High precision A_1 and g_1 measurements at ePIC in the Early Running of EIC

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EIC early science

Current Early Science Matrix

	Species	Energy (GeV)	Luminosity/year (fb-1)	Electron polarization	p/A polarization
YEAR 1	e+Ru or e+Cu	10 x 115	0.9	NO (Commissioning)	N/A
YEAR 2	e+D e+p	10 x 130	11.4 4.95 - 5.33	LONG	NO TRANS
YEAR 3	e+p	10 x 130	4.95 - 5.33	LONG	TRANS and/or LONG
YEAR 4	e+Au e+p	10 x 100 10 x 250	0.84 6.19 - 9.18	LONG	N/A TRANS and/or LONG
YEAR 5	e+Au e+3He	10 x 100 10 x 166	0.84 8.65	LONG	N/A TRANS and/or LONG

Note: the eA luminosity is per nucleon

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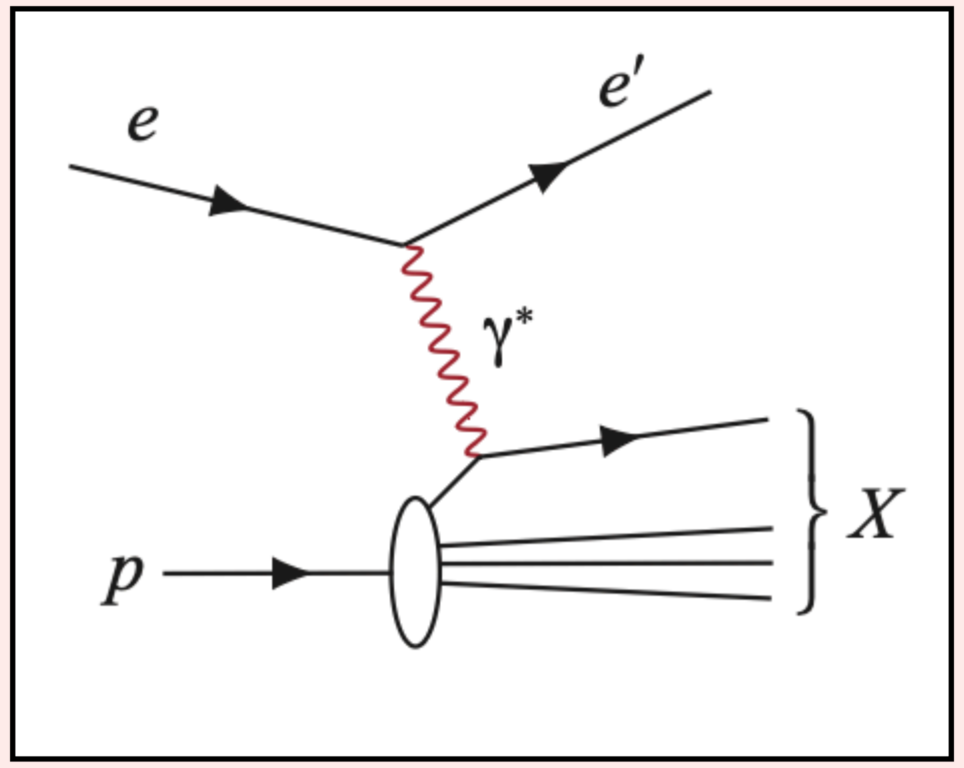
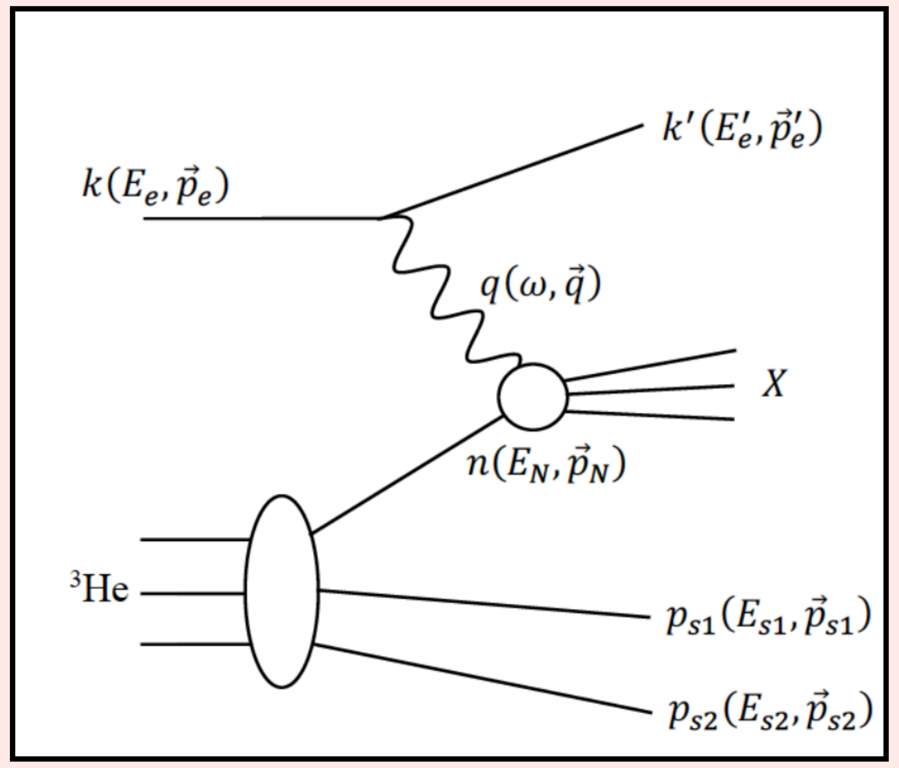
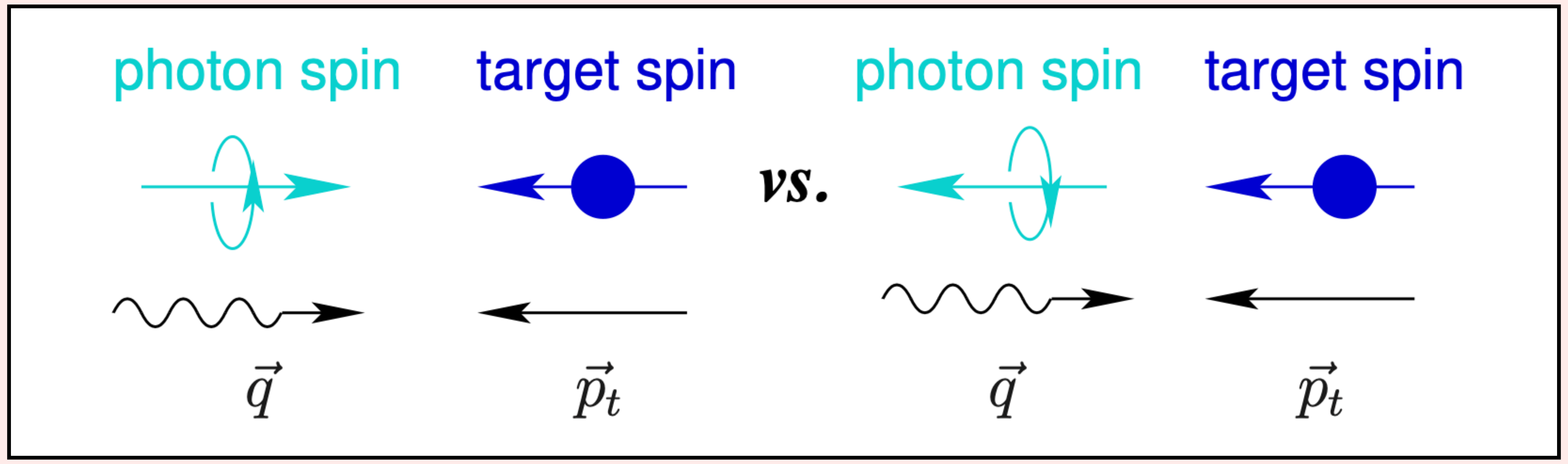




A_1^p A_1^n **Double spin asymmetry**

g_1^p g_1^n **Spin structure function**

Motivation: double spin asymmetry



$$A_1(x,Q^2) \equiv \frac{\sigma_{1/2}-\sigma_{3/2}}{\sigma_{1/2}+\sigma_{3/2}} = \frac{A_\parallel}{D(1+\eta\xi)} - \frac{\eta A_\perp}{d(1+\eta\xi)}$$

p & γ^* spins
anti-aligned

p & γ^* spins
aligned

$$A_\parallel = \frac{\sigma_{\downarrow\Uparrow}-\sigma_{\uparrow\Uparrow}}{\sigma_{\downarrow\Uparrow}+\sigma_{\uparrow\Uparrow}}$$

p & e spins
anti-aligned

p & e spins
aligned

$$A_\perp = \frac{\sigma_{\downarrow\Rightarrow}-\sigma_{\uparrow\Rightarrow}}{\sigma_{\downarrow\Rightarrow}+\sigma_{\uparrow\Rightarrow}}$$

p & e spins
perpendicular

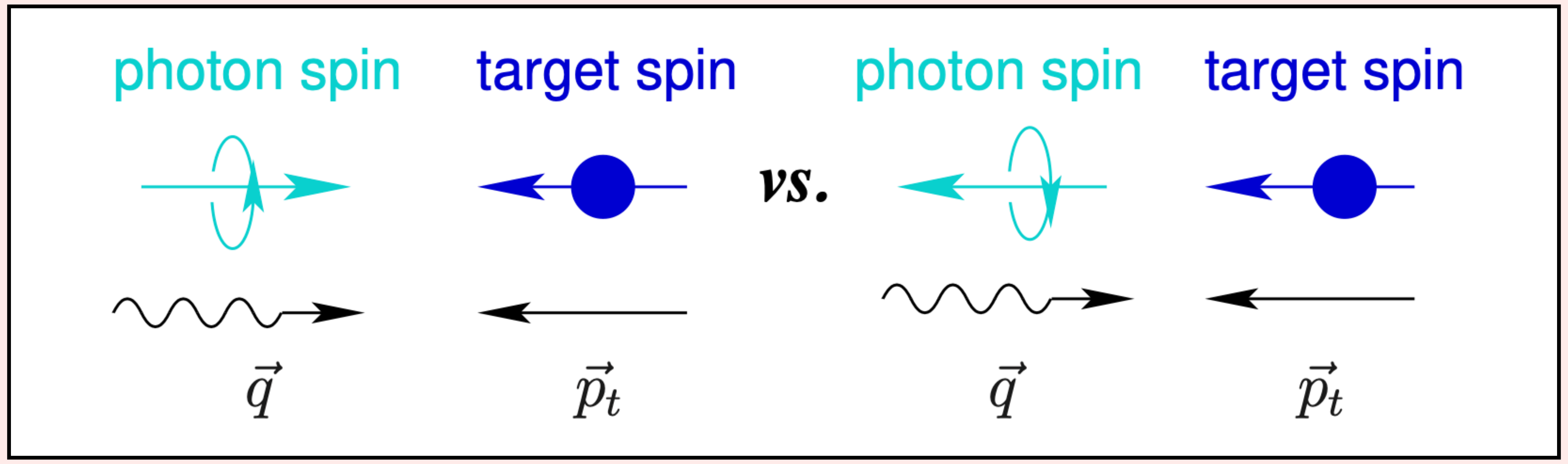
$$D = \frac{y(2-y)(2+\gamma^2 y)}{2(1+\gamma^2)y^2+(4(1-y)-\gamma^2y^2)(1+R)}$$

$$R \equiv \frac{\sigma_L}{\sigma_T} = \frac{F_L}{F_2-F_L}$$

$$d = \frac{D\sqrt{4(1-y)-\gamma^2y^2}}{2-y}$$

$$\gamma^2 = \frac{4M^2x^2}{Q^2} \qquad \eta = \frac{4(1-y)-\gamma^2y^2}{(2-y)(2+\gamma^2 y)} \qquad \xi = \frac{\gamma(2-y)}{2+\gamma^2 y}$$

Motivation: spin-dependent structure function



$$A_1(x, Q^2) \equiv \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} = \frac{A_\parallel}{D(1+\eta\xi)} - \frac{\eta A_\perp}{d(1+\eta\xi)}$$

p & γ^* spins anti-aligned

p & γ^* spins aligned

$$g_1 = \frac{F_2}{2x(1+R)}(A_1 + \gamma A_2)$$

Spin-dependent structure function

$$A_\parallel = \frac{\sigma_{\downarrow\Uparrow} - \sigma_{\uparrow\Uparrow}}{\sigma_{\downarrow\Uparrow} + \sigma_{\uparrow\Uparrow}}$$

p & e spins anti-aligned

p & e spins aligned

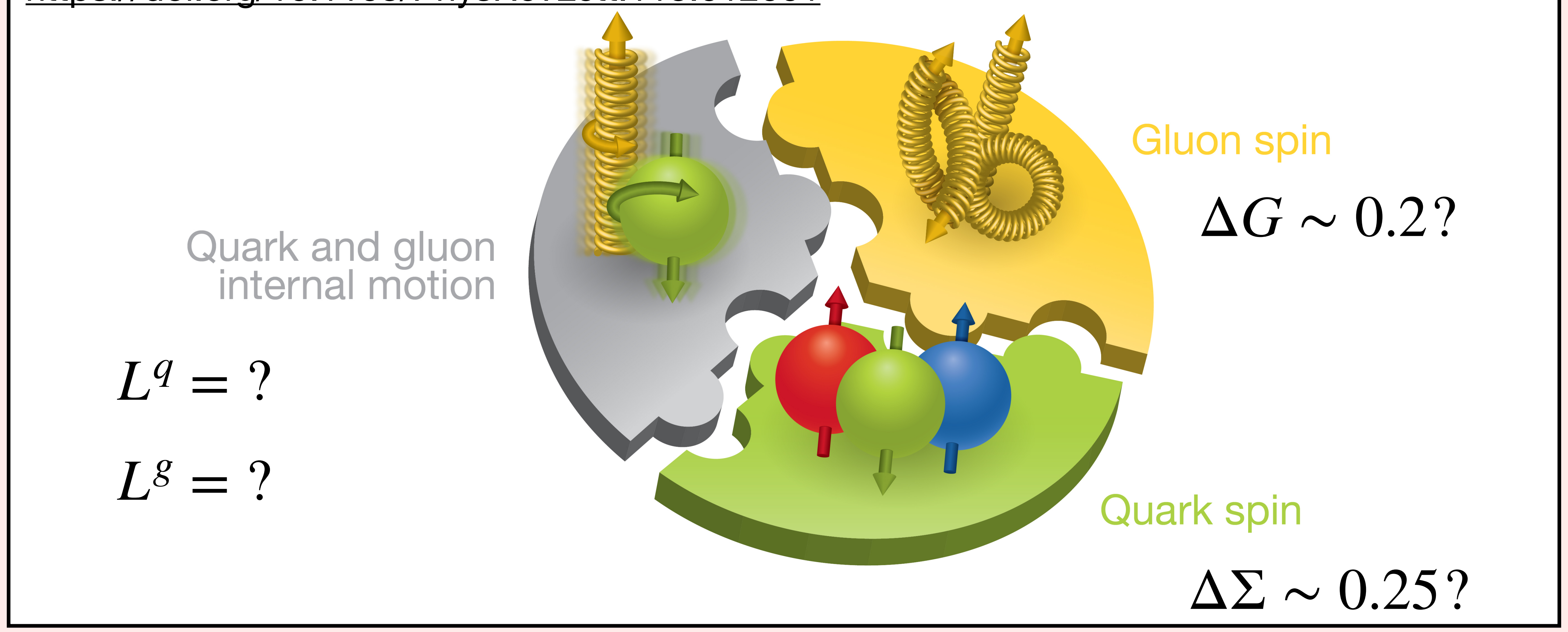
$$A_\perp = \frac{\sigma_{\downarrow\Rightarrow} - \sigma_{\uparrow\Rightarrow}}{\sigma_{\downarrow\Rightarrow} + \sigma_{\uparrow\Rightarrow}}$$

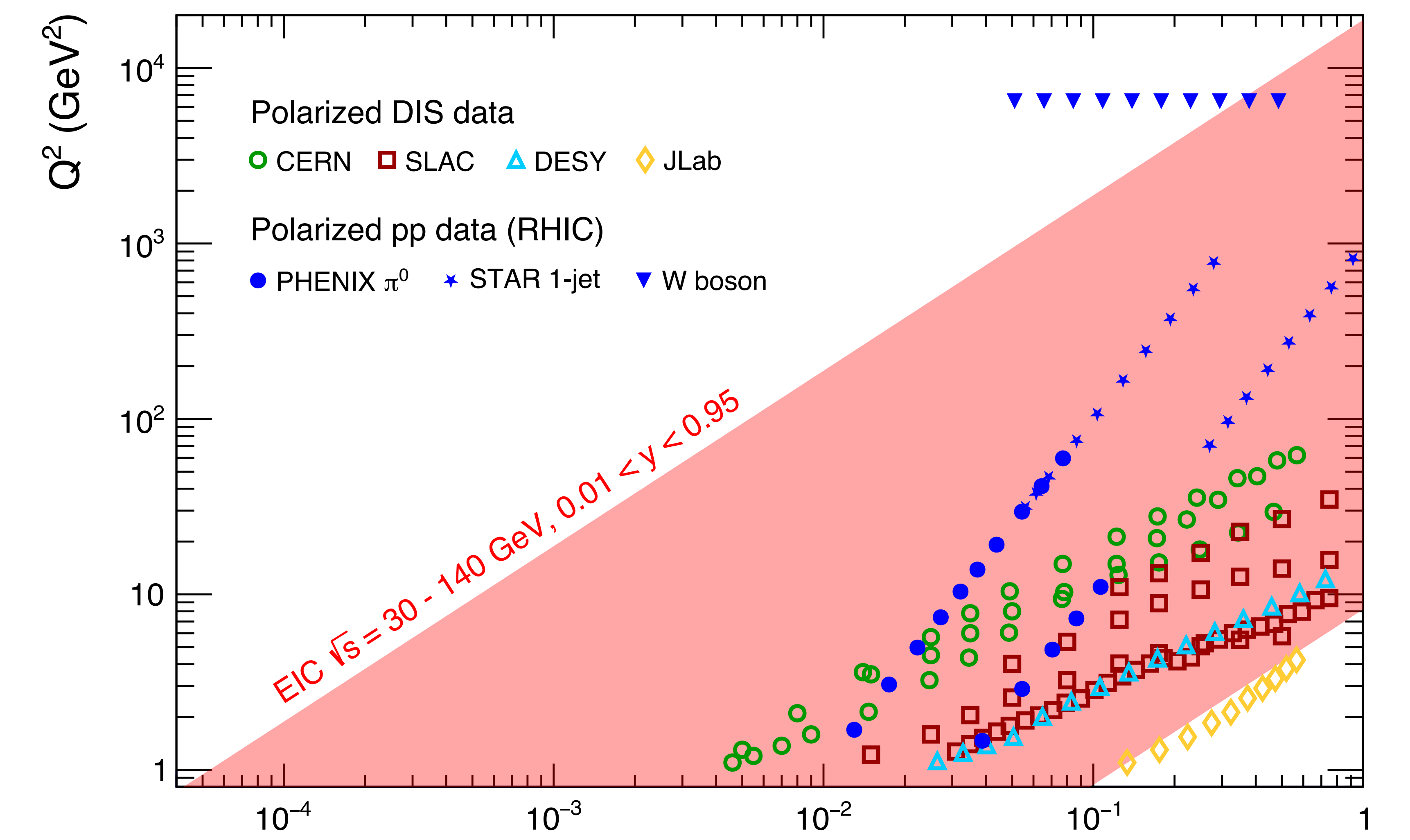
p & e spins perpendicular

$$A_2(x, Q^2) \equiv \frac{2\sigma_{LT}}{\sigma_{1/2} + \sigma_{3/2}} = \frac{\xi A_\parallel}{D(1+\eta\xi)} - \frac{A_\perp}{d(1+\eta\xi)}$$

Motivation: spin composition, Bjorken sum, α_s

https://doi.org/10.1103/PhysRevLett.113.012001





https://doi.org/10.48550/arXiv.1212.1701

Perturbative QCD:

$$g_1(x,t) = \frac{1}{2}\sum_{k=1}^{n_f}\frac{e_k^2}{n_f}\int_x^1\frac{dy}{y}\left[C_q^S\left(\frac{x}{y},\alpha_s(t)\right)\Delta\Sigma(y,t)\right.$$
$$+2n_f C_g\left(\frac{x}{y},\alpha_s(t)\right)\Delta G(y,t)$$
$$\left.+C_q^{\mathrm{NS}}\left(\frac{x}{y},\alpha_s(t)\right)\Delta q_{\mathrm{NS}}(y,t)\right]$$

Bjorken sum:

$$\Gamma_1^{\mathrm{p-n}}(\alpha_s) = \Gamma_1^{\mathrm{p-n}}(Q^2) = \int_0^{1^-}(g_1^p(Q^2) - g_1^n(Q^2))\,dx$$
$$= \sum_{n>0}\frac{\mu_{2n}^{p-n}(\alpha_s)}{Q^{2n-2}} = \frac{g_A}{6}\left[1 - \frac{\alpha_S(Q^2)}{\pi} - 3.58\left(\frac{\alpha_S(Q^2)}{\pi}\right)^2\right.$$
$$\left.-20.21\left(\frac{\alpha_S(Q^2)}{\pi}\right)^3 - 175.7\left(\frac{\alpha_S(Q^2)}{\pi}\right)^4 - \mathscr{O}((\alpha_S)^5)\right]$$

at finite Q^2

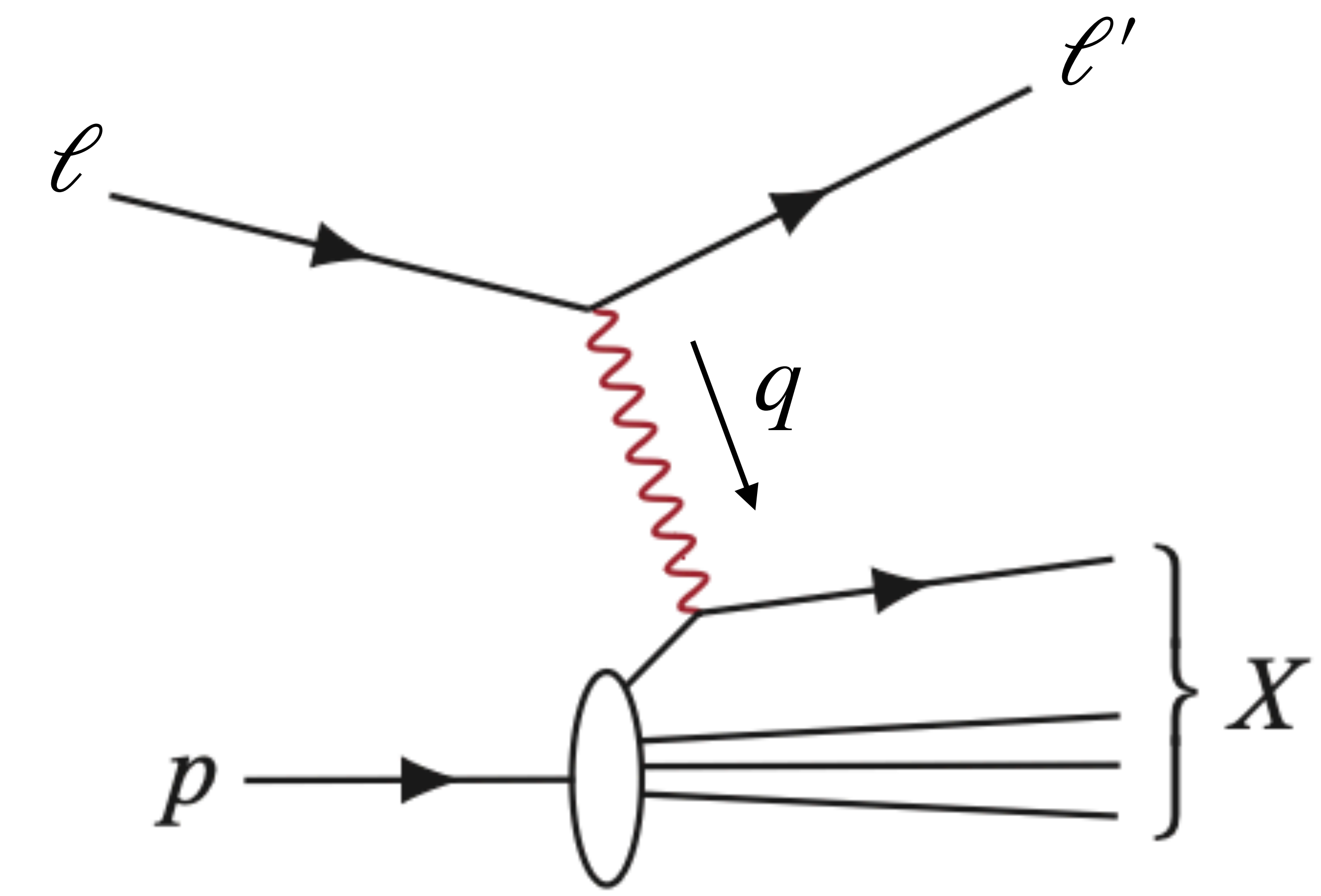
Why measuring double spin asymmetry

$$\frac{d^3\sigma(\beta)}{dQ^2dxd\phi} = \boxed{\frac{d^3\sigma_0}{dQ^2dxd\phi}} - \boxed{\frac{d^3\Delta\sigma(\beta)}{dQ^2dxd\phi}}$$

$$\frac{d^2\sigma}{dQ^2dx} = \frac{4\pi\alpha^2}{Q^4}\frac{1}{x}\left[xy^2F_1(x,Q^2) + \left(1 - y - \frac{Mxy}{2E}F_2(x,Q^2)\right)\right]$$

