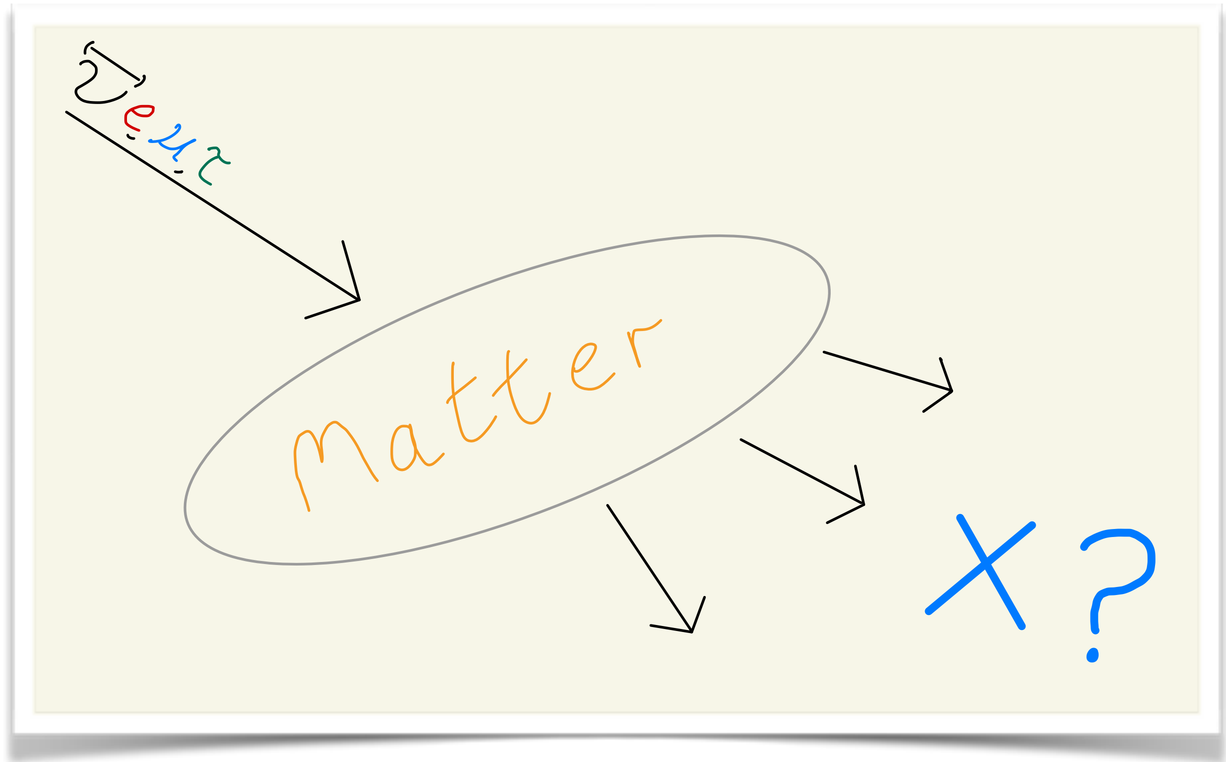
The theory of high-energy neutrino scattering



Rhorry Gauld

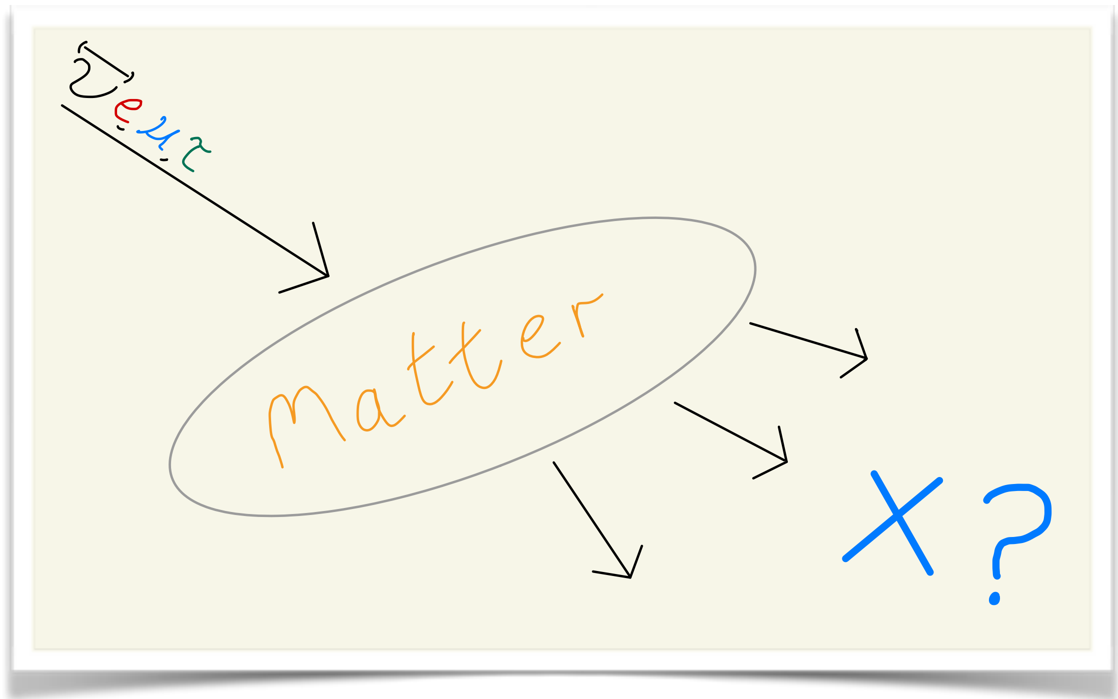
Theory Meets Experiment (15/05/2020)
High-energetic neutrino scattering processes and interactions of cosmic rays

NWO Netherlands Organisation for Scientific Research

Nikhef

Intro:

- Increase theory/experiment dialogue

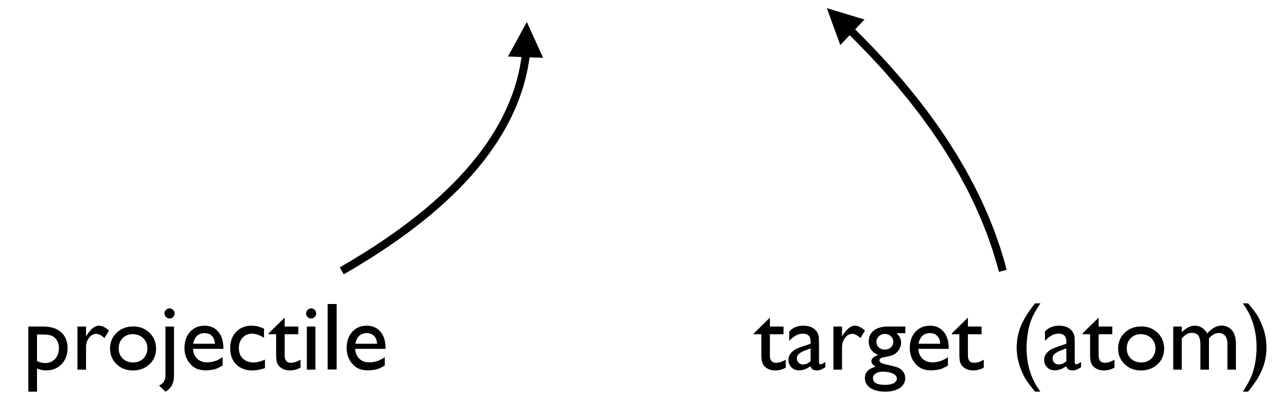


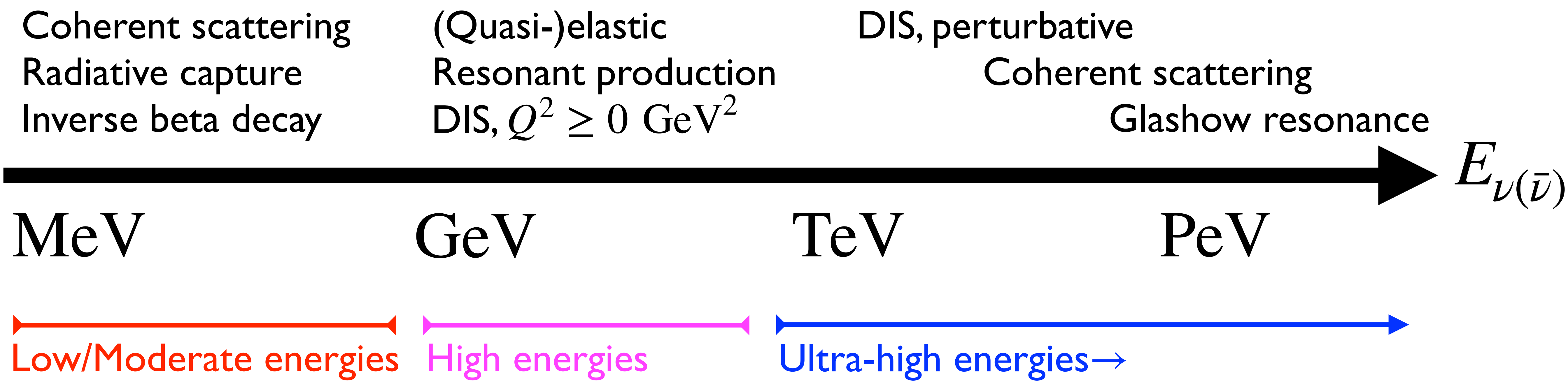
- Summary of recent theoretical progress

- Highlight the current limitations

- Avenues for future work

We will discuss the process: $\nu(\bar{\nu}) + A \rightarrow X$





We will discuss the process: $\nu(\bar{\nu}) + A \rightarrow X$

projectile — target (atom)

