S_{RC}^{IDIS}@BAND

Tagged SIDIS study

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S_{RC}^{IDIS}@BAND | Executive summary

- We study SRC via $d(e, e'\pi)$ measurements tagged by a fast recoil n
- Within the Parton model terminology, data show structure modification for high-virtuality p
- The effect is large
- The effect is flavor dependent
- Nucleons in pairs are not in extreme configuration

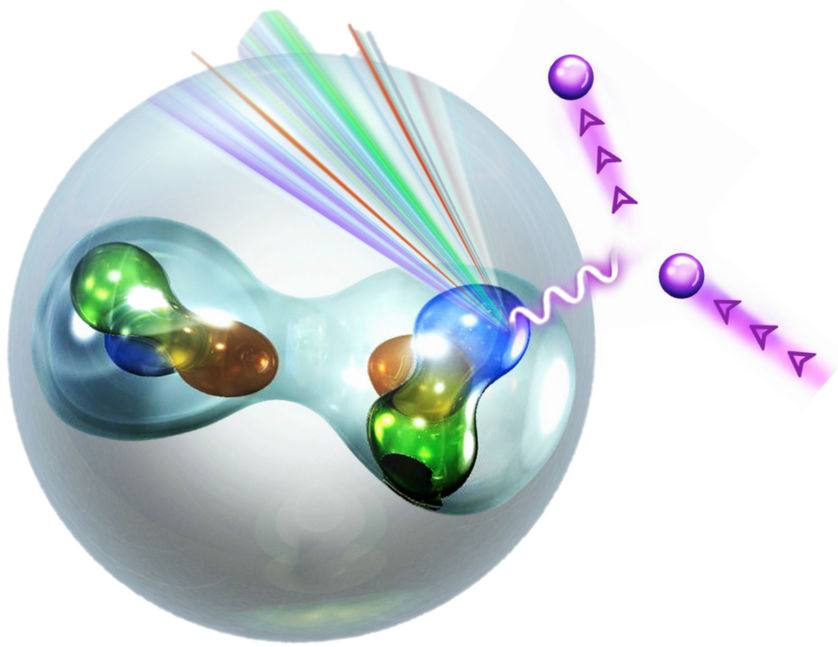
Motivation and goals

S_{RC}^{IDIS}@BAND | DIS π^+/π^- production cross-section ratio

- The u and d quark structure functions in a bound p are potentially different from these in free p

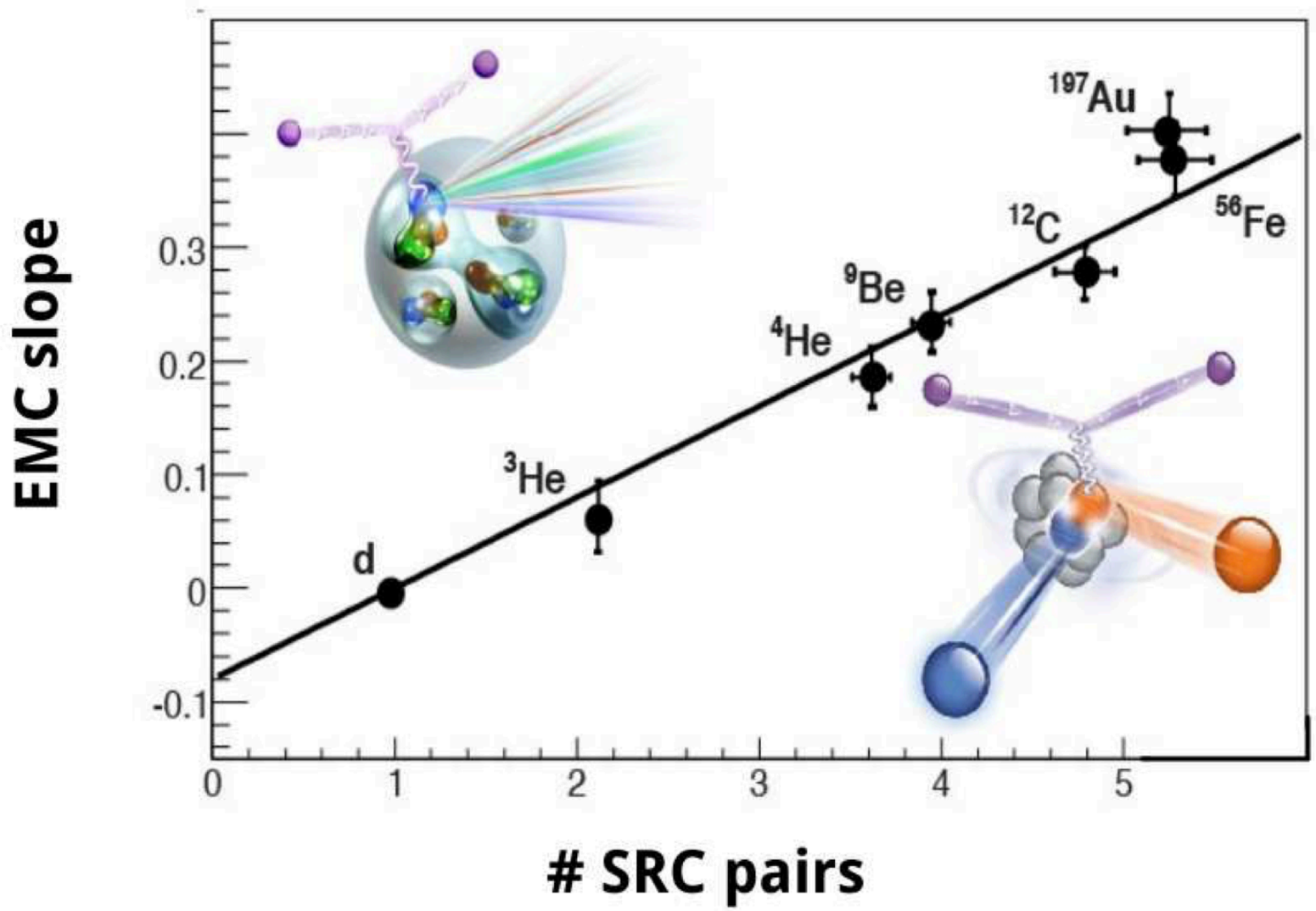
- Structure modification can be associated with u or d using π^+/π^- production cross-section ratio at high z

(π^+ is $u\bar{d}$, π^- is $d\bar{u}$)



- Some of the modification can be attributed to SRC
- We study this ratio for a "tagged *p*" from a SRC pairs

(using a deuteron with CLAS)



L. Weinstein, et al., PRL 106, 052301 (2011)
O. Hen, et al., PRC 85, 047301 (2012)
J. Arrington, et al., PRC 86, 065204 (2012)

S_{RC}^{IDIS}@BAND | Extracting the cross-section super-ratio

- This super-ratio is less sensitive to some of the experimental uncertainties:
  - *n*-detection efficiency
  - π^+/π^- detection differences

$$\frac{\left(\frac{\sigma(e,e'\pi^+)}{\sigma(e,e'\pi^-)}\right)_{n>275\ \mathrm{MeV/c}}}{\left(\frac{\sigma(e,e'\pi^+)}{\sigma(e,e'\pi^-)}\right)_{all\ events}}$$

Mainly scatter off a high-virtuality *p* in *np*-SRC

Scatter off *n* or *p* in *d*

Expectation from naive Parton model

- The Mott cross section for the scattering off a quark

ξ is $\sigma_{(e,e'\xi)} \propto q_\xi^2 f_\xi$ ← f_ξ is the quark structure function

- For a π^+ production off a p, this means

$$\sigma_p^{\pi^+}(x,z) \propto \left[4D^+(z) + D^-(z)\right]\left[u_v(x) + d_v(x)\right] + (sea\ contributions)$$

- Denote $r = D^-/D^+$ - the ratio unfavored/favored fragmentation probability, to get

$$\sigma_p^{\pi^+} \propto 4u_v + \mathit{r}d_v + (sea\ contributions)$$

$r(x, z, p_\perp) = D^-/D^+$

$D^+ \equiv D_p^{\pi^+} = D_n^{\pi^-}$ Favored fragmentation

$D^- \equiv D_p^{\pi^-} = D_n^{\pi^+}$ Unfavored fragmentation

S_{RC}^{IDIS}@BAND | What should we expect for scattering off a d?

- We assume isospin symmetry, i.e. $u_n = d_p, d_n = u_p$

- With this, we can write

$$\sigma_p^{\pi^+} \propto 4u_v + rd_v + (sea\ contributions)$$
$$\sigma_p^{\pi^-} \propto 4ru_v + d_v + (sea\ contributions)$$
$$\sigma_n^{\pi^+} \propto 4d_v + ru_v + (sea\ contributions)$$
$$\sigma_n^{\pi^-} \propto 4rd_v + u_v + (sea\ contributions)$$

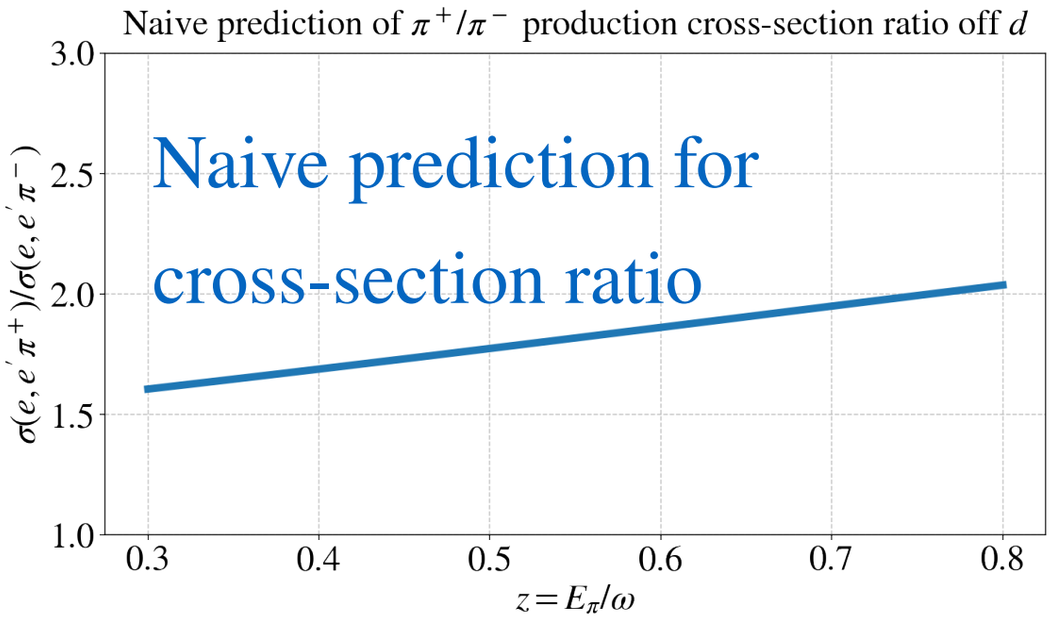
- For $d = p + n$,

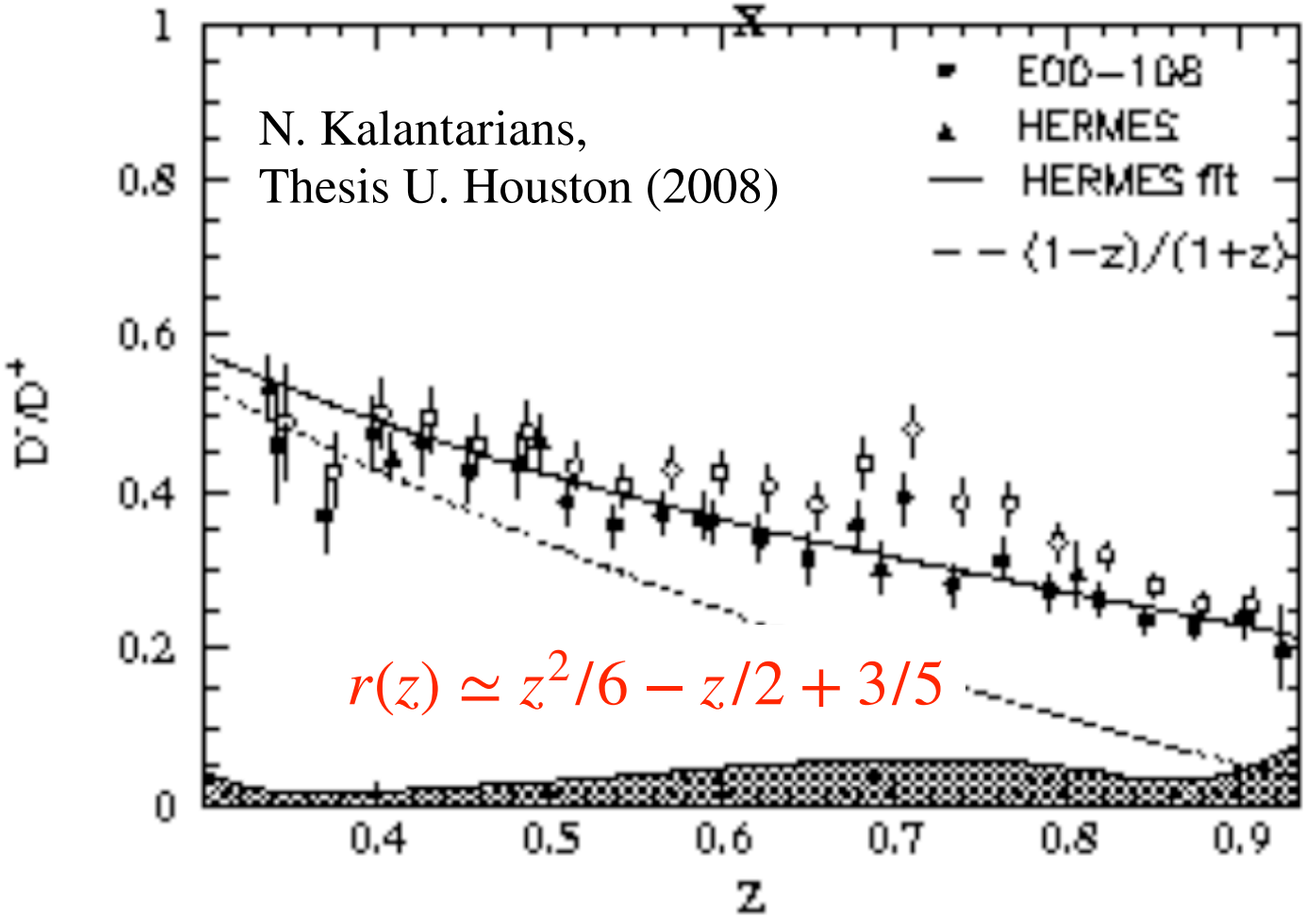
$$\sigma_d^{\pi^+} = \sigma_p^{\pi^+} + \sigma_n^{\pi^+} \sim (4 + r)(u_v + d_v) + (sea\ contributions)$$
$$\sigma_d^{\pi^-} = \sigma_p^{\pi^-} + \sigma_n^{\pi^-} \sim (4r + 1)(d_v + u_v) + (sea\ contributions)$$

- Neglecting sea contributions, the π^+/π^- cross-section ratio gets a simple form

$$\sigma_d^{\pi^+}/\sigma_d^{\pi^-} \sim \frac{4+r}{4r+1}$$

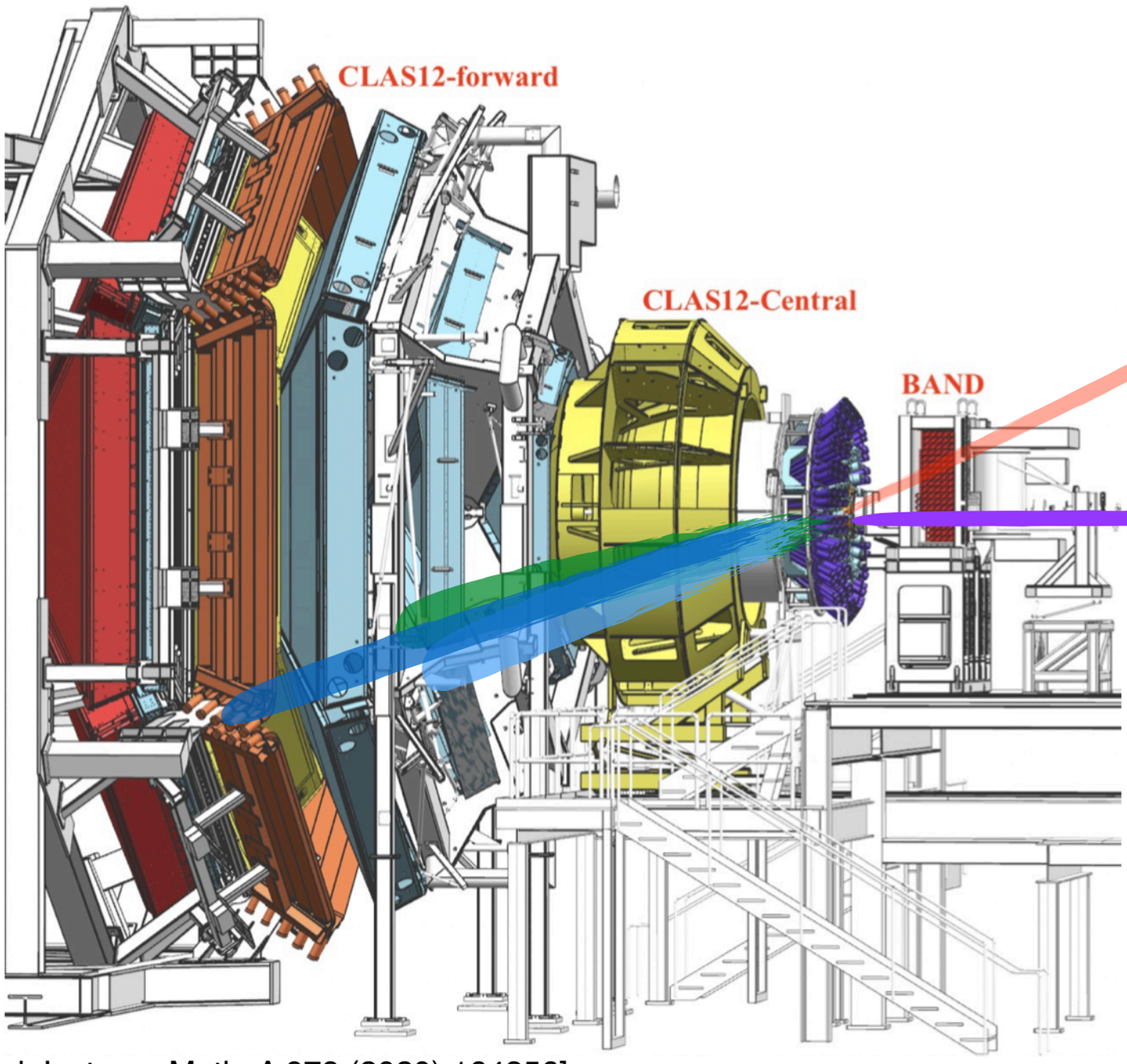
- r was measured e.g. at HERMES

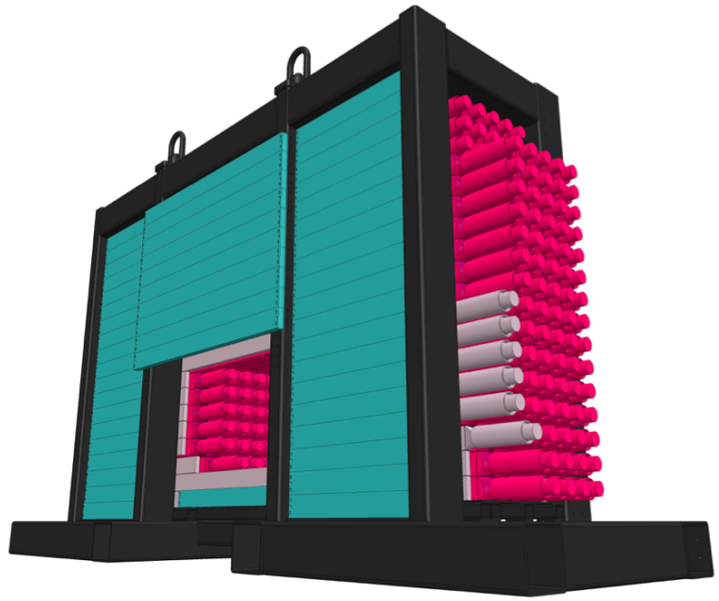




BAND Data

- BAND is a dedicated detector to tag SRC events with a backward recoiling neutron





n

e

[Nucl. Instrum. Meth. A 978 (2020) 164356]

S_{RC}^{IDIS}@BAND | $(e, e'\pi^+ n)/(e, e'\pi^- n)$ ratio study methods

Requirement: $(e, e'\pi)$ events with a fast neutron recoiling to BAND

Option 1

RGB "SIDIS" skimming

RGA skimming method

+

neutron from BAND

Option 2

Pion information

+

recoil-neutron data

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Work in progress: The focus of this talk

Option 2

Pion information

+

recoil-neutron data

S_{RC}^{IDIS}@BAND | Event selection criteria - untagged SIDIS

e and π Particle ID

e and π fiducial cuts (PCAL, DC)

Calorimetry energy deposition

$5^\circ < \theta_e\,, \theta_\pi < 35^\circ$

$|v_z^e - v_z^\pi| < 20$ cm (to be tightened)

$1.25 < p_\pi < 5.0$ GeV/c (π/K separation)

$0.3 < z < 1.0$

π^+/π^- acceptance matching in $p - \theta$ plane

3 GeV/c $< p_e < p_{\text{beam}}$

2.5 GeV $< M_x(e, e'\pi)$

DIS

2 (GeV/c)$^2 < Q^2 <$ 10 (GeV/c)^2

2.5 (GeV/c)$^2 < W$

$y = \dfrac{\omega}{E_{beam}} < 0.75$ (avoid QE)

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Approved PID developed by RGA SIDIS group

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$3\ \mathrm{GeV/c} < p_e < p_{\mathrm{beam}}$

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"Cleaning" the event-sample

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Neutrons in BAND

- "Good - n" cluster algorithm
- Fiducial cuts
- 5 MeV $< \Delta E_{dep}$
- Cut on top TOF bars in BAND
- 0.275 GeV/c $< p_n$

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BAND analysis

Neutrons in BAND

- "Good - n" cluster algorithm
- Fiducial cuts
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- 0.275 GeV/c $< p_n$

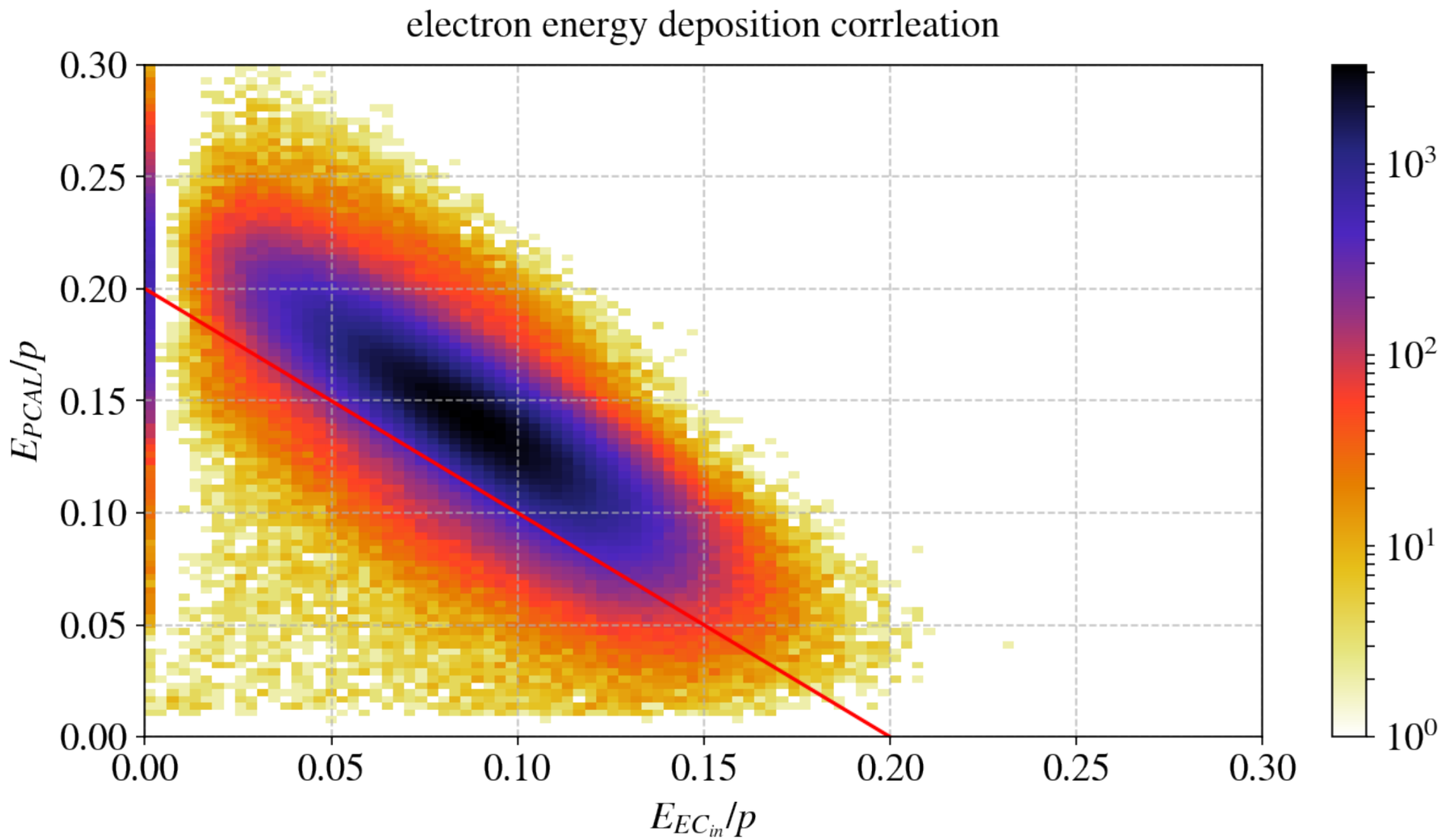
S_{RC}^{IDIS}@BAND | Example: *e*-PID "refinement"

- PCAL minimal energy deposit

$$E_{PCAL} > 0.07 \text{ GeV}$$

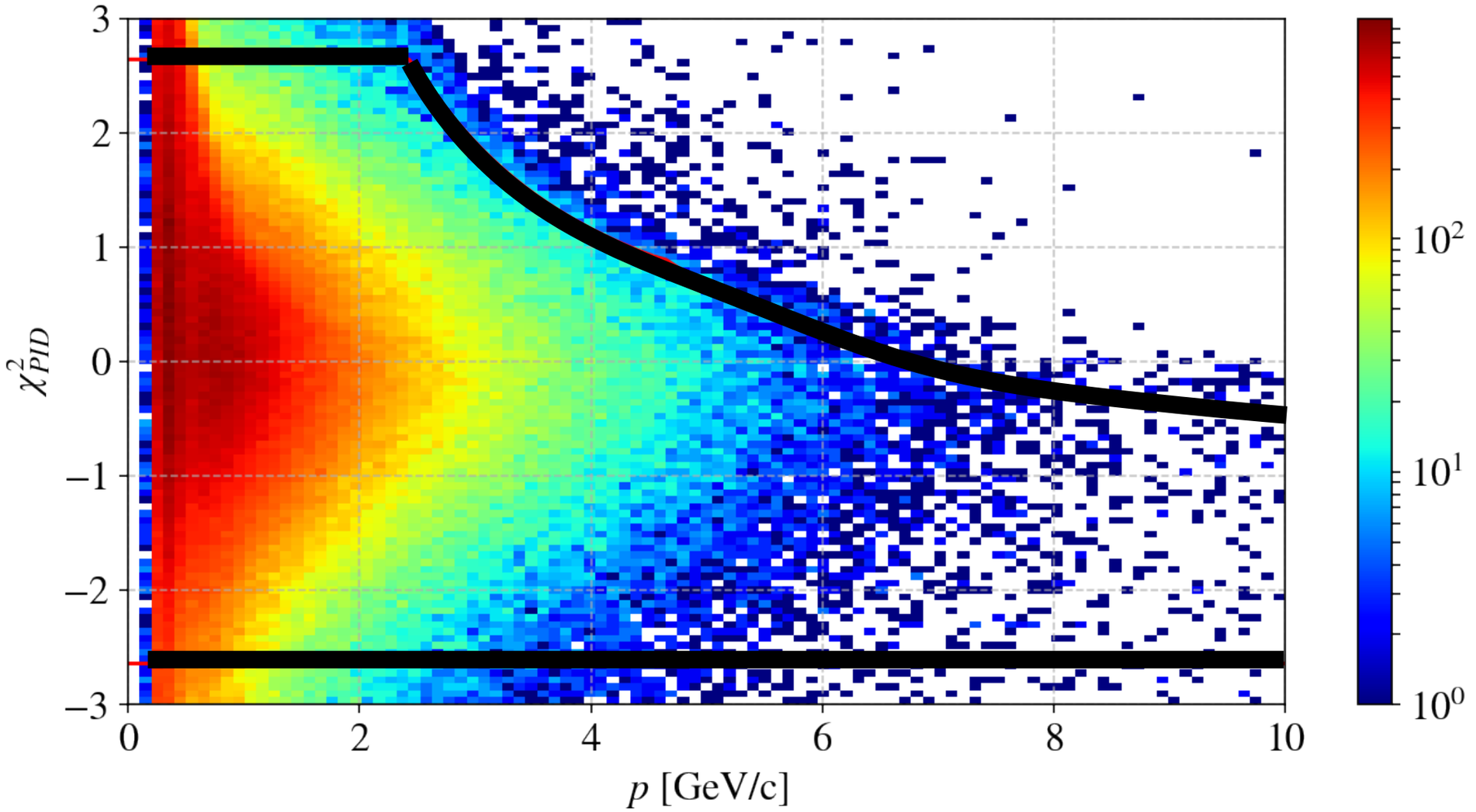
- Sampling fraction cut

$$\frac{E_{PCAL} + E_{EC}^{in} + E_{EC}^{out}}{p} > 0.17\frac{E_{EC}^{in}}{p} > 0.2 - \frac{E_{PCAL}}{p}$$



[Diehl & Joo, "A …study of SIDIS…" v. 4 Dec-1,2020]

