QCD at the LHC

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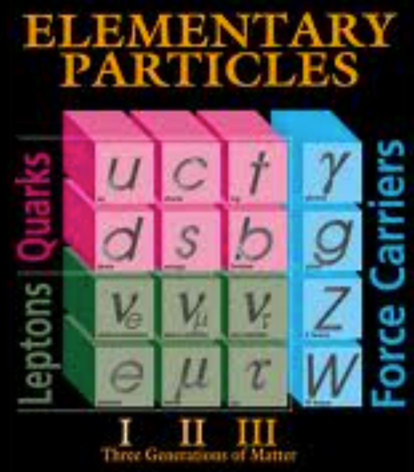
NBIA-Oxford Colloquium, 14th April 2015, Copenhagen

Status of particle physics



- Standard Model (SM): successful theory of describing strong (QCD), electroweak (EW) elementary interactions
- Yet, no fundamental theory:
  theoretical issues + unexplained phenomena (e.g. gravity, matter anti-matter asymmetry, dark matter, dark energy, ...)
- Main focus today on LHC experiment. It was designed to
  - ☑ unravel EW symmetry breaking (origin of mass)
  - ☐ find physics beyond the SM

Perturbation theory

At LHC energies, QCD and EW interactions are weak. We can compute expansions in the (small) coupling. Higher-order terms will improve predictions. Different expansions:

1. fixed order

$$\frac{\sigma}{\sigma_0} = 1 \quad \text{LO}$$
$$+ c_1\alpha \quad \text{NLO}$$
$$+ c_2\alpha^2 \quad \text{NNLO}$$

2. all order (L = large

$$\ln\frac{\sigma}{\sigma_0} = \alpha^n L^{n+1} \quad \text{LL}$$
$$+ \alpha^n L^n \quad \text{NLL}$$
$$+ \alpha^n L^{n-1} \quad \text{NNLL}$$

+ go from perturbative picture (quark/gluons) to realistic final state (pions, mesons etc.) using 3. parton shower event generators

Perturbative QCD

- QCD is weakly/strongly coupled at short/large distances
- Perturbation theory is predictive for observables insensitive to large distance (low energy) effects, i.e. for infrared-safe observables
  - IR-safe: inclusive cross-sections, suitable jet cross-sections, event shapes, ...
  - not IR-safe: multiplicities, transverse momentum of hardest particle, Tevatron mid-point jet-algorithm...
- Thorough tests of perturbative QCD carried out in the past (heritage from LEP, HERA, Tevatron, ...)
- Current status: no major areas of discrepancies with data
- Today the focus is less focus on testing QCD, but emphasis on predicting and modeling QCD “backgrounds”

Why higher-order PT

- amazing results from LHC Run I
  competitive measurements of SM parameters (even of α_s), constraints on anomalous couplings, New Physics models, DM candidates, precision Higgs physics, jets spectra up several TeVs, ...)
- even better results expected for Run II (beams already circulating)
- optimal use of the machine when experimental (jet-energy scale, luminosity etc.) and theoretical systematics systematics are comparable
- currently, use and interpretation of some cross-sections already limited by large theory uncertainties (estimated via scale variations)

Main areas of development

- fully automated NLO calculations (past ten years)
- techniques to combine NLO calculations and parton showers
- sudden appearance of a number of NNLO calculations in the last two years
- merging NNLO and parton shower
- one N^{3}LO result (one month ago)!
- analytic resummations (e.g. for jet-veto ...)
- jet-substructure (look inside jets to increase discriminating power)
- parton distribution functions

Main areas of development

My choice of topics for this talk:

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Factorization

Master formula:

$$\sigma = \int dx_1 dx_2 f(x_1, \mu_F) f(x_2, \mu_F) \hat{\sigma}(x_1, x_2; \{p\}; \mu_R, \mu_F) + \mathcal{O}\left(\frac{\Lambda_{\mathrm{QCD}}}{Q}\right)^n$$

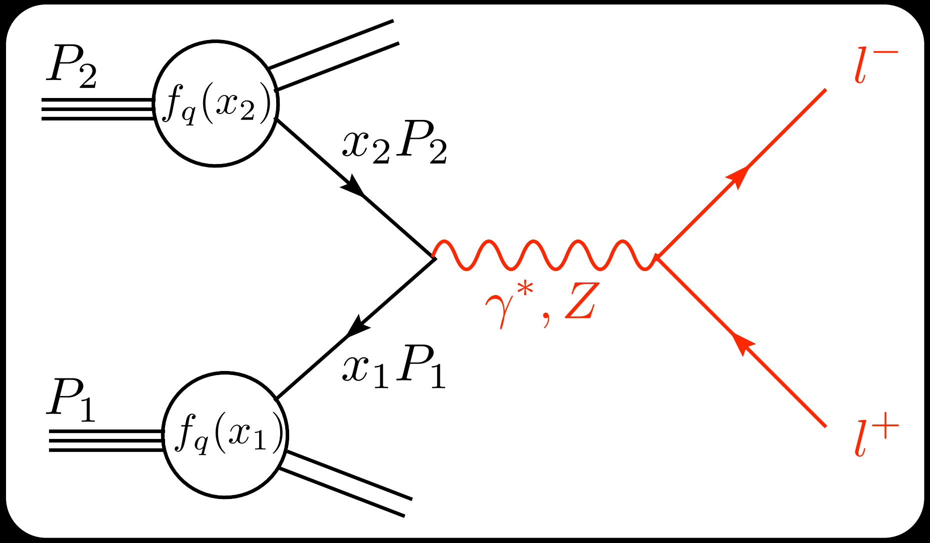
hadronic cross-section (measured)

parton distribution functions Extracted from data (but evolution is perturbative)

partonic cross-section (calculated using perturbative methods)

hadronization corrections (mostly modeled)

Example: Drell-Yan



NLO QCD: a solved problem

Process ($V \in \{Z, W, \gamma\}$)	Comments
Calculations completed since Les Houches 2005	
1. $pp \to VV$jet	WWjet completed by Dittmaier/Kallweit/Uwer [3]; Campbell/Ellis/Zanderighi [4] and Binoth/Karg/Kauer/Sanguinetti (in progress)
2. $pp \to$ Higgs+2jets	NLO QCD to the gg channel completed by Campbell/Ellis/Zanderighi [5]; NLO QCD+EW to the VBF channel completed by Ciccolini/Denner/Dittmaier [6,7]
3. $pp \to V\,V\,V$	ZZZ completed by Lazopoulos/Melnikov/Petriello [8] and WWZ by Hankele/Z[illegible] [9]
Calculations remaining from Les Houches 2005	
4. $pp \to t\bar{t}\,b\bar{b}$	re[illegible]ant for t[illegible]
5. $pp \to t\bar{t}$+2jets	re[illegible]t for t[illegible]
6. $pp \to VV\,b\bar{b}$,	releva[illegible] V[illegible] $\to VV$, $t\bar{t}H$
7. $pp \to VV$+2jets	[illegible]elevant [illegible] VB[illegible] $\to H \to VV$ VB[illegible]ributions calculated by (Bozzi/)Jäger/Oleari/Zeppenfeld [10–12]
8. $pp \to V$+3je[illegible]	various new physics signatures
NLO calculatio[illegible] added [illegible] lis[illegible] 2007	
9. $pp \to b\bar{b}b\bar{b}$	Higgs and new physics signatures
Calculations beyond NLO added in 2007	
10. $gg \to W^*W^*$ $\mathcal{O}(\alpha^2\alpha_s^3)$	backgrounds to Higgs
11. NNLO $pp \to t\bar{t}$	normalization of a benchmark process
12. NNLO to VBF and Z/γ+jet	Higgs couplings and SM benchmark
Calculations including electroweak effects	
13. NNLO QCD+NLO EW for W/Z	precision calculation of a SM benchmark

CLOSED

Table 1: The updated experimenter's wishlist for LHC processes

- Les Houches NLO wishlists are now a closed chapter (now focus on NNLO)
- Two current directions:
  - <u>more processes:</u> automation (Helac, GoSam, MadLoop, ...)
  - <u>more legs:</u> focus on one class of processes and push multiplicity (Blackhat)

Example: automated NLO

Alwall et al '14

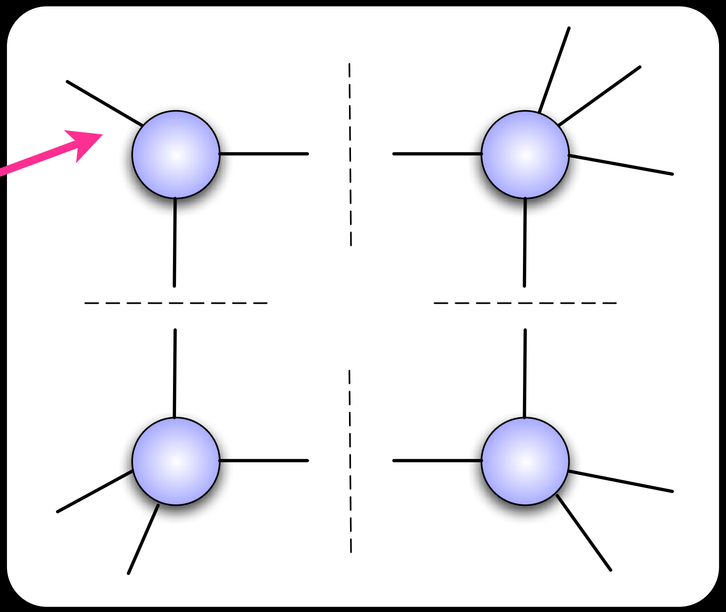
Process		Syntax	Cross section (pb)			
Heavy quarks and jets			LO 1 TeV		NLO 1 TeV	
i.1	$e^+e^- \to jj$	`e+ e- > j j`	$6.223 \pm 0.005 \cdot 10^{-1}$	$^{+0.0\%}_{-0.0\%}$	$6.389 \pm 0.013 \cdot 10^{-1}$	$^{+0.2\%}_{-0.2\%}$
i.2	$e^+e^- \to jjj$	`e+ e- > j j j`	$3.401 \pm 0.002 \cdot 10^{-1}$	$^{+9.6\%}_{-8.0\%}$	$3.166 \pm 0.019 \cdot 10^{-1}$	$^{+0.2\%}_{-2.1\%}$
i.3	$e^+e^- \to jjjj$	`e+ e- > j j j j`	$1.047 \pm 0.001 \cdot 10^{-1}$	$^{+20.0\%}_{-15.3\%}$	$1.090 \pm 0.006 \cdot 10^{-1}$	$^{+0.0\%}_{-2.8\%}$
i.4	$e^+e^- \to jjjjj$	`e+ e- > j j j j j`	$2.211 \pm 0.006 \cdot 10^{-2}$	$^{+31.4\%}_{-22.0\%}$	$2.771 \pm 0.021 \cdot 10^{-2}$	$^{+4.4\%}_{-8.6\%}$
i.5	$e^+e^- \to t\bar{t}$	`e+ e- > t t~`	$1.662 \pm 0.002 \cdot 10^{-1}$	$^{+0.0\%}_{-0.0\%}$	$1.745 \pm 0.006 \cdot 10^{-1}$	$^{+0.4\%}_{-0.4\%}$
i.6	$e^+e^- \to t\bar{t}j$	`e+ e- > t t~ j`	$4.813 \pm 0.005 \cdot 10^{-2}$	$^{+9.3\%}_{-7.8\%}$	$5.276 \pm 0.022 \cdot 10^{-2}$	$^{+1.3\%}_{-2.1\%}$
i.7*	$e^+e^- \to t\bar{t}jj$	`e+ e- > t t~ j j`	$8.614 \pm 0.009 \cdot 10^{-3}$	$^{+19.4\%}_{-15.0\%}$	$1.094 \pm 0.005 \cdot 10^{-2}$	$^{+5.0\%}_{-6.3\%}$
i.8*	$e^+e^- \to t\bar{t}jjj$	`e+ e- > t t~ j j j`	$1.044 \pm 0.002 \cdot 10^{-3}$	$^{+30.5\%}_{-21.6\%}$	$1.546 \pm 0.010 \cdot 10^{-3}$	$^{+10.6\%}_{-11.6\%}$
i.9*	$e^+e^- \to t\bar{t}t\bar{t}$	`e+ e- > t t~ t t~`	$6.456 \pm 0.016 \cdot 10^{-7}$	$^{+19.1\%}_{-14.8\%}$	$1.221 \pm 0.005 \cdot 10^{-6}$	$^{+13.2\%}_{-11.2\%}$
i.10*	$e^+e^- \to t\bar{t}t\bar{t}j$	`e+ e- > t t~ t t~ j`	$2.719 \pm 0.005 \cdot 10^{-8}$	$^{+29.9\%}_{-21.3\%}$	$5.338 \pm 0.027 \cdot 10^{-8}$	$^{+18.3\%}_{-15.4\%}$
i.11	$e^+e^- \to b\bar{b}$ (4f)	`e+ e- > b b~`	$9.198 \pm 0.004 \cdot 10^{-2}$	$^{+0.0\%}_{-0.0\%}$	$9.282 \pm 0.031 \cdot 10^{-2}$	$^{+0.0\%}_{-0.0\%}$
i.12	$e^+e^- \to b\bar{b}j$ (4f)	`e+ e- > b b~ j`	$5.029 \pm 0.003 \cdot 10^{-2}$	$^{+9.5\%}_{-8.0\%}$	$4.826 \pm 0.026 \cdot 10^{-2}$	$^{+0.5\%}_{-2.5\%}$
i.13*	$e^+e^- \to b\bar{b}jj$ (4f)	`e+ e- > b b~ j j`	$1.621 \pm 0.001 \cdot 10^{-2}$	$^{+20.0\%}_{-15.3\%}$	$1.817 \pm 0.009 \cdot 10^{-2}$	$^{+0.0\%}_{-3.1\%}$
i.14*	$e^+e^- \to b\bar{b}jjj$ (4f)	`e+ e- > b b~ j j j`	$3.641 \pm 0.009 \cdot 10^{-3}$	$^{+31.4\%}_{-22.1\%}$	$4.936 \pm 0.038 \cdot 10^{-3}$	$^{+4.8\%}_{-8.9\%}$
i.15*	$e^+e^- \to b\bar{b}b\bar{b}$ (4f)	`e+ e- > b b~ b b~`	$1.644 \pm 0.003 \cdot 10^{-4}$	$^{+19.9\%}_{-15.3\%}$	$3.601 \pm 0.017 \cdot 10^{-4}$	$^{+15.2\%}_{-12.5\%}$
i.16*	$e^+e^- \to b\bar{b}b\bar{b}j$ (4f)	`e+ e- > b b~ b b~ j`	$7.660 \pm 0.022 \cdot 10^{-5}$	$^{+31.3\%}_{-22.0\%}$	$1.537 \pm 0.011 \cdot 10^{-4}$	$^{+17.9\%}_{-15.3\%}$
i.17*	$e^+e^- \to t\bar{t}b\bar{b}$ (4f)	`e+ e- > t t~ b b~`	$1.819 \pm 0.003 \cdot 10^{-4}$	$^{+19.5\%}_{-15.0\%}$	$2.923 \pm 0.011 \cdot 10^{-4}$	$^{+9.2\%}_{-8.9\%}$
i.18*	$e^+e^- \to t\bar{t}b\bar{b}j$ (4f)	`e+ e- > t t~ b b~ j`	$4.045 \pm 0.011 \cdot 10^{-5}$	$^{+30.5\%}_{-21.6\%}$	$7.049 \pm 0.052 \cdot 10^{-5}$	$^{+13.7\%}_{-13.1\%}$

Two breakthrough ideas

Aim: NLO loop integral without doing the integration

1) "... we show how to use generalized unitarity to read off the (box) coefficients. The generalized cuts we use are quadrupole cuts ..."

