It was the year of 1995

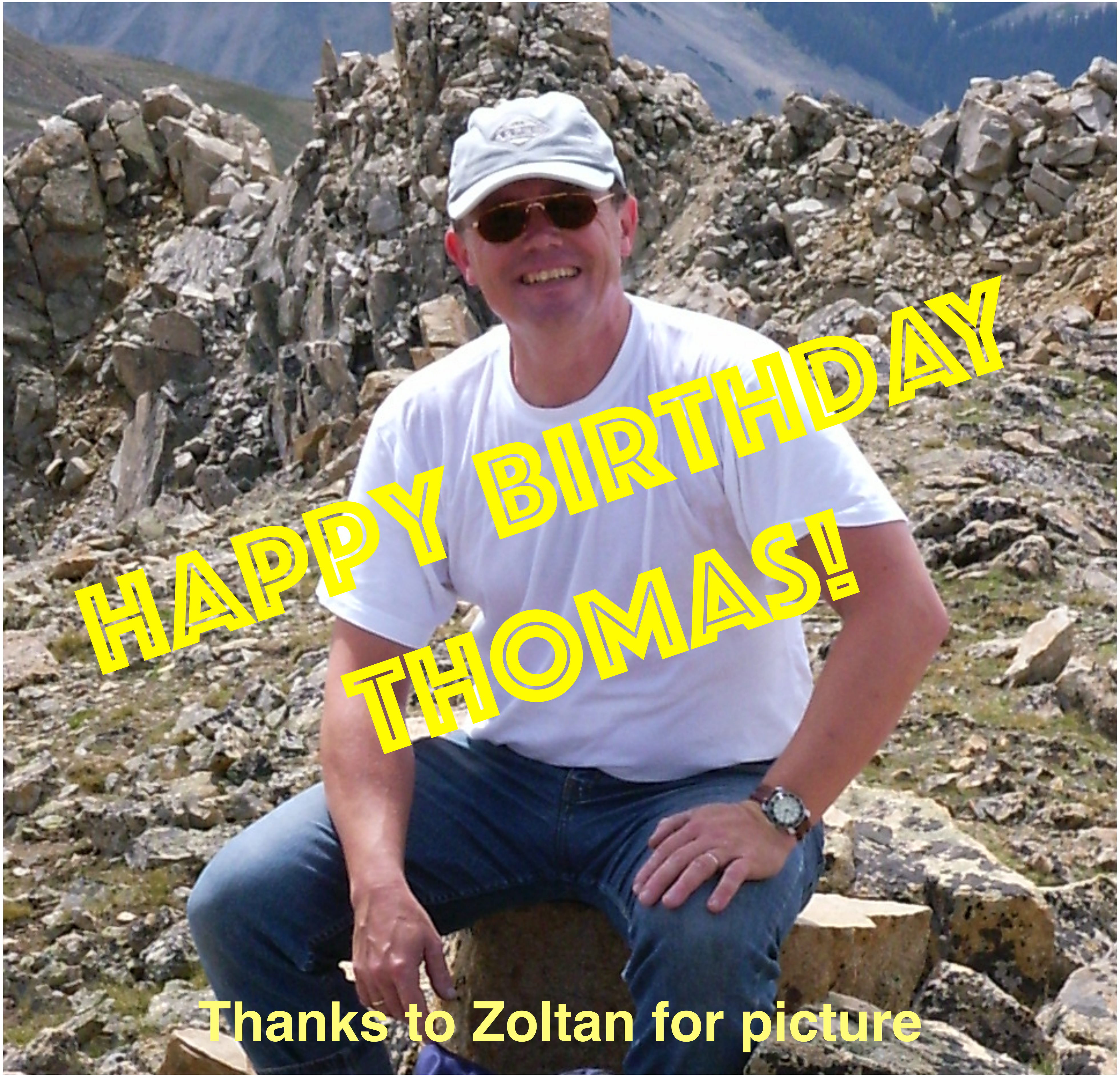
and life was good…

I was in my 8’th semester in Karlsruhe and had just been accepted into an exchange program to study for one year at the University of Toronto…

I was in a very happy relationship, and we were planning to eventually move together to Hamburg, where I would do my PhD at DESY…

And then I made the mistake to take a course on Particle physics taught by a new professor in Karlsruhe…

Thanks to Zoltan for picture



HAPPY BIRTHDAY THOMAS!

Thanks to Zoltan for picture

After a while, he asked if I was interested in doing my diplom under his supervision, and even though I told him about my planned year abroad, he was resourceful and persuasive …

He convinced Michael Luke in Toronto to jointly supervise me with him for my Diplom thesis. Having read a lot about “Luke’s theorem”, this sounded like a fantastic idea…

For quite a while I was so happy to have chosen an advisor who always had the correct answer to any question I might ask of him. Until one day he was clearly wrong…

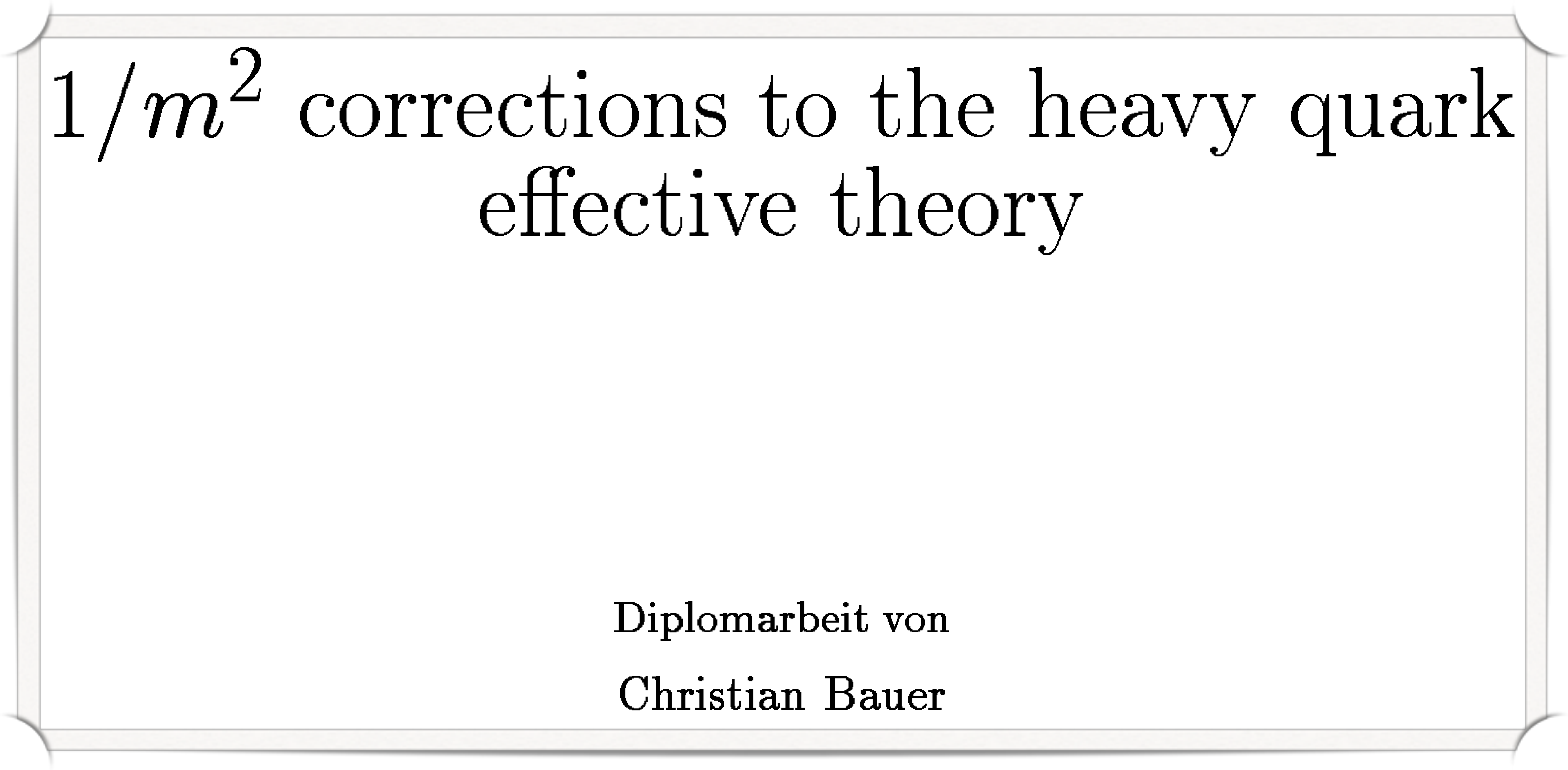
If my memory serves me right, this was shortly before I left for Toronto, and Thomas made the first statement that was so clearly wrong it was laughable…

He said:

You will probably never come back to Germany

Cleary, after 23 years abroad, I have to simply accept the Genius that Thomas really is!

I will not tell you about



$1/m^2$ corrections to the heavy quark effective theory

Diplomarbeit von

Christian Bauer

but rather about…

Breakdown of EW perturbation theory at large energies

Christian Bauer (LBNL)
Lake Tahoe, Oct 4 2018

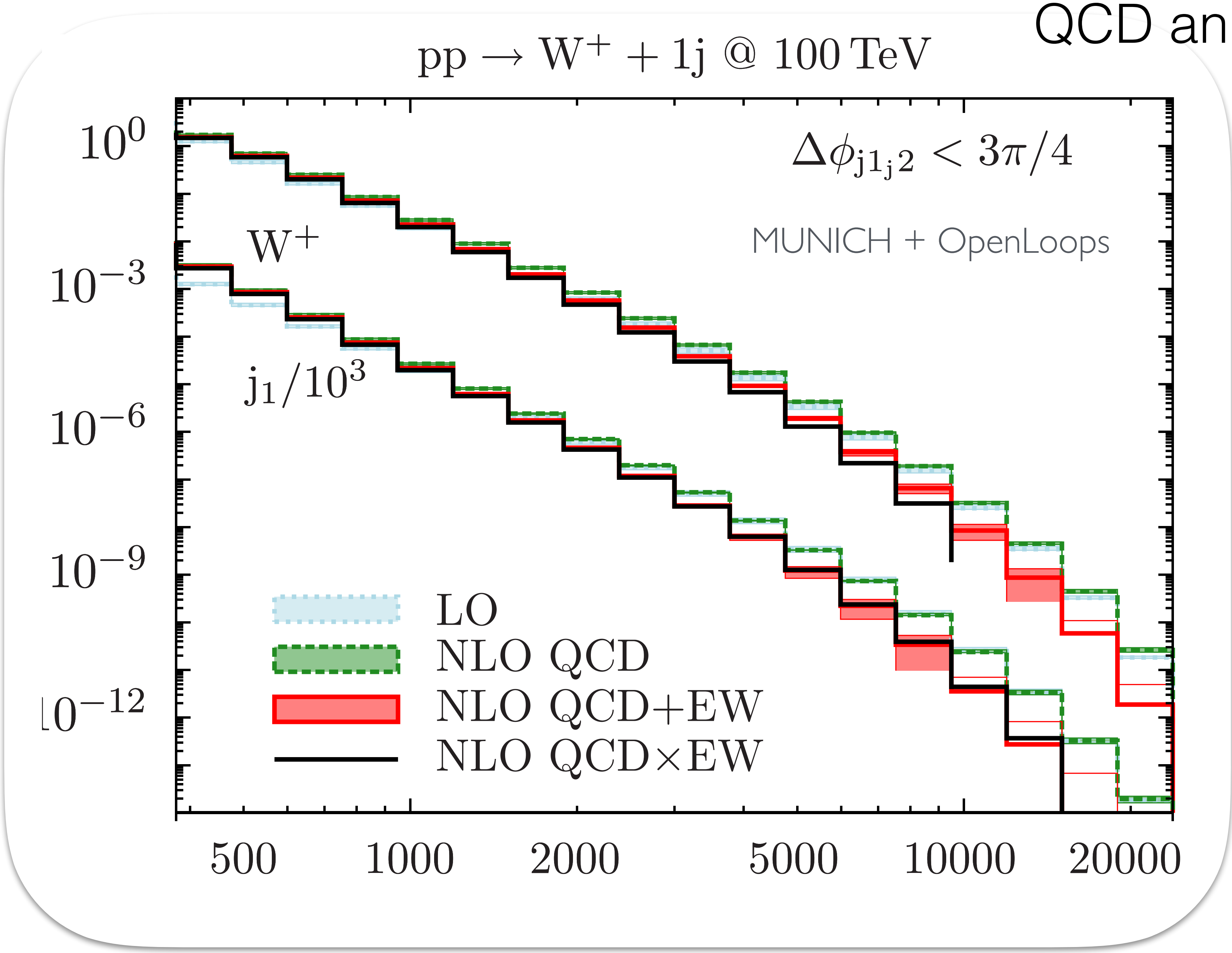
Based on
1703.08562, 1712.07147, 1806.10157, 1808.08831
(with B.R.Webber, N.Ferland, D.Provasoli)

Comparison to LHC data requires precise theoretical calculations

- To match the precision of experimental uncertainties $\mathrm{NLO_{QCD}}$ calculations are required for most observables, and NNLO calculations are becoming more and more important
- In some cases even $\mathrm{N^3LO}$ calculations are available
- While EW corrections are typically much smaller, $\mathrm{NLO_{EW}}$ are of same order as $\mathrm{NNLO_{QCD}}$ effects
- EW corrections become more and more important as energy of collision increases.