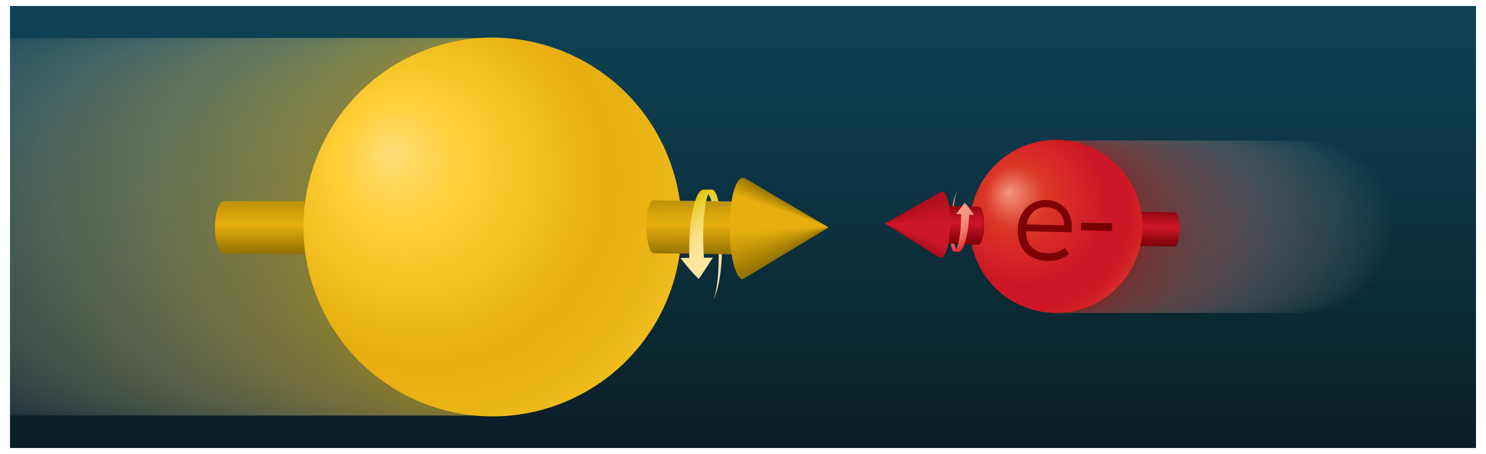
$$\frac{d^3\Delta\sigma(\beta)}{dQ^2dxd\phi} = \frac{4\alpha^2}{Q^2}y\left\{\cos\beta\left[\left(1-\frac{y}{2}-\frac{\gamma^2y^2}{4}\right)g_1(x,Q^2) - \frac{\gamma^2y}{4}g_2(x,Q^2)\right]\right.$$
$$\left. -\cos\phi\sin\beta\frac{\sqrt{Q^2}}{\nu}\left(1-y-\frac{\gamma^2y^2}{4}\right)^{\frac{1}{2}}\left[\frac{y}{2}g_1(x,Q^2)+g_2(x,Q^2)\right]\right\}$$

- Direct measurement is more challenging
- Easier to measure via cross section ratio
- Systematic is largely canceled out

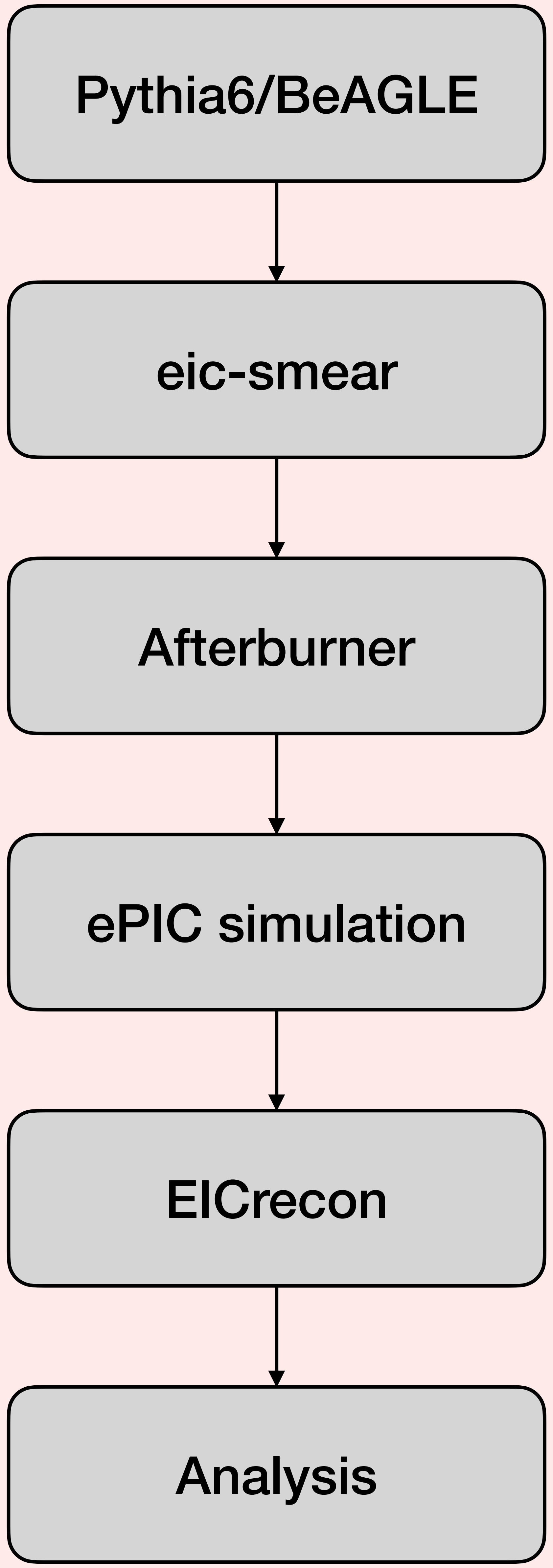


NC Inclusive DIS: $e + p \rightarrow e' + X$

https://arxiv.org/abs/2103.05419



Projection simulation & analysis flow



Pythia6/BeAGLE

eic-smear

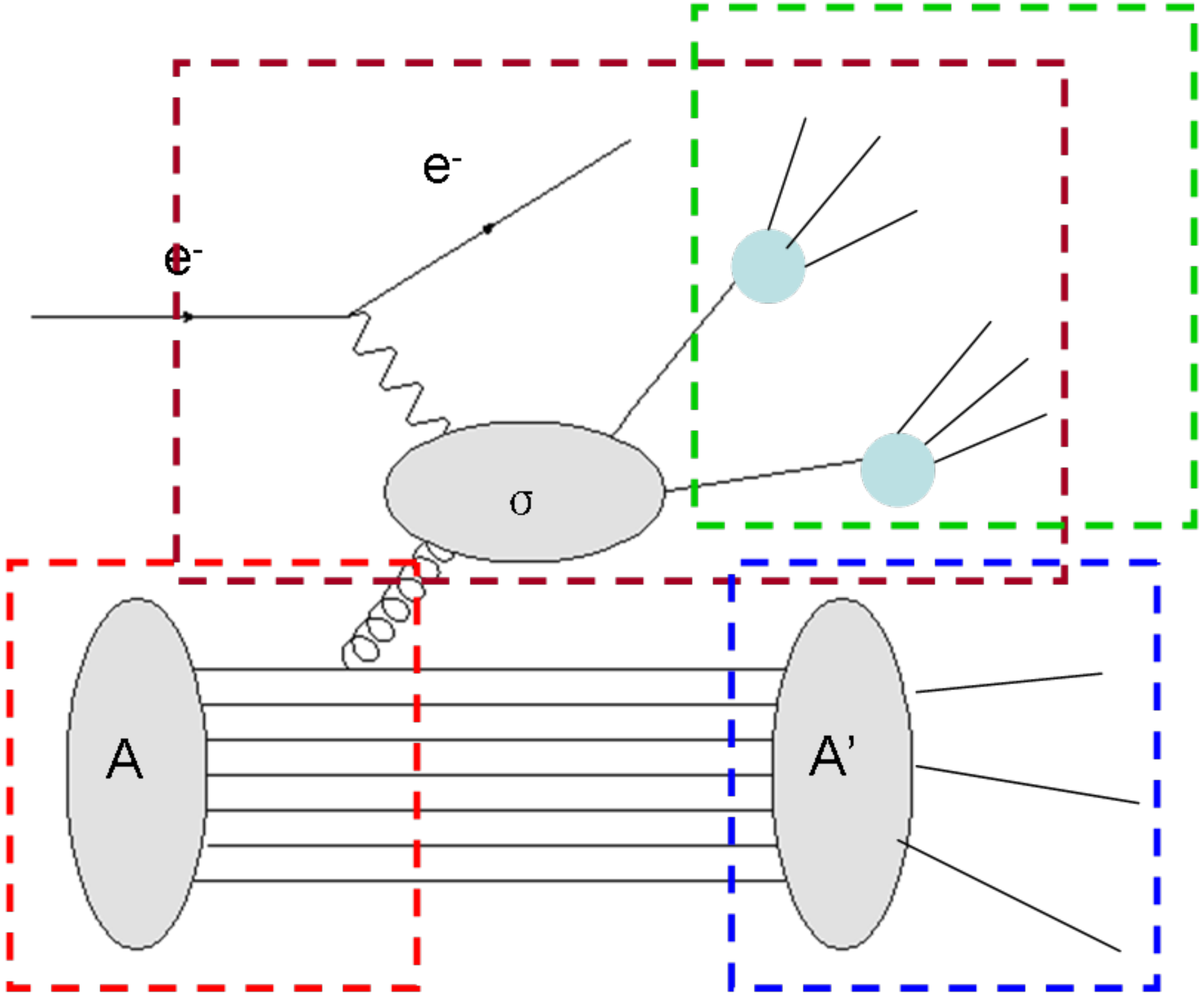
Afterburner

ePIC simulation

EICrecon

Analysis

BeAGLE: eA event generator



A hybrid model consisting of DPMJet and PYTHIA with nPDF EPS09.

Nuclear geometry by DPMJet and nPDF provided by EPS09.

Parton level interaction and jet fragmentation completed in PYTHIA.

Nuclear evaporation (gamma dexcitation/nuclear fission/fermi break up) treated by DPMJet

Energy loss effect from routine by Salgado&Wiedemann to simulate the nuclear fragmentation effect in cold nuclear matter

- ☑ Parton distribution functions
- ☑ Short-range correlations
- ☑ Fermi motion
- ☑ Partonic (or "dipole") MS
- ☑ Partonic gluon radiation
- ☑ Formation times
- ☑ Hadronic Cascade
- ☑ Nuclear evaporation, break up
- ☑ Photonic de-excitation of A*

Projection simulation & analysis flow

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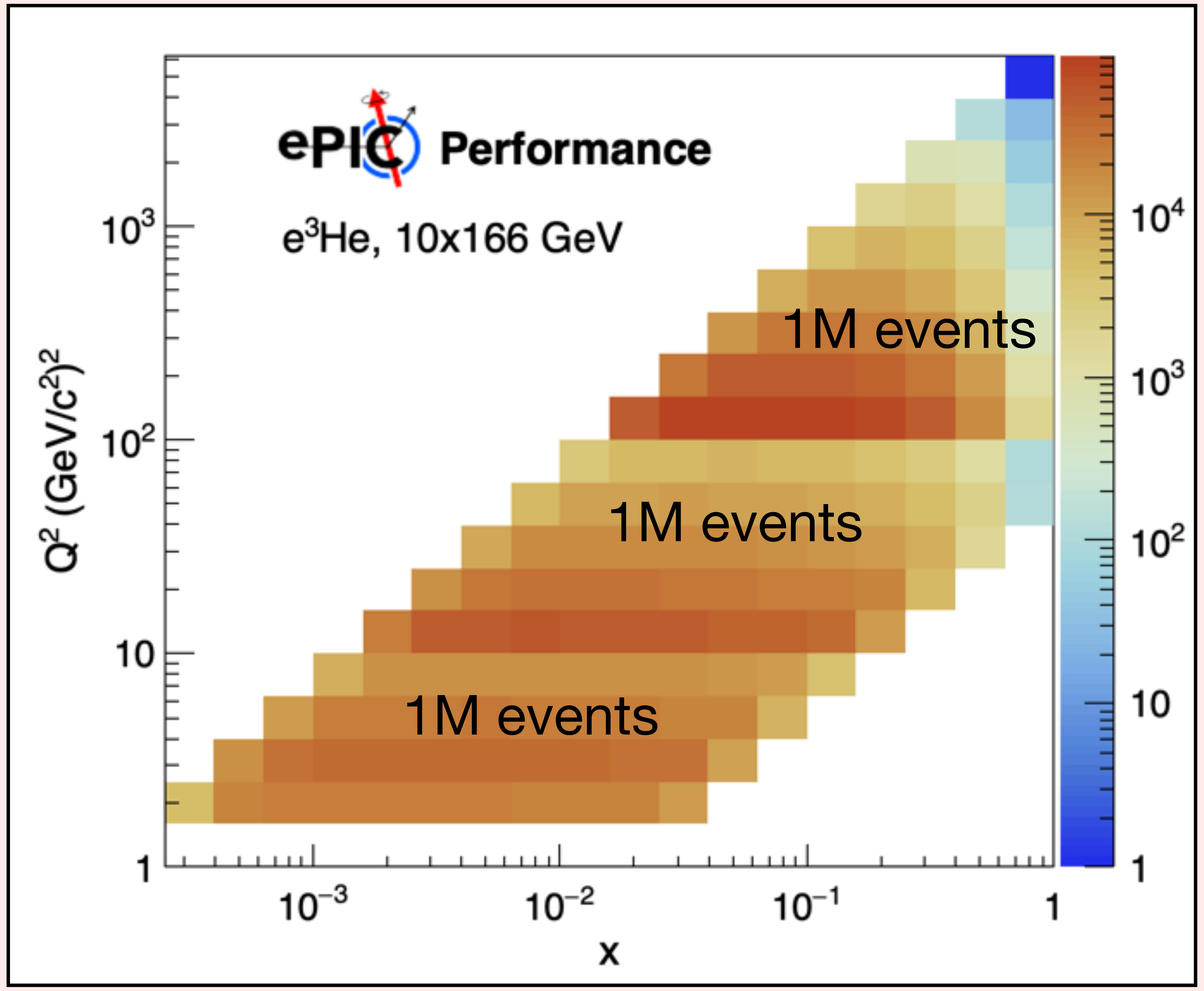
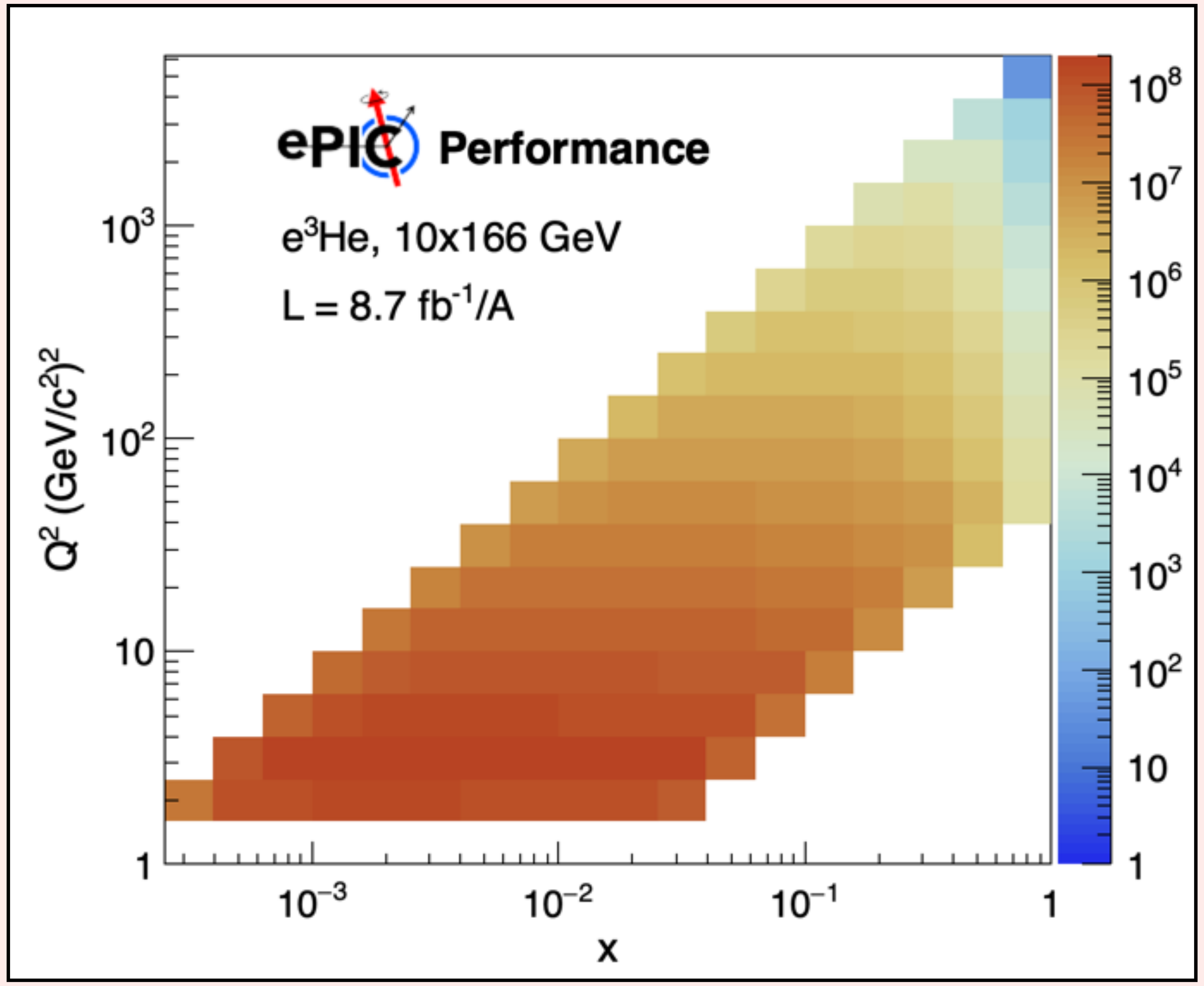
Analysis

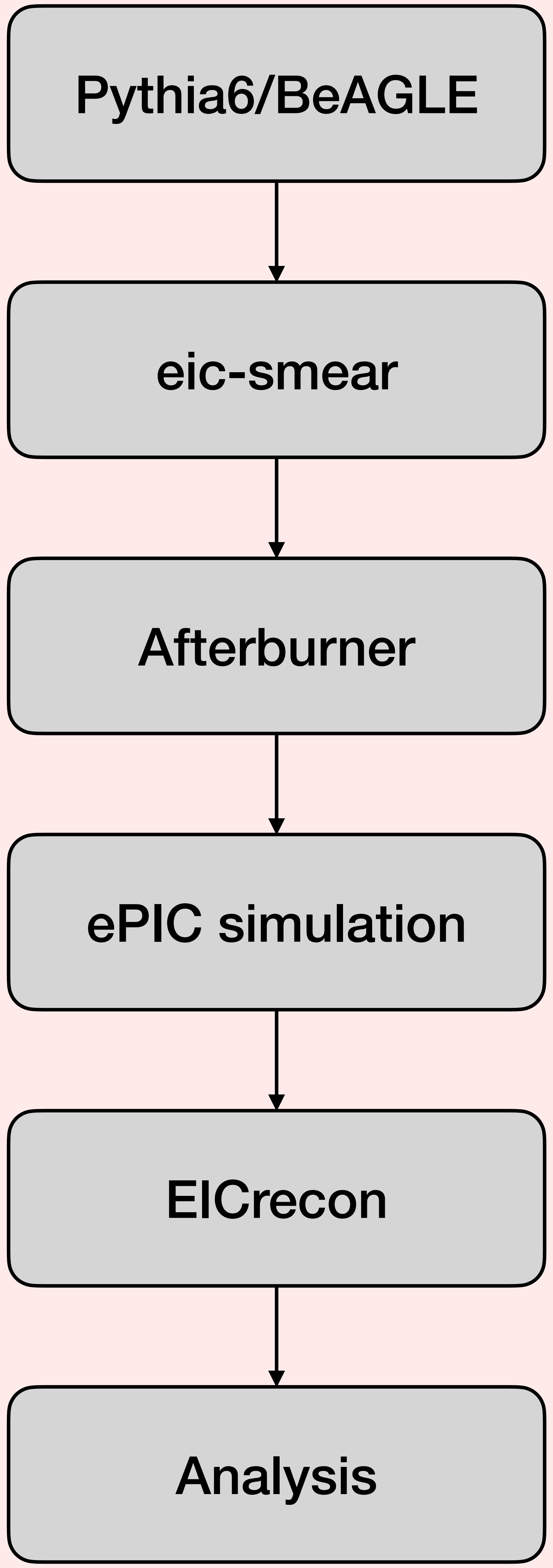
- Generated events are non-polarized, and have no QED radiative effect
- Use generated event to estimate statistical uncertainty: $\delta A_{\parallel,\perp} = \frac{1}{\sqrt{N P_e P_N}}$
- Use parameterization for central values of A_1

generated events → scaled to planned luminosity





Projection simulation & analysis flow



Pythia6/BeAGLE

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Afterburner

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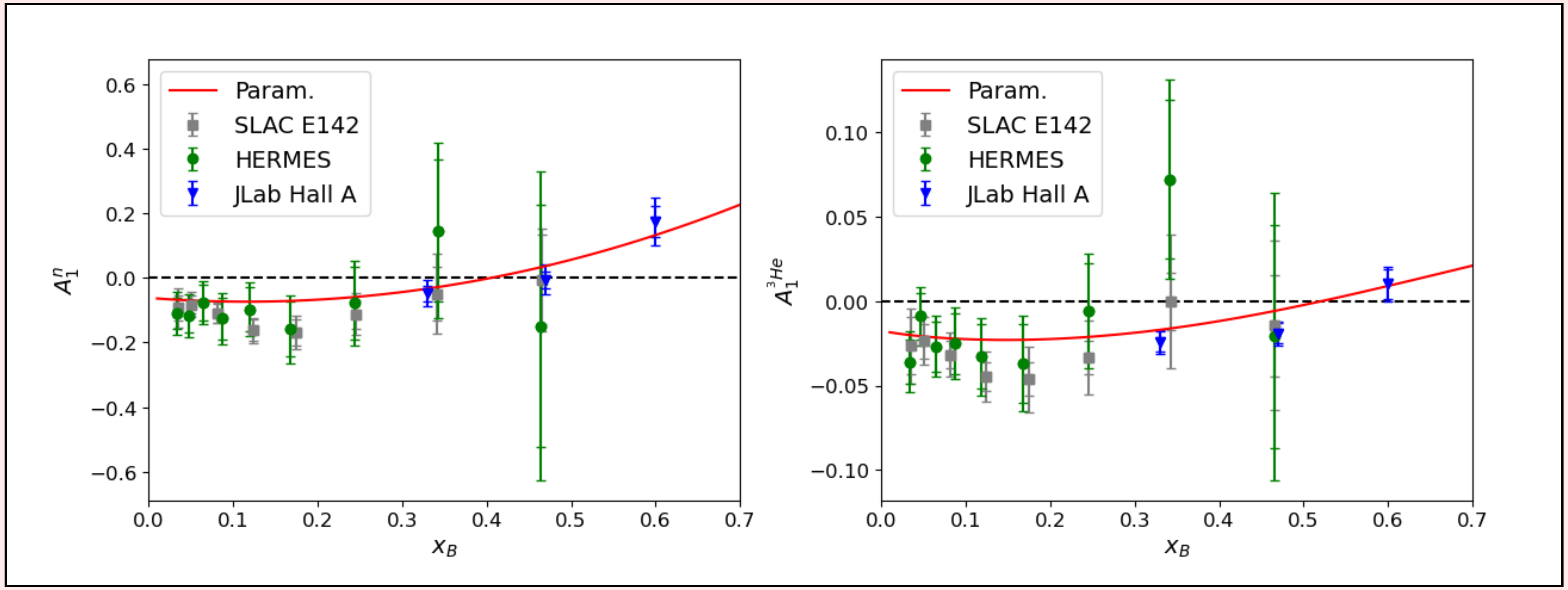
Analysis

- A_1 calculated from: Doi: 10.1103/PhysRevC.70.065207
- $$A_1^{^3\mathrm{He}} = P_n \frac{F_2^n}{F_2^{^3\mathrm{He}}} A_1^n + 2P_p \frac{F_2^p}{F_2^{^3\mathrm{He}}} A_1^p \qquad P_p = -0.028 \pm 0.004 \qquad P_n = 0.86 \pm 0.02$$
- all F_2's are taken from JAM22



- Parameterization at $Q^2 = 2.88\ \mathrm{GeV}^2$
- Data points are at various Q^2 with majority $< 5\ \mathrm{GeV}^2$

