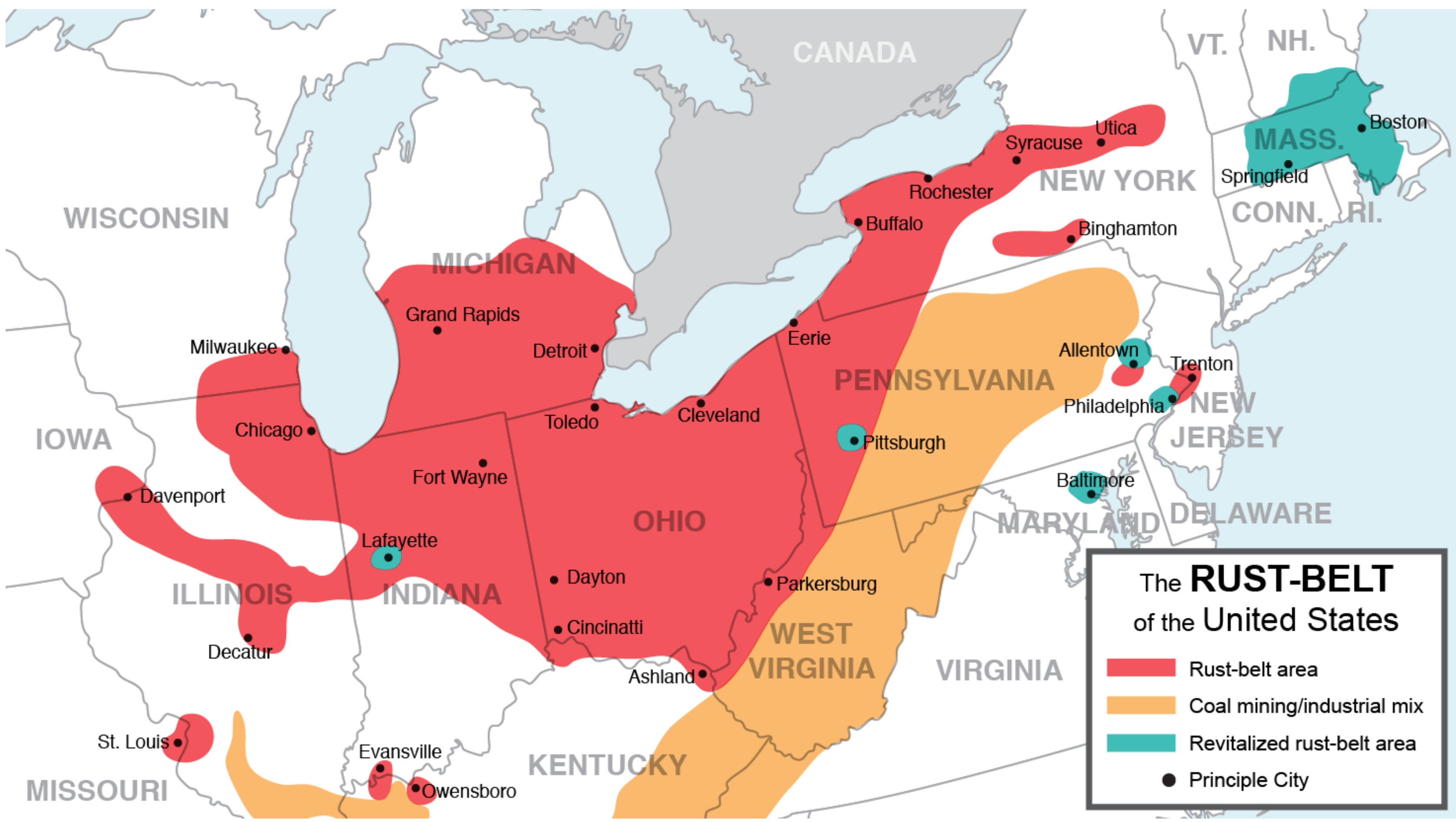
New developments in Perturbative QCD

Ciaran Williams (SUNY Buffalo)

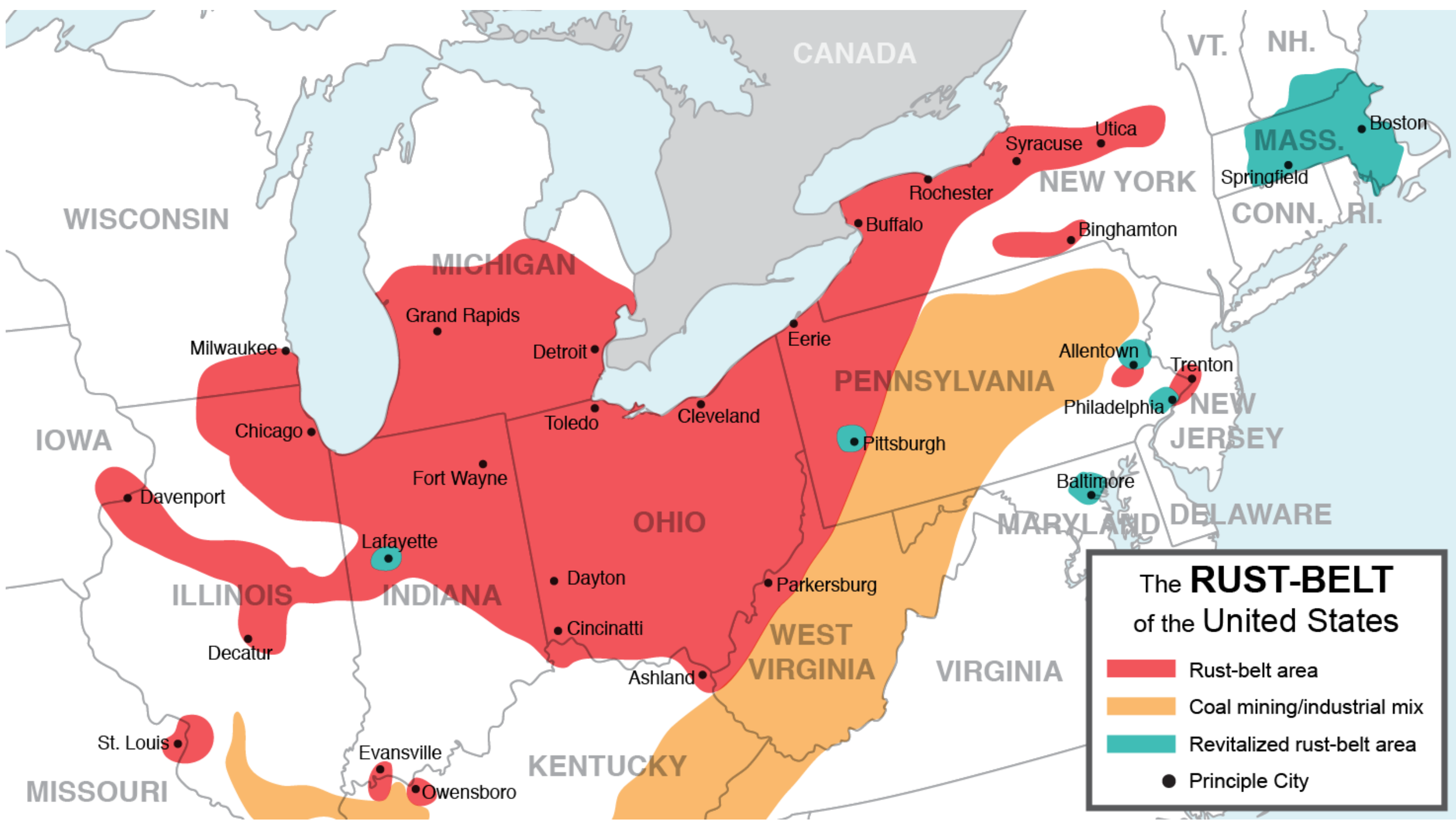


Pheno 2016

A very biased overview of

New developments in (fixed order) Perturbative QCD

Ciaran Williams (SUNY Buffalo)



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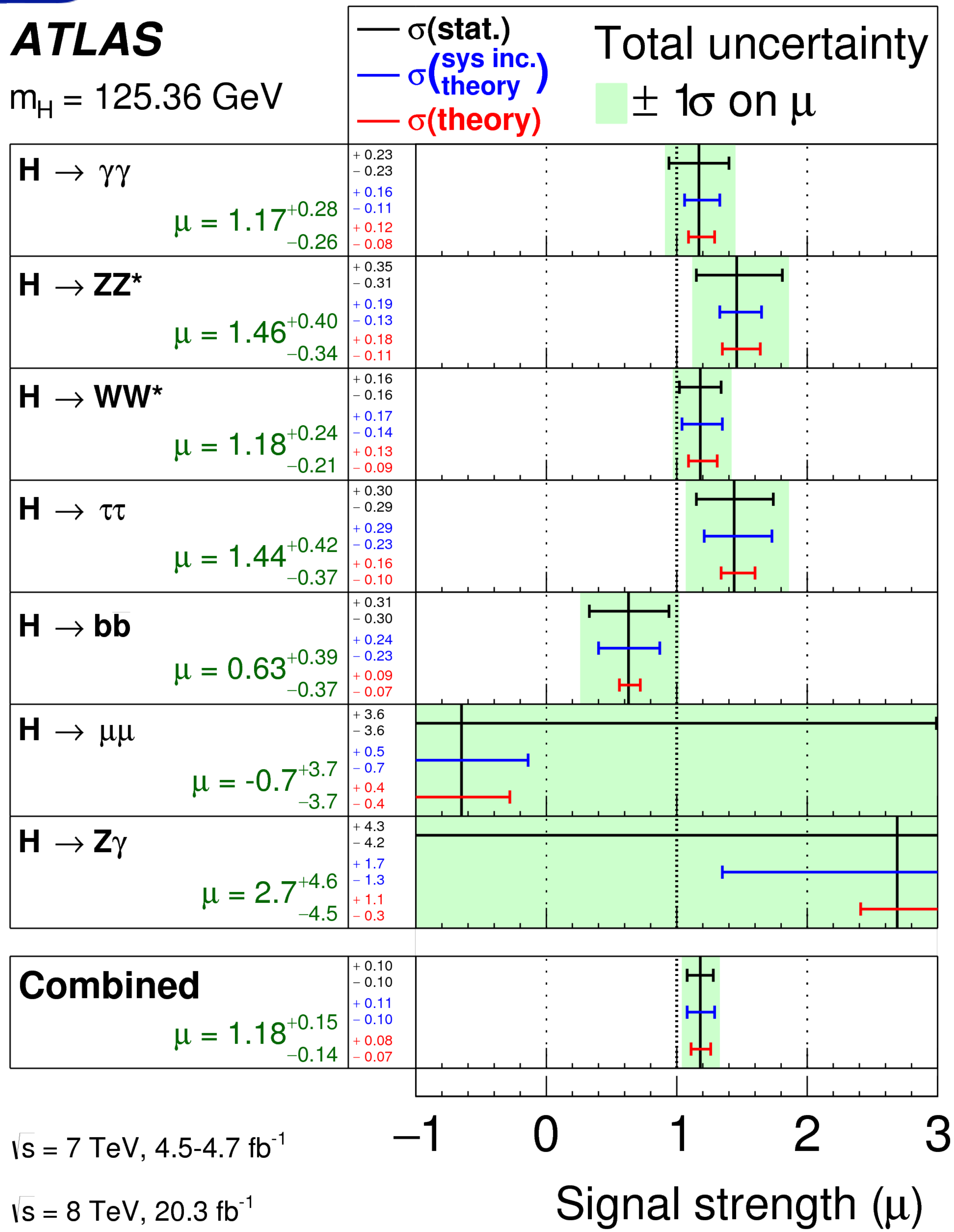
Going into Run II….



Studying the Higgs boson in ever greater detail will be one of the cornerstones of Run II.

Already with Run 1 data the theoretical uncertainties form a large part of the total systematic uncertainty.

This sets the challenge to the precision community.

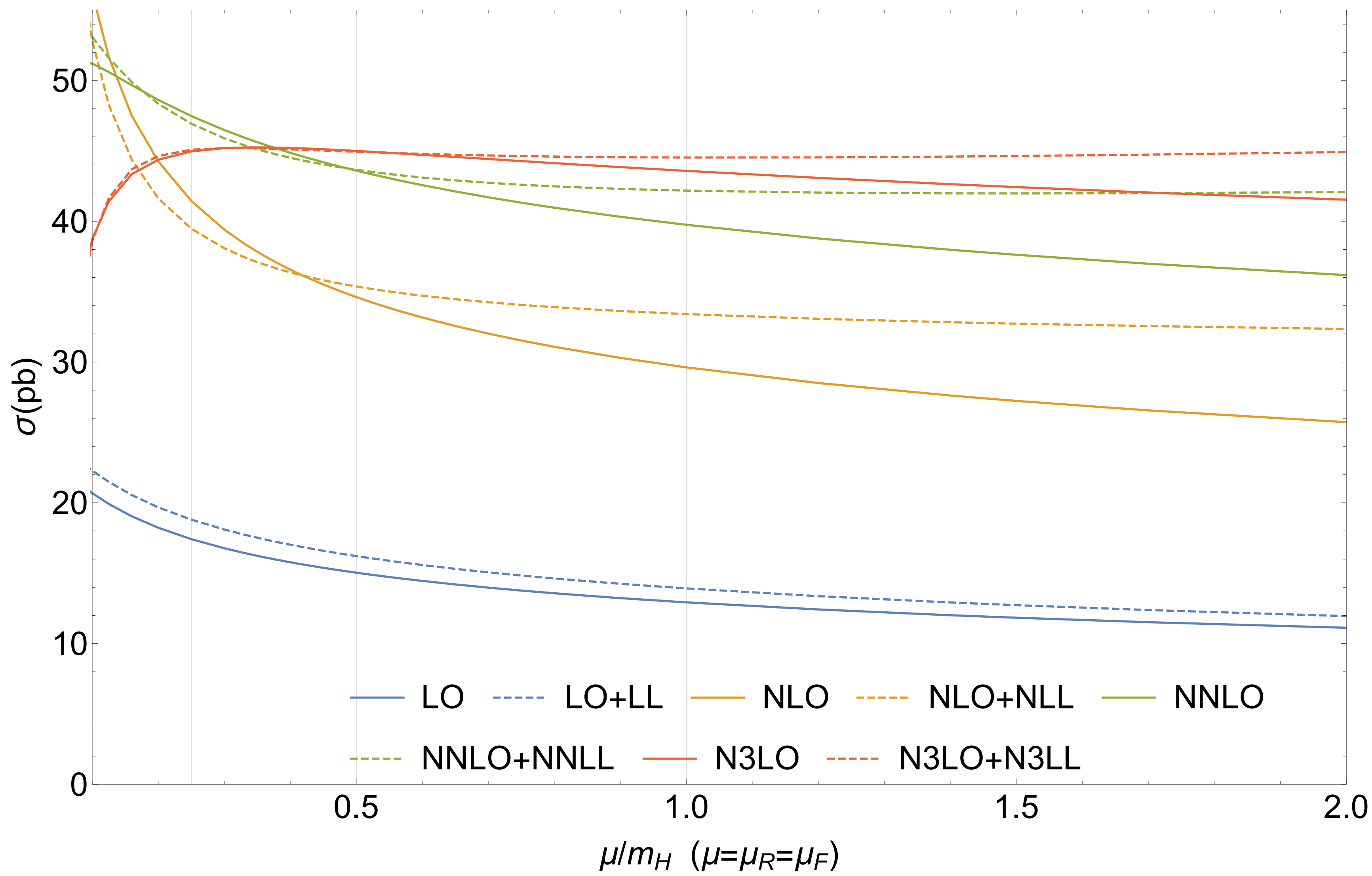
Can we provide predictions accurate enough to get the most out of the fantastic LHC data?

Probably!

A remarkable achievement

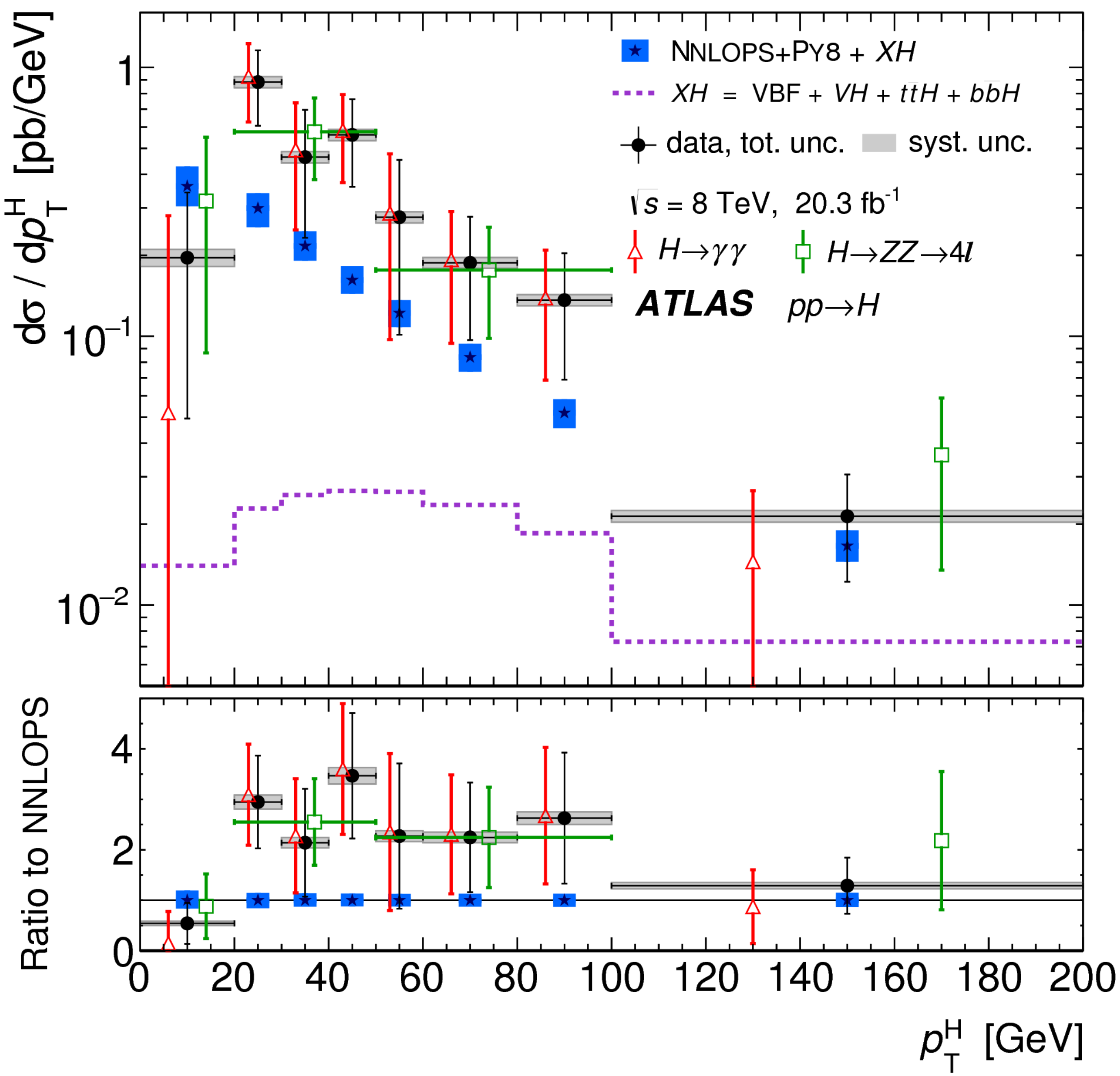
Inclusive Higgs cross section now known to N3LO!

(Anastasiou, Duhr, Dulat, Herzog, Mistlberger 15)



(Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Lazopoulos, Mistlberger 16)

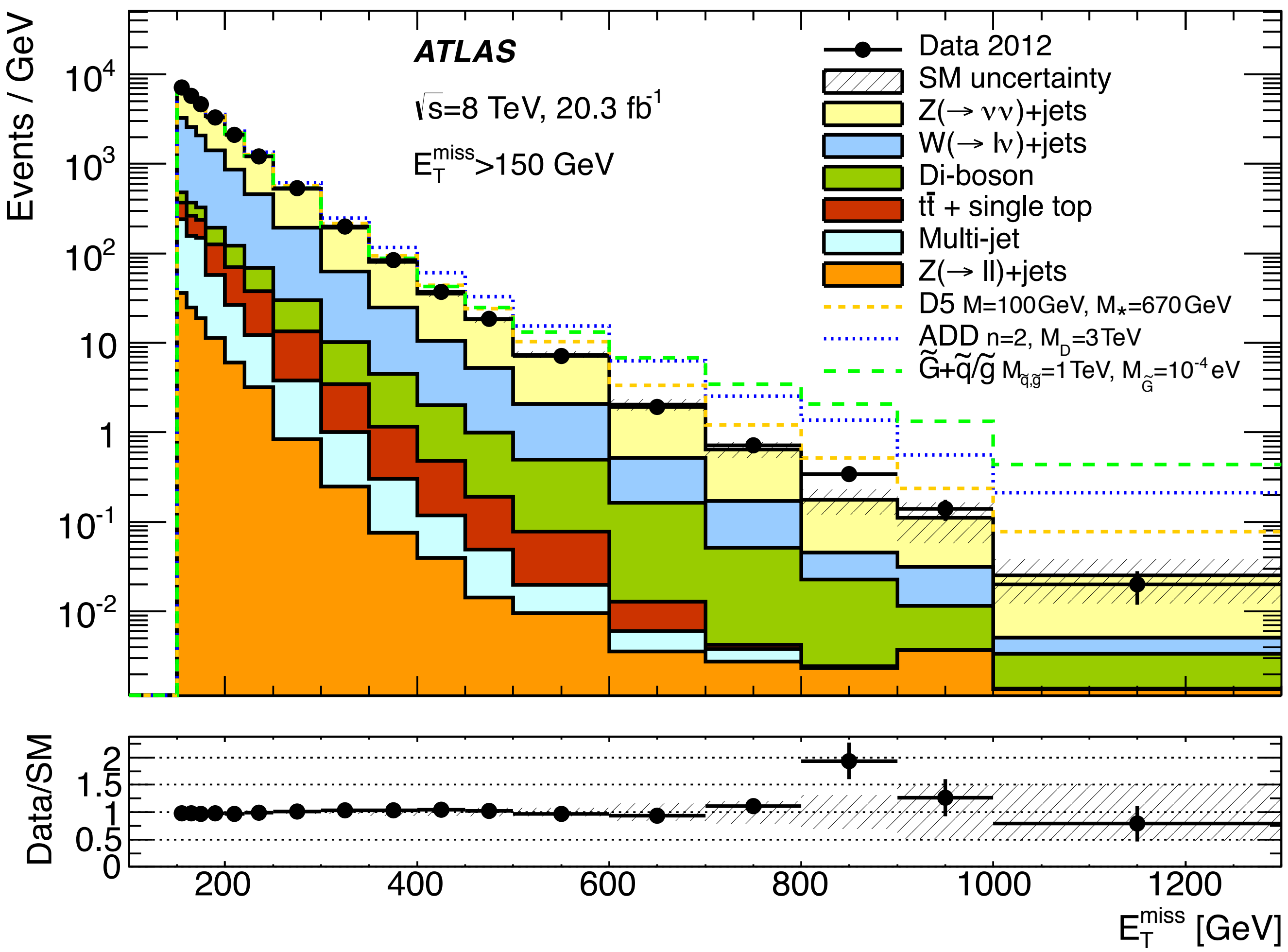
$$\sigma = 48.58\,\text{pb}^{+2.22\,\text{pb}\,(+4.56\%)}_{-3.27\,\text{pb}\,(-6.72\%)}\ (\text{theory}) \pm 1.56\,\text{pb}\,(3.20\%)\ (\text{PDF}+\alpha_s)$$

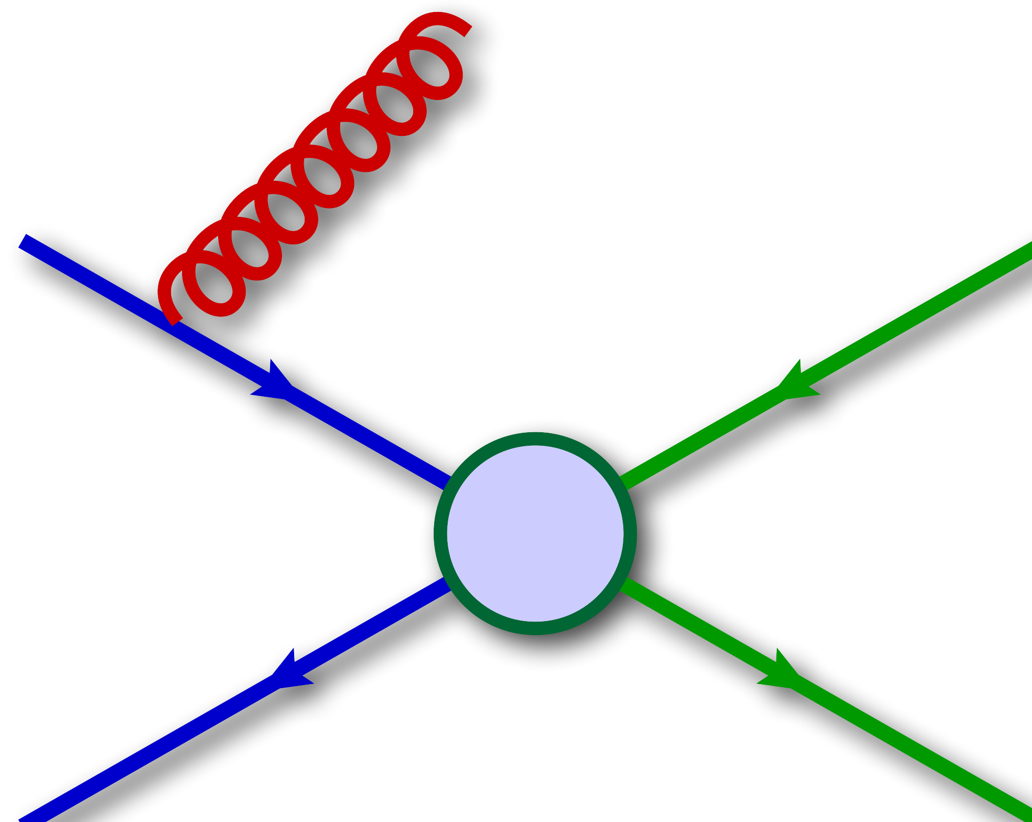


A key advantage of the LHC Run II will be the ability to study the Higgs boson differentially.