Fixed order results at a future 100 TeV machine show that EW corrections are much larger than QcD corrections

Lindert,
QCD and EW at 100 TeV colliders



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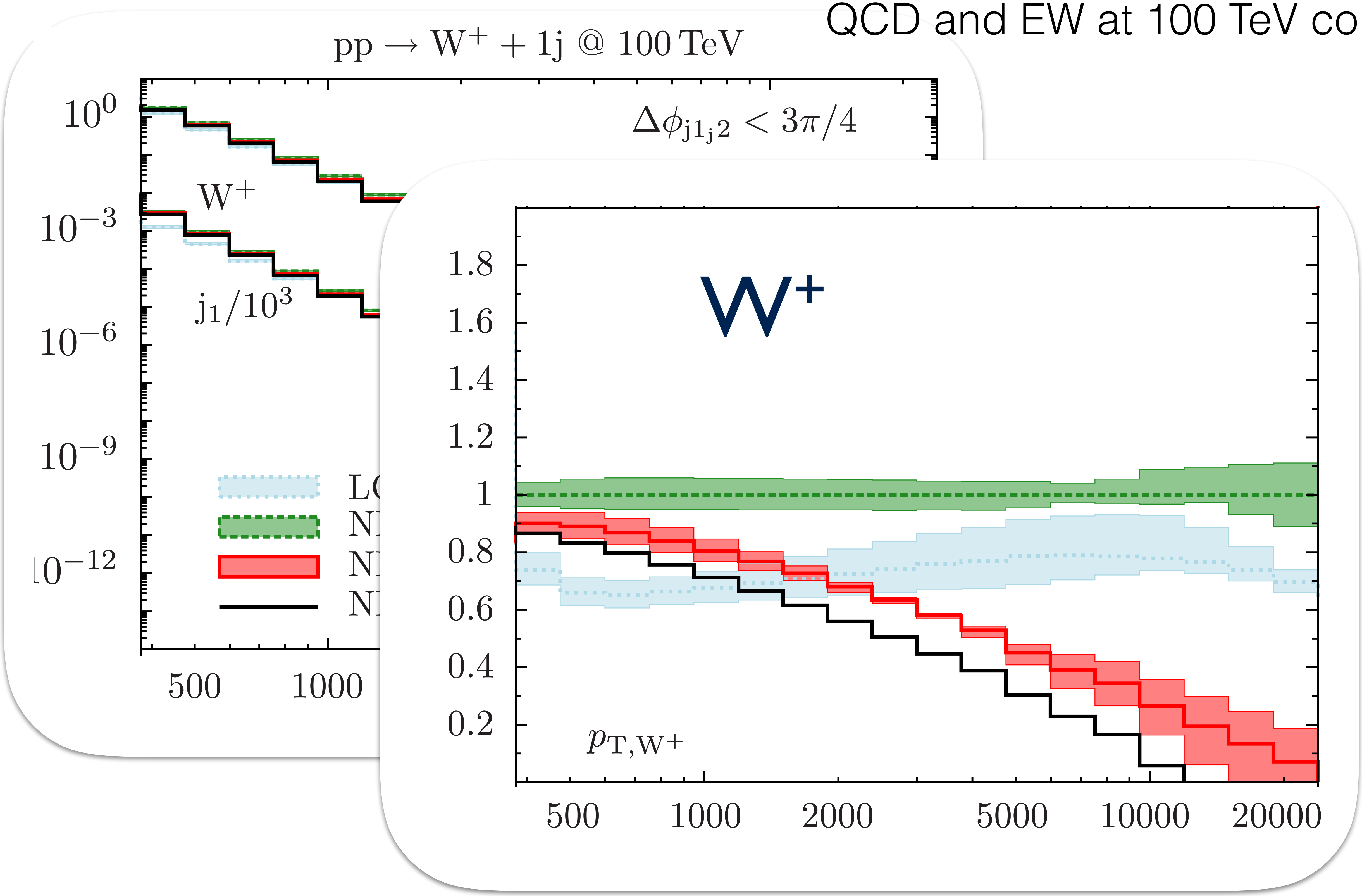


How is it possible that electroweak NLO corrections become much larger than QCD corrections?

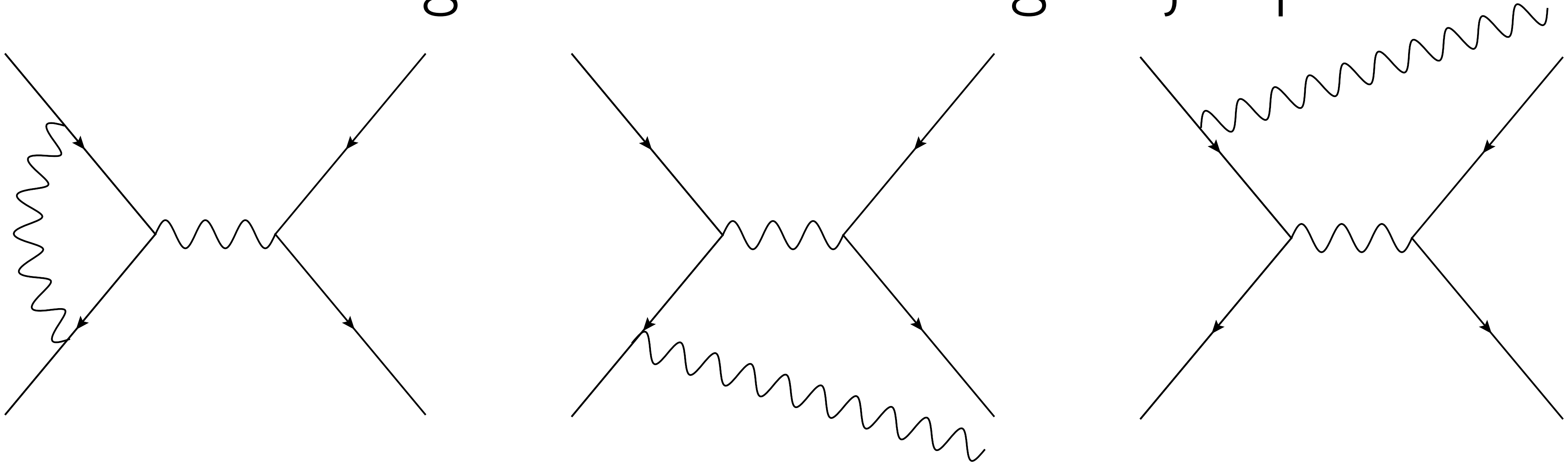
Strong interaction $\alpha_{\mathrm{S}} \approx 0.1$

Weak interaction $\alpha_{\mathrm{EW}} \approx 0.01$

????????????????

Higher order QCD calculations involve IR divergent contributions that cancel when calculating observables

Selection of diagrams contributing to jet production



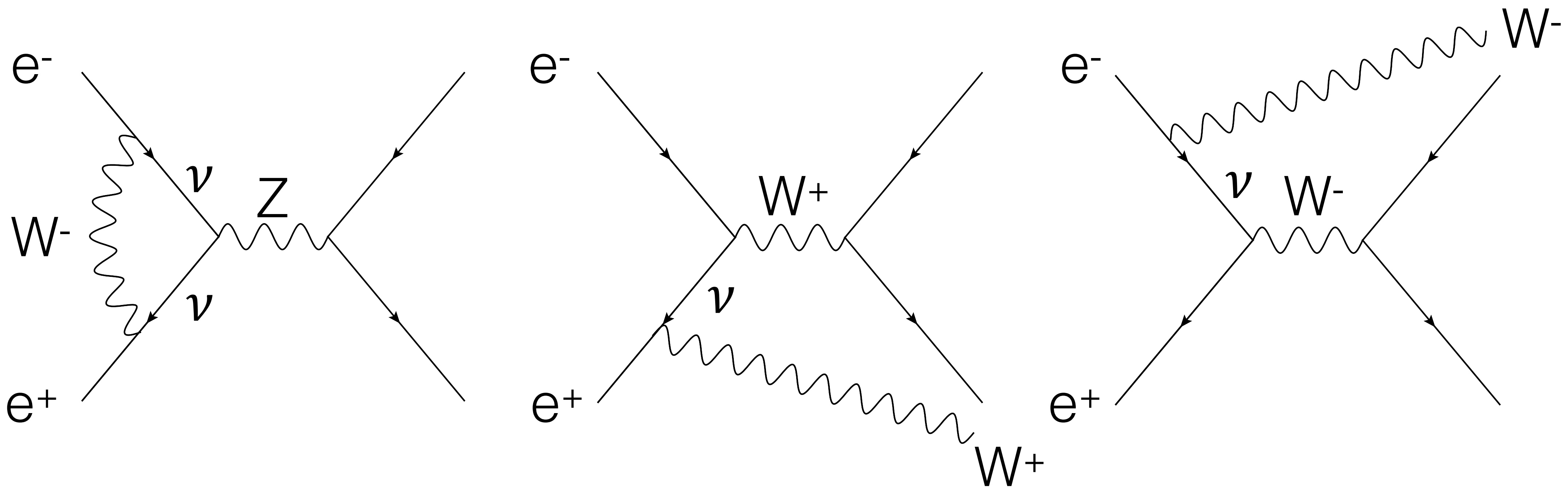
Any observable get contributions from virtual and real contributions

Both virtual and real are separately IR divergent

All divergences cancel when virtual and real are properly combined

Electroweak Sudakov logarithms arise from exchanges of electroweak gauge bosons

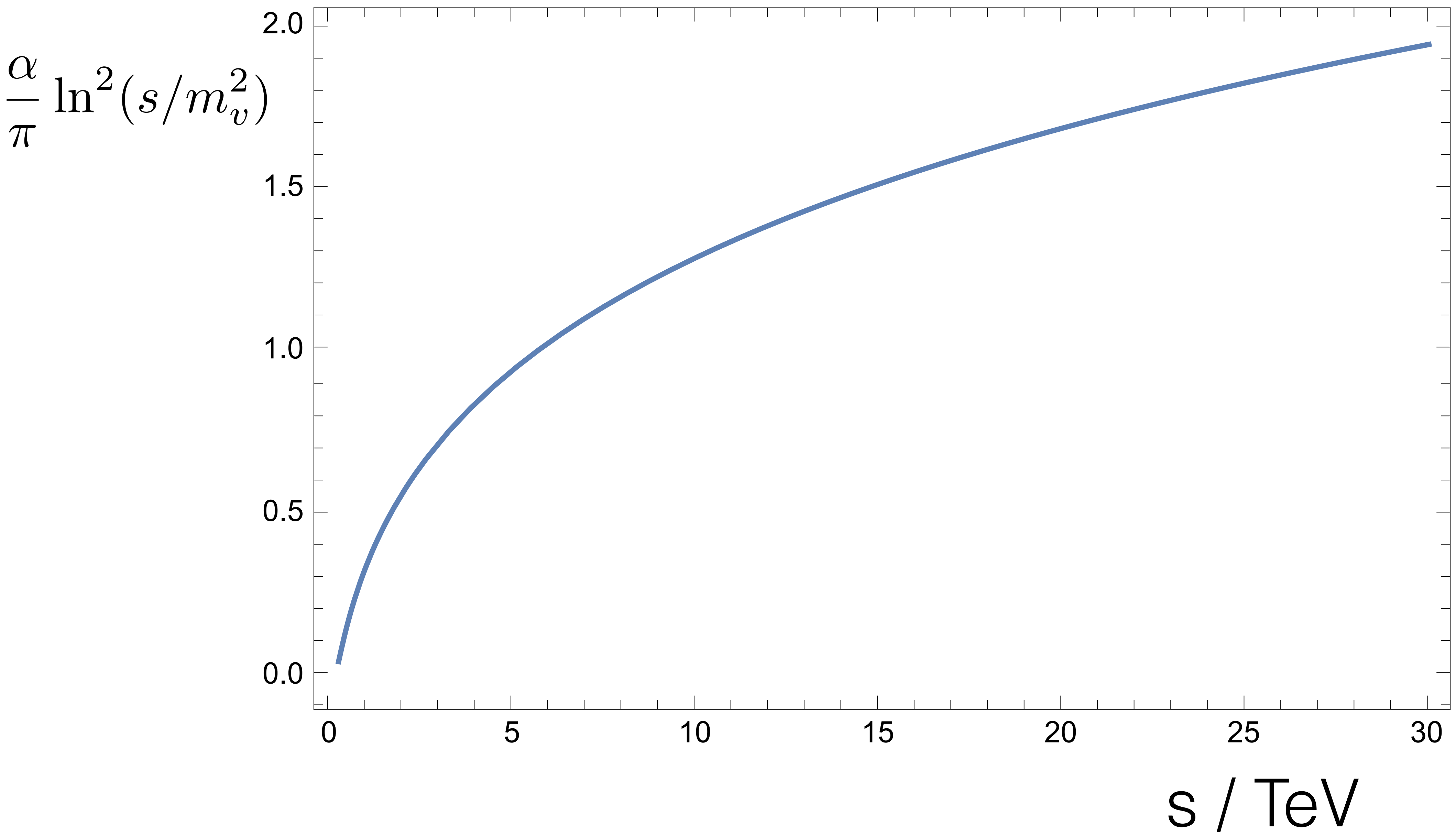
Similar set of diagrams for EW contributions, but with W / Z bosons instead of gluons



For massive W, IR divergences turn into log(m_W^2/s), and generally have two powers per power of α_s

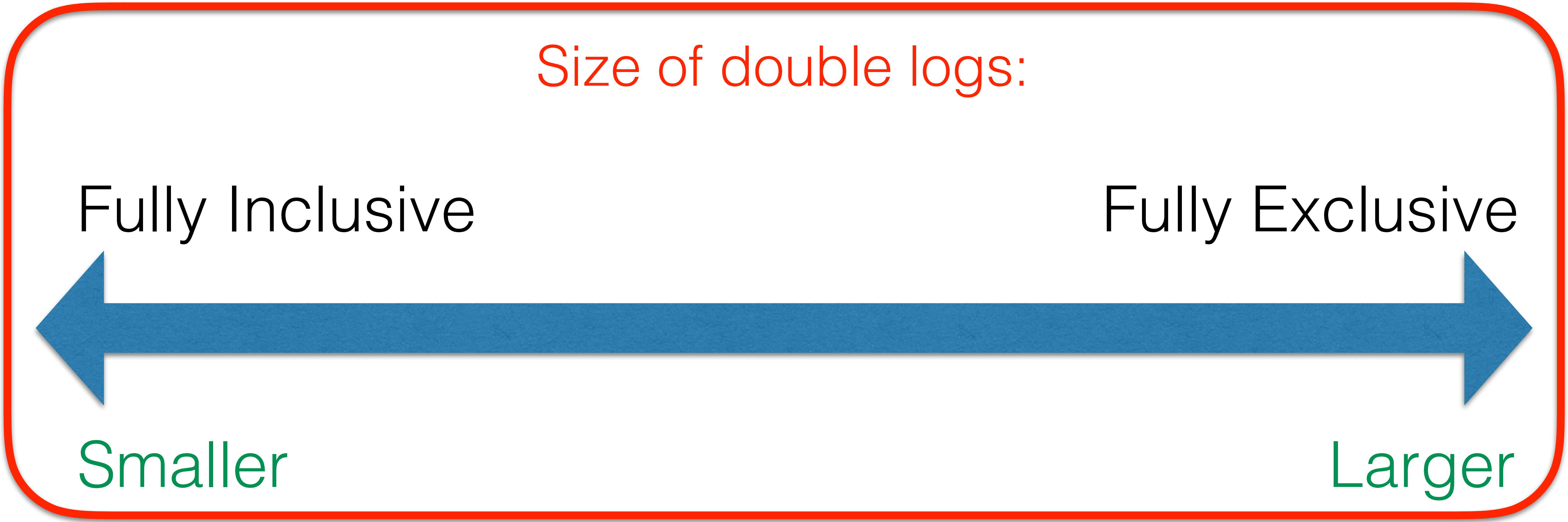
Both virtual and real sensitive to log(m_W^2/s)

