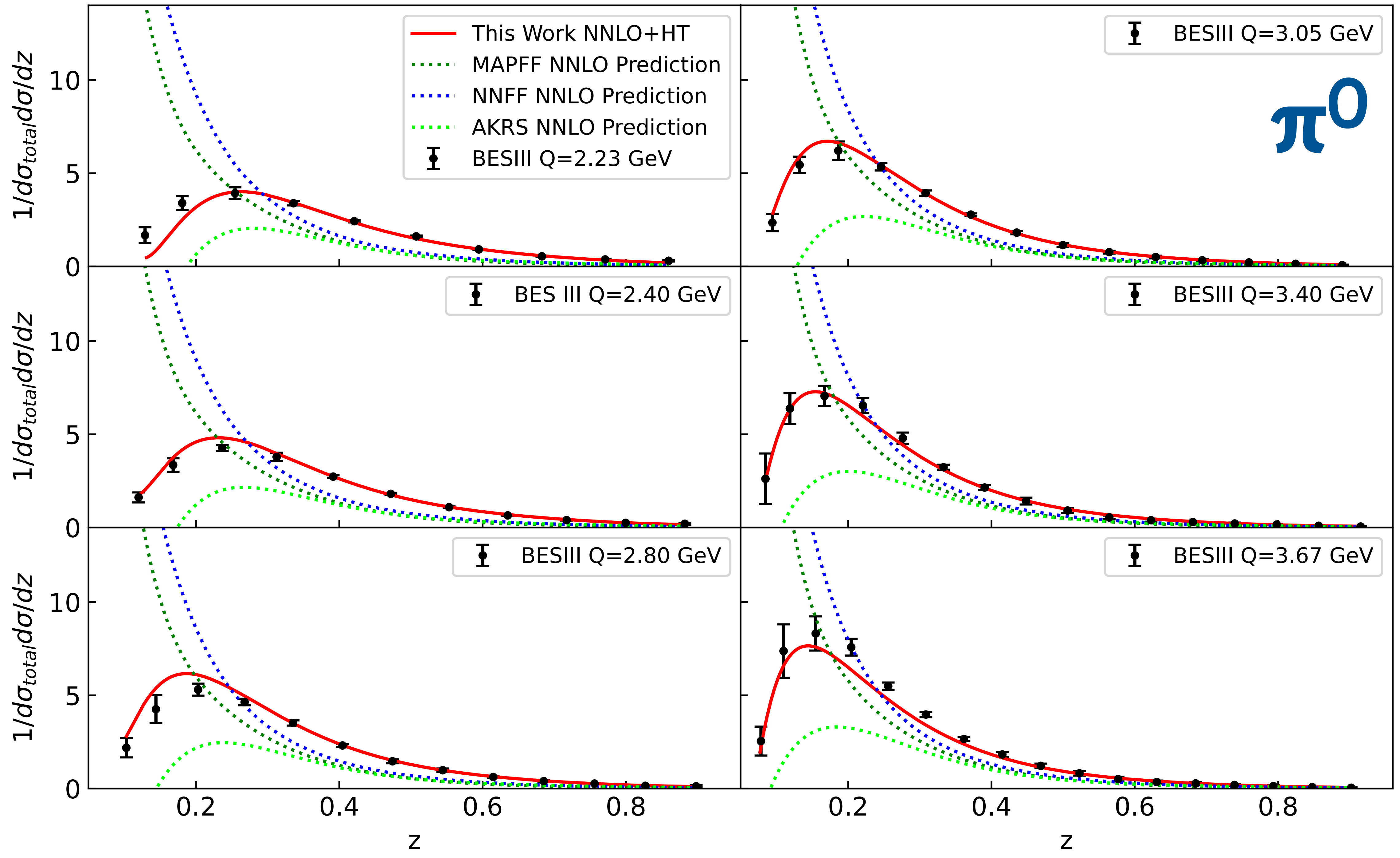


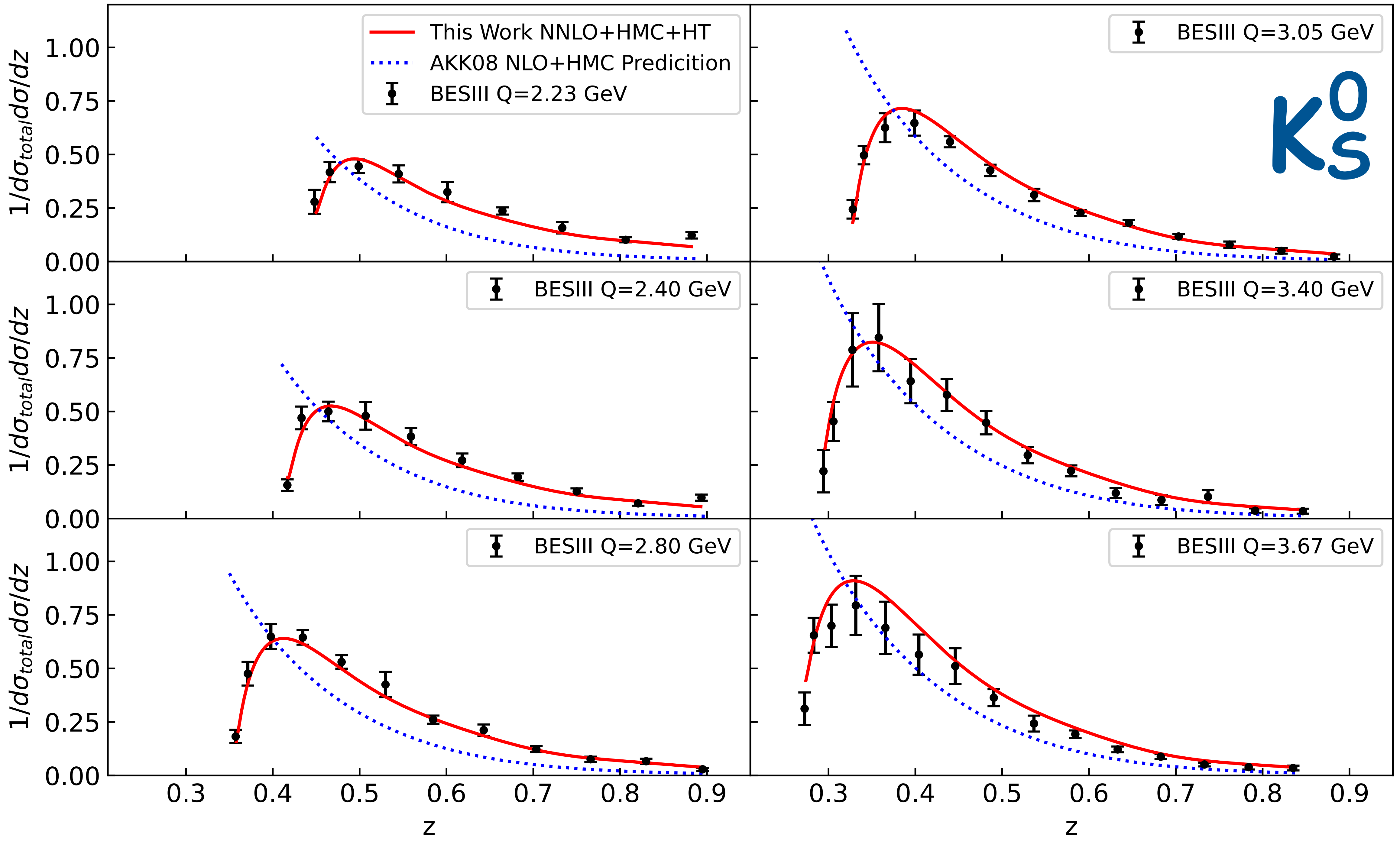
FFs including higher twist

- in view of poor description of BESIII data, include higher-twist in phenomenology
  ➥ much better description, but only SIA data



[Li et al., arXiv:2404.11527]





(see also M. Soleymaninia et al. PRD 110 (2024) 014019)

light-meson SIA data

- currently rather limited collection of SIA (and other!) data on eta production

[Li et al., arXiv:2404.11527]

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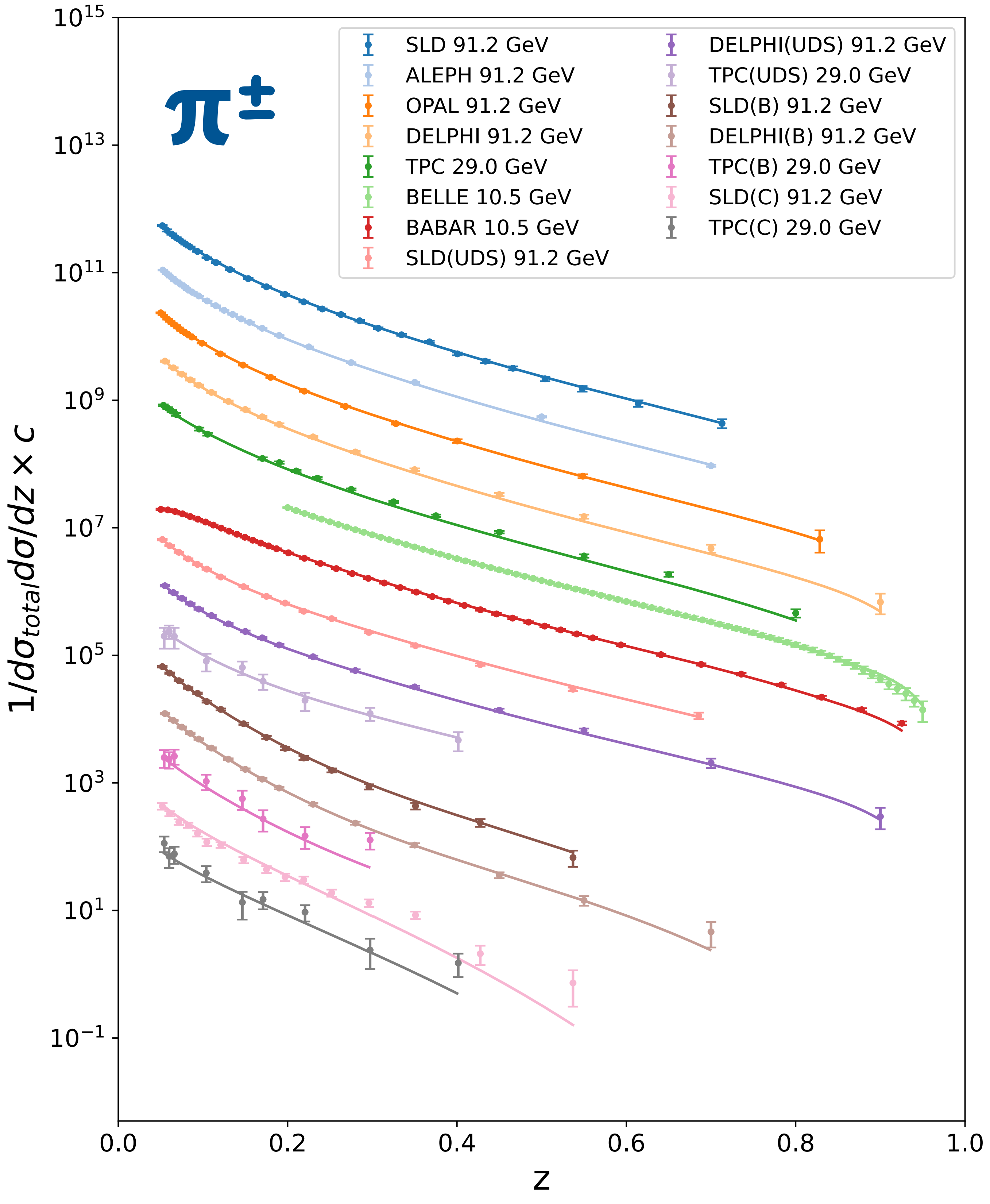

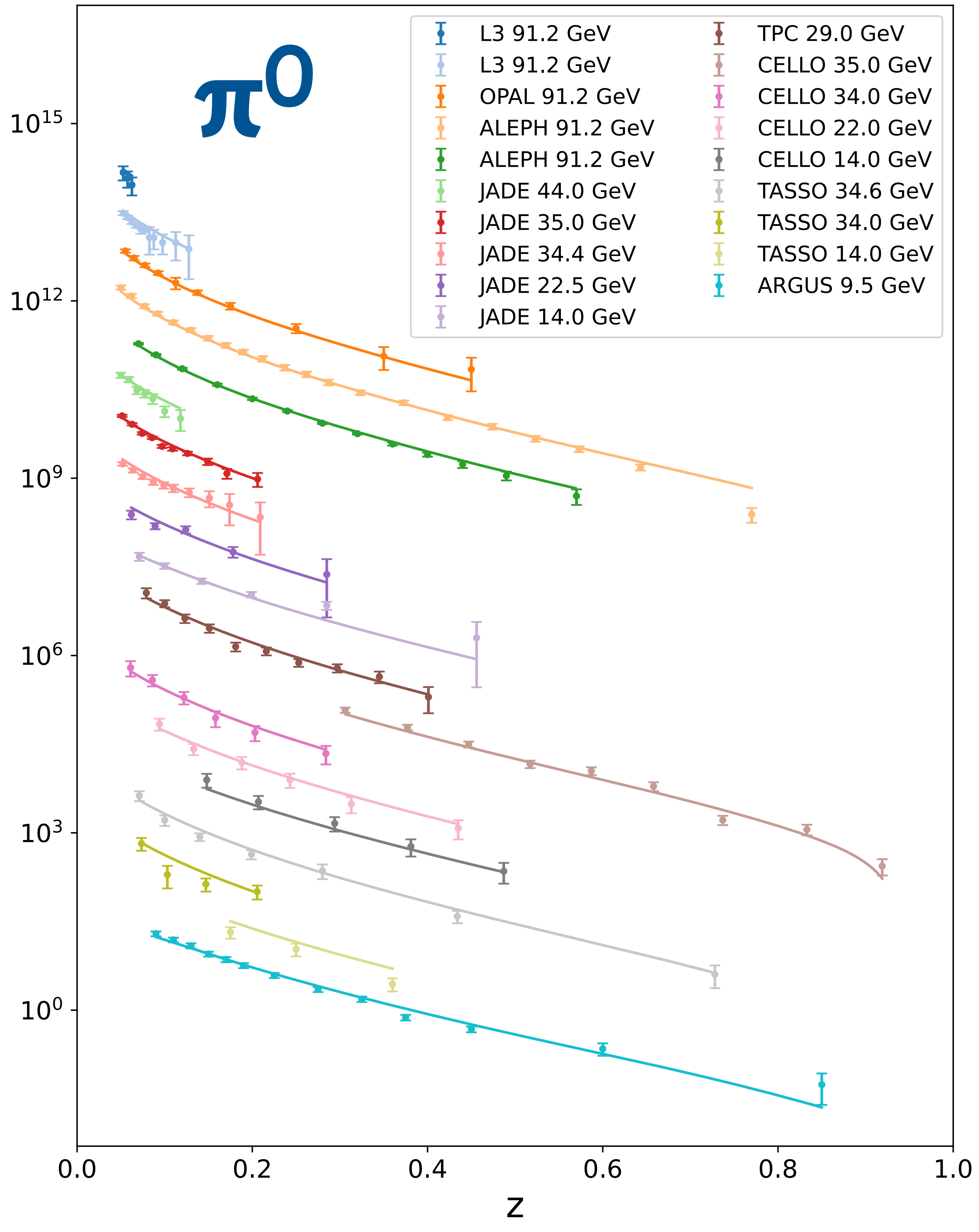

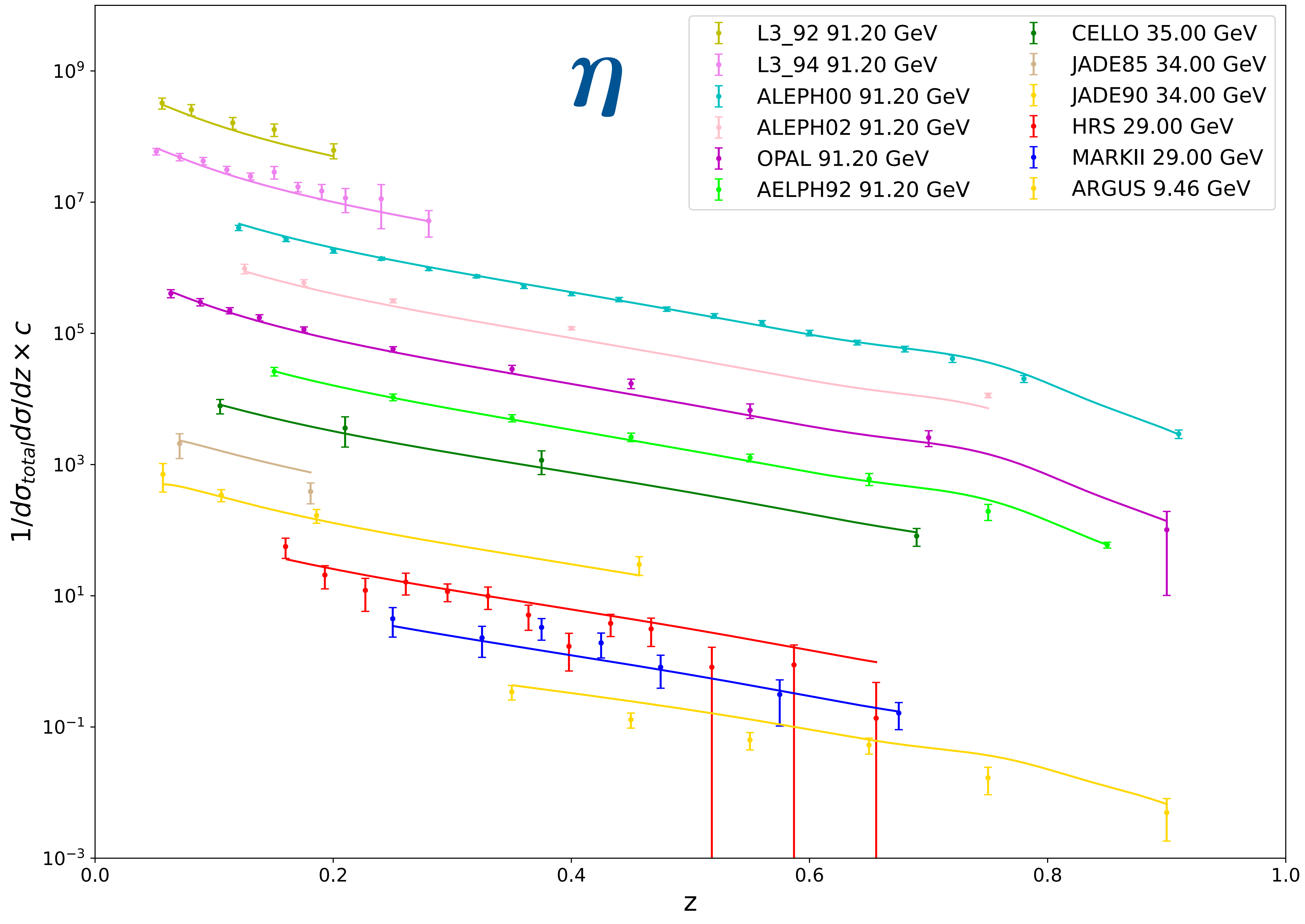

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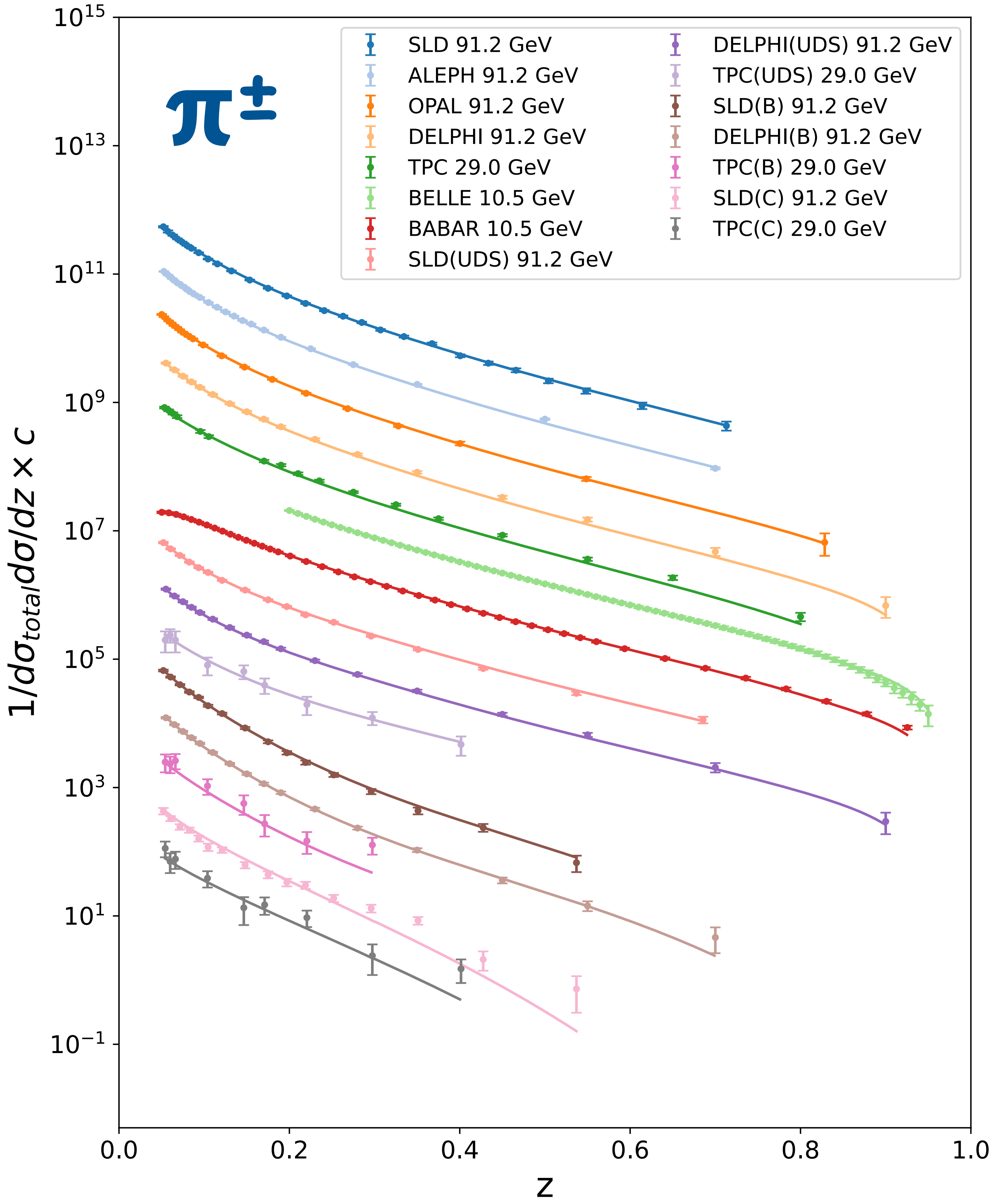

