Finite mass effects in Higgs boson plus jets production

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Based on: arXiv: 1802.00349 ; arXiv: 1608.01195

Outline

- **Introduction and motivation**
- **H+1 jets at NLO with full top-quark mass dependence:**
  - Process details
  - Numerical computation of 2-loop diagrams
- **Phenomenological results:**
  - Total cross section
  - Differential distributions
- **Conclusions and outlook**

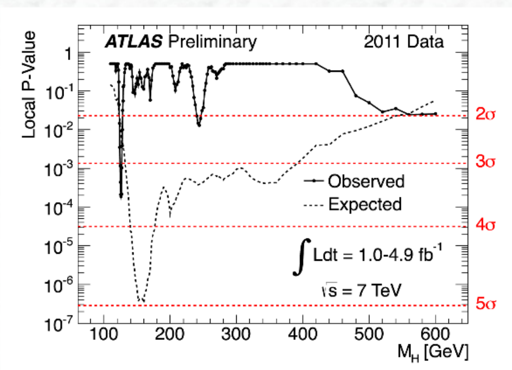
Credits: Many thanks to Mattias Kerner and Stephen Jones for sharing material and for clarifications about the technical aspects of the 2-loop computation

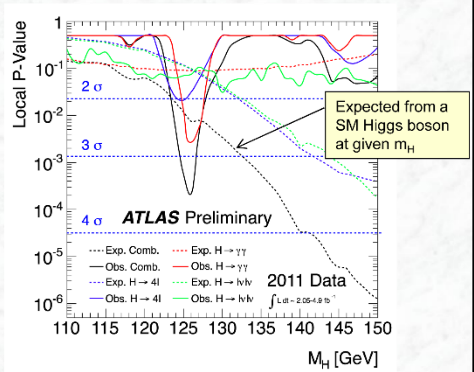
The Higgs and the LHC: a success story!!

It was 6 years ago…

… that we were looking at exclusion plots seeing some hints

Consistency of the data with the background-only expectation





- Lowest probability (p_0 = 1.9 10^{-4}) for background-only expectation observed for m_H ~126 GeV
- Local significance of excess: 3.6σ (2.8σ H → γ γ2.1σ H → 4ℓ, 1.4σ H → ℓν ℓν)
- Global significances: 2.5σ (p = 0.6%) Look-elsewhere-effect over 110 – 146 GeV
  2.2σ (p = 1.4%) Look-elsewhere-effect over 110 – 600 GeV

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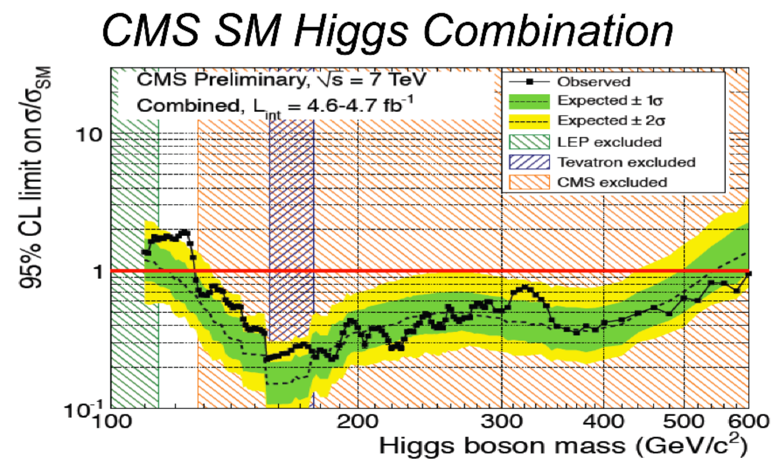
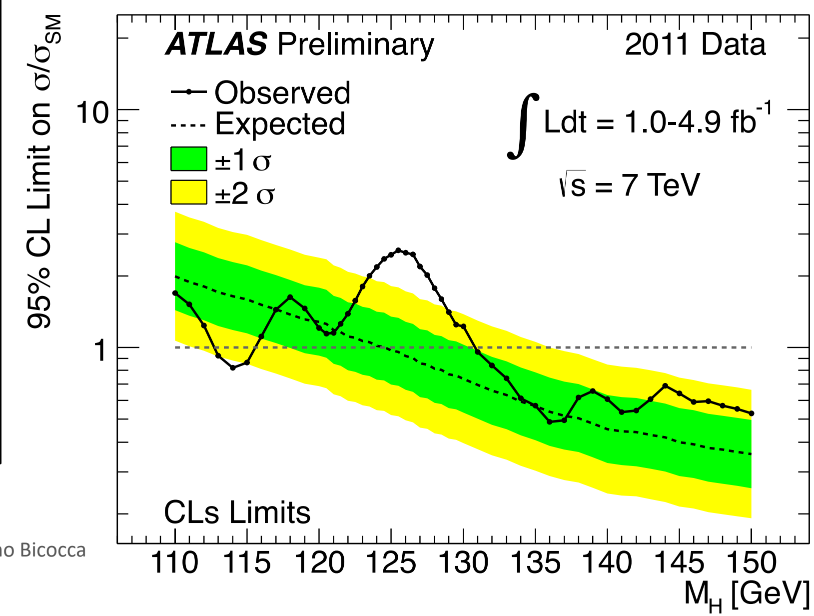
K. Jakobs – Zurich Phenomenology Workshop 2012



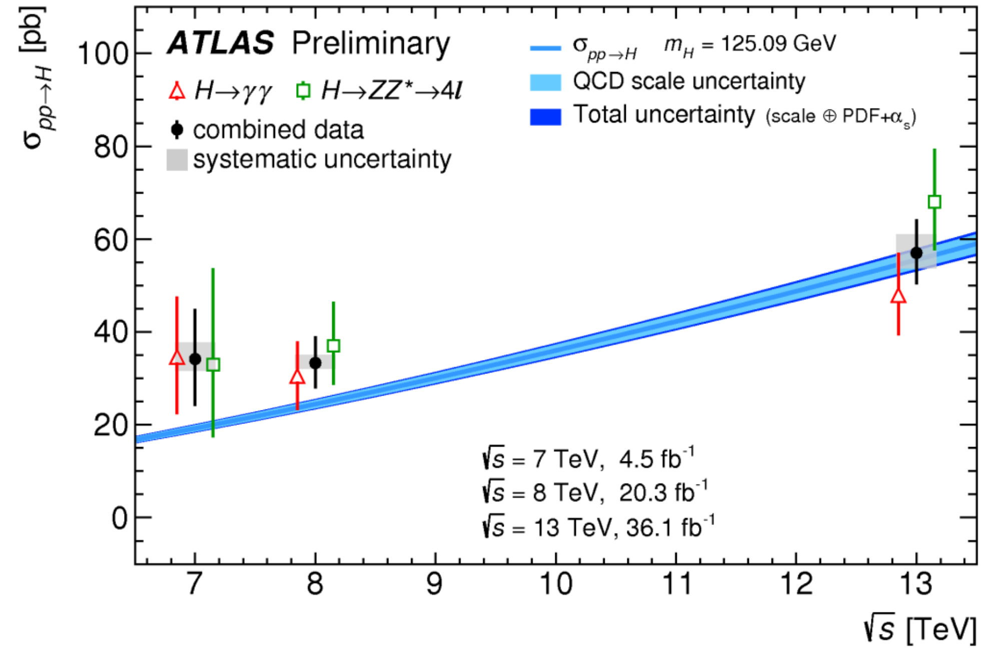
Observations
- exclude (95%): 127-600 GeV (exp. 117-583 GeV)
- exclude (99%): 129-525 GeV (exp. 128-500 GeV)

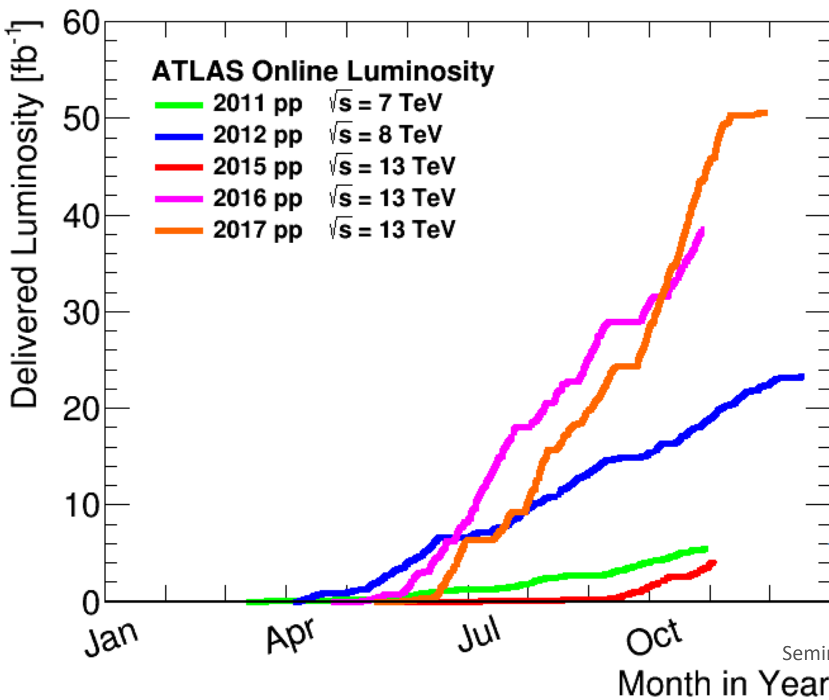
C.Paus, MIT: Recent CMS Higgs Results 54



