

CLAS12 e4ν 1 proton analysis

P. Barham Alzás
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CLAS Collaboration meeting

18/11/2026

e4ν - The Electrons for Neutrinos Collaboration



The collab at Jefferson Lab

Visit our new website!
e4nu.org

e4ν - Electrons for Neutrinos

We use electron scattering data to tackle uncertainties in the neutrino-nucleus interaction model. From a generator perspective...

$$d\sigma_X(F) \simeq \sum_{N=p,n} \int d^3p\, dE \; \underbrace{P_N(\mathbf{p}, E)}_{\text{initial nuclear state}} \; \overbrace{d\widehat{\sigma}_{XN\to\ell Y}}^{\text{primary electroweak vertex}} \; \underbrace{\mathcal{K}_A(F \mid Y, \mathbf{p}, E)}_{\text{FSI / hadronic transport}} + d\sigma_X^{\text{2-body}} + \cdots$$

Ingredient	eA	νA
$P_N(\mathbf{p}, E)$	same nuclear target	same nuclear target
vector primary current	$V_{(0)} + V_{(3)}$	$V_{(\pm)}$ from CVC/isospin
axial primary current	absent	$A_{(\pm)}$
$\mathcal{K}_A$	strong FSI	same strong FSI, conditionally

If your neutrino generator cannot describe electron data, it's wrong!

Ongoing analyses

First CLAS12 results on argon! Key for DUNE and other LAr neutrino experiments

New CLAS12 analyses are underway (2020-2022 data): high stats and angular coverage at 2, 4, and 6 GeV.

- C and Ar inclusive (Matan Goldenberg - **Previous talk!**).
- C and Ar two nucleon analysis - 2p vs 1p1n (Alon Sportes).
- C and Ar 1p0π and 1n0π (me - Pablo Barham).
- Pion transparency (Brandon Eberly).

New CLAS6 analysis under internal review: 1p1π (Júlia Tena)

And more on the way!

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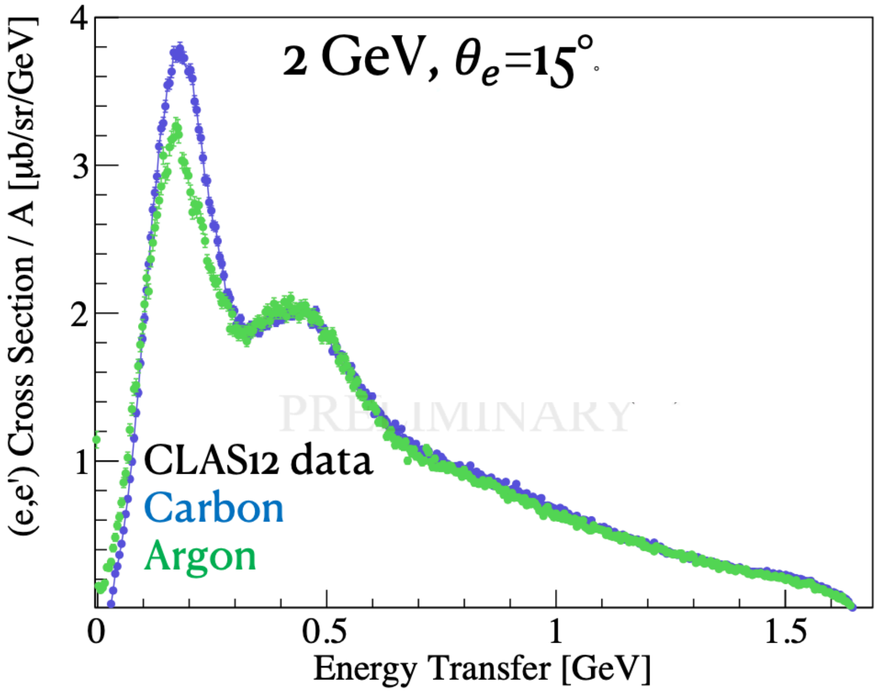
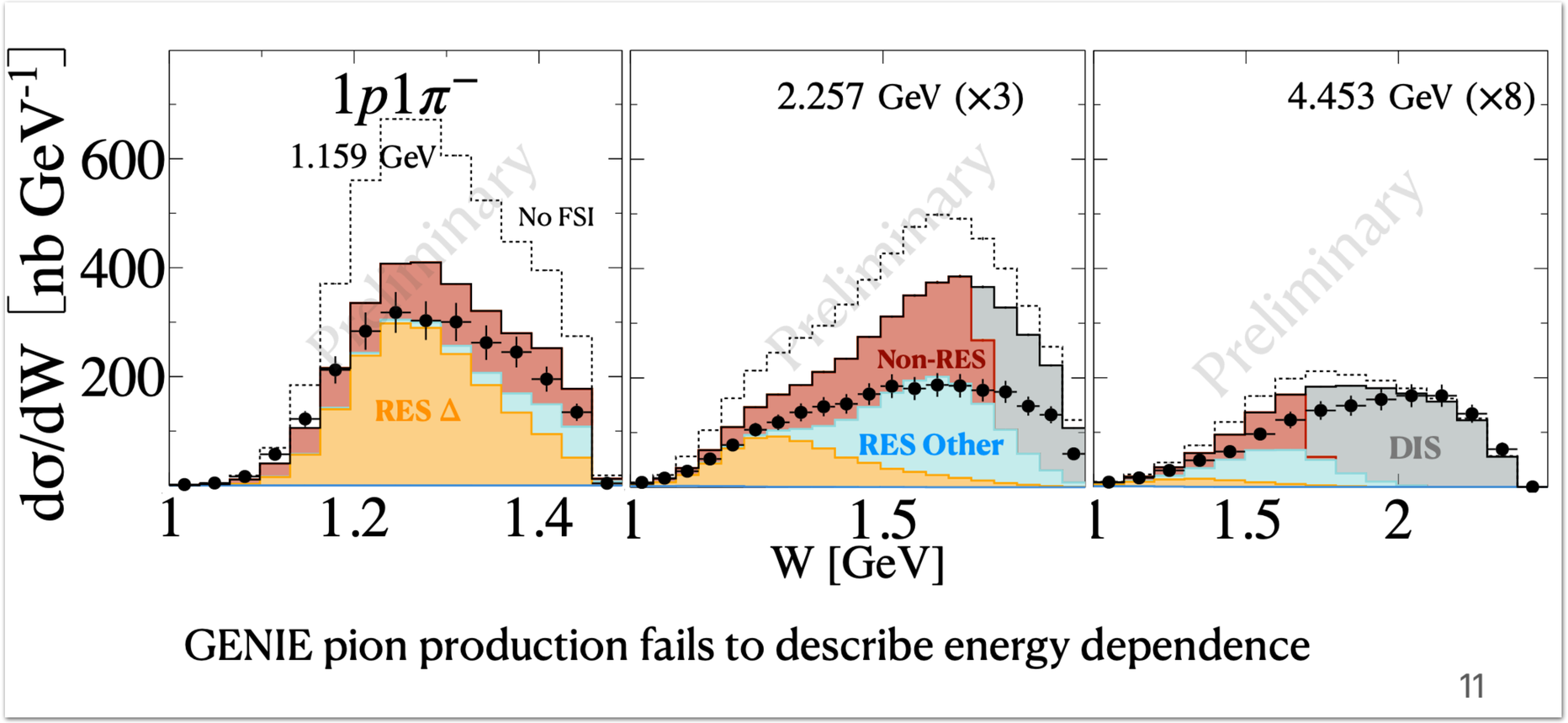


Inclusive C vs. Ar CLAS12 data (M. Goldenberg)
Available for multiple angles!

CLAS6 1p1π (J. Tena)

From J. Tena ICHEP 2026

dσ / dW



CLAS12 1p0π analysis - New results

Analysing 1p0π gives us information about the 1-body response:

- One-body spectral functions $S(E, p)$.
- Vector QE response, and constraints to 2p2h, RES contributions.
- FSI information through kinematic imbalances (TKIs, GKIs).
- Energy reconstruction biases.

High statistics enable double- and even triple-differential results.

Extension to 1n0π analysis possible!

First ever QE-like measurement on argon!

CLAS12 1p0π analysis - New results

- **Exactly 1 e^-, exactly 1 p, no charged pions or gammas above threshold.**
- **Two targets to study A-dependence:**
  - **^{40}Ar at 2, 4, and 6 GeV.**
  - **^{12}C at 2, 4, and 6 GeV.**

First ever QE-like measurement on argon!

Datasets:

- **Experimental data:** full RG-M Pass-1 Ar/C production (13 runs, fall 2021).
- **G18 MC**: "Standard" **GENIE** with Rosenbluth QE + Valencia 2p2h.
- **GEM21 MC**: **GENIE** with SuSA v2 for QE + 2p2h.

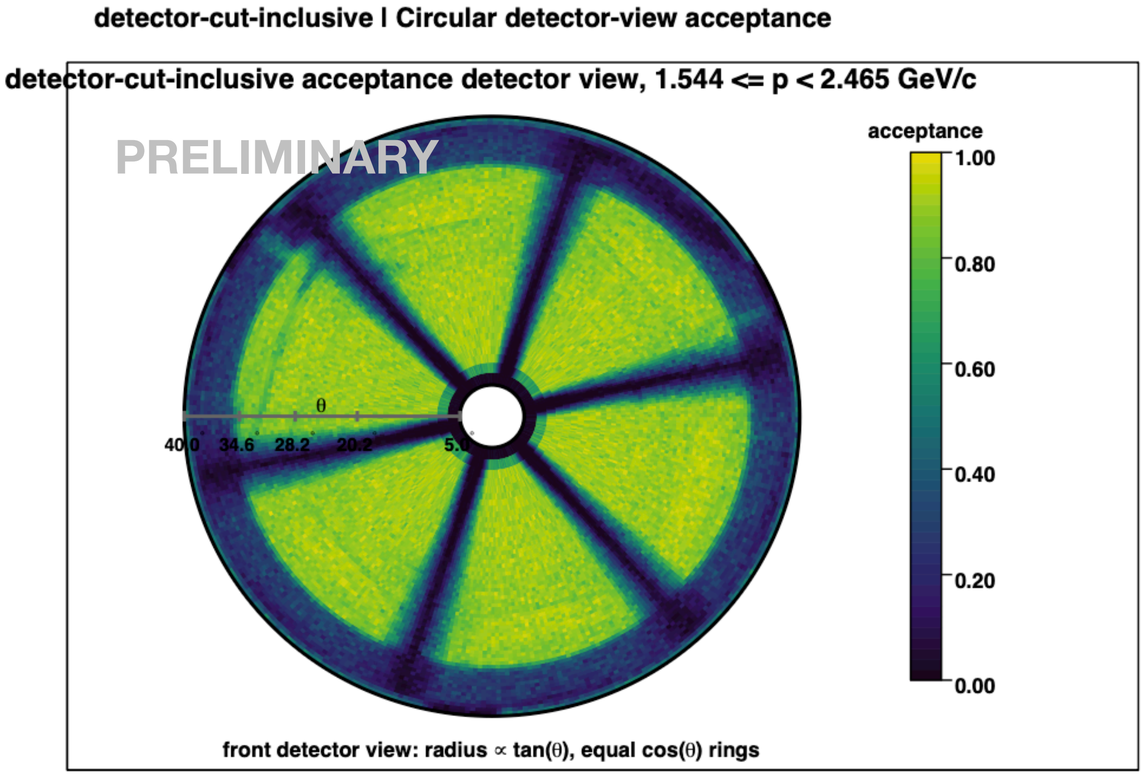
Acceptance maps

NEW! CLAS12 1p0π

- Computed for electrons, protons, and charged pions in FD and CD. ~86M events per map. **First high-res acceptance maps for CLAS12.**

- Used to estimate true event rates and the **higher-multiplicity background subtraction**.

- We zero out tracks with A>0.5 or for a given p, theta where coverage in phi is < 10%.



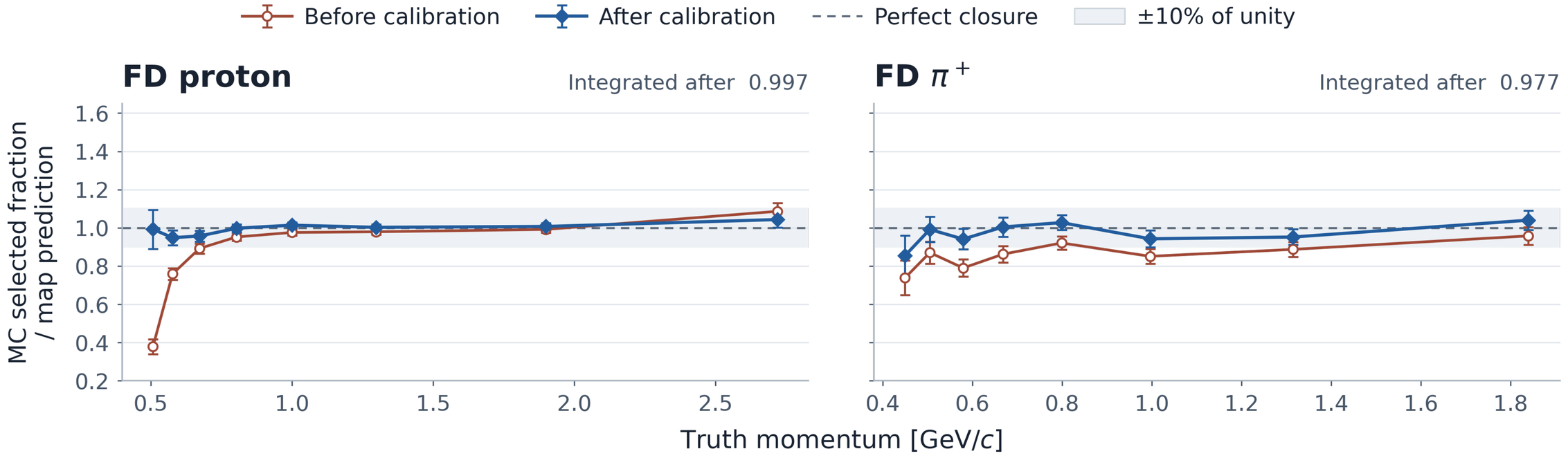
Proton FD

Acceptance maps: closure tests

NEW! CLAS12 1p0π

To test the accuracy of the acceptance maps, we run **closure tests** on MC data:

- Compare MC reconstructed fraction to that predicted by the map.
- Key finding: **factorization behaves well**.
- Other effects (extra particles, non-ideal electron, displaced vertex, track overlaps) lead to degradation in certain kinematic regions.

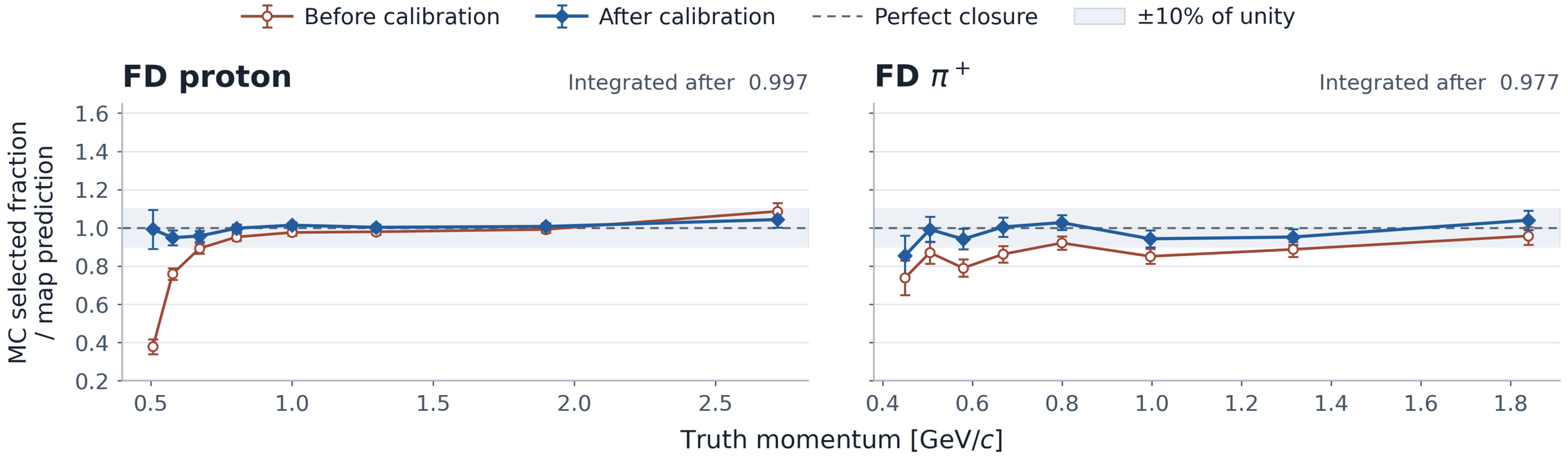


Acceptance maps: corrections

NEW! CLAS12 1p0π

- Logistic **correction** introduced to account for **discrepancies between the idealised regime the acceptance map generators were run in and the real MC data events** (extra particles, non-ideal electron, displaced vertex, track overlaps).

$$\text{logit}\, A_e^{\text{corr}} = \text{logit}\, A_e^{\text{raw}} + \delta_{\text{spatial}}(p, \theta, \phi) + \delta_p(p).$$



Higher-multiplicity background subtraction

CLAS12 1p0π

We want to estimate how often an observed signal track (1p0π in our case) comes from a true underlying event with a different topology. We do a **data-driven correction.**

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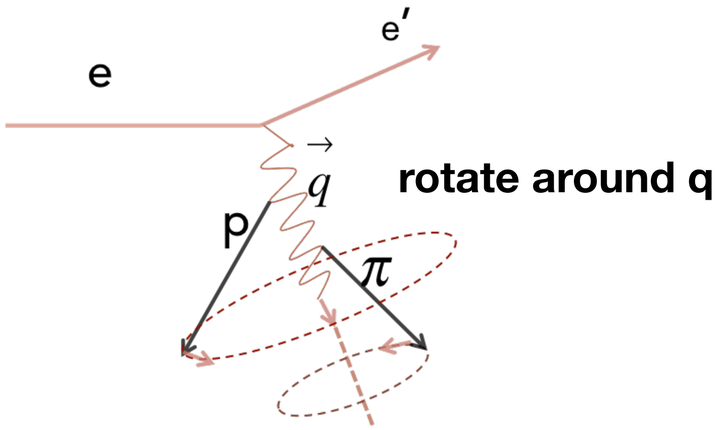

Take measured 1p1π events.

Rotate all hadrons together about **q,** exploiting approximate cross section invariance.

Determine fraction of times it appears as signal.

Higher-multiplicity background subtraction

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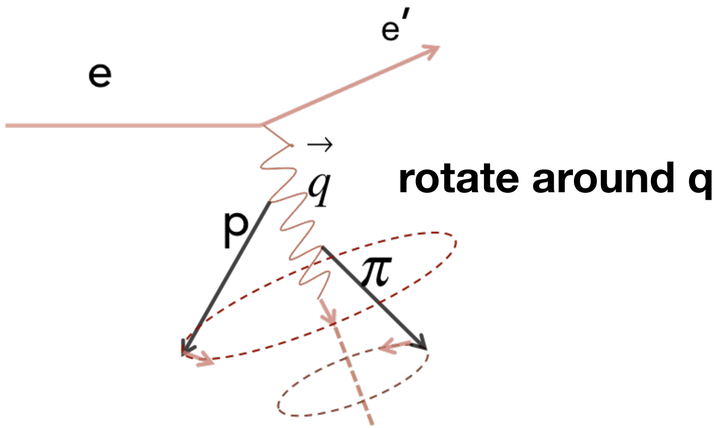

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2. Survival probability

For every charged particle, query the acceptance

$$A_i^{(r)} = A_i\left(p_i, \cos\theta_i, \phi_i^{(r)}\right)$$

Sum total contribution to signal from 1p1π events.

Higher-multiplicity background subtraction

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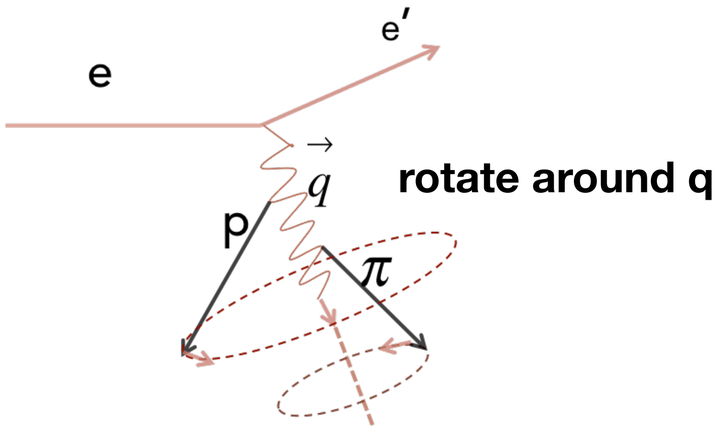

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3. Recursive subtraction

Repeat for 2p, 2p1π, 1p2π, etc..

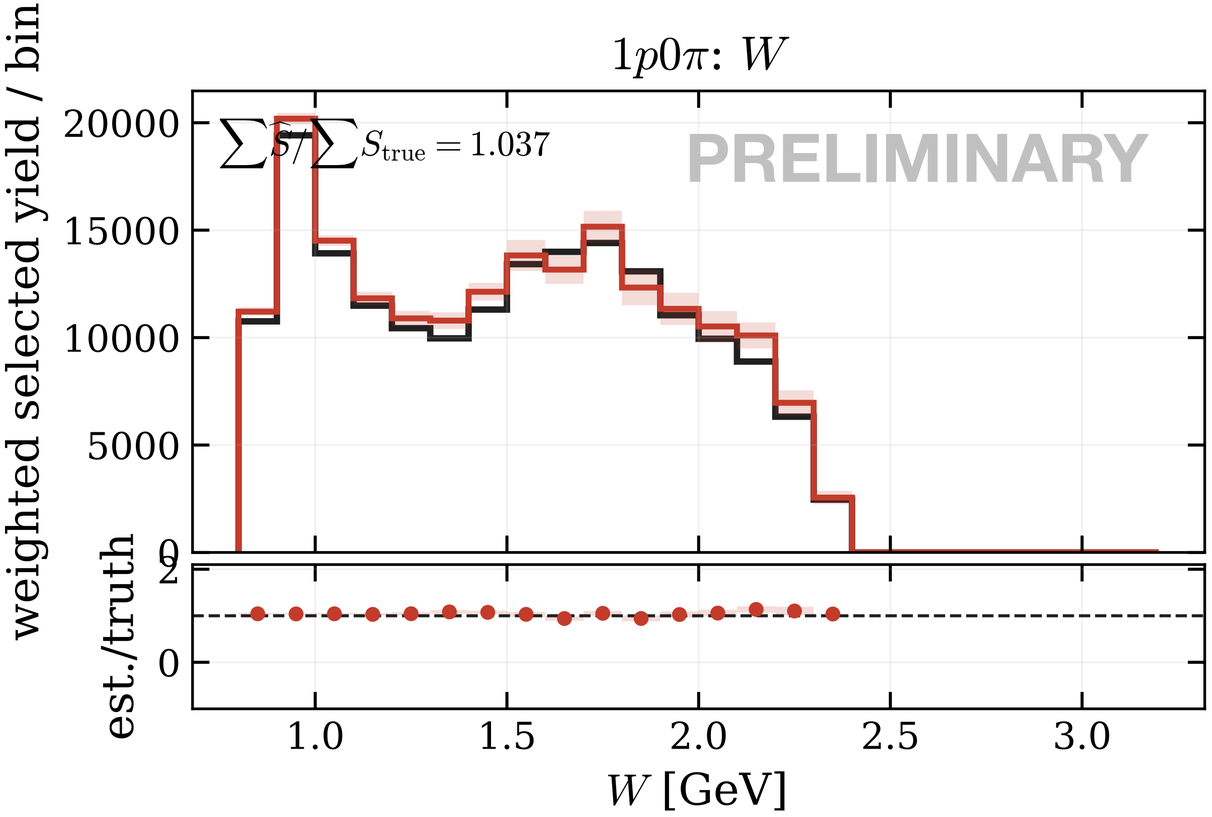
Higher topologies will contribute to the signal, both directly and **through intermediate topologies**.

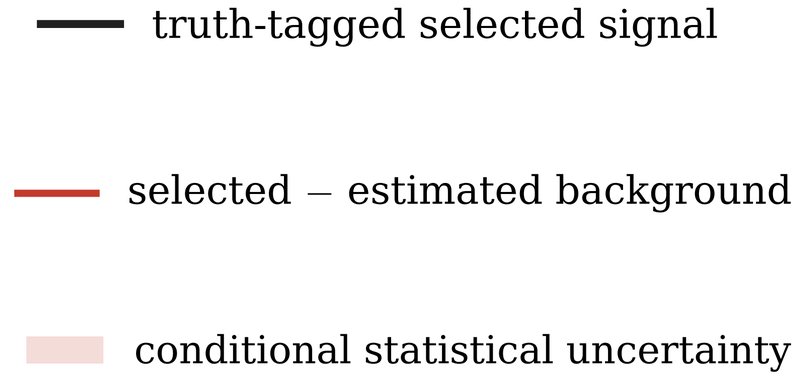
Background subtraction: MC closure

CLAS12 1p0π

Ar 4 GeV GEM21

- **We test our data-driven correction on MC data. Do we recover the true signal?**
- **Closure is robust across tunes, topologies and observables.**
- Non-closure impact is quantified as a systematic uncertainty.



