EW resummation and showers

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in collaboration with Bryan Webber, Nicholas Ferland and Nicholas Rodd

To start off, I want to make a few disclaimers:

1. I have not worked on EW logs in collider environments for several years
2. I have not looked directly at the effects of EW logs on muon colliders
3. I was only asked to give this talk about week ago

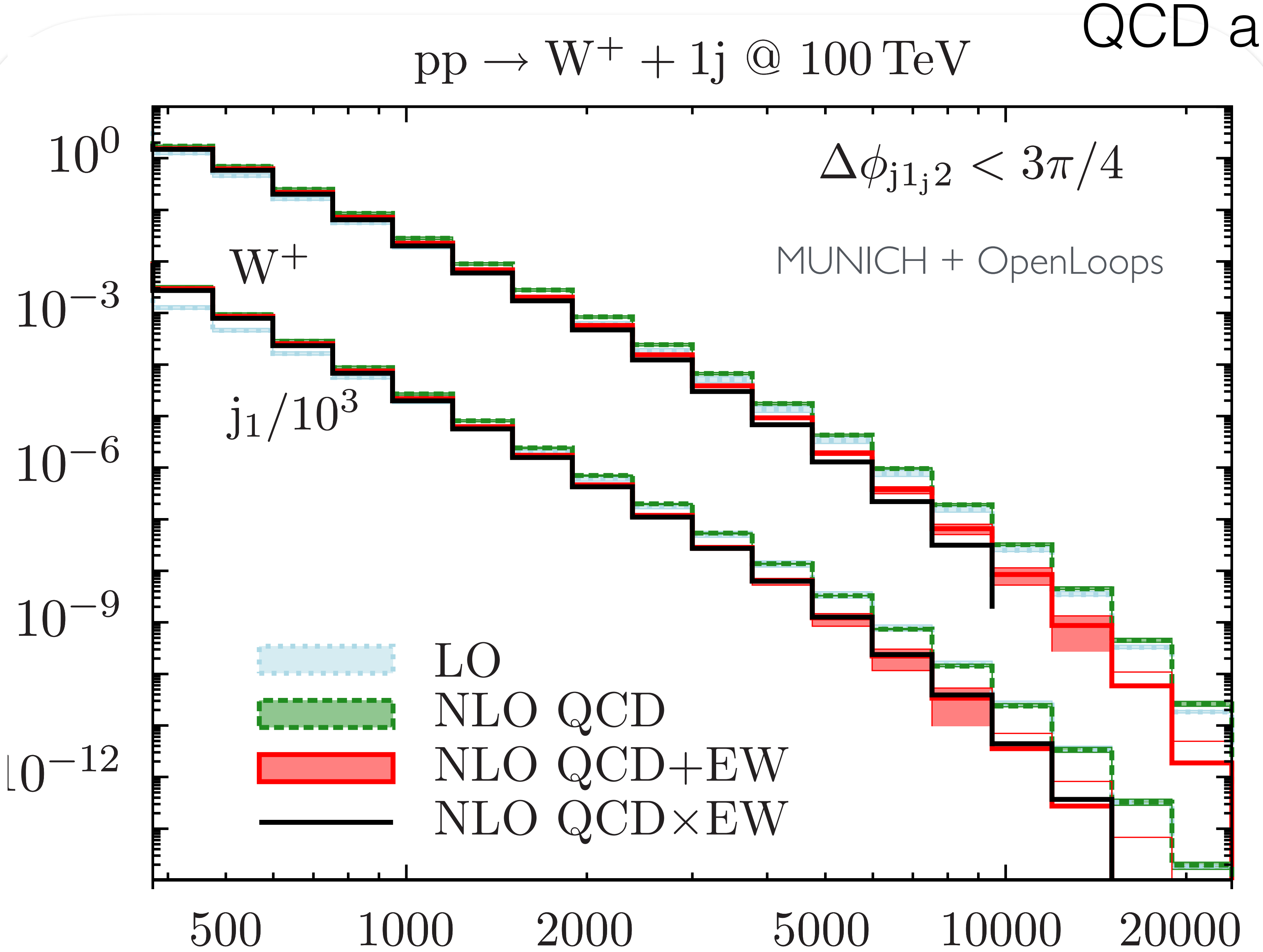
This has several consequences:

1. Results I am presenting are a few years old (but should still represent the correct physics and intuition
2. I have not looked directly at the effects of EW logs on muon colliders. Numerical results are therefore for 100TeV (or higher) pp machines

However, the setup is directly applicable to muon collider, and this workshop has motivated me to redo our analyses for the muon collider directly.

