Electrons for Neutrinos

New constraints for pion production models

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CLAS Collaboration meeting, 10 July 2025

Neutrino Physics

- The neutrino sector might hint to physics beyond the Standard model

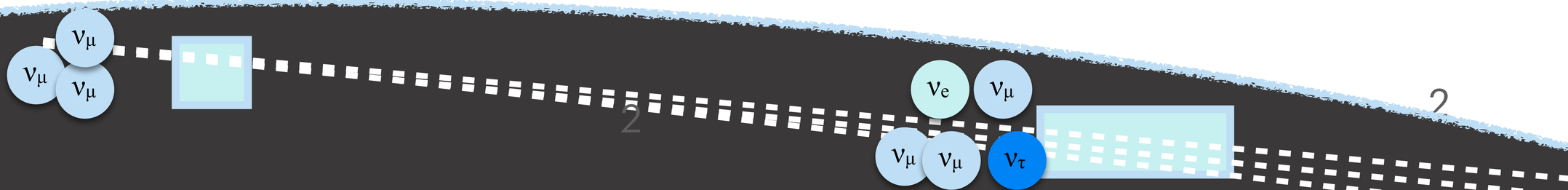
- Weakly interacting, extremely hard to detect
- Neutrino oscillations imply their mass and raises many questions

Charge-Parity (CP) violation

Precision measurements

Beyond the Standard Model physics

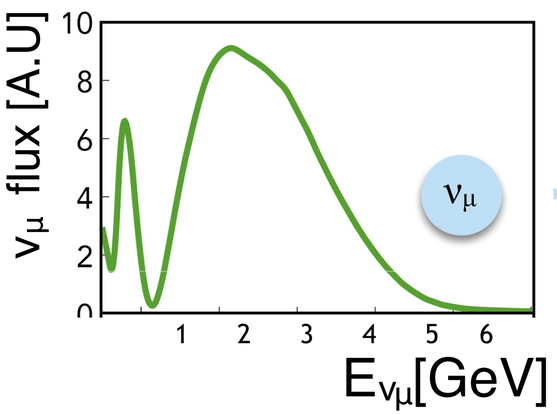
Mass Ordering

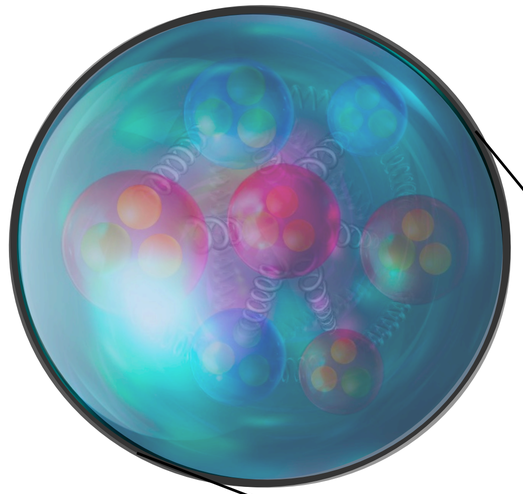


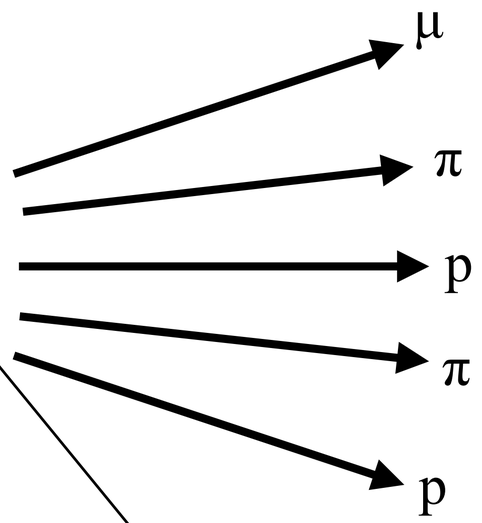
The precision era

Incoming true flux | Modelling Input | Measurement

$$\int P_{\nu_\mu \to \nu_e}(E_\nu, L)\ \Phi(E_\nu, 0)\ \ \sigma(E_\nu)\,\epsilon(E_\nu)\,S(E_\nu, E_\nu^{reco})\,dE_\nu \propto N(E_\nu^{rec}, L)$$







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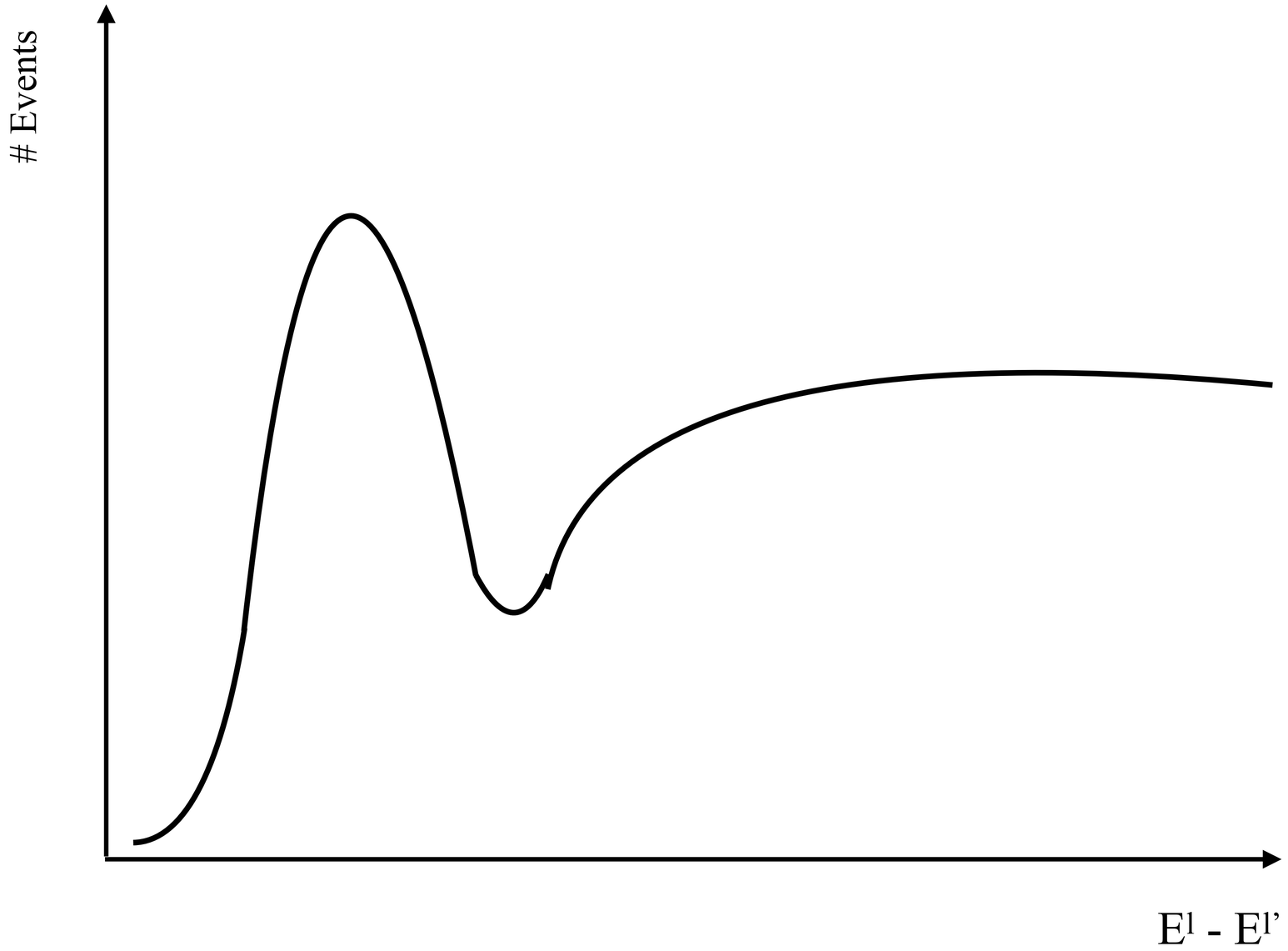
E Reconstruction Requires Interaction Modelling



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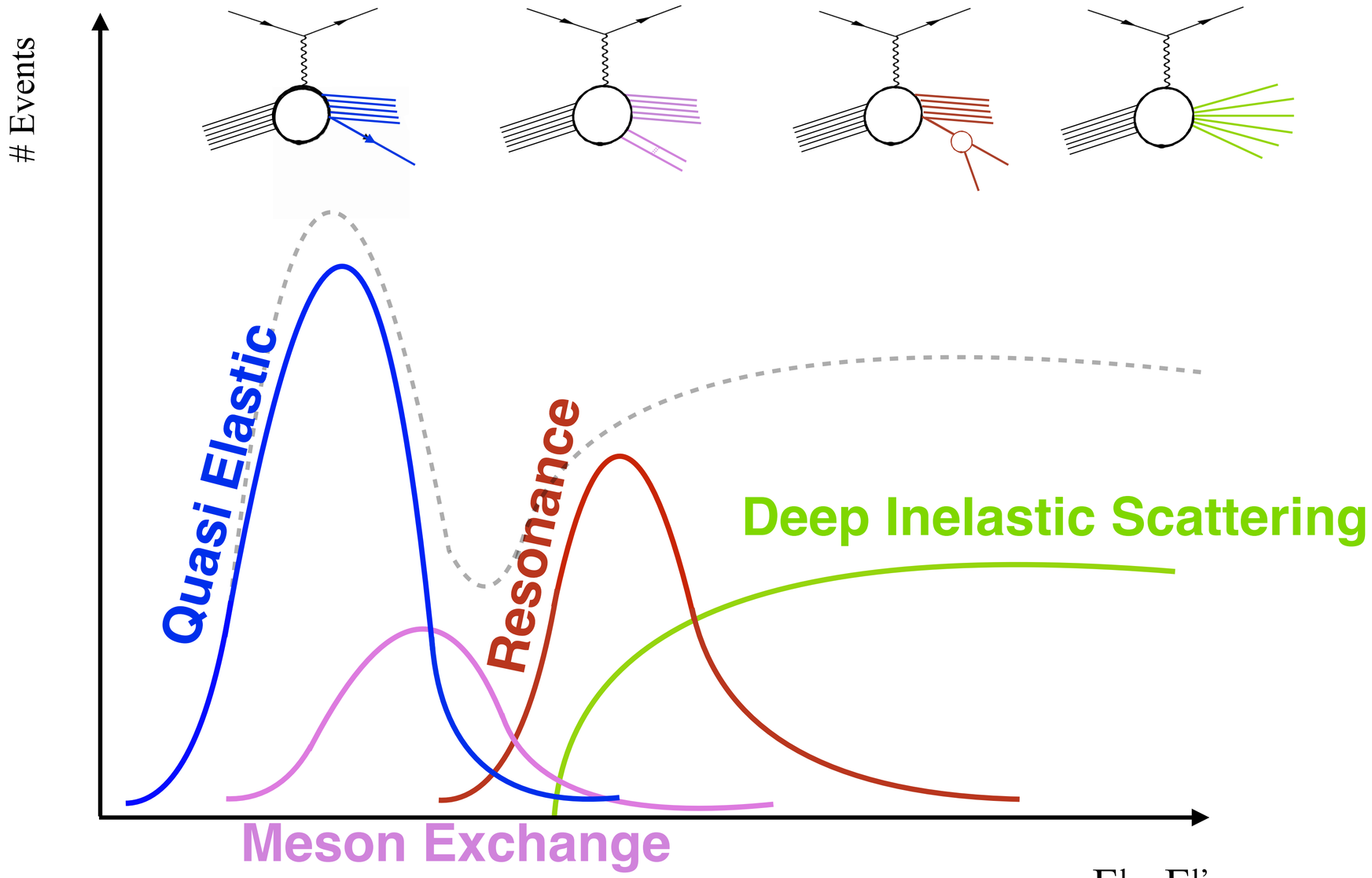
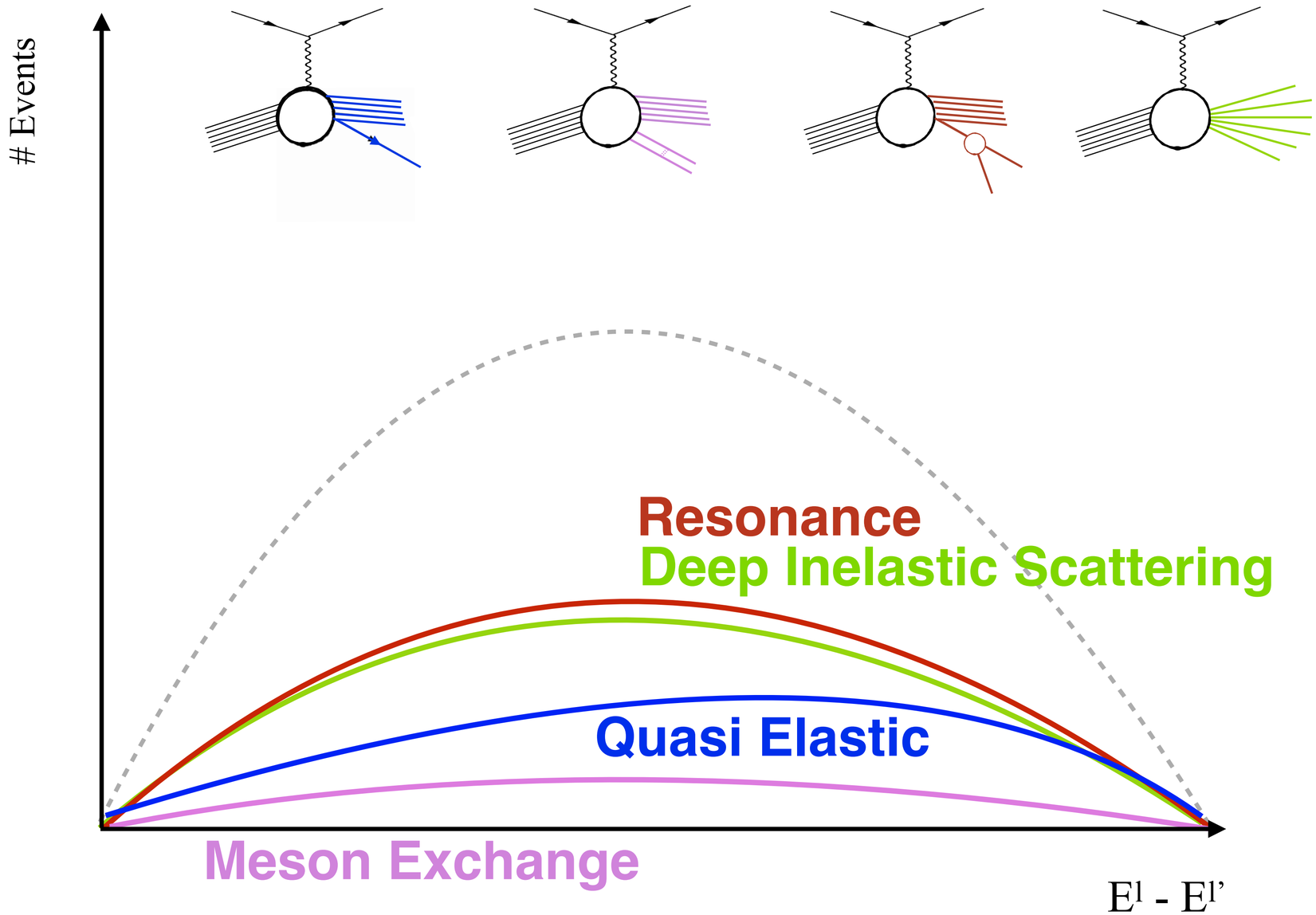
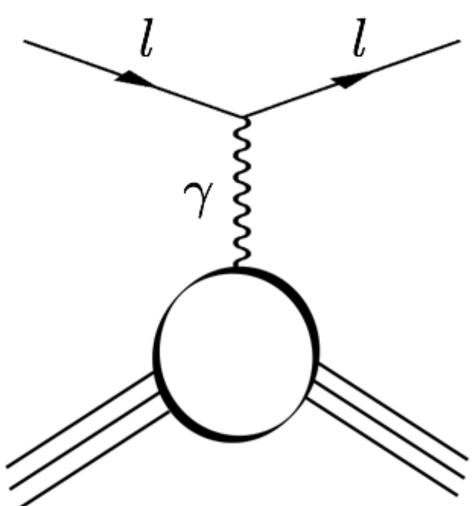


ν Experiments Fluxes Challenge our Understanding

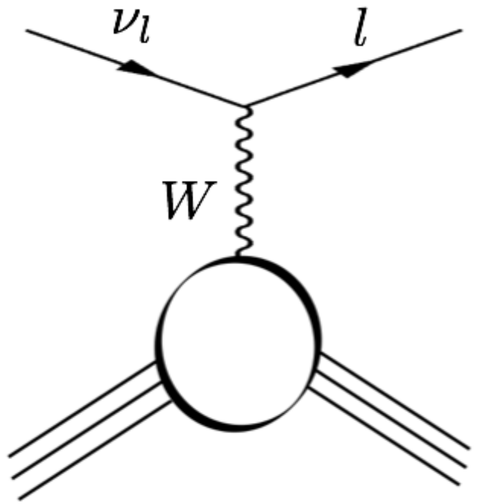


Why electrons?