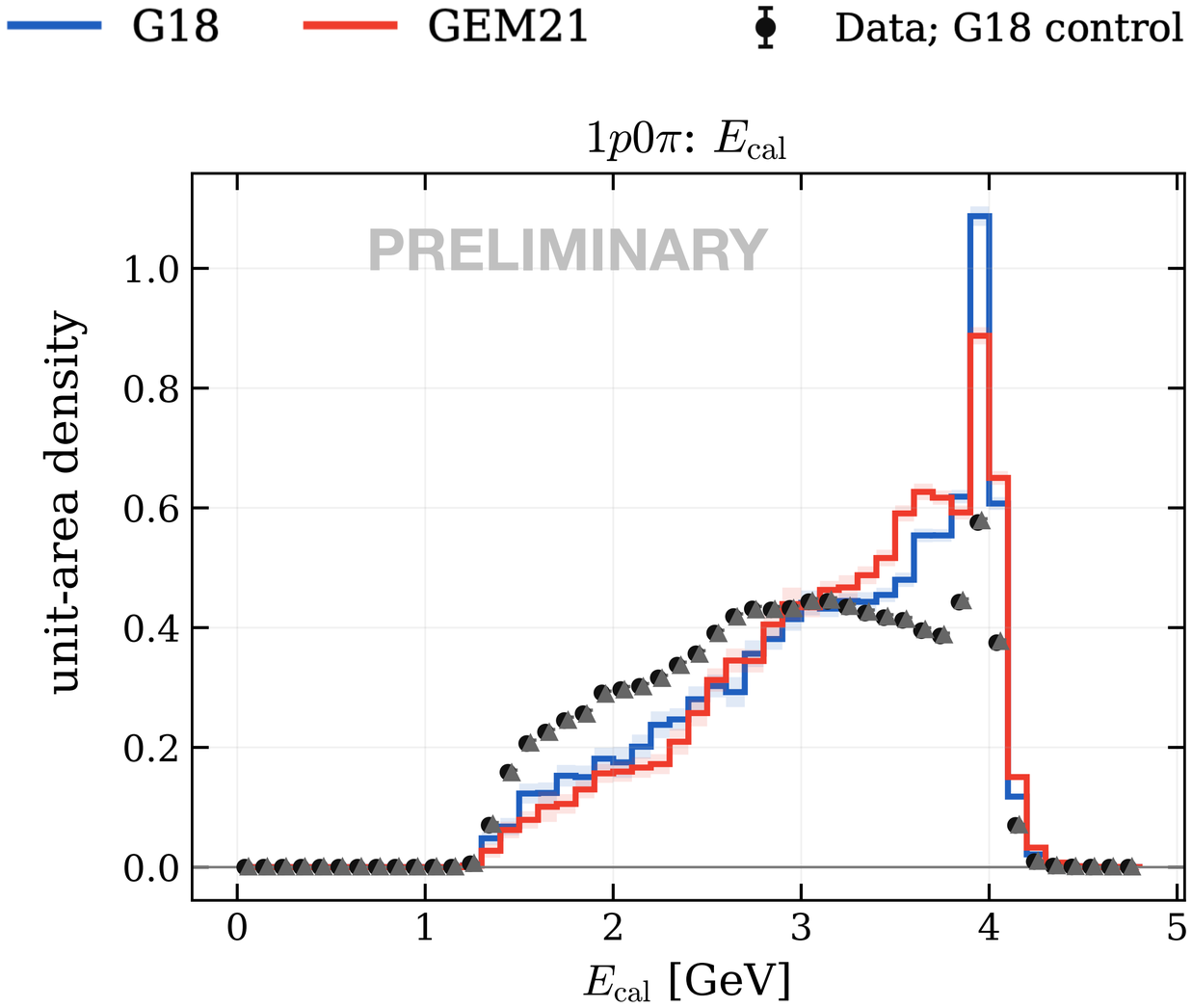


Uncertainties - Work in progress

NEW! CLAS12 1p0π

- **Statistics:** finite data/MC; finite control-rotation statistics.
- **Background subtraction:** per-bin truth–estimate discrepancies from G18 and GEM21, separated by tune, topology and observable. Next: cross-fold uncertainty estimates.
- **Acceptance maps:** electron/proton bin statistics and interpolation.
- **Analysis variations:** correction replicas, threshold/binning sensitivity, and $A \geq 0.50$ with ≥10% φ-support baseline.
- **Photon rejection uncertainties.**
- **In progress:** luminosity/target/radiative normalization, unfolding, and the broader detector-systematics program.

Results: observables (Argon 4 GeV)



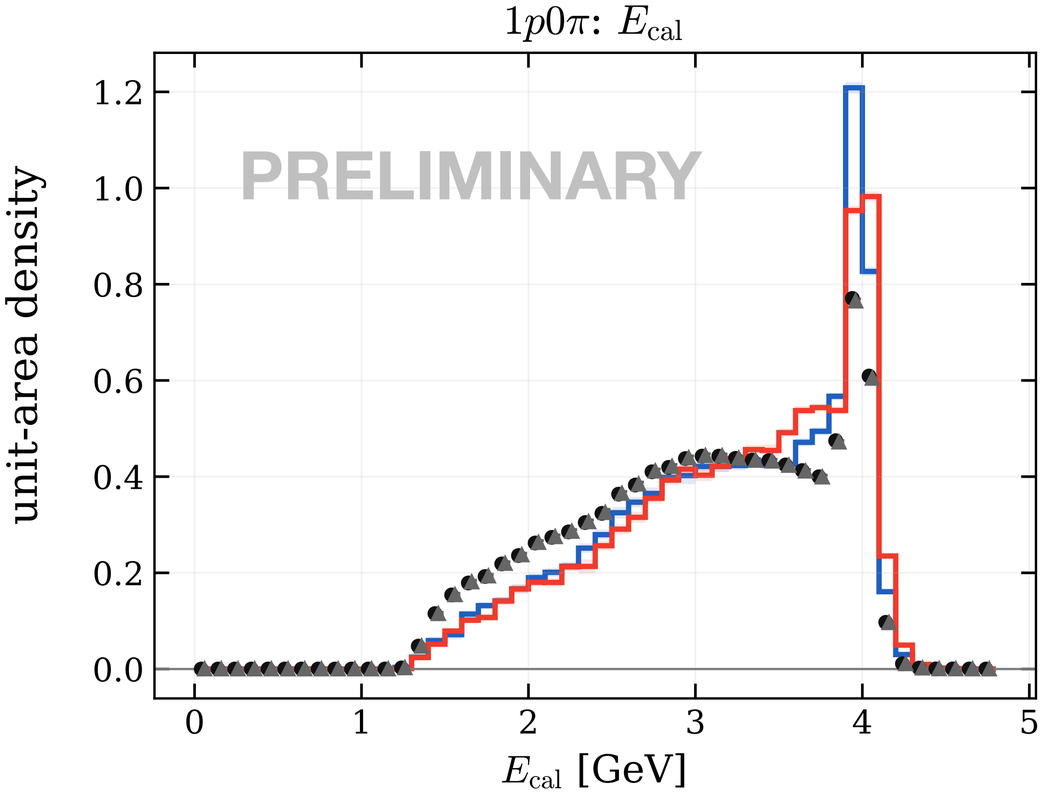
$$E_{\mathrm{cal}} = E_{e'} + T_p + \epsilon$$

- **Stat only (after background subtraction).**
- **Forward-folded.**
- **Shape-only comparison.**
- **Before radiative corrections.**

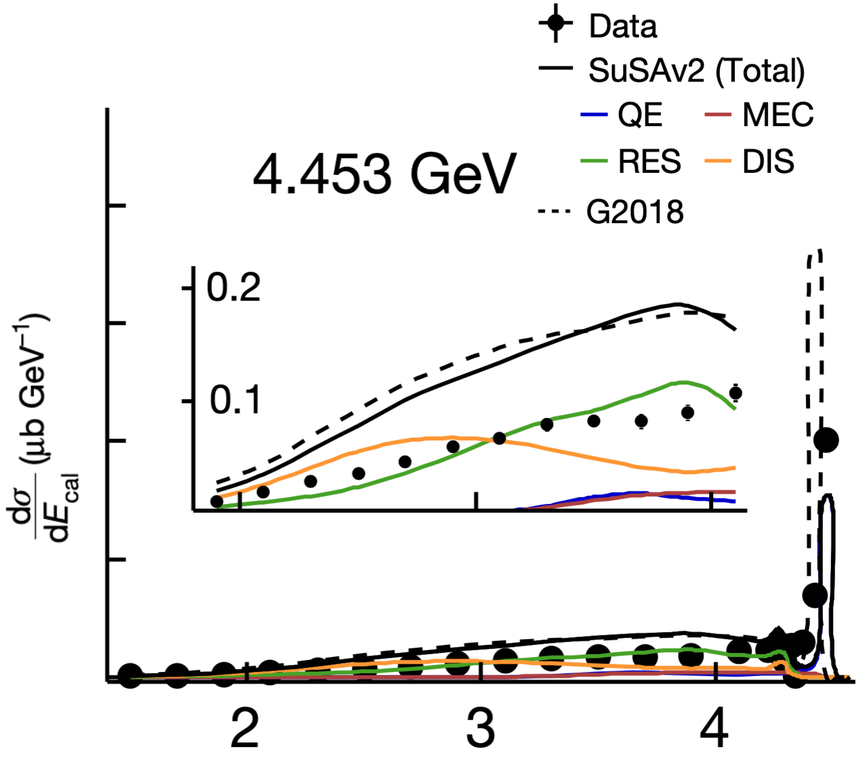
Results: observables (Carbon 4 GeV)

After background subtraction - stat only
Forward-folded
Shape-only comparison
No radiative corrections

G18 GEM21 Data; G18 control config Data; GEM21 control config



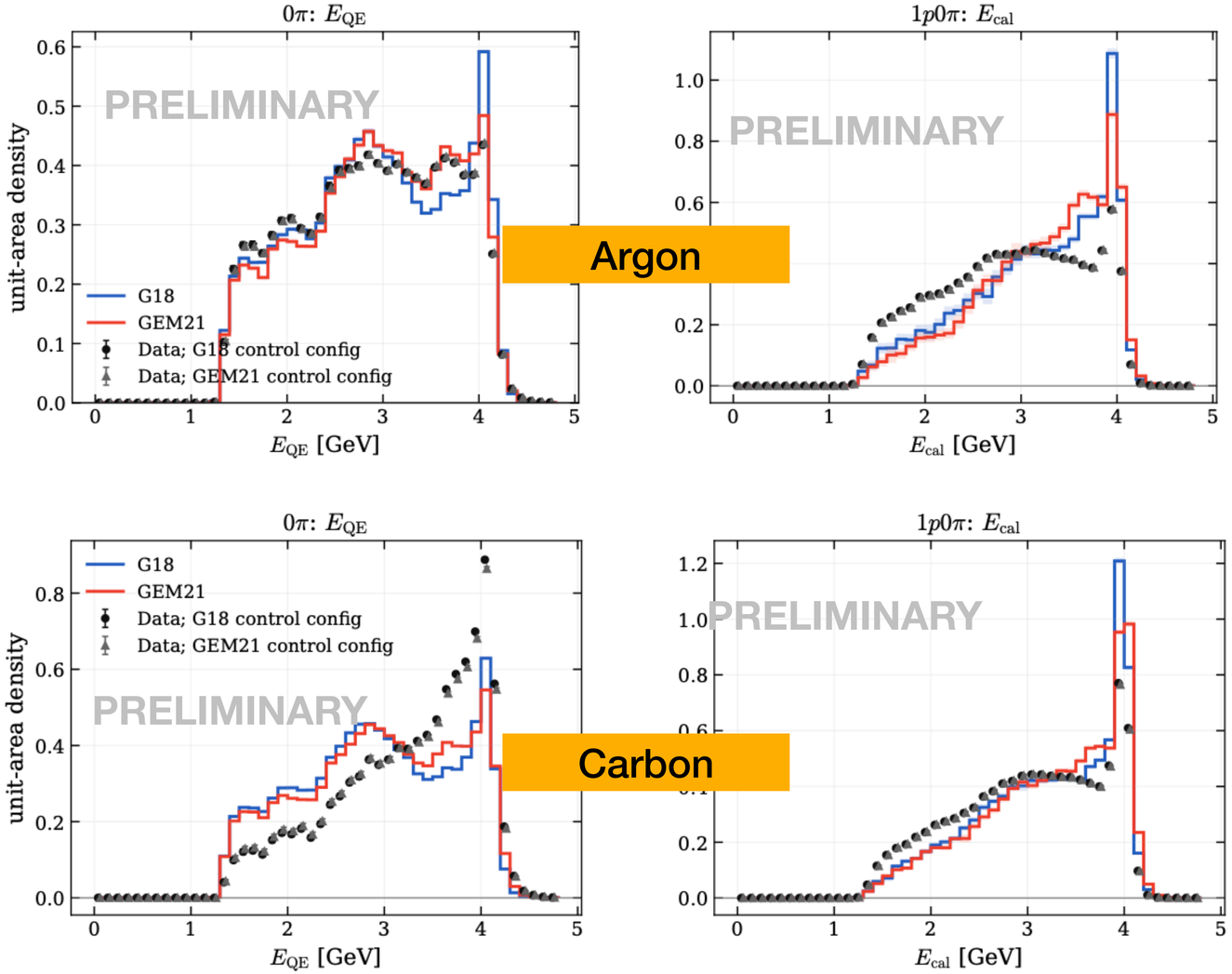
Not directly comparable



C12 from e4v Collaboration, *Nature* 599, 565–570 (2021). doi:10.1038/s41586-021-04046-5

Results: observables (4 GeV)

After background subtraction - stat only
Forward-folded
Shape-only comparison
No radiative corrections



$$E_{\text{cal}} = E_{e'} + T_p + \epsilon$$

$$E_{\text{QE}} = \frac{2m_p\left(E_{e'} + \epsilon\right) - m_e^2}{2\left(m_p - E_{e'} + p_{e'}\cos\theta_{e'}\right)}$$

Energy reconstruction predicted by our generators is biased.

The $E = E_{\text{beam}}$ peak is not seen as strongly by data.

Stay tuned!

- **New analyses being finalised**
  - CLAS6 1p1π
  - CLAS12 1p/1n
  - CLAS12 inclusive
  - CLAS12 pion transparency + multi-nucleon
- **High stats will allow for qualitatively new results (double/triple differential, exclusive) - and for the first time in argon.**
- **Working hard to provide useful tools to the neutrino community…**
  - Generator tunes
  - New ML tools

…to constrain CS uncertainties and improve oscillation experiment sensitivity.







CLAS12 e4ν
1 proton analysis

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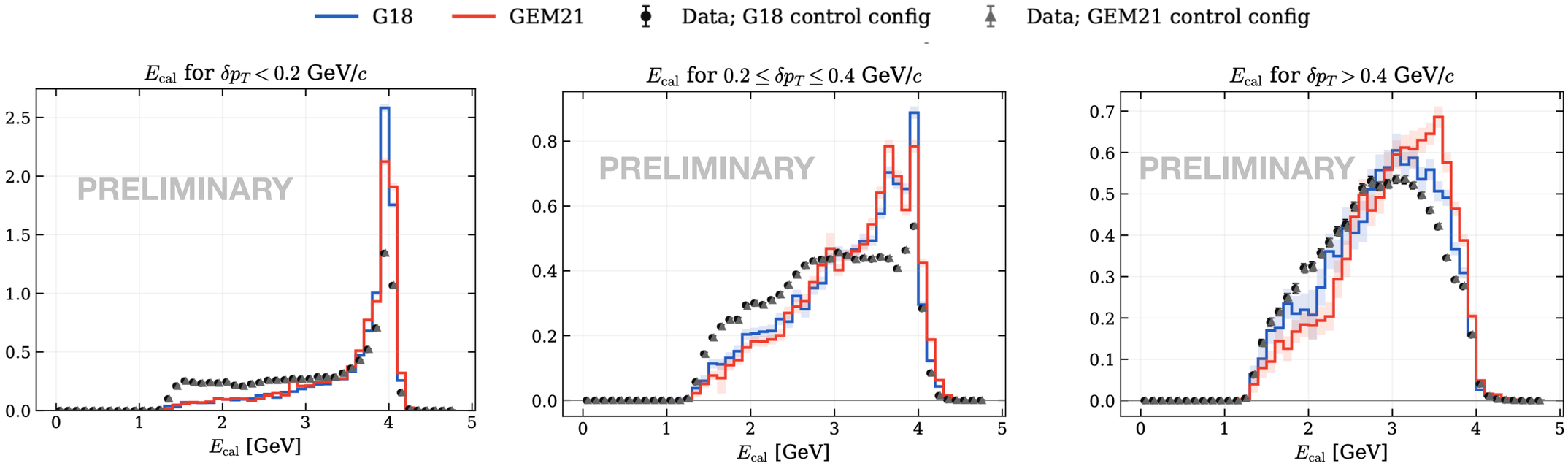


Slicing E_{cal} to understand how FSI affects energy reconstruction.

Shape mismatch (mismodelling) persists across δp_T ranges –> This is not *just* an FSI effect.

Work ongoing to investigate this and other interesting features!

e4ν - Electrons for Neutrinos

We use **electron scattering data** to tackle **uncertainties in the neutrino-nucleus interaction model.**

How?

- Compare against event generator predictions (and tune afterwards).
- Test neutrino energy reconstruction.

→ **Improving neutrino event generators.**

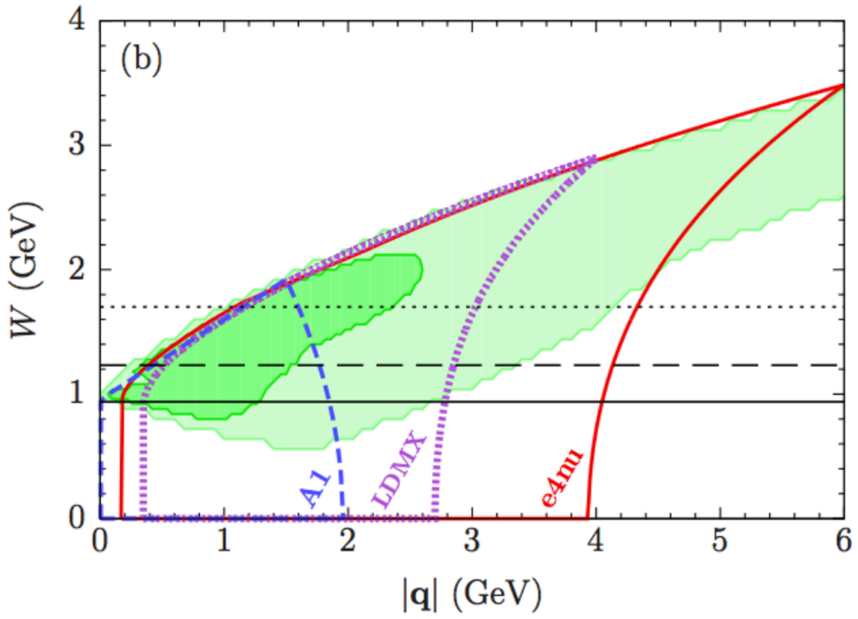


e4ν - Electrons for Neutrinos

We use **electron scattering data** to tackle **uncertainties in the neutrino-nucleus interaction model.**

Why do we do this?

- Neutrino-nucleus model uncertainties are the **leading systematic for next generation neutrino experiments.**
- Biases can limit their physics reach.
- **Current neutrino generators fail** *hard* at describing the data (even electron data!).



arXiv:2203.06853v1 [hep-ex] A NF06 Contributed White Paper

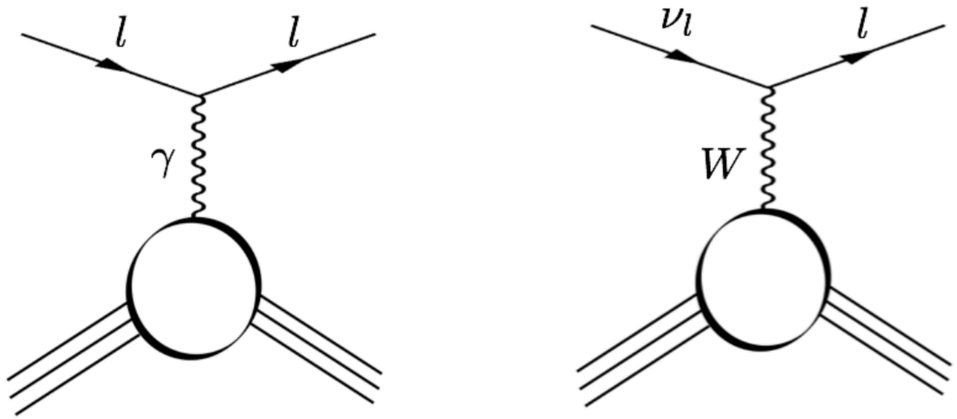
Green and dark green describe DUNE's phase space

e4ν - Electrons for Neutrinos

Why use electrons?

Exactly known beam energy (monochromatic) + higher cross sections **= high statistics, clean kinematics.**

Why are they relevant for neutrinos?



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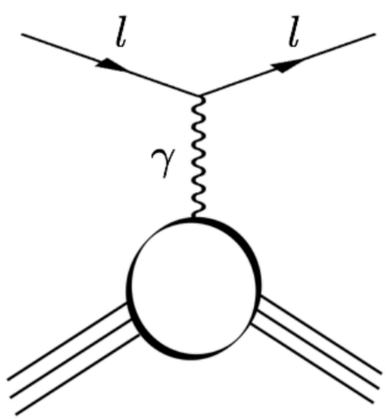
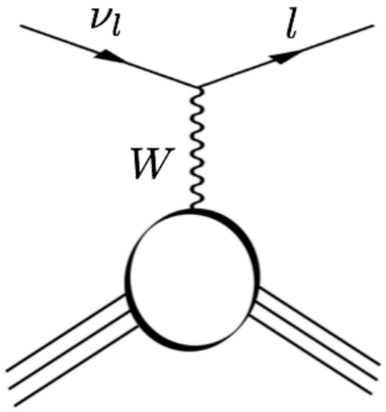
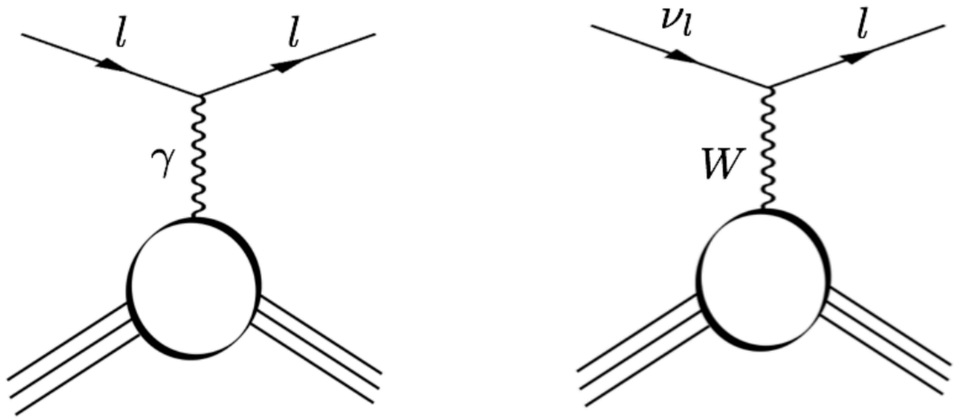




$$W_X^{\mu\nu}(q,\omega) = \langle \Psi_A | \, J_X^{\mu\dagger}(q)\, \delta(\omega + E_A - H) \; J_X^{\nu}(q) \, | \Psi_A \rangle$$

e4ν - Electrons for Neutrinos



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$$\underbrace{|\Psi_A\rangle\,,\; H}_{\text{nuclear structure and dynamics}}$$

Ground state, FSI, hadronization

e4ν - Electrons for Neutrinos

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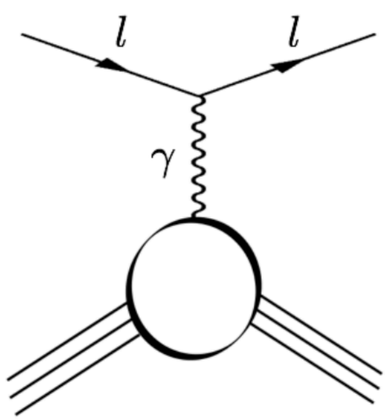

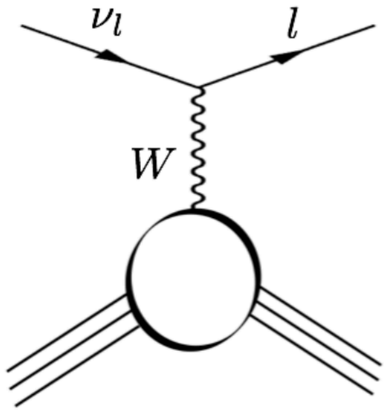

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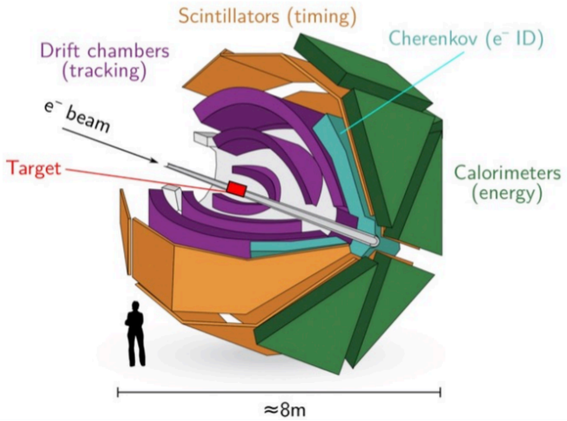
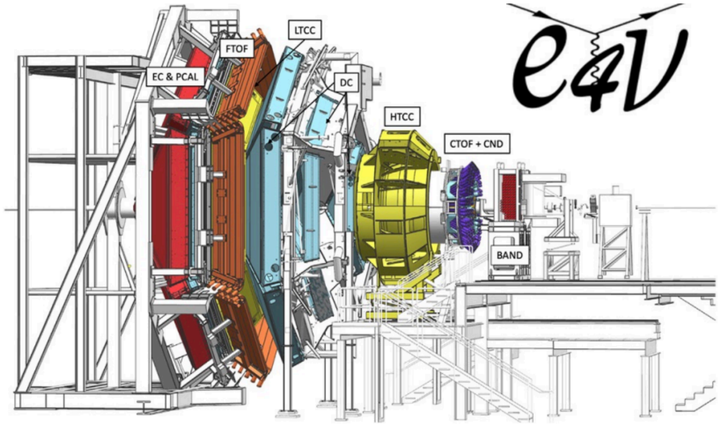
Ground state, FSI, hadronization

$\underbrace{J_X^{\mu}}_{\text{probe/current}}$

EM isovector <–> Weak vector (via CVC)

CLAS and CLAS12 at Jefferson Lab





	CLAS6	CLAS12
Run years	1996-2013	2017 - ?
Luminosity	$10^{34}\ cm^{-2}s^{-1}$	$10^{35}\ cm^{-2}s^{-1}$
Targets	^{4}He, C & Fe	H, D, ^{4}He, C, (O), ^{40}Ar and more
Beam Energy	**1.1, 2.2, 4.4 GeV**	**(1), 2, 4, 6 GeV**
Electron acceptance	$\theta_e > 15°$	$\theta_e > 5°$
Solid angle coverage	$\sim 2\pi$	$\sim 3\pi$
Magnetic field	✓	✓
Particle thresholds	150 (300) MeV/c for $\pi^{\pm}$ (p/γ)	200 (400) MeV/c for $\pi^{\pm}$ (p/n)
Events	**~10M C(e,e') events**	**~100M ^{40}Ar (e,e') events**

CLAS6 Proton Transparency (C and Fe)

OPEN ACCESS

Proton transparency and neutrino physics: New methods and modeling

S. Dytman[1], M. Betancourt[2], N. Steinberg[2], L. B. Weinstein[3], A. Ashkenazi[4], J. Tena-Vidal[4], A. Papadopoulou[5], G. Chambers-Wall[2], J. Smith[2] *et al.* (CLAS Collaboration)

Phys. Rev. D 113, 092007 – Published 12 May, 2026
DOI: https://doi.org/10.1103/7xct-5jcp

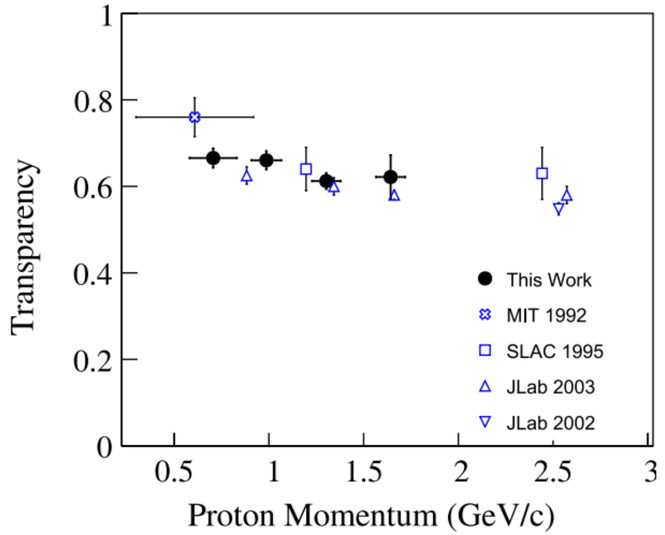


FIG. 12. Transparency of carbon for data presented in this work (black filled circles) compared to world data (blue open points). Previous data are from from Jefferson Lab [15,16,51], SLAC [17], and MIT-Bates [18]. The horizontal error bars show the range of proton momenta included in the analysis.