Coherent scattering
Radiative capture
Inverse beta decay

(Quasi-)elastic
Resonant production
DIS, $Q^2 \geq 0 \text{ GeV}^2$

DIS, perturbative
Coherent scattering
Glashow resonance

$E_{\nu(\bar{\nu})}$

MeV GeV TeV PeV

Low/Moderate energies

High energies

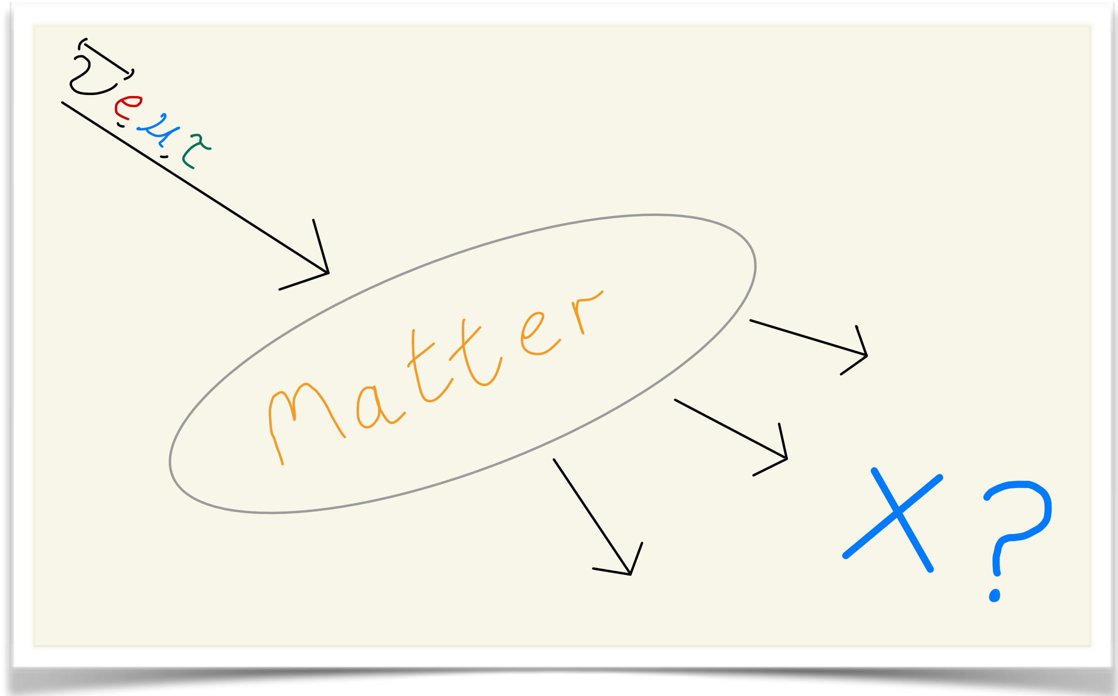
Ultra-high energies→

Recent theoretical progress in this regime

Reactors* Accelerators* Atmospheric* Astrophysical*

* appr. category of neutrino sources

Theoretical progress for $\mathcal{O}$(TeV) energy ν scattering

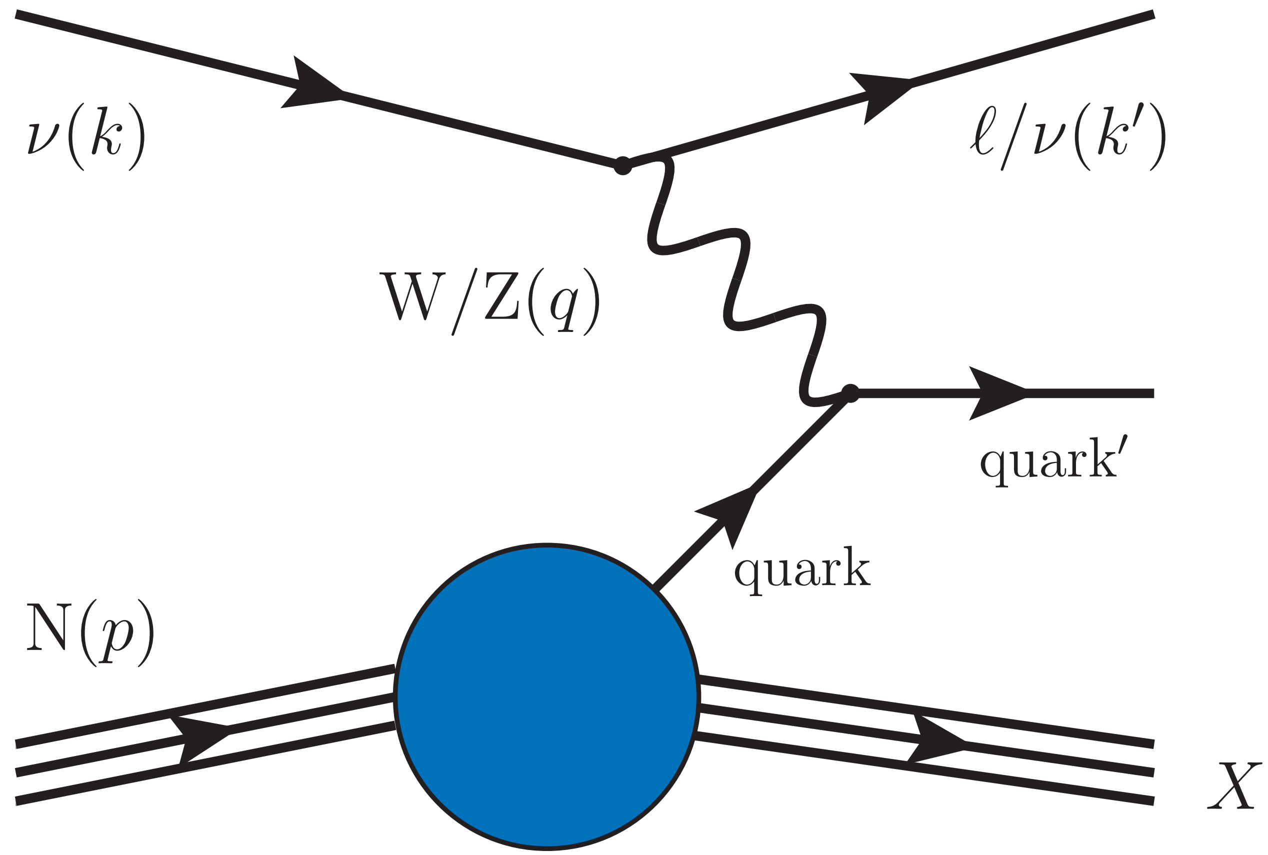


1) Deep Inelastic Scattering (DIS)
   (Bertone), Gauld, Rojo - arXiv:1610.09373, (1808.02034)
   Gauld - arXiv: 1905.03792

2) Resonant scattering (nuclear target)
   Ballett et al. - arXiv:1807.10973
   Gauld - arXiv:1905.03792
   Beacom, Zhou arXiv:1910.08090, 1910.10720

3) Scattering upon atomic electrons (Glashow resonance)
   Gauld - arXiv: 1905.03792

Neutrino-nucleon Deep Inelastic Scattering



$$s = (k+p)^2 = m_N^2 + 2m_N E_\nu$$

Total CoM Energy

$$Q^2 = -q^2 = -(k-k')^2$$

$Q^2 \in [Q^2_{\mathrm{min}}, 2m_N E_\nu]$

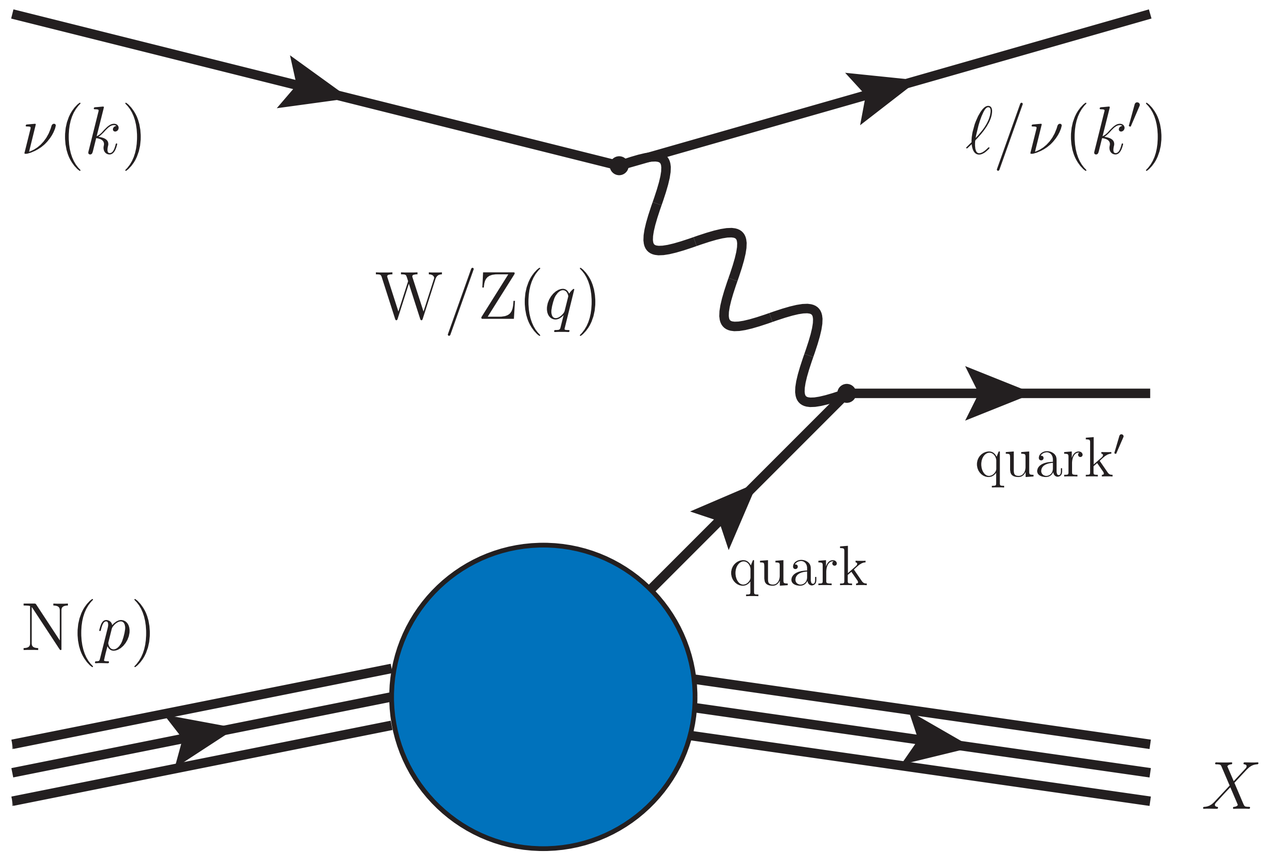
$$y = \frac{q\cdot p}{k\cdot p} = 1 - \frac{E'}{E_\nu}$$

inelasticity, $y \in [0,1]$

$$x = \frac{Q^2}{2q\cdot p} = \frac{Q^2}{2m_N y E_\nu}$$

$x \in [x_{\mathrm{min}}(Q^2_{\mathrm{min}}), 1]$

Neutrino-nucleon Deep Inelastic Scattering



$$\frac{\mathrm{d}^2\sigma^{\mathrm{CC}}_{\nu(\bar{\nu})N}(x,Q^2,E_\nu)}{\mathrm{d}x\,\mathrm{d}Q^2} = \frac{G_F^2 M_W^4}{4\pi x(Q^2+M_W^2)^2}\left(Y_+ F^{\nu(\bar{\nu})N}_{2,\mathrm{CC}}(x,Q^2) \mp Y_- x F^{\nu(\bar{\nu})N}_{3,\mathrm{CC}}(x,Q^2) - y^2 F^{\nu(\bar{\nu})N}_{L,\mathrm{CC}}(x,Q^2)\right)$$

