The Higgs boson and the top quark: precision theory for the LHC and beyond

Massimiliano Grazzini

University of Zurich

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Universität Zürich[UZH]

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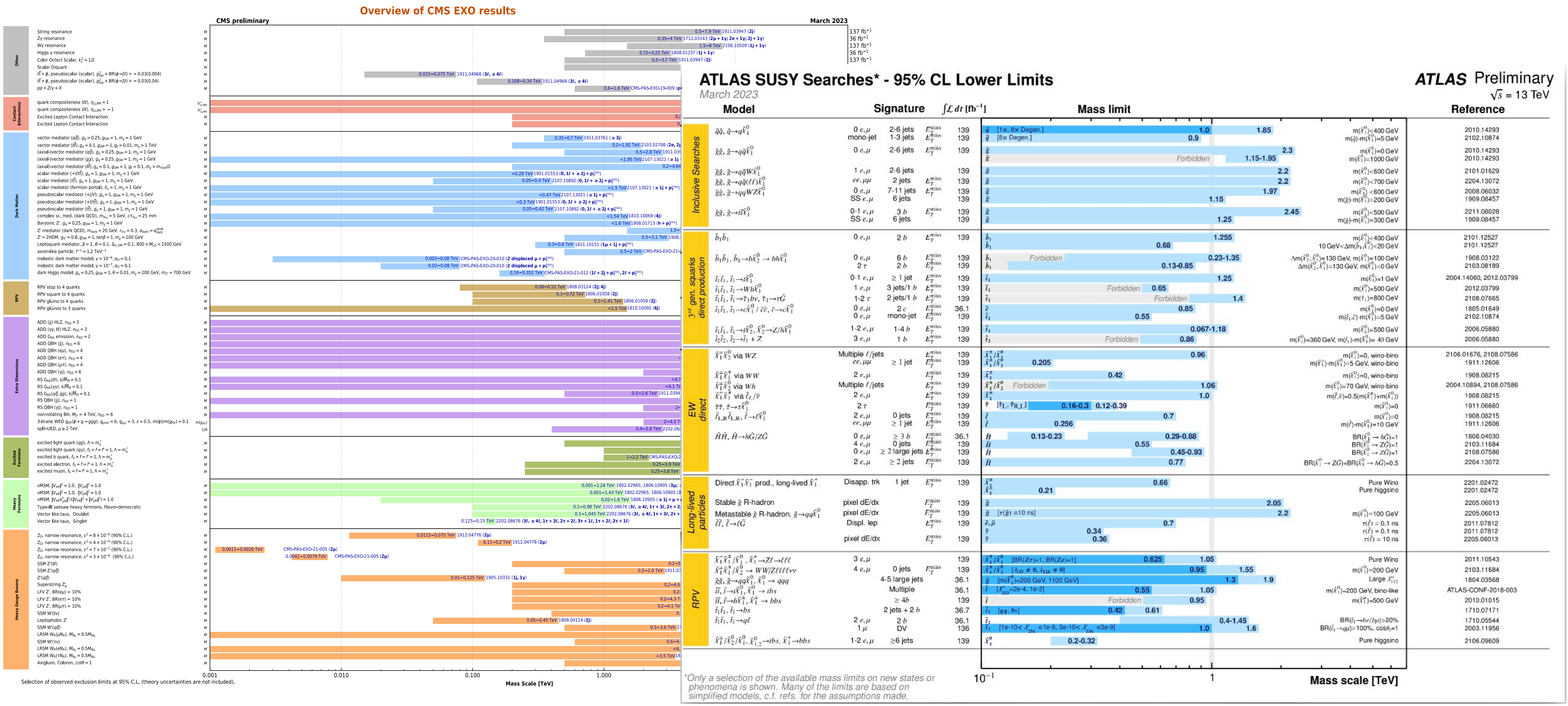
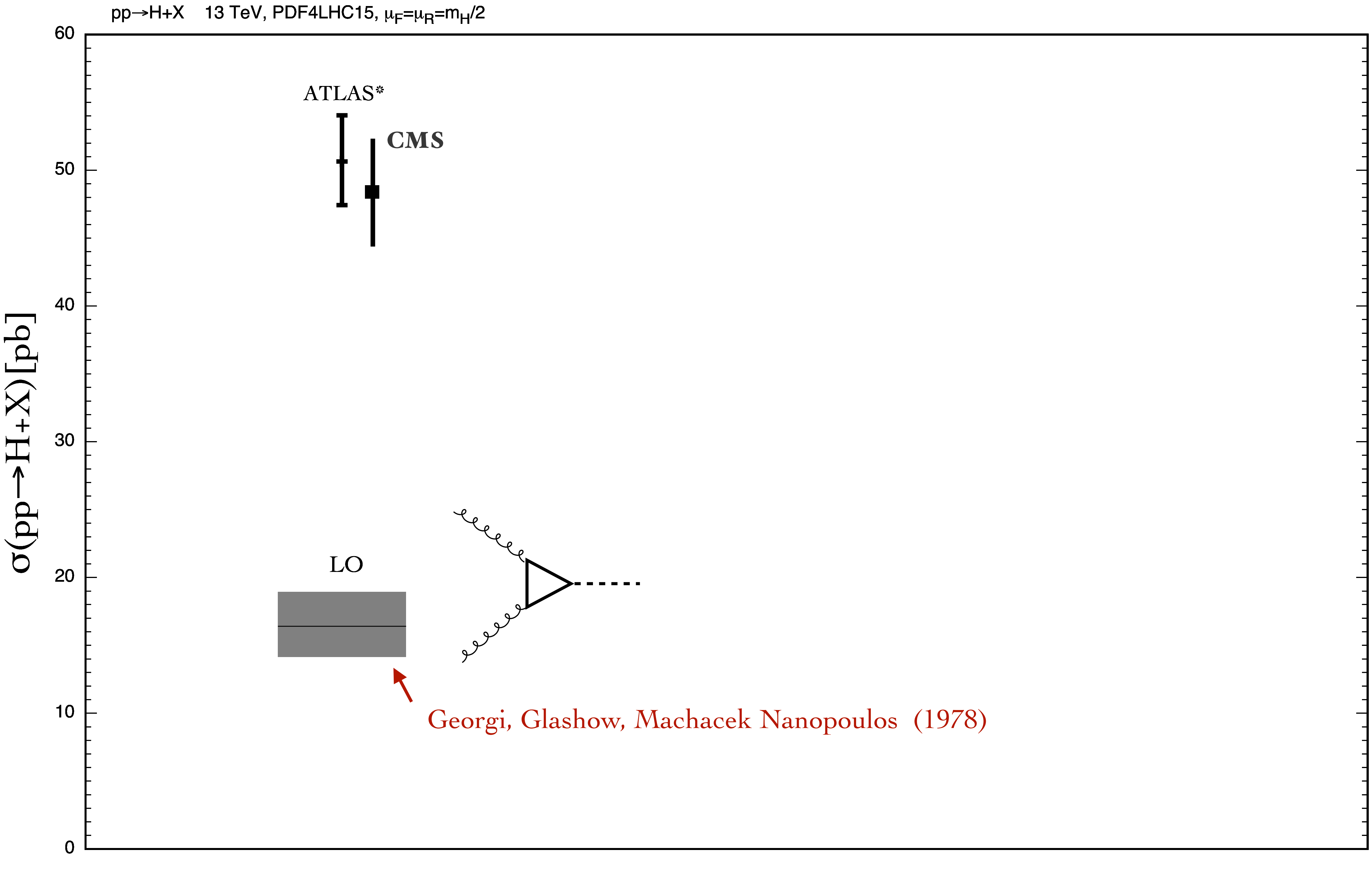
Introduction

After the discovery of the Higgs boson in 2012 no evidence of New Physics….

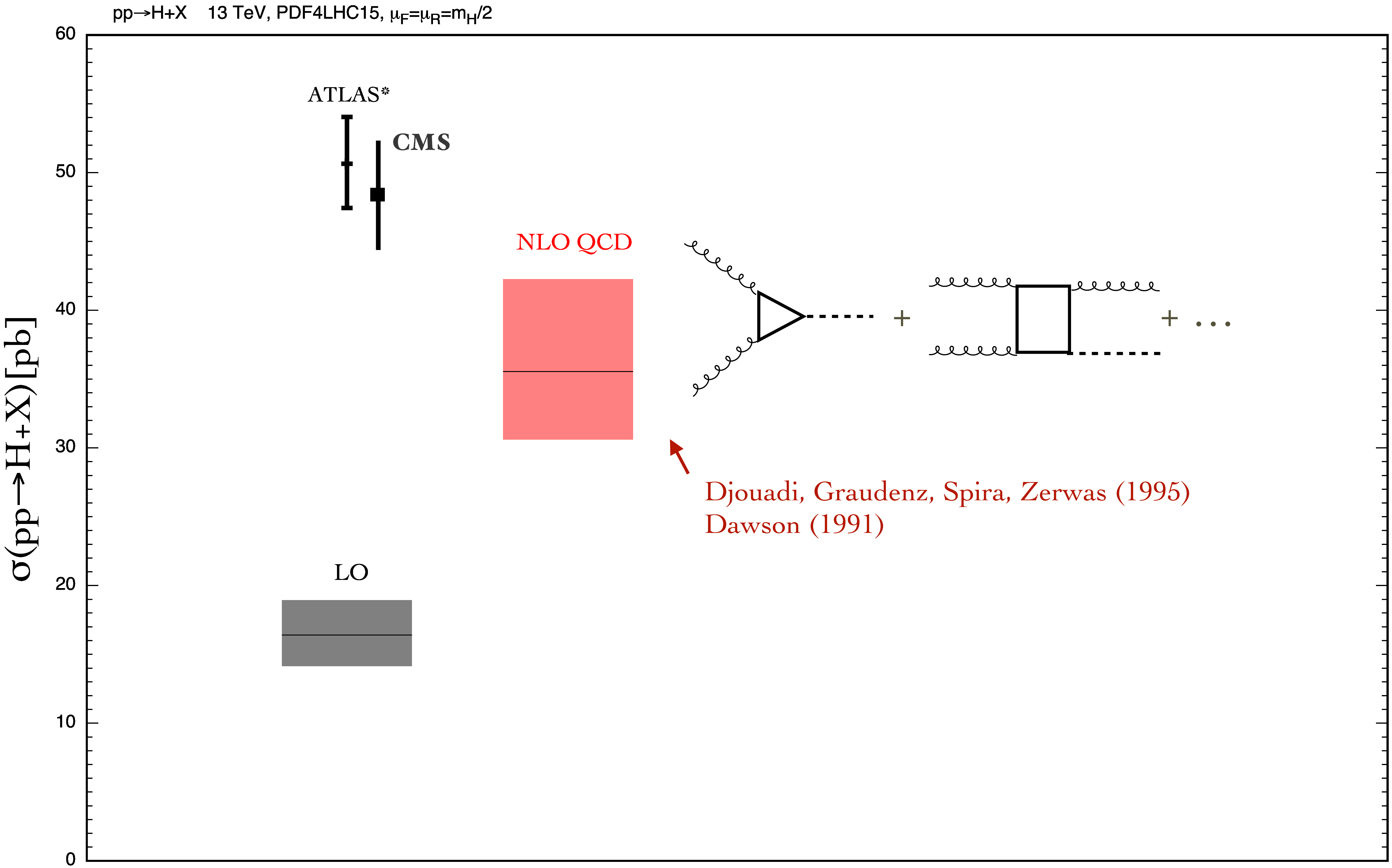


….but the LHC has accumulated less than10% of the planned integrated luminosity and surprises might well be behind the corner !

