Charting GENIE4 roadmap
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Very high energy extension

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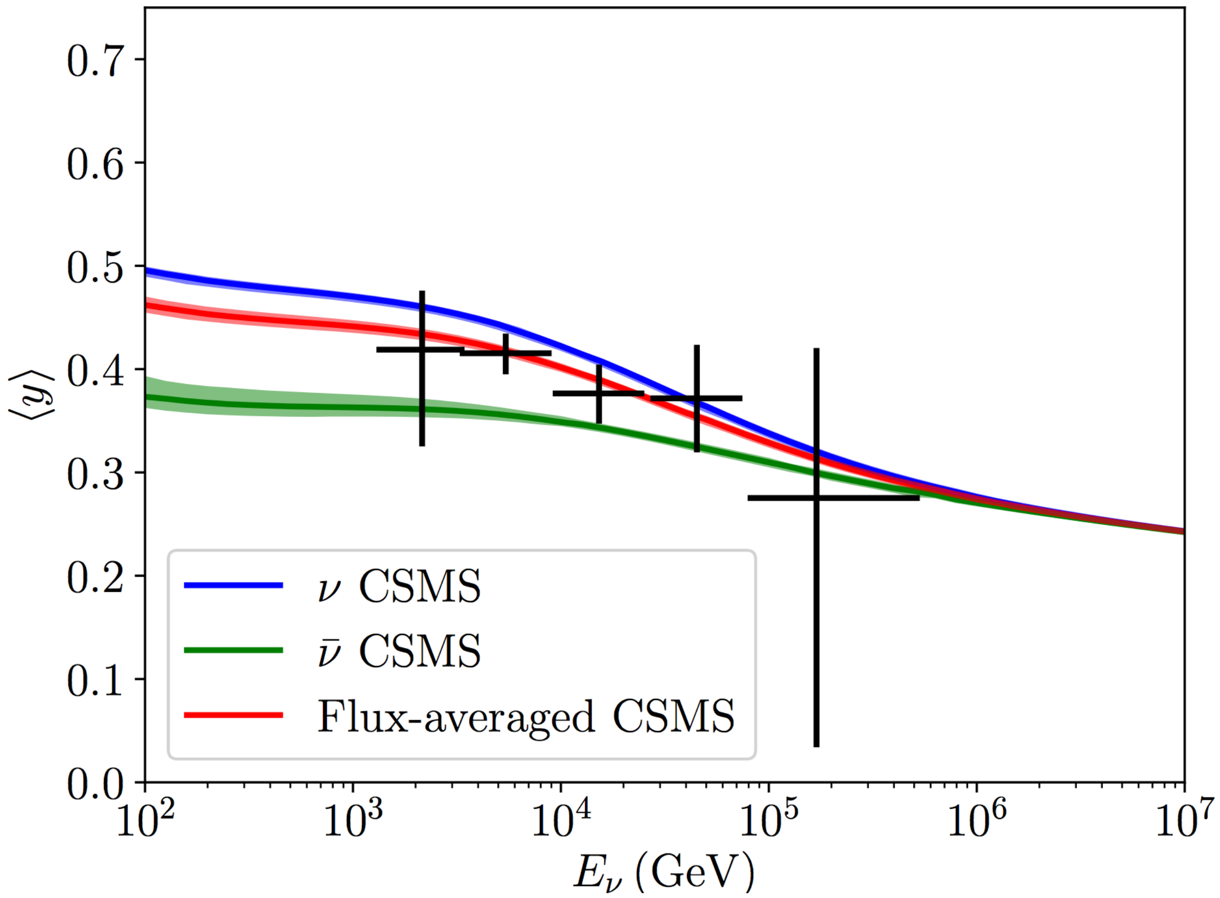
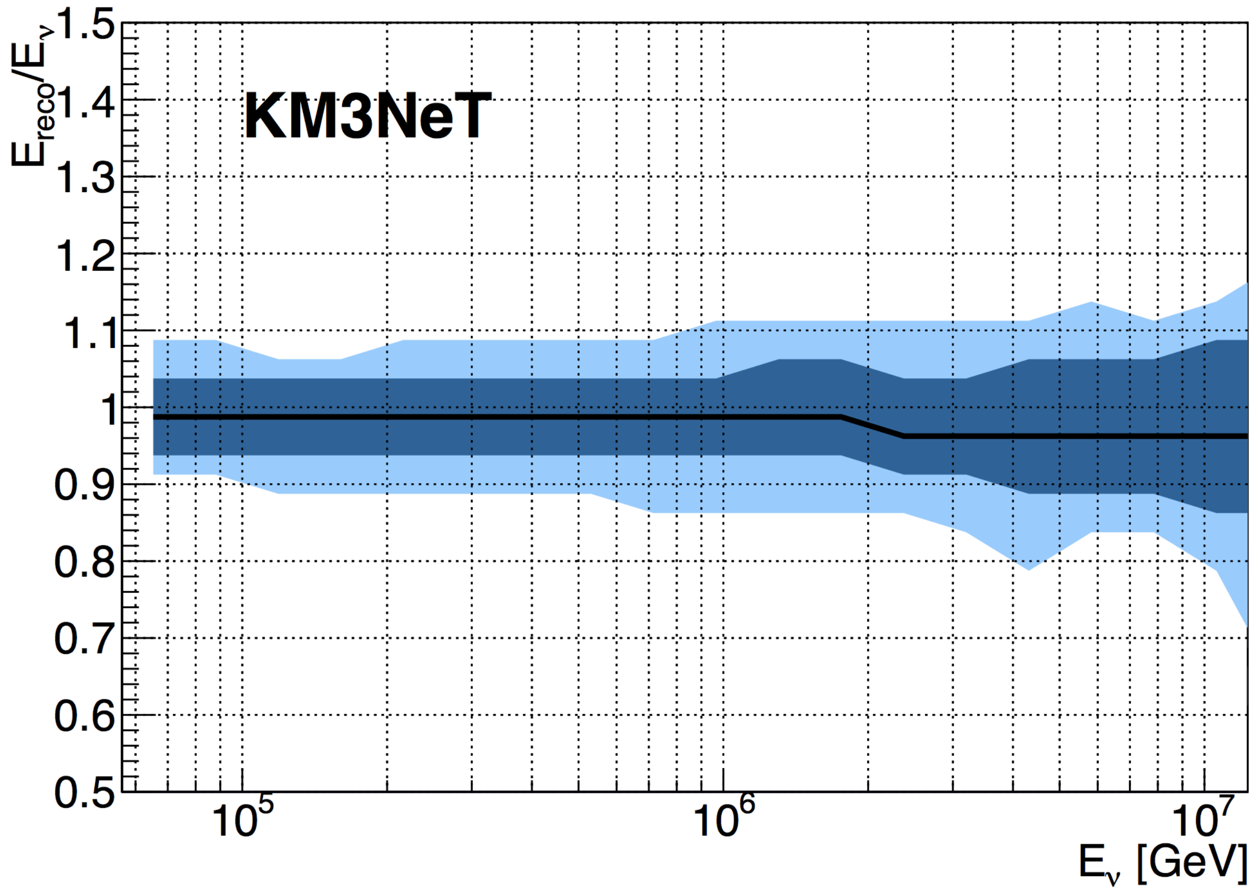
Motivation:

- Neutrino astronomy is rapidly moving forward.
- Such detectors can be used to do particle physics!
  - First measurements of cross sections at high energies from IceCube.
  - Performance from KM3NeT/ARCA will be very valuable.

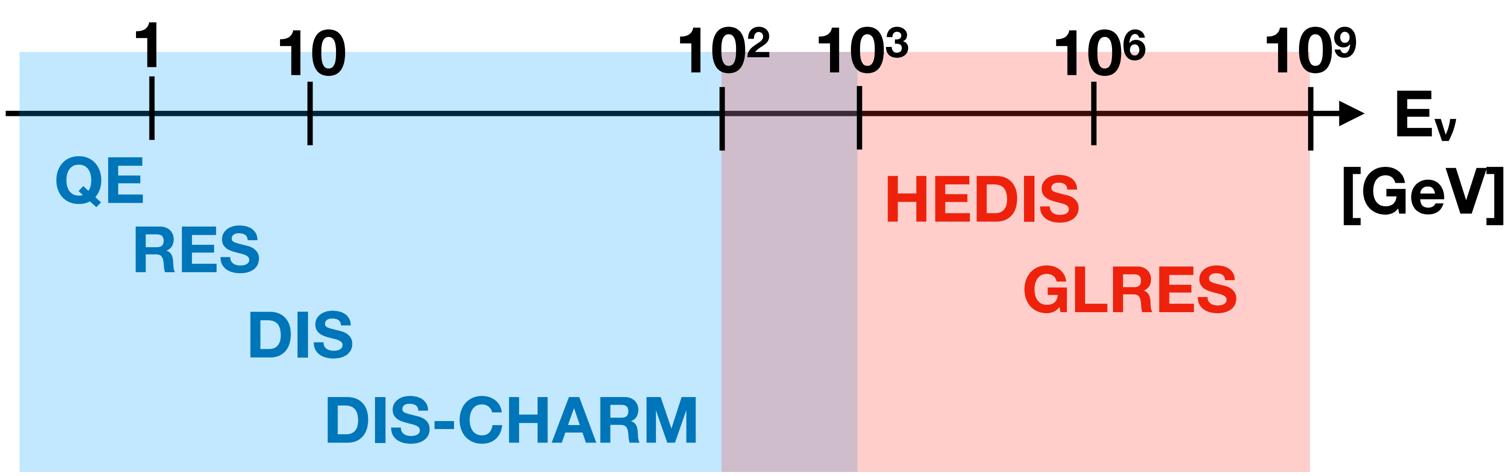




- Reliable simulations are needed.
  - GENIE offers the perfect framework.

