Probing neutrino simulations with electron scattering data

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Outline

- **Challenges in neutrino cross-sections**
- **The "Electrons for Neutrinos" (*e*4*ν*) effort**

- **Jefferson Lab & neutrino physics**

➡ **Unique BDX potential to extend JLab's physics reach**

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

Mass Ordering & CP violation

Precision measurements

Sterile neutrinos and Non-Standard Interactions

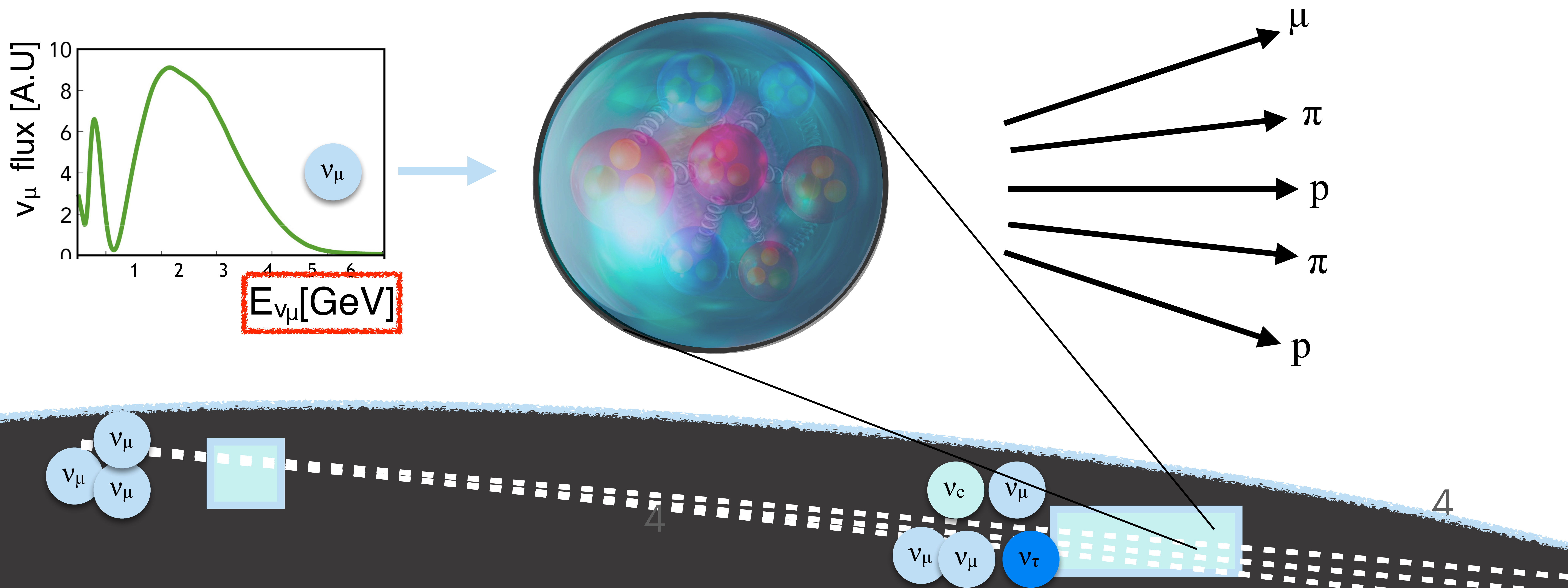
Supernova neutrinos

3

The precision era

Incoming true flux | Modelling Input | Measurement

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



The precision era

Incoming true flux | Modelling Input | Measurement

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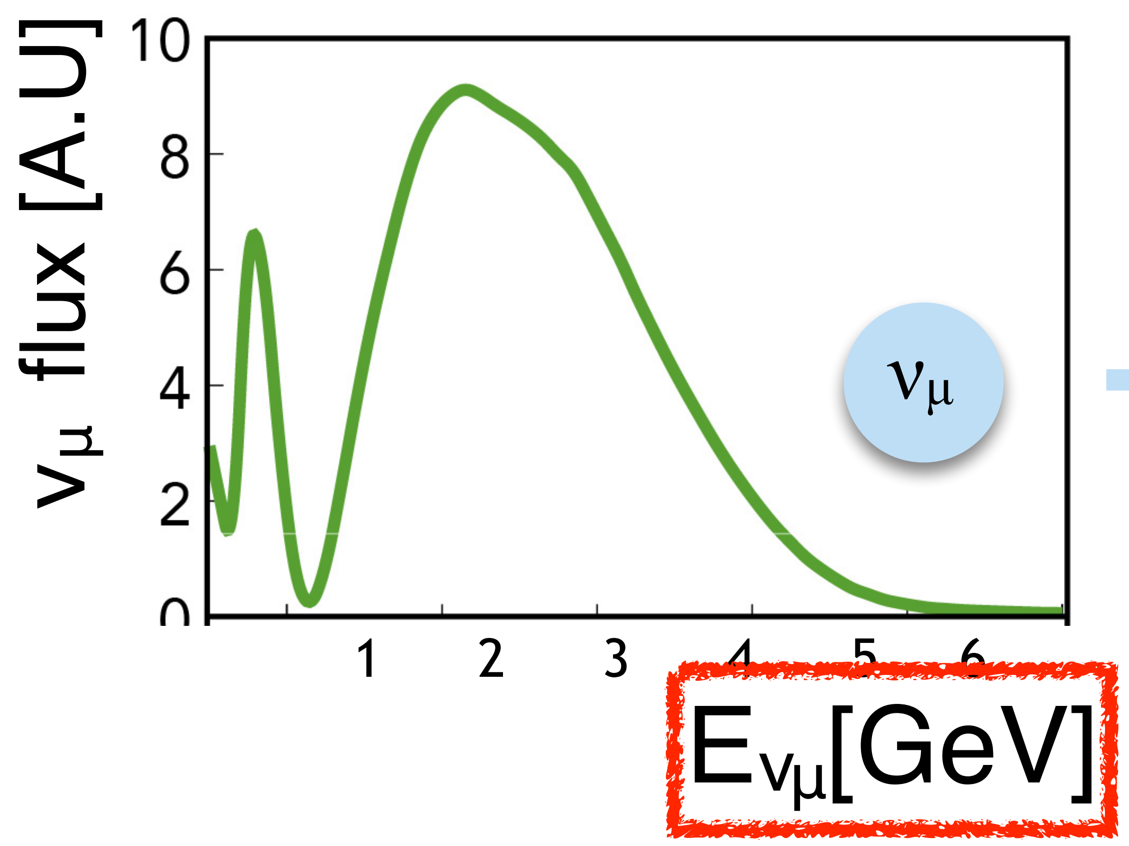
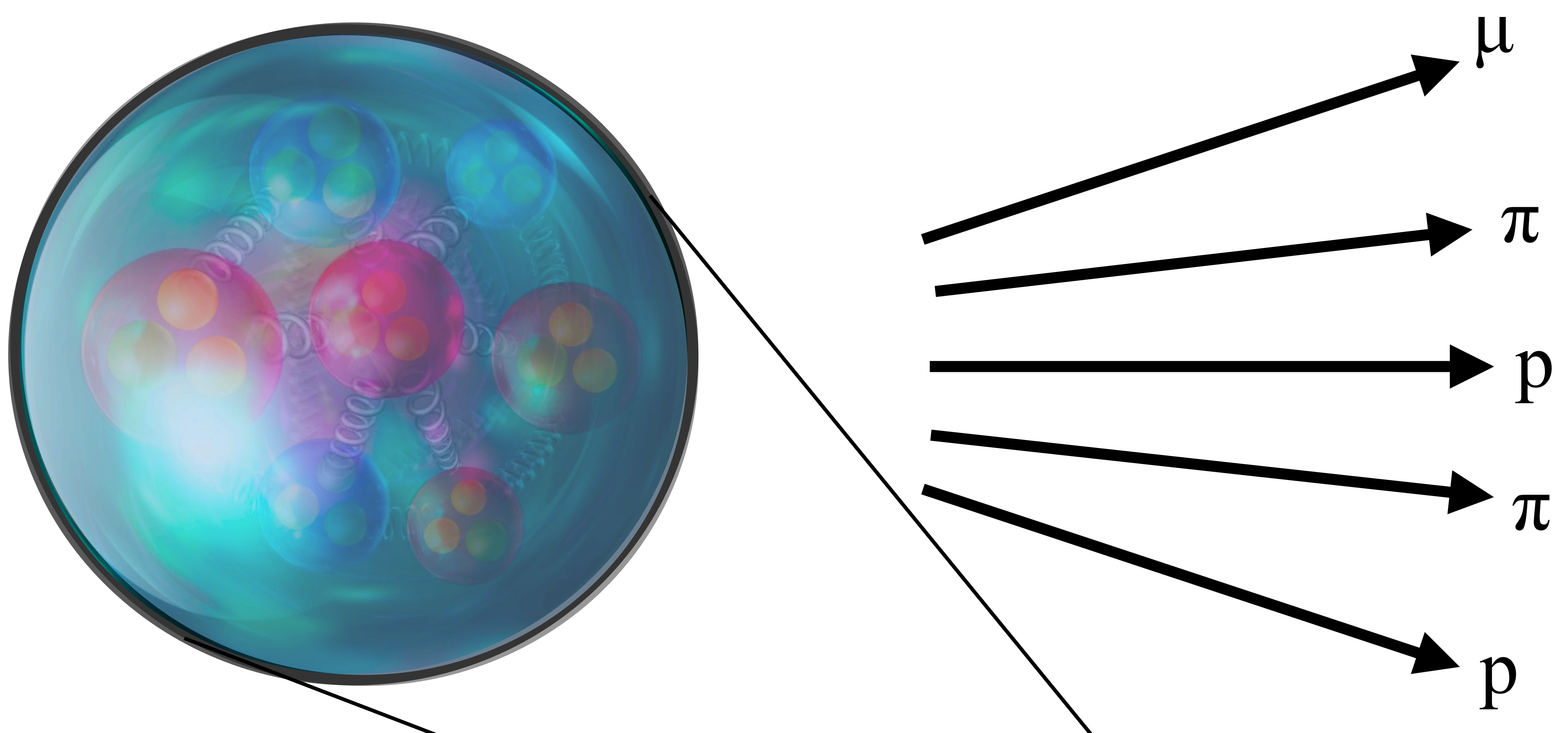
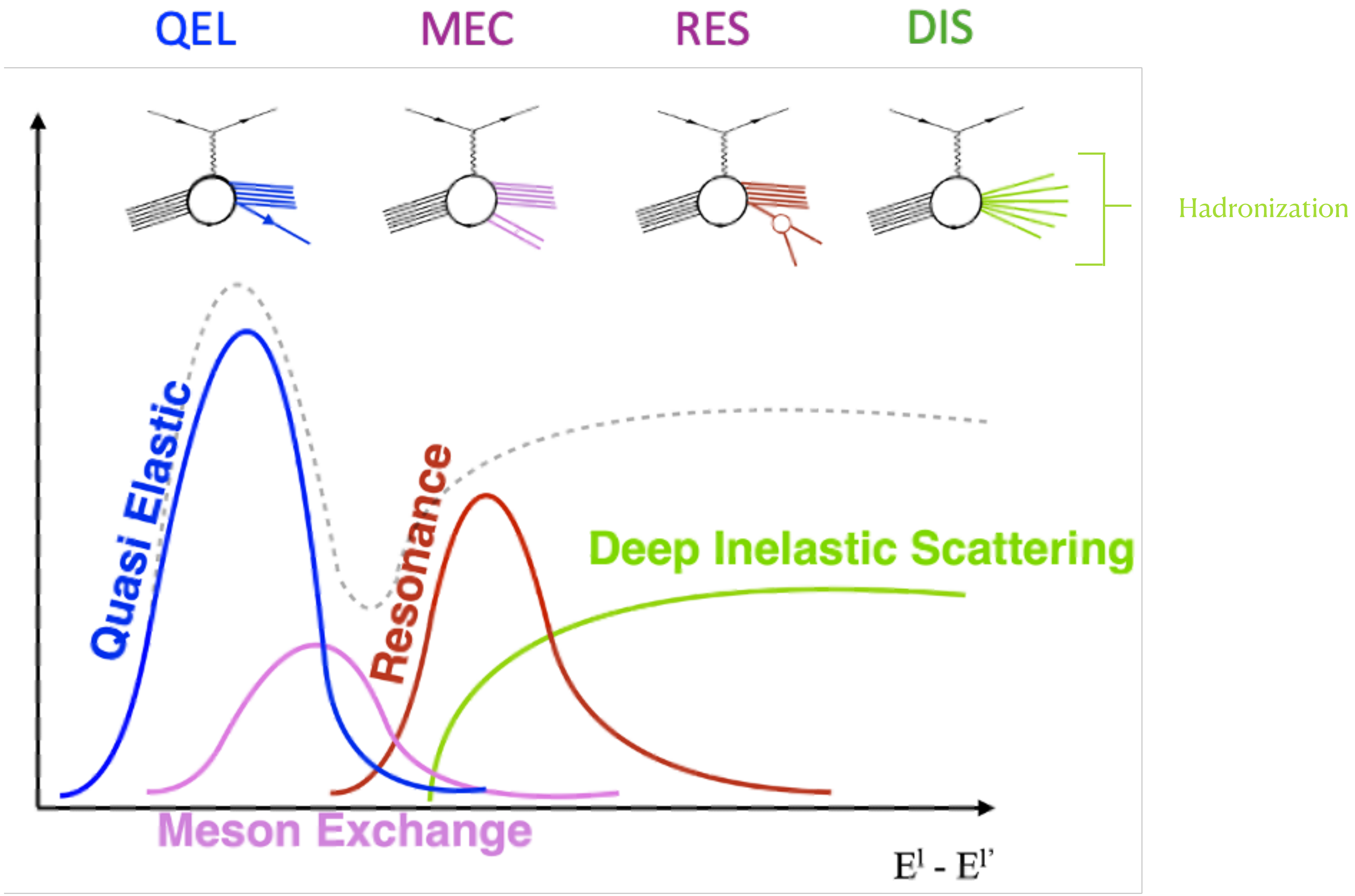
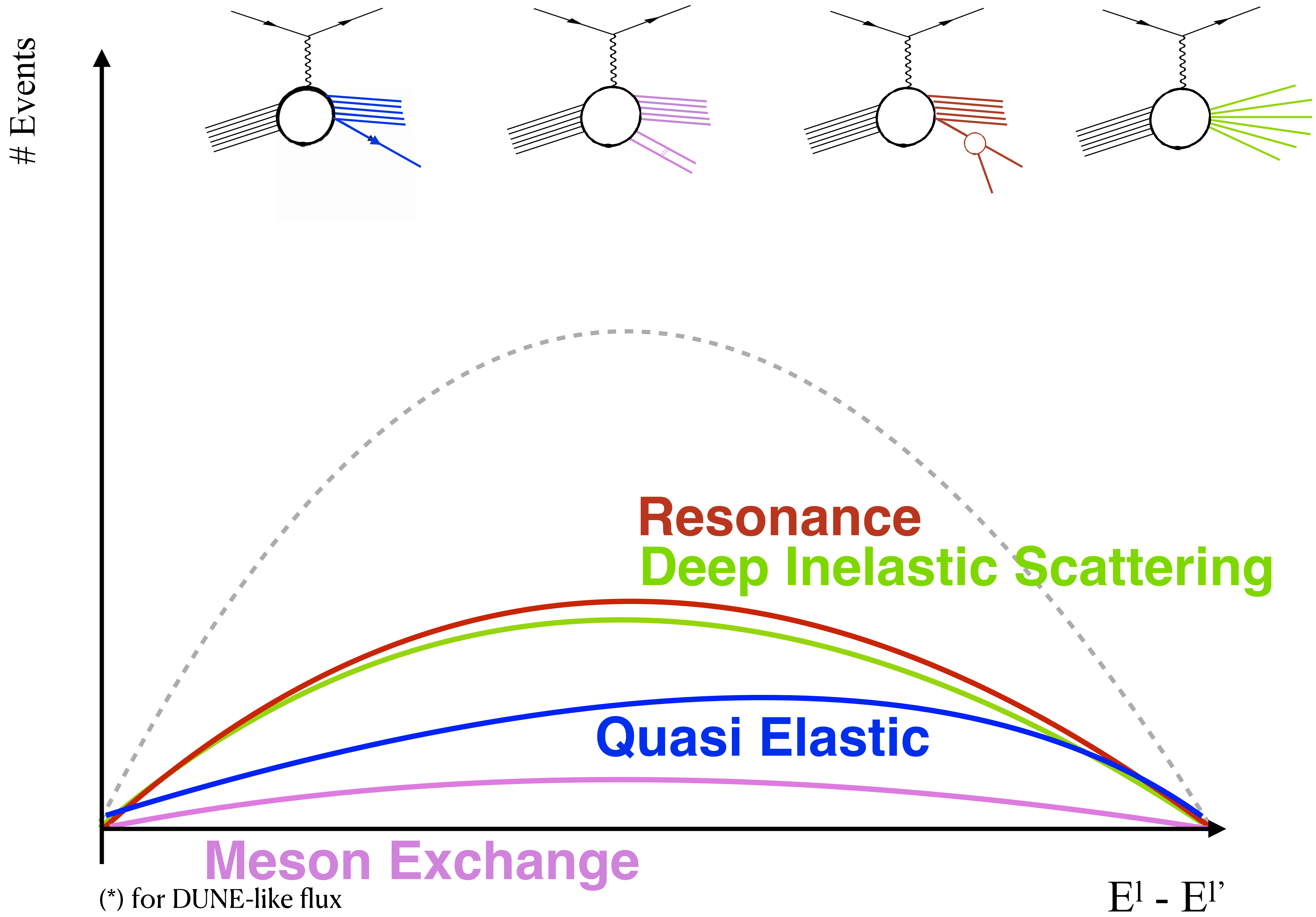




Energy reconstruction depends on νA modelling



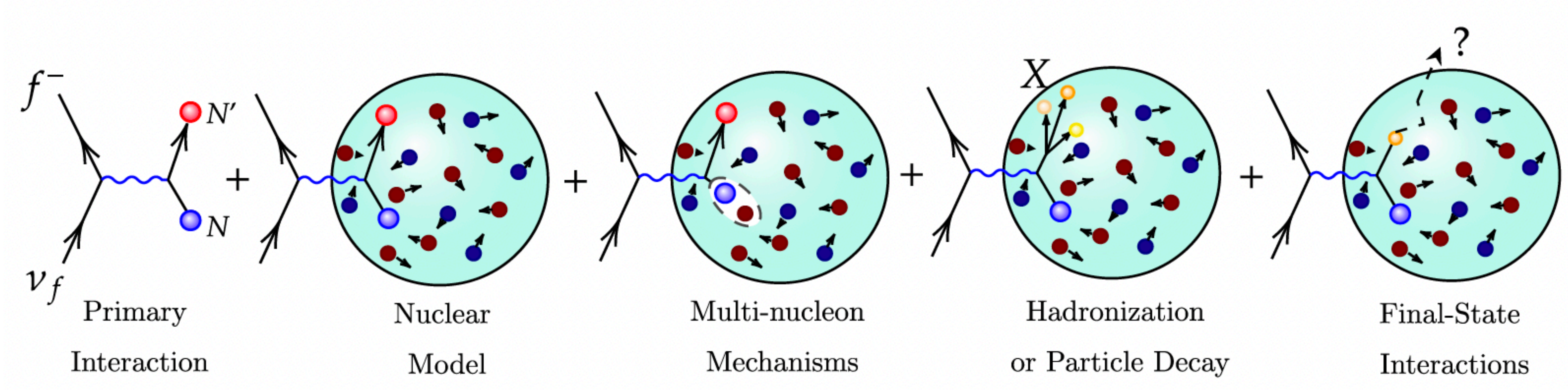
Neutrino measurements are challenging



Neutrino Event Generators

Bridge between theory and experiment

Challenge: non-perturbative QCD and nuclear physics



Many pieces & approximations lead to large modelling uncertainties

External data is needed

Electrons for Neutrinos

Dedicated effort using eA to improve νA

Jefferson's Lab & CLAS:

- $1p0\pi$ [Khachatryan M.Papadopoulou A. et. al. S. Nature (2021)]
- Proton transparency [S. Dytman et. al. arXiv.2508.01905]
- $C(e, e'1p1\pi^{\pm})$ under review by J. Tena Vidal
- $Ar(e, e')$ by Matan Goldenberg, $2N$ by Alon Sportes
- $N\pi^{\pm}$ by Caleb Folger and $1\pi^{\pm}$ by Brittany Cohen
- Pion Transparency by Petter Litton

GENIE Monte Carlo developers:

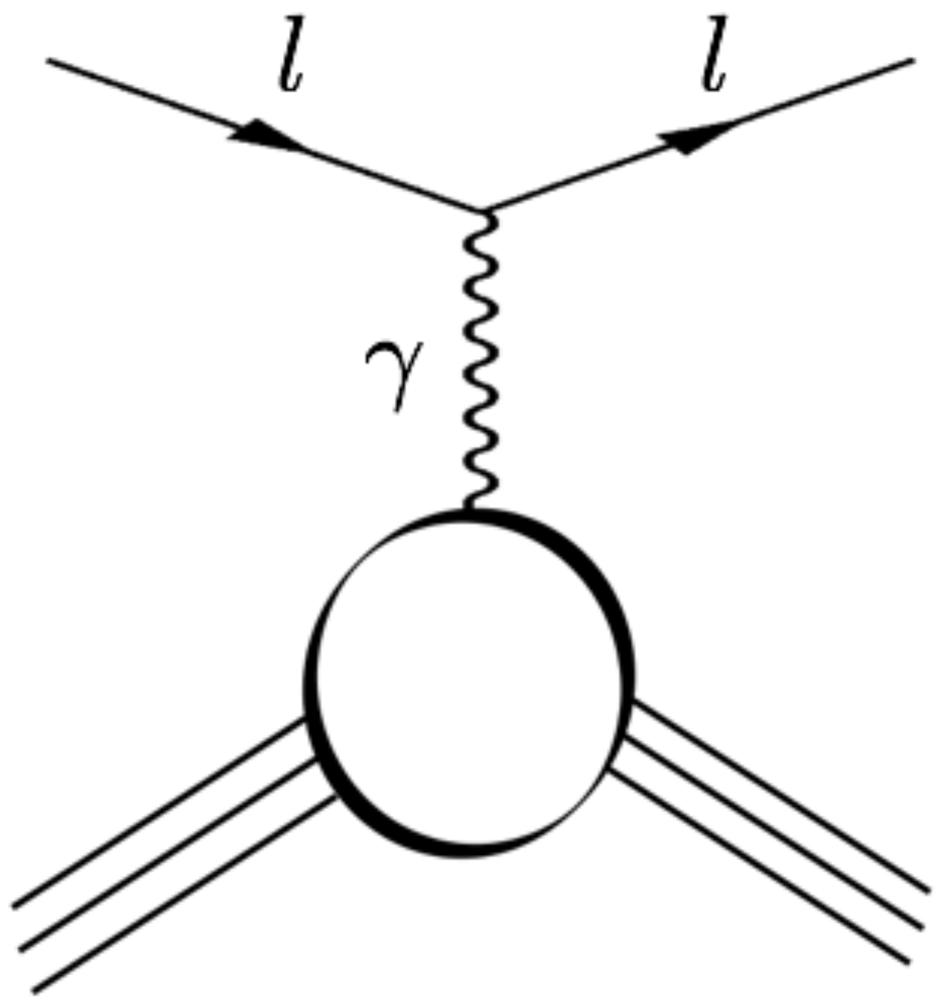
- MEC, FSI and pion production models
- by Alon Sportes, Steven Dytman and J. Tena Vidal

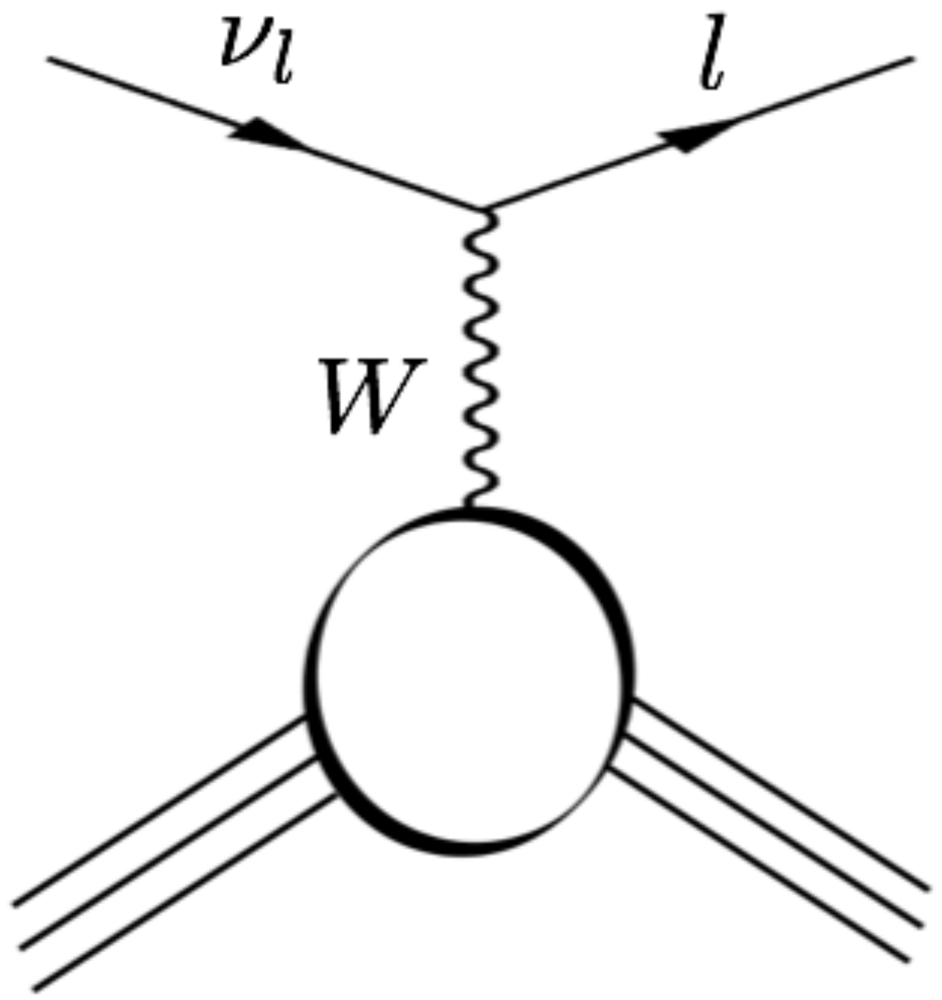
(*) Published, Under Review, Ongoing analyses

