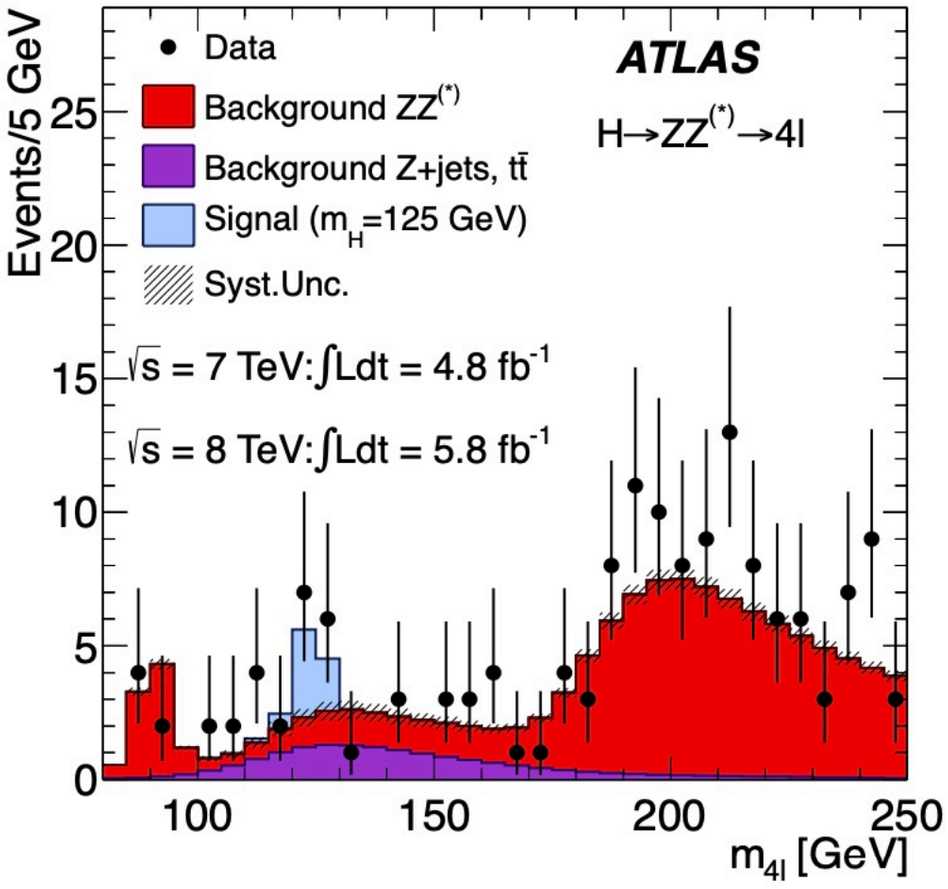
STATUS OF PRECISION CALCULATIONS FOR HIGGS PHYSICS

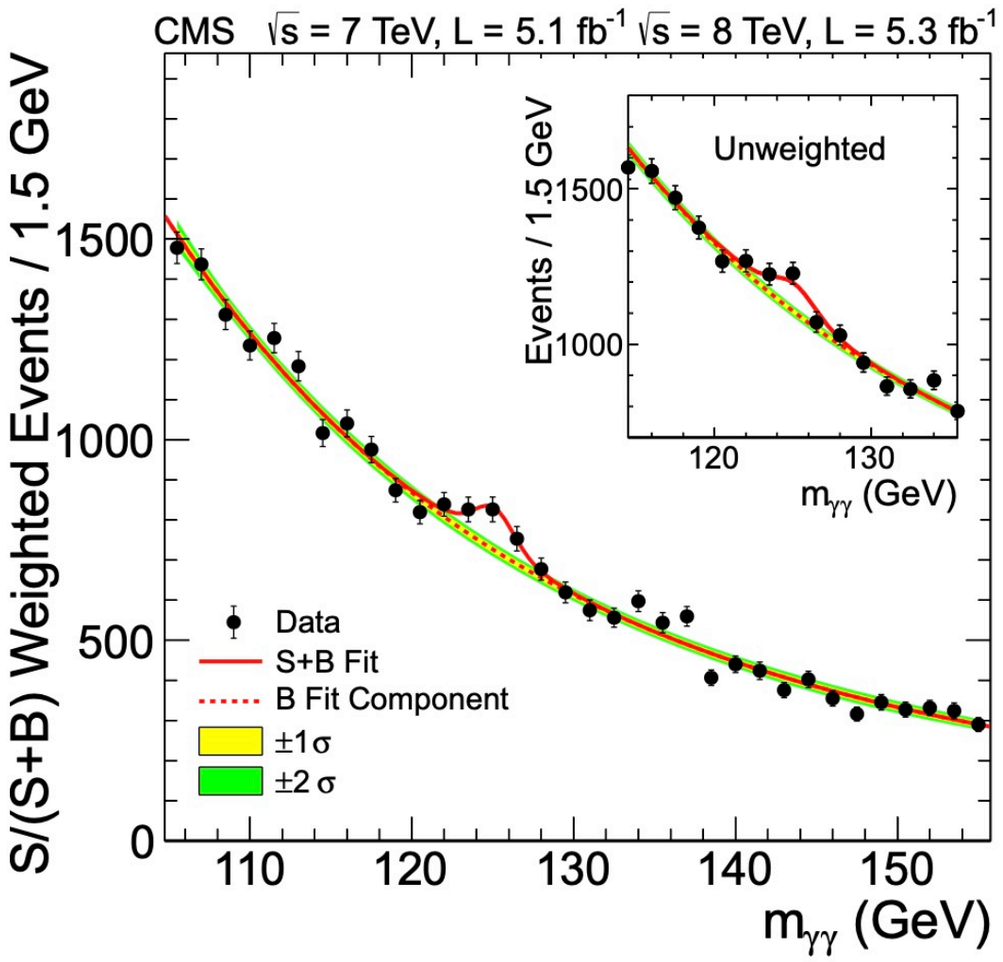
ICHEP 2022
Bologna – 08/07/2022

Lorenzo Tancredi – Technical University Munich

INTRODUCTION: WHY THE HIGGS?

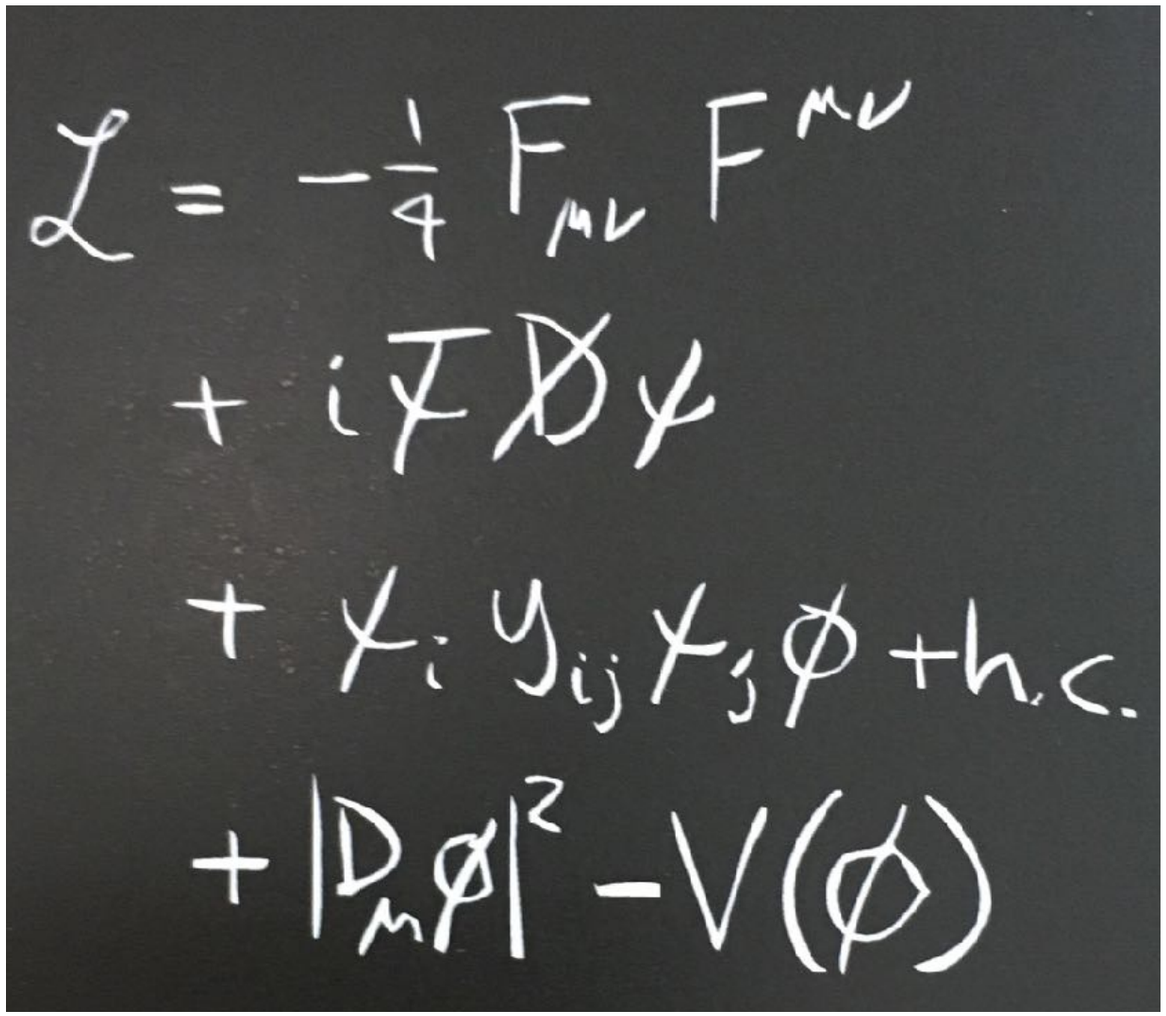
10 years after its discovery, the Higgs remains the coolest kid in the room





Higgs is "**new physics**", scalar fundamental field, main actor in SSB, origins of masses of all (?) standard model particles…

INTERACTIONS!

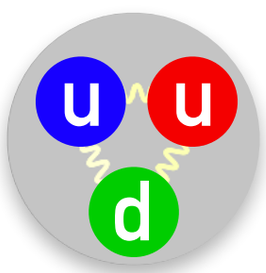


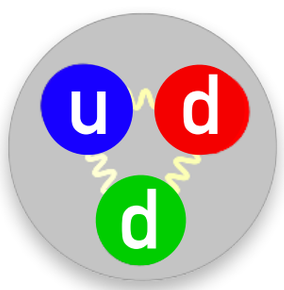
Yukawa interactions are the most mysterious…

Masses of all particles, ultimately chemistry and life!

Proton Stability !

$m_p = 938.3$ MeV

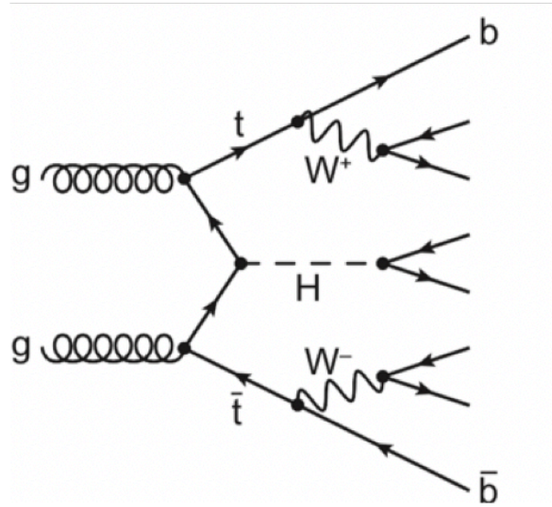




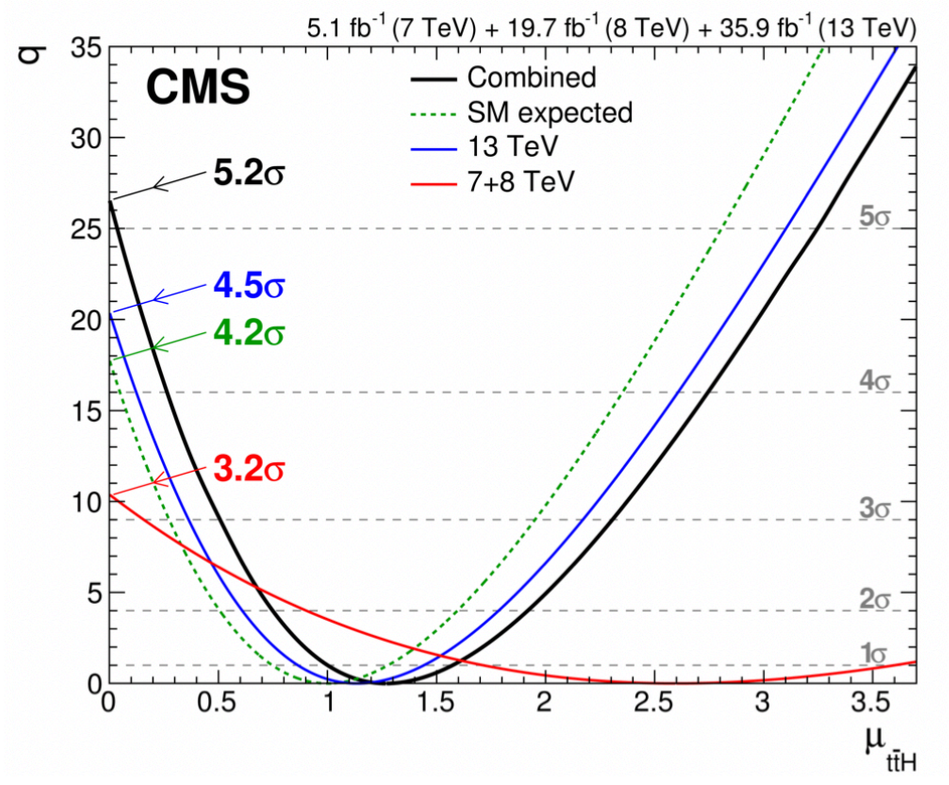
$m_n = 939.6$ MeV

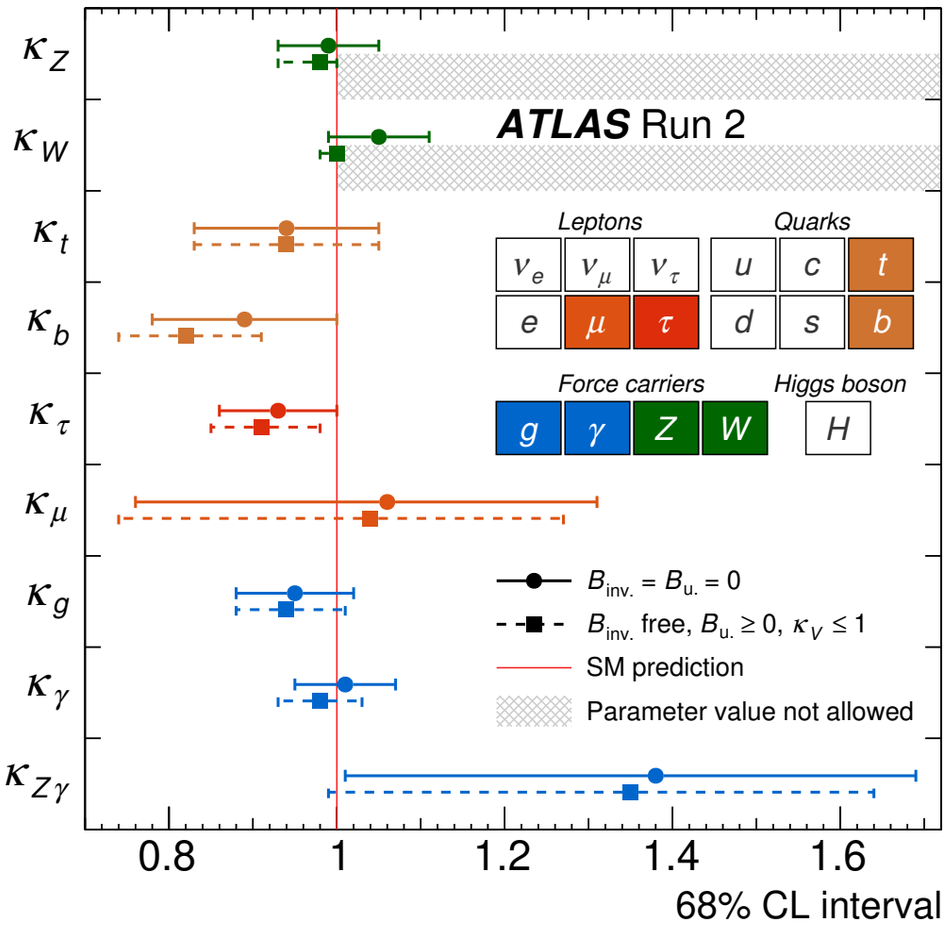
INTRODUCTION: WHY THE LHC?

The LHC is the first machine able to probe this energy scale!



Run 2 direct observation of H coupling to gauge bosons and **third family fermions**!





