Precise predictions at the LHC: electroweak corrections

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Fundamental Interactions and IAP meeting
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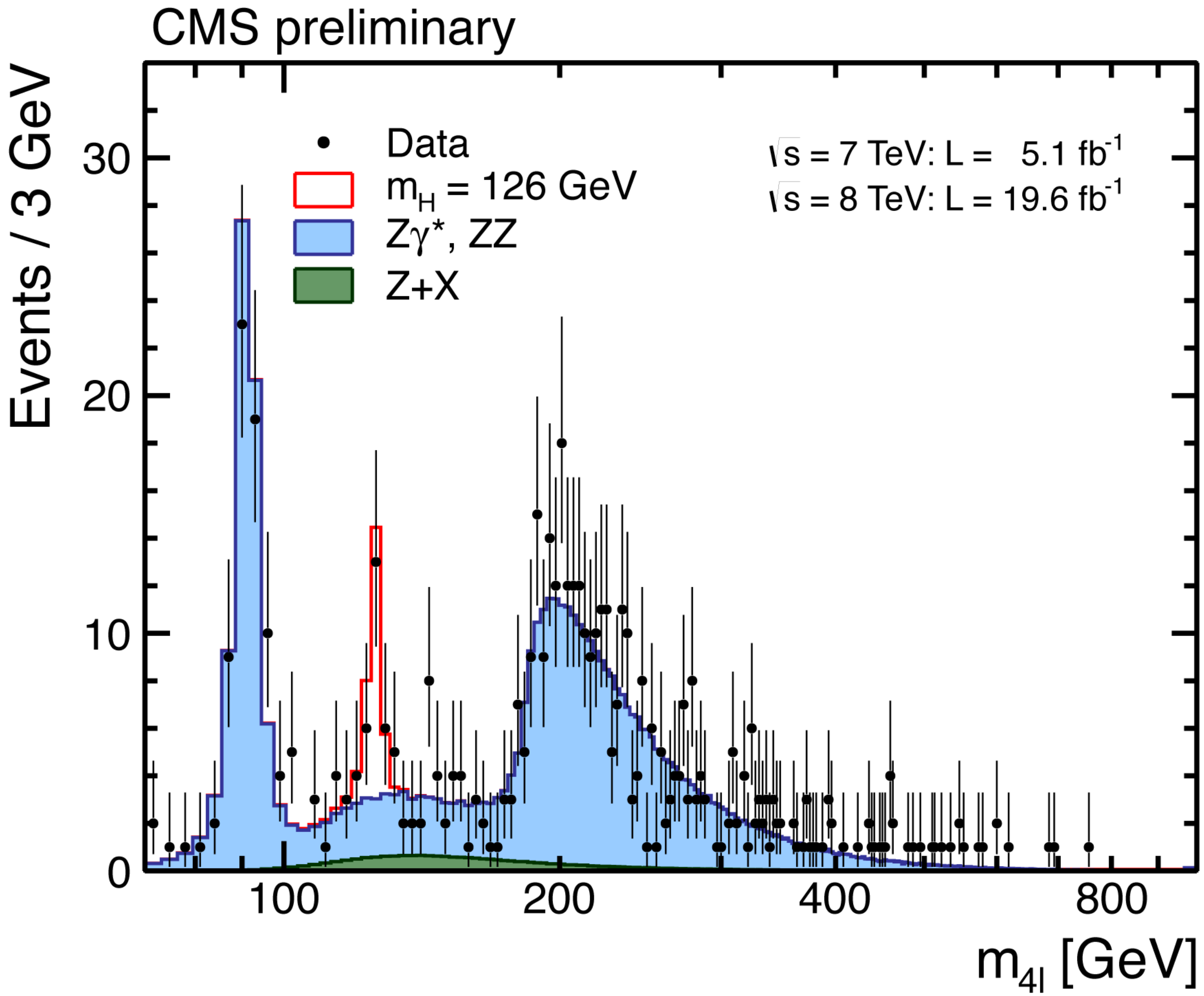
! DISCLAIMER !



This talk is **not** about the ability of identifying resonances from new physics.

Precise predictions are fundamental for correctly identifying **non-resonant** new physics effects, setting **exclusion limits** and **fully characterize** and understand both resonant and non-resonant new-physics dynamics.

Predictions at the LHC

Every prediction at the LHC starts form here:

Renormalization/factorization scale

$$\sigma_{H_1,H_2}(p_1,p_2) = \sum_{i,j} \int dx_1\, dx_2\, f_i^{(H_1)}(x_1,\mu)\; f_j^{(H_2)}(x_2,\mu)\; \hat{\sigma}_{ij}(x_1 p_1, x_2 p_2, \alpha_S(\mu), \mu)$$

PDFs | Partonic cross sections

- PDFs are fitted from experimental measurements, only the dependence on μ can be calculated in perturbation theory via DGLAP.
- Partonic cross sections can be calculated in perturbation theory via Feynman diagrams.

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PDFs

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Precise predictions at the LHC: for what?

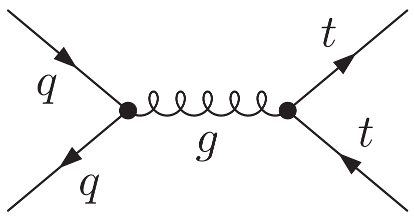
- More precise predictions for the total cross sections. (Total normalization)
- More precise differential distributions. (Kinematic-dependent corrections)
- Reduction of μ dependence. (Theoretical accuracy)

Methods/ Approximations

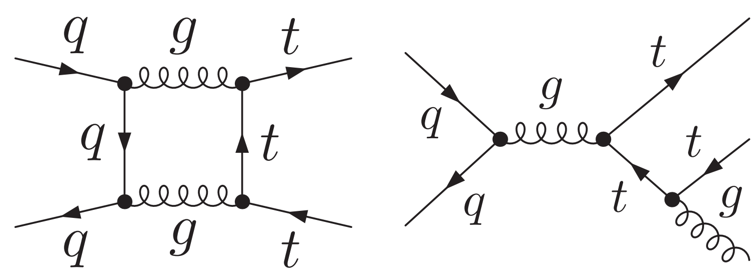
Fixed orders, Resummation, RGE, Parton Shower, Matching, Merging ………….

Fixed Order calculations

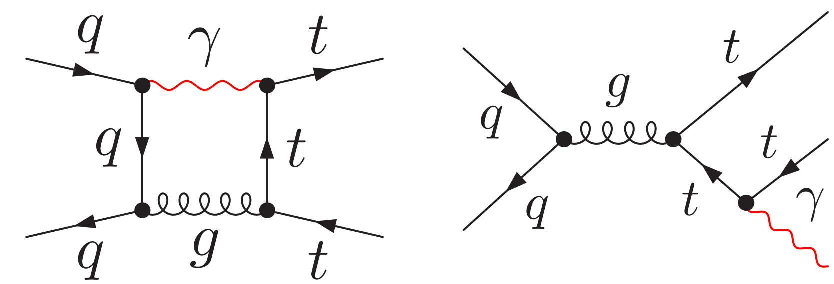
In the SM, contributions to the partonic cross section can be organized according to the powers of α_s and α (number of loop corrections and real emissions).



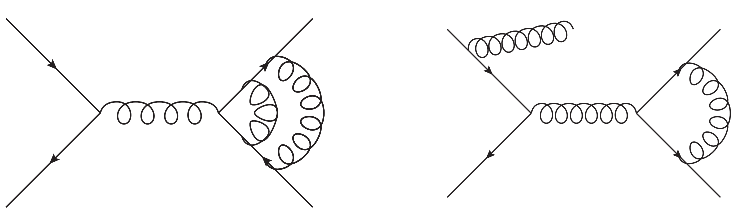
Born LO



NLO QCD
$\mathcal{O}(\alpha_s)$ corrections



NLO EW
$\mathcal{O}(\alpha)$ corrections



NNLO QCD
$\mathcal{O}(\alpha_s^2)$ corrections

NNLO EW,
NNNLO QCD
.....

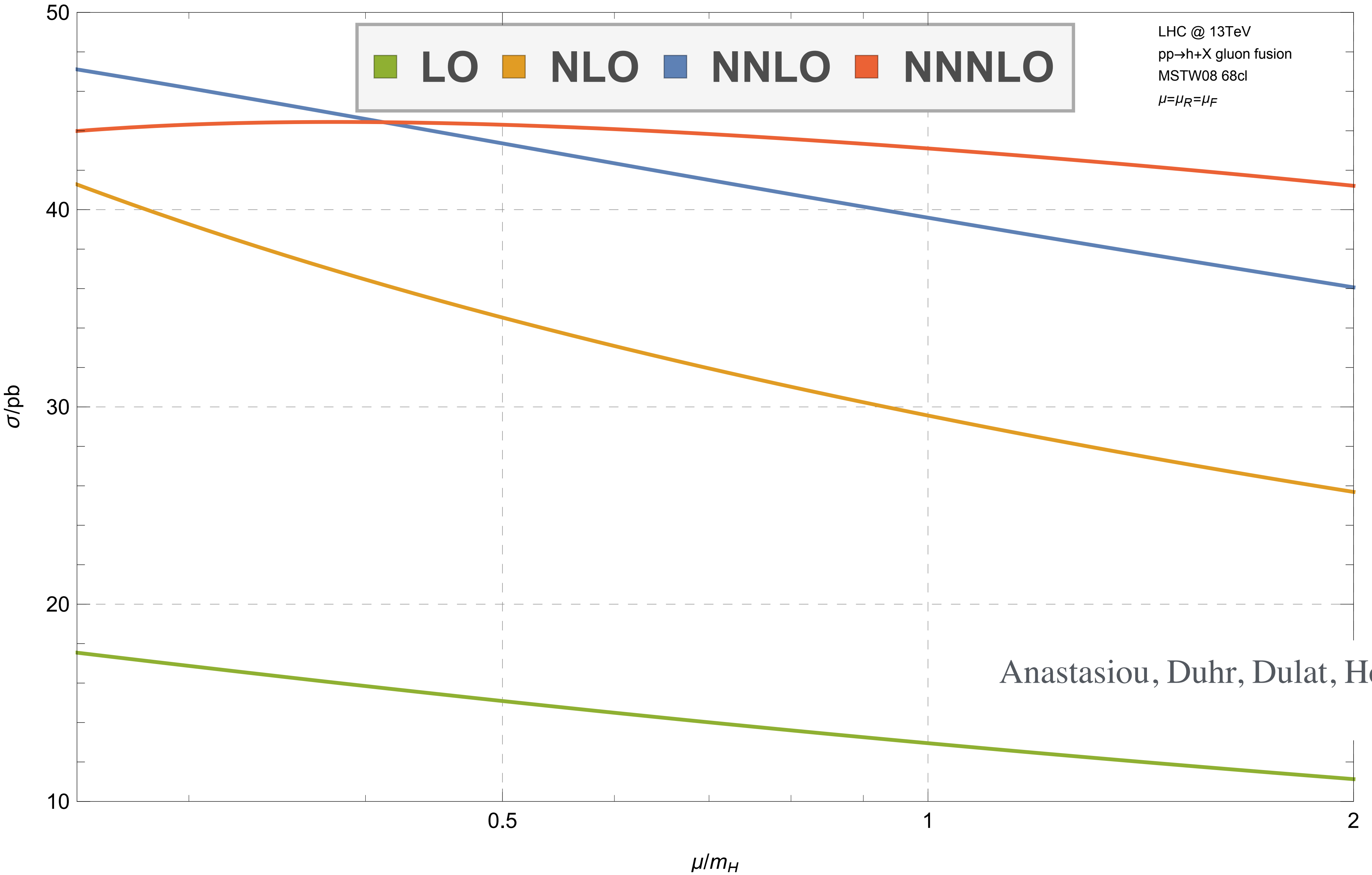
At the LHC, QCD is everywhere.
Nowadays, a "standard" prediction in the SM is at NLO QCD accuracy.

