Precise predictions for di-boson production at the LHC

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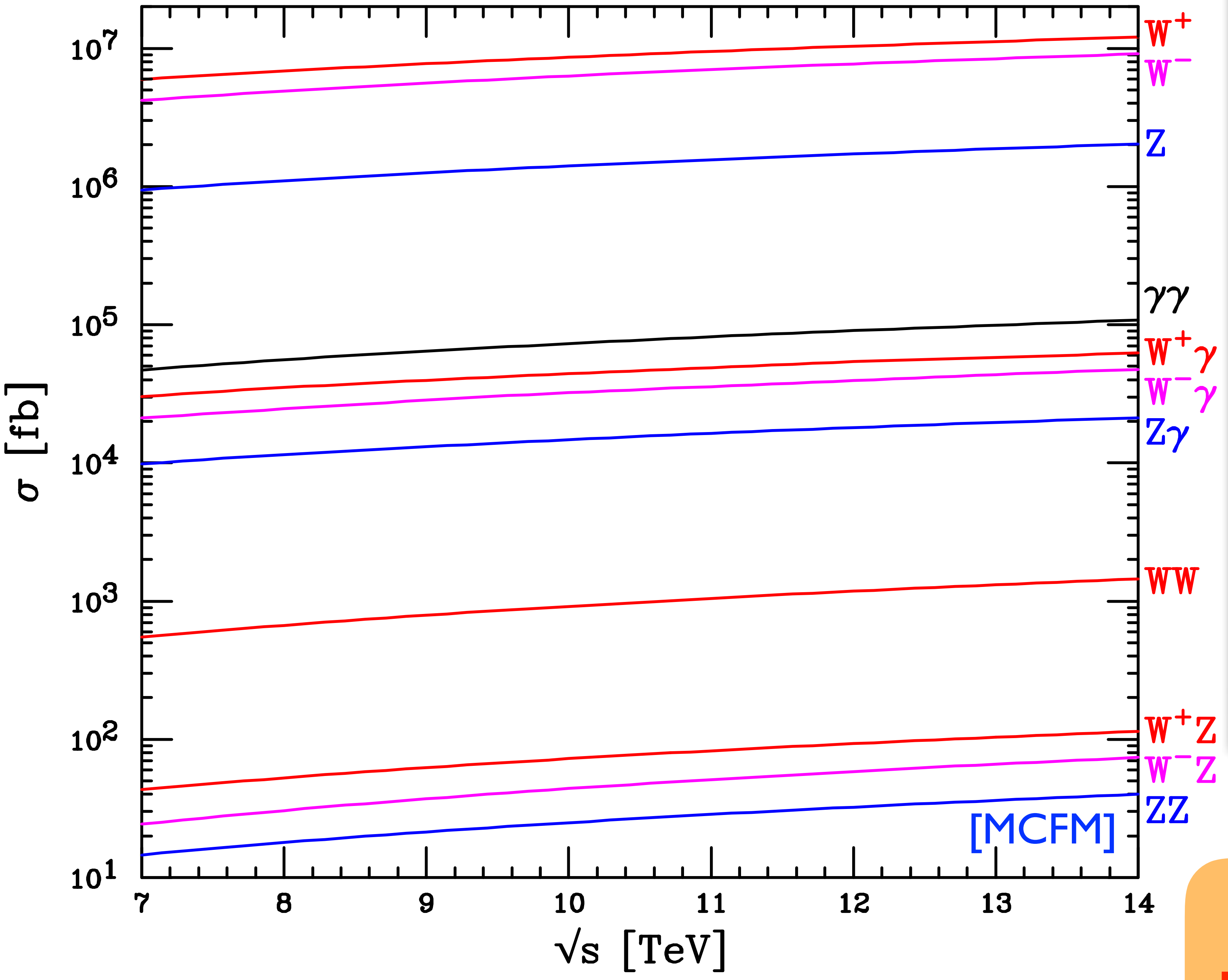
LHC Run II and the Precision Frontier, KITP, 30 Mar. 2016

Precision for di-boson: why

LHC: sizable cross-section



Good control on di-boson processes:

- Test the SU(2)xU(1) SM structure
- Higgs background, off-shell Higgs
- BSM backgrounds (leptons + $E_{t,miss}$)

LHC Run-1:
- ~10% accuracy
- no deviation from SM

PERCENT-LEVEL EXPERIMENTAL ACCURACY WITHIN REACH

Precision predictions for di-boson production at the LHC: outline

- The quest for precision: NNLO predictions
- The importance of fiducial measurements: the WW cross section
- Large effects beyond NNLO: gg->VV @ NLO

NNLO predictions for di-boson processes

Precise predictions: what do we need

$$\mathrm{d}\sigma = \int dx_1 dx_2 f_1(x_1) f_2(x_2) \mathrm{d}\sigma_{\mathrm{part}}(x_1, x_2) F_J (1 + \mathcal{O}(\Lambda_{\mathrm{QCD}}/Q))$$

Require precise input parameters (α_s, PDFs)

High-Q physics → part we have most control on

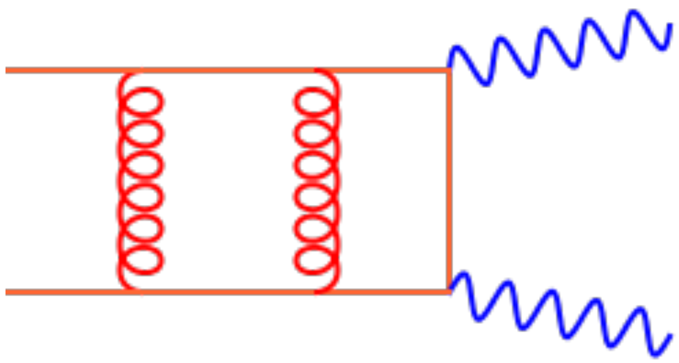
Must describe realistic conditions (fiducial cuts, arbitrary observables → fully differential)

Ultimate limitation: NP corrections.
For typical EW scale: ~ percent

Since $\alpha_s \sim 0.1$: percent-level control → NNLO PREDICTIONS

Anatomy of a NNLO computation - 1

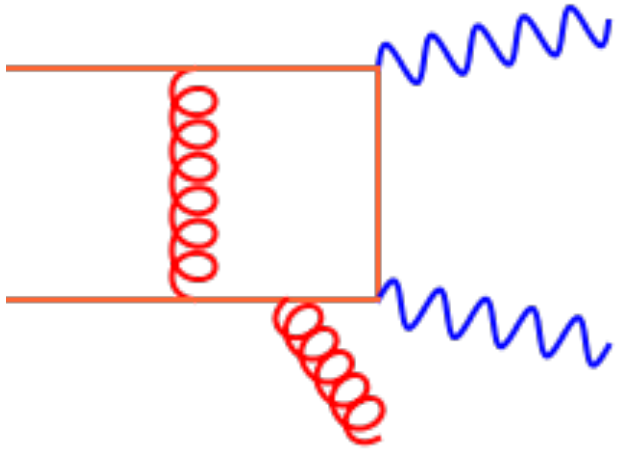
VV



UP TO TWO-LOOP FOR QQ -> VV

Amplitudes for pp -> VV -> 4l only computed recently [FC, Henn, Melnikov, Smirnov, Smirnov (2015); Gehrmann, Manteuffel, Tancredi (2015)]

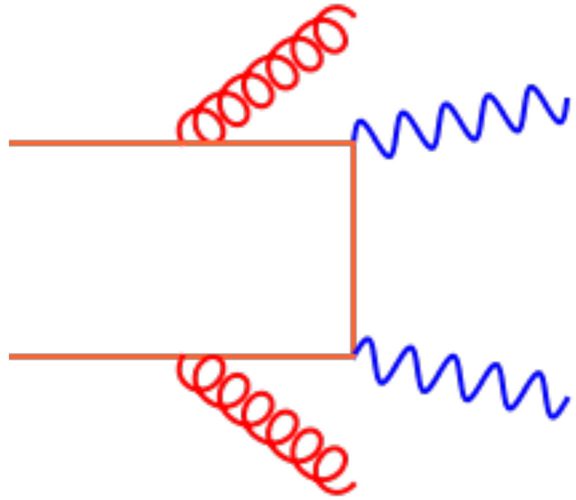
RV



UP TO ONE-LOOP FOR QQ -> VV+J

In principle, 'problem-solved'. IN PRACTICE: must be very stable and fast. For VV processes: OpenLoops proved reliable

RR



TREE-LEVEL FOR QQ -> VV+JJ

So a NNLO computation for VV 'naturally' contains a (N)LO computation for VV+(1)2 jet

Anatomy of a NNLO computation - II

- For a long time, the problem of NNLO computations was how to consistently extract IR singularity from double-real emission/real-virtual emission. Knowing all relevant amplitudes not enough (especially problematic for processes with non-trivial color structure)
- A lot of progress recently. First steps towards an optimal solution
  - Subtraction: antenna, sector-improved FKS, colorful
  - Slicing: q_T, N-jettiness
- In practice, this allowed for computations of 2->2 reactions at the LHC (top-pair, di-jet, single-top, H+J, V+J…)

NNLO: what does it buy you

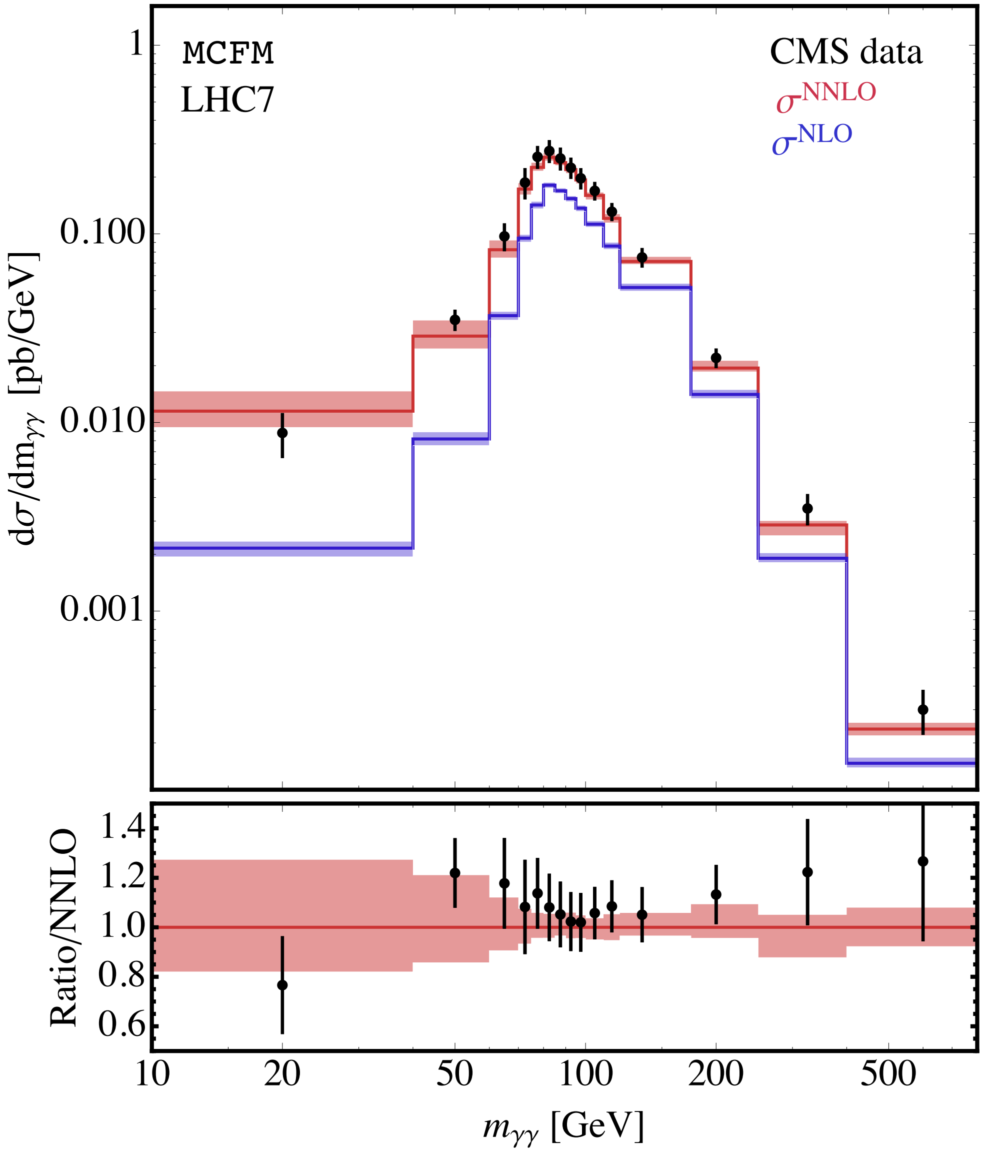
For Born-like observables (cross-section, m_{4l}, $p_{t,l}$…)