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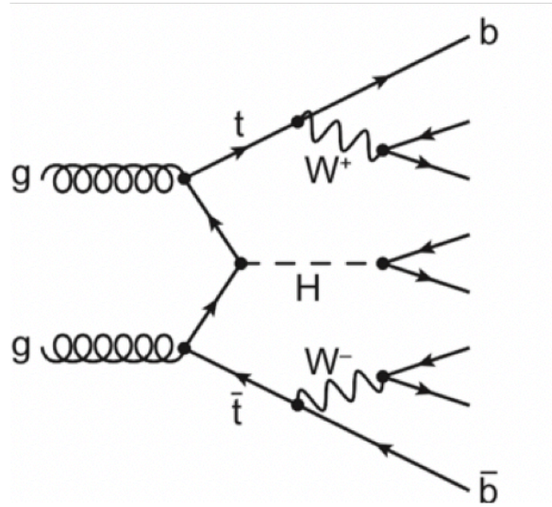

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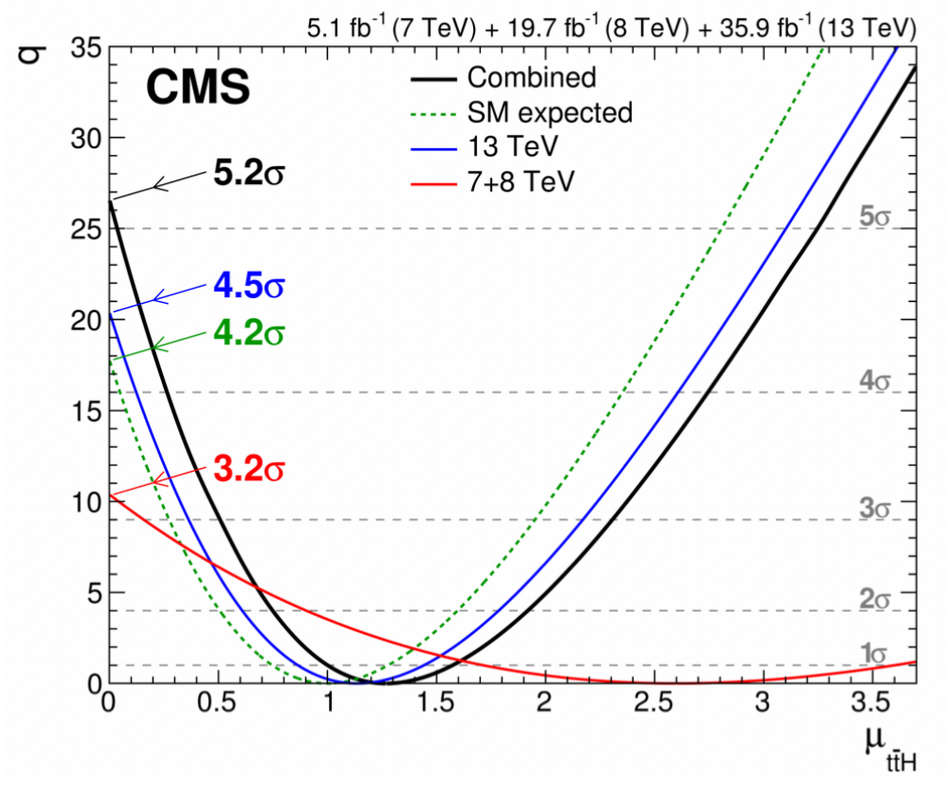
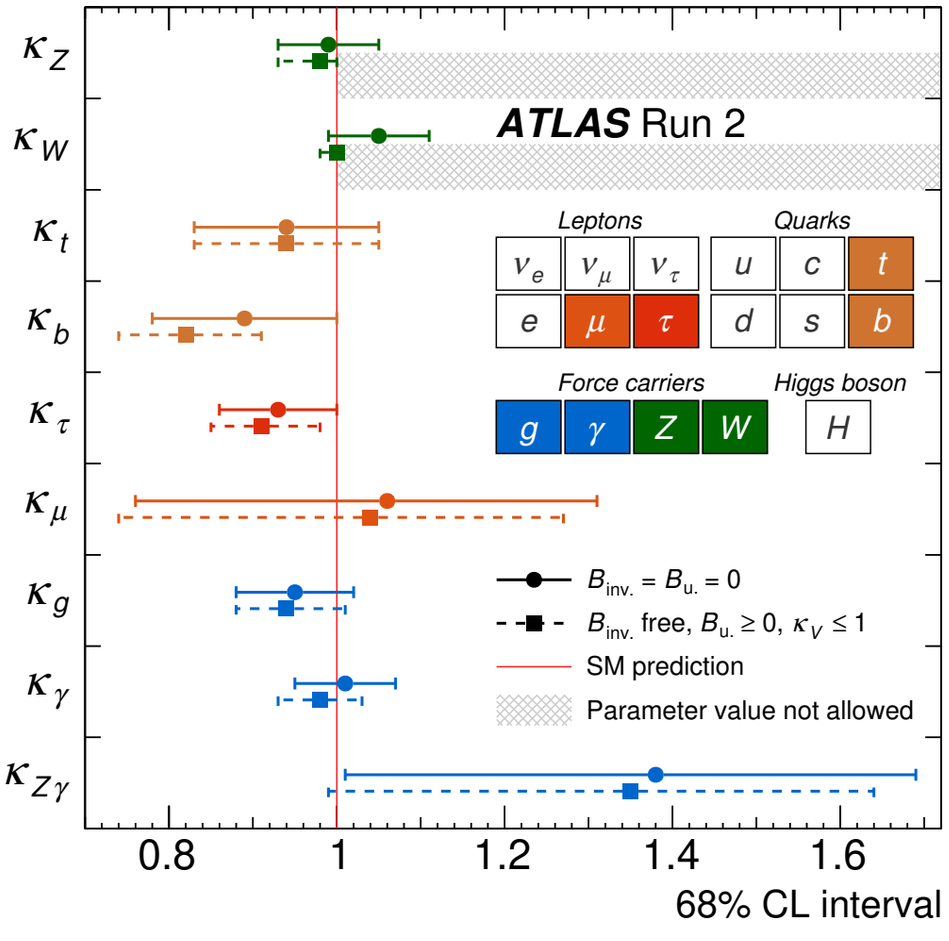
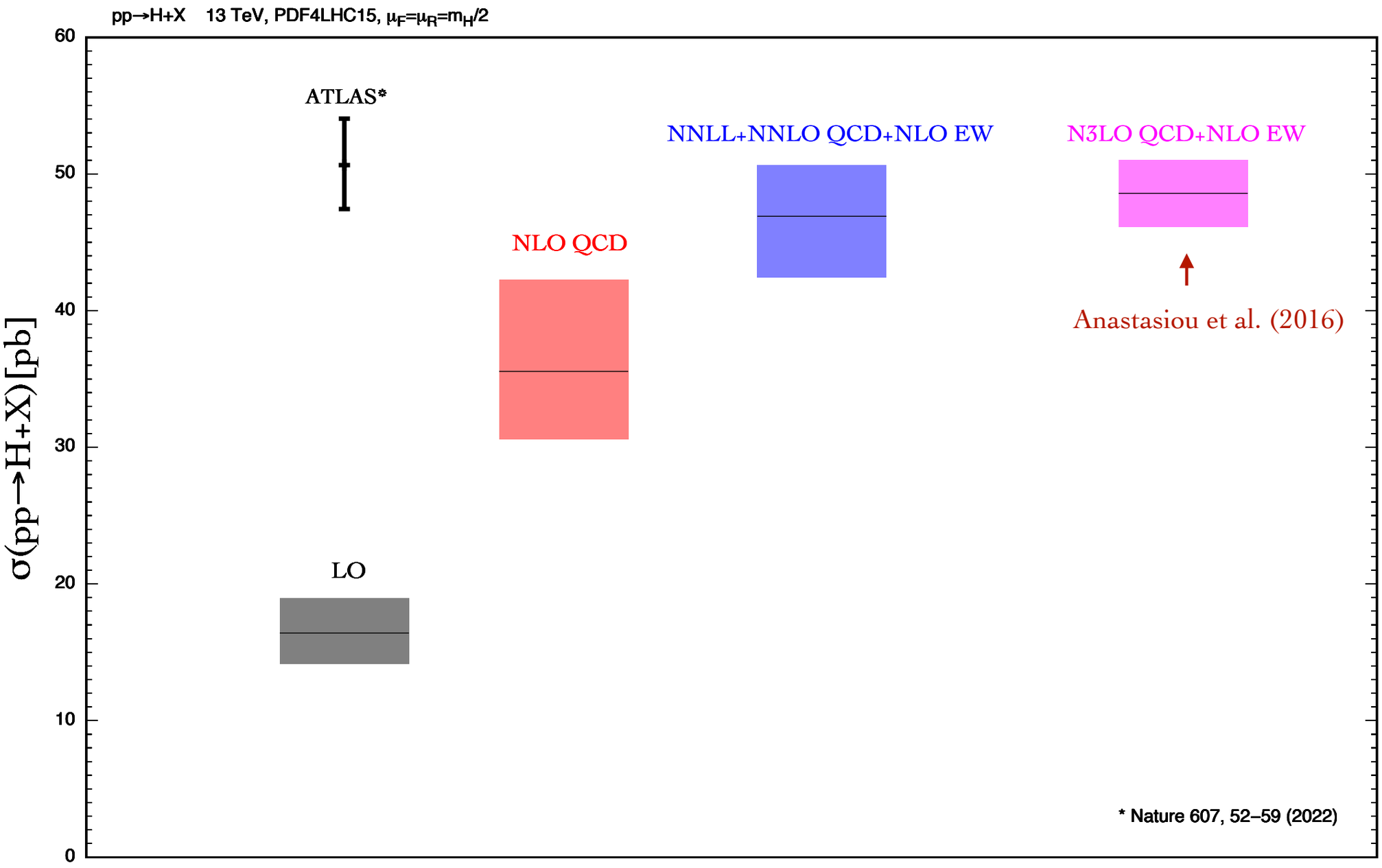




Run 3 and HL potential:

1. **Precision** measurements for third family
2. **Discovery couplings to second family**!

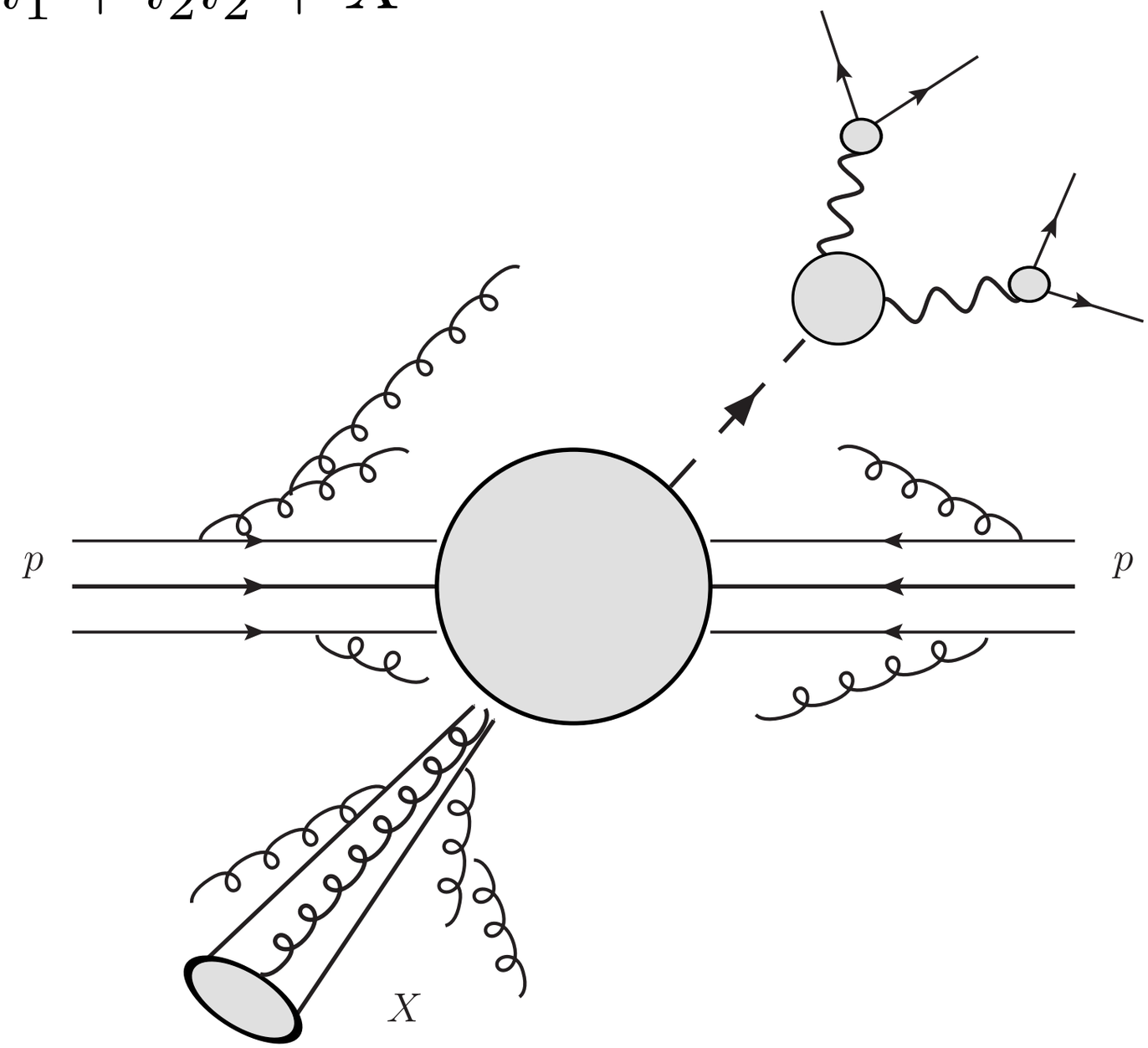
THE NEED OF PRECISION



[Slide from M. Grazzini, CERN, 4.07.22]

PRECISION PHYSICS AT THE LHC: HOW FAR CAN WE GO?

$$pp \to HX \to l_1\bar{l}_1 + l_2\bar{l}_2 + X$$

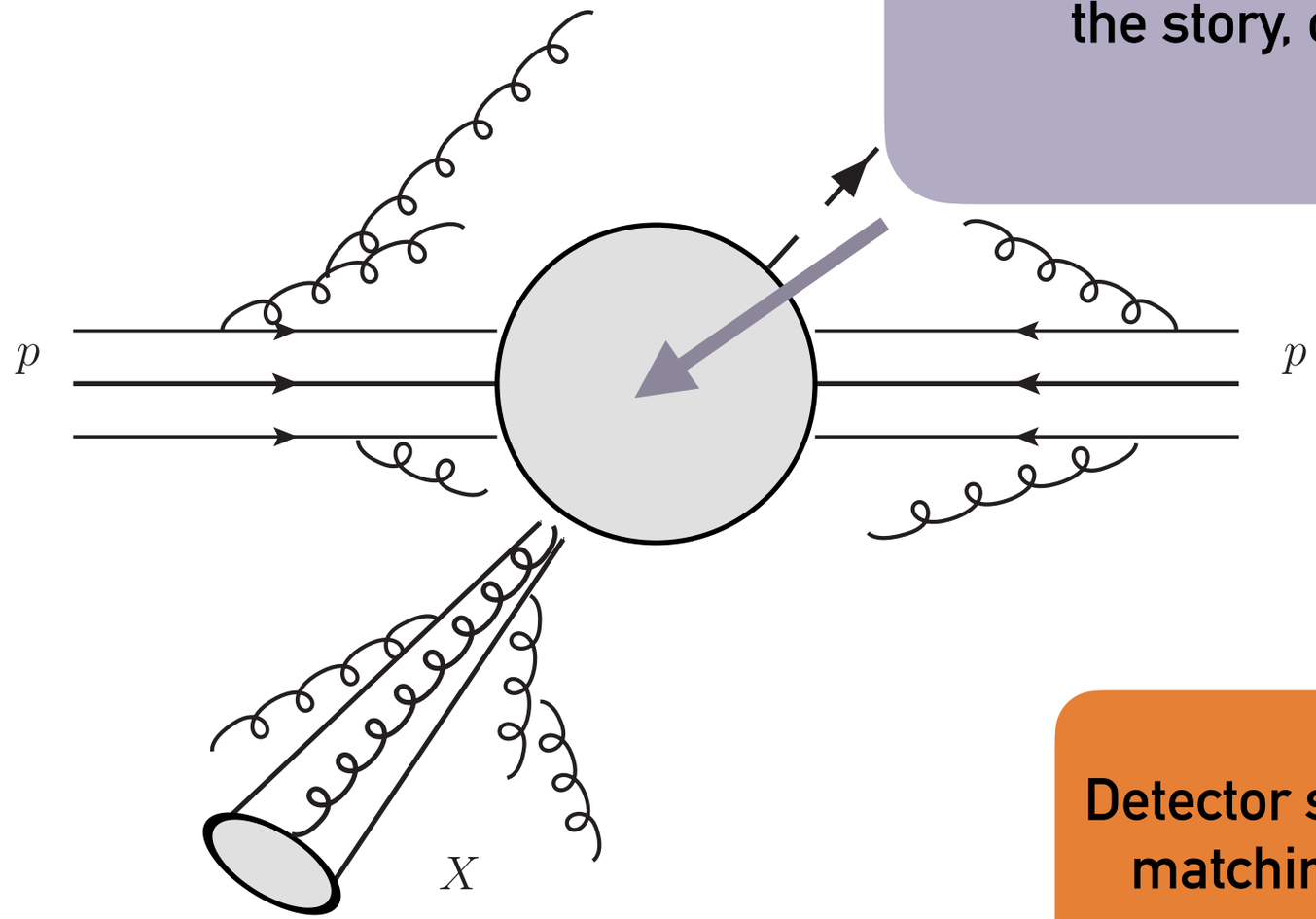


PRECISION PHYSICS AT THE LHC: HOW FAR CAN WE GO?

$$pp \to HX \to l_1\bar{l}_1 + l_2\bar{l}_2 + X$$

Factorisation theorems, PDFs…?