... in the meanwhile

... many results and steeply increasing statistics





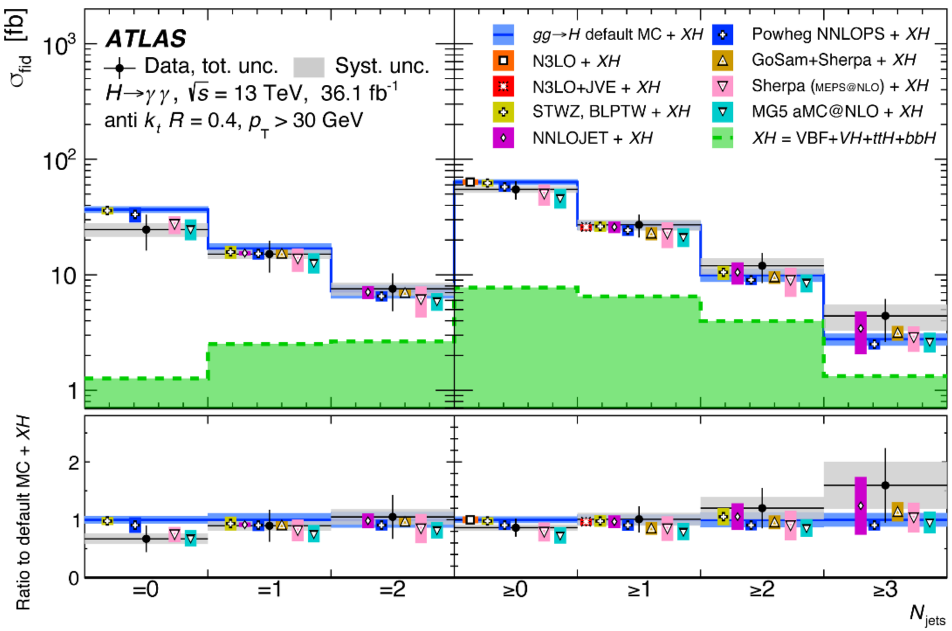
Data collected in 2017

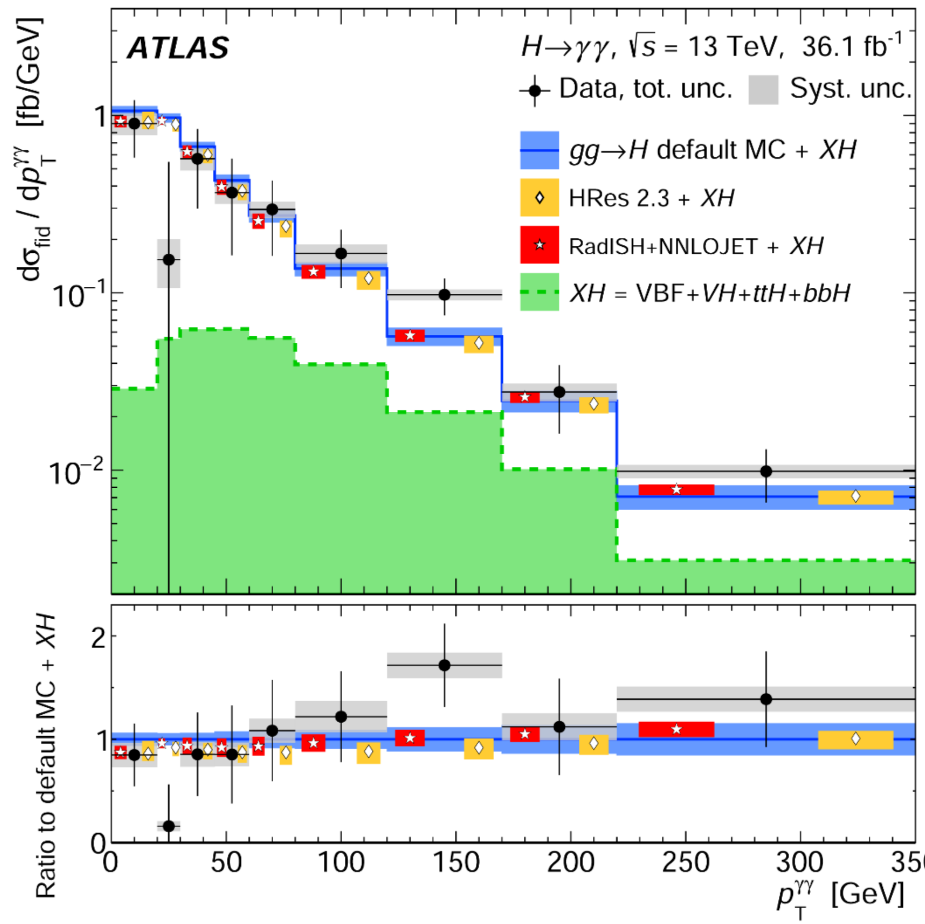
Data collected in 2011 (used for the plots in the previous slide)

New differential results at 13 TeV

- Very recent results by ATLAS:

[ATLAS, 1802.04146]



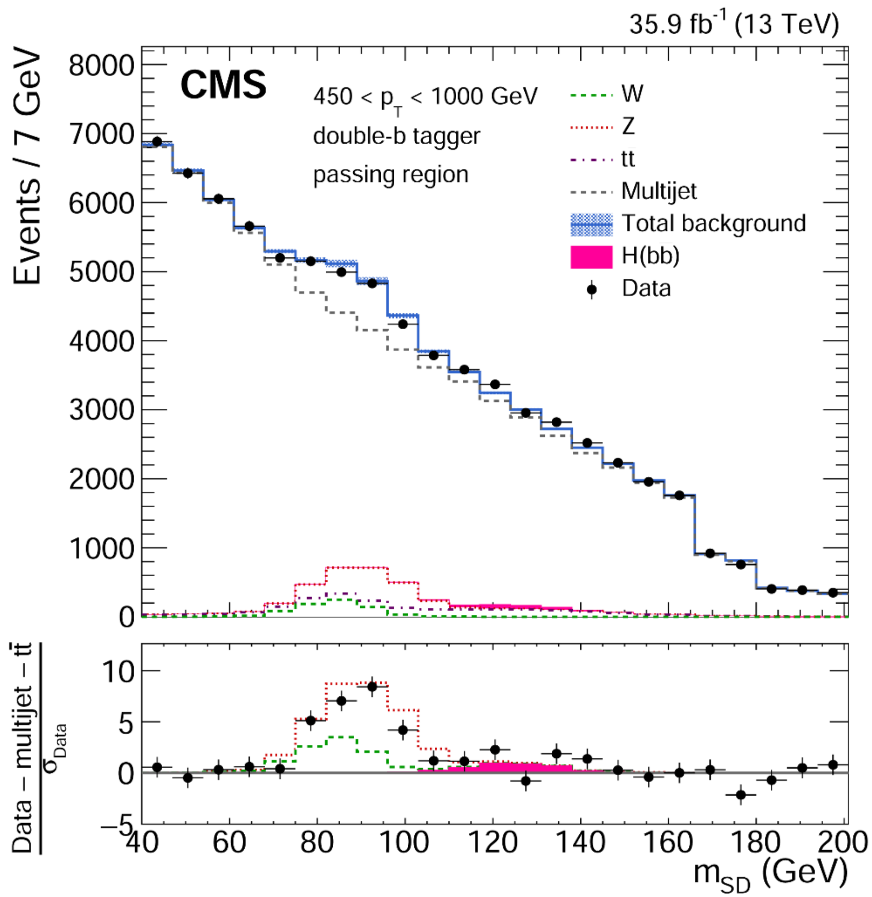


Data become more and more precise, not only for inclusive quantities, but also for more exclusive and differential observables.

New differential results at 13 TeV

- First results on boosted Higgs by CMS: [CMS, 1709.05543, PRL 120 (2018) 071802]

"Inclusive search for a highly boosted Higgs boson decaying to a bottom quark-antiquark pair"



Search for $\mathrm{H} \to \mathrm{b\bar{b}}$ with:

$$p_T > 450\,\mathrm{GeV}$$
$$-2.5 < \eta < 2.5$$

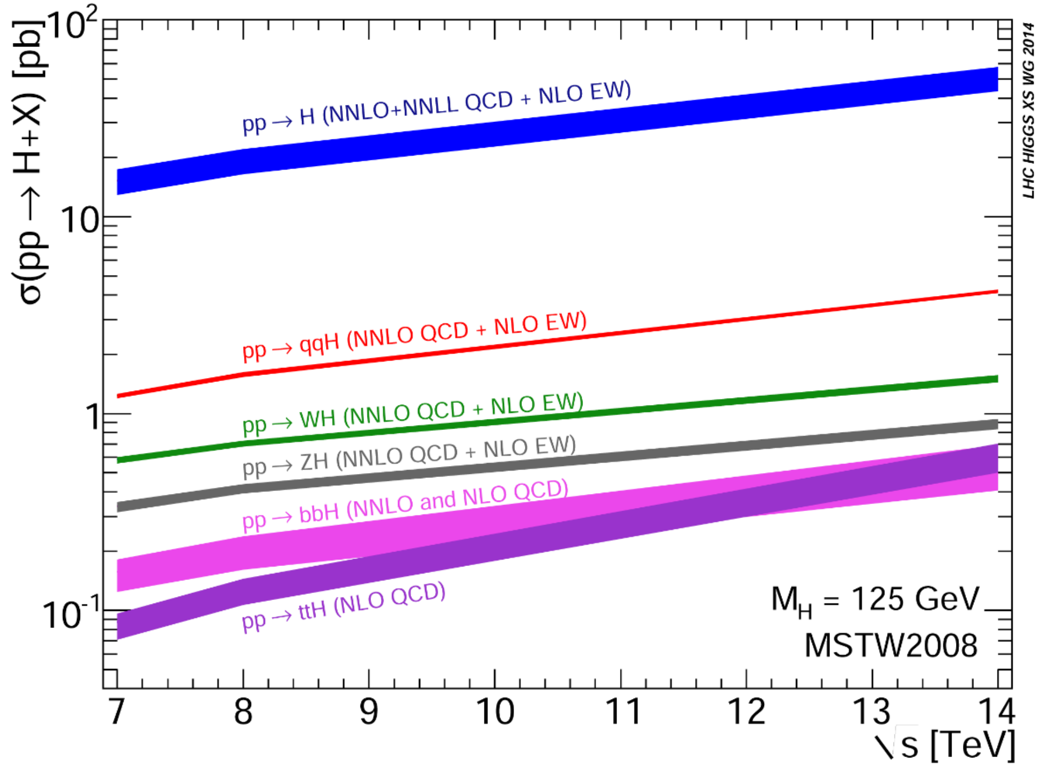
anti-k_T R = 0.8

Look for fat jet:

- Select leading p_T jet
- Apply soft-drop algorithm to groom the jet
- Reconstruct both Z and H

	H	Z
Observed signal strength	$2.3^{+1.8}_{-1.6}$	$0.78^{+0.23}_{-0.19}$
Expected UL signal strength	< 3.3	—
Observed UL signal strength	< 5.8	—
Expected significance	0.7σ	5.8σ
Observed significance	1.5σ	5.1σ

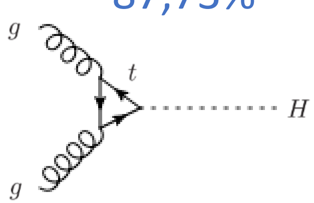
Higgs boson production channels



[Percentage for 13 TeV]