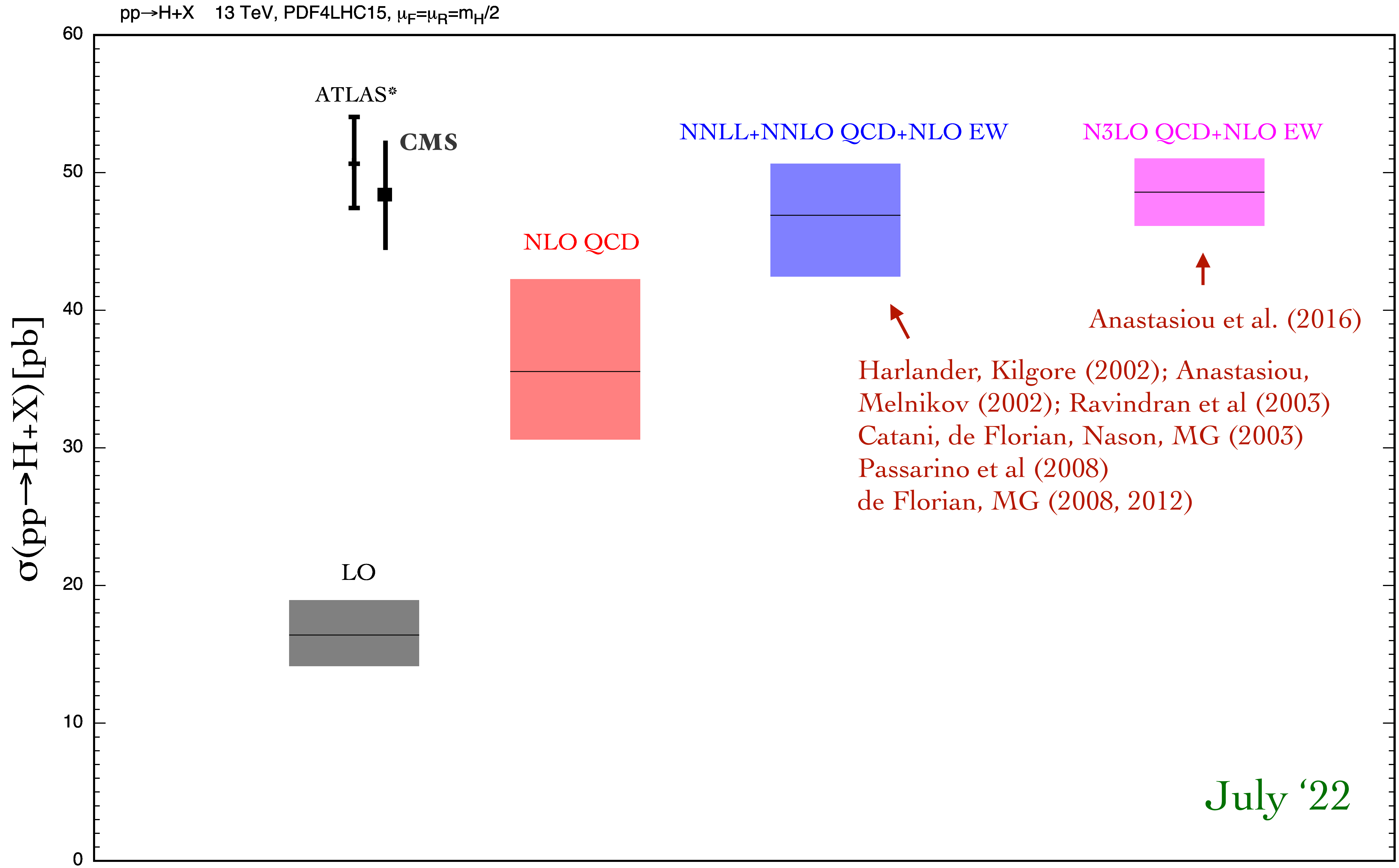
The role of precision theory



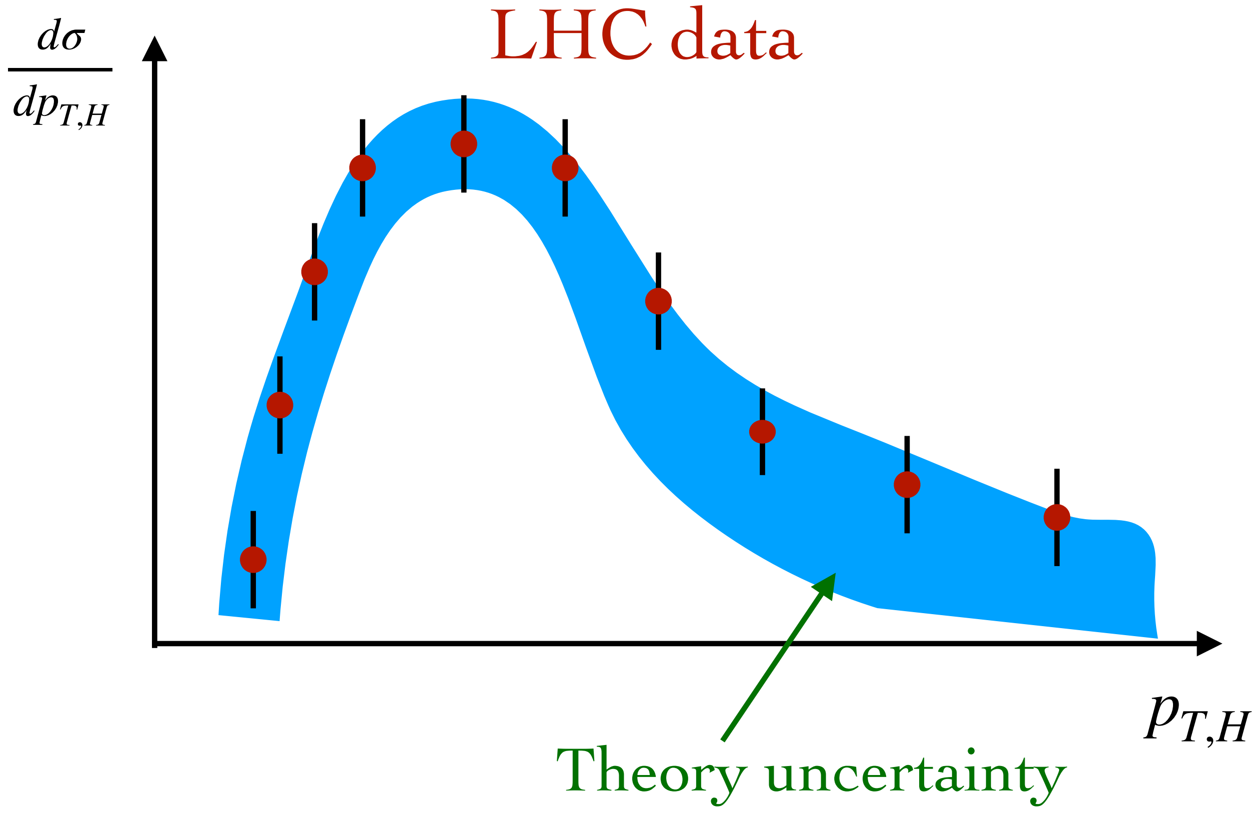
The role of precision theory



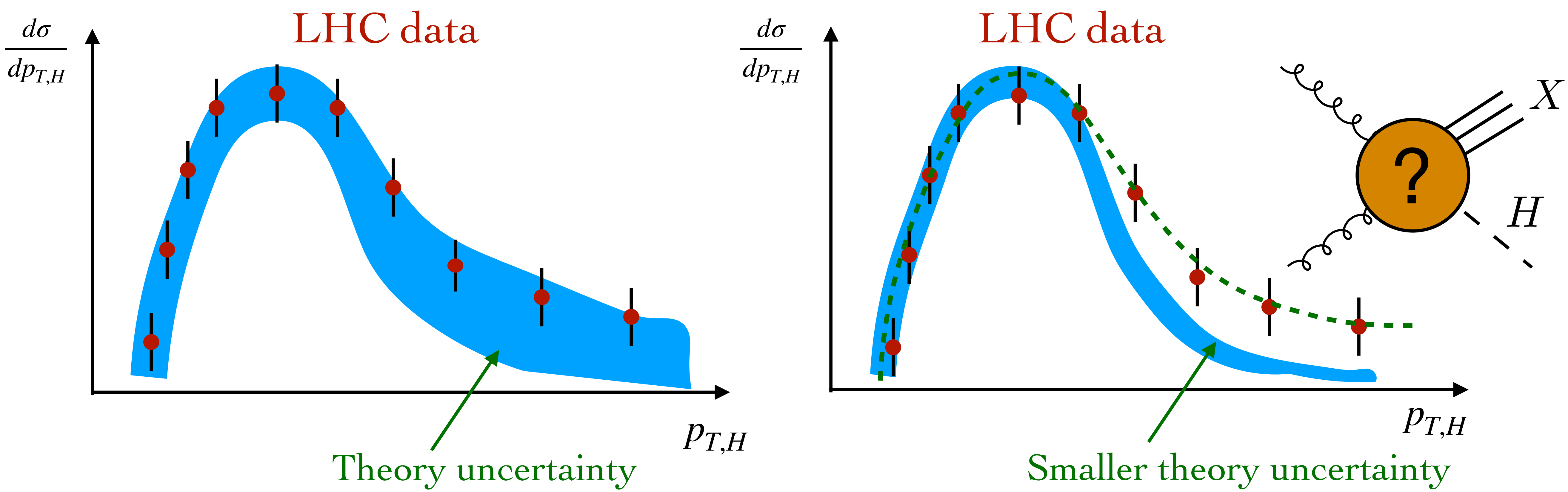
The role of precision theory



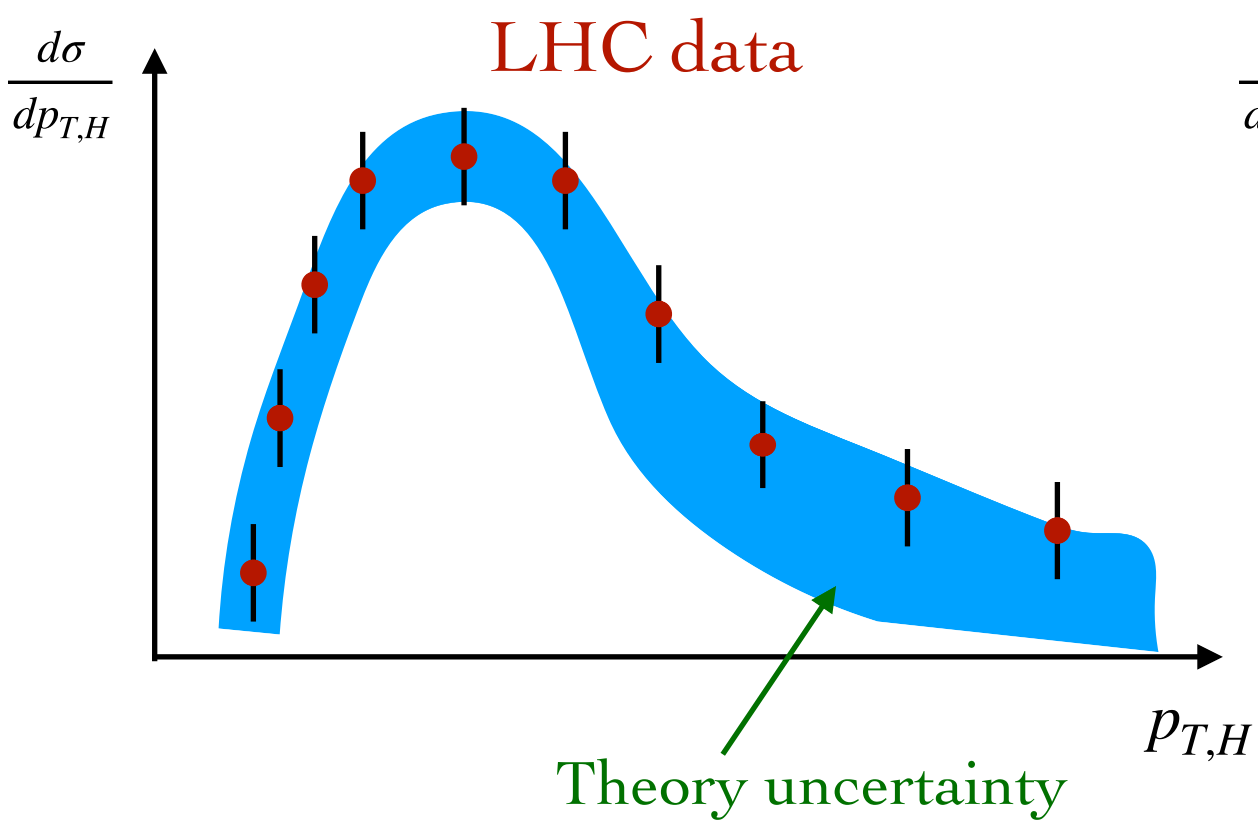
The role of precision theory

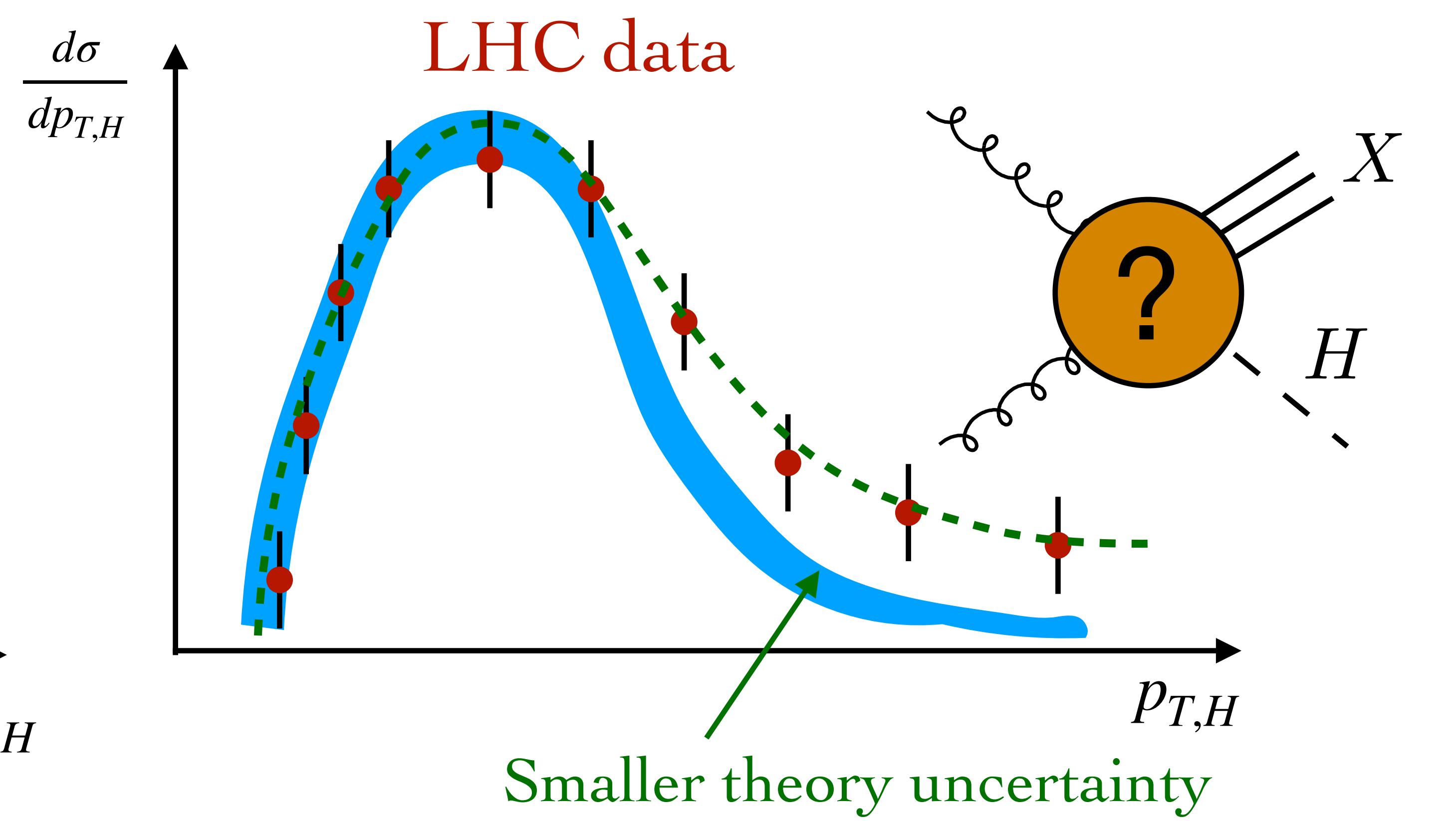


The role of precision theory



The role of precision theory





Larger theory uncertainties may lead to miss (or at least delay) new discoveries

New physics showing up in the high-p_T tail can be modelled with SMEFT

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

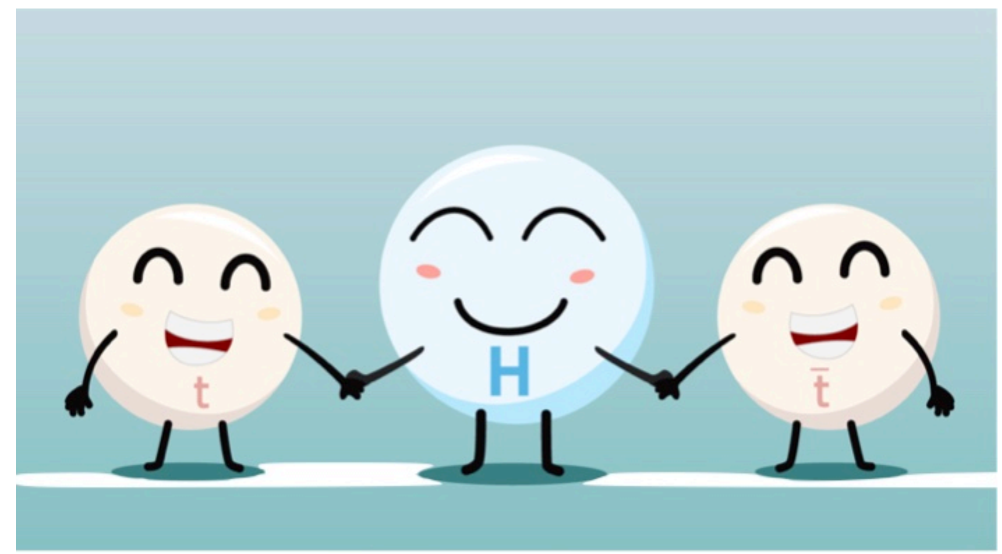
$$\begin{aligned} \mathcal{O}_1 &= |H|^2 G^a_{\mu\nu} G^{a,\mu\nu}\,, \\ \mathcal{O}_2 &= |H|^2 \bar{Q}_L H^c t_R + h.c.\,, \\ \mathcal{O}_3 &= \bar{Q}_L H \sigma^{\mu\nu} T^a t_R G^a_{\mu\nu} + h.c. \end{aligned}$$