S_{RC}^{IDIS}@BAND | Example: π-PID "refinement"



$$-3C < \chi^2_\pi < 3C \qquad p < 2.44 \text{ GeV}$$

$$-3C < \chi^2_\pi < C(0.0869 - 14.98587e^{-p/1.18236} + 1.811751e^{-p/4.86394}) \qquad 2.44 < p < 4.6 \text{ GeV}$$

$$-3C < \chi^2_\pi < C(-1.14099 + 24.14992e^{-p/1.36554} + 2.66876e^{-p/6.80552}) \qquad 4.6 \text{ GeV} < p$$

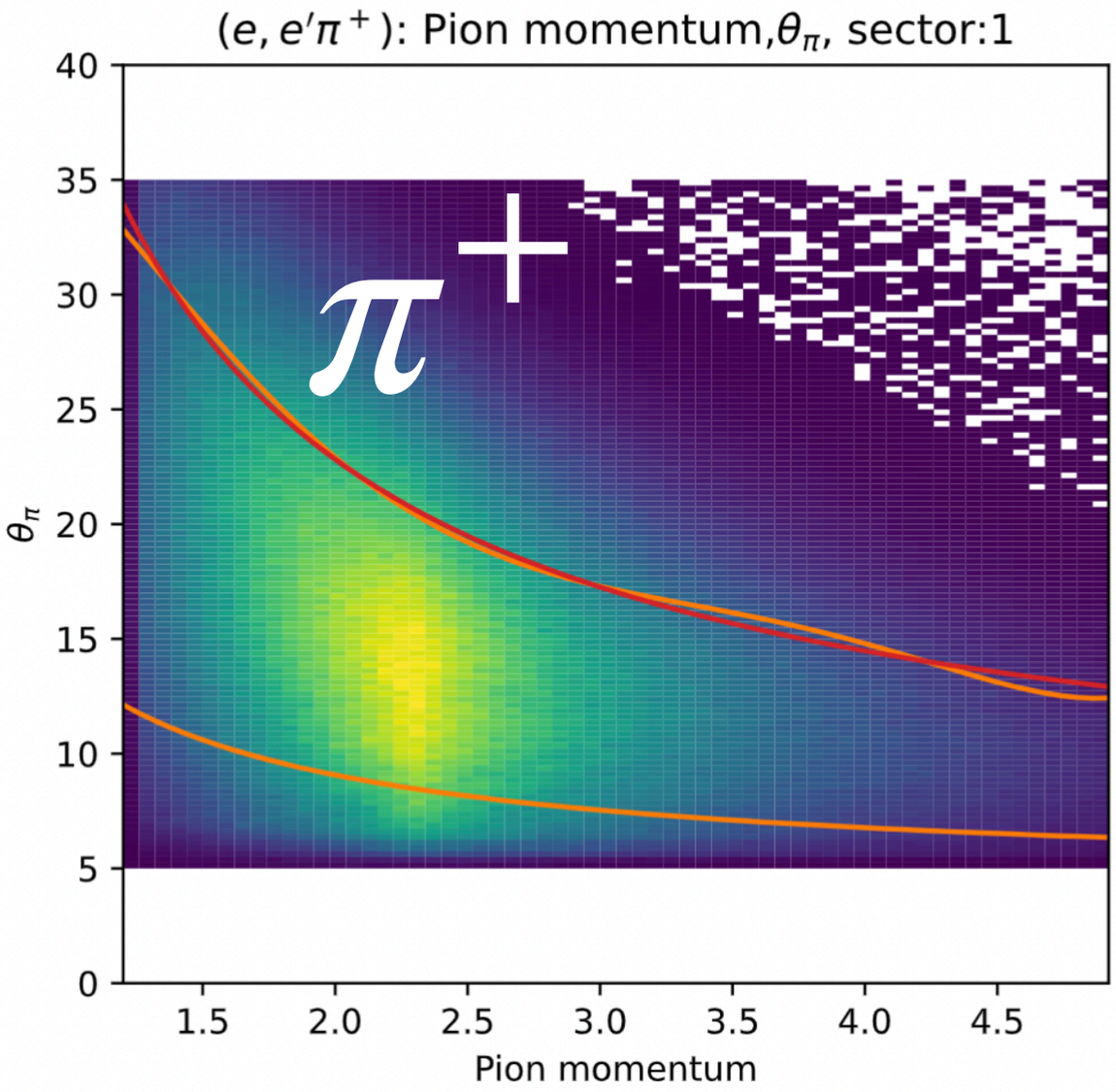
[Diehl & Joo, "A …study of SIDIS…" v. 4 Dec-1,2020]

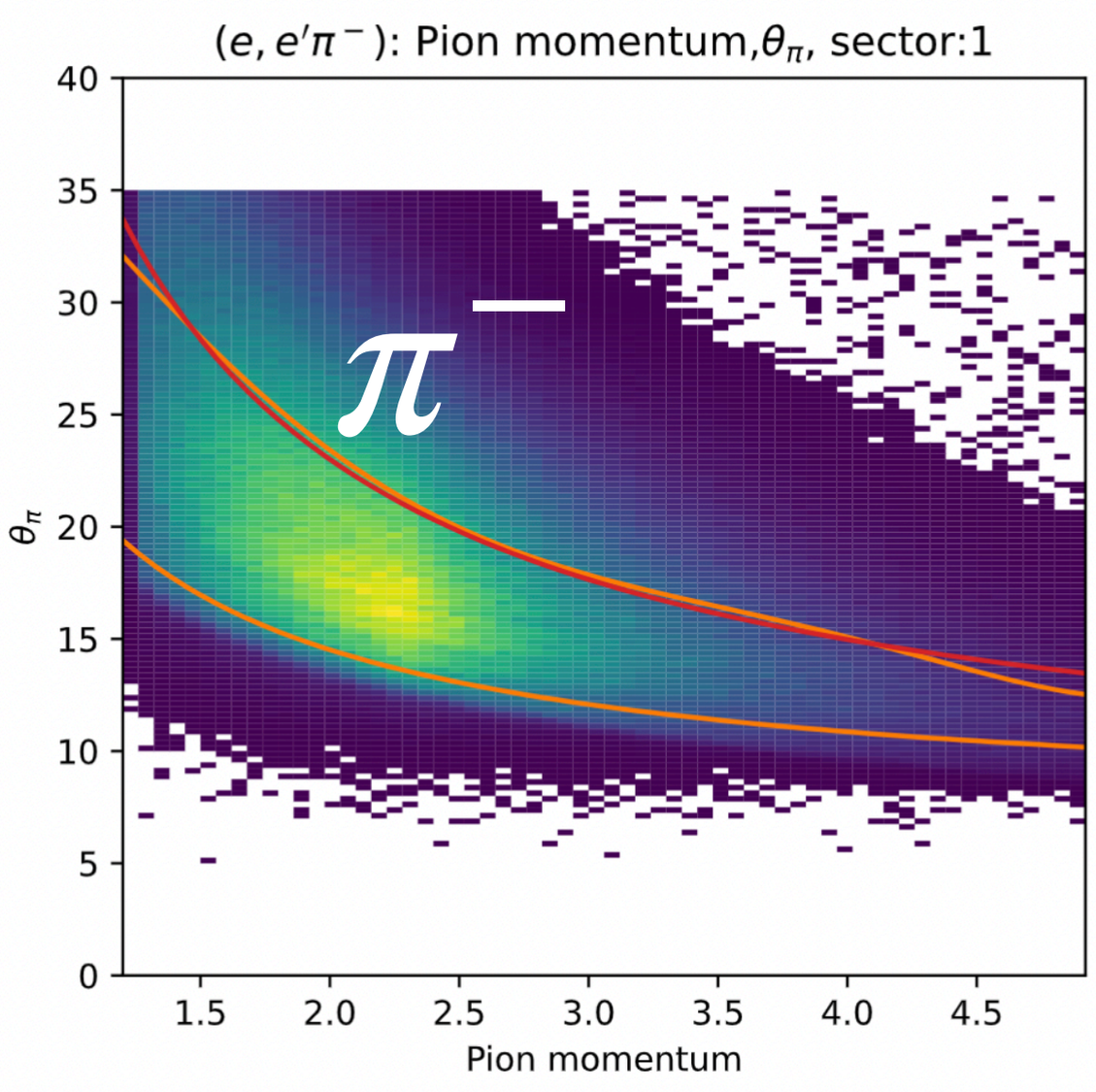
[Avakian, Baltzell et al., "CLAS RG-A - Analysis note… " v. 3 Nov-4,2020]

$C(\pi^+) = 0.88,\ C(\pi^-) = 0.93$

S_{RC}^{IDIS}@BAND | Example: π^+ and π^- acceptance matching

π^+/π^- acceptance matching/correction is in principle a multidimensional function depending on the momenta and angles of the pion and the electron.





$$\frac{\sigma(e, e'\pi^+ n)}{\sigma(e, e'\pi^- n)}$$

2.8k events

0.9k events

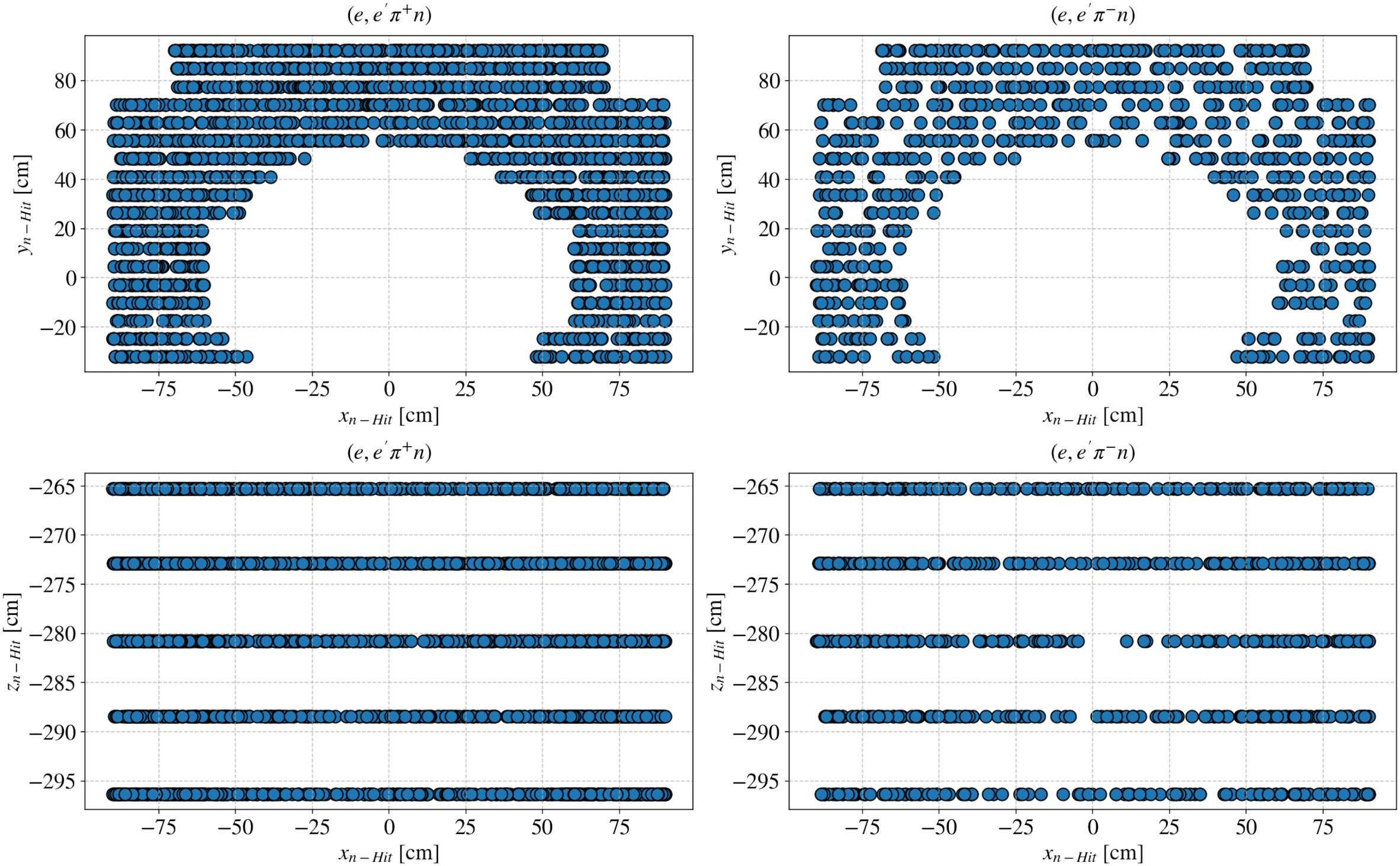
$$\frac{\sigma(e, e'\pi^+)}{\sigma(e, e'\pi^-)}$$

21.3M events

12.7M events

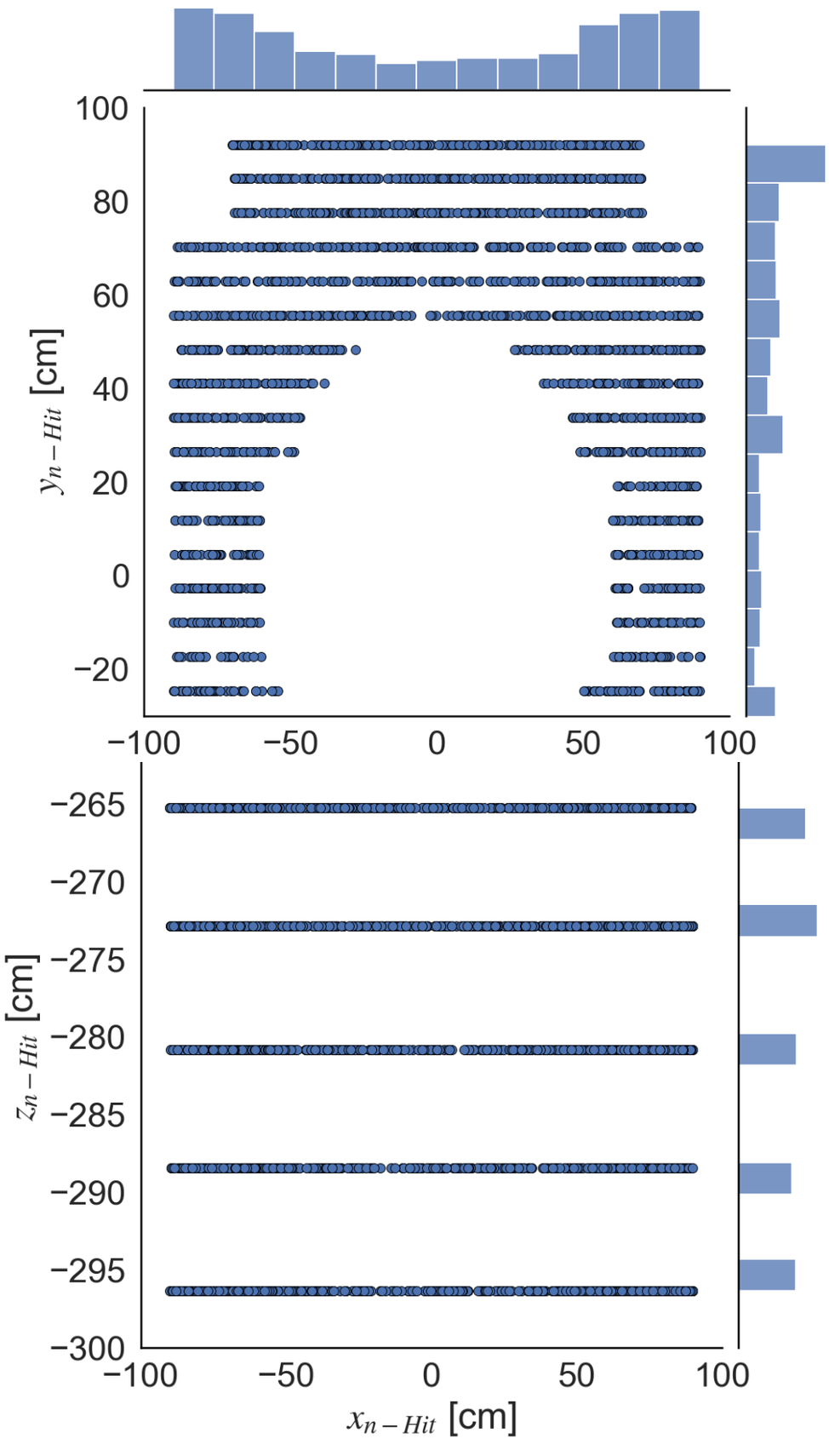
RGB + BAND: 10.2 GeV all data

S_{RC}^{IDIS}@BAND | Neutron hit position in BAND

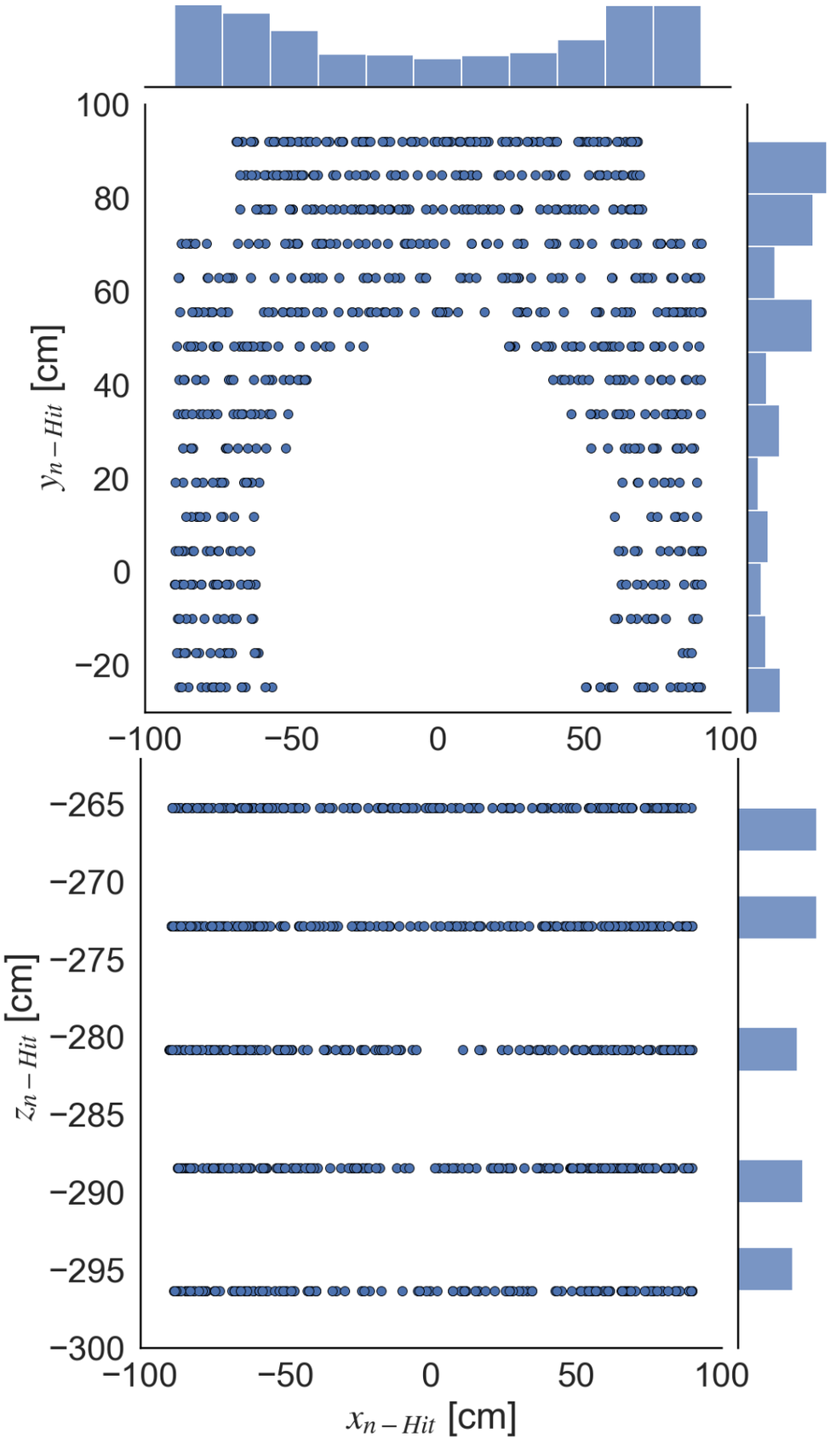


RGB + BAND: 10.2 GeV all data (Does not include 10.4 and 10.6 data)

$(e, e'\pi^+ n)$


100
80
60
40
20
0
−20
y_{n-Hit} [cm]
−100
−50
0
50
100
−265
−270
−275
−280
−285
−290
−295
−300
z_{n-Hit} [cm]
x_{n-Hit} [cm]

$(e, e'\pi^- n)$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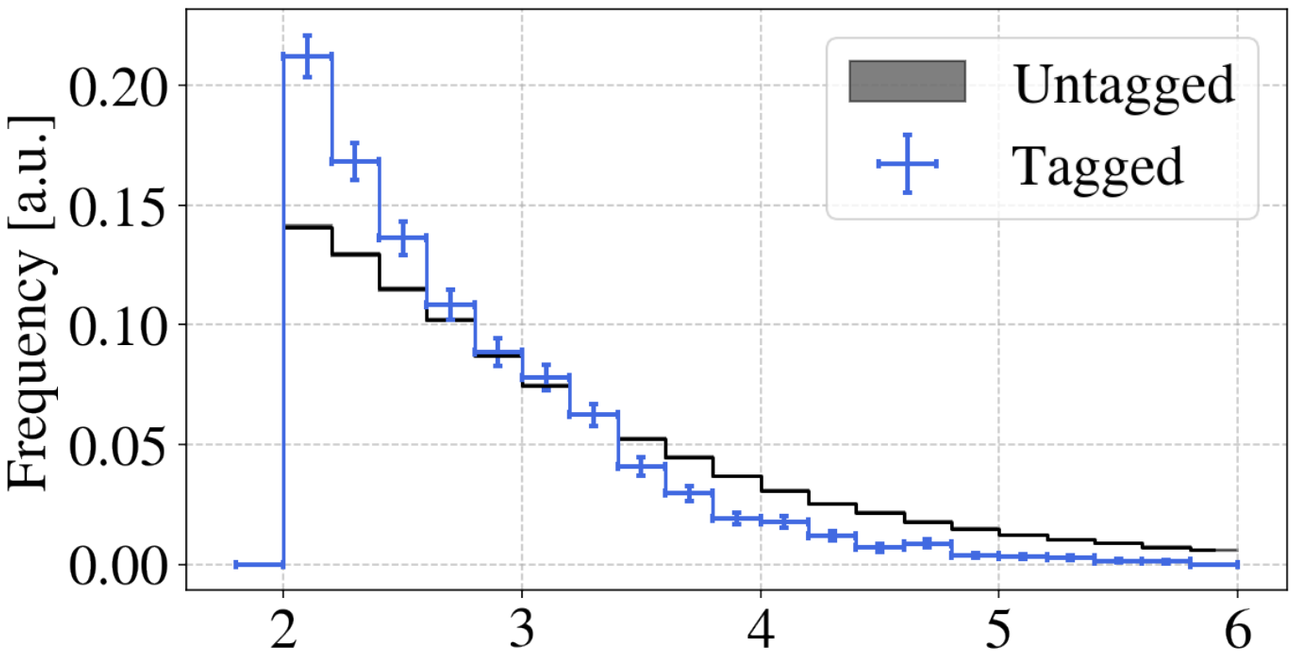
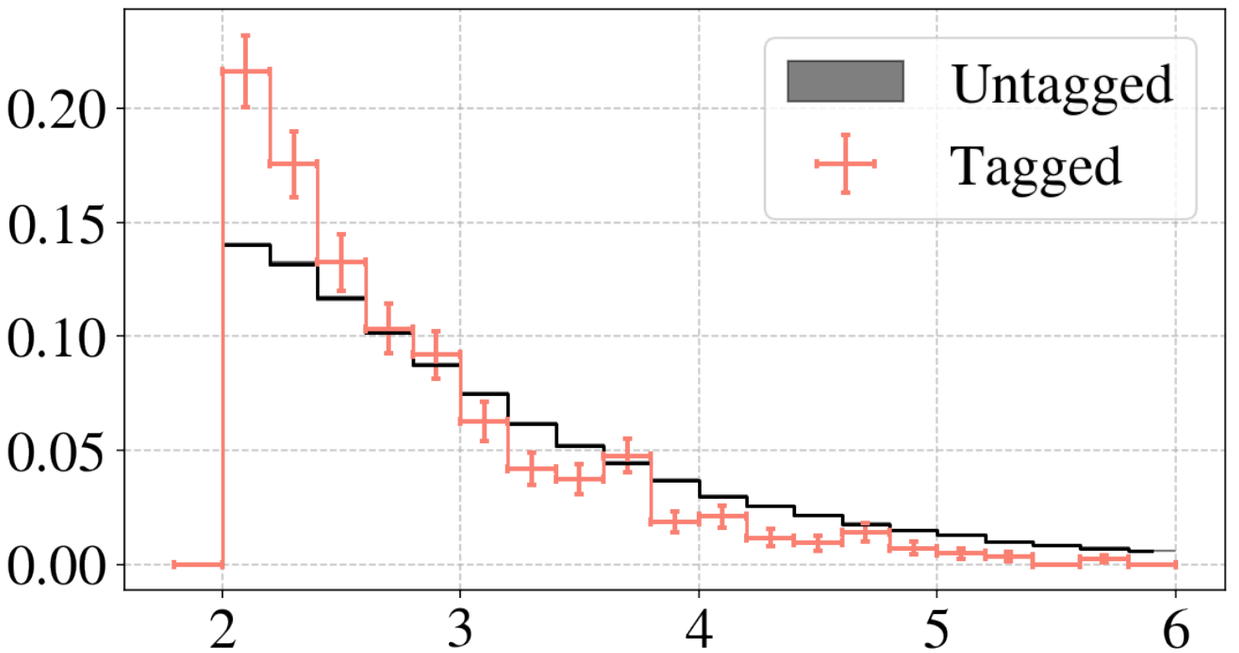
Kinematics

