Electroweak corrections with MadGraph5_aMC@NLO

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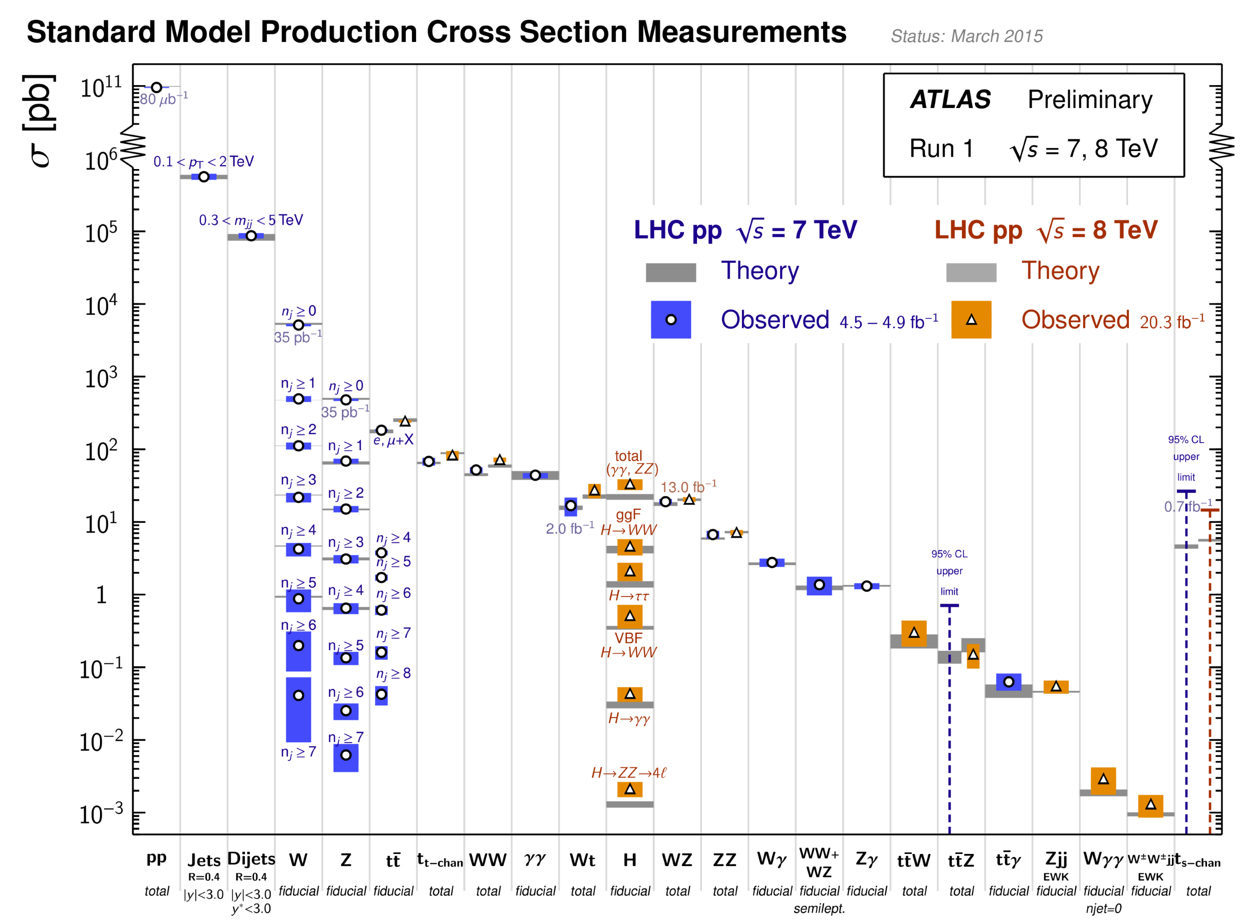
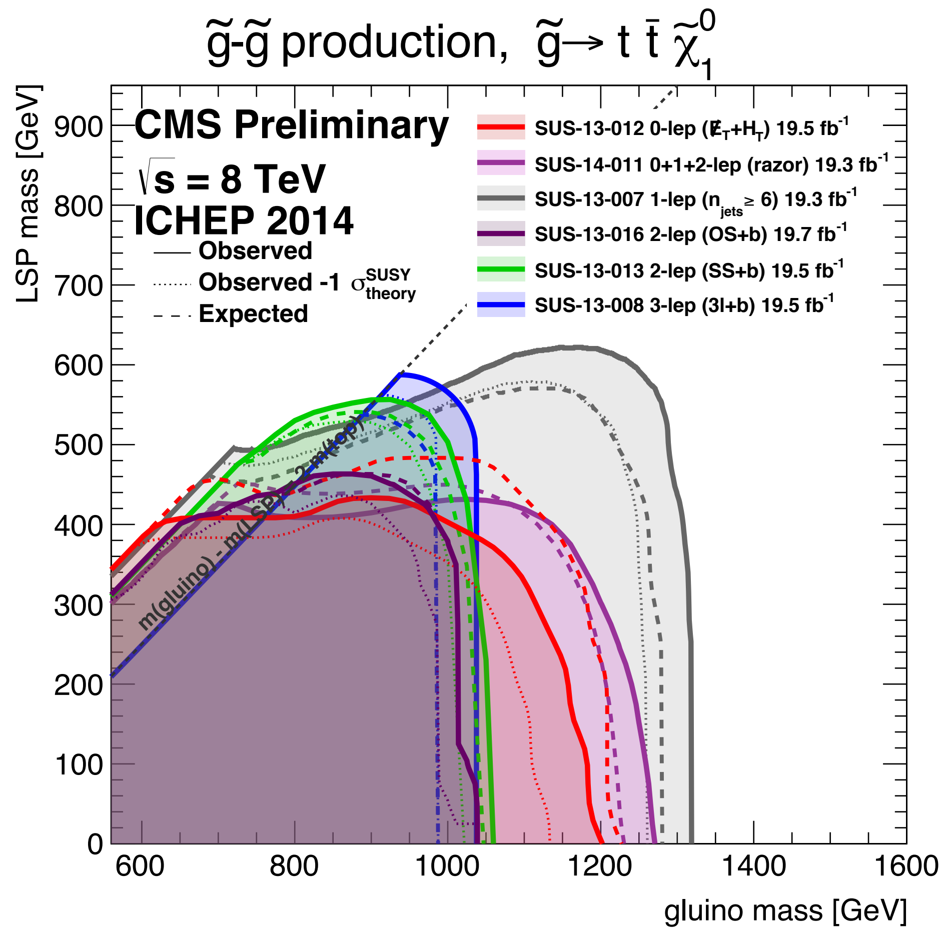
Radcor-Loopfest@UCLA
15-06-2015

Motivation

- No clear sign of new physics seen at LHC Run I, good agreement between data and SM; Run II has just started!





- New physics state will likely manifest as tiny deviations from the SM: Accurate predictions strongly needed!

Accurate predictions in a nutshell

- Expand the cross-section as a series in the couplings

LO NLO NNLO

QCD

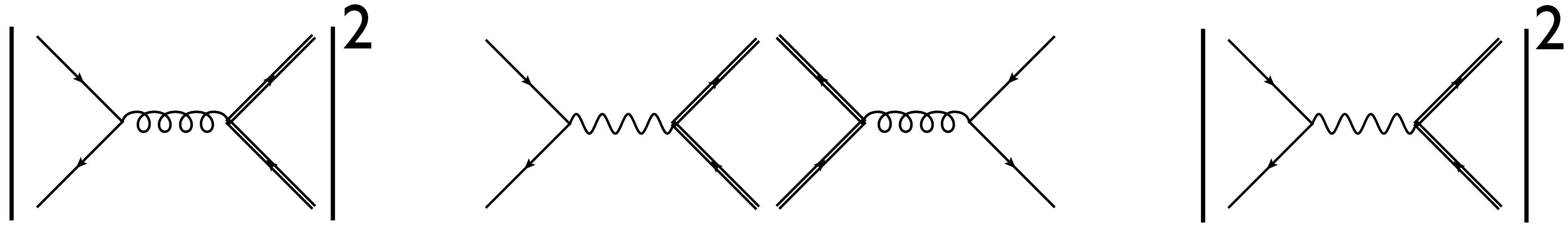
$$d\sigma = d\sigma_0 \left[1 + \frac{\alpha_s}{2\pi}\Delta_1 + \left(\frac{\alpha_s}{2\pi}\right)^2 \Delta_2 + \ldots \right.$$
$$\left. + \frac{\alpha}{2\pi}\Delta'_1 + \left(\frac{\alpha}{2\pi}\right)^2 \Delta'_2 + \ldots \right]$$

EW

- Strong coupling dominates, but non-QCD effects must be accounted to achieve precision
- Roughly speaking: NLO EW ~ NNLO QCD

EW corrections: how to

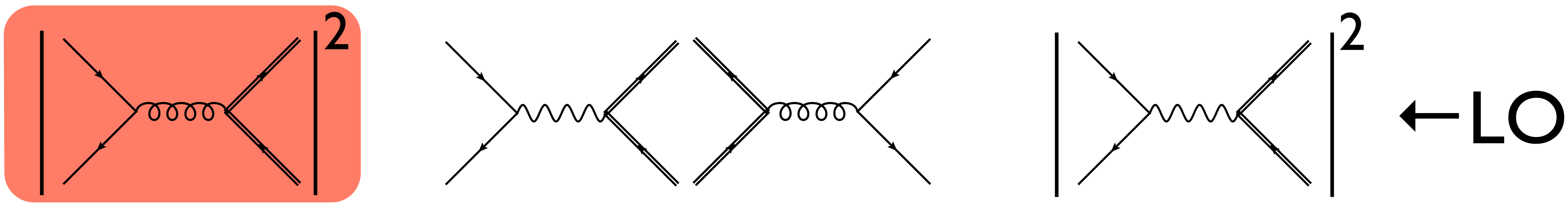
EW corrections: how to



←LO

- In the general case, several coupling combinations contribute to a given process at LO