The numerical effect of EW Sudakov logarithms becomes large at high energies



Electroweak corrections give rise to double logarithmic dependence for essentially any process

- For QCD, inclusive observables give rise to at most single logarithms
- Ensured by KLN cancellation between virtual and real
- For EW processes, can never have fully inclusive observables, since initial state not SU(2) invariant



Size of double logs:

Fully Inclusive

Fully Exclusive

Smaller

Larger

For completely inclusive processes, all logarithms must come from DGLAP evolution of initial states

- As already mentioned, in QCD this gives rise to at most single logarithmic terms
- For EW processes, DGLAP evolution gives rise to double logarithms
- As I will show, this is due to the exchange of soft and collinear massive vector bosons
- Another interesting effect is the generation of vector boson polarizations

We all know that parton distribution functions are a crucial ingredient in any prediction for collider processes

A general process at a hadron collider can be written as

$$\sigma_{pp\to X} = \sum_{ij} \int \mathrm{d}x_1 \mathrm{d}x_2\, f_{i/p}(x_1,\mu)\, f_{j/p}(x_2,\mu)\, \hat{\sigma}_{ij\to X}(x_1,x_2,\mu)$$

x_1 and x_2: momentum fractions of partons i and j

mu: appropriately chosen factorization scale

PDF's usually determined experimentally at low scale, and then evolved to high scales using DGLAP equations

We all know that parton distribution functions are a crucial ingredient in any prediction for collider processes

General form of the DGLAP equation for QCD

$$t\frac{\partial}{\partial t} f_i(x,t) = \sum_j \int_x^1 \frac{dz}{z} \frac{\alpha_S}{2\pi} P_{ij}(z) f_j(x/z,t)$$

with splitting functions

$$\begin{aligned} P_{qq}(z) &= \hat{P}_{qq}(z)_+ = C_F \left(\frac{1+z^2}{1-z}\right)_+ \\ P_{qg}(z) &= \hat{P}_{qg}(z) = T_R \left[z^2 + (1-z)^2\right] \end{aligned}$$

Because of +-distribution, singularity at z →1 is fully regulated

Does anything change in this picture if we evolve to very high energies ($\mu \gg m_{EW}$)?

See also Comelli, Ciafaloni (10)

For such high energies, electroweak gauge bosons become essentially massless

Even top quarks and Higgs bosons become almost massless

So all interactions of the SM should contribute to DGLAP evolution

But is this really phenomenologically important given that $\alpha_S \gg \alpha_{1,2}$?

DGLAP equations can be obtained including all interactions of the SM, and EW gives rise to interesting effects

General form of the DGLAP equation

$$q\frac{\partial}{\partial q}f_i(x,q) = \sum_I \frac{\alpha_I(q)}{\pi}\left[P^V_{i,I}(q)\,f_i(x,q) + \sum_j C_{ij,I}\int_x^{z^{ij,I}_{\max}(q)} \mathrm{d}z\,P^R_{ij,I}(z)f_j(x/z,q)\right]$$

Same as DGLAP equations for QCD, just with more coefficients and splitting functions

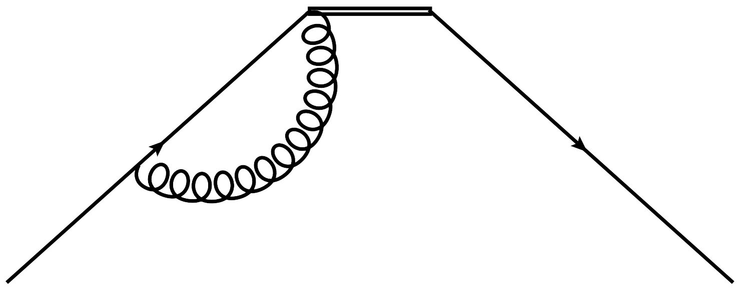
SU(2) evolution gives rise to new effects:

- Double logarithms from PDF evolution
- Generation of vector boson polarization

DGLAP equations can be obtained including all interactions of the SM, and EW gives rise to interesting effects

Double logarithms from PDF evolution

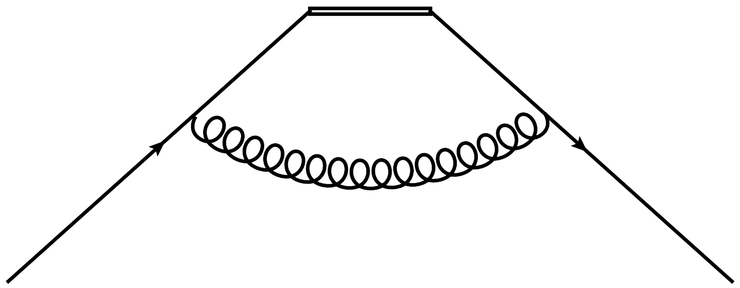
In standard QCD evolution, soft singularity cancels



Virtual

$$t\frac{\mathrm{d}}{\mathrm{d}t}f_u(x,t) = \frac{\alpha\,C_F}{\pi}P_q^V(t)f_u(x,t)$$

$$P_q^V(t) = -\int_0^{z_{\max}(t)}\mathrm{d}z\,P_{qq}(z)$$



Real

$$t\frac{\mathrm{d}}{\mathrm{d}t}f_q(x,t) = \frac{\alpha\,C_F}{\pi}\int_x^{z_{\max}(t)}\mathrm{d}z\,P_{qq}(z)f_q(x/z,t)$$

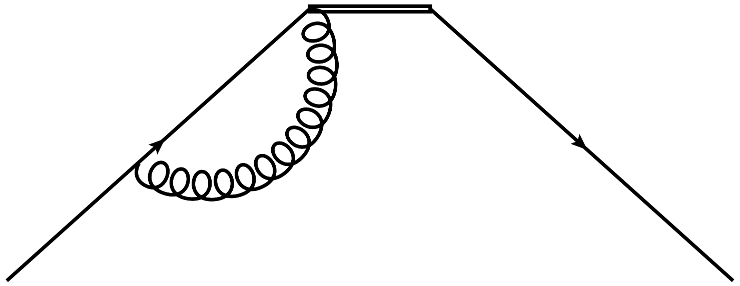
Combination

$$t\frac{\mathrm{d}}{\mathrm{d}t}f_q(x,t) = \frac{\alpha\,C_F}{\pi}\int_0^{z_{\max}(t)}\mathrm{d}z\,P_{qq}(z)\left[f_q(x/z,t) - f_q(x,t)\right] + \ldots$$

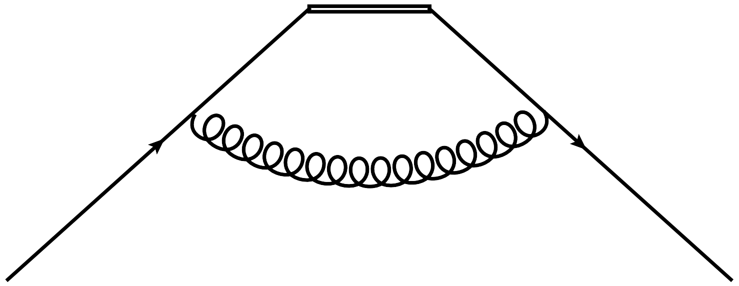
DGLAP equations can be obtained including all interactions of the SM, and EW gives rise to interesting effects

Double logarithms from PDF evolution

In SU(2) evolution, soft singularity does not cancel



Virtual



Real

$$t\frac{\mathrm{d}}{\mathrm{d}t}f_u(x,t) = \frac{\alpha\,C_F}{\pi}P_q^V(t)f_u(x,t)$$

$$t\frac{\mathrm{d}}{\mathrm{d}t}f_u(x,t) = \frac{\alpha\,C_F}{\pi}\int_0^{z_{\max}(t)}\mathrm{d}z\,P_{qq}(z) \times \left[\frac{2}{3}f_d(x/z,t)+\frac{1}{3}f_u(x/z,t)\right]$$

Real and virtual don’t cancel at z=1, due to the fact that $f_u \neq f_d$)

Double logs remain in DGLAP

DGLAP equations can be obtained including all interactions of the SM, and EW gives rise to interesting effects

Generation of polarization effects

Manohar, Waalewijn (18)

- Left- and right-handed vector bosons couple differently to left- and right-handed fermions
- Since EW interaction couple differently to f_L and f_R, polarization asymmetry is generated
- This feeds back and also affects evolution of fermions

Leads to O(1) polarization of EW vector bosons, but even gluon becomes polarized

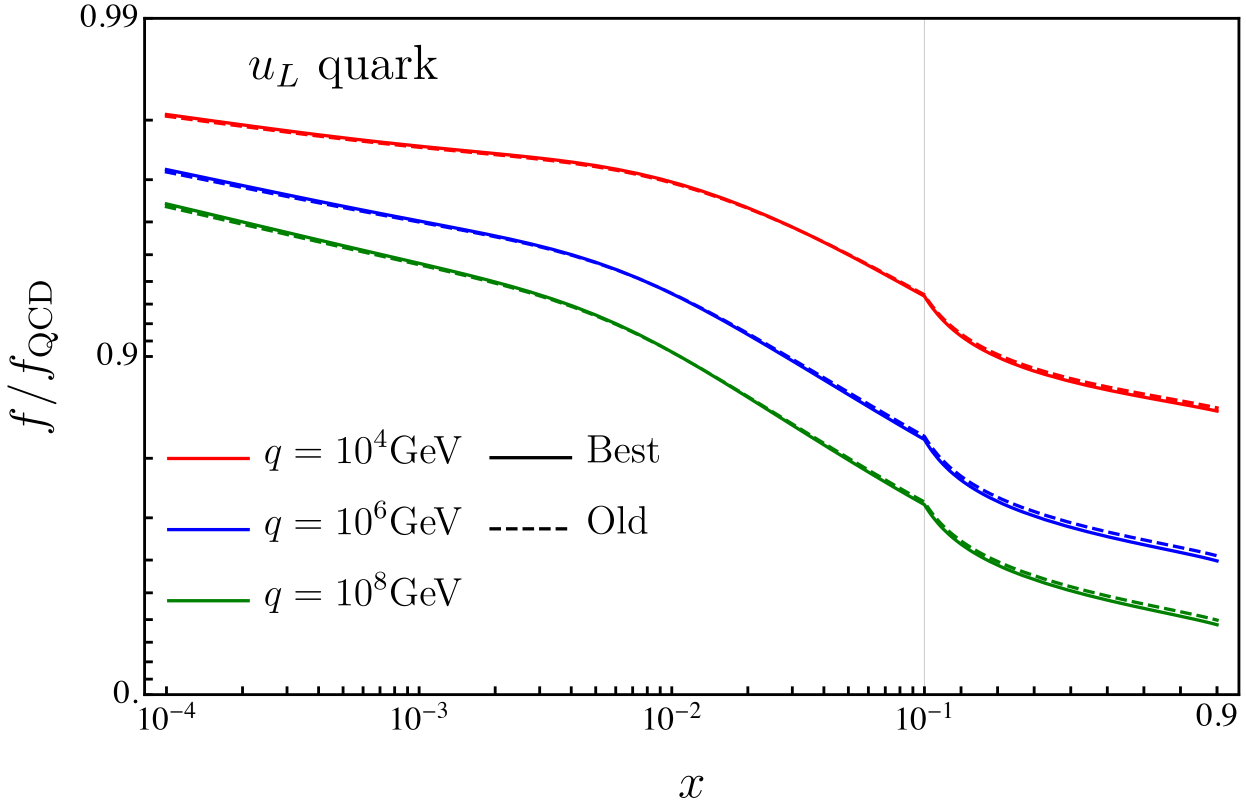
Solve the DGLAP equations using inputs at O(100 GeV) and then run to higher scales