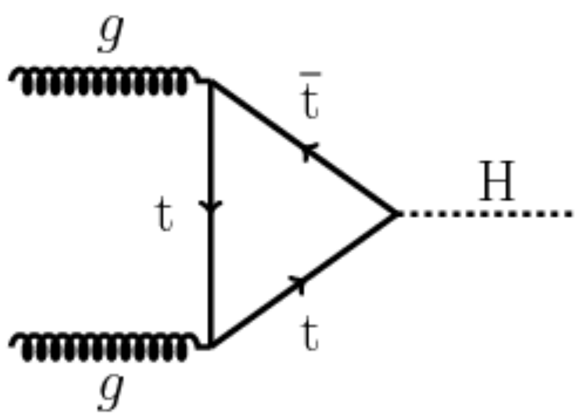
NNLO QCD is expected to be of the same order of NLO EW $\alpha_s^2 \sim \alpha$.

EW corrections grow for large pt (Sudakov logs), so they are not flat. Moreover they in general involve all the SM masses and couplings.

Importance of NNLO (and NNNLO) QCD corrections

An example: H boson production via gluon fusion.

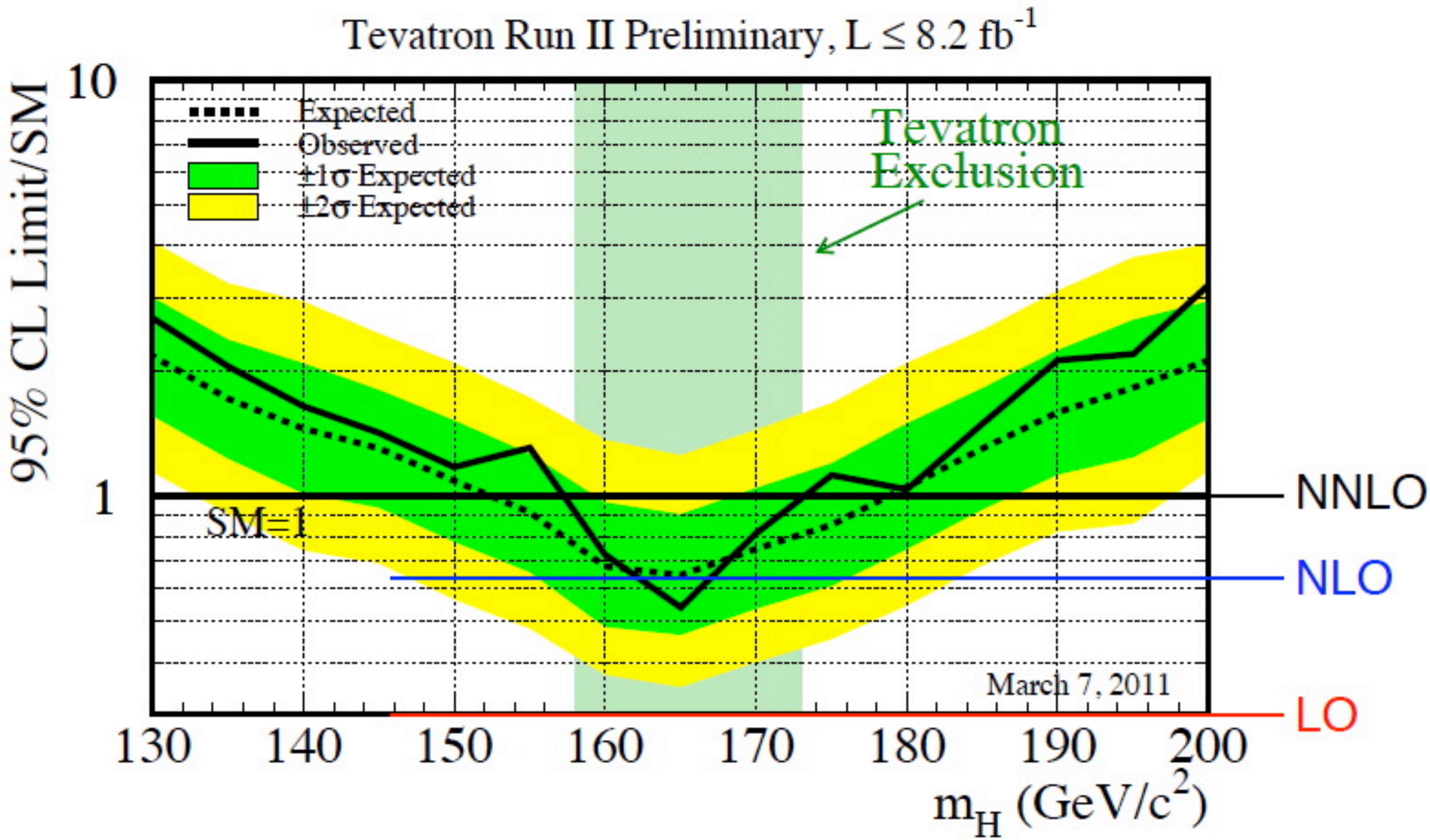




Anastasiou, Duhr, Dulat, Herzog, Mistlberger ‘15

NLO EW corrections are ~ 5 %, i.e., larger than the residual QCD scale uncertainty.

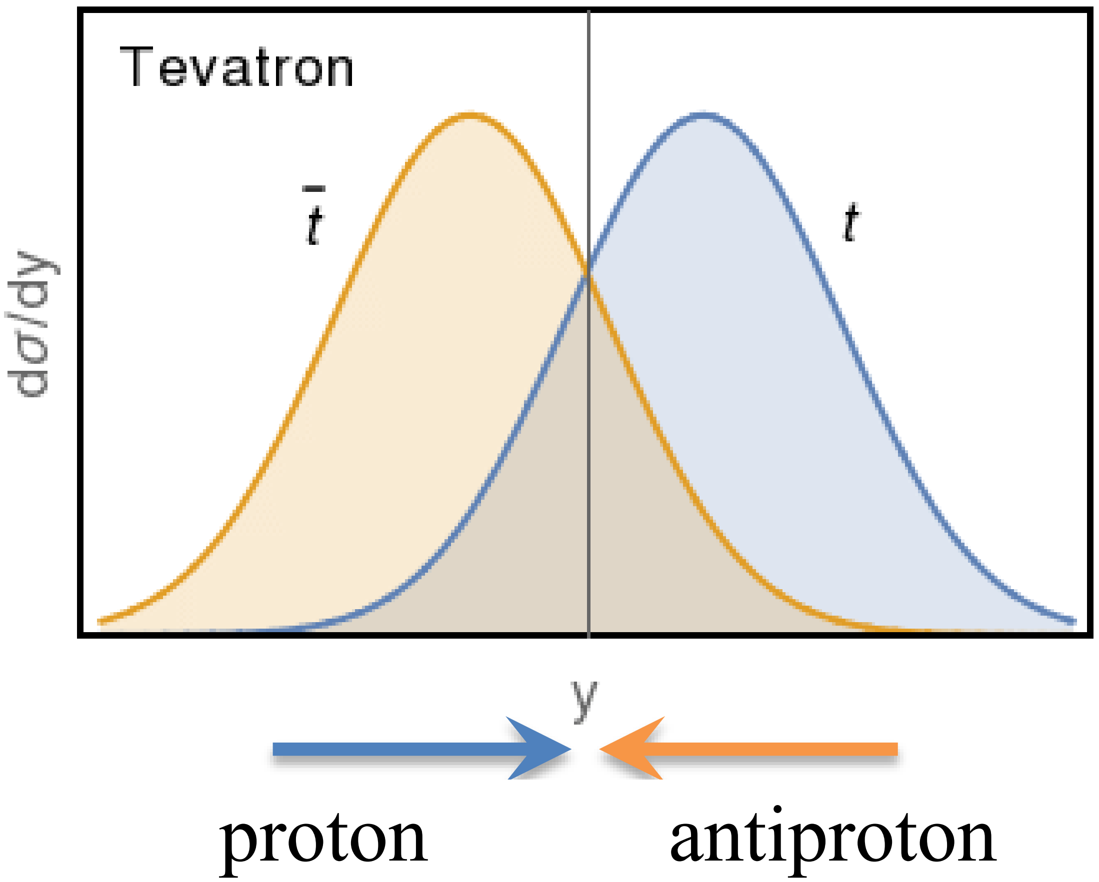
Importance of NLO and NNLO QCD corrections



be careful : just illustrative example, not very precise

Correct interpretation of the (B)SM signal

A recent story from an other hadron collider: **the top-quark forward-backward asymmetry at the Tevatron.**



$$A_{FB}^{p\bar{p}} = \frac{\sigma(y_t > 0) - \sigma(y_t < 0)}{\sigma(y_t > 0) + \sigma(y_t < 0)}$$

D0 and especially CDF measured values for the forward-backward asymmetry that are larger than the SM prediction.

But which SM prediction?

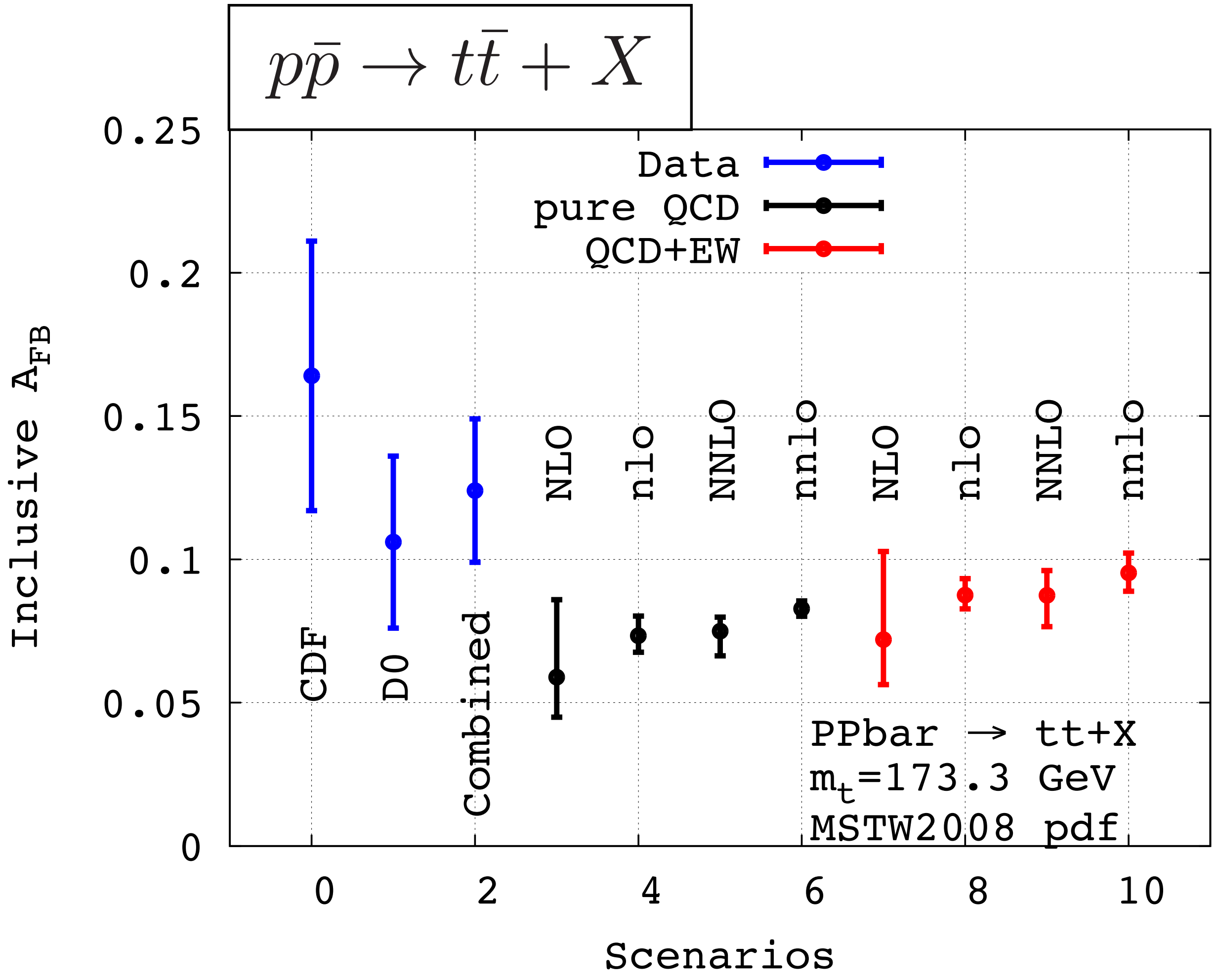
Correct interpretation of the (B)SM signal

