

DIS-SECTING THE UNIVERSE WITH HIGH-ENERGY NEUTRINOS

BASED ON A WORK WITH RHORRY GAULD, ULRICH HAISCH, ALESSIO VORONA,
GIULIA ZANDERIGHI

QCD@LHC, 28.09.2026

Lorenzo Guerra

NEUTRINO DEEP INELASTIC SCATTERING (ν -DIS)

INTRODUCTION



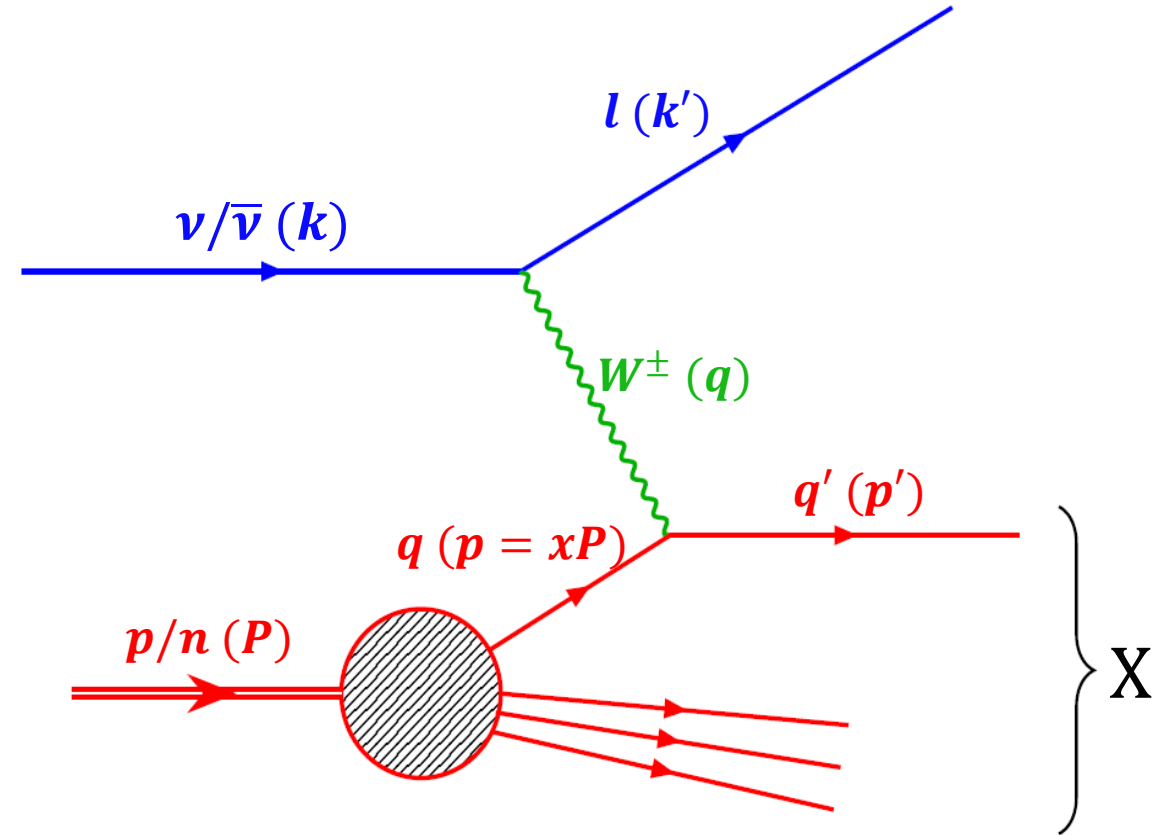
⇒ Valuable insights on **neutrino properties** and their origin in a largely **untested energy range** combined with sensitivity to **BSM physics**.

[**Overviews:** Anchordoqui et al. [2109.10905](#), Feng et al. [2203.05090](#), Ackermann et al. [2203.08096](#)]

⇒ Many **planned** and **ongoing** neutrino-focused **experiments**:

- Large-volume detectors: ANTARES, IceCube, KM3NeT, ...
- Collider facilities: FASER ν , FLArE, SHiP, SND@LHC, ...

⇒ At **multi-GeV and above energies**, the scattering rate of neutrinos with matter is dominated by **DIS** processes.



NEUTRINO DEEP INELASTIC SCATTERING (ν -DIS)

IMPORTANCE OF RADIATIVE CORRECTIONS

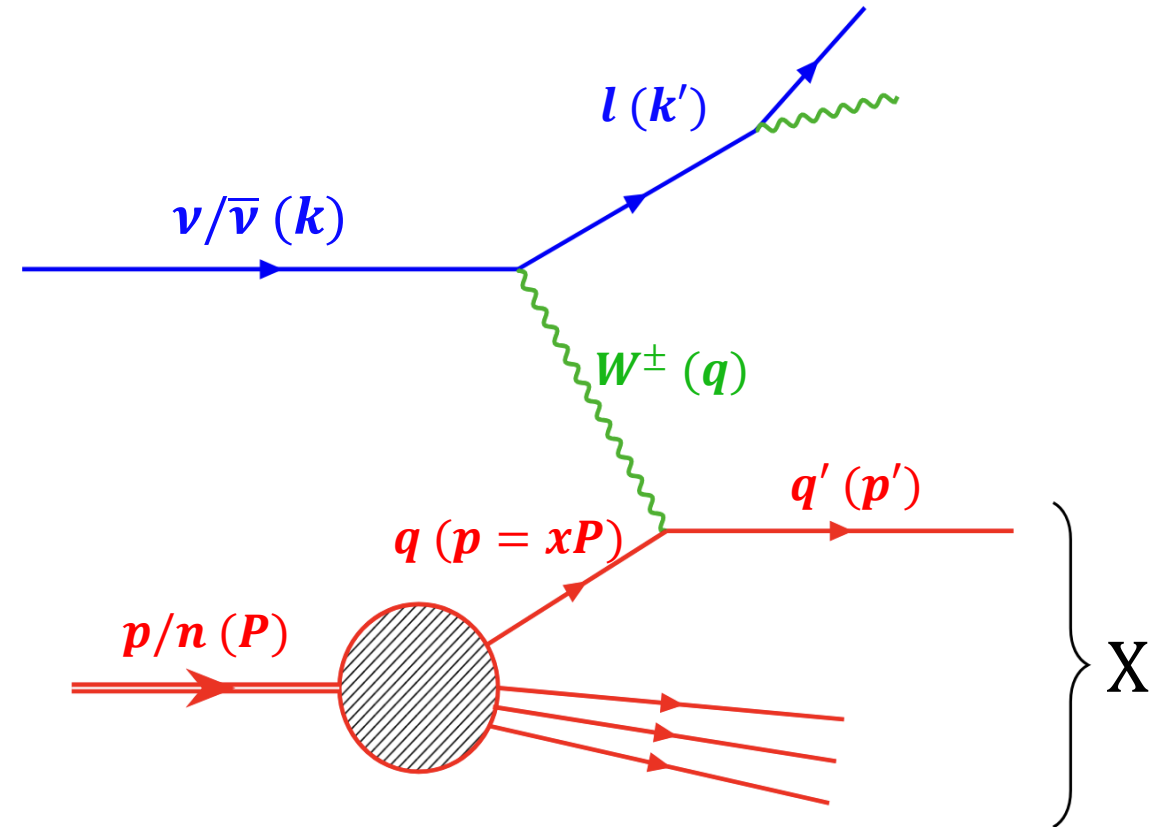


⇒ Predictions for the kinematic distribution of charged leptons in the **Charged-Current (CC) channel** can receive large **distortions** due to **final state radiations (FSR)**.

[Plestid, Zhou [2403.07984](#)]

⇒ DIS kinematic observables:

$$\begin{aligned} Q^2 &\equiv -q^2 = -(k - k')^2 \\ y_{\text{DIS}} &\equiv \frac{P \cdot q}{P \cdot k} = \frac{p \cdot q}{p \cdot k} \\ x_{\text{Bjk}} &\equiv \frac{Q^2}{2P \cdot q} \end{aligned}$$



⇒ Study of **radiative corrections** focusing on the **inelasticity**.



⇒ QCD Collinear Factorization Theorem:

$$d\sigma = \sum_i \int dx f_i(x, \mu_F^2) d\hat{\sigma}(k, x P; \mu_F, \mu_R)$$

⇒ Expansion of **partonic cross-section**:

$$d\hat{\sigma} = d\hat{\sigma}_{\text{LO}} + \frac{\alpha_s}{4\pi} d\hat{\sigma}_{\text{NLO,QCD}} + \frac{\alpha}{4\pi} d\hat{\sigma}_{\text{NLO,EW}}$$

⇒ Sum of **real** and **virtual** contributions:

$$\int d\hat{\sigma}_{\text{NLO}} = \int_2 (d\hat{\sigma}_V + d\hat{\sigma}_{V_s}) + \int_3 (d\hat{\sigma}_R + d\hat{\sigma}_{R_s})$$

⇒ **Cross-section level:**

- **FeynArts**, **FeynCalc**, **FormCalc** for the **amplitudes**.
- **Recola2** for renormalised **EW virtual** correction.
[Diener, Dittmaier, Hollik [0310364](#)]
- **Recola2**, **OpenLoops** for **numerical validation**.
- Additional cross-check against **inclusive QCD structure function** approach.
[Xie et al. [2303.13607](#), Candido et al. [2302.08527](#)]

⇒ **Quark** and **charged-lepton mass effects** fully retained.