The N3LO cross section will help with overall normalization. But we need differential predictions to search for the impact of small effects (like EFT corrections to the SM for instance)

Searches for new physics

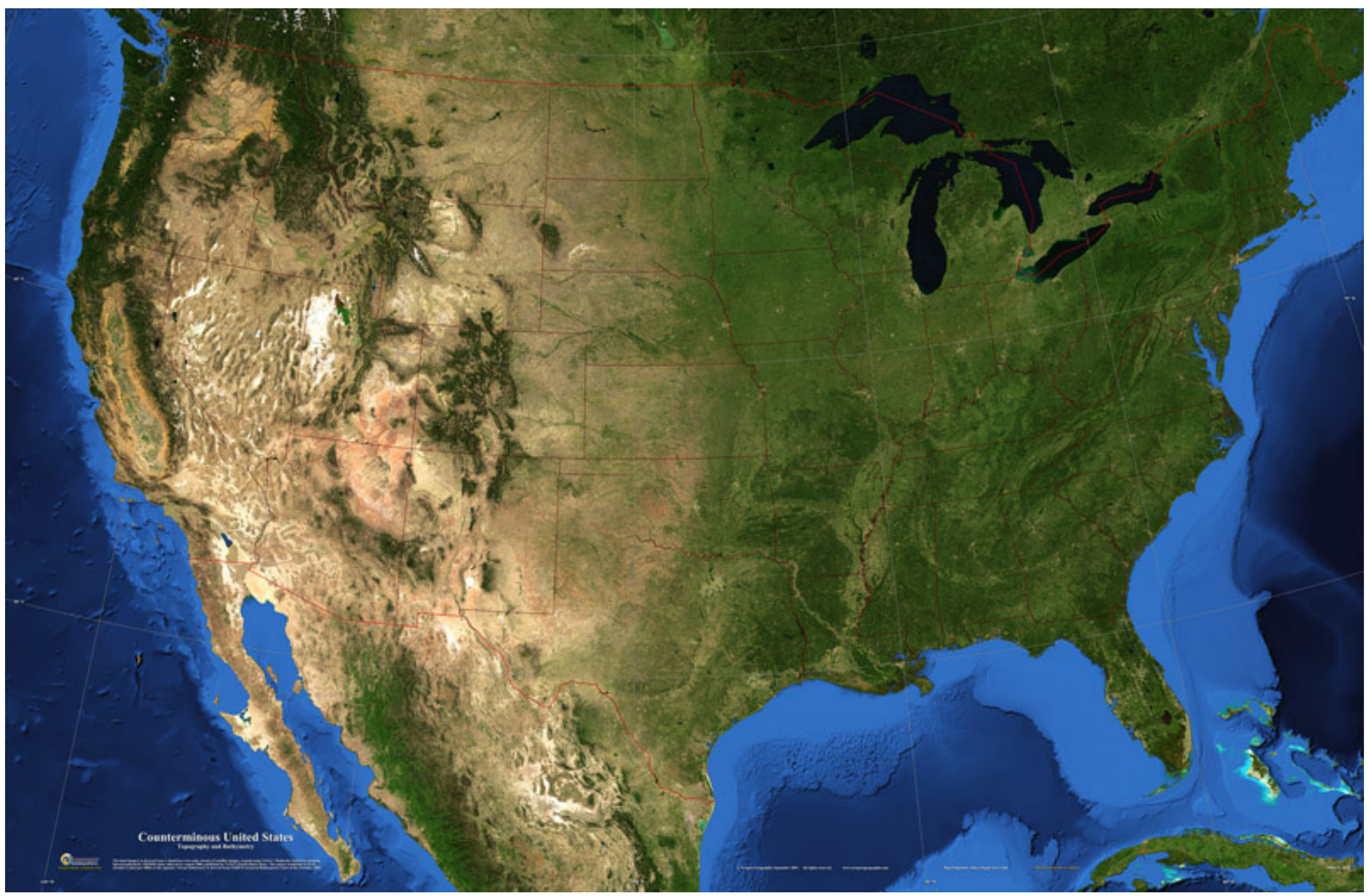


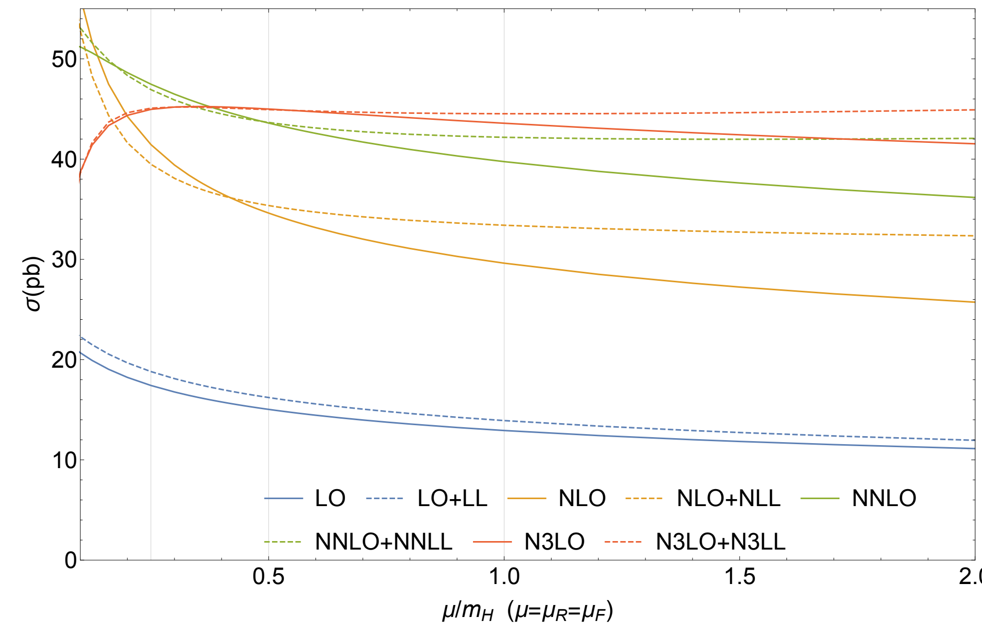


For searches which involve subtle shape changes w.r.t. SM backgrounds it is crucial we understand the SM shape (often in challenging regions of phase space)

Perturbative predictions for the LHC Run II

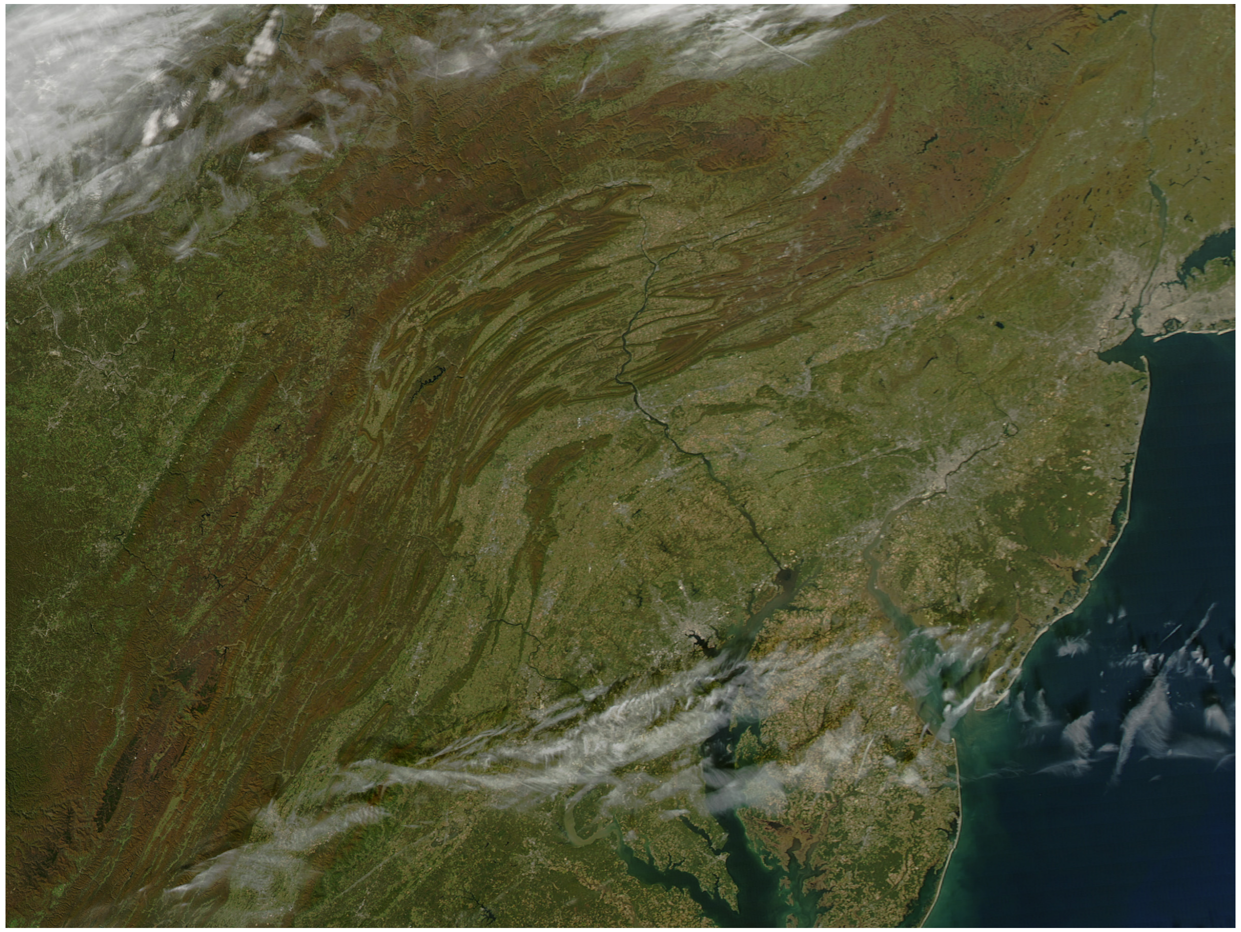
LO : Ballpark. eg *“Pheno is in the United States”*

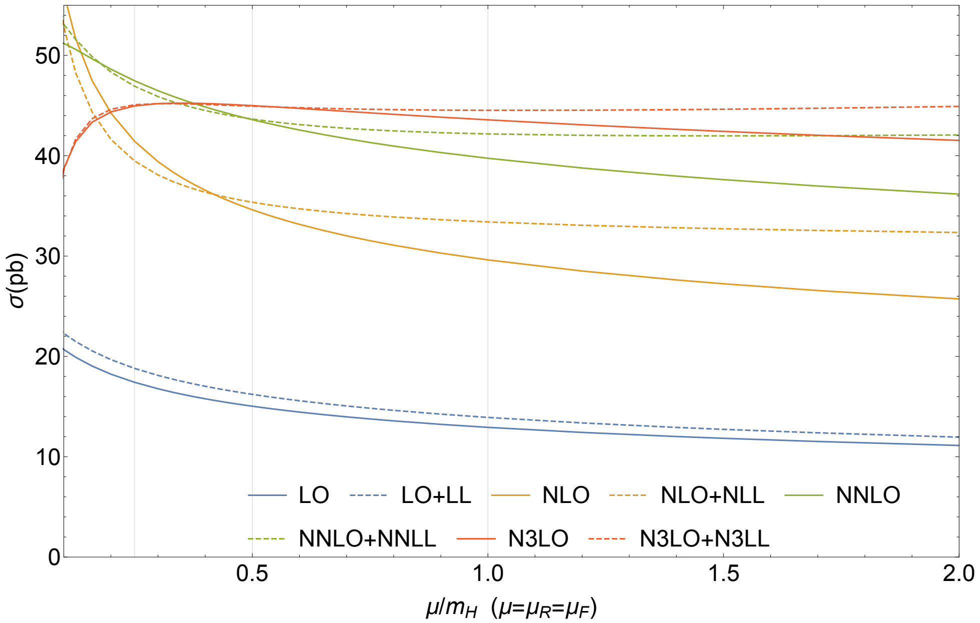




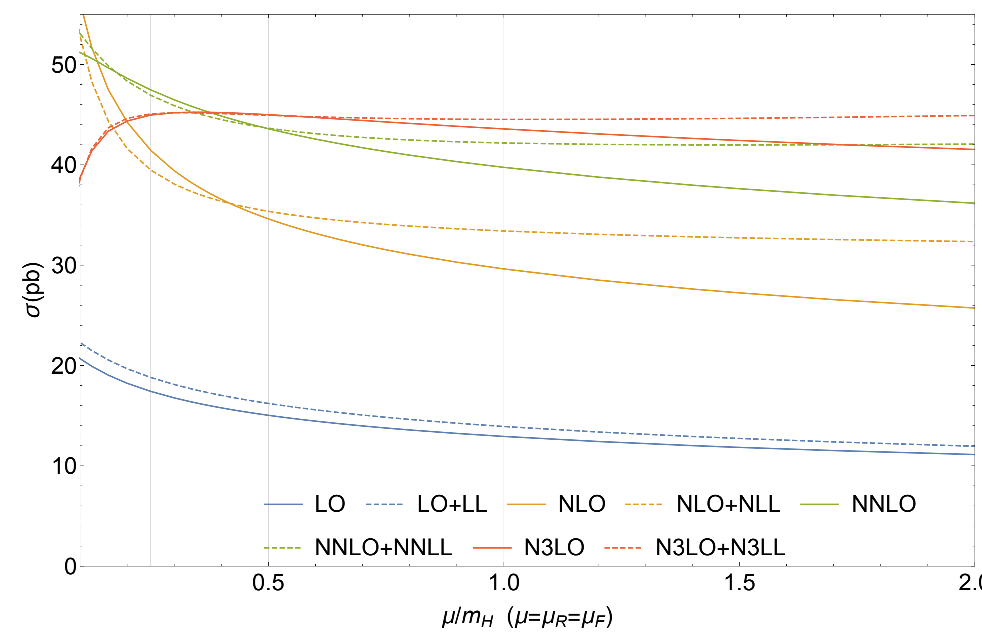
NLO : Approximate normalization but limited uncertainty estimate

eg *“Pheno is in PA (I think)”*





NNLO : Accurate rate and uncertainty estimate eg *“Pheno is in Pittsburgh”*



N3LO is like Street view (scary!)

NNLO is what we need to make precise measurements and dig out subtle signals of new physics (EFTs, wide resonances with lots of MET etc…)

At NNLO we have three types of final state phase spaces

$$\sigma_{NLO} = \int |\mathcal{M}_{VV}|^2 d^m\Phi + \int |\mathcal{M}_{RV}|^2 d^{m+1}\Phi + \int |\mathcal{M}_{RR}|^2 d^{m+2}\Phi$$

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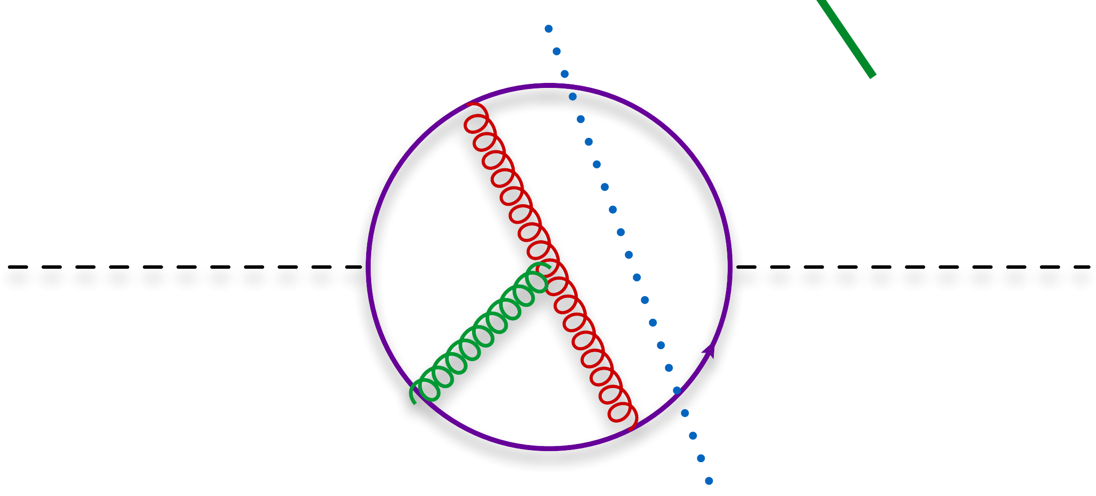
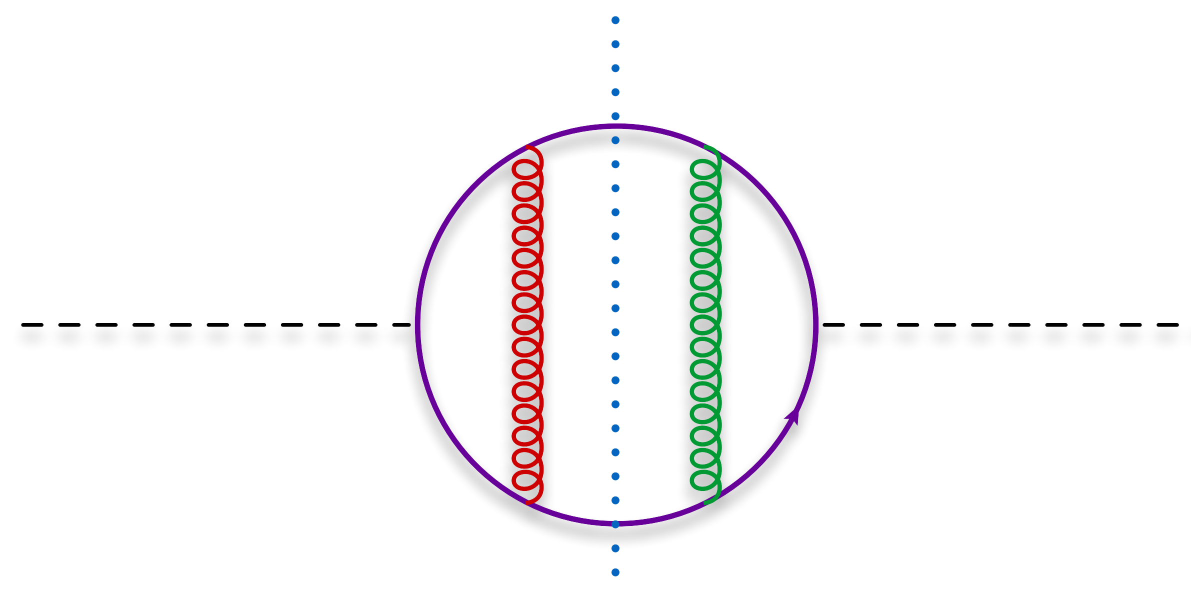


Two-loop double virtual



one-loop squared double virtual

Next to Next to Leading Order Calculations

At NNLO we have three types of final state phase spaces

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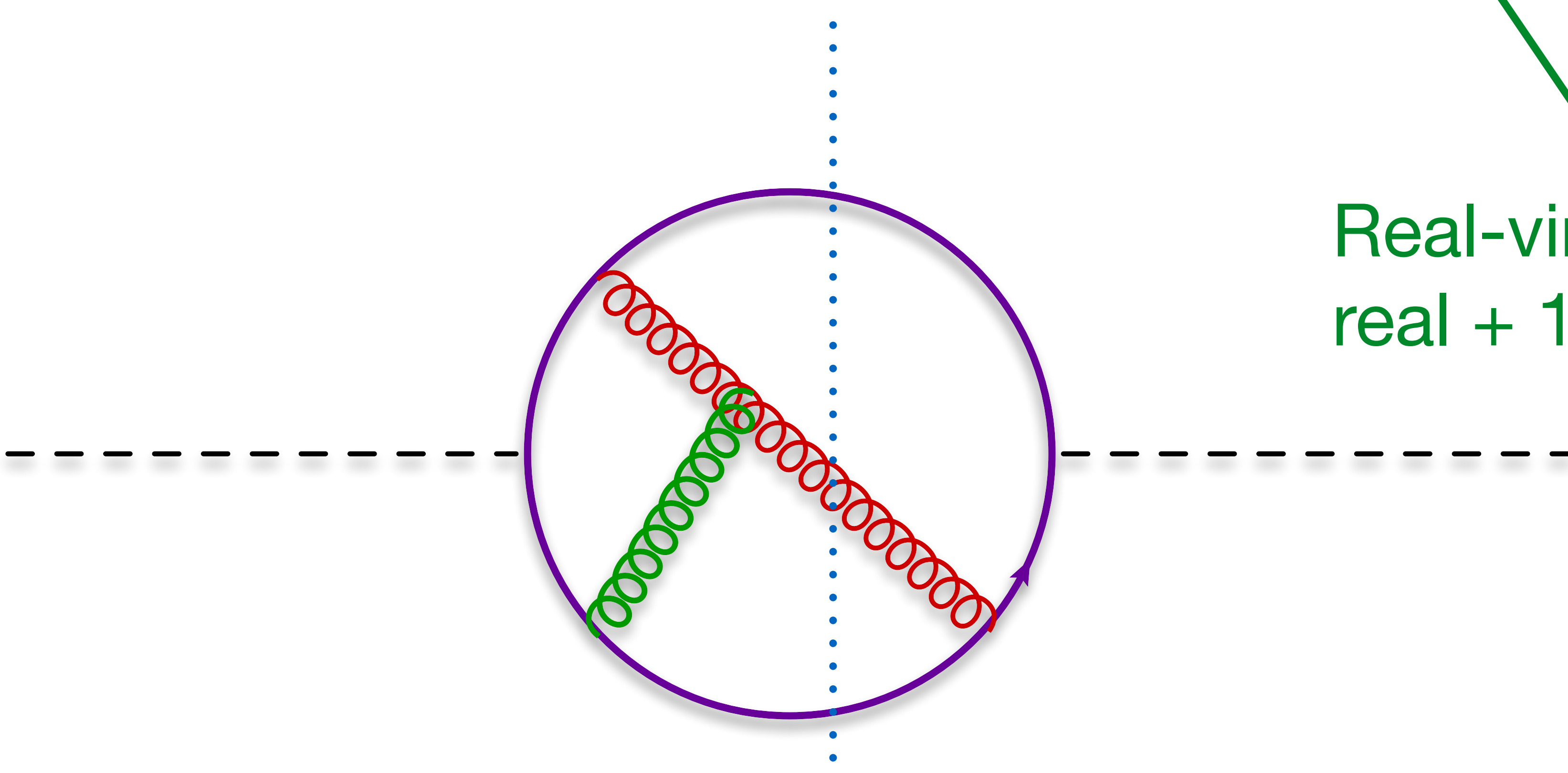

Real-virtual (one-loop +1 x real + 1)

At NNLO we have three types of final state phase spaces

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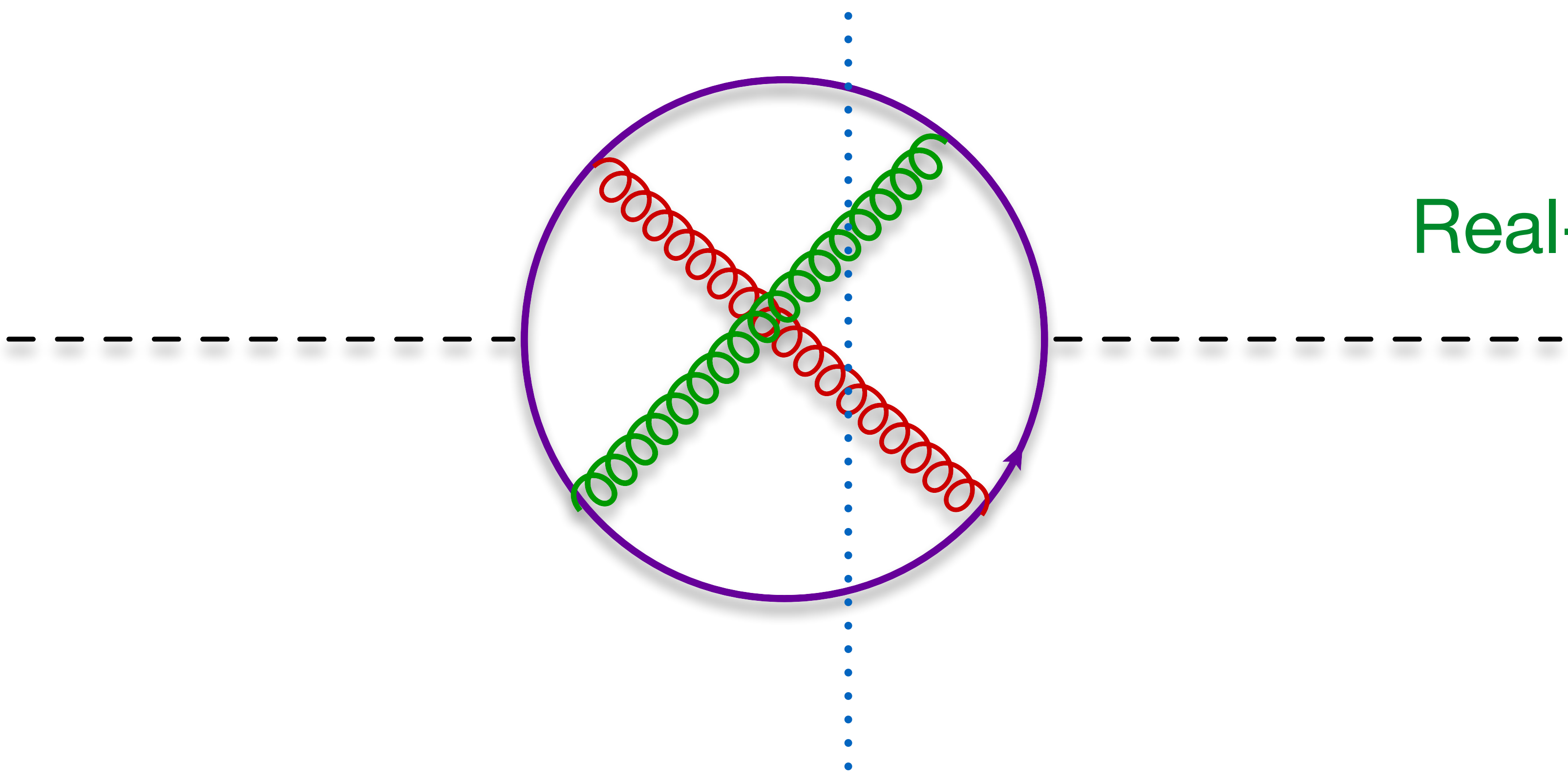
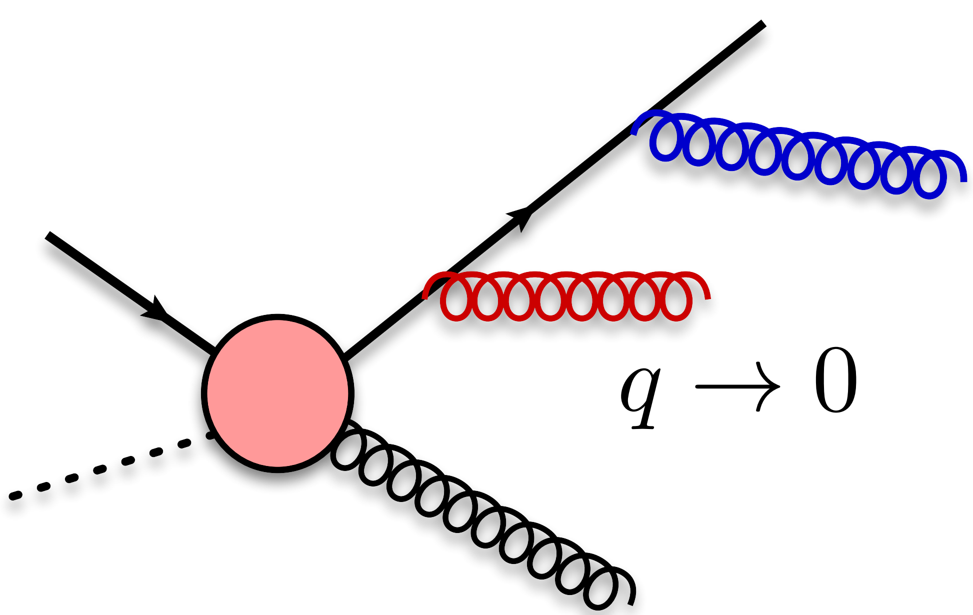