NB: non-zero because cut gives complex momenta



Britto, Cachazo, Feng '04

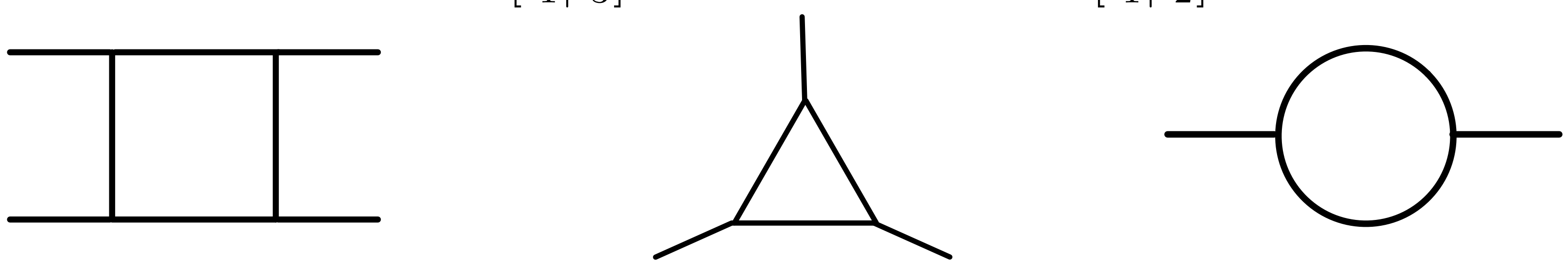
Quadrupole cuts: 4 on-shell conditions on 4 dimensional loop momentum) freezes the integration. But rational part of the amplitude, coming from D=4-2ε not 4, computed separately

Two breakthrough ideas

Aim: NLO loop integral without doing the integration

2) The OPP method: “We show how to extract the coefficients of 4-, 3-, 2- and 1-point one-loop scalar integrals....”

$$\mathcal{A}_N = \sum_{[i_1|i_4]} \left(d_{i_1 i_2 i_3 i_4}\ I^{(D)}_{i_1 i_2 i_3 i_4} \right) + \sum_{[i_1|i_3]} \left(c_{i_1 i_2 i_3}\ I^{(D)}_{i_1 i_2 i_3} \right) + \sum_{[i_1|i_2]} \left(b_{i_1 i_2}\ I^{(D)}_{i_1 i_2} \right) + \mathcal{R}$$



Ossola, Pittau, Papadopolous ’06

Coefficients can be determined by solving a purely algebraic system of equations

Modern higher-orders

- Unitarity methods very successful at one-loop

- the richness of factorization

$$i\,(-i) = 1$$

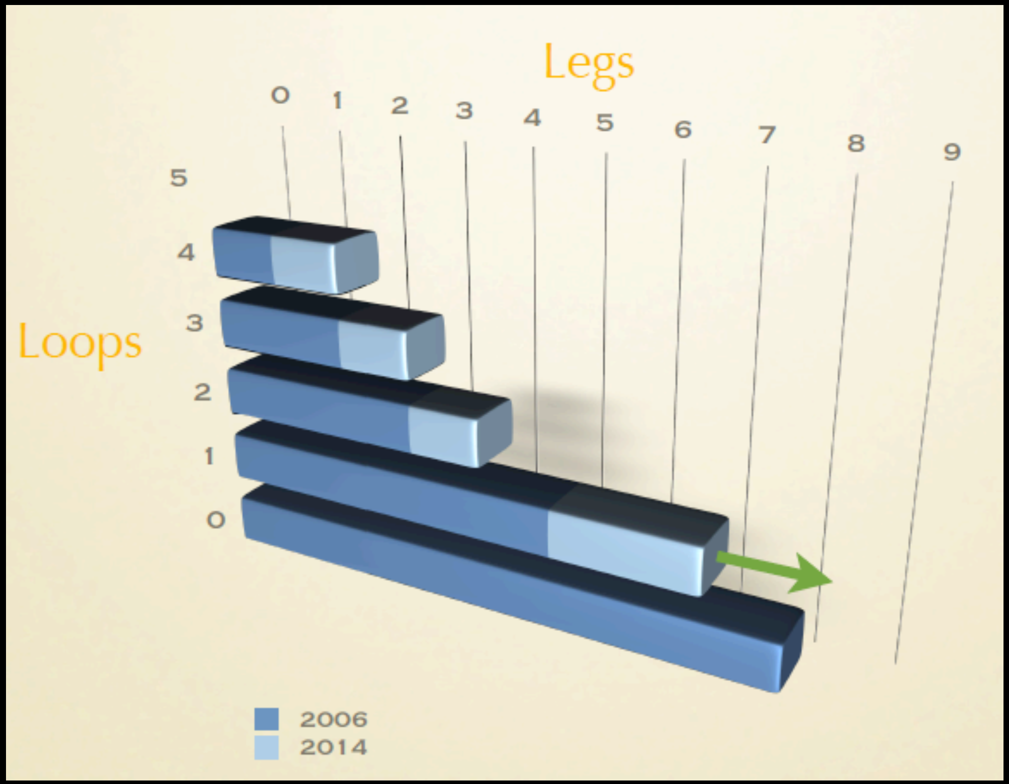
$$(p^2 - m^2) = (\not{p} - m)(\not{p} + m)$$

- the power of unitarity

$$\sum_n |\psi_n\rangle\langle\psi_n| = \mathbb{1}$$

$$-g^{\mu\nu} + \frac{k^\mu q^\nu + k^\nu q^\mu}{(k\cdot q)} \rightarrow \sum_{\text{polarization}-\lambda} \epsilon^\mu_\lambda(k)\left(\epsilon^\nu_\lambda(k)\right)^*$$

$$(\not{p} + m) \rightarrow \sum_{\text{spin}-s} u_s(p)\,\bar{u}_s(p)$$



<u>Future directions:</u>

- one-loop: automated analytic result
- two and multi-loop: internal masses, more legs ...

NLO QCD & EW

Kallweit et al '14

Application to QCD & EW corrections to (onshell) W+1,2,3 jet production in OPENLOOPS, MUNICH and SHERPA

NLO EW corrections technically much more complicated then just NLO QCD, involves lots of subtleties ...

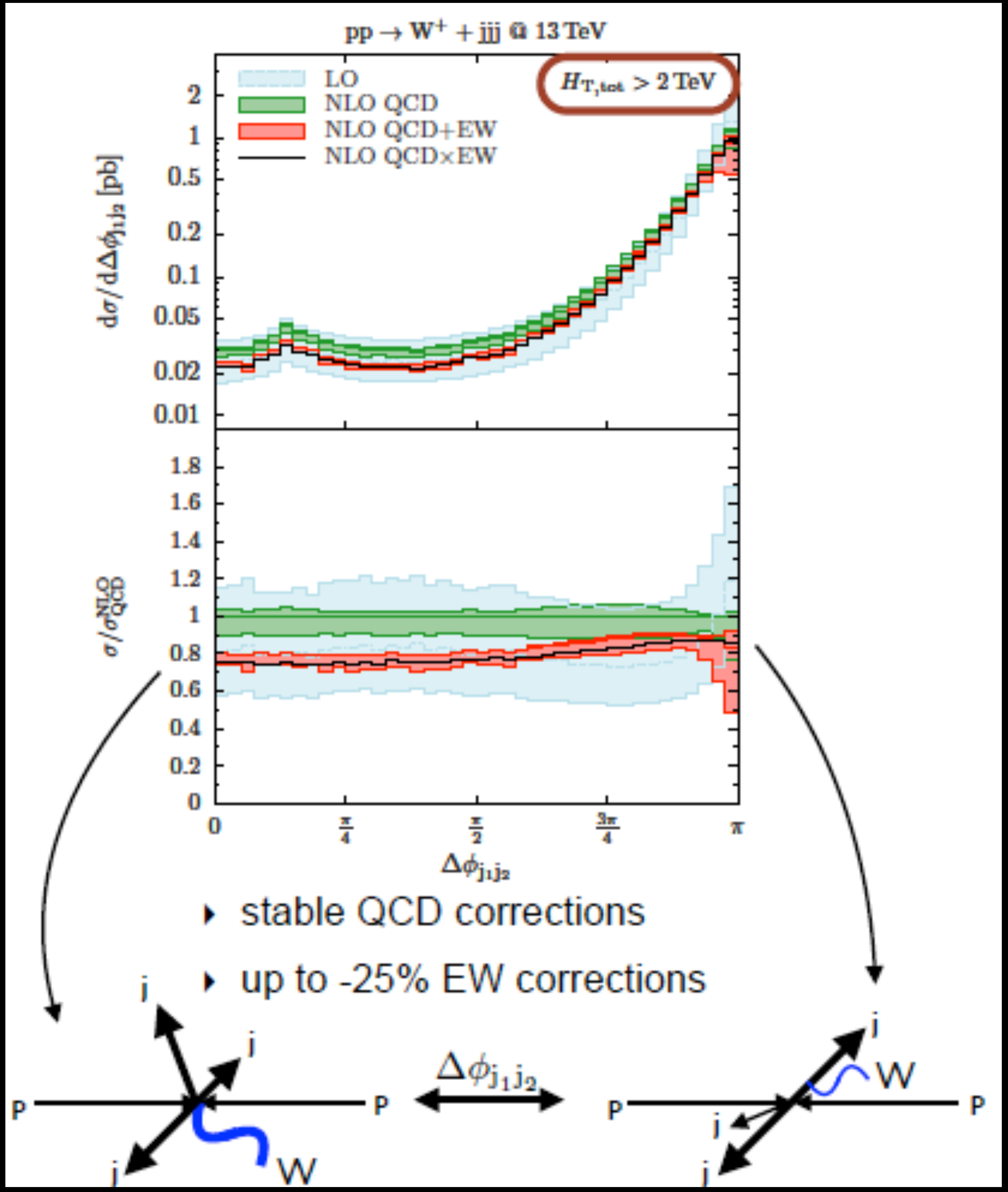
Main message: EW corrections important in TeV region (all order Sudakov effects should be also included). Very rich phenomenology (non-trivial dependence on jet multiplicity)

Key role for tests of SM and BSM searches based on signatures with jets, lepton and MET

NLO QCD & EW

Kallweit et al '14

Just one example...



NNLO

Lots of theoretical work in several (competing) teams [...]

- Two-loop $2 \to 2$ amplitudes: massless ($\gamma\gamma$, di-jets) amplitudes computed 13-15 years ago [Anastasiou et al. '00-'02], still many years to get full NNLO results
- Massive two-loop amplitudes (e.g. for VV) much more difficult, but groundbreaking technique based on differential equations for integrals found recently by [Henn in '13]. Two-loop amplitudes for generic $2 \to 2$ now feasible
- Not the end of the story: need 1-loop graphs squared, one-loop with one real, two real emissions + canceling out all IR divergences.
- Currently, various methods to carry out cancelation exist (q_T subtraction, antenna subtraction, sector decomposition, extension of Frixione-Kunszt-Signer method to NNLO ...)

  these methods are now giving first results for LHC processes

LHC processes at NNLO

More and more $2 \to 2$ processes at the LHC fully known at NNLO

- Di-boson processes ($\gamma\gamma$, ZZ, WW, VH, Wγ)
- single top
- top-pair production
- H+1jet, W+1jet

or partially known

- dijets
- Z+1jet

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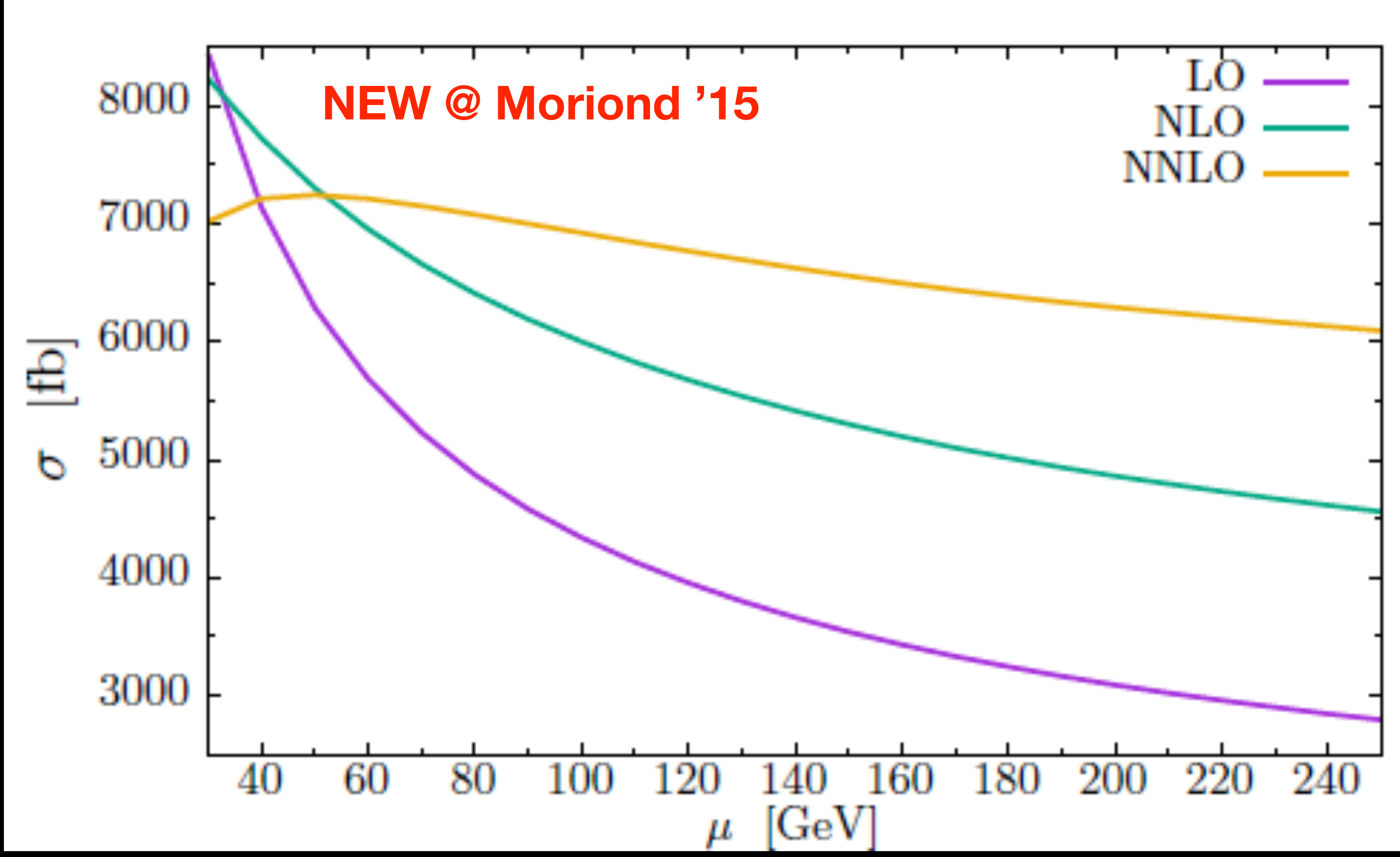
But pressure on releasing a codes (different $p_{t,j}$ cuts, jet-radius, pdf/scale uncertainties, different observables ...)