S_{RC}^{IDIS}@BAND | Kinematical distributions - momentum transfer

$(e, e'\pi^+)$ events as a function of Q^2

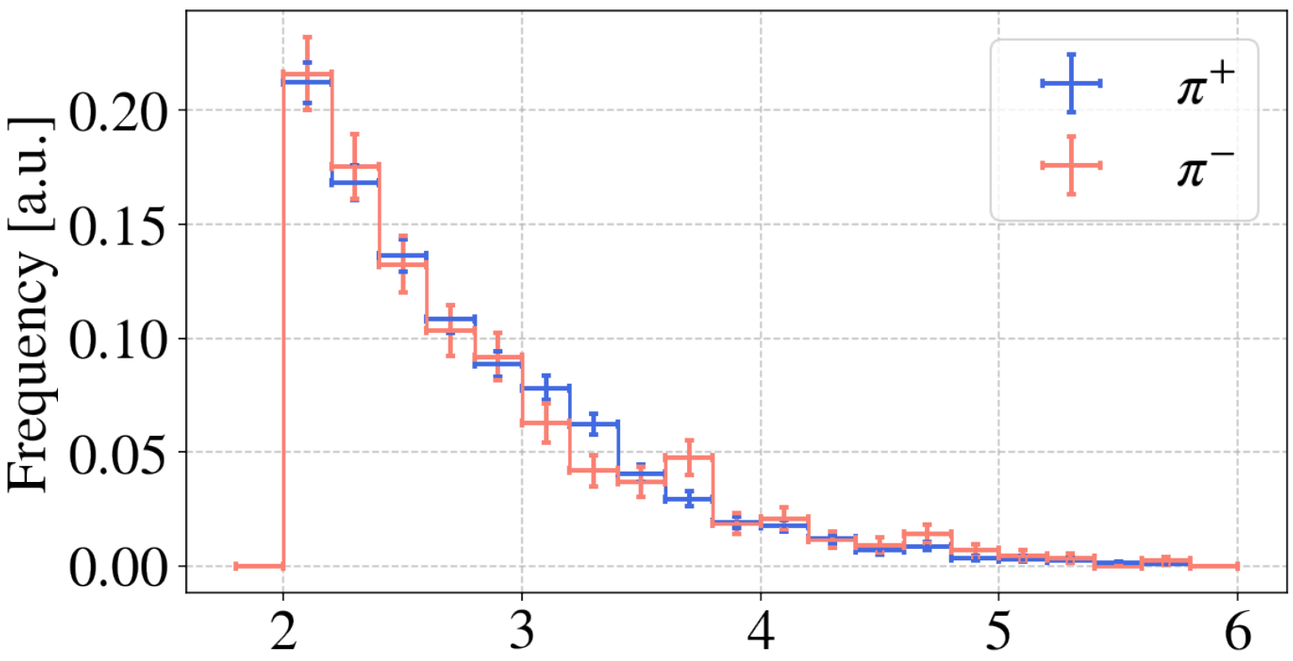


$(e, e'\pi^-)$ events as a function of Q^2



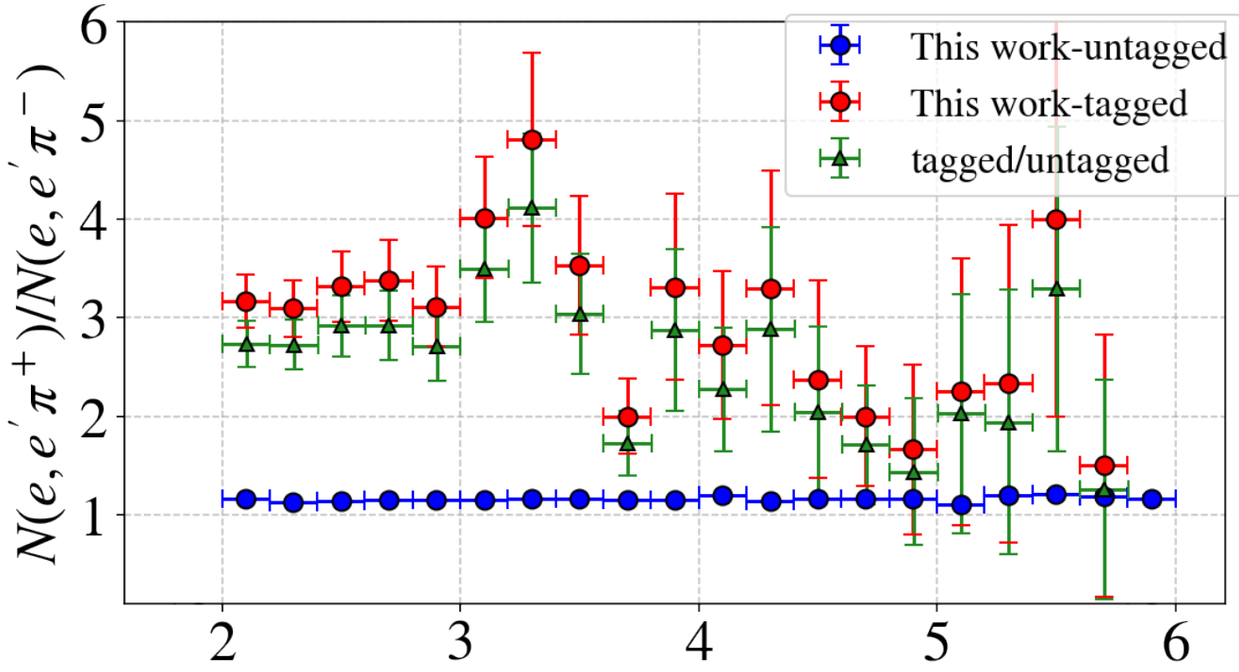
$Q^2[(\mathrm{GeV/c})^2]$

Tagged events: $\pi^{\pm}$ comparison



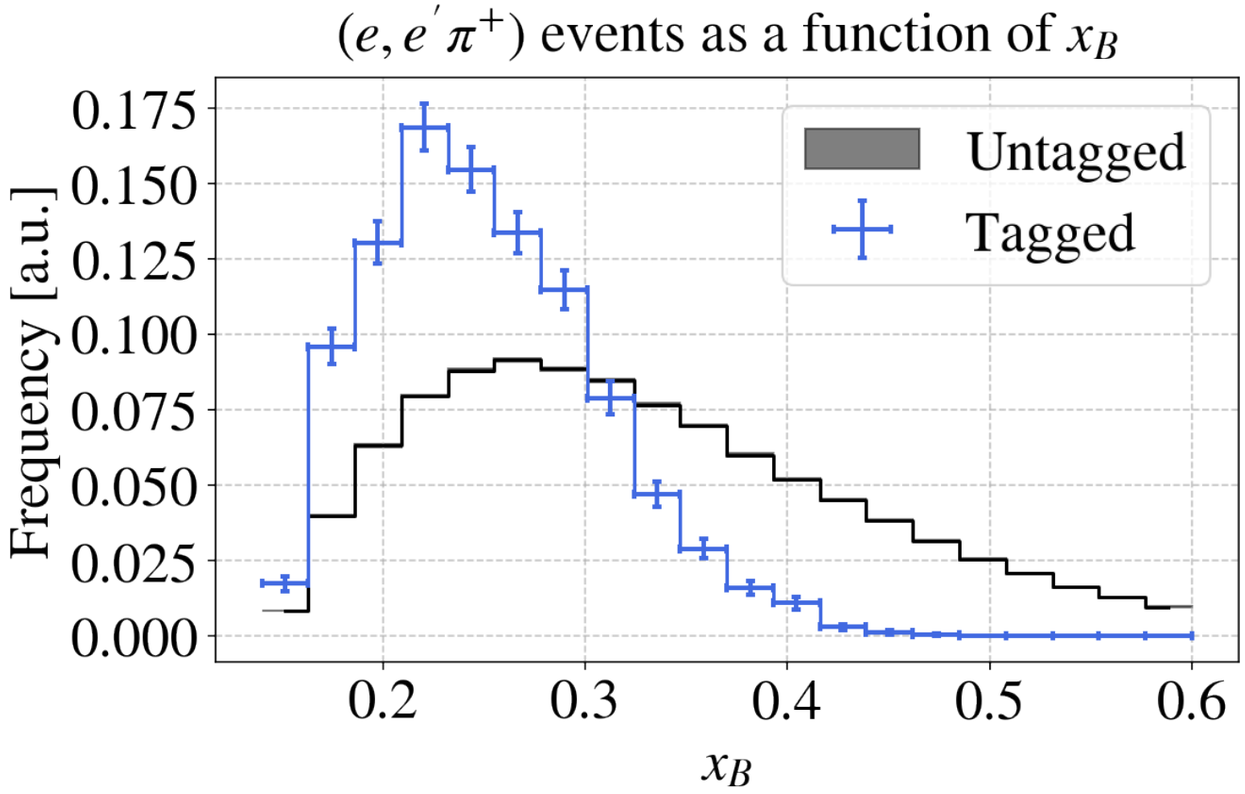
$Q^2[(\mathrm{GeV/c})^2]$

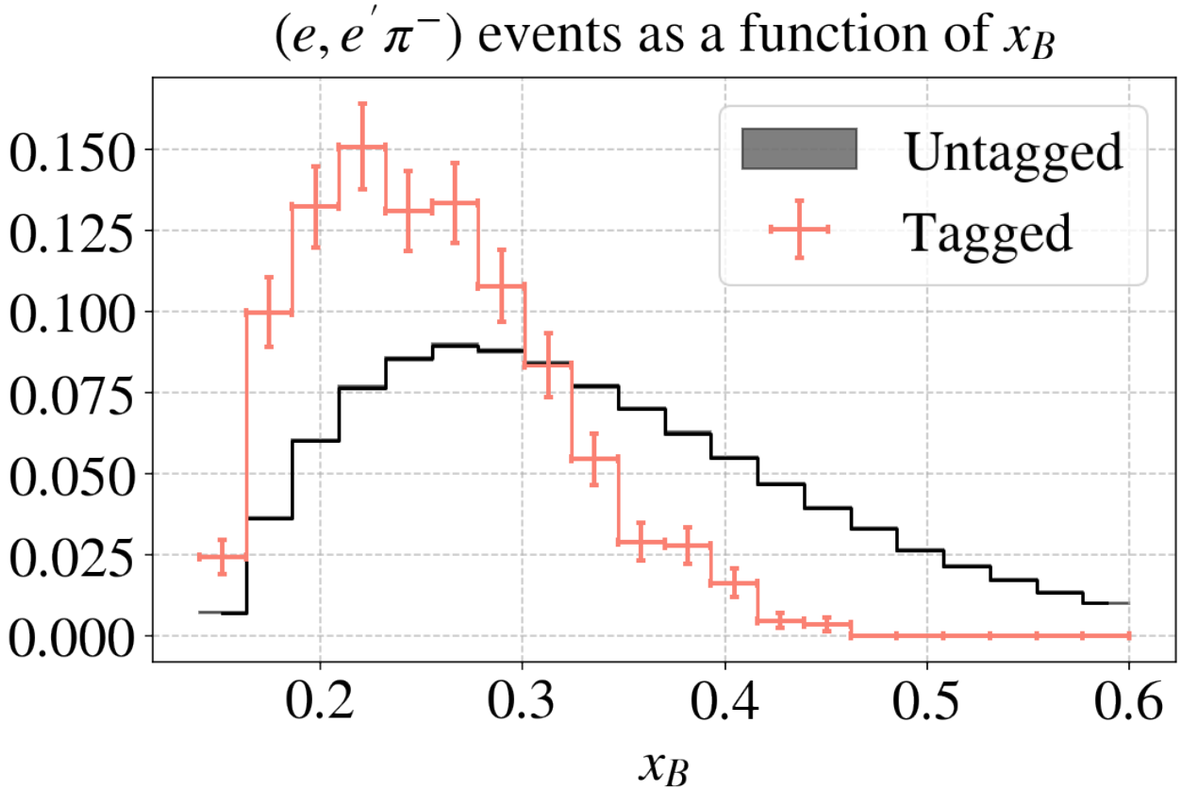
Cross-section ratio π^+/π^-

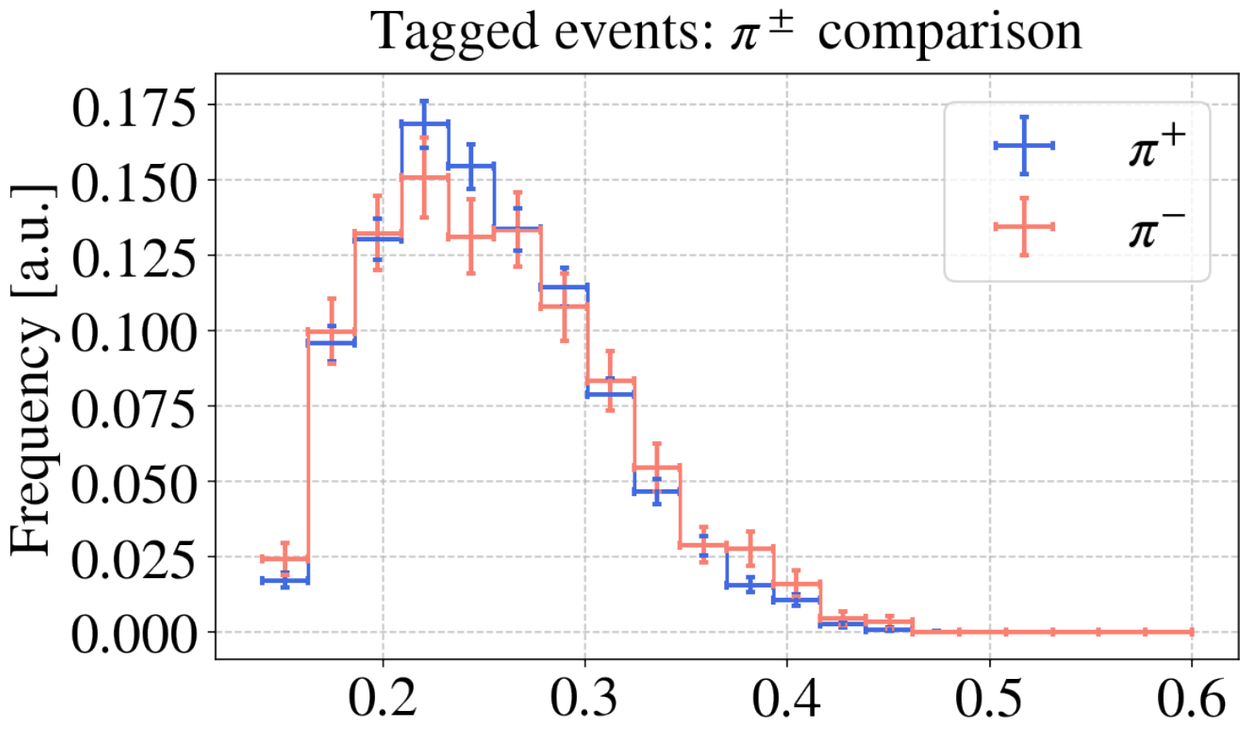


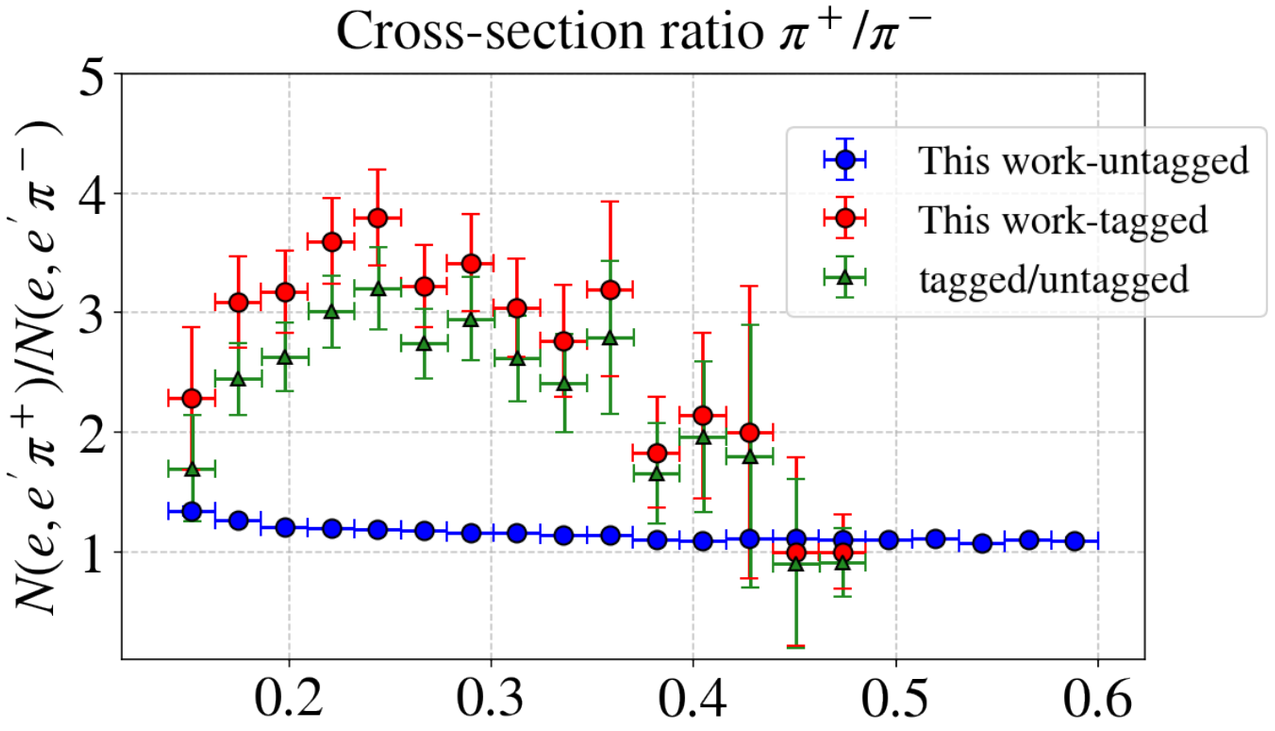
RGB + BAND: 10.2 GeV all data

S_{RC}^{IDIS}@BAND | Kinematical distributions - Bjorken scaling





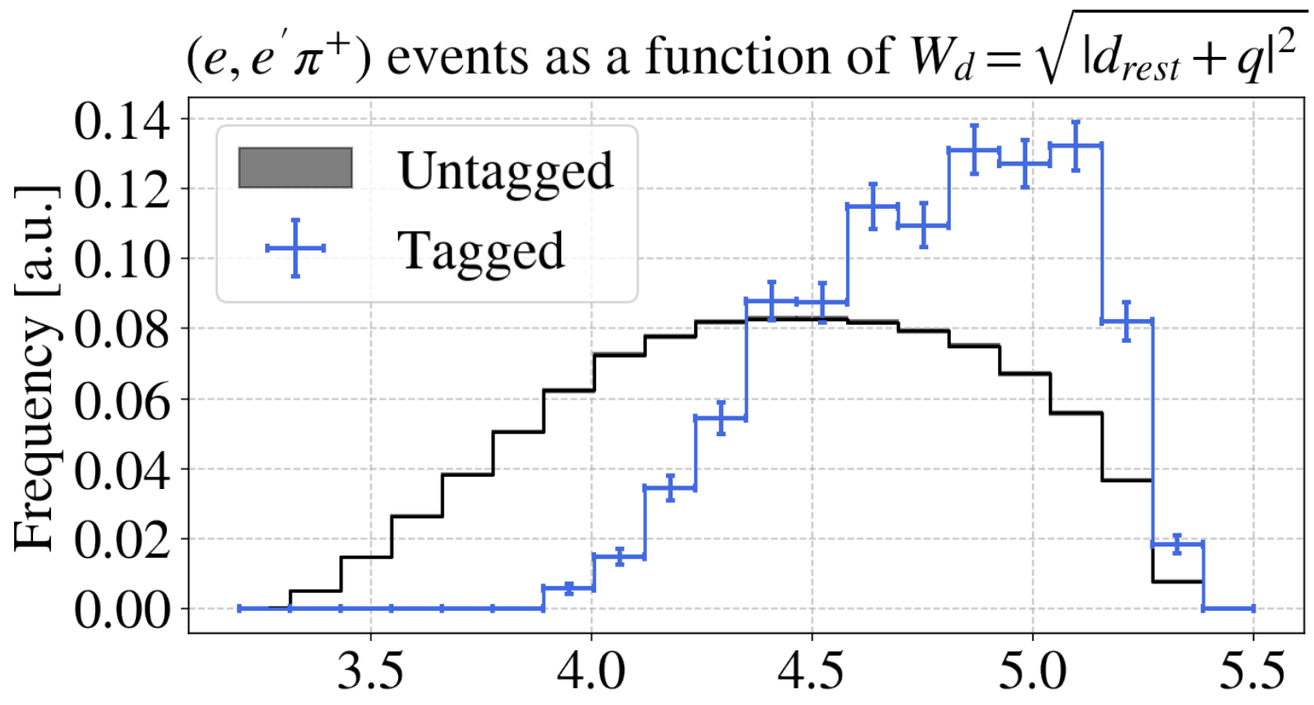


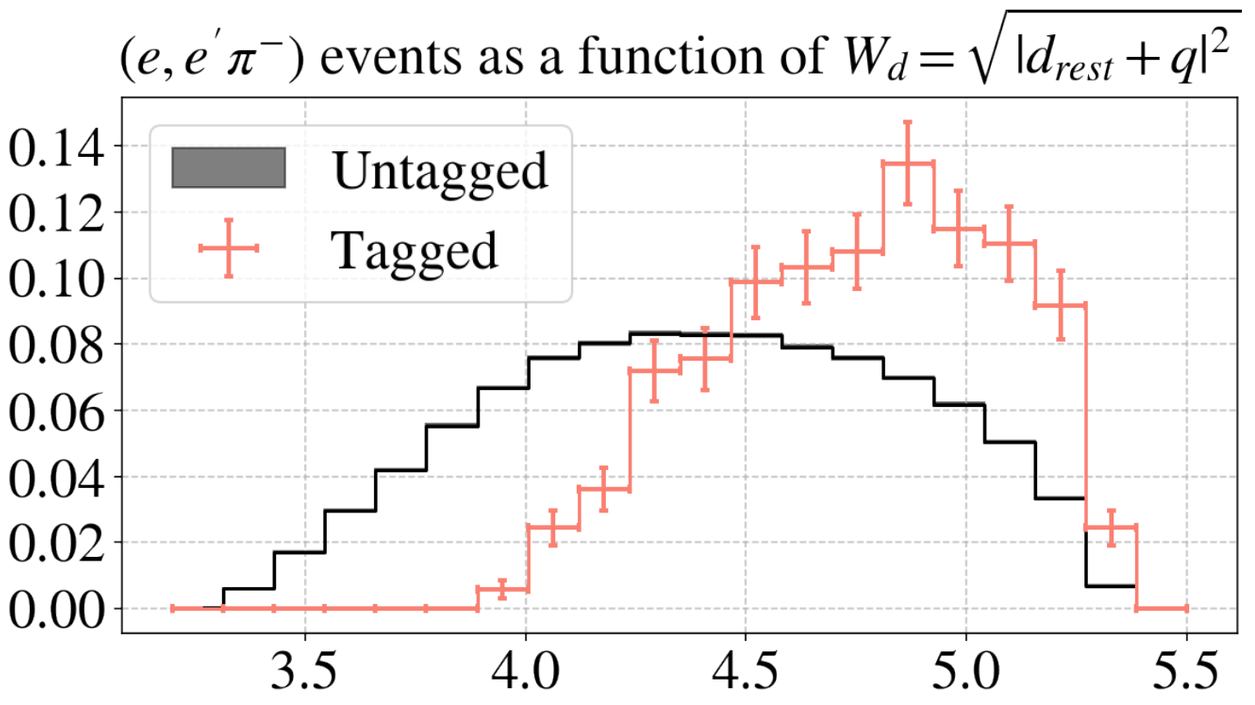


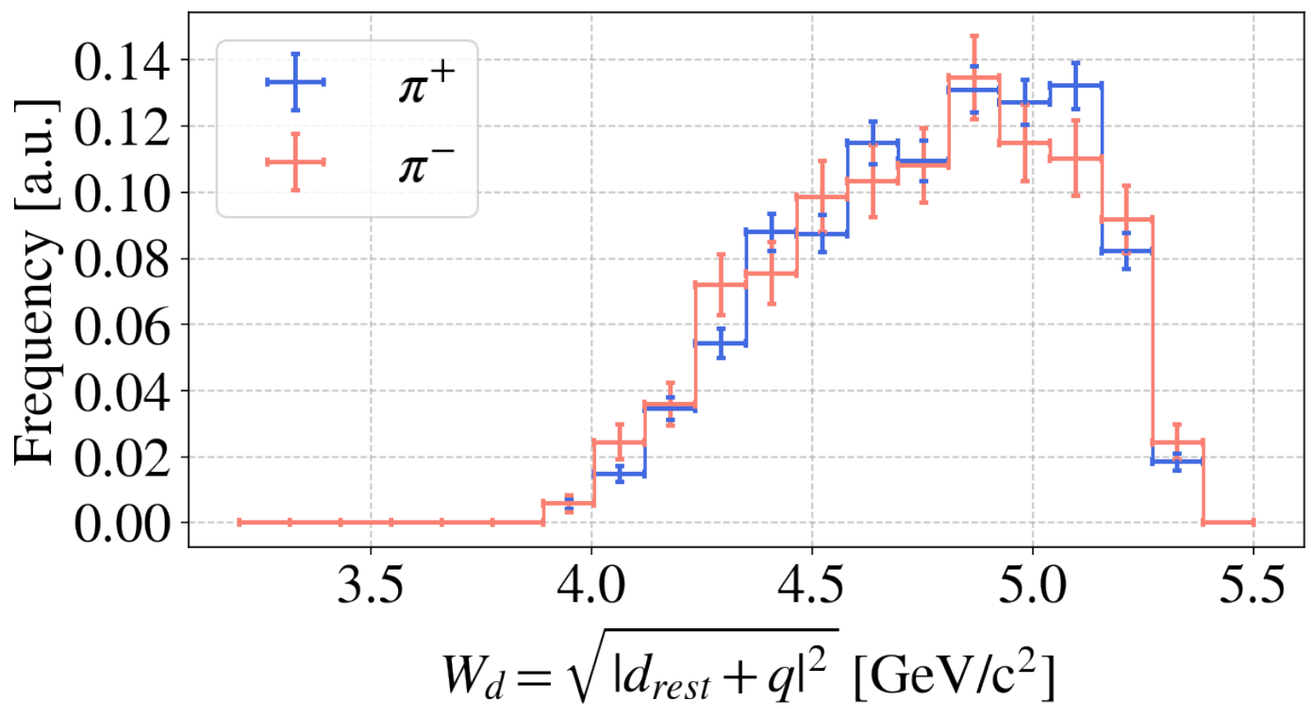
RGB + BAND: 10.2 GeV all data

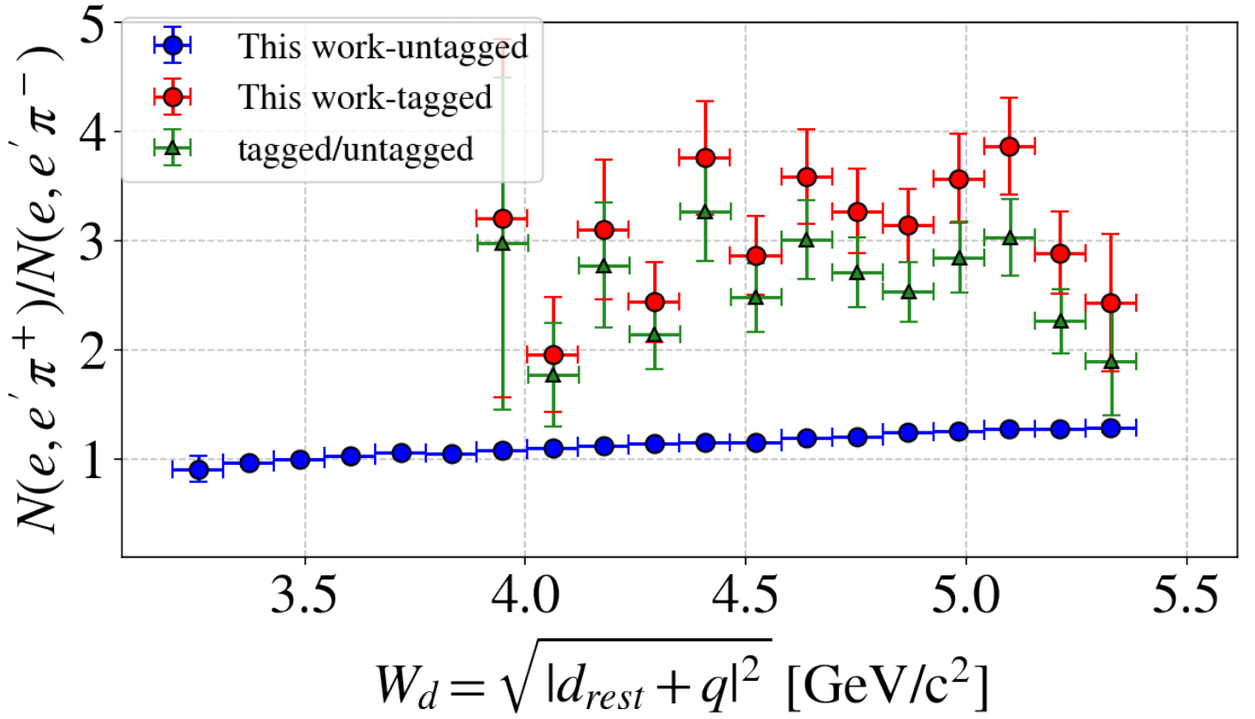
S_{RC}^{IDIS}@BAND | Hadronic mass: standing d

$d_{rest} = (0,0,0,m_d)$





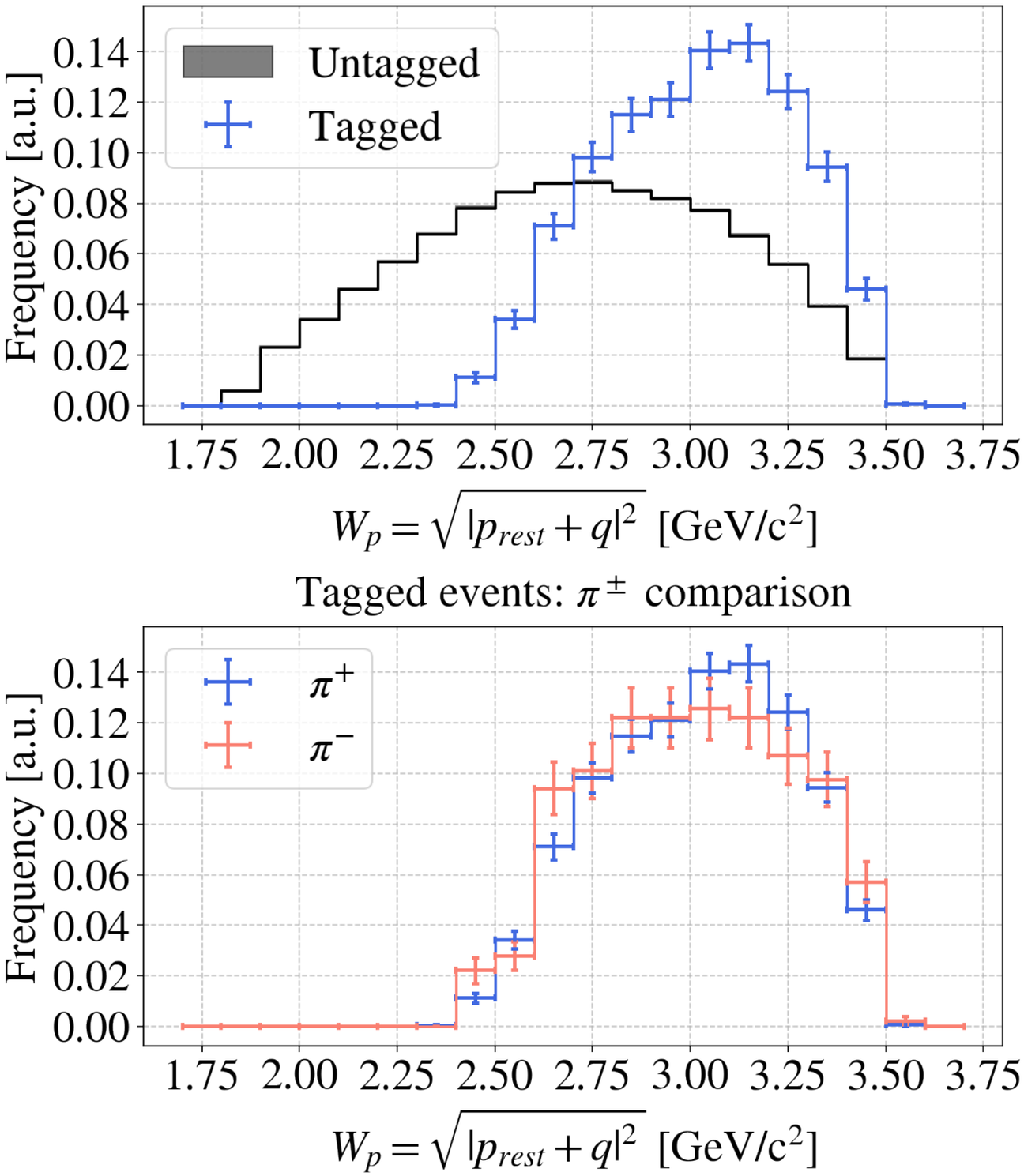




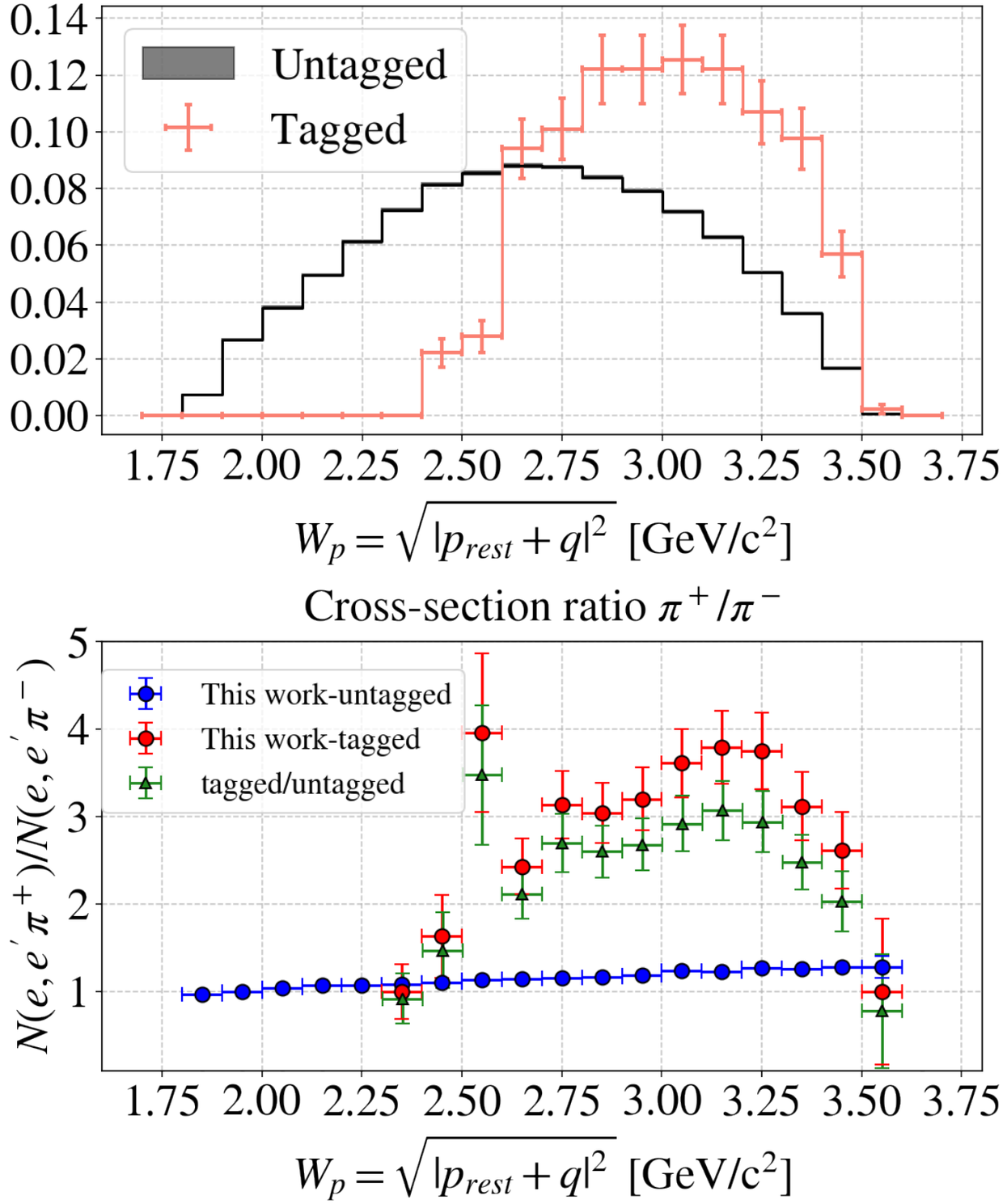
S_{RC}^{IDIS}@BAND | Hadronic mass: standing p

