Charting GENIE4 roadmap
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Very high energy extension

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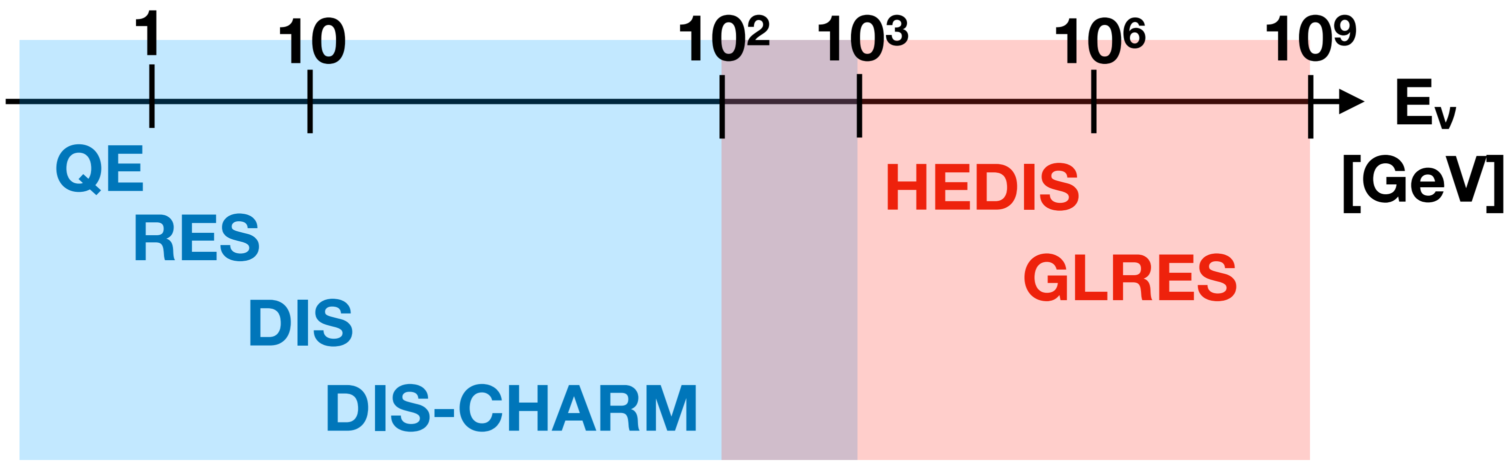
Overview:

- Current status of GENIE in the high energy regime:

    - DIS channel based on Bodek-Yang model -> optimised for the low Q^2 range.
    - BY model uses as input GRV98LO PDFs -> limited Q^2 range $[0.8, 2\cdot10^6]$.
    - Contributions from heavy quarks are not included (except for charm production).
    - Predictions above 1TeV become unreliable.

- We have been developing a new package (HEDIS) to overcome this limitation.

    - Newer PDFs with broader Q^2 phase space.
    - NLO QCD corrections in the structure functions.
    - Account for the heavy quark contributions.



Theory:

- DIS differential cross section is well known.
    - Structure functions (SF) include all the QCD information about the nucleons.
    - PDFs quantify the contribution from quarks (and gluon) in different regions of the phase space.

CC

$$\frac{d\sigma^{\nu,\bar{\nu}}}{dxdy} = \frac{G_F^2 M E_\nu}{\pi}\left[y\left(xy + \frac{m_l^2}{2E_\nu M}\right) F_1 + \left(1 - y - \frac{Mxy}{2E_\nu} - \frac{m_l^2}{4E_\nu^2}\right) F_2 \pm \left[xy\left(1-\frac{y}{2}\right) - y\frac{m_l^2}{4ME_\nu}\right] F_3 + \left(xy\frac{m_l^2}{2ME_\nu} + \frac{m_l^4}{4M^2E_\nu^2}\right) F_4 - \frac{m_l^2}{2ME_\nu} F_5 \right],$$

Structure Functions (x,Q^2)

