Higgs Boson Transverse Momentum Spectrum at the LHC

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MC@NNLO

Goal of precision studies of Higgs Boson

- Constrain the Standard Model (SM) and discover physics beyond SM.

Higgs transverse momentum (pT) measurements at the LHC

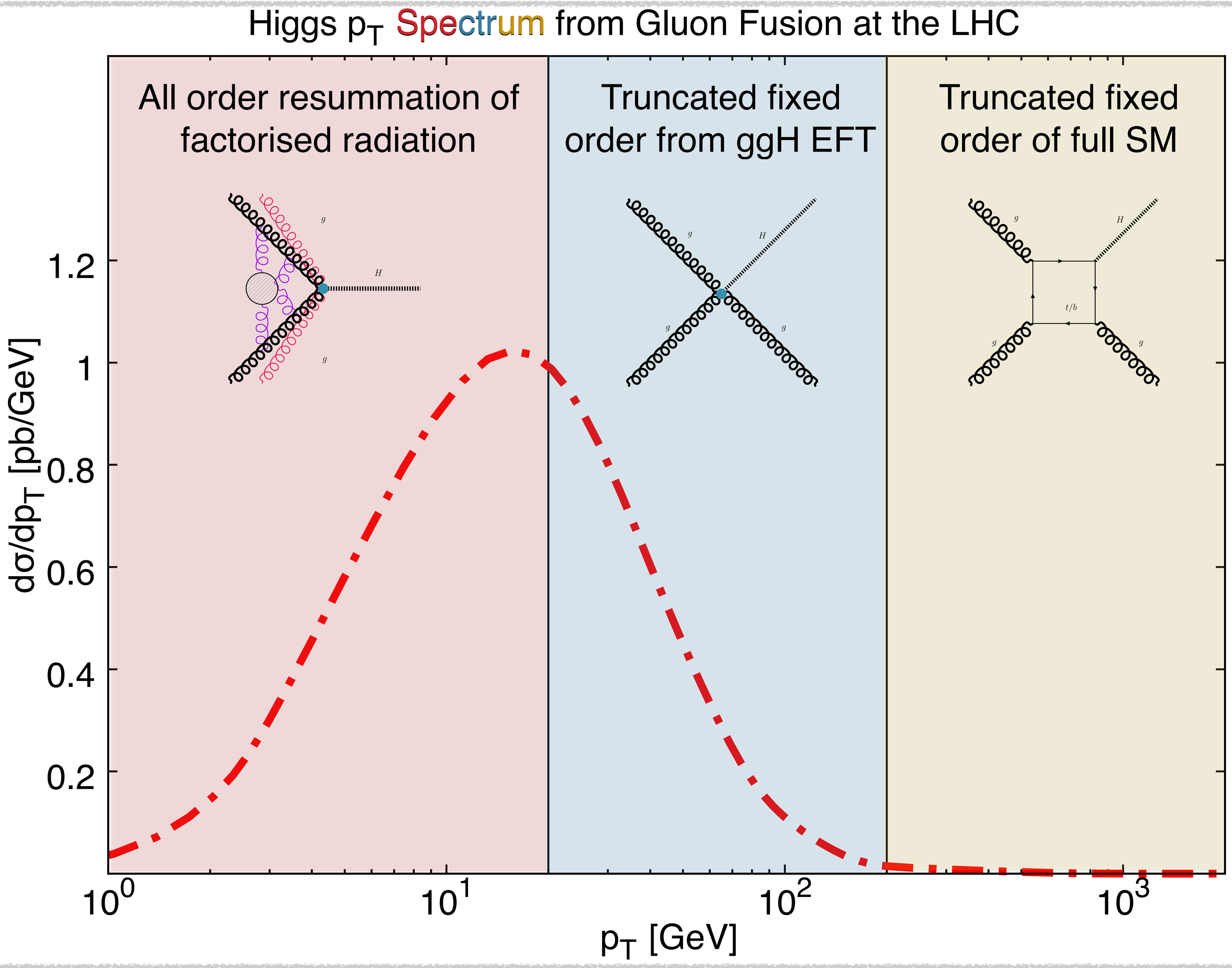
- LHC Run III and HL-LHC expect to achieve $\pm 10\,\%$ accuracy.
- pT spectrum covering wide energy range constrains SM in different aspects.

Predictions of Higgs boson pT spectrum at the LHC

- The dominant Higgs boson production channel at the LHC is gluon fusion through a quark loop.
- Introduce effective fields (**EFT**) from SM (integrating out heavy quark loops) to simplify Higgs-gluon couplings:

$$\mathscr{L}_{EFT} = -\frac{\lambda}{4} G^{\mu\nu} G_{\mu\nu} H$$

- **Right:** Sketch of the Higgs pT spectrum from the gluon fusion channel.