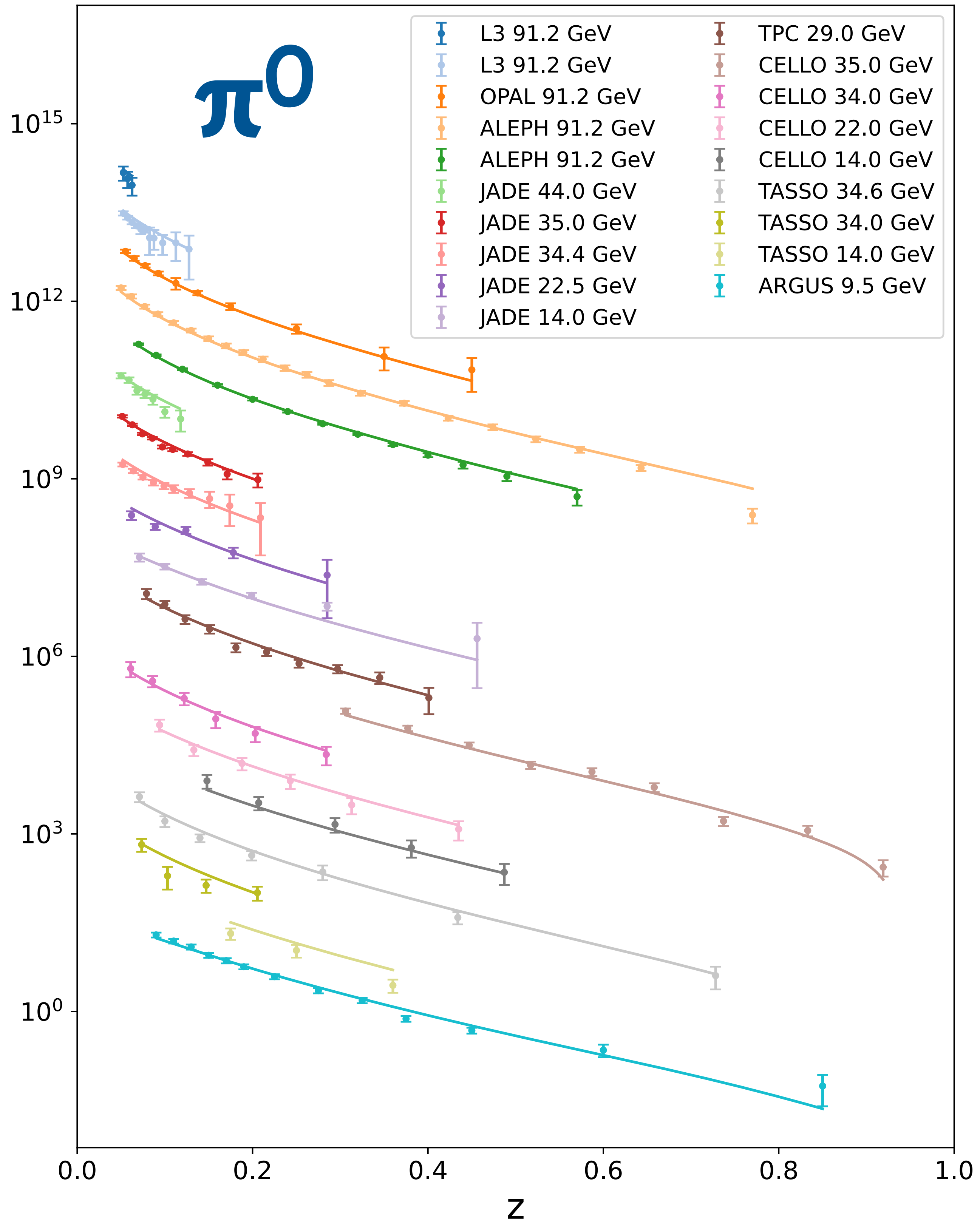

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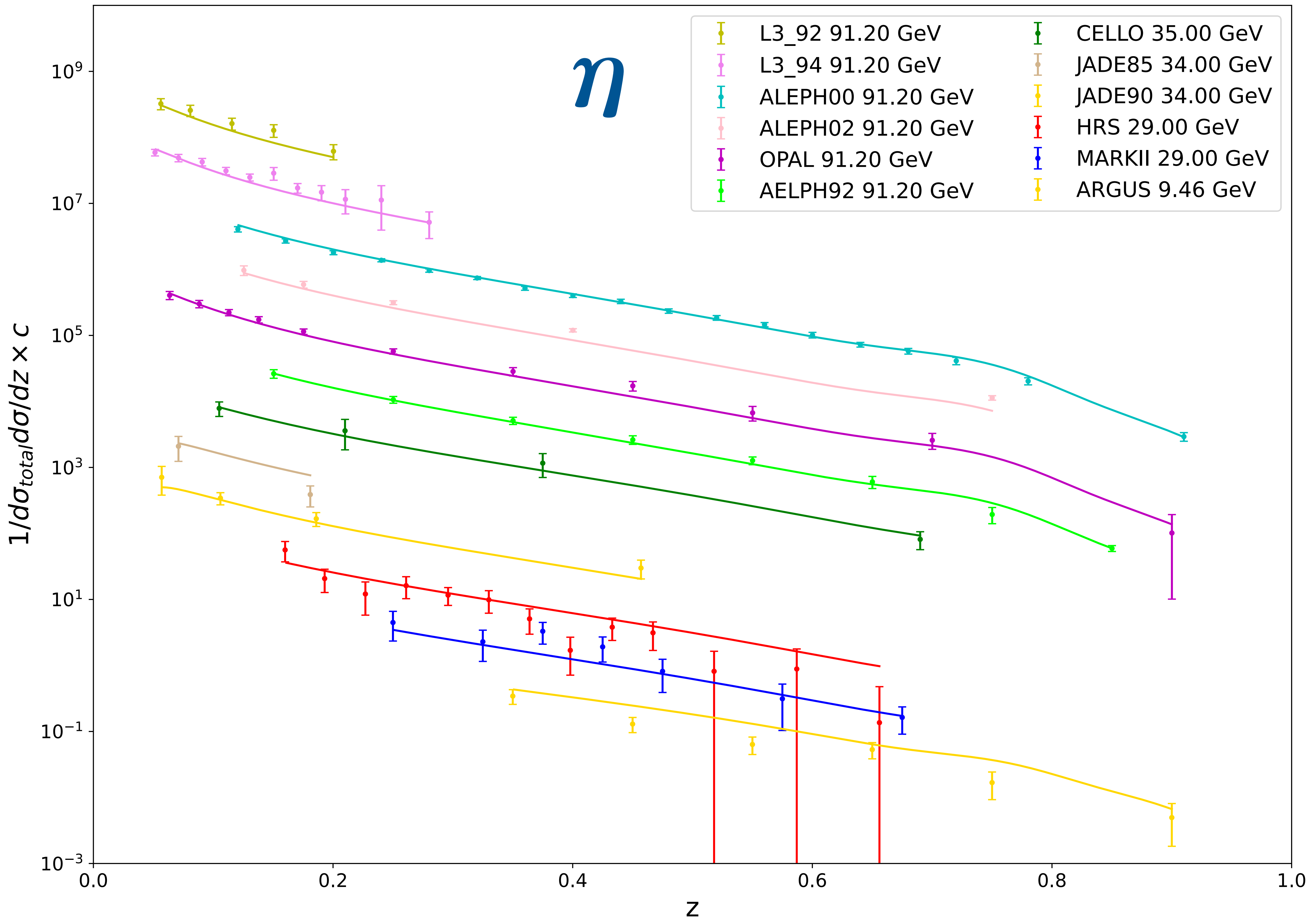
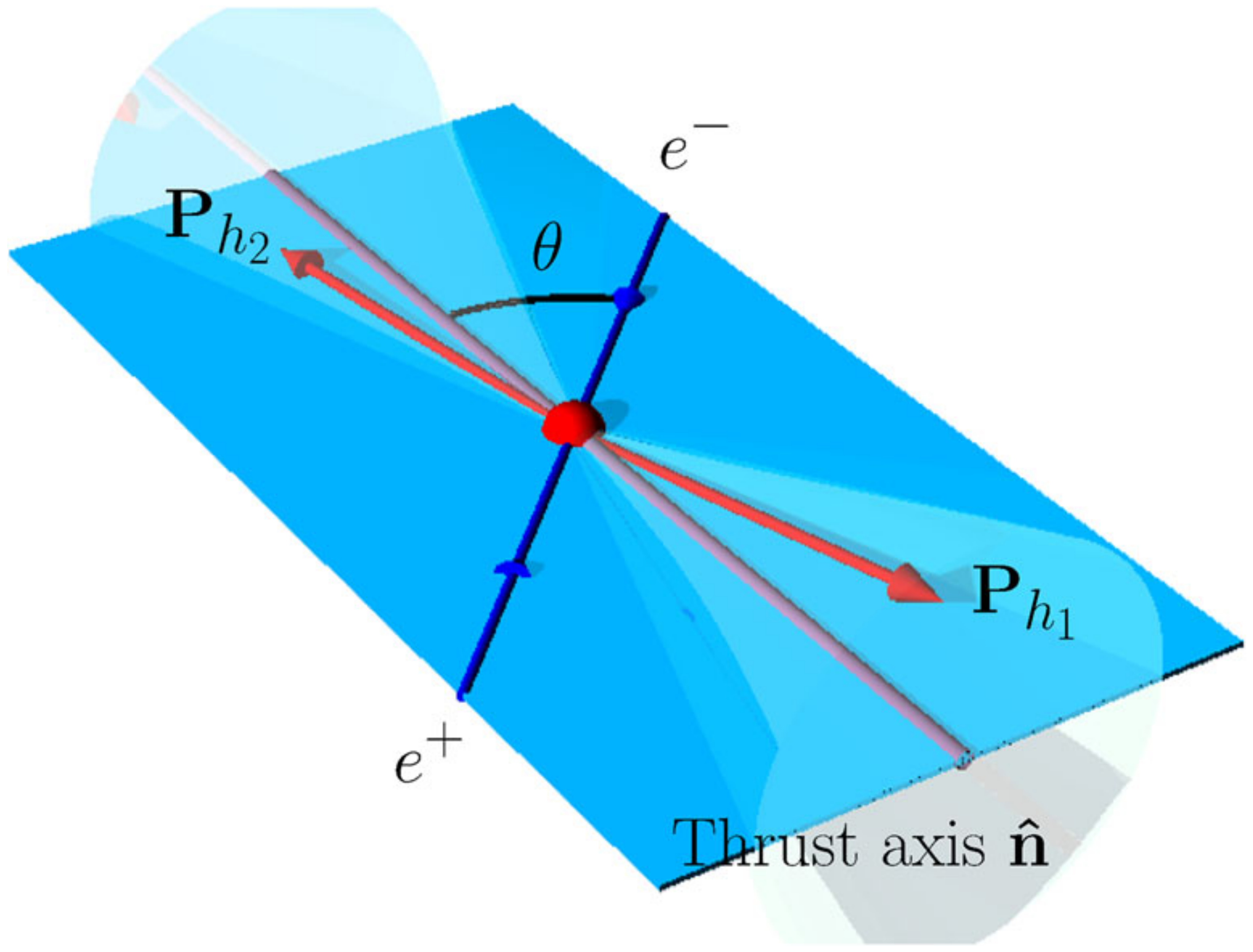


- **new data from Belle to come out soon**

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, e.g.,

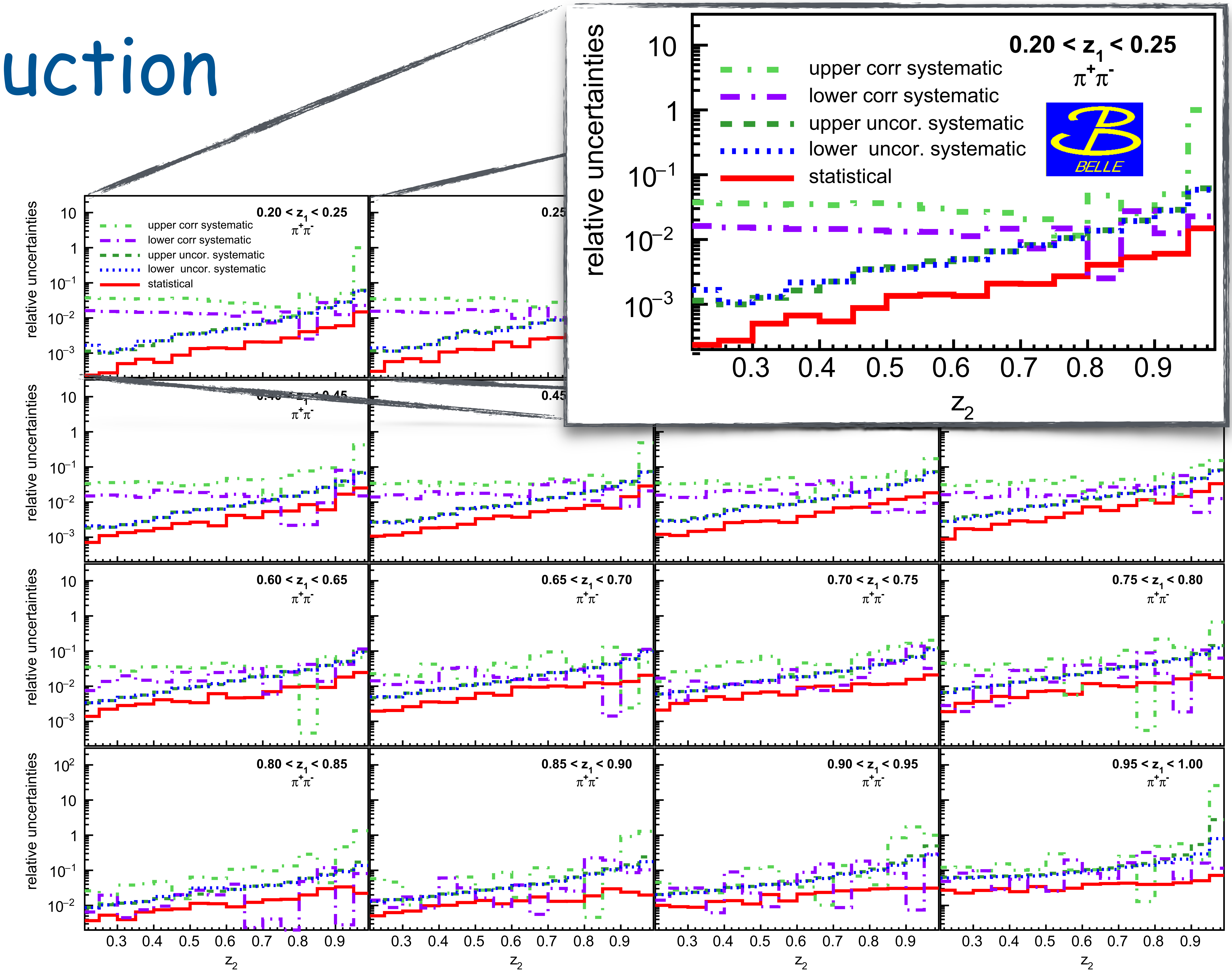


$$\sigma^{e^+e^-\to h_1 h_2 X} \propto \sum_q e_q^2 \left(D_1^{q\to h_1} D_1^{\bar{q}\to h_2} + D_1^{\bar{q}\to h_1} D_1^{q\to h_2} \right)$$

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

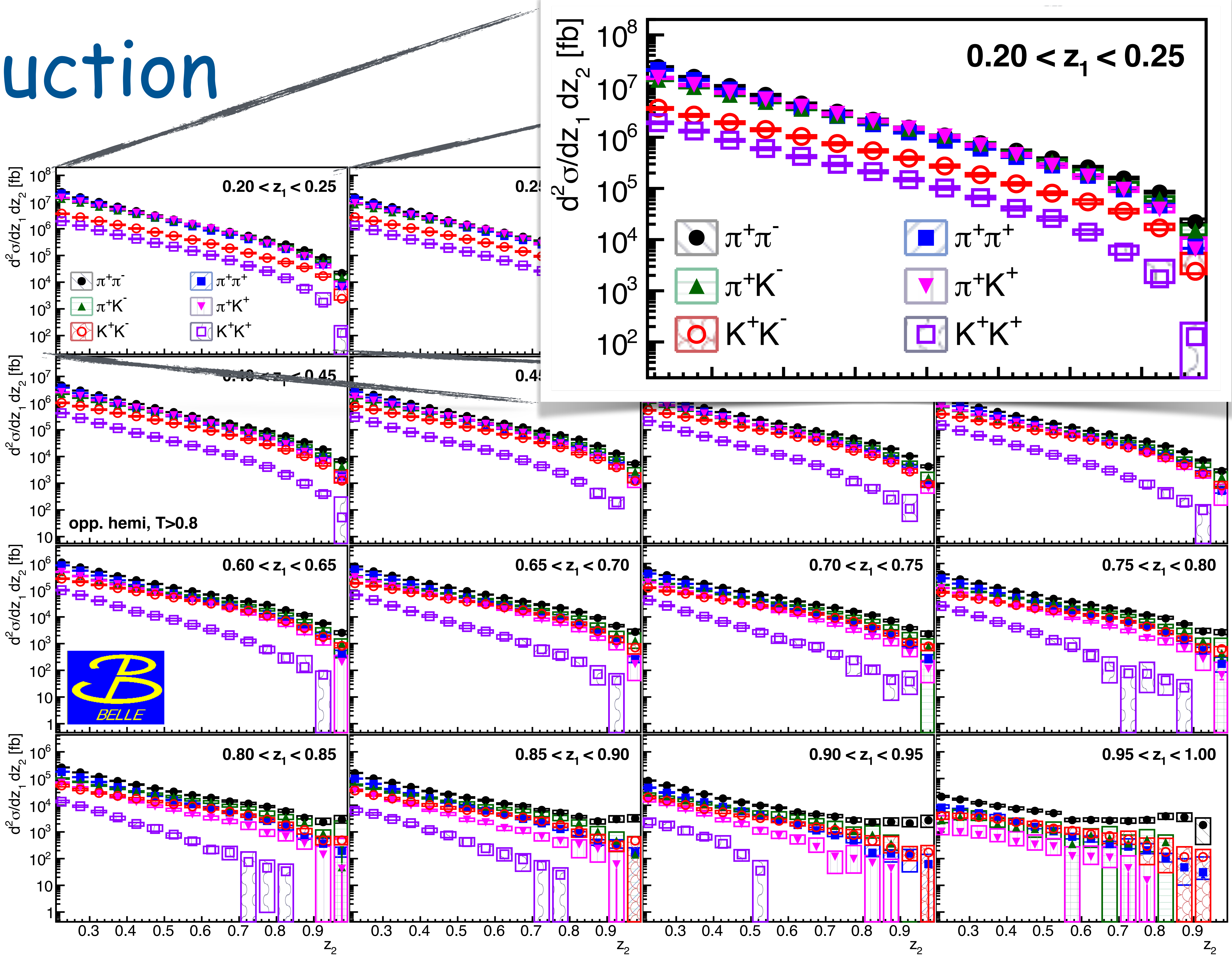
light-meson pair production

- systematics-dominated over entire kinematic range
  - strongly asymmetric systematics
  - main contribution from Monte Carlo tune dependence



light-meson pair production

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



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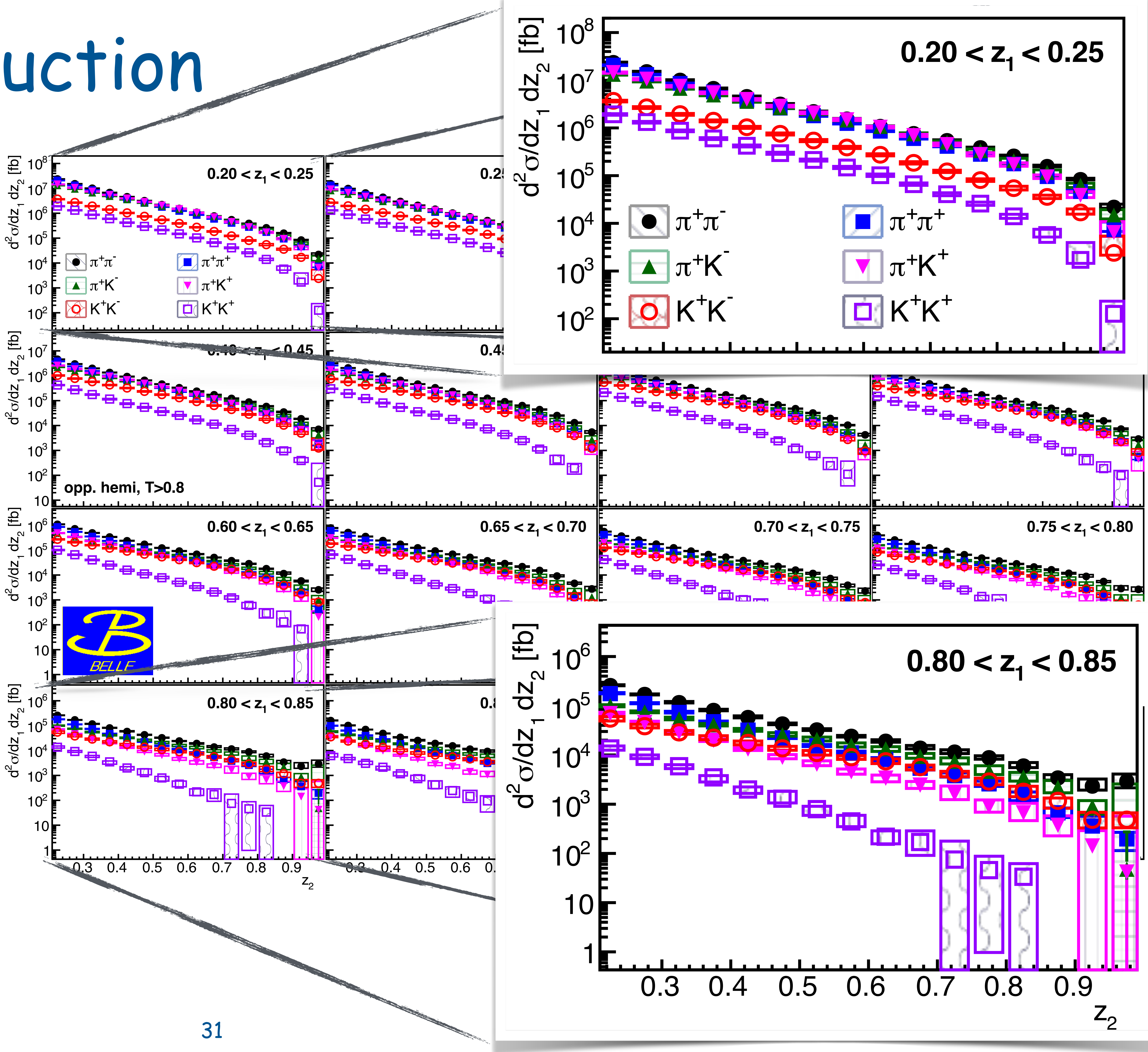
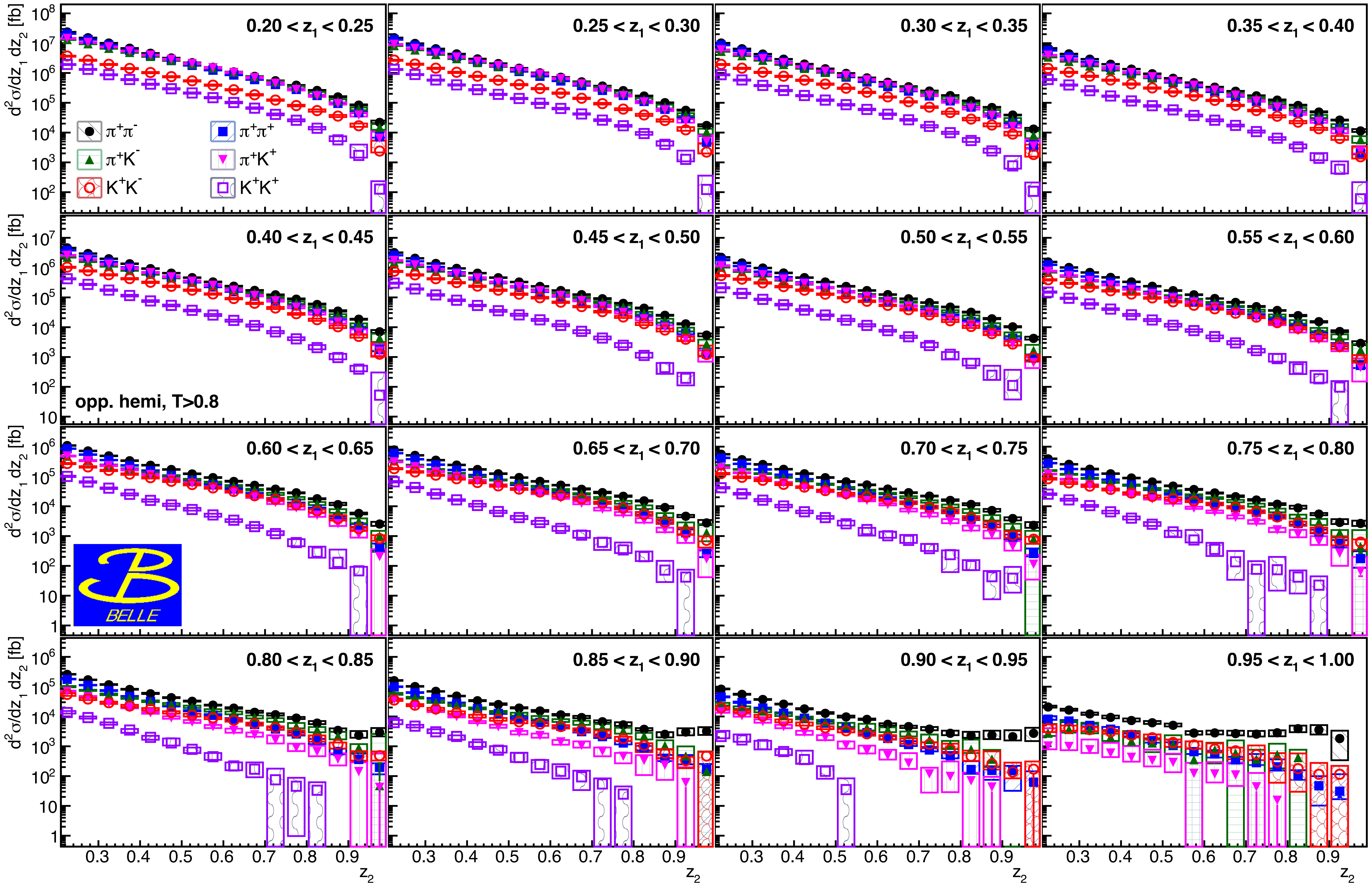