Recent highlights: H+1jet

Full Higgs + 1 jet cross-section at NNLO: first NNLO calculation of LHC process involving a jet in the final state



$$\sigma_{\mathrm{LO}} = 3.9^{+1.7}_{-1.1}\ \mathrm{pb}$$

$$\sigma_{\mathrm{NLO}} = 5.6^{+1.3}_{-1.1}\ \mathrm{pb}$$

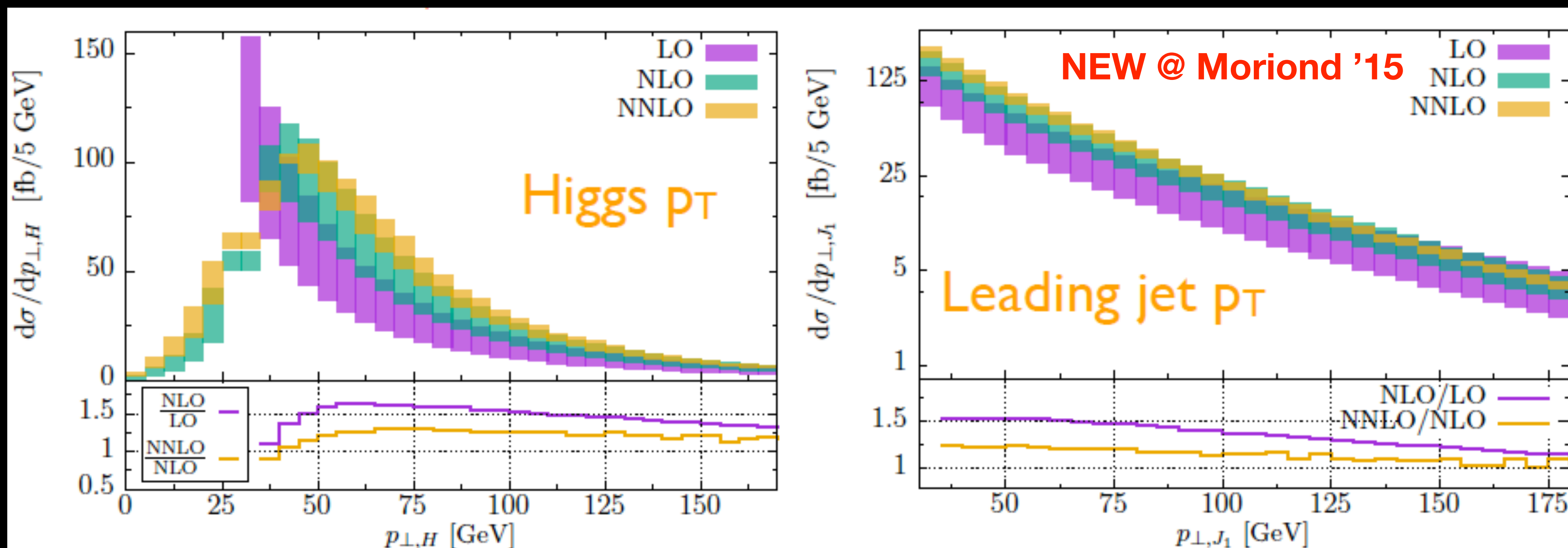
$$\sigma_{\mathrm{NNLO}} = 6.7^{+0.5}_{-0.6}\ \mathrm{pb}$$

$$K_{\mathrm{NNLO}} \sim 20\%$$

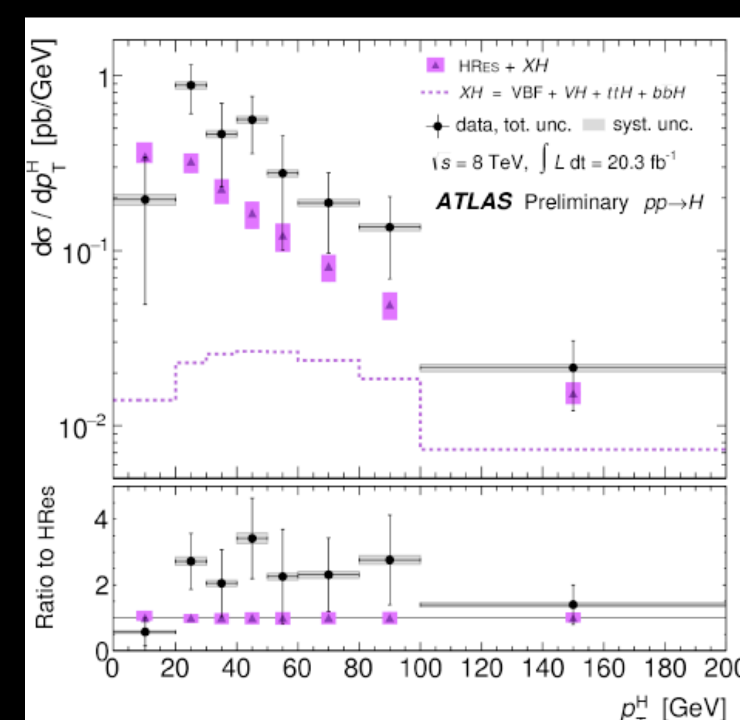
$$\delta_{\mathrm{PDF}} \sim 5\%$$

Sizable corrections. Significantly improved scale dependence.

Recent highlights: H+1jet



- Distributions for Higgs + 1 jet at NNLO also under control
- Good control of p_t spectra required soon



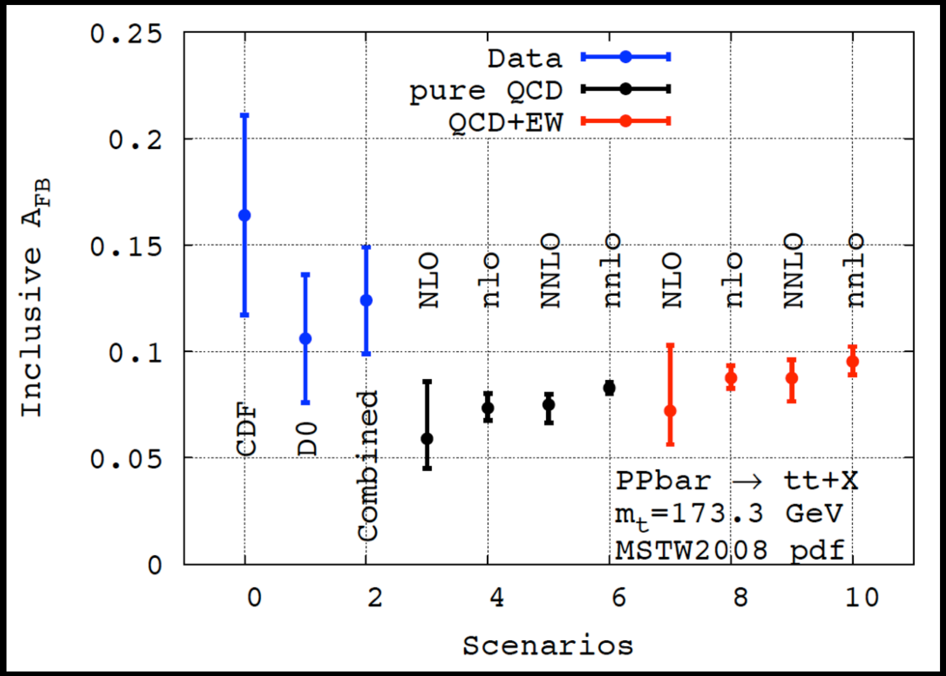
Tevatron FB top asymmetry

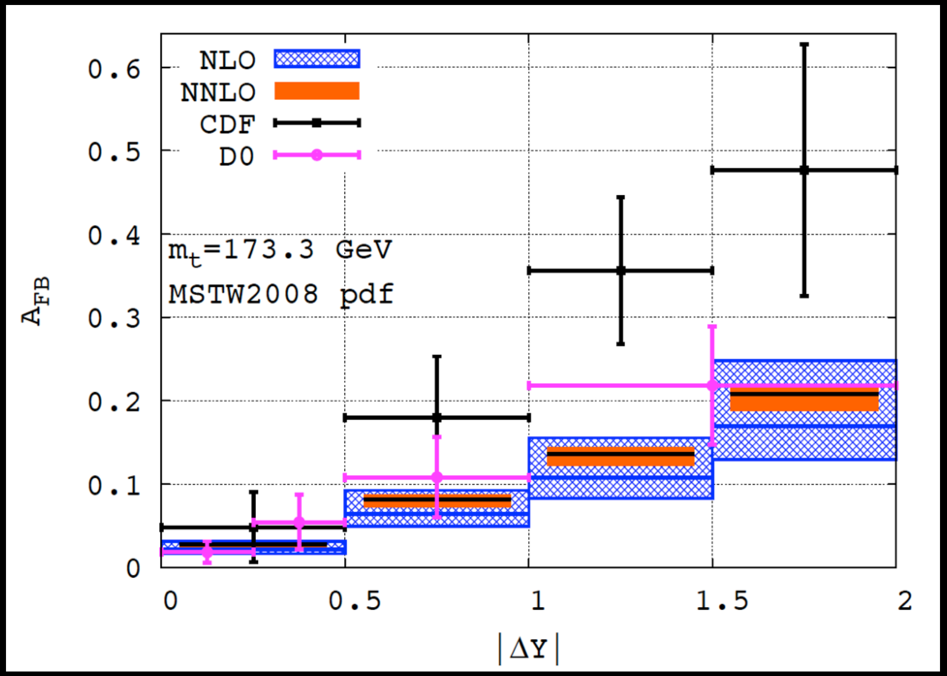
Czakon, Fiedler, Mitov '14

- long-standing tension between SM predictions and Tevatron measurements of the forward-backward asymmetry
- lots of tentative BSM explanations in the past [...]
- recently theory prediction upgraded with full NNLO corrections
  - limitation: stable tops (i.e. inclusive in decay)
  - ambiguities: A_{FB} is a ratio. Expand it (nnlo) or not (NNLO)? how to combine EW and QCD corrections?

Tevatron FB top asymmetry

Czakon, Fiedler, Mitov ’14





perfect agreement with D0, 1.5σ below CDF measurements

<u>Future:</u> use completely new software based on four-dimensional formulation of subtraction scheme ⇒ STRIPPER

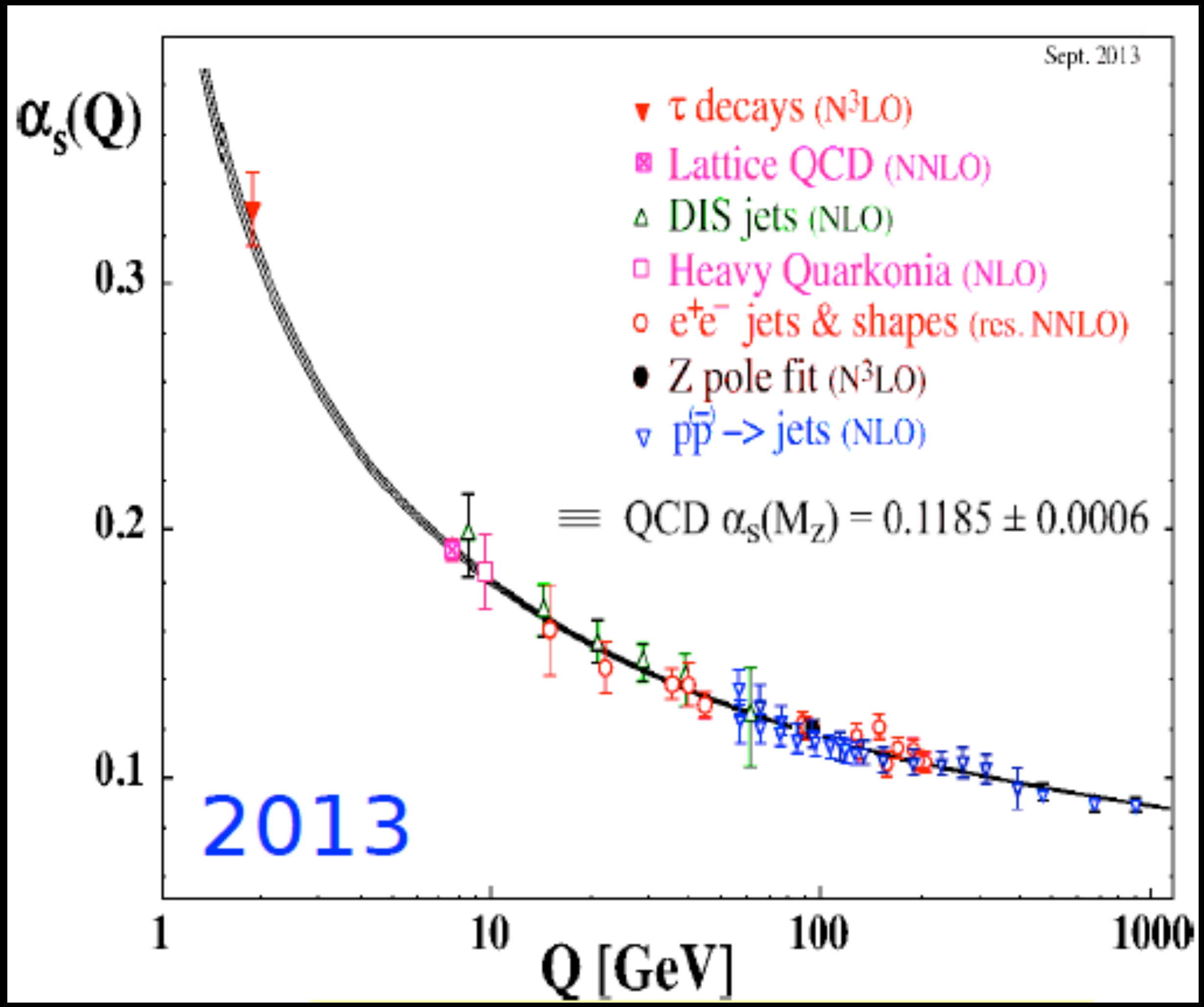
Fit of α_s

- α_s least precise known of all couplings (0.5-1%?)
- impacts all LHC cross-sections
- key for SM precision fits + relevant in BSM (couplings at GUT)

World average:

$$\alpha_s(M_Z) \sim 0.1185 \pm 0.0006$$

- average currently dominated by lattice results
- possible improvement e.g. from di-jets or V+jet at NNLO

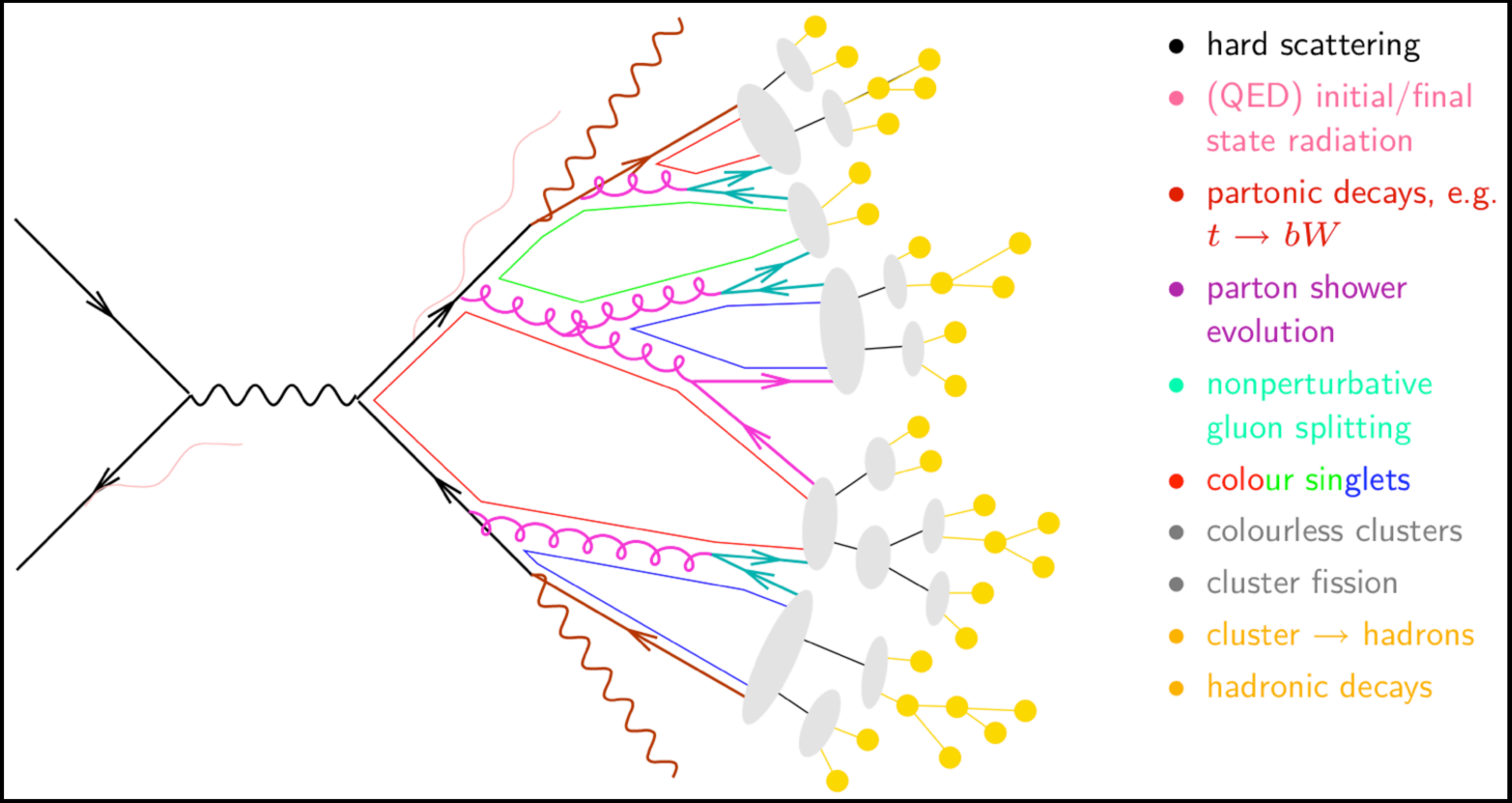


Summary on NNLO

- after 15 years of efforts, lots of results begin delivered now
- main message: NNLO technology getting ready to cope with LHC demands
- the role of NNLO can not be understated. In view of often large NLO corrections for hadronic processes, NNLO result gives us confidence that we are not dealing with an asymptotic expansions that are diverging already at the first terms ...