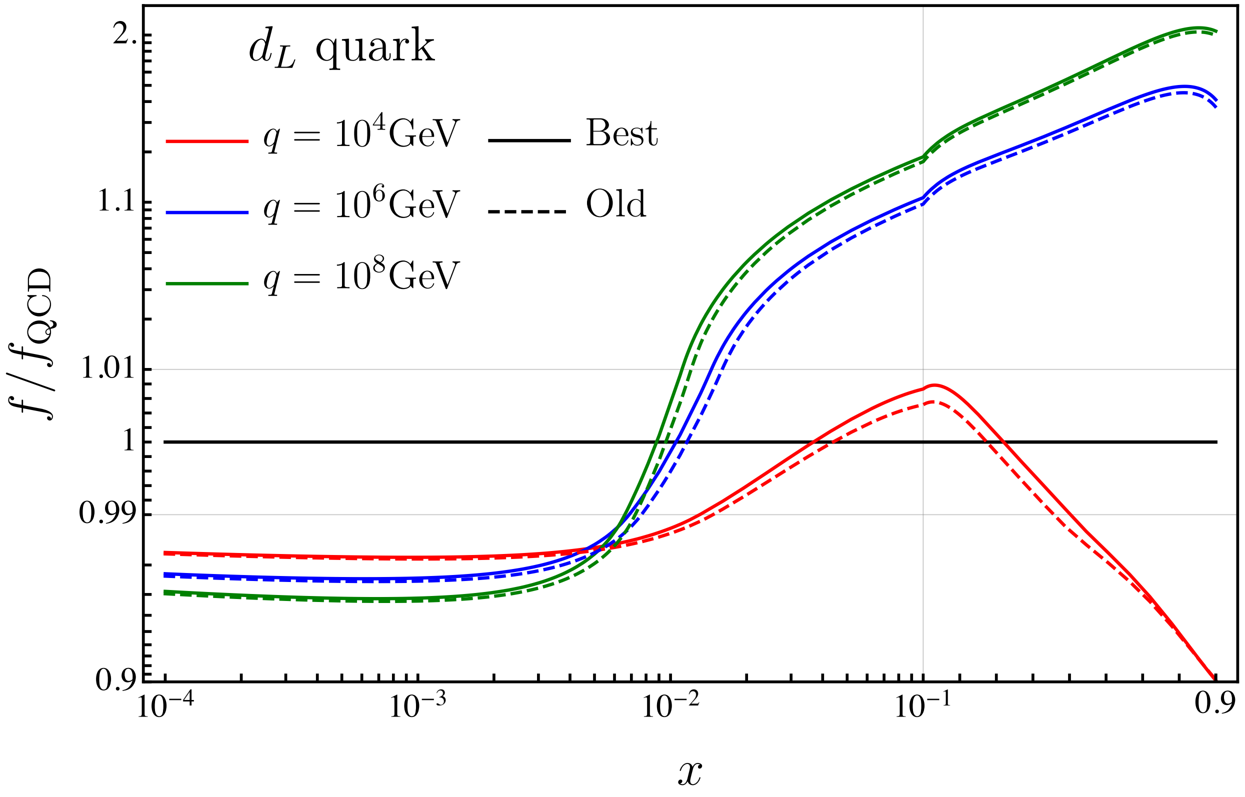
Inputs at 100 GeV

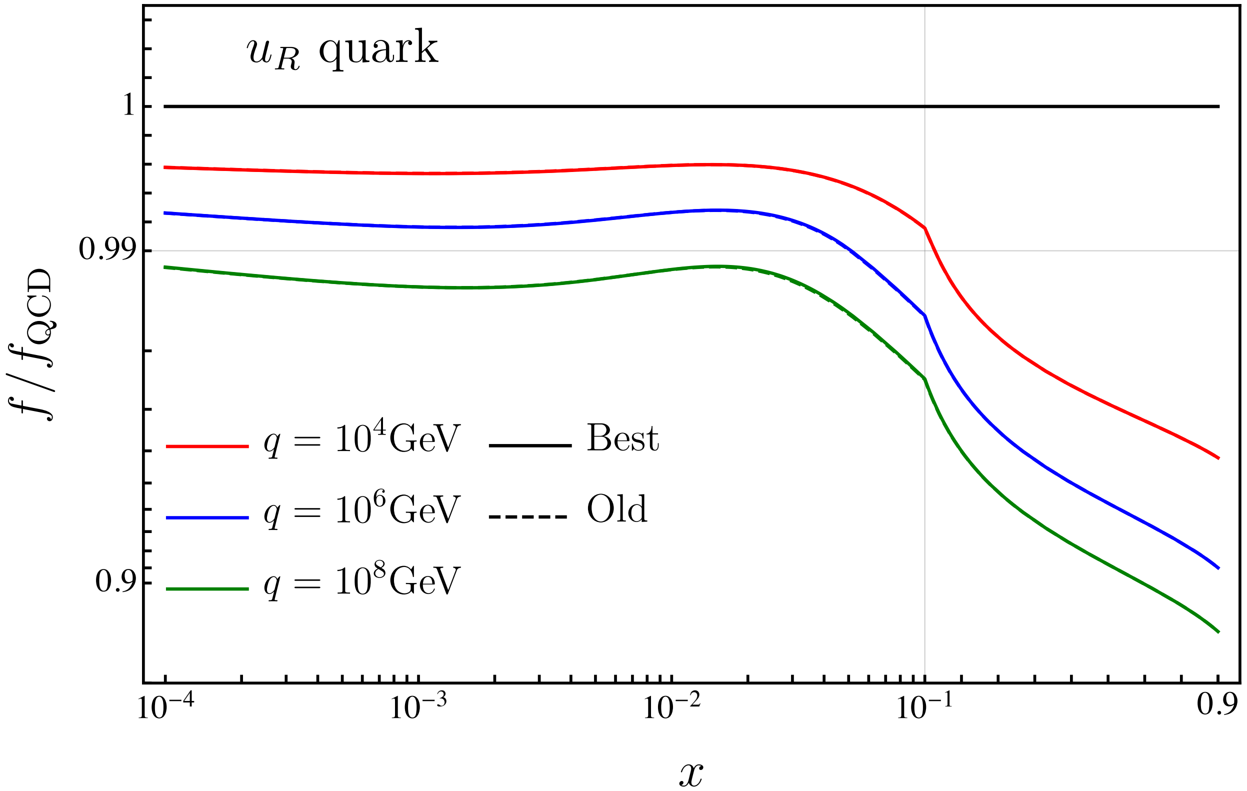
- Quarks, gluon, photon, leptons: Use input of quark, gluon, photon at low energies and then run up using SU(3) x $U(1)_{EM}$ [Photon from Manohar, Nason, Salam, Zanderighi (16)]
- Massive gauge bosons: Use perturbative input (using LUX mechanism) Fornal, Manohar, Waalewijn (18)
- Longitudinal gauge bosons, top quark: Zero

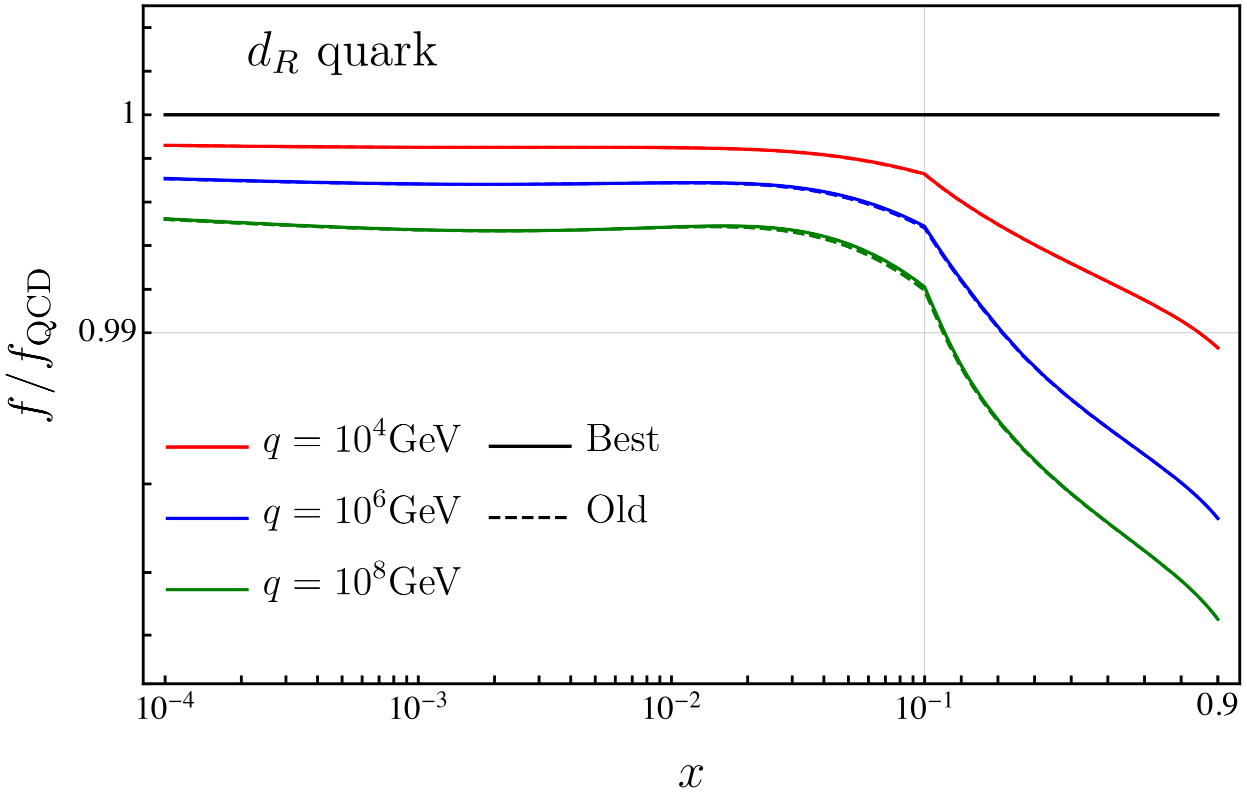
Have shown that results at very high energies are relatively insensitive to details of the input

EW evolution has noticeable effect on “standard” PDFs compared to pure QCD evolution