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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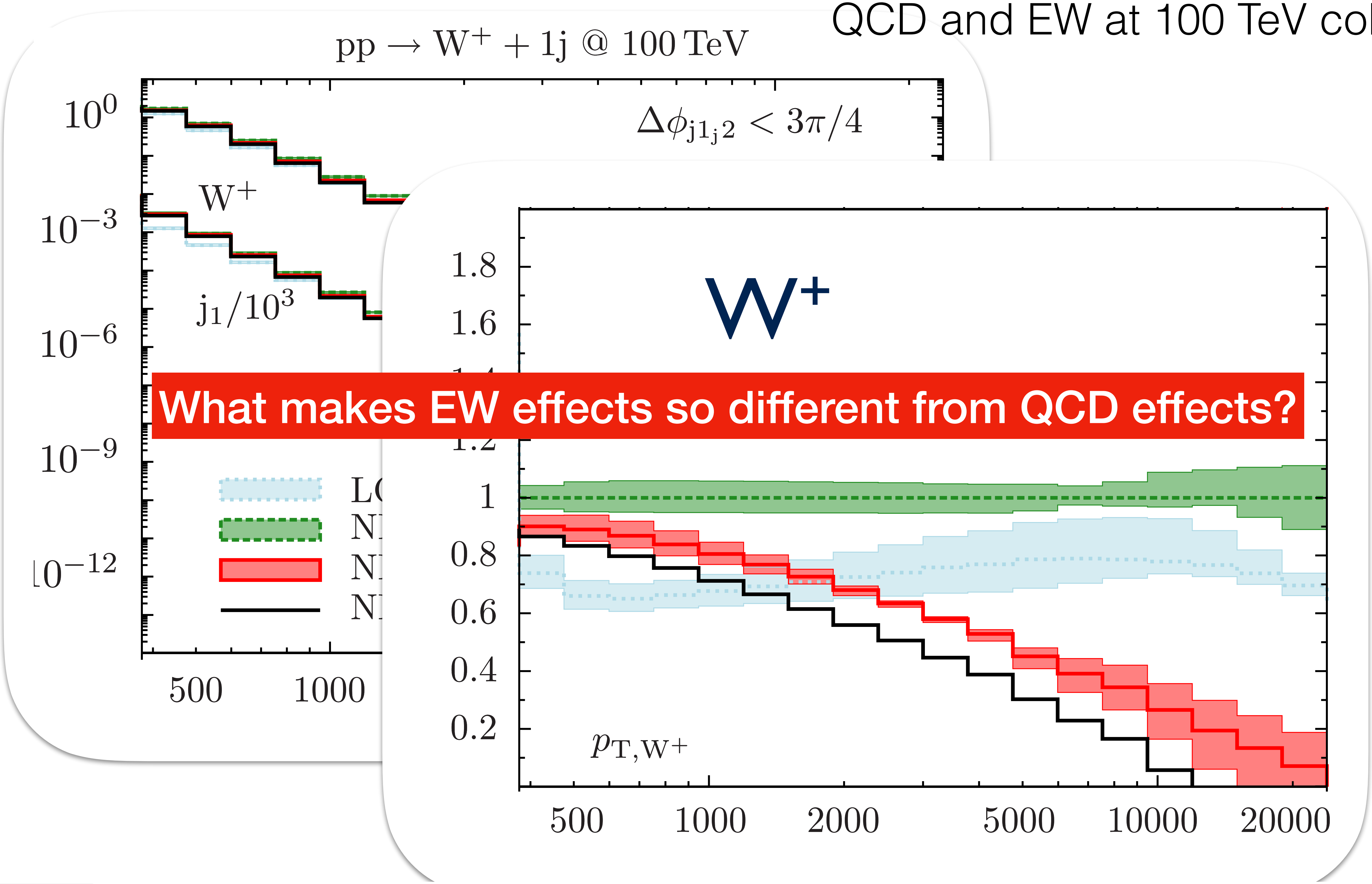
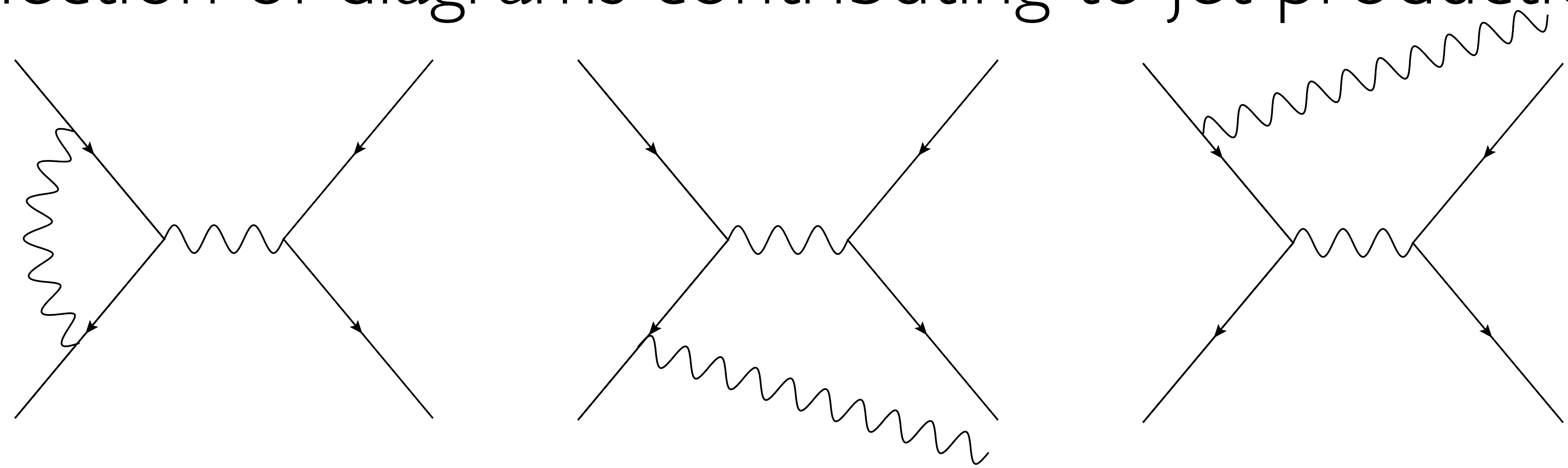