- Stabilization of the perturbative expansion

Example: Zγ, ATLAS setup [Grazzini, Kallweit, Rathlev (2015)]

$\sigma_{LO} = 0.81^{+8\%}_{-9.3\%}$, $\sigma_{LO} = 1.031^{+2.7\%}_{-4.3\%}$, $\sigma_{NNLO} = 1.059^{+0.7\%}_{-1.4\%}$ or

$K_{NLO} = +27\%$, $K_{NNLO} = +3\%$



- More reliable scale uncertainty estimates, typically reduced (→ discussions about 'right' scale less important)

For VV processes: no α_s at Born-level, lowest order scale uncertainty badly underestimates corrections (also, new channels open up)

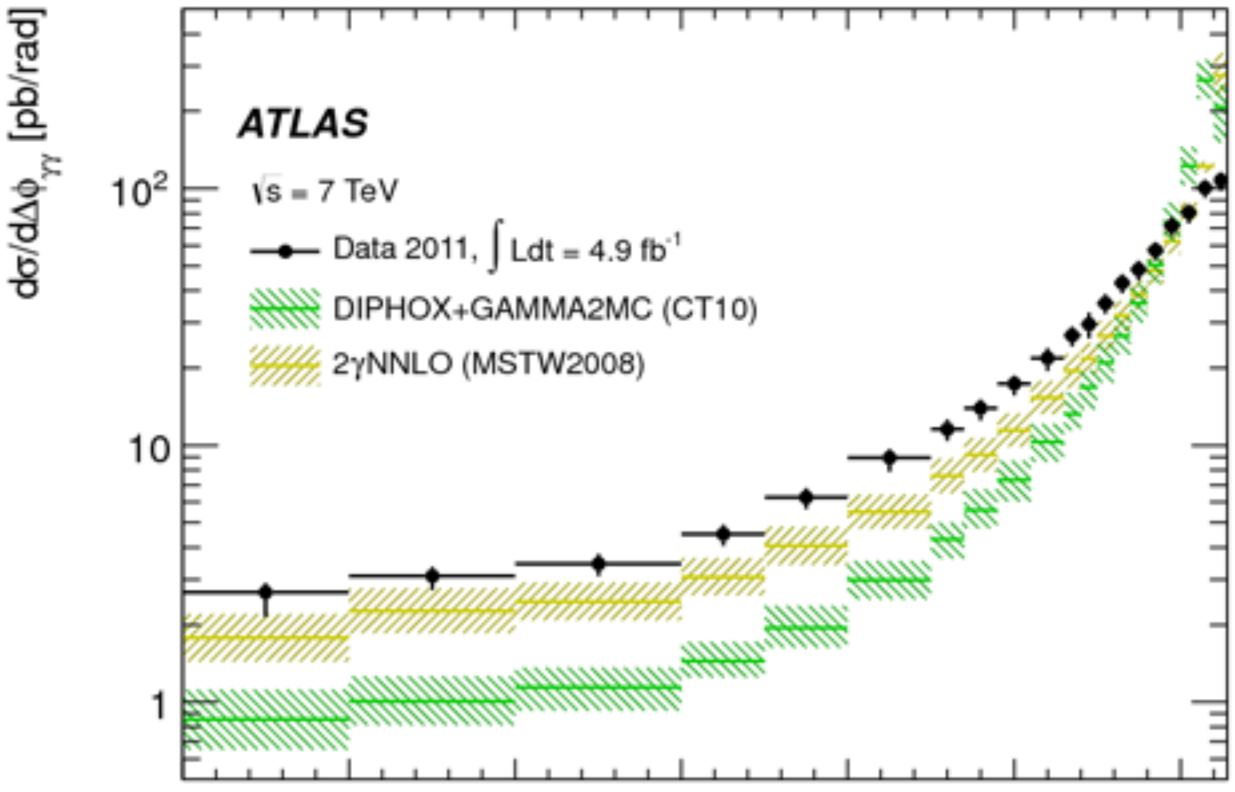
←**Example**: di-photon, $m_{\gamma\gamma}$, CMS setup [Campbell, Ellis, Li, Williams (2016)]

NNLO: what does it not buy you

For configurations dominated by extra hard radiation, NNLO VV predictions are the same of NLO predictions for VV+J. Example: di-photon opening angle

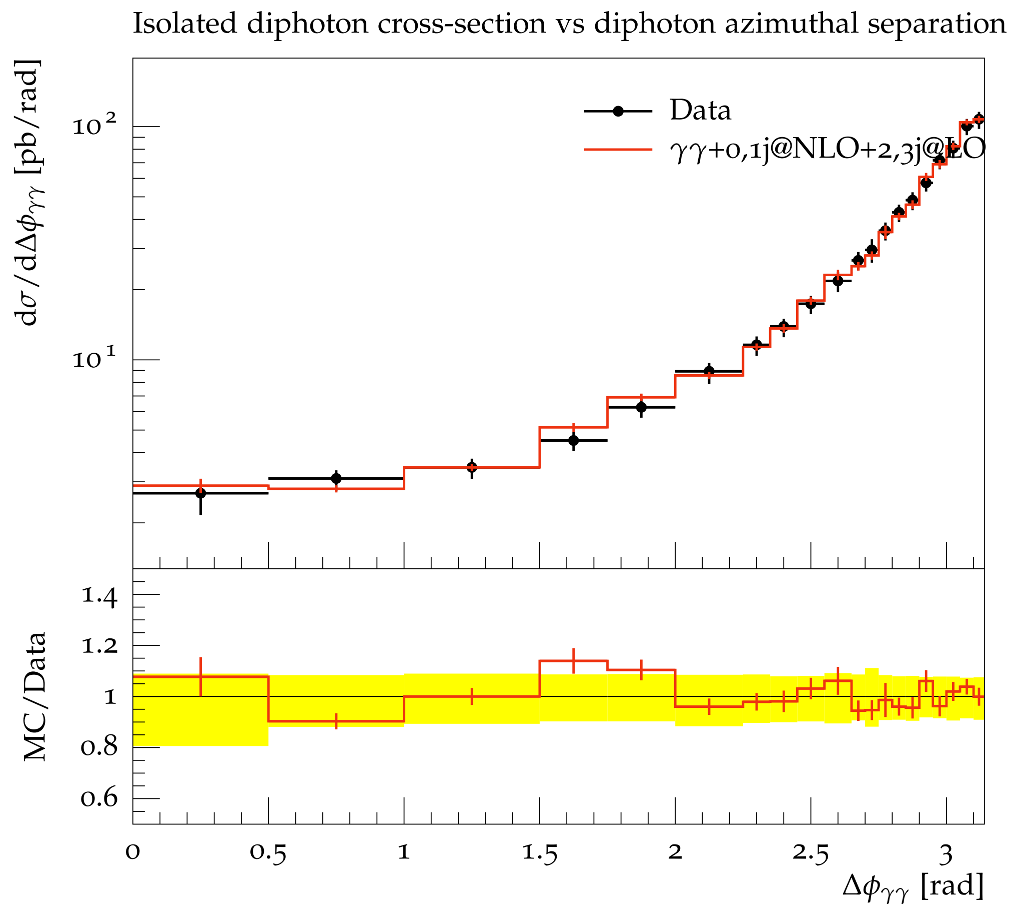
NNLO

[Catani et al. (2012)]



Merged NLO

[Höche and Siegert, SHERPA]



γγ@NNLO gives you γγJ@NLO for free, but nothing more

NNLO: where do we stand

NNLO corrections for almost all di-boson processes.

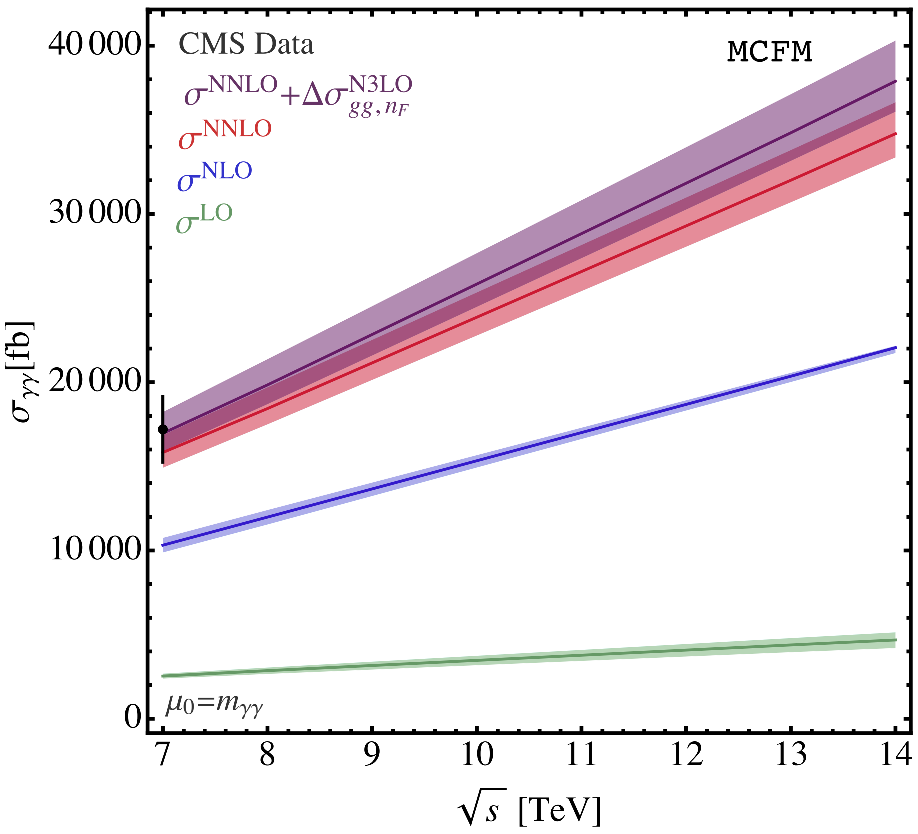
- $\gamma\gamma$: Catani et al. (2012); Campbell, Ellis, Li, Williams (2016)
- VV: Grazzini, Kallweit, Rathlev, Torre, Cascioli, Gehrmann, Maierhöfer, Manteuffel, Pozzorini, Tancredi, Weihs (2013-2015)

	Total Cross-Section	Fiducial	Higgs-region
$\gamma\gamma$	✓	✓	
$V\gamma$	✓	✓	
ZZ	✓	✓	✗
WW	✓	~	✗
WZ	✗	✗	

