Electrons for Neutrinos

New constraints for pion production models

"Lepton Interactions with Nucleons and Nuclei", Elba XVII

Neutrino Physics

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

ν_e ν_μ ν_τ

- 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

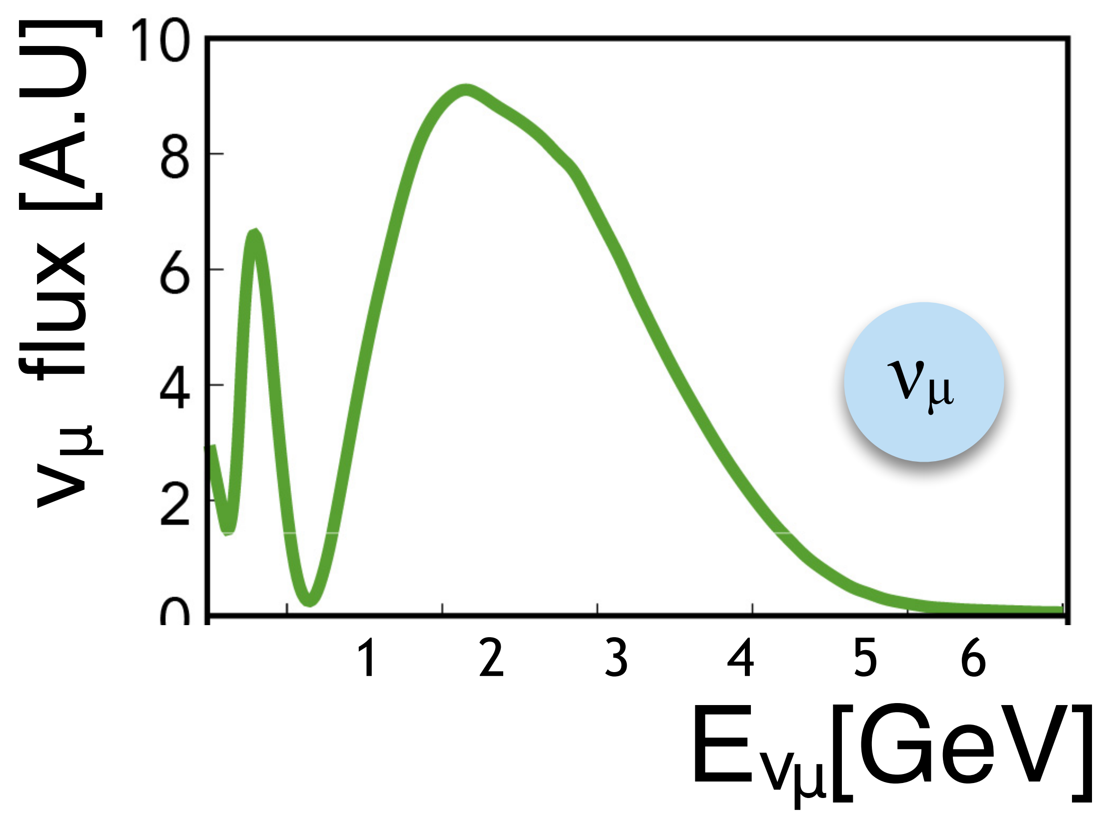
Mass Ordering

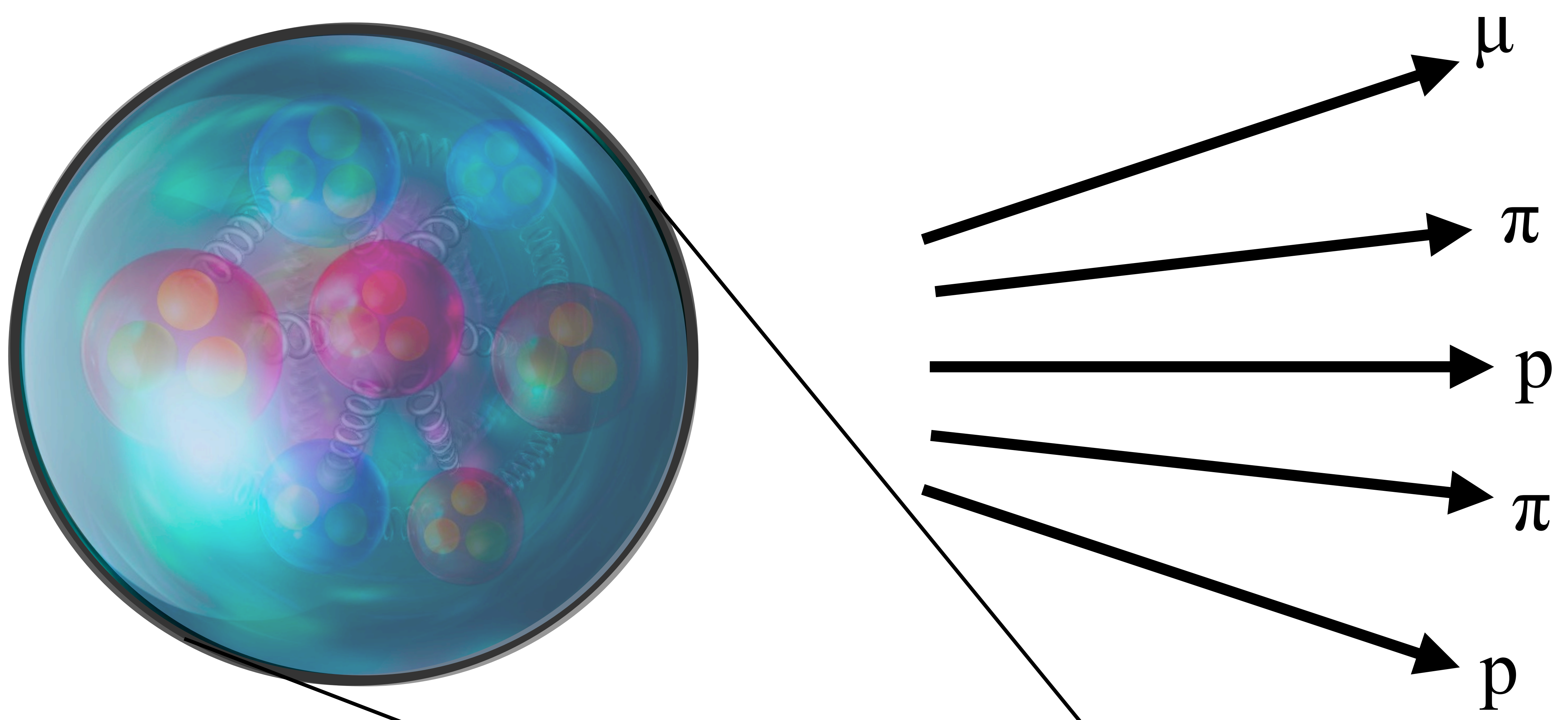
2

The precision era

Incoming true flux | Modelling Input | Measurement

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



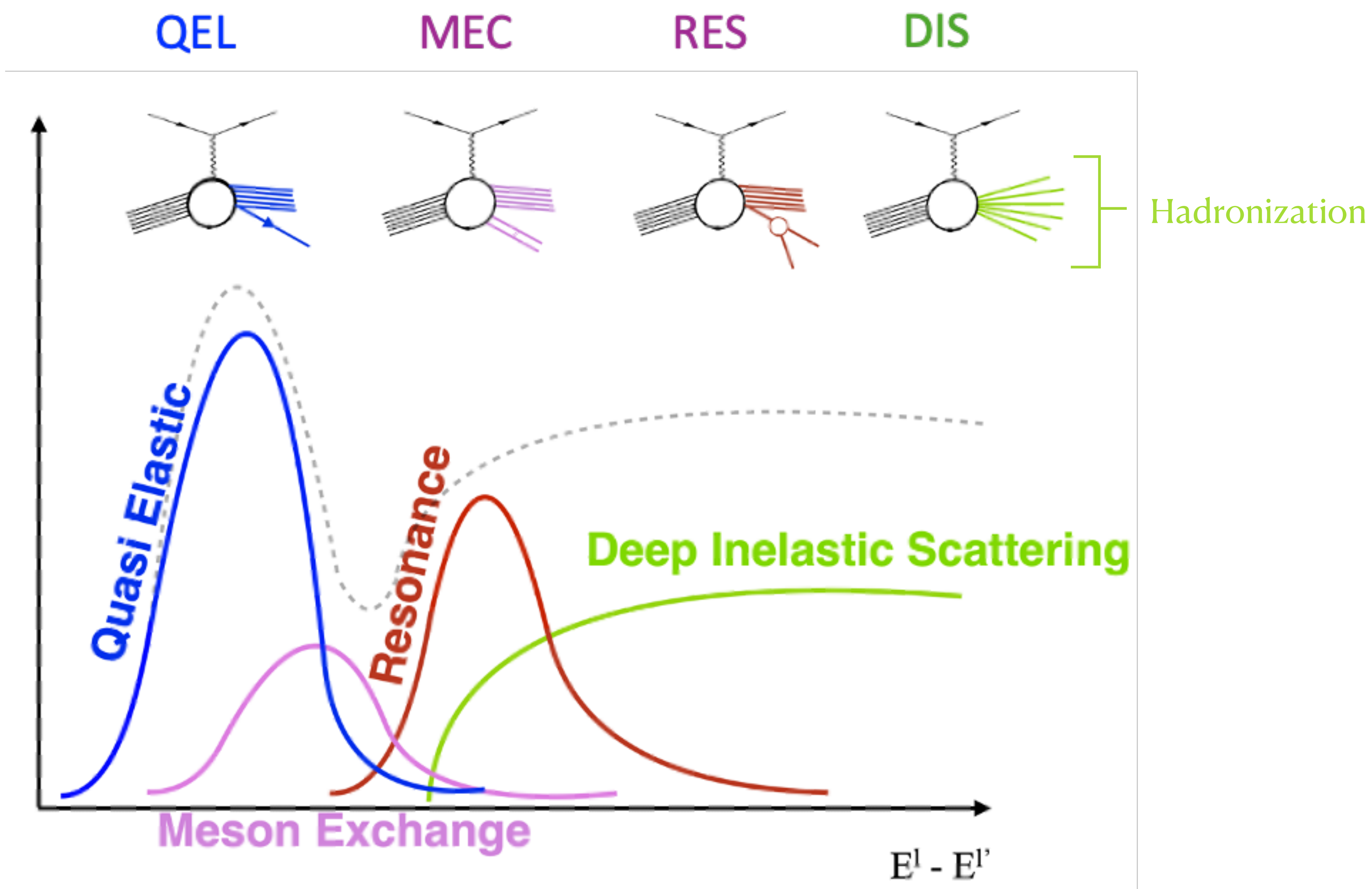


Cross-Section Modelling

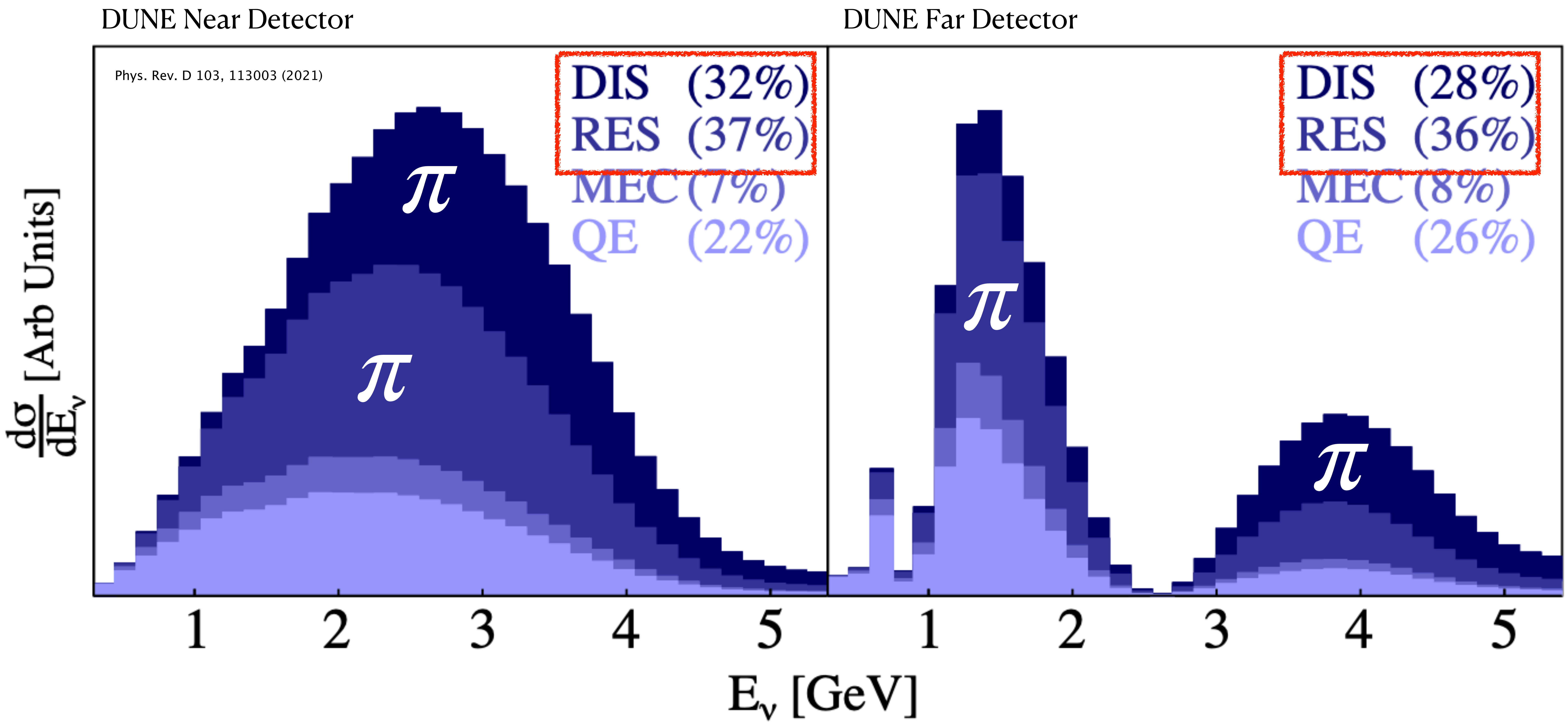
Available models for (e,e')

Ad-hoc hadron production not constraint by e-data

Lack of hadron-production data



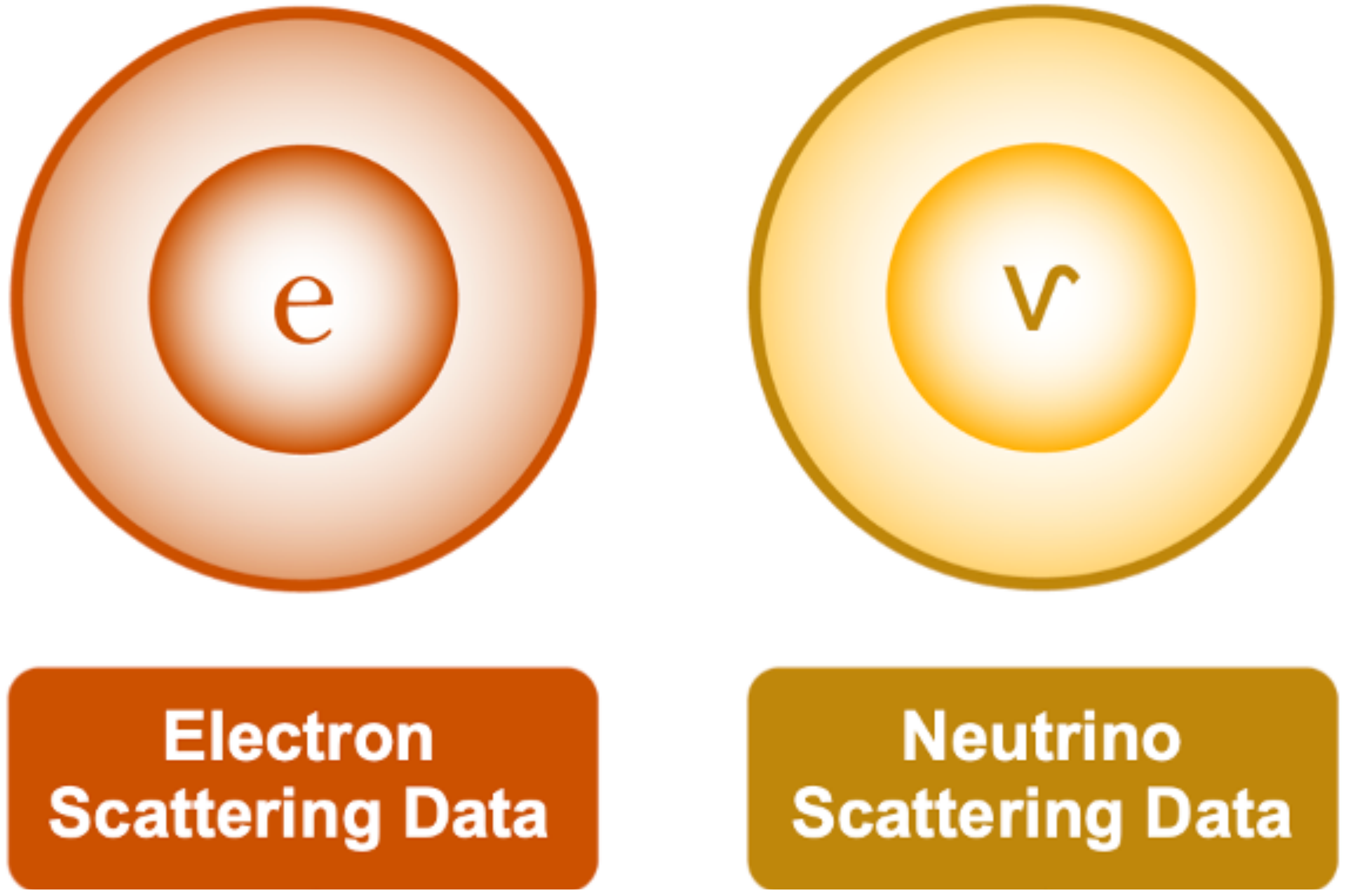
Pion-Production is key for DUNE



Main contribution from pion production events!

Neutrino event generators need constraints

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



This talk focuses on the electron-scattering effort

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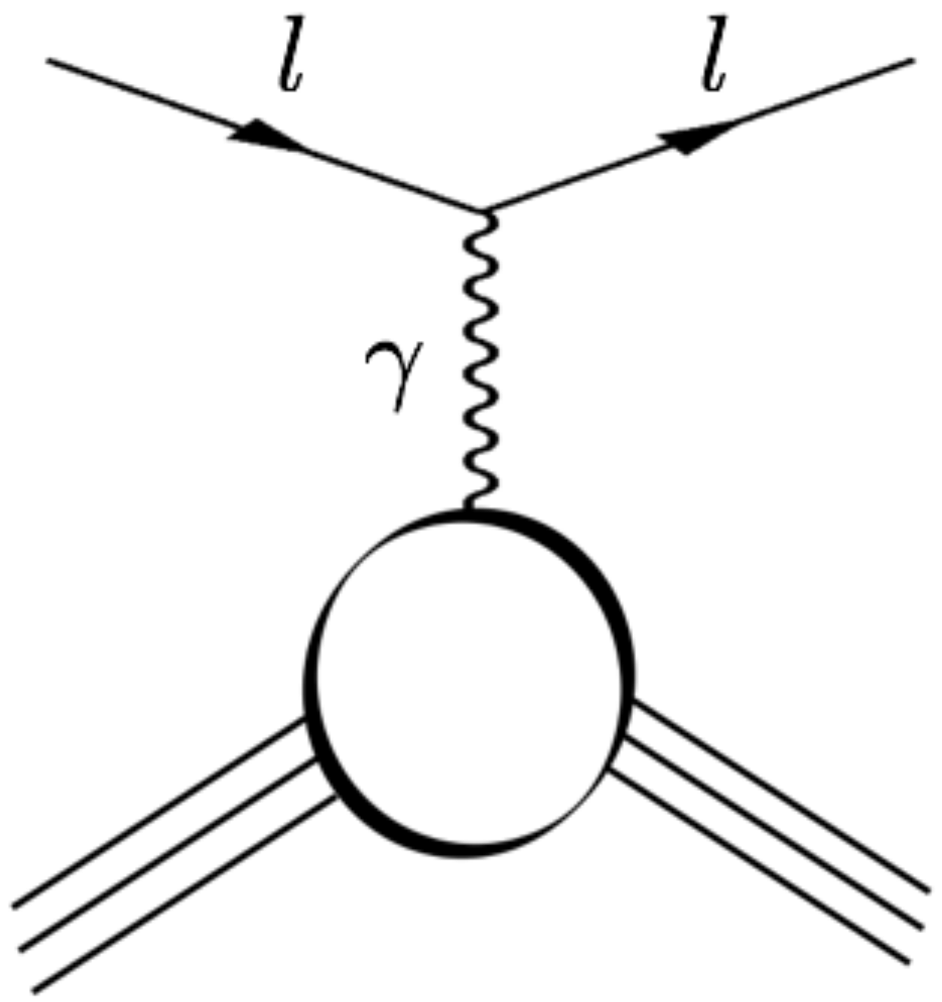
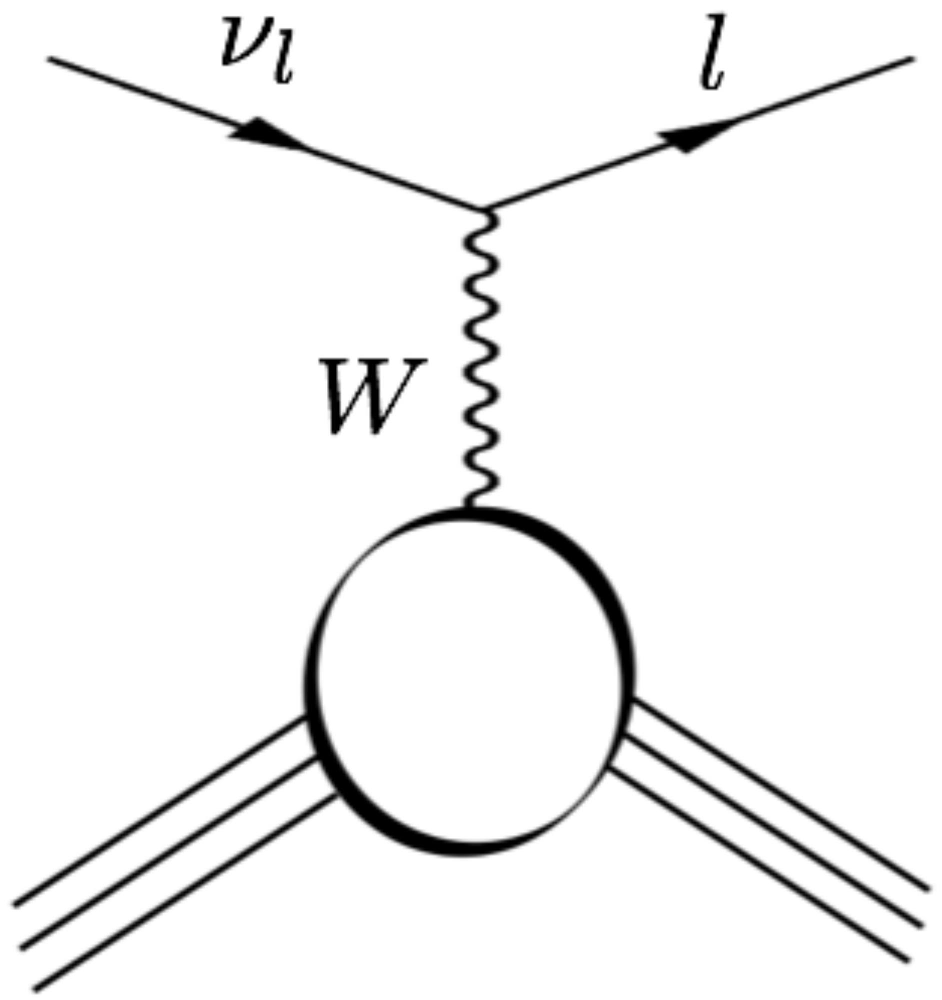
Why electrons?