What makes EW effects so different from QCD effects?

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

Selection of diagrams contributing to jet production



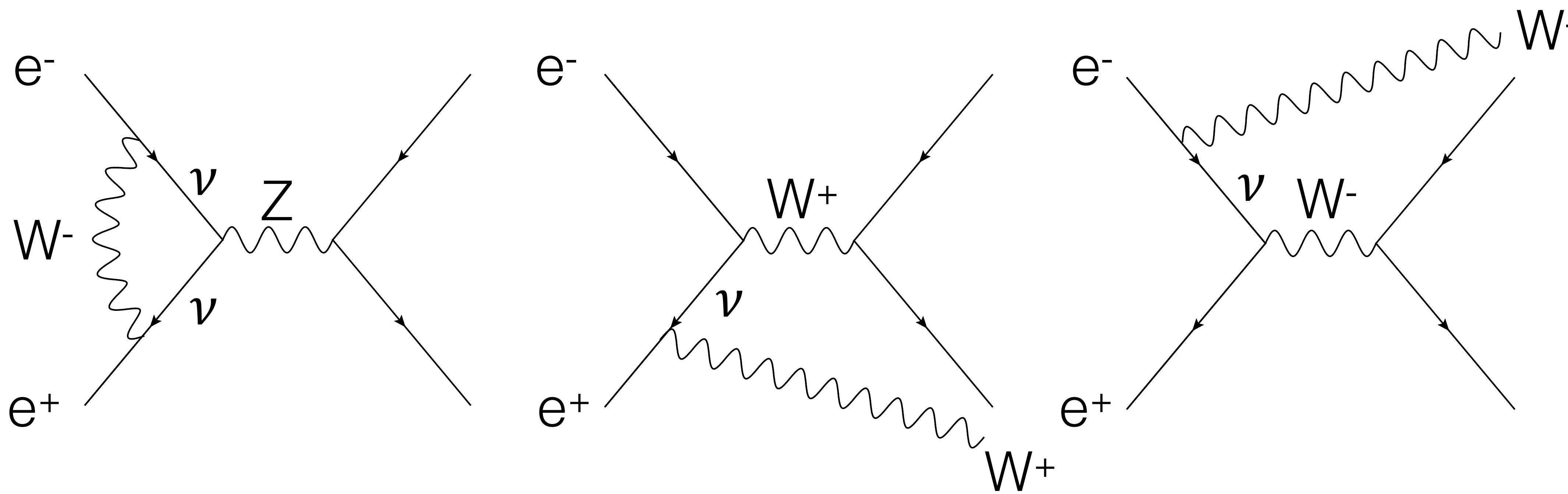
Any observable get contributions from virtual and real contributions