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 [0.8,2·10^6].
    - 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.

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

Structure Functions (x,Q²)

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,Q²)

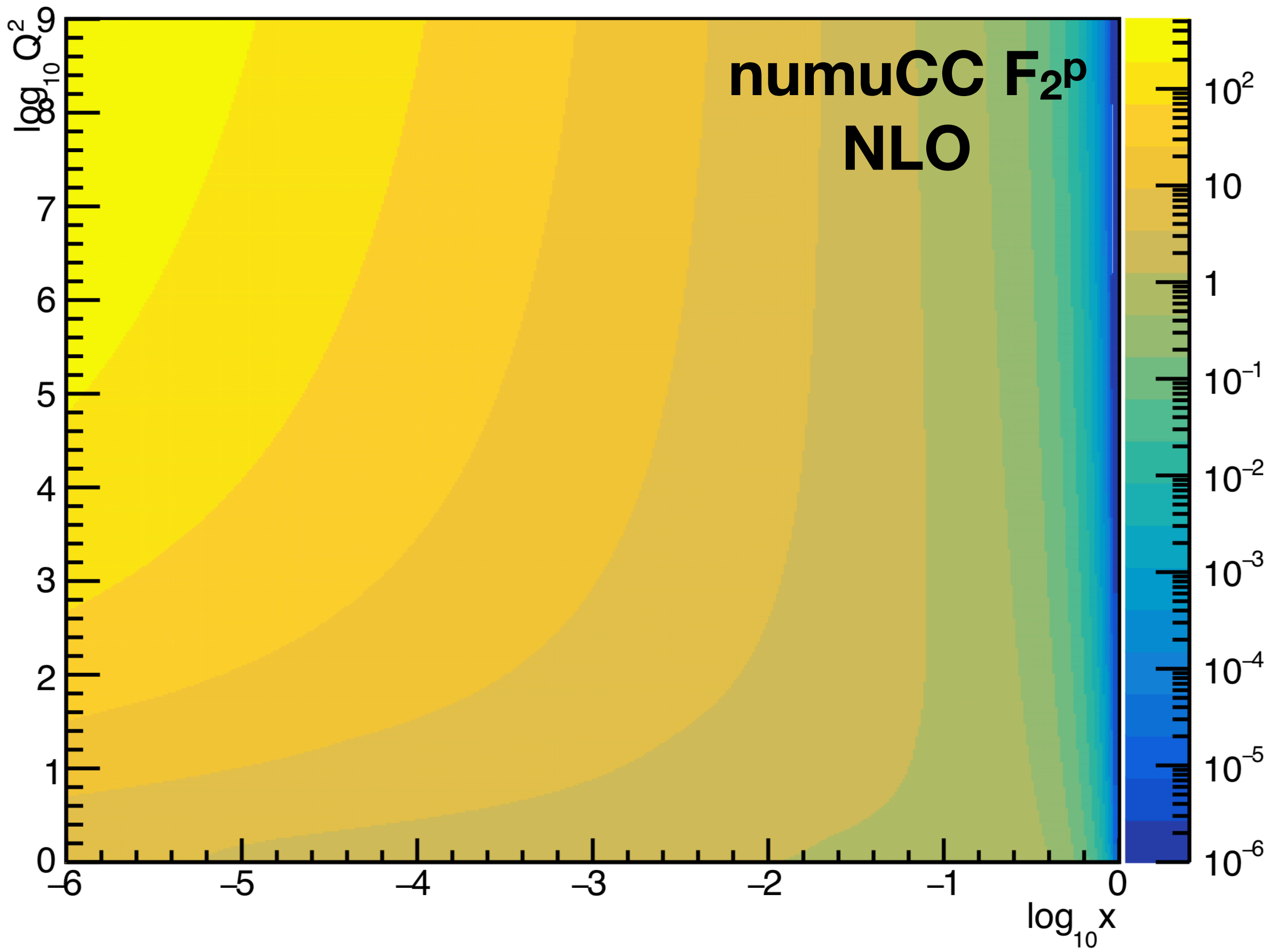
LO heavy quark → F_i^p [LO] (z,Q^2)