⇒ **Differential level:**

- Comparison to **lepton fragmentation approach** and **POWHEG-BOX-RES**.

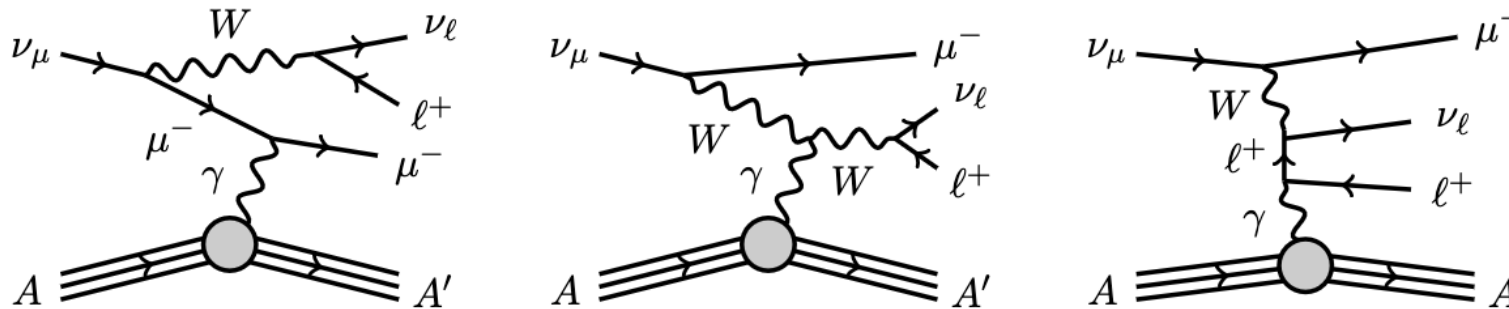


$$\nu_l + \gamma \longrightarrow l^- + f\bar{f}$$

⇒ Photon-induced processes:

- Enhanced **on-shell W boson production** ($m_{f\bar{f}} \sim m_W$)
- **Coherent scattering** on the **nucleus** with Z^2 enhancement in the cross section ($Q \lesssim 1 \text{ GeV}$)
- **Diffraction scattering** on the bounded **nucleons** ($Q \simeq 1 \text{ GeV}$)
- Scattering on **atomic electrons**: **Glashow resonance** for electron antineutrinos ($E_{\bar{\nu}_e} \simeq m_W^2 / (2m_e) \simeq 6.3 \text{ PeV}$)

[**Overviews:** *Ballett et al.* [1807.10973](#), *Glashow* [PhysRev.118.316](#)]



⇒ Photon **PDFs** formulated within the **LUXqed** framework naturally incorporates **elastic** and **inelastic** contributions.

[*Manohar, Nason, Salam, Zanderighi* [1607.04266](#), [1708.01256](#)]

IMPACT OF RADIATIVE CORRECTIONS

LEPTON FRAGMENTATION APPROACH



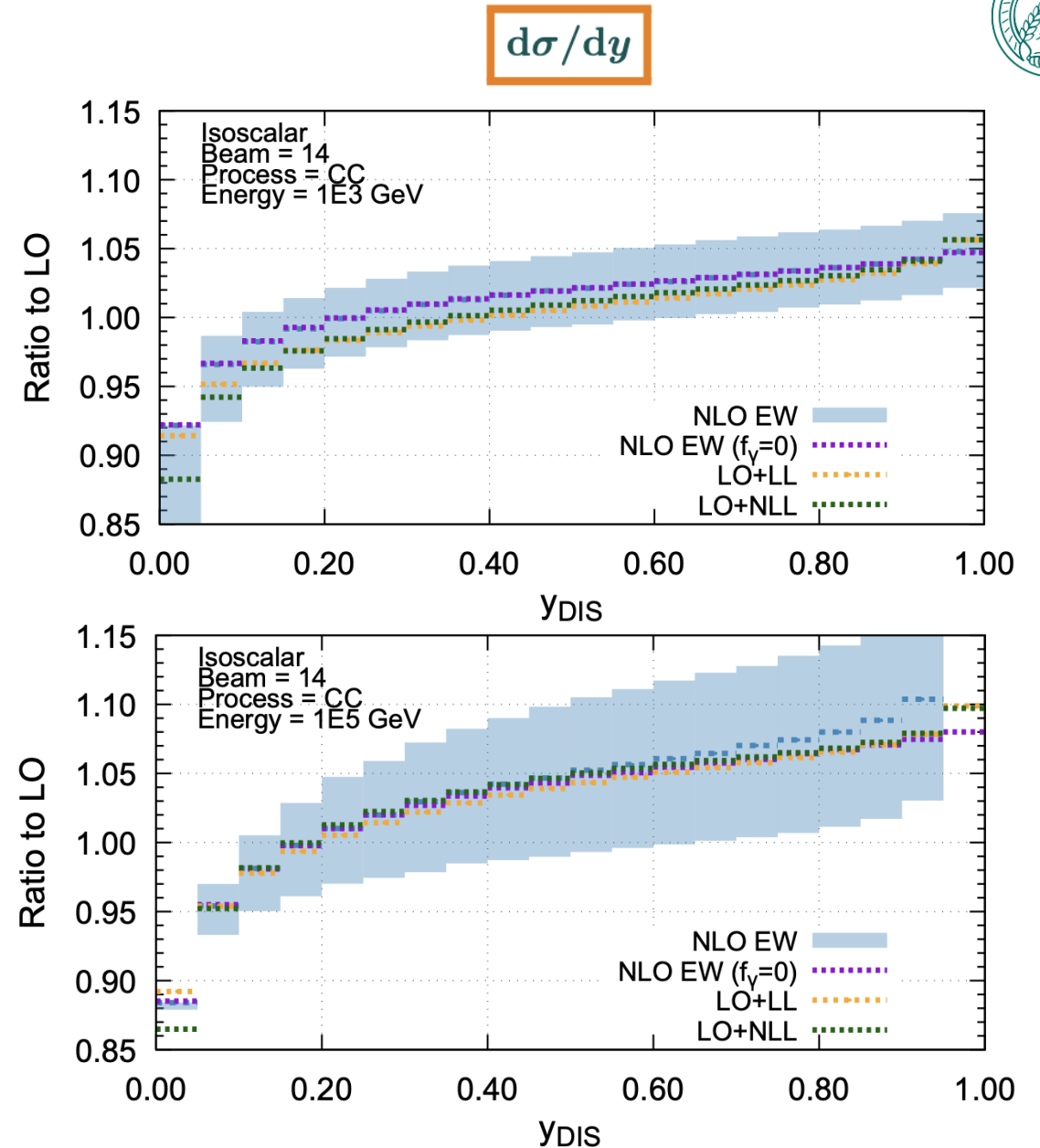
⇒ **Collinear approximation** of the $l^- \rightarrow l^- \gamma$ splitting:

$$d\hat{\sigma}_{\text{LL,QED}} = d\hat{\sigma} \int_0^1 dz \frac{\alpha}{2\pi} P_{ll}^{(0)}(z) \ln\left(\frac{\mu_h^2}{m_l^2}\right) \Theta_{\text{selection}}(z p_l)$$

⇒ Inclusion of **higher-order effects** and **subleading logs**:

$$d\hat{\sigma}_{\text{frag,QED}} = d\hat{\sigma} \int_0^1 dz D_l(z, \mu_F^2) \Theta_{\text{selection}}(z p_l)$$

[Full expressions: [Arbuzov, Melnikov 0205172](#)]



