Overview of Neutrino-Nucleus Interaction Physics

Nuintists' questions

1. Where were we from?

2. Where are we now?

3. Where will we go?

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King's College London
NuInt22, Hoam Faculty House, Seoul
Oct. 24, 2022

NuINT 2022
The 13th International Workshop on Neutrino-Nucleus Interactions in the Few GeV Regions

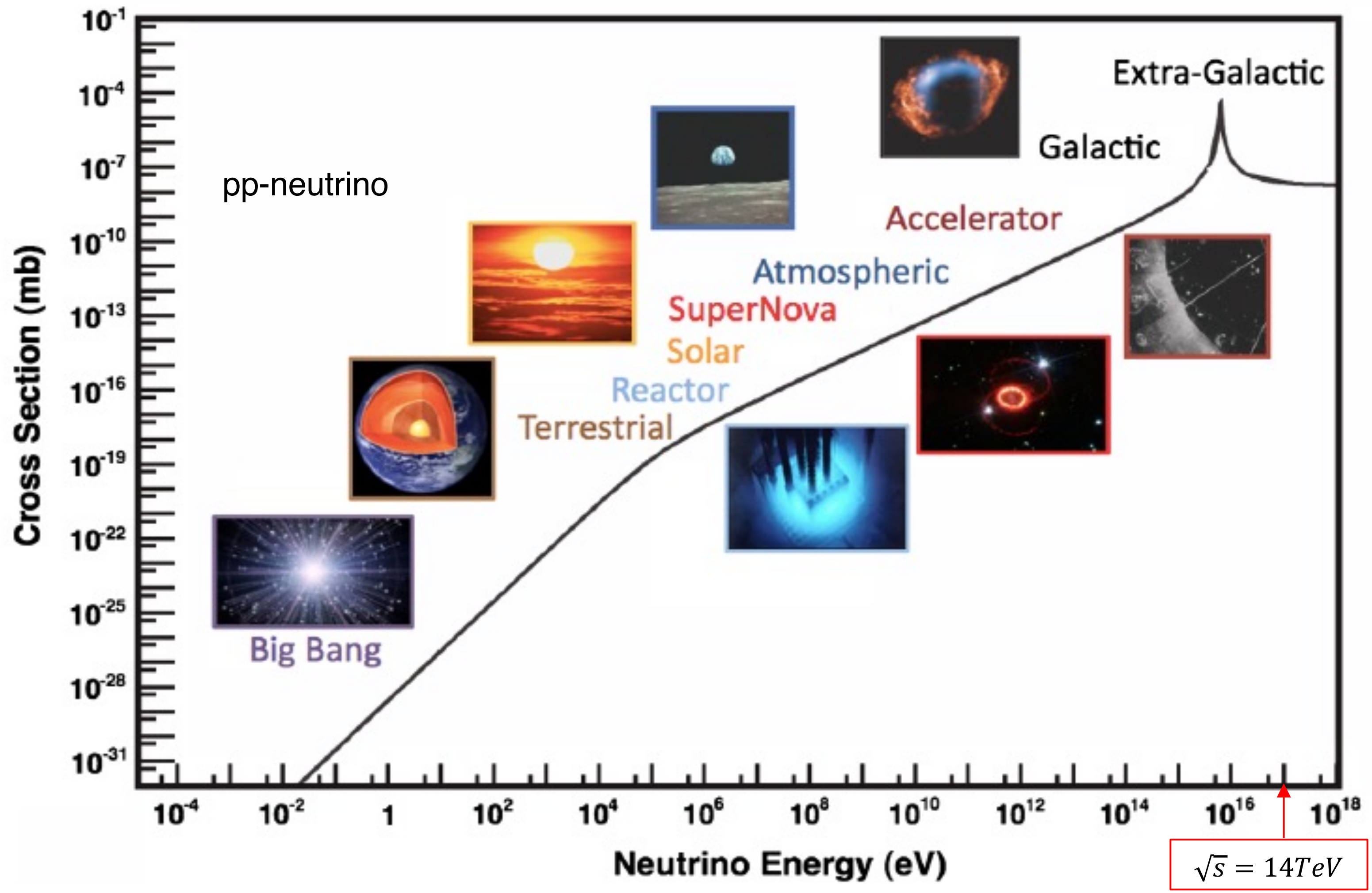
October 24 to 29, 2022 (OFFLINE)

#NuInt22
#nuxsec

Hoam Faculty House
Seoul National University
Seoul, Korea

Formaggio and Zeller, Rev.Mod.Phys.,84 (2012) 1307

From eV to EeV: Neutrino cross sections across energy scales



Formaggio and Zeller, Rev.Mod.Phys.,84 (2012) 1307

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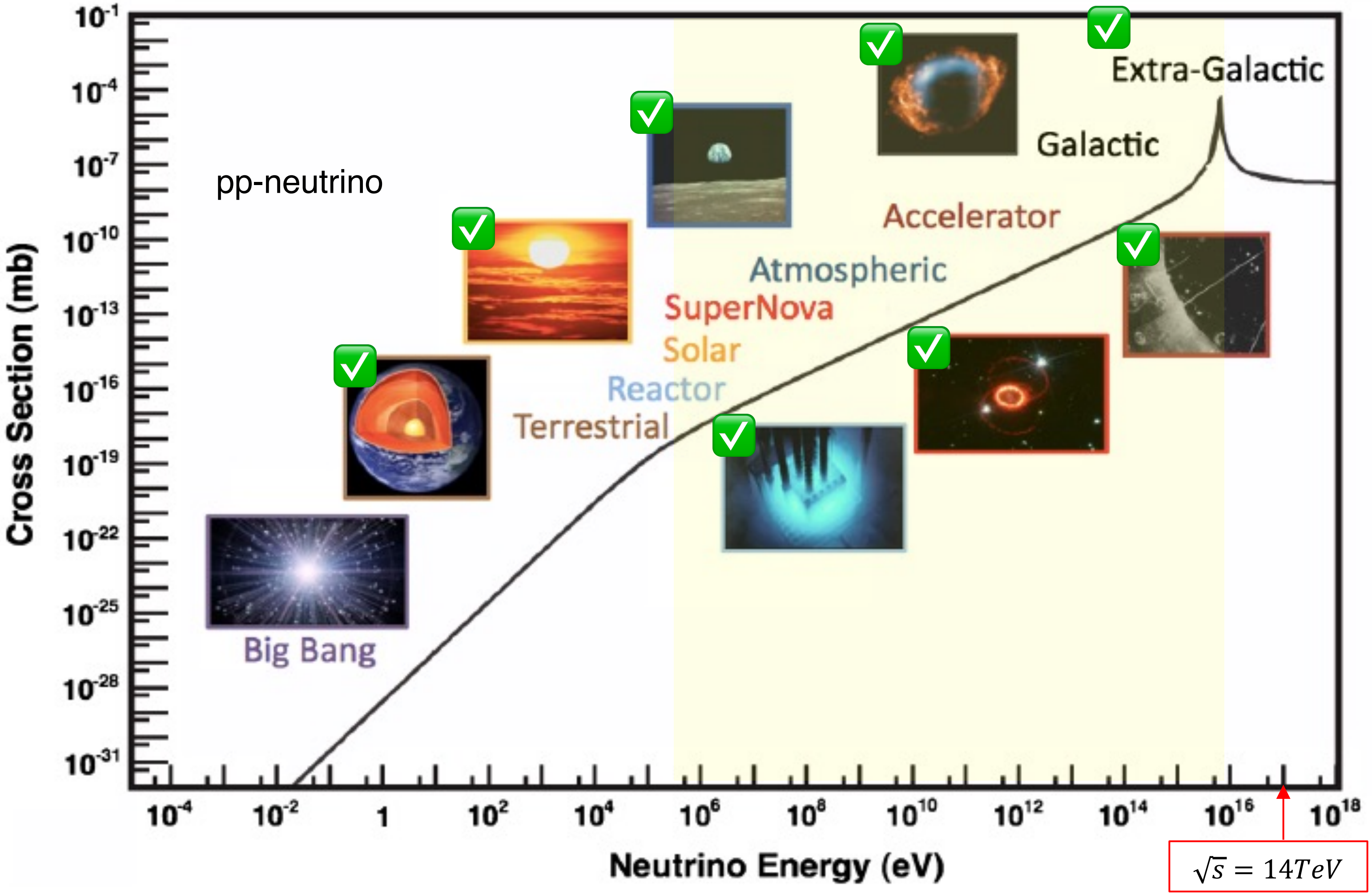

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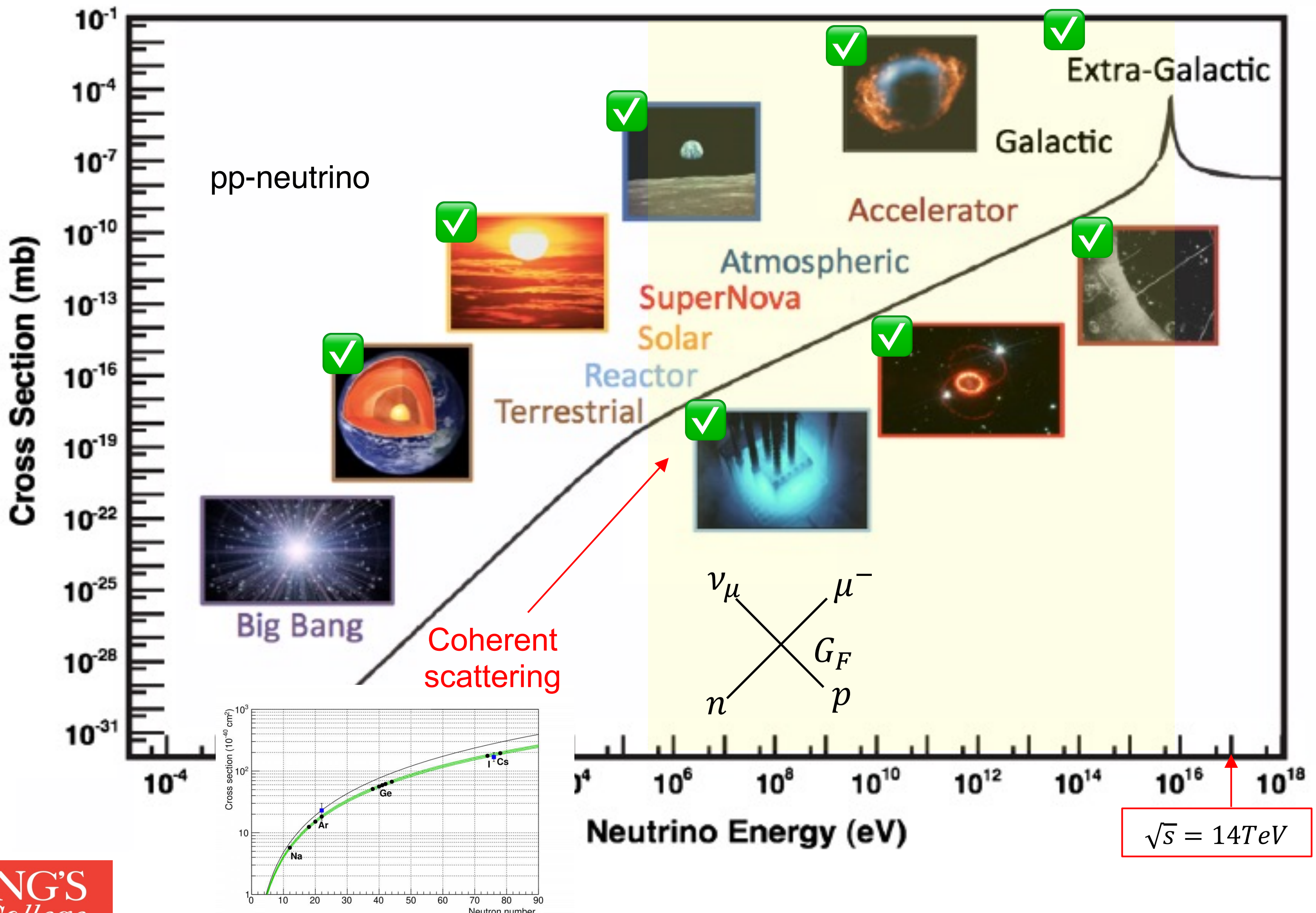
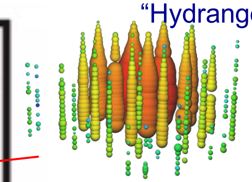