Projection simulation & analysis flow

Pythia6/BeAGLE

↓

eic-smear

↓

Afterburner

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ePIC simulation

↓

EICrecon

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Analysis

- Event reconstruction is done in ROOT codes: GitHub link

Scattered electron identification

Double spectator tagging → Projecting physics results

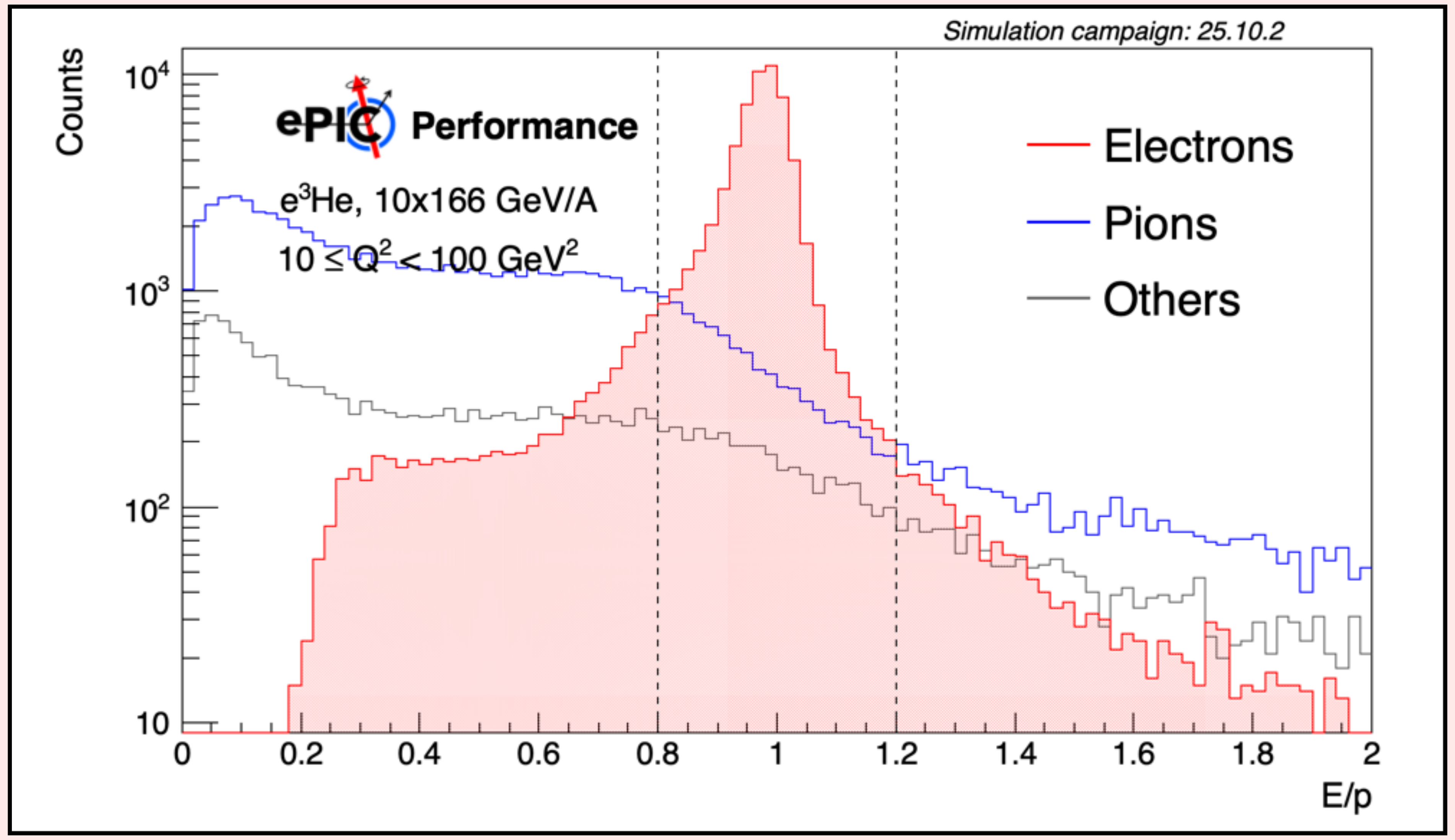
Kinematic reconstruction

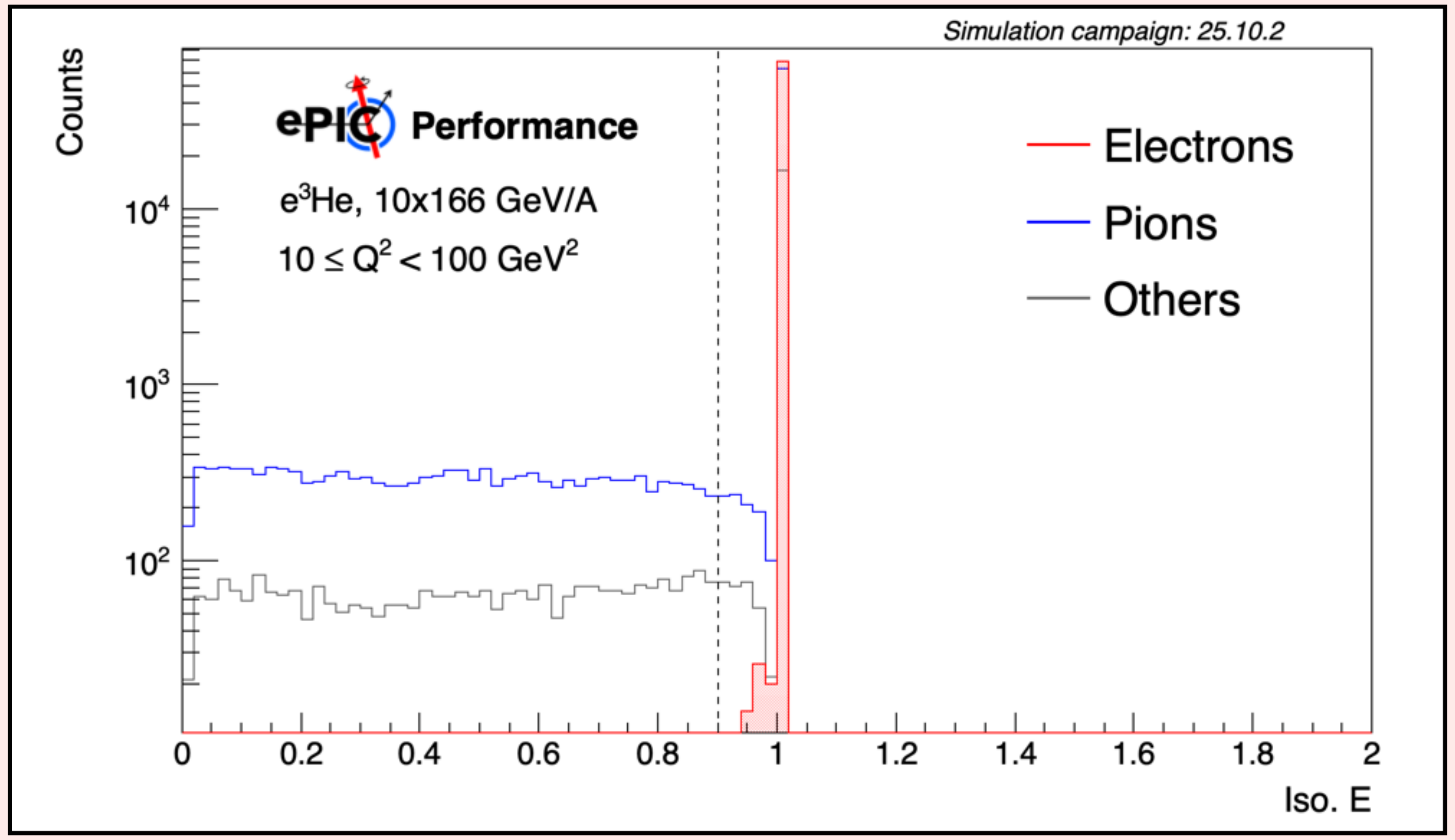
Scattered electron identification - selection criteria

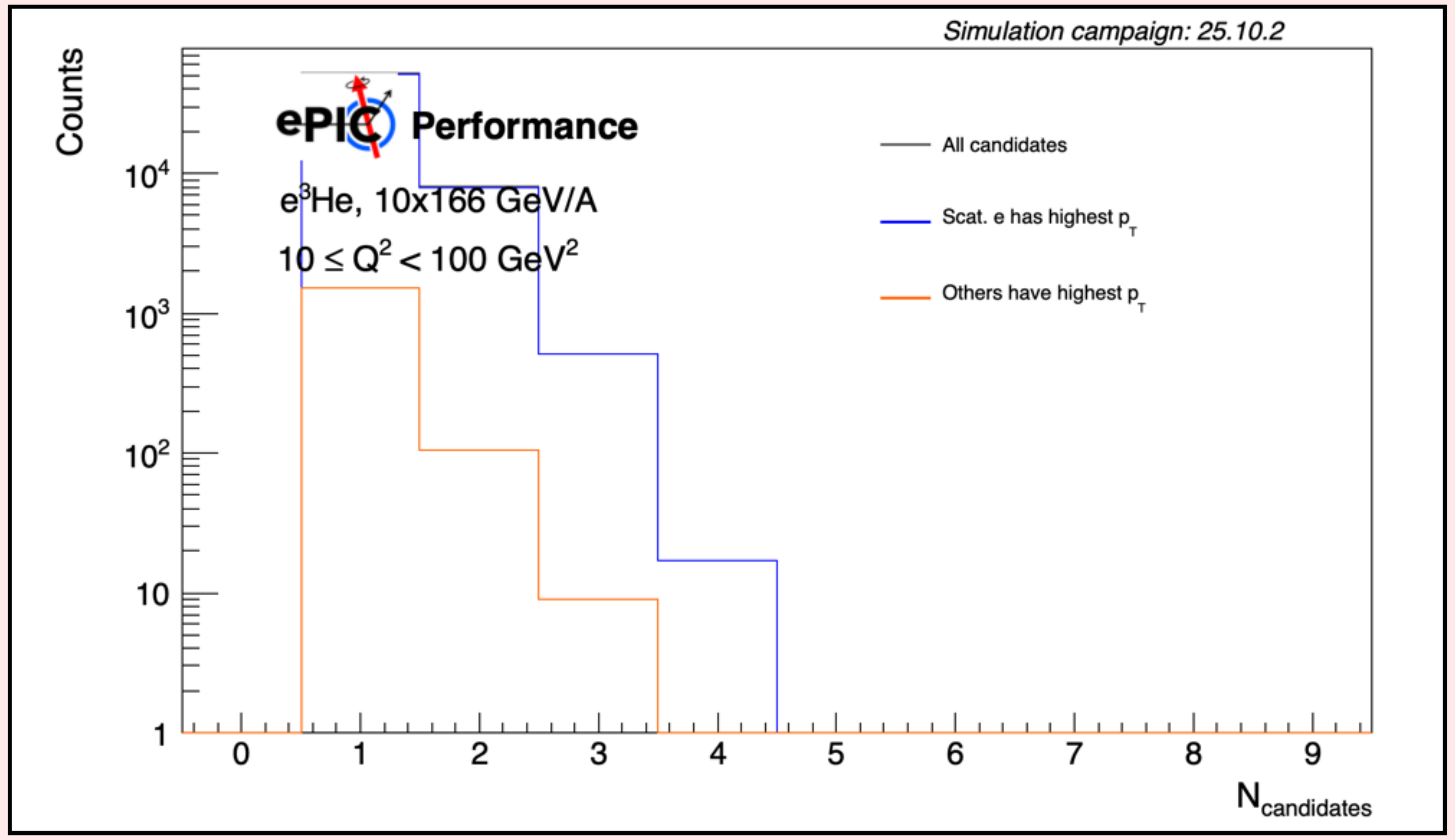
- Start from “ReconstructedParticleCollection” ⟵ Currently using MC to match clusters and tracks
- Require clusters and negative tracks
- $0.8 < E/p < 1.2$
- Isolated cluster:

$$E_0/\sum(E_{\Delta R<0.4}) > 0.9,\ \Delta R = \sqrt{\Delta\eta^2 - \Delta\phi^2}$$

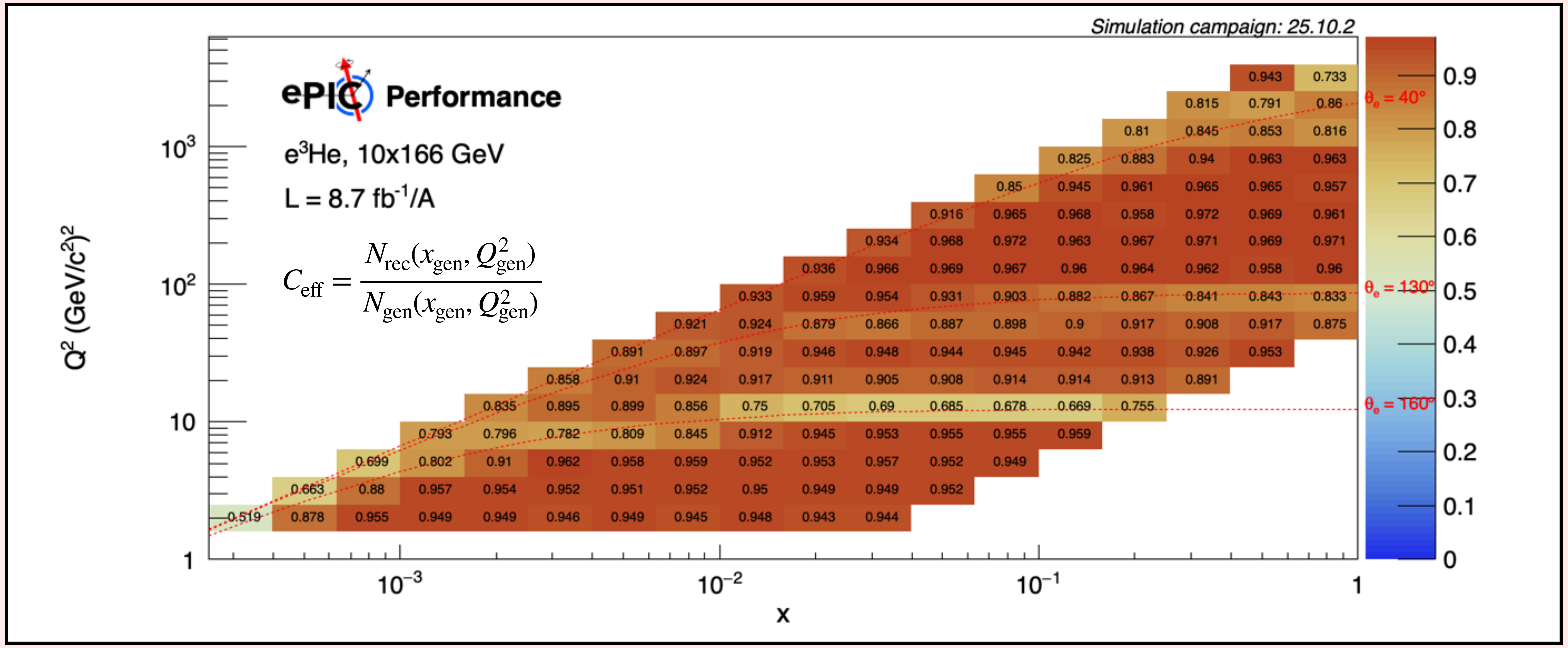
- Select the highest P_T particle



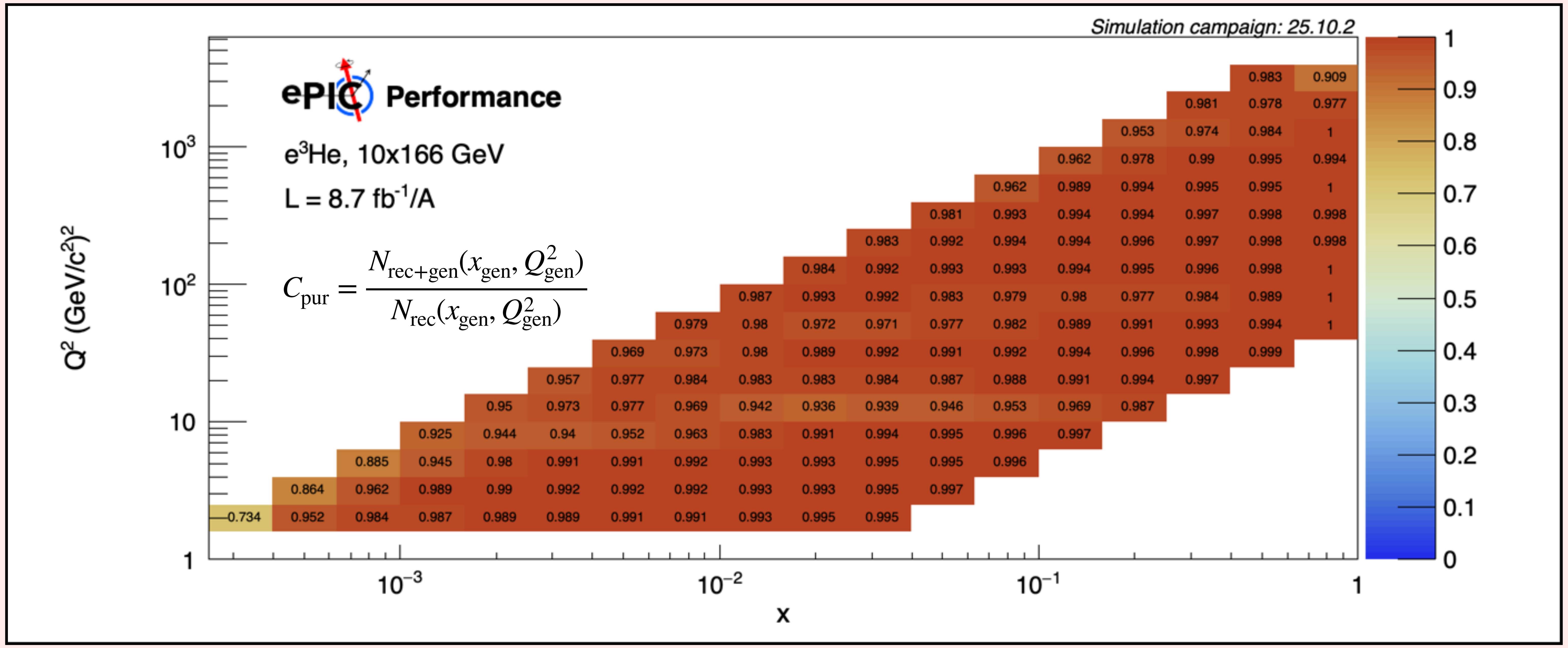




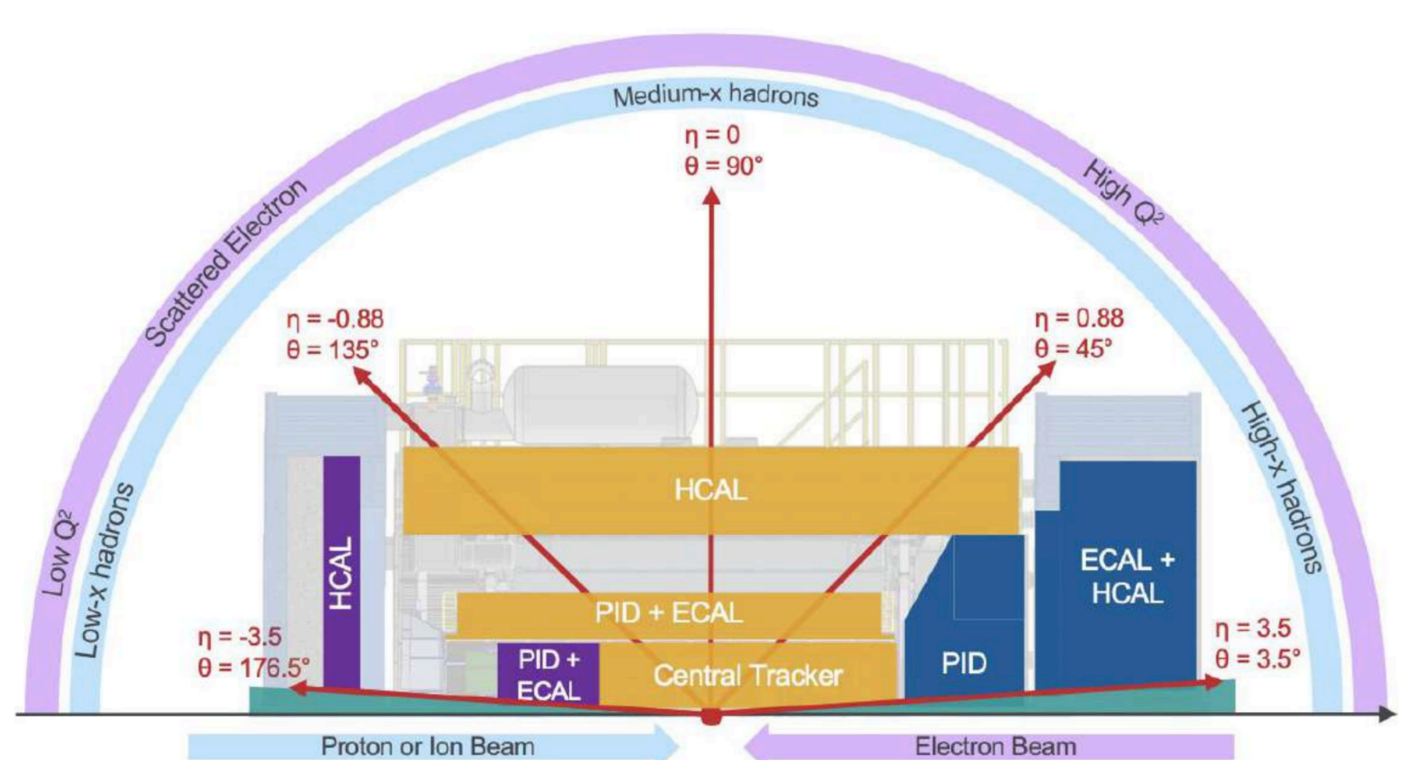
Scattered electron identification - efficiency & purity

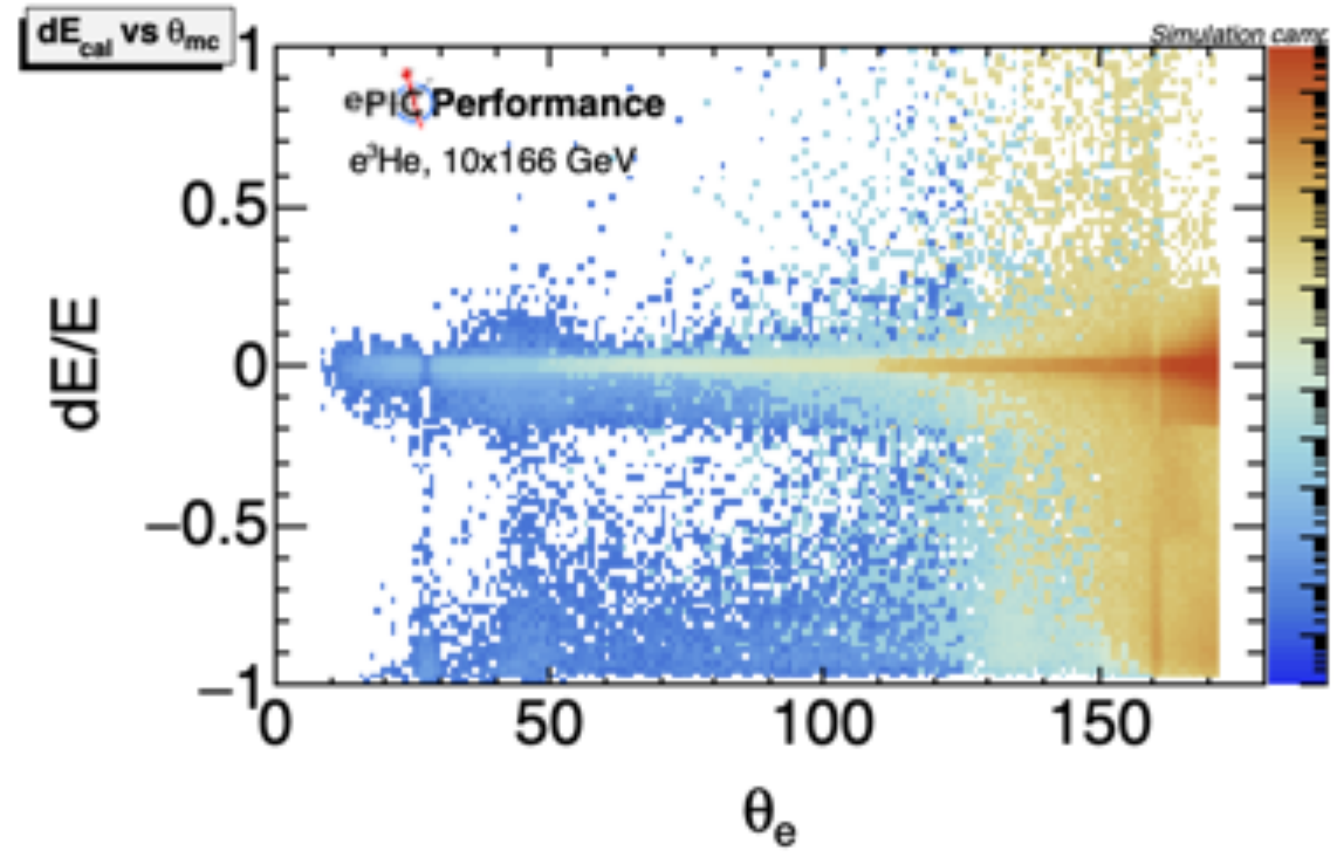


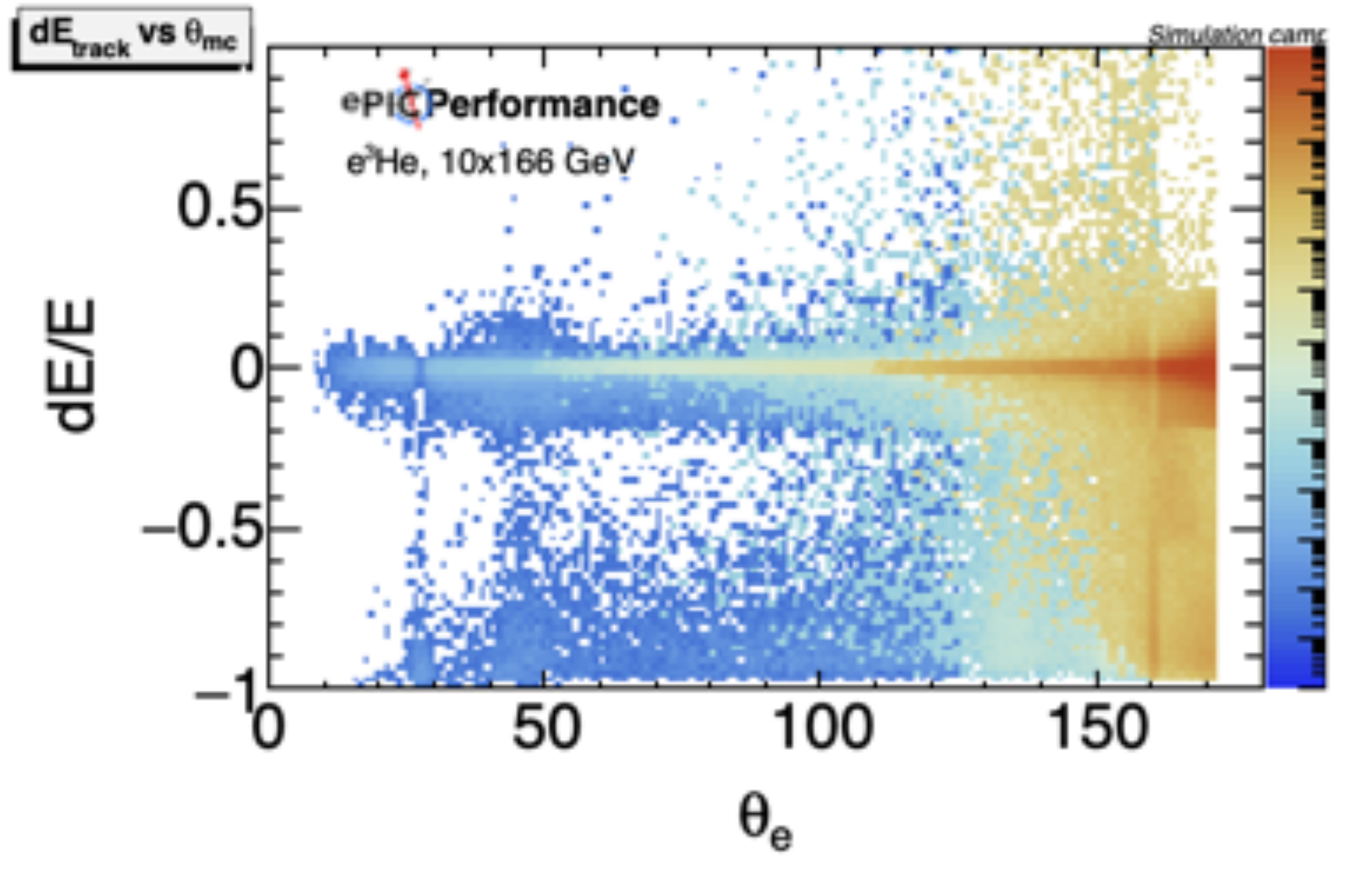
$$C_{\text{eff}} = \frac{N_{\text{rec}}(x_{\text{gen}}, Q^2_{\text{gen}})}{N_{\text{gen}}(x_{\text{gen}}, Q^2_{\text{gen}})}$$