$p_{rest} = (0,0,0,m_p)$

$(e, e'\pi^+)$ events as a function of $W_p = \sqrt{|p_{rest} + q|^2}$



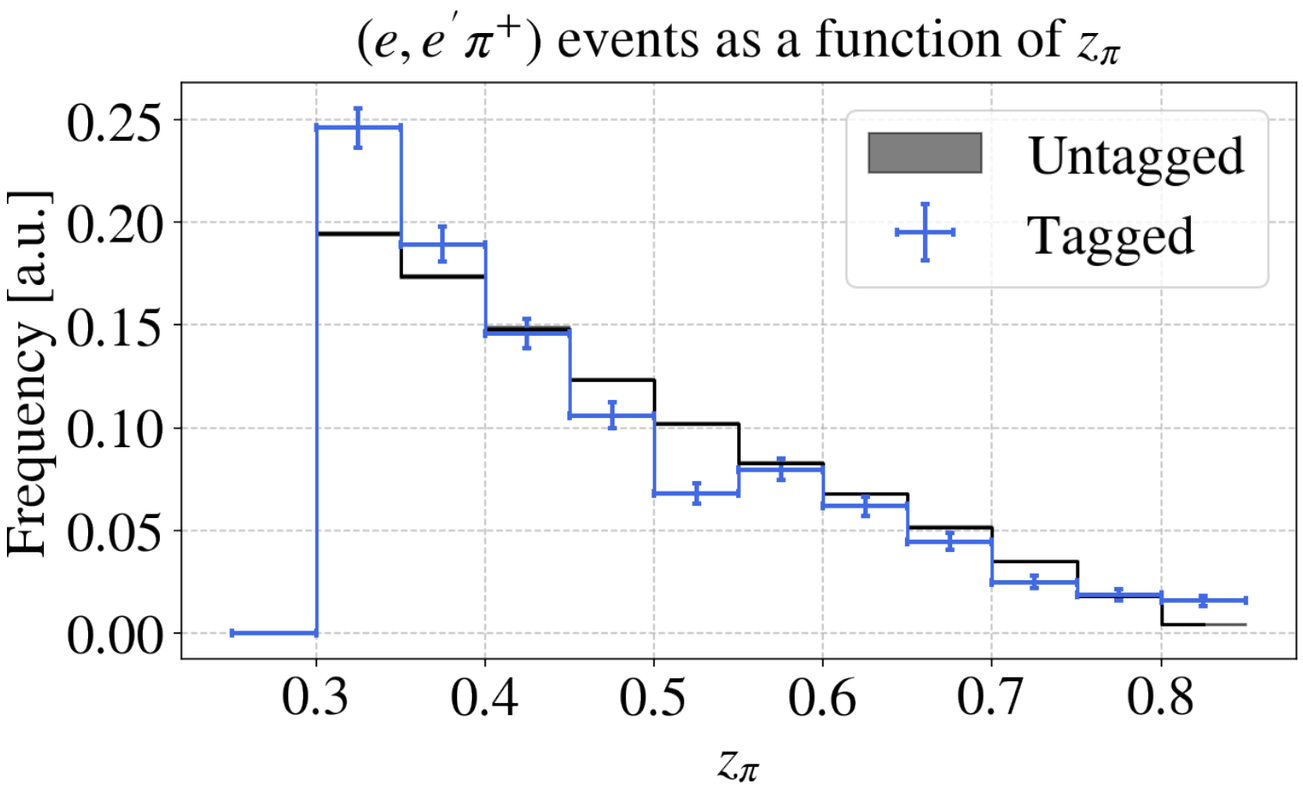
$(e, e'\pi^-)$ events as a function of $W_p = \sqrt{|p_{rest} + q|^2}$

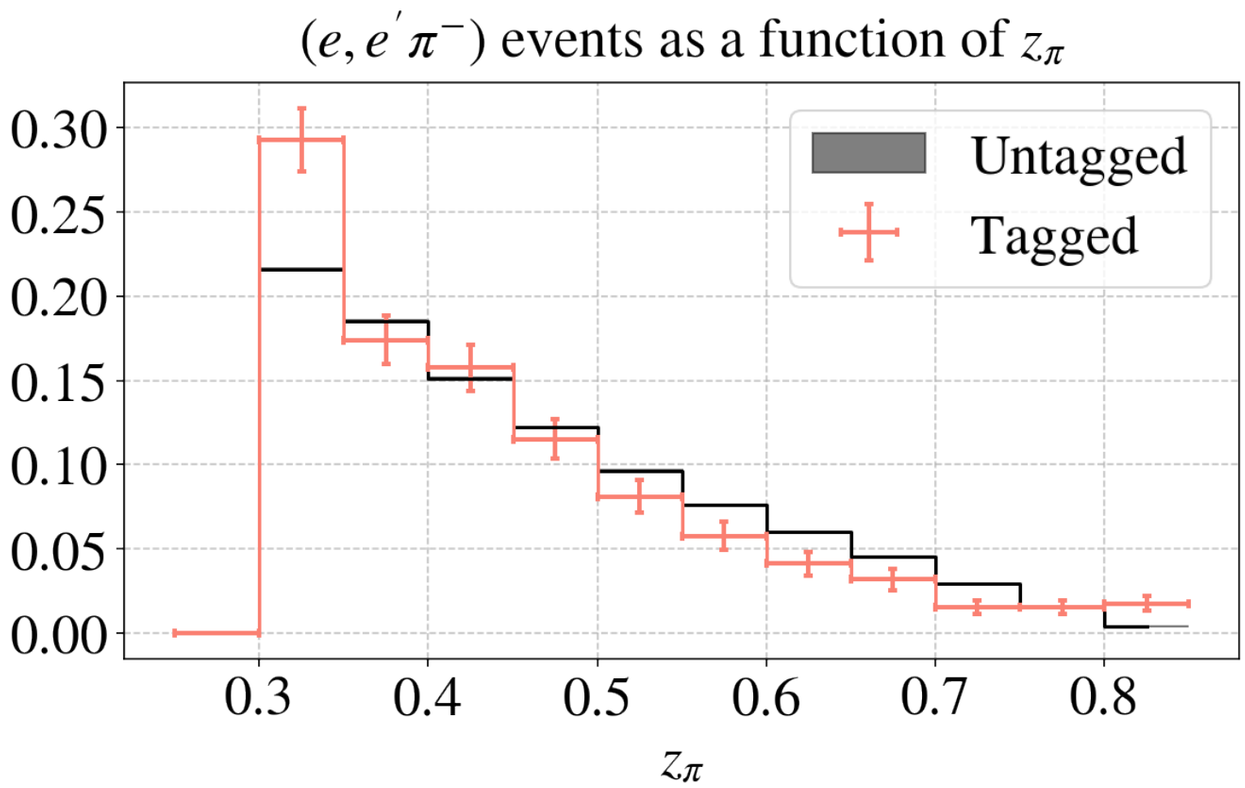


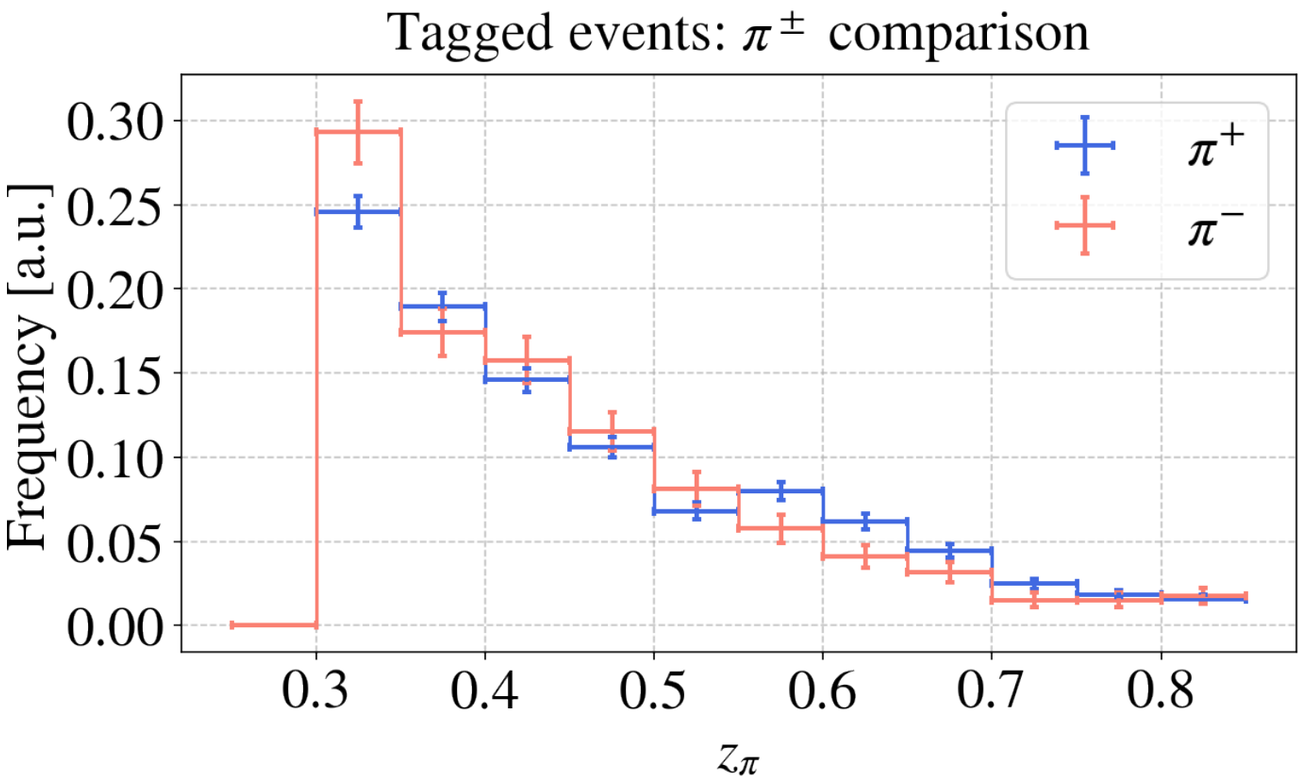
Tagged events: $\pi^{\pm}$ comparison

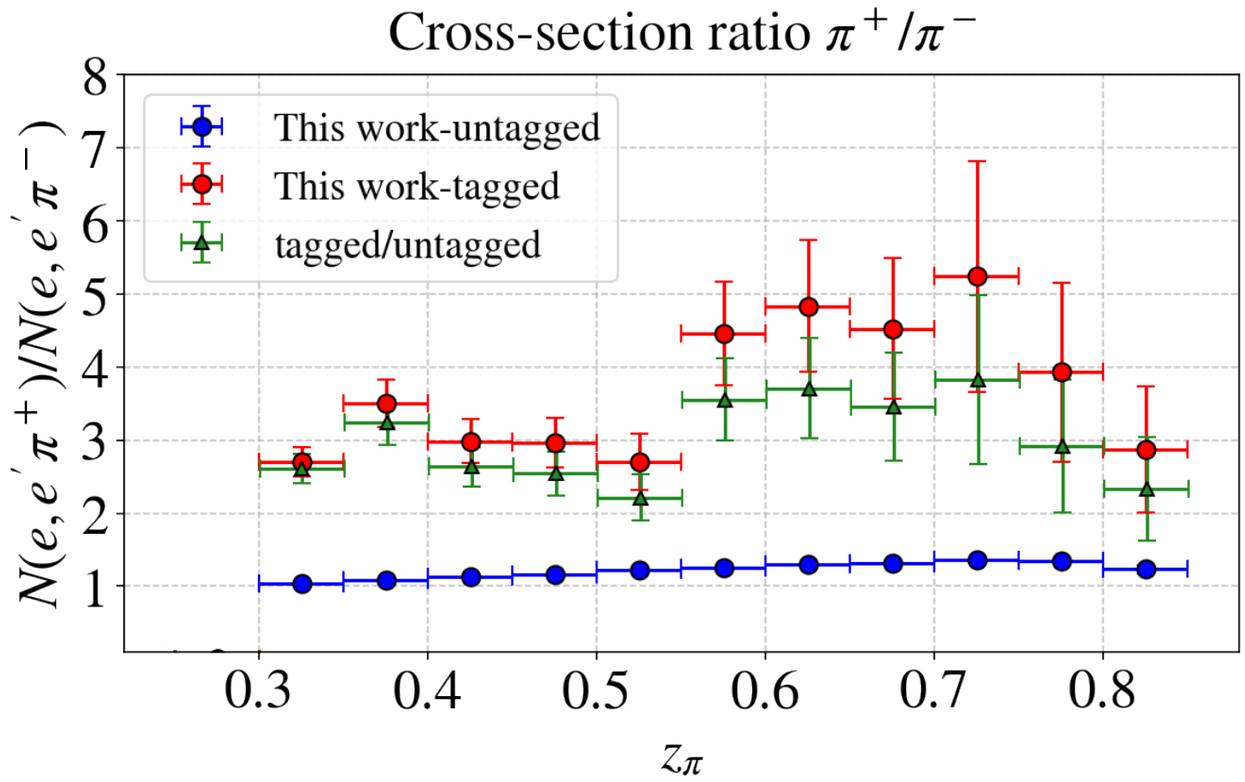
Cross-section ratio π^+/π^-

S_{RC}^{IDIS}@BAND | Kinematical distributions - π energy fraction

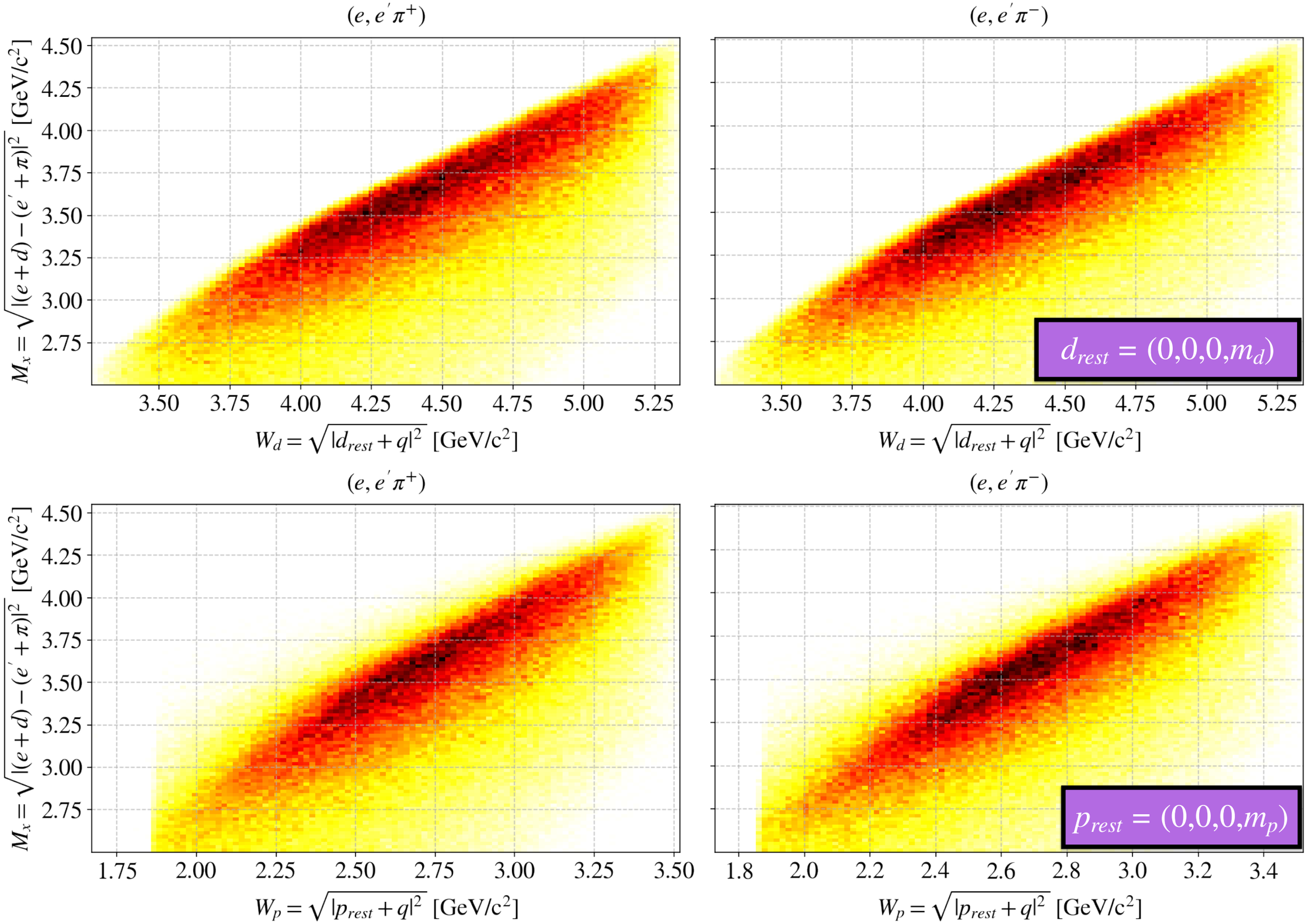




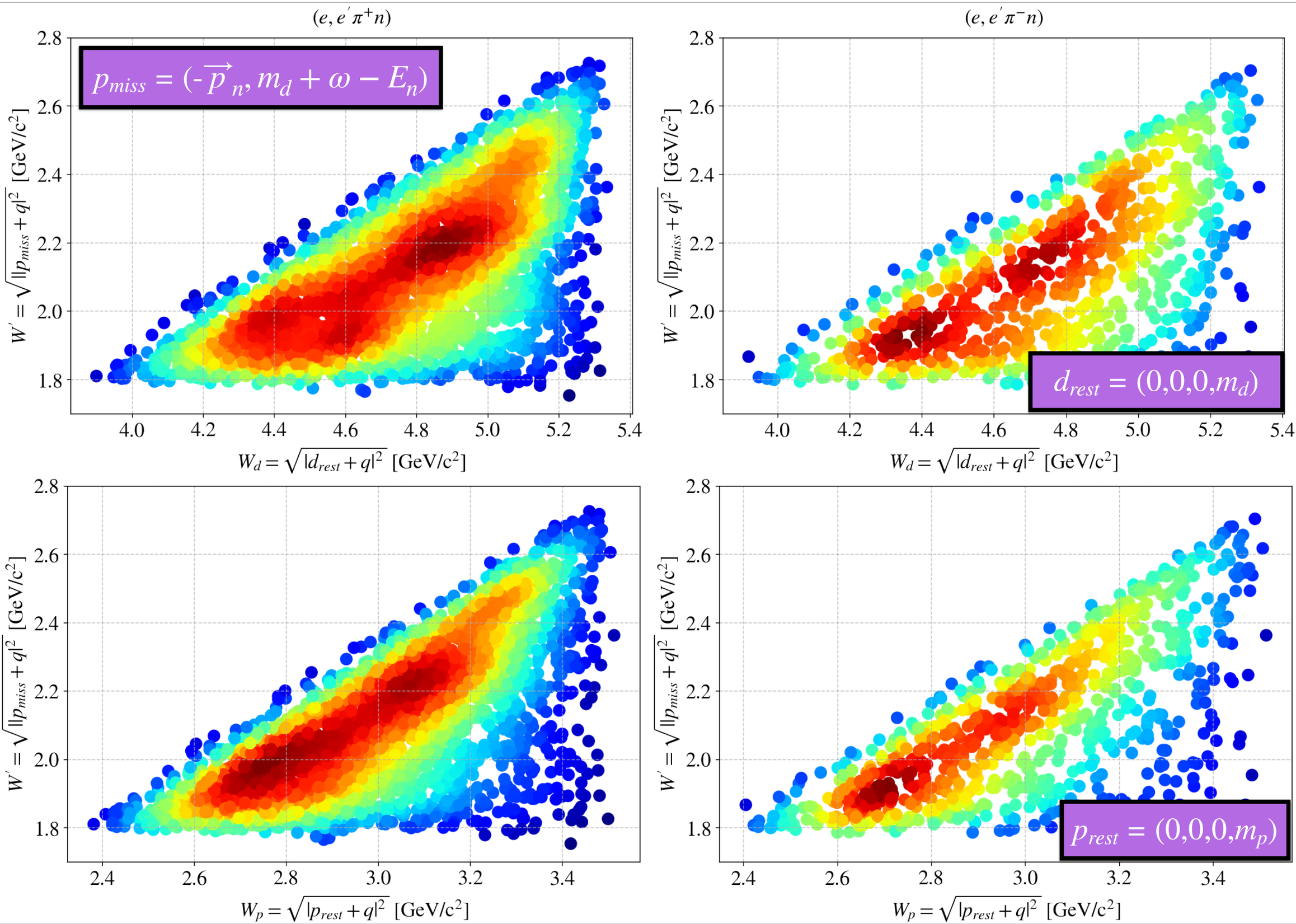




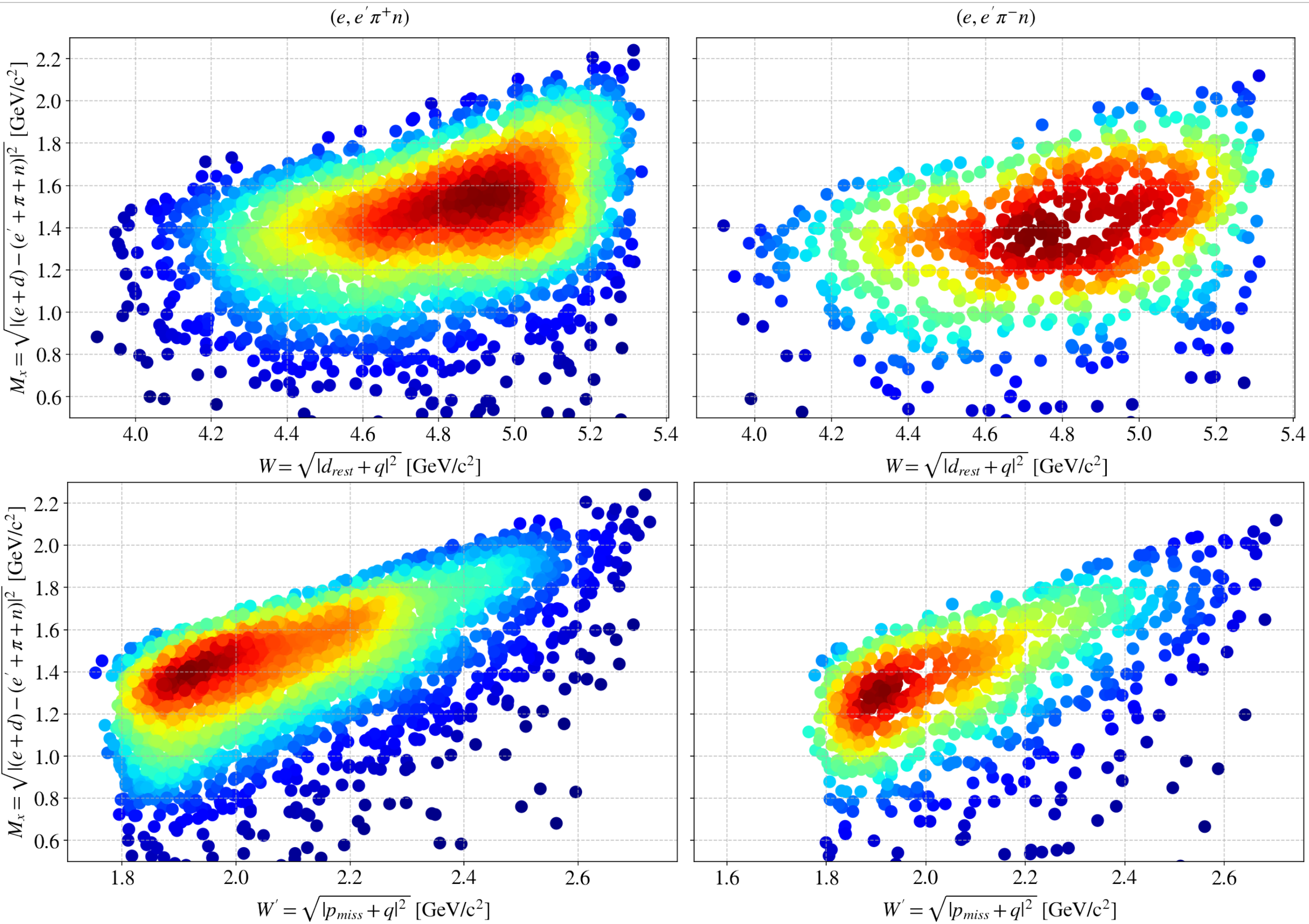
S_{RC}^{IDIS}@BAND | Hadronic invariant mass vs. missing mass



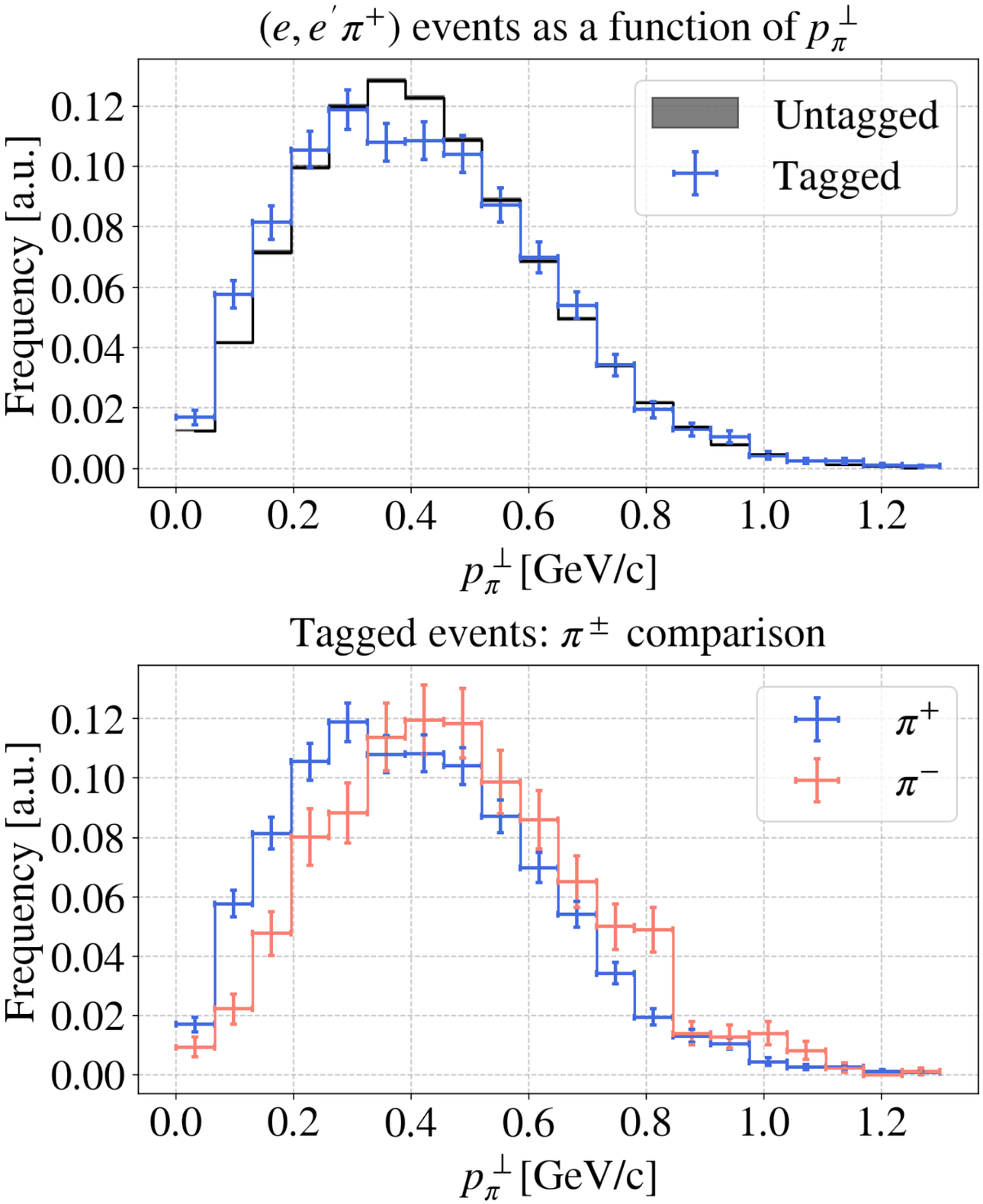
S_{RC}^{IDIS}@BAND | Hadronic invariant mass: *W'* vs *W*