EW corrections: how to



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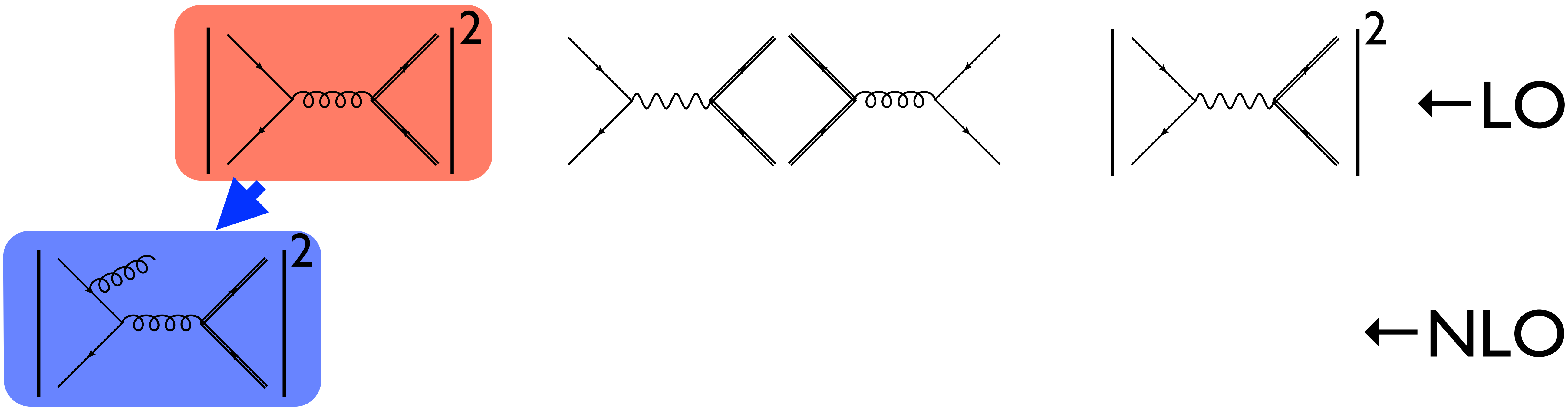
- Typically the 'LO' is identified with the blob featuring the largest power of α_s

EW corrections: how to



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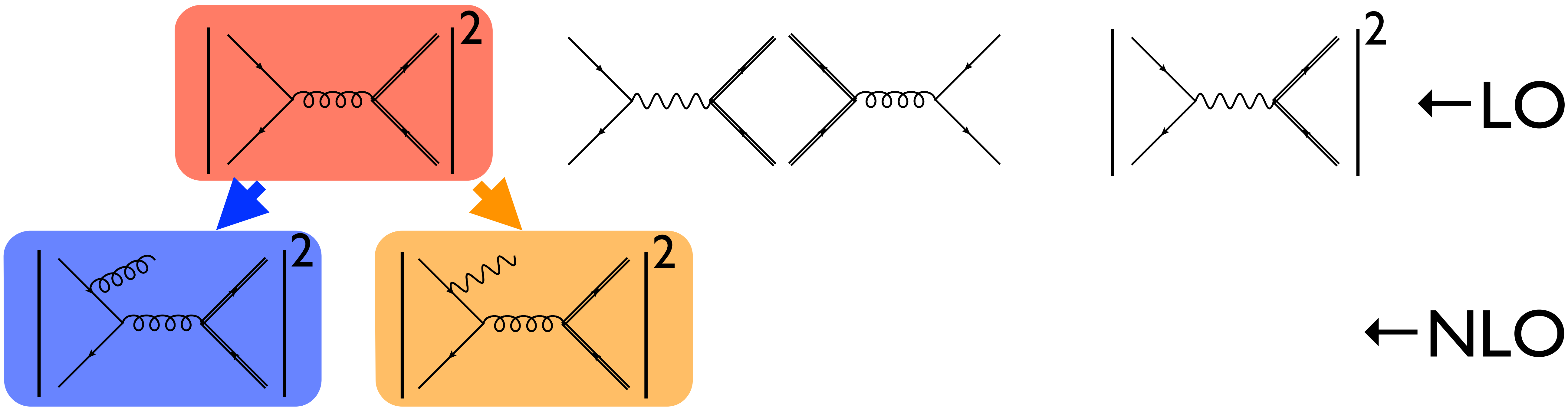
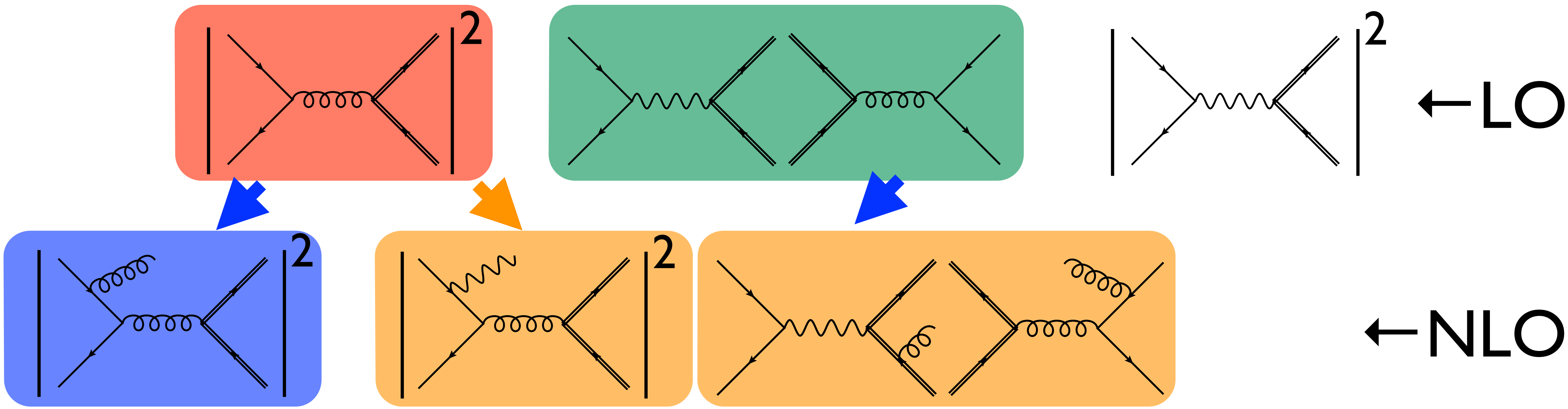
- NLO QCD corrections can be computed by attaching QCD particles to the LO

EW corrections: how to



- In the general case, several coupling combinations contribute to a given process at LO
- Typically the 'LO' is identified with the blob featuring the largest power of α_s
- NLO QCD corrections can be computed by attaching QCD particles to the LO
- NLO EW corrections can be computed by attaching EW particles to the LO…

EW corrections: how to



- In the general case, several coupling combinations contribute to a given process at LO
- Typically the 'LO' is identified with the blob featuring the largest power of α_s
- NLO QCD corrections can be computed by attaching QCD particles to the LO
- NLO EW corrections can be computed by attaching EW particles to the LO…
- … and attaching QCD particles to the LO with one less power of α_s

In practice:

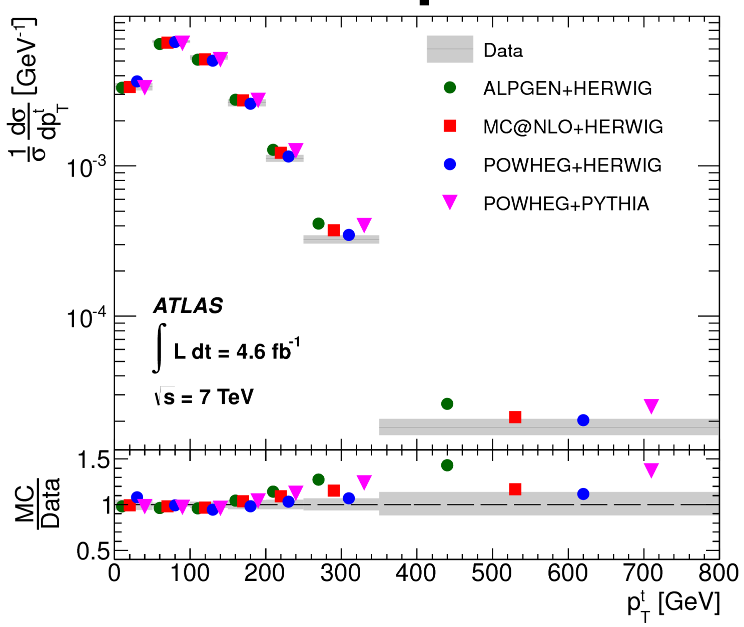
- EW corrections are a more complex problem, yet similar to QCD ones
- Lot of book-keeping (in particular on coupling orders)
- Loops:
  - Renormalize the full model
  - Higher rank loop integrals (still R≤D)
  - Interfere QCD loops with EW borns (and viceversa)
- Real emissions: keep track of the splitting type to generate the correct born-like counterterms
- Modern techniques for QCD corrections can be extended to tackle EW ones