$F_1^p\,[LO] = (F_2^p - F_L^p)/2x$

$F_2^p\,[LO] = 2x(d_v + d_s + s_s + b_s + \bar{u}_s + \bar{c}_s)$

$F_3^p\,[LO] = 2(d_v + d_s + s_s + b_s - \bar{u}_s - \bar{c}_s)$

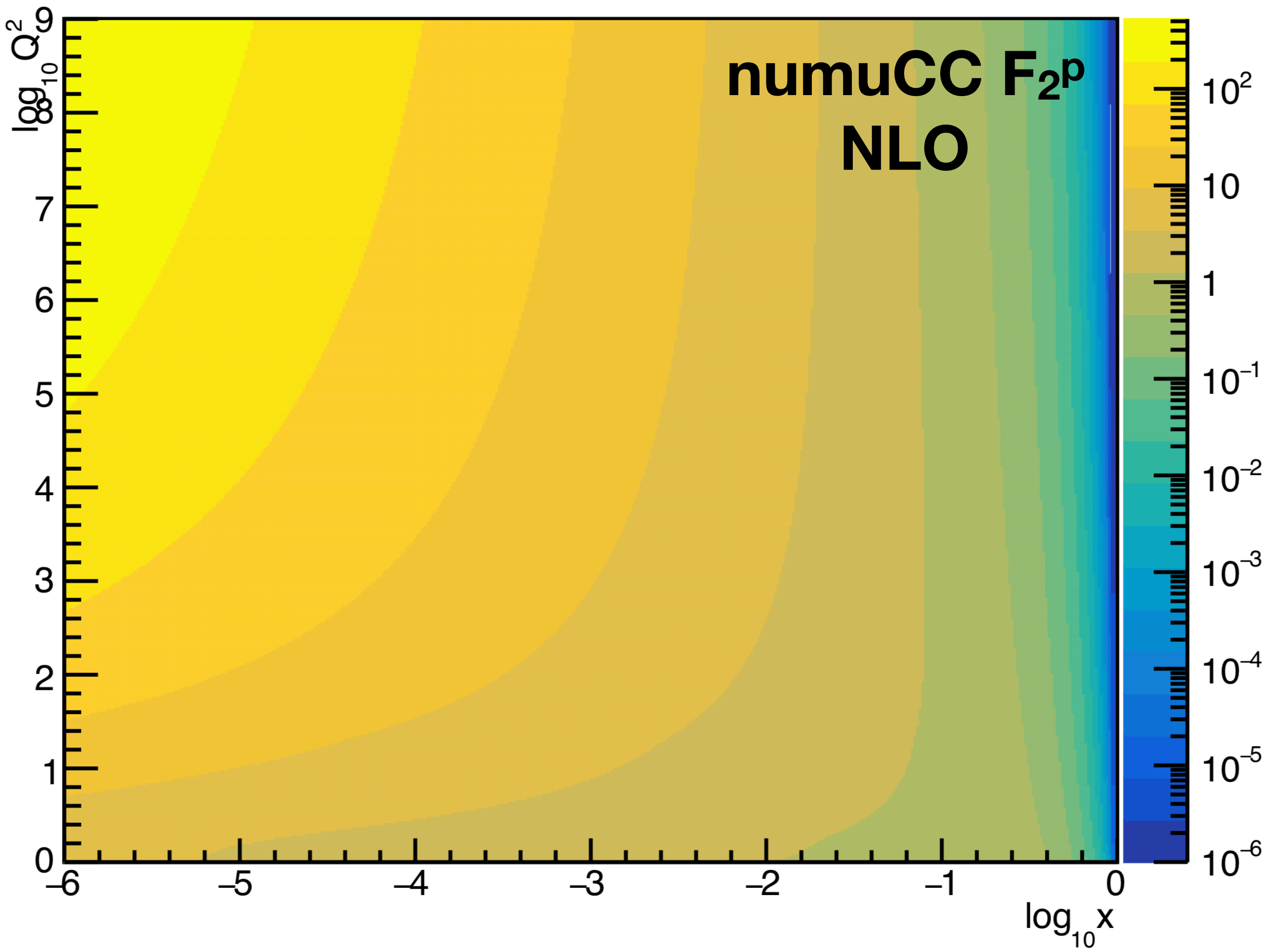
Parton Density Functions (x,Q^2)

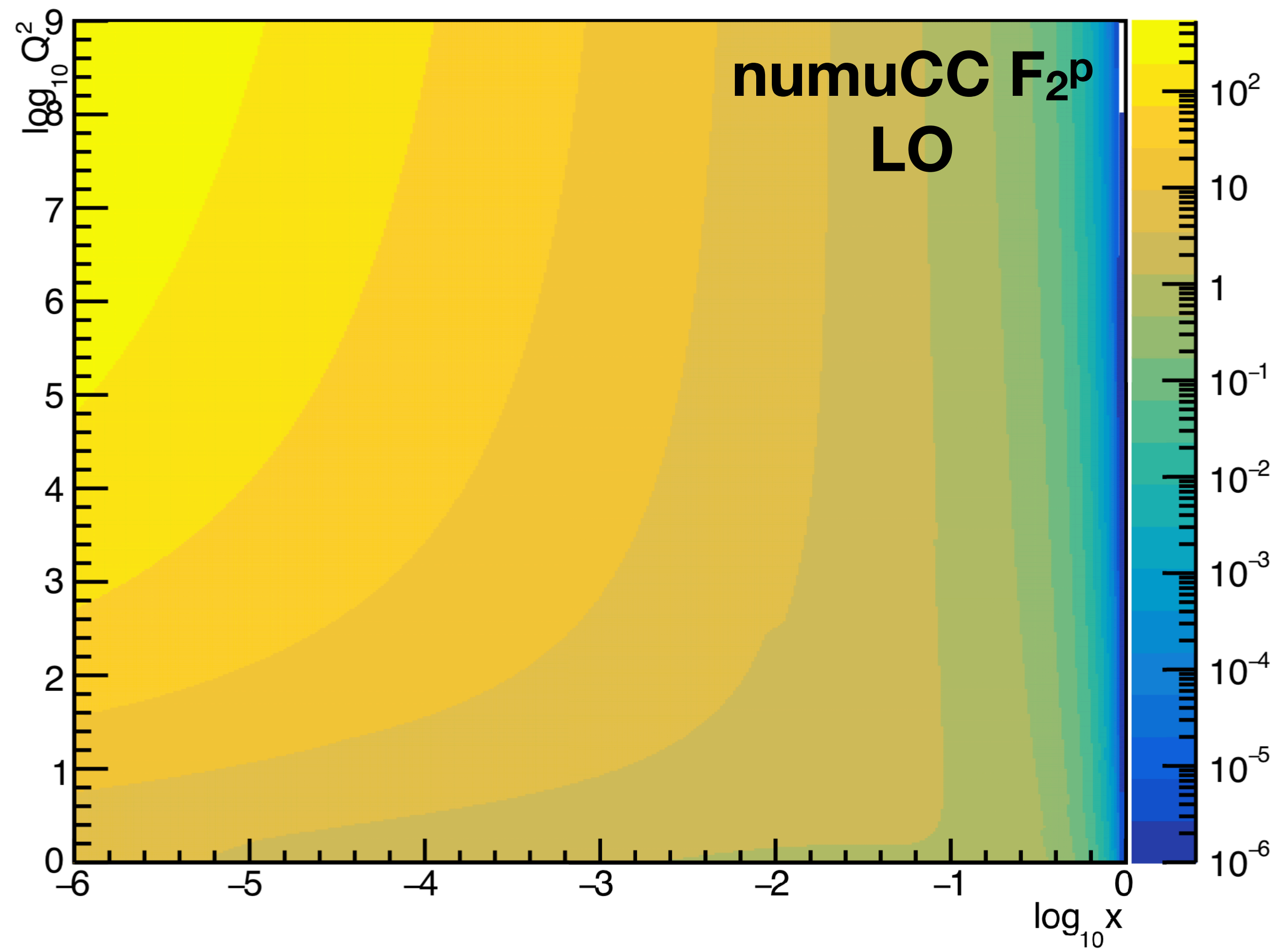
LO heavy quark → **F_i^p [LO] (z,Q^2), $z = x(1+m_{fq}^2/Q^2)$**