Hard scattering is only a part of the story, of course



Parton Shower, Hadronisation, Fragmentation …

Detector simulation matching, etc…

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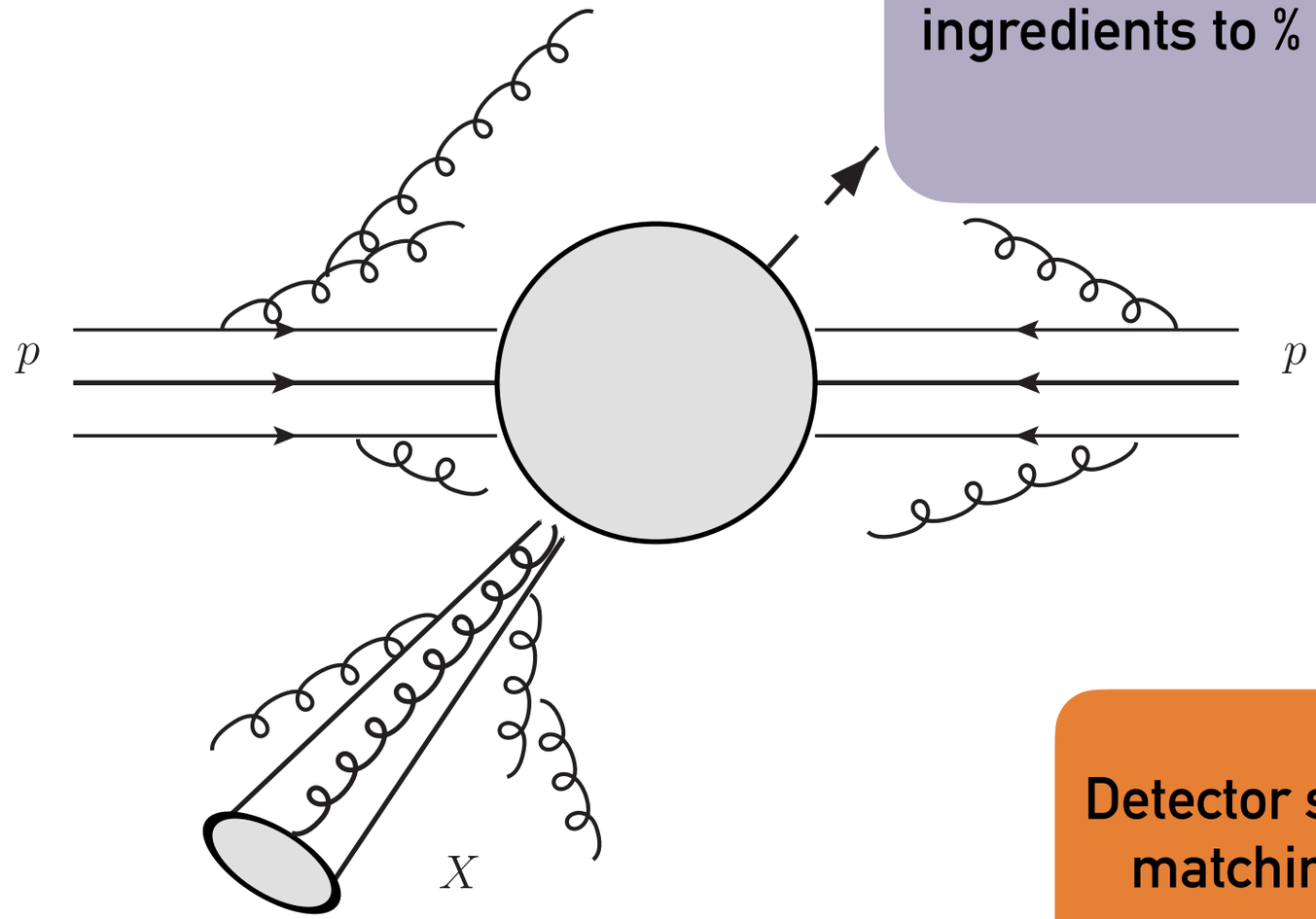


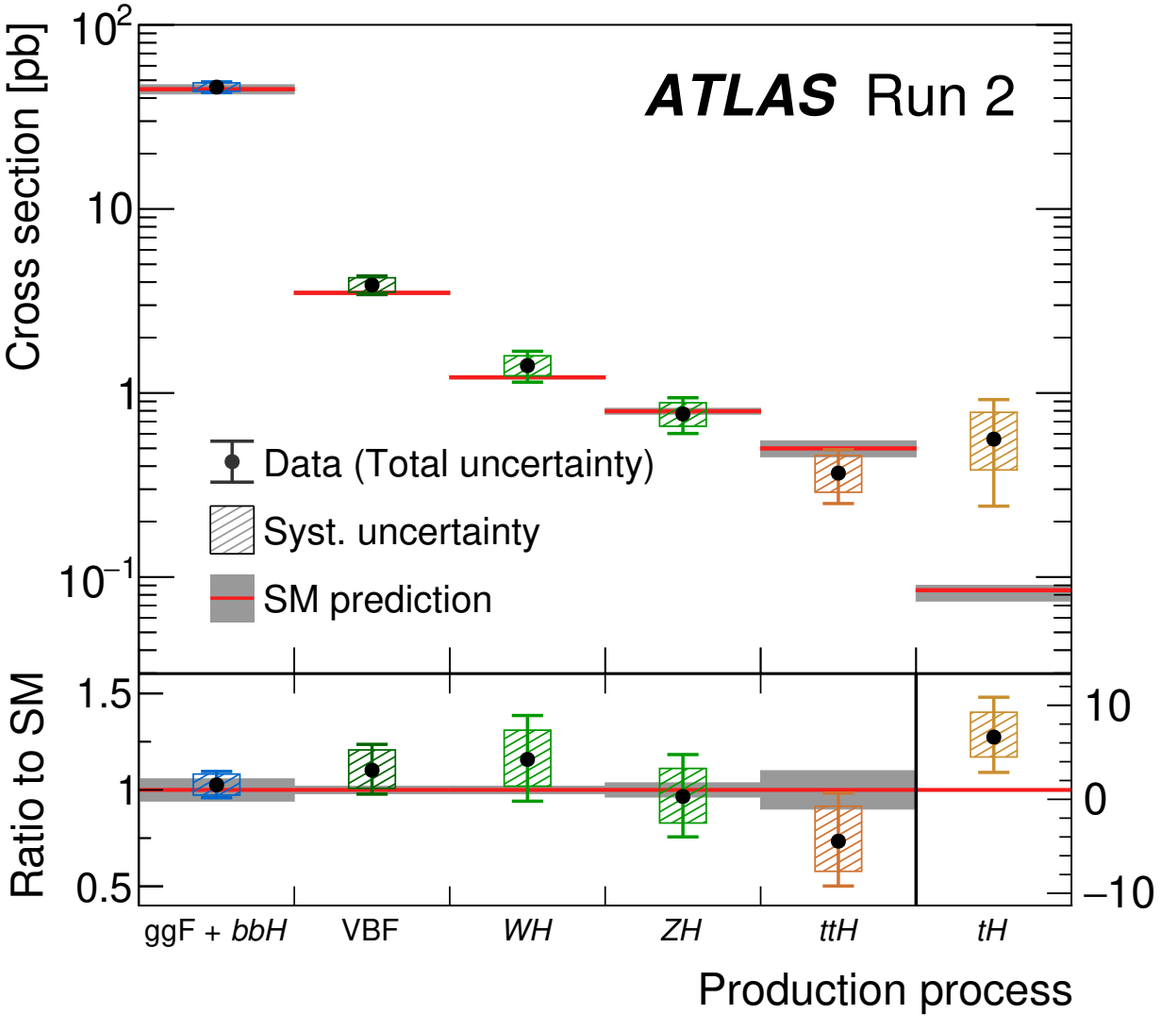
Theorist's goal: push all these ingredients to % level precision!

Parton Shower, Hadronisation, Fragmentation …

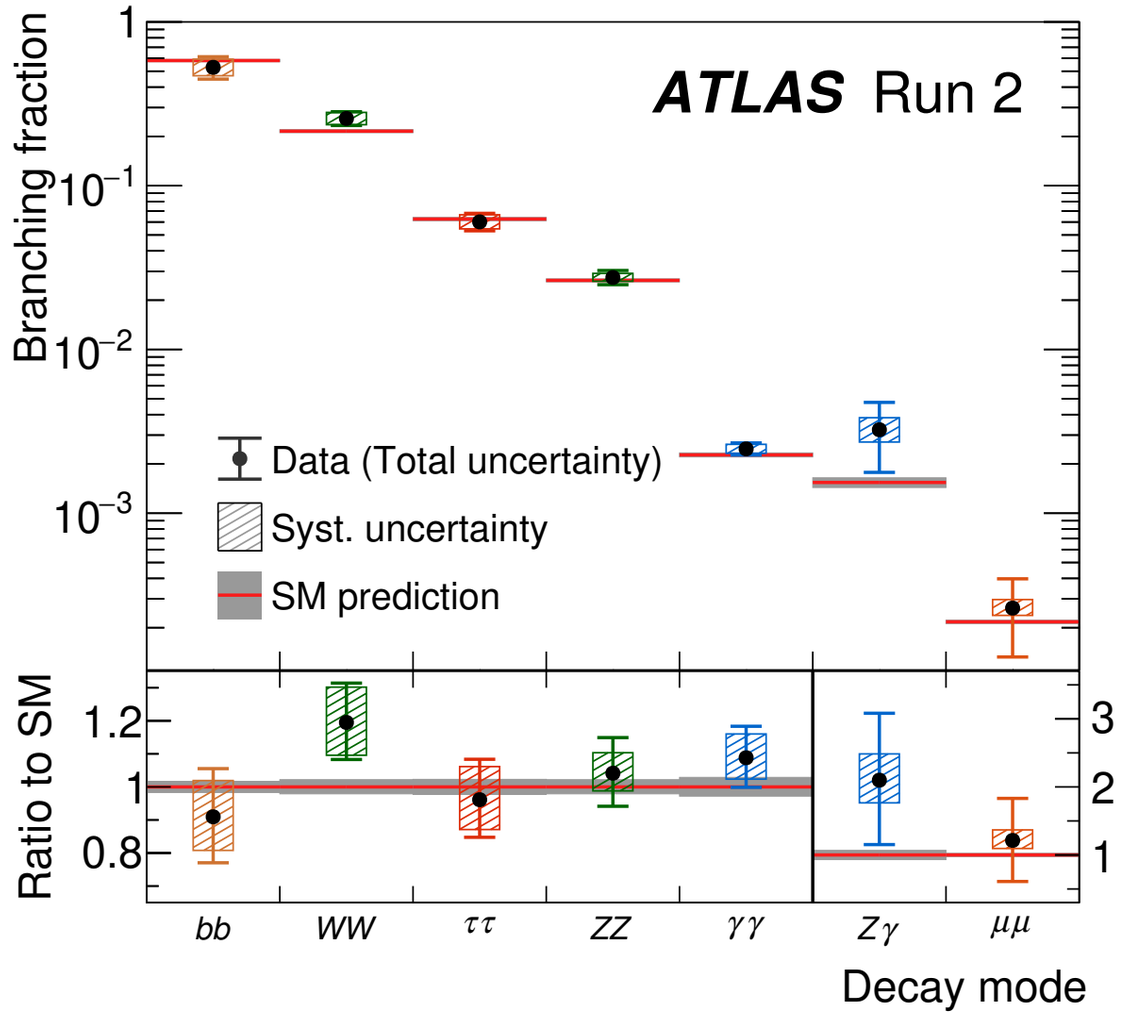
Detector simulation matching, etc…

HIGGS PRODUCTION AND DECAYS

Production channels



Decay channels



[ATLAS arXiv:2207.00092]

HIGGS PRODUCTION AND DECAYS

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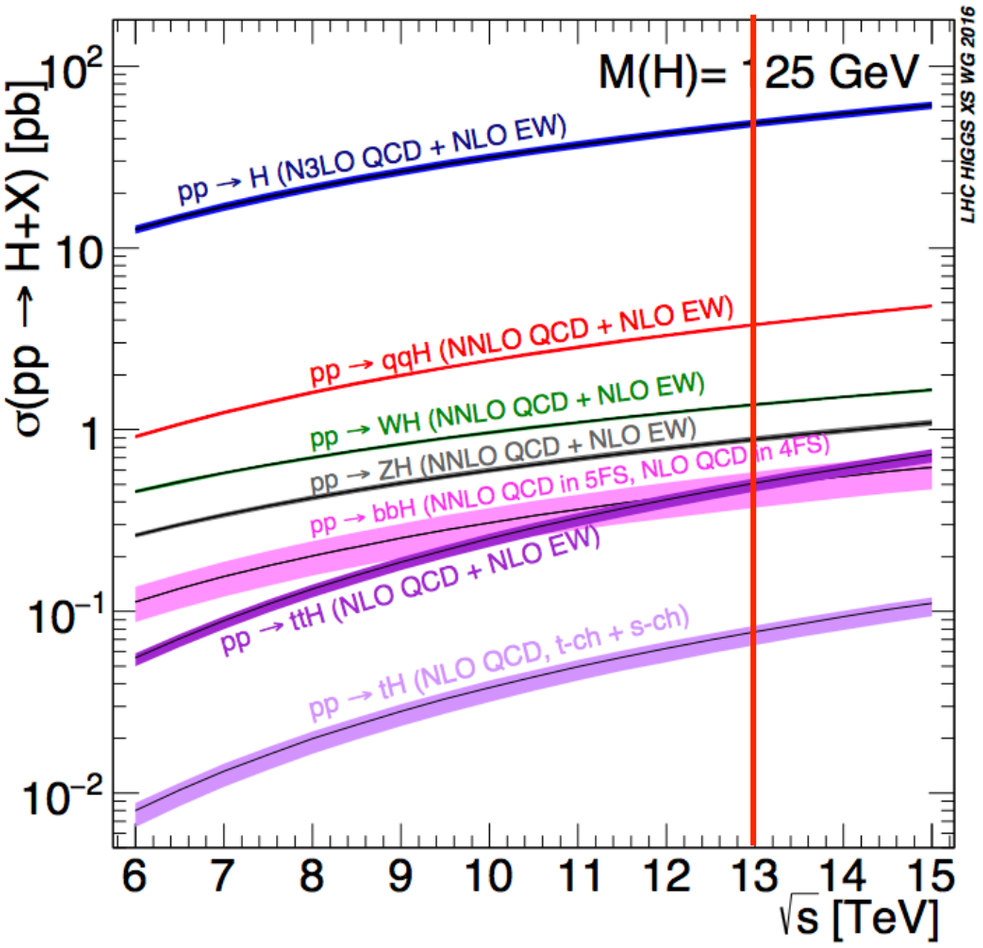

$\sqrt{s}$ (TeV)	Production cross section (in pb) for $m_H = 125\,\text{GeV}$					
	ggF	VBF	WH	ZH	$t\bar{t}H$	total
13	$48.6^{+5\%}_{-5\%}$	$3.78^{+2\%}_{-2\%}$	$1.37^{+2\%}_{-2\%}$	$0.88^{+5\%}_{-5\%}$	$0.50^{+9\%}_{-13\%}$	55.1

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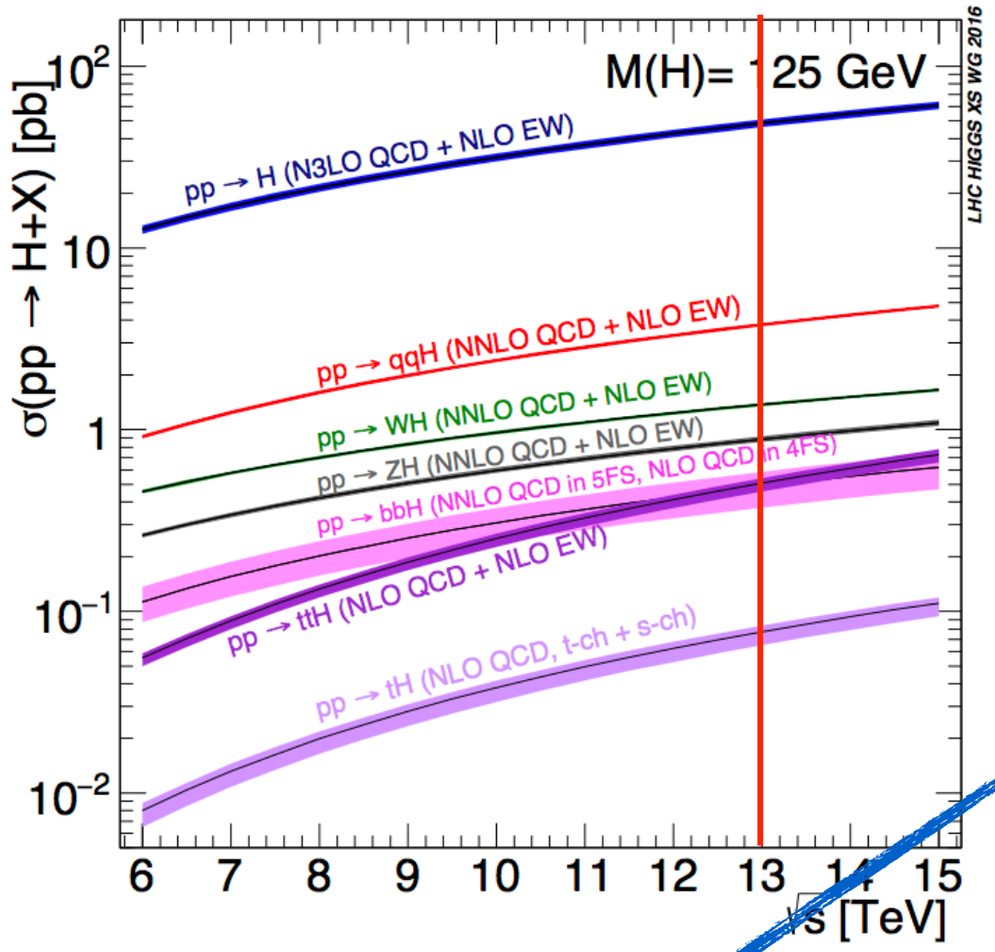

