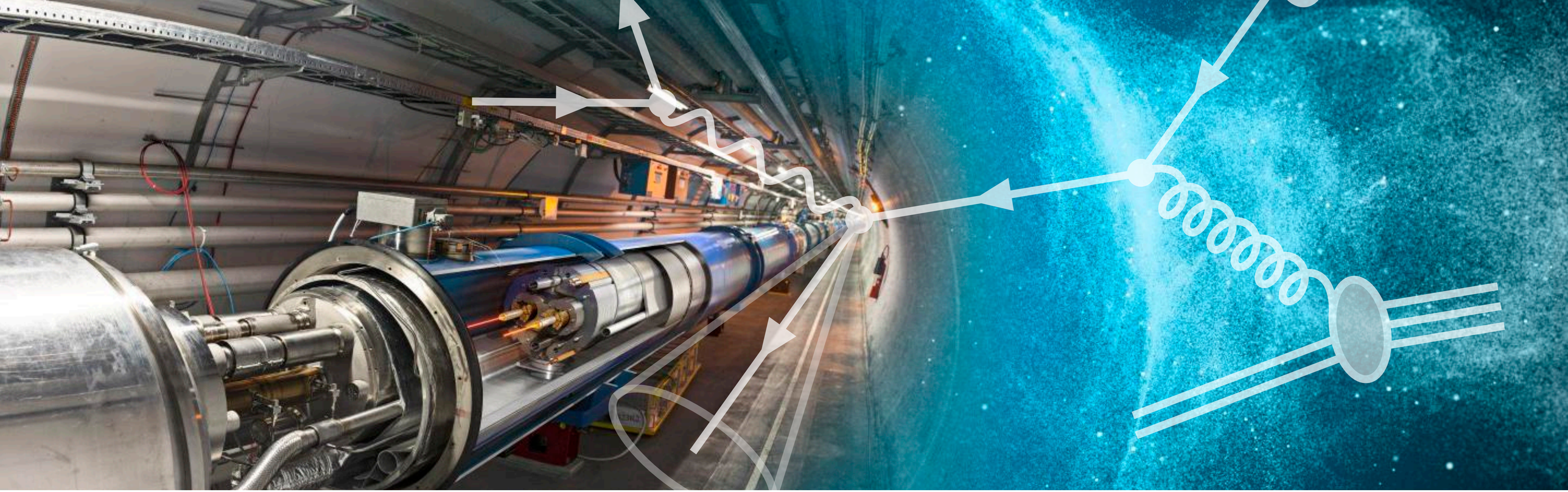


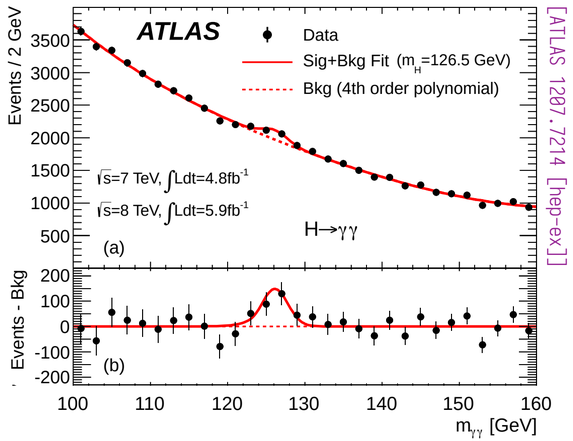
RECENT PROGRESS IN PRECISION CALCULATIONS

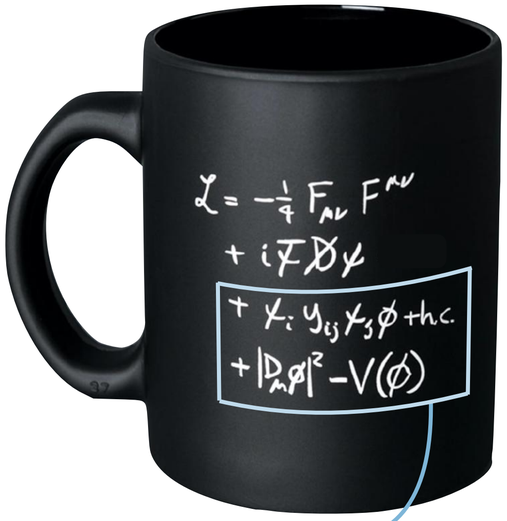
Alexander Huss

Higgs 2021 — October 19th 2021

THE HIGGS @ LHC

2012



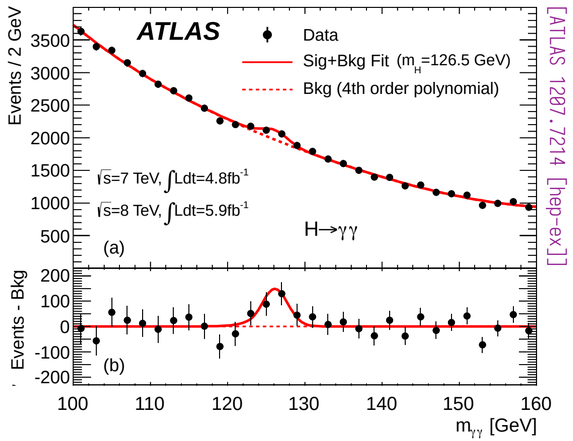


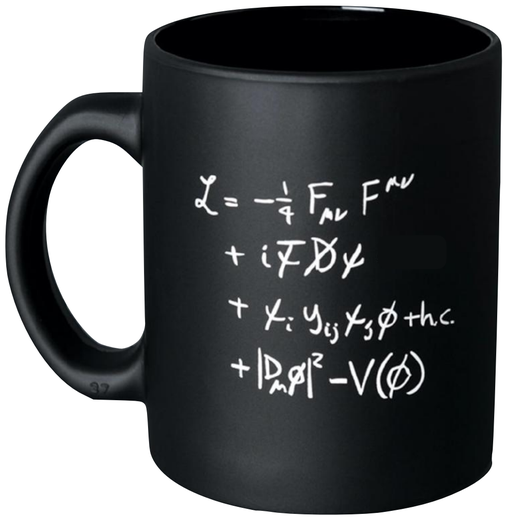
S. Thomas

- is it really the SM Higgs?
- what is the potential $V(\phi)$?
- establish Yukawa's Y_{ij}
- …

THE HIGGS @ LHC

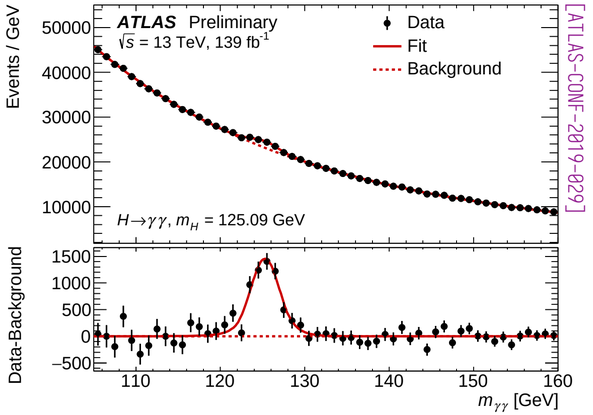
2012

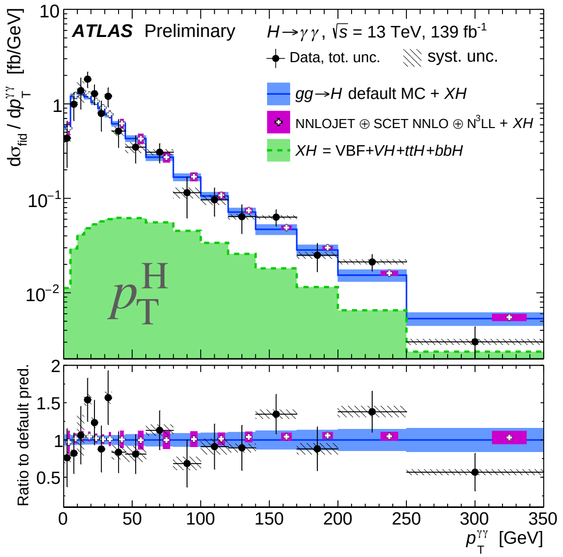




< 10 years

Today



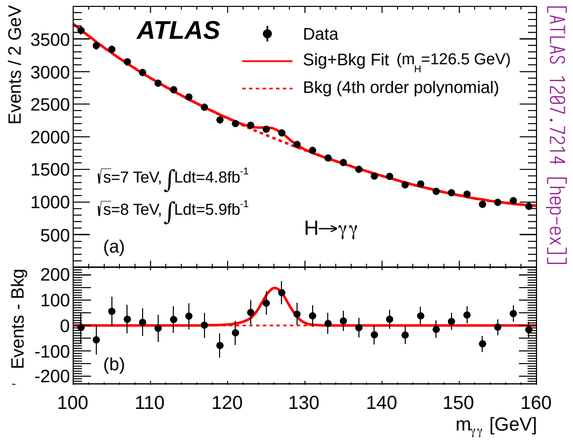


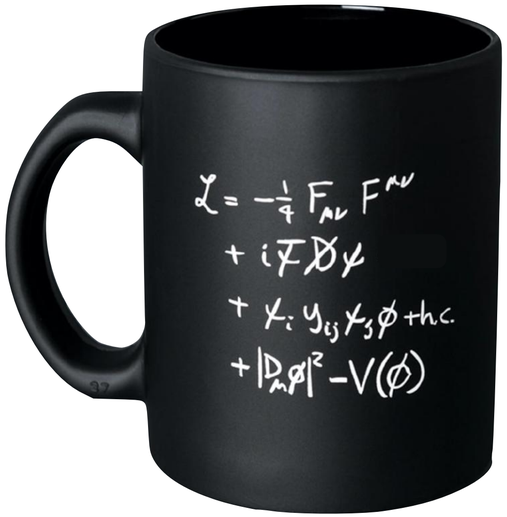
Higgs for precision pheno!

- signal strengths
  - ⇝ differential spectra
- Higgs properties (couplings, potential, …)
- …