Same nuclear ground state, Final State Interactions (FSI), Hadronization
Similar interactions with nuclei



EM current [V]



CC current [V + A]

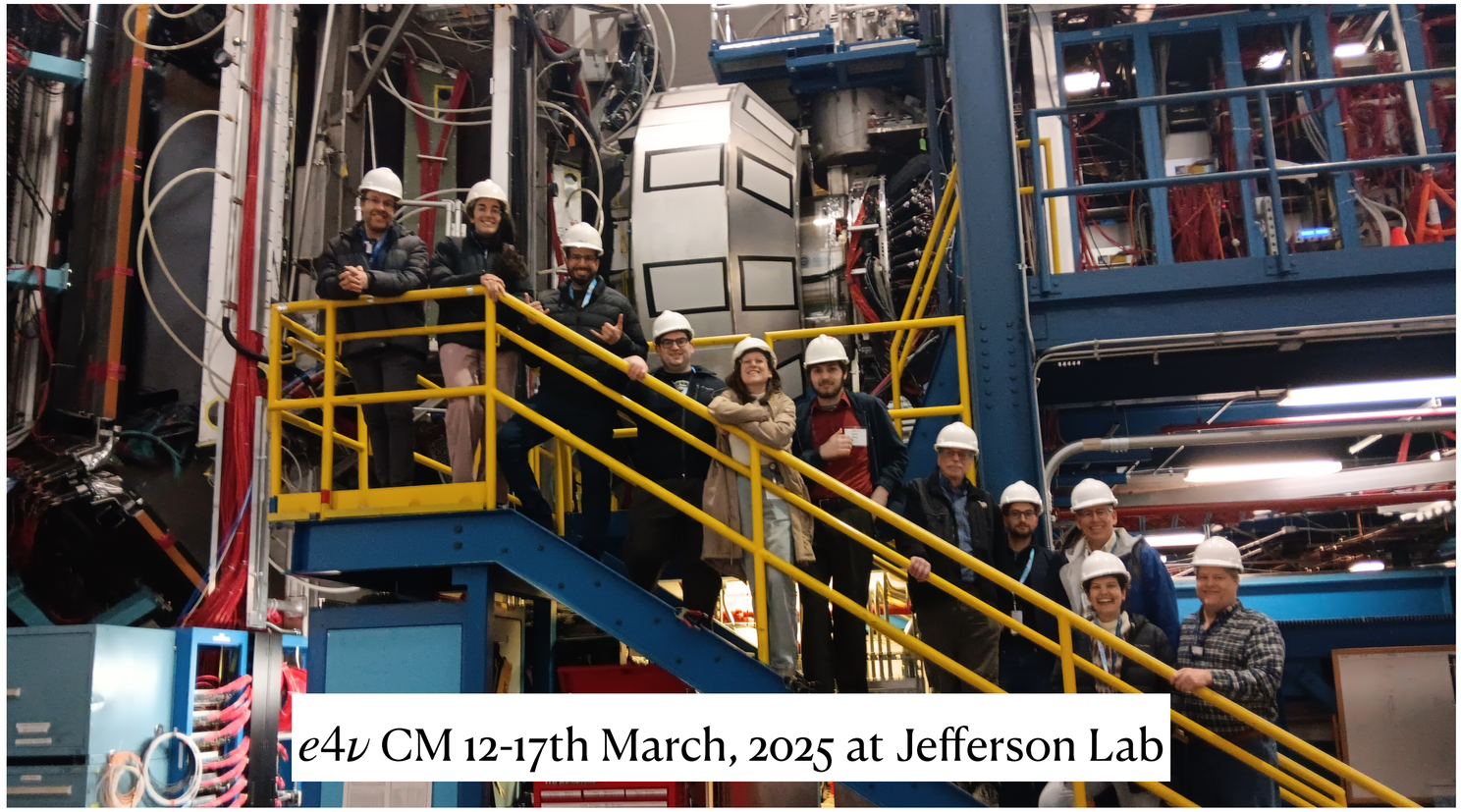
Monochromatic beam
High statistics

Wide-energy beam
Lower statistics

eA useful to test νA energy reconstruction methods

The e4ν Collaboration

- Dedicated group analysing data from CLAS for neutrino experiments
  - Targets (C, Ar, ...) and energies (1-6 GeV) of **interest for neutrino experiments**
  - **Exclusive final states** with large acceptance spectrometers

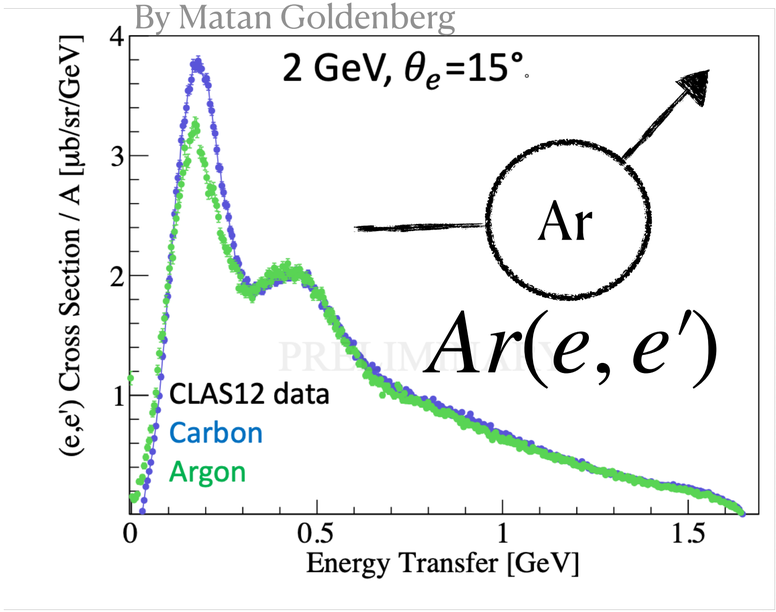


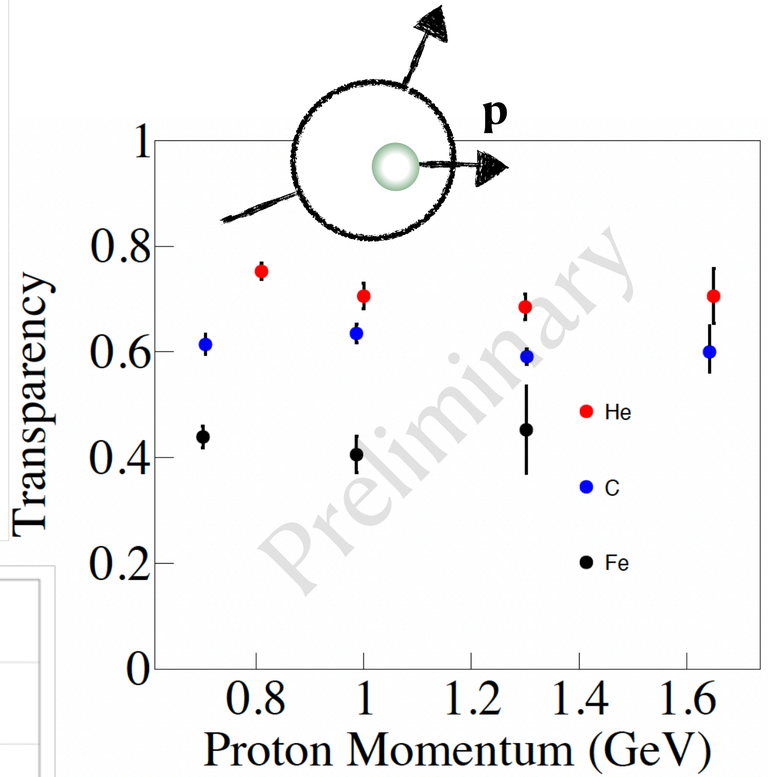
*e*4ν CM 12-17th March, 2025 at Jefferson Lab

New hadron electron production data

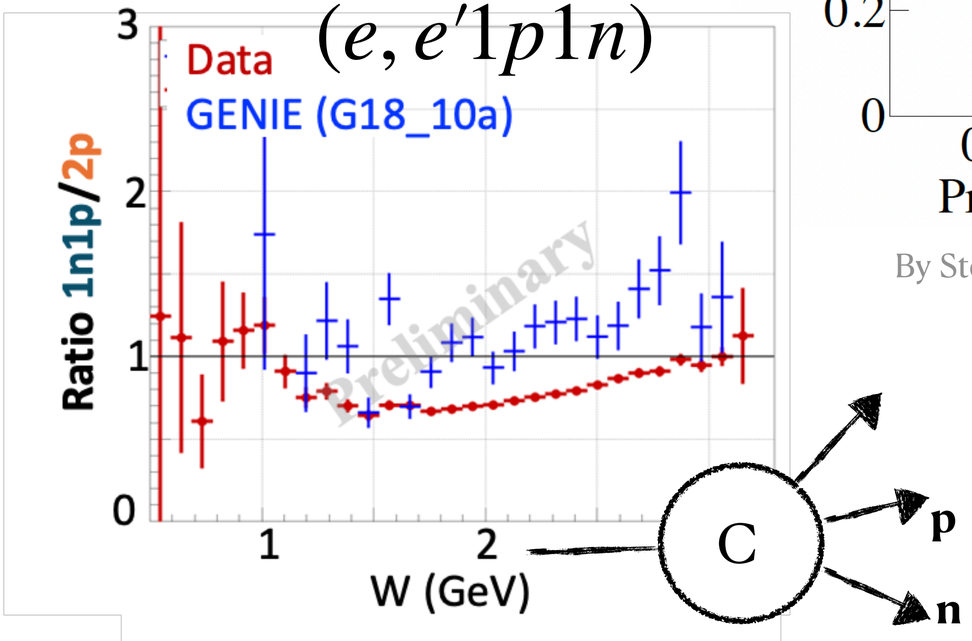
New pion production data
- **This talk**
- **Caleb's talk**

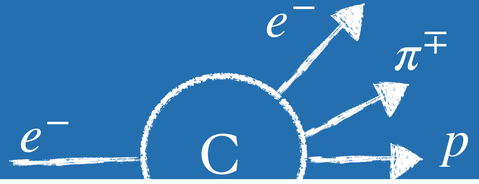
By Matan Goldenberg





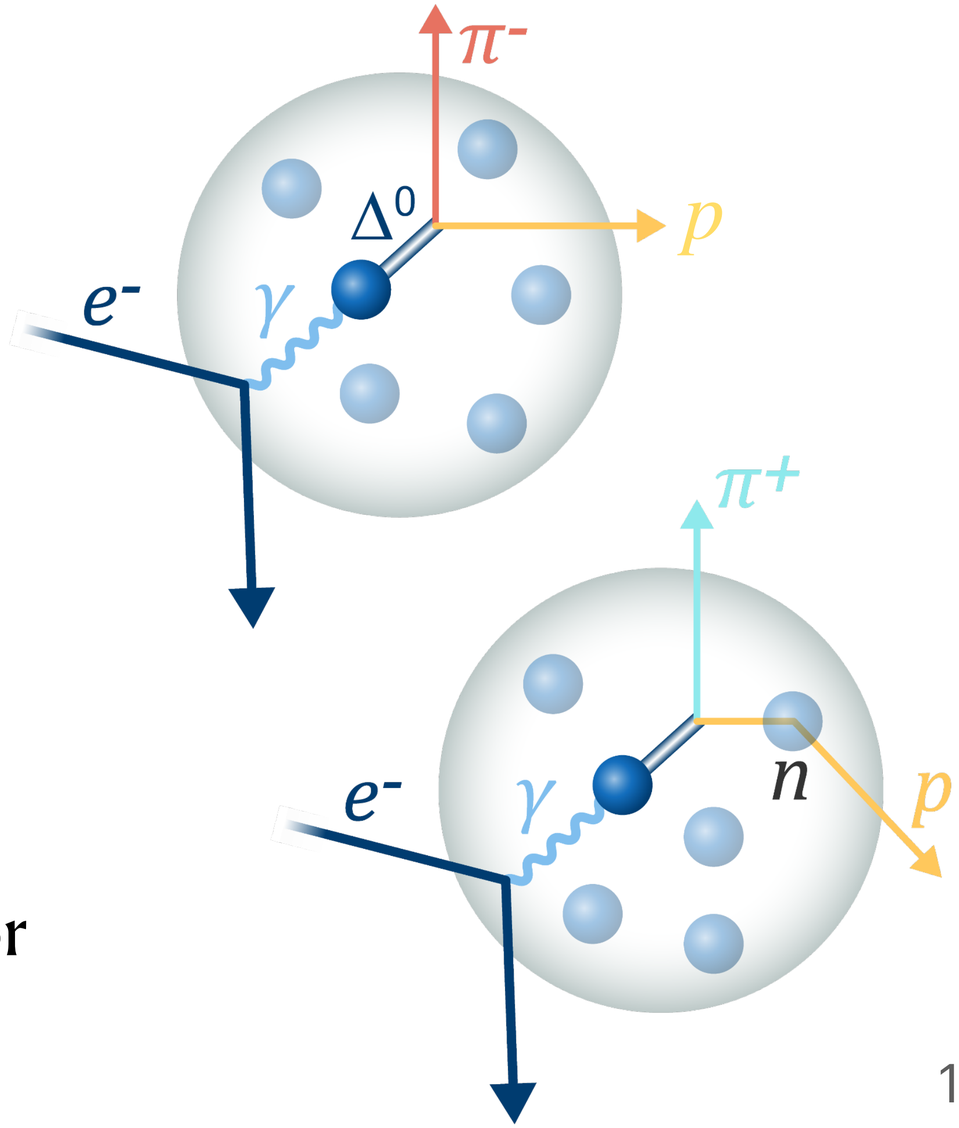
By Steven Dytman and Noah Steinberg





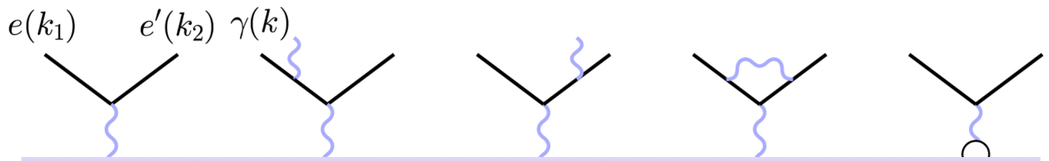
First look at C(e,e'1p1$\pi^\mp$)

- Carbon data, 1-4 GeV
- $1p1\pi^-$ and $1p1\pi^+$, no additional hadrons or photons
  - With $\pi^\mp$ above 150 MeV
  - With γ above 300 MeV
- $1p1\pi^-$ Possible at free nucleon level
- $1p1\pi^+$ needs two or more nucleons and or undetected particles (FSI)



Challenges of semi-exclusive measurements

Additional considerations are needed to measure semi-exclusive final states



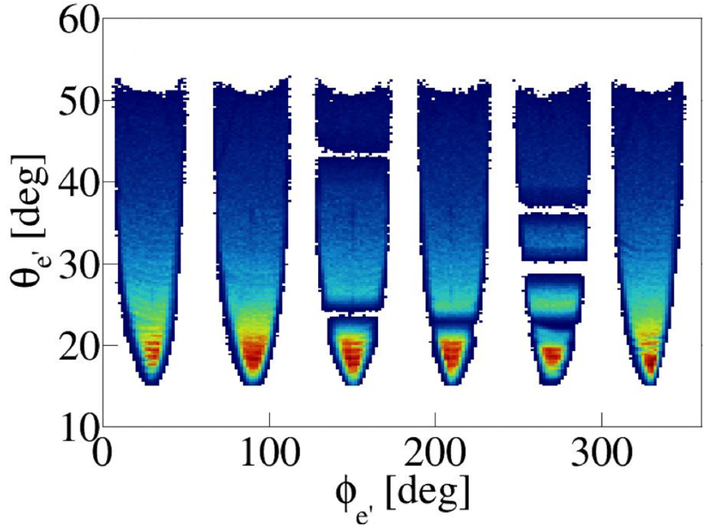
Radiative effects

- Need to correct the data
- Standard codes focus on (e,e')
- Limited to process, topology and kinematics

Not sufficient for large-acceptance (e,e'X) measurements

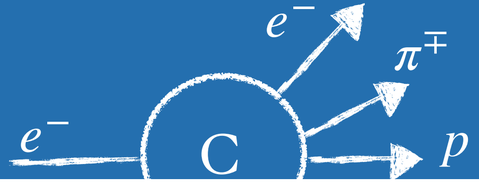
$\sim 2\pi$ acceptance for CLAS6

Incomplete acceptance

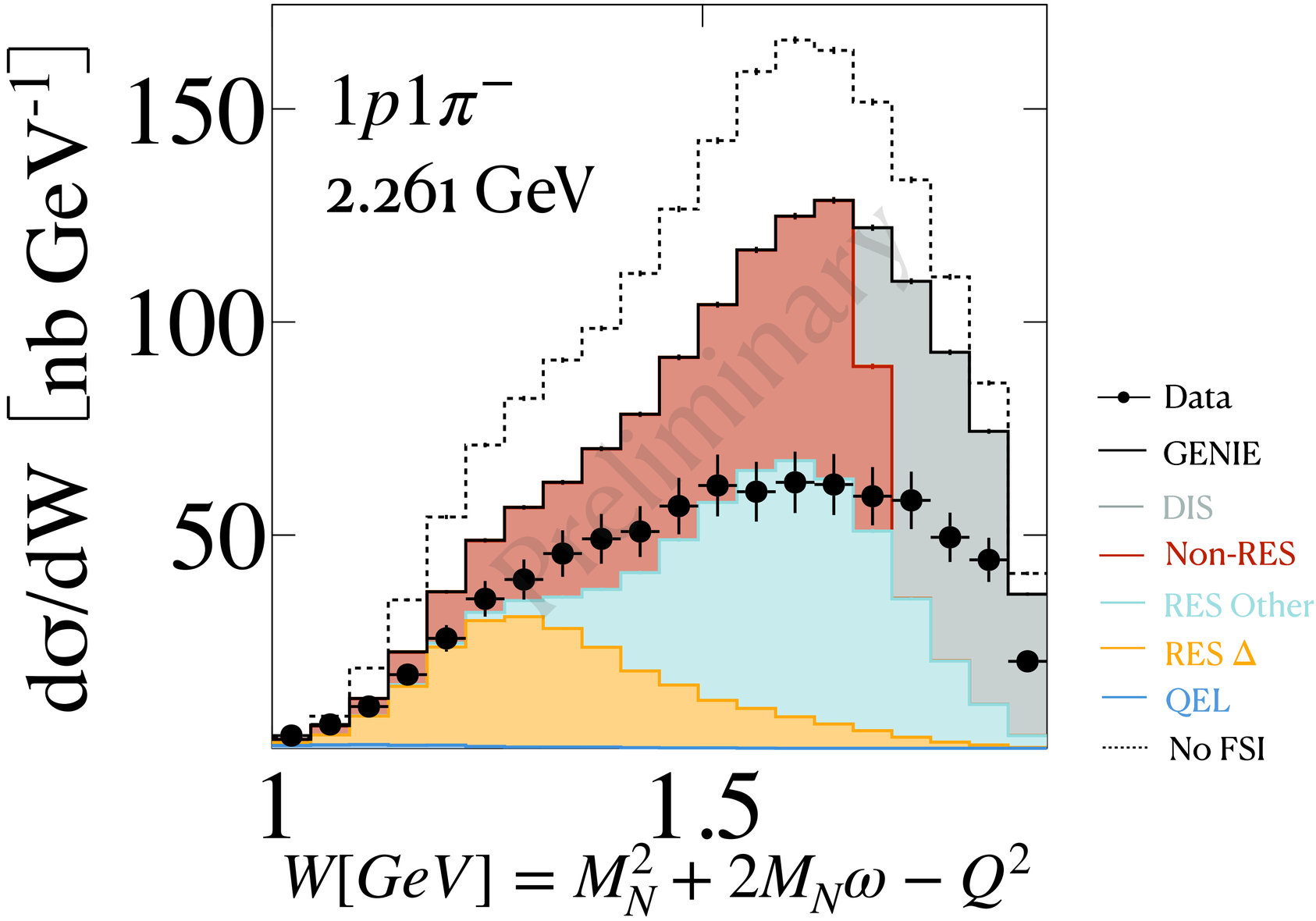


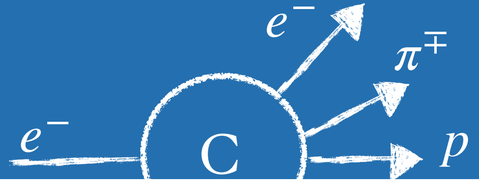
Multi-particle background

JTV et. al. [Comput. Phys. Commun. 294, 109509 (2025)]