light-meson pair production

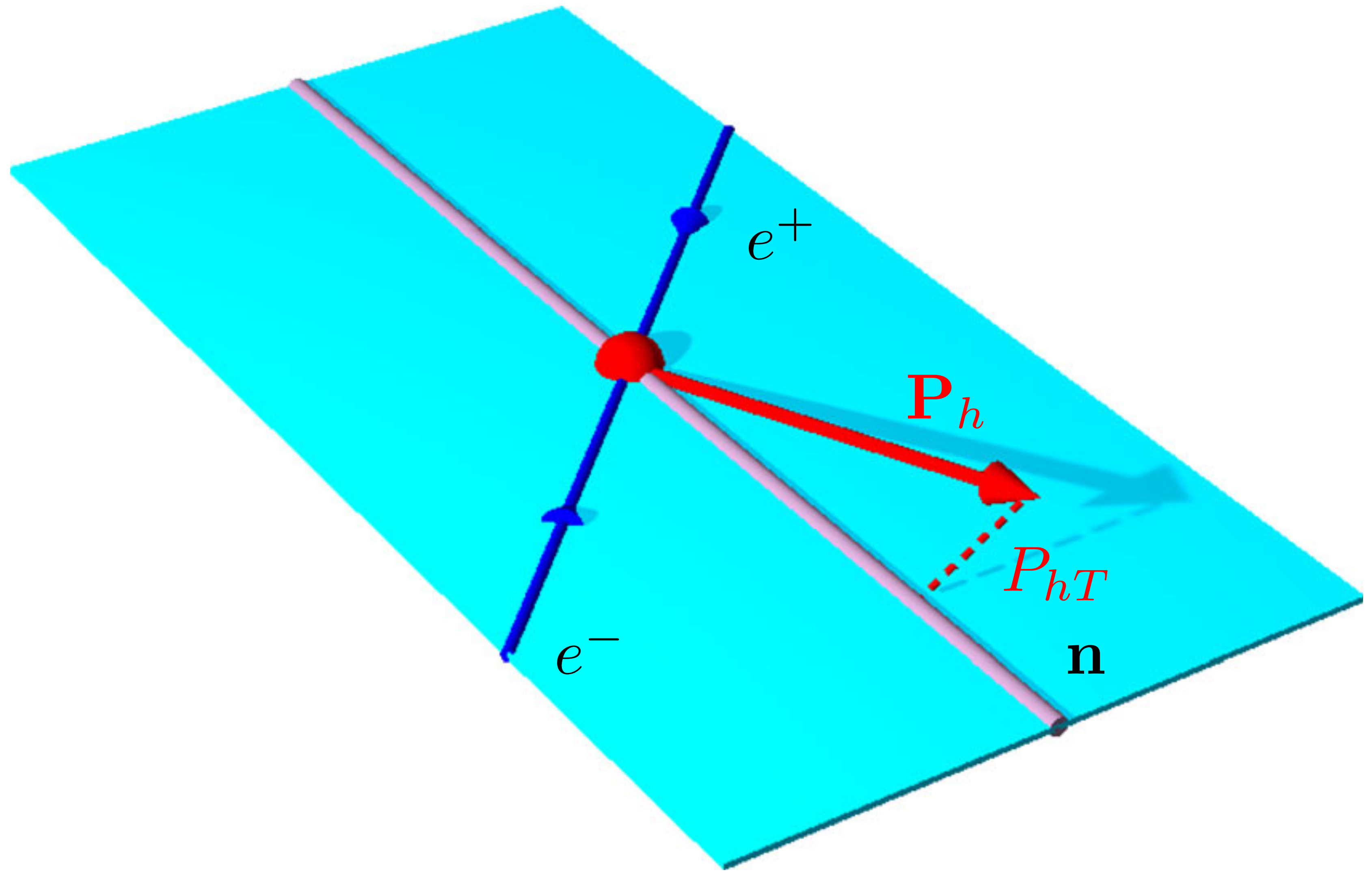
[PRD 101 (2020) 092004]

- systematics-dominated over entire kinematic range
- clear flavor dependence
  - suppression of kaons
  - suppression of like-sign pairs
  - more pronounced at large z (stronger flavor sensitivity)
- rich but currently still mainly unexplored set of data on flavor-dependence of FFs



inclusive hadrons - transverse momentum

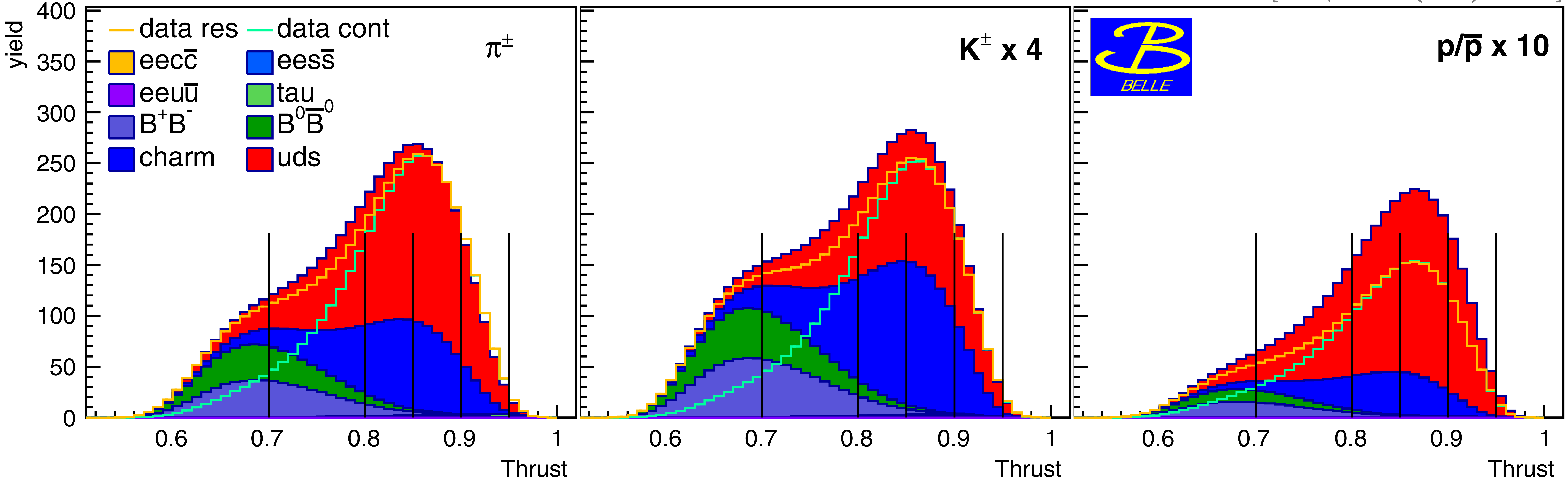
- quasi-inclusive hadron production gives access to transverse momentum in fragmentation
- transverse momentum measured with respect to thrust axis n
- analysis performed differential in z & P_{hT}, in various slices in thrust T (➠ 18x20x6 bins)
- correction steps similar as for P_{hT}-integrated cross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



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

thrust distribution: process contributions

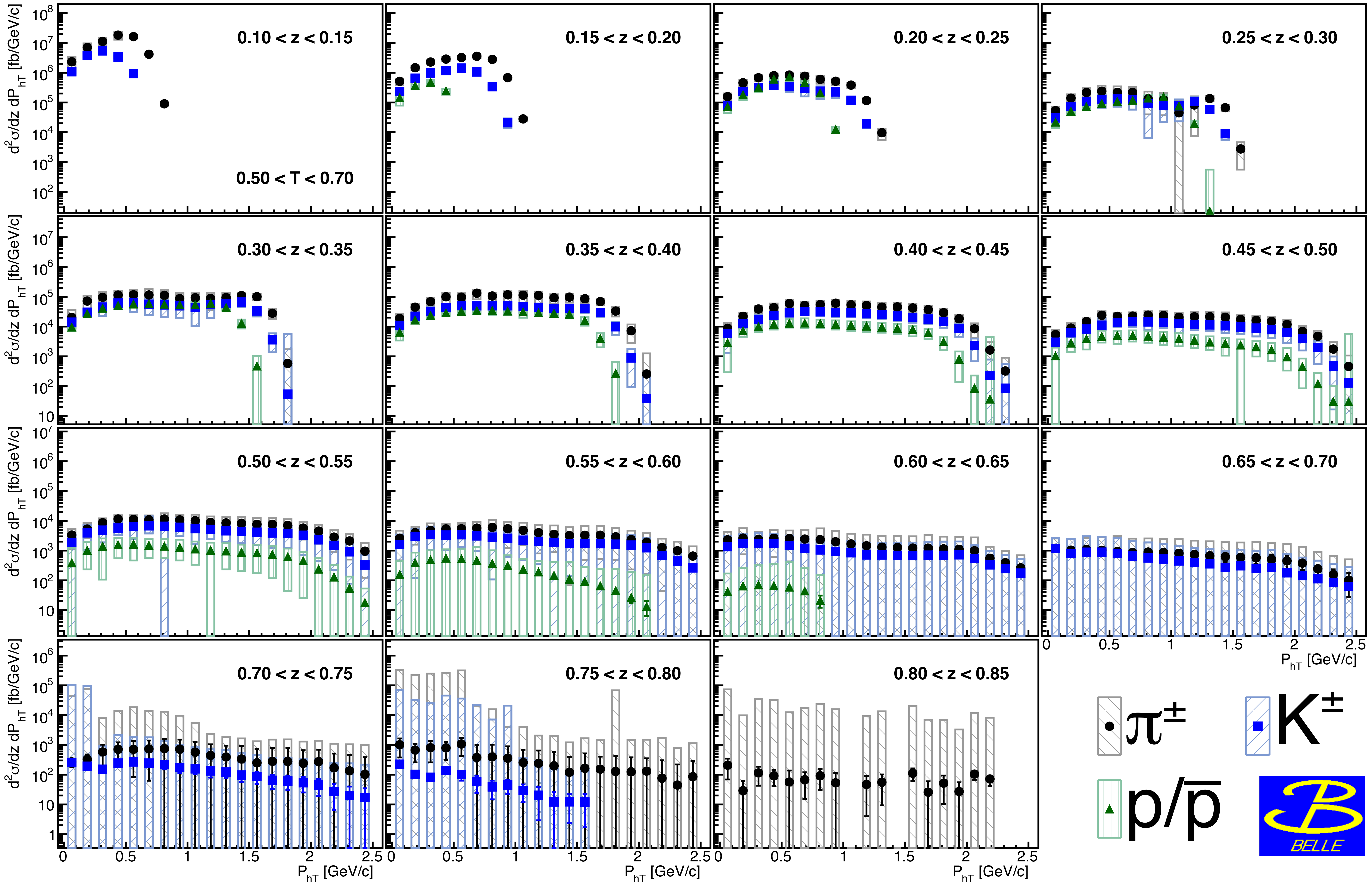
[Belle, PRD 99 (2019) 112006]



- large contribution from $B\bar{B}$ at lower thrust
- large thrust dominated by uds and charm fragmentation (at very large T significant τ contribution for pions, not visible here)

transverse-momentum distributions

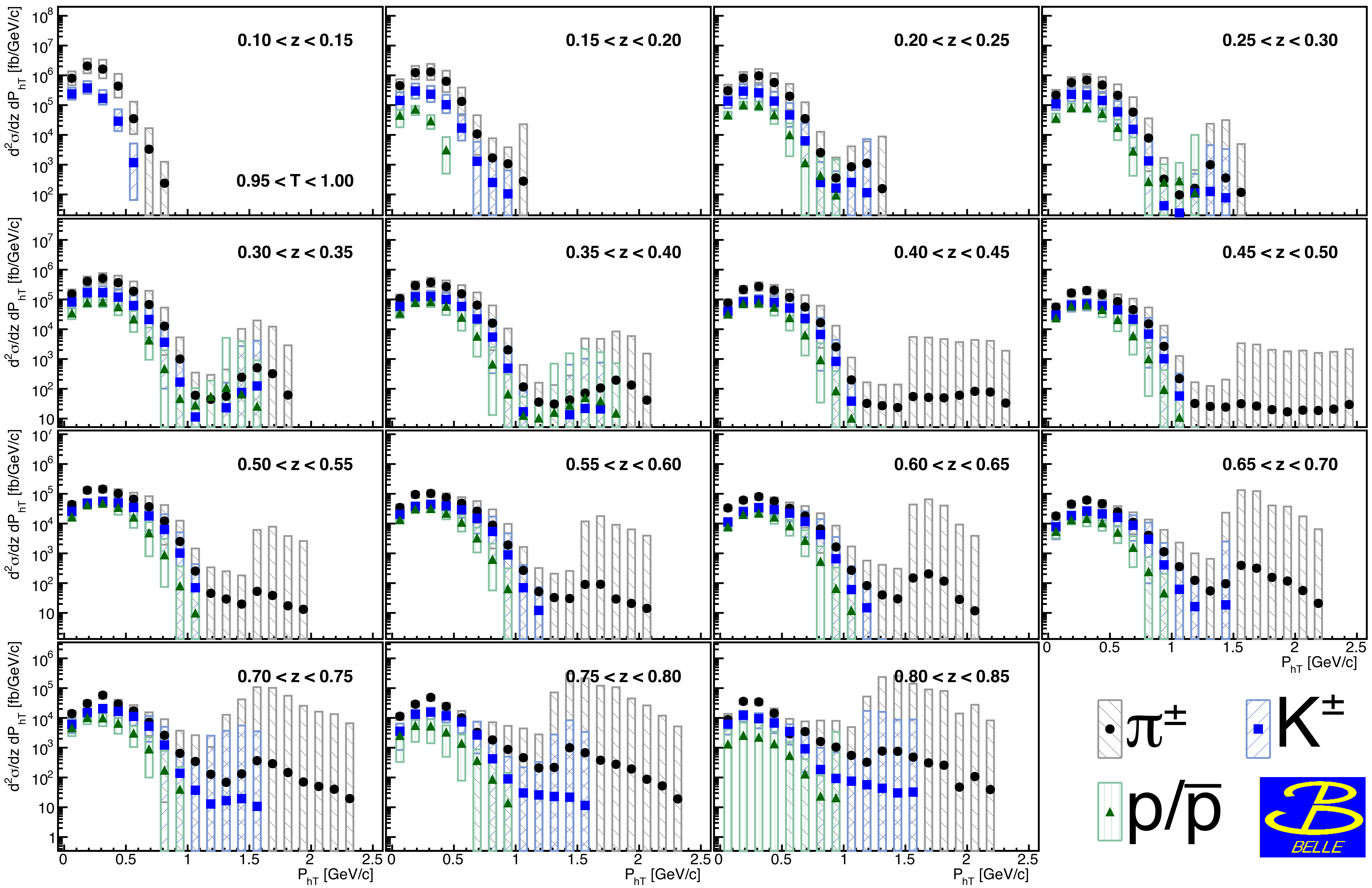
- **lowest T bin**
  -> rather spherical events
  - transverse momenta almost uniformly distributed in medium-z bins
  - faster drop for heavier hadrons



[PRD 99 (2019) 112006]

transverse-momentum distributions

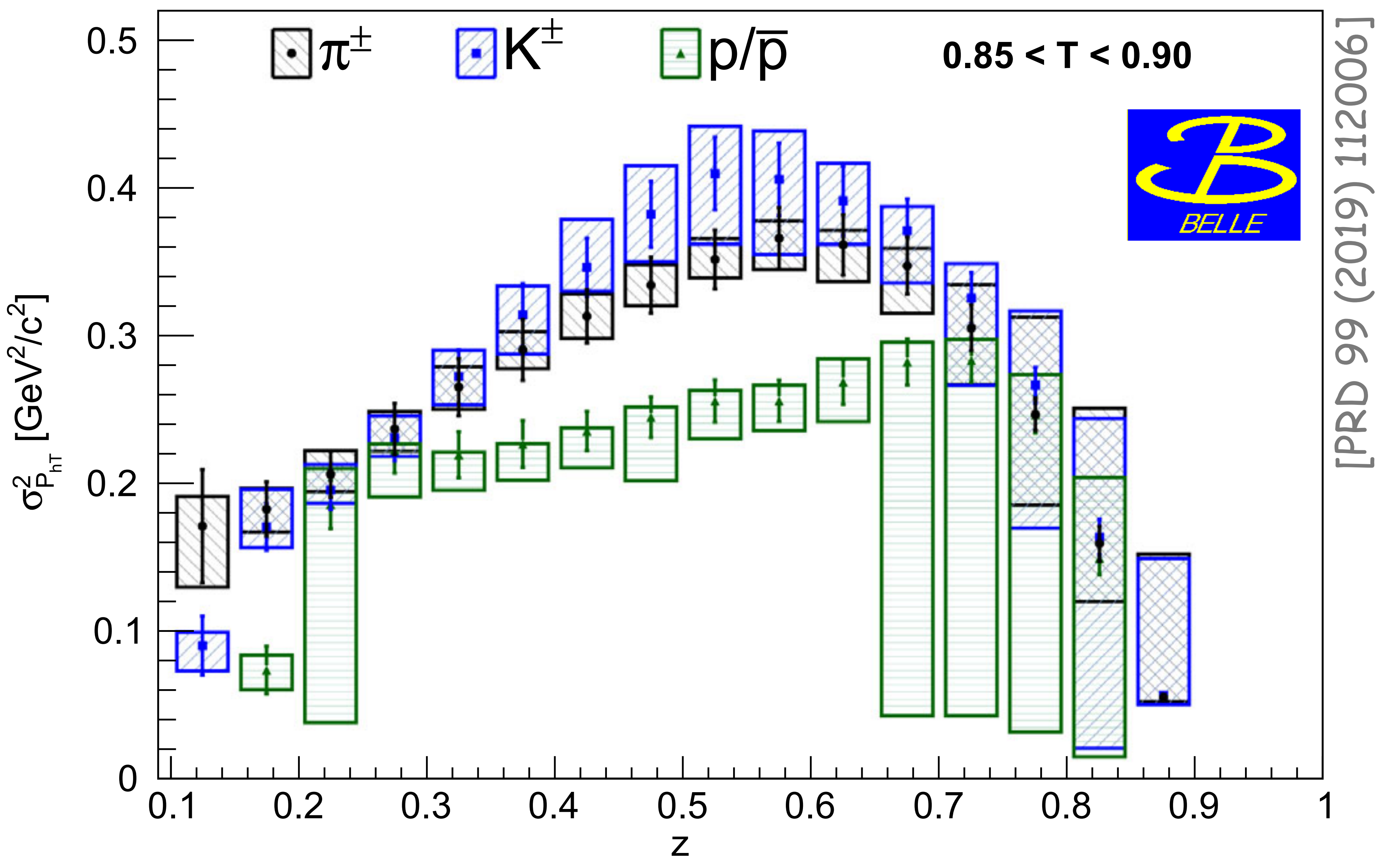
- 0.95<T<1.0
  - transverse momenta mostly Gaussian distributed
  - widths very narrow as particles now very collimated

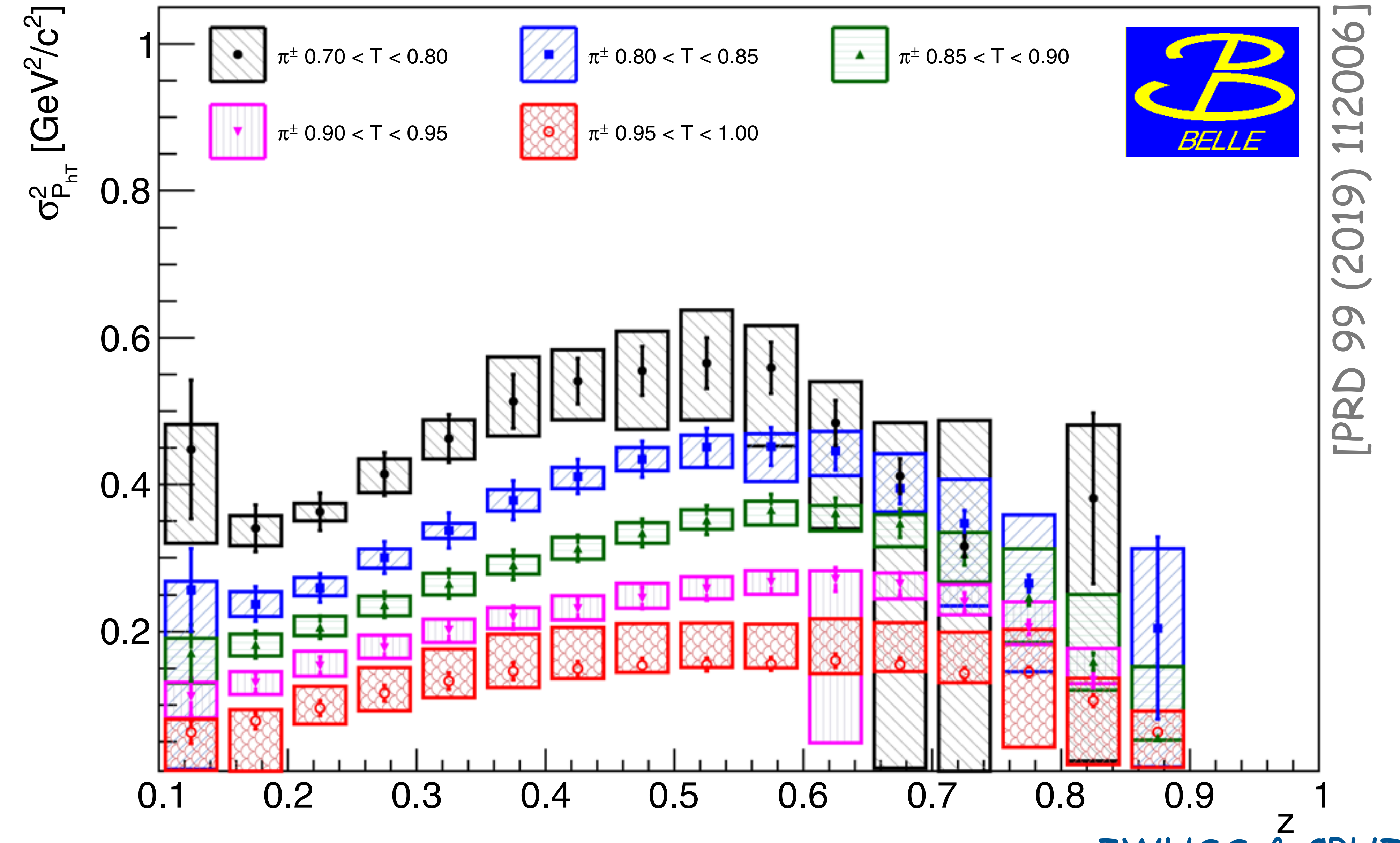


[PRD 99 (2019) 112006]

transverse-momentum: Gaussian widths

- fit Gaussian to low-P_{hT} data
- Gaussian widths depend on z and T
  - general increase with z with turnover at larger values of z
  - clear decrease of widths with increase of T
    - particles more and more collimated