THE HIGGS @ LHC

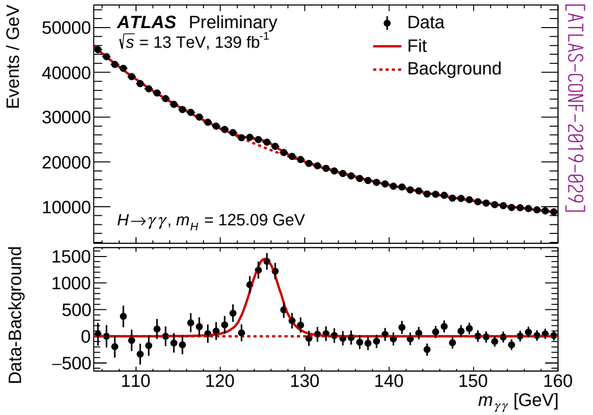
2012

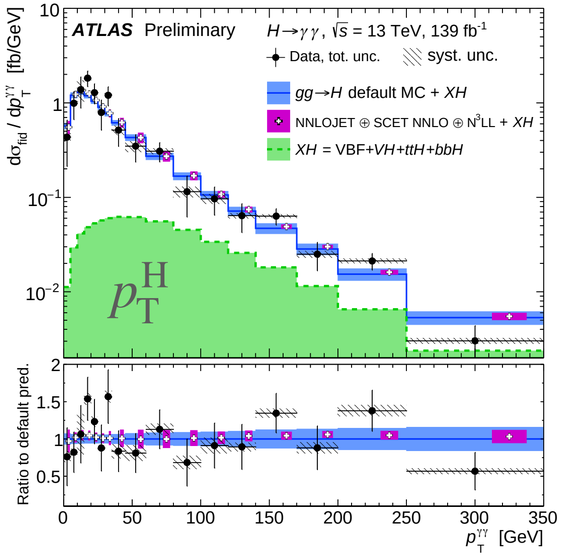




< 10 years

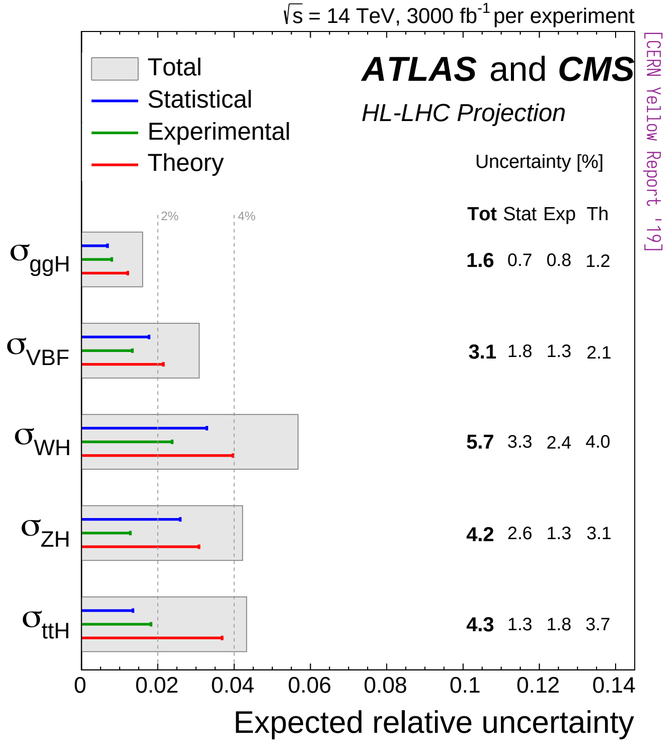
Today





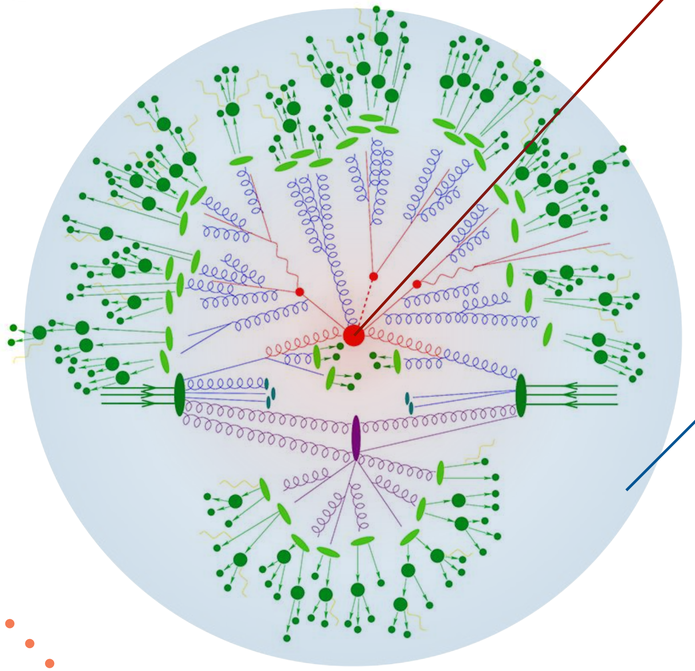
+20 years

HL-LHC (3000 fb^{-1})



theory uncertainties
scaled down by factor 2!

How do we predict this from Theory?

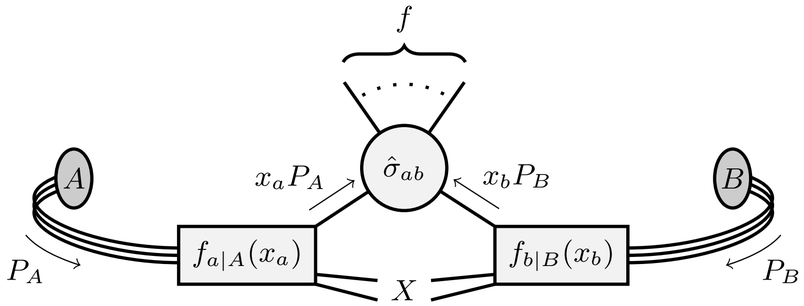


- **Short** distance **"hard"**
  - high scales: 10^2—10^3 GeV

evolution towards a physical observable state

- **Long** distance **"soft"**
  - low scales: $\mathcal{O}$(few GeV)

S. Plätzer & F. Siegert



$$\sigma_{AB} = \sum_{ab} \int_0^1 \mathrm{d}x_a \int_0^1 \mathrm{d}x_b \, f_{a|A}(x_a)\, f_{b|B}(x_b)\, \hat{\sigma}_{ab}(x_a, x_b)\, (1+\mathcal{O}(\Lambda_{\mathrm{QCD}}/Q))$$

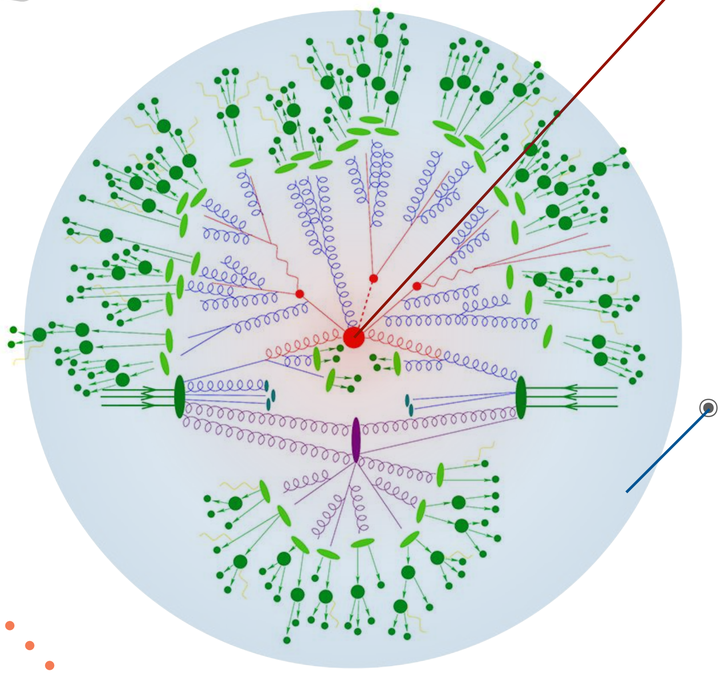
parton distribution functions (PDFs)
(non-perturbative, universal)

hard scattering
(perturbation theory)

non-perturbative effects
(power suppressed)

G. Salam

How do we predict this from Theory?



- **Short** distance **"hard"**
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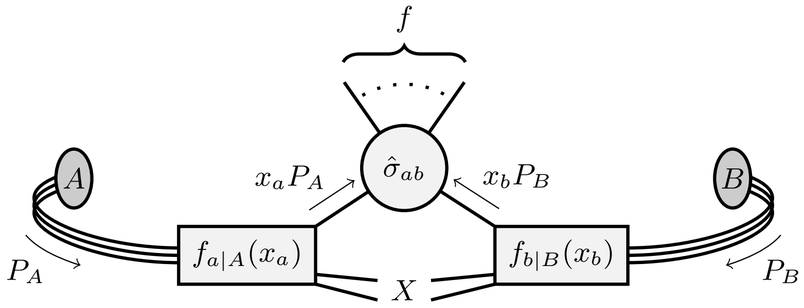
S. Plätzer & F. Siegert



$$\sigma_{AB} = \sum_{ab} \int_0^1 \mathrm{d}x_a \int_0^1 \mathrm{d}x_b \; f_{a|A}(x_a)\; f_{b|B}(x_b)\; \hat{\sigma}_{ab}(x_a, x_b)\; \left(1+\mathcal{O}(\Lambda_{\mathrm{QCD}}/Q)\right)$$

$$\sigma = \sigma_0 \times \left(1 + \alpha_s + \alpha_s^2 + \alpha_s^3 + \ldots\right)$$

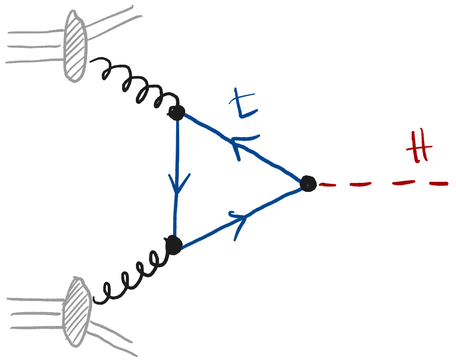
fixed order: LO NLO NNLO N³LO …

$$\sigma = \sigma_0 \cdot \exp\left(\alpha_s^n L^{n+1} + \alpha_s^n L^n + \alpha_s^n L^{n-1} + \ldots\right)$$

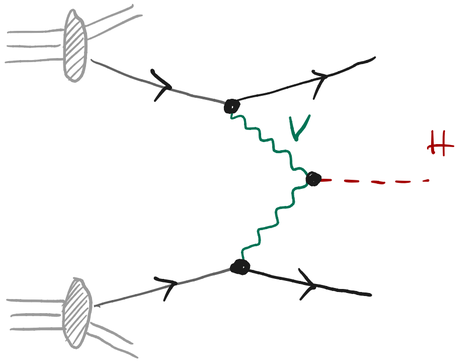
resummation: LL NLL NNLL …

Where do we stand?

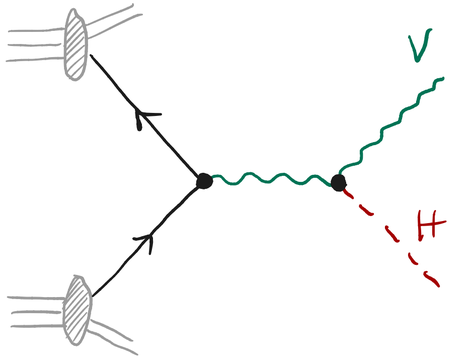
ggF (~ 88.2 %)



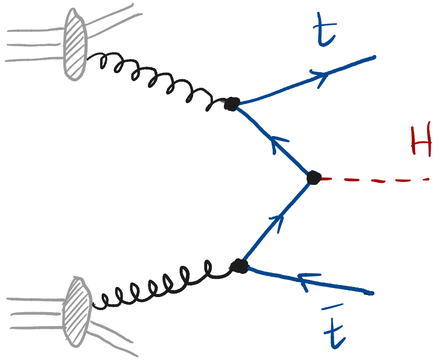
VBF (~ 6.8 %)



VH (~ 4.1 %)



ttH (~ 0.9 %)



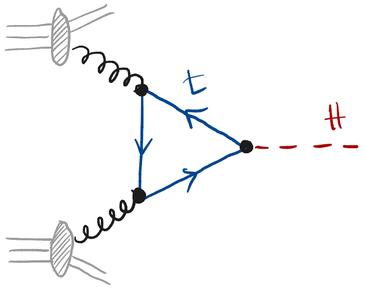
Unprecedented level of sophistication:

- inclusive production @ $N^3\cancel{N}LO_{QCD}$
  & differential @ $NNLO_{QCD}$ $(\neg\ t\bar{t}H)$
  + NLO_{EW}
- all decay channels @ (at least)
  $NNLO_{QCD}$ + NLO_{EW}
- in association with jets:
  NLO_{QCD} + PS