General picture: good theory/data agreement

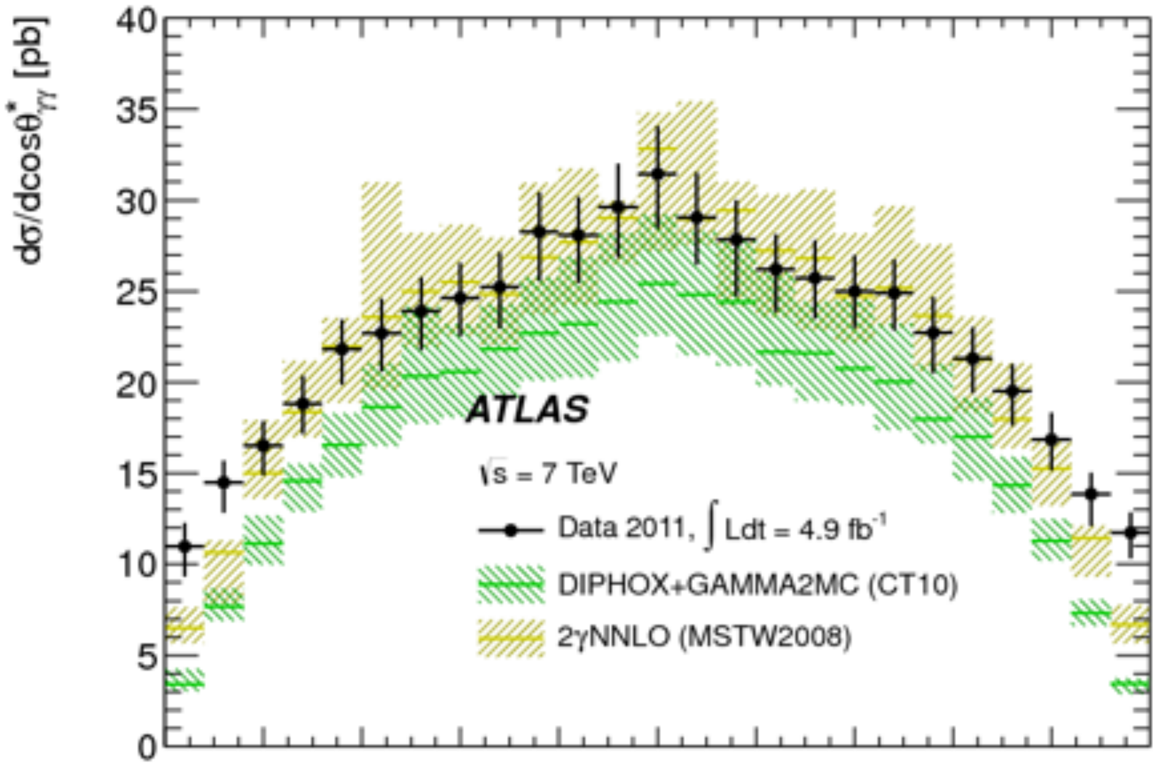
Sample results: γγ

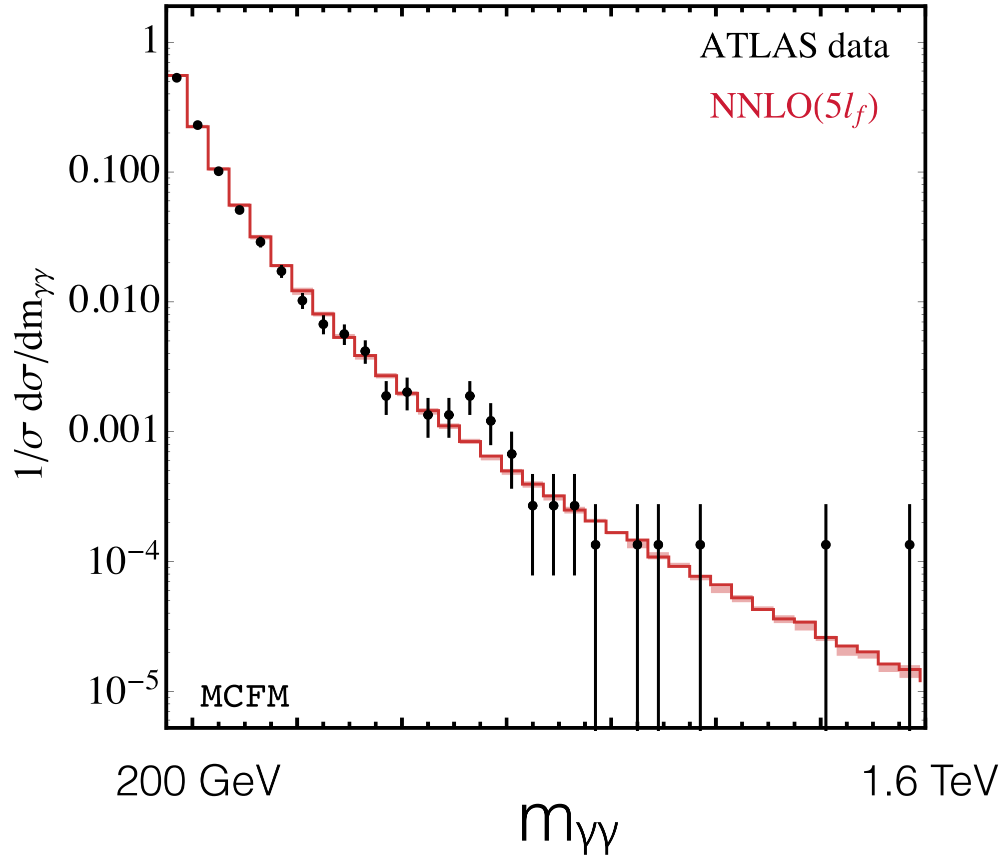
σ_{CMS} = 17.2 ± 0.2 (stat) ± 1.9 (syst) ± 0.4 (lumi) pb



σ_{MCFM} = 17.0 ± 1.2 pb [with gg@NLO]

- Excellent data/NNLO agreement
- gg@NLO sizable effect
- Nice validation with functional forms used for data-driven fits





Sample results: Vγ

[Grazzini, Kallweit, Rathlev, Torre (2013); Grazzini, Kallweit, Rathlev (2015)]

Fiducial region: NNLO vs ATLAS 7 TeV data

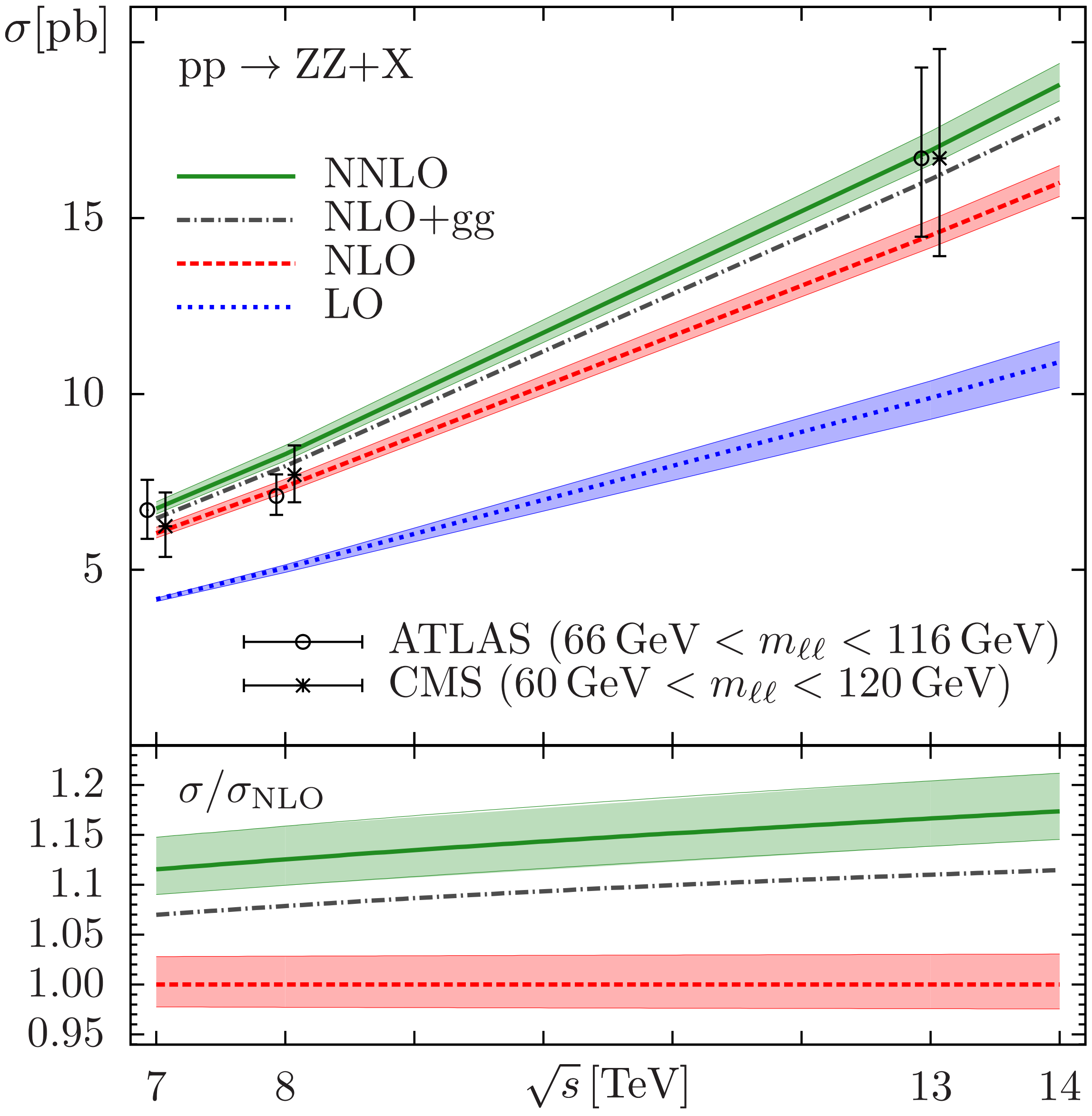
Kallweit, Moriond 2016

process	$p_{\mathrm{T,cut}}^{\gamma}$	N_{jet}	σ_{LO} [pb]	σ_{NLO} [pb]	σ_{NNLO} [pb]	σ_{ATLAS} [pb]	$\frac{\sigma_{\mathrm{NLO}}}{\sigma_{\mathrm{LO}}}$	$\frac{\sigma_{\mathrm{NNLO}}}{\sigma_{\mathrm{NLO}}}$
$\mathbf{Z}\gamma \to \ell\ell\gamma$	soft	≥ 0	$0.8149^{+8.0\%}_{-9.3\%}$	$1.222^{+4.2\%}_{-5.3\%}$	$1.320^{+1.3\%}_{-2.3\%}$	1.31 ±0.02 (stat) ±0.11 (syst) ±0.05 (lumi)	+50%	+8%
		$= 0$		$1.031^{+2.7\%}_{-4.3\%}$	$1.059^{+0.7\%}_{-1.4\%}$	1.05 ±0.02 (stat) ±0.10 (syst) ±0.04 (lumi)	+27%	+3%
	hard	≥ 0	$0.0736^{+3.4\%}_{-4.5\%}$	$0.1320^{+4.2\%}_{-4.0\%}$	$0.1543^{+3.1\%}_{-2.8\%}$		+79%	+17%
$\mathbf{Z}\gamma \to \nu\nu\gamma$		≥ 0	$0.0788^{+0.3\%}_{-0.9\%}$	$0.1237^{+4.1\%}_{-3.1\%}$	$0.1380^{+2.5\%}_{-2.3\%}$	0.133 ±0.013 (stat) ±0.020 (syst) ±0.005 (lumi)	+57%	+12%
		$= 0$		$0.0881^{+1.2\%}_{-1.3\%}$	$0.0866^{+1.0\%}_{-0.9\%}$	0.116 ±0.010 (stat) ±0.013 (syst) ±0.004 (lumi)	+12%	−2%
$\mathbf{W}\gamma \to \ell\nu\gamma$	soft	≥ 0	$0.8726^{+6.8\%}_{-8.1\%}$	$2.058^{+6.8\%}_{-6.8\%}$	$2.453^{+4.1\%}_{-4.1\%}$	2.77 ±0.03 (stat) ±0.33 (syst) ±0.14 (lumi)	+136%	+19%
		$= 0$		$1.395^{+5.2\%}_{-5.8\%}$	$1.493^{+1.7\%}_{-2.7\%}$	1.76 ±0.03 (stat) ±0.21 (syst) ±0.08 (lumi)	+60%	+7%
	hard	≥ 0	$0.1158^{+2.6\%}_{-3.7\%}$	$0.3959^{+9.0\%}_{-7.3\%}$	$0.4971^{+5.3\%}_{-4.7\%}$		+242%	+26%