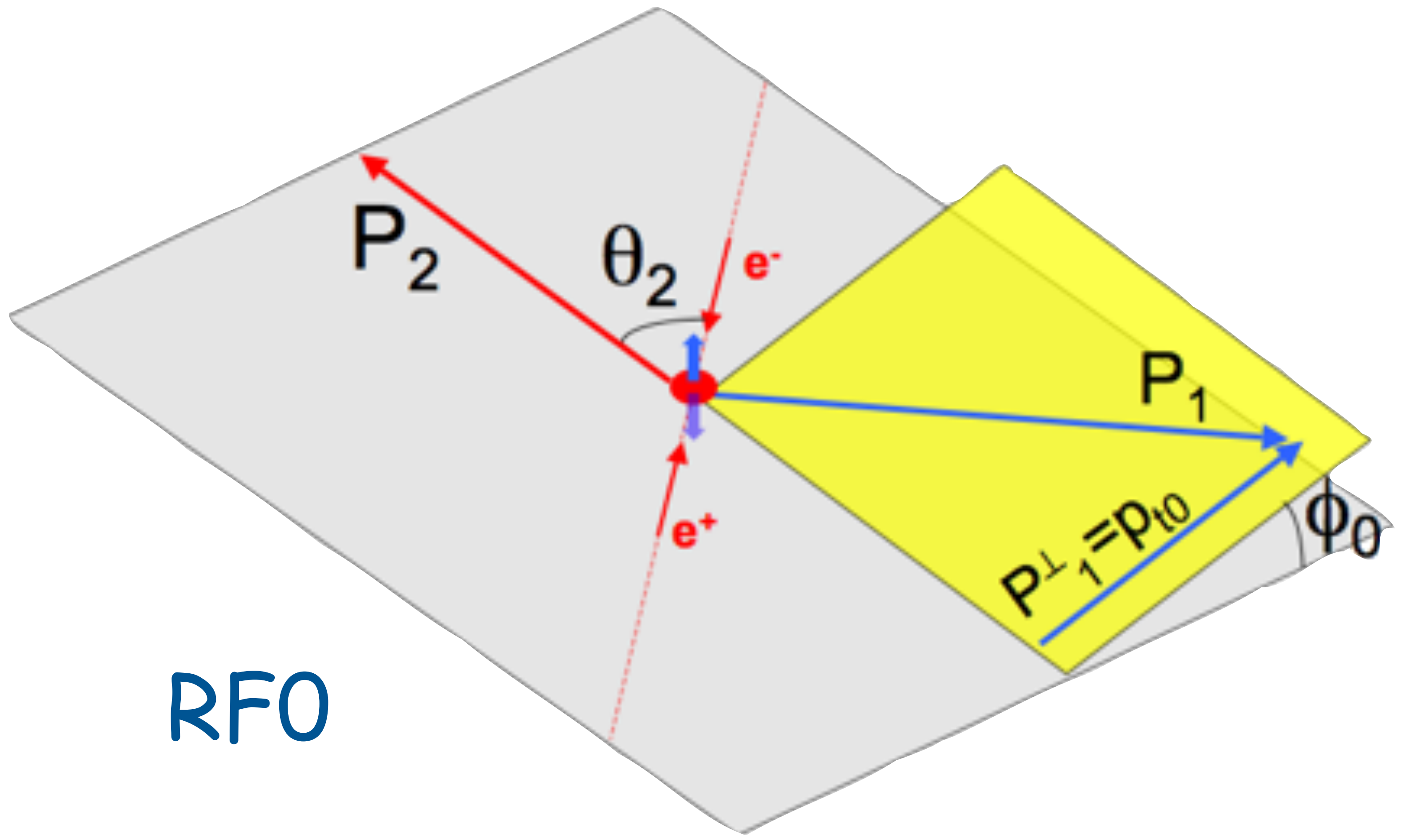


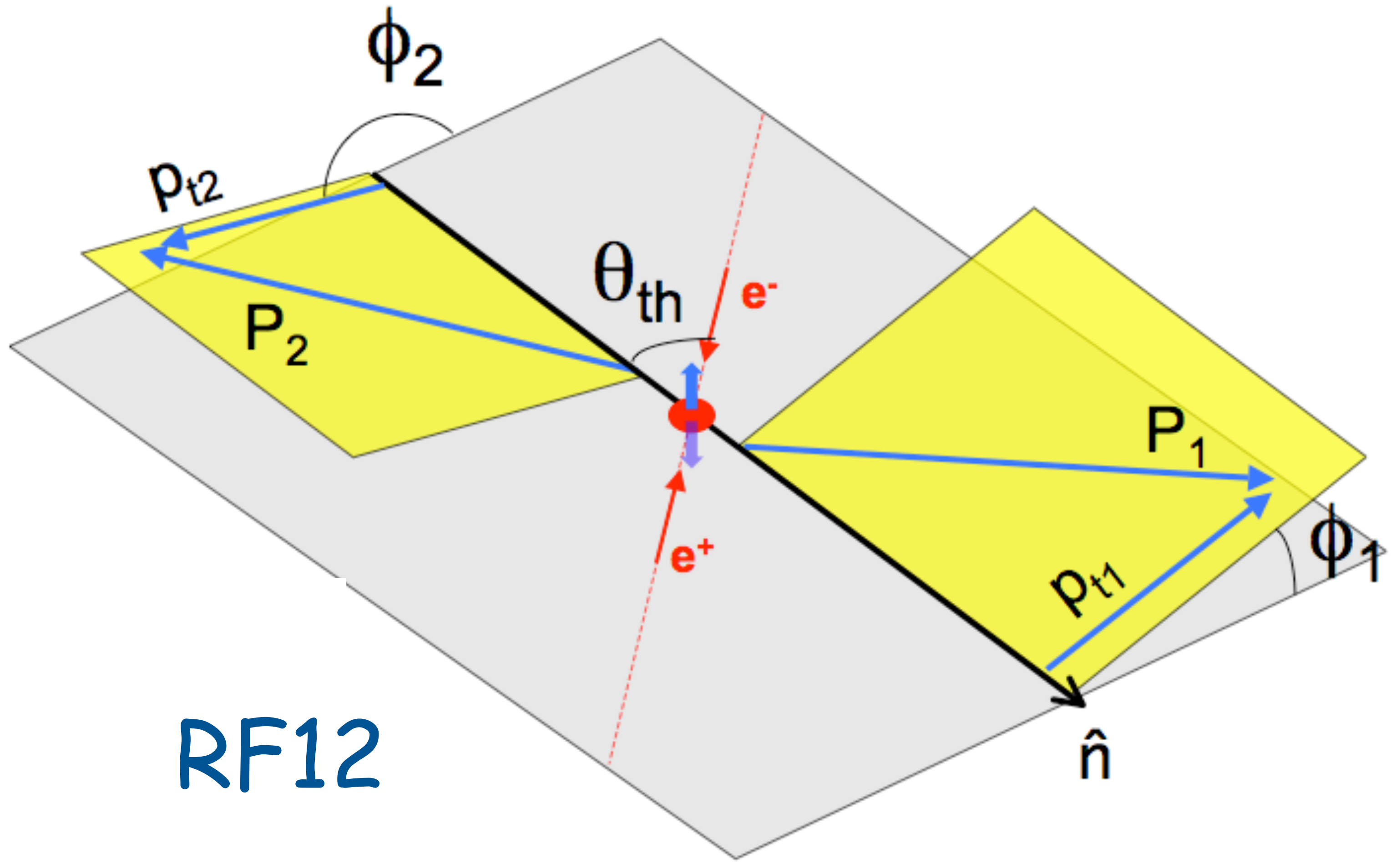
polarization effects

despite unpolarized initial & states

hadron pairs: angular correlations

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



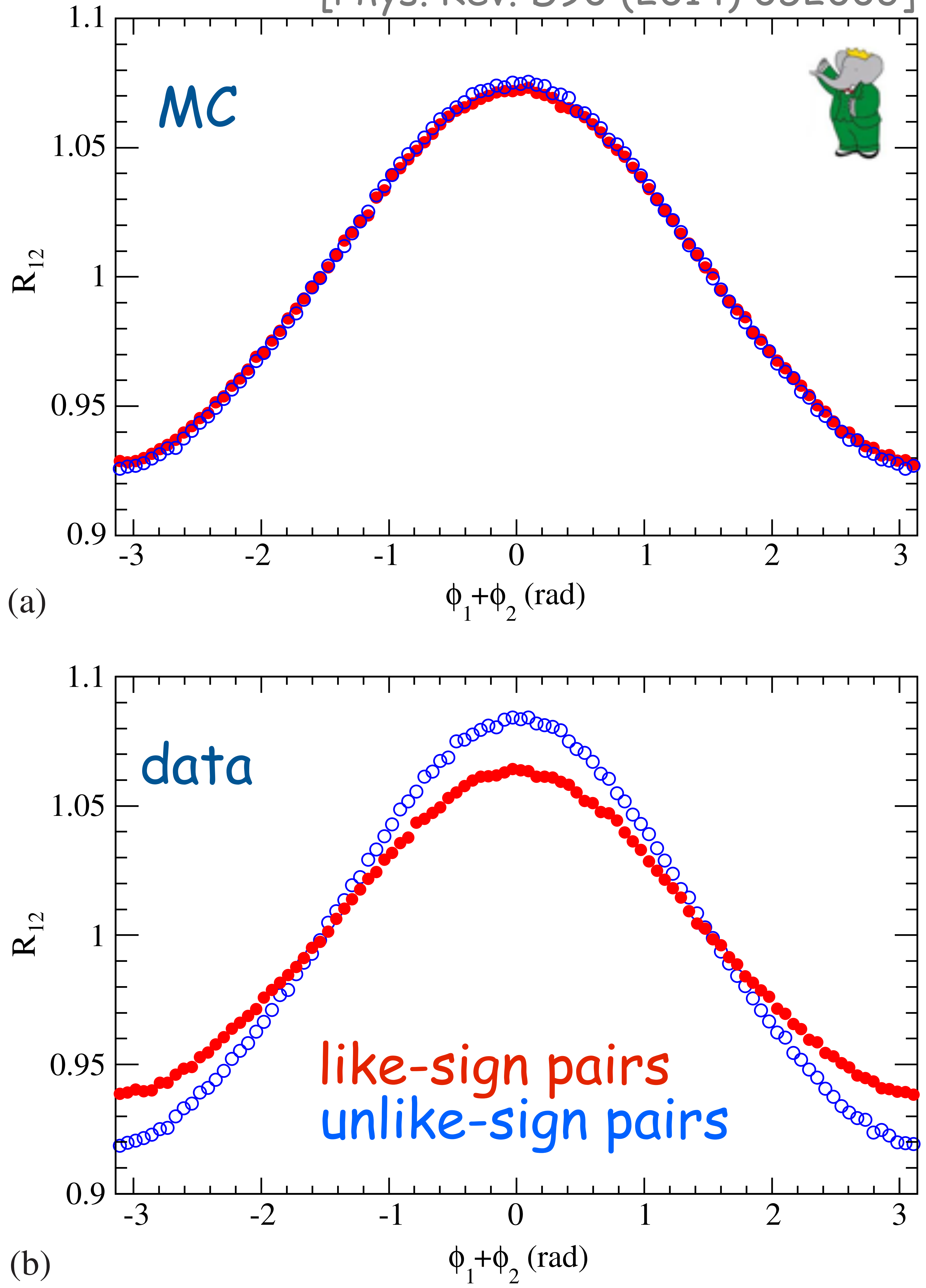


- RF0 and RF12: different convolutions over transverse momenta
- debatable: MC used to “correct” thrust axis to $q\bar{q}$ axis

hadron pairs: angular correlations

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

[Phys. Rev. D90 (2014) 052003]



hadron pairs: angular correlations

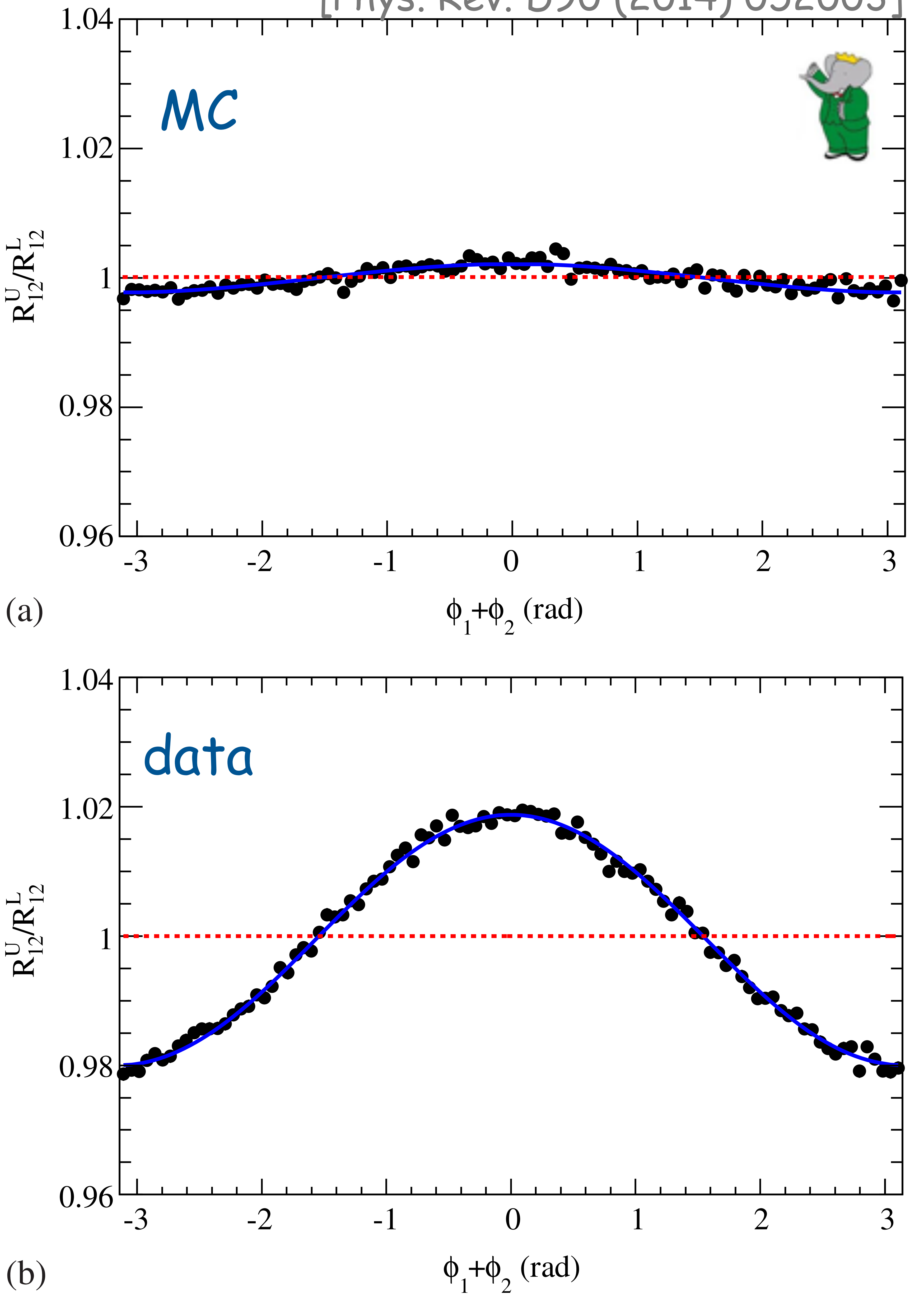
- challenge: large modulations even without Collins effect (e.g., in PYTHIA MC)
- construct double ratio of normalized-yield distributions R_{12}, e.g. unlike-/like-sign:

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

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

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

[Phys. Rev. D90 (2014) 052003]



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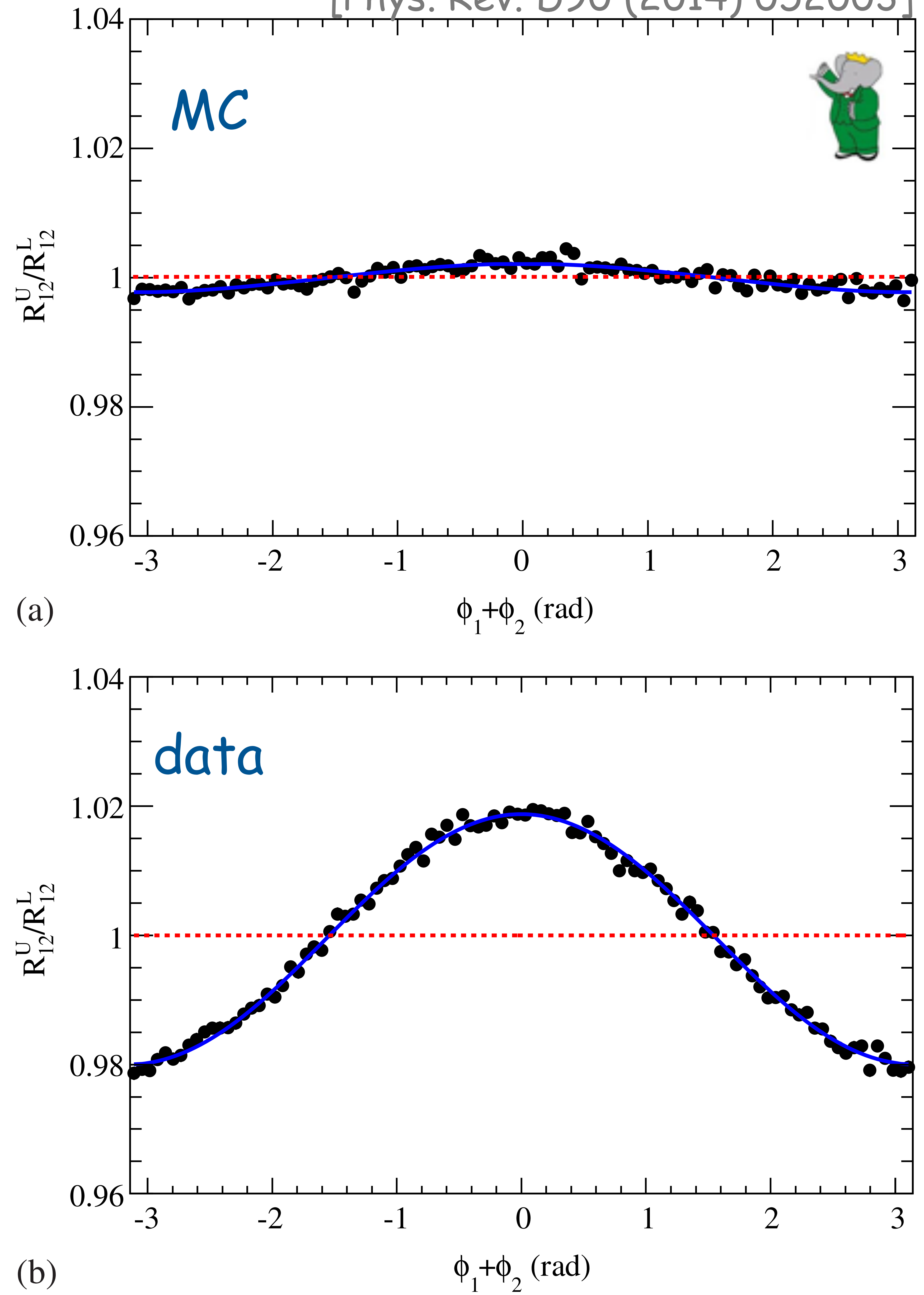
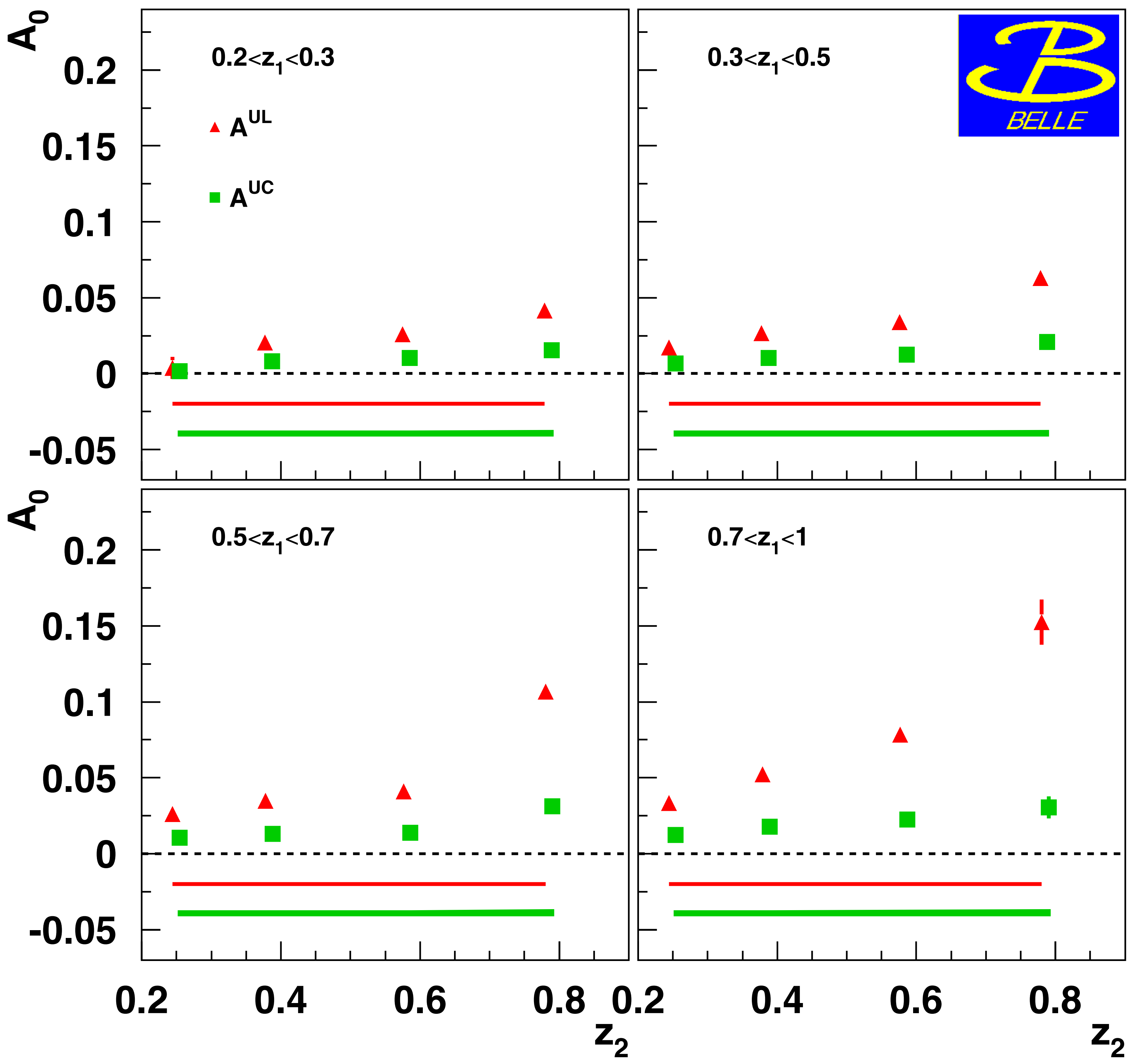
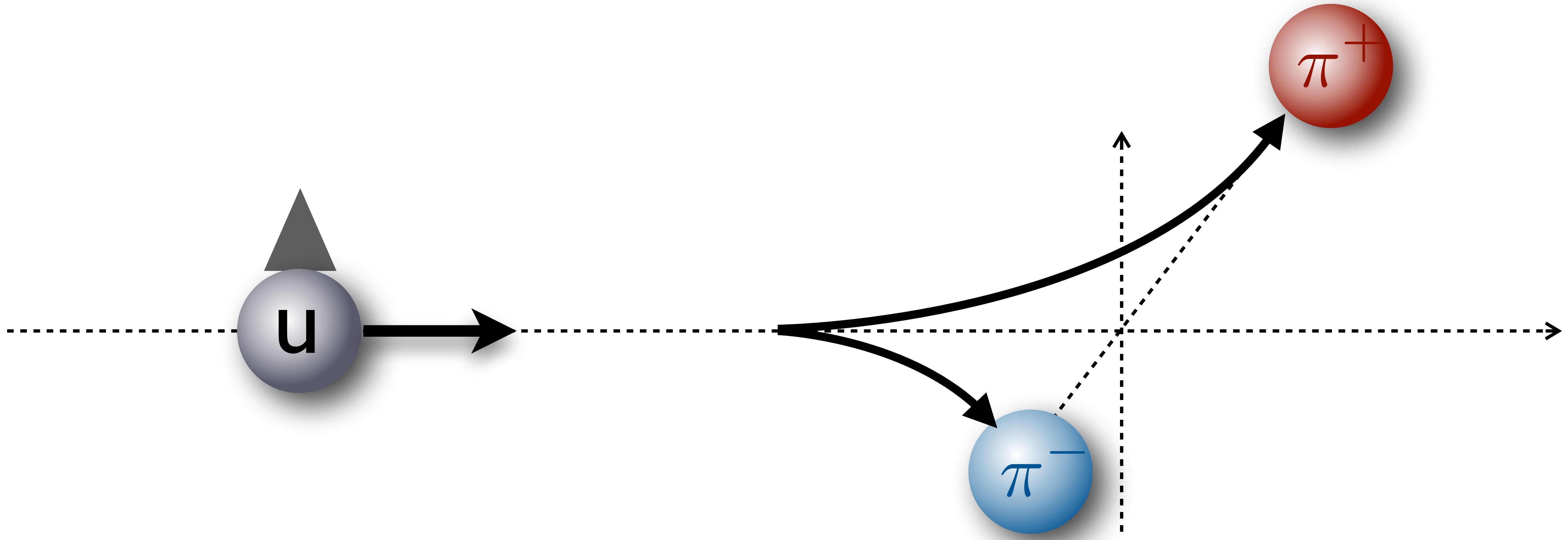