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]

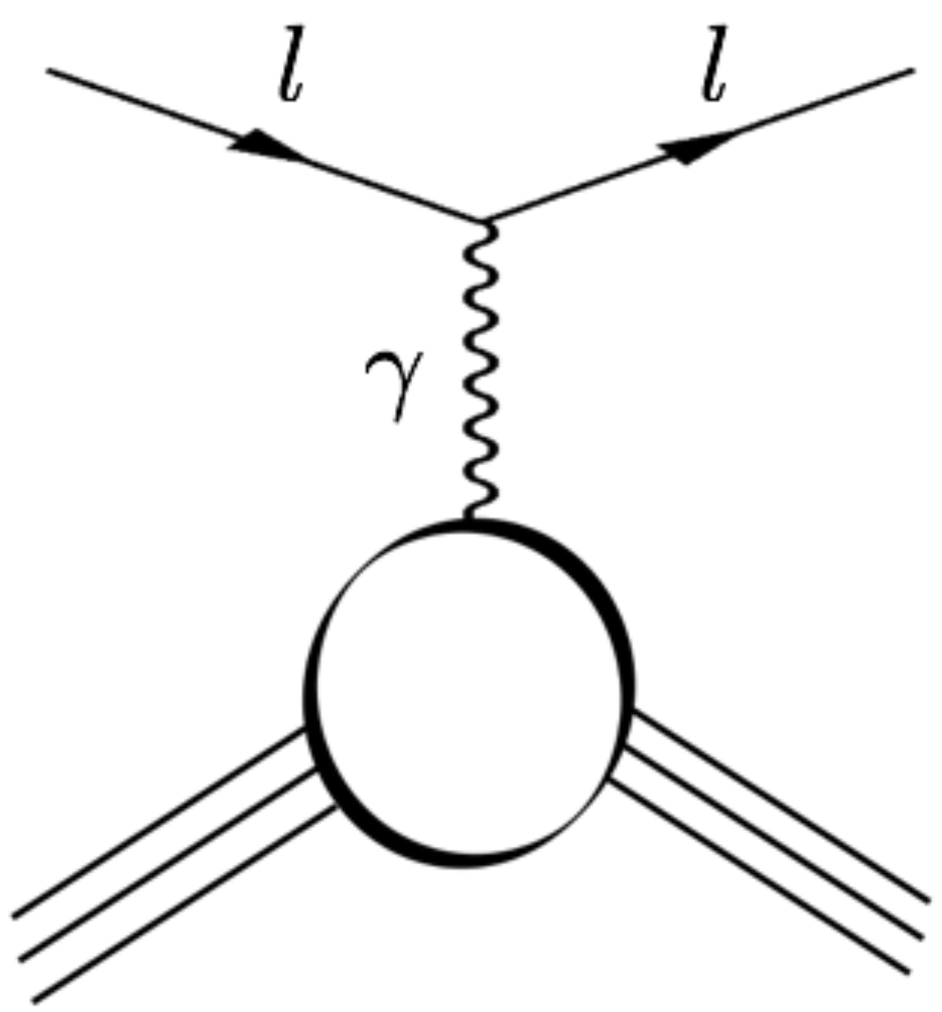
$$j_\mu^{\pm} = \bar{u}\frac{-ig_W}{2\sqrt{2}}(\gamma^\mu - \gamma^\mu\gamma^5)u$$

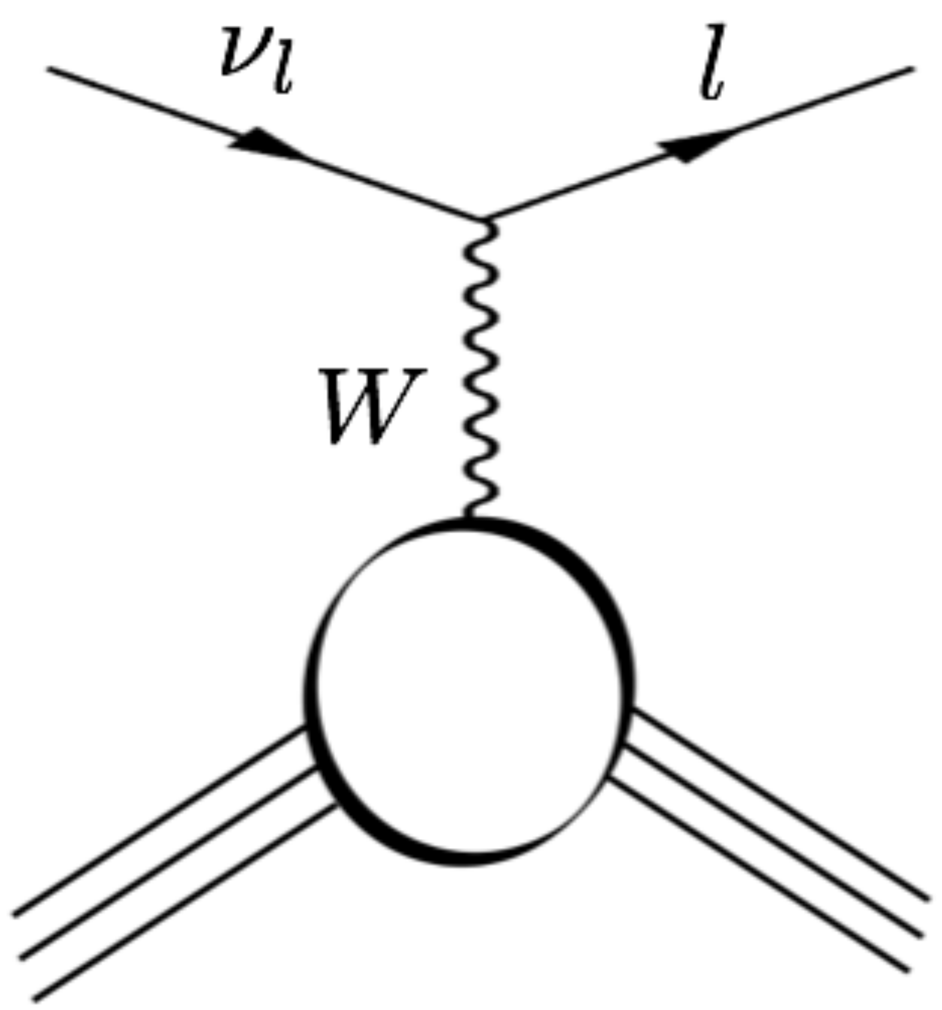
eA useful to constrain νA model uncertainties

Why electrons?

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

Similar interactions with nuclei



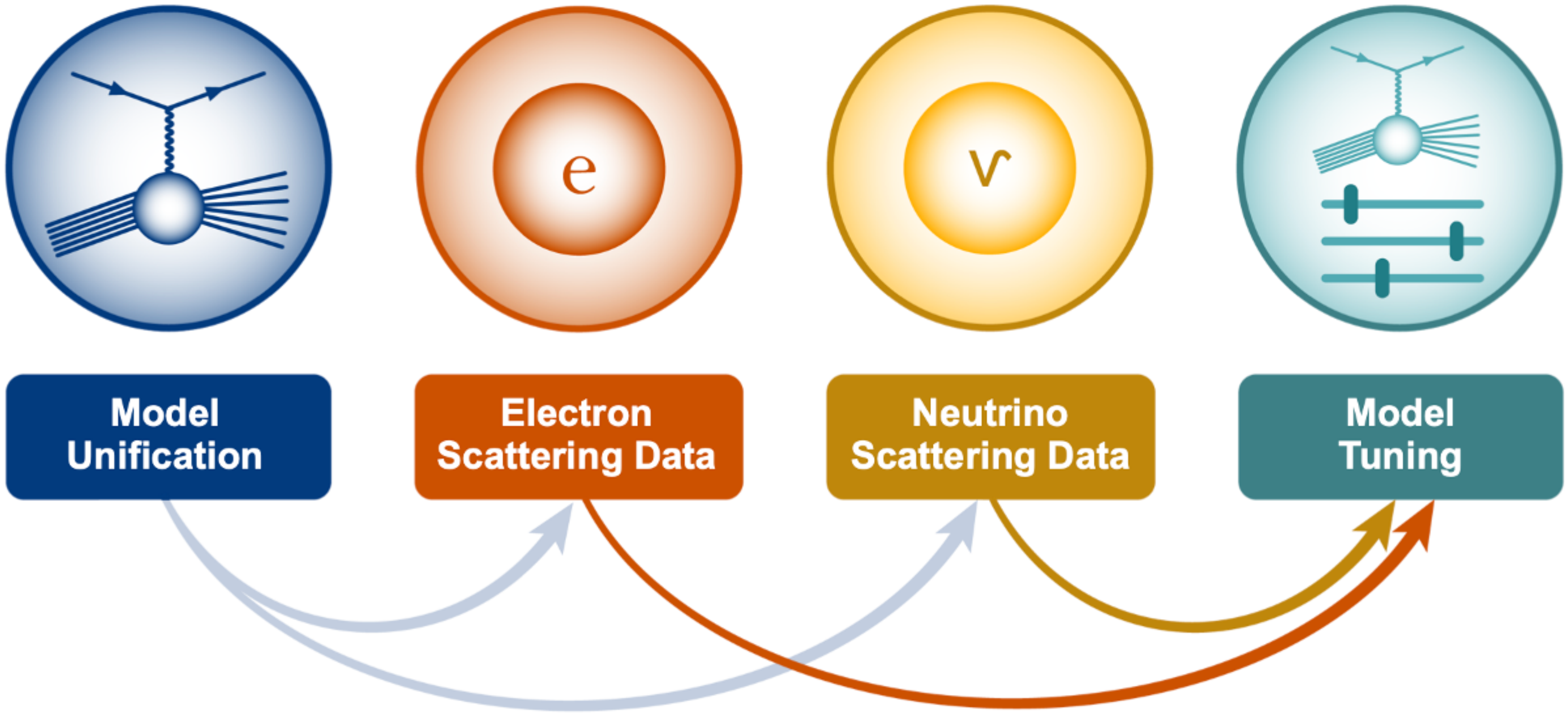


Monochromatic beam
High statistics

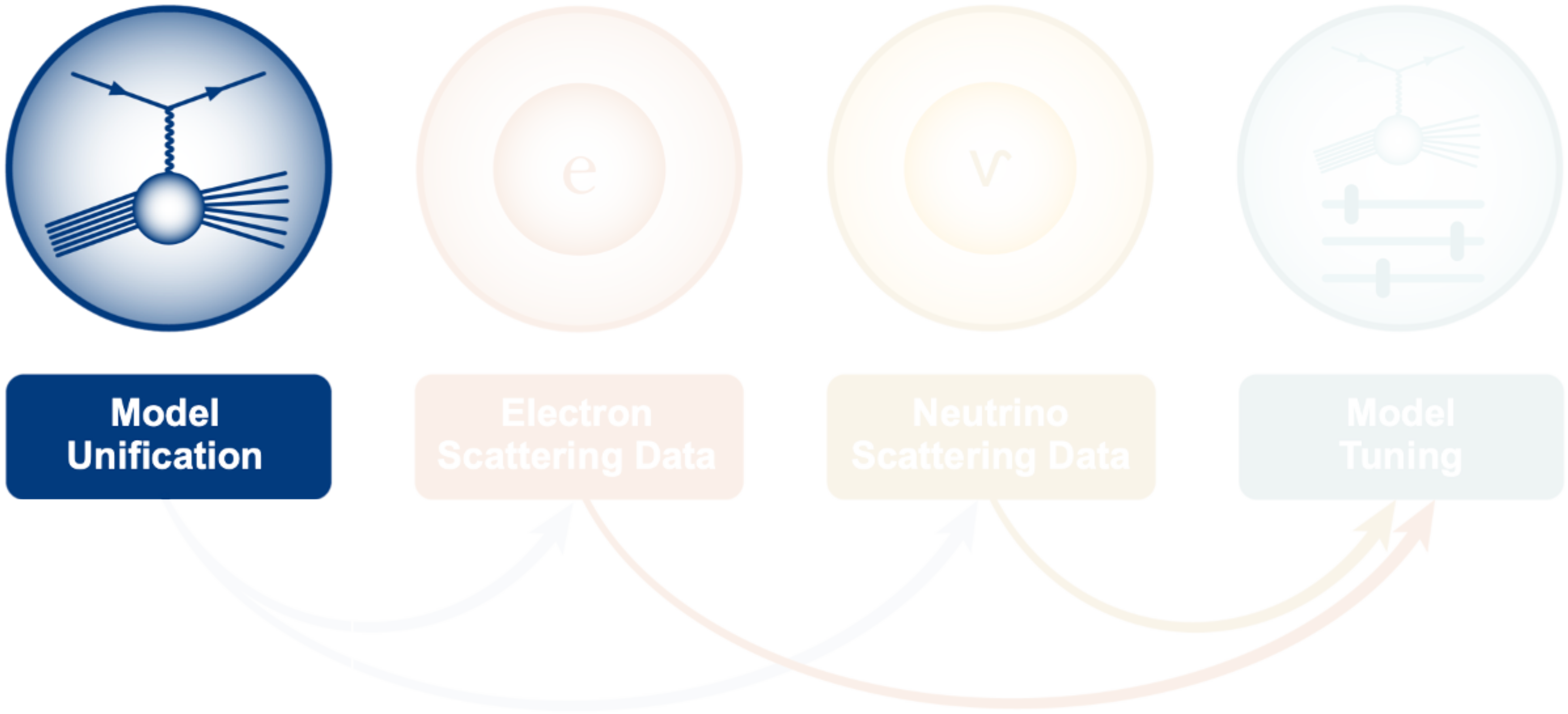
Wide-energy beam
Lower statistics

eA useful to test νA energy reconstruction methods

Roadmap for improving event generators



Roadmap for improving event generators



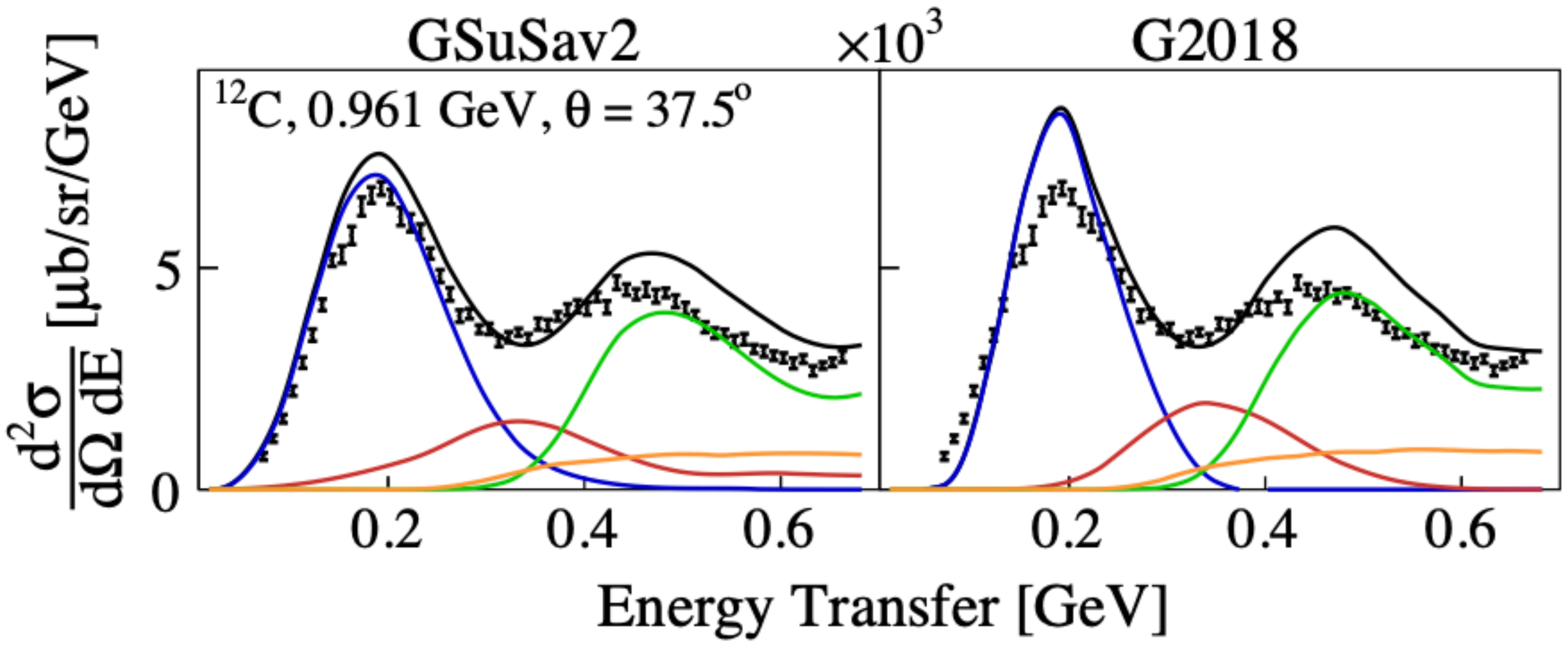
νA and eA MC Event Generators

UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

- νA, eA and h-A event generator
- From MeV to PeV, all targets
- All interaction mechanisms and targets
- Widely used in $\nu-$experiments

Used for e4ν analysis and model development

- **Full description for electrons**
- **Originally developed for neutrinos**
- **Common code for νA, eA processes**
  - [*Physical Review D (2021)*,10.1103/PhysRevD.103.113003]
- Radiative effects with *emMCRadCorr* Software
  - [CPC, **Volume 310**, **May 2025, 109509**]
- Supported by $e4\nu$ collaborators

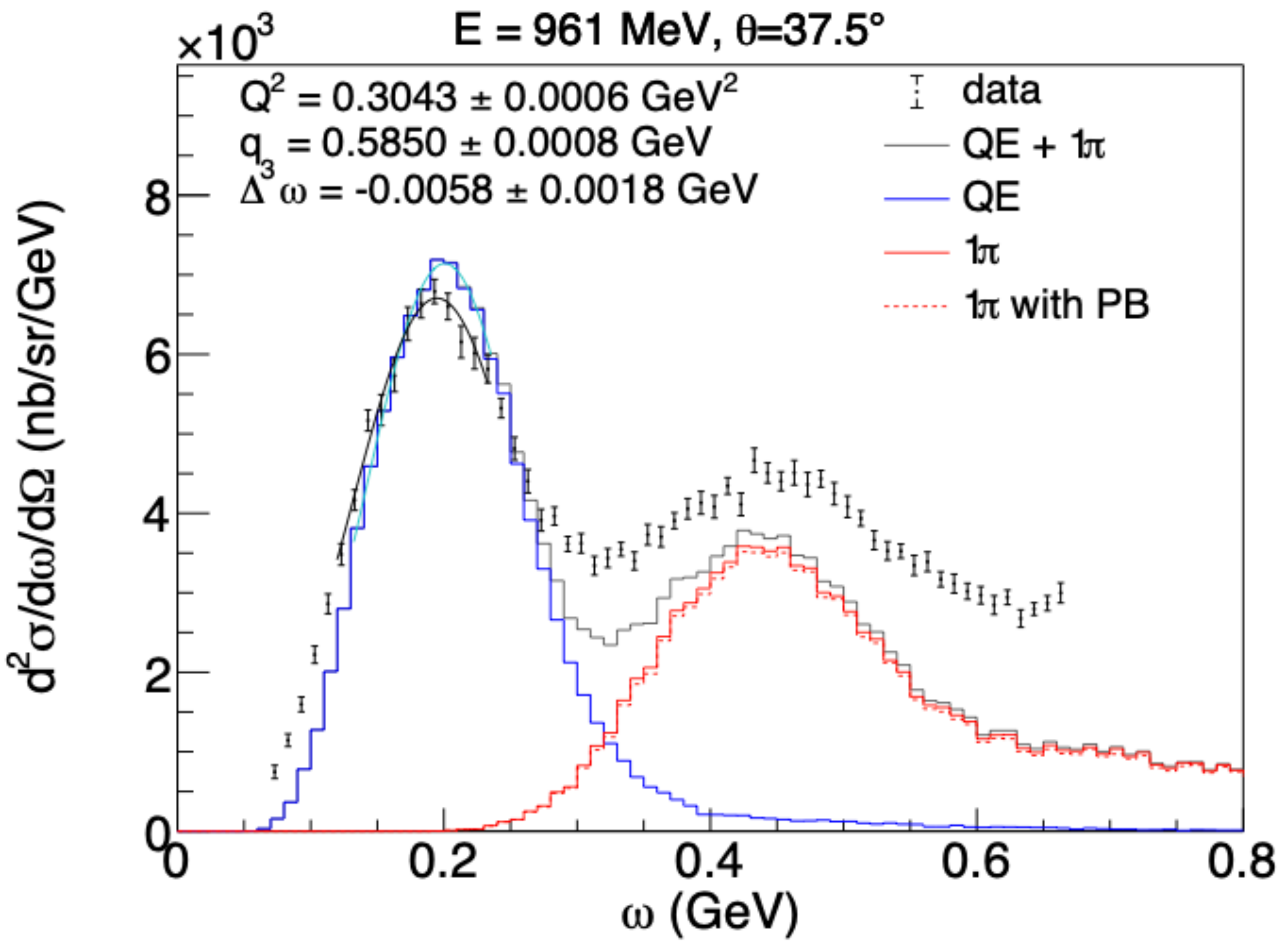


νA and eA MC Event Generators

Renewed interest on *eA*

- GiBUU [Phys.Rev.C79:034601,2009]
  - All interaction mechanisms available
- NEUT [Phys. Rev. D 111, 033006]
- Achilles (QEL, RES only)
- NuWro has separated codes
- *e4ν* data used to validate event generators
  - Tuning projects ongoing

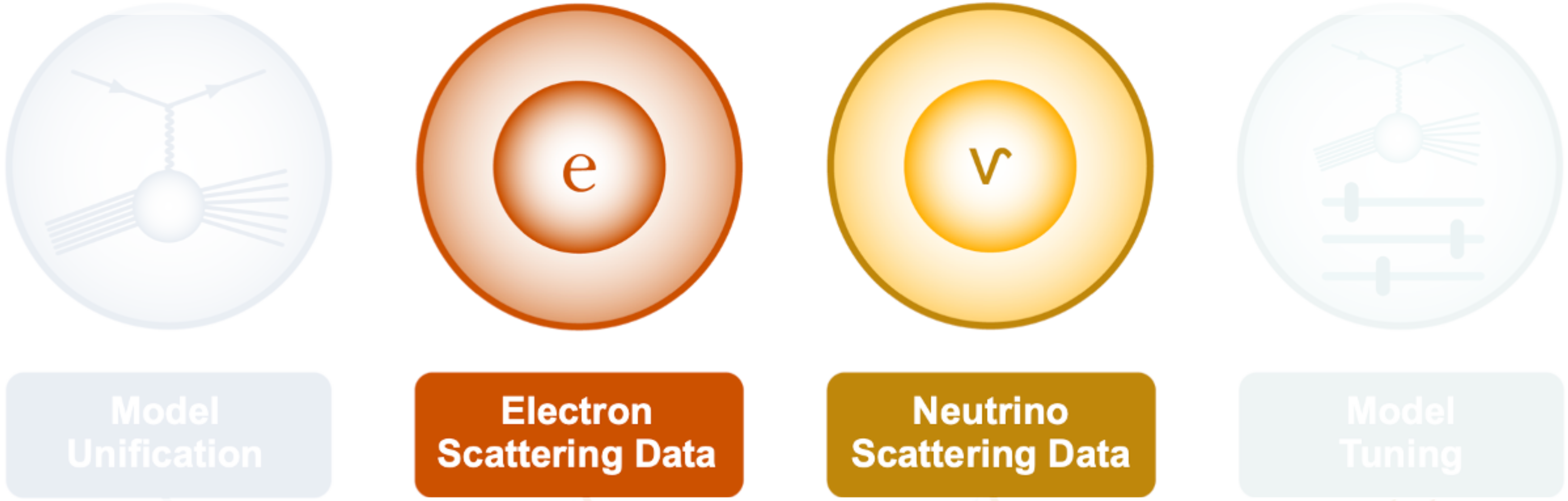
NEUT Event Generator



Not all mechanisms yet available!

