Neutrino scattering at multi-TeV and PeV energies

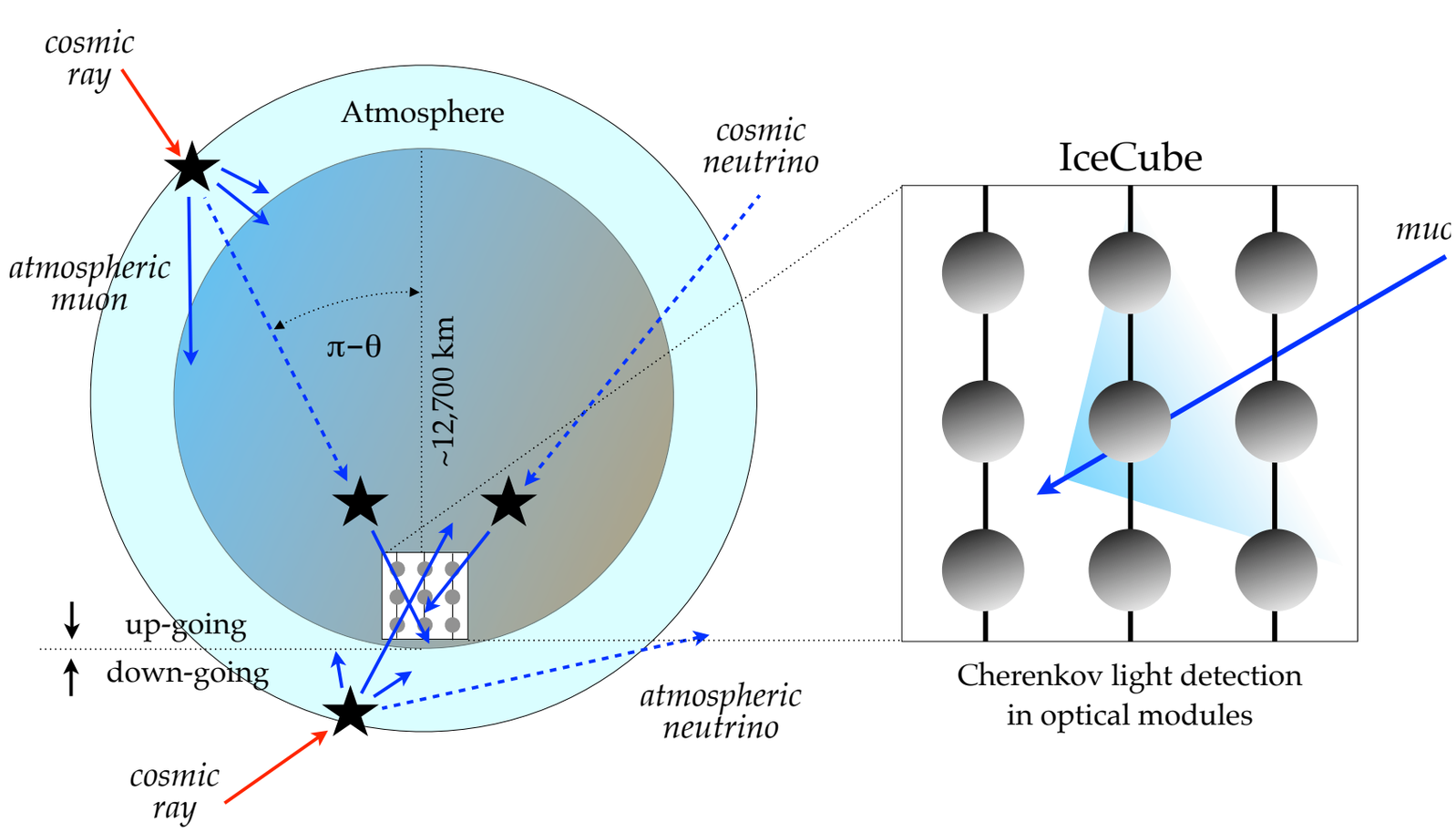
Rhorry Gauld

Heavy-Quark Hadroproduction from Collider to Astroparticle Physics

03/10/2019

NWO | Netherlands Organisation for Scientific Research

Nikhef

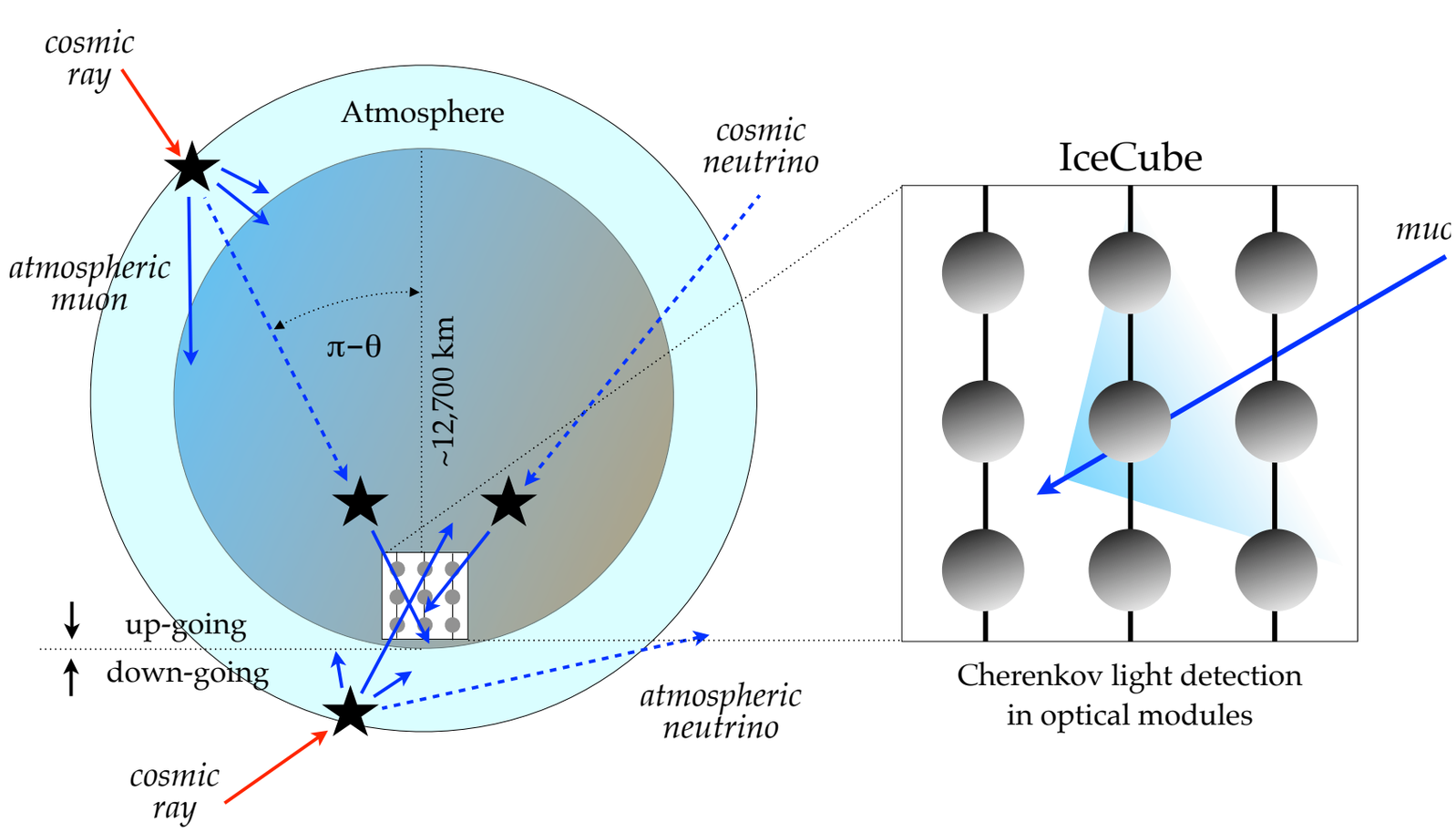


time exposure effective volume cross-section neutrino flux

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

This workshop:

$$\Phi_\nu^{\mathrm{Prompt}}(E_\nu) = \Phi_{\mathrm{N_{cr}}} \otimes \sigma \left[\mathrm{N_{cr}A} \xrightarrow[Q+X]{} \nu + X'\right](E_\nu)$$



time exposure effective volume cross-section neutrino flux

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

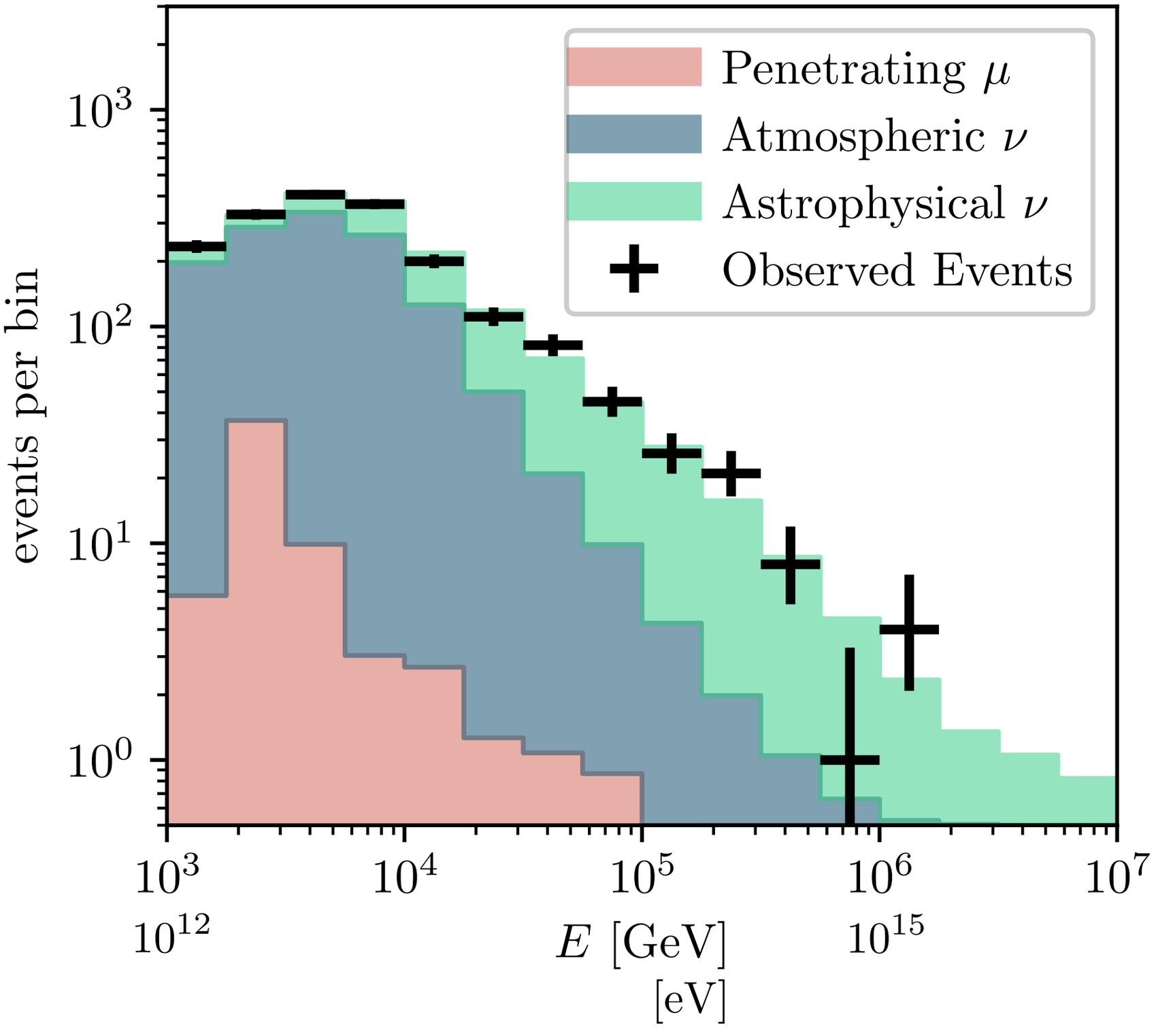
This talk:

$$\sigma_{\nu i}\left(E_\nu\right) = \sigma_{\nu N}\left(E_\nu\right) + \sigma_{\bar{\nu}+e^-}\left(E_{\bar{\nu}}\right)$$

nucleon target electron target

Sources of multi-TeV and PeV neutrinos

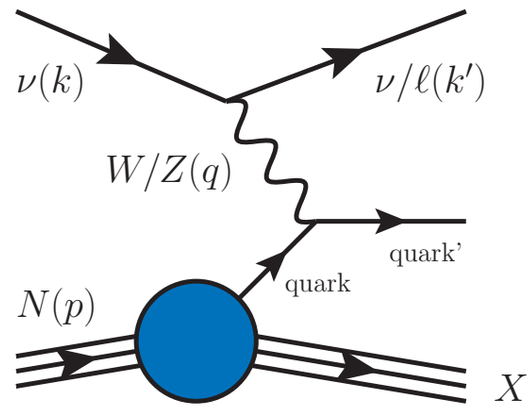
IceCube, arXiv: 1907.06714 (cascade events)



Layout of talk

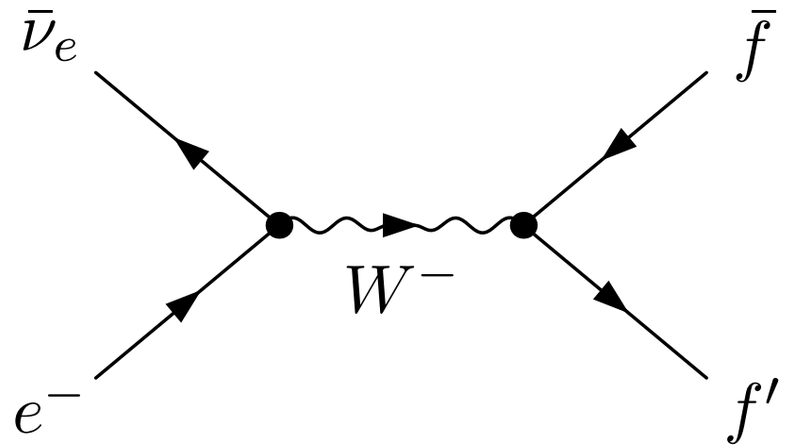
Neutrino scattering upon nucleons

- CC and NC Deep Inelastic Scattering
- Resonant contributions within photon field

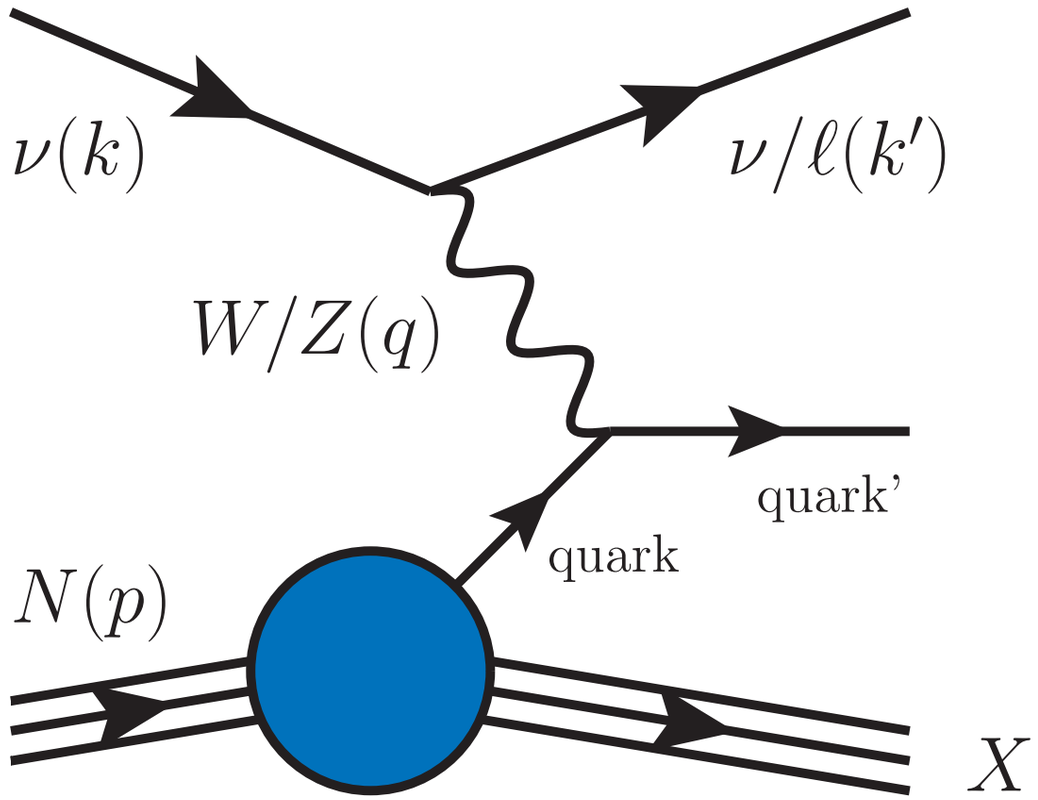


Neutrino scattering upon electrons

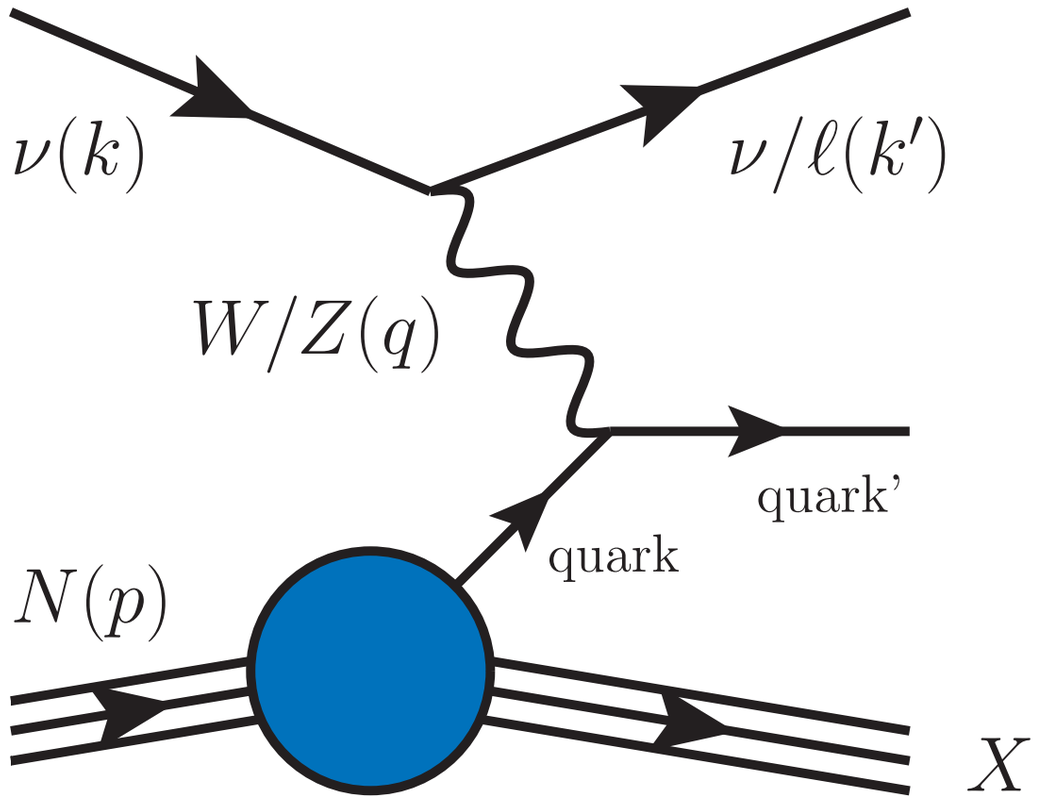
- Introduction to the Glashow resonance
- Theoretical progress
- Experimental prospects



