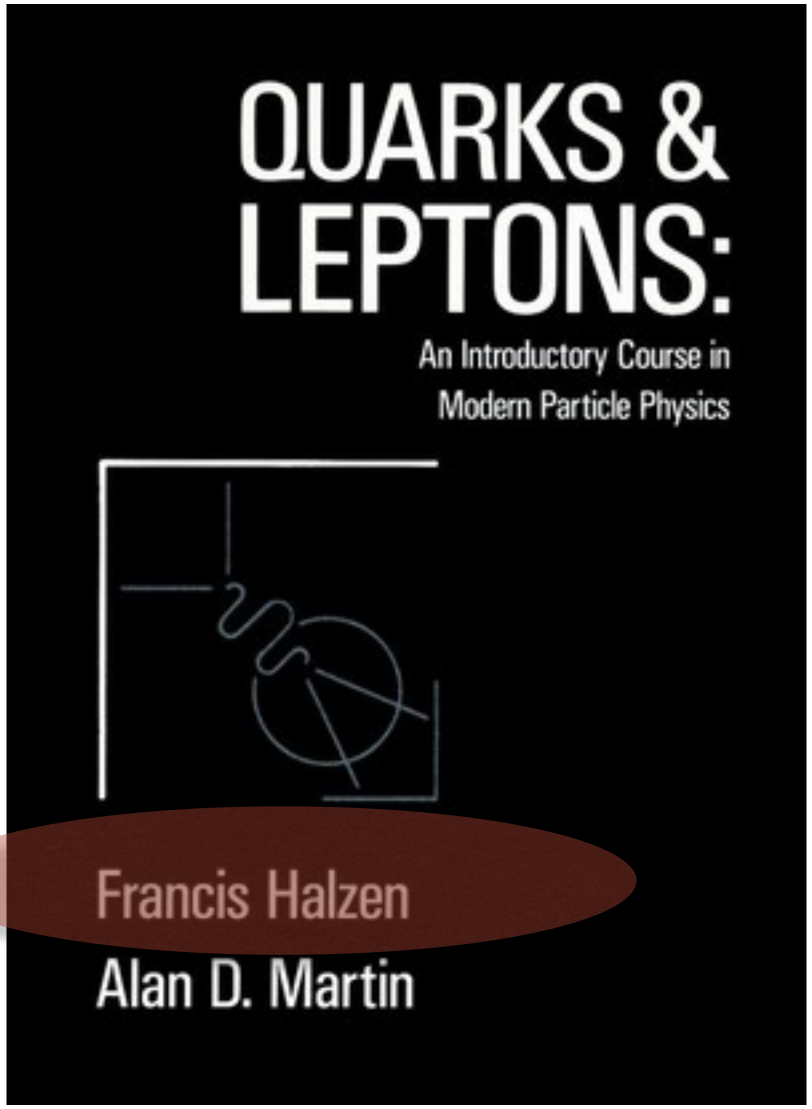
Multi-boson interactions

Ciaran Williams (SUNY Buffalo)

MBI in WI?



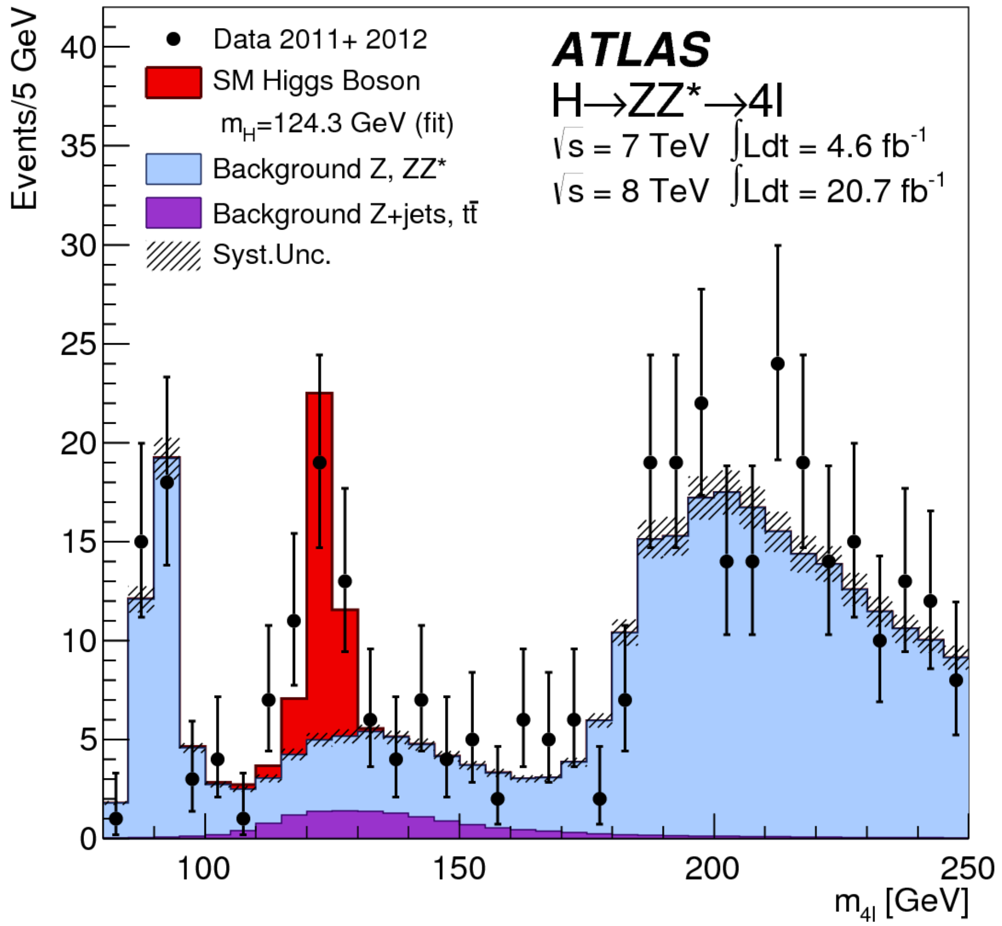
I always thought UW Madison was more of a fermion place….

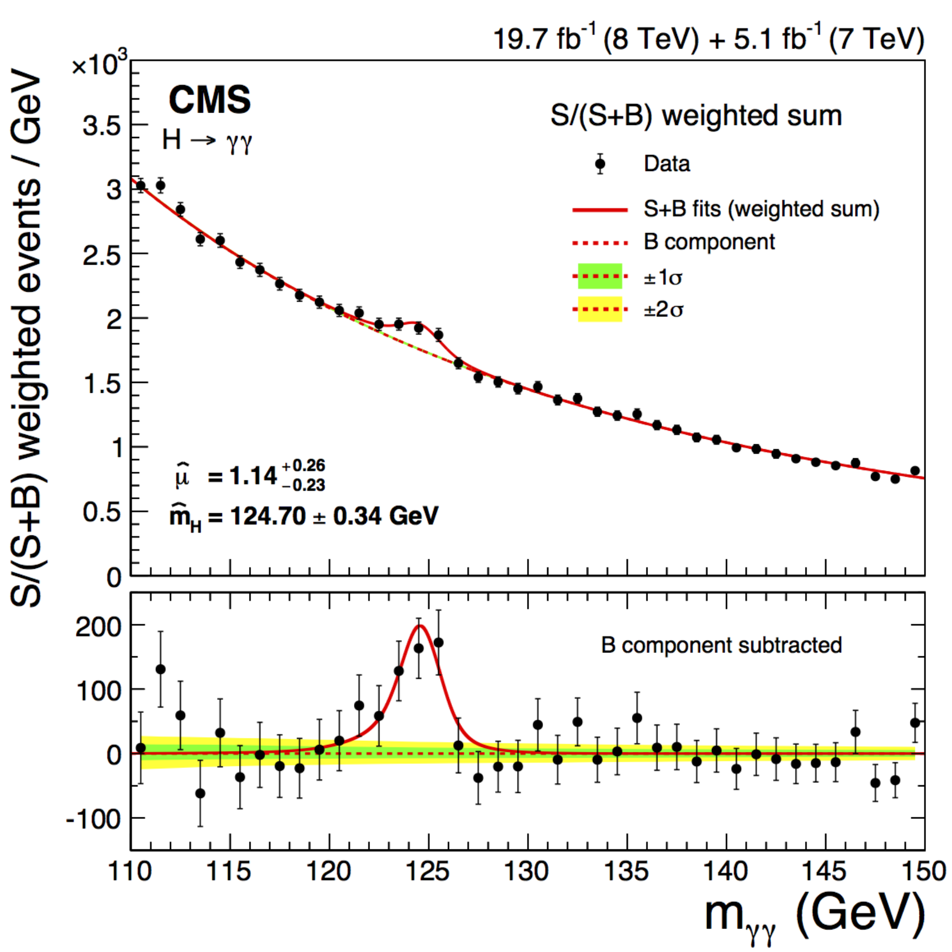
Outline

- Why MBI?
- The need for NNLO for MBI
- What goes into an NNLO calculation?
- Slicing methods for NNLO calculations
- Recent results for Diboson studies

Why MBI?

Diboson at the LHC have given us the defining results of the collider: the discovery of the Higgs boson





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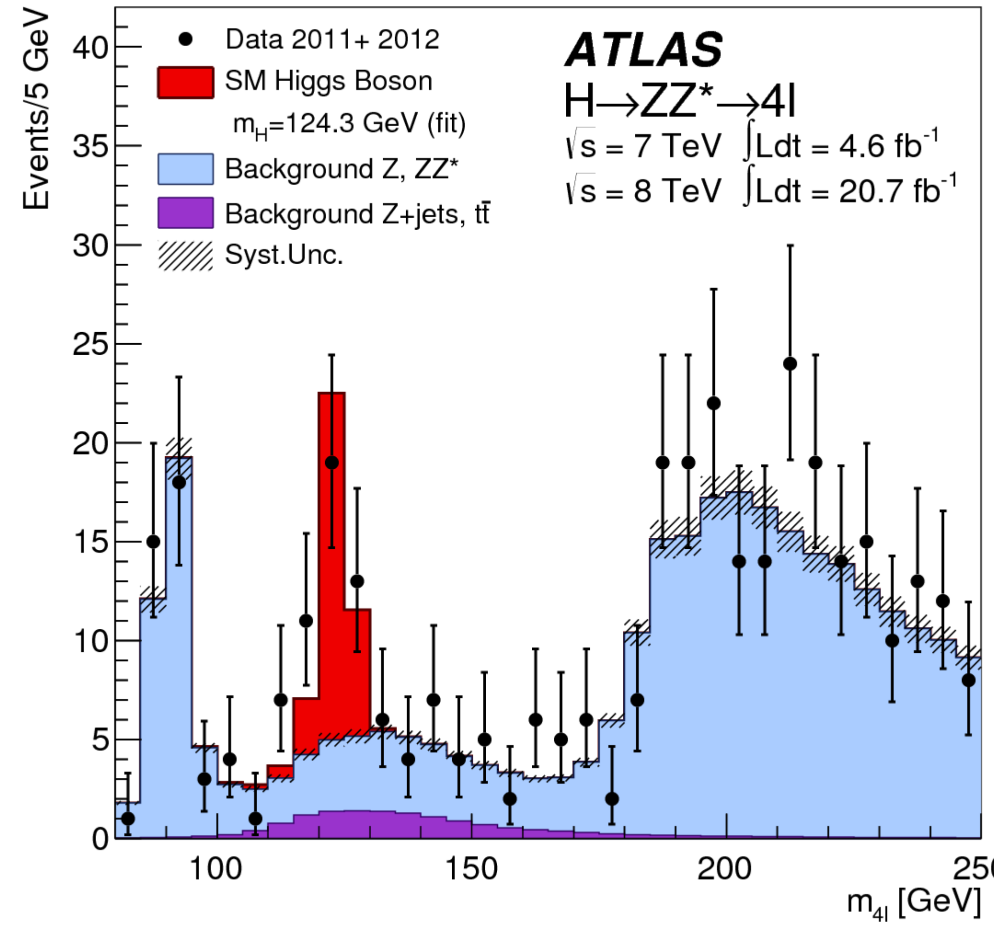
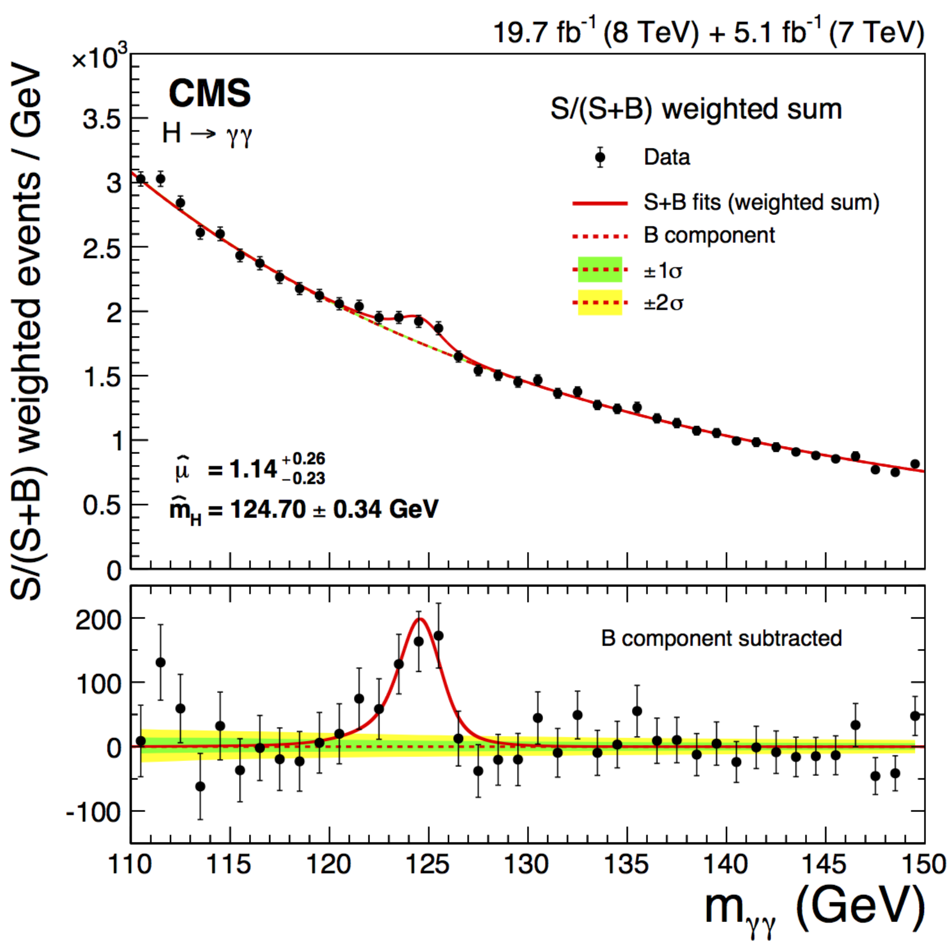
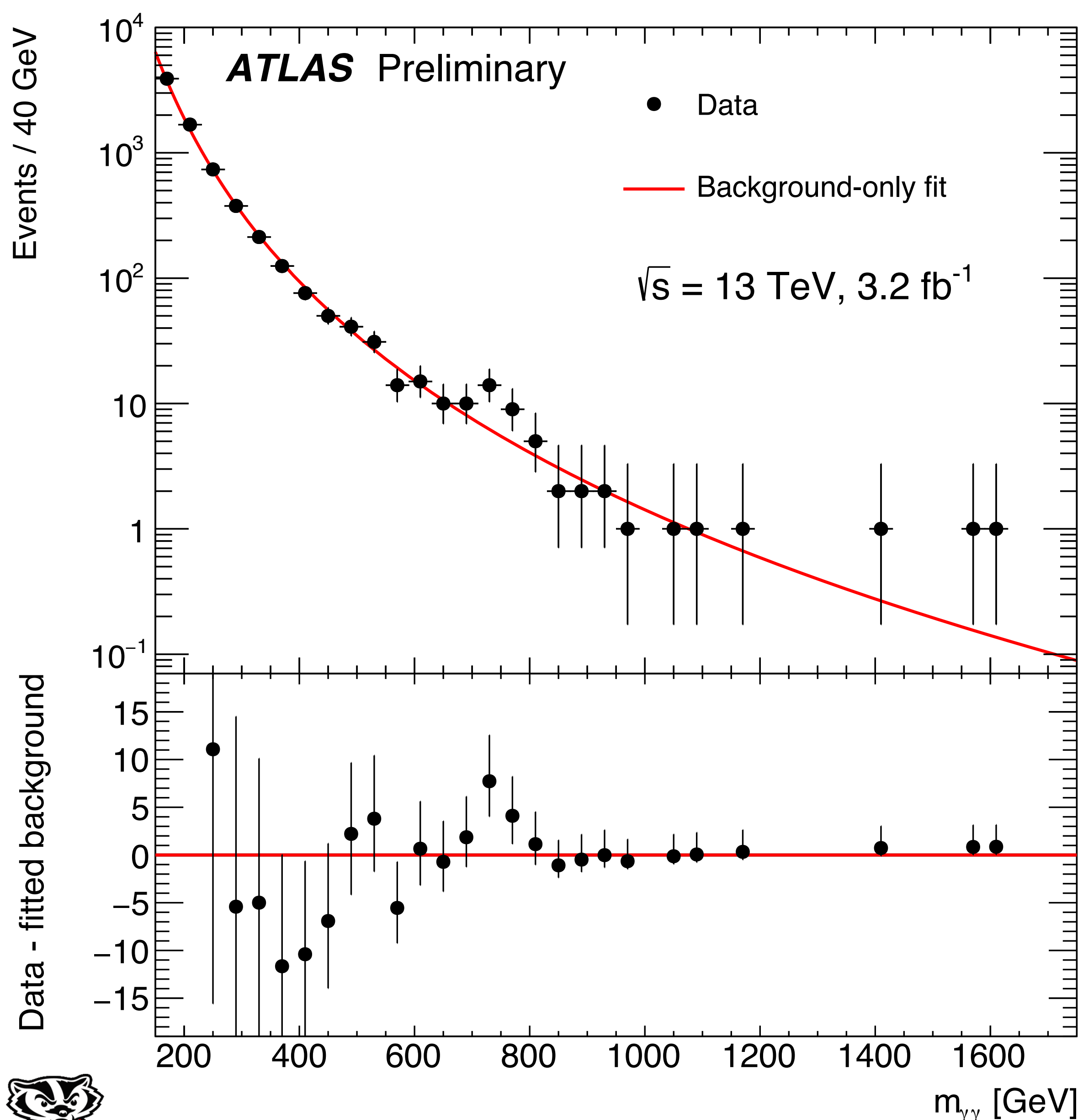
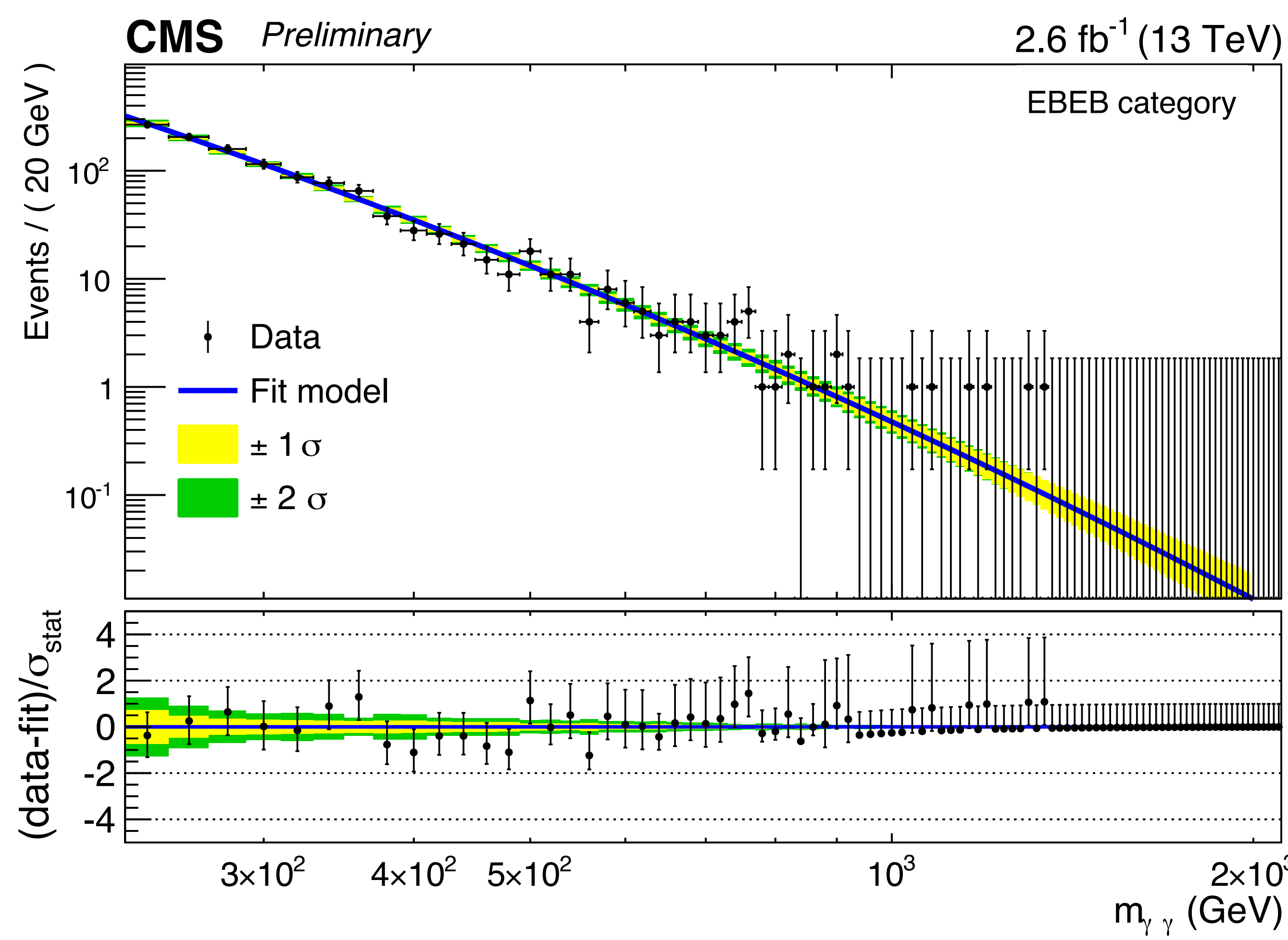
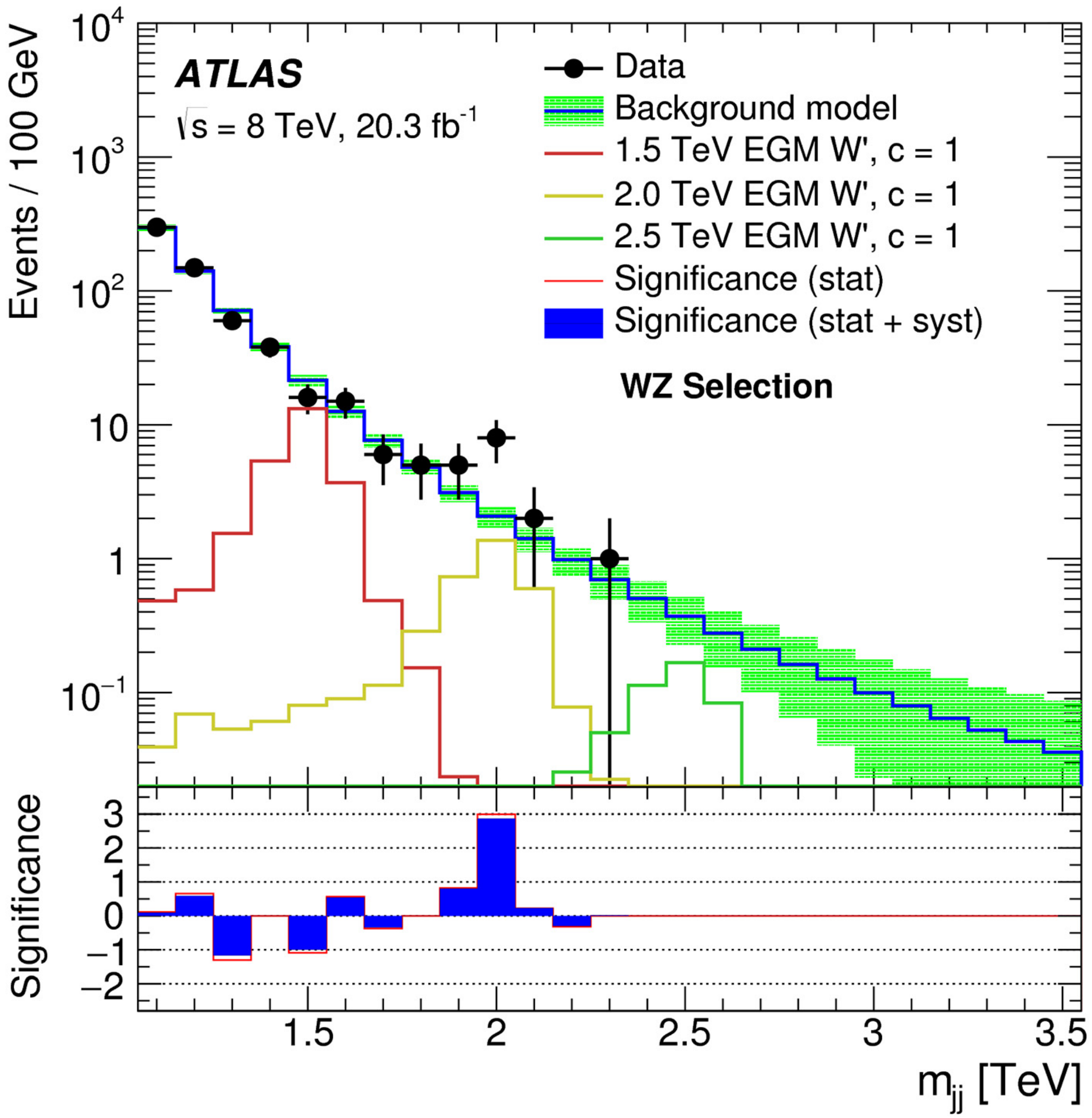


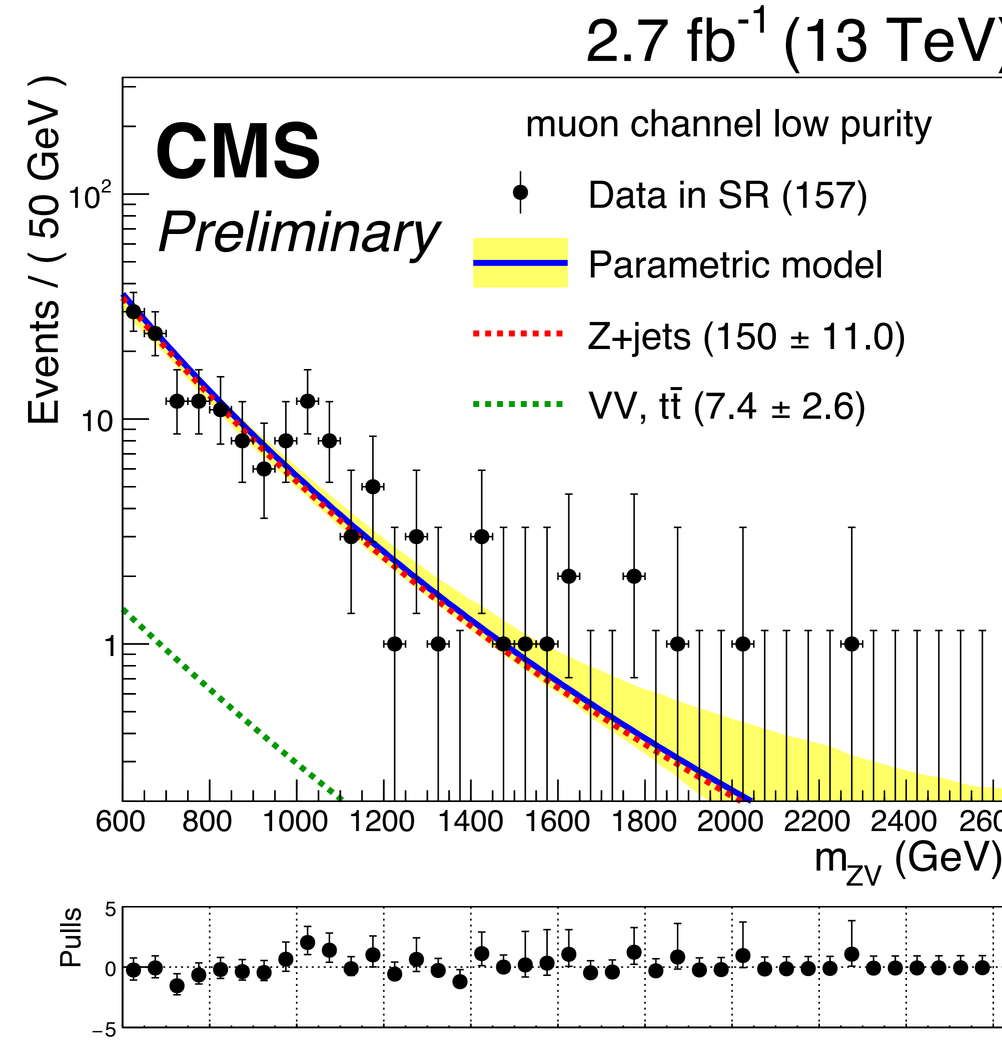


And famously stole Christmas…









	Measured $\sigma_{WW}^{\mathrm{fid}}$ (fb)	Predicted $\sigma_{WW}^{\mathrm{fid}}$ (fb)	Measured σ_{WW} (pb)	Predicted σ_{WW} (pb)
ee	$56.4 \pm 6.8 \pm 9.8 \pm 2.2$	54.6 ± 3.7	$46.9 \pm 5.7 \pm 8.2 \pm 1.8$	$44.7^{+2.1}_{-1.9}$
$\mu\mu$	$73.9 \pm 5.9 \pm 6.9 \pm 2.9$	58.9 ± 4.0	$56.7 \pm 4.5 \pm 5.5 \pm 2.2$	$44.7^{+2.1}_{-1.9}$
$e\mu$	$262.3 \pm 12.3 \pm 20.7 \pm 10.2$	231.4 ± 15.7	$51.1 \pm 2.4 \pm 4.2 \pm 2.0$	$44.7^{+2.1}_{-1.9}$
Combined	$\cdots$	$\cdots$	$51.9 \pm 2.0 \pm 3.9 \pm 2.0$	$44.7^{+2.1}_{-1.9}$

In fact Dibosons generate excitement almost continually….

Although thus far, we haven't quite cracked the SM nut….

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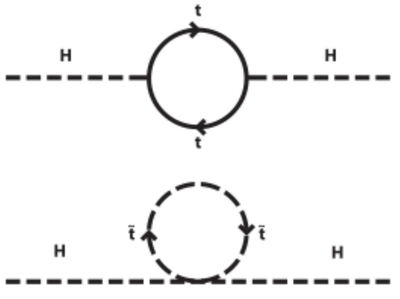
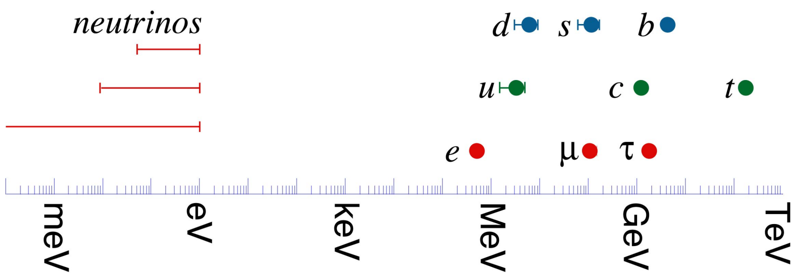
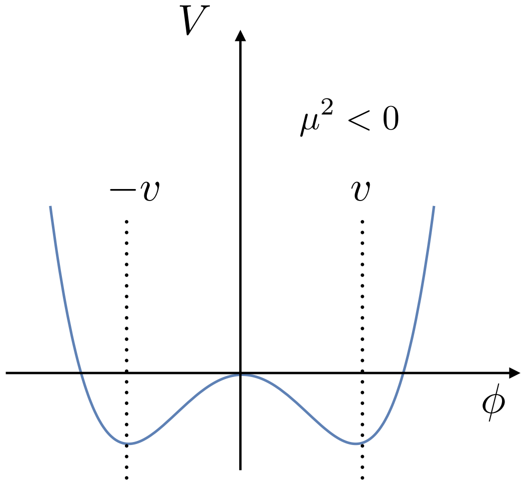
The "Smug" SM should be careful….



- Hierarchy Problem
- Dark Matter (WIMP miracle?)
- Neutrino masses?
- Origin of EWSB
- CP violation + flavour puzzles





The "Smug" SM should be careful….