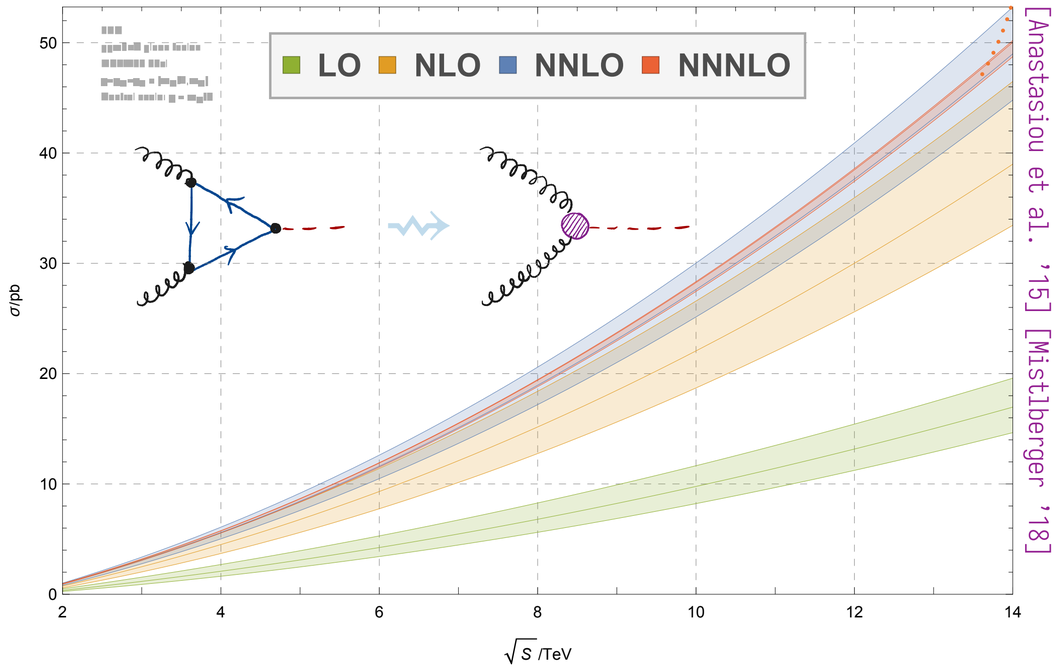
S. Plätzer & F. Siegert

$b\bar{b} \to H$ @ N^3LO [Duhr, Dulat, Mistlberger '19]

Gluon Fusion

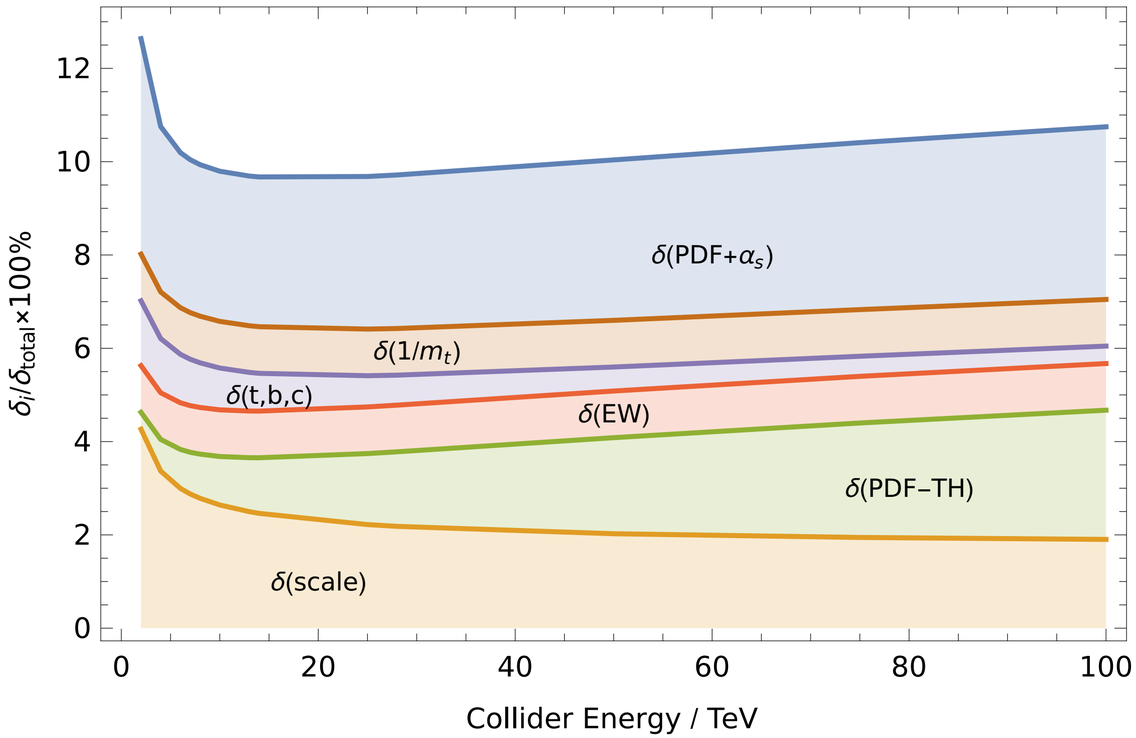


- Large QCD corrections
  - ↪ known to N³LO



[Anastasiou et al. '15] [Mistlberger '18]

Sources of Uncertainties:

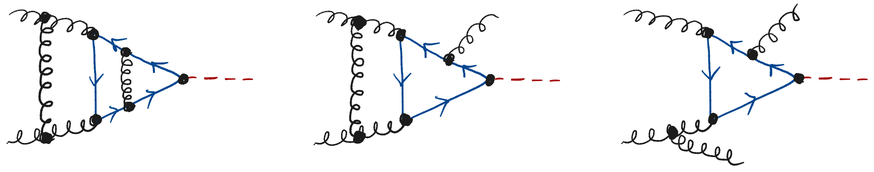


[Dulat, Lazopoulos, Mistlberger '18]

many small effects!
challenge: need to tackle all

FULL m_t @ NNLO

[Czakon, Harlander, Klappert, Niggetiedt '20]



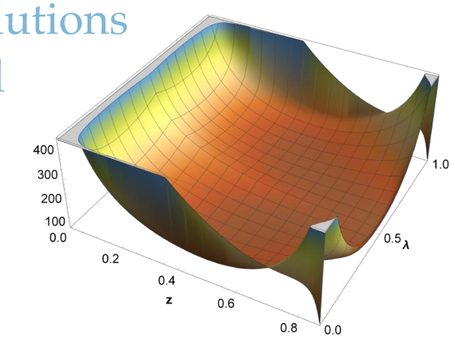
[Davies, Gröber, Maier, Rauh, Steinhauser '19] [Czakon, Niggetiedt '20]

[Jones, Kerner, Luisoni '18] [Frellesvig, Hidding, Maestri, Moriello, Salvatori '20]

big obstacle!
(stability & efficiency)

- Result: $\delta\sigma = -0.26\,\%$ $(\sqrt{s} = 13\ \text{TeV})$
- intricate cancellations
  - positive $(+0.62\,\%)$ corrections to gg
  - negative $(-15\,\%)$ corrections to qg & qq

numerical solutions to differential equations



$$2\text{Re}\langle M^{(1)}_{\text{exact}} | M^{(2)}_{\text{exact}} \rangle \big|_{\text{regulated}}$$

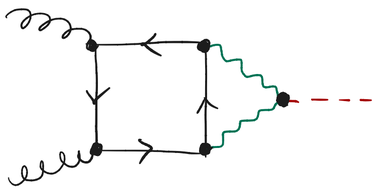
channel	$\sigma^{\text{NNLO}}_{\text{HEFT}}$ [pb] $\mathcal{O}(\alpha_s^2) + \mathcal{O}(\alpha_s^3) + \mathcal{O}(\alpha_s^4)$	$(\sigma^{\text{NNLO}}_{\text{exact}} - \sigma^{\text{NNLO}}_{\text{HEFT}})$ [pb] $\mathcal{O}(\alpha_s^3)$	$\mathcal{O}(\alpha_s^4)$	$(\sigma^{\text{NNLO}}_{\text{exact}}/\sigma^{\text{NNLO}}_{\text{HEFT}} - 1)$ [%]
		$\sqrt{s} = 8\,\text{TeV}$		
gg	$7.39 + 8.58 + 3.88$	$+0.0353$	$+0.0879 \pm 0.0005$	$+0.62$
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	$+0.0667 \pm 0.0007$	-0.10
		$\sqrt{s} = 13\,\text{TeV}$		
gg	$16.30 + 19.64 + 8.76$	$+0.0345$	$+0.2431 \pm 0.0020$	$+0.62$
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	$+0.1815 \pm 0.0023$	-0.26

Mixed QCD×EW Effects

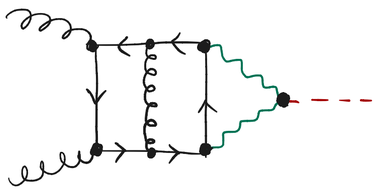
[Becchetti, Bonciani, Del Duca, Hirschi, Moriello, Schweitzer '20]

Dominant light-quark contribution to gluon fusion:

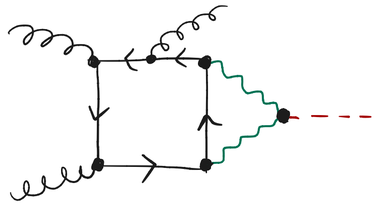
LO



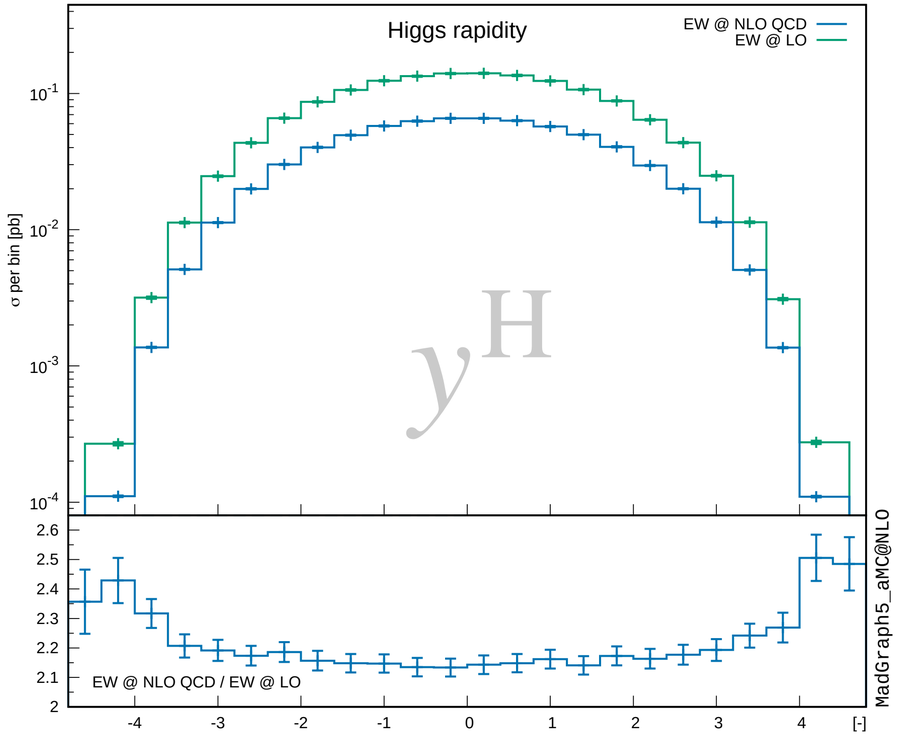
NLO$_{\text{QCD}}$



[Bonetti, Melnikov, Tancredi '17]



[Bonetti, Panzer, Smirnov, Tancredi '20]
[Becchetti, Bonciani, Del Duca, Hirschi, Moriello, Schweitzer '20]



Previous estimates:

- soft approx. 5.4 %
  [Bonetti, Melnikov, Tancredi '18]
- $M_{\text{H}} \ll M_V$ 5.2 %
  [Anastasiou, Boughezal, Petriello '09]
- $M_{\text{H}} \gg M_V$ 5.4 %
  [Anastasiou, Del Duca, Furlan, Mistlberger, Moriello, Schweitzer, Specchia '19]

Exact:

5.1 %

uncertainty:
$\delta(\text{EW}) \sim 0.6\,\%$

- flat K-factor in Y_{H}
- favours *factorized* EW corrections:
  $\sigma = \sigma_{\text{LO}}\,(1+\delta_{\text{QCD}}) \times (1+\delta_{\text{EW}})$

Gluon Fusion — The Error Budget

[Czakon, Harlander, Klappert, Niggetiedt '20]

Remove one source of uncertainty!