Neutrino-nucleon Deep Inelastic Scattering



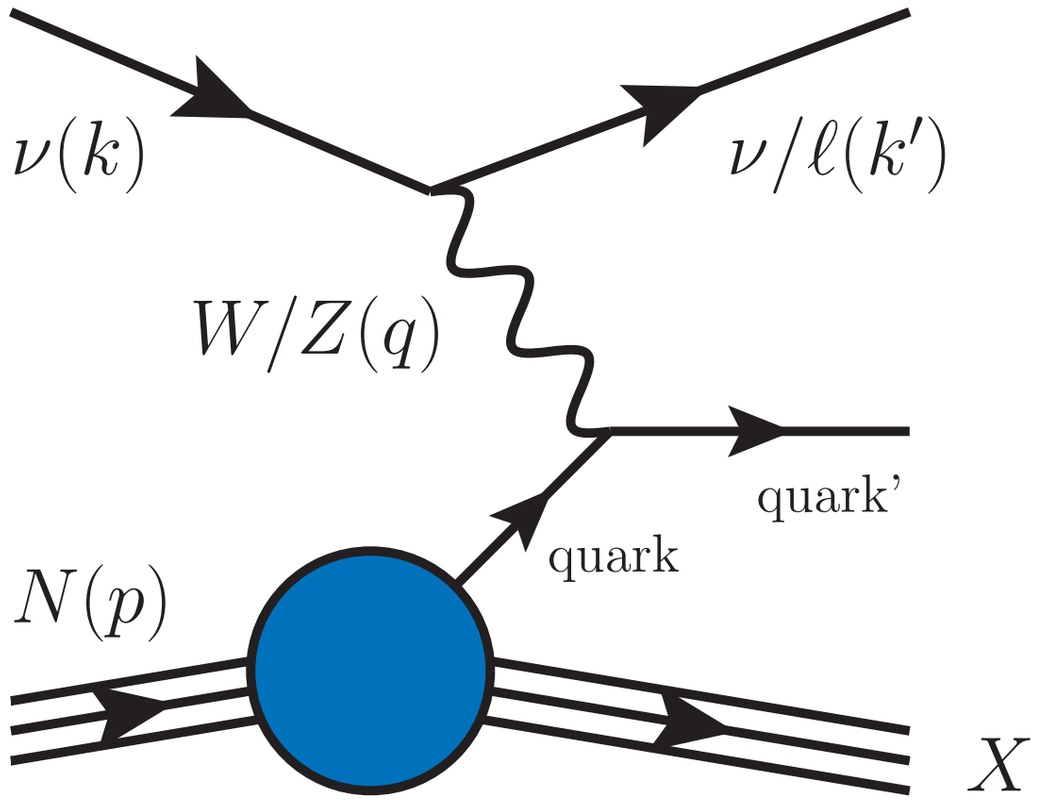
Neutrino-nucleon Deep Inelastic Scattering



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

Total CoM Energy

Neutrino-nucleon Deep Inelastic Scattering



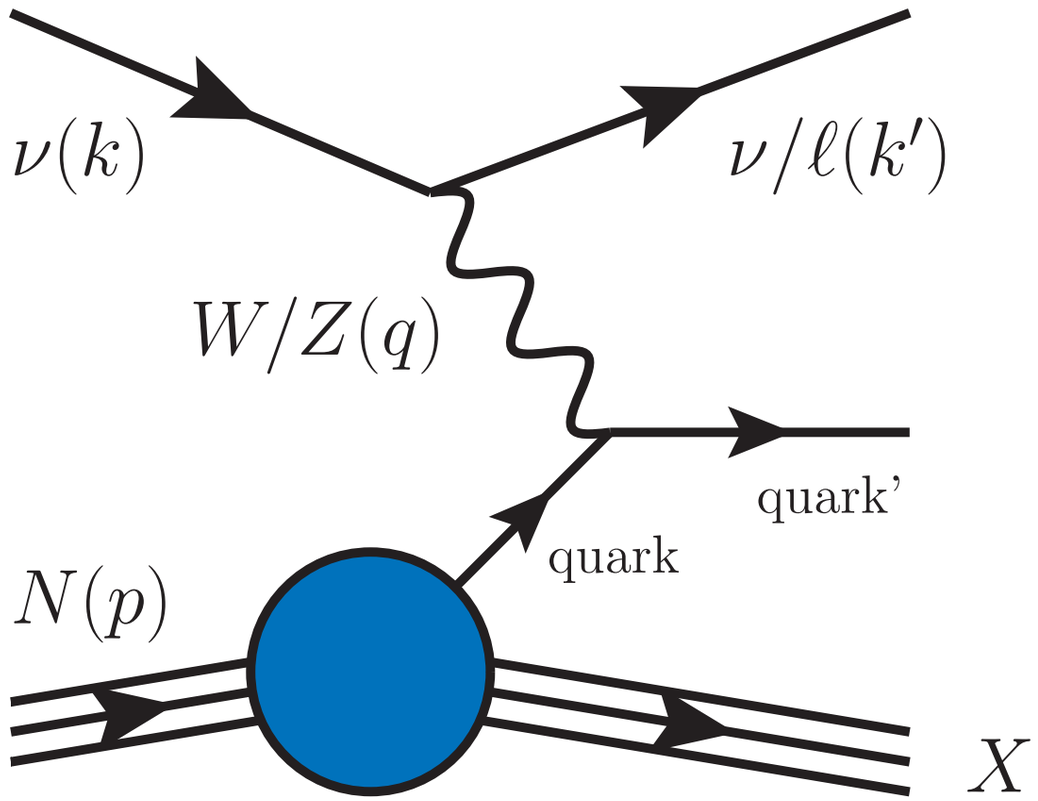
$$s = (k+p)^2 = m_N^2 + 2m_N E_\nu$$

Total CoM Energy

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

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

Neutrino-nucleon Deep Inelastic Scattering



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

Total CoM Energy

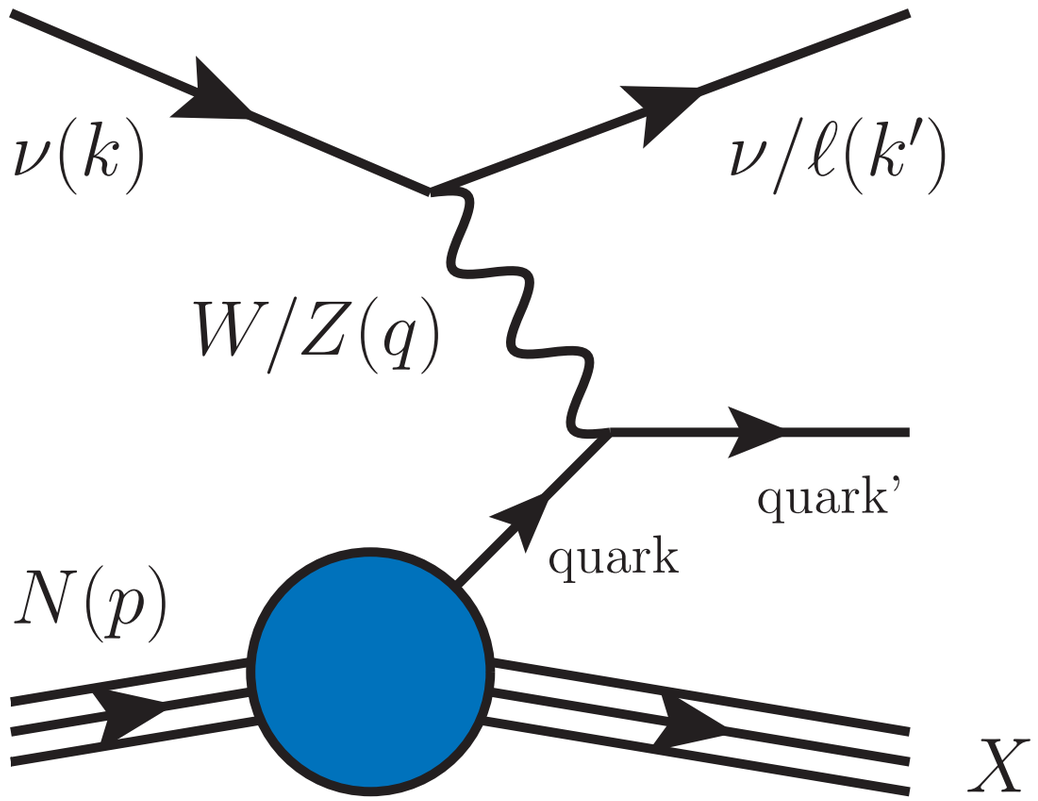
$$Q^2 = -q^2 = -(k-k')^2$$

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

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

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

Neutrino-nucleon Deep Inelastic Scattering



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

Total CoM Energy

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

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

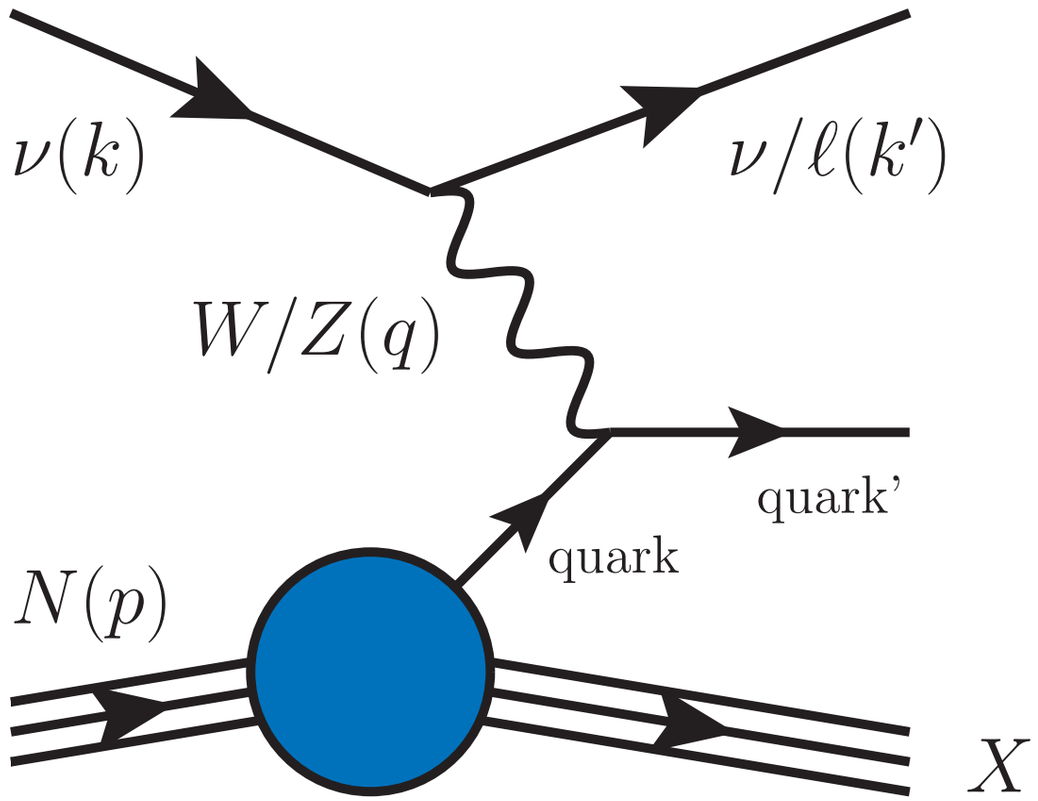
$$y = \frac{q \cdot p}{k \cdot p} = 1 - \frac{E'}{E_\nu}$$

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

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

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

Neutrino-nucleon Deep Inelastic Scattering



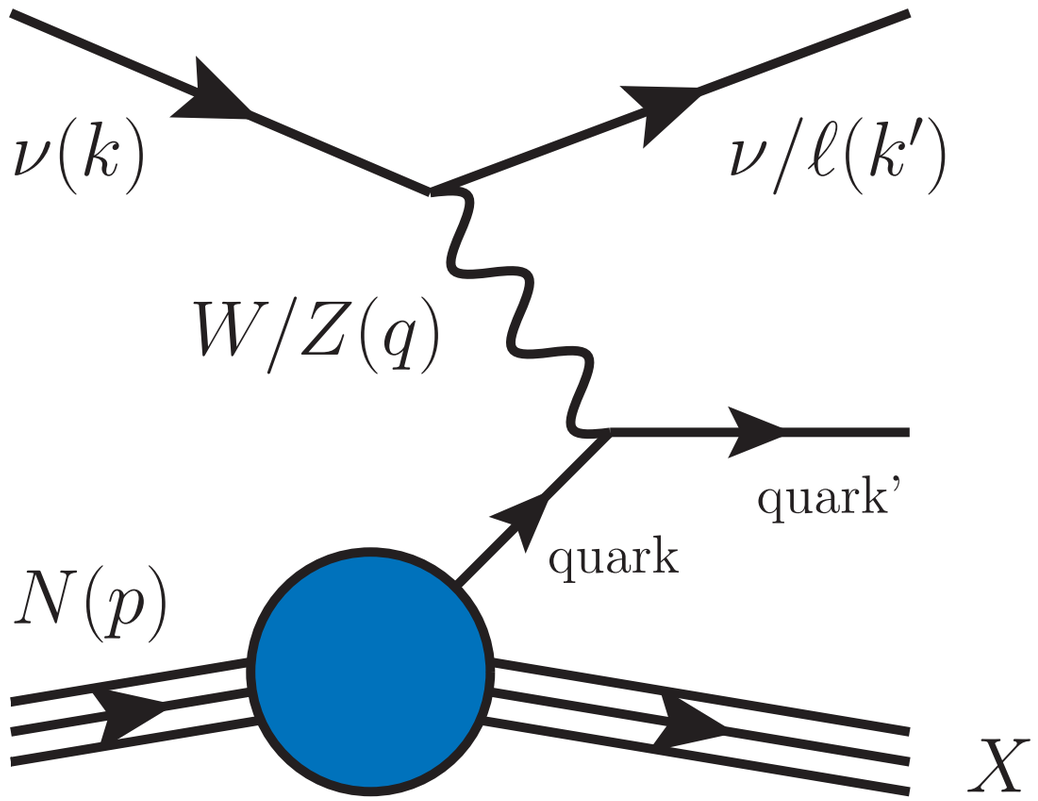
$$\frac{\mathrm{d}^2\sigma^{\mathrm{CC}}_{\nu(\bar{\nu})N}(x,Q^2,E_\nu)}{\mathrm{d}x\,\mathrm{d}Q^2} = \frac{G_F^2 M_W^4}{4\pi x(Q^2+M_W^2)^2}\left(Y_+ F_{2,\mathrm{CC}}^{\nu(\bar{\nu})N}(x,Q^2) \mp Y_- x F_{3,\mathrm{CC}}^{\nu(\bar{\nu})N}(x,Q^2) - y^2 F_{L,\mathrm{CC}}^{\nu(\bar{\nu})N}(x,Q^2)\right)$$

Kinematic pre-factor

$F_i(x,Q^2)$ — DIS Structure functions (QCD)