Collins asymmetries (RF0)

- 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





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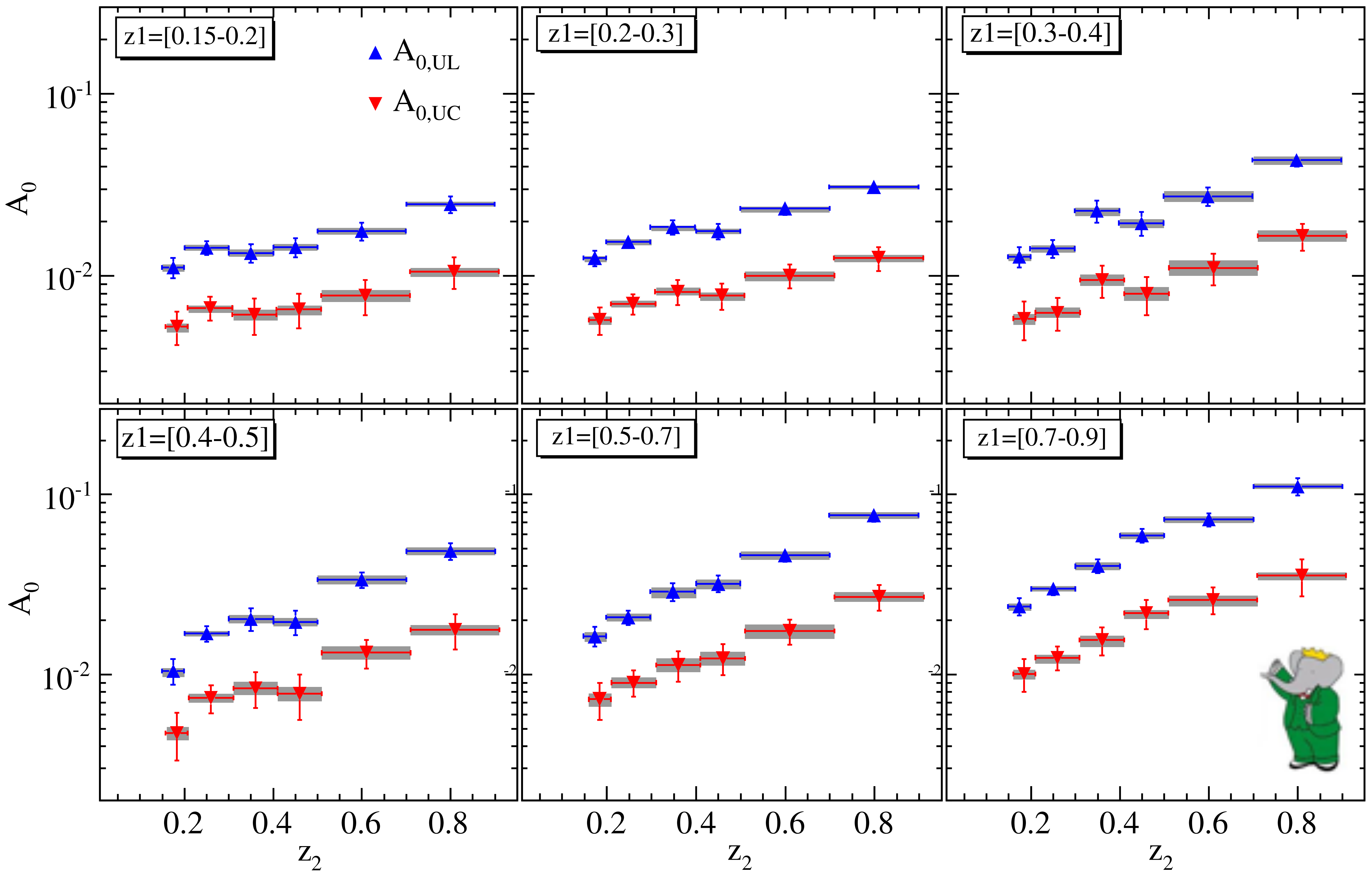
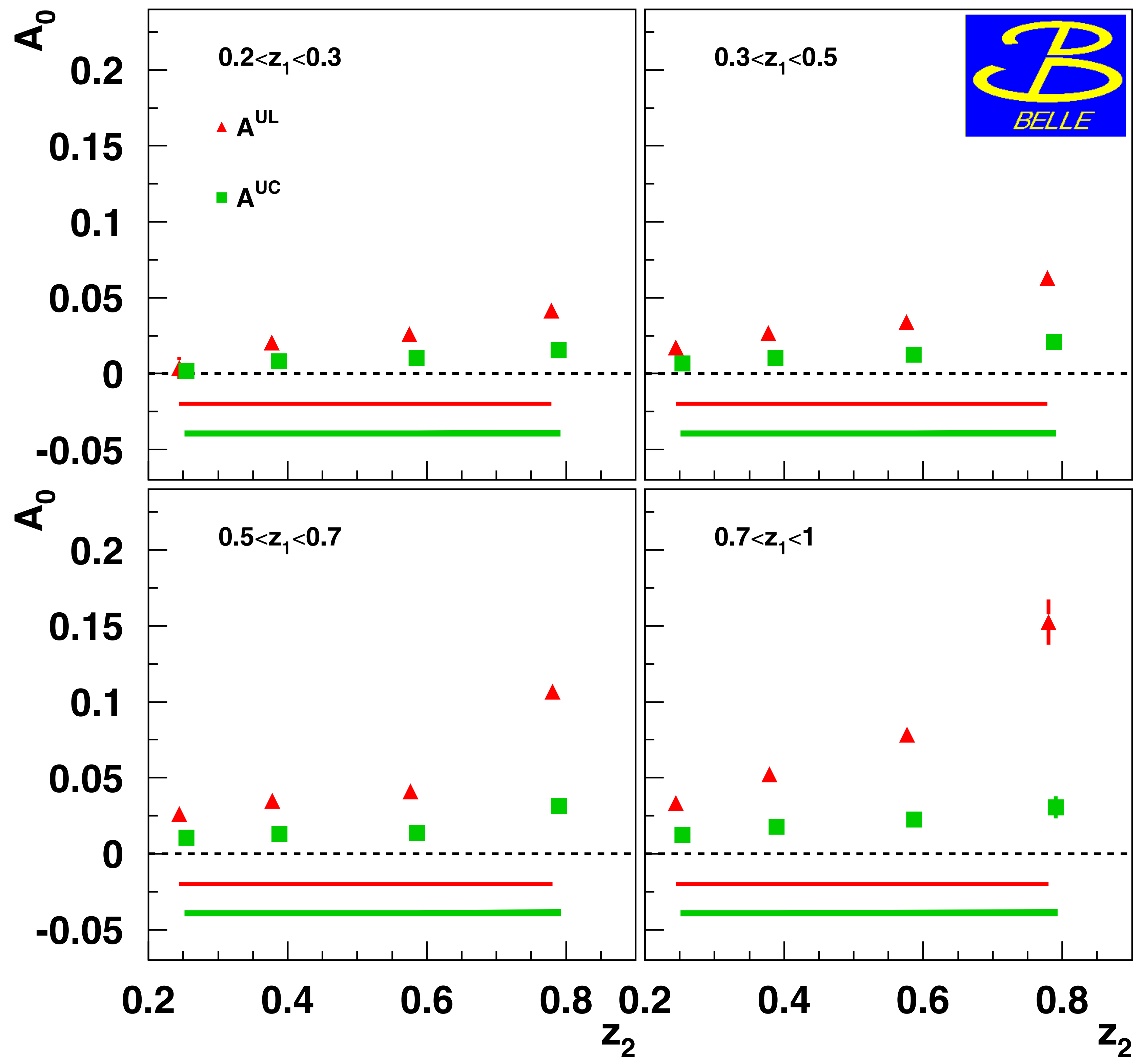
[Phys. Rev. D90 (2014) 052003]

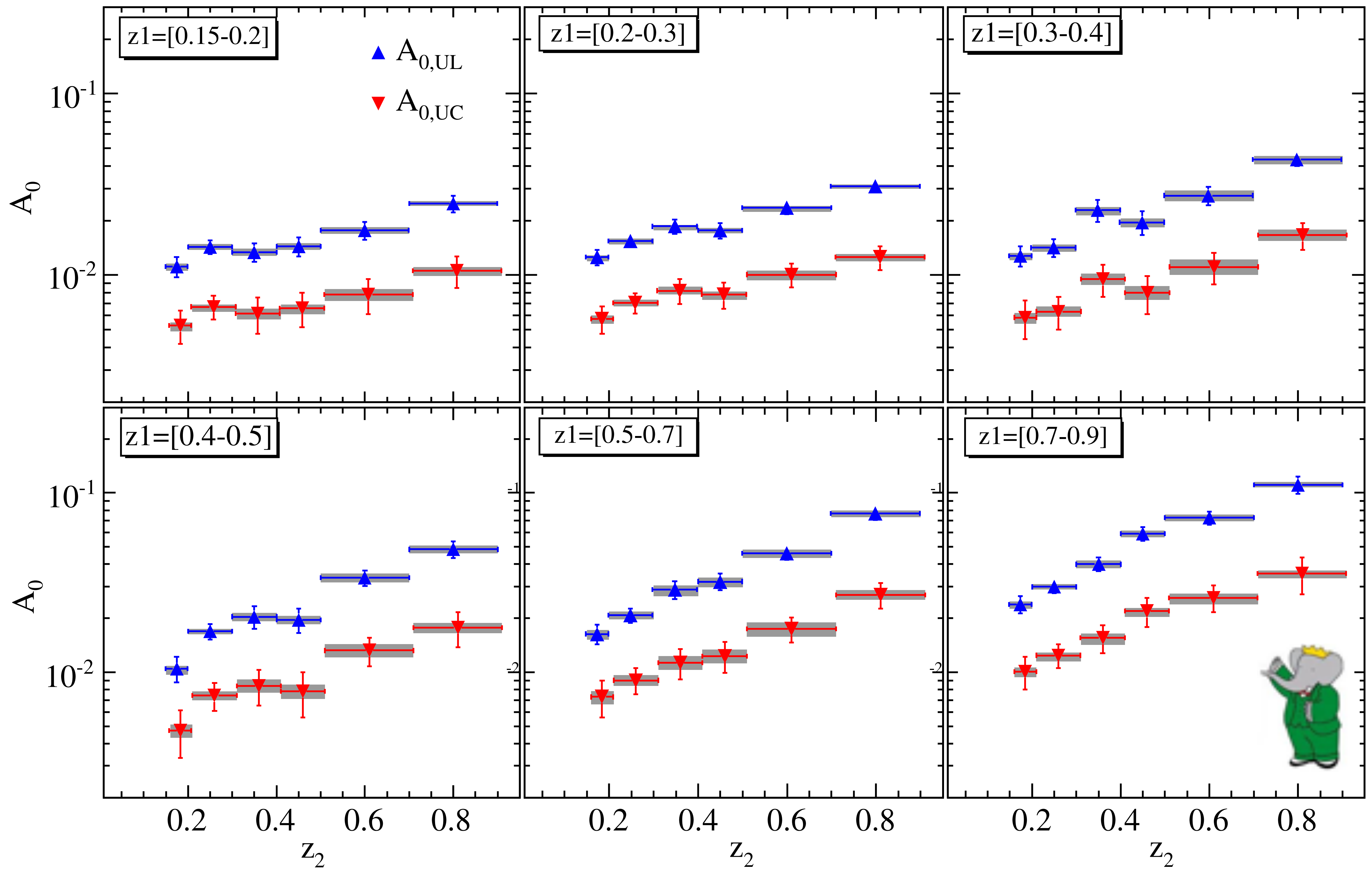


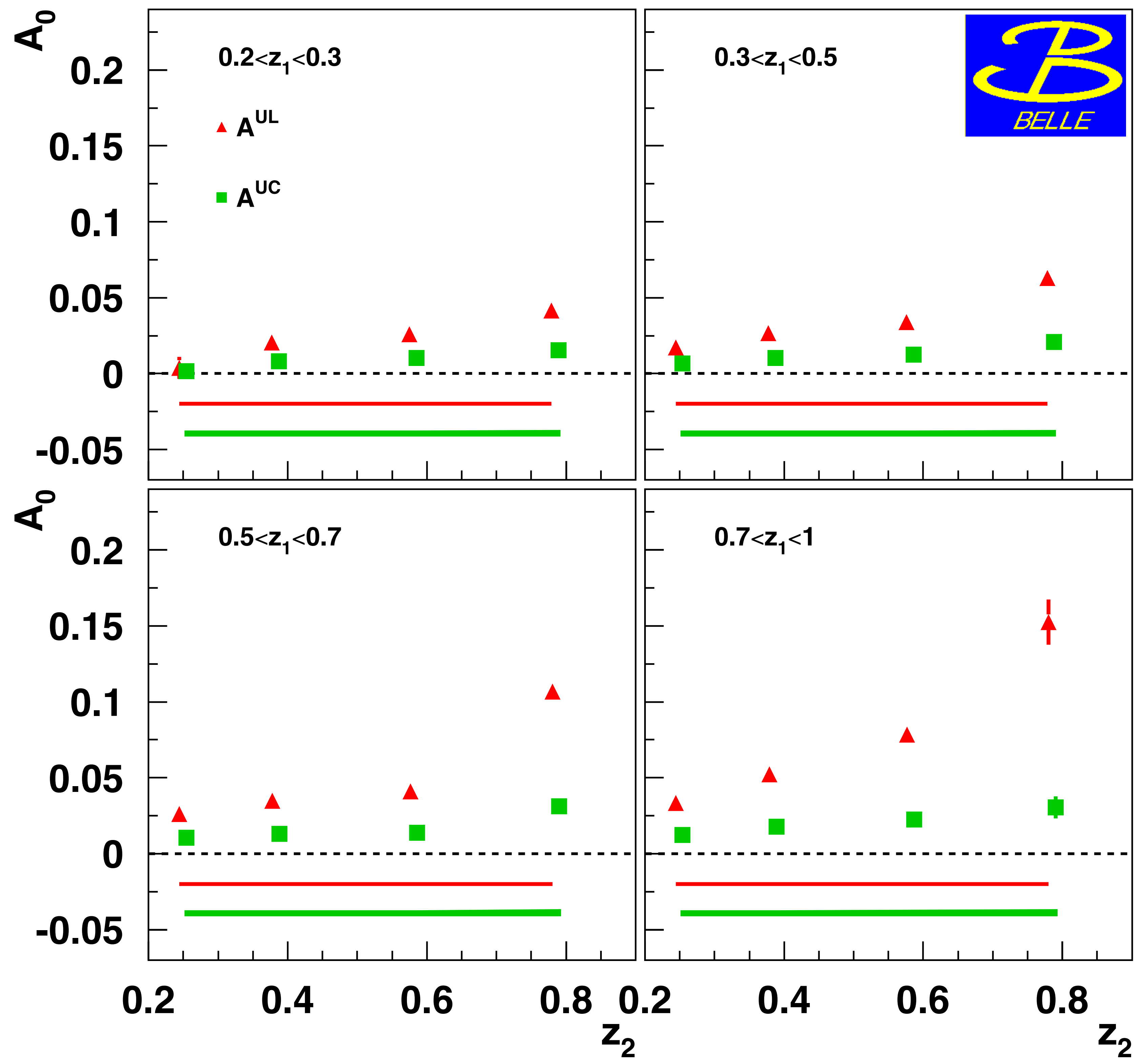


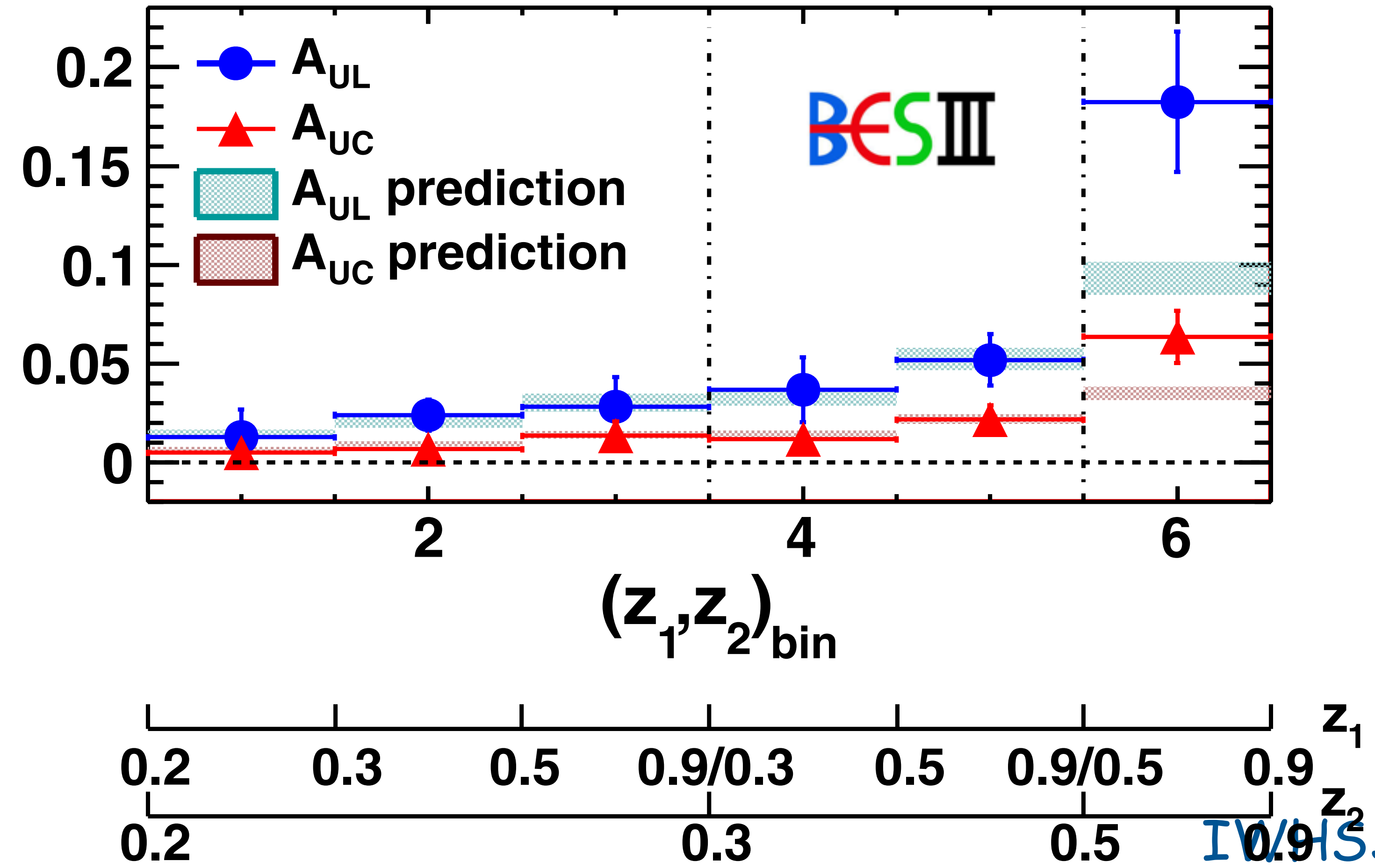
- BaBar results [PRD 90 (2014) 052003] consistent with Belle

Collins asymmetries (RF0)

[Phys. Rev. D90 (2014) 052003]

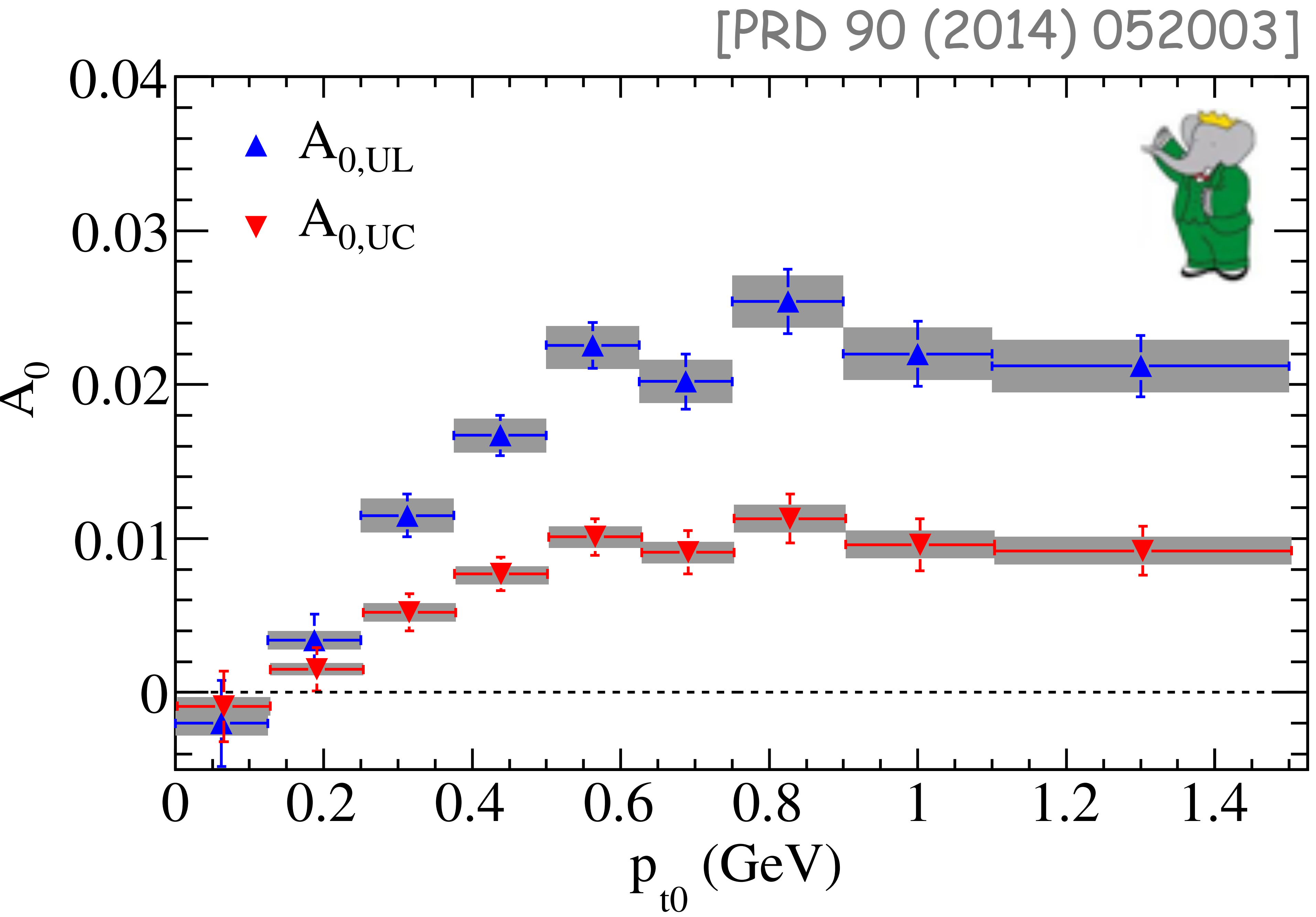


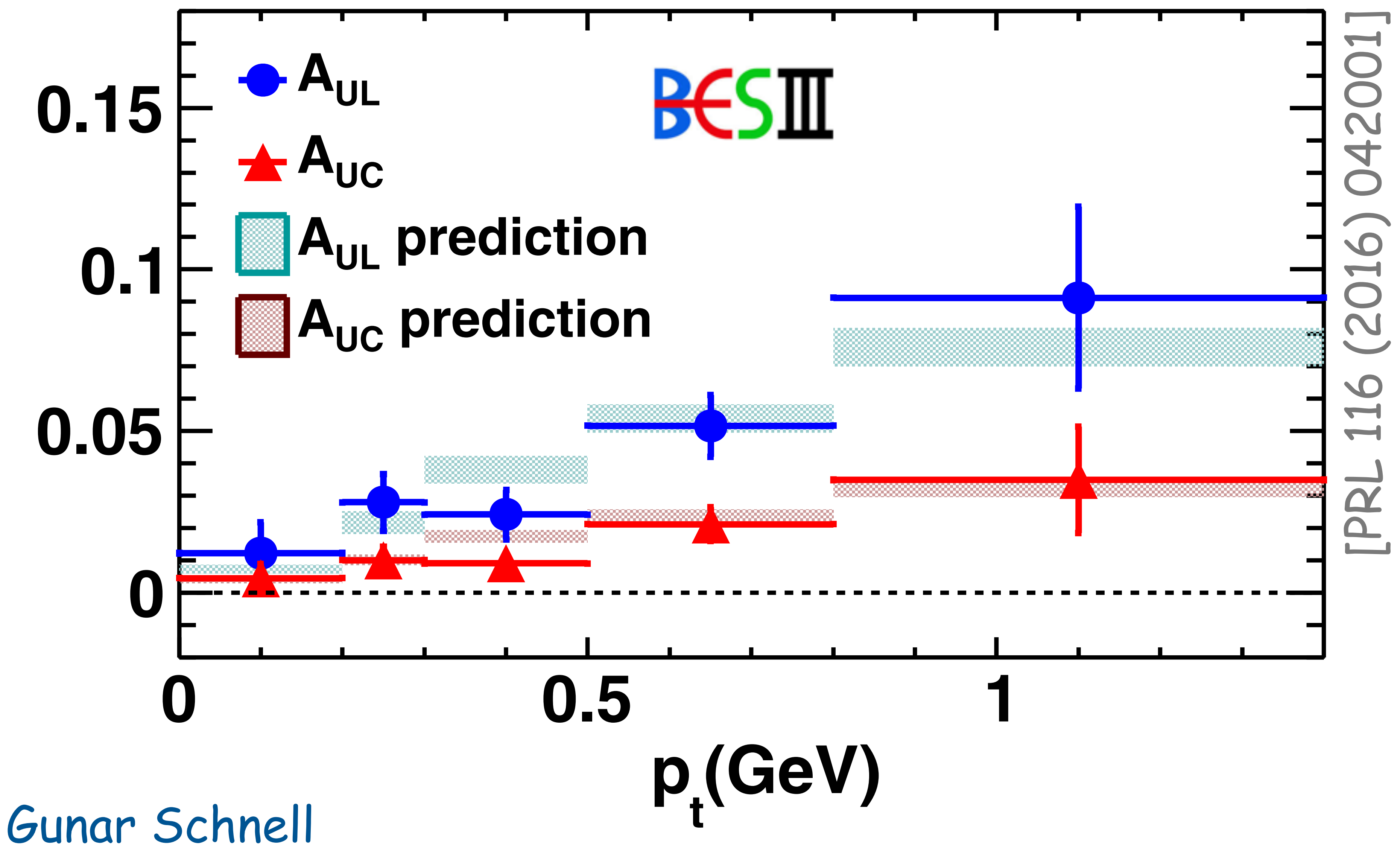




- BaBar results [PRD 90 (2014) 052003] consistent with Belle
- BESIII [PRL 116 (2016) 042001] (at smaller s) consistent with TMD evolution [Kang et al., PRD 93 (2016) 014009]