- Hierarchy Problem
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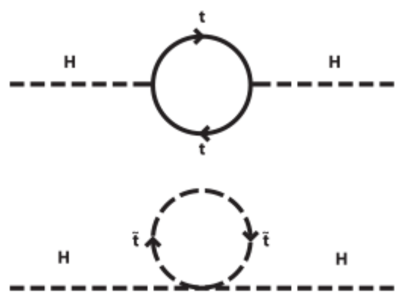
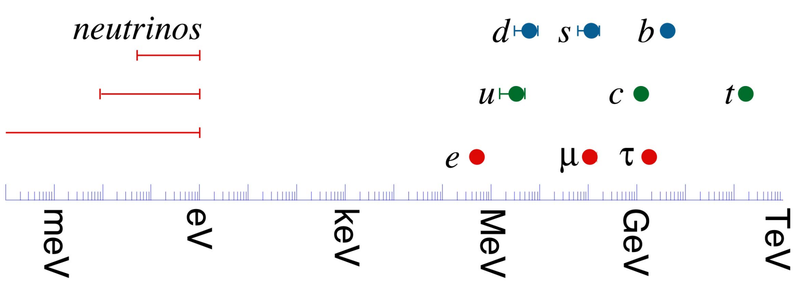
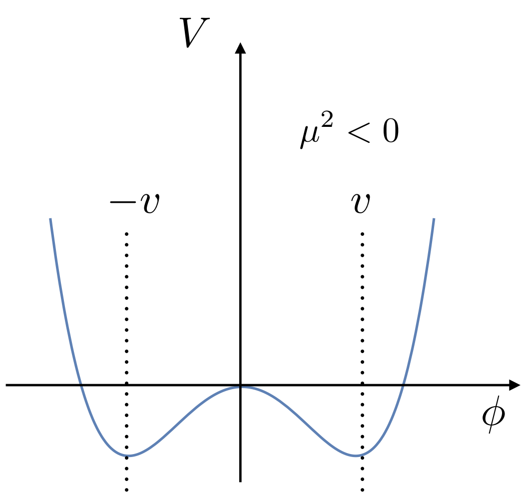
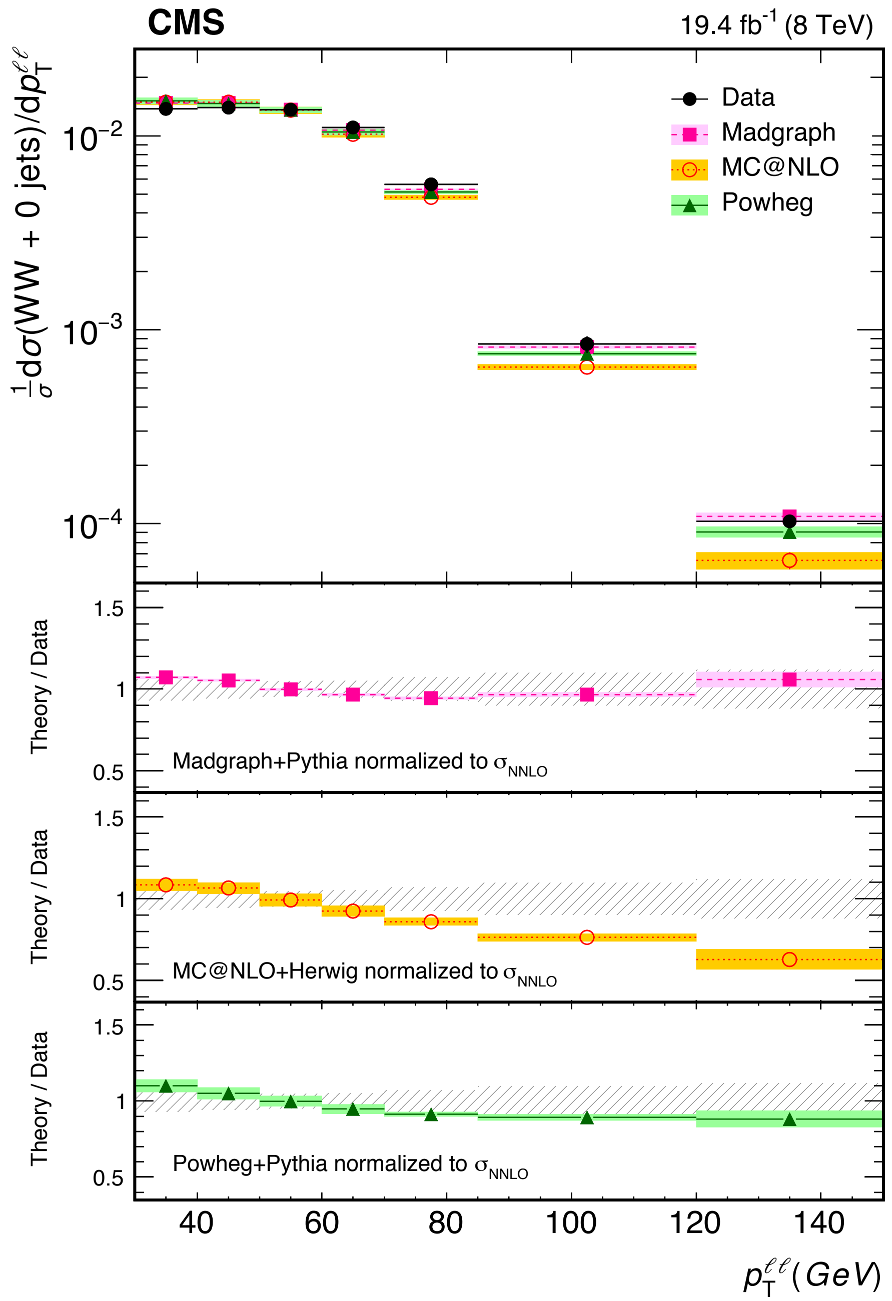
All are intimately related to the weak sector, and hence MBI interactions.







1507.03268



If Run II fails to find directly produced resonances. Then precision measurements to constrain anomalous interactions are vital.

NLO+PS tools tend to give a wide spectrum of predictions in the tails, due to different mechanisms of exponentiation.

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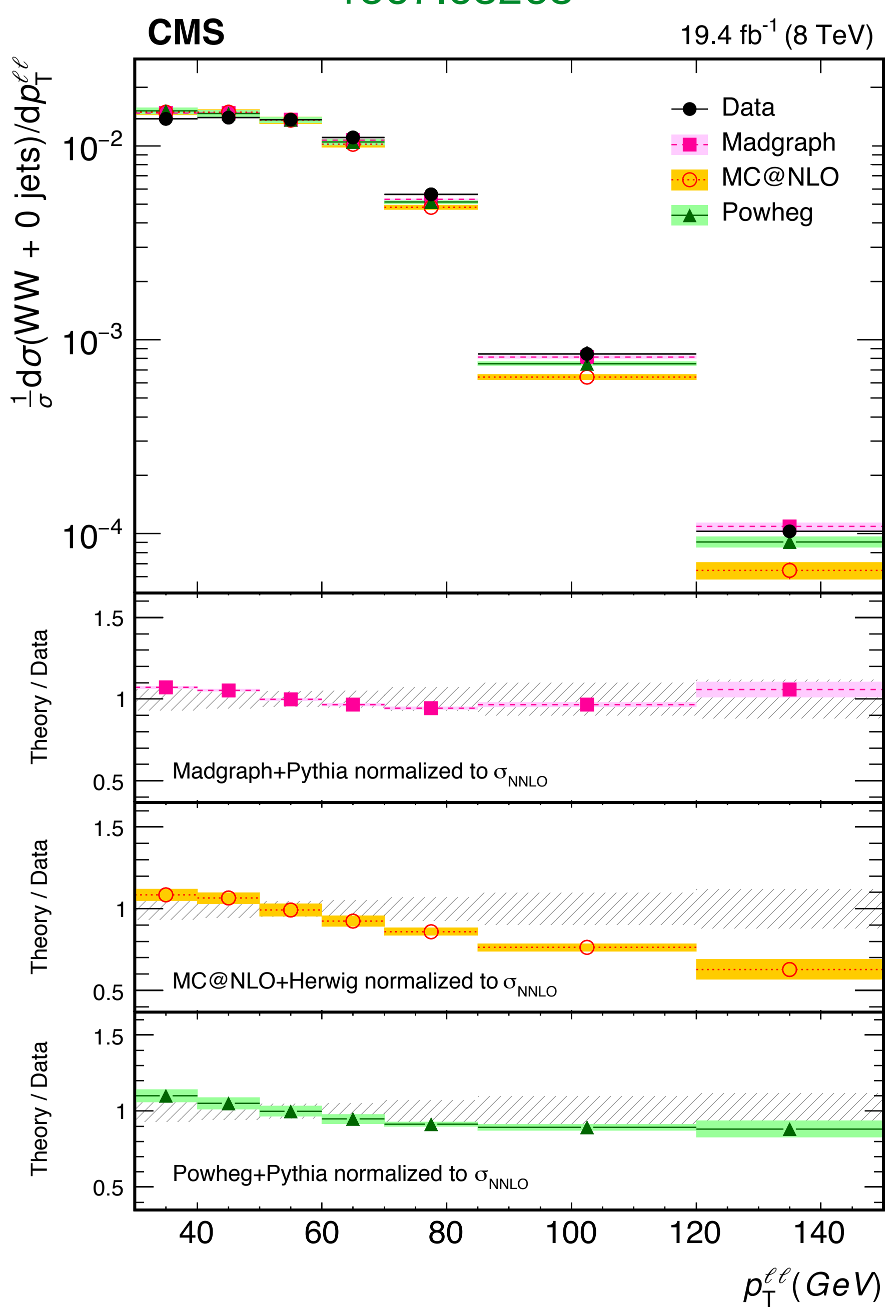
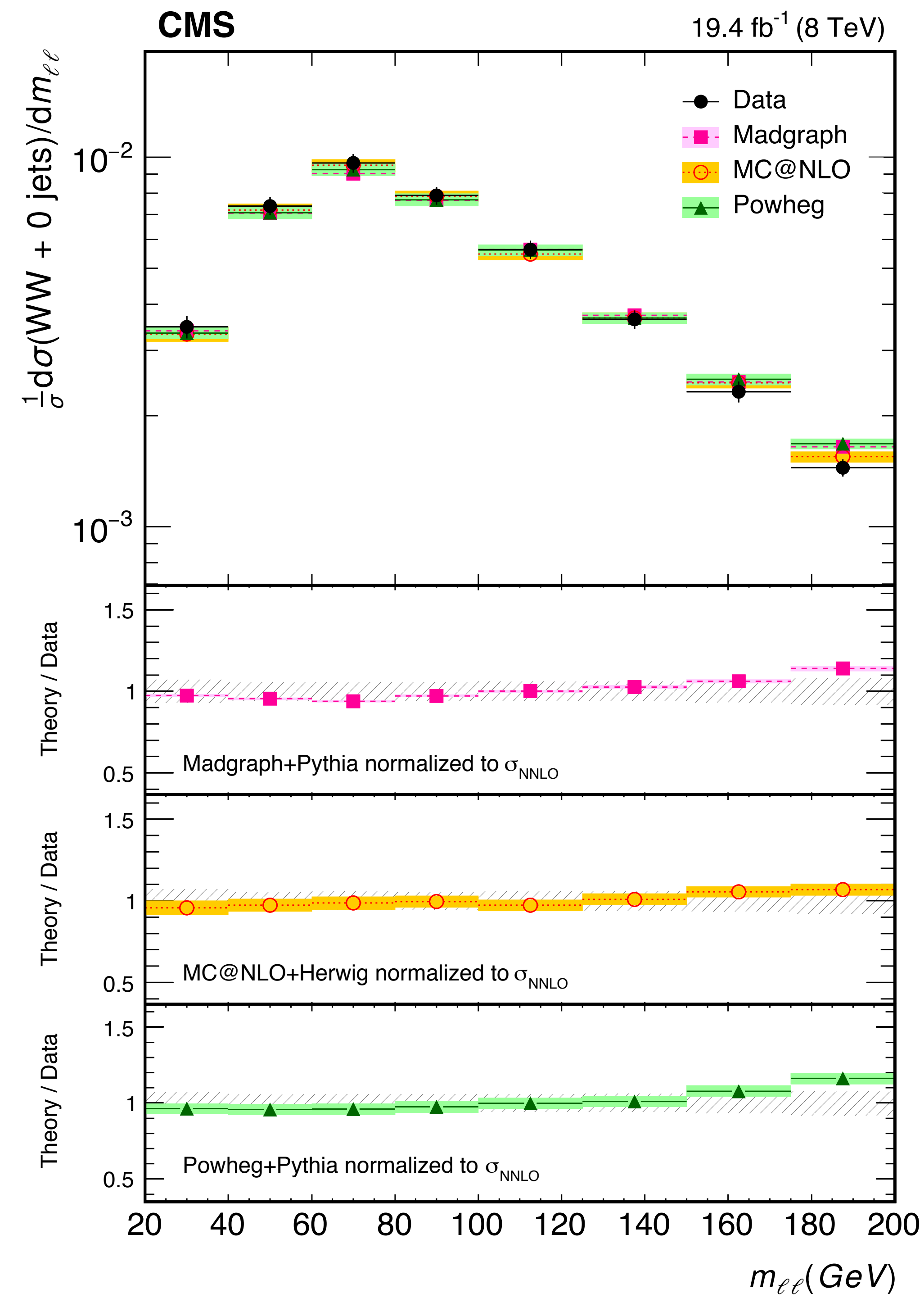


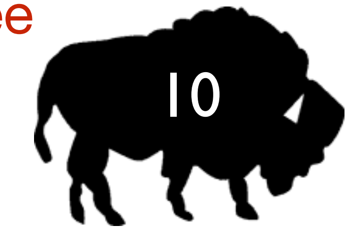
If Run II fails to find directly produced resonances. Then precision measurements to constrain anomalous interactions are vital.

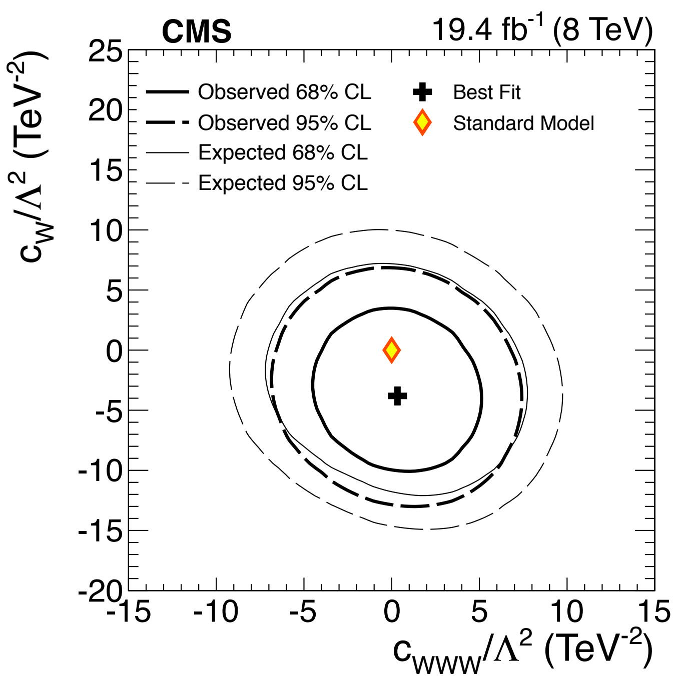
NLO+PS tools tend to give a wide spectrum of predictions in the tails, due to different mechanisms of exponentiation.

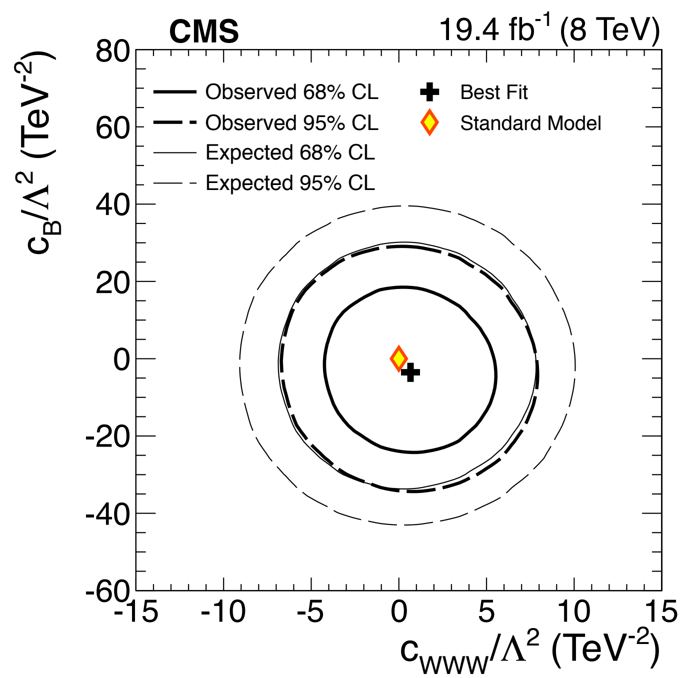
Minimizing this differences by choosing the right observables is crucial.

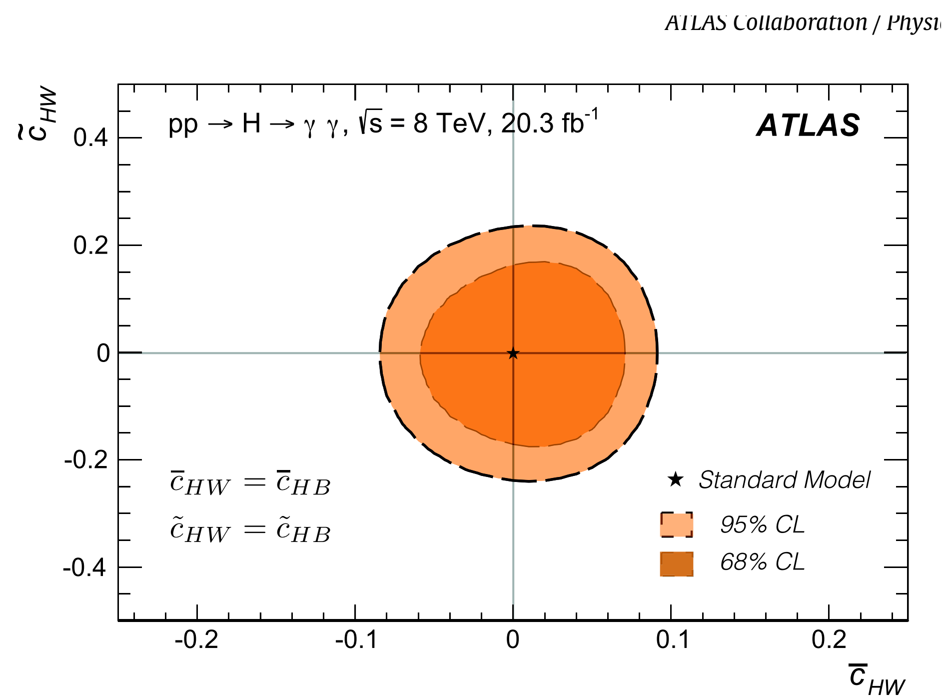


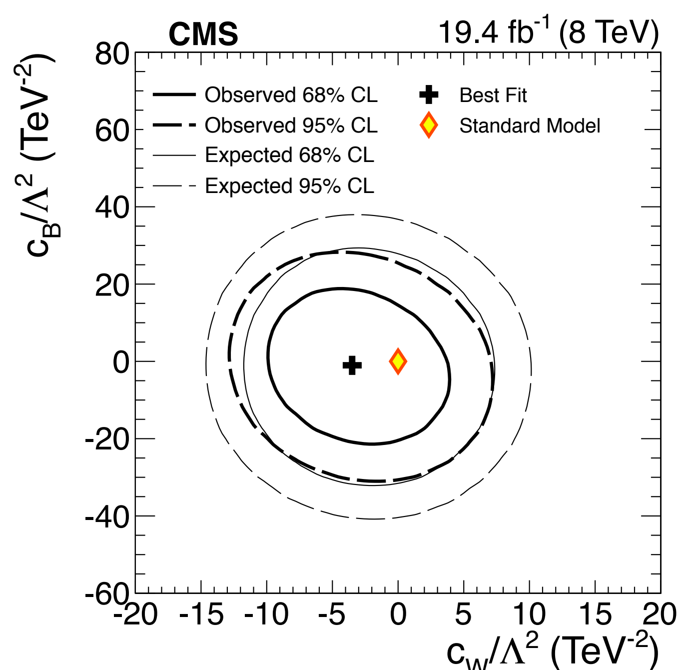
(IMO) Will be a very interesting application of NNLO to "debug" the NLO+PS tails and see which procedure reproduces NNLO predictions more consistently…









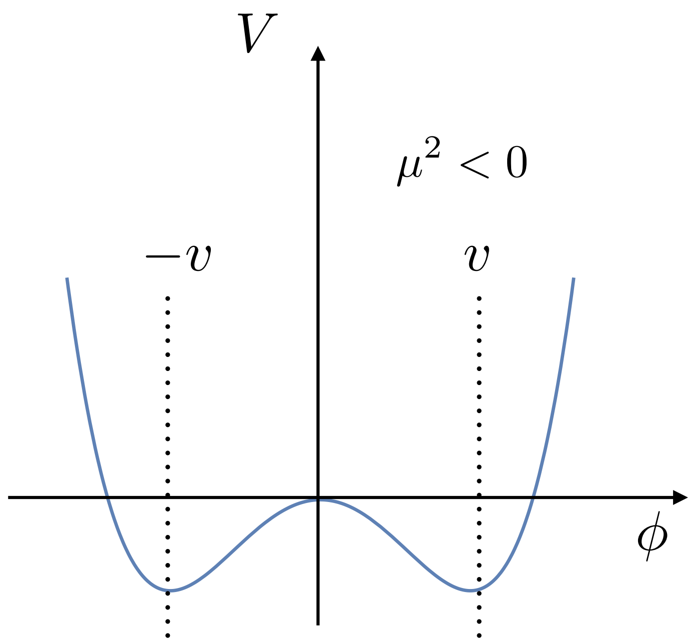


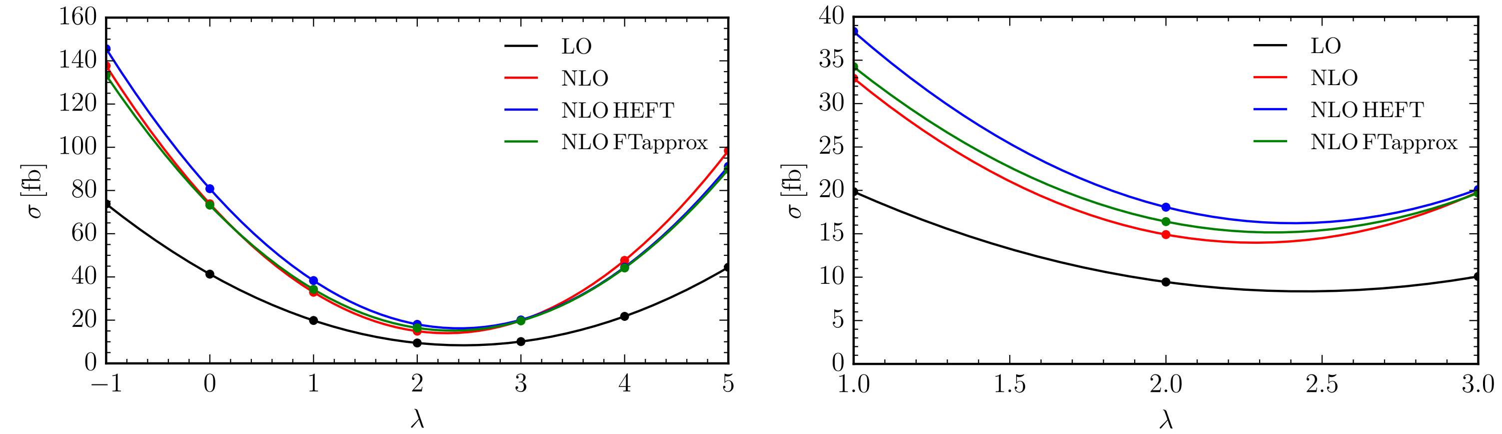
$$\frac{c_{WWW}}{\Lambda^2}\mathcal{O}_{WWW} = \frac{c_{WWW}}{\Lambda^2}\mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W_{\rho}^{\mu}],$$
$$\frac{c_{W}}{\Lambda^2}\mathcal{O}_{W} = \frac{c_{W}}{\Lambda^2}(D^{\mu}\Phi)^{\dagger}W_{\mu\nu}(D^{\nu}\Phi),$$
$$\frac{c_{B}}{\Lambda^2}\mathcal{O}_{B} = \frac{c_{B}}{\Lambda^2}(D^{\mu}\Phi)^{\dagger}B_{\mu\nu}(D^{\nu}\Phi).$$

Improving the precision of a variety of observables will allow for greater dynamics in constraining anomalous interactions.

Again, my opinion: the most important issue is to try to constrain the scale of NP. I don't advocate fits to 50 (or more) parameters in the EFT-SM. What we need to know is what energy we should shoot for for direct production of the UV sector.

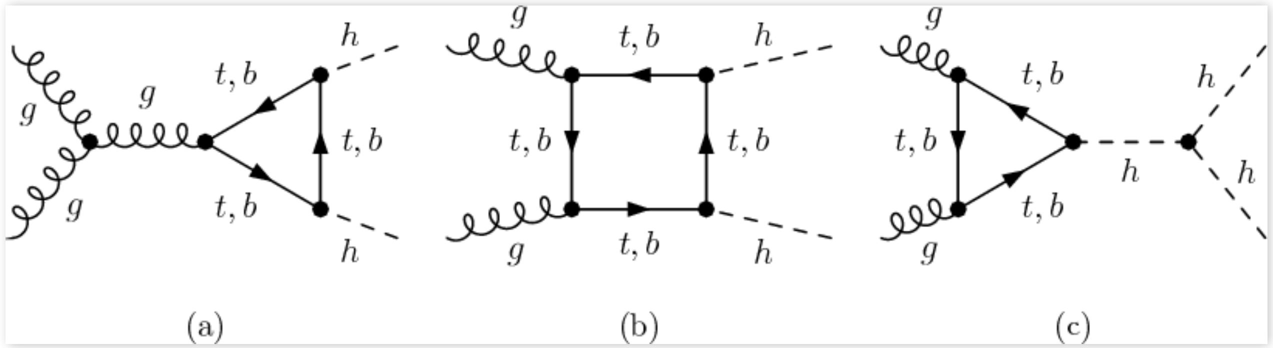
The ultimate MBI

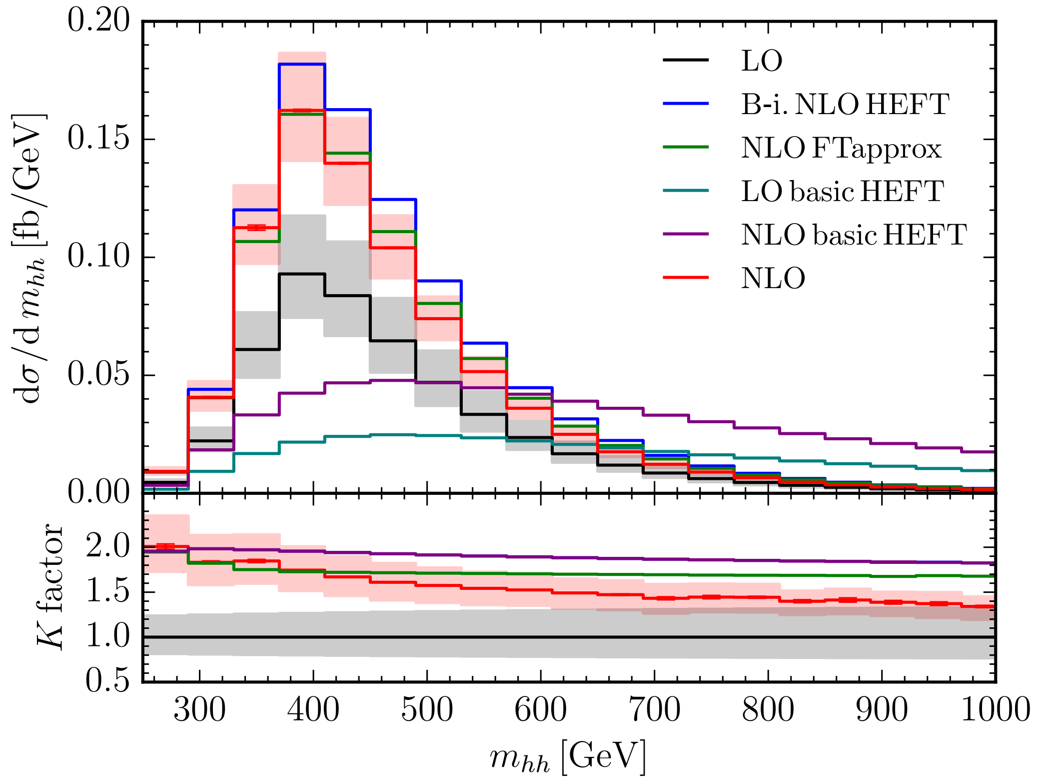




Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Zirke 16

$$V = \left(\frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4 \right)$$





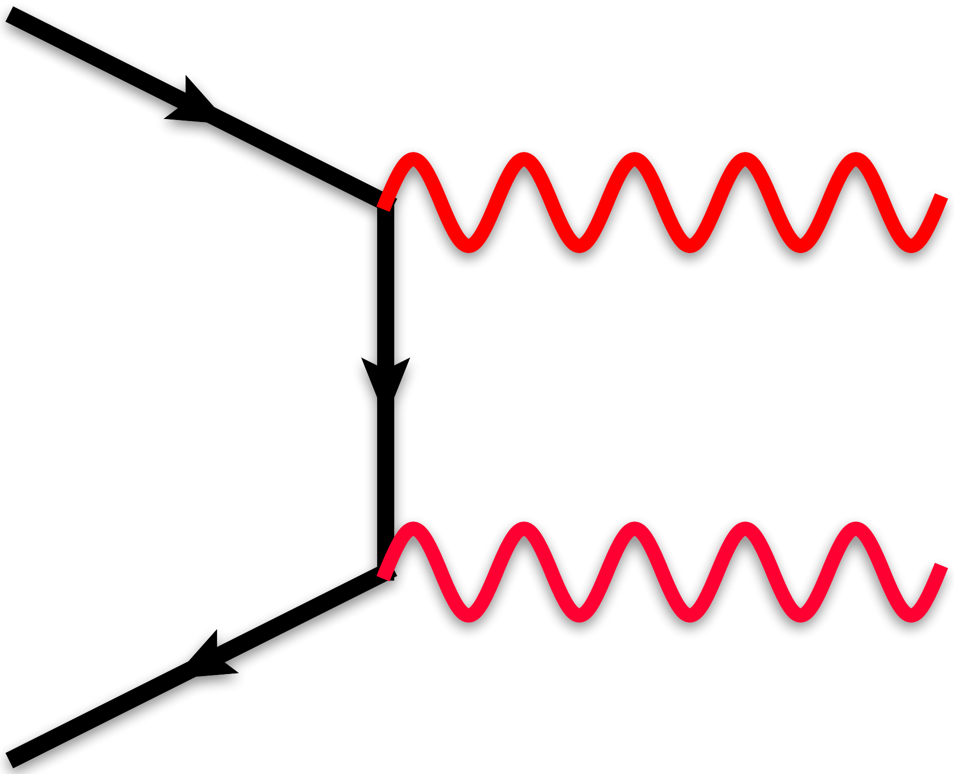
Why MBI @ NNLO?

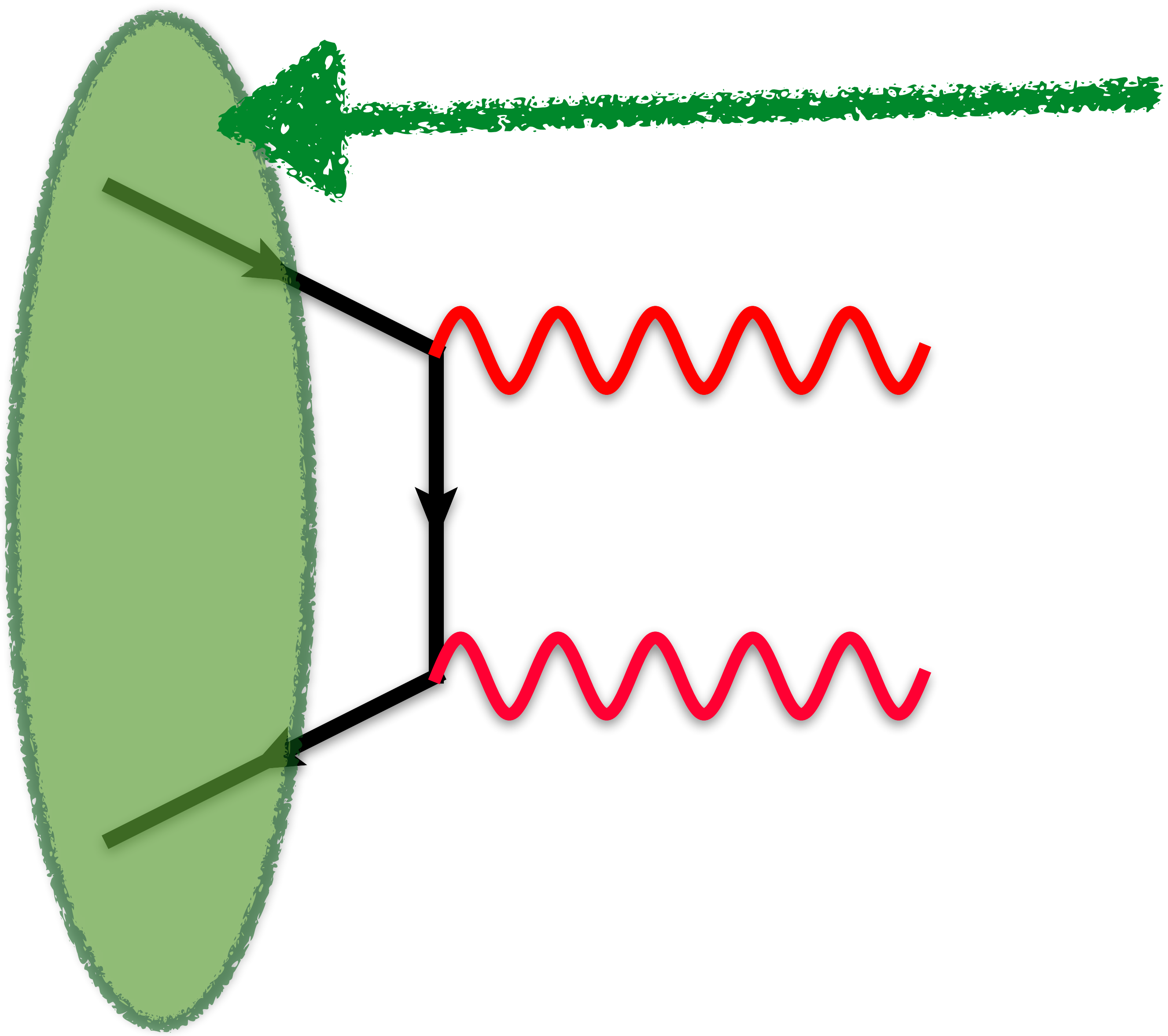
Legal Disclaimer: For the purposes of this talk NNLO means NNLO with slicing methods. The field of NNLO is in rapid development. Other methods exist and are producing cutting edge results, but thus far slicing methods have been the most widely applied to dibosons so I'll focus on them for this talk….