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

Neutrino-nucleon Deep Inelastic Scattering



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

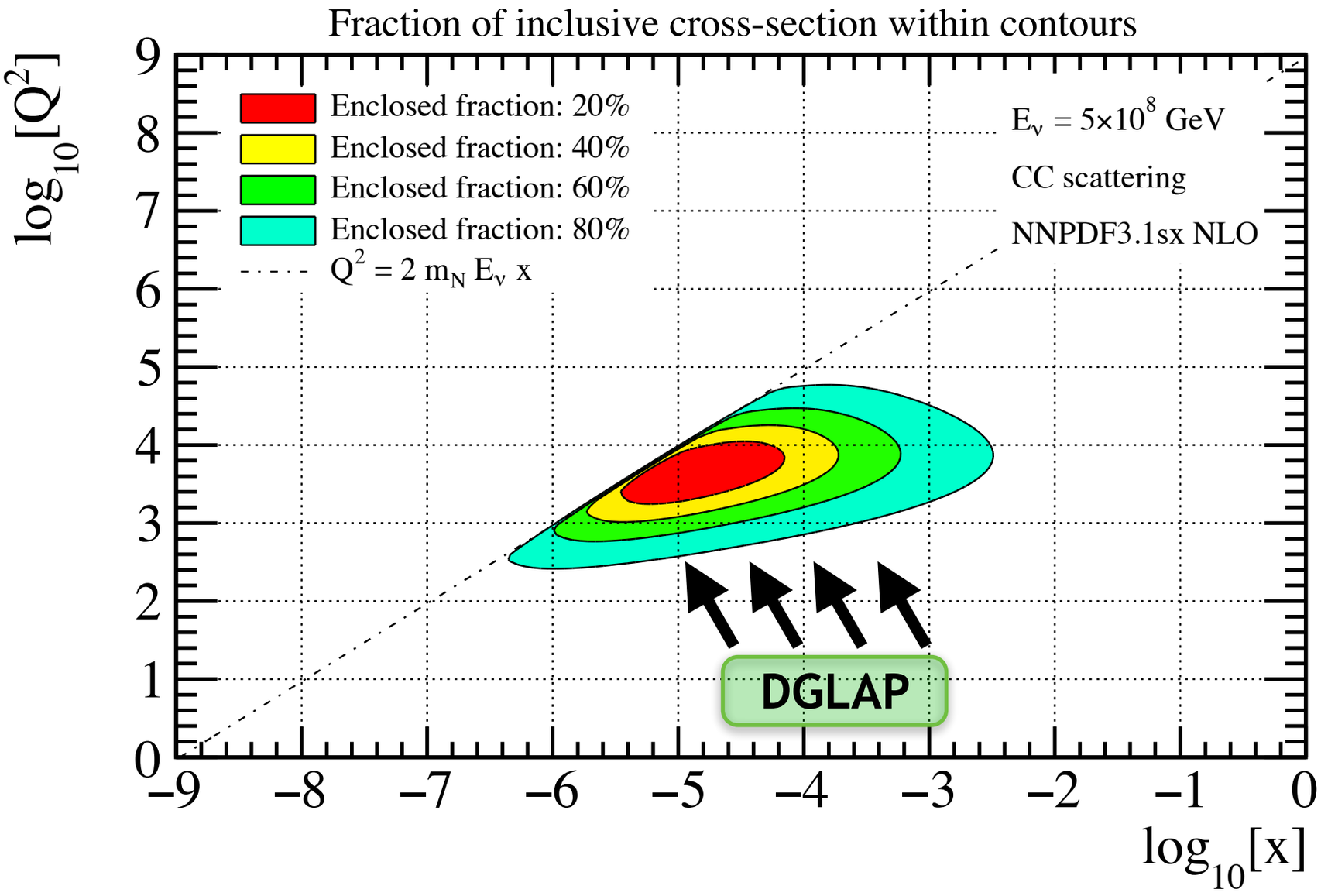
Kinematic pre-factor

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

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

Neutrino-nucleon Deep Inelastic Scattering

Example, 500 PeV neutrino $\left(5 \times 10^8 \text{ GeV}\right)$



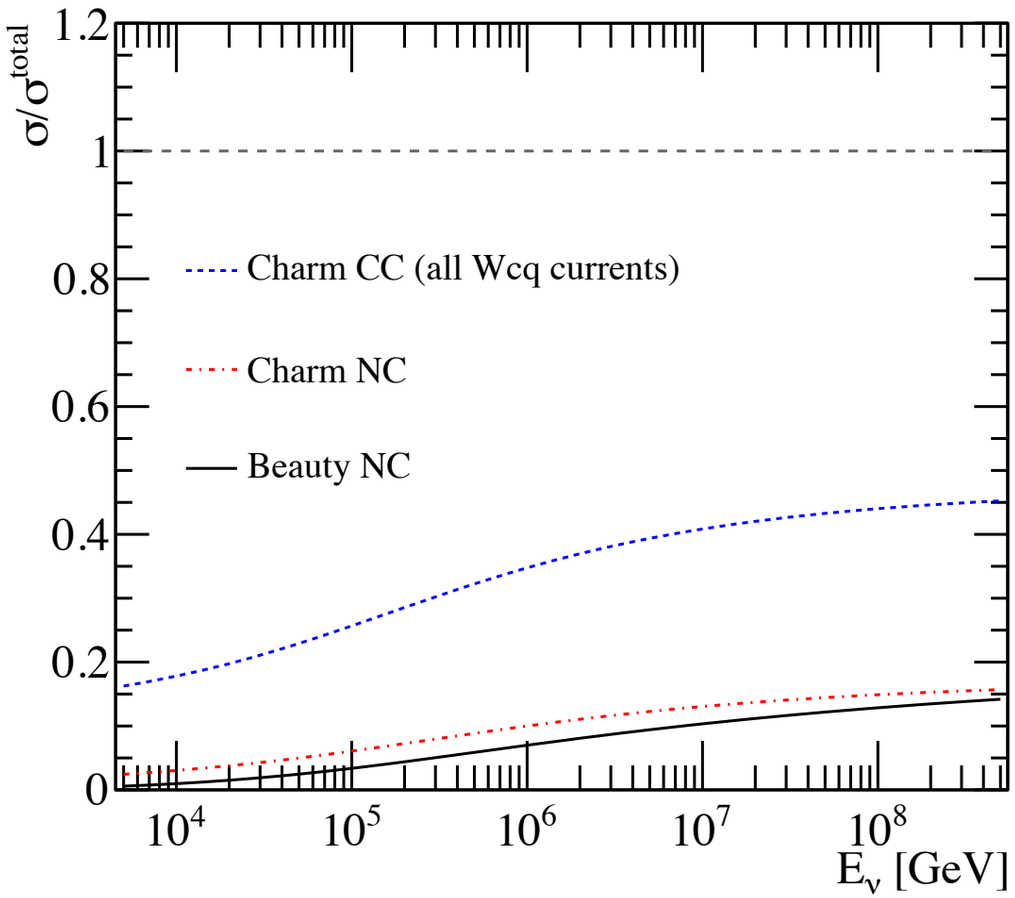
$$\frac{\mathrm{d}^2\sigma^{CC}_{\nu I}}{\mathrm{d}x\,\mathrm{d}Q^2}\left(x, Q^2, E_\nu\right)$$

Note! W/Z bosons set scale

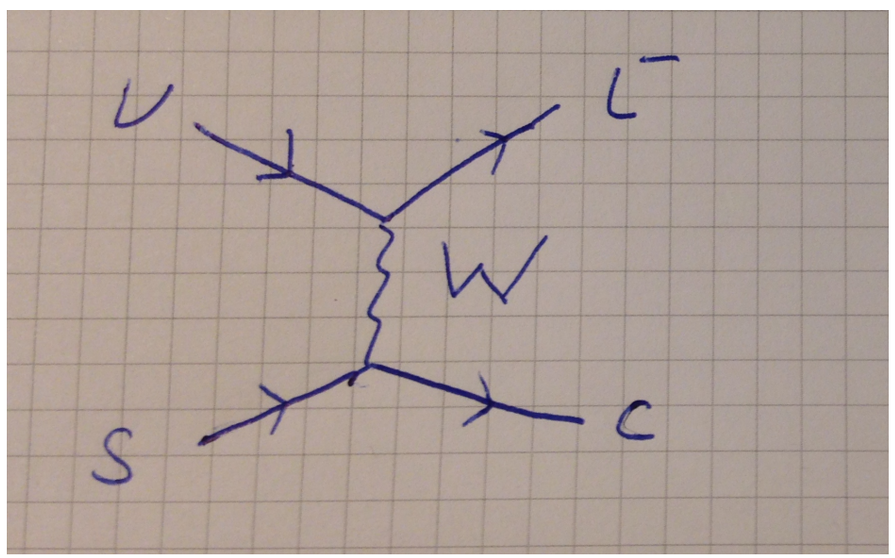
$$\mathrm{d}\sigma \propto \frac{F_i(x, Q^2)}{(Q^2 + M_V^2)^2}$$