IMPACT OF RADIATIVE CORRECTIONS

POWHEG-BOX-RES GENERATOR

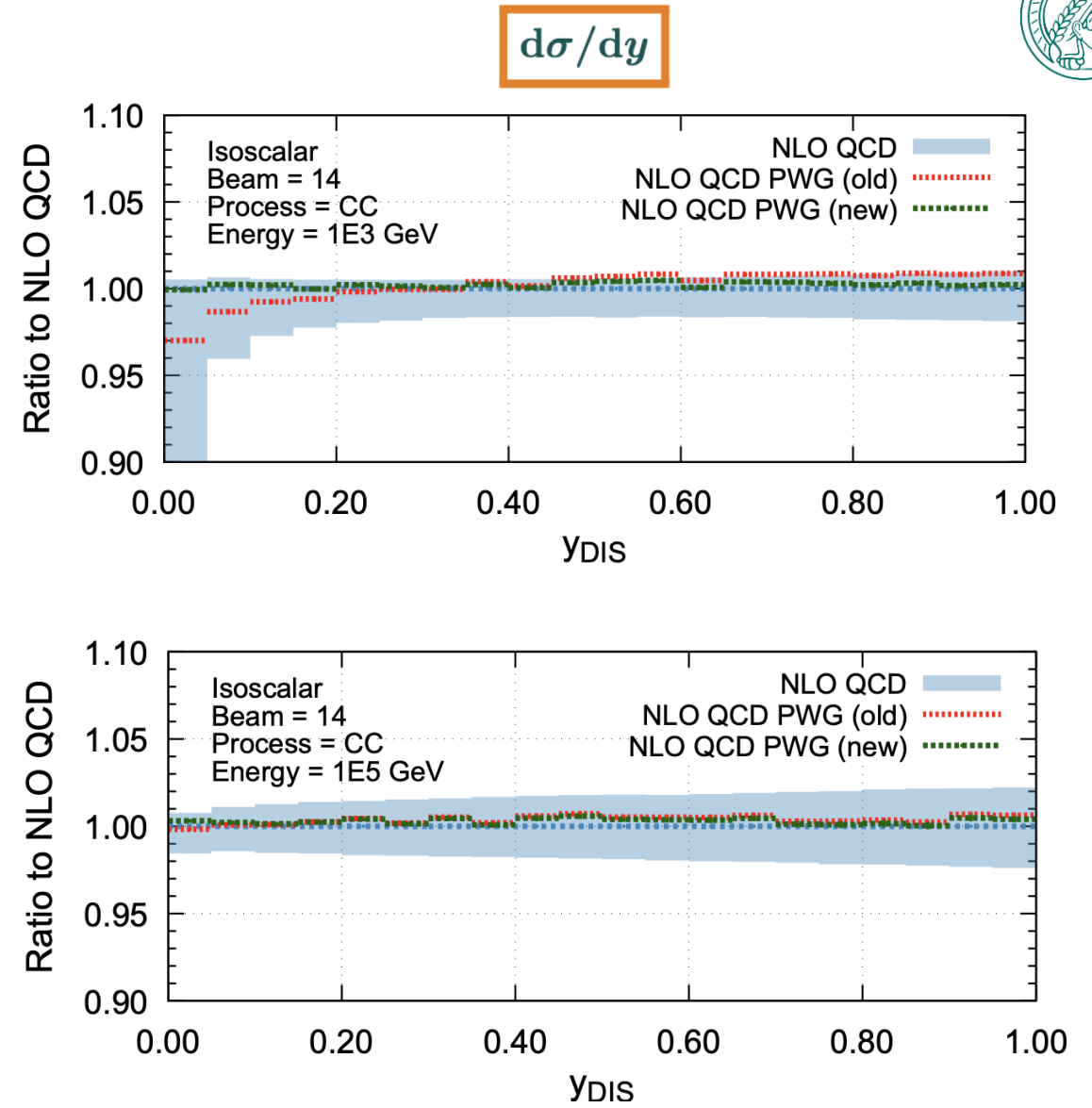


⇒ **POWHEG-BOX-RES generator** matched to **PYTHIA parton shower**.

[**DIS generator**: *Banfi et al.* [2309.02127](#), *Ferrario Ravasio et al.* [2407.03894](#)]

⇒ **New DIS-specific reshuffling procedure** to give **mass** to final-state particles.

⇒ **Fully exclusive** event simulation, suitable for **experimental analyses**.



IMPACT OF RADIATIVE CORRECTIONS

POWHEG-BOX-RES GENERATOR



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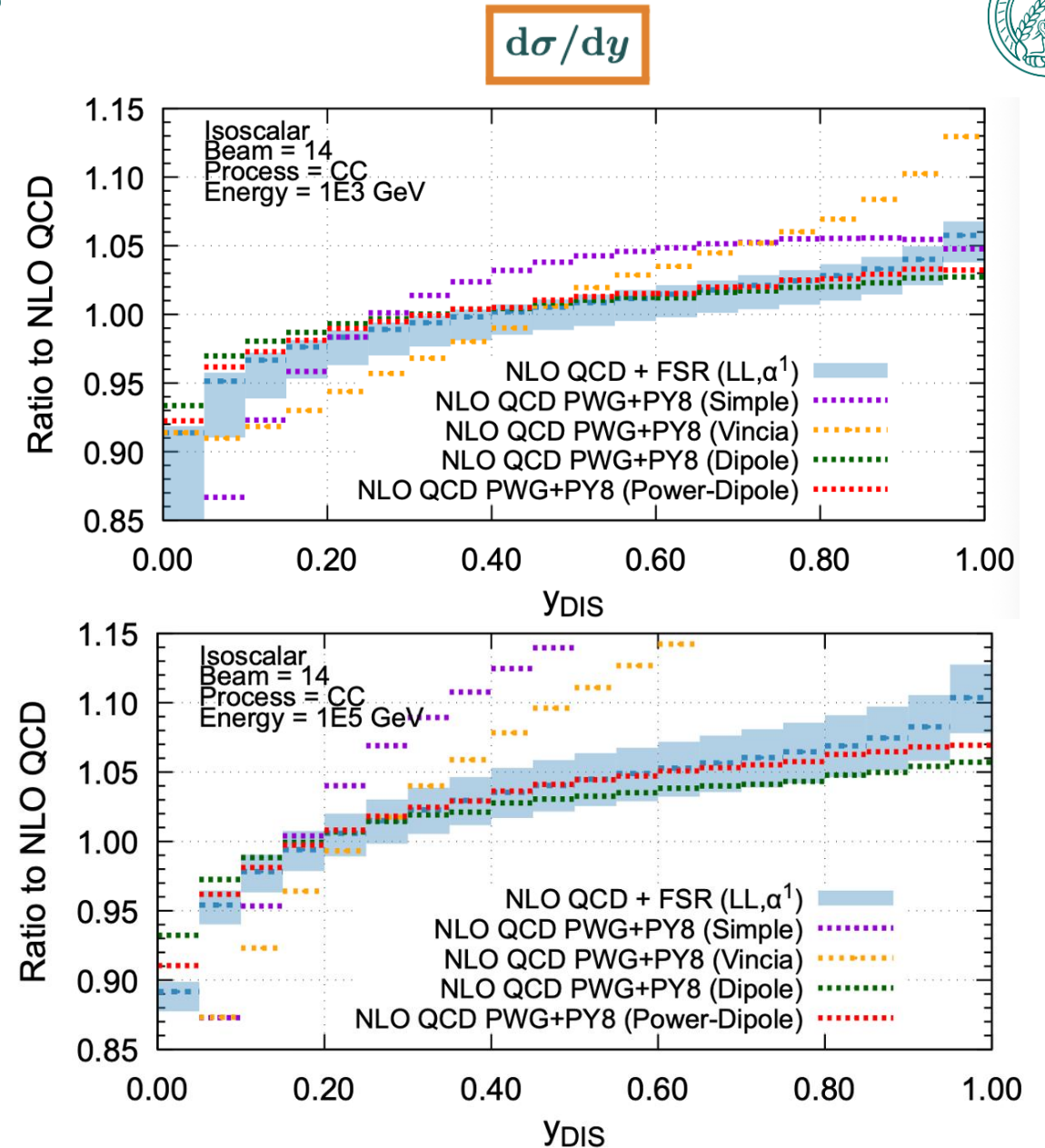
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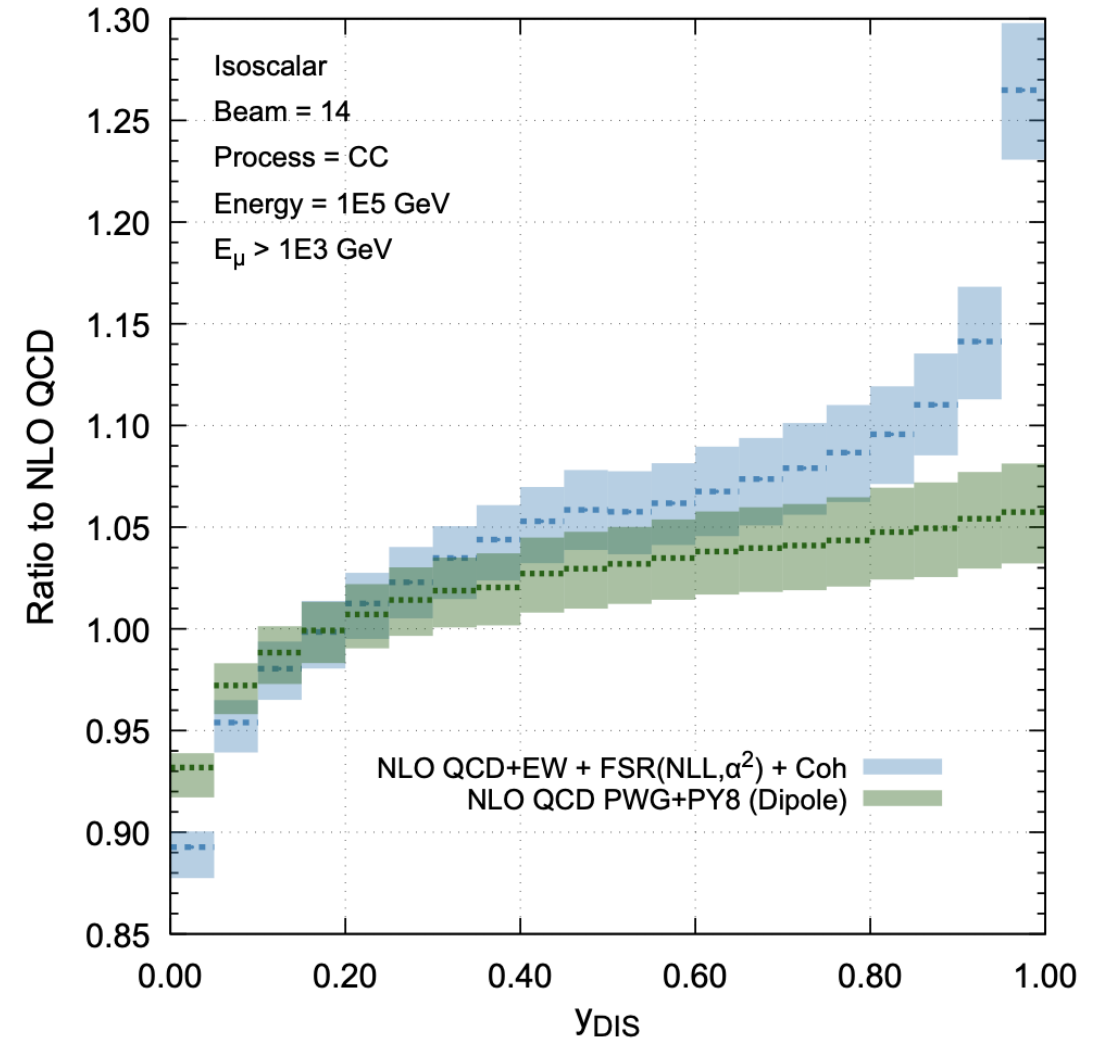
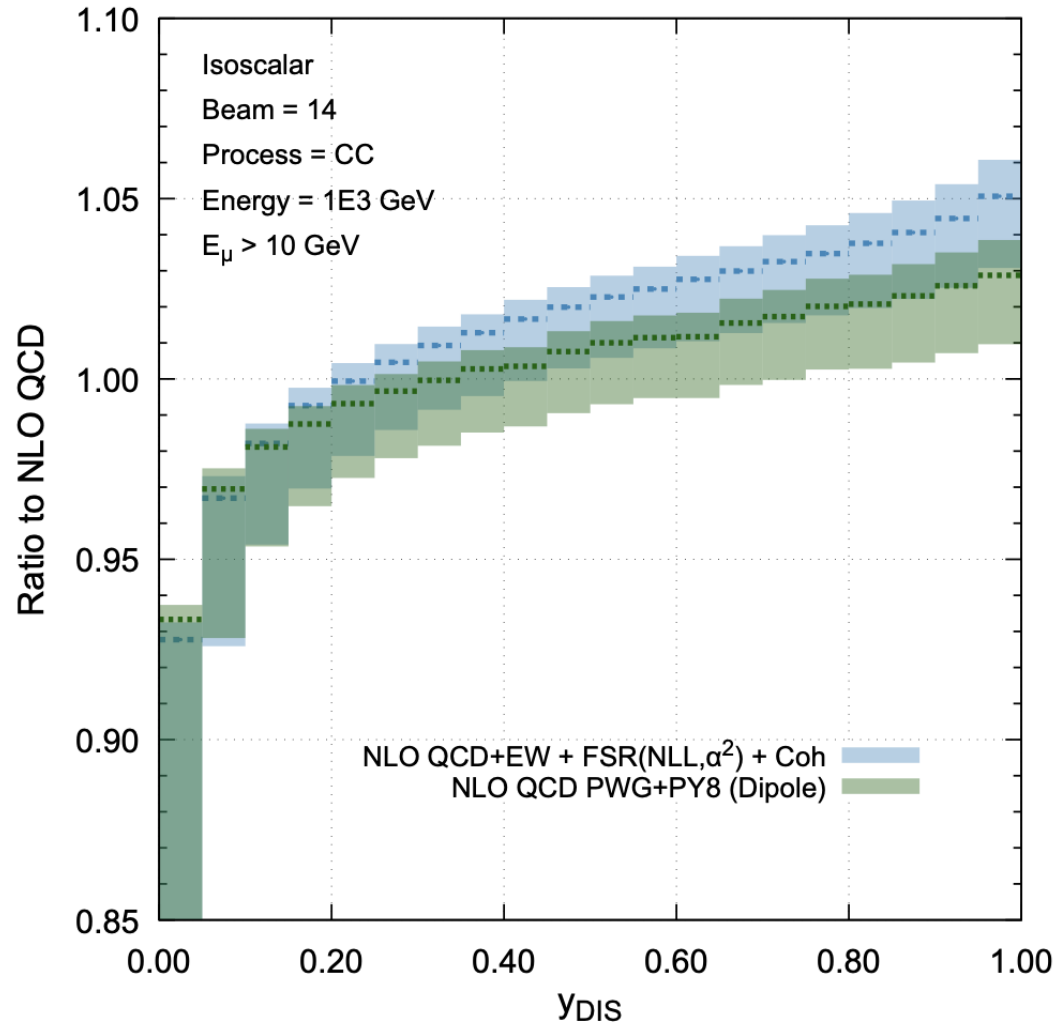
⇒ Matching to PS using the **dipole recoil option**.