Collins asymmetries - going further



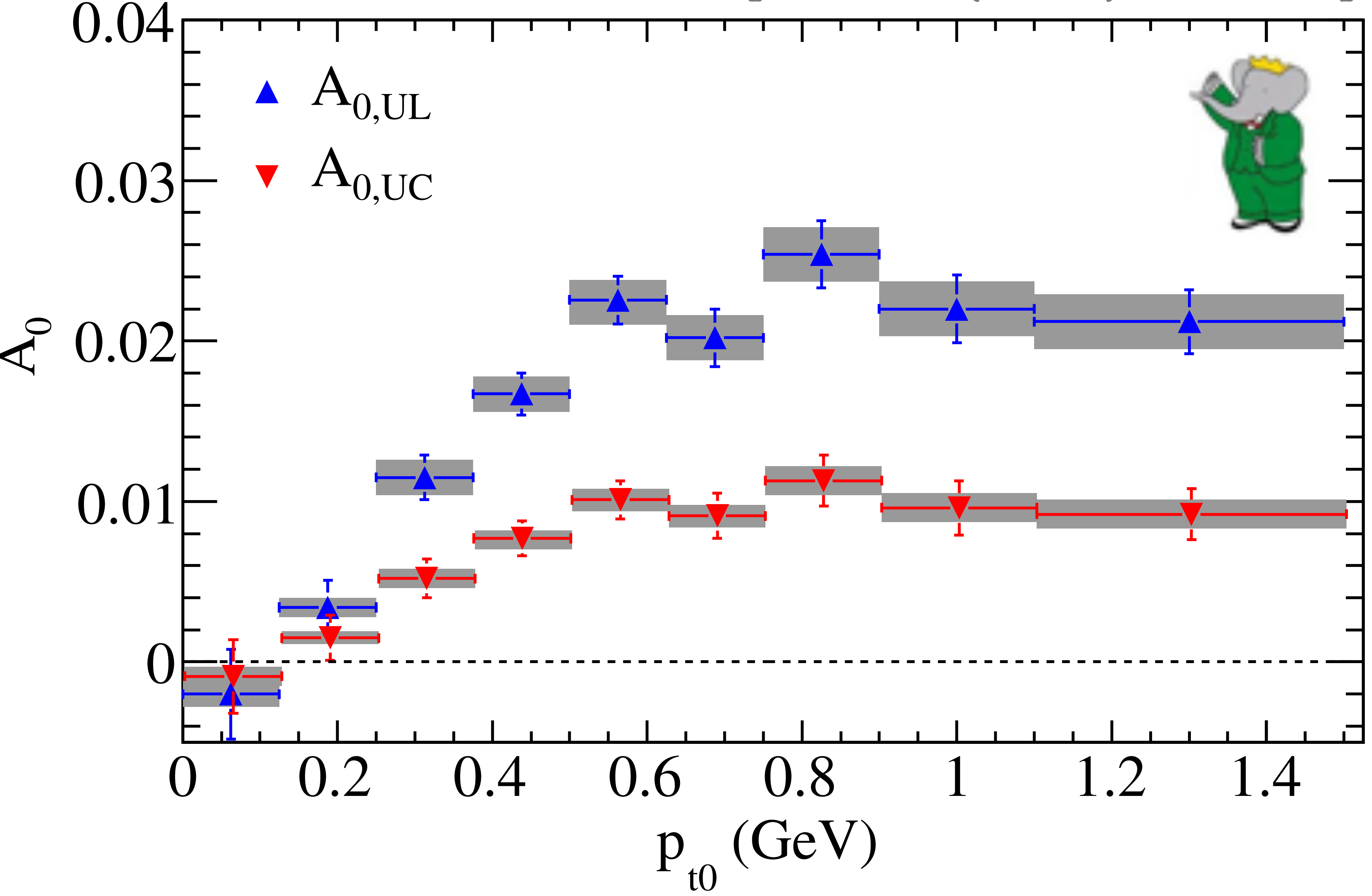


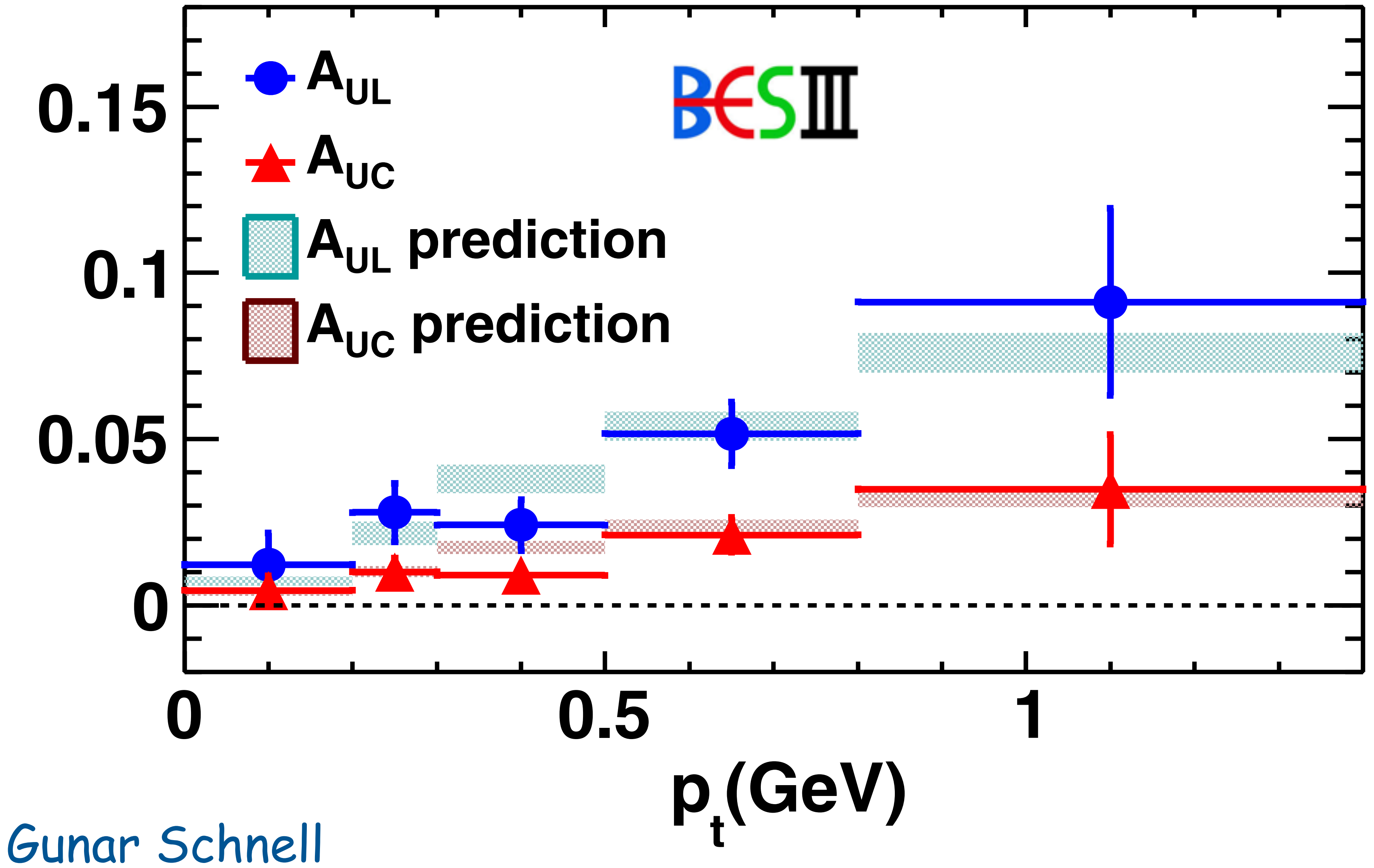
- p_T dependence for charged pions from BaBar & BESIII
  - typical rise with p_T; turnover around 0.8 GeV

Collins asymmetries - going further

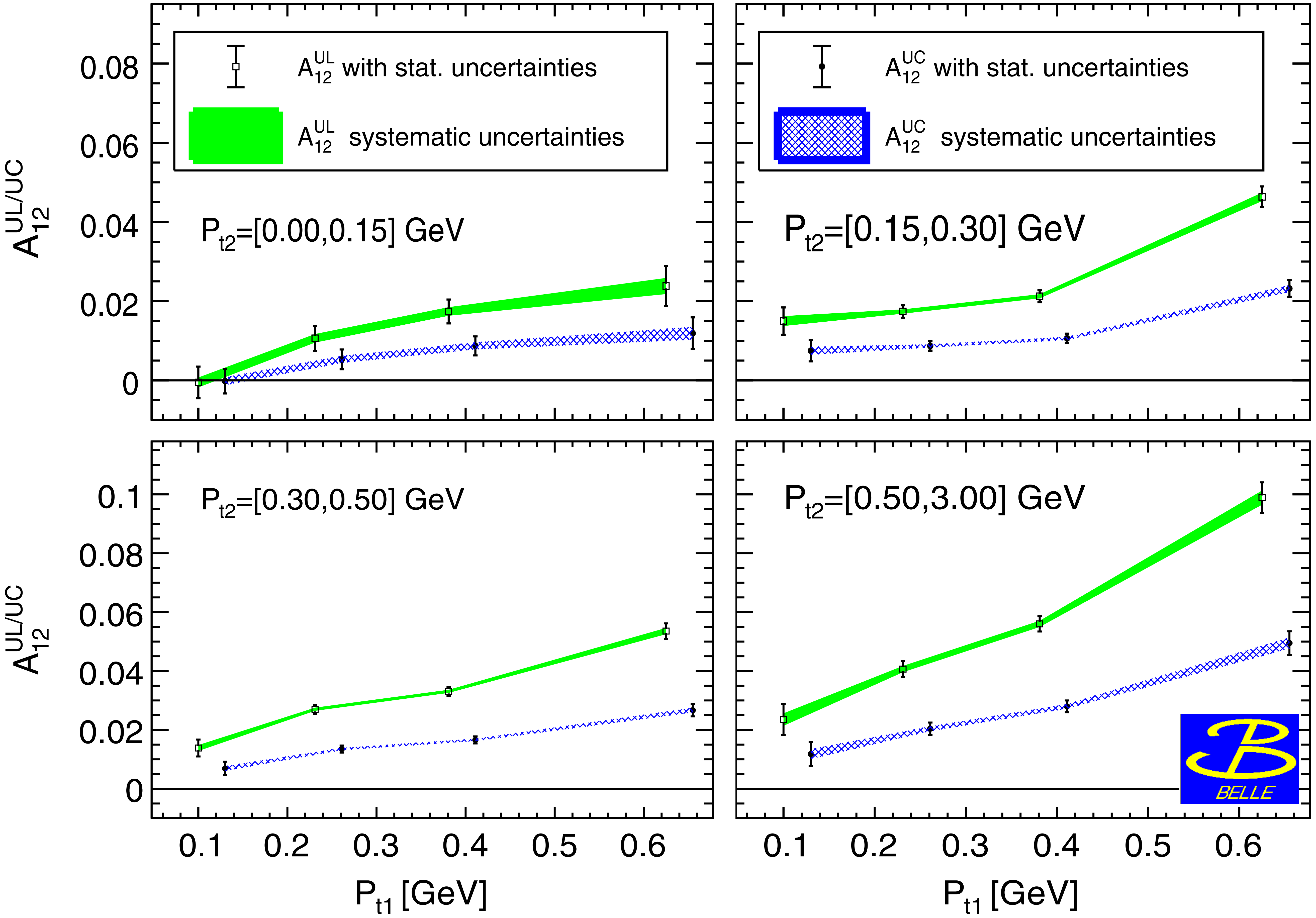
- p_T dependence for charged pions from BaBar & BESIII
  - typical rise with p_T; turnover around 0.8 GeV
- … now also from Belle in R12 frame:

[PRD 90 (2014) 052003]





[PRL 116 (2016) 042001]



[PRD 100 (2019) 92008]

Collins asymmetries - going further

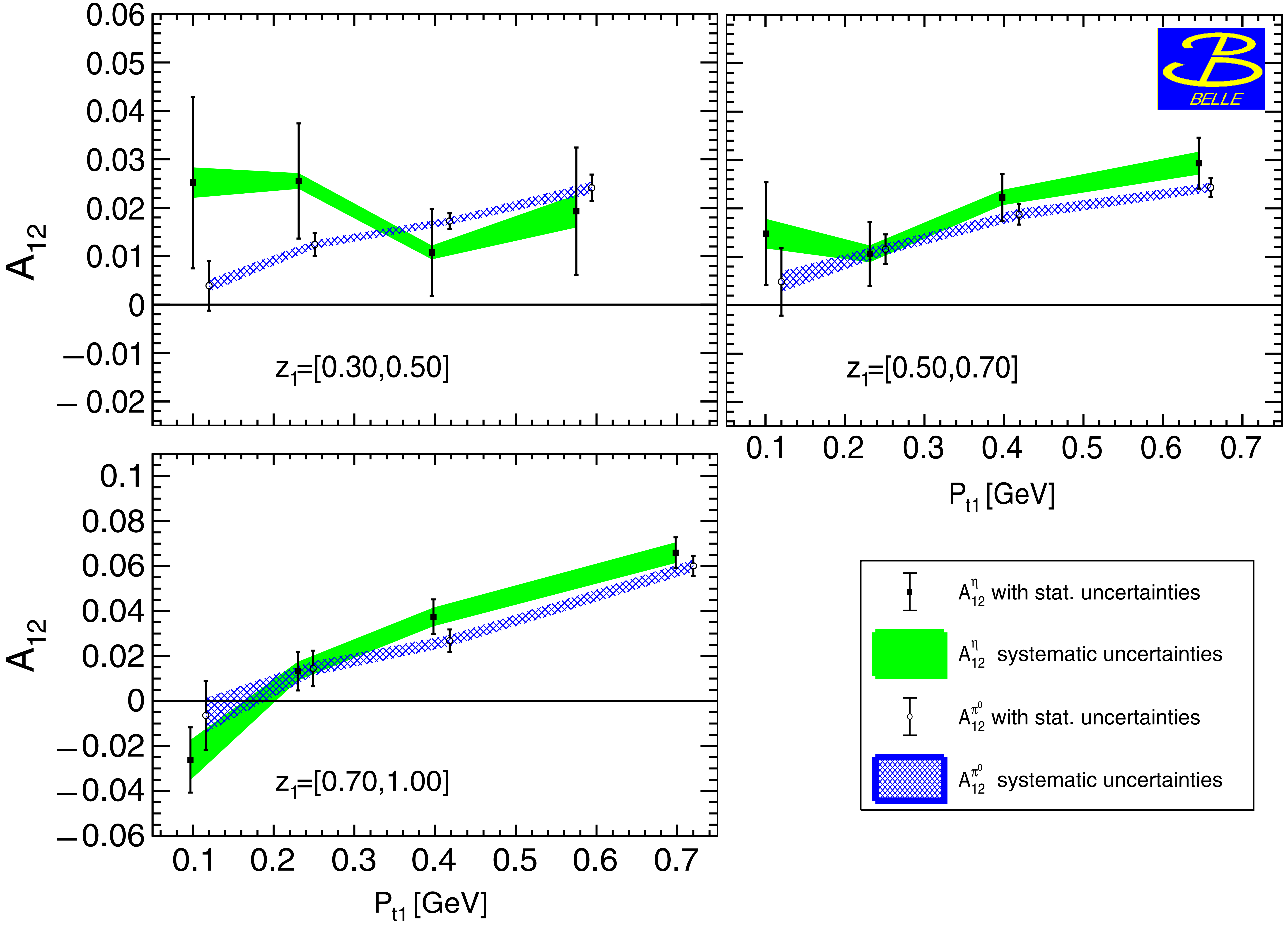
- … as well as for neutral pion and eta

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

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

- no significant differences observed

[PRD 100 (2019) 92008]



Collins asymmetries - going further

$$R_{12}^{\pi^0} = \frac{R_{12}^{0\pm}}{R_{12}^{L}} \approx 1 + \cos(\phi_{12}) \frac{\sin^2(\theta)}{1+\cos^2(\theta)}$$

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$$\left. - \frac{5(H_1^{\perp,fav} \otimes H_1^{\perp,dis} + H_1^{\perp,dis} \otimes H_1^{\perp,fav}) + 2H_{1,s\to\pi}^{\perp,dis} H_{1,s\to\pi}^{\perp,dis}}{5(D_1^{fav} \otimes D_1^{dis} + D_1^{dis} \otimes D_1^{fav}) + 2D_{1,s\to\pi}^{dis} \otimes D_{1,s\to\pi}^{dis}} \right\}.$$

$$\overset{\text{isospin}}{=} A_{12}^{UL} - A_{12}^{UC}$$

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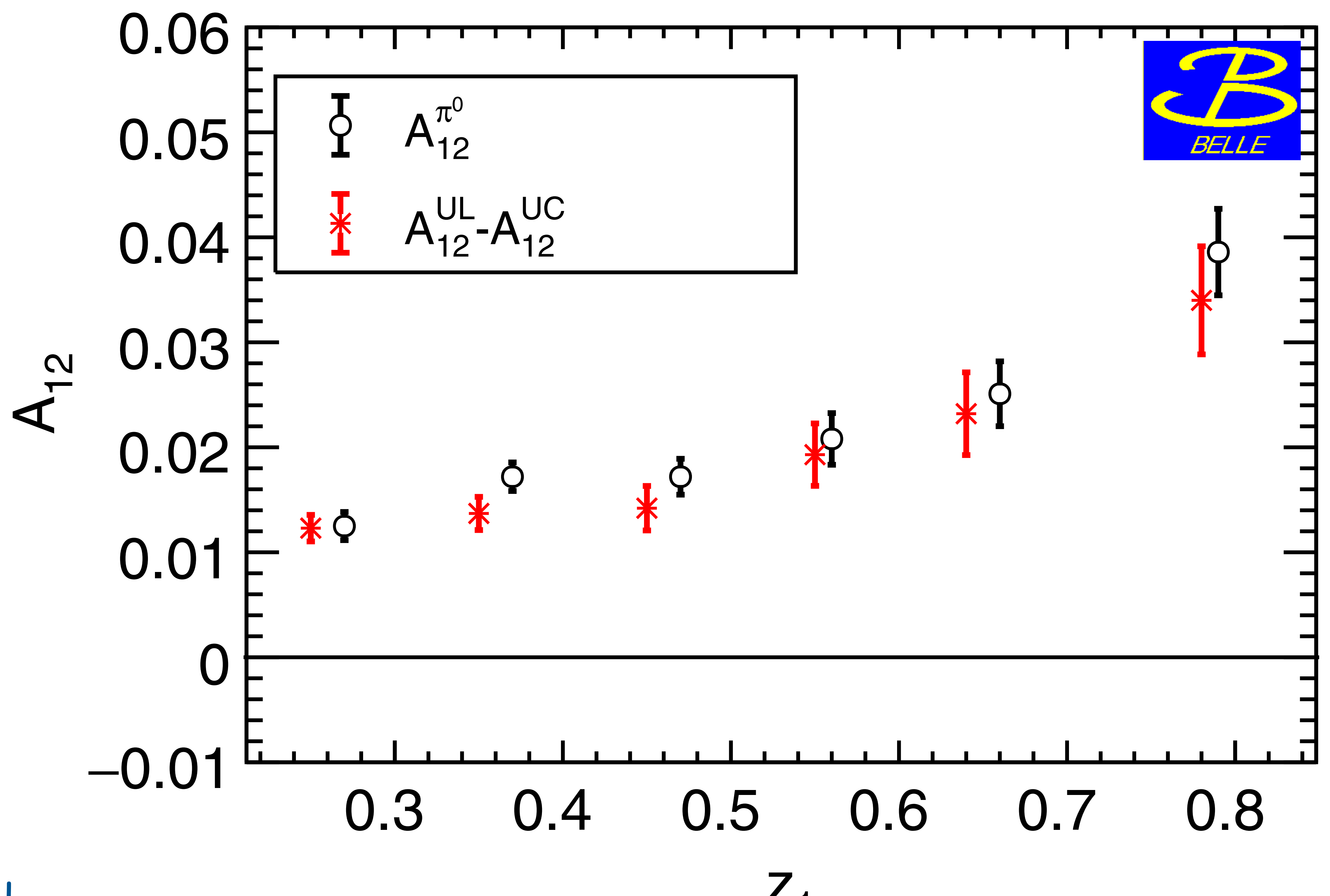

- consistency between neutral and charged pions
  - typical rise with z also seen for neutral pions