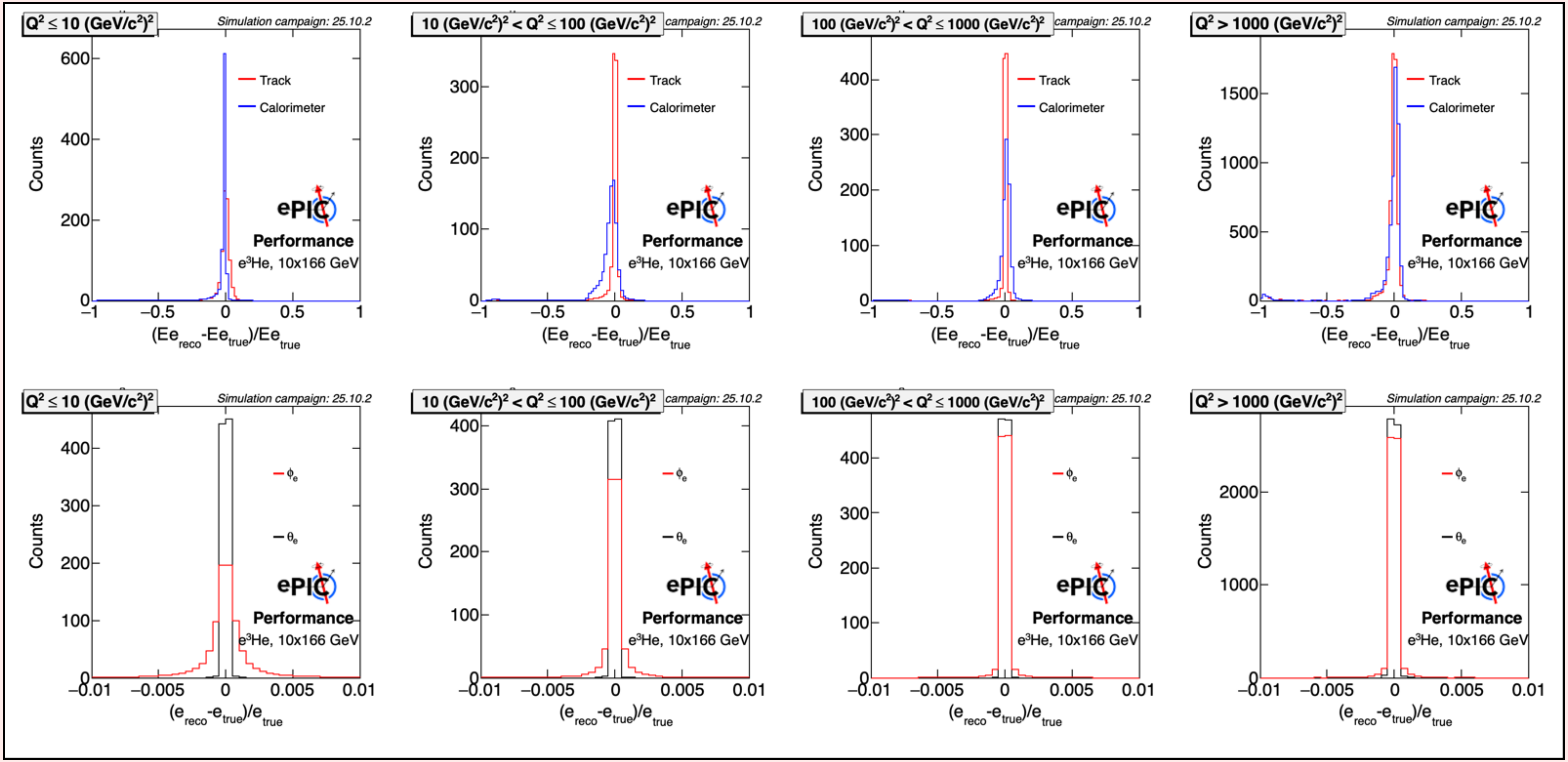
$$C_{\text{pur}} = \frac{N_{\text{rec+gen}}(x_{\text{gen}}, Q^2_{\text{gen}})}{N_{\text{rec}}(x_{\text{gen}}, Q^2_{\text{gen}})}$$







Kinematic reconstruction - energy from track vs. cluster



Kinematic reconstruction - algorithms

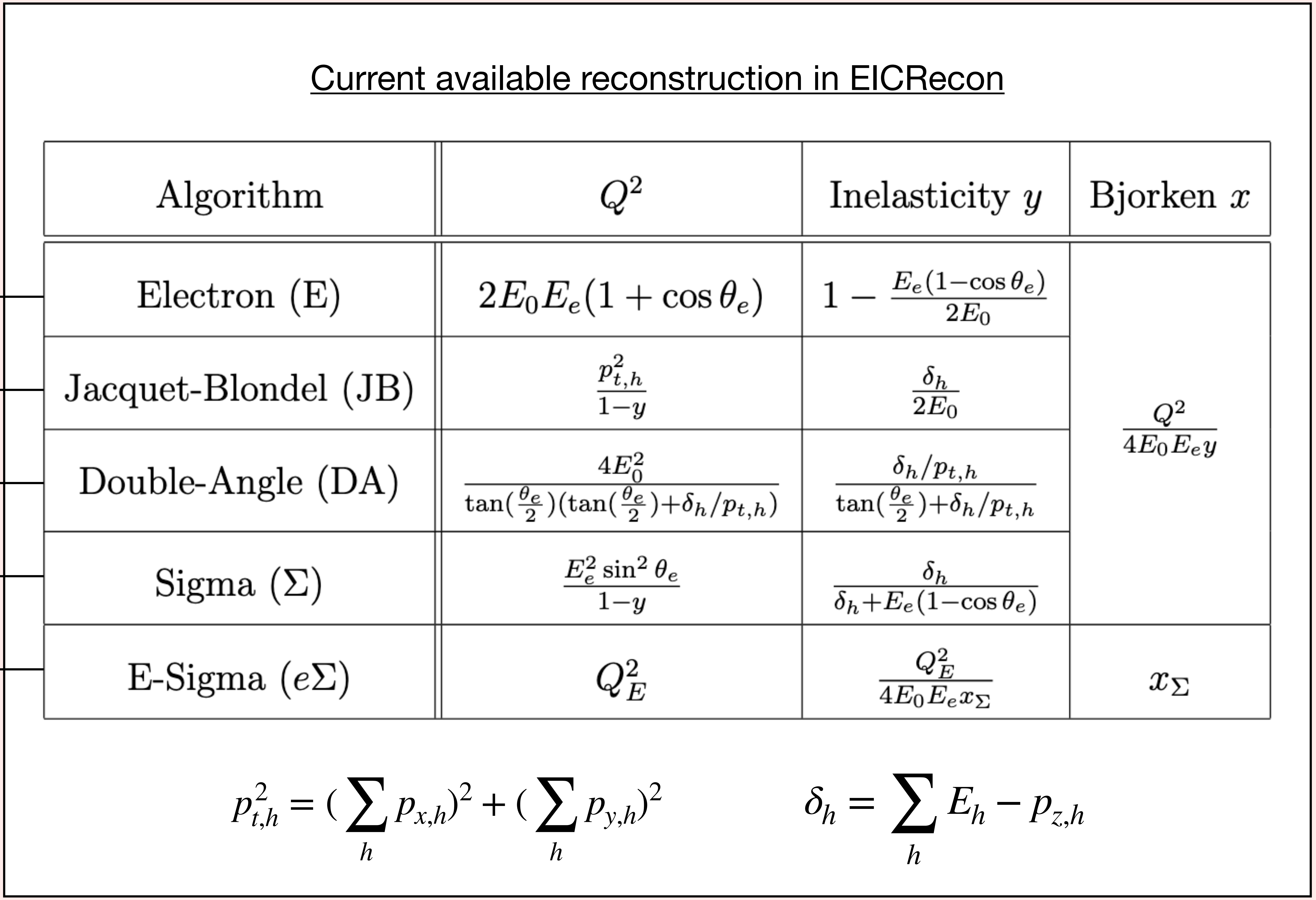
Uses only scattered e^- info

Uses everything else

No use of scattered E_e

No use of scattered E_0

Combine E and Σ method

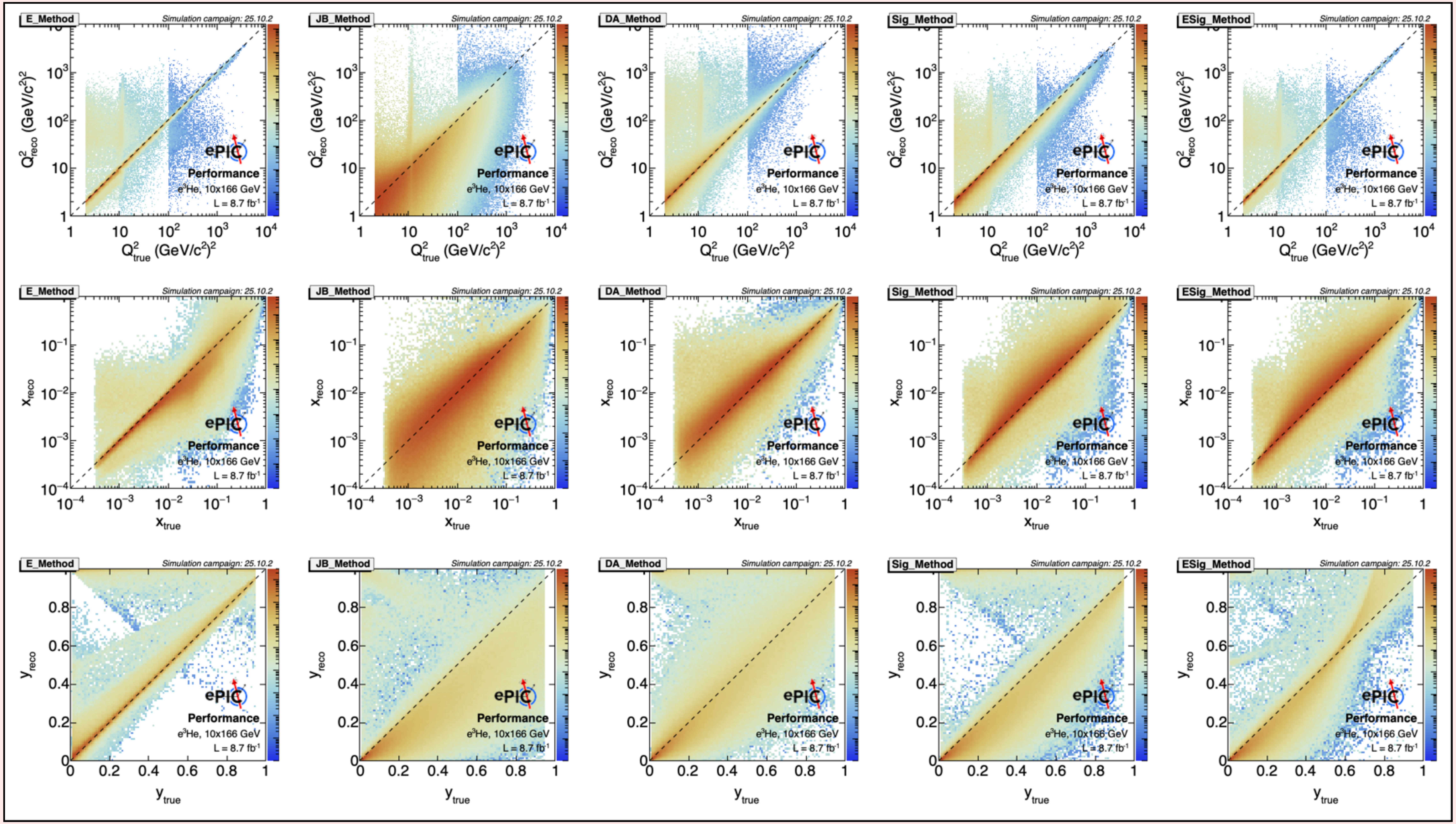


Current available reconstruction in EICRecon

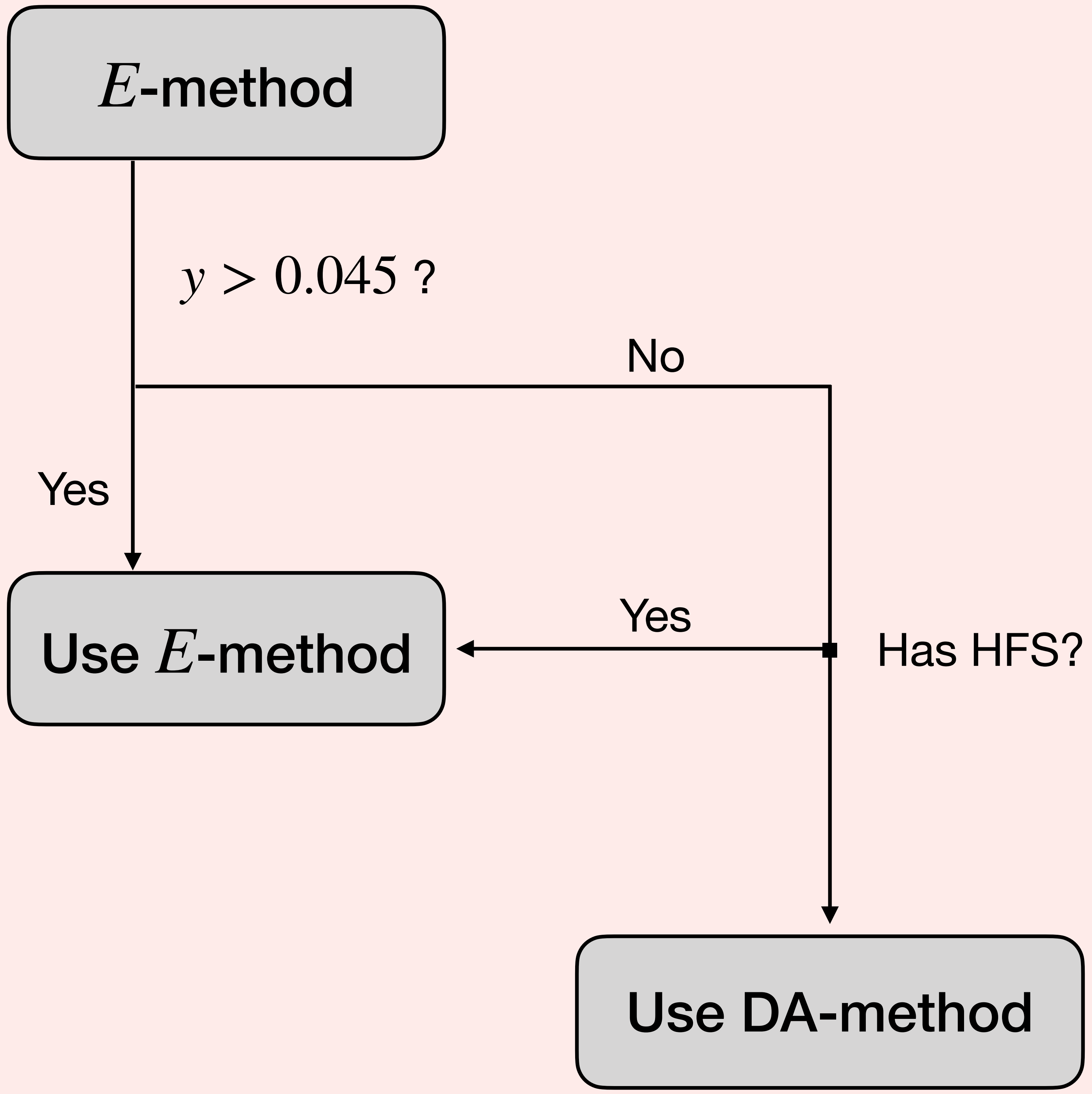
Algorithm	Q^2	Inelasticity y	Bjorken x
Electron (E)	$2E_0E_e(1+\cos\theta_e)$	$1-\frac{E_e(1-\cos\theta_e)}{2E_0}$	$\frac{Q^2}{4E_0E_ey}$
Jacquet-Blondel (JB)	$\frac{p_{t,h}^2}{1-y}$	$\frac{\delta_h}{2E_0}$	
Double-Angle (DA)	$\frac{4E_0^2}{\tan(\frac{\theta_e}{2})(\tan(\frac{\theta_e}{2})+\delta_h/p_{t,h})}$	$\frac{\delta_h/p_{t,h}}{\tan(\frac{\theta_e}{2})+\delta_h/p_{t,h}}$	
Sigma (Σ)	$\frac{E_e^2\sin^2\theta_e}{1-y}$	$\frac{\delta_h}{\delta_h+E_e(1-\cos\theta_e)}$	
E-Sigma ($e\Sigma$)	Q_E^2	$\frac{Q_E^2}{4E_0E_ex_\Sigma}$	x_Σ

$$p_{t,h}^2 = (\sum_h p_{x,h})^2 + (\sum_h p_{y,h})^2 \qquad \delta_h = \sum_h E_h - p_{z,h}$$

Kinematic reconstruction - qualities



Kinematic reconstruction - algorithms selection



E-method

$y > 0.045$?

No

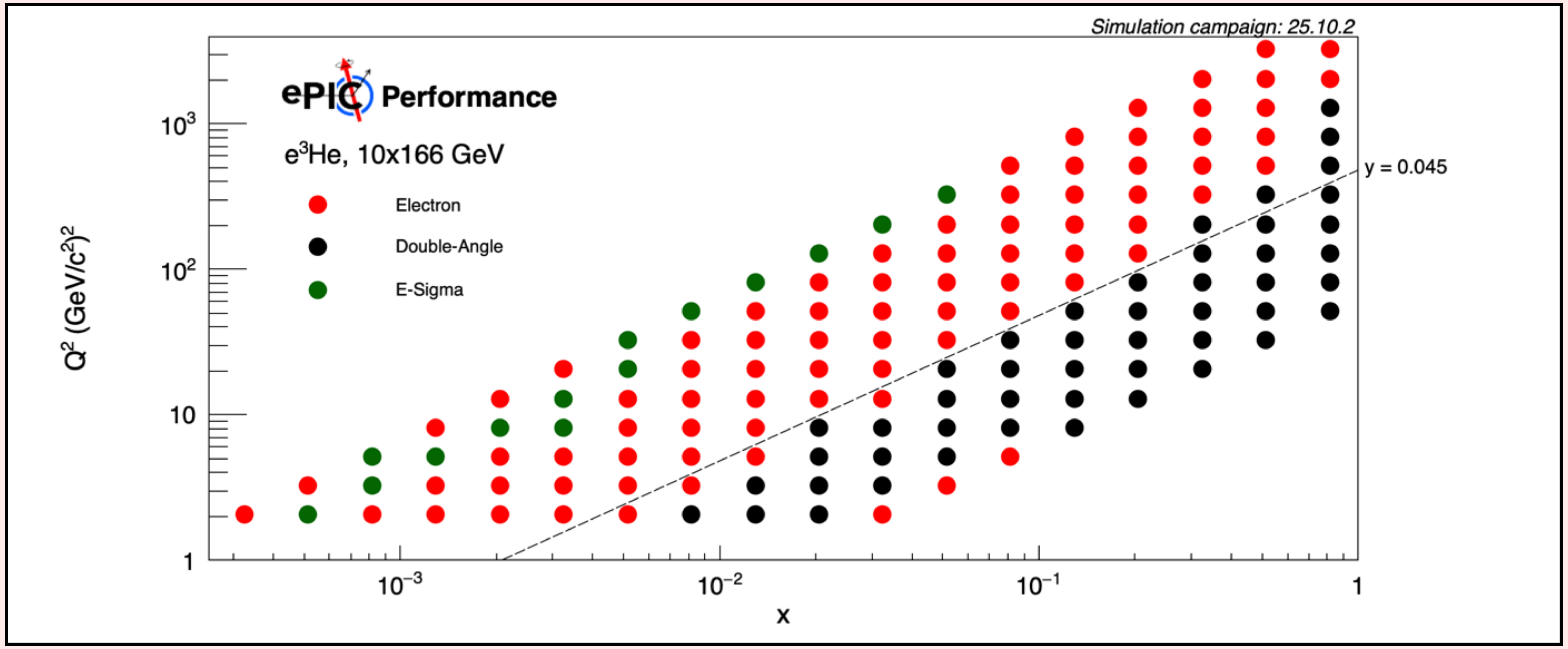
Yes

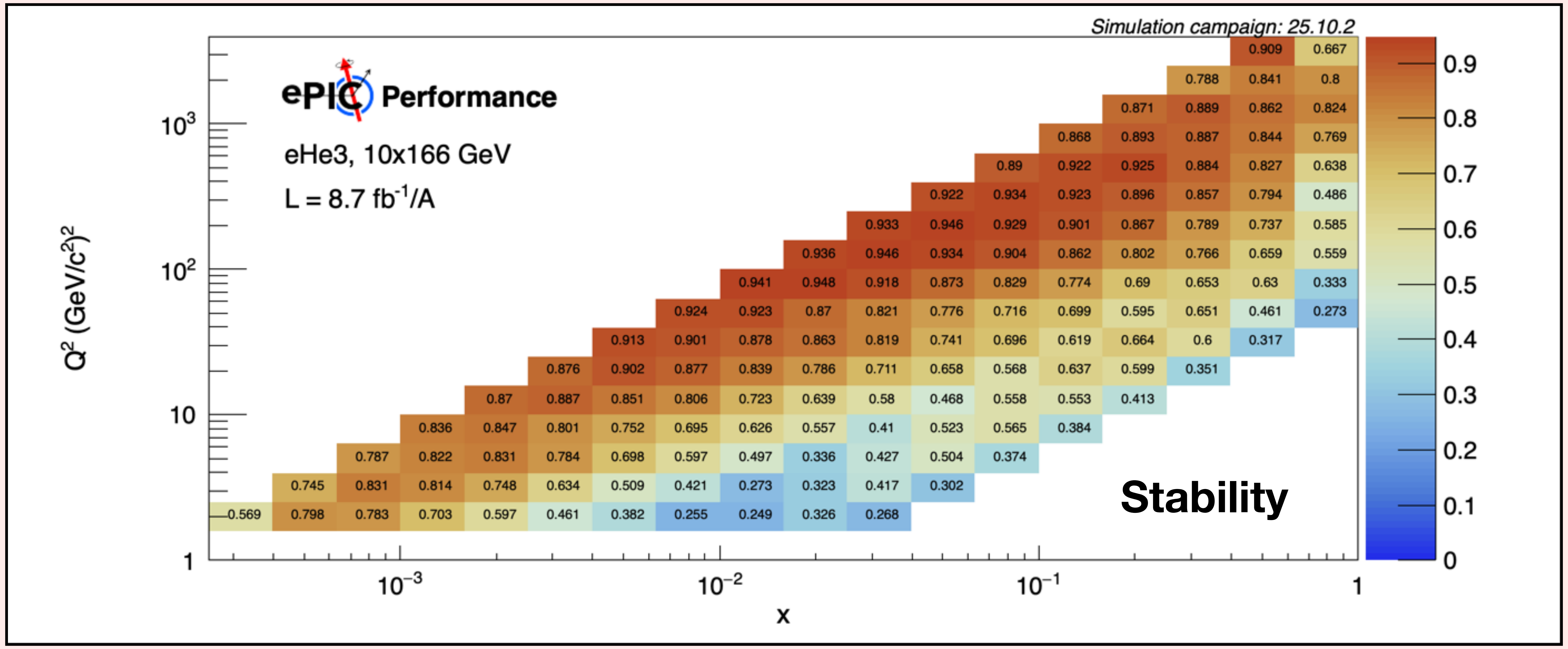
Use E-method

Yes

Has HFS?