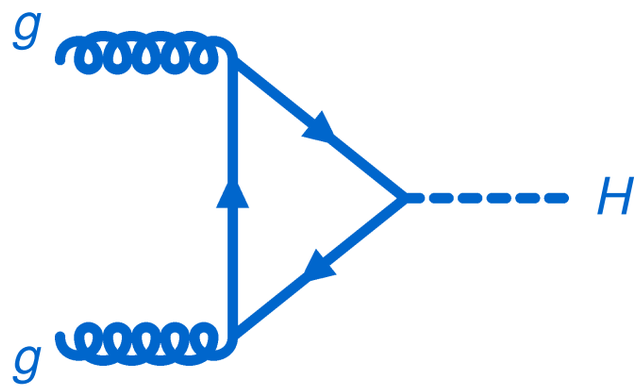

~ 87%

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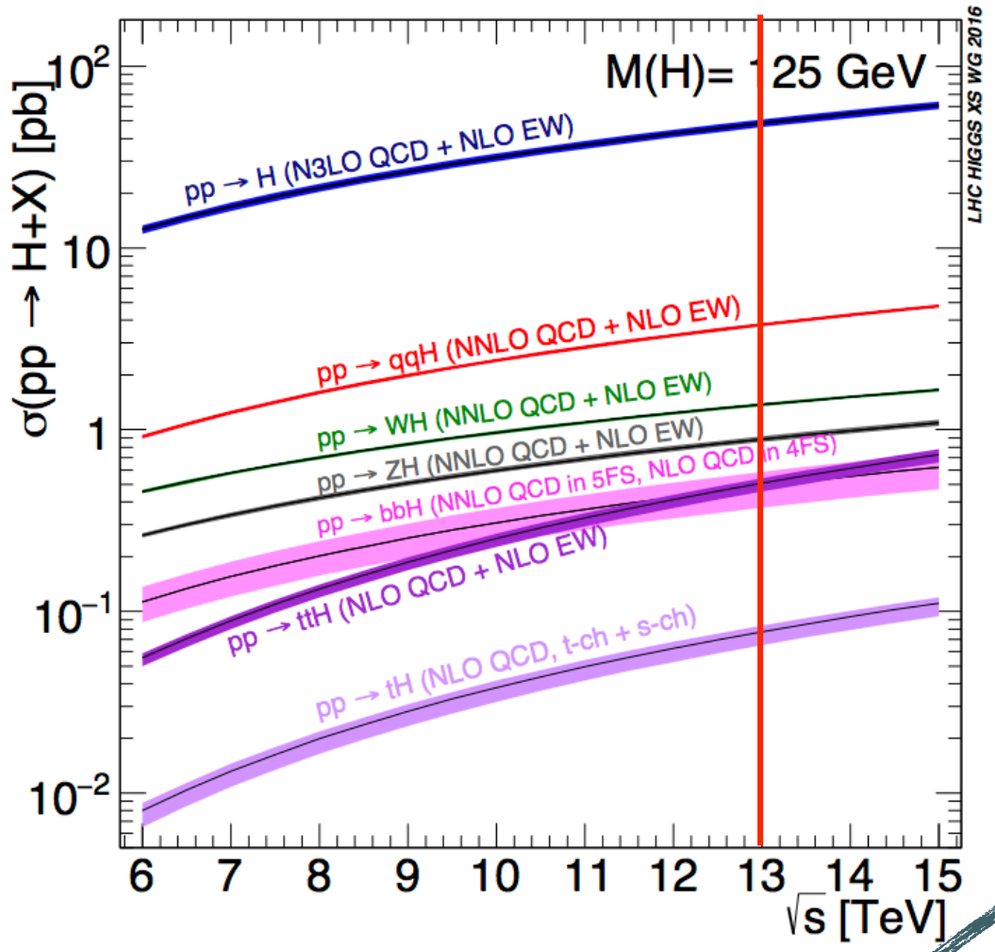
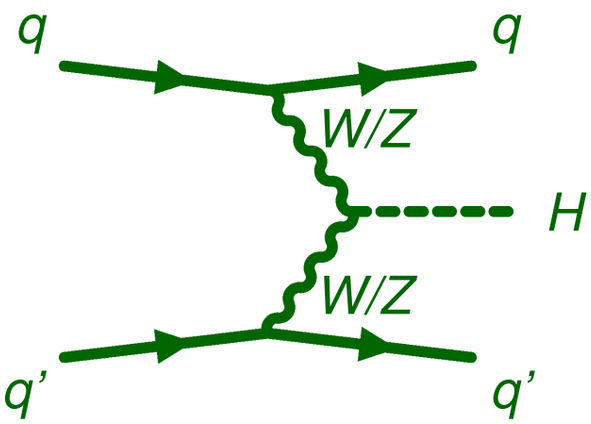
ggF main focus

HIGGS PRODUCTION AND DECAYS

Production channels





~ 7%

$\sqrt{s}$ (TeV)	Production cross section (in pb) for $m_H = 125\,\text{GeV}$					
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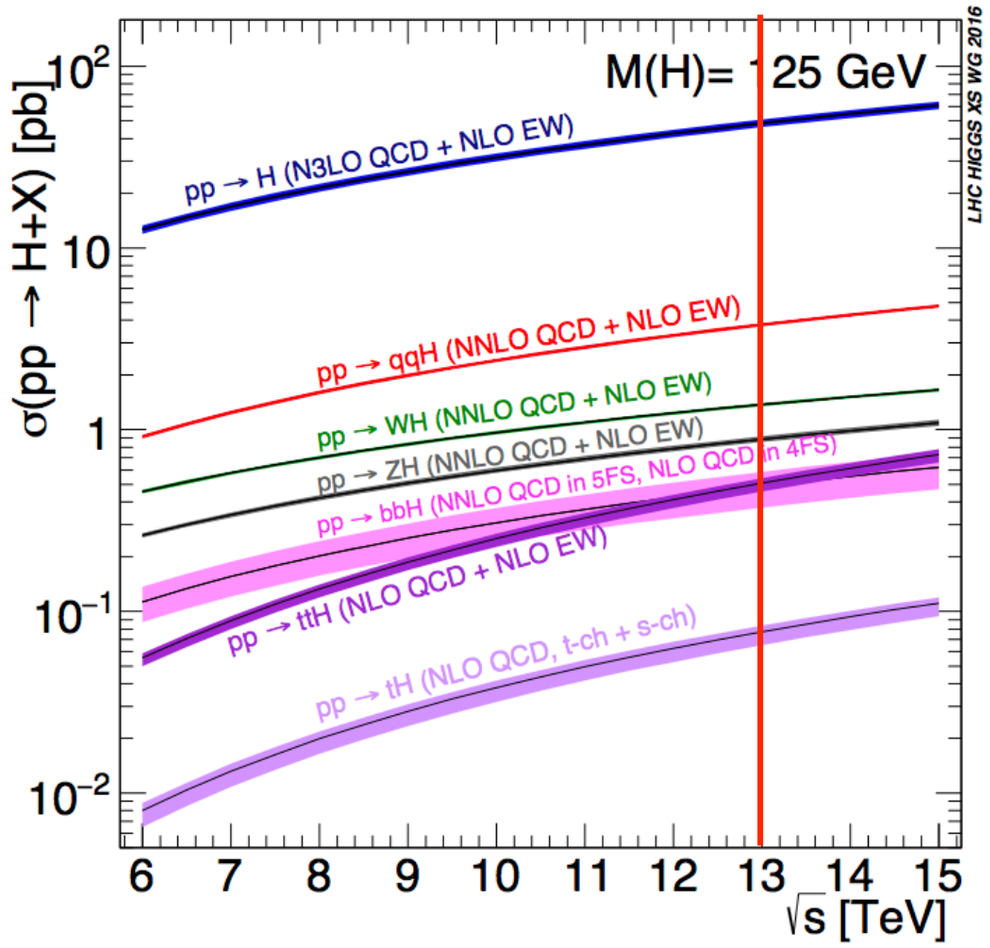
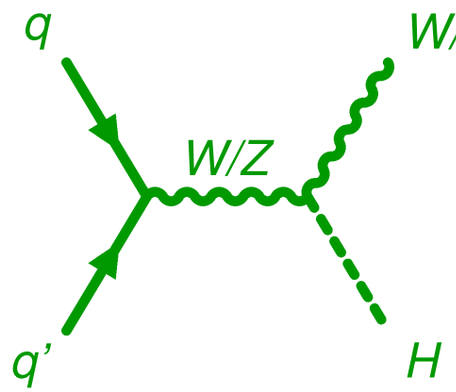
See Xuan Chen's Talk!

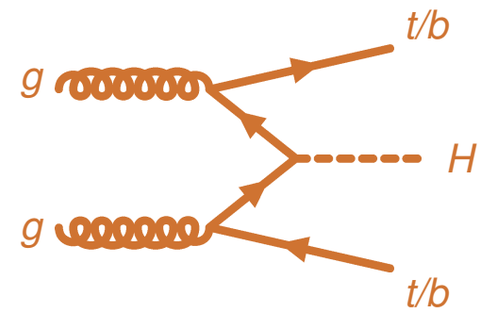
HIGGS PRODUCTION AND DECAYS

Production channels



~ 4%





~ 1%

$\sqrt{s}$ (TeV)	Production cross section (in pb) for $m_H = 125\,\text{GeV}$					
	ggF	VBF	WH	ZH	$t\bar{t}H$	total
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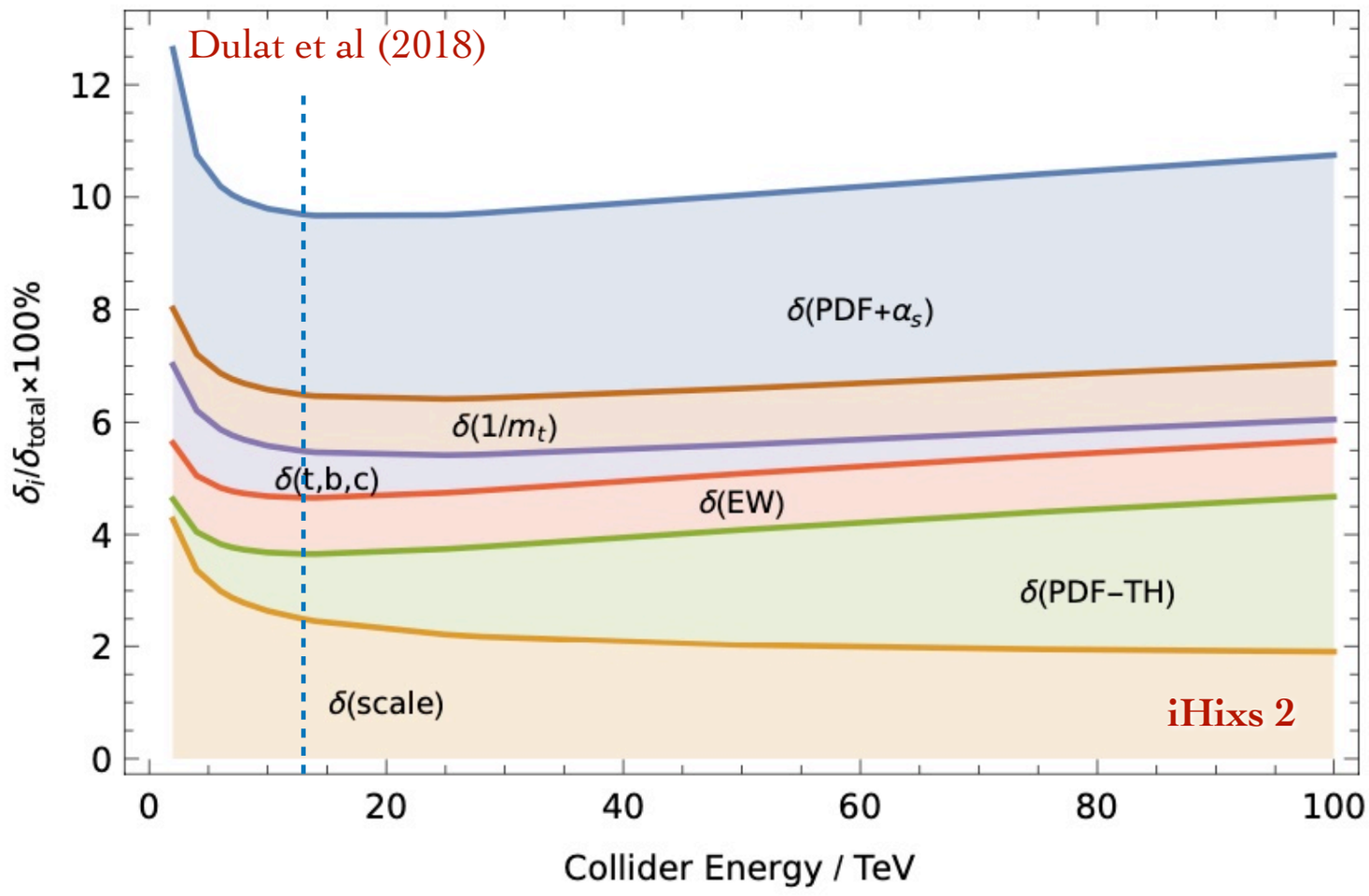
if aiming at % level precision, they are desirable

GLUON FUSION

THEORY STATUS FOR GGF HIGGS

QCD was long main priority: amount to **95%** of the ggF channel!

ggF known at N^3LO in HEFT ~ 1-2% uncertainty



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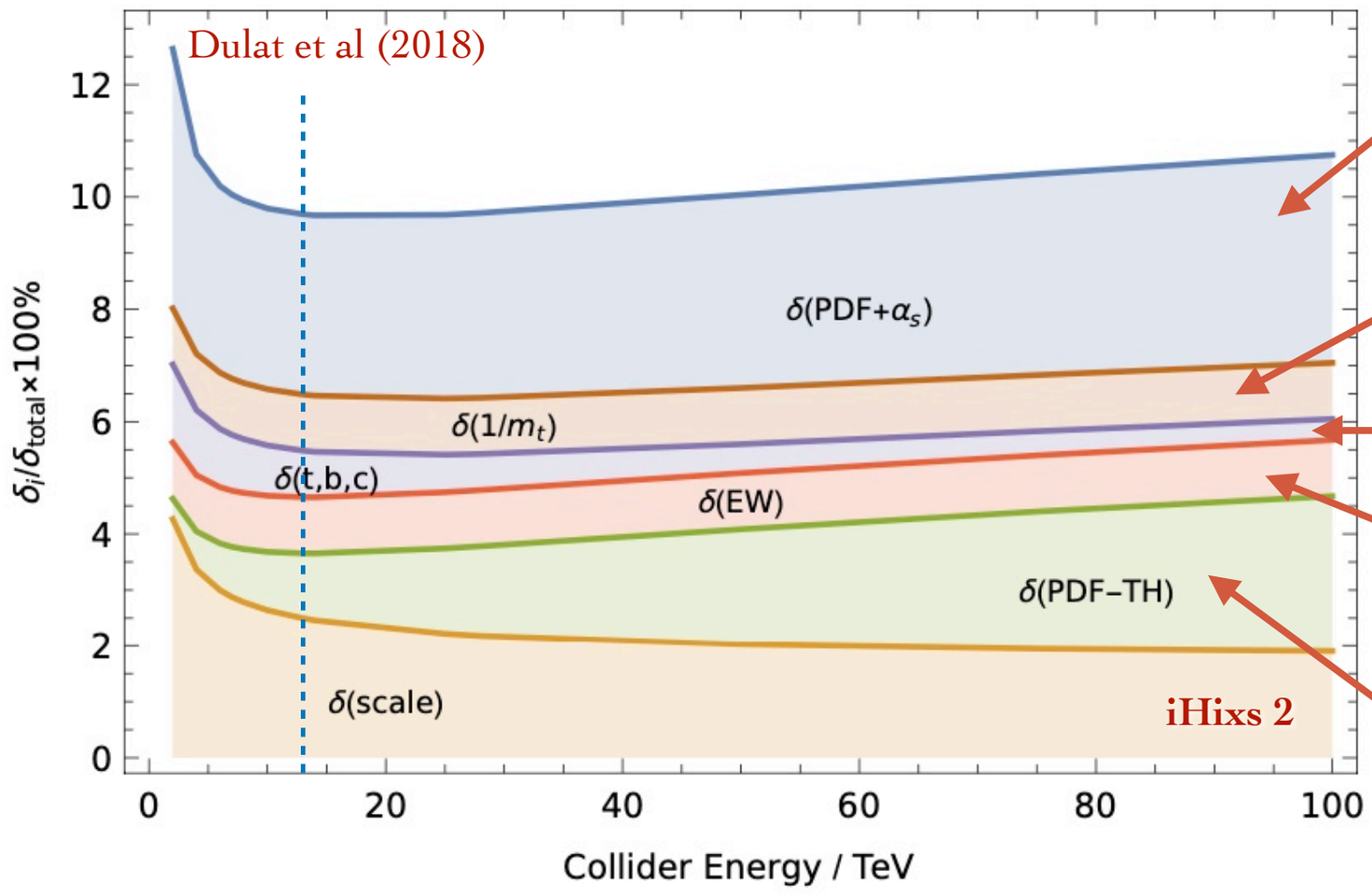


$\alpha_s = 0.118 \pm 0.001 \rightarrow \mathcal{O}(2\%)$
uncertainty on x-section