Historical Dibosons

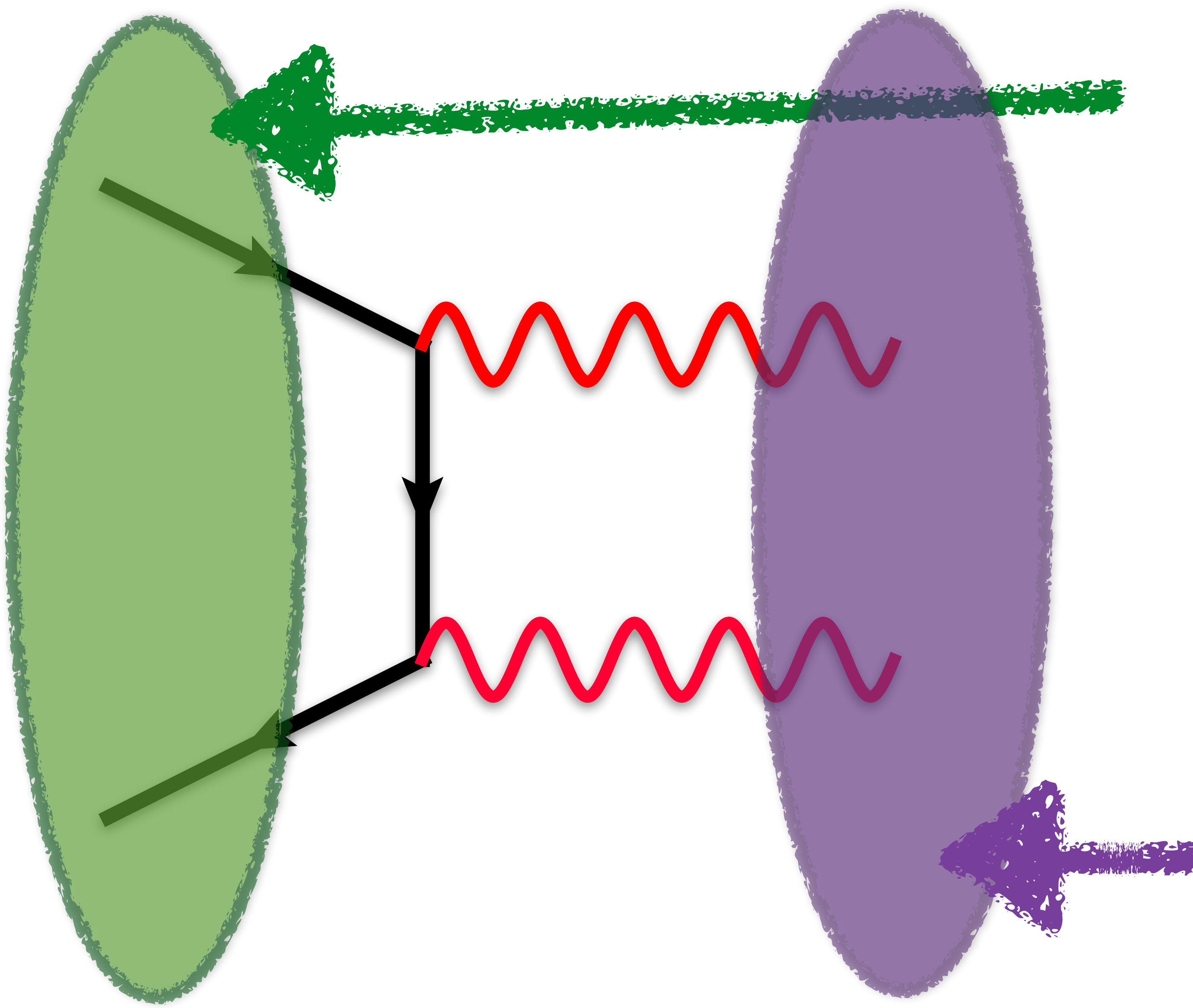
Historical Dibosons

(ie)



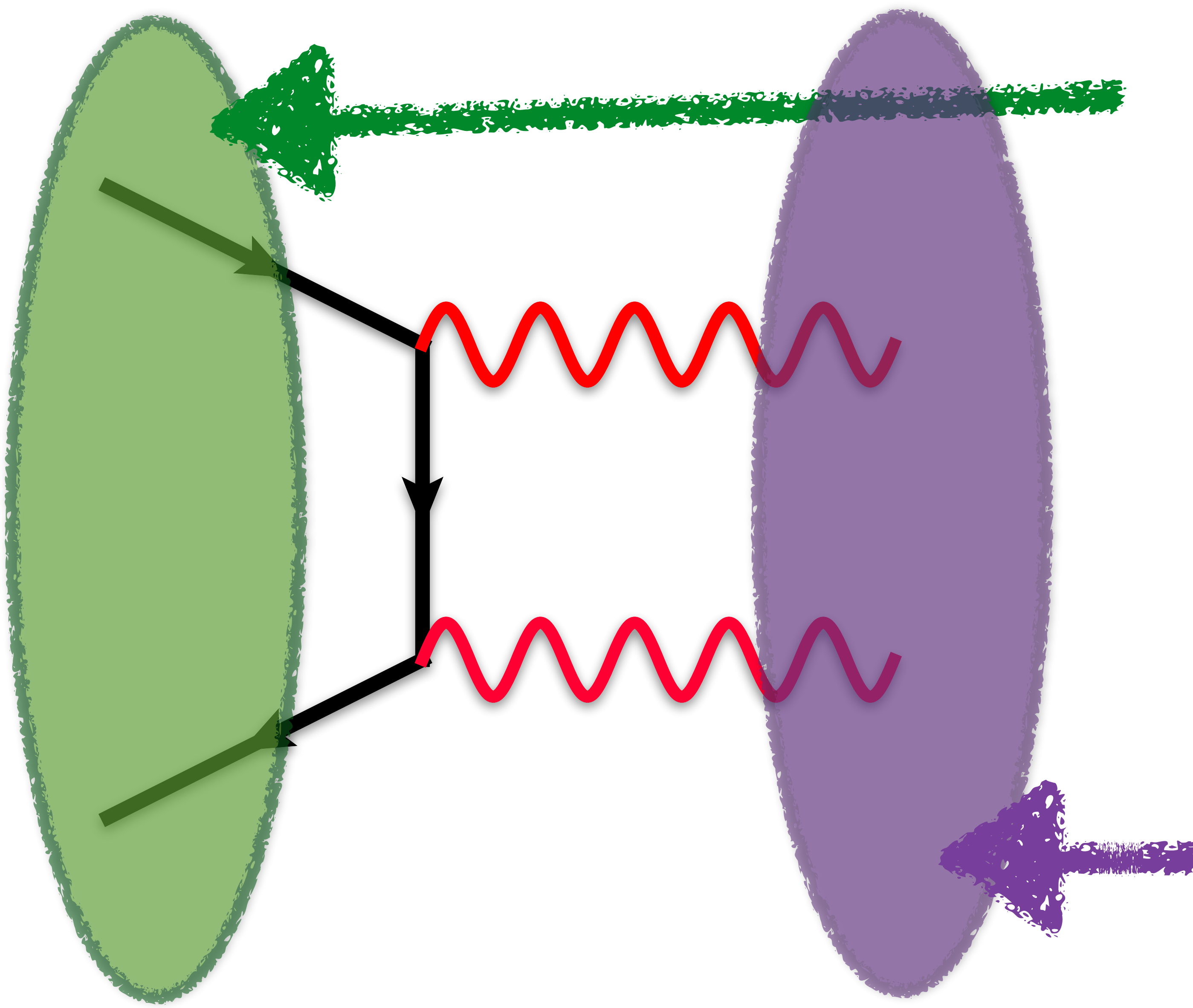


Initial State, is favorable to LO due to PDFs



Initial State, is favorable to LO due to PDFs

Final State, production of 2 heavy bosons leaves small phase space for additional emissions

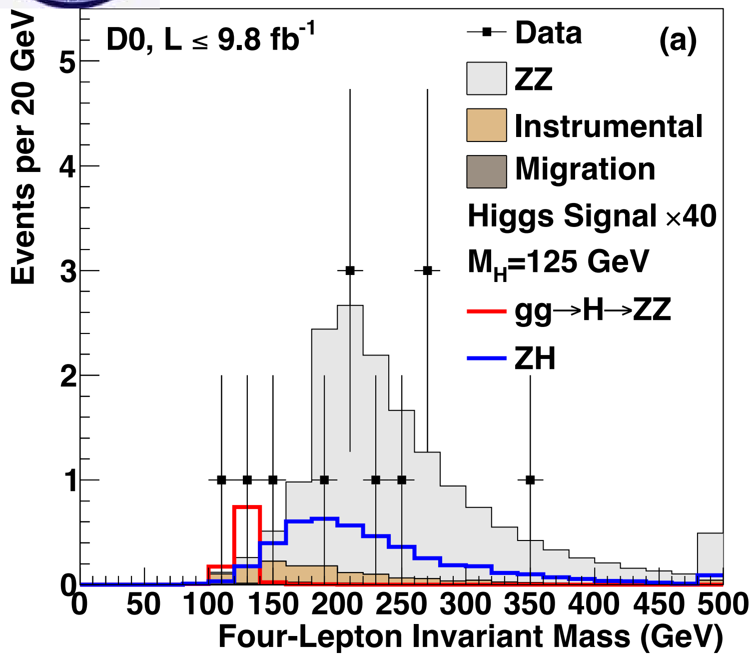


Initial State, is favorable to LO due to PDFs

Final State, production of 2 heavy bosons leaves small phase space for additional emissions

HIGHER ORDER CORRECTIONS SHOULD BE SMALL

$ZZ \to ll l' l'$ Analysis and Result



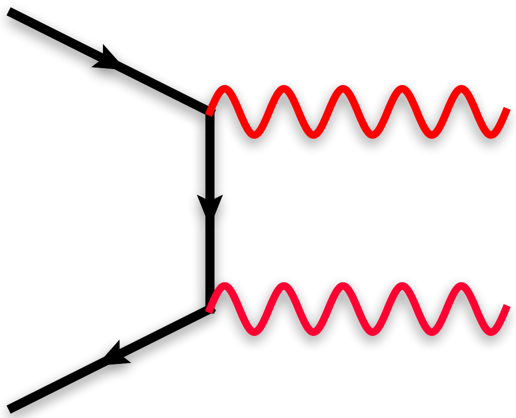
Process	Yield(CDF)	Yield(D0)
ZZ	9.59 ± 1.55	15.31 ± 1.84
Bkg.	0.06 ± 0.03	1.48 ± 0.31
Data	7	13

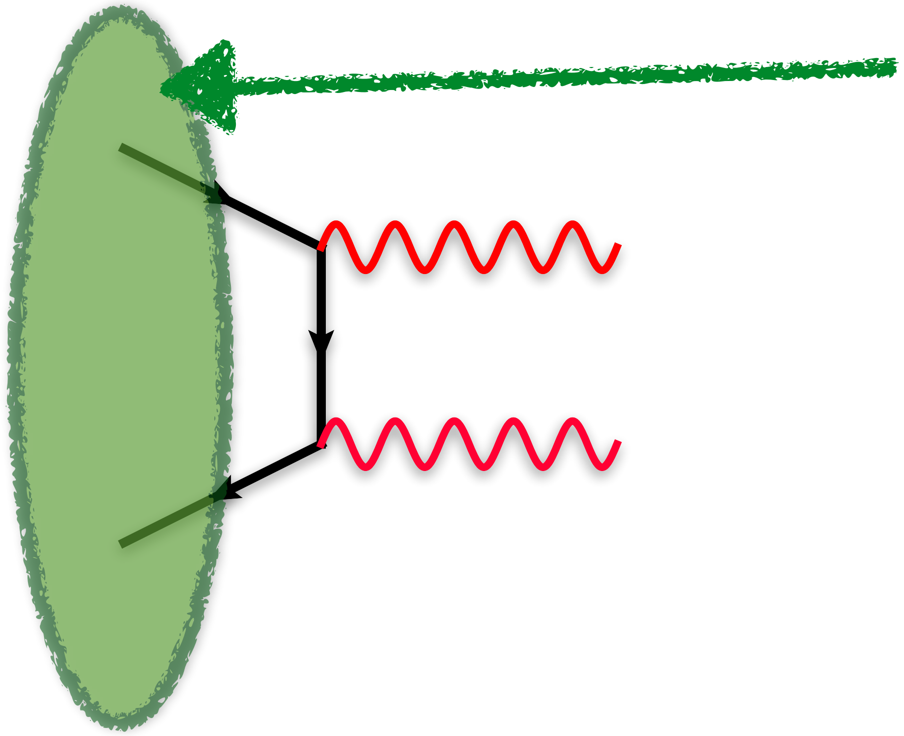
- Instrumental background: Z/γ^* with two additional misidentified jets/photons
- Fake rate from jet-trigger events
- Applied to 2/3 lepton + jets events
- D0: Looser acceptance, separate lepton categories

	$\sigma(p\bar{p} \to ZZ)$ (pb) ($ll l' l'$)
CDF	$0.99^{+0.45}_{-0.35}(\mathrm{stat})^{+0.11}_{-0.07}(\mathrm{syst})$
D0	$1.05^{+0.37}_{-0.30}(\mathrm{stat})^{+0.14}_{-0.12}(\mathrm{syst}) \pm 0.06(\mathrm{lumi})$
MCFM	1.4 ± 0.1

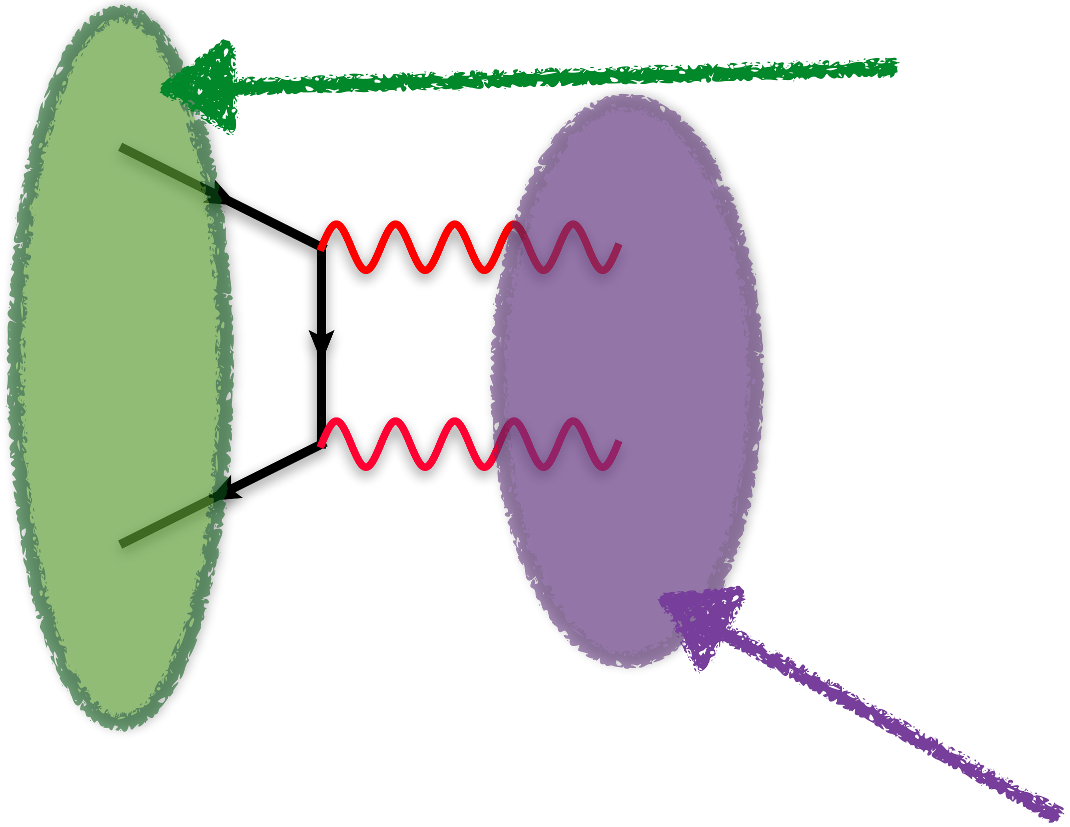
CDF: PRD 89, 112001 (2014); D0: PRD 88, 032008 (2013)

TNG MBI





Initial State, is **unfavorable** to LO due to PDFs



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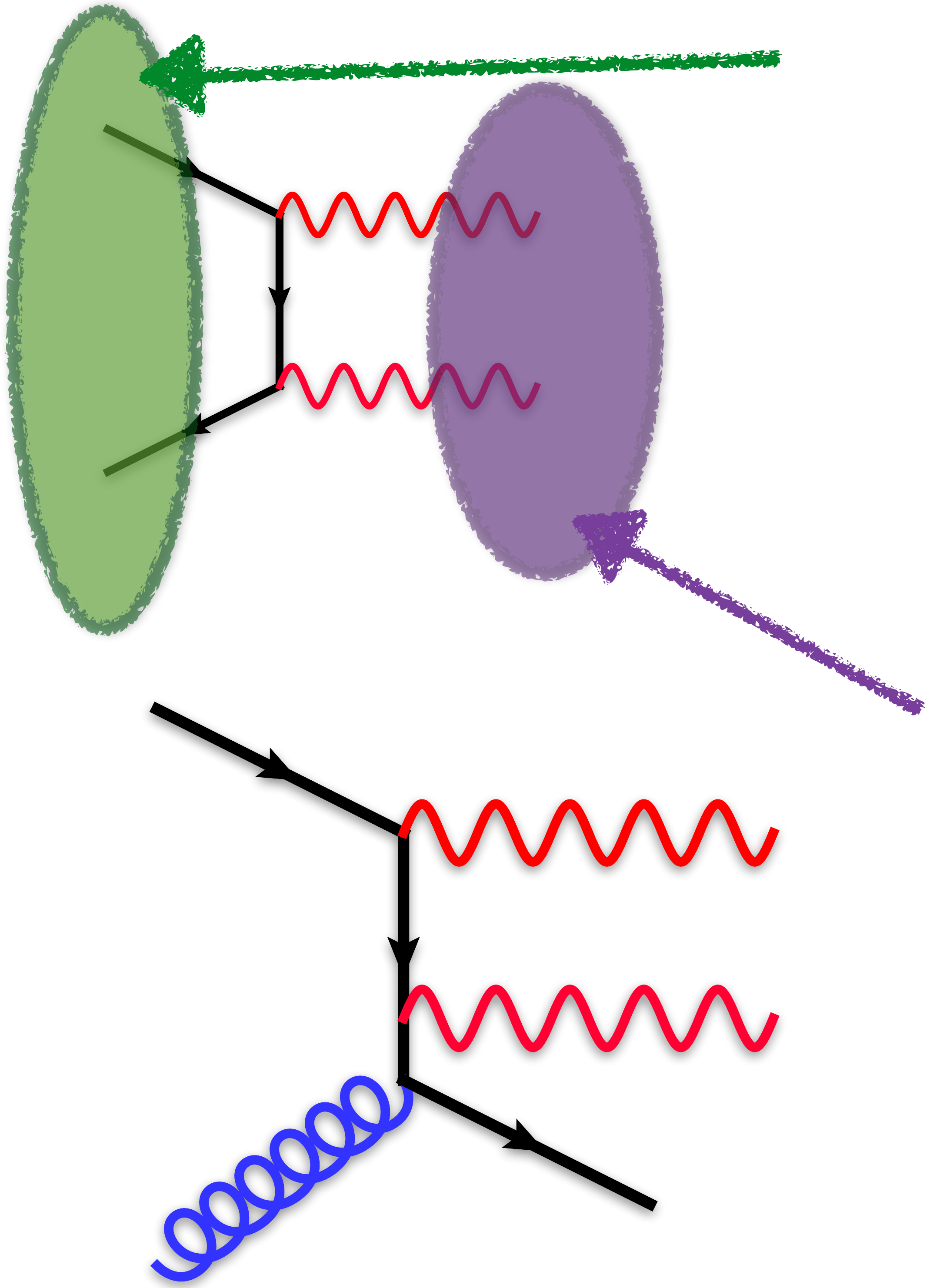
Final State, production of heavy bosons is cheap given large center of mass energy. Lots of phase space for emissions!



Initial State, is **unfavorable** to LO due to PDFs

Final State, production of heavy bosons is cheap given large center of mass energy. Lots of phase space for emissions!

So this type of contributions is critical to obtain a decent prediction.

NLO = "LO"! Higher order corrections large

What goes into an NNLO calculation?

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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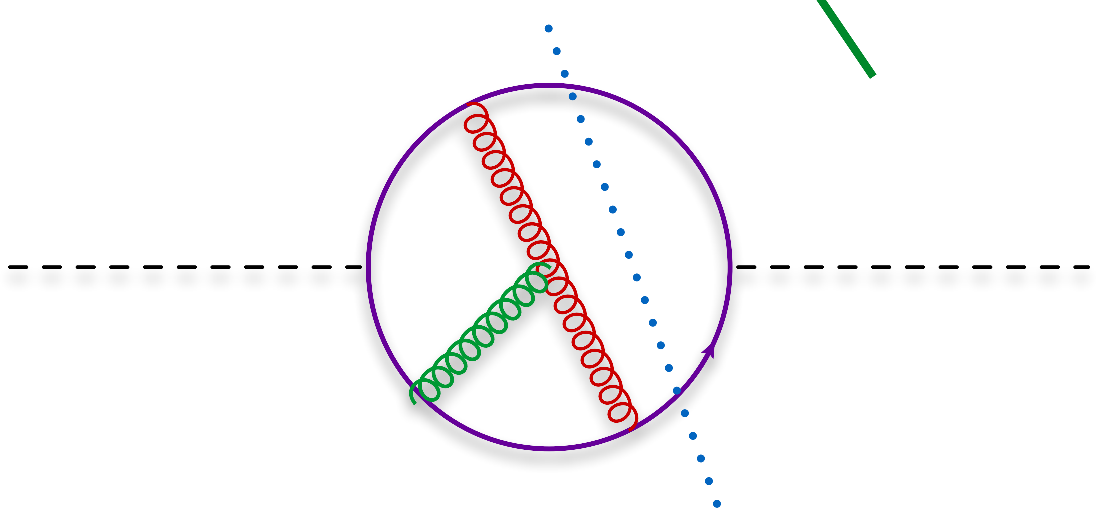
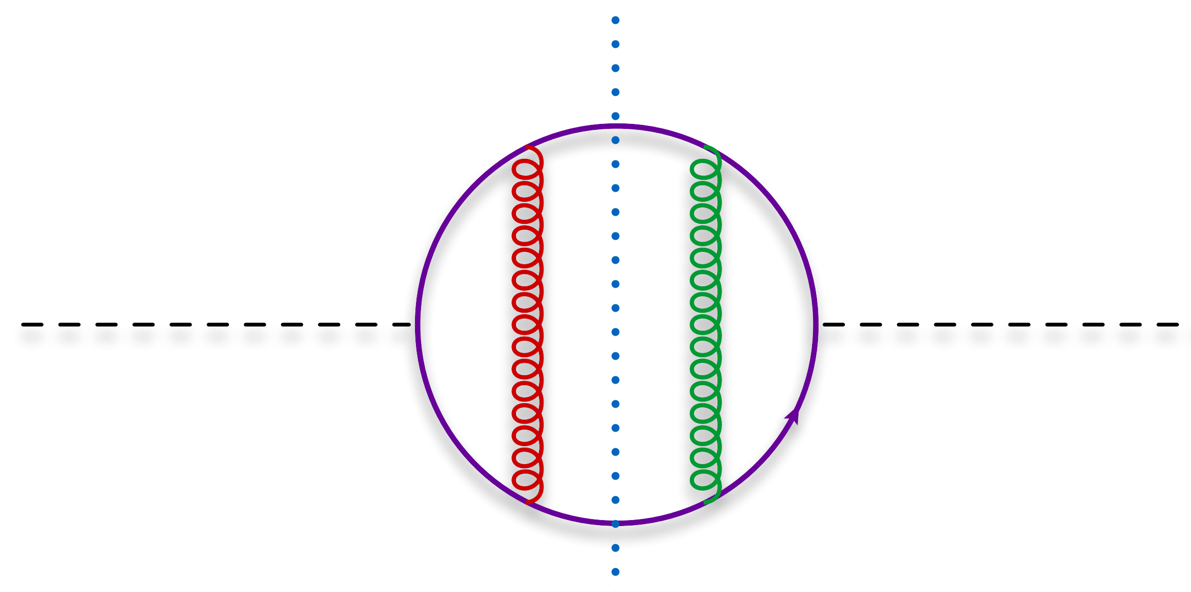


Two-loop double virtual



one-loop squared double virtual

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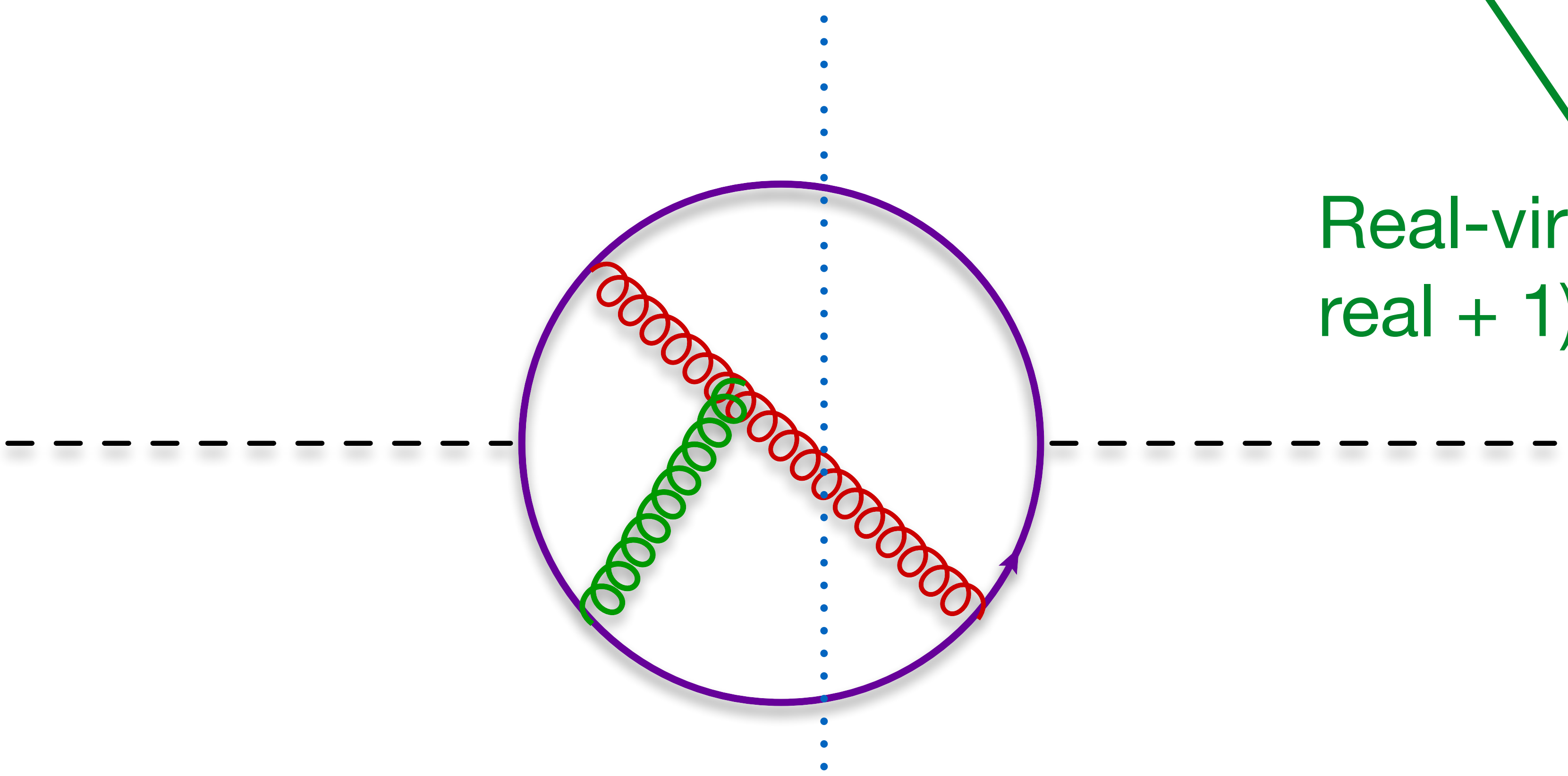

Real-virtual (one-loop +1 x real + 1)

At NNLO we have three types of final state phase spaces

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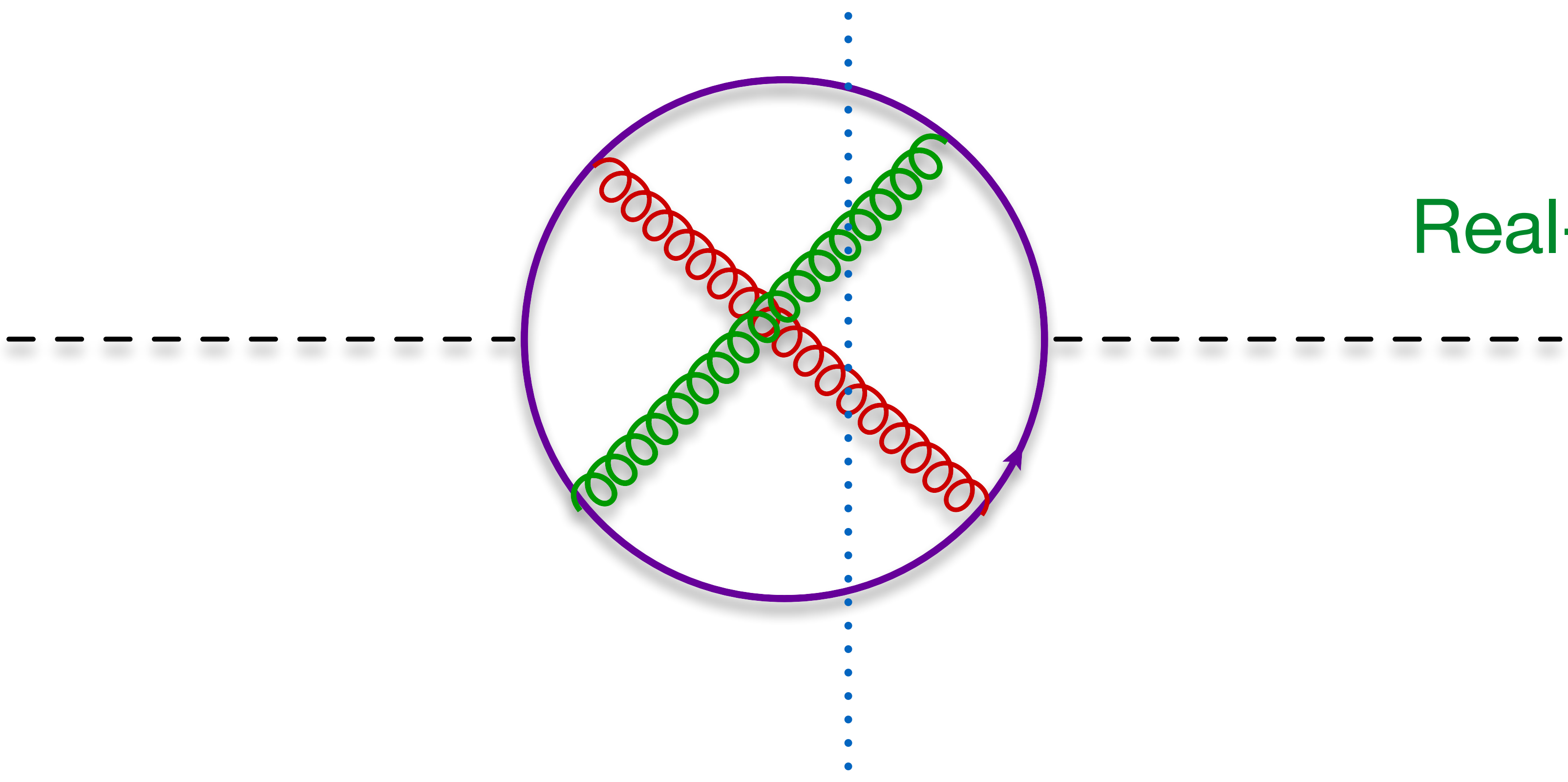
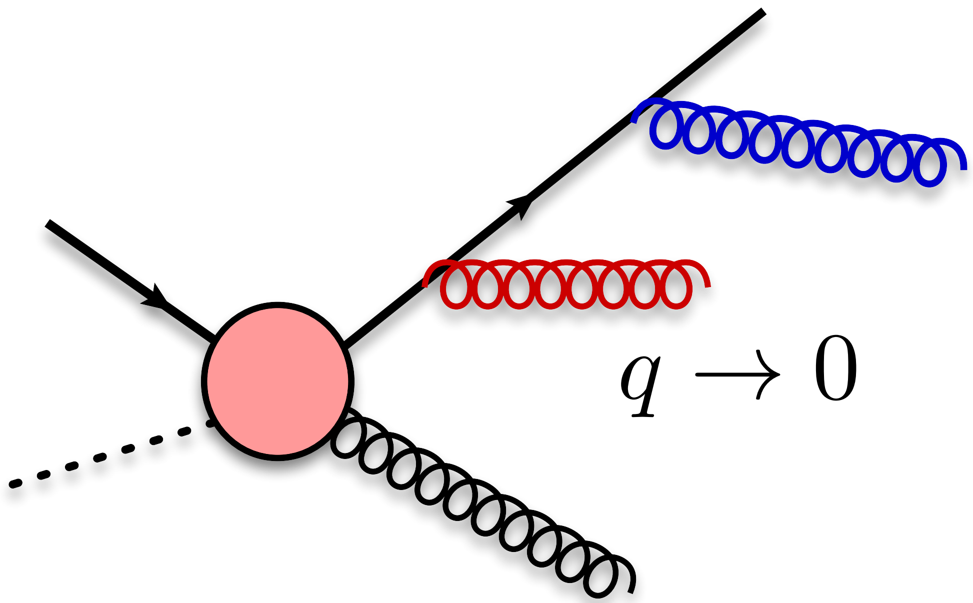