[*Cabouat, Sjöstrand* [1710.00391](#)]



IMPACT OF RADIATIVE CORRECTIONS

COMPLETE COMPARISON



DOUBLE-DIFFERENTIAL GRIDS

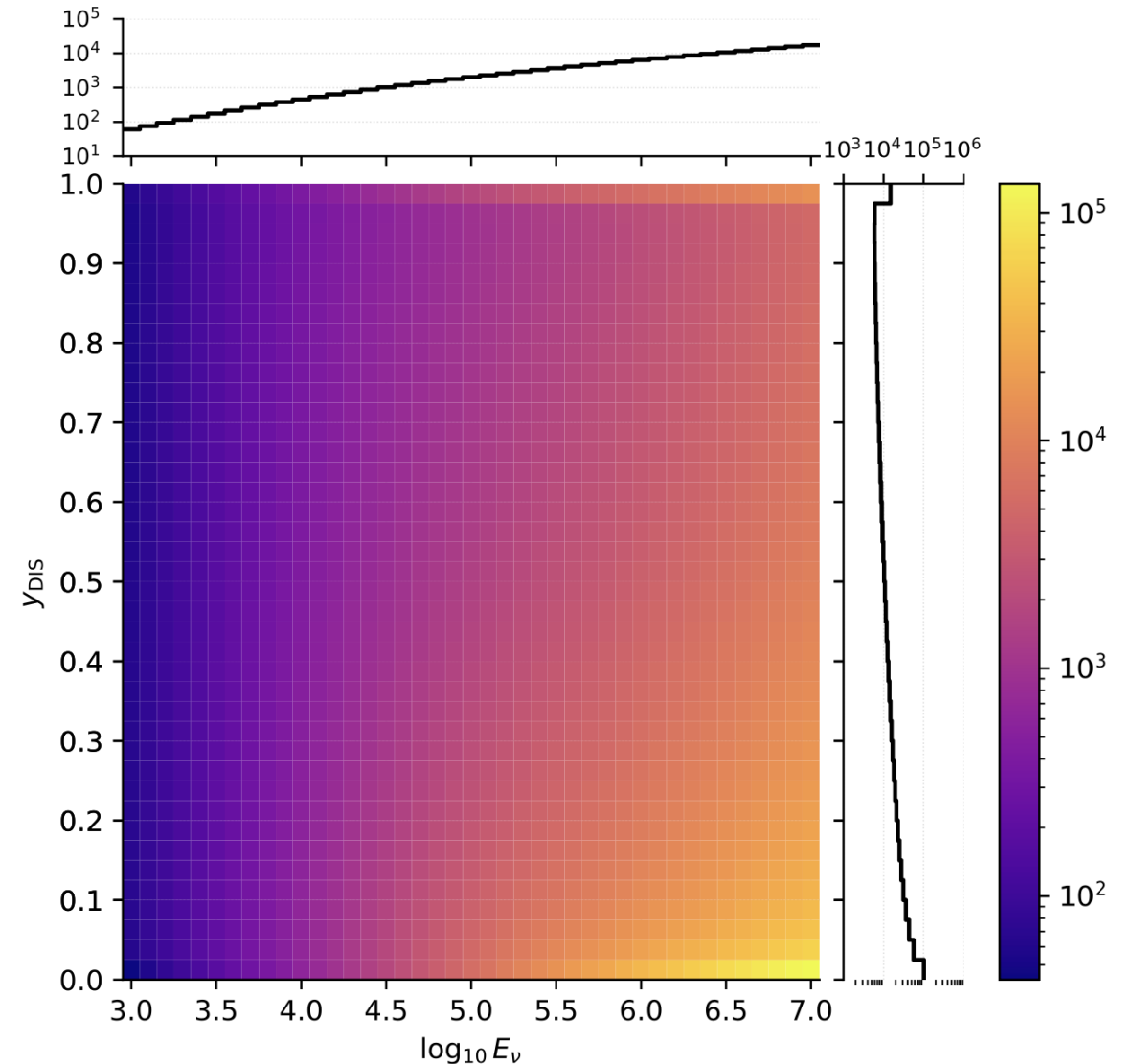
FULL RESULT



$$\left(\frac{d^2\sigma}{d \log_{10} E_\nu dy} \right)_{\text{NLO QCD+EW} + \text{FSR}}$$

⇒ **Discretized double-differential grid** using internal MC framework.

⇒ Accessible set of predictions for **future experimental** and **theoretical studies** of neutrino-matter scattering.