NLO → **DGLAP evolution equations**

Deliverables:

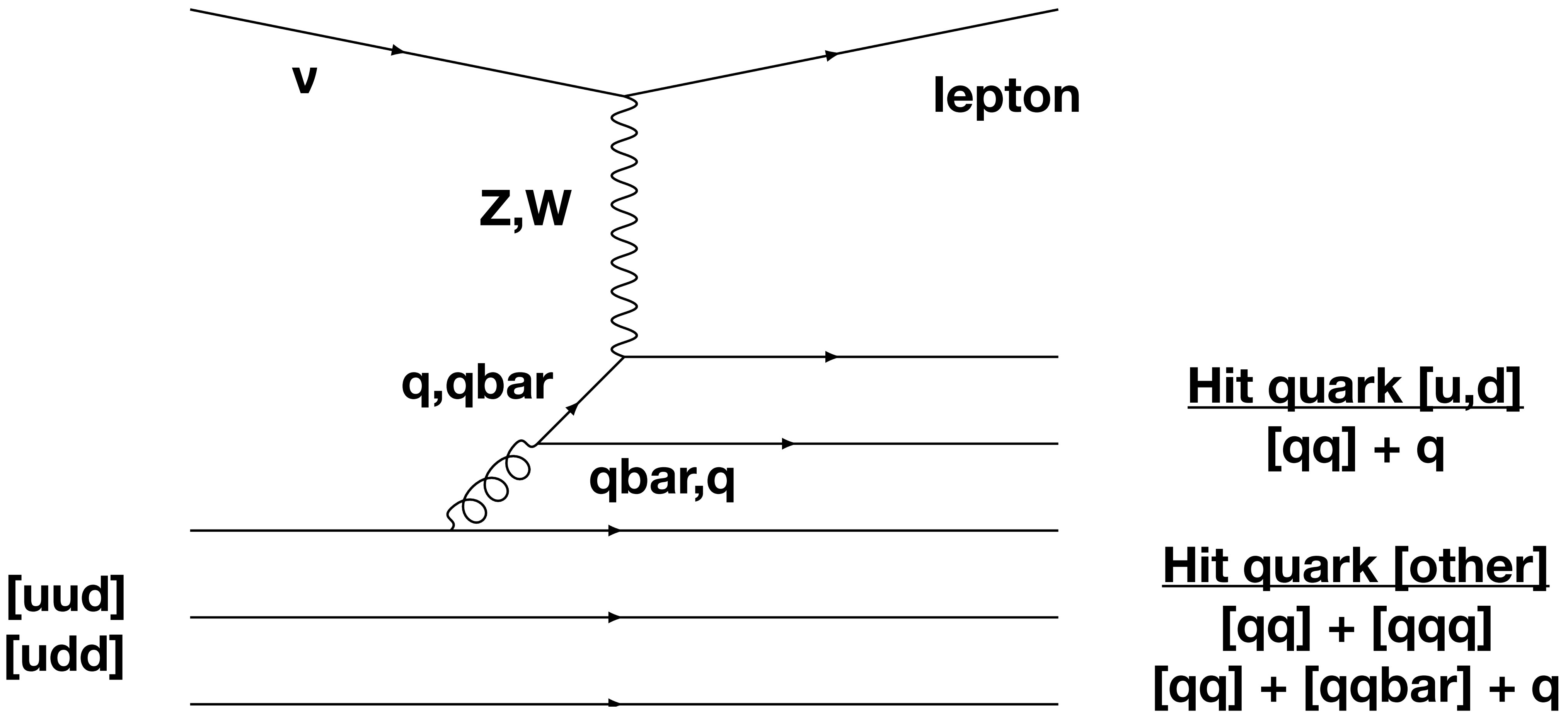
- Double differential cross section using LO or NLO QCD structure function .
  - New framework to compute $F_L^{p,n}$, $F_2^{p,n}$, $F_3^{p,n}$ using external software QCDNUM17, which interacts with LHAPDF6 to read the PDFs.
  - SF are stored in BLI2DNonUnifGrid [$\log_{10}x$,$\log_{10}Q2$], in the range of validity from the PDFs.
  - DDXsec calculated using precomputed (not on the fly) SF.
  - Currently assuming scalability to any nuclei.