Same nuclear ground state, Final State Interactions (FSI), Hadronization

Similar interactions with nuclei





EM current [V]

$$j_\mu^{em} = \bar{u}\gamma^\mu u$$

CC weak current [V + A]

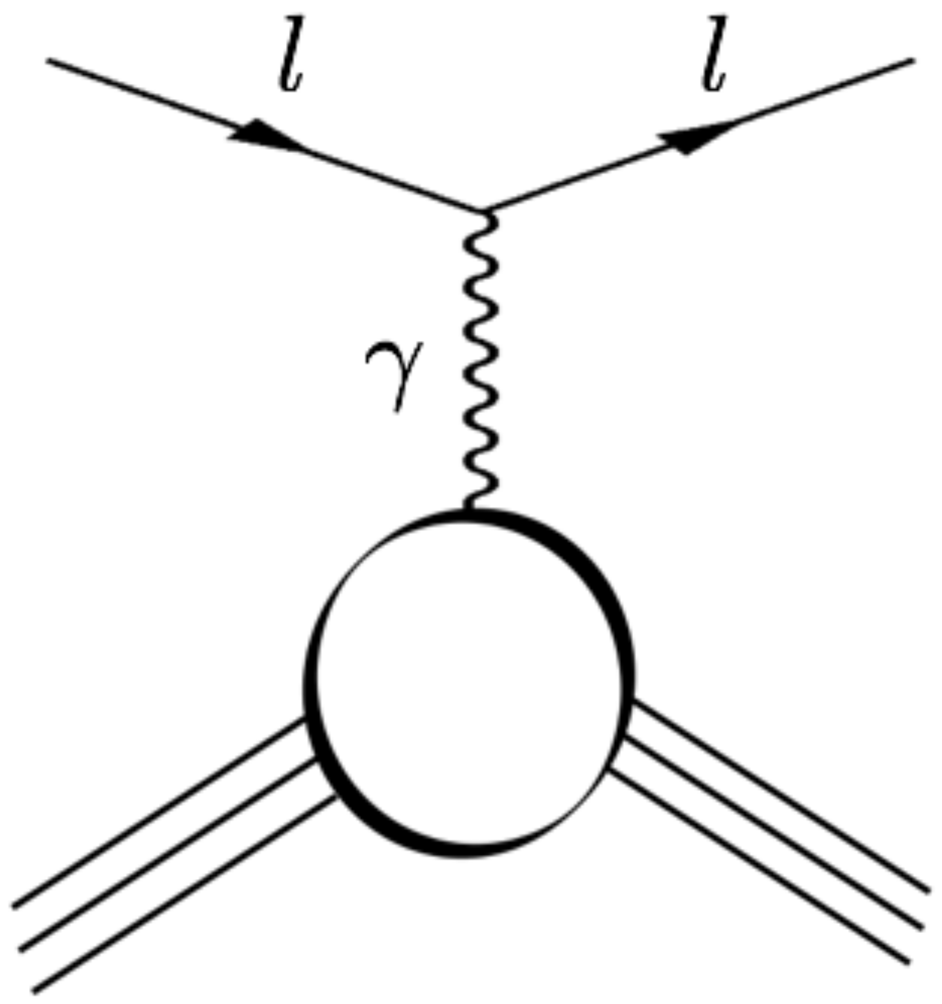
$$j_\mu^{\pm} = \bar{u}\frac{-ig_W}{2\sqrt{2}}(\gamma^\mu - \gamma^\mu\gamma^5)u$$

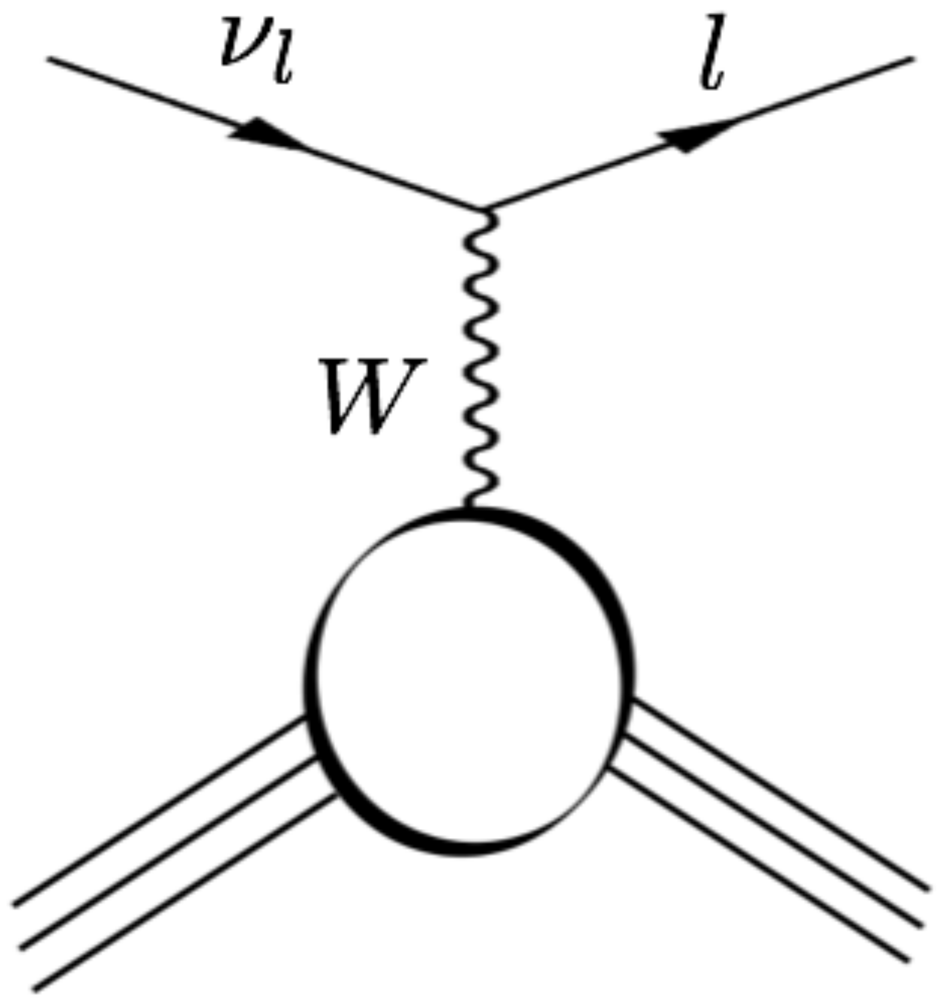
eA useful to constrain νA model uncertainties

Why electrons?

Same nuclear ground state, Final State Interactions (FSI), Hadronization

Similar interactions with nuclei





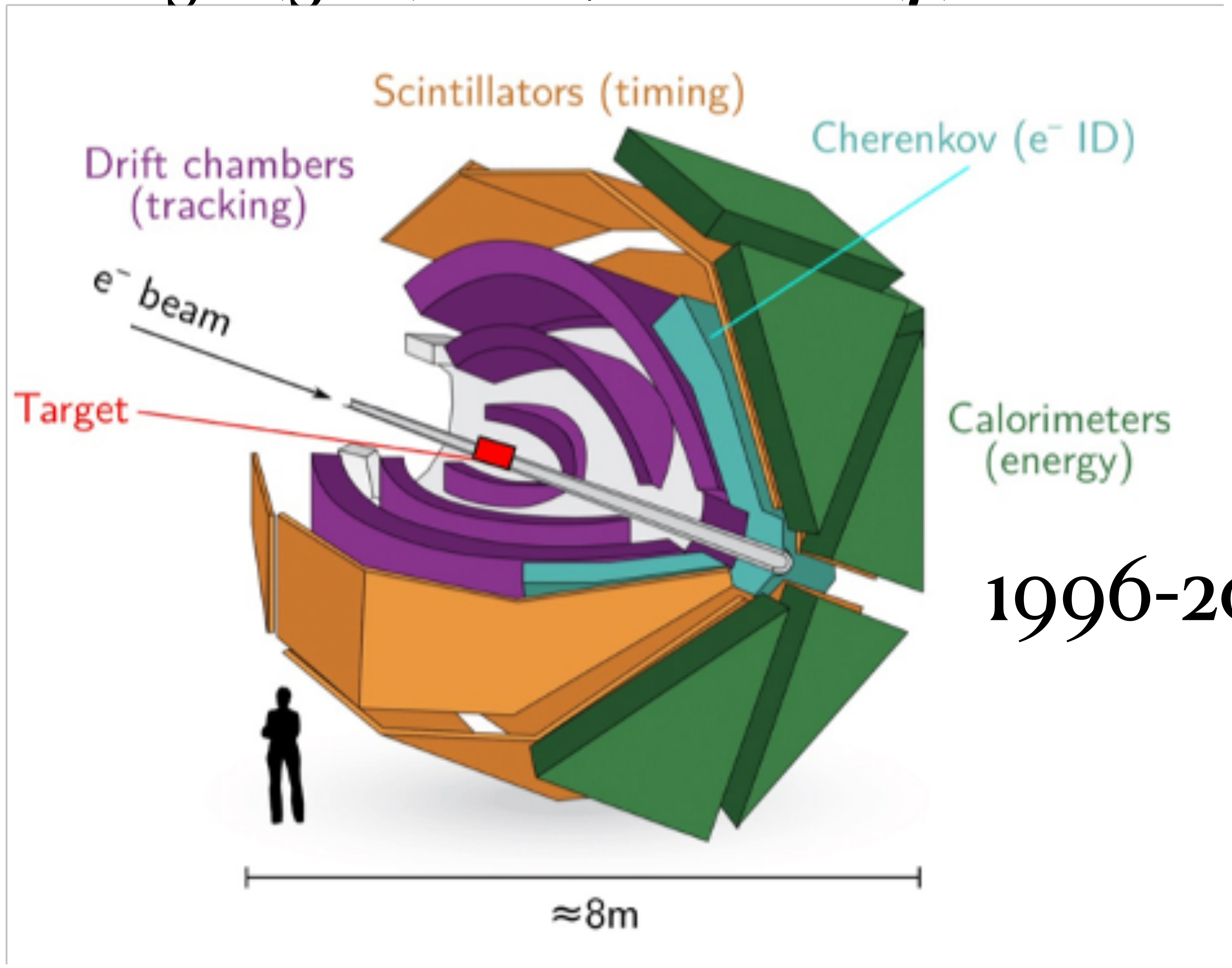
Monochromatic beam
High statistics

Wide-energy beam
Lower statistics

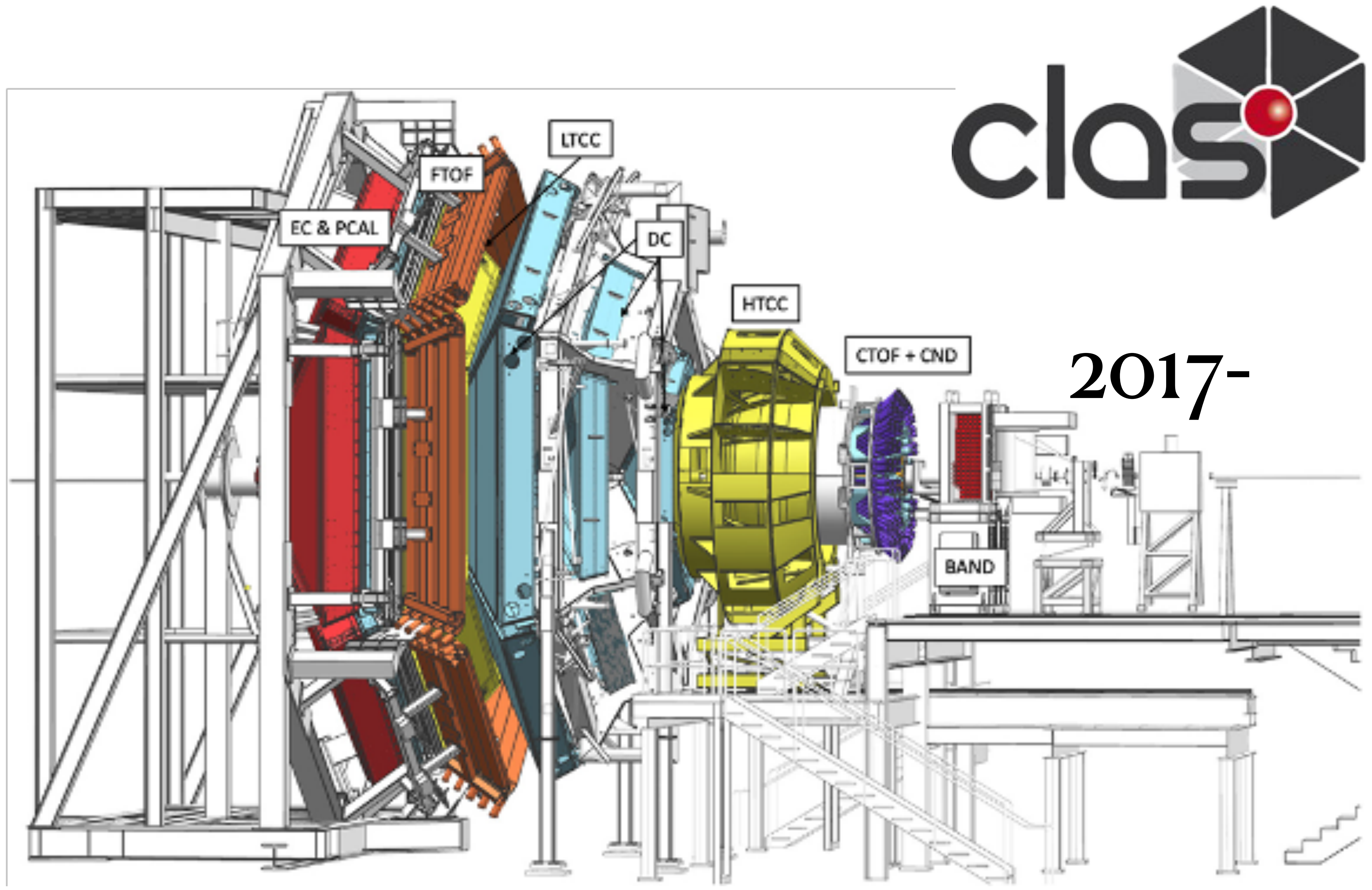
eA useful to test νA energy reconstruction methods

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)



1996-2013



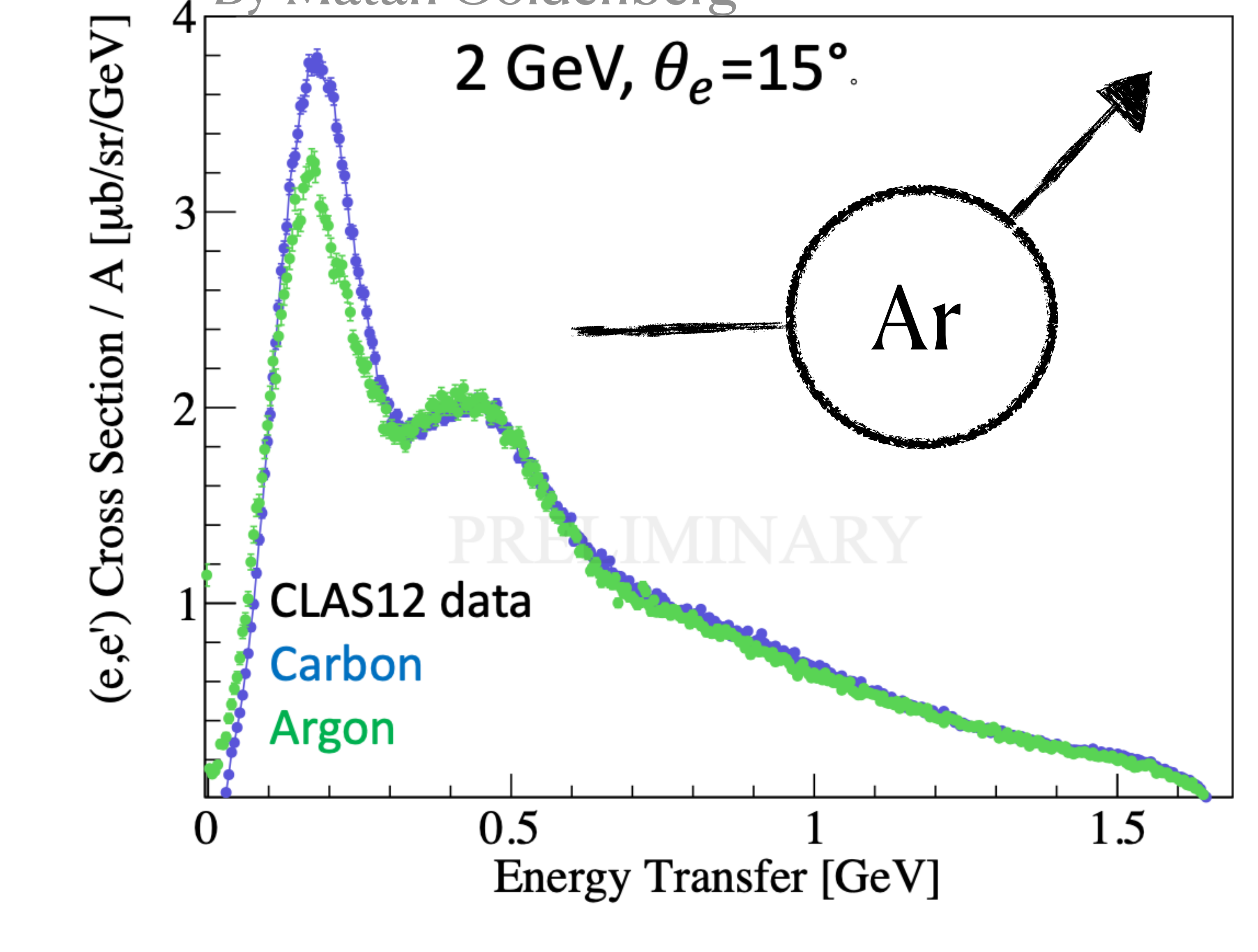
2017-

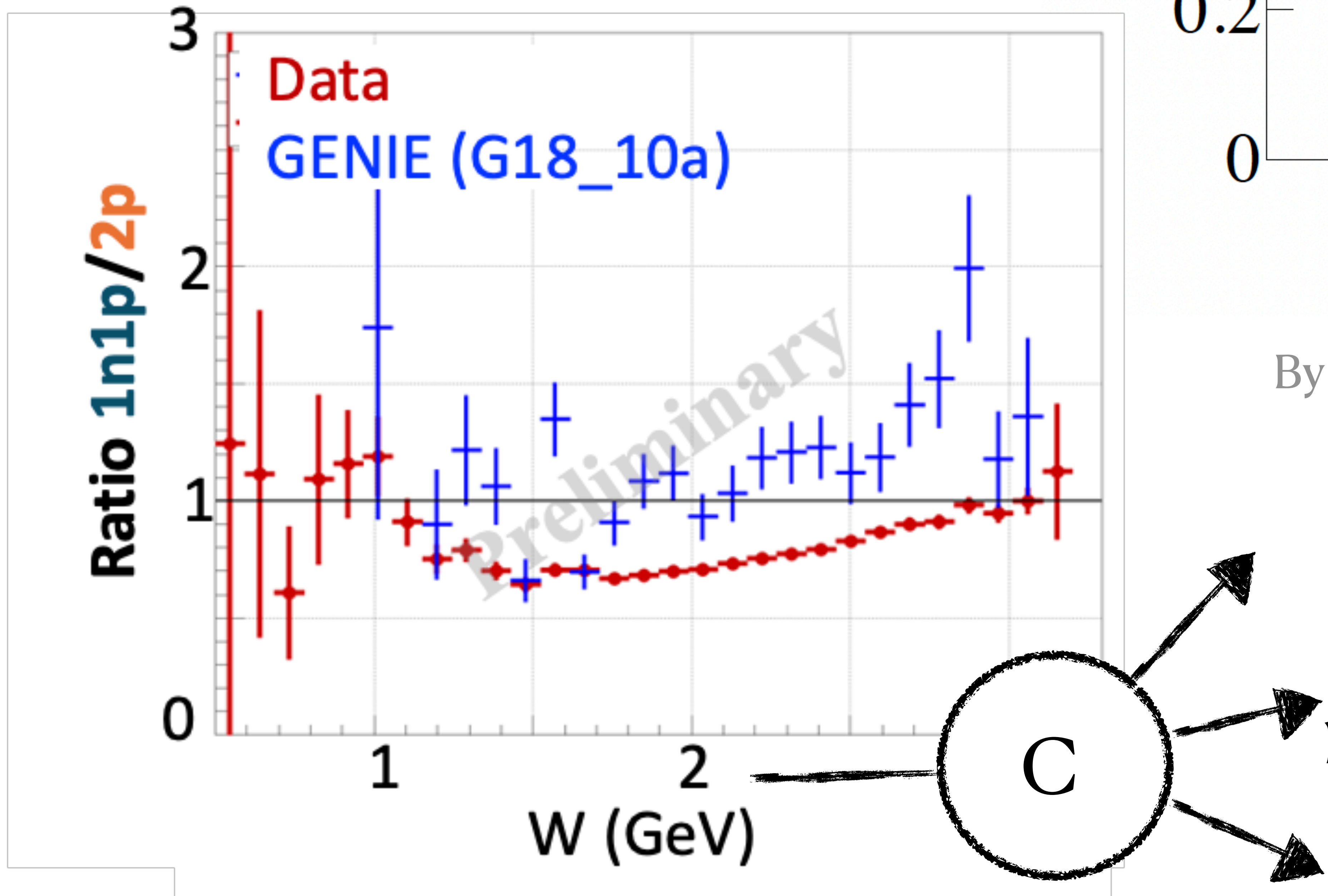
New hadron electron production data

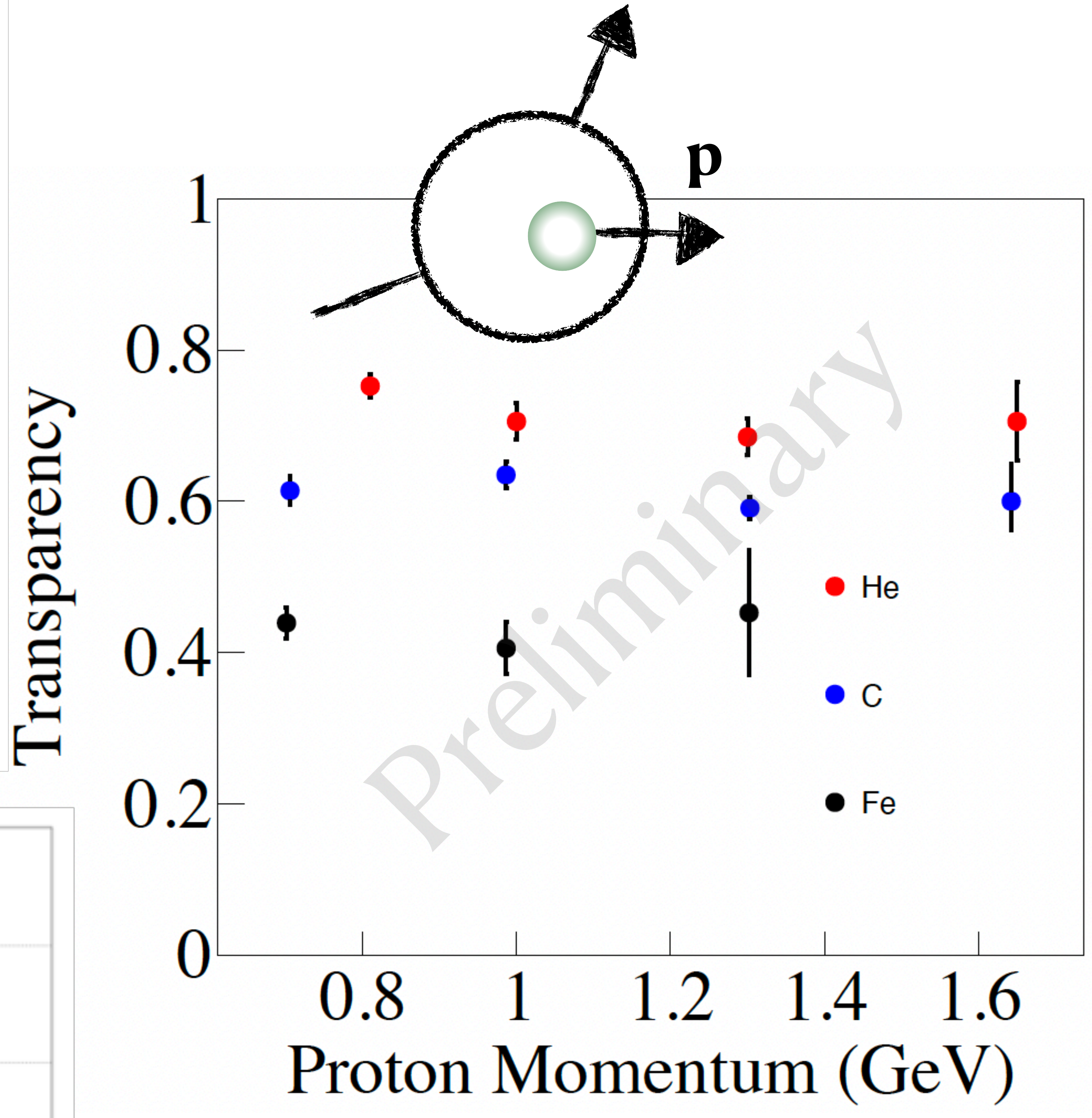
1-6 GeV electrons for many targets (e.g. carbon, **argon**)