NLO + parton showers

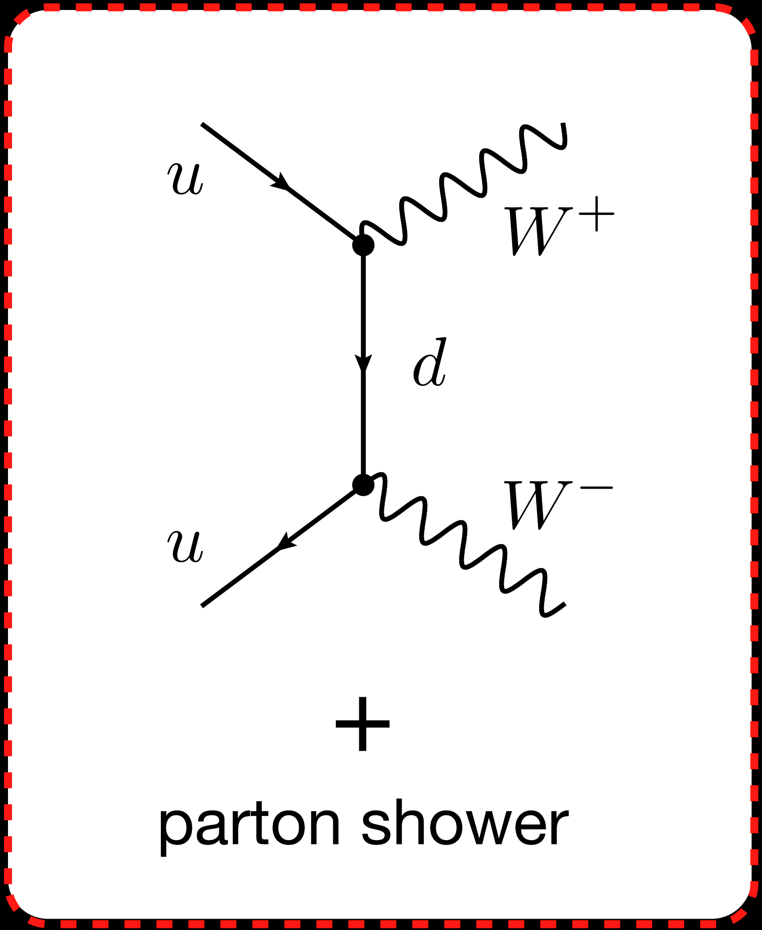
- Parton Shower Monte Carlo simulate hadronic production processes merging together an approximate perturbative part (the shower) and a non-perturbative model for hadron formation



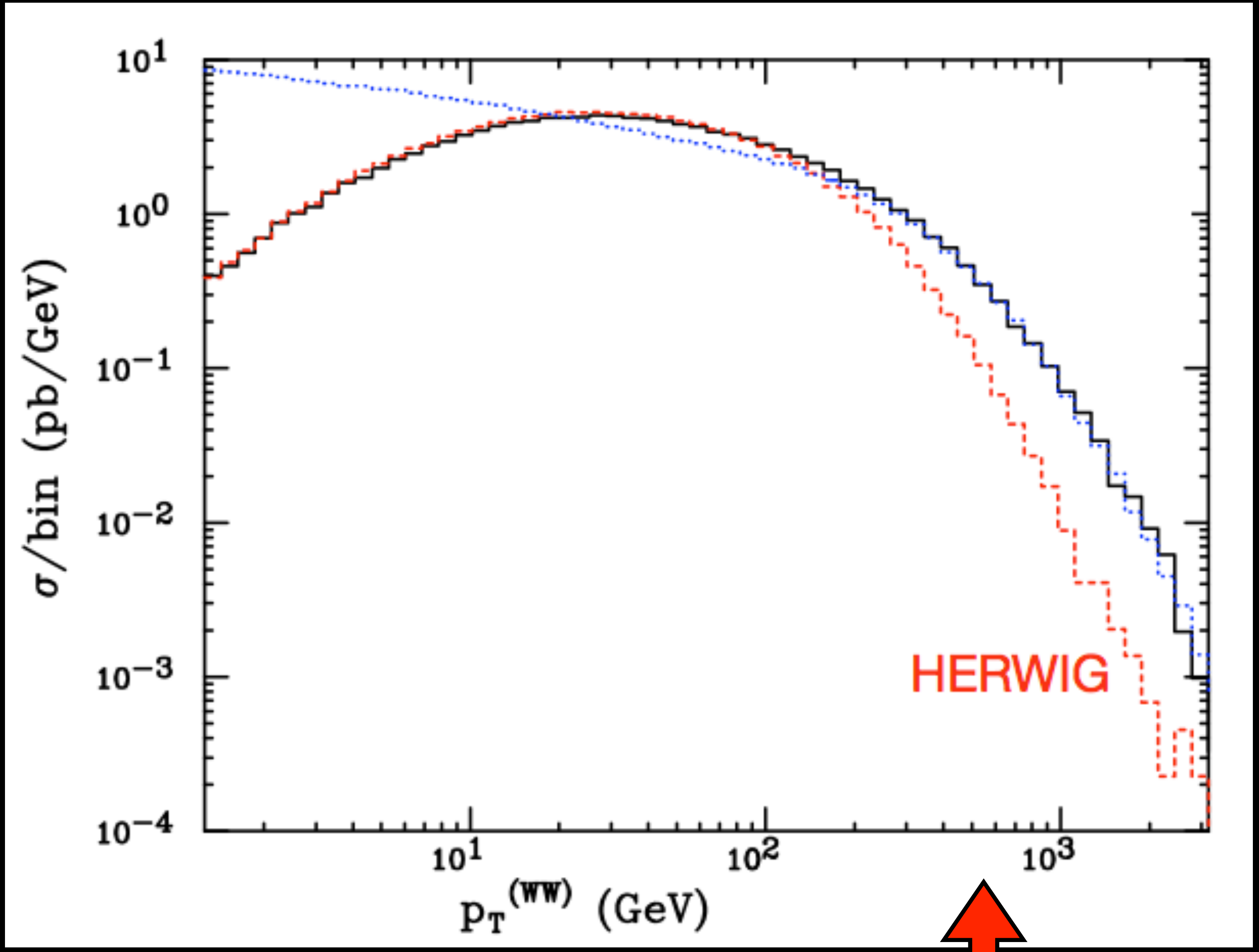
NLO + parton showers

- Parton Shower Monte Carlo simulate hadronic production processes merging together an approximate perturbative part (the shower) and a non-perturbative model for hadron formation
- the shower typically uses QCD evolution equations that rely on the soft-collinear approximation of QCD amplitudes
- pure parton showers: poor control on normalization (cross-sections), bad description of hard radiation
- NLO+PS achieved almost 10 years ago (POWHEG, MC@NLO): difficult because need to avoid double counting
- Today used in all advances LHC analysis