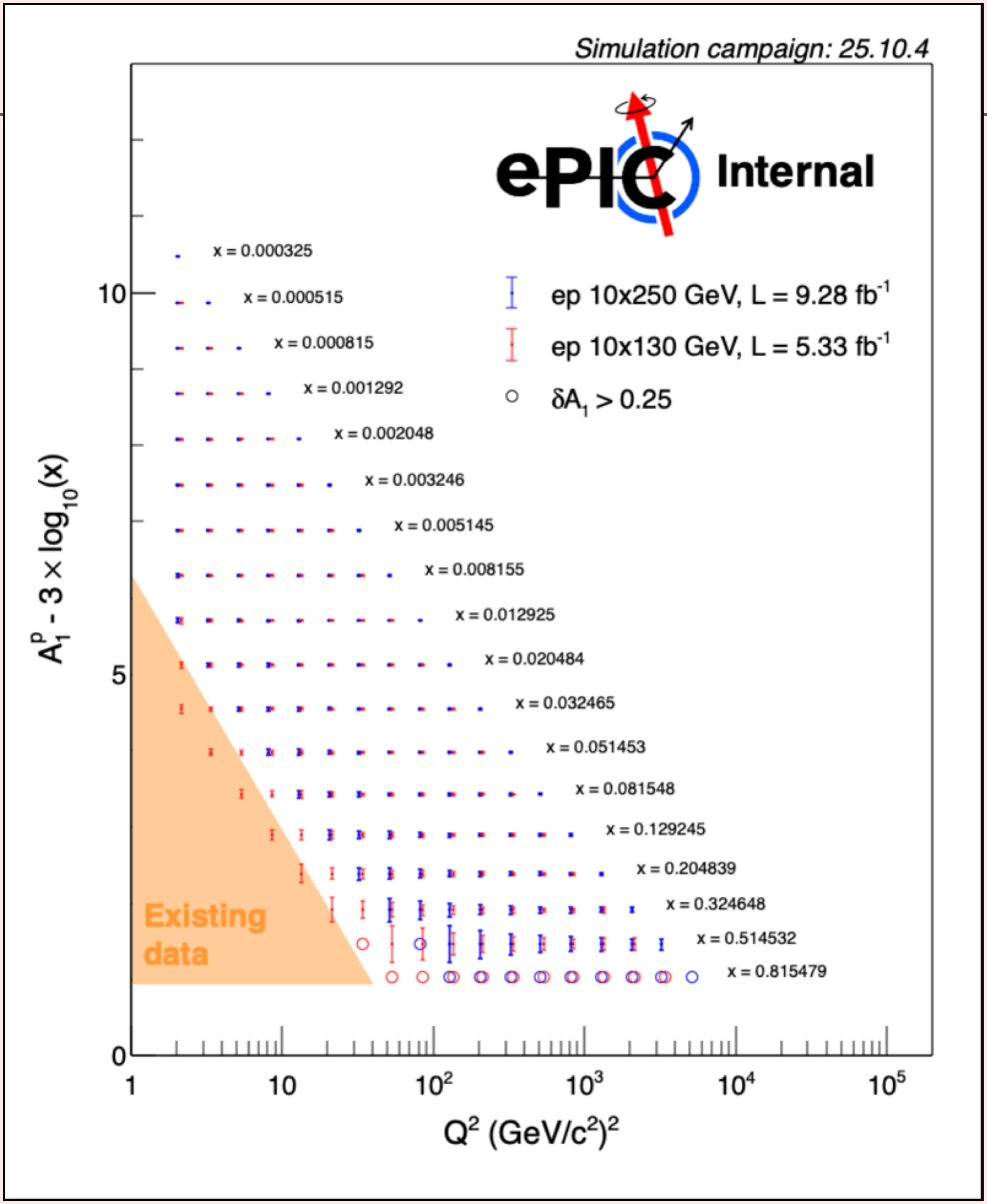
Use DA-method





Projected A_1^p

- $A_1(x,Q^2) \equiv \frac{\sigma_{1/2}-\sigma_{3/2}}{\sigma_{1/2}+\sigma_{3/2}} = \frac{A_{\parallel}}{D(1+\eta\xi)} - \frac{\eta A_{\perp}}{d(1+\eta\xi)}$
- $\delta A_{\parallel,\perp} = \frac{1}{\sqrt{NP_eP_N}}$
- $P_e = P_p = 70\,\%$
- Data split evenly between $A_{\parallel}$ and $A_{\perp}$
- R calculated from https://doi.org/10.1016/S0370-2693(99)00244-0
- Statistical uncertainty only



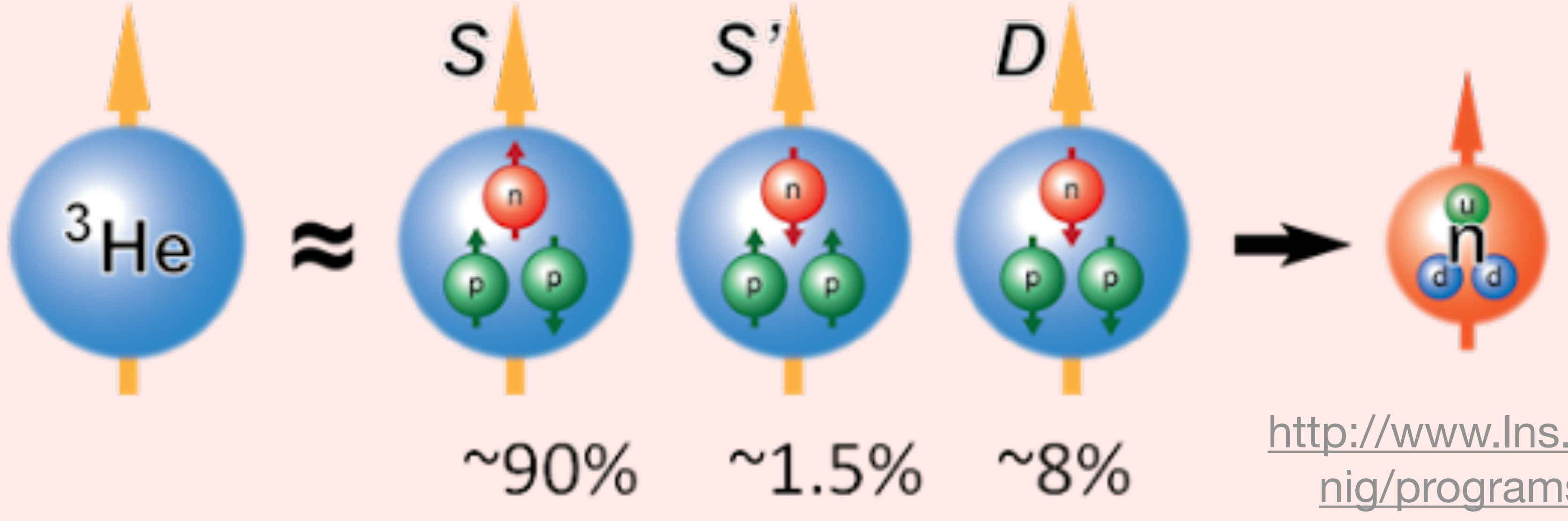
A_1^n from $e^3\mathrm{He}$ DIS:

What about A_1^n ?

- Can be extracted from $A_1^{^3\mathrm{He}} = P_n \frac{F_2^n}{F_2^{^3\mathrm{He}}} A_1^n + 2P_p \frac{F_2^p}{F_2^{^3\mathrm{He}}} A_1^p$

$$P_n = 0.86 \pm 0.02 \qquad P_p = -0.028 \pm 0.004$$

https://doi.org/10.1103/PhysRevC.64.024004



http://www.lns.mit.edu/nig/programs.html

A_1^n from $e^3\mathrm{He}$ DIS:

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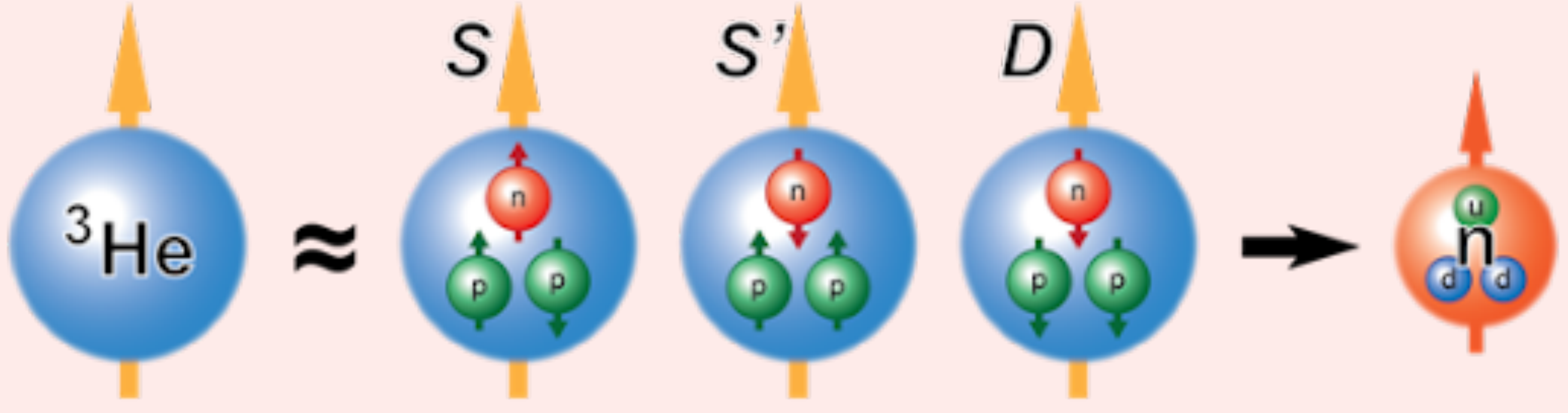
$$P_n = 0.86 \pm 0.02 \qquad P_p = -0.028 \pm 0.004$$

- Or **directly** measured double spectator tagging:



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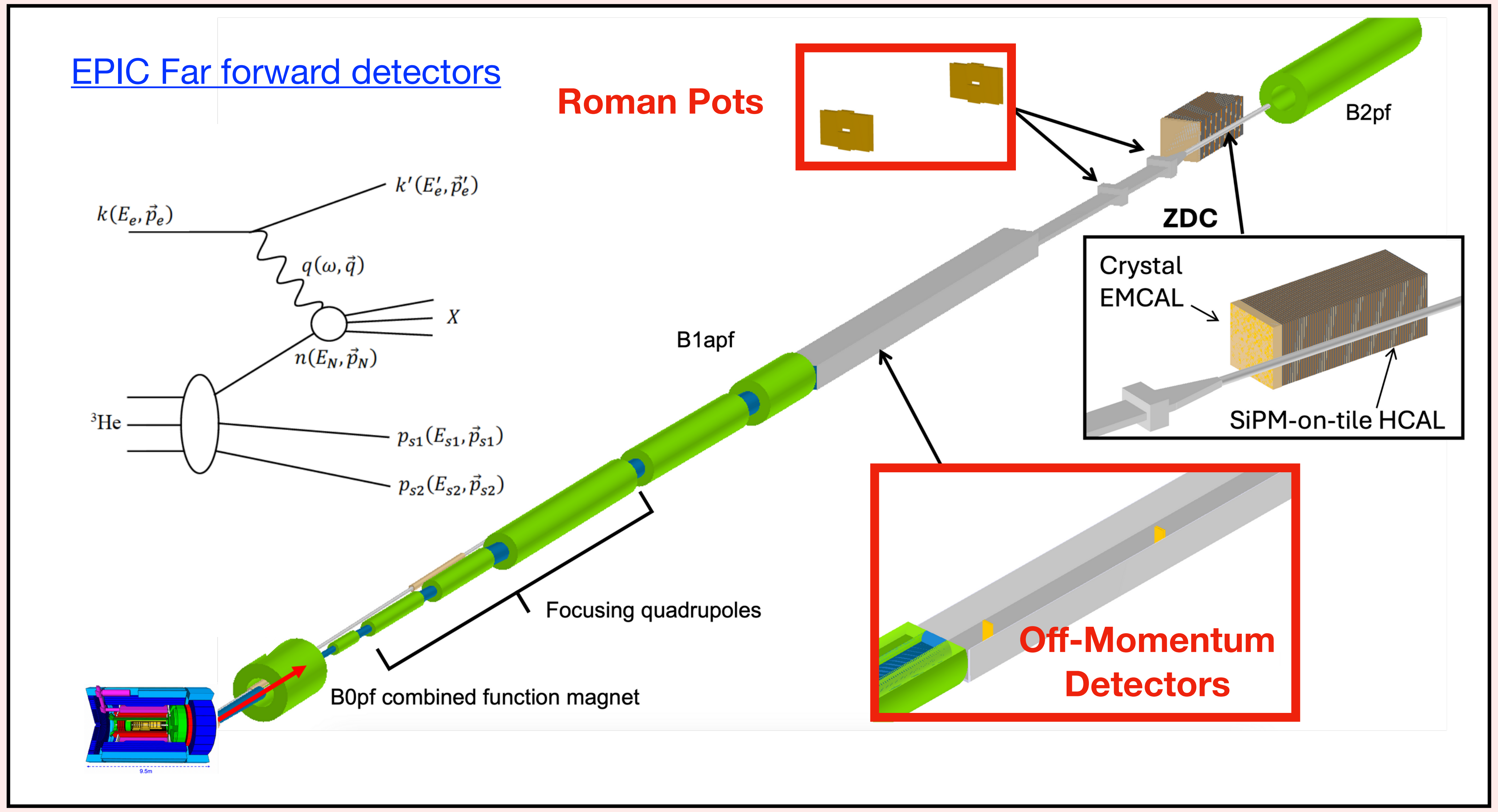
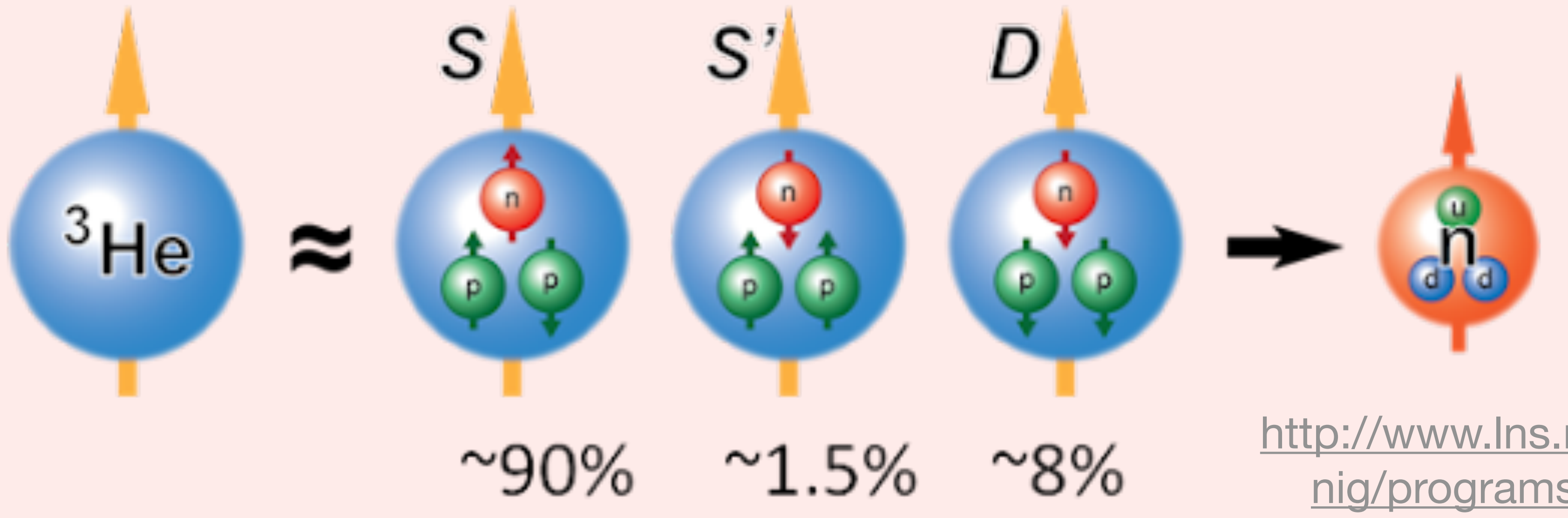


A_1^n from e^3He DIS:

What about A_1^n ?

- Can be extracted from $A_1^{^3\mathrm{He}} = P_n \frac{F_2^n}{F_2^{^3\mathrm{He}}} A_1^n + 2P_p \frac{F_2^p}{F_2^{^3\mathrm{He}}} A_1^p$

$$P_n = 0.86 \pm 0.02 \qquad P_p = -0.028 \pm 0.004$$



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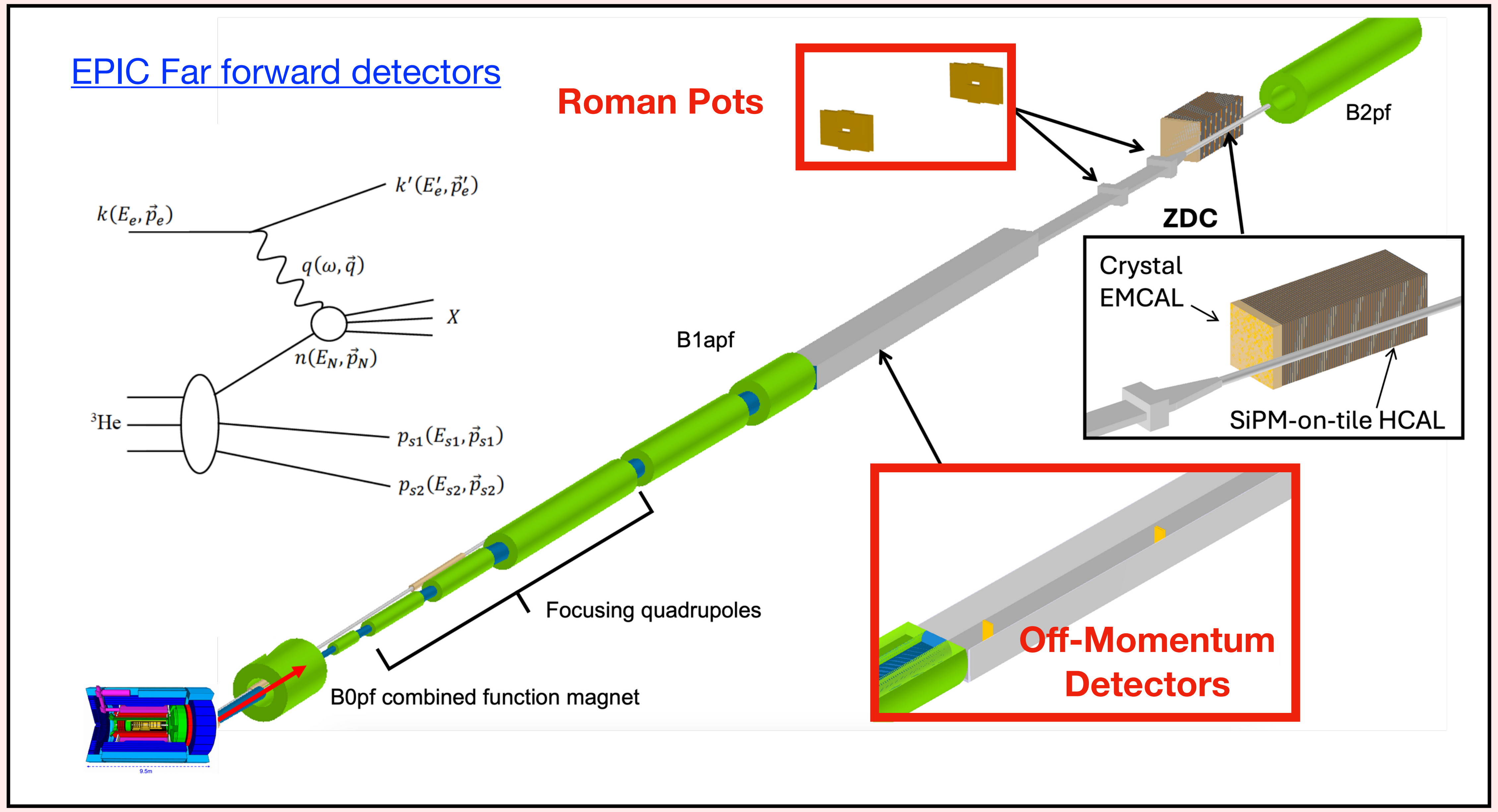
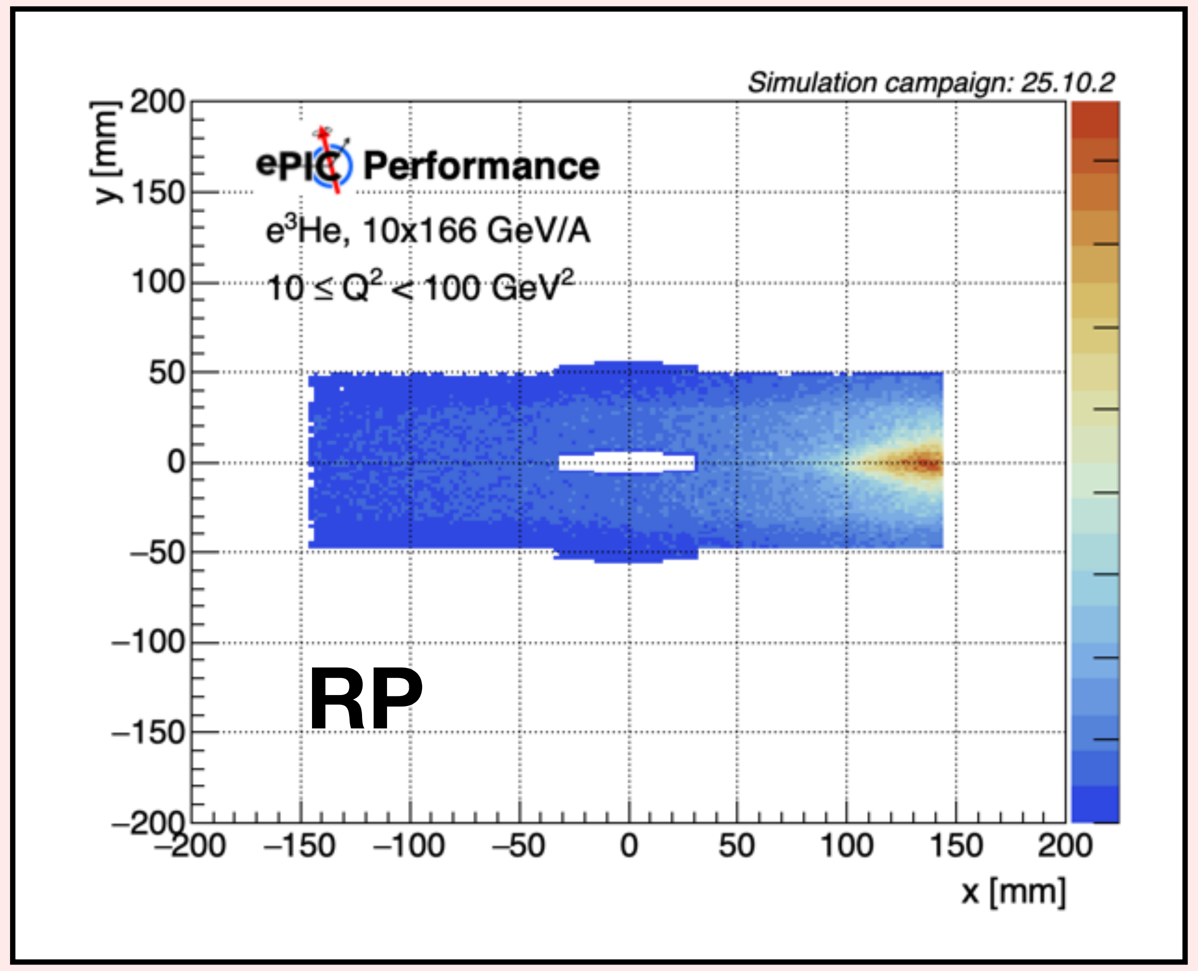
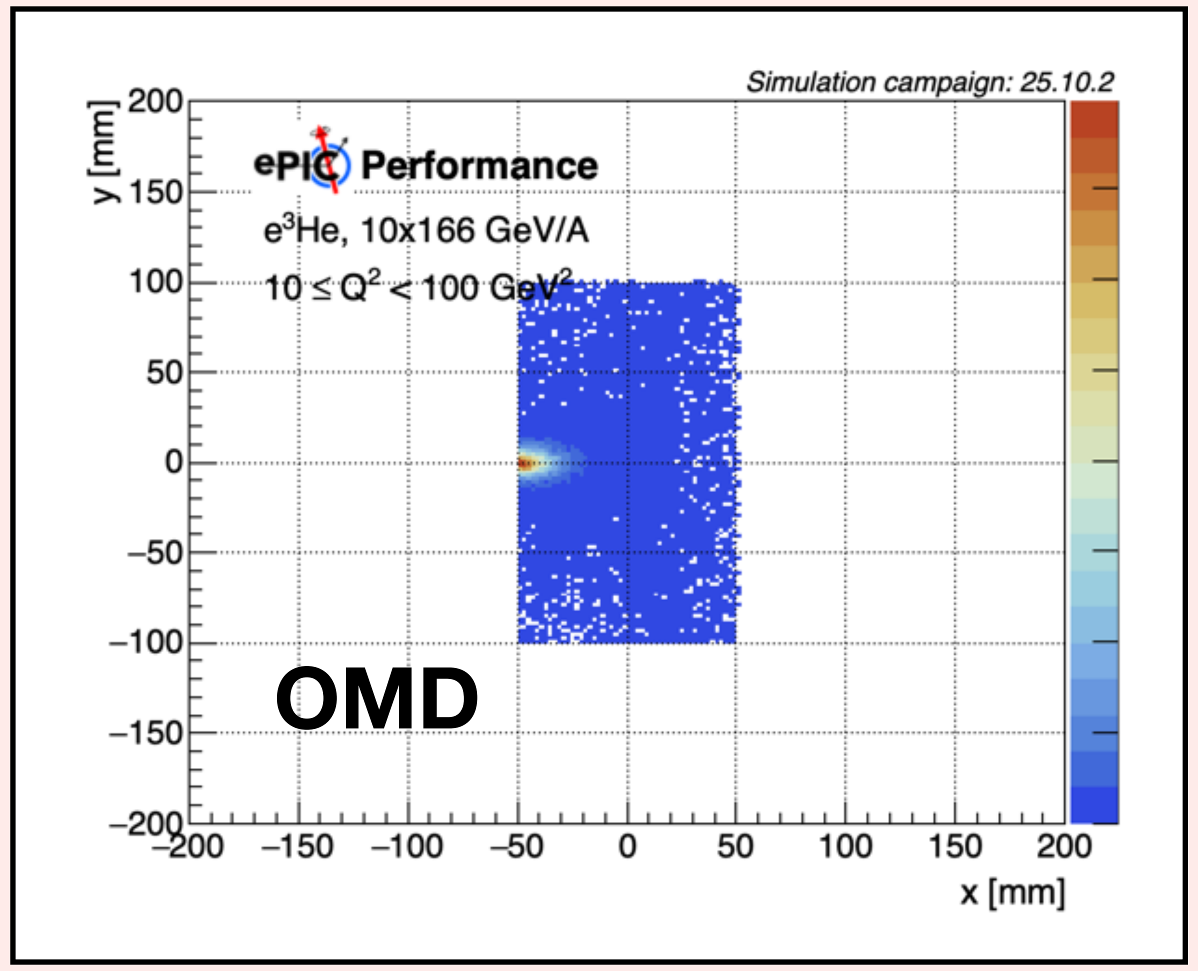
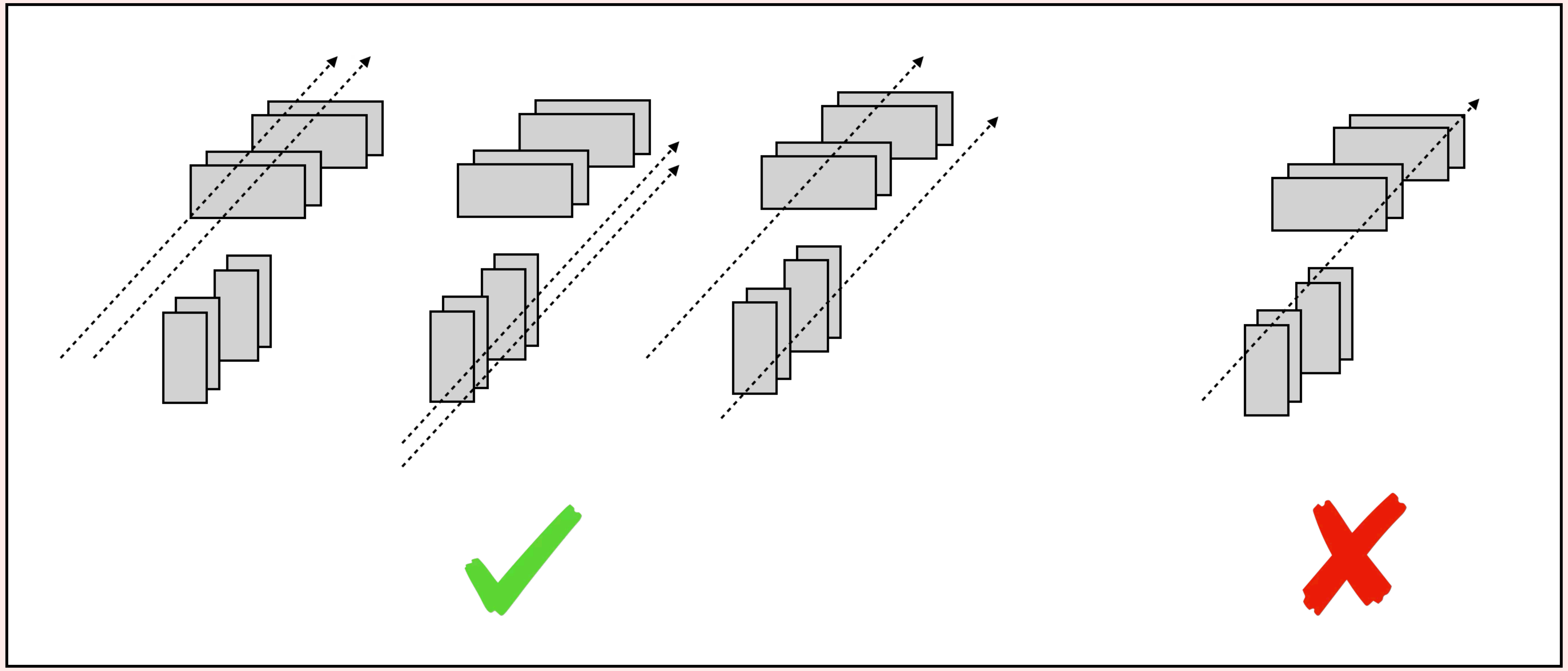