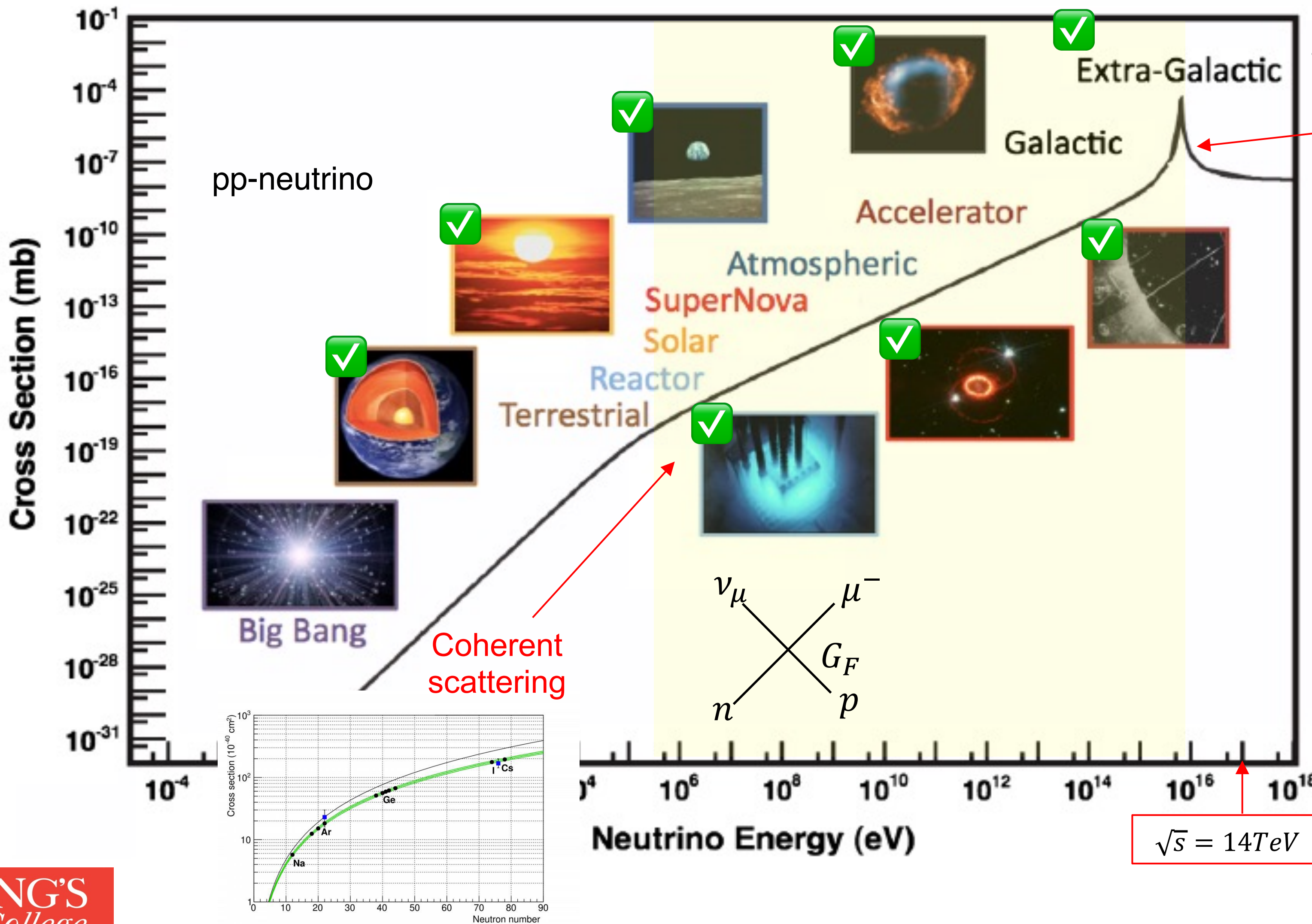
Pershey, Neutrino 2022

Formaggio and Zeller, Rev.Mod.Phys.,84 (2012) 1307

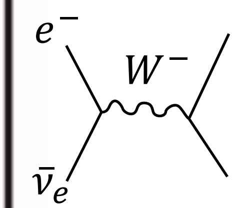
From eV to EeV: Neutrino cross sections across energy scales

IceCube, Nature591(2021)220
"Hydrangea"





Glashow resonance



$\sqrt{s} = 14TeV$

Pershey, Neutrino 2022

Formaggio and Zeller, Rev.Mod.Phys.,84 (2012) 1307

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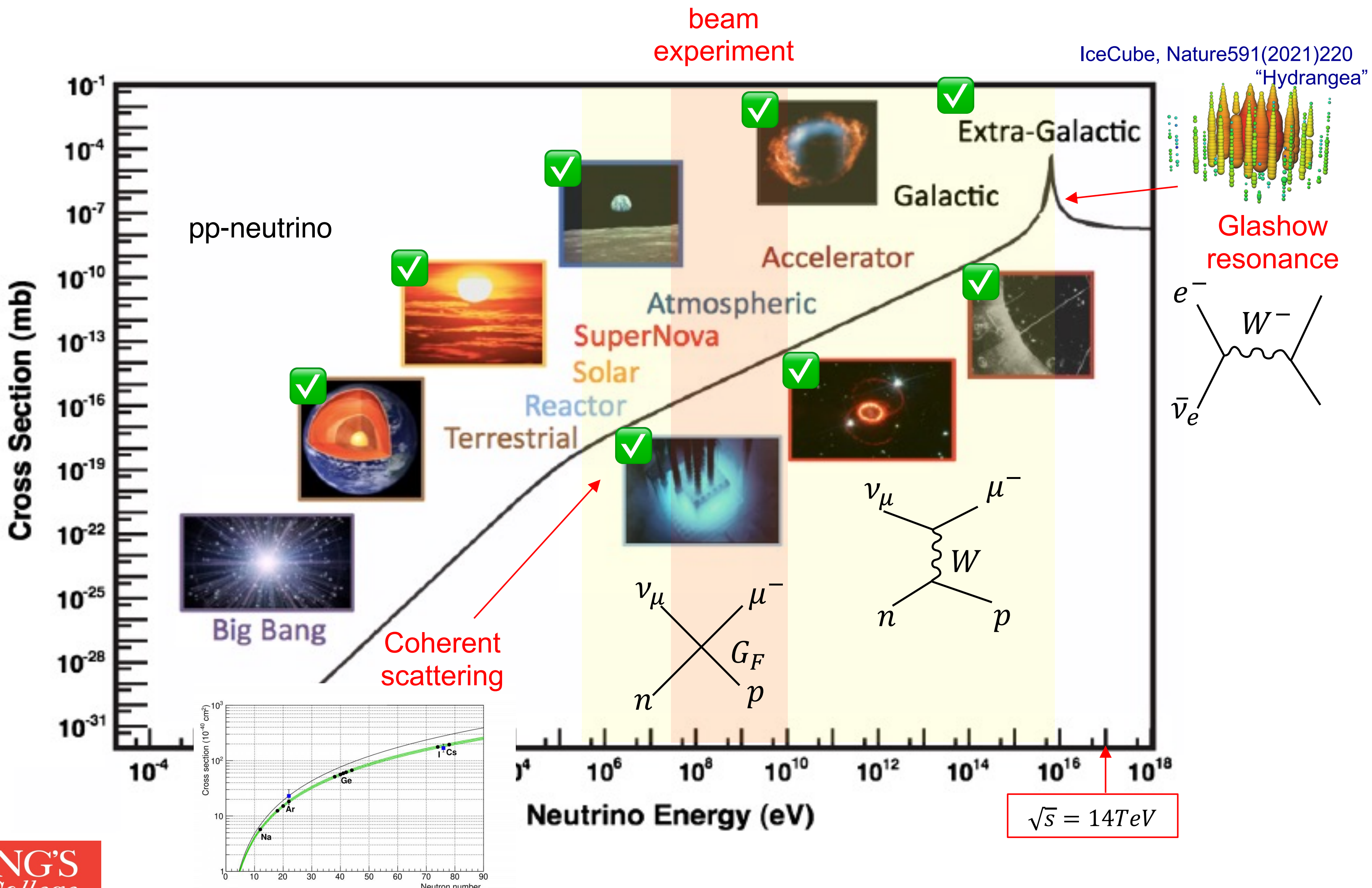


Pershey, Neutrino 2022

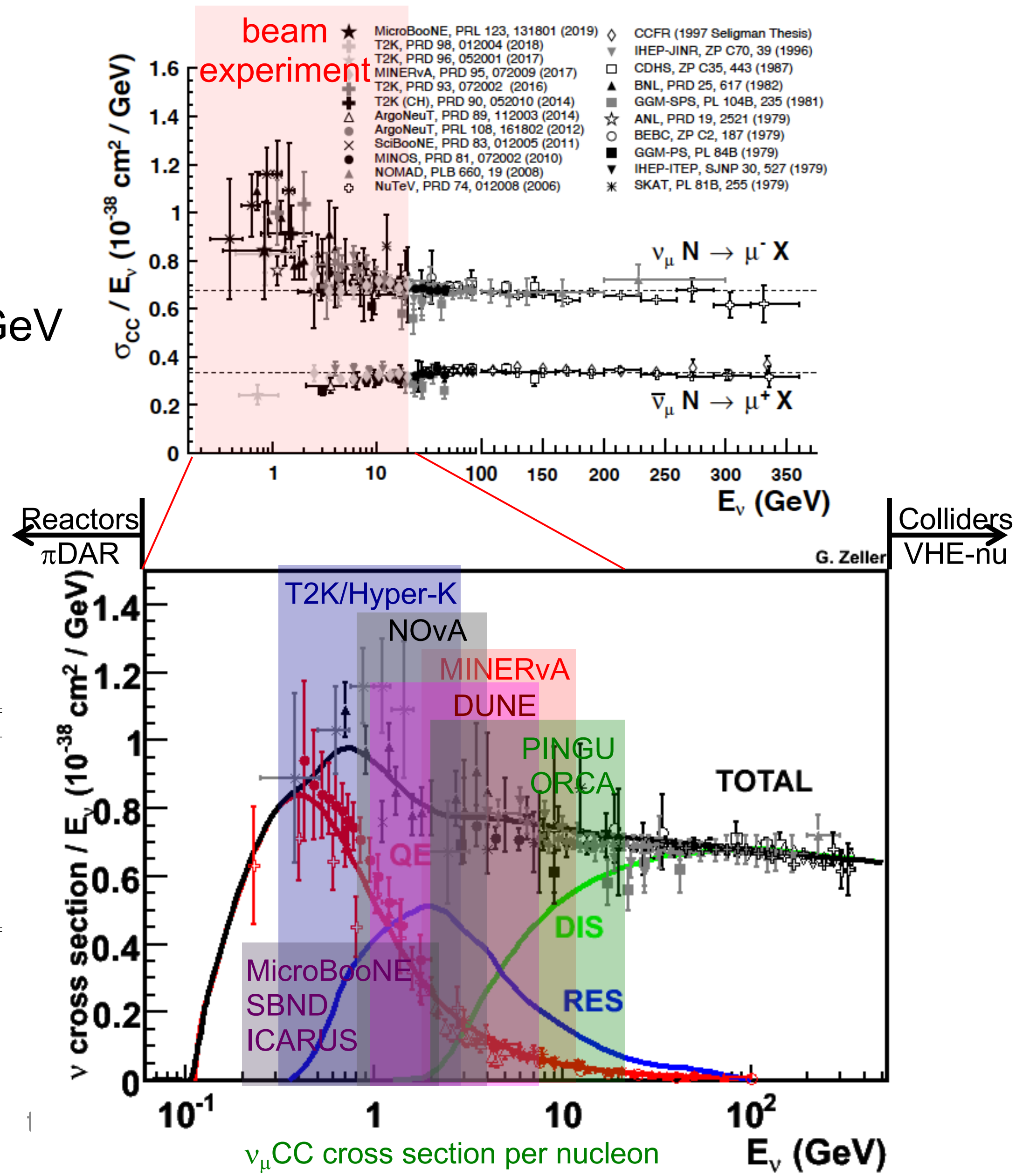
PDG: Neutrino Cross Section Measurements

PDG has a summary of neutrino cross-section data since 2012!

Focus of this talk is around a few GeV

Table 52.2: Published measurements of neutrino and antineutrino CC inclusive cross sections from modern accelerator-based neutrino experiments.

experiment	measurement	target
ArgoNeuT	ν_μ [6, 7], $\overline{\nu}_\mu$ [7]	Ar
MicroBooNE	ν_μ [8, 26], ν_e [22]	Ar
MINERνA	ν_μ [9–11, 16, 17, 27], $\overline{\nu}_\mu$ [27], $\overline{\nu}_\mu/\nu_\mu$ [28]	CH, C/CH, Fe/CH, Pb/CH
MINOS	ν_μ [29], $\overline{\nu}_\mu$ [29]	Fe
NINJA	ν_μ [12], $\overline{\nu}_\mu$ [12]	H_2O
NOMAD	ν_μ [30]	C
SciBooNE	ν_μ [31]	CH
T2K	ν_μ [13, 14, 32–34], ν_e [23–25], $\overline{\nu}_\mu/\nu_\mu$ [15]	CH, H_2O, Fe



Where were we from?

Where are we now?

Where will we go?

Good old days of neutrino interaction physics

Nuclear Physics B133 (1978) 205–219

TOTAL CROSS SECTIONS FOR ν_e AND $\overline{\nu}_e$ INTERACTIONS AND SEARCH FOR NEUTRINO OSCILLATIONS AND DECAY

Gargamelle Collaboration

J. BLIETSCHAU, H. DEDEN, F.J. HASERT, W. KRENZ, D. LANSKE, J. MORFIN, M. POHL, K. SCHULTZE, H. SCHUMACHER, H. WEERTS and L.C. WELCH
III. Physikalisches Institut der Technischen Hochschule, Aachen, Germany

G. BERTRAND-COREMANS, M. DEWIT *, H. MULKENS **, J. SACTON and W. VAN DONINCK ***
Interuniversity Institute for High Energies, ULB, VUB Brussels, Belgium

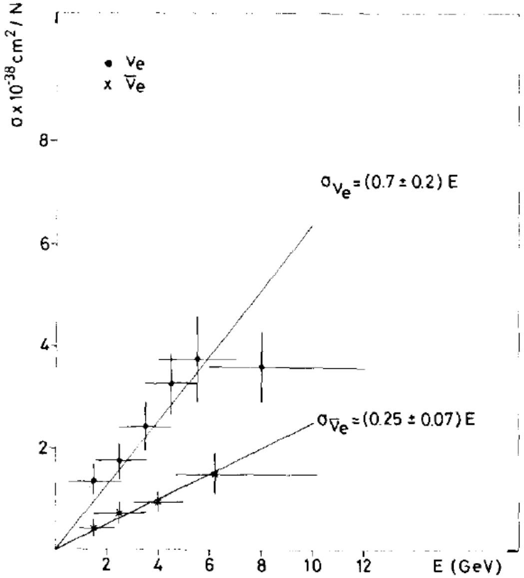
D. HAIDT, C. MATTEUZZI, P. MUSSET, B. PATTISON, F. ROMANO +, J.P. VIALLE ++ and A. WACHSMUTH
CERN, European Organization for Nuclear Research, Geneva, Switzerland

A. BLONDEL, V. BRISSON, B. DEGRANGE, T. FRANÇOIS, M. HAGUENAUER, U. NGUYEN-KHAC and P. PETIAU
Laboratoire de Phys. Nucl. des Hautes Energies, Ecole Polytechnique, Paris, France