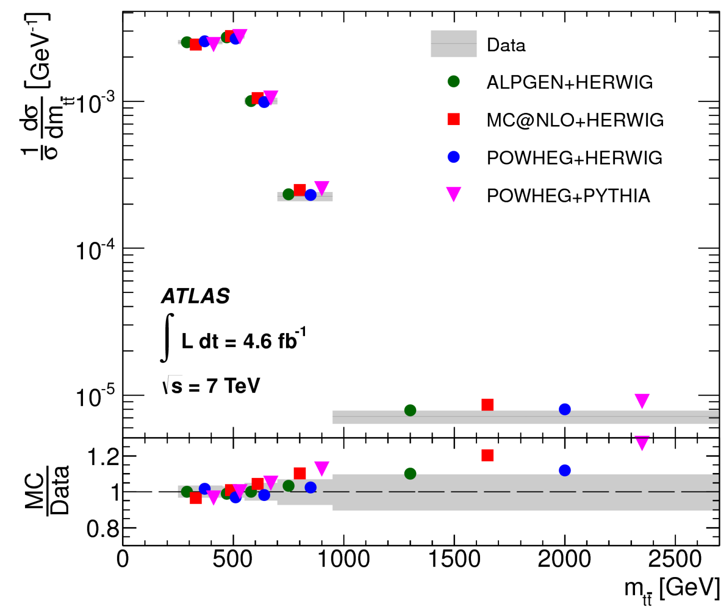
EW corrections in MADGRAPH5_AMC@NLO

- Loop computation: MadLoop Hirschi et al, arXiv:1103.0621
  - Uses OPP or TIR
  - UV renormalisation in the $\alpha(m_Z)$ or G_μ scheme (model feature)
  - Well advanced validation for complex-mass scheme
- IR subtraction and integration: MadFKS Frederix et al, arXiv:0908.4272
  - Code modified to account for more than one type of counterterms
  - All kind of EW/QCD splittings are accounted for
  - New version will be able to keep track of contributions from different coupling order combinations, and exact scale uncertainties via reweight
- MC@NLO Matching with parton shower
  - Work in progress

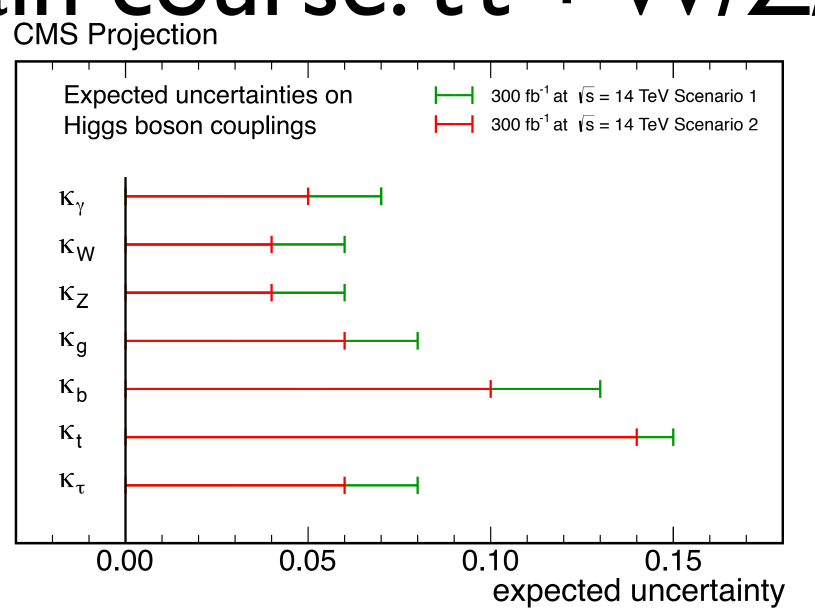
Physics results

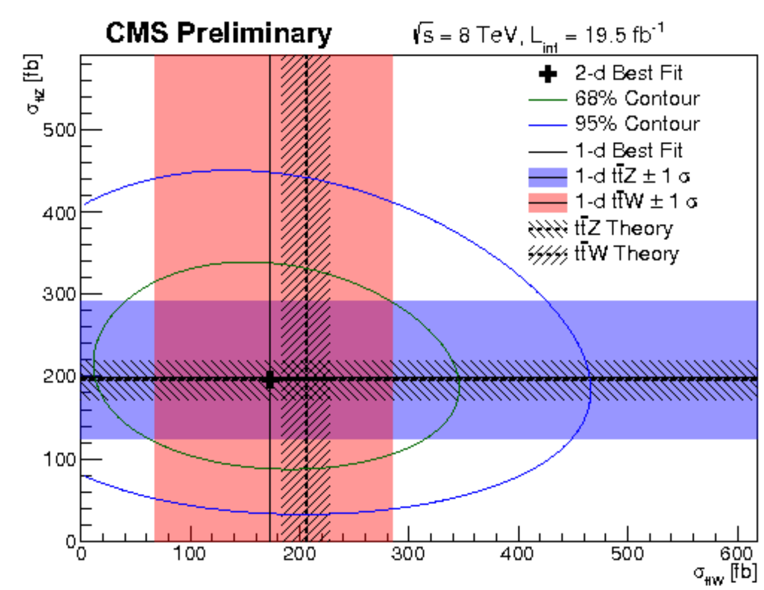
- Appetizer: $t\bar{t}$ production at the LHC





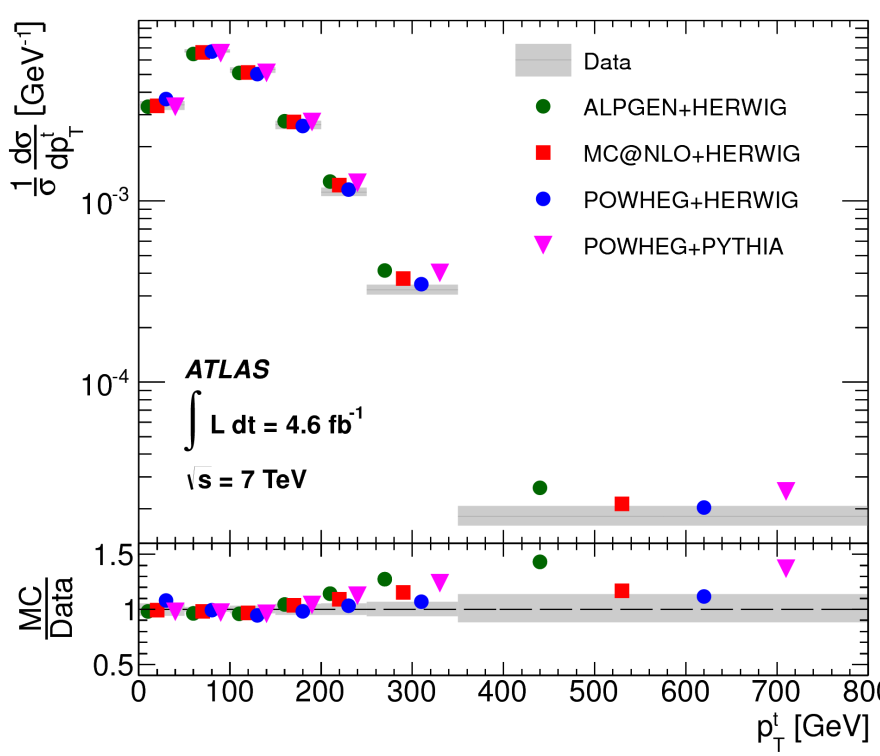
- Main course: $t\bar{t}$ + W/Z/H production at the LHC