Exact top mass dependence

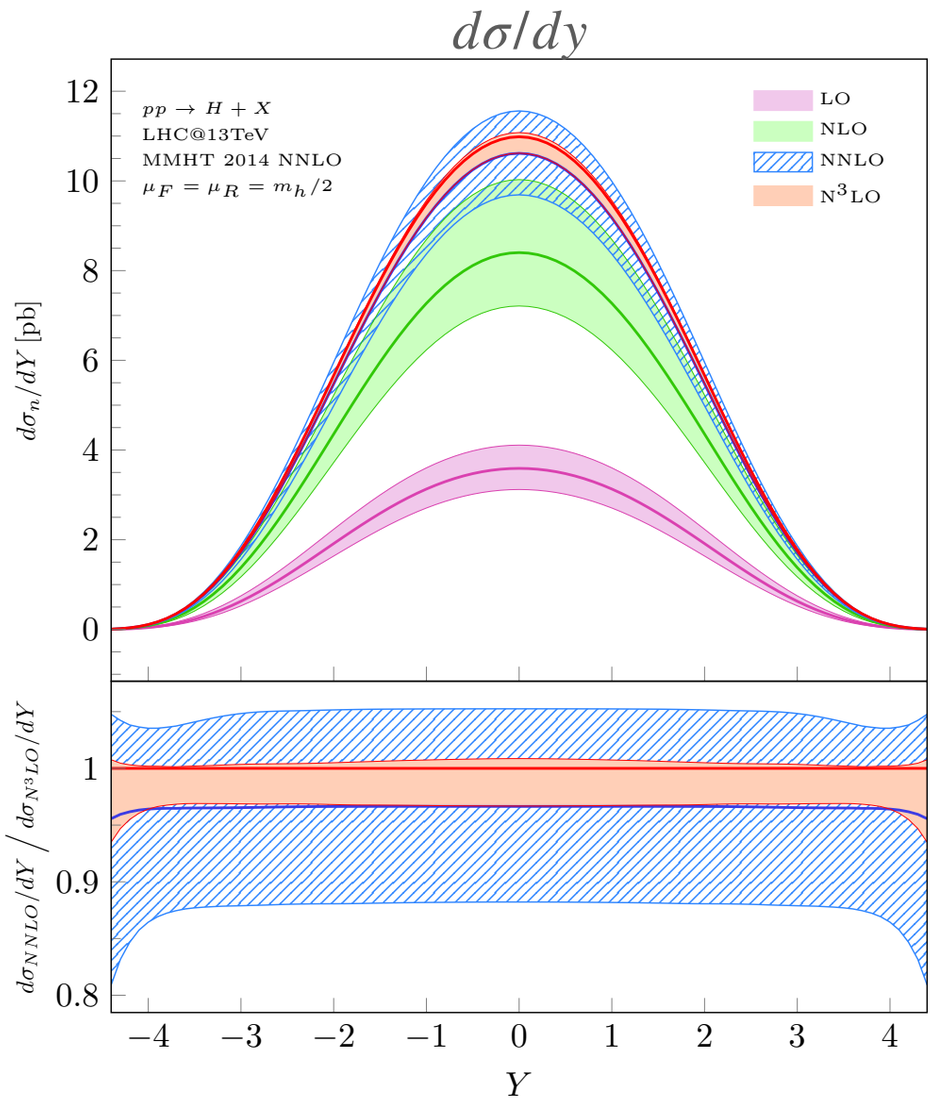
Bottom mass contribution

QCD+EW mixed contributions

requires N^{3}LO PDFs

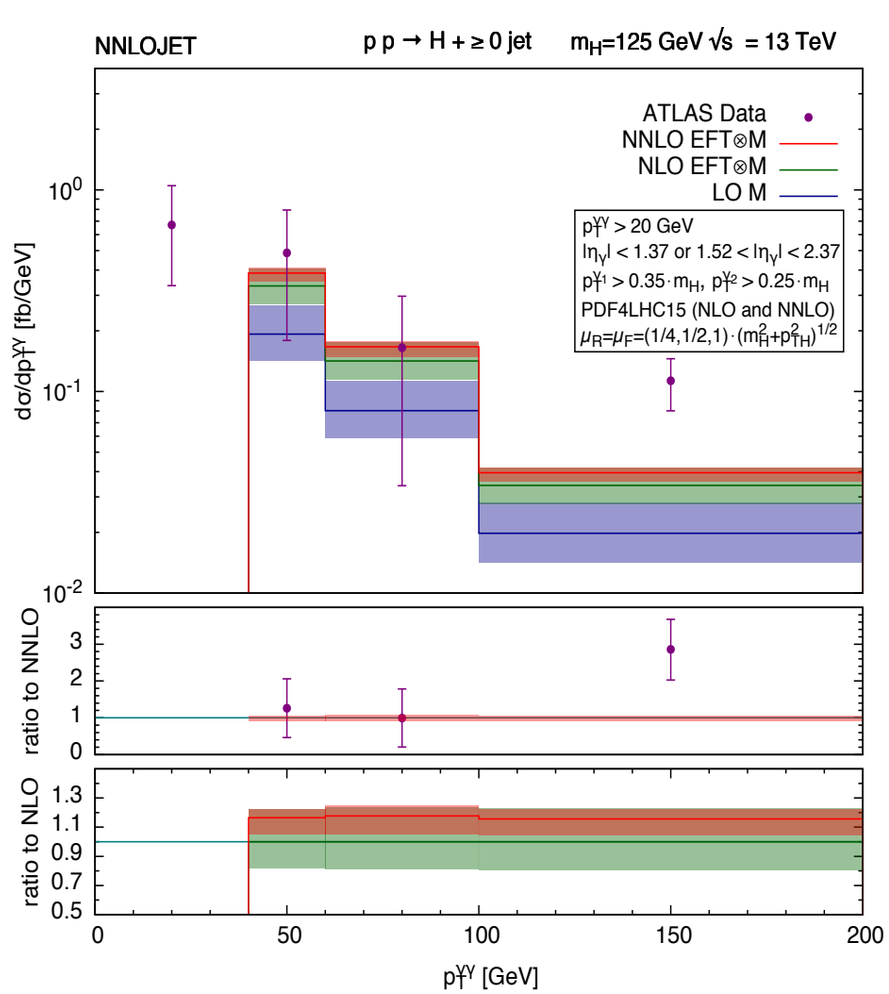
GLUON FUSION IN QCD

First impressive example of N^3LO calculation, both inclusive and **fully differential**…



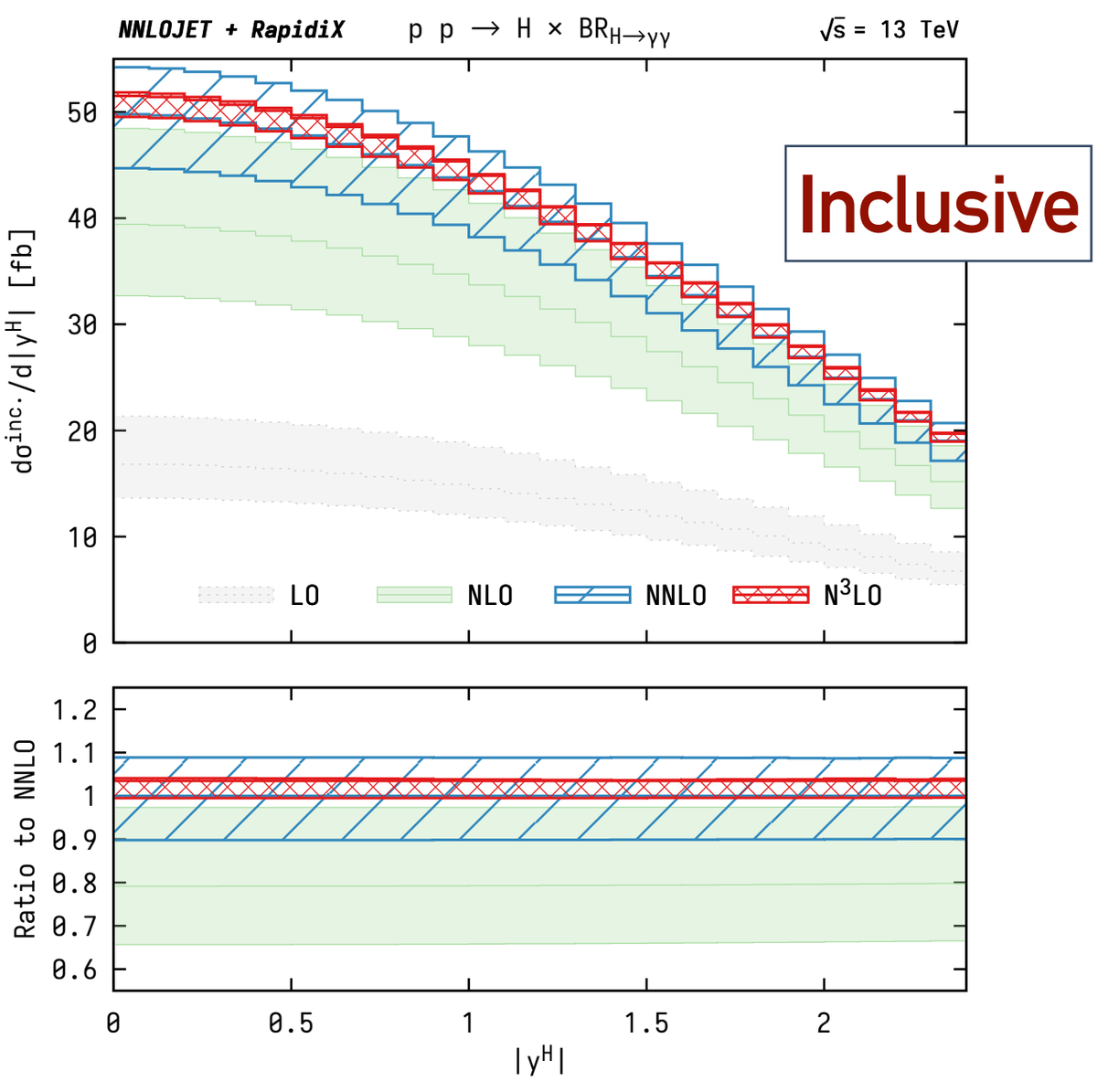
INGREDIENTS

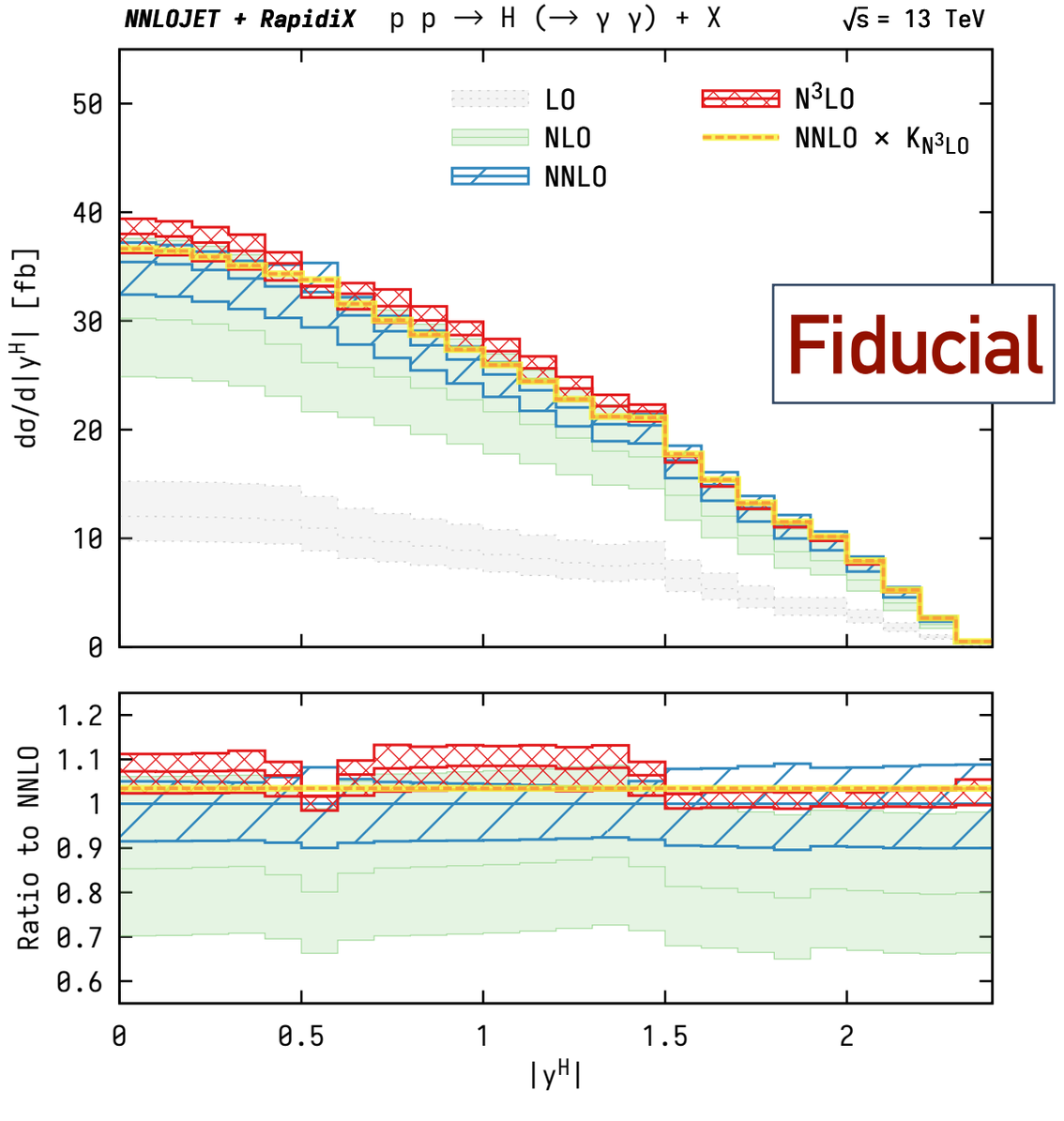
1. Fully Inclusive N^3LO (analytic!) **[Mistlberger 2018]**
2. Results for rapidity distribution **[Dulat, Mistlberger, Pelloni 2018]**
3. Precise numerical control on H+j **[NNLOjet collaboration]**



GLUON FUSION IN QCD FULLY DIFFERENTIAL N3LO

Put everything together with **Projection to Born** method [Cacciari, Dreyer, Karlberg, Salam, Zanderighi 2015]





[Chen, Gehrmann, Glover, Huss, Mistlberger, Pelloni 2021]

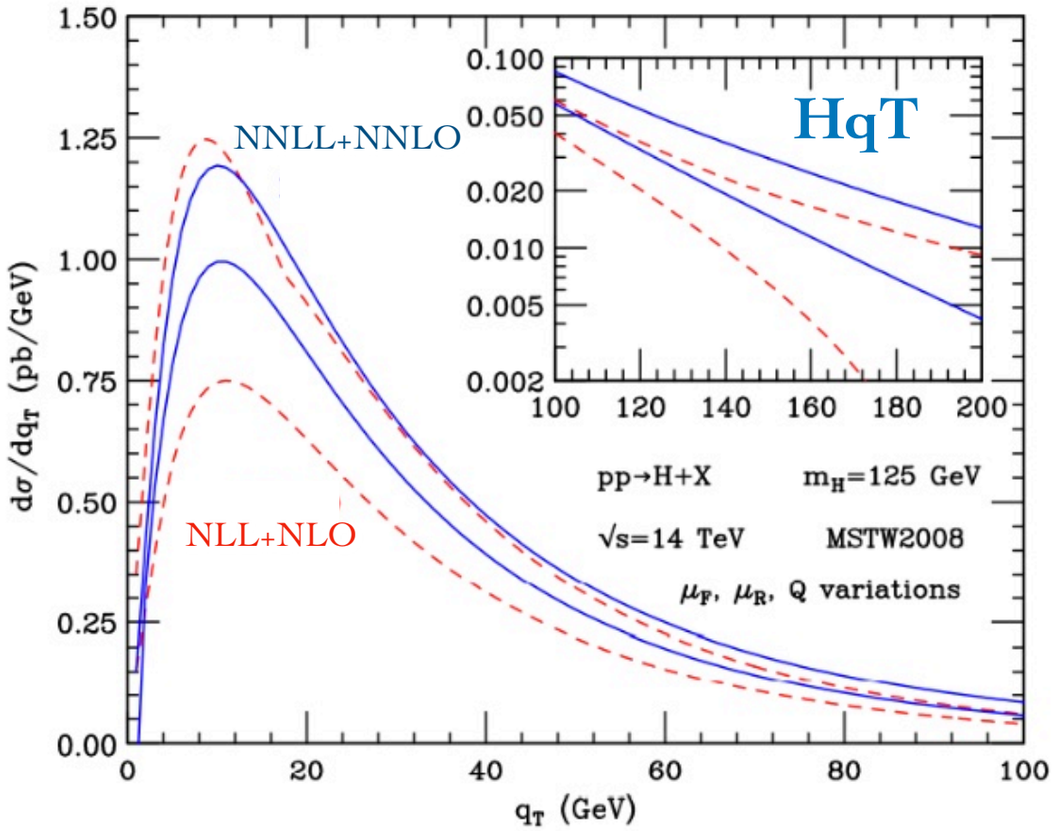
GLUON FUSION IN QCD PT SPECTRUM

Differentially, one of the most interesting observables is the pT spectrum:

info on QCD radiation, Higgs couplings…

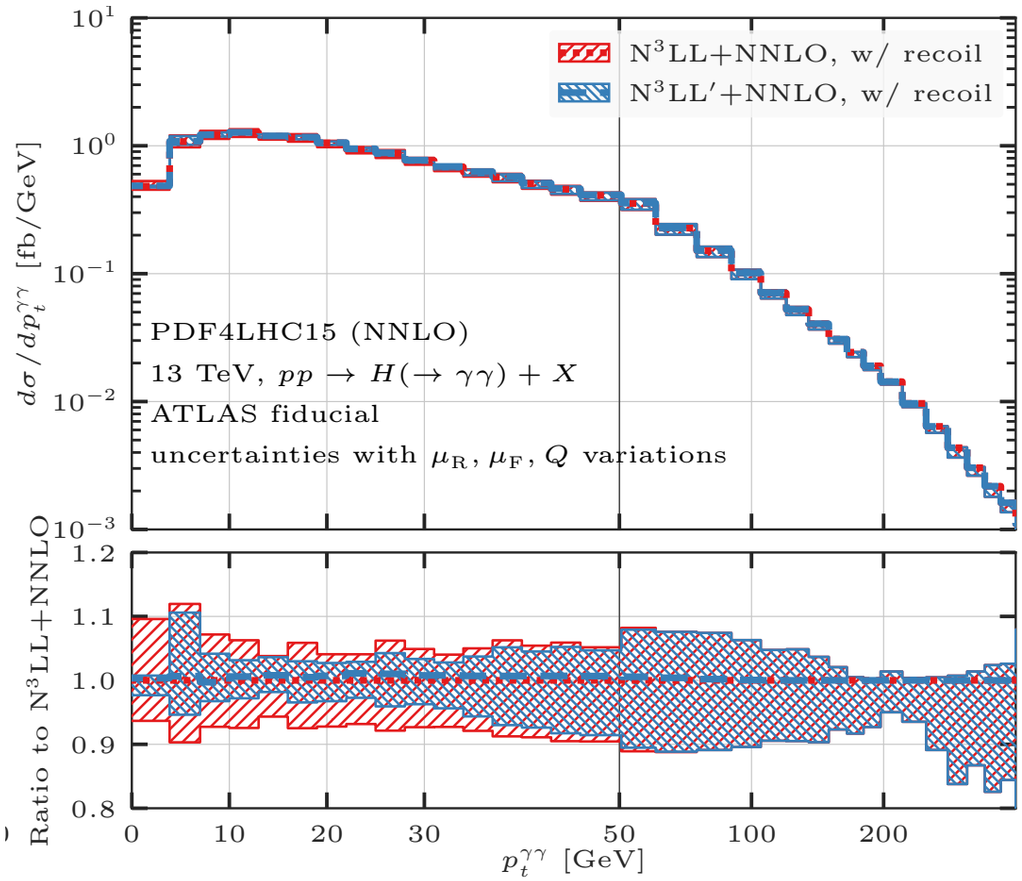
In **low pT regime**, multiparton emission accounted for by resummation (and Parton Showers, see new developments by **PanScale project**)

[Talk by S. Ferrario Ravasio earlier today]



[Bozzi, Catani, de Florian 2005]

Under control to N^{3}LL

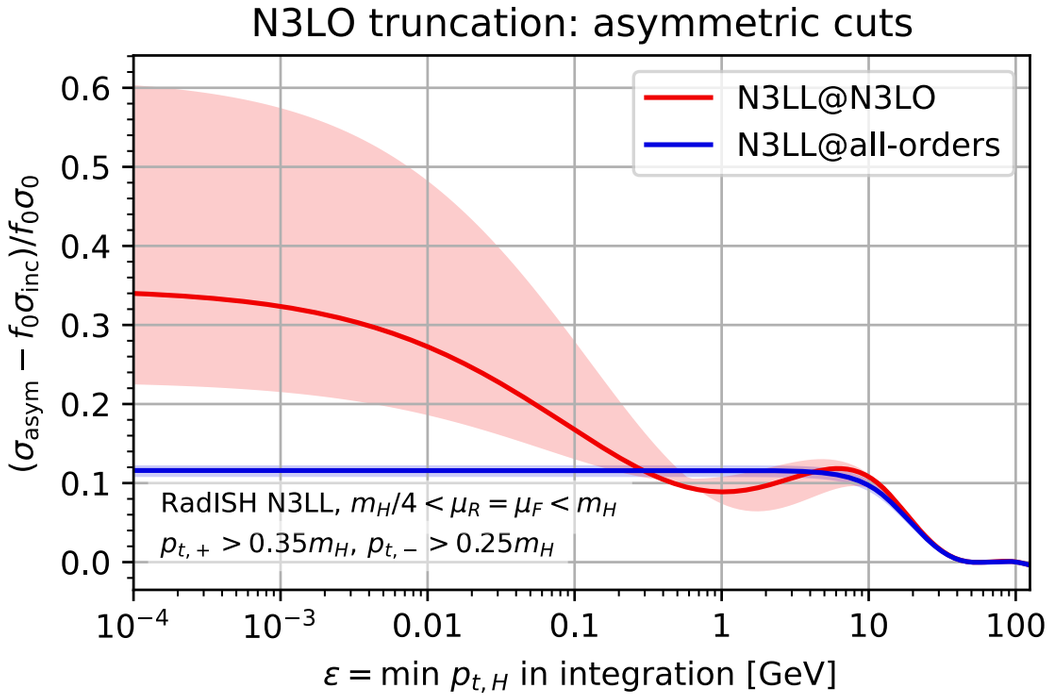


[Re, Rottoli, Torrielli 2021]