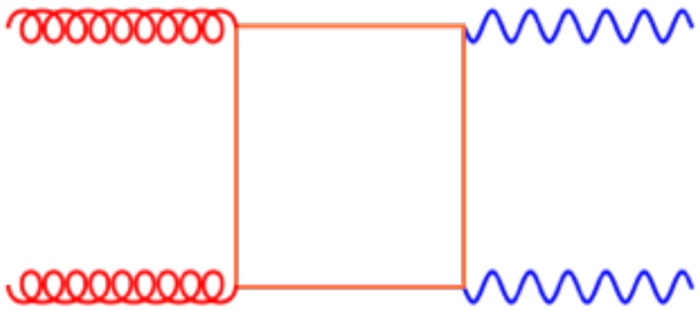
- In general, very good agreement, apart for Z→νν (under investigation)
- NLO scale variation fails to capture NNLO
- Negligible impact of gg channel

Sample results: ZZ

[Cascioli et al (2014); Grazzini, Kallweit, Rathlev (2015)]



- Largest contribution to NNLO from gg channel (~60%). LO-contribution



- Good agreement at 7, 8 and 13 TeV
- Perfect agreement for eμ channel, consistent within 1σ for ee, μμ channels

ATLAS 8 TeV fiducial

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

WW: total vs fiducial

The WW puzzle

Early LHC measurements

$\sigma_{\mathrm{ATLAS},8} = 71.4^{+1.2}_{-1.2}\,(\mathrm{stat})^{+5.0}_{-4.4}\,(\mathrm{syst})^{+2.2}_{-2.1}\,(\mathrm{lumi})\ \mathrm{pb}$

$\sigma_{\mathrm{CMS},8} = 69.9 \pm 2.8\,(\mathrm{stat}) \pm 5.6\,(\mathrm{syst}) \pm 3.1\,(\mathrm{lumi})\ \mathrm{pb}$

Theoretical prediction (MCFM)

$\sigma_{\mathrm{NLO}} = 56.5^{+1.5}_{-1.1}\ \mathrm{pb}$

NNLO corrections: ~ 10 %

SOME TENSION, FOR BOTH ATLAS AND CMS

The WW puzzle

However, if one looks at the FIDUCIAL REGION

	ATLAS @ 8 TeV	$pp \to l^+l^-\nu\bar{\nu}$	$pp \to H \to l^+l^-\nu\bar{\nu}$	total
$e^+\mu^- + e^-\mu^+$	$377.8^{+6.9}_{-6.8}(\text{stat.})^{+25.1}_{-22.2}(\text{syst.})^{+11.4}_{-10.7}(\text{lumi.})$	$332.4^{+4.7}_{-2.3}$	$9.8^{+0.0}_{-1.2}$	$342.2^{+4.7}_{-2.6}$
e^+e^-	$68.5^{+4.2}_{-4.1}(\text{stat.})^{+7.7}_{-6.6}(\text{syst.})^{+2.1}_{-2.0}(\text{lumi.})$	$63.7^{+0.8}_{-0.4}$	$2.2^{+0.0}_{-0.2}$	$65.9^{+0.8}_{-0.4}$
$\mu^+\mu^-$	$74.4^{+3.3}_{-3.2}(\text{stat.})^{+7.0}_{-6.0}(\text{syst.})^{+2.3}_{-2.1}(\text{lumi.})$	$69.3^{+0.9}_{-0.4}$	$2.4^{+0.0}_{-0.2}$	$71.7^{+0.9}_{-0.5}$

[Monni, Zanderighi (2014)]

TENSION SIGNIFICANTLY ALLEVIATED

In other words, comparing NLO predictions to what is ACTUALLY MEASURED leads to reasonable data/theory agreement.

Note: same data, same theory →

WHAT IS GOING ON?

(ATLAS) analysis for dummies

1. Perform the measurement. By definition, in the fiducial region.
   Agreement data/theory

2. Use your favorite toy, let's say POWHEG, to extrapolate from the fiducial region to the total cross-section

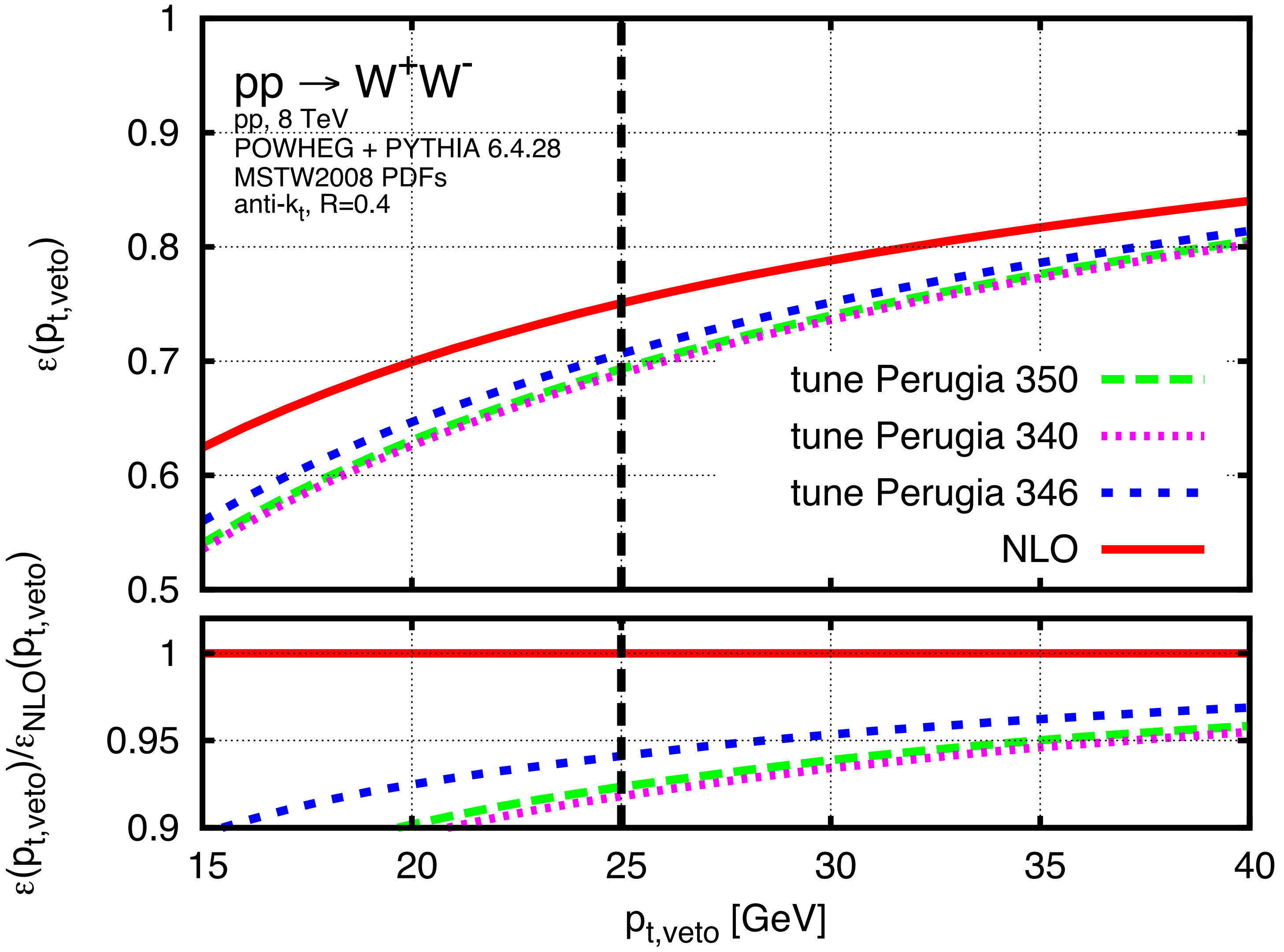
3. Get the total cross section and compare
   → Disagreement data/theory

Step 2 introduced a (a-priori non-needed) theory dependence on the result, and this time got it wrong

The problem with extrapolation: jet veto modeling

[Monni, Zanderighi (2014)]

To suppress the large top background, WW analysis require a harsh jet veto, $p_{t,veto}$ = 25 GeV



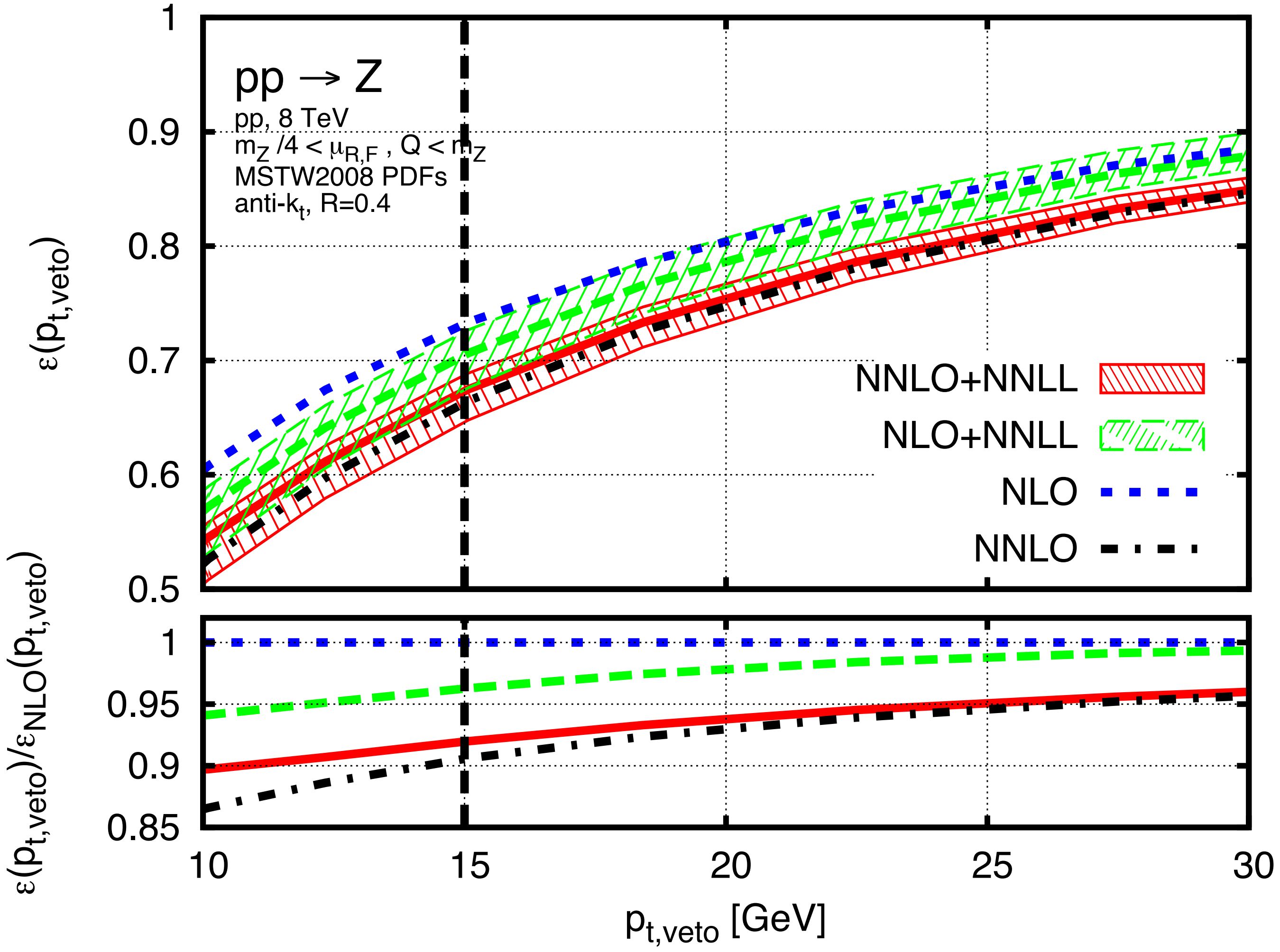
- Independent on tunes, POWHEG fails to properly model the jet veto efficiency and predicts fiducial cross section which are systematically lower
- When used for acceptance corrections, it then leads to overestimate the inclusive cross section