Future:

- light-quark mass effects
  - large logs to resum?

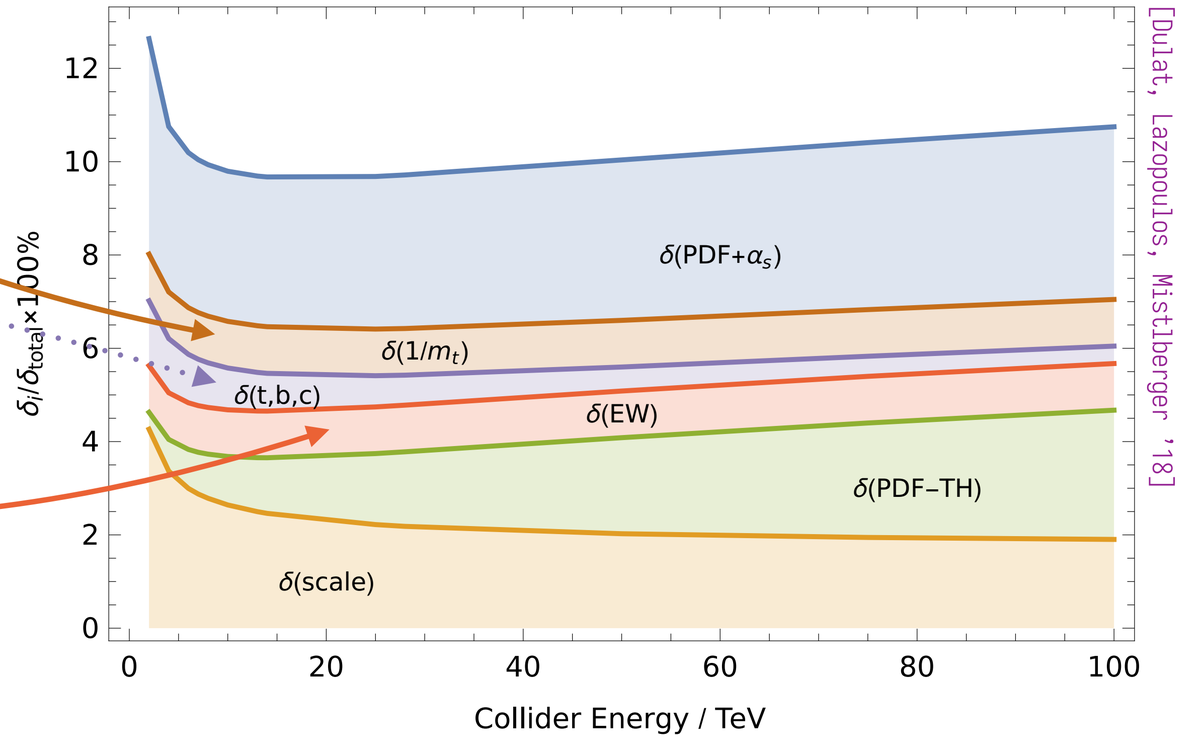
[Becchetti, Bonciani, Del Duca, Hirschi, Moriello, Schweitzer '20]

Reduce uncertainty: $\sim 1\,\% \to 0.6\,\%$

Future:

- quark-induced EW contributions
- large p_T^H?
- m_t dependence in QCD amplitude?

Sources of Uncertainties:



G. Salam

- $\delta(\text{PDF} + \alpha_s)$ — more data & accurate determinations
- $\delta(\text{PDF} - \text{TH})$ — missing N³LO PDFs (AP kernels)

Higgs @ N³LO ⇝ Going Differential

- What is the probability of producing a Higgs boson?

  [Anastasiou et al. '15] [Mistlberger '18]

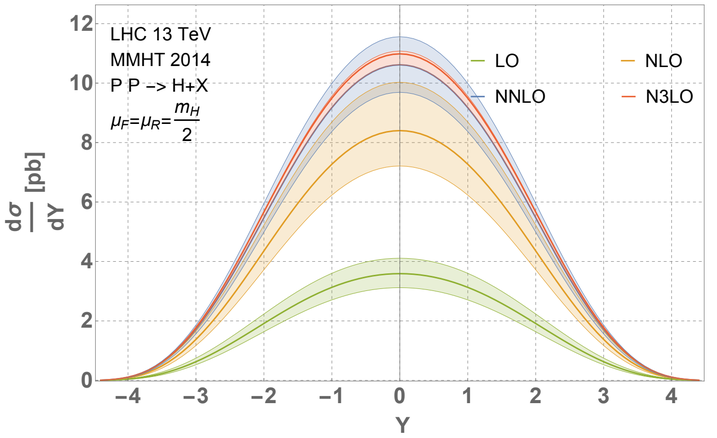
$$\sigma_{tot}^{pp\to H}$$

$$\sigma_{tot}^{N^3LO} = 48.68\ \text{pb}^{+2.07\ \text{pb}}_{-3.16\ \text{pb}}$$

- ... in direction $Y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$

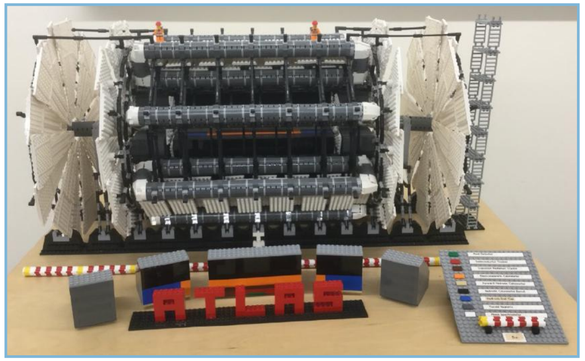
  [Dulat, Mistlberger, Pelloni '18]

$$\frac{d\sigma^{pp\to H}}{dY}$$



... where the Higgs decays into a pair of photons, $H \to \gamma\gamma$, and the leading and sub-leading photon have a transverse momentum that is larger than 35% and 25% of the Higgs boson mass, respectively, and are produced within the rapidity interval $|y_\gamma| < 2.37$, where the barrel-endcap region $1.37 < |y_\gamma| < 1.52$ is excluded. Photons are further required to be isolated from additional QCD activity by requiring that the scalar sum of the transverse momenta of hadrons in a cone of $\Delta R = 0.2$ around the photons is less than 5 % of the photon transverse energy E_T.

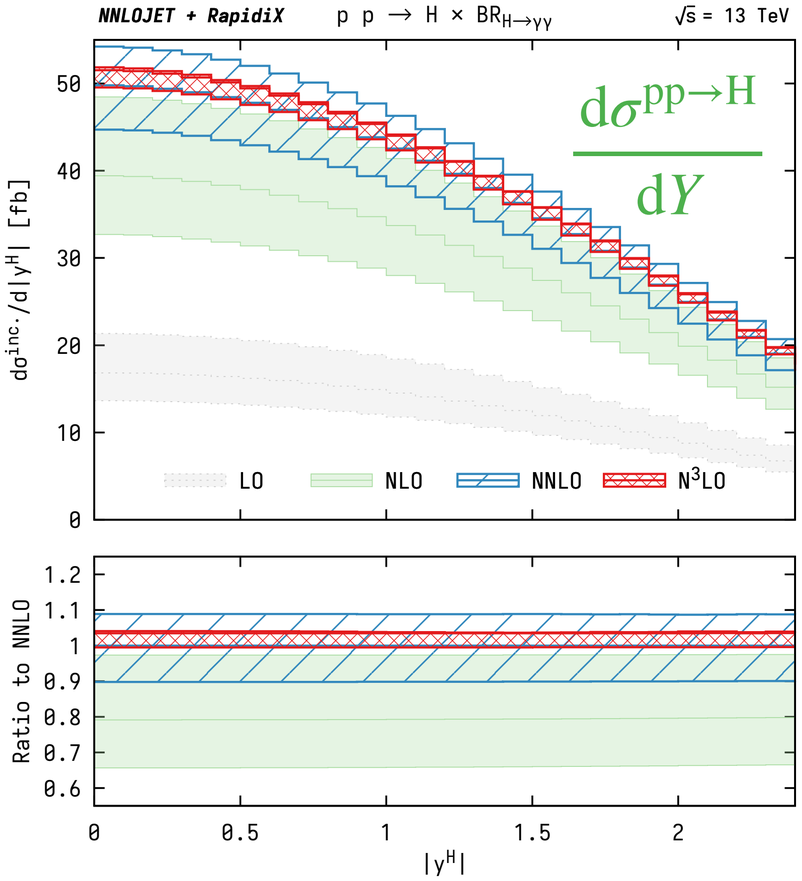
$$d\sigma^{pp\to H}$$



Fully Differential Higgs @ N³LO

[Chen, Gehrmann, Glover, AH, Mistlberger, Pelloni '21]

Inclusive

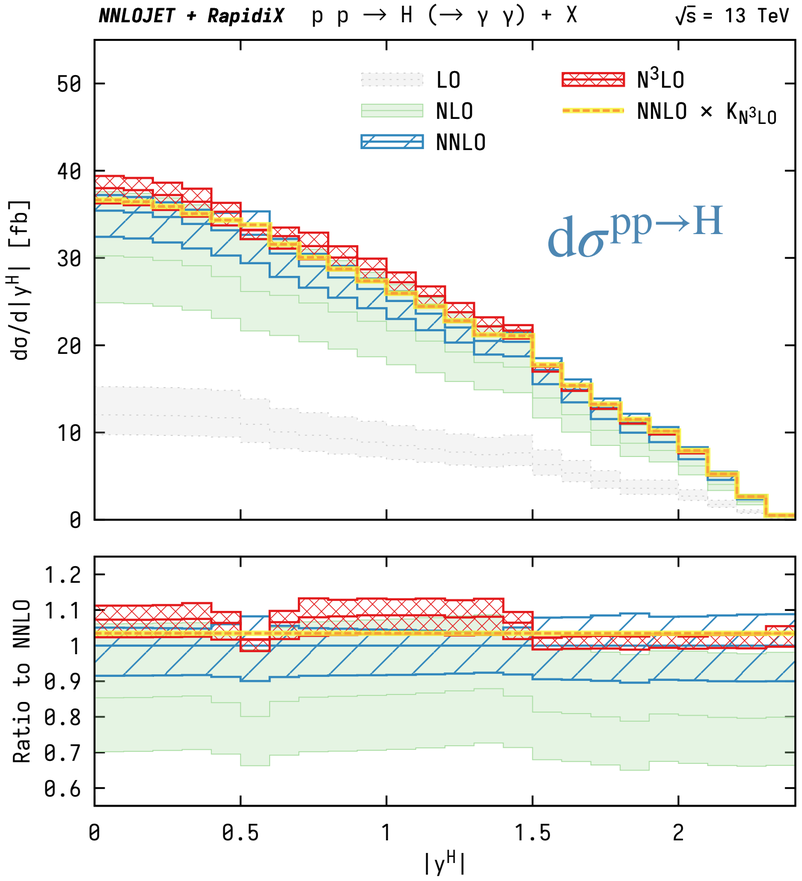


- $p_T^{\gamma 1} > 0.35 \cdot m_{\gamma\gamma}$
- $p_T^{\gamma 2} > 0.25 \cdot m_{\gamma\gamma}$
- $|y^\gamma| < 2.37$
- reject $1.37 < |y^\gamma| < 1.52$ (barrel-endcap)
- *photon isolation* in $\Delta R < 0.2$

  $\hookrightarrow \sum_{\Delta R_{i\gamma}<0.2} p_{T,i} < 0.05 \cdot E_T^\gamma$

- NNLO × K_{N^3LO} ≈ N³LO
- reduced uncertainties
- some "features"

Fiducial (ATLAS)