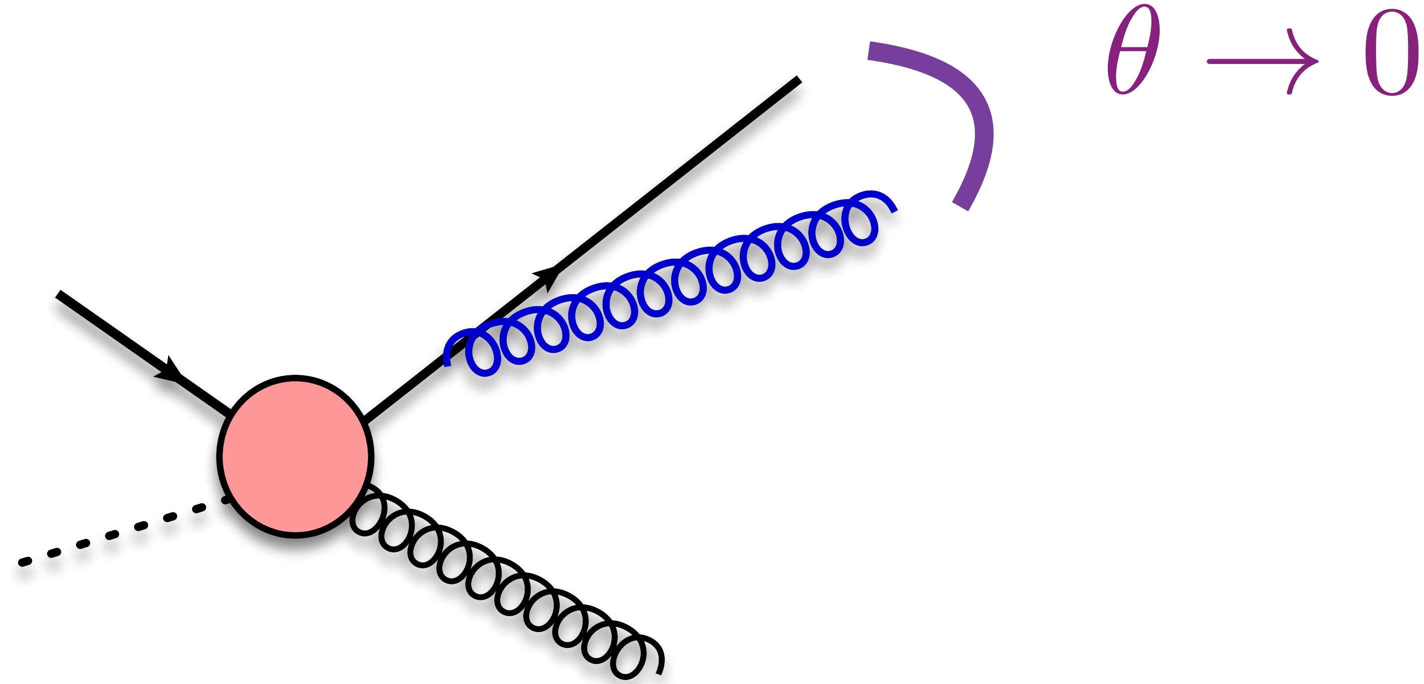
Real-real

All of our contributions (VV, RV, RR) are divergent, of particular menace are the Infra Red poles.

There are two types of IR pole in real matrix element,



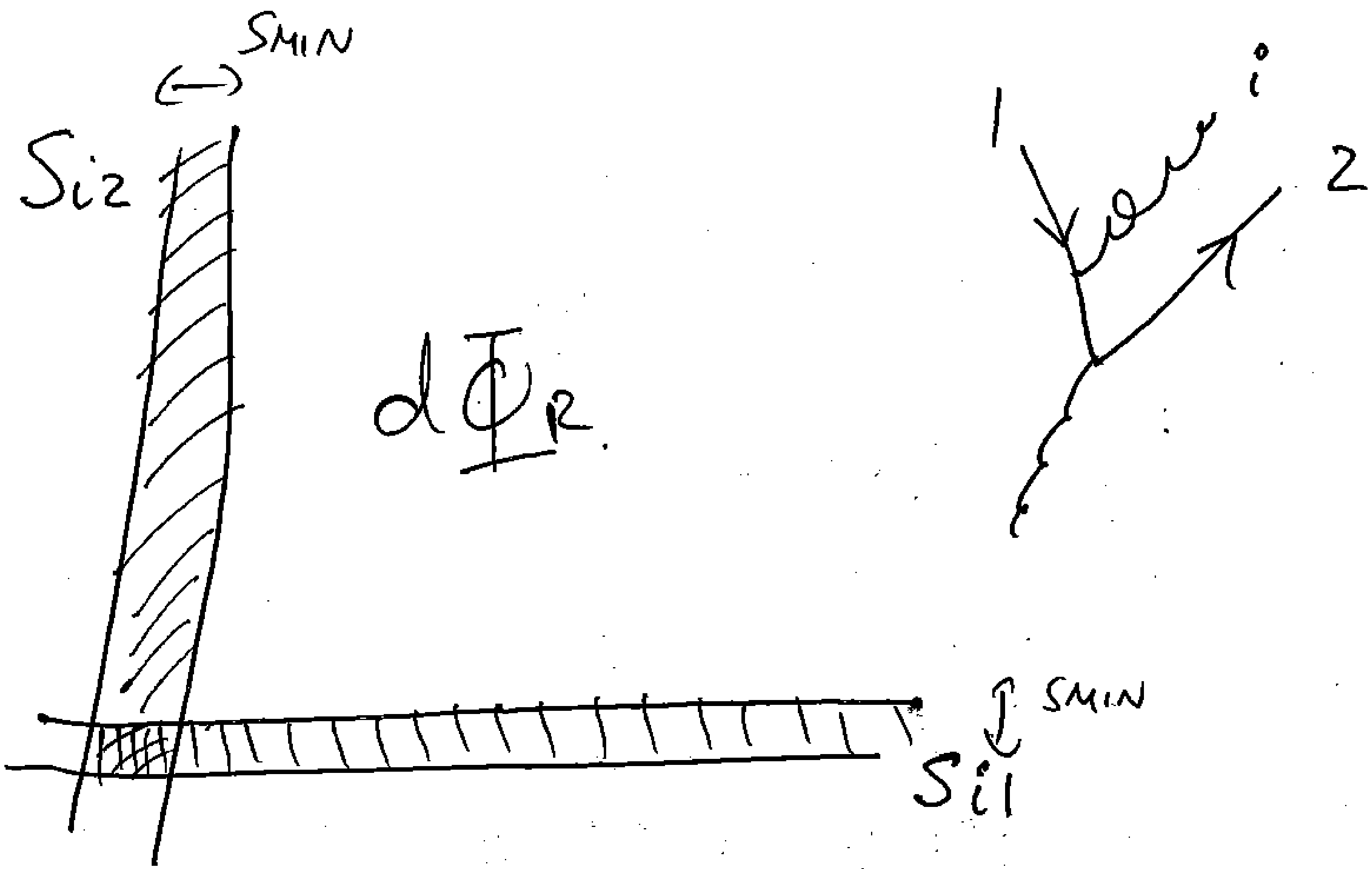
Soft (particle momenta vanishes)



Collinear (angle between two massless particles vanishes)

At NNLO there are many ways to lose two partons, (double soft, triple collinear etc etc….)

A “simple” way of dealing with the singularities is phase space slicing (Giele Glover 92)



Phase space slicing

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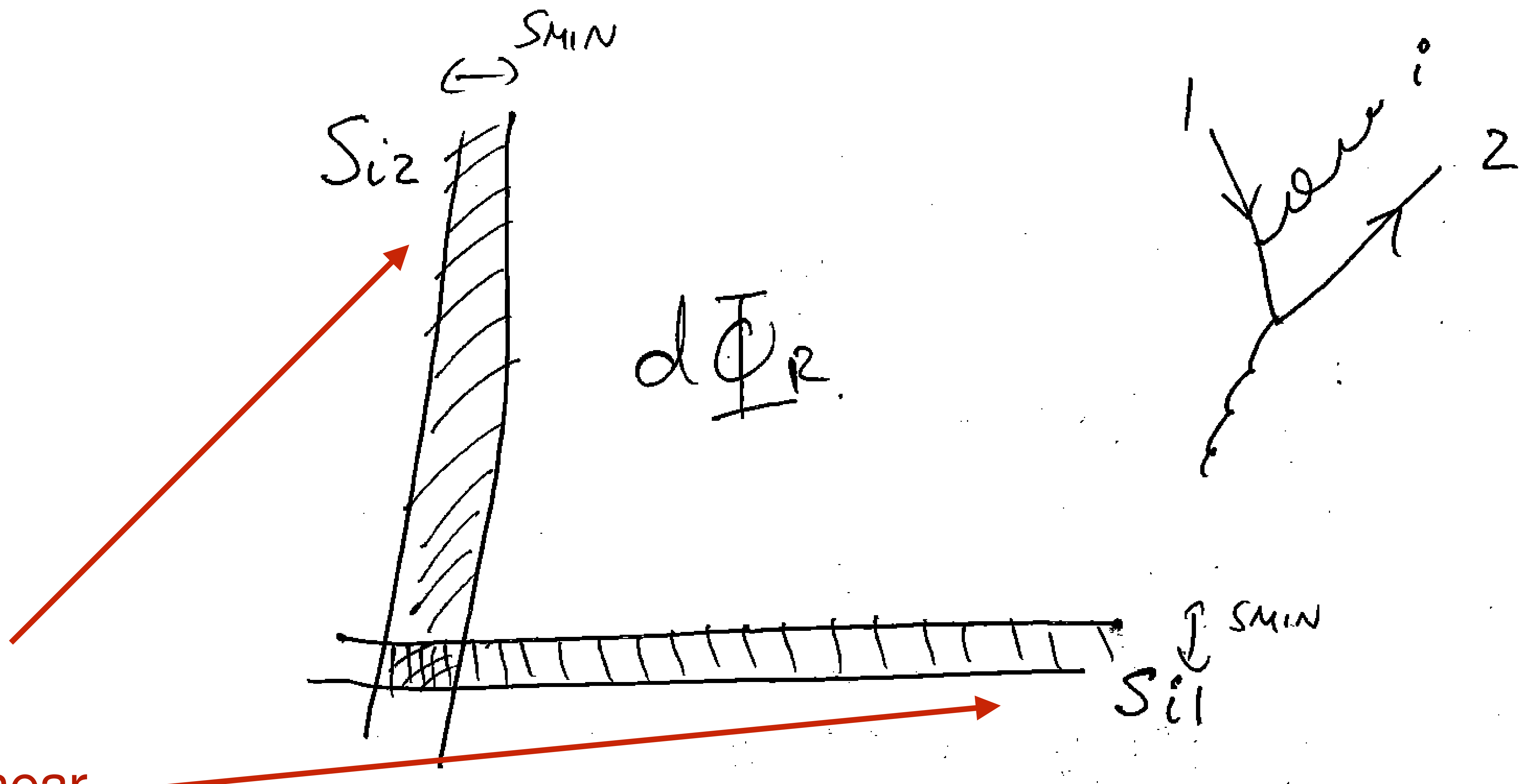

Collinear

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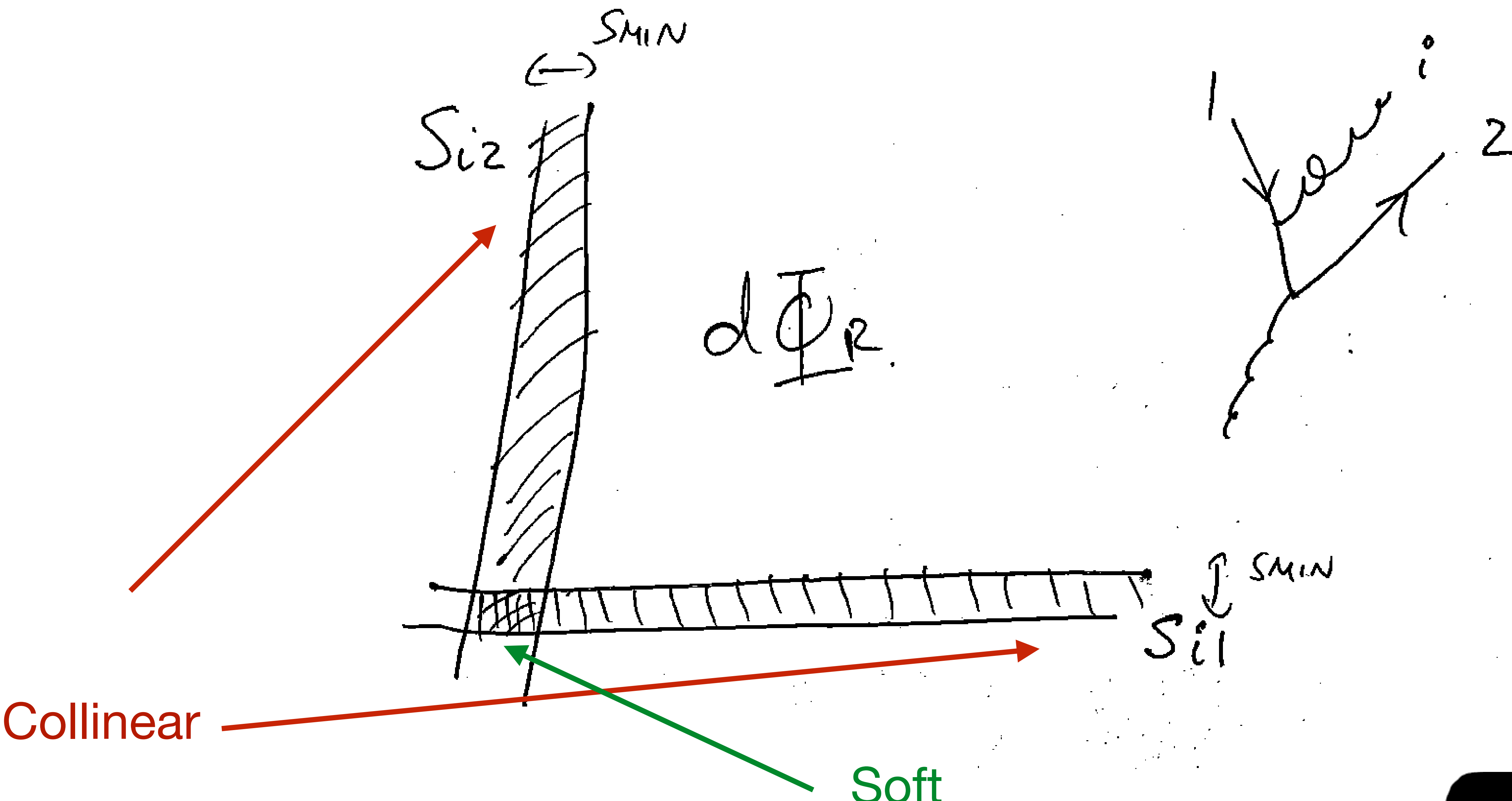
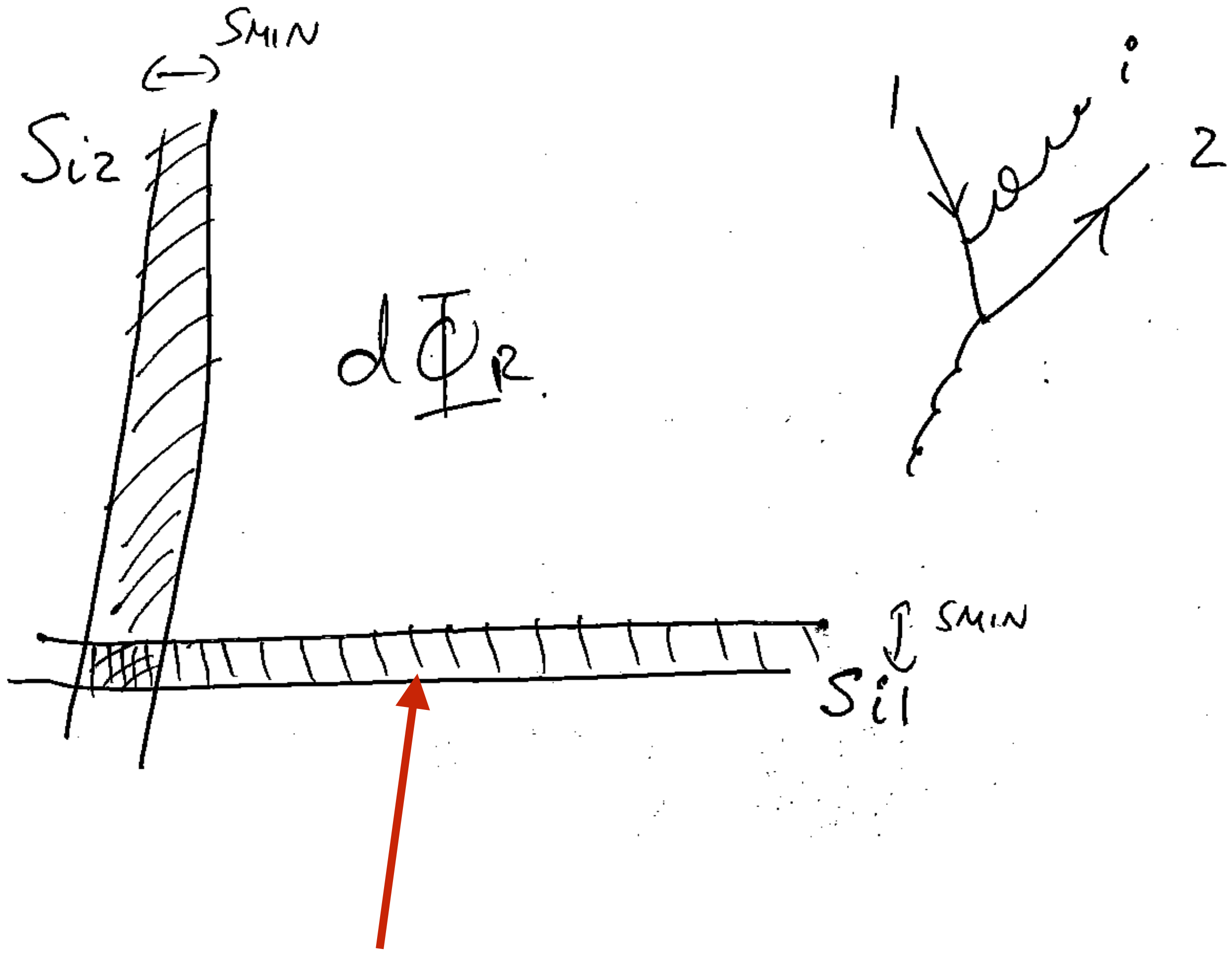
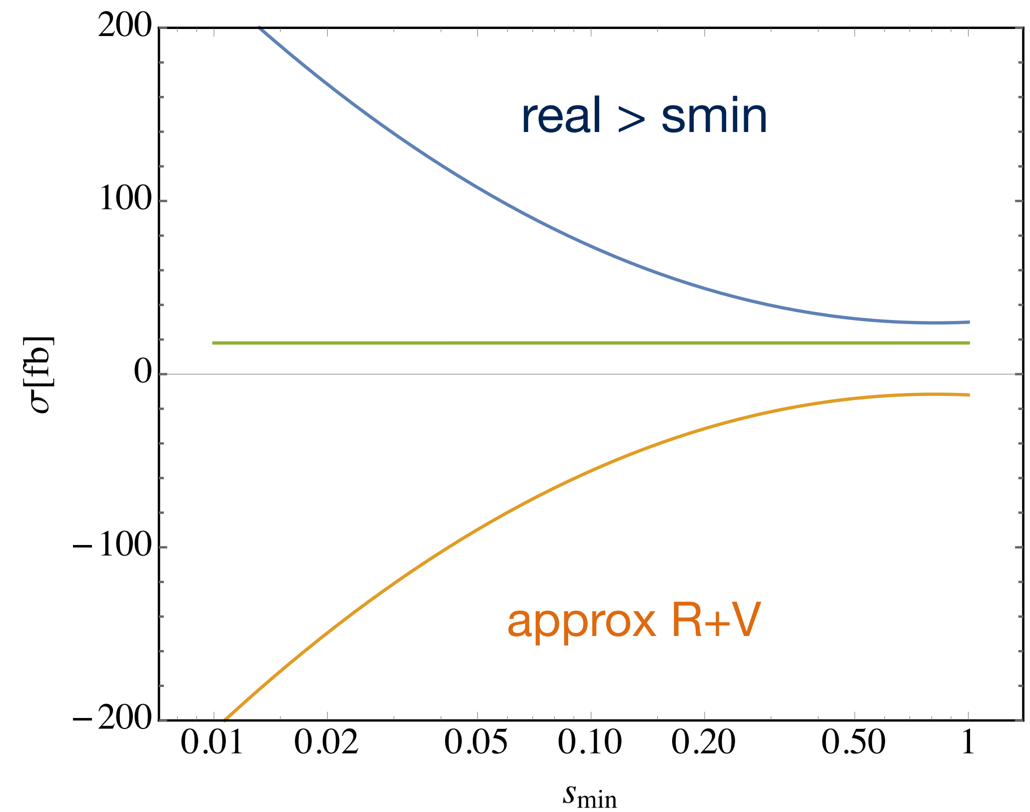


Phase space slicing



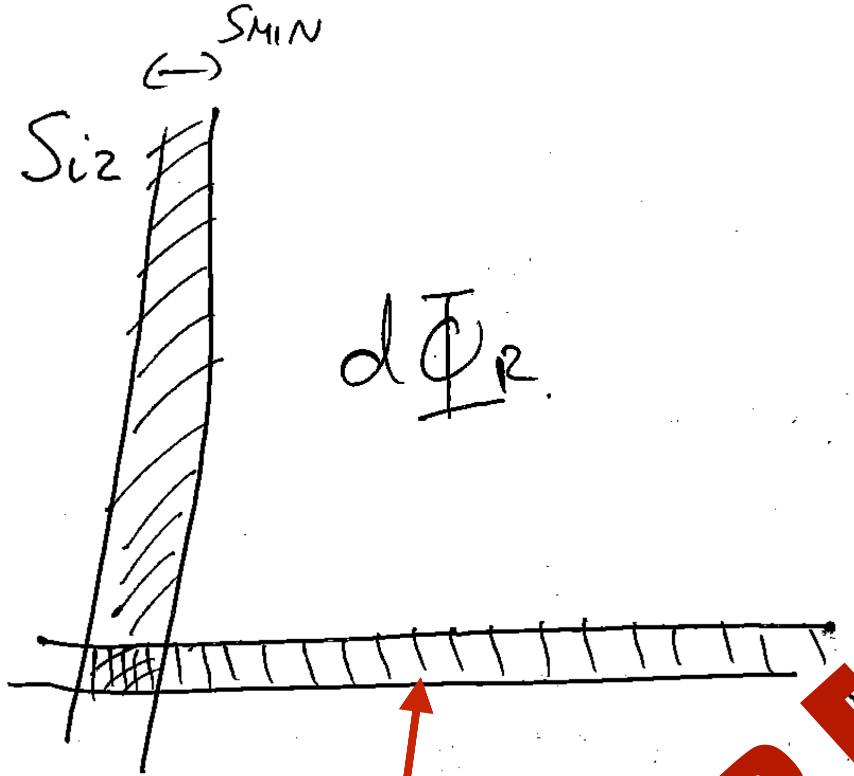


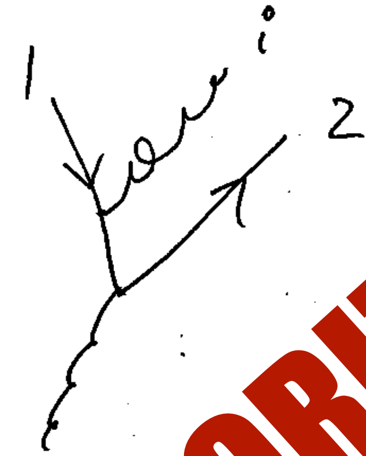
In these regions both the phase space and the matrix element can be approximated by known IR factorization e.g.