Heavy quark contributions

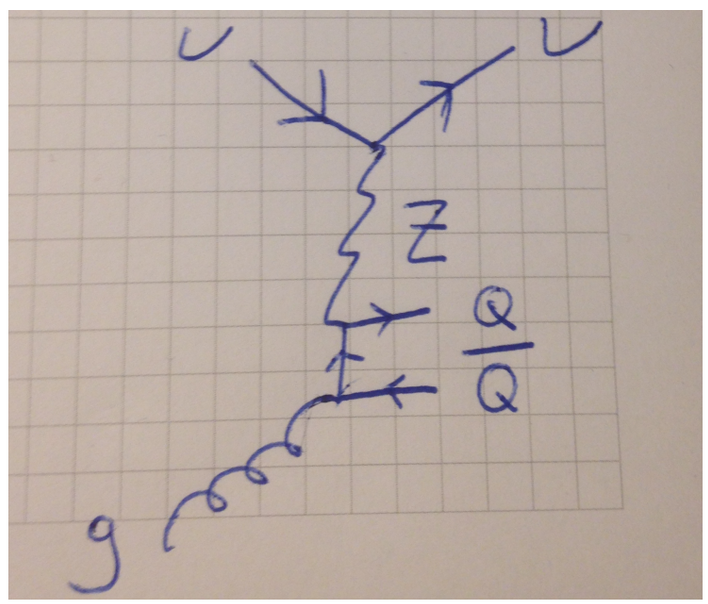
Disclaimer:
Made plot 30min ago



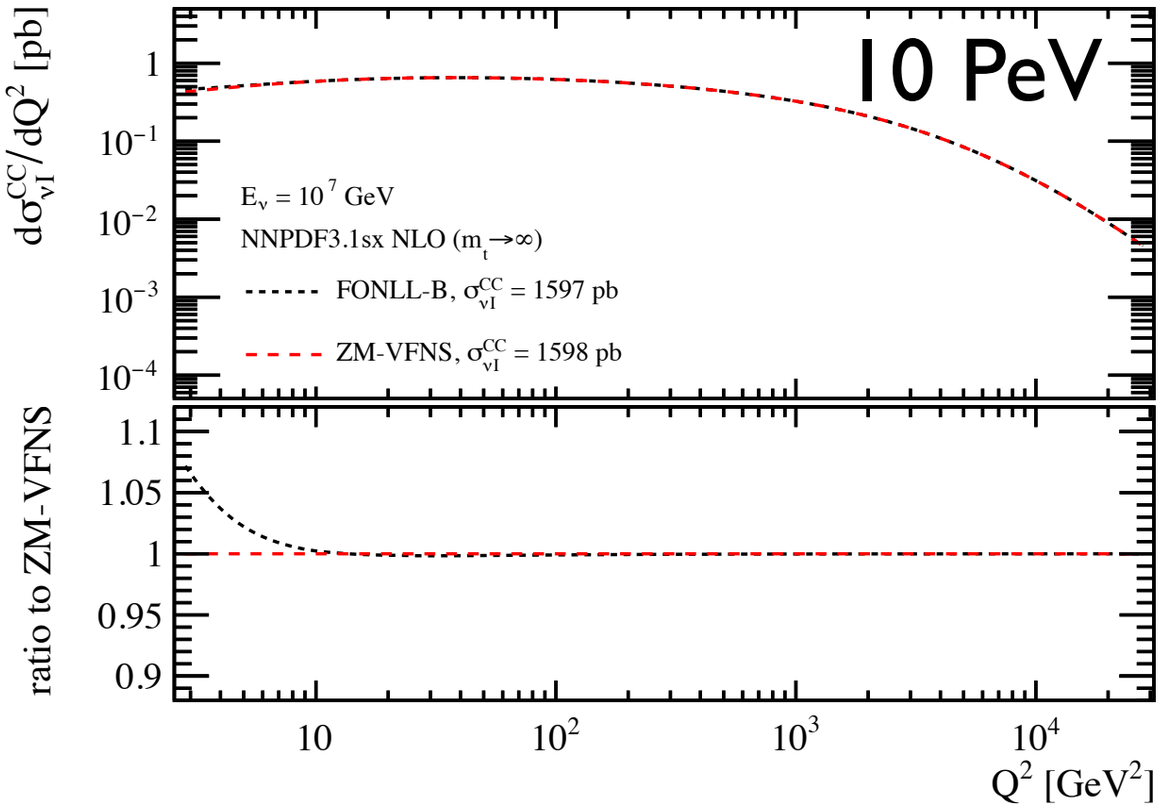
Charged Current

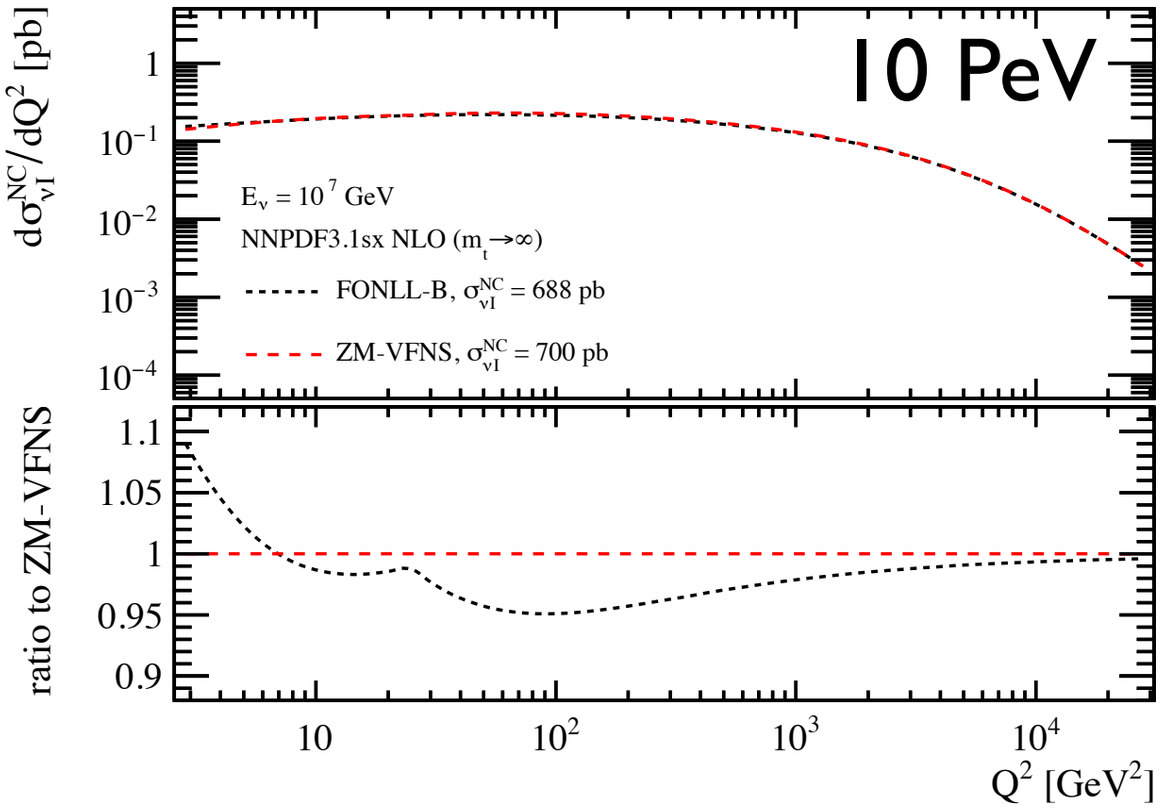


Neutral Current

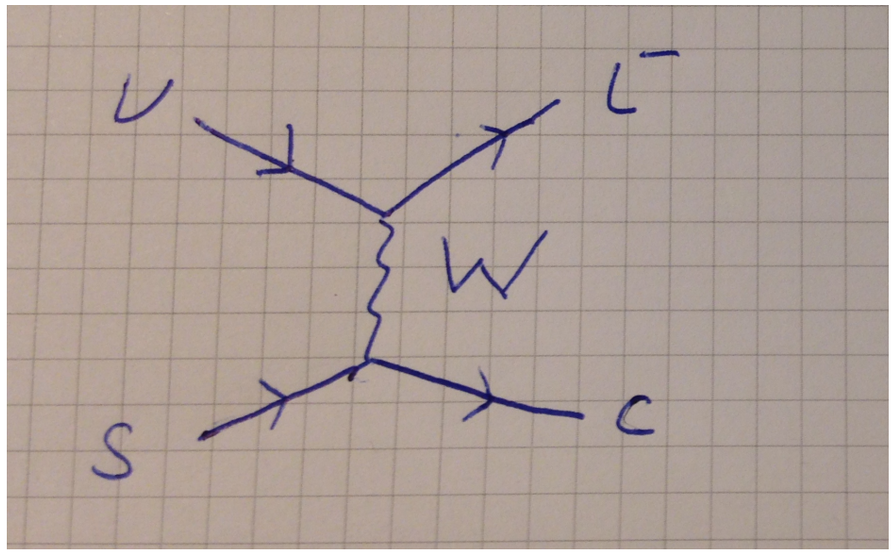


Heavy quark mass effects

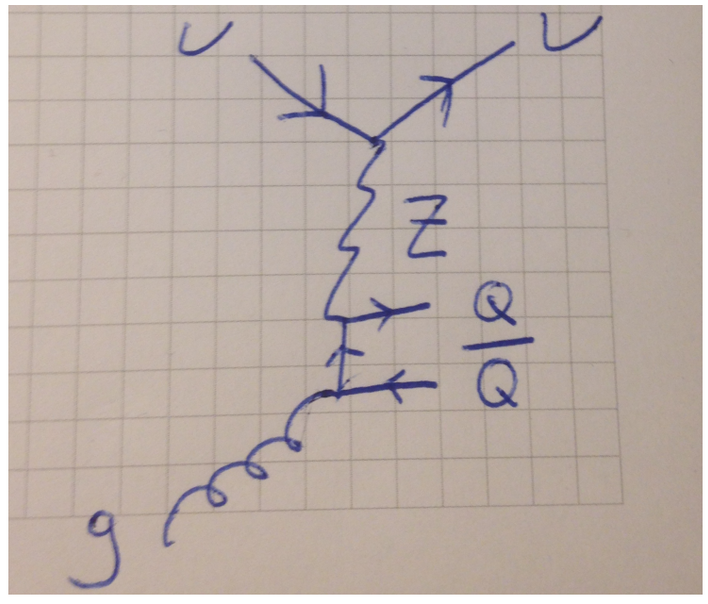




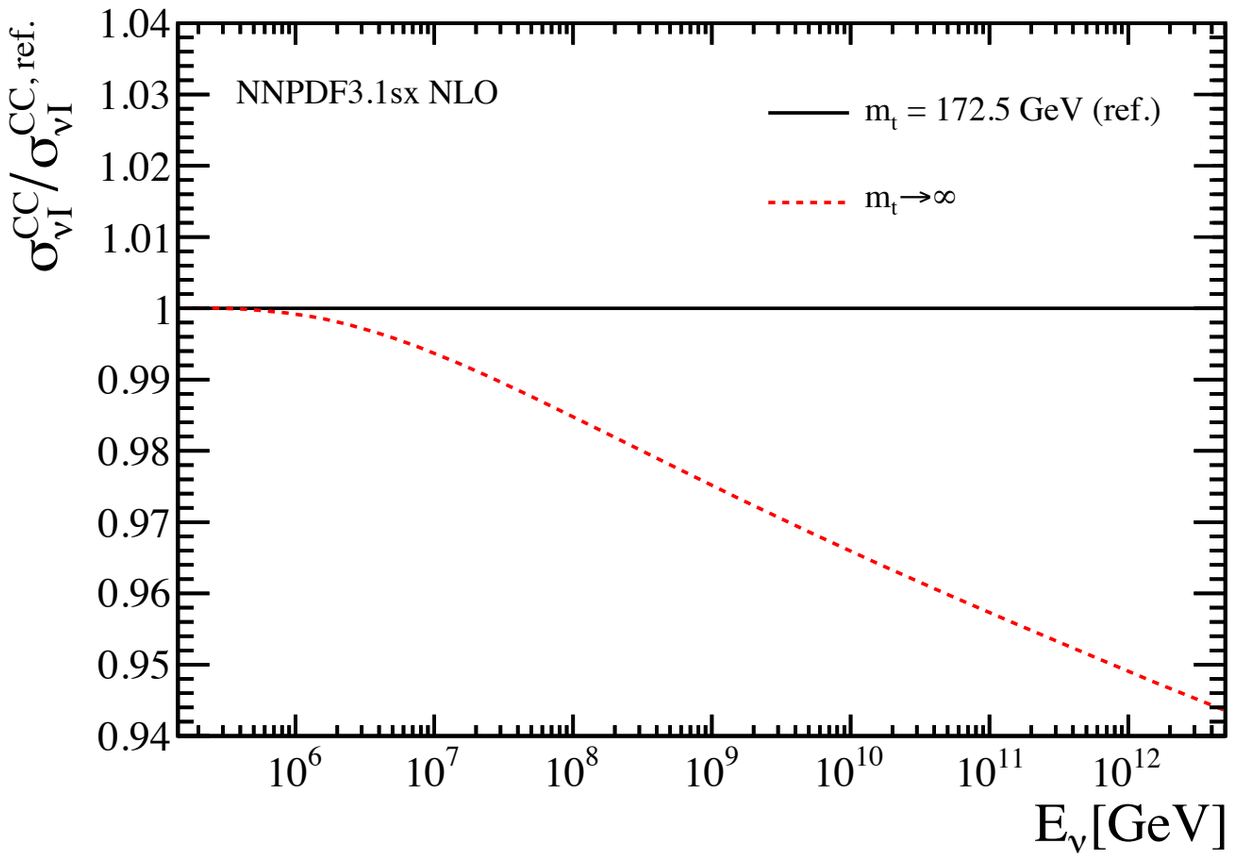
Charged Current

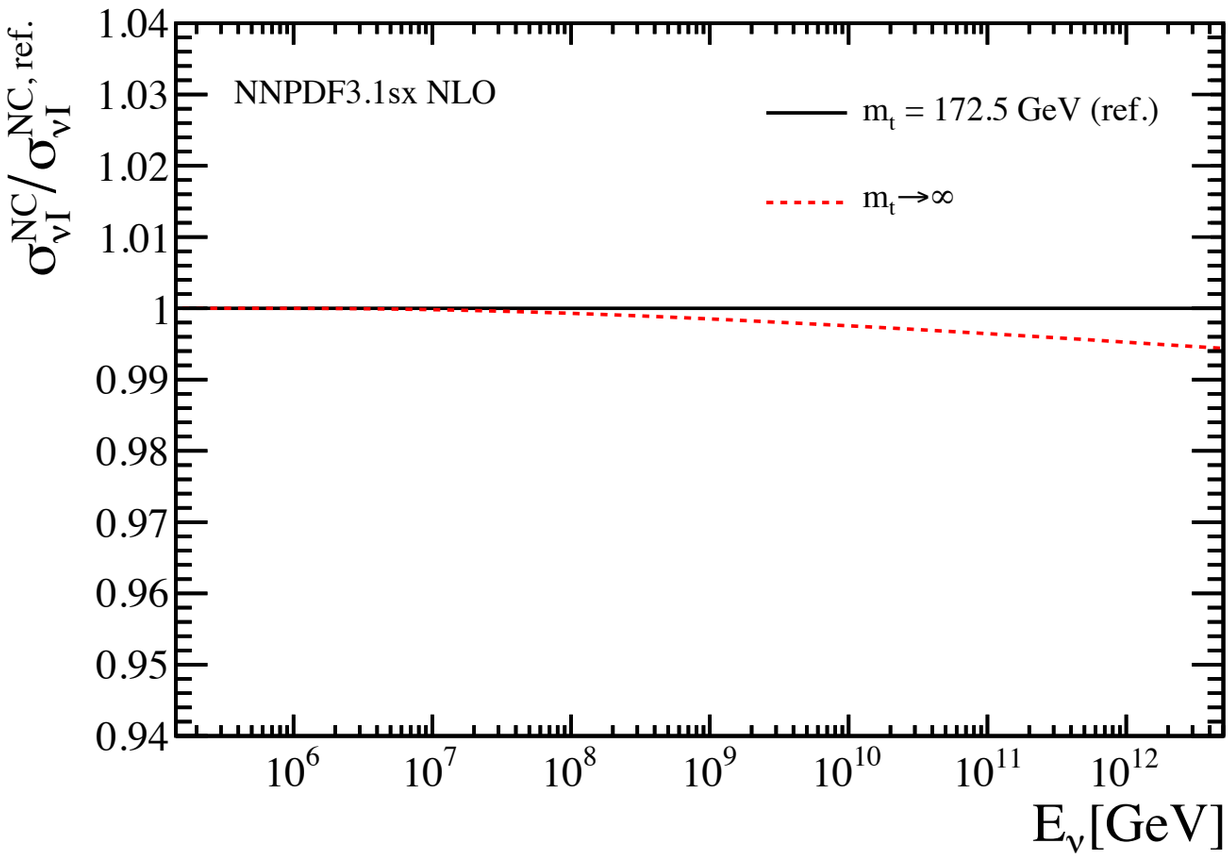


Neutral Current



Heavy quarks (top)





Charged Current

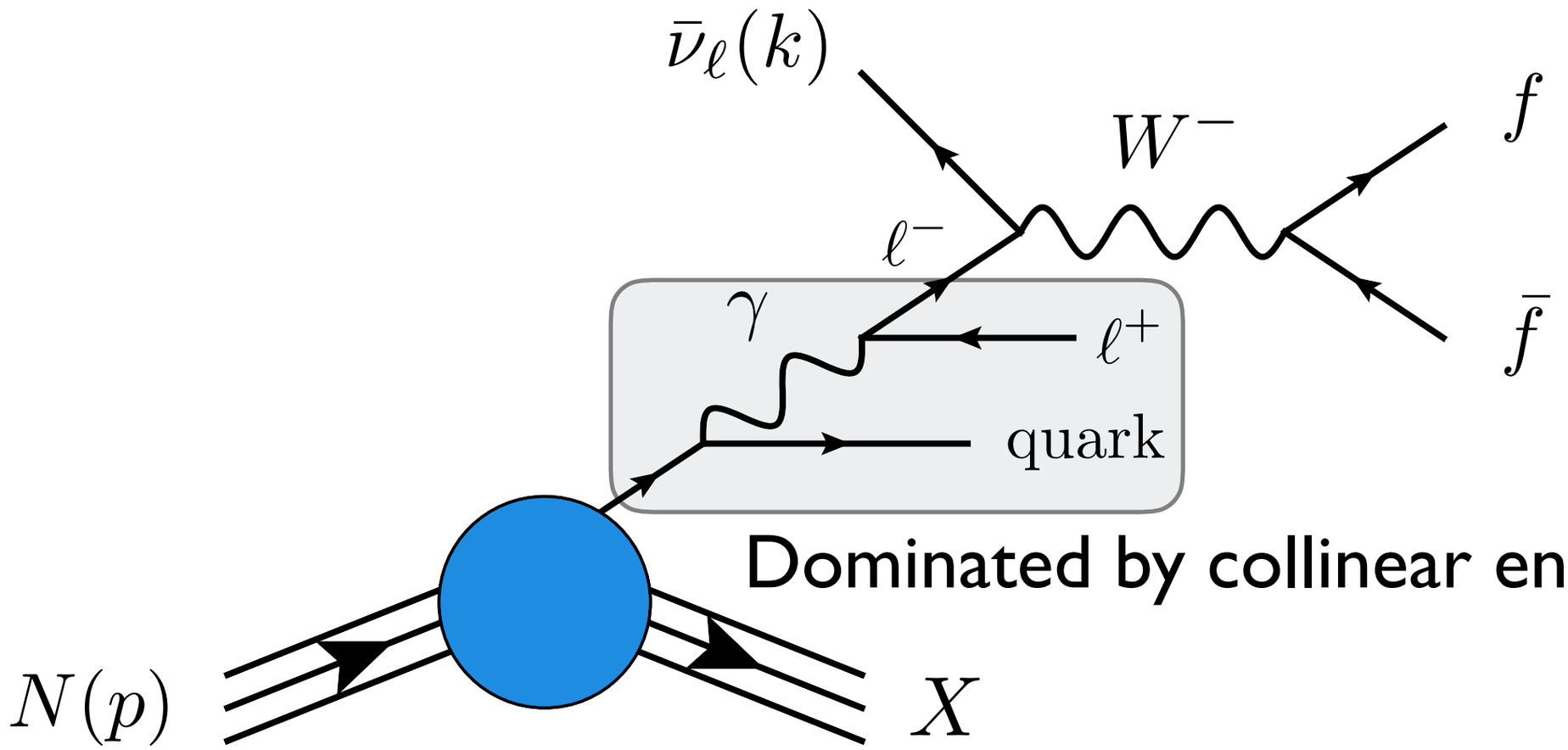
$$W^2 = \frac{Q^2(1-x)}{x} \sim \frac{Q^2}{x} \geq m_t^2$$

Large gluon at low-x, $g \to b\bar{b}$

Neutral Current

$$W^2 \geq 4\, m_t^2$$

Neutrino-nucleon resonant contributions



Dominated by collinear enhancement

Roughly suppressed (relative to CC/NC) by $\alpha^2 Q_q^2 \frac{M_W^2}{\Gamma_W^2} \sim 4\%$

Just fully factorise the QED contributions into PDFs!

$$\int \mathrm{d}x\, f_\ell(x, \mu_F^2)\, \mathrm{d}\hat{\sigma}_{\ell\bar{\nu}\to f\bar{f}'}(\hat{s}, \cos\theta_{\nu f}, \mu_F^2)$$

Theoretical set-up

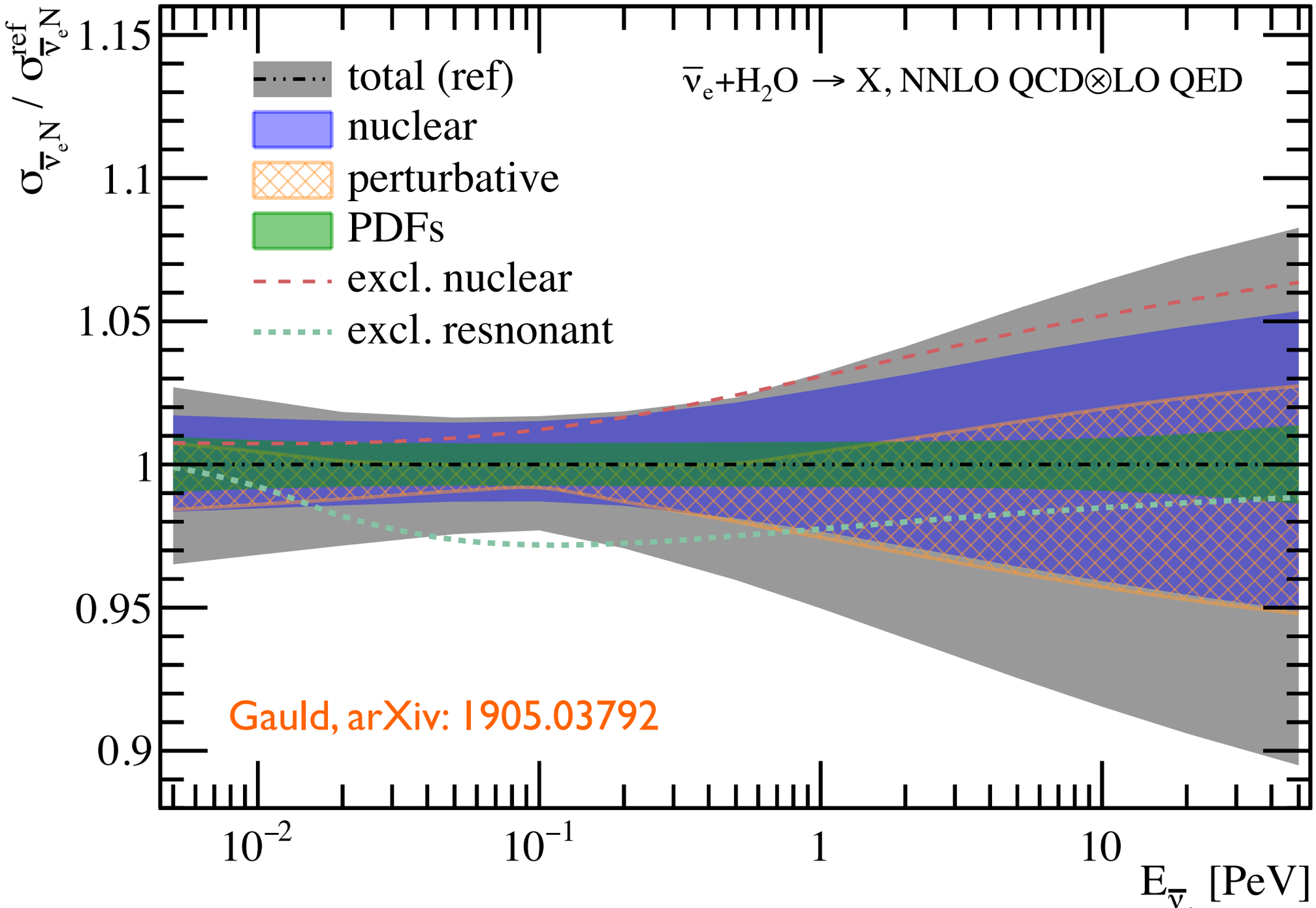
- NNPDF3.1luxQED set as input at Q_0 = 1.64 GeV
  Bertone et al. arXiv:1712.07053
- Generate lepton PDFs according to ansatz:
  Bertone et al. arXiv:1508.07002, arXiv: 1310.1394

$$\ell^{\pm}(x,Q_0) = \frac{\alpha}{4\pi}\ln\left[\frac{Q_0^2}{m_\ell^2}\right]\int_x^1 \frac{\mathrm{d}y}{y} P_{\gamma\ell}^{(0)}\left(\frac{x}{y}\right)\gamma(y,Q_0)$$

- Mass corrections via FONLL (NLO for CC)
- Compute predictions NNLO QCD⊗LO QED
  Gauld, arXiv: 1905.03792, and APFEL - Bertone et al. arXiv: 1310.1394
- Nuclear corrections (e.g. H_2O nucleon)
  Eksola et al. arXiv:1612.05741

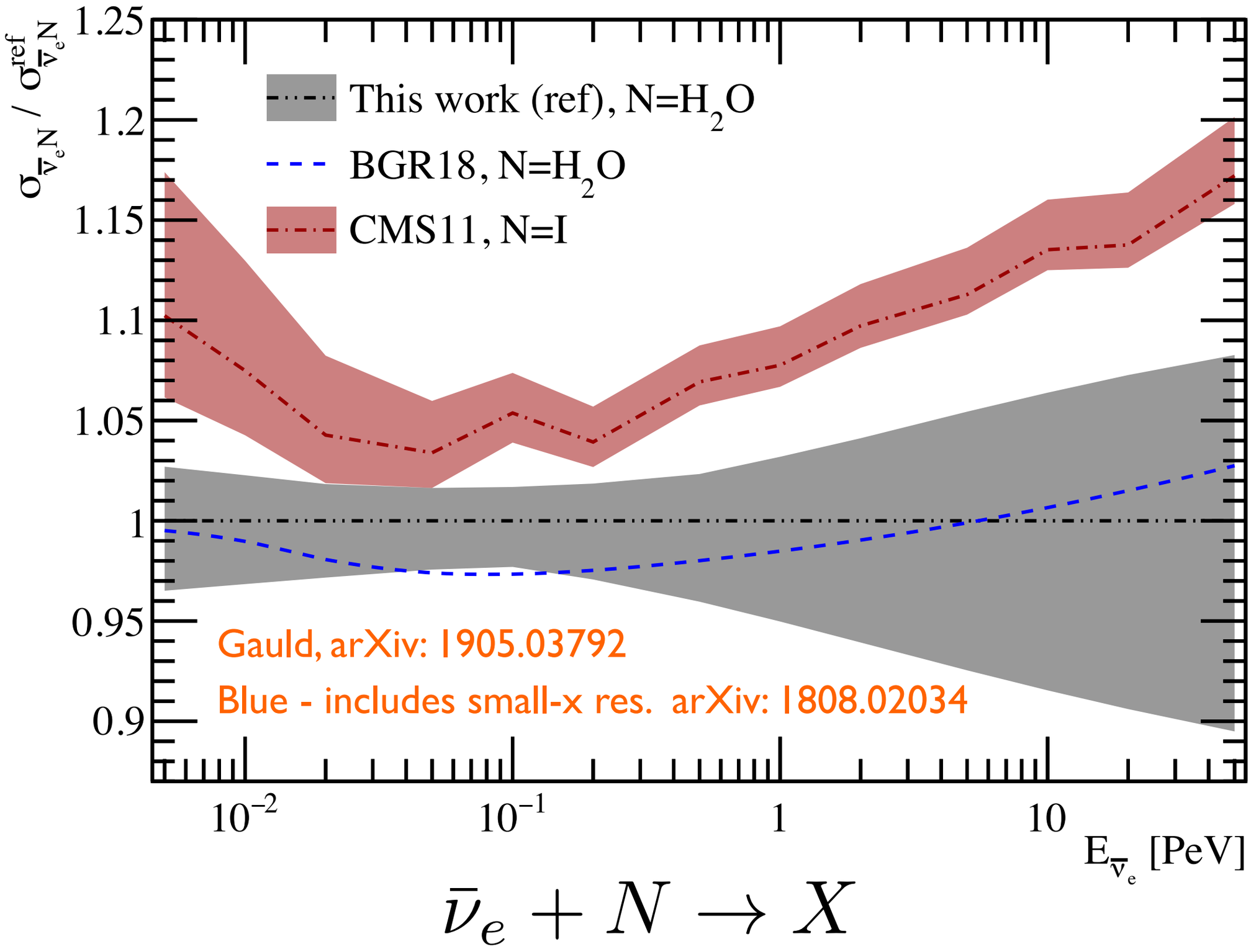
$$F^{\mathrm{H_2O}} = \frac{1}{2+A}\left(2F^p + ZF^{p,A} + NF^{n,A}\right) \qquad R_{\nu A}(E_\nu) = \left(\frac{\sigma_{\nu A}^{\mathrm{EPPS16}}(E_\nu)}{\sigma_{\nu I}^{\mathrm{free}}(E_\nu)}\right)$$