DOUBLE-DIFFERENTIAL GRIDS

NEUTRINO FLUX IMPLEMENTATION IN POWHEG



$$\left(\frac{d^2 N_{\text{int}}}{d \log_{10} E_\nu dy} \right)_{\text{NLO QCD} + \text{PS}}$$

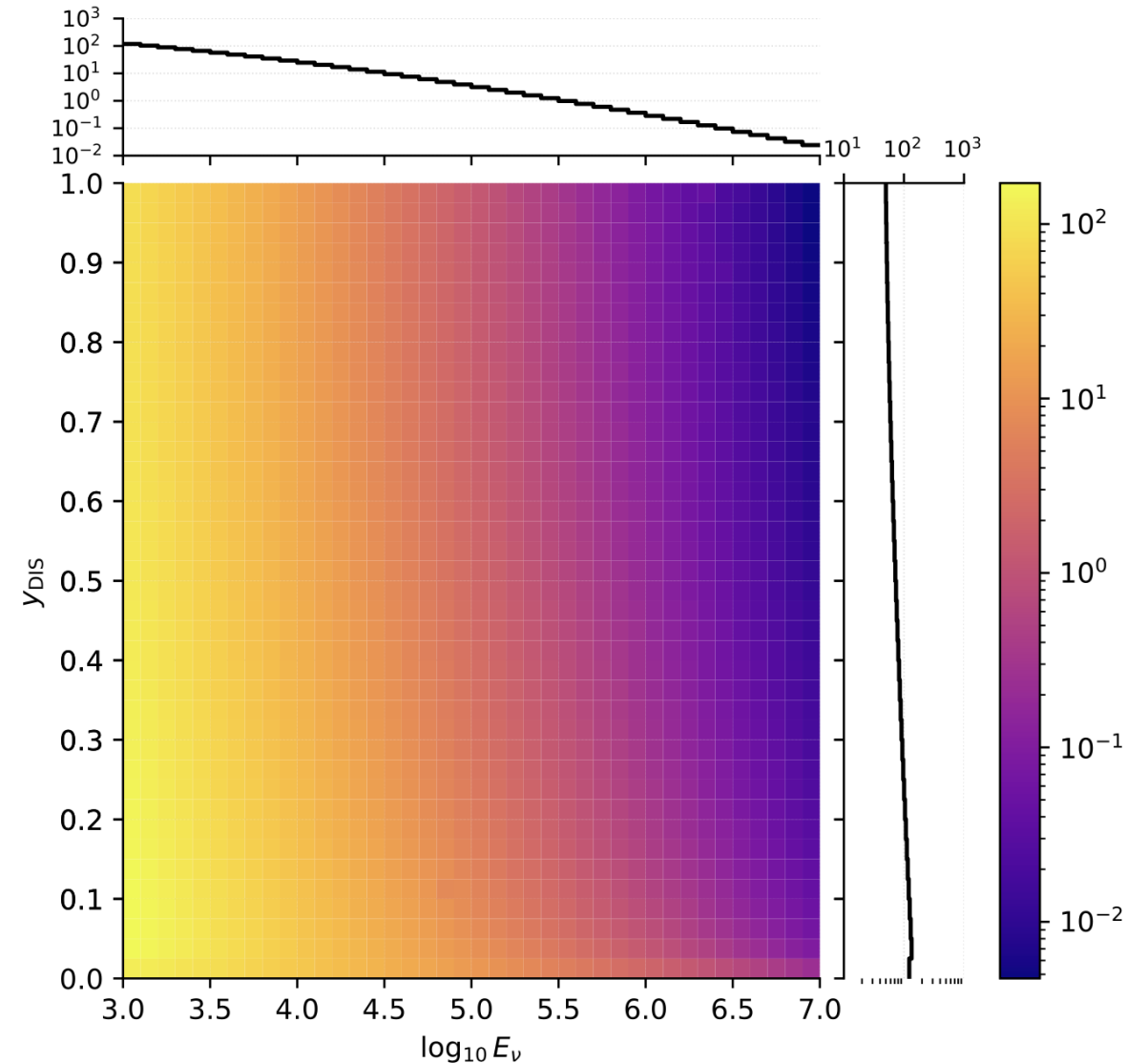
⇒ Implementation of **neutrino flux** in **POWHEG-BOX** generator (both **neutrino PDFs** and **astronomical flux**).

[*van Beekveld et al.* [2407.09611](#)]

⇒ In the plot: **Single Power Law** astronomical flux.

$$\Phi(E_\nu) \propto E_\nu^{-\gamma}$$

[*Abbasi et al.* [2402.18026](#)]



DOUBLE-DIFFERENTIAL GRIDS

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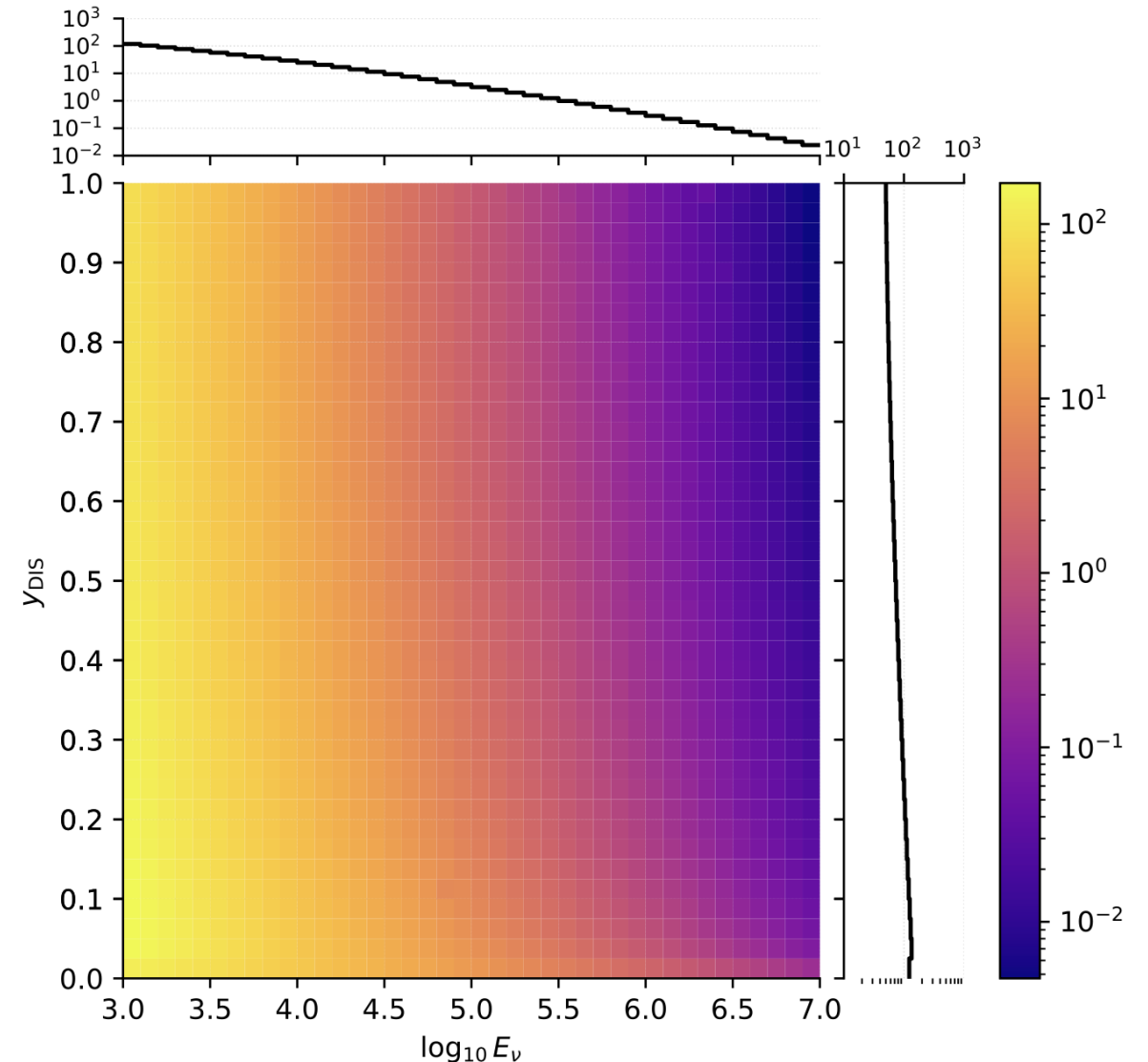
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⇒ Switch back to **discretized grid** for **matching to PS** due to variable neutrino energy not supported in **PYTHIA8** (yet).