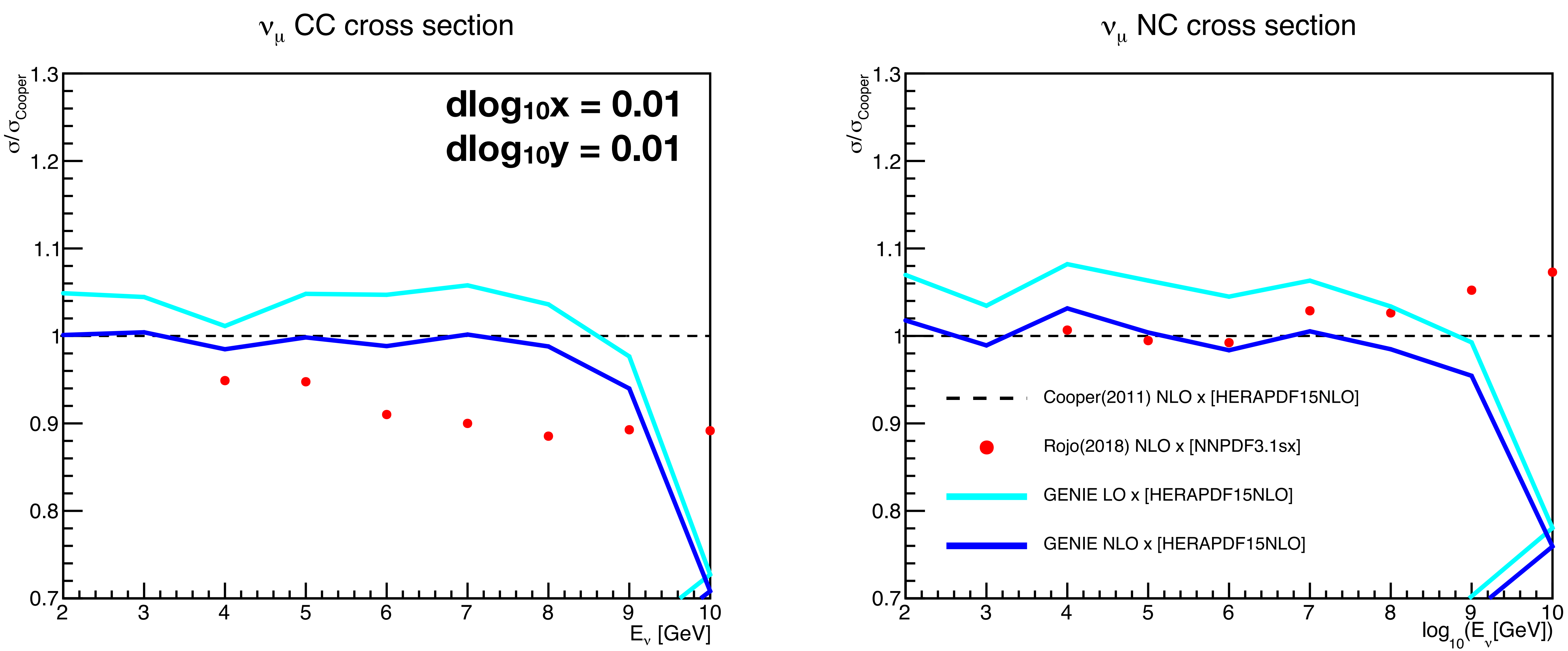
Deliverables:

- New hadronzation scheme to account for heavy quark production.
    - Contribution of each initial&final quark to the DDXSec is stored (using LO expression).
    - Hadronization started using hit/struck quark method (similar to current implementation).
    - Core of the hadronization is handle by PYTHIA6.
    - Top quark forced to decay before hadronizing.