Gluon-Gluon Fusion

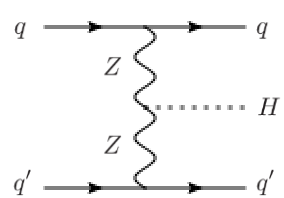
87,73%



- Largest production mechanism
- Huge background

Vector Boson Fusion

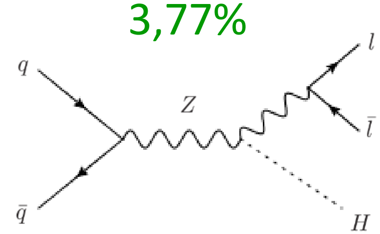
7,49%



- Characteristic signature
- Coupling to VBs

Higgs Strahlung

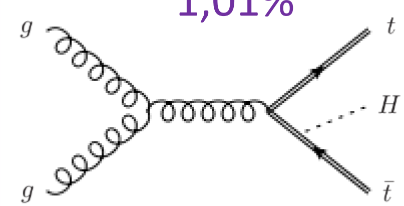
3,77%



- Clean final state
- Measure H -> bb

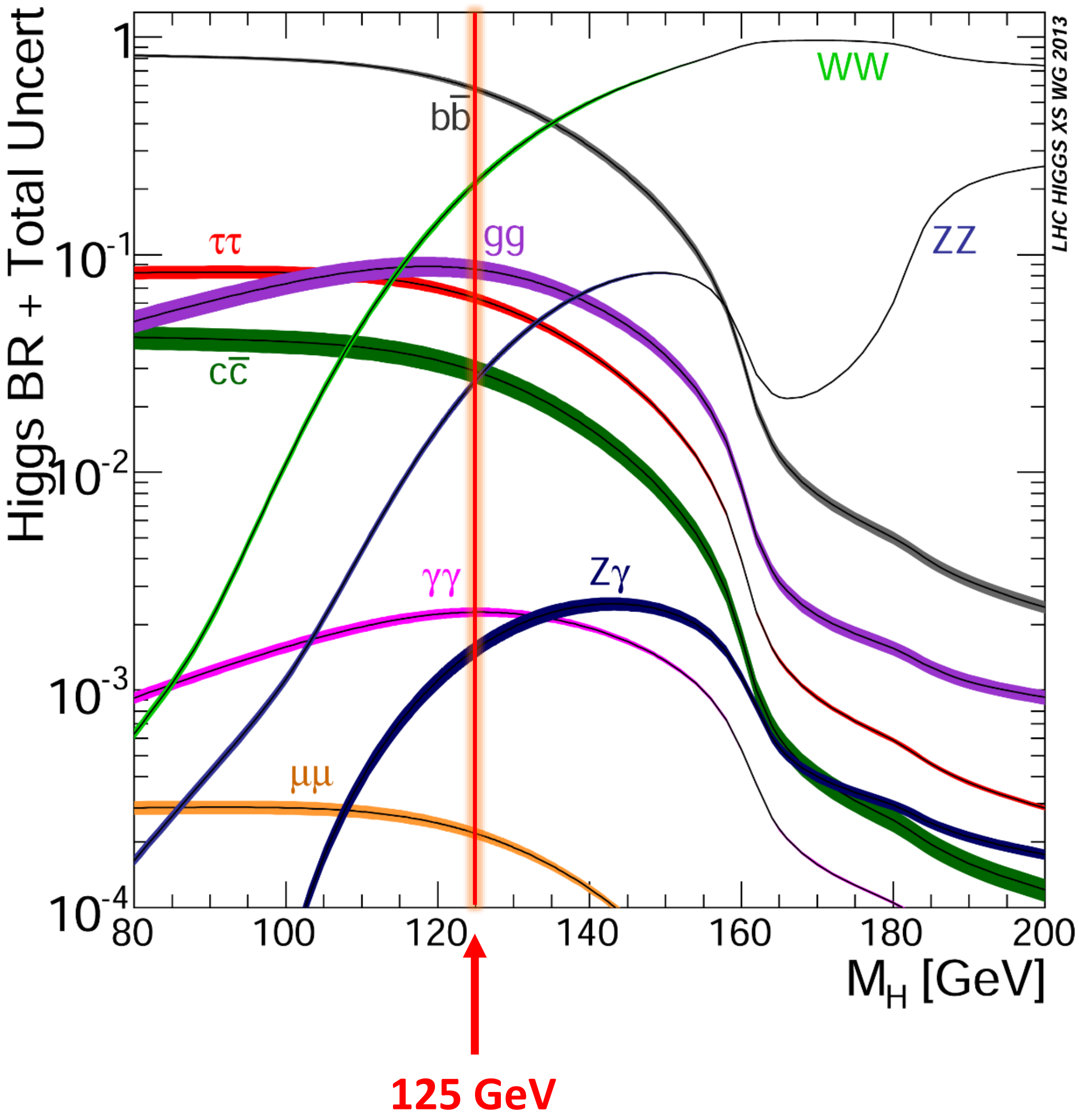
ttH

1,01%



- Small signal
- Top-Yukawa coupling

Higgs boson decay rates in the SM

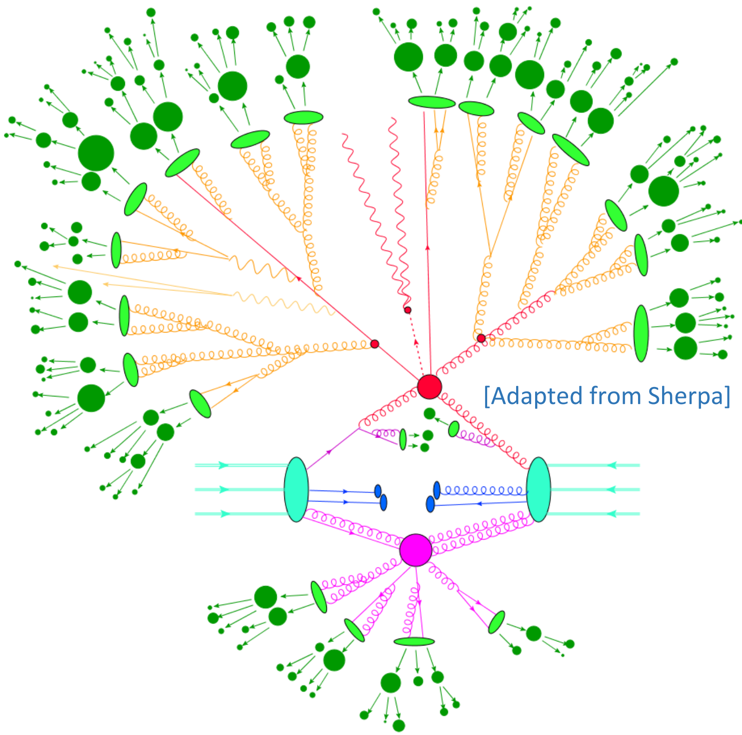


- Several different decay channels:
  - Experimental analyses tuned to the different decay channels in order to optimize the signal to background ratio
  - The number of accompanying jets also plays an important role

Refined analyses and a very high theoretical accuracy to make the most out of the LHC data!

LHC is a tough environment for precision..

- QCD is omnipresent at LHC:
  - PDF
  - Hard scattering and loop corrections
  - Parton Shower
  - Hadronization
  - Further non perturbative effects



- Master formula:

$$\sigma_{h_1 h_2 \to X} = \sum_{a,b} \int_0^1 dx_1 dx_2 \, f_{h_1/a}(x_1, \mu_F^2) \, f_{h_2/b}(x_2, \mu_F^2) \times \hat{\sigma}_{a,b \to X}\left(x_1, x_2, \alpha_s(\mu_R^2), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2}\right) \left[+ \mathcal{O}\left(\frac{1}{Q^2}\right)\right]$$

PDFs | partonic cross section | power corrections

- All components need to determined with high accuracy!

Fixed order calculations for H + n Jets

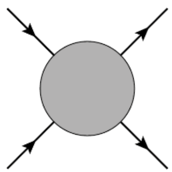
- Partonic cross section:

For Higgs+jets in gluon-fusion

$$\hat{\sigma}_{pp\to H+nJ} = \alpha_s^{2+n}\left[\sigma_0 + \alpha_s\sigma_1 + \alpha_s^2\sigma_2 + \alpha_s^3\sigma_3 + \mathcal{O}(\alpha_s^4)\right]$$

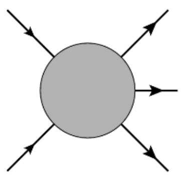
LO | NLO | NNLO | N^{3}LO

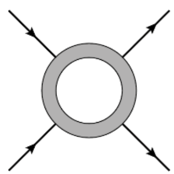
- LO:



Predicts only the order of magnitude:
- ➢ Scale only rough estimate
- ➢ 1 parton ⟷ 1 jet

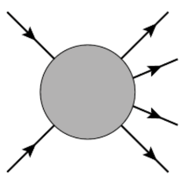
- NLO:

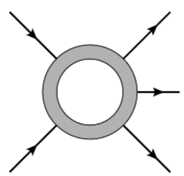


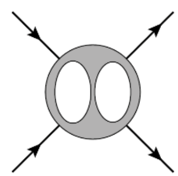


First reliable predictions:
- ➢ scale choices can be made
- ➢ first description of jet substructure

- NNLO:





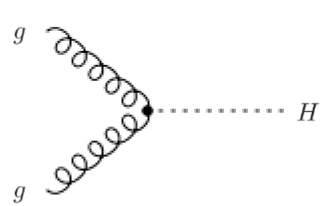


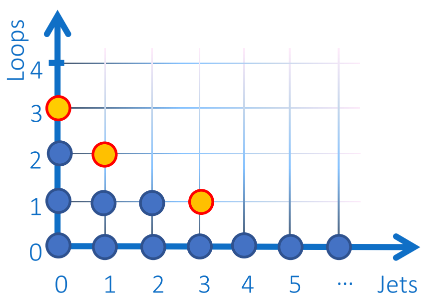
Possible to quantify uncertainties:
- ➢ convergence can be checked
- ➢ richer jet substructure

State of the art of the theoretical predictions

ME level · Shower/Hadron level · New result (2015-2017)

- Gluon-gluon fusion





Latest results:

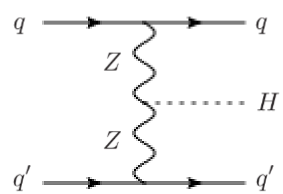
[H: 1503.06056, 1602.00695, 1610.05497]

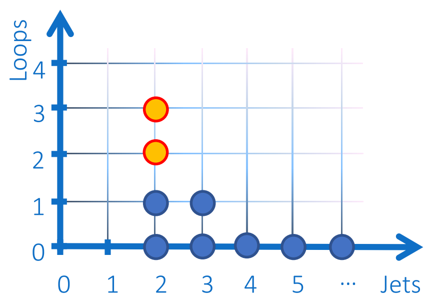
[H+1j: 1504.07922, 1505.03893, 1508.02684, 1607.08817]

[H+3j: 1307.4737, 1506.01016]

[… and more (see later slide)]

- Weak boson fusion

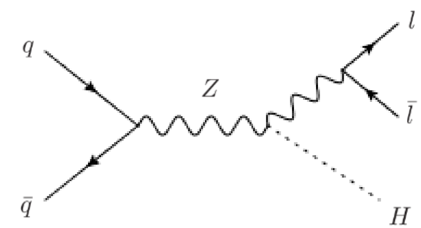


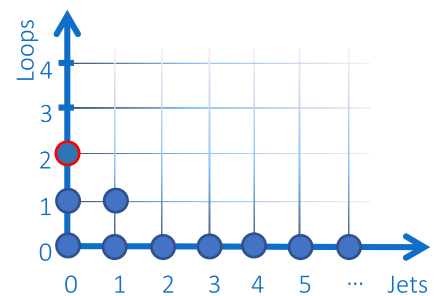


Latest results:

[H+2j: 1506.02660, 1606.00840]

- Higgs Strahlung





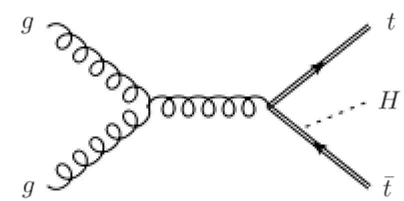
Latest results:

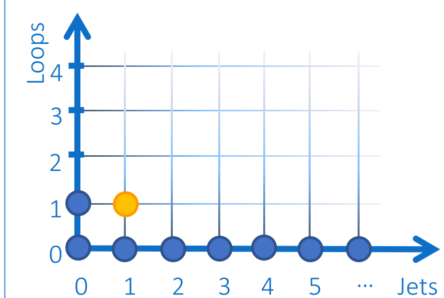
[HW NNLO+PS: 1603.01620]

[HW NNLO prod+bb-dec: 1705.10304]

[HW NNLO prod+bb-dec: 1712.06954]

- ttH





Latest results:

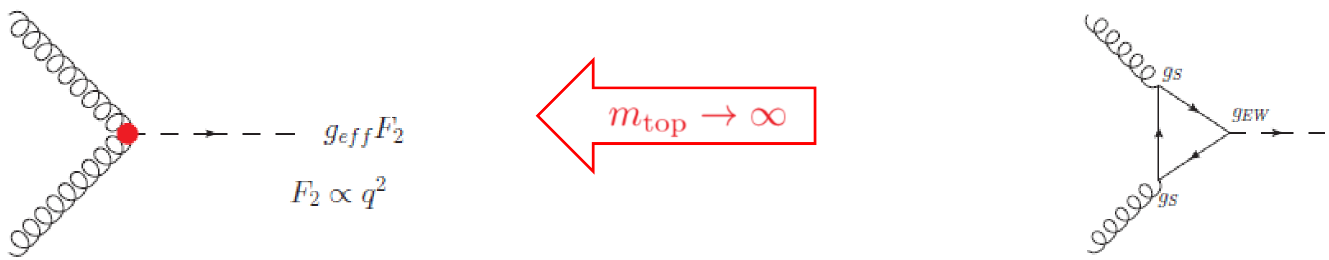
- Full off-shell effects at 1 loop

[Off-shell: 1506.07448, 1612.07138]

[I tried not to miss any contribution, my apologies for any omission]

Gluon fusion

- Theoretically gluon fusion has two important key aspects



1. It's loop induced (Born is a 1-loop process): huge increase in complexity

However:

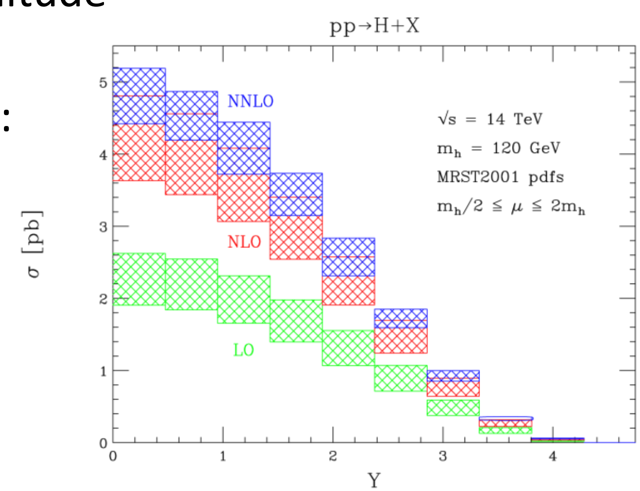
- Since $m_{\rm top} > m_{\rm H}$ we can integrate out top quark and compute in an effective theory where the Born is a tree-level amplitude

2. It suffers from very large perturbative corrections:

- Huge NLO [O(100%)] and NNLO [O(20%)] effects!
- Now known at N^3LO:

LO	$15.05 \pm 14.8\%$
NLO	$38.2 \pm 16.6\%$
NNLO	$45.1 \pm 8.8\%$
N3LO	$45.2 \pm 1.9\%$

[Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Lazopoulos, Mistlberger, '15-'16]



[Anastasiou, Melnikov, Petriello, '05]

Gluon fusion

- LHC Higgs results allowed to **exclude** a 4th SM-like generation

- New physics in the Higgs sector could however still hide in the **transverse momentum tail**. How to nail this down?