Roadmap for improving event generators

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



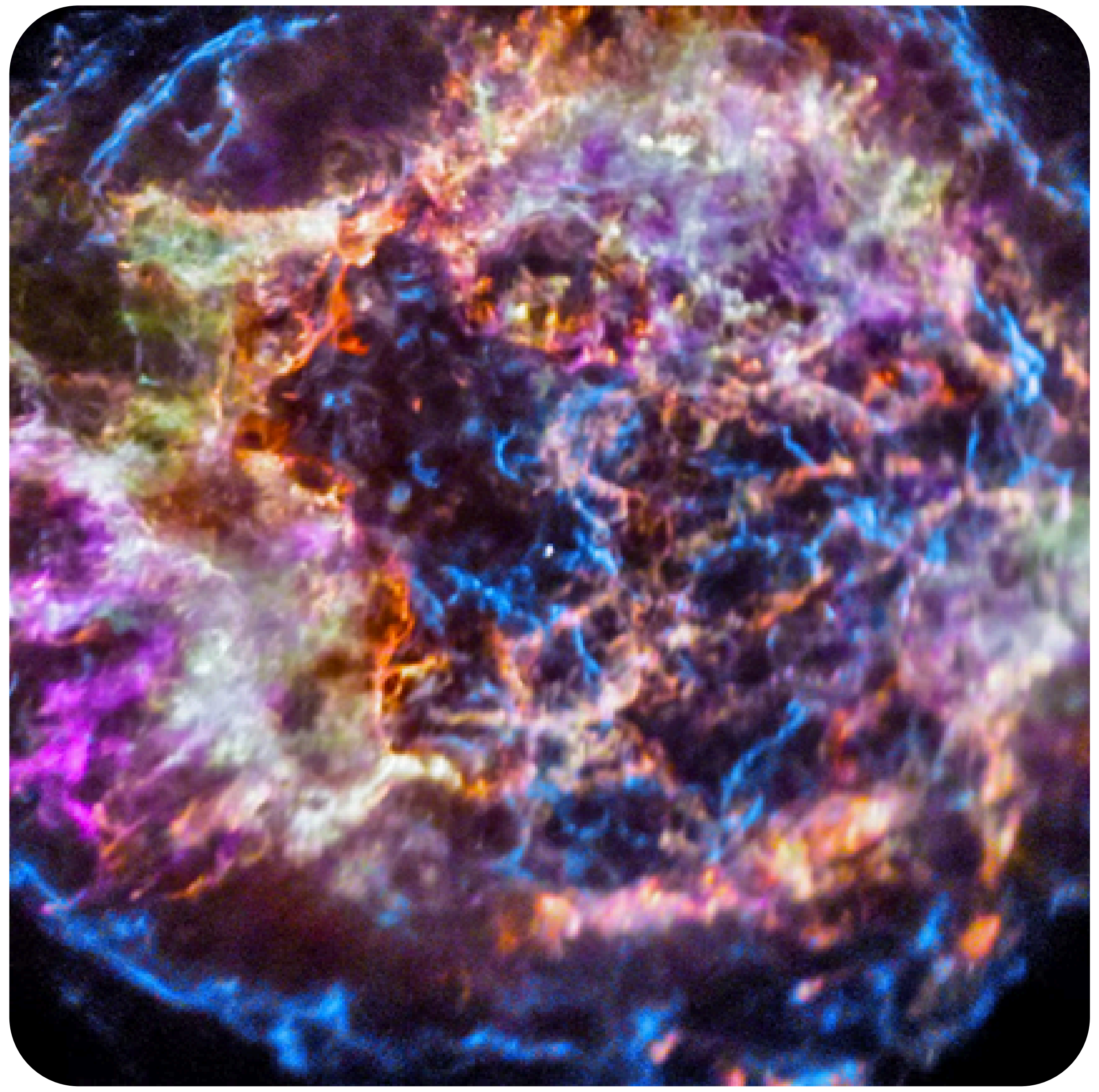
Jefferson Lab contributes to precise e-A & ν-A data

Different Experiments, different needs

Reactor

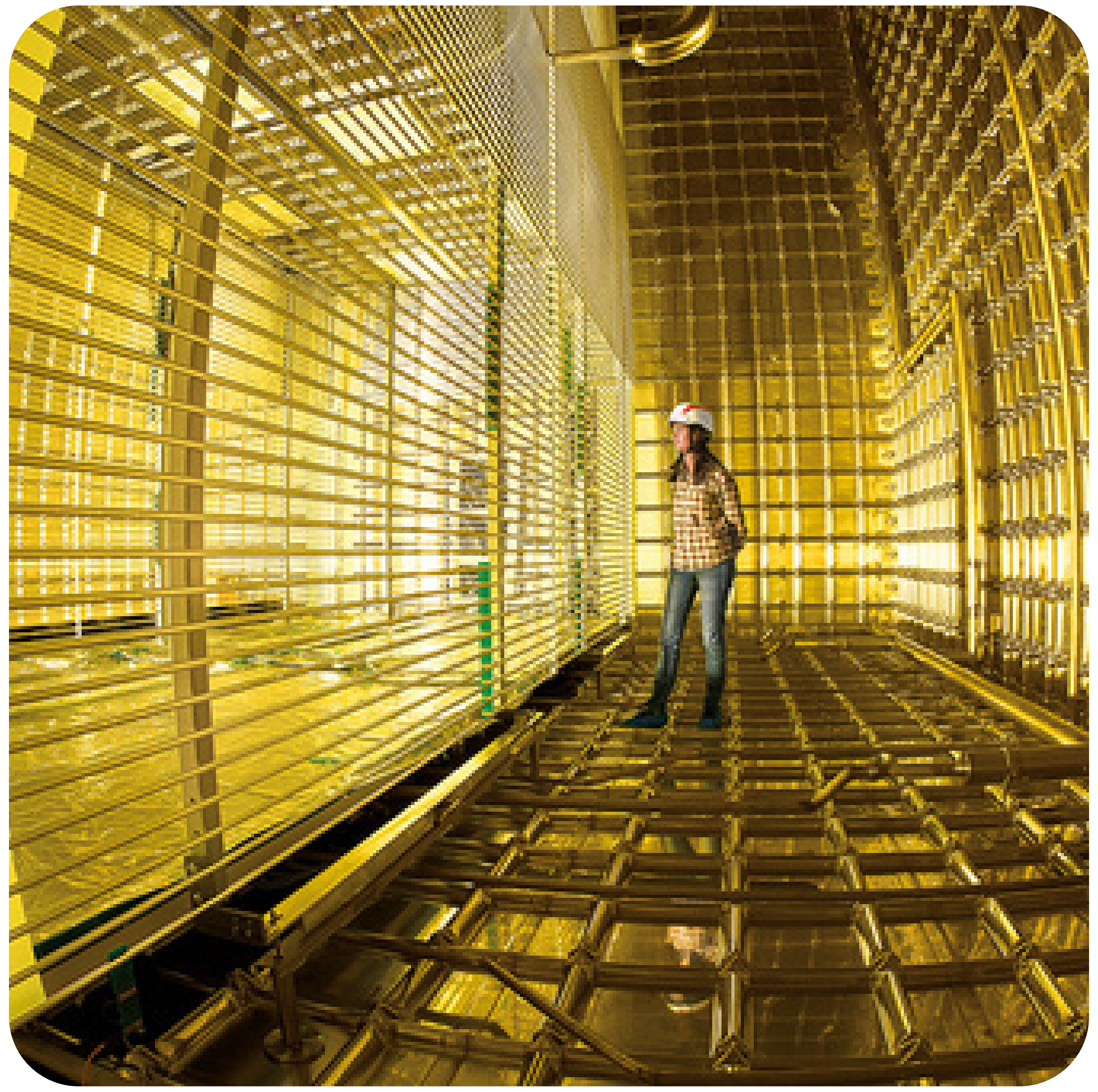
1 – 10 MeV

Supernova



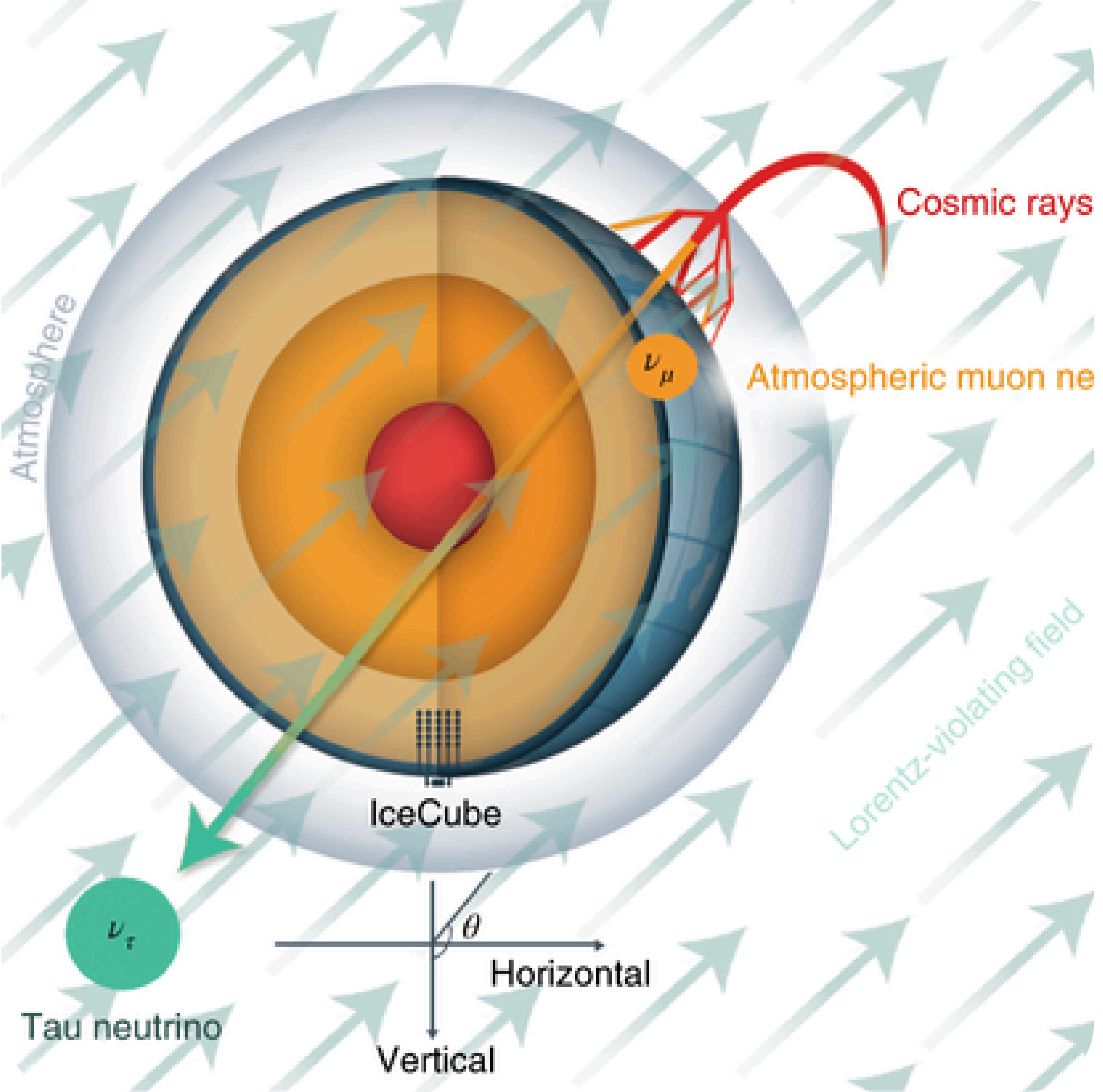
10 – 20 MeV

Accelerator



0.1 – 10 GeV

Atmospheric



0.1 – 100 GeV

E_ν [GeV]

Accelerator Neutrino Experiments

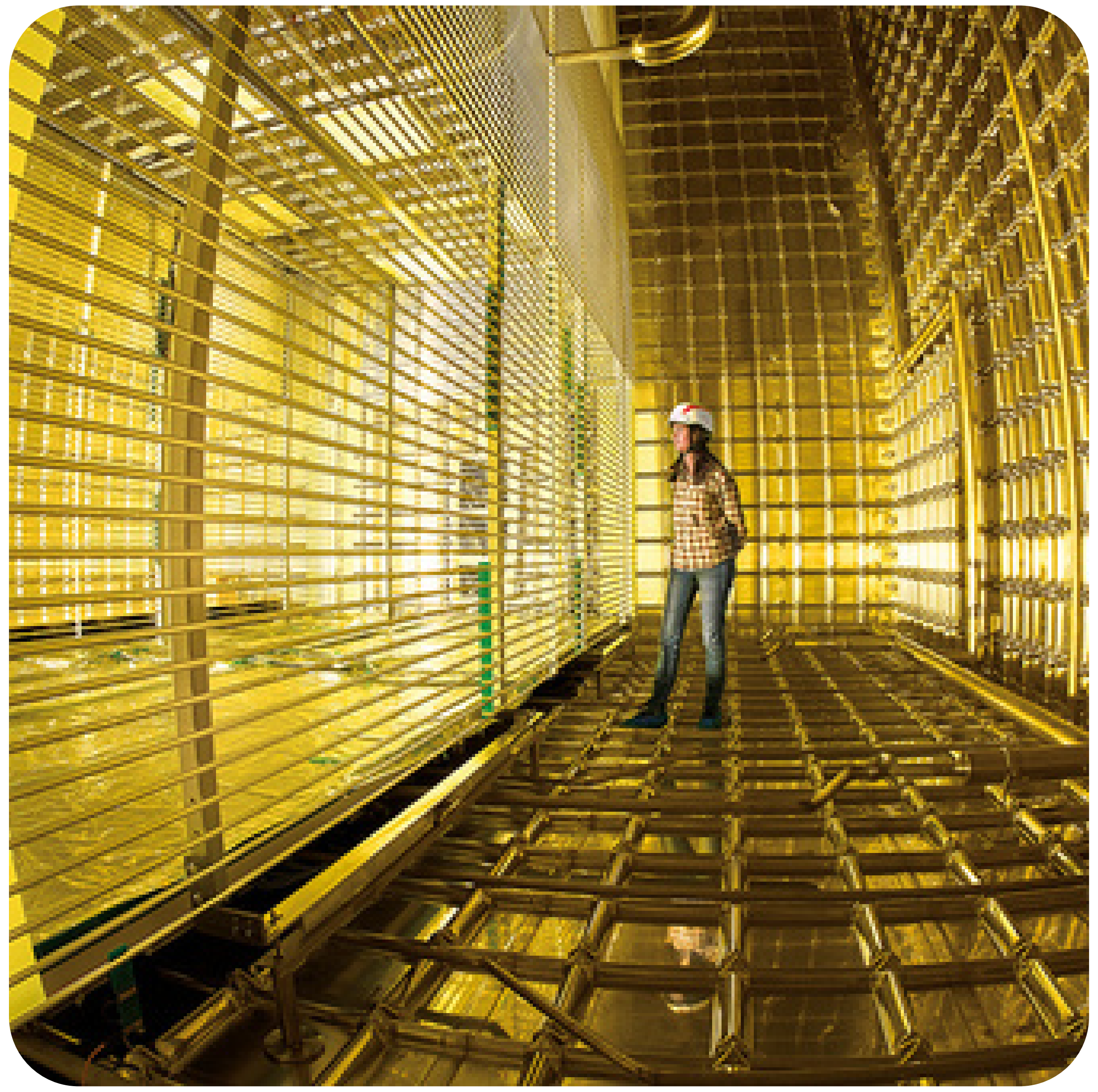
Reactor

1 – 10 MeV

Supernova

10 – 20 MeV

Accelerator



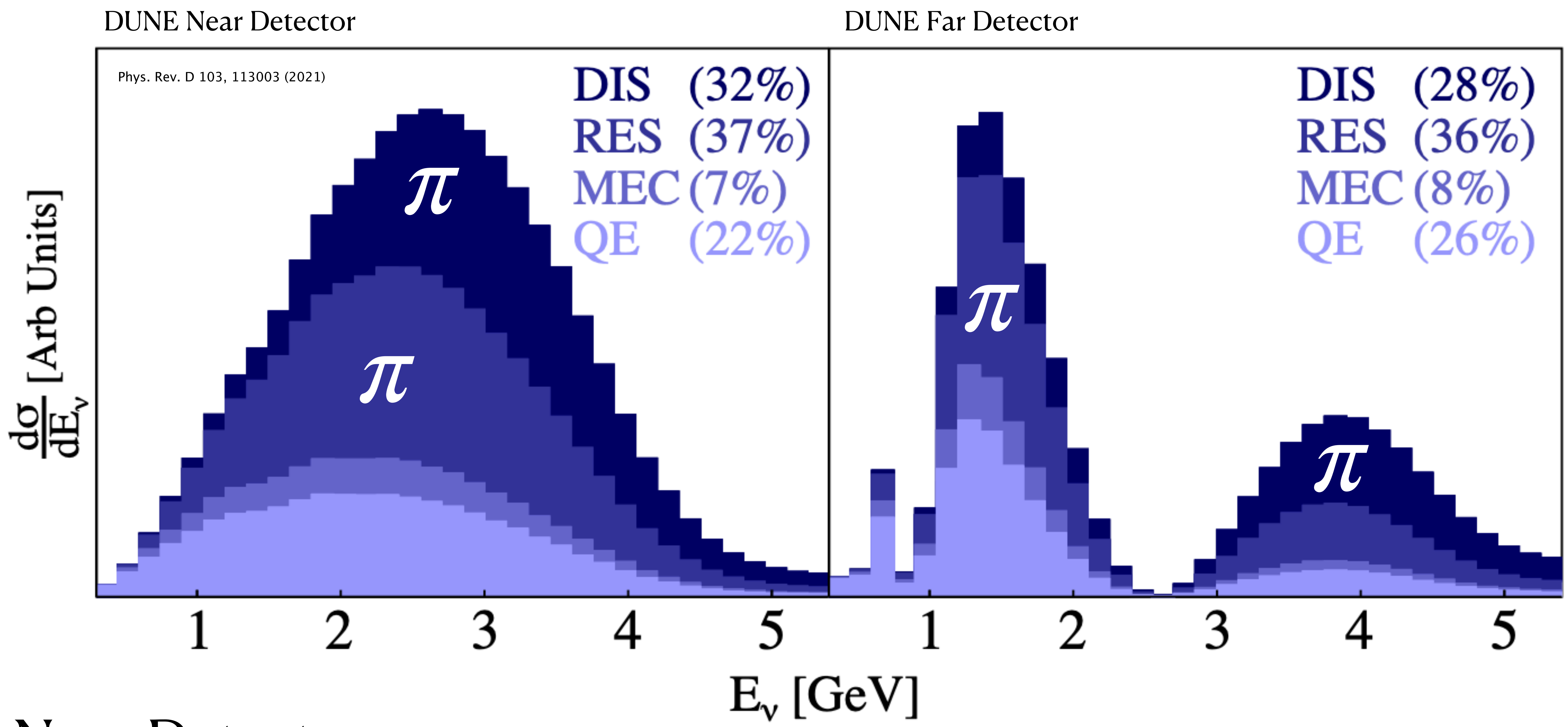
0.1 – 10 GeV

Atmospheric

0.1 – 100 GeV

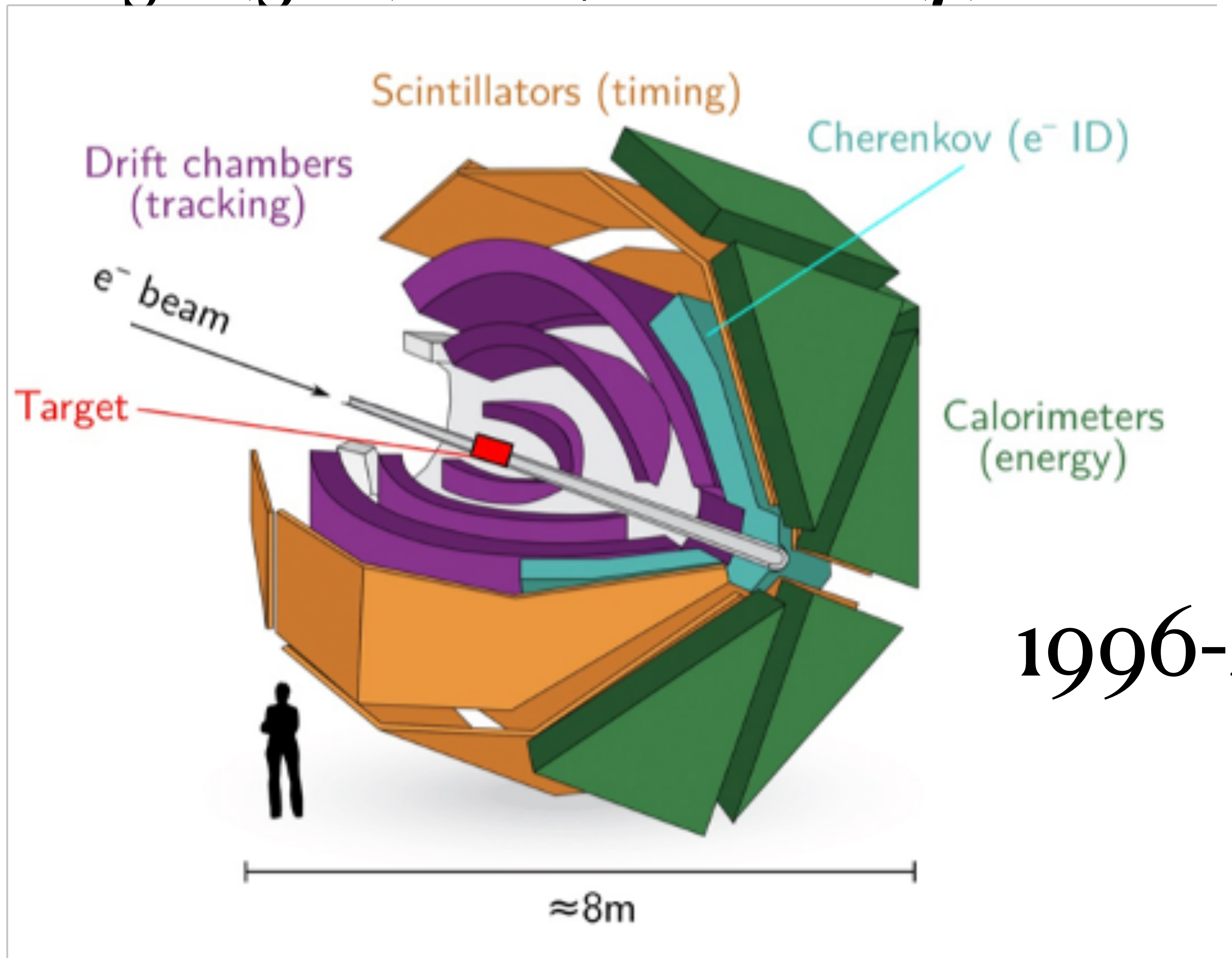
E_ν [GeV]

Accelerator Neutrino Experiments

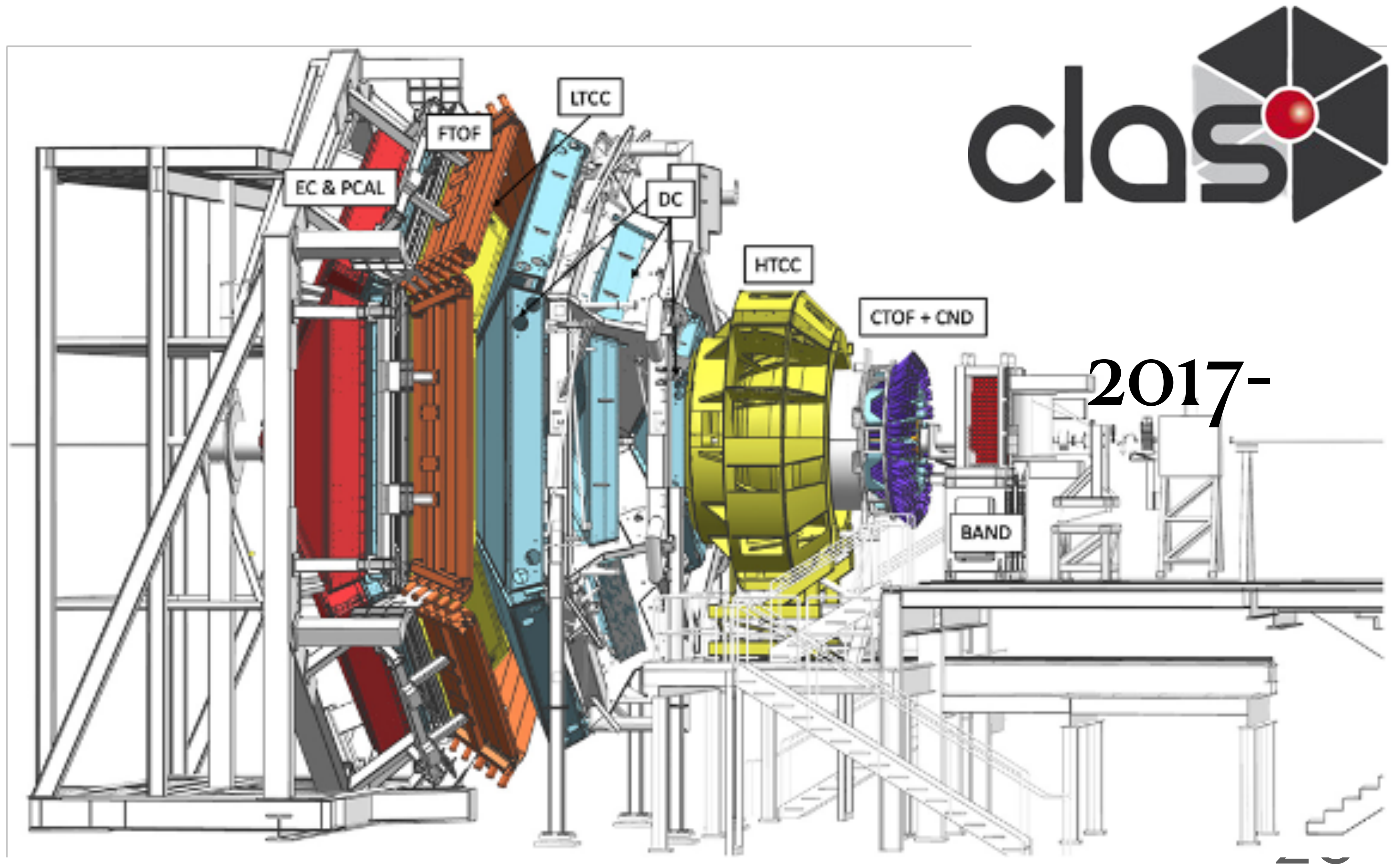


Hadron production with CLAS

- 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)

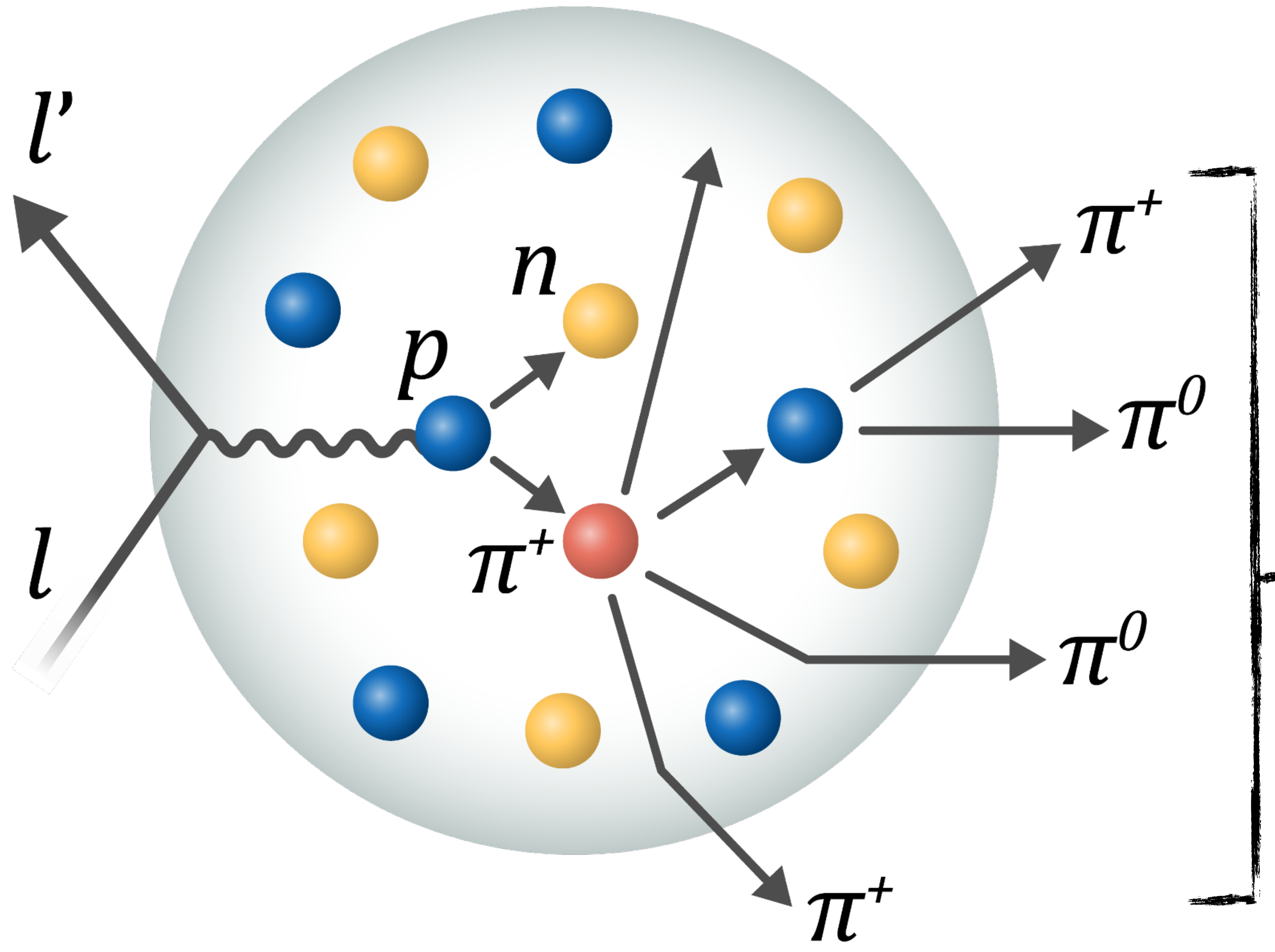


1996-2013



2017-

Complex Pion Production modelling needs data



Rich limits for few-GeV experiments:

$1p1\pi^{\pm}$ data to test cross-section and FSI models

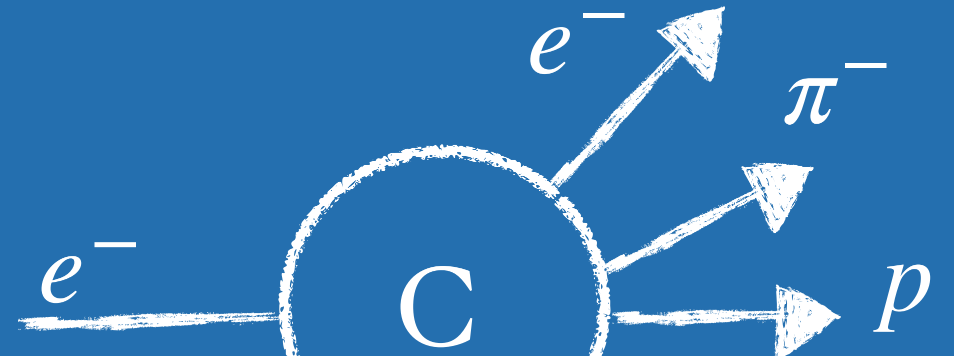
Many other analysis ongoing!