A recent story from an other hadron collider: **the top-quark forward-backward asymmetry at the Tevatron.**

Surprisingly (No Sudakov enhancement), the NLO EW induces corrections of order 20-25%.

$$R_{QED}(Q_q) = \frac{\alpha \tilde{N}_1^{QED}}{\alpha_s N_1} = Q_q Q_t \frac{36}{5} \frac{\alpha}{\alpha_s}$$

DP, Hollik '11



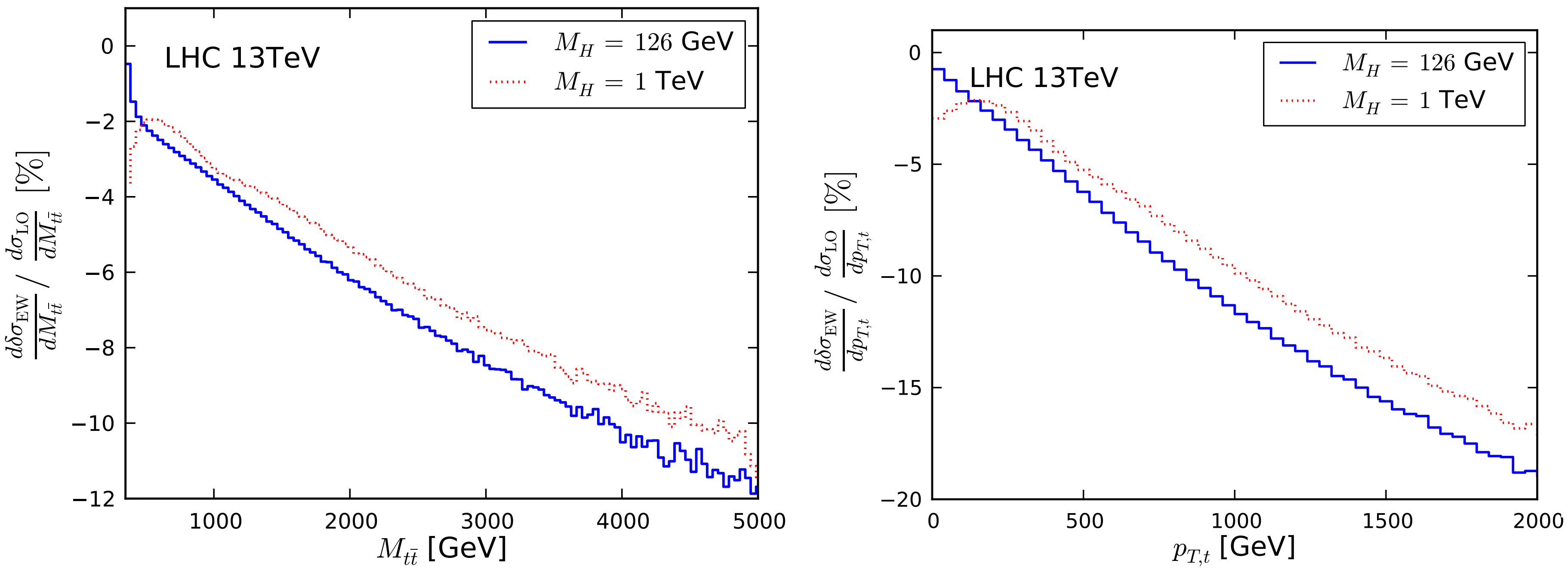
NNLO QCD and NLO EW are essential for a reliable theoretical prediction.

Missing higher-orders in the theoretical predictions may be misinterpreted as BSM signals.

Czakon, Fiedler, Mitov '14

Sudakov enhancement

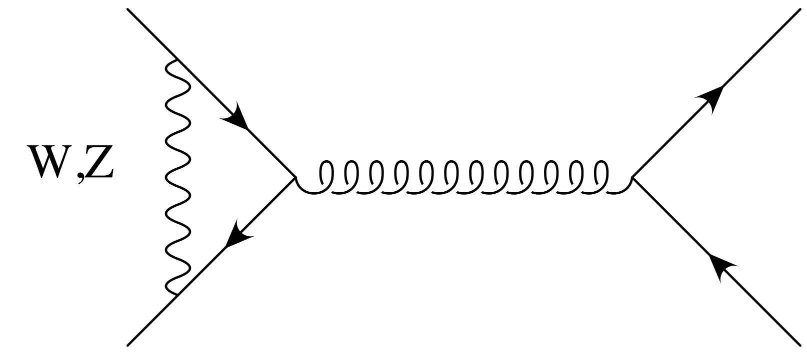
Not surprisingly, weak corrections at large scales are not negligible for a general process due to the Sudakov Logarithms $\sim \alpha \ln^2\left(\frac{s}{M_W^2}\right)$



Kühn, Scharf, Uwer '13

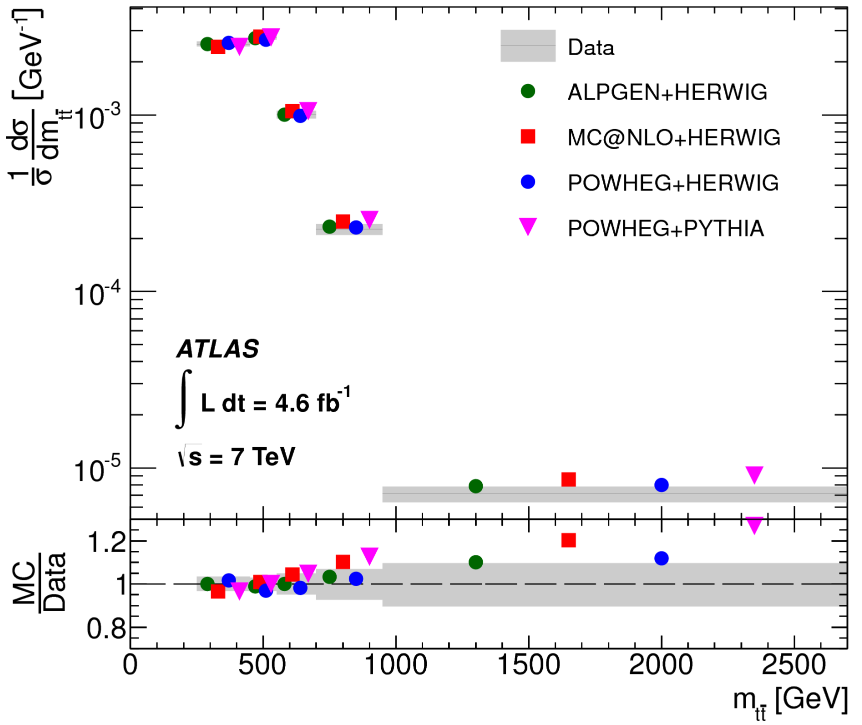
Example:

$$pp \to t\bar{t} + X$$



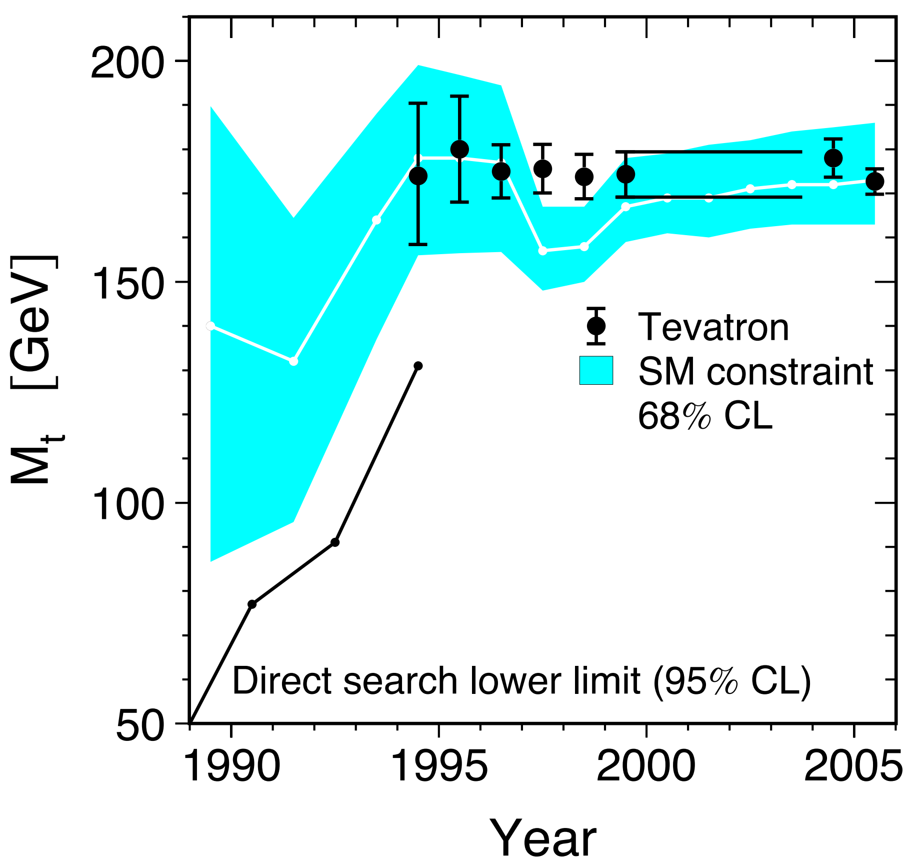
Results from Run-I:

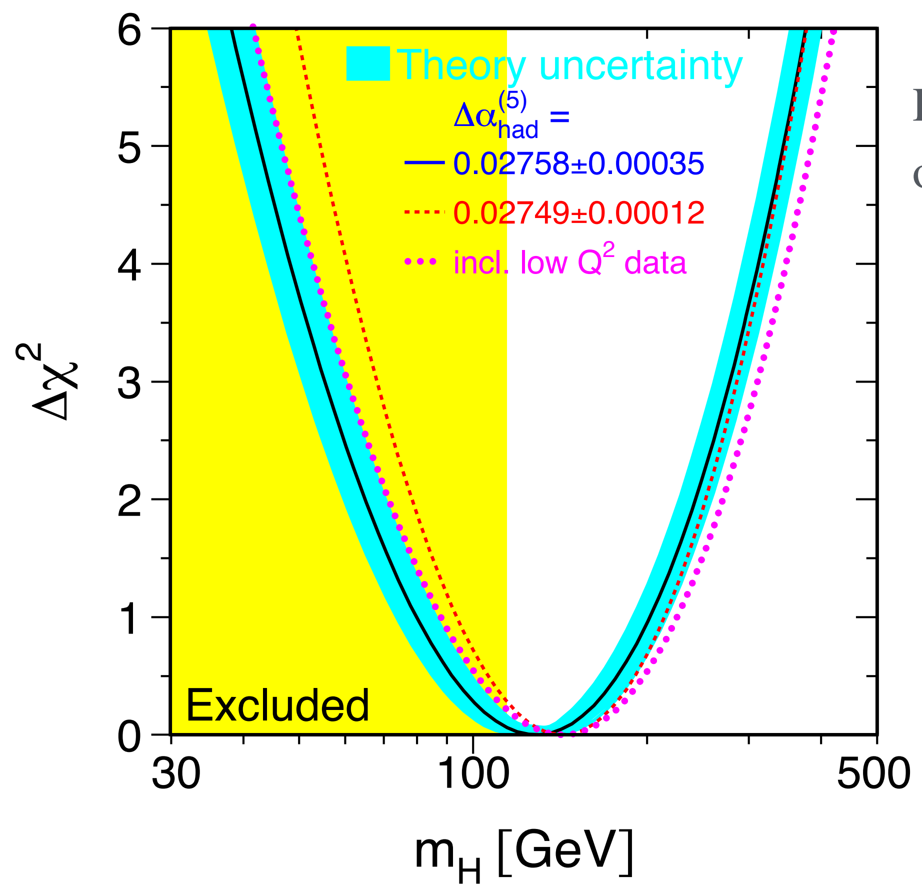
Is it BSM, EW Sudakov or something else?