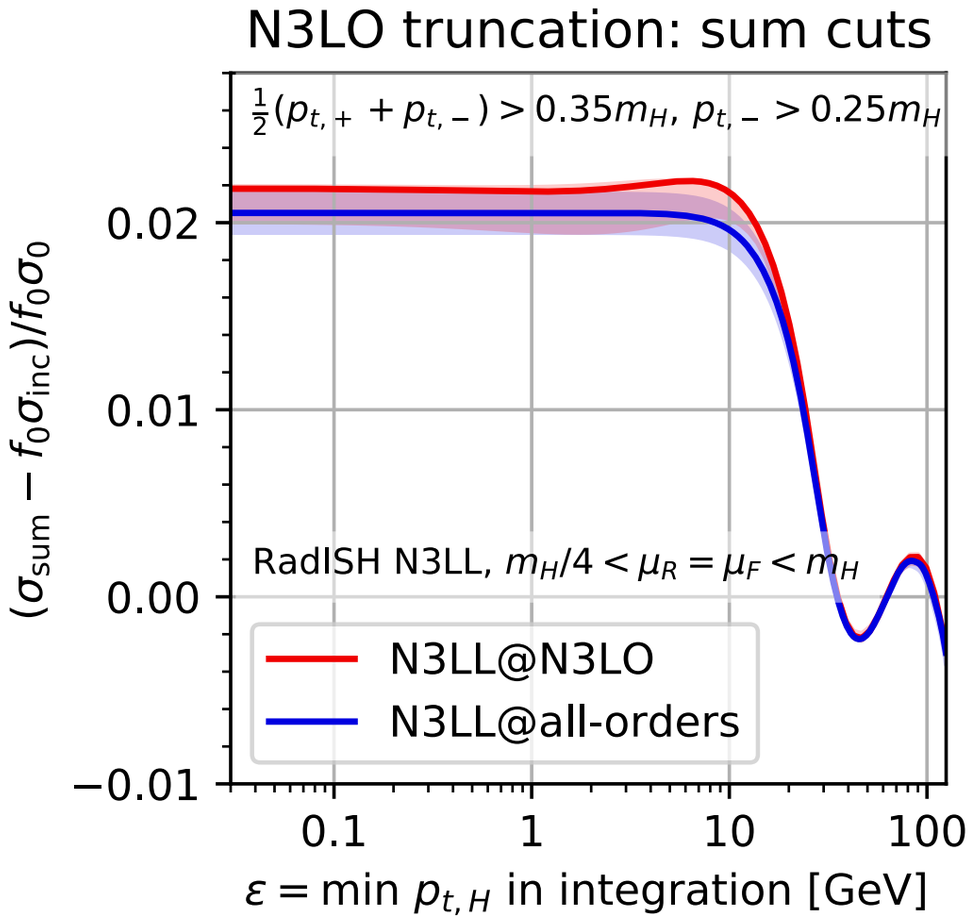
GLUON FUSION IN QCD SPURIOUS FIDUCIAL EFFECTS

Fixed order calculation has large spurious effects when looking at fiducial cuts!

→ ATLAS/CMS cuts induce IR sensitivity **New cuts with low IR sensitivity** **[Salam, Slade 2021]**



$$p_{t,1} > 0.35m_H\,, p_{t,2} > 0.25m_H$$

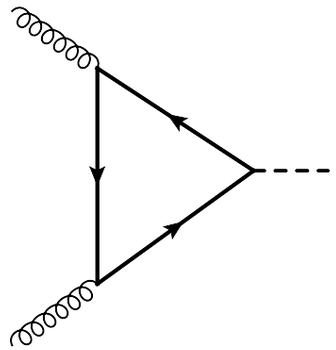


$$p_{t,2} > 0.25m_H\,, \frac{p_{t,1} + p_{t,2}}{2} > 0.35m_H$$

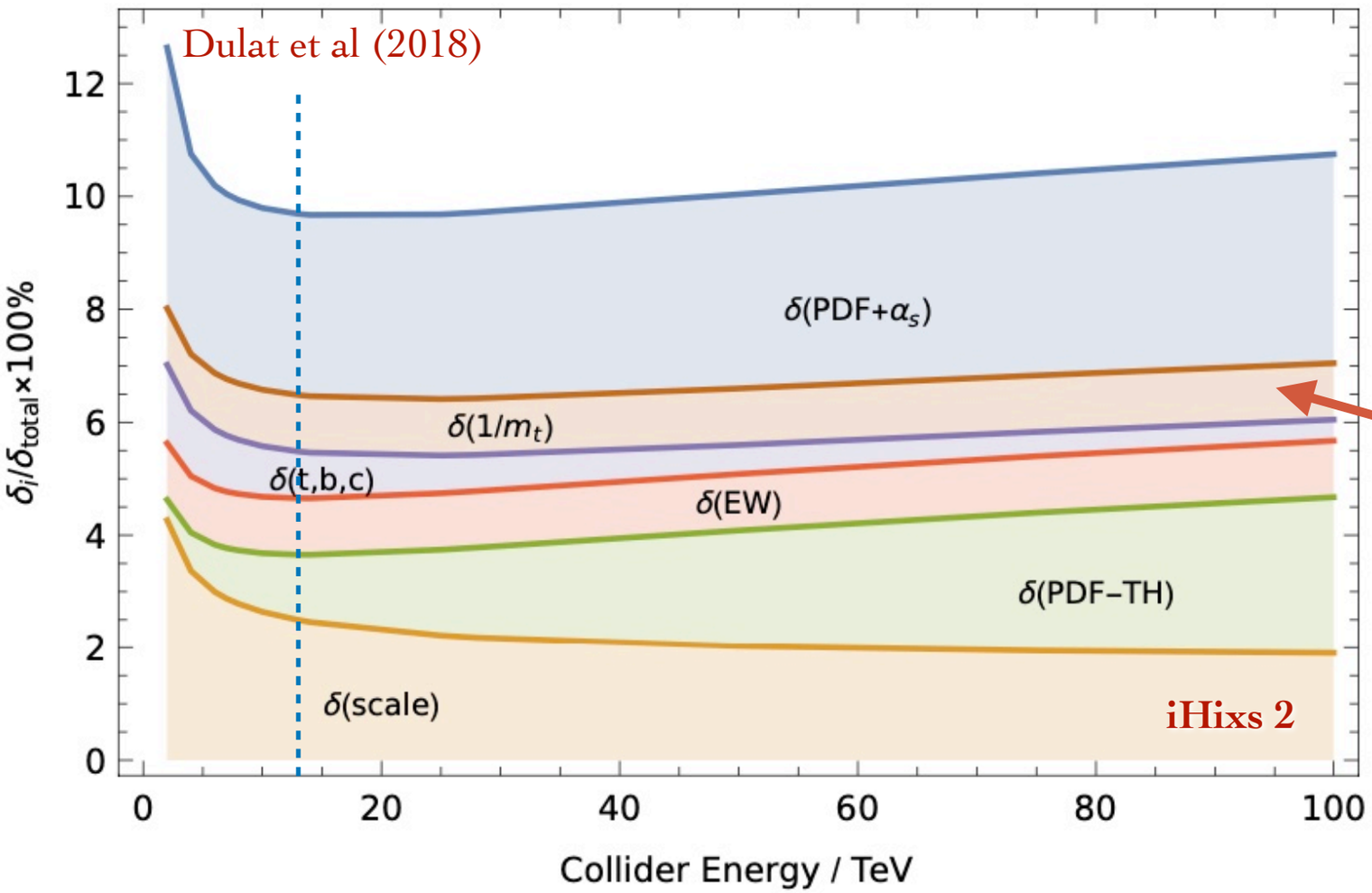
MASS AND EW EFFECTS

TOP MASS EFFECTS INCLUSIVE CROSS SECTION

Loop initiated:

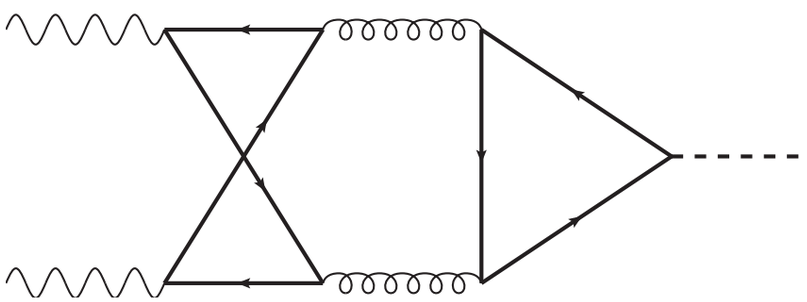


till recently known up to **NLO** *(2 loop calculation!)*



Exact mass effects at NNLO remained important source of uncertainty

TOP MASS EFFECTS INCLUSIVE CROSS SECTION



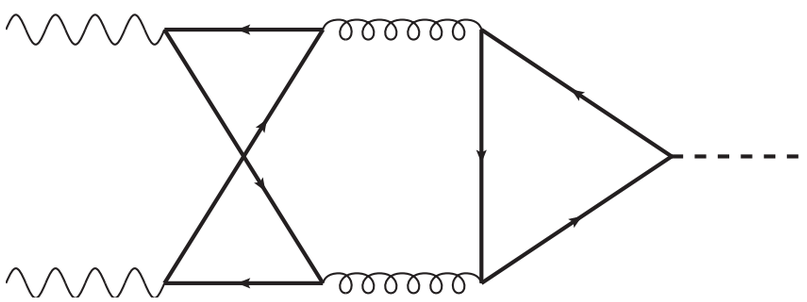
Recently **full NNLO inclusive calculation completed**! It requires complicated 3 loop graphs

[Czakon, Harlander, Klappert, Niggetiedt '21]

channel	$\sigma^{\rm NNLO}_{\rm HEFT}$ [pb] $\mathcal{O}(\alpha_s^2)+\mathcal{O}(\alpha_s^3)+\mathcal{O}(\alpha_s^4)$	$(\sigma^{\rm NNLO}_{\rm exact}-\sigma^{\rm NNLO}_{\rm HEFT})$ [pb] $\mathcal{O}(\alpha_s^3)$	$\mathcal{O}(\alpha_s^4)$	$(\sigma^{\rm NNLO}_{\rm exact}/\sigma^{\rm NNLO}_{\rm HEFT}-1)$ [%]
		$\sqrt{s}=8\,\text{TeV}$		
gg	$7.39+8.58+3.88$	$+0.0353$	$+0.0879\pm0.0005$	$+0.62$
qg	$0.55+0.26$	-0.1397	-0.0021 ± 0.0005	-18
qq	$0.01+0.04$	$+0.0171$	-0.0191 ± 0.0002	-4
total	$7.39+9.15+4.18$	-0.0873	$+0.0667\pm0.0007$	-0.10
		$\sqrt{s}=13\,\text{TeV}$		
gg	$16.30+19.64+8.76$	$+0.0345$	$+0.2431\pm0.0020$	$+0.62$
qg	$1.49+0.84$	-0.3696	-0.0115 ± 0.0010	-16
qq	$0.02+0.10$	$+0.0322$	-0.0501 ± 0.0006	-15
total	$16.30+21.15+9.79$	-0.3029	$+0.1815\pm0.0023$	-0.26

Very large effects in qg and qq channels!

TOP MASS EFFECTS INCLUSIVE CROSS SECTION



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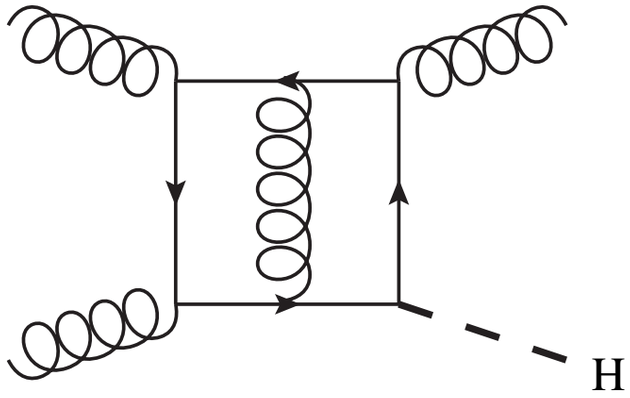
Nevertheless, cancellations bring differences down to $\sim 0.26\,\%$ at 13 TeV

Confirms "expectations" from HEFT and **removes this source of uncertainty!**

TOP MASS EFFECTS DIFFERENTIAL IN HIGGS PT

Exact dependence on the top-mass is very relevant at **high pT!**



- Top-mass effects increase NLO of ~9%.
- Different scaling HEFT vs Full Theory

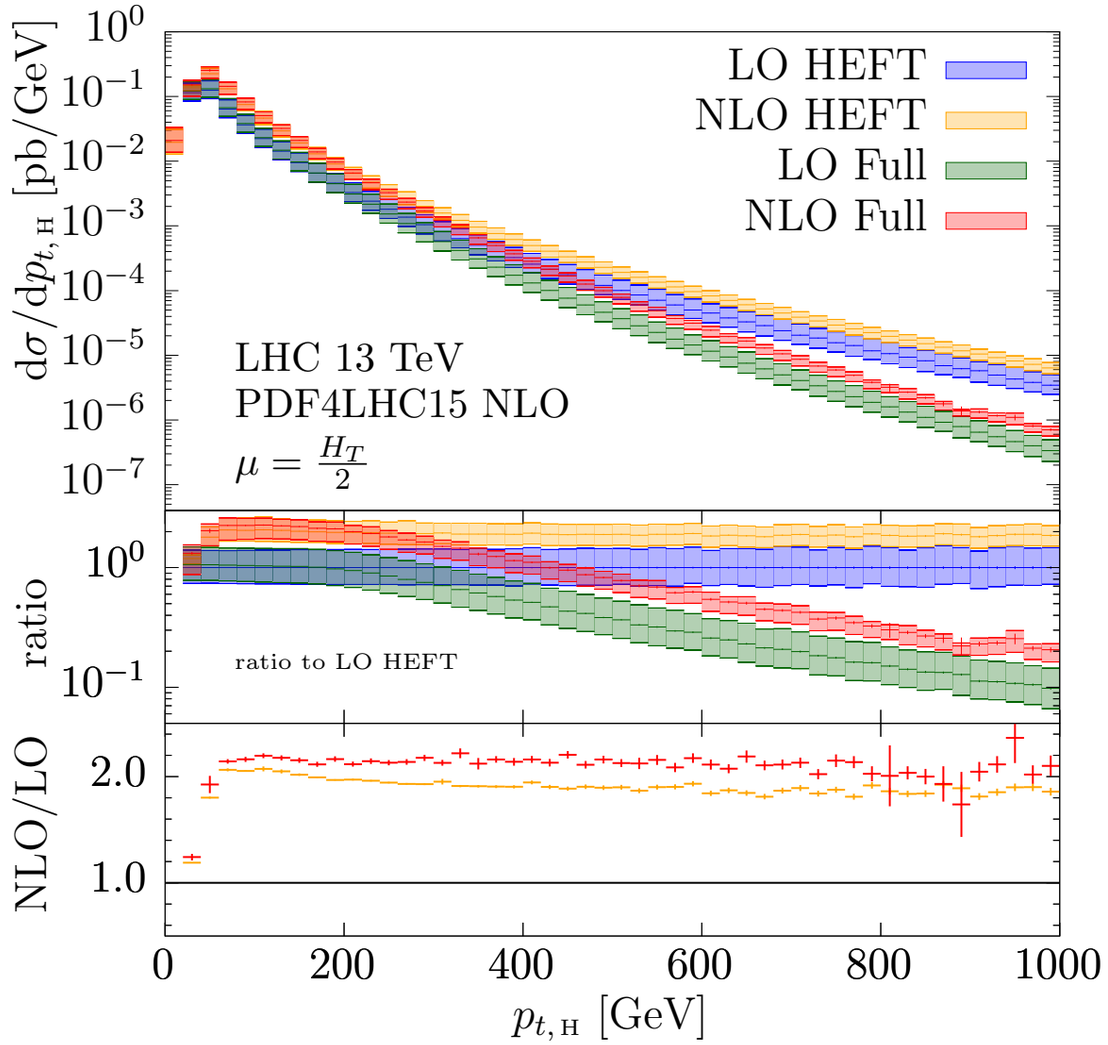
$$\frac{d\sigma}{dp_\perp^2} \sim p_\perp^{-2} \quad \text{HEFT}$$

$$\frac{d\sigma}{dp_\perp^2} \sim p_\perp^{-4} \quad \text{full theory}$$

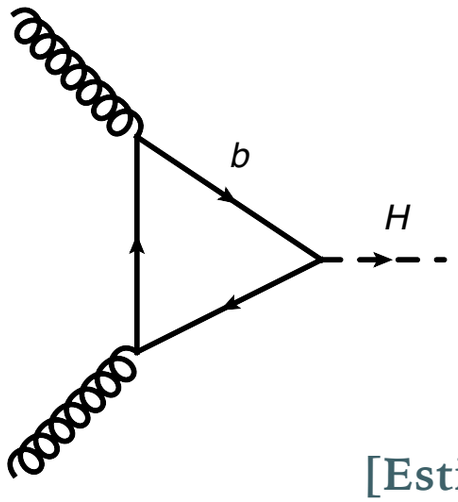
- Nearly constant K factor @ NLO in full theory

[Jones, Kerner, Luisoni '18]

[Chen, Huss, Jones, Kerner, Lang, Lindert, Zhang '21]



BOTTOM MASS EFFECTS: INCLUSIVE CROSS SECTION



$$\sim -\frac{3}{2}\frac{m_b^2}{m_H^2}\,\ln^2\frac{m_H^2}{m_b^2}\,\mathcal{M}^t_{gg\to H}$$

[Estimate of the logs by Penin, Melnikov '16; Liu Penin '17,'18; Anastasiou, Penin '20]

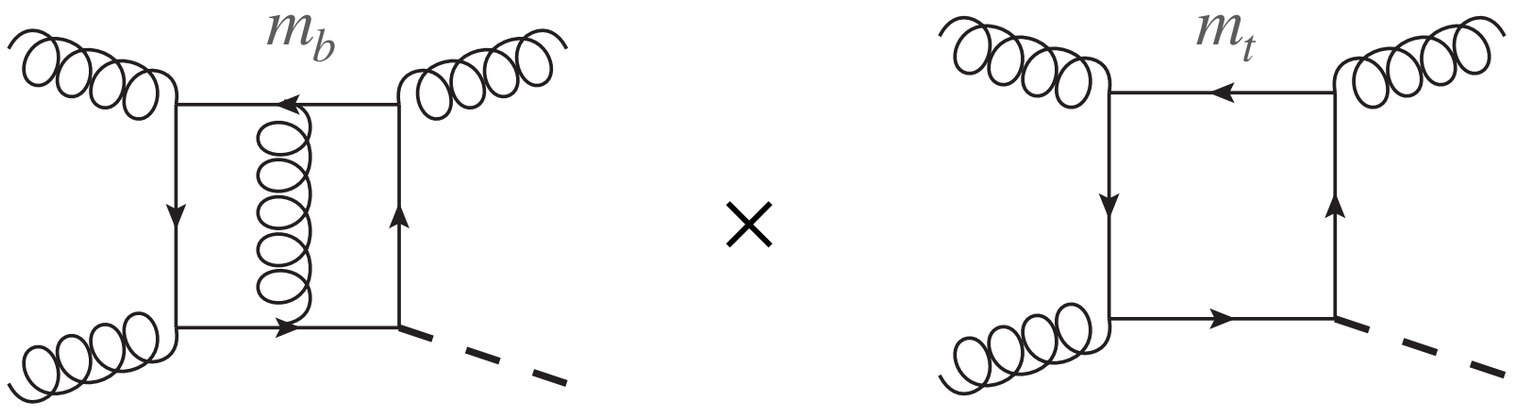
	LO	NLO	NNLO	N^{3}LO
$\delta\sigma^{\rm LL}_{pp\to H+X}$	-1.420	-1.640	-1.667	-1.670
$\delta\sigma^{\rm NLL}_{pp\to H+X}$	-1.420	-2.048	-2.183	-2.204
$\delta\sigma_{pp\to H+X}$	-1.023	-2.000		

[Anastasiou, Penin '20]

Exact calculation for m_t could be used here too!