E. BELLOTTI, S. BONETTI, D. CAVALLI, E. FIORINI, A. PULLIA and M. ROLLIER
Istituto di Fisica dell'Università and INFN, Milano, Italy

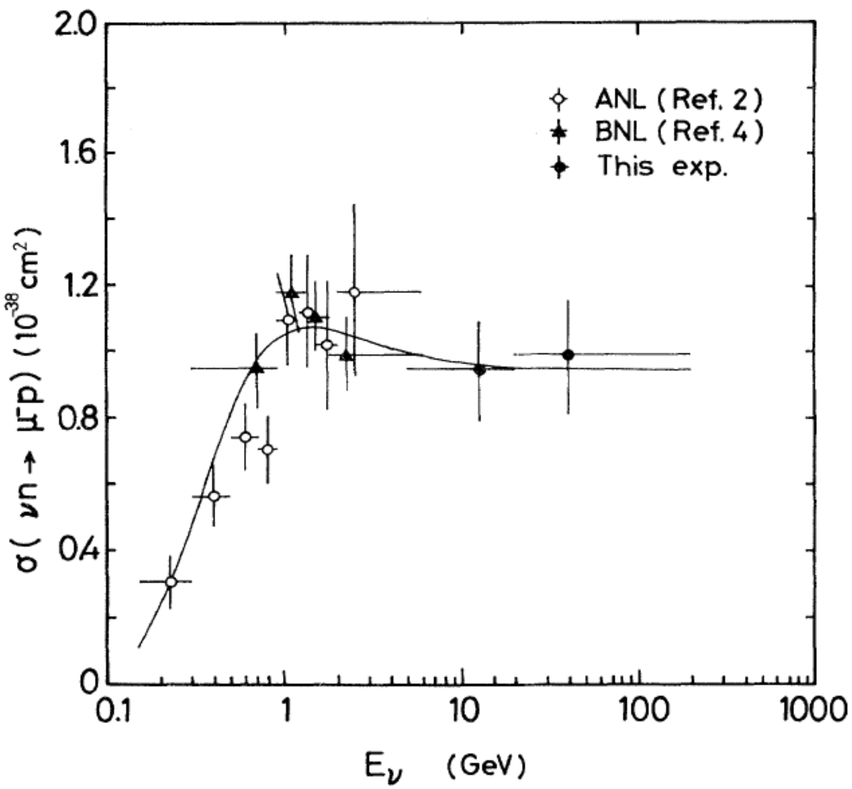
B. AUBERT, D. BLUM, A.M. LUTZ and C. PASCAUD
Laboratoire de l'Accélérateur Linéaire, Orsay, France

F.W. BULLOCK and A.G. MICHETTE +++
University College London, London, UK



Good old days of neutrino interaction physics

Deuterium bubble chamber
- MA fit to Q2 distribution
- All data agree with MA~1 GeV



It seems everything is alright...

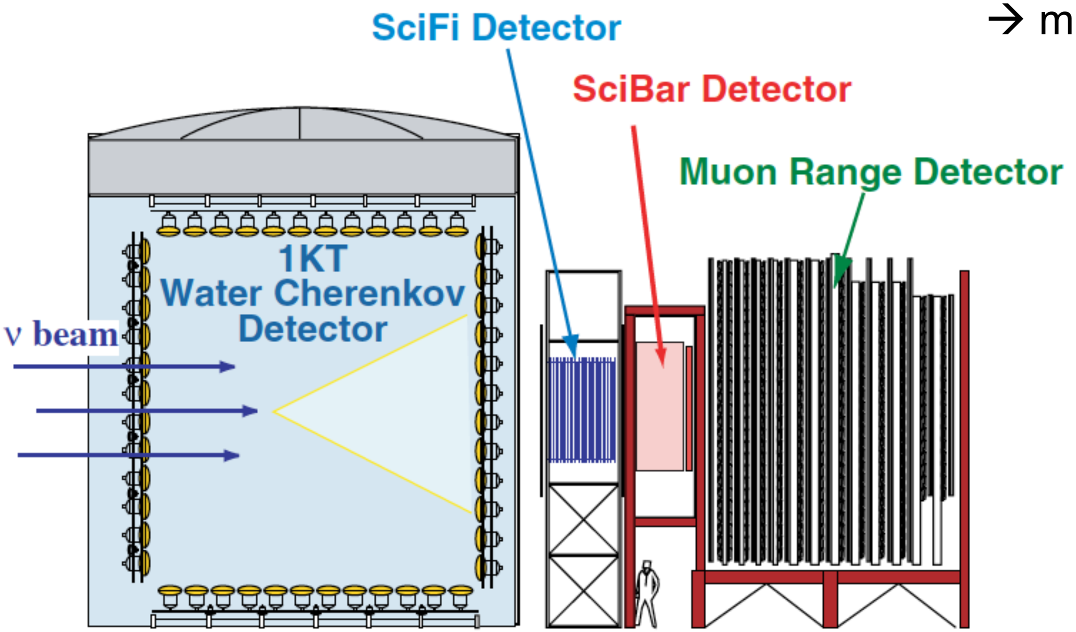
Neutrinos are useful tools to study the Weak theory and quark model

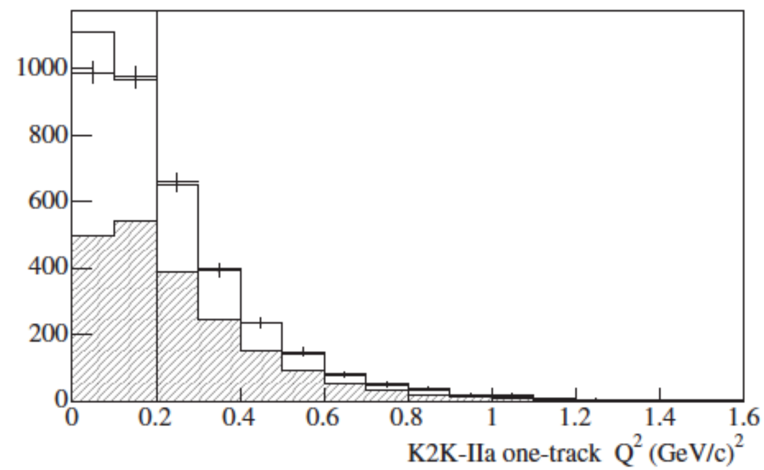
We know the neutrino interaction cross-section exactly. Why we measure it?!

K2K M_A fit

First long-baseline neutrino oscillation experiment
- Forward-type tracker
- MA=1.20±0.12 GeV
- Origin of CCQE puzzle

CCQE puzzle
1. low Q2 suppression
→ efficiency of forward going muon is wrong?
2. high Q2 enhancement
→ maybe flux prediction is wrong?





MiniBooNE M_A fit

Short-baseline neutrino oscillation experiment

- 4π Cherenkov detector
- MA=1.23±0.20 GeV

CCQE puzzle

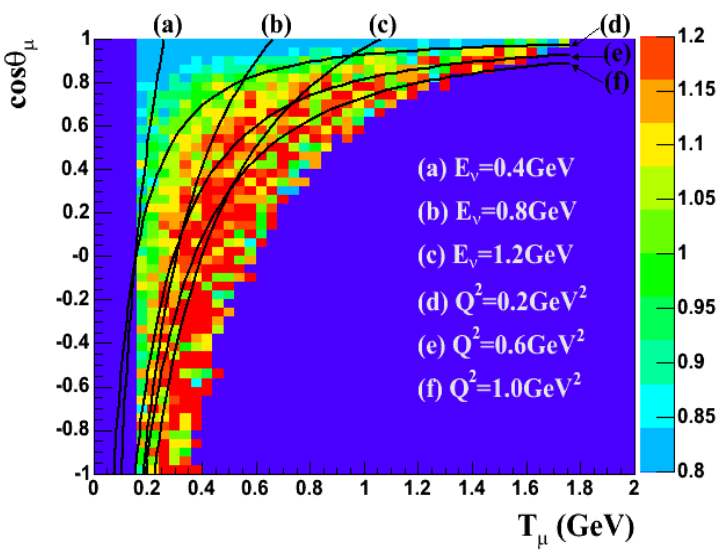
1. low Q2 suppression

~~→ efficiency of forward going muon is wrong?~~

2. high Q2 enhancement

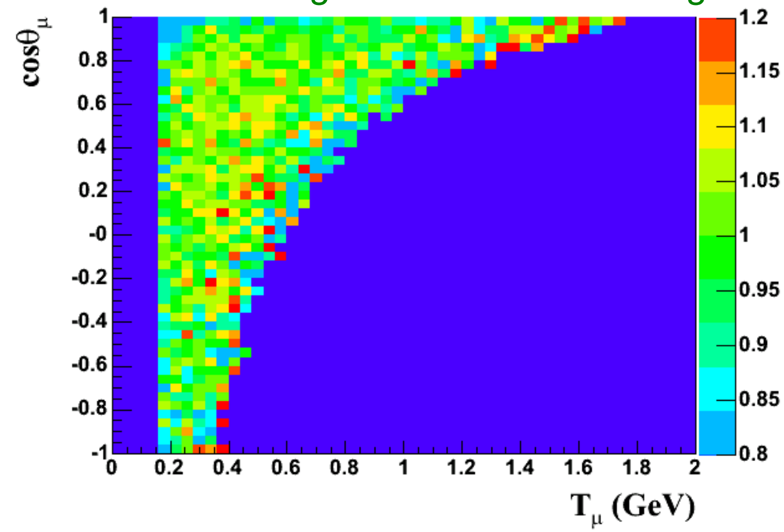
~~→ maybe flux prediction is wrong?~~

Data-MC ratio is wrong along constant Q2, not Ev
→ It looks CCQE puzzle is not detector or beam effect



→

After tuning MA and Pauli blocking



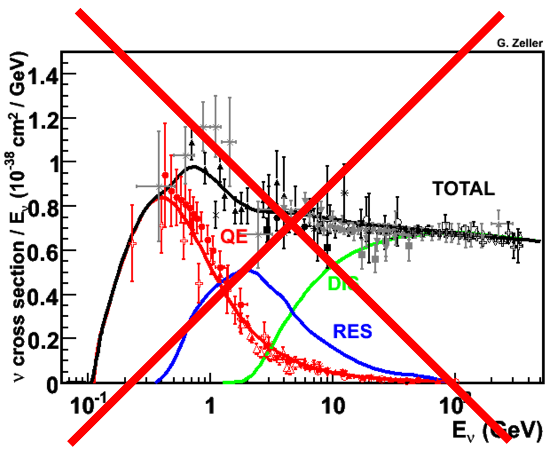
Community effort to understand the problem

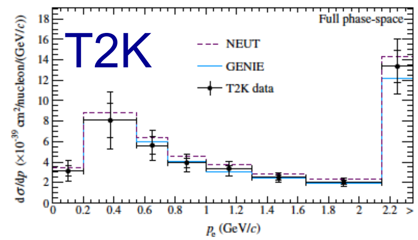
Model parameters are tuned within experimental simulations. Theorists have no idea how to interpret the data

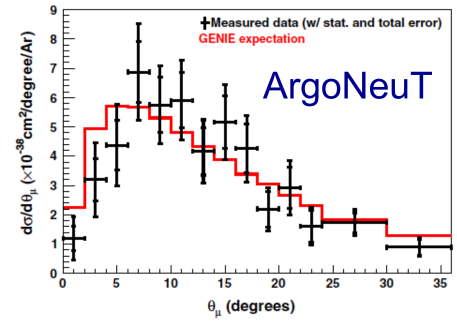
But if experimentalists unfold neutrino flux (model-dependent), the data loses details of measurements…

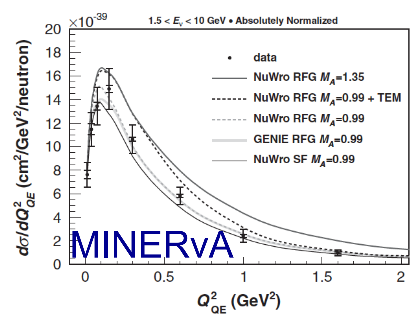
We need “a common language” which theorists and experimentalists can discuss about the data

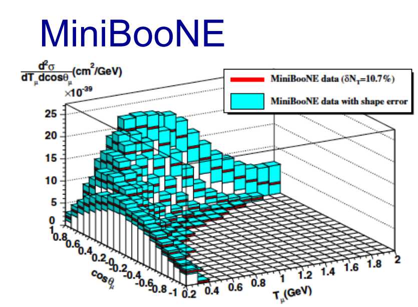
Flux-averaged differential cross-section











Flux-averaged differential cross-section

Flux-averaged differential cross-section data allow theorists and experimentalists talk directly

$$\frac{d^2\sigma}{dT_l\, d\cos\theta} = \frac{1}{\int \Phi(E_\nu)\, dE_\nu} \int dE_\nu \left[\frac{d^2\sigma}{d\omega\, d\cos\theta}\right]_{\omega=E_\nu-E_l} \Phi(E_\nu)$$

Theorists

Experimentalists

$$\frac{d^2\sigma}{dT_l cos\theta} = \frac{\sum_j U_{ij}(d_j - b_j)}{\Phi \cdot T \cdot \varepsilon_i \cdot (\Delta T_l, \Delta cos\theta)_i}$$