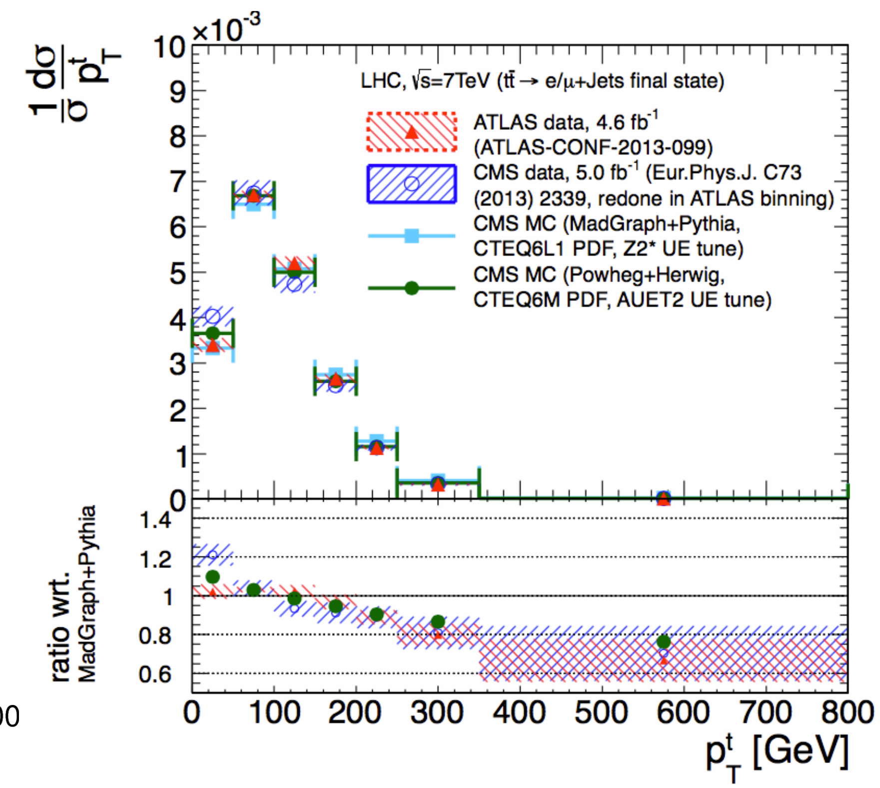


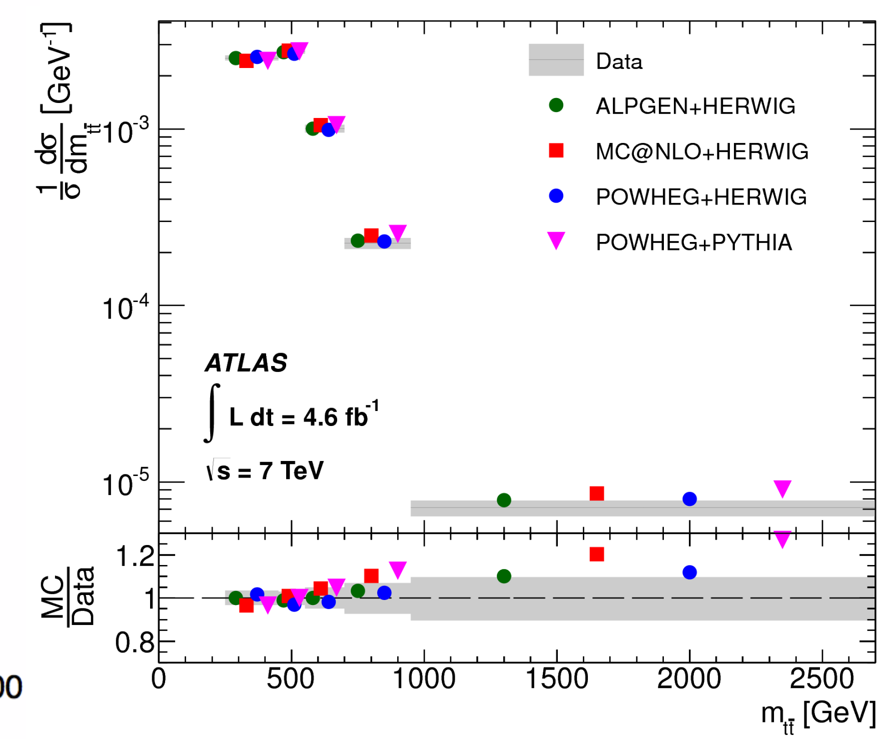


EW corrections to $t\bar{t}$ production Motivation

- ATLAS and CMS see some 'anomaly' on the top p_T distribution and $t\bar{t}$ invariant mass
- Data are softer than NLO QCD MonteCarlos (up to 30-40%)

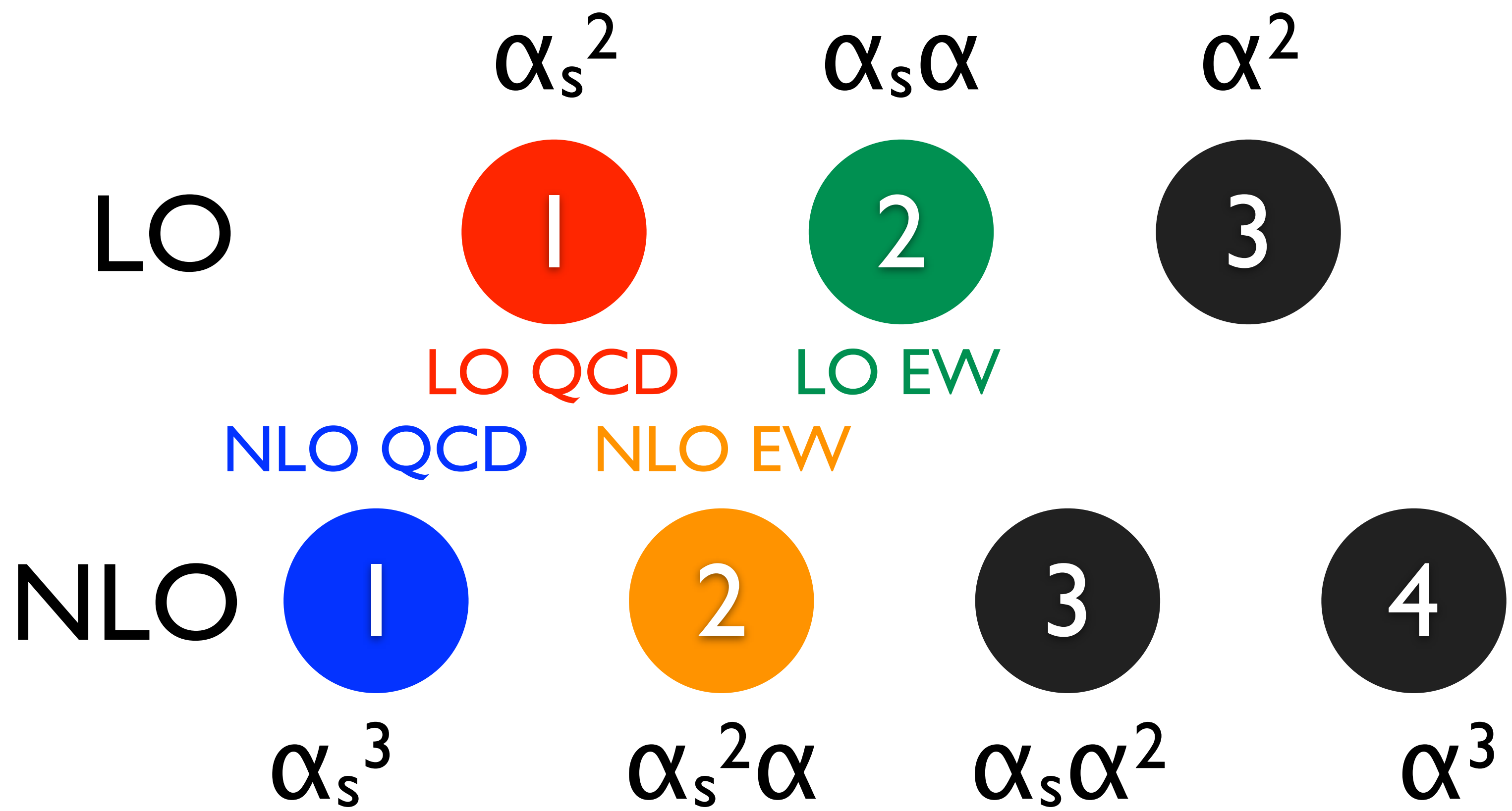






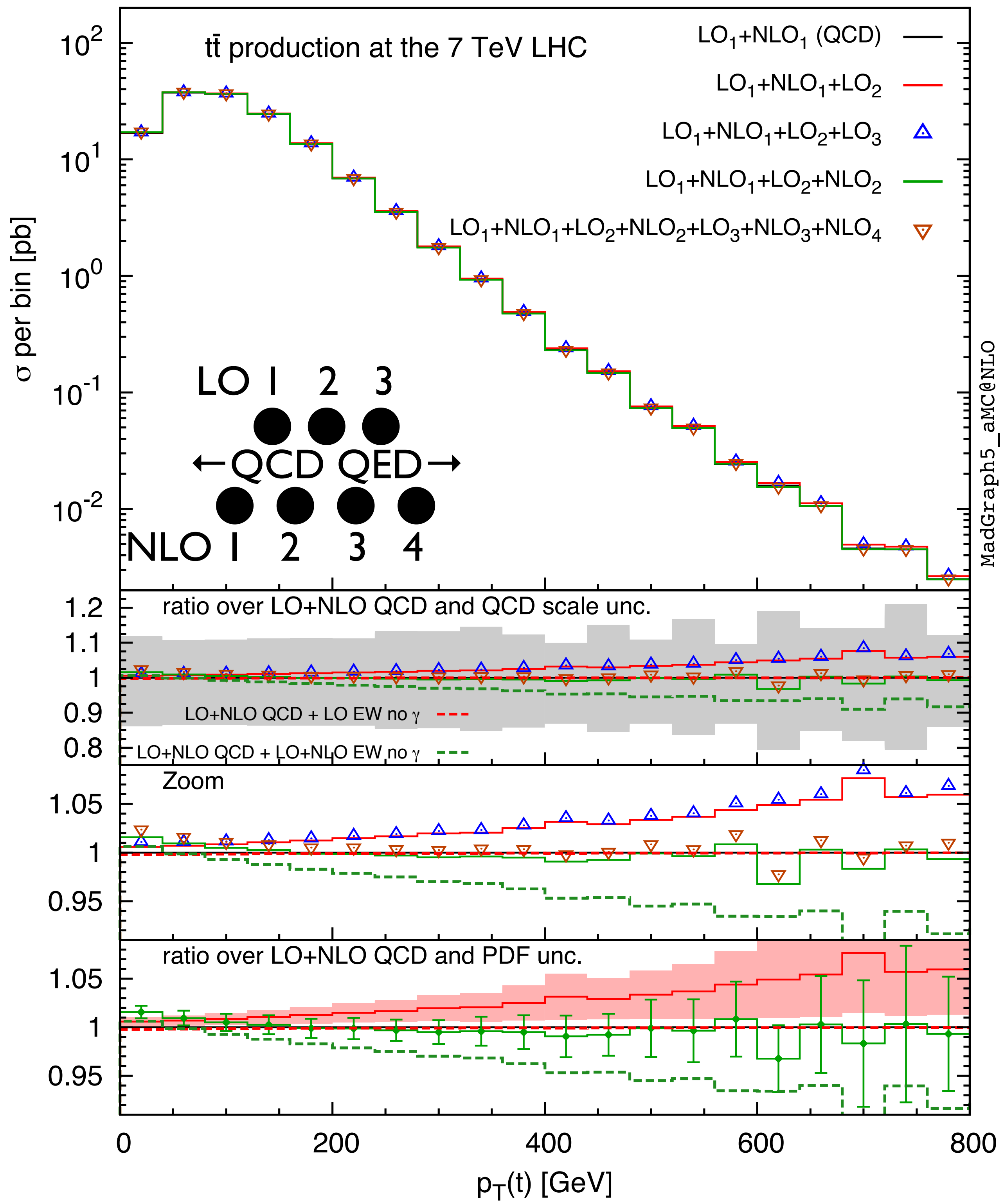
- Is it an EW effect?