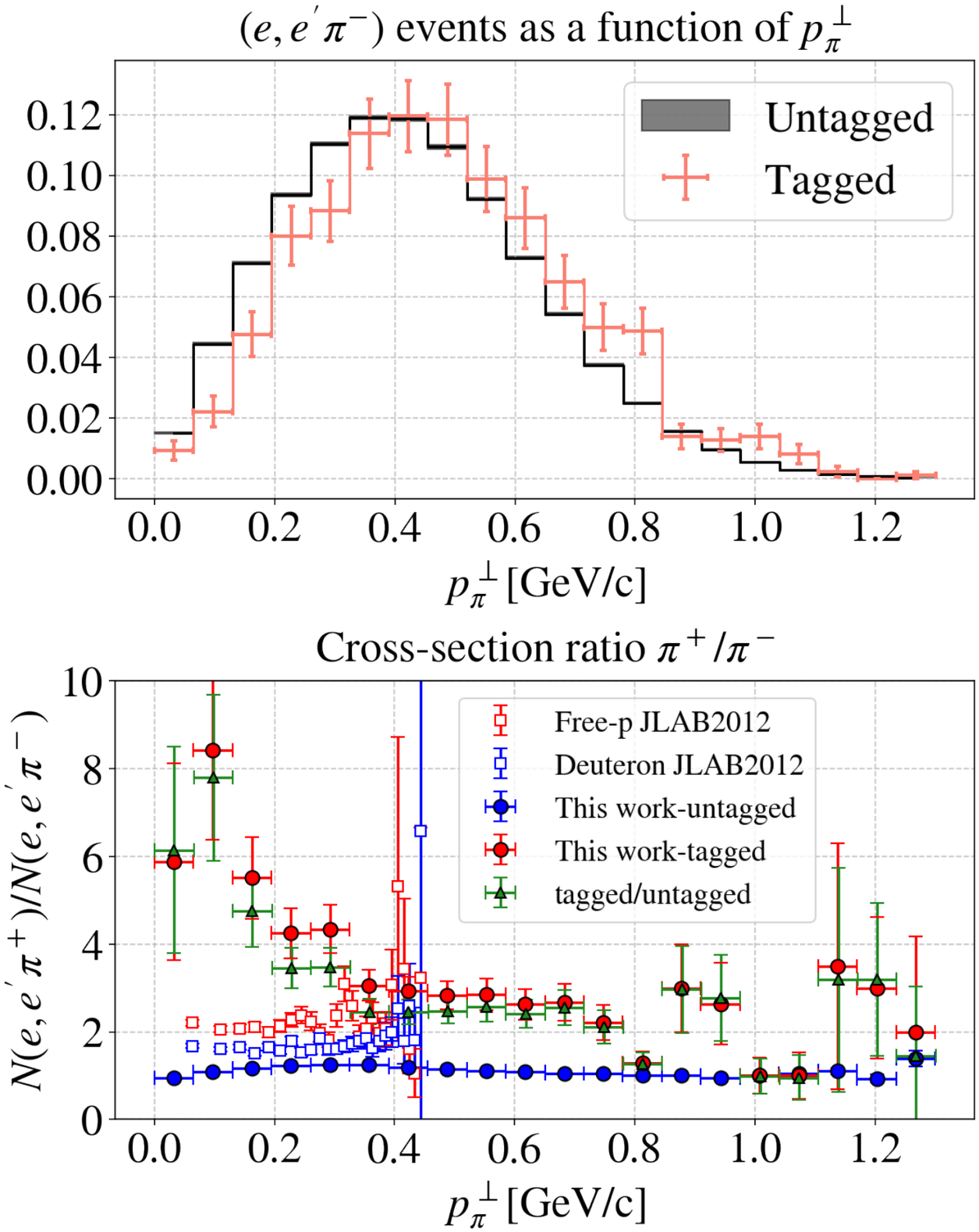


S_{RC}^{IDIS}@BAND | Hadronic invariant mass vs. missing mass



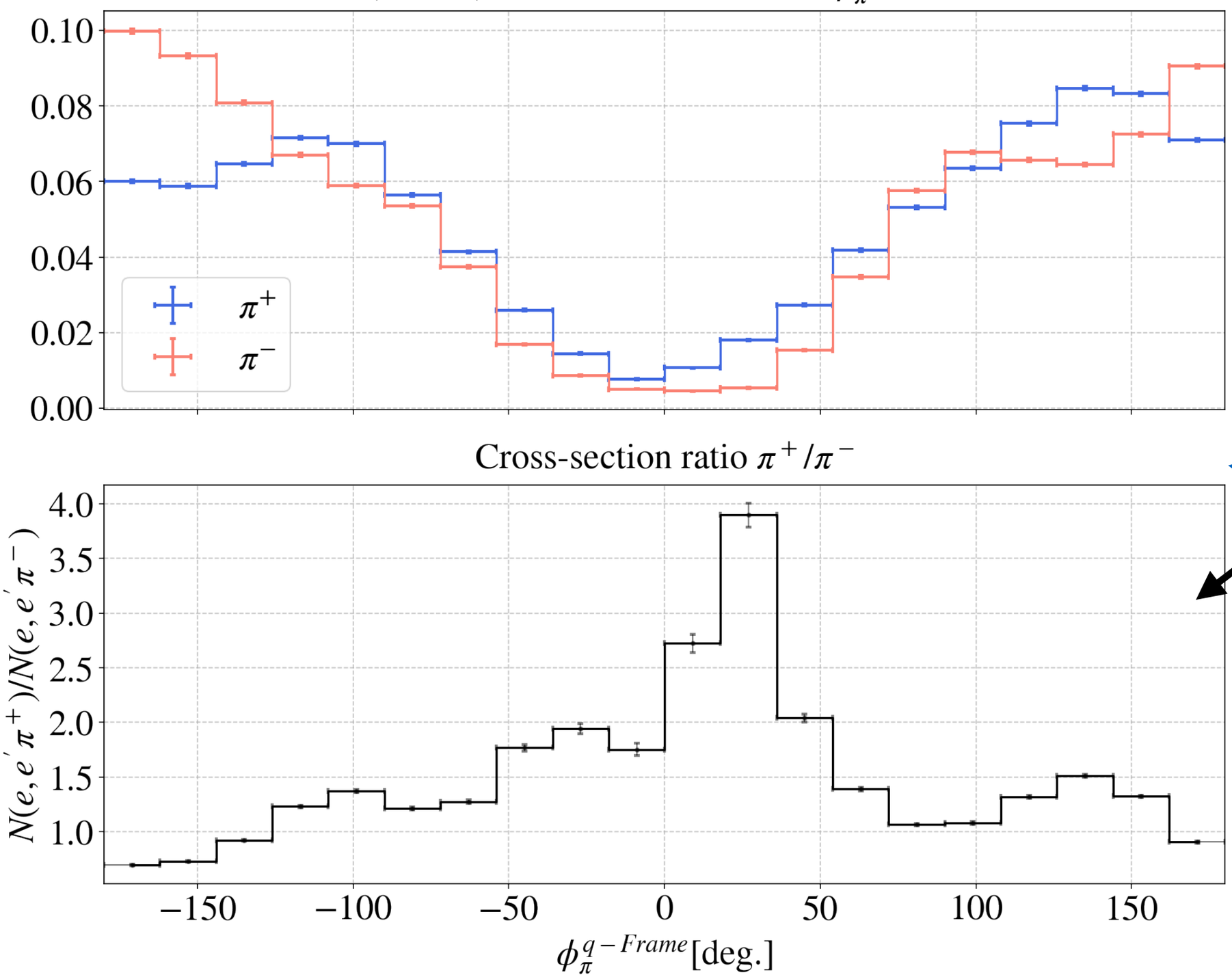
S_{RC}^{IDIS}@BAND | Kinematical distributions - transverse momentum to q

