PRECISION STUDIES OF VECTOR BOSON PRODUCTION

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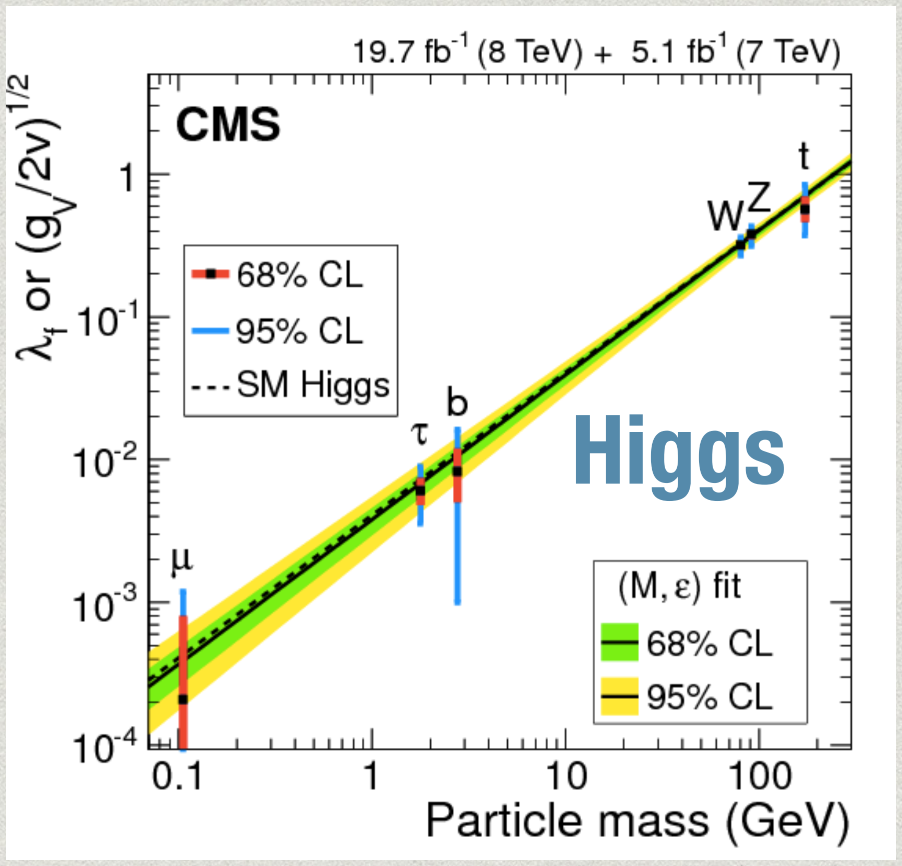
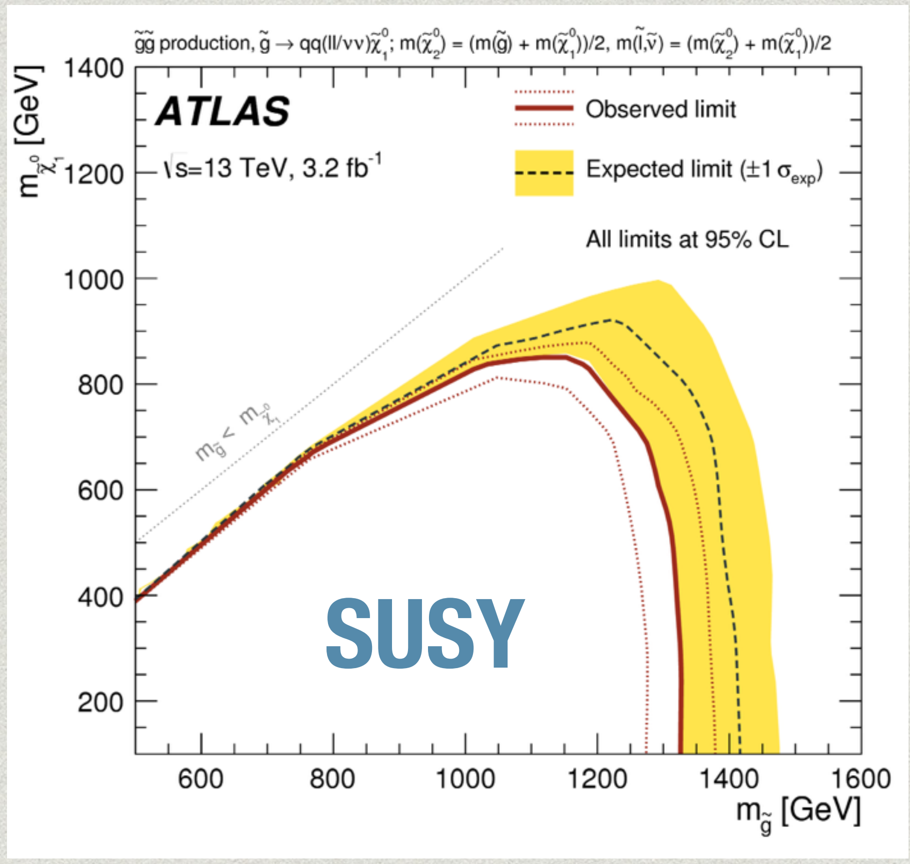
STRESS-TESTING THE STANDARD MODEL AT THE LHC

What next for the LHC?

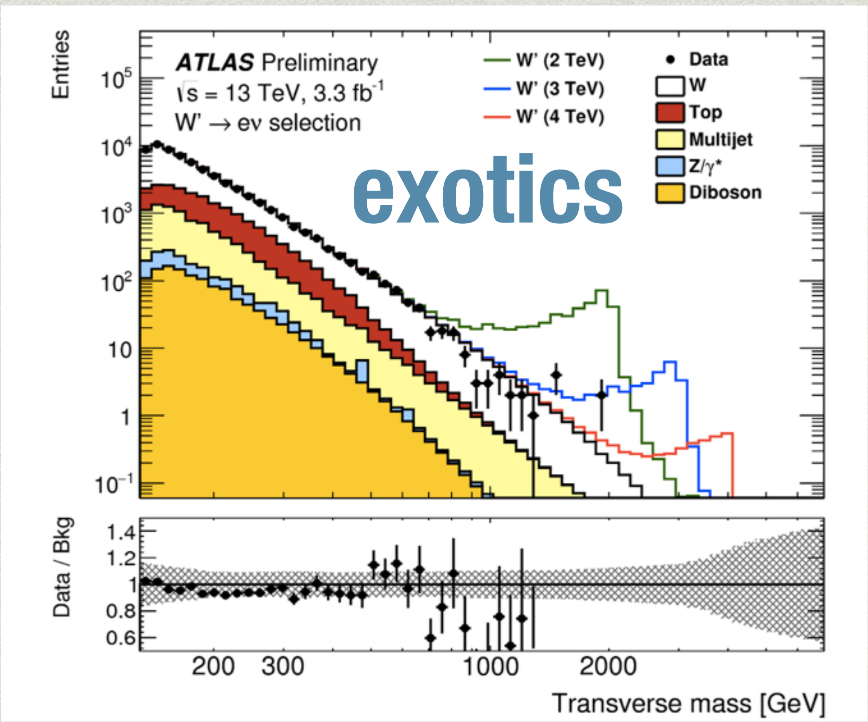
CMS, arXiv: 1412.8662



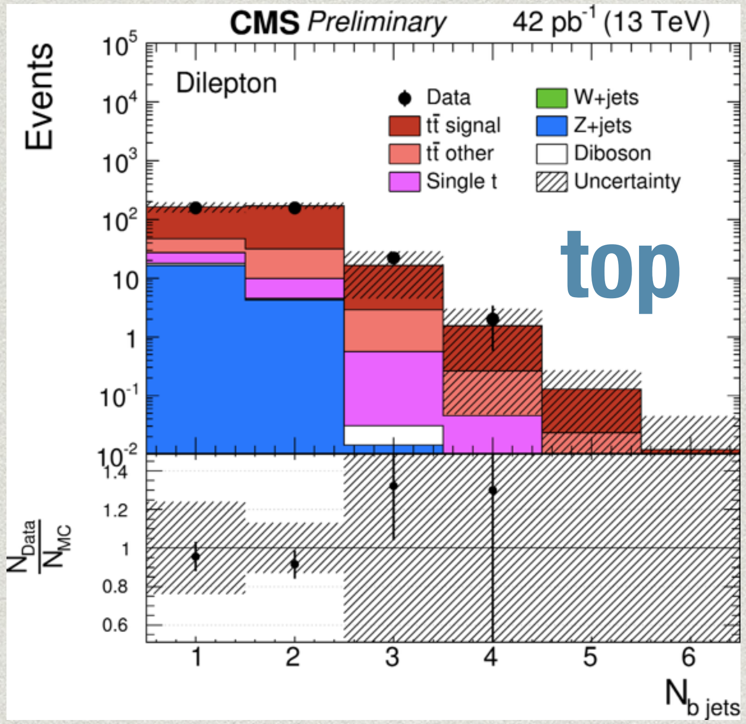
ATLAS, arXiv: 1602.09058



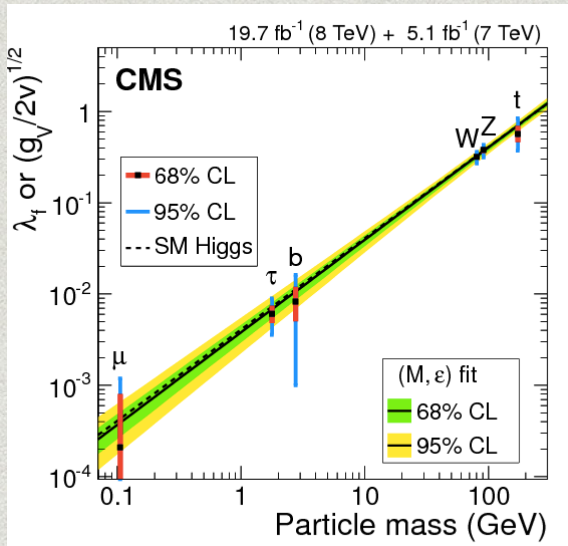
ATLAS-CONF-2015-063

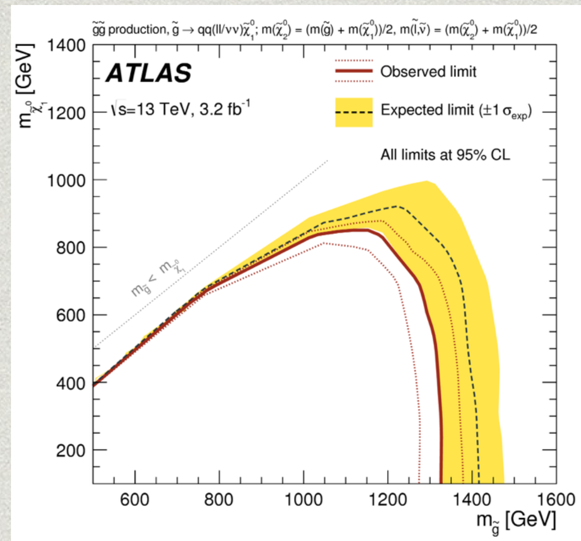


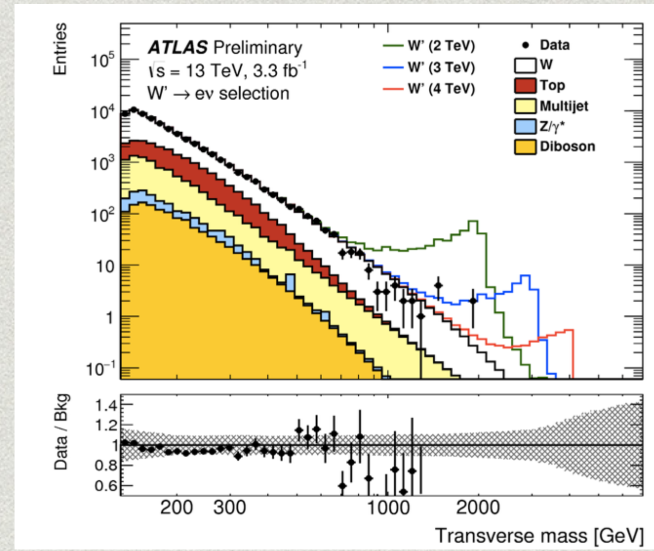
CMS-PAS-TOP-15-010

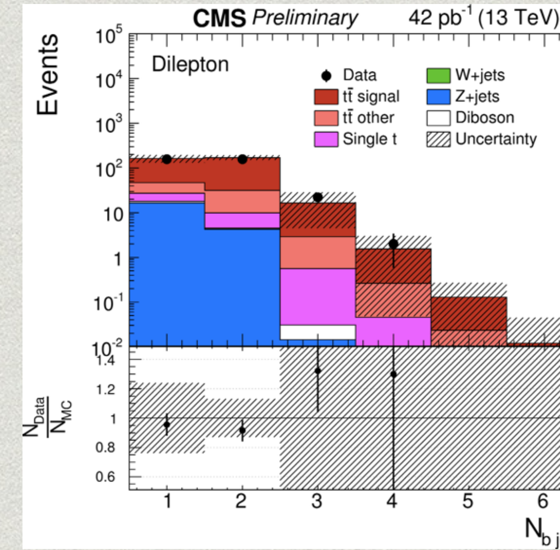


Vector bosons as backgrounds





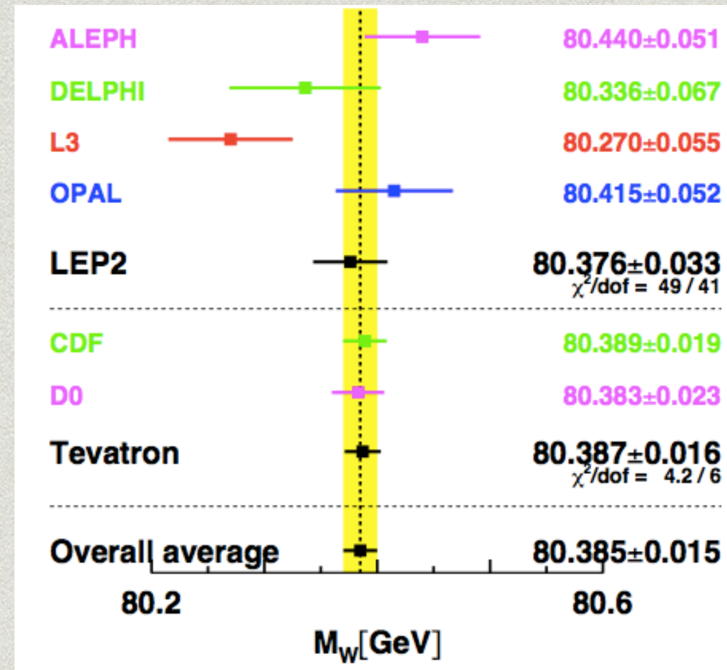


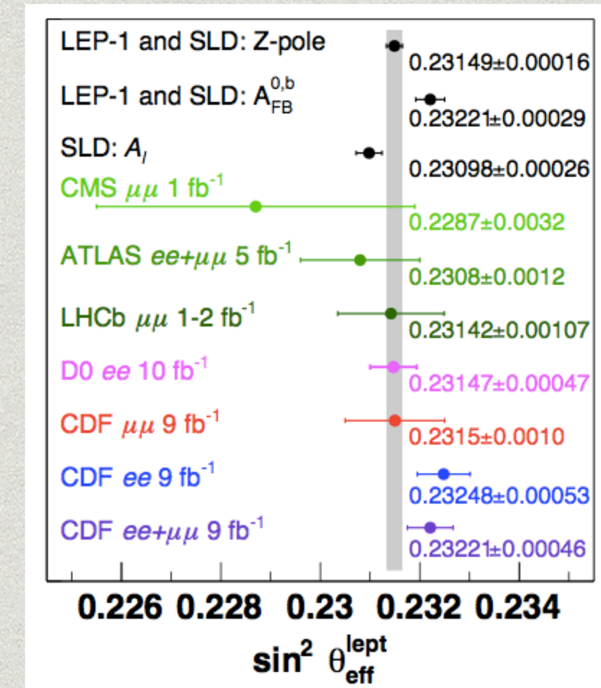


- **How well do we understand these key backgrounds?**
  - higher-order QCD and EW corrections, parton showers.
  - how do we combine for the most precise predictions?
- As theoretical calculations become more sophisticated …
  - what becomes most important when the corrections, or their associated uncertainties, become small?
  - which approximations can we lift?

… and as probes of the SM

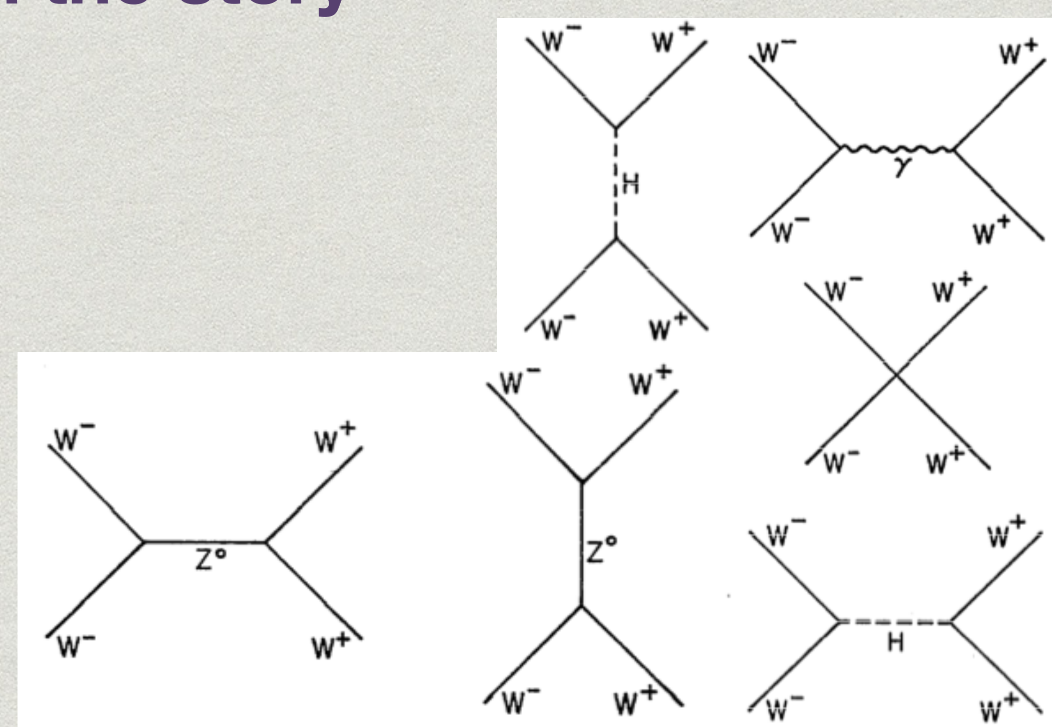
- **Precision measurement** of Standard Model parameters.

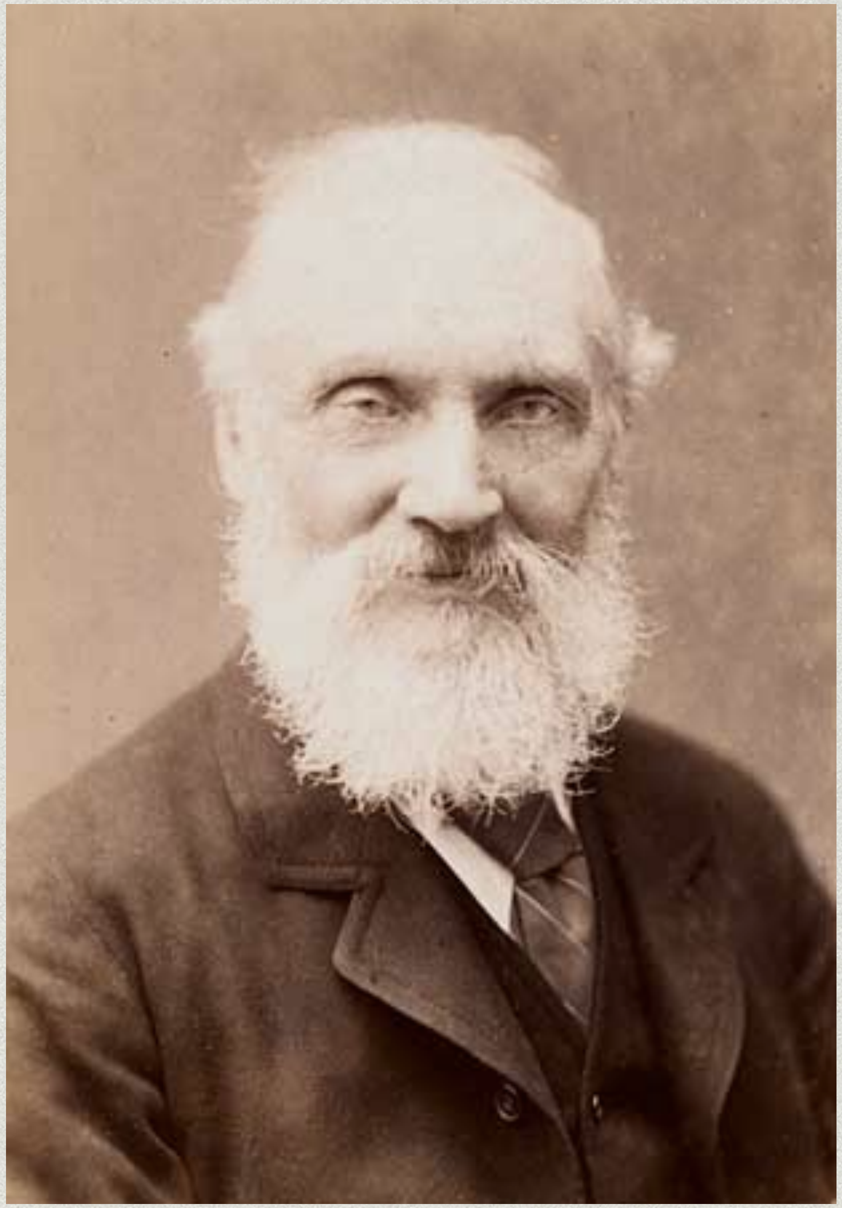




- **Is the electroweak sector richer than the story we have uncovered so far?**
  - Can we probe the mechanism that ensures unitarity is respected at high energies?
  - Is the SM 125 GeV Higgs boson the whole story?

see, e.g. Lee, Quigg, Thacker, PRD16, 1977





Lord Kelvin

REPORT

OF THE

FORTY-FIRST MEETING

OF THE

BRITISH ASSOCIATION

FOR THE

ADVANCEMENT OF SCIENCE;

HELD AT

EDINBURGH IN AUGUST 1871.

Stress-testing the Standard Model at the LHC

Coordinators: Bryan Webber, Eric Laenen, Tom LeCompte, and Doreen Wackeroth and W. Thomson

a less lofty and dignified work than looking for something new. But nearly all the grandest discoveries of science have been but the rewards of accurate measurement and patient long-continued labour in the minute sifting of numerical results. The popular idea of Newton's grandest discovery is that

DRELL-YAN PROCESSES

Current precision

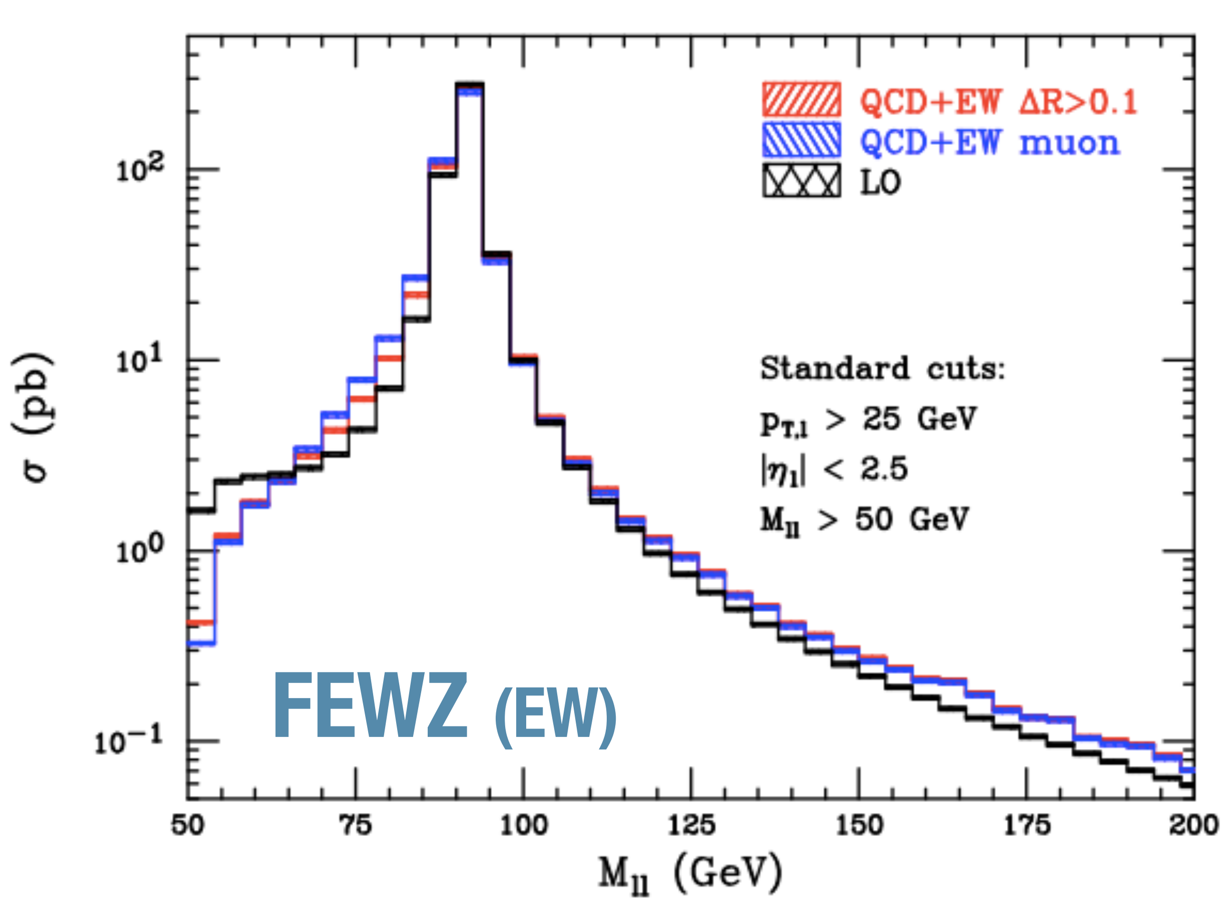
- Known to NNLO QCD for a long time.