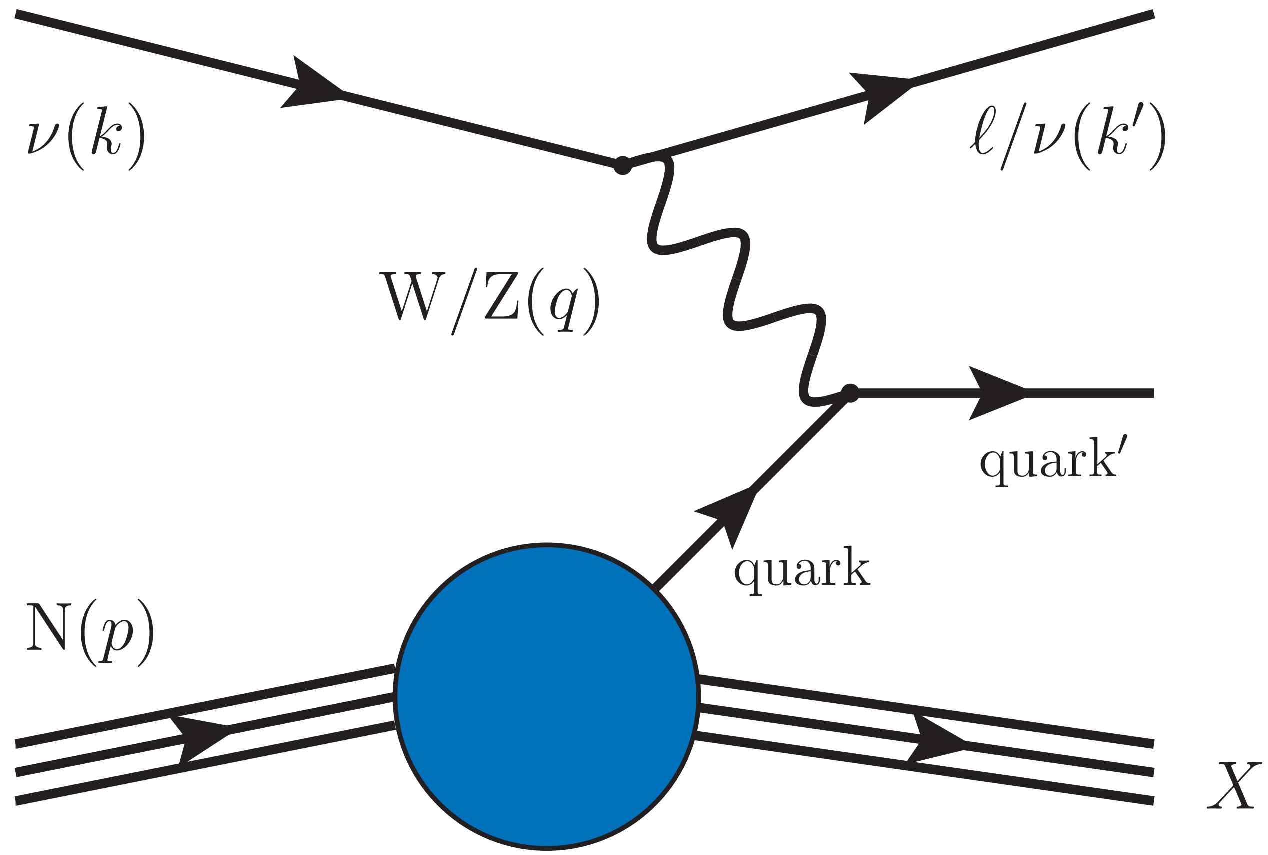
Kinematic pre-factor

$$F_i(x,Q^2) = \sum_{a=g,q}\int_x^1 \frac{dz}{z} C_{i,a}\left(\frac{x}{z},Q^2\right) f_a\left(z,Q^2\right)$$

$$Y_\pm = 1 \pm (1-y)^2$$

DIS structure functions

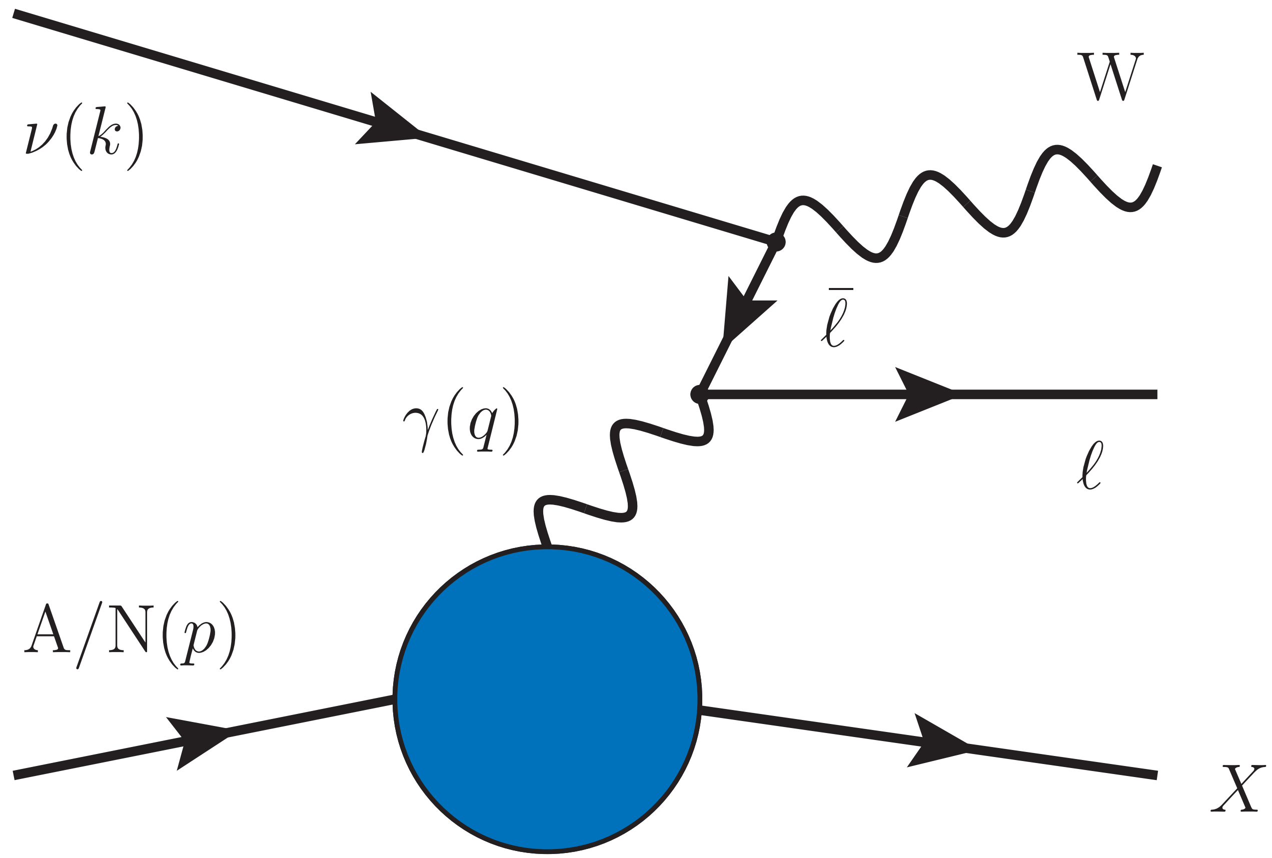
Neutrino-nucleon Deep Inelastic Scattering



Lots of recent progress: DIS structure functions

- Modern PDF sets including LHCb data
  NNPDF3.1sx+LHCb arXiv:1710.05935, 1808.02034
- Include nuclear corrections (and uncertainties)
  EPPS16 arXiv:1612.05741 , nNNPDF1.0 arXiv:1904.00018
- Account for heavy quark mass effects
  FONLL (Forte et al.) arXiv:1001.2312
- Describe with DGLAP and small-x resummation effects
  HELL-x (Bonvini et al.) arXiv:1610.02153, 1708.07510, 1805.06460, 1805.08785
  APFEL (Bertone et al.) arXiv:1310.1394

Resonant scattering processes



$Q^2 = -q^2$

Incoming neutrino probes the photon field of the nucleus A

1) $Q^2 \sim m_W^2$: probe inelastic photon field of nucleons

Gauld - arXiv:1905.03792

luxQED (Manohar et al.) arXiv:1607.04266, DGLAP (Bertone et al.) arXiv: 1508.07002