Complex Physics





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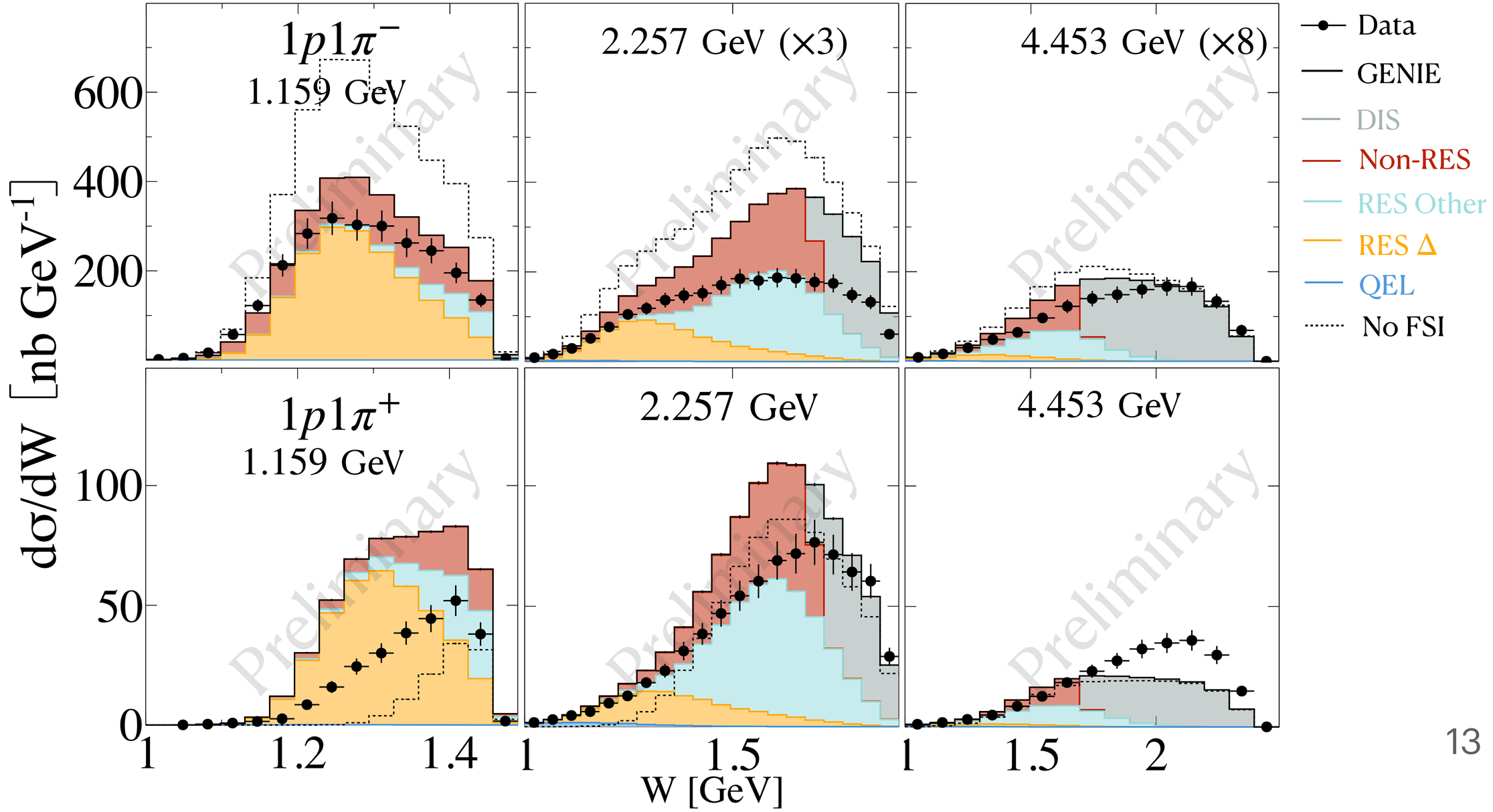
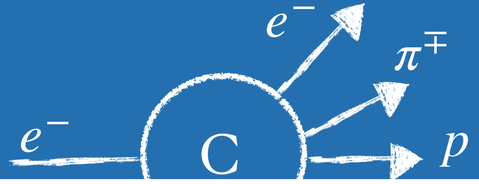
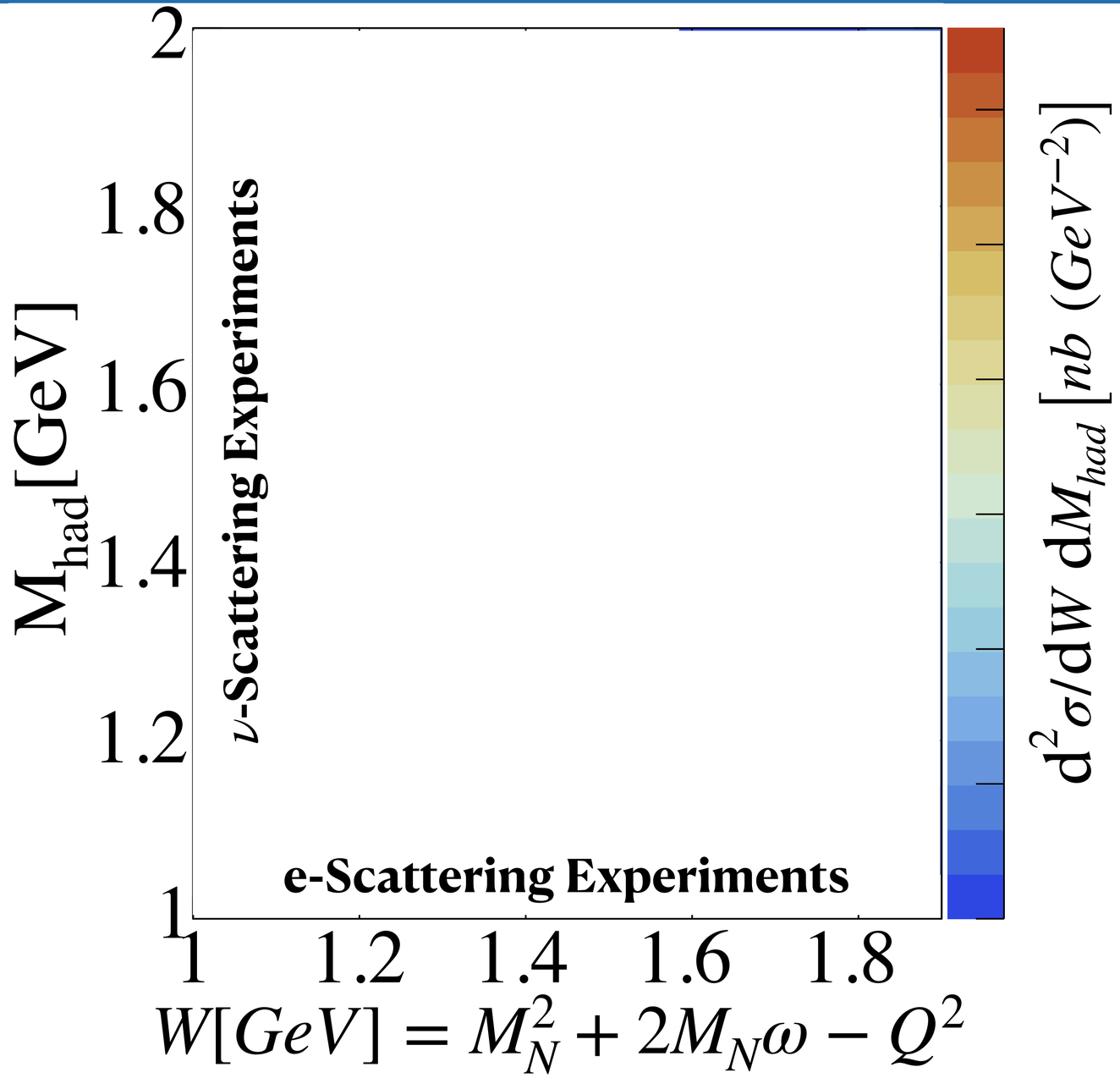
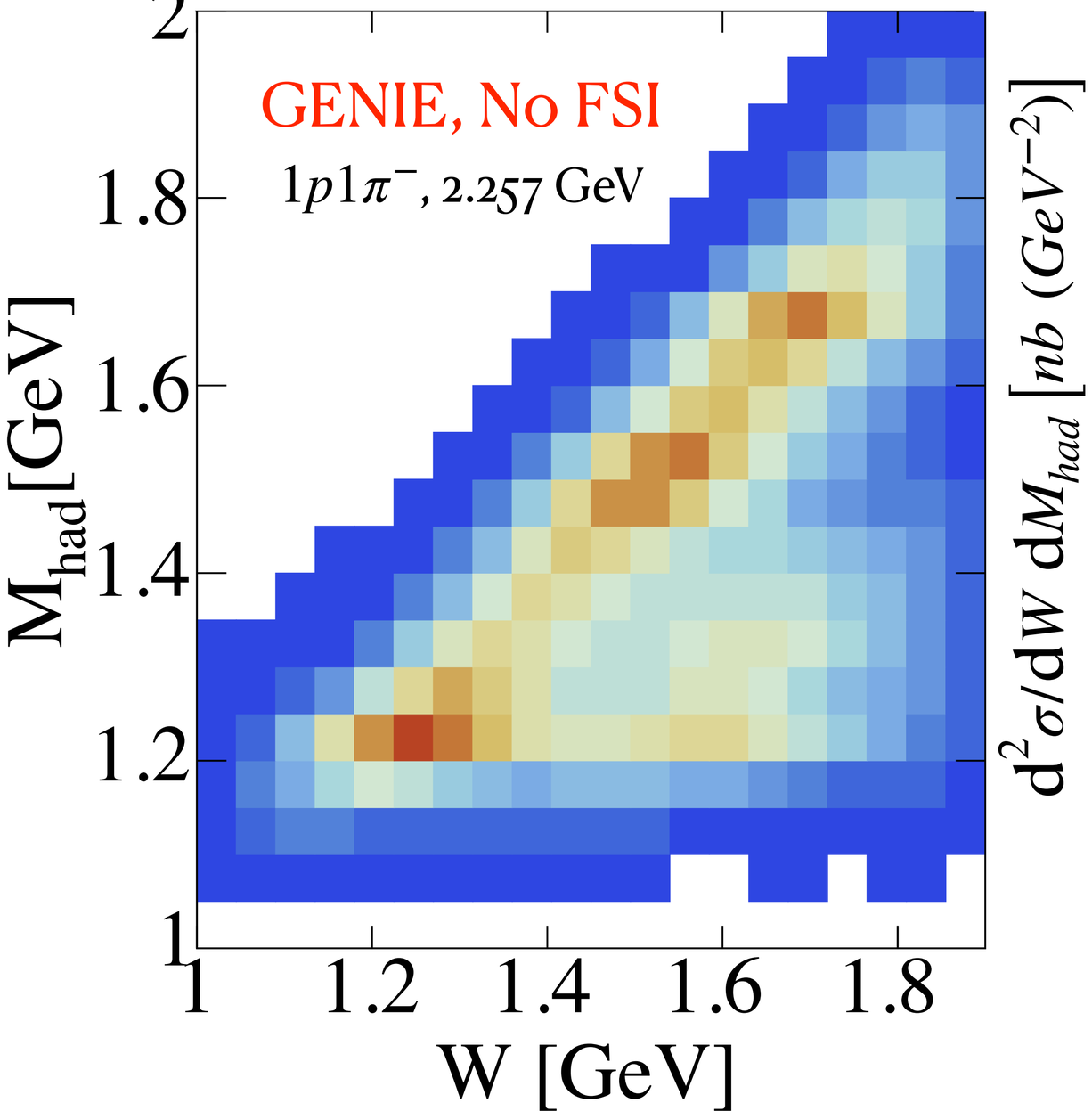


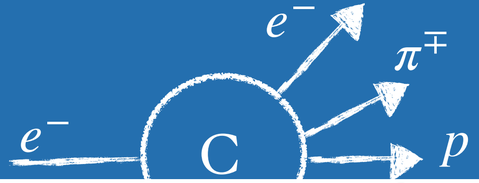


Hadronic Invariant Mass Bias



GENIE missmodels hadronization





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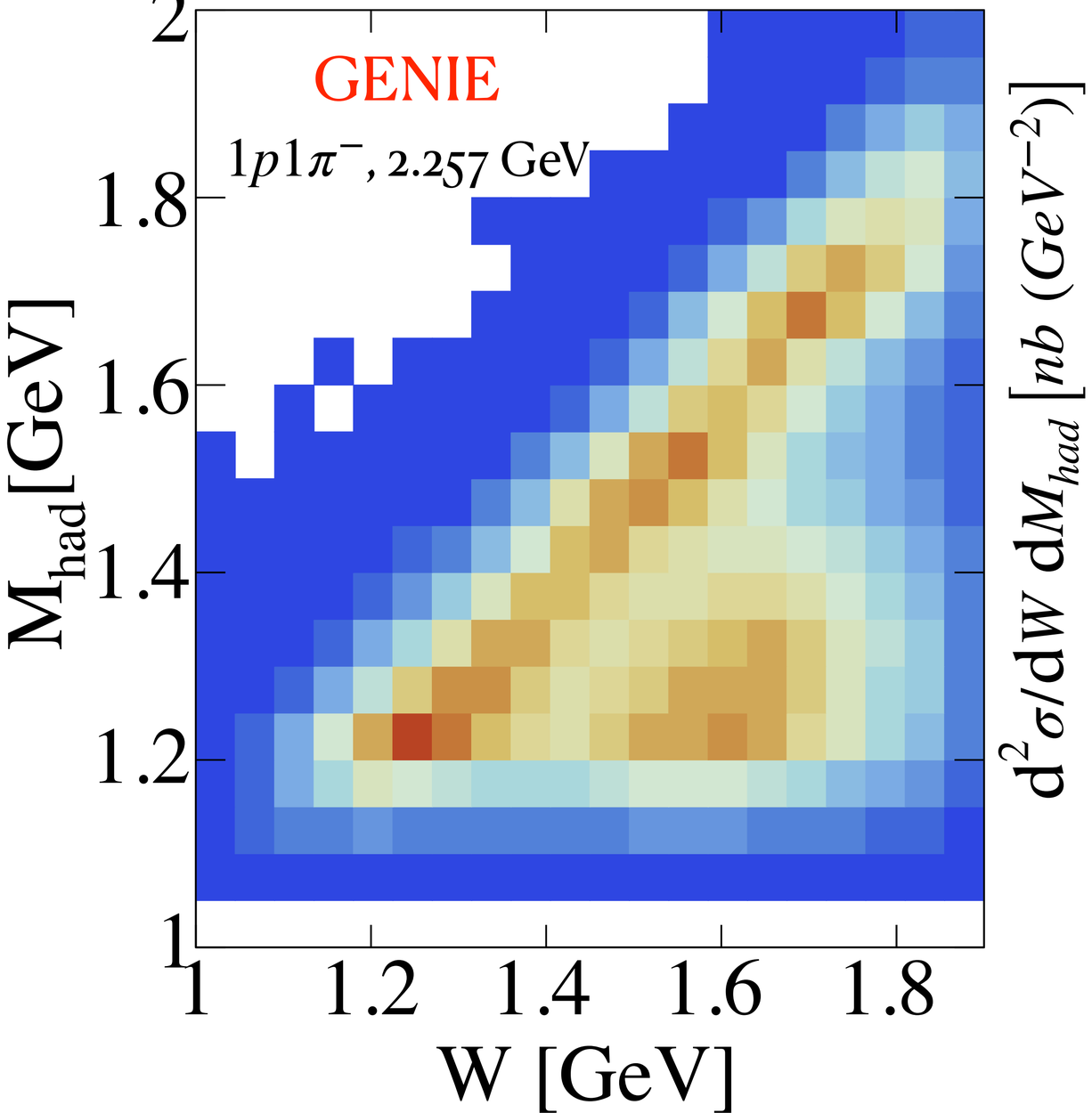

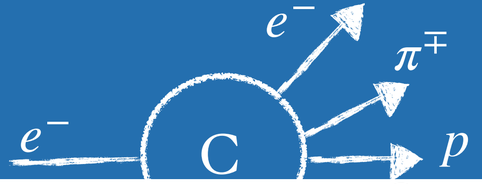

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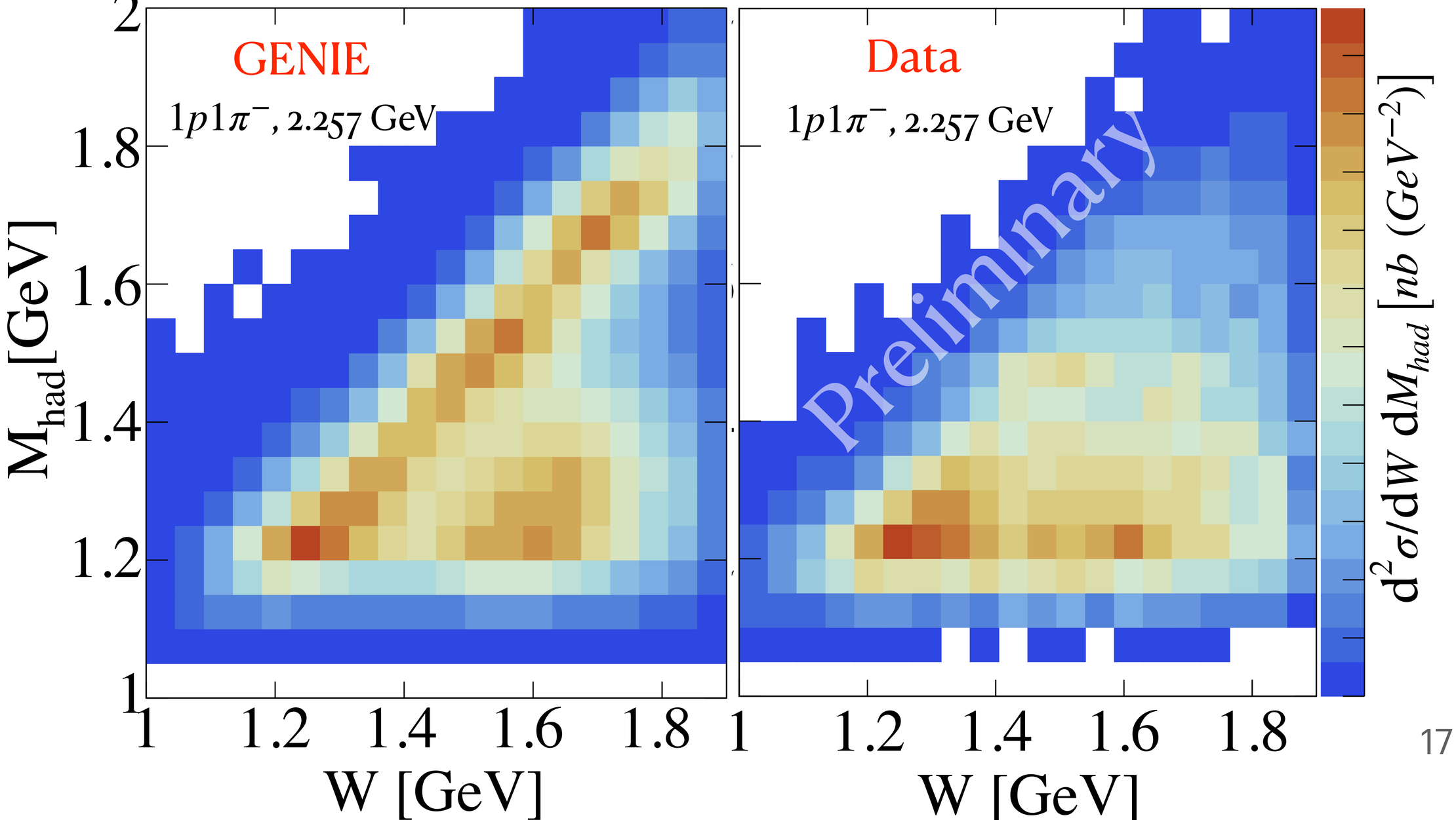