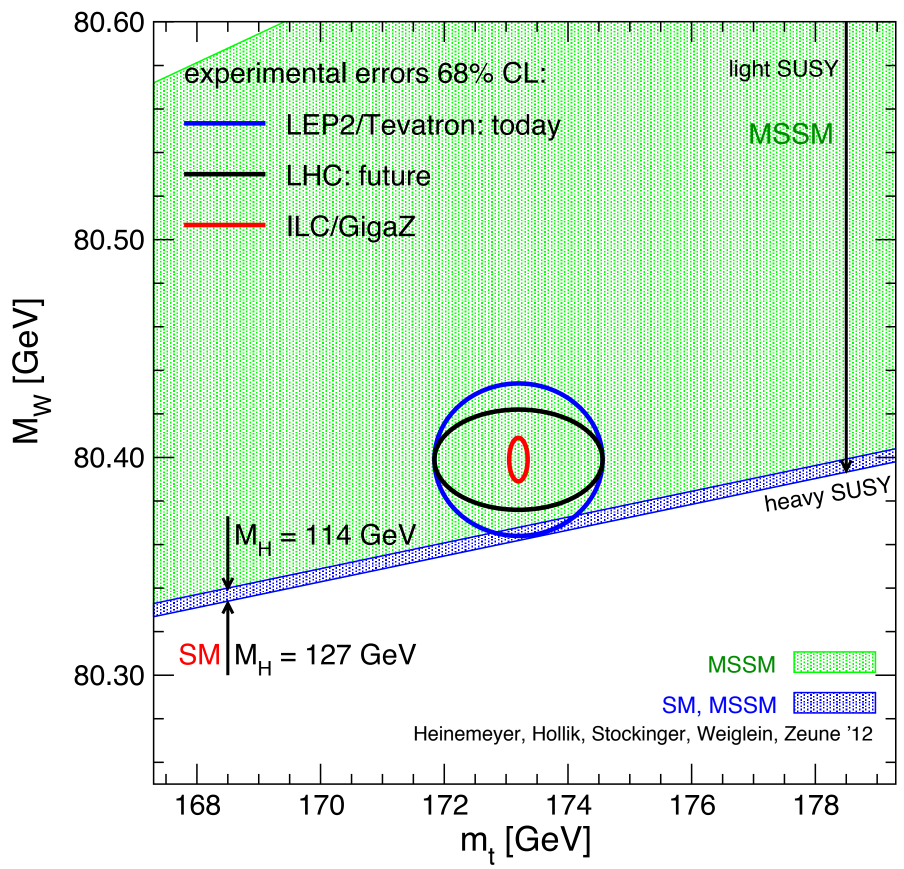
Plot taken from Varouchas talk at the: Top LHC France workshop

EWPO (past and future)



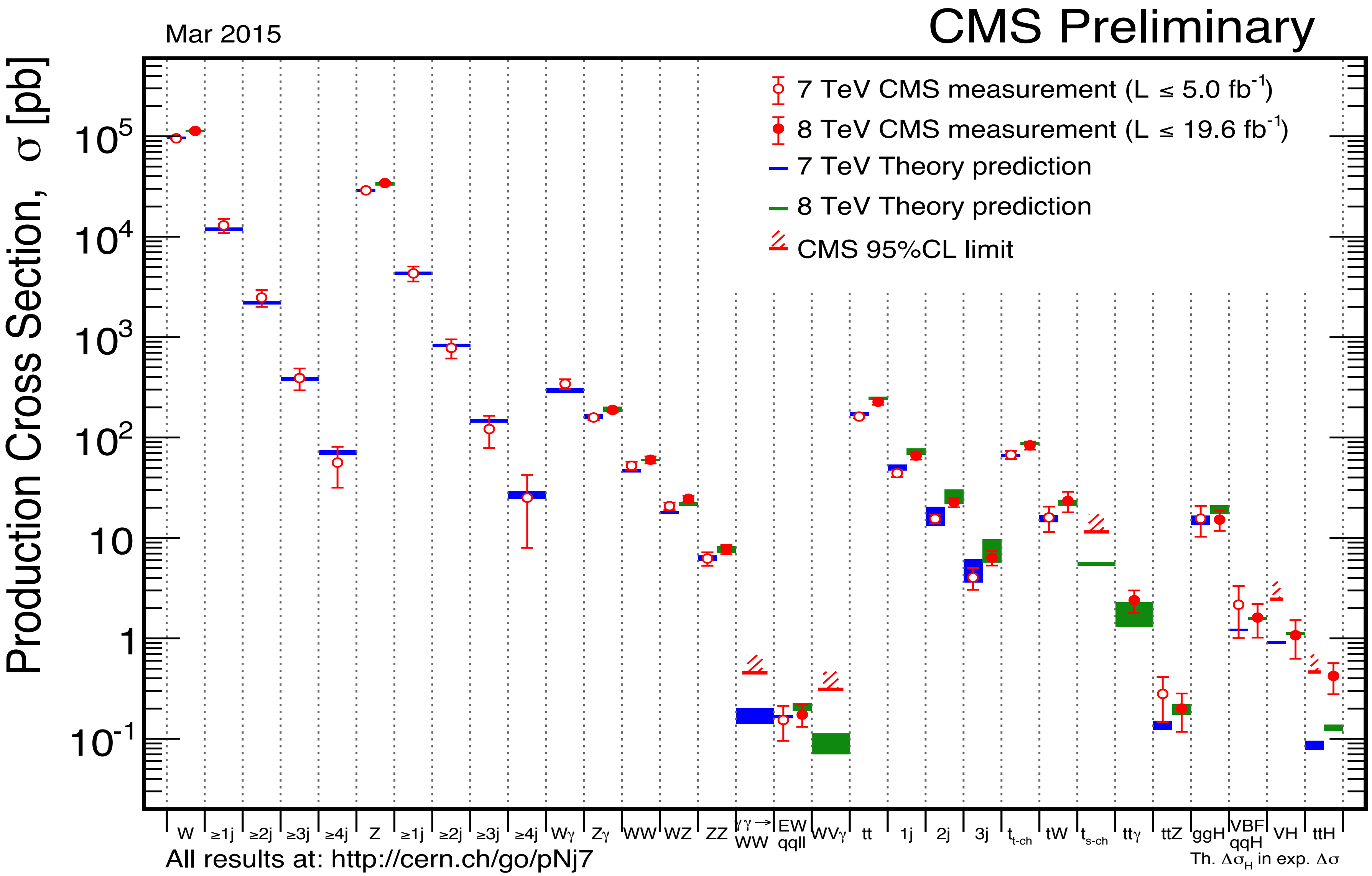


Precision Electroweak measurements on the Z resonance hep-ex/0509008



EWPO were crucial in order to constrain the H-boson and top-quark mass.
Today EWPO can be used to check the internal consistency of the SM.
In models where they can be calculated, as in the MSSM, EWPO can be used to constrain the parameter space.

SM at the LHC



With higher energy and higher luminosity, at the LHC more processes will be measurable and the accuracy of all measurements will in general increase.

Precise predictions are necessary for the Run-II of the LHC, especially if no clear sign of new physics will appear. In order to match the experimental precision, NLO EW corrections are in general essential.

Automation of NLO EW

NLO QCD corrections, matched to shower effects, have already been completely automated in event generators via **aMC@NLO_MadGraph5**.

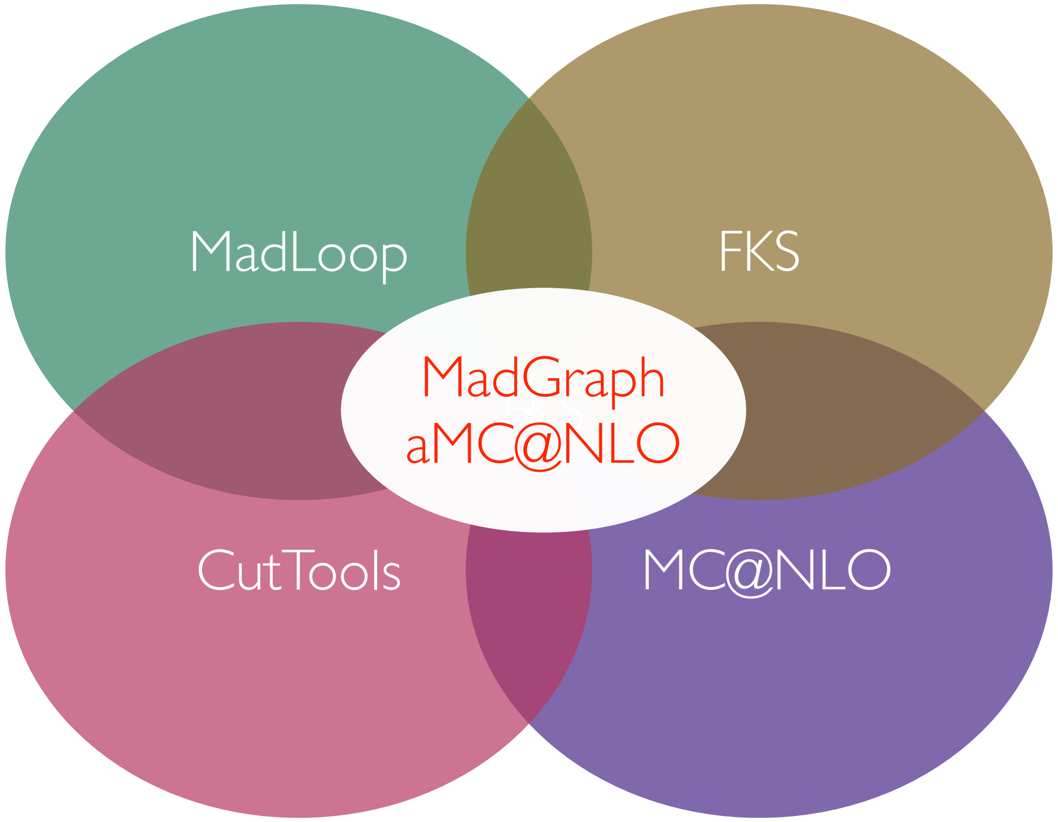
Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Shao, Stelzer, Torrielli, Zaro ‘14

NNLO (QCD) automation is out of our theoretical capabilities at the moment, (Subtraction schemes, Two-loop integrals).

NLO EW corrections can be automated and are being automated in **aMC@NLO_MadGraph5**.

Generation of all the ME.
EW loops and real emissions have a more complex structure.

Evaluation of loops and CTs.
UV CTs and R2 are many more in NLO EW corrections.



Regularization of IRC sing.
Not only gluons and quarks, buy also photons.