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

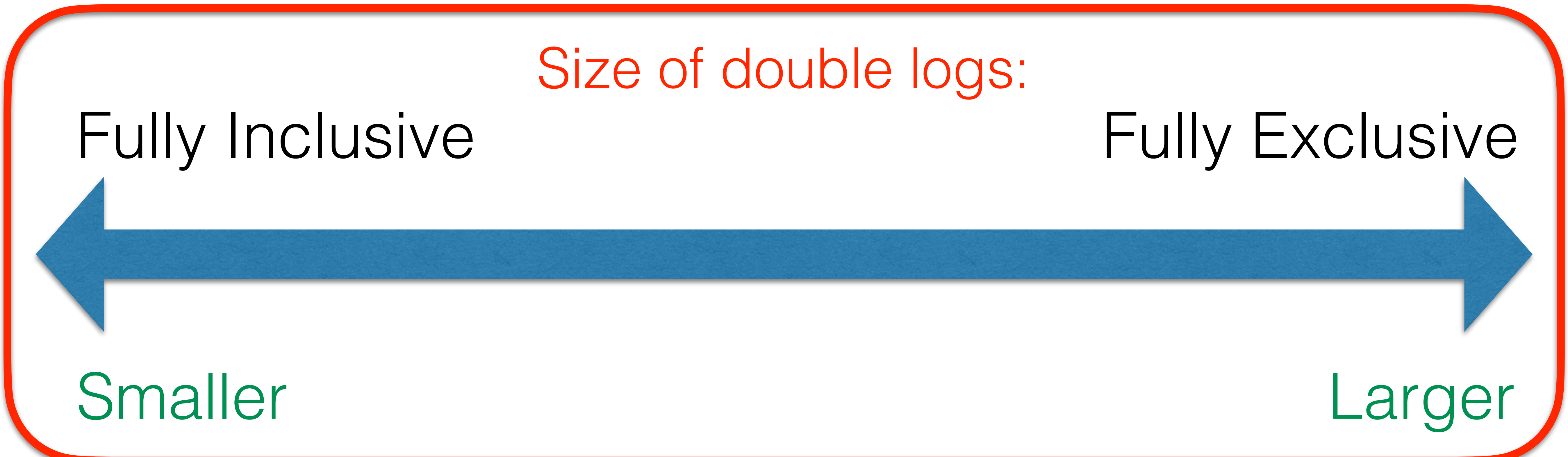


For massive W, IR divergences turn into log(m_W^2/s), and generally have two powers per power of α_s

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

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



There are 3 different ways one can include large EW effects into calculations

1. Calculation of PDFs and FFs which include the full EW SM evolution

Ciafaloni, Comelli ('05), Martin et. al. ('05), Roth et. al. ('05)
Ferland, CWB, Webber ('17)

2. Using a full EFT treatment, with soft and jet functions in the full SM

Manohar, Waalewijn ('18)

3. Using Parton shower approach that treats all interactions of the SM on the same footing

Han, Tweedie ('16)
CWB, Rodd, Webber (WIP)

Effective theories (SCET) can be used to make predictions for inclusive cross sections

Standard Model parton distributions at very high energies

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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:

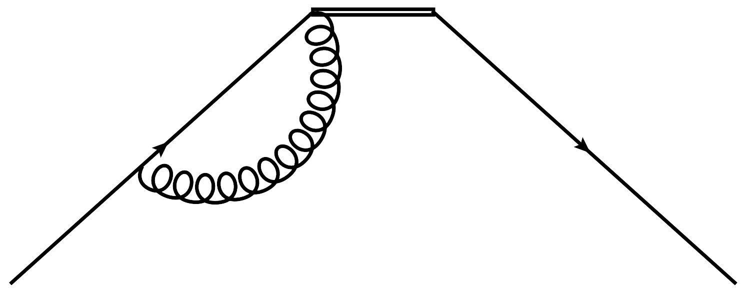
- Double logarithms from PDF evolution
- Generation of vector boson polarization

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

Ciafaloni, Comelli ('05), Martin et. al. ('05), Roth et. al. ('05)
CWB, Ferland, Webber ('17-'18)

Double logarithms from PDF evolution

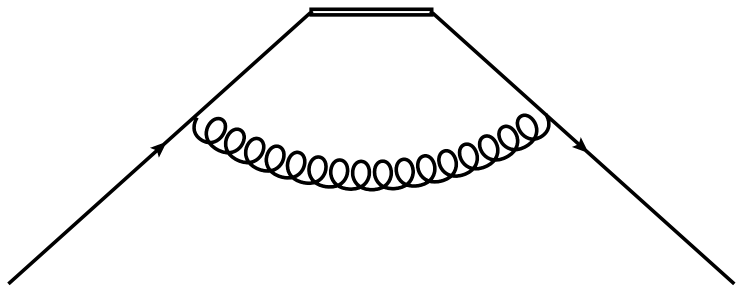
In standard QCD evolution, soft singularity cancels



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

Ciafaloni, Comelli ('05), Martin et. al. ('05), Roth et. al. ('05)
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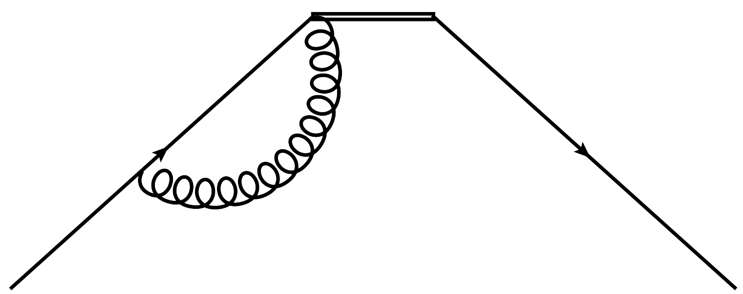
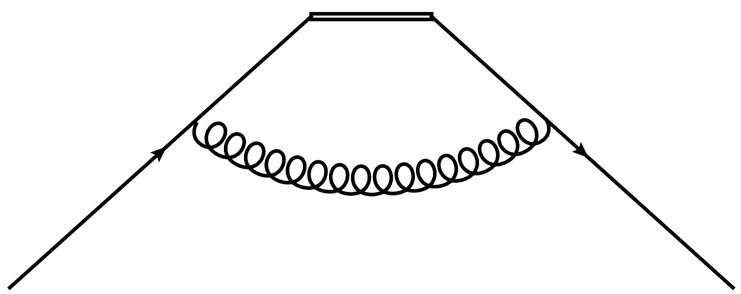
Double logarithms from PDF evolution