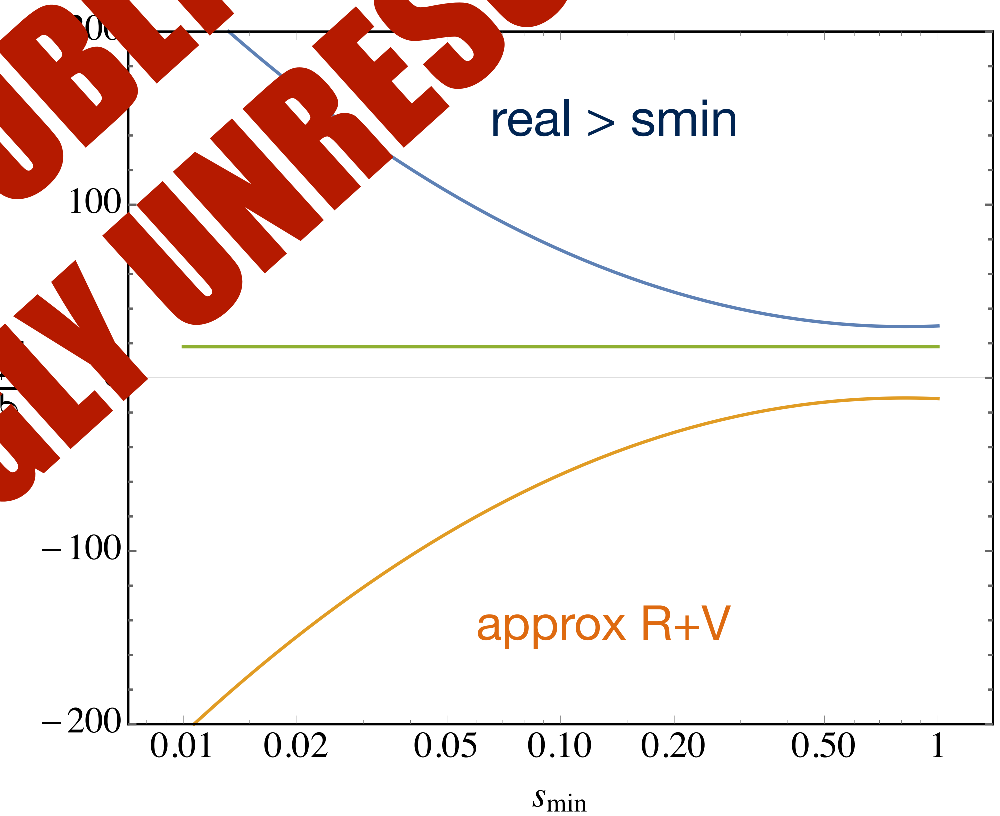
$$\int_{s_{i1}<s_{min}} |\mathcal{M}_R|^2 d\Phi^R \approx \int P_{ij}(z)|\mathcal{M}_{LO}|^2 d\phi^C d\Phi_{LO} + \mathcal{O}(s_{min})$$

This can be integrated analytically and combined with the virtual to cancel the poles

Phase space slicing







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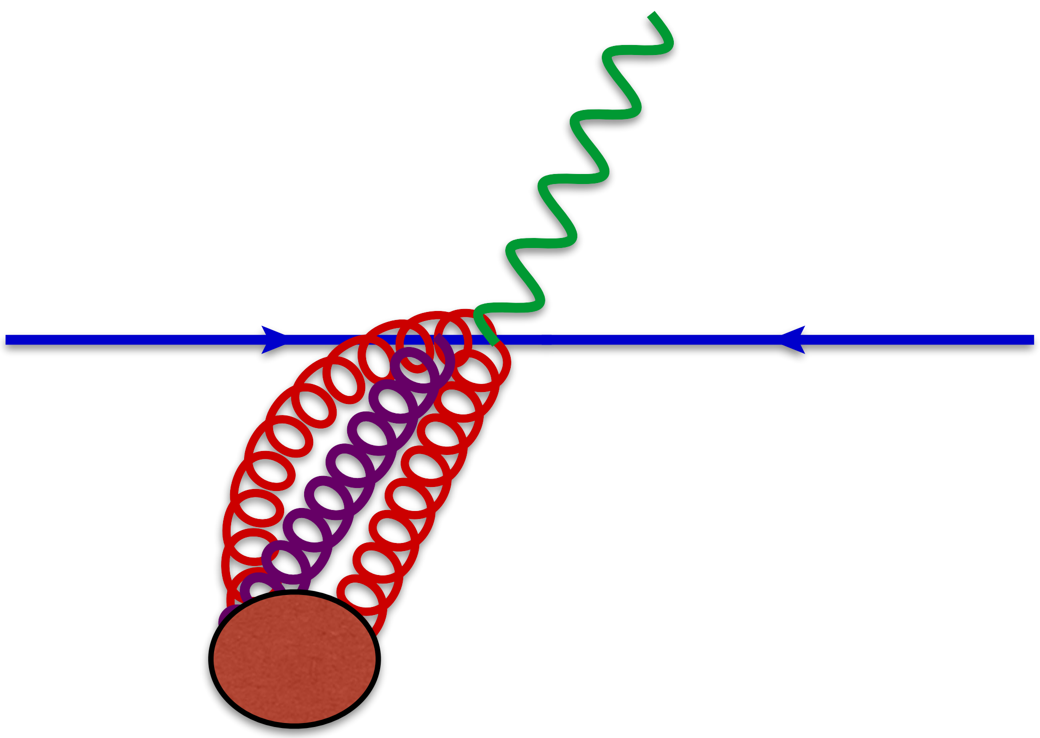
This can be integrated analytically and combined with the virtual to cancel the poles

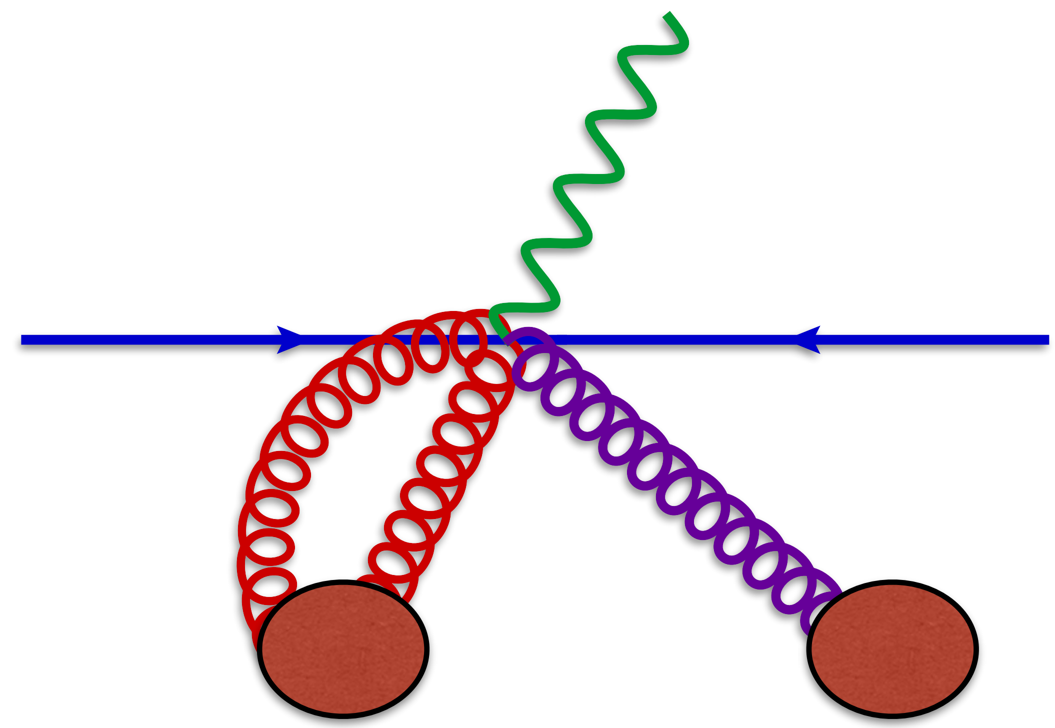
NEED A SIMILAR FACTORIZATION THEOREM TO SEPARATE DOUBLY UNRESOLVED FROM SINGLY UNRESOLVED LIMITS AT NNLO!

The idea is to use the event shape variable N-jettiness (Stewart, Tackmann, Waalewijn 09) to separate the phase space into two regions (Boughezal, Liu, Petreillo 15', Gaunt, Stahlhofen, Tackmann Walsh 15) which separates the doubly-from singly unresolved regions.



Doubly unresolved

Small N-jettiness, use factorization theorem.



Singly unresolved

"Large" N-jettiness, is an NLO calculation. Can use existing tools, like MCFM

We need to understand the below cut region for the method to be applied. Happily, a factorization theorem (Stewart, Tackmann, Waalewijn 09), based upon SCET has been derived

$$\sigma(\tau_N < \tau_N^{cut}) = \int H \otimes B \otimes B \otimes S \otimes \left[\prod_n^N J_n\right] + \mathcal{O}(\tau_N^{cut})$$

- B@NNLO : Gaunt, Stahlhofen, Tackmann (14) …
- S@NNLO : Boughezal, Liu, Petreillo (15) ….
- J@NNLO : Becher, Neubert (06), Becher, Bell (11) ….

We need to understand the below cut region for the method to be applied. Happily, a factorization theorem (Stewart, Tackmann, Waalewijn 09), based upon SCET has been derived

Beam functions, describes radiation collinear to initial state

Jet functions, describes radiation collinear to final state jets

$$\sigma(\tau_N < \tau_N^{cut}) = \int H \otimes B \otimes B \otimes S \otimes \left[\prod_n^N J_n\right] + \mathcal{O}(\tau_N^{cut})$$

Hard function, includes 2-loop virtual

Soft function, describes soft radiation

- B@NNLO : Gaunt, Stahlhofen, Tackmann (14) …
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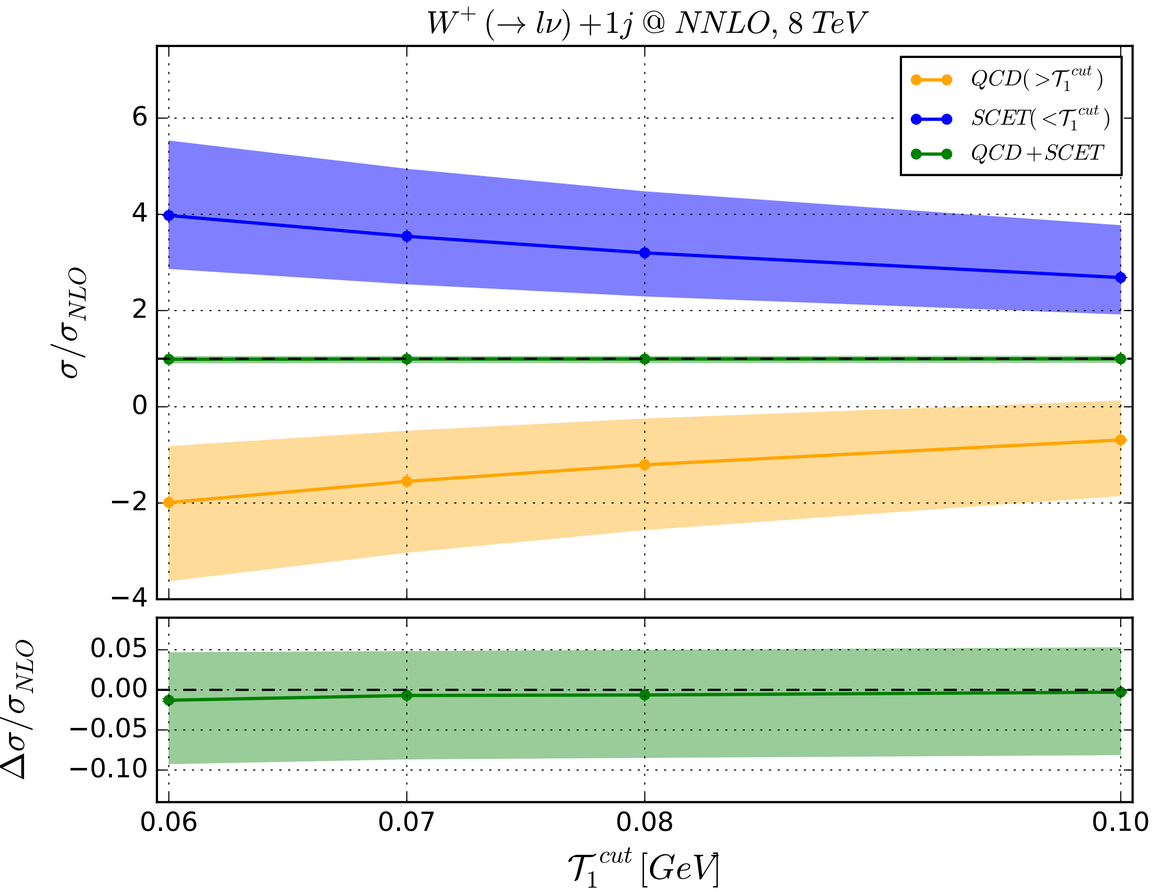
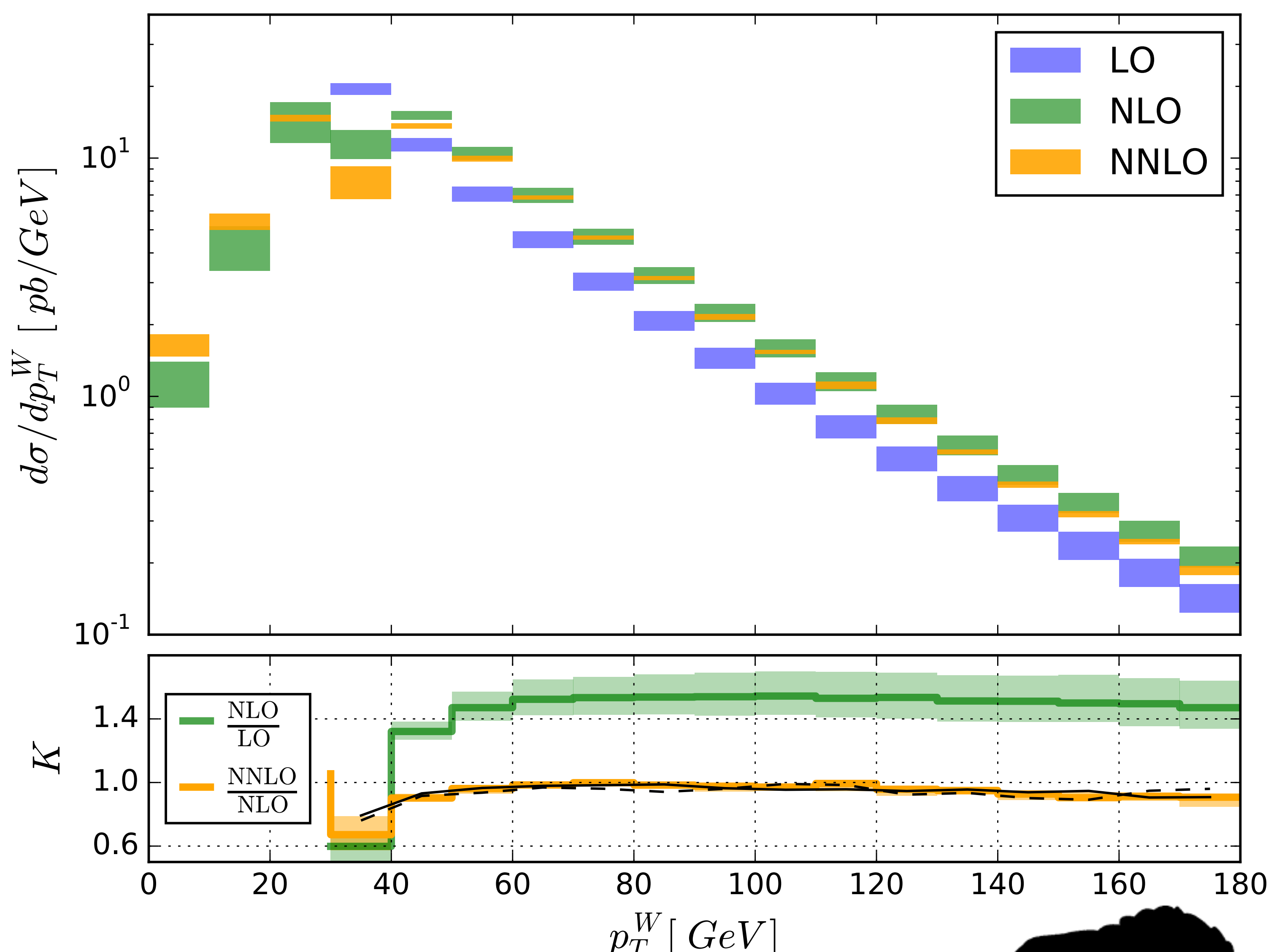
LHC Pheno with N-jettiness slicing

W + jet

Boughezal, Focke, Liu, Petriello 15



The first application of the new slicing method was to the calculation of W+ jet at NNLO.

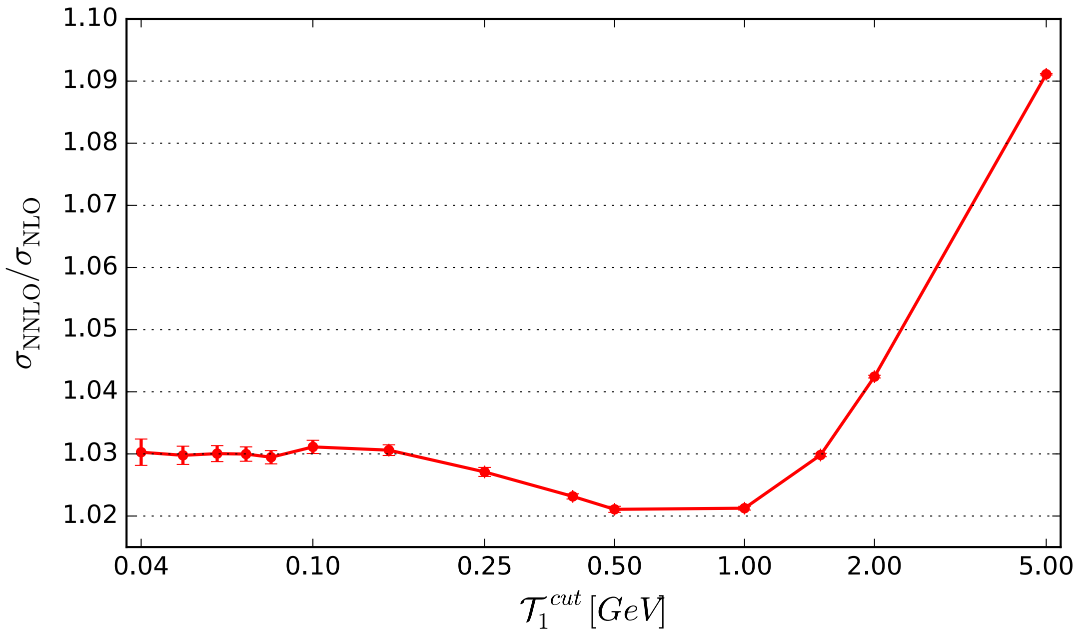


Corrections are small, and scale variation is very minor (especially once the full NNLO phase space is obtained)

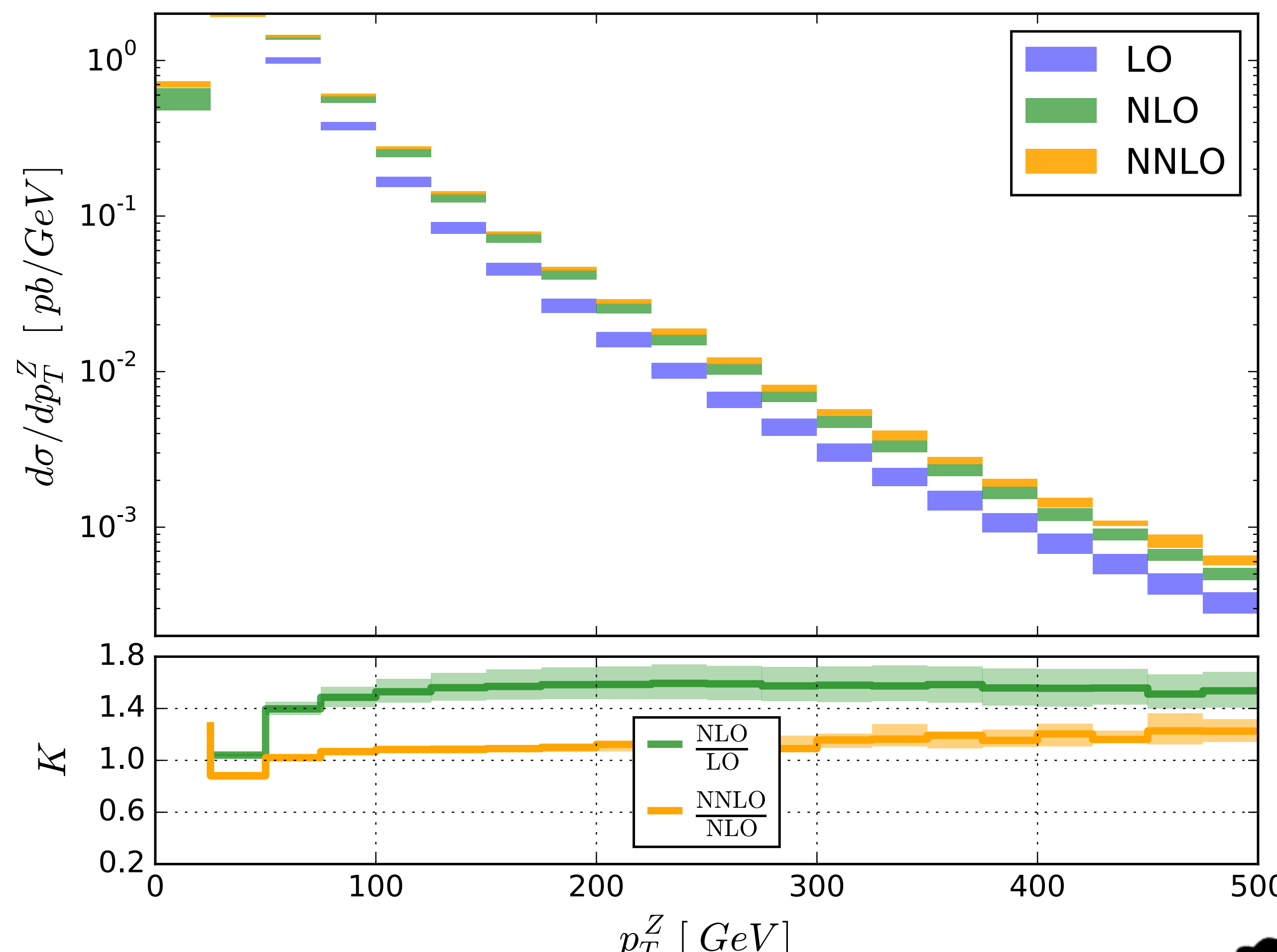
Can be used for precision pheno studies (e.g. BSM searches, PDF tests)

Z + jet

Boughezal, Campbell, Ellis, Focke, Giele, Liu, Petriello 16



A related calculation is that of Z +jet at NNLO.

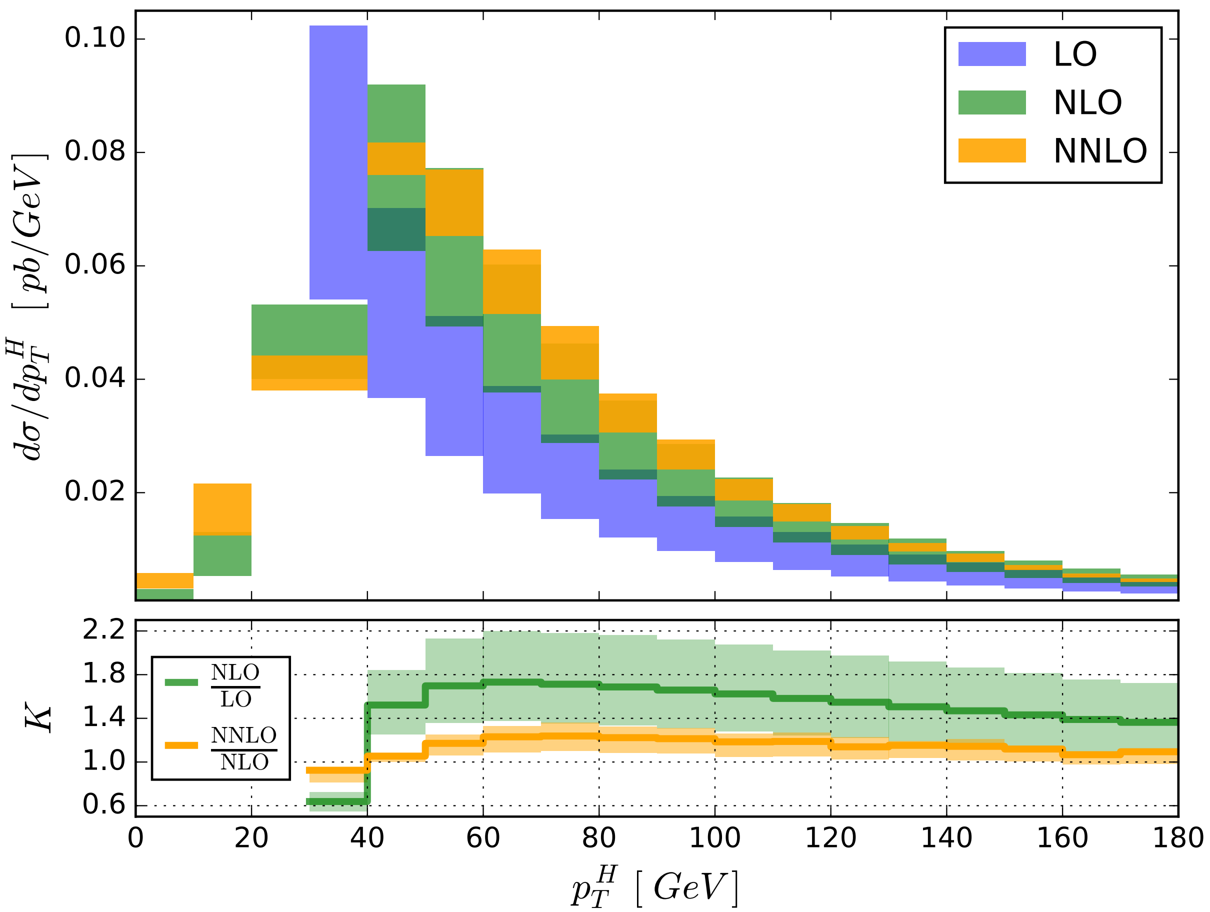


Again corrections are not huge, but allow for a precision prediction in the context of the SM.