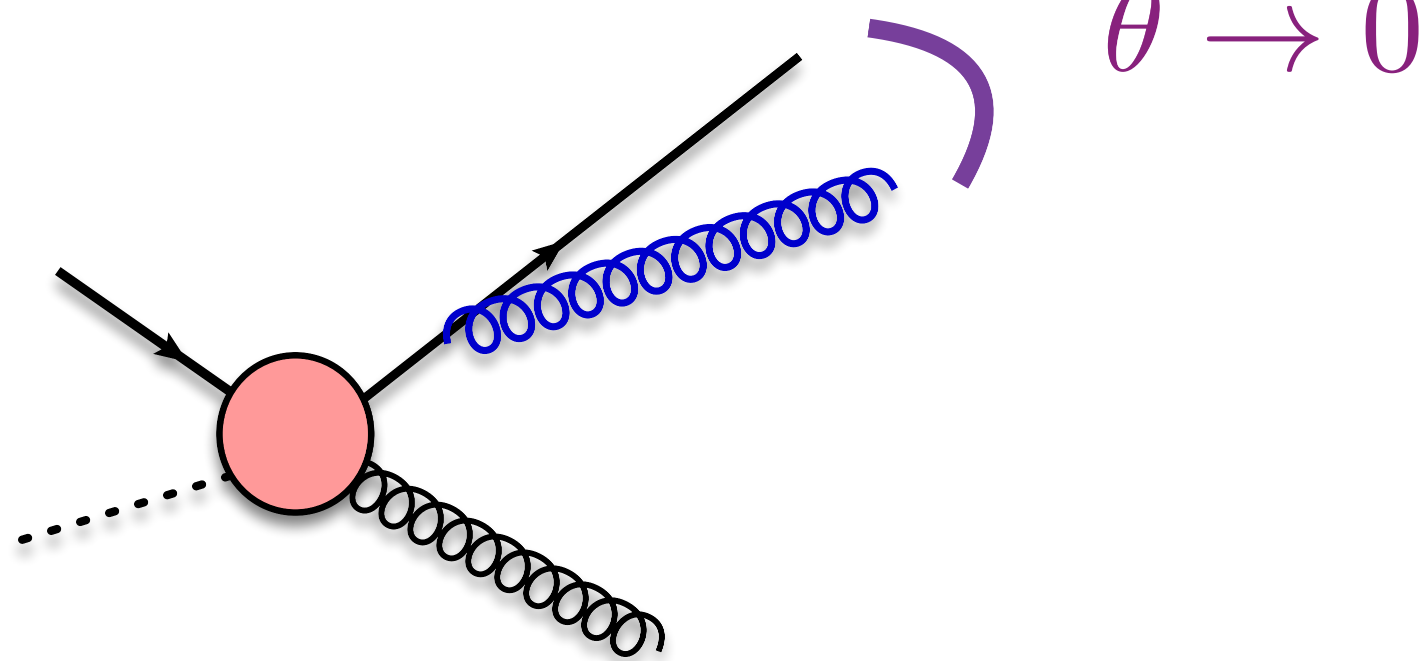
Real-real

IR poles

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,





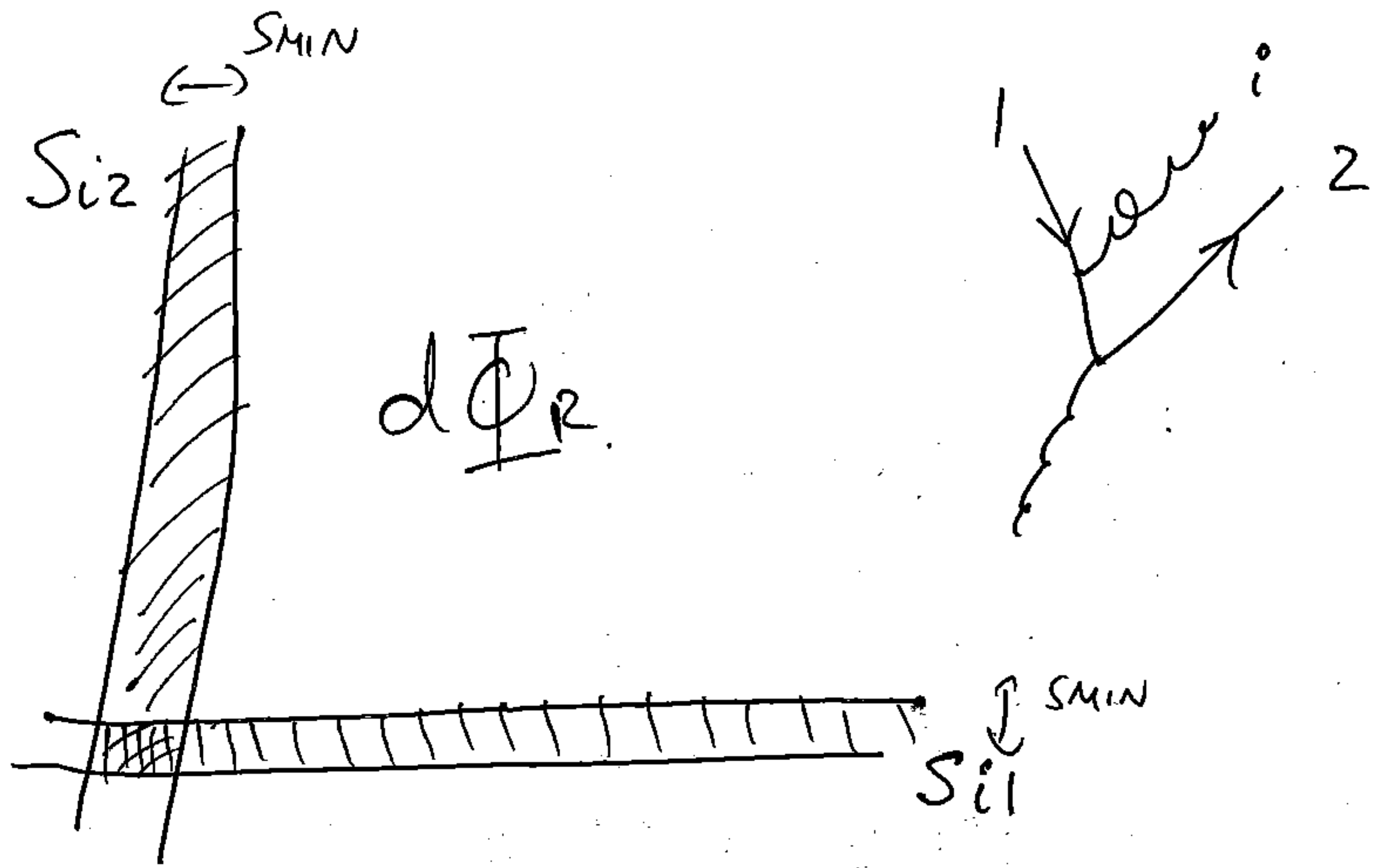
Soft (particle momenta vanishes)

Collinear (angle between two massless particles vanishes)

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

Slicing methods at NNLO

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



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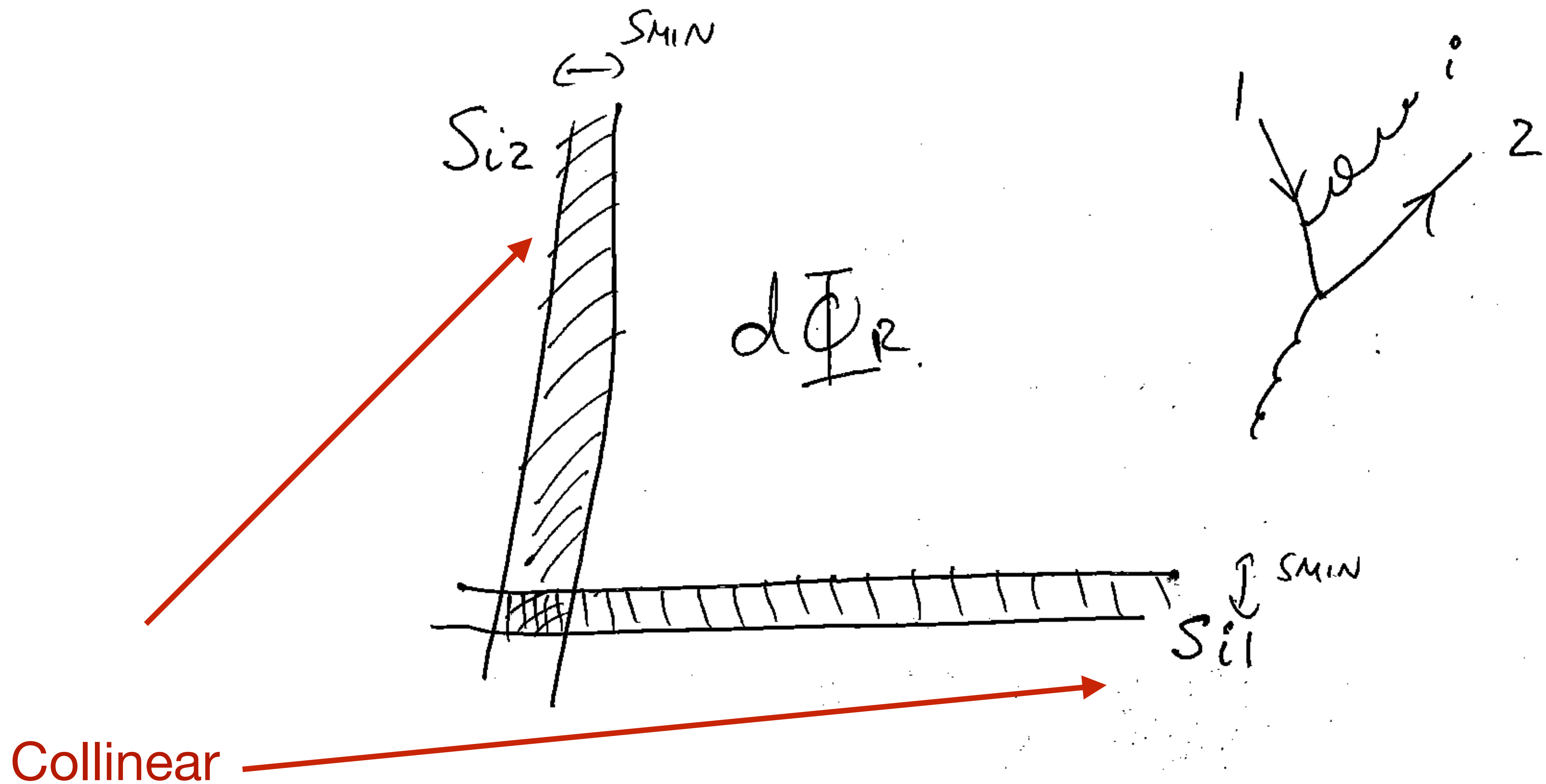

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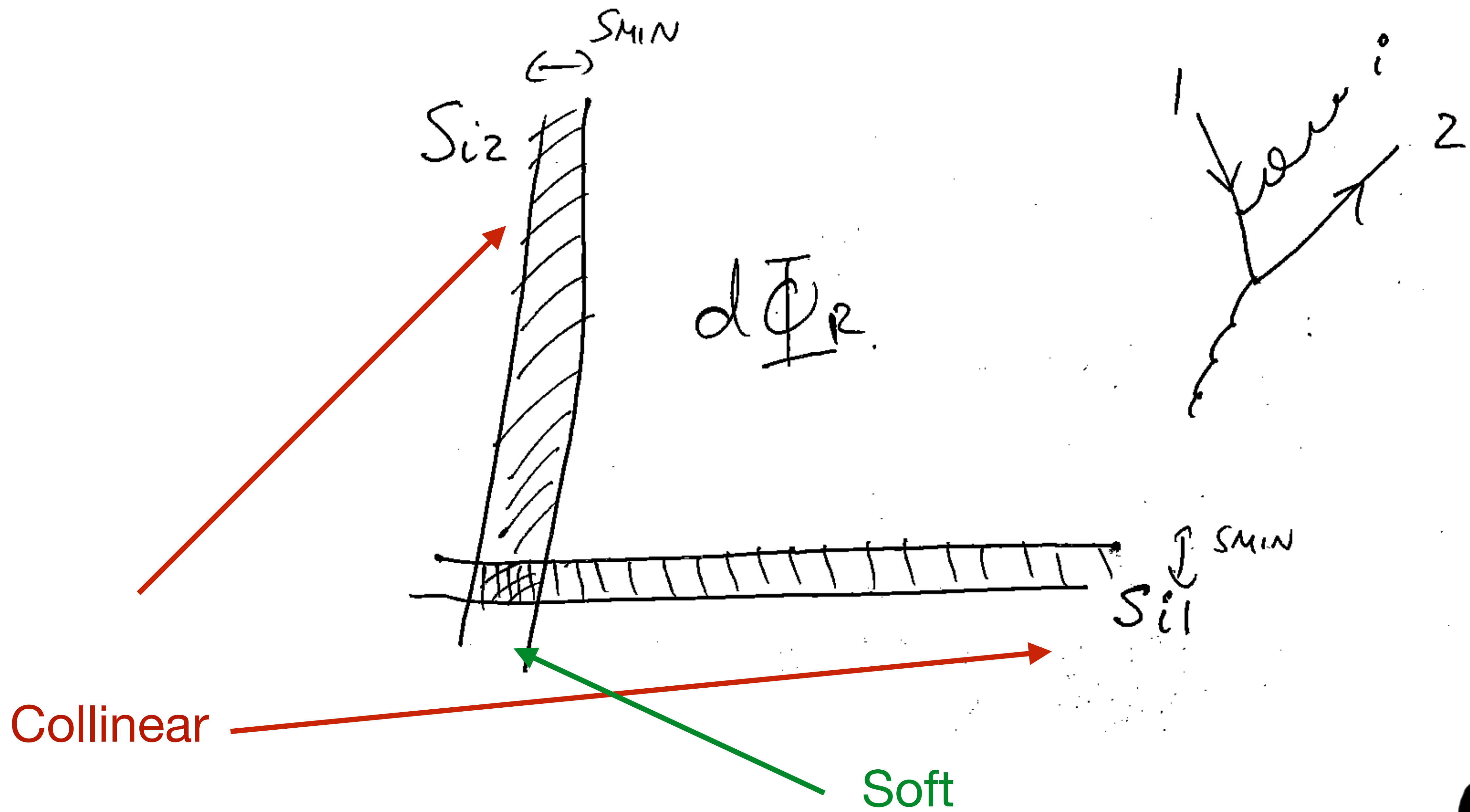

Q_T Subtraction

For color neutral final states the transverse momentum of the recoiling EW particles determines the double and singly unresolved regions of phase space. (Catani Grazzini 07)

$$\sigma_{NNLO} = \int dq_T \frac{d\sigma}{dq_T} \theta(q_T^{cut} - q_T) + \int dq_T \frac{d\sigma}{dq_T} \theta(q_T - q_T^{cut})$$

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Obtained from the Collins-Soper-Sterman factorization theorem for small q_T

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Obtained from the Collins-Soper-Sterman factorization theorem for small q_T

This is an NLO cross section for one additional parton

For color neutral final states the transverse momentum of the recoiling EW particles determines the double and singly unresolved regions of phase space. (Catani Grazzini 07)

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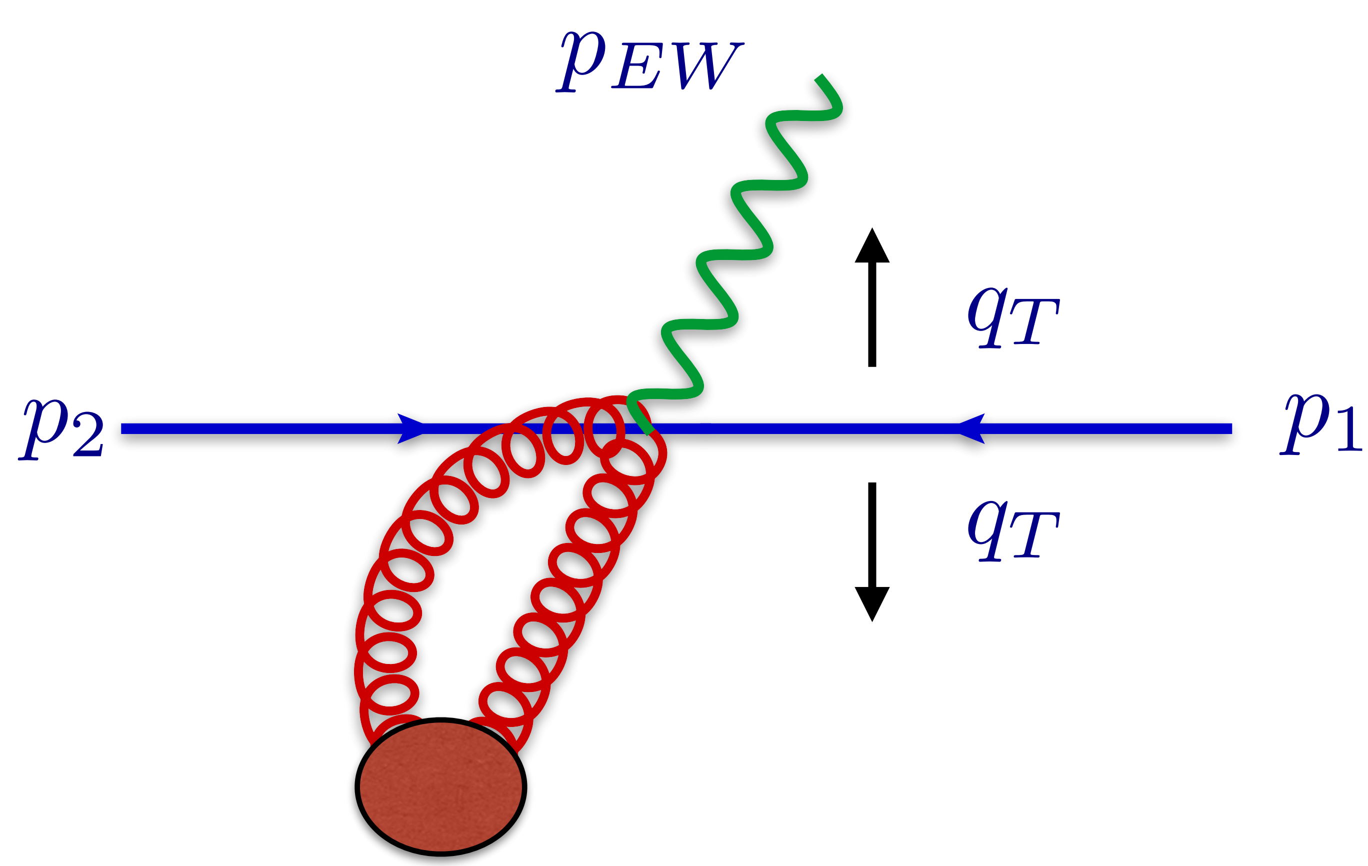
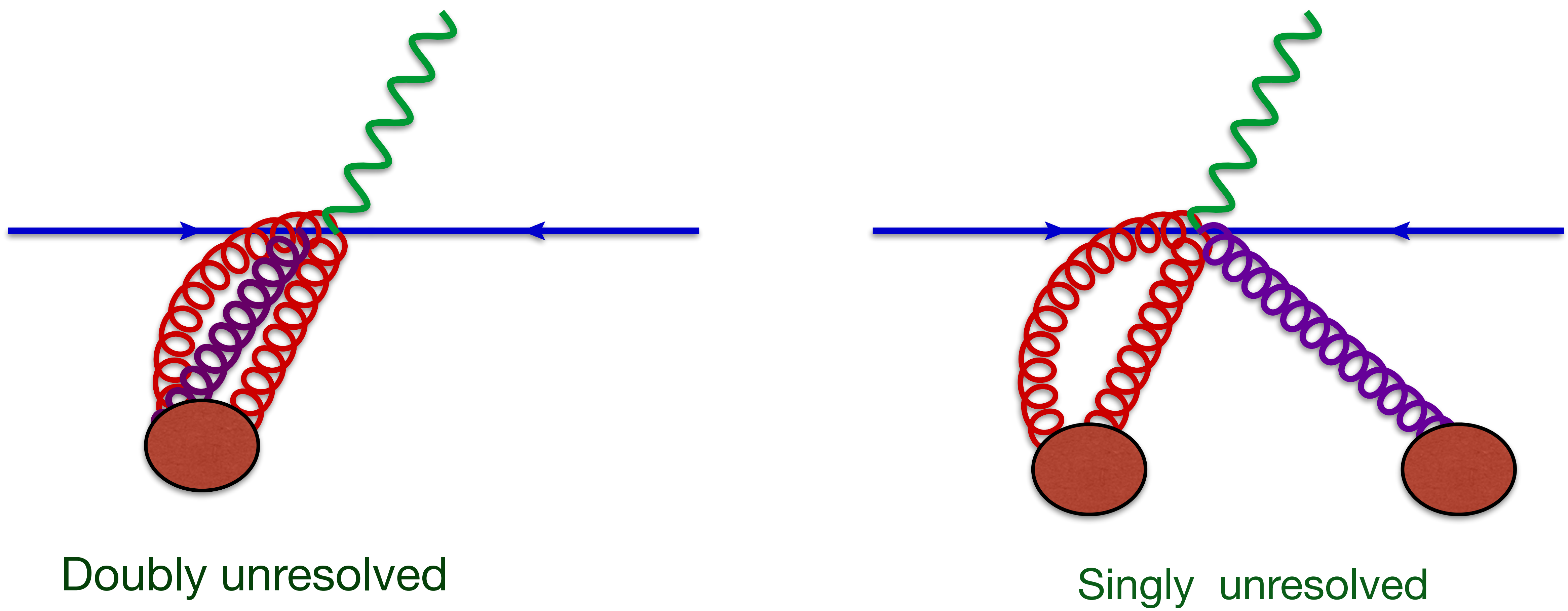


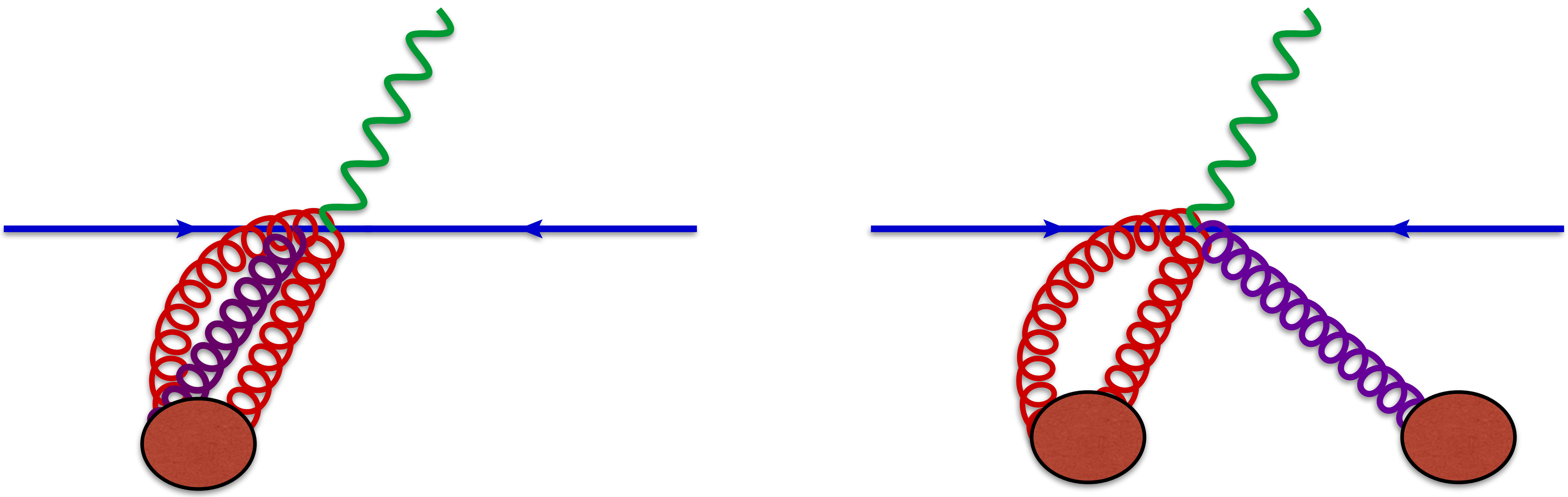
The subtraction scheme fails when final state jets are present at LO, since then there is no separation of the doubly and singly unresolved regions based on q_T



We need a resolution parameter which separates out the regions, but works for final state jets too!

N-jettiness slicing

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. Of X + 1 jet

N-jettiness is an event shape variable, designed to veto final state jets (Stewart, Tackmann, Waalewijn 09)

$$\mathcal{T}_N(\Phi_M) = \sum_{k=1}^{M} \min_i \left\{ \frac{2q_i \cdot p_k}{Q_i} \right\}$$

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$$\mathcal{T}_N(\Phi_M) = \sum_{k=1}^{M} \min_i \left\{ \frac{2 q_i \cdot p_k}{Q_i} \right\}$$

Number of final state jets

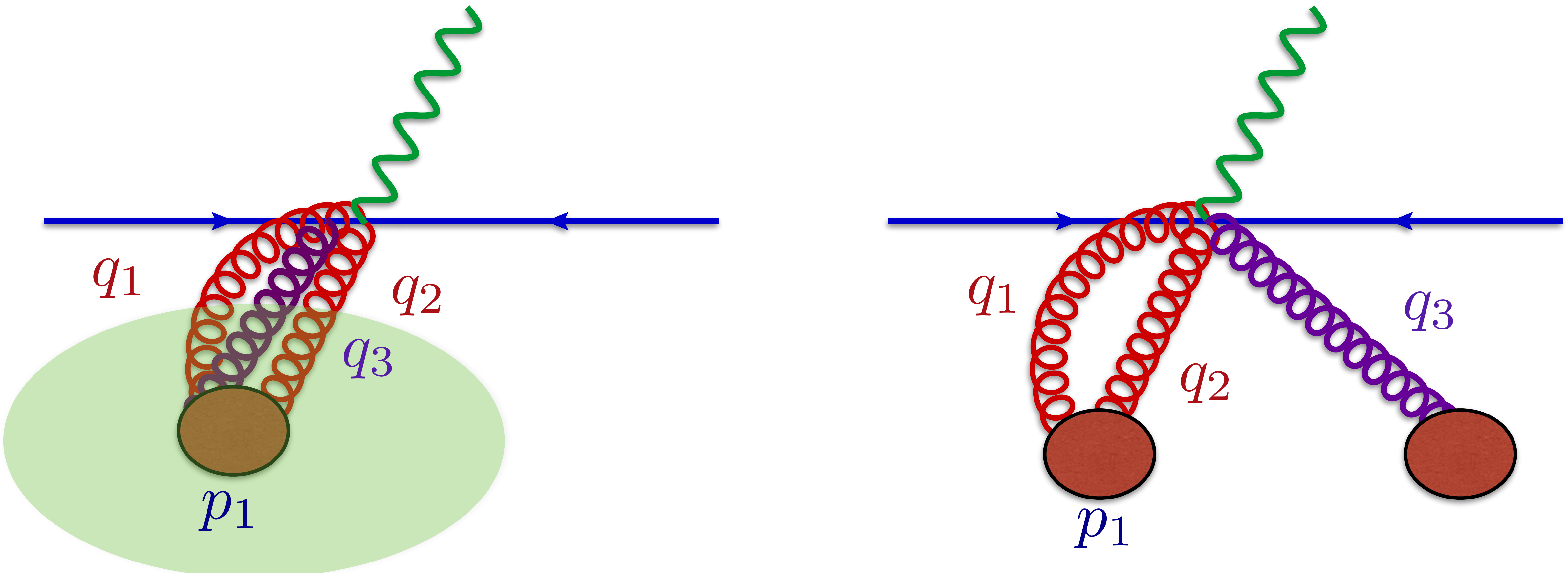
Number of final state patrons

All final state patrons

A hard scale (e.g. Energy of jets)

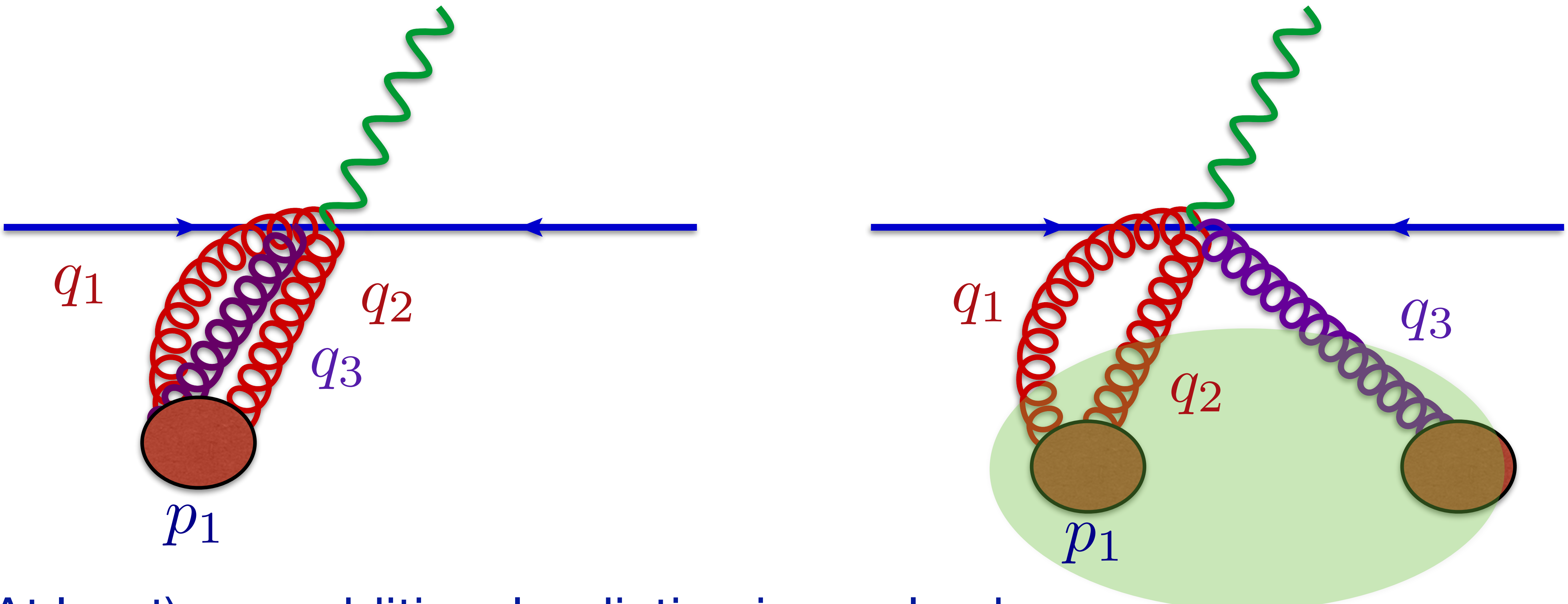
Momentum of final state jets and beams

$$\tau_N \approx 0 \qquad \mathcal{T}_N(\Phi_M) = \sum_{k=1}^{M} \min_i \left\{ \frac{2q_i \cdot p_k}{Q_i} \right\}$$



All radiation is either soft or collinear to a beam/jet

$$\tau_N > 0 \qquad \mathcal{T}_N(\Phi_M) = \sum_{k=1}^{M} \min_i \left\{ \frac{2q_i \cdot p_k}{Q_i} \right\}$$



(At least) one additional radiation is resolved,
(looks like an NLO N+1 parton calculation)

This parameter can be used to separate the doubly and singly unresolved regions of phase space!