  (DYNNLO) Catani, Cieri, Ferrera, de Florian, Grazzini, arXiv:0903.2120
  (FEWZ) Gavin, Li, Petriello, Quackenbush, arXiv:1011.3540, 1201.5896

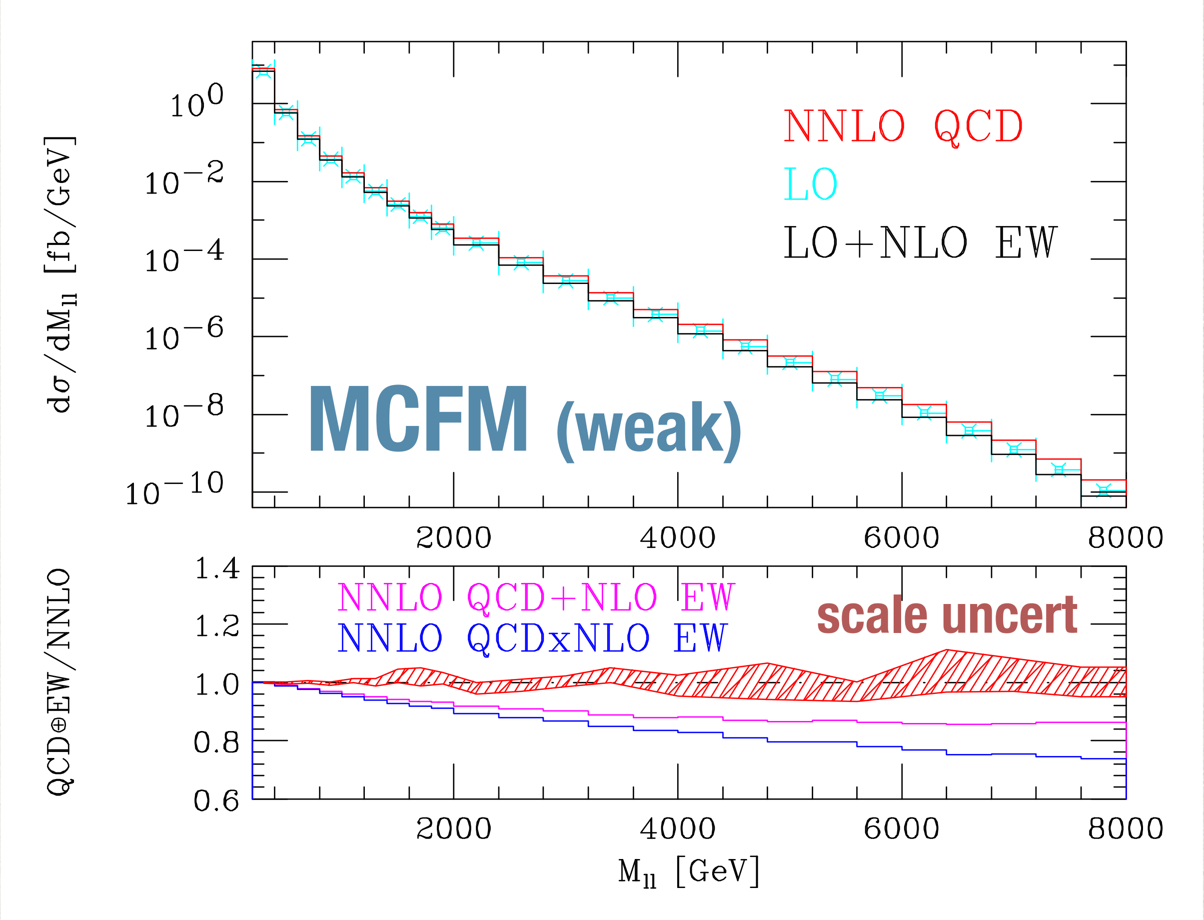
  - and including NNLL q_T resummation;

  (DYRES) Catani, Ferrera, de Florian, Grazzini, arXiv:1507.06937

  - or combined with calculation of NLO (electro)weak. → **F. Piccinini**



Li, Petriello, arXiv:1208.5967

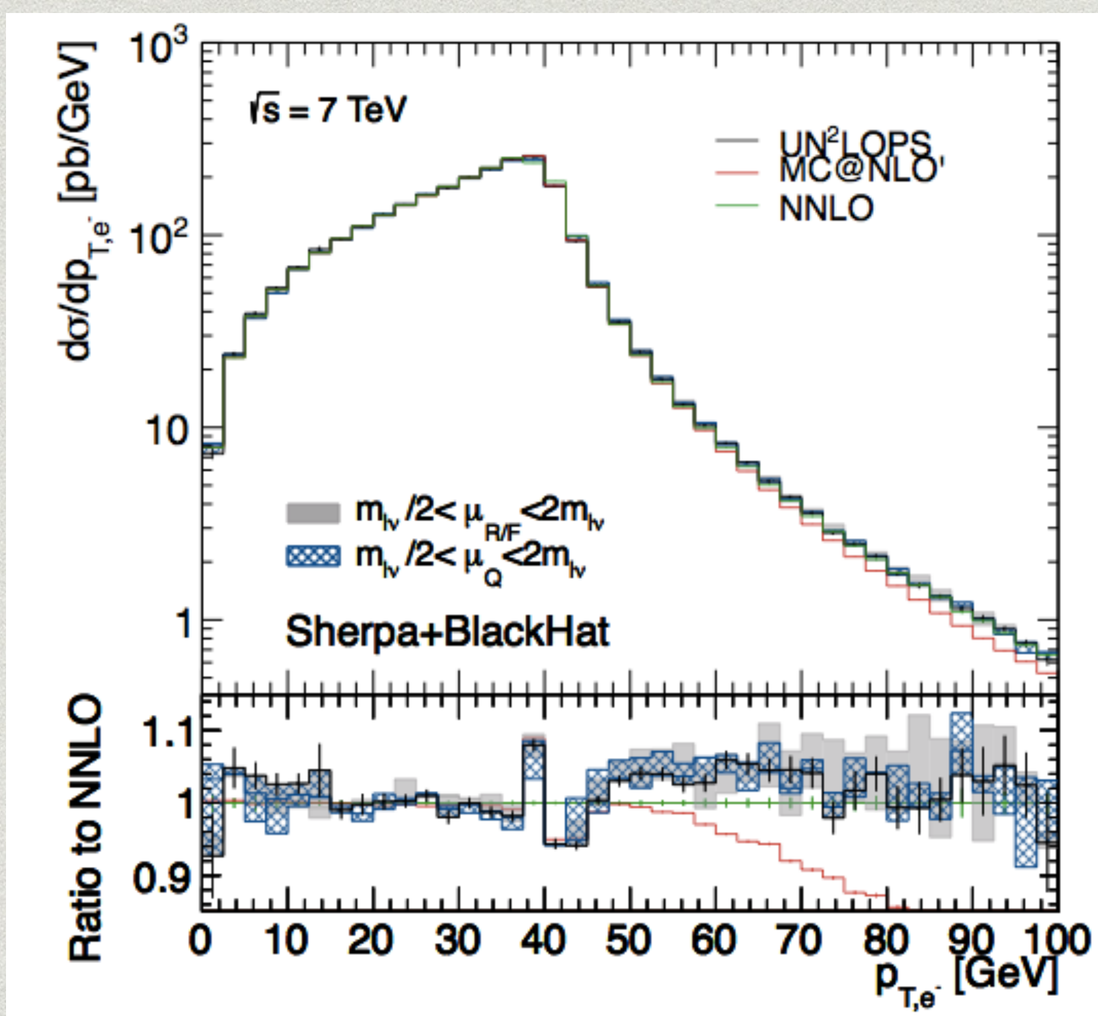


R. Boughezal et al, MCFM-8.0, to appear
JC, Wackeroth, Zhou, in preparation

NNLO+parton shower

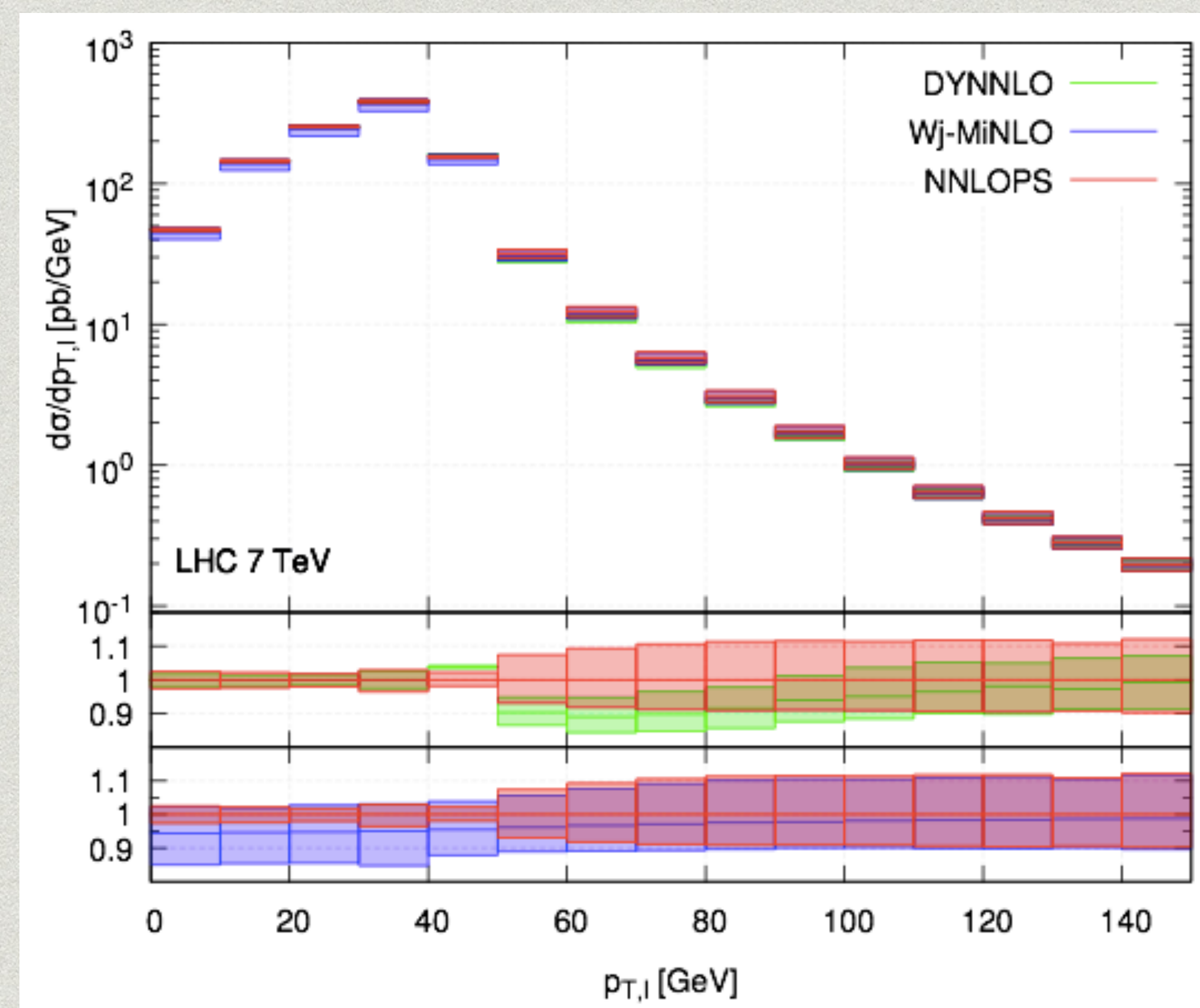
- UN^2LOPS approach implemented in SHERPA+BlackHat. → **S. Hoeche**
  - pure NNLO effects restricted to Born-like configurations.

Hoeche, Li, Prestel, arXiv: 1405.3607



- MiNLO procedure, using DYNNLO to upgrade POWHEG.
  - showering ensures NNLO effects beyond Born configurations

Karlberg, Re, Zanderighi, arXiv: 1407.2940

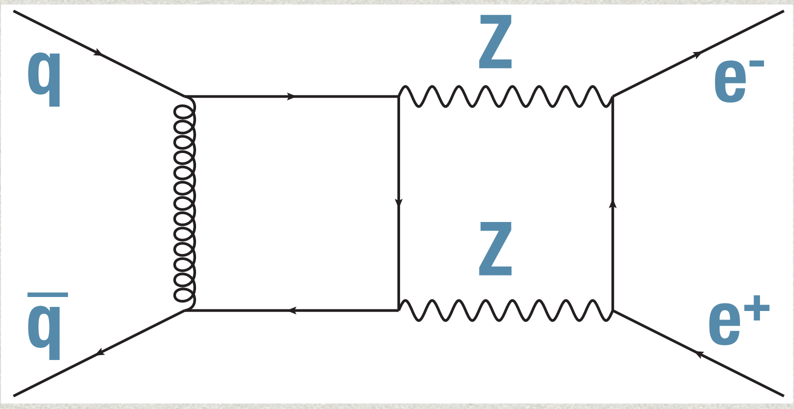


see also Alioli, Bauer, Berggren, Tackmann, Walsh, arXiv: 1508.01475 → C. Bauer

Mixed QCD-EW corrections

Dittmaier, Huss, Schwinn, arXiv: 1511.08016

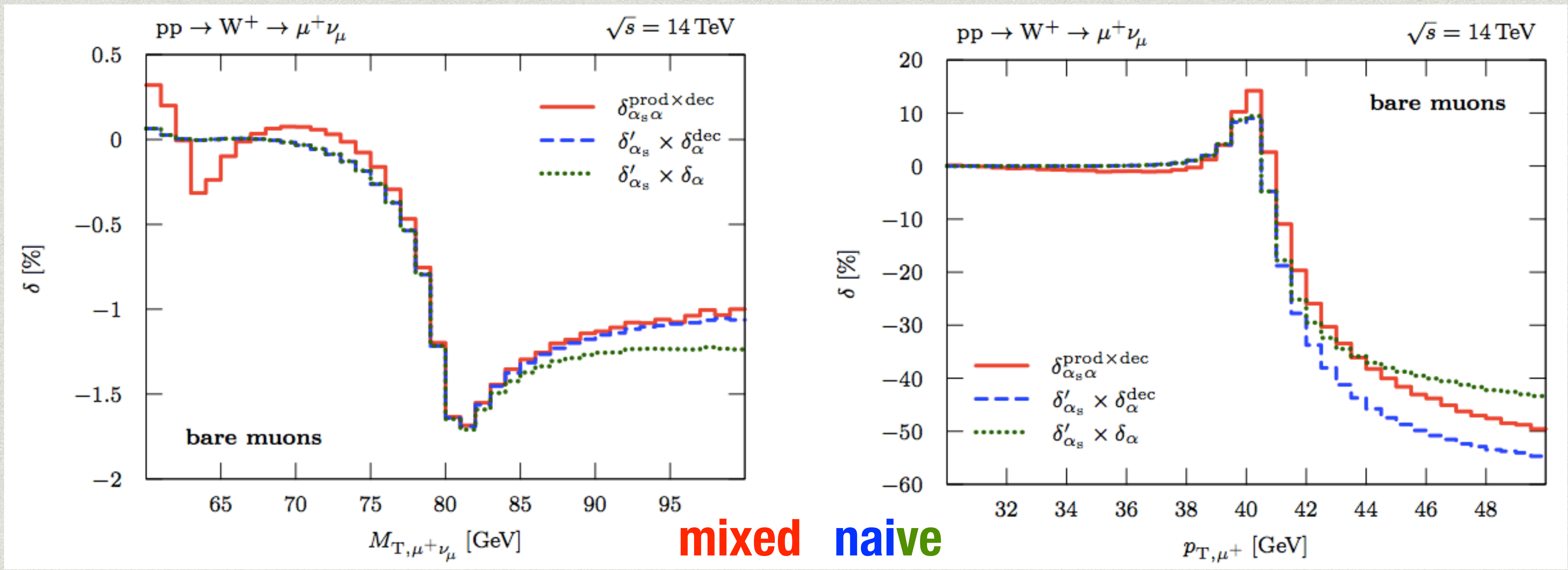
- Ideally, would not approximate combination but compute exactly: start with mixed QCD-EW correction, $O(\alpha\alpha_s)$.



- Not there yet, but necessary two-loop master integrals now known.

Bonciani, Di Vita, Mastrolia, Schubert, arXiv: 1604.08581

- In resonance region, can instead use pole approximation.
  - previously validated at 0.1% level in resonance-dominated distributions.



Impact on W-mass extraction

- Fit transverse mass distribution, no modelling of finite detector resolution.

	bare muons		dressed leptons	
	M_W^{fit} [GeV]	ΔM_W	M_W^{fit} [GeV]	ΔM_W
LO	80.385	$-$ 90 MeV	80.385	$-$ 40 MeV
NLO_{ew}	80.295		80.345	
$NLO_{s\oplus ew}$	80.374	$-$ 14 MeV	80.417	$-$ 4 MeV
NNLO	80.360		80.413	

- **similar shift from mixed QCD-EW as using simple QCD x EW**
- **as large as final-state multi-photon corrections from PHOTOS**
- **shift > 10 MeV, inclusion of this effect imperative**

W-mass from LHCb

- Inherent disadvantages: smaller rate, not hermetic coverage
  - but can exploit anti-correlation in pdf uncertainties over much greater rapidity range.
- Exploratory study of improved sensitivity based on a LHCb measurement of the muon p_T in Run 2 ($7 fb^{-1}$).

Bozzi, Citelli, Vesterinen, Vicini, arXiv: 1508.06954

LHCb estimate

	Run-I $3\ fb^{-1}$		Run-II $7\ fb^{-1}$	
	W^+	W^-	W^+	W^-
Signal yields, $\times 10^6$	1.2	0.7	5.4	3.4
Z/γ^* background, (B/S)	0.15	0.15	0.15	0.15
QCD background, (B/S)	0.15	0.15	0.15	0.15
δm_W (MeV)				
Statistical	19	29	9	12
Momentum scale	7	7	4	4
Quadrature sum	20	30	10	13

Scenario	Experiments	δm_W (MeV) Tot	Exp	PDF
Default	2×GPD + LHCb	9.0	4.7	7.7
Default	1×GPD + LHCb	10.1	6.5	7.7
Default	2×GPD	12.0	5.8	10.5
PDF4LHC(3-sets)	2×GPD + LHCb	13.6	4.8	12.7
PDF4LHC(3-sets)	1×GPD + LHCb	14.6	7.3	12.7
PDF4LHC(3-sets)	2×GPD	17.7	5.5	16.9

25% improvement in extraction of M_W

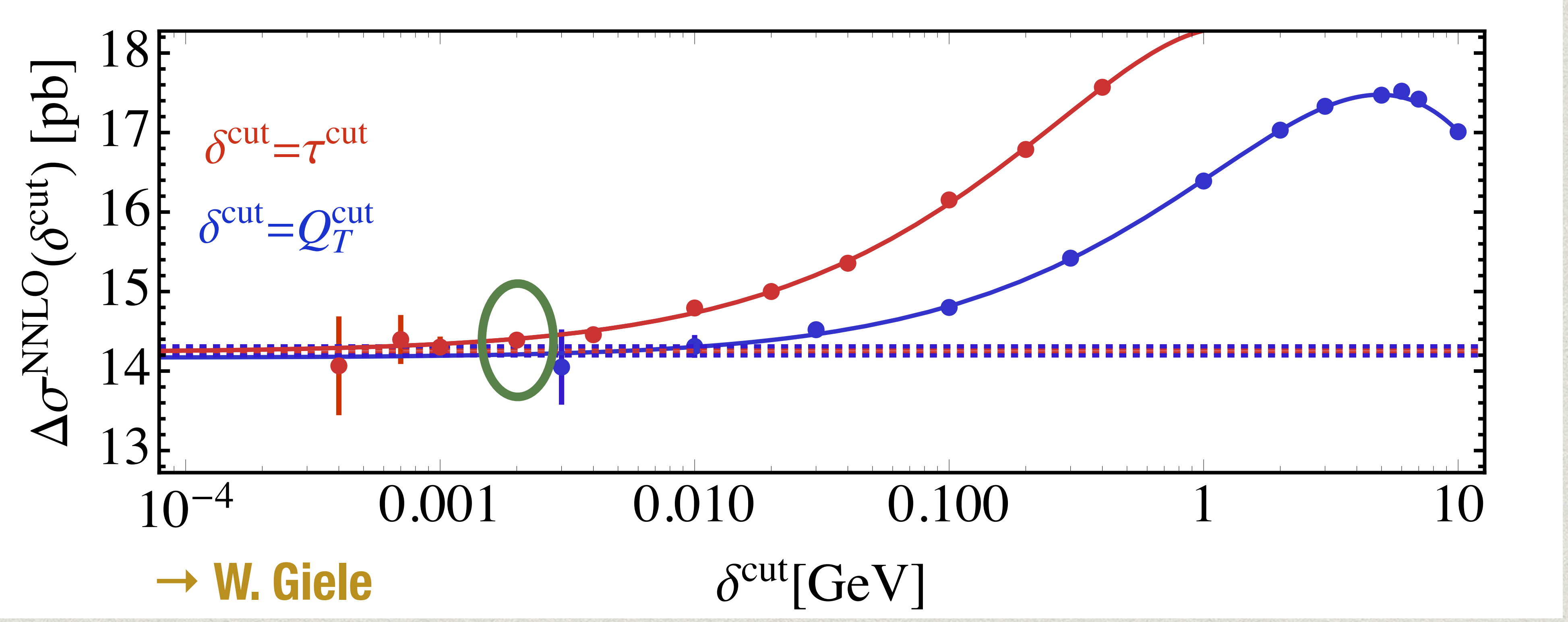
→ A. Freitas

PHOTON PROCESSES

Diphotons at NNLO

JC, Ellis, Li, Williams, arXiv: 1603.02663

- Two NNLO QCD slicing calculations in MCFM based on infrared regularization using diphoton Q_T and 0-jettiness. → F. Petriello, A. Mitov
  - cross-check with independent Q_T calculation.
- Residual dependence on regularizing parameter well-controlled.
  - expect remaining power corrections < few per mille effect.



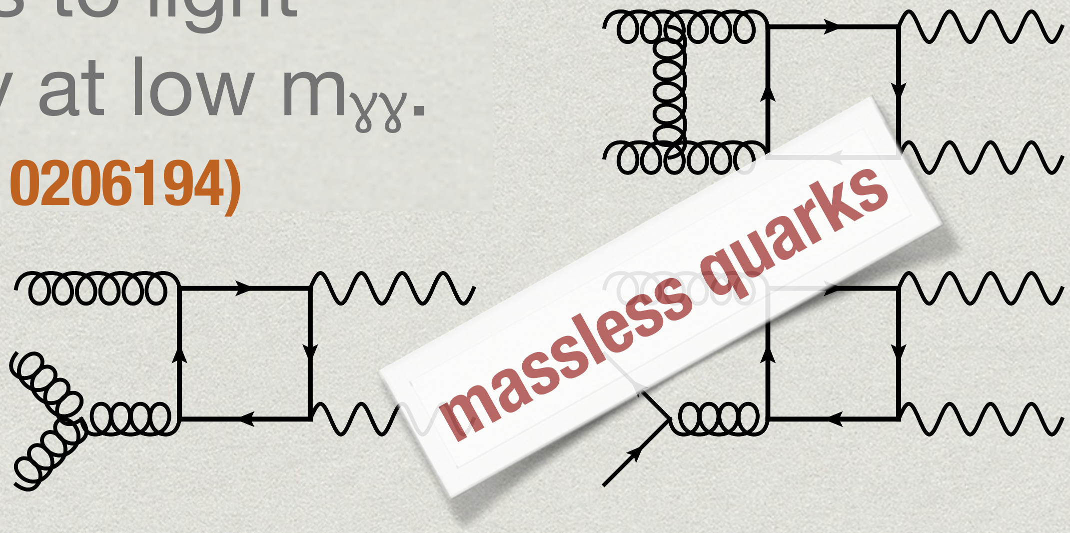
→ W. Giele

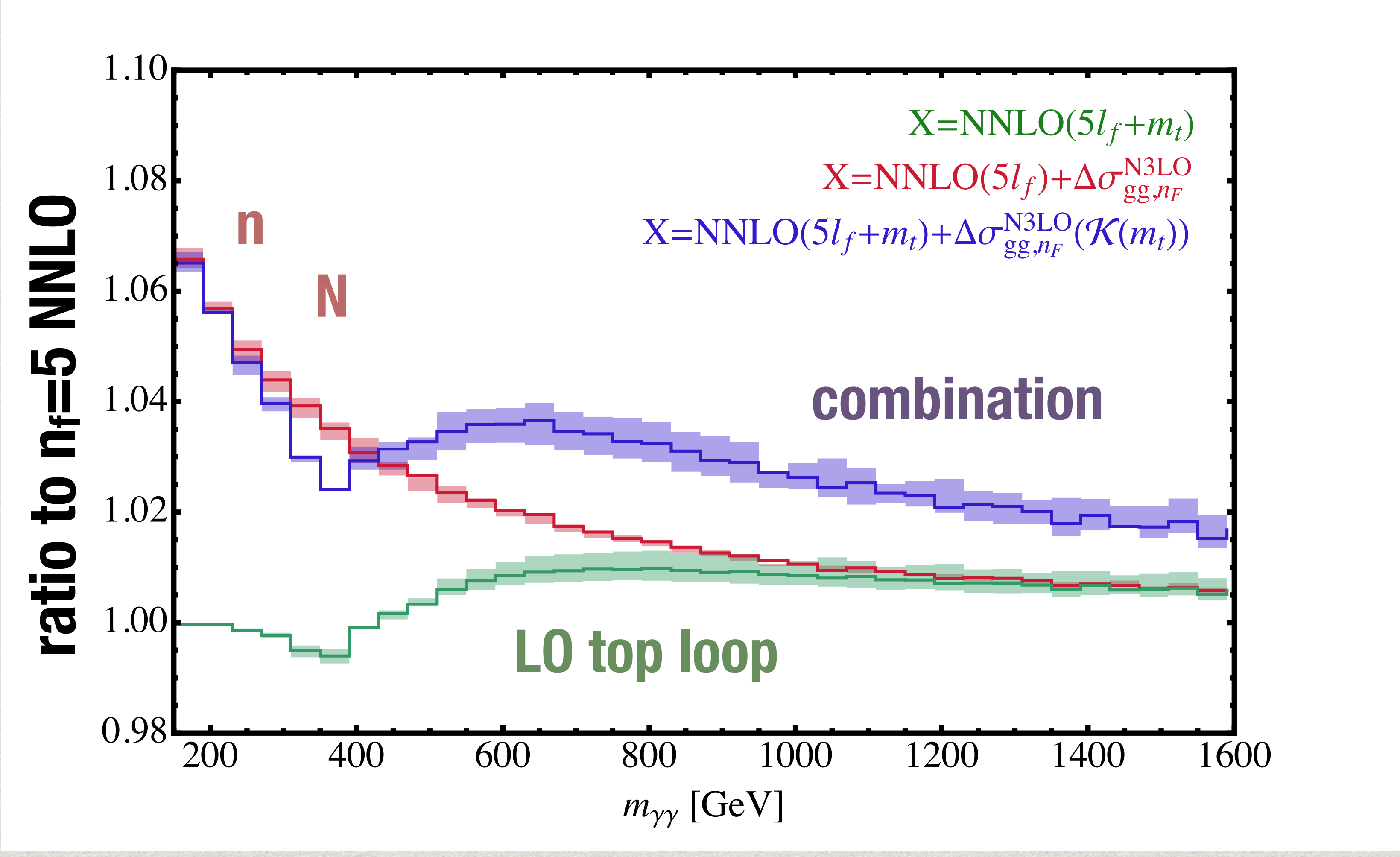
NNLO coeff. approx. 20% lower than original calculation (7% in total)

Catani et al, arXiv: 1110.2375

Improved treatment of quark loops

- Modest impact from NLO corrections to light quark loops (partial N³LO), especially at low $m_{\gamma\gamma}$. **(originally considered in Bern, Dixon, Schmidt, arXiv: 0206194)**
- Smaller effect from including LO top quark loops, above 500 GeV.