The problem with extrapolation: jet veto modeling

[Monni, Zanderighi (2014)]

A more refined analysis: POWHEG vs NNLL resummation

- For $p_{t,veto}$ = 25 GeV, NNLL resummation effects decrease pure NLO by 3-4%
- POWHEG prediction: -9%
- Also, other small effects in POWHEG further decrease efficiency
- NNLO+NNLL partially compensates for NNLO K-factor → agreement in the fiducial region should persist / improve at NNLO



THESE EFFECTS COMPLETELY EXPLAIN THE EXCESS IN THE INCLUSIVE ‘MEASUREMENT’

New analysis: approximate NLO+NNLL

$$\sigma_{\mathrm{ATLAS},8} = 71.1^{+1.1}_{-1.1}\,(\mathrm{stat})^{+5.7}_{-5.}\,(\mathrm{syst})^{+1.4}_{-1.4}\,(\mathrm{lumi})\ \mathrm{pb}$$

[Higgs contribution included]

$$\sigma_{\mathrm{CMS},8} = 60.1 \pm 0.9\,(\mathrm{stat}) \pm 3.2\,(\mathrm{exp}) \pm 3.1\,(\mathrm{th}) \pm 1.6\,(\mathrm{th})\ \mathrm{pb}$$

[Higgs contribution subtracted]

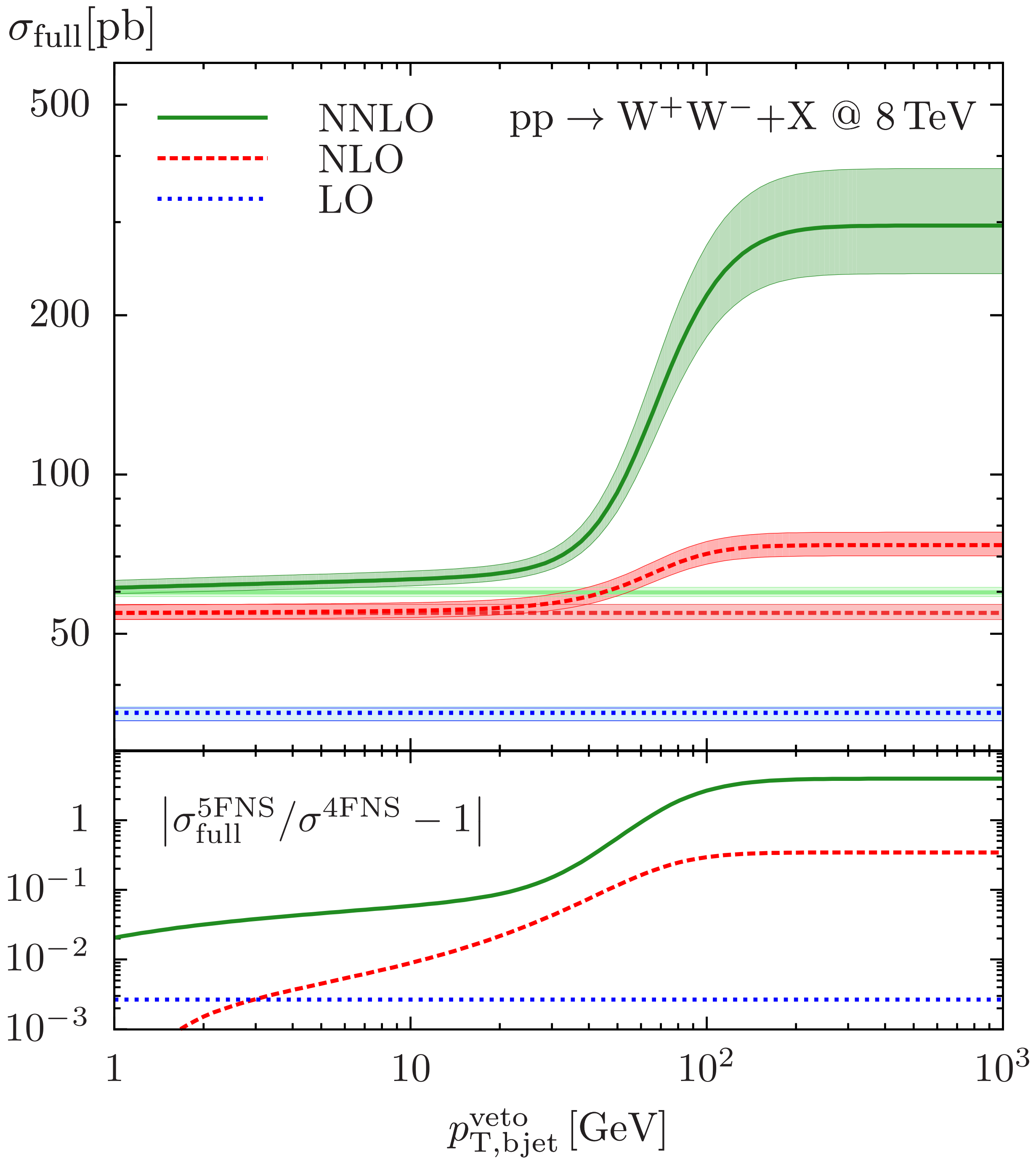
$$\sigma_{\mathrm{NNLO}} = 59.84\ ^{+2.2\%}_{-1.9\%} + 4.14\ ^{+7.2\%}_{-7.2\%}\,(\mathrm{Higgs})\ \mathrm{pb}$$

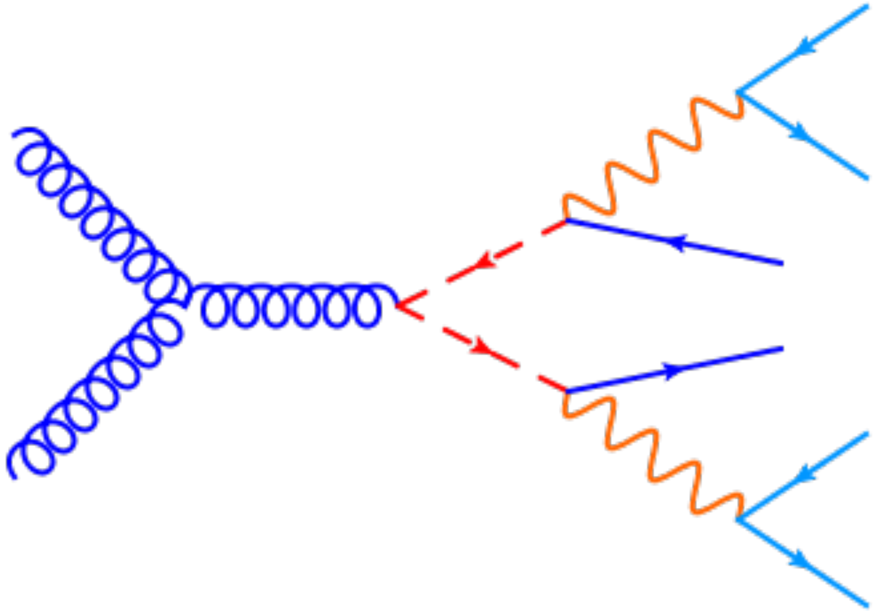
- Perfect agreement for CMS
- Slight ~1.5σ tension with ATLAS

Calls for Comparisons in the Fiducial Region
(all ingredients are available, minimize theory error)

Why fiducial region 2: top contamination

At NNLO: huge contamination from (LO) tt production for the inclusive cross-section



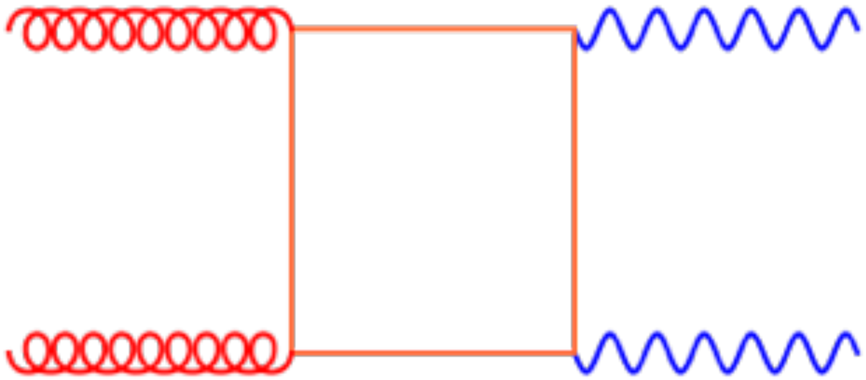


- Different approaches studies for defining the total cross-section (4FNS, b-veto, resonance expansion)
- Should greatly simplify in the FIDUCIAL REGION

VV: gluon channel at NLO

gg->VV

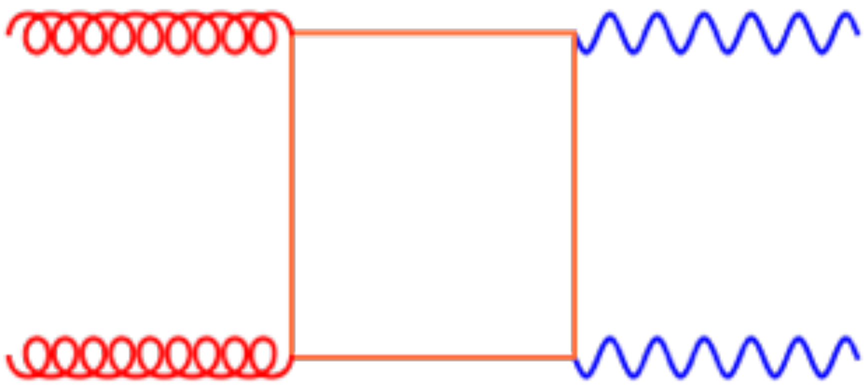
- At NNLO, the gg channel enters for the first time



- Because of the large gluon flux at the LHC, this contribution is usually big (ZZ/WW: 60%/35% of NNLO corrections)
- They are separately finite and gauge-invariant → usually already included in NLO predictions
- non trivial interference pattern with Higgs, especially in the high invariant mass region → very important for off-shell / interference analysis