WW: shower only

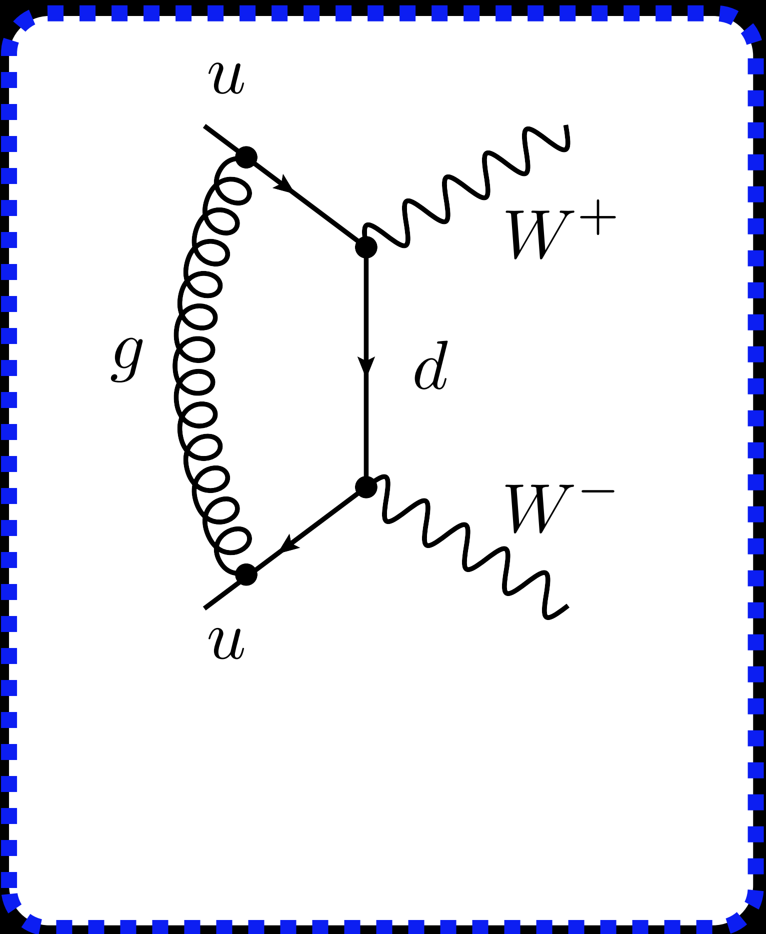


HERWIG

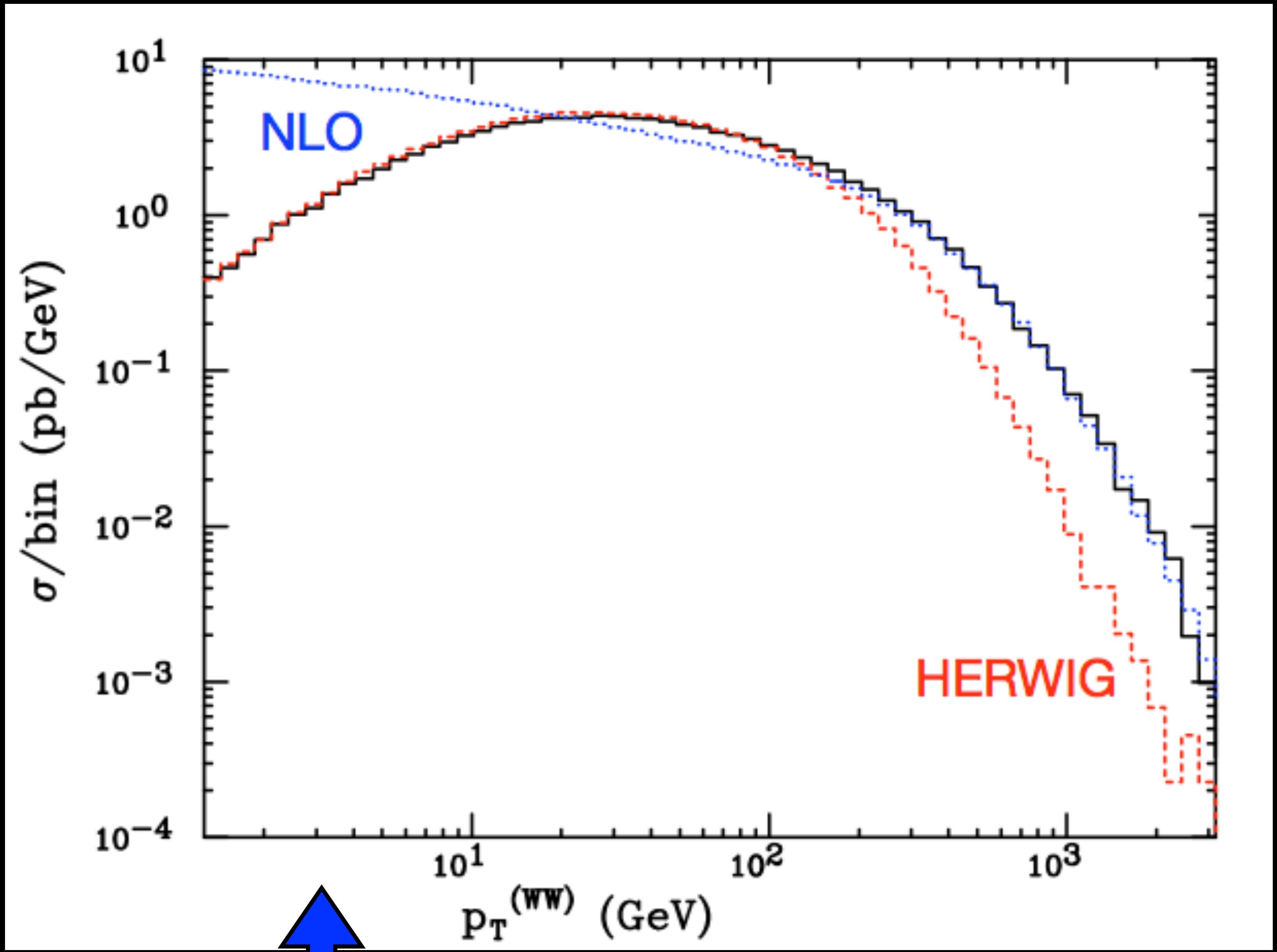


Herwig too soft in the high-p_t region

WW: NLO only

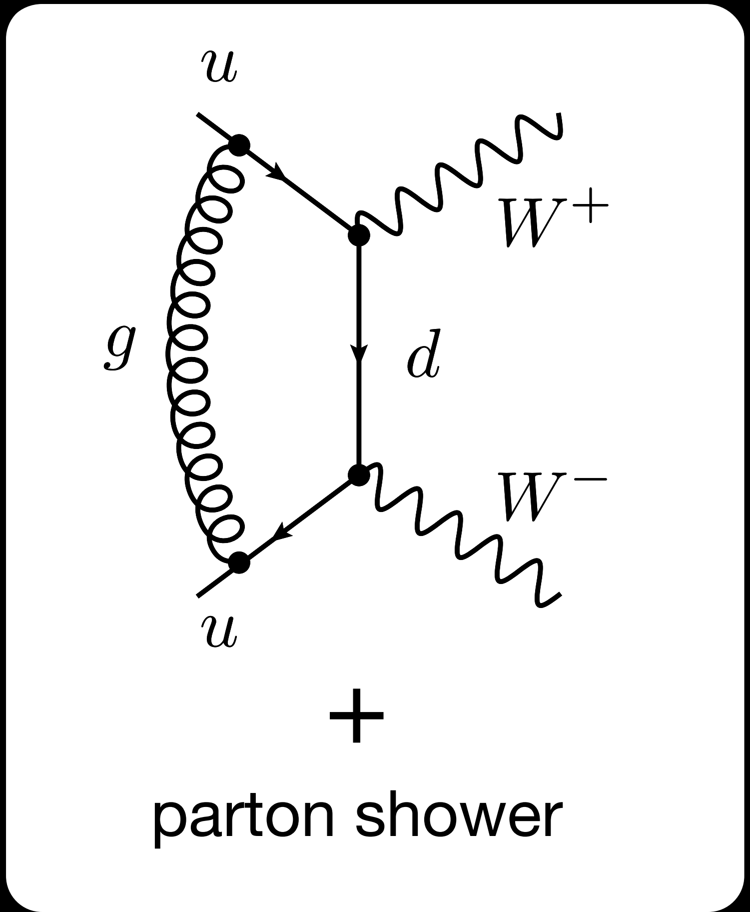


NLO

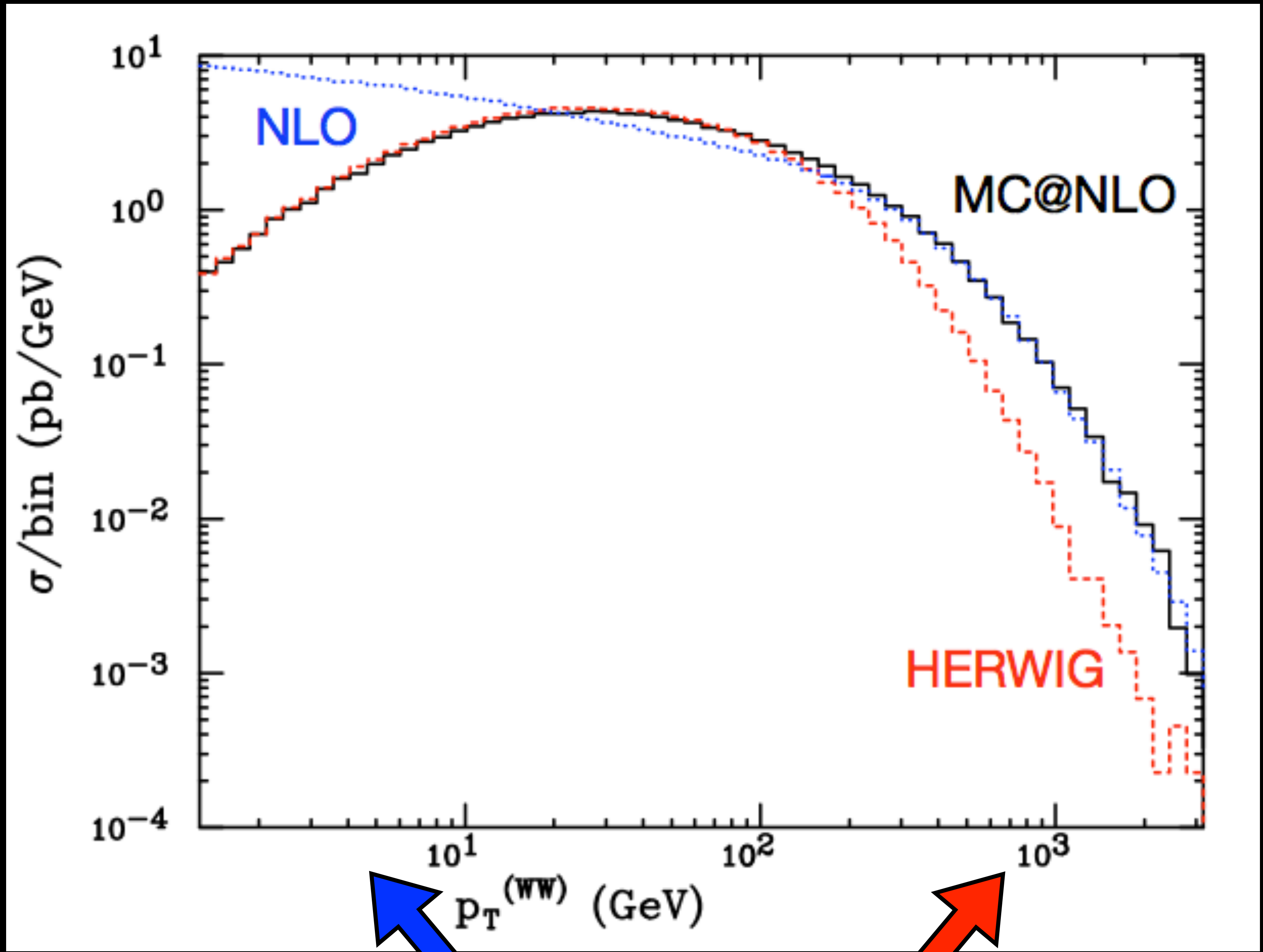


NLO divergent
in the soft region

WW: NLO + parton showers



MC@NLO



MC@NLO correctly interpolates between the two regimes

NNLO + parton shower

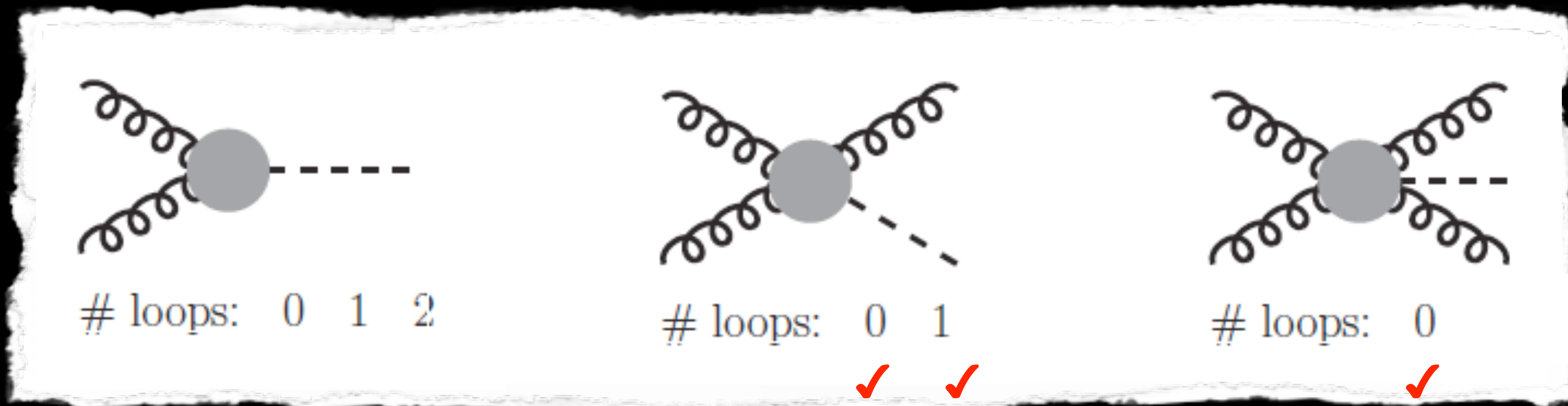
- 2013-15 remarkable years for NNLO calculations
- Progress in NLO went hand in hand with development of NLO+PS
- Natural to aim at NNLO+PS. Particularly important as indirect searches are becoming more prominent (higher mass reach) but involve no peak or resonant structure. Need highest precision.

<u>NNLO + parton shower:</u>

- realistic exclusive description of the final state (including MPI, resummation effects, hadronisation, U.E.) with state-of-the-art perturbative accuracy
- clearly a MUST for the upcoming LHC Higgs physics programme

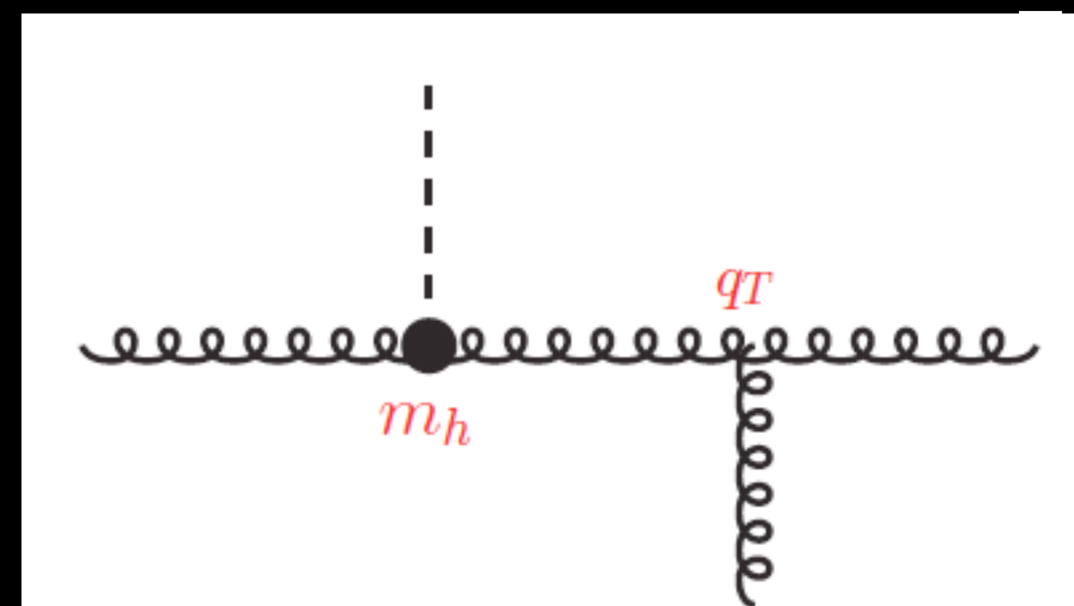
Higgs at NNLO+PS

Ingredients for Higgs at NNLO



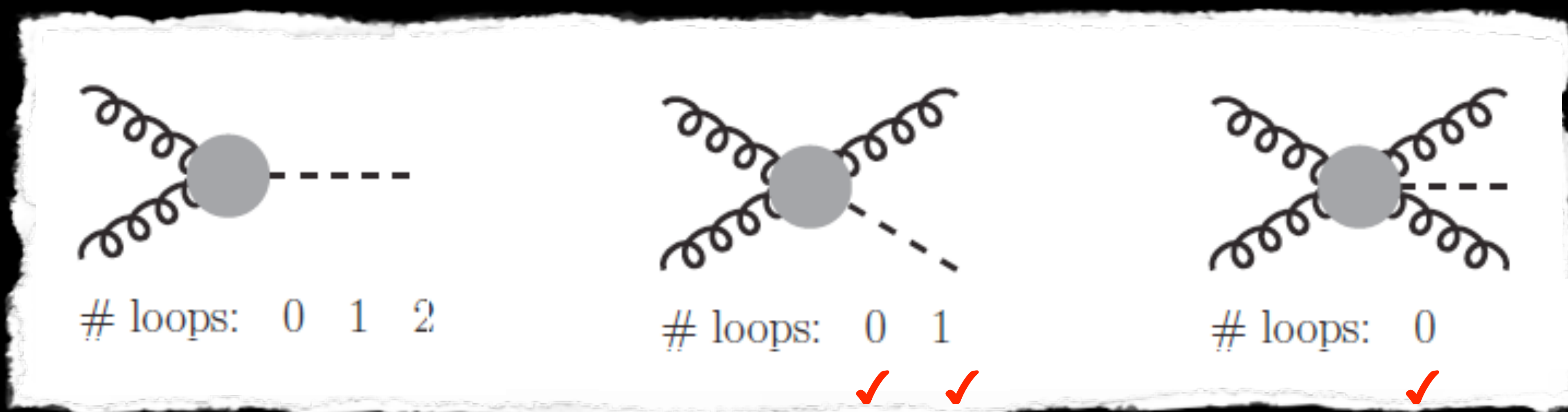
✓ Higgs + 1 jet at NLO in POWHEG

✗ but standard NLO Higgs plus one jet calculation diverges without a transverse momentum cut on the jet



Higgs at NNLO+PS

Ingredients for Higgs at NNLO



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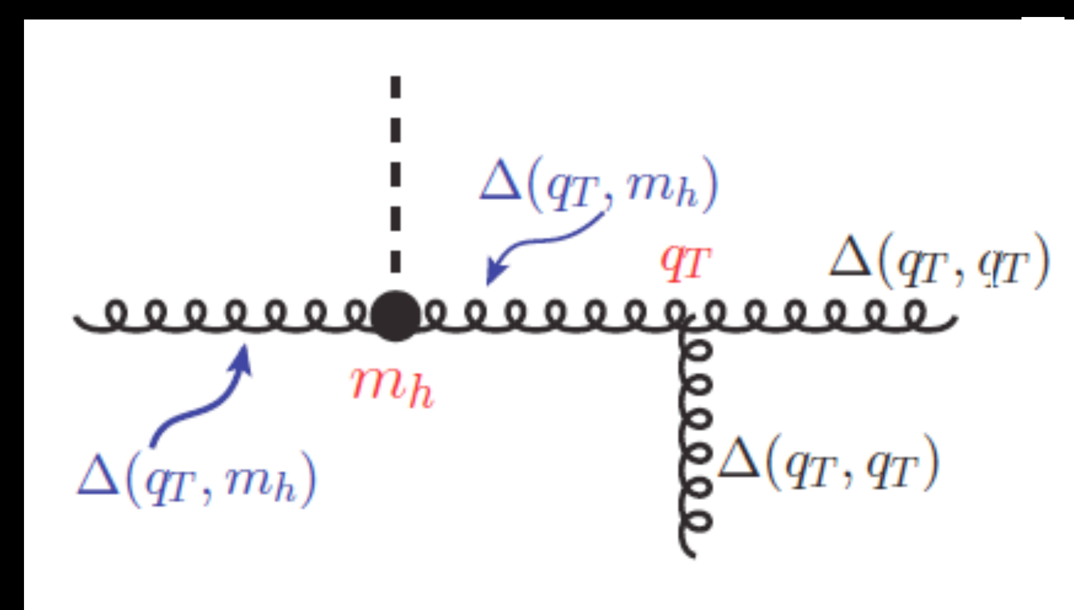
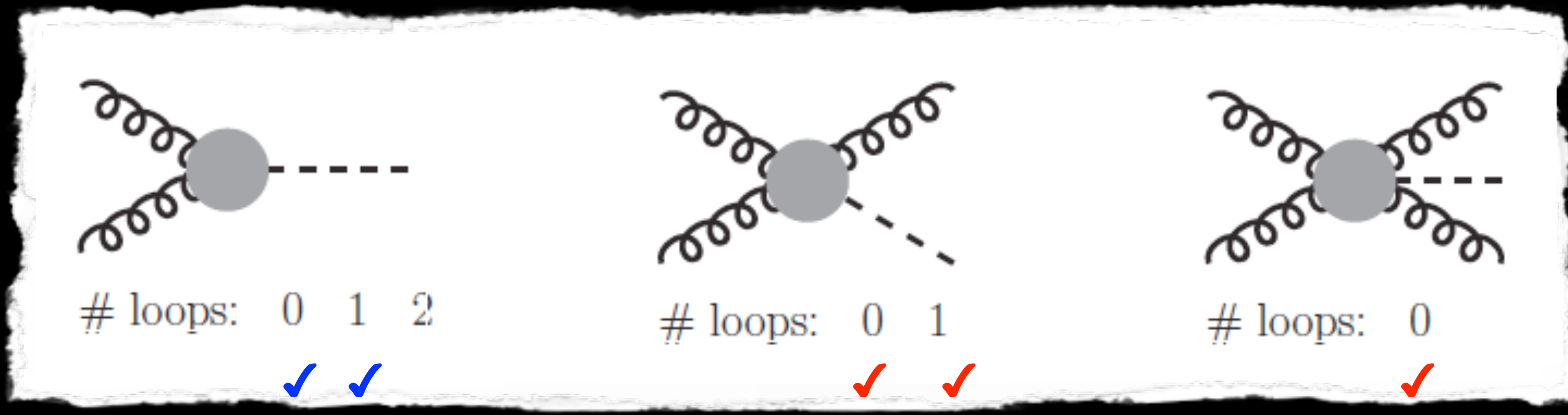


