# HIGH PRECISION PHENOMENOLOGY OF THE HIGGS BOSON

## XXVI CRACOW EPIPHANY CONFERENCE

Universität Zürich[UZH]

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*Cracow, Poland, January 10, 2020*

# OUTLINE

- **Precision measurements and predictions of the Higgs boson**
  - Current status from both theory and experiment (cherry pick)
  - Projection of HL-LHC, is it precise enough?
- **Higgs production and decay processes in NNLOJET**
- **Higgs transverse momentum distribution in full spectrum**
  - Small, medium and boosted regions
- **Higgs rapidity distribution at N3LO (ggF channel)**
- **Future work and Summary**

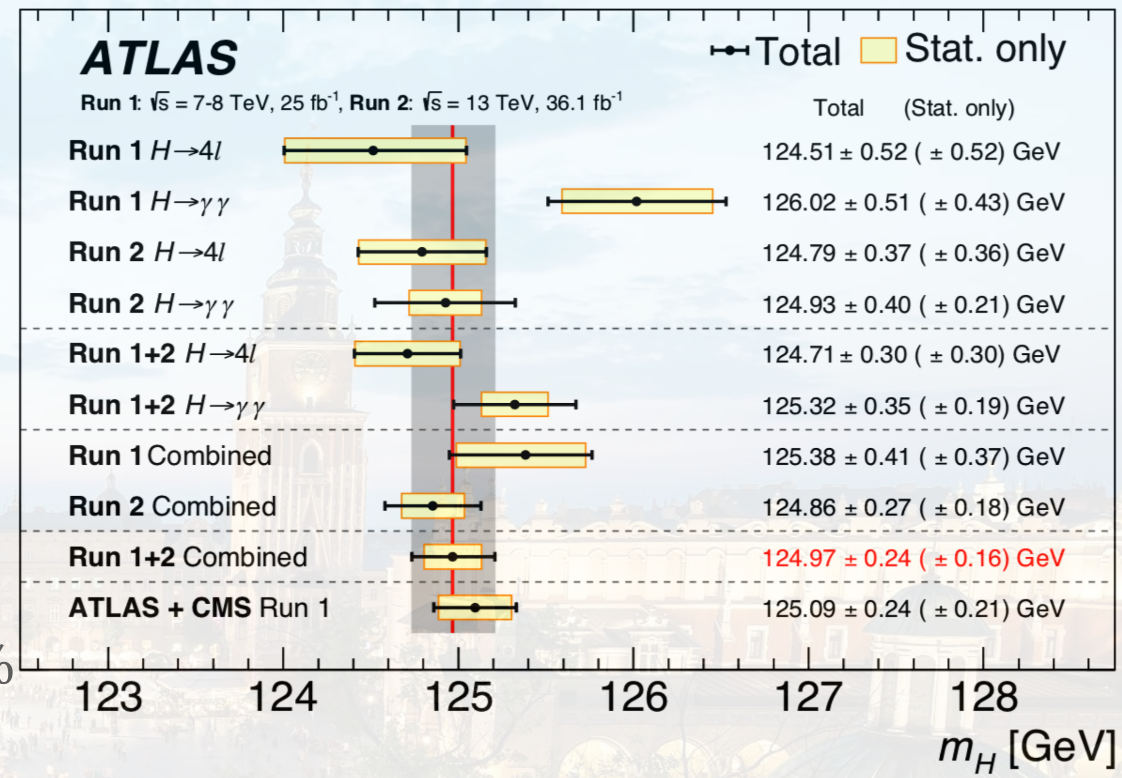
# SUCCESS OF LHC HIGGS EXPERIMENTS

- Higgs boson properties in agreement with SM
  - Bosonic (Run I) and 3rd generation fermionic couplings (Run II) observed with current precision on coupling ±10-20% (EPS2019)
  - Higgs mass uncertainty at ±0.2% level (Run I + II)
  - Fiducial total cross section measured with ±9% accuracy (Run I + II)
  - 2nd generation fermion couplings still to be established
  - HHH coupling with $\pm^{10.3}_{2.3}$ times SM limit