New e4ν π-production measurements in this talk

By Matan Goldenberg



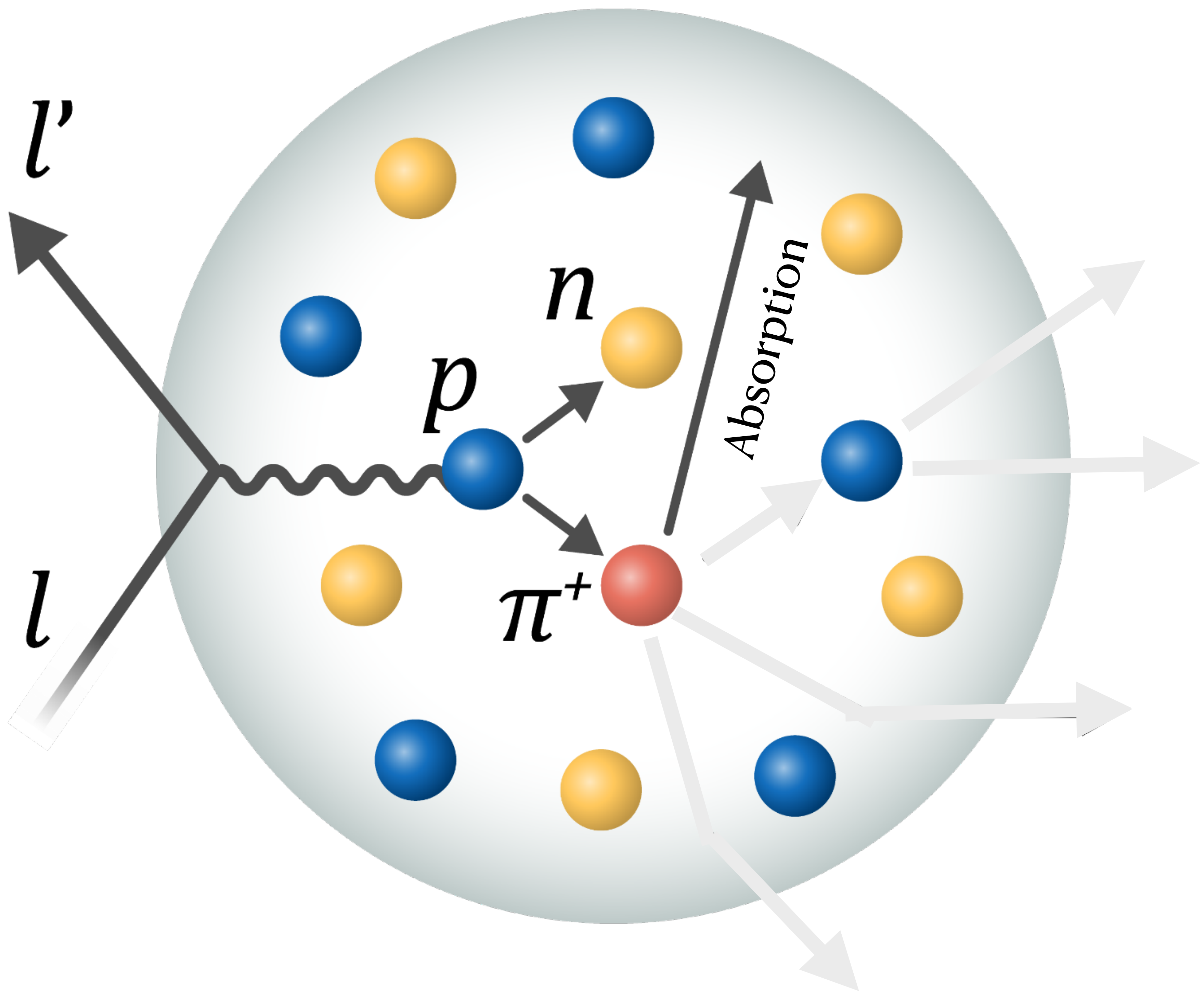




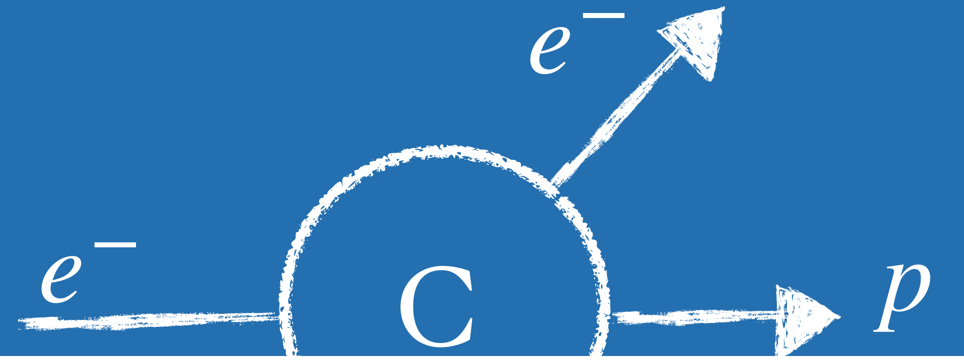
By Steven Dytman and Noah Steinberg

Pion Knockout with CLAS

$\boxed{1p0\pi}$

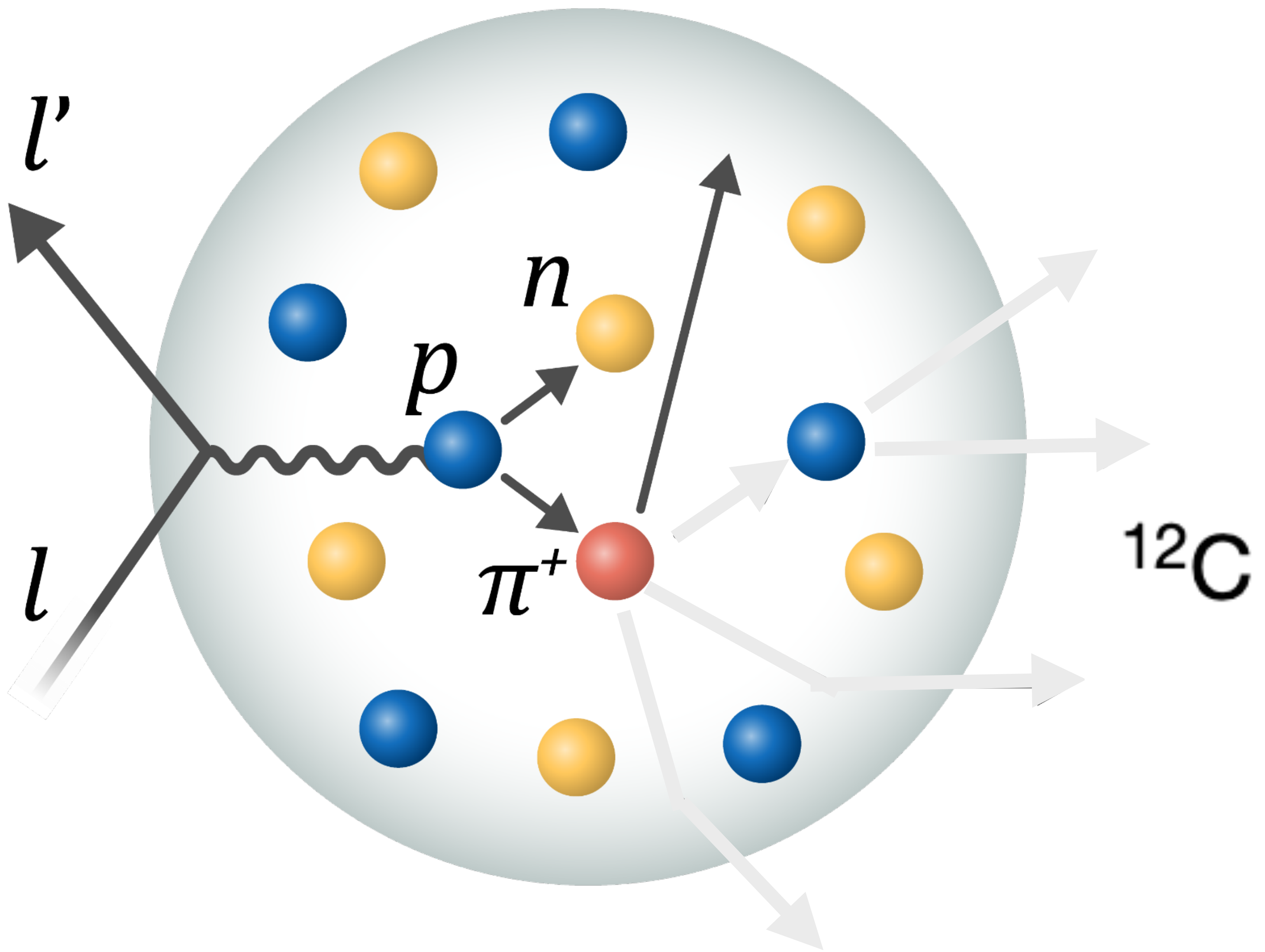


Final-State Interactions



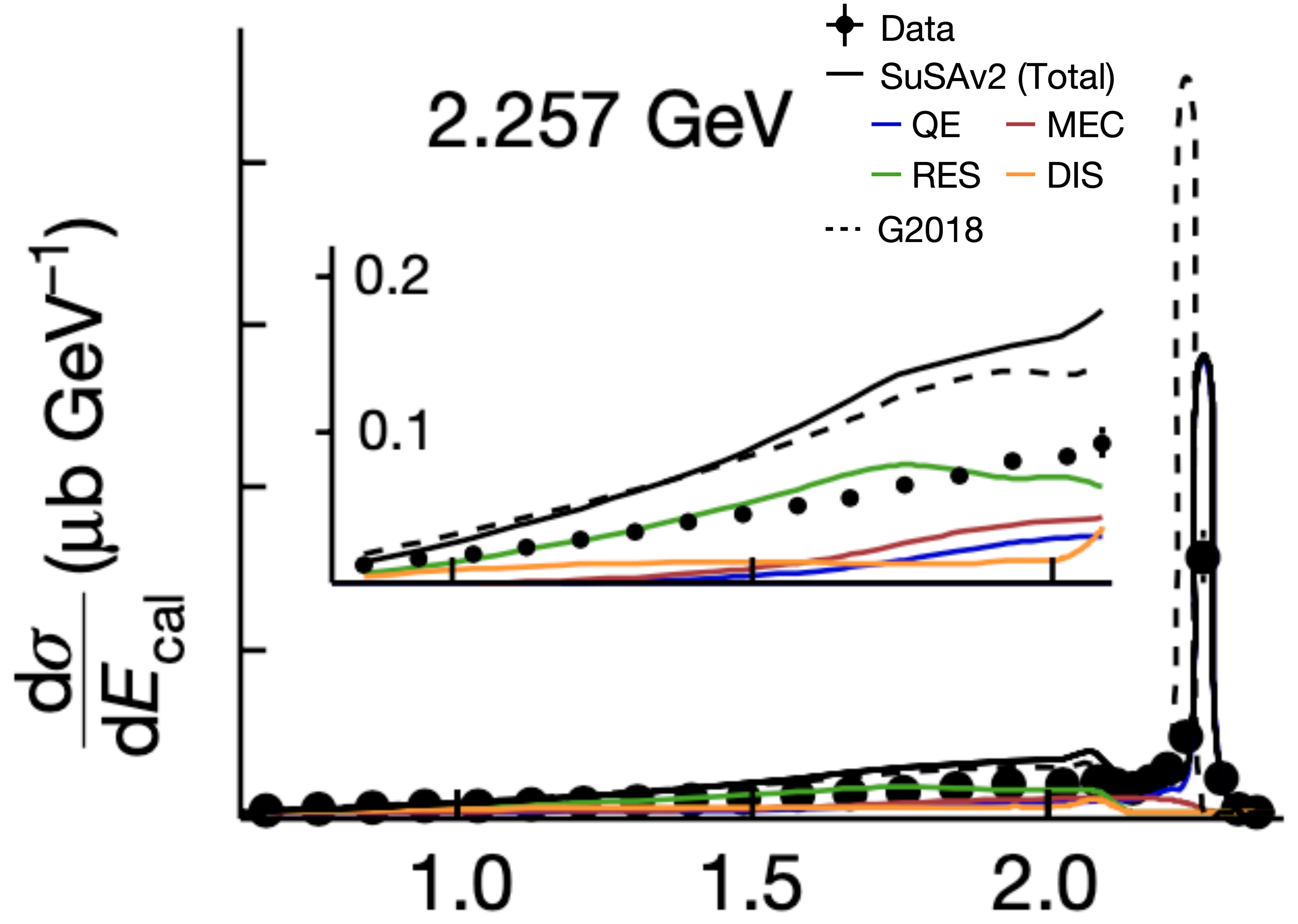
Pion Knockout with CLAS

$$\boxed{1p0\pi}$$



Direct estimation of $S(E_\nu, E_\nu^{reco})$

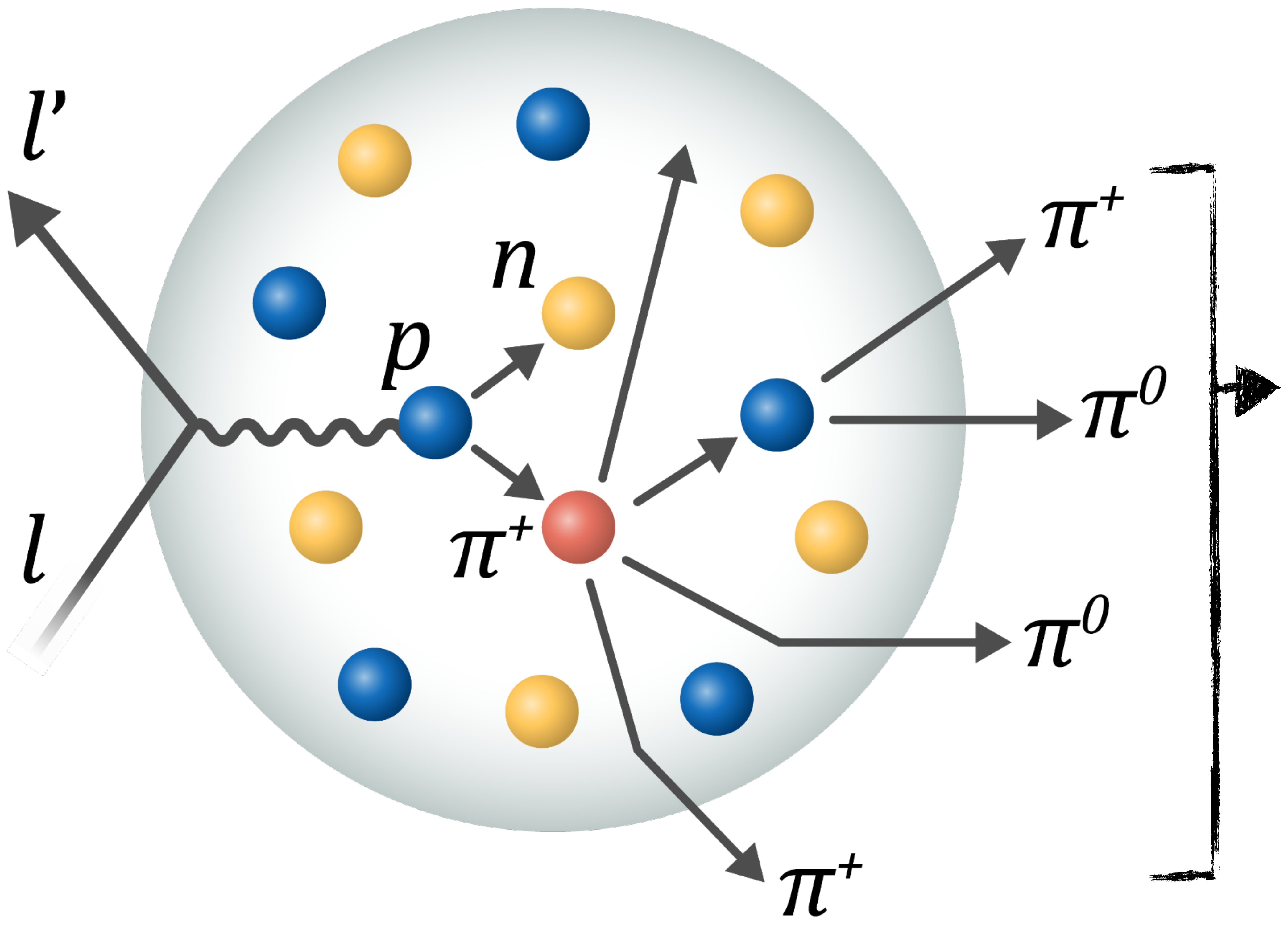
M. Khachatryan, A. Papadopoulou et. Al.
Nature volume 599, pages 565–570 (2021)



$$(e, e'1p0\pi)\ E_{Cal} = \sum (E_i + \epsilon_i)$$

Pion Production with CLAS

Complex modelling, requires **new** data



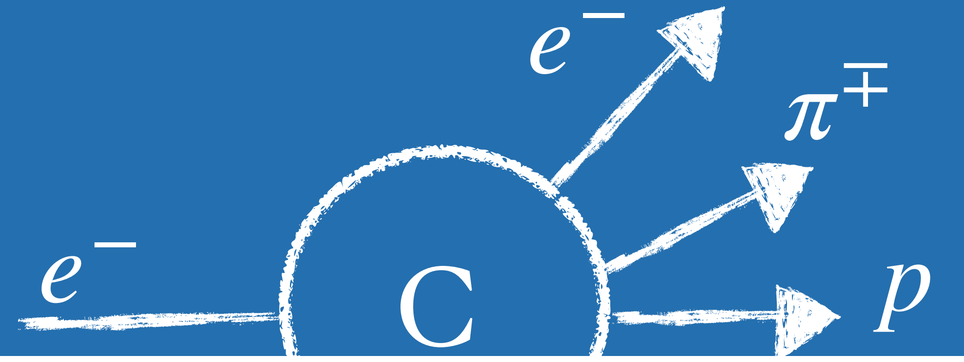
Rich limits for few-GeV experiments:

$\boxed{1p1\pi^{\pm}}$ Working towards publication!