Fully Differential Higgs @ N³LO

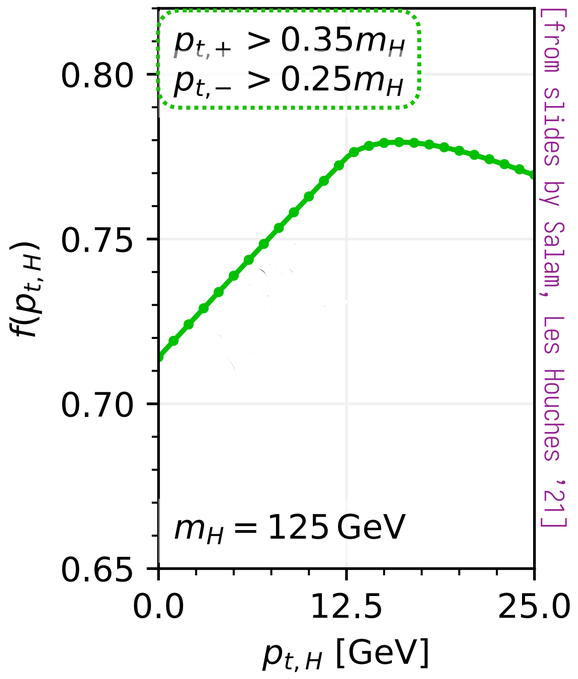
Origin: Linear acceptance ⇝ IR sensitivity

"fiducial power corrections"

[Frixione, Ridolfi '97] [Ebert, Tackmann '19 + Michel, Stewart '21] [Alekhin et al. '21]

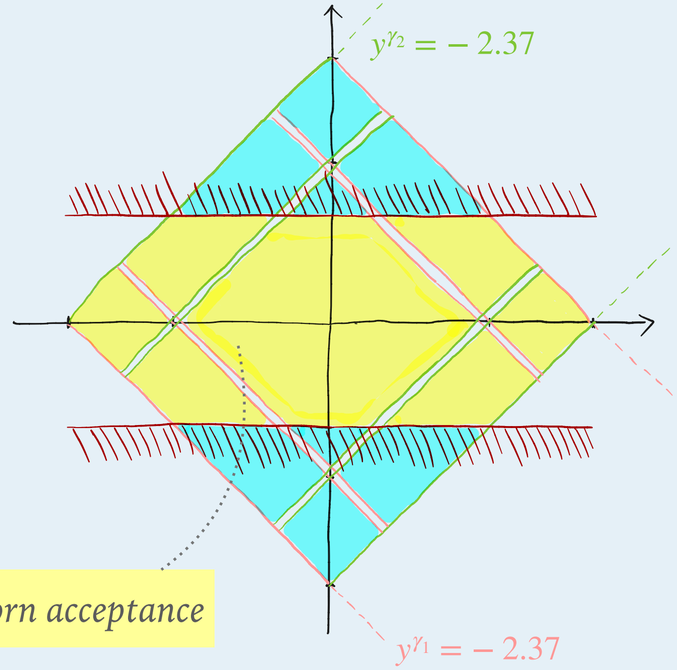
[Chen, Gehrmann, Glover, AH, Mistlberger, Pelloni '21]

"with cuts" / "no cuts"



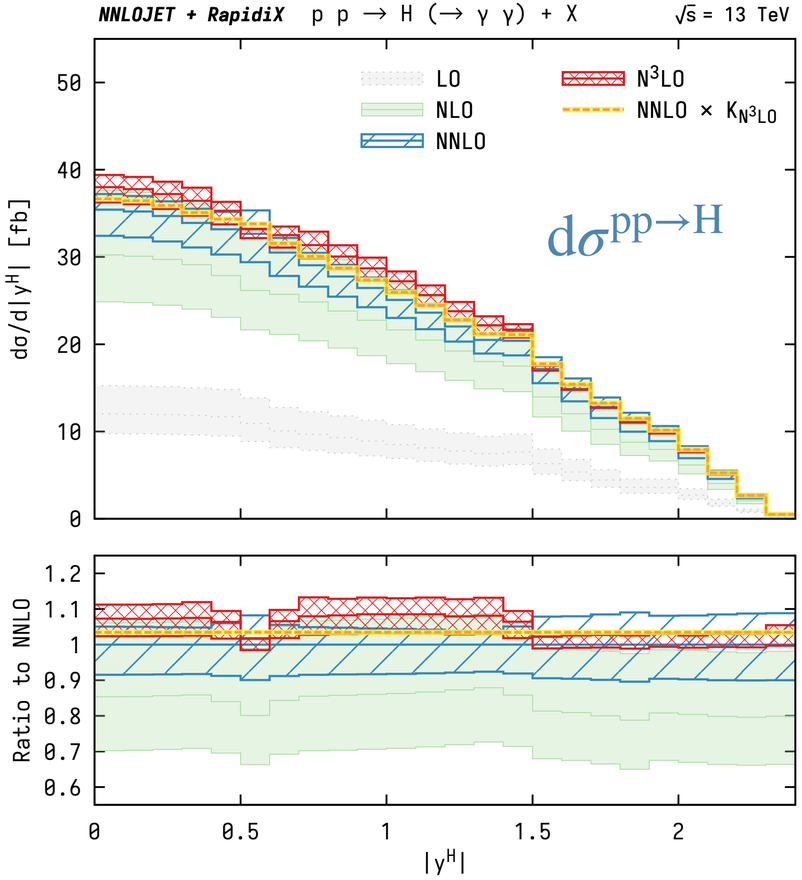
[from slides by Salam, Les Houches '21]

$$\frac{1}{2}\,|\,\Delta y(\gamma_1,\gamma_2)\,| \lesssim 0.9 \quad @\ p_{\mathrm{T}}^{\mathrm{H}} \to 0$$



Born acceptance

Fiducial (ATLAS)



Fully Differential Higgs @ N³LO

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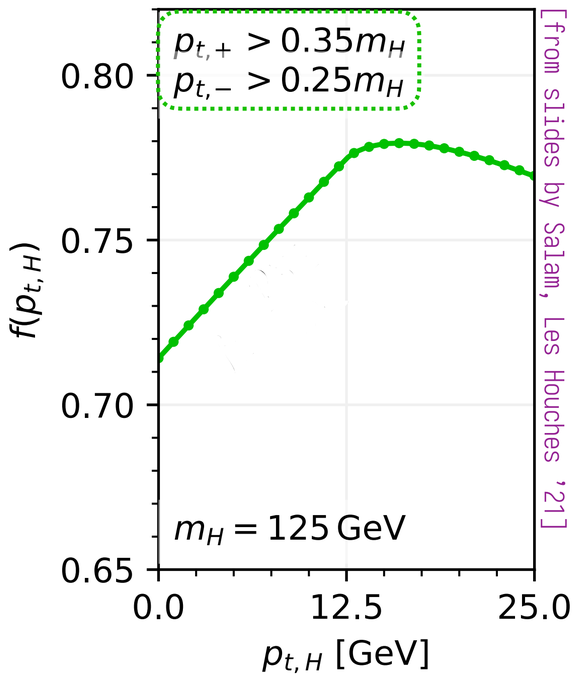
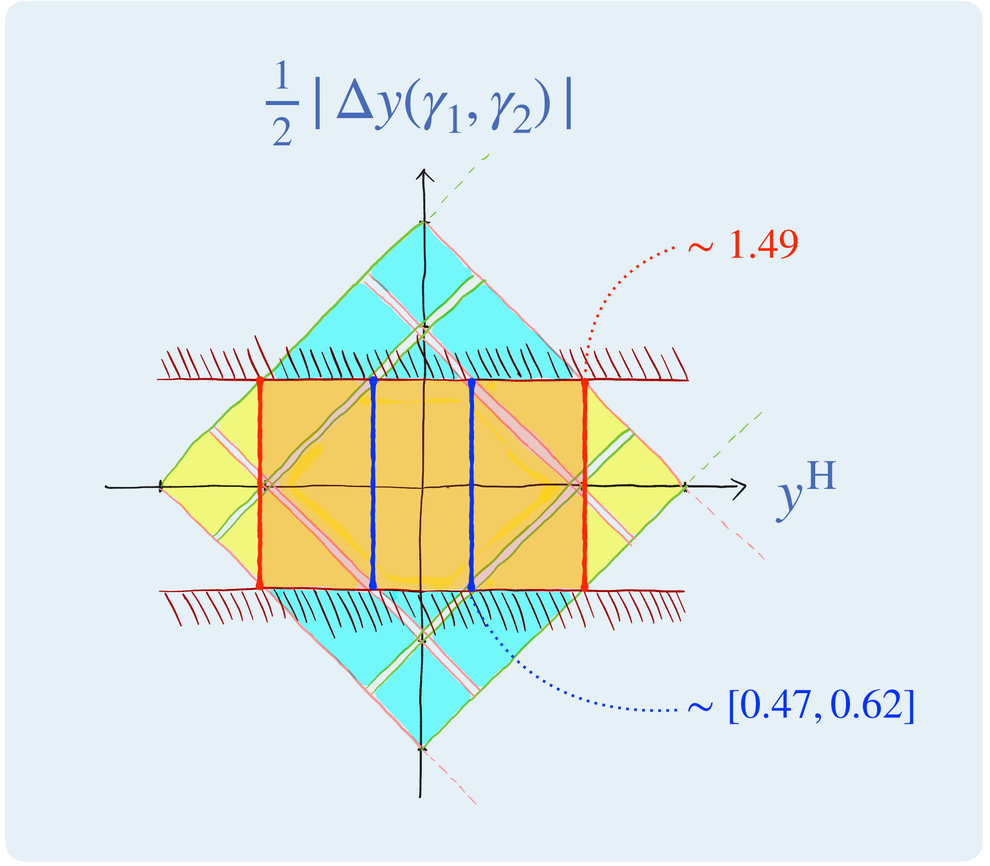
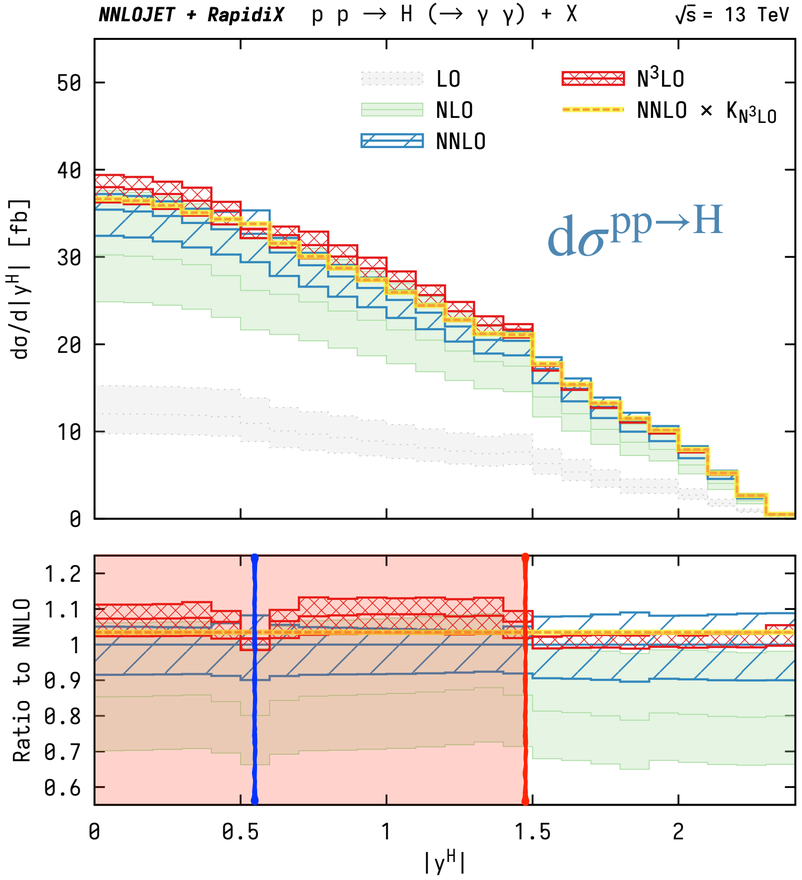