More details in Saverio's talk

- Goal for the future: improve precision
  - Differential in production and decay channels
  - Projection to HL-LHC (estimate challenge)
  - Accelerate searches of new physics

More details in yesterday morning session

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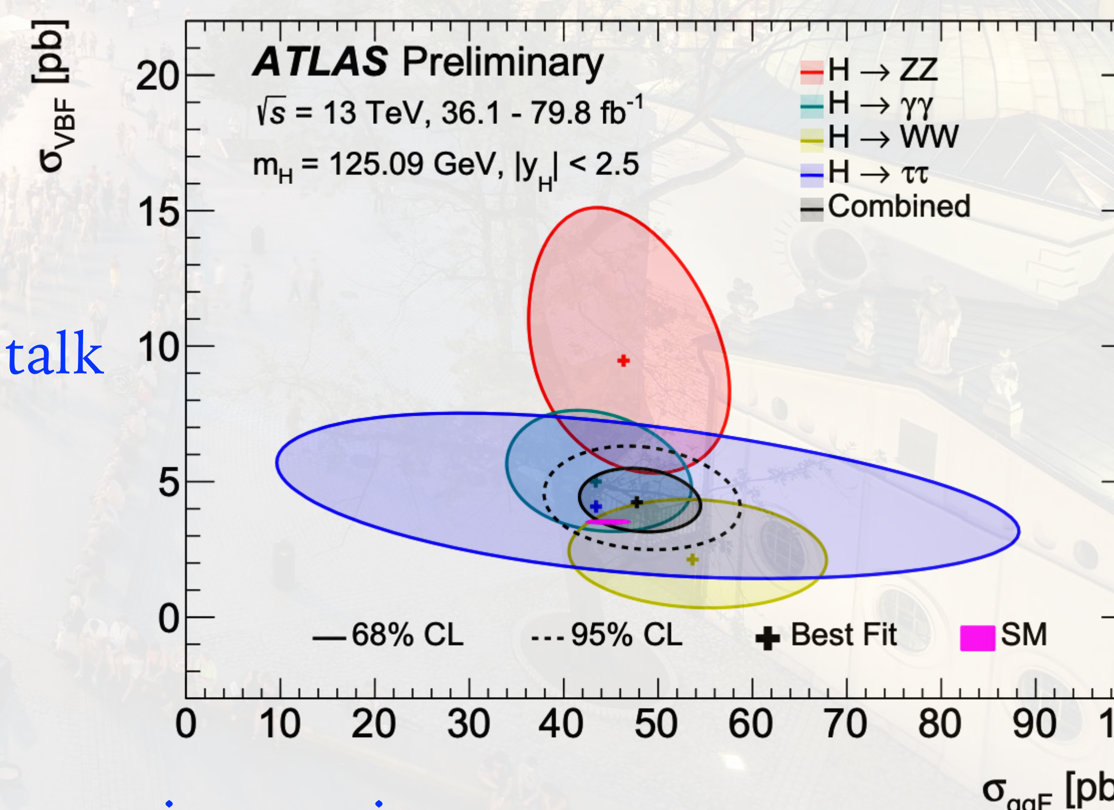
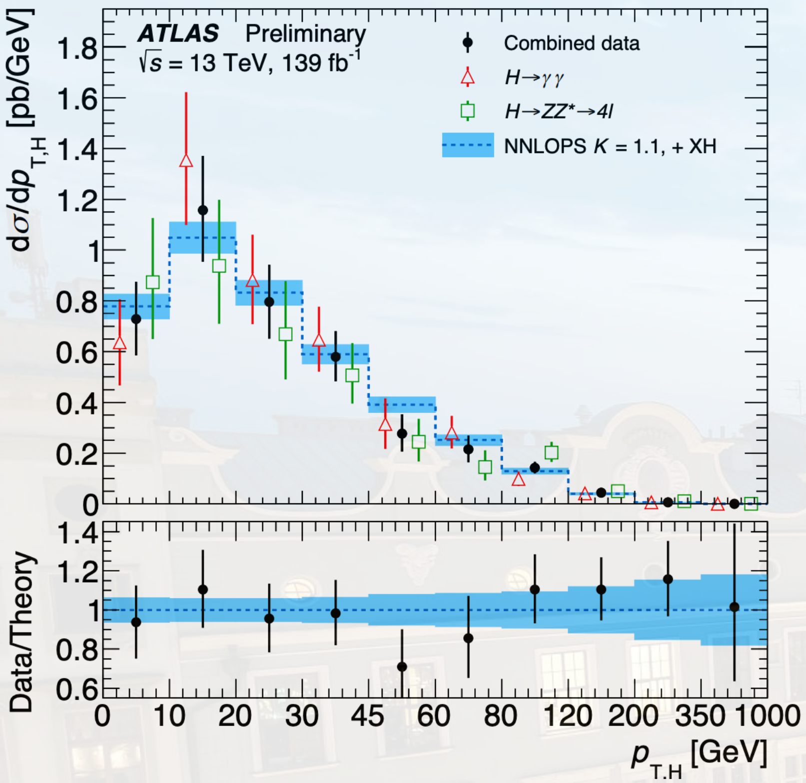
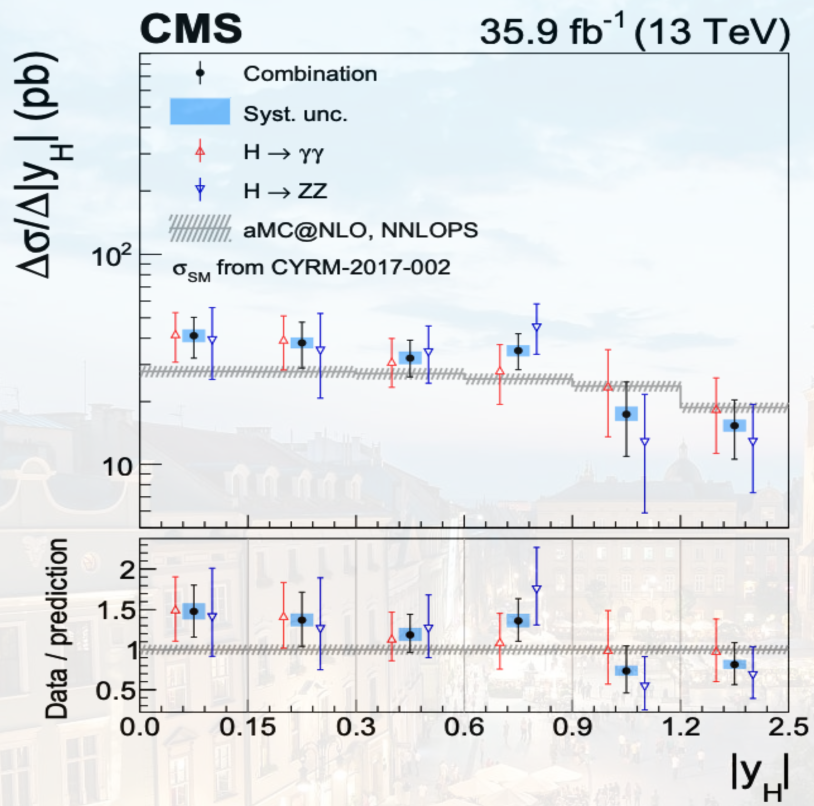
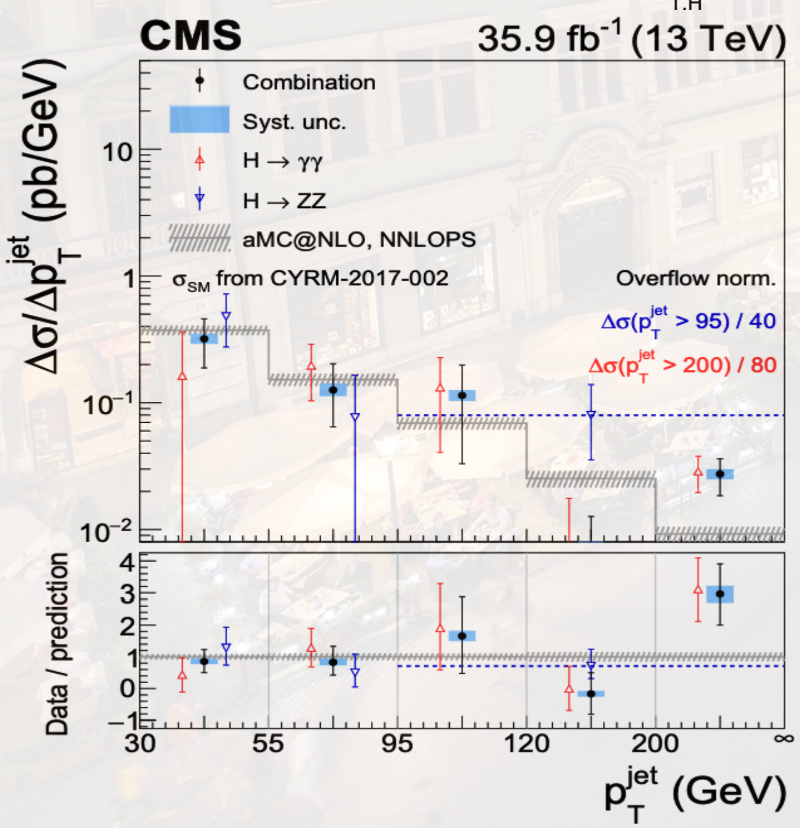