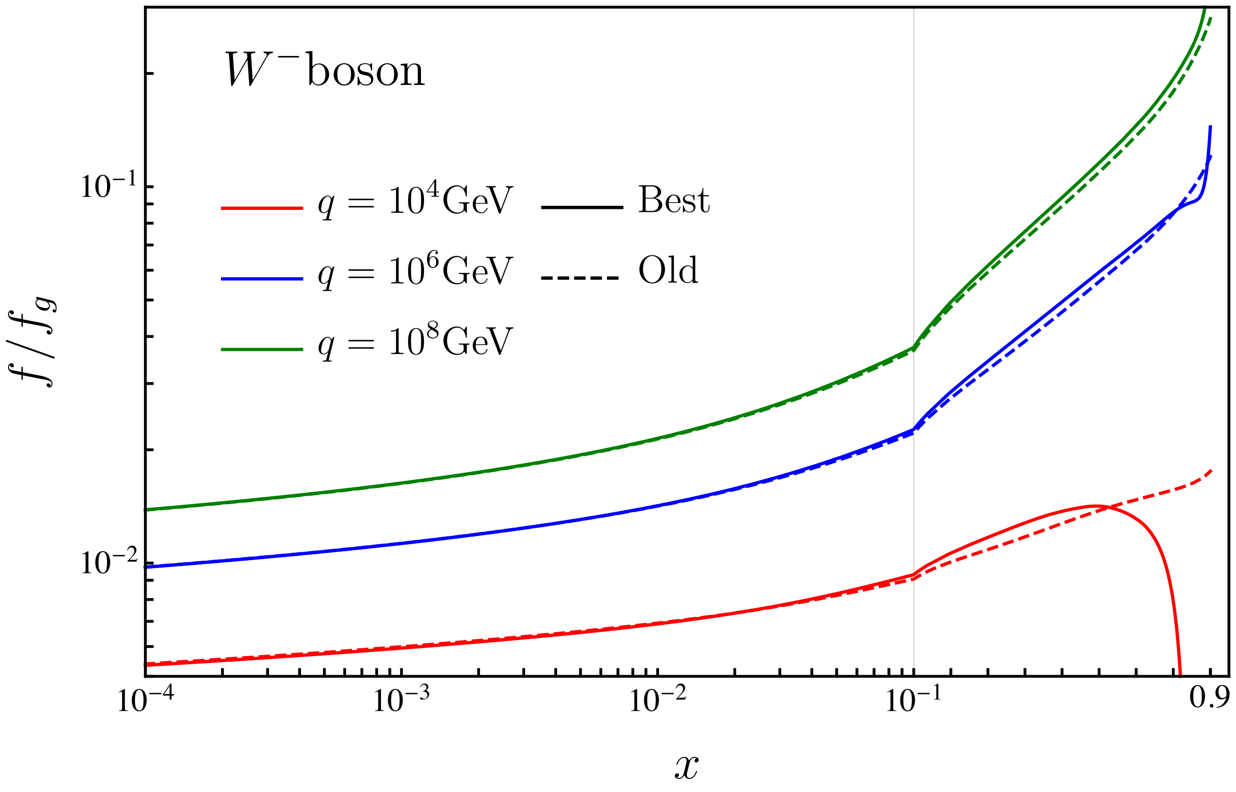


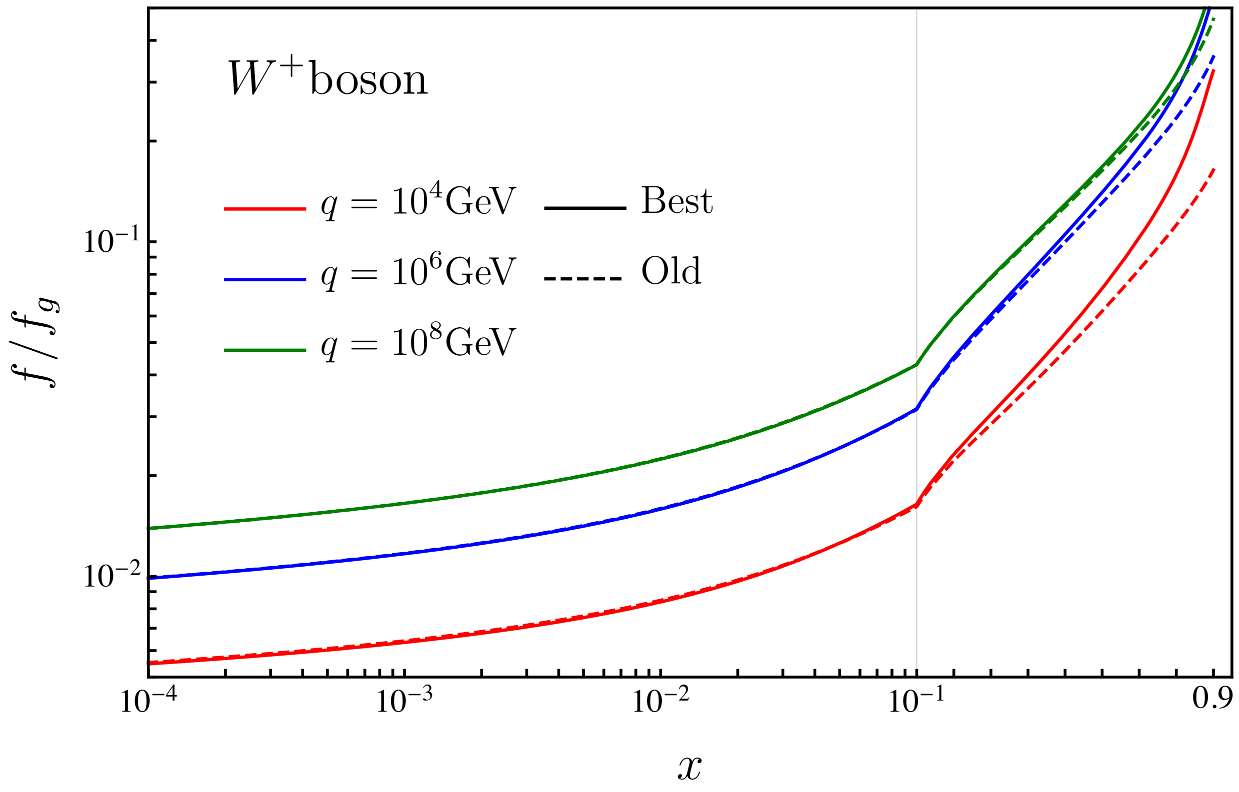


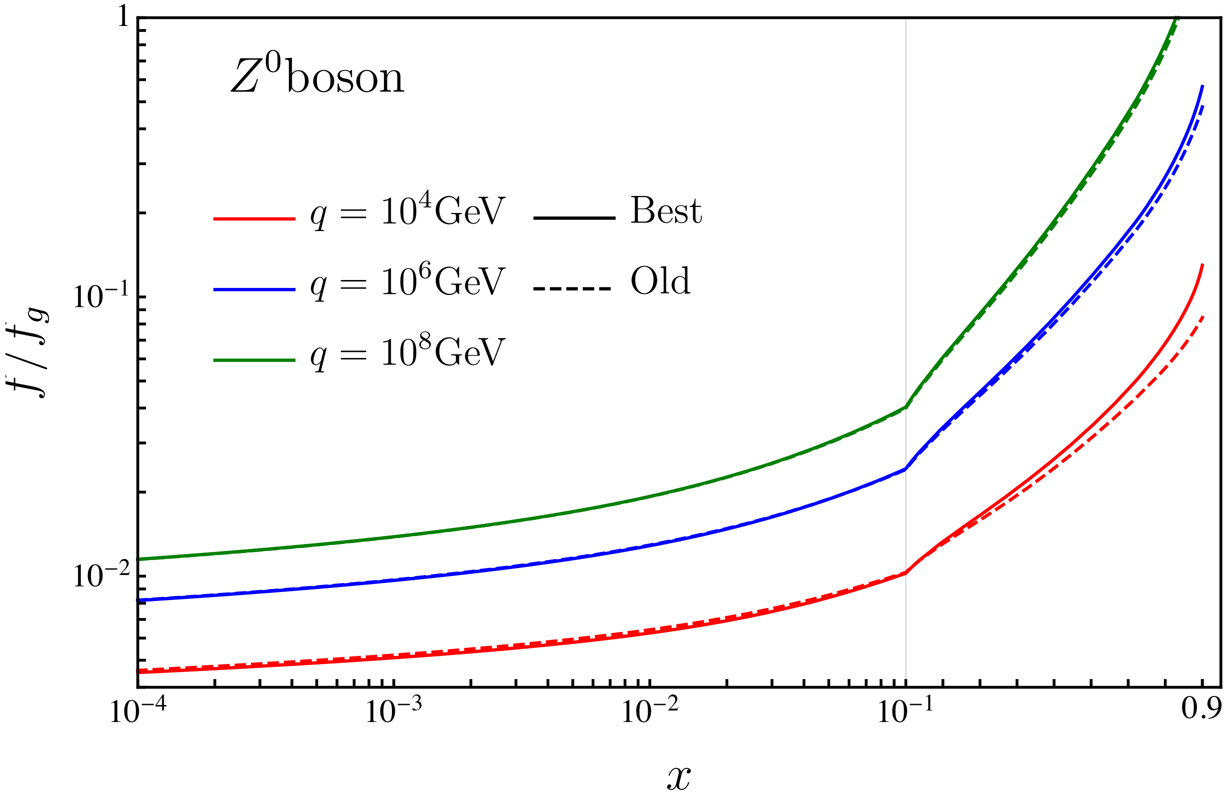


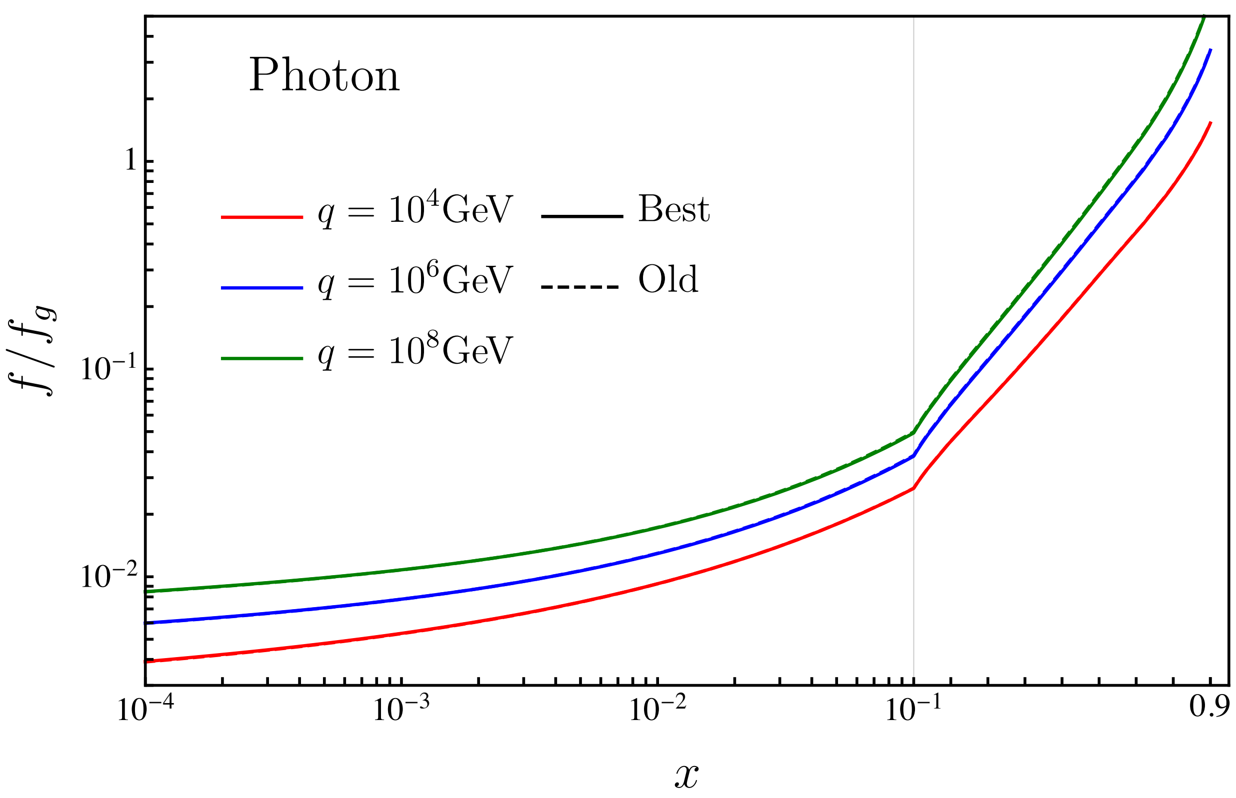


EW evolution gives large PDFs for transverse electroweak gauge bosons