- <u>Facts to consider</u>:
  - Higher order corrections are particularly **sizable** in Higgs boson production in gluon-gluon fusion (also in association with jets)

  - For a precise determination of the most important observables (e.g. the Higgs transverse momentum spectrum) a **good control over higher multiplicities** is relevant

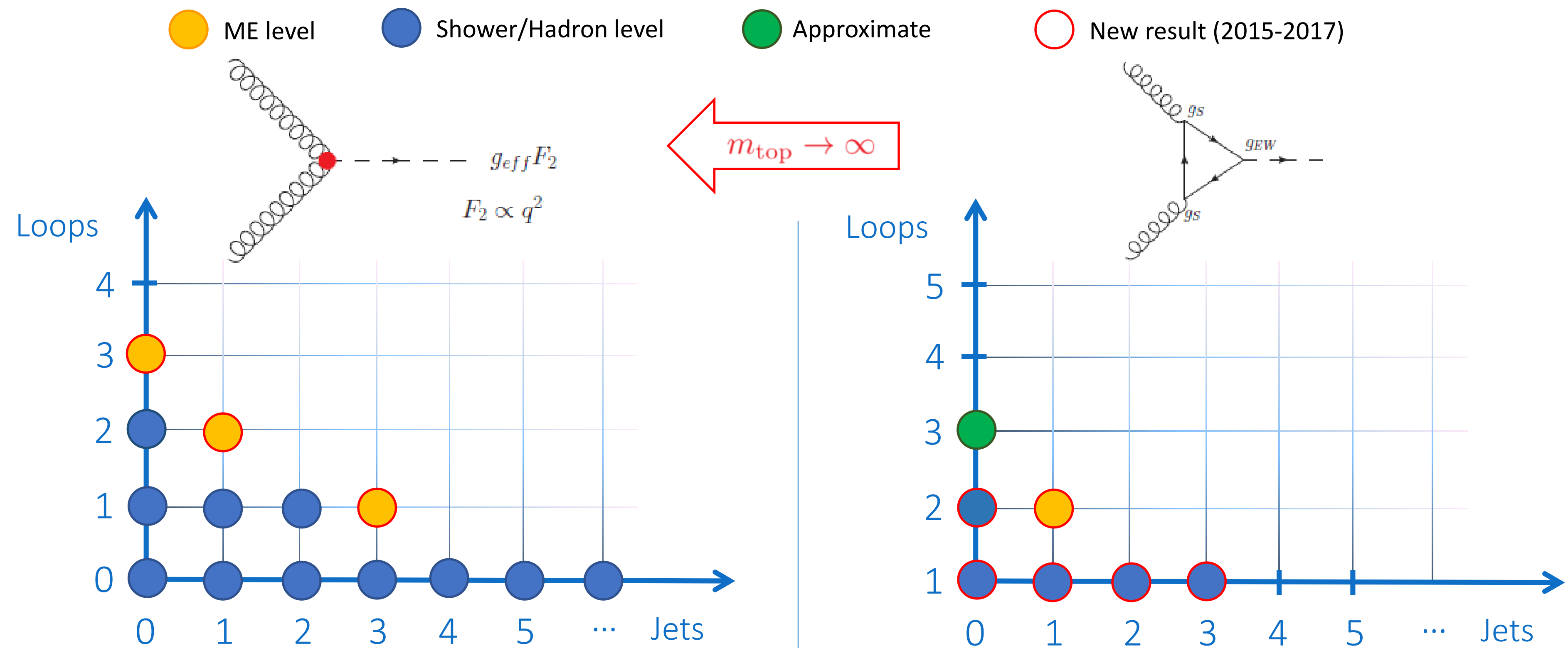
  - LHC Run II is collecting data very fast. This will soon allow for **precise Higgs boson studies** at 13 TeV

  - ➢ What are the **dominant effects**: higher order corrections or mass effects?

  - ➢ How **reliable** are effective field theory results, when do they **break down** and how are the different observables affected by mass corrections?

State of the art of the theoretical predictions

- Gluon fusion calculations in effective and full theory:



Latest results:

[H: 1503.06056, 1602.00695]

[H+1j: 1504.07922, 1505.03893,1508.02684, 1607.08817]

[H+3j: 1307.4737, 1506.01016]

Latest results:

[H+0,1,2j NLO merged + PS: 1410.5806]

[H+0,1,2j approx. NLO merged + PS: 1604.03017]

[H+1,2,3j LO: 1608.01195]

[H+1j approx. NLO: 1609.00367]

[H+1j approx. NNLO for p_T: 1607.08817]

[planar 2-loop MI: 1609.06685]

[pp->Hj for nearly massless quarks: 1610.03747, 1702.00426]

[pp->Hj at large pT: 1712.06549, 1801.08226; 1802.02981]

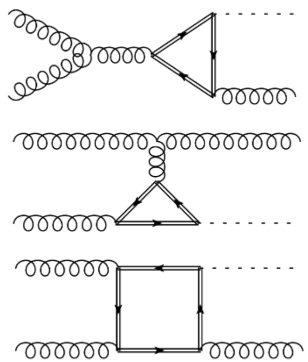
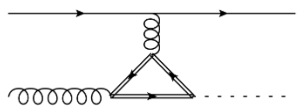
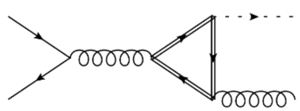
[pp->Hj with full top mass: 1802.00349]

[I tried not to miss any contribution, my apologies for any omission]

H+1j at NLO with full top-quark mass effects

Process details

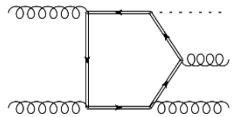
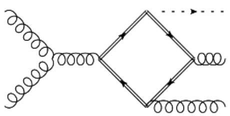
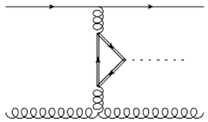
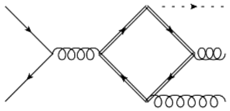
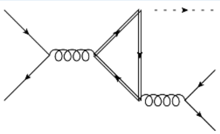
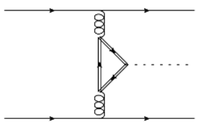
- Leading order contributions (1-loop) to $pp \to \mathrm{H+1\,jet}$:

Channel	Diagrams	$\sigma_{\mathrm{LO}(p_{t,\mathrm{j}}>30\,\mathrm{GeV})}$	$\sigma_{\mathrm{LO}(p_{t,\mathrm{j}}>500\,\mathrm{GeV})}$
$gg \to Hg$		6.32 pb (74%)	1.92 x 10^{-3} pb (52%)
$qg \to Hq,\ \bar{q}g \to H\bar{q}$		2.21 pb (26%)	1.72 x 10^{-3} pb (47%)
$q\bar{q} \to Hg$		0.04 pb (< 1%)	0.04 x 10^{-3} pb (1%)
	Tot:	8.56 pb	3.68 x 10^{-3} pb

- Computed using analytical implementation of the amplitudes [Baur, Glover 89]

Process details

- Real radiation corrections (1-loop):

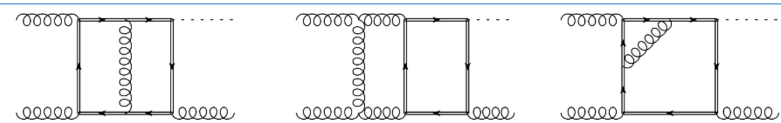
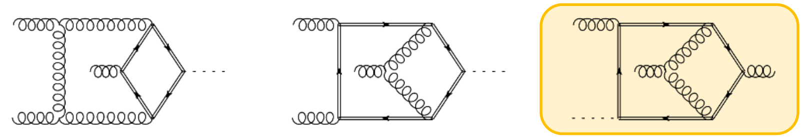
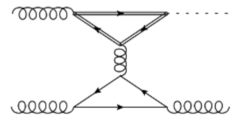
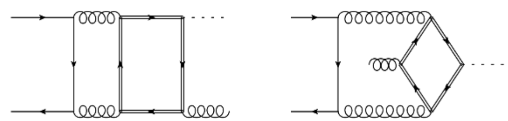
	Diagrams	# Diagrams
$gg \rightarrow Hgg$	 	98
$qg \rightarrow Hqg,\ \bar{q}g \rightarrow H\bar{q}g$		4
$q\bar{q} \rightarrow Hgg$		20
$qq \rightarrow Hq'q'$		2
$qq \rightarrow Hqq$		4

- Generated using GoSam
  - Upgraded **GoSam** generates <u>quadruple precision</u> copy of the code to rescue on-the-fly unstable point with **Ninja**

[Cullen, v. Deurzen, Greiner, Heinrich, Mastrolia, Mirabella, Ossola, Peraro, Schlenk, v. Soden-Fraunhofer, Tramontano, GL, '14]
[Mastrolia, Mirabella, Peraro '12] [Peraro '15]
[v. Deurzen, Mastrolia, Mirabella, Ossola, Peraro, GL, '14]

Process details

- Virtual corrections (2-loops):

			# Diagrams
$gg \to Hg$	planar		354
	non-planar	 vanished due to colour	
	(1-loop)^2		
$qg \to Hq,\ \bar{q}g \to H\bar{q}$ $q\bar{q} \to Hg$			57

- Computed using **2-loop extension** of GoSam, **REDUZE** and **SecDec**

[Greiner, Heinrich, Jahn, Jones, Kerner, Zirke][von Manteuffel, Studerus '12]
[Binoth, Borowka, Carter, Heinrich, Jahn, Jones, Kerner, Schlenk, Zirke]

- Analogous method used to compute **HH** production at NLO

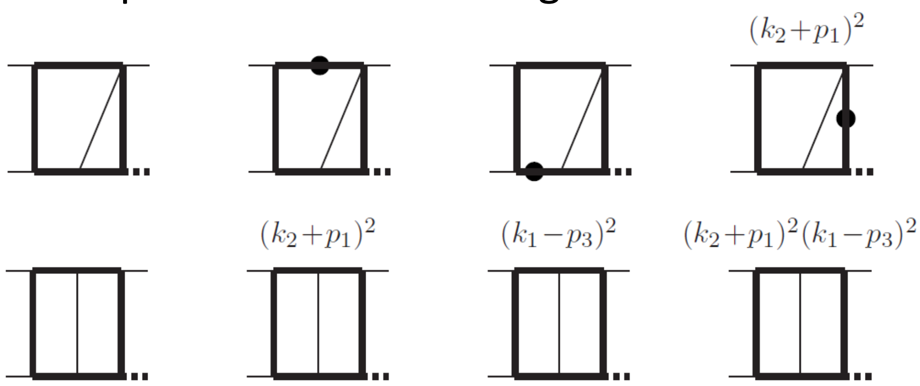
[Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zirke]

Analytic results of 2-loop diagrams

- For planar integrals an analytic result exists

[Bonciani, Del Duca, Frellesvig, Henn, Moriello, Smirnov '16]