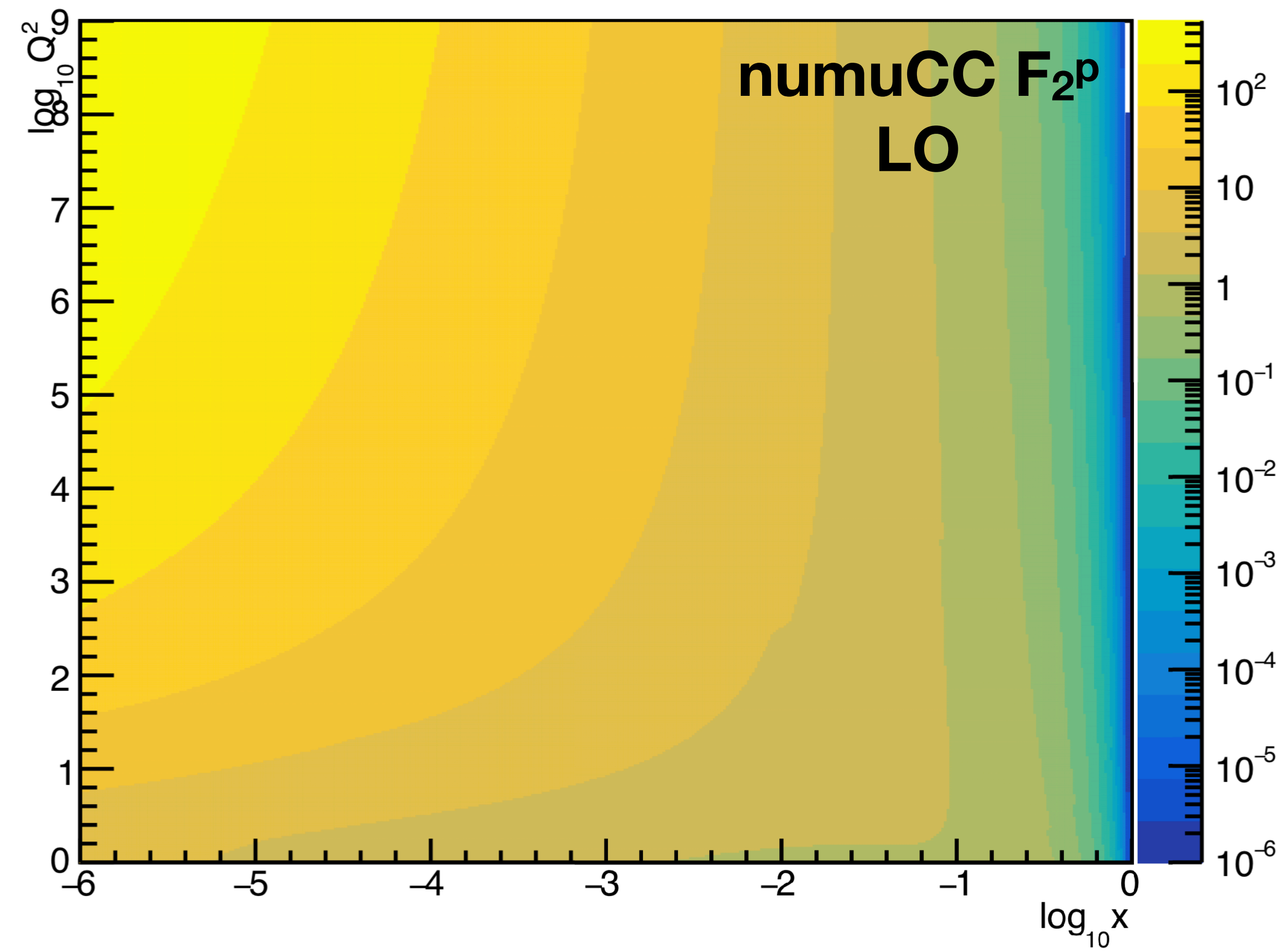
$z = x(1+m_{fq}^2/Q^2)$

NLO → **DGLAP evolution equations**

Deliverables:

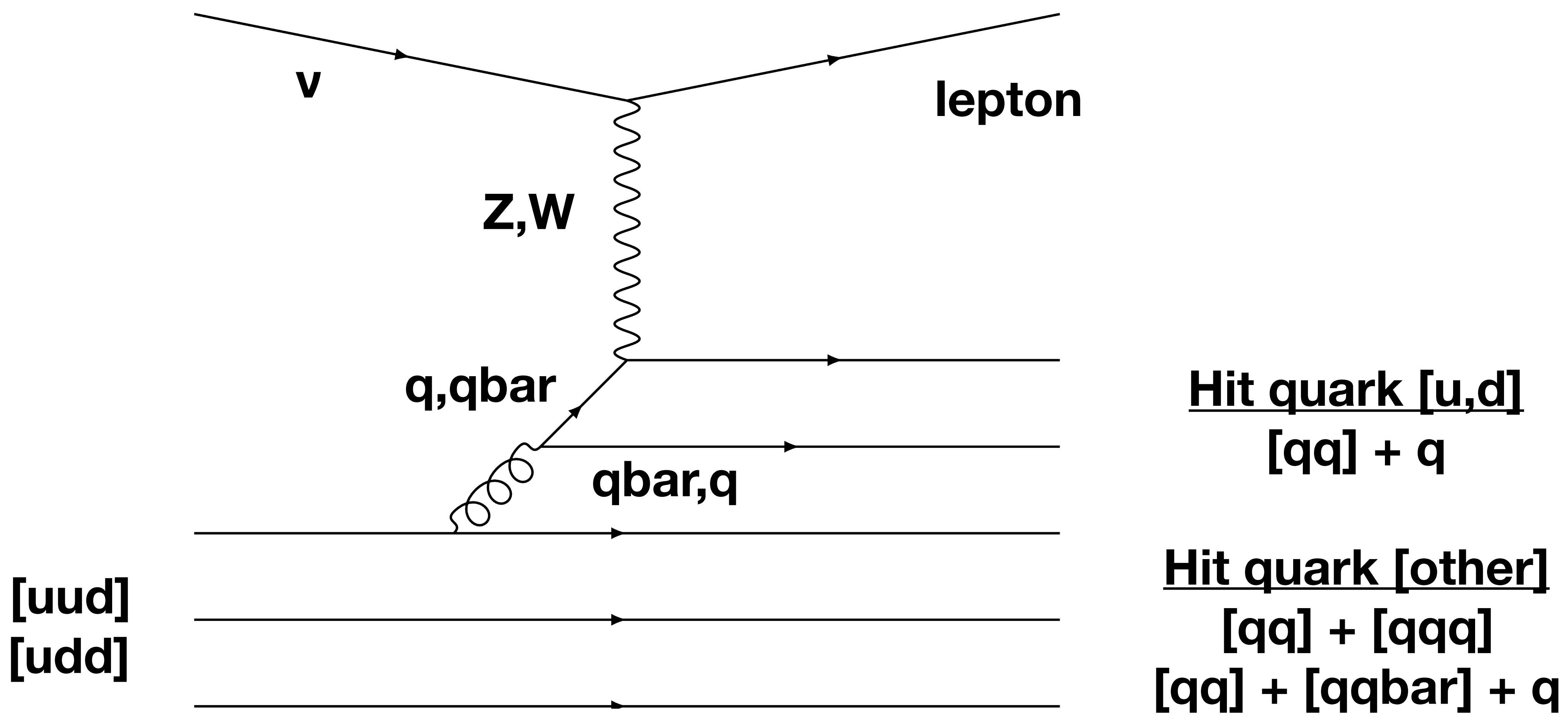
- Double differential cross section using LO or NLO QCD structure function .
    - New framework to compute $F_L^{p,n}$, $F_2^{p,n}$, $F_3^{p,n}$ using external software QCDNUM17, which interacts with LHAPDF6 to read the PDFs.
    - SF are stored in BLI2DNonUnifGrid [$\log_{10}x$,$\log_{10}Q2$], in the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