gg->VV

- At NNLO, the gg channel enters for the first time

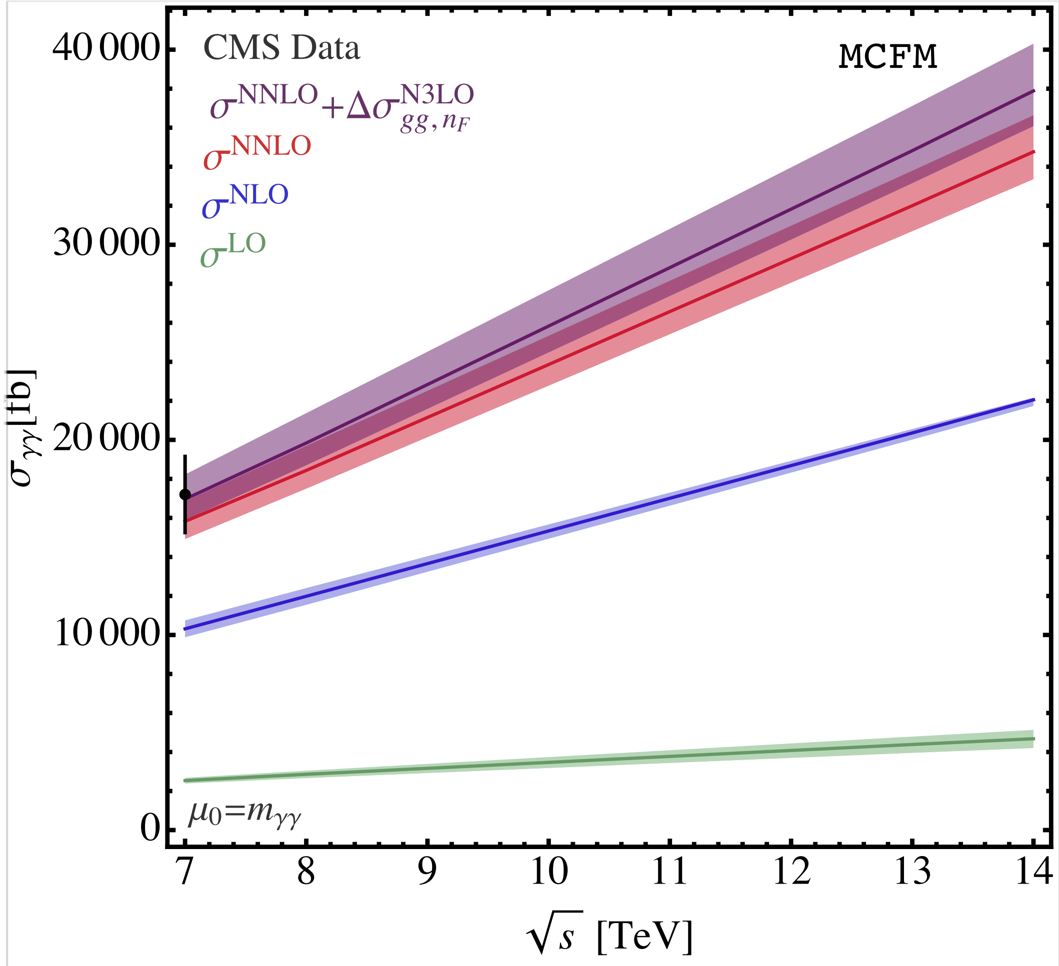


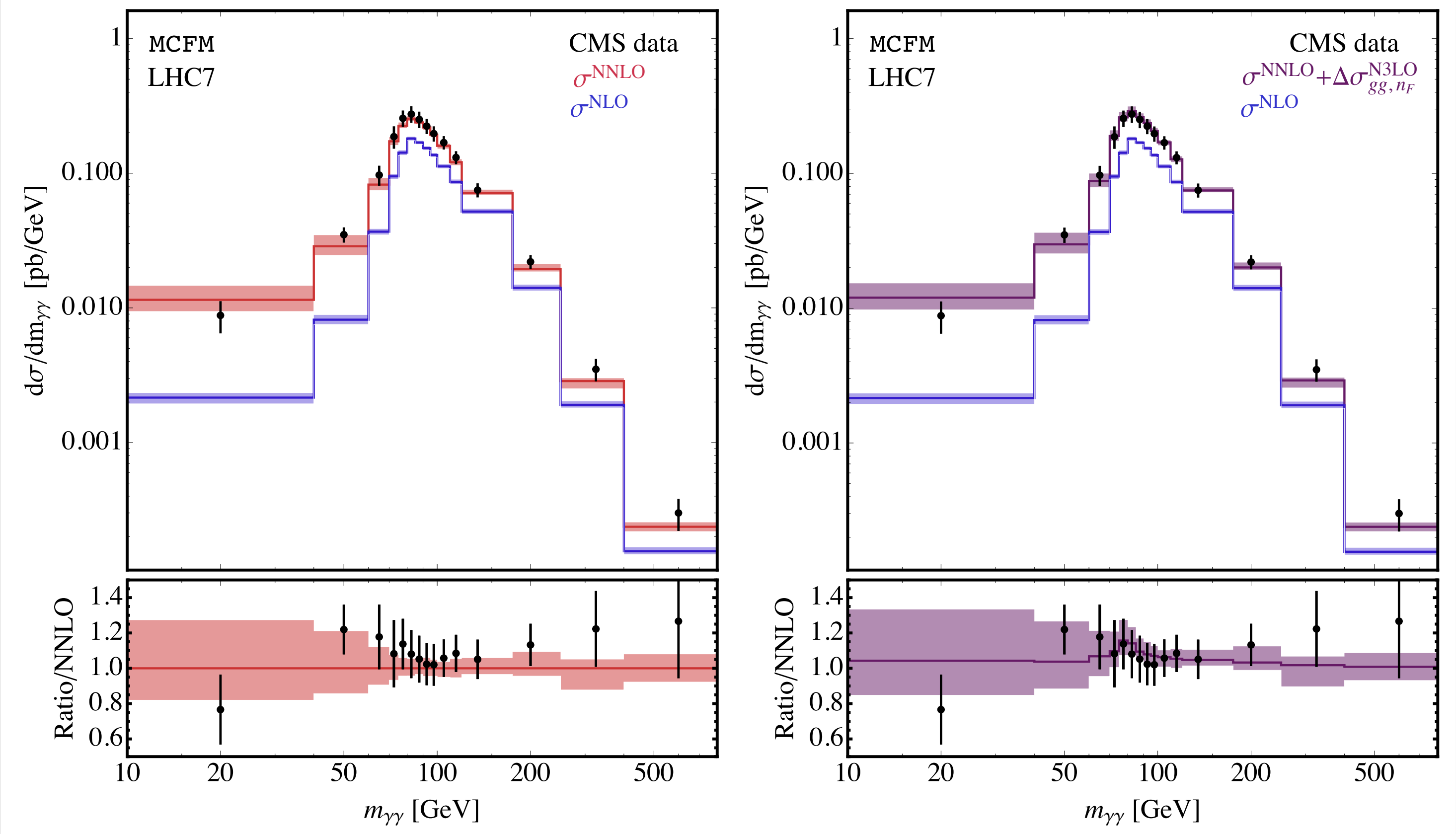
- Gluon induced process → expect large corrections. Despite being part of the NNLO computation, it is actually LO
- Corrections to gg->VV are formally part of the N^3LO corrections to pp->VV, but are expected to give sizable contribution
- NLO CORRECTIONS FOR GG->VV DESIRABLE

Example: $\gamma\gamma$

[Campbell, Ellis, Li, Williams (2016)]

σ_{CMS} = 17.2 ± 0.2 (stat) ± 1.9 (syst) ± 0.4 (lumi) pb





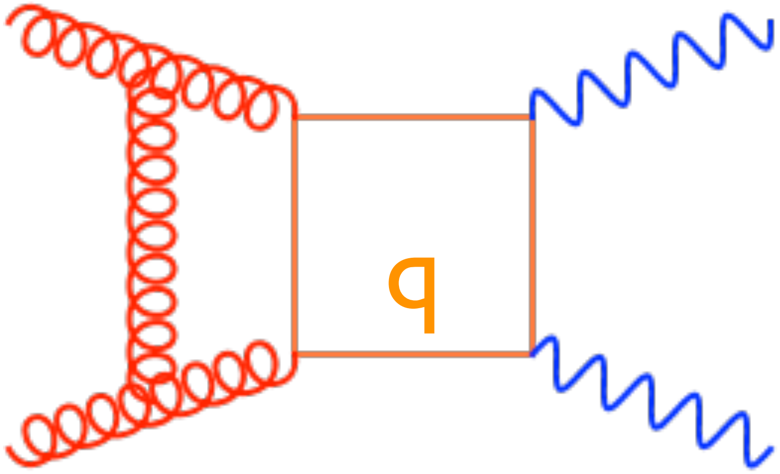
σ_{NNLO} = 15.8 ± 1 pb

$\delta\sigma_{gg\to\gamma\gamma@NLO}$ = 1.2 pb

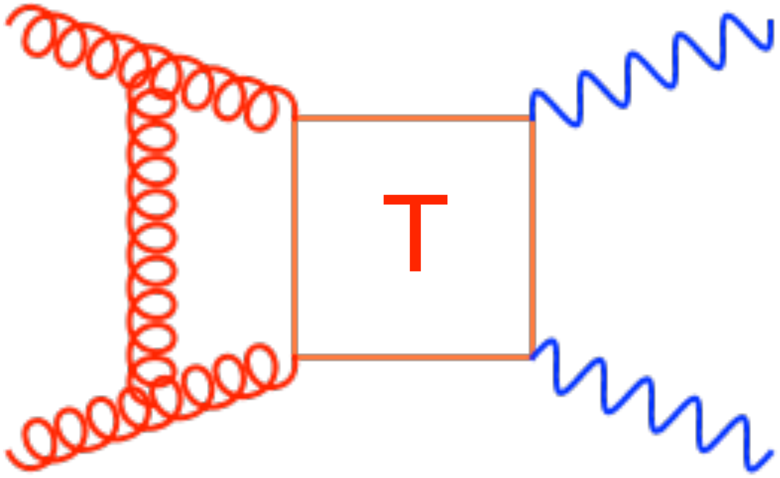
- Sizable effect
- Somewhat improves data/theory agreement

gg->WW/ZZ@NLO: problems

- Despite being a NLO computation, it involves complicated 2-loop amplitudes (LO is loop-induced). Similar amplitudes for qq->VV@NNLO
- Especially for Higgs analysis, important to go at high invariant mass → top quark contribution become relevant (same for qq->VV@NNLO)



Recently computed



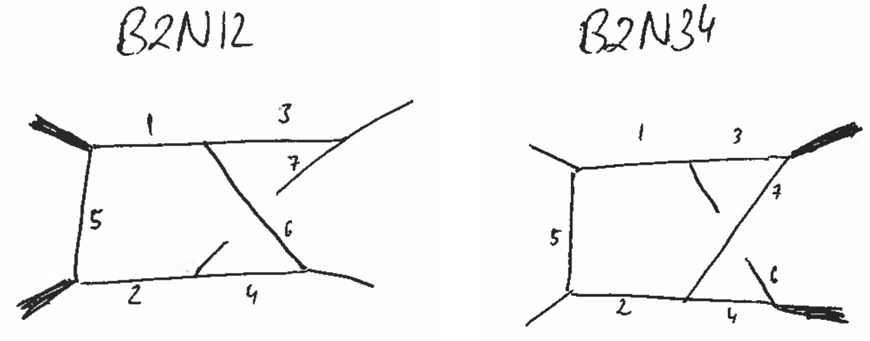
VERY HARD

[important in the off-shell region]

gg->ZZ@NLO: massless quarks

2-loop amplitude for ZZ*

new ideas
for FI
at work

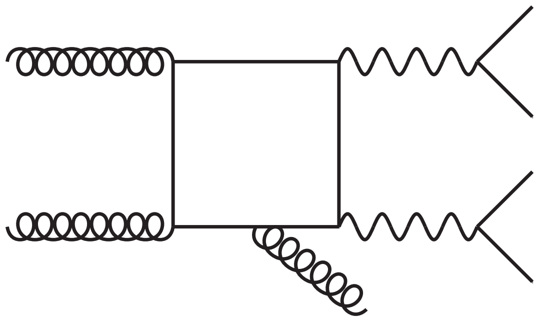


$$\partial_x \vec{f} = \epsilon \hat{A}_x(x, y, z \dots)\vec{f}$$

$$G(a_n, a_{n-1}, \dots, a_1, t) = \int_0^t \frac{\mathrm{d}t_n}{t_n - a_n} G(a_{n-1}, \dots a_1, t_n)$$

[FC, Henn, Melnikov, Smirnov, Smirnov (2014-15);
Gehrmann, Manteuffel, Tancredi (2014-15)]