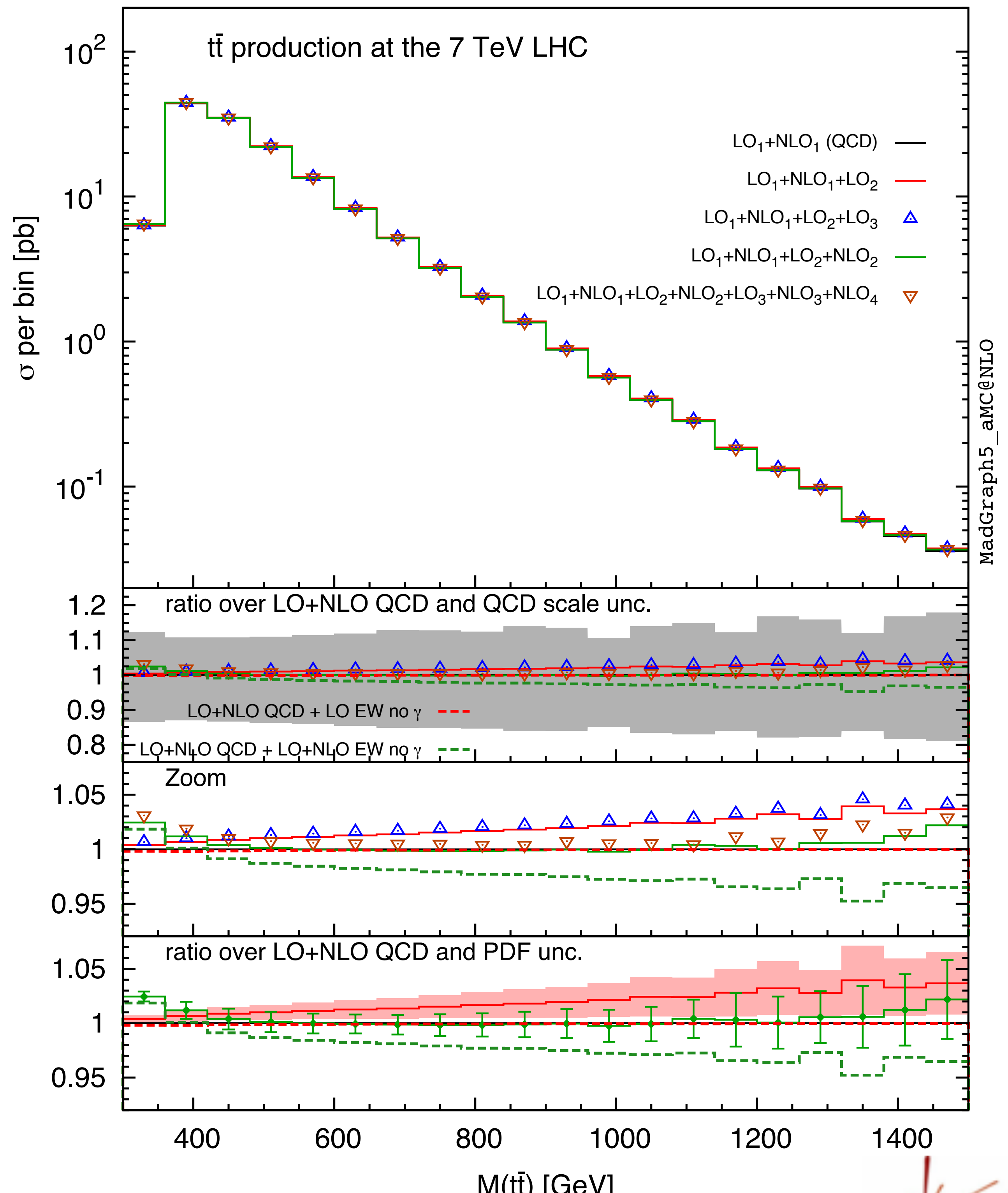
Contributions to the cross-section



- LO_2 has only $g\gamma$ and $b\bar{b}$ initial states; dominant γ-initiated contribution, need for PDFs with photons
- NLO_2 formally also includes heavy boson radiation (HBR). HBR not included for $t\bar{t}$

EW corrections to $t\bar{t}$ production



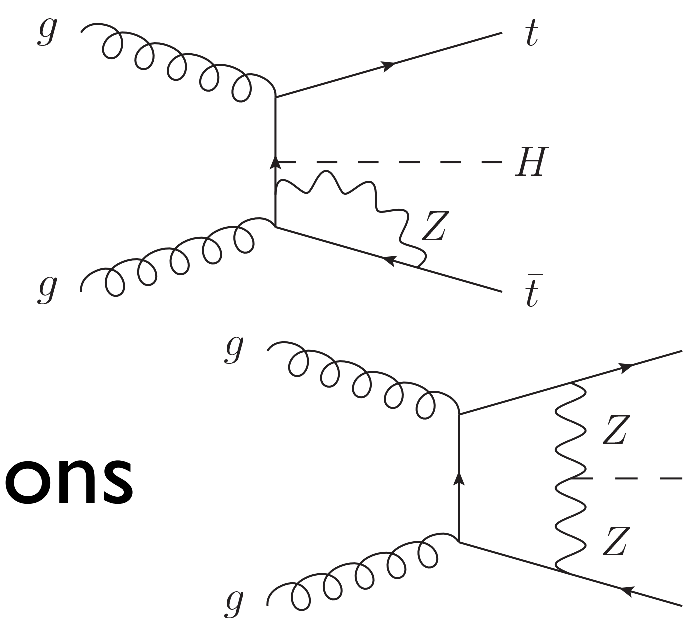


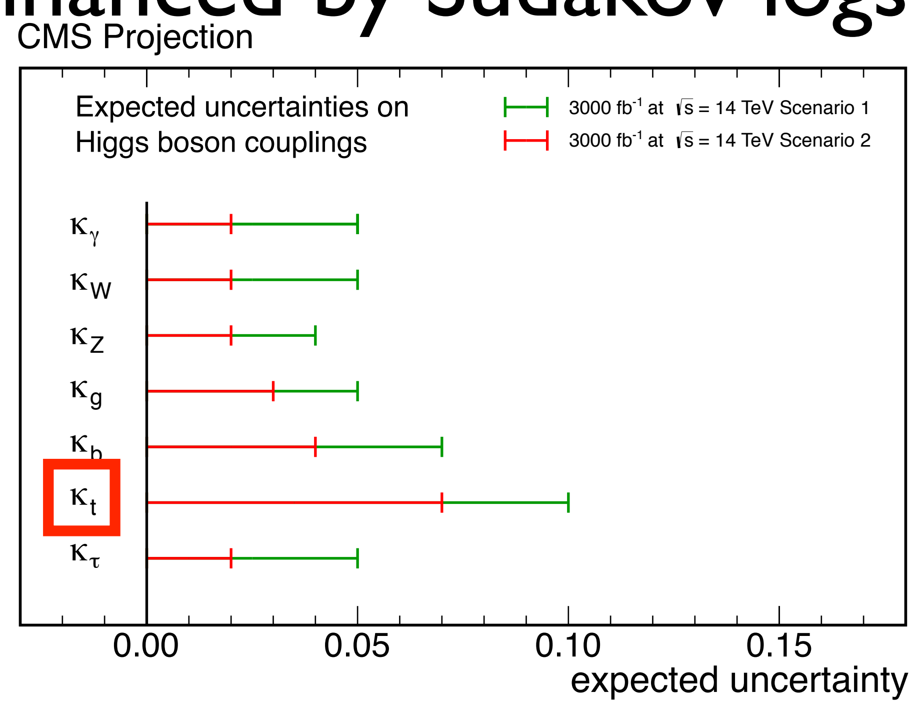
EW corrections to $t\bar{t}$ production Comments

- EW corrections account at most -10% at large p_T, -5% at large mass
- Photon effect as large as EW corrections, but almost 100% uncertain
- Subleading corrections (LO_3, $NLO_{3,4}$) very small

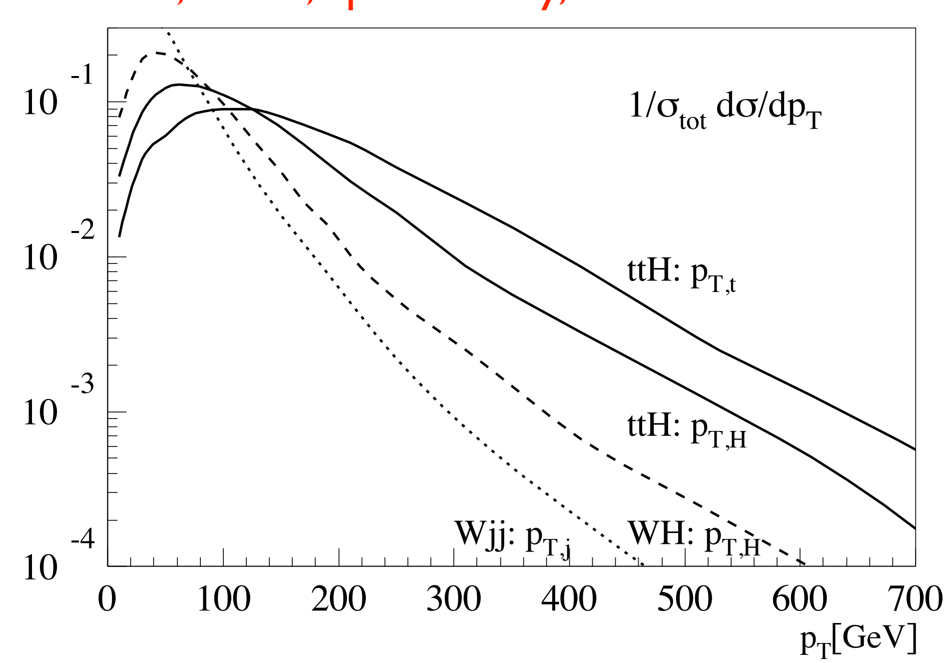
EW corrections to $t\bar{t}$ + W/Z/H
Motivation