  - Reduced to **125** Master Integrals
  - Alphabet with 3 variables, 49 letters which contain 13 square roots
  - Non elliptic master integrals in terms of **Log** and **Li_2** up to weight 2
  - Weight 3 and 4 expressed in form of 1-fold integrals
  - 2 sectors contain **elliptic functions** computed as iterated integrals over elliptic kernel



➢ First analytic computation of Feynman integrals for 4-point multiscale amplitudes involving elliptic functions

Numerical computation of 2-loop diagrams

- Decompose amplitude into **form factors**:
  - **Gluon channel**

$$\mathcal{M} = \epsilon_\mu(p_1)\epsilon_\nu(p_2)\epsilon_\rho(p_3)\mathcal{M}^{\mu\nu\rho}$$

[Glover, Frellesvig '17]

where: $$\begin{aligned}\mathcal{M}^{\mu\nu\rho} =& F_{212}(s\, g^{\mu\nu} - 2p_2^\mu p_1^\nu)(u\, p_1^\rho - t\, p_2^\rho)/(2t) \\ &+F_{332}(u\, g^{\nu\rho} - 2p_3^\nu p_2^\rho)(t\, p_2^\mu - s\, p_3^\mu)/(2s) \\ &+F_{311}(t\, g^{\rho\mu} - 2p_1^\rho p_3^\mu)(s\, p_3^\nu - u\, p_1^\nu)/(2u) \\ &+F_{312}\,(g^{\mu\nu}(u\, p_1^\rho - t\, p_2^\rho) + g^{\nu\rho}(t\, p_2^\mu - s\, p_3^\mu) + g^{\rho\mu}(s\, p_3^\nu - u\, p_1^\nu))\end{aligned}$$

  - **Quark channel**

$$\begin{aligned}\mathcal{M} =& F_q \left(\bar{u}(p_{\bar{q}})\not{p}_g v(p_q) p_q\cdot\epsilon - \bar{u}(p_{\bar{q}})\not{\epsilon} v(p_q) p_q\cdot p_g\right) \\ &+F_{\bar{q}} \left(\bar{u}(p_{\bar{q}})\not{p}_g v(p_q) p_{\bar{q}}\cdot\epsilon - \bar{u}(p_{\bar{q}})\not{\epsilon} v(p_q) p_{\bar{q}}\cdot p_g\right)\end{aligned}$$

[Gehrmann, Glover, Jaquier, Koukoutsakis '11]

- Full integration-by-part reduction obtained using **REDUZE**
  - In-house modifications:
    - Changed order of solving differential equations (sort by number of unreduced integrals)
    - Allow to specify list of required integrals (consider only equations containing these integrals)

[Chetyrkin, Tkachov '81; Laporta '01]
[von Manteuffel, Studerus '12]

Numerical computation of 2-loop diagrams

- Unreduced amplitude: 3767 integrals
  - up to 3 inverse propagators for 7-propagator integrals
  - up to 4 inverse propagators for factorizing 6-propagator integrals

- Reduced amplitude: 458 integrals
  - up to 6 master integrals per sector

- Choose quasi-finite basis of MI [von Manteuffel, Panzer, Schabinger '14]
  - requires integrals in shifted dimension [Tarasov '96; Lee '10]
  - requires reduction of integrals with 2 inverse propagators and 2 dots

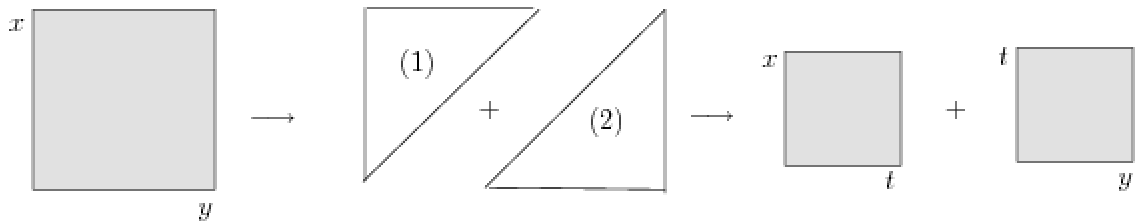
- Reduction performed keeping **fixed mass ratio**: $\frac{m_{\mathrm{H}}^2}{m_T^2} = \frac{12}{23} \quad \Leftrightarrow \quad \begin{array}{l} m_{\mathrm{H}} = 125\,\mathrm{GeV} \\ m_{\mathrm{T}} = 173.055\,\mathrm{GeV} \end{array}$
  - Total size of REDUZE reduction directory: .... 250 GB
  - Size of reduced amplitude (symbolic d-dependent coeff.): .... 780 MB
  - Size of C++ code (for coefficients after expansion in ε): .... 340 MB
  - ➢ Does **NOT** allow inclusion of **massive bottom** quark and **Higgs width**

Numerical computation of 2-loop diagrams

- Loop integrals evaluated numerically using **sector decomposition** and the program **SecDec-3.0**

  [Hepp '66; Denner, Roth '96, Binoth, Heinrich '00]
  [Borowka, Heinrich, Jahn, Jones, Kerner, Schlenk, Zirke]

  - Method to factorize overlapping singularities:



  - Factorization of poles in dim-regulator ε and expansion in Laurent series
  - Contour deformation (analytic continuation from Euclidian to physical region)

  [Soper '00; Binoth et al. '05; Nagy, Soper '06; Borowka et al. '12]

- <u>Output</u>:
  - **finite** integrals at each order in ε
  - can be integrated **numerically**

H+1j 2-loop amplitude written in terms of **22675** finite integrals

- Python version now also available: **pySecDec**

  [Borowka, Heinrich, Jahn, Jones, Kerner, Schlenk, Zirke '17]

  - on Github / uses python and FORM
  - creates library of the integrand functions which can be linked to external code

Numerical computation of 2-loop diagrams

- Loop integrals with r propagators and s inverse propagators can be written as:

$$I_{r,s}(s,t,m_H^2,m_T^2) = (M^2)^{-L\epsilon}(M^2)^{2L-r+s} I_{r,s}\left(\frac{s}{M^2},\frac{t}{M^2},\frac{m_H^2}{M^2},\frac{m_T^2}{M^2}\right)$$

and renormalized form factors as

$$F^{\text{virt}} = a^{3/2}\left(F^{(1)} + a(\frac{n_g}{2}\delta Z_A + \frac{3}{2}\delta Z_a)F^{(1)} + a\delta m_T^2 \mathcal{F}^{ct,(1)} + aF^{(2)} + \mathcal{O}(a^2)\right)$$

$$F^{(1)} = \left(\frac{\mu_R^2}{M^2}\right)^{\varepsilon}\left[b_0^{(1)} + b_1^{(1)}\varepsilon + b_2^{(1)}\varepsilon^2 + \mathcal{O}(\varepsilon^3)\right]$$

$$F^{ct,(1)} = \left(\frac{\mu_R^2}{M^2}\right)^{\varepsilon}\left[c_0^{(1)} + c_1^{(1)}\varepsilon + \mathcal{O}(\varepsilon^2)\right]$$

$$F^{(2)} = \left(\frac{\mu_R^2}{M^2}\right)^{2\varepsilon}\left[\frac{b_{-2}^{(2)}}{\varepsilon^2} + \frac{b_{-1}^{(2)}}{\varepsilon} + b_0^{(2)} + \mathcal{O}(\varepsilon)\right]$$

- ➢ Coefficients $b_i^{(n)}$, $c_i^{(n)}$ do not need to be recomputed for scale variation
- ➢ Compute each $b_i^{(n)}$ coefficient optimizing the accuracy needed from each integral

Numerical computation of 2-loop diagrams

- Finite integrals evaluated using **Quasi-Monte-Carlo** integration
  - After sector decomposition and expansion in ε amplitude is written in terms of **22'675 finite integrals**

  - QMC rank-1 lattice rule: [See Dick, Kuo and Sloan for a review]

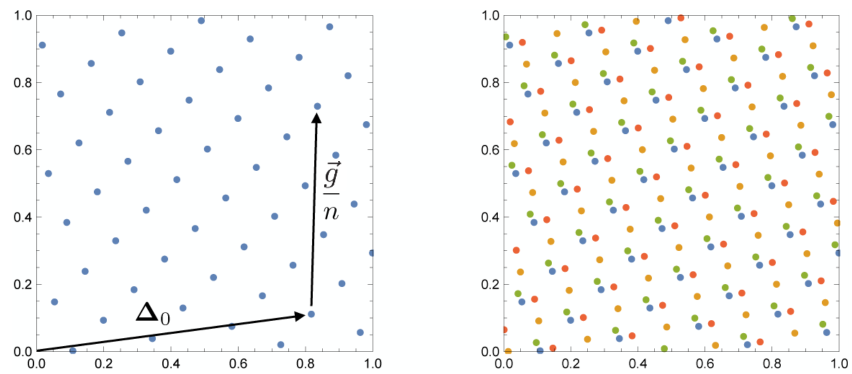
$$I = \int \mathrm{d}\vec{x} f(\vec{x}) \approx I_k = \frac{1}{n} \sum_{i=1}^{n} f(\vec{x}_{i,k})$$

$$\vec{x}_{i,k} = \left\{ \frac{i \cdot \vec{g}}{n} + \vec{\Delta}_k \right\}$$

$\{\ldots\}$ = fractional part

$\vec{g}$ = generating vector

$\vec{\Delta}_k$ = randomized shift



[Pictures by S.Jones, 1608.03846]

  - Compute m different estimates $I_1 \ldots I_m$ to estimate the error
  - Error scales as $\mathcal{O}(n^{-1})$
  - Generating vector constructed component-by-component [Nuyens '07]

- Dynamically set n for each integral, minimizing

$$T = \sum_{\text{integral } i} t_i + \lambda \left(\sigma^2 - \sum_i \sigma_i^2 \right) \qquad \sigma_i = c_i \cdot t_i^{-e}$$

σ_i = error estimate (including coefficients in amplitude)

λ = Lagrange multiplier $\qquad \sigma$ = precision goal

→ Computed on GPU [Li, Wang, Yan, Zhao '15]

Numerical computation of 2-loop diagrams

- Comparison between H+1j and HH virtual 2-loop amplitudes

	HJ production	HH production
#Form factors	4+2	2
Full reduction	✓	only planar
(quasi-) finite basis	✓	only planar
#Master integrals including crossings	458	327
#Master integrals neglecting crossings	120	215
#Integrals after sector decomposition and expansion in ε	22675	11244
Code size coefficients	~340 MB	~80 MB
Code size integrals	~330 MB	~580 MB
Compile time coefficients	~ 2 weeks	few days
Compile time integrals	~4 hours	~1-2 days
Time for linking the program	~3-4 days	few hours

[M.Kerner, RADCOR2017]

NLO calculation

- Separate integration over **phase space** for **B+I+RS** and **V**:

  - **B+I+RS**:
    - 1-loop Born and real radiation matrix elements implemented in the POWHEG-BOX-V2 [Alioli, Nason, Oleari, Re '10]
    - easy to interface
    - easy to be made public
    - straightforward matching to parton-shower [Frixione, Nason, Oleari '07]
    - further phenomenological developments (MiNLO, NNLOPS, …) [Hamilton, Nason, Oleari, Zanderighi '12; Hamilton, Nason, Re, Zanderighi '13]

  - **V**:
    - generated unweighted events based on differential LO cross section
    - included additional p_T-dependent reweighting factor to sample sufficiently also at large transverse momenta

- Contributions combined at the level of the differential histograms

Phenomenological results

Results

- Consider the following setup:

  LHC @ 13 TeV:

  scale: $\frac{H_T}{2} = \frac{1}{2}\left(\sqrt{m_{\rm H}^2 + p_{t,\rm H}^2} + \sum_i |p_{t,i}|\right)$, uncertainty with 7-pt variation

  jets: anti-kt with R = 0.4, $p_{t,\rm j} > 30 \;\; \rm GeV$

  PDFs: PDF4LHC15_nlo_30_pdfas

- We compare three different computations
  - Higgs Effective Field Theory (HEFT):

$$\mathrm{d}\sigma^{\rm HEFT}_{\rm NLO} = \int \mathrm{d}PS_2\, (\mathrm{d}\sigma^{\rm HEFT}_{\rm B} + \mathrm{d}\sigma^{\rm HEFT}_{\rm V}) + \int \mathrm{d}PS_3\, \mathrm{d}\sigma^{\rm HEFT}_{\rm R}$$