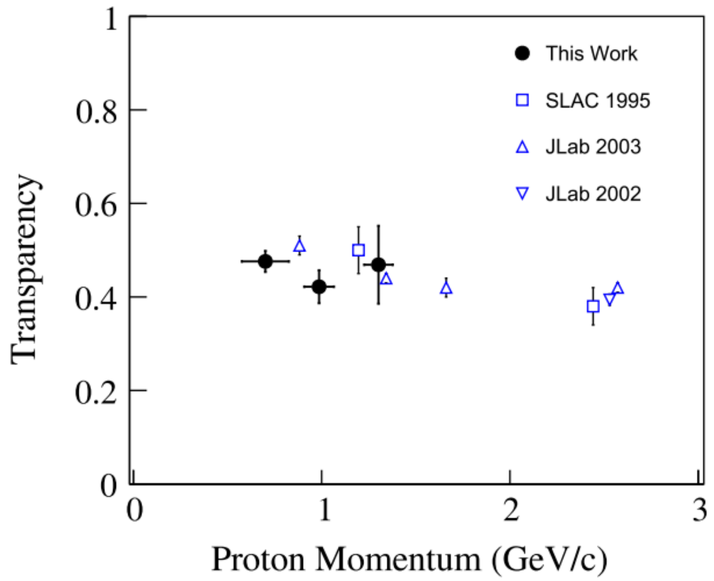
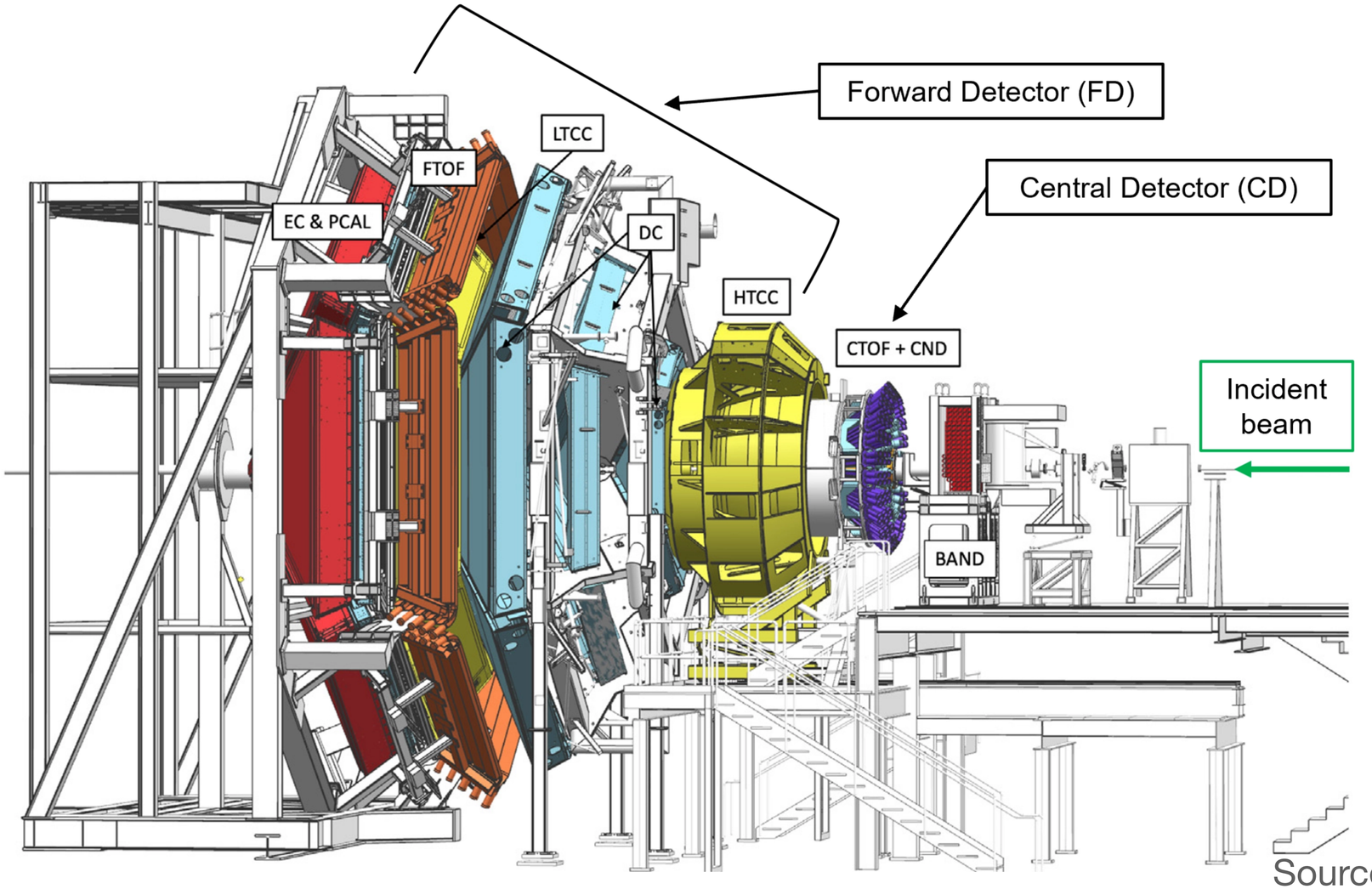


FIG. 13. Transparency of iron for data presented in this work (black full circles) compared to world data (blue open points). Previous data are from Jefferson Lab [15,16] and SLAC [17]. The horizontal error bars show the range of proton momenta included in the analysis.

CLAS12



CLAS12 at a glance

- Polar-angle coverage: FD 5°–35° | CD 35°–125°
- Charged-particle Δp/p: <1% (FD) | <3% (CD)
- Forward tracking angular resolution: ~1 mrad
- FTOF timing resolution: ~60–180 ps
- Luminosity: ~10^{35} cm^{-2} s^{-1}

Source: Burkert et al., NIM A 959 (2020) 163419

Signal definition

CLAS12 1p0π

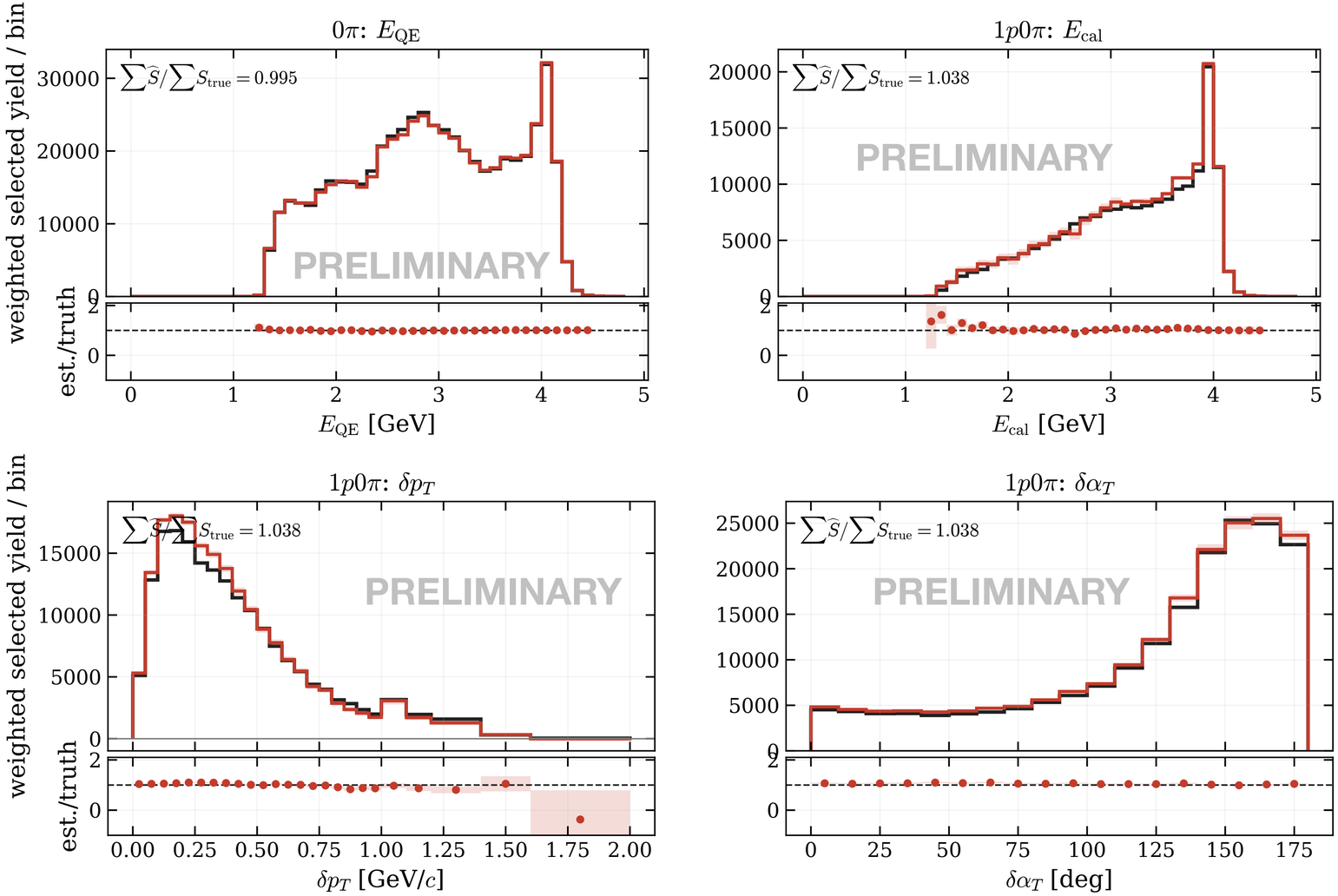
- **Exactly 1 e^-**: p ≥ 0.8 GeV/c; FD only; θ ≥ 7.444 + 13.761/p and θ ≤ 40°.
- **Exactly 1 p**: FD p ≥ 0.4, 8.5° ≤ θ ≤ 40°; CD p ≥ 0.3, 39.5° ≤ θ ≤ 140°.
- **No π^+**: p ≥ 0.25; FD 7.5°–40° or CD 39.5°–140°.
- **No π^-**: p ≥ 0.25; FD θ ≥ 8.492 + 11.482/p to 40°, or CD 40°–140°.
- **No final-state γ** with E ≥ 0.30 GeV and 8° ≤ θ ≤ 45° (π^0 gamma rejection).
- Neutrons and all below-threshold particles are unrestricted.

Background subtraction: closure

CLAS12 1p0π

Ar 4 GeV GEM21

- **Closure is robust across tunes, topologies and observables.**
- Non-closure impact is quantified as a systematic uncertainty.



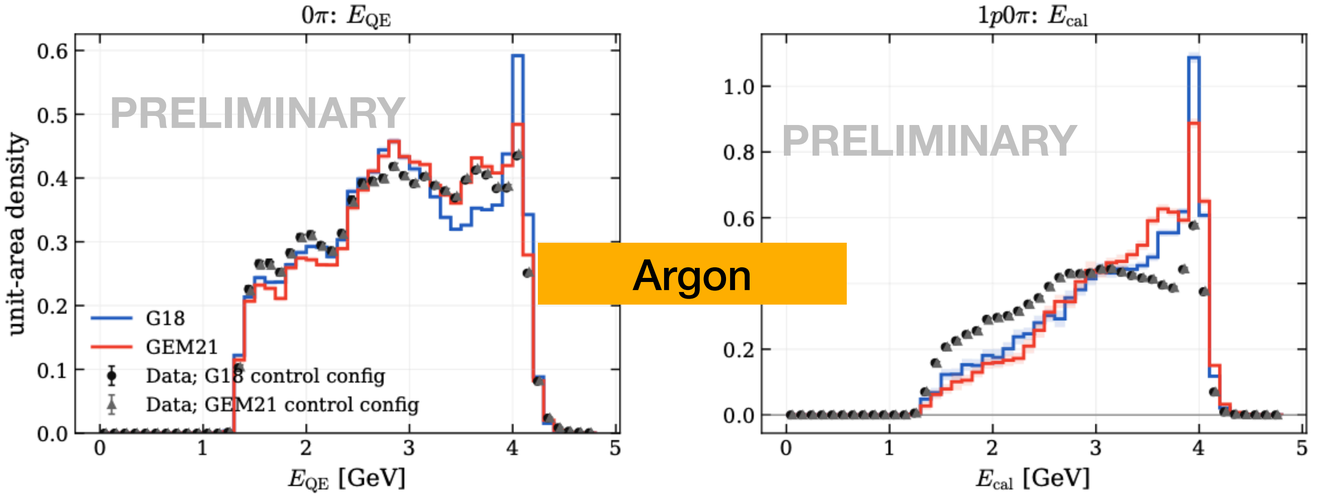
truth-tagged selected signal

selected − estimated background

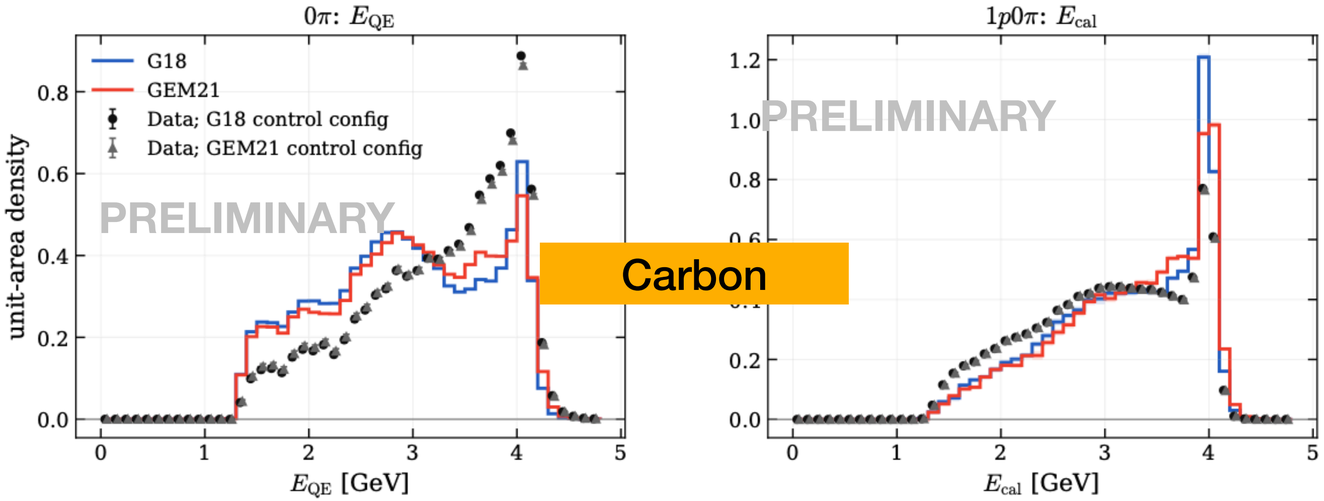
conditional statistical uncertainty

Results: observables (4 GeV)

After background subtraction - stat only
Forward-folded
Shape-only comparison
Before radiative corrections

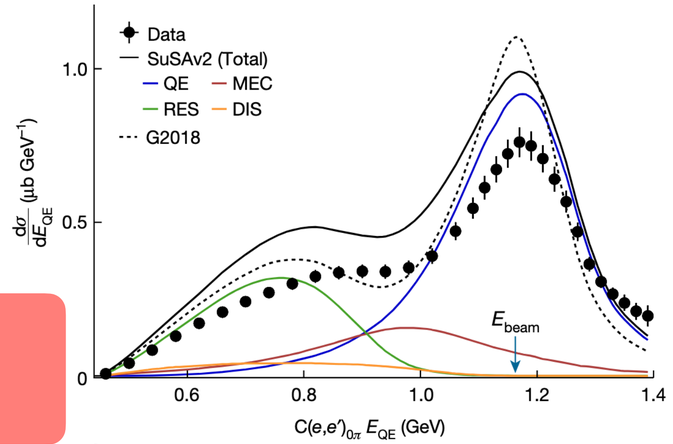


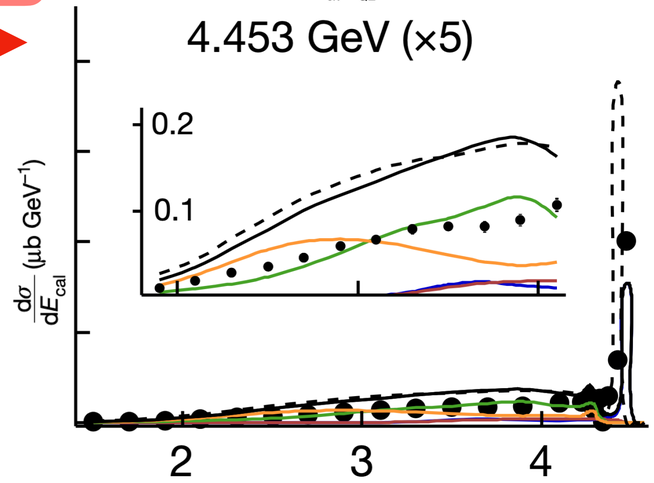
Argon



Carbon

Not directly comparable

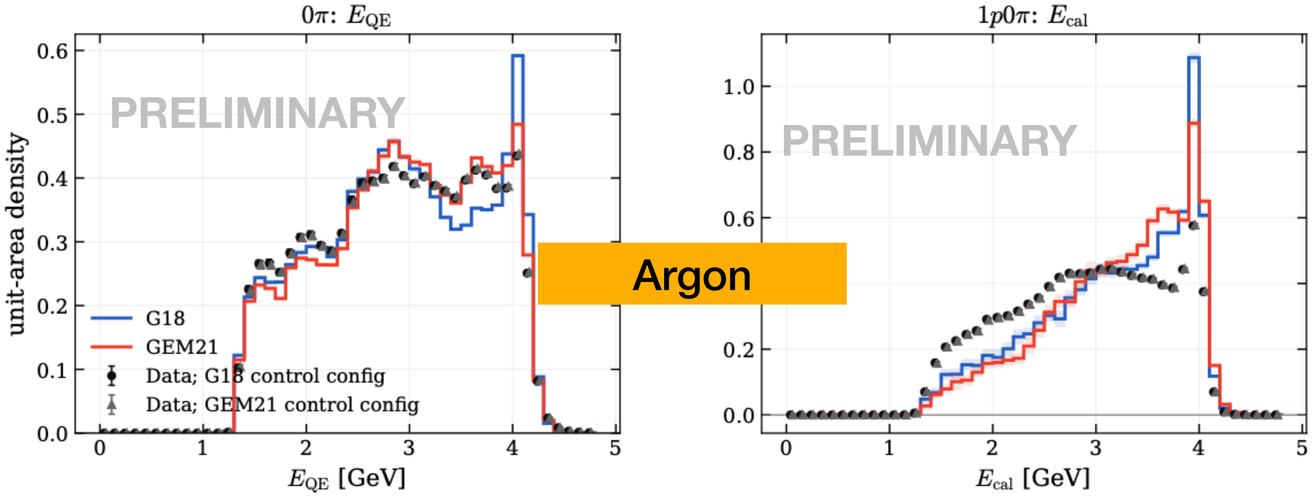




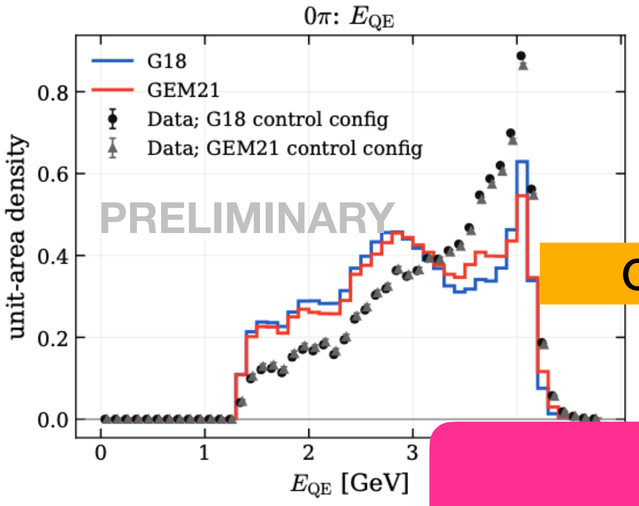
C12 from e4v Collaboration, *Nature* 599, 565–570 (2021). doi:10.1038/s41586-021-04046-5

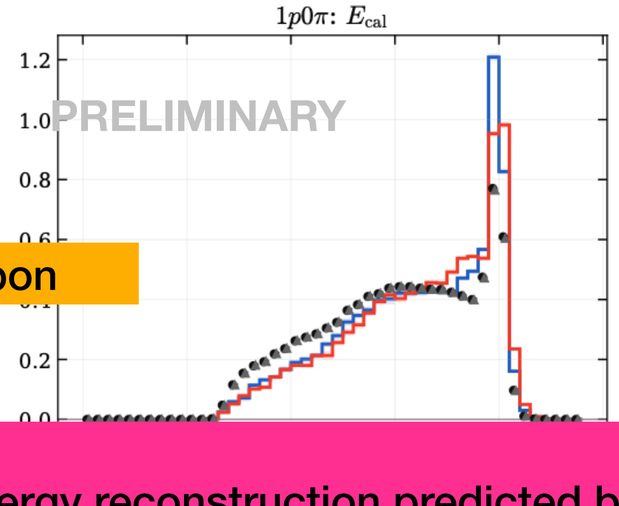
Results: observables (4 GeV)

After background subtraction - stat only
Forward-folded
Shape-only comparison
Before radiative corrections



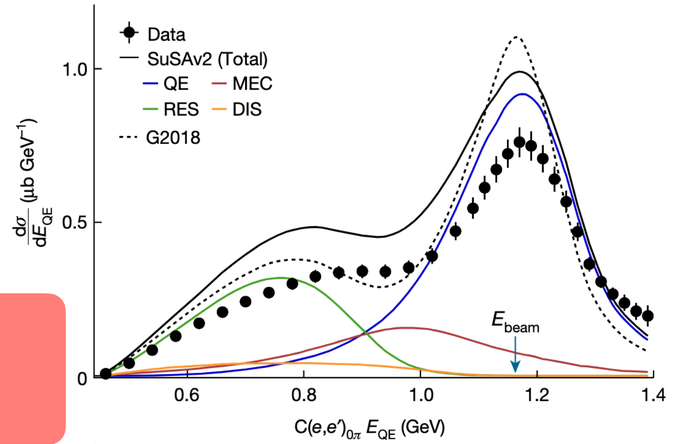
Argon

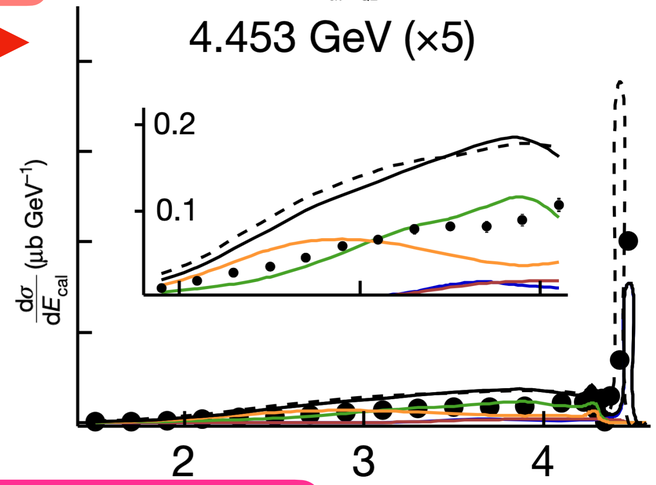




Carbon

Not directly comparable





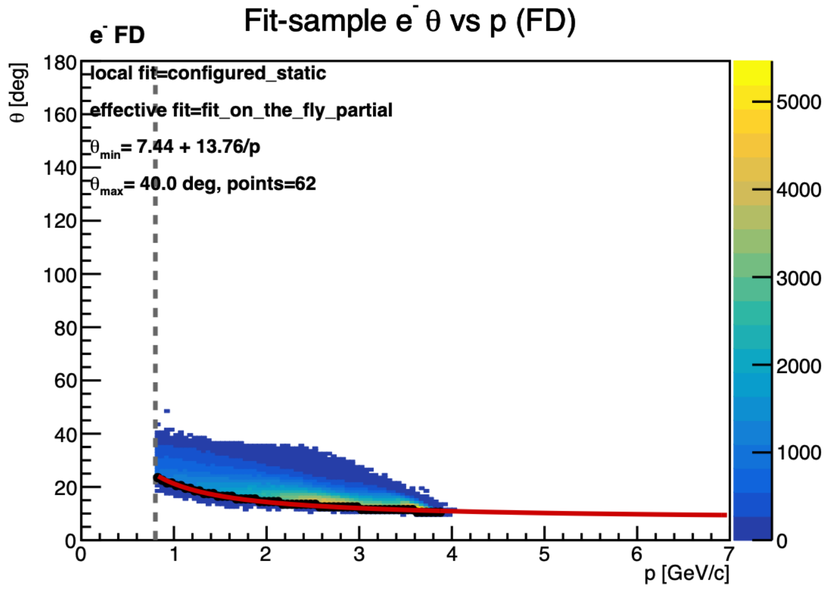
...ollaboration, *Nature* ...(2021). doi:10.1038/...021-04046-5

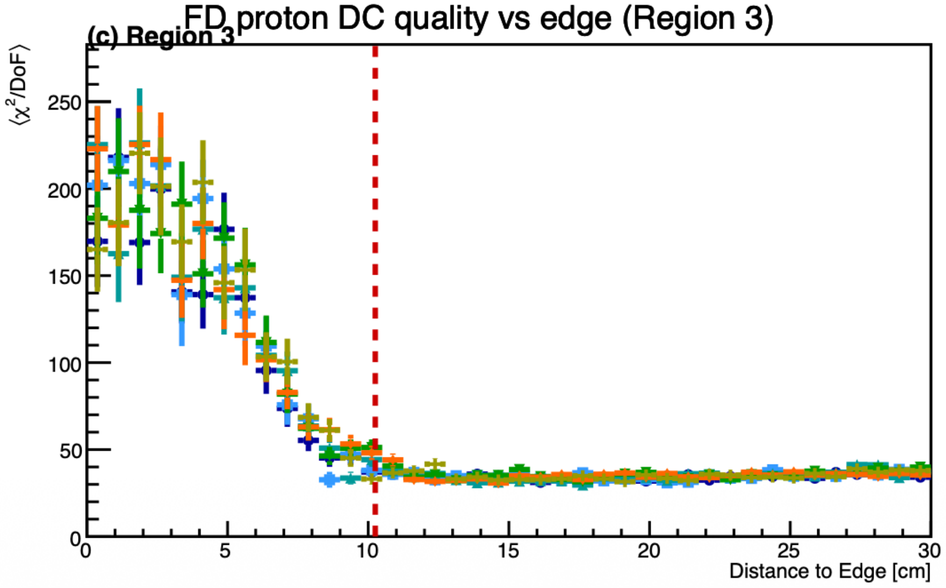
Energy reconstruction predicted by our generators is biased.
The $E = E_{\mathrm{beam}}$ peak is not seen as strongly by data.