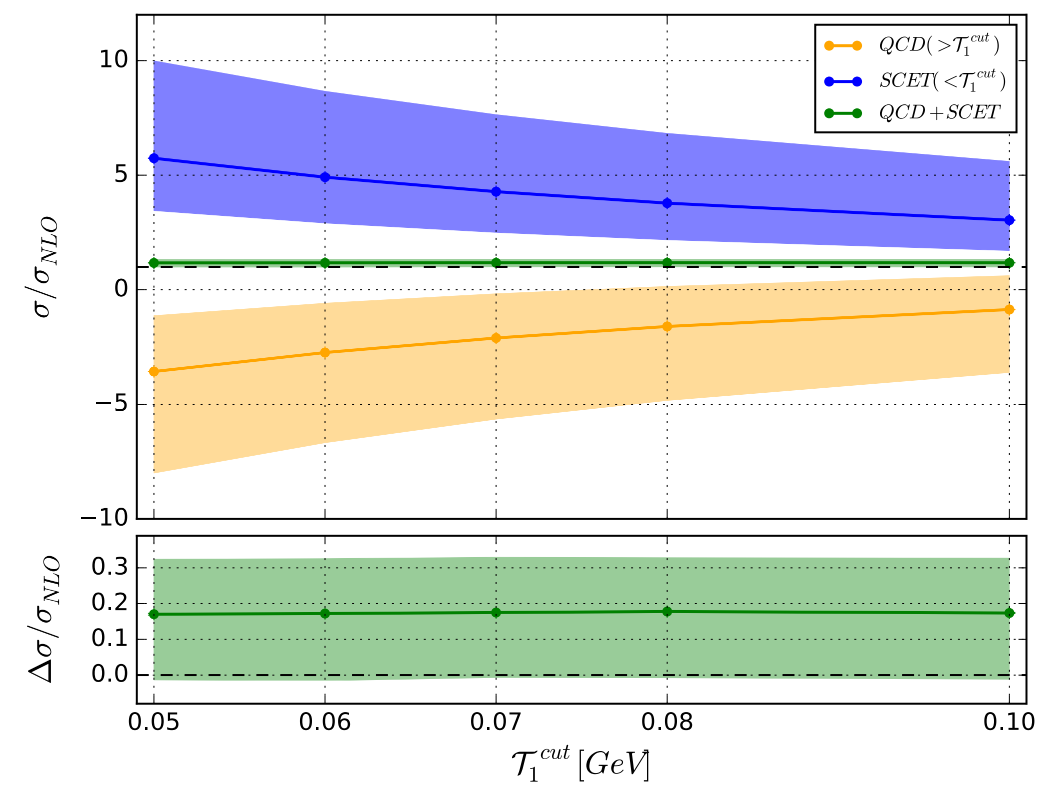
This will allow us to have smaller uncertainties on the shape of the MET+jet spectrum => Better DM limits in run II (and SUSY)

H+ jet

Boughezal, Focke, Giele, Liu, Petriello 16



A different type of calculation is H +jet @ NNLO. Here the corrections are much larger (both at NLO and NNLO).



This new calculation will allow for better understanding of the differential Higgs boson.

Tools for pheno

- Process calculated at NNLO by theorists.
- Process “done”
- Plots in paper
- No public offering

Advertisement

Tools for pheno

- Process calculated at NNLO by theorists.
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Advertisement Reality

(Rotated to most appealing angle)

- Results not easily reproducible
- Needs direct contact with authors to obtain plots (time consuming for everyone)
- Limited to author’s computer resources
- Version control

Our attempt to address this is,

MCFM 8

Boughezal, Campbell, Ellis, Focke, Giele, Liu, Petriello and CW (in prep),

MCFM 8

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Lots of work by many people upgrading MCFM to NNLO version, including MPI on top of OMP (Campbell, Giele, Ellis 14) version. Hope to release initial public code very soon.

Process	v8.0 ($\sim$ weeks)	v8.x ($\sim$ months)	Calculation in MCFM framework
H	X		
W/Z	X		
HW/HZ	X		
$\gamma\gamma$	X		
$V\gamma$		X	
VV		X	
$Z+j$			[1]
$W+j$			[2]
$H+j$			[3]

[1] Boughezal, Campbell, Ellis, Focke, Giele, Liu and Petriello, 15'

[2] Boughezal, Focke, Liu and Petriello, 15'

[3] Boughezal, Focke, Giele, Liu and Petriello, 15'

MCFM 8

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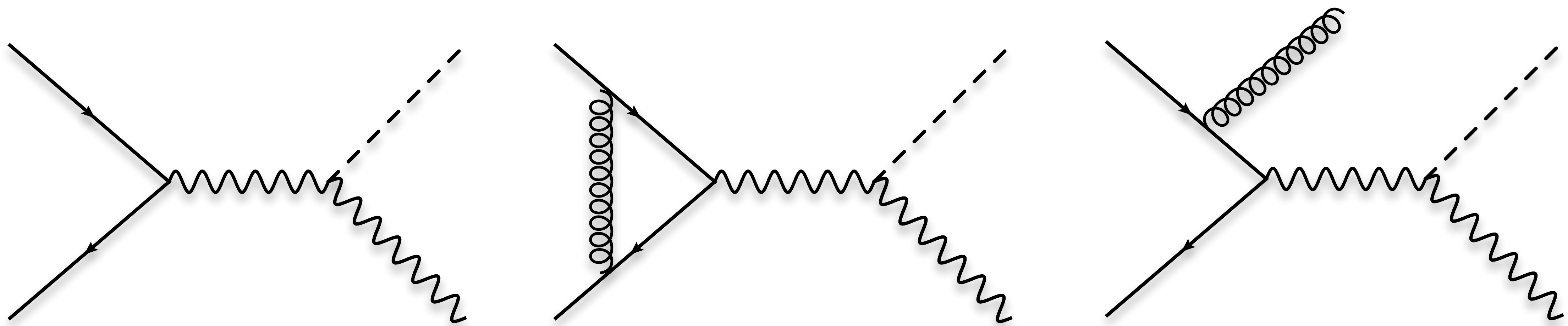
Campbell Ellis CW 16

Campbell Ellis, Li, CW 16

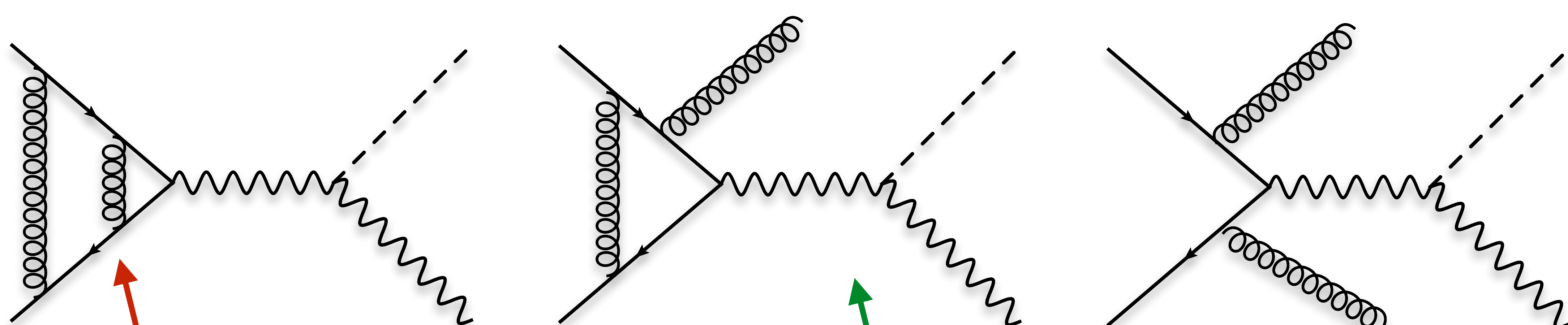
VH

Campbell, Ellis, CW 16

At LO and NLO we have topologies which are the same as for single vector boson production (Drell-Yan)



At NNLO we have extensions to these topologies

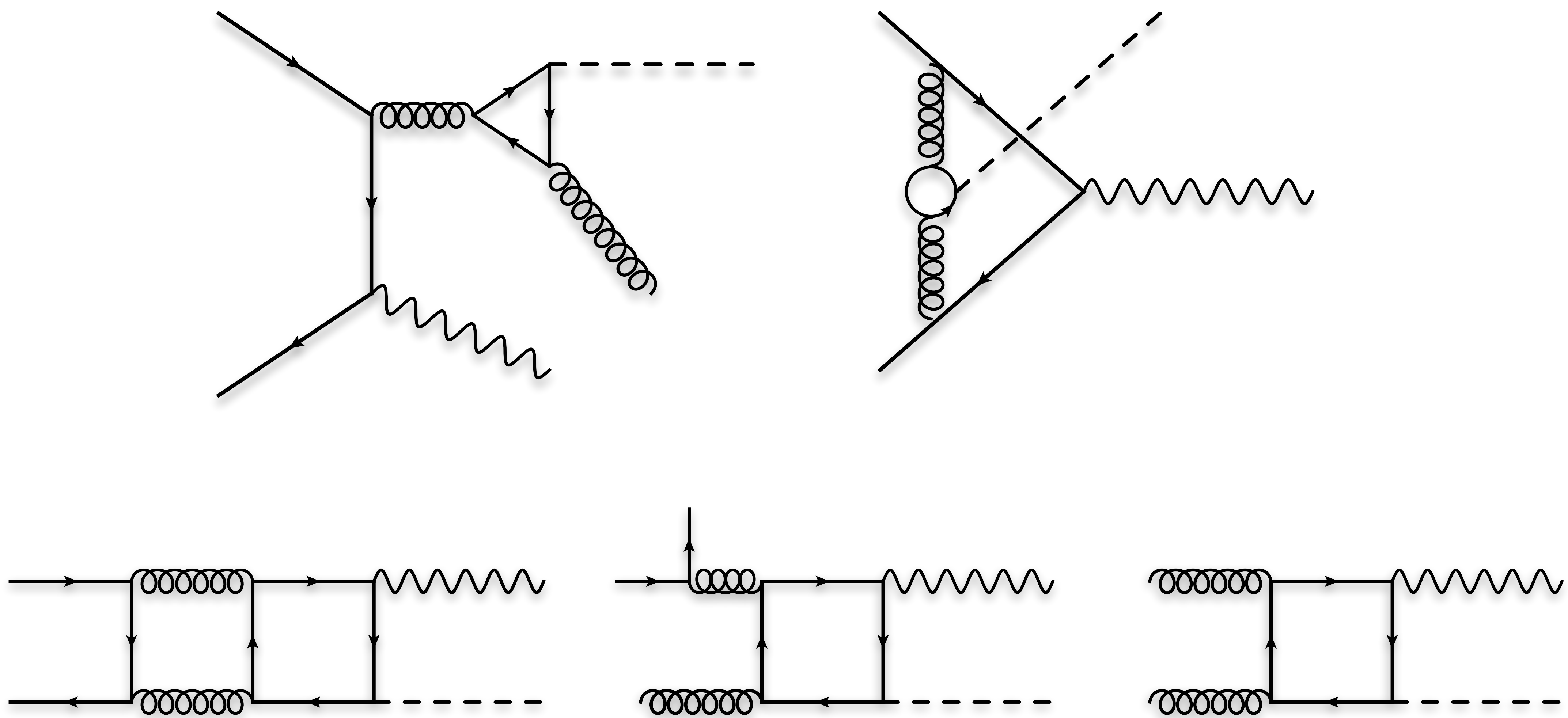


Double virtual, Can be obtained from classic form factor calculation

WH1 jet @ NLO

Top induced NNLO terms

In addition at NNLO there are new channels which open up which depend on the top Yukawa coupling (and not through HVV)



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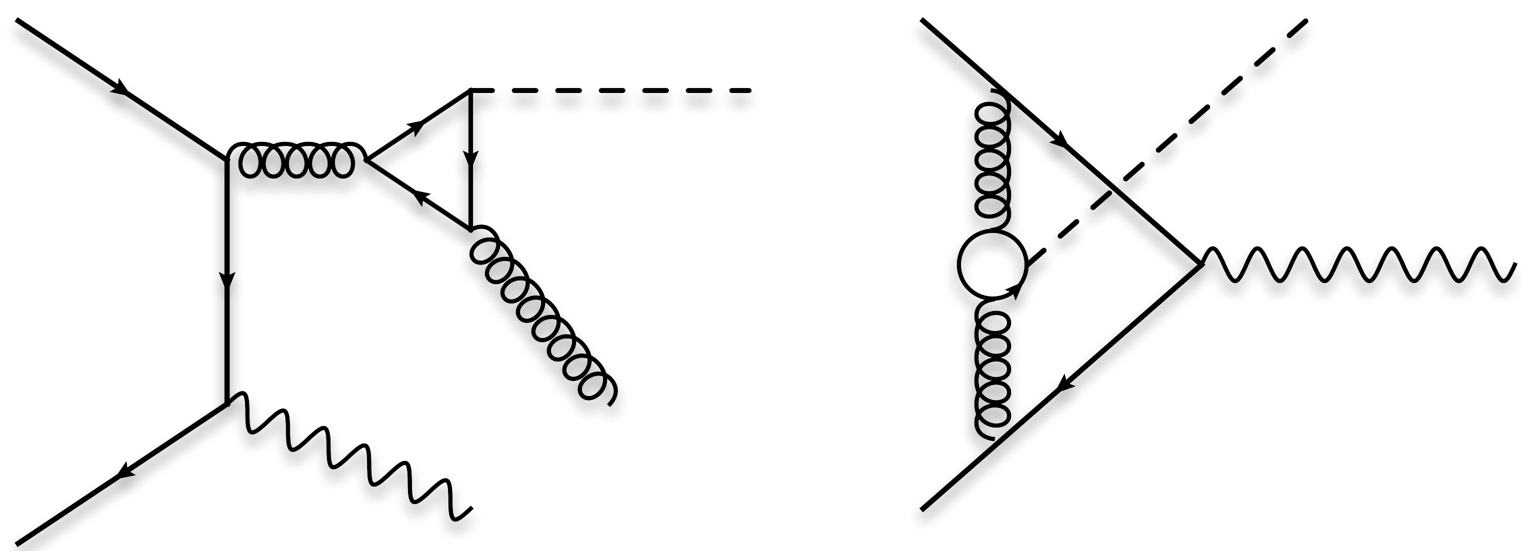
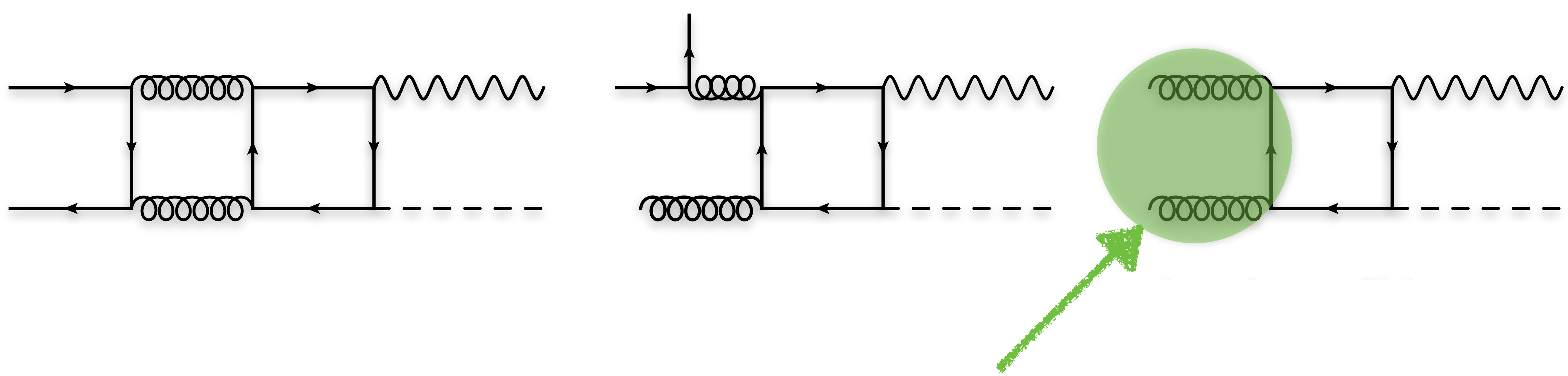
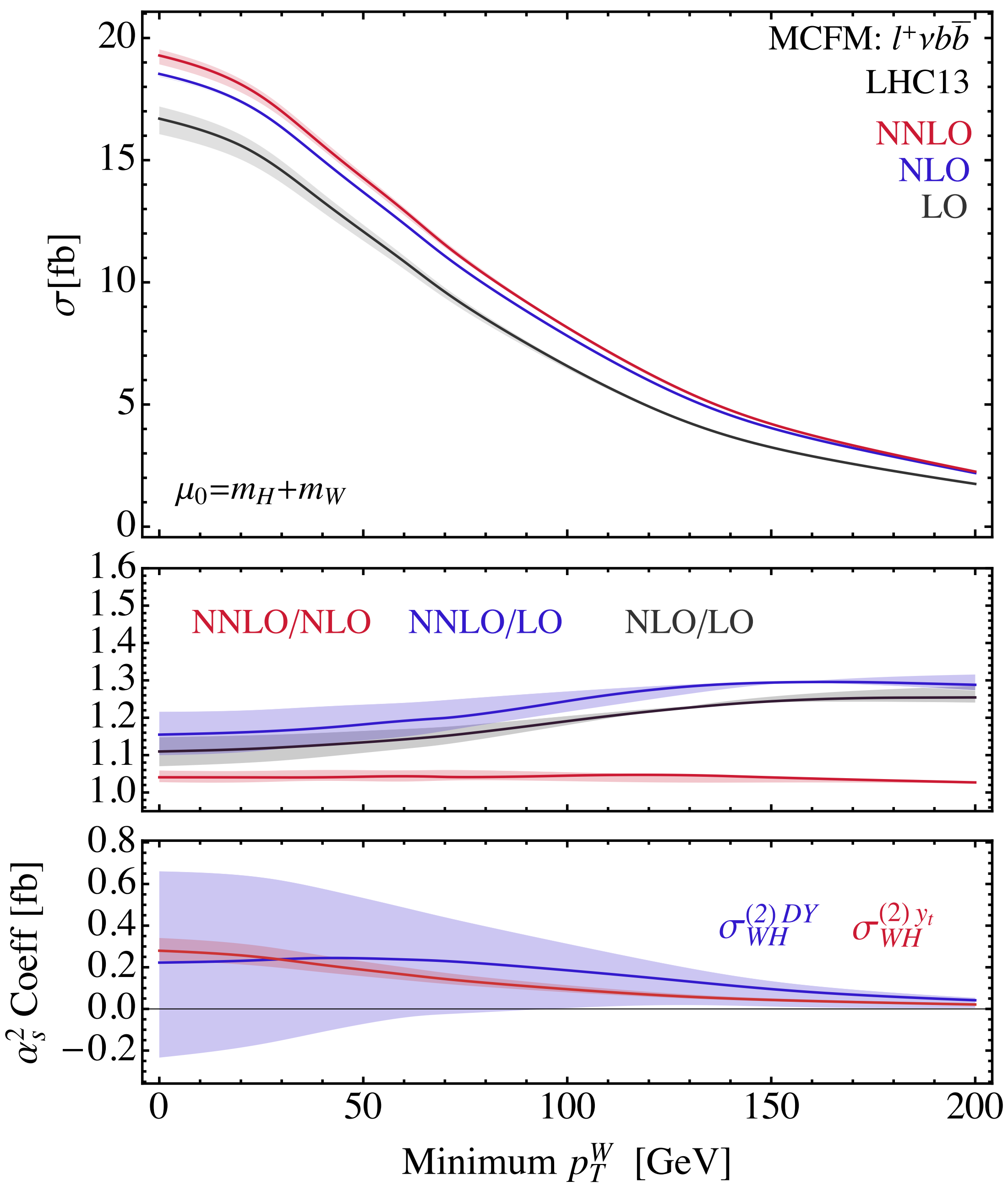
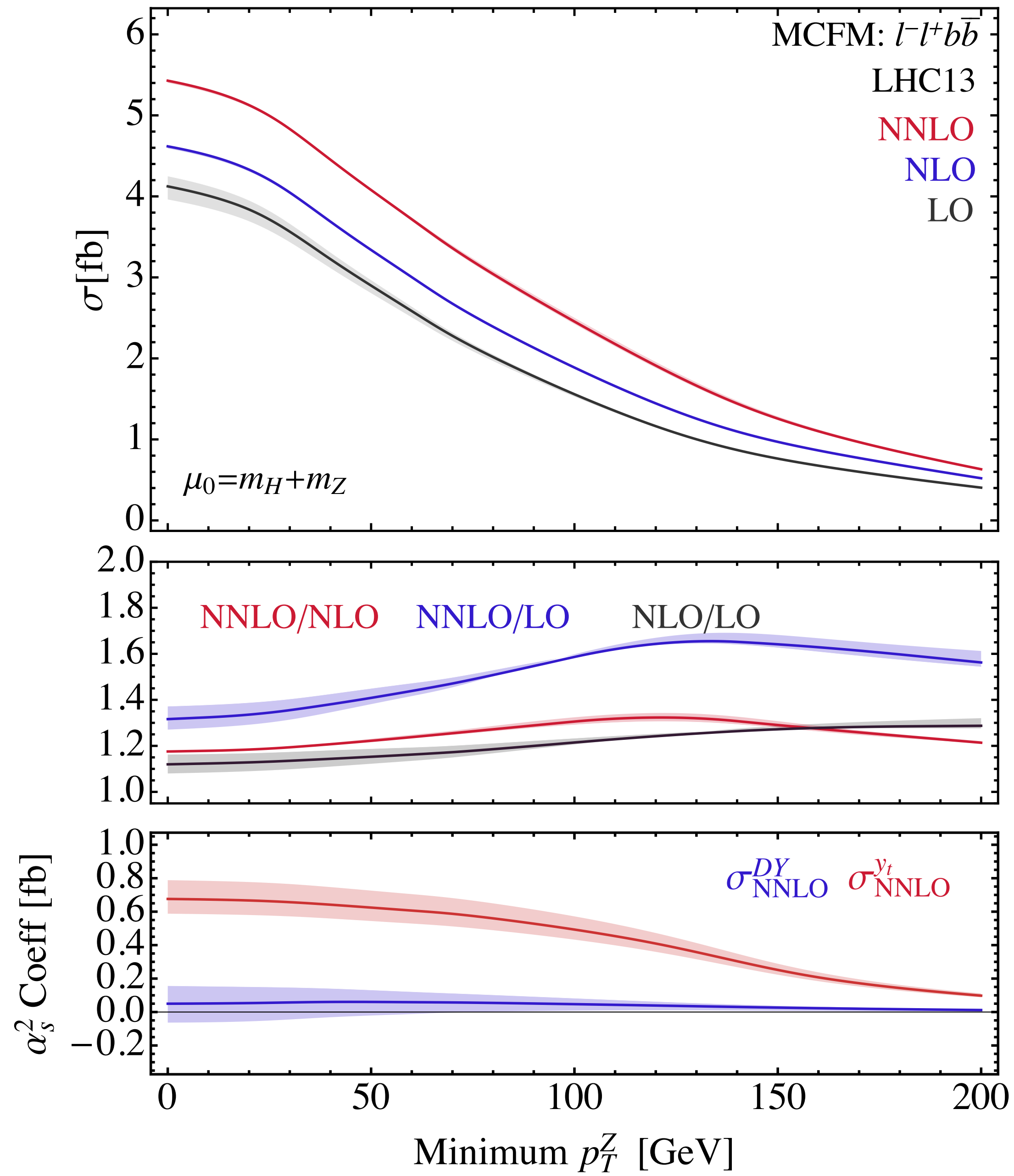




Gluon PDFS will make this bit important!

Dependence on the recoil of the vector boson





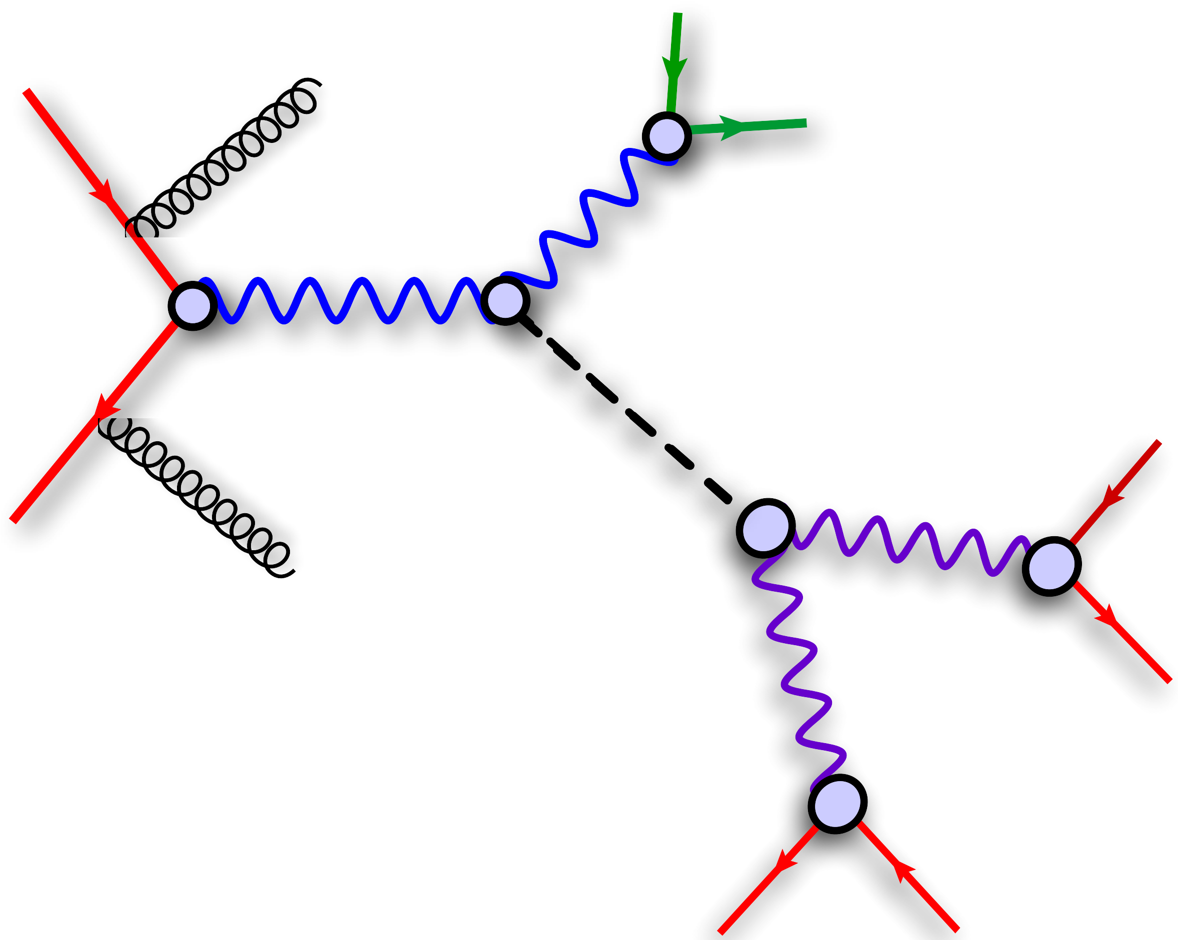
Experimental analysis require fairly hard cuts on vector boson transverse momenta to suppress top backgrounds.