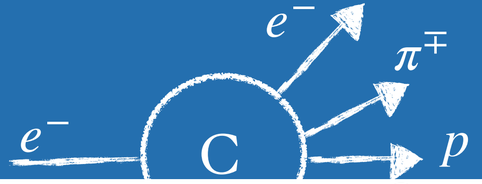

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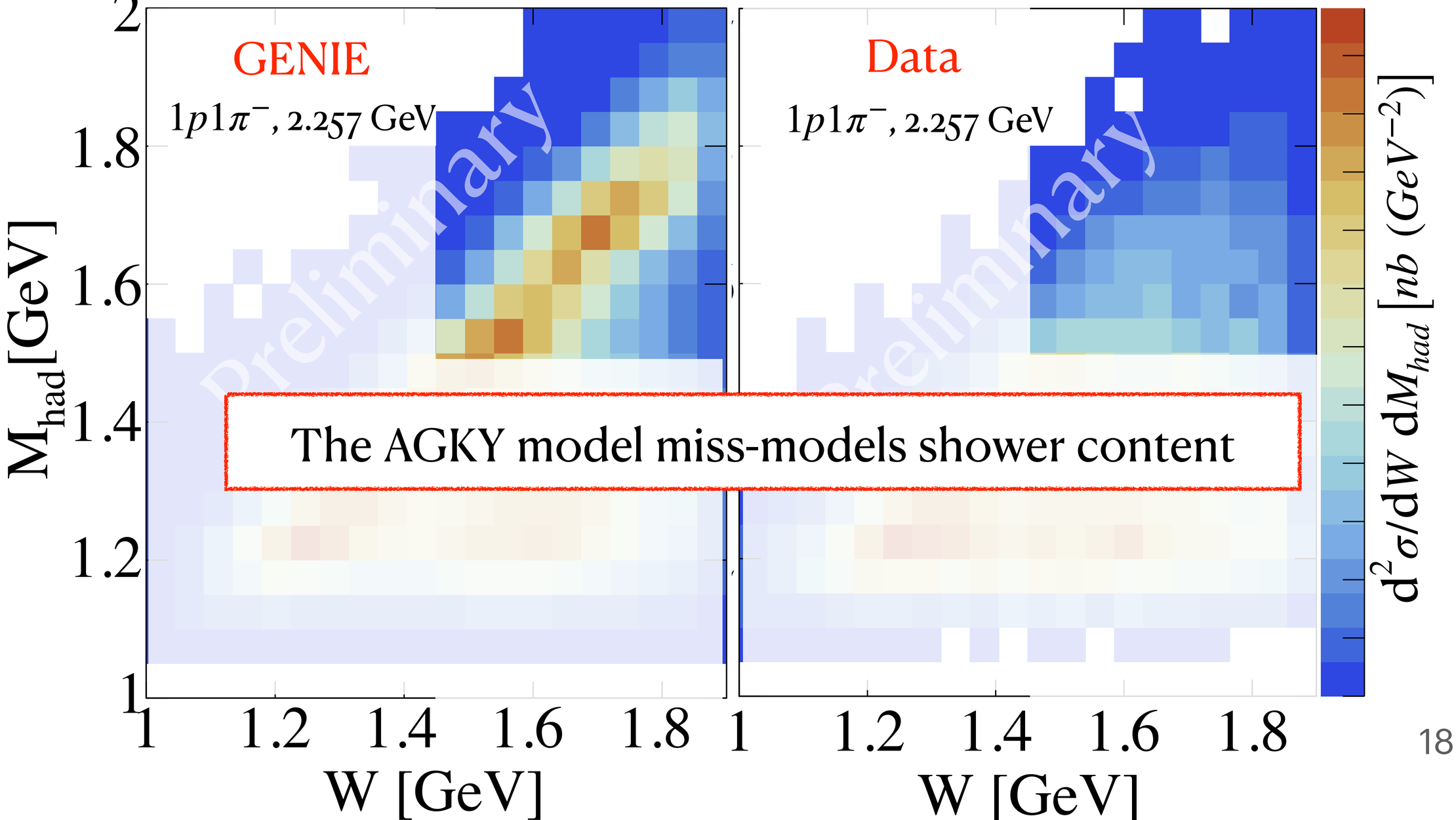
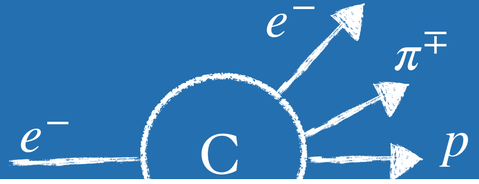
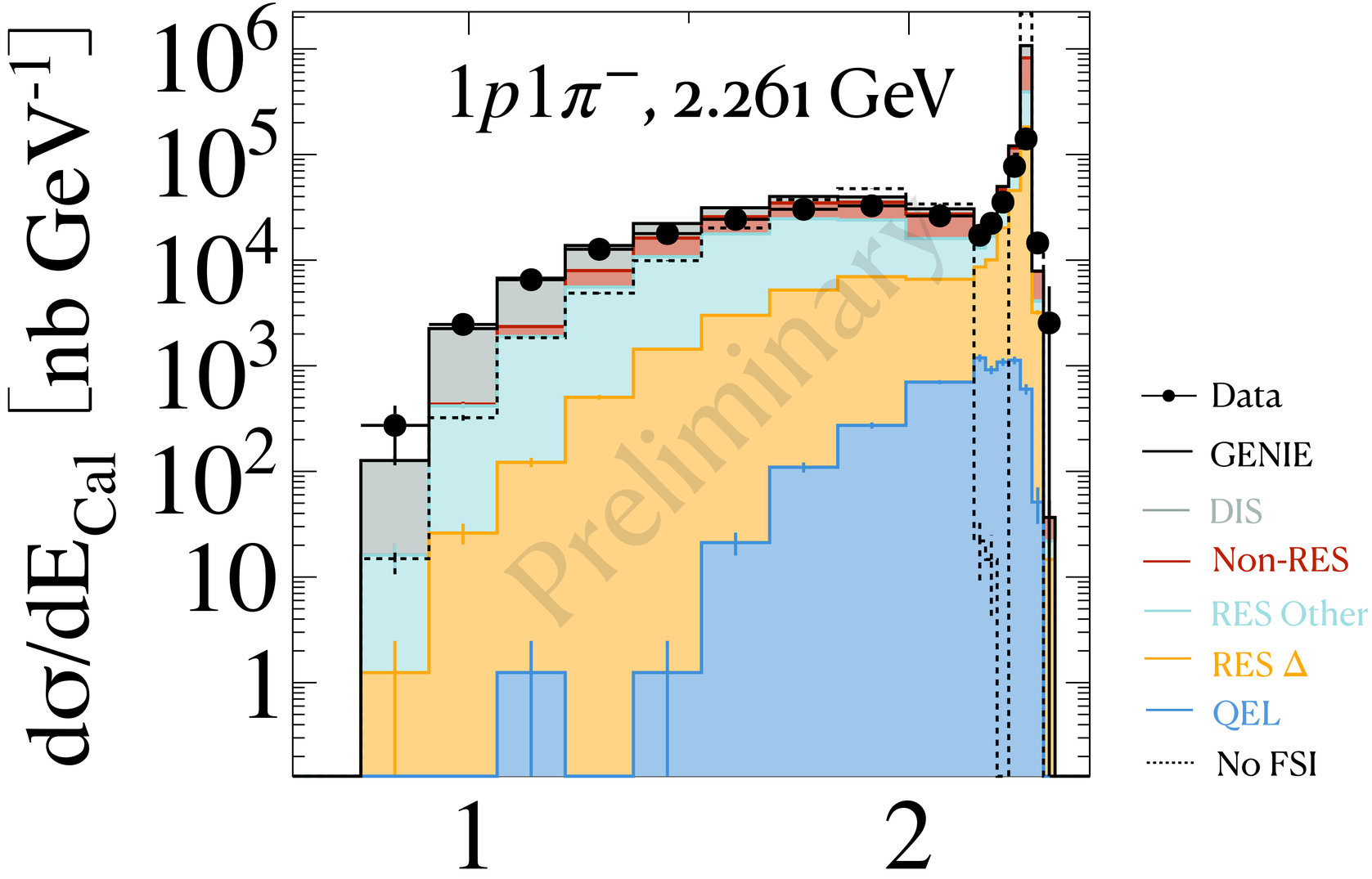