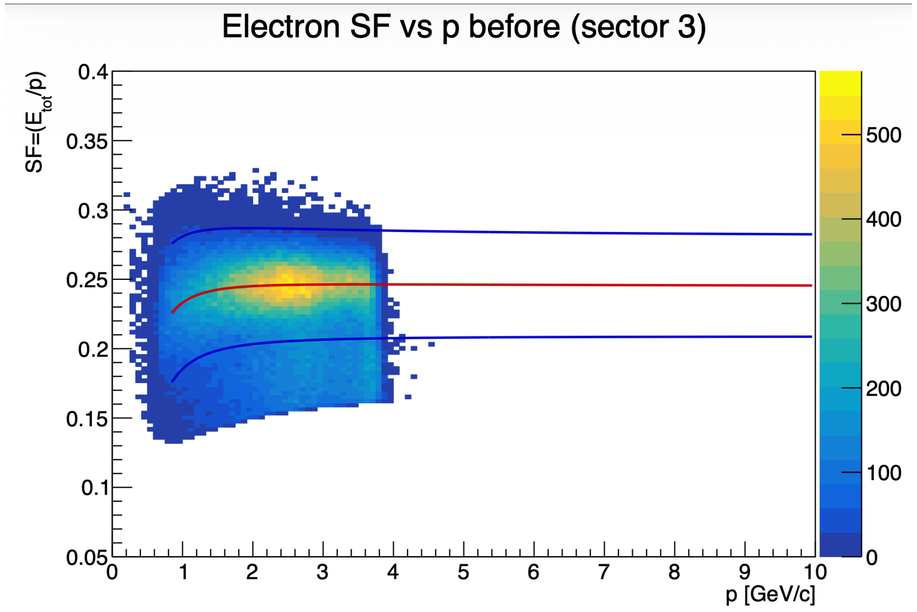
Detector cuts

- The detector-cut pipeline is run on the Ar40 (C12) experimental data, from which cuts are frozen for the rest of the analysis.

- Procedure was taken from the **RGM tech note, with some cuts refit + pion cuts.**







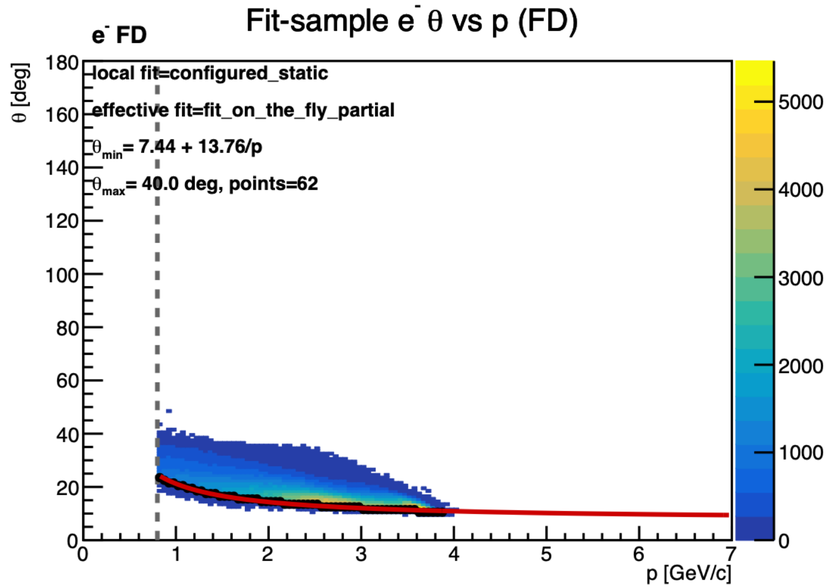
Detector cuts

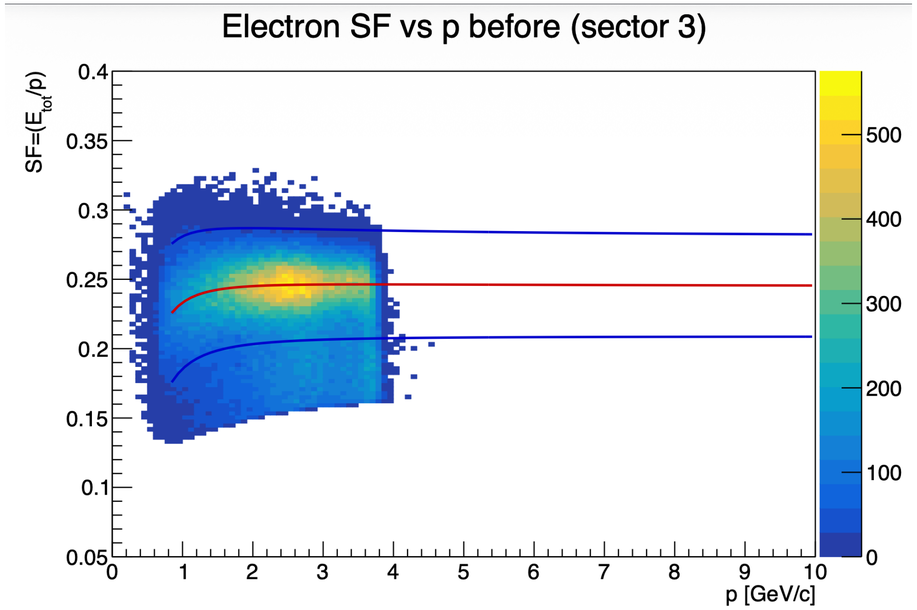
- The detector-cut pipeline is run on the Ar40 (C12) experimental data, from which cuts are frozen for the rest of the analysis.

- Procedure was taken from the **RGM tech note, with some cuts refit + pion cuts.**

3.1.1 Electron identification cuts

Cut	Applied value	Fit status
Event Builder identity	Electron, PID 11; negative track	**Fixed**
Detector region	Forward Detector only	**Fixed**
HTCC photoelectrons	$N_{\mathrm{phe}} > 2$	**Fixed**
Electron momentum	$p \geq 0.8\ \mathrm{GeV}/c$	**Fixed**
PCAL deposited energy	$E_{\mathrm{PCAL}} > 0.06\ \mathrm{GeV}$	**Fixed**
Electron lower-angle boundary	$\theta \geq 7.44447 + 13.761/p$ degrees	**Prefit-derived**
Electron upper angle	$\theta \leq 40^{\circ}$	**Fixed**
Sampling fraction versus momentum	Sector-dependent mean $\pm 3\sigma$	**Prefit-derived**
Sampling fraction versus PCAL energy	Sector-dependent mean $\pm 3\sigma$	**Prefit-derived**
Diagonal ECAL cut	Disabled	**Not applied**





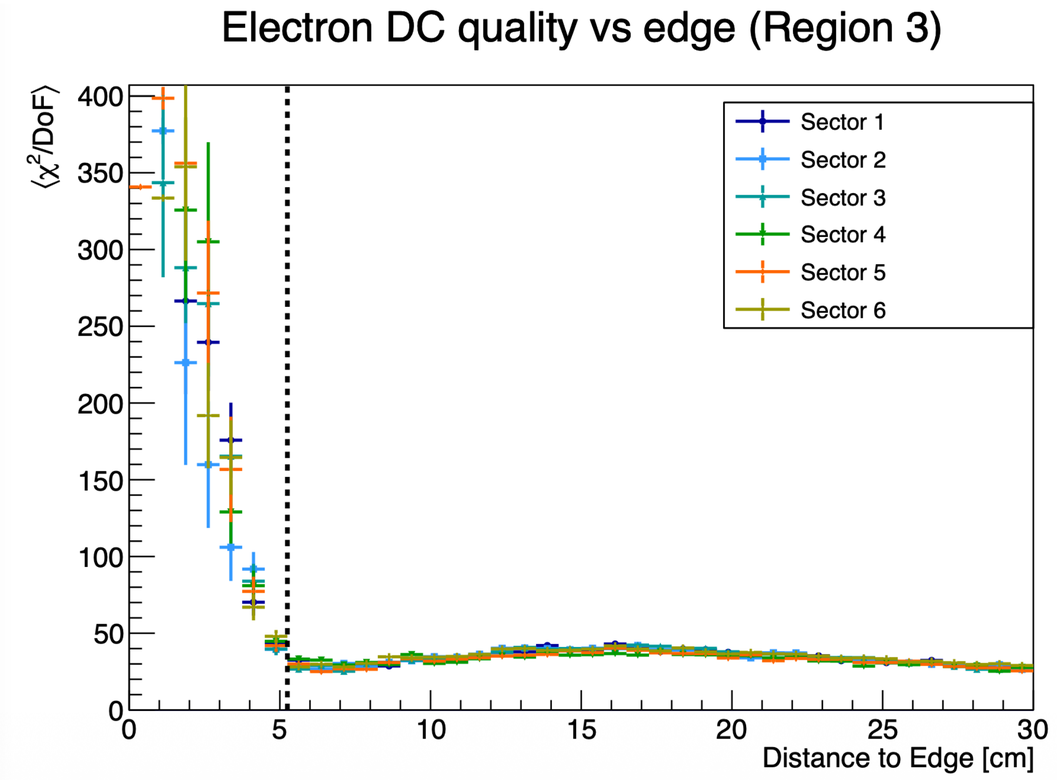
Detector cuts

3.1.2 Electron fiducial cuts

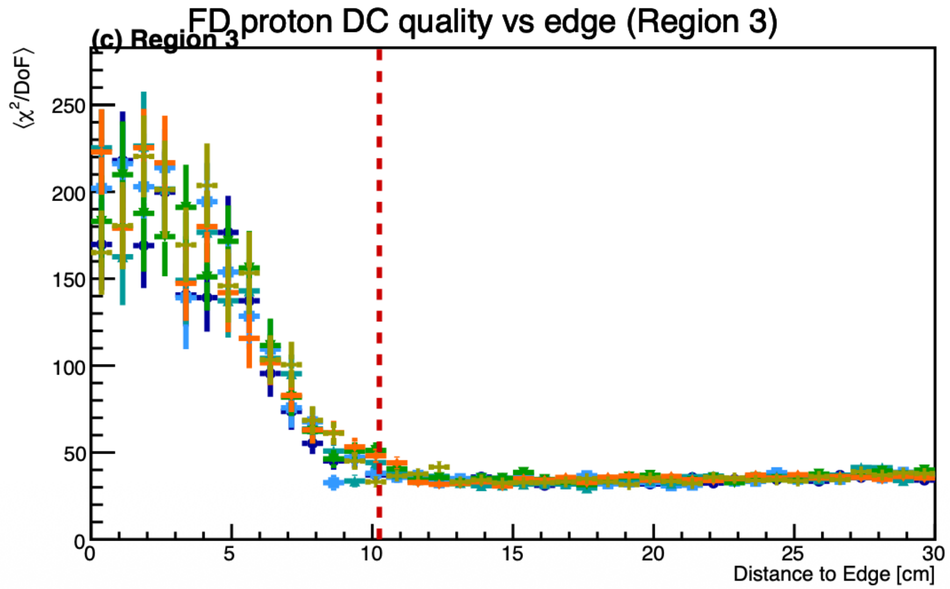
Cut	Applied value	Fit status
PCAL L_v edge	$L_v > 14$ cm	**Fixed**
PCAL L_w edge	$L_w > 14$ cm	**Fixed**
PCAL L_u edge	None	**Not applied**
DC region 1 edge	Distance > 2.75 cm	**Prefit-derived**
DC region 2 edge	Distance > 1.25 cm	**Prefit-derived**
DC region 3 edge	Distance > 5.25 cm	**Prefit-derived**

3.1.3 Electron vertex cuts

Cut	Applied value	Fit status
Argon electron longitudinal vertex	$-7.5 < v_z < -2.8$ cm	**Fixed**
Transverse vertex, v_x/v_y	No restrictive cut	**Not applied**



Detector cuts



3.2.1 Proton fiducial cuts

Cut	Applied value	Fit status
FD momentum	$p \geq 0.40$ GeV/c	Fixed
FD polar angle	$8.5^\circ \leq \theta \leq 40^\circ$	Fixed
CD momentum	$p \geq 0.30$ GeV/c	Fixed
CD polar angle in subsequent analysis	$39.5^\circ \leq \theta \leq 125^\circ$	Later analysis policy
FD DC region 1 edge	Distance > 2.25 cm	Prefit-derived
FD DC region 2 edge	Distance > 0.75 cm	Prefit-derived
FD DC region 3 edge	Distance > 10.25 cm	Prefit-derived
CD CVT layer 7 edge	Distance > 0.50 cm	Fixed
CD CVT layer 12 edge	Distance > 0.50 cm	Fixed
CD sector/region continuity	First and last hits in the same sector/region	Fixed
Ghost-track rejection	Enabled	Fixed

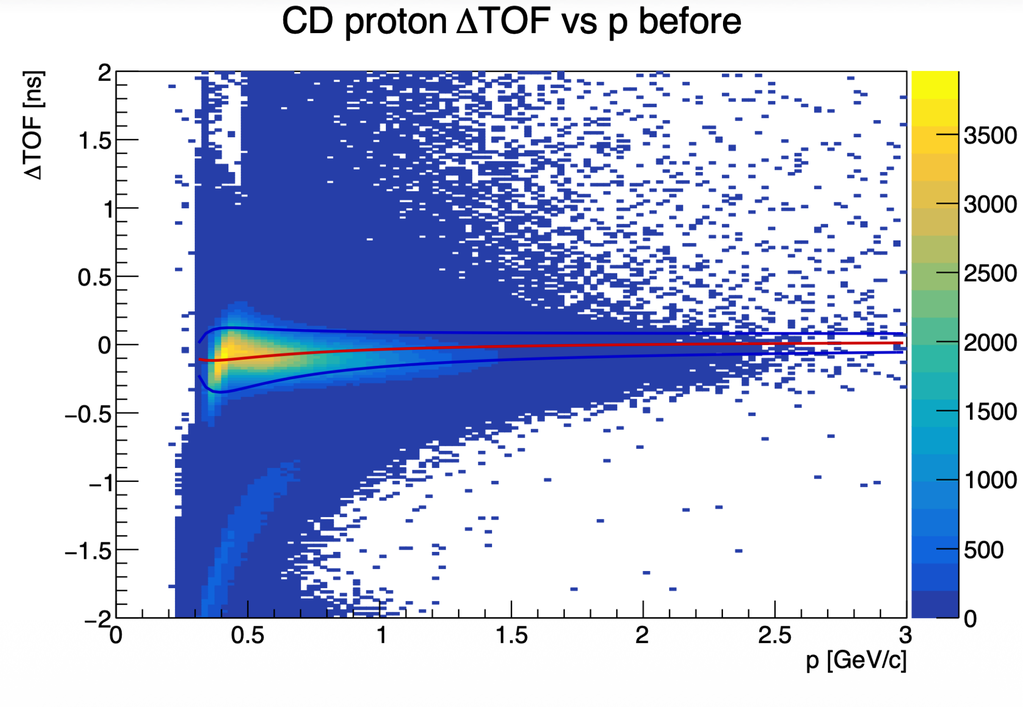
Detector cuts

3.2.2 Proton identification cuts

Cut	Applied value	Fit status
Forward Detector		
Event Builder identity	Proton, PID 2212	**Fixed**
FD χ^2_{PID} window	$-5.294848 < \chi^2_{\mathrm{PID}} < 3.158590$	**Prefit-derived**
Equivalent parameterization	Center -1.068129; half-width 4.226719	**Prefit-derived**
Band width	Approximately mean $\pm 3\sigma$	**Fixed multiplier**
Central Detector		
Charge	Positive	**Fixed**
Basic timing validity	$\beta > 0.001$	**Fixed**
Proton timing selection	$\mu(p) - 2\sigma(p) < \Delta\mathrm{TOF} < \mu(p) + 2\sigma(p)$	**Prefit-derived**
CD χ^2_{PID} cut	Disabled	**Not applied**

3.2.3 Proton vertex cuts

Cut	Applied value	Fit status
FD proton vertex	$-9.9 < v_z < -2.6$ cm	**Fixed**
CD proton vertex	$-6.7 < v_z < -4.8$ cm	**Fixed**
FD electron–proton correlation	$-3.5 < v_z(e) - v_z(p) < 5.8$ cm	**Fixed**
CD electron–proton correlation	$-1.8 < v_z(e) - v_z(p) < 3.1$ cm	**Fixed**



GENIE



https://genie-mc.github.io/

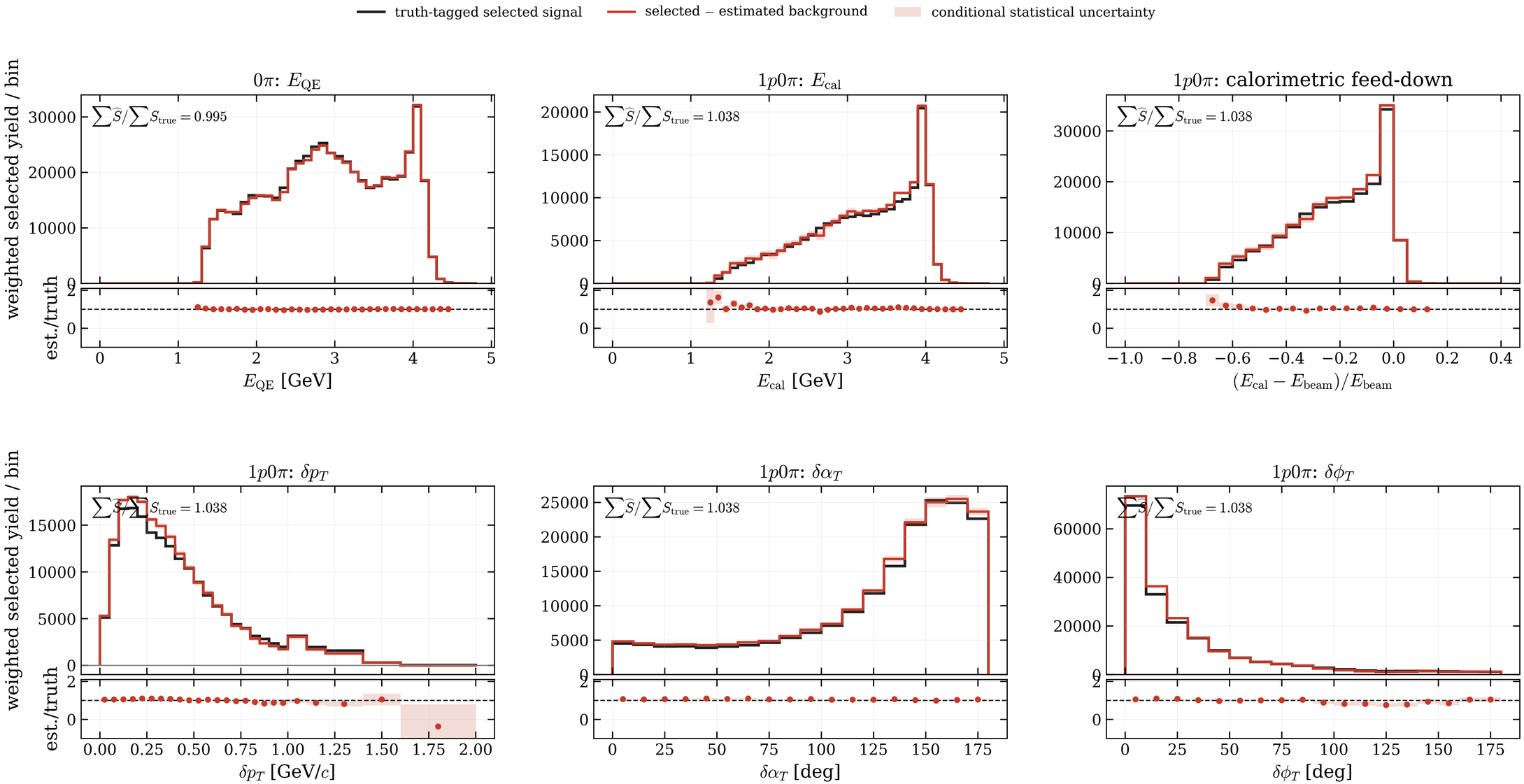
Tune name in GENIE: GEM21_11a_00_000

Process	Model
Quasi-ELastic and Two-Particle Two-	SUSAv2 model
RESonance Production	Berger-Sehgal model
Non-RESonance (SIS)	Bodek-Yang model, scaled with multiplicity dependent parameters
Deep Inelastic Scattering	Bodek-Yang model
Final State Interaction model	hA model
Hadronization model	AGKY model (KNO+Pythia)
Nuclear Model	Local Fermi Gas

(*) This is the GENIE model used in the talk

PRELIMINARY / NON-PROMOTABLE — Ar-40, 4.02962 GeV, matched-statistics symmetric subtraction — G18

Raw no-fold MC signal closure with tune-global corrected schema-7 acceptance maps



Raw $A \geq 0.50$ and compatible-region ϕ support ≥ 0.10. Band: estimate conditional source-event and finite-rotation statistics only; truth and shared closure covariance are not stored.

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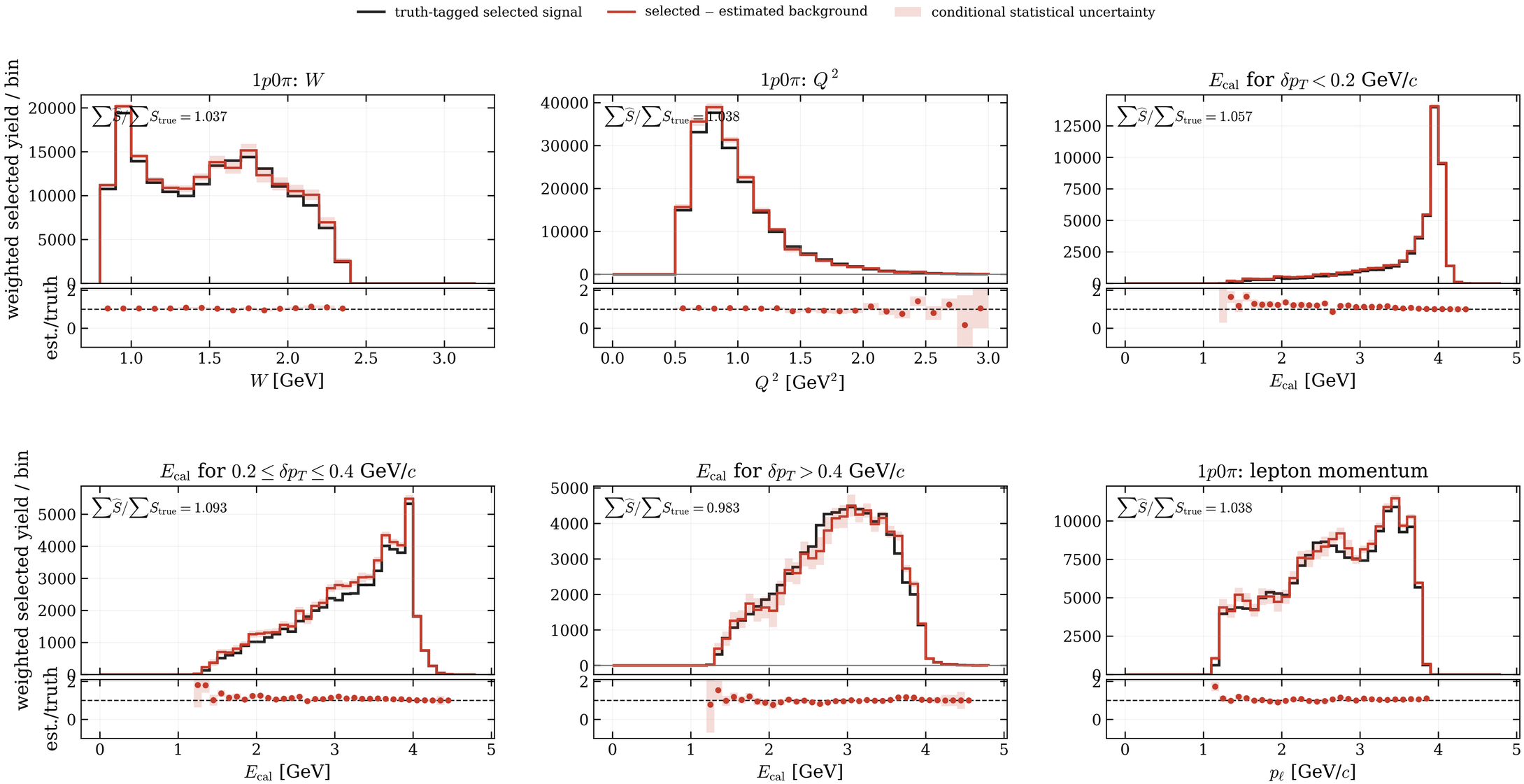