Results



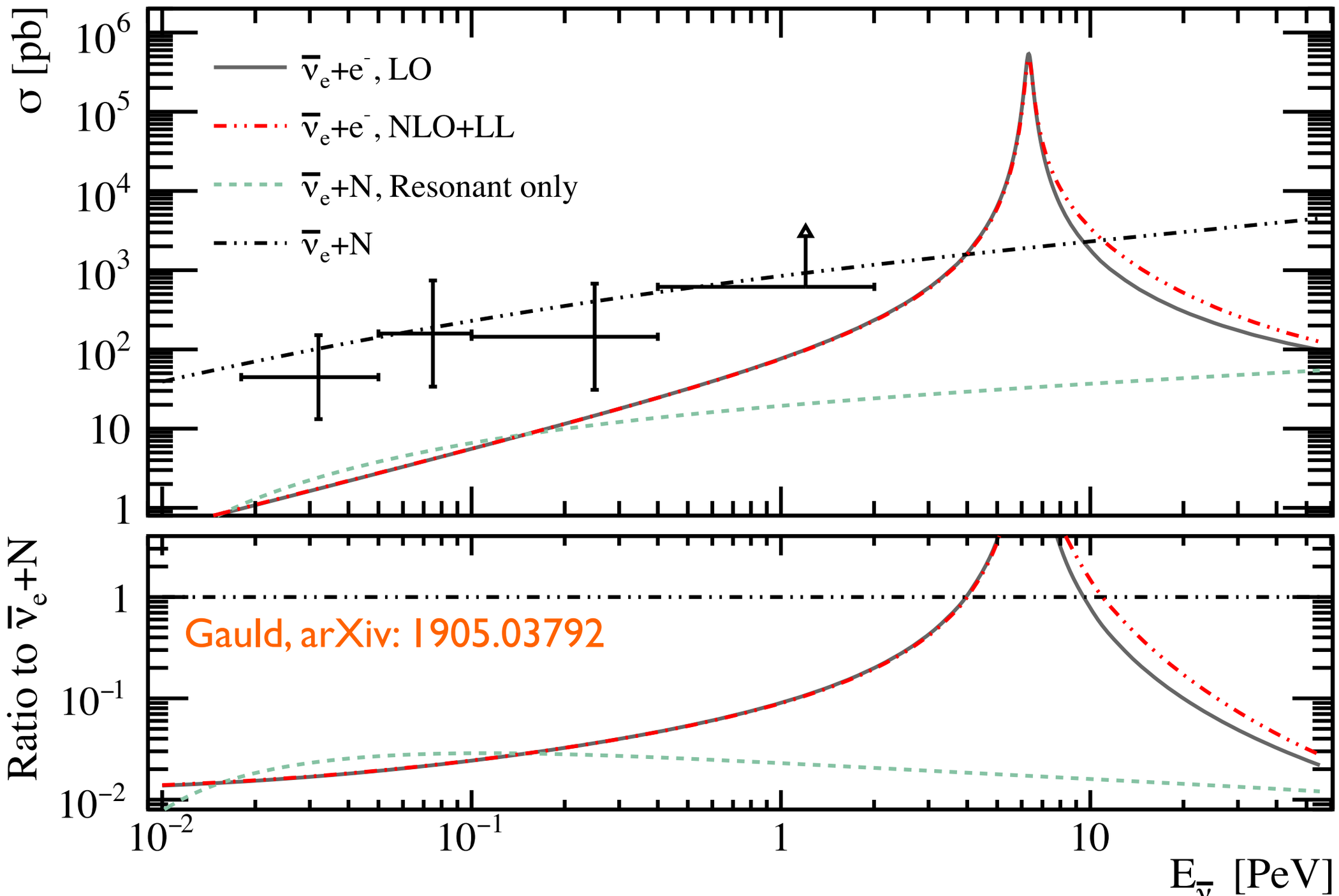
$$\bar{\nu}_e + N \rightarrow X$$

Results



$$\bar{\nu}_e + N \rightarrow X$$

Results

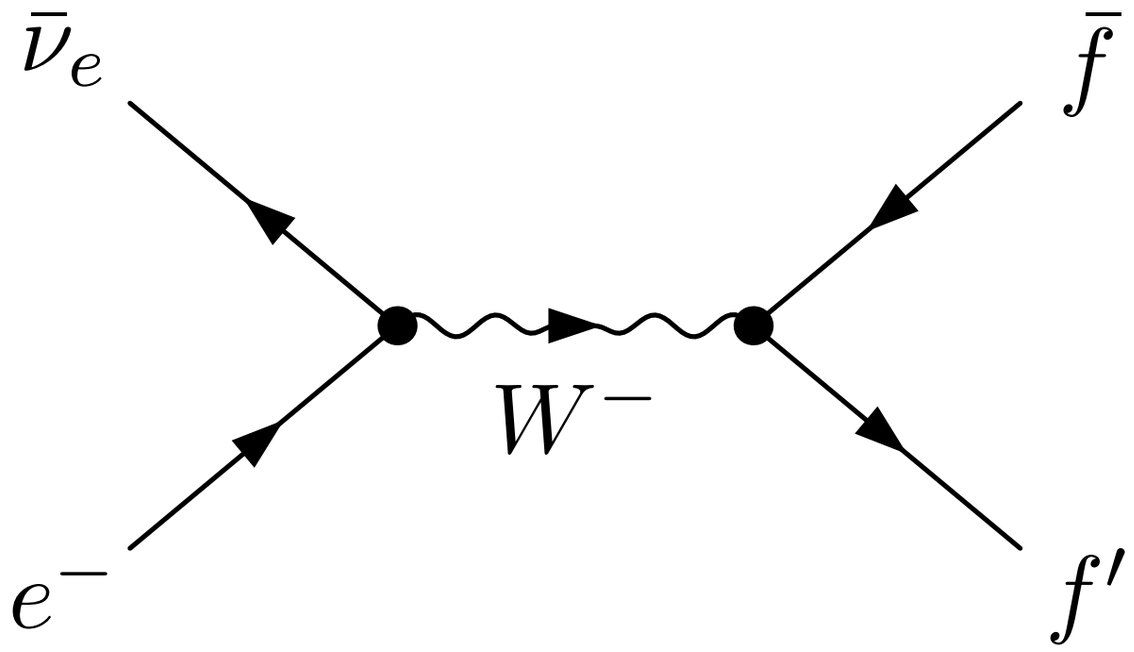


~ IceCube HESE (for comparison)

$$\bar{\nu}_e + \mathrm{H_2O} \to X$$

Bustamante et al., arXiv: 1711.11043

Neutrino scattering on electron target: why?



PeV neutrinos dominated by Glashow-type contributions

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

Time — Effective volume — cross-section — Neutrino flux

Direct measurement of the astrophysical flux: $\Phi_{\bar{\nu}_e}^{\mathrm{Earth}}$

Use to interpret sources of astrophysical neutrinos (CRs)

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
- 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

Preformed differential 2to2 calculation at NLO+ISR LL

Gauld, arXiv: 1905.03792

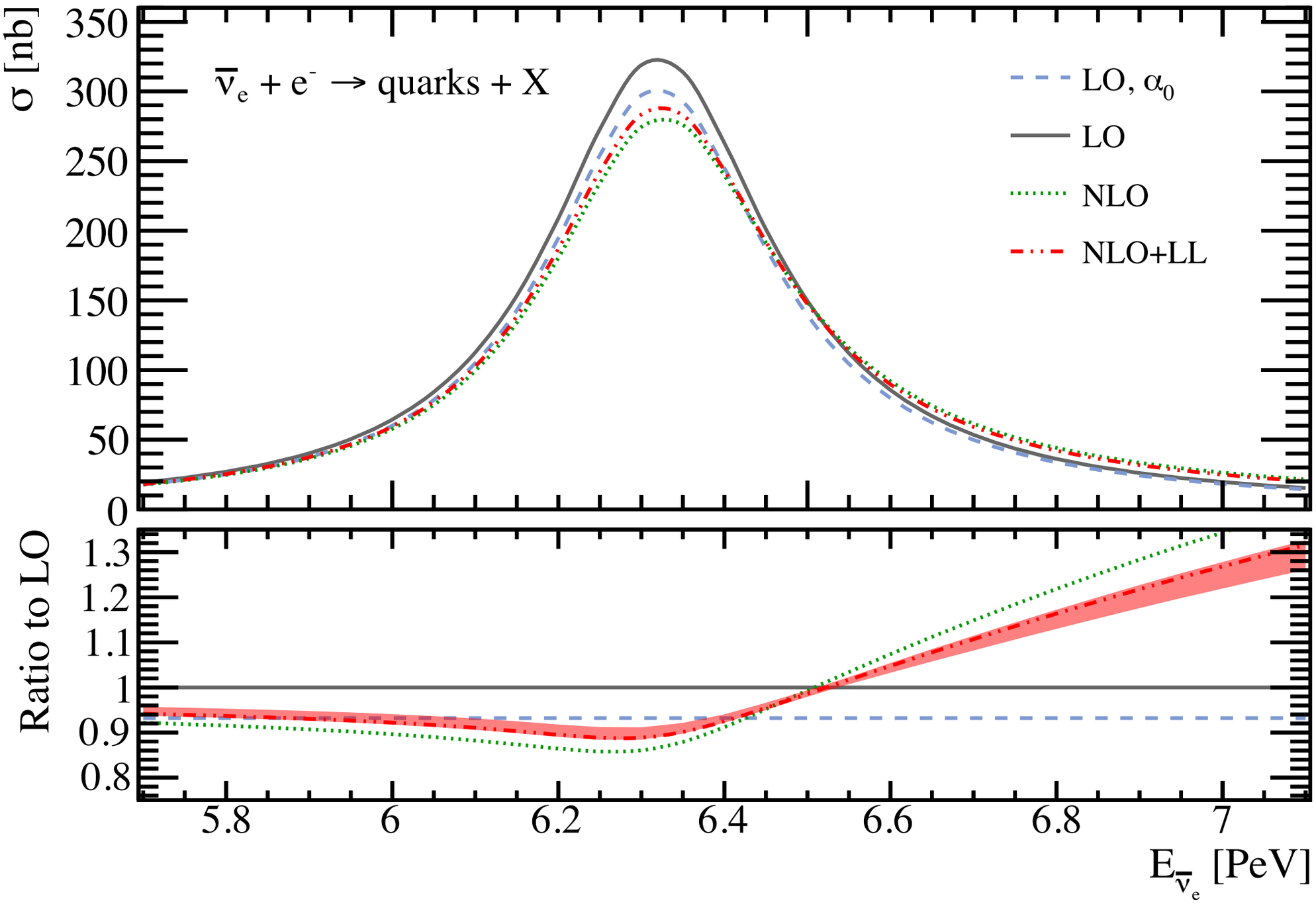
```
! ME2 (box): nue (p1) + e-(p2) > ubar(p3) + d(p4)
function ME2_box_quarks(shat, that, mudim )
  implicit none
  real(8), intent(in) :: shat, that, mudim
  real(8) :: uhat
  COMPLEX(kind(1d0)) :: chiw_s, ME2_box_quarks(0:2)
  COMPLEX(kind(1d0)) :: b0s0w(0:2), b0swz(0:2), b0t00(0:2)
  COMPLEX(kind(1d0)) :: c0t00000(0:2), c0t0000z(0:2), c0t0000w(0:2)
  COMPLEX(kind(1d0)) :: c000S00w(0:2), c00S000w(0:2),  c00S00wz(0:2)
  COMPLEX(kind(1d0)) :: d00000TS0w0z(0:2), d00000TS000w(0:2)
  COMPLEX(kind(1d0)) :: d00000US000w(0:2), d00000US0w0z(0:2)
  !> complex propagator
  !chiw_s = 1d0/CMPLX( shat-MW**2, gw*mw)
  chiw_s = 1d0/(shat-mw2c)
  !> define u = -t -s, mandelstam
  uhat = -shat-that
  !> B0 functions
  call B0function( shat, zeroc, mw2c, mudim, b0s0w )
  call B0function( shat, mw2c, mz2c, mudim, b0swz )
  call B0function( that, zeroc, zeroc, mudim, b0t00 )
  !> C0 functions
  call C0function( 0d0, 0d0, that, zeroc, zeroc, zeroc, mudim, c0t00000 )
  call C0function( that, 0d0, 0d0, zeroc, zeroc, mz2c, mudim, c0t0000z )
  call C0function( that, 0d0, 0d0, zeroc, zeroc, mw2c, mudim, c0t0000w )
  call C0function( 0d0, 0d0, shat, zeroc, zeroc, mw2c, mudim, c000S00w )
  call C0function( 0d0, shat, 0d0, zeroc, zeroc, mw2c, mudim, c00S000w )
  call C0function( 0d0, shat, 0d0, zeroc, mw2c, mz2c, mudim,  c00S00wz )
  !> D0 functions
  call D0function( 0d0, 0d0, 0d0, 0d0, that, shat, &
    zeroc, mw2c, zeroc, mz2c, mudim, d00000TS0w0z )
  call D0function( 0d0, 0d0, 0d0, 0d0, uhat, shat, &
    zeroc, mw2c, zeroc, mz2c, mudim, d00000US0w0z )
  call D0function( 0d0, 0d0, 0d0, 0d0, that, shat, &
    zeroc, zeroc, zeroc, mw2c, mudim,d00000TS000w )
  call D0function( 0d0, 0d0, 0d0, 0d0, uhat, shat, &
    zeroc, zeroc, zeroc, mw2c, mudim,d00000US000w )
  !> ME2
  ME2_box_quarks = &
  !> a0 vanishes
  !> b0
     12*(-(b0Swz*(gLd*gLe + gLnu*gLu)) - b0S0w*QD*QE + b0T00*(gLd*gLe + gLnu*gLu + QD*QE))*uhat &
  !> c0
    +(&
    -6*c0T0000w*that*(QD*QE*(mw2c - shat - 2*uhat) + gLd*gLe*(mw2c + mz2c - shat - 2*uhat) &
      + gLnu*gLu*(mw2c + mz2c - shat - 2*uhat)) &
    -6*c0T00000*QD*QE*that*(mw2c - shat - 2*uhat) &
    -6*c0T0000z*(gLd*gLe + gLnu*gLu)*that*(mw2c + mz2c - shat - 2*uhat) &
    -6*c000S00w*QE*(mw2c*QD*shat + 2*QU*uhat**2 - QD*(shat**2 + 2*shat*uhat + 2*uhat**2)) &
    -6*c00S000w*QE*(mw2c*QD*shat + 2*QU*uhat**2 - QD*(shat**2 + 2*shat*uhat + 2*uhat**2)) &
    -12*c00S00wz*(gLd*(2*gLnu*uhat**2 + gLe*(mw2c*shat + mz2c*shat - shat**2 - 2*shat*uhat &
      - 2*uhat**2)) +gLu*(2*gLe*uhat**2 &
      + gLnu*(mw2c*shat + mz2c*shat - shat**2 - 2*shat*uhat - 2*uhat**2))) &
  !> d0
    +6*(2*d00000US0w0z*(gLd*gLnu + gLe*gLu)*uhat**3 &
      + 2*d00000US000w*QE*QU*uhat**3 &
      - d00000TS000w*QD*QE*that*(mw2c**2 + shat**2 + 2*mw2c*that + 2*shat*uhat + 2*uhat**2) &
      + d00000TS0w0z*(gLd*gLe + gLnu*gLu)*(-(mw2c**2*that) + 2*mw2c*(mz2c*shat - that**2) &
        -that*(mz2c**2 + shat**2 + 2*mz2c*that + 2*shat*uhat + 2*uhat**2))) )
  !> Add on finite part (0)
  !> Prefactor
  ME2_box_quarks = ME2_box_quarks * alpha * pi * (alpha / sw2) * CONJG(alpha * chiw_s /sw2)
end function ME2_box_quarks
```