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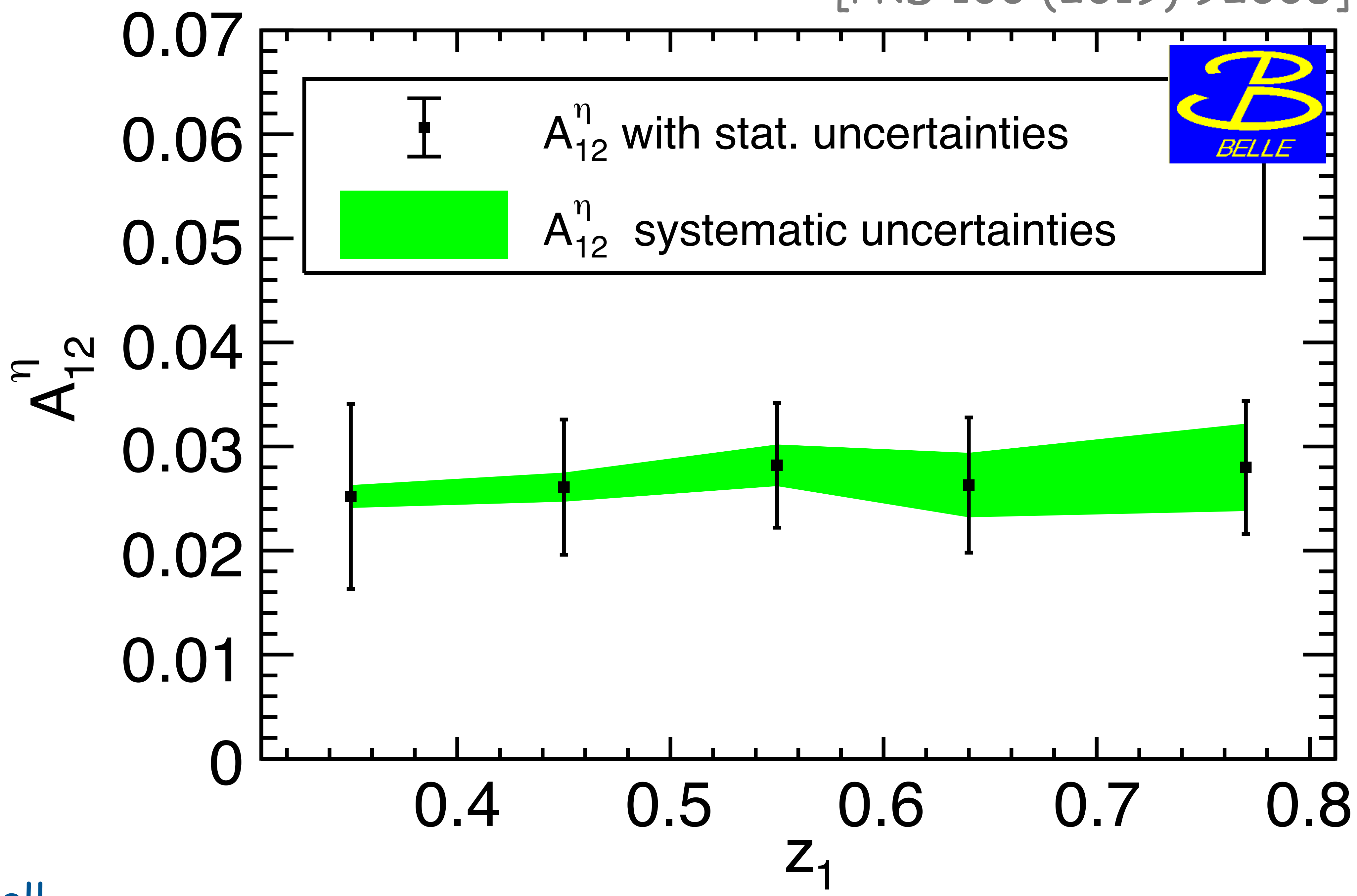
[PRD 100 (2019) 92008]



- consistency between neutral and charged pions
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  - … while basically flat for eta

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  - double ratio dominated by terms involving charged-pion yields
  - only numerator of first term related to π^0 or η
- **non-zero results could, in principle, arise entirely from charged-pion Collins FFs**

a likely future

- several analyses still in the pipeline, e.g.,
  - k_T-dependent D_1 FFs (back-to-back hadrons) (Belle, BESIII & possibly BaBar)
  - Collins asymmetries:
    - pion update w/ increased statistics (BESIII)
    - kaon & pion-kaon pairs; k_T dependence of Collins asymmetries (Belle, BESIII)
    - Collins asymmetries w/o double ratios (BaBar)
  - single-hadron production
    - **short-lived mesons and resonances** (Belle)
    - charged pions and kaon at lower s (BESIII)

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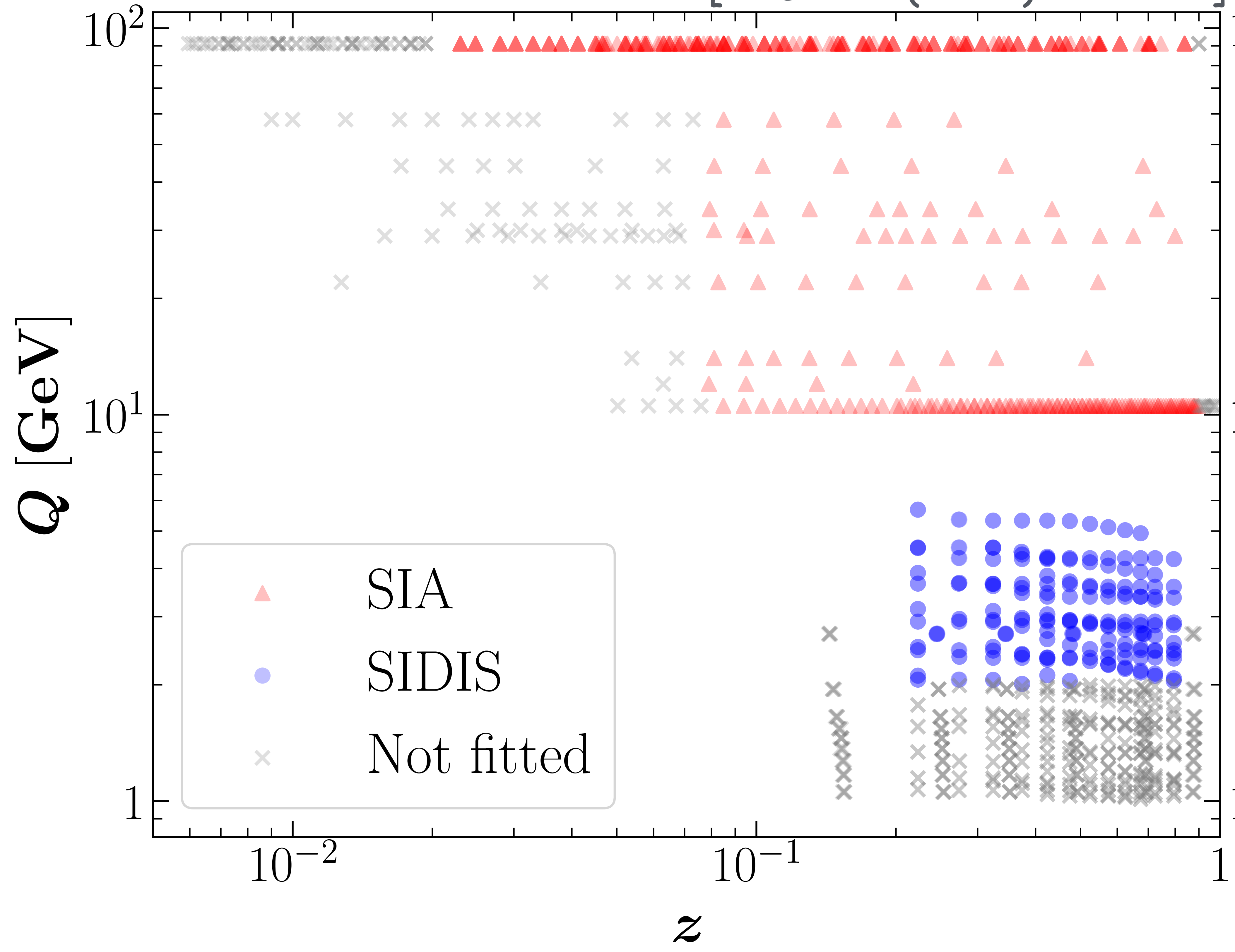
[PRD 104 (2021) 034007]



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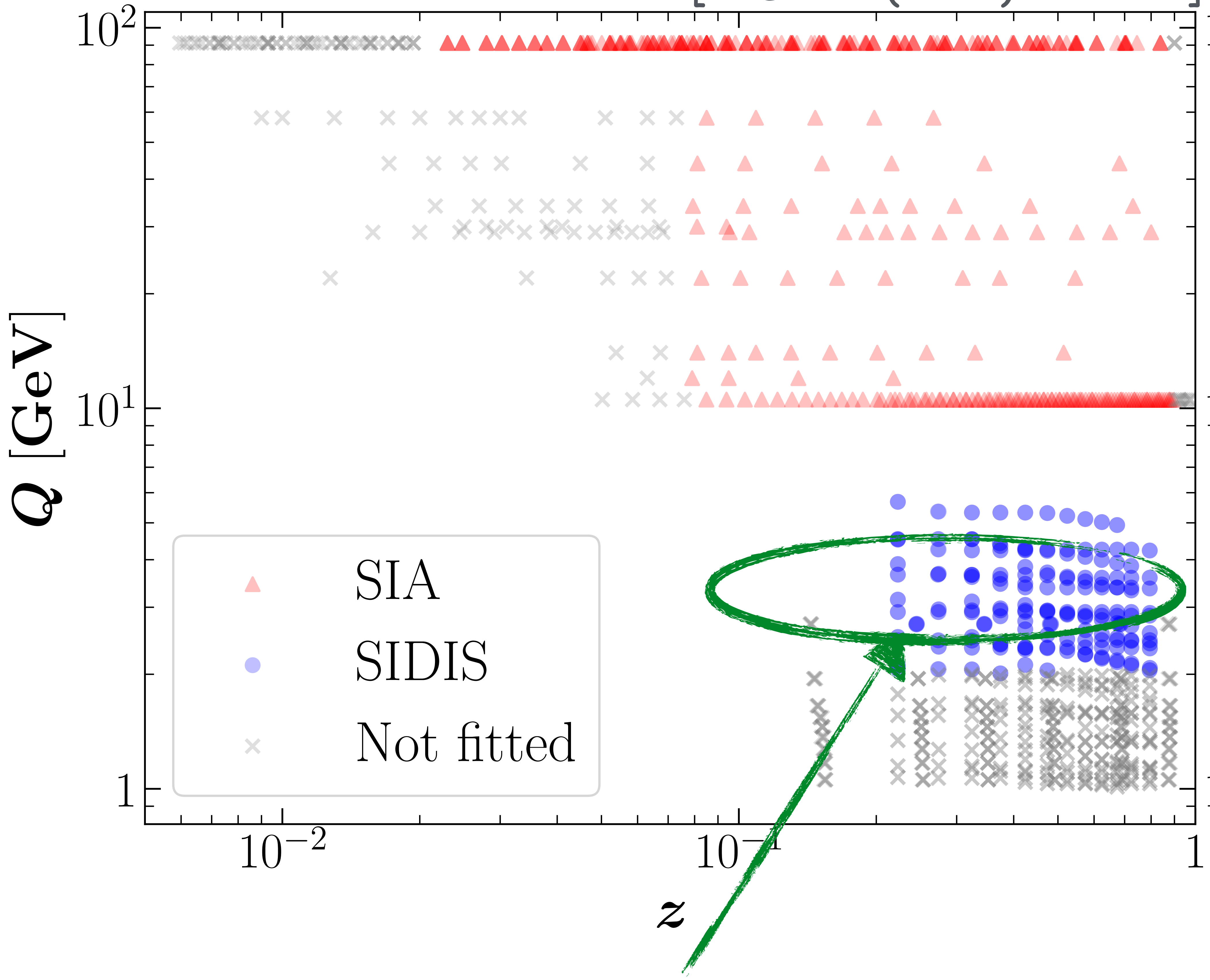
[PRD 104 (2021) 034007]



BESIII region

~62pb[-1] @3.52 GeV used for Collins asym's

aim at **250pb[-1]** data set

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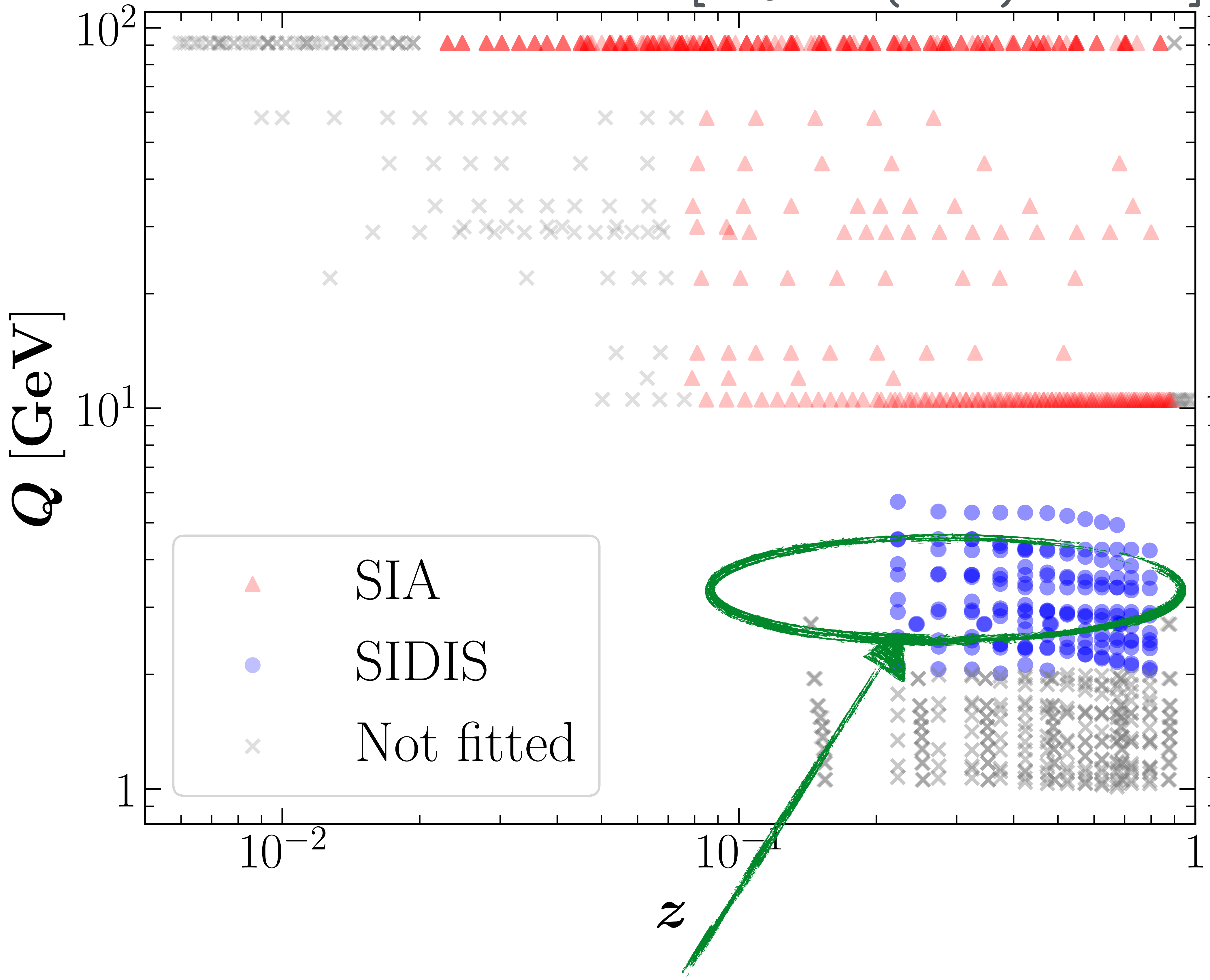
    - pion update w/ increased statistics (BESIII)
    - kaon & pion-kaon pairs; k_T dependence of Collins asymmetries (Belle, BESIII)
    - Collins asymmetries w/o double ratios (BaBar)
  - single-hadron production
    - **short-lived mesons and resonances** (Belle)
    - charged pions and kaon at lower s (BESIII)
- new data from Belle II

[PRD 104 (2021) 034007]



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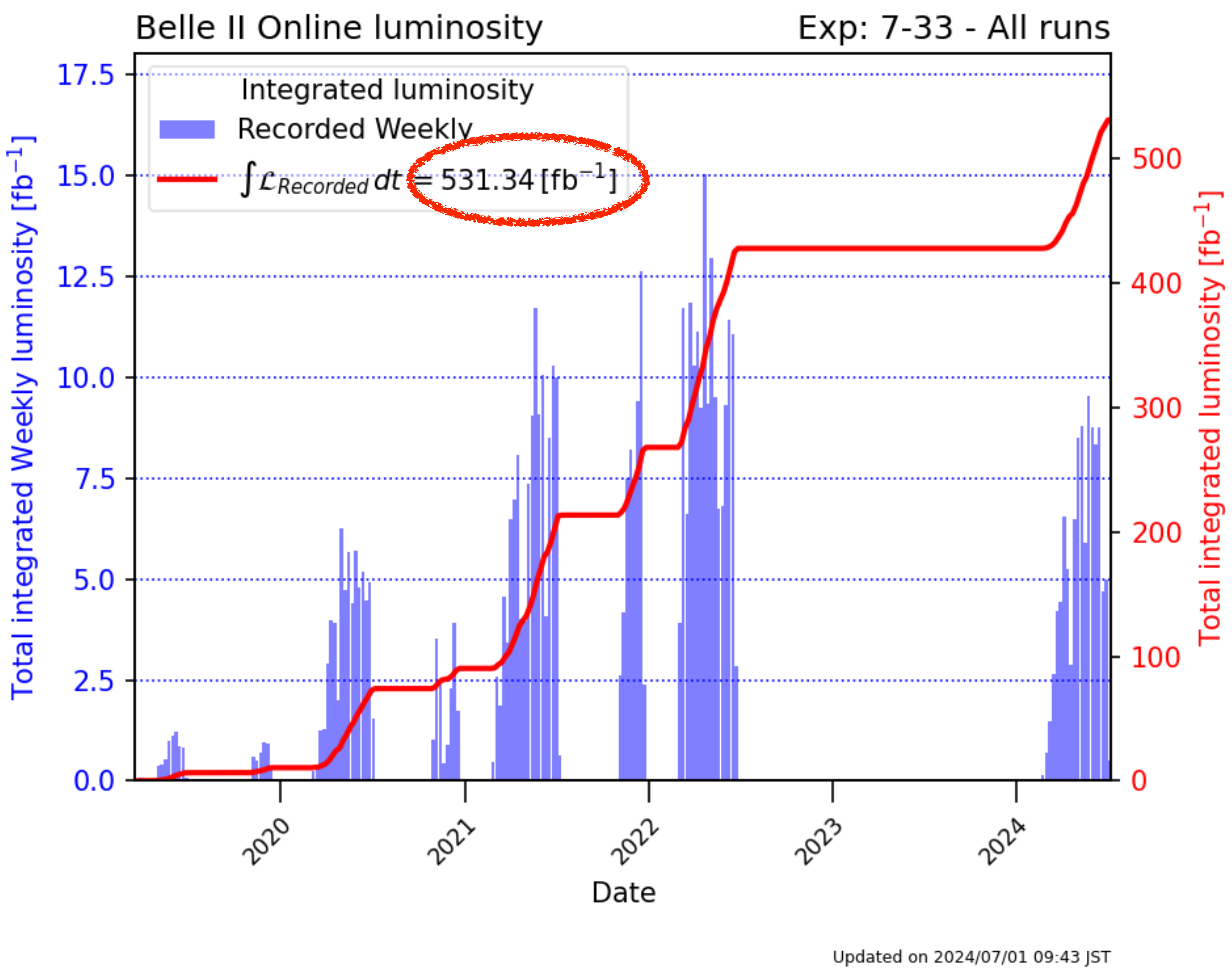
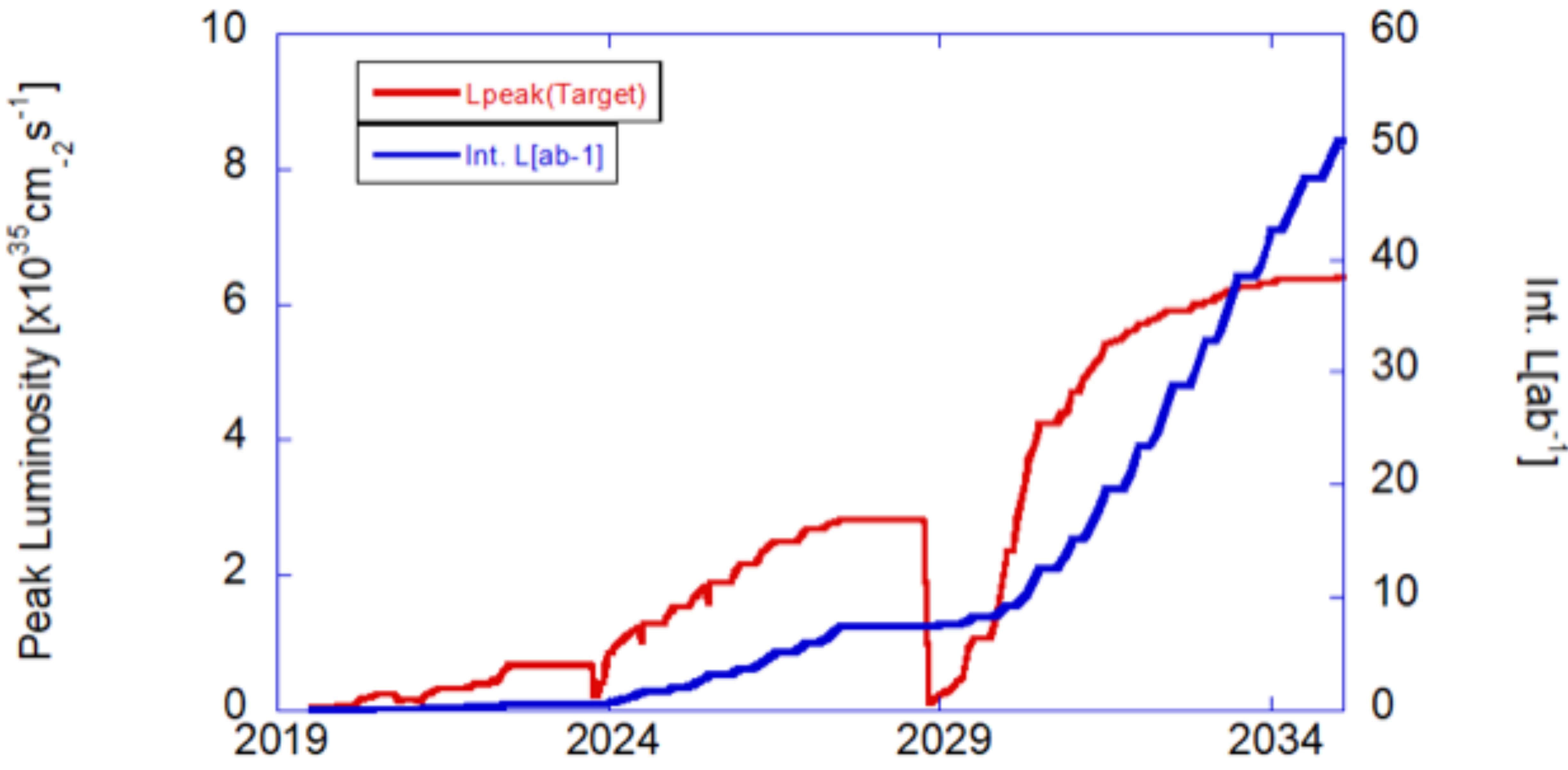
Belle II data taking