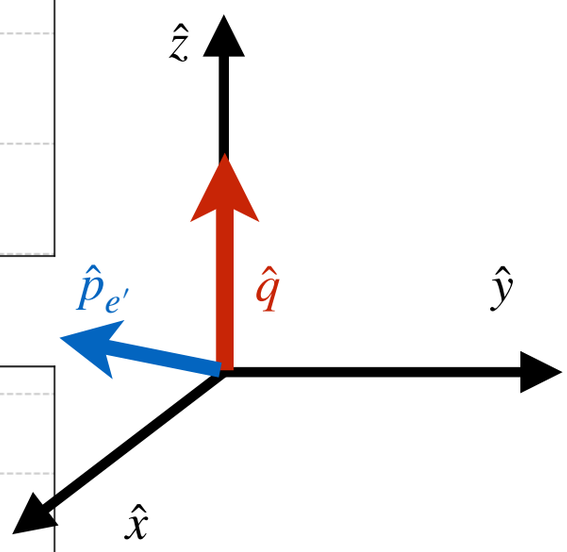




S_{RC}^{IDIS}@BAND | π azimuthal angle in the q - frame

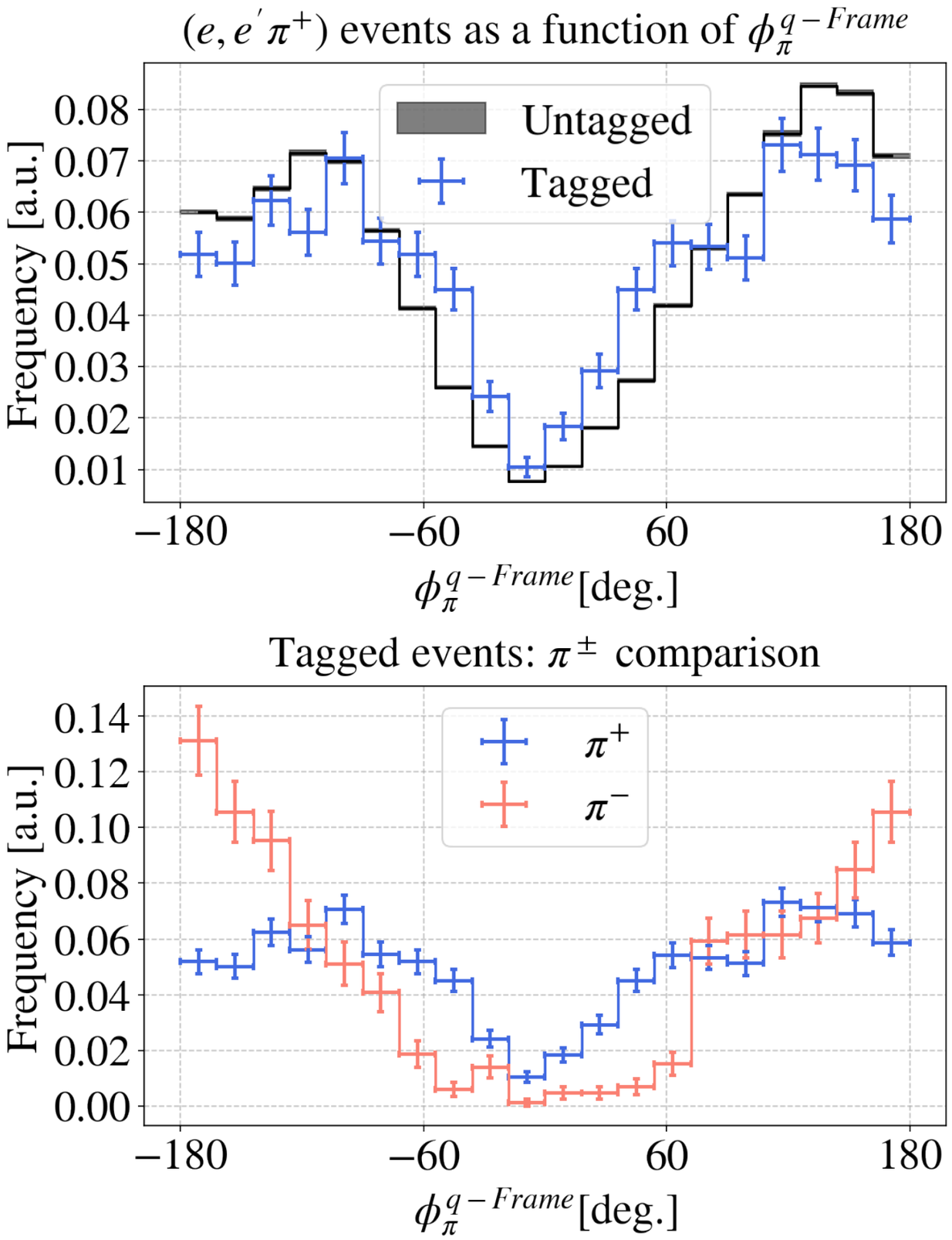
Untagged data

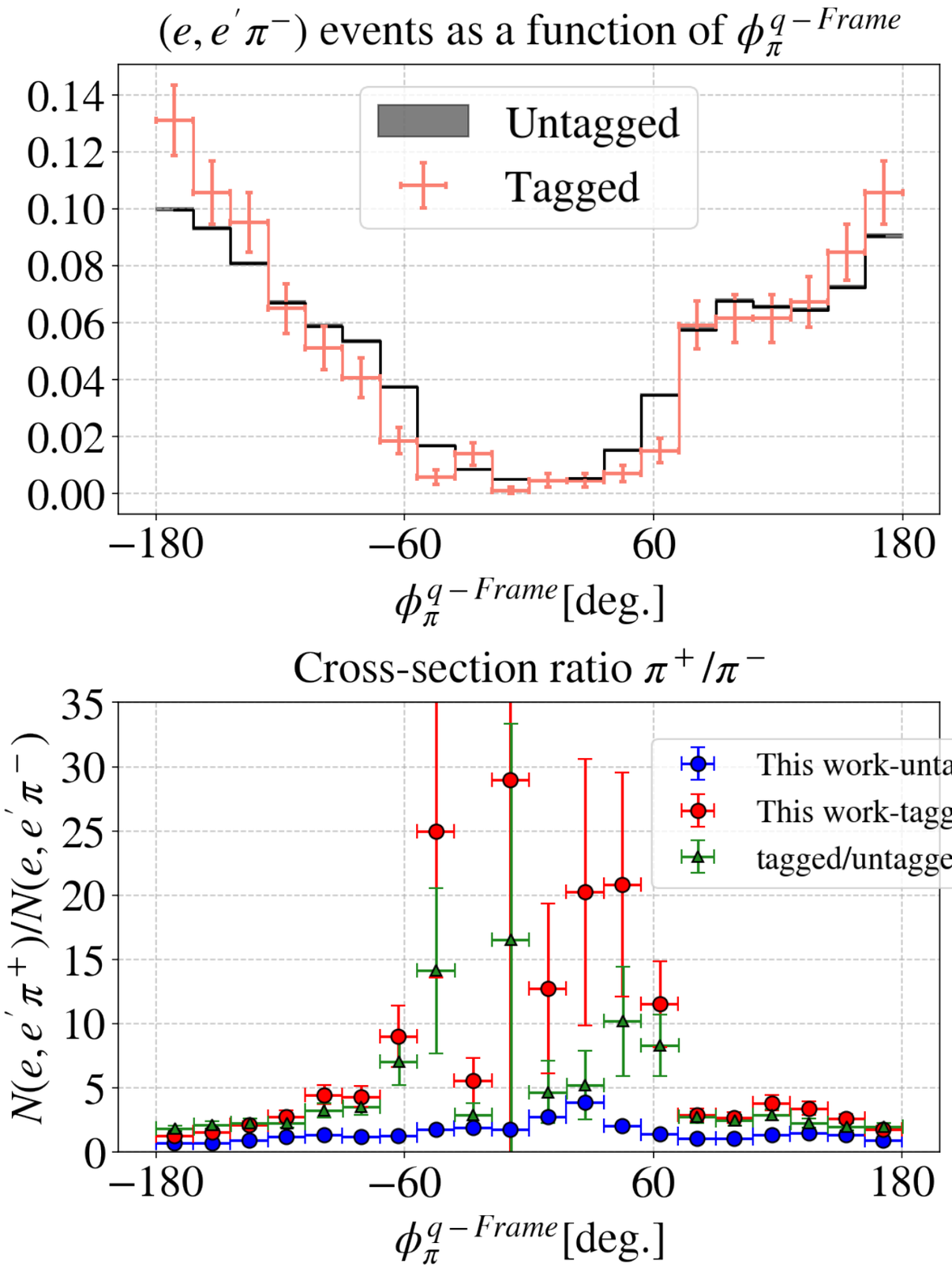




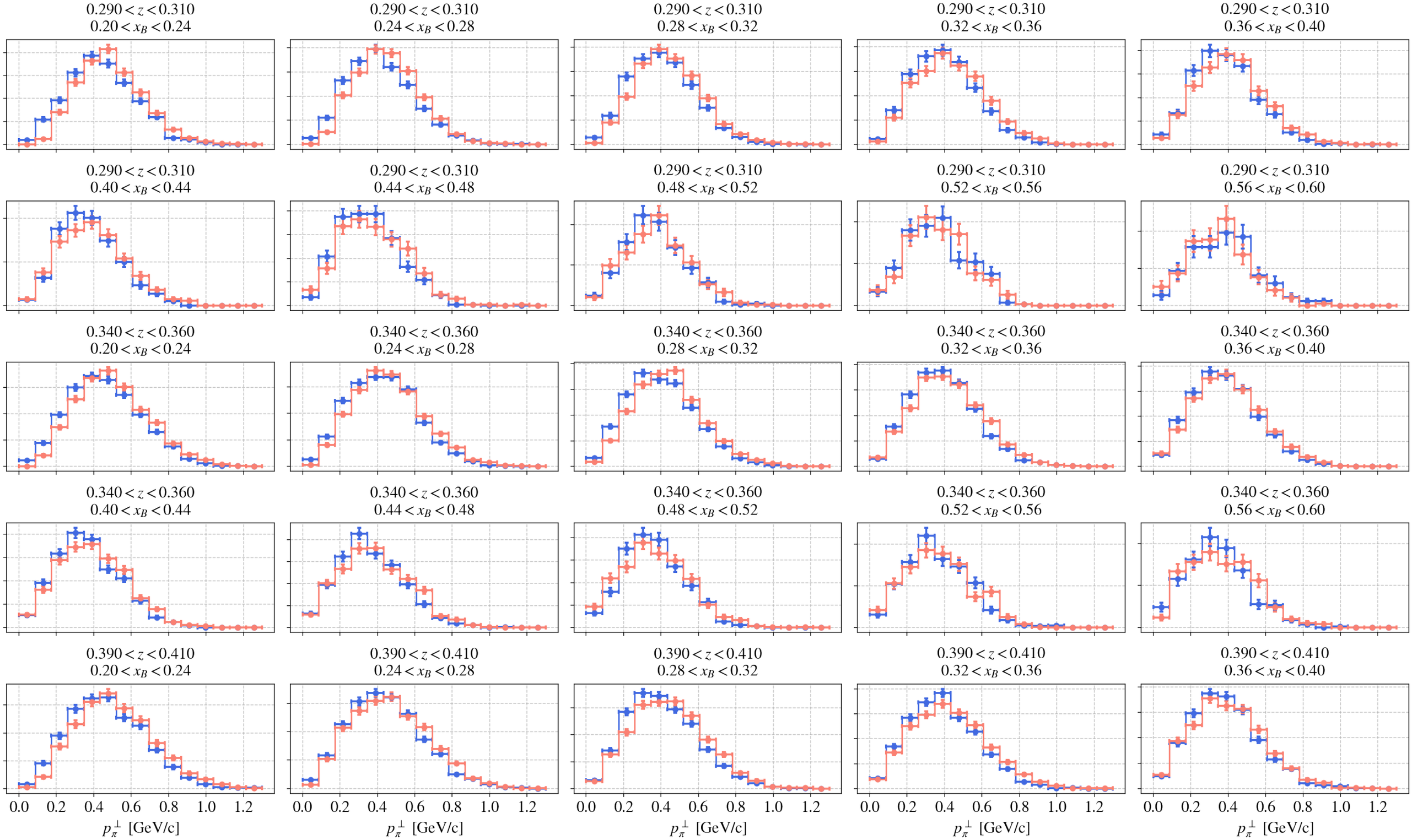
RGB + BAND: 10.2 GeV all data

S_{RC}^{IDIS}@BAND | π azimuthal angle in the q - frame



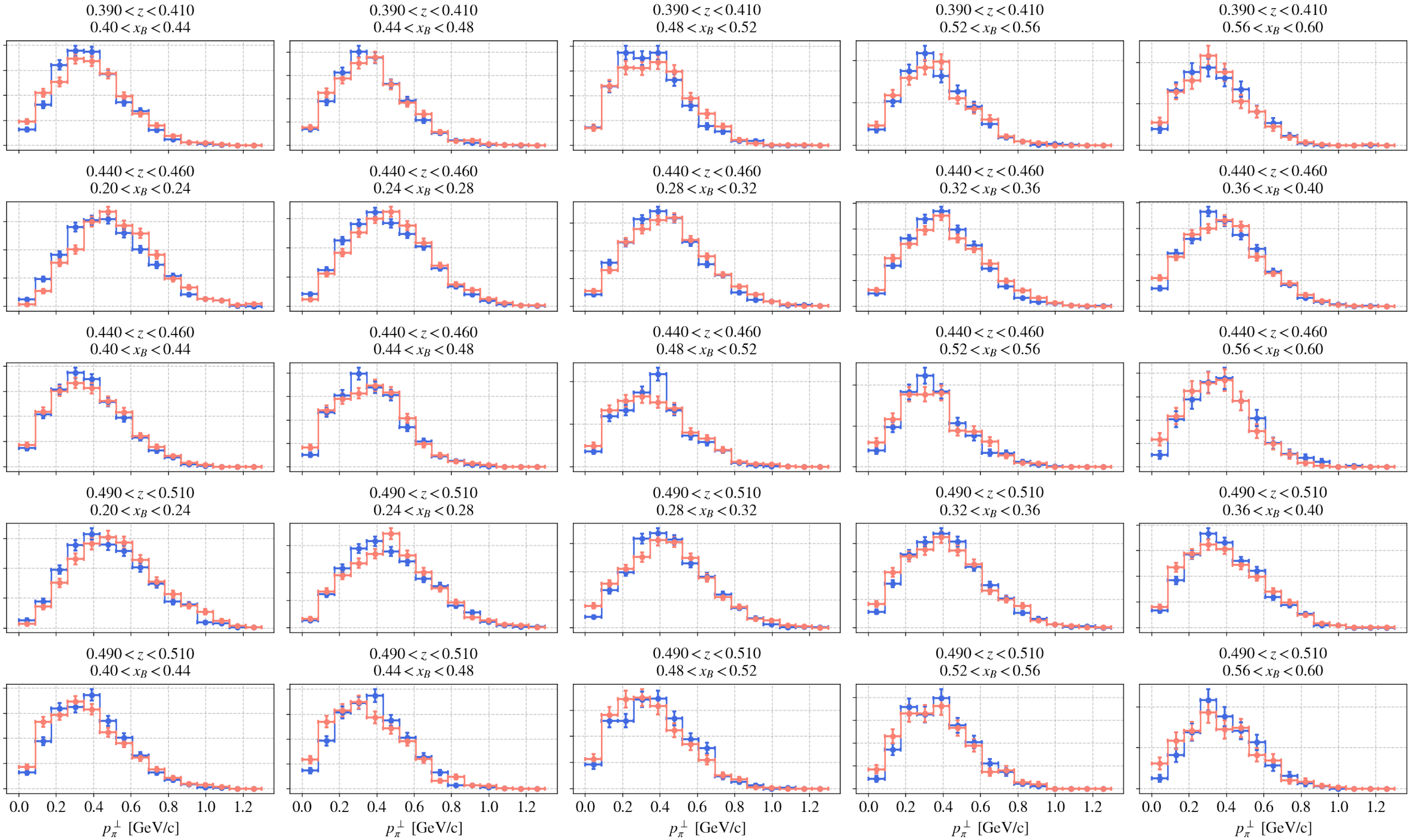


S_{RC}^{IDIS}@BAND | Transverse π momentum - untagged data



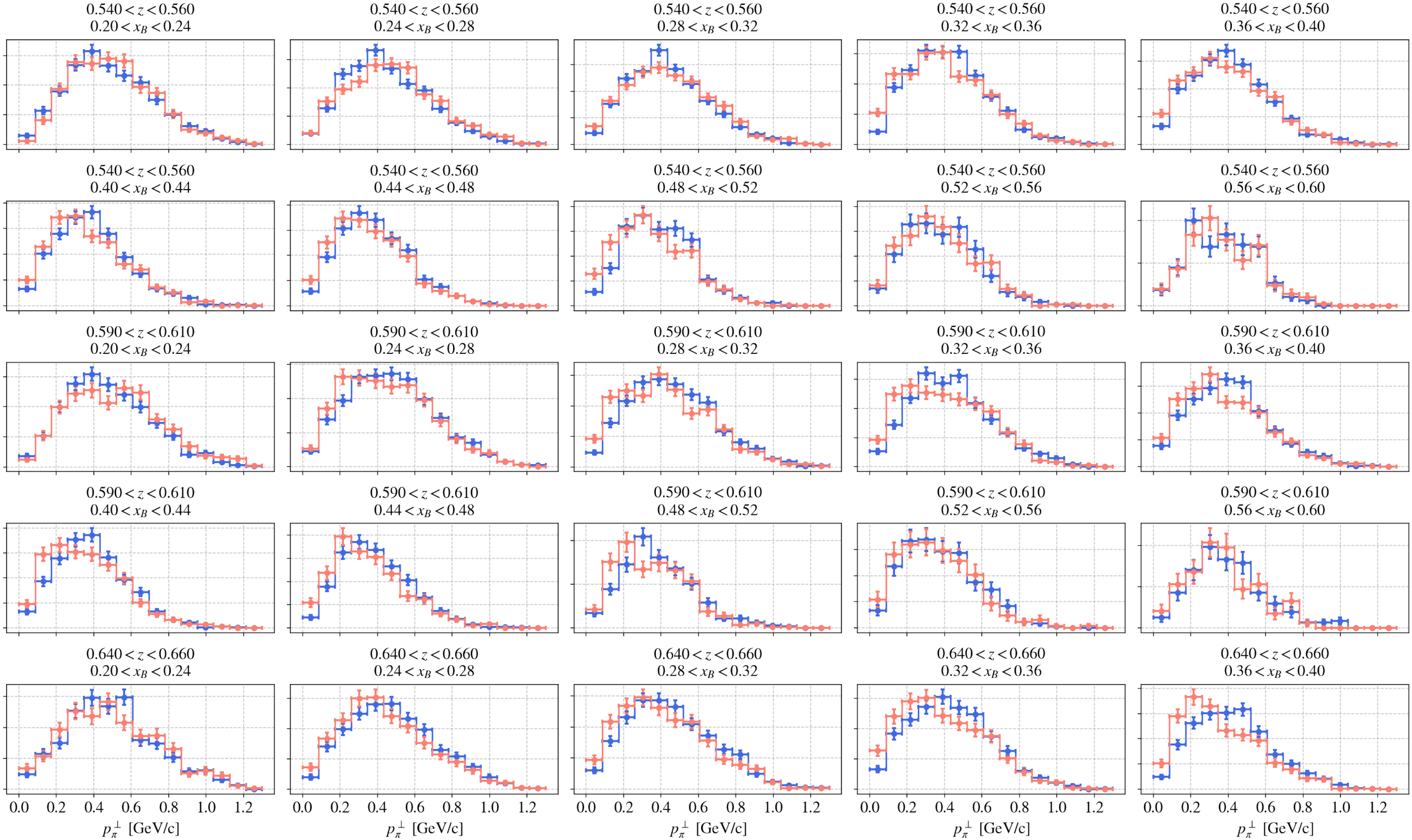
RGB + BAND: 10.2 GeV all data

S_{RC}^{IDIS}@BAND | Transverse π momentum - untagged data



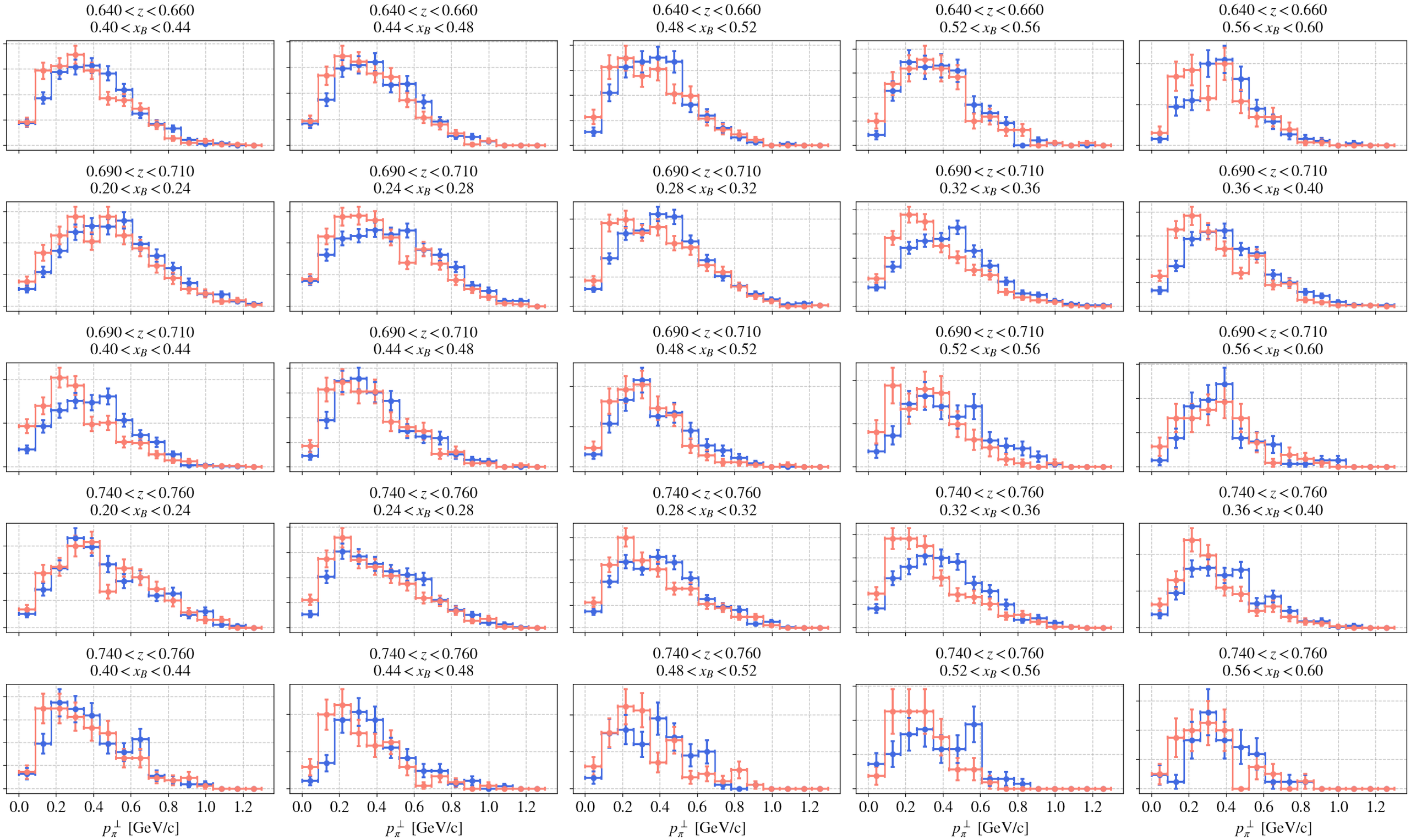
RGB + BAND: 10.2 GeV all data

S_{RC}^{IDIS}@BAND | Transverse π momentum - untagged data



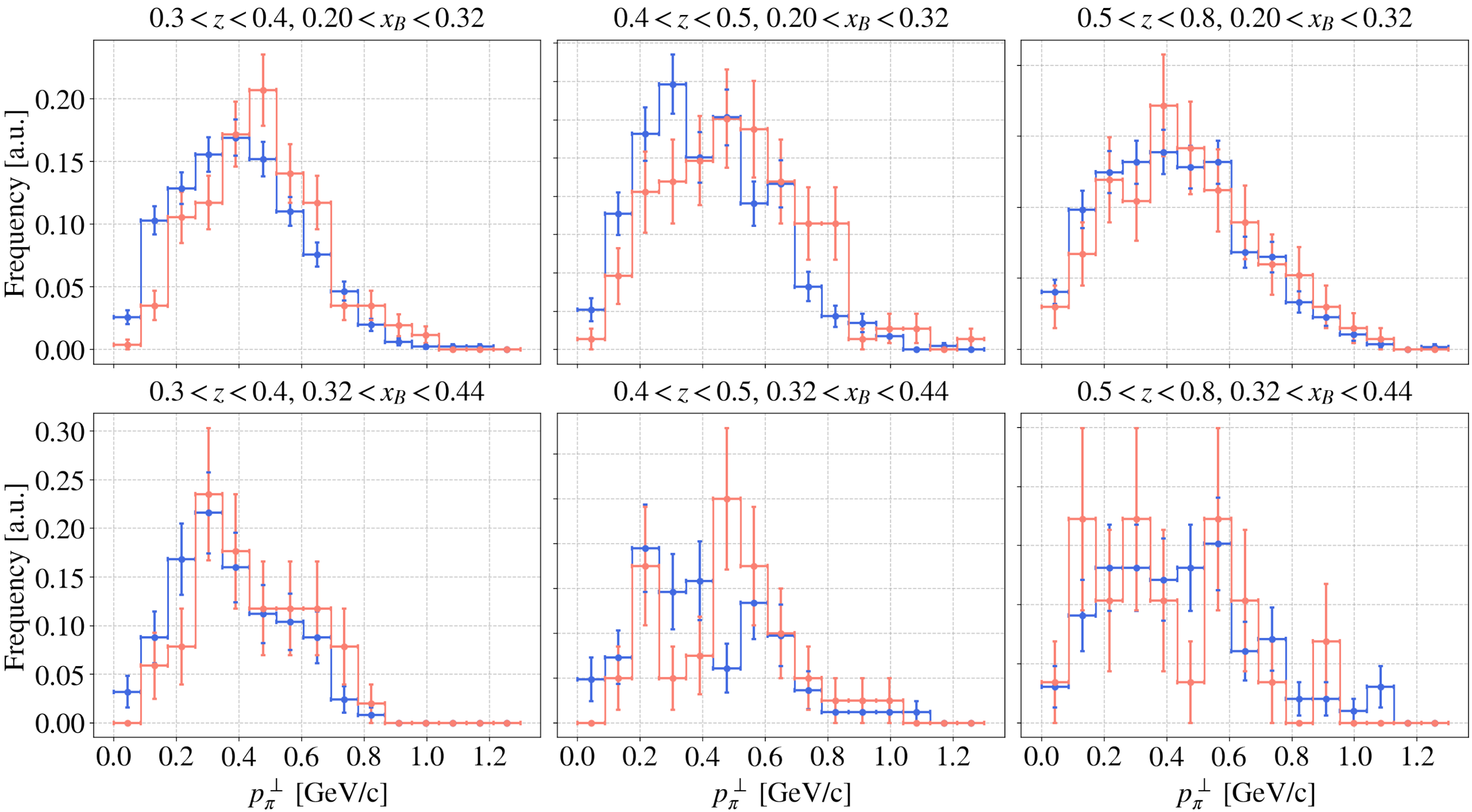
RGB + BAND: 10.2 GeV all data

S_{RC}^{IDIS}@BAND | Transverse π momentum - untagged data



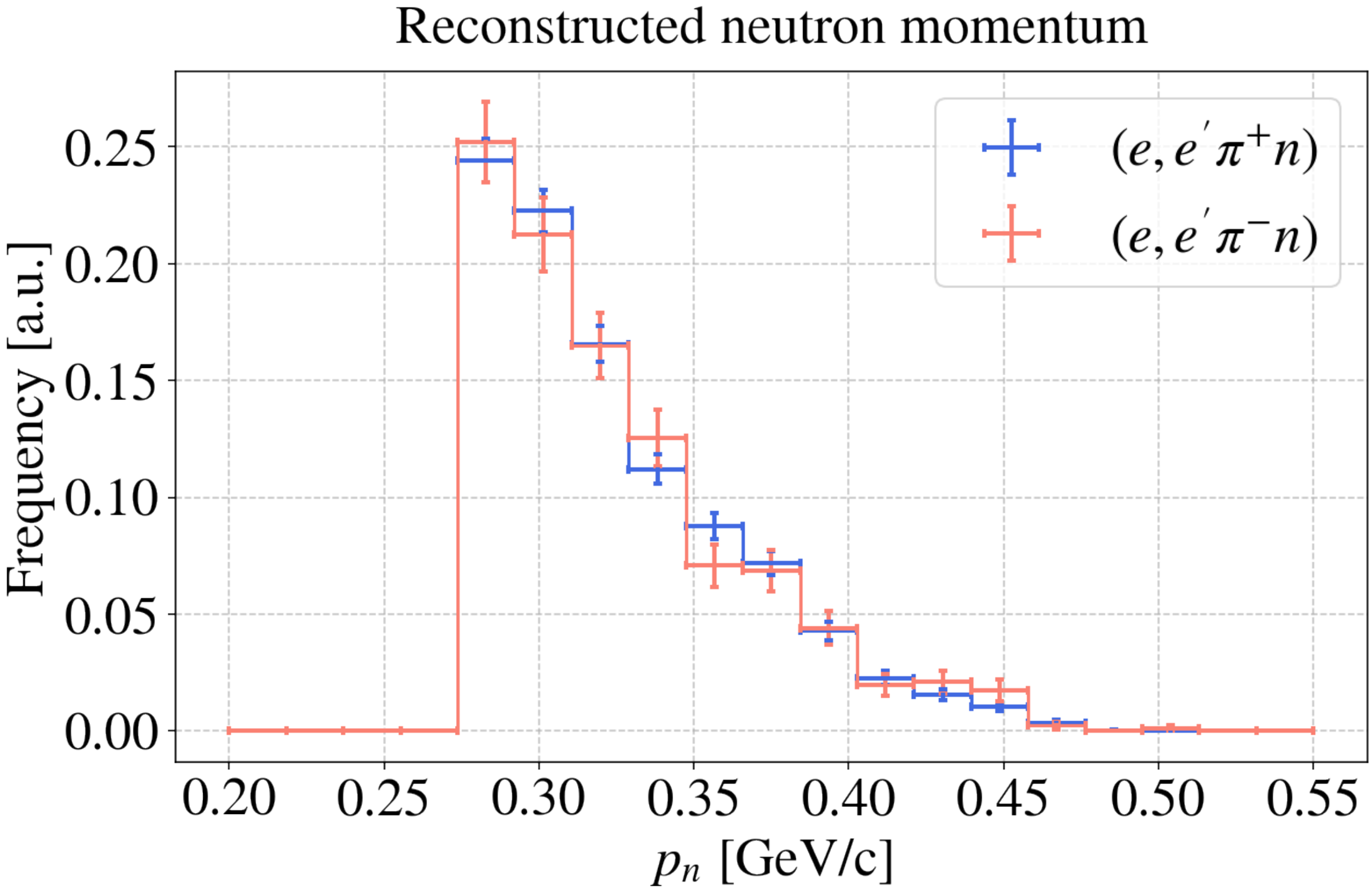
RGB + BAND: 10.2 GeV all data

S_{RC}^{IDIS}@BAND | Transverse pion momentum - tagged data



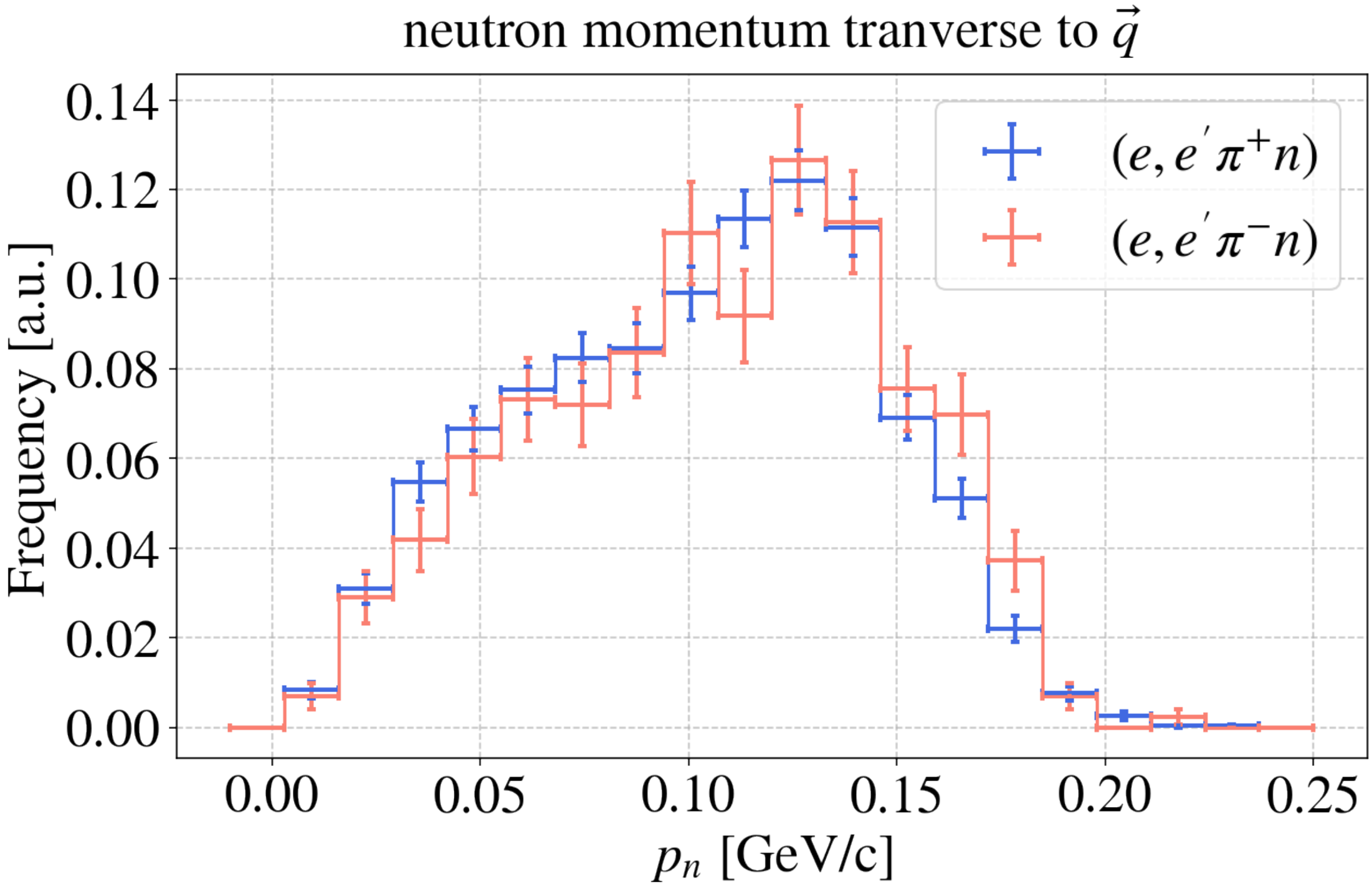
RGB + BAND: 10.2 GeV all data

S_{RC}^{IDIS}@BAND | Recoil neutron momentum distribution



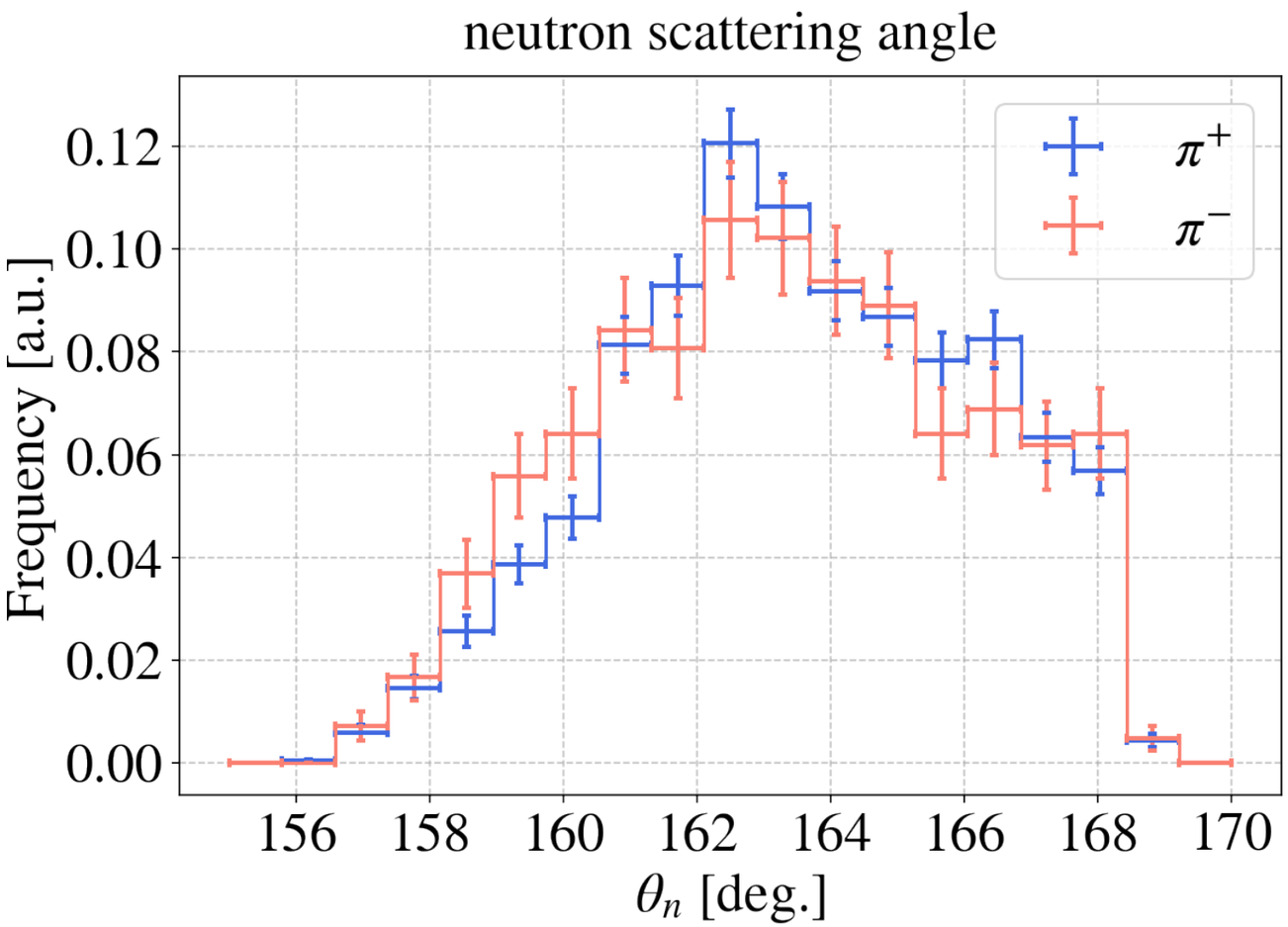
RGB + BAND: 10.2 GeV all data

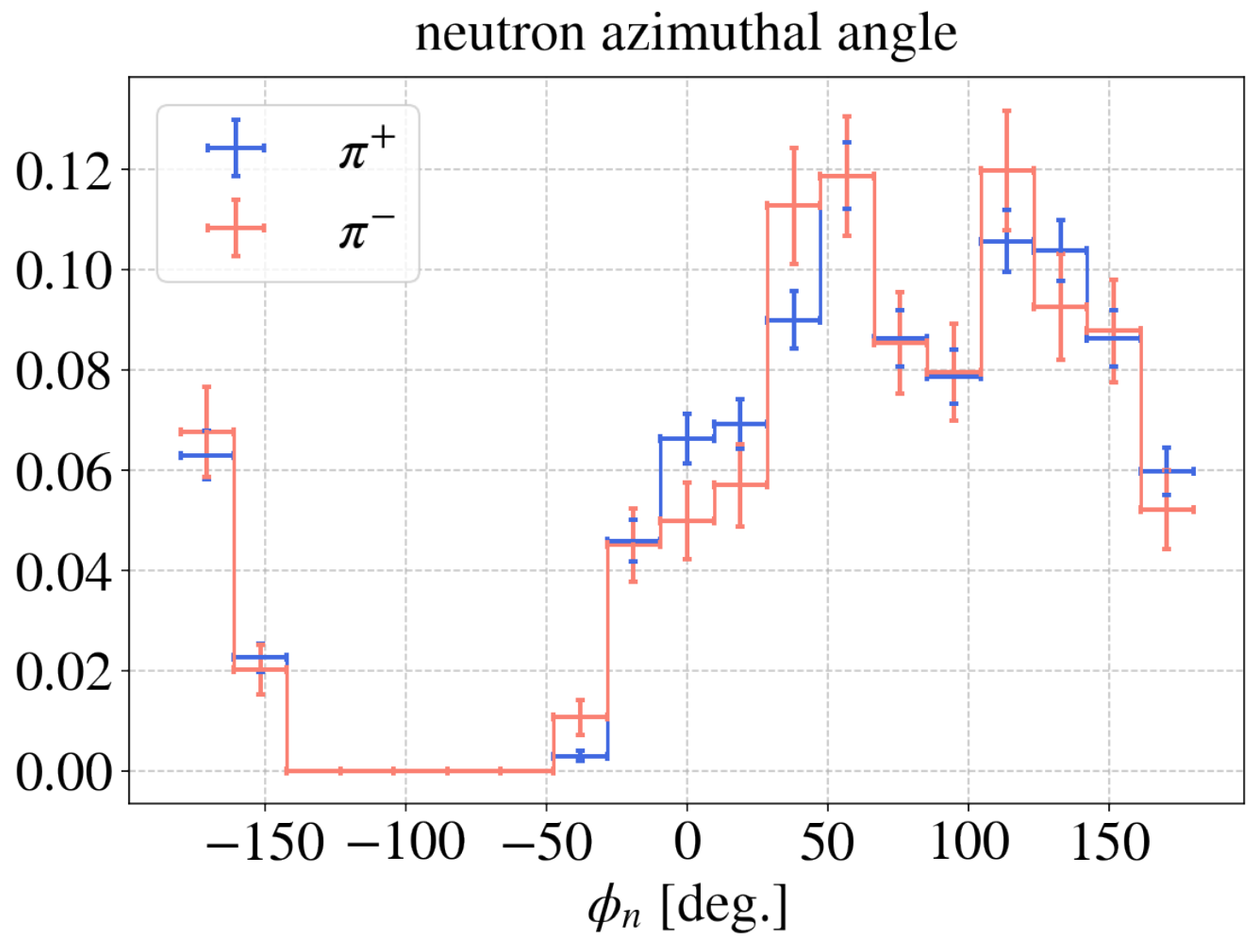
S_{RC}^{IDIS}@BAND | Transverse neutron momentum



RGB + BAND: 10.2 GeV all data

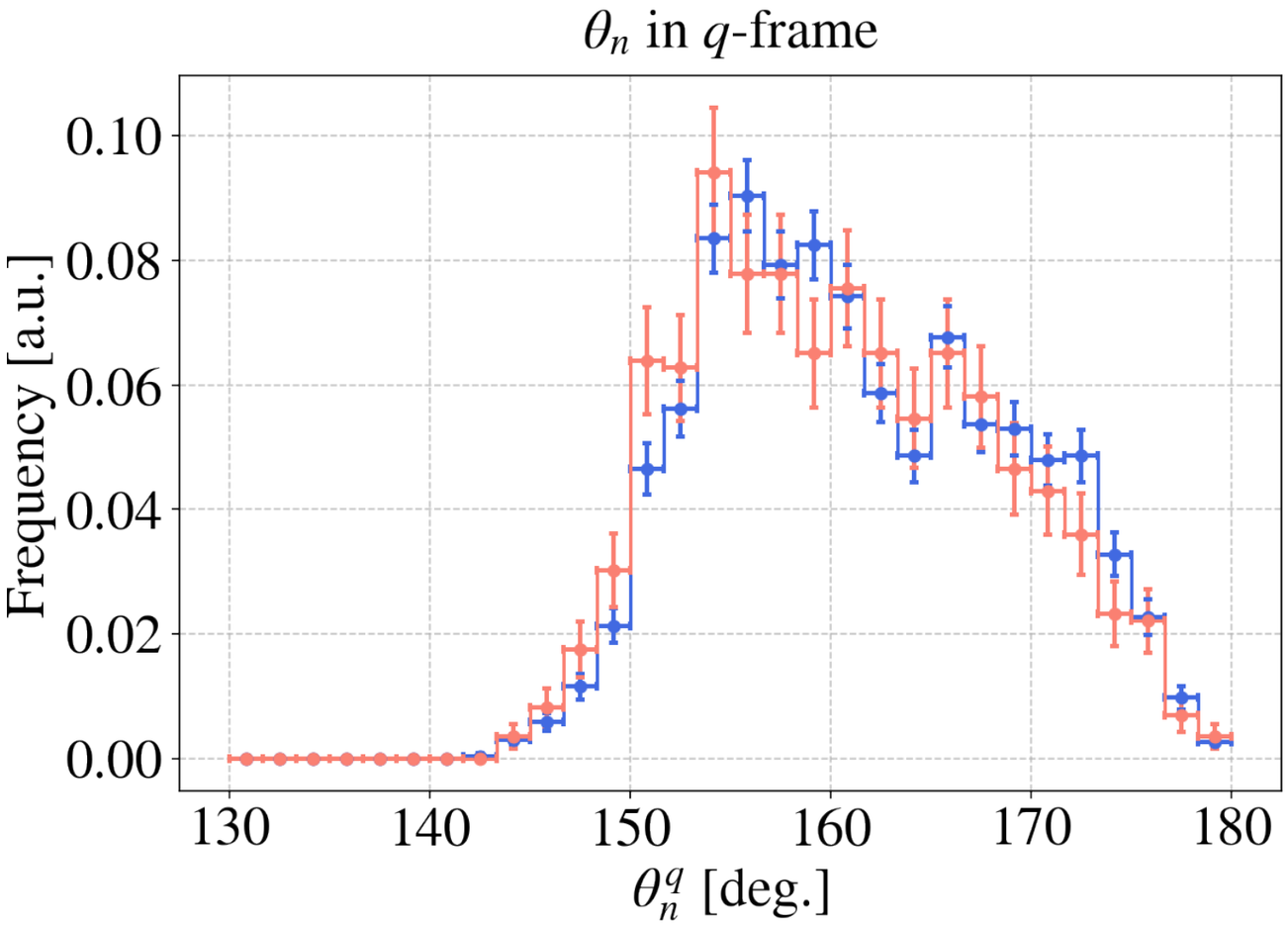
S_{RC}^{IDIS}@BAND | Recoil neutron direction in lab frame

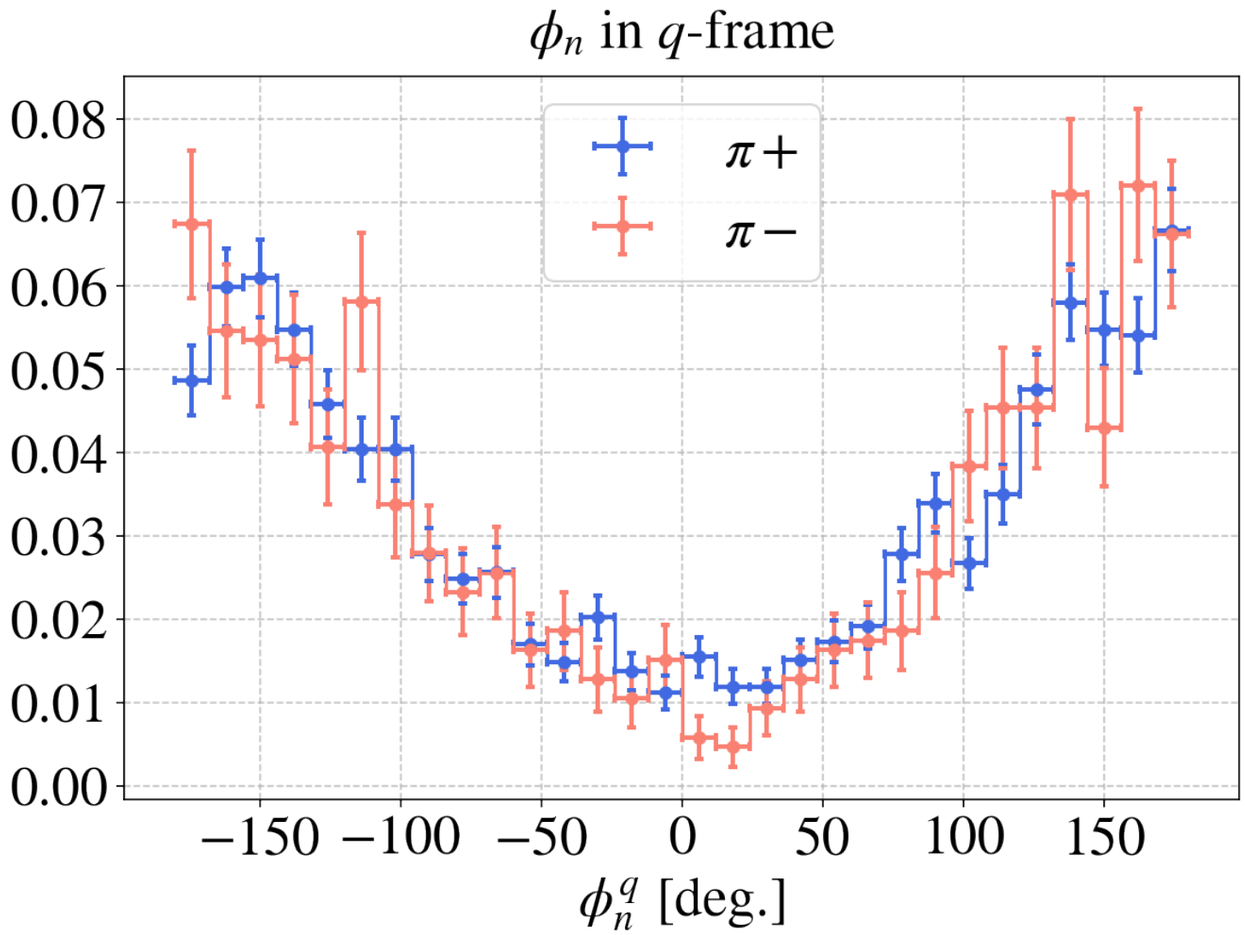




RGB + BAND: 10.2 GeV all data

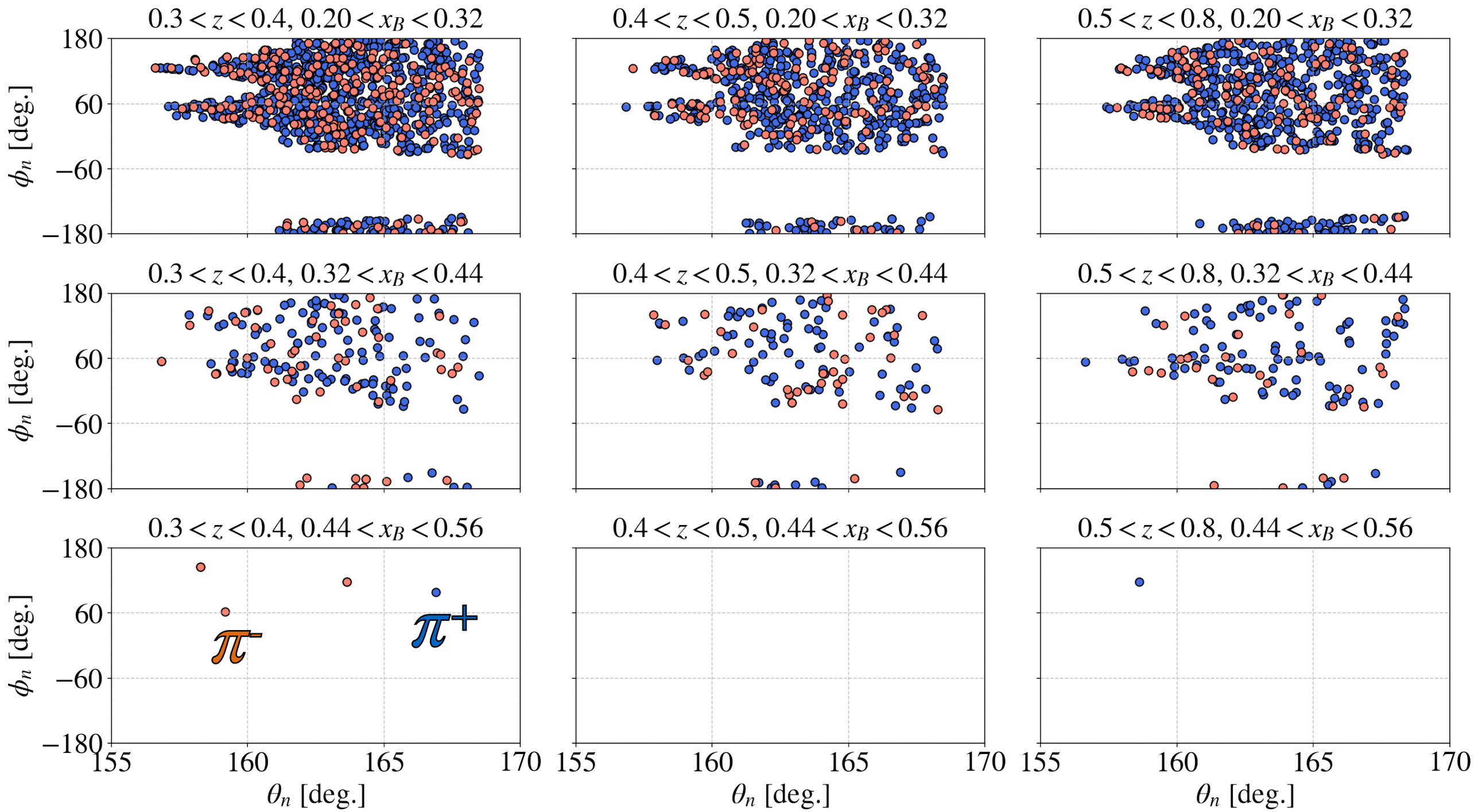
S_{RC}^{IDIS}@BAND | Recoil neutron direction in q frame