$1p1\pi^{0}$

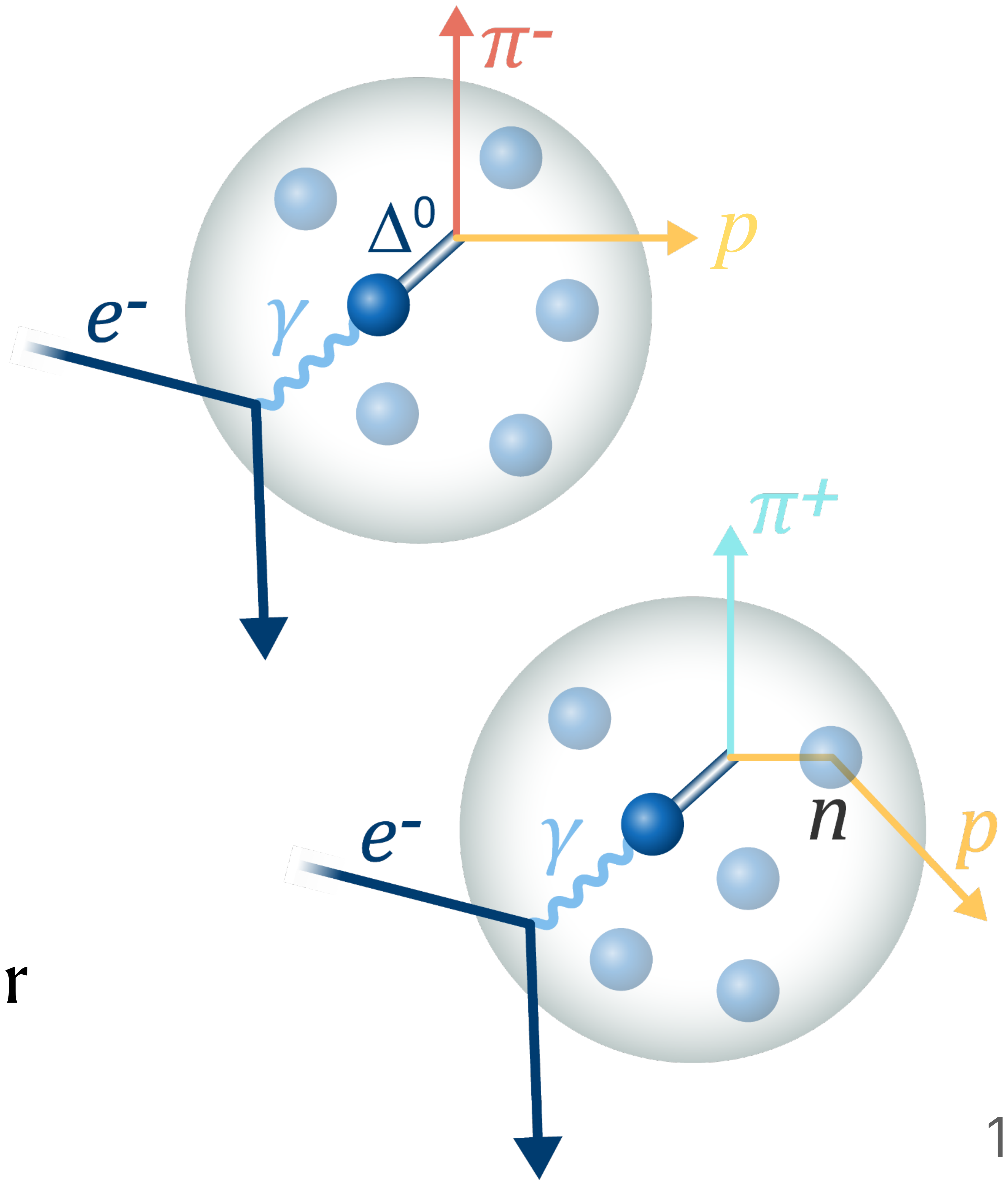
$N\pi^{\pm}$

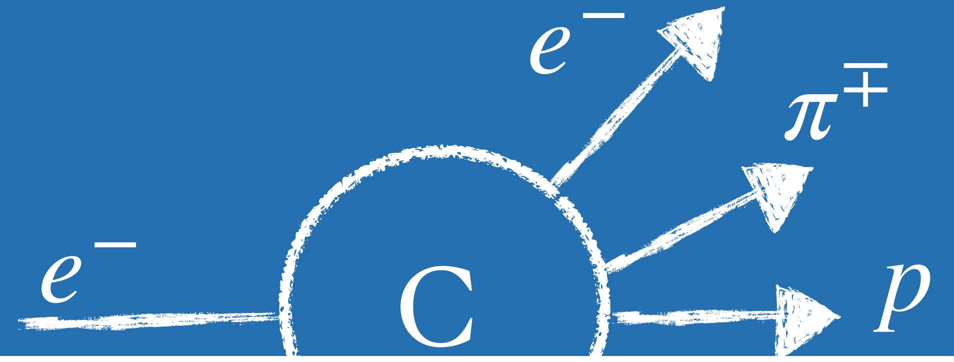
$\dots$



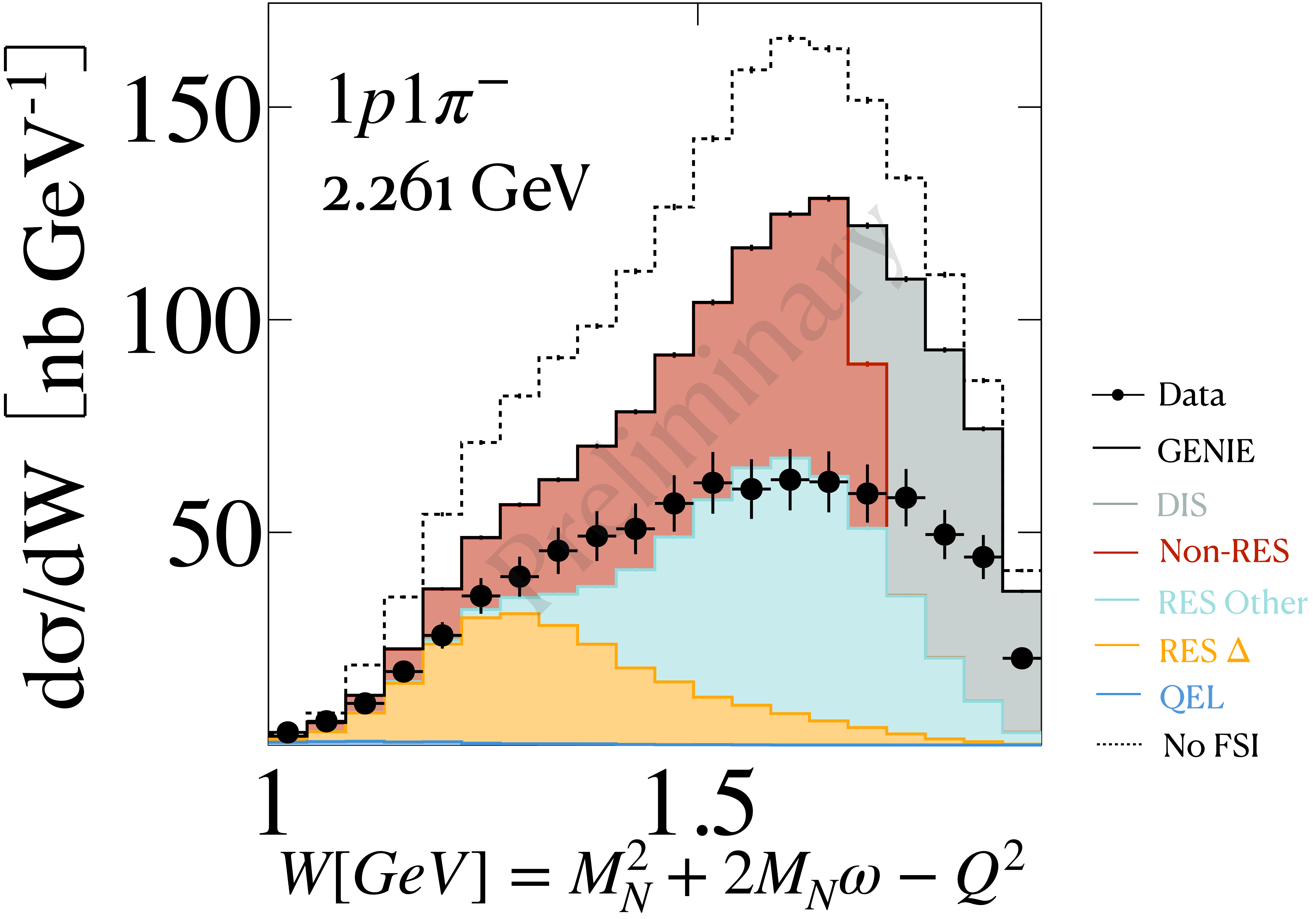
First look at C(e,e'$1p1\pi^{\mp}$)

- 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)