See e.g. Ilnicka, Spira, Wiesemann, MG (2016)
Battaglia, Spira, Wiesemann , MG(2021)

The Higgs and the top

The Higgs boson and the top quark are the heaviest elementary particles known to date

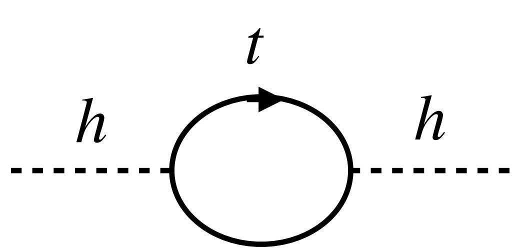
Since in the SM the Higgs boson couplings are proportional to particle masses the top-Higgs interaction is strong



$$m_t = y_t v/\sqrt{2} \sim 173\,\text{GeV}$$

$$\Rightarrow \quad y_t \sim 1$$

The top-Higgs interaction can open the window to new physics

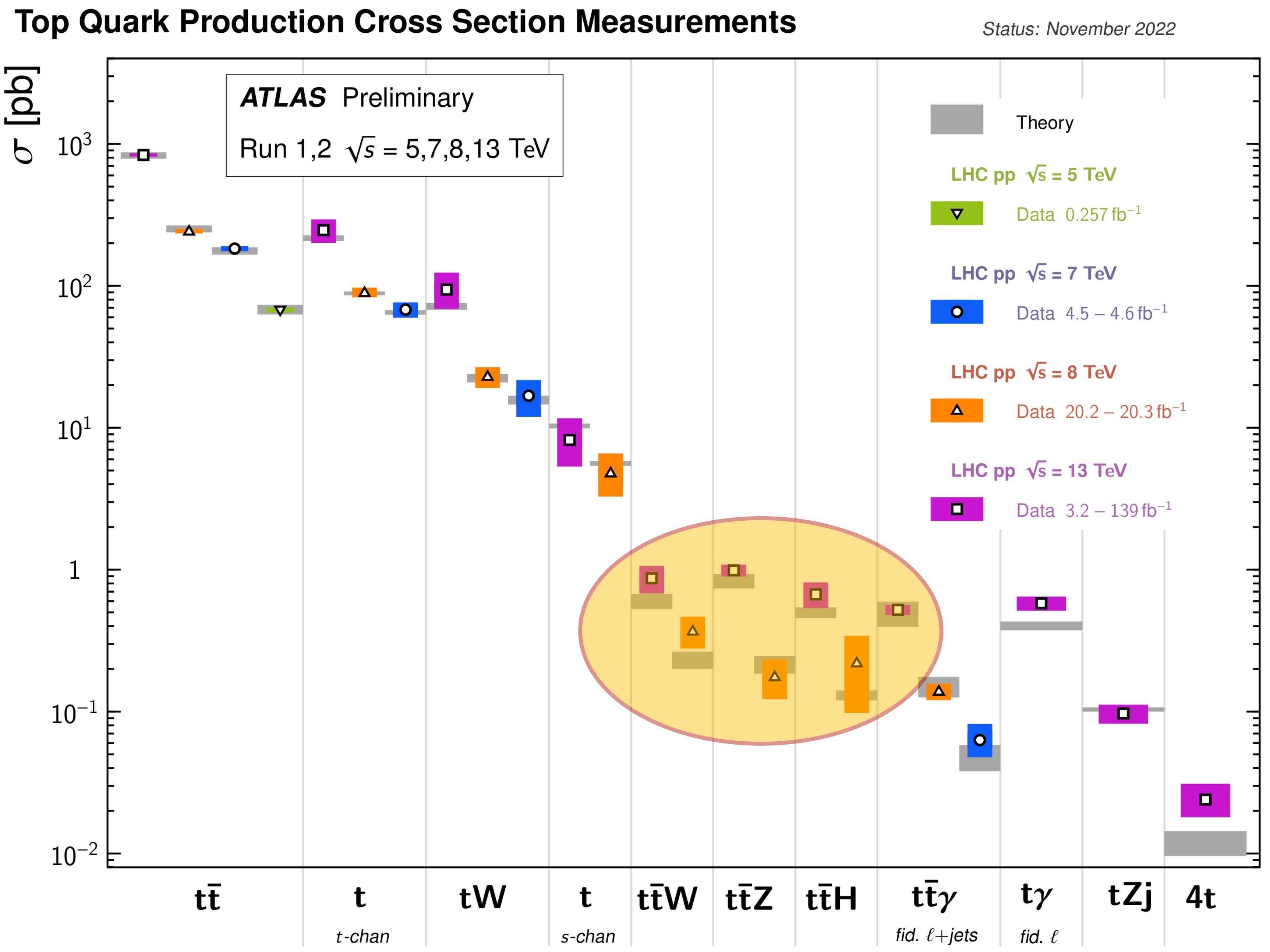


$$\sim \frac{y_t^2}{8\pi^2}\Lambda_{UV}^2$$

Events with top quarks provide an ubiquitous background to Higgs measurements and new-physics searches

ttV, ttH…

The production of a top-quark pair together with a vector or Higgs boson is among the most massive SM signatures at hadron colliders



The cross sections are much smaller than tt but already measured

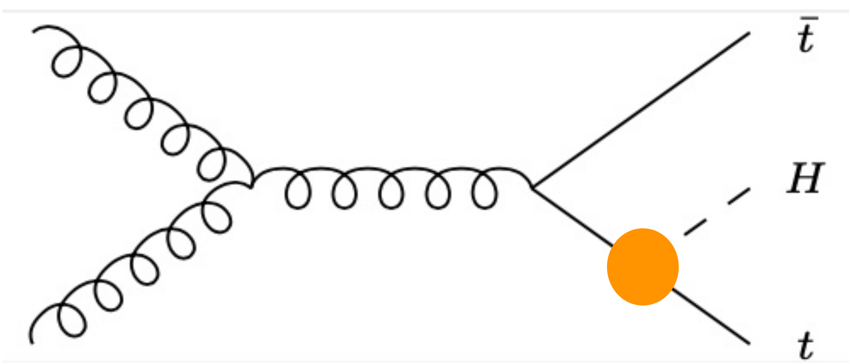
A deep understanding of these processes is crucial to characterise the top-quark interactions

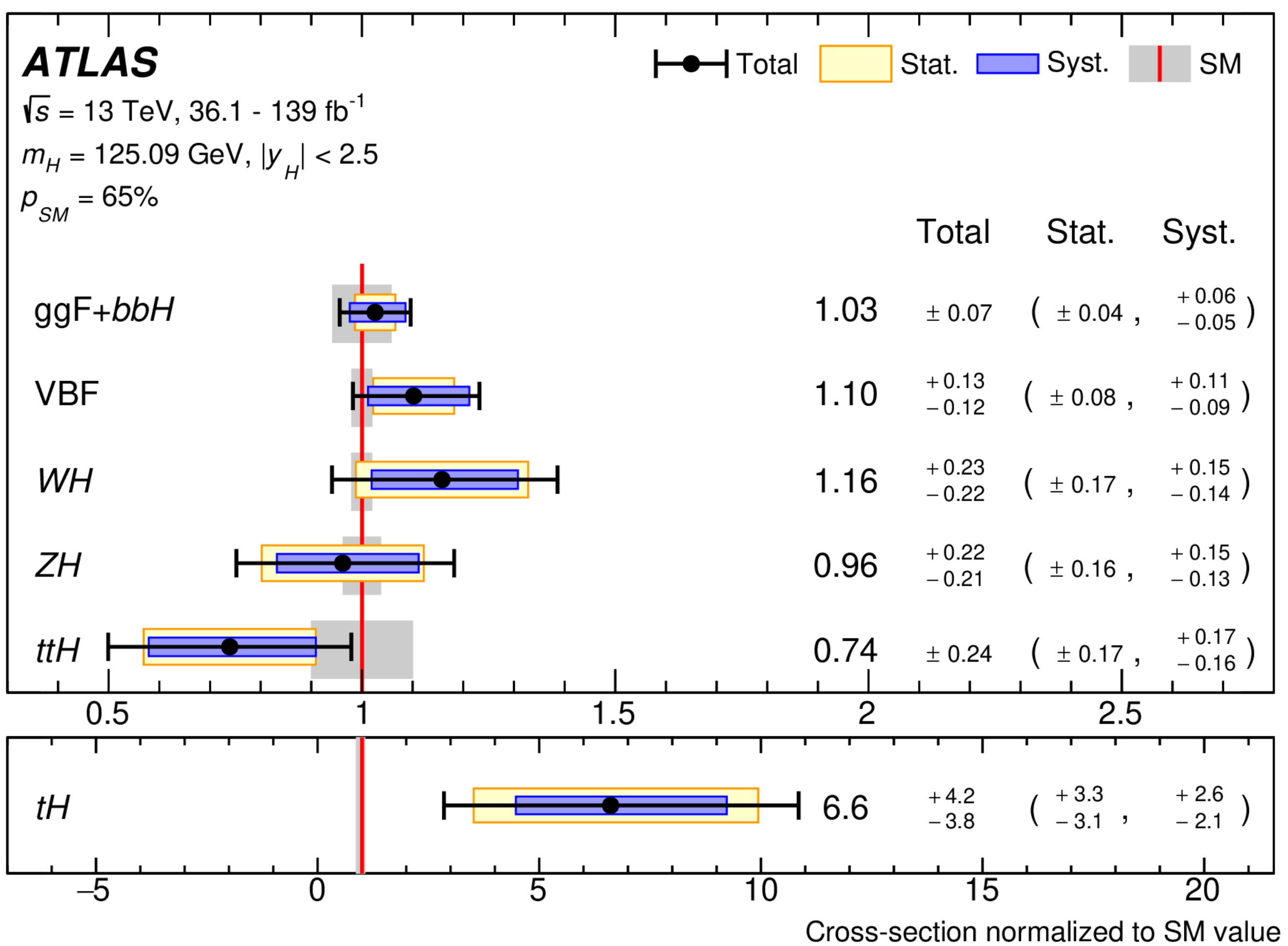
ttH

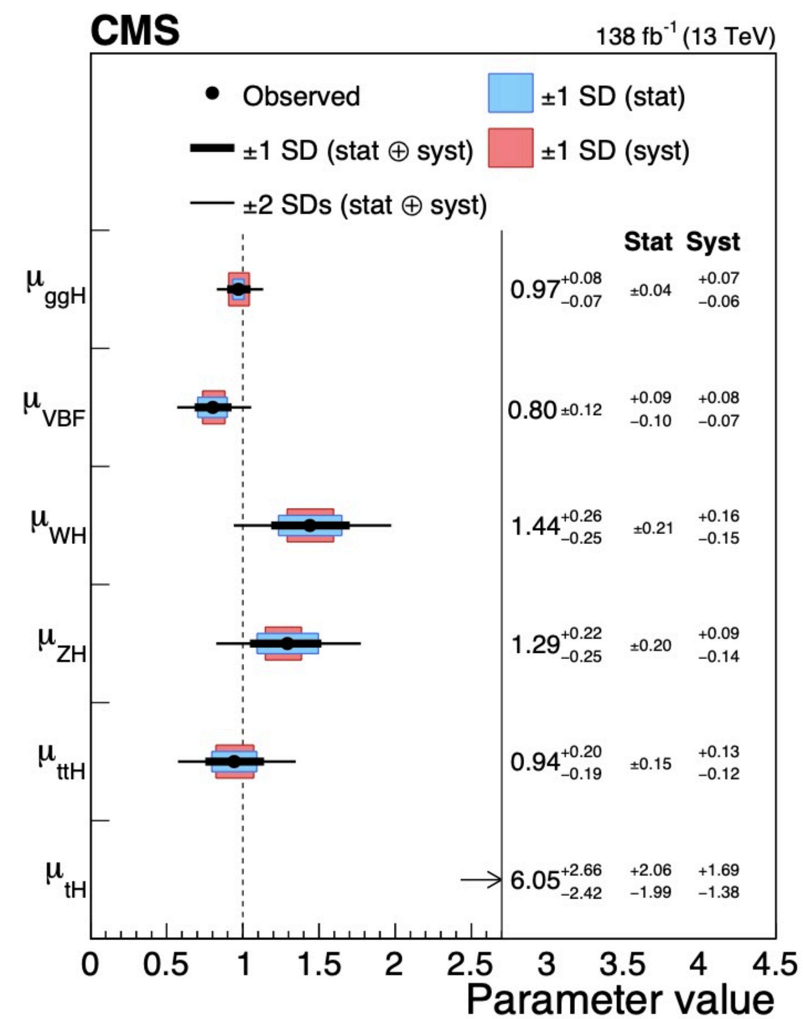
The associated production of the Higgs boson with a top-quark pair is a crucial process at the LHC