All order resummation at small pT

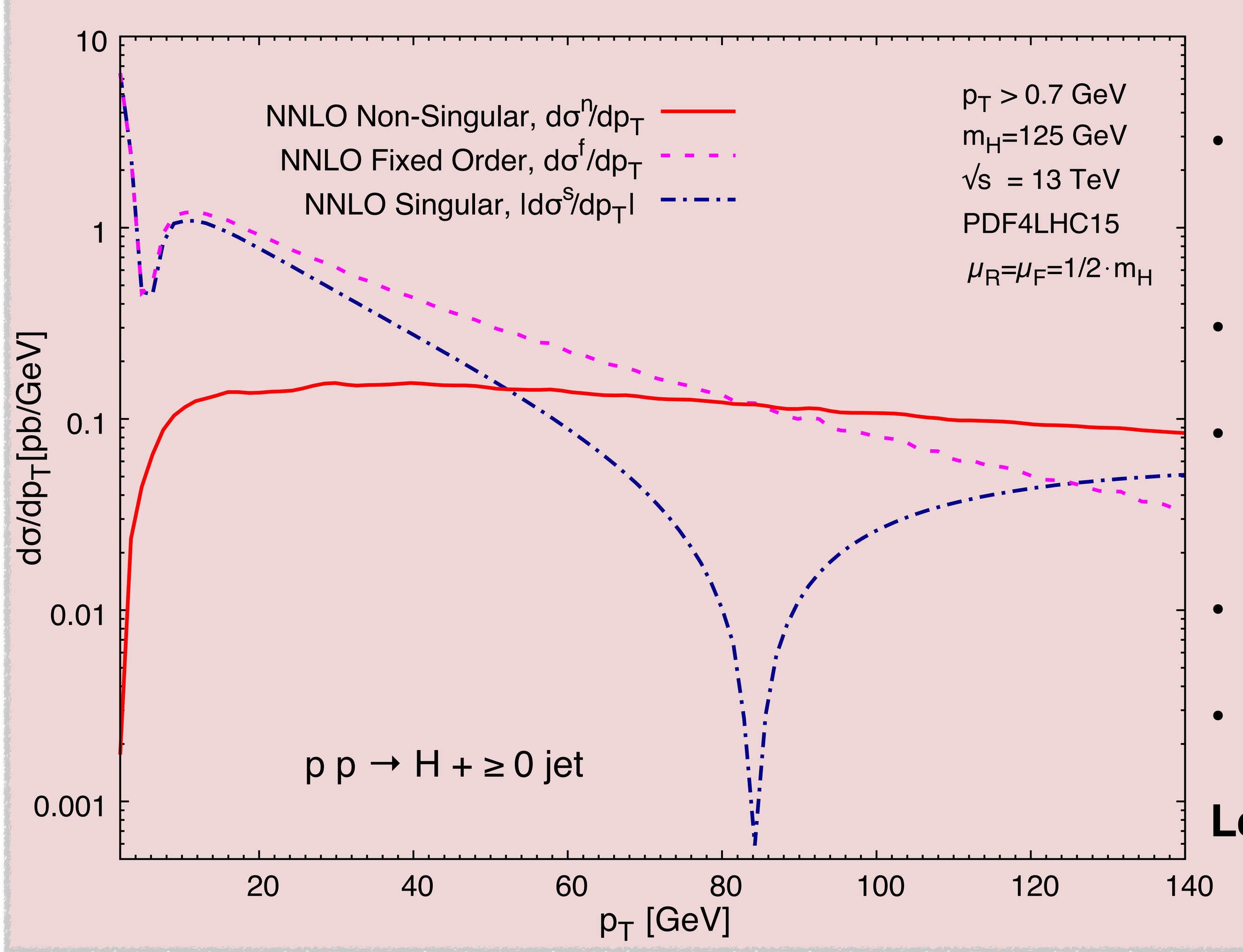
- Unphysical contributions from singular log terms:

$$\ln^k(m_H^2/p_T^2)/p_T^2$$

- Soft and collinear radiations factorise from hard process.
- Cross check of singular log behaviour (red line in left):

$$[d\sigma^F/dp_T^2 - d\sigma^S/dp_T^2] \xrightarrow{p_T \to 0} 0$$

- Use renormalisation group to resume the singular terms.
- State-of-the-art precision is N^3LL resummation of N^3LO [1].