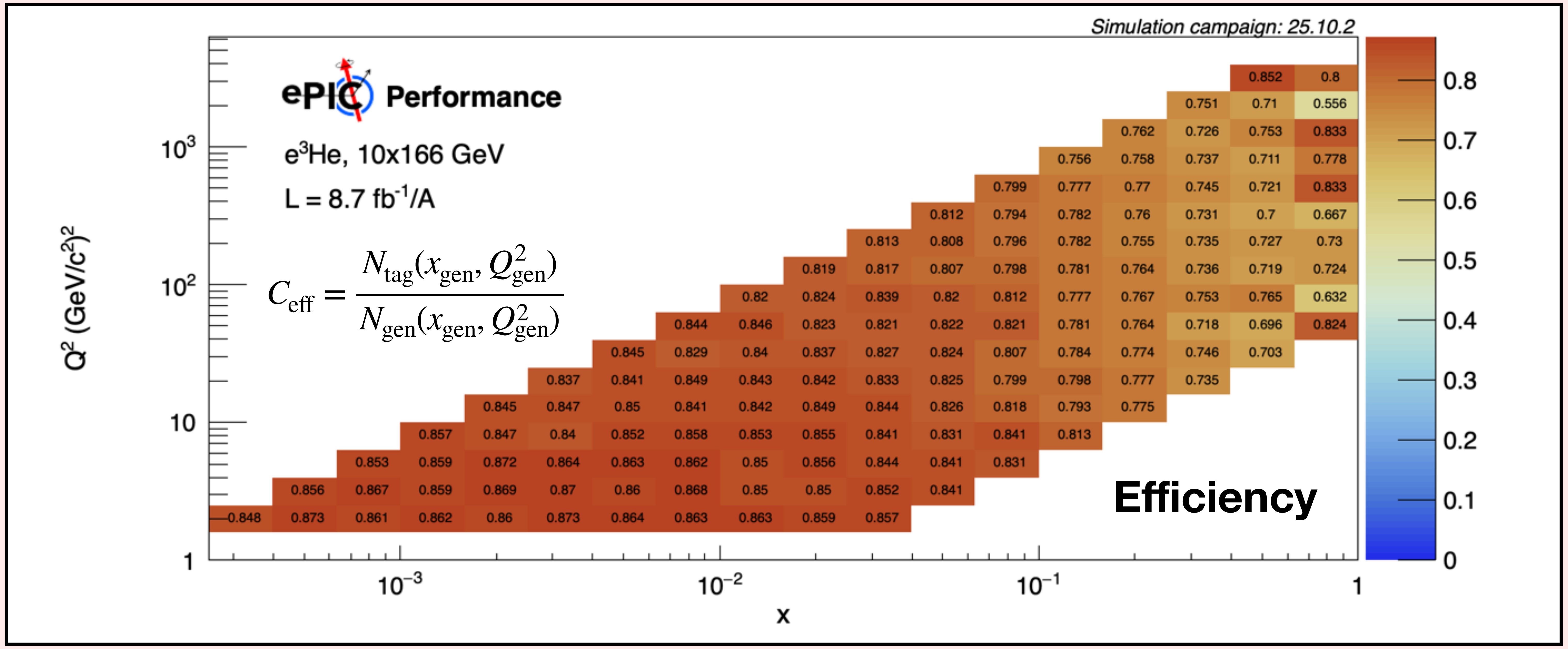
Double spectator tagging - method

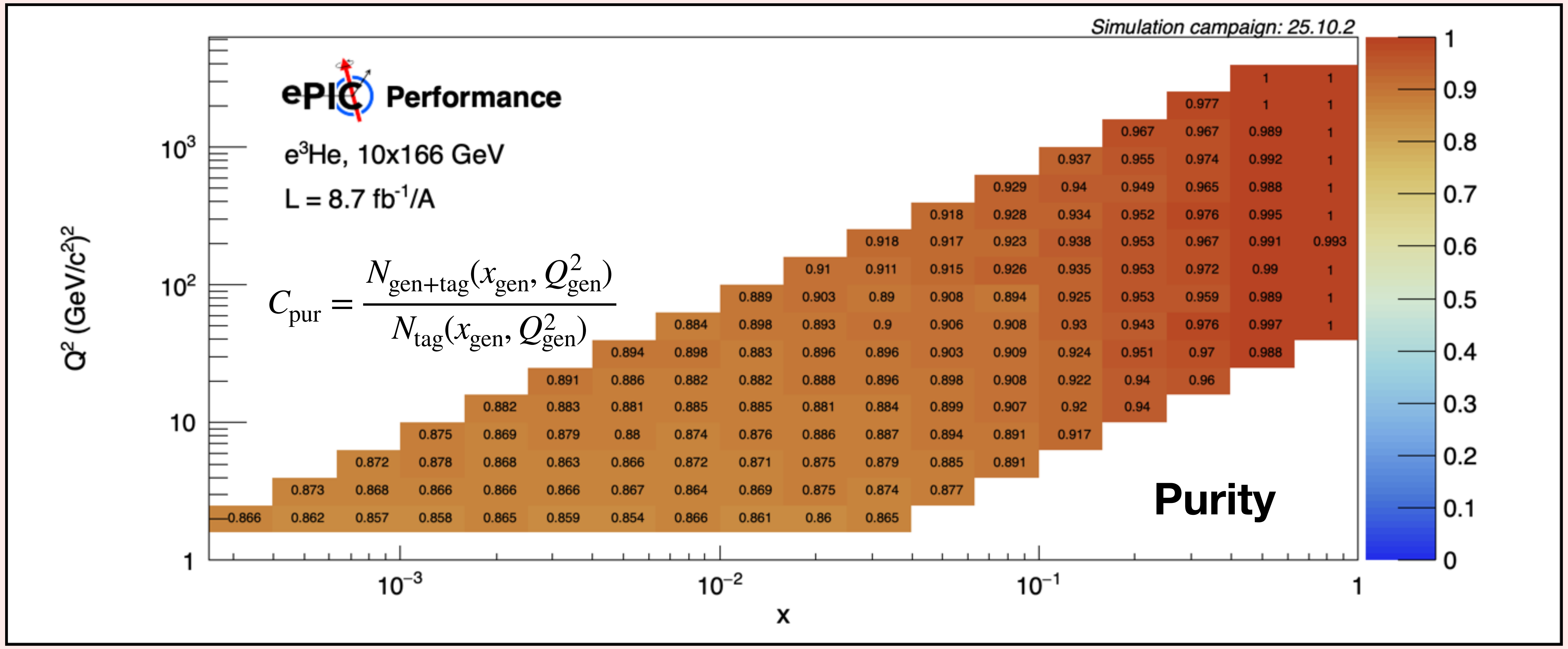
- Hit-based tagging algorithm
- Number of proton tracks = min number of hits per plane per detector
- If number of proton tracks > 2, then tag as double spectator



Double spectator tagging - efficiency & purity

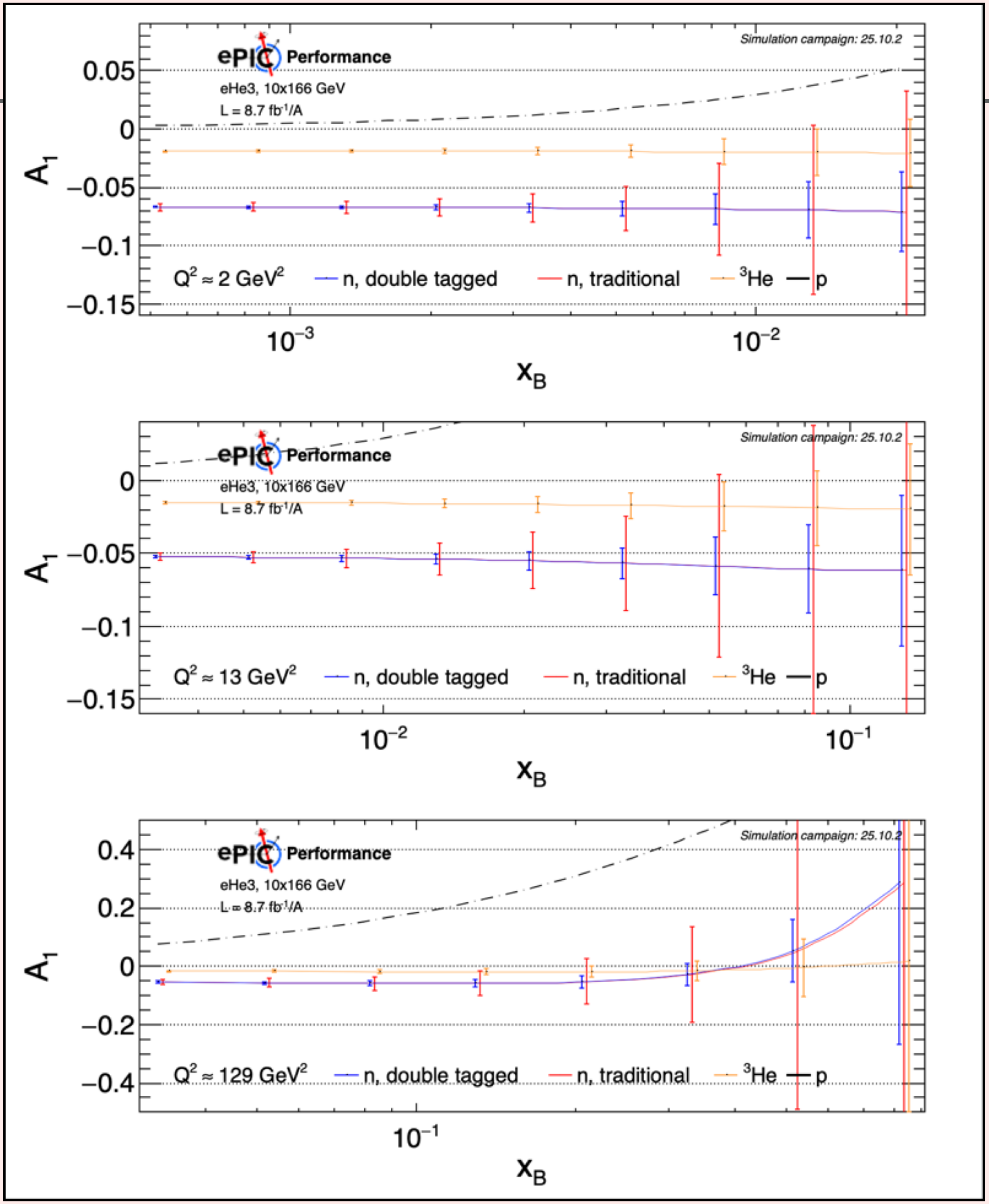
- Hit-based tagging algorithm
- Number of proton tracks = min number of hits per plane per detector
- If number of proton tracks > 2, then tag as double spectator





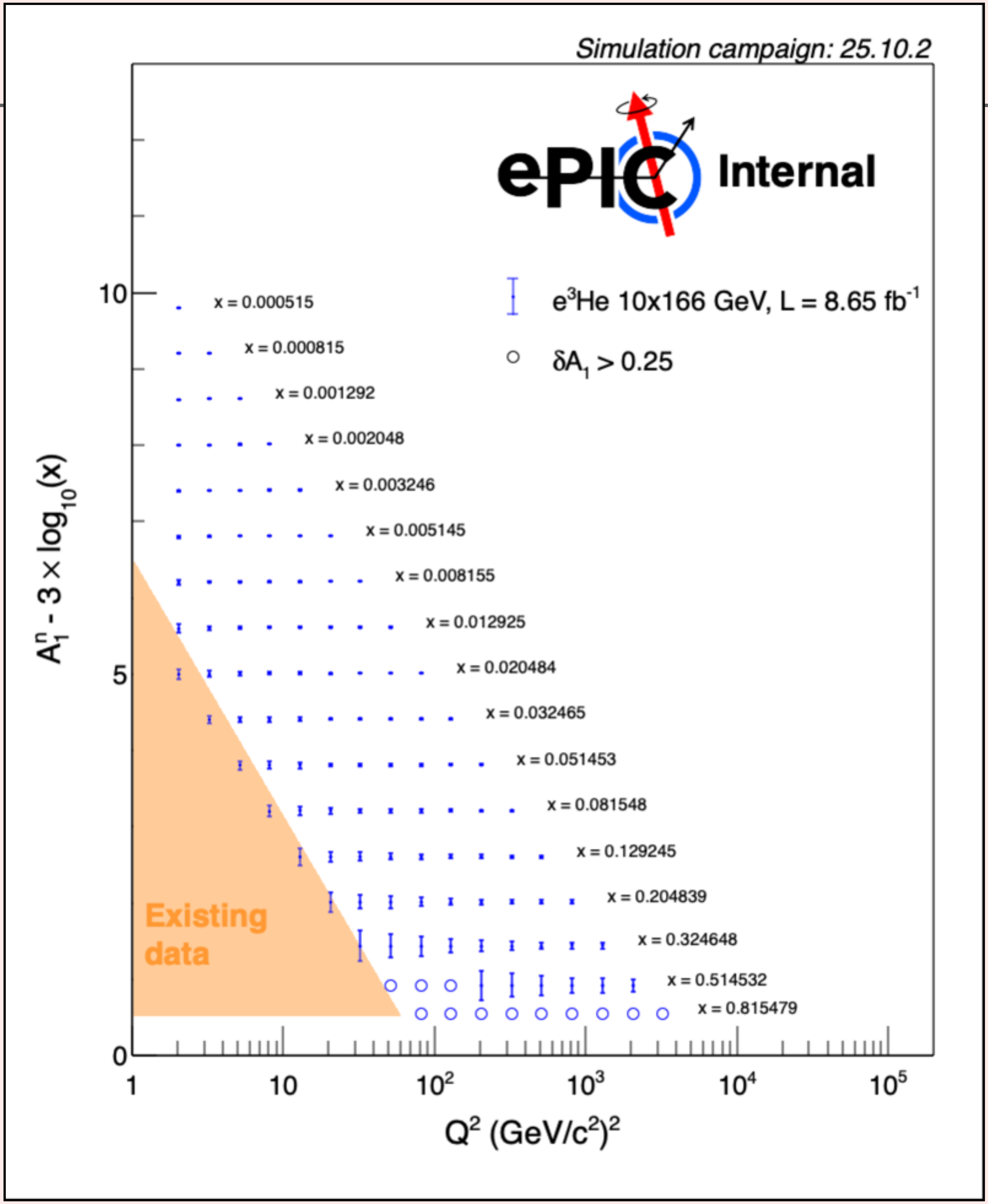
Projected A_1^n from $e^3\mathrm{He}$ DIS:

- $A_1(x, Q^2) \equiv \dfrac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} = \dfrac{A_\parallel}{D(1+\eta\xi)} - \dfrac{\eta A_\perp}{d(1+\eta\xi)}$
- $\delta A_{\parallel,\perp} = \dfrac{1}{\sqrt{N} P_e P_N}$
- $P_e = P_n = 70\,\%$
- $0.01 < y < 0.95,\ Q^2 \geq 2,\ W^2 > 4$
- R calculated from https://doi.org/10.1016/S0370-2693(99)00244-0
- Included statistical uncertainty and model uncertainties



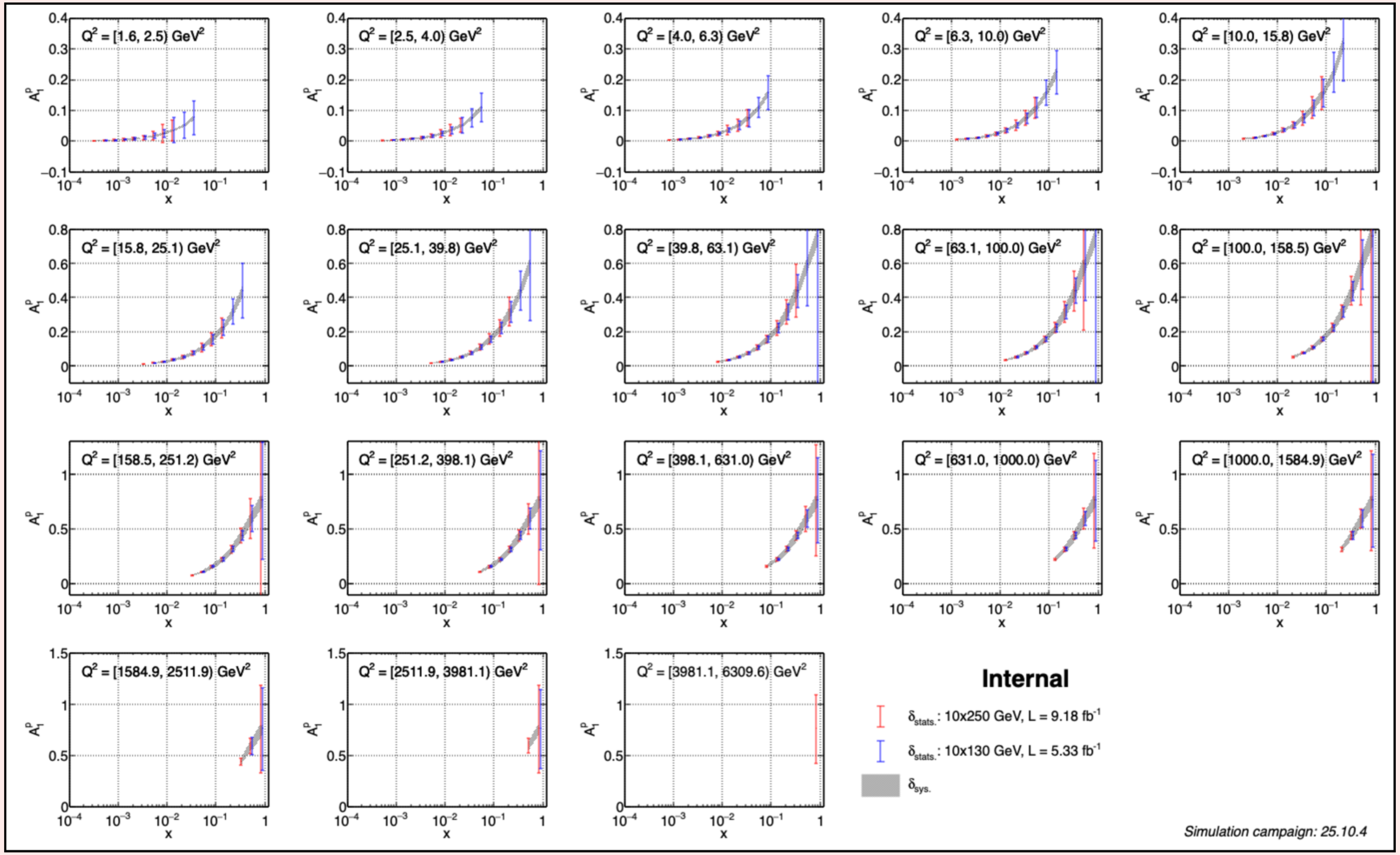
Projected A_1^n:

- $A_1(x, Q^2) \equiv \dfrac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} = \dfrac{A_\parallel}{D(1 + \eta\xi)} - \dfrac{\eta A_\perp}{d(1 + \eta\xi)}$
- $\delta A_{\parallel,\perp} = \dfrac{1}{\sqrt{N P_e P_N}}$
- $P_e = P_p = 70\,\%$
- Data split evenly between $A_\parallel$ and $A_\perp$
- R calculated from https://doi.org/10.1016/S0370-2693(99)00244-0
- Statistical uncertainty only



Systematic uncertainty

- estimation for ATHENA for $A_{\|}$
  - 1.5% point-by-point uncorrelated
  - 3% pion contamination
  - 4.7% normalization
    - 3% δP_e, 3% δP_N
    - 1-2% detector effects
- Estimated using $A_1 \approx \dfrac{A_{\|}}{D}$
- Systematics to be studied in more details