- $t\bar{t}H$ offers unique access to top Yukawa coupling
- Unlike QCD, EW effects introduce non $\sim y_t^2$ dependence of the cross-section
- Expected accuracy on y_t at Run II: 10-5% with 300-3000 fb^{-1}
- Searches in the boosted scenario: EW corrections enhanced by Sudakov logs ($\log(p_T/m_W)$)



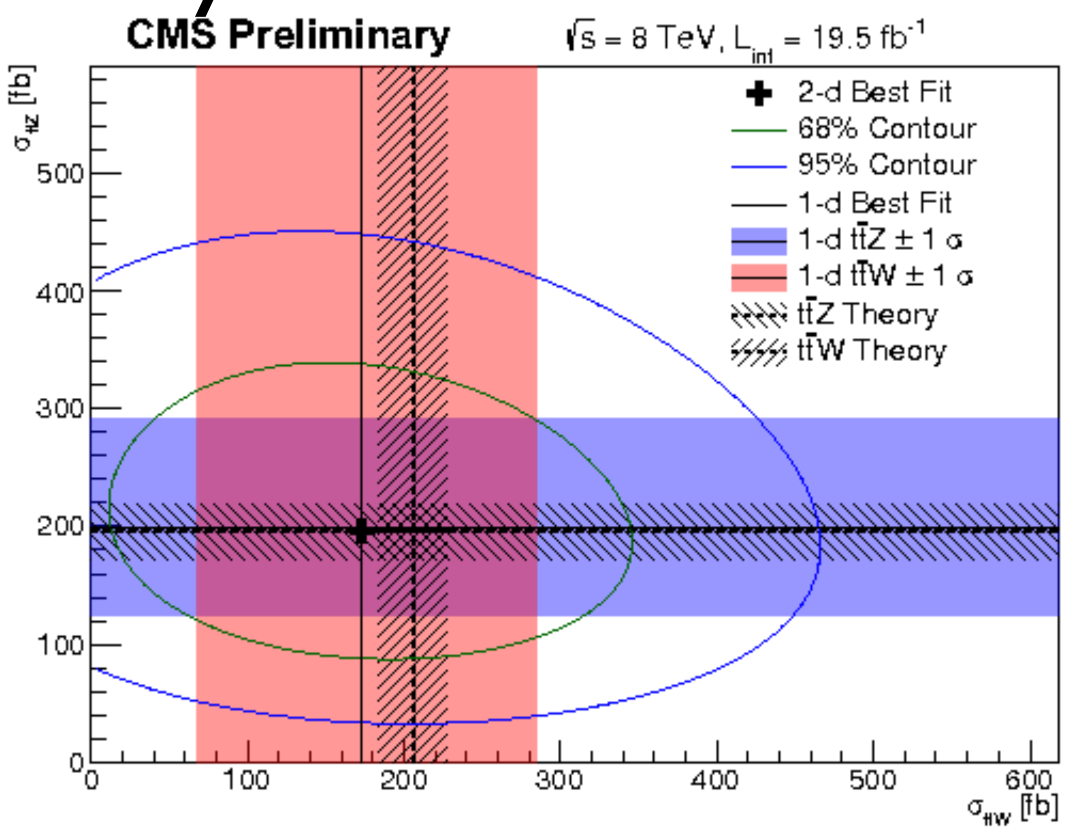


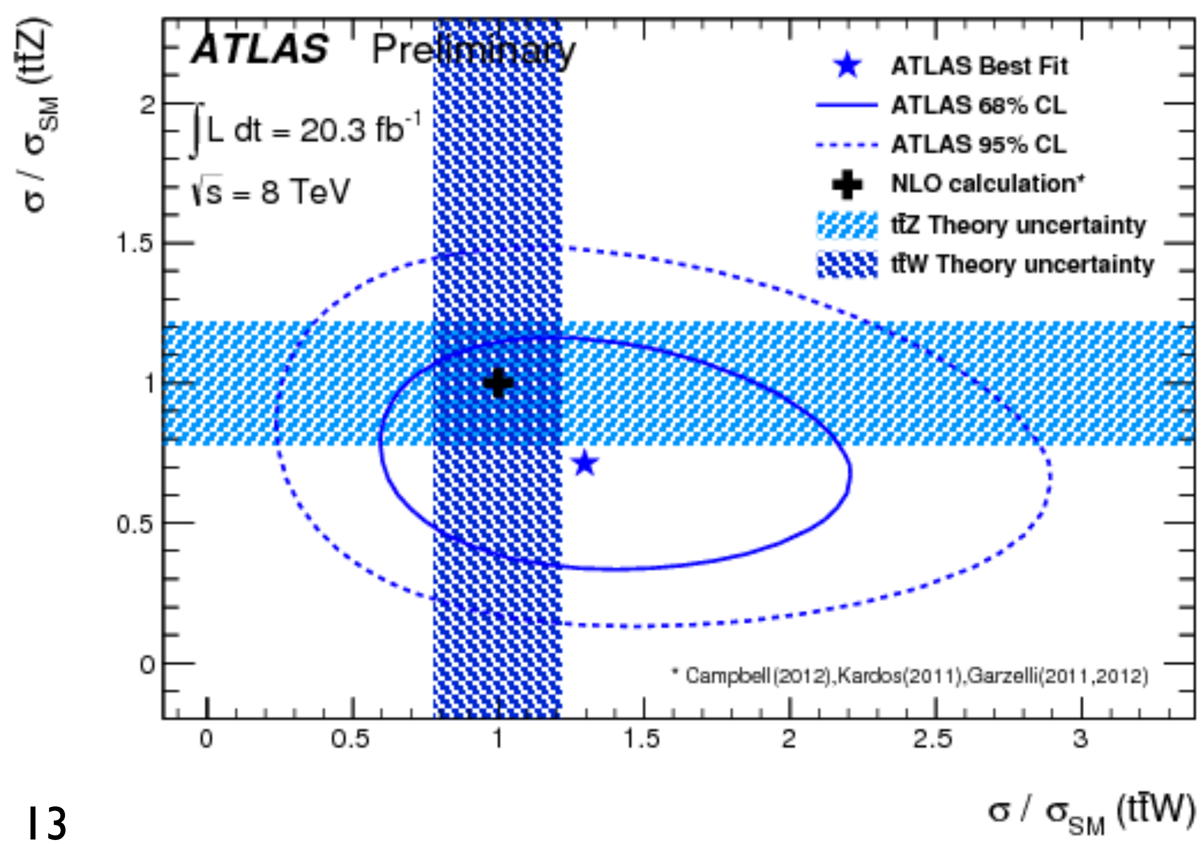
Plehn, Salam, Spannowsky, arXiv:0910.5472



EW corrections to $t\bar{t} + W/Z/H$
Motivation

- $t\bar{t}V$ measured at Run I, still large statistical uncertainties
- EW corrections needed for high-precision Run II measurements
- Multilepton/leptons+jets signatures: $t\bar{t}V$ background to many BSM searches and to $t\bar{t}H$





Setup

more in Frixione, Hirschi, Shao, Zaro, arXiv:1504.03446

- EW corrections computed in the $\alpha(m_Z)$ scheme (G_μ also available)
- Particle masses:
  - m_t=173.3 GeV m_H=125 GeV
  - m_W=80.385 GeV m_Z=91.188 GeV
- NNPDF2.3 QED PDF, quoted uncertainties @68%CL
- Ren./Fac. scale choice:

$$\mu = \frac{H_T}{2}$$

- LO+NLO QCD scale uncertainties in the range

$$\frac{1}{2}\mu \leq \mu_R, \mu_F \leq 2\mu$$

- Two scenarios: inclusive and boosted: $p_T(t,\bar{t},W/Z/H)>200$ GeV

Results for $t\bar{t}H$ and $t\bar{t}Z$: total rates (within boosted cuts)

$t\bar{t}H$: σ(pb)	13 TeV
LO QCD	$3.617 \cdot 10^{-1}$ $(1.338 \cdot 10^{-2})$
NLO QCD	$1.073 \cdot 10^{-1}$ $(3.230 \cdot 10^{-3})$
LO EW	$4.437 \cdot 10^{-3}$ $(3.758 \cdot 10^{-4})$
LO EW no γ	$-1.390 \cdot 10^{-3}$ $(-2.452 \cdot 10^{-5})$
NLO EW	$-4.408 \cdot 10^{-3}$ $(-1.097 \cdot 10^{-3})$
NLO EW no γ	$-4.919 \cdot 10^{-3}$ $(-1.131 \cdot 10^{-3})$
HBR	$3.216 \cdot 10^{-3}$ $(2.496 \cdot 10^{-4})$