DOUBLE-DIFFERENTIAL GRIDS

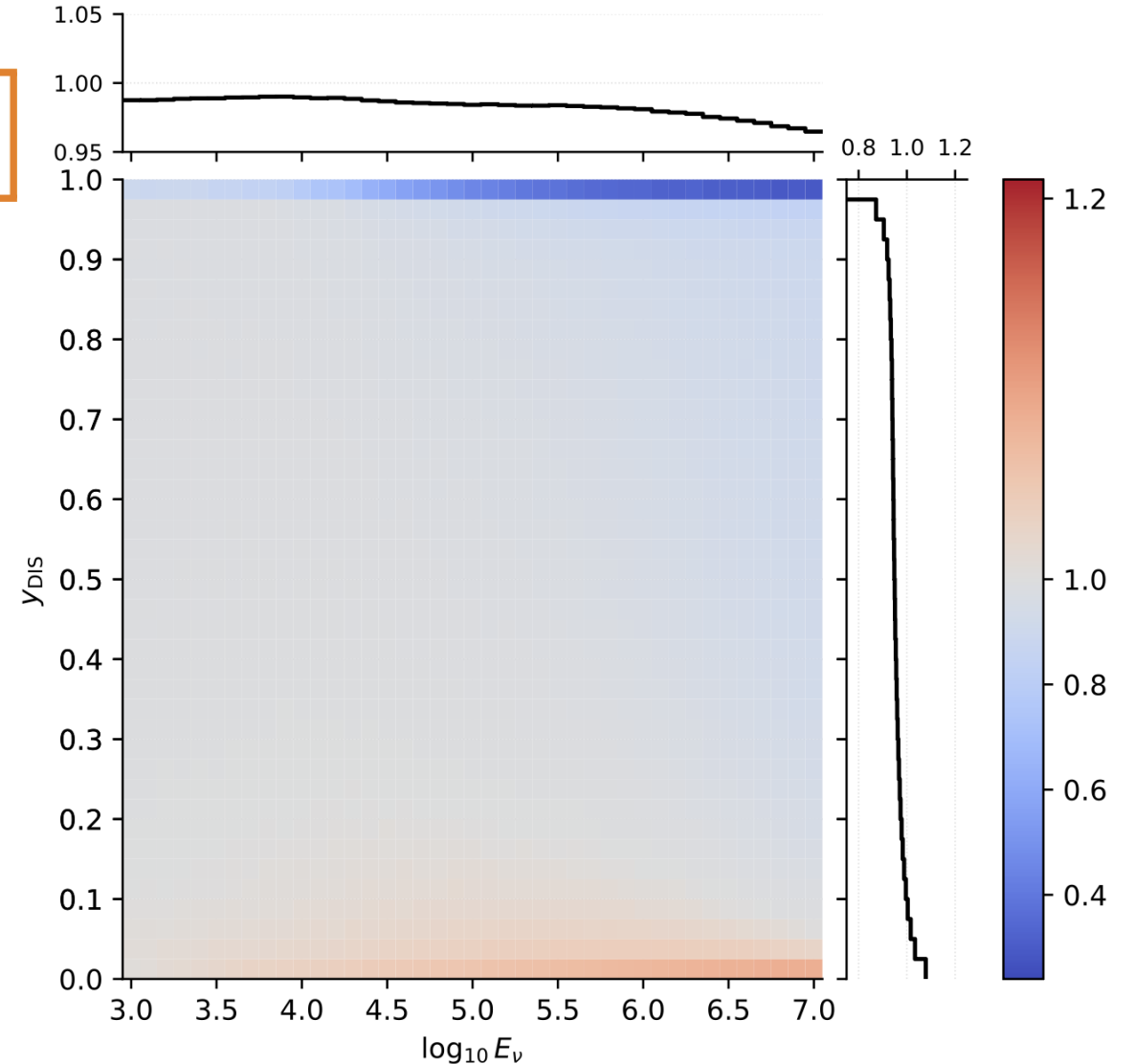
COMPARISON FOR DISCRETIZED GRIDS



$$\left(\frac{d^2\sigma}{d \log_{10} E_\nu dy} \right)_{\text{NLO QCD} + \text{PS}} / \left(\frac{d^2\sigma}{d \log_{10} E_\nu dy} \right)_{\text{NLO QCD+EW} + \text{FSR}}$$

⇒ Collinear **FSR** and **photon-induced** contribution relevant for $E_\nu \gtrsim 10^4 - 10^5$ GeV.

⇒ Missing **top-quark mass** contribution in the **POWHEG** generator relevant for $E_\nu \gtrsim 10^6$ GeV.