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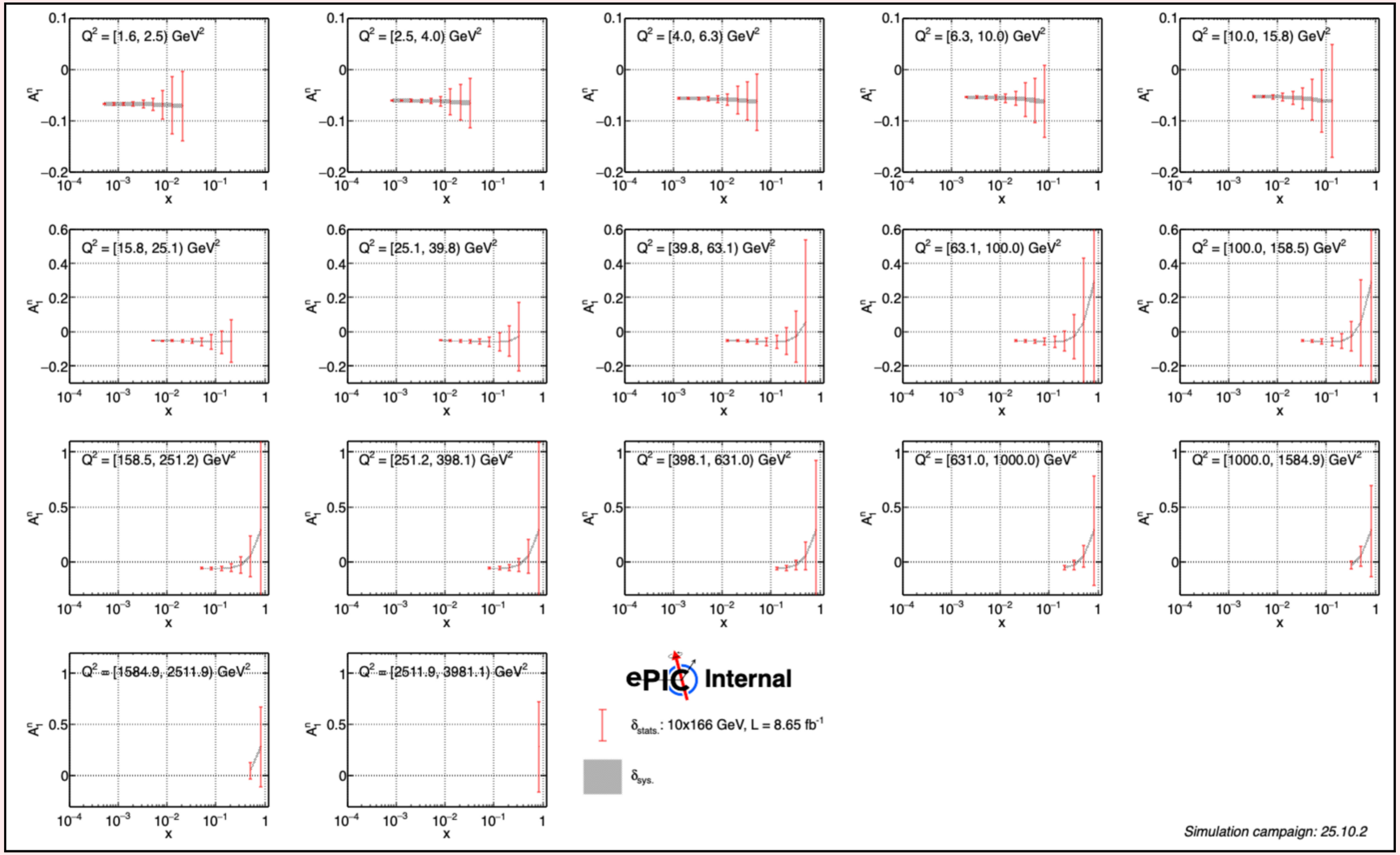
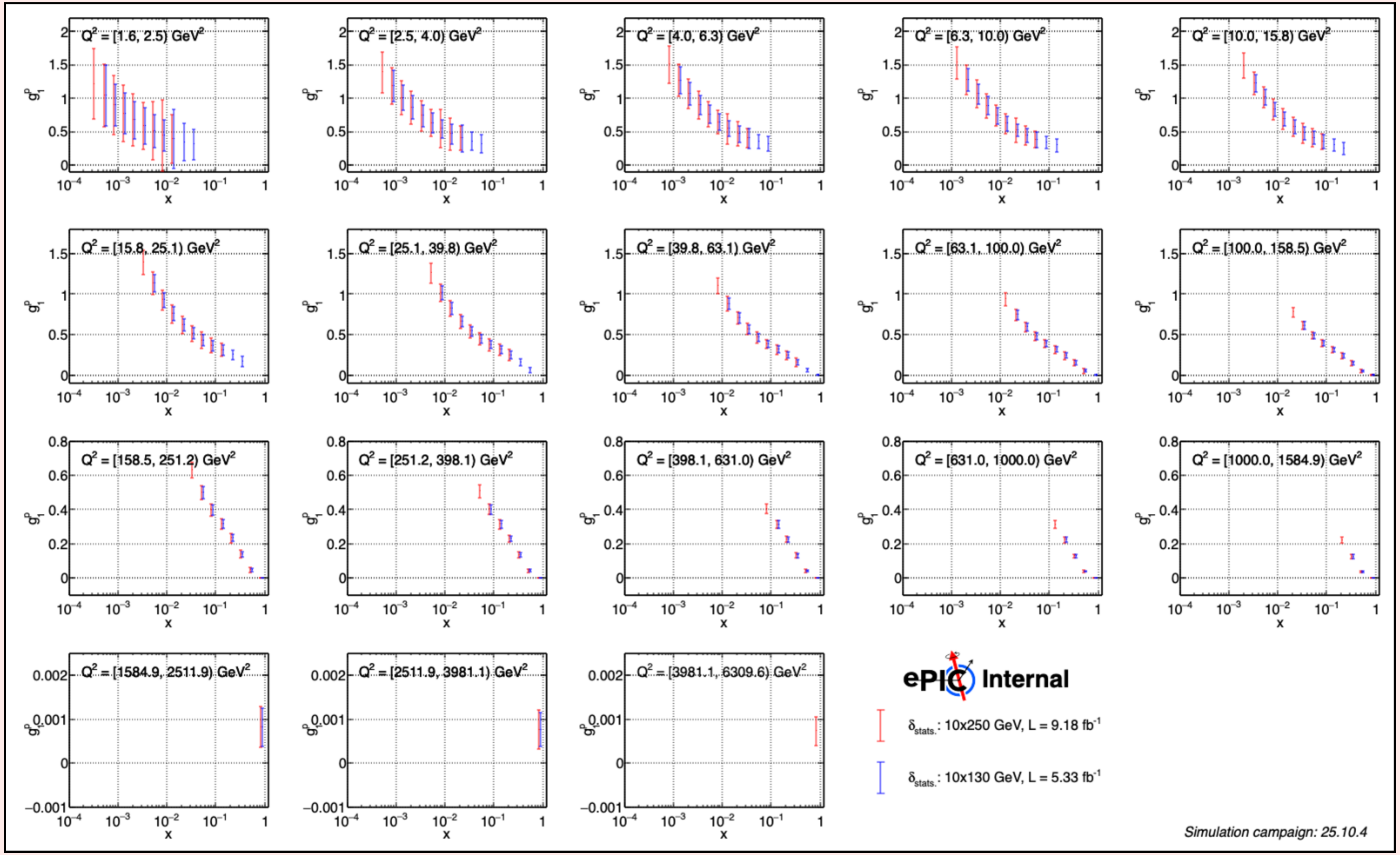


Projected g_1

- $A_1 \approx g_1/F_1$ with F_1 calculated from JAM22



Projected g_1

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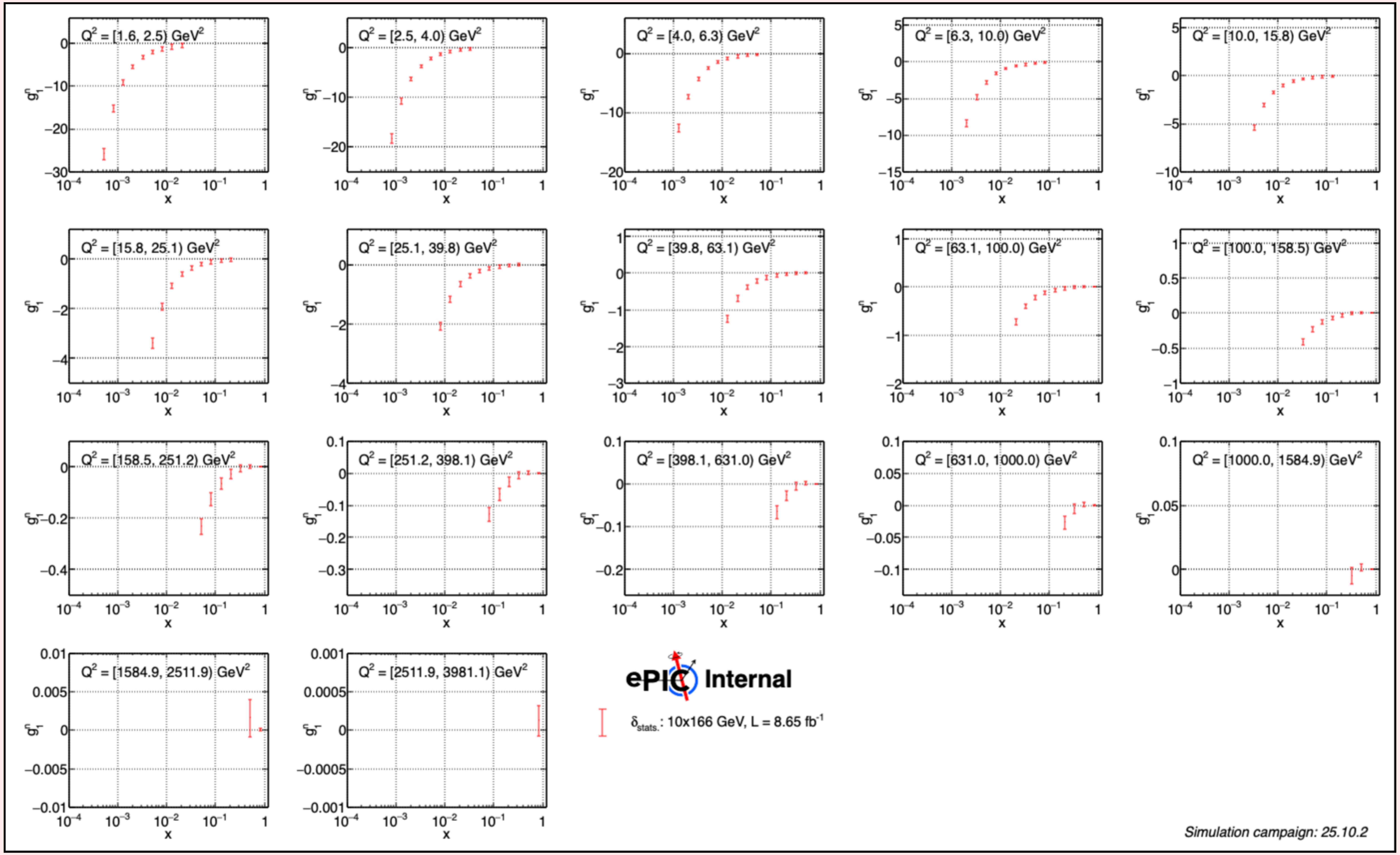
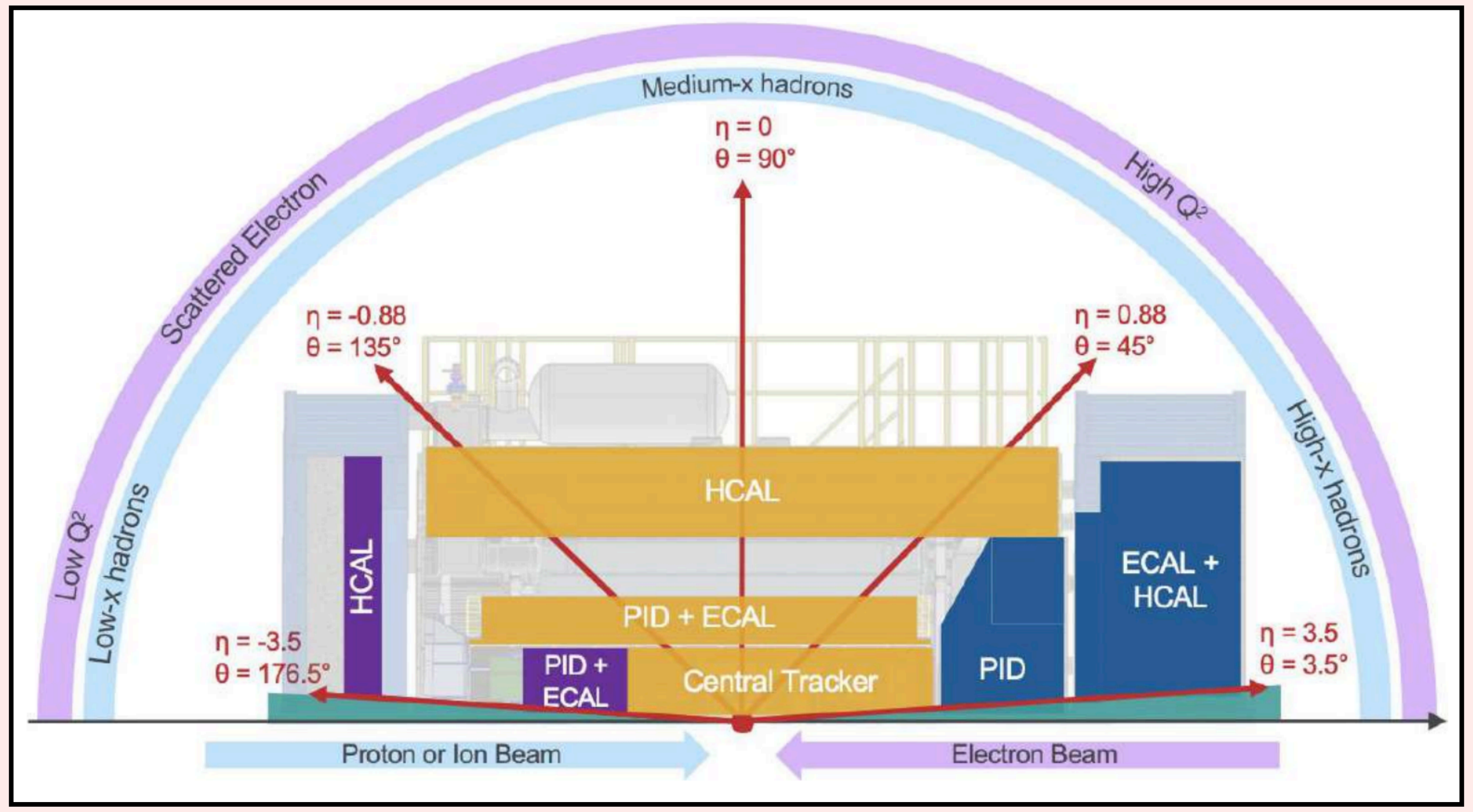


Backgrounds in measurements

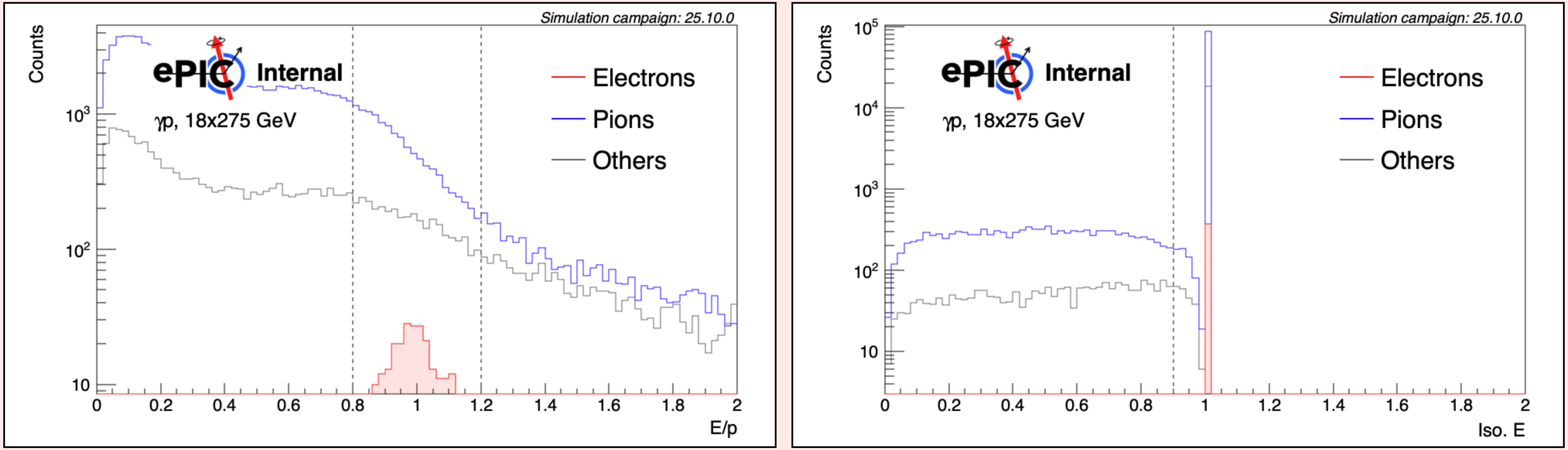
- Pion contamination?
- Beam background?
- Radiative corrections?
- …

Photoproduction background

π background lower the purity at very high y at low x and low Q^2

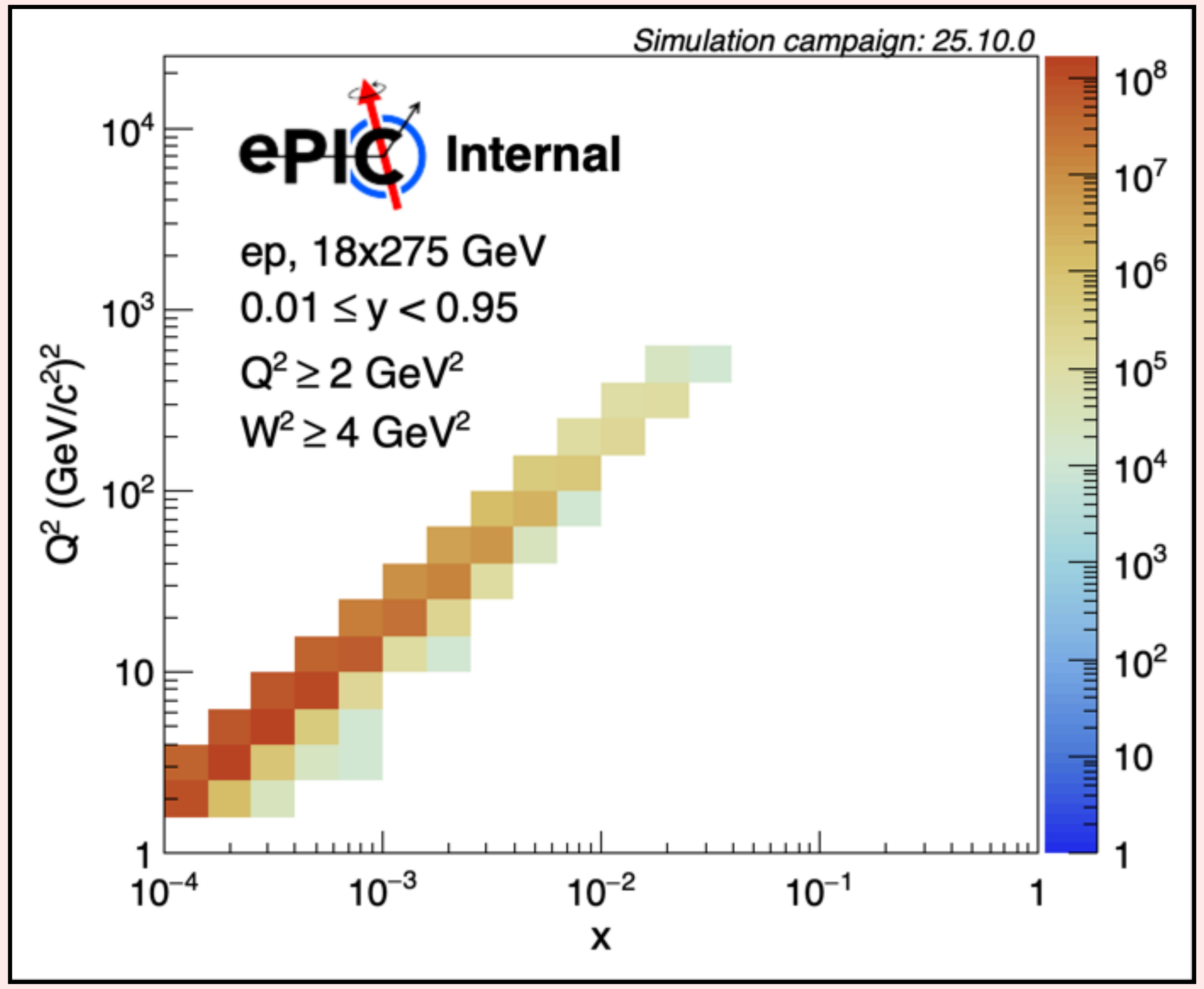


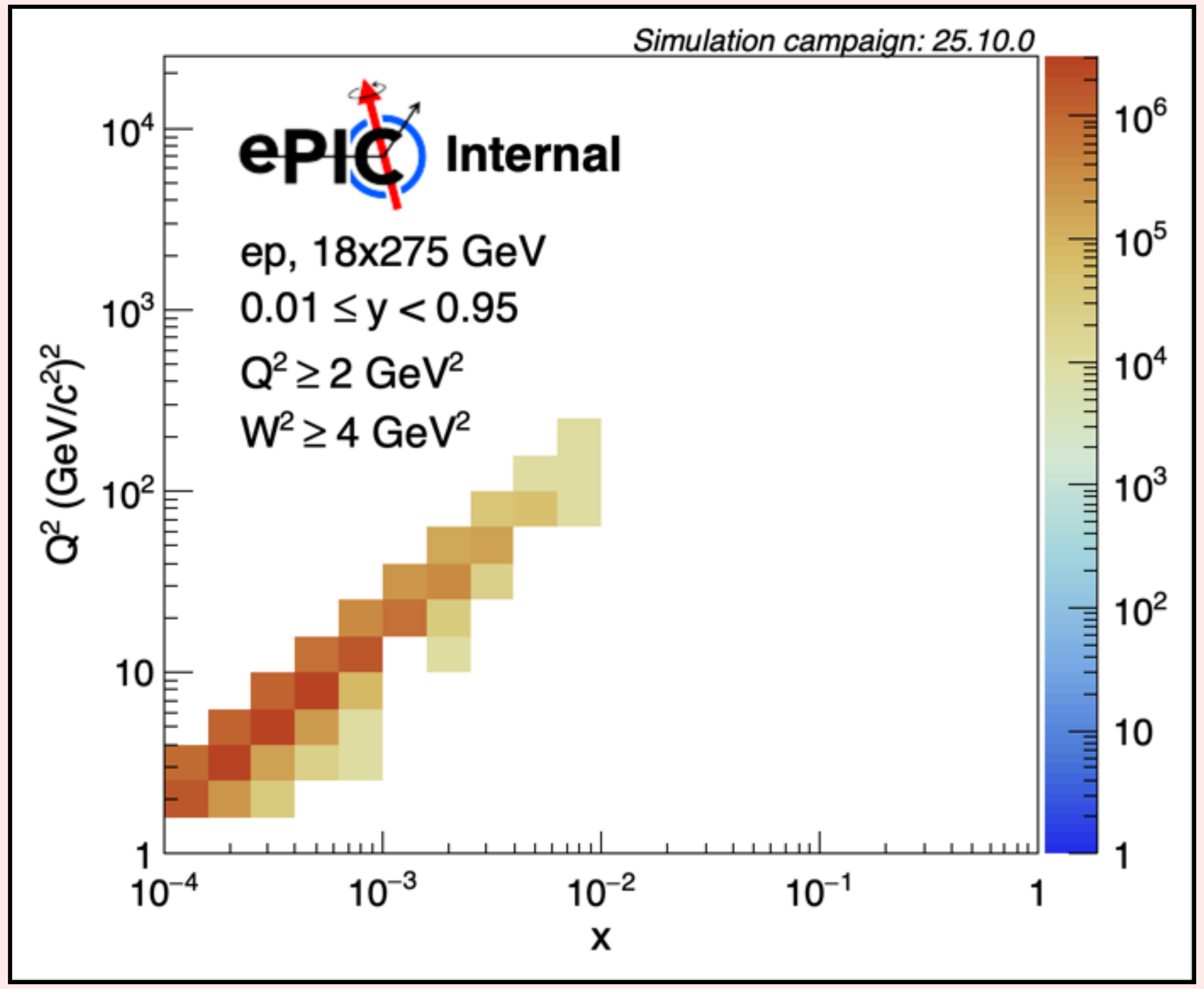
Low Q^2 event samples:
SIDIS/pythia6-eic/
1.0.0/18x275/q2_0to1/