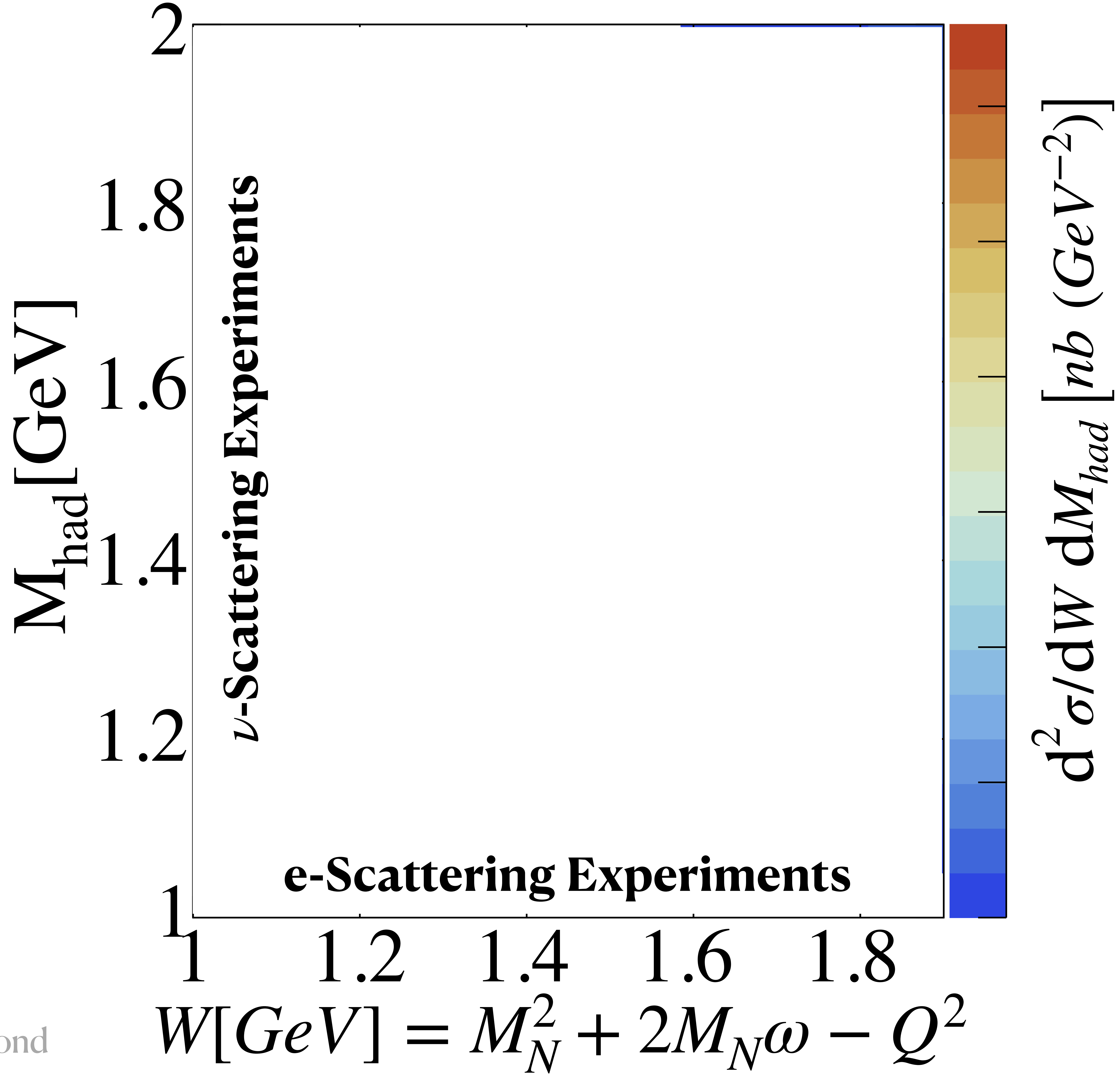
Answers to key questions for νA experiments:

Can we reconstruct E_ν?
i.e. Can we describe the final state?

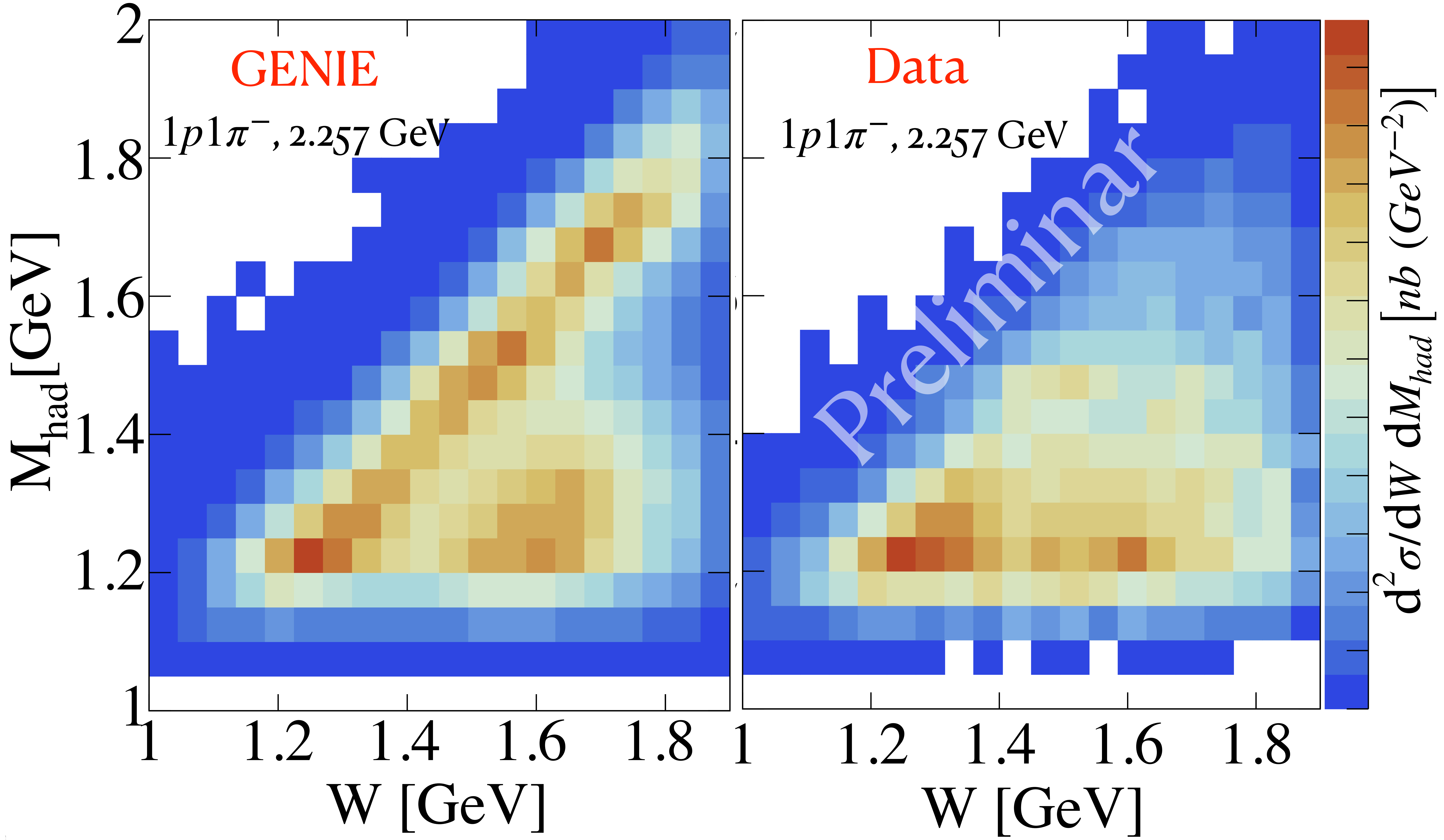
Is FSI correctly modelled?

Hadronic Invariant Mass Bias



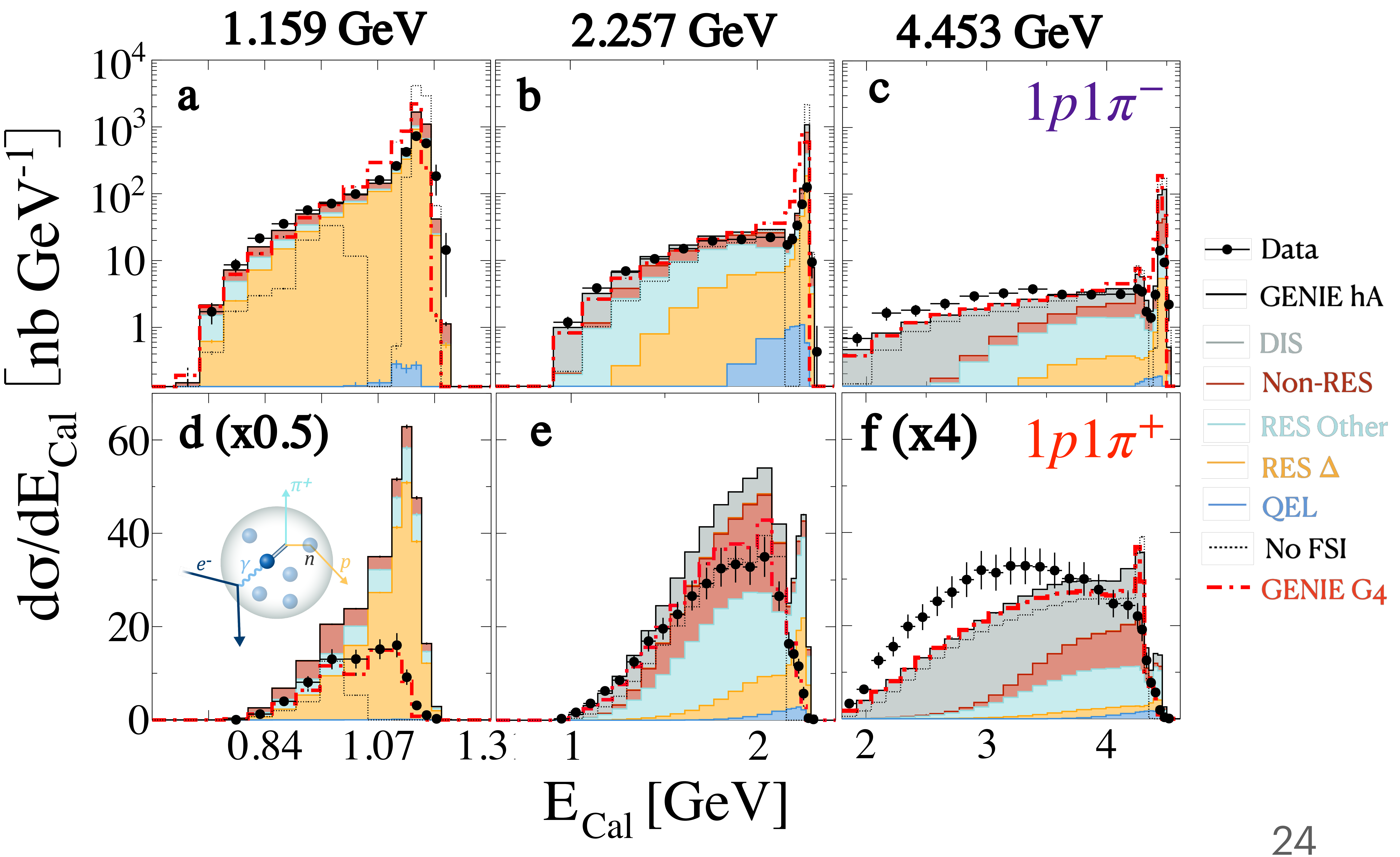


Current models fail to describe the final state



Simple FSI models do not describe data

$1p1\pi^+$ data has increased sensitivity to FSI models



Atmospheric Neutrino Experiments

Reactor

1 – 10 MeV

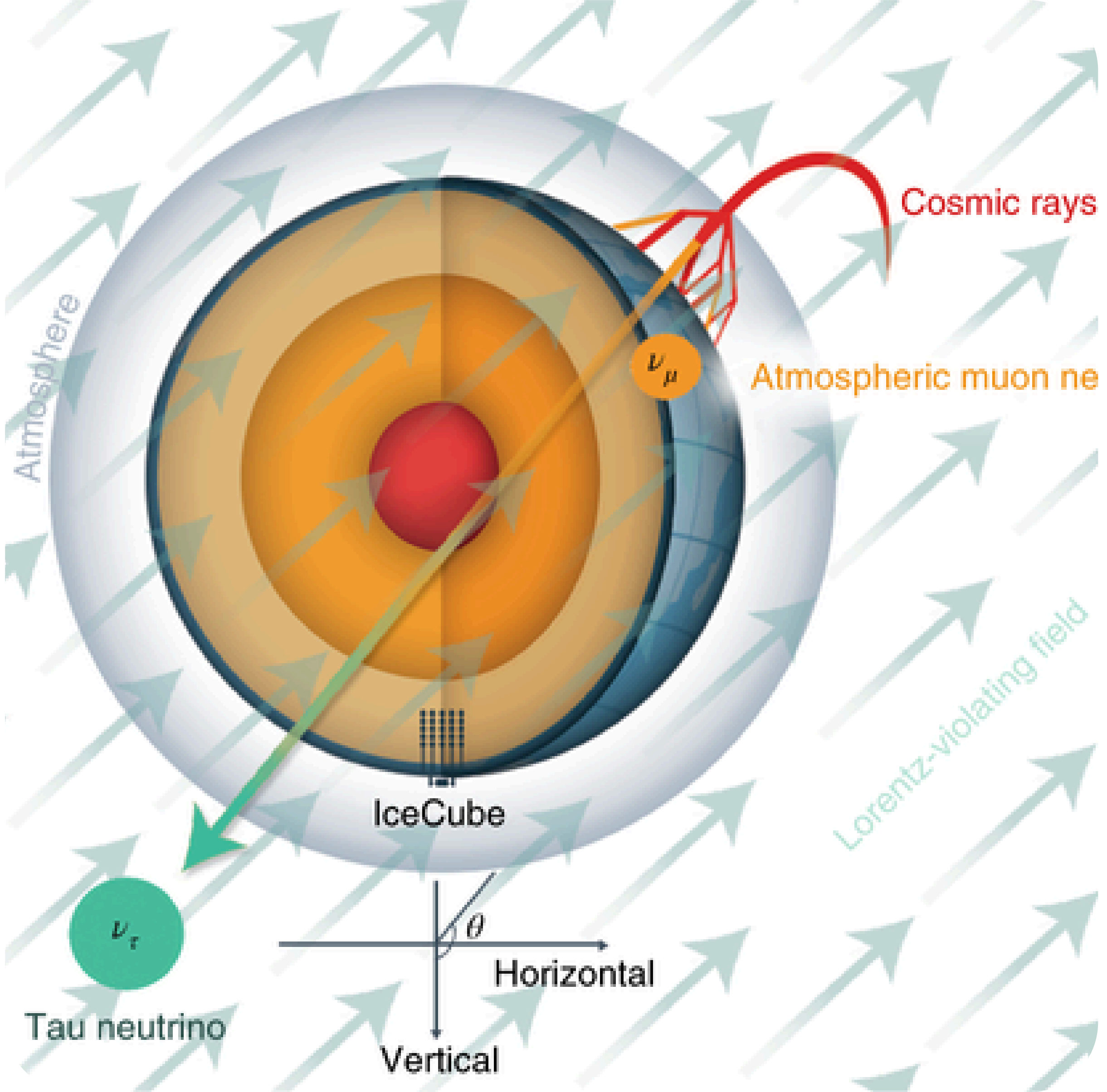
Supernova

10 – 20 MeV

Accelerator

0.1 – 10 GeV

Atmospheric



0.1 – 100 GeV

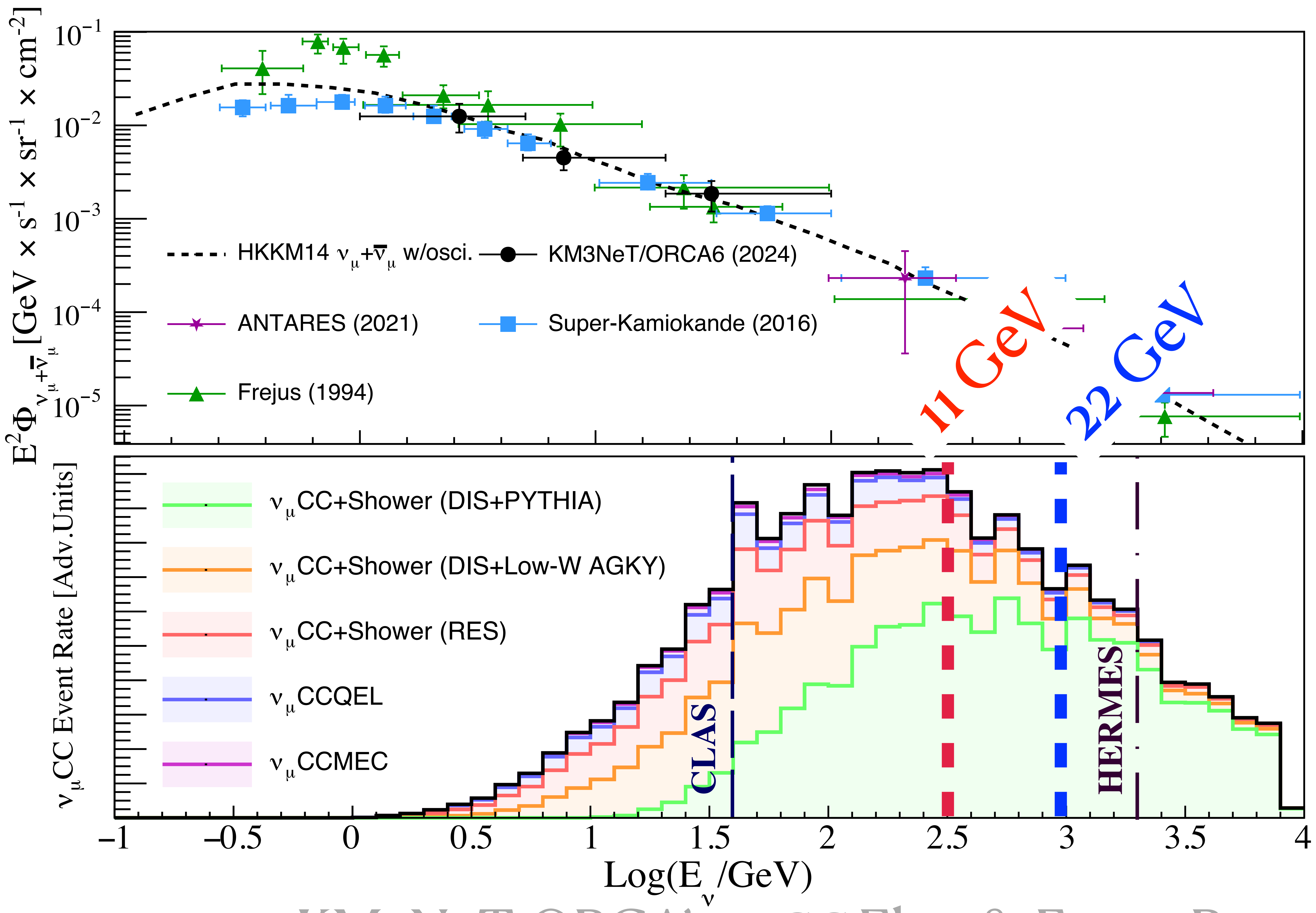
E_ν [GeV]

New $e4\nu$ effort for atmospheric experiments

Many atmospheric ν-experiments are dominated by DIS events

- ν-direction and energy measured from the deposited energy
- Hadronization modelling is essential but incomplete
- **Goal: use CLAS data to constrain key KM3NeT systematics**
  - Currently over-looked
  - New data (11 & **22 GeV**) will be crucial

New $e4\nu$ effort to leverage ongoing CLAS hadronization efforts (W. Brooks, M. Arratia et. al.) for the ν-community



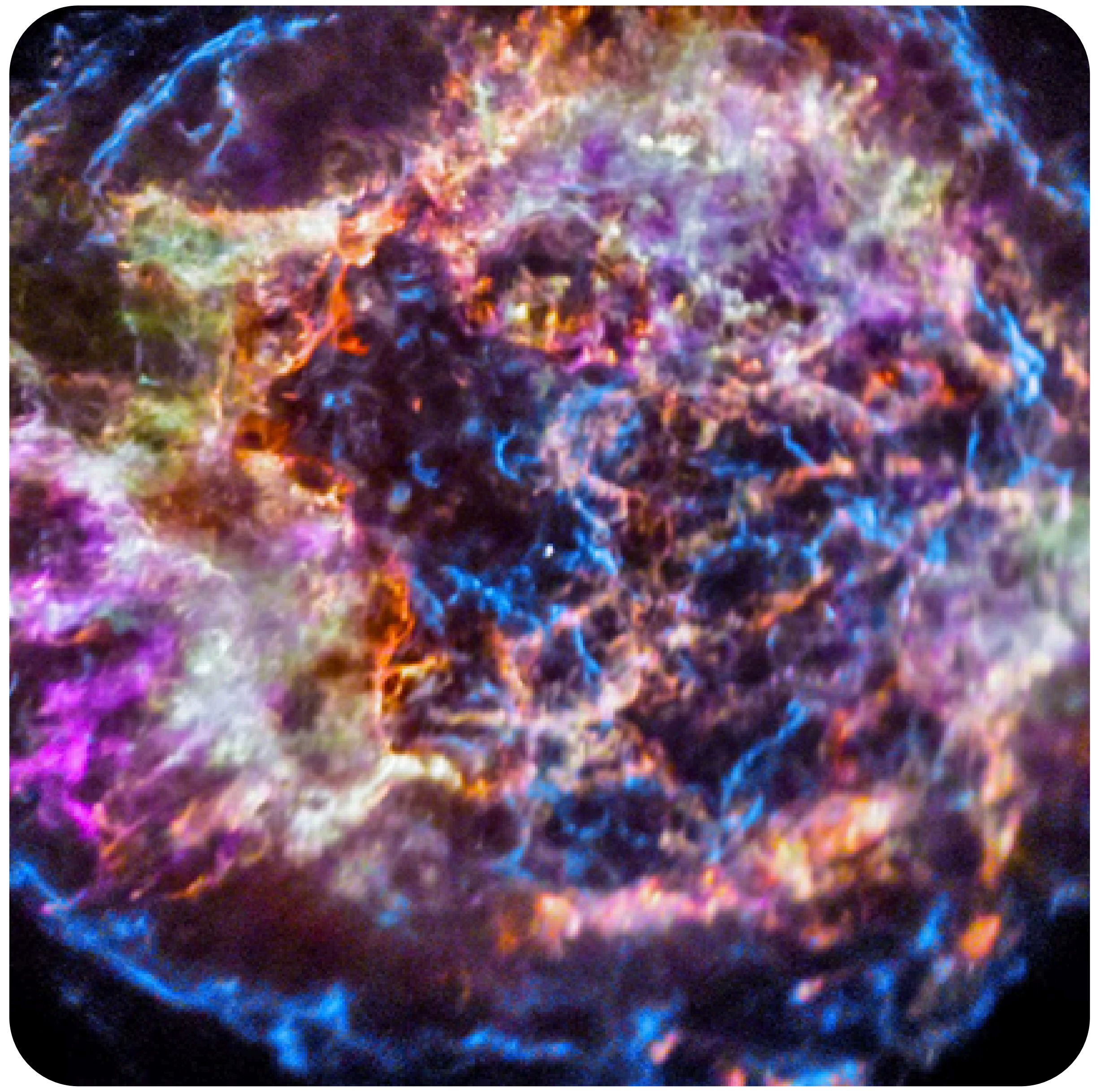
KM3NeT ORCA's $\nu_\mu CC$ Flux & Event Rate