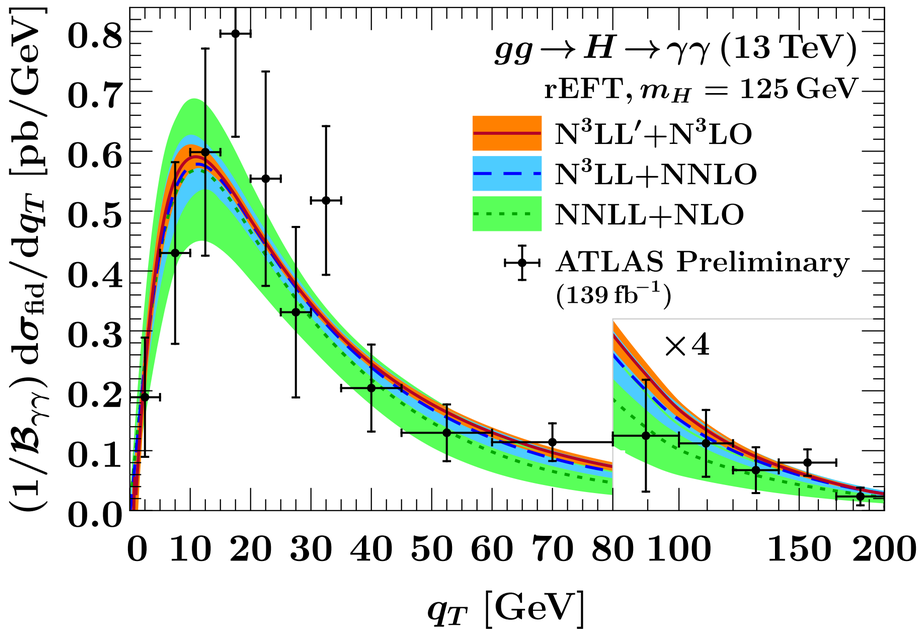
[Chen, Gehrmann, Glover, AH, Mistlberger, Pelloni '21]

Fiducial (ATLAS)

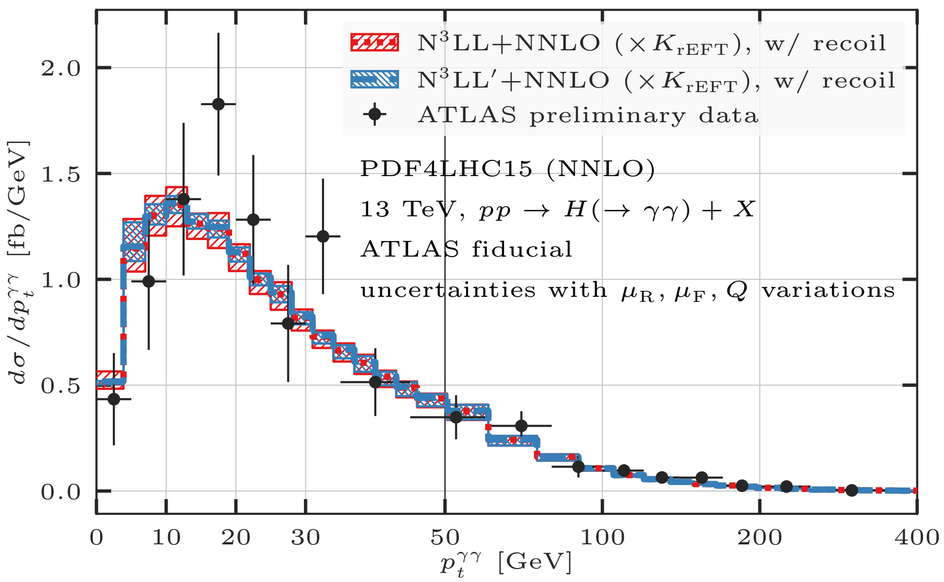


Higgs p_T @ N³LL′+NNLO₁

[Billis, Dehnadi, Ebert, Michel, Tackmann '21]



[Re, Rottoli, Torrielli '21]



Enabled by various ingredients:

- …
- "N³LO beam function" *last missing*

[Behring, Melnikov, Rietkerk, Tancredi, Wever '19]
[Luo, Yang, Zhu, Zhu '20] [Ebert, Mistlberger, Vita '20]

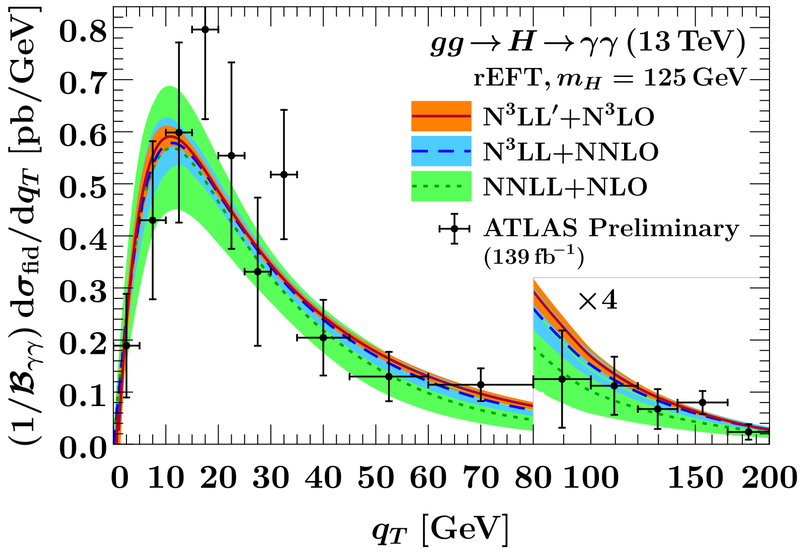
→ *colour-singlet @ N³LO*

fiducial power corrections
absorbed by recoiling Higgs

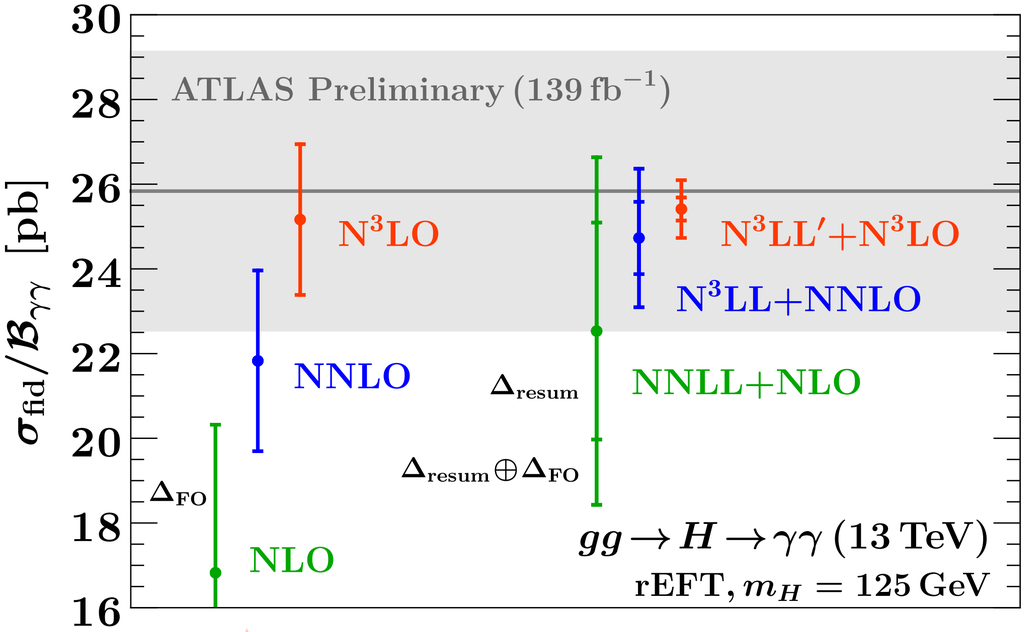
[Catani, de Florian, Ferrera, Grazzini, '15]
[Ebert, Michel, Stewart, Tackmann '20]

HIGGS @ N³LL′+N³LO₀

[Billis, Dehnadi, Ebert, Michel, Tackmann '21]



$$\sigma = \int \mathrm{d}q_T \, \frac{\mathrm{d}\sigma}{\mathrm{d}q_T}$$

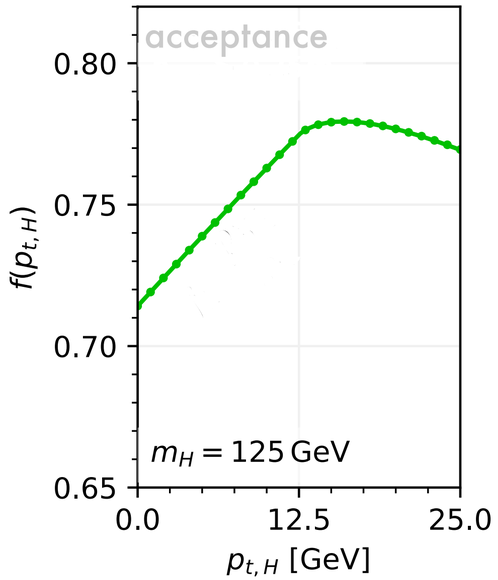


- N³LO corrections larger than incl. $K_{\mathrm{N^3LO}}$
  - impact of *fiducial power corrections* (fpc)
- improved convergence with "+N³LL"

resummation necessary to define a "hard" fiducial cross section?!

$$\begin{aligned}\sigma^{\mathrm{FO}}_{\mathrm{fid}}/\mathcal{B}_{\gamma\gamma} = 6.928\,[1 &+ (1.300 + 0.129_{\mathrm{fpc}}) \\ &+ (0.784 - 0.061_{\mathrm{fpc}}) \\ &+ (0.331 + 0.150_{\mathrm{fpc}})]\,\mathrm{pb}\,.\end{aligned}$$

CUTS TO REMOVE THE IR SENSITIVITY

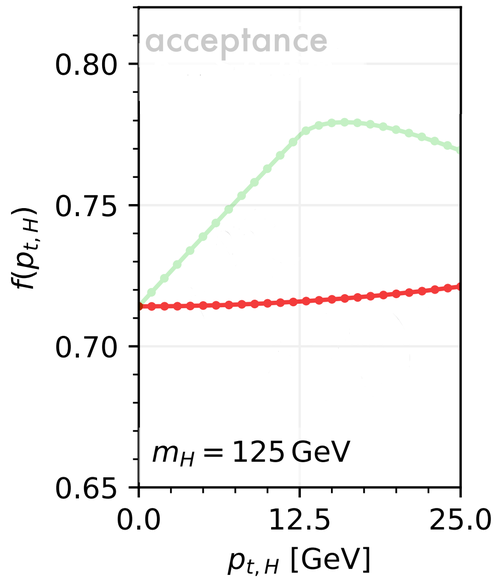


ATLAS

$$p_{\mathrm{T}}^{\gamma_1} \geq 0.35 \cdot M_{\mathrm{H}}$$

$$p_{\mathrm{T}}^{\gamma_2} \geq 0.25 \cdot M_{\mathrm{H}}$$

$$f(p_{\mathrm{T}}^{\mathrm{H}}) = f_0 + f_1 \cdot p_{\mathrm{T}}^{\mathrm{H}} + \mathcal{O}\left((p_{\mathrm{T}}^{\mathrm{H}})^2\right)$$