BOTTOM MASS EFFECTS HIGGS PT DISTRIBUTION

Possible important effect from top-bottom interference on Higgs $p_\perp$ distribution



$$A_{gg\to Hg} \sim \left\{ \frac{m_b^2}{m_H^2} \log^2\left(\frac{m_H^2}{m_b^2}\right),\ \frac{m_b^2}{m_H^2} \log^2\left(\frac{p_\perp^2}{m_b^2}\right) \right\}$$

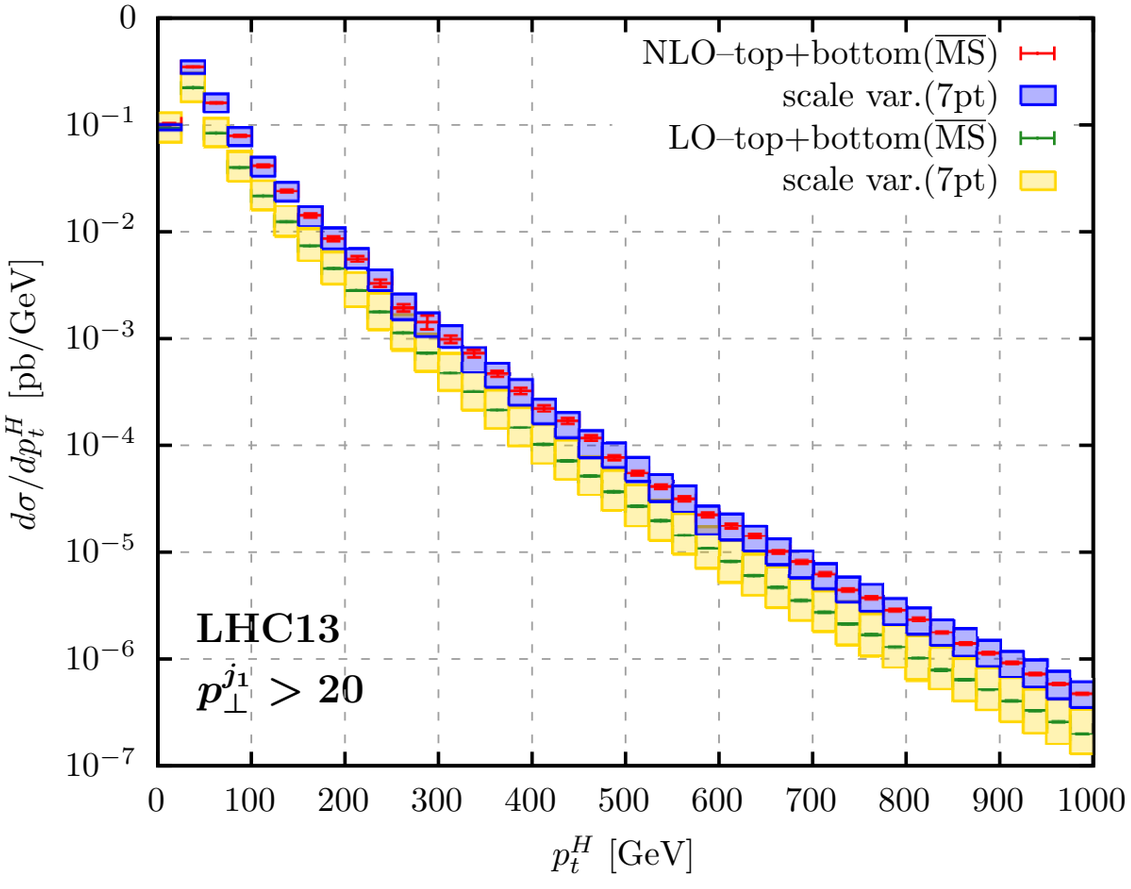
$$m_H = 125\,\mathrm{GeV}$$
$$m_b \sim 4.7\ \mathrm{GeV}$$
$$p_\perp^{\mathrm{typ}} \sim 30\,\mathrm{GeV}$$

Effect of logs (and finite piece) on Higgs pT by **[Lindert, Melnikov, Tancredi, Wever ‘17]**

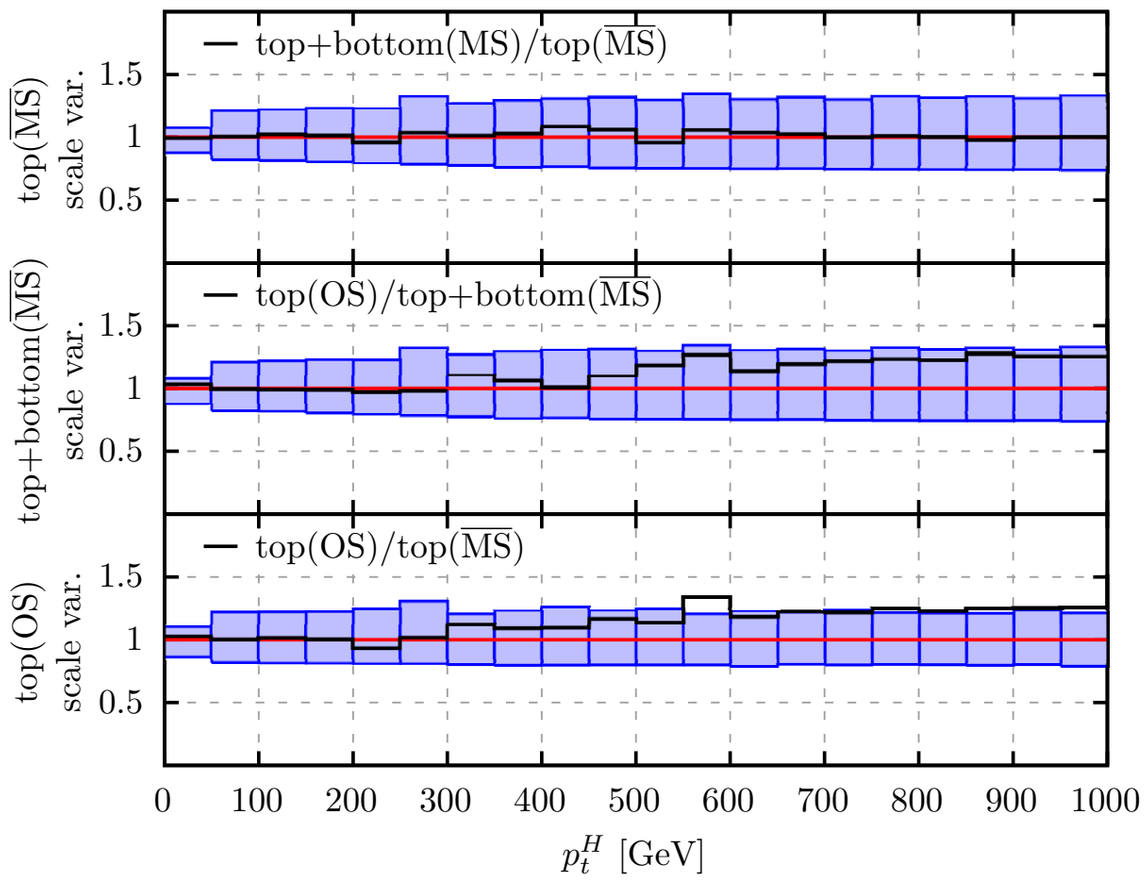
[Caola, Lindert, Melnikov, Monni, Tancredi, Wever ’18]

BOTTOM MASS EFFECTS HIGGS PT DISTRIBUTION

Top-Bottom interference up to NLO [Bonciani, Del Duca, et al 2022]



Higgs p_T distribution with top- and bottom-quarks

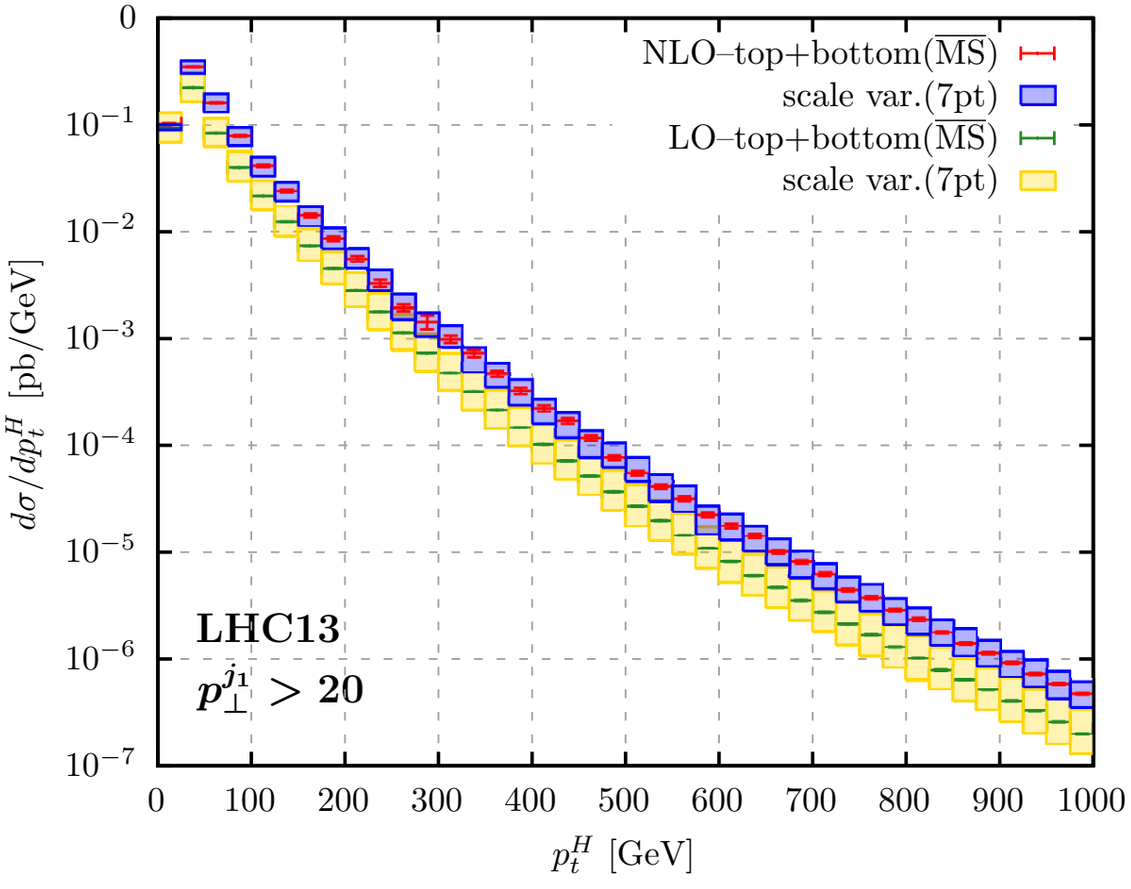


Ratio of Higgs p_T distributions at NLO

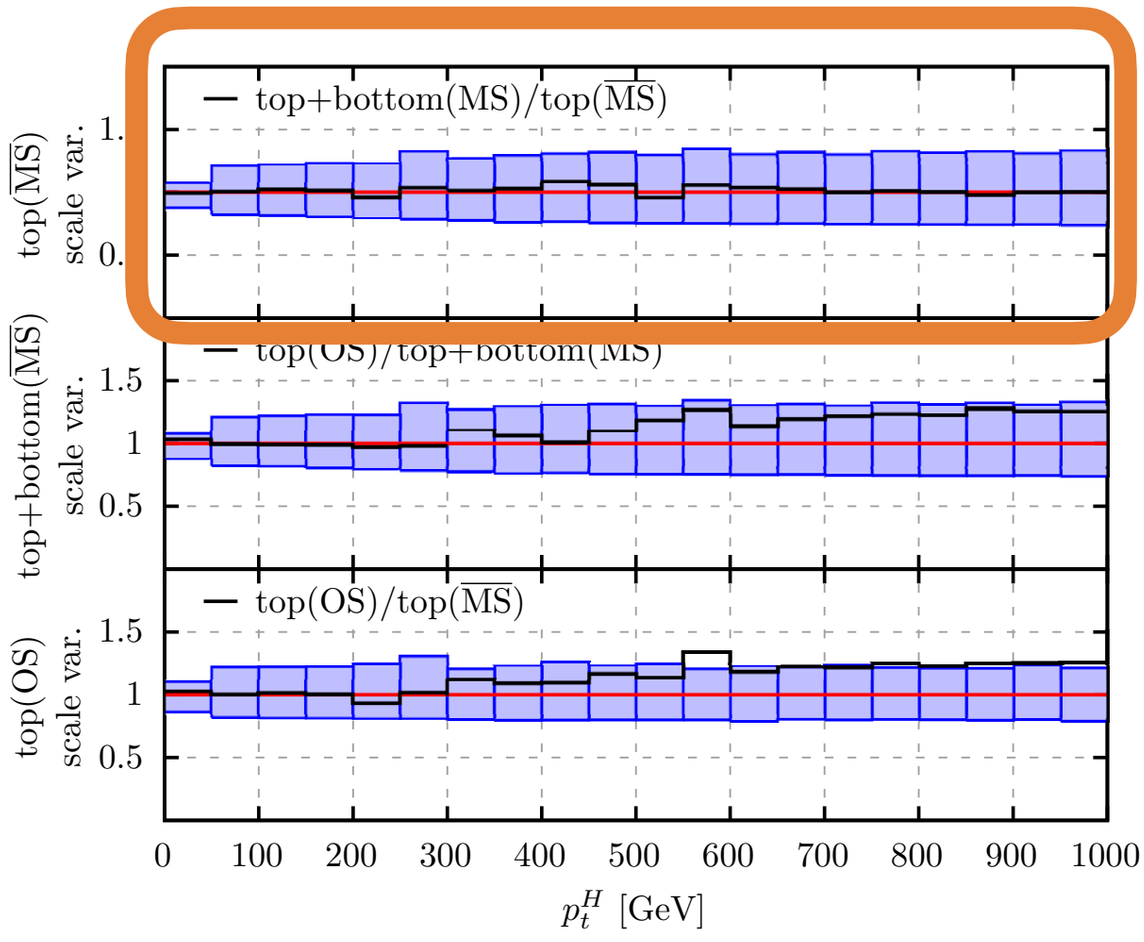
BOTTOM MASS EFFECTS HIGGS PT DISTRIBUTION

Top-Bottom interference up to NLO

[Bonciani, Del Duca, et al 2022]



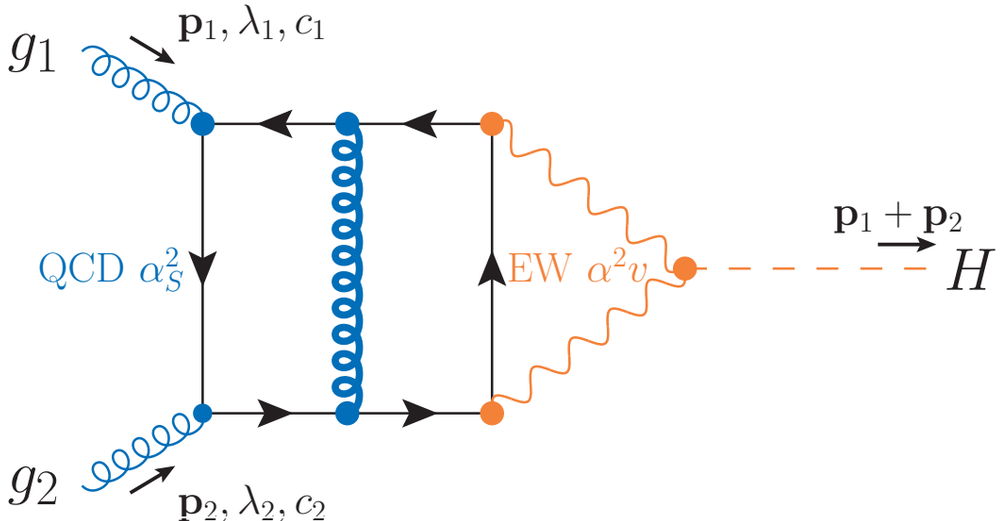
Higgs p_T distribution with top- and bottom-quarks



Ratio of Higgs p_T distributions at NLO

We find that within the scale uncertainty the LO contribution of the bottom quark, and thus of the top-bottom interference, to the Higgs boson production is almost erased at inclusive level by the NLO corrections. On the other hand, at the low end of the p_T distribution, the interference induces a non trivial change of shape.