  - Full Theory approximated ($\mathrm{FT}_{\mathrm{approx}}$):

$$\mathrm{d}\sigma^{\rm FT_{approx}}_{\rm NLO} = \int \mathrm{d}PS_2 \left(\mathrm{d}\sigma^{\rm Full}_{\rm B} + \frac{\mathrm{d}\sigma^{\rm Full}_{\rm B}}{\mathrm{d}\sigma^{\rm HEFT}_{\rm B}}\, \mathrm{d}\sigma^{\rm HEFT}_{\rm V}\right) + \int \mathrm{d}PS_3\, \mathrm{d}\sigma^{\rm Full}_{\rm R}$$

  - Full theory (Full)

$$\mathrm{d}\sigma^{\rm Full}_{\rm NLO} = \int \mathrm{d}PS_2\, (\mathrm{d}\sigma^{\rm Full}_{\rm B} + \mathrm{d}\sigma^{\rm Full}_{\rm V}) + \int \mathrm{d}PS_3\, \mathrm{d}\sigma^{\rm Full}_{\rm R}$$

Results: total cross section

Theory	LO [pb]	NLO [pb]
HEFT:	$\sigma_{\mathrm{LO}} = 8.22^{+3.17}_{-2.15}$	$\sigma_{\mathrm{NLO}} = 14.63^{+3.30}_{-2.54}$
$\mathrm{FT}_{\mathrm{approx}}$:	$\sigma_{\mathrm{LO}} = 8.57^{+3.31}_{-2.24}$	$\sigma_{\mathrm{NLO}} = 15.07^{+2.89}_{-2.54}$
Full:	$\sigma_{\mathrm{LO}} = 8.57^{+3.31}_{-2.24}$	$\sigma_{\mathrm{NLO}} = 16.01^{+1.59}_{-3.73}$

- Top-quark mass effects: **LO**: + 4.3% **NLO**: + 9% (+ 6% compared with $\mathrm{FT}_{\mathrm{approx}}$)
- However for inclusive cross section non-negligible **top-bottom** interference for H+1 jet production:

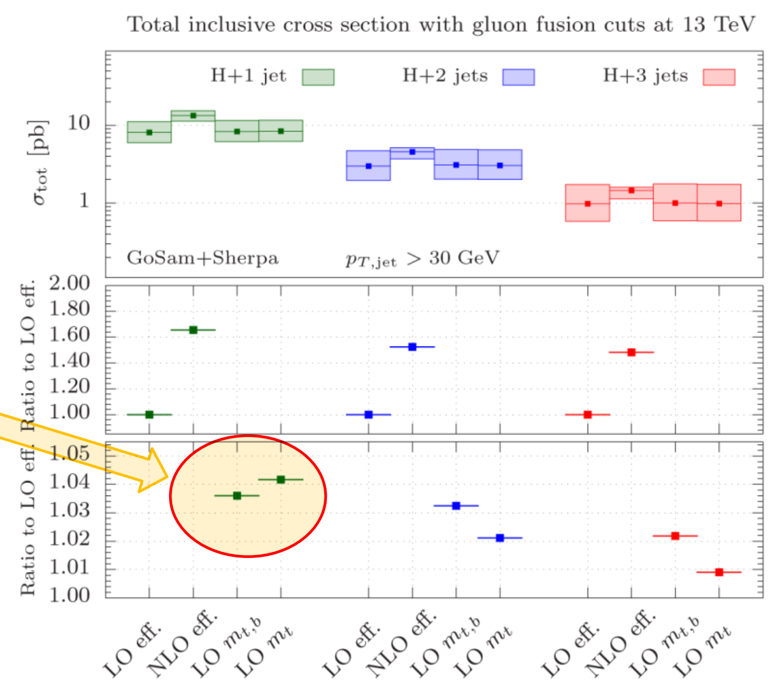
  At LO:

  - $\sigma_{\mathrm{LO},\, m_{t,b}}$: top- and bottom-quark loops
  - $\sigma_{\mathrm{LO},\, m_t}$: top-quark loops only

$$\sigma_{\mathrm{LO},\, m_{t,b}} = |M_t|^2 + |M_b|^2 + 2\Re\left(M_t M_b\right)$$

positive definite

potentially negative



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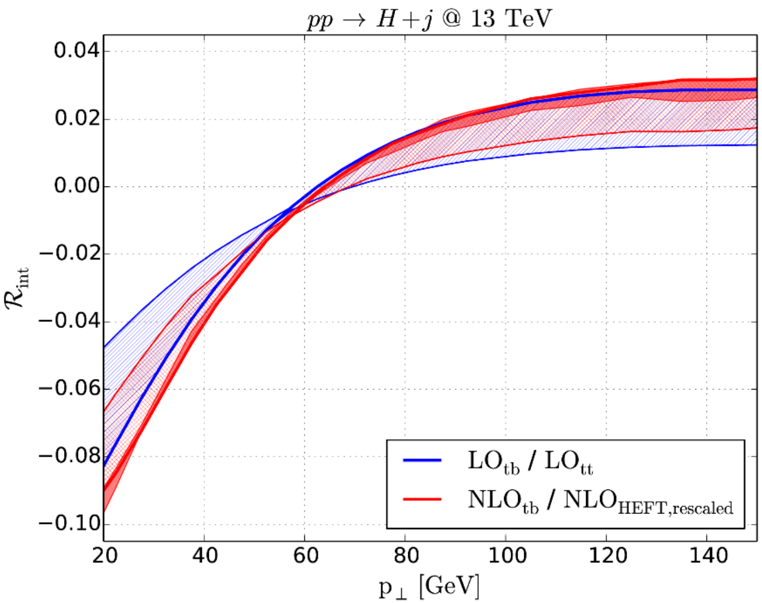
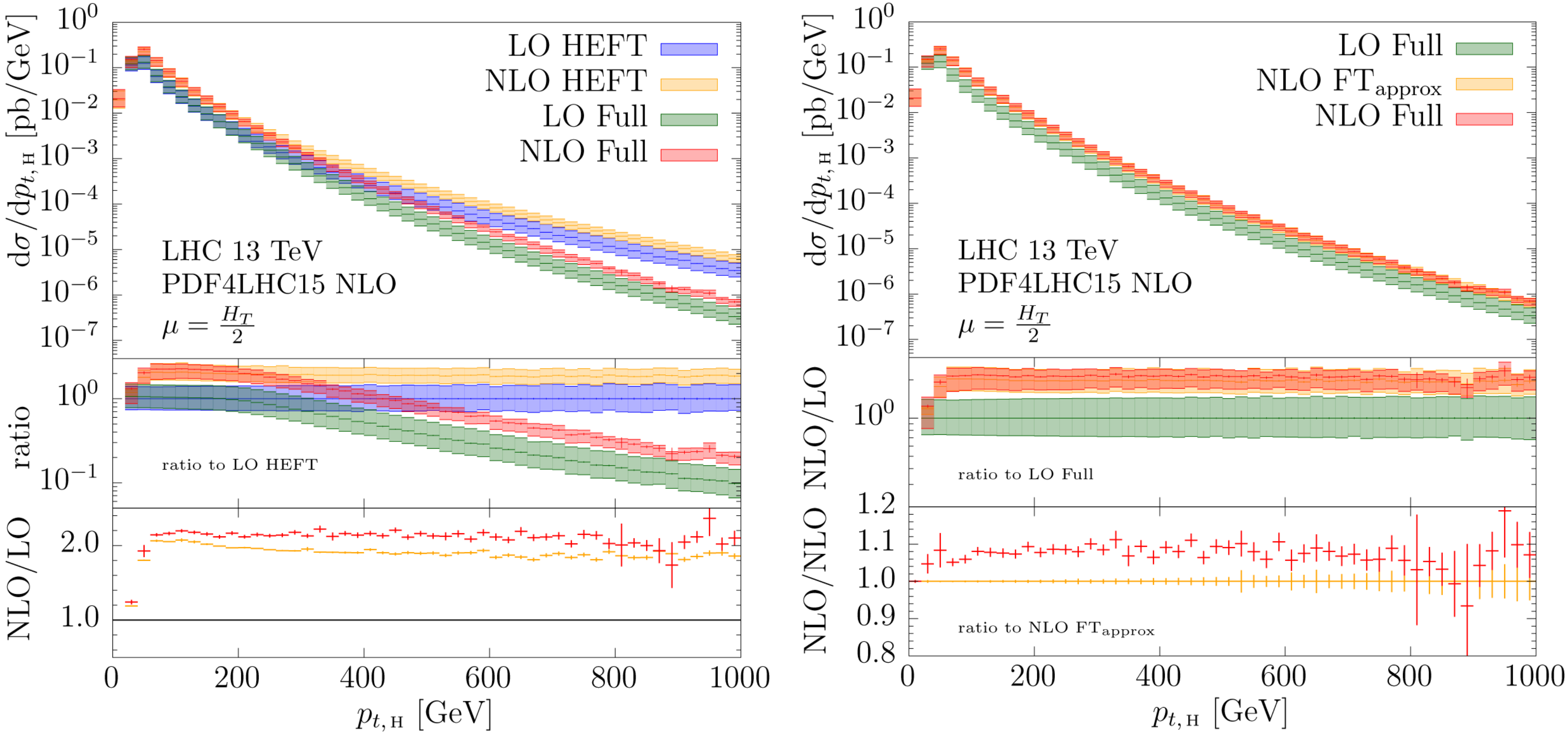
At NLO:

[Lindert, Melnikov, Tancredi, Wever '17]

$$\mathcal{R}_{\rm int}\,[\mathcal{O}] = \frac{\int {\rm d}\sigma_{tb}\;\delta(\mathcal{O}-\mathcal{O}(\vec{x}))}{\int {\rm d}\sigma_{tt}\;\delta(\mathcal{O}-\mathcal{O}(\vec{x}))}$$