It allows a direct extraction of the top Yukawa

Experimental uncertainties are now at the $\mathcal{O}(20\%)$ level



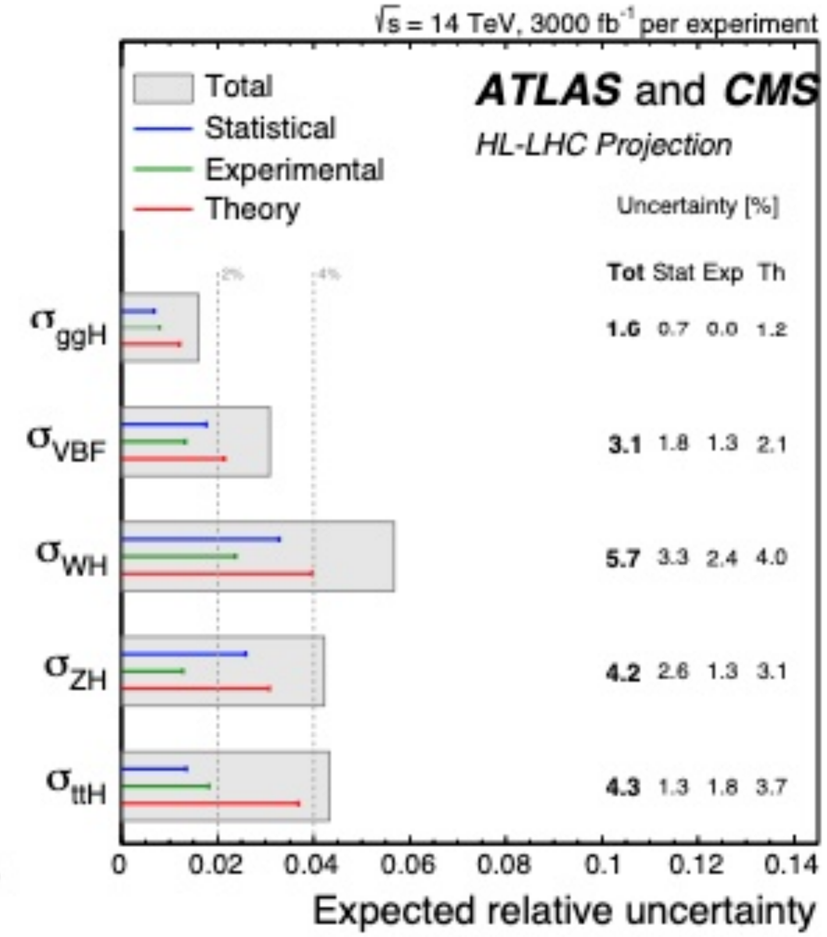




ttH

Catani, Devoto, Kallweit, Mazzitelli, Savoini, MG (2022)

Experimental precision expected to get to the $\mathcal{O}(2\%)$ level at the end of HL-LHC

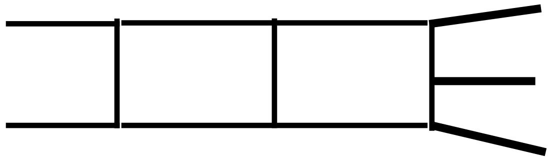


Current predictions based on NLO QCD+EW (+ resummations) and affected by $\mathcal{O}(10\%)$ uncertainty

NNLO QCD needed to bring theory uncertainty down to the $\mathcal{O}(2\%)$ level expected

Missing ingredients are the two-loop $gg \to t\bar{t}H$ and $q\bar{q} \to t\bar{t}H$ amplitudes

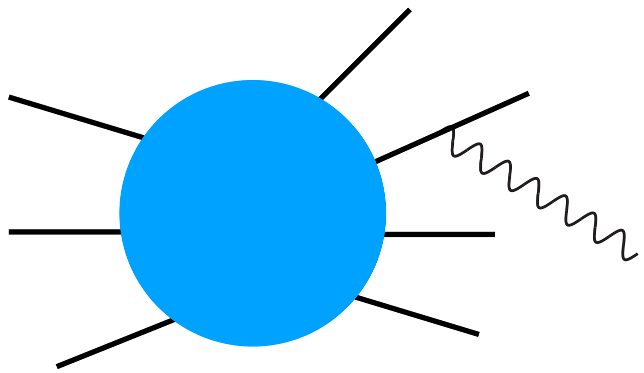
Massive $2 \to 3$ amplitudes: at the frontier of current techniques



The idea: use an approximation for the missing two-loop amplitude

Soft-Higgs radiation

When a soft photon (or gluon) is emitted in a high-energy process the corresponding amplitudes obey well known factorisation formulae



$$\mathcal{M}(\{p_i\},k) \simeq J^\mu(k)\epsilon_\mu(k)\mathcal{M}(\{p_i\}) \qquad J^\mu(k) = \sum_i e_i \frac{p_i^\mu}{p_i \cdot k}$$

Soft photon: large wavelength

→ Does not "see" the details of the hard process but only external charges

An analogous formula holds for the emission of a soft scalar off heavy quarks

$$\mathcal{M}(\{p_i\},k) \simeq J(k)\mathcal{M}(\{p_i\})$$

At tree level it is straightforward to show that

heavy-quark mass

$$J(k) = \sum_i \frac{m}{v}\frac{m}{p_i \cdot k}$$

heavy-quark momenta

Soft-Higgs radiation

This formula can be extended to all orders in the QCD coupling α_S

$$\mathcal{M}(\{p_i\}, k) \simeq F(\alpha_S(\mu_R); m/\mu_R)\, J(k) \mathcal{M}(\{p_i\})$$

The perturbative function $F(\alpha_S(\mu_R); m/\mu_R)$ can be extracted from the soft limit of the scalar form factor of the heavy quark

Bernreuther et al (2005)
Blümlein et al (2017)
Fael, Lange, Schönwald, Steinhauser (2022)

Alternatively, it can be derived by using Higgs low-energy theorems

See e.g. Kniehl and Spira (1995)

We have done several checks of our factorisation formula by assuming a very light and soft Higgs boson

We have tested it numerically up to one-loop order in the case of $t\bar{t}H$ and $t\bar{t}t\bar{t}H$ production ✅

Will it work for a physical Higgs ?

The computation

We use the q_T subtraction method

Catani, MG (2007)

$$d\sigma^{t\bar{t}H}_{NNLO} = \mathcal{H}^{t\bar{t}H}_{NNLO} \otimes d\sigma^{t\bar{t}H}_{LO} + \left[d\sigma^{t\bar{t}H+\text{jets}}_{NLO} - d\sigma^{CT}_{NNLO} \right]$$

Virtual after subtraction of IR singularities + collinear and soft contributions

Real contribution with one additional resolved jet, divergent as $q_T \to 0$

Subtraction counterterm that cancels the $q_T \to 0$ singularity

The computation

We use the q_T subtraction method

Catani, MG (2007)

$$d\sigma^{t\bar{t}H}_{NNLO} = \mathcal{H}^{t\bar{t}H}_{NNLO} \otimes d\sigma^{t\bar{t}H}_{LO} + \left[d\sigma^{t\bar{t}H+\text{jets}}_{NLO} - d\sigma^{CT}_{NNLO} \right]$$

All the ingredients in this formula are now available and implemented in MATRIX except the two-loop virtual amplitudes entering $\mathcal{H}$

We define

$$\mathcal{H} = H\delta(1-z_1)\delta(1-z_2) + \delta\mathcal{H}$$

$$H^{(n)} = \frac{2\text{Re}\left(\mathcal{M}^{(n)}_{\text{fin}}\mathcal{M}^{(0)*}\right)}{|\mathcal{M}^{(0)}|^2}$$

with

$$H = 1 + \frac{\alpha_S(\mu_R)}{2\pi}H^{(1)} + \left(\frac{\alpha_S(\mu_R)}{2\pi}\right)^2 H^{(2)} + \ldots.$$

$$|\mathcal{M}_{\text{fin}}(\mu_{IR})\rangle = \mathbf{Z}^{-1}(\mu_{IR})\,|\mathcal{M}\rangle$$

IR subtraction

For $n = 2$ this definition allows us to single out the only missing ingredient in the NNLO calculation, that is, the coefficient $H^{(2)}$

All required tree-level and one-loop amplitudes are obtained using Openloops

	$\sqrt{s} = 13$ TeV		$\sqrt{s} = 100$ TeV	
σ [fb]	gg	$q\bar{q}$	gg	$q\bar{q}$
σ_{LO}	261.58	129.47	23055	2323.7
$\Delta\sigma_{\mathrm{NLO,H}}$	88.62	7.826	8205	217.0
$\Delta\sigma_{\mathrm{NLO,H}}\big\vert_{\mathrm{soft}}$	61.98	7.413	5612	206.0

At NLO we can compare the exact contribution from $H^{(1)}$ to the one computed in the soft approximation

The hard contribution computed in the soft approximation is underestimated by just 30 % in the gg channel and by 5 % in the $q\bar{q}$

The mismatch that we observe at NLO can be used to estimate the uncertainty of our approximation at NNLO

The quality of our final result will depend on the size of the contribution we approximate

	$\sqrt{s} = 13$ TeV		$\sqrt{s} = 100$ TeV	
σ [fb]	gg	$q\bar{q}$	gg	$q\bar{q}$
$\sigma_{\rm LO}$	261.58	129.47	23055	2323.7
$\Delta\sigma_{\rm NLO,H}$	88.62	7.826	8205	217.0
$\Delta\sigma_{\rm NLO,H}\|_{\rm soft}$	61.98	7.413	5612	206.0
$\Delta\sigma_{\rm NNLO,H}\|_{\rm soft}$	−2.980(3)	2.622(0)	−239.4(4)	65.45(1)

At NNLO the hard contribution is about 1% of the LO cross section in the gg channel and 2% in the $q\bar{q}$ channel

We can therefore anticipate that at NNLO the uncertainties due to the soft approximation will be rather small, but how to estimate it ?

We multiply the differences we observe at NLO by a tolerance factor of 3

This factor is chosen after a careful study of the other possible sources of uncertainties in the definition of the hard contribution

We finally combine the gg and $q\bar{q}$ uncertainties linearly → $\pm 0.6\,\%$ on σ_{NNLO}

Results

σ [pb]	$\sqrt{s} = 13\,\text{TeV}$	$\sqrt{s} = 100\,\text{TeV}$
σ_{LO}	$0.3910\,^{+31.3\%}_{-22.2\%}$	$25.38\,^{+21.1\%}_{-16.0\%}$
σ_{NLO}	$0.4875\,^{+5.6\%}_{-9.1\%}$	$36.43\,^{+9.4\%}_{-8.7\%}$
σ_{NNLO}	$0.5070\,(31)^{+0.9\%}_{-3.0\%}$	$37.20(25)\,^{+0.1\%}_{-2.2\%}$

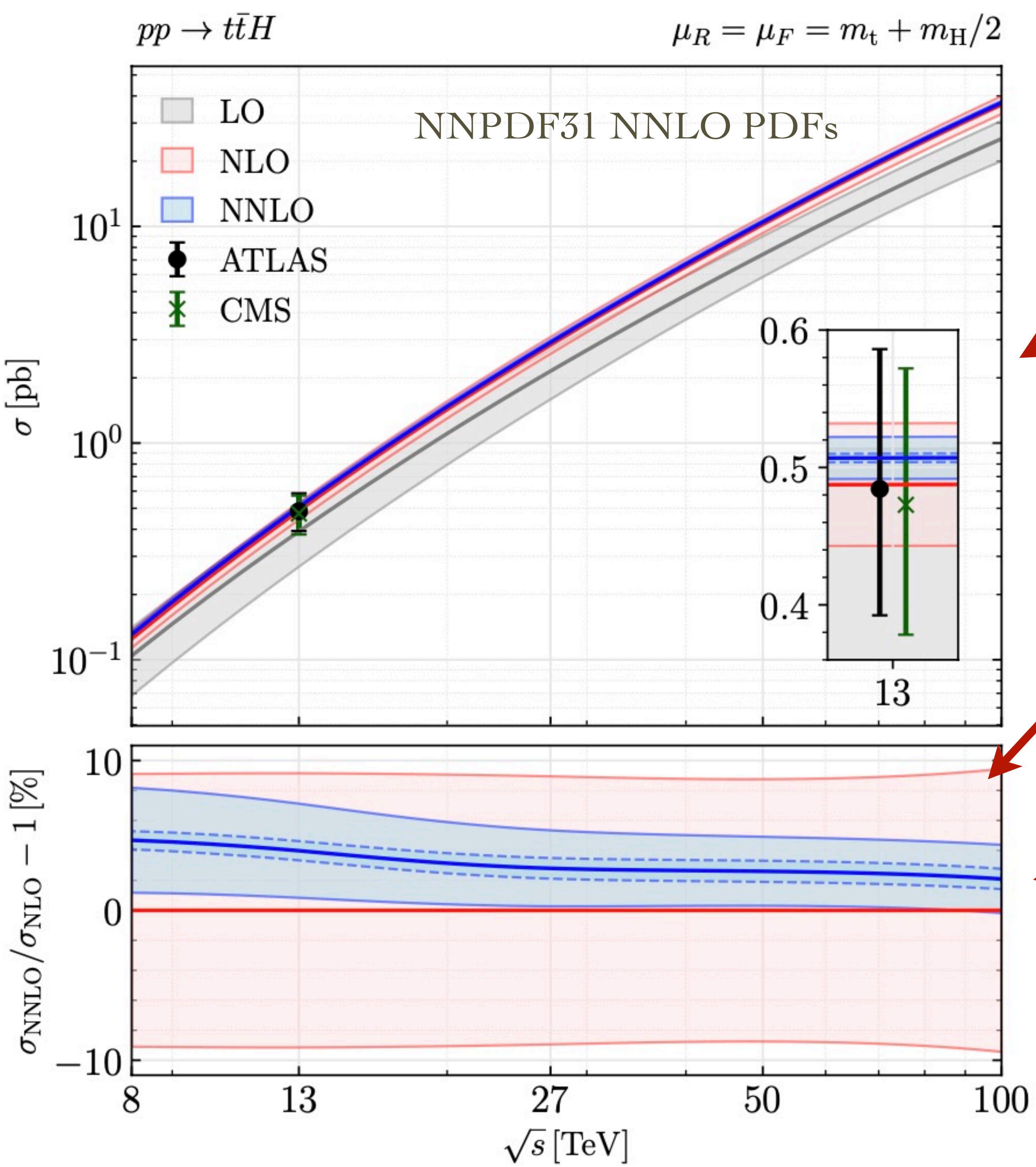
NLO effect is about +25 % at 13 TeV and +44 % at 100 TeV

NNLO effect is about +4 % at 13 TeV and +2 % at 100 TeV

Significant reduction of perturbative uncertainties

Errors in bracket obtained combining uncertainty from the soft approximation and the systematic uncertainty in the NNLO computation