2) $Q^2 \sim m_N^2$: probe elastic photon field of nucleons

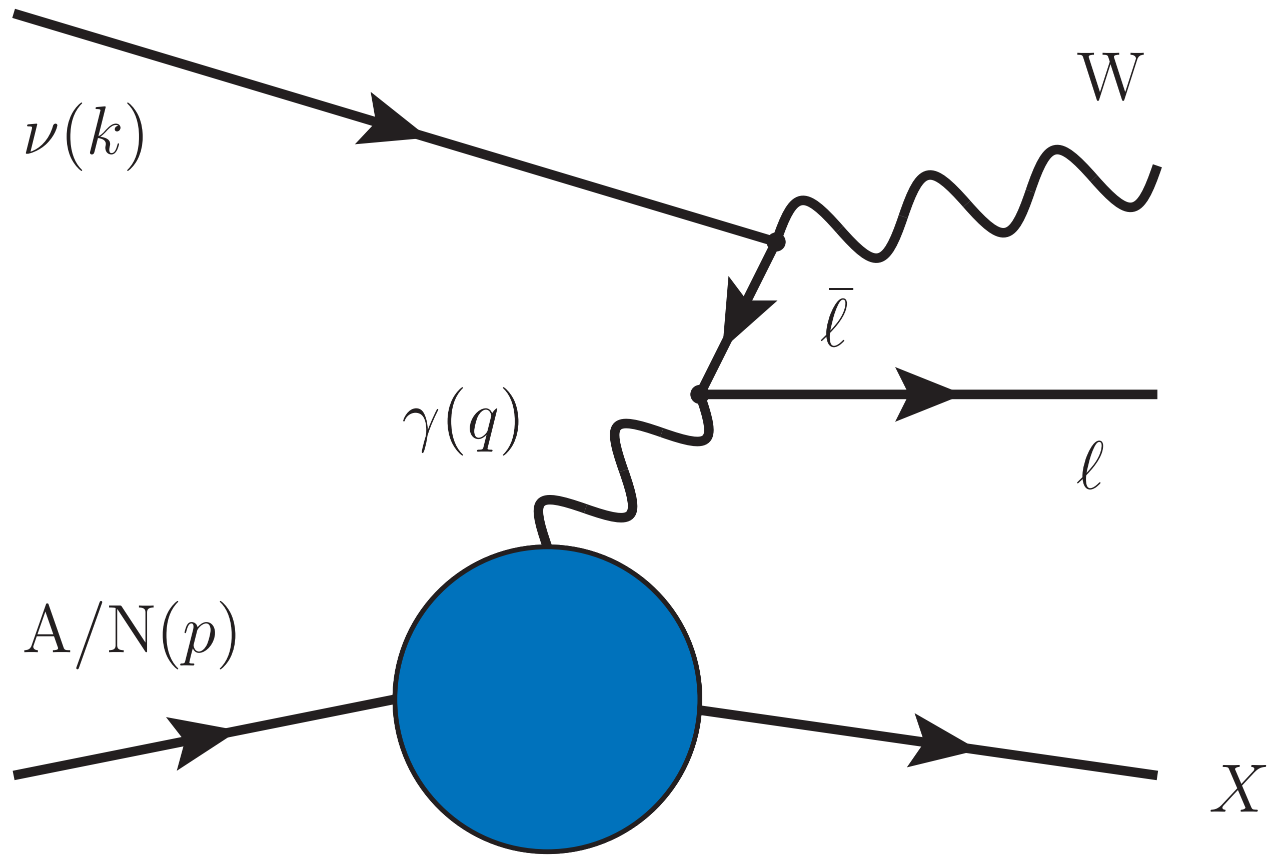
Gauld - arXiv:1905.03792

3) $Q^2 \lesssim m_N^2$: resolve photon field of entire nucleus

Ballett et al. - arXiv:1807.10973

Beacom, Zhou arXiv:1910.08090, 1910.10720

Resonant scattering processes



$Q^2 = -q^2$

Incoming neutrino probes the photon field of the nucleus A

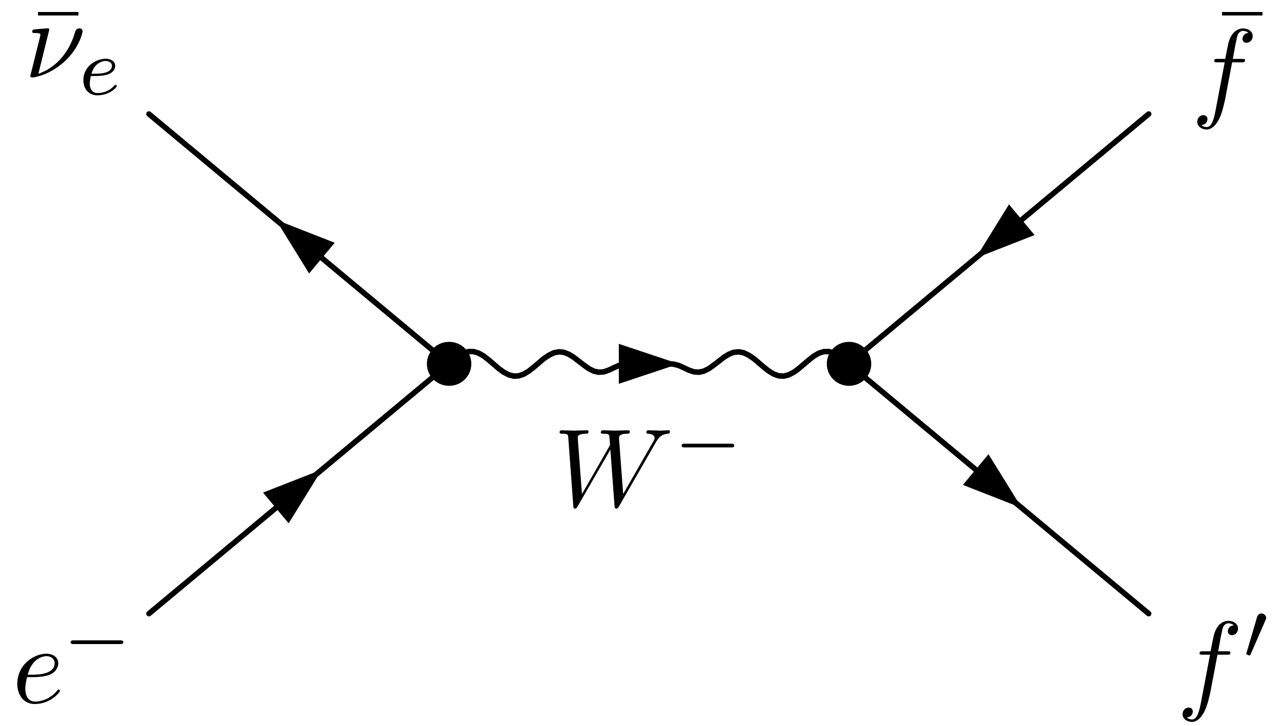
All approaches have a common form:

$$\mathrm{d}\sigma_{\nu T} = h_\gamma^T(\hat{s}, Q^2)\,\mathrm{d}\hat{\sigma}_{\nu\gamma\to X}(\hat{s}, Q^2)$$

hadronic flux of photons

partonic cross-section for $\nu\gamma \to W\ell$

Glashow resonance



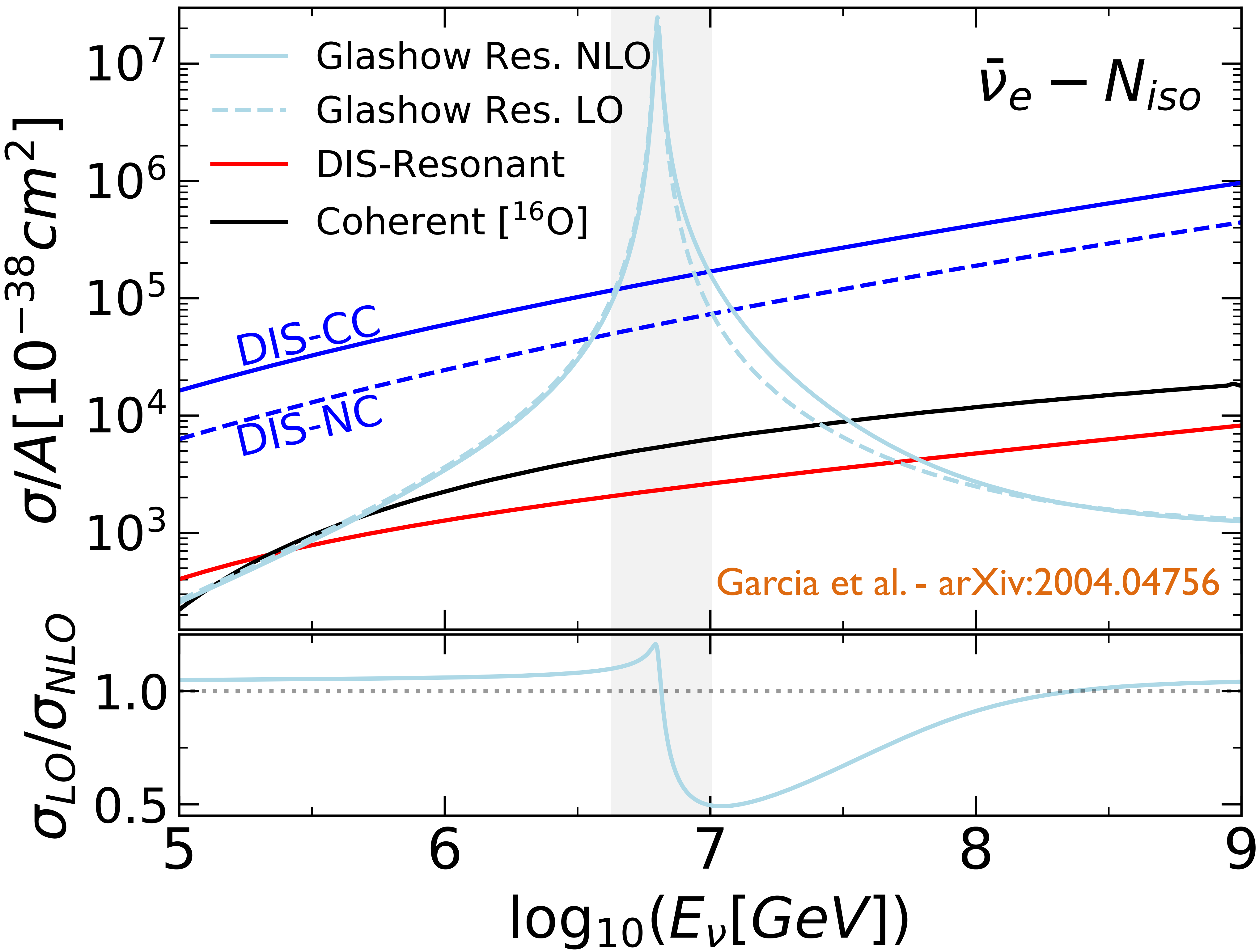
Neutrino scatters on atomic electron: $s = (p_e + p_\nu)^2 \approx 2\, m_e E_\nu$

$$2\, m_e E_\nu \approx m_w^2, \text{ for } E_\nu \sim 6 \text{ PeV}$$

- Fully differential NLO QCD+EW computation
- Accounts for off-shell, non-factorisable, ISR LL corrections
- Resultant predictions: 10% corrections (1% uncertainty)