Top loops make up ~30-50% of total NNLO correction (not in previous MC)

NNLO effects are much larger in ZH, due to gg=>ZH loops.

Already in Run I pp=>V(H=>WW)=> leptons was an experimentally viable channel. In Run II its going to be studied in much greater detail.

For us the process is particularly interesting, since it provides a great test of N-jettiness slicing for a challenging final state phase space.



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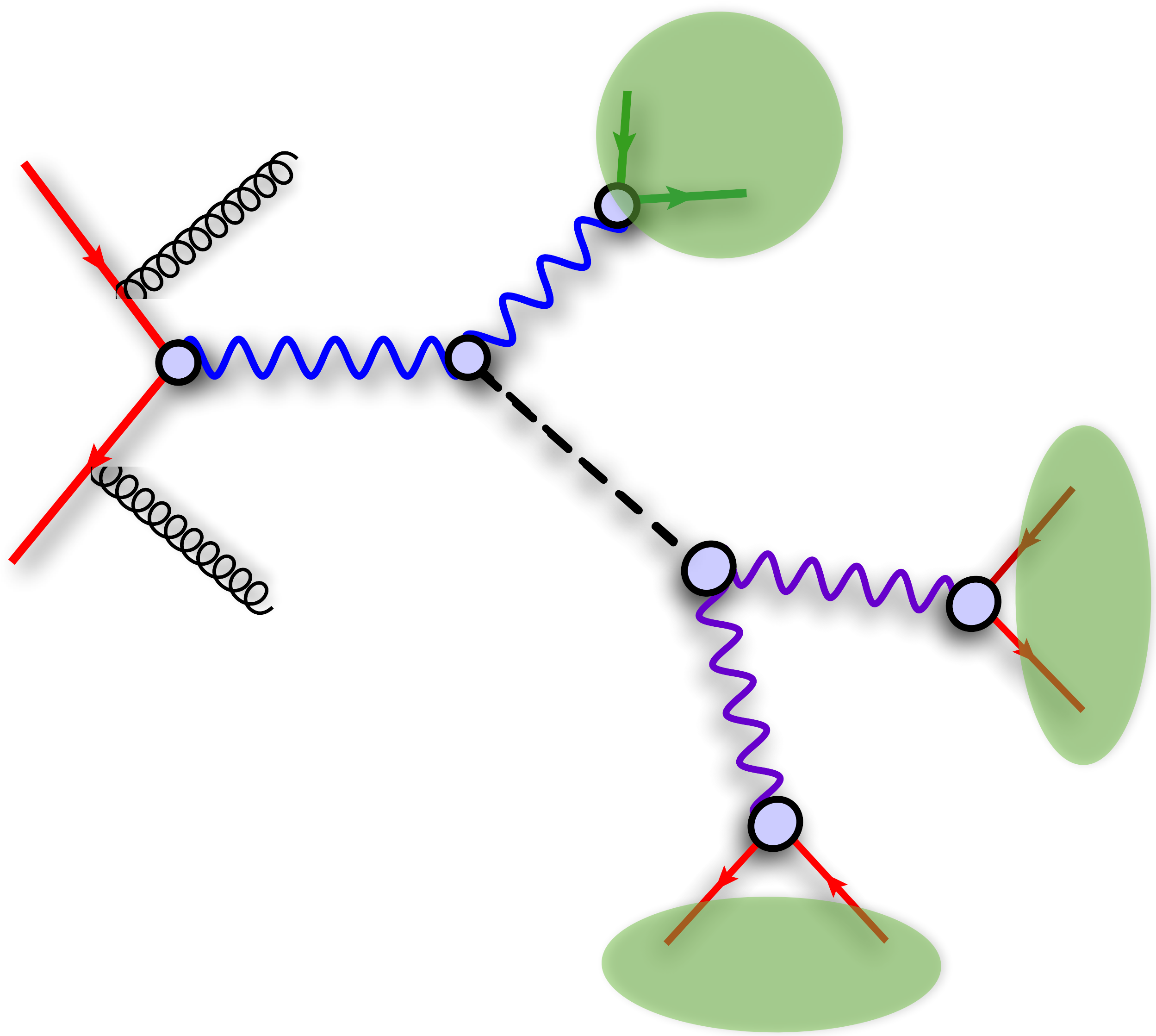

The LO phase space is 16 dimensional

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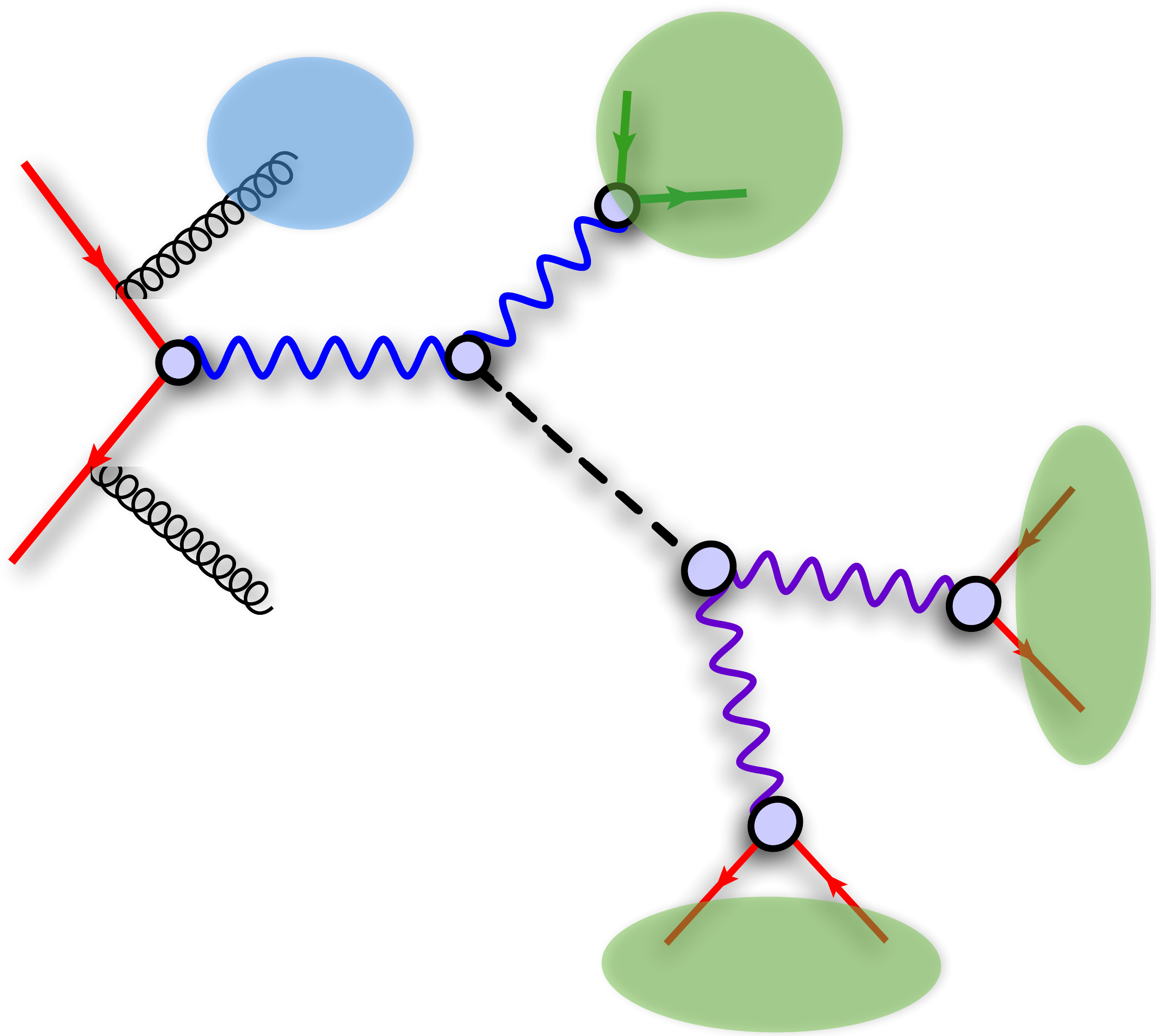

The LO phase space is 16 dimensional

Real phase space at NLO is 19 dimensional

H=> WW

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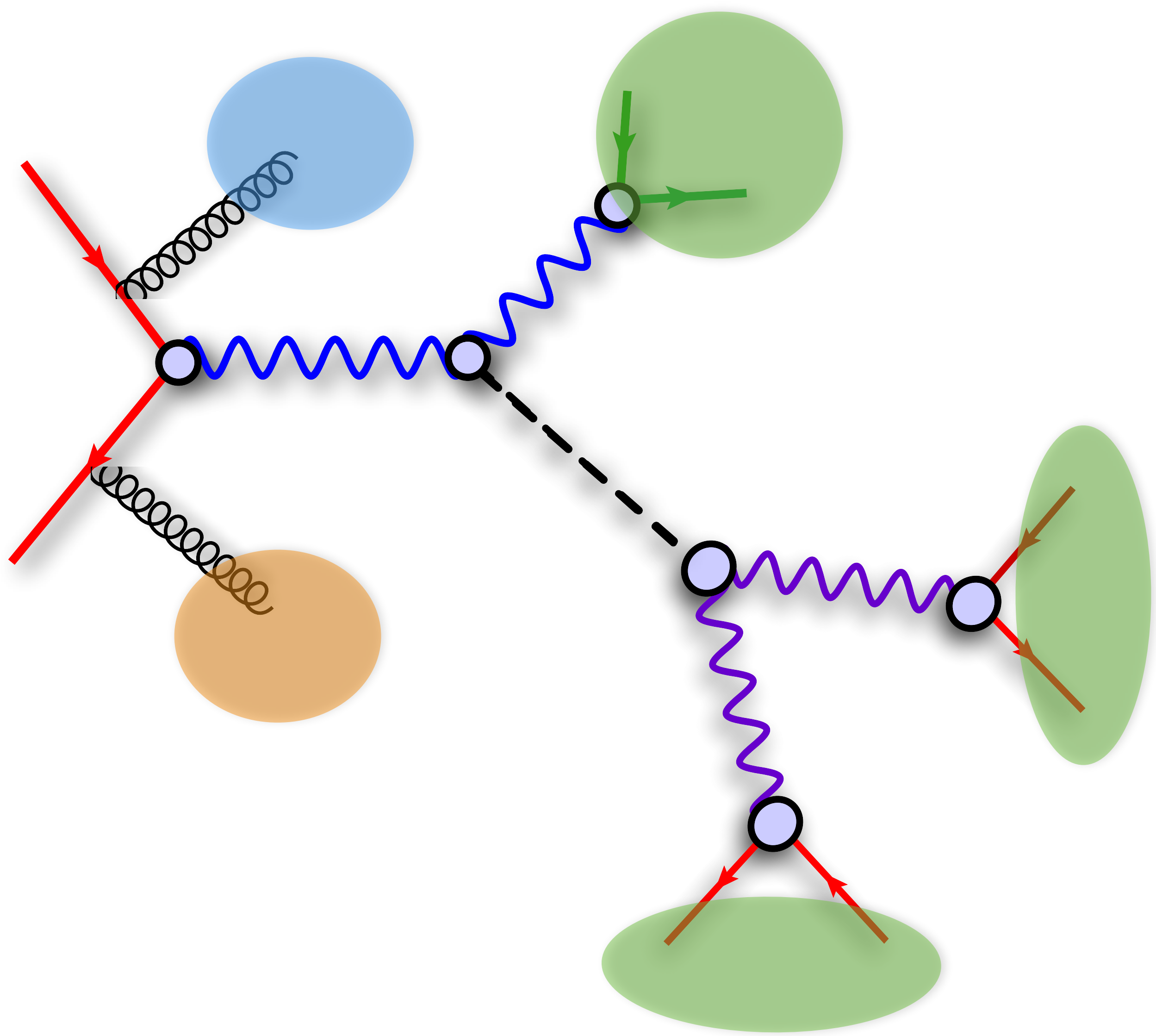


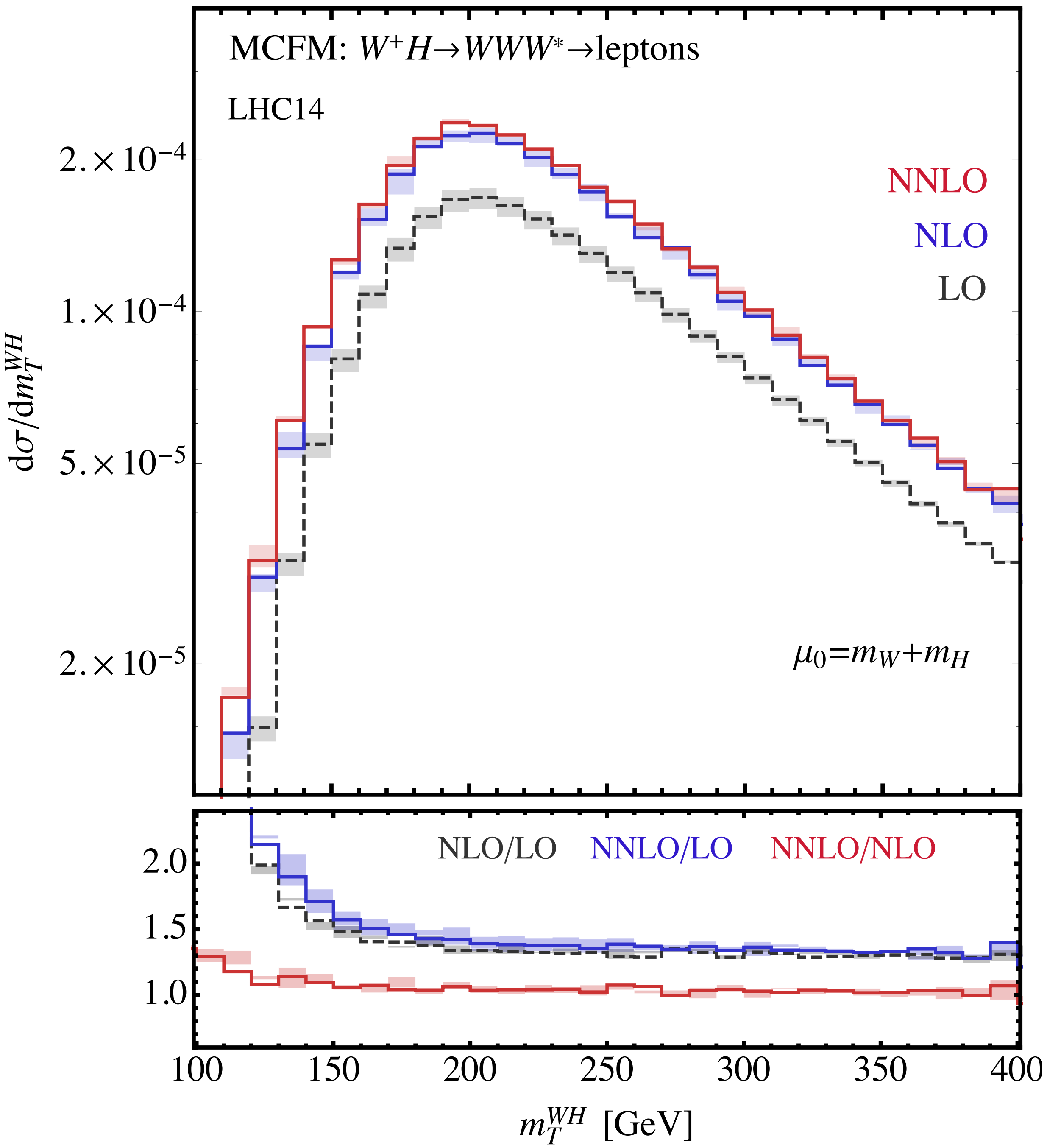
The LO phase space is 16 dimensional

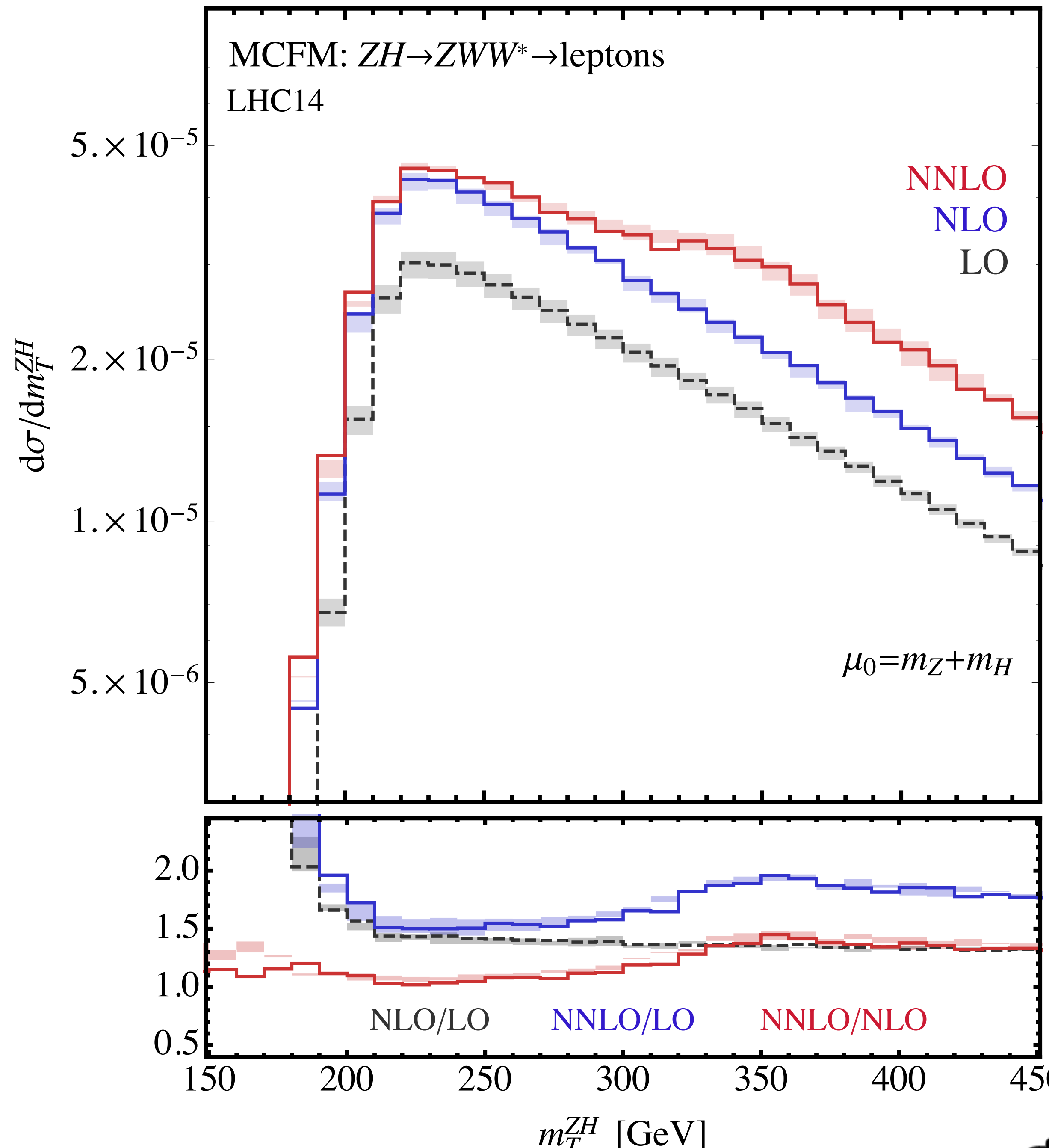
Real phase space at NLO is 19 dimensional

Double real phase space is 22 dimensional

Impact of higher orders in decay

We are able to run the code at NNLO and make distributions!





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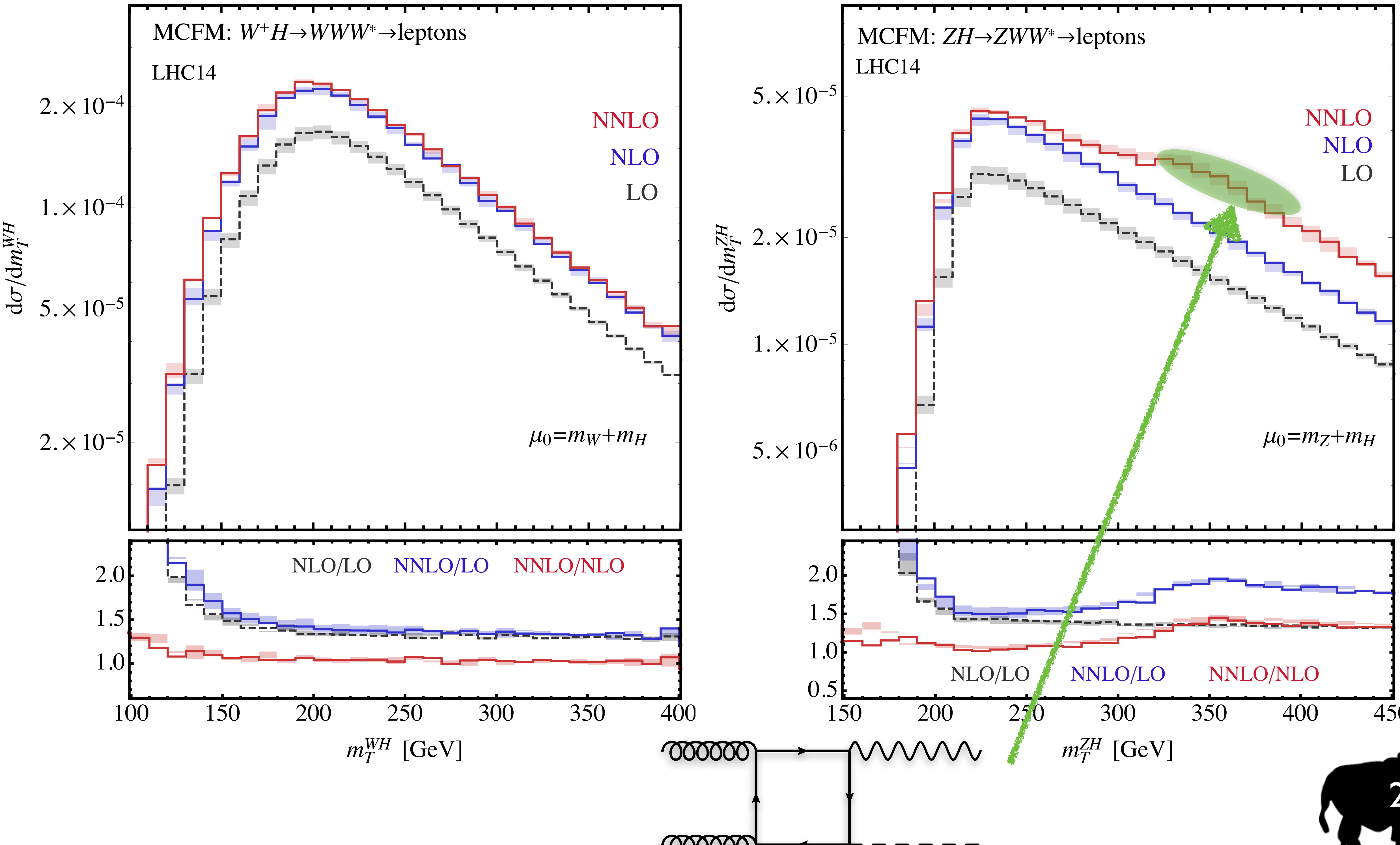
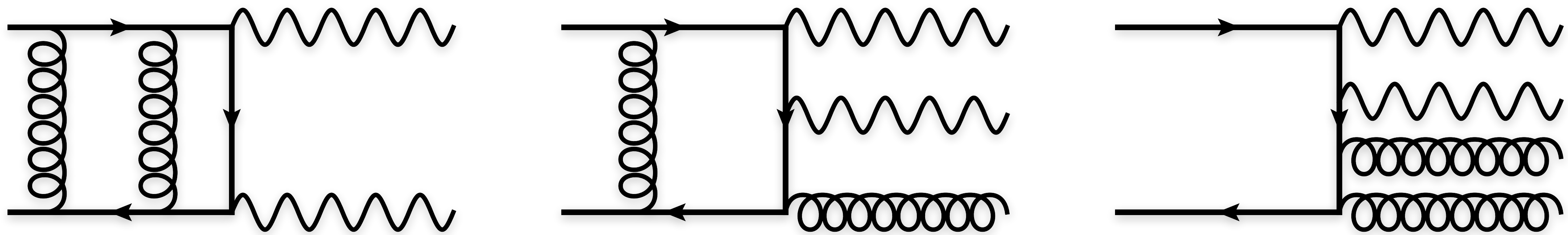


$\gamma\gamma$@NNLO

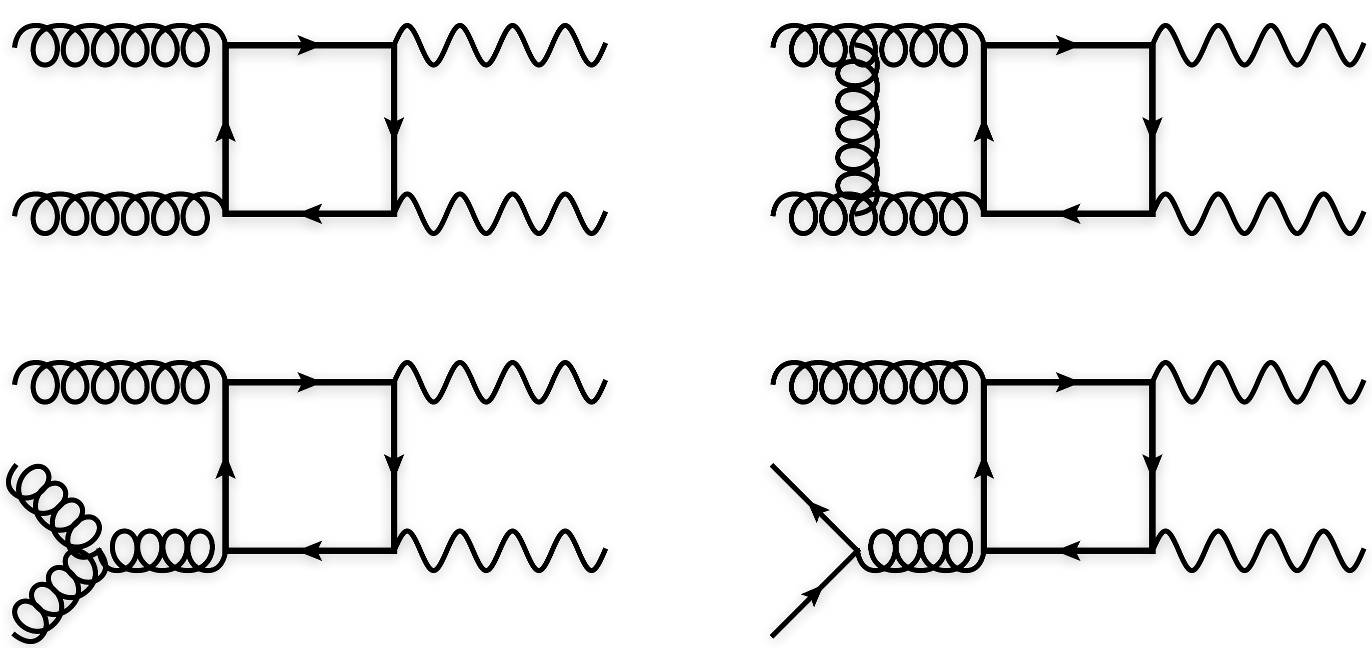
Campbell, Ellis, Li, CW 16

Campbell, CW 14



(Anastasiou, Glover, Tejeda-Yeomans 02)

$$\sigma^{\mathrm{NNLO}} + \Delta\sigma^{\mathrm{N3LO}}_{gg,n_F}$$



Aside from the regular $q\bar{q}$ NNLO topologies, there are interesting effects from gg initiated pieces too.