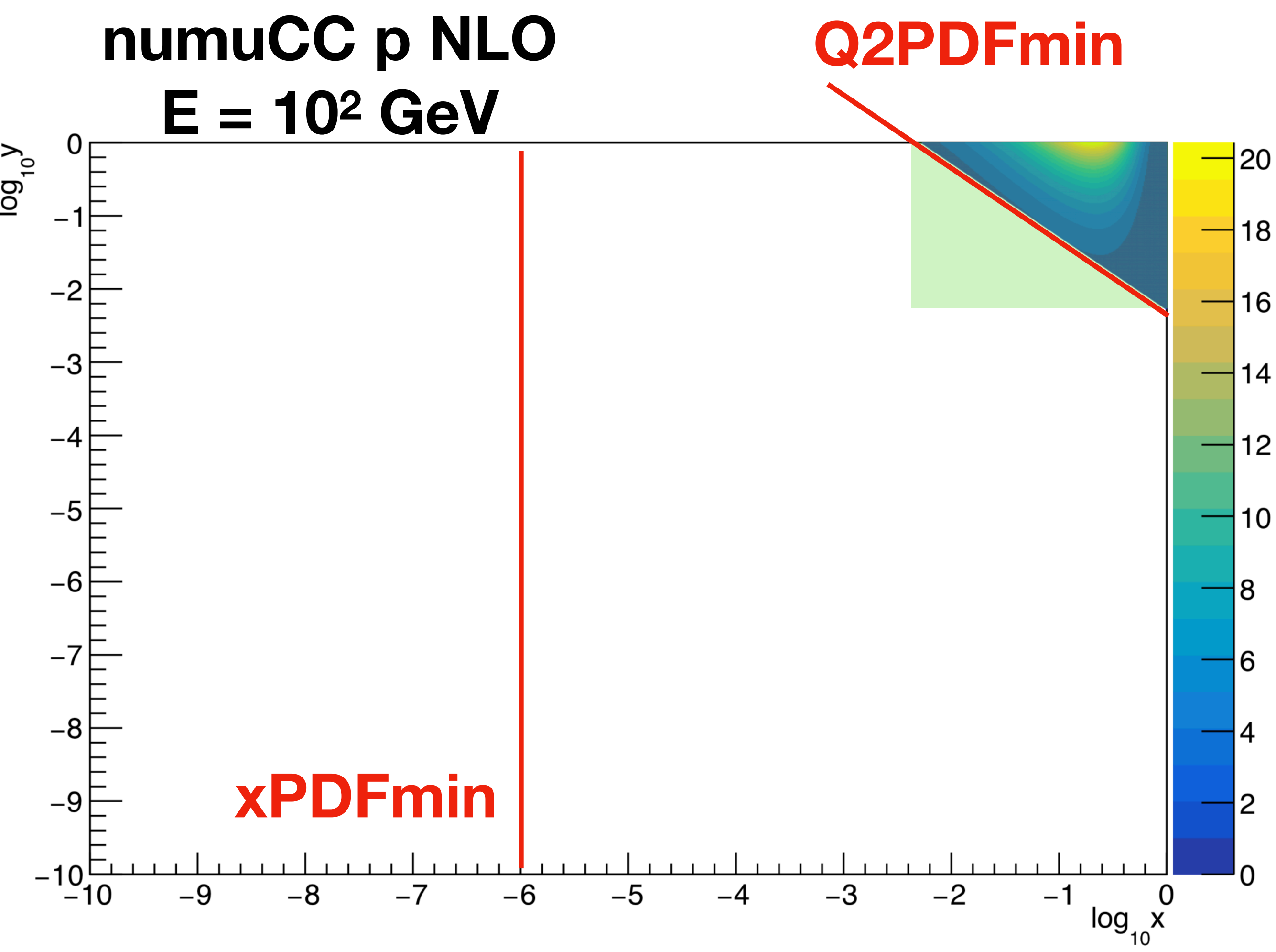
Implementation:

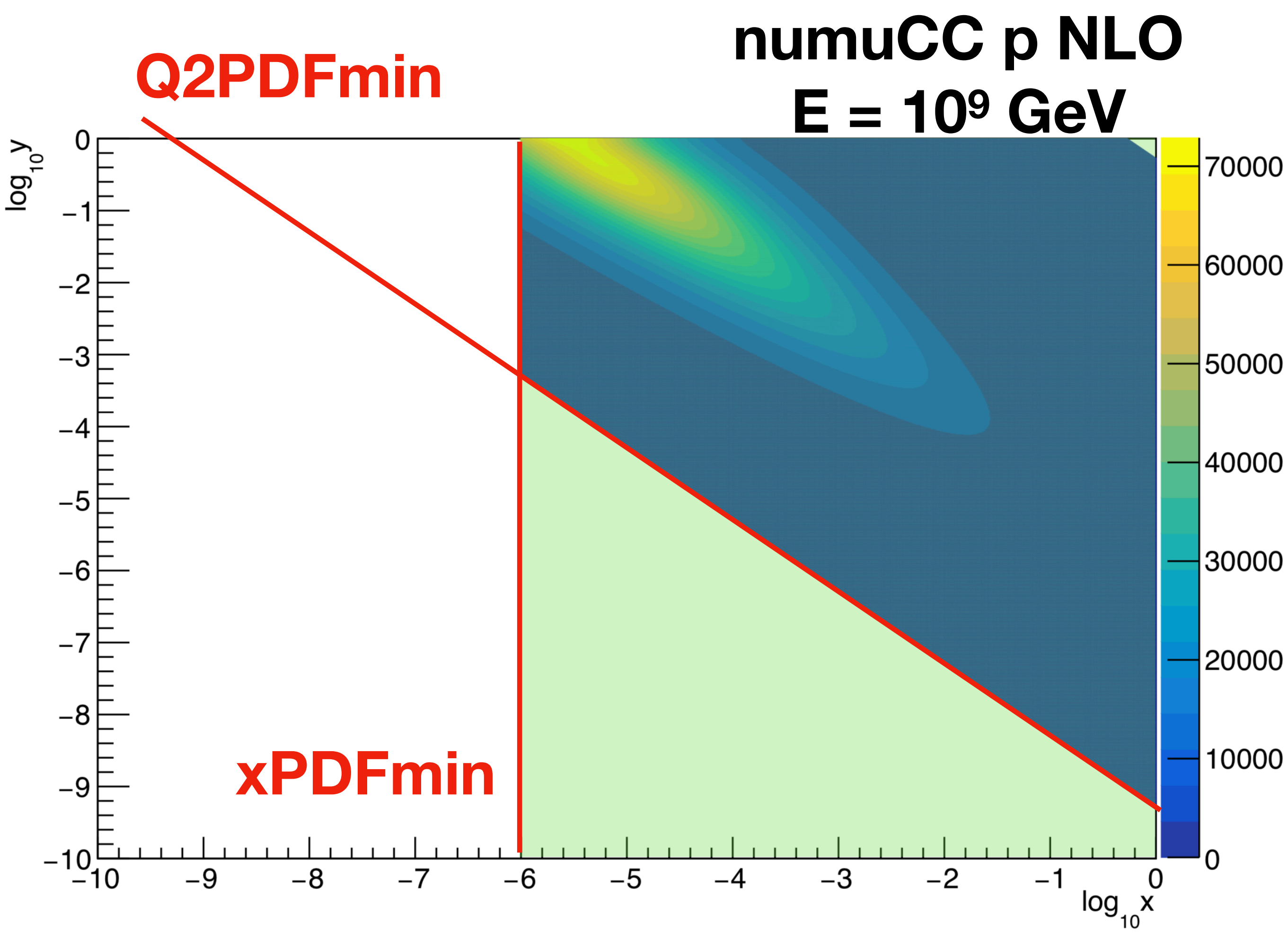
- Integrated cross section:
  - Using a simple grid [$\log_{10}x$,$\log_{10}y$] we can get very similar performance to MC methods.
    - Maximal xsec for each energy is obtained "for free".