RGB + BAND: 10.2 GeV all data

S_{RC}^{IDIS}@BAND | neutron direction in the lab (bins of z and x_B)

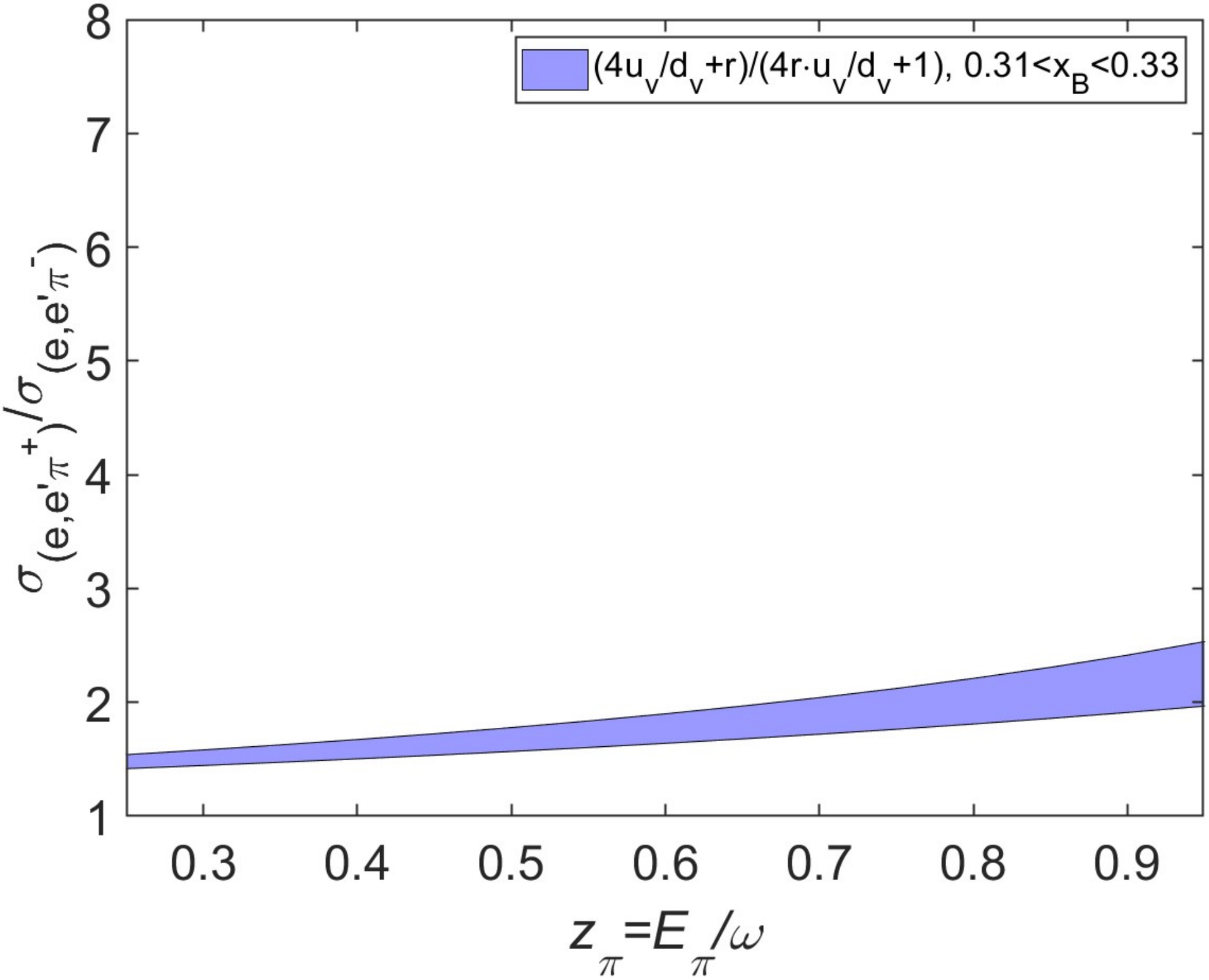


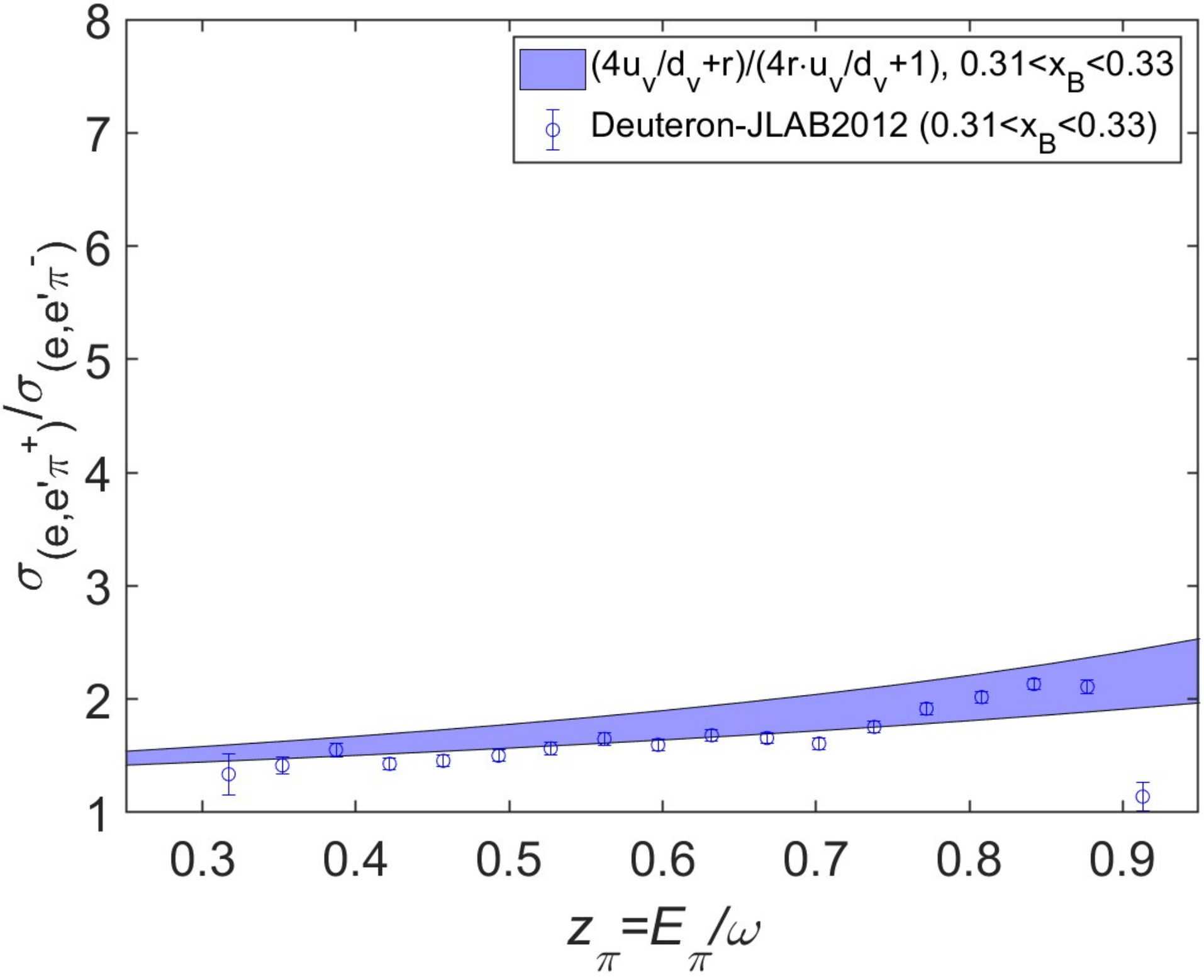
RGB + BAND: 10.2 GeV all data

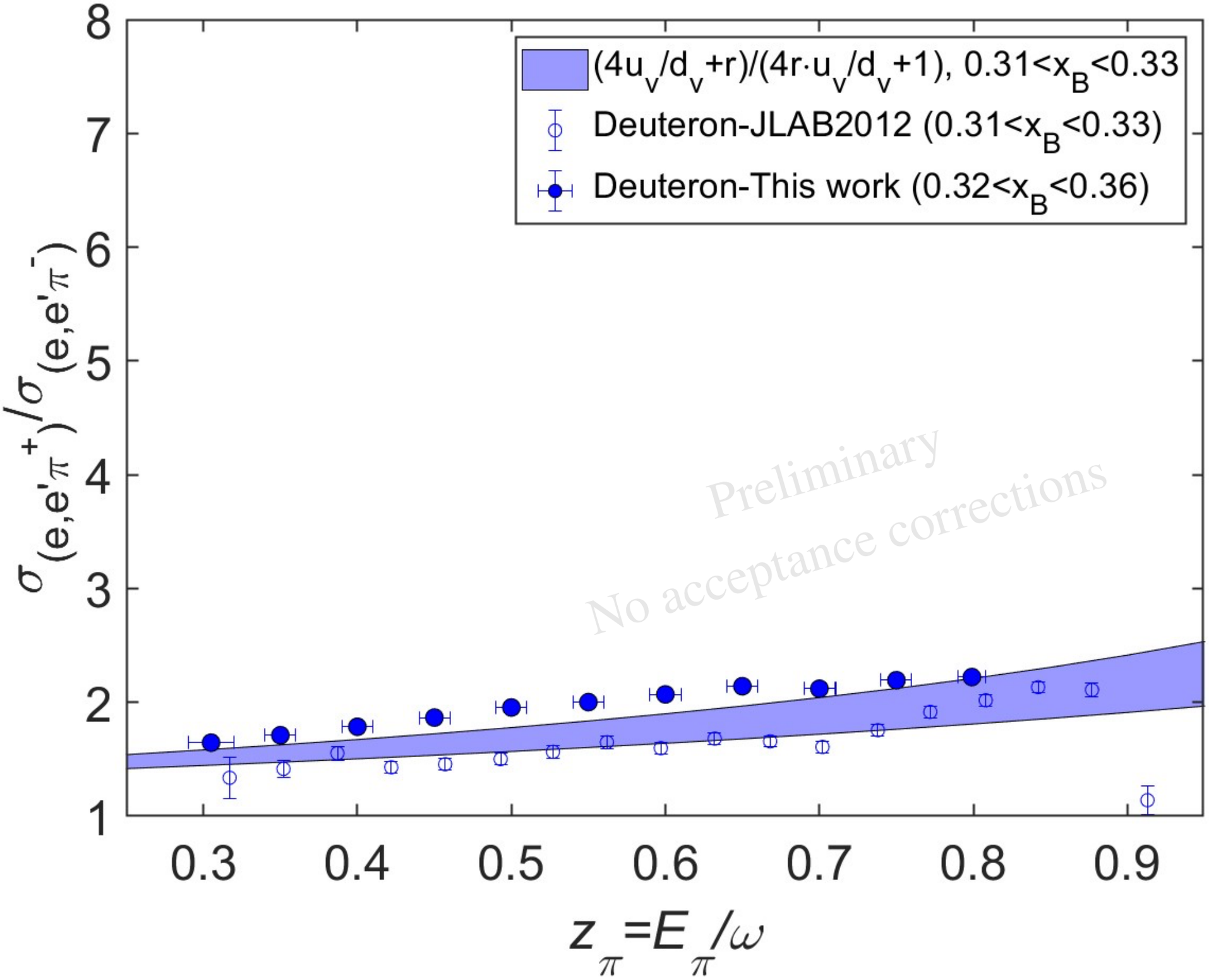
S_{RC}^{IDIS}@BAND

Results

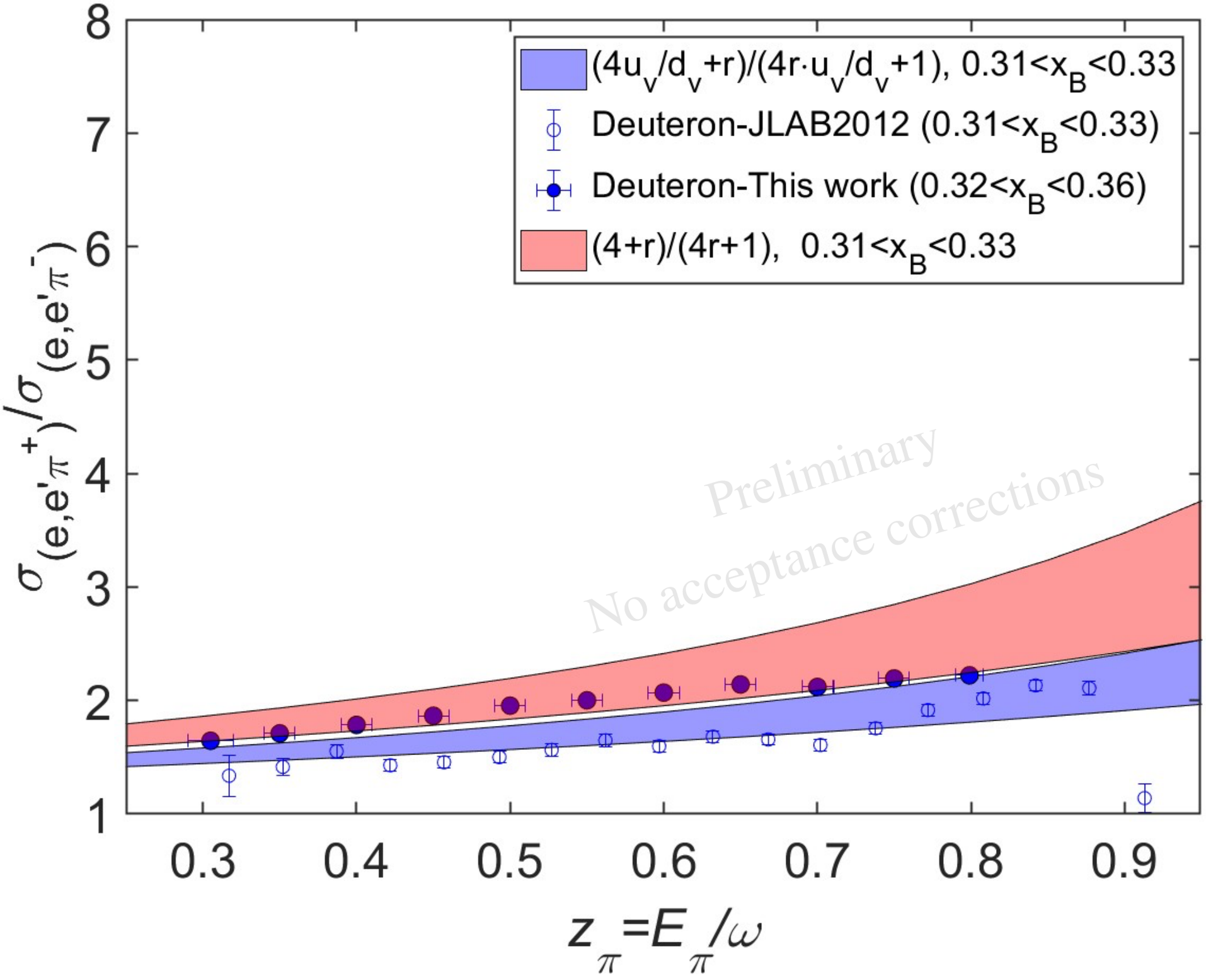
(Preliminary)


(4u_v/d_v+r)/(4r·u_v/d_v+1), 0.31<x_B<0.33
σ(e,e'π+)/σ(e,e'π-)
z_π=E_π/ω
1
2
3
4
5
6
7
8
0.3
0.4
0.5
0.6
0.7
0.8
0.9

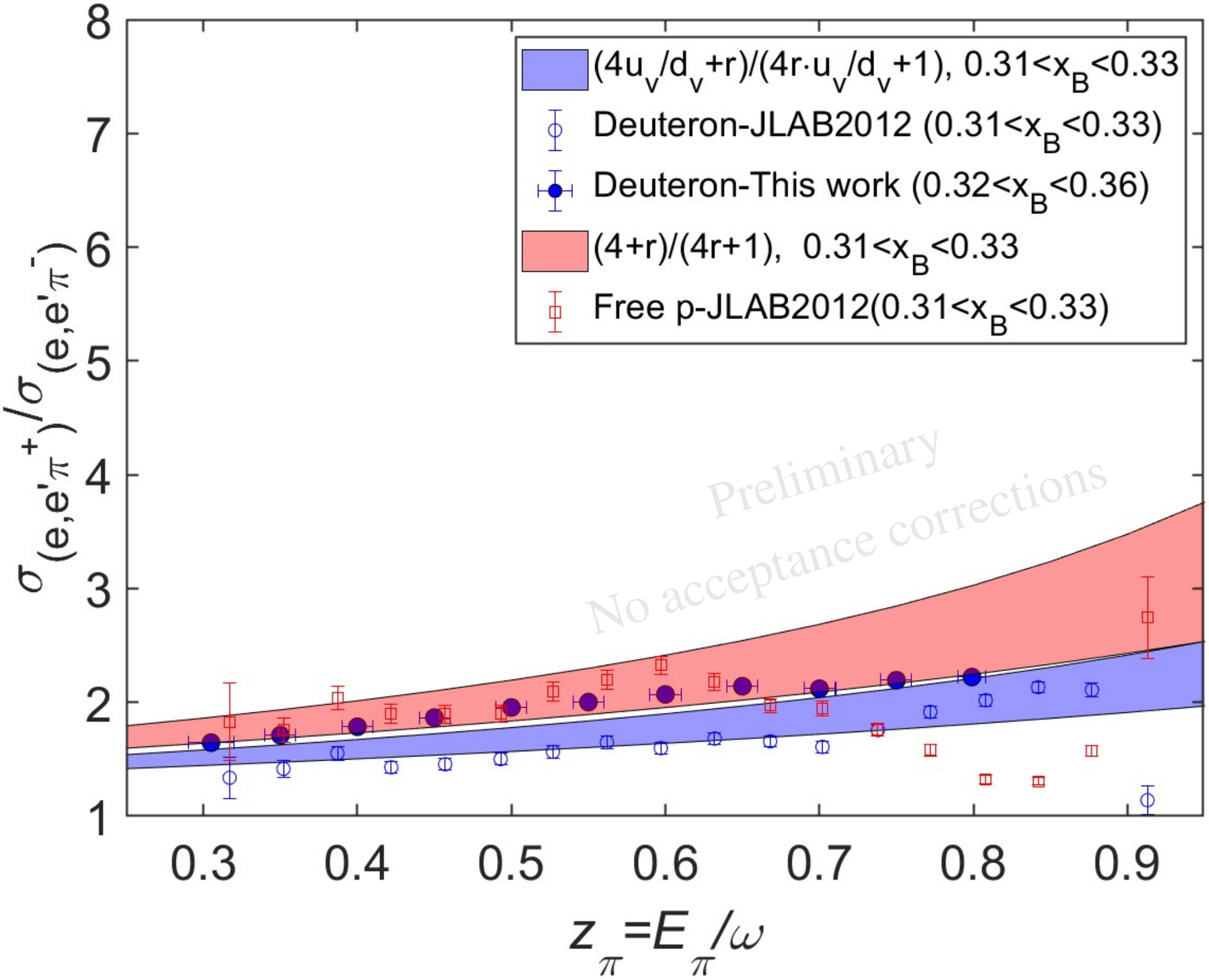

(4u_v/d_v+r)/(4r·u_v/d_v+1), 0.31<x_B<0.33
Deuteron-JLAB2012 (0.31<x_B<0.33)
σ(e,e'π+)/σ(e,e'π-)
z_π=E_π/ω
8
7
6
5
4
3
2
1
0.3
0.4
0.5
0.6
0.7
0.8
0.9