The method can be used as a regularization scheme (Boughezal, Focke, Liu, Petriello 15, Gaunt, Stahlhofen, Tackmann Walsh 15) using N-jettiness to separate the doubly and singly unresolved regions.

$$\sigma_{NNLO} = \int d\Phi_N |\mathcal{M}_N|^2 + \int d\Phi_{N+1} |\mathcal{M}_{N+1}|^2 \theta_N^< + \int d\Phi_{N+2} |\mathcal{M}_{N+2}|^2 \theta_N^< + \int d\Phi_{N+1} |\mathcal{M}_{N+1}|^2 \theta_N^> + \int d\Phi_{N+2} |\mathcal{M}_{N+2}|^2 \theta_N^>$$

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= Below the cut (can use factorization theorem)

= Above the cut (can use NLO code)

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 (Bauer, Stewart *et al* 00's), 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 (14)
- J@NNLO : Becher Neubert (06), Becher, Bell (11)

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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)
- S@NNLO : Boughezal, Liu, Petreillo (14)
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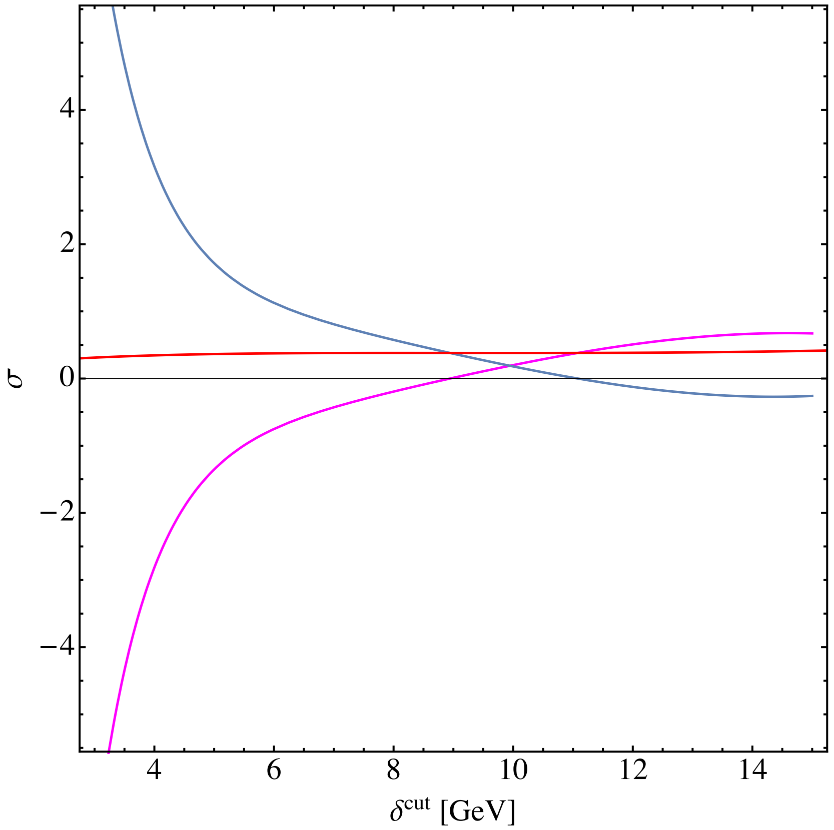
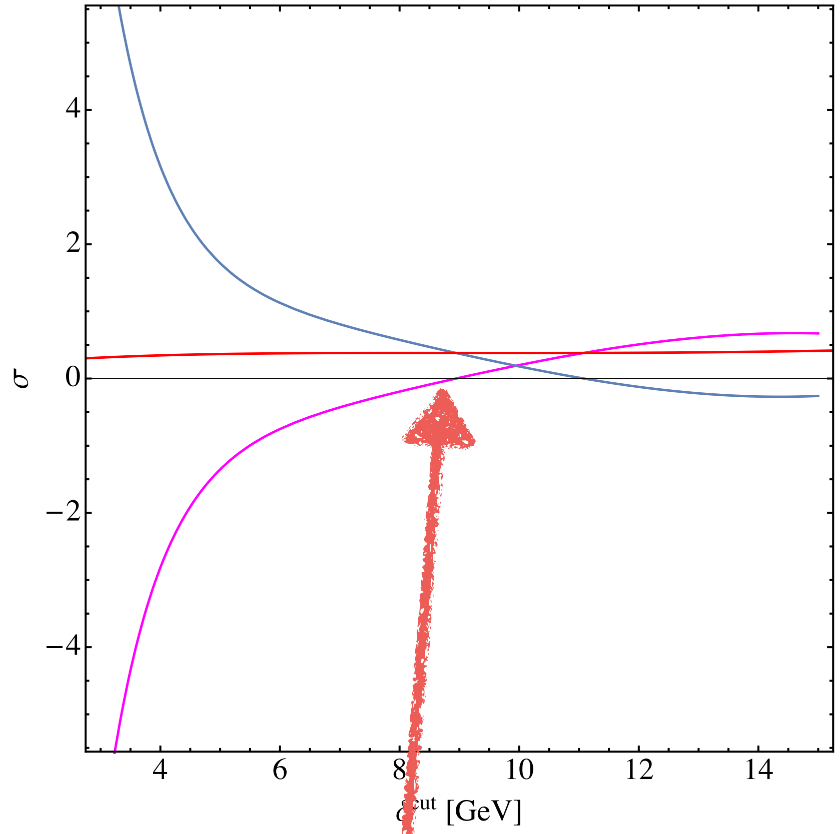
Perils of slicing

Power Corrections



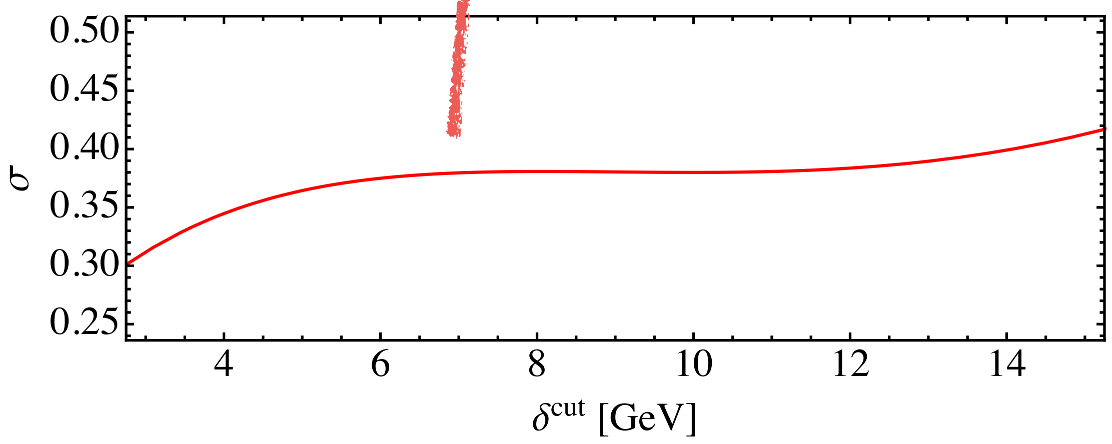
When doing a slicing calculation, it is always tempting to make this sort of plot showing above and below cut cancellations.

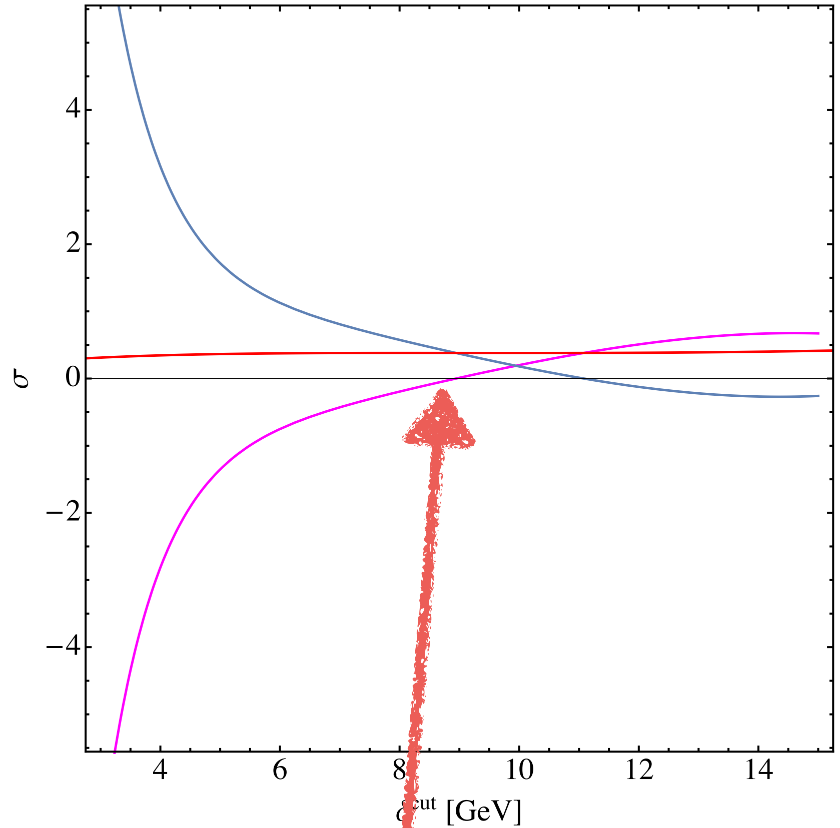
Power Corrections



When doing a slicing calculation, it is always tempting to make this sort of plot showing above and below cut cancellations.

However, you cant trust this plot. Its a scam. It completely hides the power corrections of the thing I'm actually providing you with. The NNLO coefficient.





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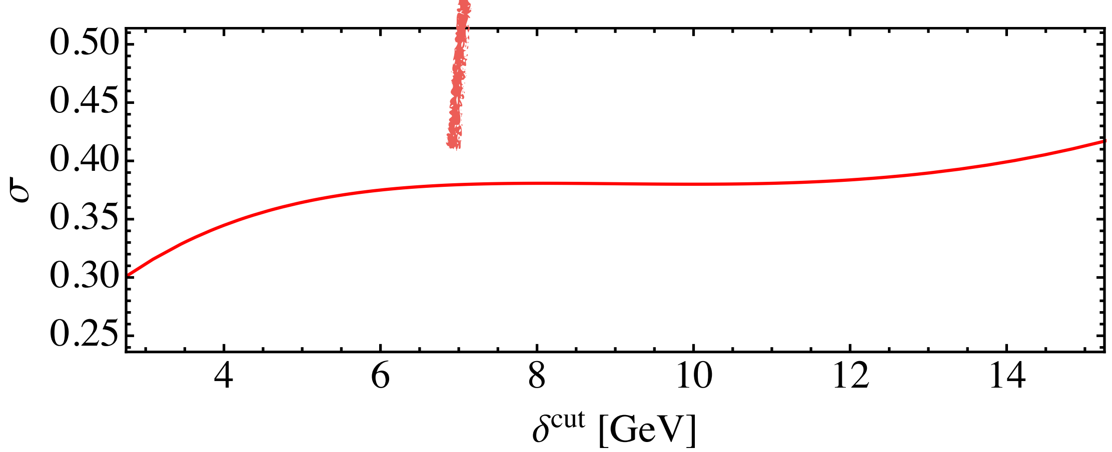
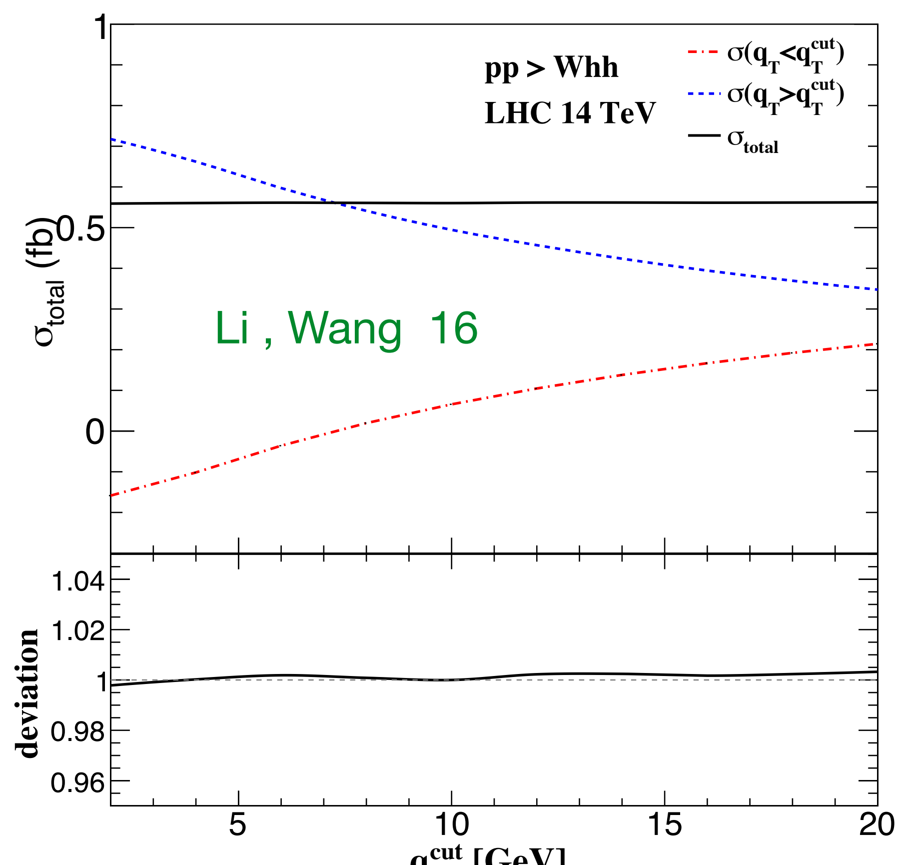
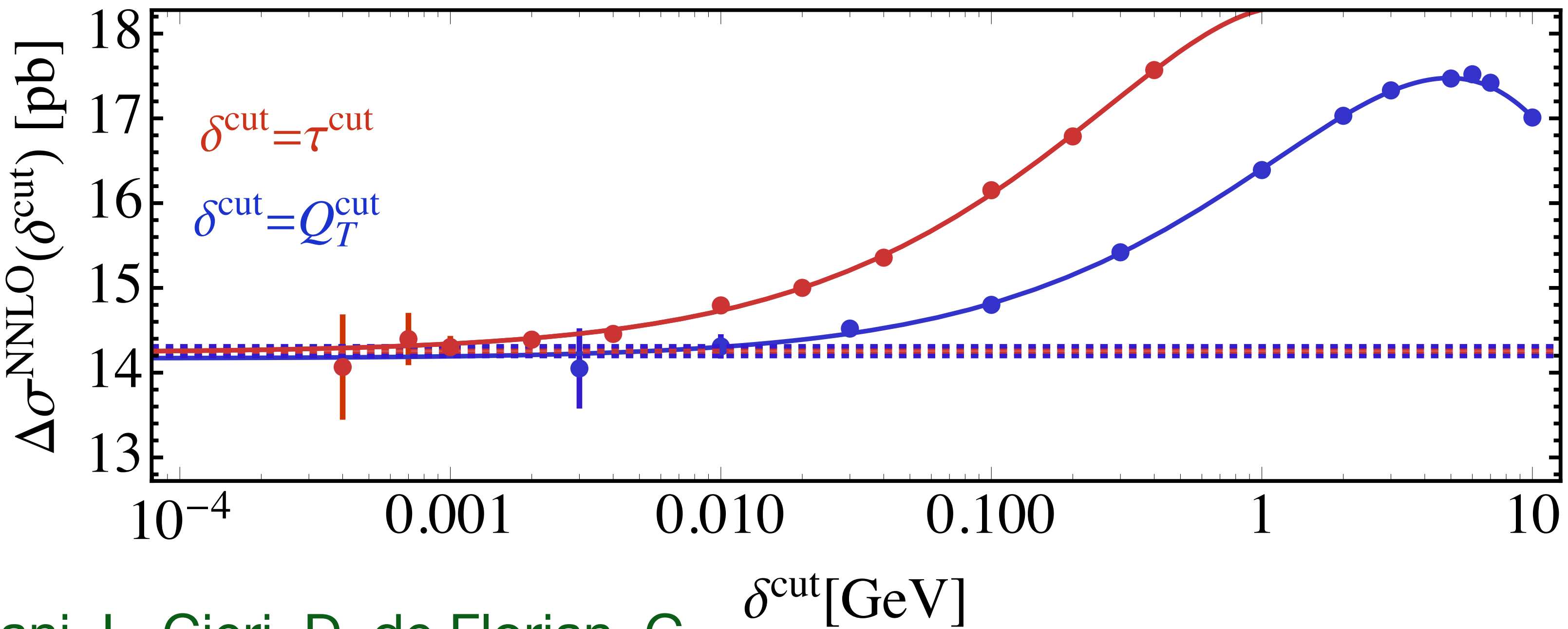
Sadly these plots are still in the literature, I need further convincing that the power corrections are under control here for instance….







(S. Catani, L. Cieri, D. de Florian, G. Ferrera and M. Grazini 11)

MCFM (Campbell, Ellis Li CW 16)

σ[fb]	LO	NLO	NNLO
$\mu_F = \mu_R = m_{\gamma\gamma}/2$	5045 ± 1	26581 ± 23	45588 ± 97
$\mu_F = \mu_R = m_{\gamma\gamma}$	5712 ± 2	26402 ± 25	43315 ± 54
$\mu_F = \mu_R = 2m_{\gamma\gamma}$	6319 ± 2	26045 ± 24	41794 ± 77

σ[fb]	LO	NLO	NNLO
$\mu_F = \mu_R = m_{\gamma\gamma}/2$	5043 ± 1	26578 ± 13	42685 ± 35
$\mu_F = \mu_R = m_{\gamma\gamma}$	5710 ± 1	26444 ± 12	40453 ± 30
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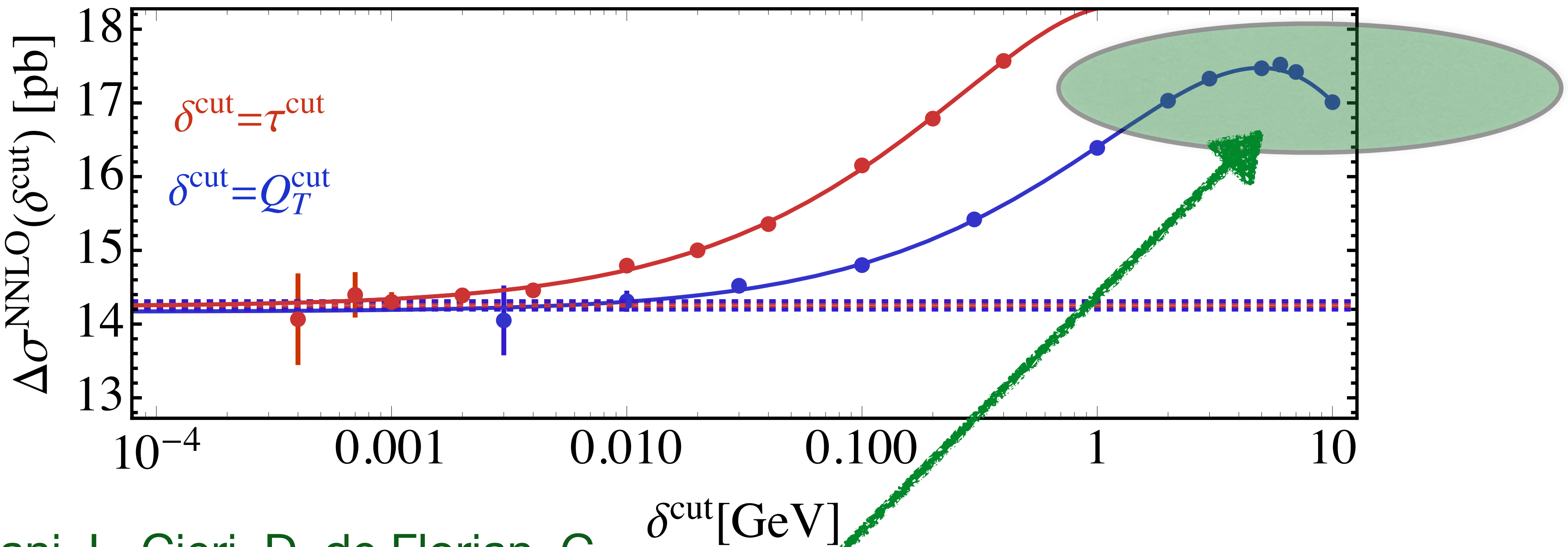

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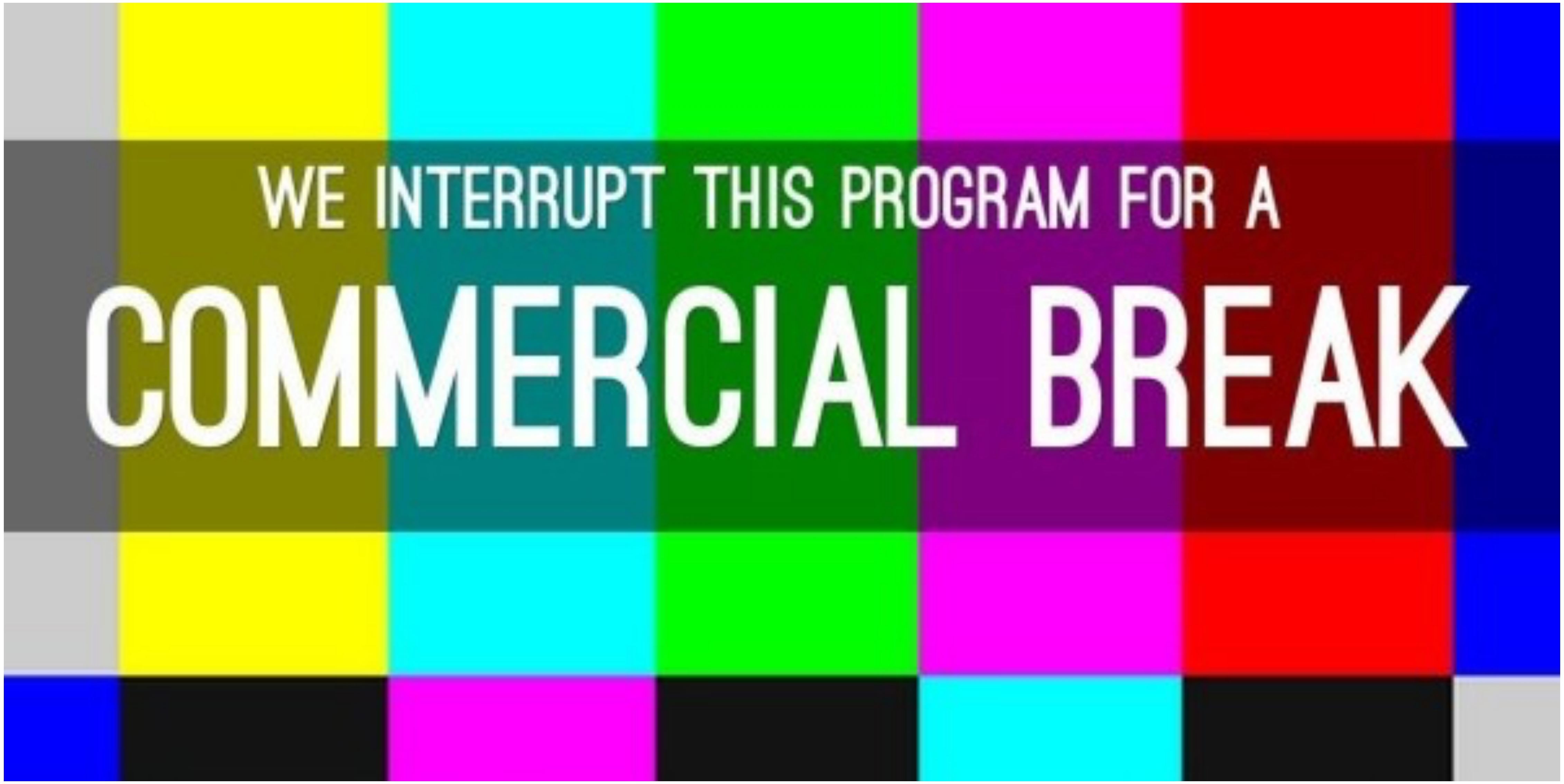
Has since been corrected to numbers consistent with the MCFM calculation.


WE INTERRUPT THIS PROGRAM FOR A
COMMERCIAL BREAK

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

Advertisement

- Process calculated at NNLO by theorists.
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Advertisement **Reality**

(Rotated to most appealing angle)

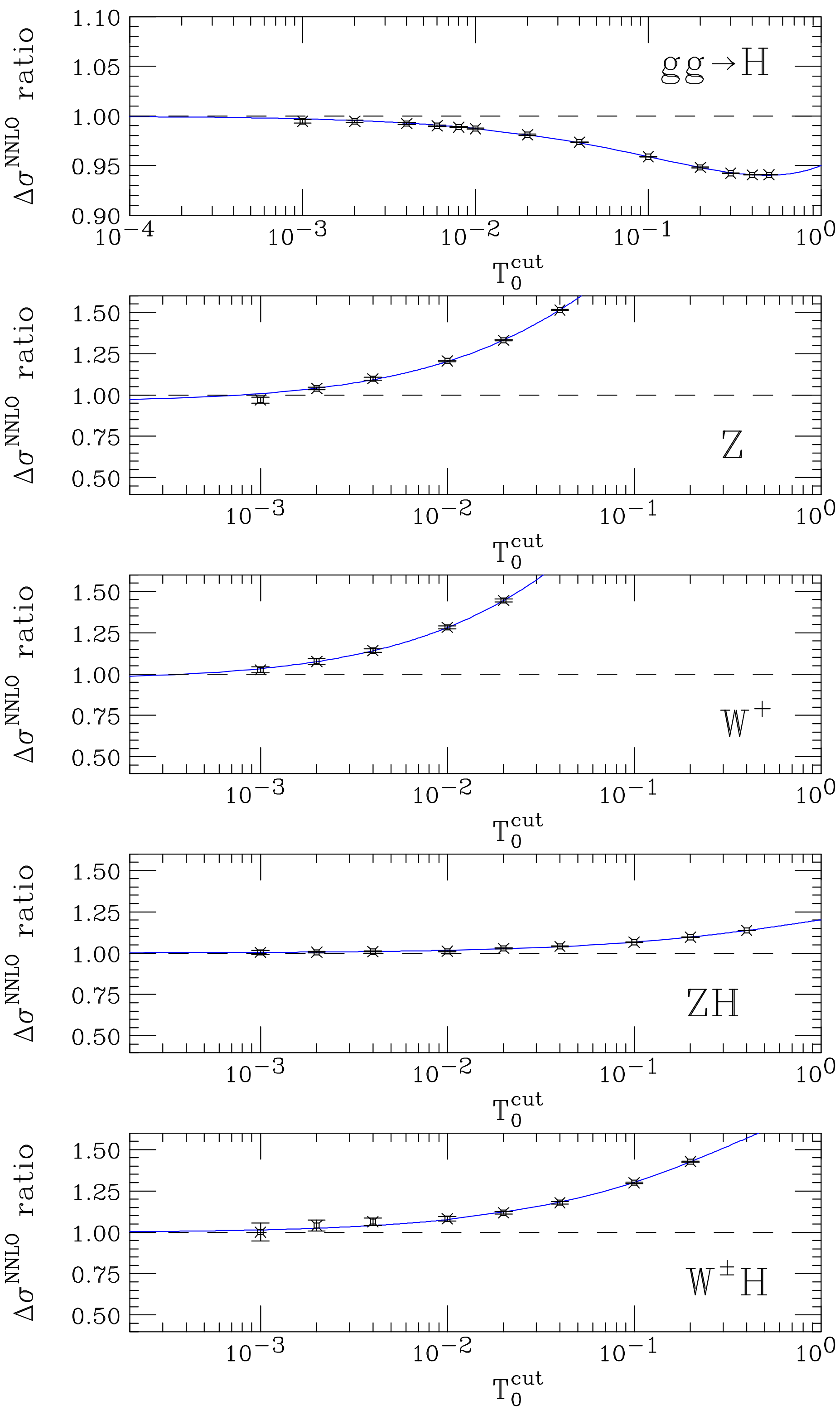
- Results not easily reproducible
- Needs direct contact with authors to obtain plots (time consuming for everyone)
- Limited to author’s computer resources
- Version control

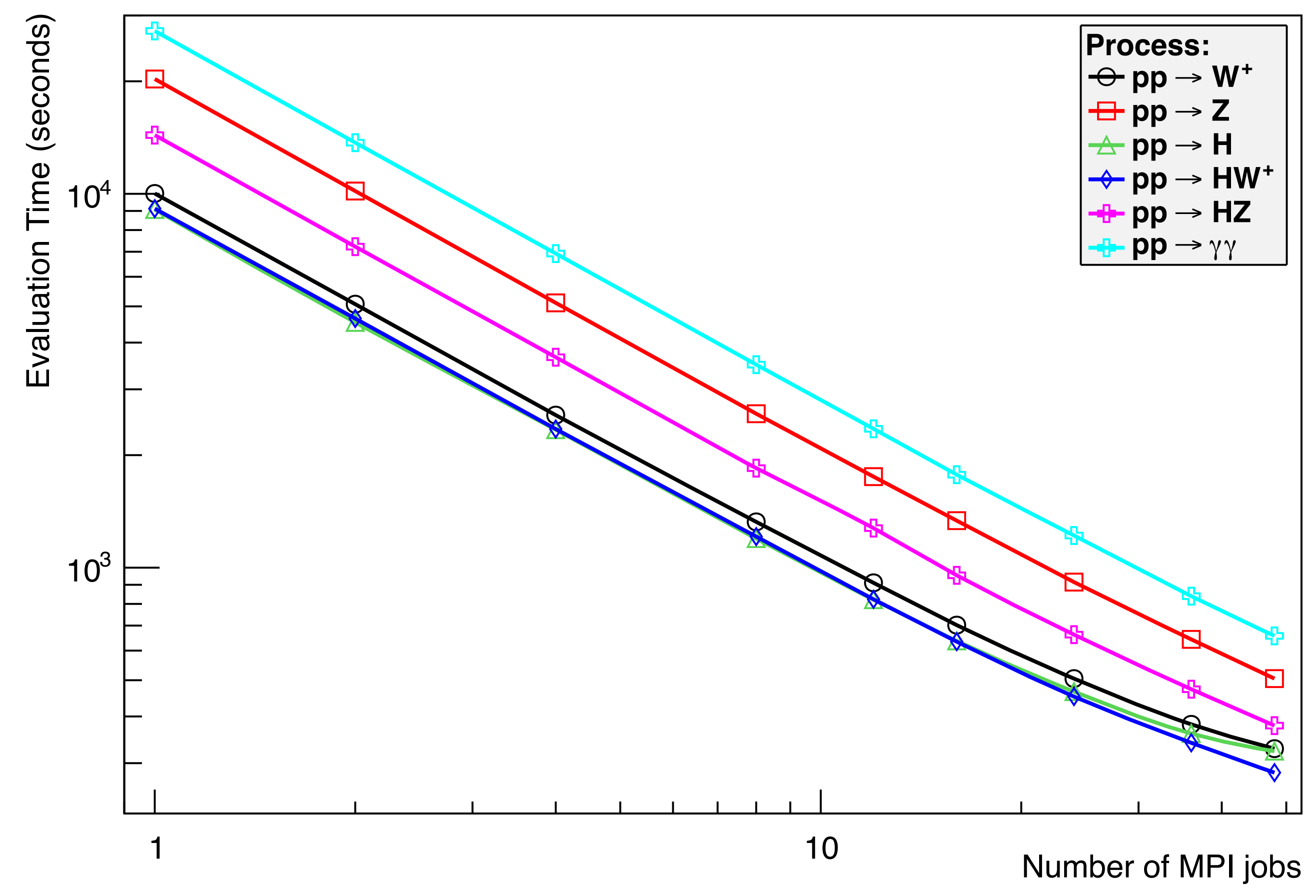
Our attempt to address this is,

MCFM 8

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

Processes in 8.0





Code is public and can be downloaded from mcfm.fnal.gov

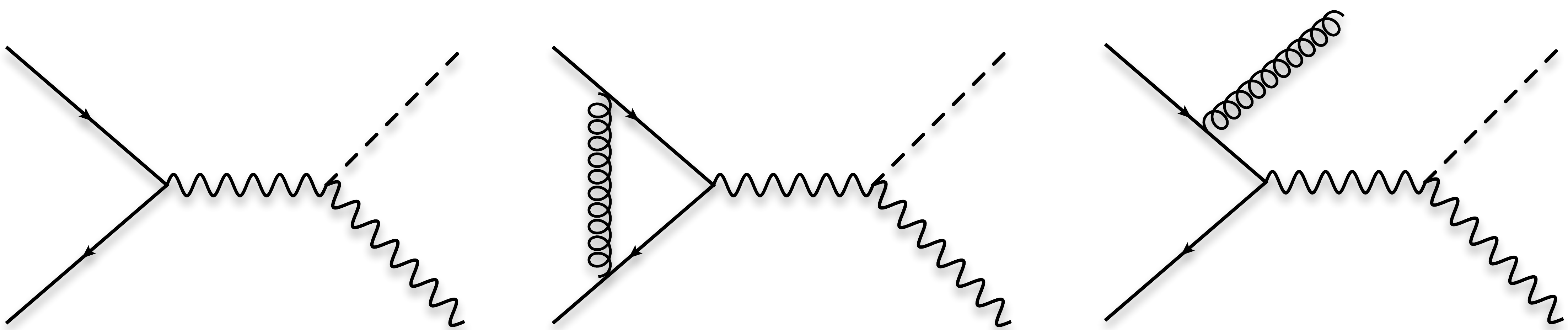
We are interested in feedback from users on how easy it is to run/install the code. How stable it is etc. A successful run out of the singlet code may make future release of a public NNLO +jet more likely…