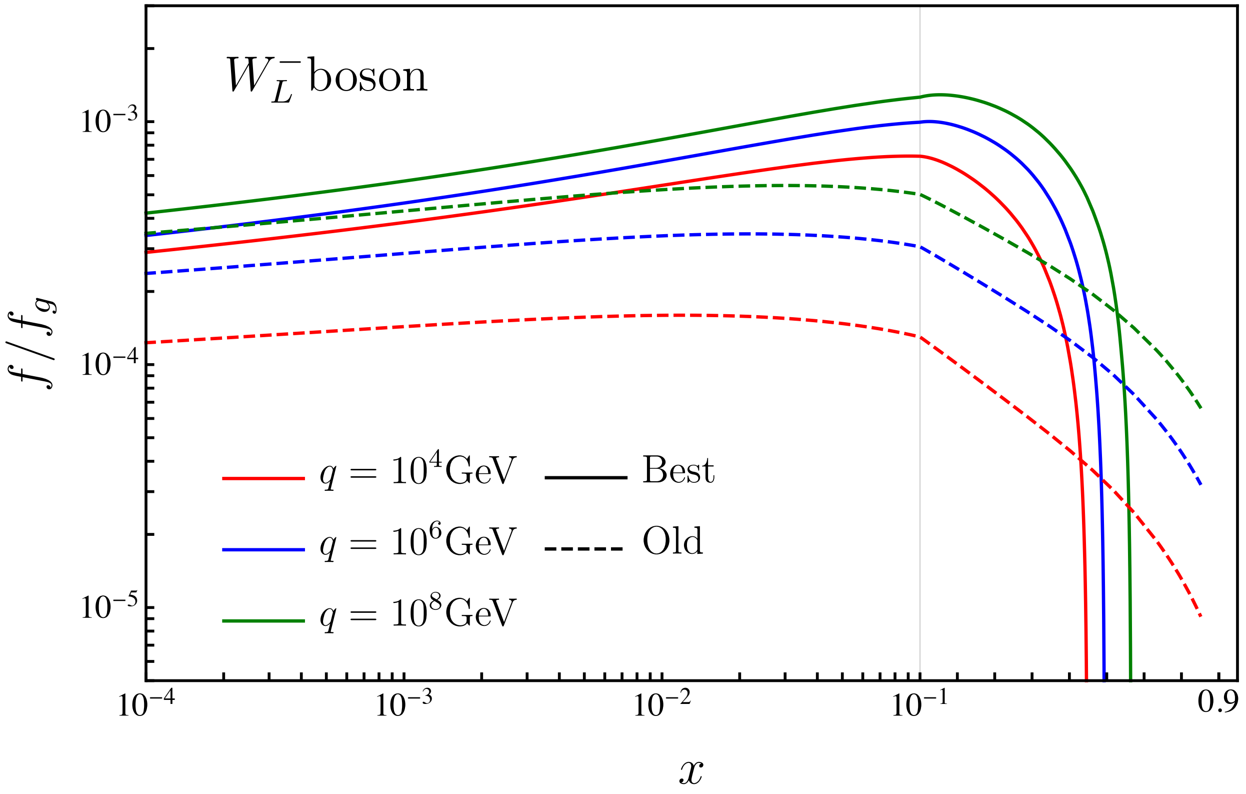


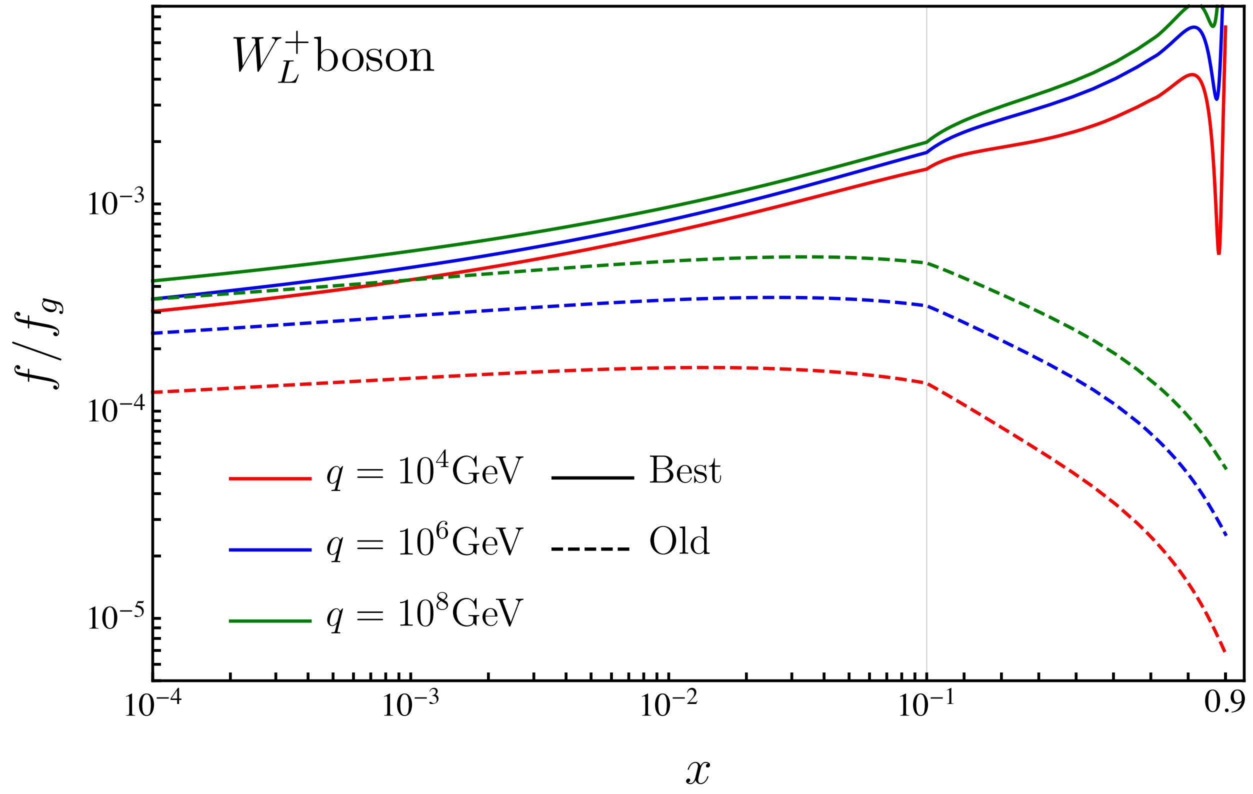


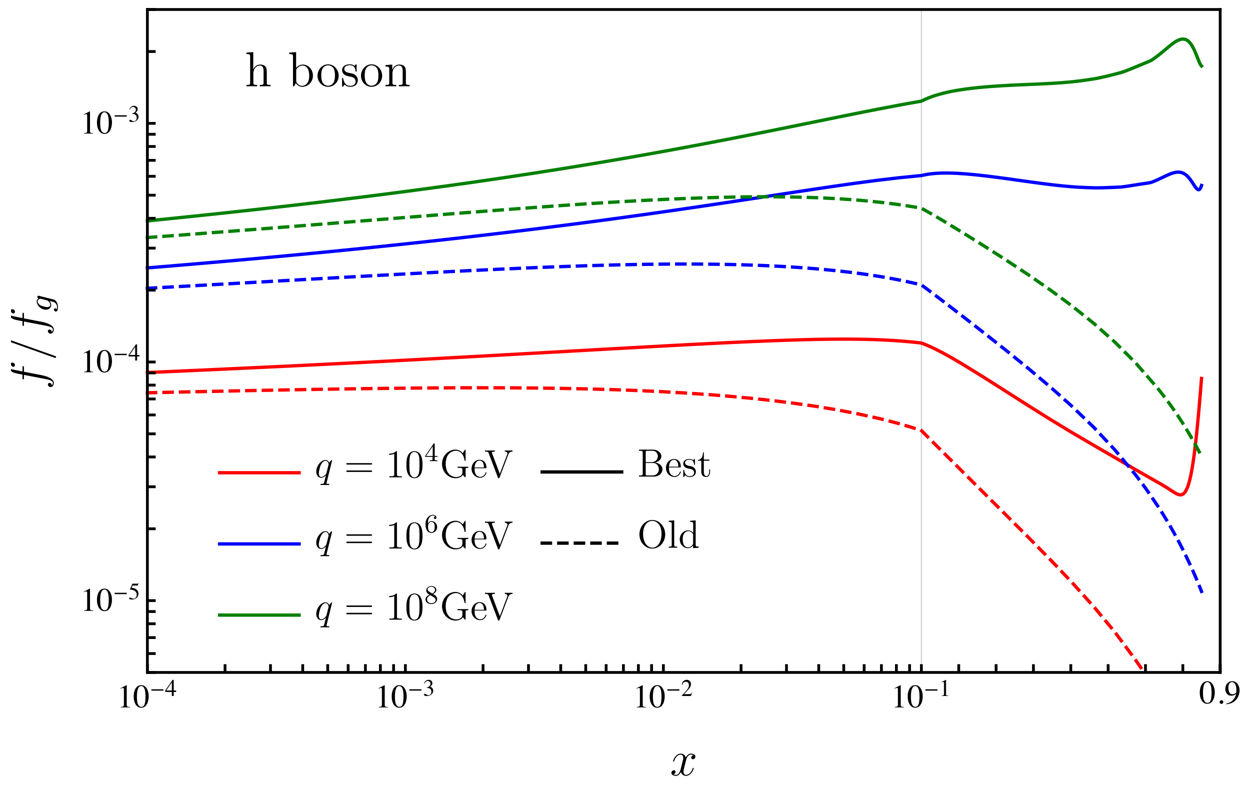


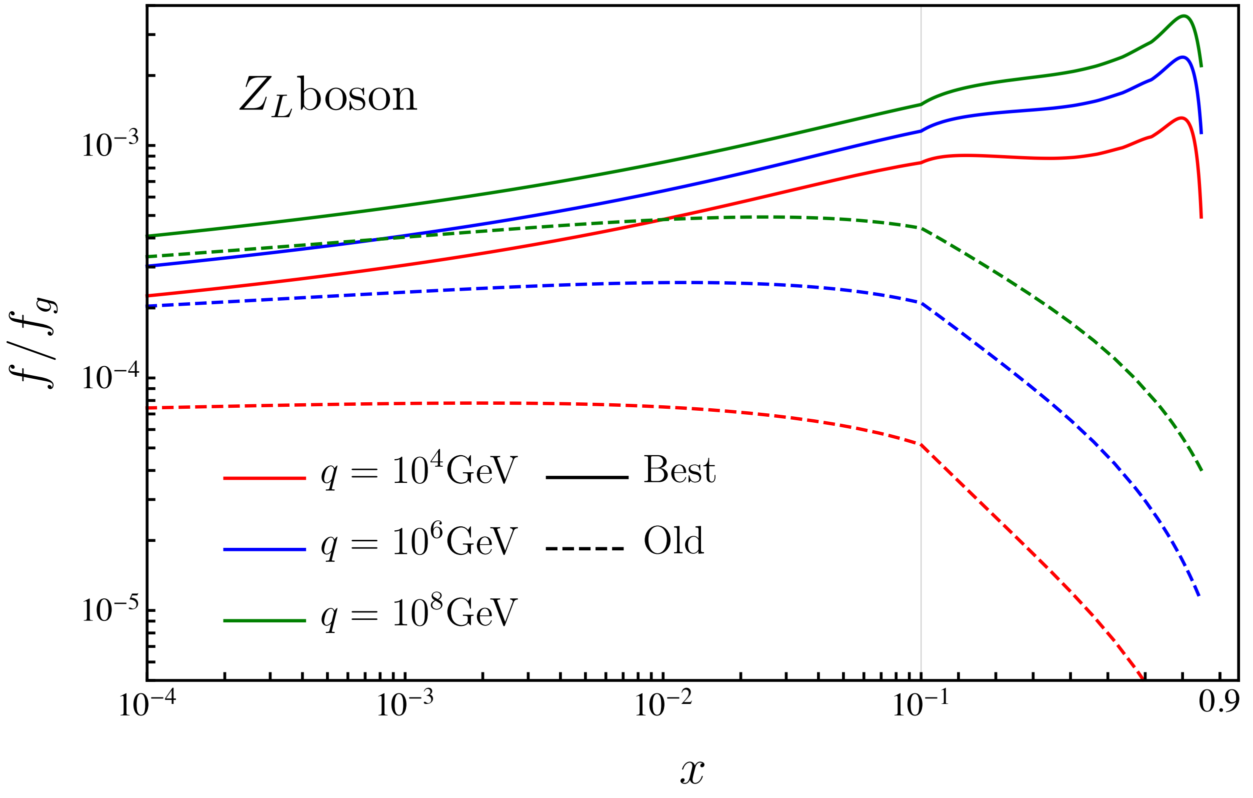


Longitudinal gauge bosons smaller, since generated through higher order effects