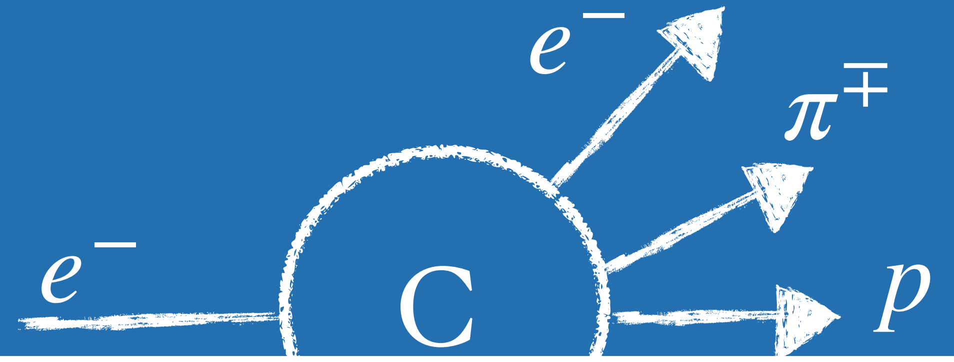


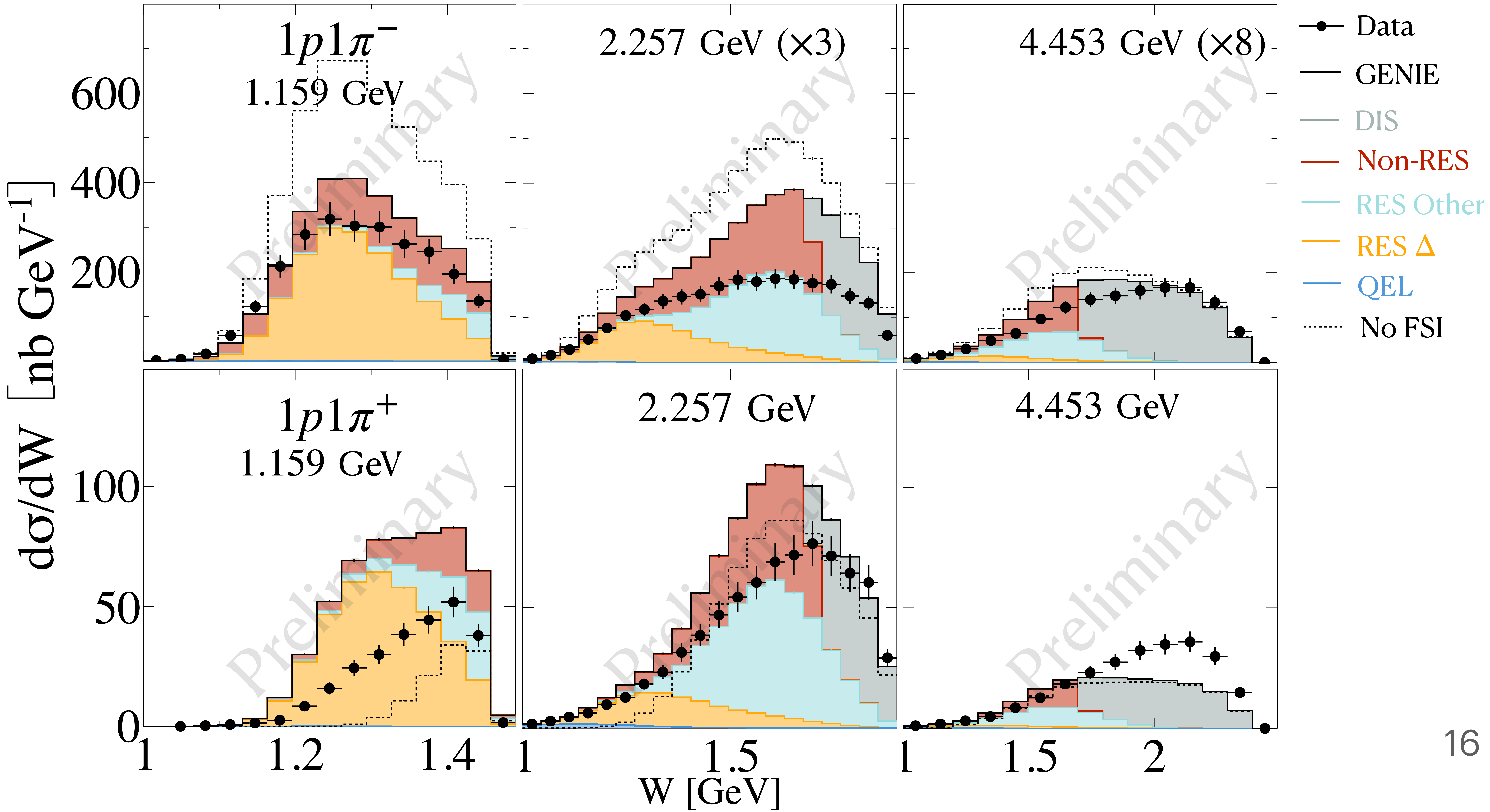


Complex Physics

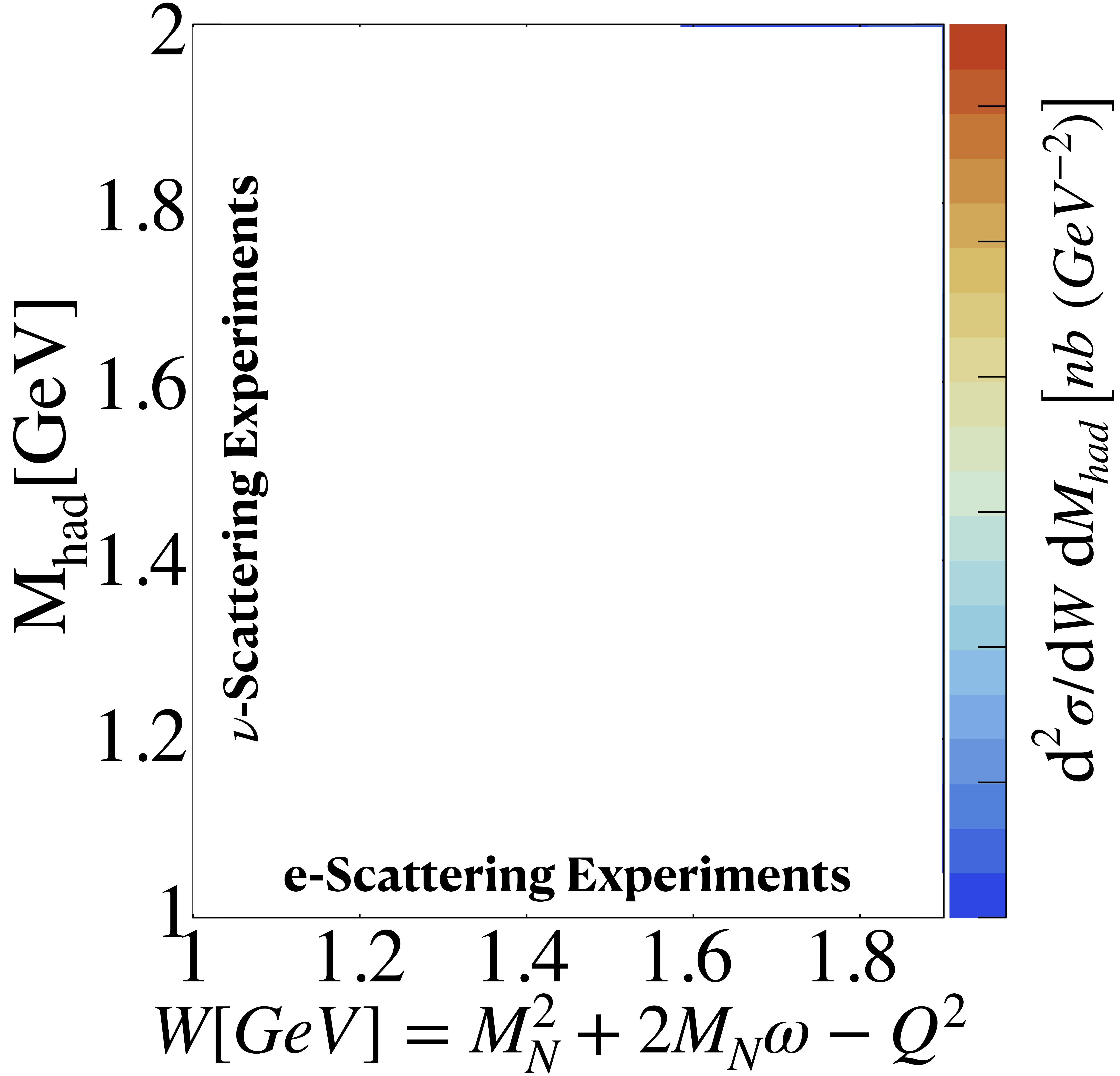


Complex Physics

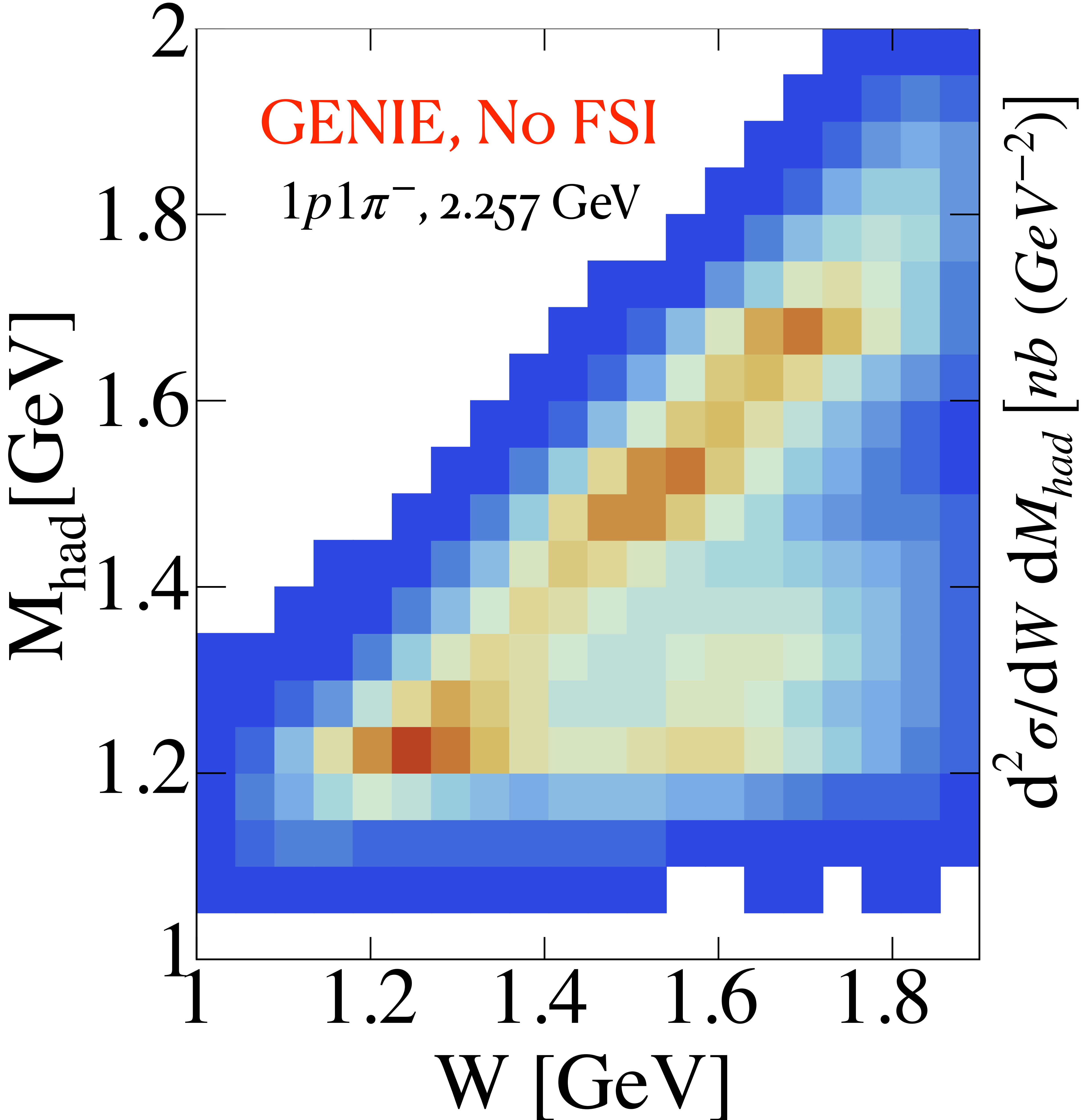




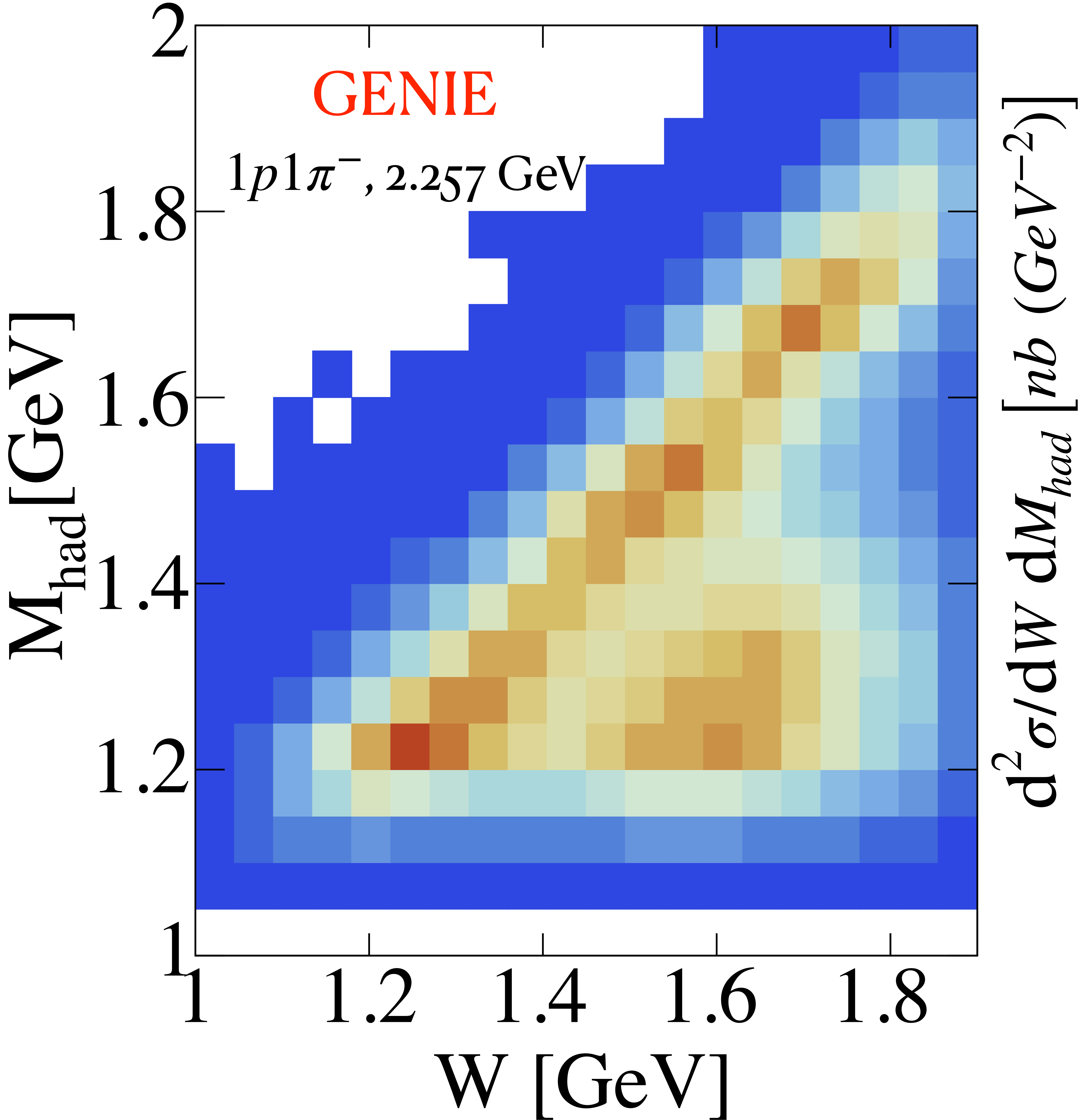
Hadronic Invariant Mass Bias

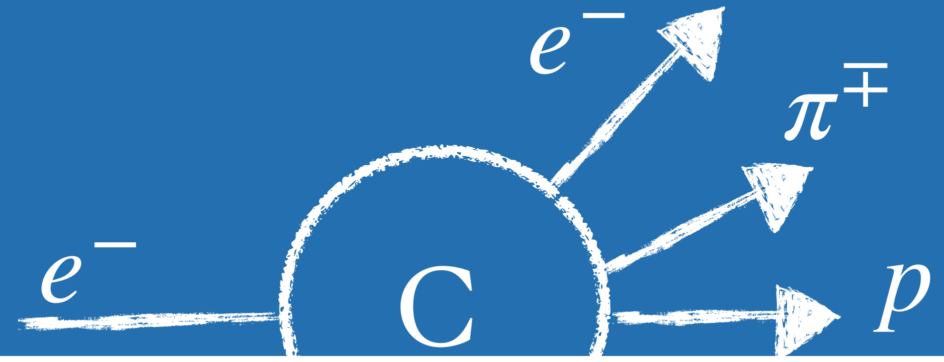


GENIE missmodels hadronization

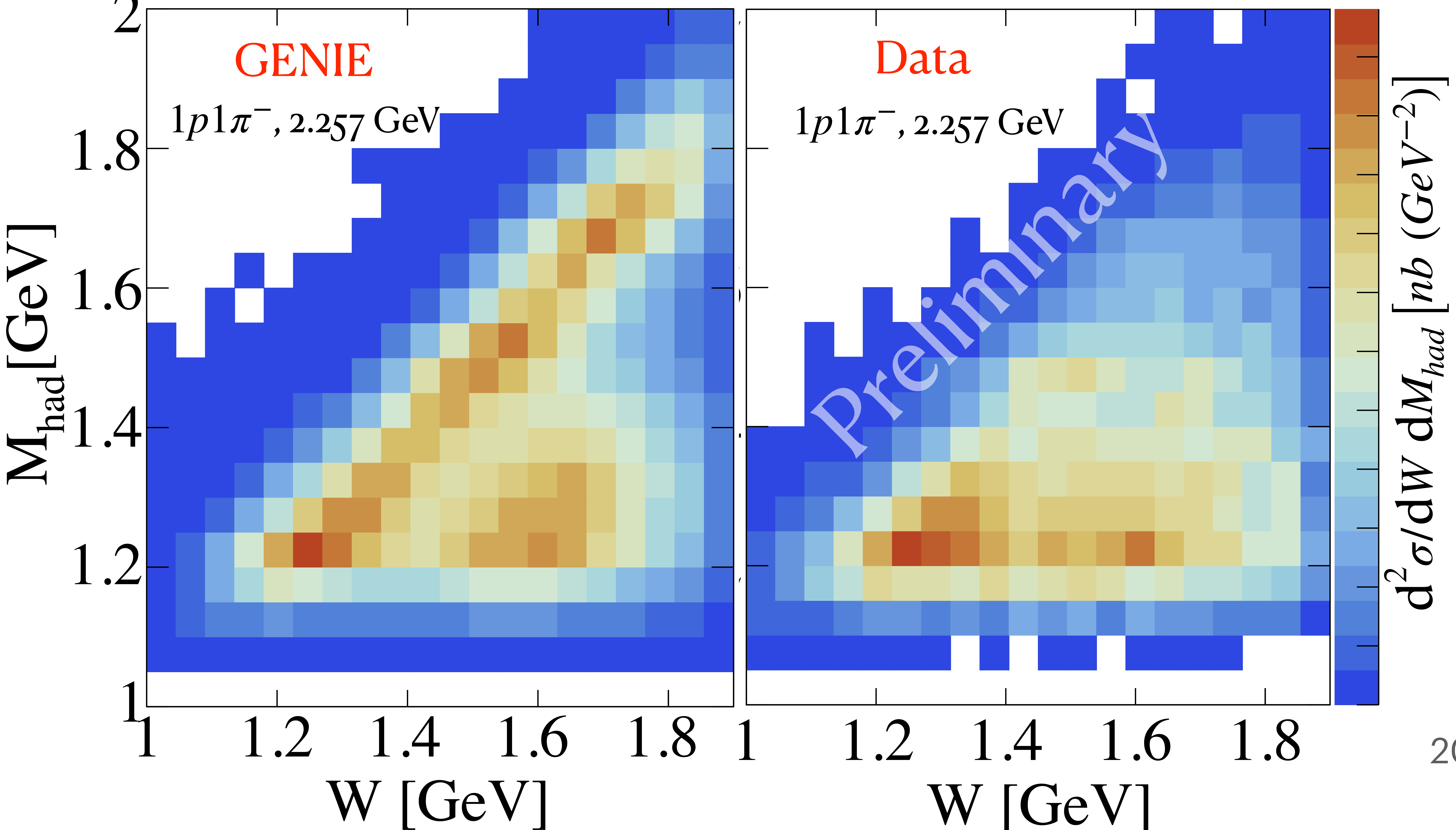


GENIE missmodels hadronization

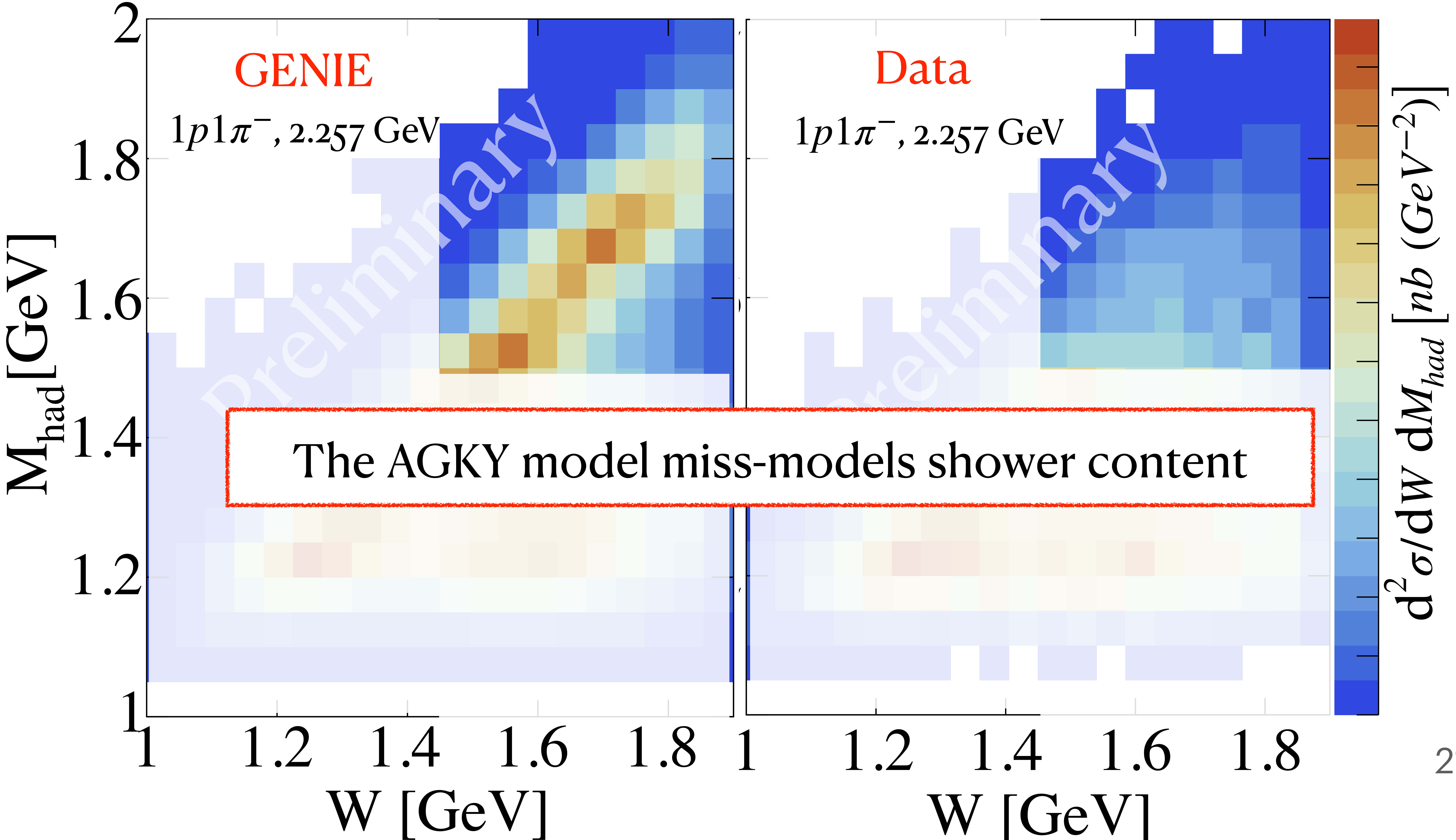




GENIE missmodels hadronization

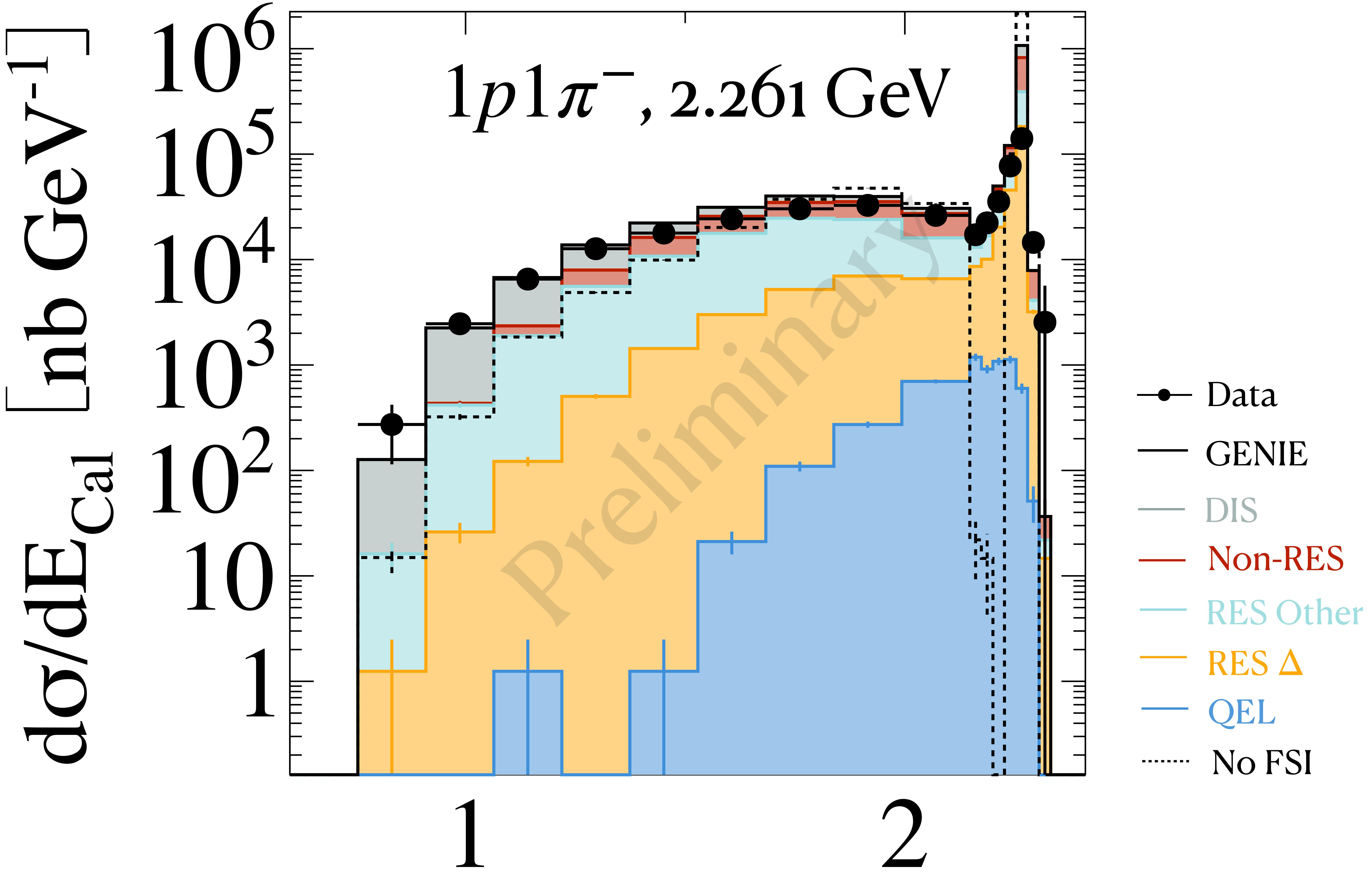


GENIE missmodels hadronization



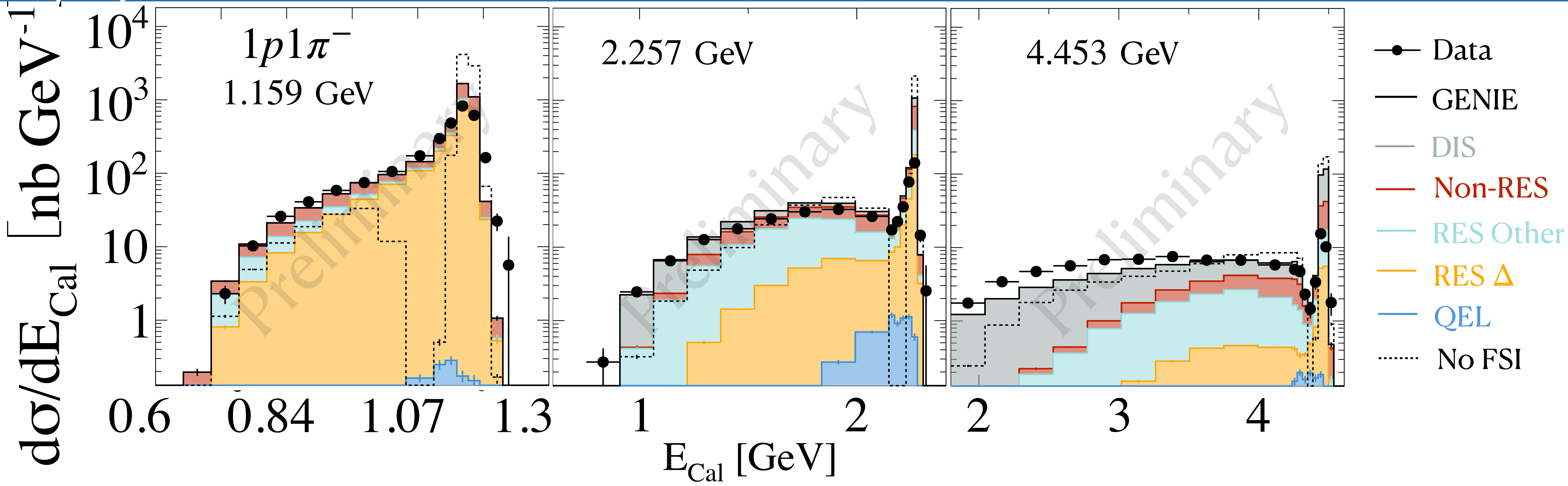
The AGKY model miss-models shower content

Energy Bias Quantification

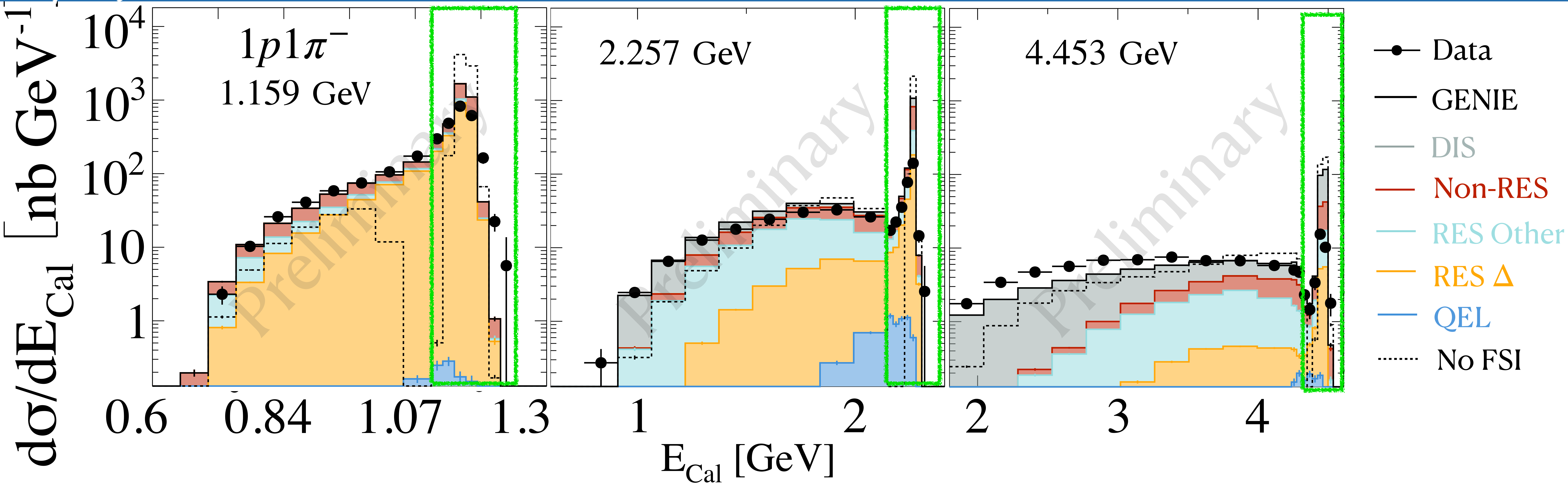


$(e, e'1p1\pi^-)\, E_{Cal}[\mathrm{GeV}] = E_{e'} + E_\pi + T_p + \epsilon_i$

Beam energy miss-reconstruction



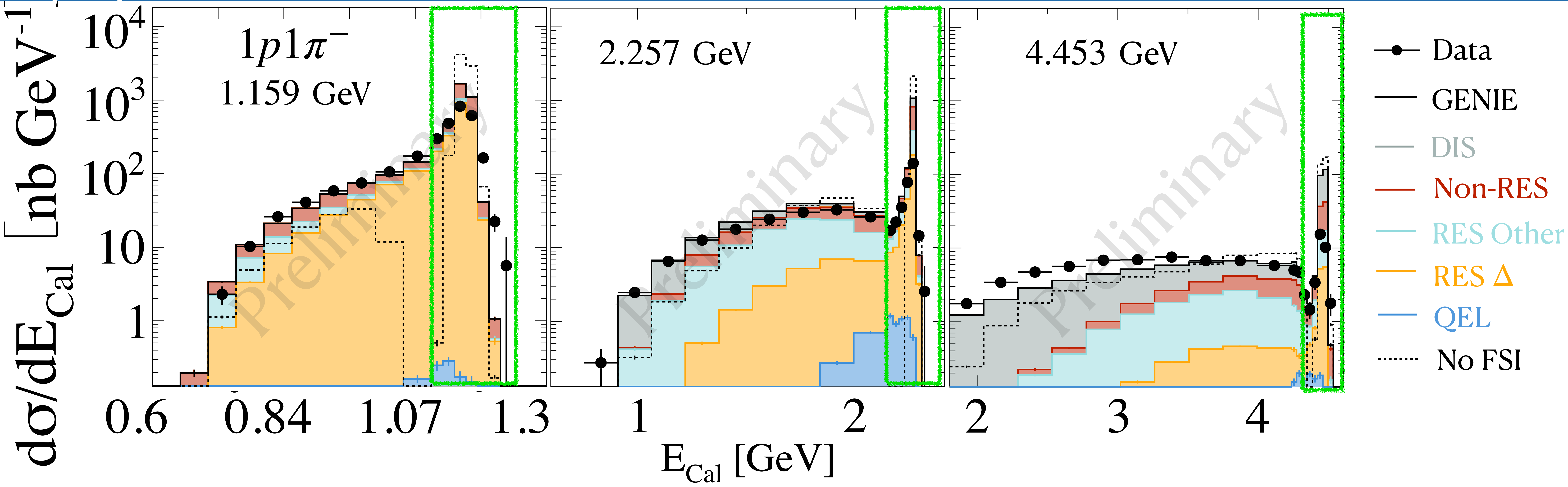
Beam energy miss-reconstruction



% 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

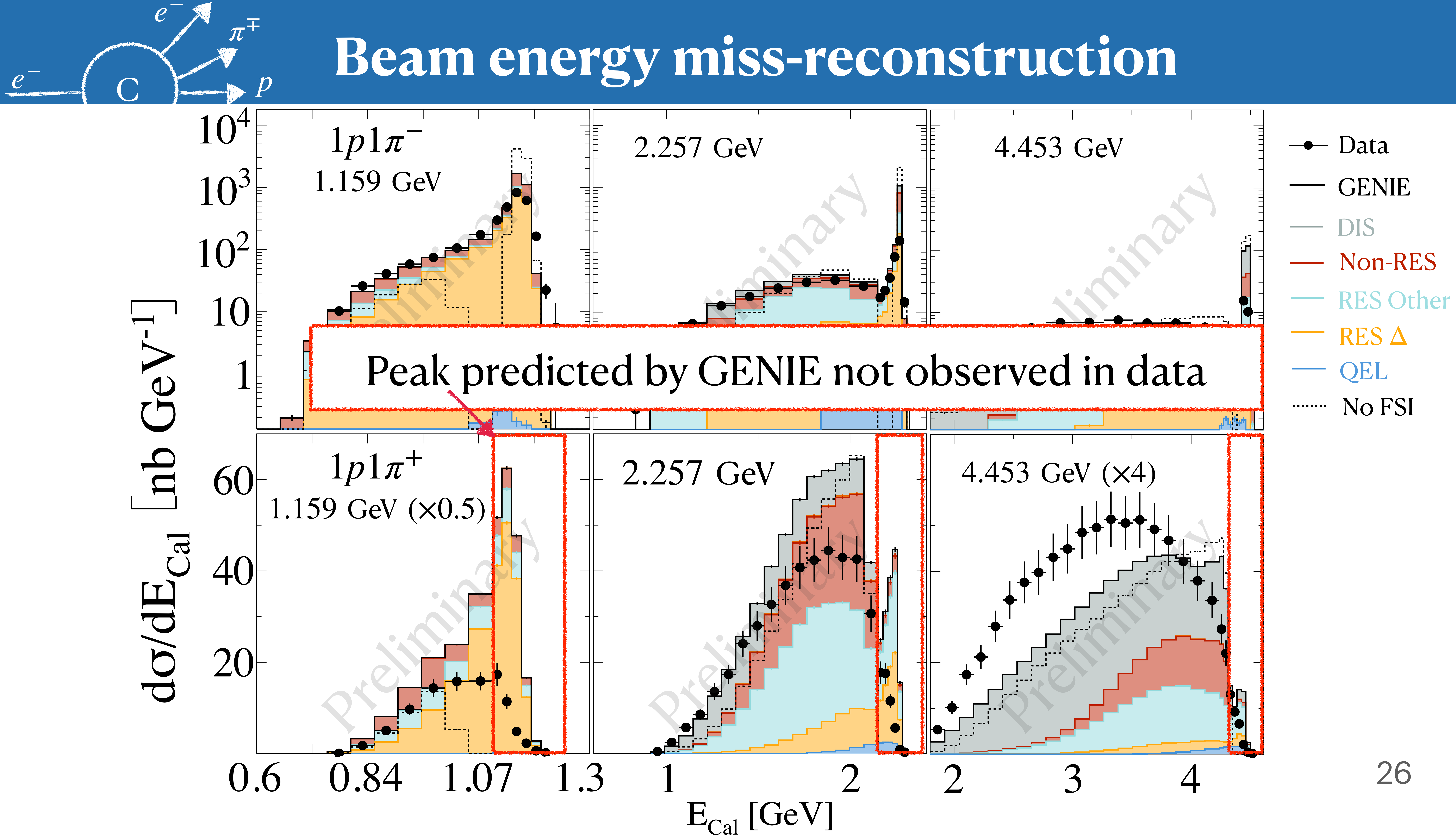
MC does not describe bias



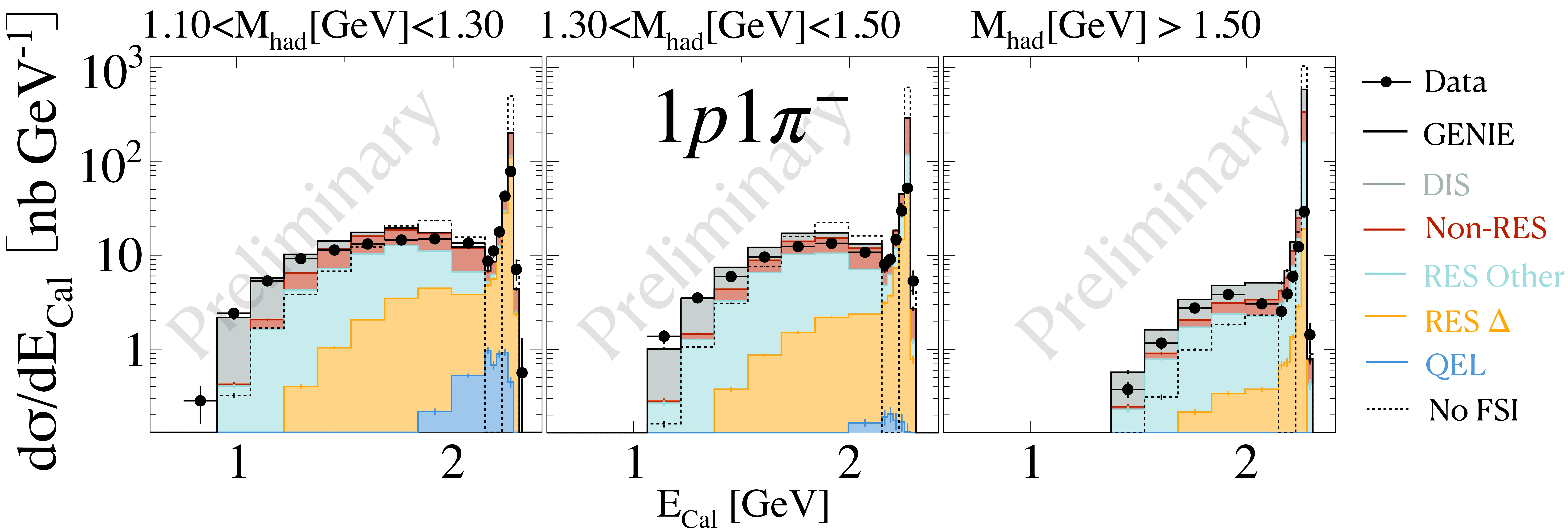
% Peak)	1.159	2.257	4.453
$1p1\pi^-$ **Data**	67%	22%	8%
GENIE	77%	52%	41%