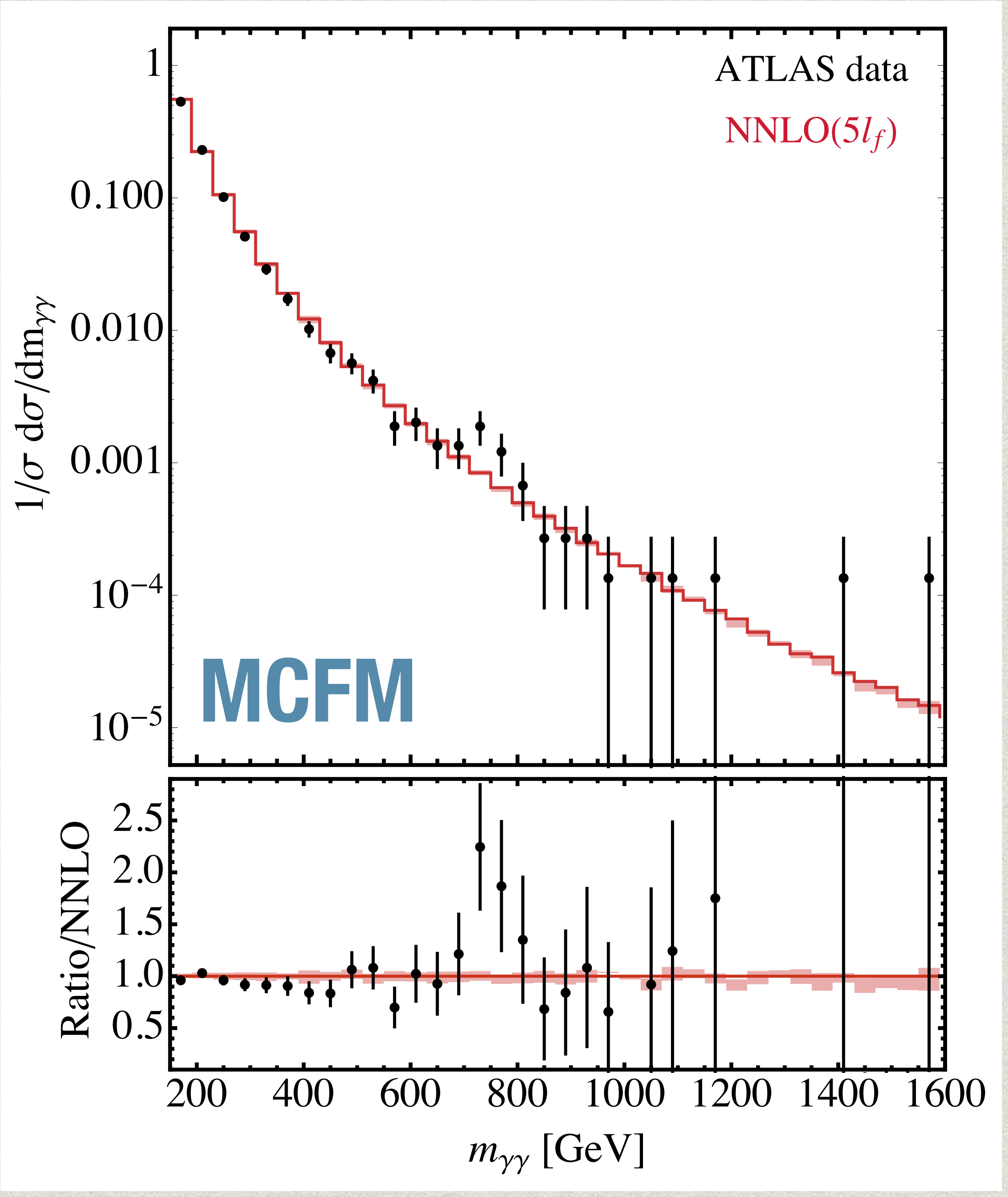


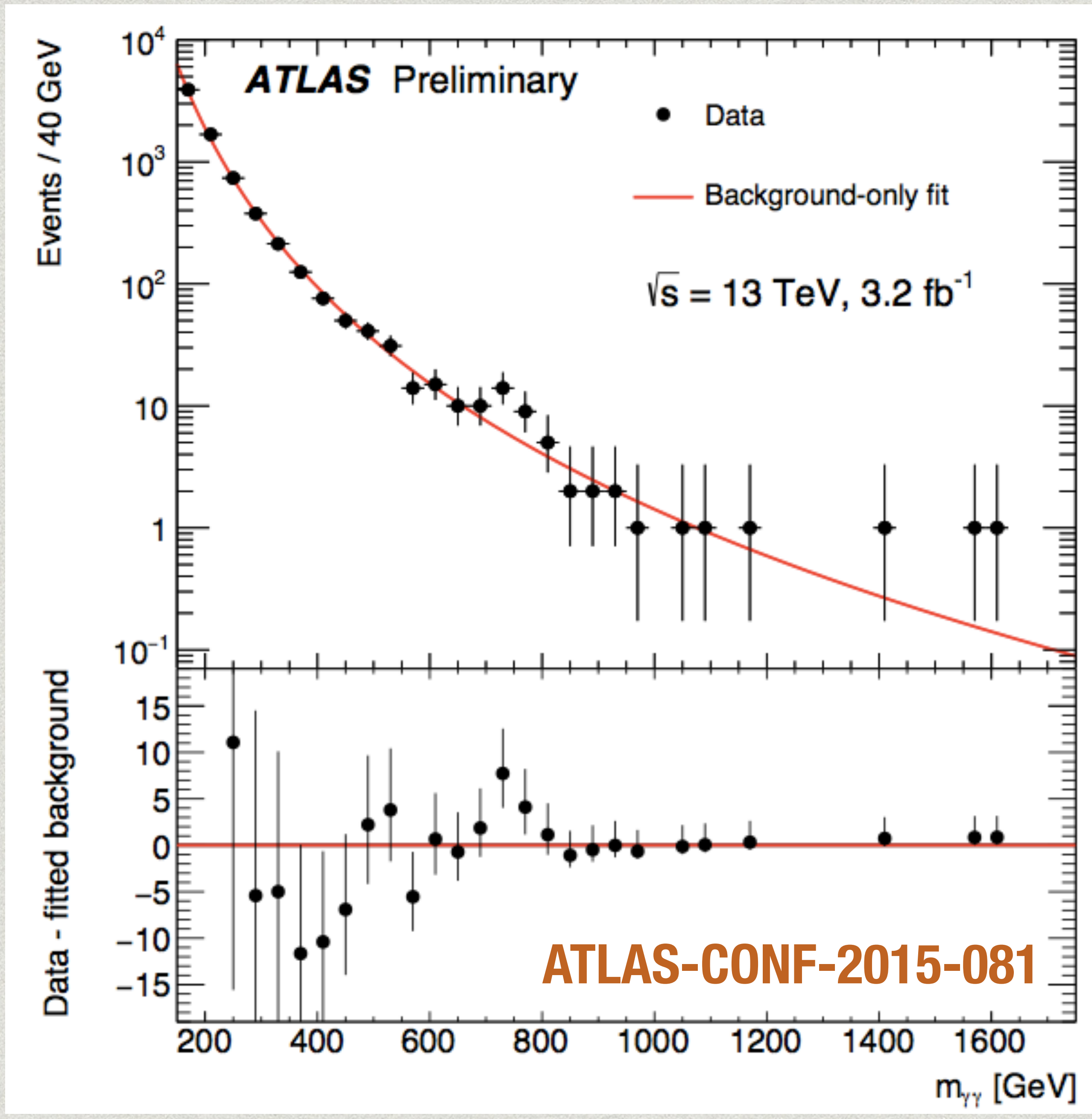


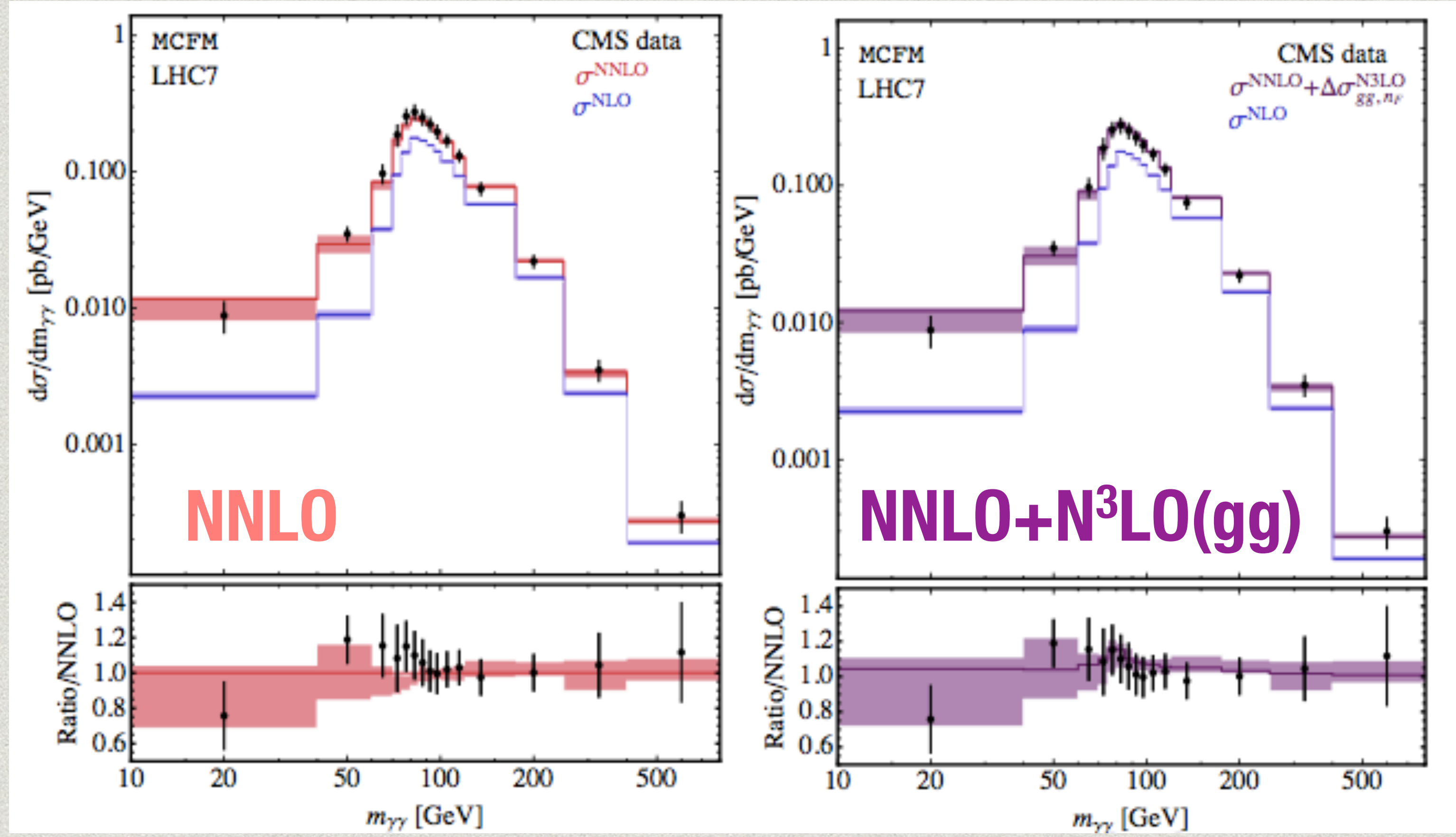
→ **few-percent distortions, small shape change**

Comparison with ATLAS 13 TeV

- Good agreement "out of the box".
  - no accounting for fake rate or efficiencies.



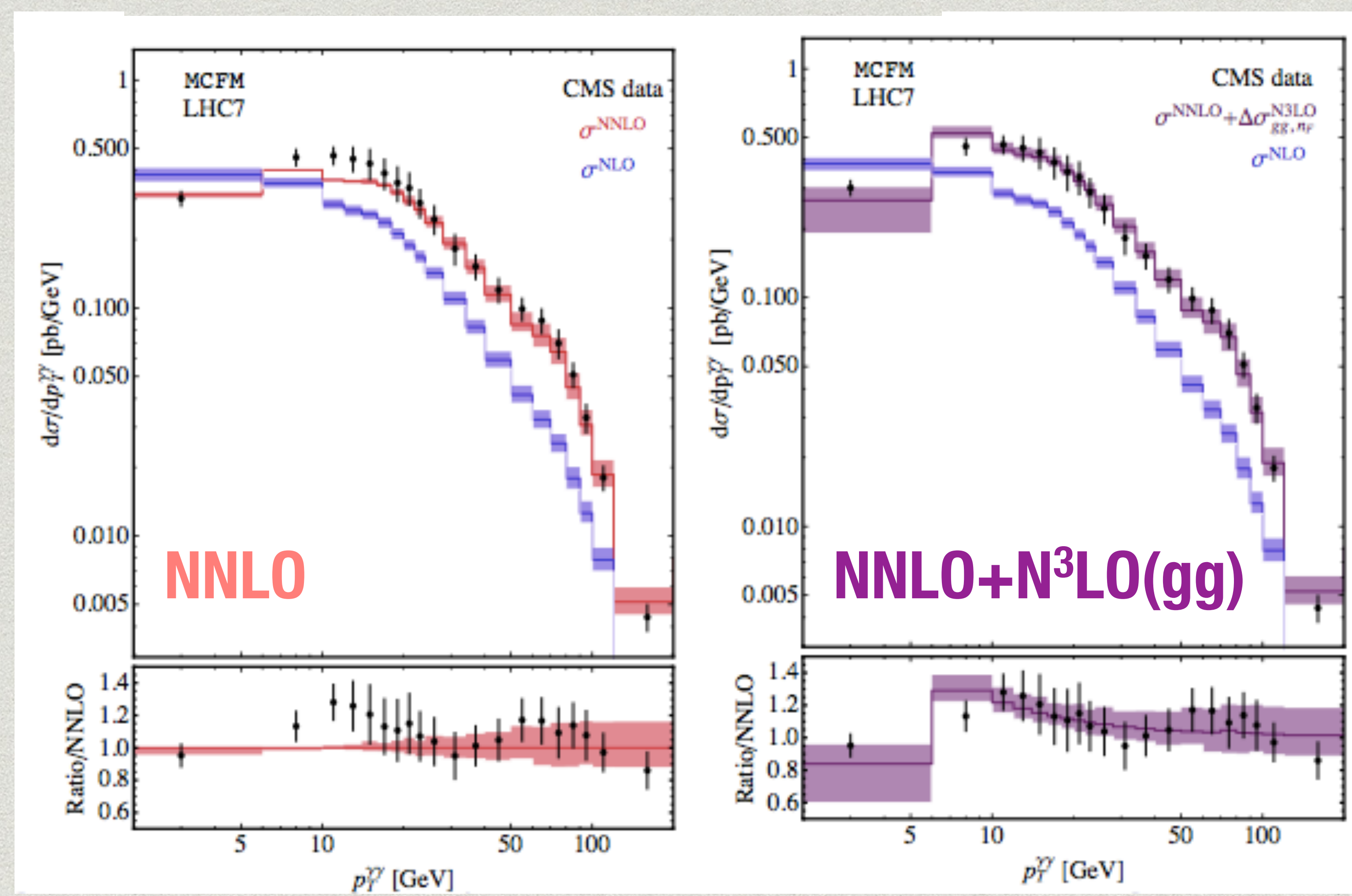




Compared to 7 TeV data from CMS, arXiv: 1406.7225

$m_{\gamma\gamma}$ well-described

slightly improved by addition of gg N^{3}LO contribution



$p_T(\gamma\gamma)$ prediction really only NLO

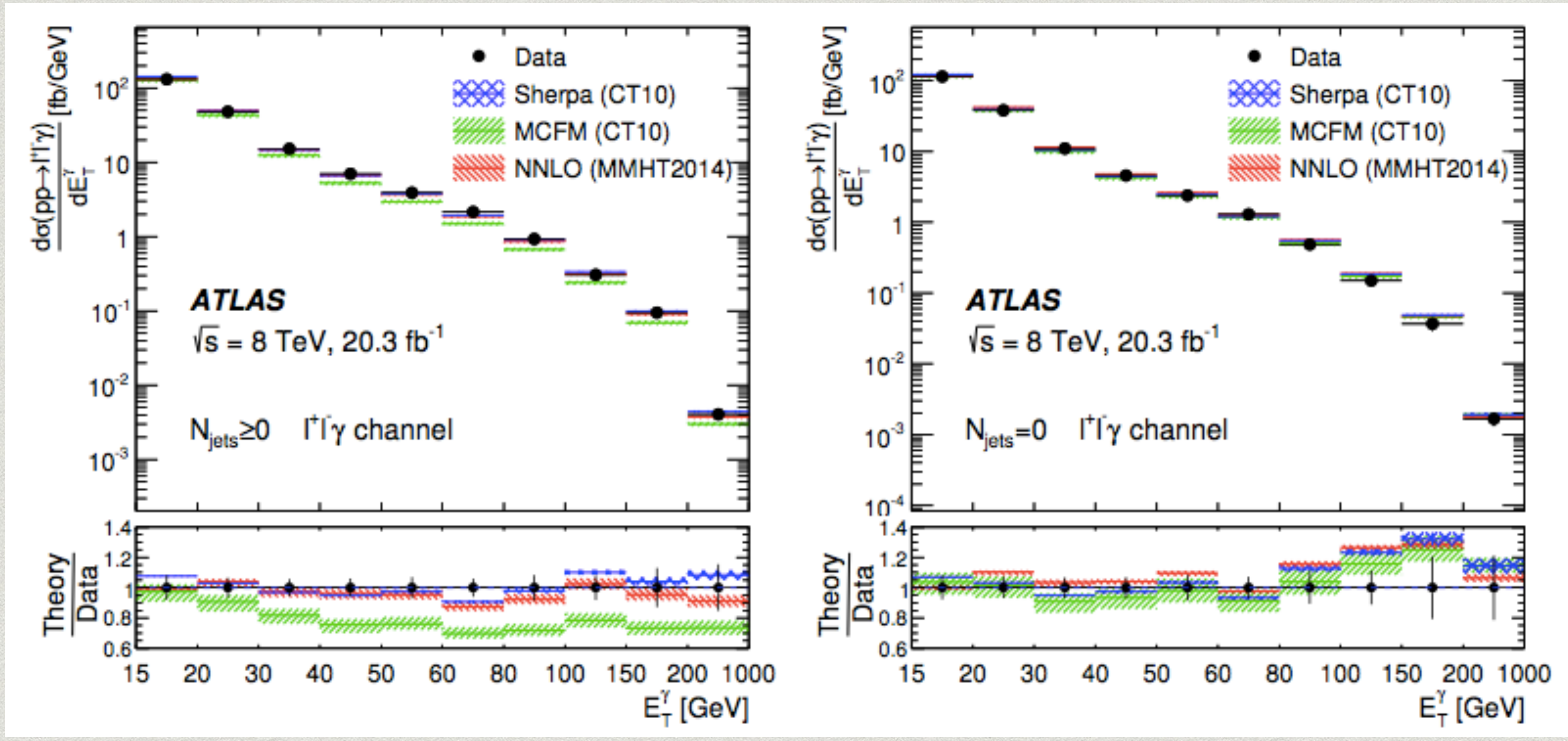
gg N^{3}LO contribution significant since LO $gg \to \gamma\gamma$ trivial

V+photon processes

Grazzini, Kallweit, Rathlev, arXiv: 1504.01330

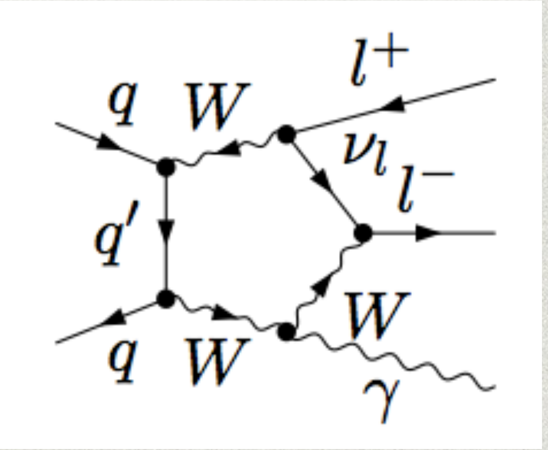
- Fully-differential NNLO QCD, including all off-shell effects and radiation from leptons in decay.
- Moderate corrections, especially small in the case of a jet veto.