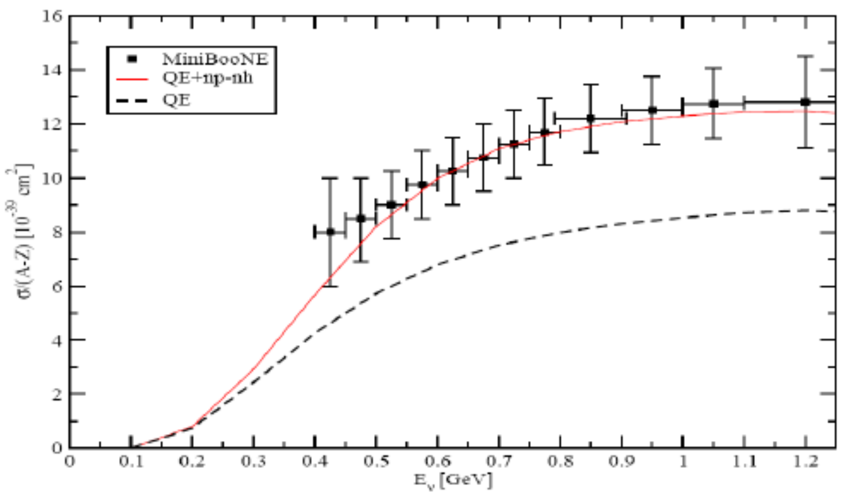
The solution of CCQE puzzle

Presence of 2-body current

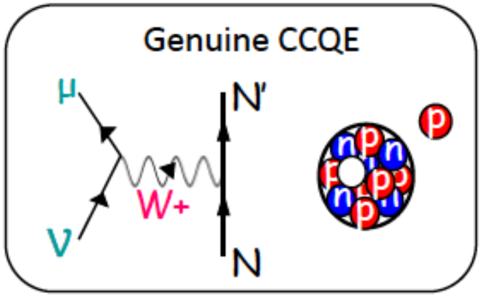
- Martini et al showed 2p-2h effect can add up more cross section
- Consistent result by Nieves et al (Valencia 2p2h model)
- Phenomenological model results are supported by nuclear ab initio calculation

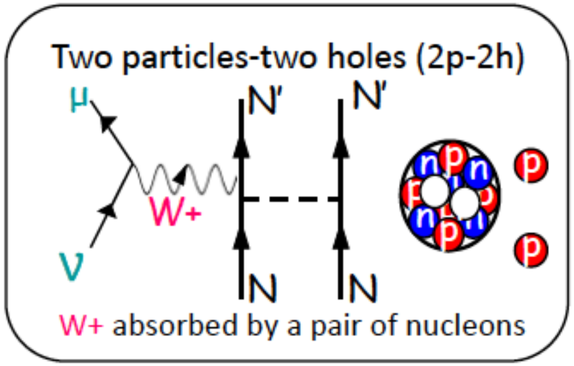
An explanation of this puzzle

Inclusion of the multinucleon emission channel (np-nh)



Martini model vs. MiniBooNE CCQE total cross-section





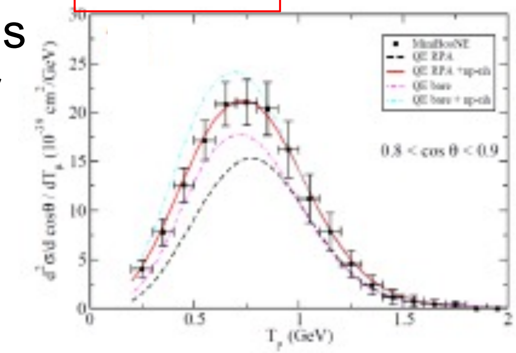
2. Models using 2p-2h

Flux-averaged differential cross-sections allow nuclear theorists to compare their models with data without implementing them in generators

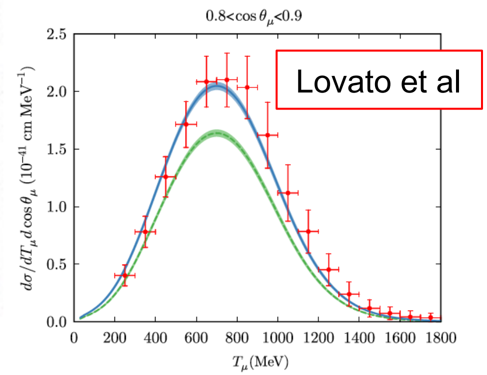
Martini et al – Lyon 2p2ph model
Nieves et al – Valencia 2p2h model
SuSAv2 – Superscaling+MEC
Giusti et al – Relativistic Green's function
Butkevich et al – RDWIA+MEC
Lovato et al – GFMC
Jachowicz et al – CRPA+MEC

All models can fit with data, are they all correct models?

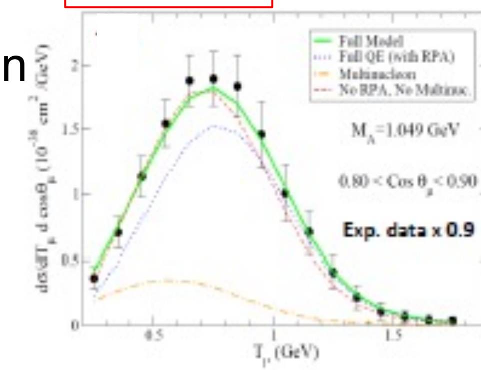
Martini et al



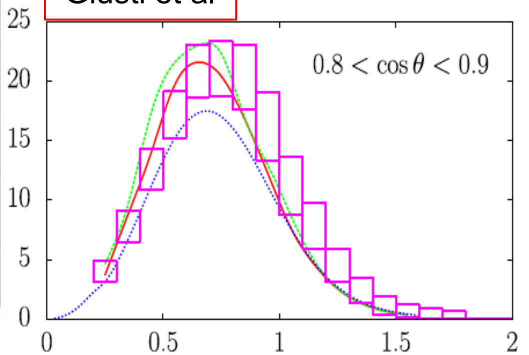
Lovato et al



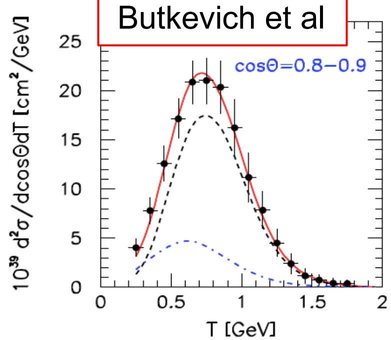
Nieves et al



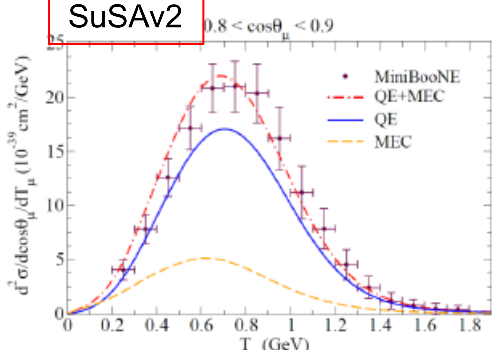
Giusti et al



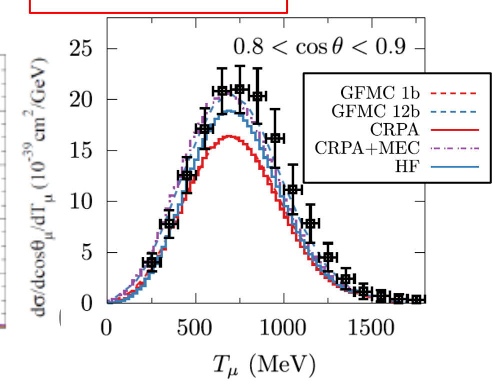
Butkevich et al



SuSAv2



Jachowicz et al



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Where were we from?

Where are we now?

Where will we go?

Benhar et al, PRL105(2010)132301, EPJST230(2021)4309
TK, Martini, JPhysG45(2017)1

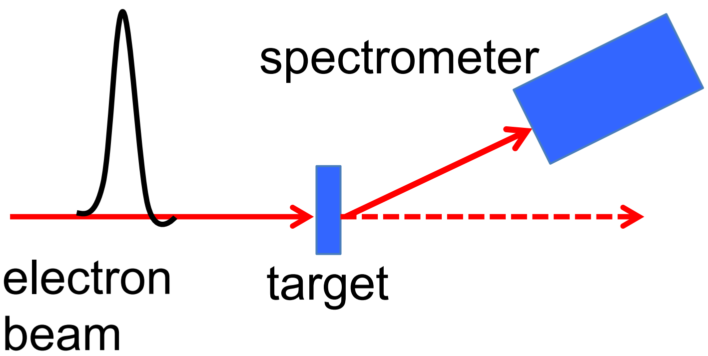
New paradigm of lepton scattering experiments

Flux-averaged differential cross-section
- Incomplete kinematics, reconstruction of Ev, Q2, q3, W, x, y,… depends on models

Electron scattering
- well defined energy, well known flux

→ reconstruct energy-momentum transfer

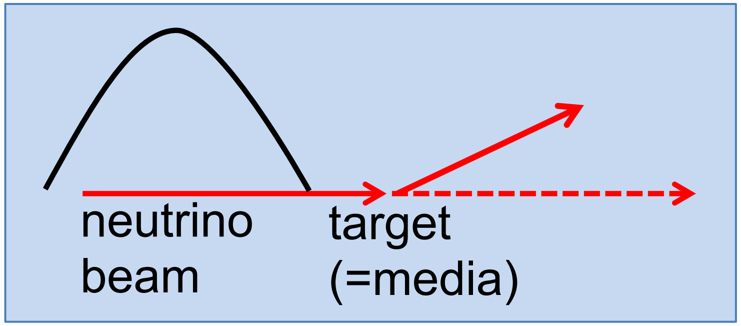
→ measure each process



Neutrino scattering
- Wideband beam (unknown Ev)

→ cannot fix kinematics

→ inclusive measurement (CCQE, RES...)



Khachatryan et al., Nature 599(2021)565

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Electron scattering

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→ measure each process

Neutrino experiment don't reconstruct Ev (and Q2) with great precision

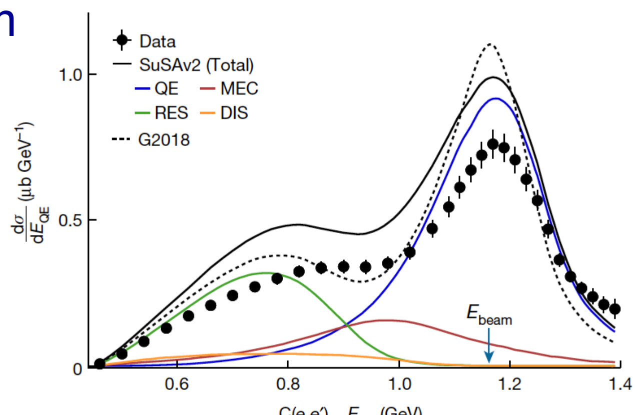
$$E_\nu^{QE} = \frac{ME_\nu - 0.5m_\mu^2}{M - E_\mu + p_\mu cos\theta}$$

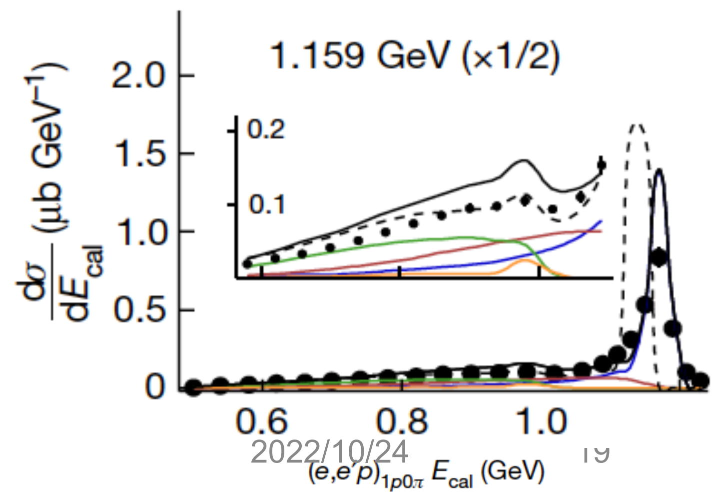
$$E_\nu^{Cal} = E_\mu + \sum^{all} E_{had}^i$$

Reconstructed beam electron energy spectrum

by

- QE formula (HyperK)
- Calorimetric (DUNE)





New paradigm of lepton scattering experiments

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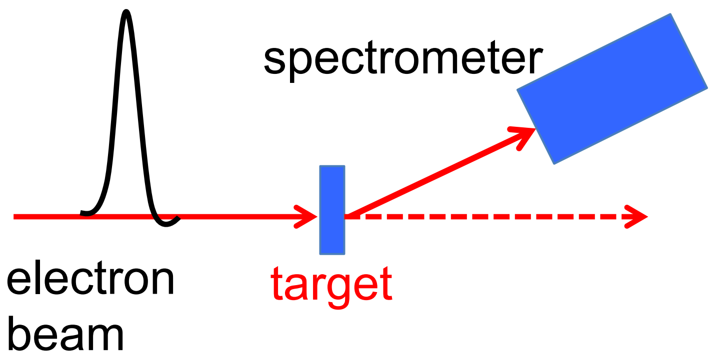

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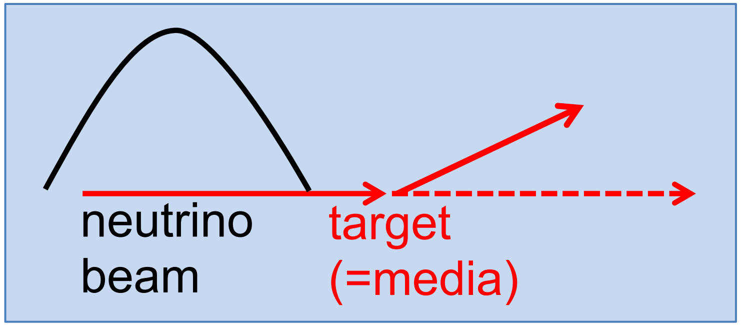

Fully active target

- To maximize interaction rate
- Not always high-resolution
- 4π hadron measurement