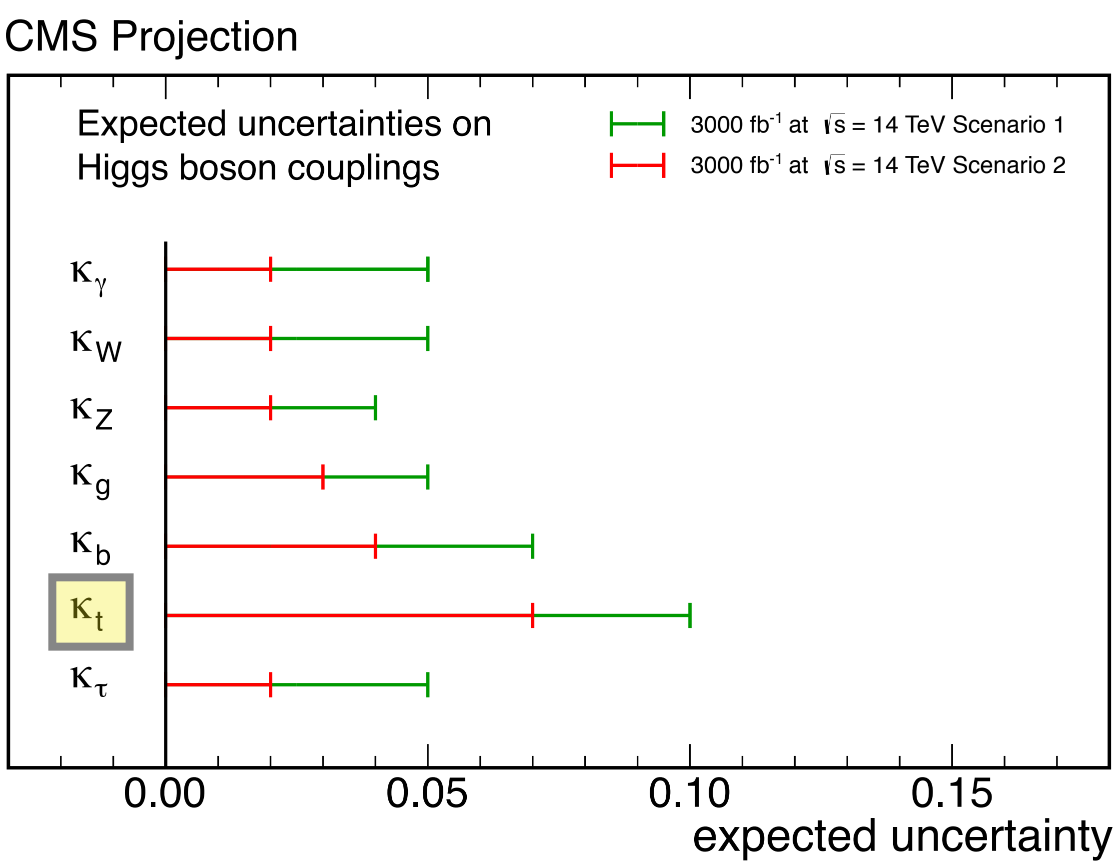
Matching with shower.
Not only QCD but also QED (EW) LL.

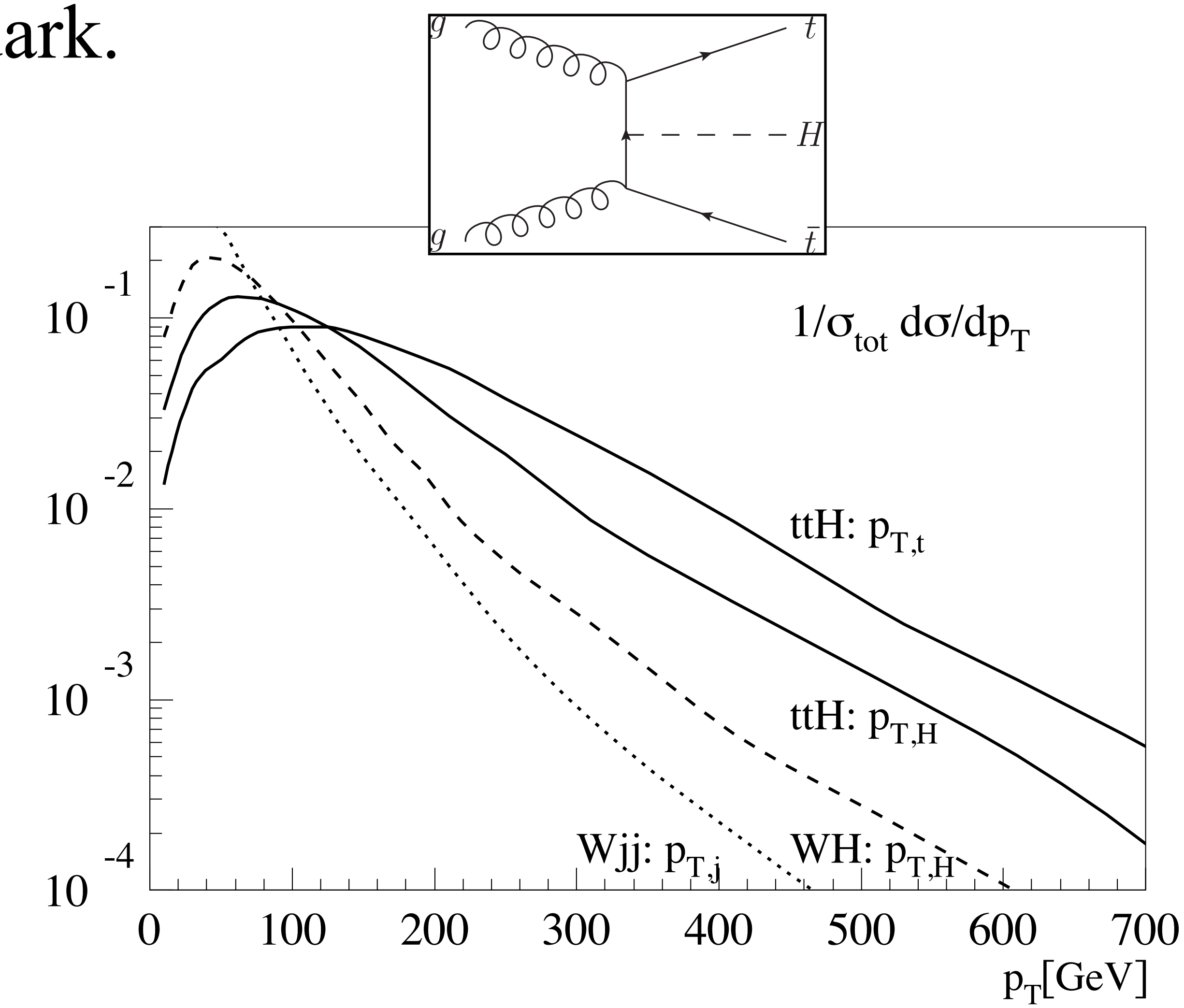
Pheno results with aMC@NLO_MadGraph5

NLO QCD and EW corrections to $t\bar{t}V$ $V = H, W, Z$
in a completely automated approach.

Frixione, Hirschi, DP, Shao, Zaro '14, '15

$t\bar{t}Z$ and $t\bar{t}H$ production respectively provide a direct measurement of the Z and H boson interaction with the top quark.

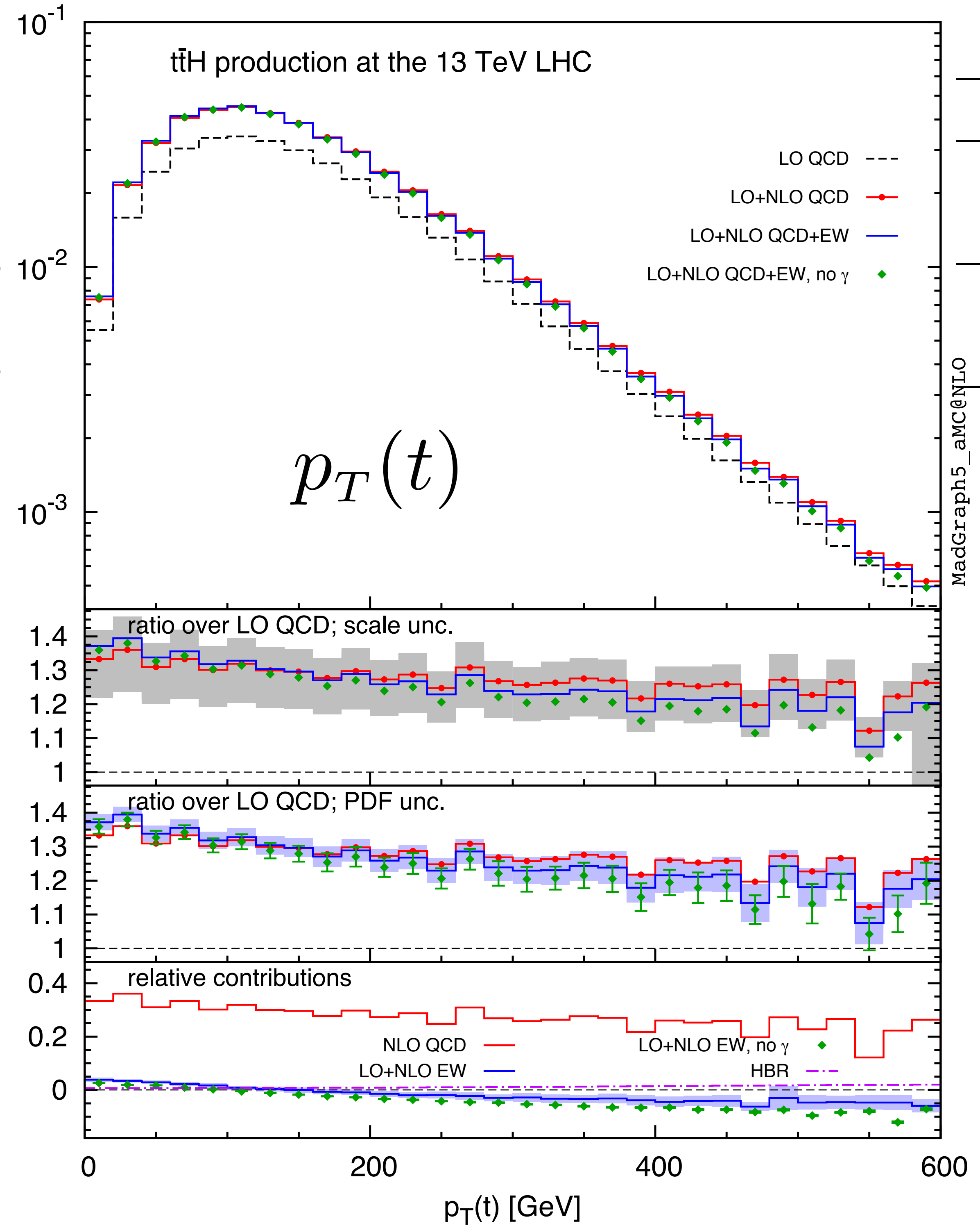




Plehn, Salam, Spannowsky '10

S/B increases for boosted tops and H.
Sudakov logs are relevant in these regions!