Peak largely over-predicted by GENIE

Beam energy miss-reconstruction

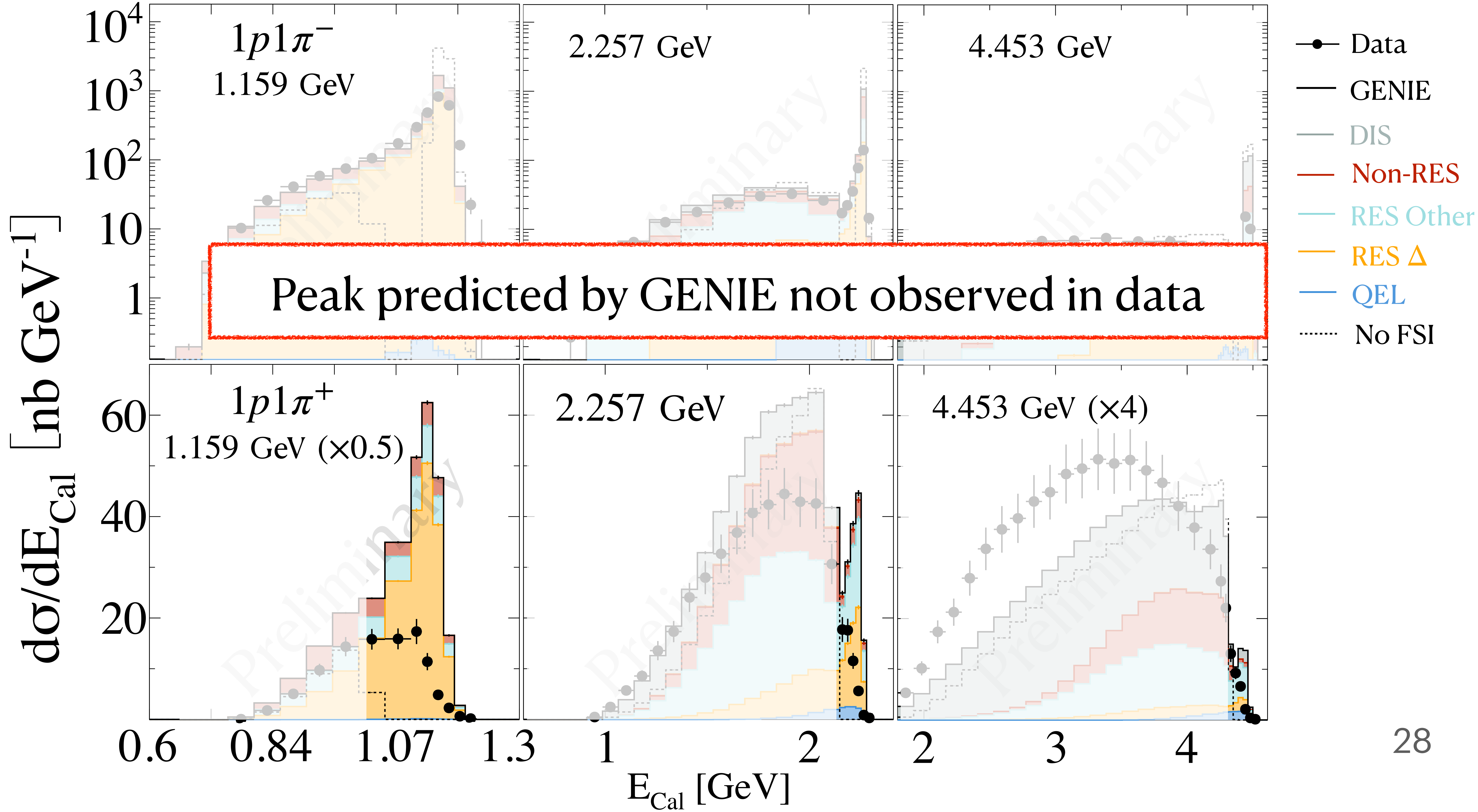


Hadronization biases E_{Cal}



% 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 <u>varies across beam energies</u>
  - <u>Incorrect shower</u> content due to simplistic hadronization model biases W and E_{Cal}
  - GENIE bias reduced for $M_{had} < 1.30$ GeV
- Stay tuned for upcoming measurements!
  - More analysis ongoing for 1-6 GeV electrons on He, C, Ar and many others!


More data on the way!
e4V
C
p
N
Ar
C
π
X
π
p
D
US GENERAL
Thank you for your attention!

The GENIE Event Generator

UNIVERSAL NEUTRINO GENERATOR
& GLOBAL FIT

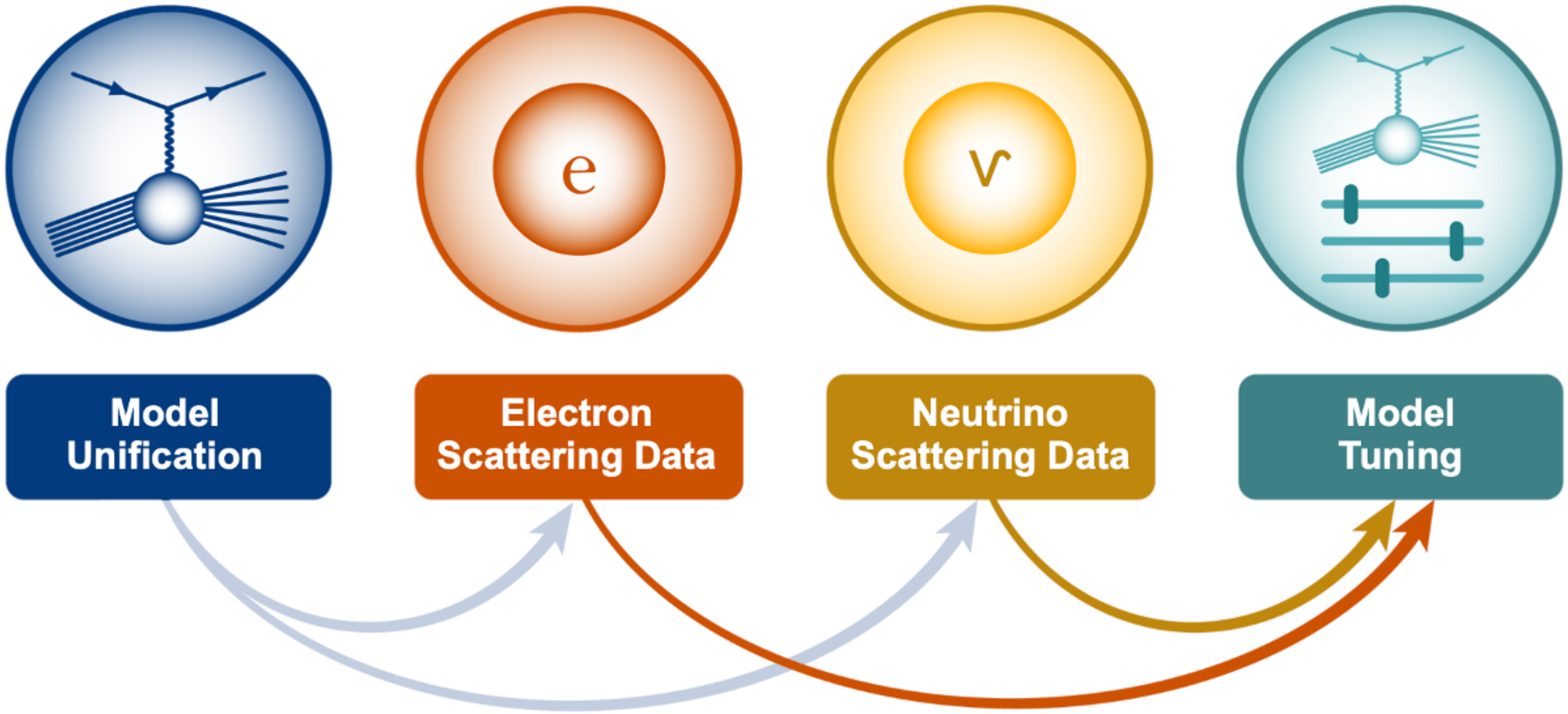
https://genie-mc.github.io/

Tune name in GENIE: GEM21_11a_00_000

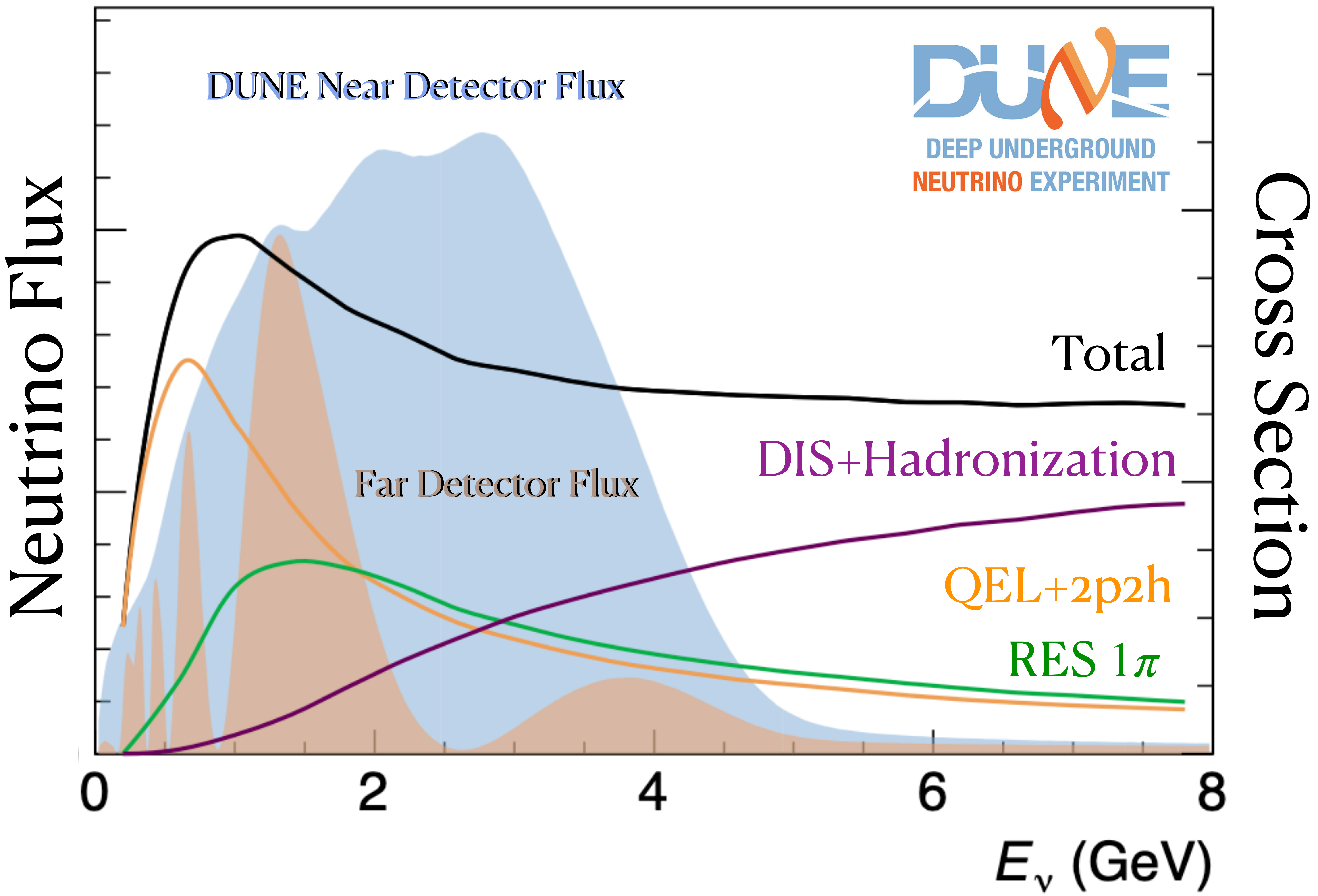
Process	Model
Quasi-ELastic and Two-Particle Two-	SUSAv2 model
RESonance Production	Berger-Sehgal model
Non-RESonance (SIS)	Bodek-Yang model, scaled with multiplicity dependent parameters
Deep Inelastic Scattering	Bodek-Yang model
Final State Interaction model	hA model
Hadronization model	AGKY model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