MIXED QCD-EW EFFECTS



1. **Mixed QCD-EW** effects amount to 5% of the ggF cross section
2. **LO is 2 loop!** gluon initiated, large corrections expected
3. 1% precision requires at least **NLO calculation**

Very complex calculation, up to **three loop** integrals with masses

First estimates in unphysical limit $m_W \gg m_H$ **[Anastasiou et al 2009]**

Consistent with **soft gluon** approximation **[Bonetti, Melnikov, Tancredi 2017]**

$$\sigma_{\text{LO}}^{\text{QCD}} = 20.6\,\text{pb} \qquad \sigma_{\text{LO}}^{\text{QCD-EW}} = 21.7\,\text{pb} \quad \Rightarrow \quad +5.3\% \text{ at LO}$$

$$\sigma_{\text{NLO}}^{\text{QCD}} = 32.7\,\text{pb} \qquad \sigma_{\text{NLO}}^{\text{QCD-EW}} = 34.4\,\text{pb} \quad \Rightarrow \quad +5.2\% \text{ at NLO}$$

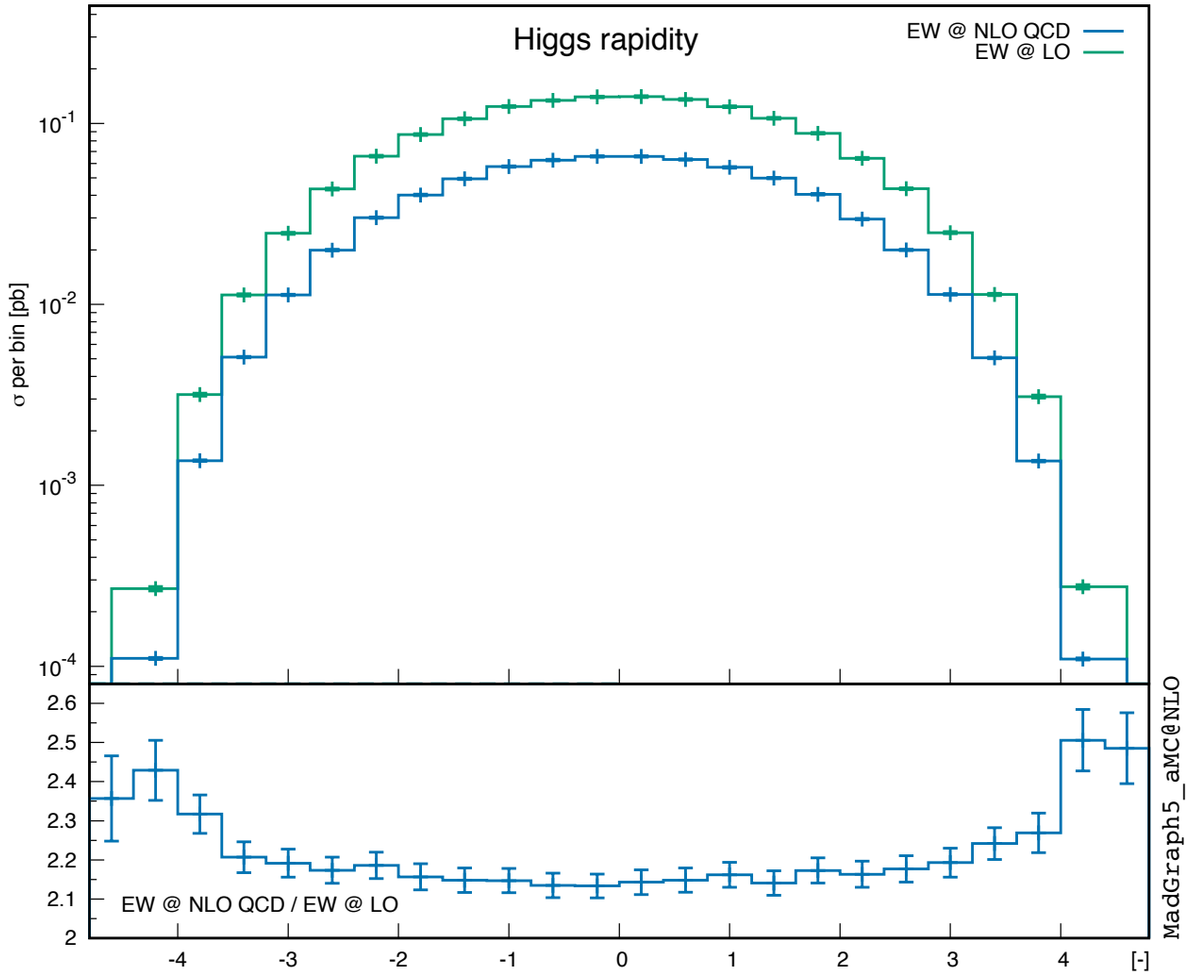
Residual 1% uncertainty on Higgs cross sections

MIXED QCD-EW EFFECTS

Recently last missing building block computed analytically, real amplitudes for $gggH$ and $q\bar{q}gH$

[Bonetti, Panzer, Smirnov, Tancredi 2020]
[Bonetti, Panzer, Tancredi 2022]

Effects on main channel gggH by **[Becchetti, Bonciani, del Duca, Hirschi, Moriello, Schweizer 2020]**



Expectations from previous approximations largely confirmed

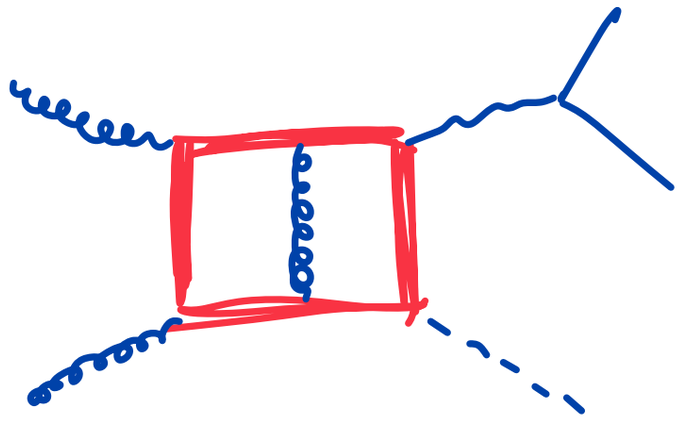
1% residual uncertainty on Higgs cross-section

See talk by M. Bonetti

BEYOND $gg \to H + X$

ZH PRODUCTION @ NLO

$gg \to ZH$ @ NLO is formally NNLO, but it's gluon induced: **expect very large corrections!**



$gg \to ZH$ very desirable to **control uncertainty % level**

$\sqrt{s}$ [TeV]	$\sigma_{\text{NNLO QCD}\otimes\text{NLO EW}}$ [pb]	Δ_{scale} [%]	$\Delta_{\text{PDF}\oplus\alpha_s}$ [%]
13	0.831	$^{+0.74}_{-0.73}$	1.79

W+H

$\sqrt{s}$ [TeV]	$\sigma_{\text{NNLO QCD}\otimes\text{NLO EW}}$ [pb]	Δ_{scale} [%]	$\Delta_{\text{PDF}\oplus\alpha_s}$ [%]
13	0.880	$^{+3.50}_{-2.68}$	1.65

ZH, full

$\sqrt{s}$ [TeV]	$\sigma_{\text{NNLO QCD}\otimes\text{NLO EW}}$ [pb]	Δ_{scale} [%]	$\Delta_{\text{PDF}\oplus\alpha_s}$ [%]
13	0.758	$^{+0.49}_{-0.61}$	1.78

ZH, no gg

$\sqrt{s}$ [TeV]	$\sigma_{\text{NNLO QCD}\otimes\text{NLO EW}}$ [pb]	Δ_{scale} [%]	$\Delta_{\text{PDF}\oplus\alpha_s}$ [%]
13	0.123	$^{+24.9}_{-18.8}$	4.37

ZH, gg only

[From F. Caola, PANIC 2021]

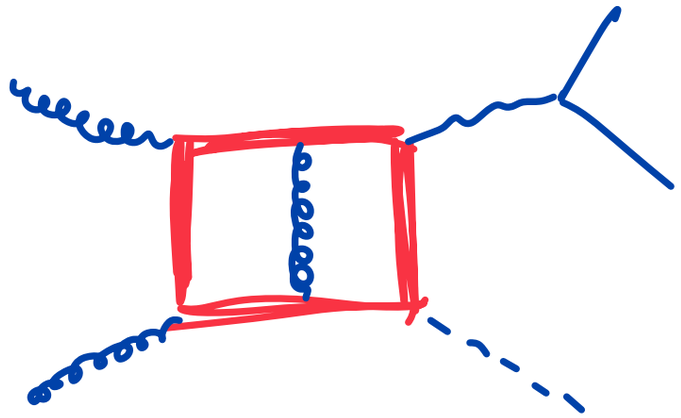
ZH PRODUCTION @ NLO

Very complicated 2 loop amplitudes, much work done recently:

[Davies, Mishima, Steinhauser, 2020]

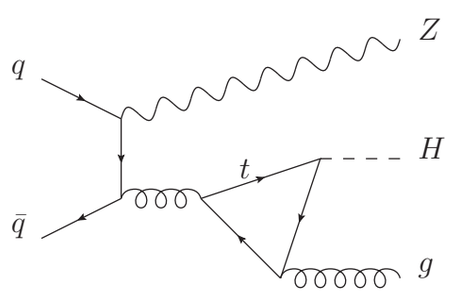
[Chen, Heinrich et al 2020]

[Alasfar, Degrassi et al 2021]

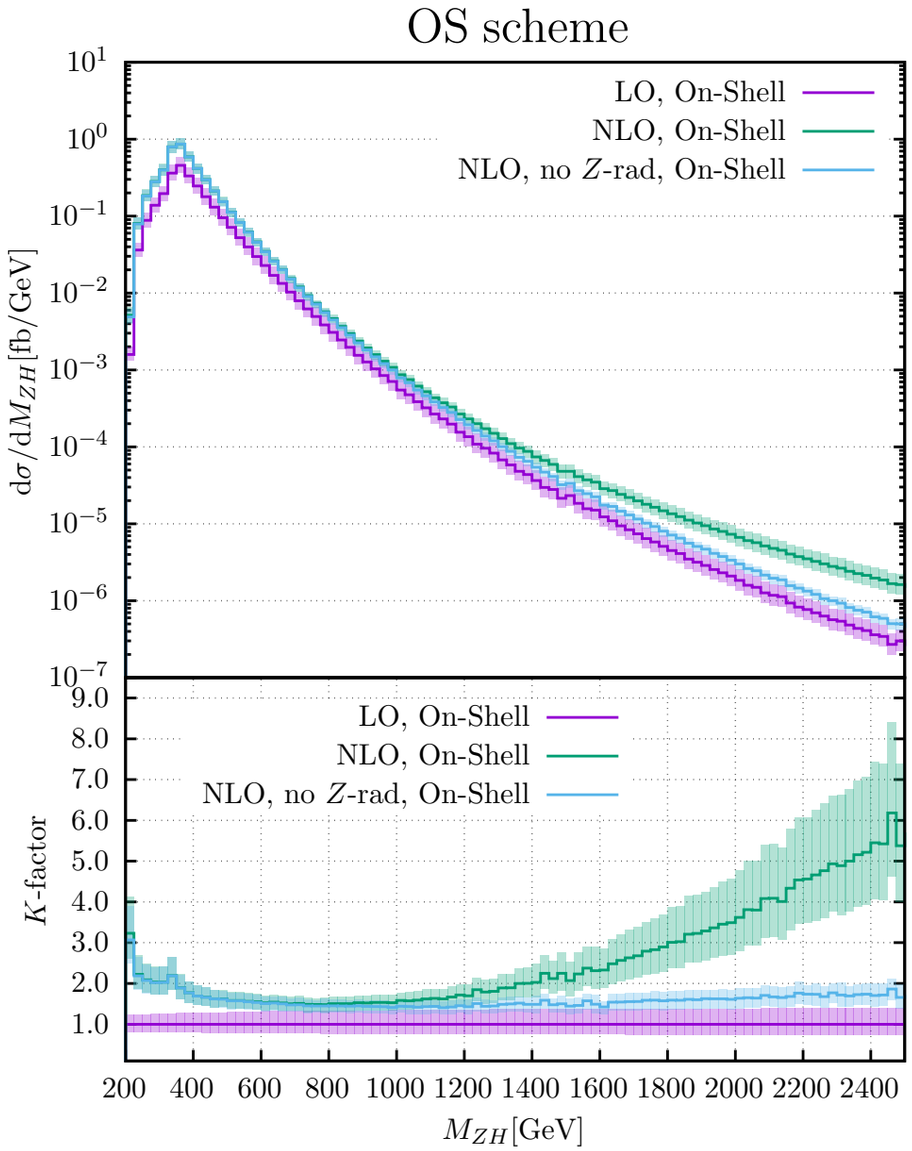


All ingredients put recently together at NLO

1. As expected, NLO same size as LO up to 1 TeV (K∼1)
2. For higher M_{ZH} they become larger (Z emission from open quark line) → K ∼ 6 at 2.5 TeV (OS)!



Due to large $\log \frac{m_Z^2}{m_{ZH}^2}$ in qg channel (qq suppressed by PDFs)



[Degrassi, Gröber, Vitti, Zhao, '22]

$t\bar{t}H$ PRODUCTION (THE HOLY GRAIL…)

Current theory prediction based on NLO QCD + EW + resummation, uncertainty $\sim 8\%$

Run 3 and HL due to bring down uncertainty to few % ($\sim 2\%$?).

NNLO QCD required: bottleneck here are **2 loop virtual amplitudes:** very non trivial, but there is progress, at least hope to get them "brute force" with numerical approach.

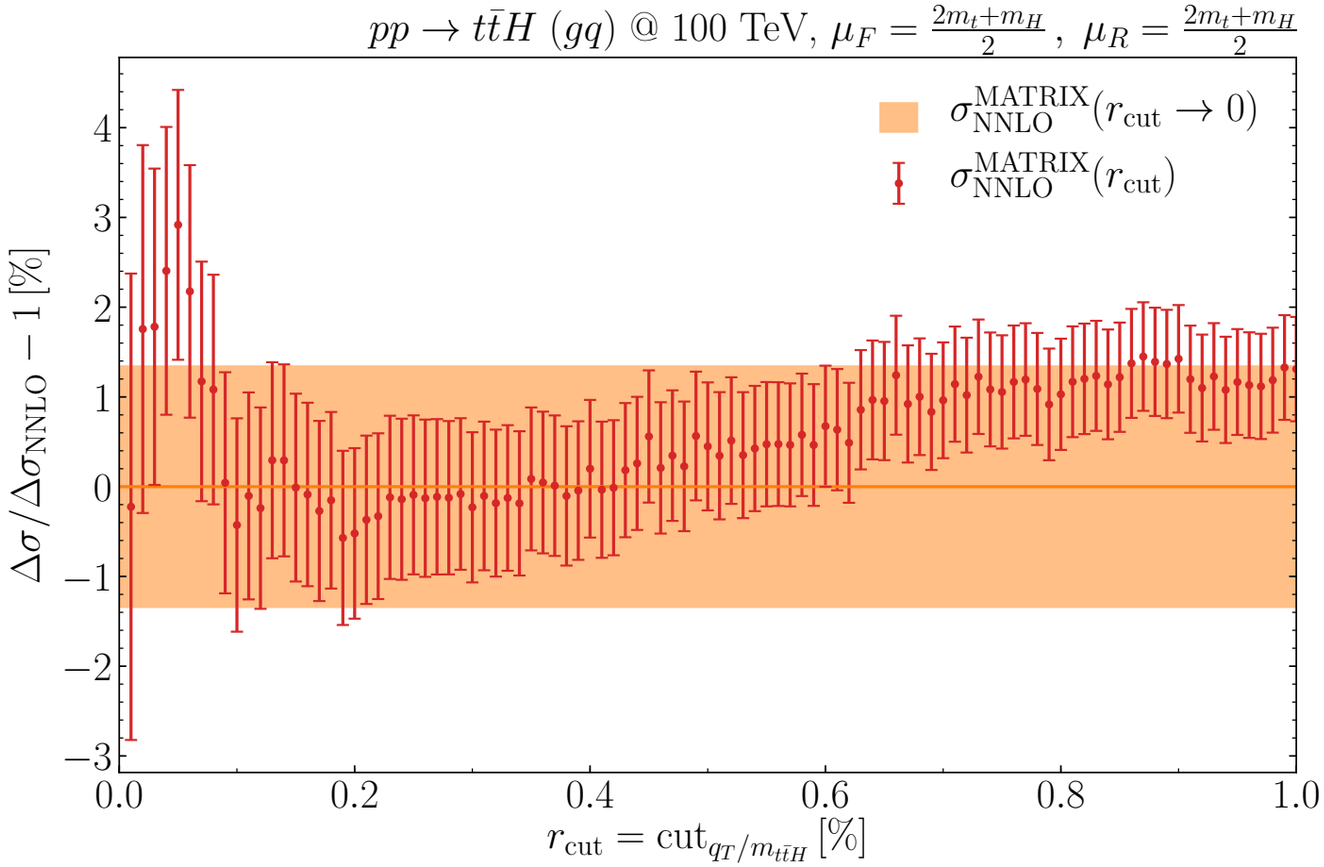
Everything else ready:

first proof of concept by evaluation of **non-diagonal partonic channels**

[Catani, Fabre, Kallweit, Grazzini '20]

Notice also: very difficult background modelling $t\bar{t}b\bar{b}$

See S. Pozzorini @ HXSWG 2020



CONCLUSIONS

- Higgs remains the most fascinating discovery of the past few decades
- To understand its properties, sophisticated interplay of **exquisite experimental studies** and **complex theoretical calculations**:
- Fixed order: N3LO, QCD-EW, massive amplitudes, new mathematical methods
- In addition, all order resummation to N3LL, good definition of fiducial regions etc
- Beyond perturbation theory: α_S from lattice, PDFs at N3LO etc…

Impressive progress in the past decade, still a lot to be done → towards $\mathcal{O}(1\%)$

Very interesting times ahead, both for experiment and theory!