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

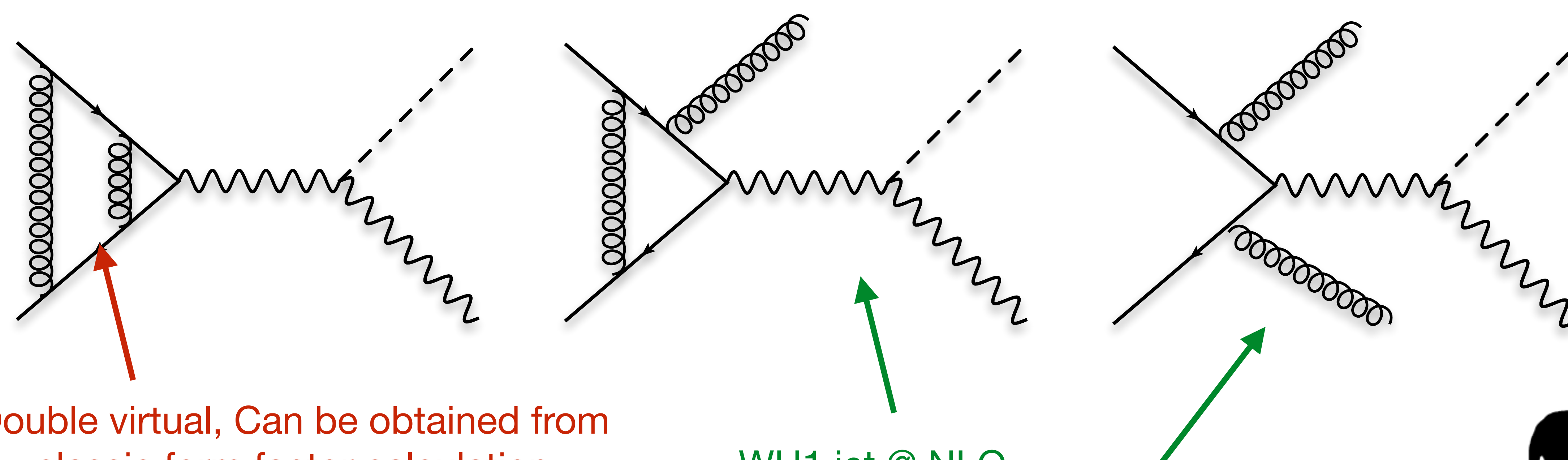
Recent results for Dibosons

Campbell, Ellis, CW 16

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



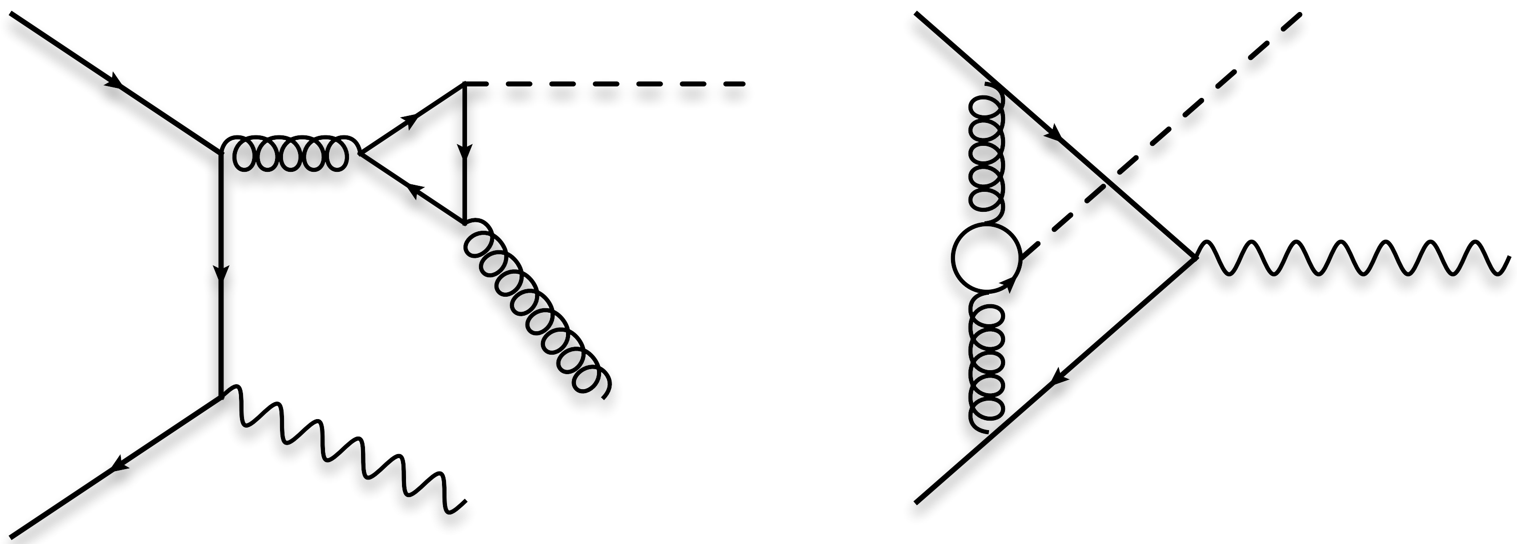
At NNLO we have extensions to these topologies

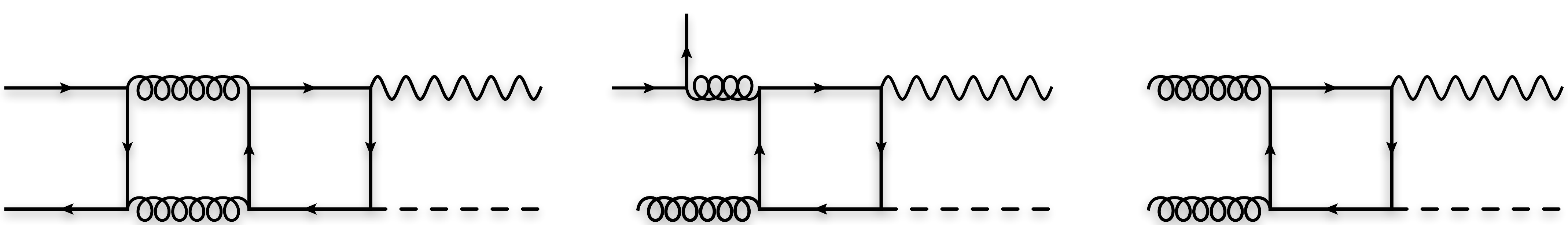


Double virtual, Can be obtained from classic form factor calculation

WH1 jet @ NLO

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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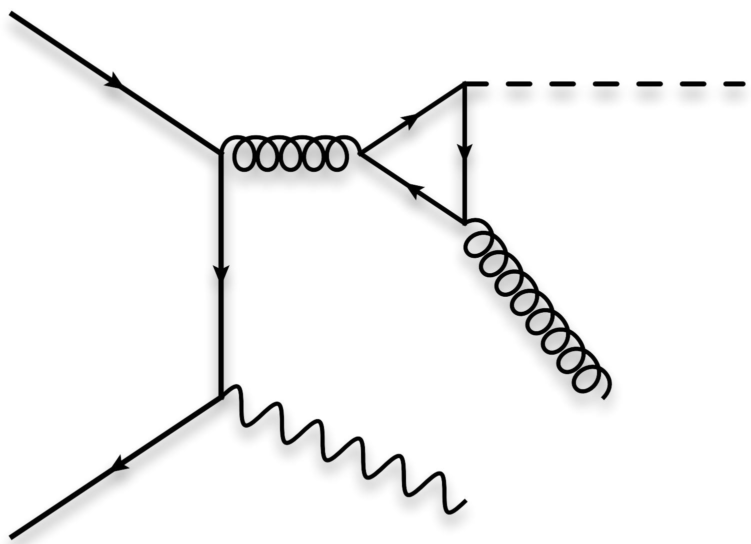
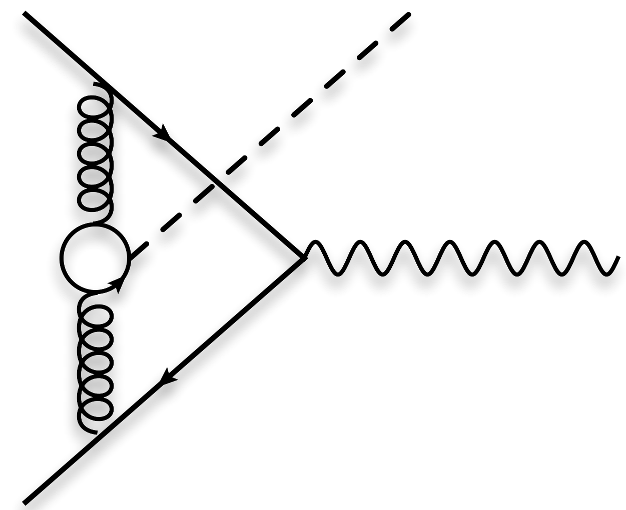
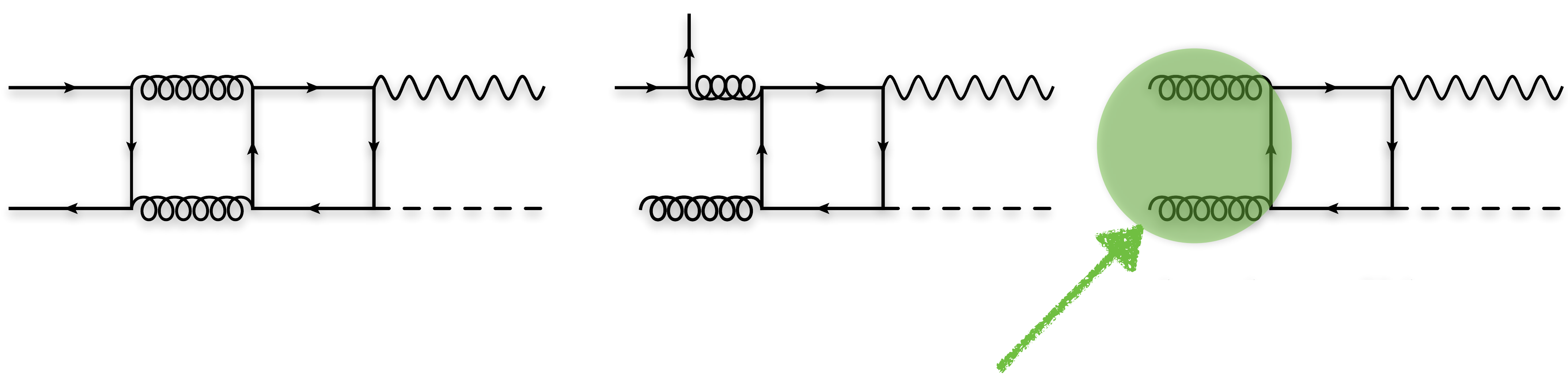
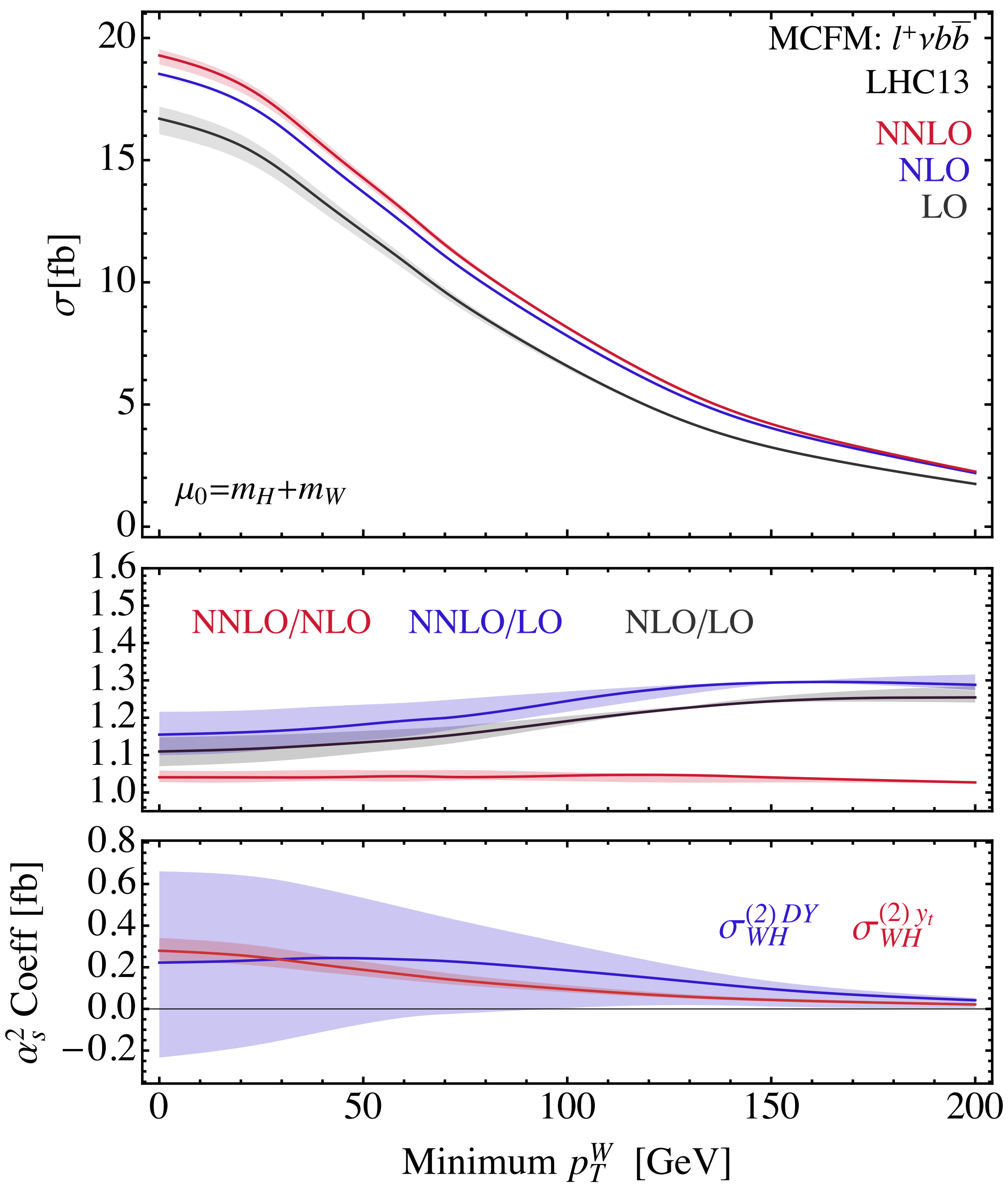
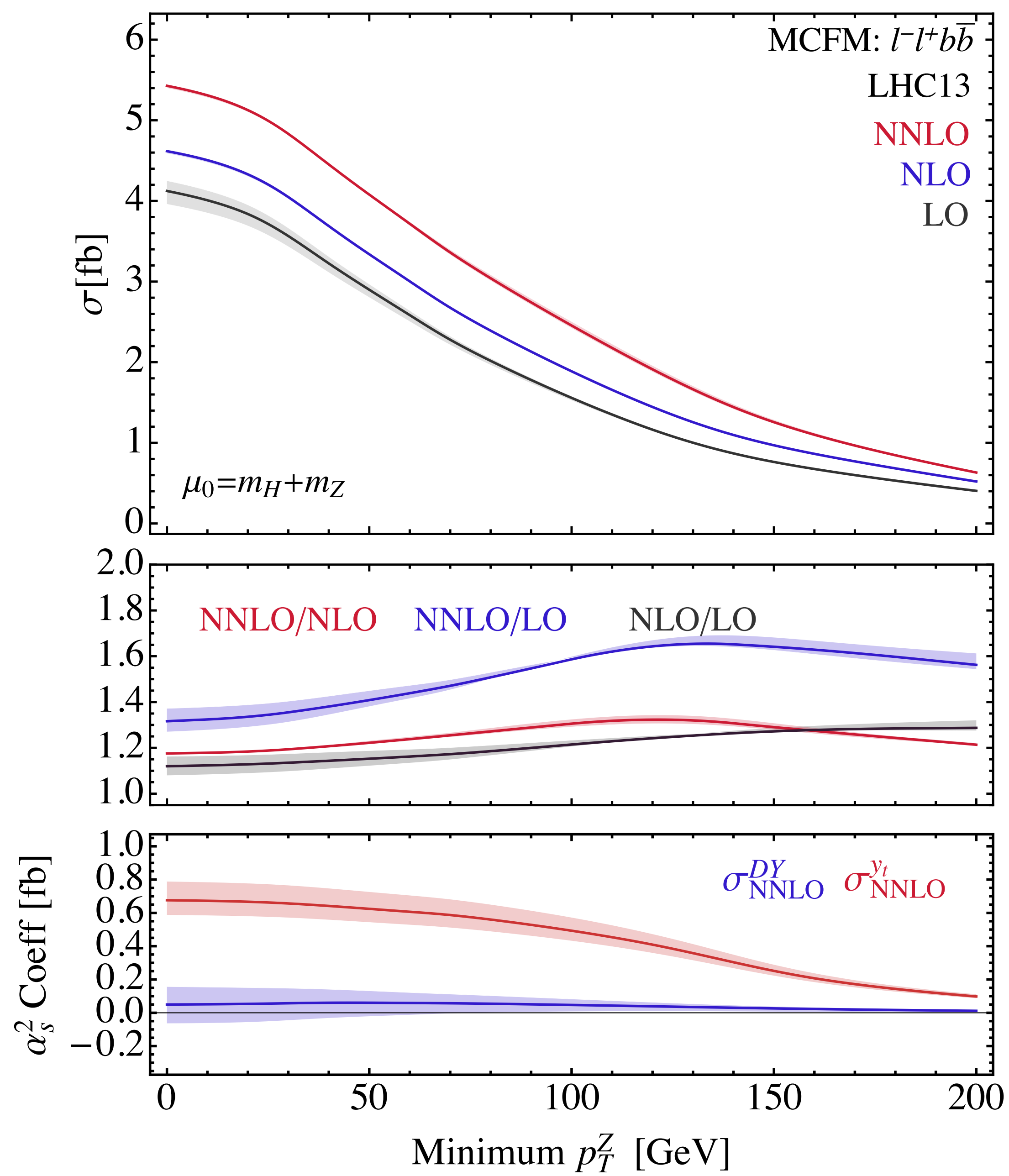






Gluon PDFS will make this bit important!





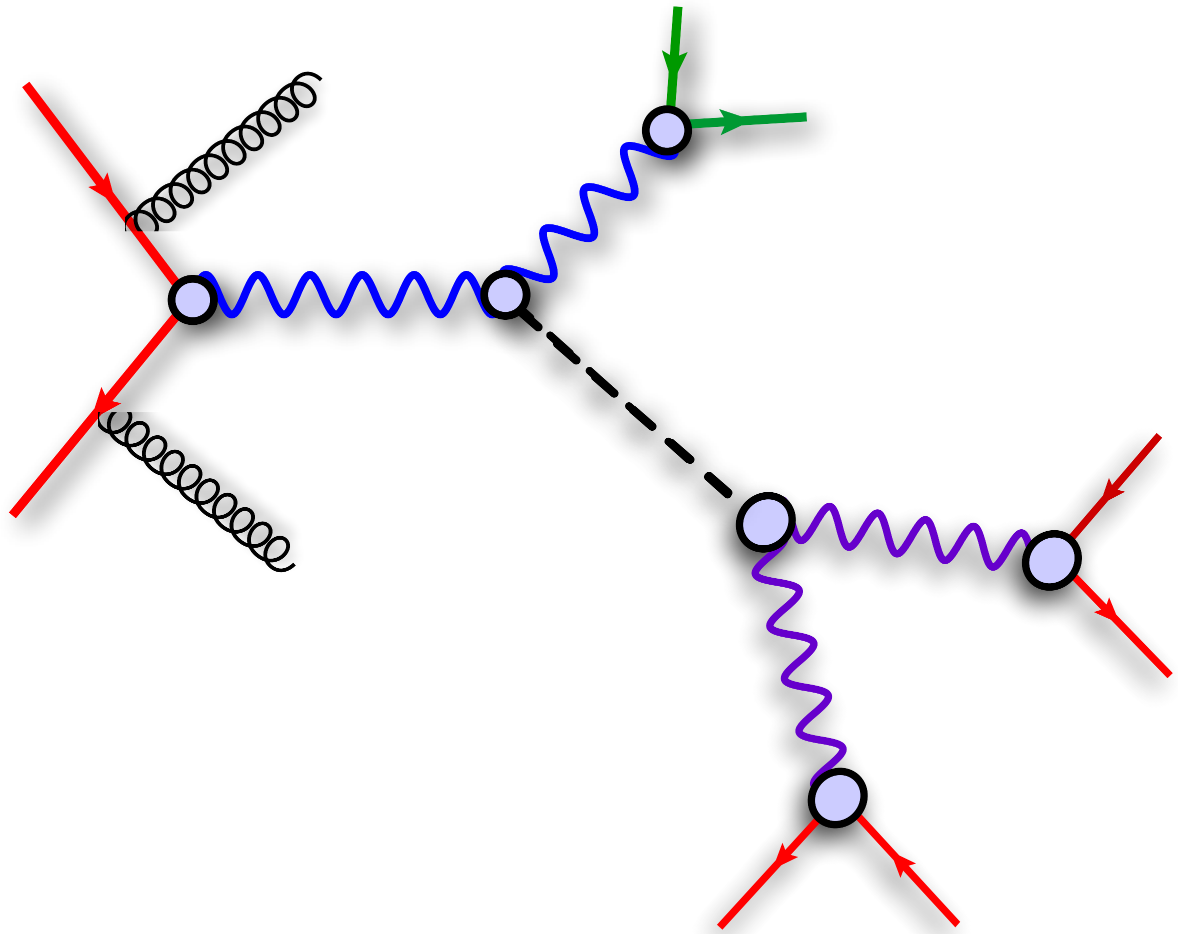
Experimental analysis require fairly hard cuts on vector boson transverse momenta to suppress top backgrounds.

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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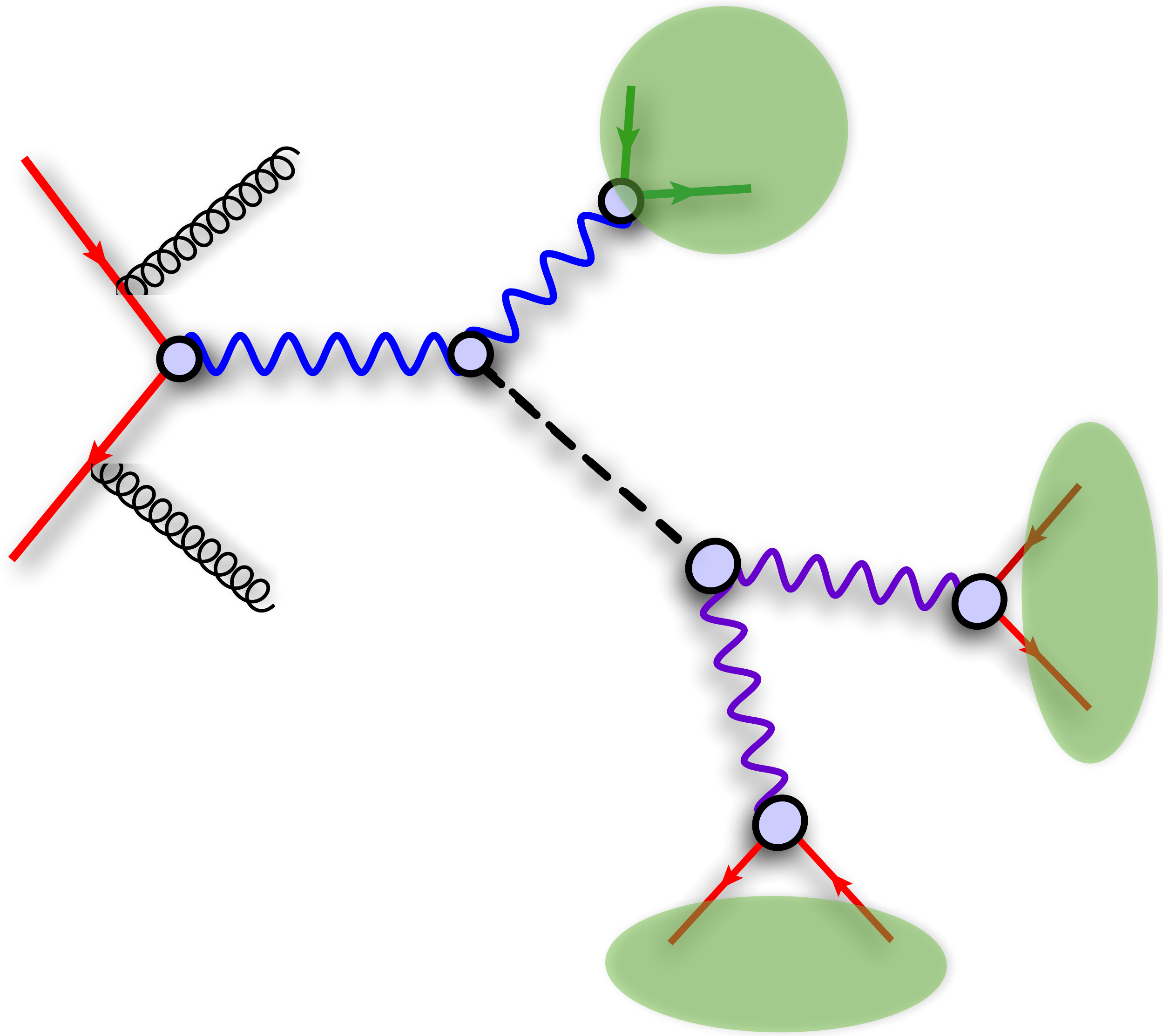

The LO phase space is 16 dimensional

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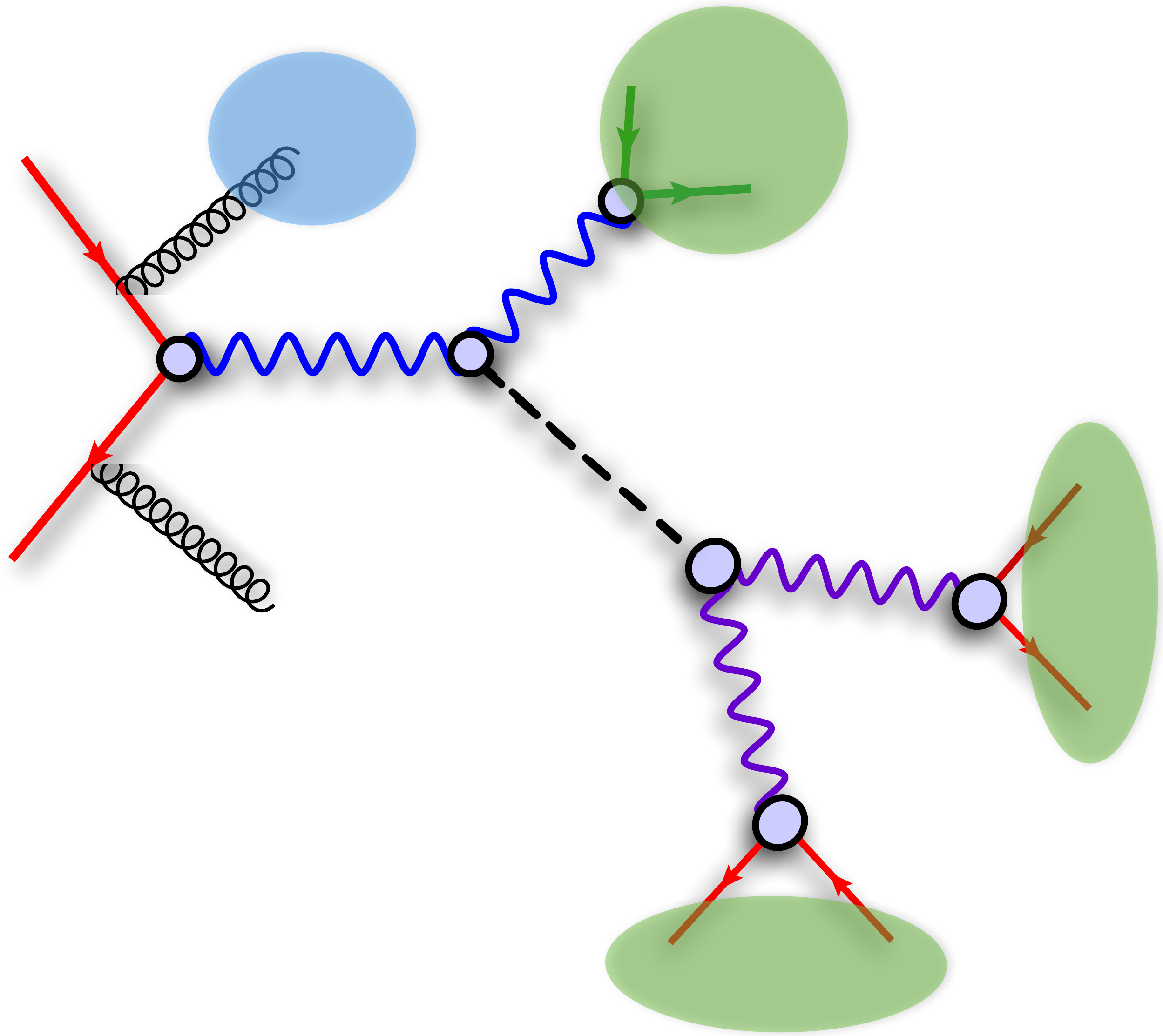