Implementation:

- Sampling kinematics -> great improvement in speed (x30)!
  - MaxXsec for different energies loaded from ASCII files in Splines.
  - Random generation using $\log_{10}x$,$\log_{10}y$ and restricting to the PDFs valid phase space.

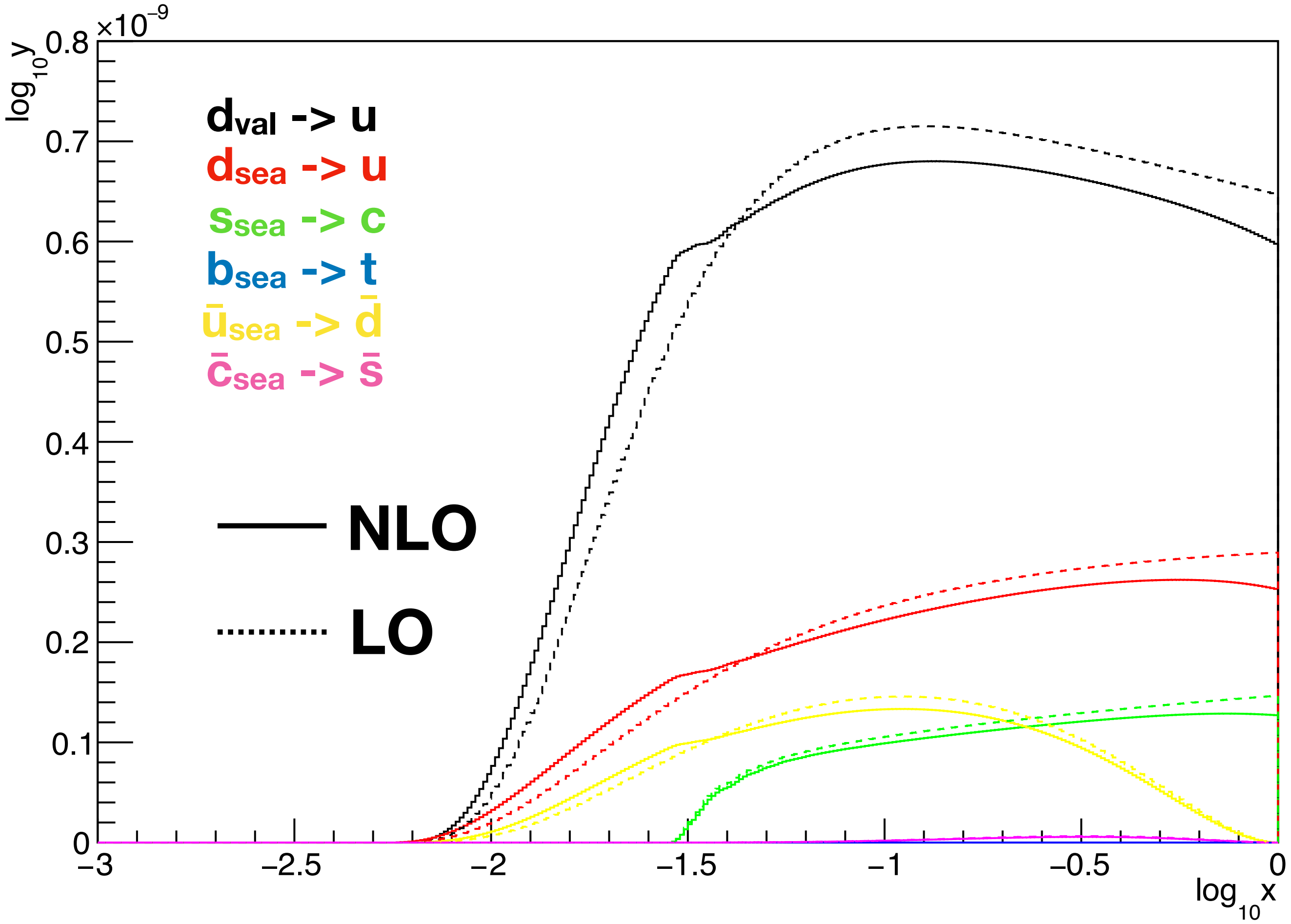




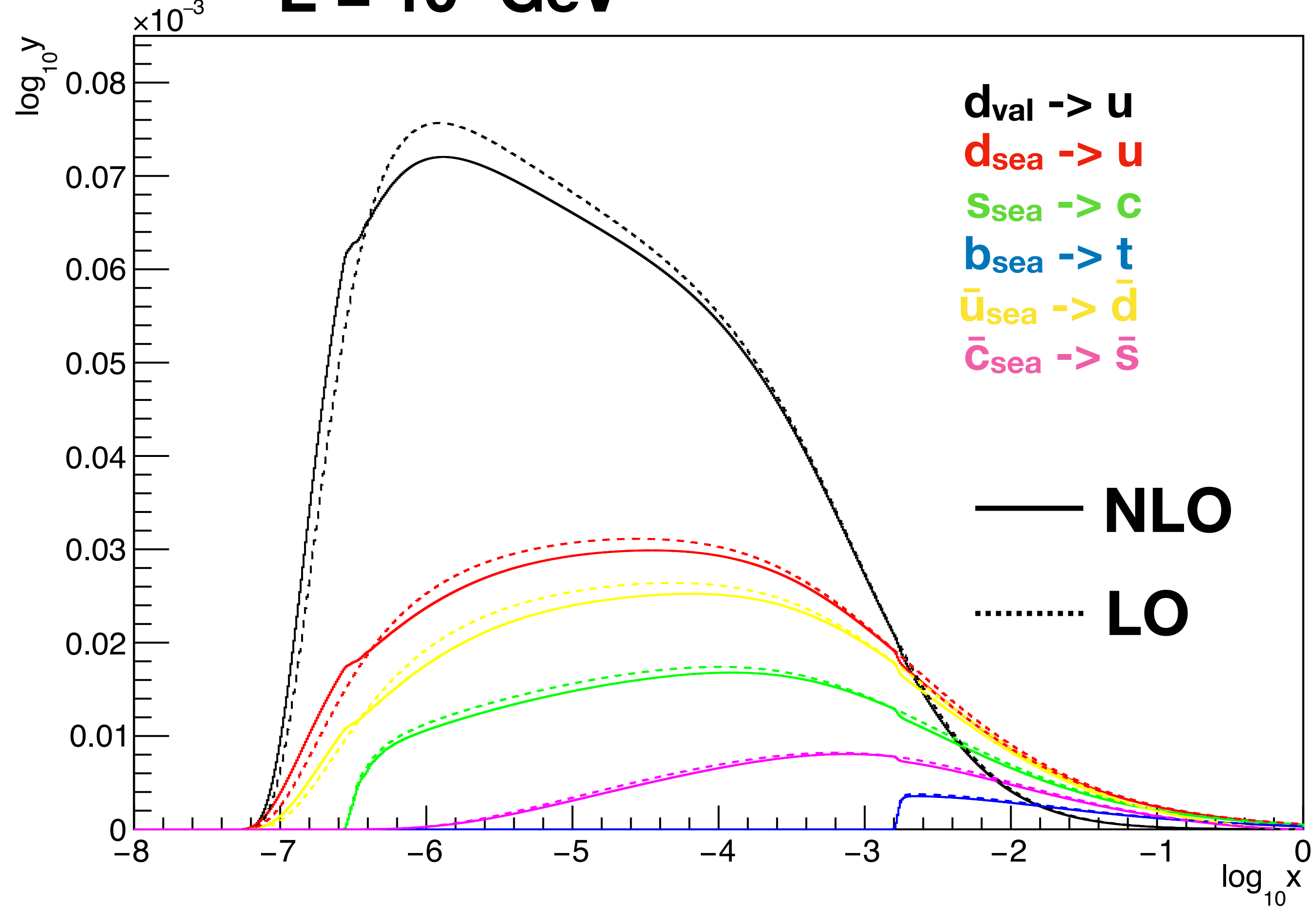
Implementation:

- Hadronization:
  - At NLO the parton picture is not valid anymore -> more complex hadronization.
  - In order to use the parton picture we quantify the contribution from each quark at LO to the DDXSec for each nucleon.

numuCC p
E = 10^2 GeV



numuCC p
E = 10^7 GeV



Implementation:

- Outgoing particles:
  - No initial/final nuclear effects are taking into account.
  - Less restrictions in the “on-shell” of outgoing particles (dominated by precision of double).