Results



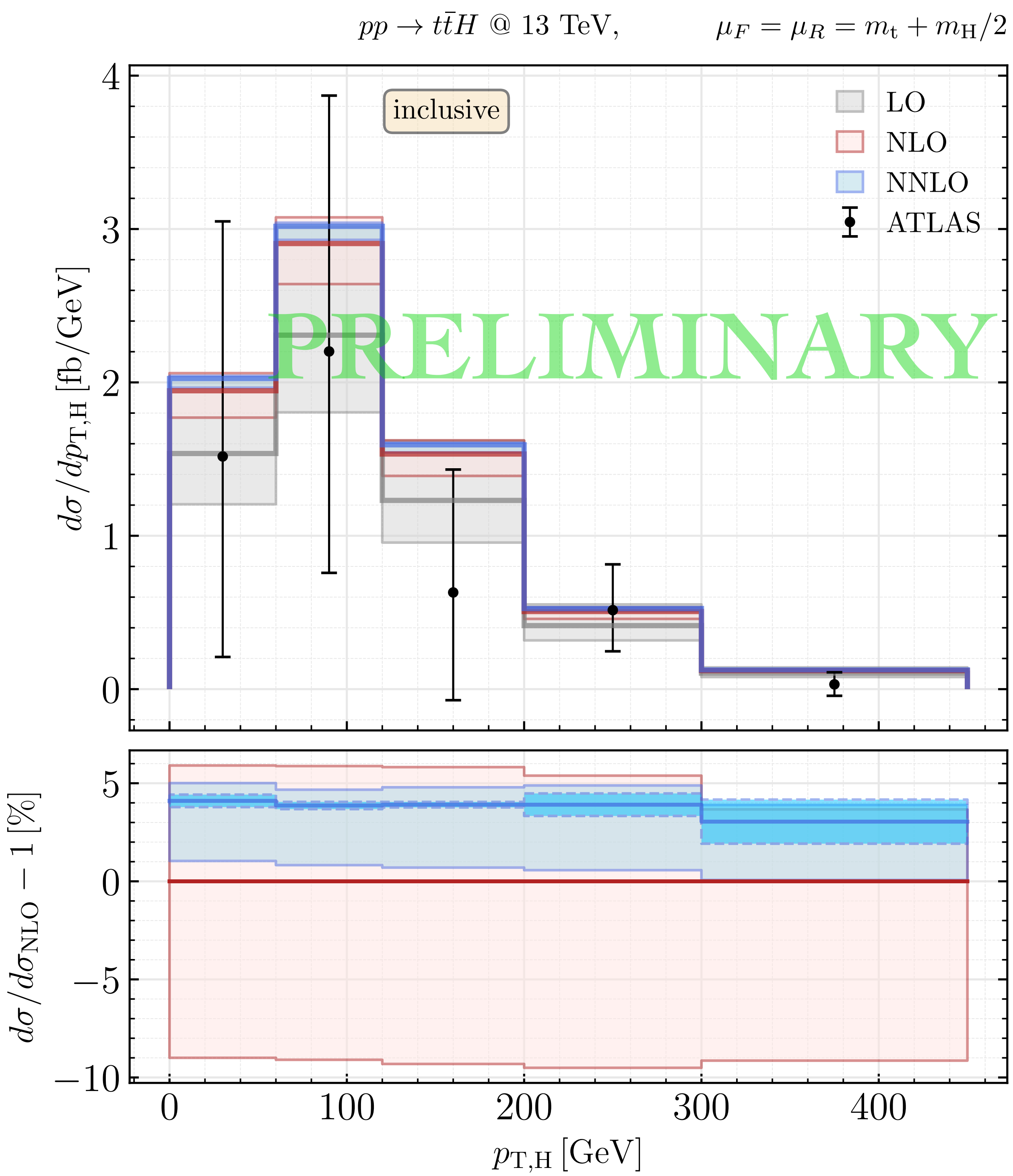
ATLAS and CMS results from Nature 2022 papers

Perturbative uncertainties estimated by symmetrising the standard 7-point scale variation

Dashed band: residual error from soft approx+systematics

Note that: sensible comparison with data should eventually be done including NLO EW corrections ($+1.7\,\%$ at $\sqrt{s} = 13\,\mathrm{TeV}$)

Higgs p_T spectrum



First comparison with ATLAS data

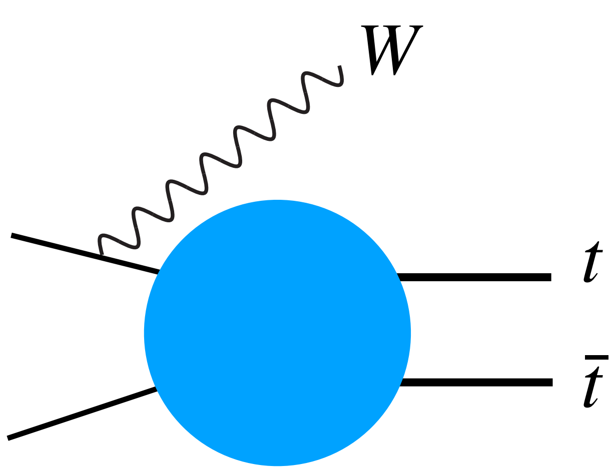
ttW

Among the ttV signatures, ttW is special because it involves both EW and top sectors

It is at the same time a signal and a background to ttH and tttt and new physics searches

Since the top quark quickly decays into a W and a b jet, the signature is characterised by 3 W bosons

→ It provides an irreducible source of same-sign dilepton pairs relevant for many BSM searches



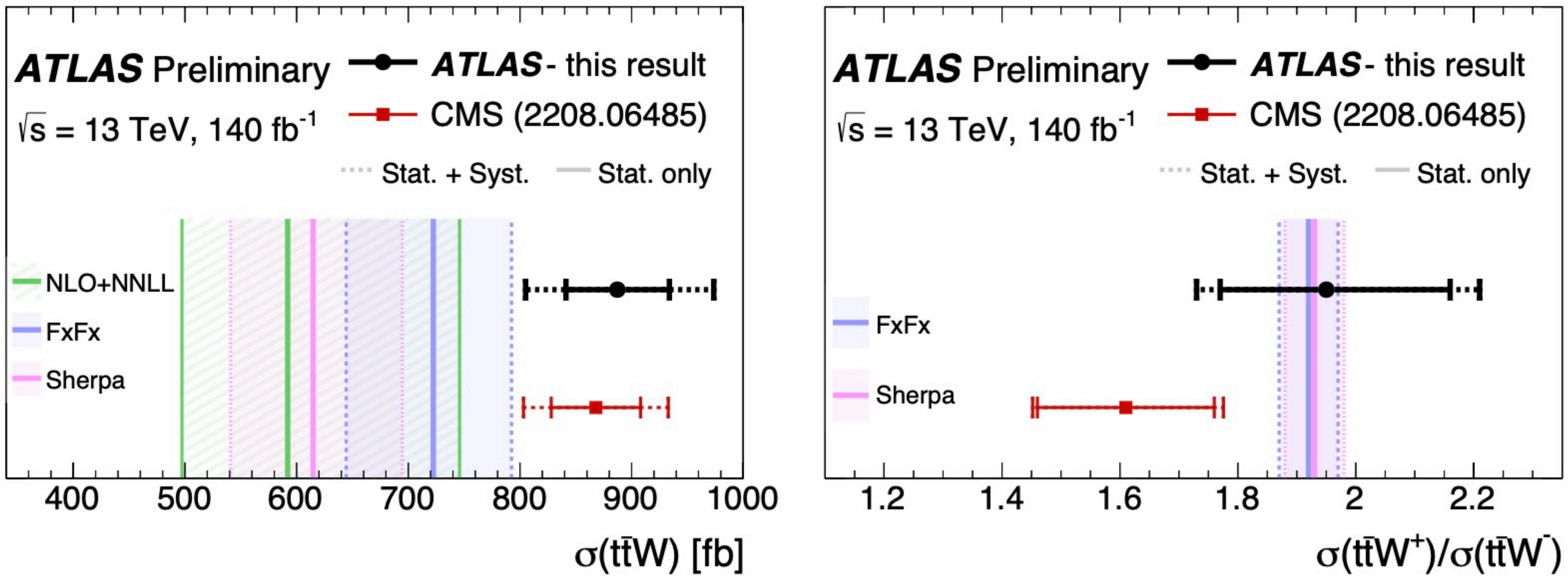
It is special compared to other ttF $(F = H, Z, \gamma)$ signatures because the W can only be emitted by the initial-state light quarks (no gg channel at LO)

$t\bar{t}W$

Measurements by ATLAS and CMS at $\sqrt{s} = 8\,\text{TeV}$ and $\sqrt{s} = 13\,\text{TeV}$ showed that the $t\bar{t}W$ rate is consistently higher than the SM prediction

This discrepancy is also confirmed by indirect measurements of $t\bar{t}W$ in the context of $t\bar{t}H$ and 4top analyses

The most recent measurements confirm this picture with a slight excess at the $1\sigma - 2\sigma$ level



ttW

Theory predictions still essentially based on NLO QCD and EW predictions

Badger, Campbell, Ellis (2010); Campbell, Ellis (2012);
Frixione, Hirschi, Pagani, Shao, Zaro (2015);
Bevilacqua et al. (2020); Denner, Pellicciolli (2020)

+ soft-gluon resummation

Broggio et al (2016); Kulesza et al (2019)

+ multijet merging (FxFx)

Frixione, Frederix (2010); Frederix, Tsinikos (2021)

Current theory reference

NNLO computation could be carried out analogously to ttH if the two-loop Wtt amplitude were available

Can we obtain an estimate of the missing two-loop contribution ? Yes !

We constructed and tested two different approximations of the two-loop amplitude

1) Use soft approximation for W emission to express ttW amplitude in terms of the $q\bar{q} \to t\bar{t}$ amplitude

Bärnreuther et al. (2013)
Mastrolia et al (2022)

$$\mathcal{M}(\{p_i\}, k) \simeq J^{(0)\mu}(k)\epsilon_\mu(k)\mathcal{M}(\{p_i\})$$

$$J^{(0)\mu}(k) = \frac{g}{\sqrt{2}} \sum_{i=1,2} \left(\sigma_i \frac{p_i^\mu}{p_i \cdot k} \right) \frac{1-\gamma_5}{2}$$

$\sigma_i = -1(+1)$ incoming (anti)quark

2) Start from massless W+4 parton amplitudes

Abreu et al. (2021)

Use a "massification" procedure to obtain the leading terms in a $m_Q/Q \ll 1$ expansion

Moch, Mitov (2007)
Becher, Melnikov (2007)

$$\mathcal{M}(\{p_i\}, k; \mu, \epsilon) \simeq Z_{[q]}^{(m_Q|0)}(\alpha_S(\mu), m_Q/\mu, \epsilon)\mathcal{M}^{(m_Q=0)}(\{p_i\}, k; \mu, \epsilon) + m_Q^2/Q^2$$

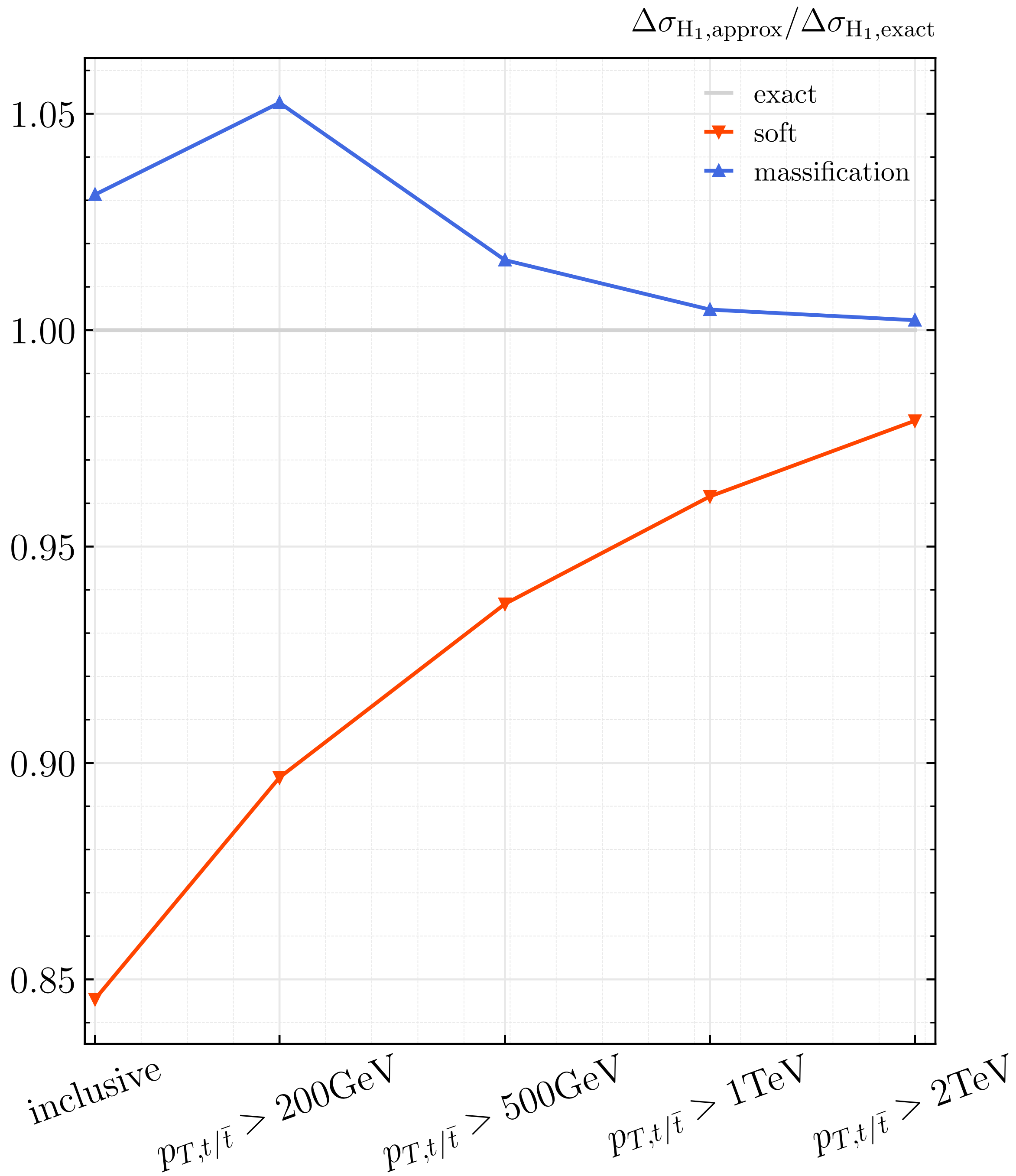
Universal perturbatively computable factor