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



Virtual

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



Real

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

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

Ciafaloni, Comelli ('05), Martin et. al. ('05), Roth et. al. ('05)
CWB, Ferland, Webber ('17-'18)

Generation of polarization effects

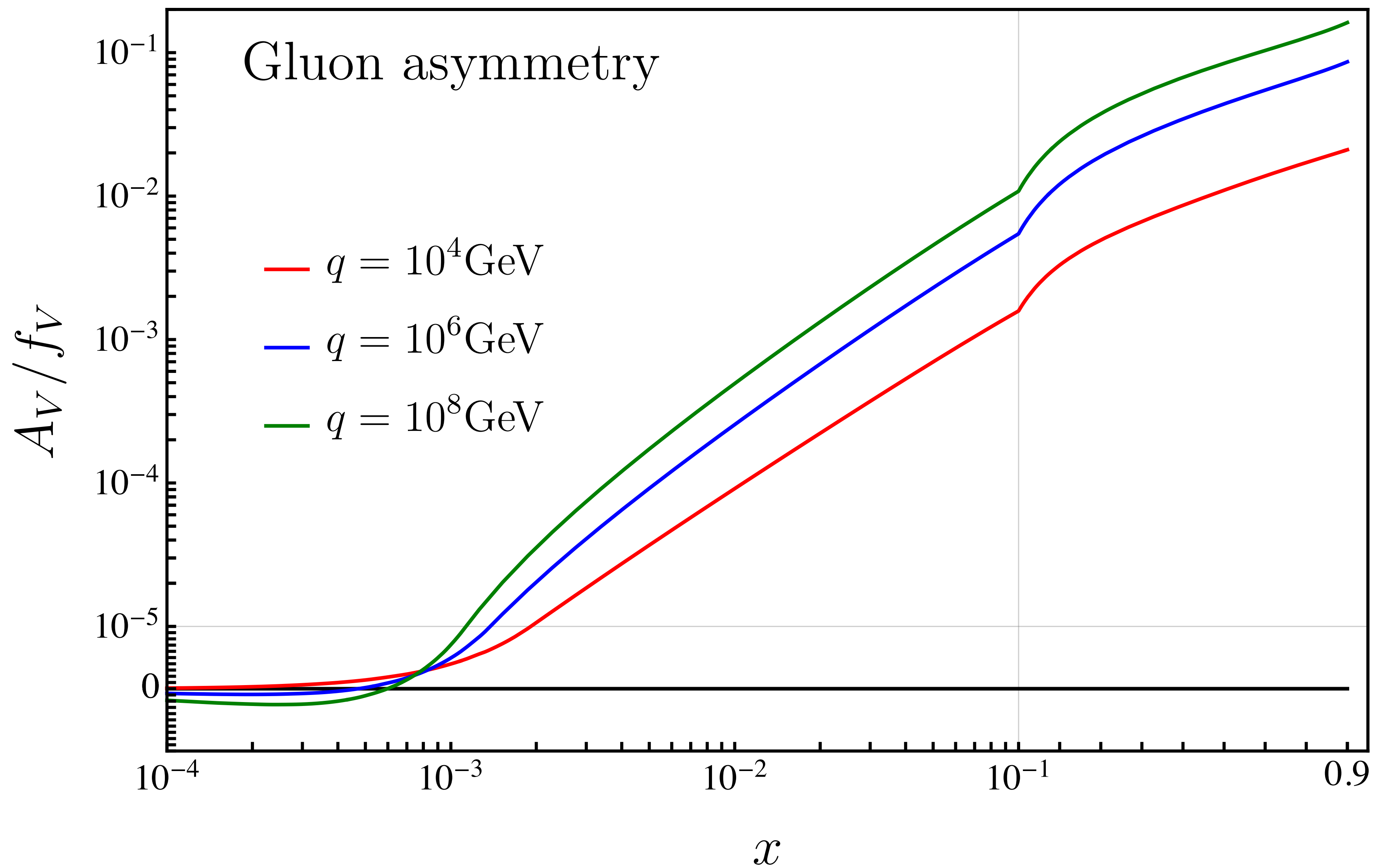
Manohar, Waalewijn (18)