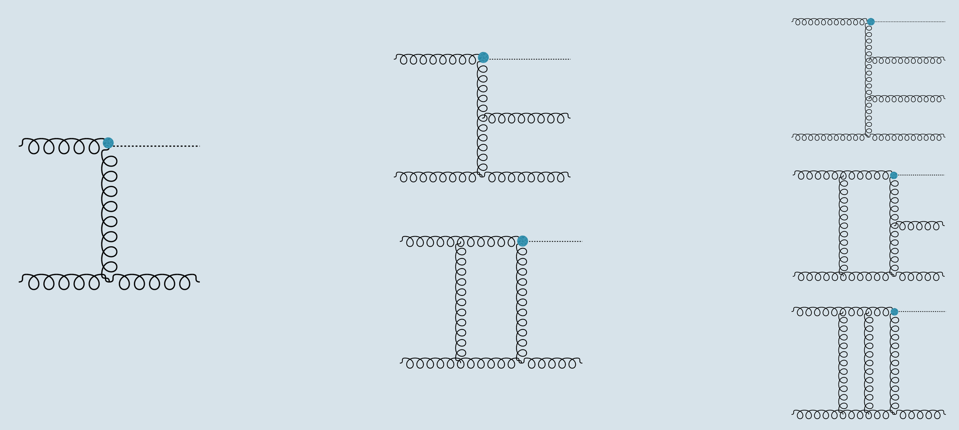
Left: Higgs pT spectrum from fixed order (F), singular (S) and non-singular (N = FO − S) contributions.

α_s counting	$\ln W(x_a, x_b, m_H, \vec{b}, \mu = b_0/b) \sim$						
α_s	$\ln^2(b^2 m_H^2)$	$\ln(b^2 m_H^2)$	1				$\frac{d\hat{\sigma}^H_{NLO}}{dp_T^H}$
α_s^2	$\ln^3(b^2 m_H^2)$	$\ln^2(b^2 m_H^2)$	$\ln(b^2 m_H^2)$	1			$\frac{d\hat{\sigma}^H_{NNLO}}{dp_T^H}$
α_s^3	$\ln^4(b^2 m_H^2)$	$\ln^3(b^2 m_H^2)$	$\ln^2(b^2 m_H^2)$	$\ln(b^2 m_H^2)$	1		$\frac{d\hat{\sigma}^H_{N^3LO}}{dp_T^H}$
…	…	…	…	…	…	…	…
α_s^k	$\ln^{k+1}(b^2 m_H^2)$	$\ln^k(b^2 m_H^2)$	$\ln^{k-1}(b^2 m_H^2)$	$\ln^{k-2}(b^2 m_H^2)$	…	1	$\frac{d\hat{\sigma}^H_{N^kLO}}{dp_T^H}$
…	…	…	…	…	…	…	…
Resum order	LL	NLL	NNLL	N3LL	…	$N^{k+1}LL$	
A expansion	A_1	A_2	A_3	A_4	…	A_{k+2}	
B expansion		B_1	B_2	B_3	…	B_{k+1}	