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

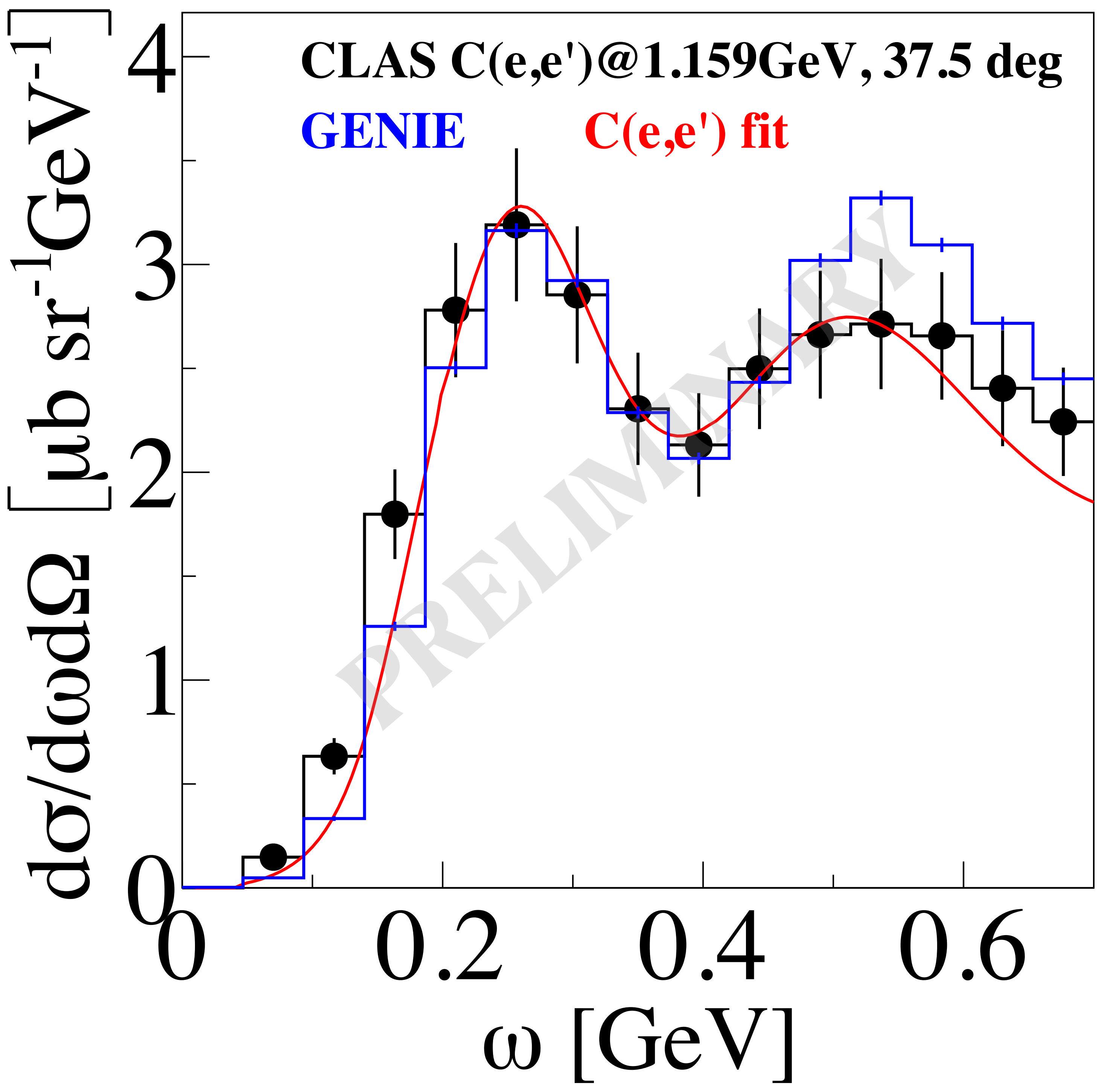
Roadmap for improving event generators

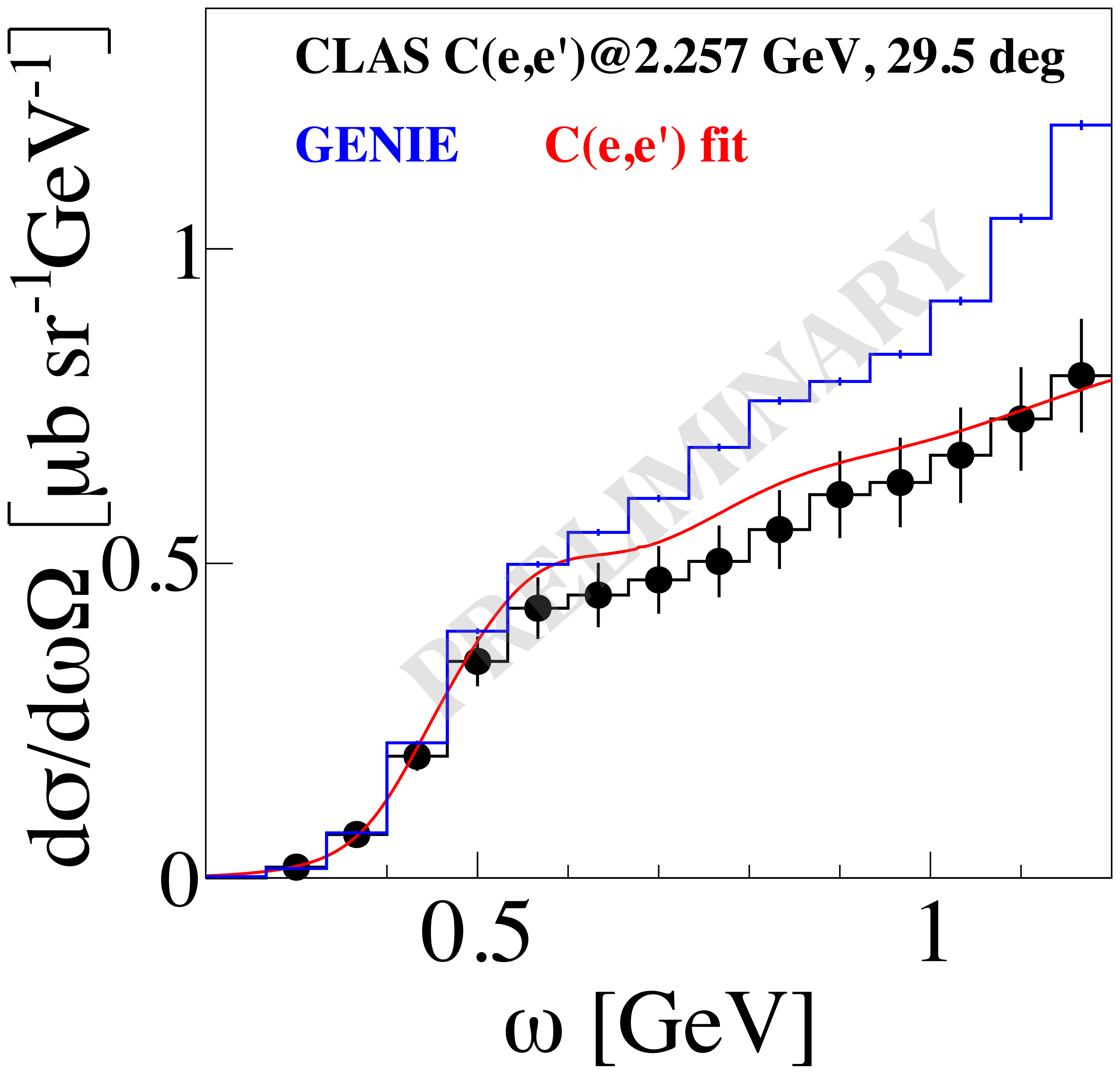


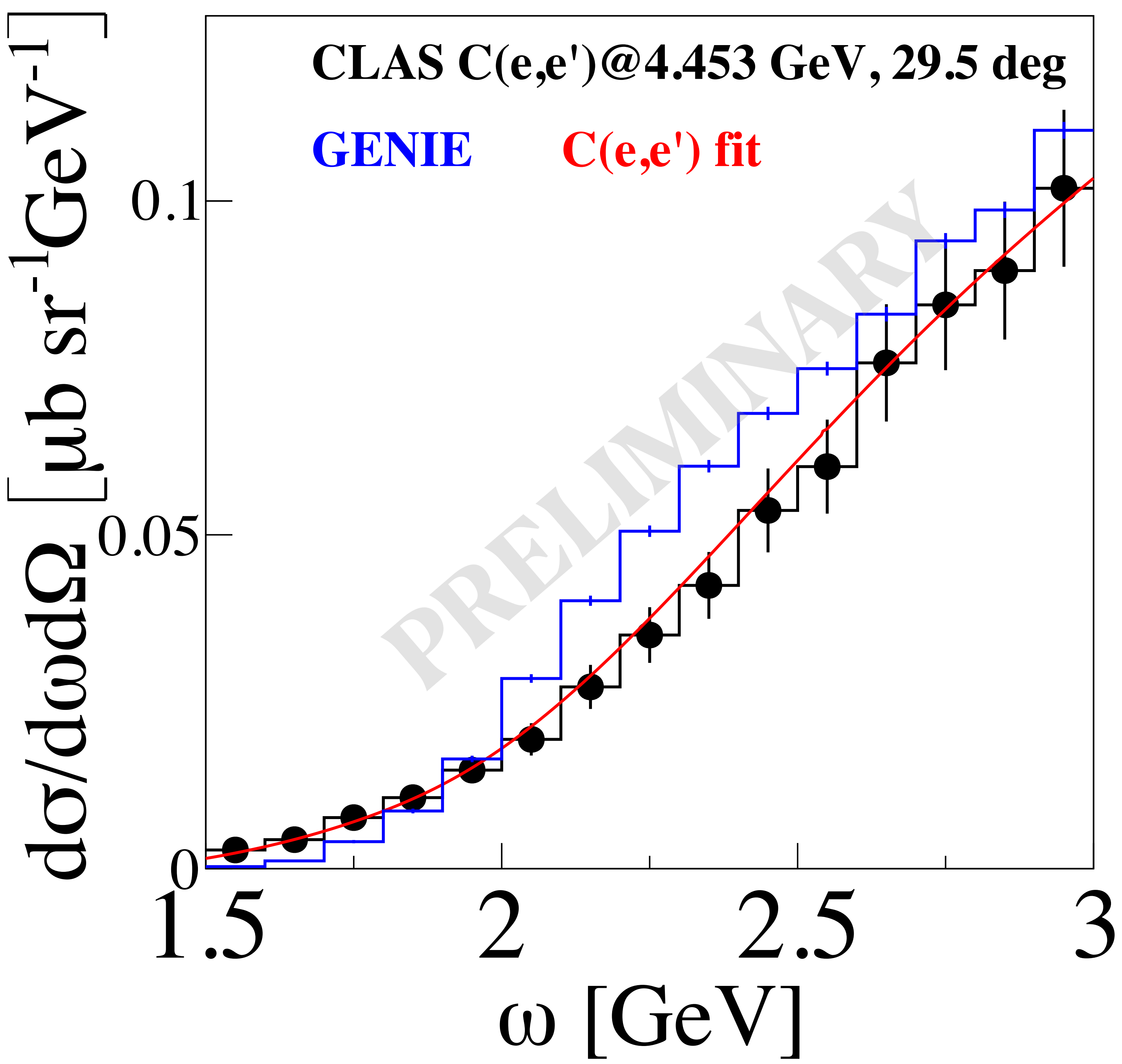
Pion-Production is key for Oscillations



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

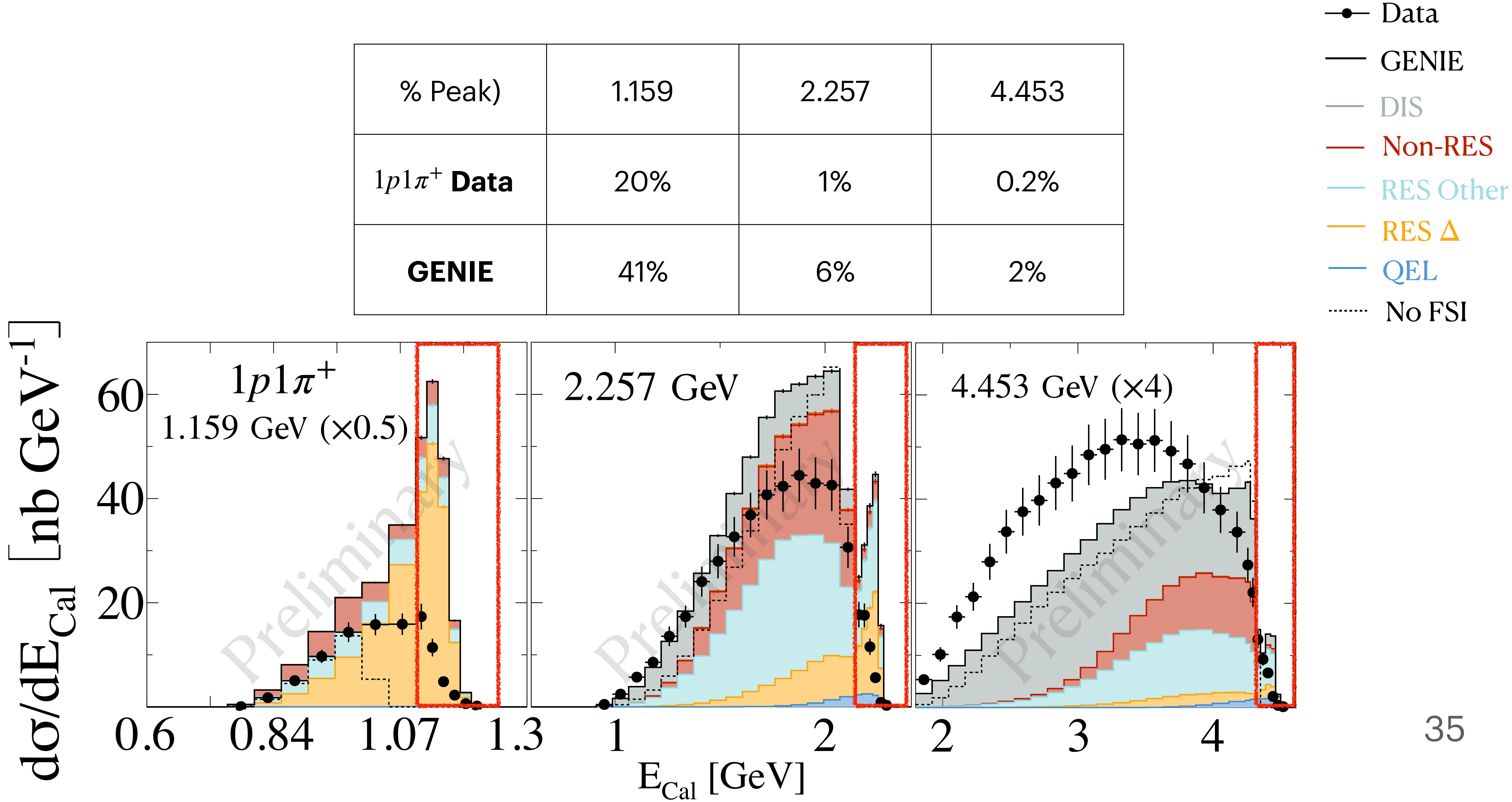




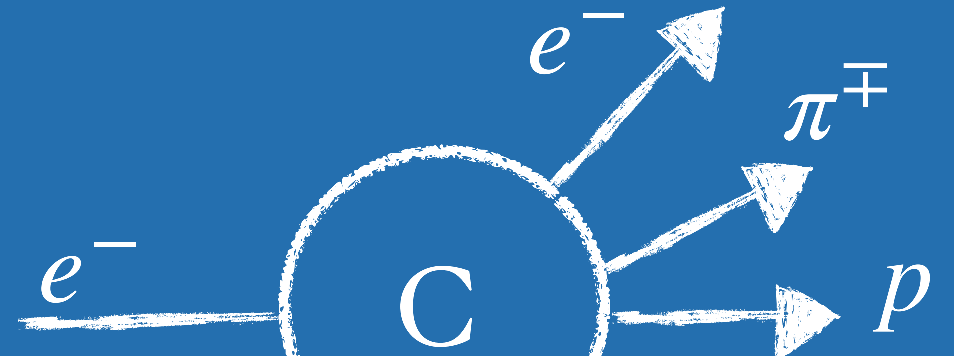


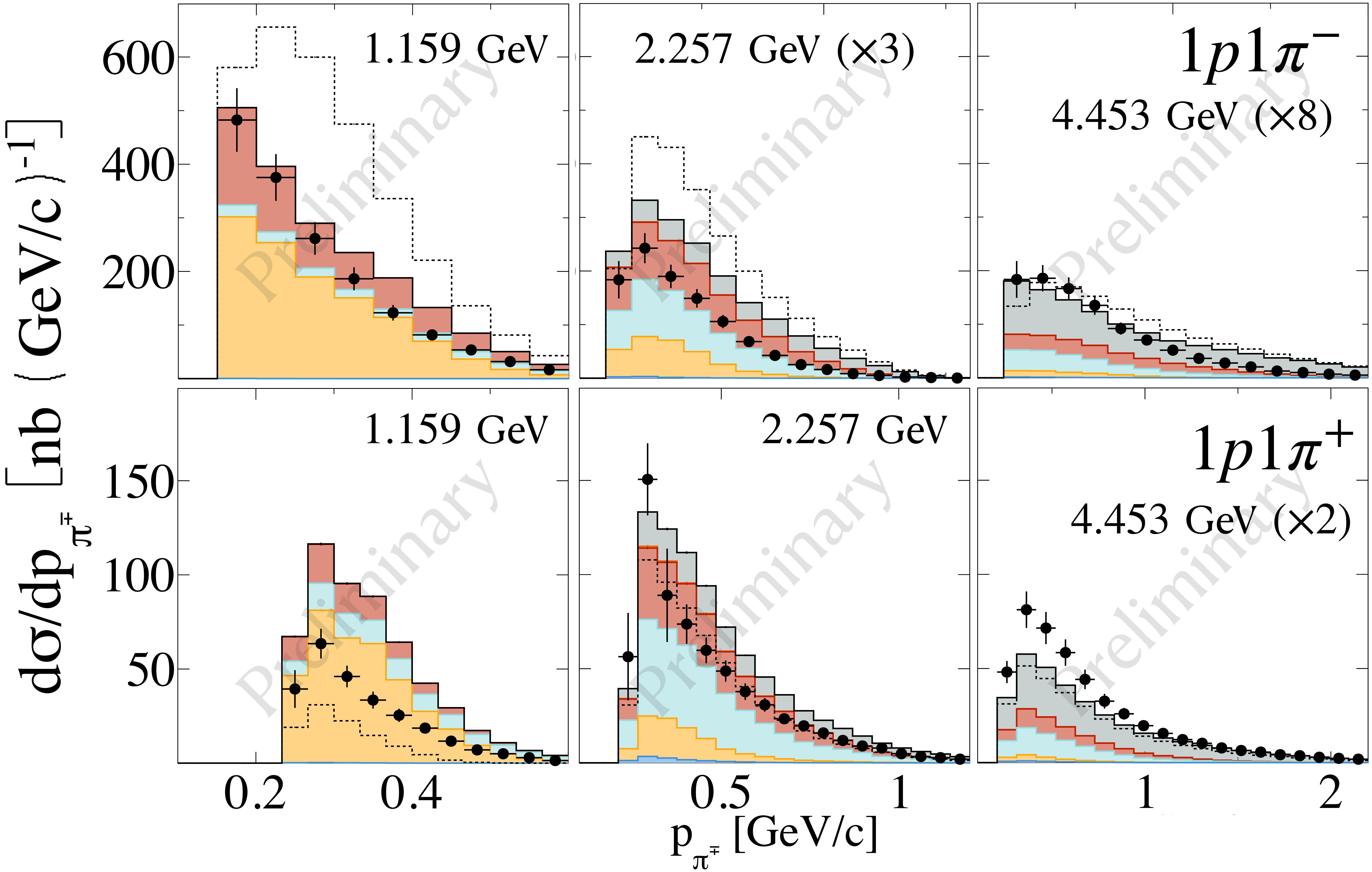
MC induces bias

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

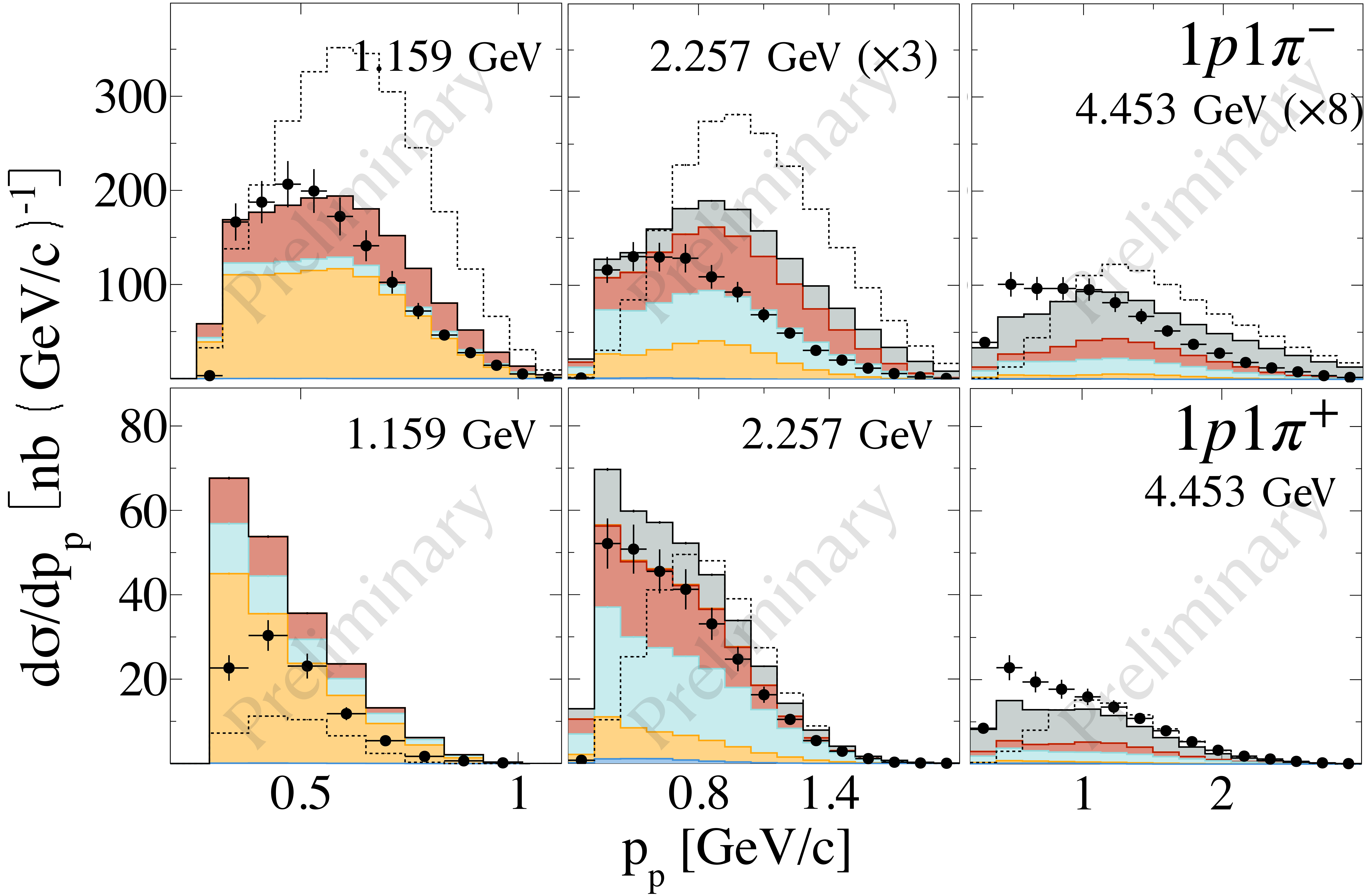


Pion Kinematic Constraints

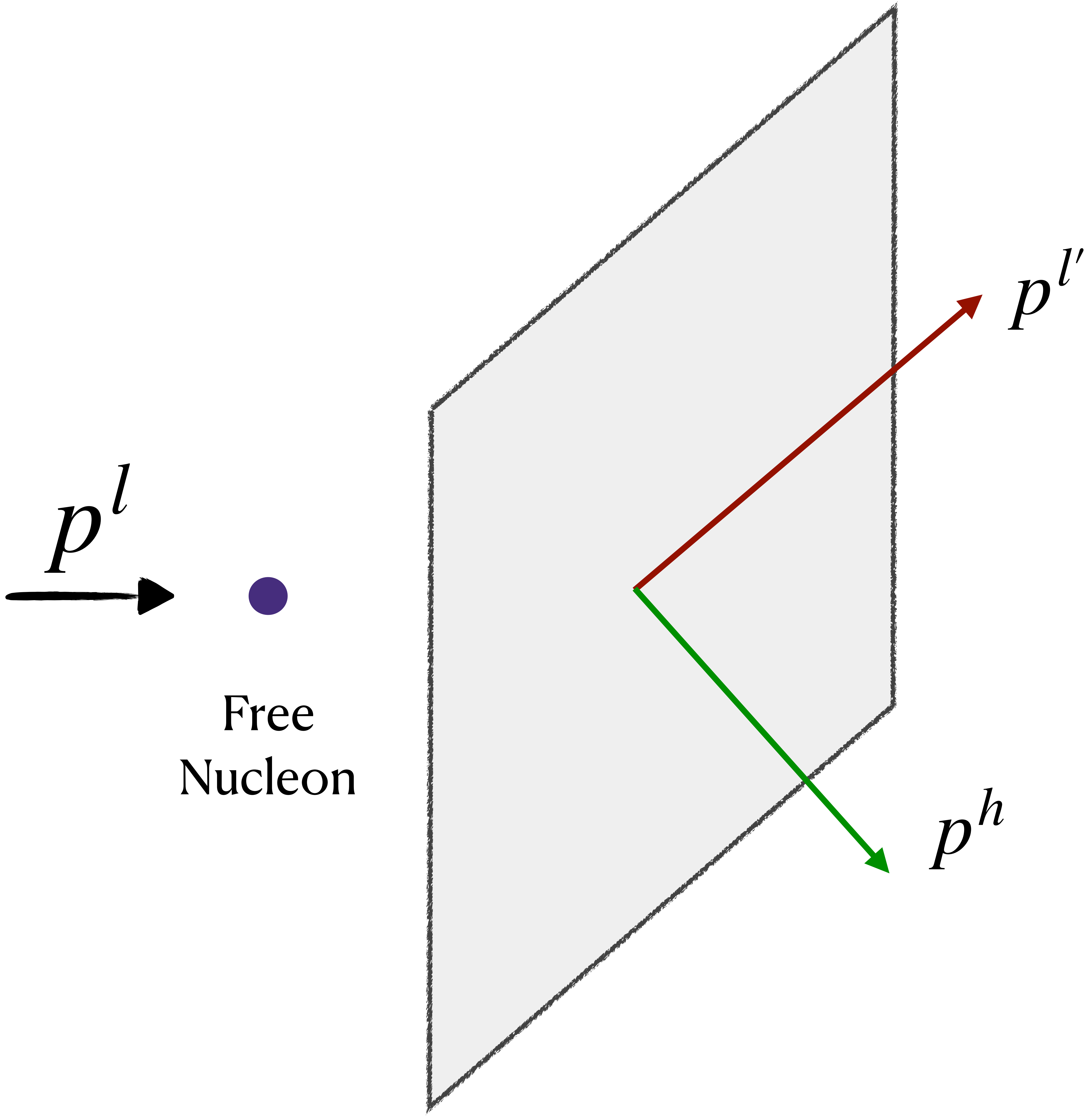




Proton Kinematic Constraints

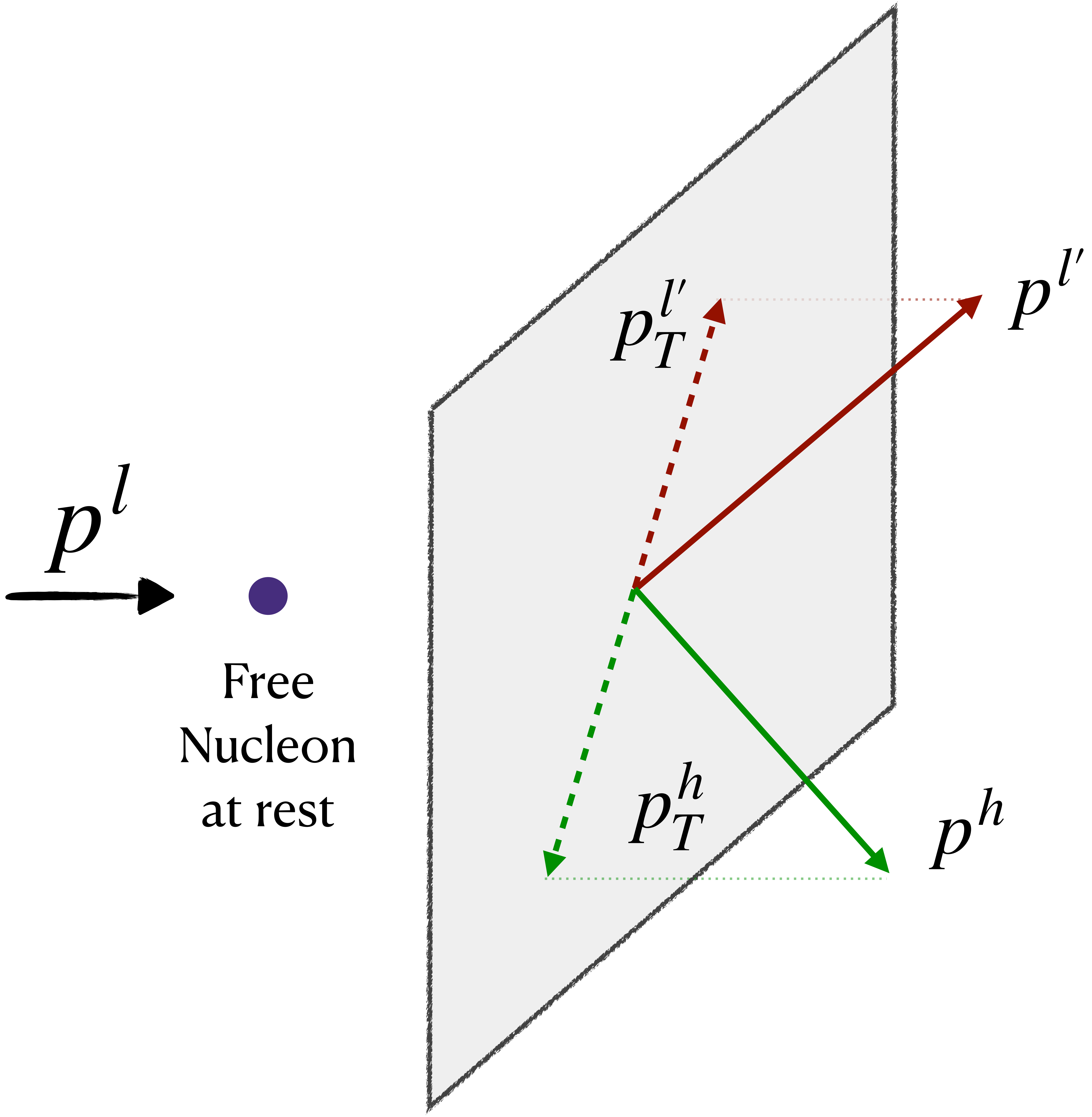


Transverse Kinematic Imbalance (TKI)