- 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

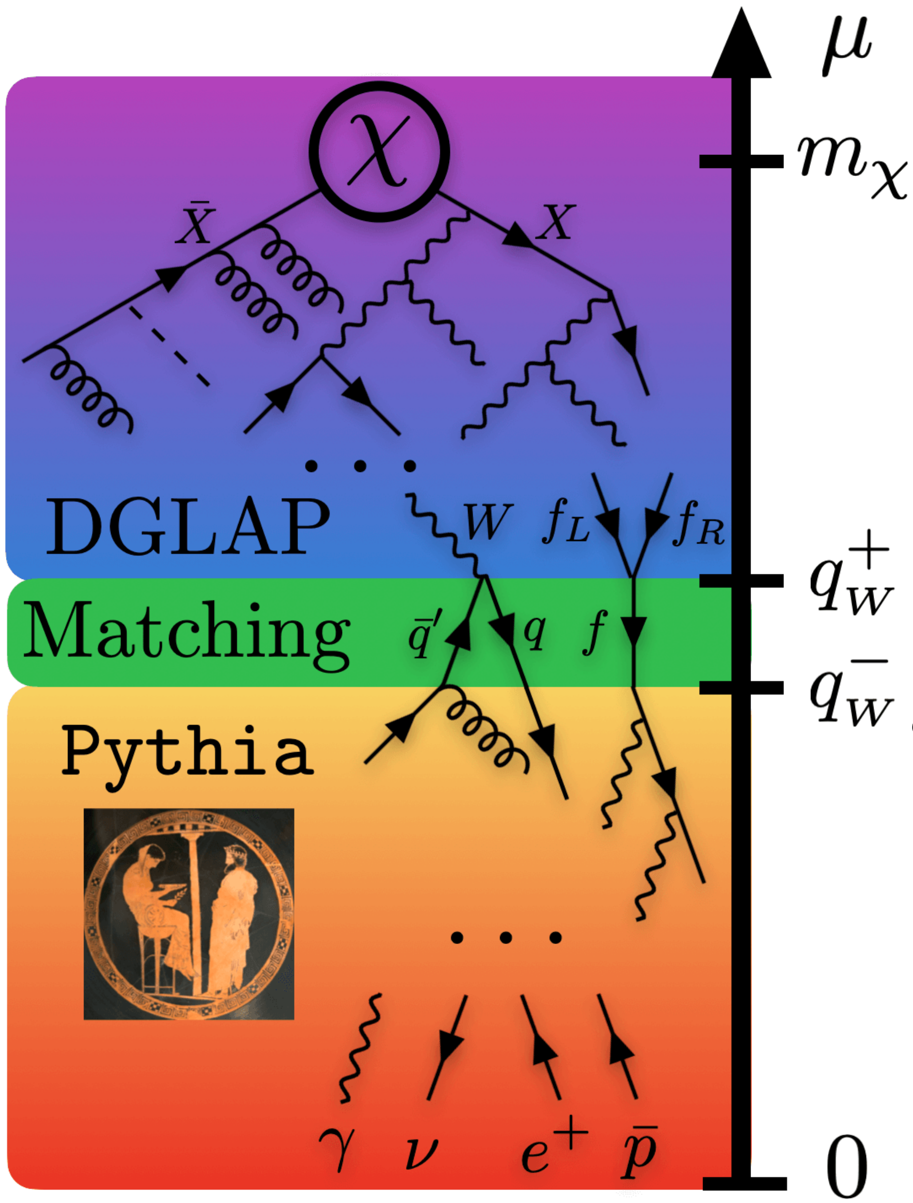
DGLAP evolution is generating significant polarization asymmetries for vector bosons

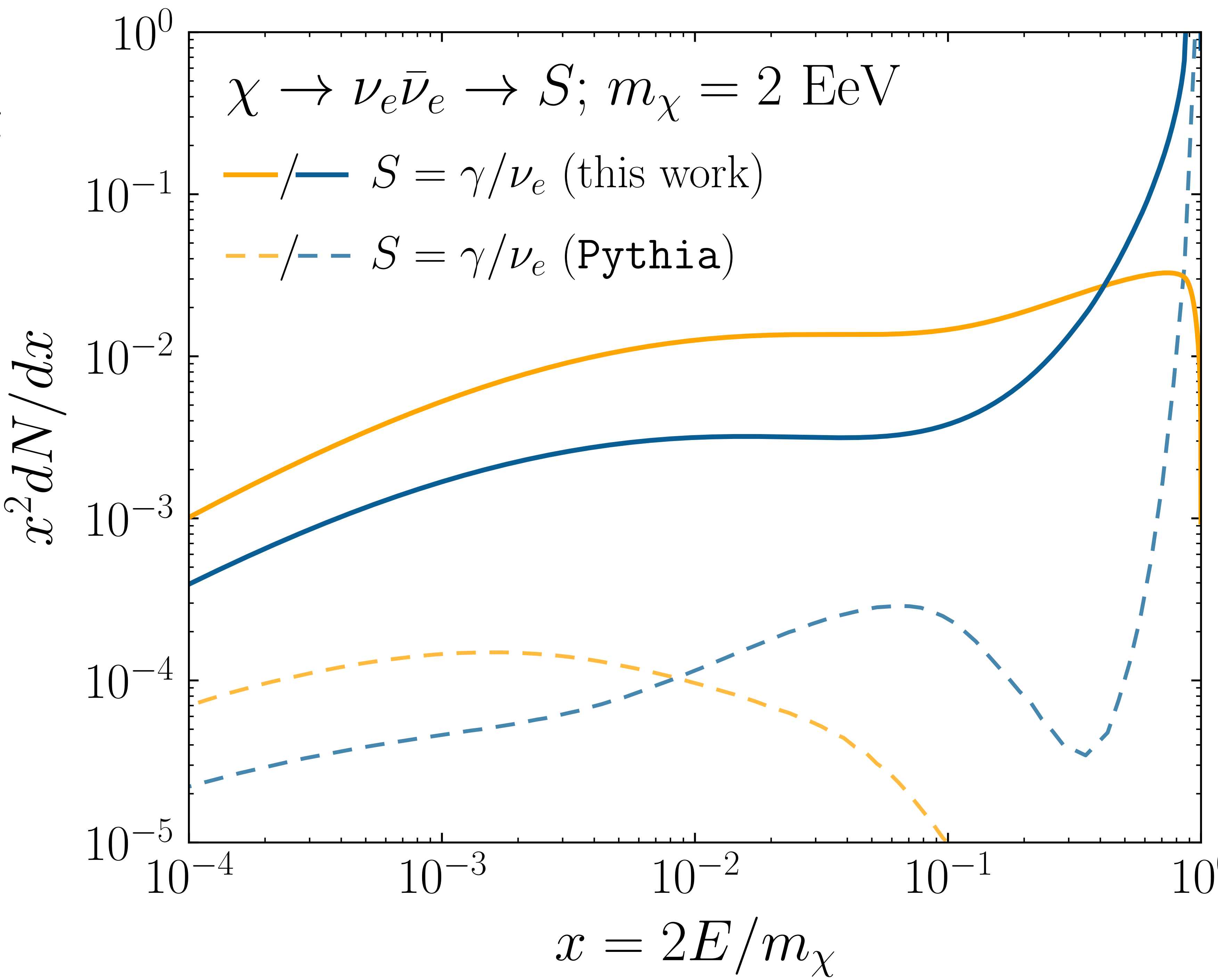
CWB, Ferland, Webber ('18)