MINERvA, PRL116(2016)071802,PRD99(2019)012004
NOvA, EPJC80(2020)1119

New paradigm of lepton scattering experiments

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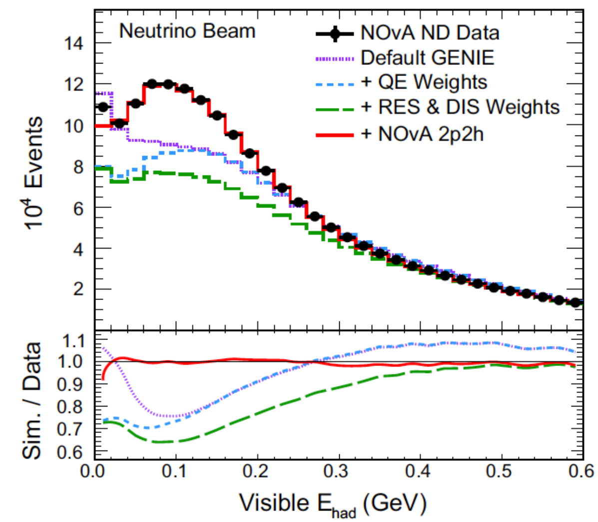
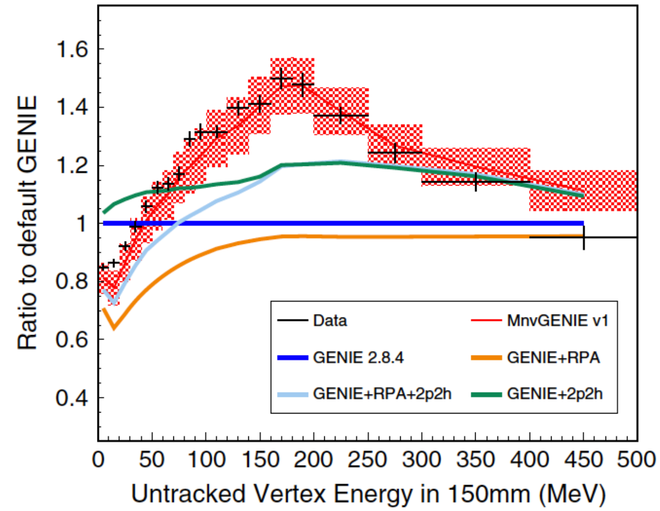
Visible hadronic energy deposit: E_{had}, E_{avail}

- Sum of all hadron energy deposit
- Strongly correlated to energy transfer (q_0 or ω or ν)
- Sensitive to 2p2h



Vertex activity

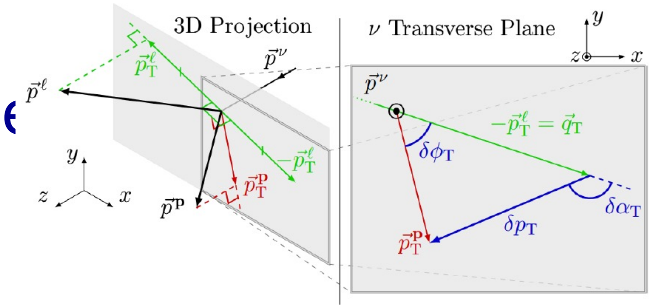
- Some of all hadronic activities around the vertex
- Low energy nucleons (=2 nucleon emission)



teppei.katori@kcl.ac.uk

MINERvA, PRL116(2016)071802,PRD99(2019)012004,EPJST230(2021) 4243, PRL121(2018)022504
NOvA, EPJC80(2020)1119 , Buizza Avanzini et al., PRD105(2022)092004, T2K, PRD98(2018)032003,

New paradigm of lepton scattering experime



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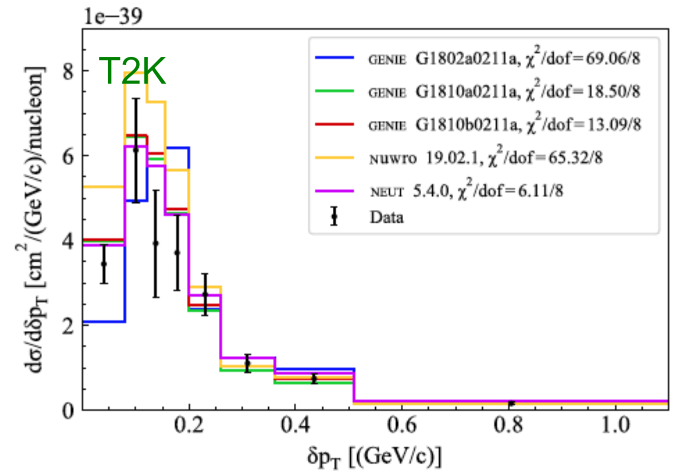
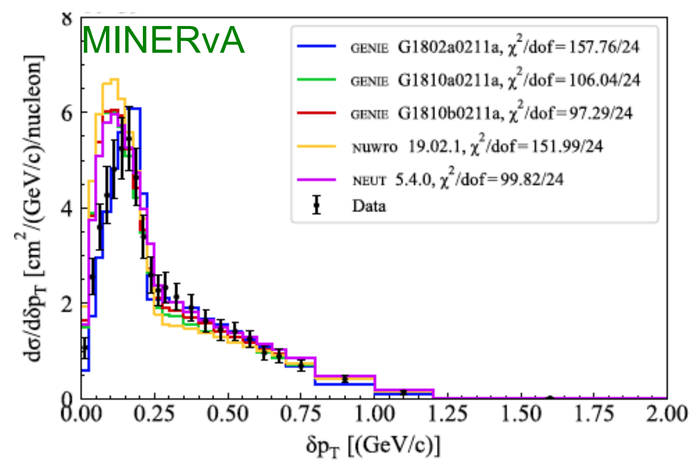
Transverse kinematic Imbalance (TKI) variables

δP_T ~ nucleon momentum distribution

$\delta\alpha_T$ ~ FSI





These studies suggest no nuclear models fit neutrino data without tuning

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Generator implementation is our bottleneck

Flux-averaged differential cross-section
- Incomplete kinematics, reconstruction of Ev, Q2, q3, W, x, y,… depends on models
- New kinematic variables from hadrons

Hadron variables
- Visible hadronic energy deposit: E_{had}, E_{avail}
- Vertex activity
- Transverse kinematic Imbalance (TKI) variables

Hadrons are affected by FSIs
- Without implementing in generators, theoretical nuclear models cannot be compared with data
- Generator implementation is continuously a problem of our community

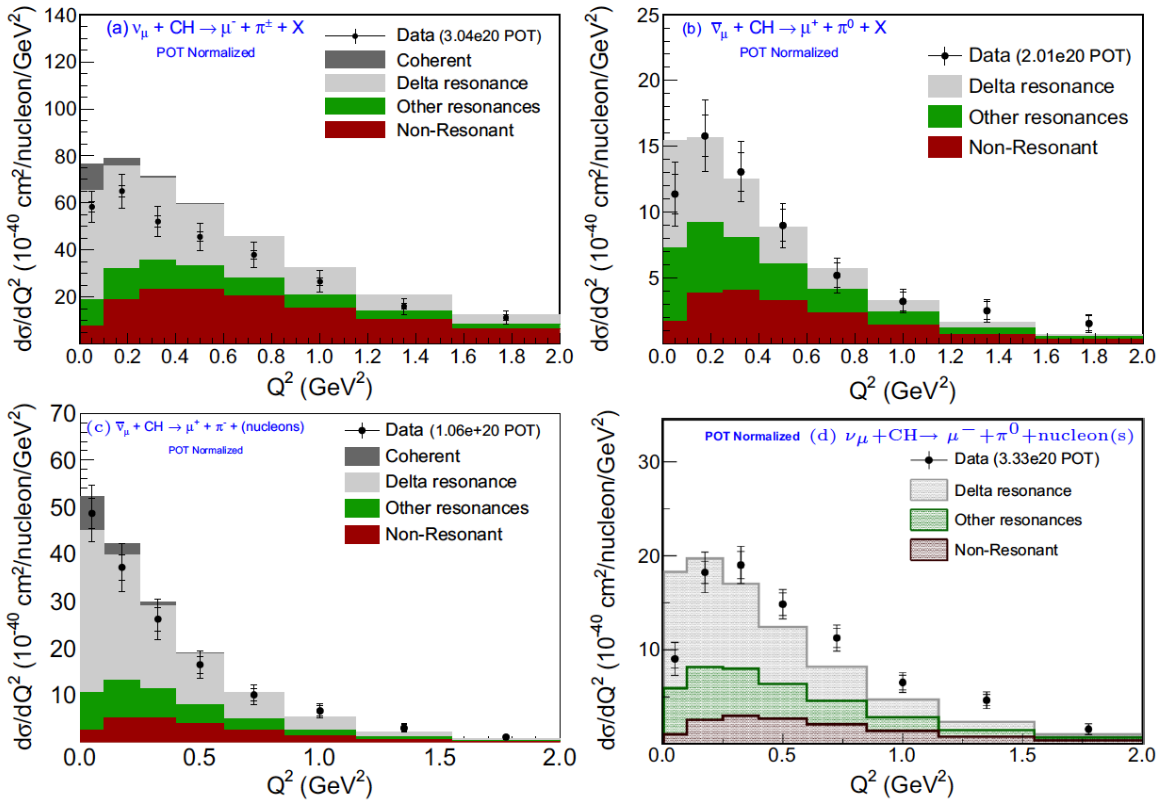
Generator implementation is our bottleneck

Data tension – internal: MINERvA pion data

- It is extremely difficult to tune pion and/or FSI parameters to fit all pion data
  - $\nu_\mu CC\pi^\pm$, low Q2 suppression, over-predicted
  - $\nu_\mu CC\pi^0$, strong low Q2 suppression
  - $\bar{\nu}_\mu CC\pi^-$, no low Q2 suppression
  - $\bar{\nu}_\mu CC\pi^0$, low Q2 suppression, under-predicted

The study relies of available knobs in the generator

It looks the simulation doesn't have good knobs to tune



M. Betancourt et al.,Phys.Rep.773(2018)1.
Buizza Avanzini et al., PRD105(2022)092004

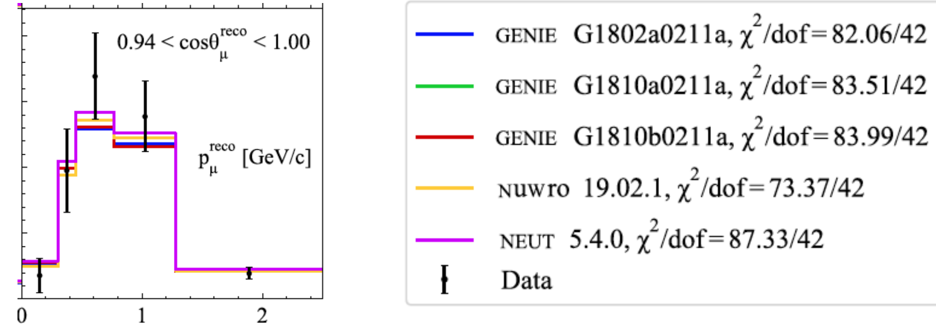
Generator implementation is our bottleneck

Comparison is not easy without generators

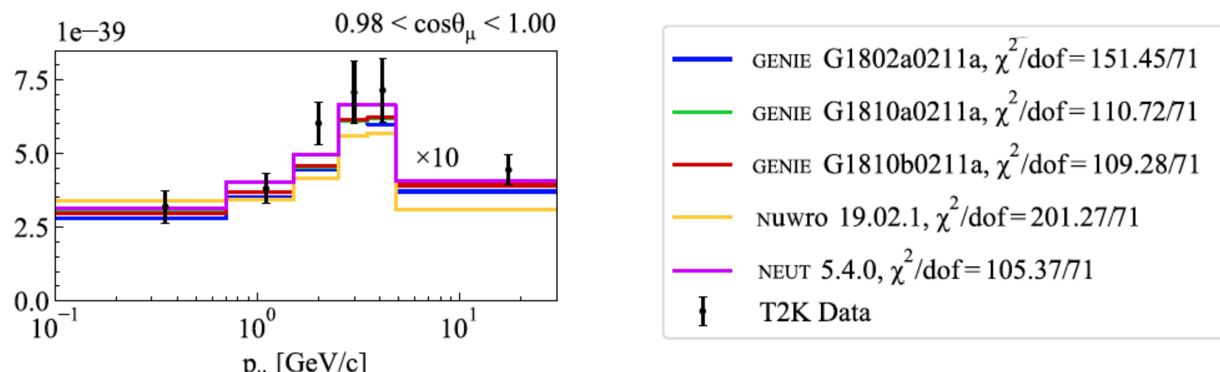
Data tension – external: T2K vs. MINERvA vs. MicroBooNE

- Different kinematic coverage, different target

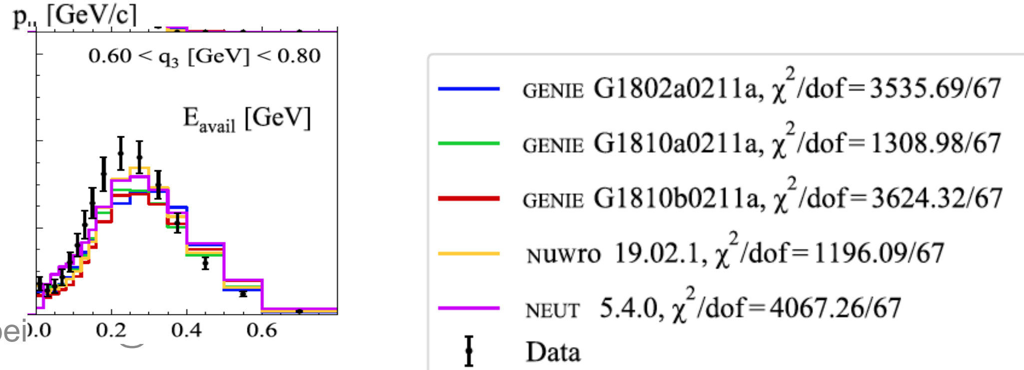
MicroBooNE CC inclusive double differential cross-section



T2K CC inclusive double differential cross-section



MINERvA CC inclusive double differential cross-section



Where were we from?

Where are we now?

Where will we go?

Great road to the Future!

Neutrino physicists, riding a great road with a broken car

Neutrino physicists
- Driving a car with beautiful front wheels, no back wheels, on a rough road.