e.g. Quark boxes

```
!> define u = -t -s, mandelstam
uhat = -shat-that
!> complex propagator
chiW = 1d0/(shat-mw2c)
chiZ = 1d0/(uhat-mz2c)
call B0function( uhat, mb2c, mb2c, mudim, b0ubb )
call B0function( uhat, mt2c, mt2c, mudim, b0utt )
call B0function( uhat, zeroc, zeroc, mudim, b0u00 )
call B0function( uhat, mw2c, mw2c, mudim, b0uww )
call B0function( uhat, mh2c, mz2c, mudim, b0uhz )
call B0function( shat, zeroc, mw2c, mudim, b0s0w )
call B0function( shat, zeroc, zeroc, mudim, b0s00 )
call B0function( shat, mb2c, mt2c, mudim, b0sbt )
call B0function( shat, mh2c, mw2c, mudim, b0shw )
call B0function( shat, mw2c, mz2c, mudim, b0swz )
!> ME2
ME2_self_ele = (&
!> a0
6*a0b*(64*chiZ**2*gLnu*(gLd**2 + gRd**2)*gRe*shat**2*Conjg(chiZ*gLnu*gRe) + (64*chiZ*gLnu*(gLd &
  + gRd)*shat**2*Conjg(chiZ*gLnu*gRe))/(3d0*uhat) &
+ (32*chiZ**2*gLe*gLnu*(gLd**2 + gRd**2)*that**2*(Conjg(chiW) &
  + 2*Conjg(chiZ*gLe*gLnu*sw2)))/Conjg(sw2) &
- (2*chiW**2*(mb2c - mt2c - 2*shat)*that**2*(Conjg(chiW) + 2*Conjg(chiZ*gLe*gLnu*sw2))) &
& /(shat*sw2**2*Conjg(sw2)) + (32*chiZ*gLnu*(gLd + gRd)*that**2*(Conjg(chiW) &
  + 2*Conjg(chiZ*gLe*gLnu*sw2)))/(3d0*uhat*Conjg(sw2))) &
+4*a0t*(96*chiZ**2*gLnu*gRe*(gLu**2 + gRu**2)*shat**2*Conjg(chiZ*gLnu*gRe) &
  - (64*chiZ*gLnu*(gLu + gRu)*shat**2*Conjg(chiZ*gLnu*gRe))/uhat &
  + (48*chiZ**2*gLe*gLnu*(gLu**2 + gRu**2)*that**2*(Conjg(chiW) &
    + 2*Conjg(chiZ*gLe*gLnu*sw2)))/Conjg(sw2) +(3*chiW**2*(mb2c - mt2c &
    + 2*shat)*that**2*(Conjg(chiW) + 2*Conjg(chiZ*gLe*gLnu*sw2)))/(shat*sw2**2*Conjg(sw2)) &
    - (32*chiZ*gLnu*(gLu + gRu)*that**2*(Conjg(chiW) &
      + 2*Conjg(chiZ*gLe*gLnu*sw2)))/(uhat*Conjg(sw2))) &
+a0w*((-32*chiZ**2*gLnu*gRe*(12*mw2c**2 - 4*mw2c*mz2c + mz2c**2)*shat**2 &
  & *Conjg(chiZ*gLnu*gRe))/(mw2c*mz2c*sw2) + (64*chiZ*(-1 + 6*cw2)*gLnu*shat**2 &
  & *Conjg(chiZ*gLnu*gRe))/(cw*sw*uhat) - (2*chiW**2*(mh2c - 2*mw2c + mz2c &
    + 20*shat)*that**2*(Conjg(chiW) + 2*Conjg(chiZ*gLe*gLnu*sw2)))/(shat*sw2**2*Conjg(sw2)) &
  - (16*chiZ**2*gLe*gLnu*(12*mw2c**2 - 4*mw2c*mz2c + mz2c**2)*that**2*(Conjg(chiW) &
    + 2*Conjg(chiZ*gLe*gLnu*sw2)))/(mw2c*mz2c*sw2*Conjg(sw2)) + (32*chiZ*(-1 &
    + 6*cw2)*gLnu*that**2*(Conjg(chiW) + 2*Conjg(chiZ*gLe*gLnu*sw2)))/(cw*sw*uhat*Conjg(sw2))) &
-(a0z*((8*chiZ**2*gLnu*gRe*shat**2*sw2*(mh2c - mz2c + 2*uhat)*Conjg(chiZ*gLnu*gRe))/(cw2*uhat) &
  - (2*chiW**2*(8*mw2c + mz2c)*(-2*shat + mz2c*sw2)*that**2*(Conjg(chiW) &
    + 2*Conjg(chiZ*gLe*gLnu*sw2)))/(mz2c*shat*Conjg(sw2)) &
  + (4*chiZ**2*gLe*gLnu*sw2*that**2*(mh2c - mz2c + 2*uhat)*(Conjg(chiW) &
    + 2*Conjg(chiZ*gLe*gLnu*sw2)))/(cw2*uhat*Conjg(sw2))))/sw2**2 &
+(a0m*((-8*chiZ**2*gLnu*gRe*shat**2*sw2*(-mh2c + mz2c + 2*uhat) &
  & *Conjg(chiZ*gLnu*gRe))/(cw2*uhat) &
+(2*chiW**2*(mh2c - mw2c - 2*shat)*that**2*(2*Conjg(chiZ*gLe*gLnu) + Conjg(chiW/sw2)))/shat &
-(4*chiZ**2*gLe*gLnu*sw2*that**2*(-mh2c + mz2c + 2*uhat)*(Conjg(chiW) &
  + 2*Conjg(chiZ*gLe*gLnu*sw2)))/(cw2*uhat*Conjg(sw2))))/sw2**2)/12d0 &
!> b0
+((-2*b0Uhz*chiZ**2*gLnu*(mh2c**2 + mz2c**2 + 10*mz2c*uhat + uhat**2 - 2*mh2c*(mz2c + uhat))* &
  & (gLe*that**2*Conjg(chiW) + 2*(gLe*that**2*Conjg(gLe) + gRe*shat**2*Conjg(gRe)) &
    & *Conjg(chiZ*gLnu*sw2)))/(cw2*sw2*uhat*Conjg(sw2)) &
+(2*b0Uww*chiZ*gLnu*(that**2*(48*mw2c**4*mzc - chiZ*gLe*mwc*mz2c**3*sw*uhat**2 &
  - 4*mw2c**3*(8*mz2c*mzc - 9*mzc*uhat - 12*chiZ*gLe*mwc*mz2c*sw*uhat) &
  + 2*mw2c*mz2c**2*uhat*(-mzc + 2*chiZ*gLe*mwc*sw*(-5*mz2c + uhat)) &
  + 2*mw2c**2*mz2c*(2*chiZ*gLe*mwc*sw*uhat*(8*mz2c + 9*uhat) - mzc*(8*mz2c &
    + 17*uhat)))*Conjg(chiW) + 2*(that**2*(48*mw2c**4*mzc - chiZ*gLe*mwc*mz2c**3*sw*uhat**2 &
- 4*mw2c**3*(8*mz2c*mzc - 9*mzc*uhat - 12*chiZ*gLe*mwc*mz2c*sw*uhat) &
+ 2*mw2c*mz2c**2*uhat*(-mzc + 2*chiZ*gLe*mwc*sw*(-5*mz2c + uhat)) &
+ 2*mw2c**2*mz2c*(2*chiZ*gLe*mwc*sw*uhat*(8*mz2c + 9*uhat) - mzc*(8*mz2c + 17*uhat)))*Conjg(gLe) + &
    + shat**2*(48*mw2c**4*mzc - chiZ*gRe*mwc*mz2c**3*sw*uhat**2 - 4*mw2c**3*(8*mz2c*mzc &
      - 9*mzc*uhat - 12*chiZ*gRe*mwc*mz2c*sw*uhat) &
    + 2*mw2c*mz2c**2*uhat*(-mzc + 2*chiZ*gRe*mwc*sw*(-5*mz2c + uhat)) &
    + 2*mw2c**2*mz2c*(2*chiZ*gRe*mwc*sw*uhat*(8*mz2c + 9*uhat) - mzc*(8*mz2c &
      + 17*uhat)))*Conjg(gRe))*Conjg(chiZ*gLnu*sw2)))/(mw2c*mwc*mz2c**2*sw*sw2*uhat*Conjg(sw2)) &
+(36*b0S00*chiW**2*shat*that**2*(Conjg(chiW) + 2*Conjg(chiZ*gLe*gLnu*sw2)))/(sw2**2*Conjg(sw2)) &
+(6*b0Sbt*chiW**2*(mb2c**2 + mt2c**2 + mt2c*shat - 2*shat**2 + mb2c*(-2*mt2c &
  + shat))*that**2*(Conjg(chiW) + 2*Conjg(chiZ*gLe*gLnu*sw2)))/(shat*sw2**2*Conjg(sw2)) &
- (b0Shw*chiW**2*(mh2c**2 + mw2c**2 + 10*mw2c*shat + shat**2 - 2*mh2c*(mw2c + shat))*that**2* &
  & (Conjg(chiW) + 2*Conjg(chiZ*gLe*gLnu*sw2)))/(shat*sw2**2*Conjg(sw2)) &
- (b0Swz*chiW**2*(8*mw2c**3 - mw2c**2*(15*mz2c + 16*shat) + mw2c*(6*mz2c**2 - 54*mz2c*shat &
  - 40*shat**2) + mz2c*(mz2c**2 + 10*mz2c*shat + shat**2))*that**2*(Conjg(chiW) &
+ 2*Conjg(chiZ*gLe*gLnu*sw2)))/(mz2c*shat*sw2**2*Conjg(sw2)) &
+ (8*b0S0w*chiW**2*(-mw2c**2 + 2*mw2c*shat + 5*shat**2)*that**2*(Conjg(chiW) &
  + 2*Conjg(chiZ*gLe*gLnu*sw2)))/(shat*sw2*Conjg(sw2)) &
+ 24*b0U00*chiZ*gLnu*((-4*(2*gLd + 3*gLe - 4*gLu + 2*gRd + 3*gRe &
  - 4*gRu)*shat**2*Conjg(chiZ*gLnu*gRe))/3d0 &
- 4*chiZ*gRe*(gLe**2 + gLnu**2 + 2*(gLd**2 + gLu**2) + gRe**2 + 2*(gRd**2 &
  + gRu**2))*shat**2*uhat*Conjg(chiZ*gLnu*gRe) &
- 2*chiZ*gLe*(2*gLd**2 + gLe**2 + gLnu**2 + 2*gLu**2 + 2*gRd**2 + gRe**2 &
  + 2*gRu**2)*that**2*uhat*(2*Conjg(chiZ*gLe*gLnu) &
  + Conjg(chiW/sw2)) - (2*(2*gLd + 3*gLe - 4*gLu + 2*gRd + 3*gRe - 4*gRu)*that**2*(Conjg(chiW) &
    + 2*Conjg(chiZ*gLe*gLnu*sw2)))/(3d0*Conjg(sw2))) &
+ 8*b0Ubb*chiZ*gLnu*(-4*(gLd + gRd)*shat**2*Conjg(chiZ*gLnu*gRe) &
  - 12*chiZ*gRe*shat**2*(6*gLd*gRd*mb2c - (gLd**2 + gRd**2)*(mb2c - uhat))*Conjg(chiZ*gLnu*gRe) &
  - (8*(gLd + gRd)*mb2c*shat**2*Conjg(chiZ*gLnu*gRe))/uhat &
  - 6*chiZ*gLe*that**2*(6*gLd*gRd*mb2c - (gLd**2 + gRd**2)*(mb2c-uhat))*(2*Conjg(chiZ*gLe*gLnu) &
    + Conjg(chiW/sw2)) &
  - (2*(gLd + gRd)*that**2*(Conjg(chiW) + 2*Conjg(chiZ*gLe*gLnu*sw2)))/Conjg(sw2) &
  - (4*(gLd + gRd)*mb2c*that**2*(Conjg(chiW) + 2*Conjg(chiZ*gLe*gLnu*sw2)))/(uhat*Conjg(sw2))) &
+ 8*b0Utt*chiZ*gLnu*(8*(gLu + gRu)*shat**2*Conjg(chiZ*gLnu*gRe) &
  - 12*chiZ*gRe*shat**2*(6*gLu*gRu*mt2c - (gLu**2 + gRu**2)*(mt2c - uhat))*Conjg(chiZ*gLnu*gRe) &
  + (16*(gLu + gRu)*mt2c*shat**2*Conjg(chiZ*gLnu*gRe))/uhat &
  - 6*chiZ*gLe*that**2*(6*gLu*gRu*mt2c - (gLu**2 + gRu**2)*(mt2c-uhat))*(2*Conjg(chiZ*gLe*gLnu) &
    + Conjg(chiW/sw2)) + (4*(gLu + gRu)*that**2*(Conjg(chiW) &
      + 2*Conjg(chiZ*gLe*gLnu*sw2)))/Conjg(sw2) + (8*(gLu + gRu)*mt2c*that**2*(Conjg(chiW) &
      + 2*Conjg(chiZ*gLe*gLnu*sw2)))/(uhat*Conjg(sw2))))/6d0
!> Add on finite part
ME2_self_ele(0) = ME2_self_ele(0) &
+((-16*chiZ*gLnu*shat**2*(mzc - 6*(gLd + gLe - 2*gLu + gRd + gRe &
  - 2*gRu)*mwc*sw)*Conjg(chiZ*gLnu*gRe))/(mwc*sw) &
- (96*chiZ*gLnu*shat**2*(6*mw2c**2*mzc - mw2c*mz2c*mzc + 2*(gLd*mb2c + gRd*mb2c - 2*(gLu &
  + gRu)*mt2c)*mwc*mz2c*sw)*Conjg(chiZ*gLnu*gRe))/(mwc*mz2c*sw*uhat) &
+ (8*chiZ**2*gLnu*gRe*shat**2*(3*mh2c + 3*mz2c + 6*mw2c*sw2**2 - uhat - sw2**2*uhat &
  + (3*mw2c**2*(18*mw2c + uhat))/mz2c**2 + 2*cw2*sw2*(-36*gLu**2*mt2c - 36*gRu**2*mt2c &
    - 6*mw2c + uhat + 6*gLe**2*uhat + 6*gLnu**2*uhat + 18*gLu**2*uhat + 6*gRe**2*uhat &
    + 18*gRu**2*uhat + 18*gLd**2*(-2*mb2c + uhat) + 18*gRd**2*(-2*mb2c &
```

e.g. Electron self energies..

Neutrino scattering on electron target: results



Uncertainties

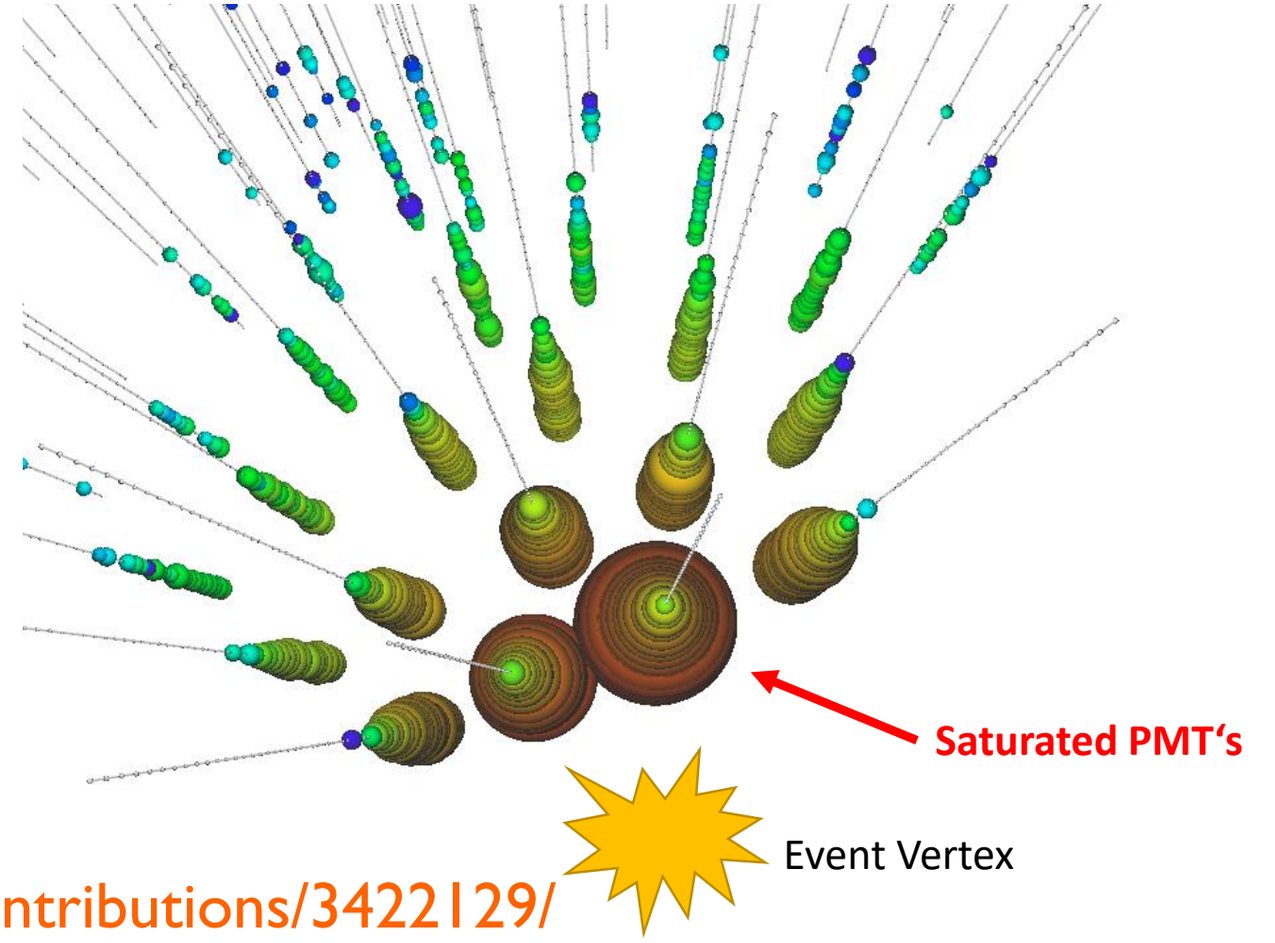
~ 10% correction at NLO (1% uncertainty)

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/

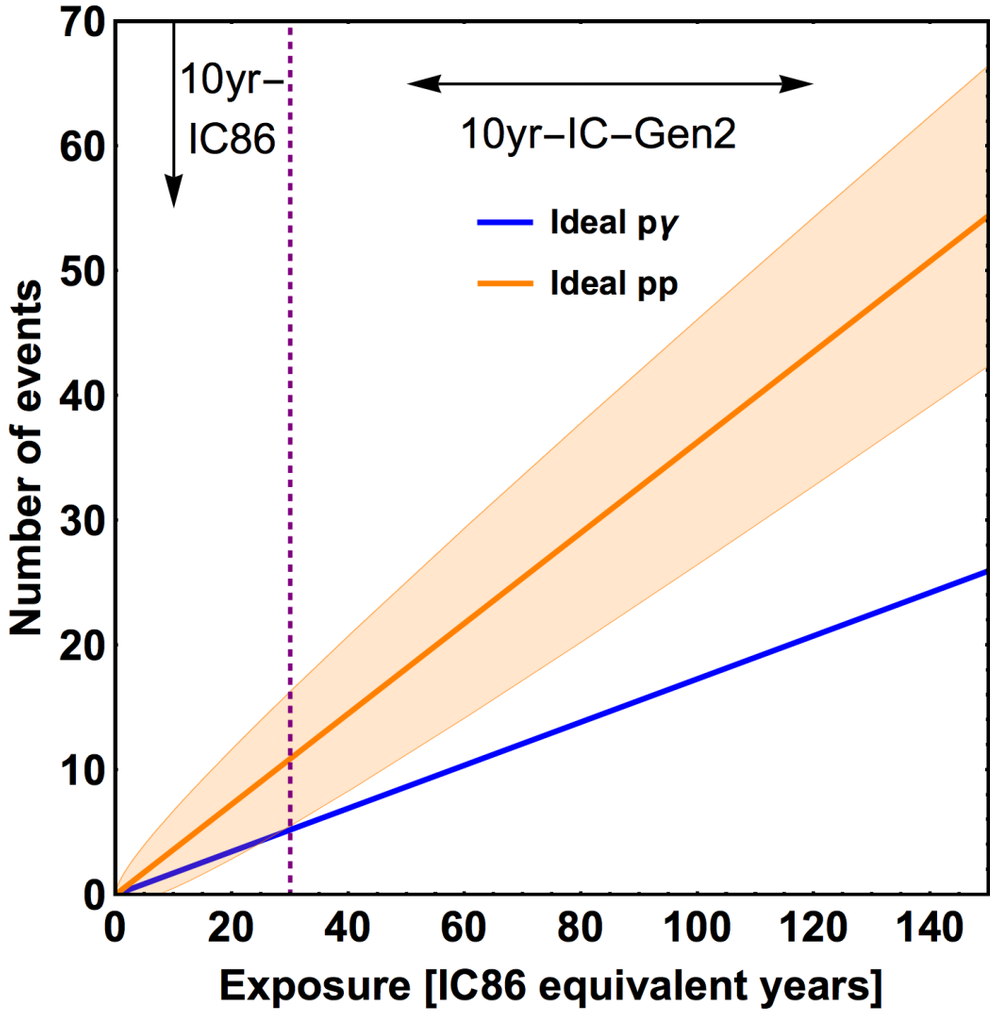


IceCube-Gen2: ~30 events with 10 years of data
Biehl et al. arXiv: 1611.07983

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

Neutrino scattering on electron target: data

Biehl et al. arXiv: 1611.07983



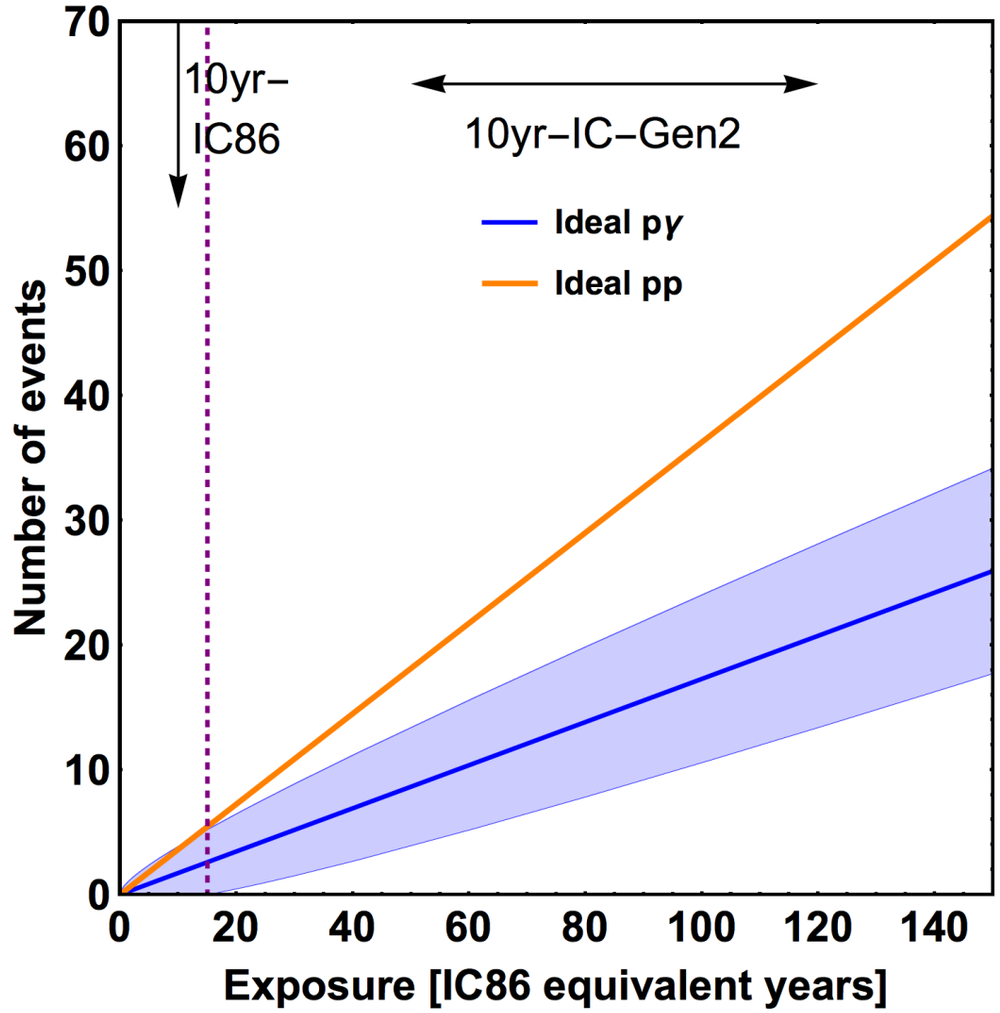


FIG. 1: *Expected number of Glashow events in the ideal pp and pγ scenarios as a function of the exposure for* $\alpha = 2.0$. *The bands represents the 90% C.L. interval from the statistical (Poissonian) uncertainty and the model uncertainties on the oscillation parameters, assuming a true pp and pγ 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