Can have extremely important effects at extremely high energies, relevant for spectra from UH DM

CWB, Rodd, Webber ('20)





Effective theories (SCET) can be used to make predictions for inclusive cross sections

Manohar, Waalewijn ('18)

Electroweak logarithms in inclusive cross sections

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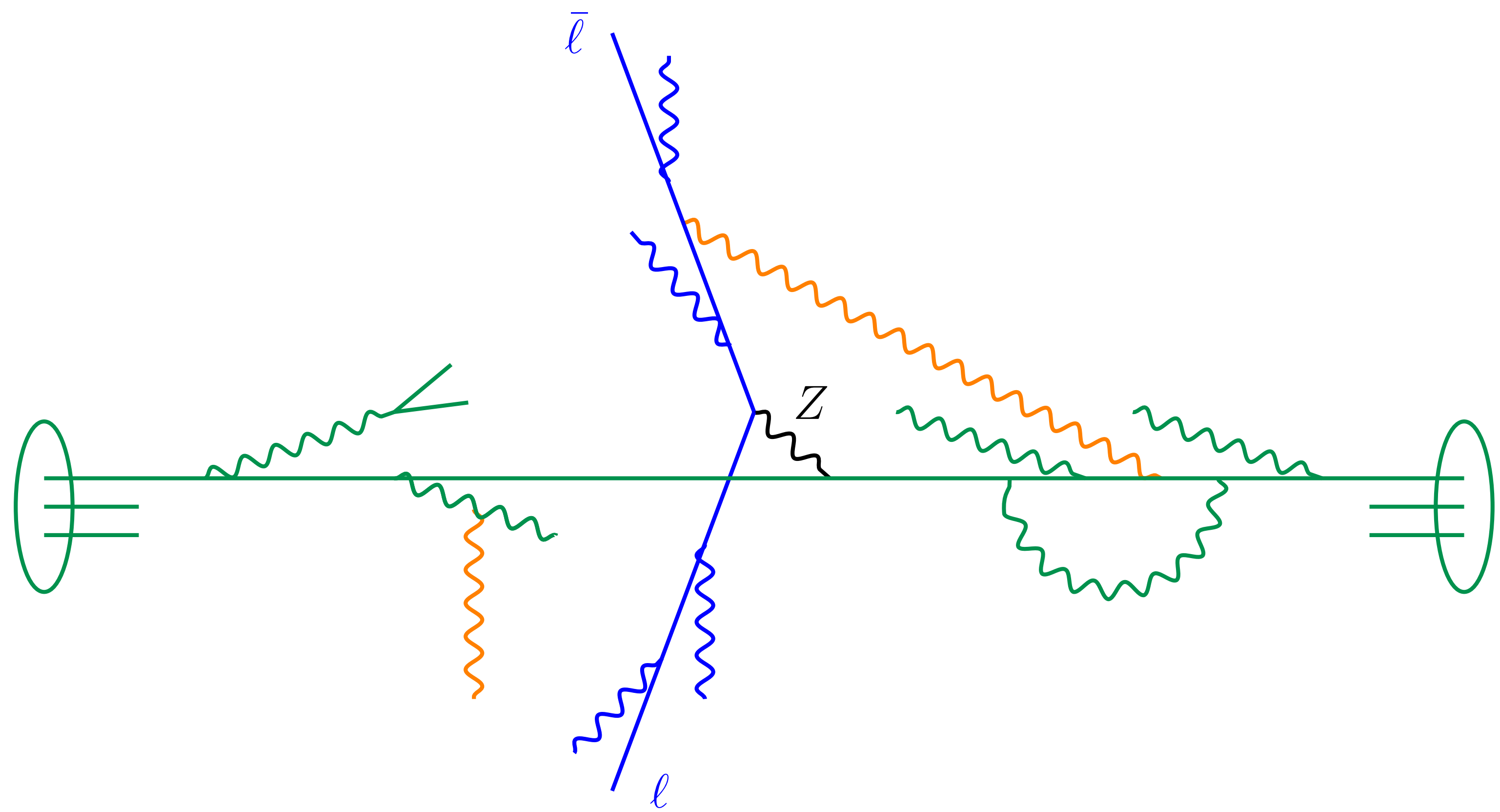
Effective theories (SCET) can be used to make predictions for inclusive cross sections