Results: Higgs p_T spectrum

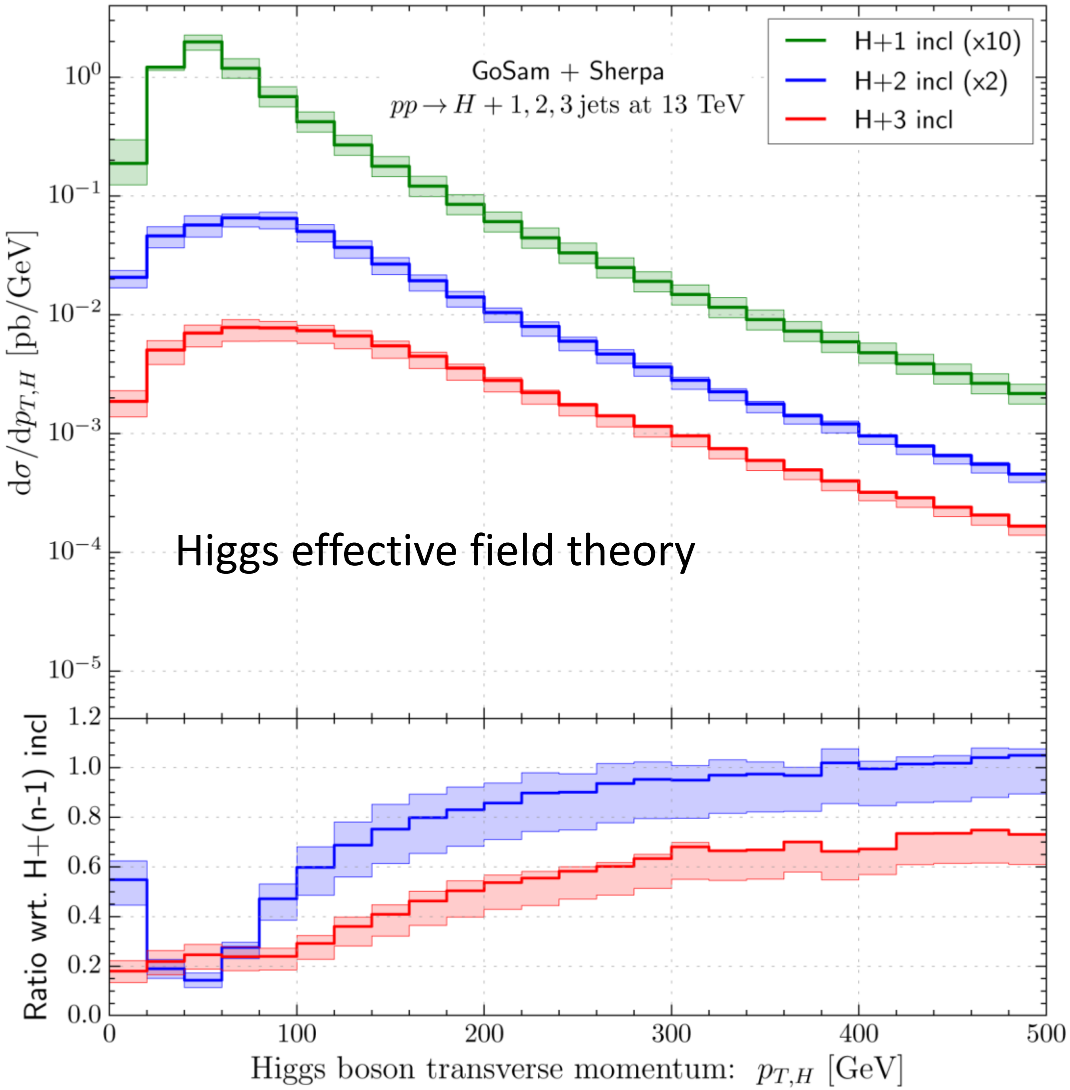


- Full theory and HEFT start **deviating** substantially for p_T > 200 GeV
- Above 150 GeV **stable** K-factor (peculiar to this scale choice?)
- Scale uncertainty slightly **reduced** compared to FT_{approx}
- Full virtual gives **+8%** correction w.r.t. HEFT virtual

[Broad agreement with observations of Lindert, Kudashkin, Melnikov, Wever '18]

Higgs transverse momentum spectrum at 13 TeV

- Importance of H+2j and H+3j contributions in Higgs p_T spectrum:



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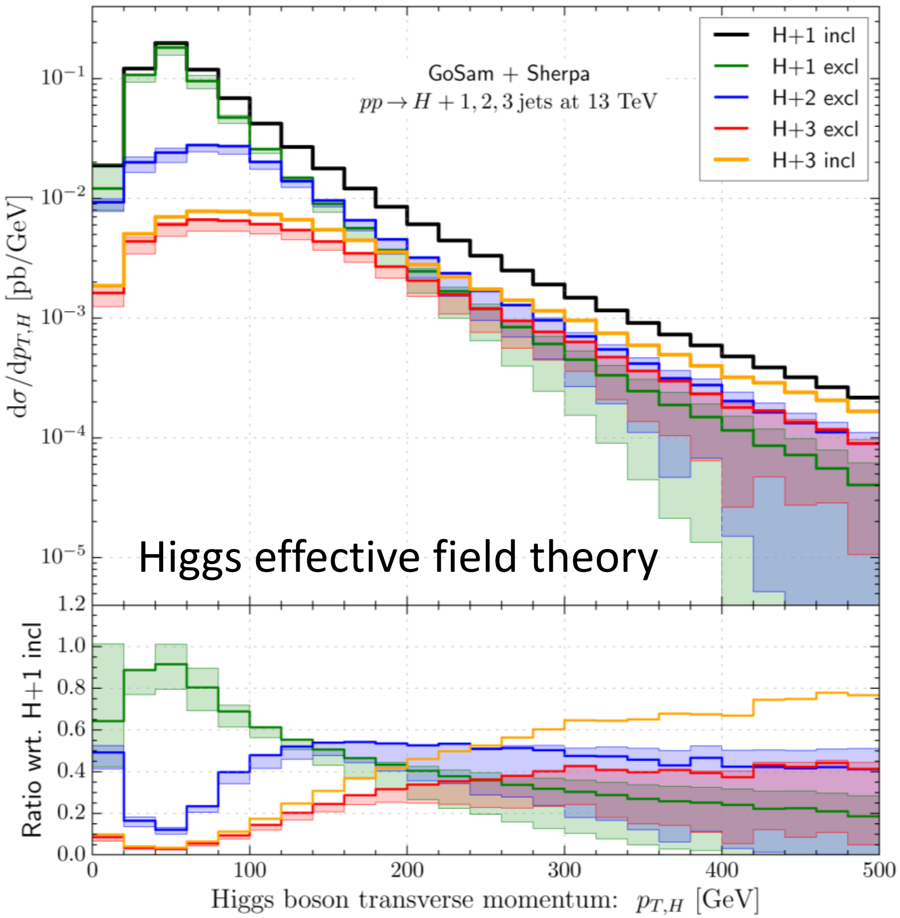
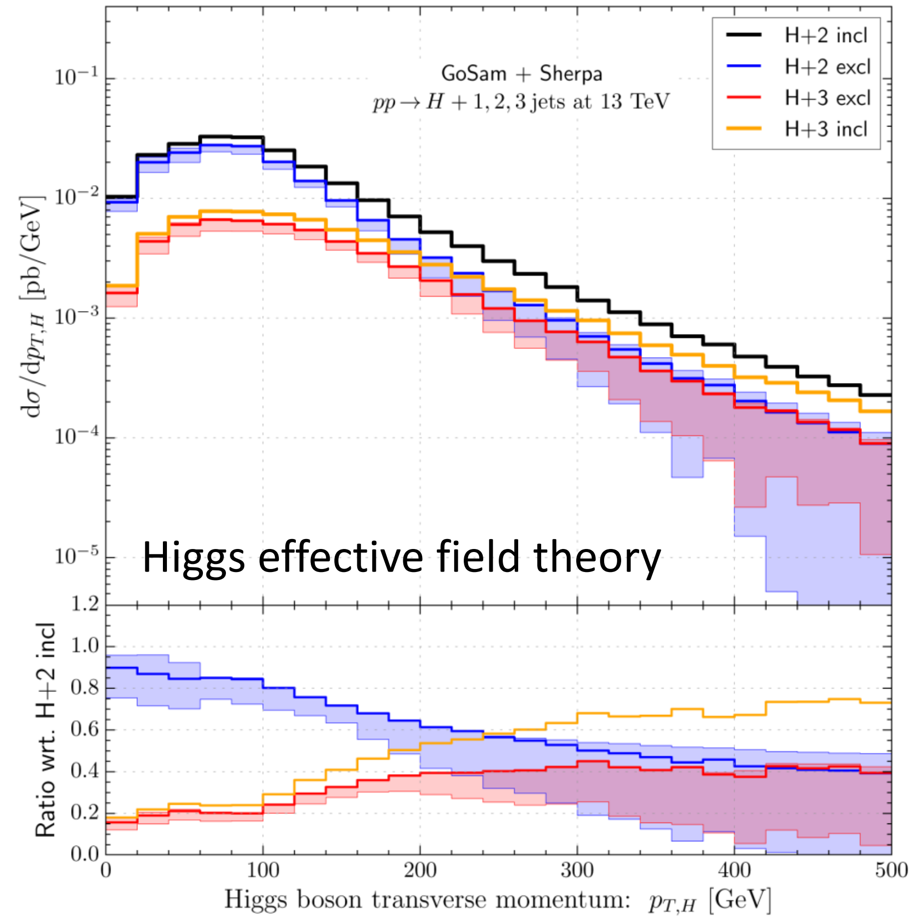


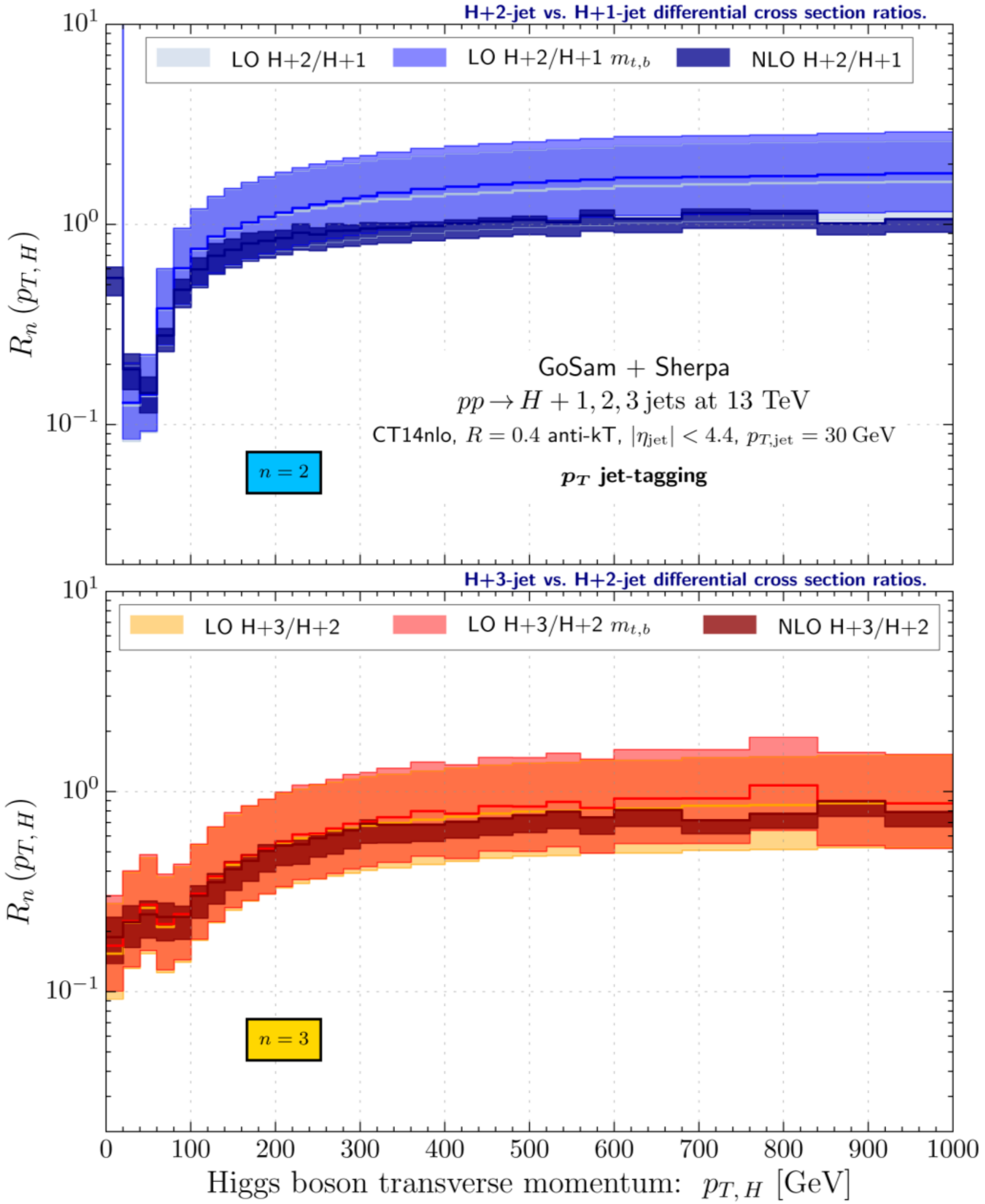


Higgs transverse momentum spectrum at 13 TeV

- Ratios of successive differential cross sections:

$$R_n(O) = \frac{\frac{\mathrm{d}\sigma}{\mathrm{d}O}(\mathrm{H}+n\,\mathrm{jets})}{\frac{\mathrm{d}\sigma}{\mathrm{d}O}(\mathrm{H}+(n-1)\,\mathrm{jets})}$$