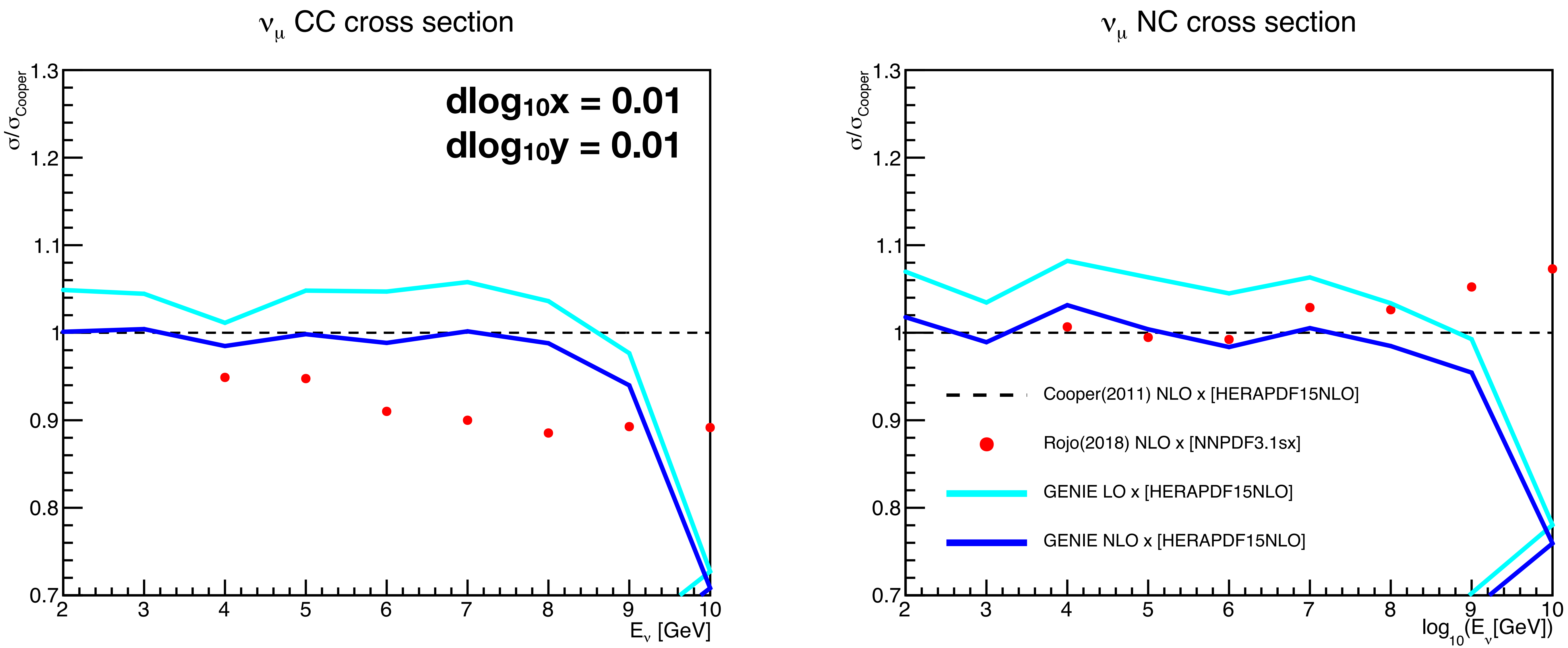
Deliverables:

- 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.



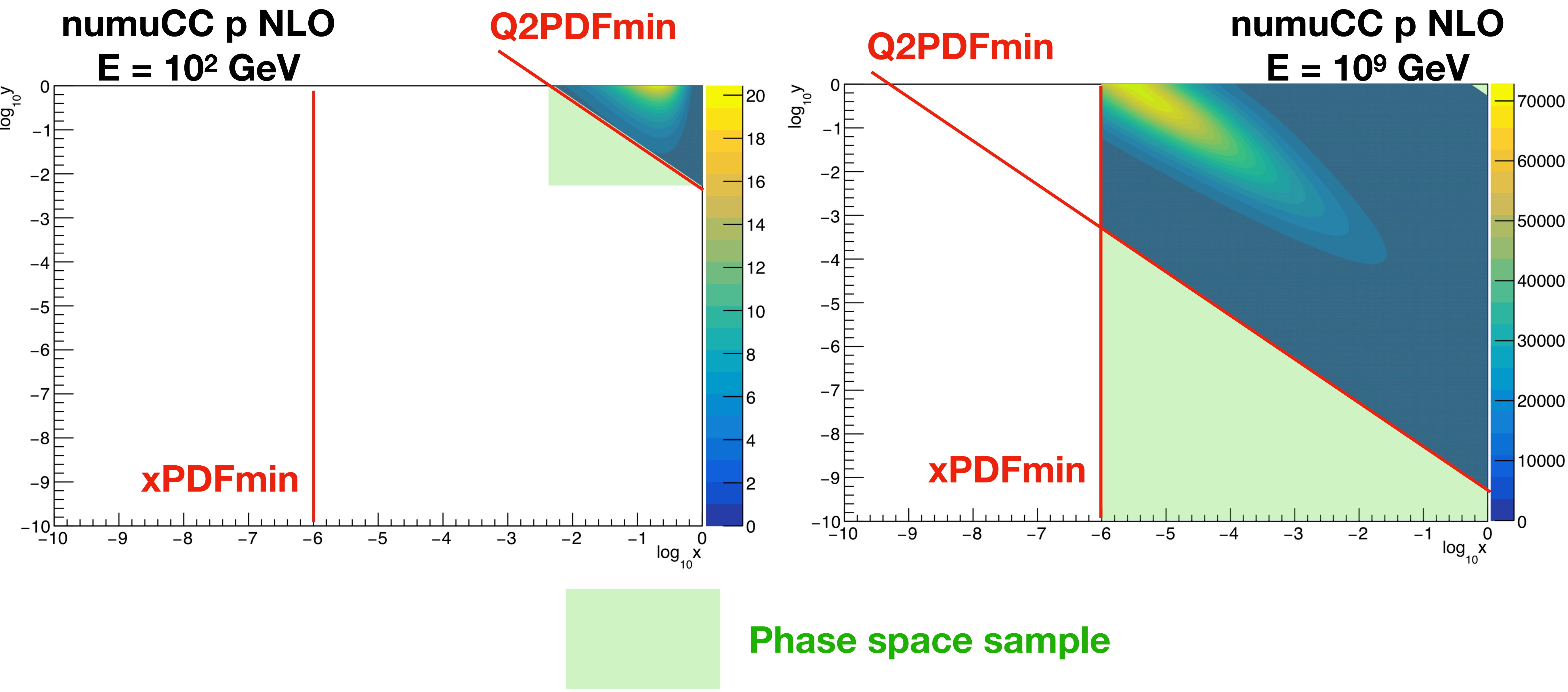
Implementation:

- 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:

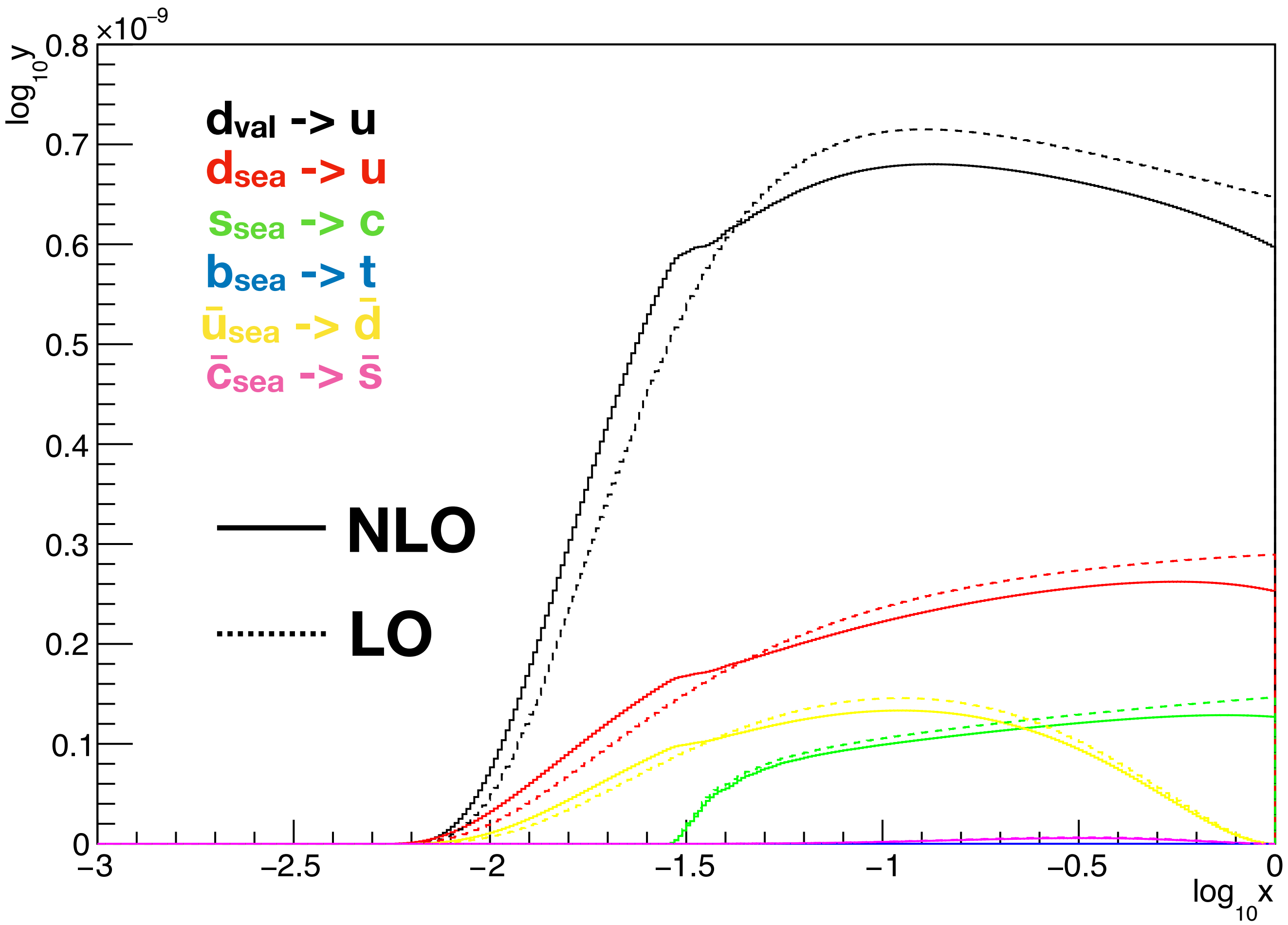
- Sampling kinematics -> great improvement in speed (x30)!
  - MaxXsec for different energies loaded from ASCII files in Splines.
  - Random generation using $\log_{10}x$,$\log_{10}y$ and restricting to the PDFs valid phase space.