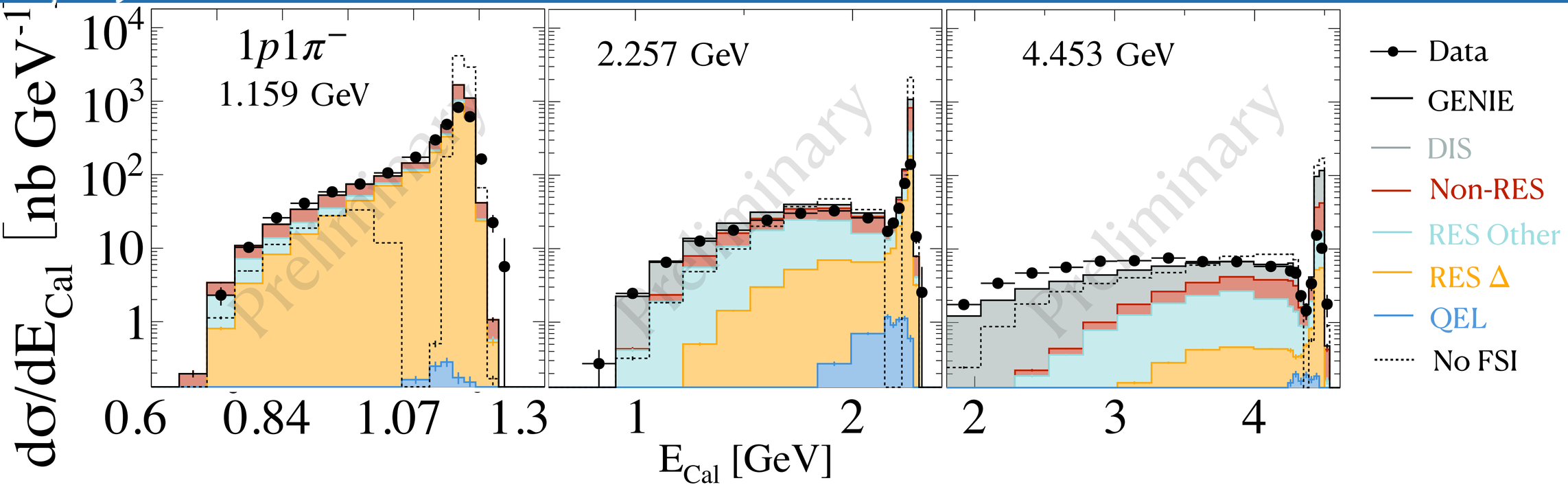


Energy Bias Quantification

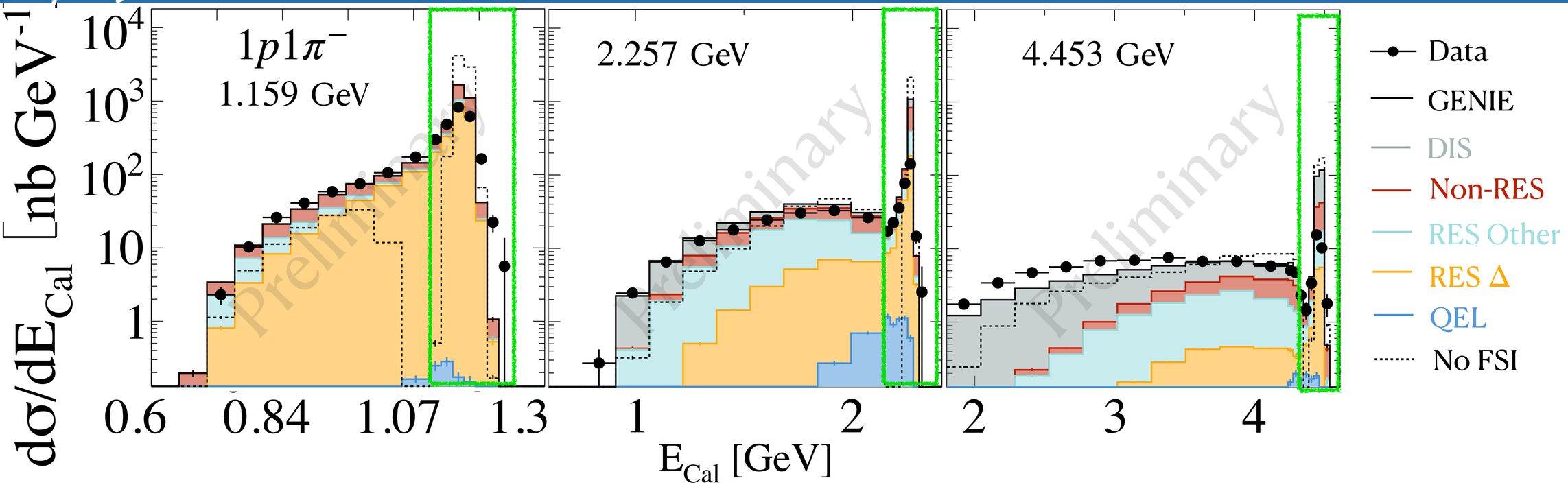


$$(e, e'1p1\pi^-)\, E_{Cal}[\text{GeV}] = E_{e'} + E_\pi + T_p + \epsilon_i$$

Beam energy miss-reconstruction



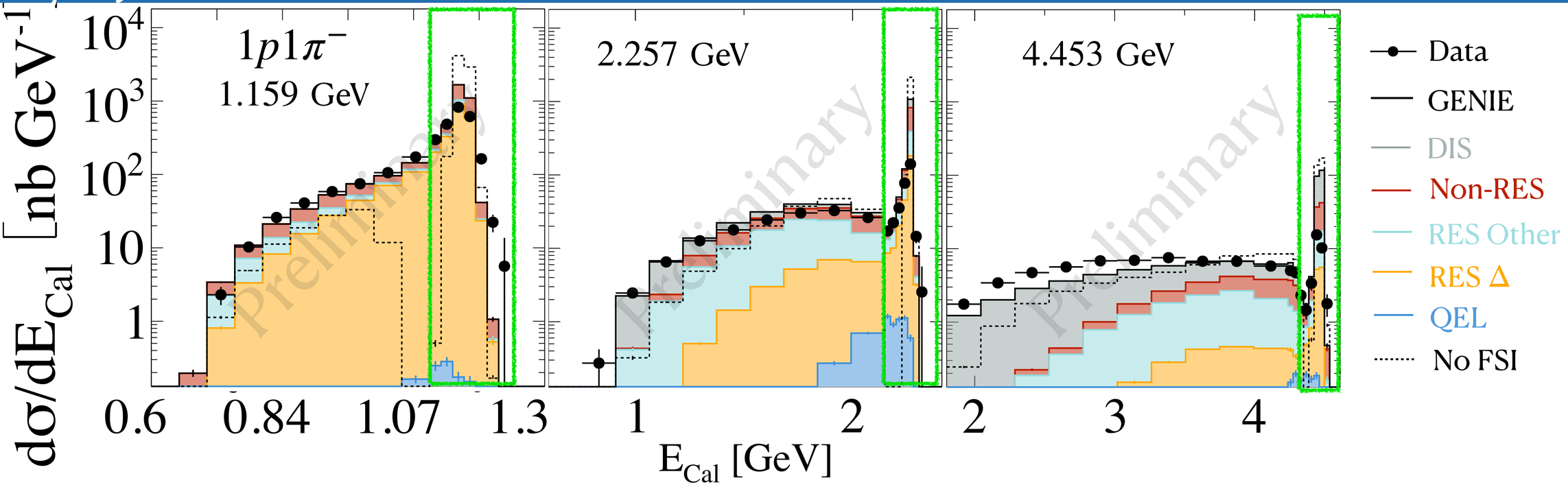
Beam energy miss-reconstruction



% Peak)	1.159	2.257	4.453
Data	67%	22%	8%
GENIE	77%	52%	41%

Only a fraction of events at 5% of real beam energy

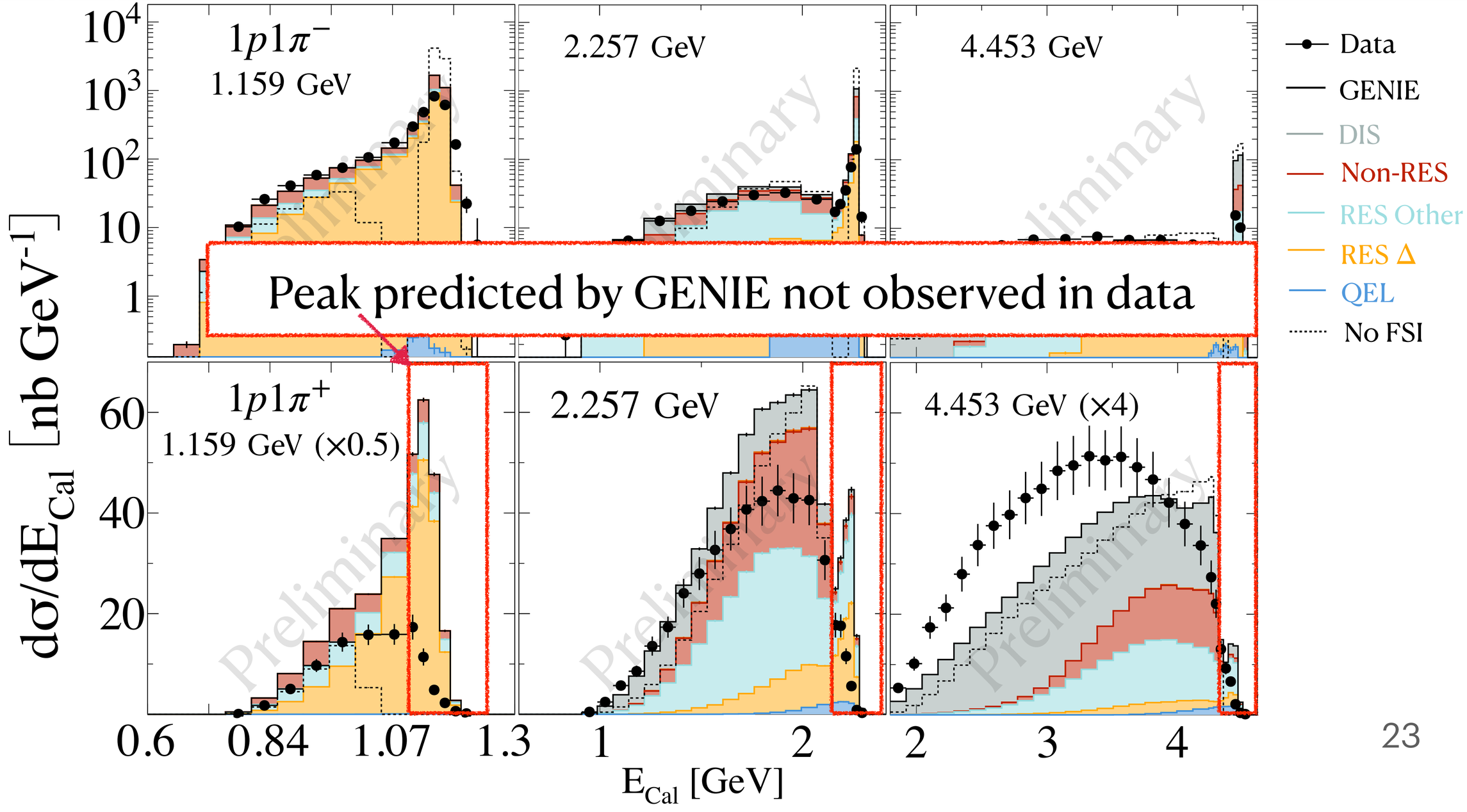
MC does not describe bias

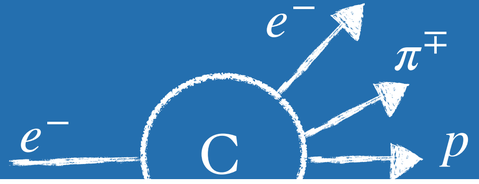


% Peak)	1.159	2.257	4.453
$1p1\pi^-$ **Data**	67%	22%	8%
GENIE	77%	52%	41%

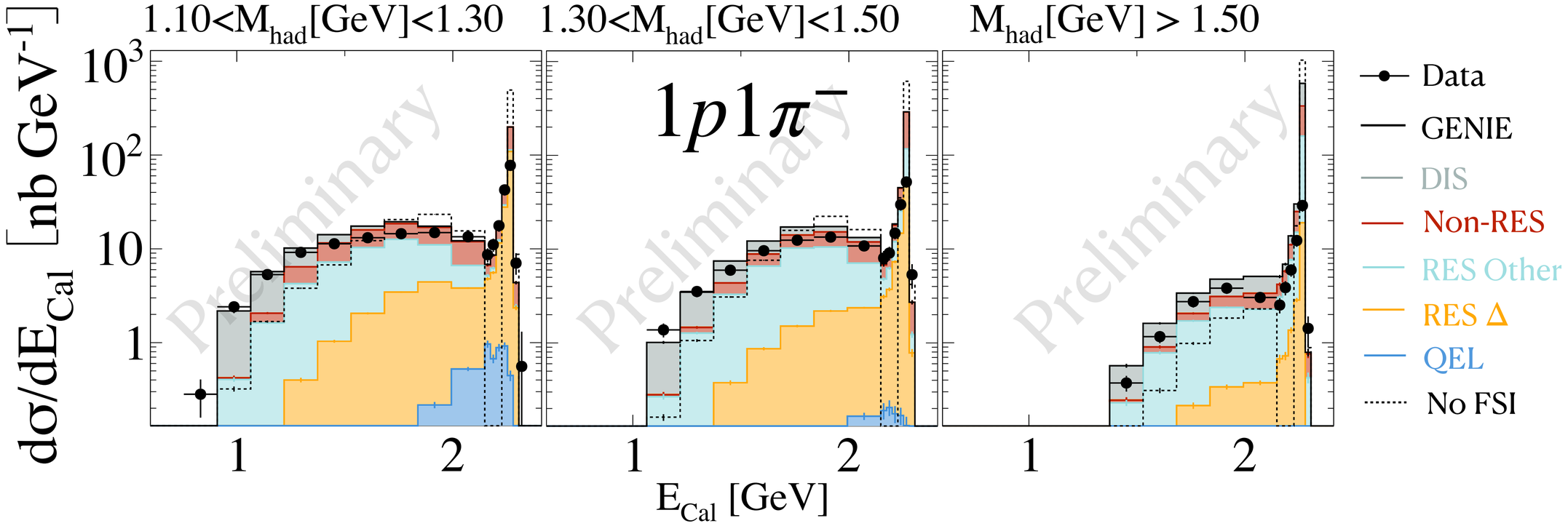
Peak largely over-predicted by GENIE

Beam energy miss-reconstruction

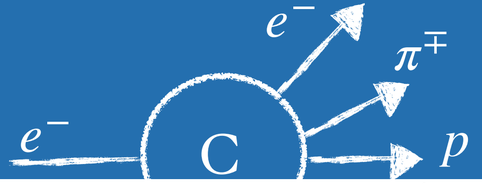




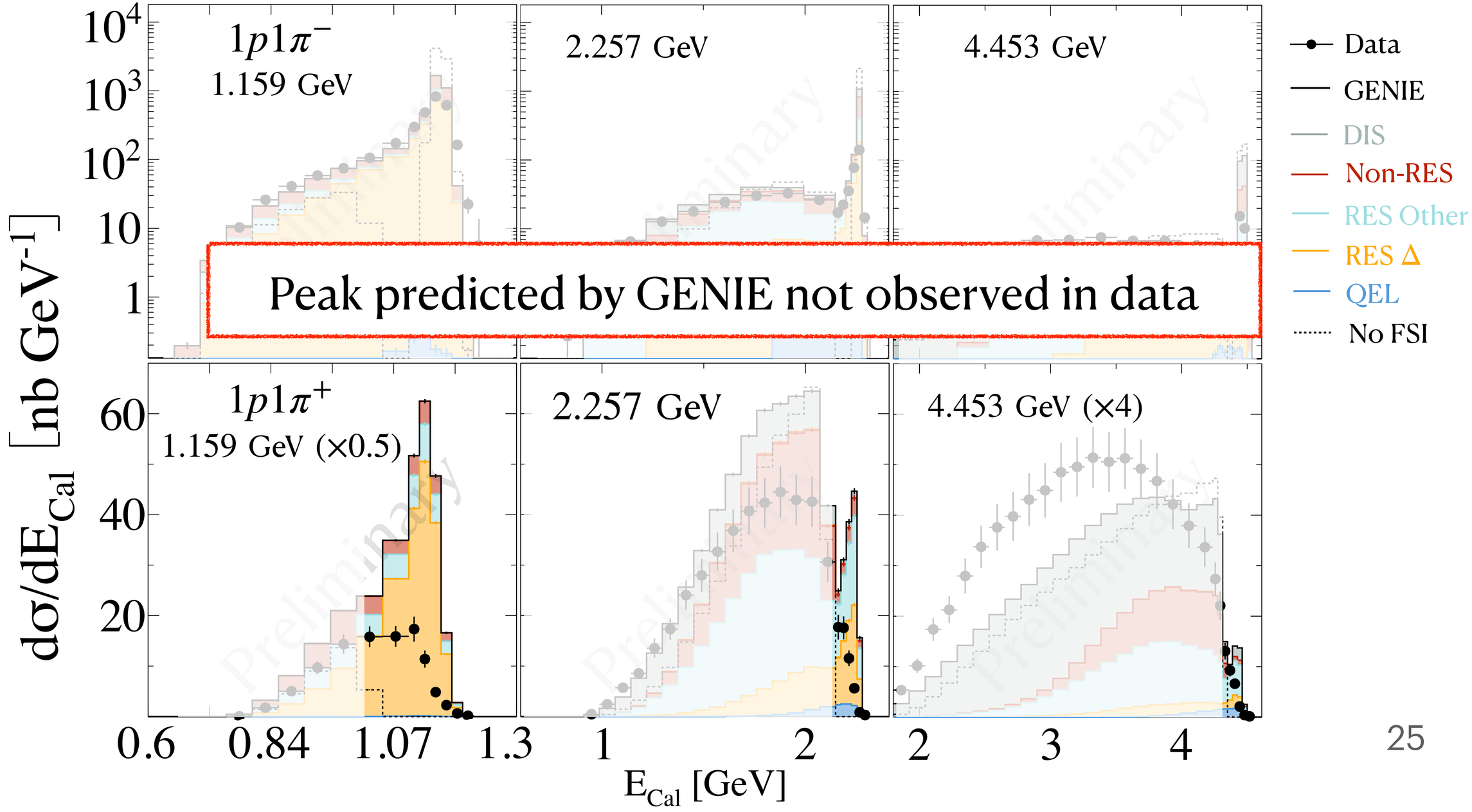
Hadronization biases E_{Cal}



% Peak)	Total	$M_{had} \subset [1.10,1.30]$ GeV	$M_{had} \subset [1.30,1.50]$ GeV	$M_{had} > 1.50$ GeV
$1p1\pi^-$ **Data**	22%	**22%**	22%	40%
GENIE	52%	**31%**	45%	85%



Larger bias for $1p1\pi^+$

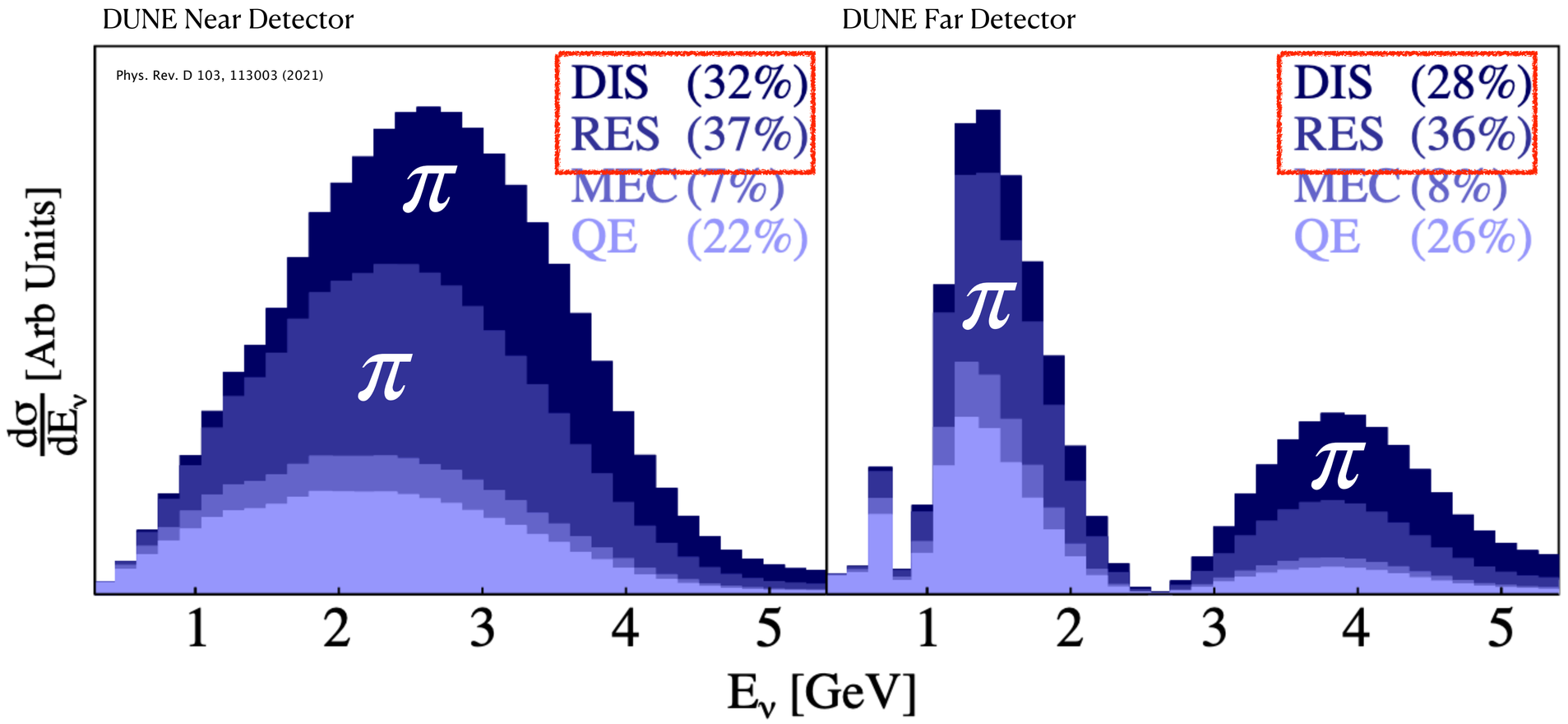


Take aways

- e-data is key to **reduce large cross-section systematics** in oscillation experiments
- First $^{12}C(e, e'1p1\pi^{\mp})$ analysis sets **new constraints for event generators**
  - Less than 30% of events reconstructed within 5% true energy at 2 & 4 GeV
  - GENIE does not describe bias, quality of reconstruction varies across beam energies
  - Incorrect shower content due to simplistic hadronization model biases W and E_{Cal}
  - GENIE bias reduced for $M_{had} < 1.30$ GeV
- Analysis note under review, working on a new publication

Thank you for your attention!

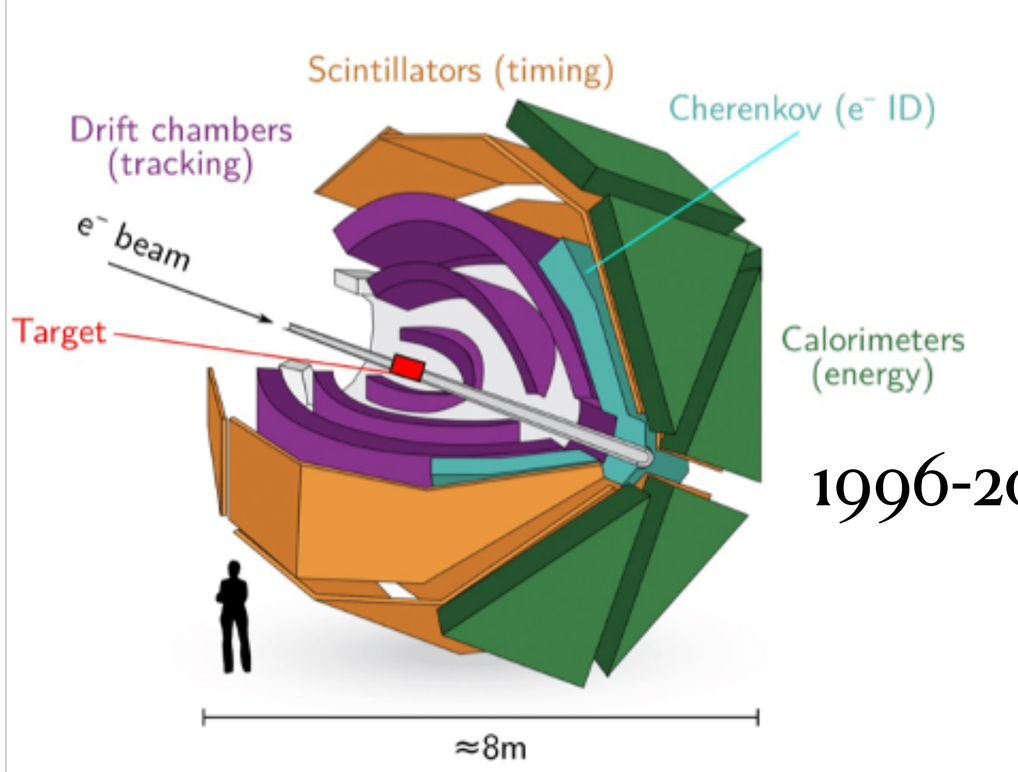
Pion-Production is key for DUNE



Main contribution from pion production events!

Hadron production with CLAS

- Multi-purpose experiments, **large acceptance**
- Targets (H, D, C, Ar, etc) and energies (1-6 GeV) of interest for neutrino community
- Low-detection threshold comparable to neutrino experiments
  - 150 (300) MeV/c for $\pi^{\pm}$ (γ)



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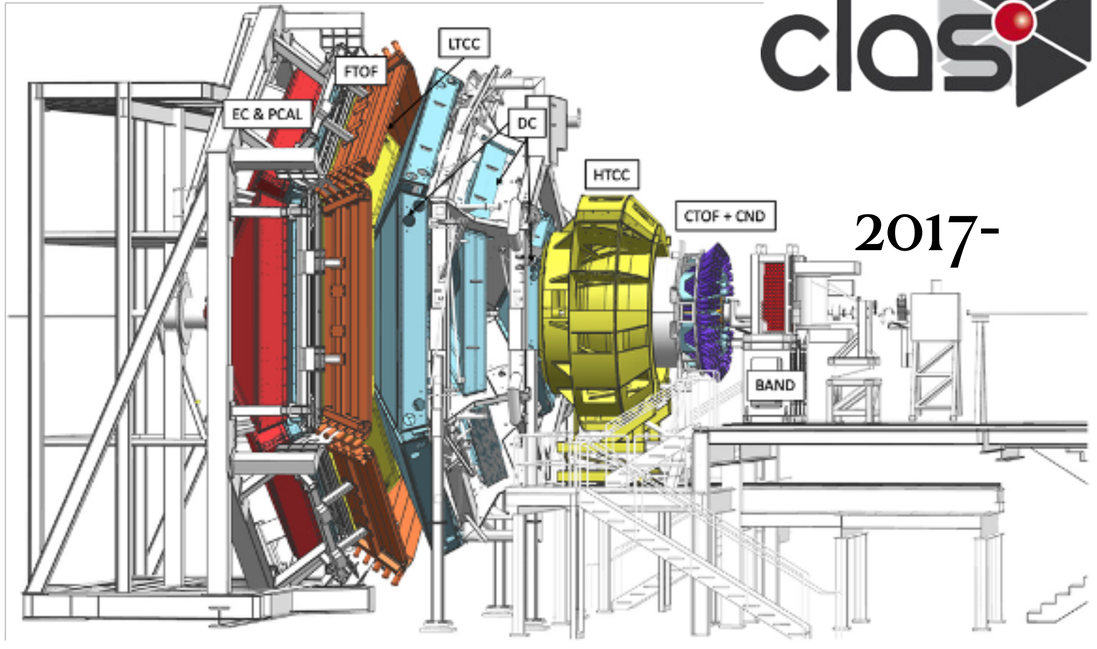