Successfully applied to the NNLO computation of Wbb

Buonocore et al (2023)

ttW

Buonocore, Devoto, Kallweit,
Mazzitelli, Rottoli, Savoini, MG (to appear)



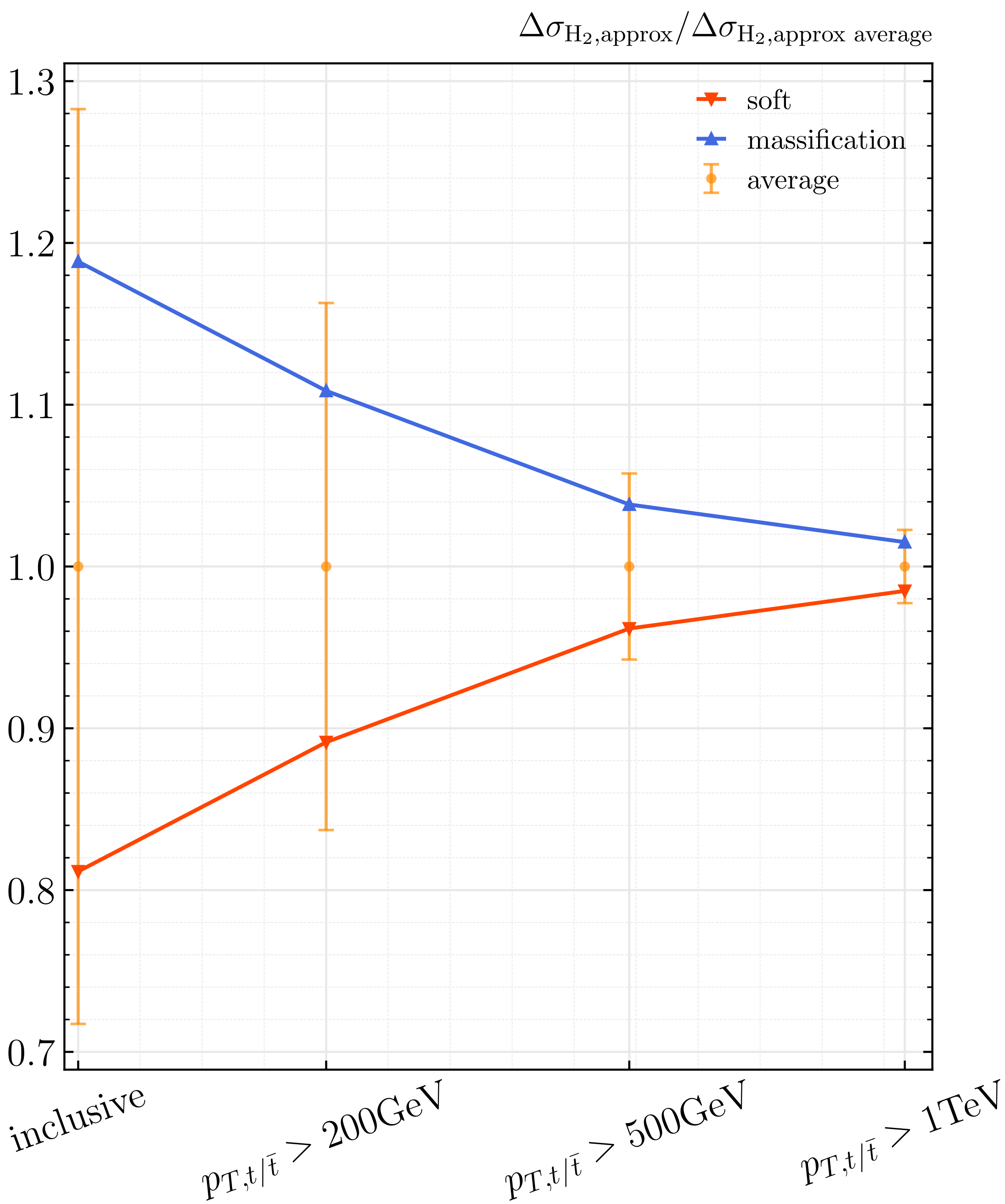
Both approximations provide a good estimate of the exact one-loop contribution

Soft approximation overshoots the exact results while massification tends to overshoot it

Clear asymptotic behaviour towards exact result for high p_T of the top quarks where both approximations are expected to work

ttW

Buonocore, Devoto, Kallweit, Mazzitelli,Rottoli, Savoini, MG (to appear)



The pattern is preserved at NNLO: massified result systematically higher than soft approximation

→ Our best prediction as average of the two

Uncertainty conservatively defined as the semi difference multiplied by tolerance factor 1.5

Final uncertainty on two-loop contribution about 30% and similar to what obtained in recent 2 → 3 calculations in large-N approximation

Abreu et al (2023)

ttW

order	$\sigma_{t\bar{t}W^+}$ [fb]	$\sigma_{t\bar{t}W^-}$ [fb]	ratio
$\mathrm{LO_{QCD}}$	$272.4^{+25.1\%}_{-18.7\%}$	$136.5^{+25.0\%}_{-18.7\%}$	1.996
$\mathrm{NLO_{QCD}}$	$404.4^{+12.8\%}_{-11.5\%}$	$206.0^{+13.4\%}_{-11.8\%}$	1.963
$\mathrm{NNLO_{QCD}}$	$462.2^{+6.2\%}_{-4.8\%} \pm 2.3\%$	$237.0^{+6.7\%}_{-5.1\%} \pm 2.5\%$	1.950
$\mathrm{NNLO_{QCD} + NLO_{EW}}$	$485.2^{+6.6\%}_{-5.4\%} \pm 2.2\%$	$250.0^{+6.8\%}_{-5.6\%} \pm 2.4\%$	1.941

Conservative estimate of uncertainty from missing exact two-loop amplitudes

Large NLO QCD corrections (+50%)

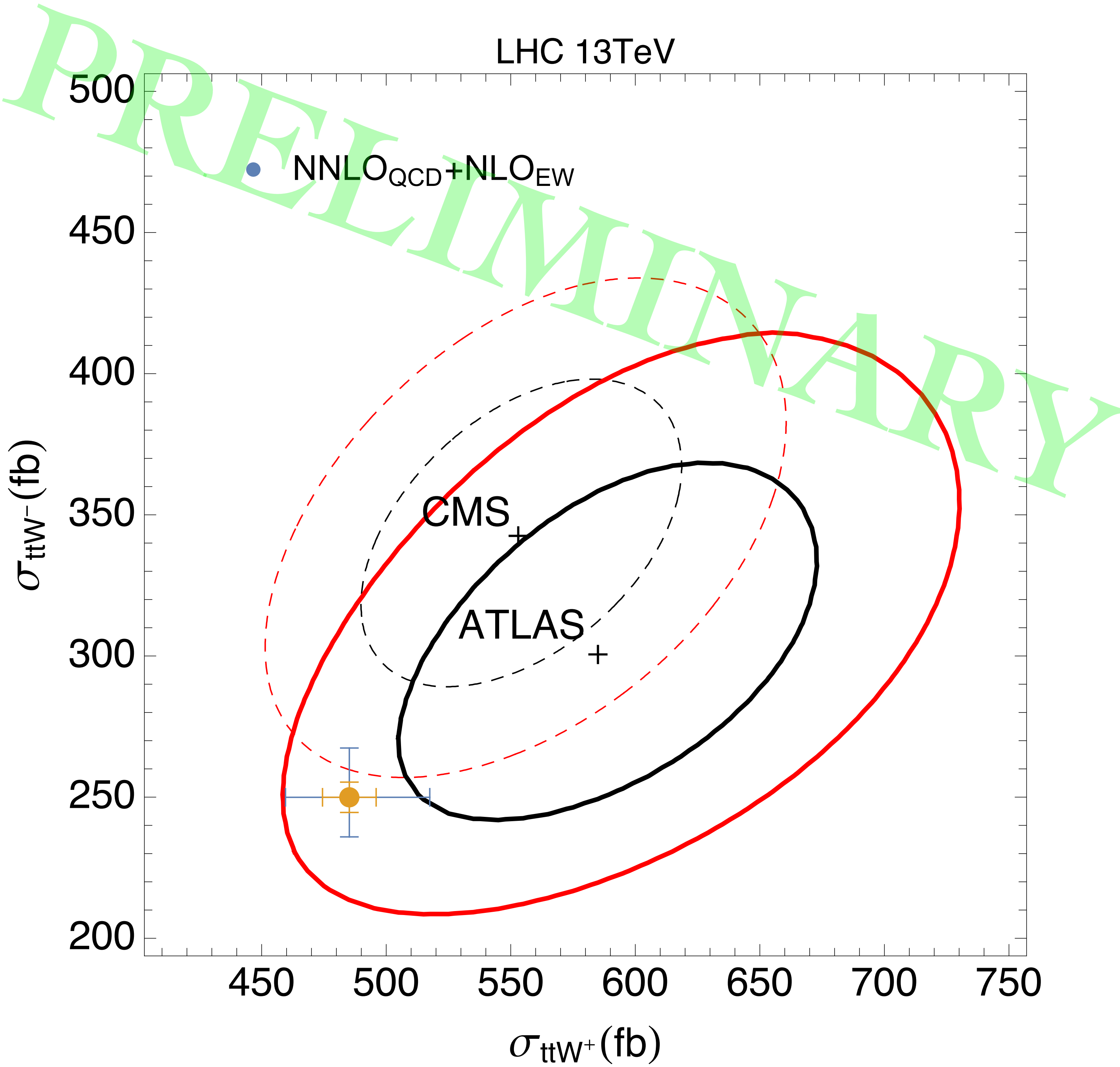
Setup: NNLO LUXPDF4LHC15
$\sqrt{s} = 13\,\mathrm{TeV}$ $\mu_F = \mu_R = m_t + m_W/2$

Moderate NNLO corrections (+14-15%)

All subdominant LO and NLO contributions at $\mathcal{O}(\alpha^3)$, $\mathcal{O}(\alpha_S^2\alpha^2)$, $\mathcal{O}(\alpha_S\alpha^3)$, $\mathcal{O}(\alpha^4)$ consistently included and denoted as NLO EW

$\sigma(t\bar{t}W^+)/\sigma(t\bar{t}W^-)$ only slightly decreases increasing the perturbative order

ttW



The comparison with the ATLAS and CMS results shows that discrepancy remains at the 1-2σ level

Inclusion of NNLO corrections significantly reduces perturbative uncertainties

Result consistent with FxFx prediction but with smaller uncertainties

Summary & Outlook

- The production of a top-quark pair together with a vector or Higgs boson is among the most massive SM signatures at hadron colliders
- We have presented the first calculations of NNLO QCD corrections to $t\bar{t}H$ and $t\bar{t}W$ production at hadron colliders
- In the case of $t\bar{t}H$ the missing two-loop amplitudes have been estimated by using a soft-Higgs approximation
- In the case of $t\bar{t}W$ the missing two-loop amplitudes have been computed using two completely different approximations leading to consistent results
- NNLO corrections for both processes are moderate and lead to a significant reduction of theoretical uncertainties
- In the case of $t\bar{t}W$ the tension with the data remains at the 1-2σ level

Backup

Soft-Higgs radiation

The basic observation is that at the bare amplitude level we have

$$\lim_{k\to 0} \mathscr{M}^{\text{bare}}(\{p_i\}, k) = \frac{m_0}{v} \sum_i \frac{m_0}{p_i \cdot k} \mathscr{M}^{\text{bare}}(\{p_i\})$$

The renormalisation of the heavy-quark mass and wave-function induce a modification of the Higgs coupling to the heavy quark

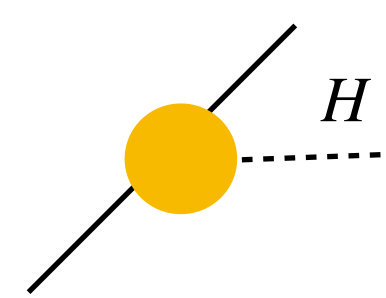
The bare amplitude for the soft-scalar emission is

$$\lim_{k\to 0} \mathscr{M}^{\text{bare}}_{Q\to QH}(p, k) = \frac{1}{v} m_0 \frac{\partial}{\partial m_0} \mathscr{M}^{\text{bare}}_{Q\to Q}(p) \Big|_{p^2=m^2}$$

By using the results of the $\mathcal{O}(\alpha_S^2)$ contribution to the heavy-quark self energy and carrying out the wave function and mass renormalisation we recover the function $F(\alpha_S(\mu_R); m/\mu_R)$ discussed before

Broadhurst, Gray, Schilcher (1991)
Gray, Broadhurst, Grafe, Schilcher (1990)

Note that intermediate results are gauge dependent: gauge invariance recovered only in the final on-shell limit



Differences with other approaches

The idea of a treating the Higgs as a parton radiating off the top quark was used already in the past

Effective Higgs approximation in early NLO calculations: introduce a function expressing the probability to extract the Higgs boson from the top quark

Dawson and Reina (1997)

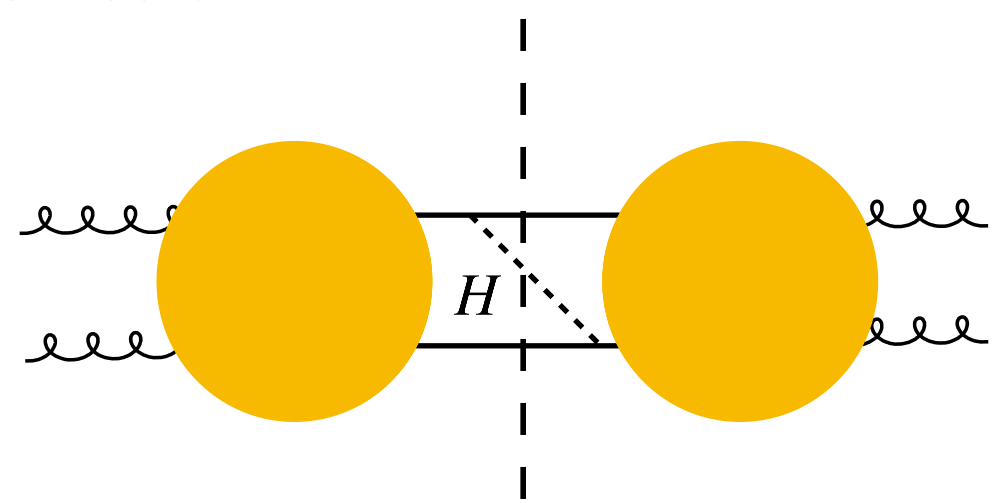
Fragmentation functions $D_{t\to H}$ and $D_{g\to H}$ evaluated at NLO