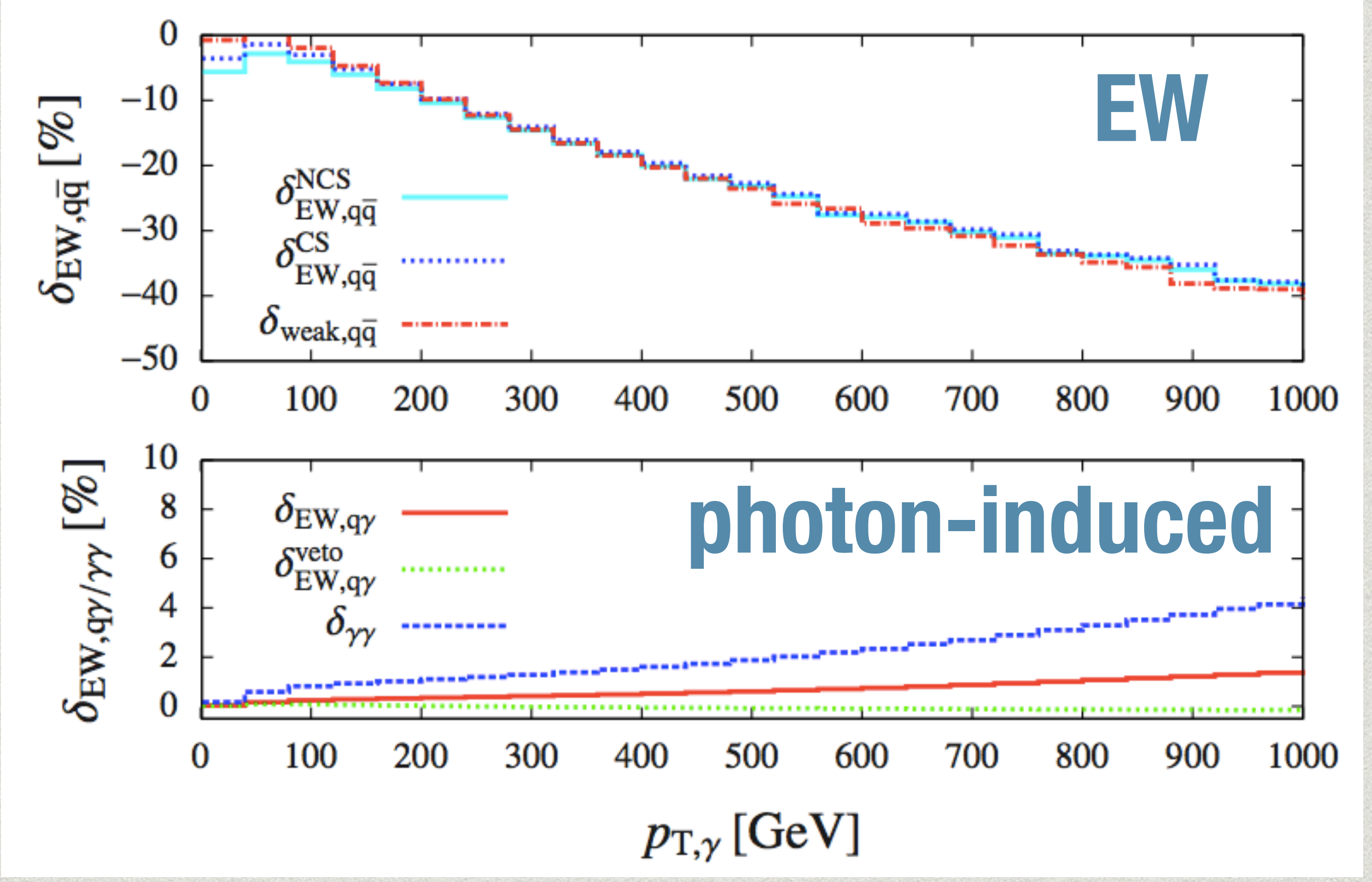
Excellent agreement with recent ATLAS analysis, arXiv: 1604.05232

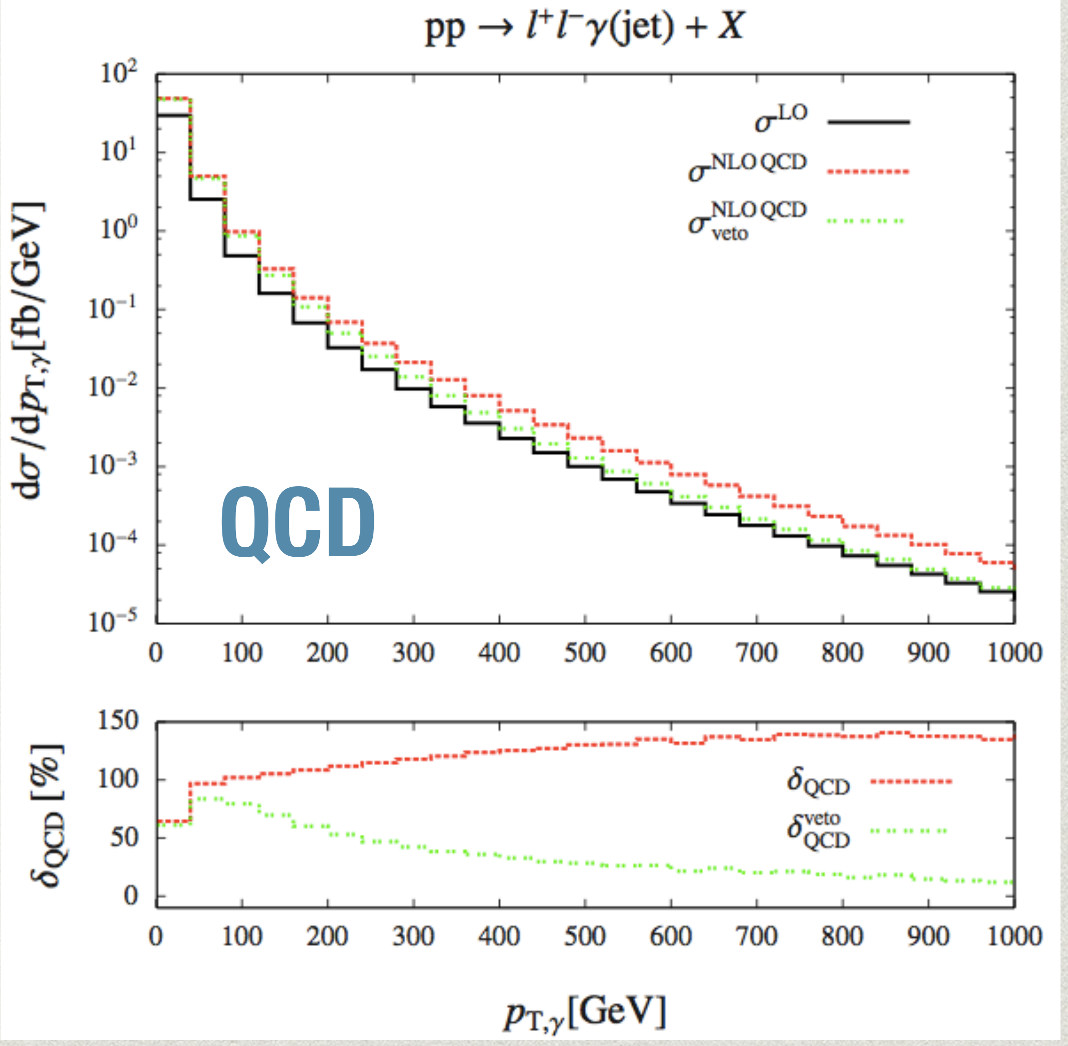


EW corrections

- Full off-shell calculations, including fragmentation.
  Denner, Dittmaier, Hecht, Pasold, arXiv:1412.7421 (Wɣ), arXiv:1510.08742 (Zɣ)
- Significant EW effects compared to QCD, particularly in the case of a jet veto.





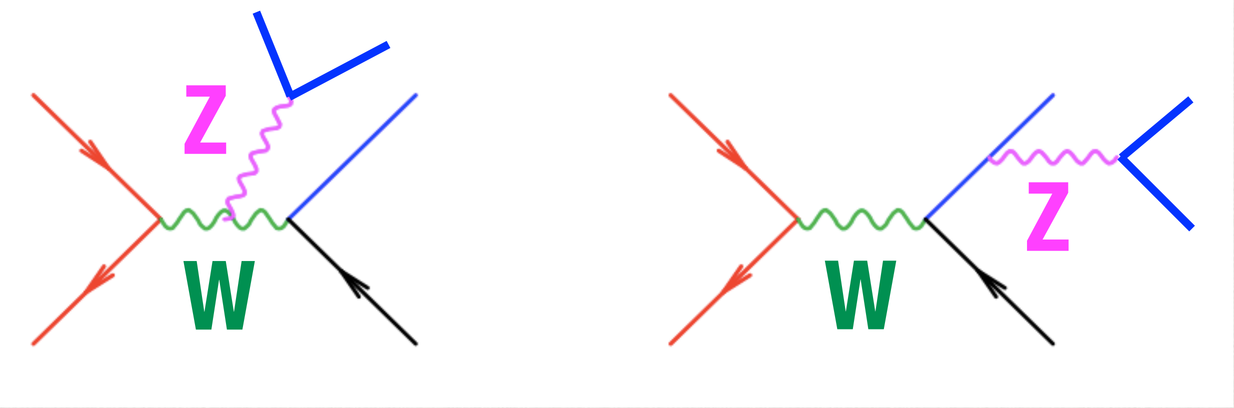


EW up to -10% for current analyses;
in future, leading contribution for N_{jet}=0

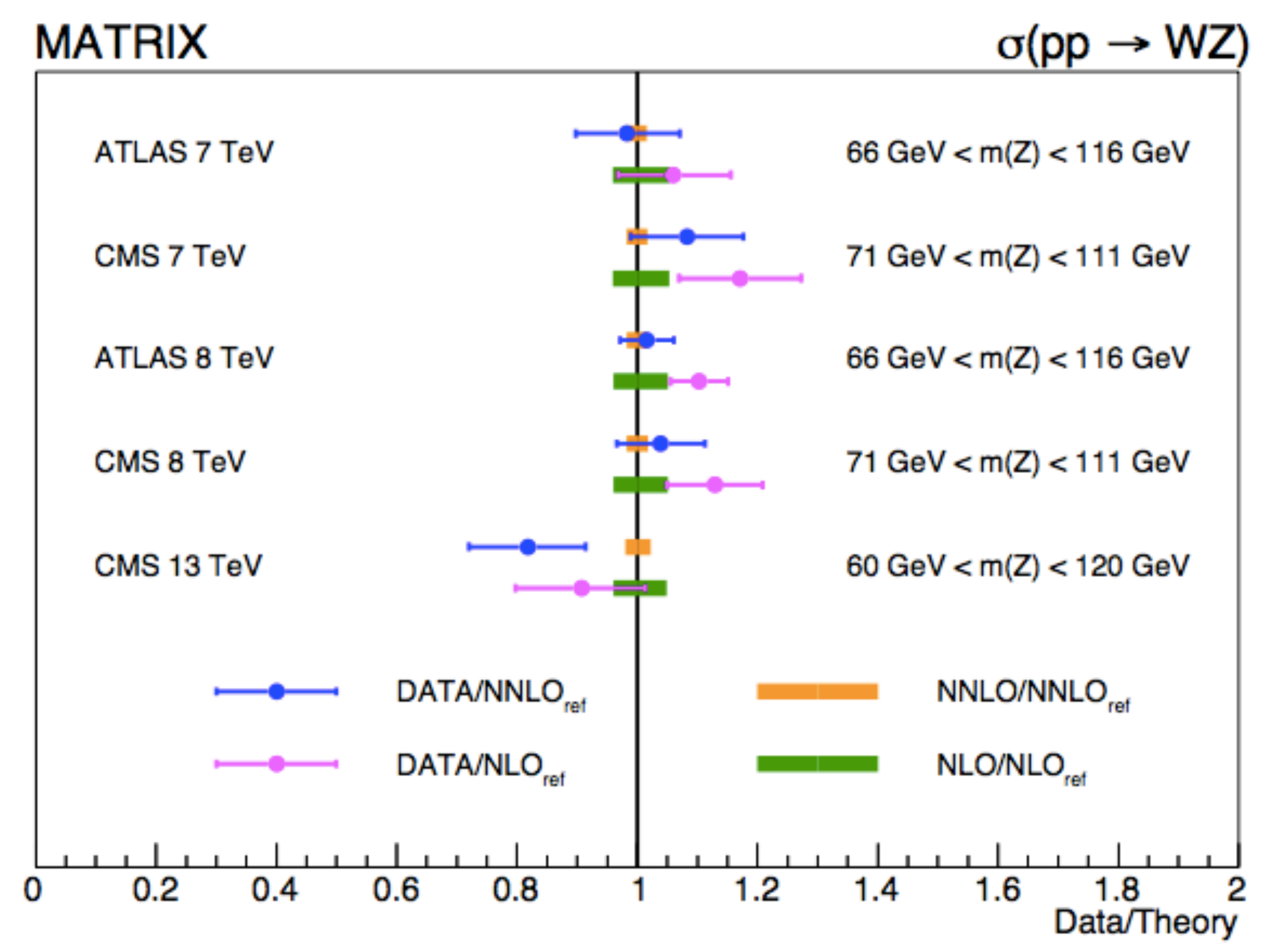
Closely related: WZ production

Grazzini, Kallweit, Rathlev, Wiesemann, arXiv: 1604.08576

- Also computed to NNLO QCD.
  - includes off-shell effects, single-resonant diagrams, virtual photons.
  - approx. radiation zero means higher orders particularly important.



$\sqrt{s}$	process	σ_{NLO}/σ_{LO}	$\sigma_{NNLO}/\sigma_{NLO}$
7	W^+Z	+61.6%	+ 7.8%
	W^-Z	+65.4%	+ 8.3%
8	W^+Z	+65.2%	+ 8.4%
	W^-Z	+69.1%	+ 8.8%
13	W^+Z	+79.0%	+10.9%
	W^-Z	+83.1%	+11.0%
14	W^+Z	+81.1%	+11.3%
	W^-Z	+85.3%	+11.4%



W AND Z PAIR PRODUCTION

WW production at NNLO

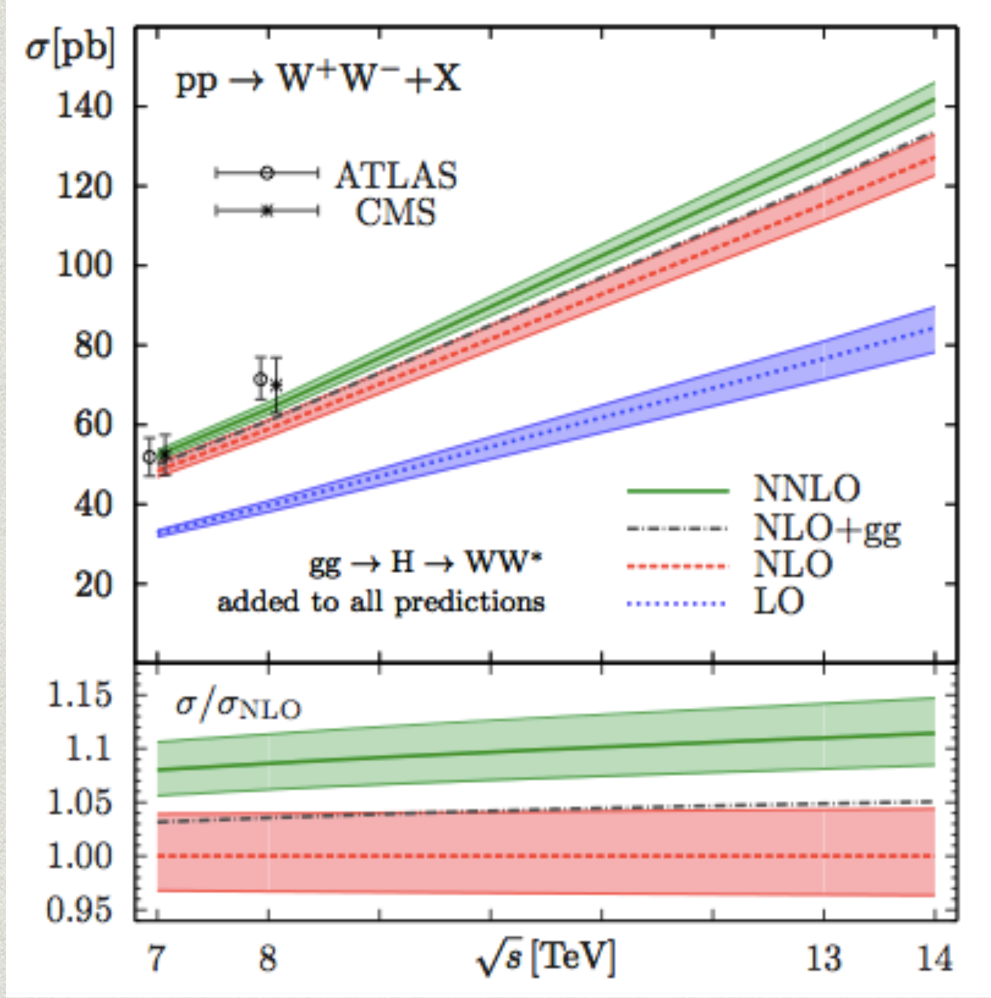
- Color-singlet production amenable to known methods at NNLO (sector decomposition, Q_T-subtraction, etc.).
- Crucial missing ingredients computed in 2014-15: two-loop helicity amplitudes.

Caola, Henn, Melnikov, Smirnov, Smirnov, arXiv: 1408.6409
Gehrmann, von Manteuffel, Tancredi, arXiv: 1503.04812

- First phenomenology at NNLO.

Gehrmann, Grazzini, Kallweit, Maierhofer, von Manteuffel, Pozzorini, Rathlev, Tancredi, arXiv: 1408.5243

  - approx. 10% correction, 3% residual uncertainty.
  - top contamination ambiguity (e.g. tt→WWbb) around 1-2%.

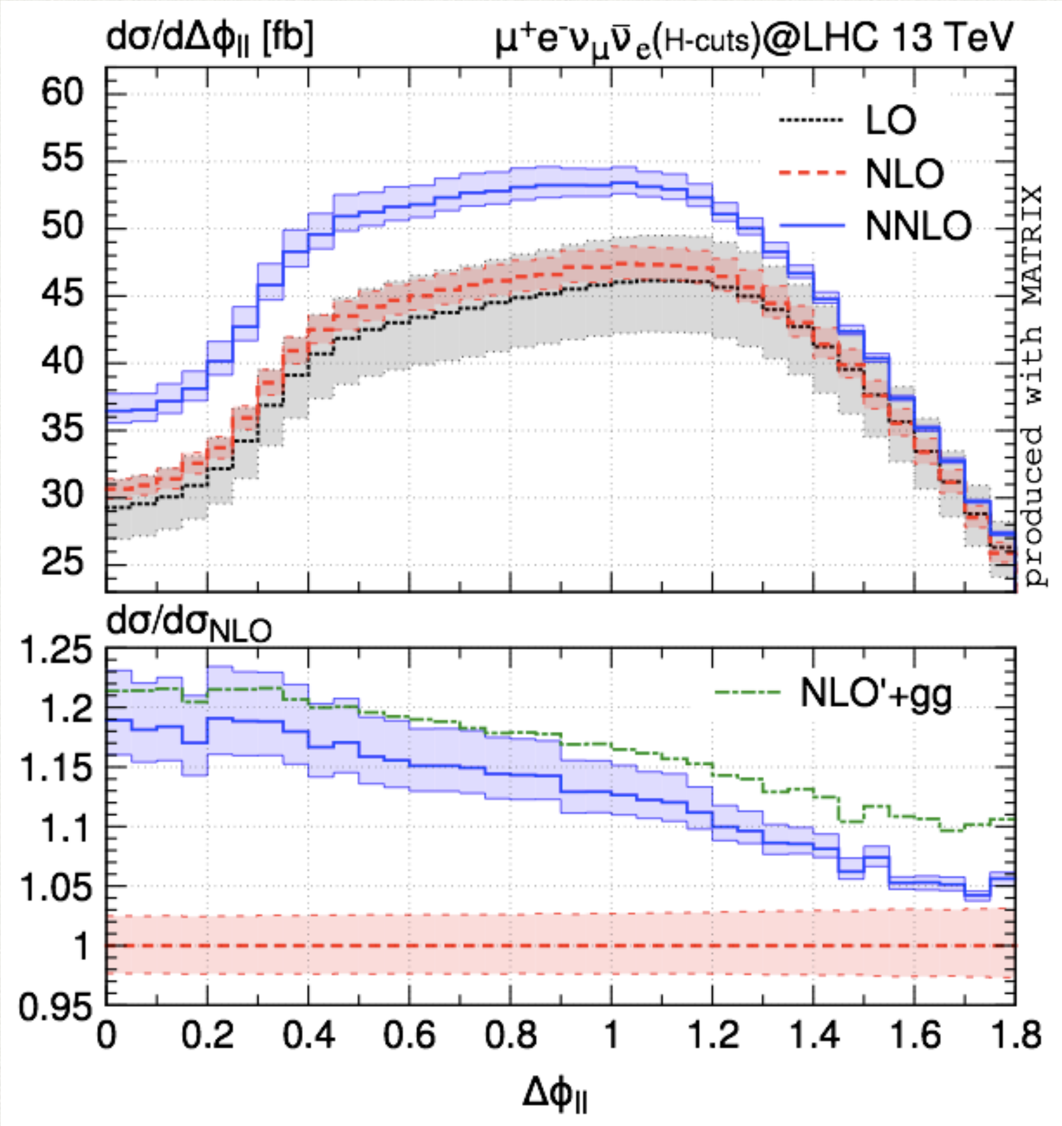


WW update

Grazzini, Kallweit, Pozzorini, Rathlev, Wiesemann, arXiv: 1605.02716

- Very recent detailed phenomenological study.
  - in framework of MATRIX, general framework for NNLO calculations of this type; utilizes OPENLOOPS, COLLIER.
  - accounts for single-resonant diagrams, ZZ contributions for same-flavor leptons

	$\epsilon = \sigma_{\text{fiducial}}(W^+W^-\text{-cuts})/\sigma_{\text{inclusive}}$		$\epsilon/\epsilon_{\text{NLO}} - 1$	
$\sqrt{s}$	8 TeV	13 TeV	8 TeV	13 TeV
LO	$0.34608(7)^{+0.6\%}_{-0.7\%}$	$0.29915(6)^{+0.8\%}_{-1.0\%}$	+41.0%	+52.6%
NLO	$0.24552(5)^{+4.4\%}_{-4.7\%}$	$0.19599(4)^{+4.4\%}_{-4.7\%}$	0	0
NNLO	$0.2378(4)\ ^{+1.3\%}_{-0.9\%}$	$0.1907(3)\ ^{+1.2\%}_{-0.9\%}$	− 3.2%	− 2.7%

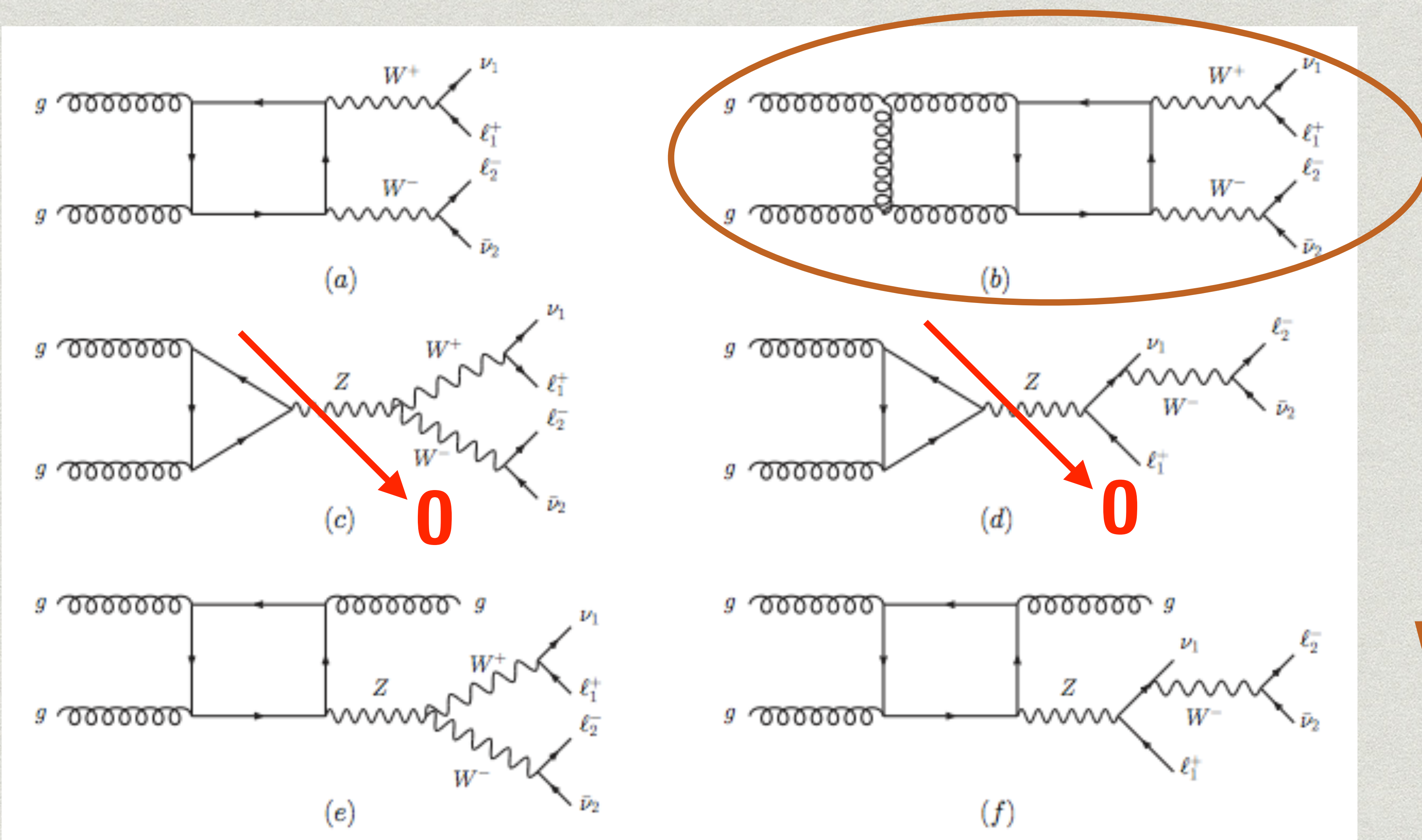


significant difference between effect of NNLO in inclusive and fiducial regions → impact on efficiencies

Corrections to gg→W^+W^-

Caola, Melnikov, Rontsch, Tancredi, arXiv:1511.08617

- More complicated than diphotons due to W virtualities; in principle also top mass, but 3rd gen. not included.
- Assess impact on continuum WW cross-section (partial N^{3}LO), i.e. do not need Higgs diagrams yet.



Caola, Henn, Melnikov, Smirnov, Smirnov, arXiv: 1503.08759

von Manteuffel, Tancredi, arXiv: 1503.08835

Results for $gg \to W^+W^-$

- Cross-sections at 8 TeV, no cuts applied.

No cuts	gg @ LO	gg @ NLO
gg alone	20.9 (+6.8, -4.8) fb	32.2 (+2.3, -3.1) fb
+ remainder of NNLO	698 fb	710 fb

- ATLAS fiducial cuts (CONF-2014-033), *e* and *μ*.