- ➢ suggests that the different transverse momentum scaling of effective and full theory also holds for higher multiplicities
- ➢ relative importance of higher multiplicities remains stable under mass corrections

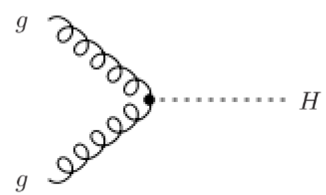


Transverse momentum scaling for large p_T

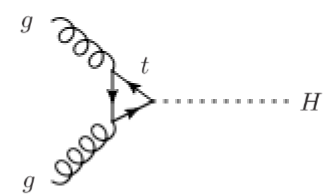
Interludio: Effective vs. Full theory scaling

- Breakdown of effective theory can be understood comparing the high energy limit of a pointlike ggH interaction with that of a loop-mediated one:

  - Consider the transverse momentum behaviour of the g*g* --> H amplitude (i.e. when gluons are off shell) [Catani, Ciafaloni, Hautmann, '91] [Hautmann, '02] [Pasechnik, Teryaev, Szczurek, '06] [Marzani, Ball, Del Duca, Forte, Vicini, '08]



Transverse momenta can reach kinematic limit given by CM energy



Contribution from large transverse momenta suppressed by massive quark loop

$$\hat{\sigma} \underset{\hat{s}\to\infty}{\sim} \begin{cases} \sum_{k=1}^{\infty} \alpha_s^k \ln^{2k-1}\left(\frac{\hat{s}}{m_H^2}\right) & \text{pointlike: } m_t \to \infty \\ \sum_{k=1}^{\infty} \alpha_s^k \ln^{k-1}\left(\frac{\hat{s}}{m_H^2}\right) & \text{resolved: finite } m_t \end{cases}$$

Corresponding scaling in Higgs p_T computed recently: [Forte Muselli, '15] [Caola, Forte, Marzani, Muselli, Vita, '16]

- as $p_{T,H} \to \infty$ differential cross section (in p_T^2):

drops like $(p_{T,H}^2)^{-1}$

drops like $(p_{T,H}^2)^{-2}$

Previous LO analysis:

- Effective theory starts to break down at about $p_{T,H} \approx 200$ GeV and NLO corrections start to become subdominant compared to mass effects.

- Define $R_{m_{t,b}}(O) \equiv \frac{\frac{d\sigma}{dO}\big|_{m_{t,b}}}{\frac{d\sigma}{dO}\big|_{\text{eff.}}}$

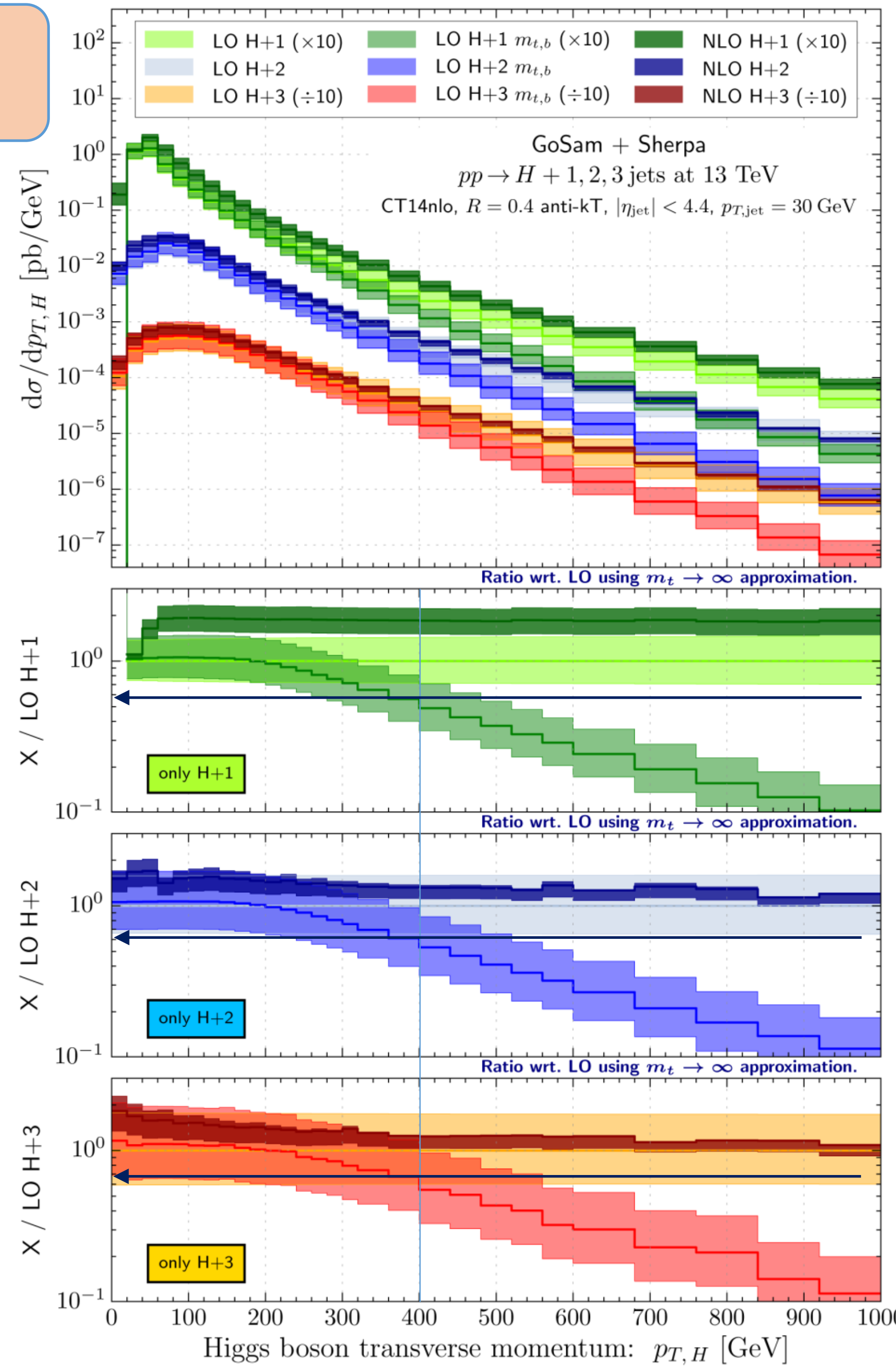
  then the rough scaling behavior from plots is given by

$$\frac{R_{m_{t,b}}(p_{T,H} = 1.0\ \text{TeV})}{R_{m_{t,b}}(p_{T,H} = 0.4\ \text{TeV})} \approx \frac{10\%}{60\%} = \frac{1}{6} = 0.167$$

  while the high energy limit prediction is

$$\left(\frac{400\ \text{GeV}}{1000\ \text{GeV}}\right)^2 = \frac{4}{25} = 0.16$$

➢ Very **similar** behavior for the three different multiplicities



New update at NLO:

- Check on double logarithmic scale:

- Consider points at 100 GeV and 1 TeV:

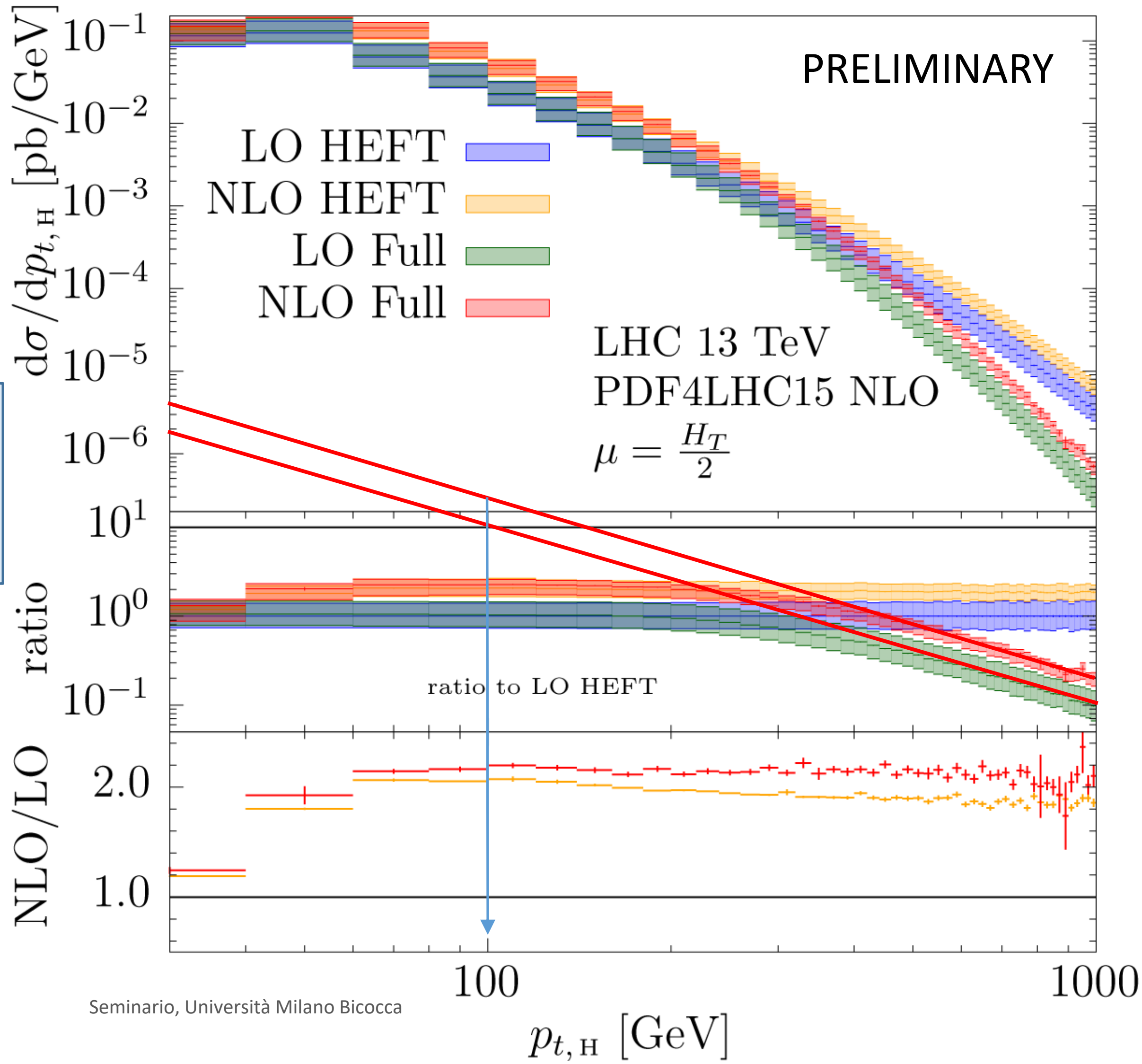
$$\left(\frac{100\ \mathrm{GeV}}{1000\ \mathrm{GeV}}\right)^2 = \frac{1}{100}$$

$$\frac{R_{m_t}(p_{T,H} = 1.0\ \mathrm{TeV})}{R_{m_t}(p_{T,H} = 0.1\ \mathrm{TeV})} \approx \frac{10\%}{x\%} \stackrel{!}{=} \frac{1}{100}$$

$$\Longrightarrow x = 1000$$

So at 100 GeV Full should be a factor of 10 larger, as confirmed from the plot

At NLO **same scaling**!



Conclusions and Outlook

- Presented new NLO QCD results on **top-quark mass** effects in H+1 jet production
  - NLO cross section is **enhanced** compared to HEFT (beware of bottom-quark effects)
  - **Stable K-factor** for transverse momentum distribution
  - **Slight increase** compared to NLO in FT_{approx}

- This opens the possibility for many further computations:
  - H+1 jet with full **top-** and **bottom-quark** mass effects
  - Matching to **parton shower** / MiNLO / NNLOPS (POWHEG BOX, Geneva, …)
  - Matching to analytical **resummation**
  - Inclusive Higgs production with full mass dependence at **NNLO** in QCD