Reactor and Supernova Neutrinos & BDX

Reactor

1 – 10 MeV

Supernova



10 – 20 MeV

Accelerator

0.1 – 10 GeV

Atmospheric

0.1 – 100 GeV

E_ν [GeV]

SuperNova Neutrinos @ DUNE

The DUNE Far Detector is sensitive to Solar and core-collapse supernova-ν with $E \sim 5 - 100$ MeV

1. Charged-Current (CC) on Ar

$$\nu_e +^{40} Ar \rightarrow^{40} Kr^* + e^-$$

$$\bar{\nu}_e +^{40} Ar \rightarrow^{40} Cl^* + e^+$$

2. Elastic Scattering on electrons (ES)

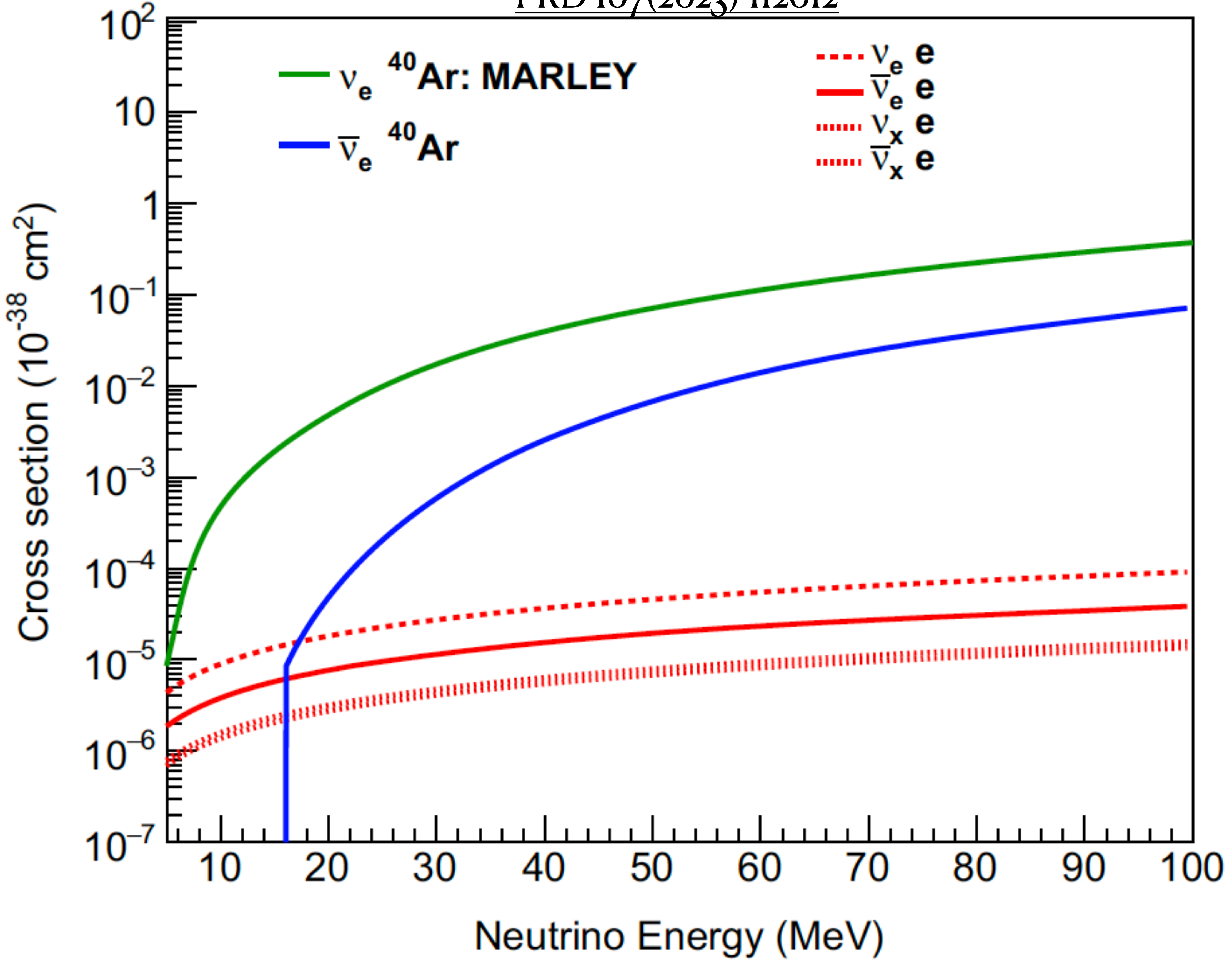
$$\nu_x + e^- \rightarrow \nu_x + e^-$$

3. Neutral Current (NC) on Ar

$$\nu_x +^{40} Ar \rightarrow \nu_x +^{40} Ar^*$$

More details in Clara Cuesta's talk at NuFact 2025

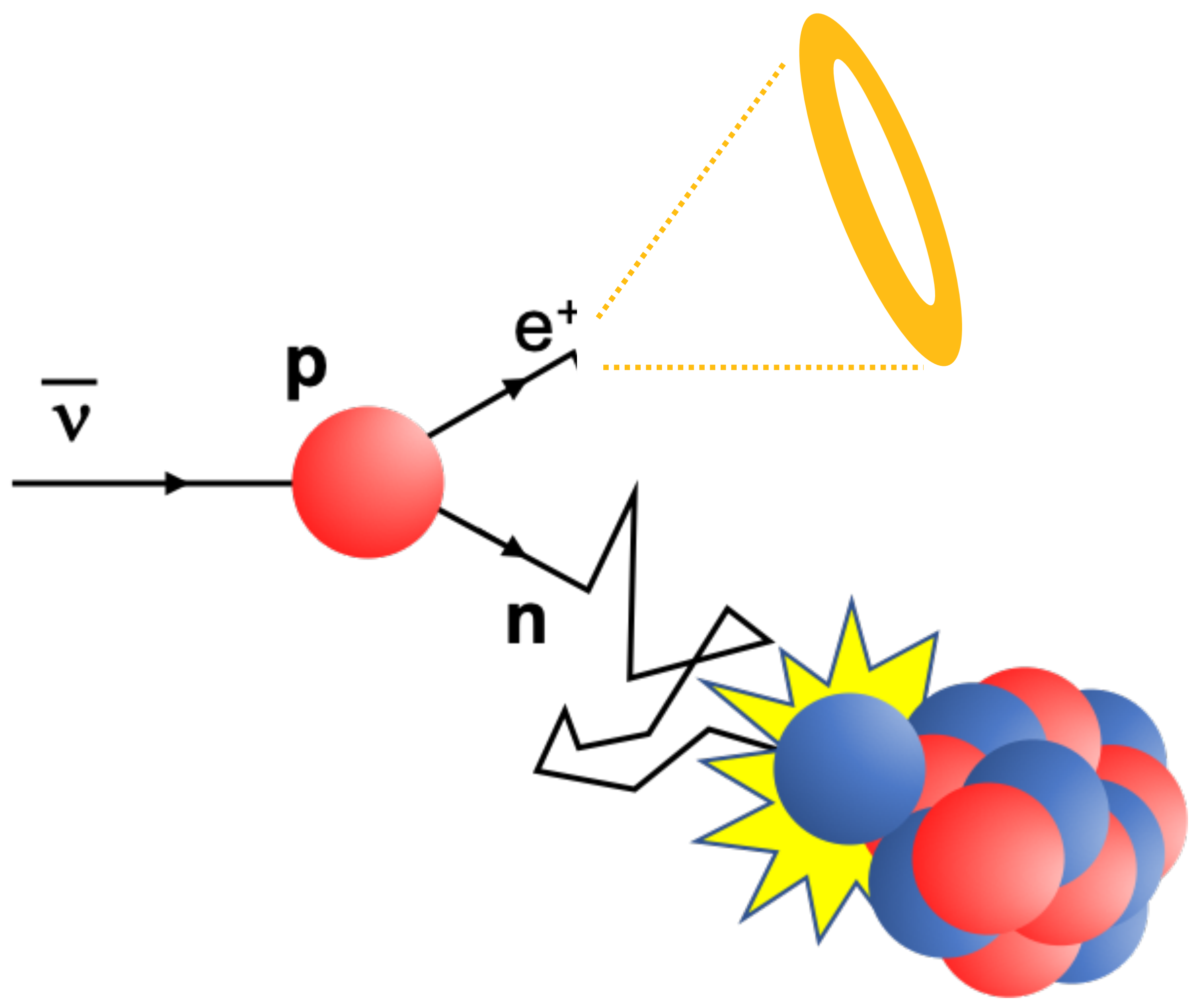
PRD 107(2023) 112012



Large theoretical uncertainties on $\sigma(E_\nu)$, while DUNE requires $\sigma(E_\nu) < 5\%$ uncertainty for supernova neutrino spectral parameter fitting. A direct measurement of low-energy ν_e-Ar scattering would be invaluable.

SuperNova Neutrino Energy Reconstruction

- **Scintillator & water Cherenkov detectors**
  - Inverse Beta Decay (IBD): e^+energy is sufficient for good resolution
  - Might measure neutron capture signal



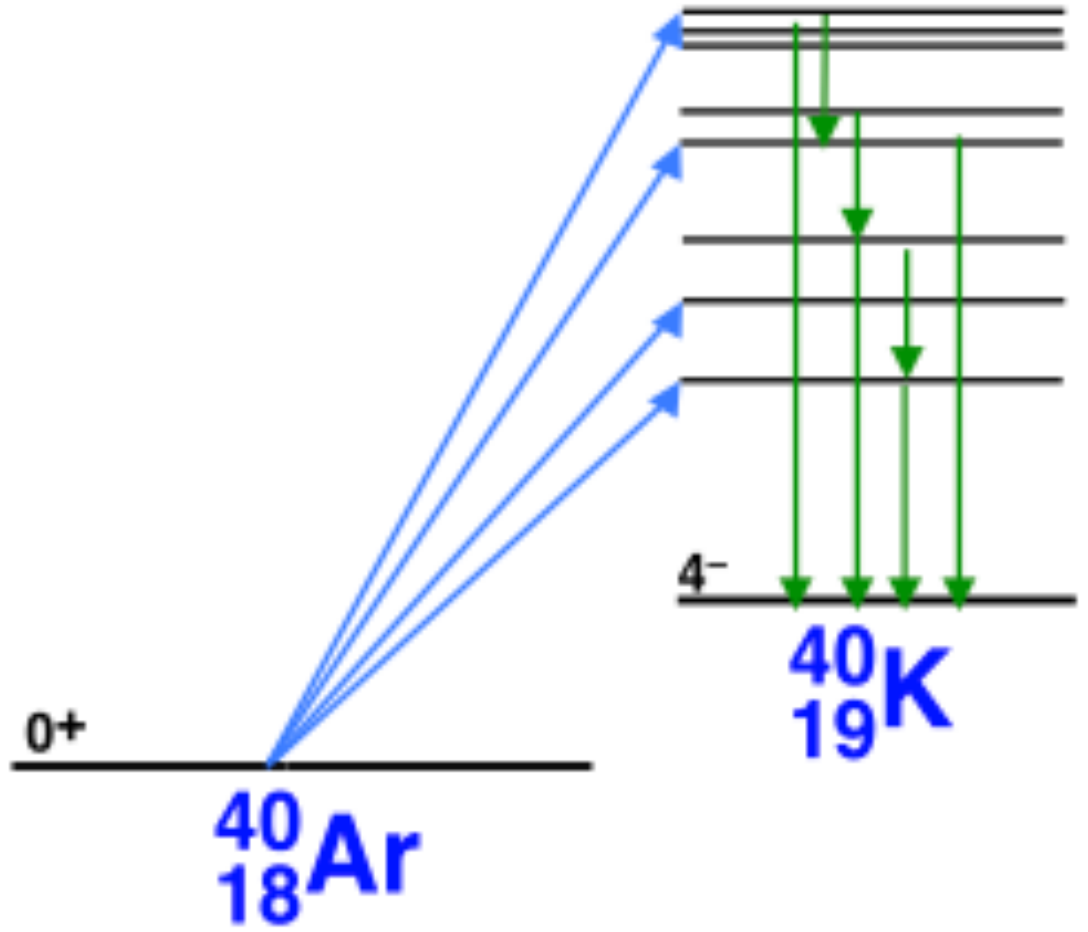
Outgoing e⁺ energy — Neutron proton mass difference — Recoil energy of neutron (negligible)

$$E_{\bar{\nu}} = E_e + \Delta + K_{\text{recoil}}$$

- **LArTPCs (i.e. DUNE)**
  - Inelastic and elastic channels
  - Complex nuclear target, transitions
  - De-excitation products must be measured ($E_{\gamma's} \rightarrow Q$)
  - Correct for missing energy (i.e. n)

MARLEY seeks to provide a realistic treatment of the de-excitation physics

$$\nu_e + {}^{40}\text{Ar} \rightarrow {}^{40}\text{K}^* + e^-$$



Outgoing e⁻ Energy — Energy donated to transition — Recoil Energy of Nucleus (negligible)

$$E_\nu = E_e + Q + K_{\text{recoil}}$$

Need exclusive information

Event Generators Challenges at MeV regime

- Complex de-excitation physics, nuclear effects - Inclusive theory calculations
- **<u>MARLEY</u> is the first event generator providing MeV-exclusive calculations**
- Few measurements with limited precision are available:

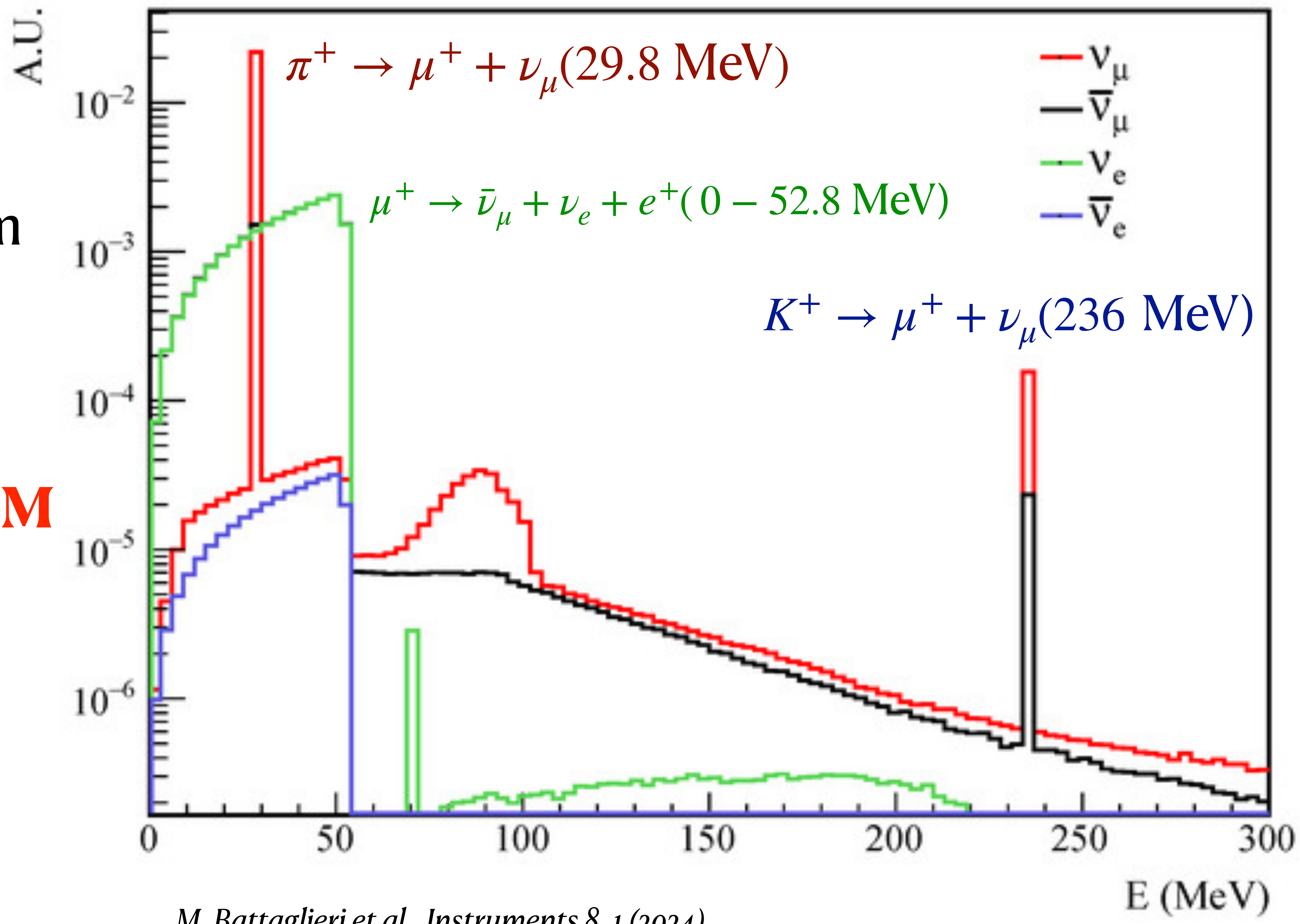
https://arxiv.org/pdf/1705.08629, Table III

Reaction	Neutrino Source	Accuracy	Reference
$^{12}C(\nu_e,e^-)^{12}N_{g.s.}$	Accelerator ν	$\sim$10%	[22] [23]
$^{12}C(\nu_e,e^-)^{12}N^*$	Accelerator ν	$\sim$15%	[22] [23]
$^{12}C(\nu,\nu')^{12}C(1^+1)$	Accelerator ν	$\sim$20%	[22] [23]
$^{13}C(\nu_e,e^-)^{13}N$	Accelerator ν	76%	[22]
$^{56}Fe(\nu_e,e^-)^{56}Ni$	Accelerator ν	37%	[22]
$^{71}Ga(\nu_e,e^-)^{71}Ge$	RI (^{51}Cr)	11%	[24] [25]
$^{127}I(\nu_e,e^-)^{127}Xe$	Accelerator ν	33%	[26]

Lack of Ar data & exclusive measurements

BDX & Secondary neutrino beam

- Secondary neutrino beam with a decay-at-rest (DAR) energy spectrum
- ~7×10^{-5} ν/EOT for a 1 m² detector 10 m above the beam dump
- Delivered charge of 10^{22} EOT per year
- **Important input for supernova, BSM physics, MeV-Monte Carlo models**
  - MARLEY ν-Ar @ $E_\nu < 100$ MeV
  - See Vishvas Pandey talk for more physics goals



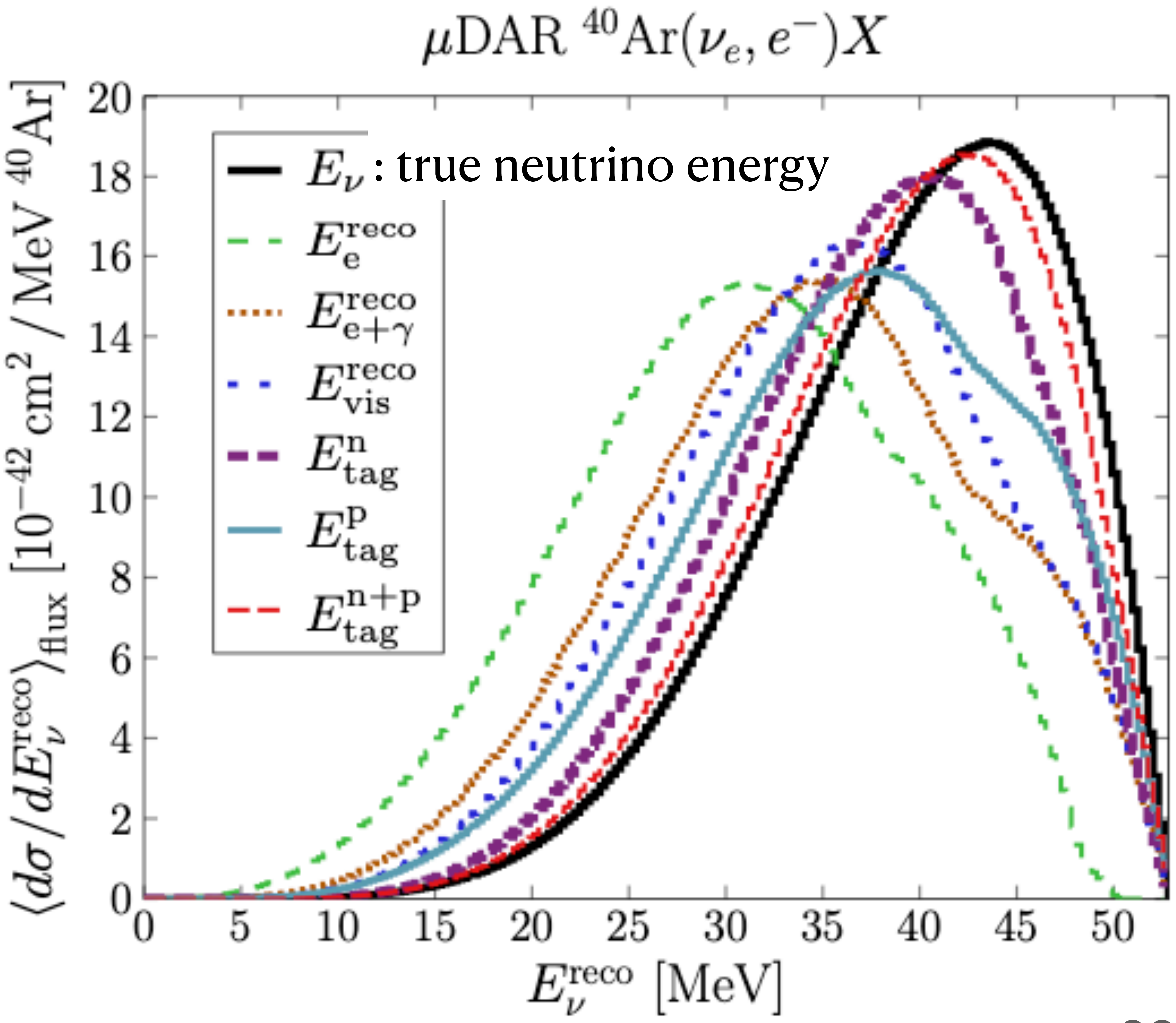
M. Battaglieri et al., Instruments 8, 1 (2024)

BDX Potential Measurements

Reconstruction techniques

- E_e^{reco}: E_e+ minimum B.E
- $E_{e+\gamma}^{reco} = E_e^{reco}$+de-excitation γ-rays
- $E_{vis}^{reco} = E_{e+\gamma}^{reco}$+Ch. hadrons K.E.
- $E_{tag}^{n/p} = E_{vis}^{reco} + \delta_{n/p}\epsilon_{bind}^{l(n/p)}$
- $E_{\rm tag}^{\rm n+p} \equiv E_{\rm vis}^{\rm reco} + \delta_{\rm n}\,(1-\delta_{\rm ch})\,\epsilon_{\rm bind}^{\rm 1n} + \delta_{\rm ch}\,(1-\delta_{\rm n})\,\epsilon_{\rm bind}^{\rm 1p} + \delta_{\rm n}\,\delta_{\rm ch}\,\epsilon_{\rm bind}^{\rm 1n1p}$

Can we measure these processes?
→ Uncertainty in the SN models

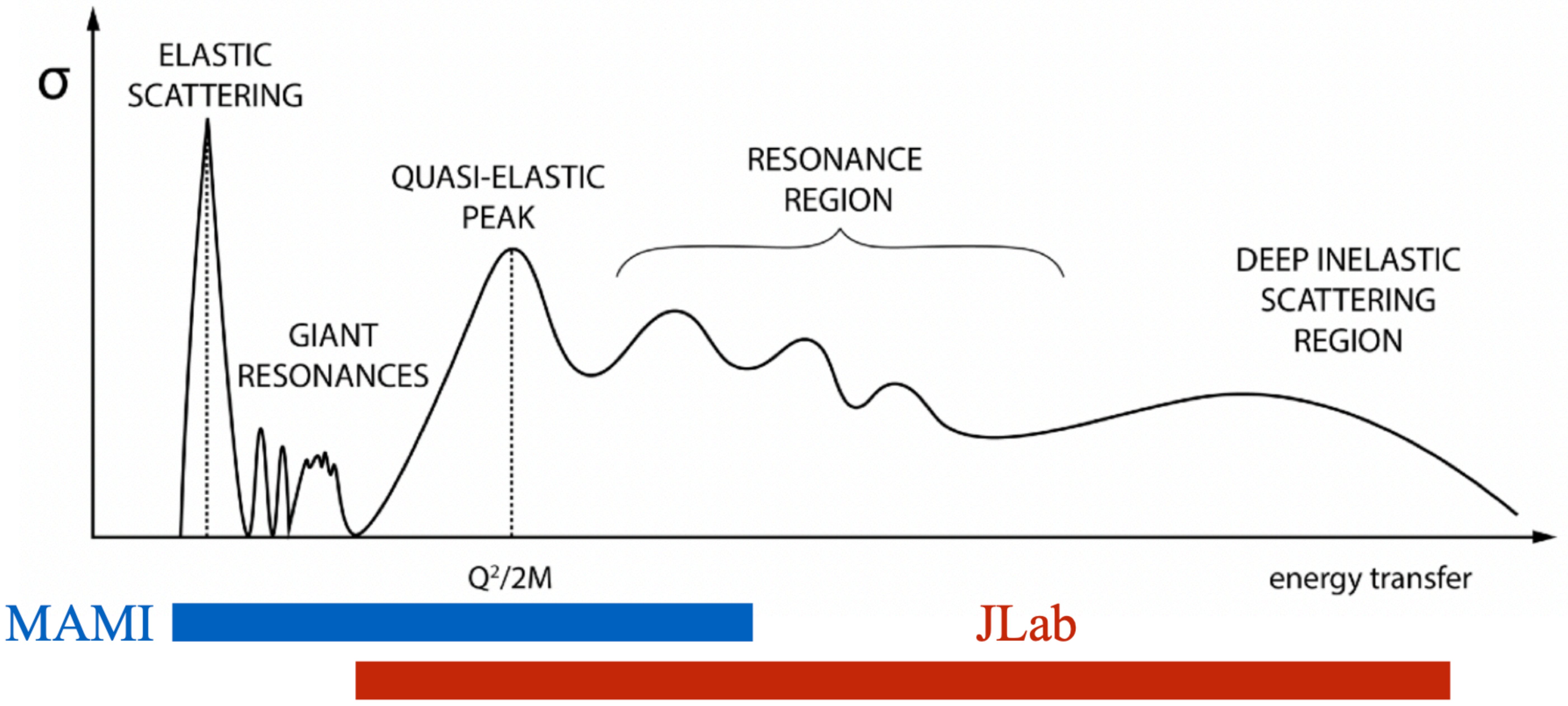


https://arxiv.org/pdf/2010.02393

Complementary to MAMI & MESA data

e-Facilities in Mainz - See Luca Doria's talk

- MAMI, up to 1.6 GeV / 10-100 uA current / CW beam / polarized
- MAGIX (under construction) 105 MeV
- MESA (under construction) 150 MeV / mA currents / CW beam / polarized