Gauld - arXiv:1905.03792

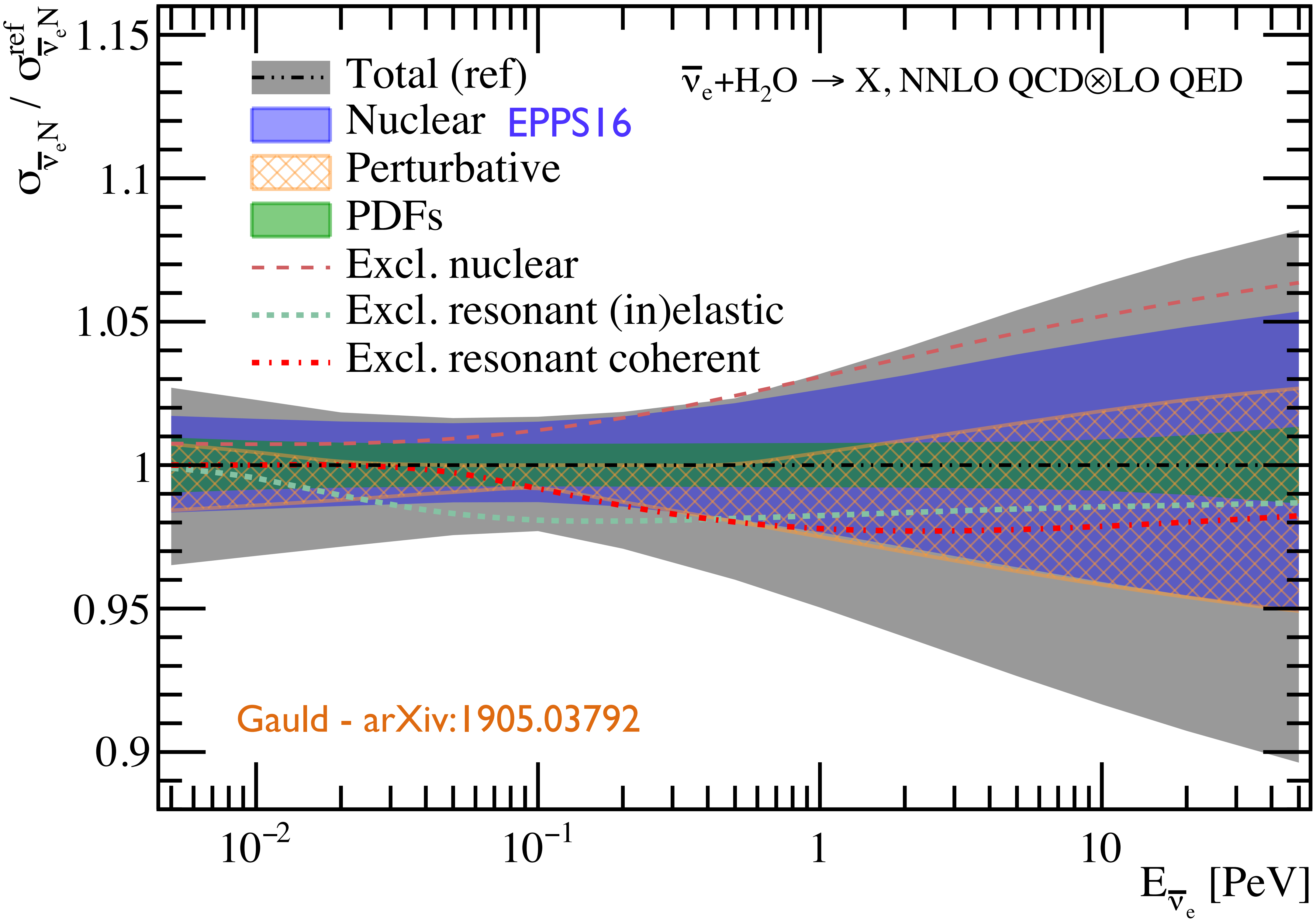
Total cross-section



All processes implemented within GENIE-HEDIS module

See Alfonso's talk for related discussion and attenuation effects

Error budget



DIS nuclear uncertainties (bound PDFs) are limiting factor

See my back-up or Juan's talk for more details

Progress/limitations: Part I

DIS: reliable predictions for $\mathcal{O}(\mathrm{TeV})$ neutrino energies

- Modern inputs and (N)NLO computations available
- Bottleneck is the knowledge of nuclear corrections (which will improve with input from collider data)

DIS: predictions less reliable for $\mathcal{O}(\mathrm{GeV})$ neutrino energies

- Requires careful extrapolation of $F_i^{\nu}(x, Q^2 \rightarrow 0)$
- Not currently available (rely on model-based approach)

$$N = T \cdot \mathrm{d}\Omega \int A_{\mathrm{eff}}^{i,\mathrm{Detector}}\left(E_{\nu}\right) \cdot \sigma_{\nu i}\left(E_{\nu}\right) \cdot \Phi_{\nu}^{\mathrm{Detector}}\left(E_{\nu}\right) \mathrm{dE}_{\nu}$$

Time | Effective area | cross-section | Neutrino flux

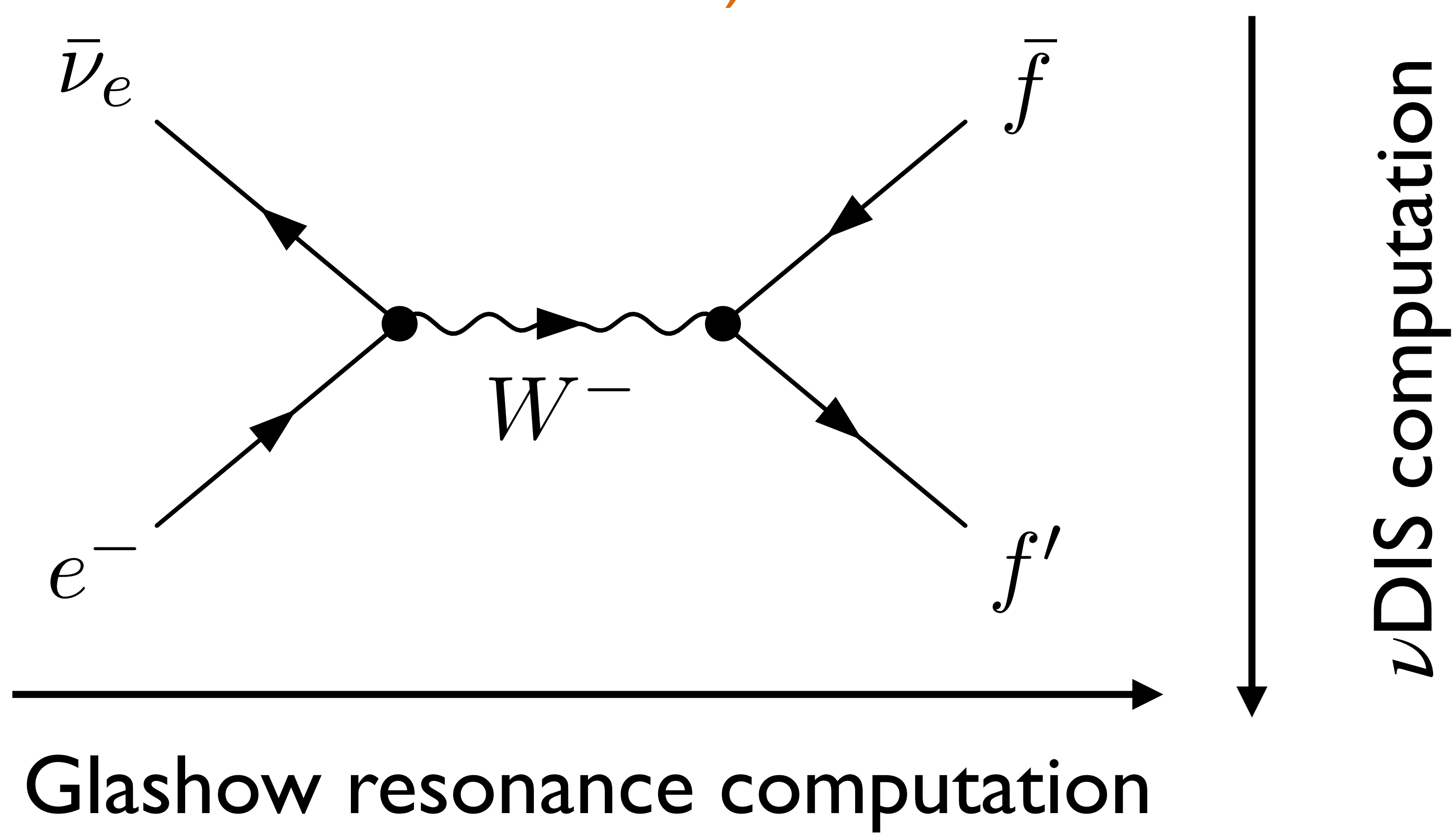
DIS: not differential in QCD (based on structure functions)

- If goal is to reconstruct E_{ν} an exclusive approach desired

Progress/limitations: Part II

DIS: only QCD corrections included

- Weak corrections (partly) absorbed by choice of $s^2_{\mathrm{w,eff}}$
- Typically fine for PDF fits, whose DIS data (mostly charged lepton processes) is less sensitive to EW parameters (see talk from Maarten also)



All ingredients computed in Gauld - arXiv:1905.03792

Many recent theoretical developments:

- νDIS predictions more reliable
- Formalism/predictions for resonant channels
- See Alfonso's talk for recent applications

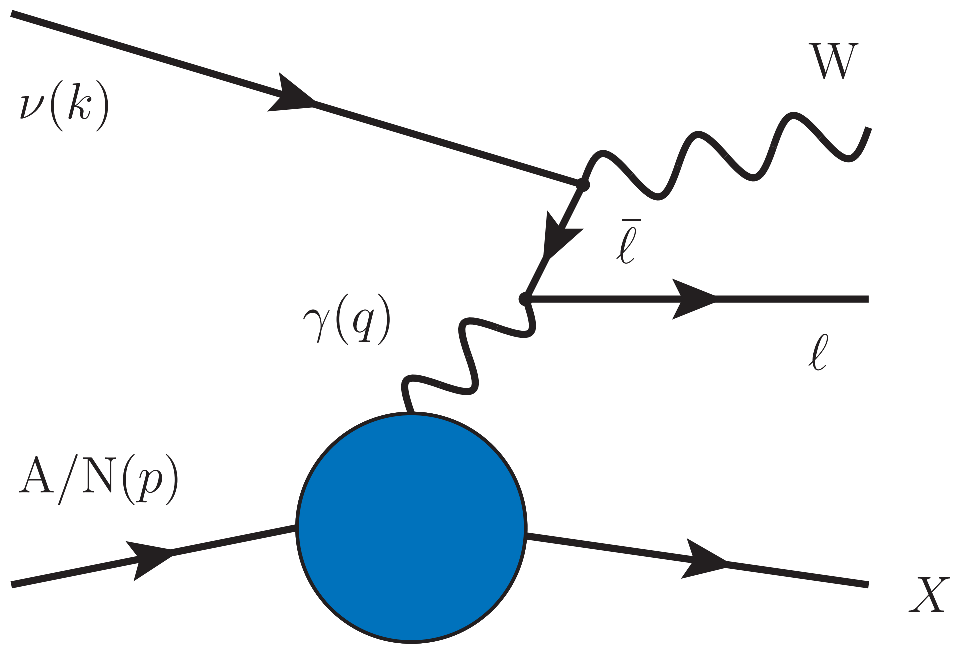
Lots to be done:

- NNLOPS for νDIS predictions (fully exclusive)
- Extrapolation of νDIS for $Q^2 \to 0$
- EW corrections for νDIS
- Inclusion of LHC nuclear constraints

…

Thanks for your attention. Comments welcome!