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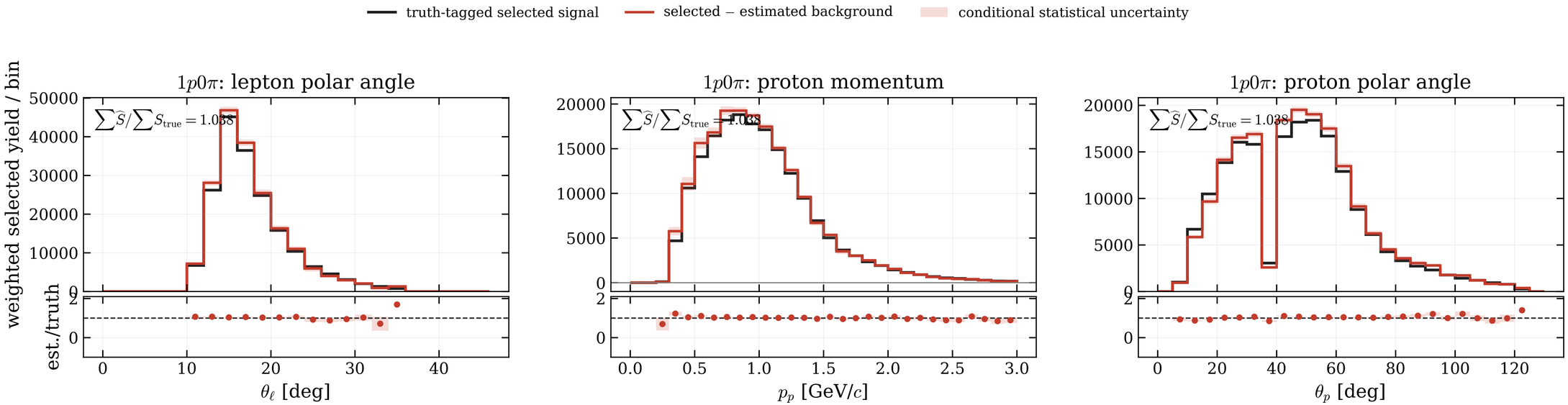

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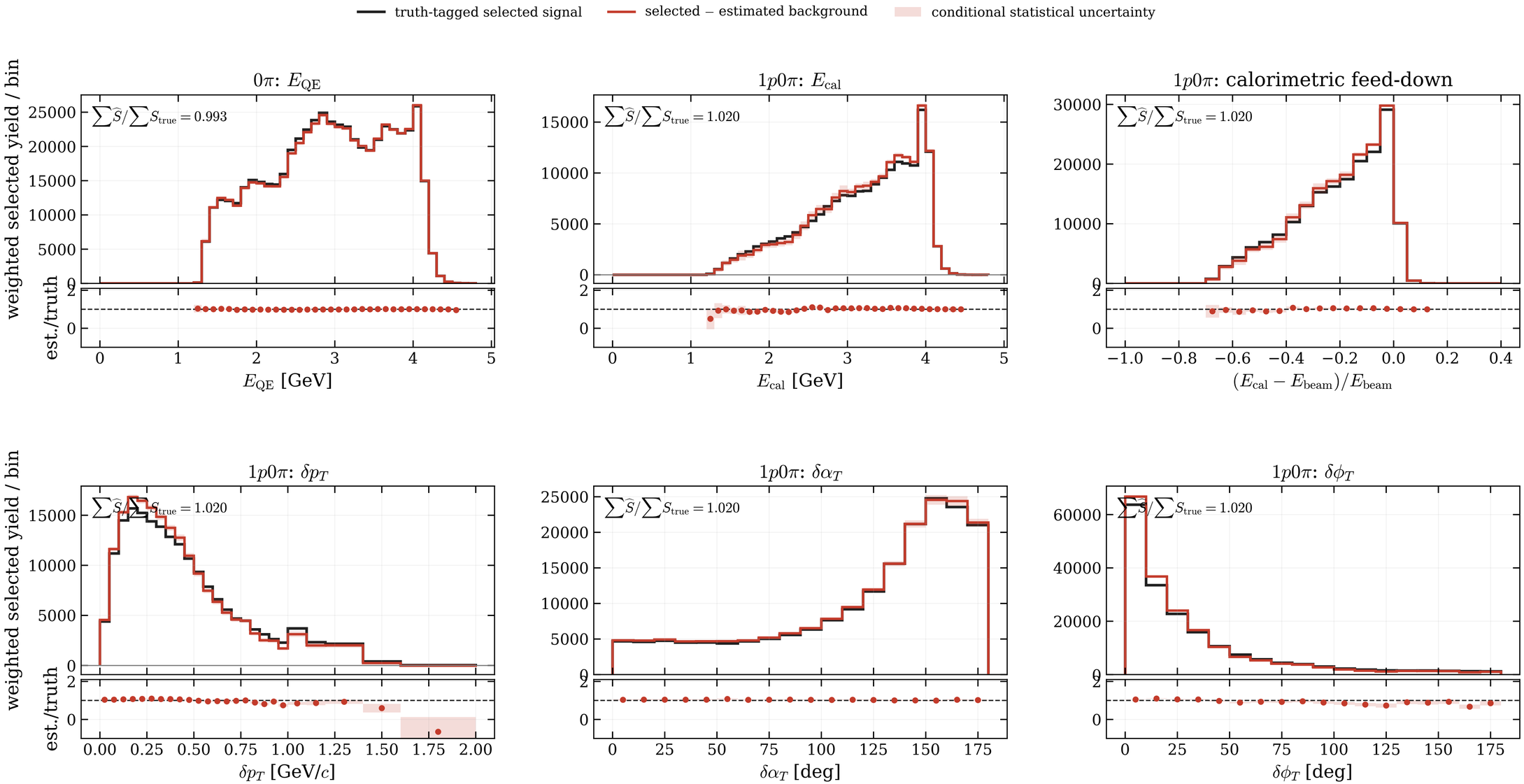

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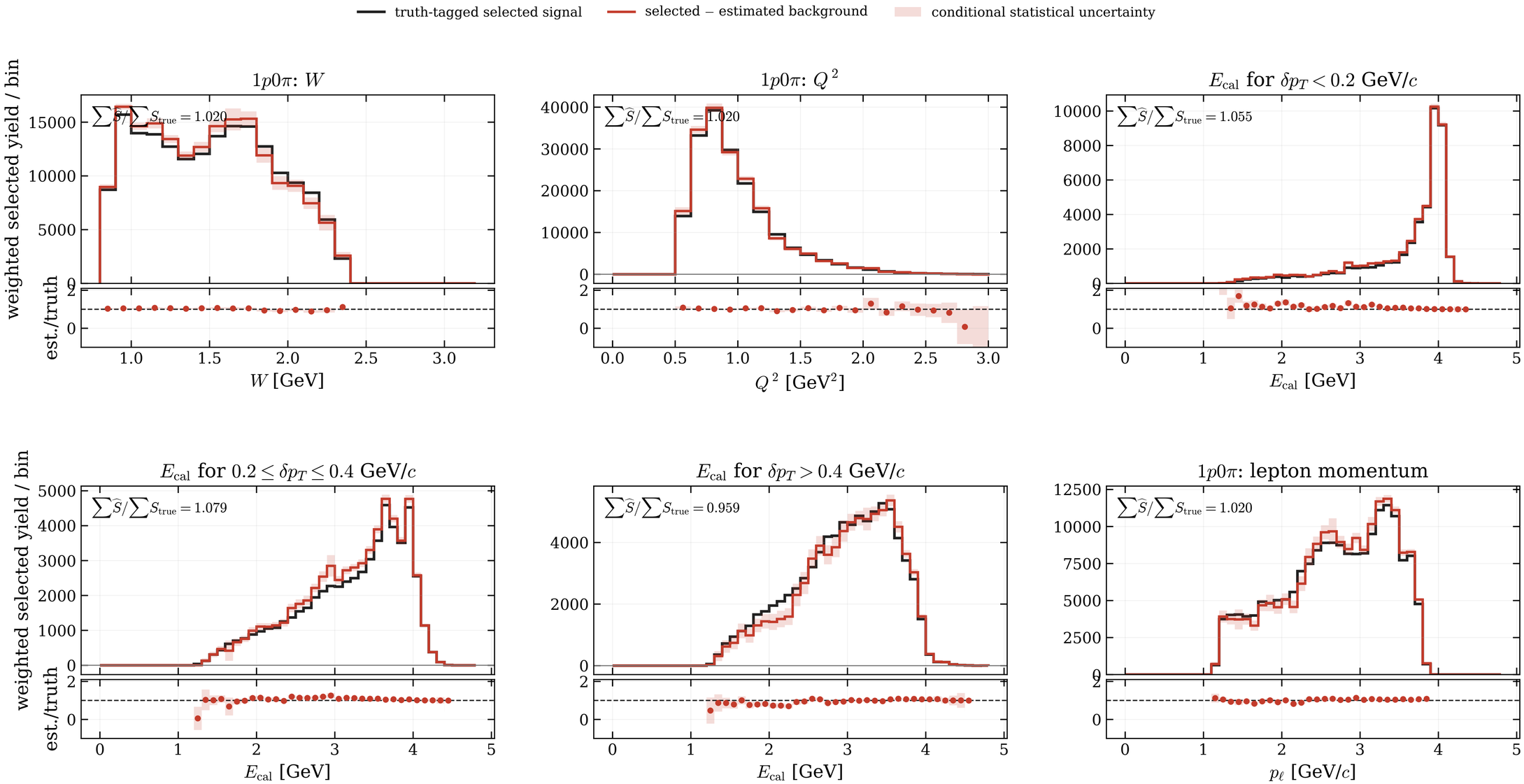

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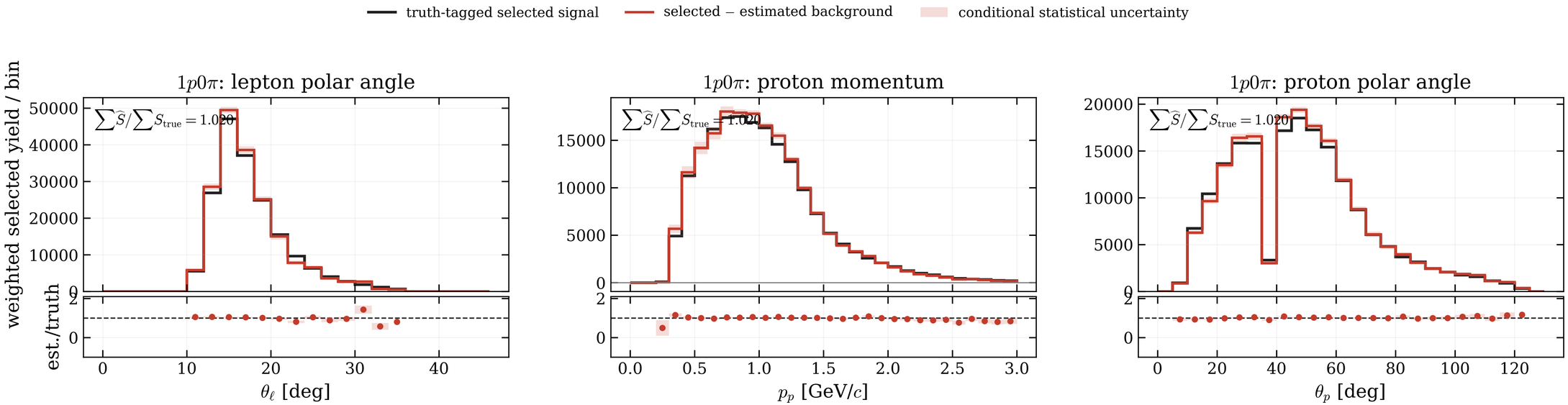

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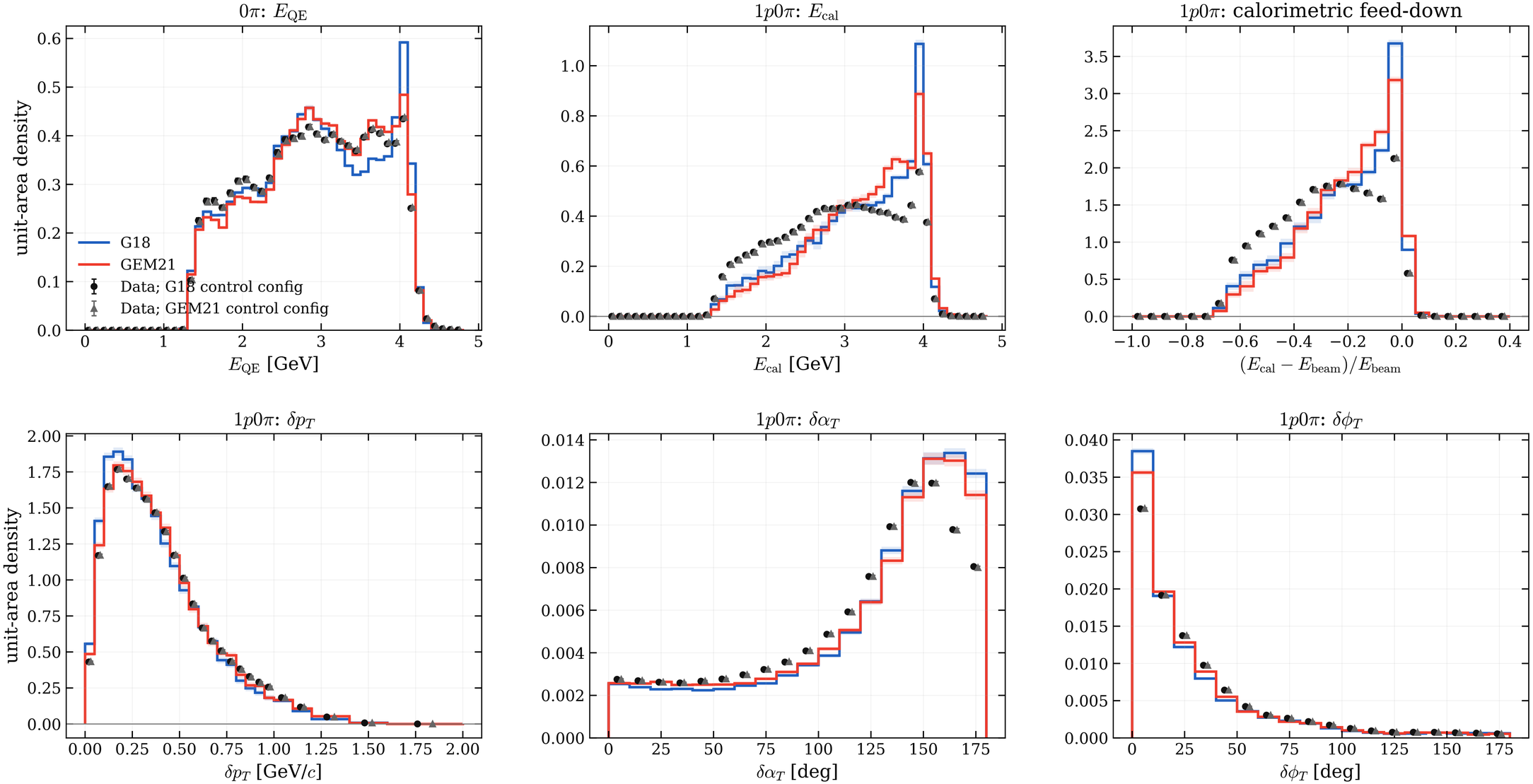
PRELIMINARY / NON-PROMOTABLE — Ar-40, 4.02962 GeV, matched-statistics symmetric subtraction
Raw no-fold background-subtracted data vs. detector MC with tune-global corrected schema-7 acceptance maps



Each curve is independently unit-area normalized. Raw $A \geq 0.50$; compatible-region ϕ support ≥ 0.10. Bands/error bars contain source-event and finite-rotation statistics only.

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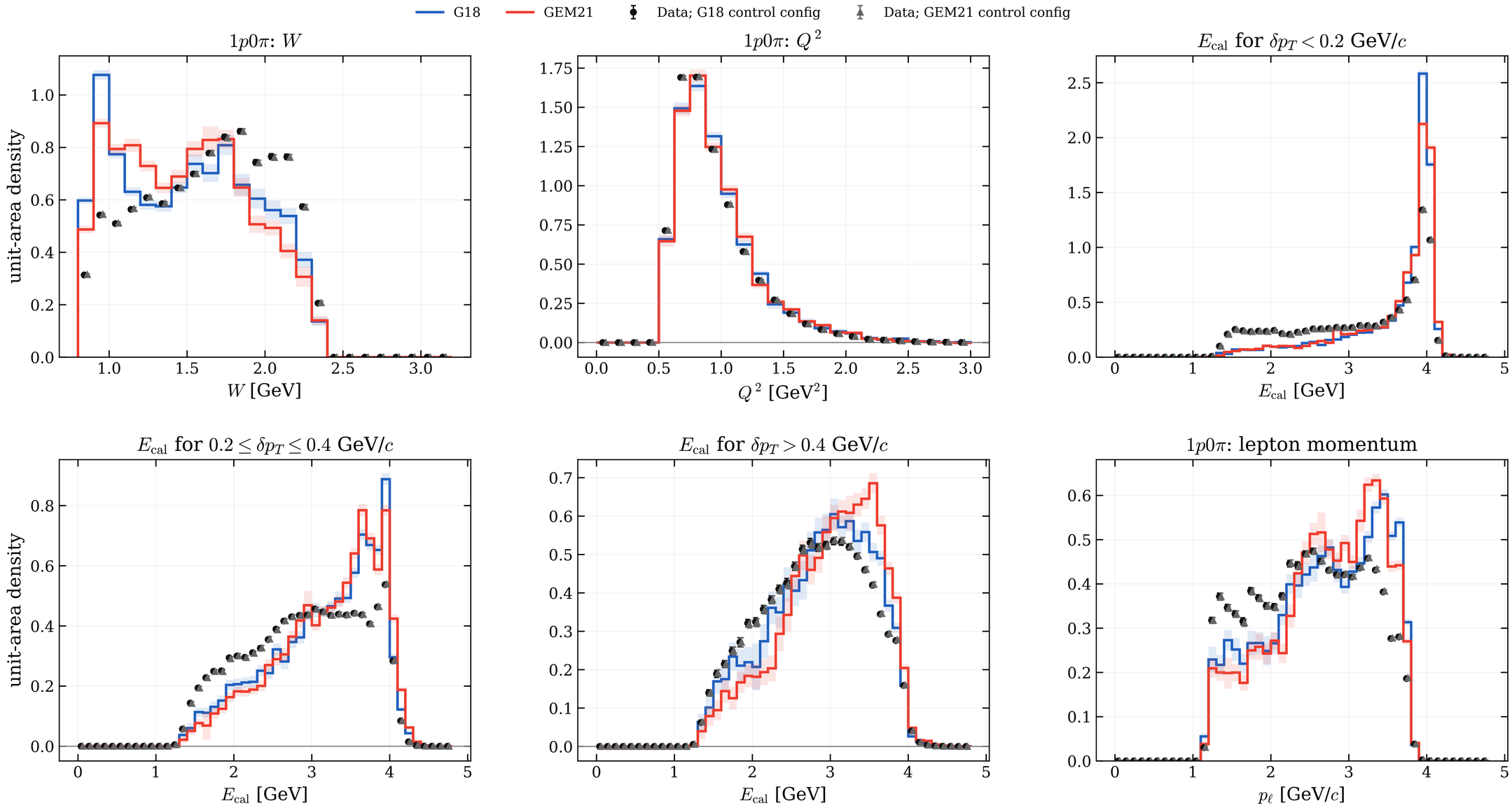

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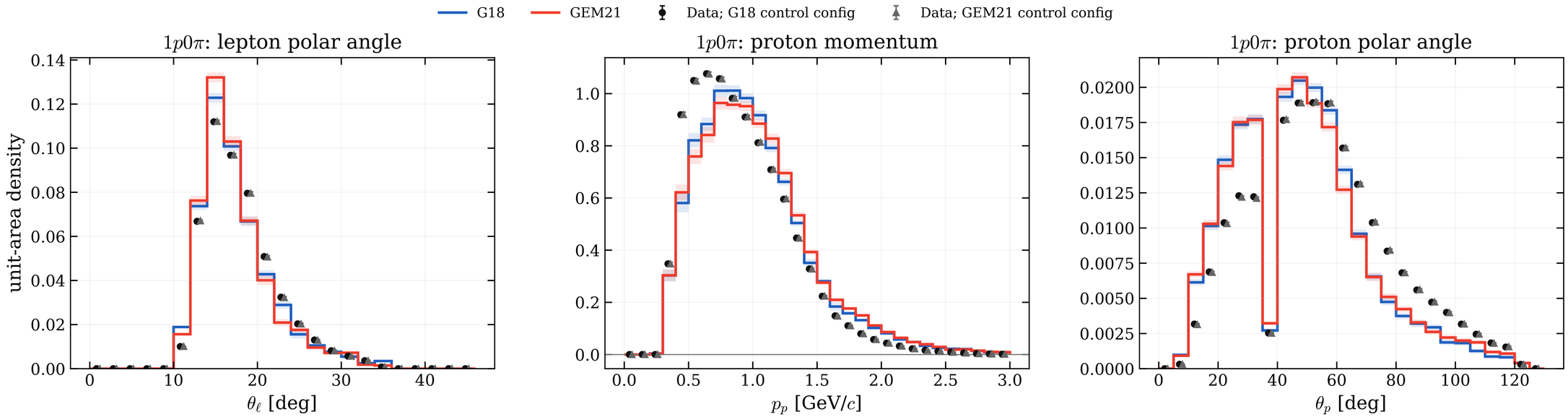

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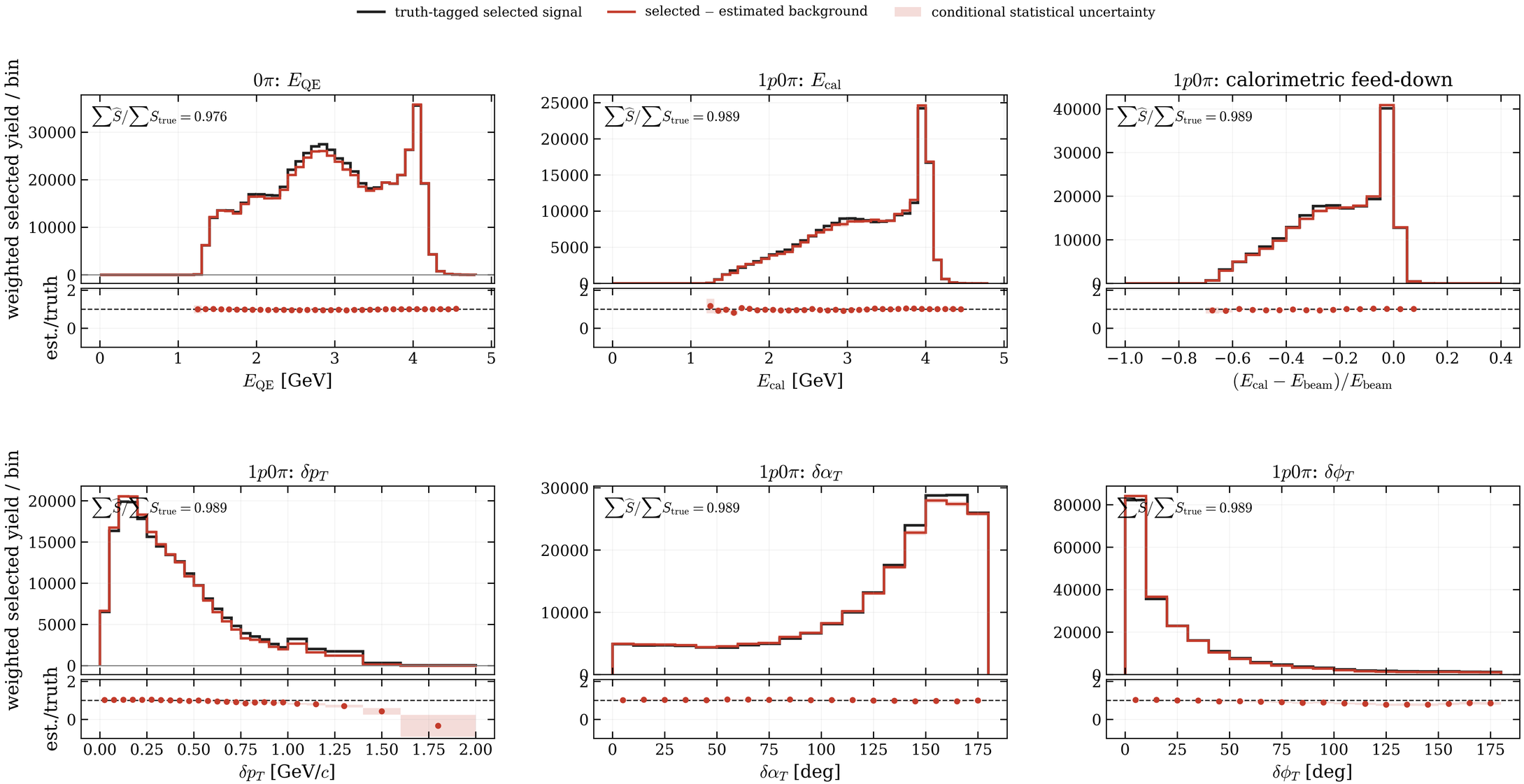
PRELIMINARY / NON-PROMOTABLE — C-12, 4.02962 GeV, matched-statistics symmetric subtraction — G18

Raw no-fold MC signal closure with tune-global corrected schema-7 acceptance maps



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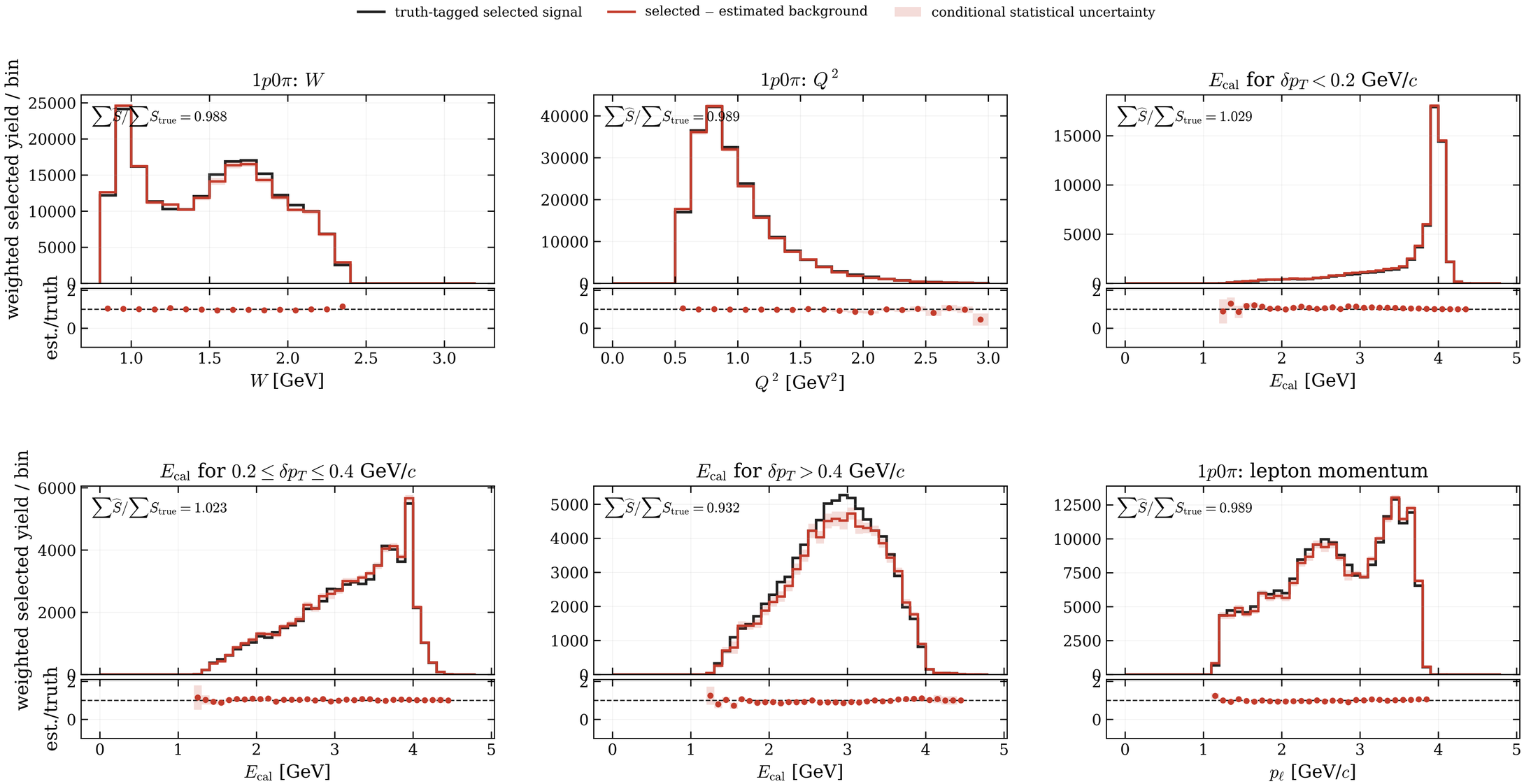