Real emission

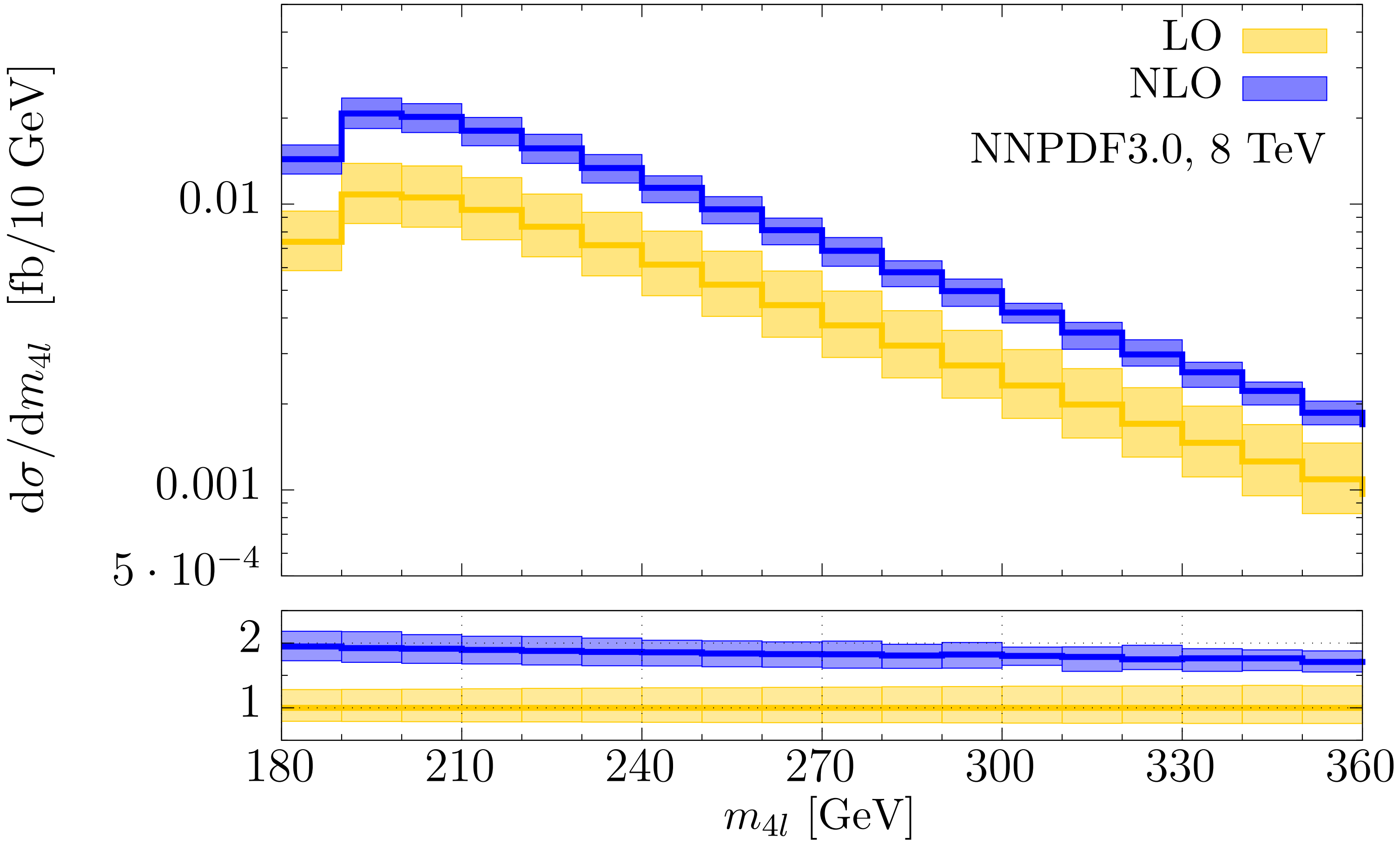


fast and stable
in soft/collinear
configurations

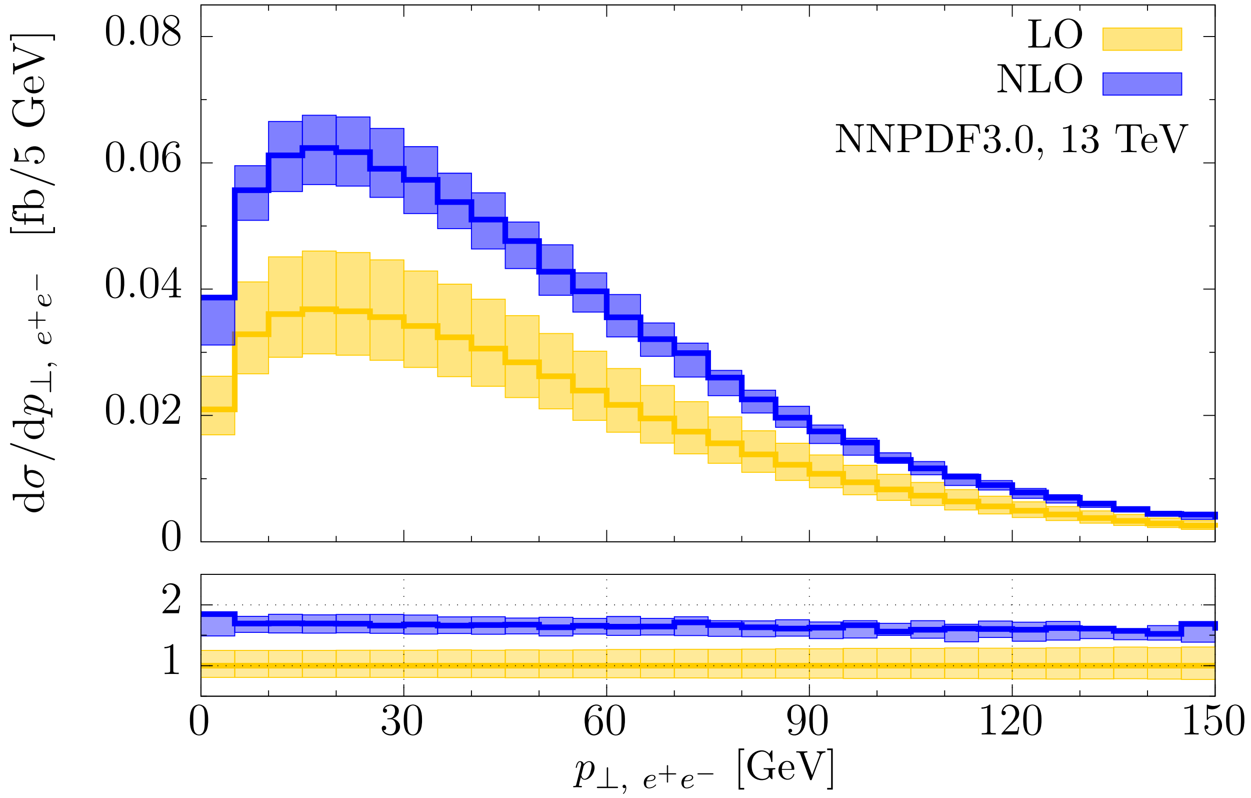
mixed analytical
+numerical unitarity

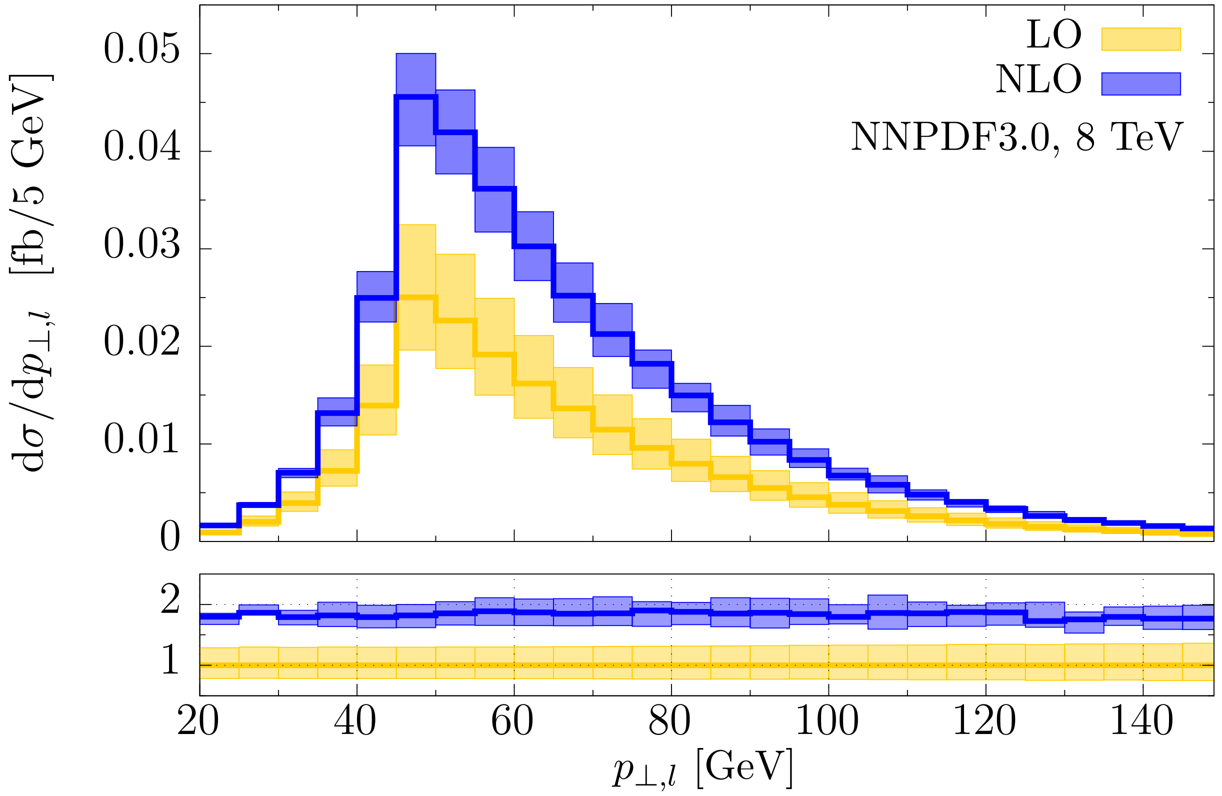
[FC, Melnikov, Röntsch, Tancredi (2015)]

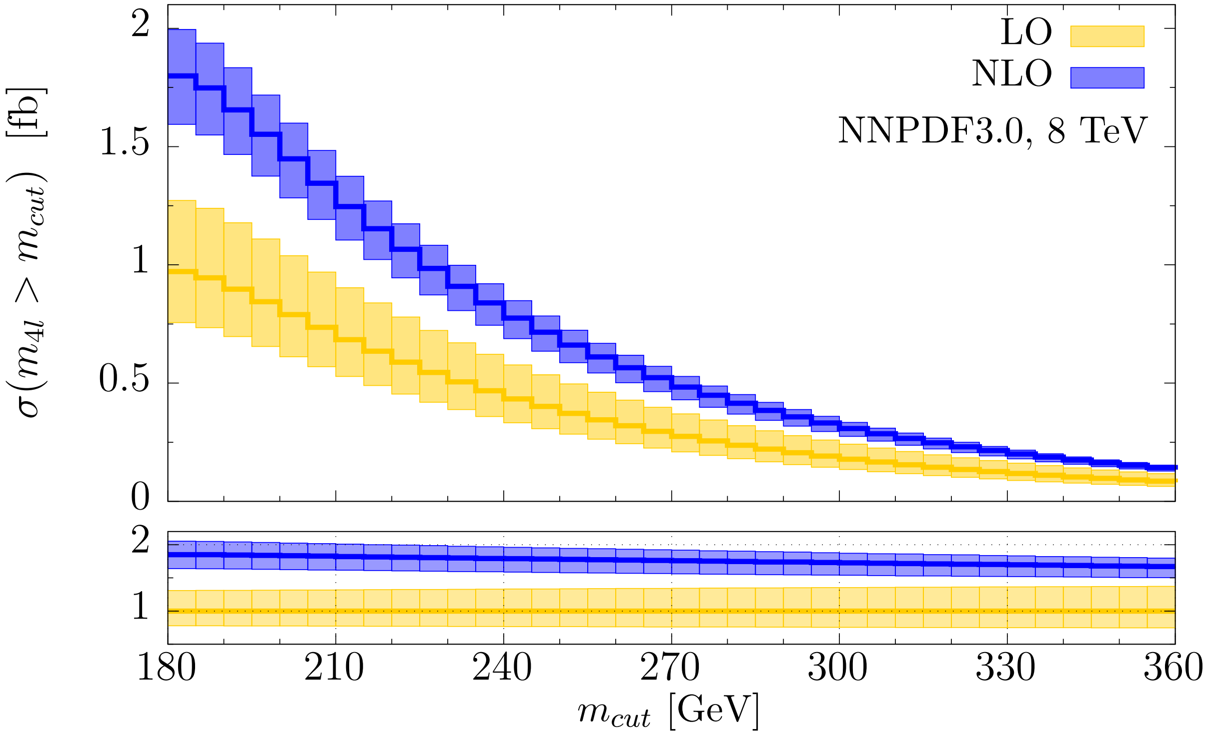
- large corrections
- effect on NNLO: +6% (NNLO scale uncertainty ~ 3%)
- massive loop contribution to σ_{tot} ~ 1%