gg@NLO was calculated first by (Bern, De Freitas Dixon 01), (Bern, Dixon, Schmidt 02)

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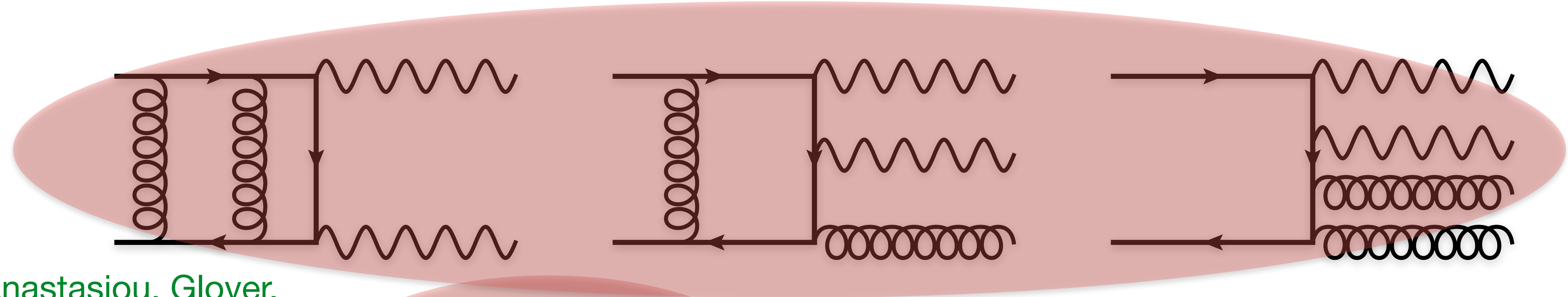

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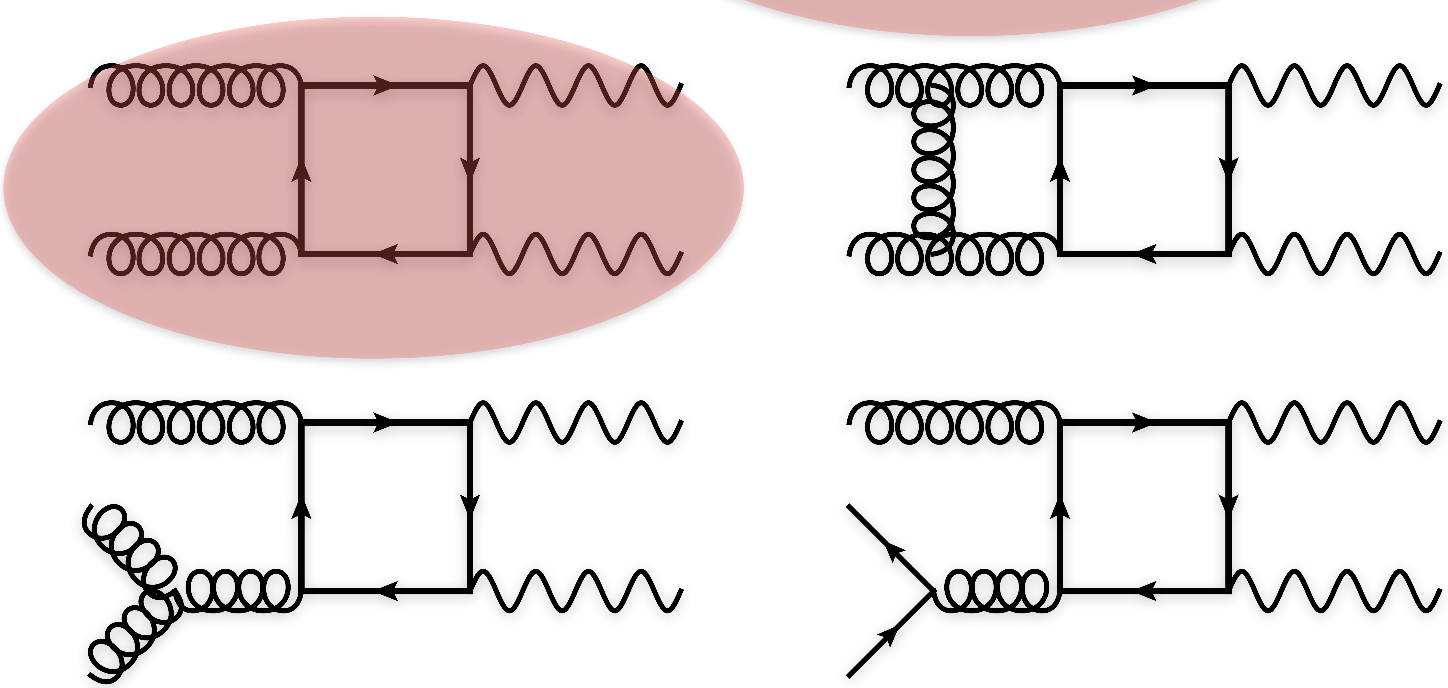

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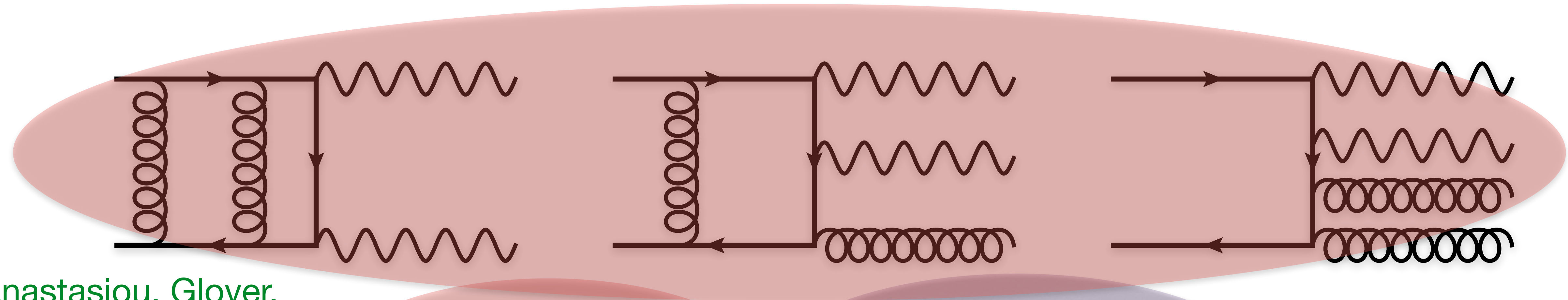

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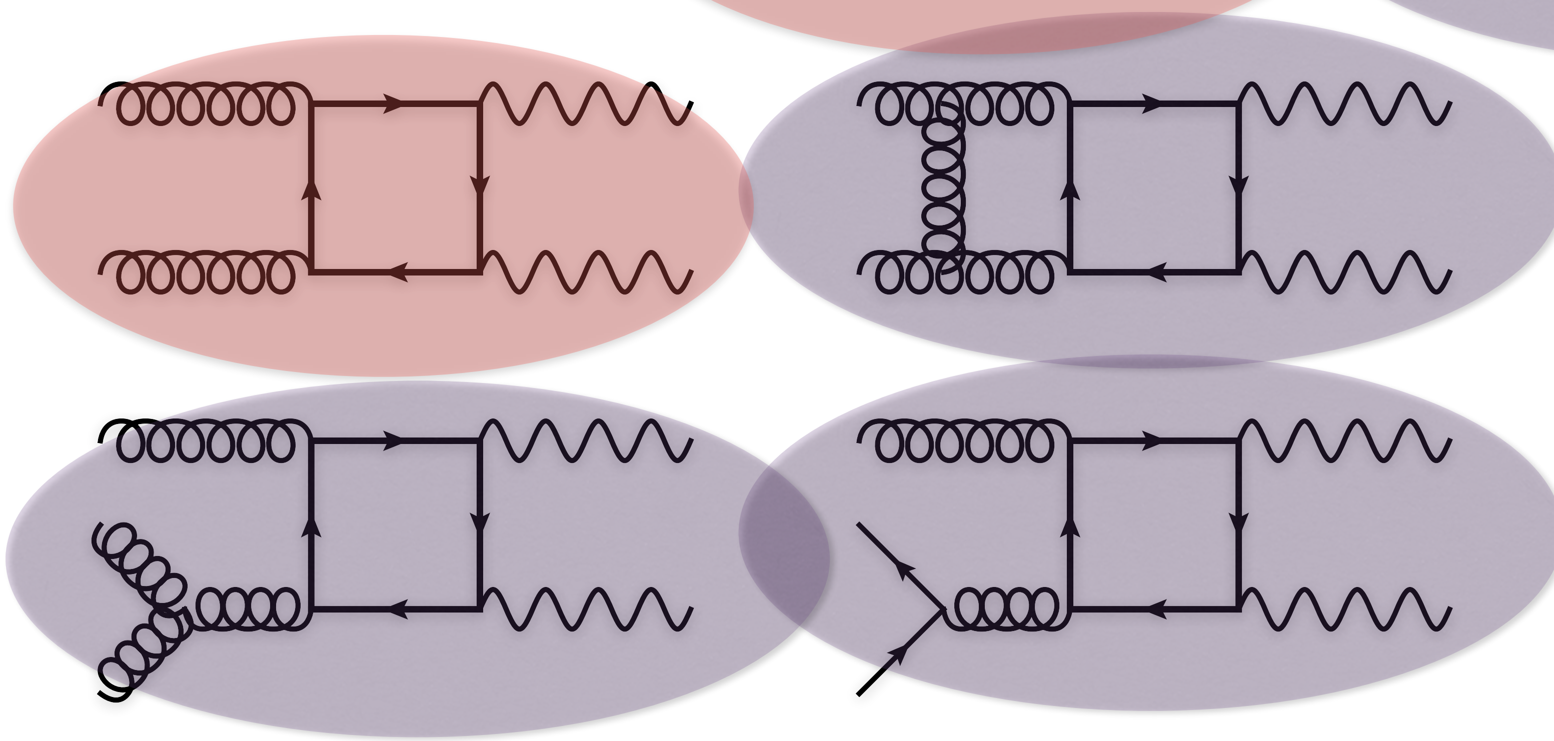

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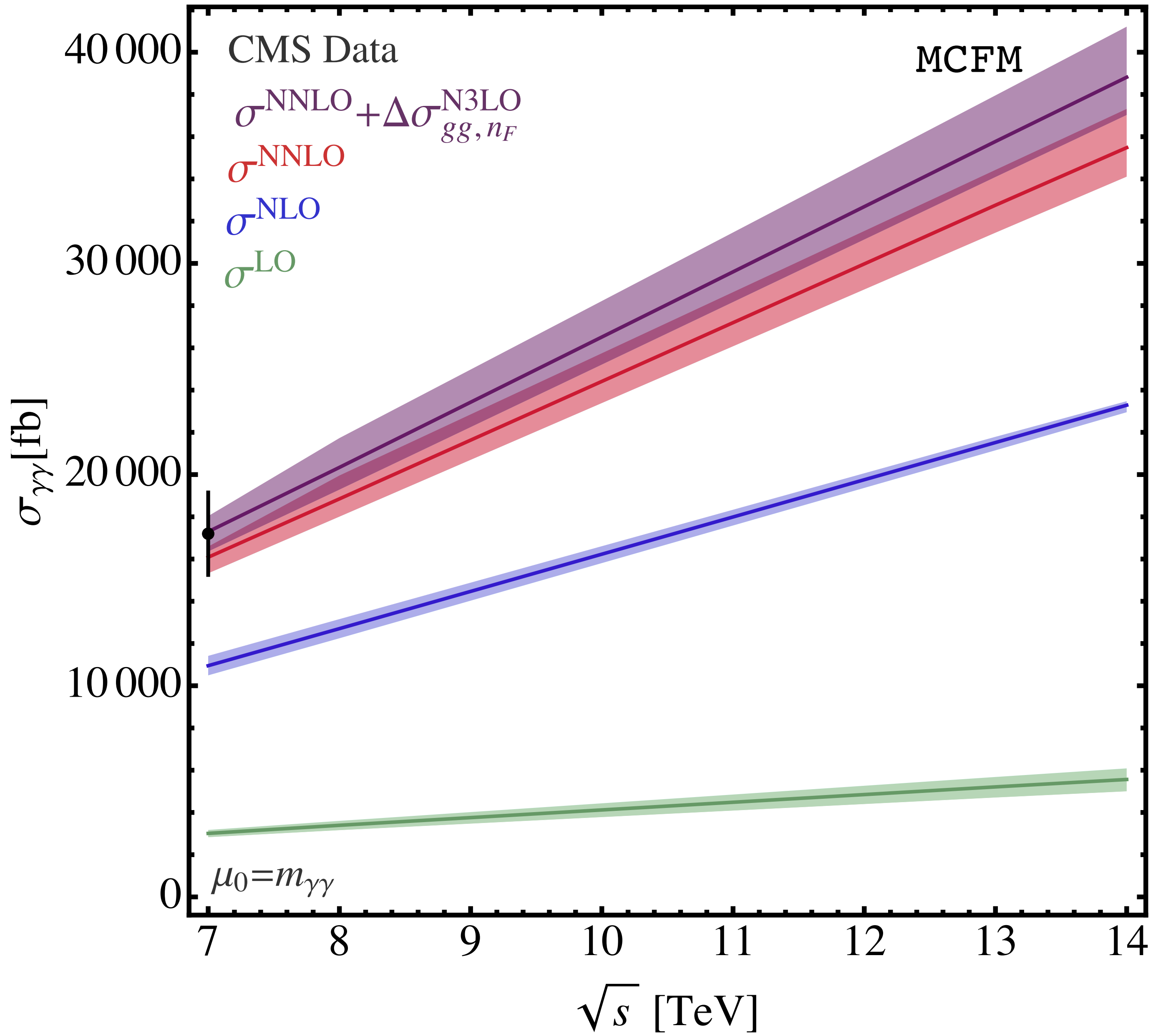
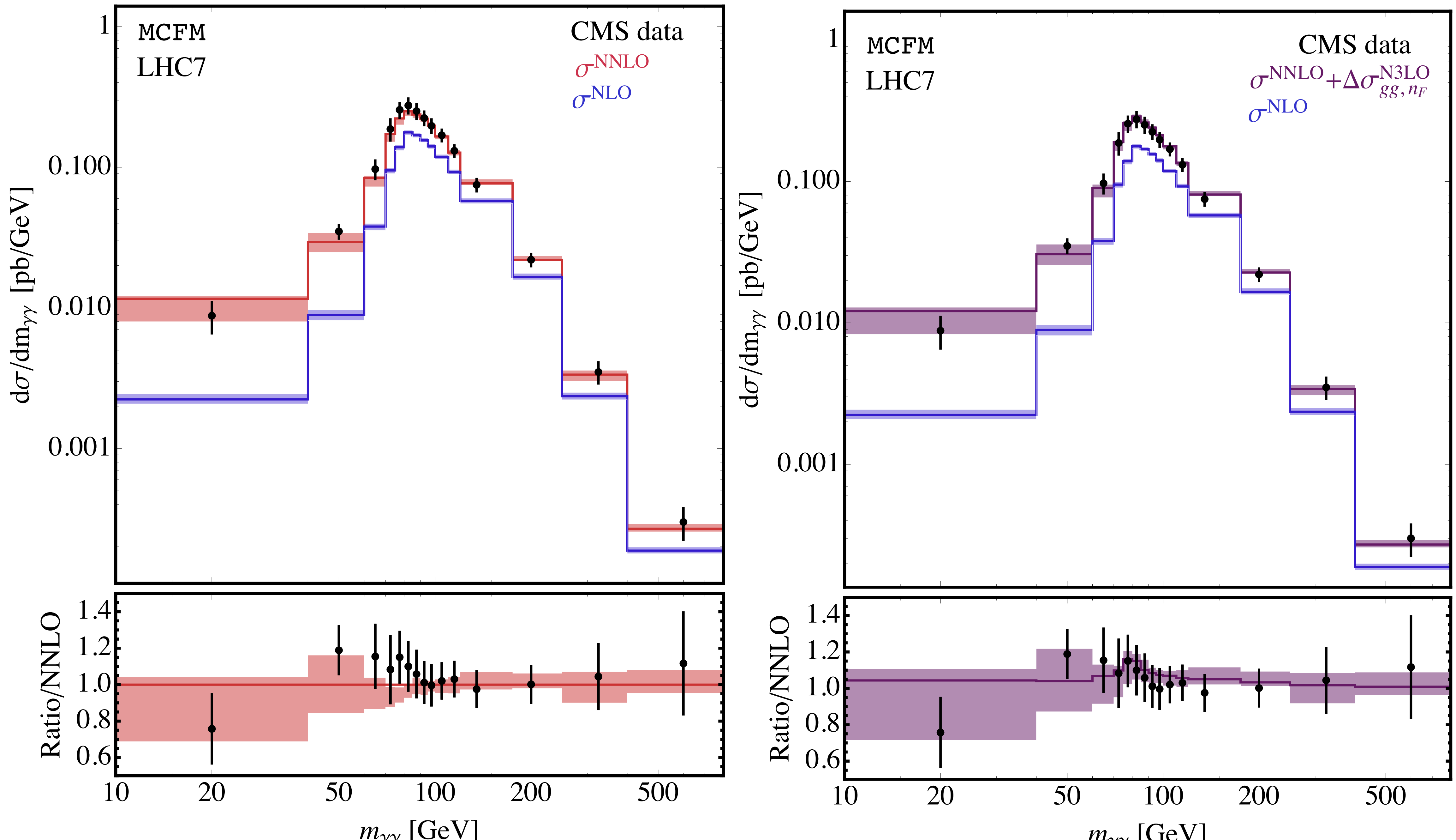
Cross sections



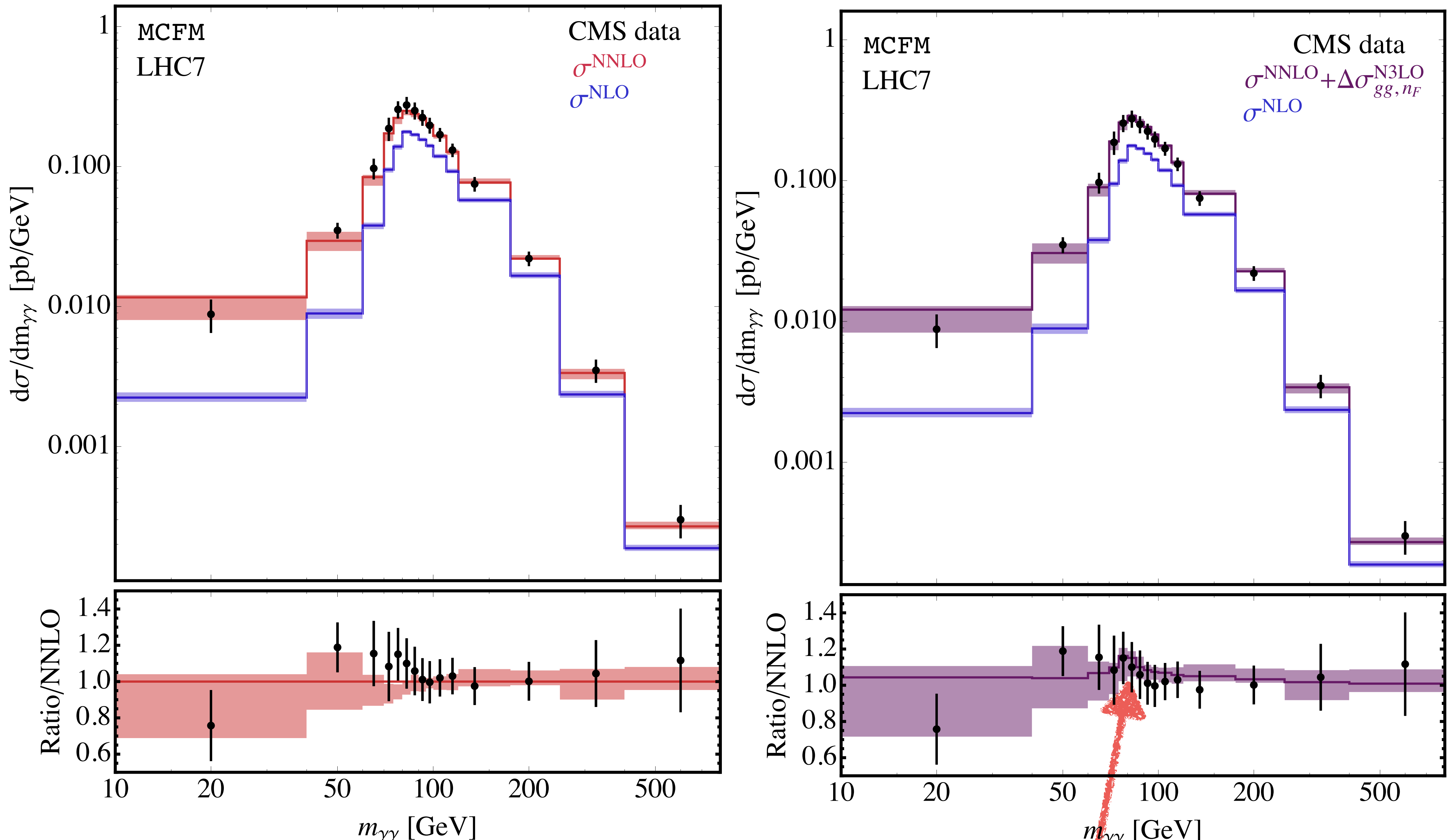
Its interesting to compare NNLO with NNLO + gg@NLO, at 7 TeV not much to tell between the two predictions and agreement with data.
At 13 TeV predictions separate, would be interesting to see which is best (its non trivial, since we are missing pieces from the N3LO prediction which could easily drive the prediction back down).

Differential predictions: Invariant masses



Out of the box NNLO does a very nice job of describing CMS 7 TeV Data

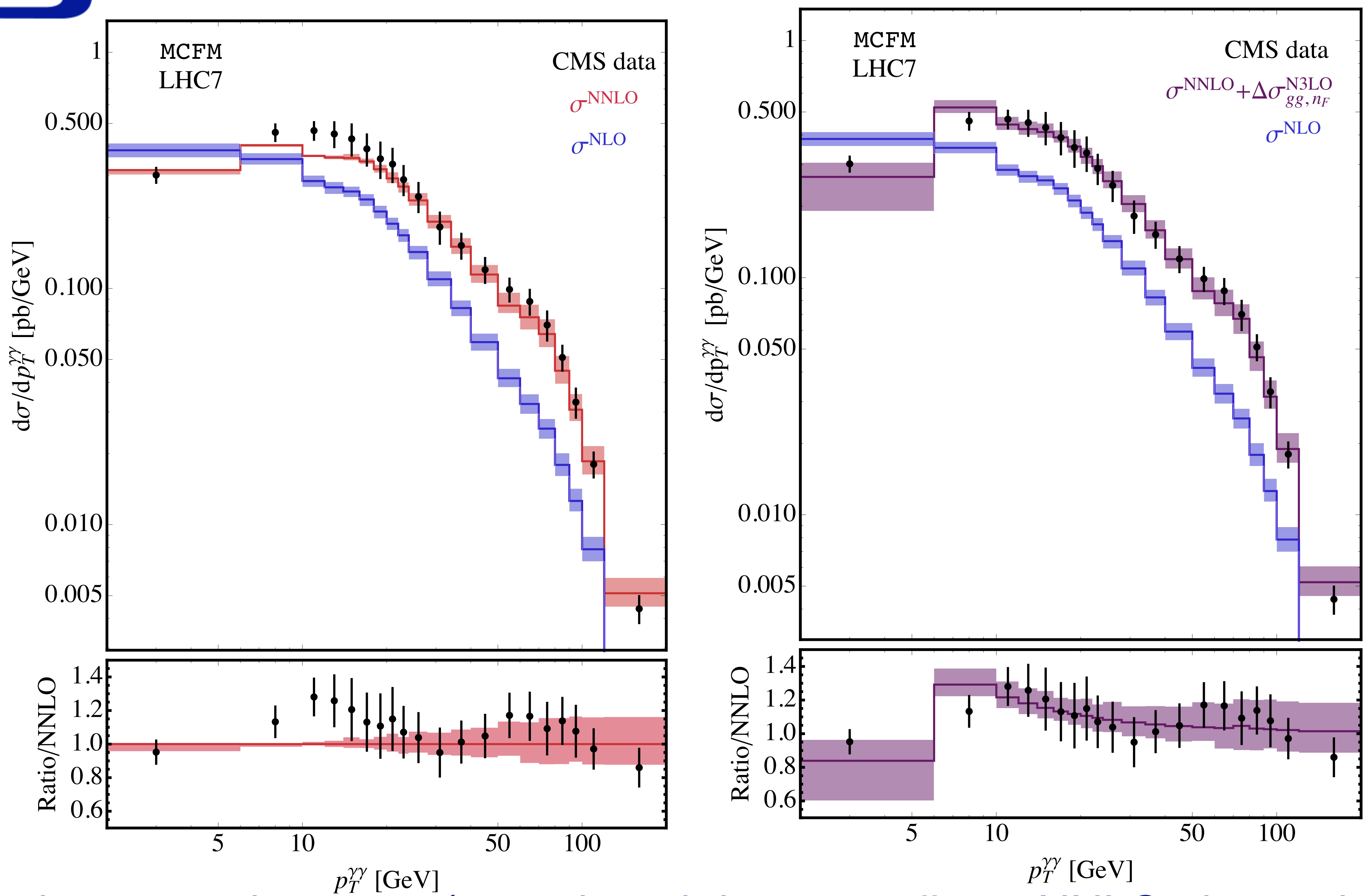
Differential predictions: Invariant masses



Out of the box NNLO does a very nice job of describing CMS 7 TeV Data

Looks like adding in additional gluon pieces helps

Differential predictions: $p_T^{\gamma\gamma}$



NNLO does great here too, (even though its not really an NNLO observable)

Additional gg pieces help at higher pt, but not really in the soft region

Predictions at high invariant masses.