Conclusions

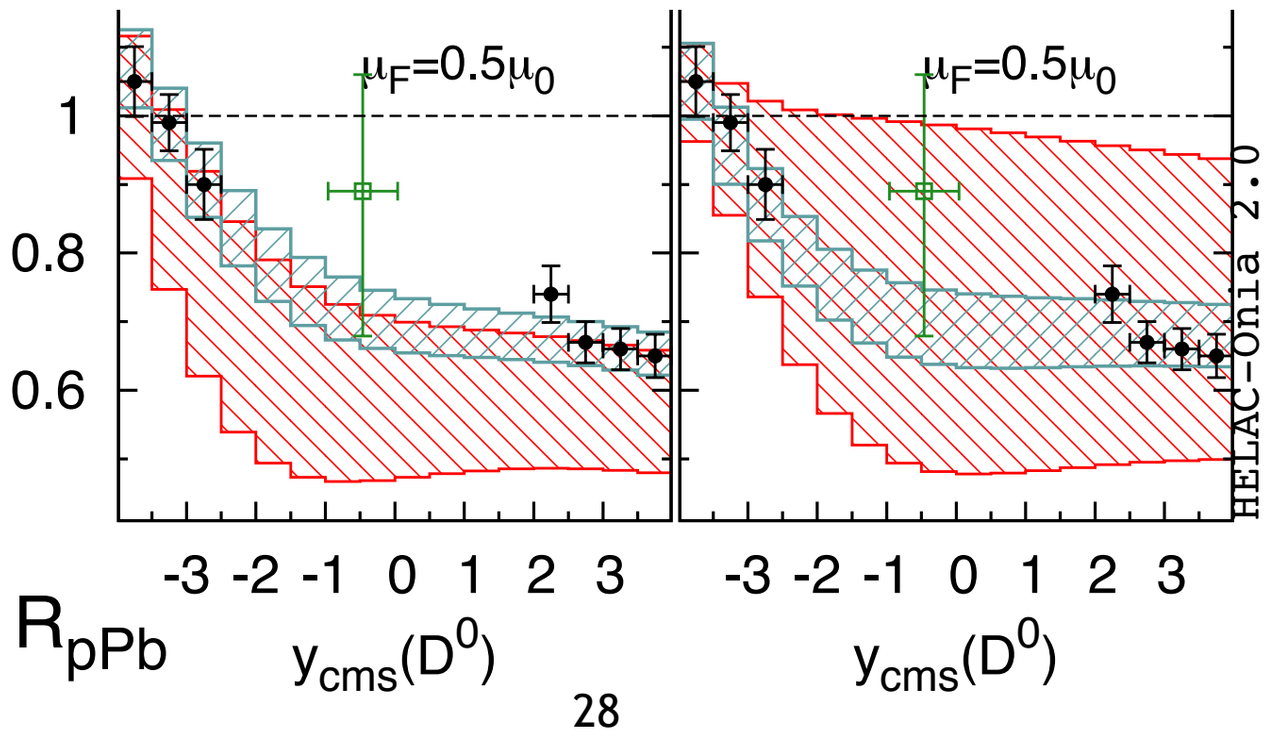
Theoretically in good shape

Limiting factor: nuclear corrections for bound nuclei

- Can use LHC data on p-Pb (extrapolate in A?)
- Oxygen data also desirable here…
- Also the case for neutrinos propagating Earth (A~30)