Brancaccio, Czakon, Gerenet, Krämer (2021)

These approaches are based on a collinear approximation

Our approximation is purely soft (collinear non-soft emissions are neglected but soft quantum interferences are included)

Moreover, we apply it only to the finite part of the two-loop contribution



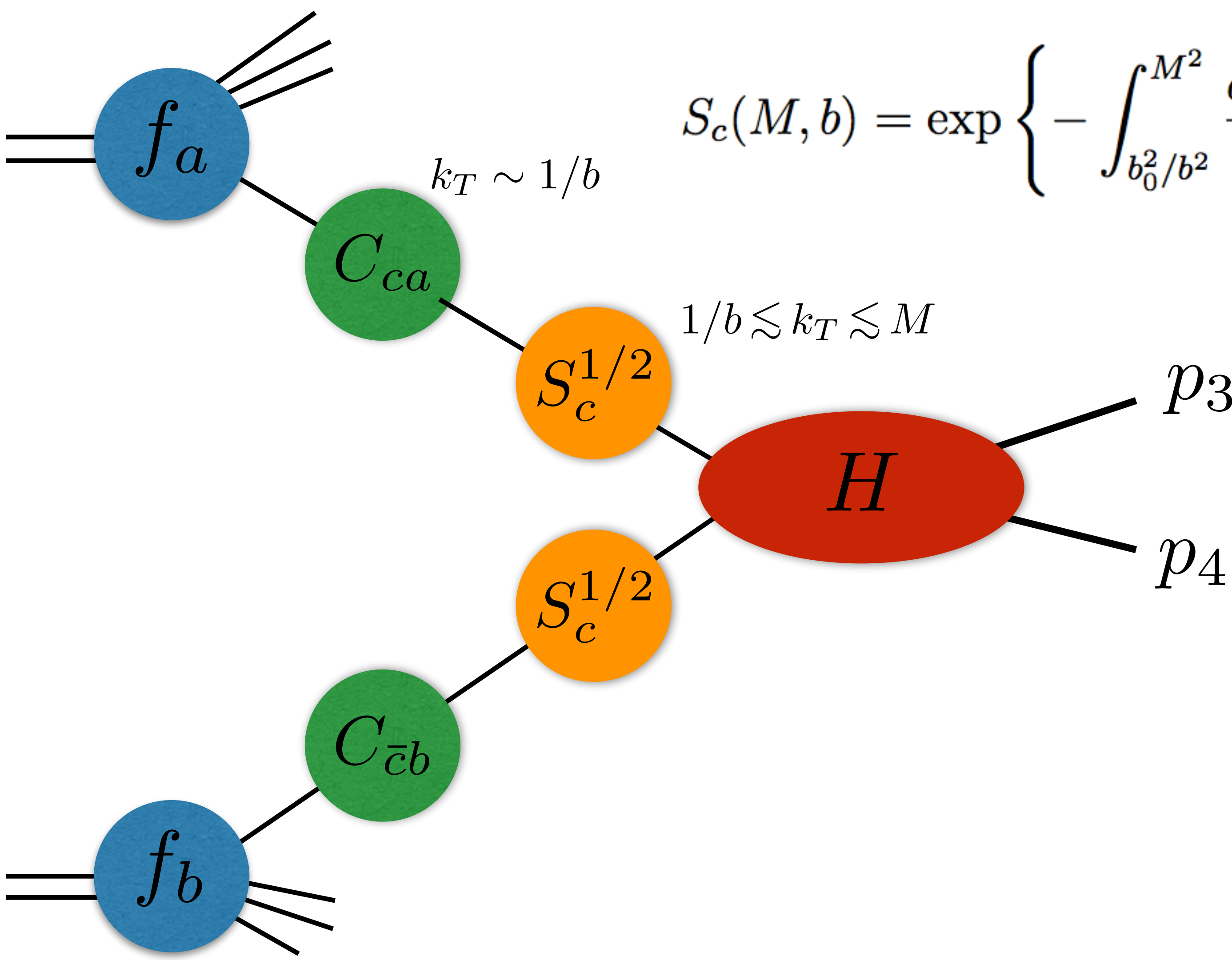
The resummation formula

Collins, Soper, Sterman (1984)
Catani, de Florian, MG (2000); Catani, MG (2010)

$$\frac{d\sigma_F^{(\mathrm{sing})}(p_1,p_2;\mathbf{q_T},M,y,\mathbf{\Omega})}{d^2\mathbf{q_T}\,dM^2\,dy\,d\mathbf{\Omega}} = \frac{M^2}{s}\sum_{c=q,\bar{q},g}\left[d\sigma^{(0)}_{c\bar{c},F}\right]\int\frac{d^2\mathbf{b}}{(2\pi)^2}\,e^{i\mathbf{b}\cdot\mathbf{q_T}}\,S_c(M,b)$$

$$\times\sum_{a_1,a_2}\int_{x_1}^{1}\frac{dz_1}{z_1}\int_{x_2}^{1}\frac{dz_2}{z_2}\,\left[H^F C_1 C_2\right]_{c\bar{c};a_1a_2}\,f_{a_1/h_1}(x_1/z_1,b_0^2/b^2)\,f_{a_2/h_2}(x_2/z_2,b_0^2/b^2)$$

$$S_c(M,b)=\exp\left\{-\int_{b_0^2/b^2}^{M^2}\frac{dq^2}{q^2}\left[A_c(\alpha_S(q^2))\,\ln\frac{M^2}{q^2}+B_c(\alpha_S(q^2))\right]\right\}$$



C coefficients embody collinear radiation at scale 1/b

S_c embodies soft and flavour conserving collinear radiation in the region $1/b < k_T < M$

H^F includes hard radiation at scales $k_T \sim M$

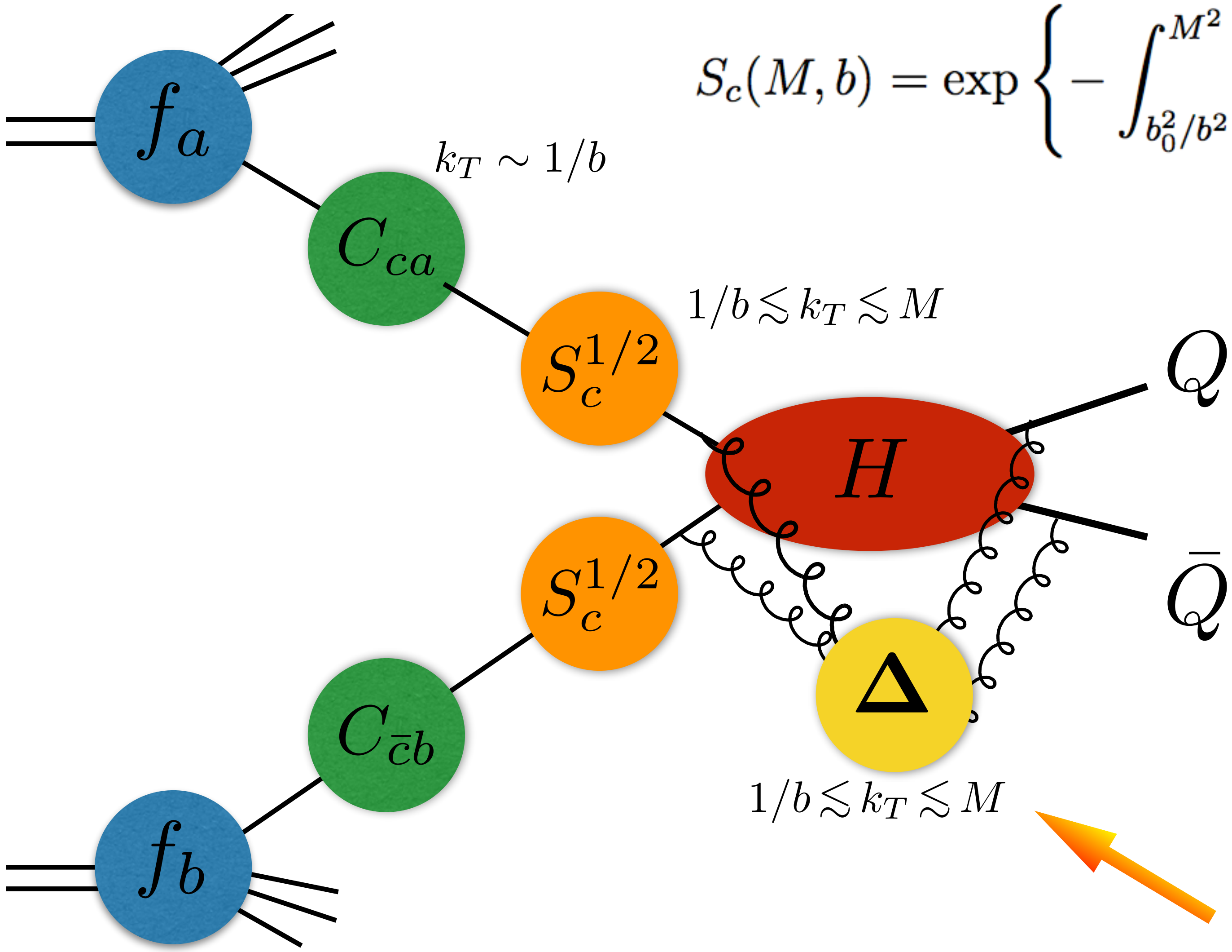
Extension to heavy-quark production

Catani, Torre, MG (2014)

$$\frac{d\sigma^{(\rm sing)}(P_1,P_2;\mathbf{q_T},M,y,\mathbf{\Omega})}{d^2\mathbf{q_T}\,dM^2\,dy\,d\mathbf{\Omega}} = \frac{M^2}{2P_1\cdot P_2}\sum_{c=q,\bar q,g}\left[d\sigma^{(0)}_{c\bar c}\right]\int\frac{d^2\mathbf{b}}{(2\pi)^2}\,e^{i\mathbf{b}\cdot\mathbf{q_T}}\,S_c(M,b)$$

$$\times\sum_{a_1,a_2}\int_{x_1}^1\frac{dz_1}{z_1}\int_{x_2}^1\frac{dz_2}{z_2}\,\left[(\mathbf{H}\,\mathbf{\Delta})\,C_1C_2\right]_{c\bar c;a_1a_2}\,f_{a_1/h_1}(x_1/z_1,b_0^2/b^2)\,f_{a_2/h_2}(x_2/z_2,b_0^2/b^2)$$

$$S_c(M,b)=\exp\left\{-\int_{b_0^2/b^2}^{M^2}\frac{dq^2}{q^2}\left[A_c(\alpha_S(q^2))\,\ln\frac{M^2}{q^2}+B_c(\alpha_S(q^2))\right]\right\}$$



C coefficients embody collinear radiation at scale 1/b

S_c embodies soft and flavour conserving collinear radiation in the region $1/b < k_T < M$

H^F includes hard radiation at scales $k_T \sim M$

Additional radiative factor of purely soft origin (starts to contribute at NLL)

Extension to heavy-quark production

➡ We obtain an analogous structure for the q_T subtraction formula with some differences

$$d\sigma^{Q\bar{Q}}_{(N)NLO} = \mathscr{H}^{Q\bar{Q}}_{(N)NLO} \otimes d\sigma^{Q\bar{Q}}_{LO} + \left[d\sigma^{Q\bar{Q}+\text{jet}}_{(N)LO} - d\sigma^{CT}_{(N)NLO} \right]$$

✅ Modified subtraction counterterm fully known

Additional perturbative ingredient: soft anomalous dimension Γ_t (known to NNLO) and related to IR singular structure of virtual amplitudes

Mitov, Sterman, Sung (2009)
Neubert et al (2009)

Extension to heavy-quark production

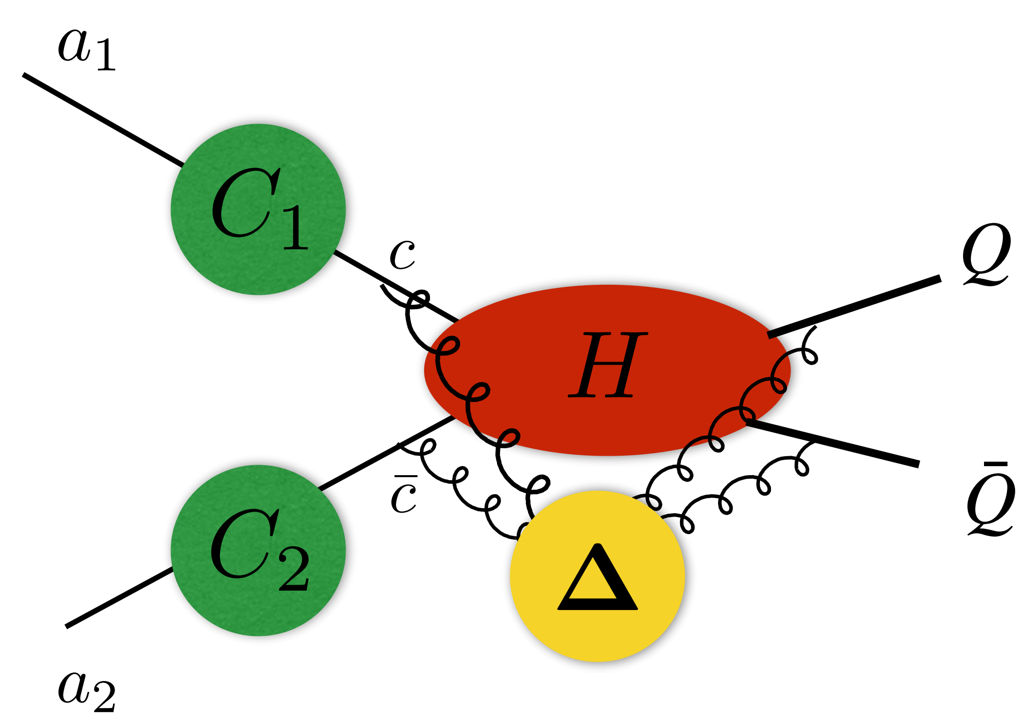
✅ Structure of hard collinear function is analogous

$$\mathscr{H}^{Q\bar{Q}} = \left[H^{Q\bar{Q}} C_1 C_2 \right]_{c\bar{c};a_1 a_2}$$

but now $H^{Q\bar{Q}} \sim \langle \tilde{\mathcal{M}} | \mathbf{\Delta} | \tilde{\mathcal{M}} \rangle$