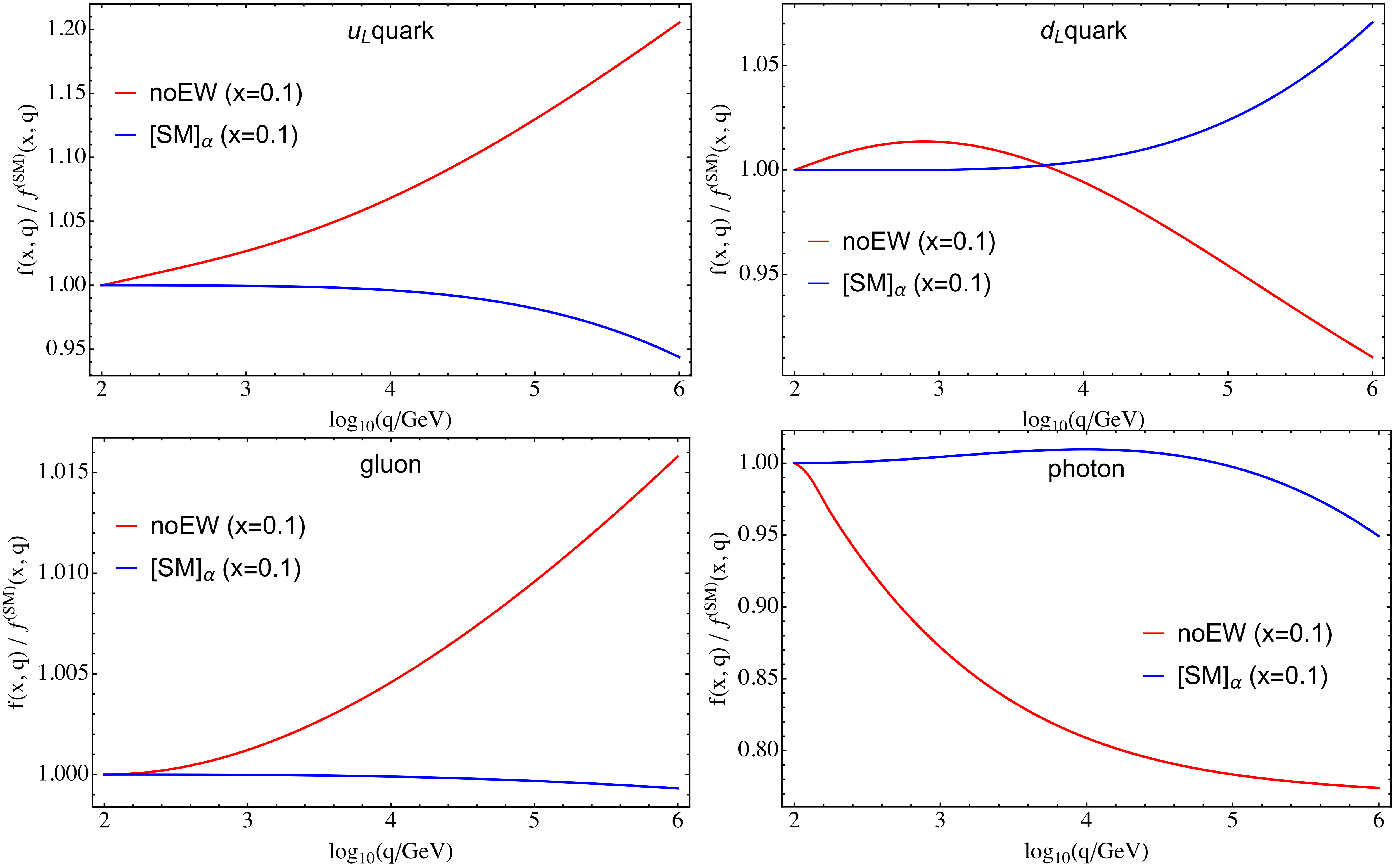




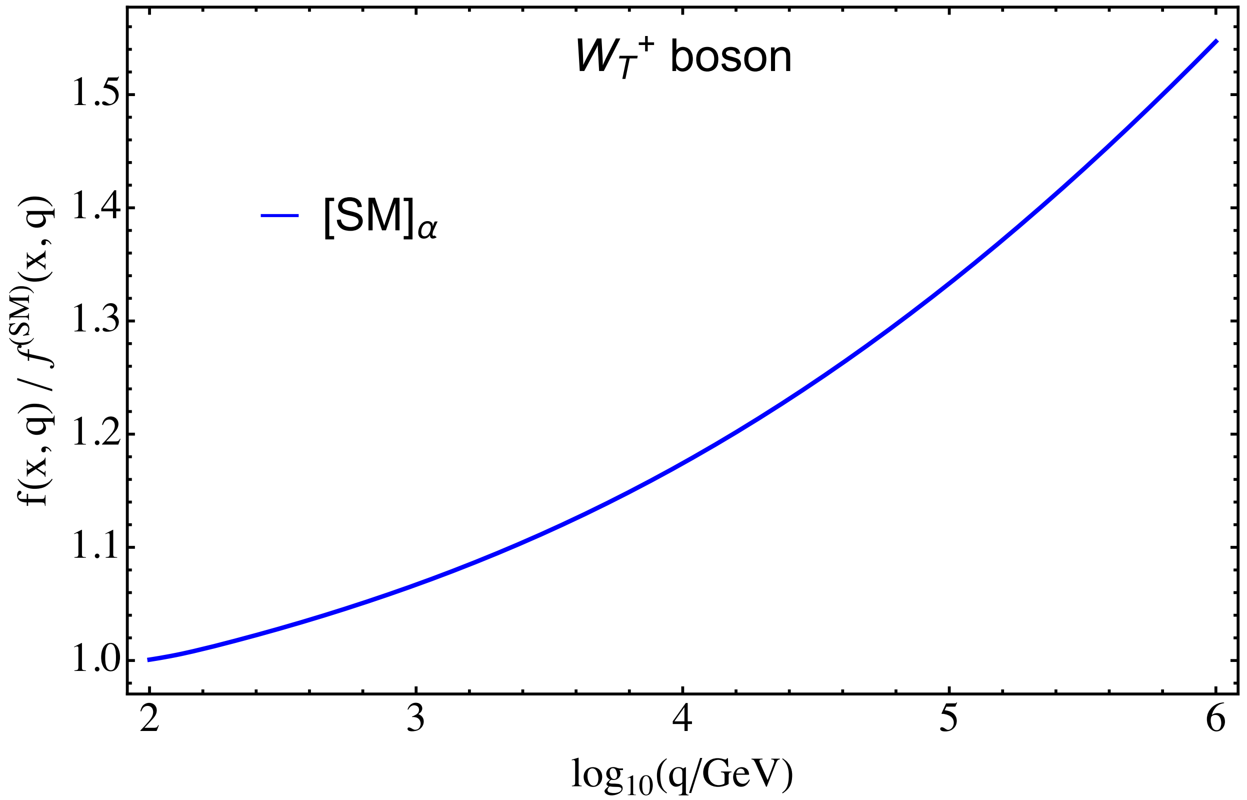


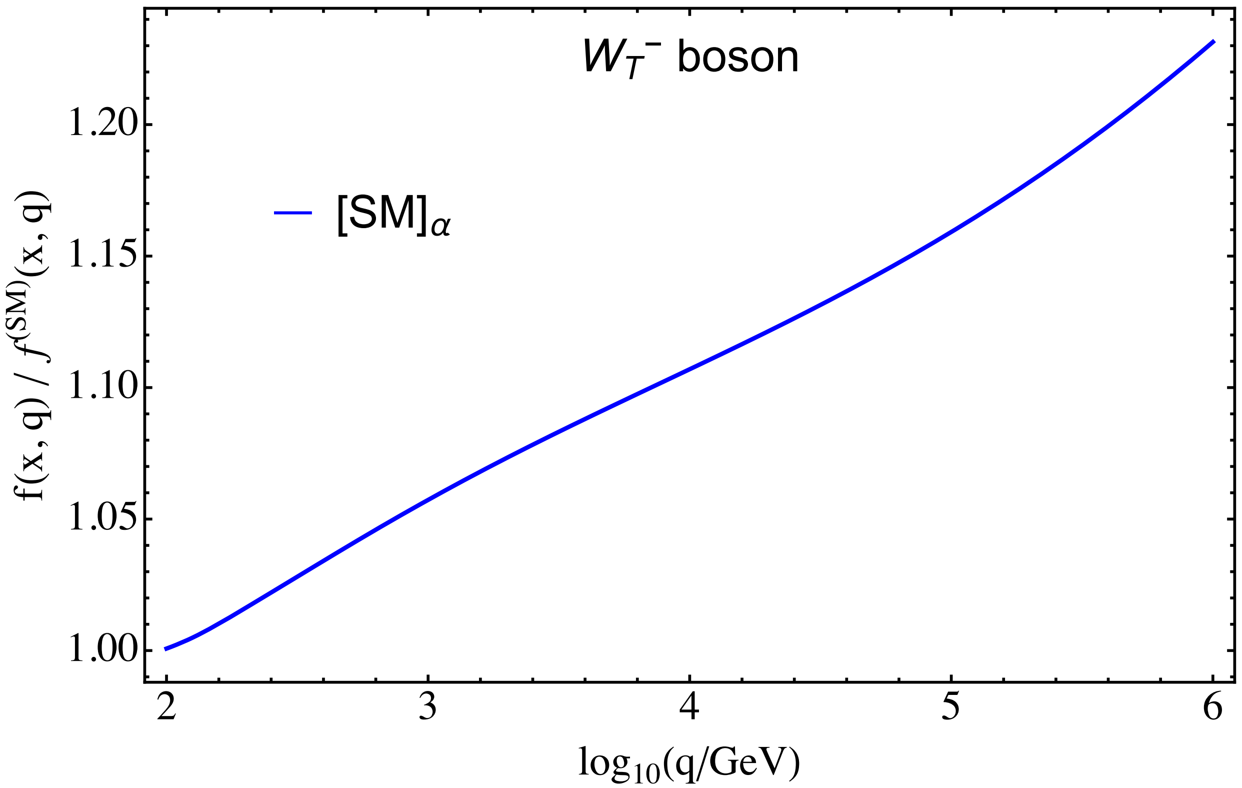


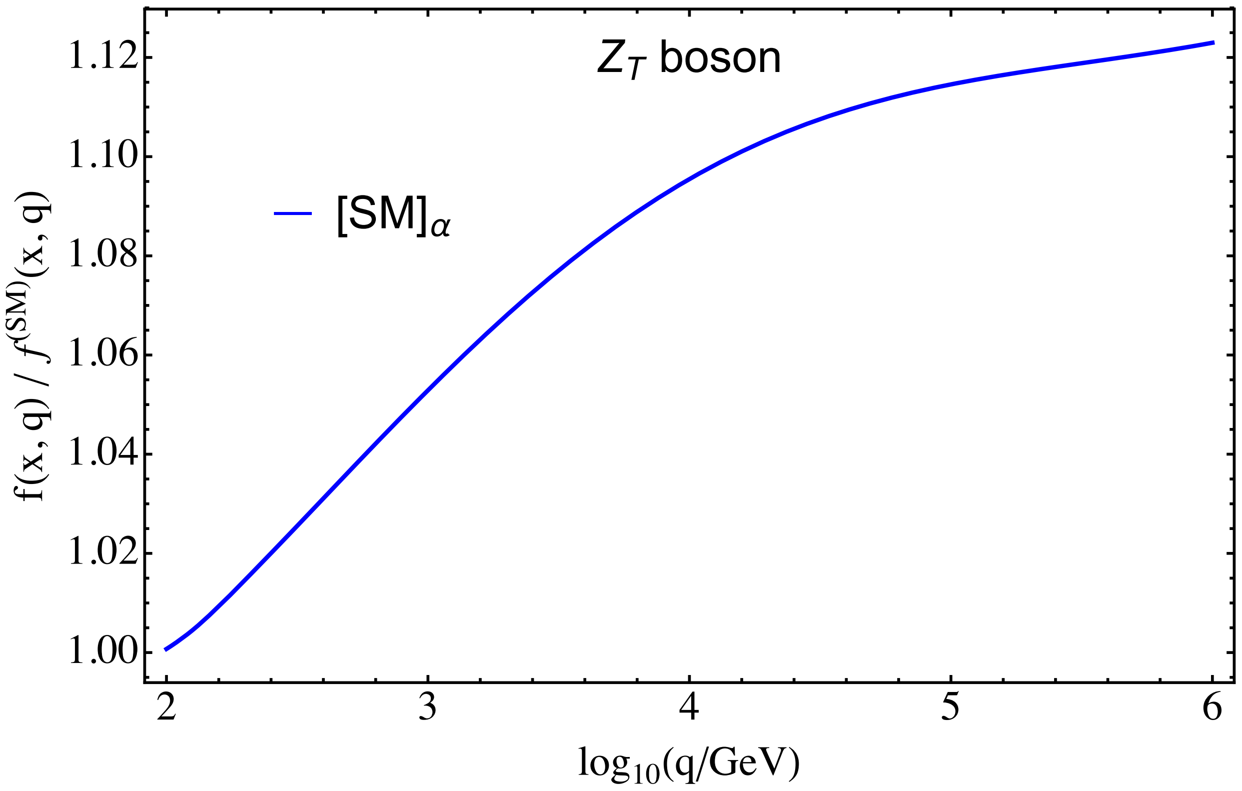
For ``regular'' PDFs, first order expansion gives good approximation to full DGLAP result