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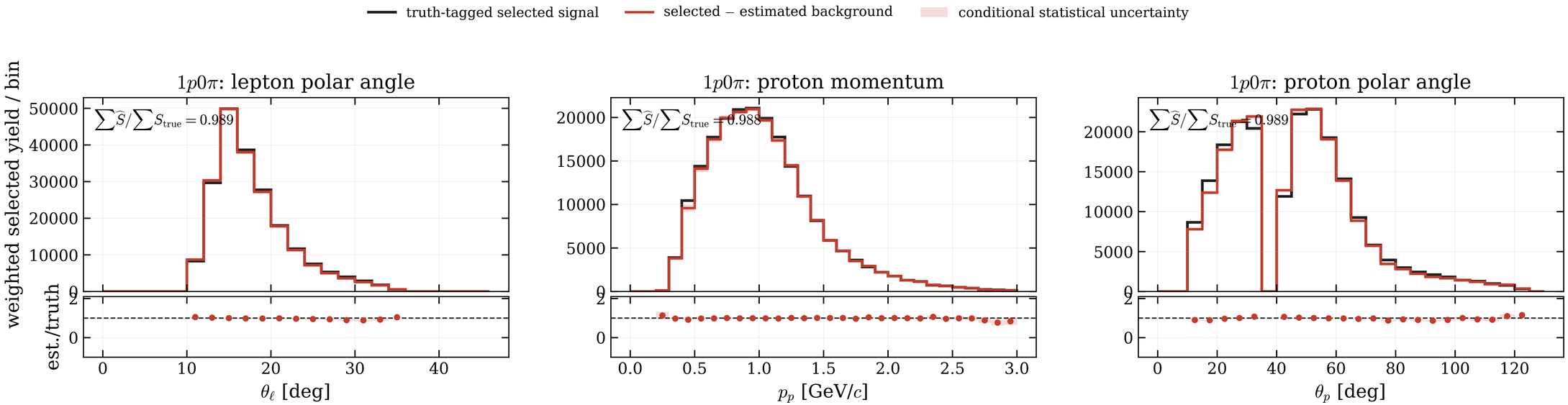

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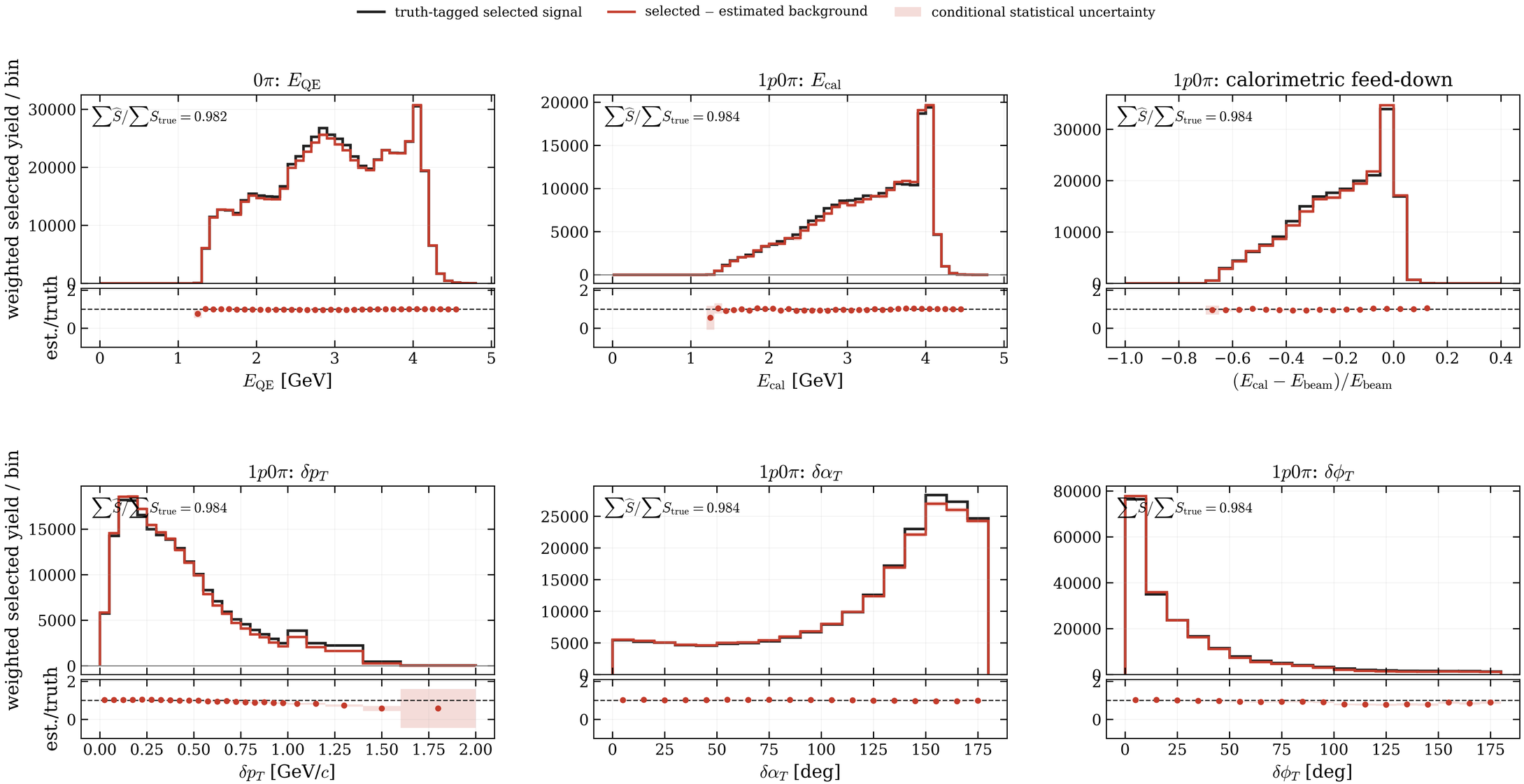

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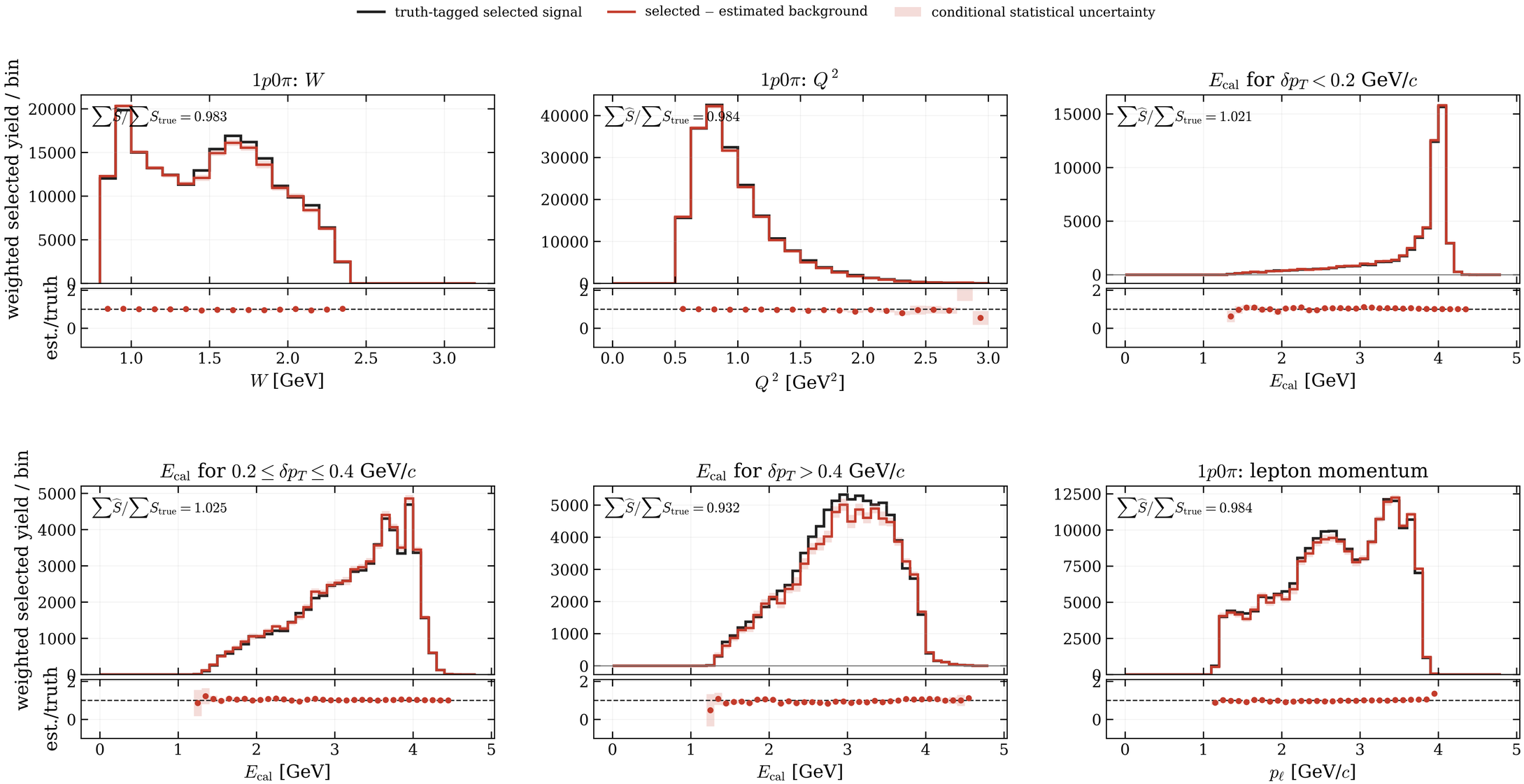

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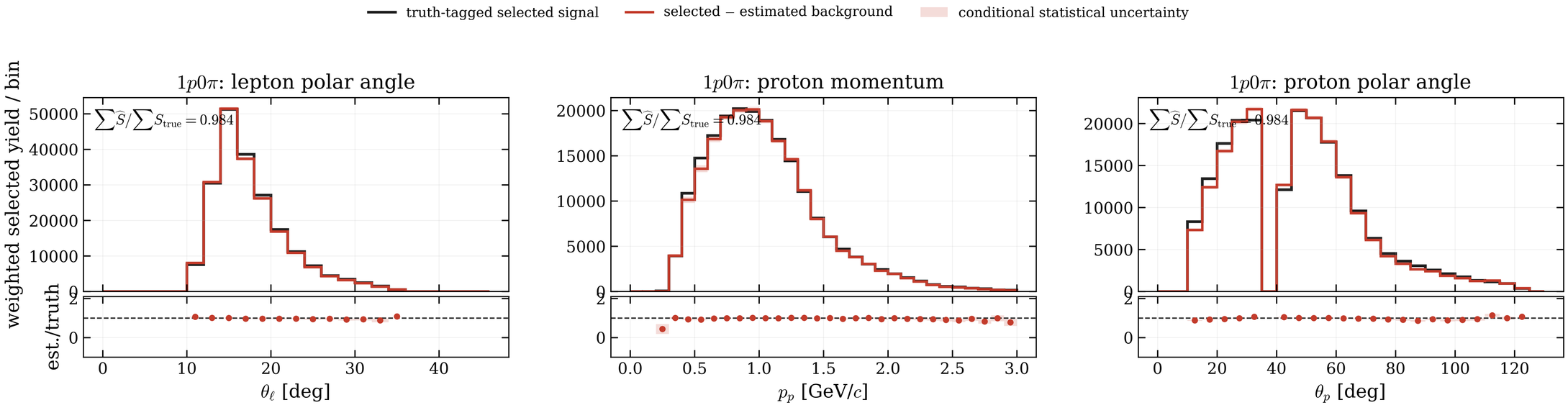

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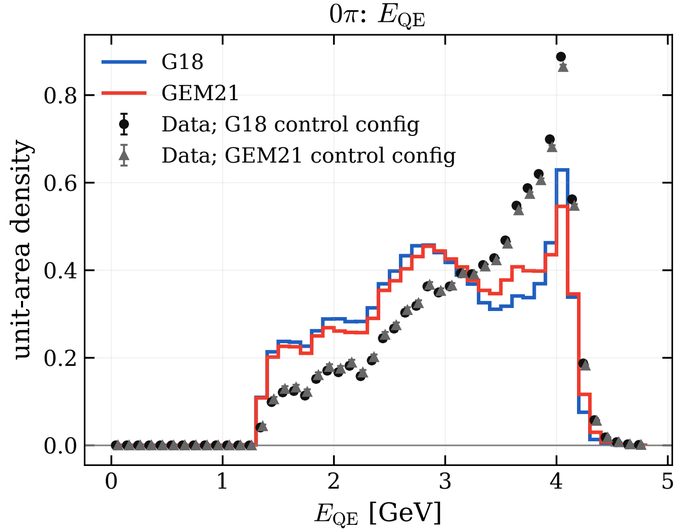
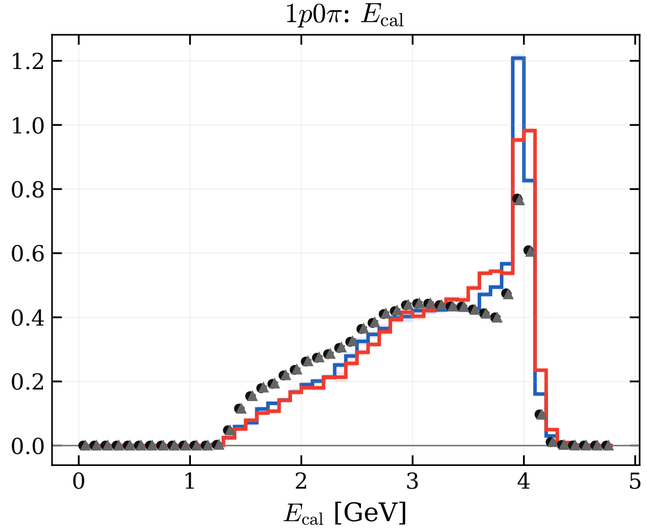
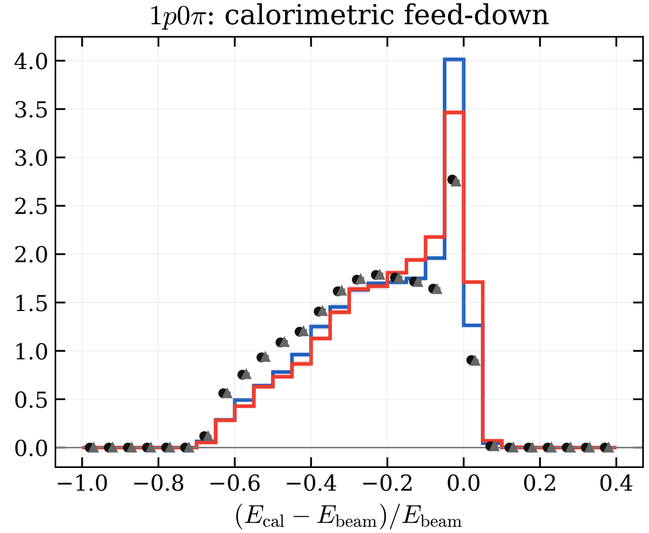
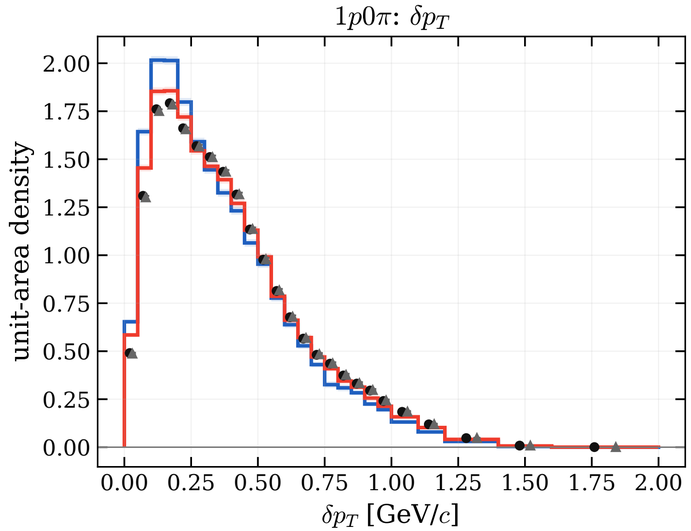
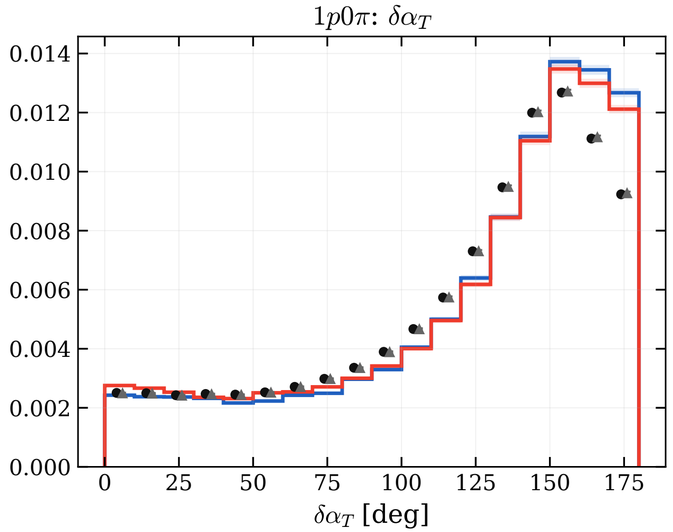
PRELIMINARY / NON-PROMOTABLE — C-12, 4.02962 GeV, matched-statistics symmetric subtraction
Raw no-fold background-subtracted data vs. detector MC with tune-global corrected schema-7 acceptance maps

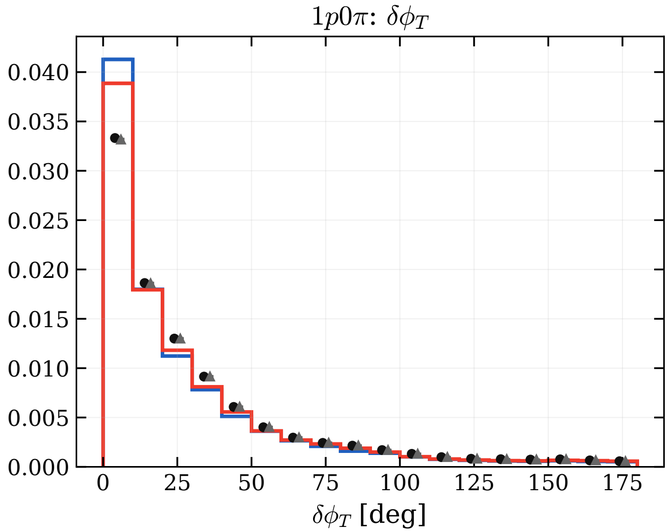












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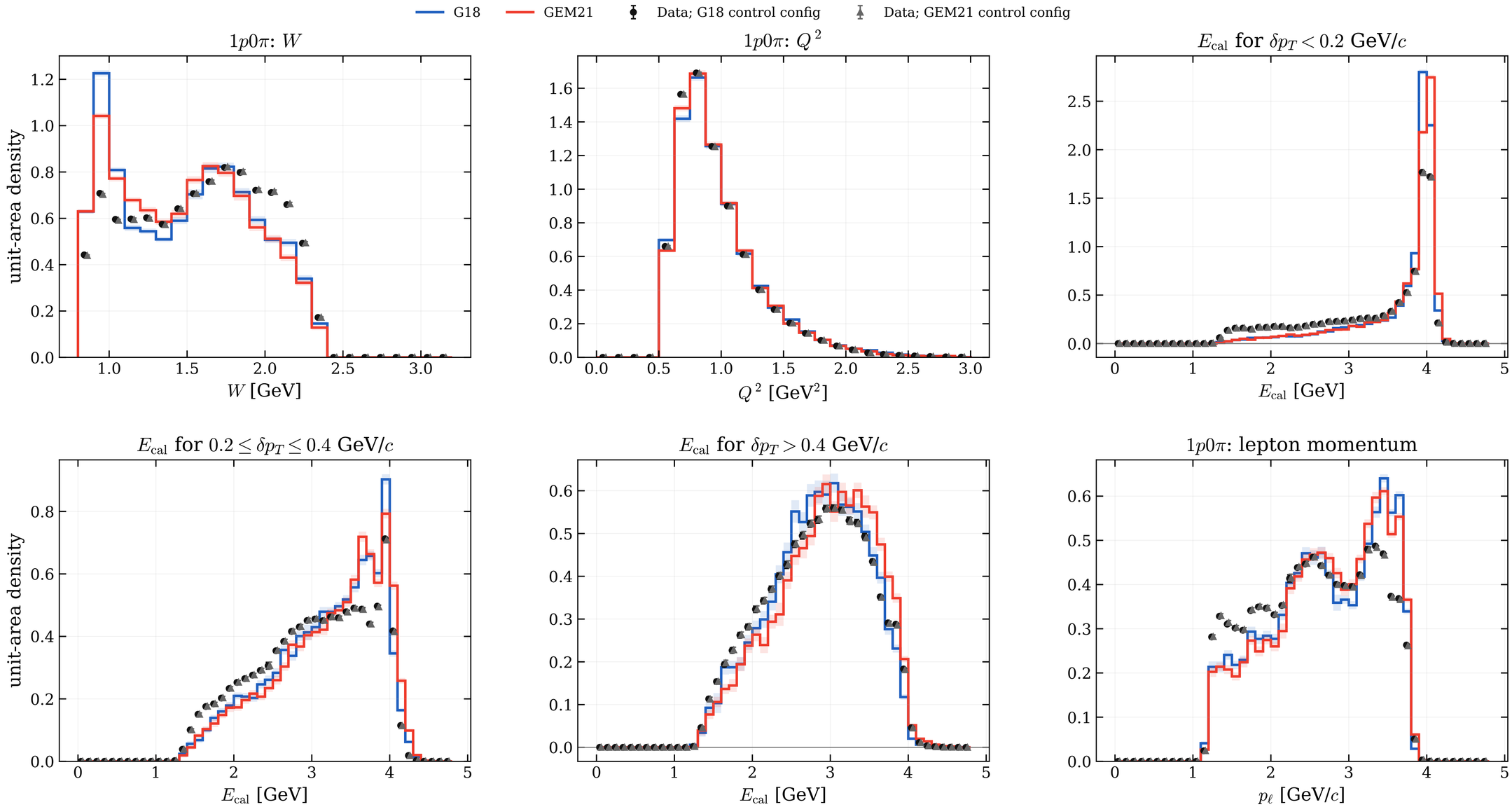
PRELIMINARY / NON-PROMOTABLE — C-12, 4.02962 GeV, matched-statistics symmetric subtraction
Raw no-fold background-subtracted data vs. detector MC with tune-global corrected schema-7 acceptance maps



Each curve is independently unit-area normalized. Raw $A \geq 0.50$; compatible-region ϕ support ≥ 0.10. Bands/error bars contain source-event and finite-rotation statistics only.