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

Missing Transverse Momentum

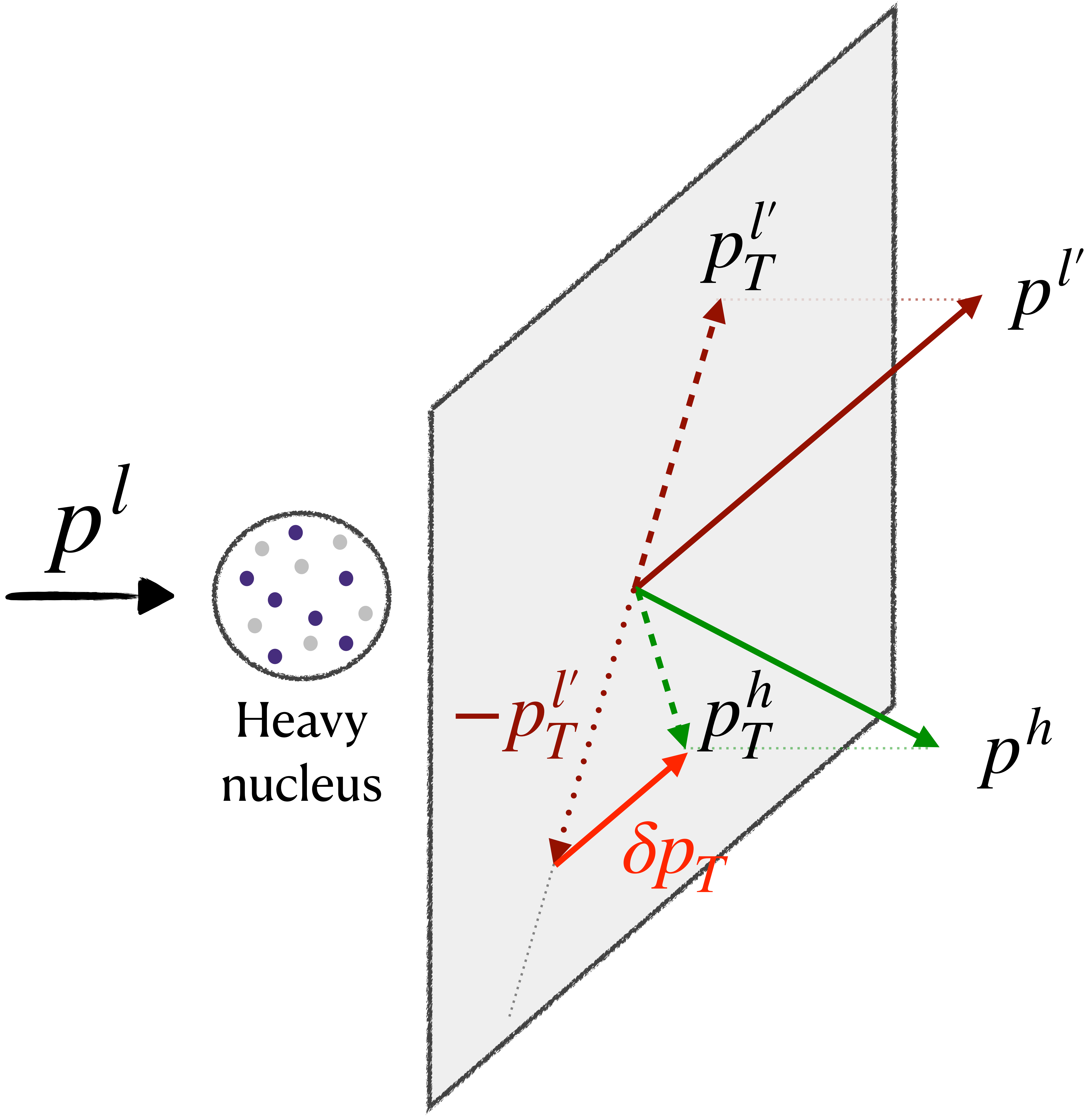


$$\delta \overrightarrow{p}_T = \overrightarrow{p}_T^{l'} + \overrightarrow{p}_T^h$$

$$\delta p_T = 0$$

Beam energy independent

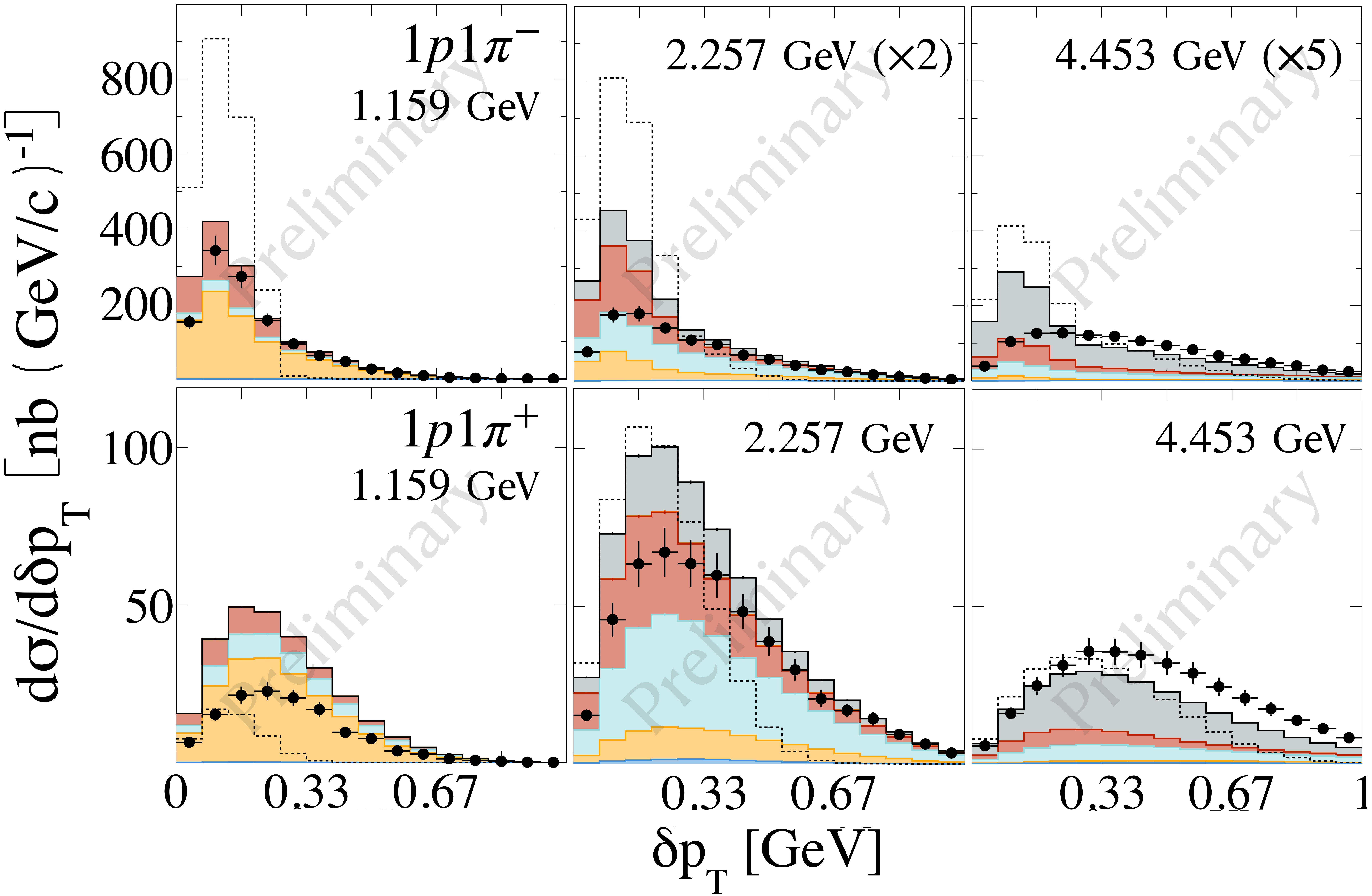
Missing Transverse Momentum



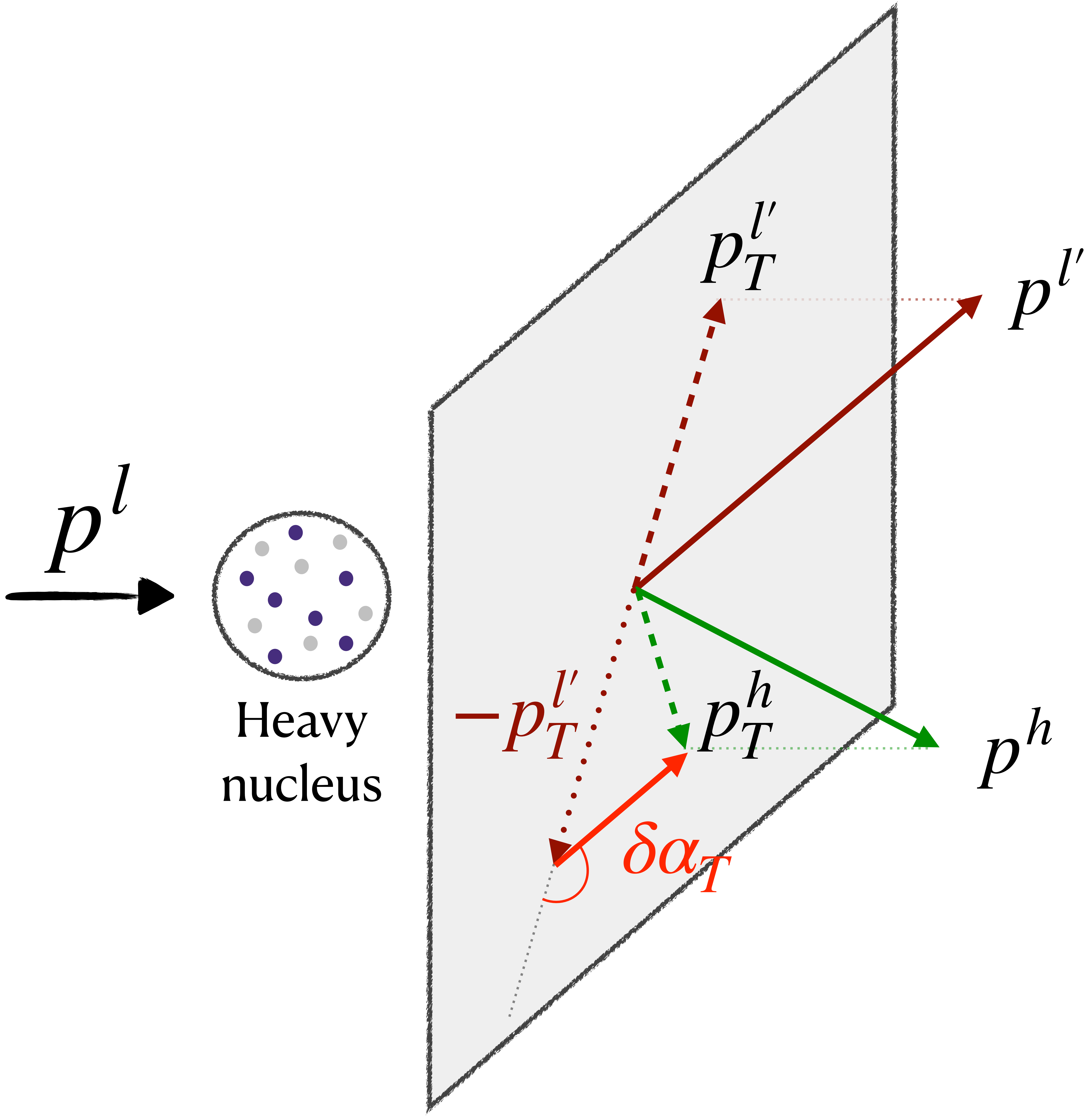
$\delta p_T \neq 0$

Sensitive to FSI and Nuclear dynamics

Missing Transverse Momentum



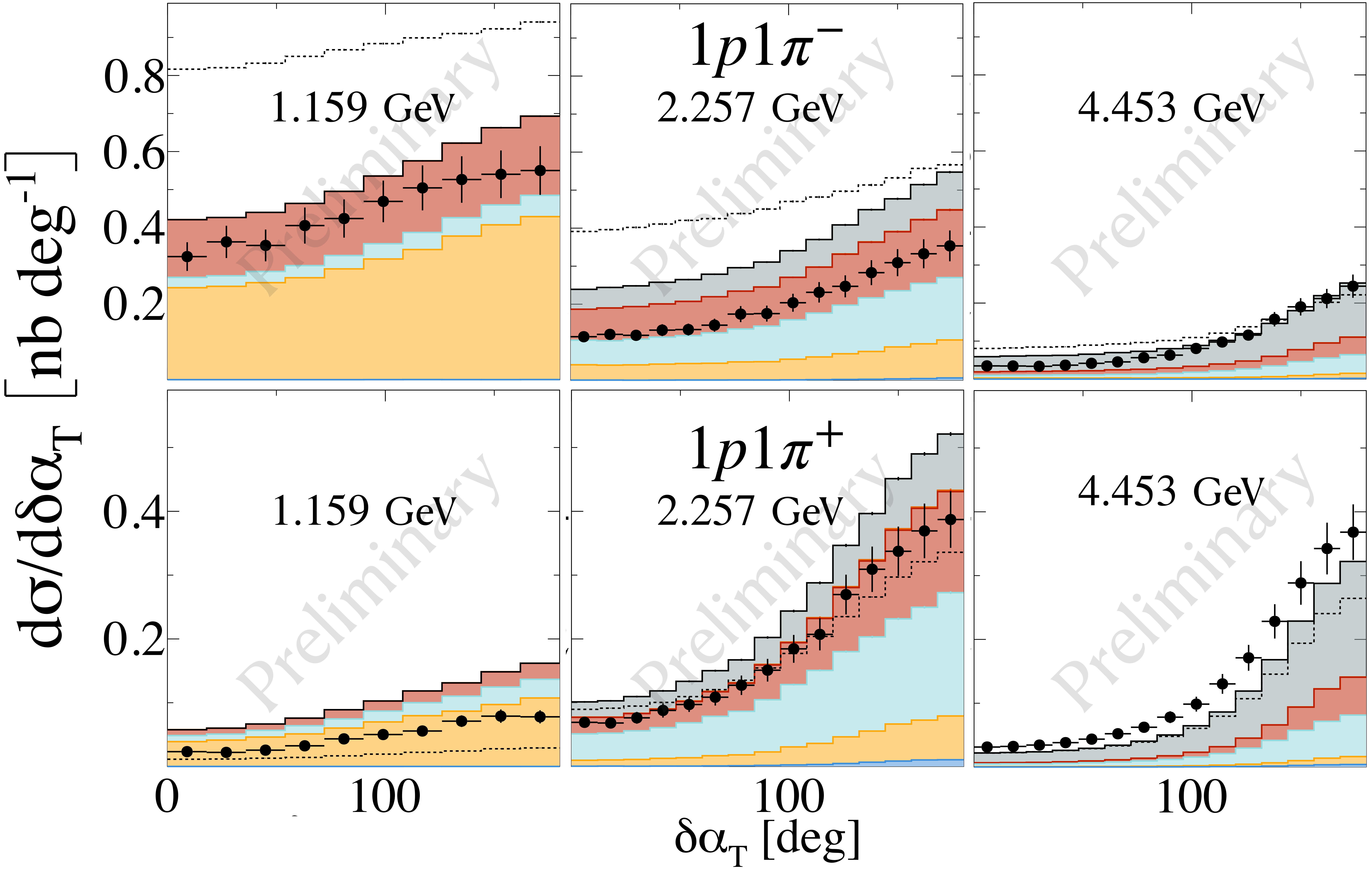
Transverse Boosting Angle



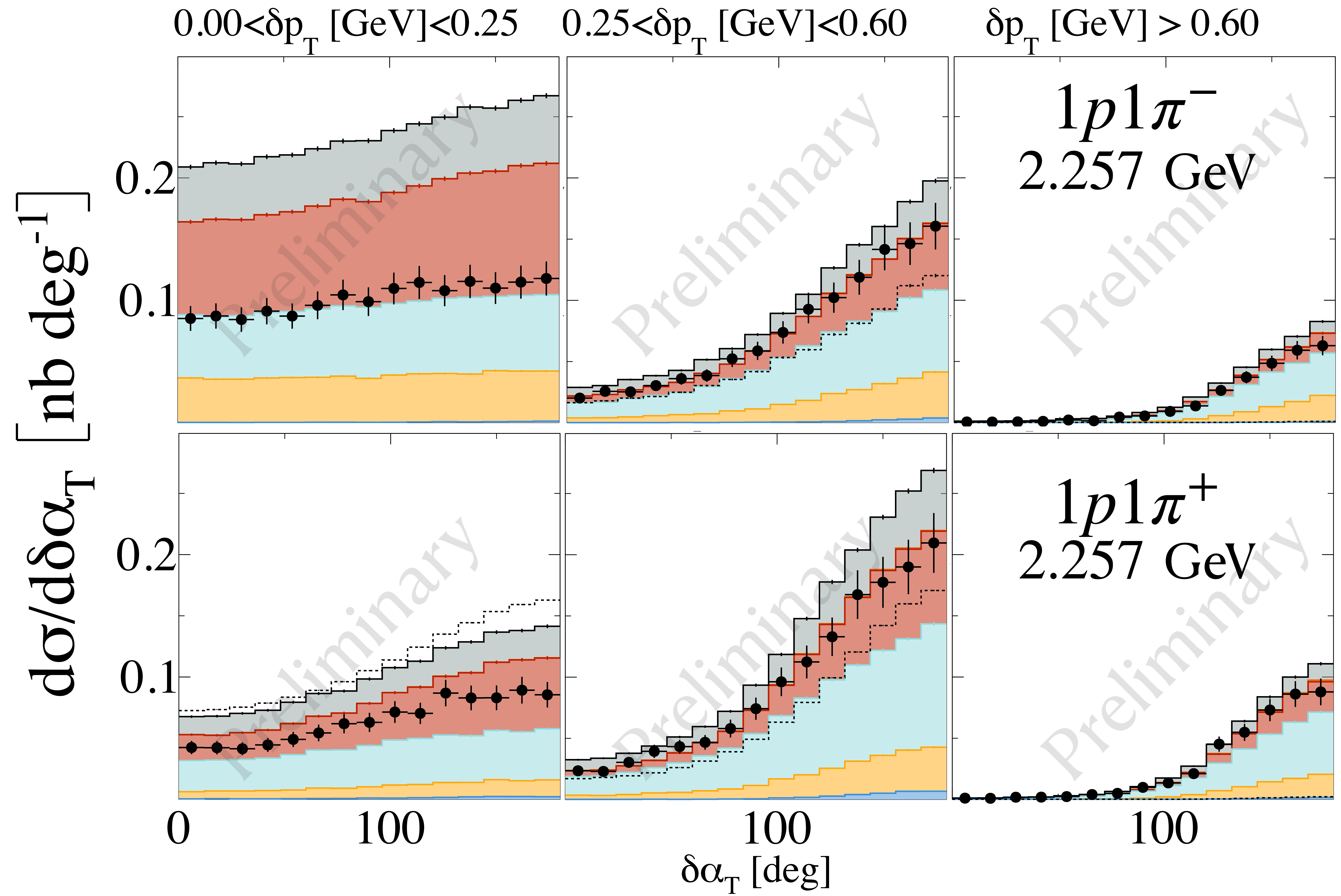
$$\delta\alpha_T = \cos^{-1}\frac{-\vec{p}_T^{\,l'}\cdot\delta\vec{p}_T}{p_T^{l'}\delta p_T}$$

Most sensitive to FSI

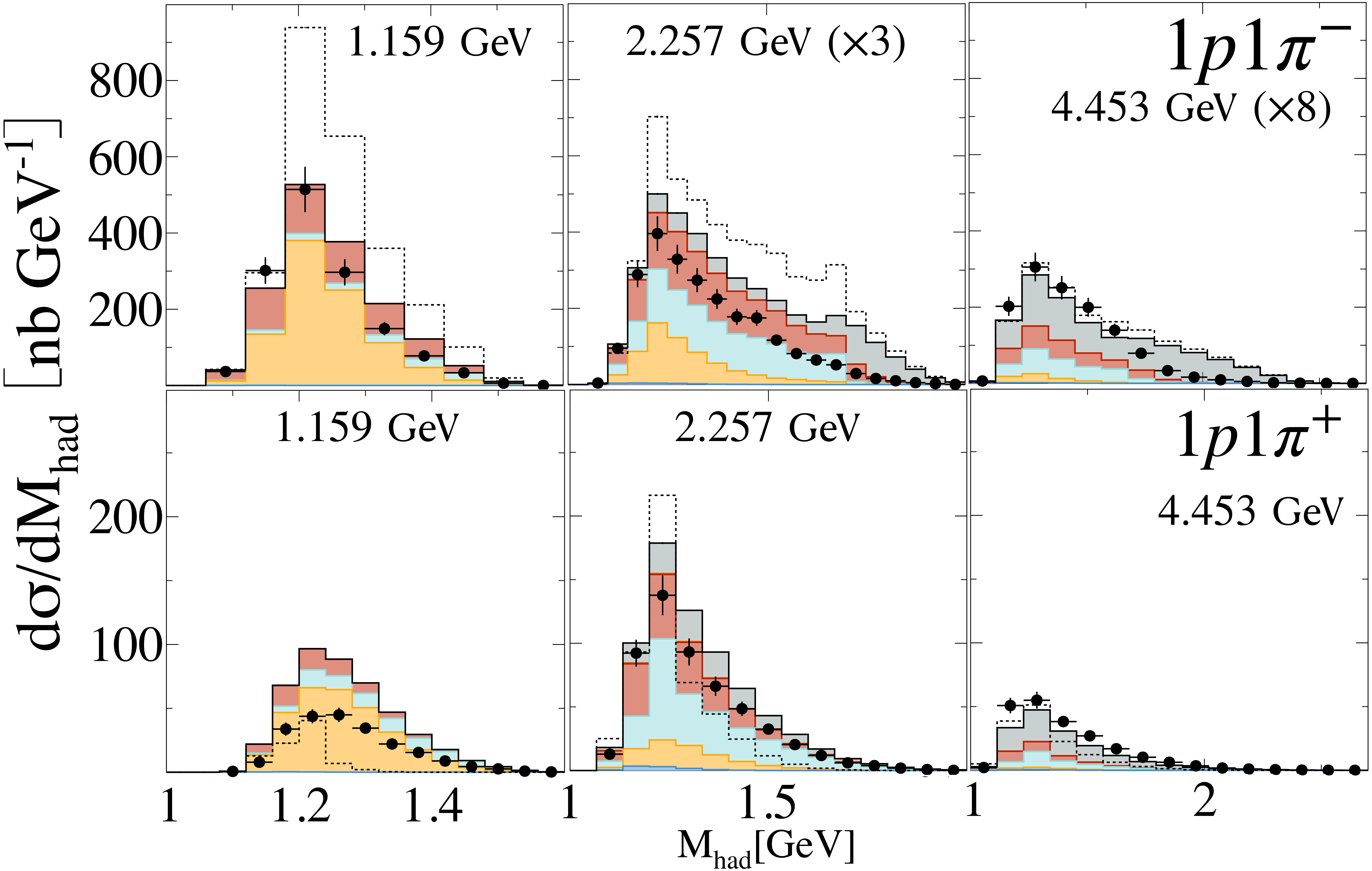
Transverse Boosting Angle



Transverse Boosting Angle



W Miss-Reconstruction



E_{Cal} dependence with δp_T