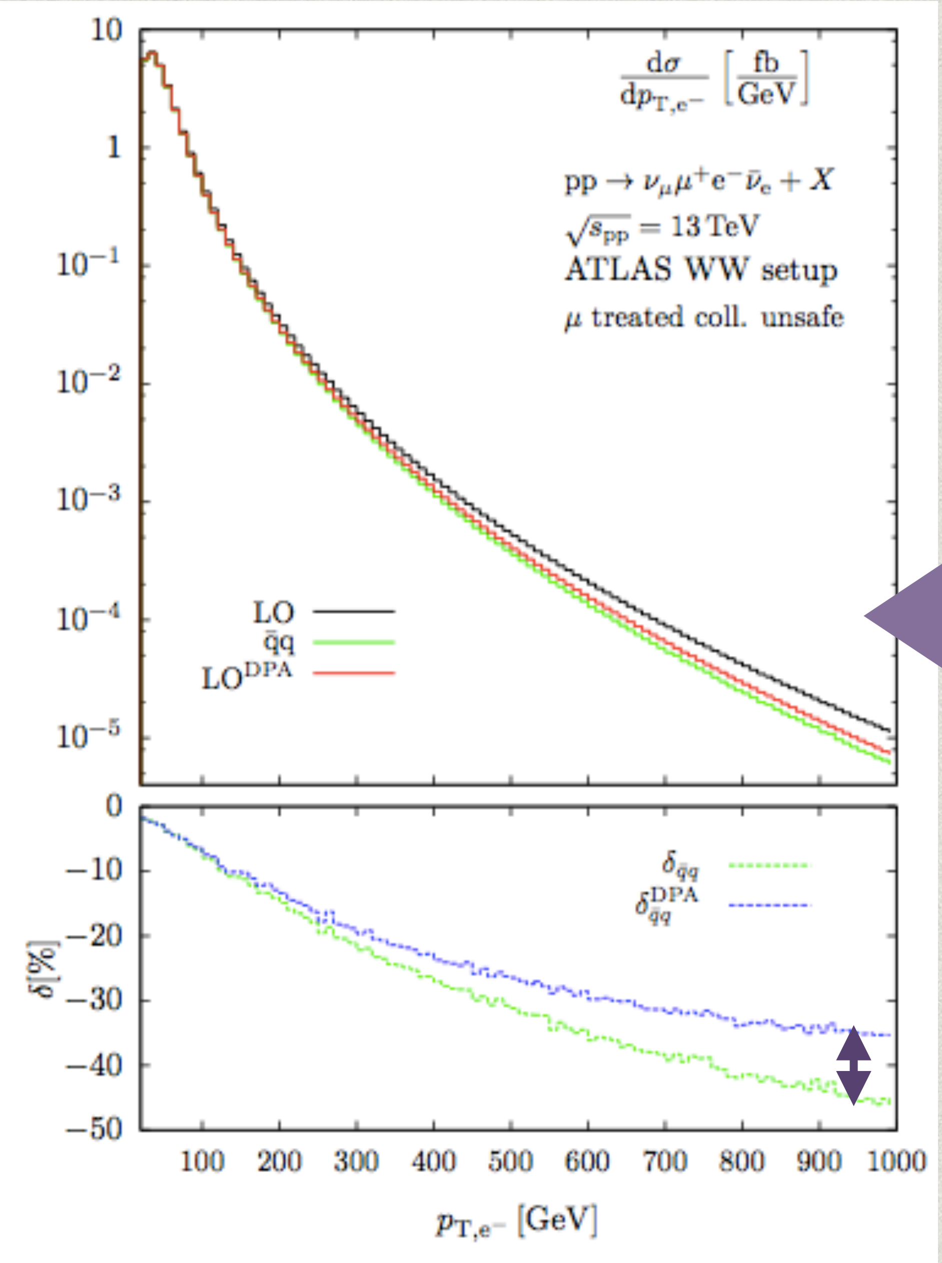
Fiducial cuts	gg @ LO	gg @ NLO
gg alone	9.8 (+3.1, -2.2) fb	11.8 (+0, -0.5) fb
+ remainder of NNLO	355 fb	357 fb

Much smaller gg@NLO corrections for fiducial cuts, mostly due to jet veto

Full electroweak corrections

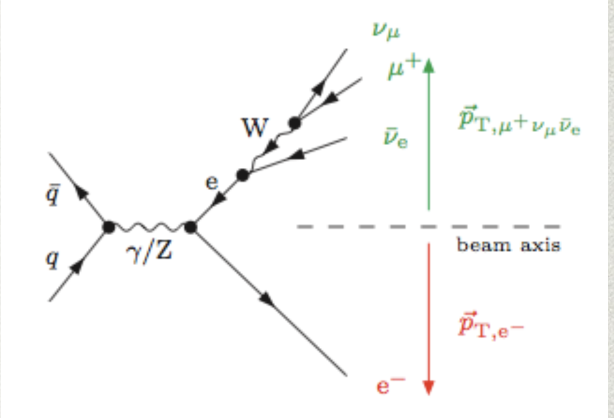
Biedermann, Biloni, Denner, Dittmaier, Hofer, Jager, Salfelder, arXiv: 1605.03419

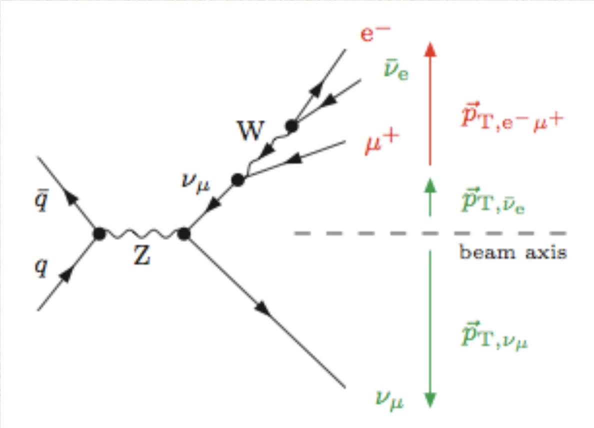
- Improvement on previous results in "double-pole approximation" (DPA), to full off-shell case.

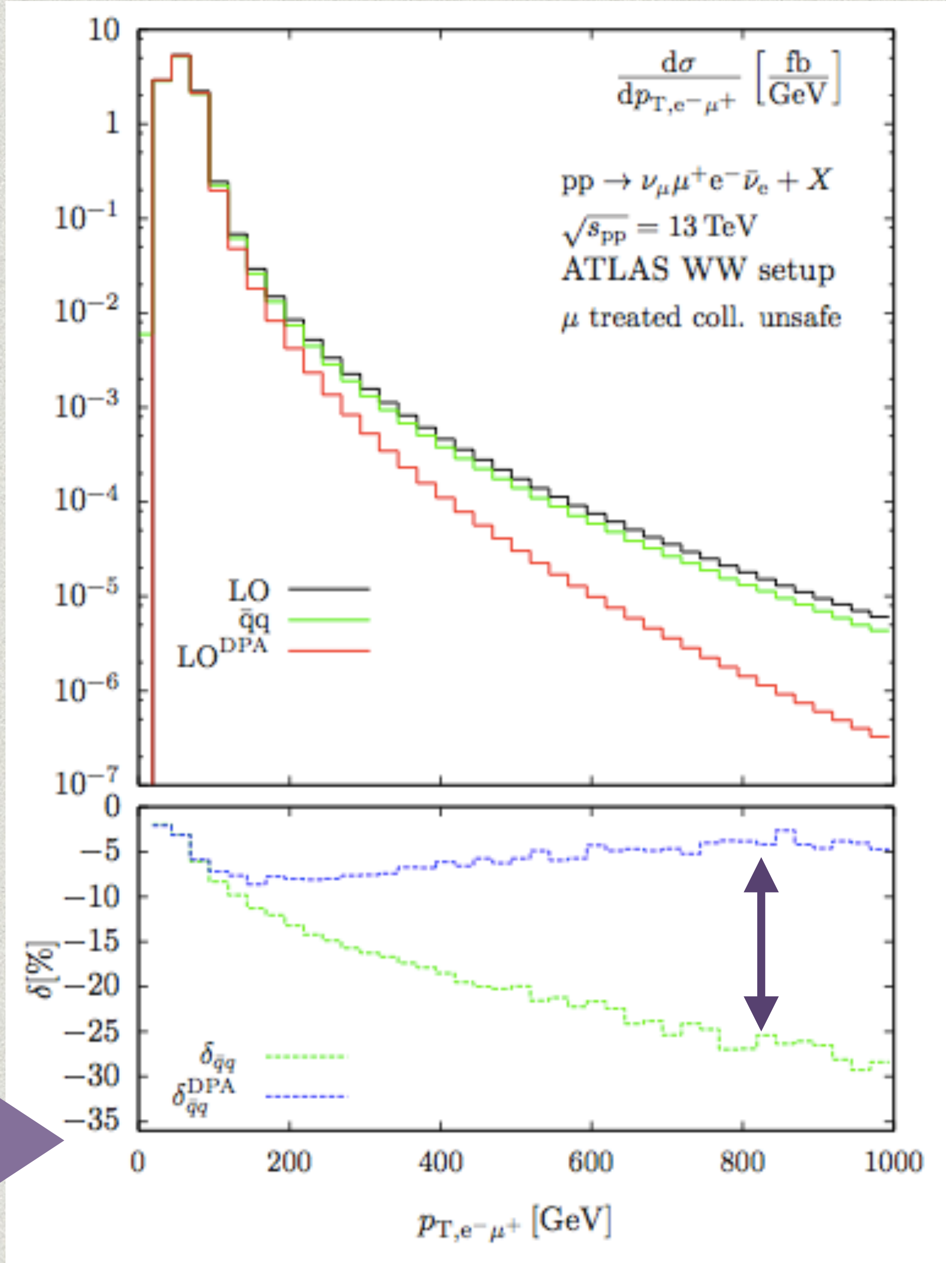


pT(electron)

differences due to single-resonant contributions







pT(electron, muon system)

ZZ production beyond NLO

- NNLO corrections known, dominated by gg loops.

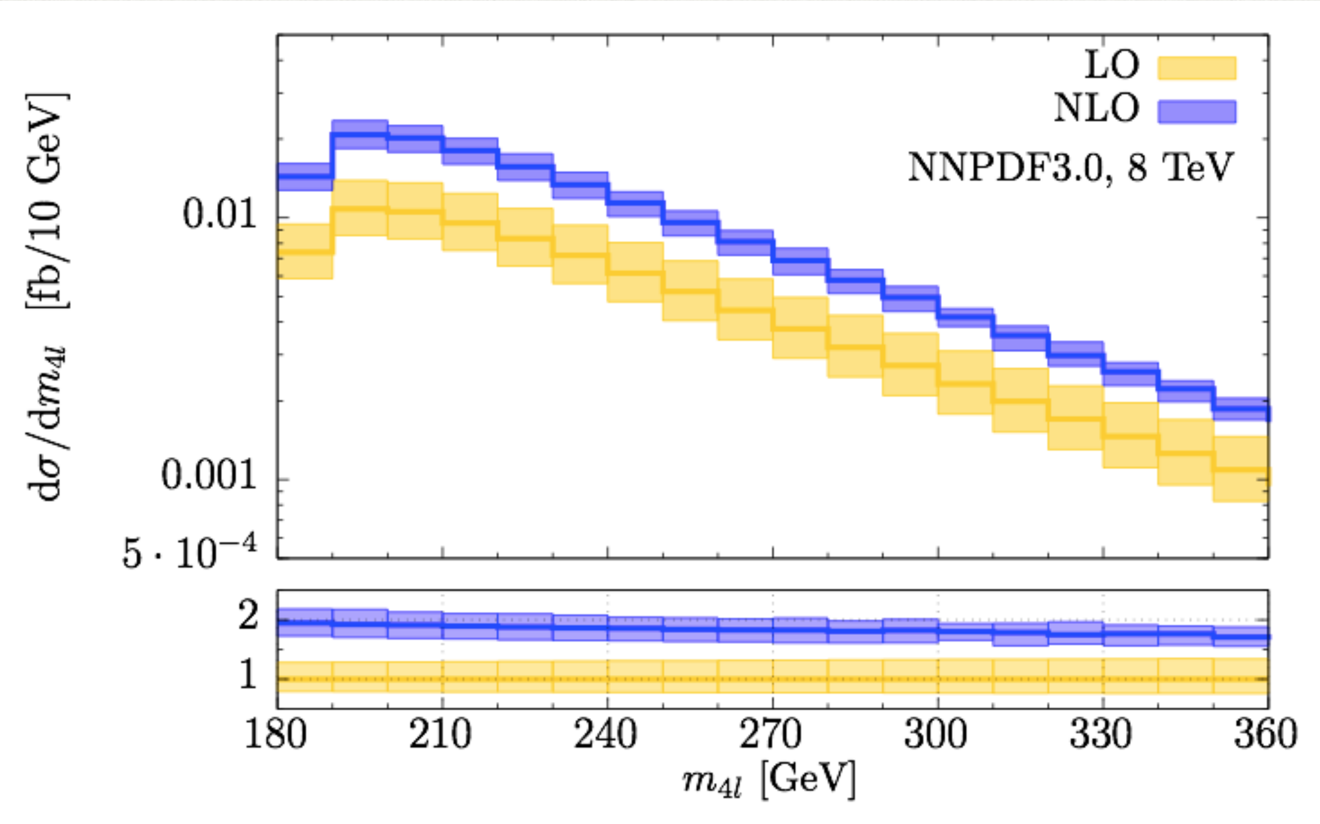
Cascioli, Gehrmann, Grazzini, Kallweit, Maierhofer, von Manteuffel, Pozzorini, Rathlev, Tancredi, Weihs, arXiv: 1408.5243; Grazzini, Kallweit, Rathlev, arXiv: 1507.06257

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

- Corrections to gg channel may be most important N^{3}LO effect.

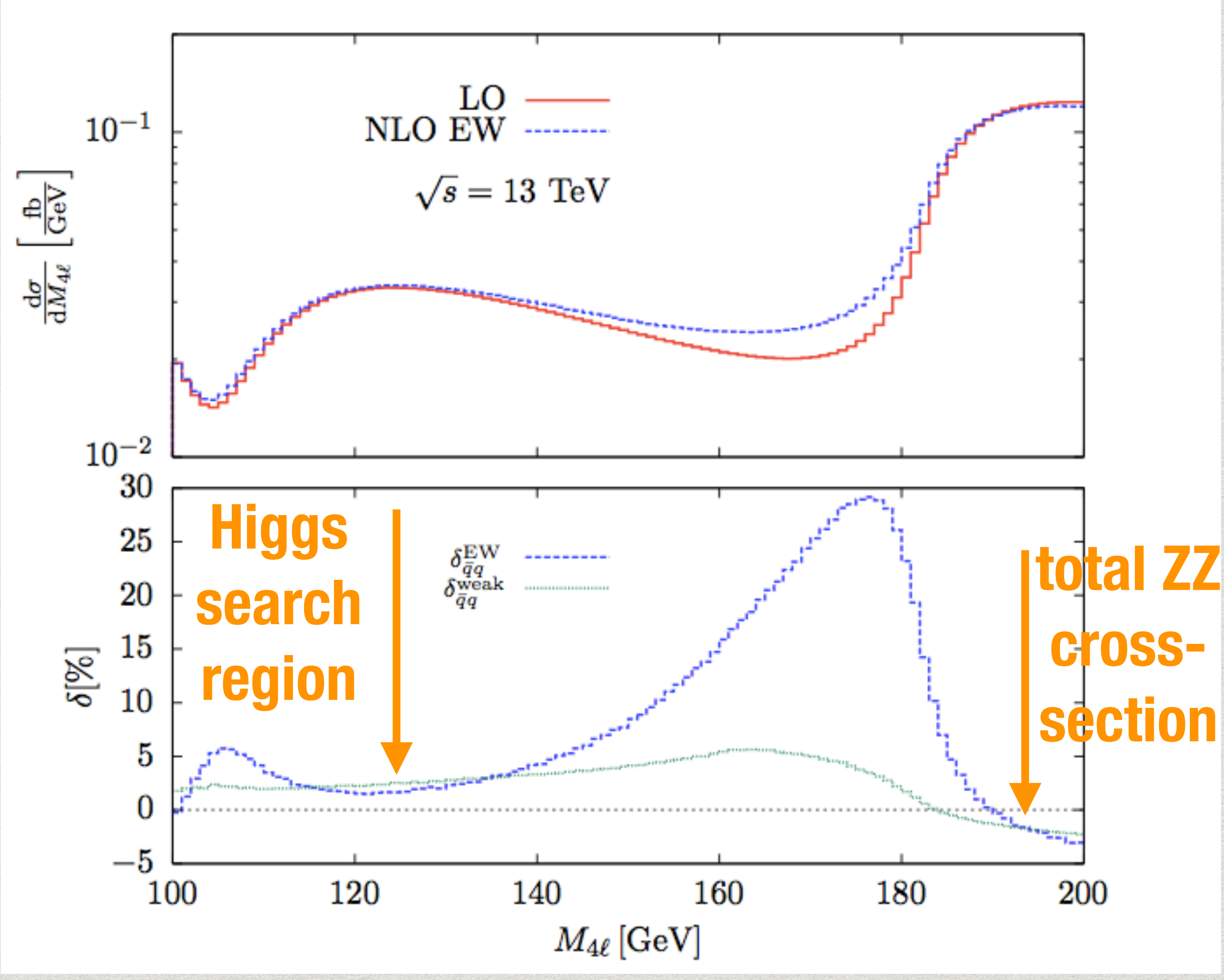
Caola, Melnikov, Rontsch, Tancredi, arXiv:1509.06734

- Computed for (dominant) loops of light quarks.



Electroweak corrections

- Most important for 4-lepton process, where exact results are now known even for off-shell production.



Biedermann, Dittmaier, Hofer, Jager, arXiv: 1601.07787

set of cuts optimized for Higgs studies:

$p_T(\ell_i) > 6\,\text{GeV}, \quad |y(\ell_i)| < 2.5$

$$40\,\text{GeV} < M_{\ell_1^+\ell_1^-} < 120\,\text{GeV}$$
$$12\,\text{GeV} < M_{\ell_2^+\ell_2^-} < 120\,\text{GeV}$$

Impact of gg loops

- Approximate combination of results for total ZZ cross-section, all channels.

Cascioli, Gehrmann, Grazzini, Kallweit, Maierhofer, von Manteuffel, Pozzorini, Rathlev, Tancredi, Weihs, arXiv: 1408.5243; Caola, Melnikov, Rontsch, Tancredi, arXiv:1509.06734

8 TeV	gg @ LO	gg @ NLO
gg alone	0.53 pb	0.95 pb
+ remainder of NNLO	8.28 pb	8.70 pb

7.1±0.6 pb (ATLAS-CONF-2013-020)

7.7±0.7 pb (CMS-SMP-13-005)

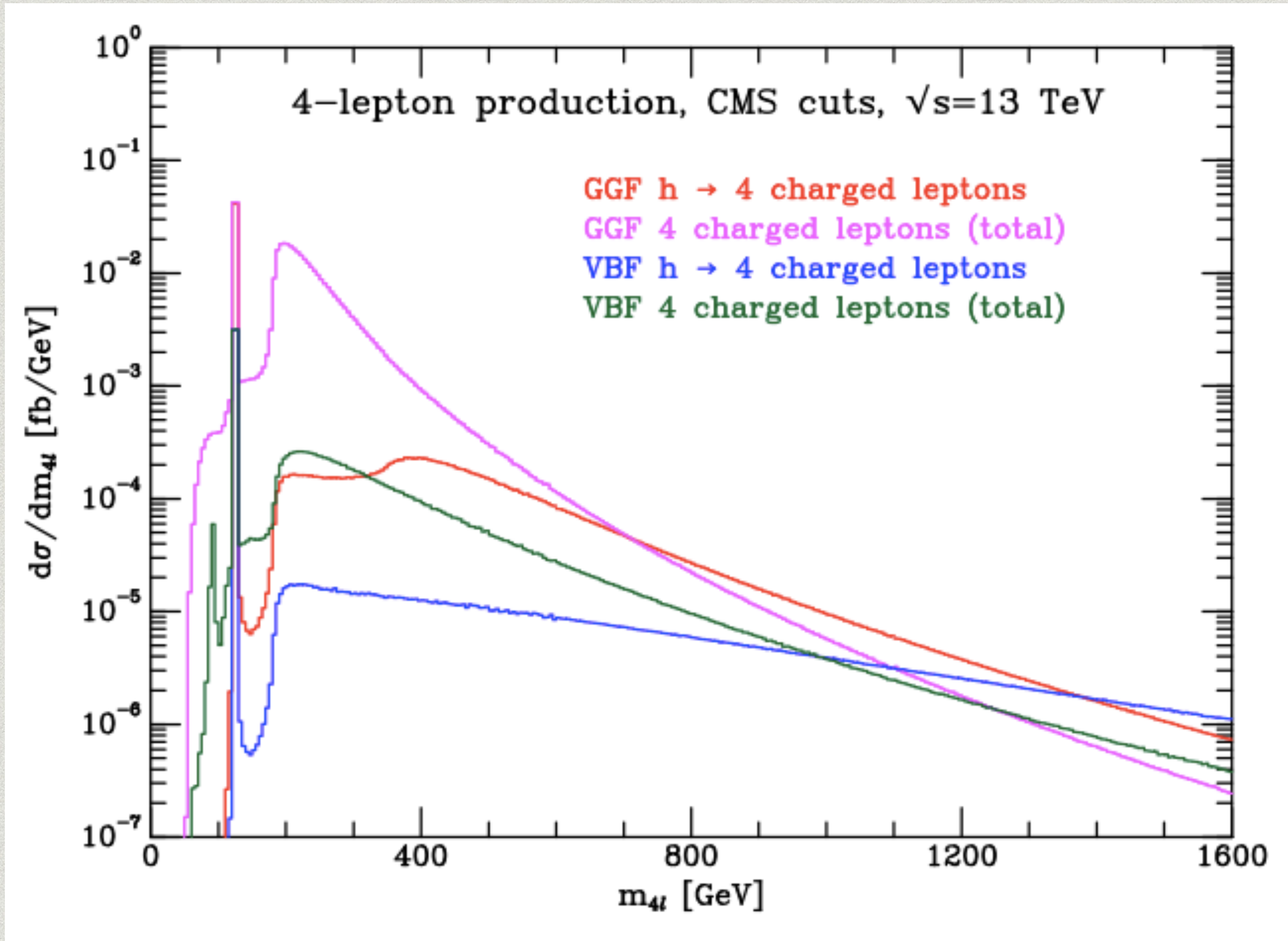
13 TeV	gg @ LO	gg @ NLO
gg alone	1.4 pb	2.4 pb
+ remainder of NNLO	16.9 pb	17.9 pb

17±3 pb (ATLAS, arXiv:1512.05314)

OFF-SHELL STUDIES

Gluon fusion vs. VBF

Ellis, JC, arXiv: 1502.02990

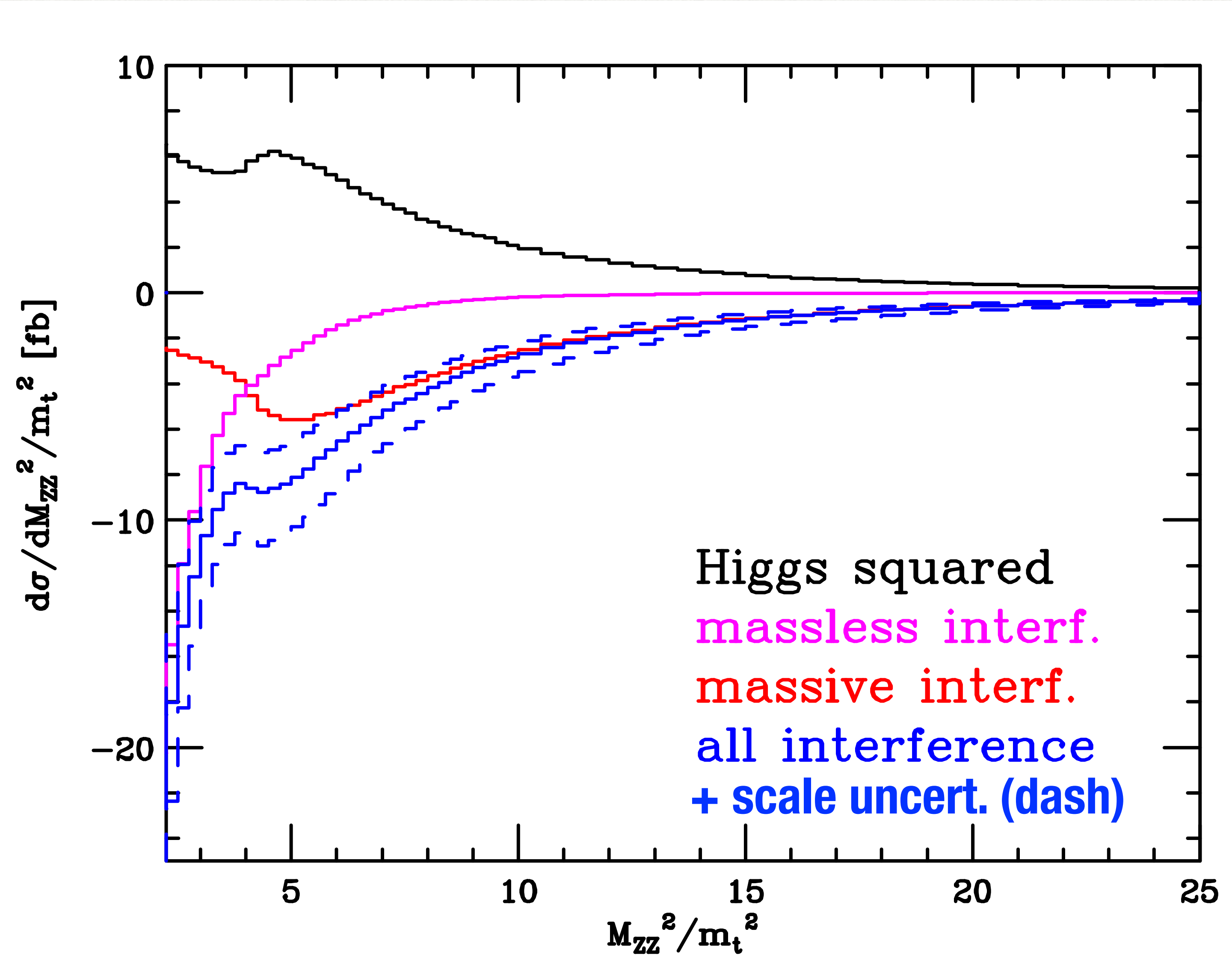


smaller rate in VBF but greater sensitivity; tree vs. loop probe

Off-shell ZZ production

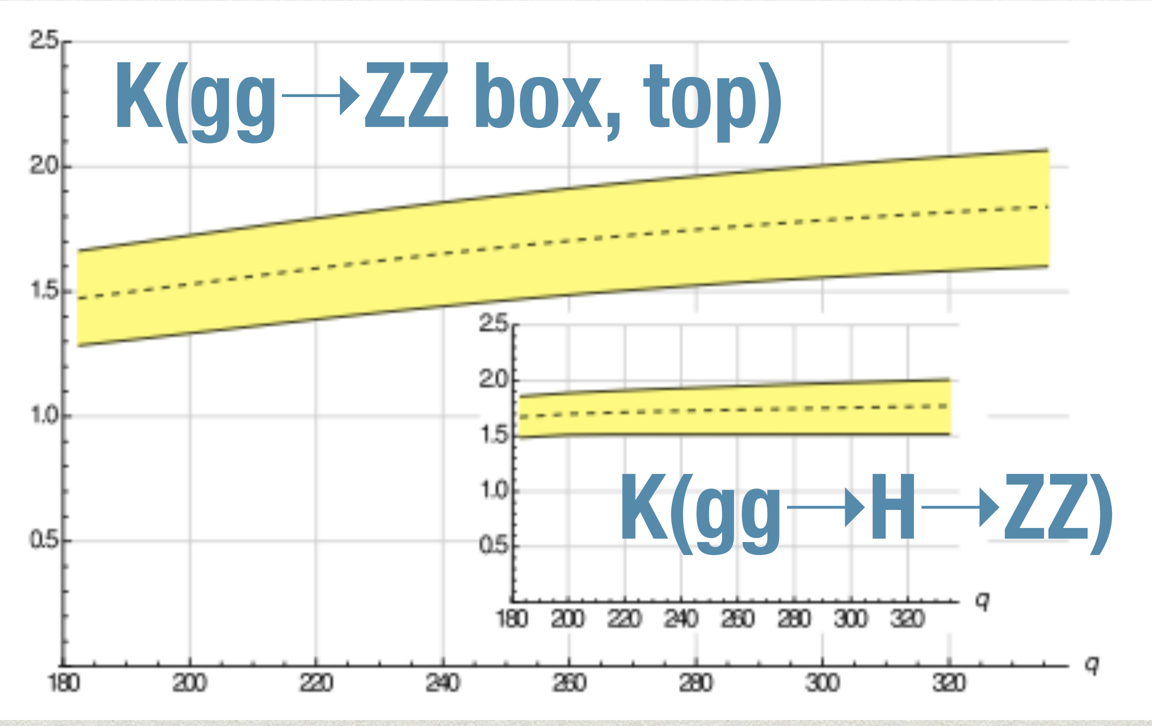
- Check cancellation demanded by unitarity: large destructive interference at high invariant masses between Higgs and continuum diagrams.
- Effect mediated by top quark loops that couple to longitudinal modes of Z's.
- Significant uncertainty in 1-loop (but LO) calculation.
  - weakens indirect constraint on Γ_H