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Cross-section model
 - Lepton kinematics
(current focus)

Hadron production model
 - Conservation laws
 - Isotropic phase space decays (no model)

FSI, hadron media effects
 - Complicated
(rough surface to move)

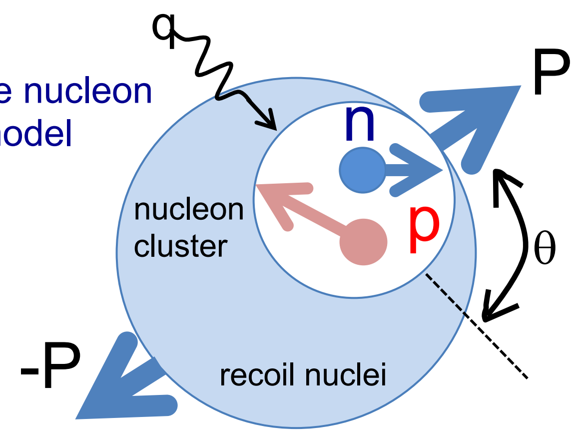
Studying neutrino-induced hadrons are hard

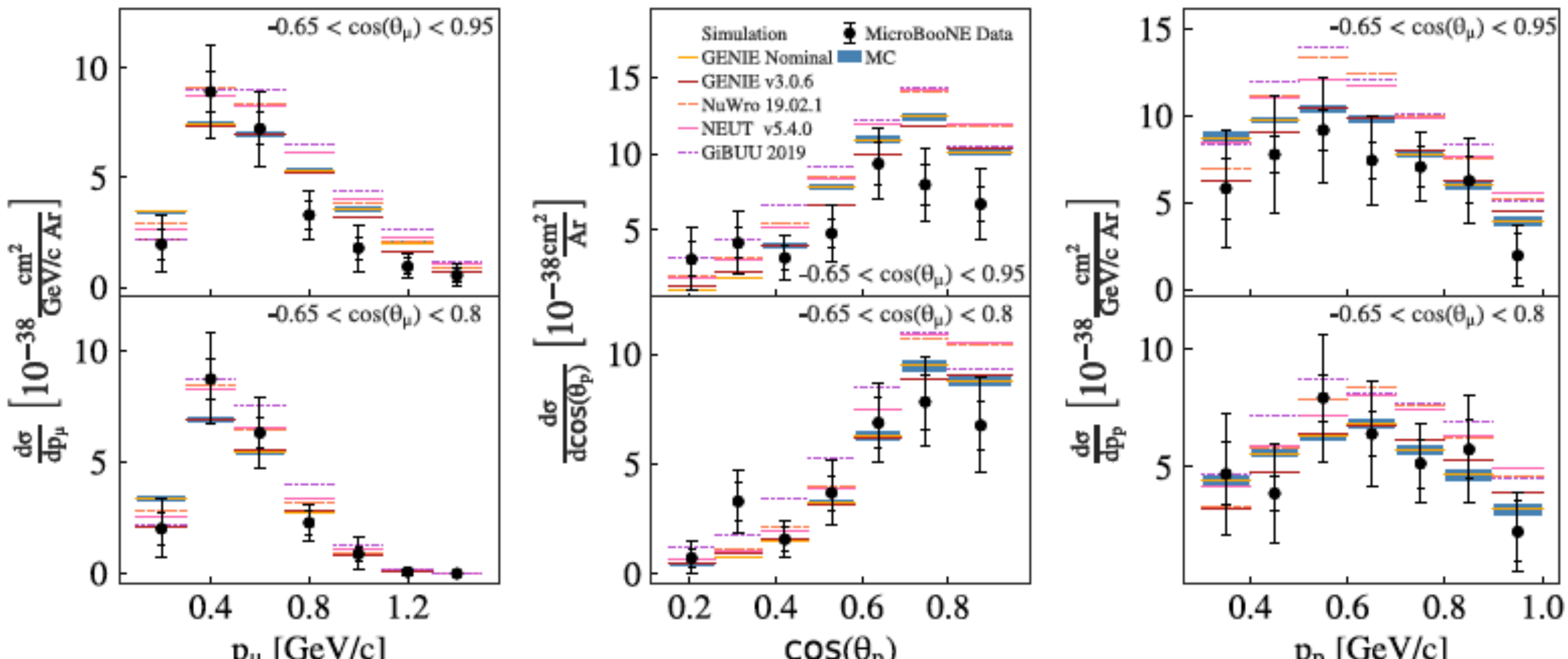
Sobcyk, PRC86(2012)015504
MicroBooNE,PRL125(2020)201803

Nucleon correlations in neutrino physics

We want to understand 2p2h models from hadron final states

We need prediction of hadronic final states
- double differential cross-section = lepton kinematics
- final hadron multiplicity/kinematics = home-made

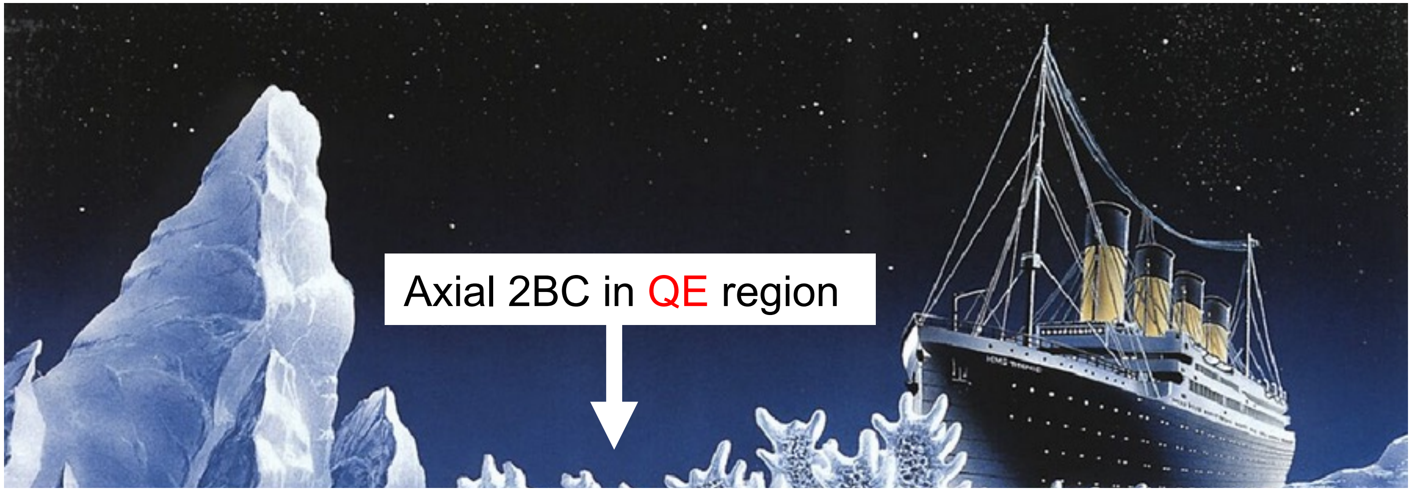




Great voyage to the Future!

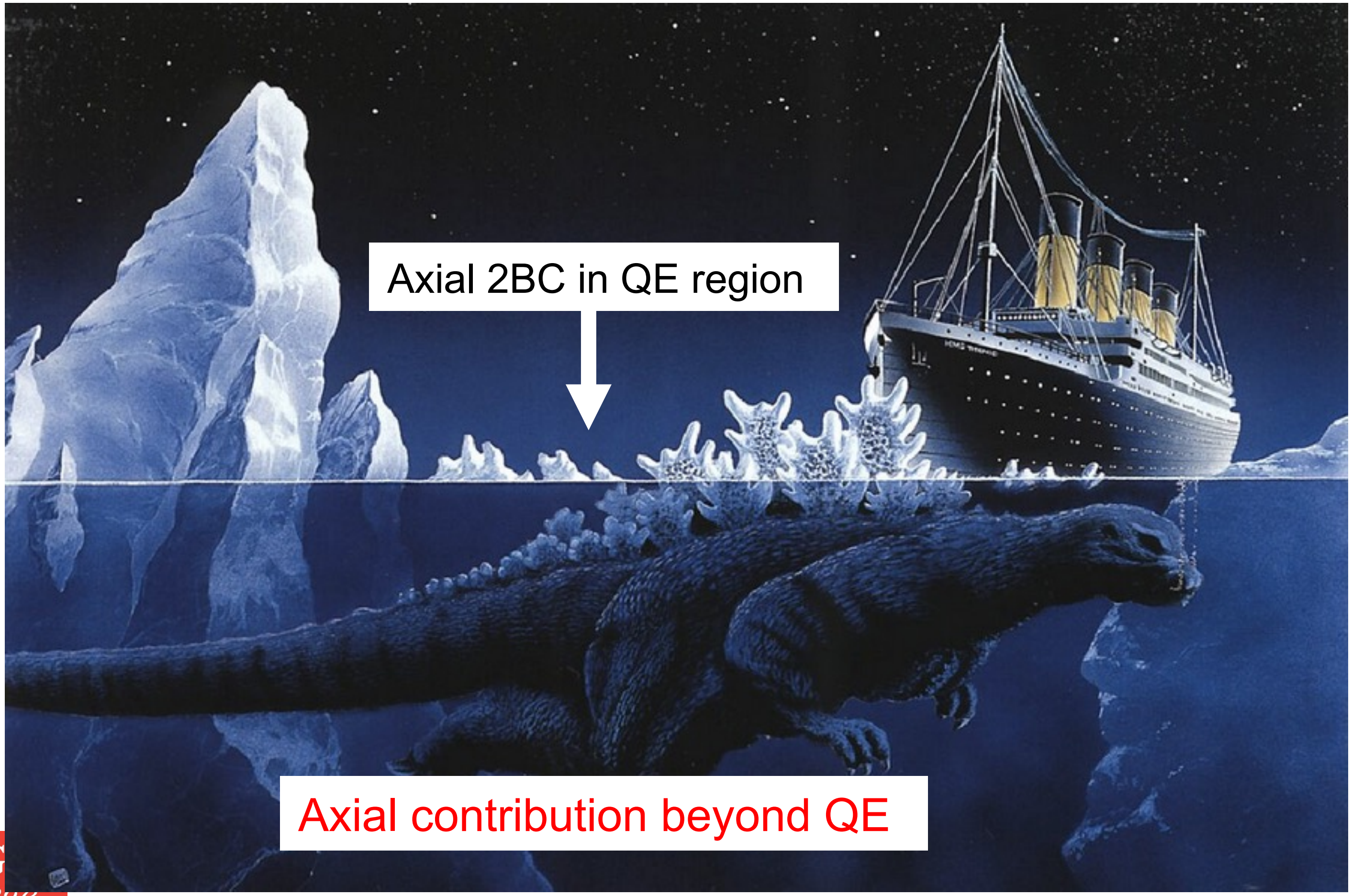
Beyond QE peak

Axial 2-body current in QE region may be a tip of the iceberg…



Beyond QE peak

Axial 2-body current in QE region may be a tip of the iceberg…,
or maybe a tip of gozilla!