2017-

The GENIE Event Generator

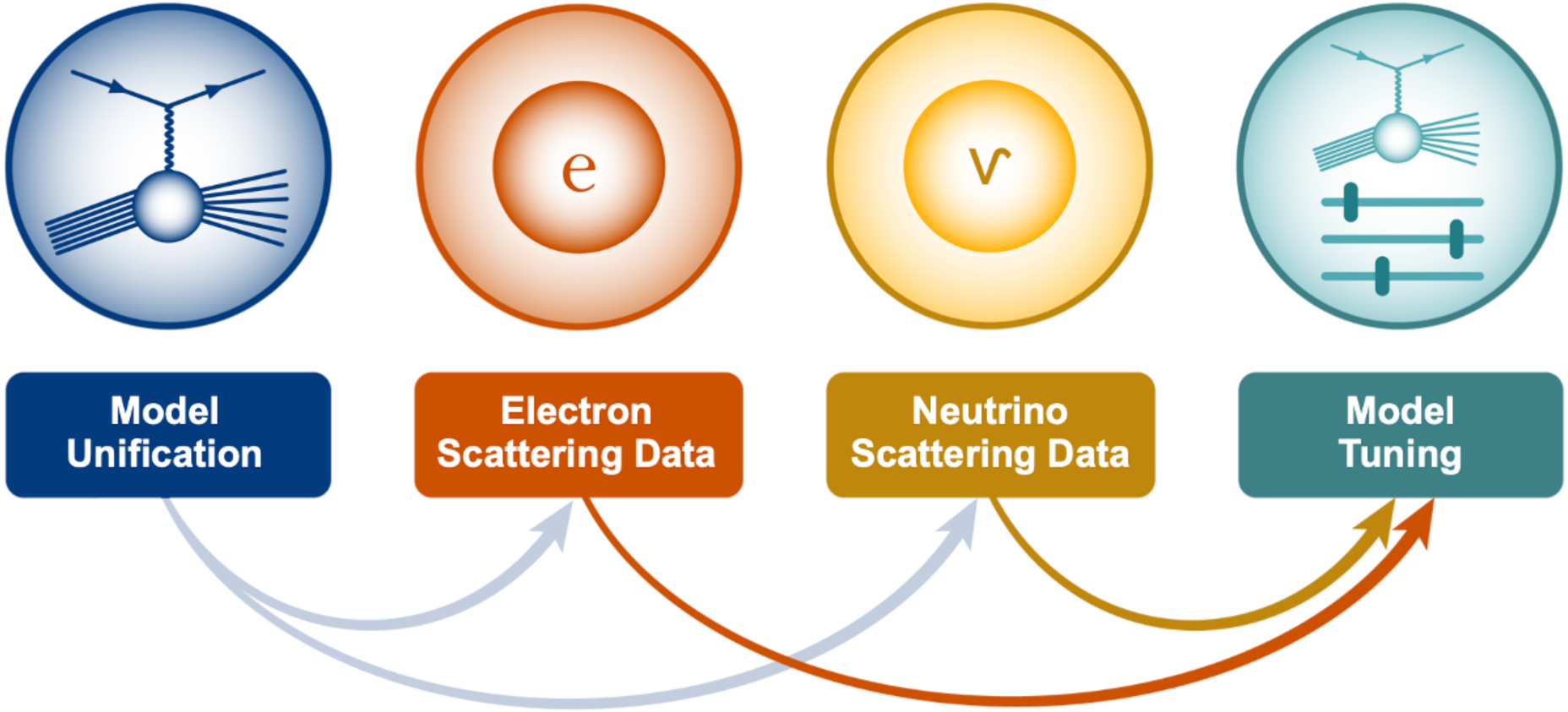
https://genie-mc.github.io/

Tune name in GENIE: GEM21_11a_00_000

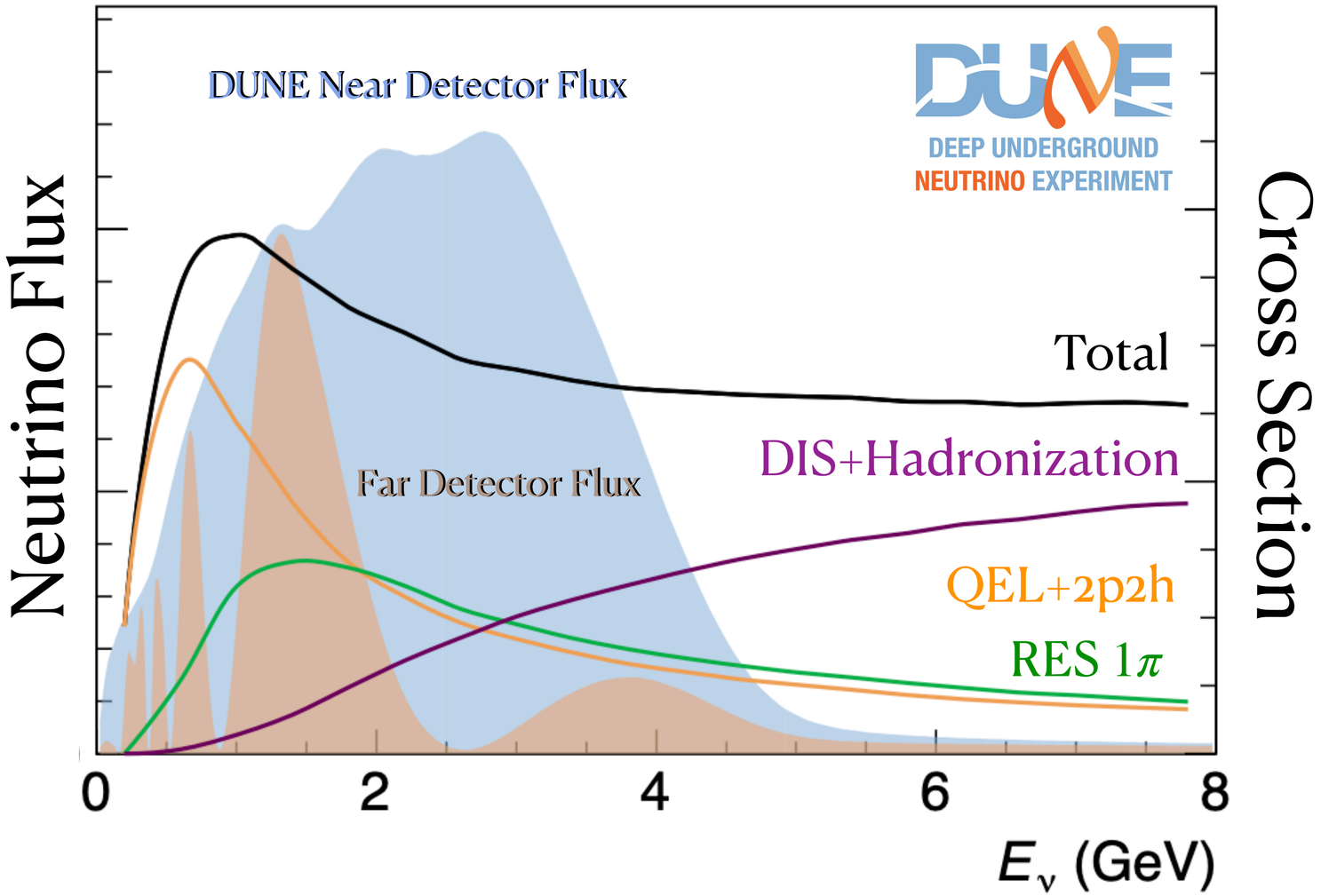
Process	Model
Quasi-ELastic and Two-Particle Two-	SUSAv2 model
RESonance Production	Berger-Sehgal model
Non-RESonance (SIS)	Bodek-Yang model, scaled with multiplicity dependent parameters
Deep Inelastic Scattering	Bodek-Yang model
Final State Interaction model	hA model
Hadronization model	AGKY model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

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

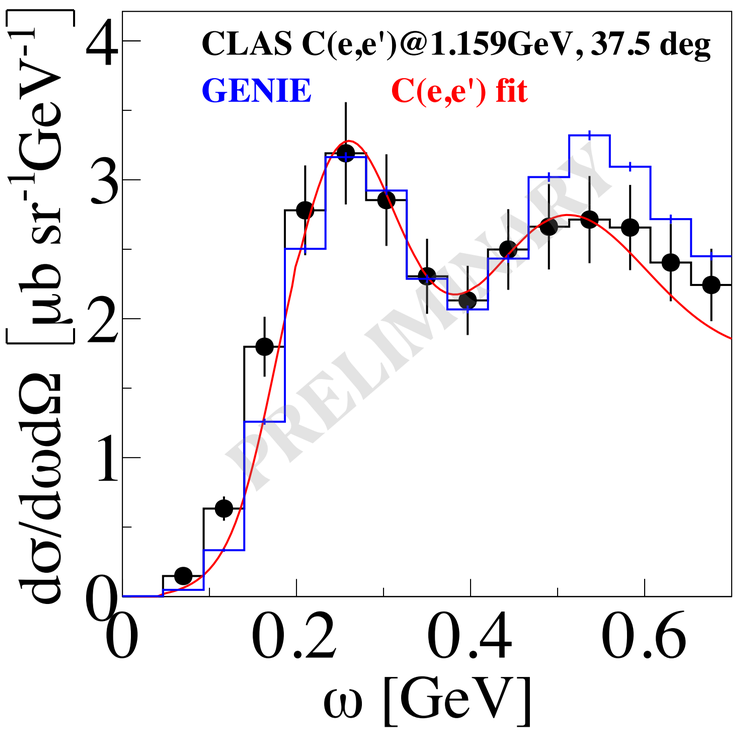
Roadmap for improving event generators

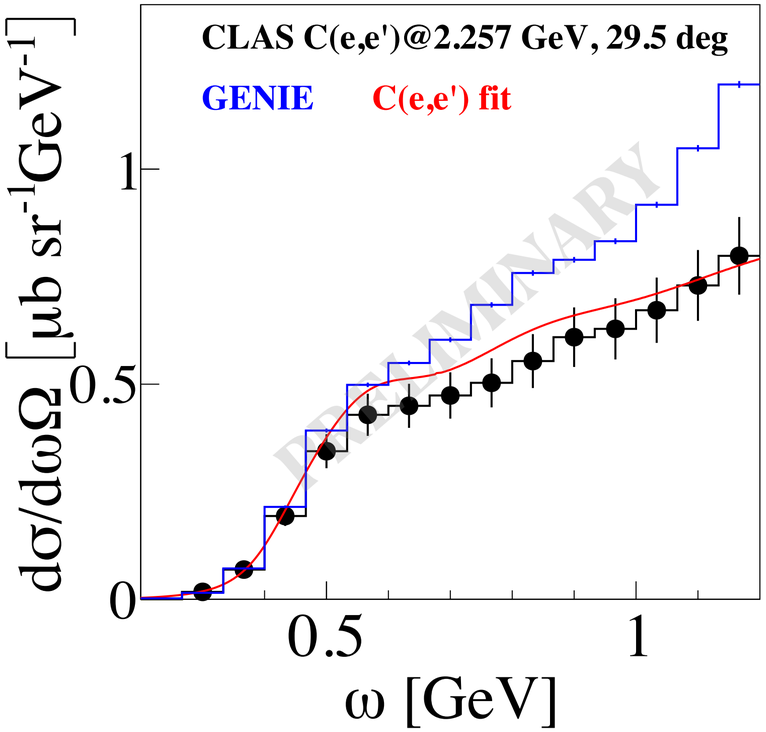


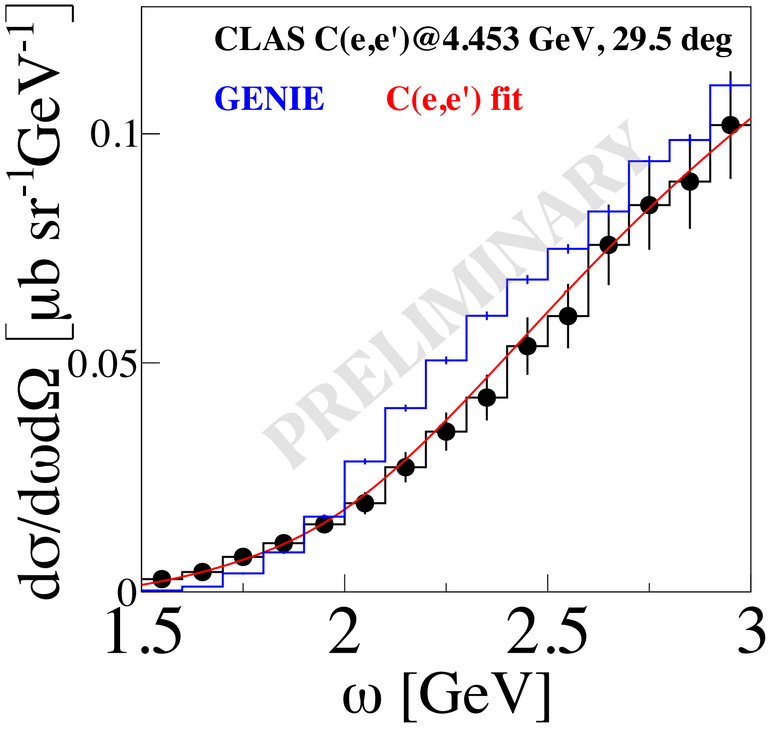
Pion-Production is key for Oscillations

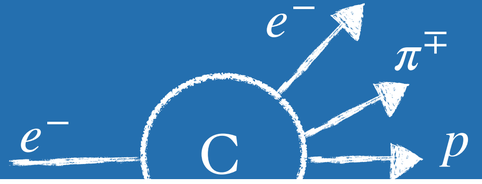


Validation with the world's fit to (e,e') data



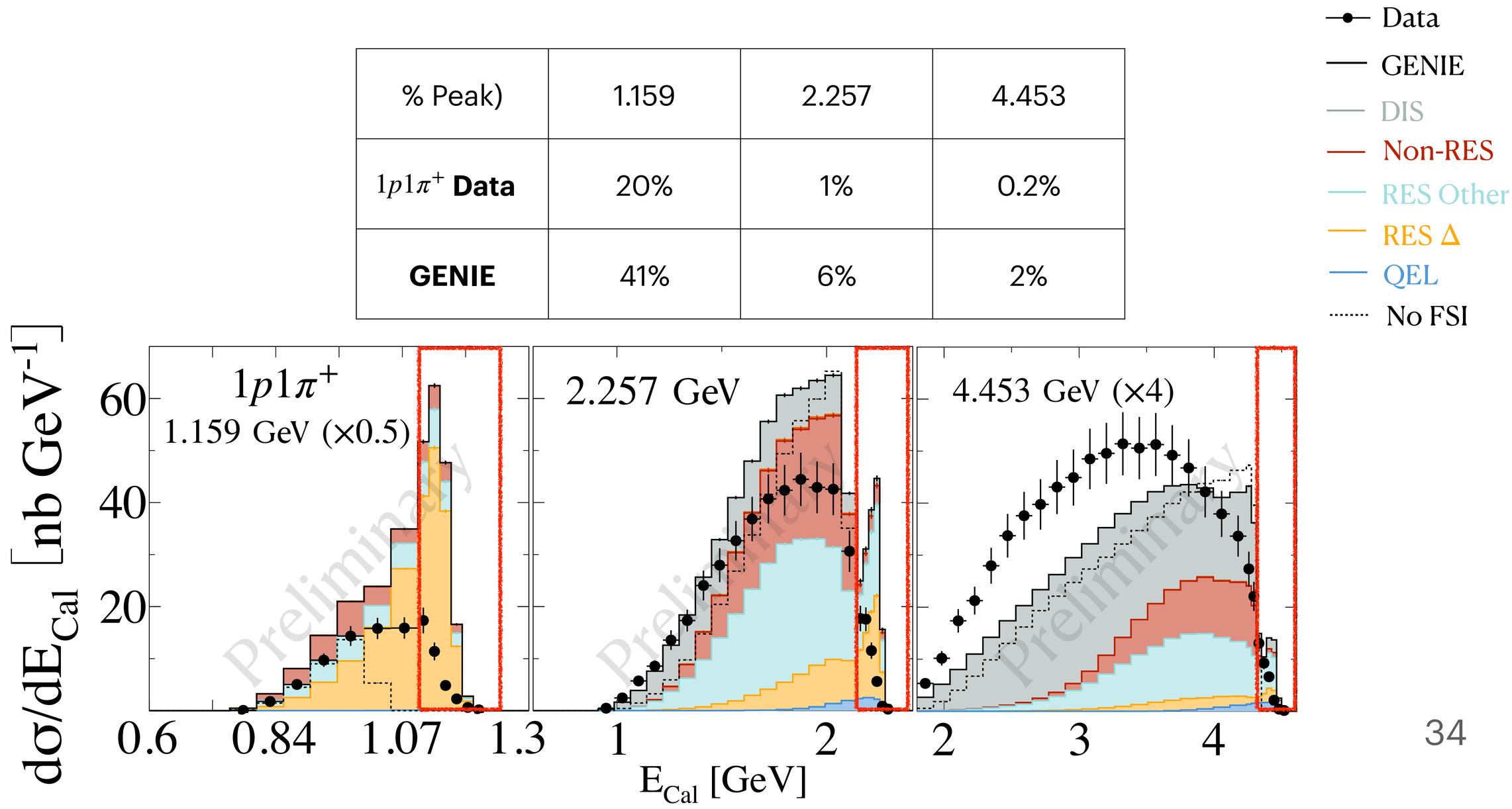


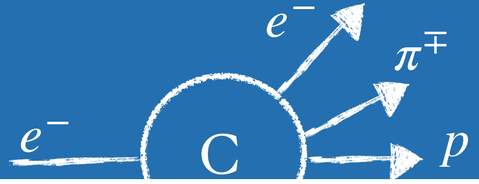




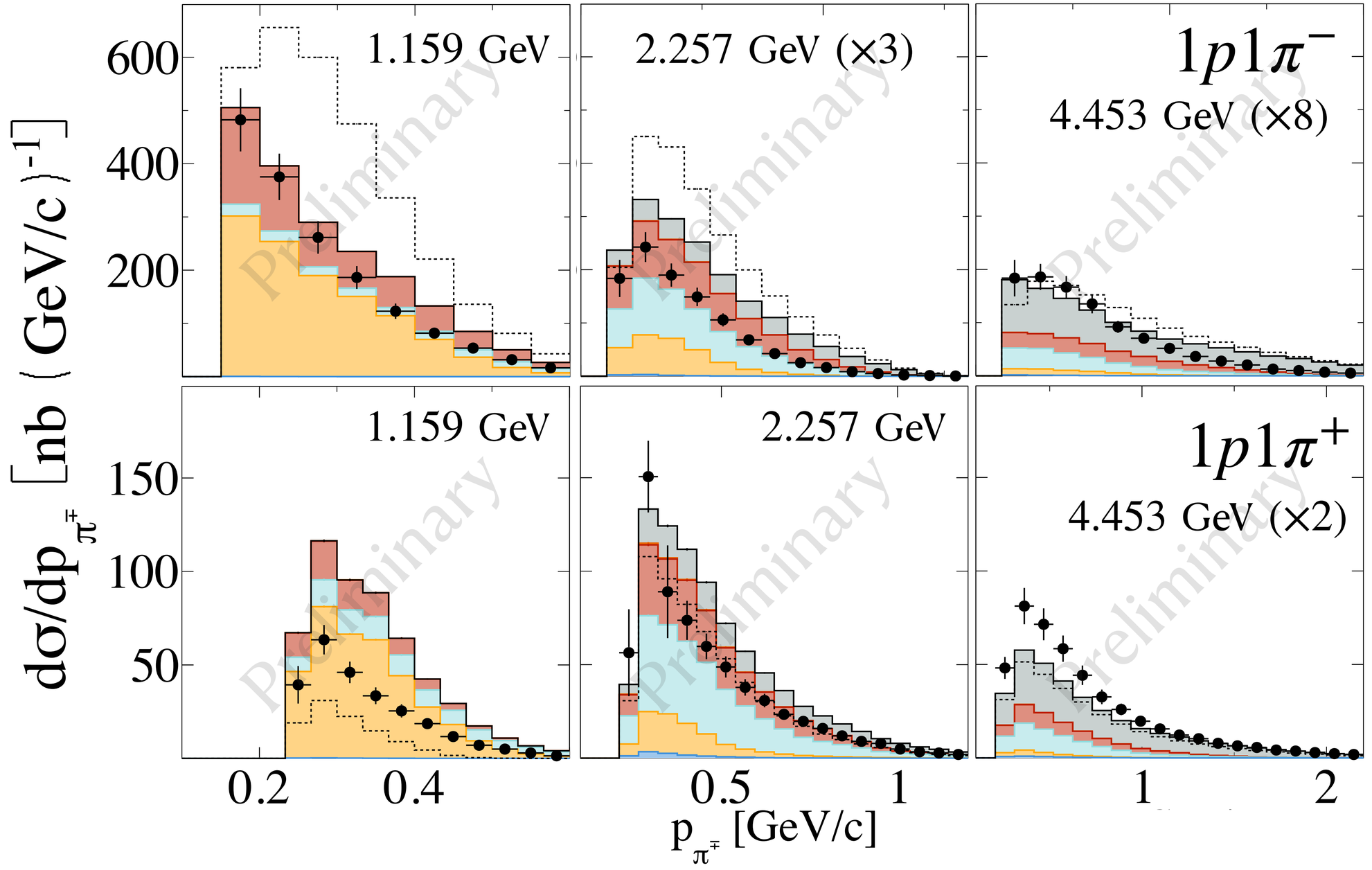
MC induces bias

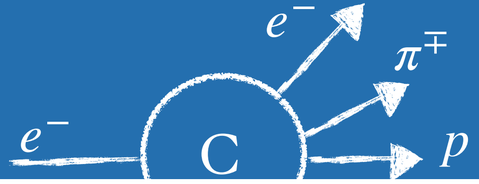
% Peak)	1.159	2.257	4.453
$1p1\pi^+$ **Data**	20%	1%	0.2%
GENIE	41%	6%	2%