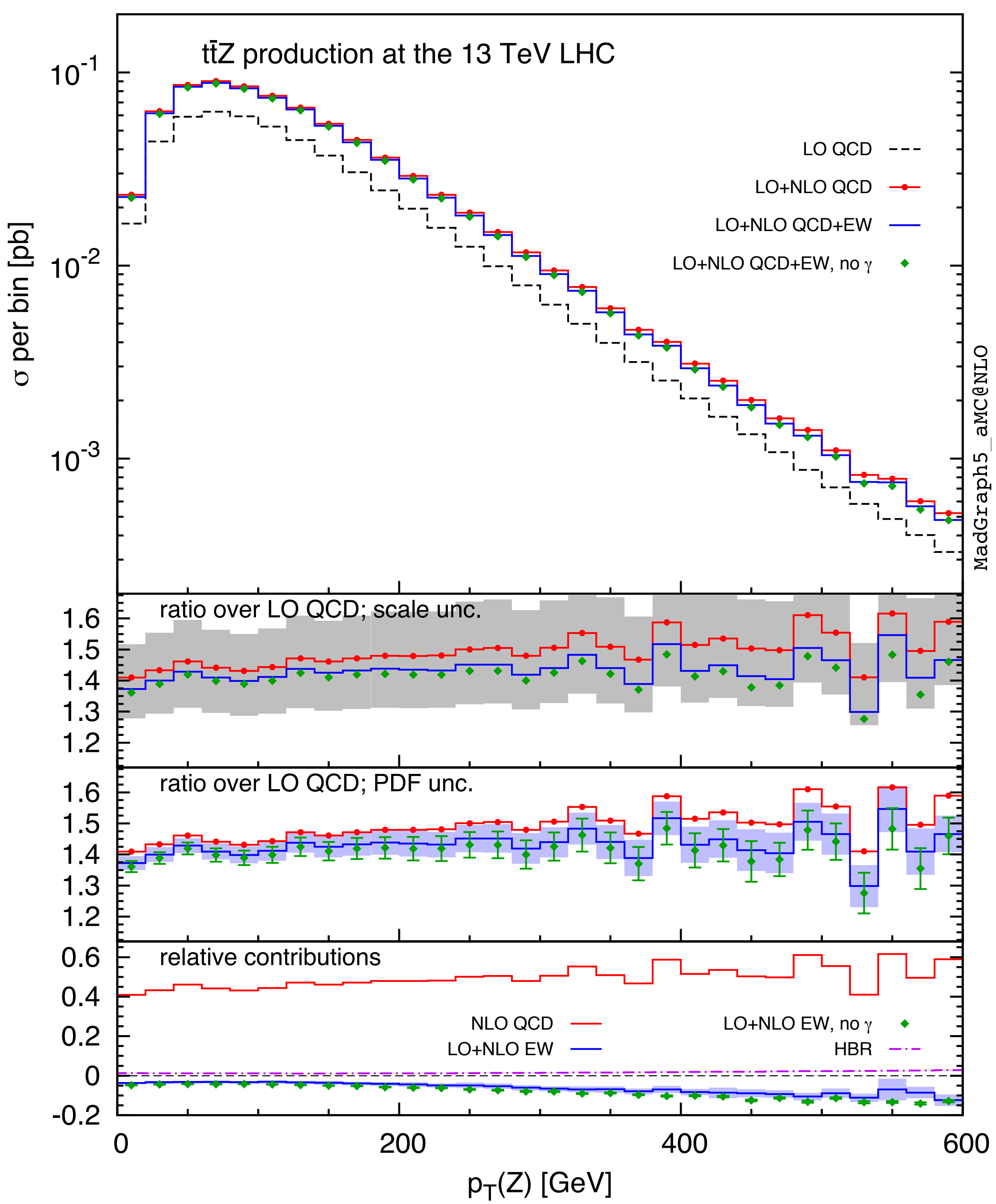
$t\bar{t}Z$: σ(pb)	13 TeV
LO QCD	$5.282 \cdot 10^{-1}$ $(1.955 \cdot 10^{-2})$
NLO QCD	$2.426 \cdot 10^{-1}$ $(7.856 \cdot 10^{-3})$
LO EW	$-2.172 \cdot 10^{-4}$ $(4.039 \cdot 10^{-4})$
LO EW no γ	$-5.771 \cdot 10^{-3}$ $(-6.179 \cdot 10^{-5})$
NLO EW	$-2.017 \cdot 10^{-2}$ $(-2.172 \cdot 10^{-3})$
NLO EW no γ	$-2.158 \cdot 10^{-2}$ $(-2.252 \cdot 10^{-3})$
HBR	$5.056 \cdot 10^{-3}$ $(4.162 \cdot 10^{-4})$

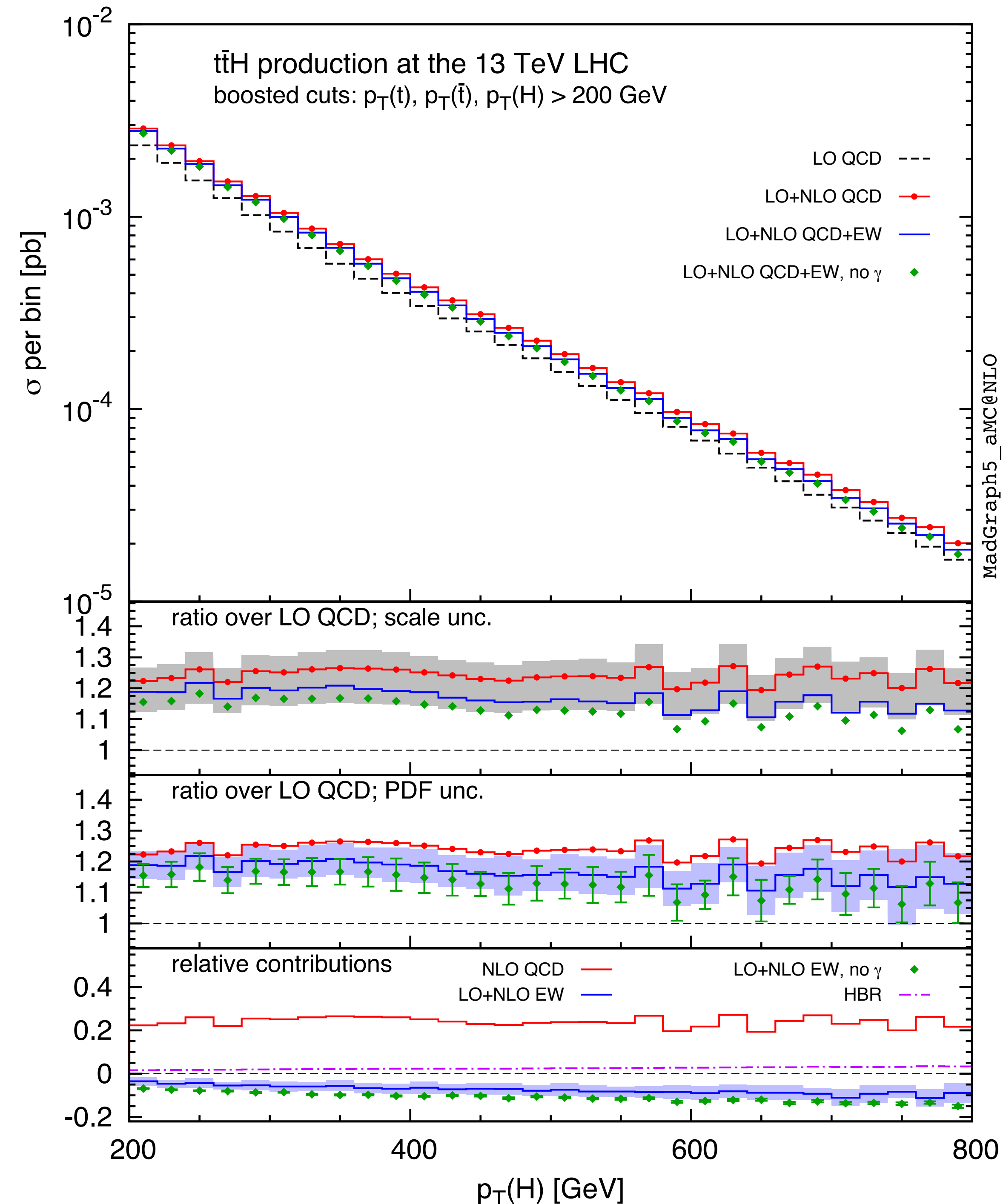
$t\bar{t}H$: $\delta(\%)$	13 TeV
NLO QCD	$29.7^{+6.8}_{-11.1} \pm 2.8$ $(24.2^{+4.8}_{-10.6} \pm 4.5)$
LO EW	1.2 ± 0.9 (2.8 ± 2.0)
LO EW no γ	-0.4 ± 0.0 (-0.2 ± 0.0)
NLO EW	-1.2 ± 0.1 (-8.2 ± 0.3)
NLO EW no γ	-1.4 ± 0.0 (-8.5 ± 0.2)
HBR	0.89 (1.87)

$t\bar{t}Z$: $\delta(\%)$	13 TeV
NLO QCD	$45.9^{+13.2}_{-15.5} \pm 2.9$ $(40.2^{+11.1}_{-15.0} \pm 4.7)$
LO EW	0.0 ± 0.7 (2.1 ± 1.6)
LO EW no γ	-1.1 ± 0.0 (-0.3 ± 0.0)
NLO EW	-3.8 ± 0.2 (-11.1 ± 0.5)
NLO EW no γ	-4.1 ± 0.1 (-11.5 ± 0.3)
HBR	0.96 (2.13)

- NLO EW correction have modest impact on inclusive xsect, but can be important in the boosted regime (same order of QCD uncertainties)
- Boosted regime enhances photon contribution in LO-EW
- HBR contributions remain small

Results for $t\bar{t}H$ and $t\bar{t}Z$: distributions





Results for $t\bar{t}W$: total rates (within boosted cuts)

$t\bar{t}W^+$: σ(pb)	13 TeV
LO QCD	$2.496 \cdot 10^{-1}$ $(7.749 \cdot 10^{-3})$
NLO QCD	$1.250 \cdot 10^{-1}$ $(4.624 \cdot 10^{-3})$
LO EW	0
LO EW no γ	0
NLO EW	$-1.931 \cdot 10^{-2}$ $(-1.490 \cdot 10^{-3})$
NLO EW no γ	$-1.988 \cdot 10^{-2}$ $(-1.546 \cdot 10^{-3})$
HBR	$9.677 \cdot 10^{-3}$ $(5.743 \cdot 10^{-4})$