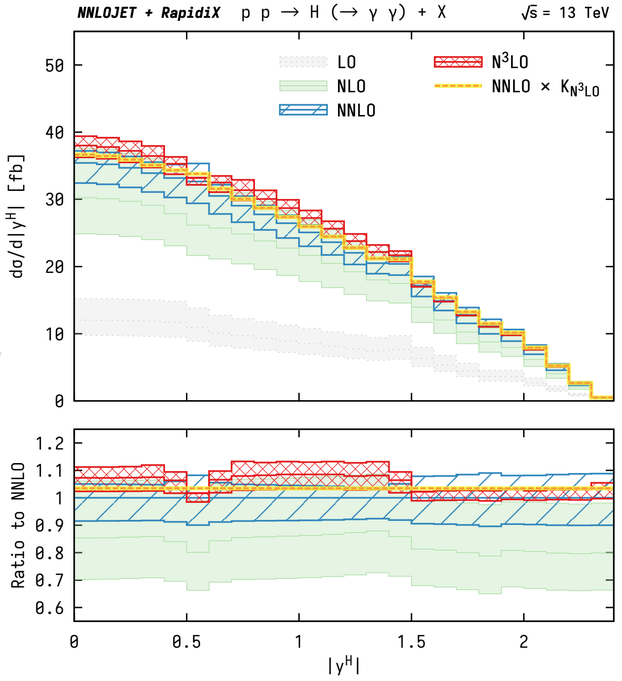


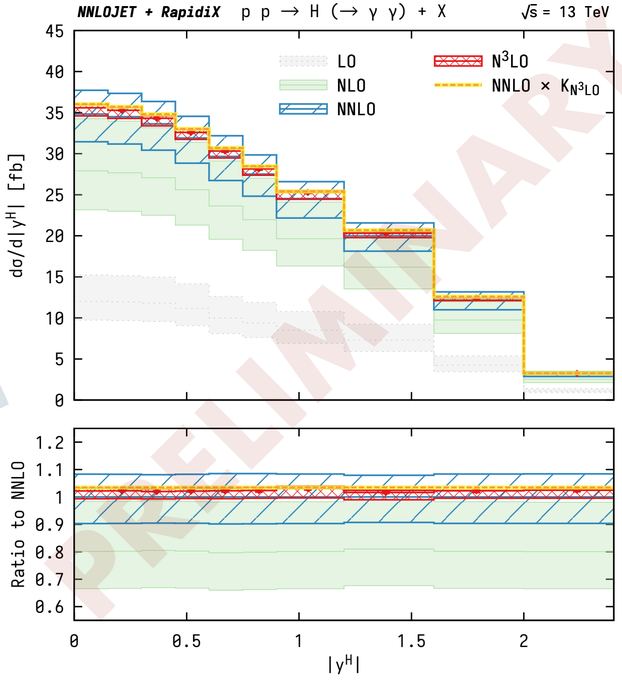
Product cuts [Salam, Slade '21]

$$\sqrt{p_{\mathrm{T}}^{\gamma_1}\, p_{\mathrm{T}}^{\gamma_2}} \geq 0.35 \cdot M_{\mathrm{H}}$$

$$p_{\mathrm{T}}^{\gamma_2} \geq 0.25 \cdot M_{\mathrm{H}}$$

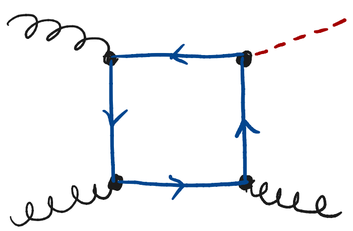
$$f(p_{\mathrm{T}}^{\mathrm{H}}) = f_0 + f_1 \cdot p_{\mathrm{T}}^{\mathrm{H}} + f_2 \cdot (p_{\mathrm{T}}^{\mathrm{H}})^2 + \mathcal{O}\left((p_{\mathrm{T}}^{\mathrm{H}})^3\right)$$





- $\mathrm{NNLO} \times \mathrm{K}_{\mathrm{N^3LO}} \approx \mathrm{N^3LO}$
- very flat
- no "features"
- robust (v.s. resummation)

Higgs @ High p_T



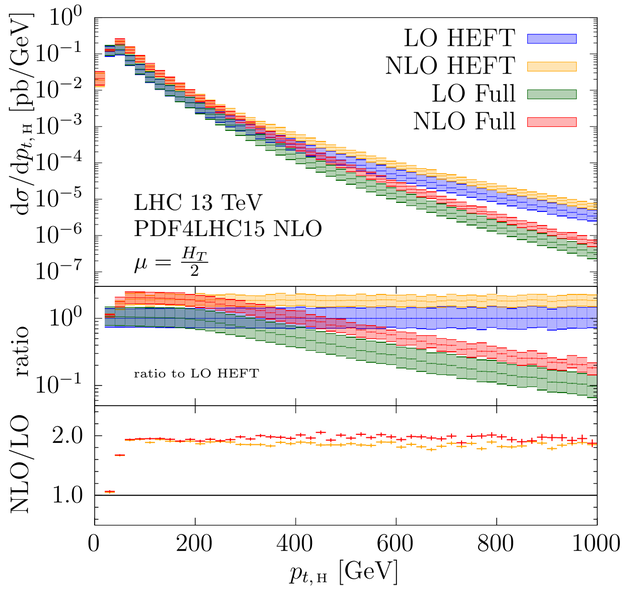
$p_T^H \gtrsim m_t$

↪ HTL not valid

↪ full mass effects

NLO H+jet:

- $p_T^H \gg m_t$ [Kudashkin, Melnikov, Wever '17 + Lindert '18, Neumann '18]
- exact [Jones, Kerner, Luisoni '18]



⊕ NNLO_{HTL} ⇝ $\delta(\text{scale}) \sim 10\,\%$ [Becker et al., LHCHXSWG note '20]

H+2jet @ NLO

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

⇝ VBF background

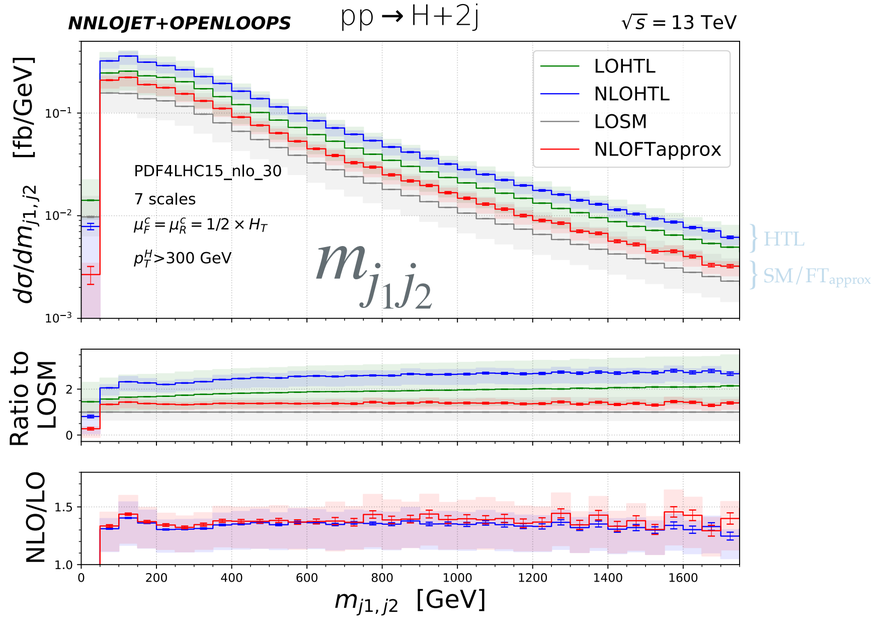
- $\text{FT}_{\text{approx}}$ [Maltoni, Vryonidou, Zaro '14]
  - ↪ exact Born & reals
    (1-loop)² [OpenLoops2]
  - ↪ approx 2-loop

$$|\mathcal{M}_4^2(m_t, \mu_R^2; \{p\})|^2$$

$$\to |\mathcal{M}_4^1(\infty, \mu_R^2; \{p\})|^2 \frac{|\mathcal{M}_4^1(m_t; \{p\})|^2}{|\mathcal{M}_4^0(\infty; \{p\})|^2}$$

- $\mathcal{O}(50\%)$ NLO corrections

see also H+jets ⊕ PS
[Frederix, Frixione, Vryonidou, Wiesemann '16]

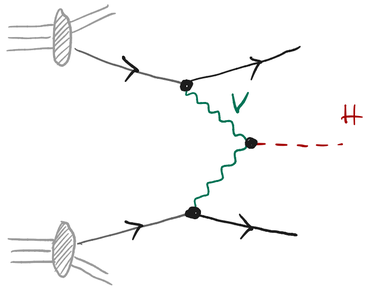


remarkable agreement of K-factors between HTL & $\text{FT}_{\text{approx}}$

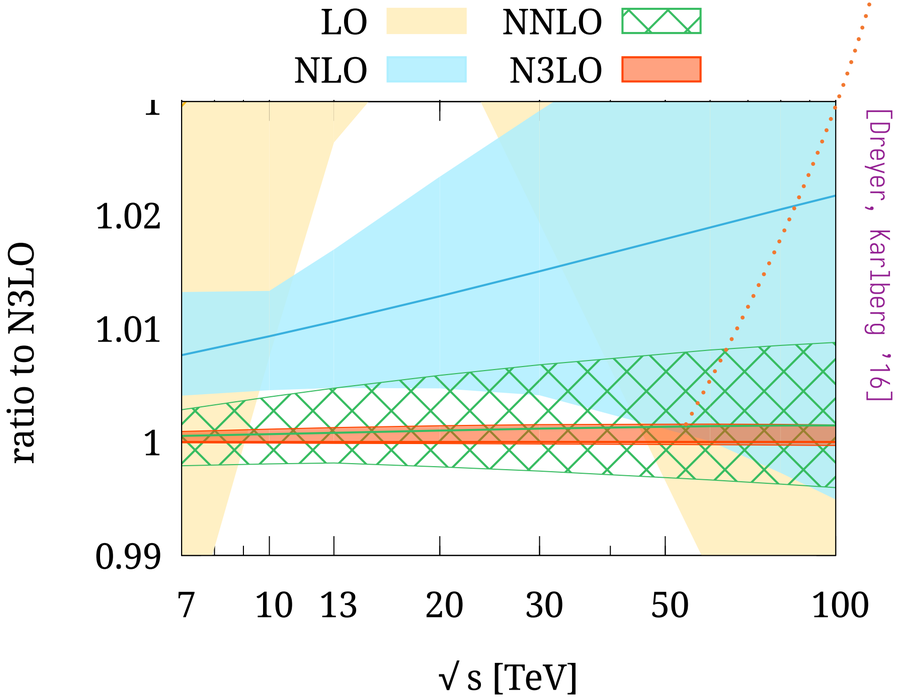
Future:

$\text{FT}_{\text{approx}}$ — H+j @ NNLO ?