Manohar, Waalewijn ('18)



Three types of radiation need to be considered:

Initial state

Final state

Soft

$$\sigma = f \otimes f \otimes J_1 \otimes \ldots \otimes J_n \otimes S$$

Effective theories (SCET) can be used to make predictions for inclusive cross sections

Manohar, Waalewijn ('18)

$$\sigma = \boxed{f \otimes f} \otimes \boxed{J_1 \otimes \ldots \otimes J_n} \otimes \boxed{S}$$

Use RGE to resum logs in different ingredients of the factorization theorem

Double logs in soft and collinear sectors combine to reproduce double logs of PDF and FF of previous approach

This approach allows to take into account the resummation of single logarithms

As in QCD, parton showers are the only way to perform general simulations for complicated final states

Han, Tweedie ('16)
CWB, Rodd, Webber (WIP)

Not providing an explicit paper, since no publicly available implementation exists to my knowledge (but a lot of results shown in paper by Han, Tweedie)

Some EW effects included in Pythia, but not enough to get proper results

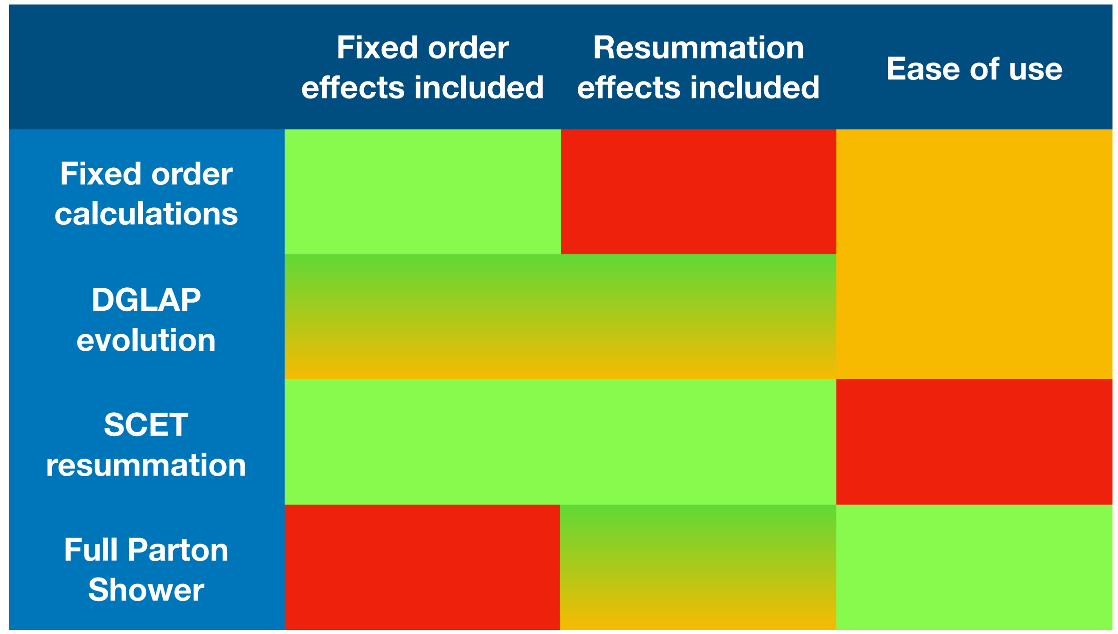
In principle can be implemented by working in the unbroken phase of the SM and including all interactions

Private code exists, but needs to be validated etc

Different approaches have different strengths

	Fixed order effects included	Resummation effects included	Ease of use
Fixed order calculations			
DGLAP evolution			
SCET resummation			
Full Parton Shower			

Which approach to take depends on relevant importance of the various categories



- For muon collider, E_{CM} might not be large enough for resummation of large logarithms to really matter. FO might be enough
- DGLAP evolution can be a very good approach to get resummation and fixed order at a high enough accuracy while still having relative ease of use
- Parton showers can become available over time (physics case for muon collider would be a strong motivator)

In conclusion, resummation of EW logs is rich subject, and one needs to carefully access available techniques

QUESTIONS?