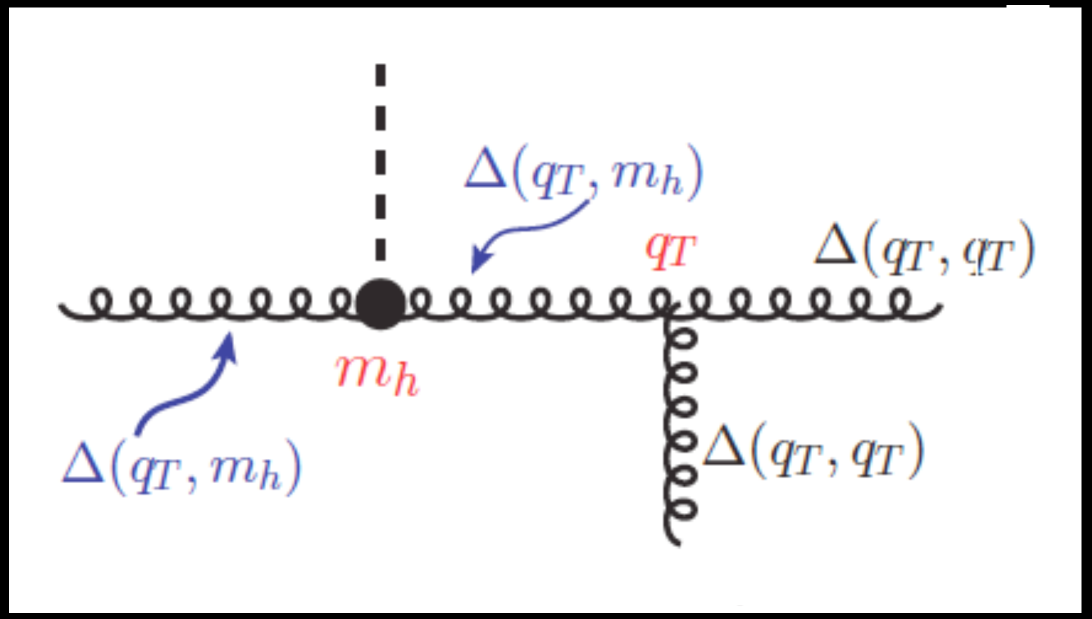
Hamilton et al. 1206.3542

Higgs at NNLO+PS

Ingredients for Higgs at NNLO



- ✓ Higgs + 1 jet at NLO in POWHEG
- ✗ but standard NLO Higgs plus one jet calculation diverges without a transverse momentum cut on the jet
- ✓ MiNLO procedure can be formulated such that the integral is the NLO inclusive Higgs cross-section



Hamilton et al. 1206.3542

Hamilton et al. 1212.4504

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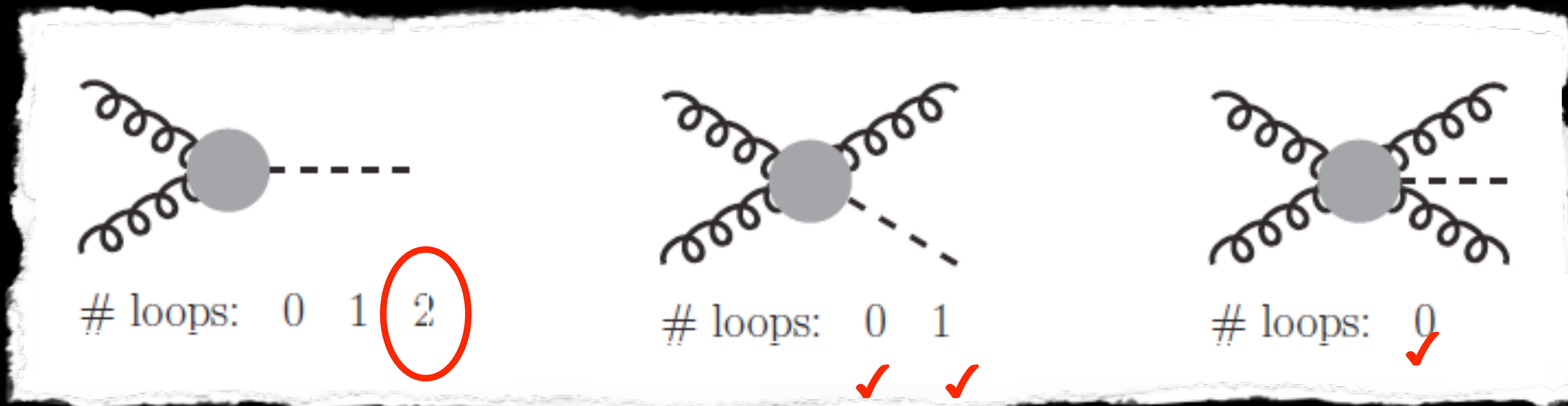
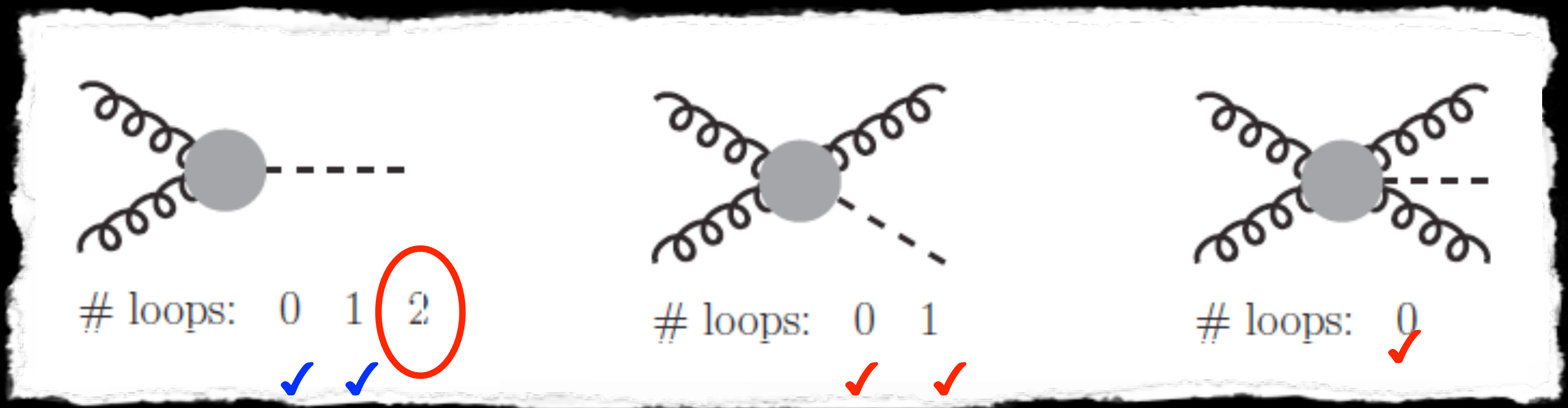
Ingredients for Higgs at NNLO



✗ still missing double virtual contribution

Higgs at NNLO+PS

Ingredients for Higgs at NNLO



✗ still missing double virtual contribution

Higgs at NNLO+PS

In other words: let take

- Higgs at NLO+PS: H-NLOPS
- Higgs + one jet at NLO+PS: HJ-NLOPS
- a merged generator that is NLO+PS for H and HJ: HJ-MiNLO
- Higgs at NNLO+PS: H-NNLOPS

	inclusive H	H+1jet (inclusive)	H+2jets (inclusive)
H-NLOPS	NLO	LO	soft-col. approx
HJ-NLOPS	divergent	NLO	LO
HJ-MiNLO	NLO	NLO	LO
H-NNLOPS	NNLO	NLO	LO

Conclusion: the HJ-MiNLO merged generator almost does the right job

NB: merging achieved by extending the validity of the NLO with a jet down to the region where the jet is unresolved (no merging scale)

Higgs at NNLO+PS

For Higgs production, the Born kinematics is fully specified by the Higgs rapidity. So consider the following distributions:

$$\left(\frac{d\sigma}{dy}\right)_{\mathrm{NNLO}} \longrightarrow$$ inclusive Higgs rapidity computed at NNLO

$$\left(\frac{d\sigma}{dy}\right)_{\mathrm{HJ-MiNLO}} \longrightarrow$$ inclusive Higgs rapidity from H+1jet-MiNLO

Since H+1jet-MiNLO (HJ-MiNLO) is NLO accurate, it follows that

$$\frac{\left(\frac{d\sigma}{dy}\right)_{\mathrm{NNLO}}}{\left(\frac{d\sigma}{dy}\right)_{\mathrm{HJ\text{-}MiNLO}}} = \frac{c_2\alpha_s^2 + c_3\alpha_s^3 + c_4\alpha_s^4}{c_2\alpha_s^2 + c_3\alpha_s^3 + d_4\alpha_s^4} \approx 1 + \frac{c_4 - d_4}{c_2}\alpha_s^2 + \mathcal{O}(\alpha_s^3)$$

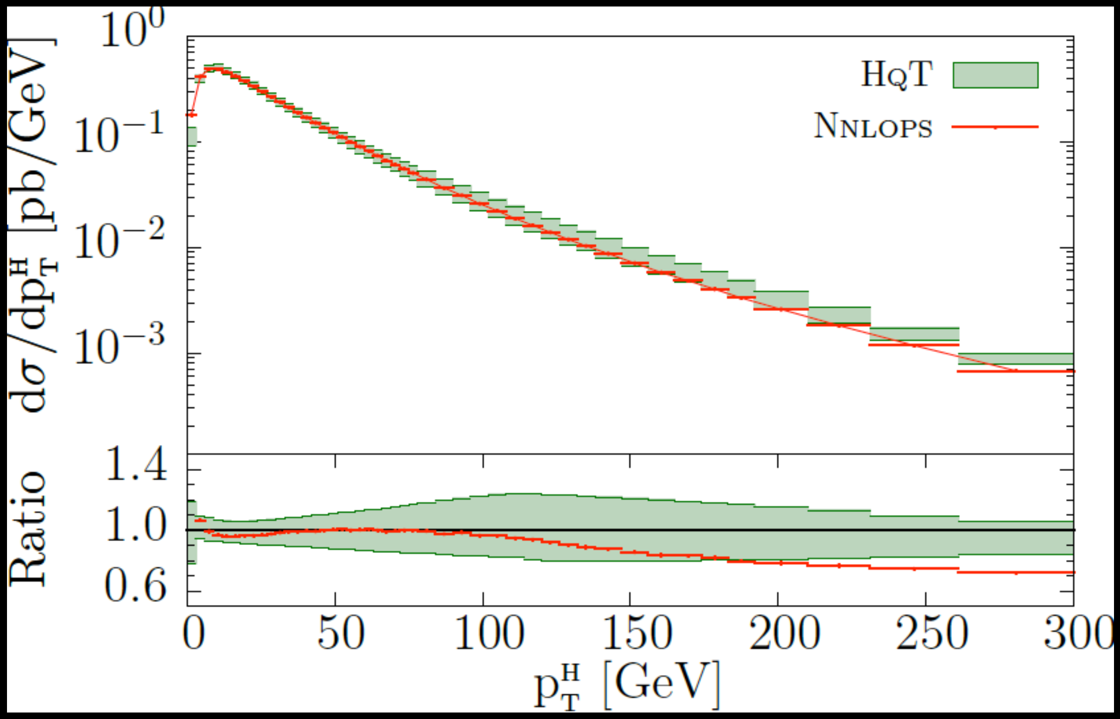
Thus, re-weighing HJ-MiNLO+Pythia results with this factor one obtains NNLO+PS accuracy

Higgs at NNLO+PS

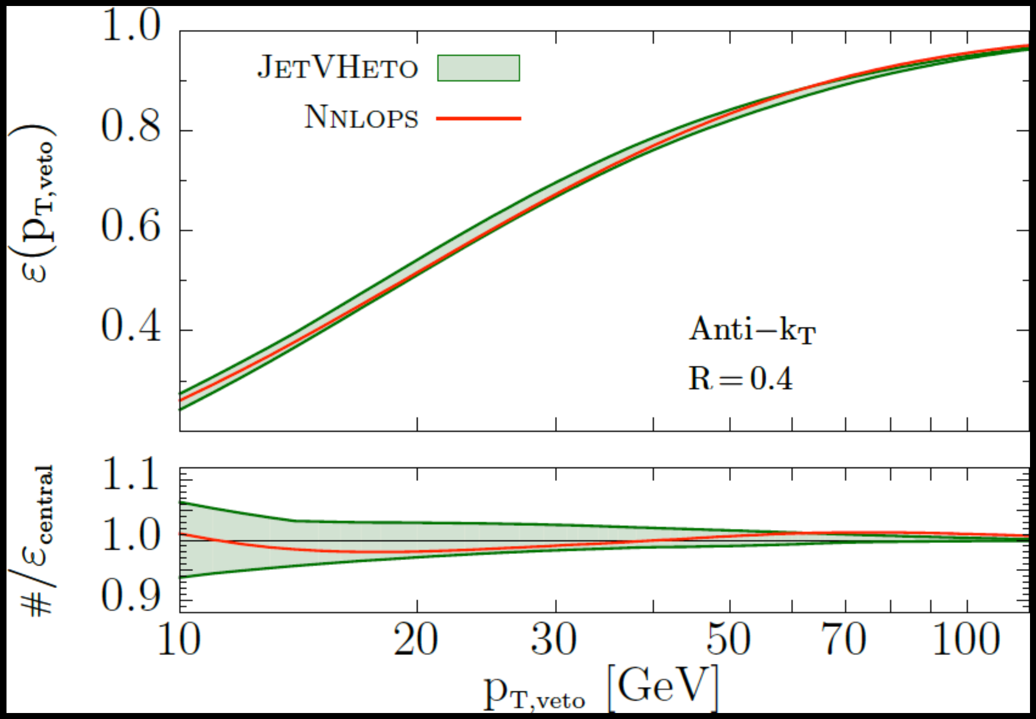
Hamilton et al.'13

First NNLO+PS accurate results for Higgs production

Higgs transverse momentum



Jet transverse momentum



HqT: DeFlorian, Ferrera, Grazzini, Tommasini '11

JetVHeto: Banfi, Monni, Salam, GZ '12

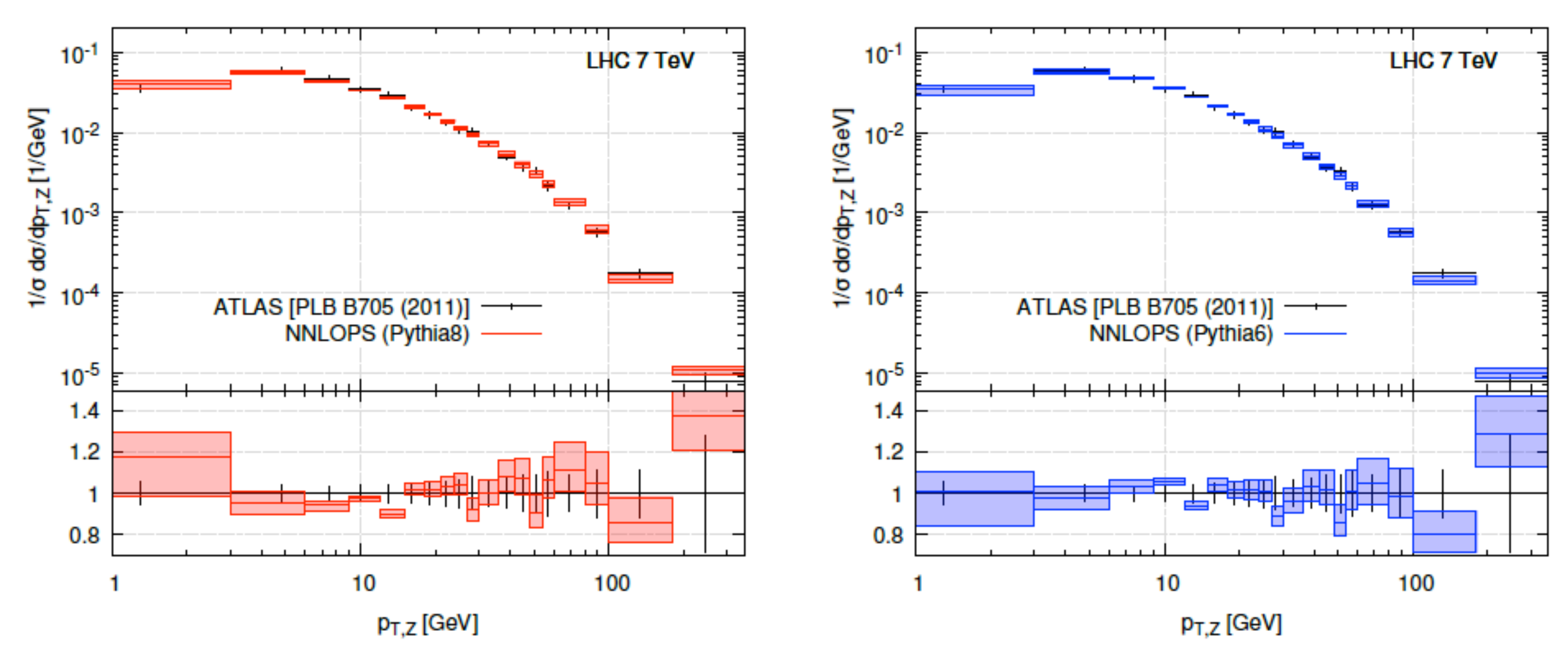
Validation of NNLO+PS in the low p_t region where formally NNLO +PS has lower accuracy