Coherent scattering on nucleus



Neutrino probes photon field of entire nucleus

See Ballett et al., arXiv:1807.10973, Beacom, Zhou, arXiv: 1910.08090, 1910.10720

$$\frac{d^2\sigma_{\nu C}}{dQ^2\, d\hat{s}} = \frac{1}{32\pi^2}\frac{1}{\hat{s}Q^2}\left[h_C^T(Q^2,\hat{s})\,\hat{\sigma}^T_{\nu\gamma}(Q^2,\hat{s}) + h_C^L(Q^2,\hat{s})\,\hat{\sigma}^L_{\nu\gamma}(Q^2,\hat{s})\right]$$

Hadronic flux: $\propto Z^2 \,|\, F\left(Q^2\right) |^2$

F: Electro-Magnetic Nuclear Form Factor

Off-shell cross-section

$$\hat{\sigma}^T_{\nu\gamma}(Q^2,\hat{s}) = \frac{1}{2\hat{s}}\int \frac{1}{2}\sum\left(-g^{\mu\nu} + \frac{4Q^2}{\hat{s}^2}k^\nu k^\nu\right)|\mathcal{M}|^2_{\mu\nu}\, d\Phi_f$$

$$\hat{\sigma}^L_{\nu\gamma}(Q^2,\hat{s}) = \frac{1}{\hat{s}}\int \sum \frac{4Q^2}{\hat{s}^2}k^\nu k^\nu |\mathcal{M}|^2_{\mu\nu}\, d\Phi_f\,,$$

Same formalism for
Diffractive/elastic scattering

Neutrino scattering on electron target: theory

Preformed differential 2to2 calculation at NLO+ISR LL

Gauld, arXiv: 1905.03792

- All fermion final states (electrons, quarks, leptons)
- Complex Mass Scheme (resonant production)
  Denner at al. hep-ph/0505042
- Includes ISR LL corrections + soft exponentiation
  YFS Annals Phys. 13, 379 (1961). Beenakker et al. hep-ph/9602351
  New calculation based on massive OME, Blumlein et al. arXiv: 1107.4638
- Analytic computation in terms of complex 1-loop scalars
  OneLOop, Van Hameren et al. arXiv 0903.4665, 1007.4716
- Results obtained numerically with CUBA (Vegas)
  Hahn, hep-ph/0404043
- Dipole subtraction for QCD+QED
  Catani, Seymour hep-ph/9605323, Dittmaier hep-ph/9904440
- All of this implemented in (f90) Glashow generator
  Gauld, arXiv: 1905.03792

Neutrino scattering on electron target: theory

Baseline predictions in the α_{G_F} − scheme:

$$\alpha_{G_F} = \alpha_0\,(1+\Delta r)\ , \qquad \delta Z_e^{G_F} = \delta Z_e - \frac{1}{2}\Delta r$$

$$\Delta r = \Delta\alpha(M_Z) - \frac{\delta s_w^2}{s_w^2} + \frac{\Sigma_T^W(0) - \Sigma_T^W(\mu_W)}{\mu_W} + \frac{\alpha_0}{4\pi s_w^2}\left(6 + \frac{7-4s_w^2}{2s_w^2}\ln[c_w^2]\right)$$

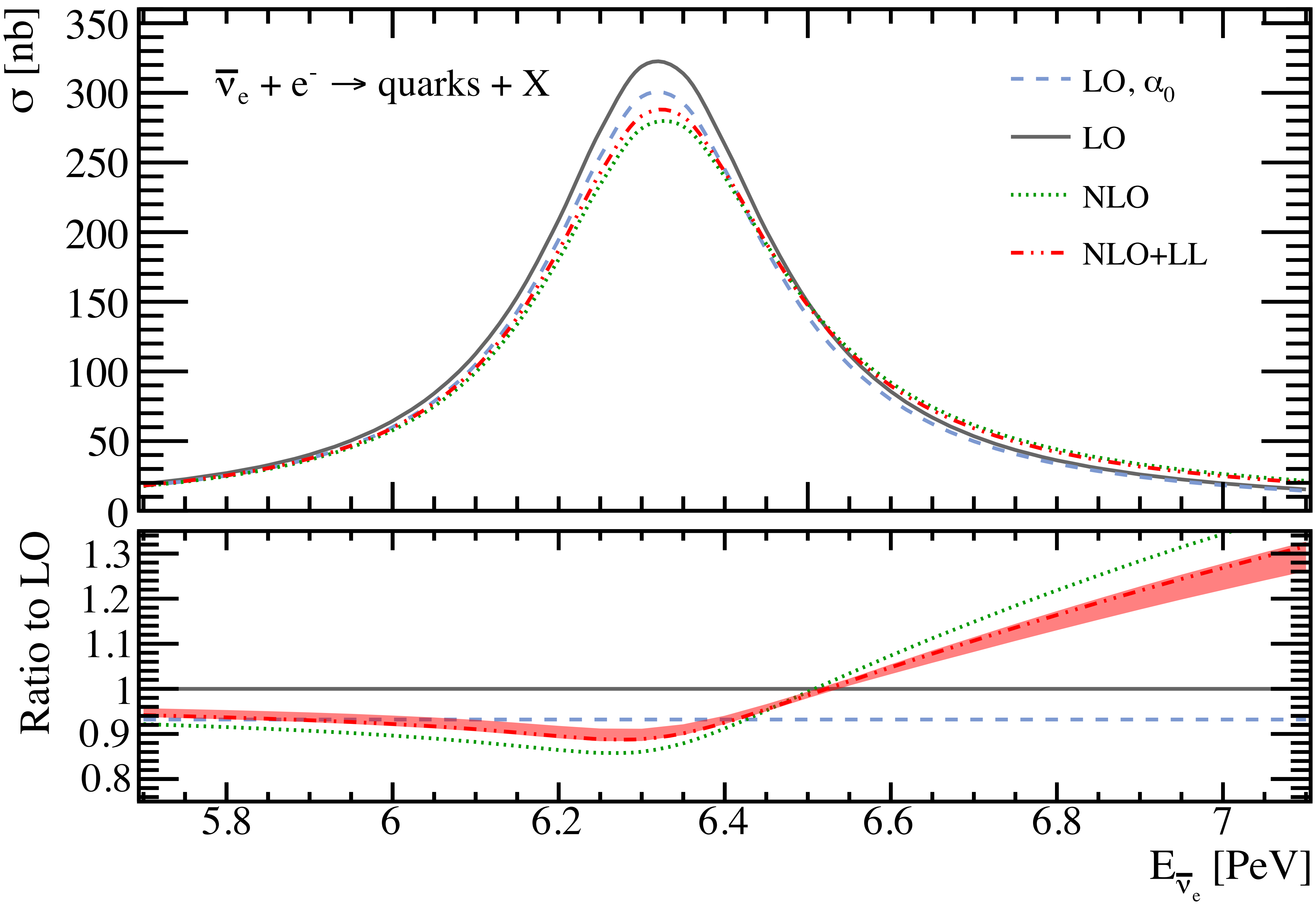
Central prediction: $\sigma^{\text{cen}} = \sigma^{LO}(1+\delta_{EW})(1+\delta_{QCD})$

Account for higher-order ISR effects using Structure Function

Assess uncertainty due to:

- μ_F and μ_R variation (ISR and α_s)
- scheme dependence (α_0)
- additive vs multiplicative QCD corrections

Neutrino scattering on electron target: results

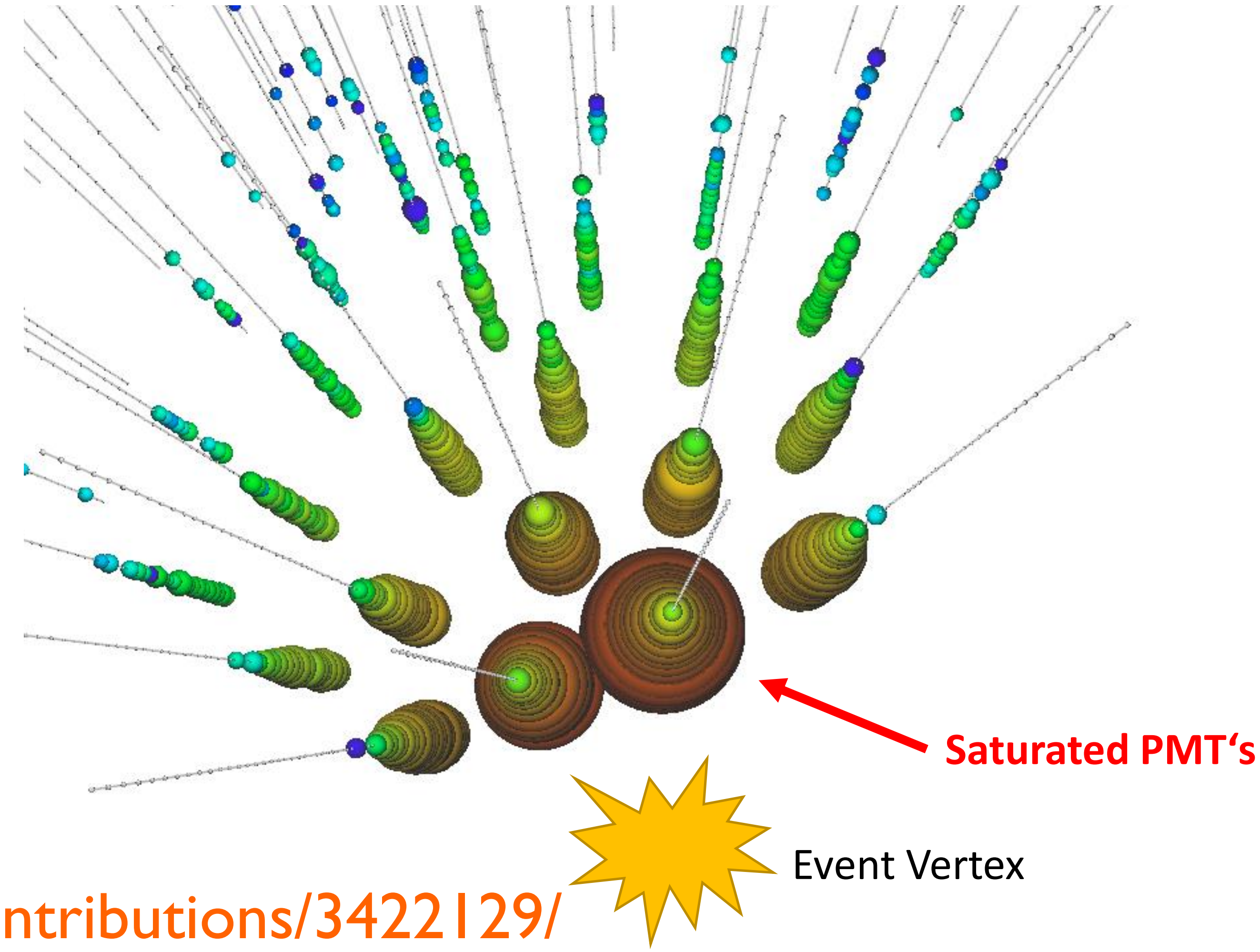


10% correction at NLO (1% uncertainty)