Additional soft contributions

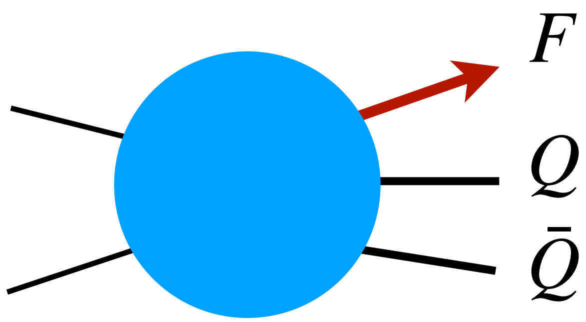
IR-subtracted virtual amplitude



✅ The soft contributions have been computed by integrating a suitably subtracted soft current

Catani, Devoto, Mazzitelli, MG (2023)

QQF



When the heavy quark pair is accompanied by a colourless system the resummation and subtraction formalisms can be applied in an analogous way with just two additional complications

Catani, Fabre, Kallweit, MG (2020)

- The colourless system takes away momentum and the computation of the additional soft contributions has to be extended accordingly

Devoto, Mazzitelli (in preparation)

- For some important processes ($t\bar{t}Z$, $WWb\bar{b}$....) three-parton correlators are non vanishing and also contribute to the soft integrals

  This is not the case for $t\bar{t}$ and $t\bar{t}H$

See eg Forshaw, Seymour and Siodmok (2012)
Czakon and Fiedler (2014)

Stability of the subtraction procedure

$$d\sigma^{F}_{(N)NLO} = \mathcal{H}^{F}_{(N)NLO} \otimes d\sigma^{F}_{LO} + \left[d\sigma^{F+\text{jets}}_{(N)LO} - d\sigma^{CT}_{(N)LO} \right]$$

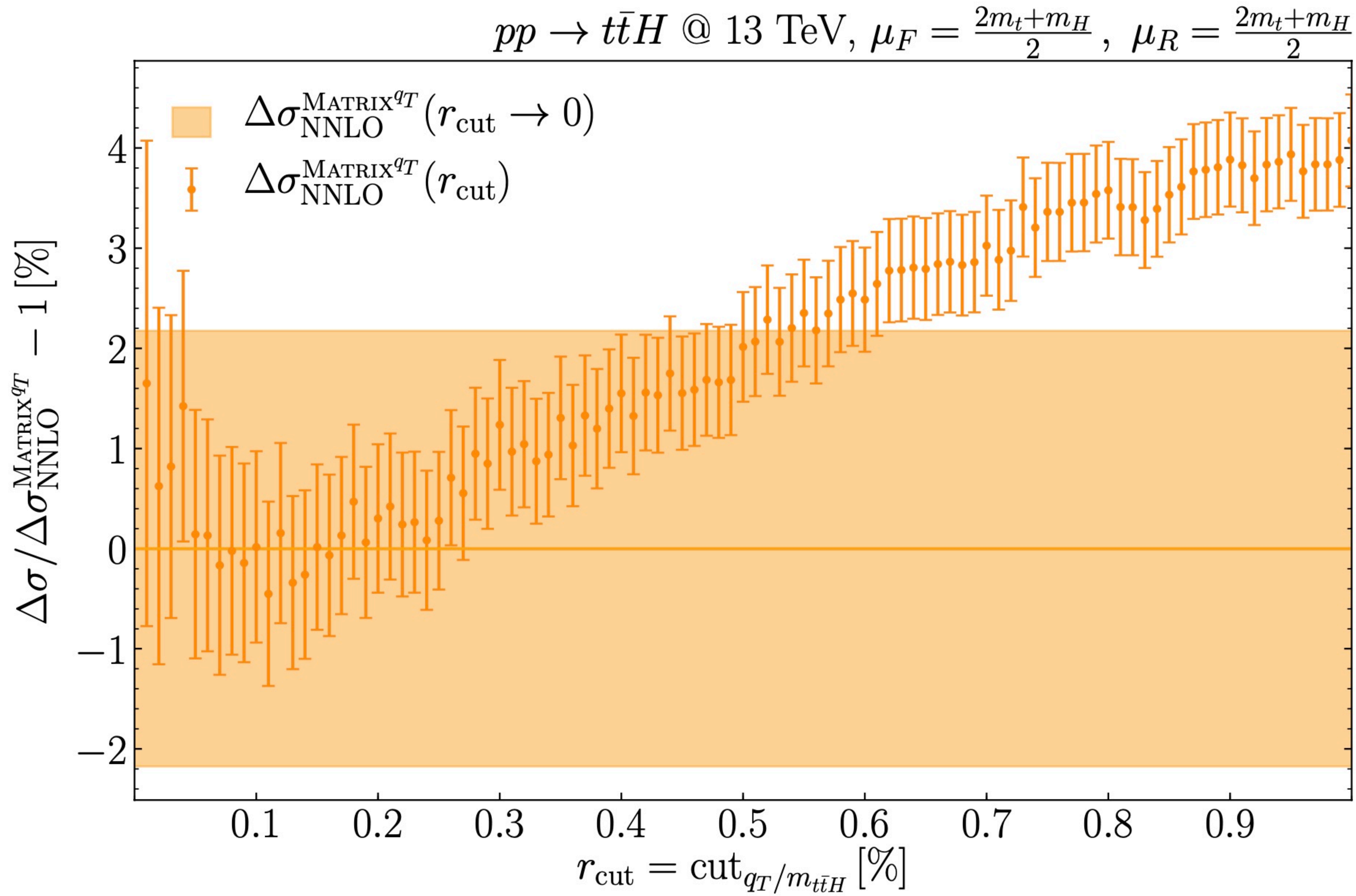
The q_T subtraction counterterm is non-local → the difference in the square bracket is evaluated with a cut-off r_{cut} on the ratio $r = q_T/Q$

In MATRIX q_T subtraction indeed works as a slicing method

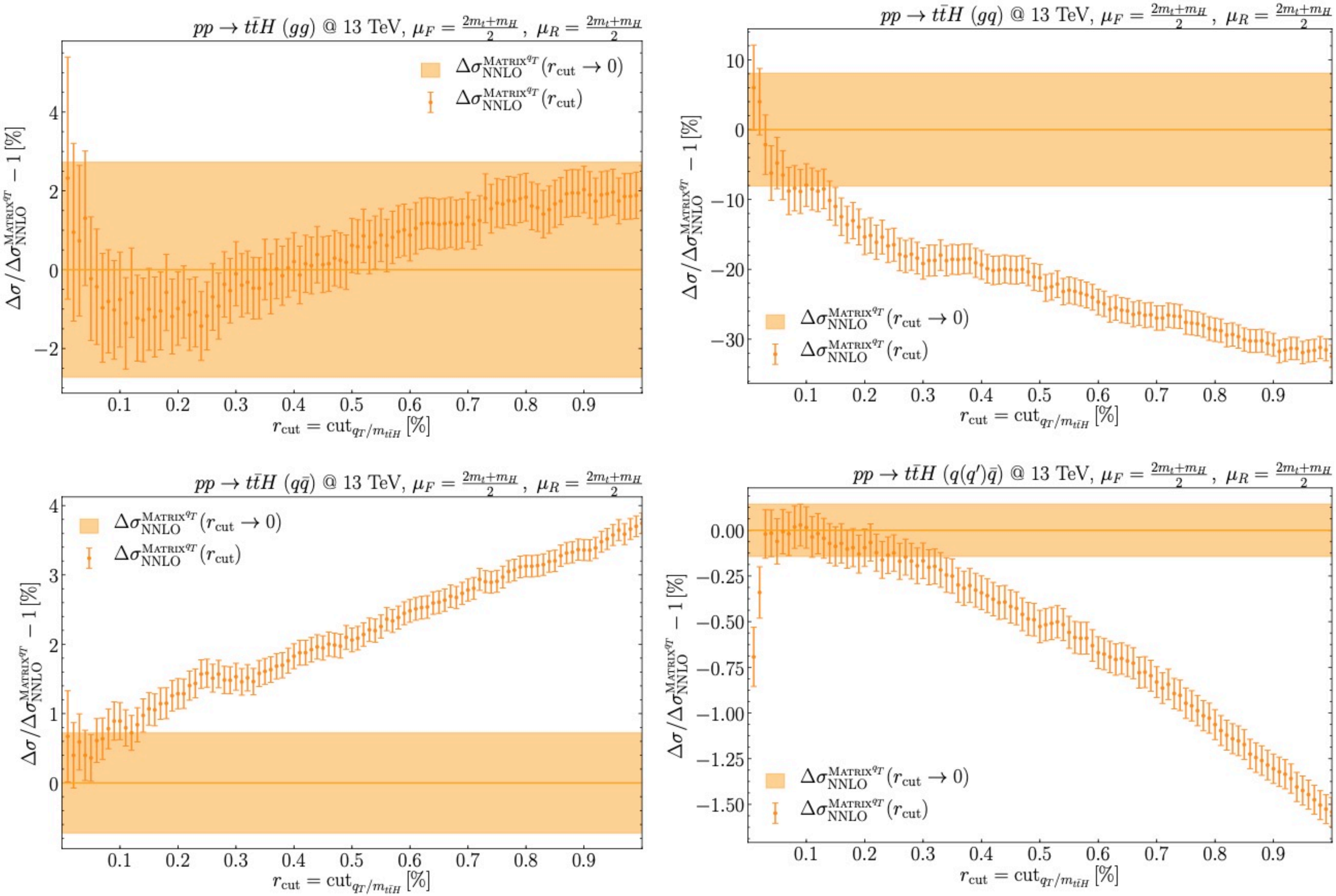
It is important to monitor the dependence of our results on r_{cut}

MATRIX allows for a simultaneous evaluation of the NNLO cross section for different values of r_{cut}

The dependence on r_{cut} is used by the code to provide an estimate of the systematic uncertainty in any NNLO run



$pp \to t\bar{t}H$ @ 13 TeV, $\mu_F = \frac{2m_t+m_H}{2}$, $\mu_R = \frac{2m_t+m_H}{2}$
$\Delta\sigma_{\rm NNLO}^{\rm MATRIX^{q_T}}(r_{\rm cut} \to 0)$
$\Delta\sigma_{\rm NNLO}^{\rm MATRIX^{q_T}}(r_{\rm cut})$
$\Delta\sigma/\Delta\sigma_{\rm NNLO}^{\rm MATRIX^{q_T}} - 1\,[\%]$
$r_{\rm cut} = {\rm cut}_{q_T/m_{t\bar{t}H}}\,[\%]$
4
3
2
1
0
−1
−2
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9



$pp \to t\bar{t}H$ (gg) @ 13 TeV, $\mu_F = \frac{2m_t+m_H}{2}$, $\mu_R = \frac{2m_t+m_H}{2}$
$\Delta\sigma^{\text{MATRIX}^{q_T}}_{\text{NNLO}}(r_{\text{cut}} \to 0)$
$\Delta\sigma^{\text{MATRIX}^{q_T}}_{\text{NNLO}}(r_{\text{cut}})$
$\Delta\sigma/\Delta\sigma^{\text{MATRIX}^{q_T}}_{\text{NNLO}} - 1$ [%]
$r_{\text{cut}} = \text{cut}_{q_T/m_{t\bar{t}H}}$ [%]
$pp \to t\bar{t}H$ (gq) @ 13 TeV, $\mu_F = \frac{2m_t+m_H}{2}$, $\mu_R = \frac{2m_t+m_H}{2}$
$\Delta\sigma^{\text{MATRIX}^{q_T}}_{\text{NNLO}}(r_{\text{cut}} \to 0)$
$\Delta\sigma^{\text{MATRIX}^{q_T}}_{\text{NNLO}}(r_{\text{cut}})$
$\Delta\sigma/\Delta\sigma^{\text{MATRIX}^{q_T}}_{\text{NNLO}} - 1$ [%]
$r_{\text{cut}} = \text{cut}_{q_T/m_{t\bar{t}H}}$ [%]
$pp \to t\bar{t}H$ $(q\bar{q})$ @ 13 TeV, $\mu_F = \frac{2m_t+m_H}{2}$, $\mu_R = \frac{2m_t+m_H}{2}$
$\Delta\sigma^{\text{MATRIX}^{q_T}}_{\text{NNLO}}(r_{\text{cut}} \to 0)$
$\Delta\sigma^{\text{MATRIX}^{q_T}}_{\text{NNLO}}(r_{\text{cut}})$
$\Delta\sigma/\Delta\sigma^{\text{MATRIX}^{q_T}}_{\text{NNLO}} - 1$ [%]
$r_{\text{cut}} = \text{cut}_{q_T/m_{t\bar{t}H}}$ [%]
$pp \to t\bar{t}H$ $(q(q')\bar{q})$ @ 13 TeV, $\mu_F = \frac{2m_t+m_H}{2}$, $\mu_R = \frac{2m_t+m_H}{2}$
$\Delta\sigma^{\text{MATRIX}^{q_T}}_{\text{NNLO}}(r_{\text{cut}} \to 0)$
$\Delta\sigma^{\text{MATRIX}^{q_T}}_{\text{NNLO}}(r_{\text{cut}})$
$\Delta\sigma/\Delta\sigma^{\text{MATRIX}^{q_T}}_{\text{NNLO}} - 1$ [%]
$r_{\text{cut}} = \text{cut}_{q_T/m_{t\bar{t}H}}$ [%]

We have used our factorisation formula to construct approximations of the $H^{(1)}$ and $H^{(2)}$ coefficients

In order to use the factorisation formula we have to introduce a mapping that from a $t\bar{t}H$ event defines a $t\bar{t}$ event with no Higgs boson

To this purpose we use the q_T recoil prescription

Catani, Ferrera, de Florian, MG (2016)

With this prescription the momentum of the Higgs boson is equally reabsorbed by the initial state partons, leaving the top and antitop momenta unchanged

The required tree-level and one-loop amplitudes are obtained using Openloops

The $q\bar{q} \to t\bar{t}$ and $gg \to t\bar{t}$ two-loop amplitudes needed to apply our approximation are those provided by Czakon et al.

Bärnreuther, Czakon, Fiedler (2013)

Setup: NNPDF31 NNLO partons with 3-loop α_S

$m_H = 125\,\mathrm{GeV}$ and $m_t = 173.3\,\mathrm{GeV}$

Central values for factorisation and renormalisation scales

$\mu_F = \mu_R = (2m_t + m_H)/2$