Nakamura et al,Rep.Prog.Phys.80(2017)056301

Higher baryonic resonances

DCC model

- Channels are coupled (πN, ππN, etc), total amplitude us conserved

Most of axial form factors are unknown

DCC model vs. electro-pionproduction data

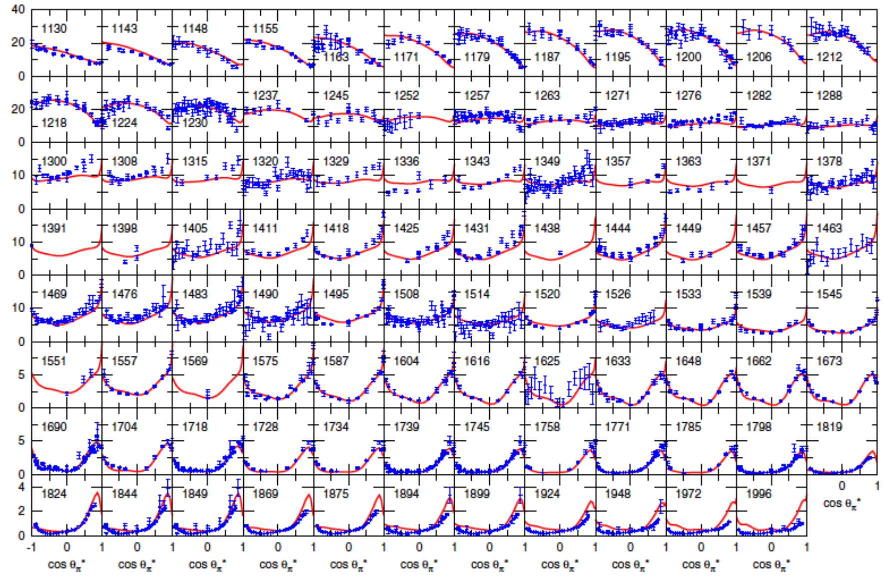
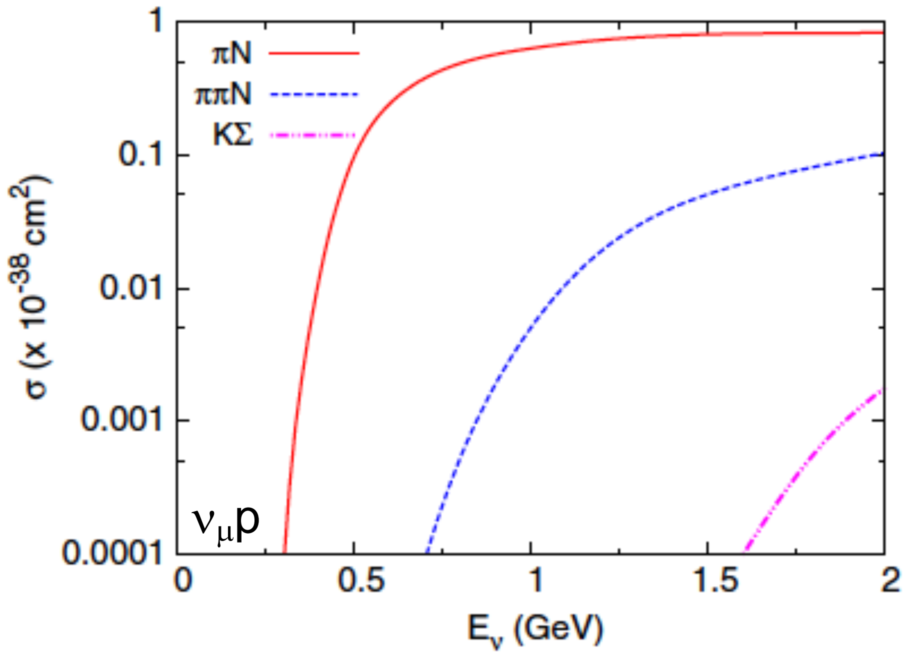
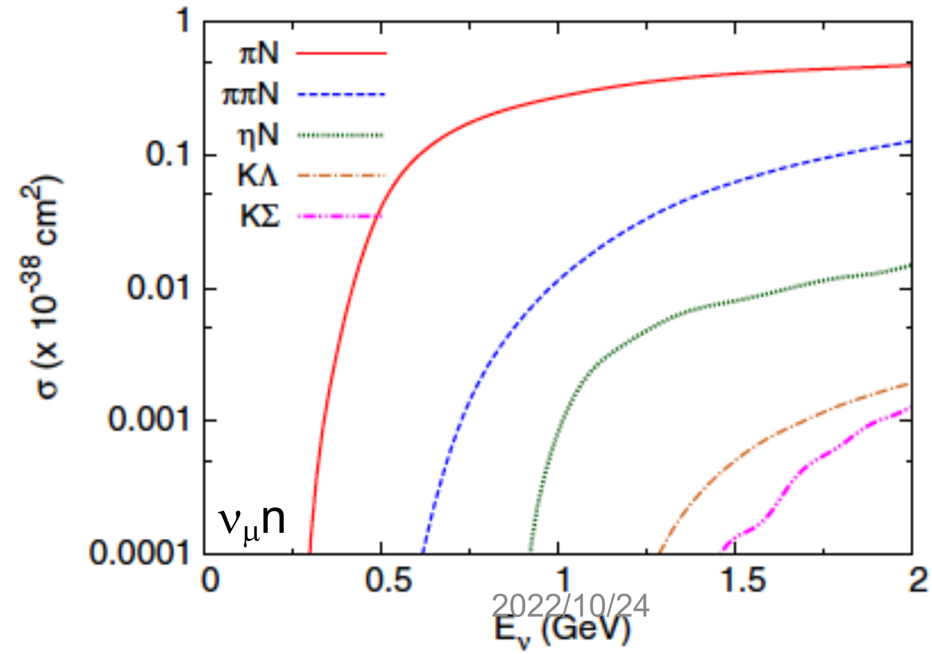


FIG. 8 (color online). Unpolarized differential cross sections, $d\sigma/d\Omega_\pi^*$ (μb/sr), for $\gamma n \to \pi^- p$. The data are from Refs. [55–78].

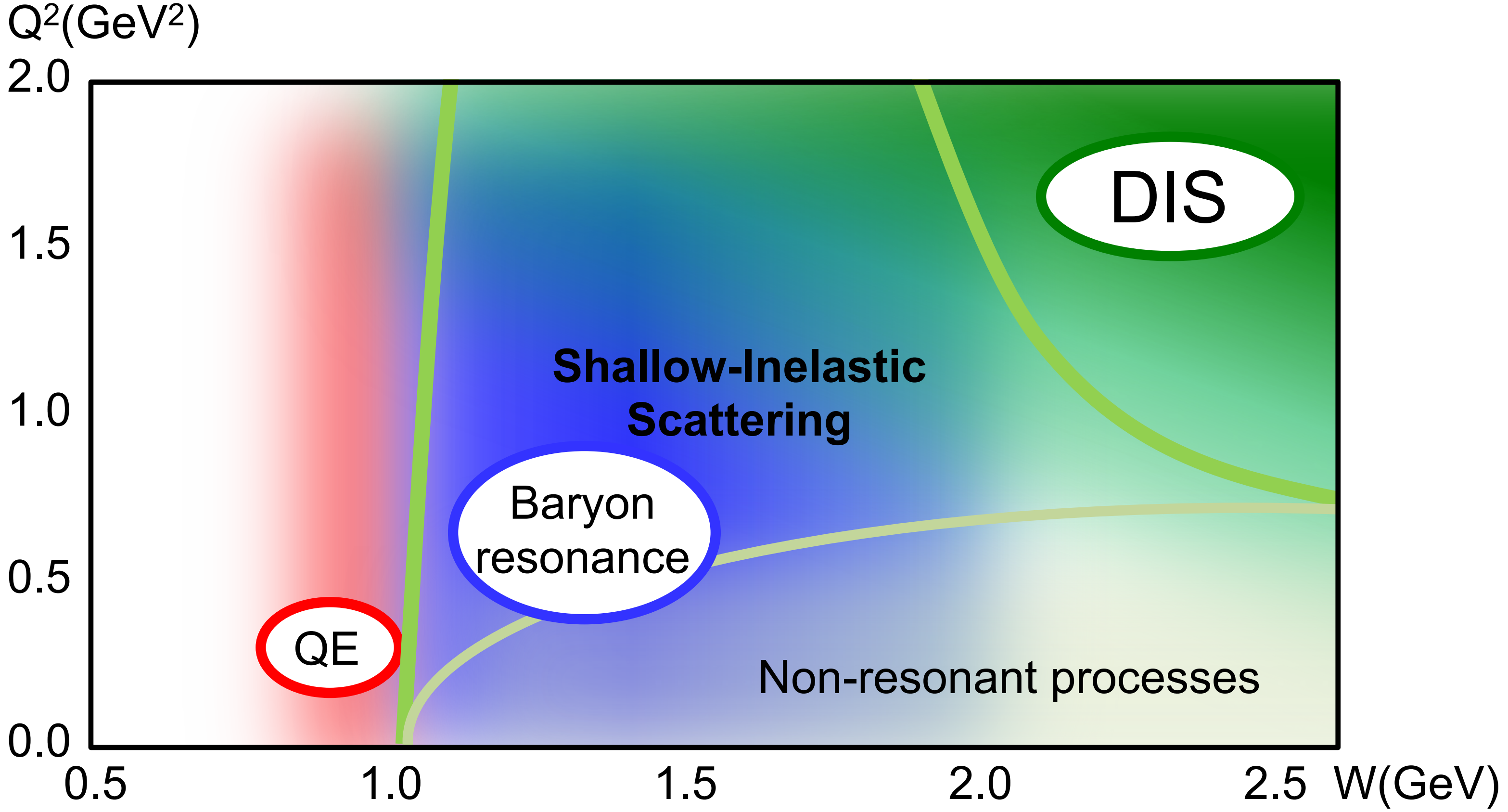




Shallow-Inelastic Scattering (SIS)

Shallow-Inelastic scattering region

- Inelastic = not elastic, W > 1.07 GeV ($=m_p+m_\pi$)
- Shallow = not deep, $Q^2 < 1$ GeV^2 for W > 2 GeV



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Shallow-Inelastic scattering region
- Inelastic = not elastic, W > 1.07 GeV (=m_p+m_π)
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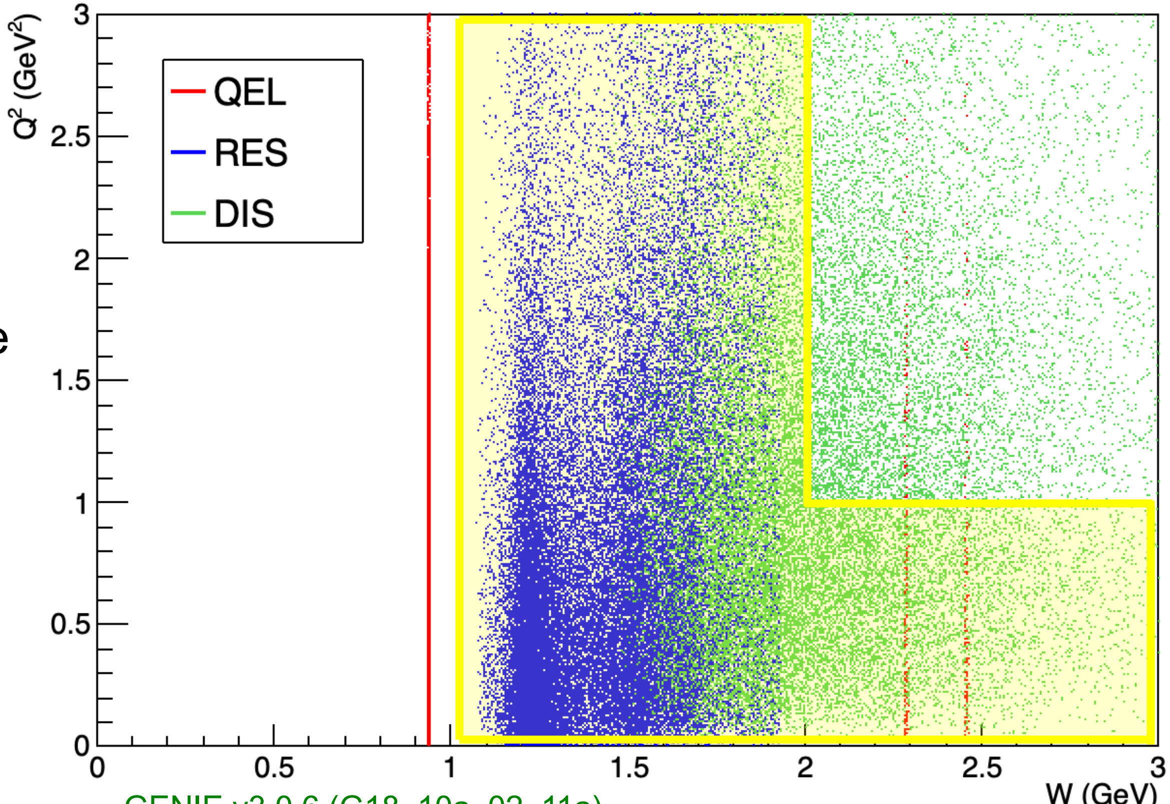
Significant fraction (~70%) of DUNE events are in SIS kinematic region

Prediction and measurement are both difficult in this region

Physics of this region is not studied with neutrinos

Q^2-W distribution with DUNE numu flux on Ar (neutrino model)



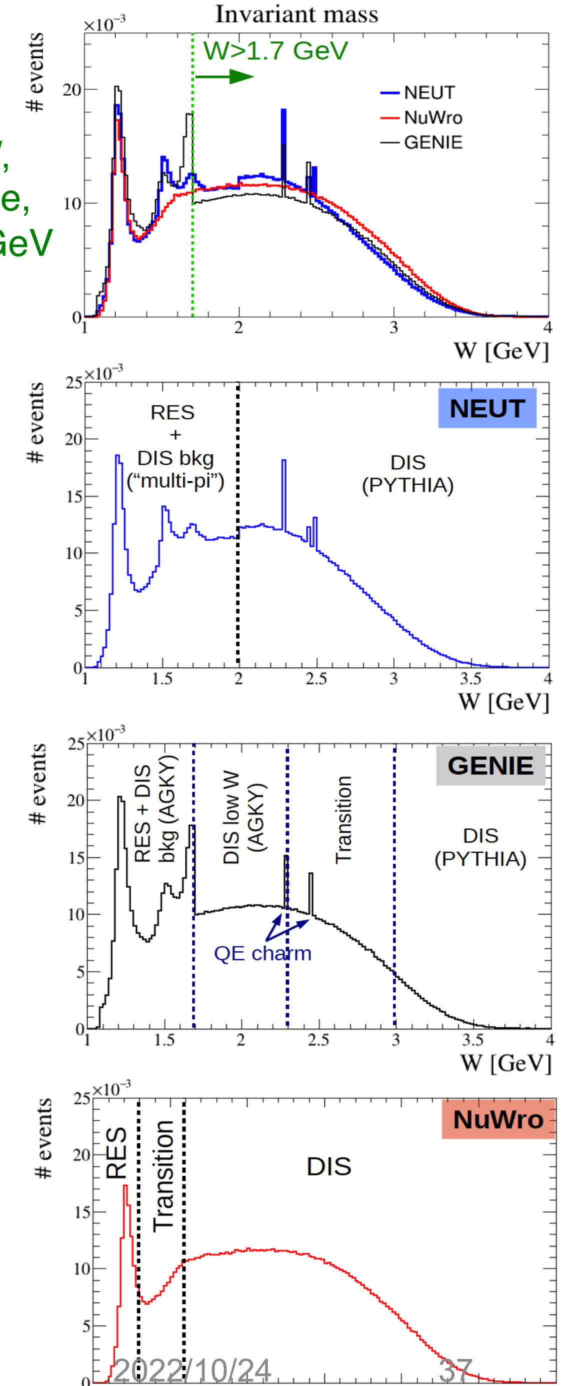
GENIE v3.0.6 (G18_10a_02_11a)