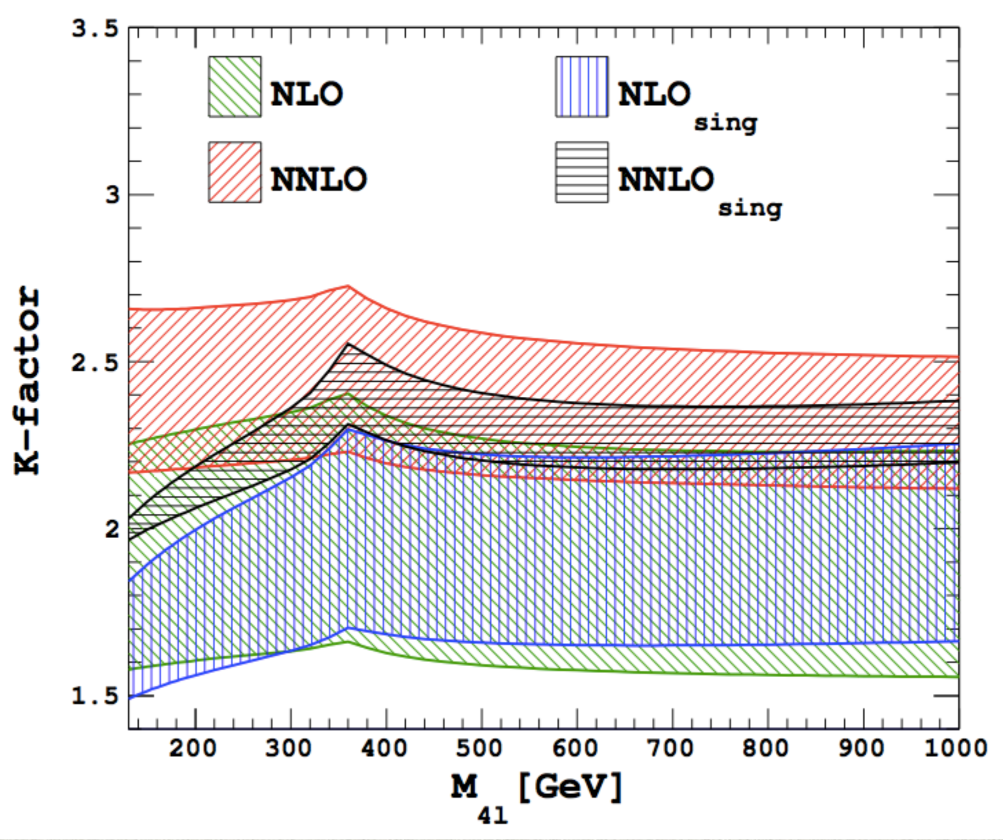
Caola, Melnikov, arXiv:1307.4935



Approximations beyond 1-loop

- Leading term in expansion of amplitudes as $m_t \to \infty$
  Melnikov, Dowling, arXiv: 1503.01274
  - only keep axial coupling (vector subleading).
  - only valid for $m_{ZZ} < 2m_t$.
- Another approach: soft gluon resummation.
  Chong Sheng Li, Hai Tao Li, Ding Yu Sao, Jian Wang, arXiv: 1504.02388
  - known parts of continuum NLO result a good approx. for Higgs.
  - based on this, find K-factors for signal and interference that are very similar.



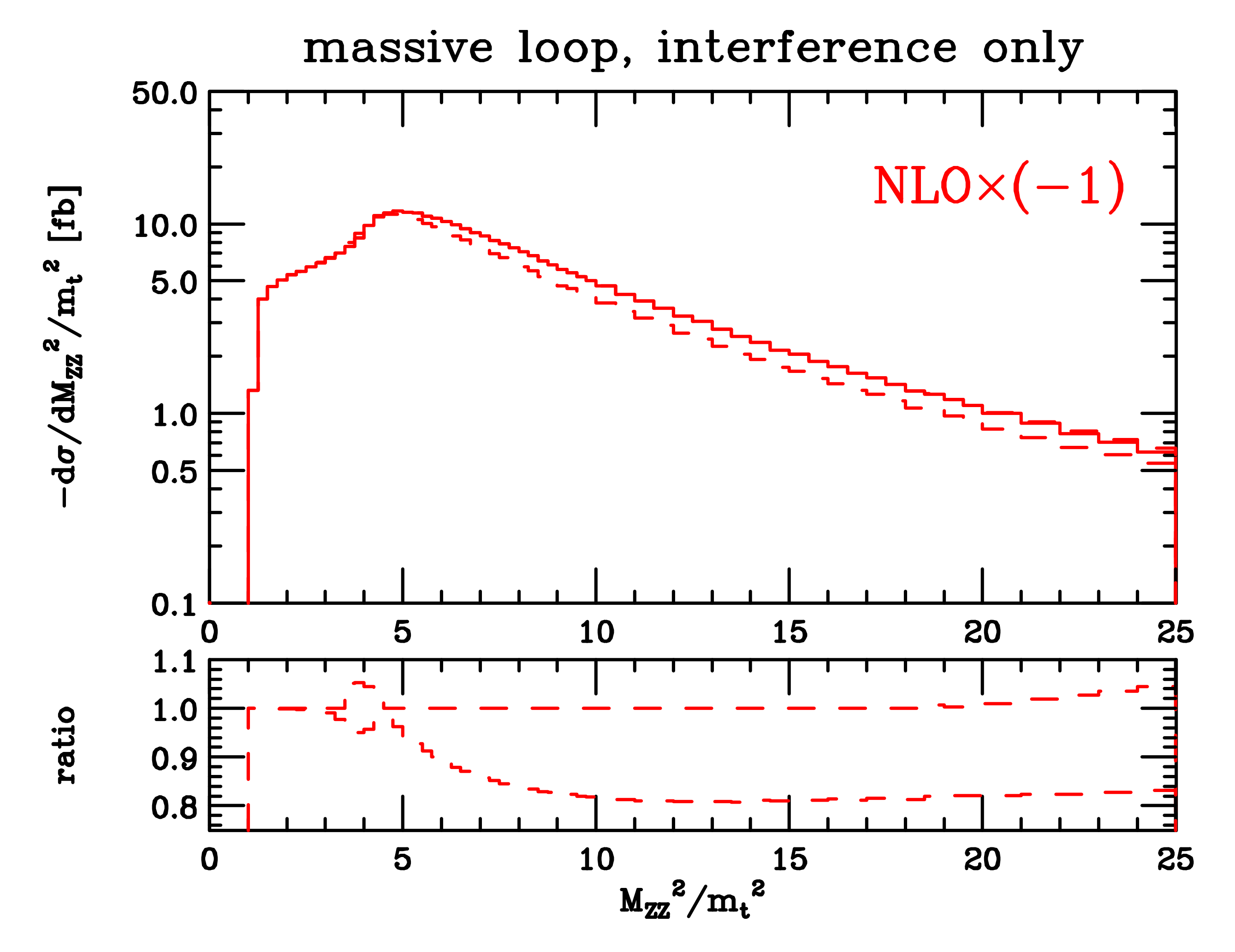


Beyond $1/m_t$

JC, Ellis, Czakon, Kirchner, arXiv: 1605.01380

- Expansion up to $1/mt^{12}$, ameliorated by conformal mapping and use of Pade approximants.
  - interference only, on-shell Z bosons.
  - improve description above $2m_t$ threshold by factoring out exact result at LO.

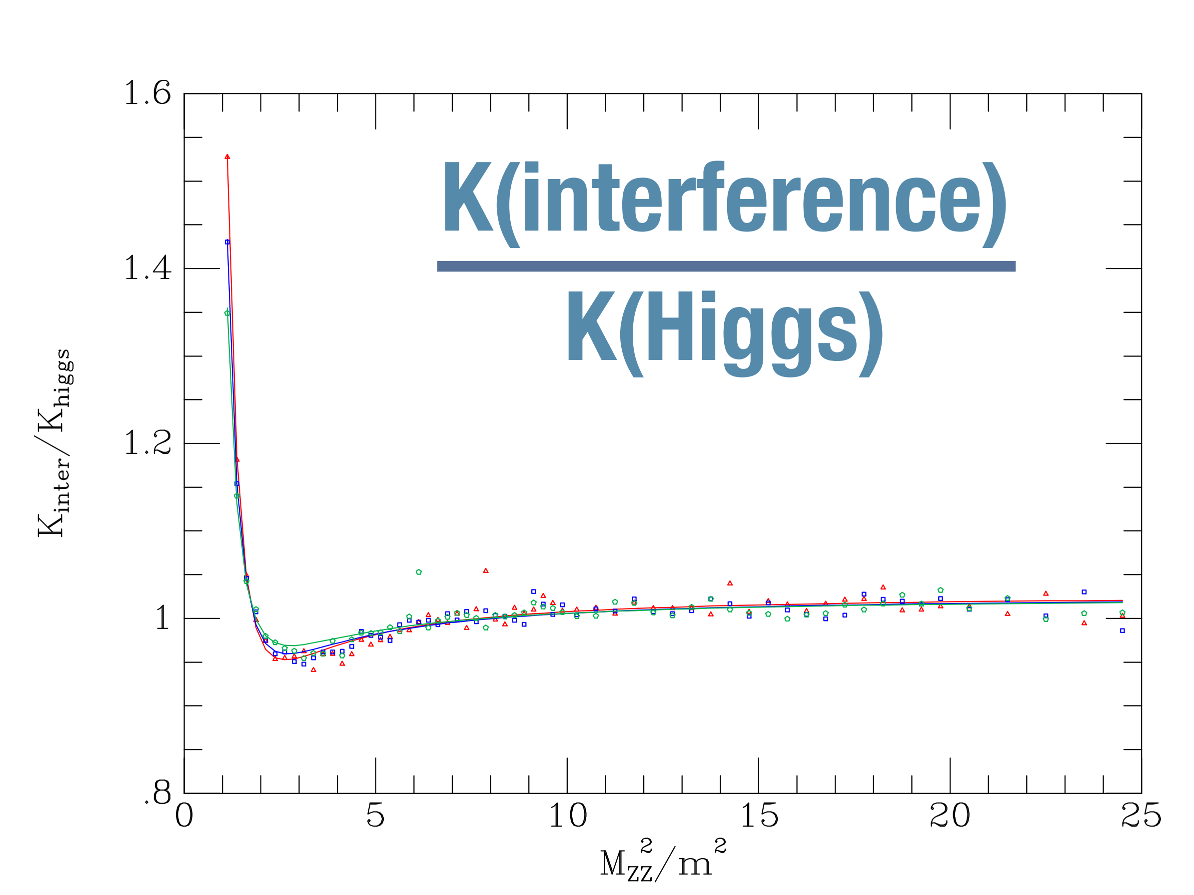
$$\sigma^{\rm NLO}_{{\rm imp},[n/m]} = \sigma^{\rm LO}_{\rm exact} \cdot \frac{\sigma^{\rm NLO}_{[n/m]}}{\sigma^{\rm LO}_{[n/m]}}$$

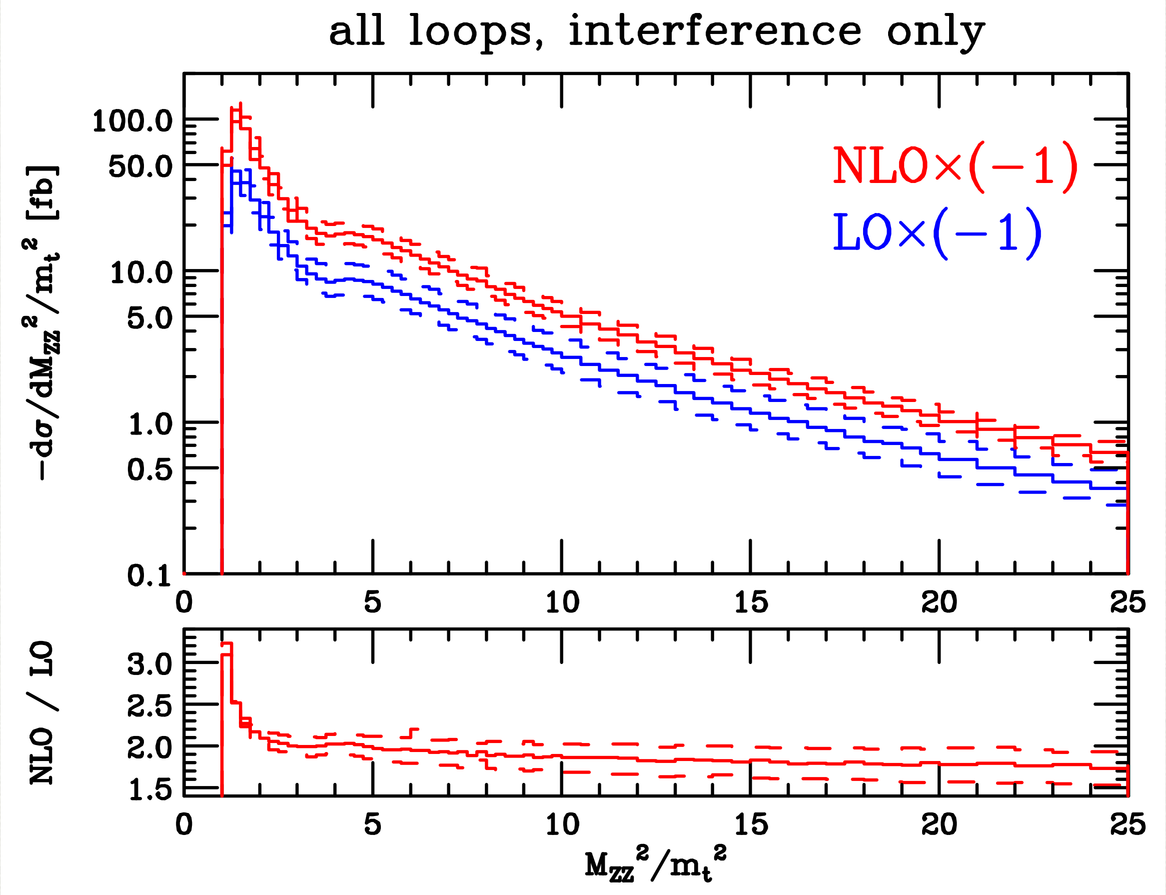


- Estimate impact of procedure by varying number of terms in approximant;
  - to be conservative, multiply this uncertainty by a factor of two.

Full interference

- Effect of massless quark loops included exactly.
- K-factor for interference almost identical to Higgs diagrams alone
  - apart from approach to ZZ threshold, due to massless loops.
- Scale uncertainty reduced, virtually identical for both cases.





Impact on indirect Γ_H constraint

- Consider cross-section in region with M_{ZZ}>300 GeV.
- Apply branching ratio into 4 leptons, no cuts.

Contribution	σ_{LO} [fb]	σ_{NLO} [fb]	σ_{NLO}/σ_{LO}
Higgs mediated diagrams	$42.1^{+12.1}_{-8.8}$	$80.7^{+14.2}_{-12.0}$	1.92
interference (total)	$-60.7^{+12.8}_{-17.4}$	$-116.3^{+17.5}_{-19.9}(\text{scale})^{+5.4}_{-0.4}(\text{LME})$	1.91
interference (massless loops)	$-12.5^{+2.5}_{-3.4}$	$-22.5^{+3.2}_{-3.2}$	1.80
interference (massive loop)	$-48.2^{+10.3}_{-14.1}$	$-93.0^{+14.0}_{-16.4}(\text{scale})^{+5.4}_{-0.4}(\text{LME})$	1.93

Limitation of LME estimated conservatively, still smaller than scale uncertainty.

"off-shell" / "on-shell"

$$\frac{\sigma_{4\ell}^{LO}(m_{4\ell} > 300\text{ GeV})}{\sigma_{4\ell}^{LO}(m_{4\ell} < 130\text{ GeV})} = (0.115^{+0.014}_{-0.010}) \times \left(\frac{\Gamma_H}{\Gamma_H^{SM}}\right) - (0.166^{+0.020}_{-0.015}) \times \sqrt{\frac{\Gamma_H}{\Gamma_H^{SM}}}$$

$$\frac{\sigma_{4\ell}^{NLO}(m_{4\ell} > 300\text{ GeV})}{\sigma_{4\ell}^{NLO}(m_{4\ell} < 130\text{ GeV})} = (0.094^{+0.000}_{-0.002}) \times \left(\frac{\Gamma_H}{\Gamma_H^{SM}}\right) - (0.135^{+0.000}_{-0.008}) \times \sqrt{\frac{\Gamma_H}{\Gamma_H^{SM}}}$$

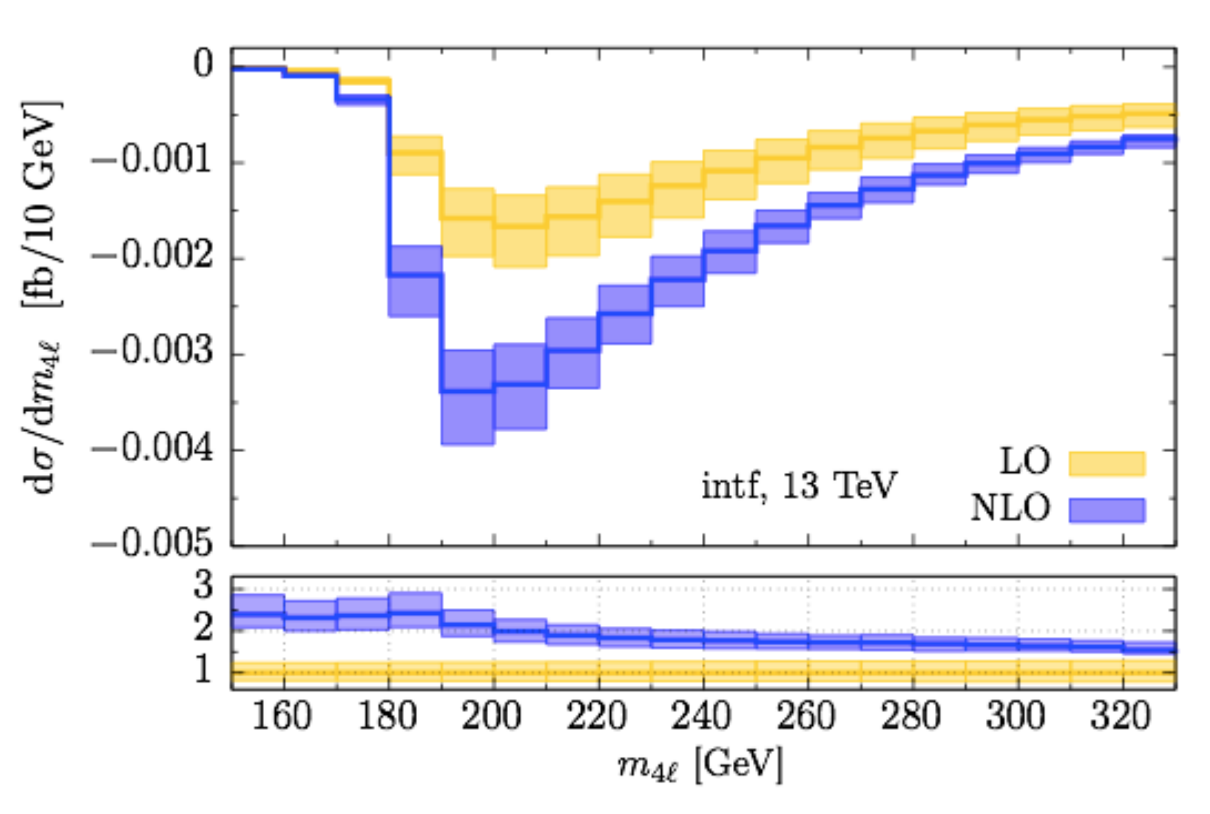
off-shell/on-shell relatively stable and scale uncertainty under control

Alternative approach

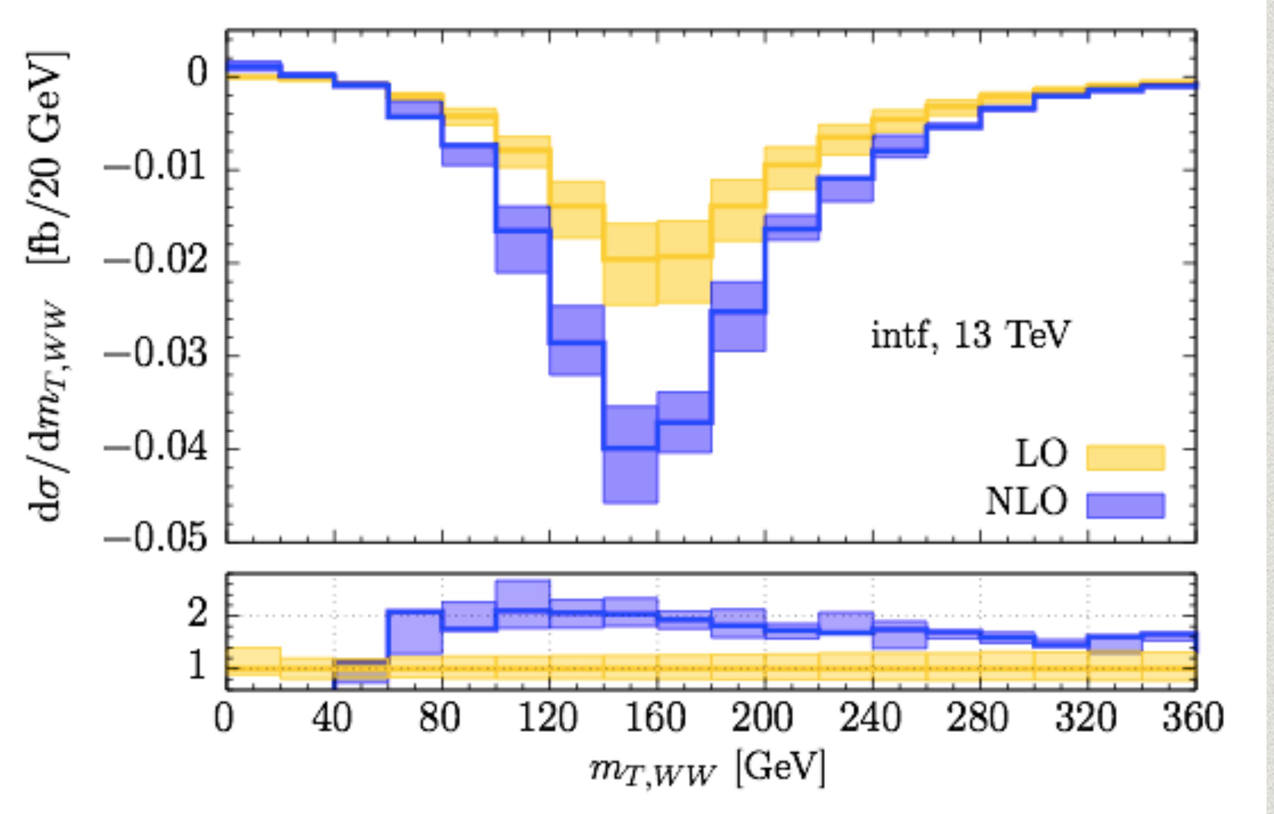
Caola, Dowling, Melnikov, Rontsch, Tancredi, arXiv: 1605.04610

- Expansion up to $1/m_t^8$, limit to region below top threshold.
  - includes Higgs signal, continuum and interference.
  - accounts for off-shell vector bosons and decays.
- Qualitatively similar findings for ZZ, new results for WW (light quarks only).