Numerical results



$t\bar{t}H$: $\delta(\%)$	8 TeV	13 TeV	100 TeV
NLO QCD	$25.9^{+5.4}_{-11.1}$	$29.7^{+6.8}_{-11.1}$ $(24.2^{+4.8}_{-10.6})$	$40.8^{+9.3}_{-9.1}$
LO EW	1.8 ± 1.3	1.2 ± 0.9 (2.8 ± 2.0)	0.0 ± 0.2
LO EW no γ	-0.3 ± 0.0	-0.4 ± 0.0 (-0.2 ± 0.0)	-0.6 ± 0.0
NLO EW	-0.6 ± 0.1	-1.2 ± 0.1 (-8.2 ± 0.3)	-2.7 ± 0.0
NLO EW no γ	-0.7 ± 0.0	-1.4 ± 0.0 (-8.5 ± 0.2)	-2.7 ± 0.0
HBR	0.88	0.89 (1.87)	0.91

(Boosted regime in brackets)

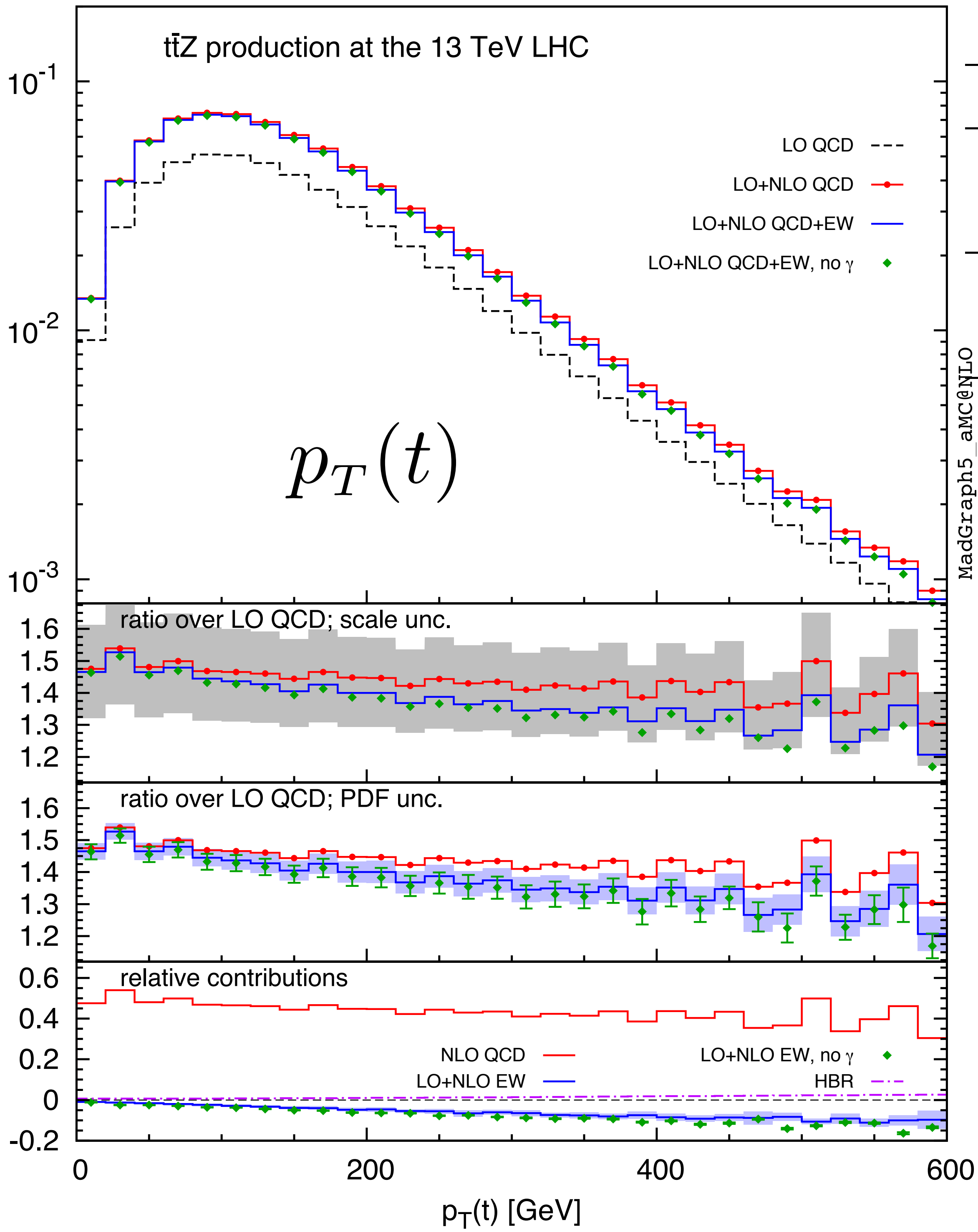
$p_T(t) \geq 200\ \text{GeV}, \quad p_T(\bar{t}) \geq 200\ \text{GeV}, \quad p_T(H) \geq 200\ \text{GeV}$

Scale variation

(NLO QCD+EW) PDF var.

$t\bar{t}H$

Numerical results



$t\bar{t}Z$: $\delta(\%)$	8 TeV	13 TeV	100 TeV
NLO QCD	$43.2^{+12.8}_{-15.9}$	$45.9^{+13.2}_{-15.5}$ $(40.2^{+11.1}_{-15.0})$	$50.4^{+11.4}_{-10.9}$
LO EW	0.5 ± 0.9	0.0 ± 0.7 (2.1 ± 1.6)	-1.1 ± 0.2
LO EW no γ	-0.8 ± 0.1	-1.1 ± 0.0 (-0.3 ± 0.0)	-1.6 ± 0.0
NLO EW	-3.3 ± 0.3	-3.8 ± 0.2 (-11.1 ± 0.5)	-5.2 ± 0.1
NLO EW no γ	-3.7 ± 0.1	-4.1 ± 0.1 (-11.5 ± 0.3)	-5.4 ± 0.0
HBR	0.95	0.96 (2.13)	0.85

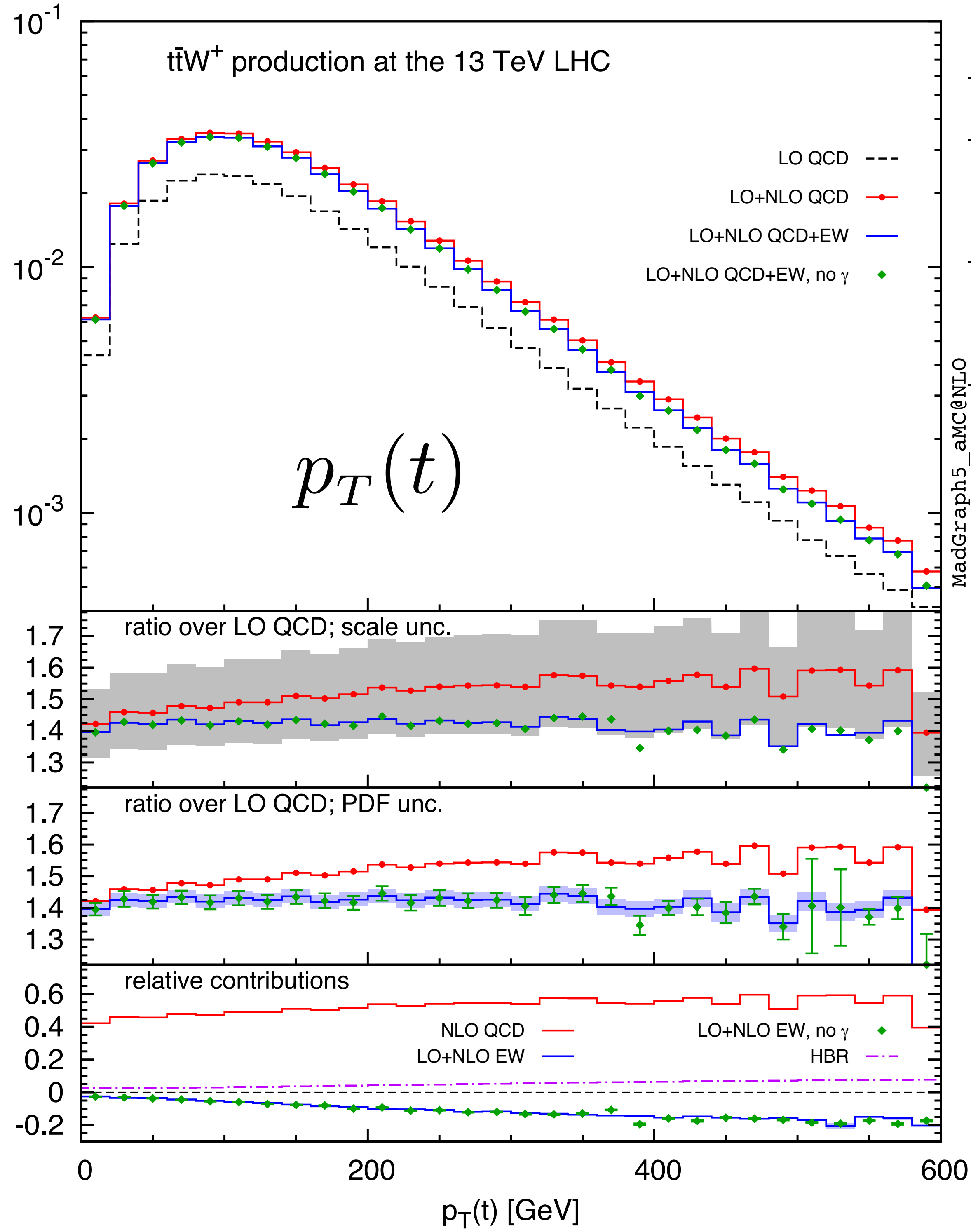
(Boosted regime in brackets)

Scale variation

(NLO QCD+EW) PDF var.

$$t\bar{t}Z$$

Numerical results



$t\bar{t}W^+ : \delta(\%)$	8 TeV	13 TeV	100 TeV
NLO QCD	$40.8^{+11.2}_{-12.3}$	$50.1^{+14.2}_{-13.5}$ $(59.7^{+18.9}_{-17.7})$	$156.4^{+38.3}_{-35.0}$
LO EW	0	0	0
LO EW no γ	0	0	0
NLO EW	-6.9 ± 0.2	-7.7 ± 0.2 (-19.2 ± 0.7)	-9.3 ± 0.2
NLO EW no γ	-7.1 ± 0.2	-8.0 ± 0.2 (-20.0 ± 0.5)	-9.6 ± 0.1
HBR	2.41	3.88 (7.41)	21.52

(Boosted regime in brackets)

Scale variation

(NLO QCD+EW) PDF var.

$t\bar{t}W^+$

CONCLUSION

Precise predictions at the LHC are essential in order to correctly identify or exclude possible BSM signals and to perform additional consistency checks for the SM.

NLO QCD corrections are the "new standard" for SM processes. For many processes, NNLO QCD and NLO EW accuracy or even more are necessary.

The automation of NLO EW and QCD corrections is in progress in **MadGraph5_aMC@NLO**. The first pheno studies in a completely automated approach have been presented for $t\bar{t}V$.

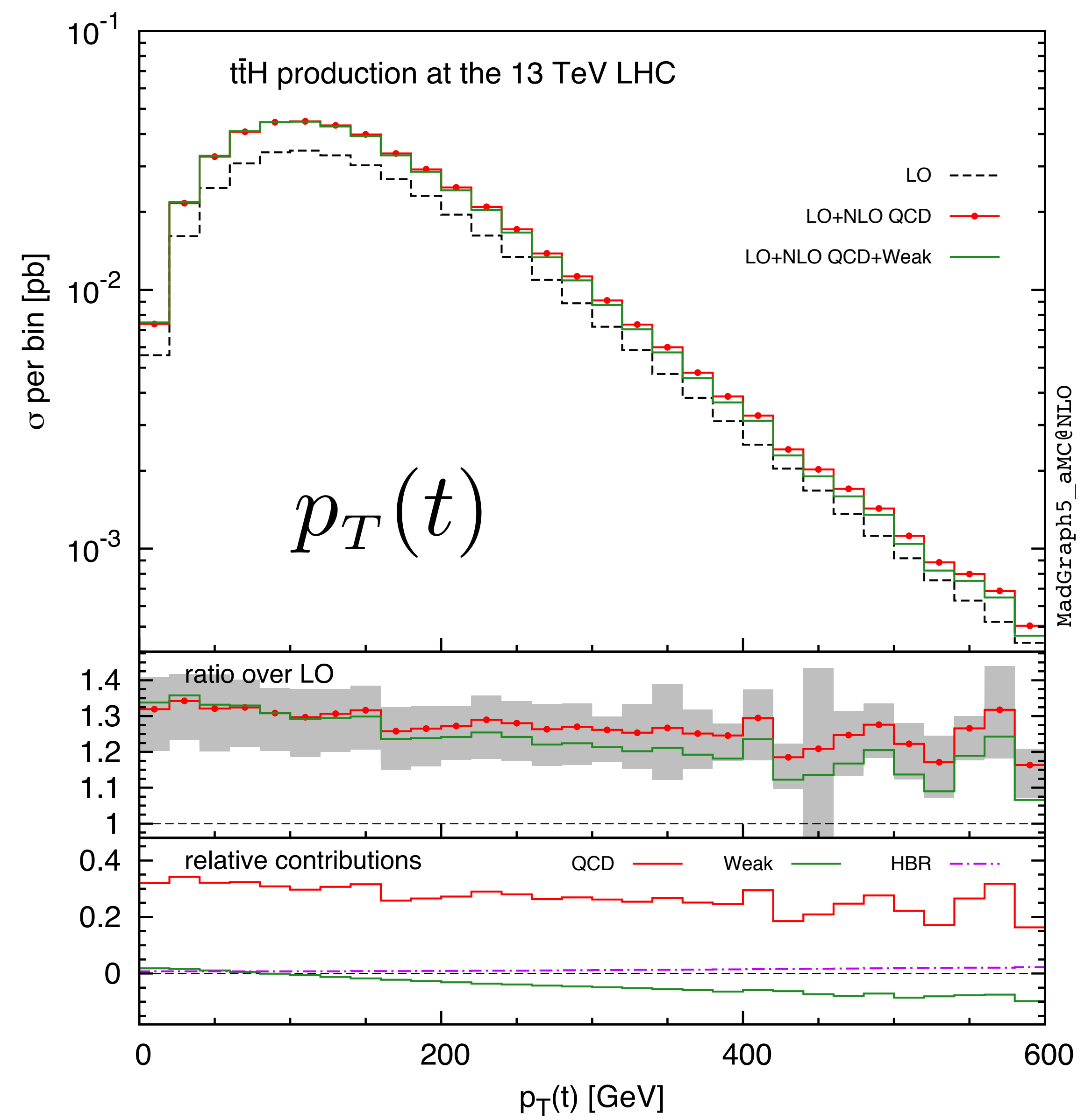
Due to the Sudakov logs, EW corrections are in general sizable for large pt's of the produced particles and in boosted regimes.