The LO phase space is 16 dimensional

Real phase space at NLO is 19 dimensional

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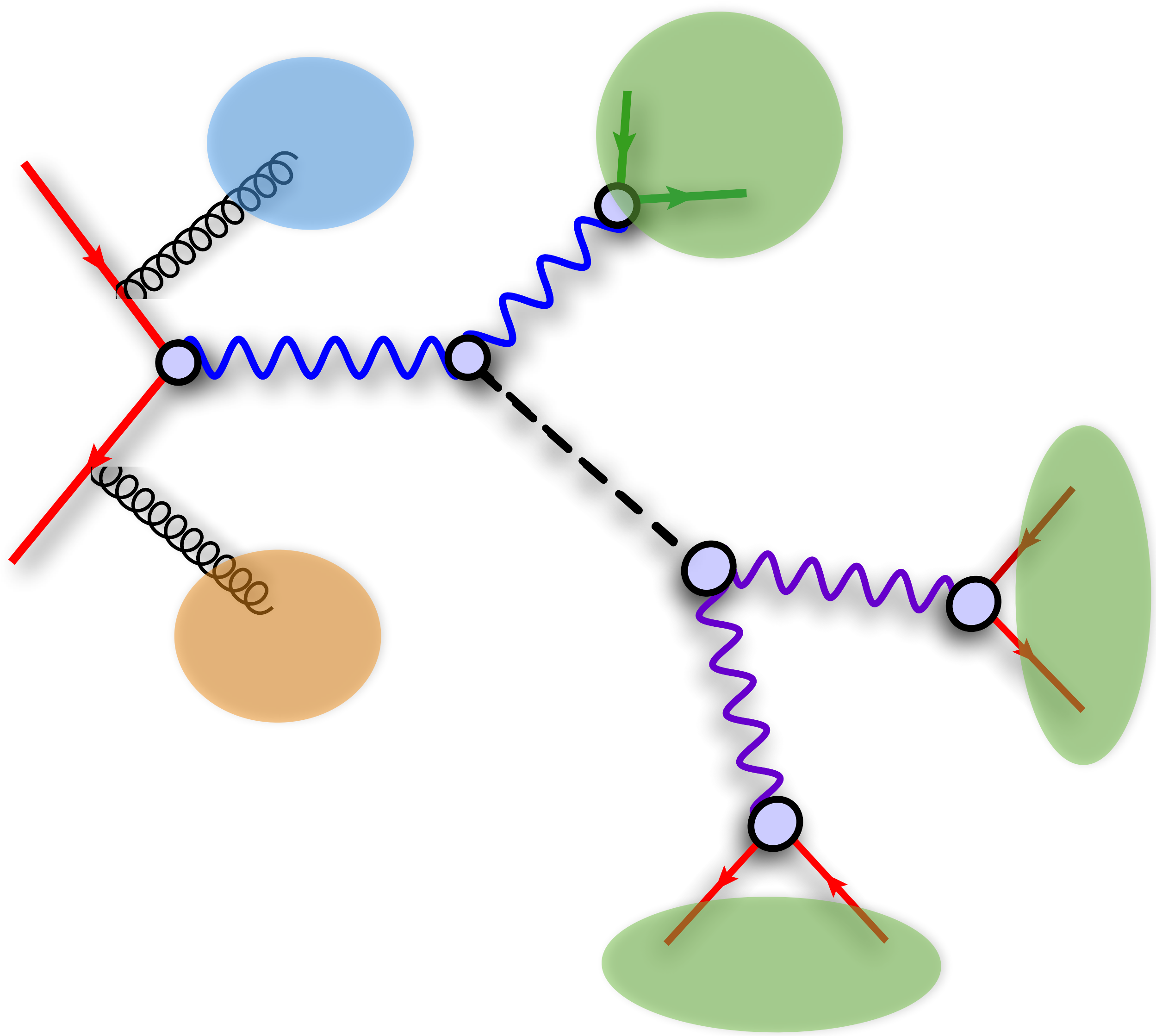
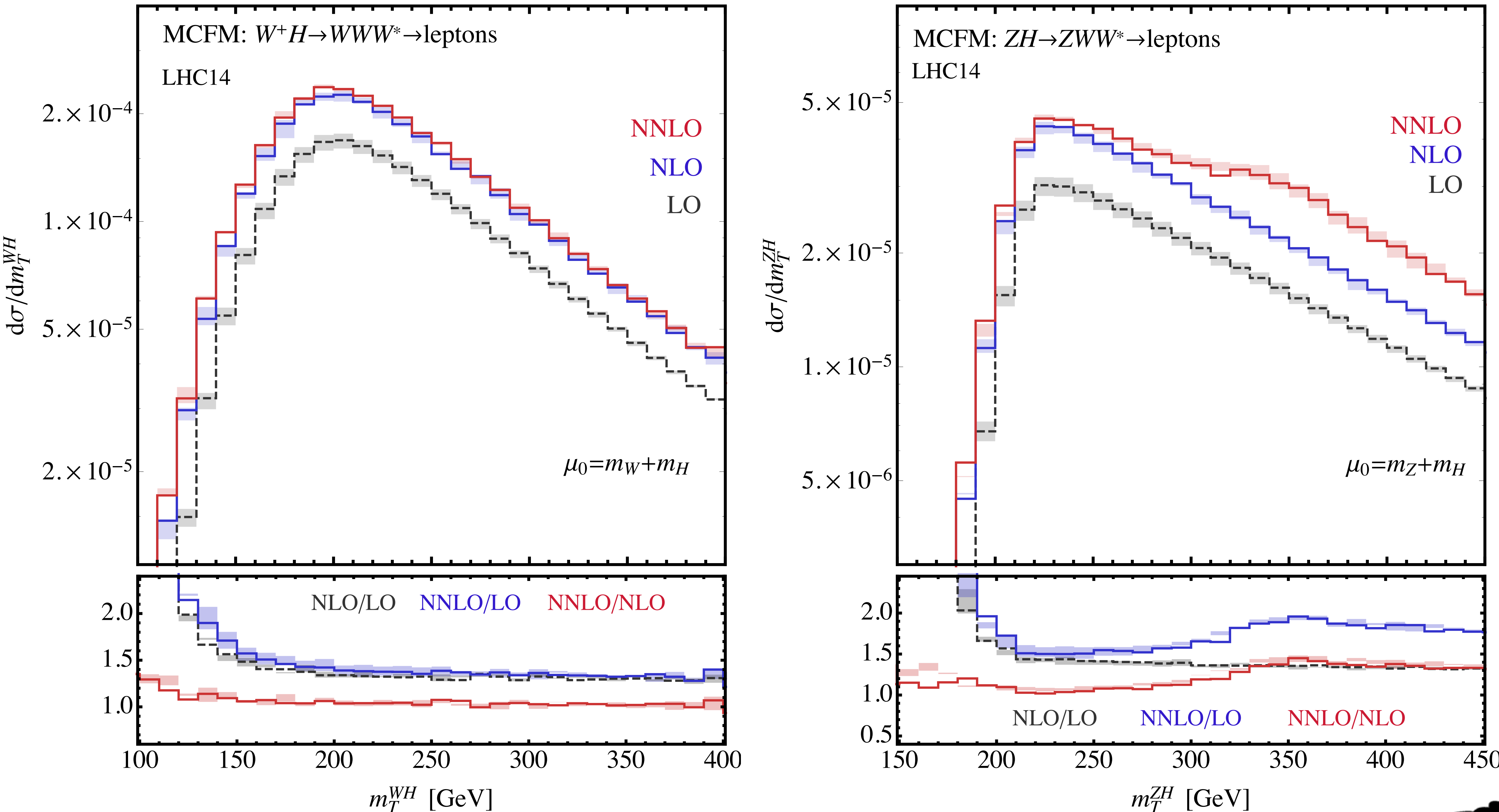


The LO phase space is 16 dimensional

Real phase space at NLO is 19 dimensional

Double real phase space is 22 dimensio

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



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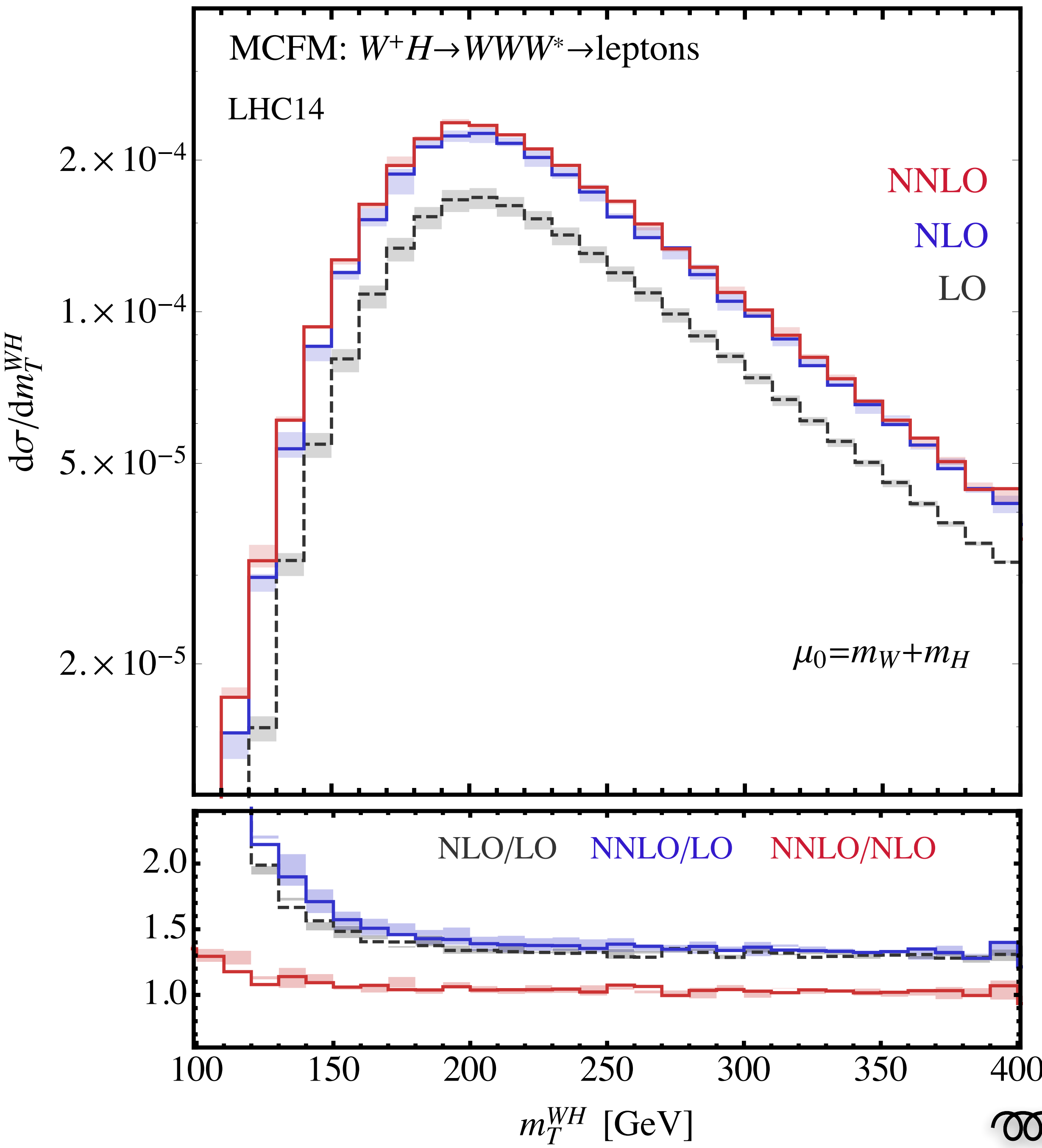
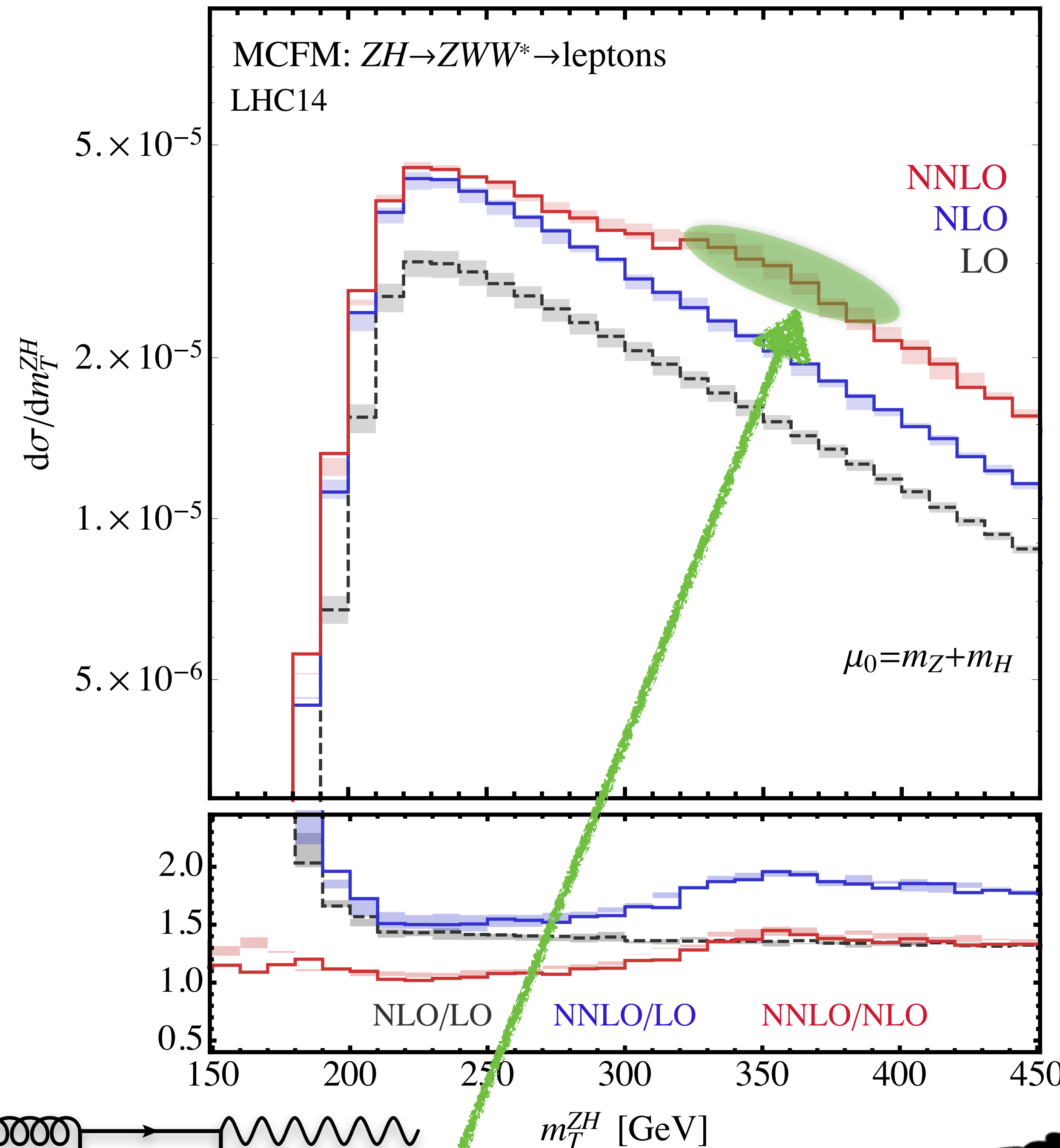
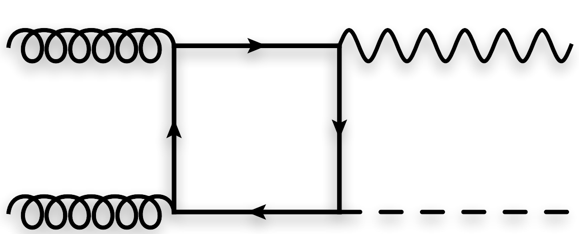
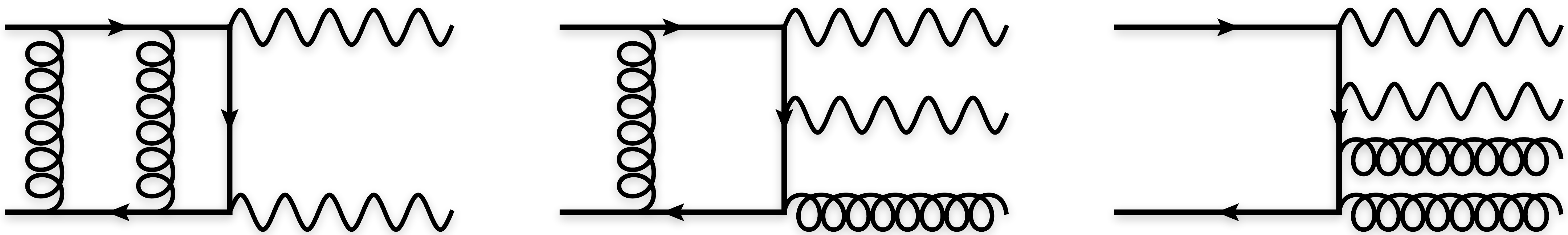






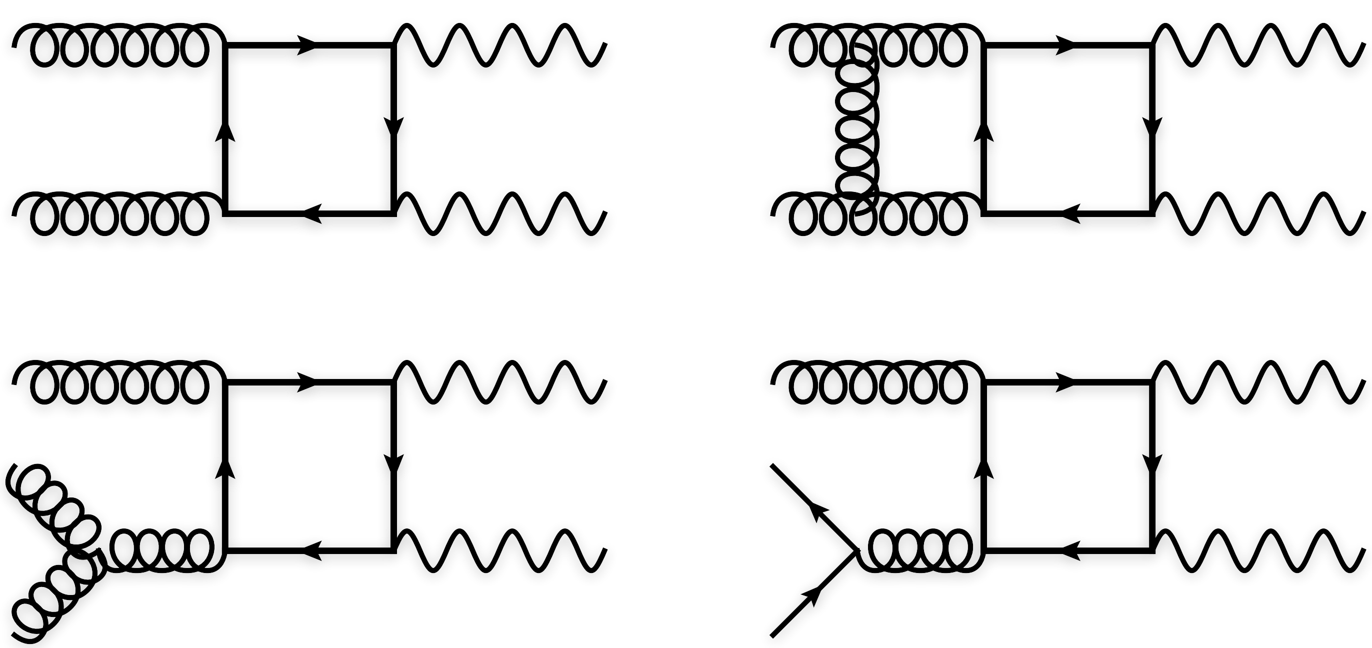
Campbell, CW 14

Campbell, Ellis, Li, CW 16



(Anastasiou, Glover, Tejeda-Yeomans 02)

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

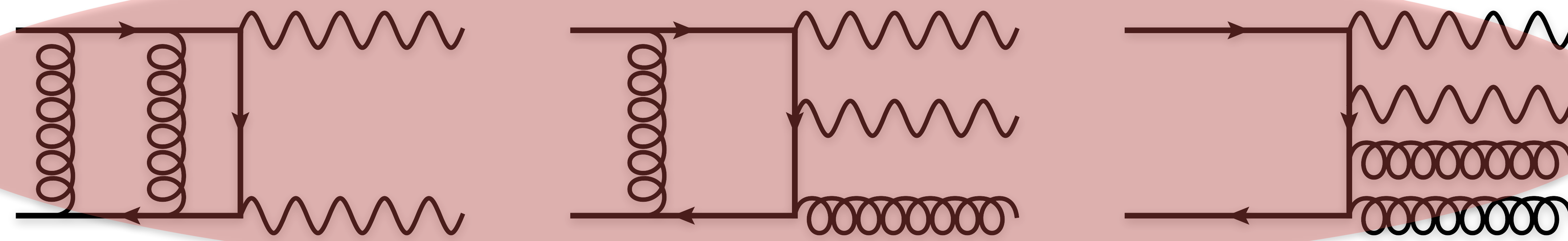


Aside from the regular $q\bar{q}$ NNLO topologies, there are interesting effects from gg initiated pieces too.

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

Campbell, Ellis, Li, CW 16

Campbell, CW 14



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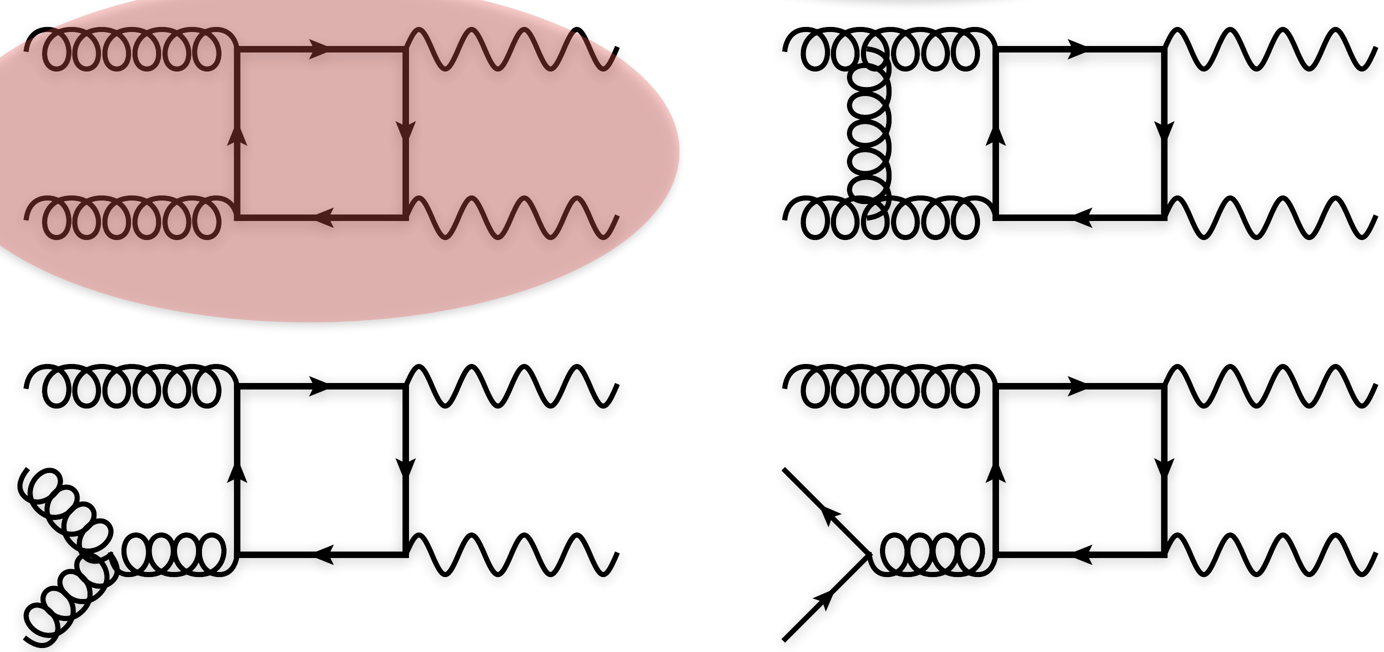

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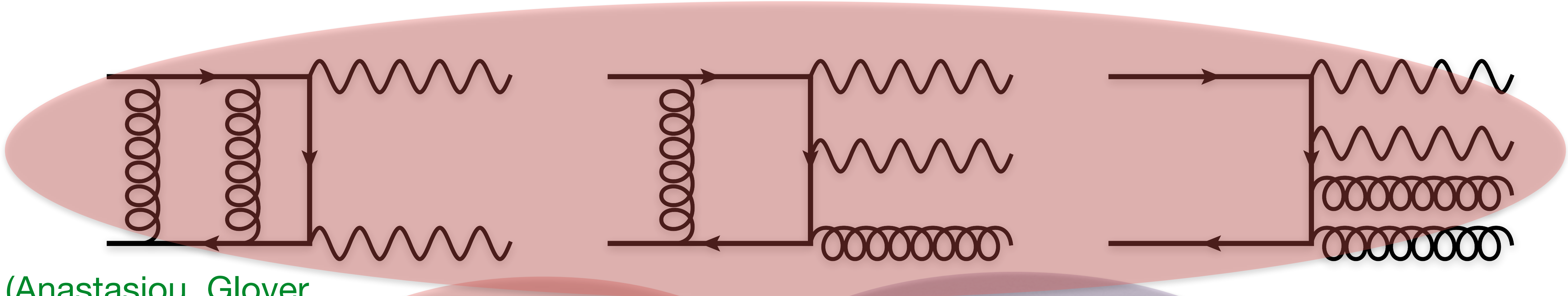

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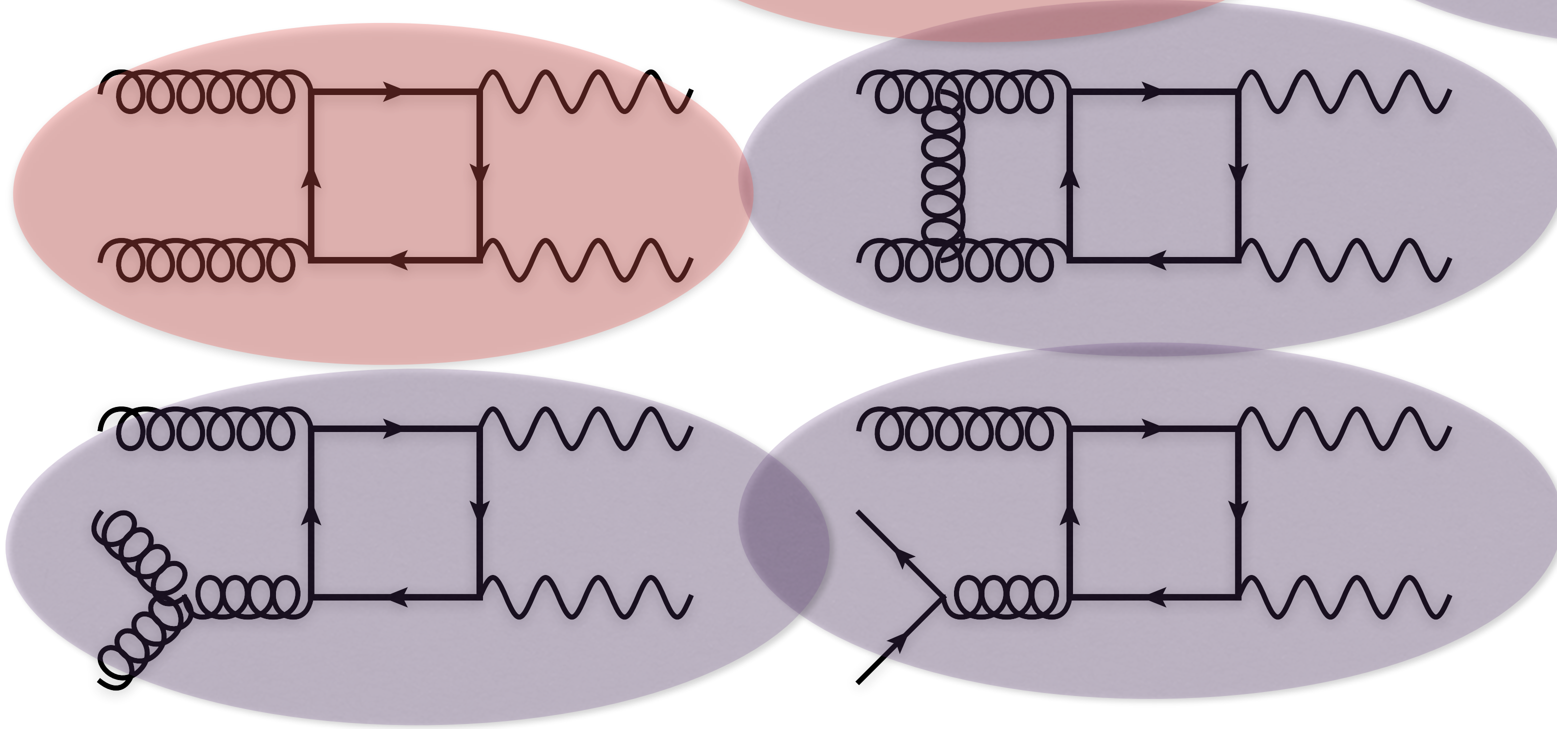

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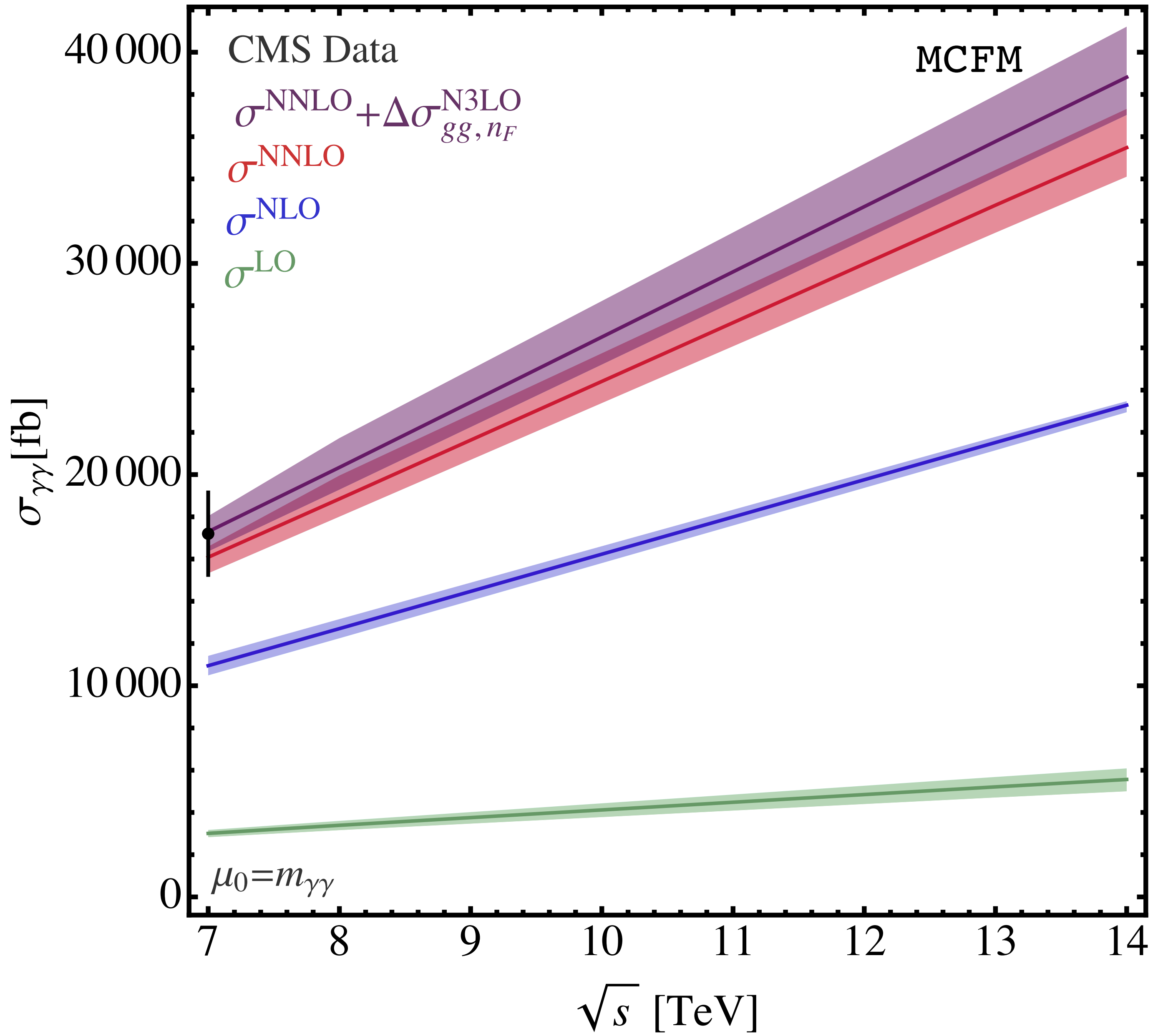
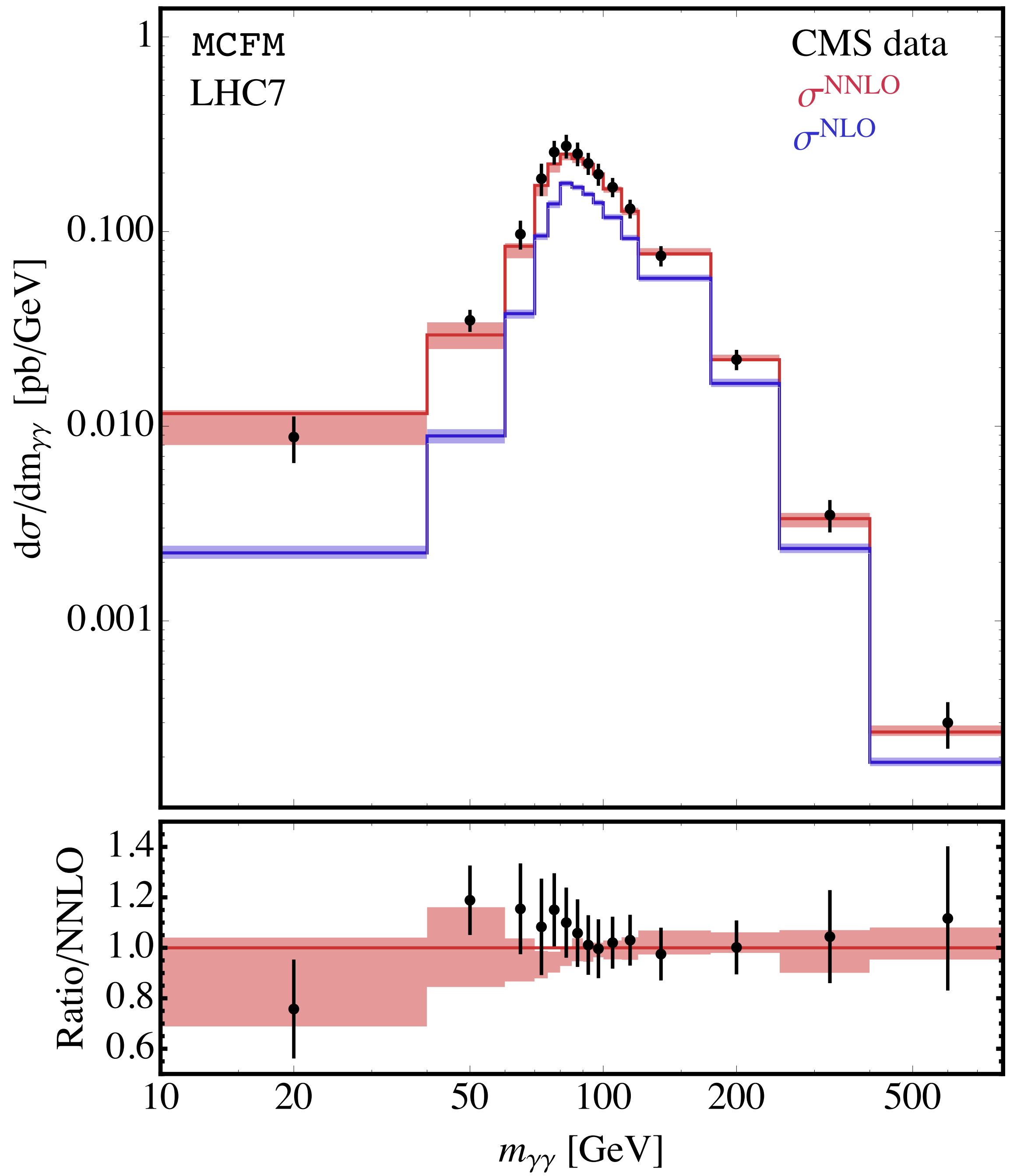
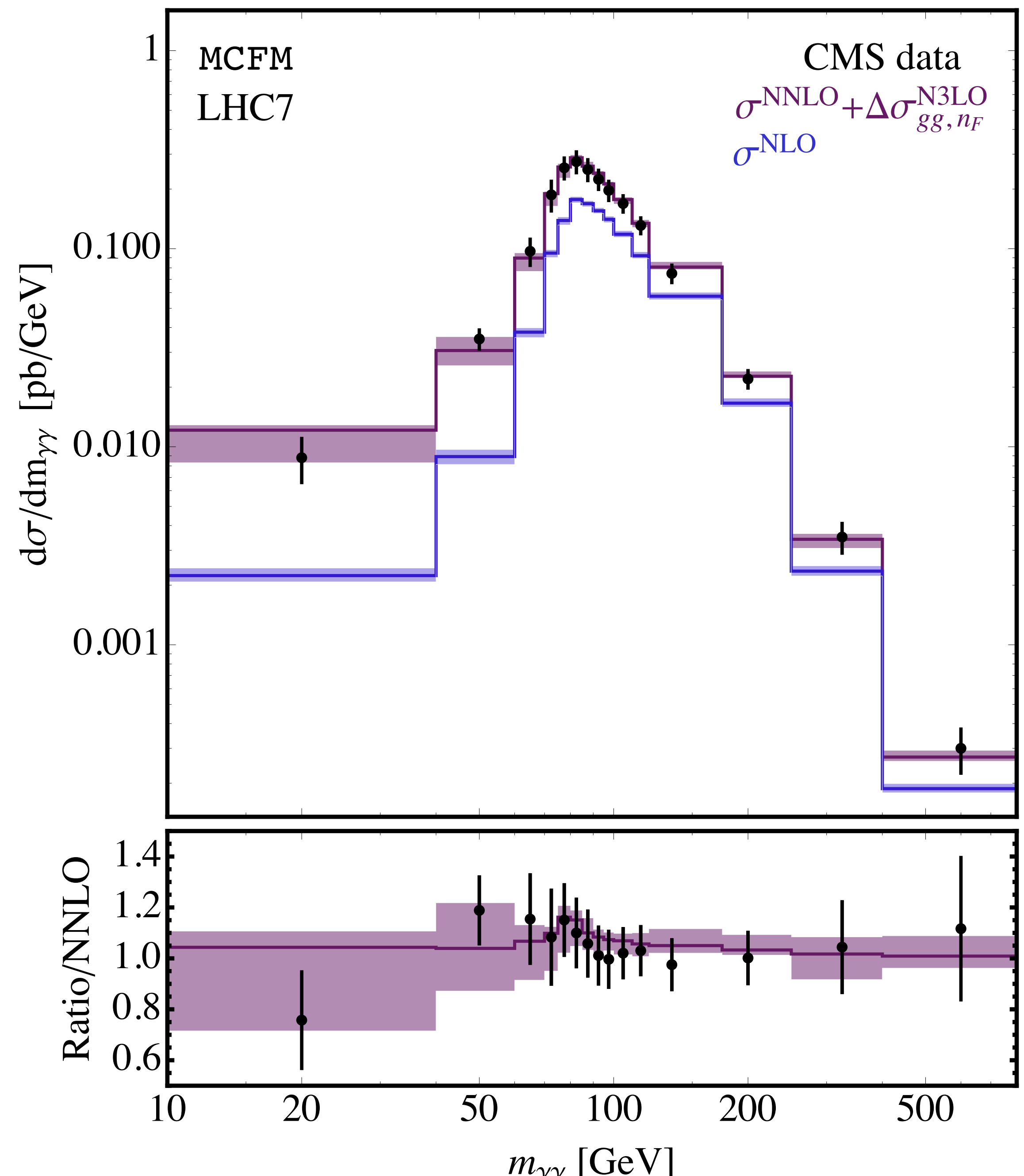
Cross sections