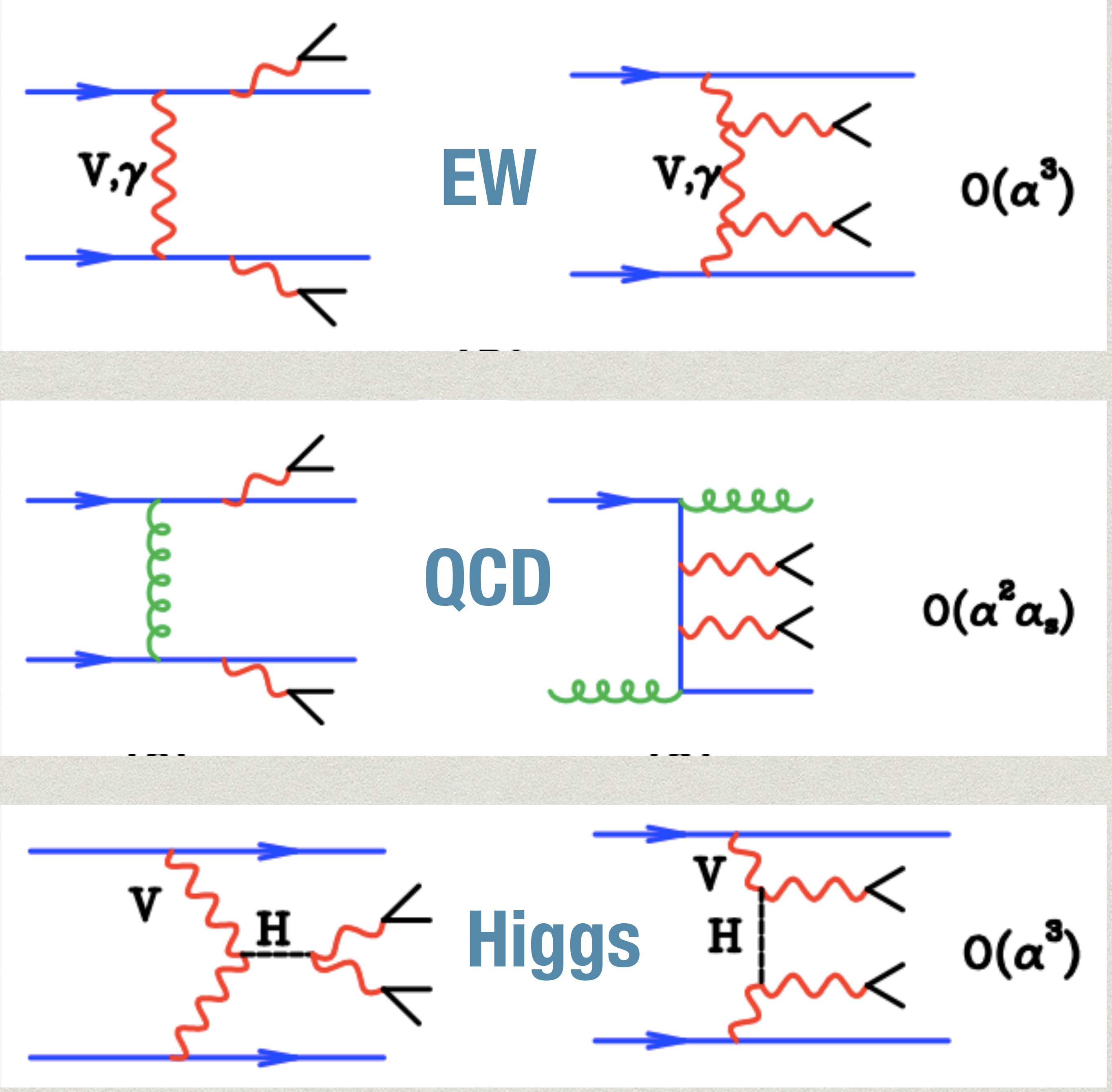
gg→ZZ interference



gg→WW interference



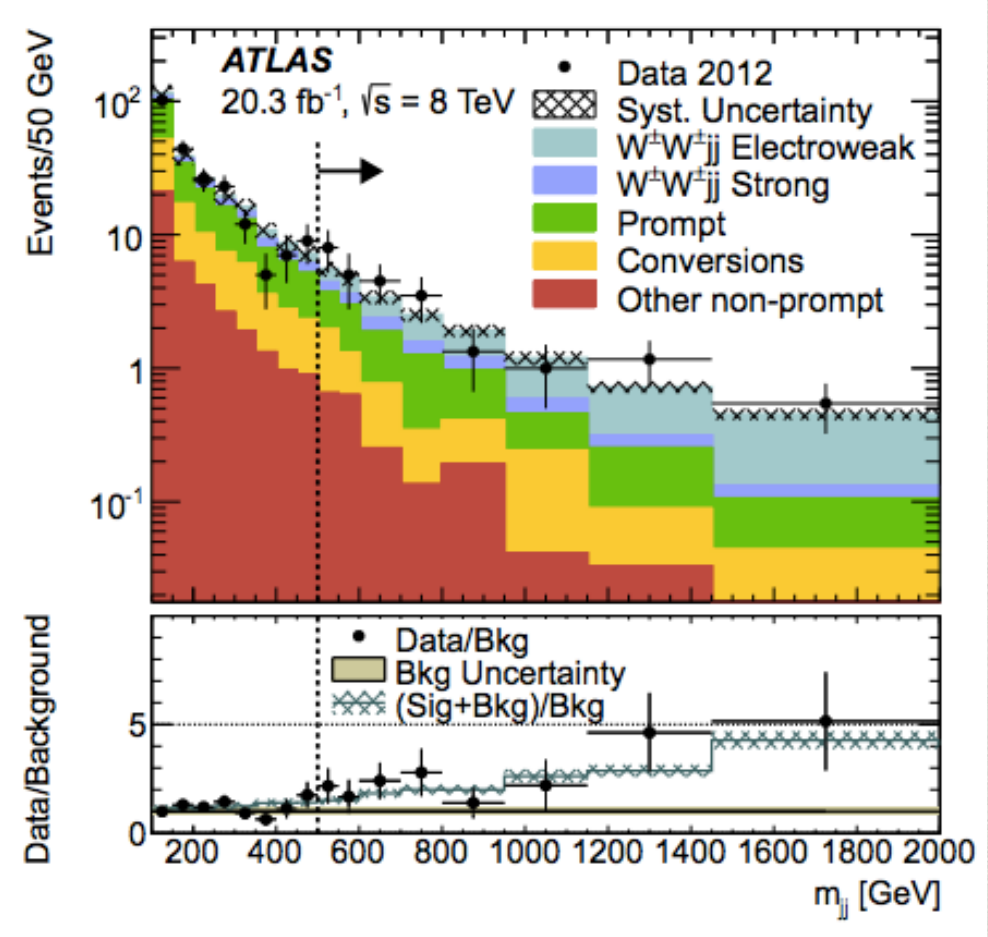
Vector boson scattering



- Full, gauge-invariant and QM treatment demands inclusion of all diagrams.
  - except, e.g. in resonance region, when subset provides good approx.
  - extension to models with additional Higgs singlet.
    Ballestrero, Maina, arXiv: 1506.02257
- Sensitivity to Higgs boson through *t*-channel, even without *s*-channel resonance, e.g. W^+W^+ production.
  Ellis, JC, arXiv: 1502.02990

Like-sign sensitivity

- $W^{\pm}W^{\pm}$ particularly interesting:
  - relatively high event rate;
  - small QCD contribution.
- Evidence already from ATLAS at 8 TeV.
  ATLAS, arXiv: 1405.6241
  (c.f. also CMS search, arXiv: 1410.6315)



- Small number of events in 20fb^{-1}, so only mild VBF cuts → not yet really probing interesting region.
- Can still reinterpret evidence as weak bound on Higgs width:

$$\Gamma_H < 60.8 \times \Gamma_H^{SM}$$ → **promising with more data at 13 TeV**

VBF/VBS at NLO

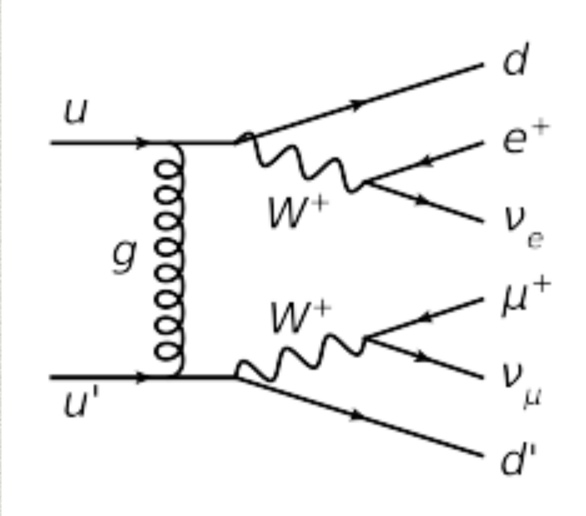
- Full suite of NLO predictions available in VBFNLO.
  - including decays, off-shell effects, spin correlations.

comprehensive review: Campanario, Kerner, Ninh, Rauch, Roth, Zeppenfeld, NPPP 261 (2015) 268

LHC Process	σ_{LO} ($\sqrt{s}$ = 8 TeV)	σ_{NLO}	K
$pp \to Hjj$ ("VBF-H")	318.33(4) fb	328.73(15) fb	1.03
$pp \to Hjjj$ ("VBF-H+jet")	27.602(8) fb	27.05(7) fb	0.98
$pp \to HHjj$ ("VBF-HH")	0.14788(3) fb	0.14622(8) fb	0.99
$pp \to H\gamma jj$ ("VBF-$H\gamma$")	4.7603(7) fb	4.837(3) fb	1.02
$pp \to \ell^+\ell^- jj$ ("VBF-Z_ℓ")	77.54(4) fb	84.27(11) fb	1.09
$pp \to \nu\bar{\nu}jj$ ("VBF-Z_ν")	192.57(10) fb	212.0(3) fb	1.10
$pp \to \ell^+\nu jj$ ("VBF-W^+")	764.14(14) fb	816.9(5) fb	1.07
$pp \to \ell^-\bar{\nu}jj$ ("VBF-W^-")	409.06(7) fb	446.9(3) fb	1.09
$pp \to \gamma jj$ ("VBF-γ")	1824.5(5) fb	2033(2) fb	1.11
$pp \to \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}jj$ ("VBF-W^+W^-")	6.023(3) fb	6.268(10) fb	1.04
$pp \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-jj$ ("VBF-$Z_\ell Z_\ell$")	49.95(4) ab	52.56(14) ab	1.05
$pp \to \ell_1^+\ell_1^-\nu_2\bar{\nu}_2jj$ ("VBF-$Z_\ell Z_\nu$")	0.3693(2) fb	0.3892(7) fb	1.05
$pp \to \ell_1^+\nu_{\ell_1}\ell_2^+\ell_2^-jj$ ("VBF-W^+Z_ℓ")	0.40346(15) fb	0.4172(4) fb	1.03
$pp \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^+\ell_2^-jj$ ("VBF-W^-Z_ℓ")	0.19374(7) fb	0.2048(2) fb	1.06
$pp \to \ell_1^+\nu_{\ell_1}\ell_2^+\nu_{\ell_2}jj$ ("VBF-W^+W^+")	1.4085(4) fb	1.4454(14) fb	1.03
$pp \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}jj$ ("VBF-W^-W^-")	0.33950(10) fb	0.3705(3) fb	1.09
$pp \to \ell^+\nu\gamma jj$ ("VBF-$W^+\gamma$")	9.412(3) fb	9.885(18) fb	1.05
$pp \to \ell^-\bar{\nu}\gamma jj$ ("VBF-$W^-\gamma$")	4.8293(13) fb	5.155(5) fb	1.07

- Also includes results for QCD-induced processes with the same final states (i.e. VV+2jet).

(no interference)

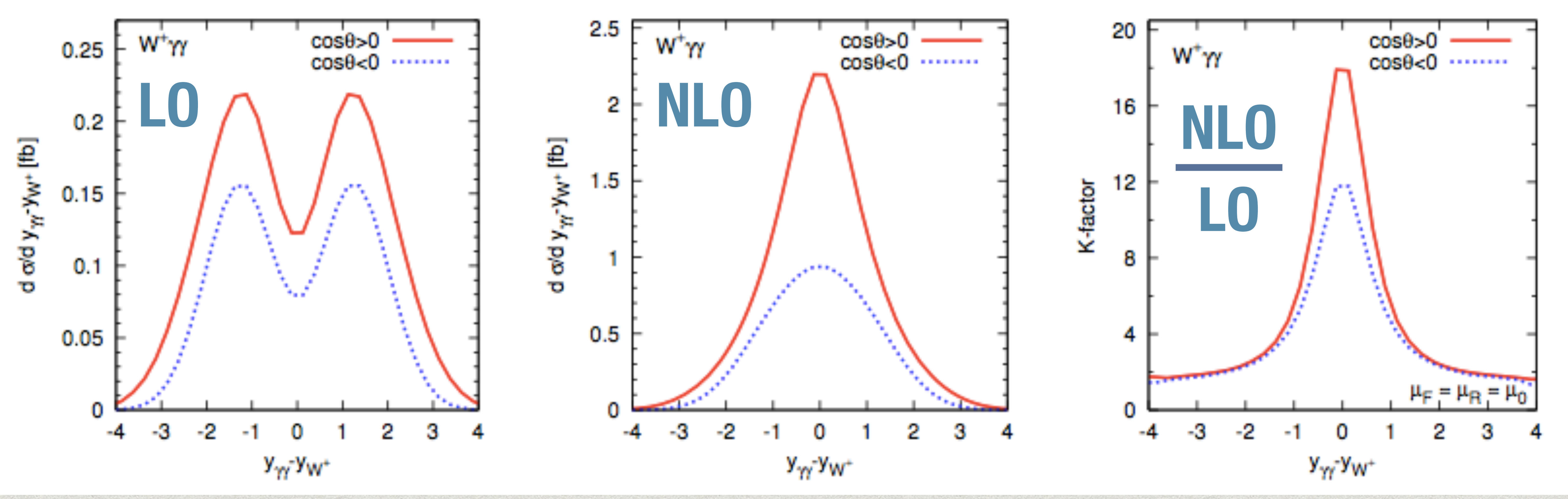


BEYOND DIBOSONS

Multi-bosons in VBFNLO

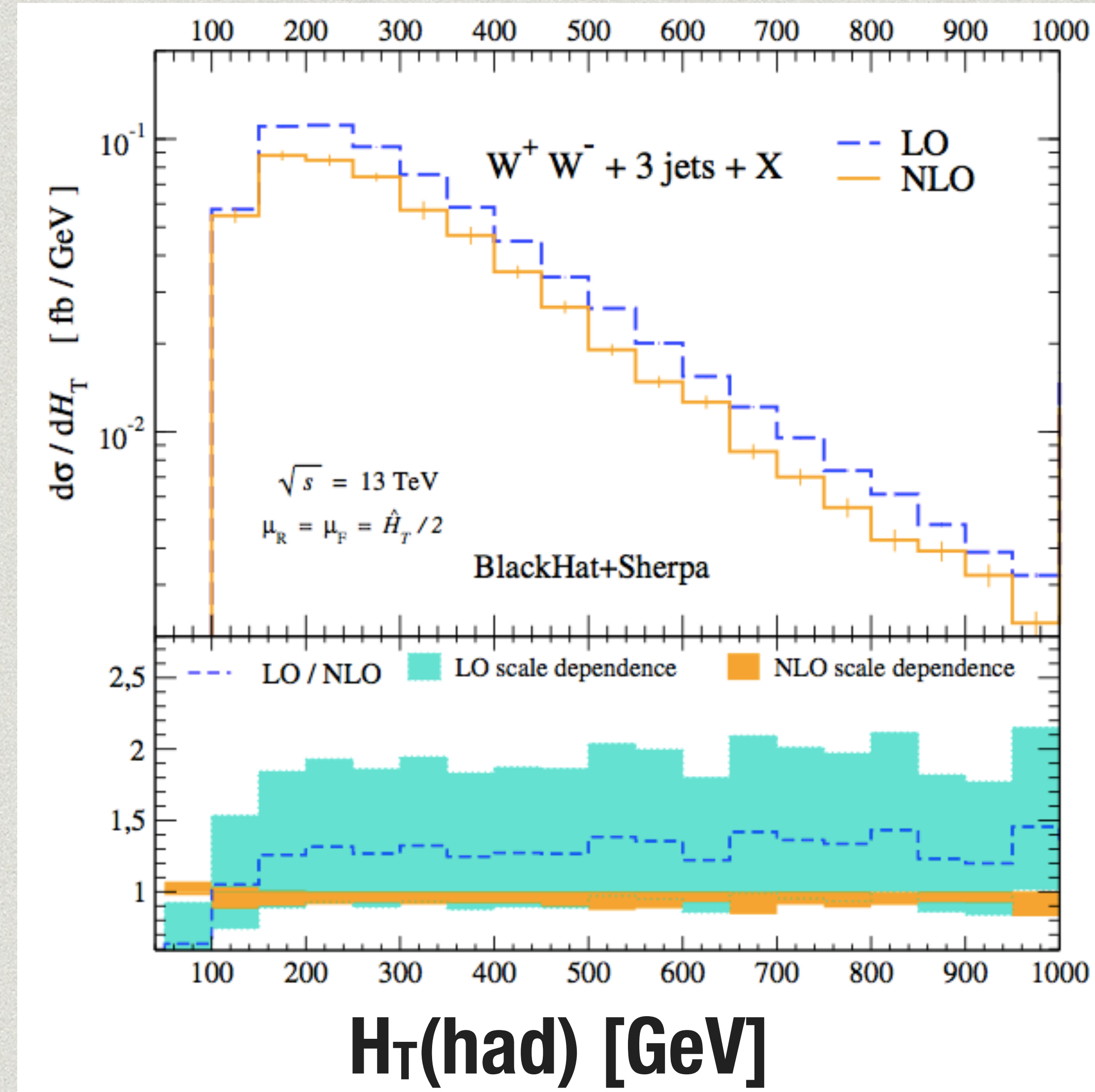
- Wγγ is of the most interesting (and accessible) channels.
  Evidence at 8 TeV from ATLAS, arXiv: 1503.03243
- pp collisions mean radiation zero in LO amplitude reflected as dip at LHC.
  - completely filled-in by NLO QCD corrections
  - huge corrections.

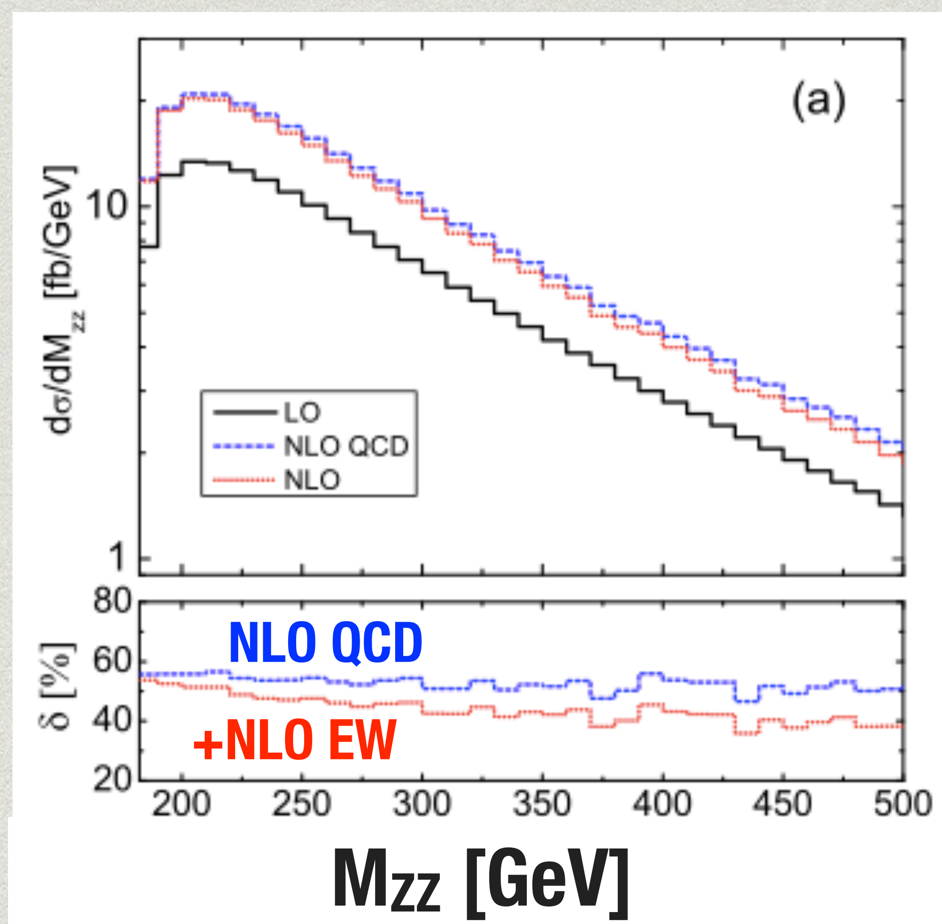
	LO	NLO	NLO/LO
$pp \to \ell^+ \nu_\ell \gamma\gamma$ ("$W^+\gamma\gamma$")	7.586(2) fb	23.806(9) fb	3.14
$pp \to \ell^- \bar{\nu}_\ell \gamma\gamma$ ("$W^-\gamma\gamma$")	5.8381(14) fb	20.260(7) fb	3.47



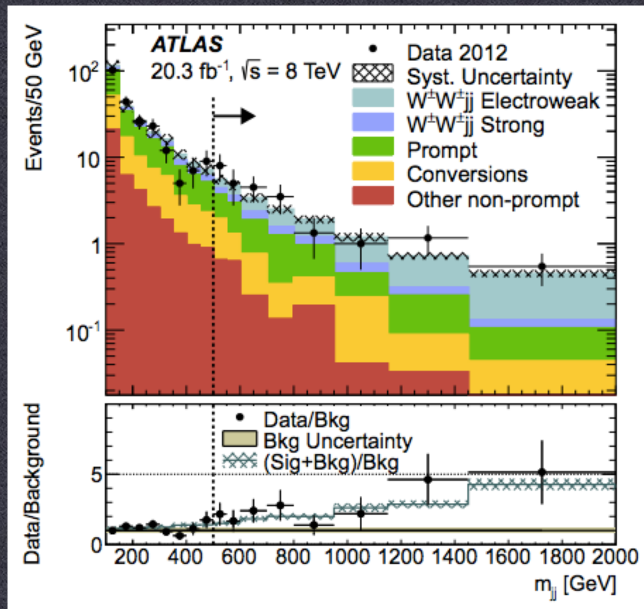
Dibosons+jets progress

- High-multiplicity: WW+3 jets now computed to NLO (BlackHat+SHERPA).
  Febres Cordero, Hofmann, Ita, arXiv: 1512.07591 → **D. Kosower**
- Precision control of top backgrounds, NP searches.