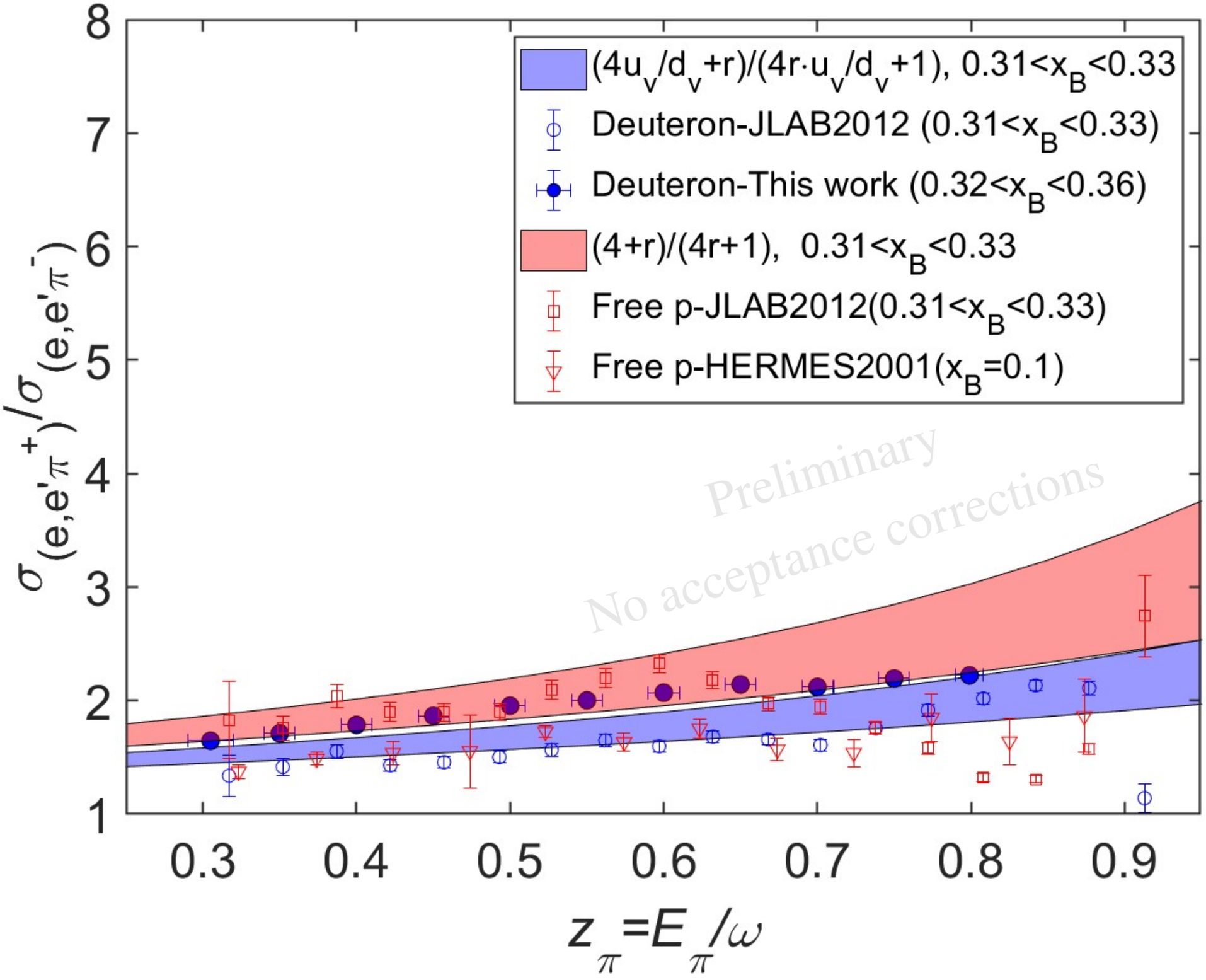
RGB + BAND: 10.2 GeV all data



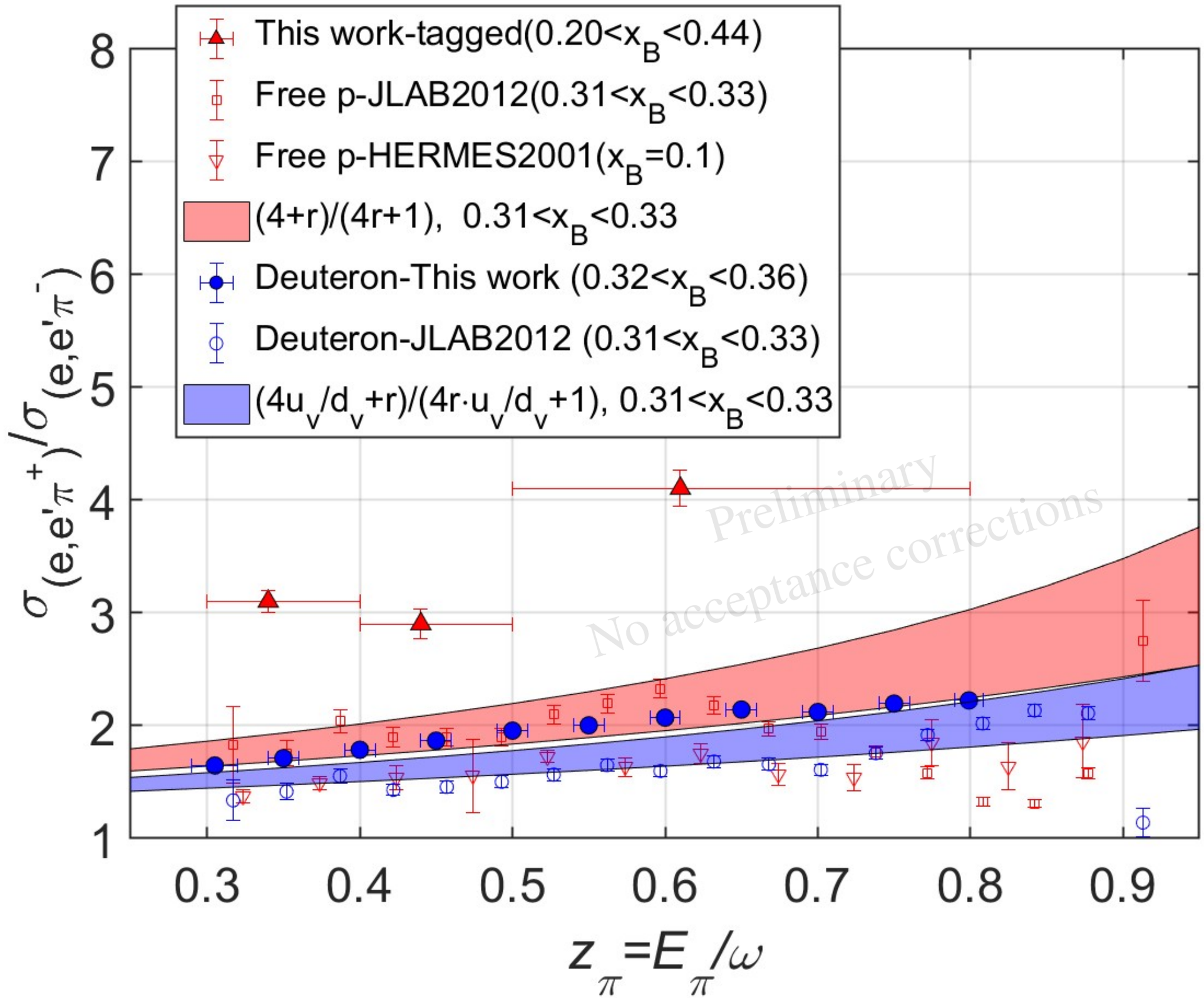
RGB + BAND: 10.2 GeV all data



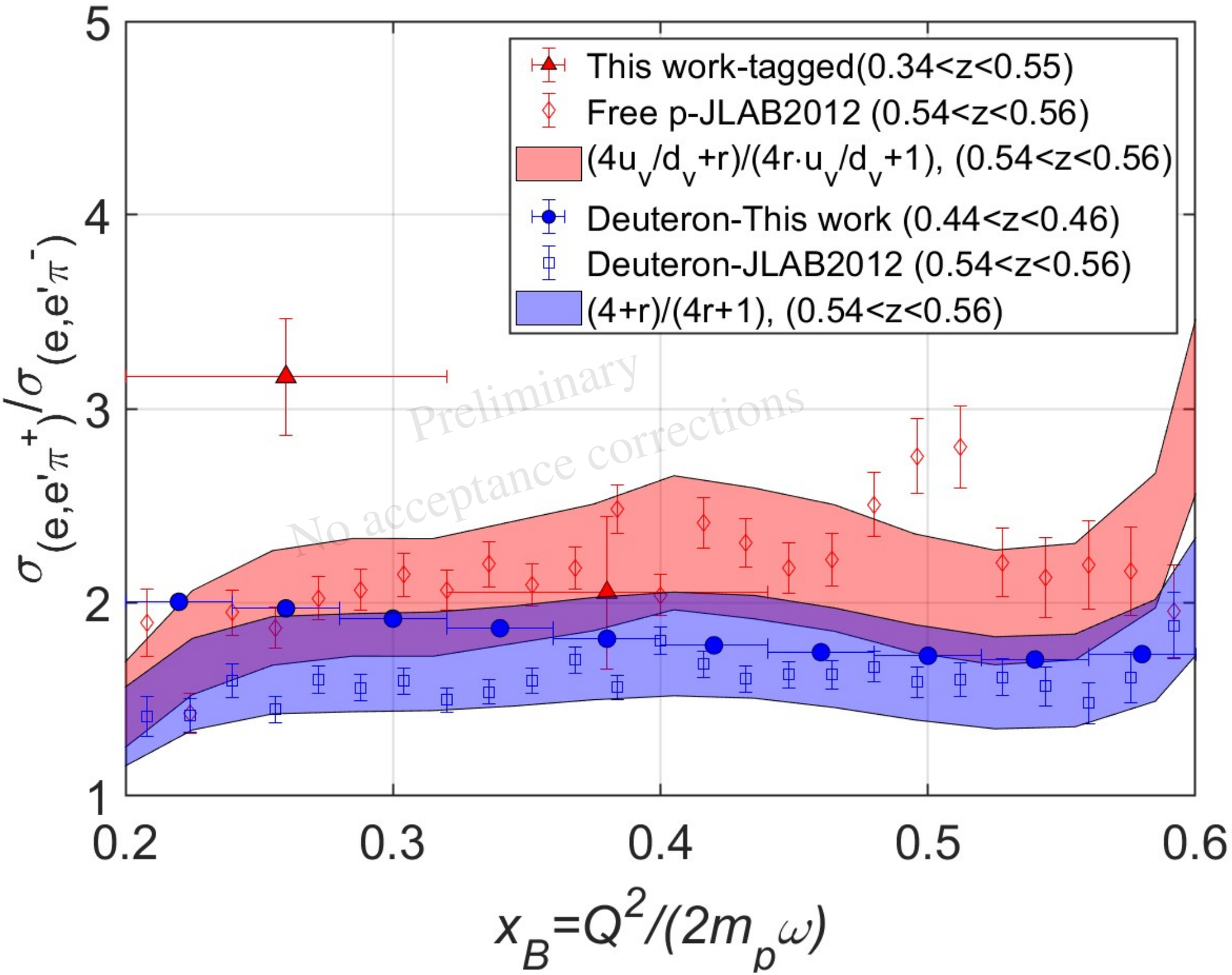
RGB + BAND: 10.2 GeV all data



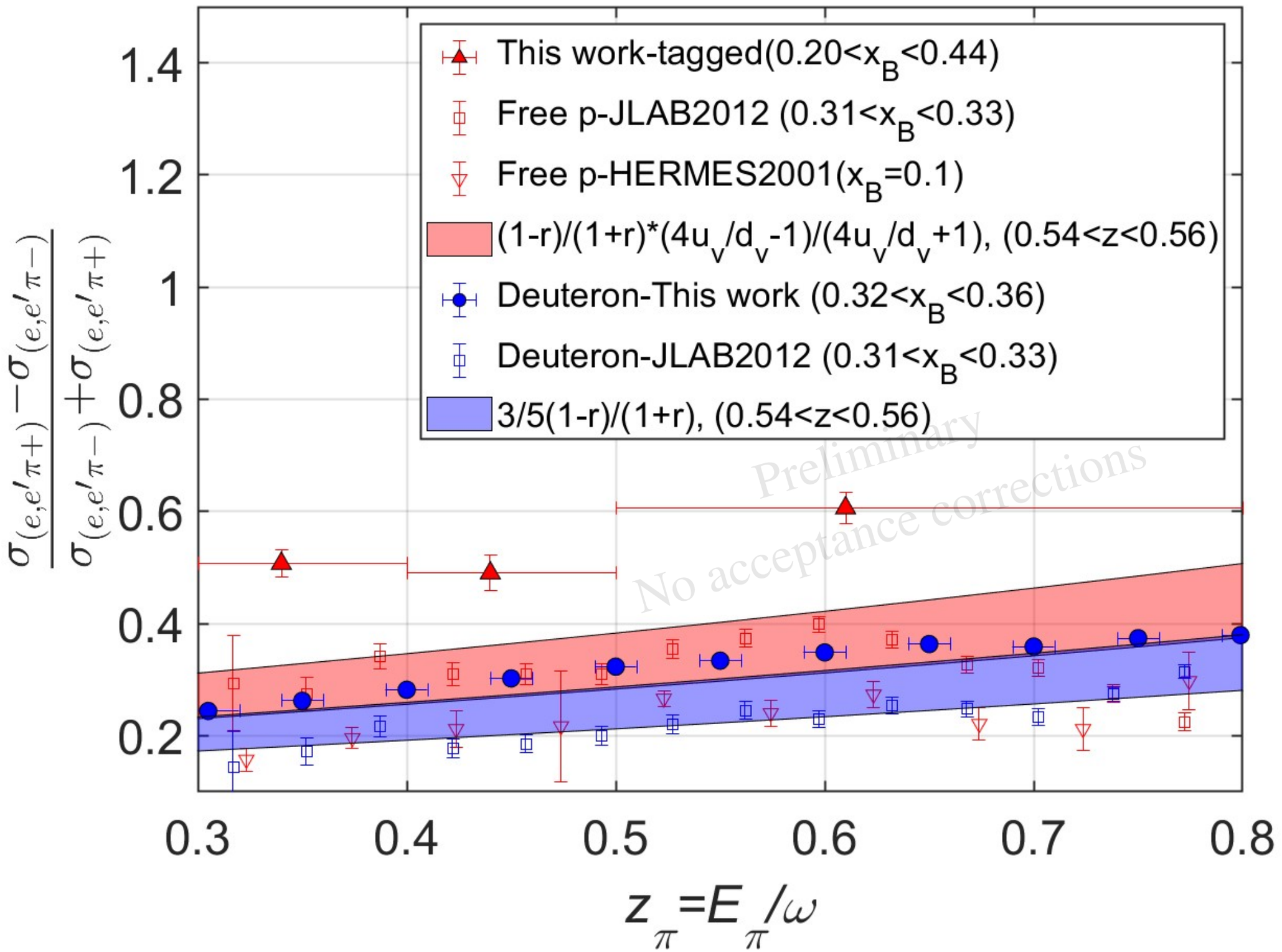
RGB + BAND: 10.2 GeV all data



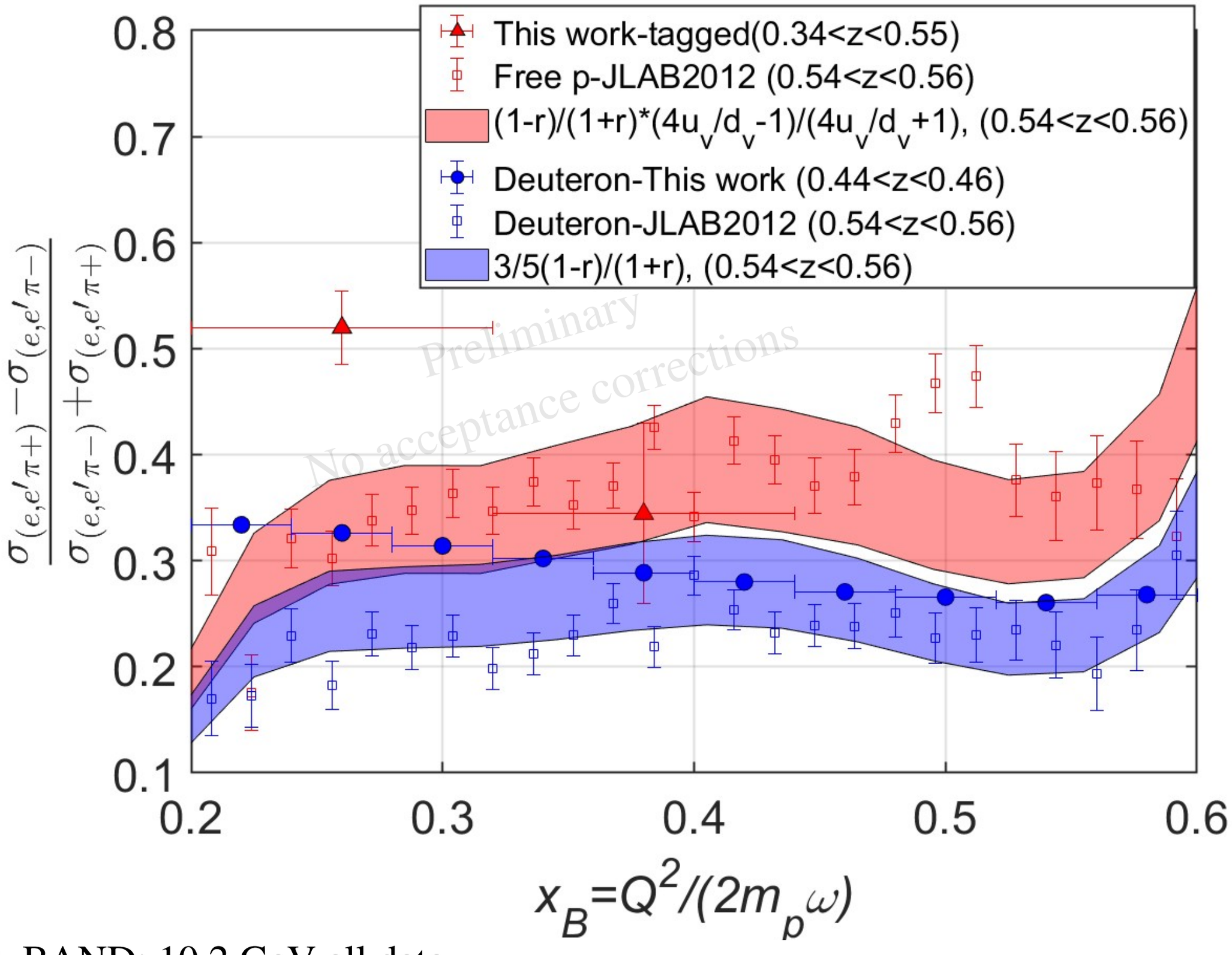
RGB + BAND: 10.2 GeV all data



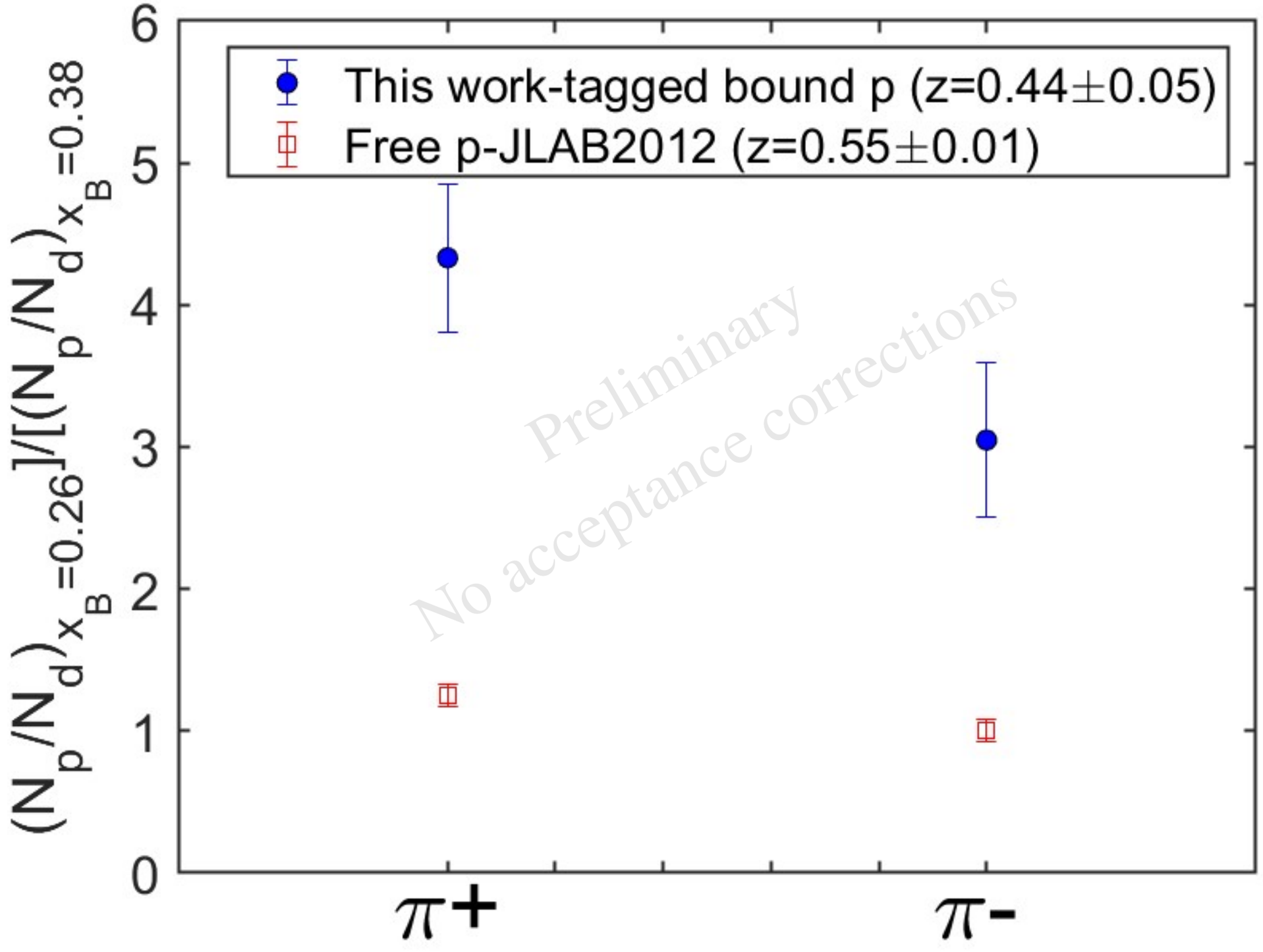
RGB + BAND: 10.2 GeV all data



RGB + BAND: 10.2 GeV all data



RGB + BAND: 10.2 GeV all data



RGB + BAND: 10.2 GeV all data

- These data do not include acceptance corrections
- Nor they account for recoil neutron random subtraction

Within Parton model terminology:

- The structure of free and high-virtuality p are different
- The effect is large
- Expected if EMC is dominated by 10-20% of the nucleons:

$$\sim 10\% \times (5-10) \sim 100\,\%\ \text{effect}$$

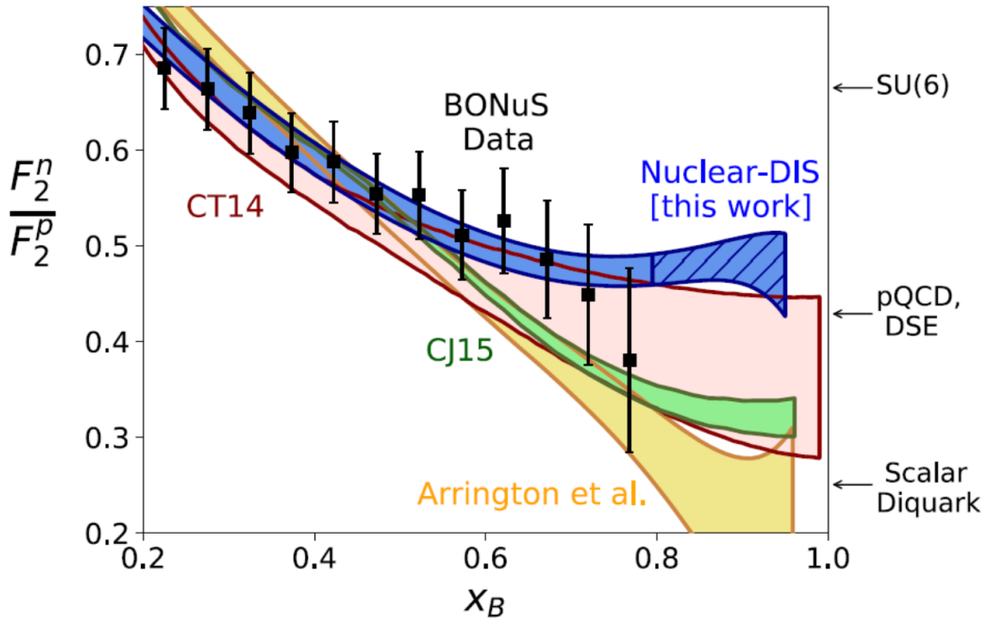
- Most of the medium-modified quarks have moderate x_B
- The effect is flavor-dependent $u^*/d^* \sim 2u/d$

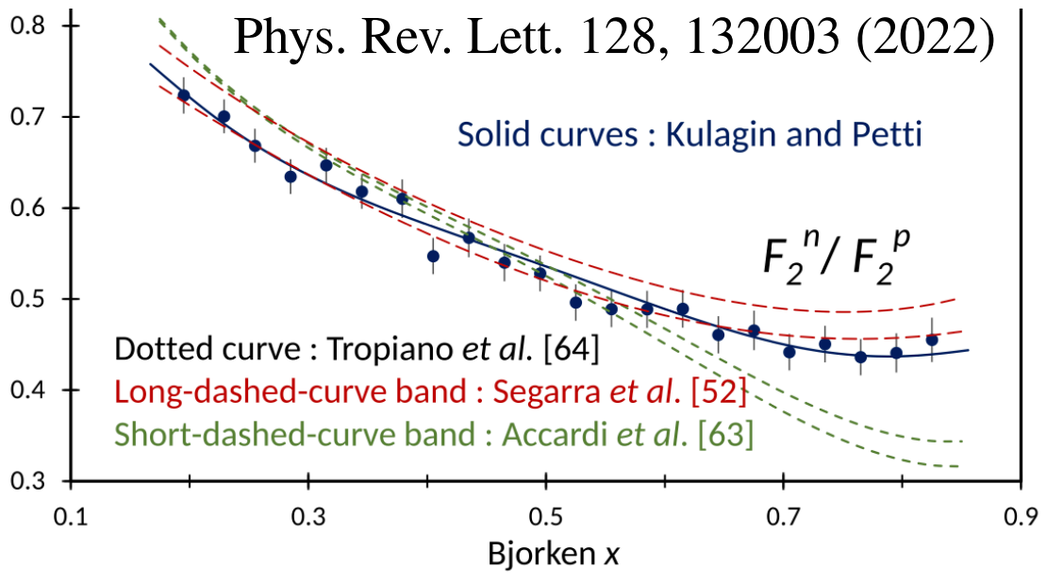
S_{RC}^{IDIS}@BAND | Summary - 2

- The EMC/SRC in deuteron changes F_2^n/F_2^p and extracted u/d, MARATHON data agree.
- Are our new SIDIS results at small x_B consistent with this picture?
- How can we explain the u/d modification in the Parton model?

Phys. Rev. Lett. 106, 052301 (2011)

Phys. Rev. Lett. 124, 092002 (2021)





S_{RC}^{IDIS}@BAND | Future plans

- Acceptance correction
- Recoil random-*n* subtraction
- Add free proton data (RGA)
- Add 10.6 and 10.4 GeV
- Publication plans:
  - untagged cross-section ratio
  - tagged cross-section ratio
  - tagged/untagged cross-section super ratio
  - asymmetry

S_{RC}^{IDIS}@BAND | ToDo list

Task	Responsibility	Priority	Estimated Time
p_T of the pion with respect to the virtual photon for each x_B and z bin in the final results	Erez	1	1 week
W' vs. M_X - for the untagged and tagged data, to see if we are in the resonance region or in the DIS one	Erez	2	1 day
Analyze first free-proton file from RGA	Erez	3	1 day
z vs. $z_{light\text{-}cone}$ (z') - for untagged and tagged data	Erez	4	1 week
The invariant mass of the un-detected system: $(q + d - n - \pi)^2$	Erez	5	1 month
Analyze (e,e') data to extract ratio of (e,e'π^+) + (e,e'π^-) to (e,e')	Erez	6	3 months
Subdivide p_n distribution to the two separate x_B bins for the tagged data	Erez	7	1 day
Tagged neutron hit position in the BAND detector	Erez	Done	1 day
θ_n and φ_n for each bin x_B and z in the final results	Erez	Done	1 week
Raise the cut on W to > 2.5 for the untagged to match the tagged data kinematics	Erez	Done	1 hr
W vs. W' - for the moving proton (tagged data)	Erez	Done	1 day
untagged Nπ+ vs. Nπ- and Nπ+/Nπ- vs Q^2 **untagged Nπ+ vs. Nπ- and Nπ+/Nπ- vs W** **tagged Nπ+ vs. Nπ- and Nπ+/Nπ- vs Q^2** **tagged Nπ+ vs. Nπ- and Nπ+/Nπ- vs W**	Erez	Done	1 day
Analyze 10.6 GeV data	Erez		1 month
Analyze 10.4 GeV data	Erez		1 month
Produce neutron skimming files with a relaxed cut on p_n>150 MeV/c	Florian/Igor		?
Correct for random neutrons	MIT		?
Correct for random pions	MIT		?
Estimate systematic uncertainties (Results with modified cuts…)	MIT		?
Analyze all available data from RGA	Erez		1 month
Polish comparison plots (Reference u/d to other data / refs. Instead of Chinese)	Ofer		?
Produce asymmetry plots	Ofer		?
Apply acceptance corrections	MIT		?
Write analysis note	Erez		2 months
Write paper draft	Eli		?

Thanks for your time

Free p-JLAB2012	PRC 85, 015202 (2012)
Deuteron-JLAB2012	PRC 85, 015202 (2012)
r parameterization	N. Kalantarians, Thesis U. Houston (2008) Nucl. Phys. A 782 142 T. Navasardyan, Thesis U. Yerevan (2007)
u/*d* parameterization	PhysRevLett.128.132003

Backup

- Again, we write the cross sections in the naive Parton model

$$\sigma_p^{\pi^+} \propto 4u_v + rd_v + (sea\ contributions)$$
$$\sigma_p^{\pi^-} \propto 4ru_v + d_v + (sea\ contributions)$$

- And neglecting see contribution we obtain for a free proton

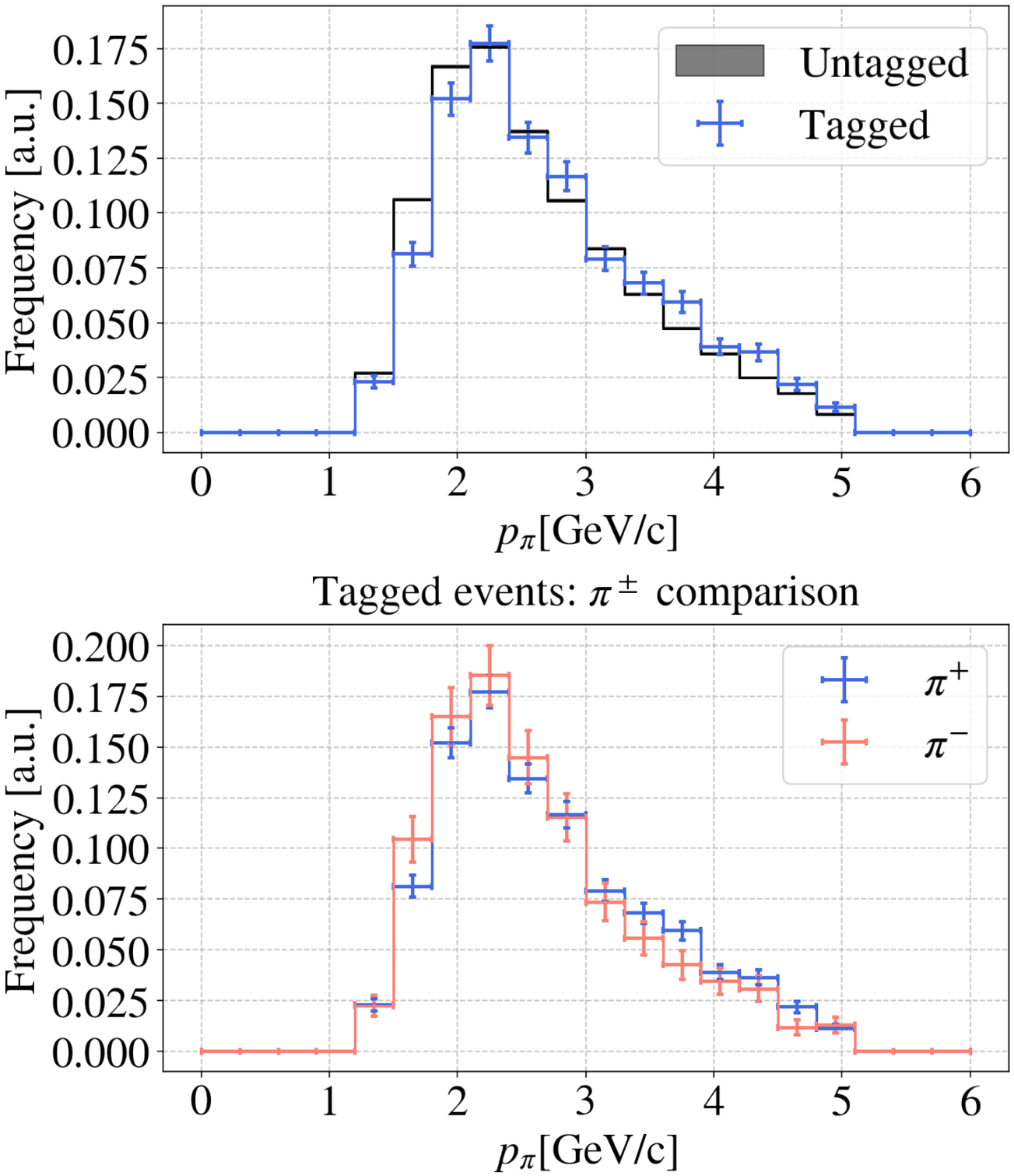
$$\sigma_p^{\pi^+}/\sigma_p^{\pi^-} \sim \frac{4(u_v/d_v) + r}{4r(u_v/d_v) + 1}$$

- For a bound proton in a deuteron, we simply write

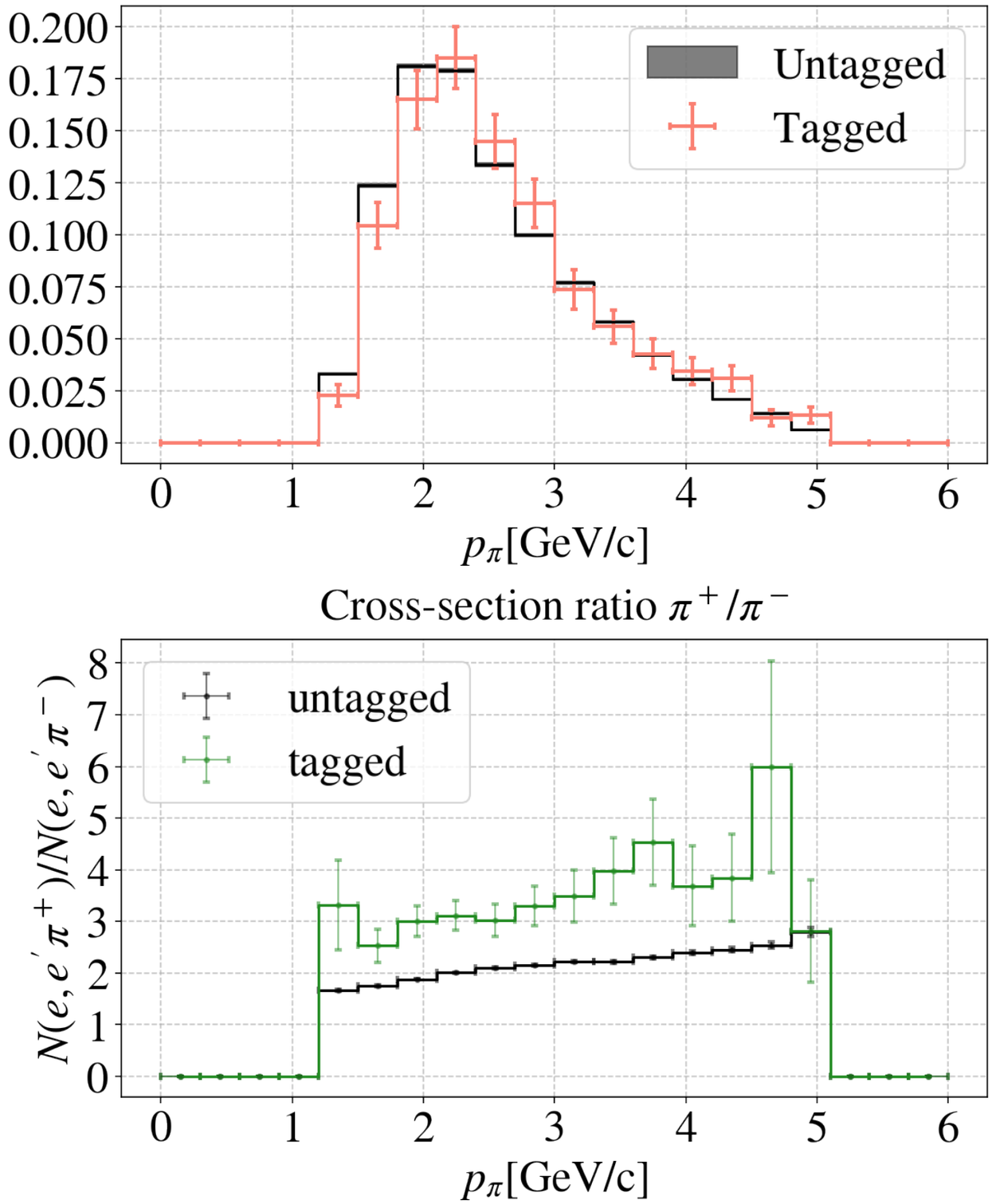
$$\sigma_{p\ in\ d}^{\pi^+}/\sigma_{p\ in\ d}^{\pi^-} \sim \frac{4(u_v^*/d_v^*) + r}{4r(u_v^*/d_v^*) + 1}$$

S_{RC}^{IDIS}@BAND | Kinematical distributions - π momentum

$(e, e'\pi^+)$ events as a function of p_π



$(e, e'\pi^-)$ events as a function of p_π



Tagged events: $\pi^\pm$ comparison

Cross-section ratio π^+/π^-