See Luca Doria's talk at Elba

Compare e^- and ν data in same energy range

BDX & Secondary muon beam

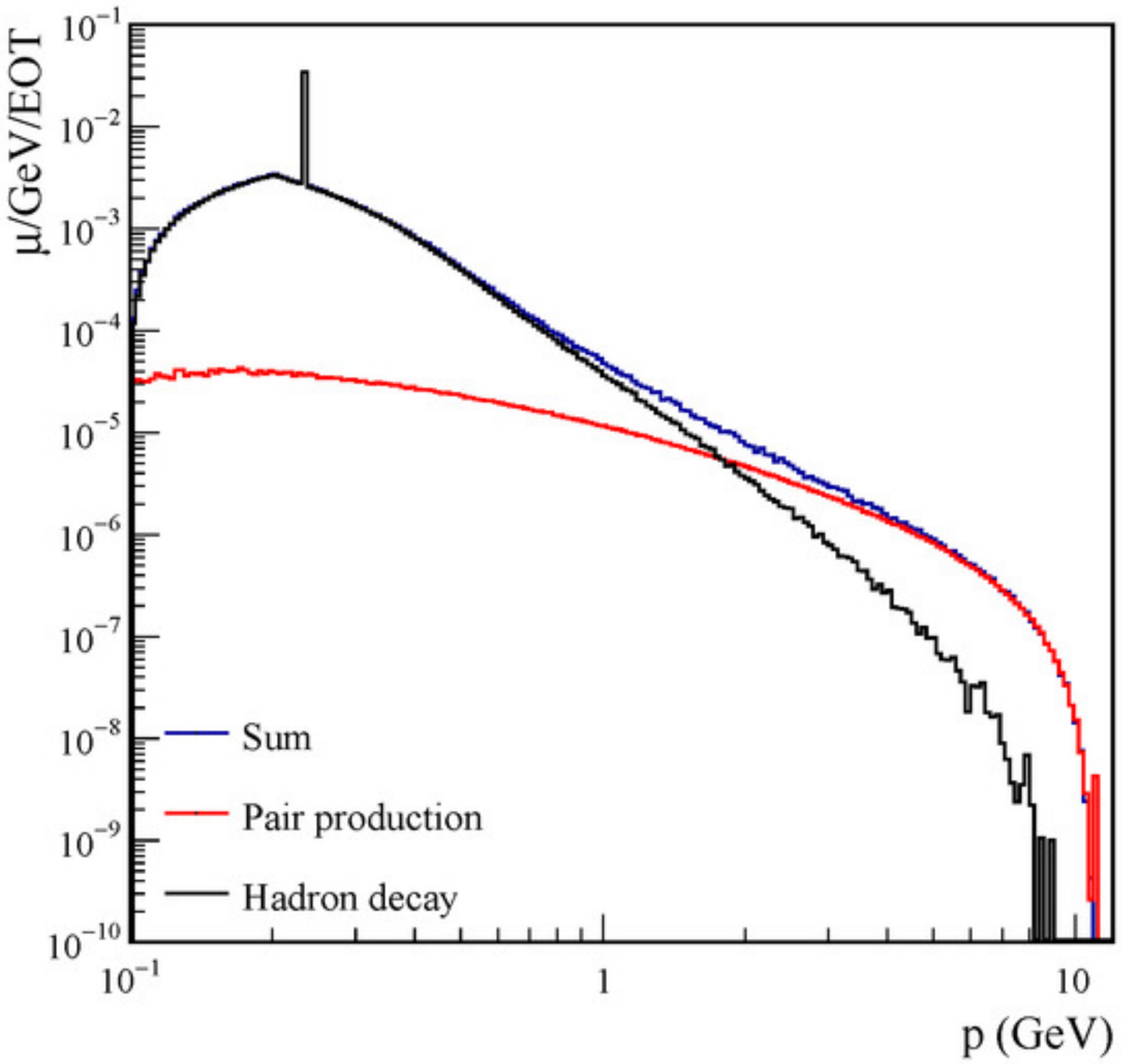
- Bremsstrahlung-like energy spectrum extending up to 5 GeV
- Yield up to ~10^{-6} μ/EOT → 10^{8} μ/s for an electron beam current of 50 μA

Tagged muon beam with per-cent resolution useful for $e4\nu$ efforts

- Energy bias measurements

- Precision measurements ν_e/ν_μ ratio

Current efforts with Cosmic Muons in LArTPCs have lower energy resolution (20-30 %)



Conclusions

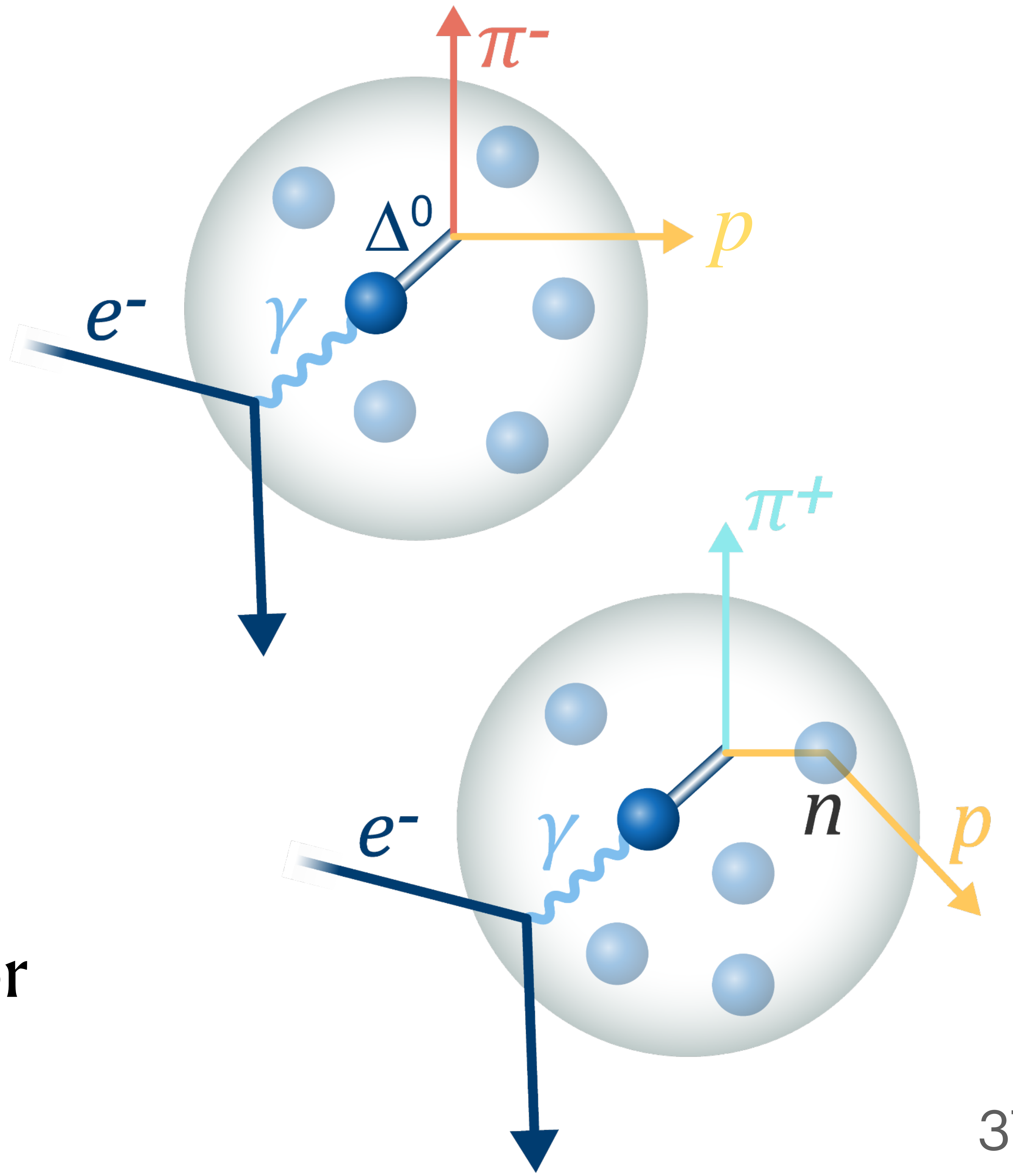
The $e4\nu$ Collaboration leverages e-scattering data to constrain $\nu - A$ models

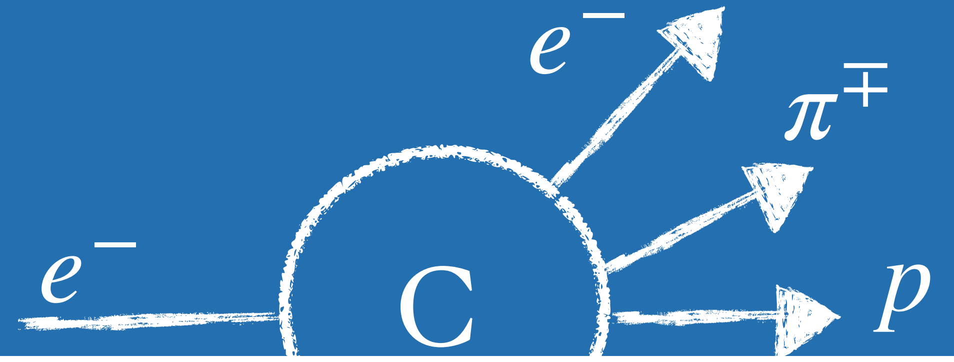
- **Two main efforts focused on accelerator experiments**
  - Data analysis with CLAS spectrometers H, C, Ar.. at 1-6 GeV
  - MC event generator (GENIE) models and tuning
- **Upcoming work for atmospheric $\nu-$experiments** with established efforts at JLab
  - 11 GeV and planned 22 GeV beam data will be key for telescope experiments
- **BDX opens the door to precise MeV $\nu-$A data - complementary to Mainz e-A data**
  - Important for Supernova, Reactor and BSM analyses
  - Tagged Muon beam with per-cent resolution useful for $e4\nu$ efforts
- **Jefferson Lab will contribute to different forefront areas of neutrino physics!**


e4V
US GENERAL
Thank you for your attention!

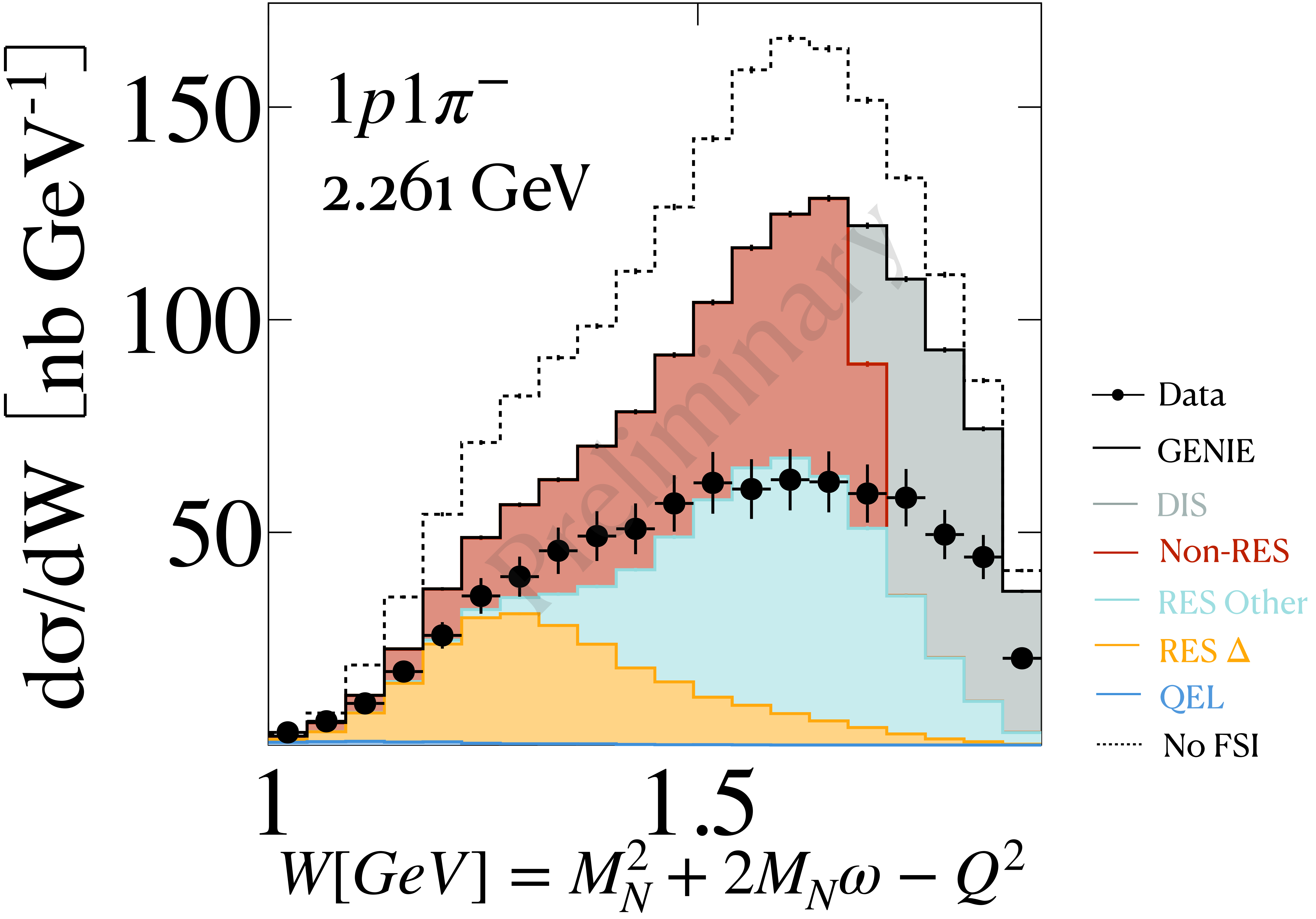
First look at C(e,e'1p1$\pi^{\mp}$)

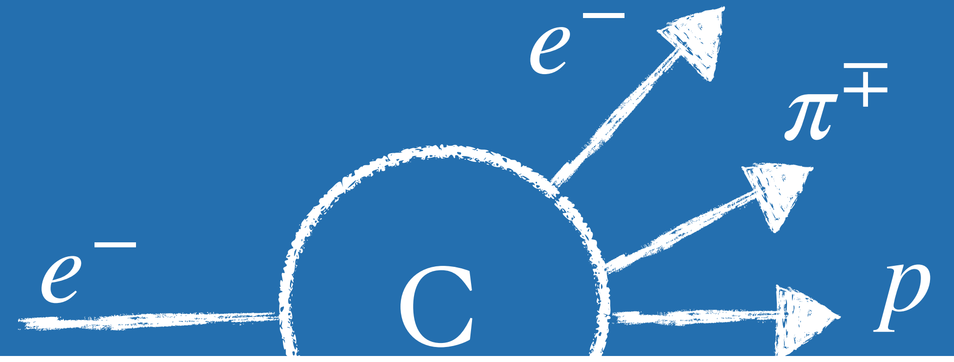
- Carbon data, 1-4 GeV
- 1p1π^- and 1p1π^+, no additional hadrons or photons
  - With $\pi^{\mp}$ above 150 MeV
  - With γ above 300 MeV
- 1p1π^- Possible at free nucleon level
- 1p1π^+ needs two or more nucleons and or undetected particles (FSI)