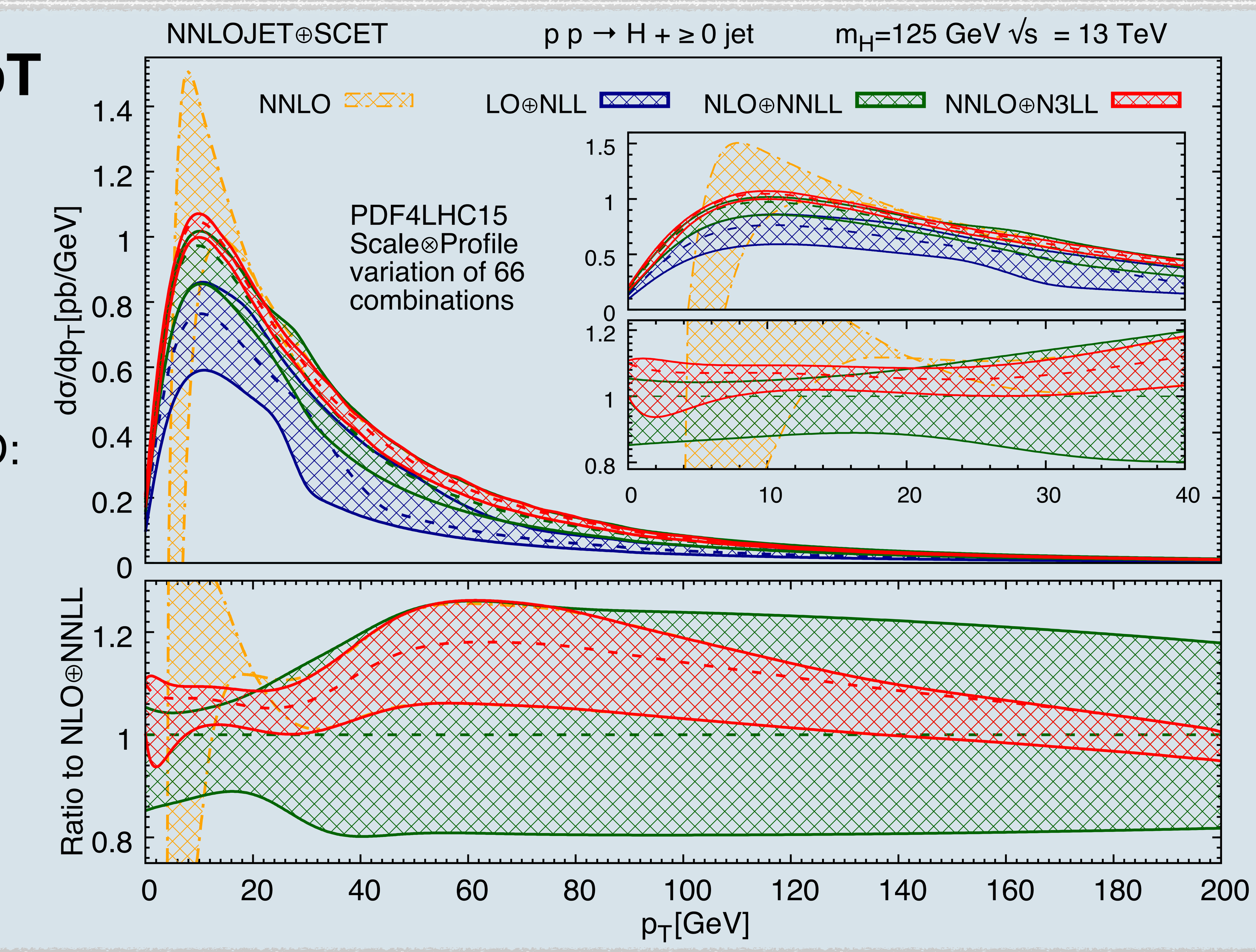
Above: Perturbative expansion of α_s and its corresponding singular log terms in soft-collinear-effective-field theory (SCET) [1].

Fixed order predictions at medium pT

- Use parton level event generator NNLOJET.
- Apply antenna subtraction to regulate NNLO infrared divergences.
- Higgs + jet production in EFT framework at NNLO:



LO EFT NLO EFT NNLO EFT

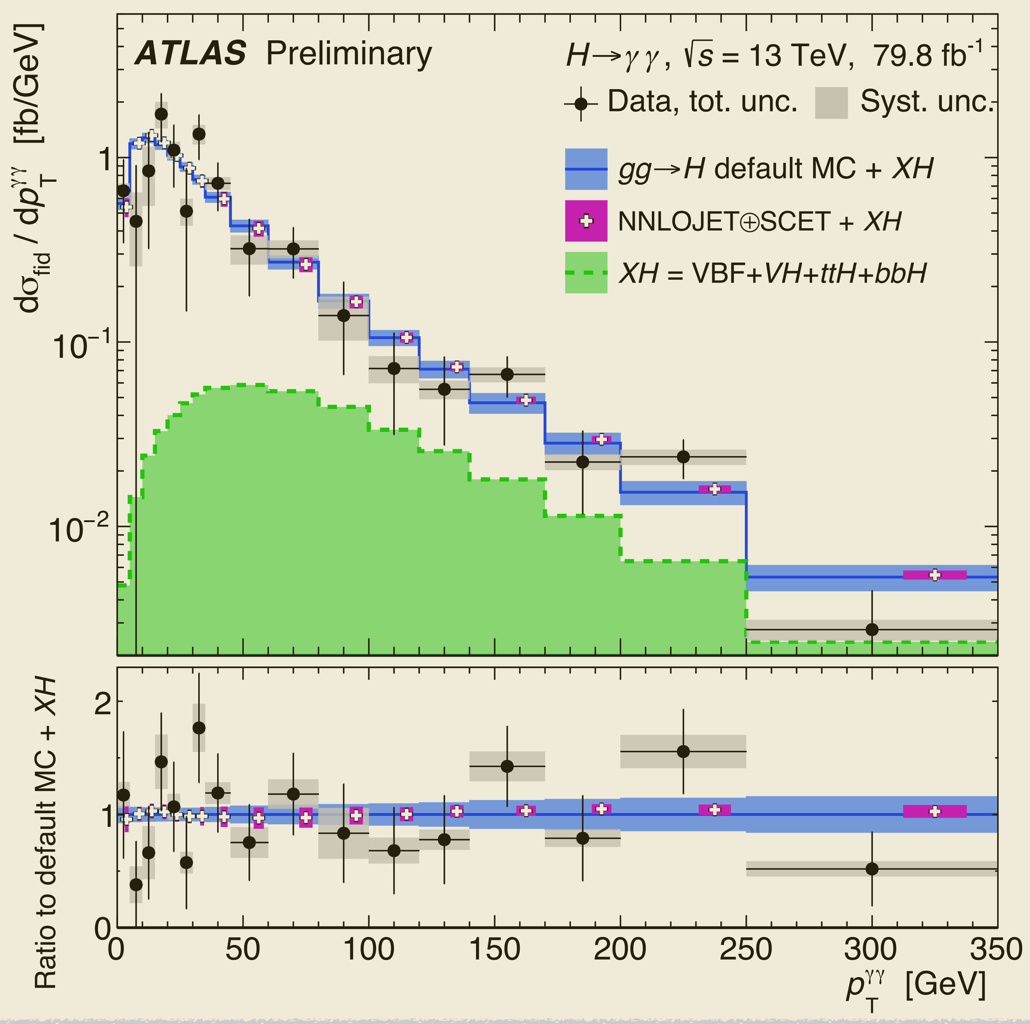


Matching small and medium pT

- Additive matching NNLOJET ⊕ SCET [1].
- Use profile function for smooth transition.
- Conservative theoretical uncertainty estimation
  - 11 combinations of scale variation
  - 6 profile functions for matching
  - Taking envelope of 66 combinations
- **Theoretical uncertainty** of Higgs pT spectrum at $N^3LL \oplus$ NNLO **reduces to at most** $\pm 10\,\%$ **.**

Left: Higgs Boson pT spectrum below 200 GeV with N^3LL resummation matched with NNLO.

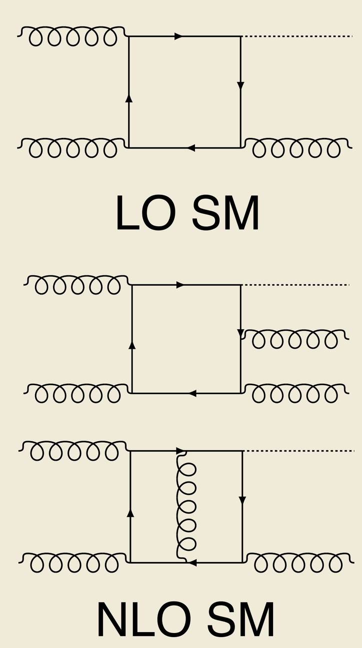
Extension to high pT region and compare the full spectrum with LHC data



- EFT approach breaks down at large pT region (> 200 GeV) due to high energy flow in the quark loop.
- Need to consider the full SM gluon fusion to Higgs boson where only the second order contribution (NLO) in the perturbative expansion is known recently [2].
- To achieve reliable predictions, we extrapolate LO mass effects to NNLO EFT by re-weighting:

$$\frac{d\sigma_{reweight}}{dp_T} = \frac{d\sigma^{EFT}_{NNLO}}{dp_T} \times \frac{d\sigma^{SM}_{LO}}{d\sigma^{EFT}_{LO}}$$

- The re-weighted pT spectrum is used by ATLAS collaboration for detailed comparison with data.



Left: Higgs pT spectrum measured by ATLAS detector at the LHC up to 350 GeV with integrated luminosity about 80 fb^{-1} [3]. Current experiment precision is about $\pm 50\,\%$ in good agreement with theory predictions from NNLOJET ⊕ SCET .

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References

[1] X. Chen, T. Gehrmann et al., Precise QCD Description of the Higgs Boson Transverse Momentum Spectrum, arXiv:1805.00736 [hep-ph].
[2] S. P. Jones, M. Kerner et al., Next-to-Leading-Order QCD Corrections to Higgs Boson Plus Jet Production with Full Top-Quark Mass Dependence Phys. Rev. Lett. 120 (2018) no.16, 162001
[3] The ATLAS collaboration, Measurements of Higgs Boson Properties in the Diphoton Decay Channel Using 80 fb^{-1} of pp Collision Data at $\sqrt{s} = 13$ TeV with the ATLAS Detector, ATLAS-CONF=2018-028.