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|---------------------------------------------------------------------------------------------------------------------|
|GENIE GHEP Event Record [print level:   3]                                                                           |
|---------------------------------------------------------------------------------------------------------------------|
| Idx |       Name | Ist |        PDG |   Mother  | Daughter  |      Px |      Py |      Pz |       E |       m  |
|---------------------------------------------------------------------------------------------------------------------|
|   0 |      nu_mu |   0 |         14 |  -1 |  -1 |   4 |   4 |   0.000 |   0.000 | 100000000.000 | 100000000.000 |   0.000 |
|   1 |        O16 |   0 | 1000080160 |  -1 |  -1 |   2 |   3 |   0.000 |   0.000 |   0.000 |  14.895 |  14.895 |
|   2 |    neutron |  11 |       2112 |   1 |  -1 |   5 |   5 |   0.000 |   0.000 |   0.000 |   0.940 |   0.940 |
|   3 |        O15 |   1 | 1000080150 |   1 |  -1 |  -1 |  -1 |  -0.000 |  -0.000 |  -0.000 |  13.971 |  13.971 |
|   4 |        mu- |   1 |         13 |   0 |  -1 |  -1 |  -1 |  51.242 |  -2.051 | 99566238.801 | 99566238.801 | **0.106 | M = 0.000
|   5 |   HadrSyst |  12 | 2000000001 |   2 |  -1 |   6 |   7 | -51.242 |   2.051 | 433761.199 | 433762.138 | **0.000 | M = 901.362
|   6 |          u |  12 |          2 |   5 |  -1 |   8 |   8 | -51.032 |   2.279 | 433761.438 | 433761.441 | **0.330 | M = 0.310
|   7 |       ud_0 |  12 |       2101 |   5 |  -1 |   8 |   8 |  -0.210 |  -0.228 |  -0.248 |   0.689 | **0.579 | M = 0.562
|   8 |     string |  12 |         92 |   6 |  -1 |   9 |  24 | -51.242 |   2.051 | 433761.190 | 433762.130 | **0.000 | M = 901.362
|   9 |        eta |  12 |        221 |   8 |  -1 |  25 |  27 |  -3.155 |   0.143 | 27211.064 | 27211.064 |   0.547 |
|  10 |        pi0 |  12 |        111 |   8 |  -1 |  28 |  29 |  -2.812 |  -0.012 | 24382.528 | 24382.529 |   0.135 |
|  11 |        pi+ |   1 |        211 |   8 |  -1 |  -1 |  -1 | -12.867 |   0.208 | 109111.665 | 109111.666 |   0.140 |
|  12 |        pi0 |  12 |        111 |   8 |  -1 |  30 |  31 |  -3.439 |   0.750 | 26935.912 | 26935.912 |   0.135 |
|  13 |        K*0 |  12 |        313 |   8 |  -1 |  32 |  33 | -17.745 |   0.904 | 156591.819 | 156591.820 | **0.896 | M = 0.878
|  14 |         K- |   1 |       -321 |   8 |  -1 |  -1 |  -1 |  -4.702 |   0.017 | 35668.433 | 35668.434 |   0.494 |
|  15 |        pi+ |   1 |        211 |   8 |  -1 |  -1 |  -1 |  -1.477 |   0.813 | 12064.206 | 12064.207 |   0.140 |
|  16 |       rho- |  12 |       -213 |   8 |  -1 |  34 |  35 |  -4.524 |  -1.131 | 33585.325 | 33585.326 | **0.767 | M = 0.690
|  17 |        pi+ |   1 |        211 |   8 |  -1 |  -1 |  -1 |   0.342 |   0.844 | 2419.853 | 2419.853 |   0.140 |
|  18 |        pi0 |  12 |        111 |   8 |  -1 |  36 |  37 |   0.033 |  -0.023 |  29.972 |  29.972 |   0.135 |
|  19 |       rho- |  12 |       -213 |   8 |  -1 |  38 |  39 |  -0.831 |  -0.243 | 5720.206 | 5720.207 | **0.767 | M = 0.708
|  20 |       rho+ |  12 |        213 |   8 |  -1 |  40 |  41 |  -0.039 |  -0.554 |  31.815 |  31.828 | **0.767 | M = 0.717
|  21 |        pi0 |  12 |        111 |   8 |  -1 |  42 |  43 |  -0.040 |   0.102 |   0.009 |   0.175 |   0.135 |
|  22 |         K0 |  12 |        311 |   8 |  -1 |  44 |  44 |   0.599 |   0.538 |   5.309 |   5.393 |   0.498 |
|  23 |        K*- |  12 |       -323 |   8 |  -1 |  45 |  46 |  -0.723 |  -0.251 |   1.902 |   2.240 | **0.892 | M = 0.902
|  24 |     proton |   1 |       2212 |   8 |  -1 |  -1 |  -1 |   0.138 |  -0.053 |   1.176 |   1.512 |   0.938 |
|  25 |        pi0 |  12 |        111 |   9 |  -1 |  47 |  48 |  -1.178 |  -0.095 | 9491.799 | 9491.799 |   0.135 |
|  26 |        pi0 |  12 |        111 |   9 |  -1 |  49 |  50 |  -1.238 |   0.110 | 11081.490 | 11081.490 |   0.135 |
|  27 |        pi0 |  12 |        111 |   9 |  -1 |  51 |  52 |  -0.739 |   0.128 | 6637.775 | 6637.775 |   0.135 |
|  28 |      gamma |   1 |         22 |  10 |  -1 |  -1 |  -1 |  -1.522 |  -0.054 | 13610.820 | 13610.820 | **0.000 | M = -0.003
|  29 |      gamma |   1 |         22 |  10 |  -1 |  -1 |  -1 |  -1.290 |   0.041 | 10771.708 | 10771.708 | **0.000 | M = 0.002
|  30 |      gamma |   1 |         22 |  12 |  -1 |  -1 |  -1 |  -2.332 |   0.559 | 18637.051 | 18637.051 | **0.000 | M = 0.004
|  31 |      gamma |   1 |         22 |  12 |  -1 |  -1 |  -1 |  -1.107 |   0.191 | 8298.862 | 8298.862 | **0.000 | M = 0.002
|  32 |         K0 |  12 |        311 |  13 |  -1 |  53 |  53 | -10.298 |   0.255 | 90891.261 | 90891.262 |   0.498 |
|  33 |        pi0 |  12 |        111 |  13 |  -1 |  54 |  55 |  -7.447 |   0.649 | 65700.554 | 65700.555 |   0.135 |
|  34 |        pi- |   1 |       -211 |  16 |  -1 |  -1 |  -1 |  -1.120 |  -0.533 | 9738.346 | 9738.346 |   0.140 |
|  35 |        pi0 |  12 |        111 |  16 |  -1 |  56 |  57 |  -3.404 |  -0.598 | 23846.980 | 23846.980 |   0.135 |
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Conclusions:

- HEDIS package: **https://github.com/pochoarus/GENIE-HEDIS**
  - DIS cross section using NLO QCD expressions.
  - Hadronization including heavy quarks.

- Disclaimer:
  - Package has been tested for high energies.
    - Used PDFs are not suitable for low Q^2 region.
    - New integrated cross section and sampling methods are optimal above 100GeV.
    - Very simplistic picture of nuclear effects.
  - At low energies all these aspects should be reviewed.

- Look into the future:
  - Compare QCDNUM with other softwares (APFEL).
  - Couple NLO matrix elements to NLO parton showering (using PYTHIA8?).