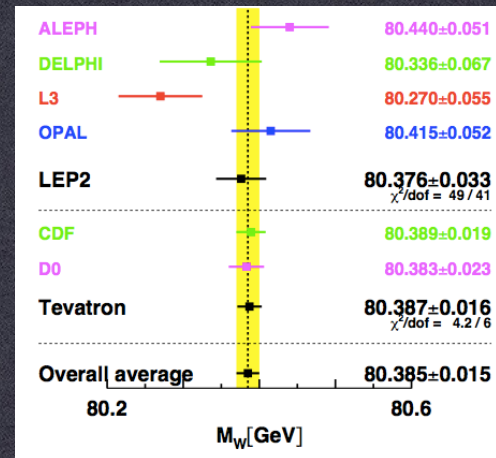




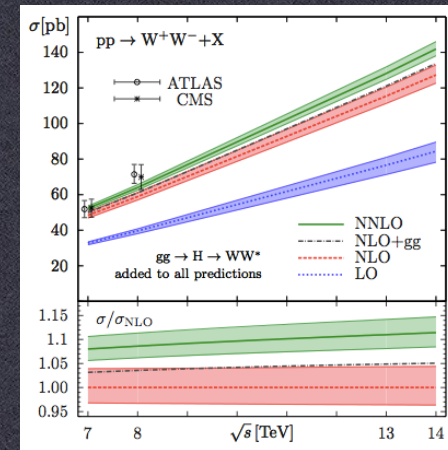
- NLO QCD and EW corrections to WW+jet, ZZ+jet production.
  Wei-Hua Li, Ren-You Zhang, Wen-Gan Ma, Lei Guo, Xiao-Zhou Li, Yu Zhang, arXiv: 1507.07332
  Wang Yong, Zhang Ren-You, Ma Wen-Gan, Li Xiao-Zhou, Guo Lei, arXiv: 1604.04080



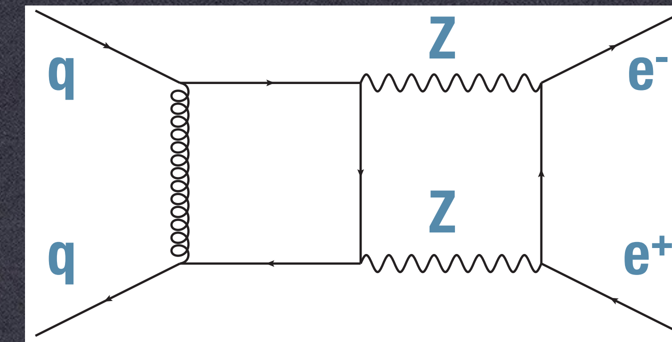
ATLAS
20.3 fb⁻¹, √s = 8 TeV
Data 2012
Syst. Uncertainty
W±W±jj Electroweak
W±W±jj Strong
Prompt
Conversions
Other non-prompt
Events/50 GeV
Data/Bkg
Bkg Uncertainty
(Sig+Bkg)/Bkg
Data/Background
m_jj [GeV]



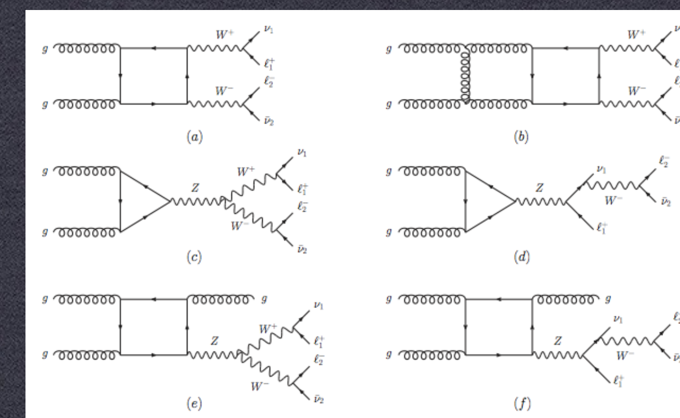
ALEPH 80.440±0.051
DELPHI 80.336±0.067
L3 80.270±0.055
OPAL 80.415±0.052
LEP2 80.376±0.033
χ²/dof = 49 / 41
CDF 80.389±0.019
D0 80.383±0.023
Tevatron 80.387±0.016
χ²/dof = 4.2 / 6
Overall average 80.385±0.015
80.2
80.6
M_W [GeV]

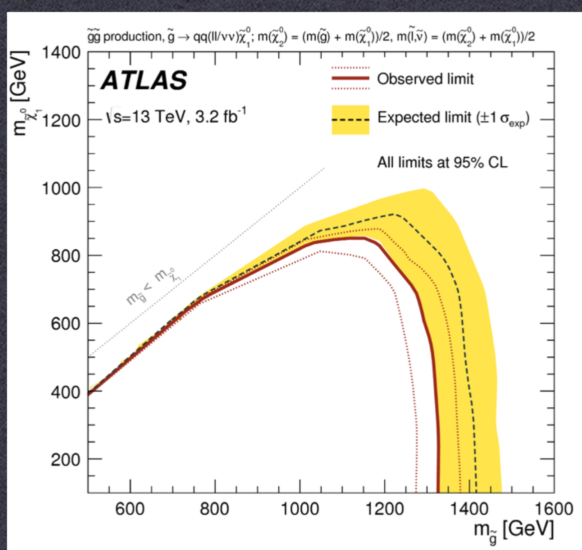


σ[pb]
pp → W⁺W⁻+X
ATLAS
CMS
gg → H → WW*
added to all predictions
NNLO
NLO+gg
NLO
LO
σ/σ_NLO
√s [TeV]



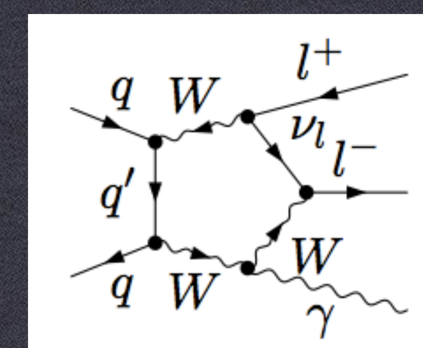
q
q
Z
Z
e⁻
e⁺



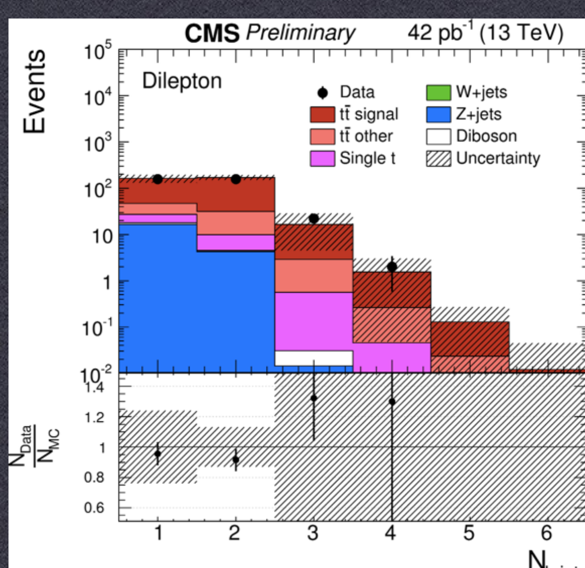


ATLAS
√s=13 TeV, 3.2 fb⁻¹
Observed limit
Expected limit (±1 σ_exp)
All limits at 95% CL
m_g̃ [GeV]

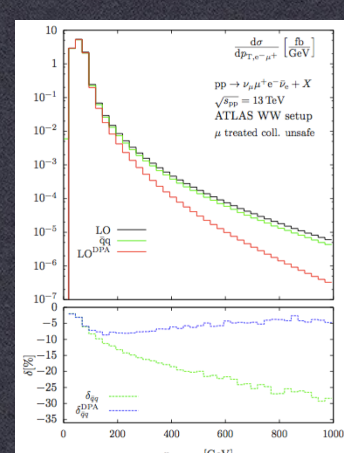
ACCURATE MEASUREMENT
LONG-CONTINUED LABOUR
MINUTE-SIFTING OF RESULTS

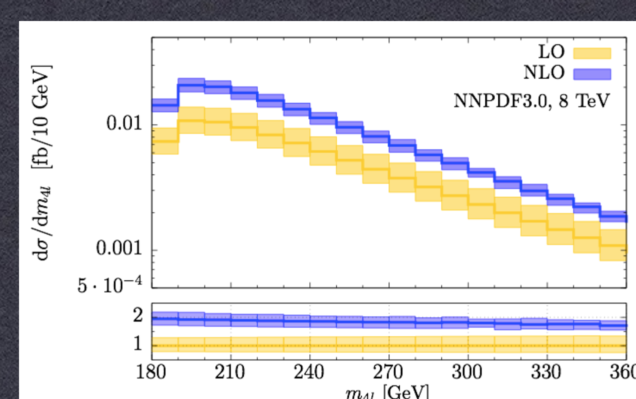


q
W
l⁺
ν_l
l⁻
q′
q
W
W
γ

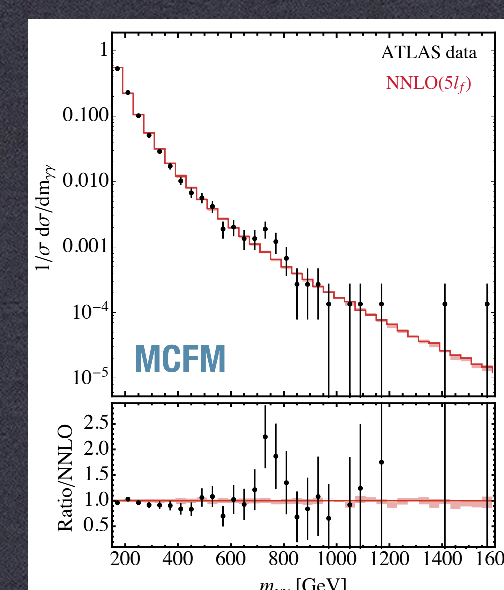


CMS Preliminary
42 pb⁻¹ (13 TeV)
Dilepton
Data
tt̄ signal
tt̄ other
Single t
W+jets
Z+jets
Diboson
Uncertainty
Events
N_Data/N_MC
N_b jets

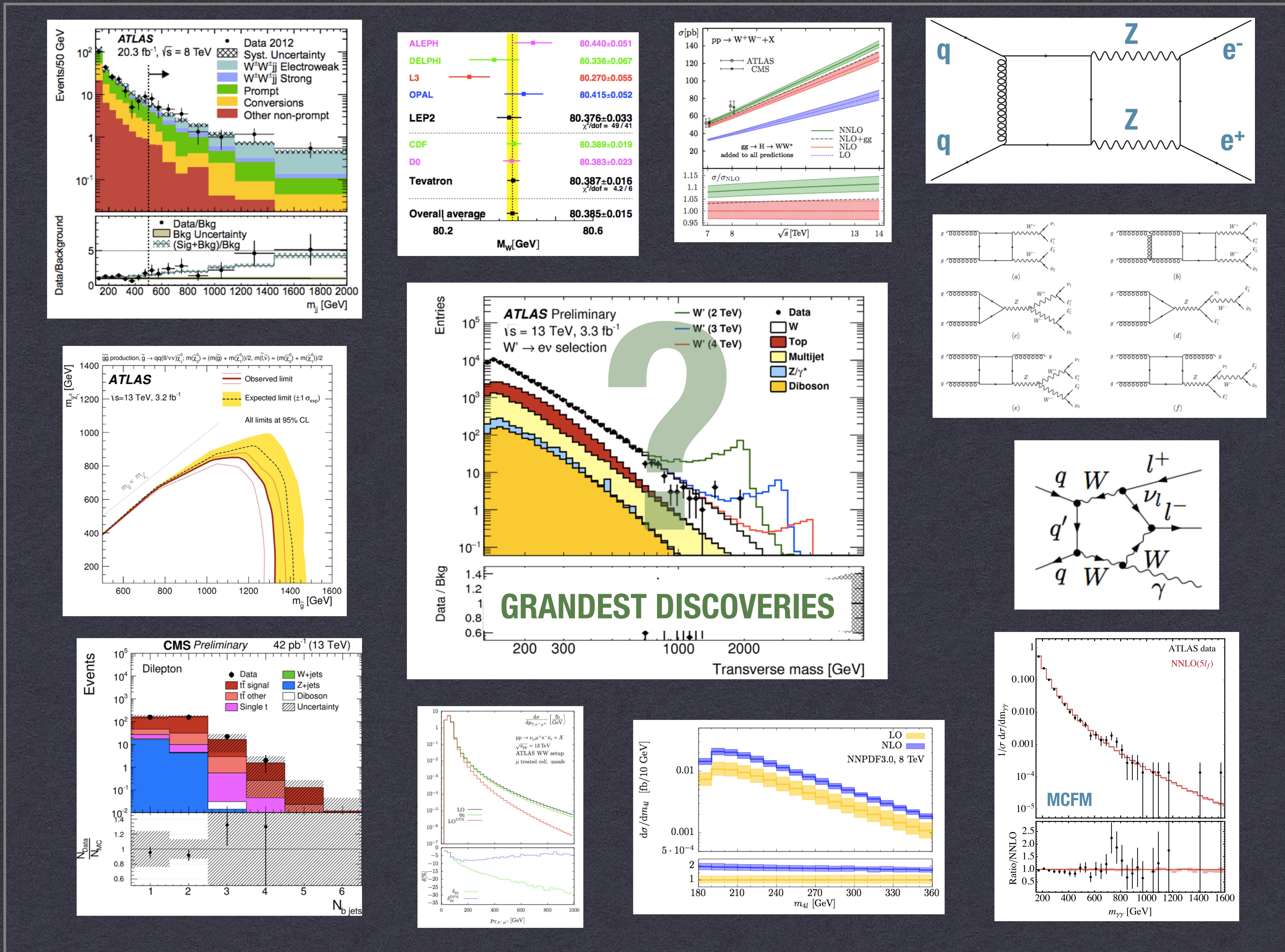




LO
NLO
NNPDF3.0, 8 TeV
dσ/dm_4l [fb/10 GeV]
m_4l [GeV]



ATLAS data
NNLO(5l_f)
MCFM
1/σ dσ/dm_γγ
Ratio/NNLO
m_γγ [GeV]



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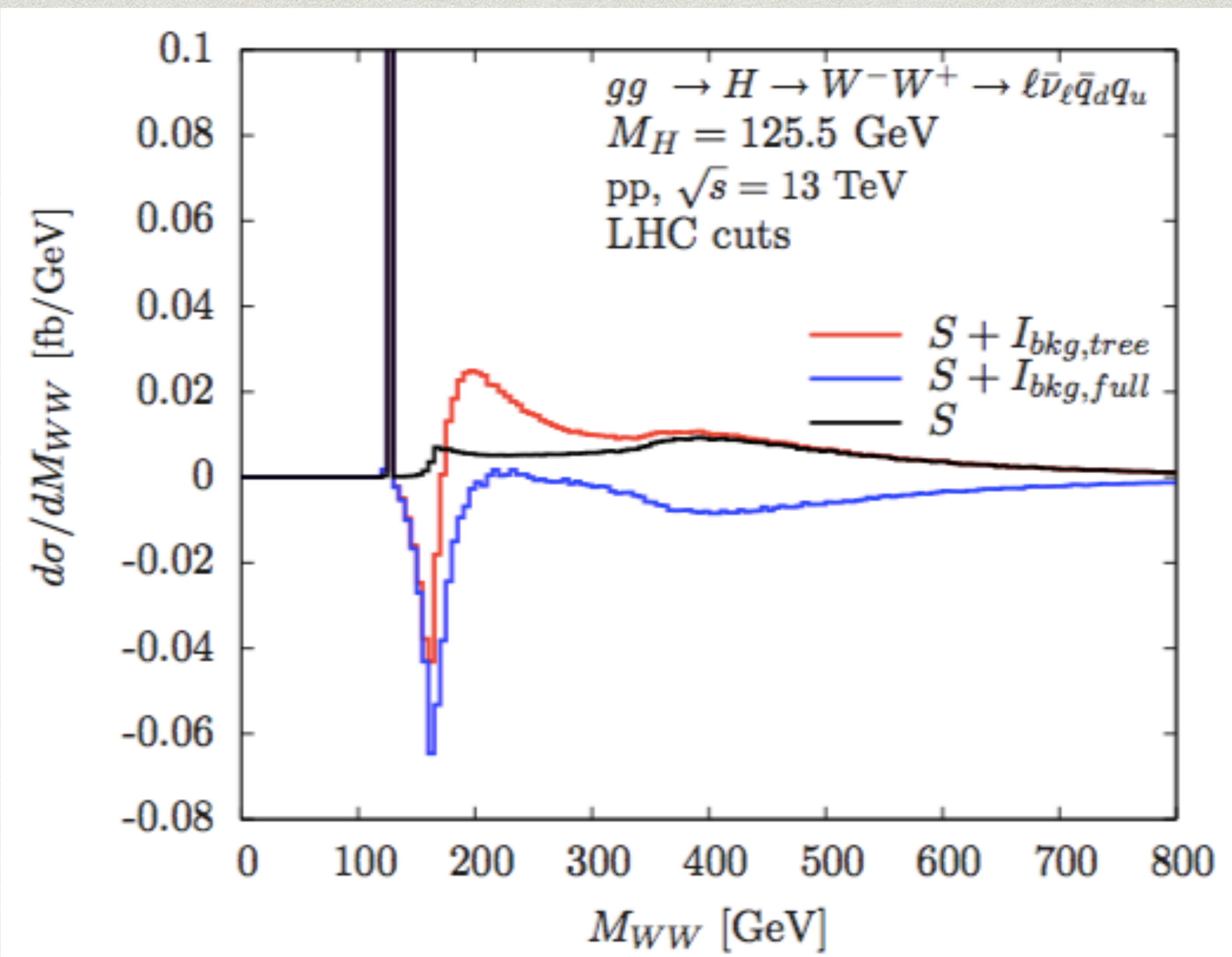
CDF 80.389±0.019
D0 80.383±0.023
Tevatron 80.387±0.016
Overall average 80.385±0.015
M_W [GeV]
pp → W⁺W⁻+X
ATLAS
CMS
NNLO
NLO+gg
NLO
LO
gg → H → WW*
added to all predictions
√s [TeV]
q
q
Z
Z
e⁻
e⁺
ATLAS
√s=13 TeV, 3.2 fb⁻¹
Observed limit
Expected limit
All limits at 95% CL
ATLAS Preliminary
√s = 13 TeV, 3.3 fb⁻¹
W' → eν selection
W' (2 TeV)
W' (3 TeV)
W' (4 TeV)
Data
W
Top
Multijet
Z/γ*
Diboson
Entries
Data / Bkg
GRANDEST DISCOVERIES
Transverse mass [GeV]
CMS Preliminary
42 pb⁻¹ (13 TeV)
Dilepton
Data
tt̄ signal
tt̄ other
Single t
W+jets
Z+jets
Diboson
Uncertainty
Events
N_b jets
LO
NLO
NNPDF3.0, 8 TeV
m_4l [GeV]
ATLAS data
MCFM
Ratio/NNLO
m_γγ [GeV]

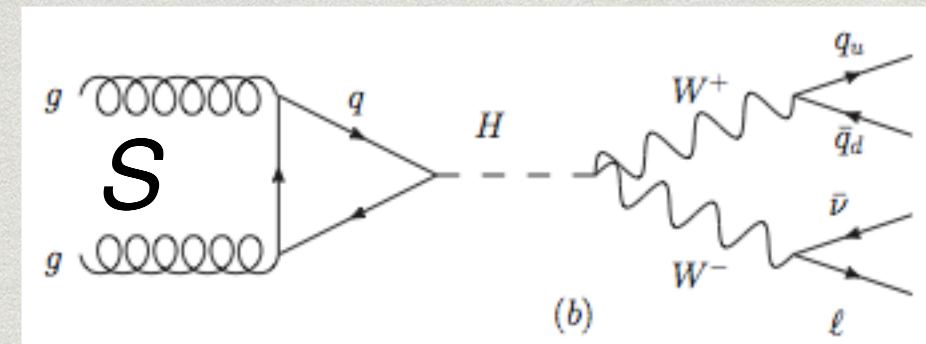
BACKUP SLIDES

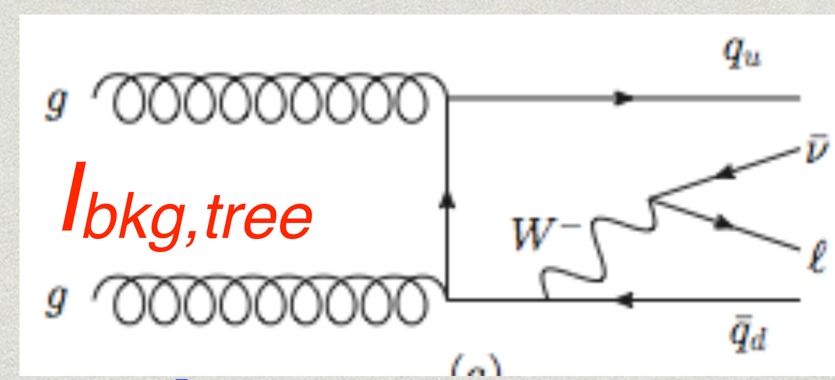
Interference in semileptonic WW

Kauer, O'Brien, Vryonidou, arXiv: 1506.01694

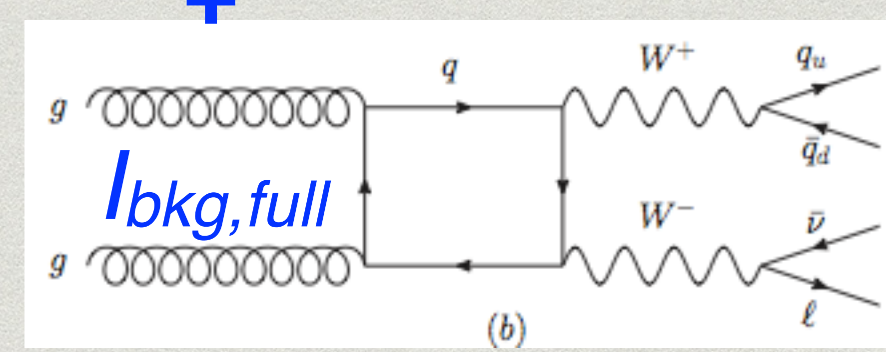
- Study of tree and loop level interference contributions with one W decaying hadronically; (also for ZZ).







+

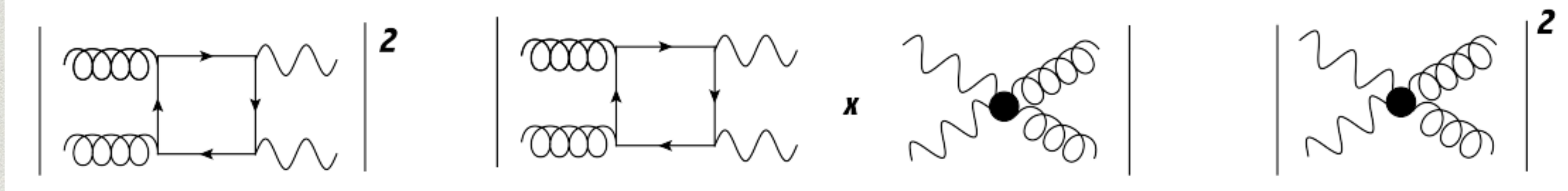


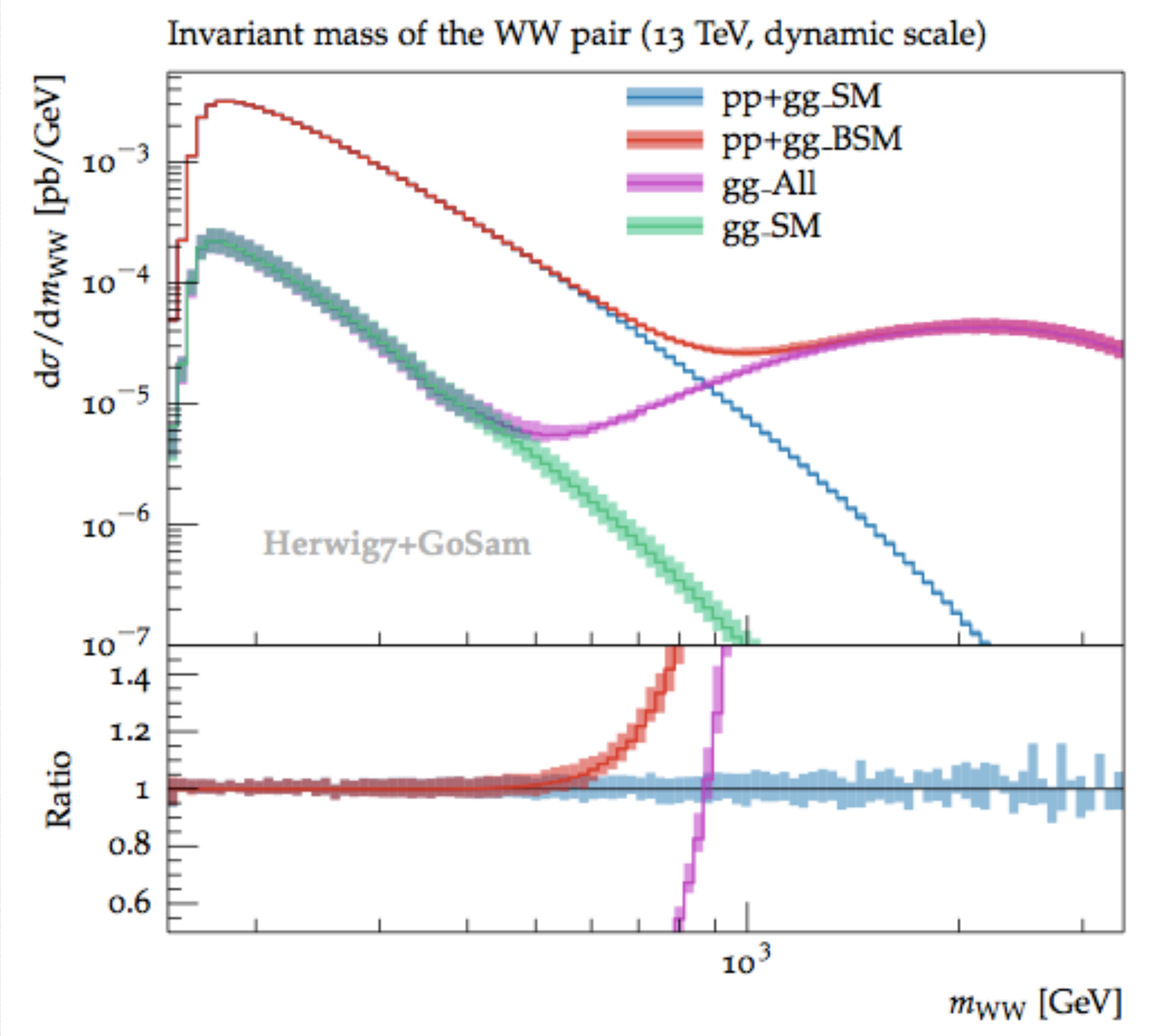
tree-level interference approx. 10% in total, much less as M_{WW} cut increases

Probe of anomalous ggWW couplings

Bellm, Gieseke, Greiner, Heinrich, Platzer, Reuschle, von Soden-Fraunhofen, arXiv: 1602.05141

- Possible sensitivity to dimension 8 ggWW couplings.





$$\mathcal{O}_1 = \frac{c_1}{\Lambda^4} G^a_{\mu\nu} G^{a,\mu\nu} W^I_{\rho\sigma} W^{I,\rho\sigma} = \frac{c_1}{\Lambda^4} \tilde{\mathcal{O}}_1$$

$$\mathcal{O}_2 = \frac{c_2}{\Lambda^4} \tilde{G}^a_{\mu\nu} G^{a,\mu\nu} W^I_{\rho\sigma} W^{I,\rho\sigma} = \frac{c_2}{\Lambda^4} \tilde{\mathcal{O}}_2$$

$$\mathcal{O}_3 = \frac{c_3}{\Lambda^4} G^a_{\mu\nu} G^{a,\mu\nu} \tilde{W}^I_{\rho\sigma} W^{I,\rho\sigma} = \frac{c_3}{\Lambda^4} \tilde{\mathcal{O}}_3$$

$$\frac{c_1}{\Lambda^4} = \frac{c_2}{\Lambda^4} = \frac{c_3}{\Lambda^4} = 0.1\ \mathrm{TeV}^{-4}$$

uncertainties mean small window for sensitivity before breakdown of EFT