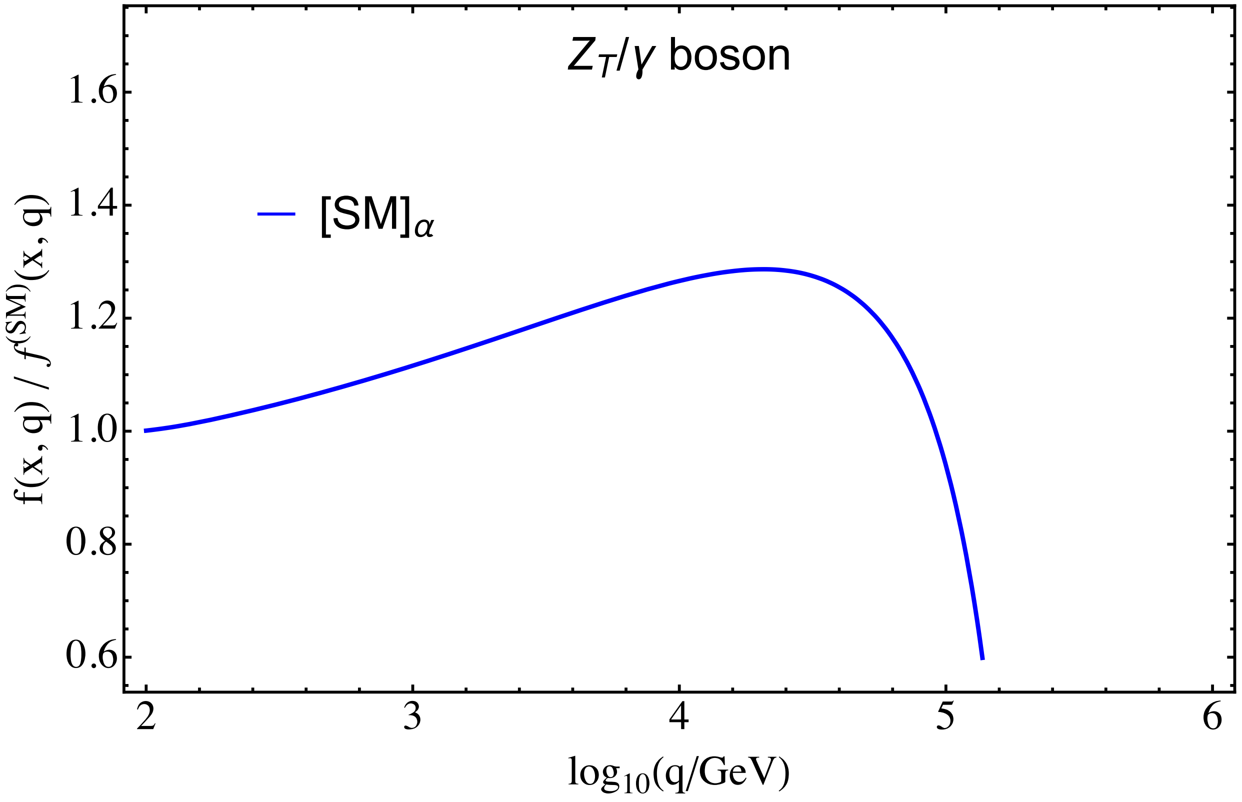


For EW gauge boson PDFs, entire resummation needs to be taking into account

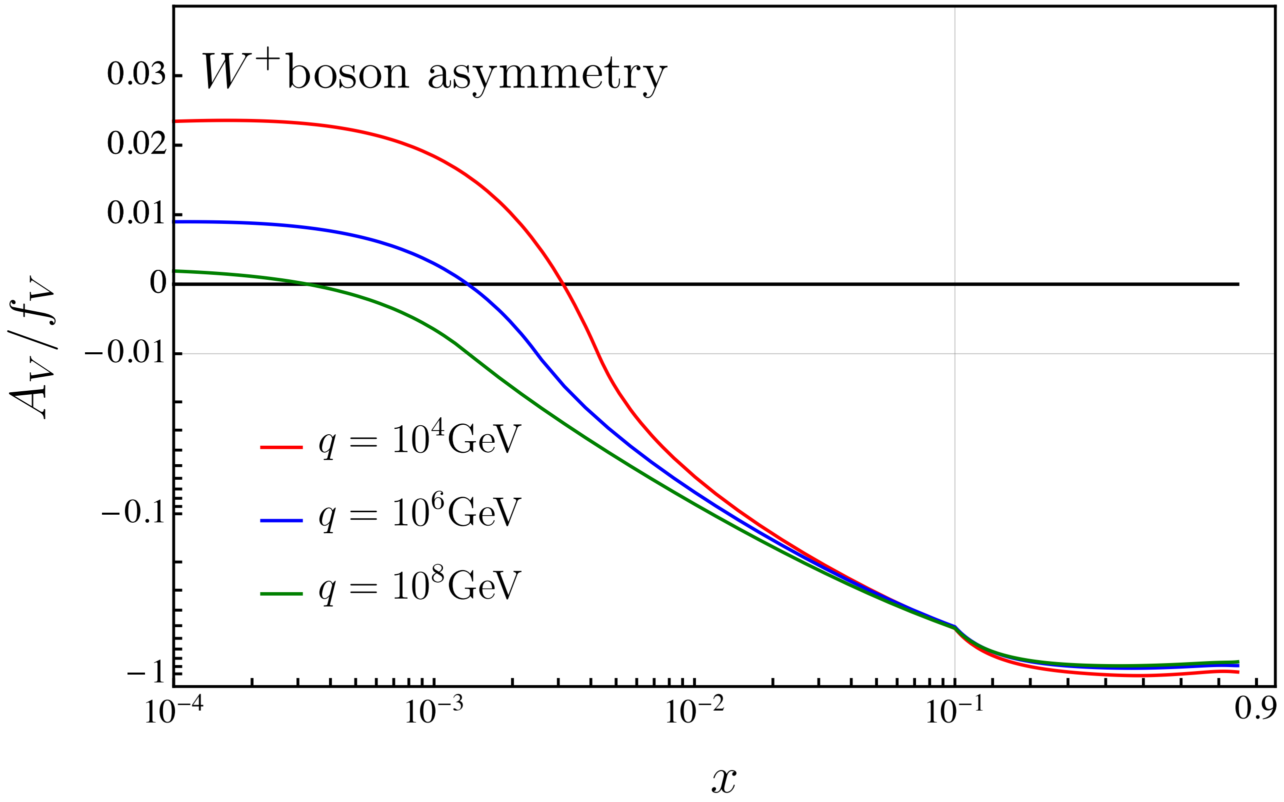


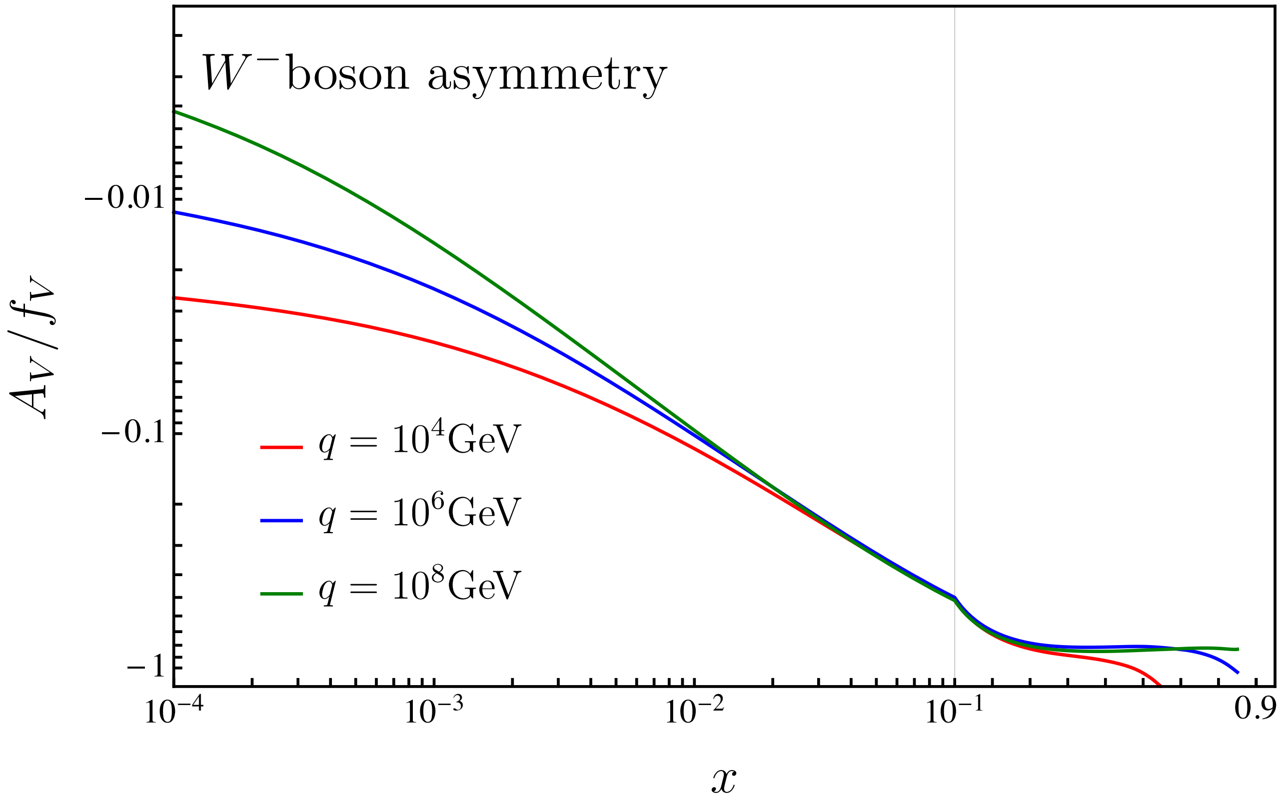


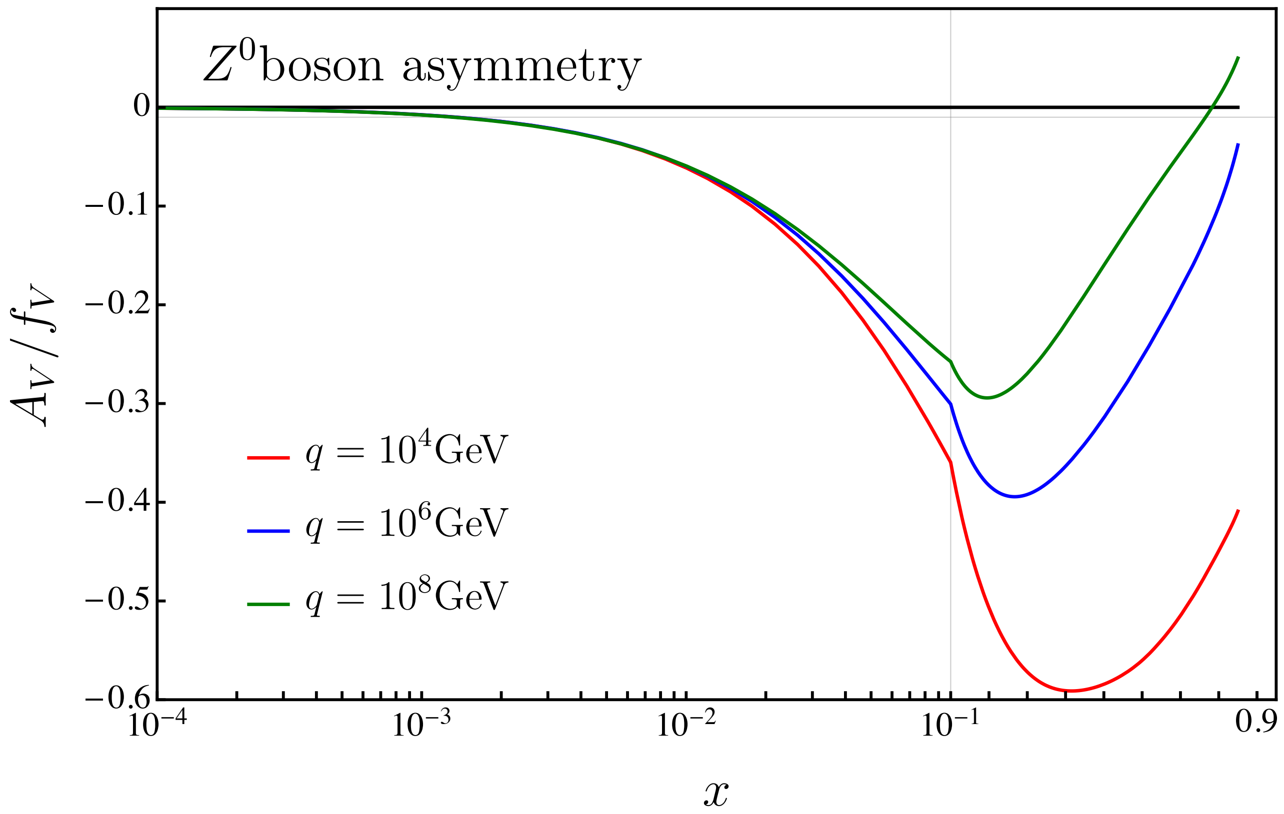


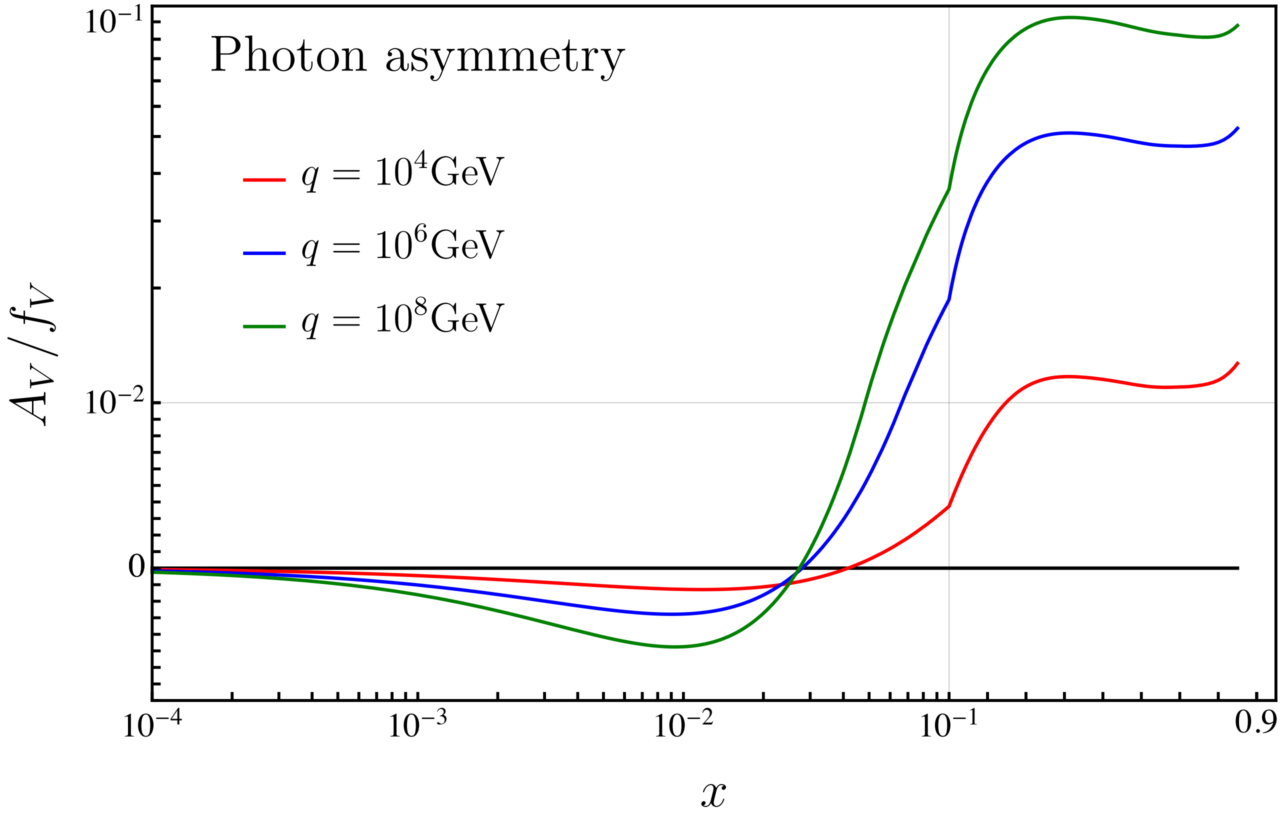


DGLAP evolution is generating significant polarization asymmetries for vector bosons

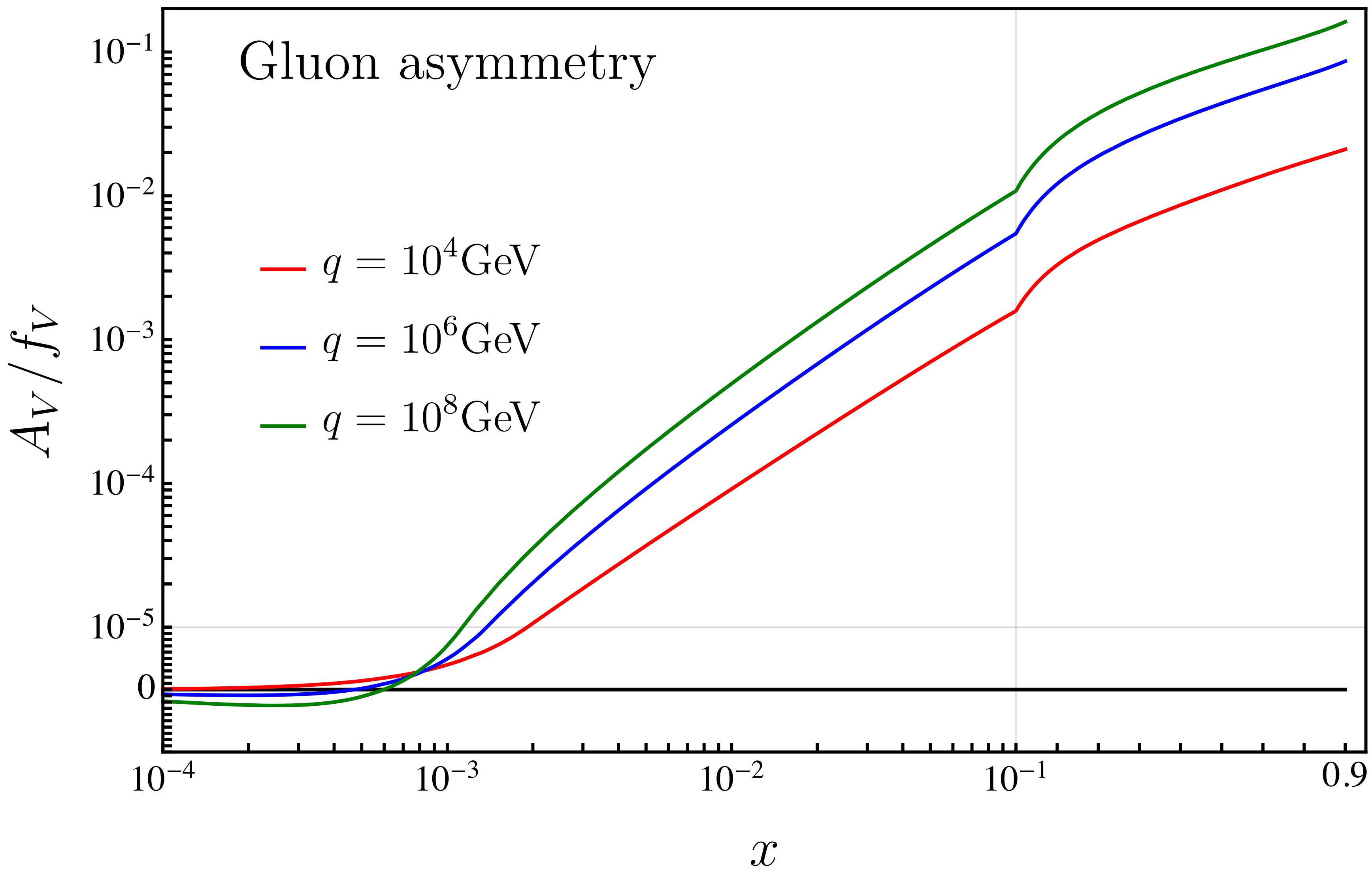






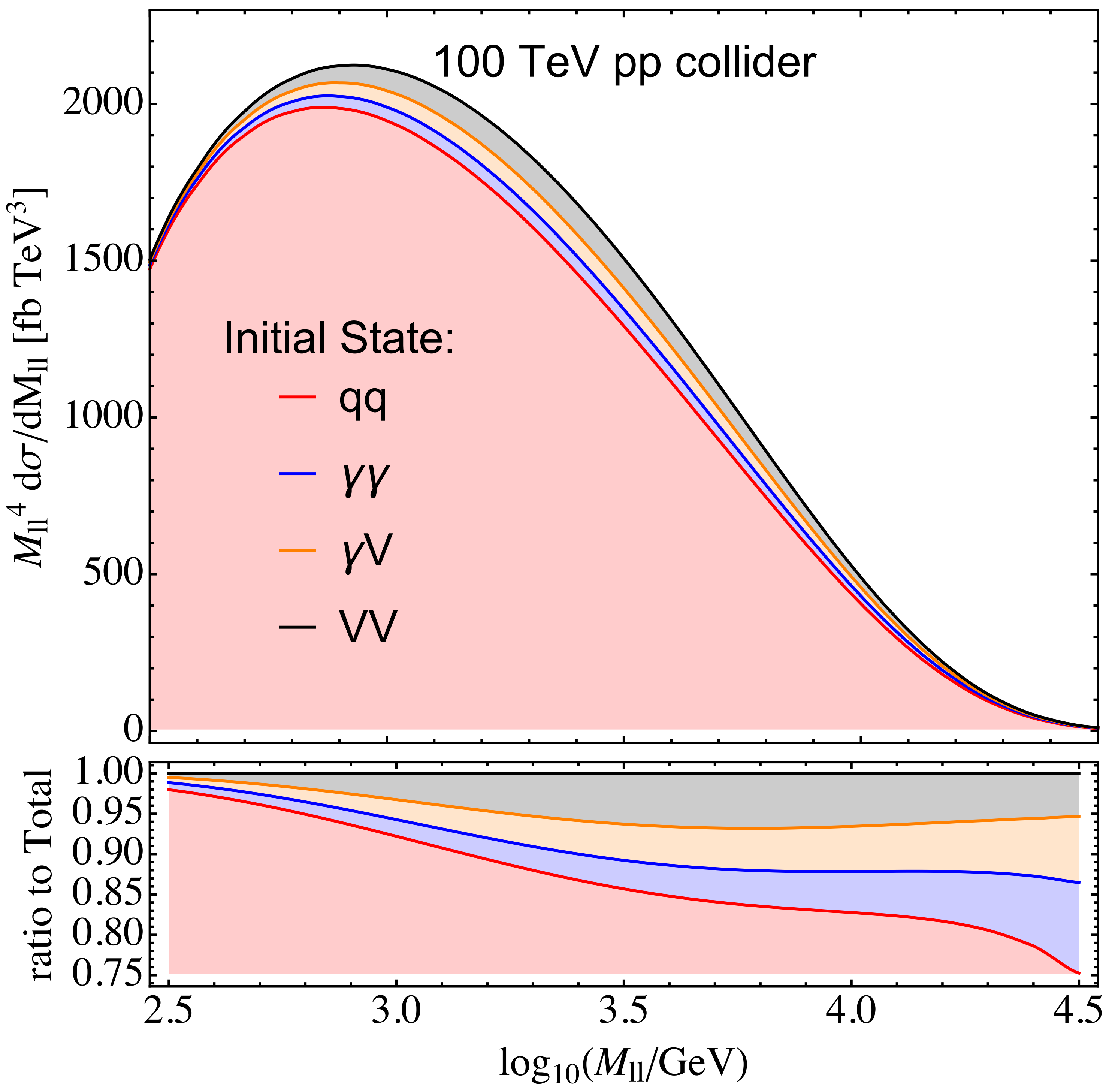


DGLAP evolution is generating significant polarization asymmetries for vector bosons



Let’s study the importance for a benchmark process at a 100 TeV collider

Di-lepton production at 100 TeV



In summary, EW logarithms are important at high energies, and resummation is important for several processes