PRELIMINARY / NON-PROMOTABLE — C-12, 4.02962 GeV, matched-statistics symmetric subtraction
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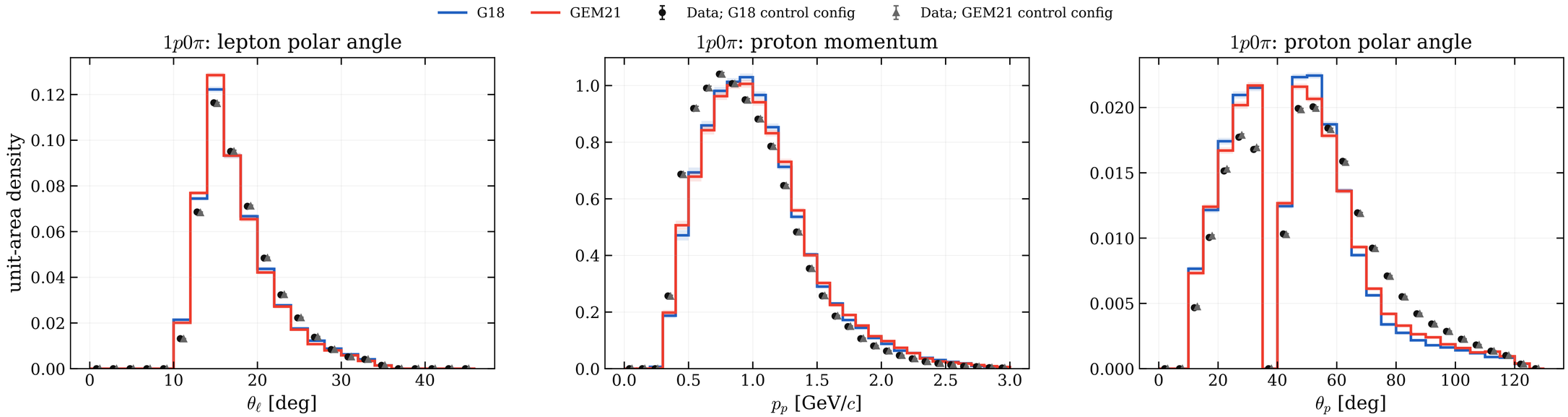
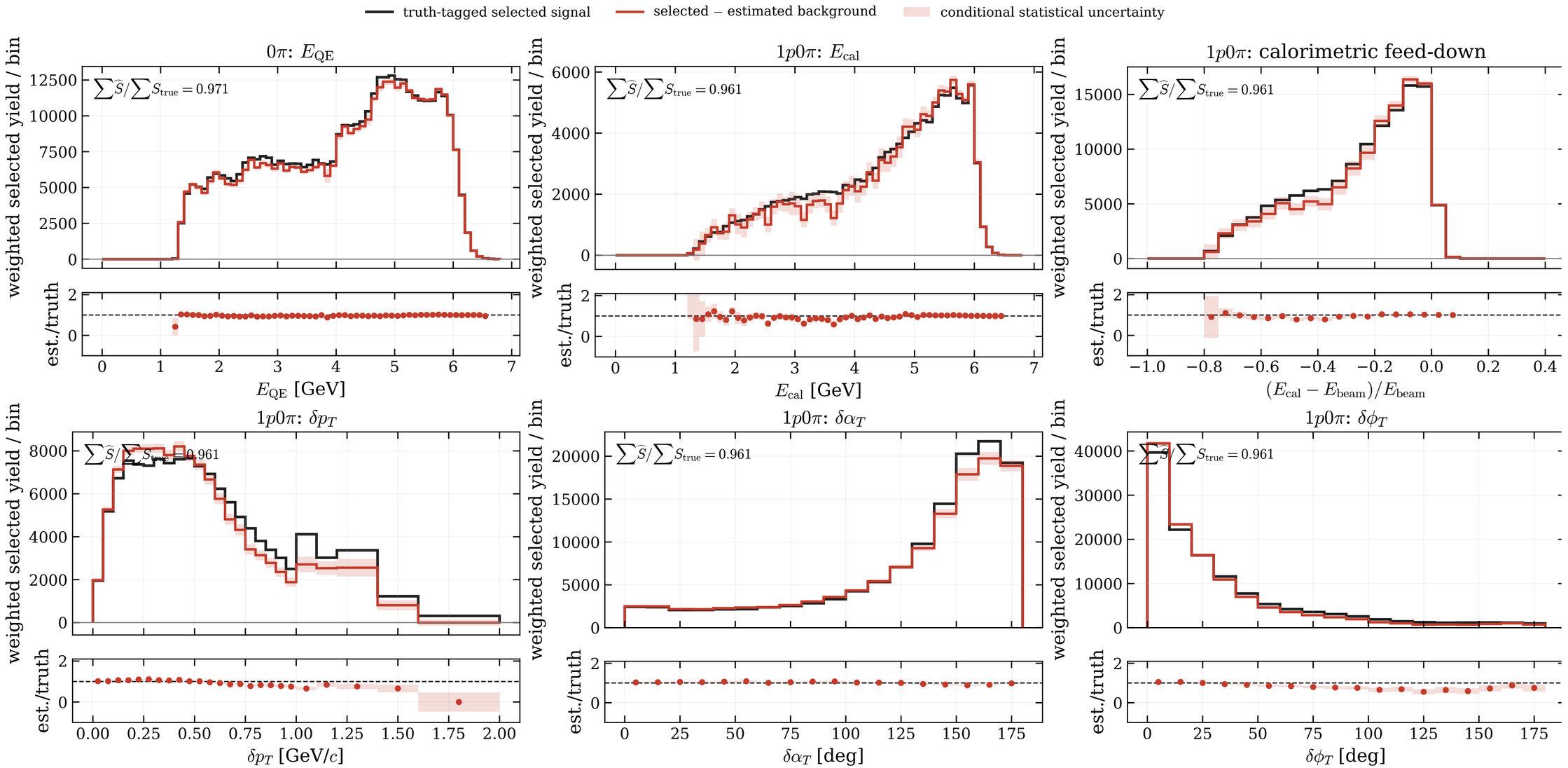


Each curve is independently unit-area normalized. Raw $A \geq 0.50$; compatible-region ϕ support ≥ 0.10. Bands/error bars contain source-event and finite-rotation statistics only.

PRELIMINARY / NON-PROMOTABLE — Ar-40, 5.98636 GeV, matched-statistics symmetric subtraction — GEM21

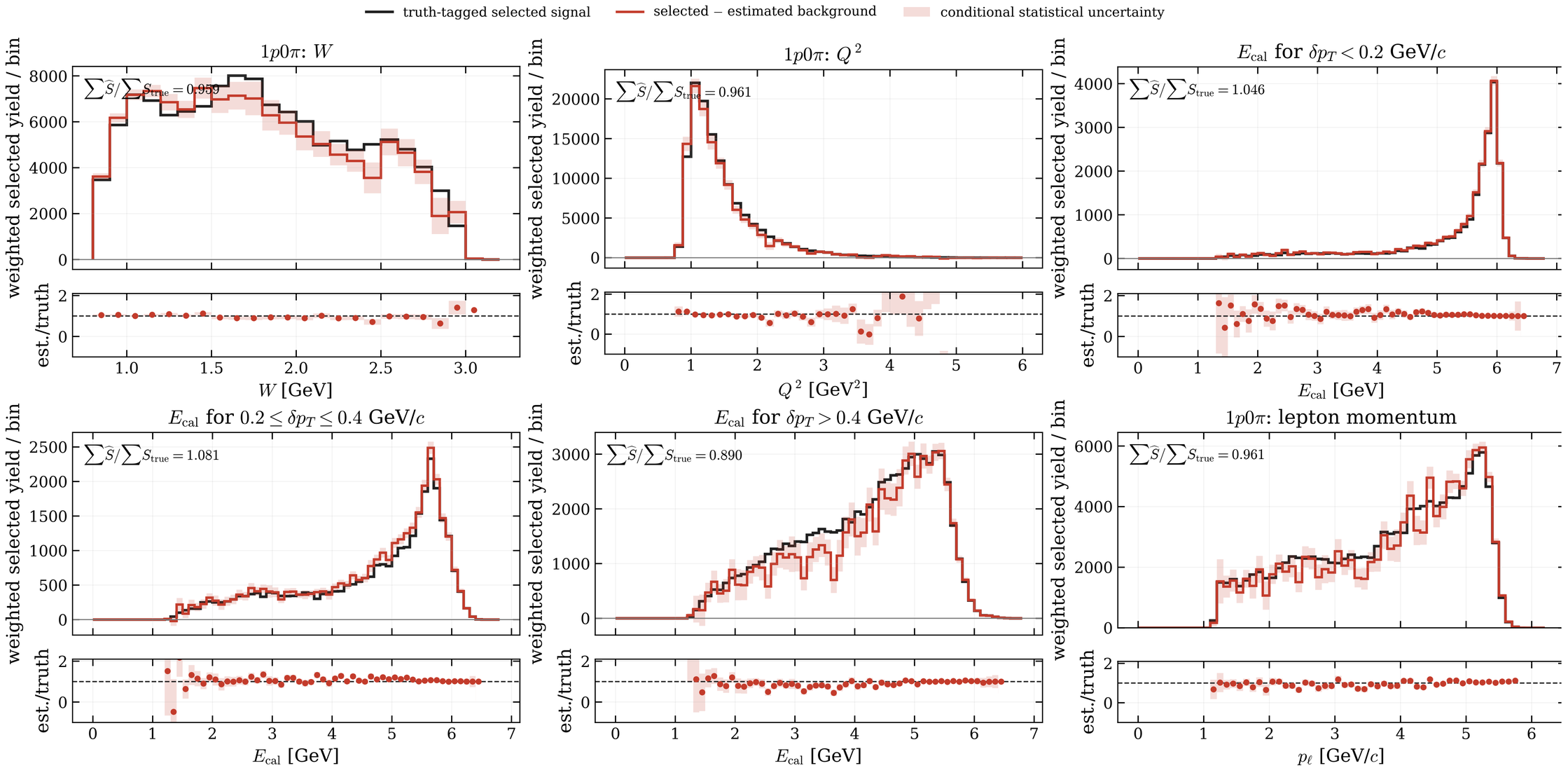
Raw no-fold MC signal closure with tune-global corrected schema-7 acceptance maps



Raw $A \geq 0.50$ and compatible-region ϕ support ≥ 0.10. Band: estimate conditional source-event and finite-rotation statistics only; truth and shared closure covariance are not stored.

PRELIMINARY / NON-PROMOTABLE — Ar-40, 5.98636 GeV, matched-statistics symmetric subtraction — GEM21

Raw no-fold MC signal closure with tune-global corrected schema-7 acceptance maps



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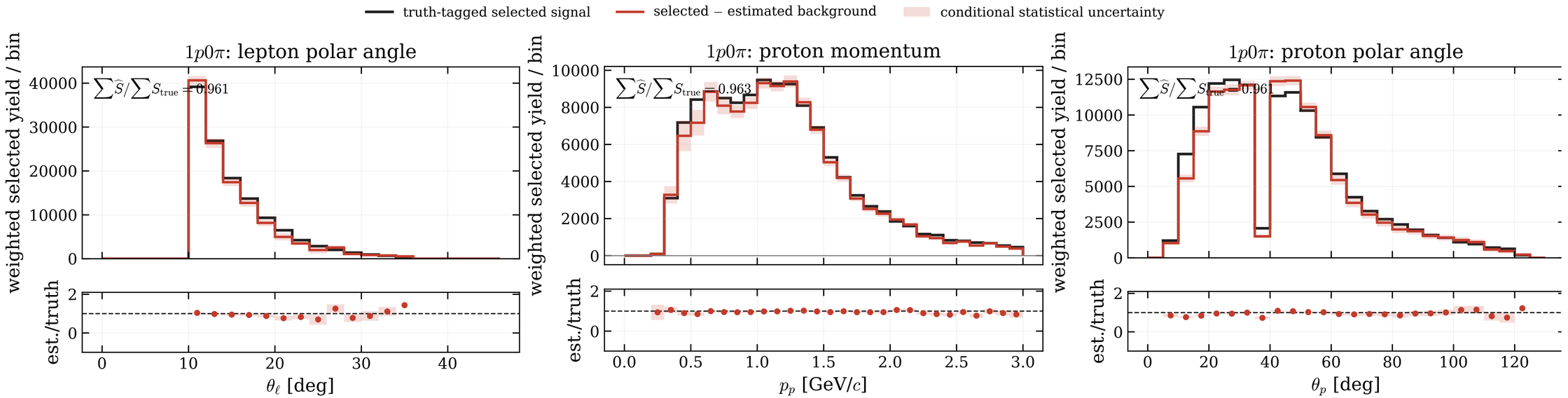
Raw no-fold MC signal closure with tune-global corrected schema-7 acceptance maps



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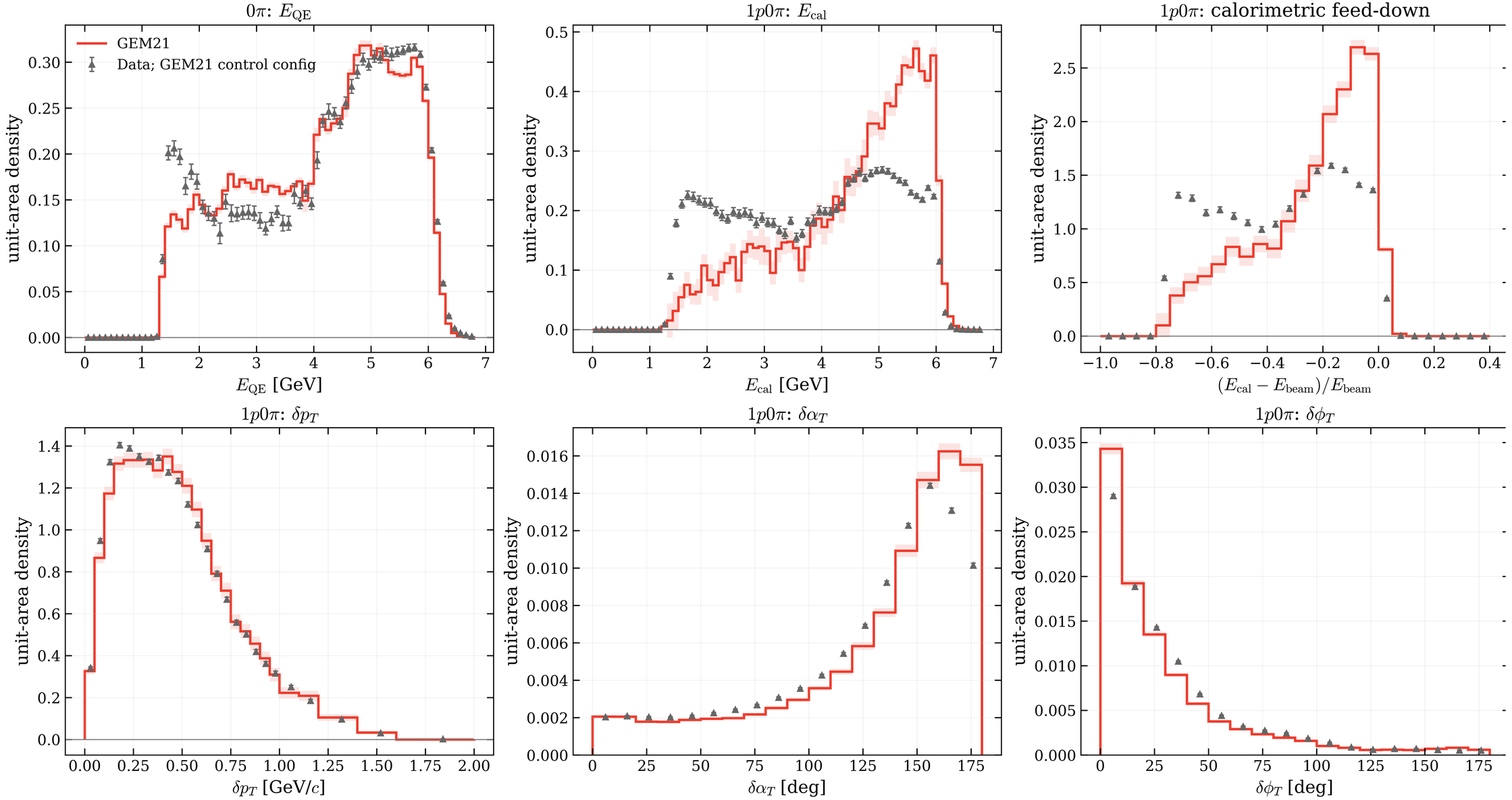
PRELIMINARY / NON-PROMOTABLE — Ar-40, 5.98636 GeV, matched-statistics symmetric subtraction

Raw no-fold background-subtracted data vs. detector MC with tune-global corrected schema-7 acceptance maps



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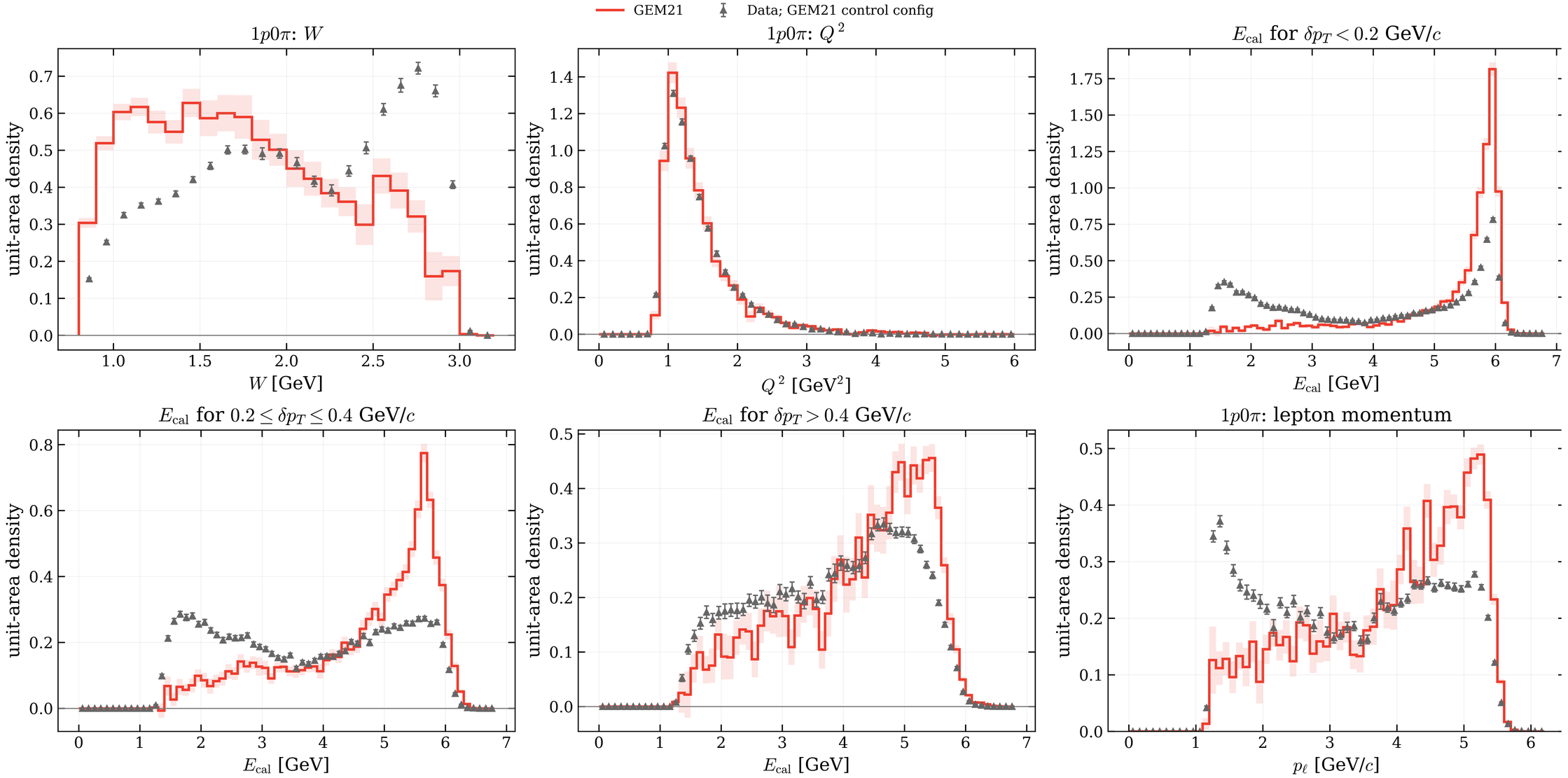

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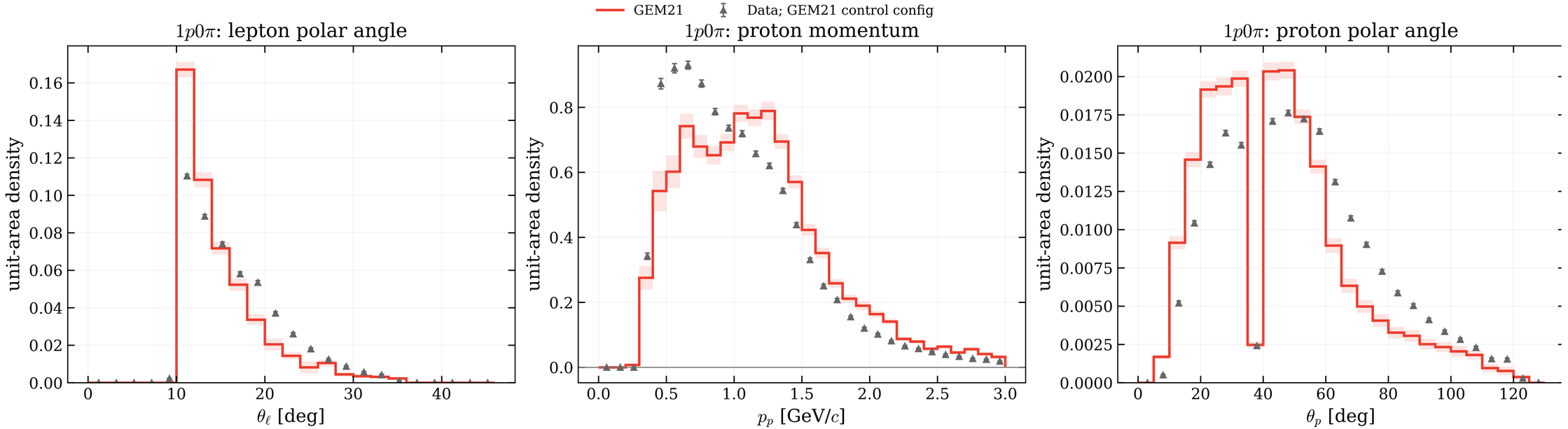
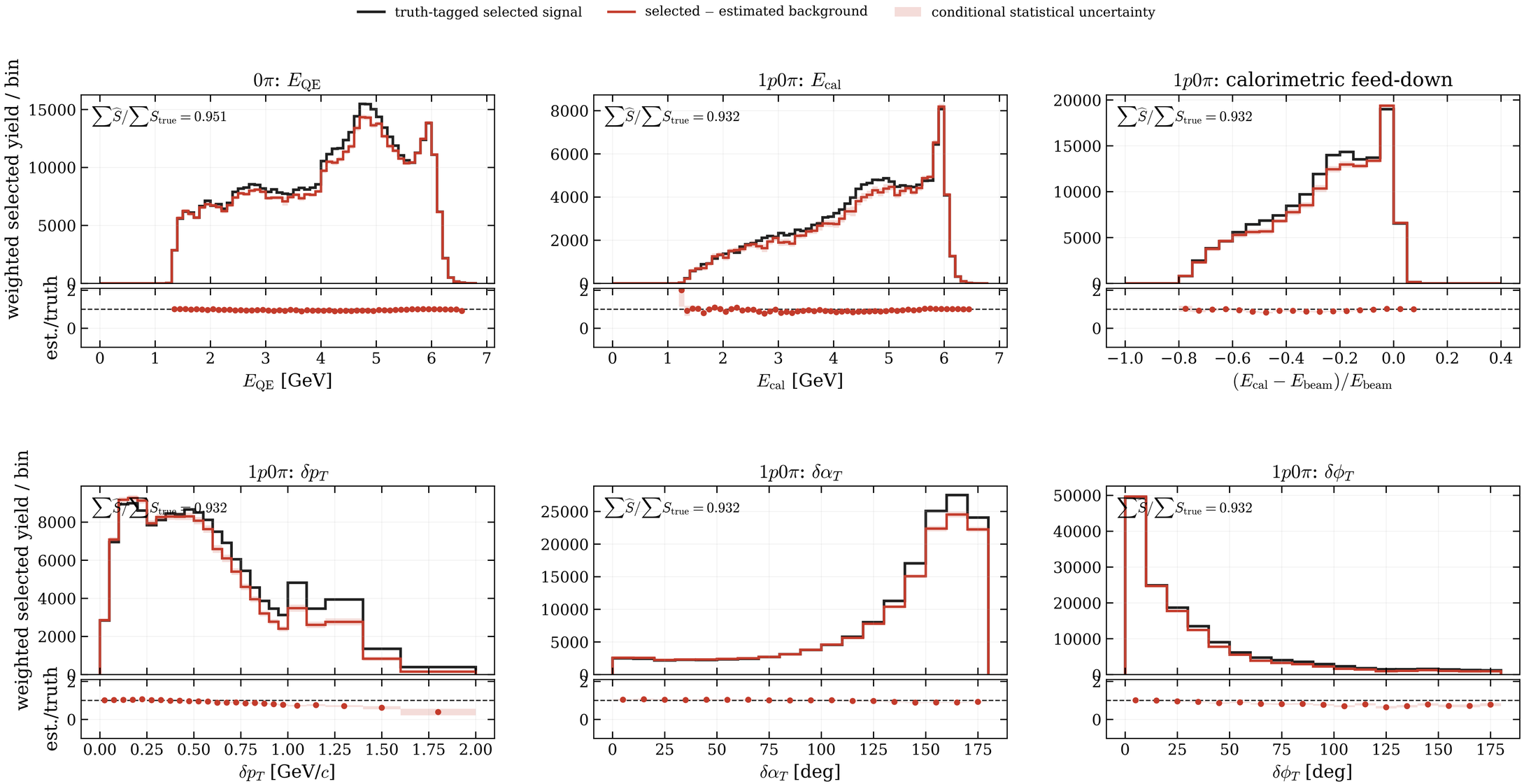


Each curve is independently unit-area normalized. Raw $A \geq 0.50$; compatible-region ϕ support ≥ 0.10. Bands/error bars contain source-event and finite-rotation statistics only.

PRELIMINARY / NON-PROMOTABLE — C-12, 5.98636 GeV, matched-statistics symmetric subtraction — G18

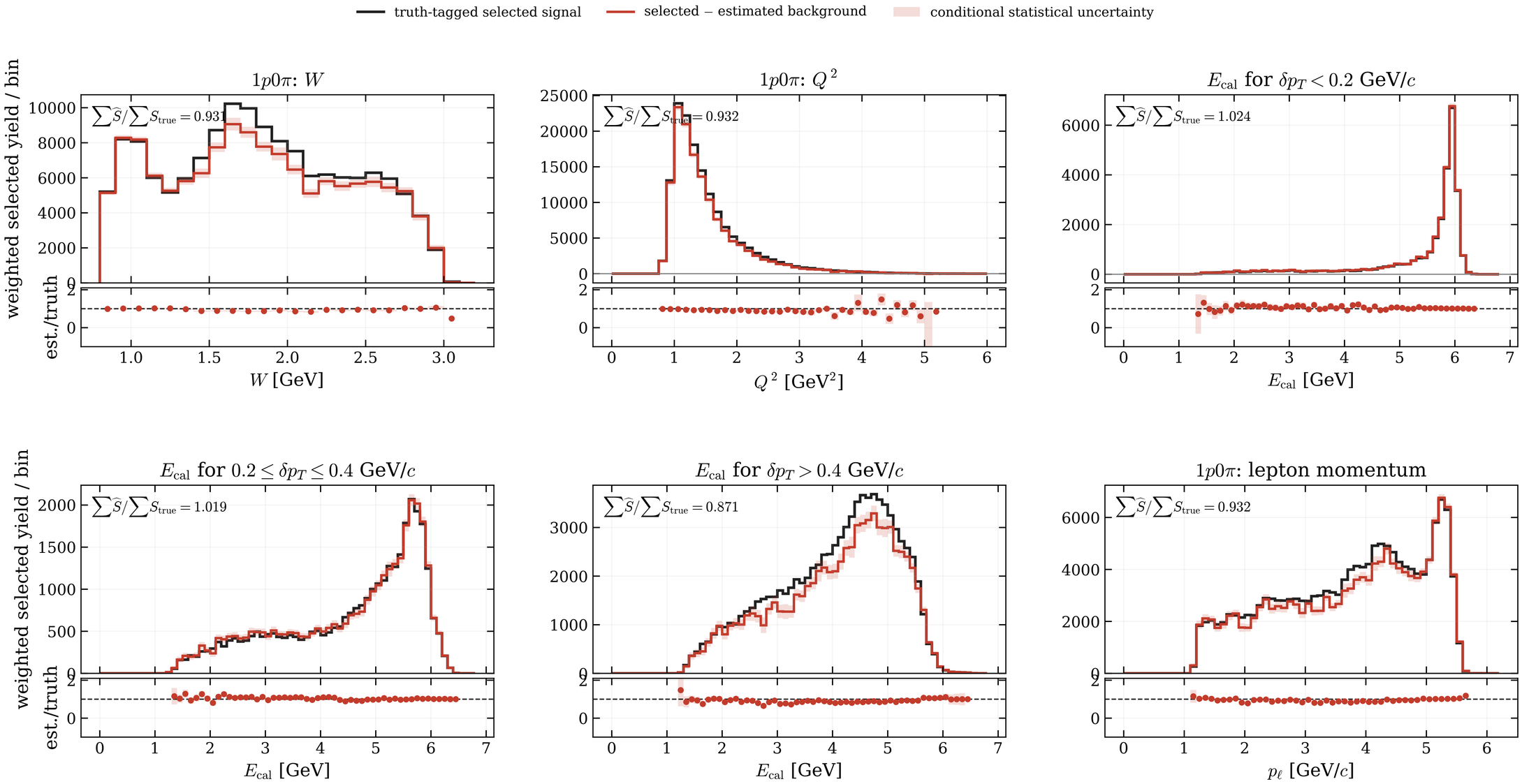
Raw no-fold MC signal closure with tune-global corrected schema-7 acceptance maps



Raw $A \geq 0.50$ and compatible-region ϕ support ≥ 0.10. Band: estimate conditional source-event and finite-rotation statistics only; truth and shared closure covariance are not stored.