Main effect is ISR: $\alpha/\pi \ln(m_w/m_e)P_{ee}(z)$

Neutrino scattering on electron target: data

Glashow event observed!
IceCube (hadronic chan.)



$$E_{\text{rec.}} = 6.04^{+0.63}_{-0.61}\ \text{PeV}$$

Christian Haack
EPS HEP 2019
https://indico.cern.ch/event/577856/contributions/3422129/

IceCube-Gen2: ~30 events with 10 years of data
Biehl et al. arXiv: 1611.07983

KM3NeT: ~6 events with 15years of data
KM3NeT: pos.sissa.it/358/955

Impact of NLO+LL corrections on event rate:
(most importantly: it is precise)

$$1 - \frac{N^{\text{NLO+LL}}}{N^{\text{LO}}} = 0.07$$

Neutrino scattering on electron target: data

Biehl et al. arXiv: 1611.07983

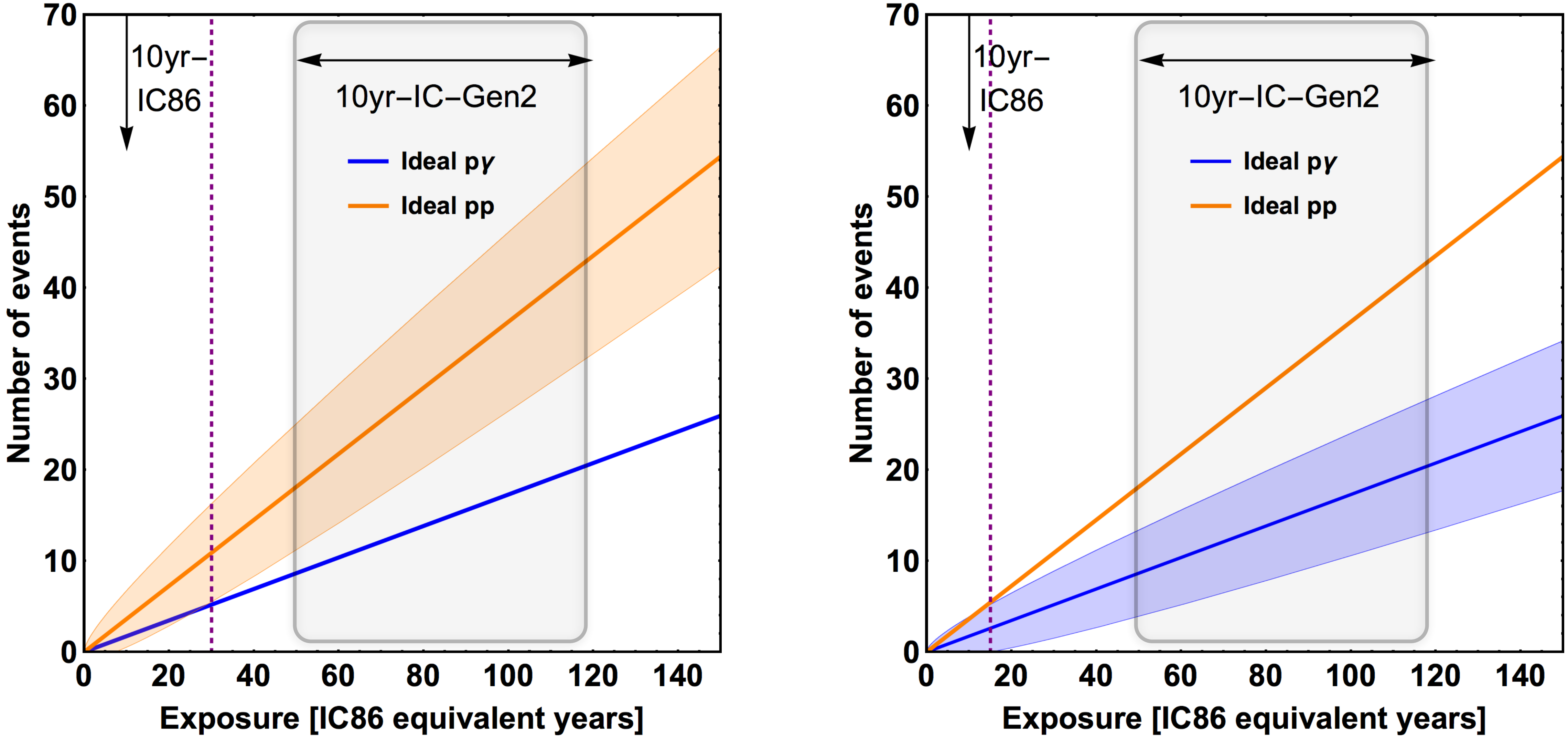
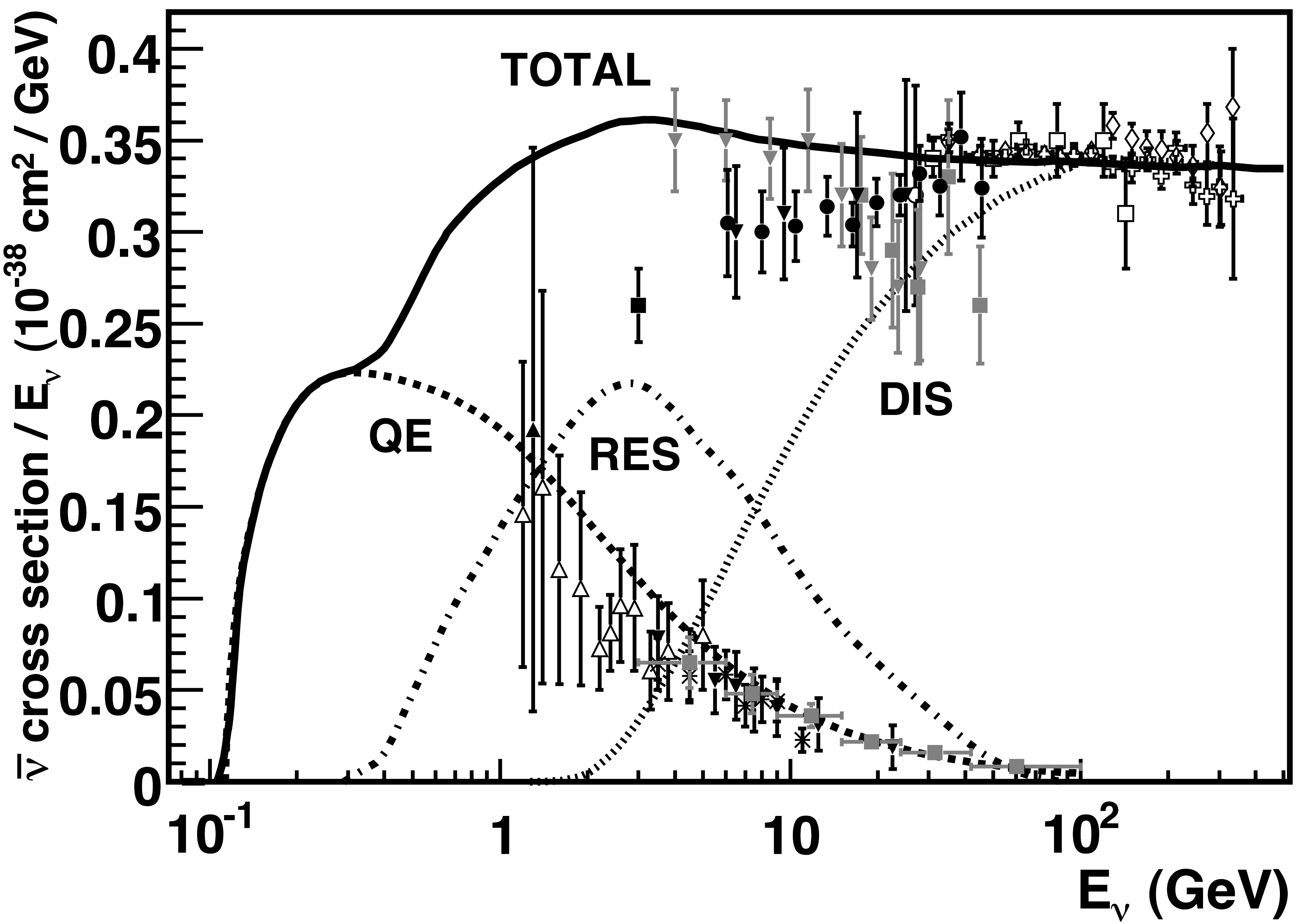


FIG. 1: *Expected number of Glashow events in the ideal pp and pγ scenarios as a function of the exposure for* $\alpha = 2.0$. *The bands represents the 90% C.L. interval from the statistical (Poissonian) uncertainty and the model uncertainties on the oscillation parameters, assuming a true pp and pγ scenario in the left and right panel, respectively. The vertical lines indicate when the other scenario can be excluded.*

Testing neutrino generation scenarios (UHE cosmic rays)
Will be meaningful in ~2030 or so

Low/Moderate energy neutrino scattering



Neutrino-nucleon Deep Inelastic Scattering

$$F_i(x,Q^2) = \sum_{a=g,q} \int_x^1 \frac{dz}{z} C_{i,a}\left(\frac{x}{z}, Q^2\right) f_a\left(z, Q^2\right)$$