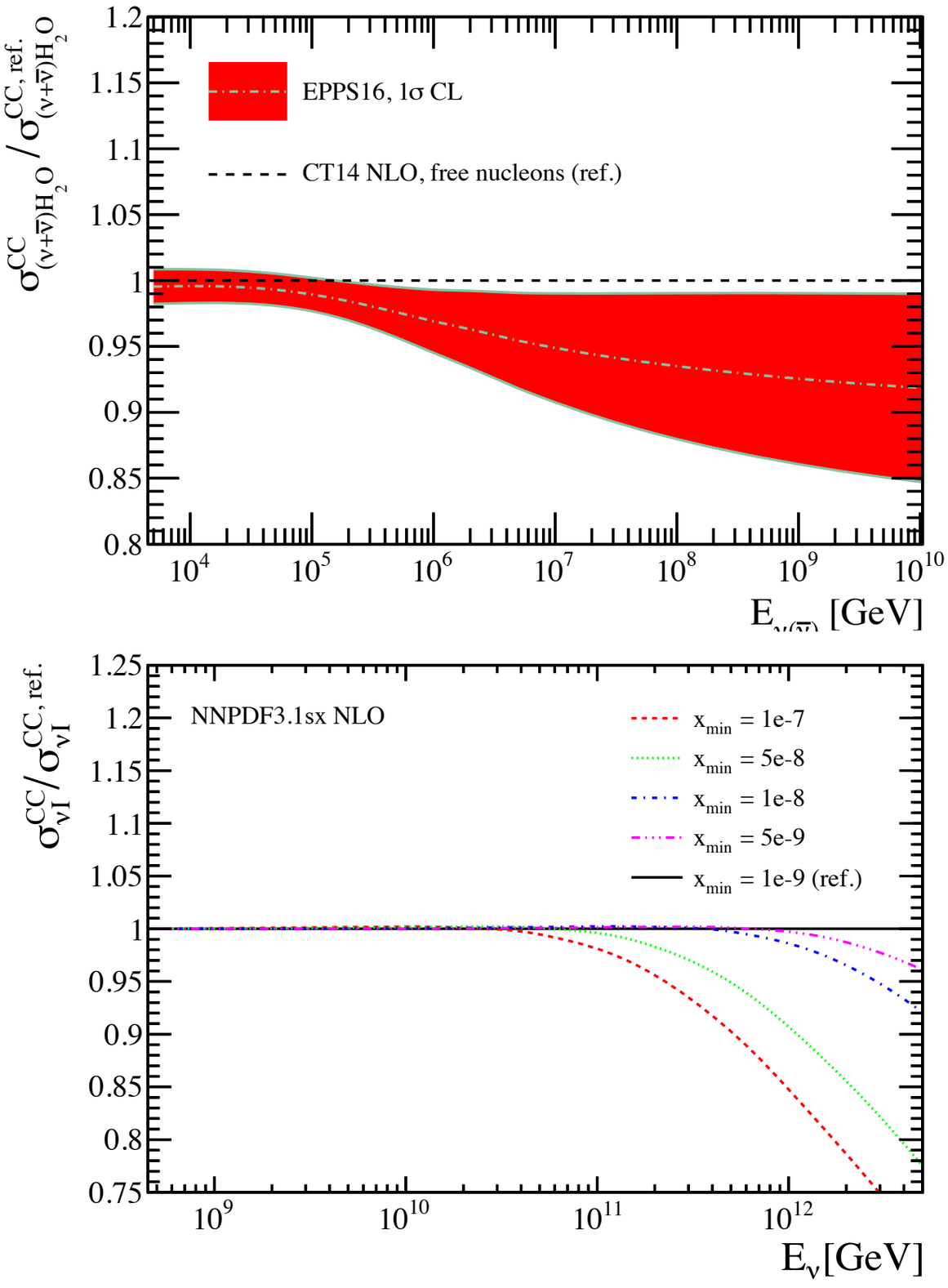
Kusina et al. arXiv: 1712.07024

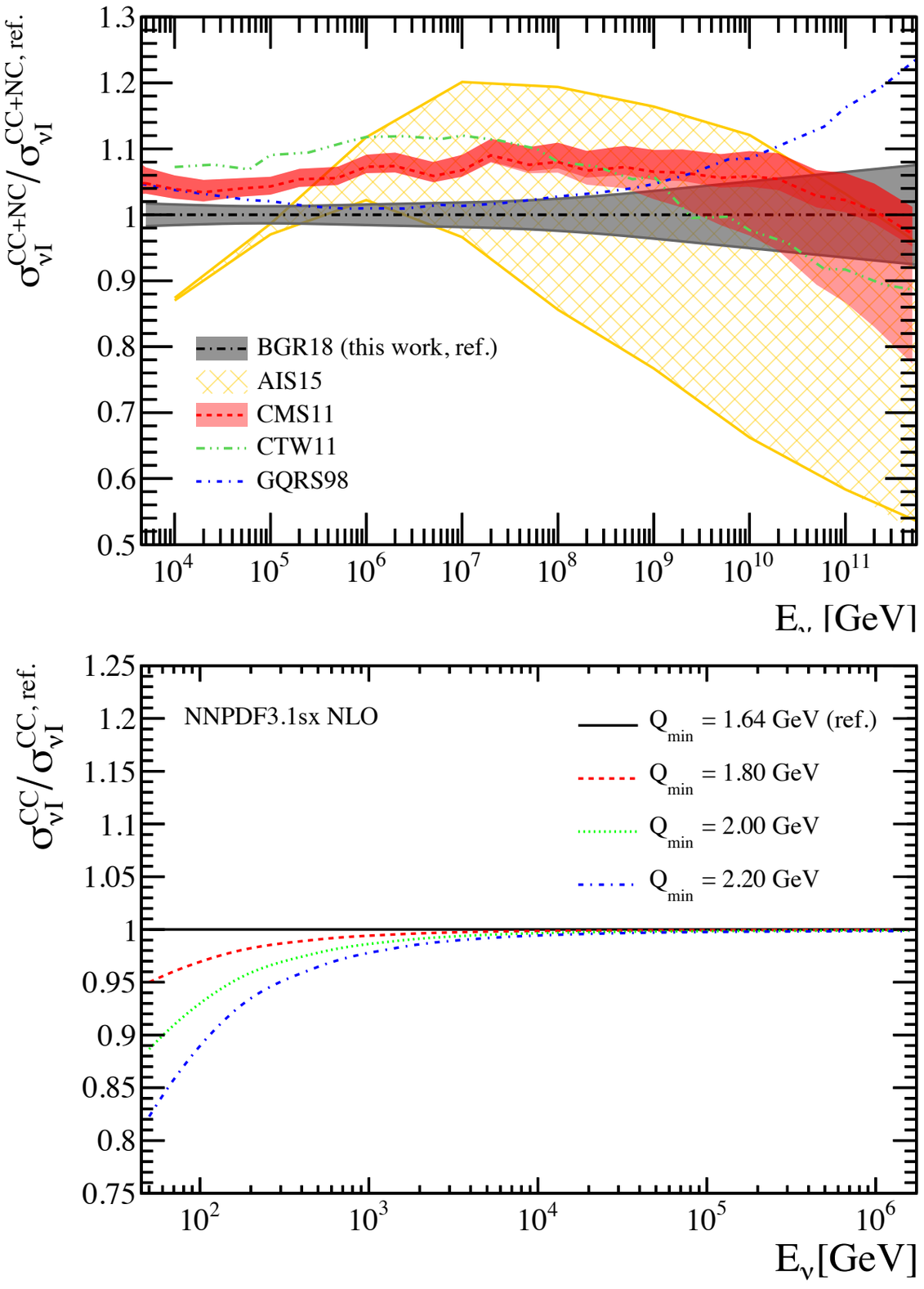
nCTEQ15



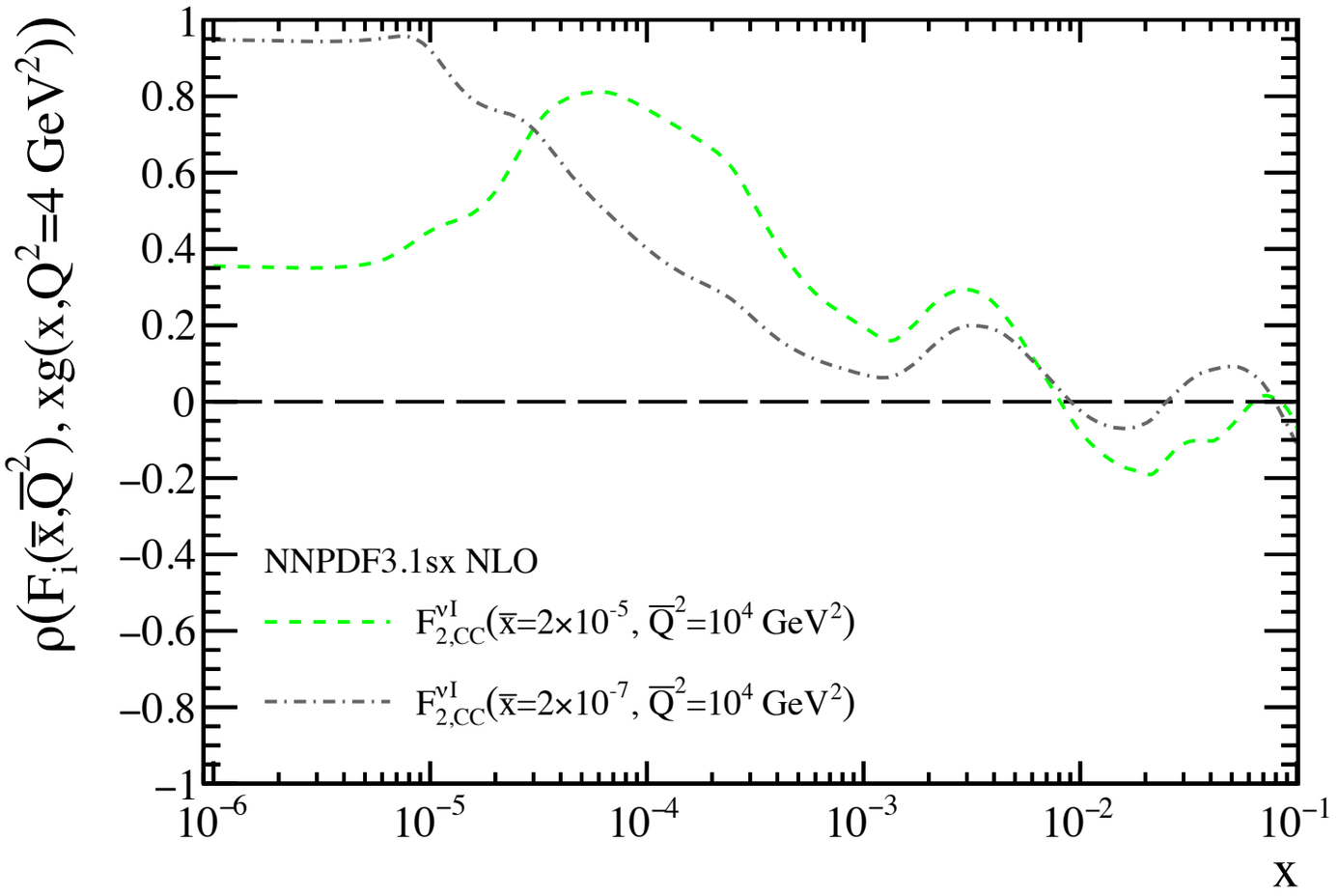
EPPS16

Additional plots

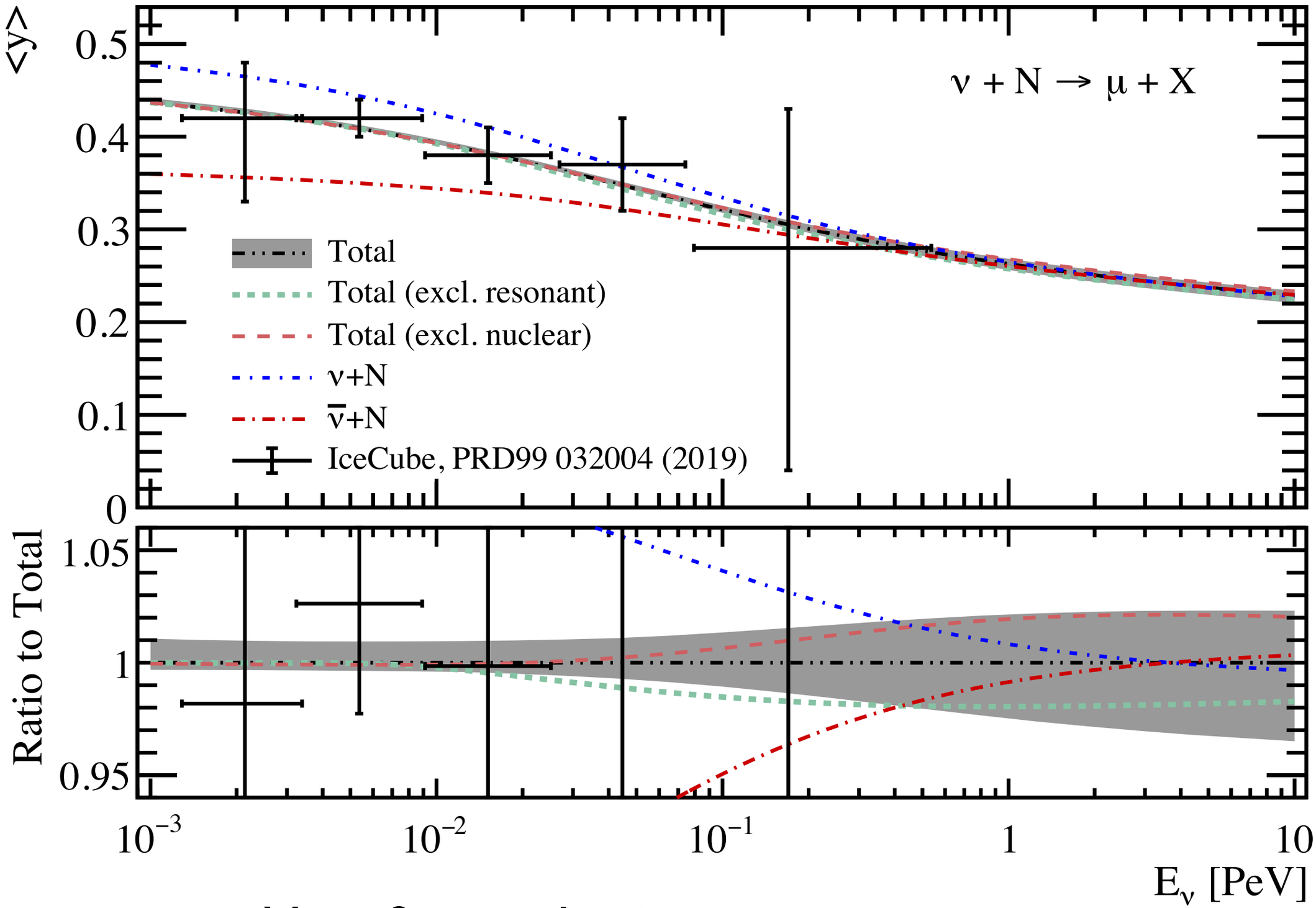




Additional plots

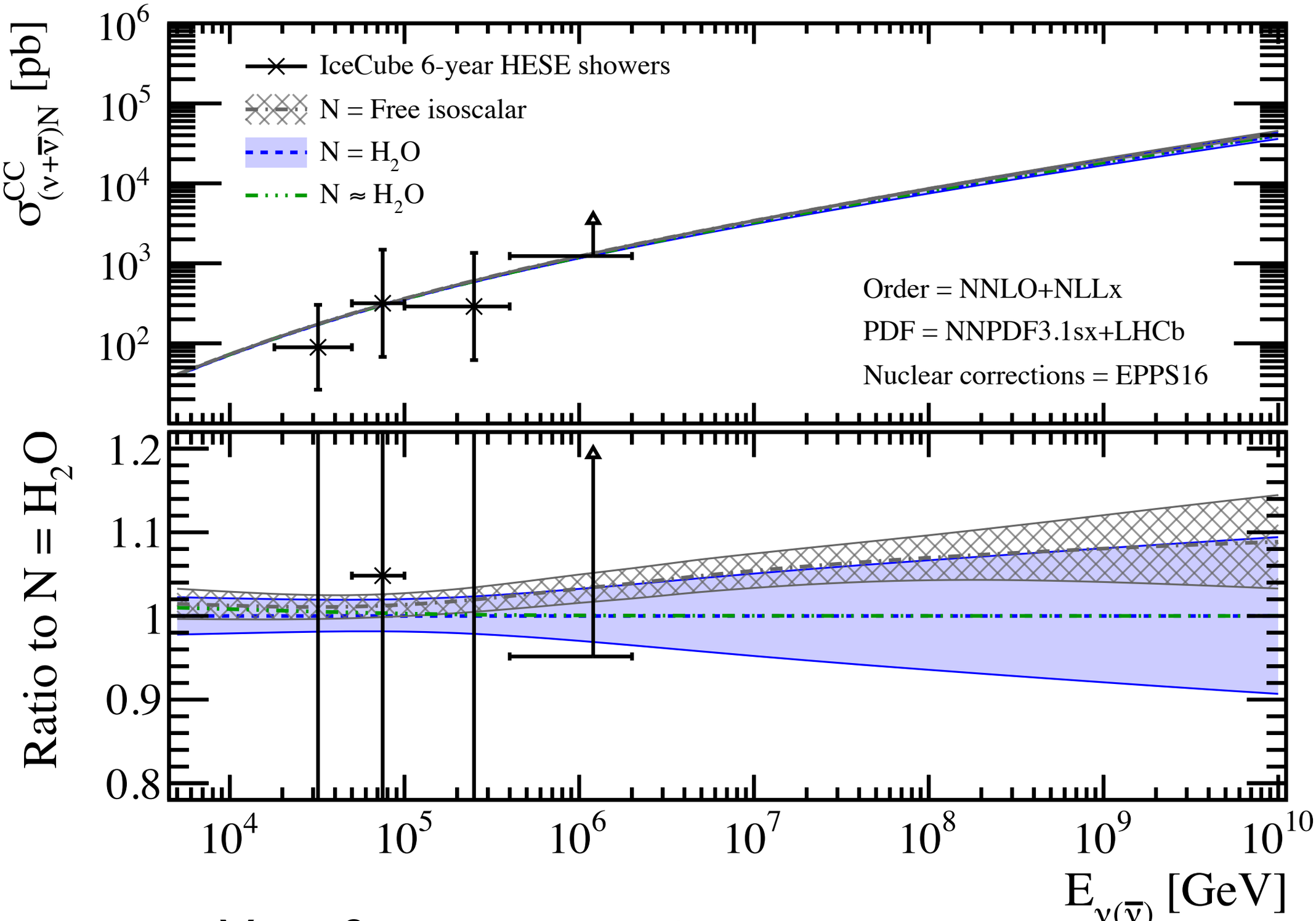


Some other comparisons



Very first inelasticity measurements

Some other comparisons



Very first cross-section measurements

Coupled DGLAP (QCD QED)

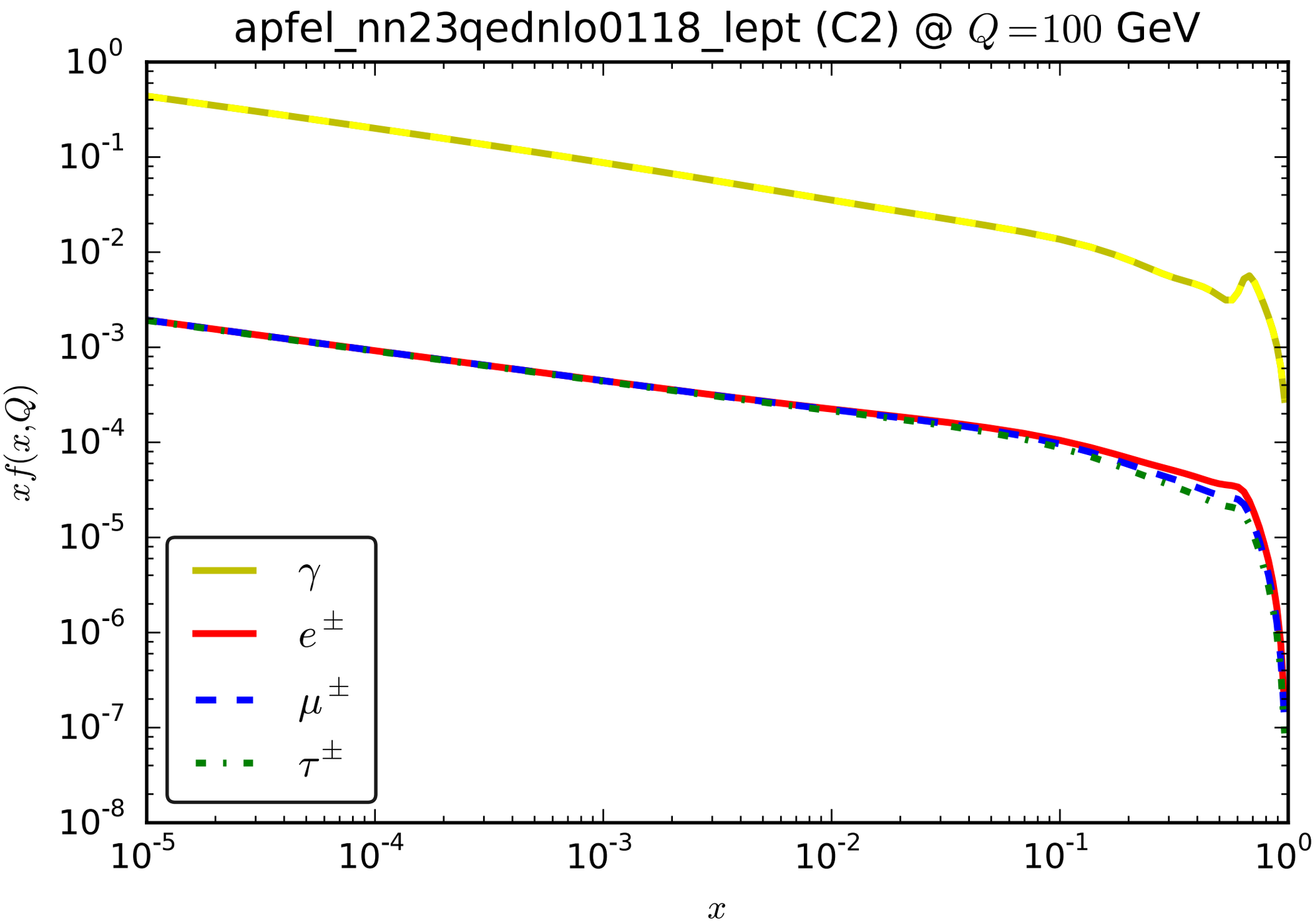
Bertone et al. arXiv:1508.07002

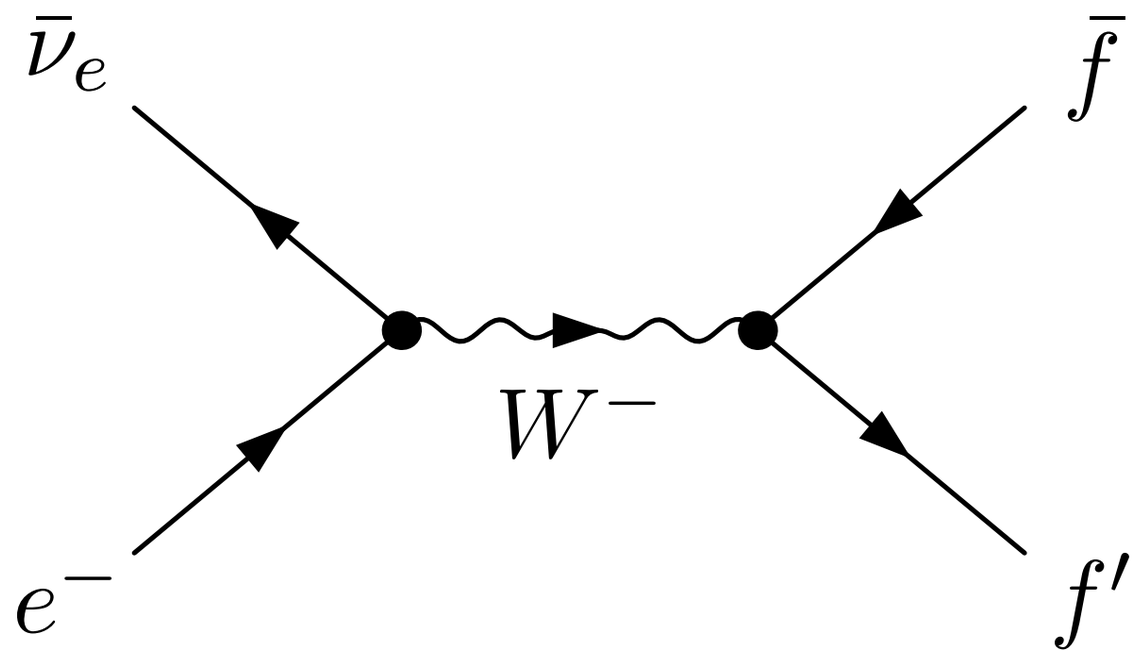
- the singlet sector:

$$\mu^2 \frac{\partial}{\partial \mu^2} \begin{pmatrix} g \\ \gamma \\ \Sigma \\ \Delta_\Sigma \\ \Sigma_\ell \end{pmatrix} = \left[\begin{pmatrix} \widetilde{P}_{gg} & 0 & \widetilde{P}_{gq} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 2n_f \widetilde{P}_{qg} & 0 & \widetilde{P}_{qq} & 0 & 0 \\ \frac{n_u - n_d}{n_f} 2n_f \widetilde{P}_{qg} & 0 & \frac{n_u - n_d}{n_f} (\widetilde{P}_{qq} - \widetilde{P}^+) & \widetilde{P}^+ & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix} \right. \\ \left. + \begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & e_\Sigma^2 \bar{P}_{\gamma\gamma} & \eta^+ \bar{P}_{\gamma q} & \eta^- \bar{P}_{\gamma q} & \bar{P}_{\gamma q} \\ 0 & 2e_\Sigma^2 \bar{P}_{q\gamma} & \eta^+ \bar{P}_{qq} & \eta^- \bar{P}_{qq} & 0 \\ 0 & 2\delta_e^2 \bar{P}_{q\gamma} & \eta^- \bar{P}_{qq} & \eta^+ \bar{P}_{qq} & 0 \\ 0 & 2n_\ell \bar{P}_{q\gamma} & 0 & 0 & \bar{P}_{qq} \end{pmatrix} \right] \otimes \begin{pmatrix} g \\ \gamma \\ \Sigma \\ \Delta_\Sigma \\ \Sigma_\ell \end{pmatrix} , \tag{A.4}$$

Lepton vs photon

Bertone et al. arXiv:1508.07002





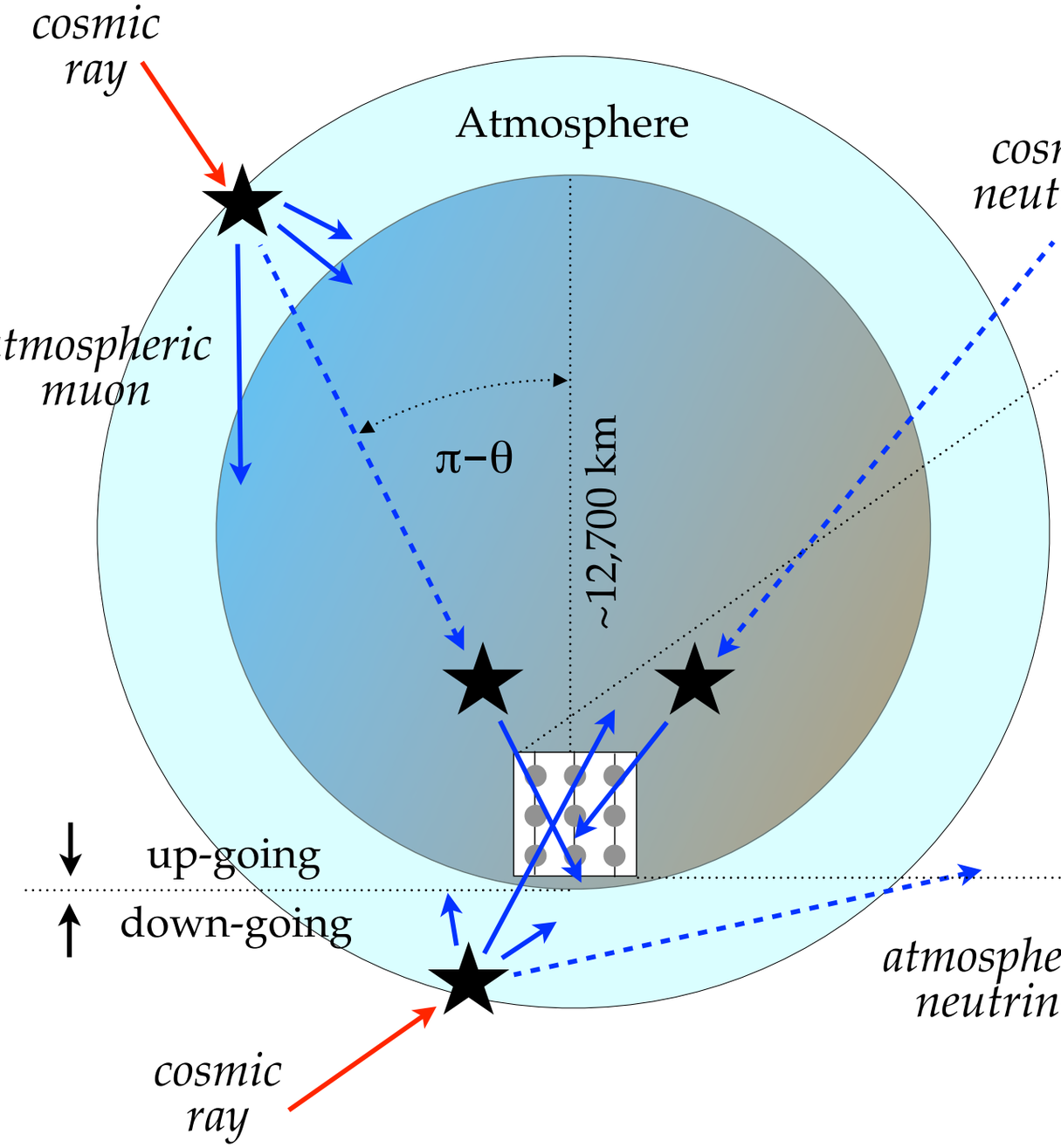
Glashow's example with modern inputs:

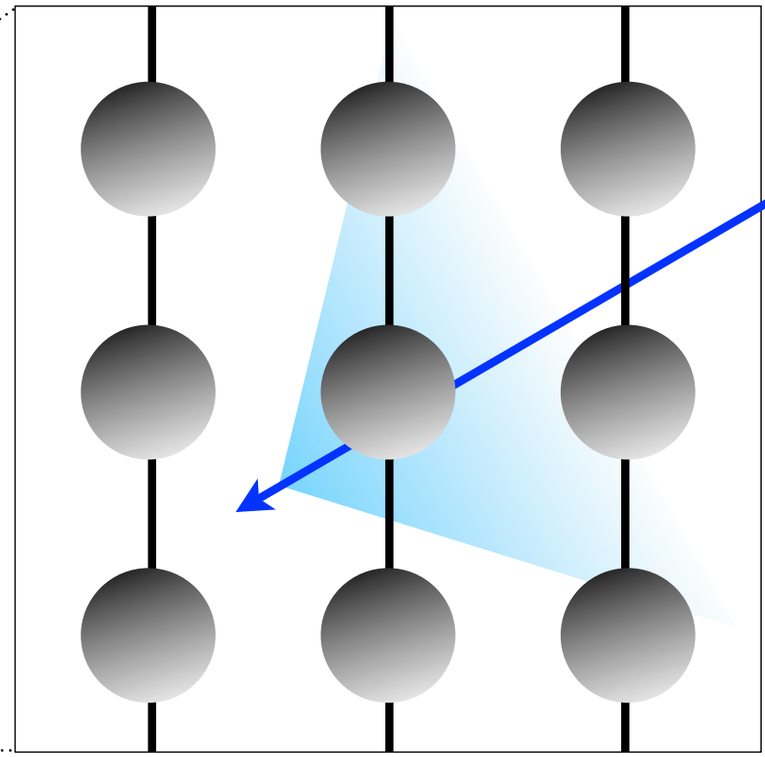
$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta} = \frac{1}{2\,s}\frac{1}{16\pi}\overline{\sum}|\mathcal{A}_{\bar{\nu}_e+e^-\to\mu^-+\bar{\nu}_\mu}|^2$$

$$8\pi^2 t^2 \left(\frac{\chi_w \alpha}{s_w^2}\right)\left(\frac{\chi_w \alpha}{s_w^2}\right)^* , \quad \chi_w = \frac{1}{s-\mu_w^2} , \quad t = -\frac{s}{2}(1-\cos\theta)$$

$$\chi_w \chi_w^* = \frac{1}{(s-m_w^2)^2 + \Gamma_w^2 M_w^2}$$

Sources of multi-TeV and PeV neutrinos





Cherenkov light detection in optical modules

Atmospheric: cosmic rays collide hit Earth's atmosphere
Astrophysical: neutrinos produced at cosmic-rays source