PRELIMINARY / NON-PROMOTABLE — C-12, 5.98636 GeV, matched-statistics symmetric subtraction — G18

Raw no-fold MC signal closure with tune-global corrected schema-7 acceptance maps



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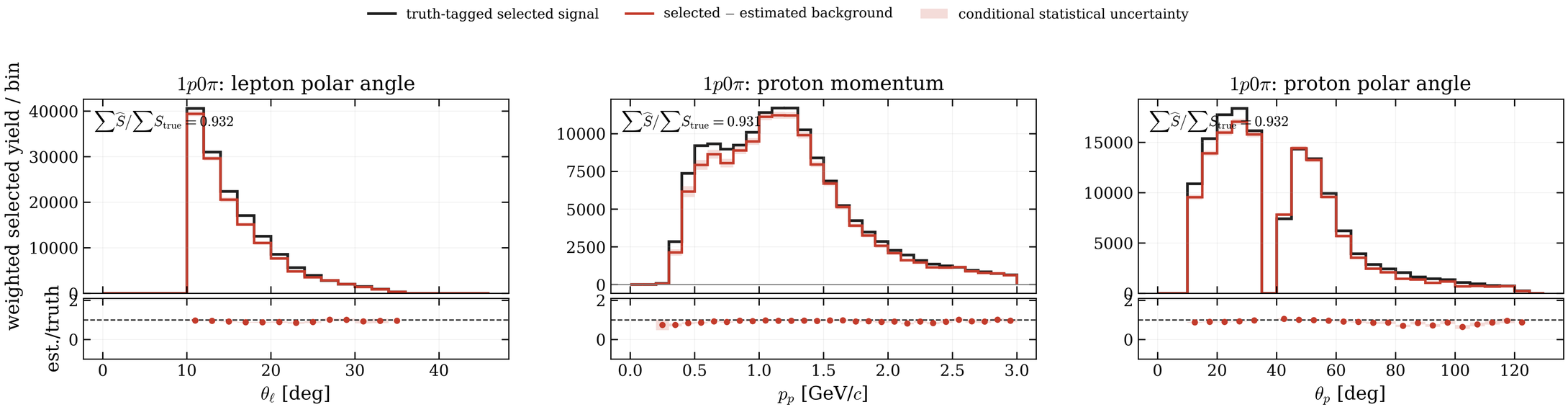
PRELIMINARY / NON-PROMOTABLE — C-12, 5.98636 GeV, matched-statistics symmetric subtraction — G18

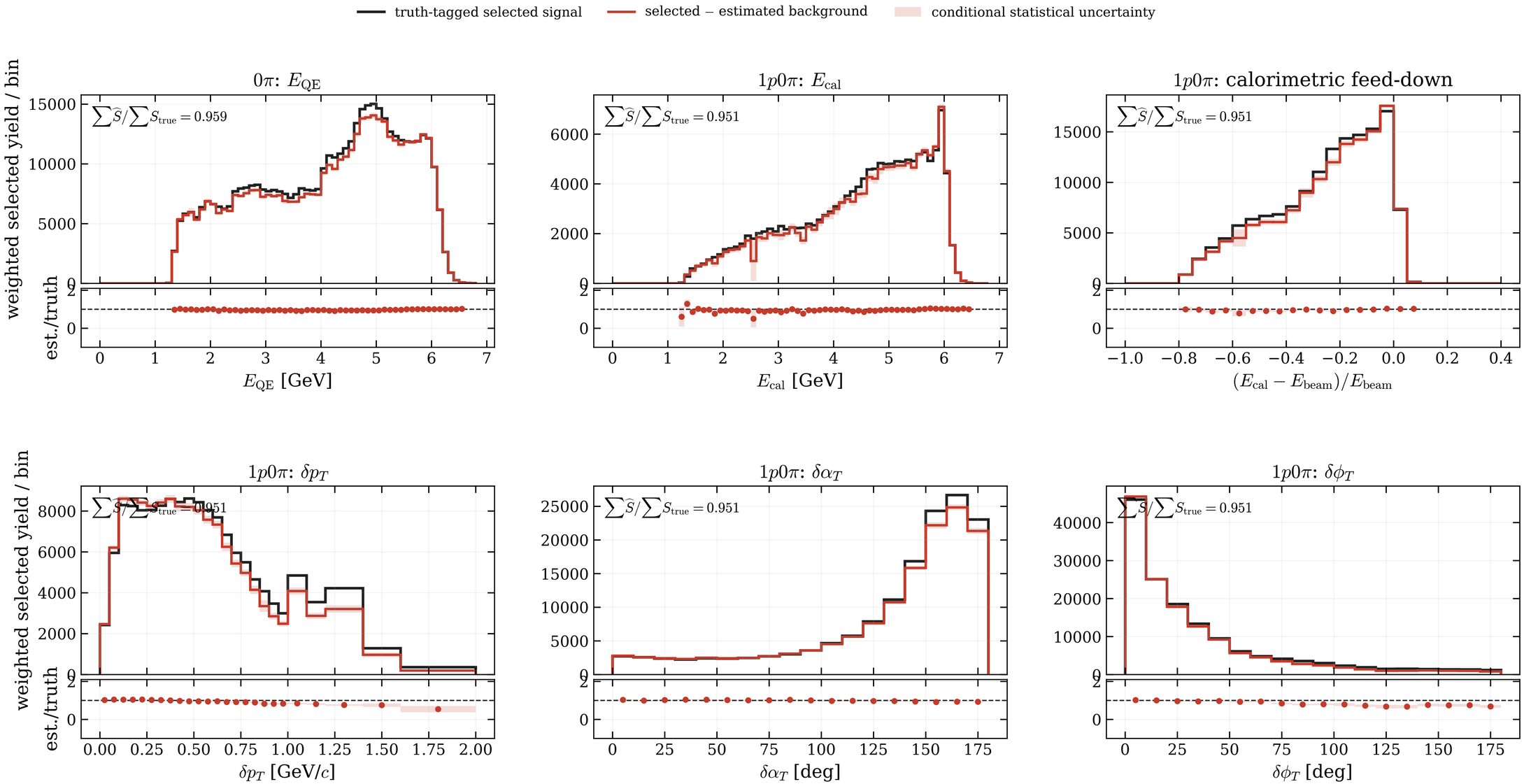
Raw no-fold MC signal closure with tune-global corrected schema-7 acceptance maps



Raw $A \geq 0.50$ and compatible-region ϕ support ≥ 0.10. Band: estimate conditional source-event and finite-rotation statistics only; truth and shared closure covariance are not stored.

PRELIMINARY / NON-PROMOTABLE — C-12, 5.98636 GeV, matched-statistics symmetric subtraction — GEM21

Raw no-fold MC signal closure with tune-global corrected schema-7 acceptance maps



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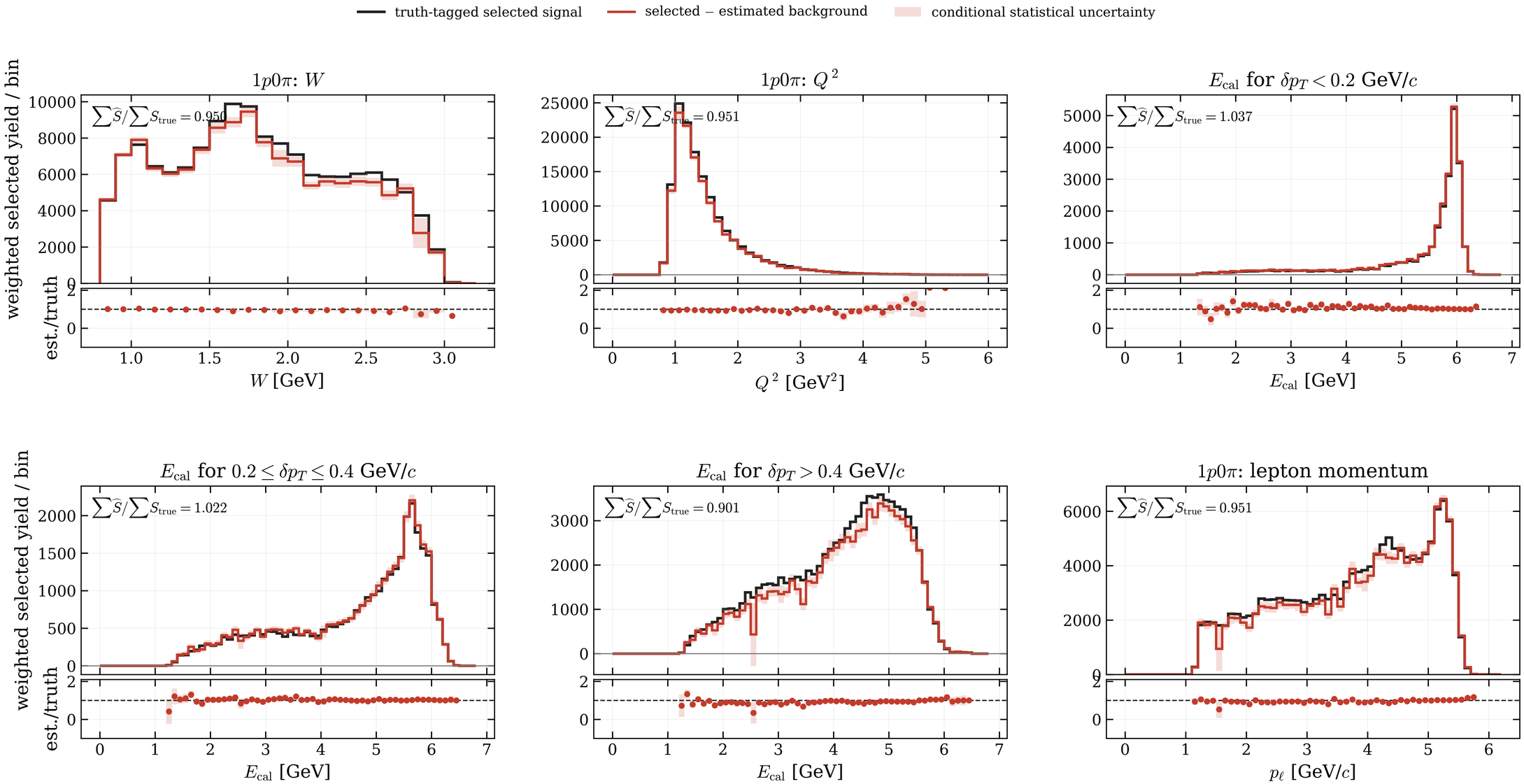
PRELIMINARY / NON-PROMOTABLE — C-12, 5.98636 GeV, matched-statistics symmetric subtraction — GEM21

Raw no-fold MC signal closure with tune-global corrected schema-7 acceptance maps



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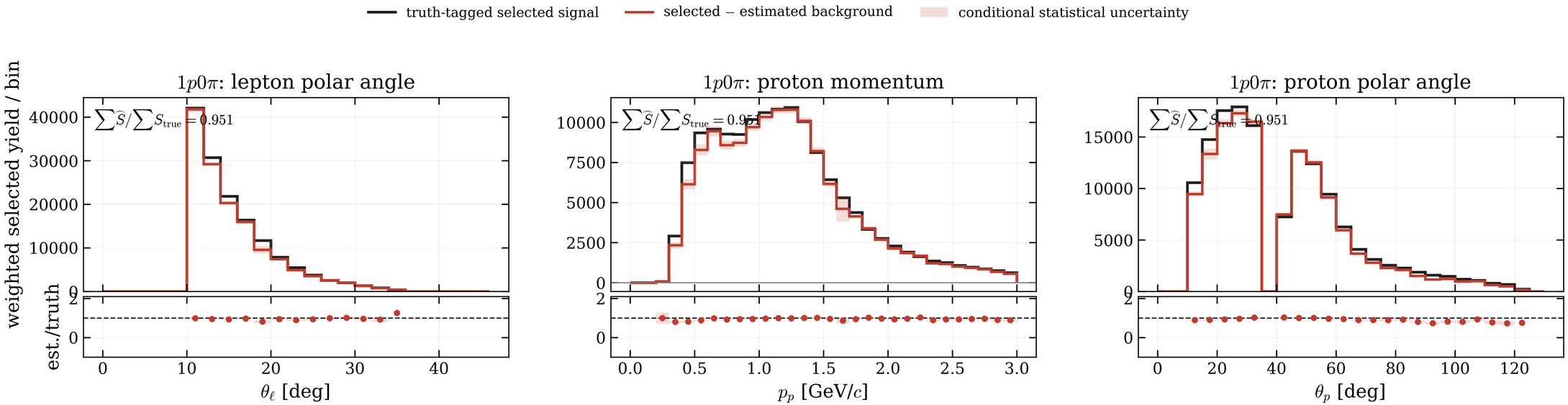
Raw no-fold MC signal closure with tune-global corrected schema-7 acceptance maps



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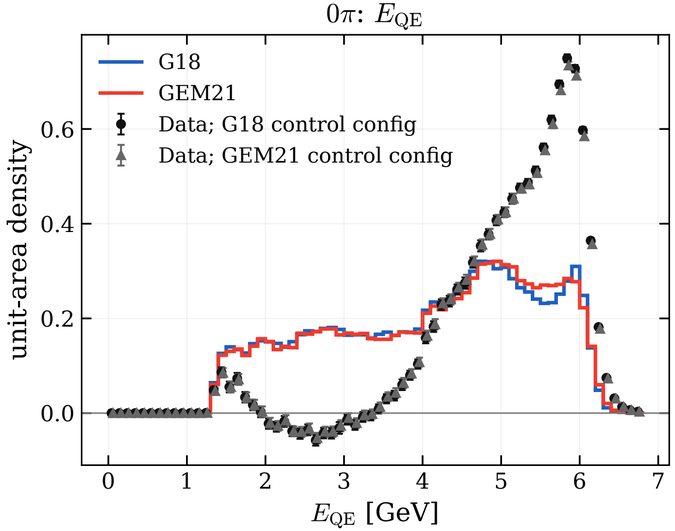
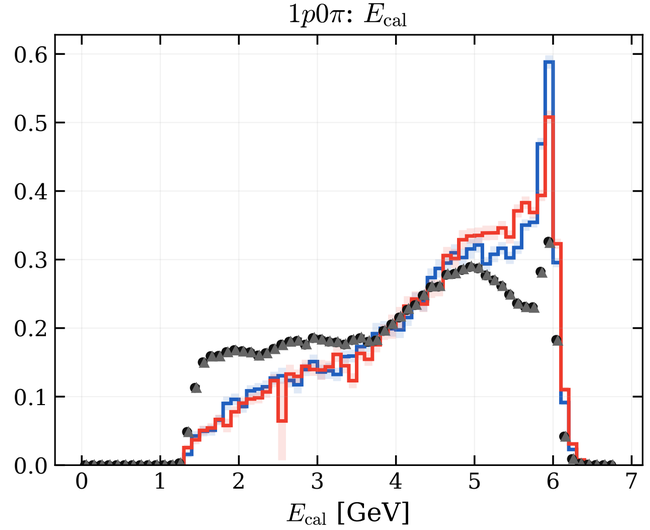
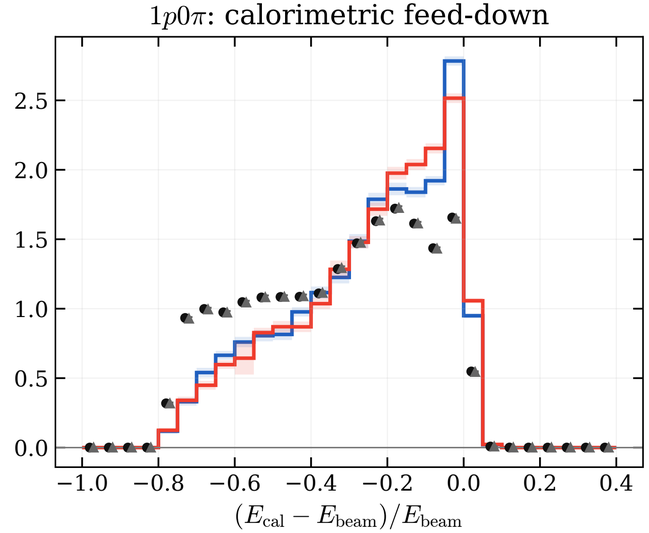
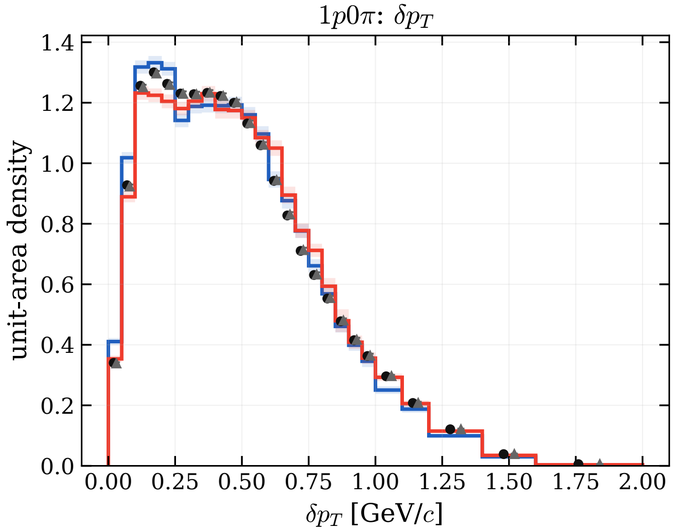
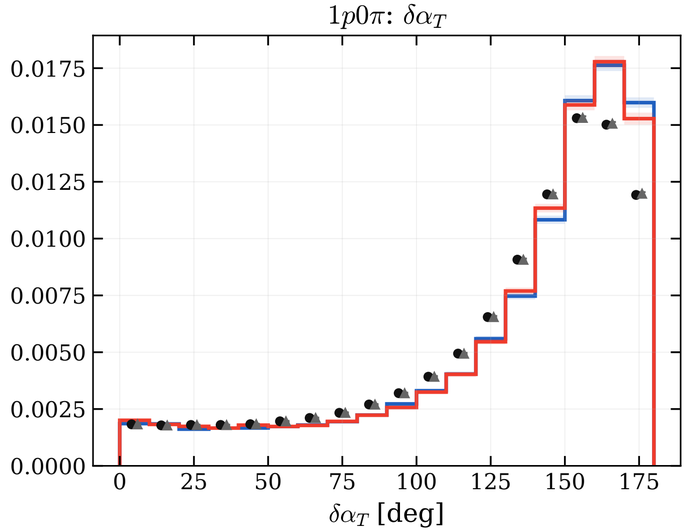
PRELIMINARY / NON-PROMOTABLE — C-12, 5.98636 GeV, matched-statistics symmetric subtraction
Raw no-fold background-subtracted data vs. detector MC with tune-global corrected schema-7 acceptance maps

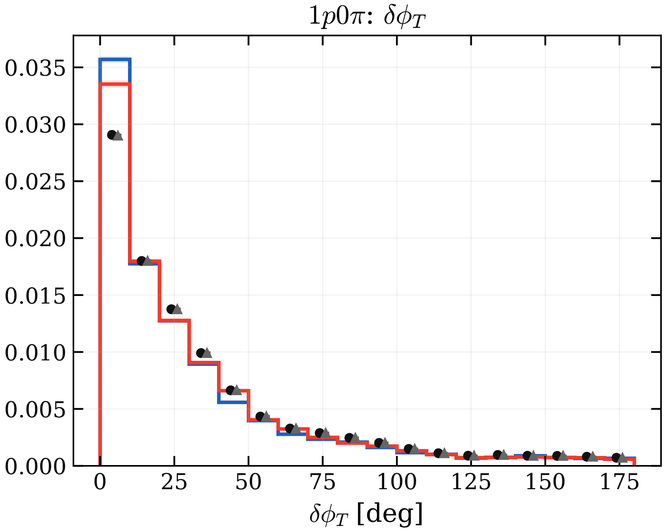












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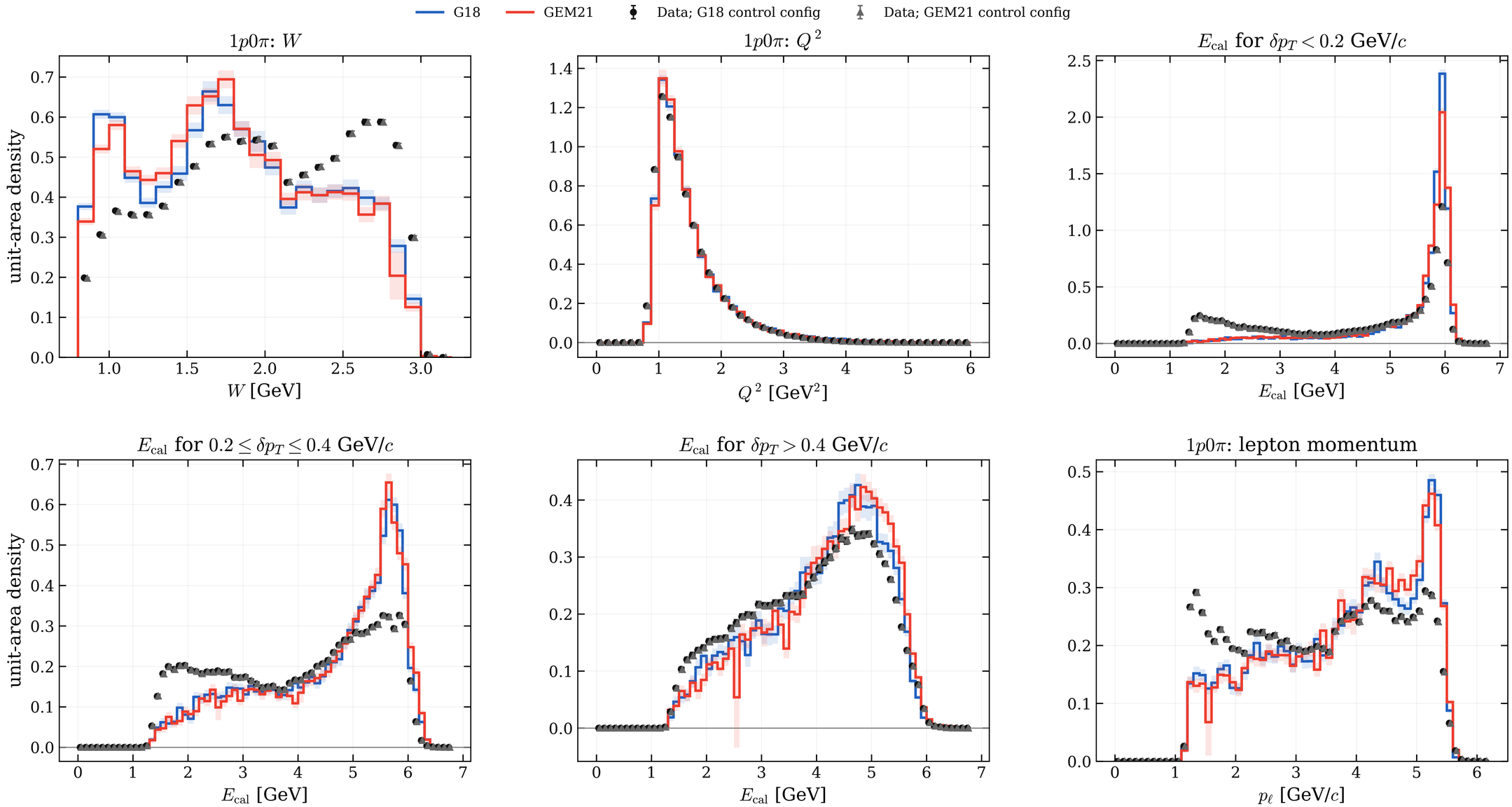

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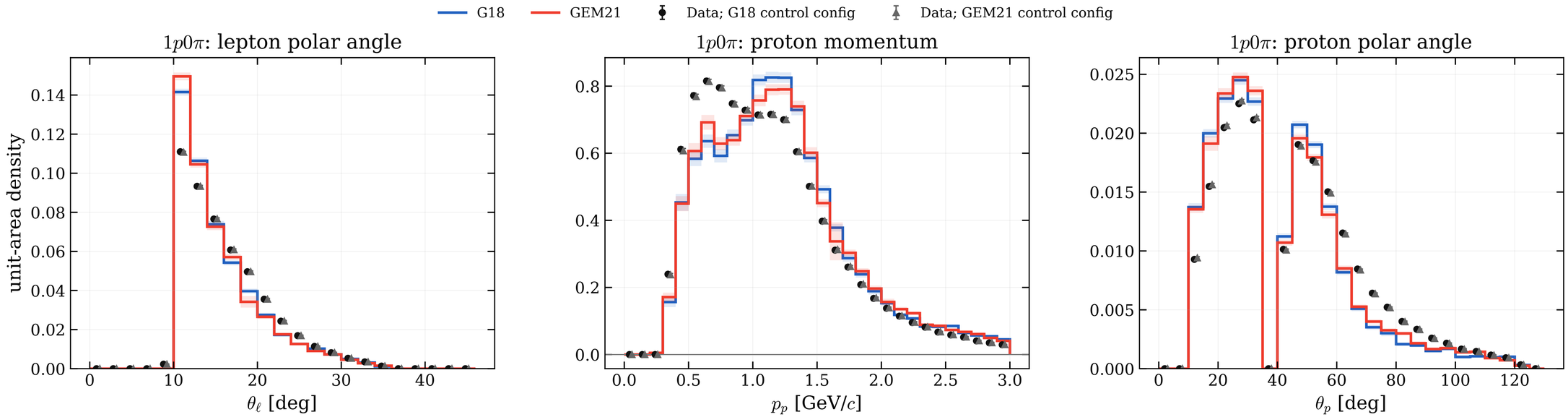

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