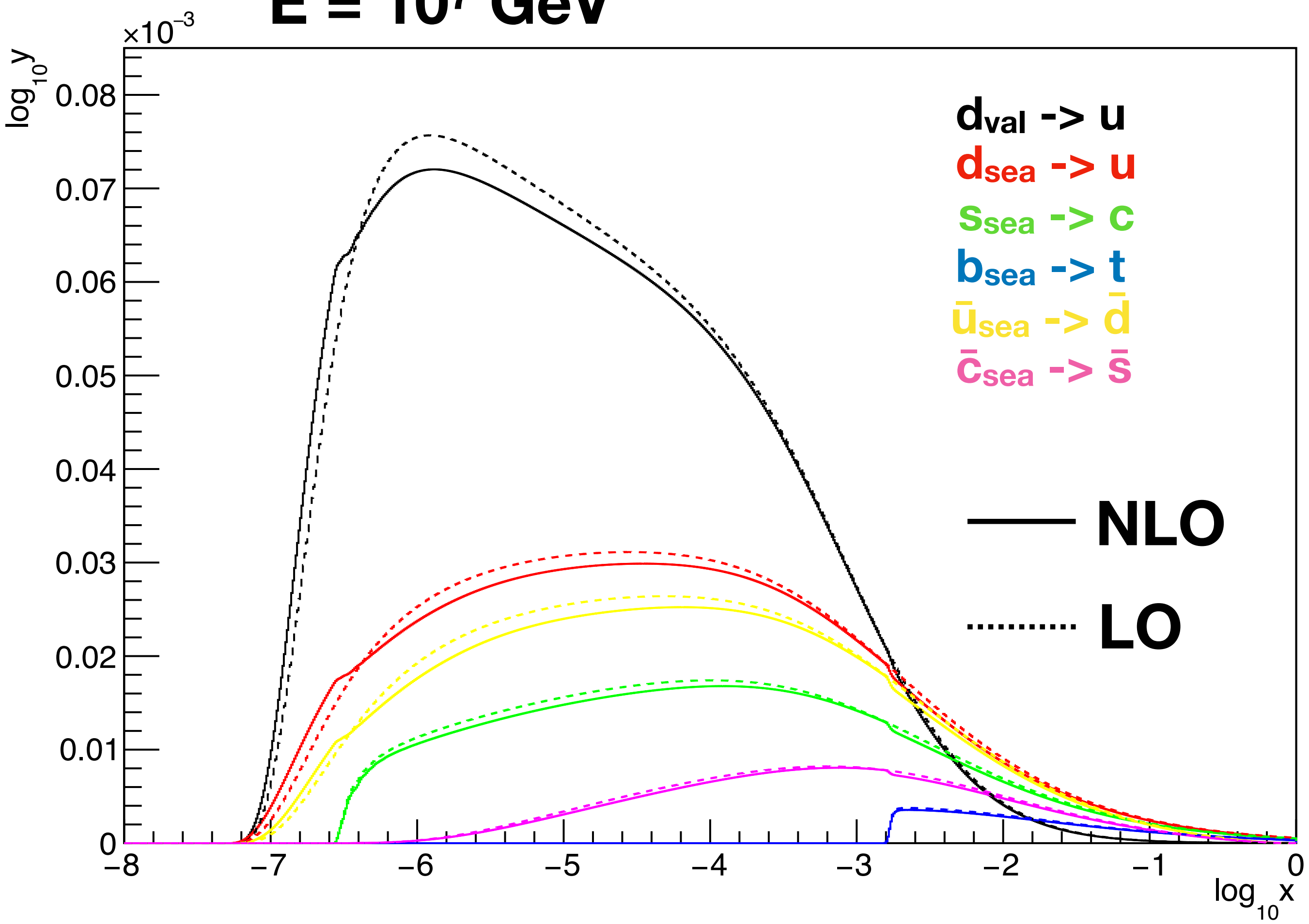
Implementation:

- 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 = 10² GeV



numuCC p
E = 10⁷ 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).

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?).