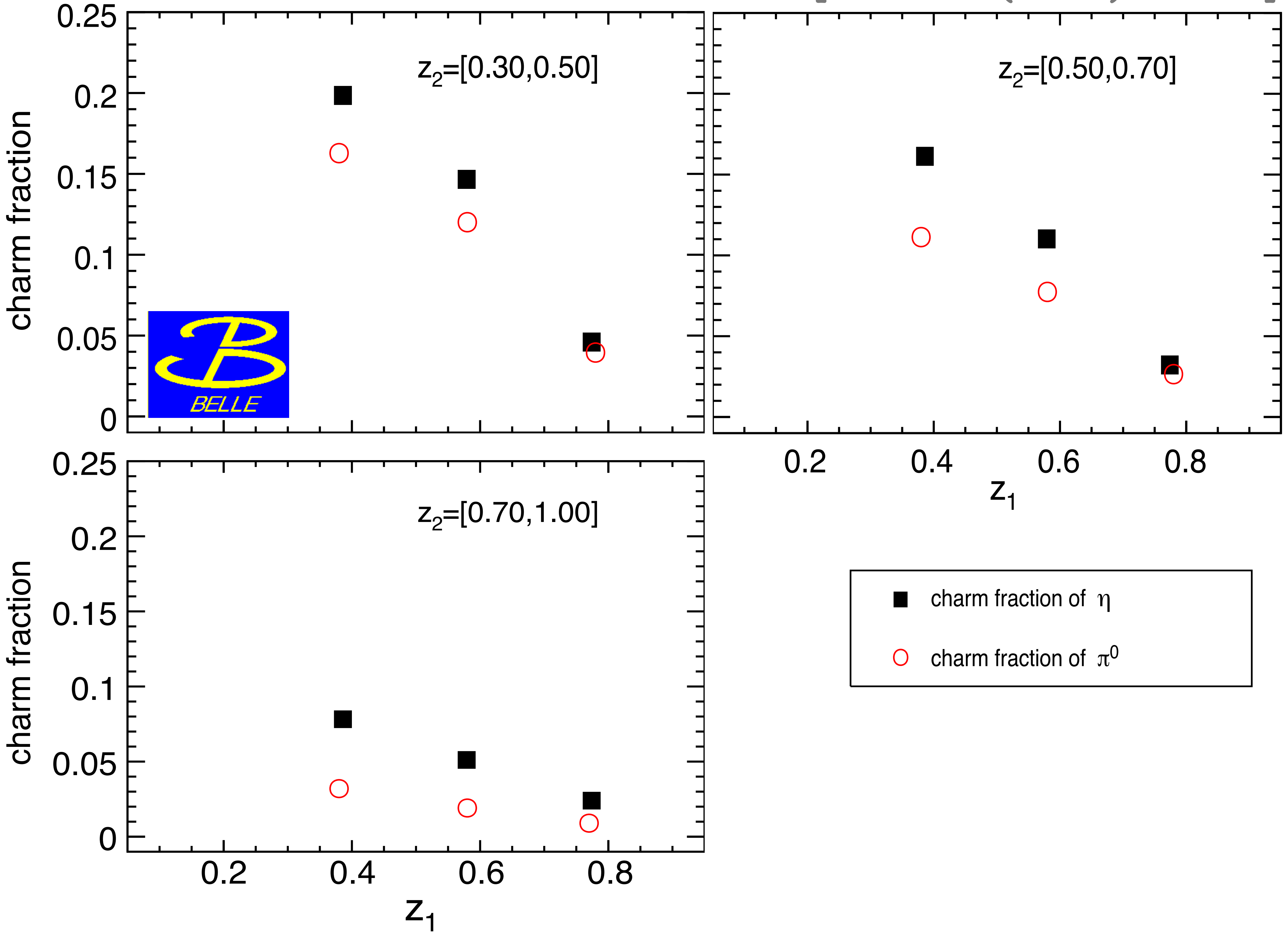
➡ similar data sample as at 1st-generation B-factories "soonish"

backup slides

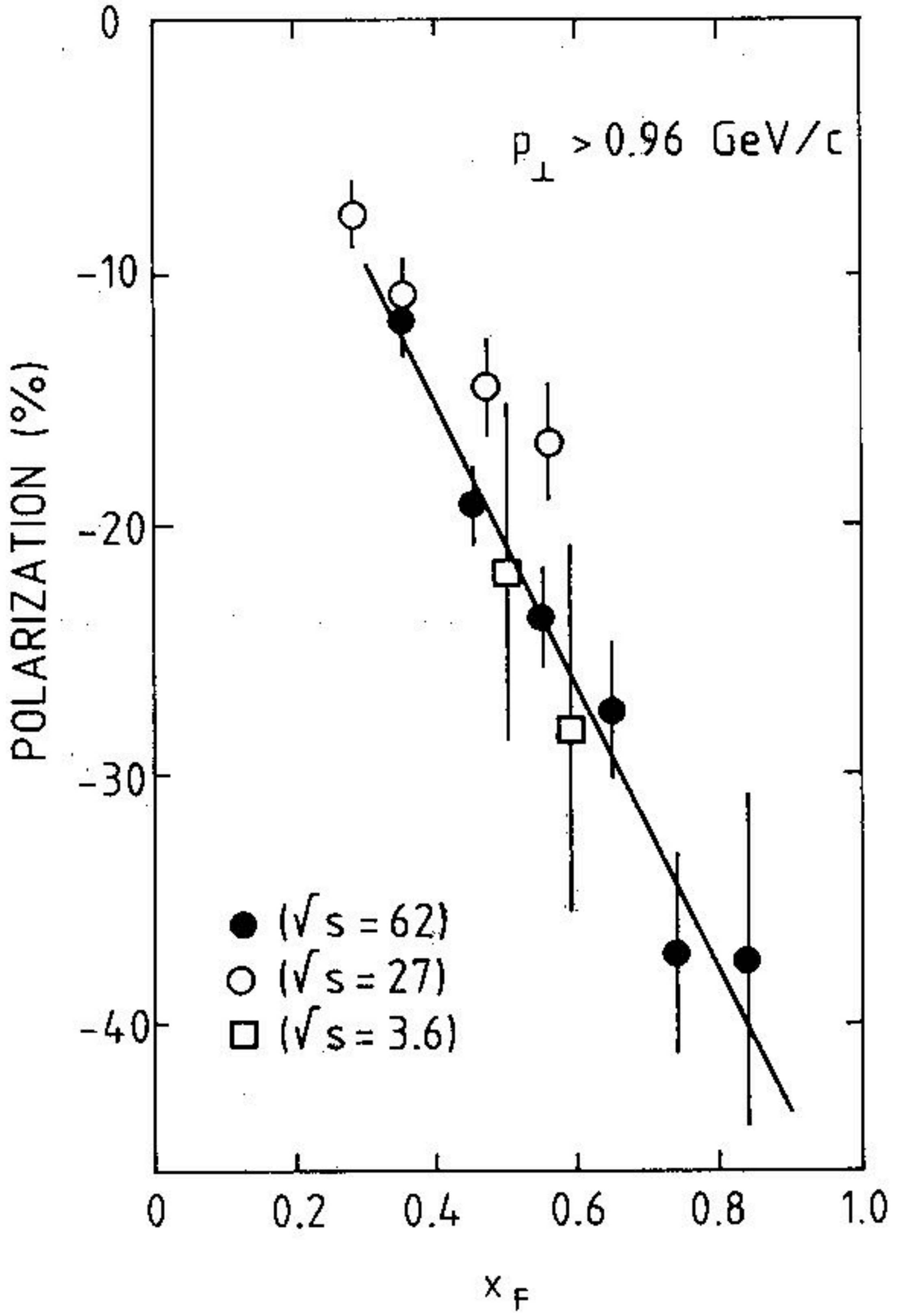
Collins asymmetries - differences w.r.t. old analysis

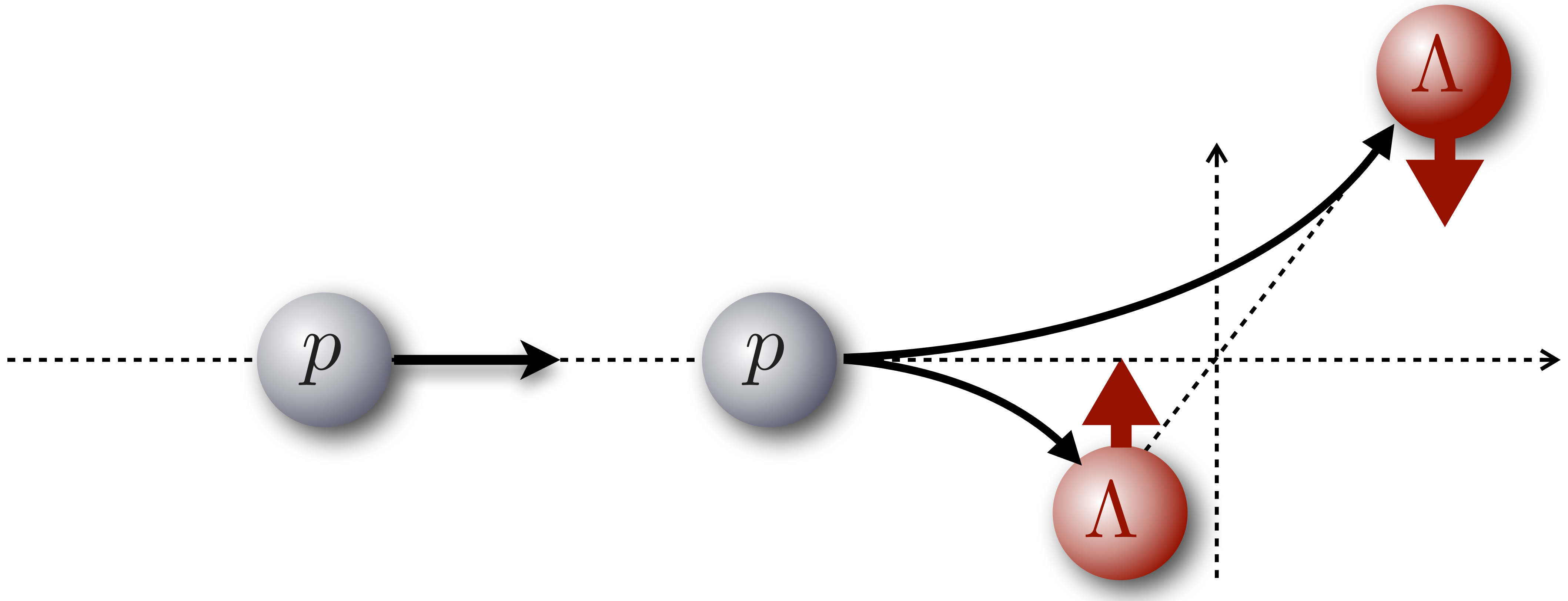
- qualitative changes in 2019 Belle analysis w.r.t. previous Belle analyses:
  - no correction to $q\bar{q}$ axis;
    ➟ rather to thrust axis, which is observable
  - upper limit on opening angle imposed
  - no correction for charm contribution;
    ➟ provide charm fraction

[PRD 100 (2019) 92008]



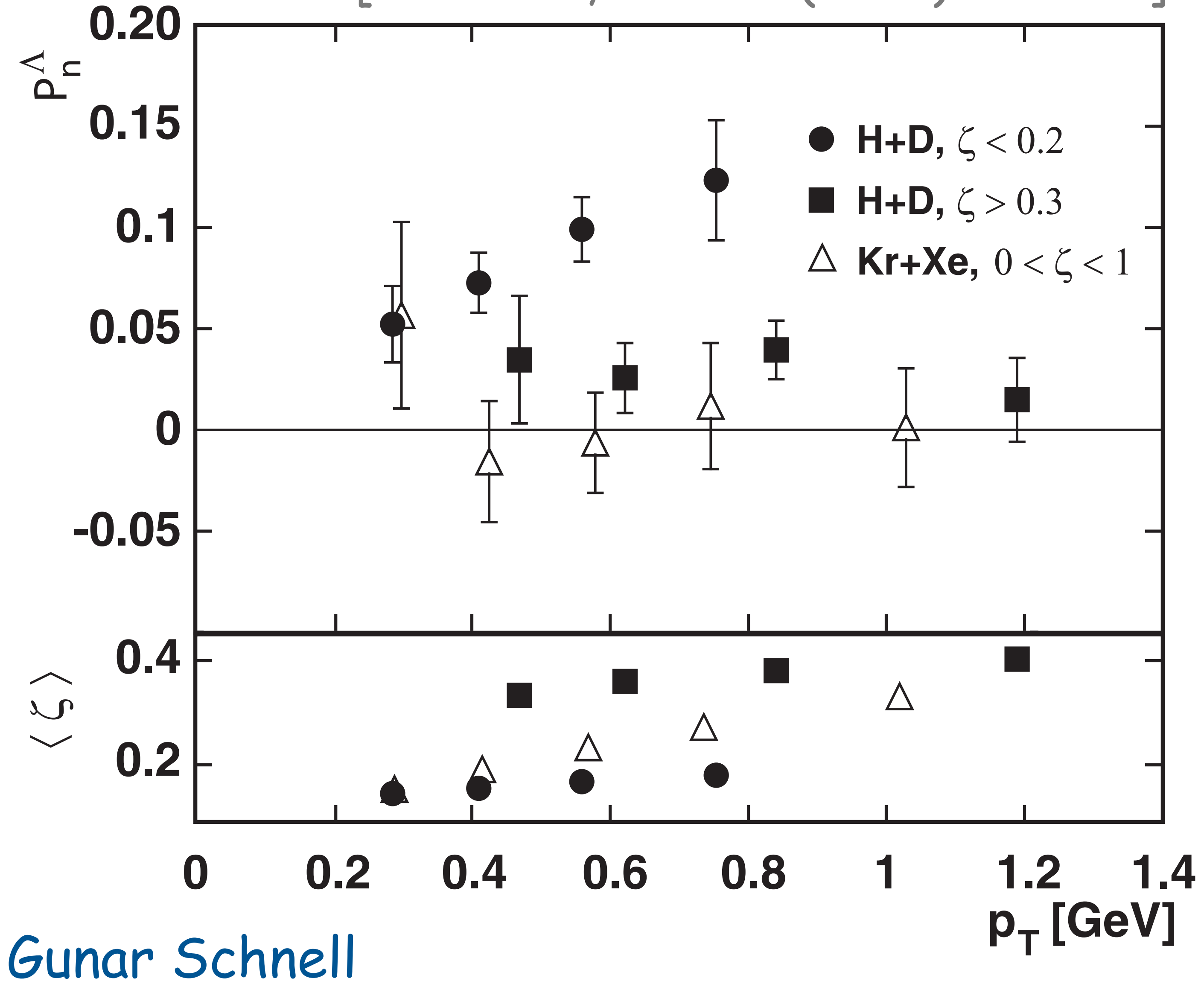
polarizing fragmentation

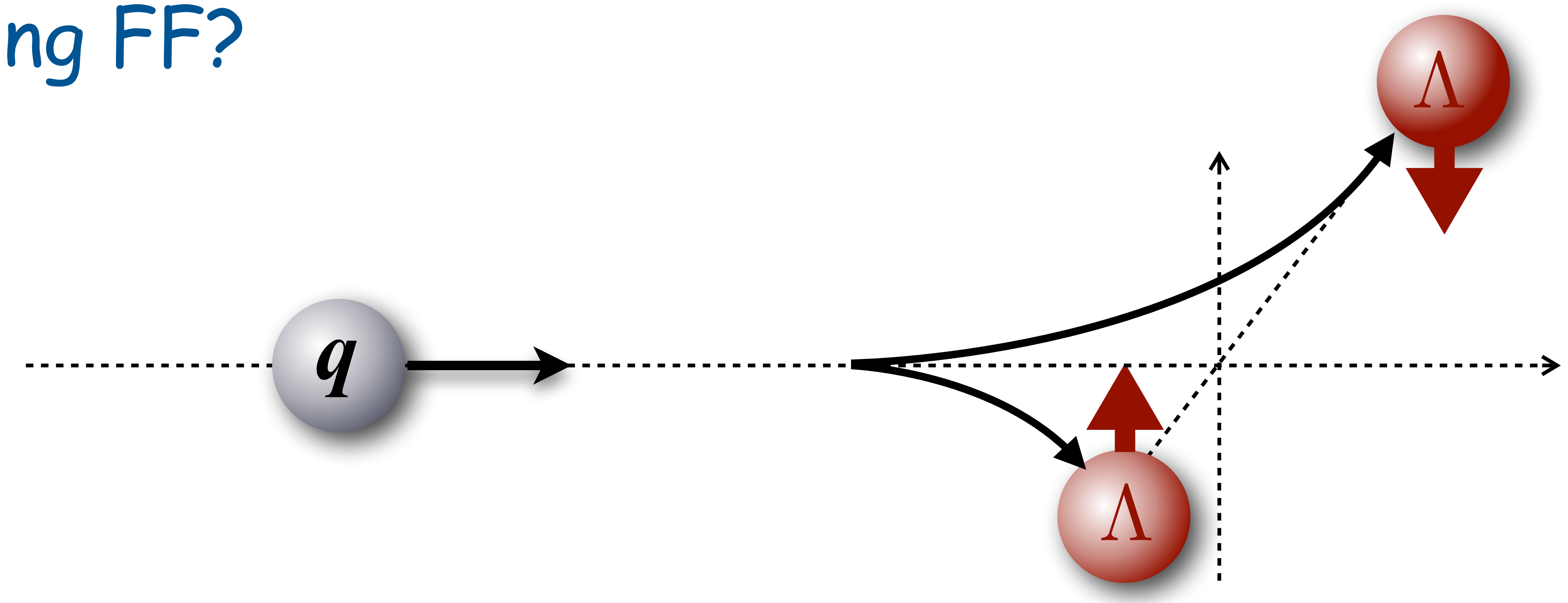




- large hyperon polarization in unpolarized hadron collision observed
- … as well as in inclusive lepto-production
- caused by polarizing FF?

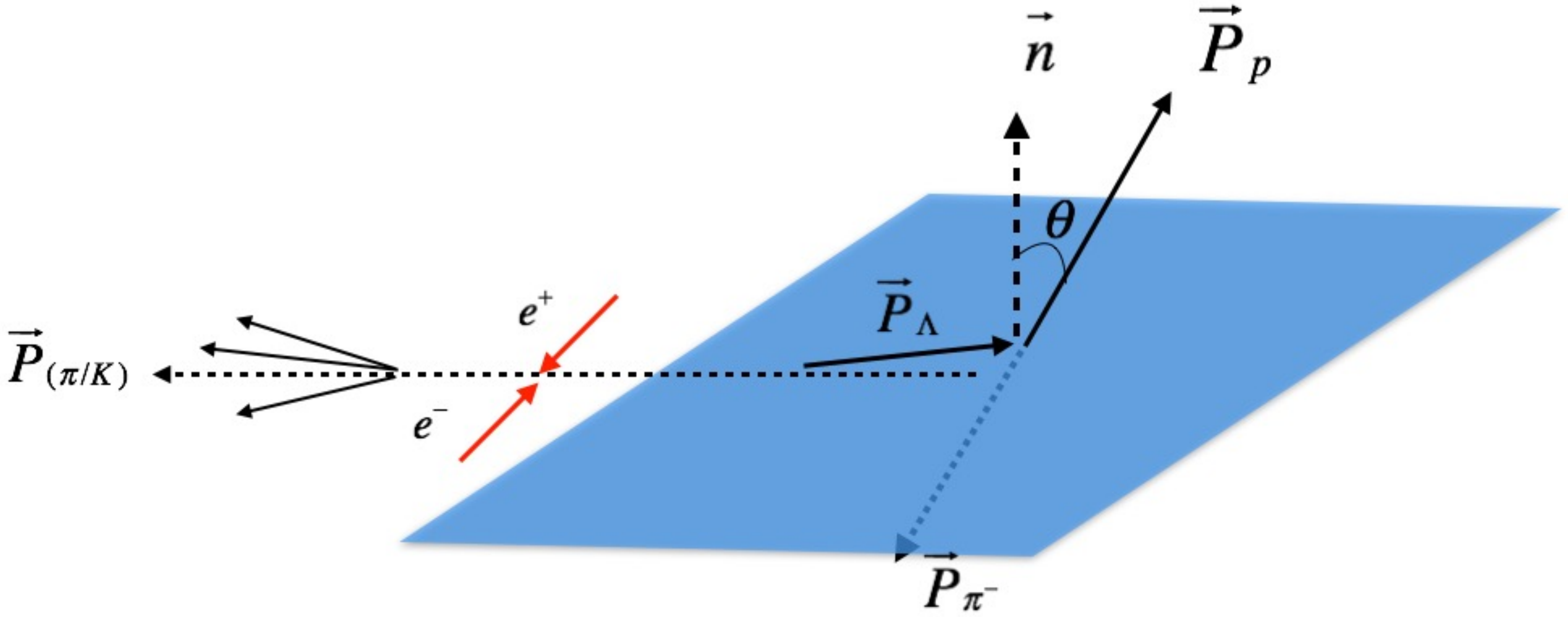
[HERMES, PRD 90 (2014) 072007]





polarizing fragmentation function

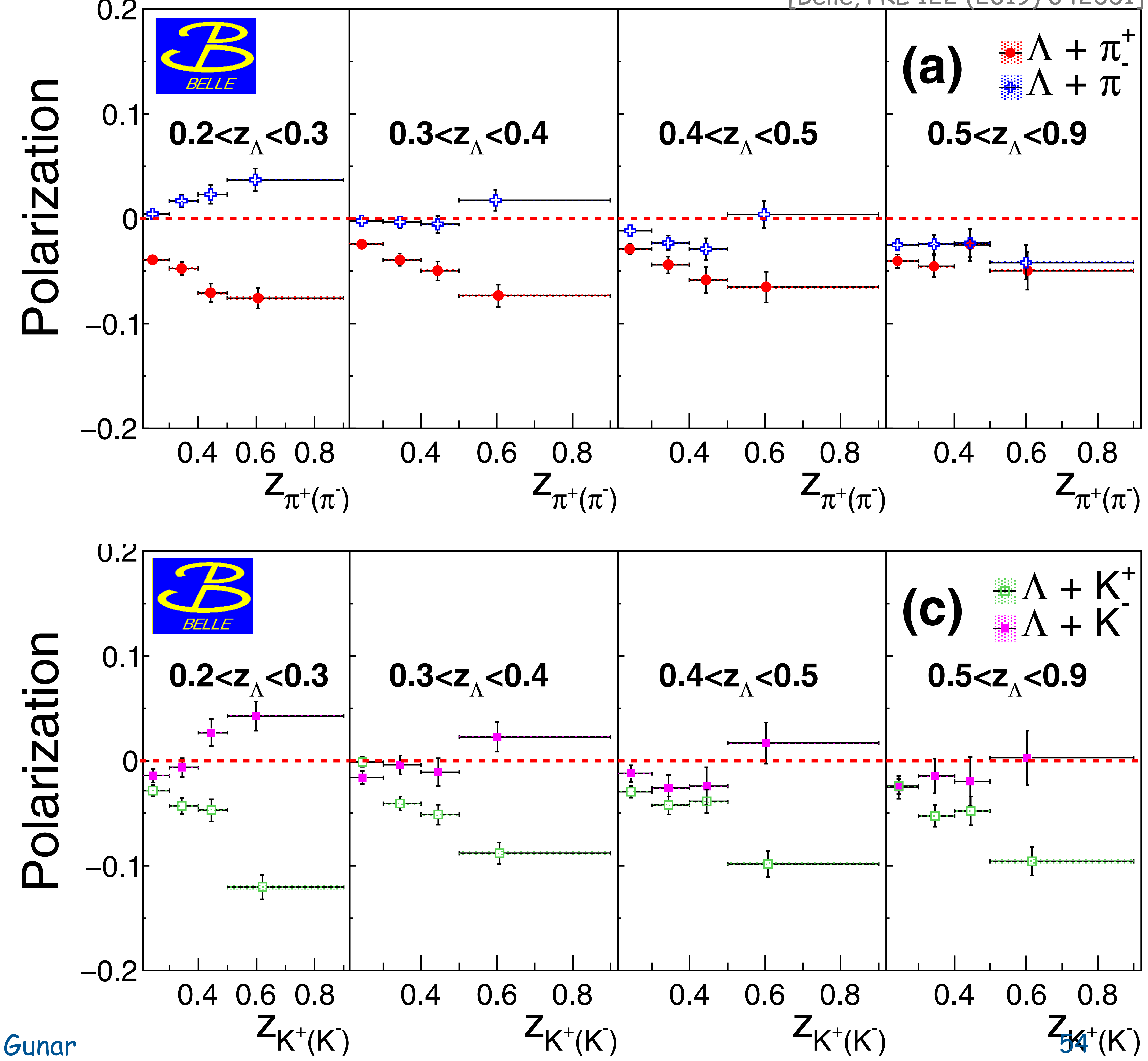
- polarization measured normal to production plane, i.e. $\propto$ ("P_q" × P_Λ)



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

polarizing fragmentation function

[Belle, PRL 122 (2019) 042001]



- flavor tagging through hadrons in opposite hemisphere:

  - large-z_h hadrons tag quark flavor more efficiently

  ➡ enlarges differences between oppositely charged hadrons

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