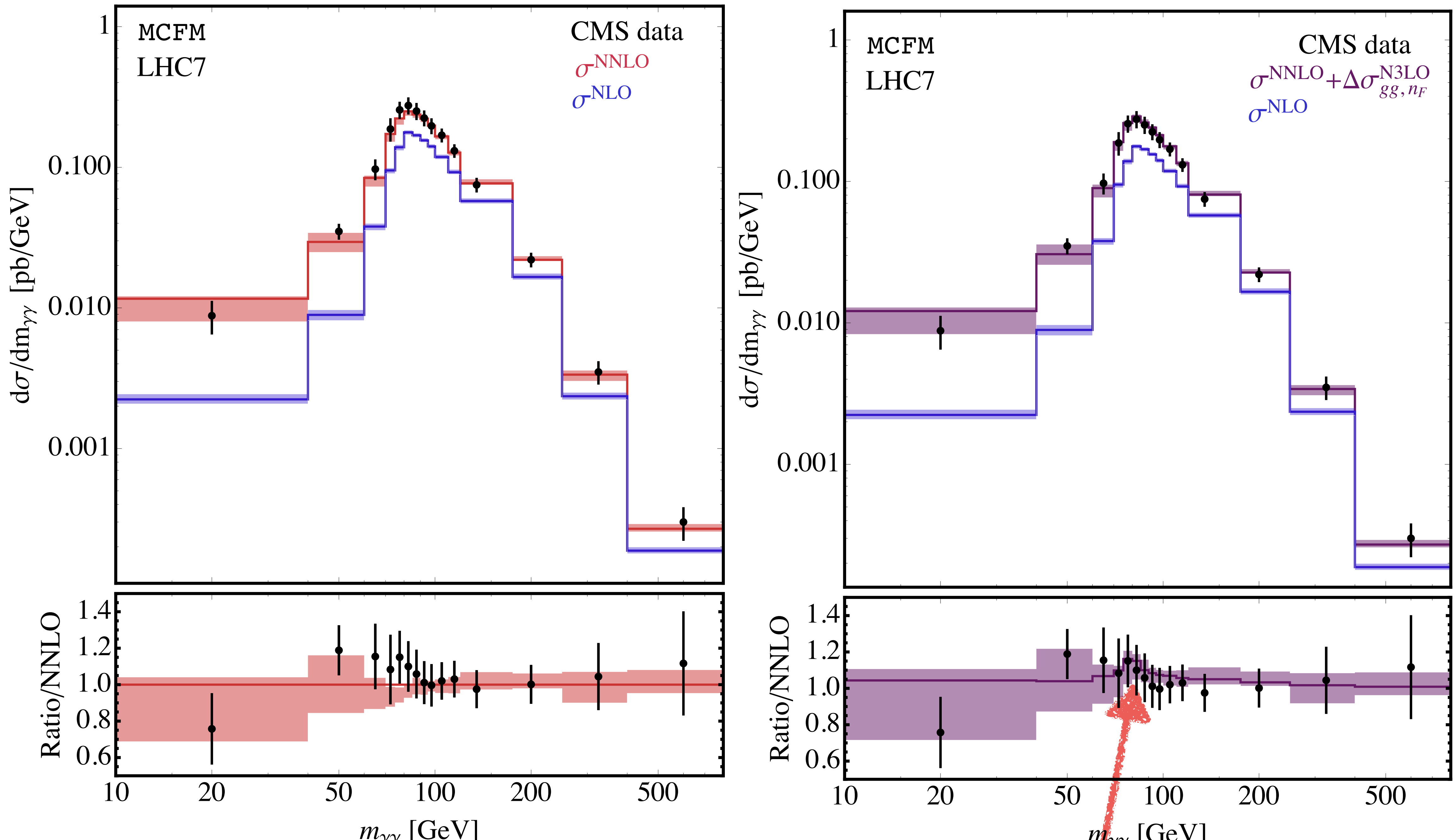


Its interesting to compare NNLO with NNLO + gg@NLO, at 7 TeV not much to tell between the two predictions and agreement with data.
At 13 TeV predictions separate, would be interesting to see which is best (its non trivial, since we are missing pieces from the N3LO prediction which could easily drive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



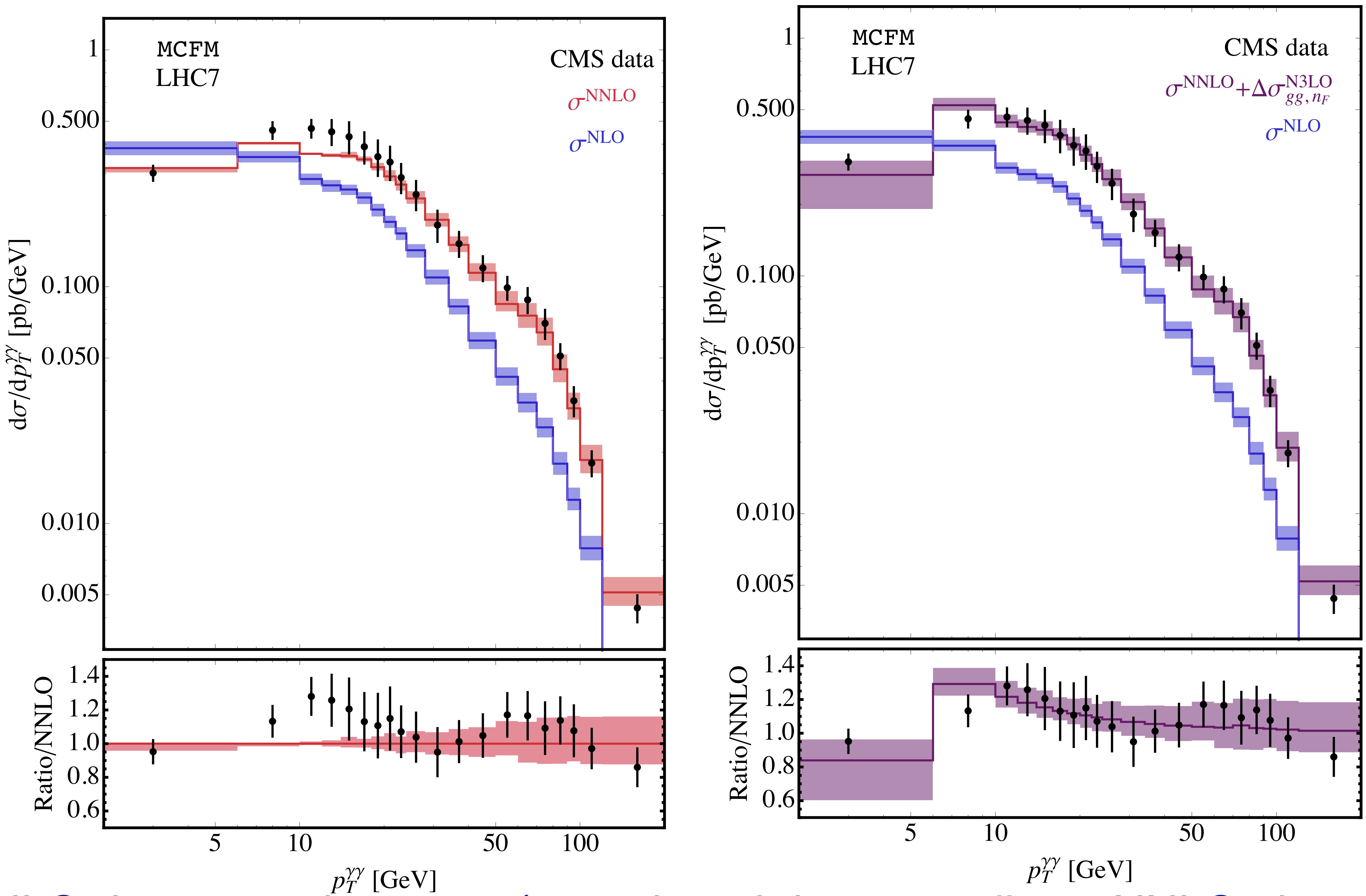


Out of the box NNLO does a very nice job of describing CMS 7 TeV Data



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

Looks like adding in additional gluon pieces helps

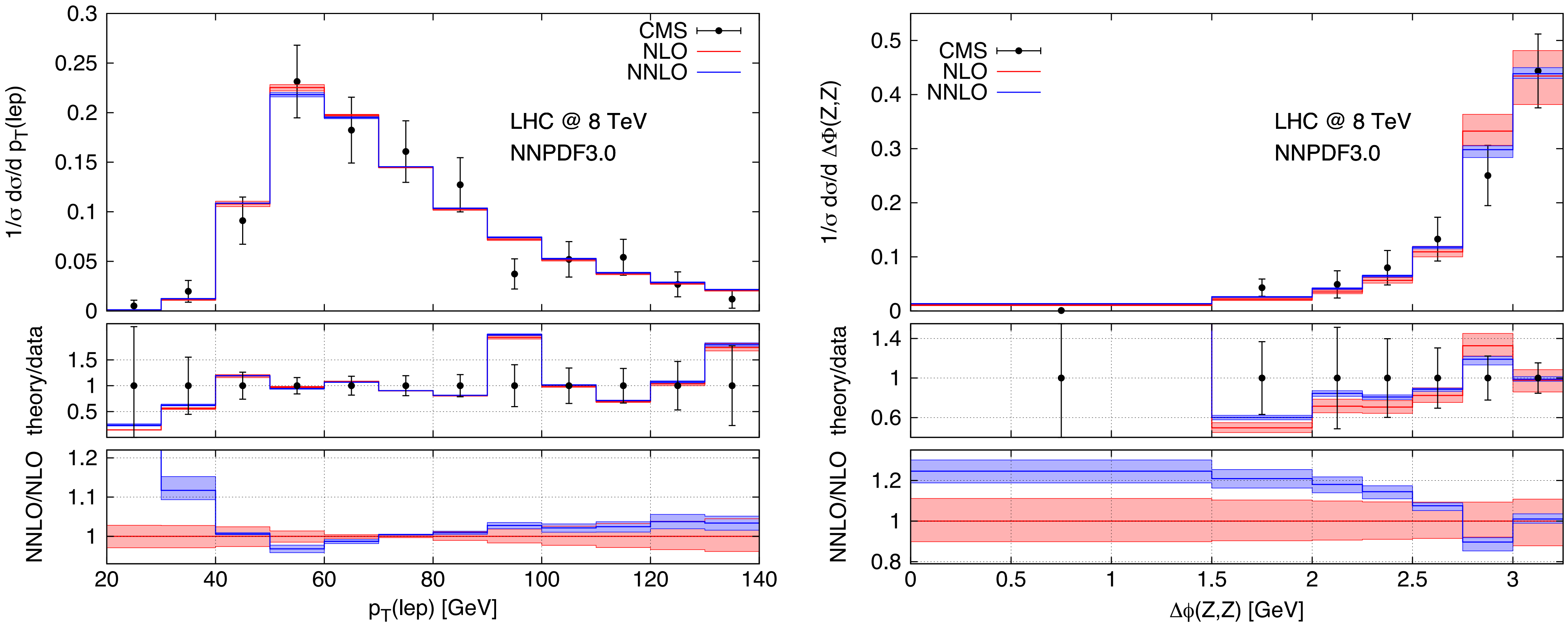


NNLO does great here too, (even though its not really an NNLO observable)

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

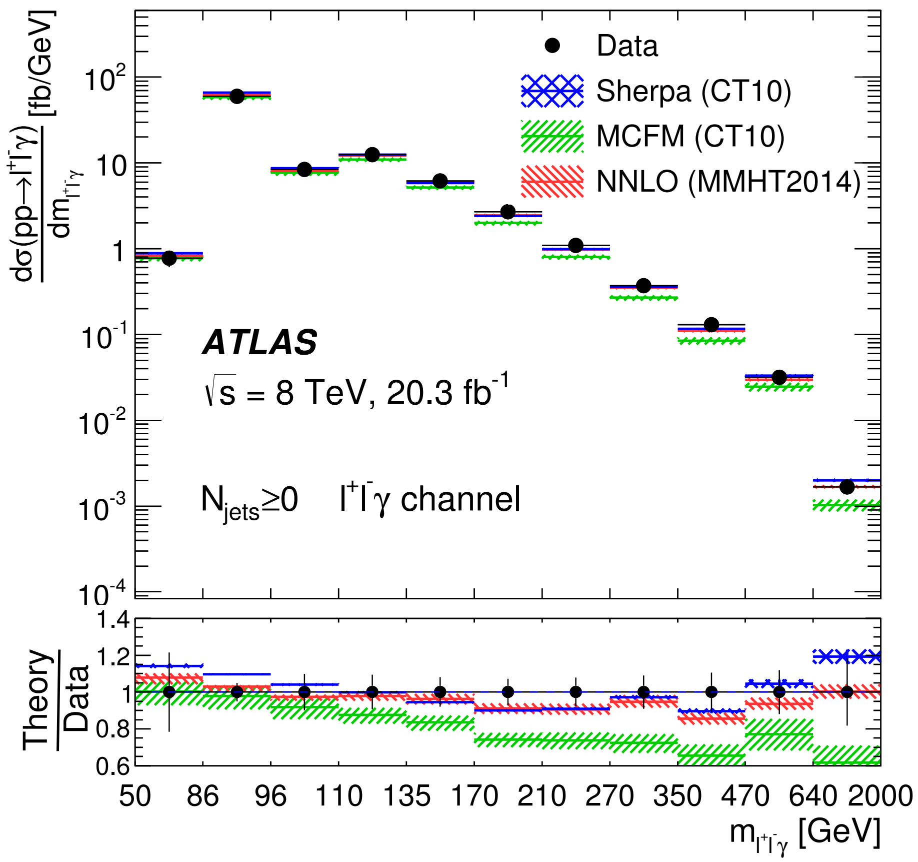
ZZ

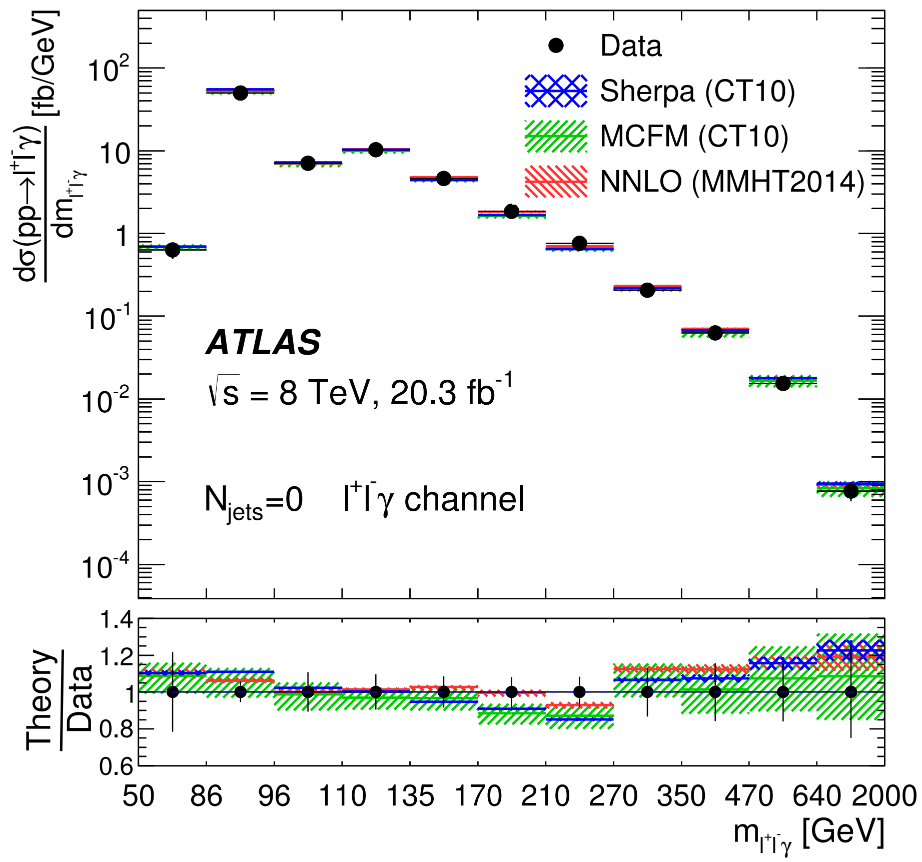
Grazzini, Kallweit, Rathlev 15



Channel	$\sigma_{\rm LO}$ (fb)	$\sigma_{\rm NLO}$ (fb)	$\sigma_{\rm NNLO}$ (fb)	$\sigma_{\rm exp}$ (fb)
$e^+e^-e^+e^-$	$3.547(1)^{+2.9\%}_{-3.9\%}$	$5.047(1)^{+2.8\%}_{-2.3\%}$	$5.79(2)^{+3.4\%}_{-2.6\%}$	$4.6^{+0.8}_{-0.7}(\text{stat})^{+0.4}_{-0.4}(\text{syst.})^{+0.1}_{-0.1}(\text{lumi.})$
$\mu^+\mu^-\mu^+\mu^-$				$5.0^{+0.6}_{-0.5}(\text{stat})^{+0.2}_{-0.2}(\text{syst.})^{+0.2}_{-0.2}(\text{lumi.})$
$e^+e^-\mu^+\mu^-$	$6.950(1)^{+2.9\%}_{-3.9\%}$	$9.864(2)^{+2.8\%}_{-2.3\%}$	$11.31(2)^{+3.2\%}_{-2.5\%}$	$11.1^{+1.0}_{-0.9}(\text{stat})^{+0.5}_{-0.5}(\text{syst.})^{+0.3}_{-0.3}(\text{lumi.})$

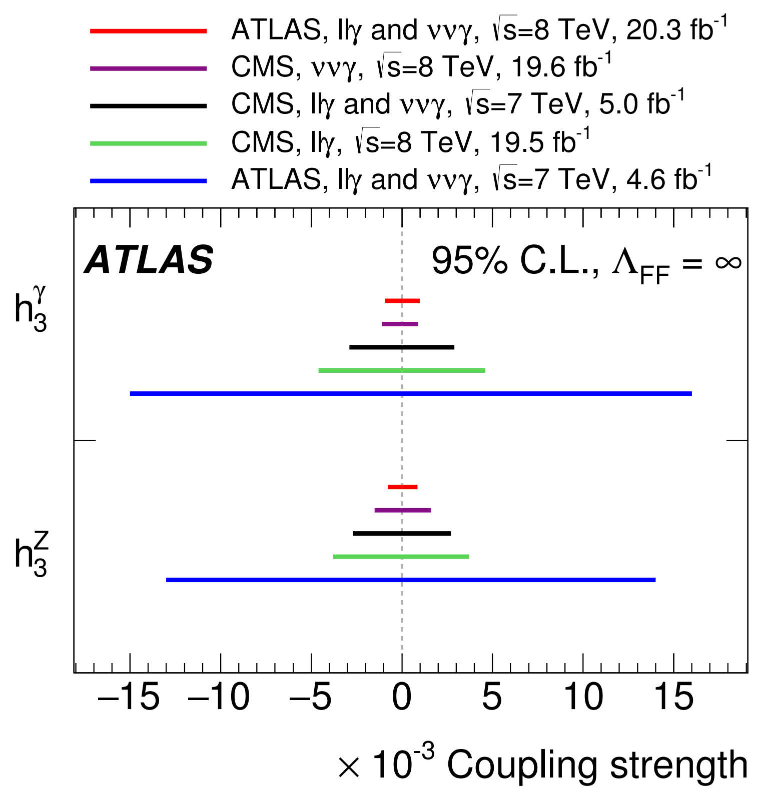
1604.05232

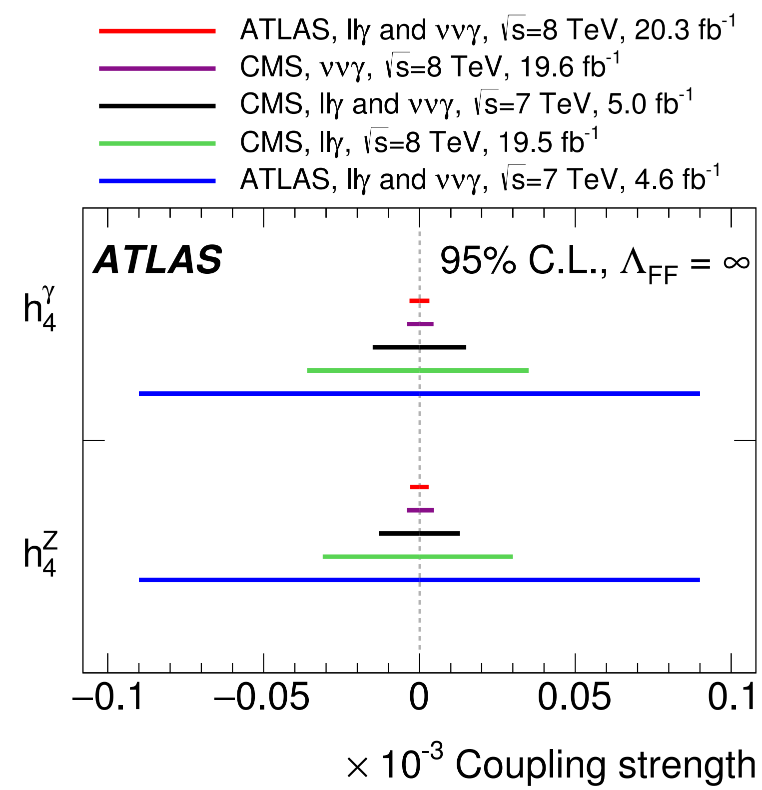




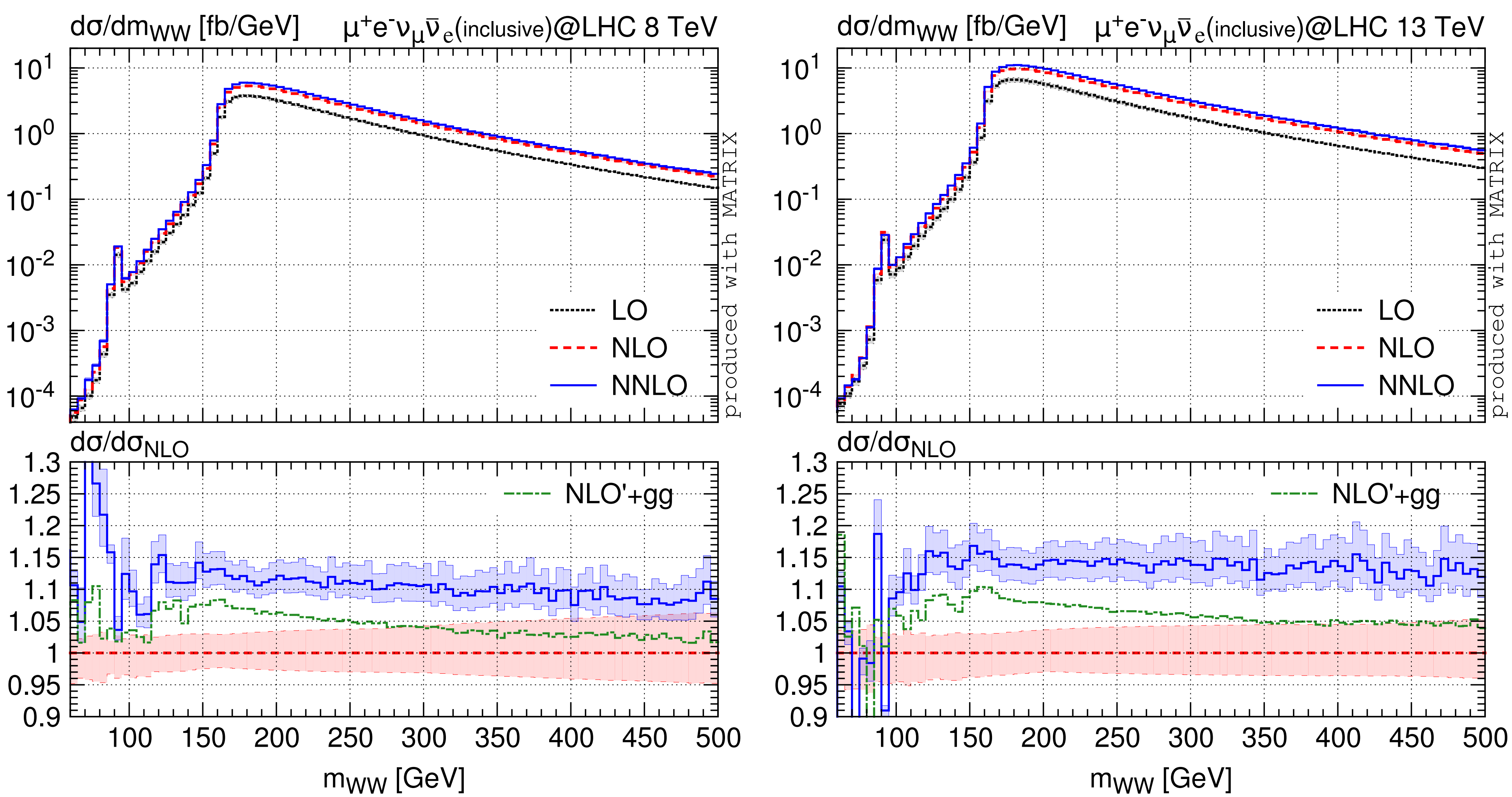
Nice agreement between NNLO prediction and data, and great limits on aTGCs.

NNLO prediction by Grazzini, Kallweit, Rathlev 15



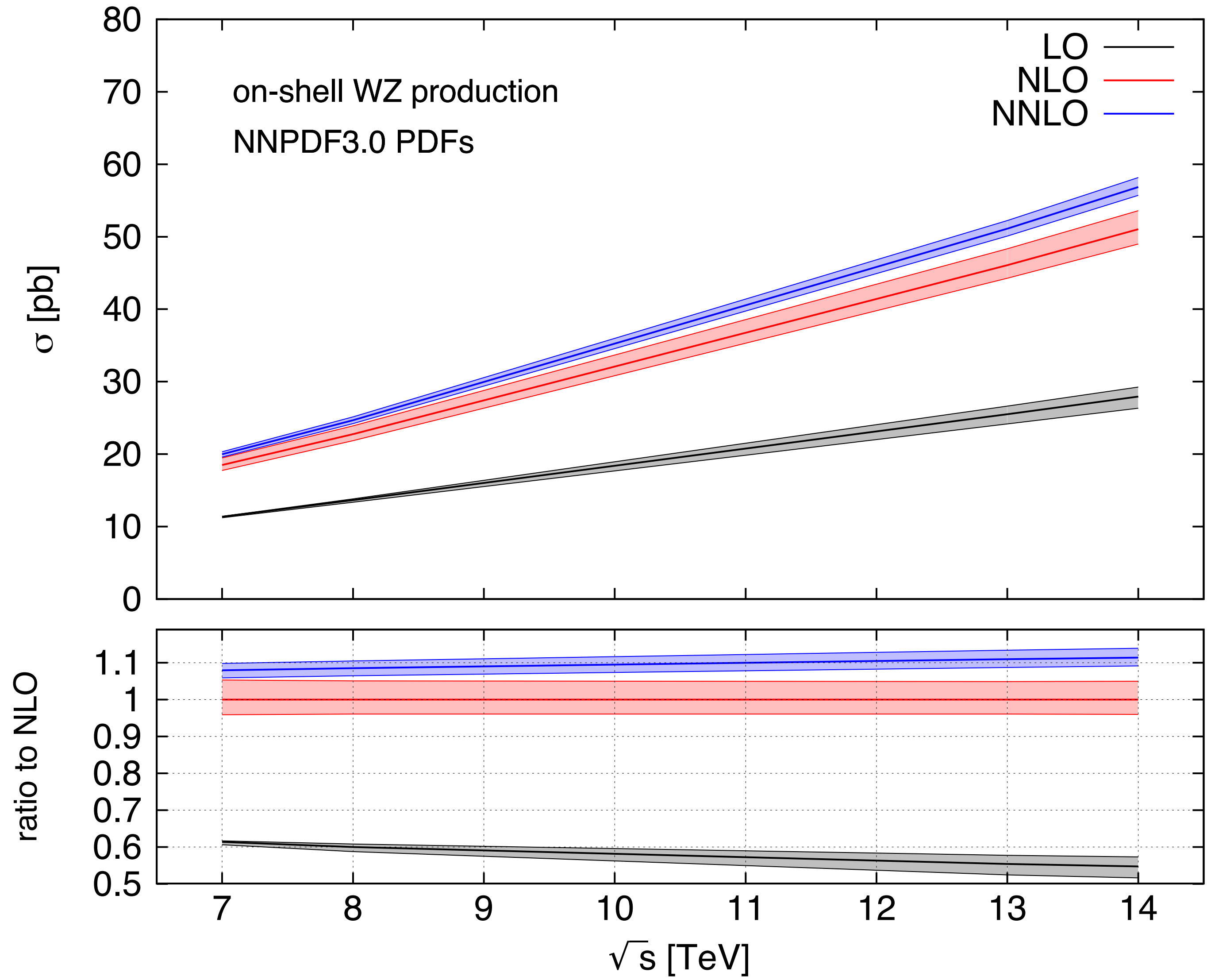


Grazzini, Kallweit, Pozzorini, Rathlev. Wiesmann 16



Inclusion of NNLO, fixes disagreement with data. Highlights need for NNLO (and kills light stops…)

Grazzini, Kallweit, Pozzorini, Rathlev. 16



WZ has also been calculated by the Zurich group, and completes the VV setup.

Conclusions

- The study of the production of multiple electroweak bosons remains a cornerstone of the LHC mission going forward.
- Given the high quality of the experimental analysis NNLO precision is mandated. At the accuracy we are shooting for EW corrections are also critical (see Ansgar's talk)
- NNLO techniques are maturing, VV is nearly all completed
- The best way to release NNLO results to the wider community is a challenging issue.
- MCFM 8.0 contains several singlet processes, with a full diboson release expected before the end of the year.