Coefficient functions: exhibit perturbative expansion of the form

$$C_{i,a} = \alpha_s^0 C_{i,a}^0 + \alpha_s^1 C_{i,a}^1 + \alpha_s^2 C_{i,a}^2 + \ldots$$

These coefficients known to second order (in some cases third)

Massless CC/NC, Zilkstra and van Neerwen (1991-1992)
Massless (third order) Moch et al. (2005)
Massive NC, Laenen et al. Nucl. Phys. B392 (1993) 162–228
Massive CC, Berger et al. arXiv 1601.05430

Form the backbone for experimental determinations of $f_a(z, Q^2)$

For this work, uses the implementation provided by APFEL

Bertone et al. arXiv:1310.1394 - https://github.com/scarrazza/apfel

Neutrino-nucleon Deep Inelastic Scattering

$$F_i(x,Q^2) = \sum_{a=g,q} \int_x^1 \frac{dz}{z} C_{i,a}\left(\frac{x}{z},Q^2\right) f_a\left(z,Q^2\right)$$

For the free PDFs, baseline is NNPDF3.1sx proton fit

NNPDF Collaboration arXiv: 1706.00428, 1710.05935 (isospin symmetry for neutron)

But don't the neutrinos probe bound nucleons?

$$f_a^{(N)}(x,Q^2,A) = R_a(x,Q^2,A) \times \frac{Z f_a^{(p)}(x,Q^2) + (A-Z) f_a^{(n)}(x,Q^2)}{A}$$

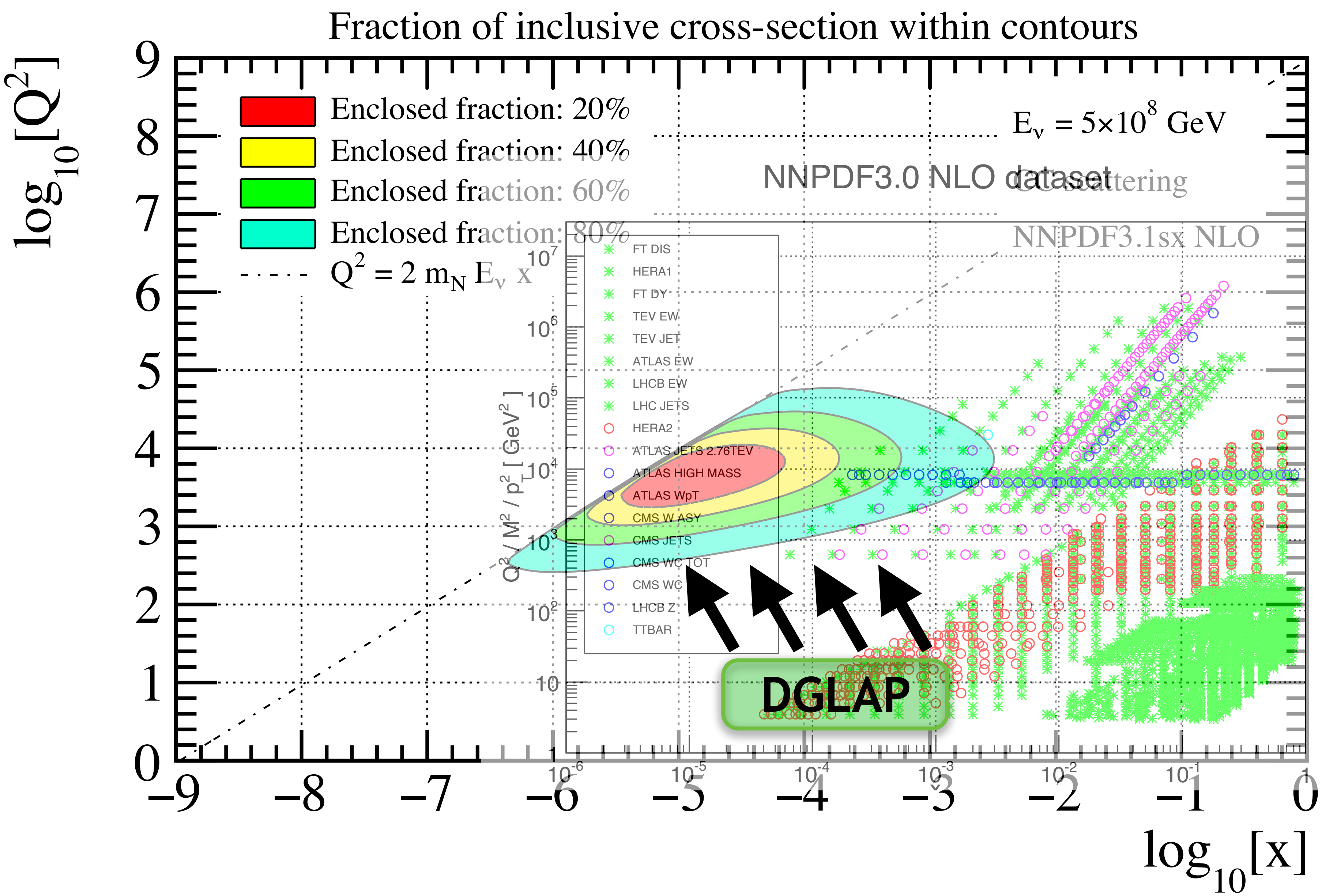
Here we use nNNPDF1.0, apply correction to diff. cross-section

NNPDF Collaboration arXiv: 1904.00018

$$R_\sigma(x,Q,A) \equiv \left(\frac{\mathrm{d}^2\sigma^{\nu N}(x,Q,A)}{\mathrm{d}x\,\mathrm{d}y} \Bigg/ \frac{\mathrm{d}^2\sigma^{\nu N}(x,Q,A=1)}{\mathrm{d}x\,\mathrm{d}y} \right) \Bigg|_{\mathrm{nNNPDF1.0}}$$

Neutrino-nucleon Deep Inelastic Scattering

Kinematics, e.g. 500 PeV neutrino, $\sqrt{s} = 30$ TeV



Free nucleon data

$$\frac{\mathrm{d}^2\sigma^{CC}_{\nu I}}{\mathrm{d}x\,\mathrm{d}Q^2}\left(x, Q^2, E_\nu\right)$$

Note! W/Z bosons set scale

$$\mathrm{d}\sigma \propto \frac{F_i(x,Q^2)}{(Q^2+M_V^2)^2}$$

Nuclear uncertainties

Issue is there very little data for pA collisions. Analyses:

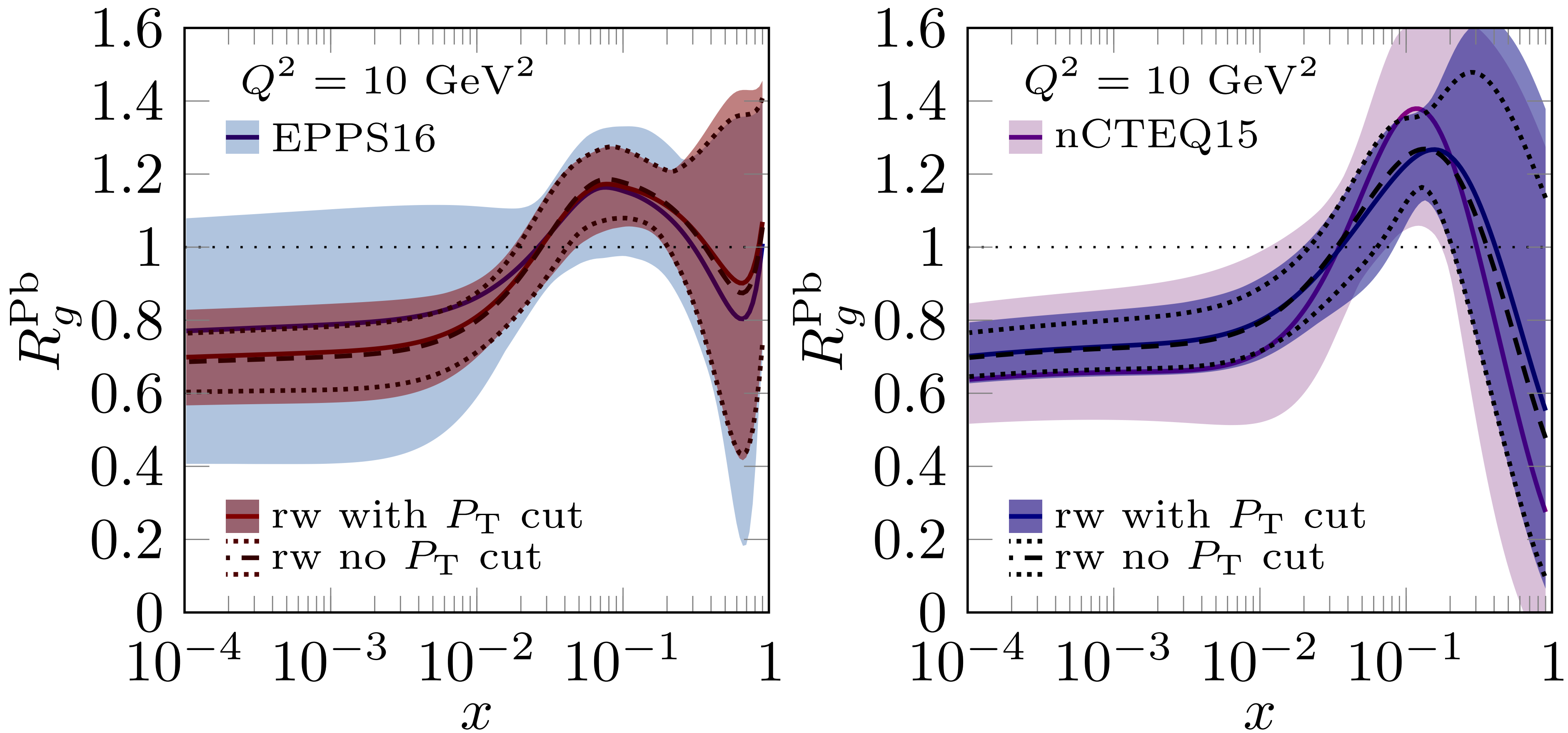
nCTEQ15, arXiv: 1509.00792

EPPS16, arXiv: 1612.05741

nNNPDF1.0, arXiv: 1904.00018

In the future, can use $pp \to D + X$ vs $p\text{Pb} \to D + X$

Gauld, arXiv: 1508.07629, LHCb arXiv: 1707.02750



Constraints on Pb gluon correlated with quarks and $A \sim 33$

Kusina et al., arXiv: 1707.02750; EPPS, arXiv: 1906.02512