gg->ZZ@NLO: massless quarks



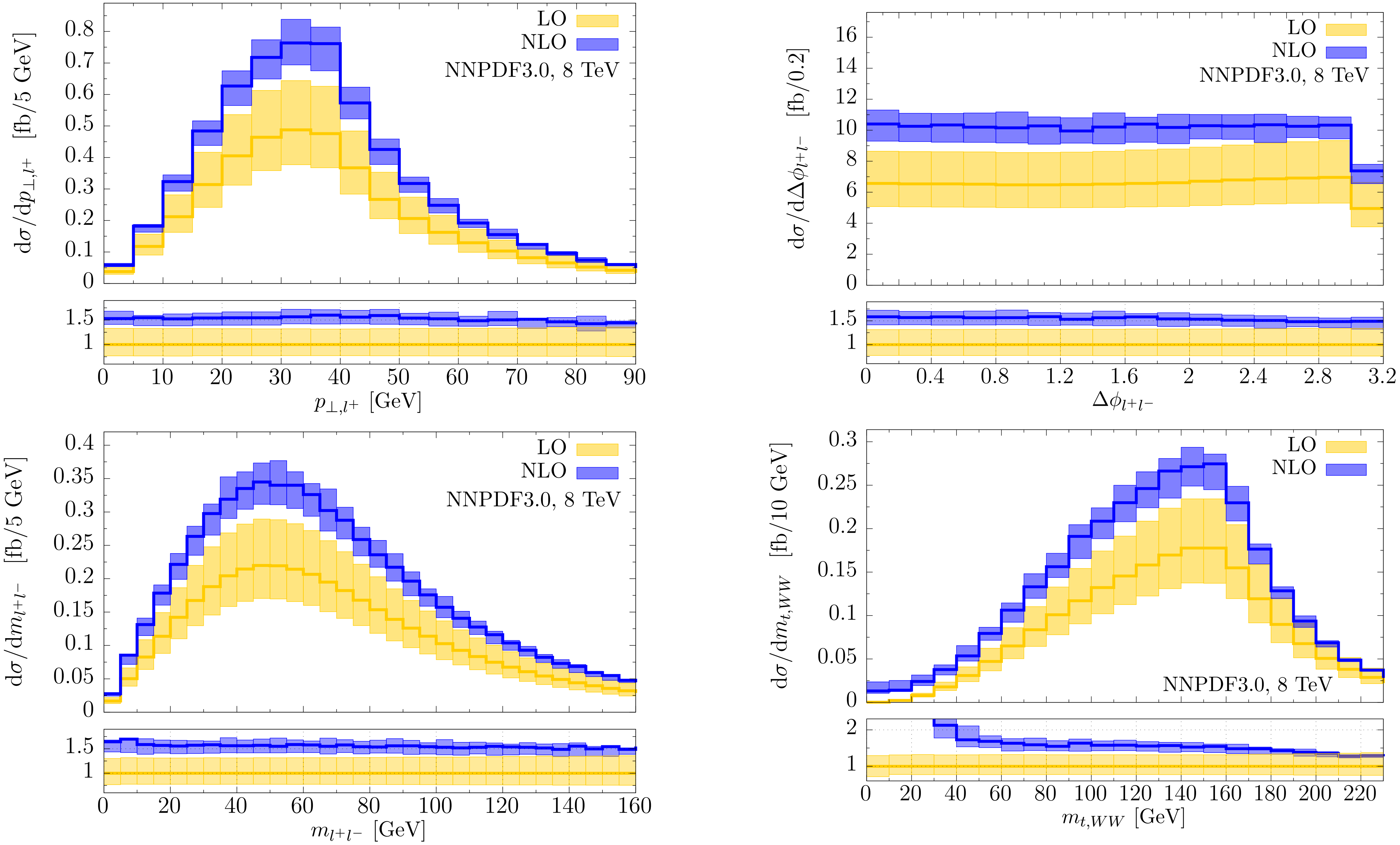




- realistic final states (leptons)
- Z off-shell, Z/γ interference (→can study on the Higgs peak)
- K-factor relatively flat

gg->WW@NLO: massless quarks

[FC, Melnikov, Röntsch, Tancredi (2015)]



- similar corrections to ZZ, K-factor typically stable
- smaller impact on NNLO (~2%)
- massive loop contribution ~ 10%

gg->WW@NLO: massless quarks

[FC, Melnikov, Röntsch, Tancredi (2015)]

- fiducial predictions, ATLAS 8TeV

	$\sigma_{\mu\mu,8\text{ TeV}}$	$\sigma_{ee,8\text{ TeV}}$	$\sigma_{e\mu,8\text{ TeV}}$
$\sigma_{gg,\text{LO}}$ [fb]	$5.94^{+1.89}_{-1.35}$	$5.40^{+1.71}_{-1.23}$	$9.79^{+3.13}_{-2.24}$
$\sigma_{gg,\text{NLO}}$ [fb]	$7.01^{-0.36}_{-0.17}$	$6.40^{-0.32}_{-0.16}$	$11.78^{-0.46}_{-0.34}$

- (rough) combination with NNLO

$$\sigma^{q\bar{q}+H+gg,\text{NLO}}_{\mu\mu,ee,e\mu+\mu e} = (72.0^{+1.3}_{-2.1},\ 66.3^{+1.2}_{-1.7},\ 337.3^{+6.3}_{-4.5})$$

- ATLAS result

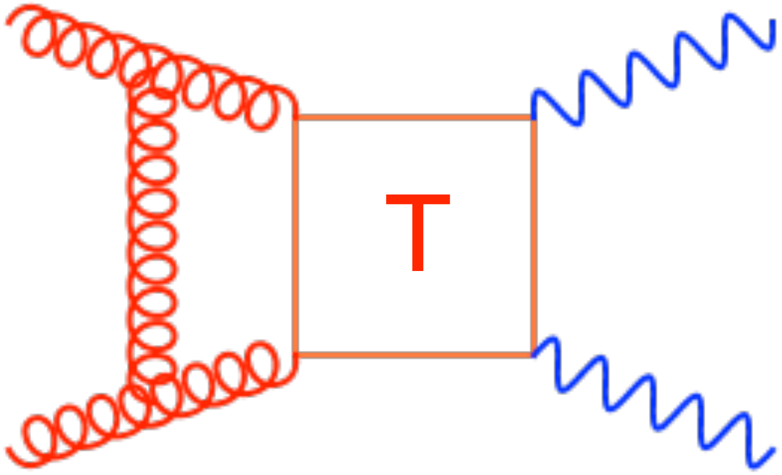
$$\sigma_{\mu\mu,ee,e\mu+\mu e} = (74.4^{+8.1}_{-7.1},\ 68.5^{+9.0}_{-8.0},\ 377.8^{+28.4}_{-25.6})$$

It would be very interesting to properly combine NNLO and gg->VV@NLO in the fiducial region

gg->VV: massive loops

[FC, Dowling, Melnikov, Röntsch, Tancredi, in progress]

- Compute exact two-loop amplitudes mediated by heavy quarks beyond current technology

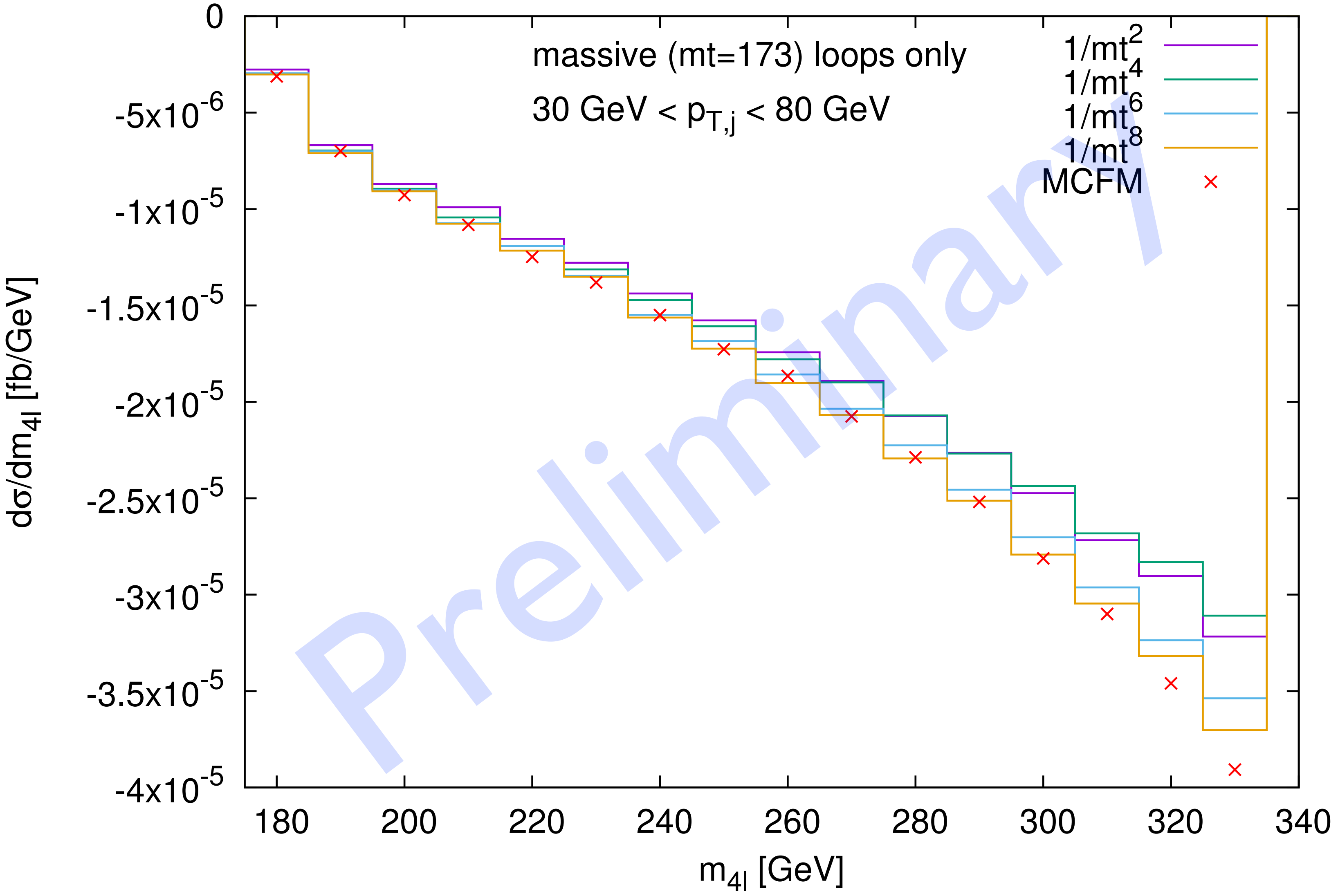


- Intermediate solution: expand in $1/m_t$
- Should give reliable results below the two-top threshold
- Validation: real emission, can be done exactly

gg->VV: massive loops

[FC, Dowling, Melnikov, Röntsch, Tancredi, in progress]

- Validation example: gg->H+j->4l+j vs gg->4l+j signal/background interference
- Exact result: [Campbell, Ellis, Furlan, Röntsch (2014)]



- If enough terms in the expansion are kept: very good agreement
- Promising results
- Will allow for accurate description up to m_{4l} ~ 340 GeV

Conclusions

- Precision physics in the di-boson sector will be possible
- Sophisticated NNLO predictions for almost all processes, almost all in the fiducial region as well
- Comparison data / theory should be compared in the fiducial region (minimize extrapolation errors, simplify theoretical definitions)
- Several small effects on top of NNLO can play a relevant role at the few-percent level. One example: gg->VV@NLO. Other example: electroweak corrections (especially at high p_T)
- Looking forward to compare against precise results from Run-2!

Thank you for
your attention!