DOUBLE-DIFFERENTIAL GRIDS

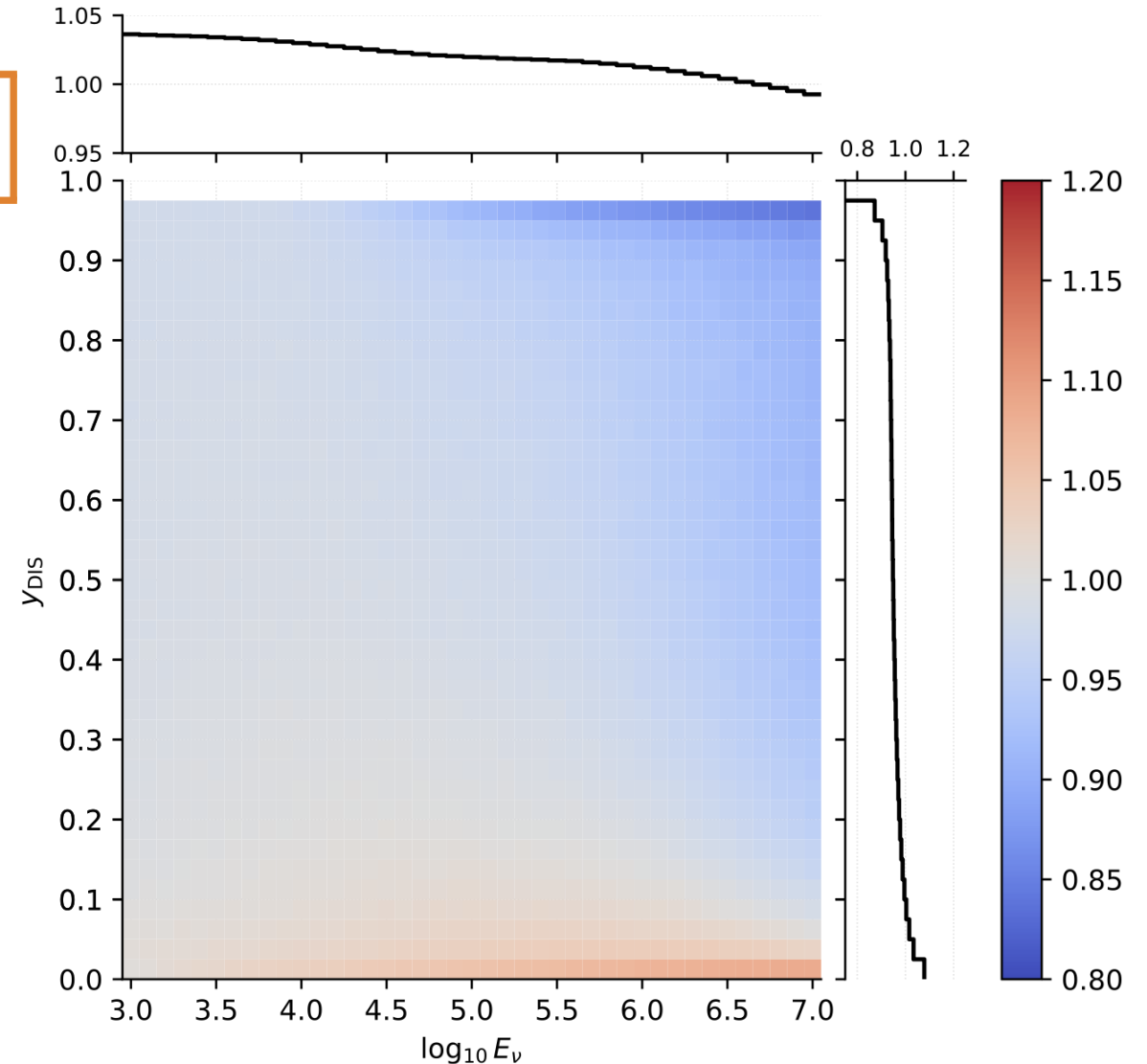
COMPARISON FOR DISCRETIZED GRIDS



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CONCLUSIONS

SUMMARY



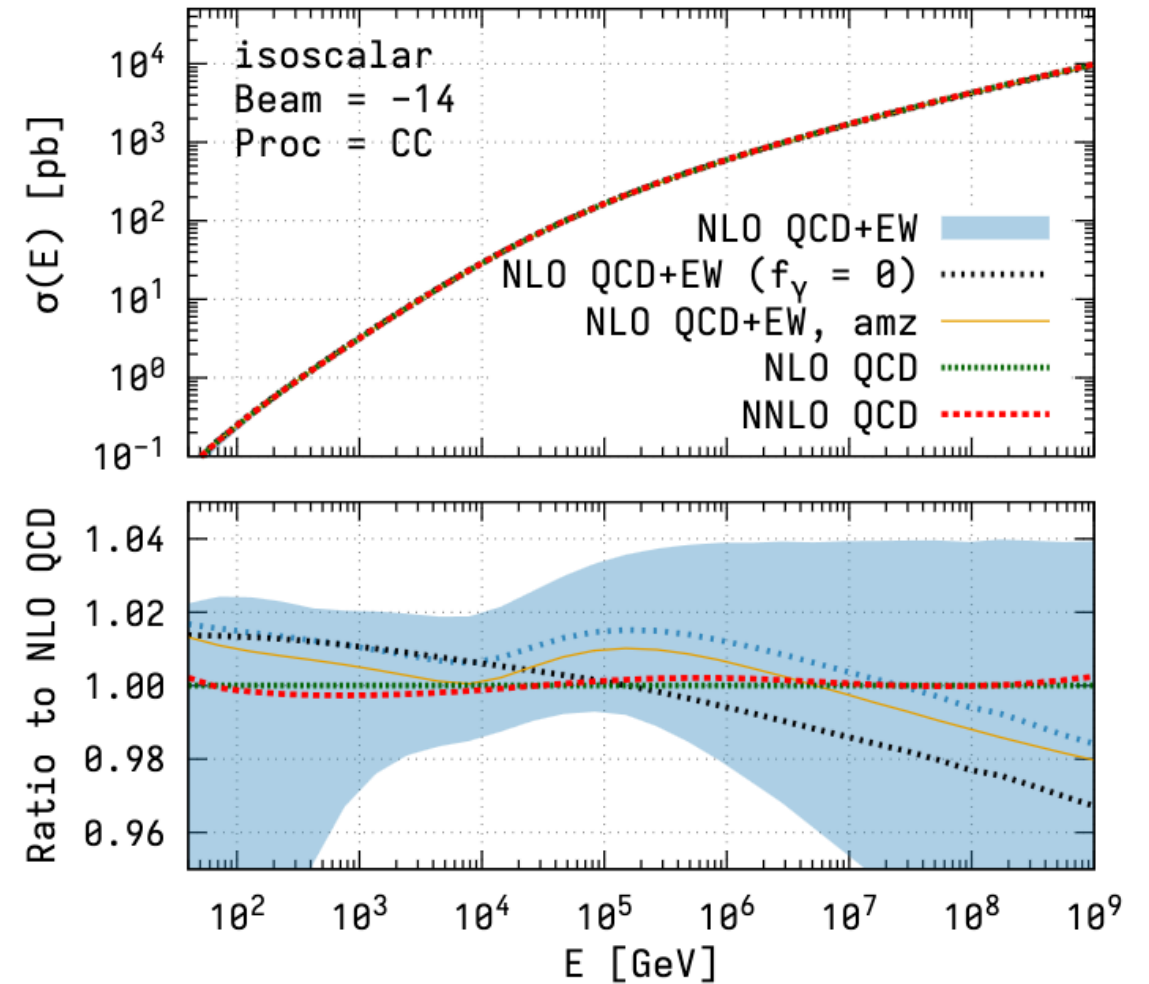
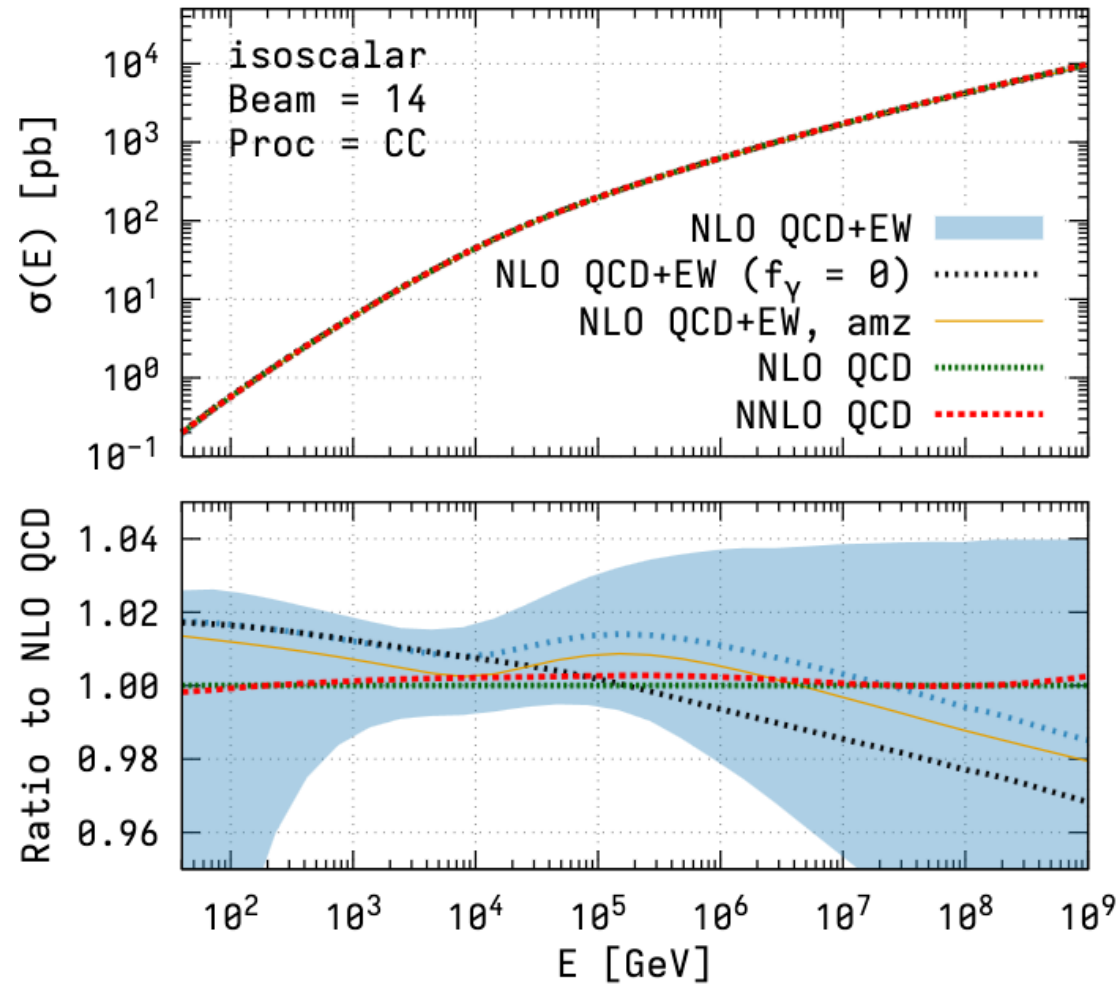
- ⇒ **Percent-level precision** possible only by accounting for **QED effects** and their impact on experimental signatures.
- ⇒ Dedicated **MC event generator** for fully differential DIS calculations including **NLO QCD+EW** and **higher-order effects** via a fragmentation function approach, together with **subleading processes**.
- ⇒ **Fully exclusive event simulation** for neutrino-DIS with **POWHEG-BOX-RES** generator. Matching to **parton shower** only recommended at **fixed neutrino energy**.
- ⇒ Possibility to **improve event generation** with **existing tools** (e.g. on-shell W-boson production, top contributions).



THANK YOU FOR THE ATTENTION!

IMPACT OF RADIATIVE CORRECTIONS

CROSS-SECTION LEVEL



LEPTON FRAGMENTATION APPROACH

FRAGMENTATION FUNCTION



⇒ Solving **DGLAP equation** by iterations: [**Full expressions:** *Arbuzov, Melnikov* [0205172](#)]

$$\mathcal{D}_1(x, \mu_F, m_l) = \delta(1-x) + \frac{\alpha}{2\pi} \left(L P_{ll}^{(0)}(x) + d_1(x, \mu_0, m_l) \right) + \left(\frac{\alpha}{2\pi} \right)^2 \left\{ L^2 \left[\frac{1}{2} P_{ll}^{(0)} \otimes P_{ll}^{(0)}(x) + \frac{1}{3} P_{ll}^{(0)}(x) + \frac{1}{2} P_{\gamma l}^{(0)} \otimes P_{l\gamma}^{(0)}(x) \right] + L \left[P_{ll}^{(0)} \otimes d_1(x) + P_{ll}^{(1)}(x) \right] \right\} + \mathcal{O}(\alpha^2 L^0, \alpha^3)$$

where $L \equiv \ln(\mu_0^2/m_l^2)$ is the mass logarithm.

⇒ The **decoupling term** $d_1(x, m_l, m_l)$ introduces a **negative correction** at **NLL**:

$$d_1(x, \mu_0 = m_l, m_l) = - \left[\frac{1+x^2}{1-x} (2 \ln(1-x) + 1) \right]_+$$

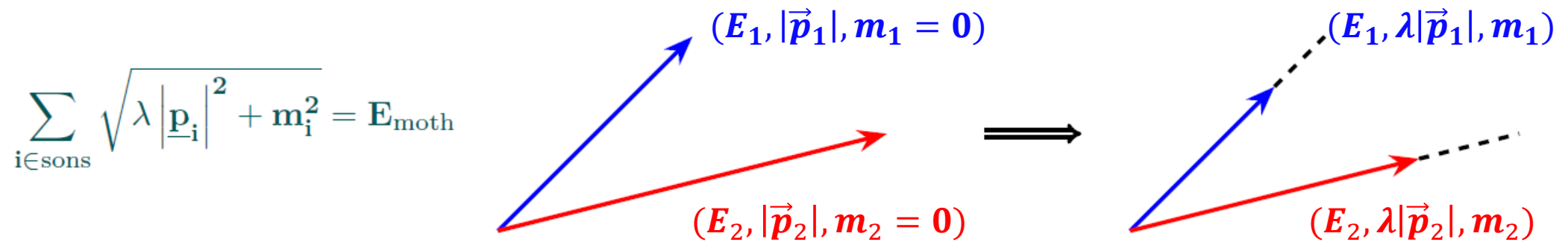
⇒ The $\mathcal{O}(\alpha^2 L)$ term $P_{\gamma l}^{(0)} \otimes P_{l\gamma}^{(0)}(x)$ introduces a **divergent behaviour** at $\mathcal{O}(\alpha^2)$:

$$P_{\gamma l}^{(0)} \otimes P_{l\gamma}^{(0)}(x) = \frac{1-x}{3x} (4 + 7x + 4x^2) + 2(1+x) \ln x$$



⇒ Generation of events with **massless particles** at **LO** and **NLO QCD**. A **reshuffling** procedure gives mass to particles before matching.

⇒ Standard reshuffling procedure **scales the spatial momenta** to give particles their mass keeping the **directions** and the **vertex total energy** unchanged.





⇒ The **default reshuffling** procedure changes the **DIS kinematic distributions** by altering the **final lepton kinematics**!