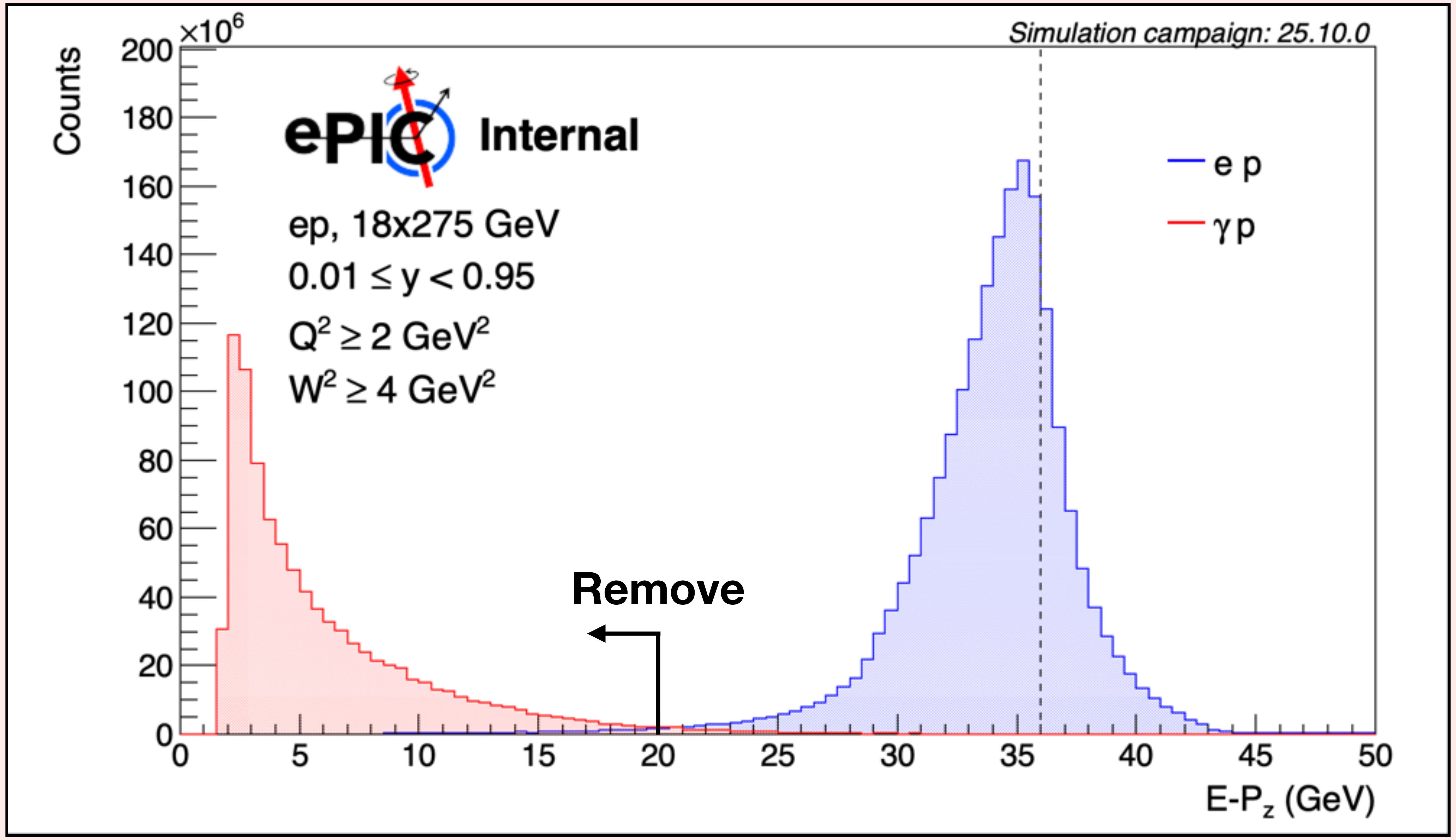


Photoproduction background

Reduced by ~97.95%

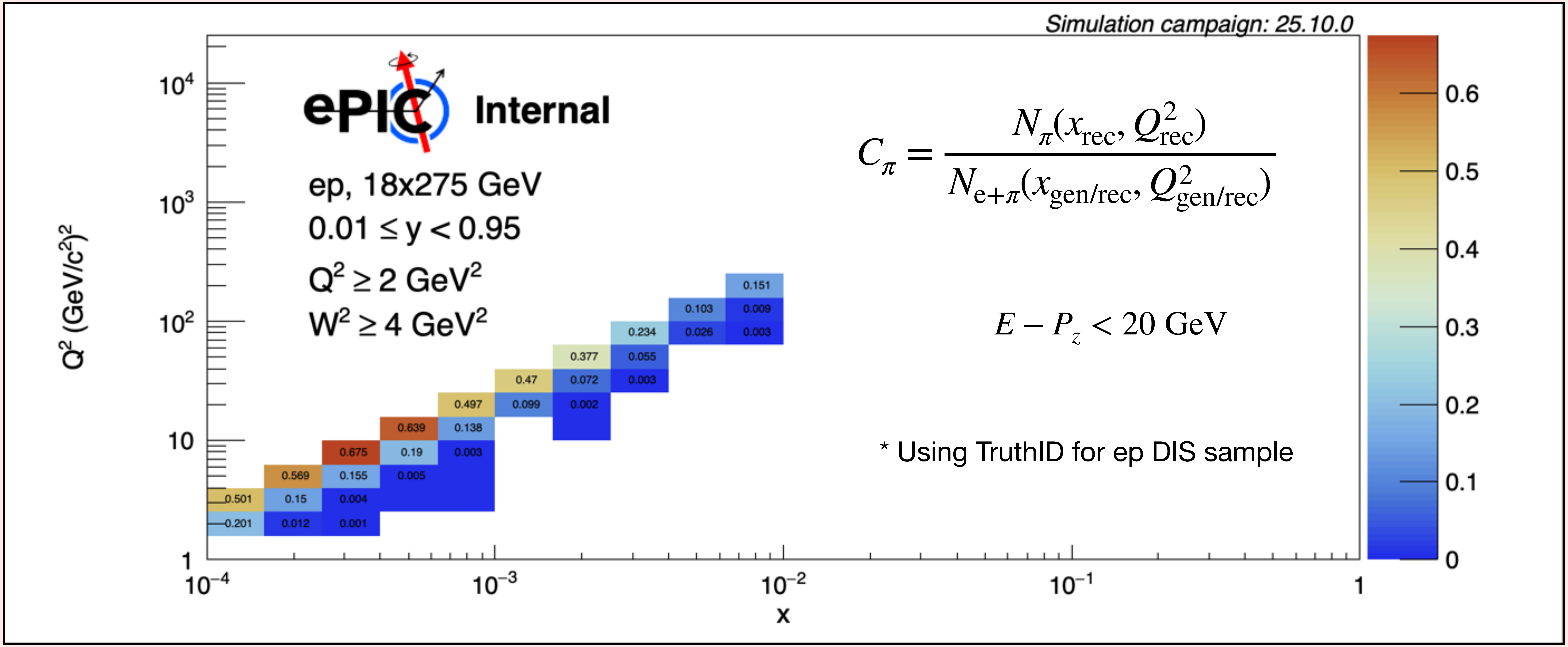






Both samples are scaled to $L = 10\ \mathrm{fb}^{-1}$

Photoproduction background

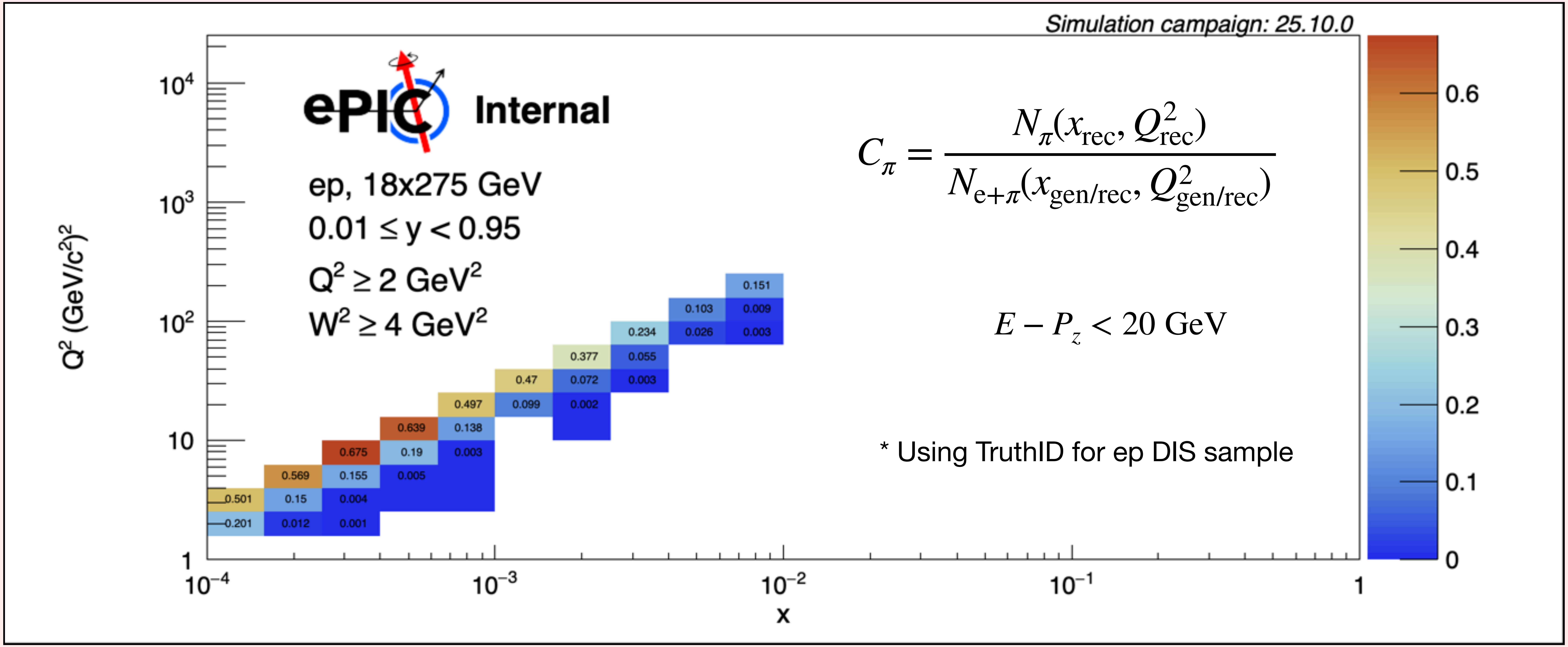


$$C_\pi = \frac{N_\pi(x_{\mathrm{rec}}, Q^2_{\mathrm{rec}})}{N_{\mathrm{e}+\pi}(x_{\mathrm{gen/rec}}, Q^2_{\mathrm{gen/rec}})}$$

$$E - P_z < 20\ \mathrm{GeV}$$

* Using TruthID for ep DIS sample

Photoproduction background



$$C_\pi = \frac{N_\pi(x_{\mathrm{rec}}, Q^2_{\mathrm{rec}})}{N_{e+\pi}(x_{\mathrm{gen/rec}}, Q^2_{\mathrm{gen/rec}})}$$

$$E - P_z < 20 \text{ GeV}$$

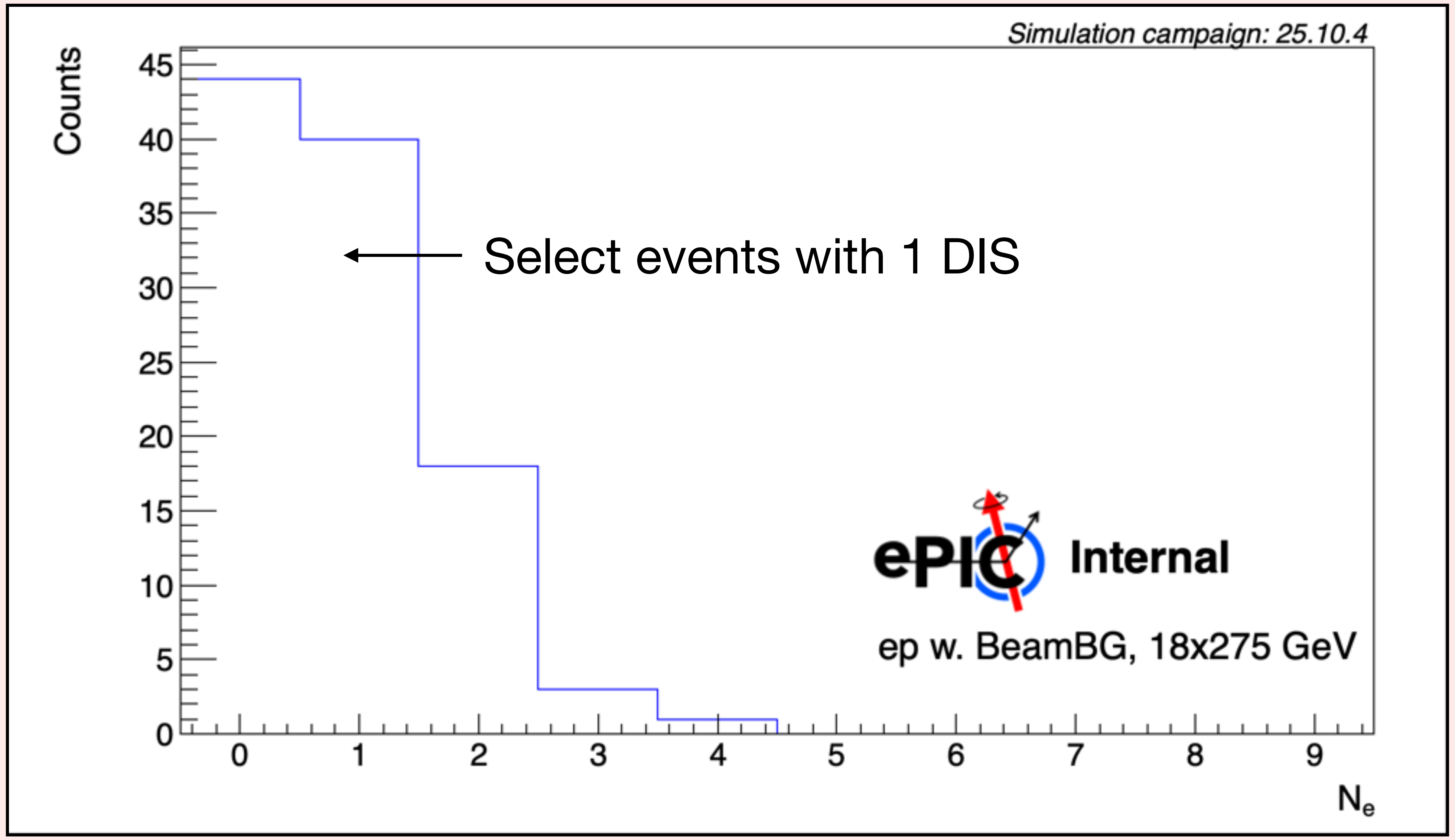
* Using TruthID for ep DIS sample

Need to use the same event generator for background and signal!

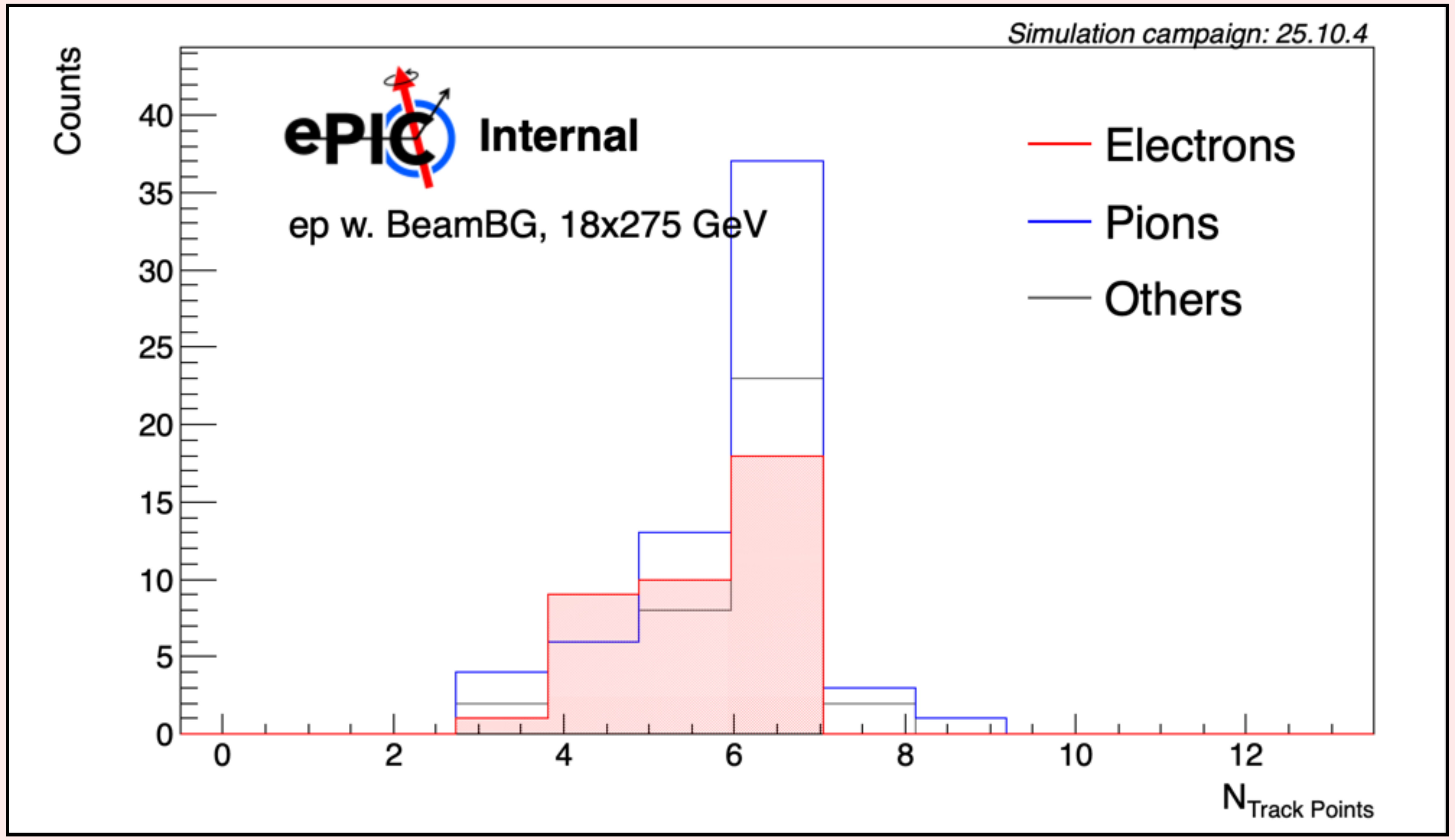
eID with beam background

Machine background sample at 18x275 GeV:

Number of scattered electrons



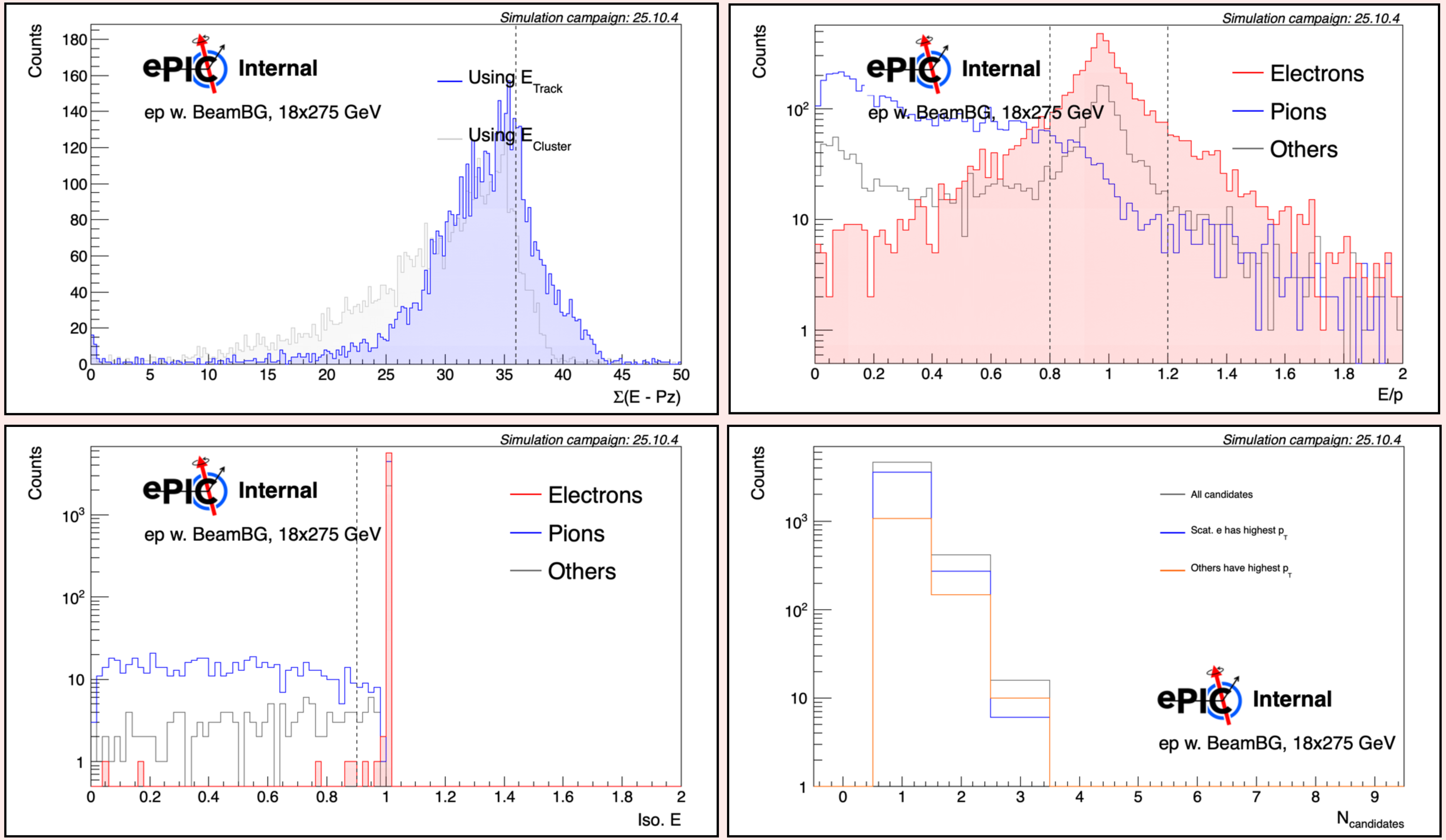
Number of points used for tracks



Beam background

- Effect on eID at 18x275 GeV is small; need to understand E and p resolution better (low resolution might be due to other problem in current simulation and analysis)
- Need to look at impact on kinematic reconstruction
- 10 GeV beam electron is expected to have larger impact. Will show study soon.

Plots shown at collaboration meeting Jan 2026



Summary

Projection and analysis status:

- ☑ Realistic physics and detector simulation

- ☑ Electron identification algorithm
- ☑ Kinematic reconstruction algorithm
- ☑ Primitive tagging algorithm

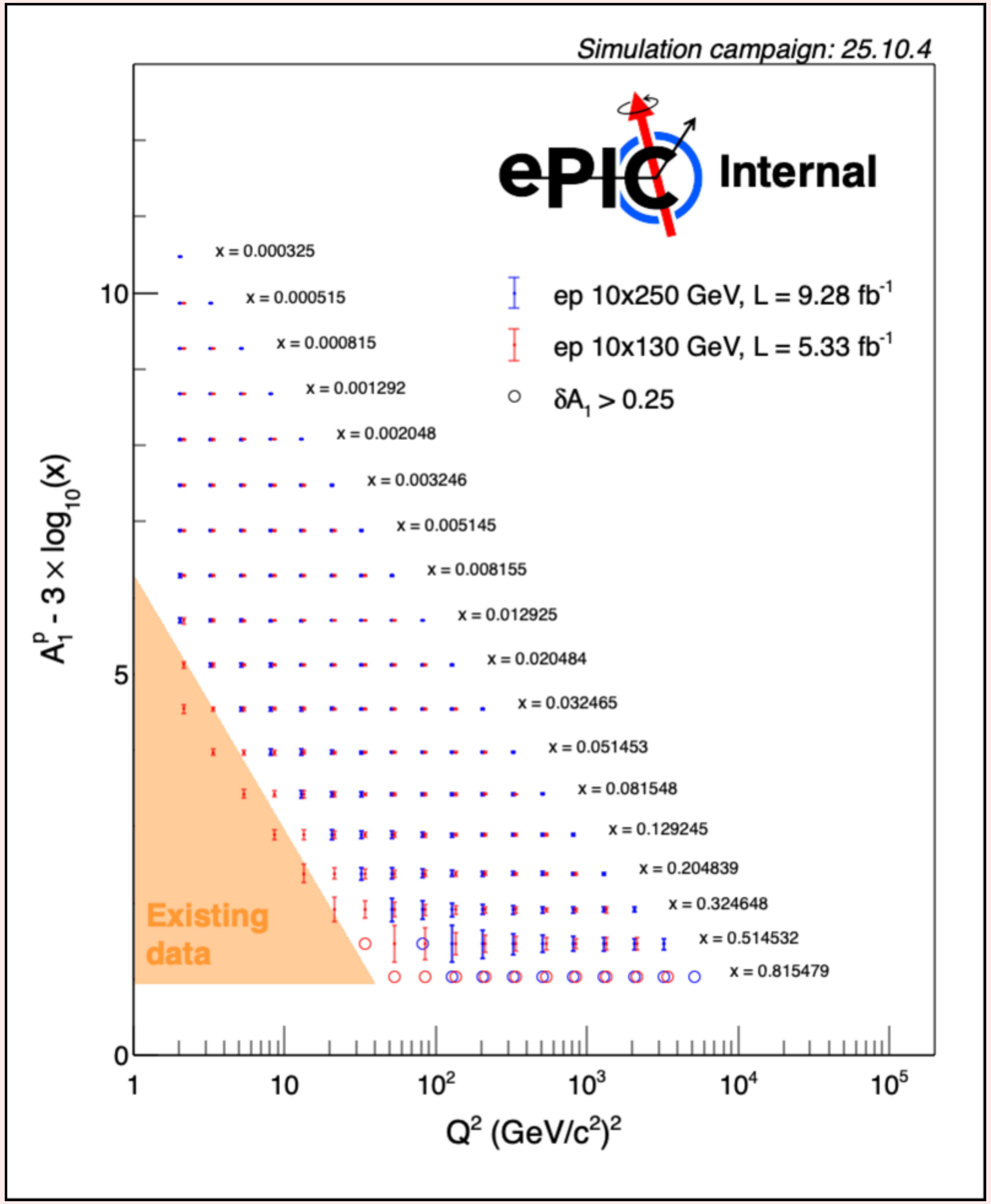
- ☑ Projected A_1^p, A_1^n with uncertainty estimate
- ☑ Projected g_1^p, g_1^n with uncertainty estimate

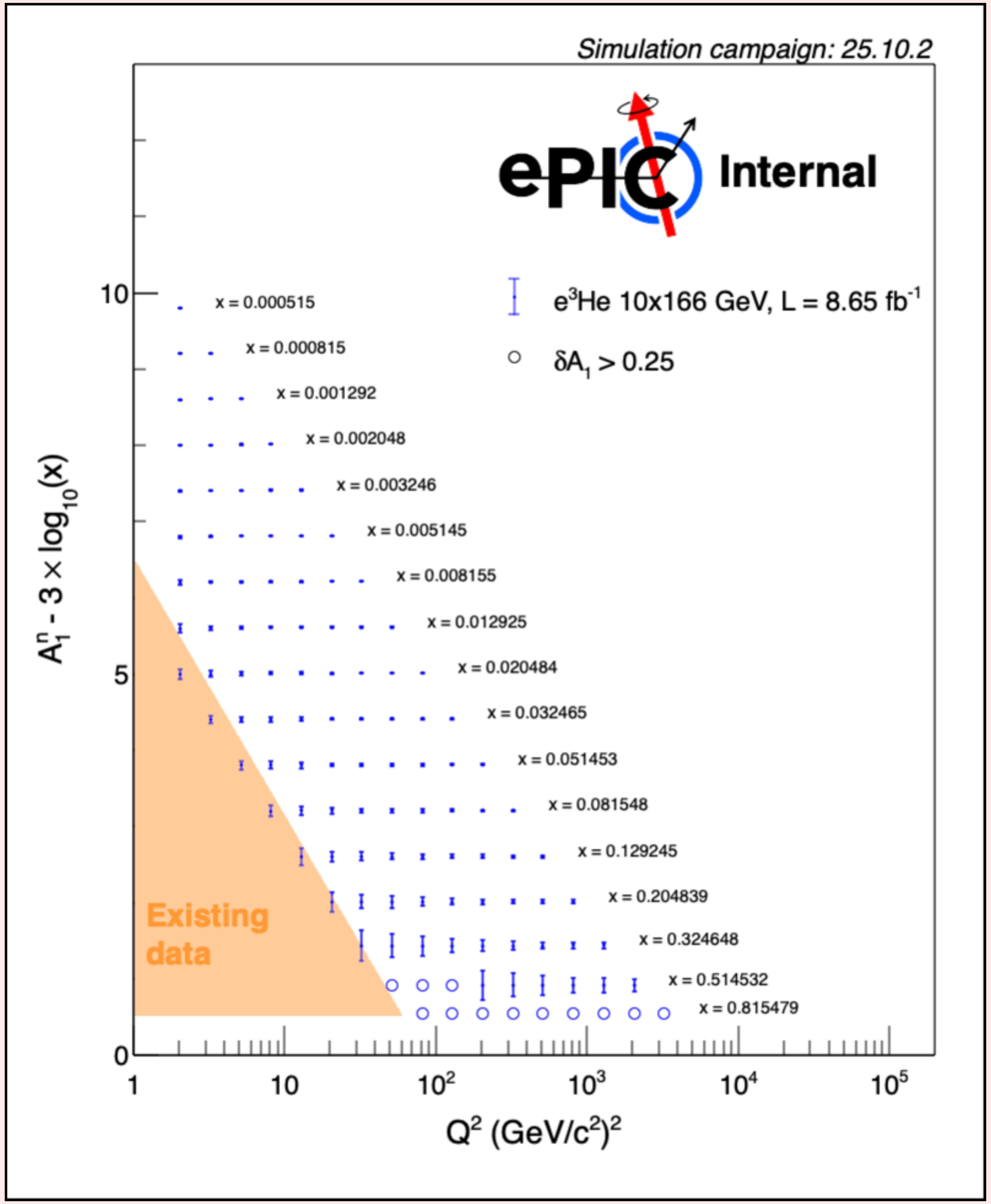
On-going study:

- ☐ Pion contamination
- ☐ Beam background

- ☐ Better tagging
- ☐ Use ZDC?

Summary





Thank you :)