Vector Boson Fusion

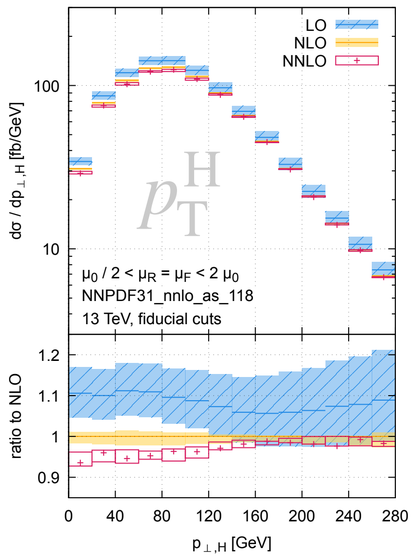


- Inclusive σ
  - ↪ known to N³LO

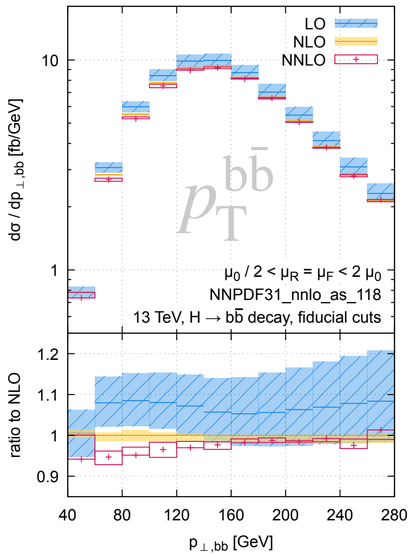


- Differential $d\sigma$
  - ↪ known to NNLO [Cacciari, Dreyer, Karlberg, Salam, Zanderighi '15] [Cruz-Martinez, Glover, Gehrmann, AH '18]
  - ↪ non-factorizable [Liu, Melnikov, Penin '19] [Dreyer, Karlberg, Tancredi '20]
- NNLO with Higgs decays (@ LO)
  - ↪ $H \to b\bar{b}$ — j_b acceptance ⇝ $p_T^H \gtrsim 150$ GeV
  - ↪ $H \to WW$ — flat acceptances

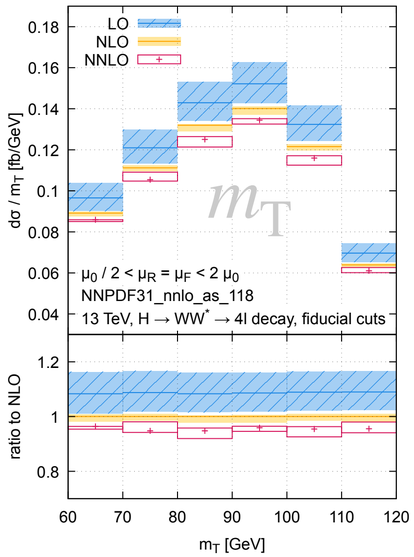
stable H



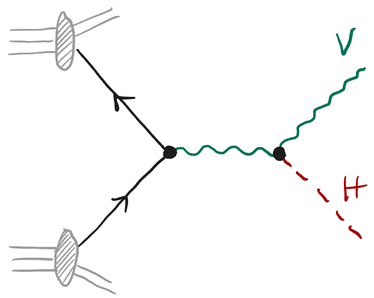
$H \to b\bar{b}$



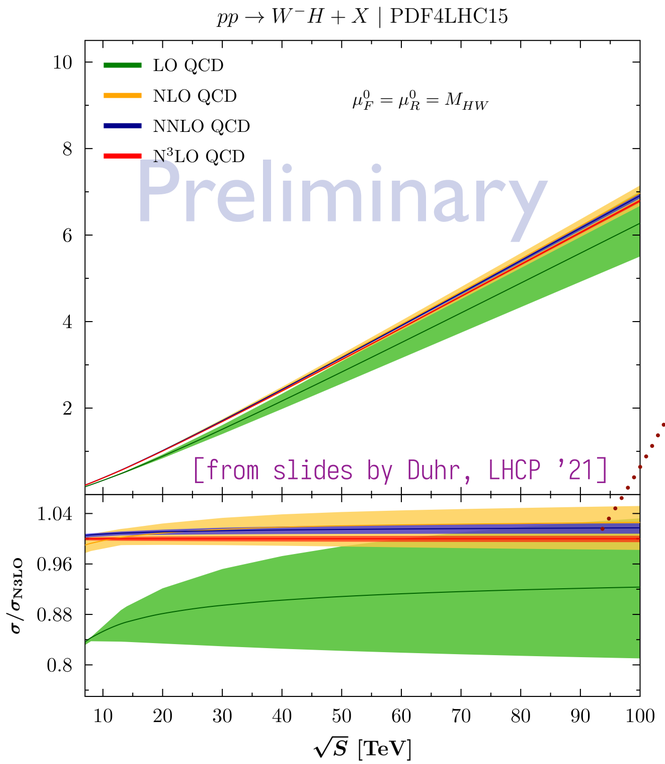
$H \to WW \to 4\ell$



Higgs Strahlung



- Inclusive σ
  - ↪ soon known to N³LO?



VH+jet @ NNLO

↭ signal modelling

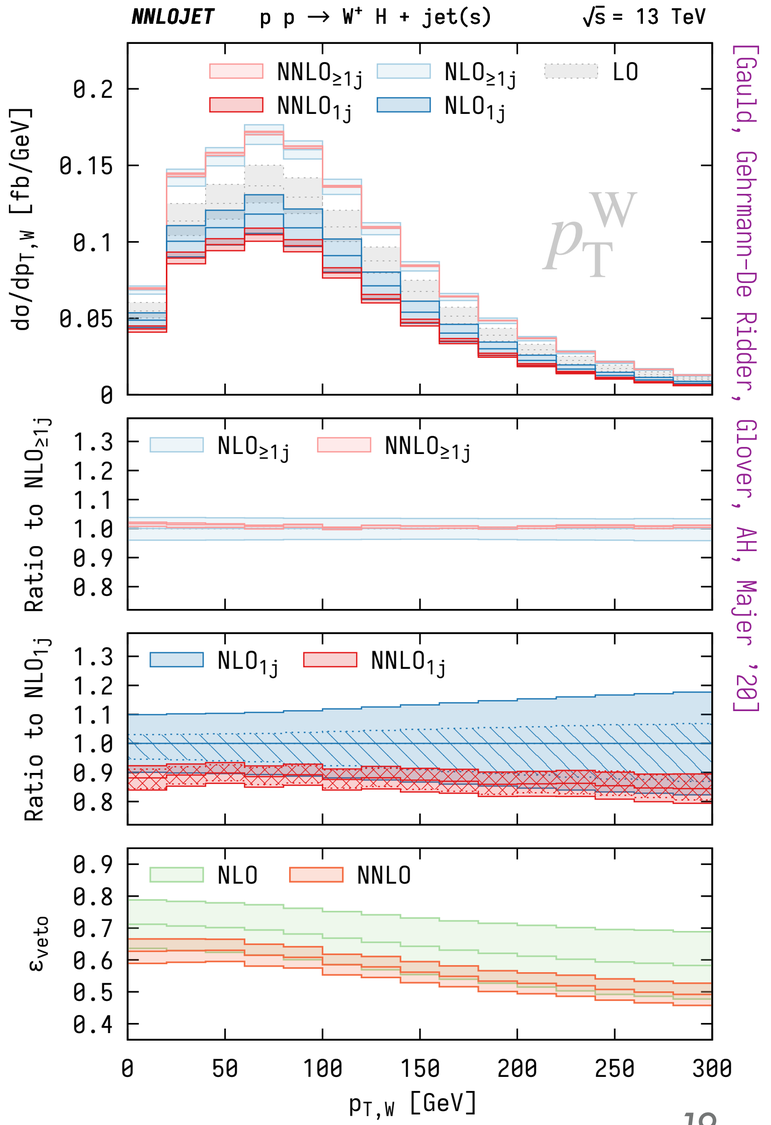
- inclusive ($n_{\text{jets}} \geq 1$)
  excellent convergence

- exclusive ($n_{\text{jets}} \equiv 1$)
  $-10\,\%$ ($\Delta_{1j} \sim 5\,\%$)

$$\sigma_{1\text{j}} \equiv \sigma_{\geq 1\text{j}} - \sigma_{\geq 2\text{j}}$$ [Stuart, Tackmann '12]

$$\Delta^2_{1\text{j}} = \Delta^2_{\geq 1\text{j}} + \Delta^2_{\geq 2\text{j}}$$

Future: differential VH @ N³LO ?



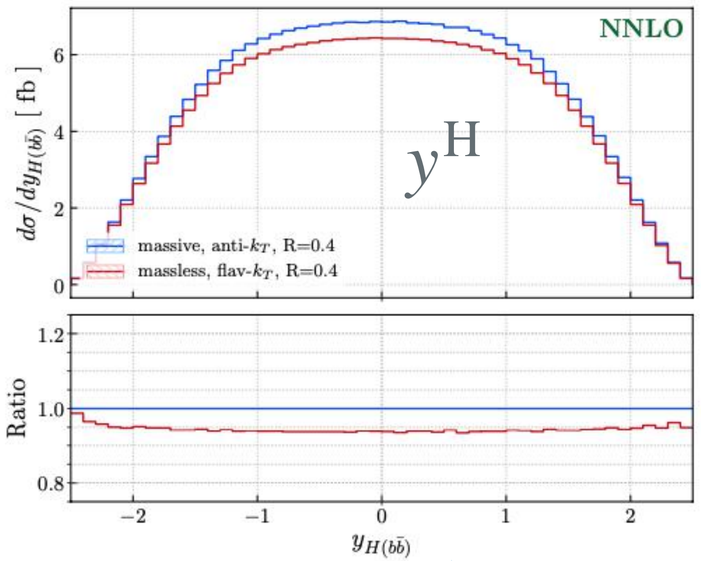
[Gauld, Gehrmann-De Ridder, Glover, AH, Majer '20]

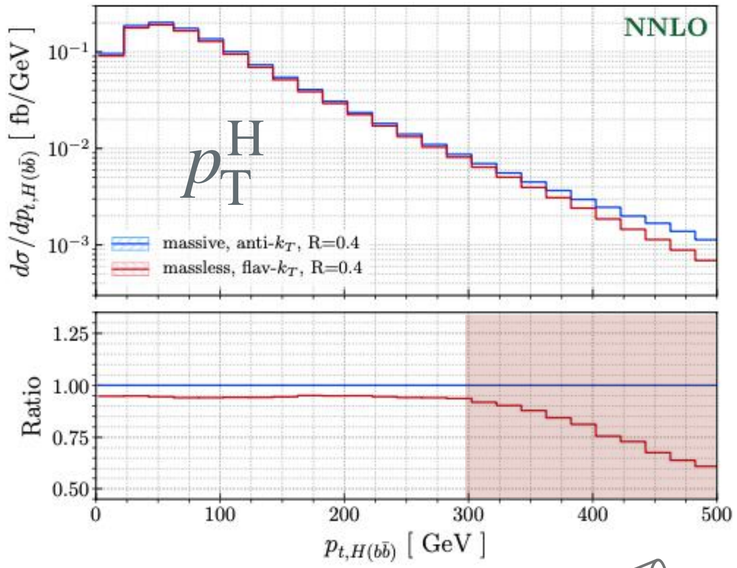
Bottom-Quark Mass Effects WH ($H \to b\bar{b}$)

Why m_b?

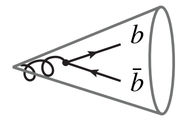
- non-singular $g^* \to b\bar{b}$
  - ↪ can use anti-k_T (~~flavour-k_T~~)
- $\mathcal{O}(y_t y_b)$ interference
  - ↪ minor (sub-percent)
- distributions sensitive to m_b

[Behring, Bizoń, Caola, Melnikov, Röntsch '20]





inclusive ⇝ re-scaling



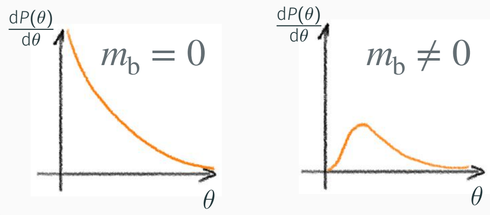
flav-k_T clusters earlier

Fiducial cross sections

Order	b quarks	σ_{fid} [fb]	σ_{fid}(boosted) [fb]
NNLO	massive	$24.225(4)^{+0.642}_{-0.742}$	$4.530(2)^{+0.071}_{-0.096}$
	massless	$22.781(3)^{+0.791}_{-0.898}$	$4.207(1)^{+0.097}_{-0.116}$

acceptance

radiation pattern



Conclusions

Incredible progress in the past few years:

- gluon fusion — various sources of uncertainties attacked
  - top-mass dependence @ NNLO & mixed QCD-EW effects @ NLO
- differential predictions @ N^{3}LO
  - surprises from IR-sensitive fiducial cuts & solutions proposed
- more subtle effects; beyond stable Higgs bosons
  - inclusion of decays & bottom-quark mass effects
- much much more…
  - VBF [LesHouches '19], VBF (HH) non-fact [Dreyer, Karlberg, Tancredi '20],
    $b\bar{b} \to H$ @ N^{3}LO [Duhr, Dulat, Hirschi, Mistlberger '20], $Hb\bar{b}$ [Pagani, Shao, Zaro '20],
    $t \to H$ fragmentation [Brancaccio, Czakon, Generet, Krämer '21],
    $t\bar{t}H$ @ NNLO non-diag [Catani, Fabre, Grazzini, Kallweit '21], …

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Thank you for your Attention!