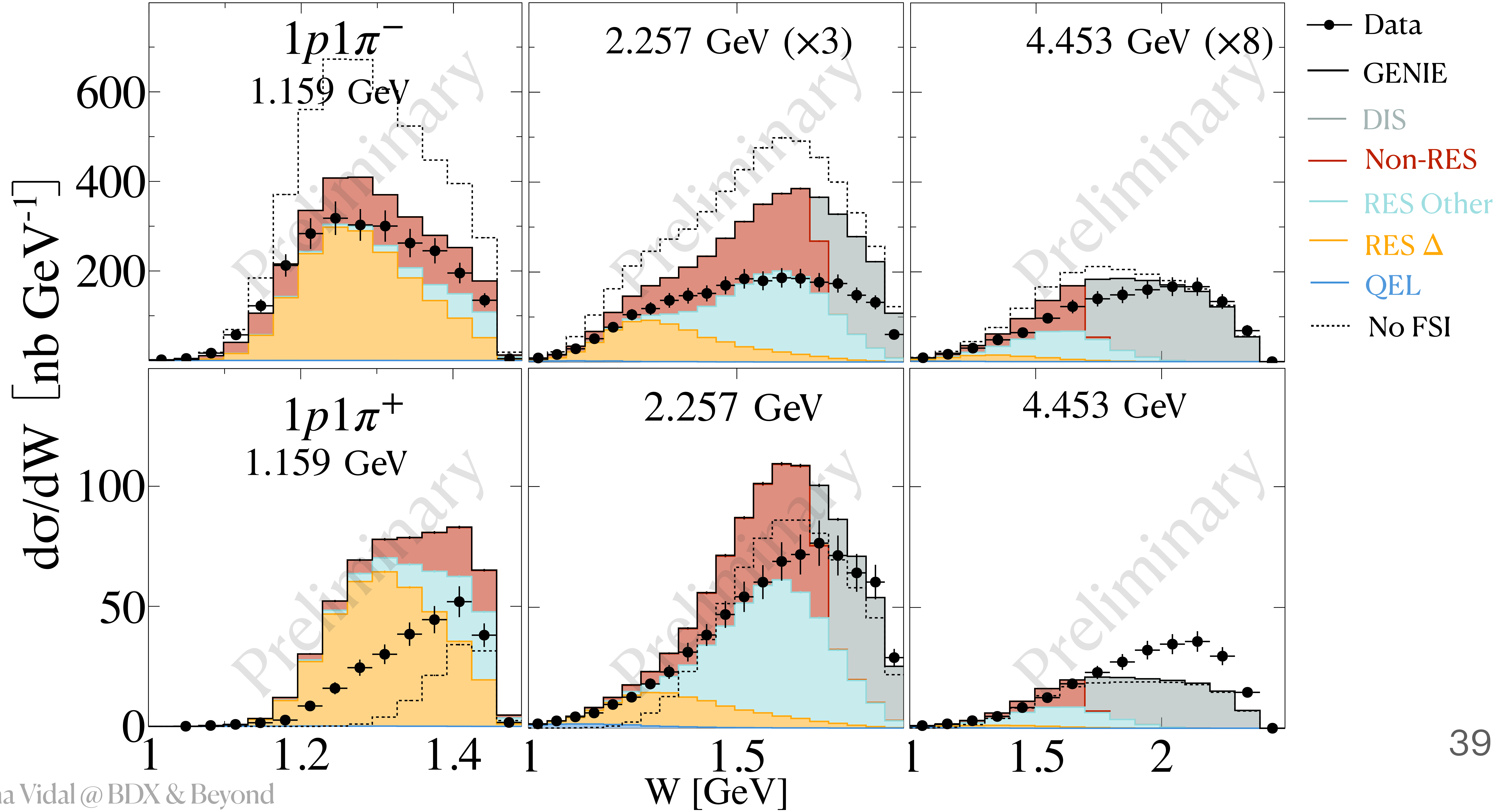


Complex Physics

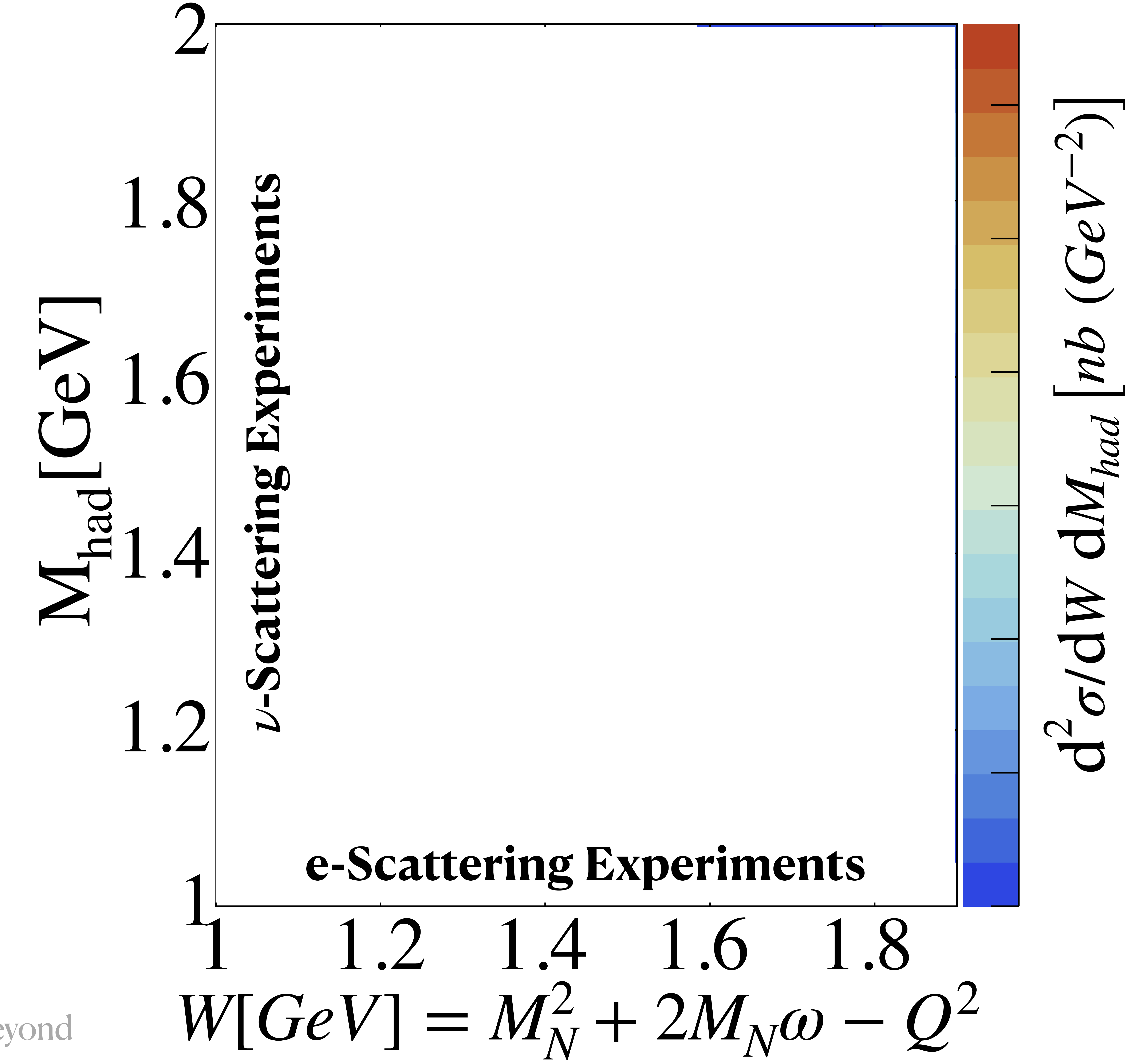




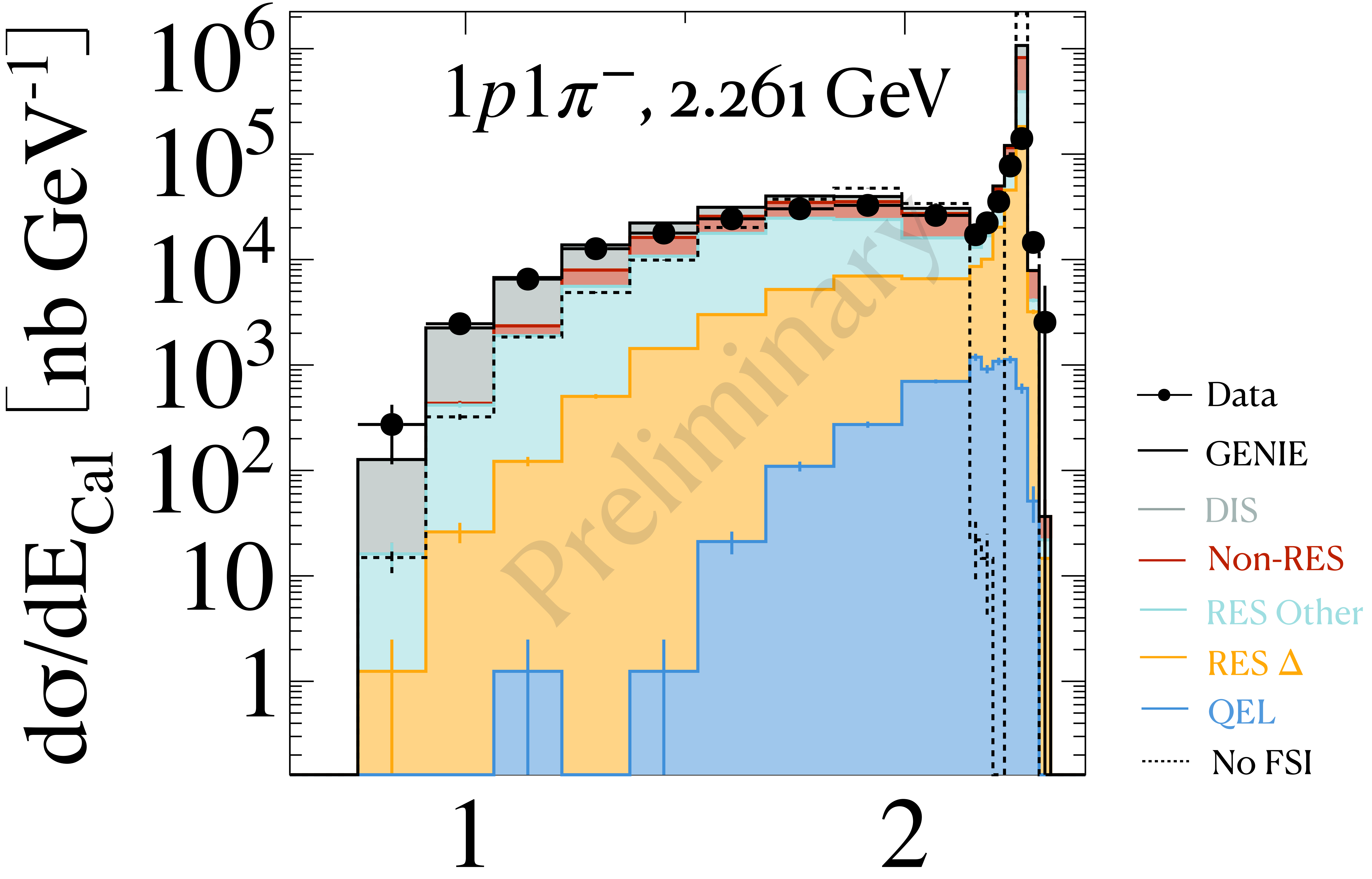
Complex Physics



Hadronic Invariant Mass Bias

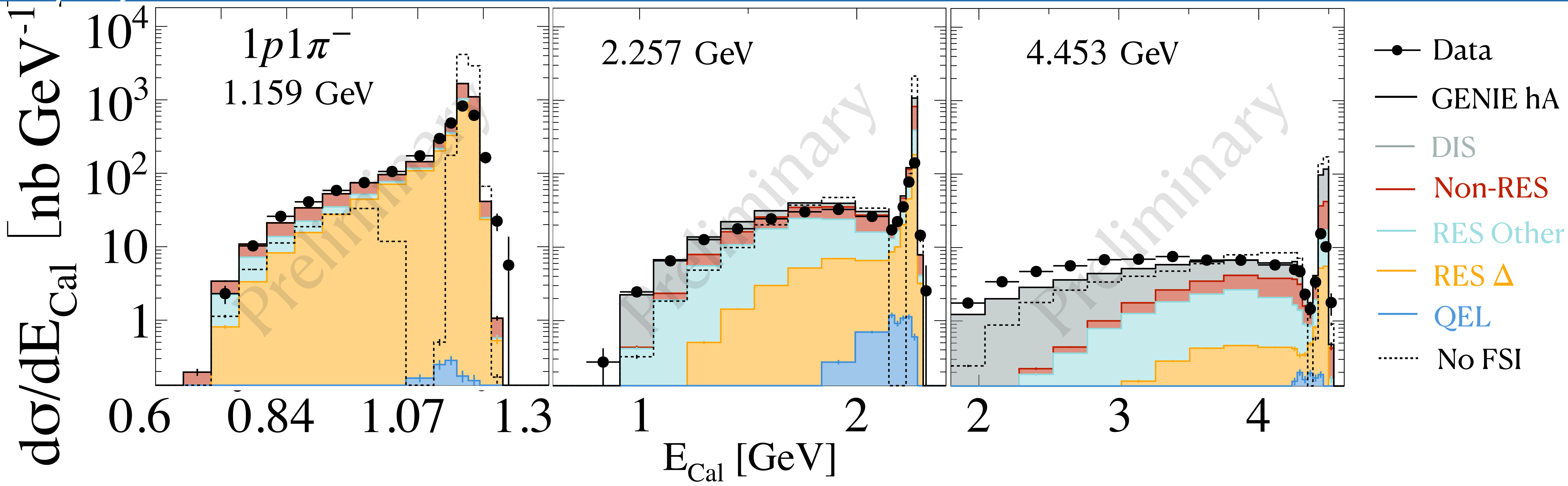


Energy Bias Quantification

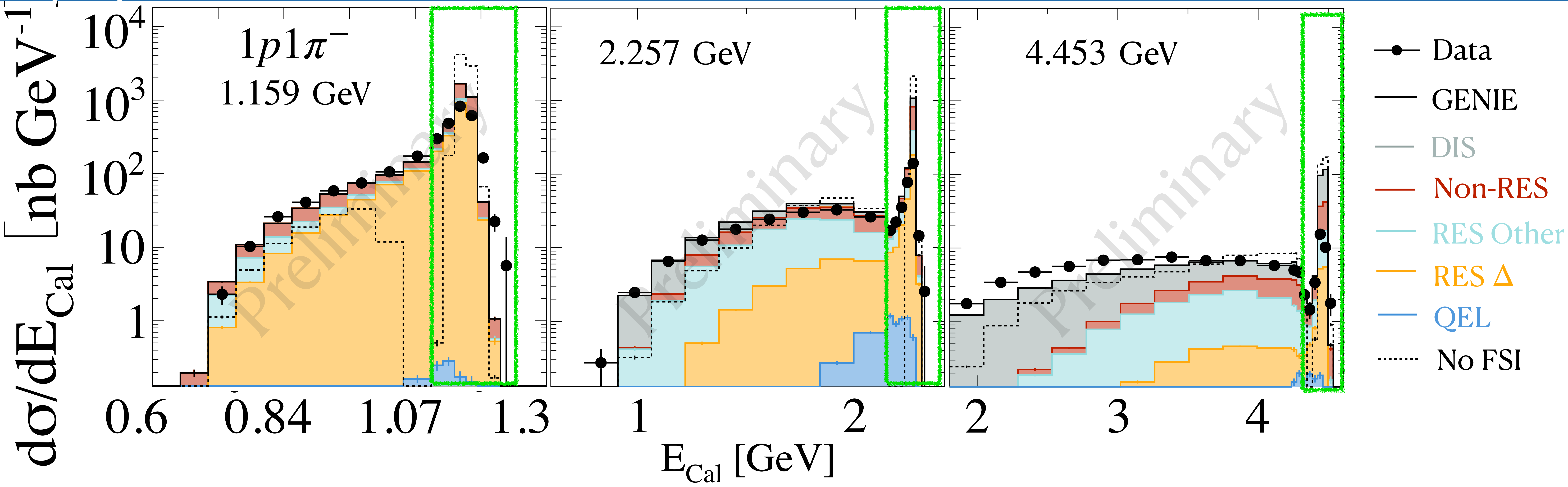


$(e, e'1p1\pi^-)\, E_{Cal}[\text{GeV}] = E_{e'} + E_\pi + T_p + \epsilon_i$

Beam energy miss-reconstruction



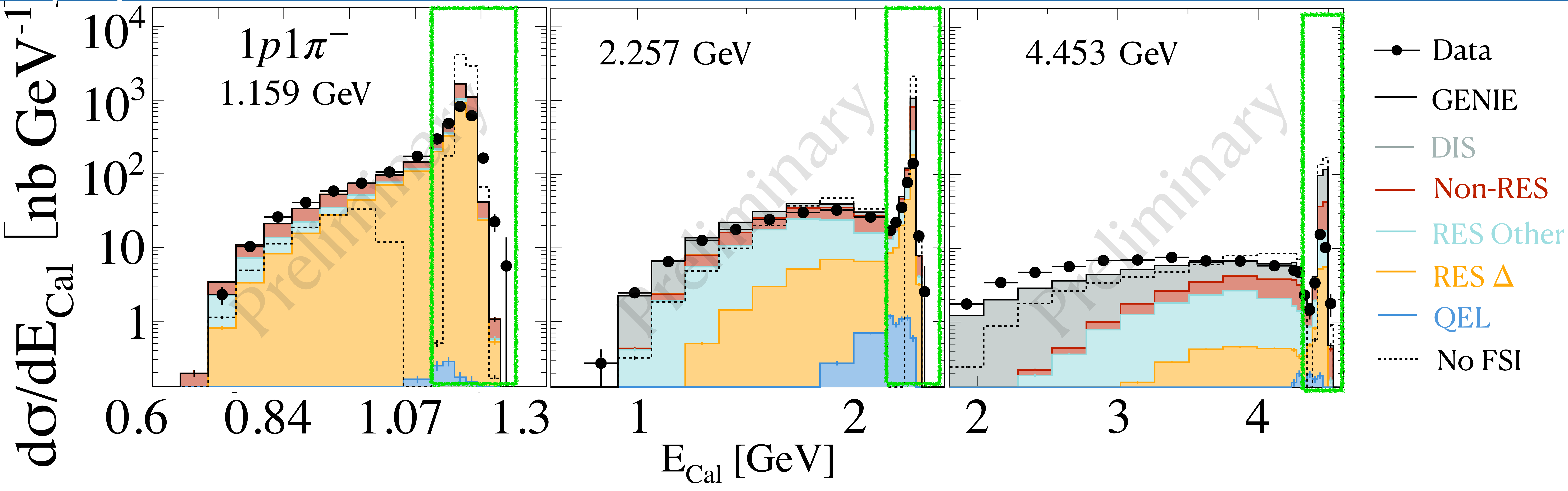
Beam energy miss-reconstruction



% Peak)	1.159	2.257	4.453
Data	68%	37.7%	19.5%
GENIE	77.9%	65%	63%

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

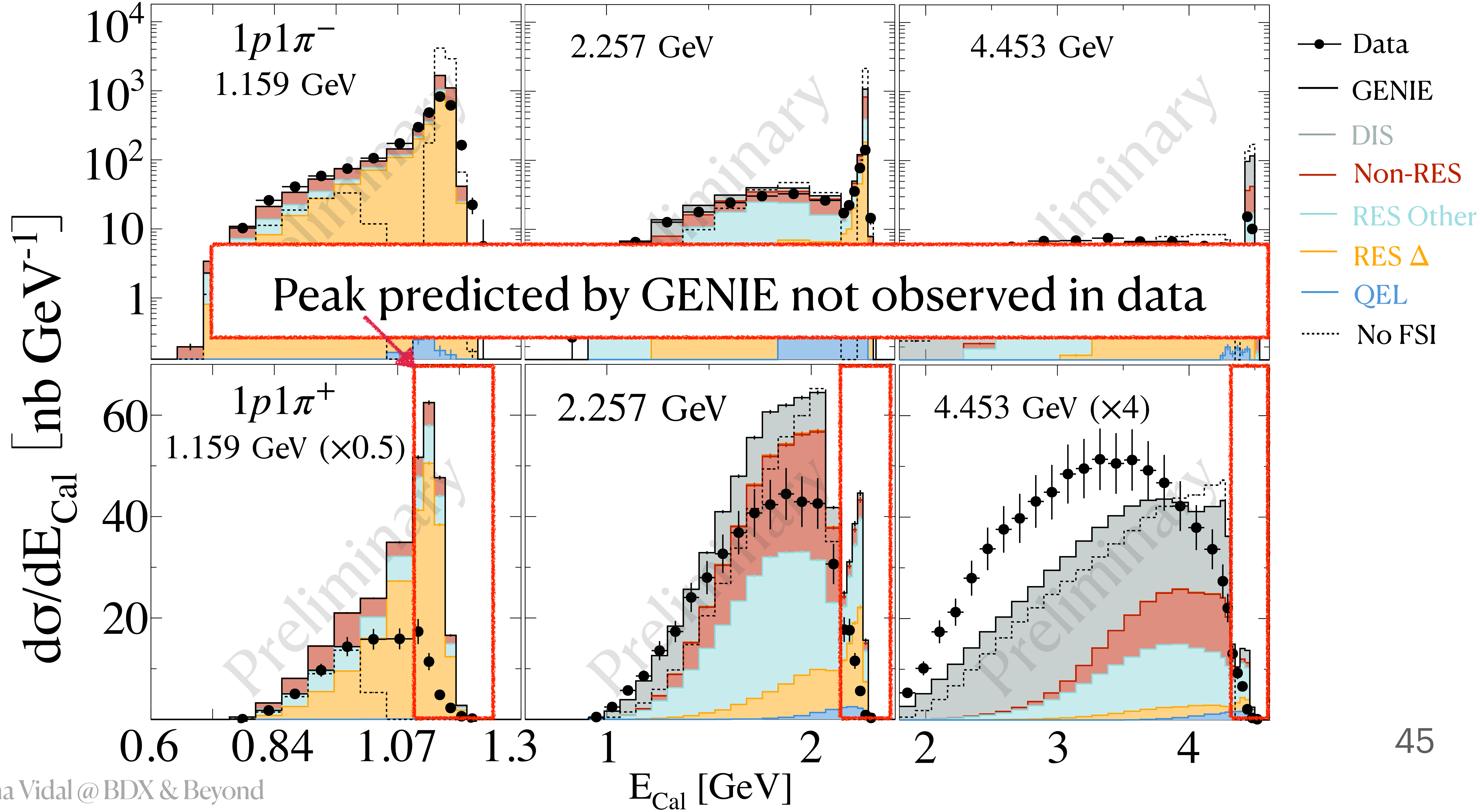
MC does not describe bias



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

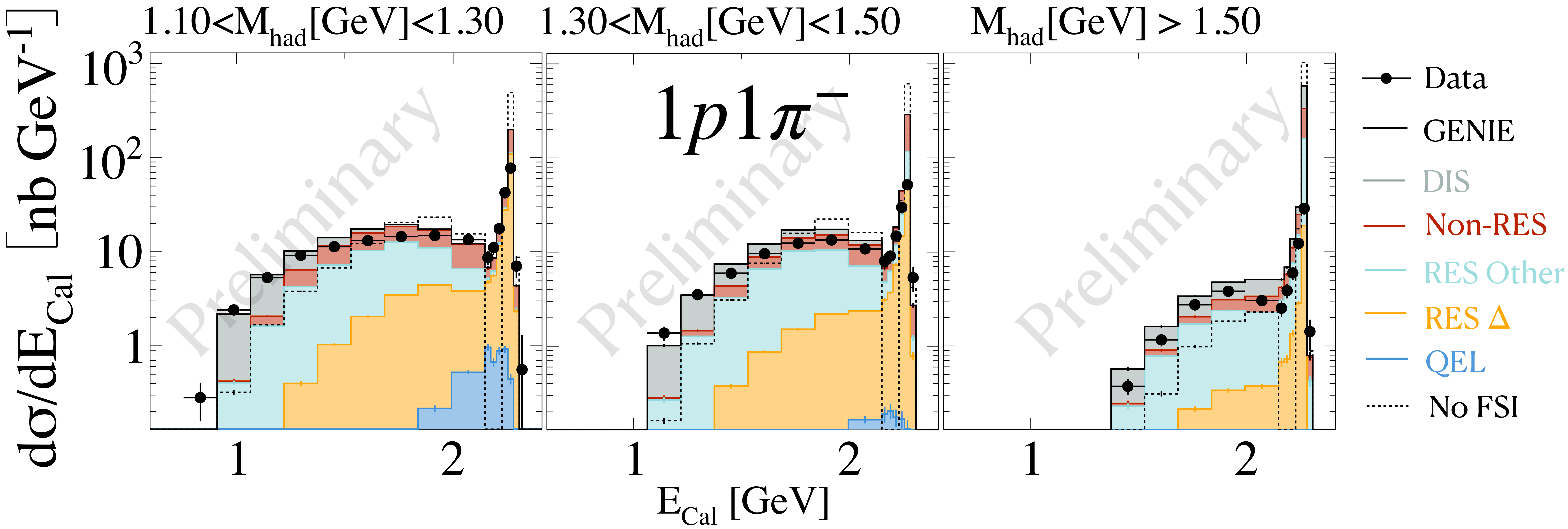
Peak largely over-predicted by GENIE

Beam energy miss-reconstruction

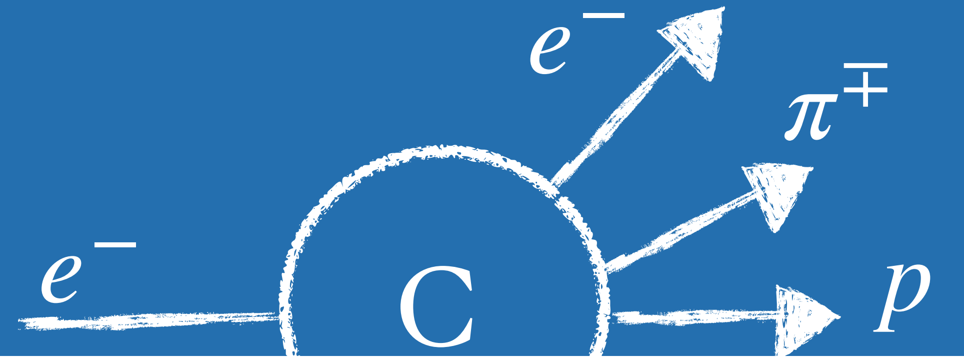


Peak predicted by GENIE not observed in data

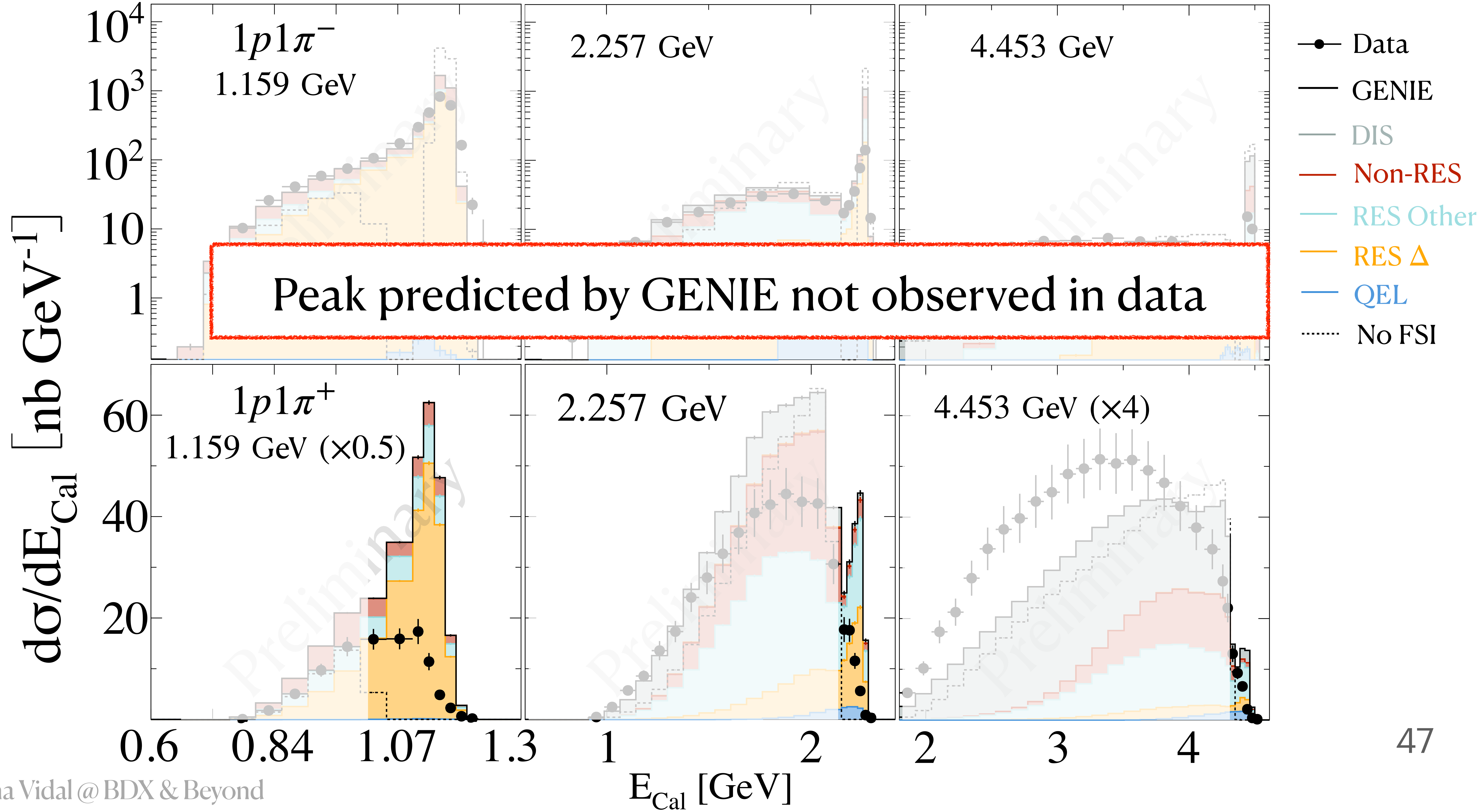
Hadronization biases E_{Cal}



% 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 $1p1\pi^+$



The GENIE Event Generator

Tune name in GENIE: GEM21_11a_00_000

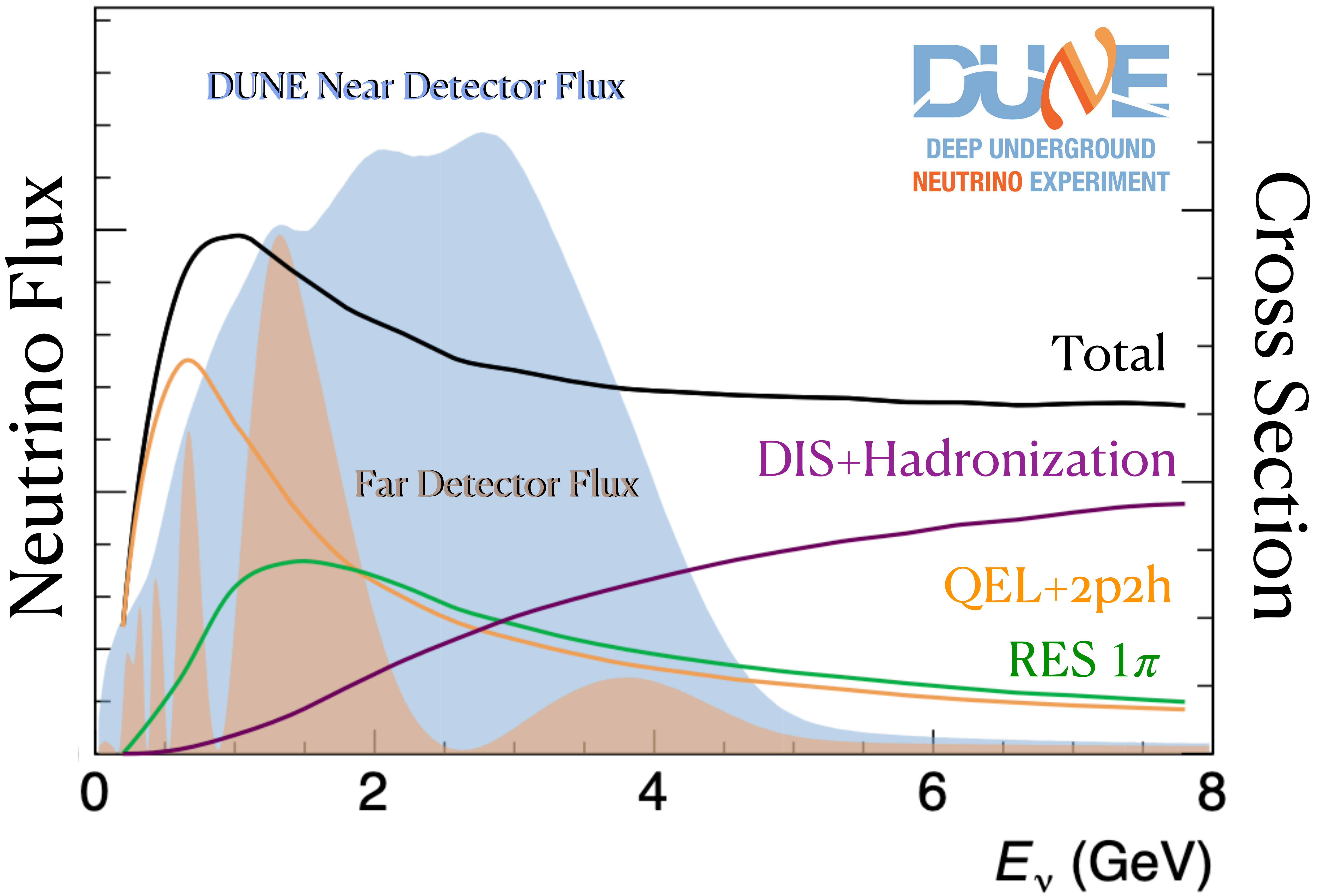
UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