EXTRA SLIDES

Pheno studies

NLO purely Weak and QCD corrections to $t\bar{t}H$ production have been produced "assembling by hand" the FKS counterterms.

Frixione, Hirschi, DP, Shao, Zaro '14



Now, for the complete NLO QCD and EW corrections, with photons in the initial state, we need to type:

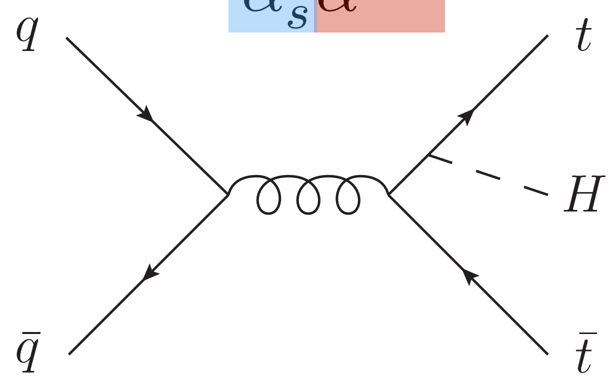
```
define p = p b b~ a
generate p p > t t~ h [QCD QED]
output ttbarh_QCD_QED
```

In this talk I will present results for NLO QCD and EW corrections to

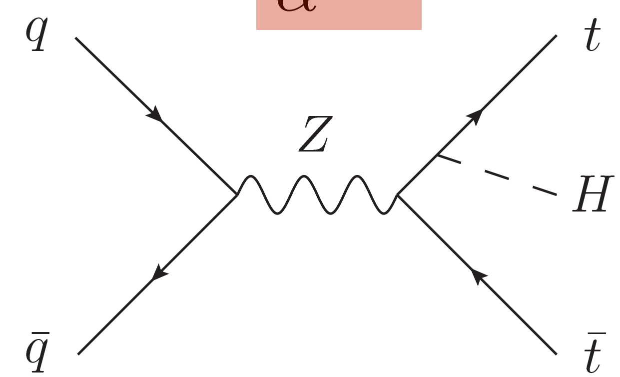
$t\bar{t}V \qquad V = H, W, Z$

Structure of NLO EW-QCD corrections

$\alpha_s^1 \alpha^{1/2}$

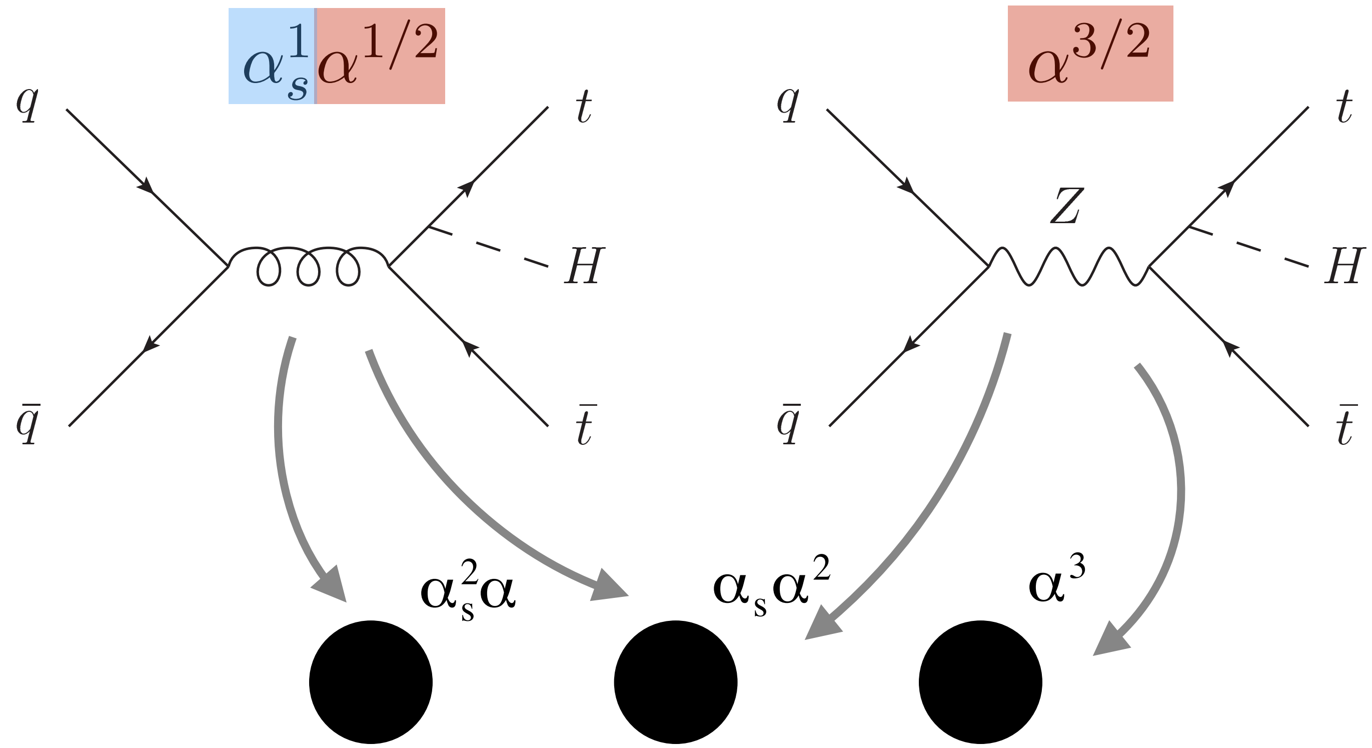


$\alpha^{3/2}$



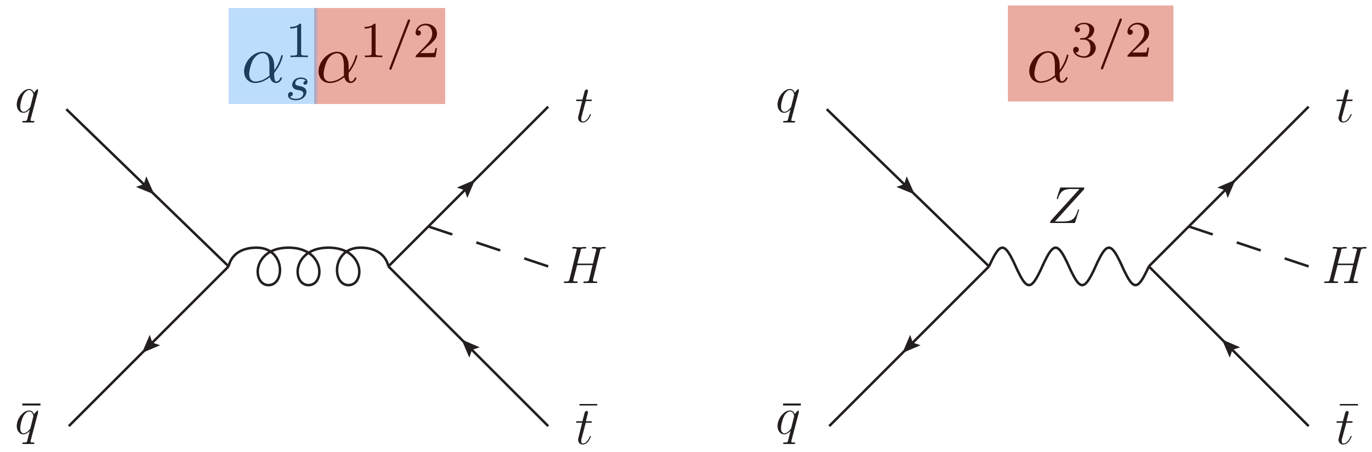
LO: $\alpha_s^2\alpha$ ● $\alpha_s\alpha^2$ ● α^3 ●