⇒ **New reshuffling** to keep the **massless prediction** for our observables **untouched**:

Before resh. $\bar{s} = \frac{Q^2}{x_{Bjk} y_{DIS}}, \quad \bar{\xi}_k = 1 - y_{DIS}(1 - x_{Bjk}), \quad \bar{y}_k = \frac{1 - y_{DIS}(1 + x_{Bjk})}{1 - y_{DIS}(1 - x_{Bjk})}$



After resh. $s = \bar{s}, \quad \xi_k = \bar{\xi}_k + \frac{m_l^2}{\bar{s}}, \quad y_k = \frac{-m_l^2 + \bar{s}\bar{\xi}_k\bar{y}_k}{\sqrt{(m_l^2 + \bar{s}\bar{\xi}_k)^2 - 4m_l^2\bar{s}}}$

⇒ This affects DIS kinematic distributions for **neutrino energies** up to $\sim 10^3 - 10^5 \text{ GeV}$

DOUBLE-DIFFERENTIAL GRIDS

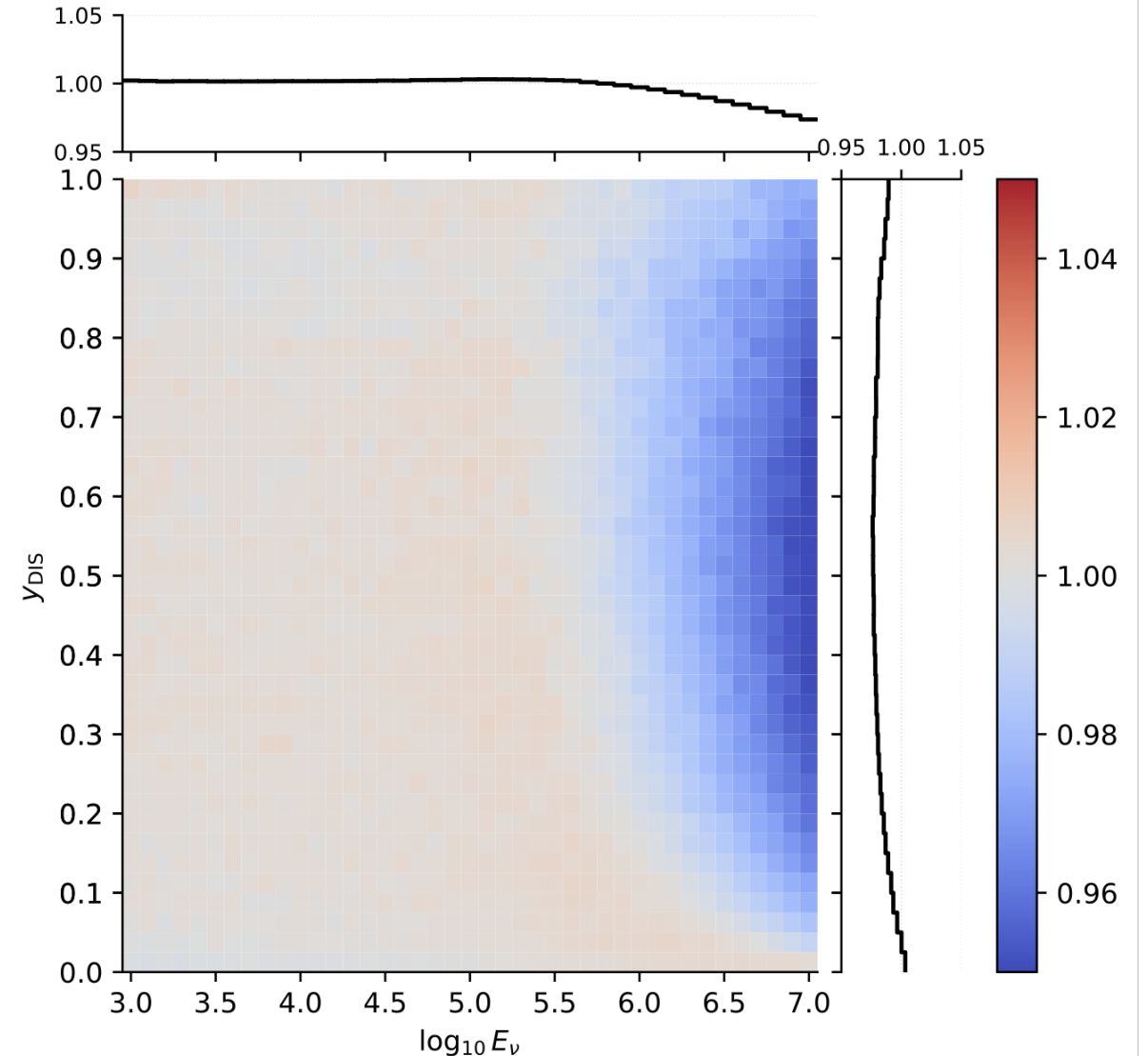
COMPARISON AT FIXED-ORDER



$$\left(\frac{d^2\sigma}{d \log_{10} E_\nu dy} \right)_{\text{NLO QCD PWG}} / \left(\frac{d^2\sigma}{d \log_{10} E_\nu dy} \right)_{\text{NLO QCD}}$$

⇒ **POWHEG** generator treats **massless** particles.

⇒ Missing **top-quark mass** contributions relevant for **high-**
and **ultra-high-energy neutrinos**.



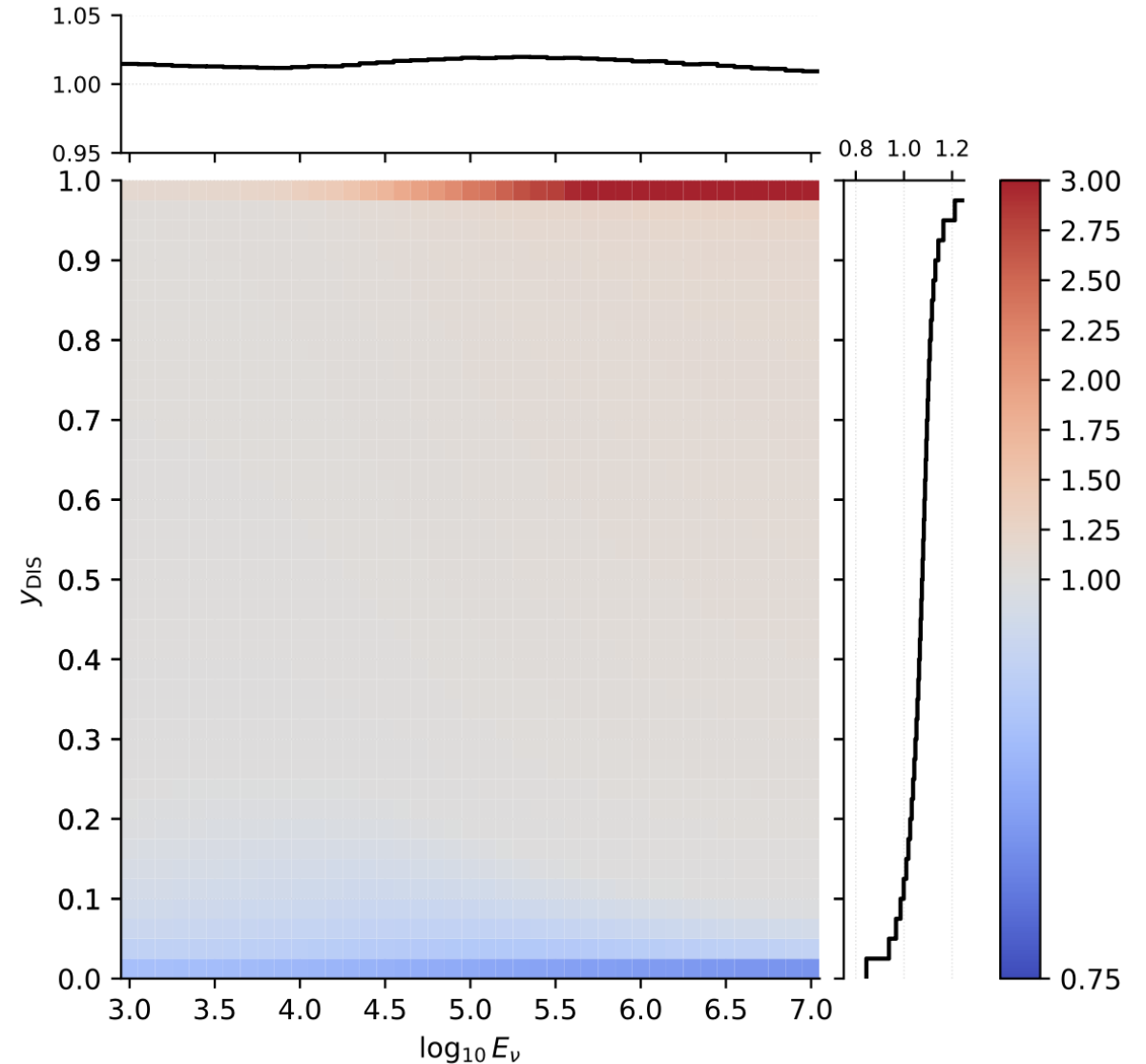
DOUBLE-DIFFERENTIAL GRIDS

IMPACT OF RADIATIVE CORRECTIONS



$$\left(\frac{d^2\sigma}{d \log_{10} E_\nu dy} \right)_{\text{NLO QCD+EW} + \text{FSR}} / \left(\frac{d^2\sigma}{d \log_{10} E_\nu dy} \right)_{\text{NLO QCD}}$$

⇒ Impact of **NLO QCD+EW** and **FSR** corrections.



DOUBLE-DIFFERENTIAL GRIDS

IMPACT OF RADIATIVE CORRECTIONS



$$\left(\frac{d^2\sigma}{d \log_{10} E_\nu dy} \right)_{\text{NLO QCD+EW} + \text{FSR}} / \left(\frac{d^2\sigma}{d \log_{10} E_\nu dy} \right)_{\text{NLO QCD}}$$

⇒ Impact of **NLO QCD+EW** and **FSR** corrections.

⇒ Last bin in **inelasticity** omitted for visualization purposes.