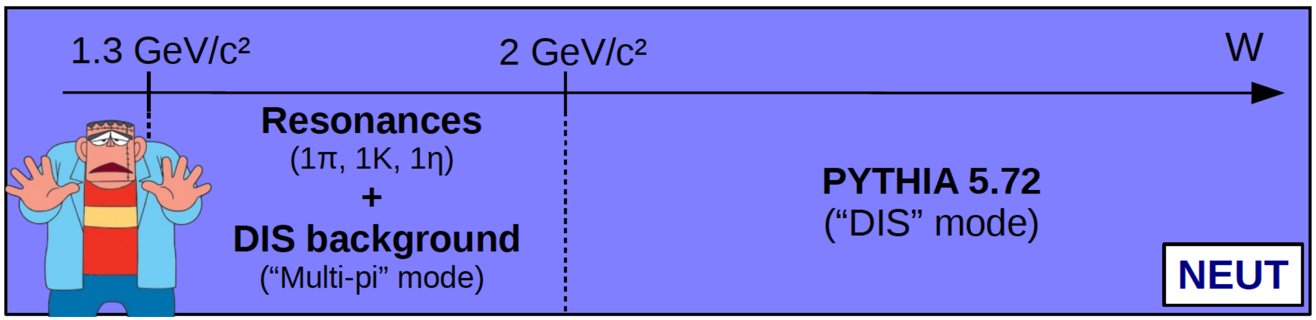
SIS in event generators

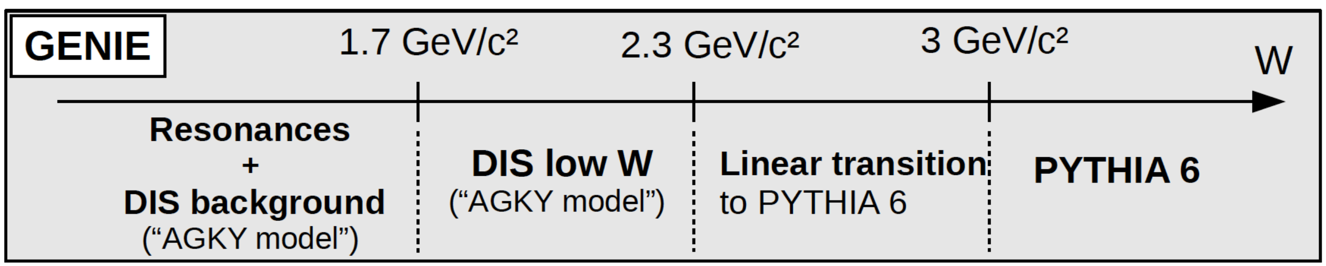
Real Frankenstein part of all generators

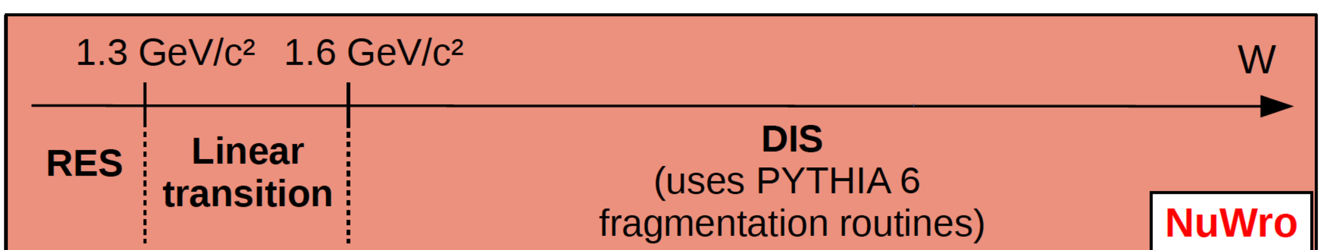
- Generators have different approach
- Definition of channels are different in generators
- Very difficult to connect different models
- Very difficult to verify models

True W,
ν_μ on Fe,
$E\nu$=6 GeV









Great journey to the Future!

Young people, we need more new ideas

Crazy ideas, new ideas, interesting ideas are always welcome!

What is the real solutions of our problems?
- Hadron simulations and measurements
- Generator implementation

e.g.) Quantum computer for jet simulation

Collider Events on a Quantum Computer

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[b] *Institute for Particle Physics Phenomenology, Department of Physics, Durham University, Durham DH1 3LE, U.K.*
[c] *High Energy Physics Group, Blackett Laboratory, Imperial College, Prince Consort Road, London, SW7 2AZ, United Kingdom*

https://arxiv.org/abs/2207.10694

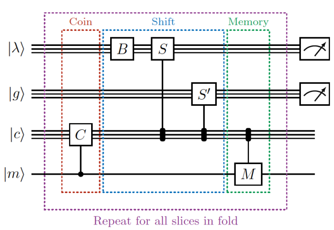
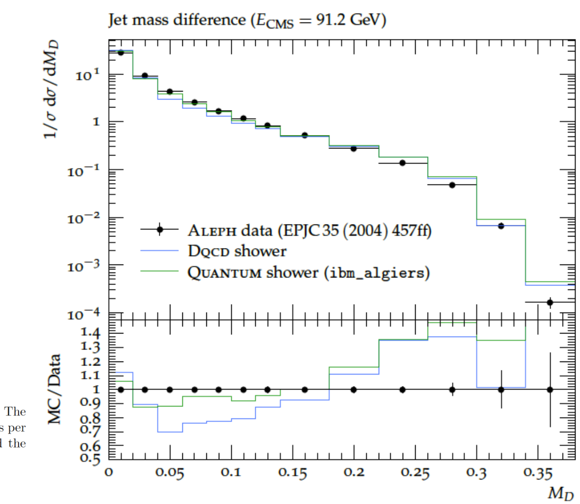
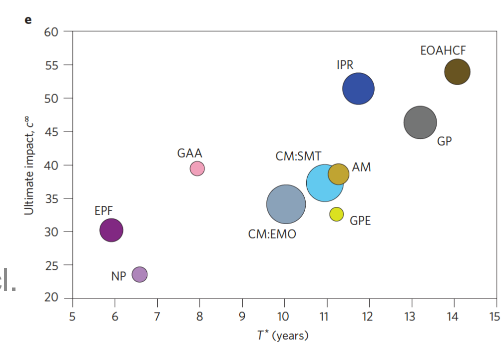


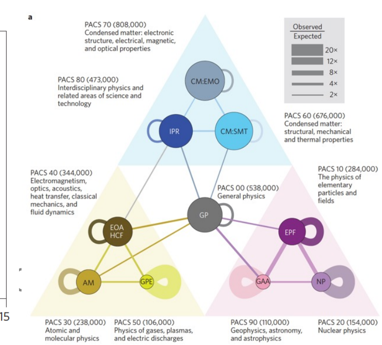
Figure 3: Schematic of the quantum Discrete QCD parton shower algorithm circuit. The algorithm is a quantum walk with memory, constructed from maximum five operations per step: the coin operation C, baseline shift B, the λ shift S, the gluon shift S', and the memory operation M.



Particle physicists and nuclear physicists are criticized as doing the same things over and over again (=not very innovative)

Nature Physics11(2015)791
"A Century of Physics"

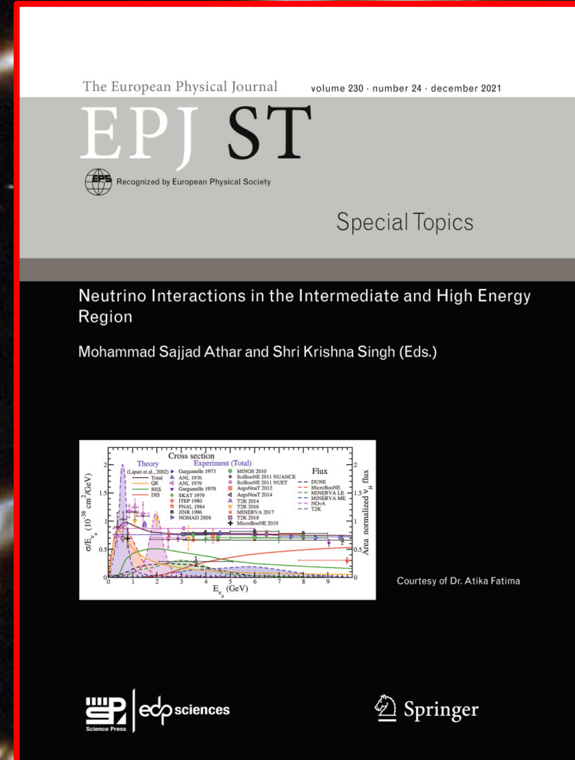




https://link.springer.com/journal/11734/volumes-and-issues/230-24

Conclusion

EPJ Special Topic
Neutrino Interactions in the Intermediate and High Energy Region



We have great success stories in the past

We have challenging problems now

We have more challenging problems in near future

NuSTEC
Neutrino Scattering Theory-Experiment Collaboration
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- subscribe mailing list, “NuSTEC-News”
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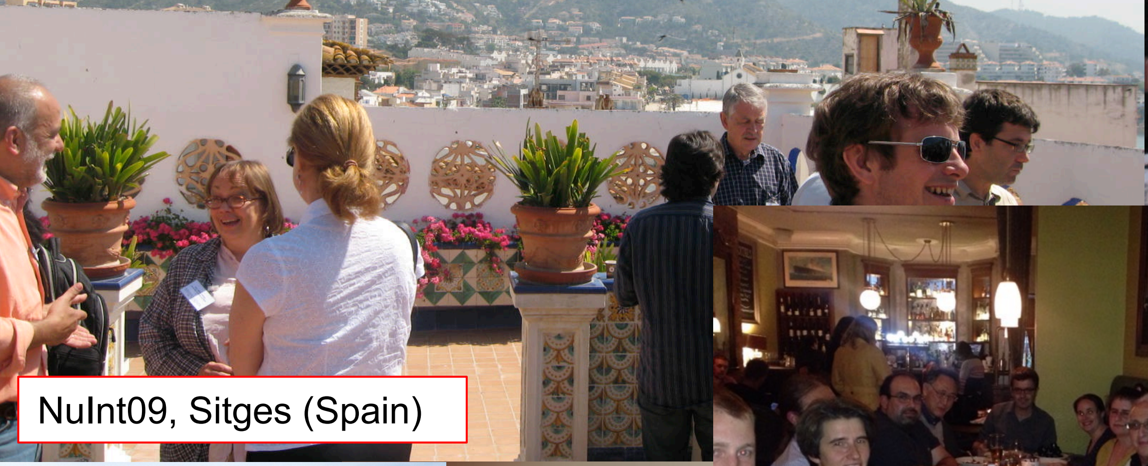
In-person meetings are great

(thank you for organizers!)

Thank you for your attention!

감사합니다



NuInt09, Sitges (Spain)

NuInt11, Dehradun (India)

NuInt15, Osaka (Japan)

NuInt17, Tronto (Canada)

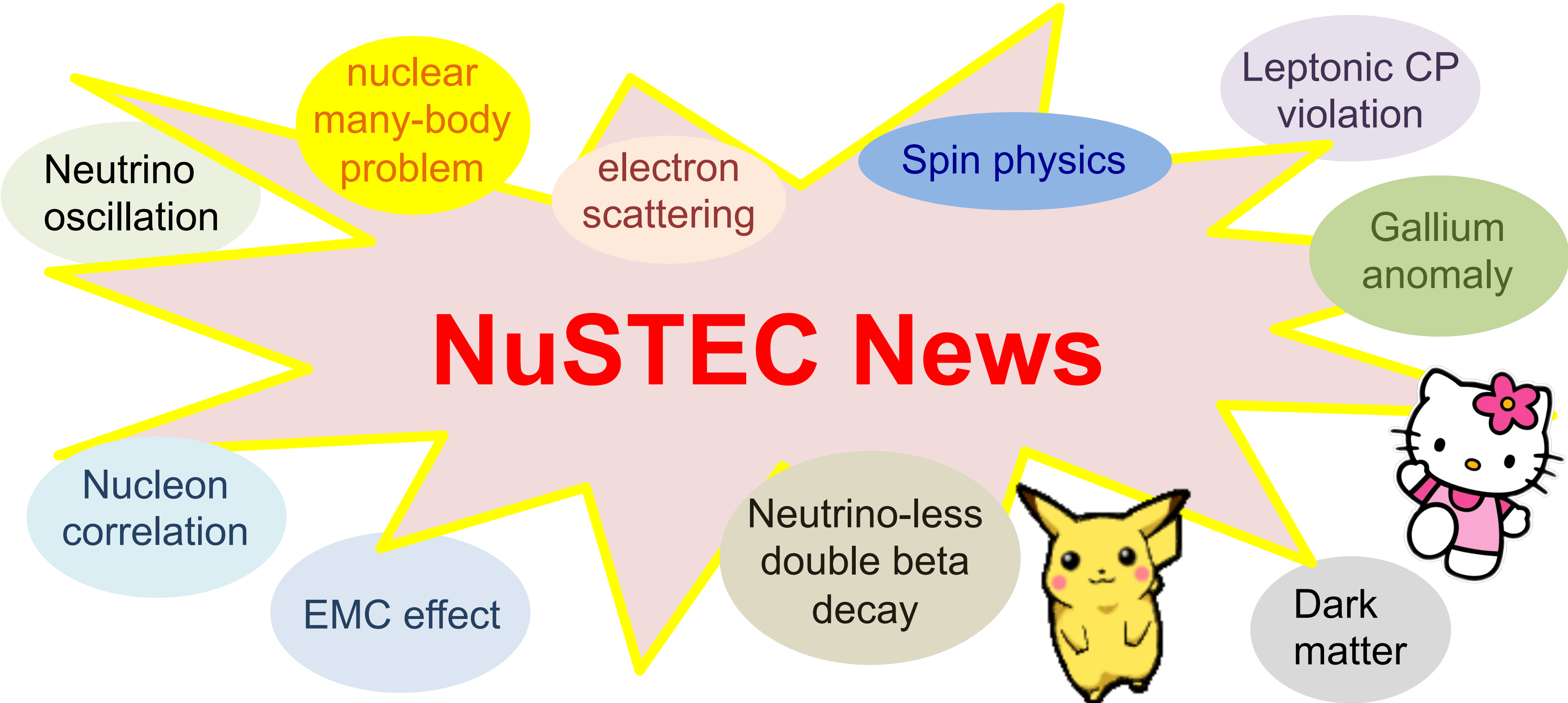
NuInt14, London (UK)

NuInt18, L'Aquila (Italy)

NuInt12, Rio de Janeiro (Brazil)

Backup

Fun Timely Intellectual Adorable!



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QE+2p-2h+RPA kills three birds with one stone

- 1st bird = high Q^2 problem
- 2nd bird = normalization
- 3rd bird = low Q^2 problem