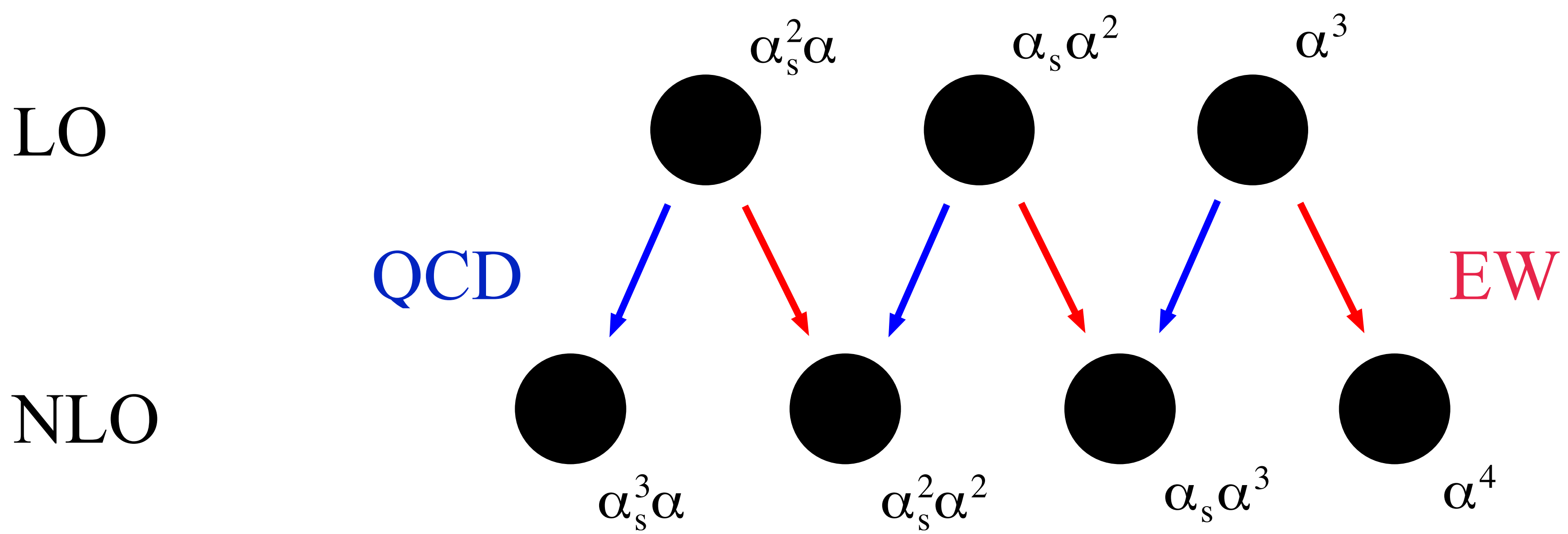
Structure of NLO EW-QCD corrections



LO

Structure of NLO EW-QCD corrections





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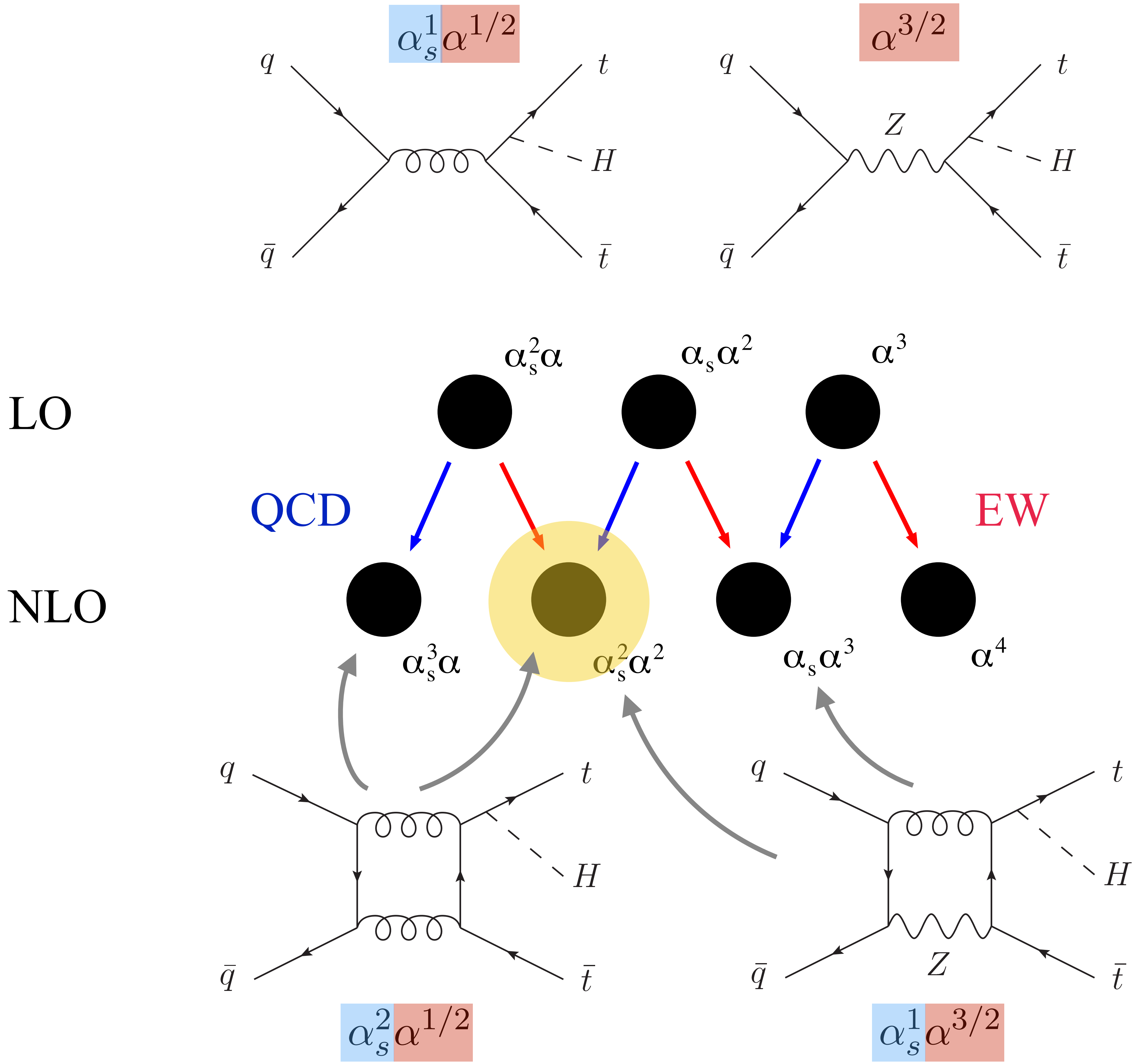

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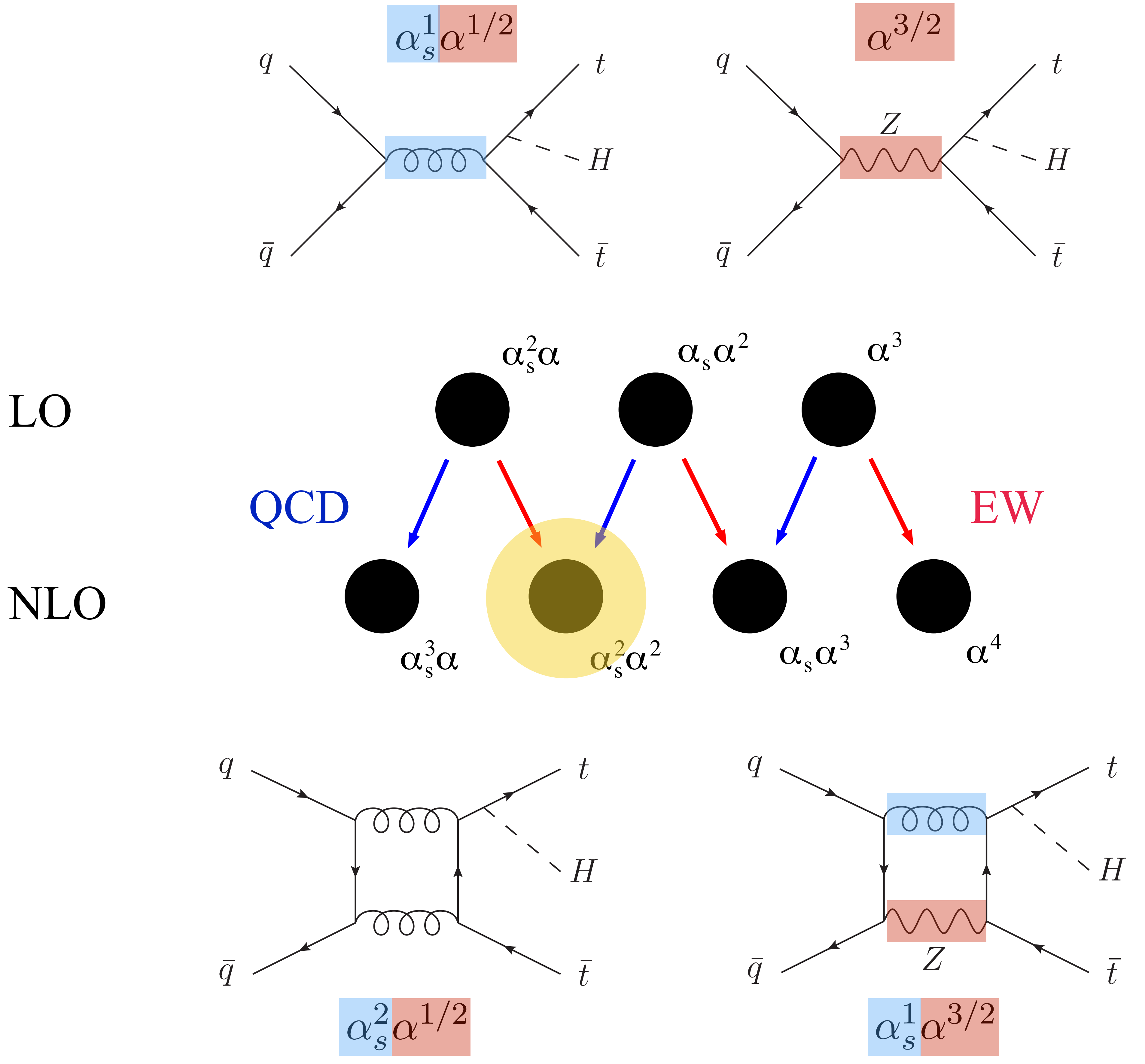
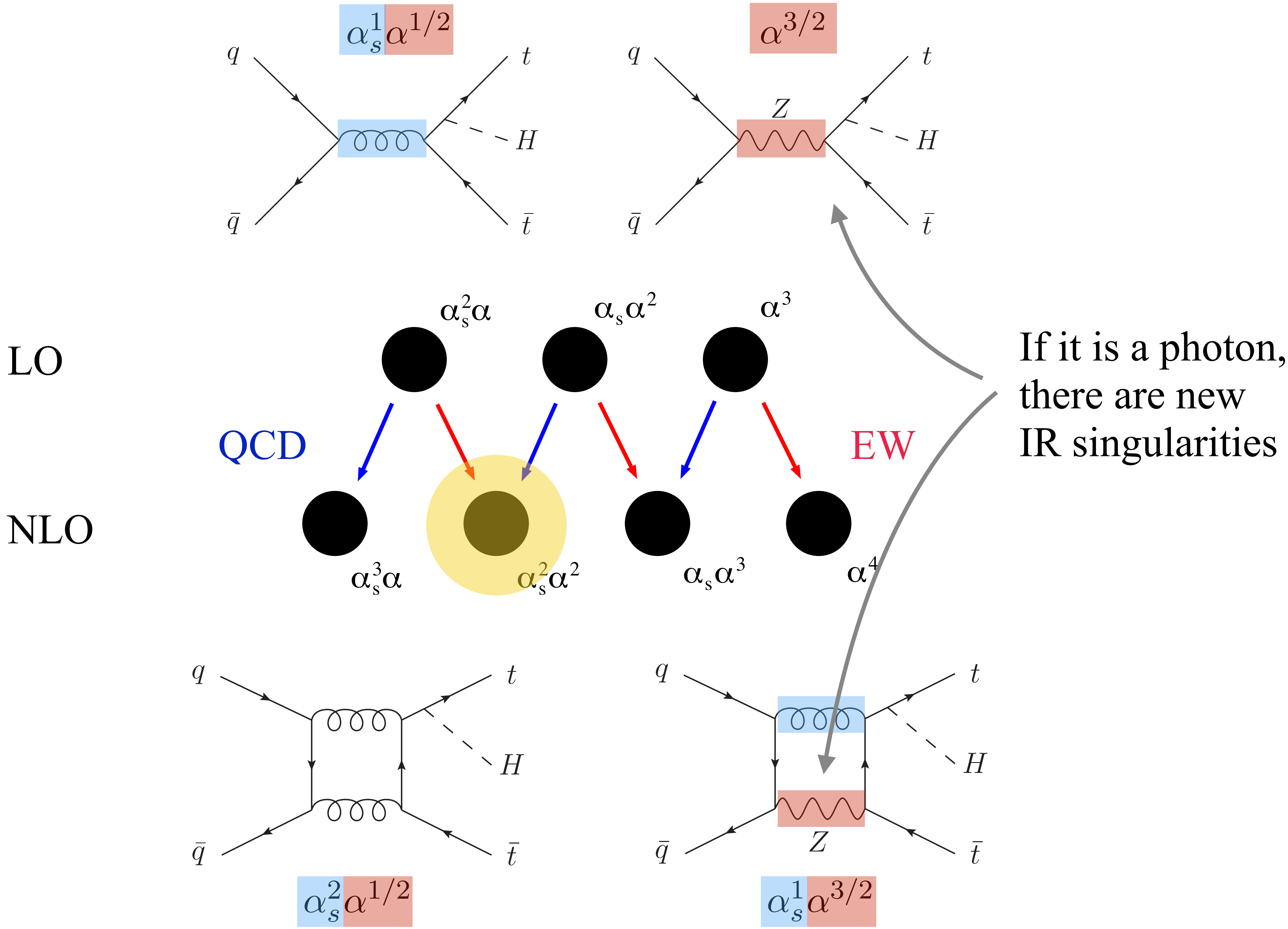


Structure of NLO EW-QCD corrections



$t\bar{t}V$ production: numerical results

Alpha(mZ)-scheme, NNPDF2.3_QED, $\mu = \frac{H_T}{2}, \quad \frac{1}{2}\mu \leq \mu_R, \mu_F \leq 2\mu$

Contributions

HBR ($pp \to t\bar{t}V + V'$) is of the same order of NLO EW.

Photon PDF (with large uncertainties) enters in LO EW and NLO EW.