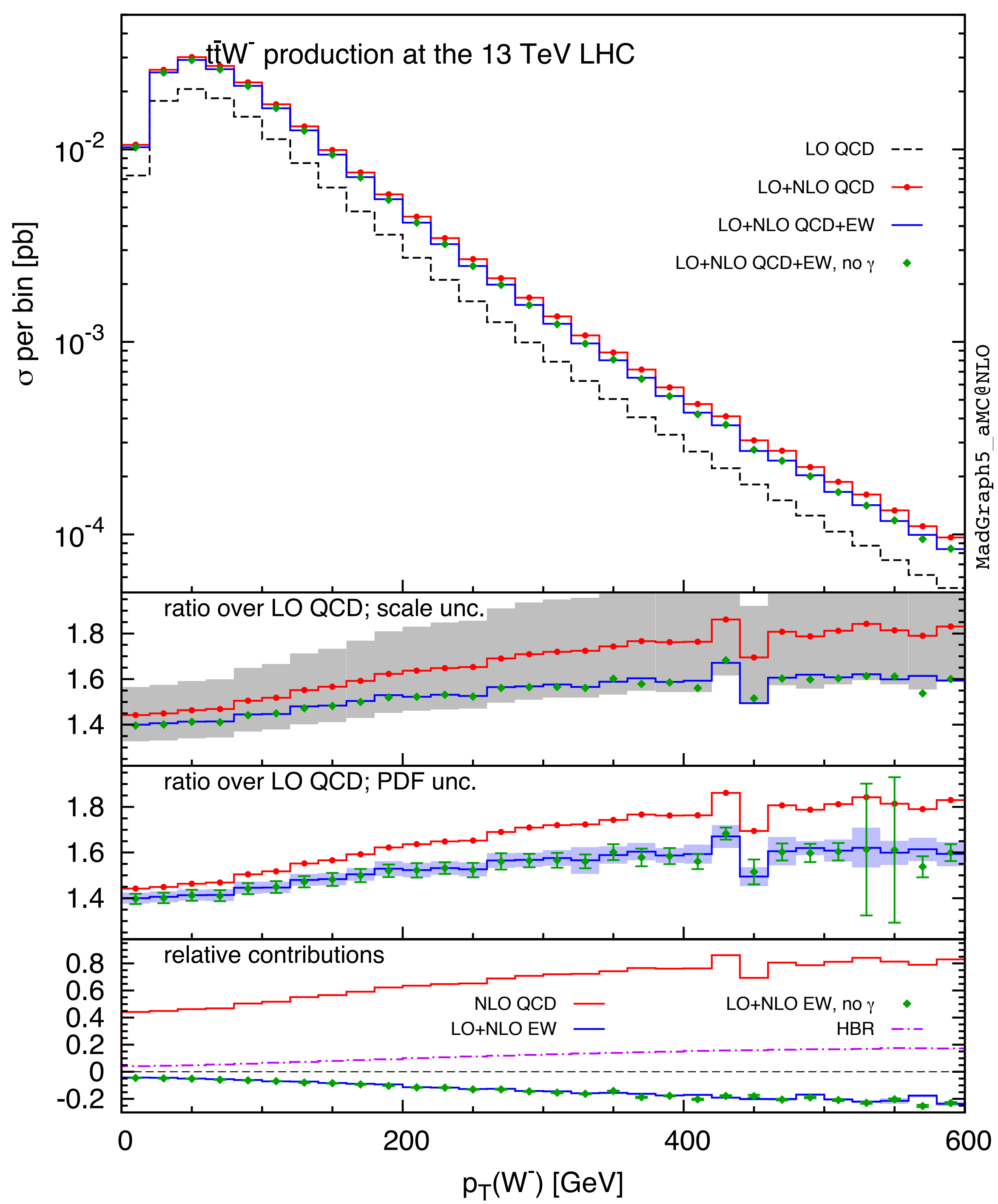
$t\bar{t}W^-$: σ(pb)	13 TeV
LO QCD	$1.265 \cdot 10^{-1}$ $(3.186 \cdot 10^{-3})$
NLO QCD	$6.515 \cdot 10^{-2}$ $(2.111 \cdot 10^{-3})$
LO EW	0
LO EW no γ	0
NLO EW	$-8.502 \cdot 10^{-3}$ $(-5.838 \cdot 10^{-4})$
NLO EW no γ	$-8.912 \cdot 10^{-3}$ $(-6.094 \cdot 10^{-4})$
HBR	$8.219 \cdot 10^{-3}$ $(4.781 \cdot 10^{-4})$

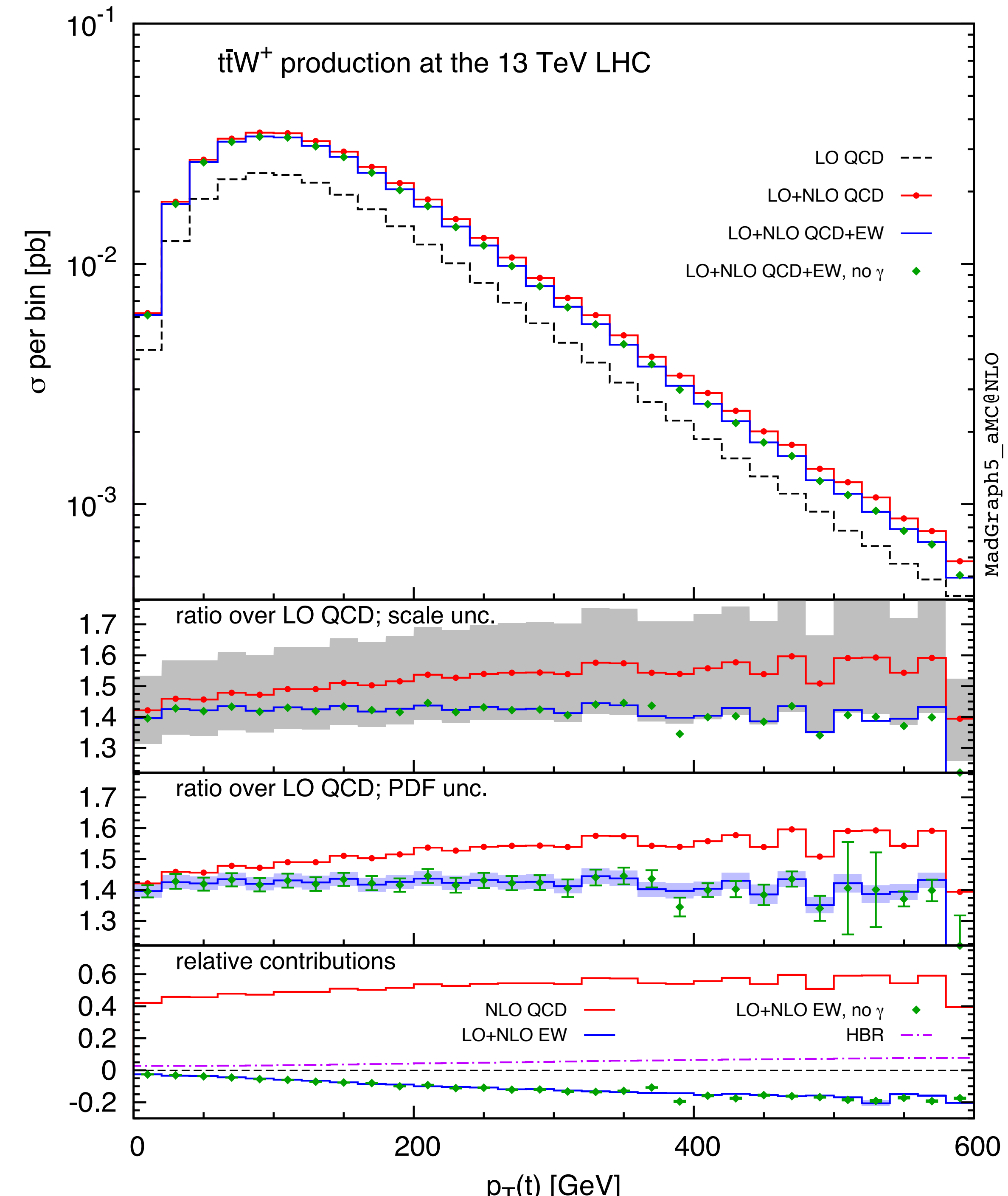
$t\bar{t}W^+$: δ(%)	13 TeV
NLO QCD	$50.1^{+14.2}_{-13.5} \pm 2.4$ $(59.7^{+18.9}_{-17.7} \pm 3.1)$
LO EW	0
LO EW no γ	0
NLO EW	-7.7 ± 0.2 (-19.2 ± 0.7)
NLO EW no γ	-8.0 ± 0.2 (-20.0 ± 0.5)
HBR	3.88 (7.41)

$t\bar{t}W^-$: δ(%)	13 TeV
NLO QCD	$51.5^{+14.8}_{-13.8} \pm 2.8$ $(66.3^{+21.7}_{-19.6} \pm 3.9)$
LO EW	0
LO EW no γ	0
NLO EW	-6.7 ± 0.2 (-18.3 ± 0.8)
NLO EW no γ	-7.0 ± 0.2 (-19.1 ± 0.6)
HBR	6.50 (15.01)

- EW corrections larger than $t\bar{t}H/Z$, in particular with boosted cuts
- HBR enhanced by parton luminosities: $t\bar{t}WW$ has gg, $t\bar{t}W$ only $q\bar{q}$

Results for $t\bar{t}W$: distributions





Conclusions

- NLO EW predictions will be very important for accurate physics at the LHC RunII
- Automation of EW corrections in MadGraph5_aMC@NLO well advanced
- Results (obtained automatically) for $t\bar{t}$ and $t\bar{t}X$ (X=H/Z/W)
  - EW corrections seem not to explain the $t\bar{t}$ 'anomaly' seen by ATLAS and CMS
  - $t\bar{t}X$ (in particular $t\bar{t}W$) can receive large corrections, specially in boosted regimes


Thank you!
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