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

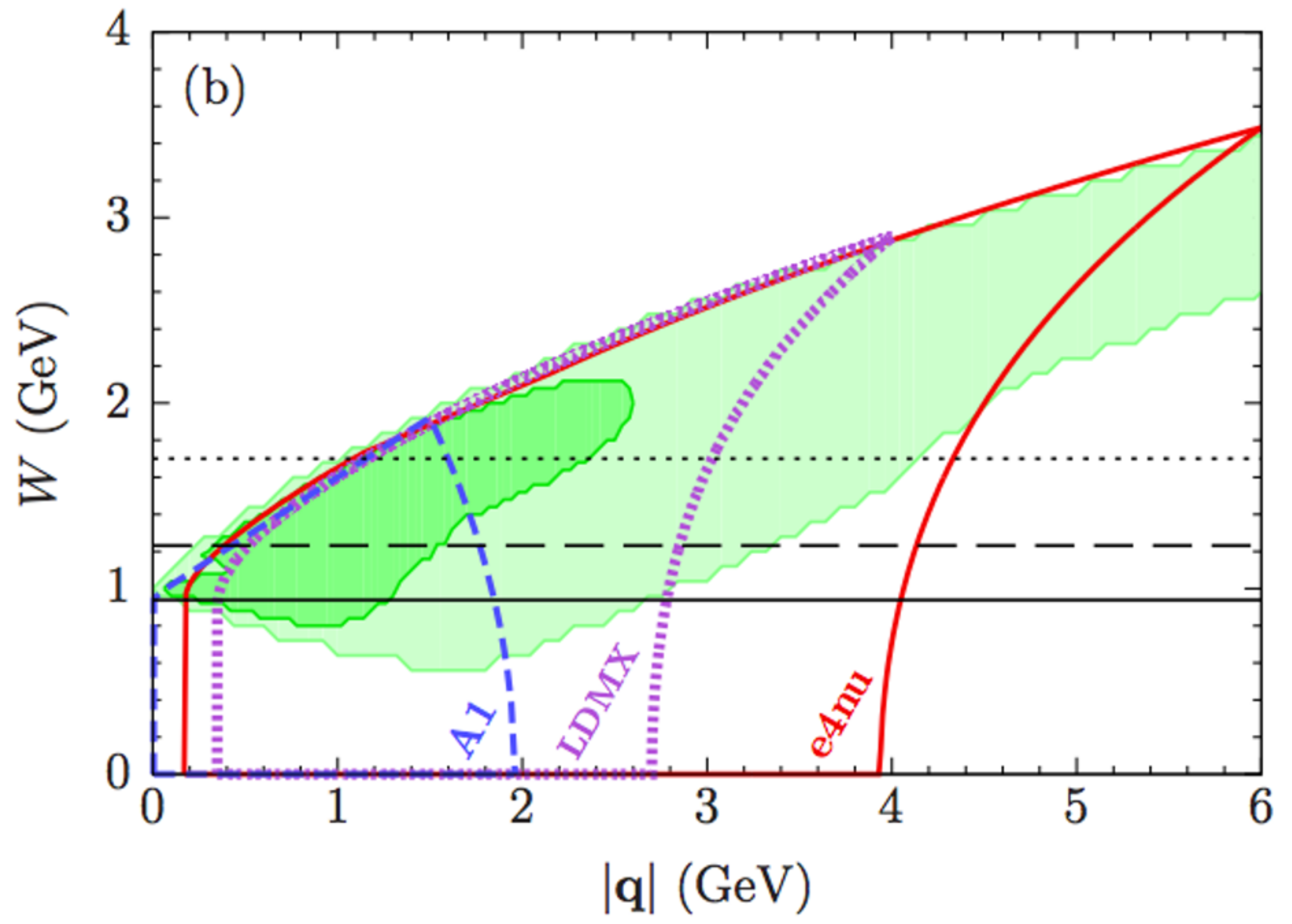
Process	Model
Quasi-ELastic and Two-Particle Two-	SUSAv2 model
RESonance Production	Berger-Sehgal model
Non-RESonance (SIS)	Bodek-Yang model, scaled with multiplicity dependent parameters
Deep Inelastic Scattering	Bodek-Yang model
Final State Interaction model	hA model
Hadronization model	AGKY model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

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

Pion-Production is key for Oscillations



Constraints for accelerator experiments



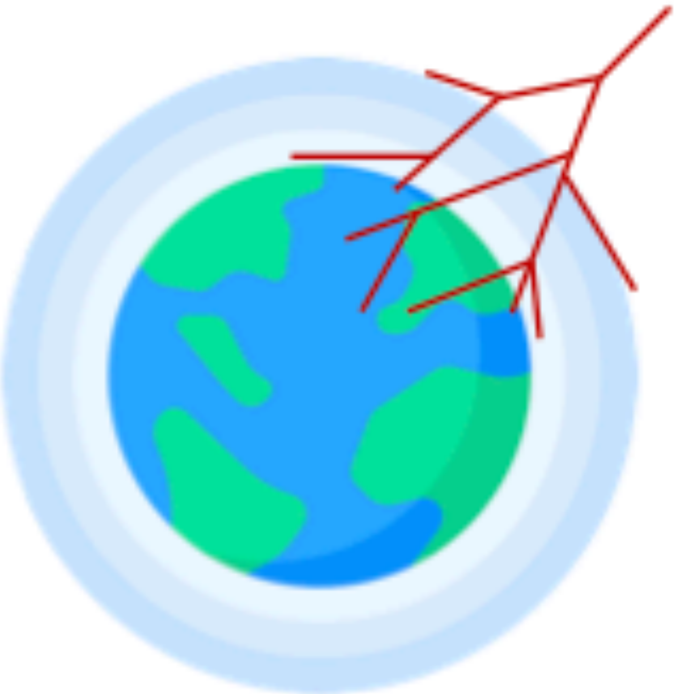
arXiv:2203.06853v1 [hep-ex] A NF06 Contributed White Paper

Complementary efforts

Collaborations	Kinematics	Targets	Scattering	Publications
E12-14-012 (JLab) (Data collected: 2017) Jefferson Lab	E_e = 2.222 GeV; θ_e = 15.5, 17.5, 20.0, 21.5; θ_p = -39.0, -44.0, -44.5, -47.0 -50.0	Ar, Ti Al, C	(e, e') $(e, e'p)$	Phys. Rev. C **99**, 054608 Phys.Rev.D **105** 112002
e4nu/CLAS (JLab) (Data collected: 1999, 2022) Jefferson Lab	E_e = 1, 2, 4, 6 GeV; $\theta_e > 5$	H, D, He, C, Ar, ^{40}Ca, ^{48}Ca, Fe, Sn	(e, e') e, p, n, π, γ in the final state	Nature **599**, 565 Phys.Rev.D **103** 113003
	Only effort with data already taken and expected exclusive measurements, best coverage			
A1 (MAMI) (Data collected:2020) (More data planned)	E_e = 1.6 GeV	H, D, He C, O, Al Ca, Ar, Xe	(e, e') 2 additional charged particles	
LDMX (SLAC) (Planned)	E_e = 4.0 GeV; $\theta_e < 40$		(e, e') e, p, n, π in the final state	
eALBA (Planned)	E_e = 500 MeV - few GeV	C, CH Be, Ca	(e, e')	

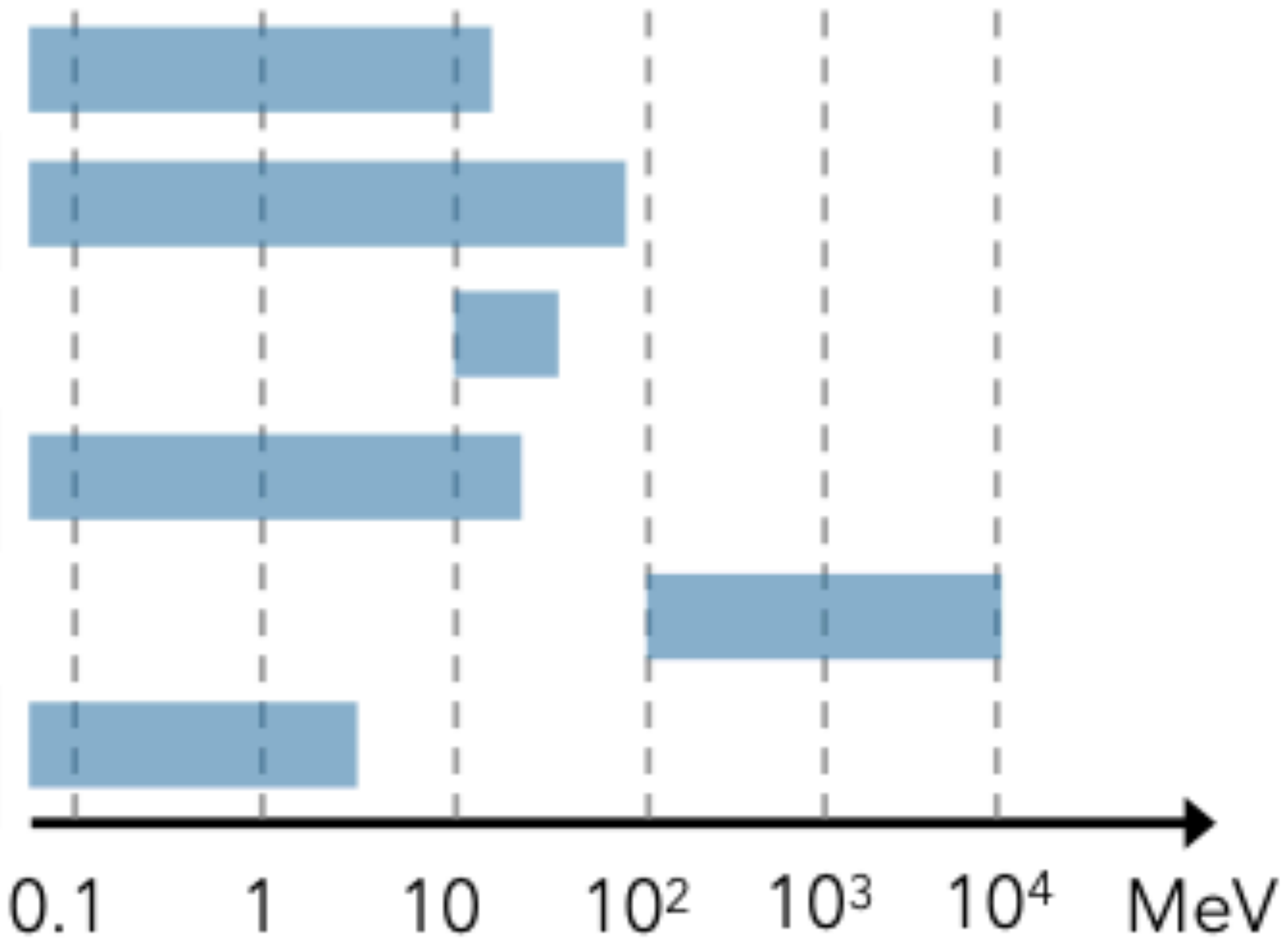
Adaptation from Proceedings of the US Community Snowmass2021

arXiv:2203.06853v1 [hep-ex]


Reactor $\bar{\nu}_e$ Atmospheric $\nu/\bar{\nu}$ Solar ν_e Supernovae Geo-neutrinos

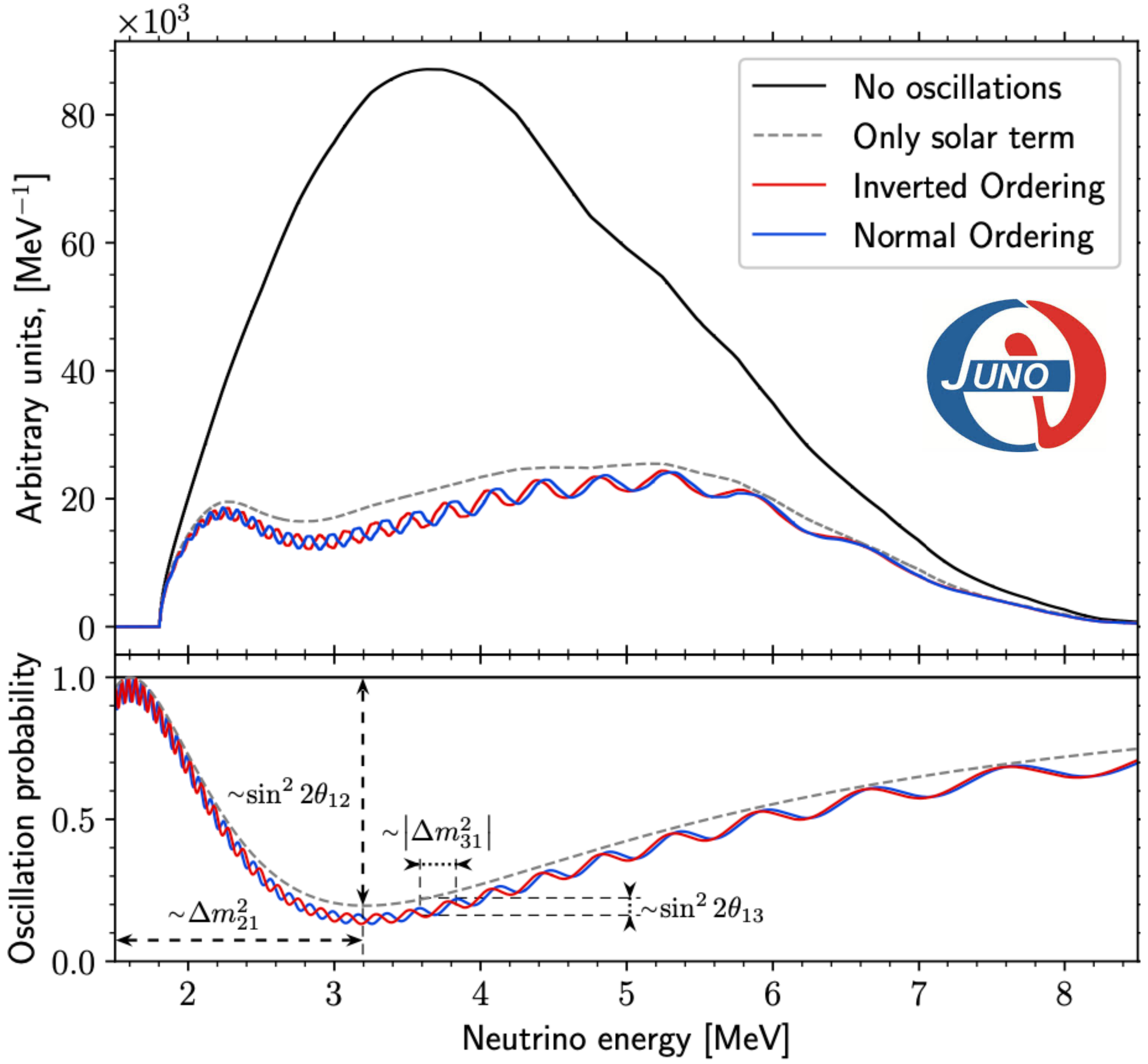
Source	Expected rate	Energy range
Reactor	~ 60 / day	
SN burst	~ 7300 @ 10 kpc in few s	
DSNB	~ 2-4 / year	
Solar (^{8}B)	O(100) / day	
Atmospheric	~ O(100) /year	
Geo-neutrinos	~ 400 / year	



Vanessa Cerrone @ NuFact 2025

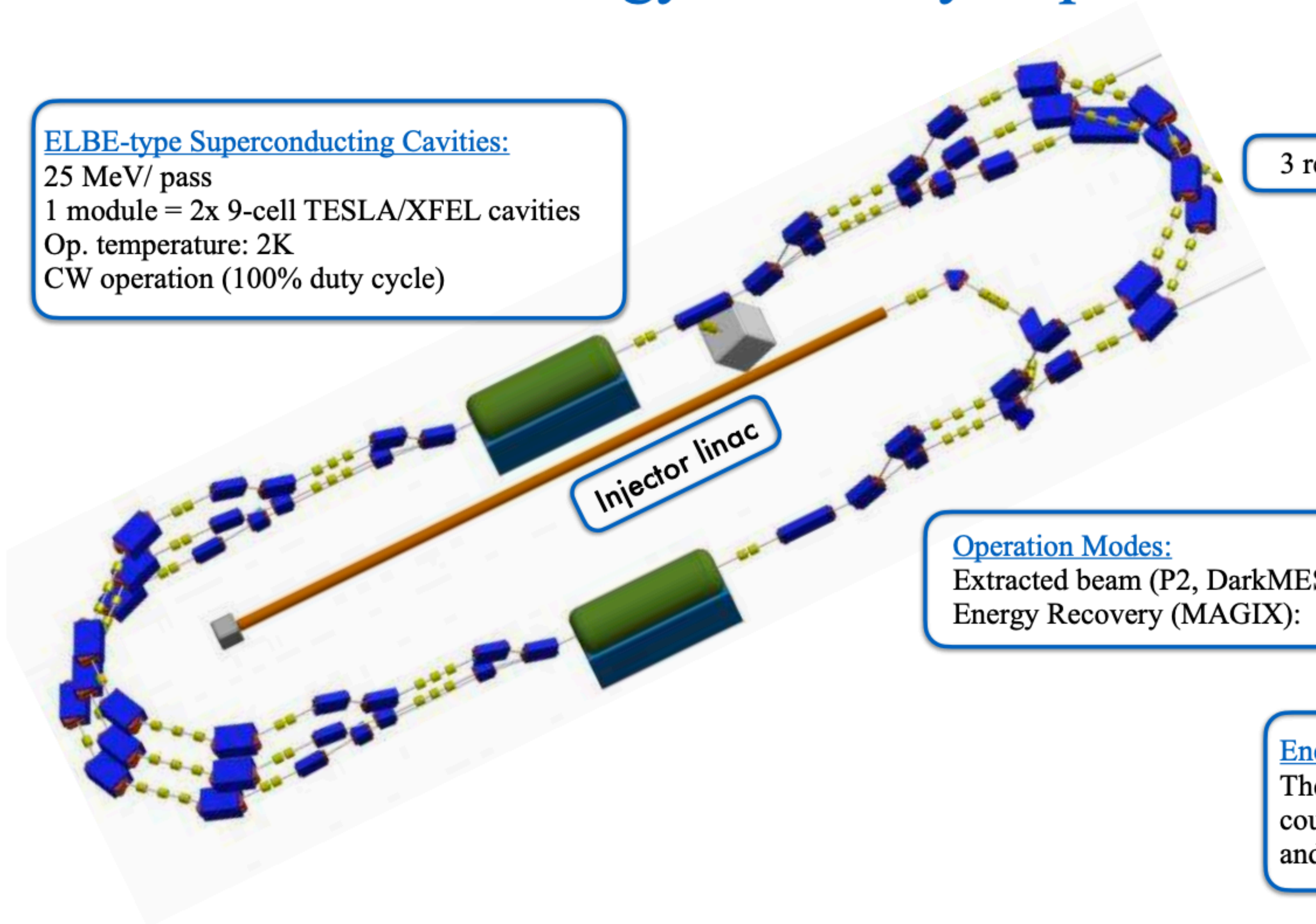
Reactor Neutrino Experiments

- Best limits to θ_{13} by reactor experiments
- JUNO set to determine ν-MO & oscillation parameters to sub-percent level
  - Water and scintillator detector
  - ν-Reactor, SuperNova, Solar, Geo., **Atm.**
  - Started data taking August 2025!
- Oscillation signal at the MeV range
- **Main signal driven by Inverse Beta Decay (IBD)**
  - Low uncertainty (0.1%) associated to this process from Cabibbo angle and Axial coupling



https://arxiv.org/pdf/2405.18008

MESA: Mainz Energy-Recovery Superconducting Accelerator



ELBE-type Superconducting Cavities:
25 MeV/ pass
1 module = 2x 9-cell TESLA/XFEL cavities
Op. temperature: 2K
CW operation (100% duty cycle)

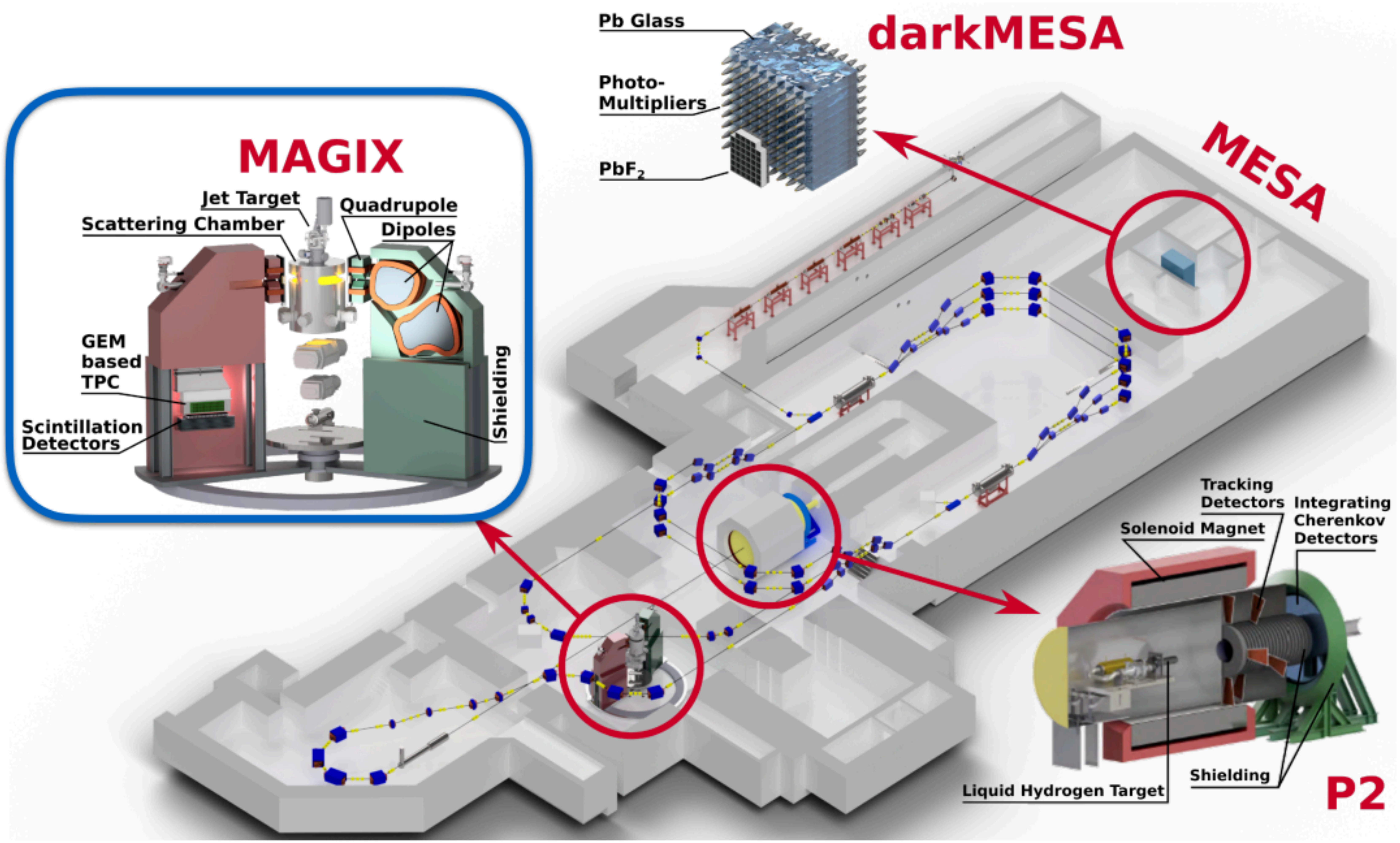
3 recirculation arcs

Operation Modes:

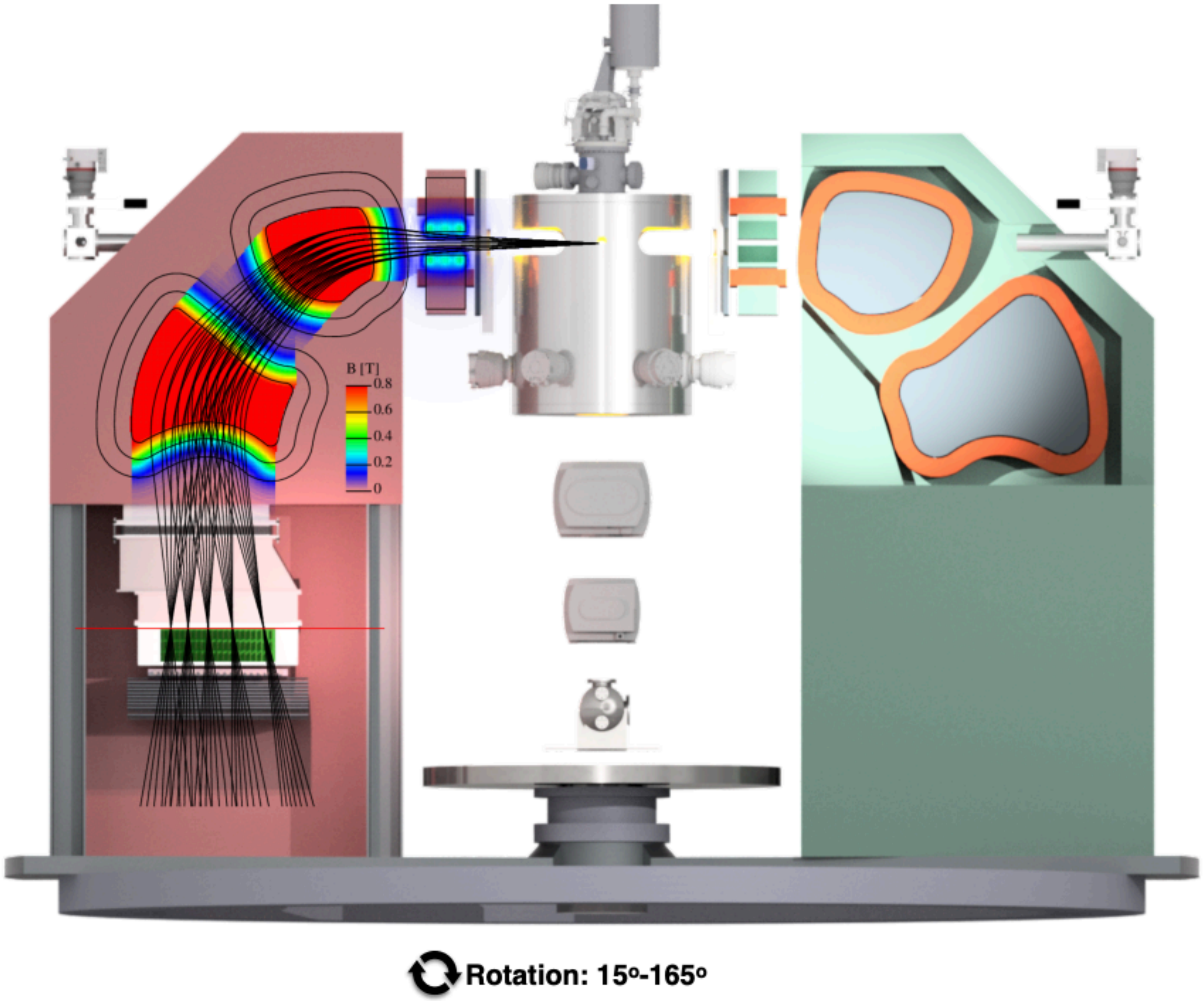
Extracted beam (P2, DarkMESA):	E_{beam} = 155 MeV, I_{beam} = 150uA
Energy Recovery (MAGIX):	E_{beam} = 105 MeV, I_{beam} = 1mA

Energy Recovery mode:
The beam is reinserted after 3 recalculations in couterphase: the energy goes back to the cavities and the beam is dumped at 5 MeV.

The MAGIX experiment



The MAGIX experiment



Detectors:

- Low-mass GEM-based TPC.
- Plastic Scintillators for triggering and veto.

Timing

- TPC trigger: ~1 ns
- coincidence time STAR↔PORT: ~100 ps

Focal Plane resolutions (p-dependent etc)

- positions: ~100 μm angles: ~3.5 mrad

Expected Resolution

- dp/p: 6×10^{-5}
- in-plane angle φ_0: 6.5 mrad
- oop angle θ_0: 1.6 mrad vertex y_0: 60 μm

Acceptances

- momentum acceptance: ± 15 %
- solid angle: 18 msr