Higgs at NNLO+PS

Karlberg et al. ’14

Method extended recently to Drell Yan (important e.g. for W mass measurement at the LHC)

Comparison to ATLAS data for $p_{t,Z}$

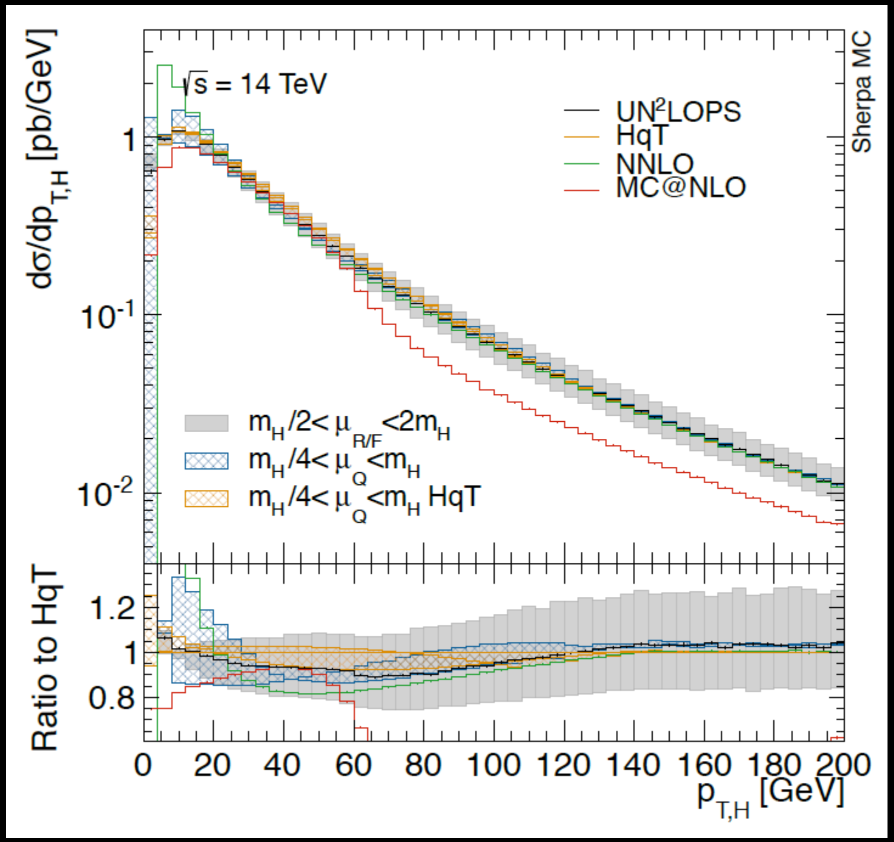


Good agreement, depends on the parton-shower tune

NNLO and parton shower

Hoeche, Li, Prestel '14

Similar results obtained with UNNLOPS method for Drell Yan and Higgs production. Third approach by Geneva collaboration.



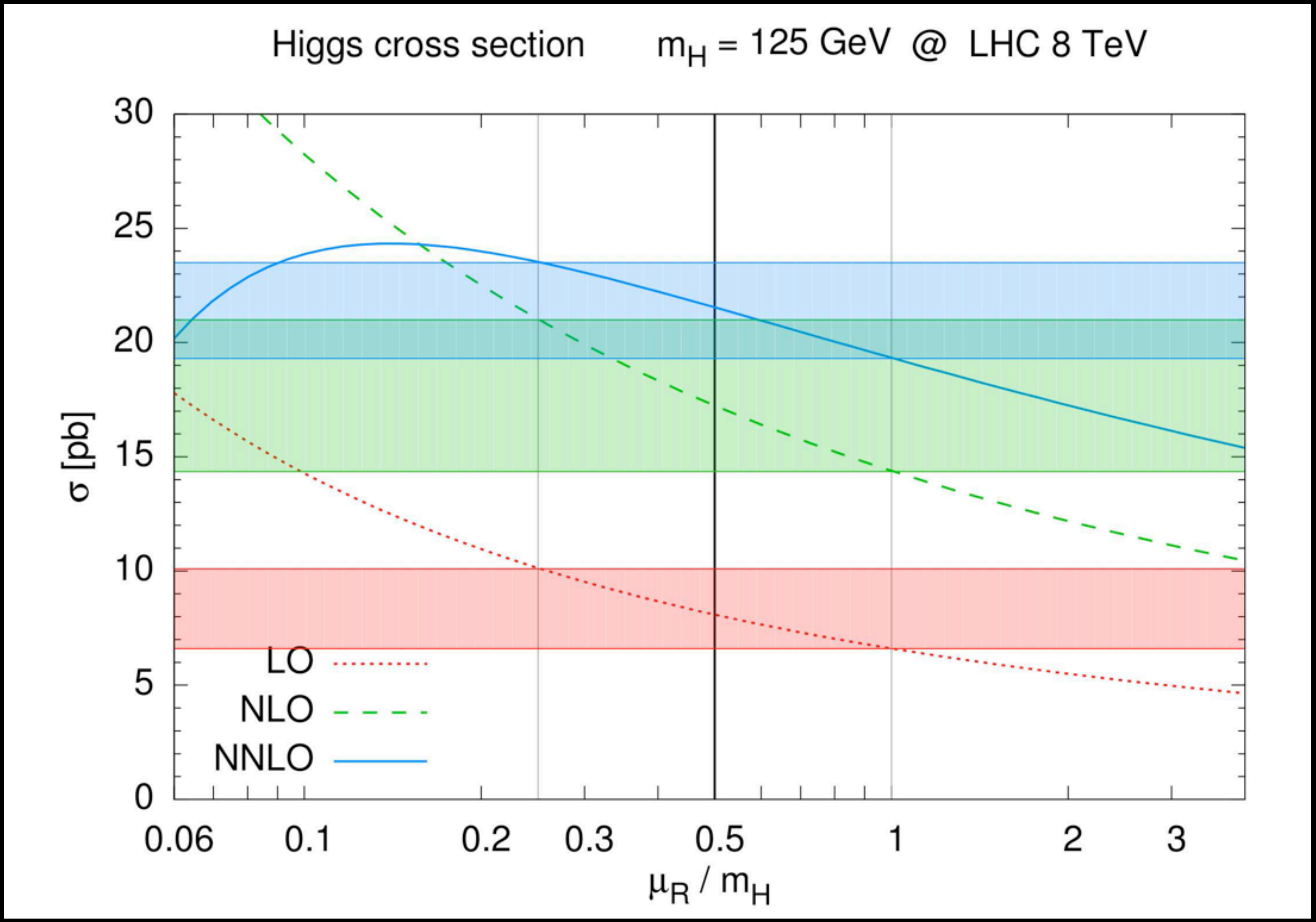
Issue:

"The zero-qT bin is clearly problematic. This can be understood as follows: In our calculation the qT spectrum is described only at NLO+NLL accuracy [24, 46]. Therefore it suffers from large scale variations, particularly in the soft and collinear region."

Whatever the method, not trivial to extend this to more complicated processes ...

Inclusive Higgs production

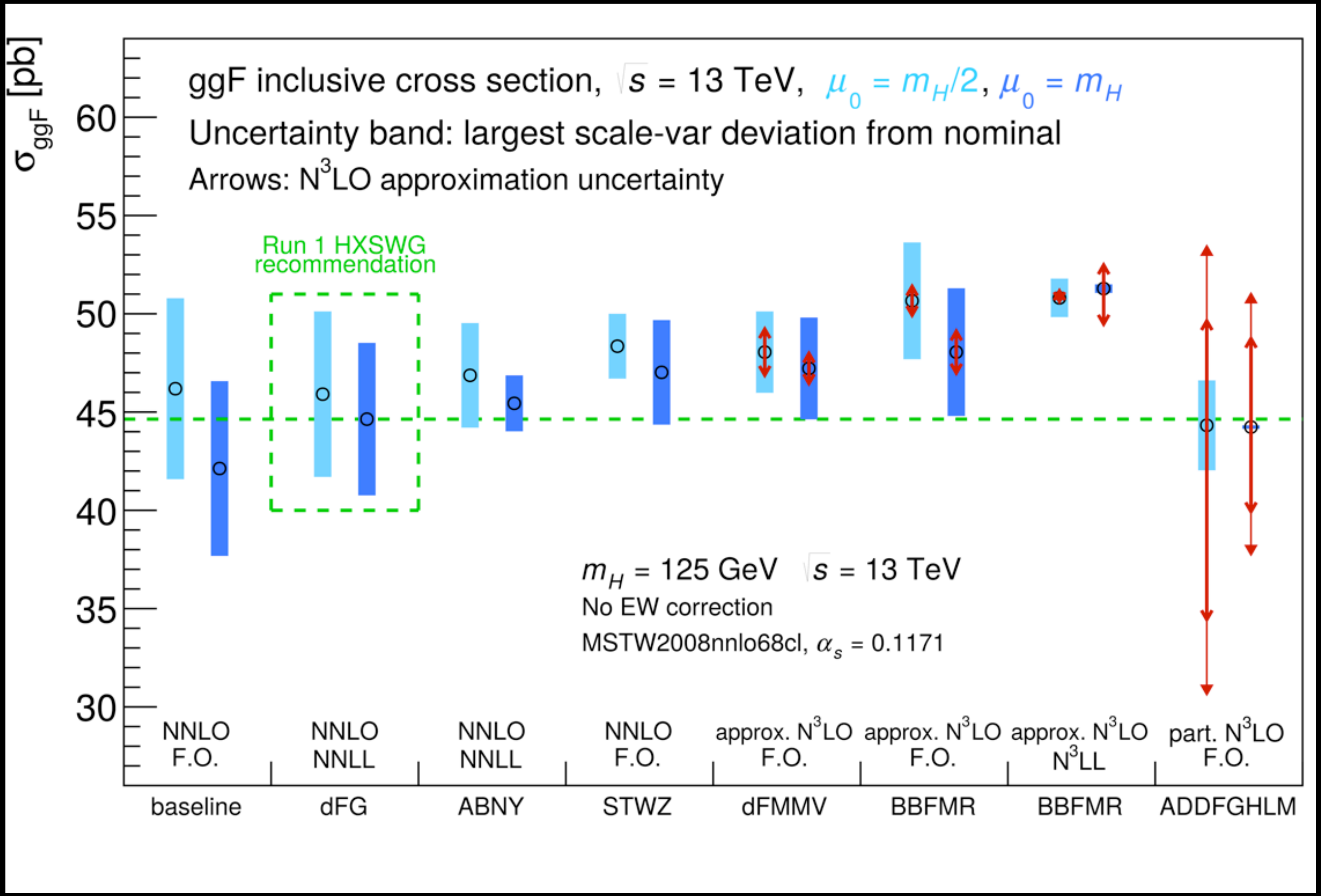
from General Assembly Higgs Cross Section Working Group Jan. 2015



- perturbative series for gg → H converges very slowly
- renormalization scale variation (commonly used to estimate theory uncertainty) underestimates the shift to the next order

Why Higgs @ N^3LO

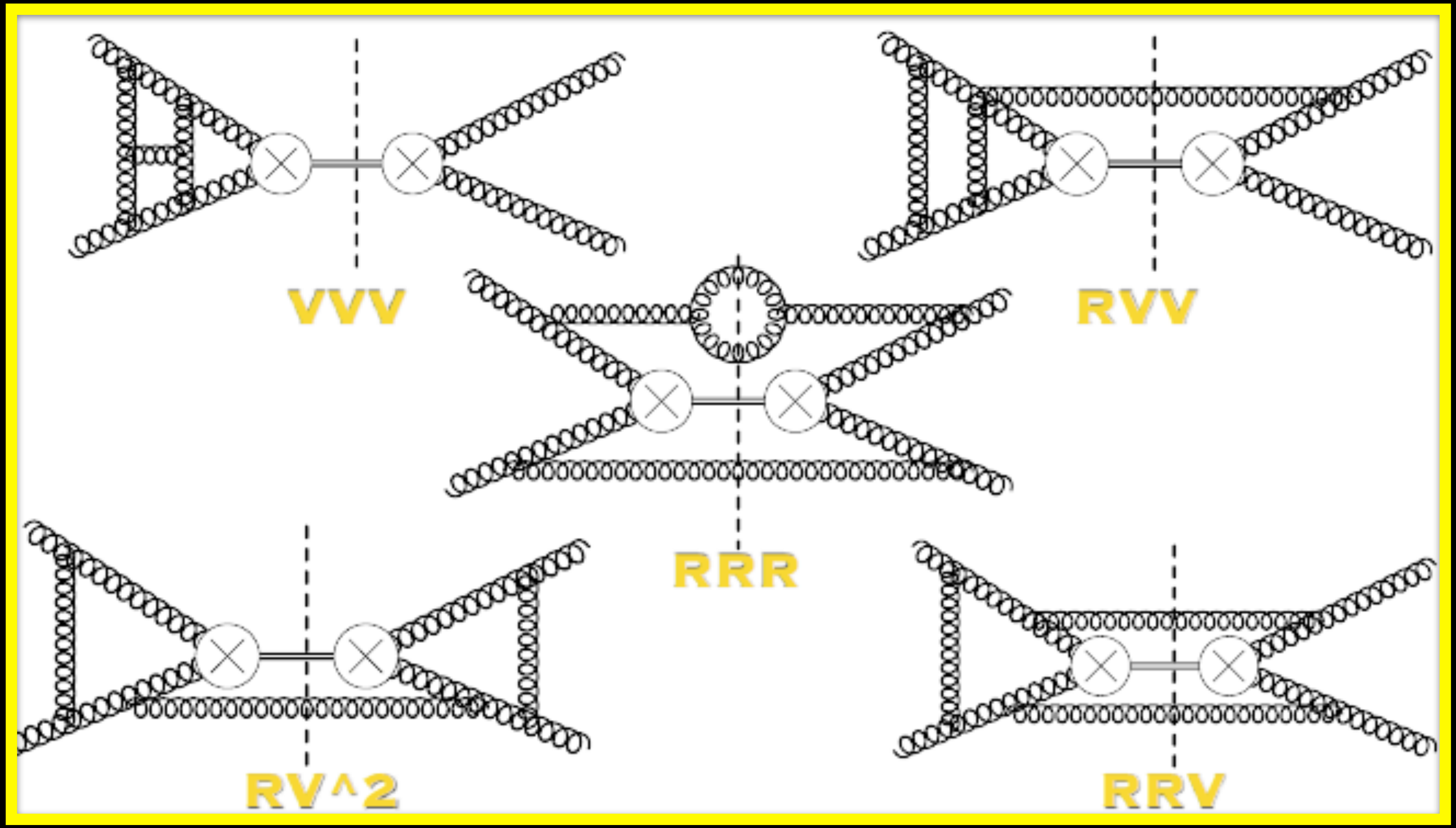
from General Assembly Higgs Cross Section Working Group Jan. 2015