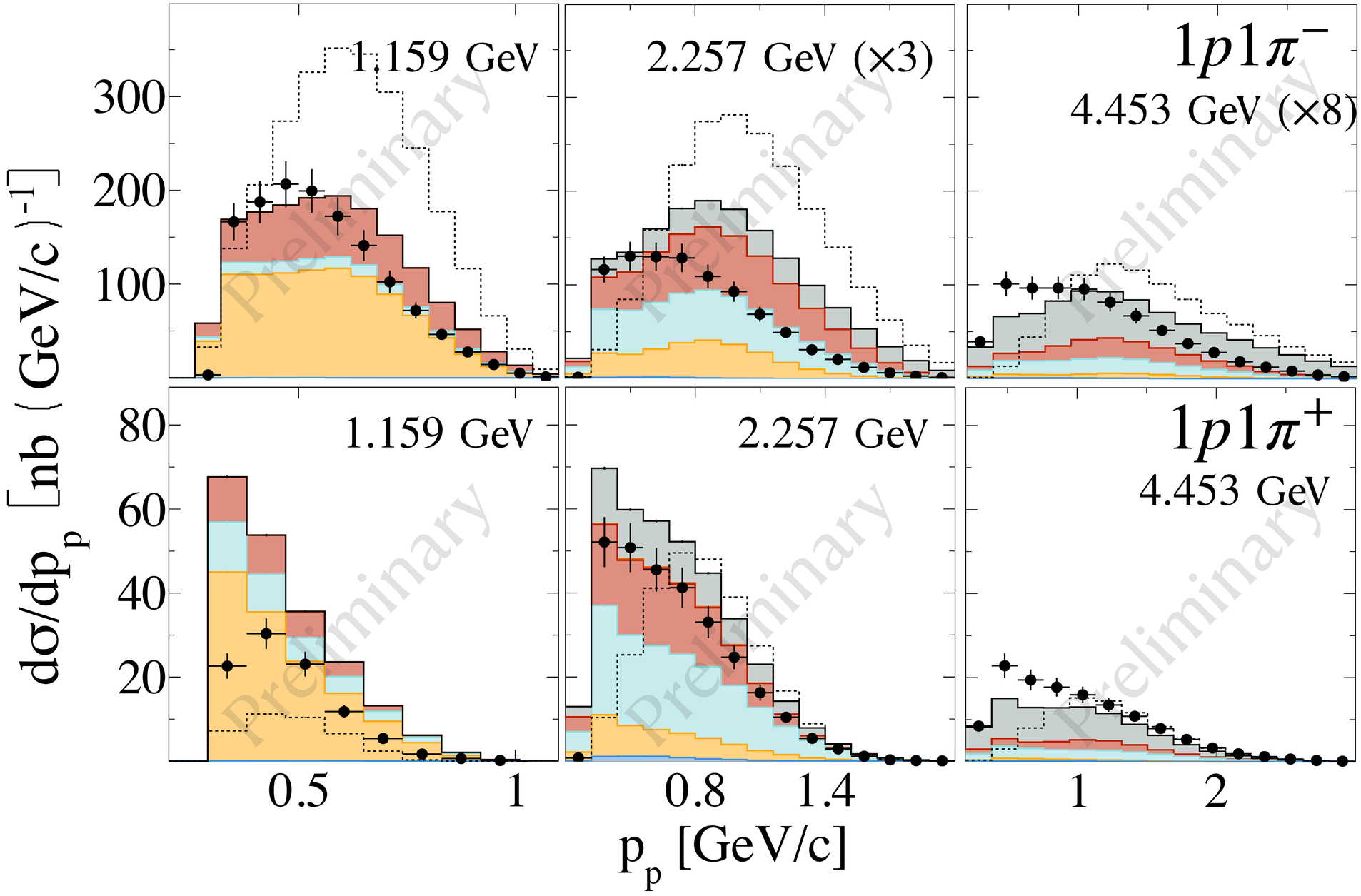


Pion Kinematic Constraints

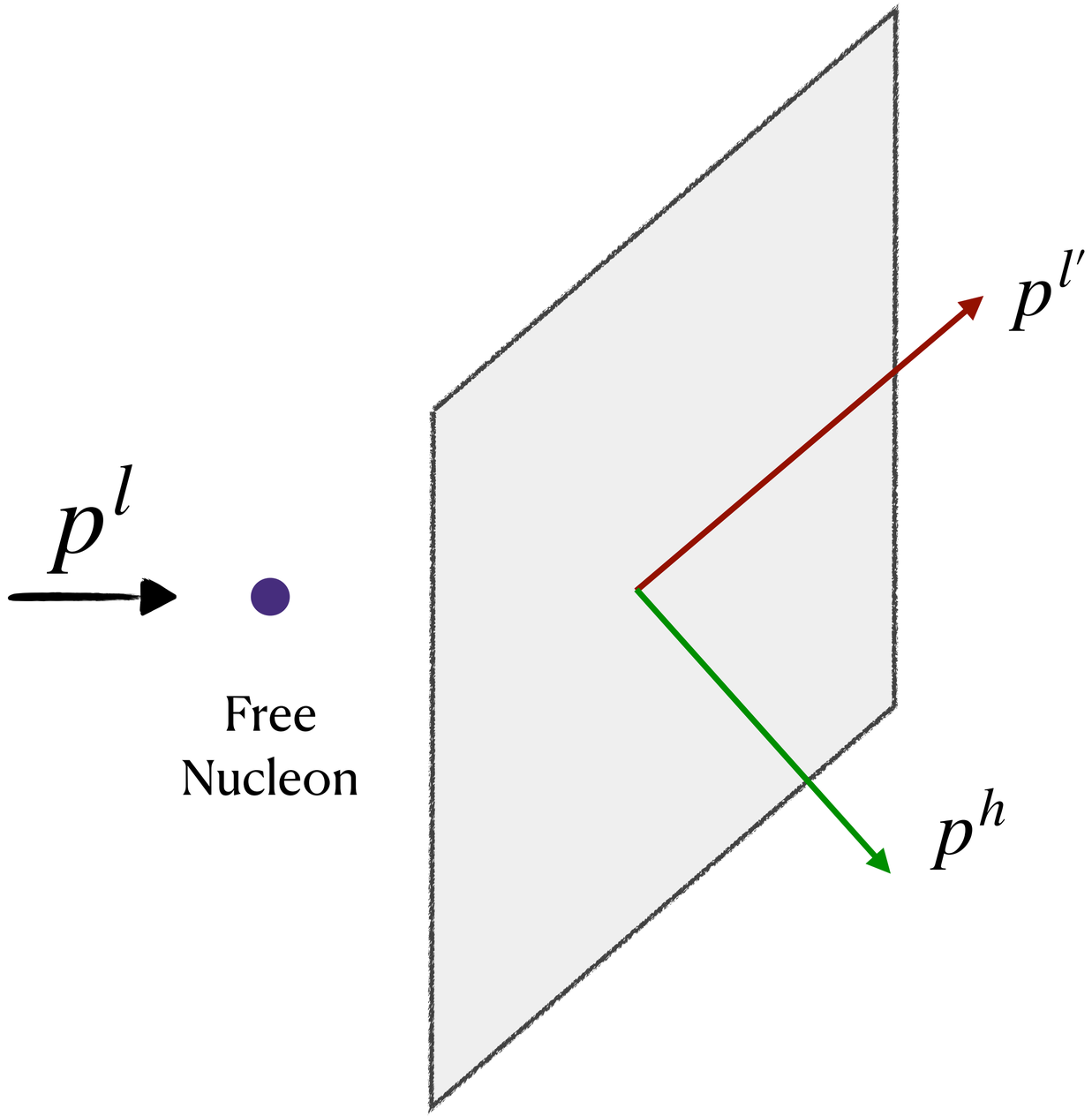




Proton Kinematic Constraints

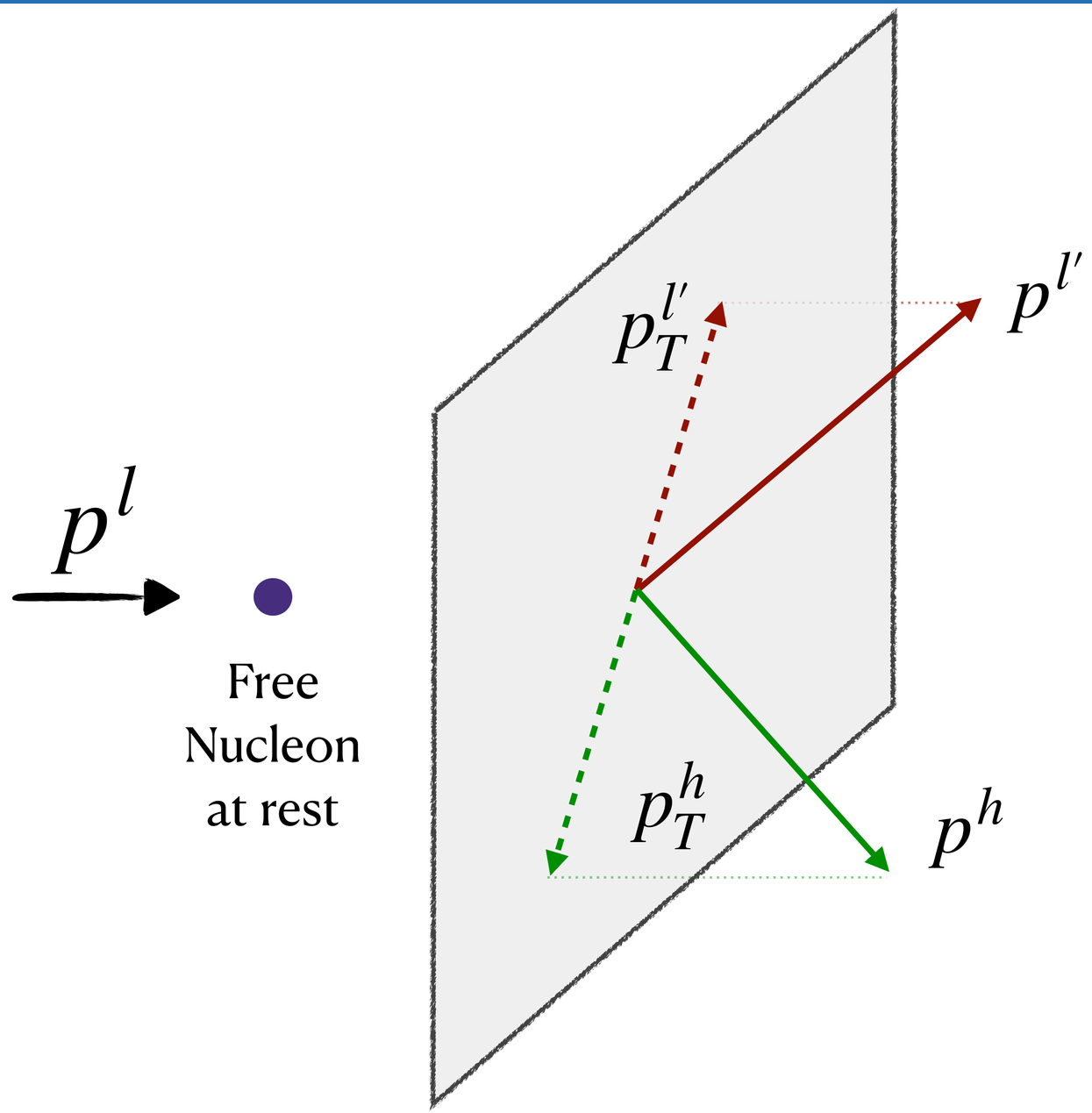


Transverse Kinematic Imbalance (TKI)