As we all know, bump hunts in the diphoton system assume a smooth function which can be fitted to the data. Begging the question,

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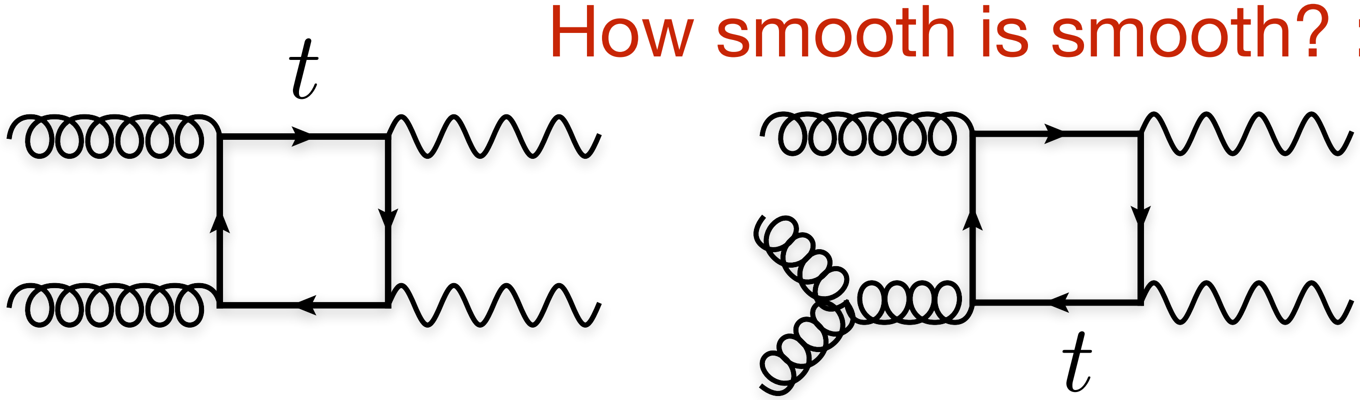

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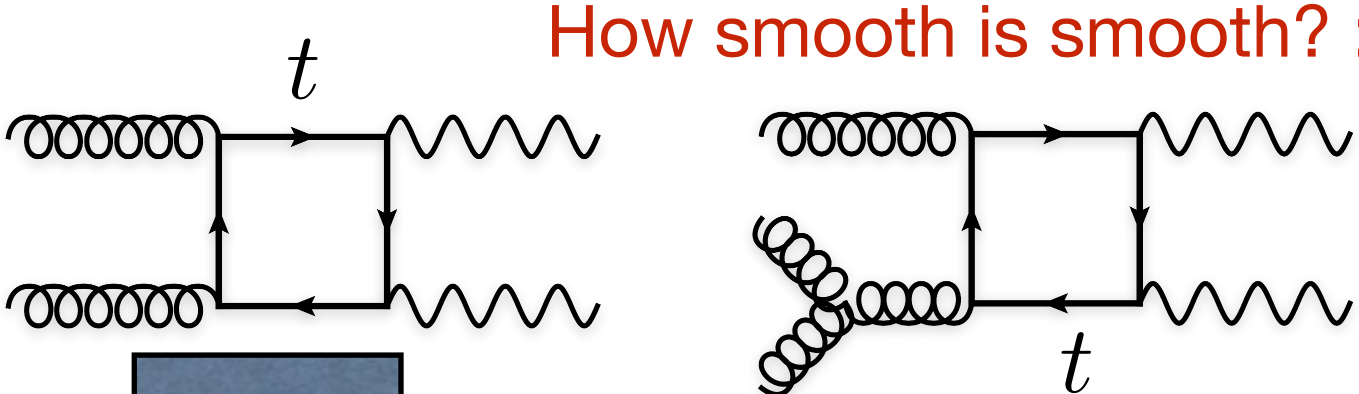

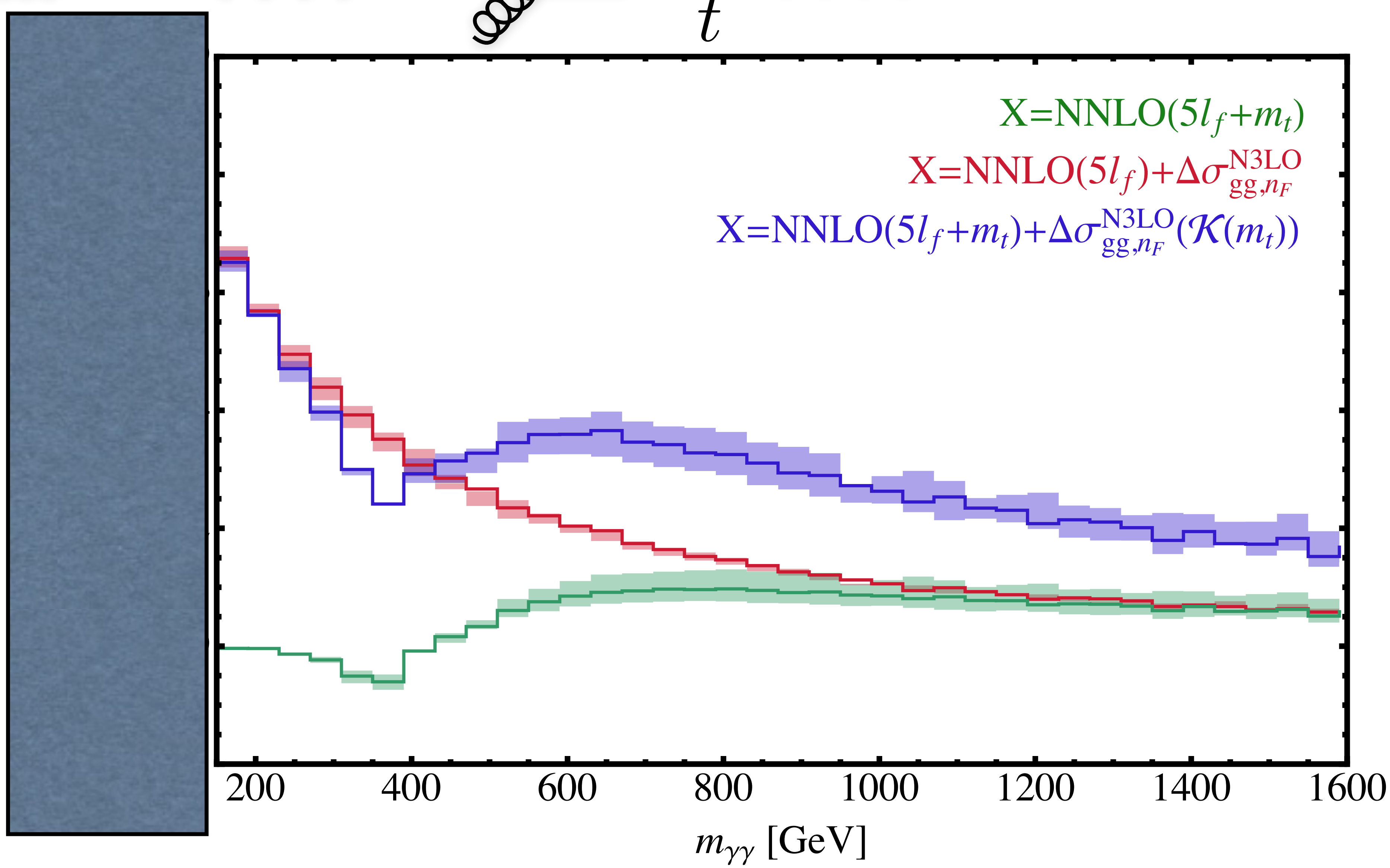

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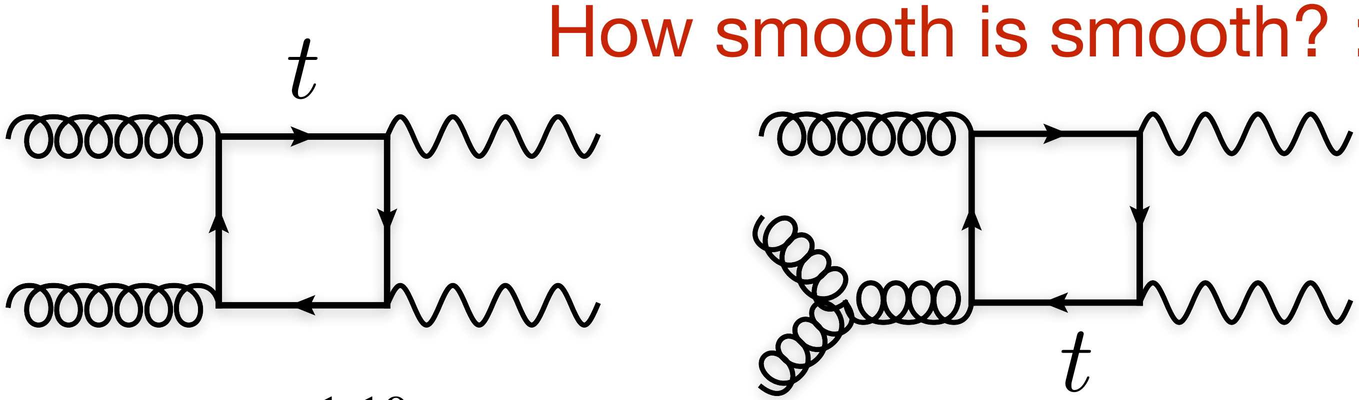
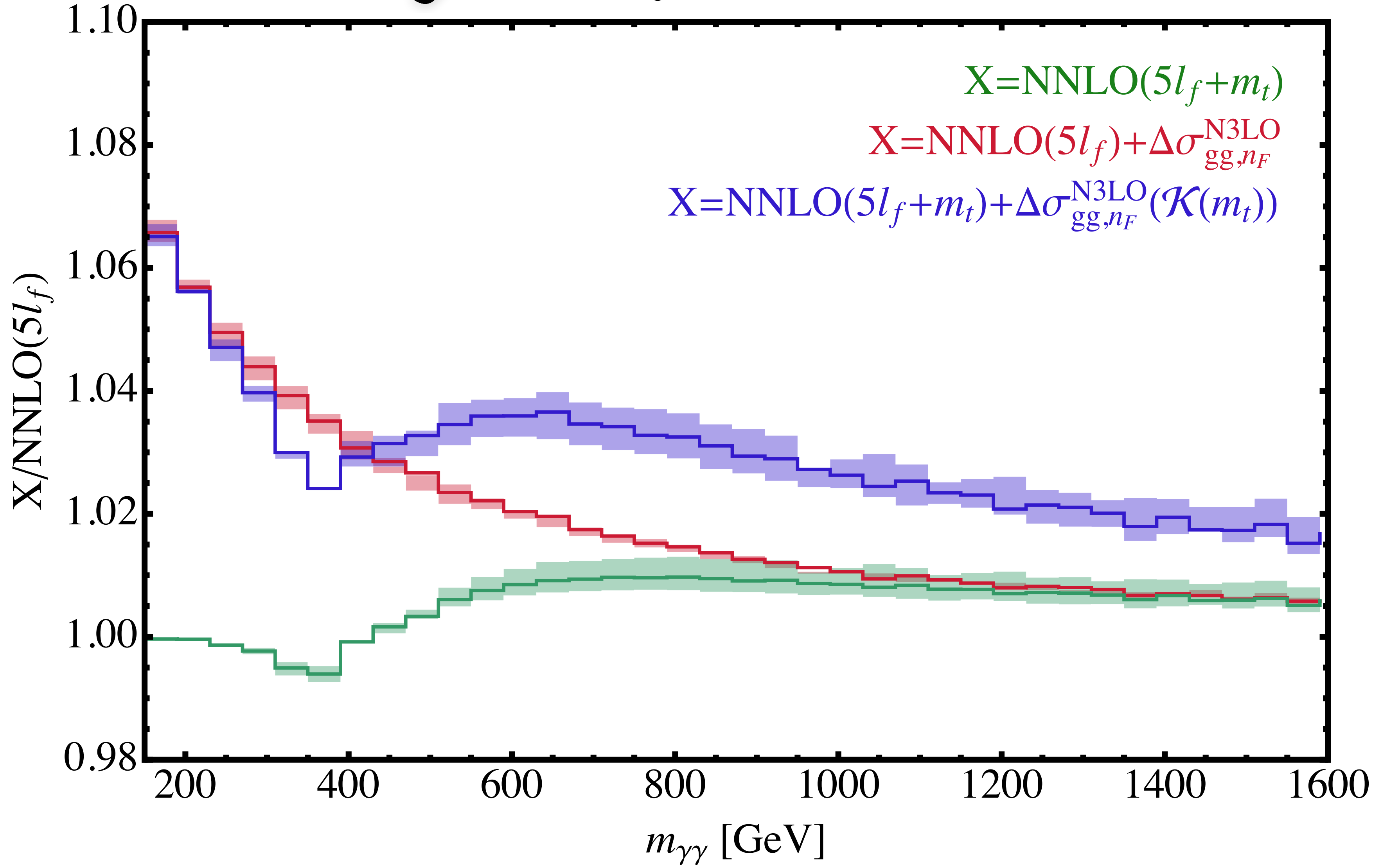
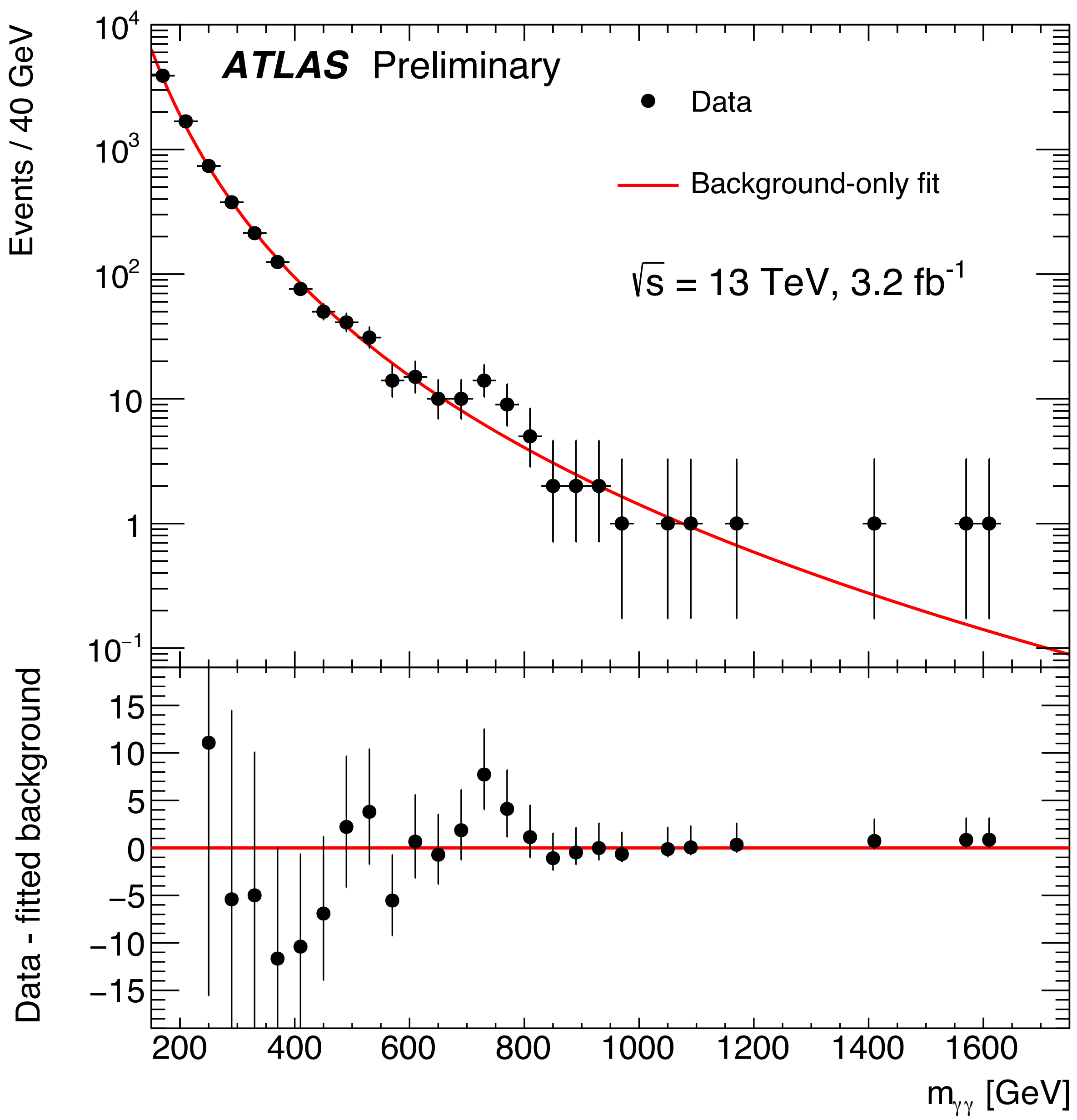




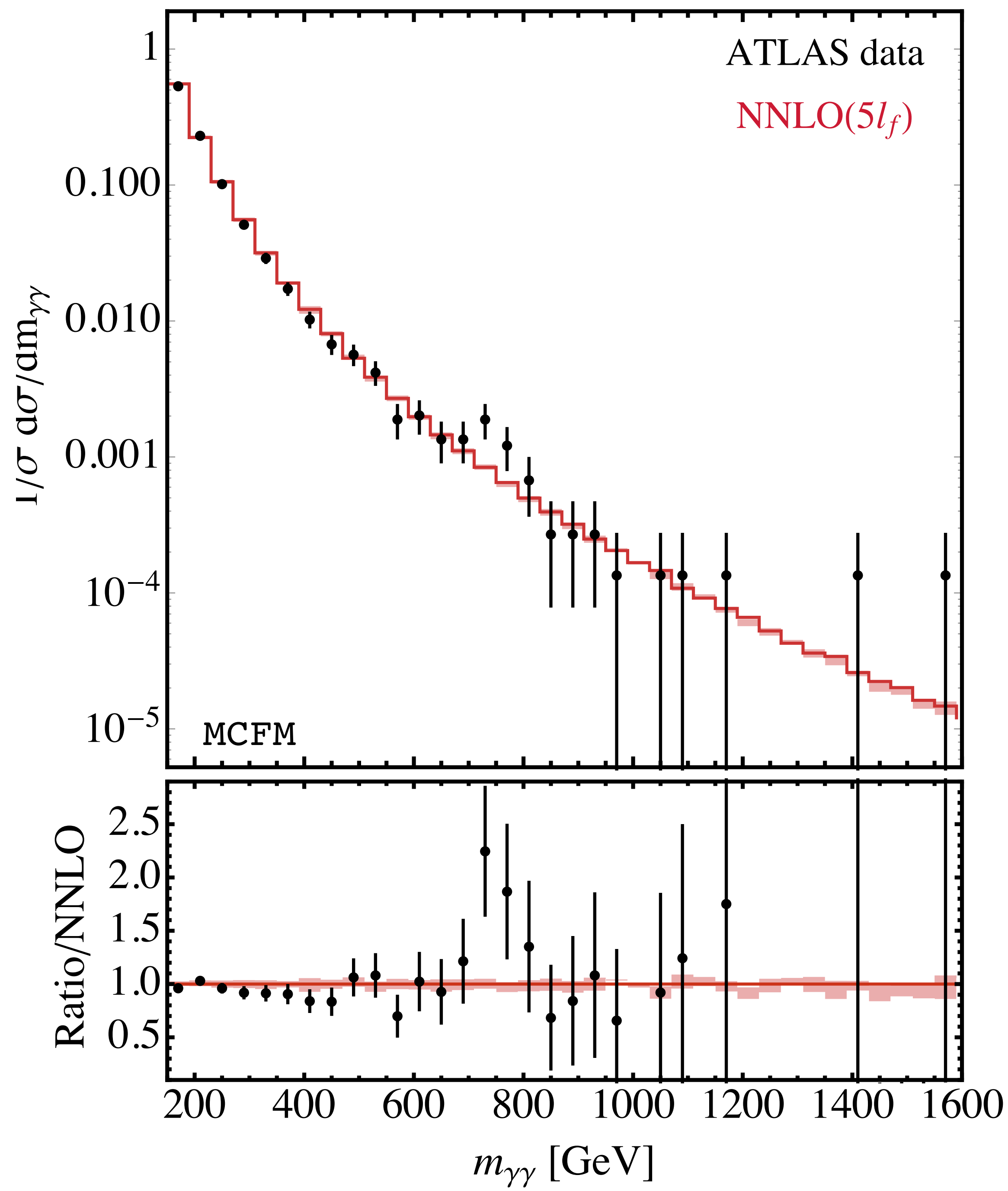
Diphoton invariant mass

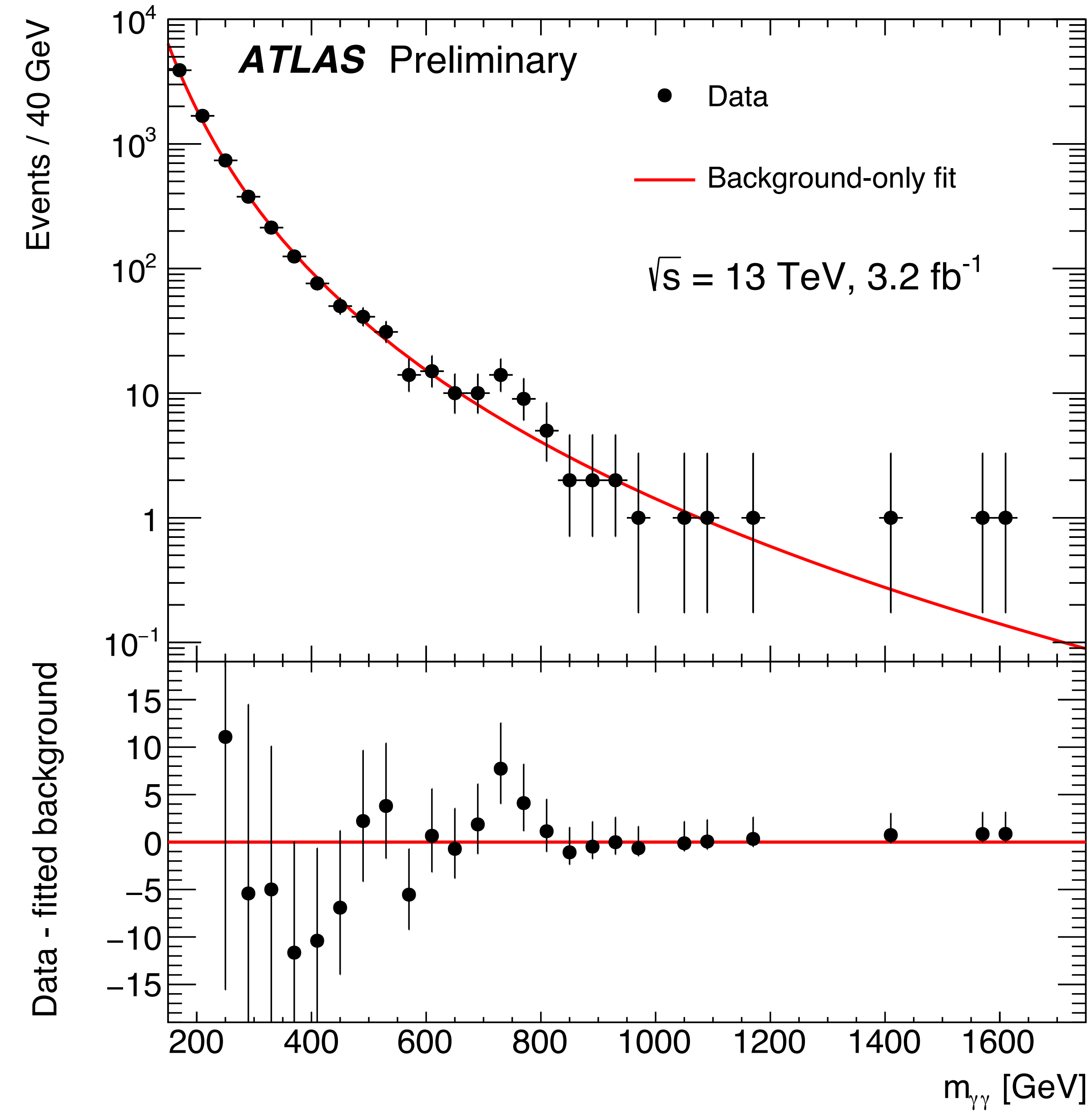
A natural concern is that the fit, while good in the region of lots of data, may not correctly describe tails with limited data.



Diphoton invariant mass

Can check with a first principles calculation of the shape of the SM prediction and compare the shape to the data.





Apologies go to….

At the beginning I warned of a significant bias in my talk. The last year has been fantastic for those developing NNLO calculations. Some of the recent results I would have loved to have highlighted are given below.

- **Antenna subtraction** (Gerhmann, Gehrmann-De Ridder, Glover et al) : H + 1 jet (Chen Gerhmann, Glover, Jaquier 16) , Z + 1 jet (Gehrmann-De-Ridder Gerhmann, Glover, Huss, Morgan 15), gg=>gg (Currie, Gehrmann-De-Ridder Gerhmann, Pires, Wells 14)

- **STRIPPER** (Czakon), top pairs (Czakon, Mitov, Heymes Fiedler 16) H + 1 jet (Boughezal, Caola, Melnikov, Petriello, Schulze 15), single top (Bruchserfeifer, Caola, Melnikov 14)

- **Q_T slicing** (Catani, Grazzini): WW (Grazzini, Kallweit Pozzorini, Rathlev Wiesemann 16), WZ (Grazzini, Kallweit, Rathlev Wiesemann 16), ZZ (Grazzini, Kallweit, Rathlev Wiesemann 15),

- **Phase space Mappings :** VBF (Cacciari, Dreyer, Karlberg Salam, Zanderighi 15)

Each of these methods are individually intricate and would have taken a lot longer than my time to discuss properly. However I hope you get the feeling that this is an incredibly exciting time for precision calculations.

LOOPFEST XV

August 15-17 2016
Buffalo NY

Radiative corrections for the LHC and Future Colliders

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