Amount of perturbative control on the cross-section has direct impact on range of New Physics searches in Higgs sector + theory breakthrough

Few facts about N^3LO

- O(100000) interference diagrams (1000 at NNLO)
- 68273802 loop and phase space integrals (47000 at NNLO)
- about 1000 master integrals (26 at NNLO)



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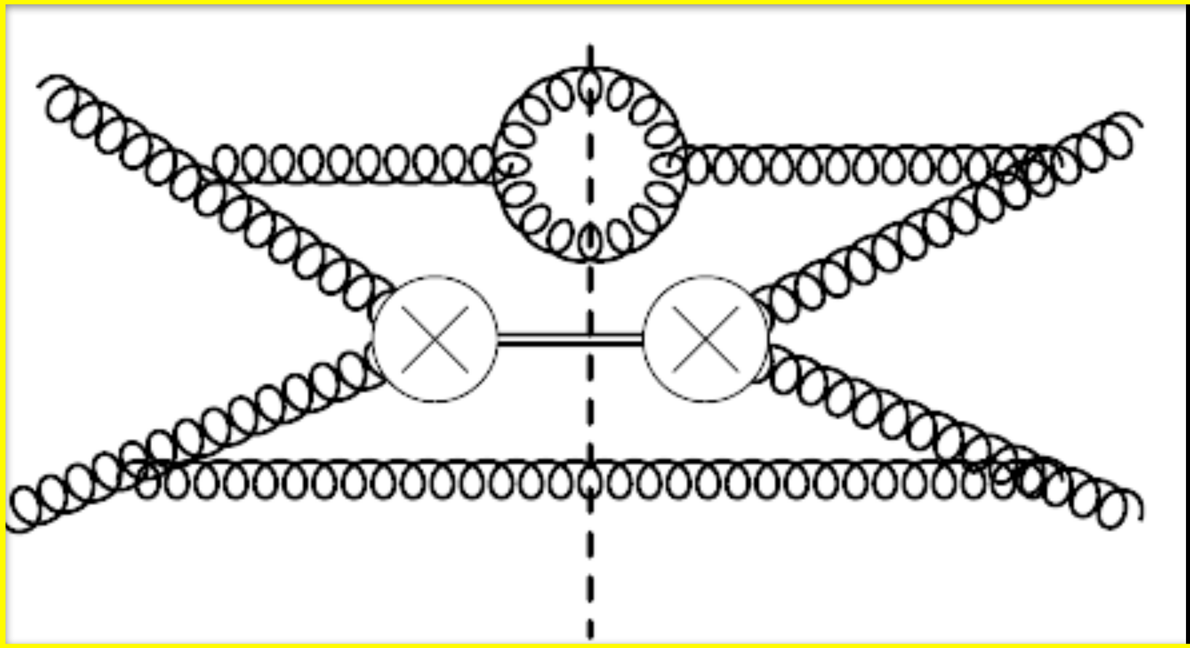

+ 68273801 integrals

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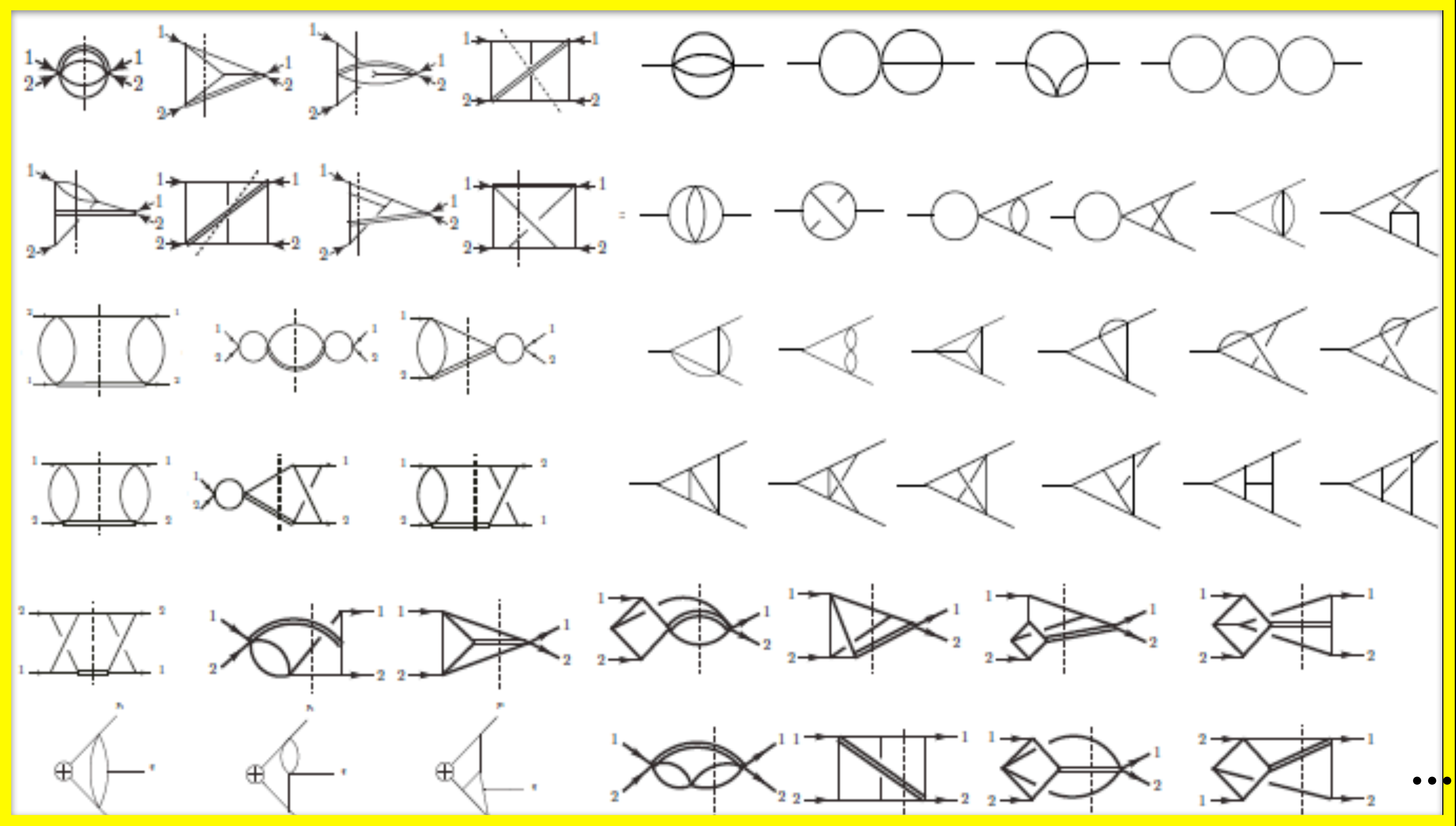
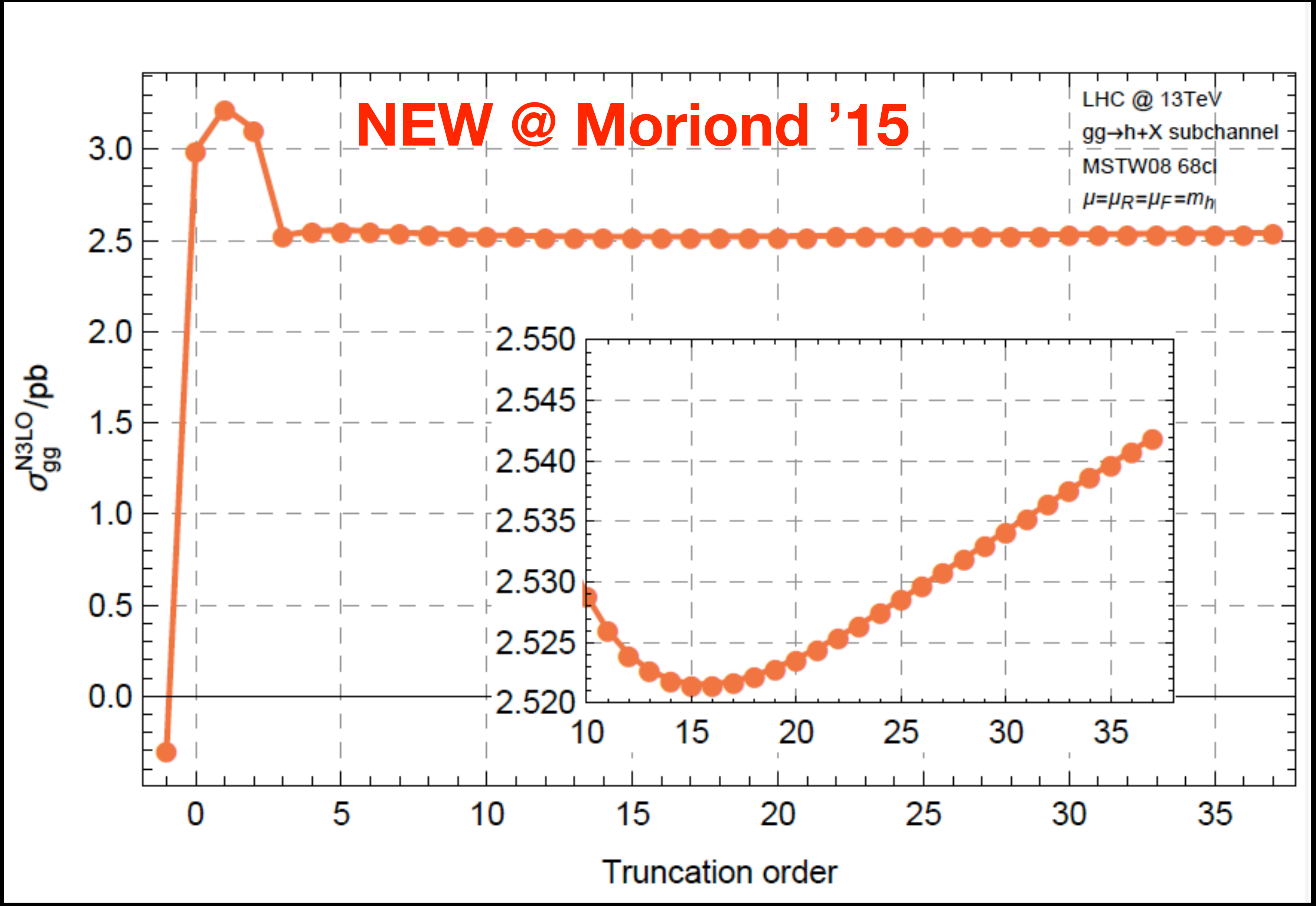


N^3LO Higgs production

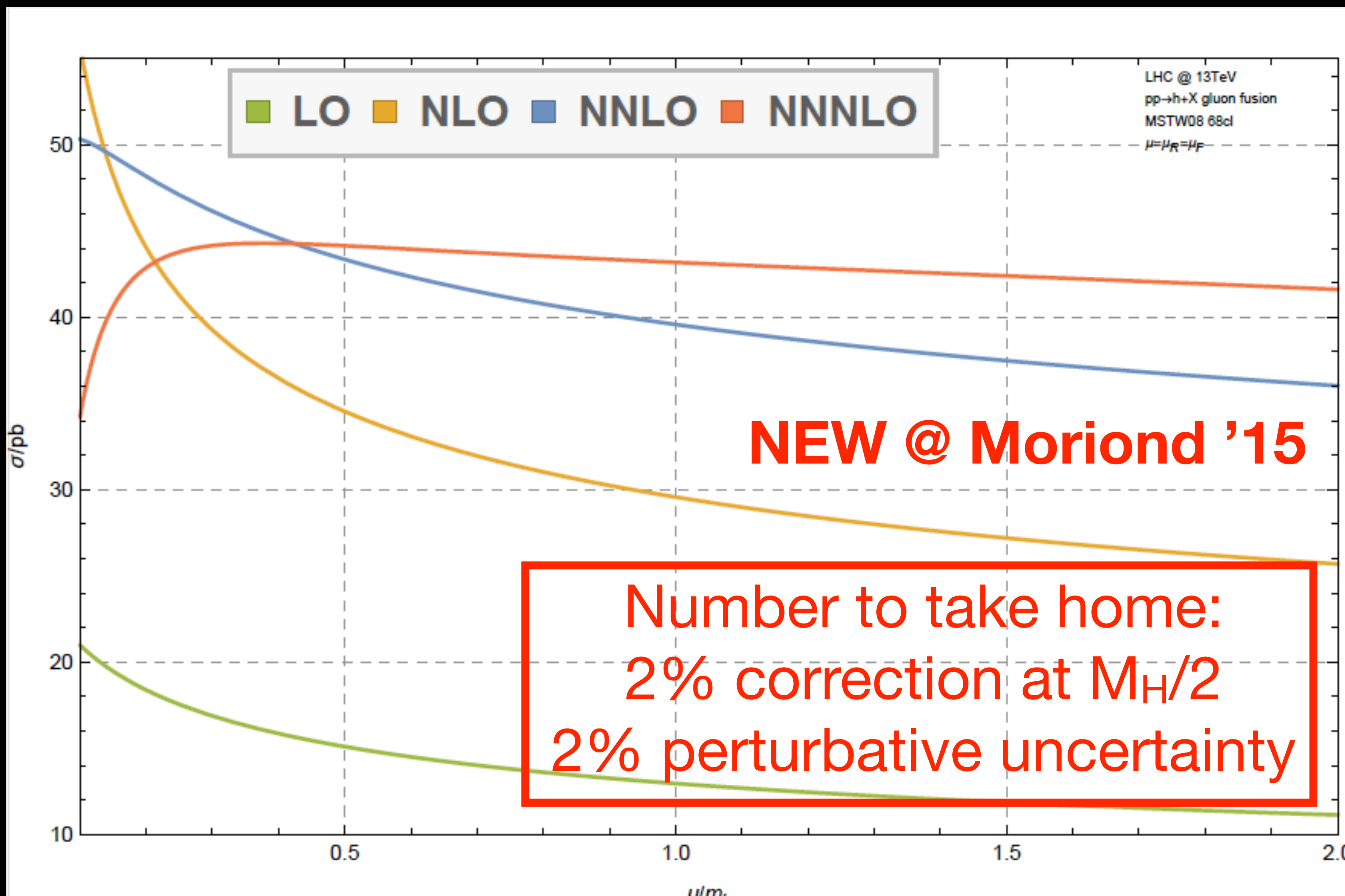
Anastasiou et al. '15



Expansion around threshold. Stability in the threshold expansion parameter.

N^3LO Higgs production

Anastasiou et al. ’15



Other uncertainties now become all important (PDFs, treatment of EW, heavy-top approximation, top-bottom interference in loops...). New predictions soon (2 months?)

Looking ahead

- physics at the LHC extremely rich: spans from most precision measurements to searches with highest reach
- experimental program supplemented by robust theory: clear effort to produce predictions and public codes that have the flexibility required for today's sophisticated experimental analysis
- this and coming years most exciting (Run II beams are already circulating ...): what if we find nothing despite the massive experimental and theoretical efforts?
- exploring the unknown is valuable in it's own right. Whatever happens we will learn something by going to a new frontier (RunII, HL-LHC, FCC ...).
- precision QCD crucial to interpret results of Run II and beyond