$$\vec{p}_h = \vec{p}_p + \vec{p}_\pi$$

Missing Transverse Momentum

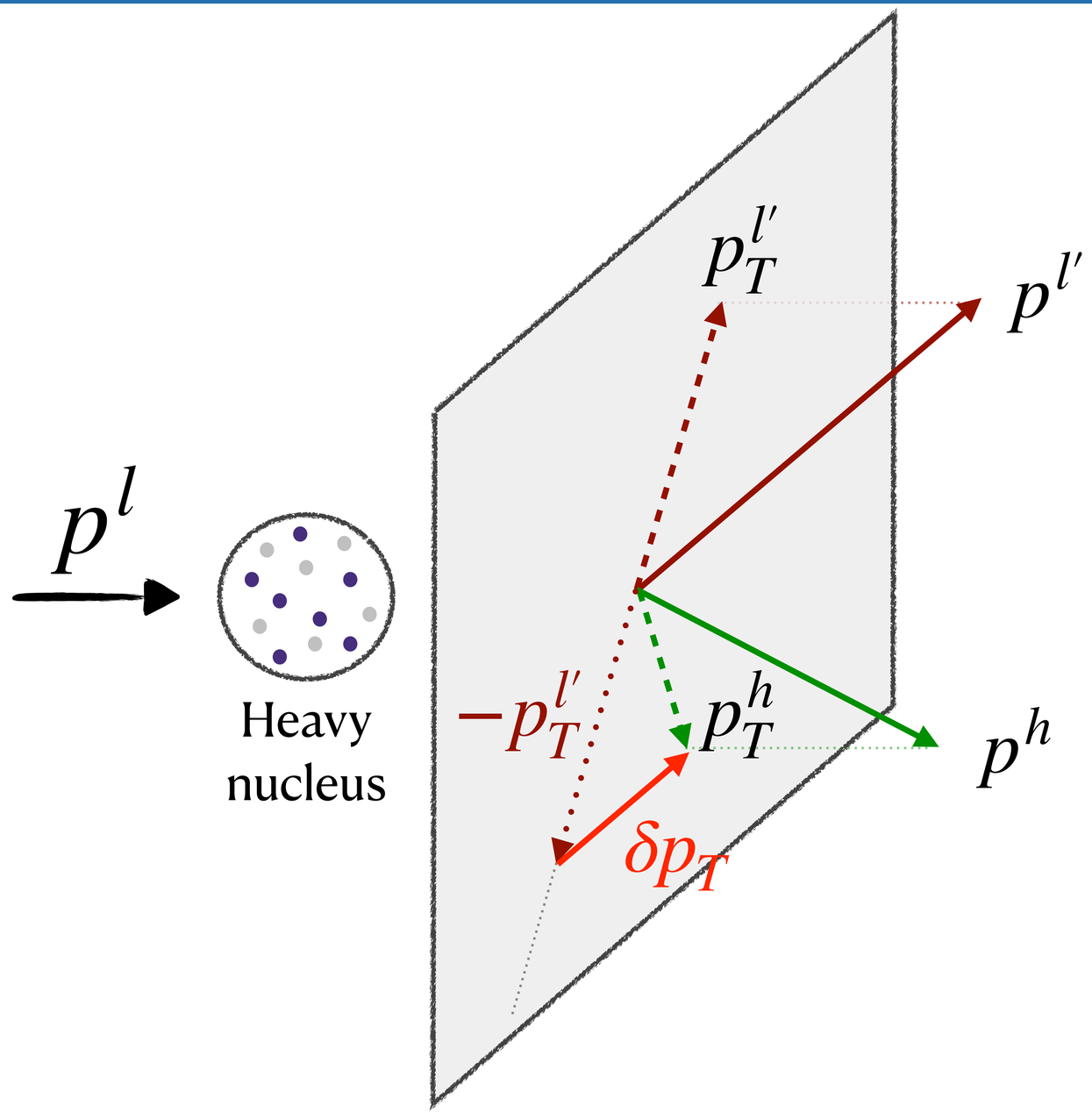


$$\delta\vec{p}_T = \vec{p}_T^{\,l'} + \vec{p}_T^{\,h}$$

$$\delta p_T = 0$$

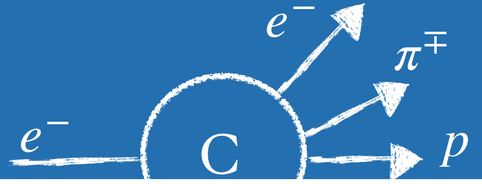
Beam energy independent

Missing Transverse Momentum

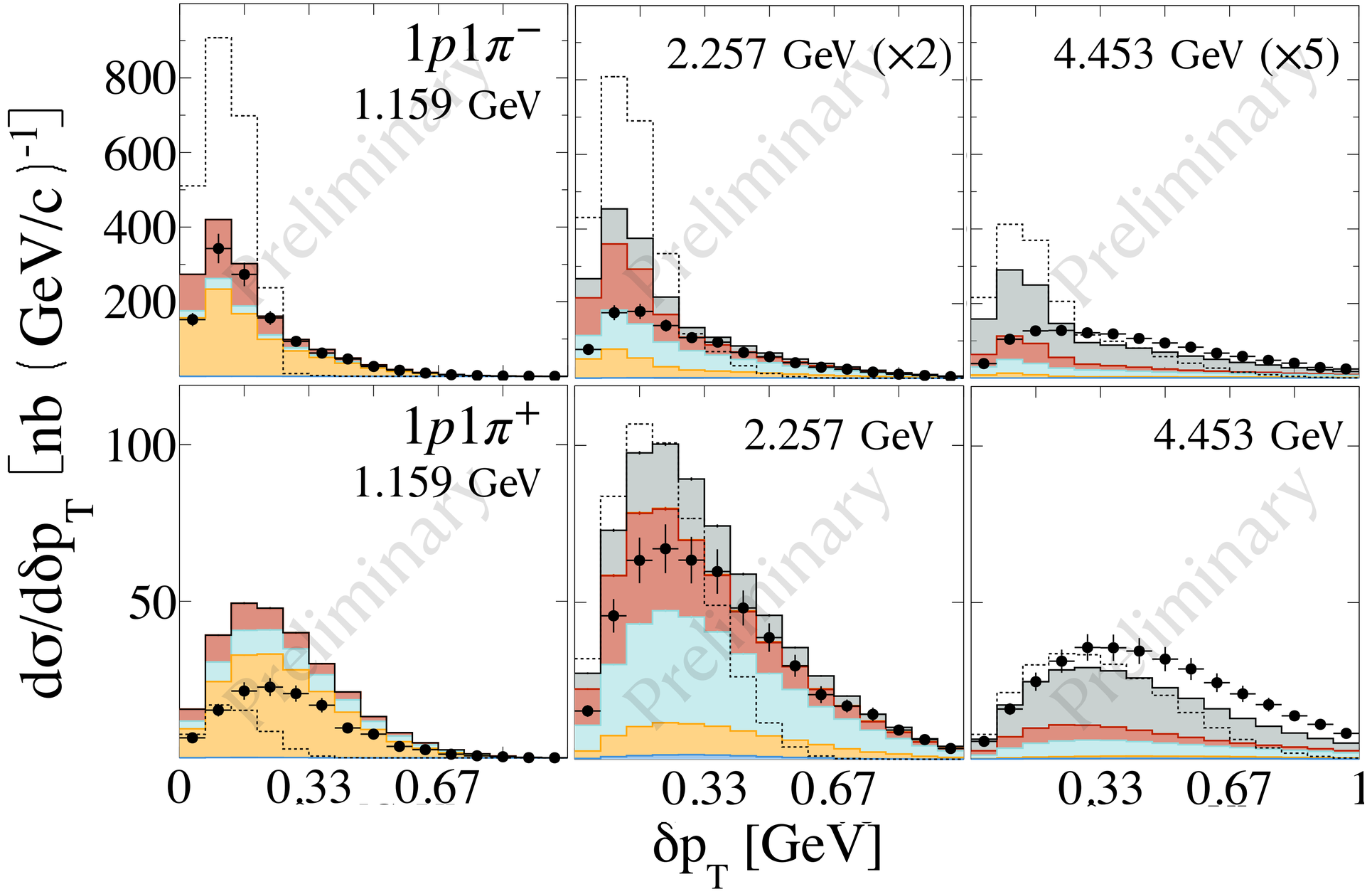


$$\delta p_T \neq 0$$

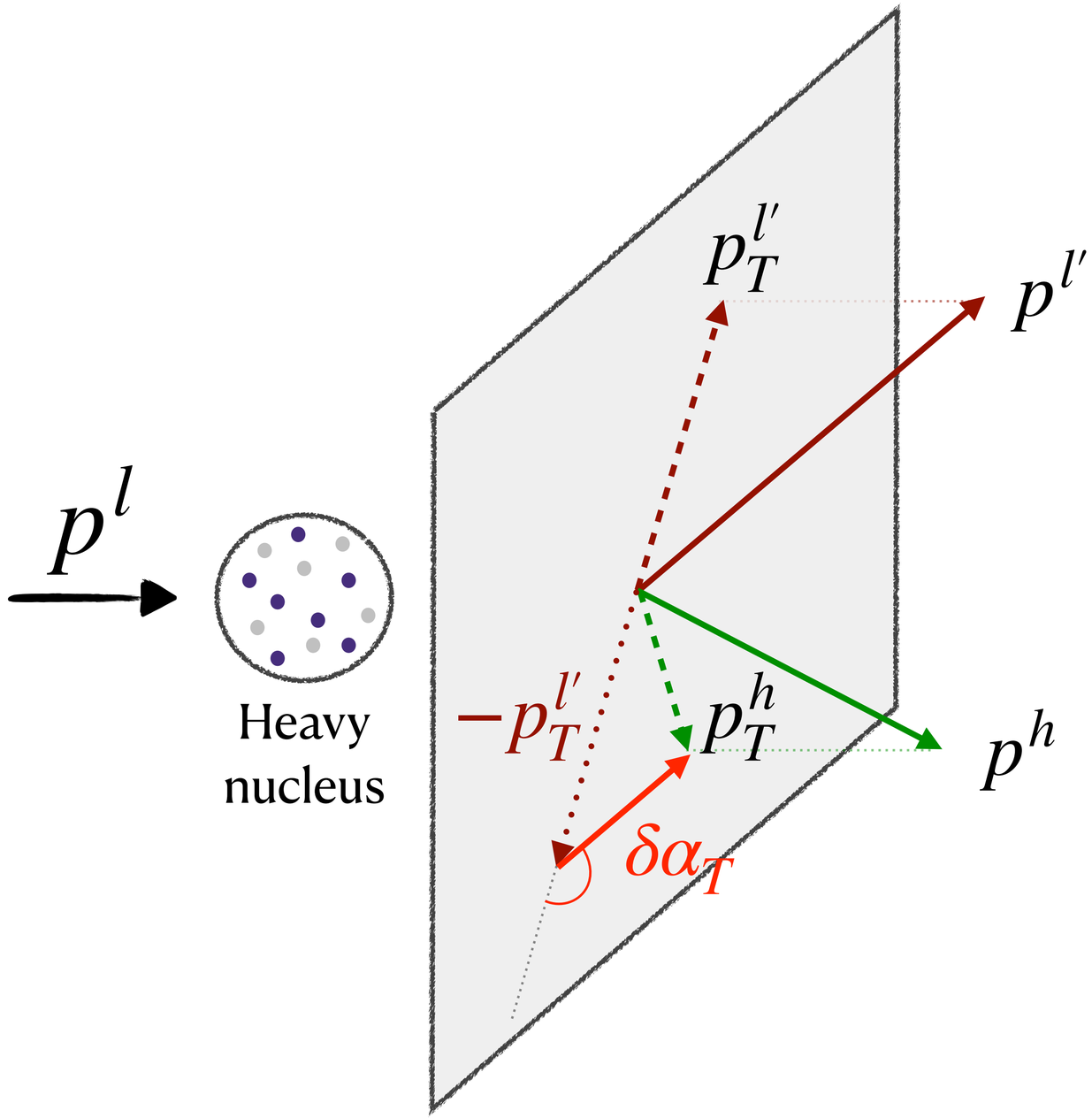
Sensitive to FSI and Nuclear dynamics



Missing Transverse Momentum



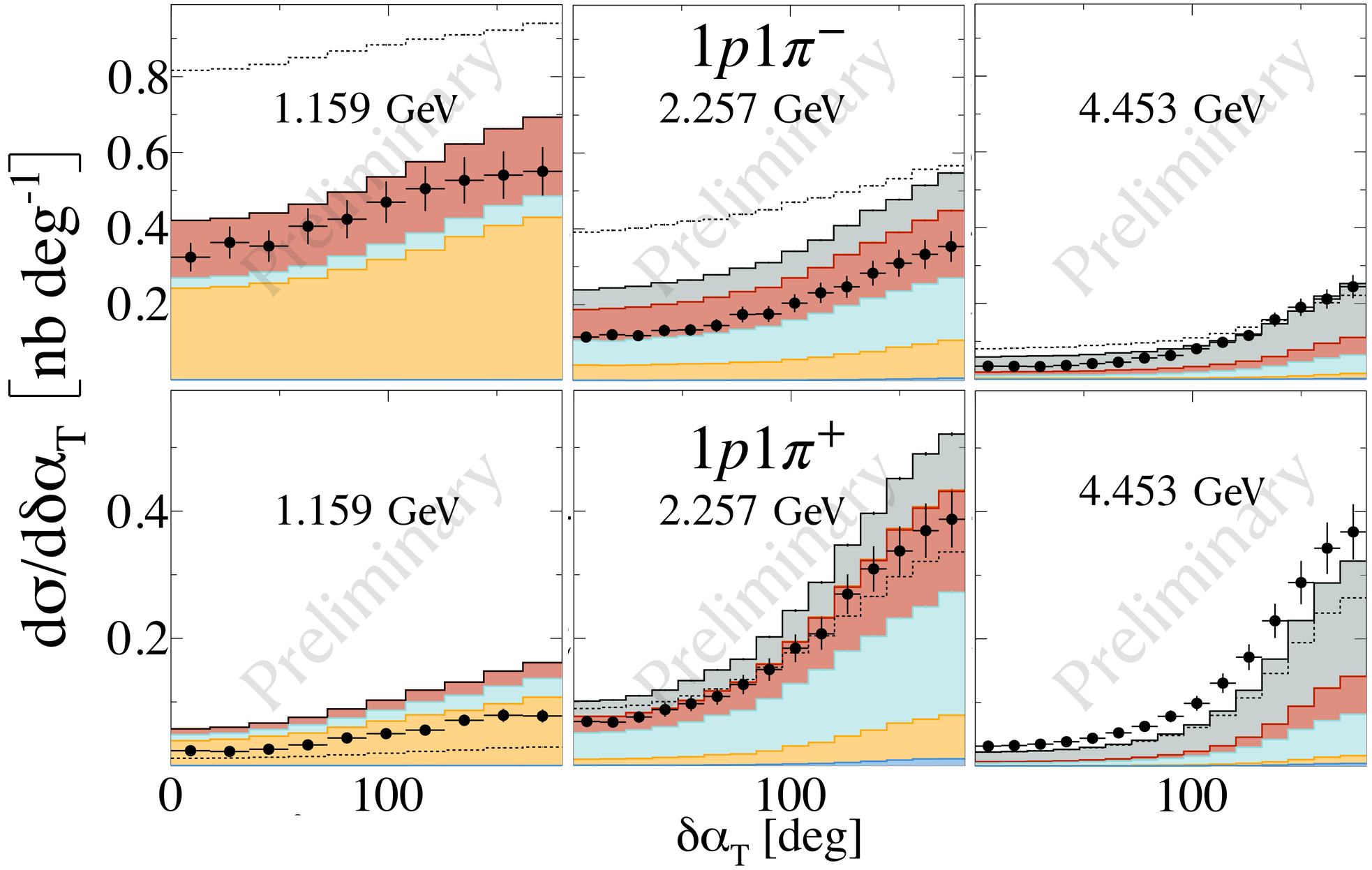
Transverse Boosting Angle



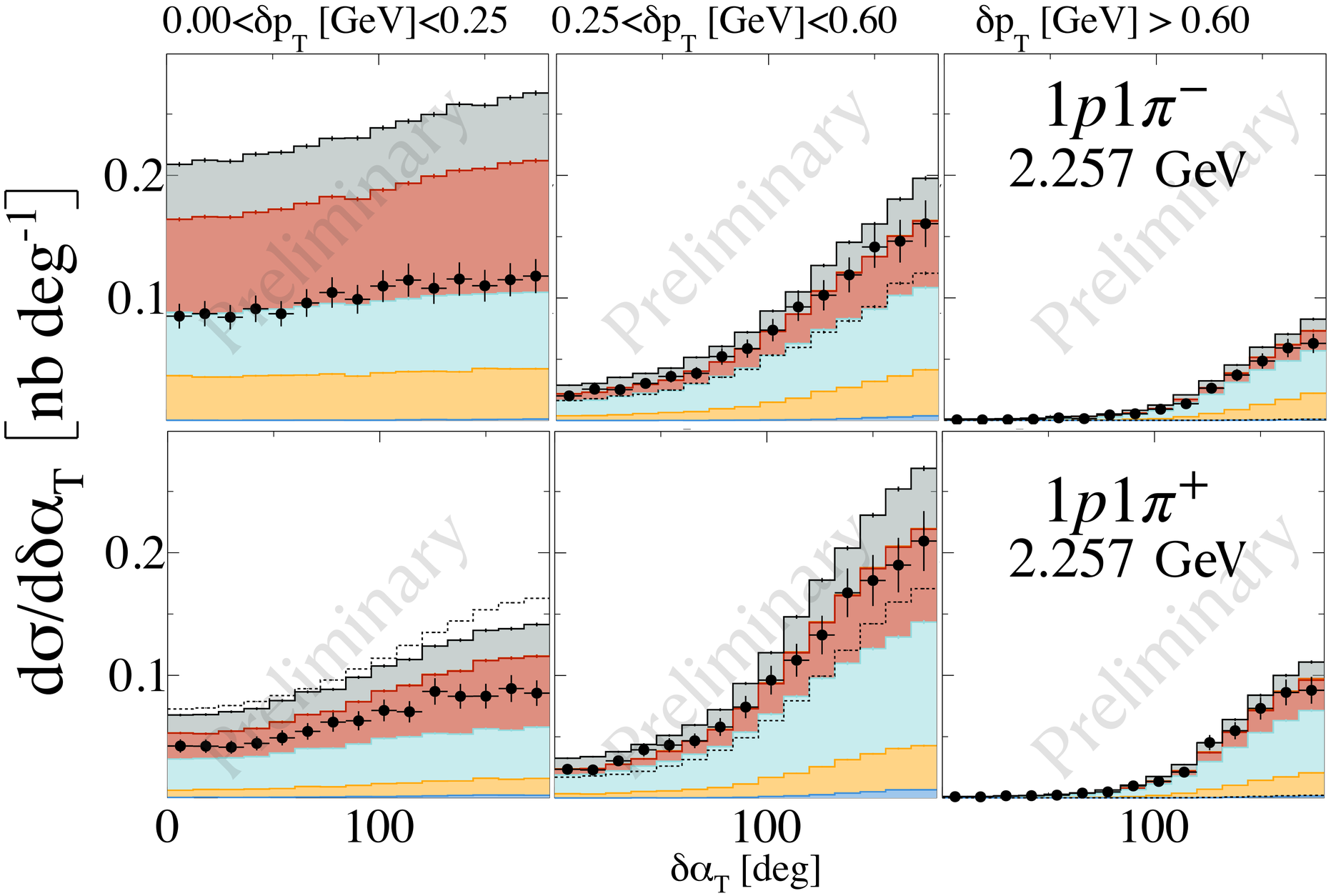
$$\delta\alpha_T = \cos^{-1}\frac{-\vec{p}_T^{\,l'}\cdot\delta\vec{p}_T}{p_T^{l'}\delta p_T}$$

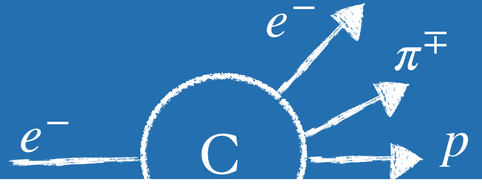
Most sensitive to FSI

Transverse Boosting Angle

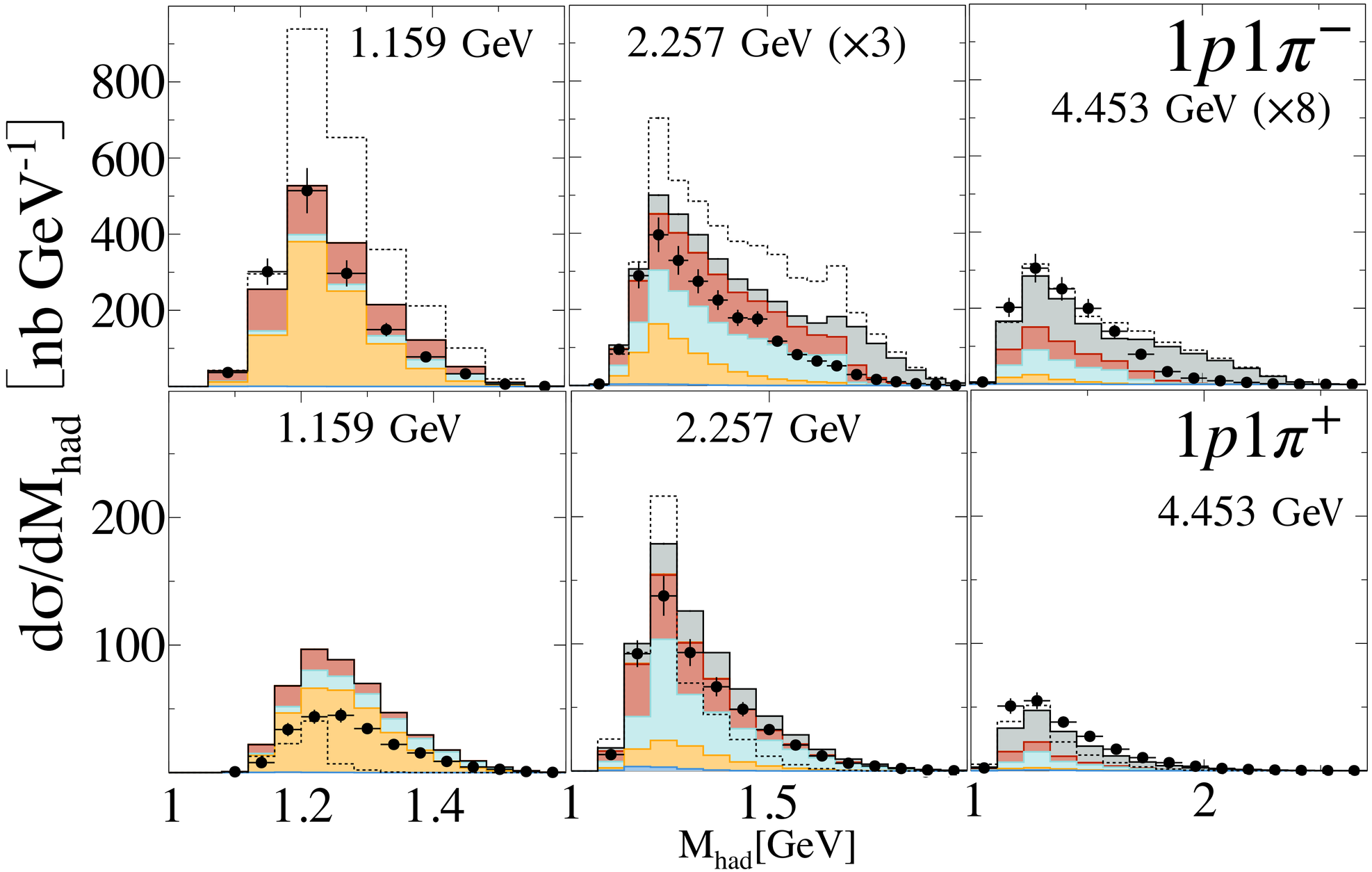


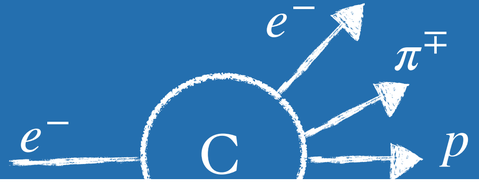
Transverse Boosting Angle





W Miss-Reconstruction





E_{Cal} dependence with δp_T