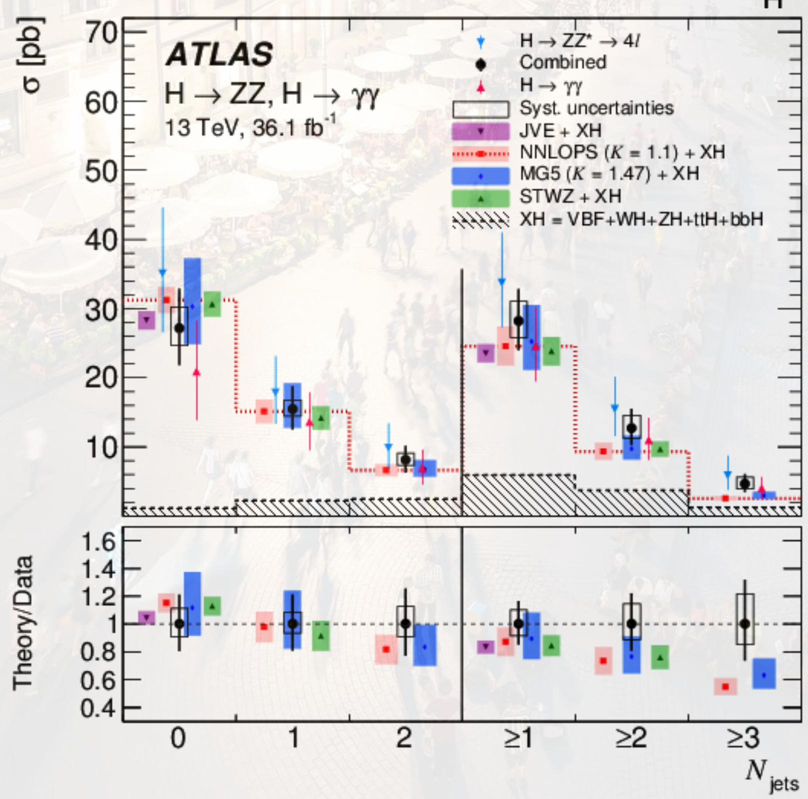

ATLAS-CONF-2018-031

# SUCCESS OF LHC HIGGS EXPERIMENTS



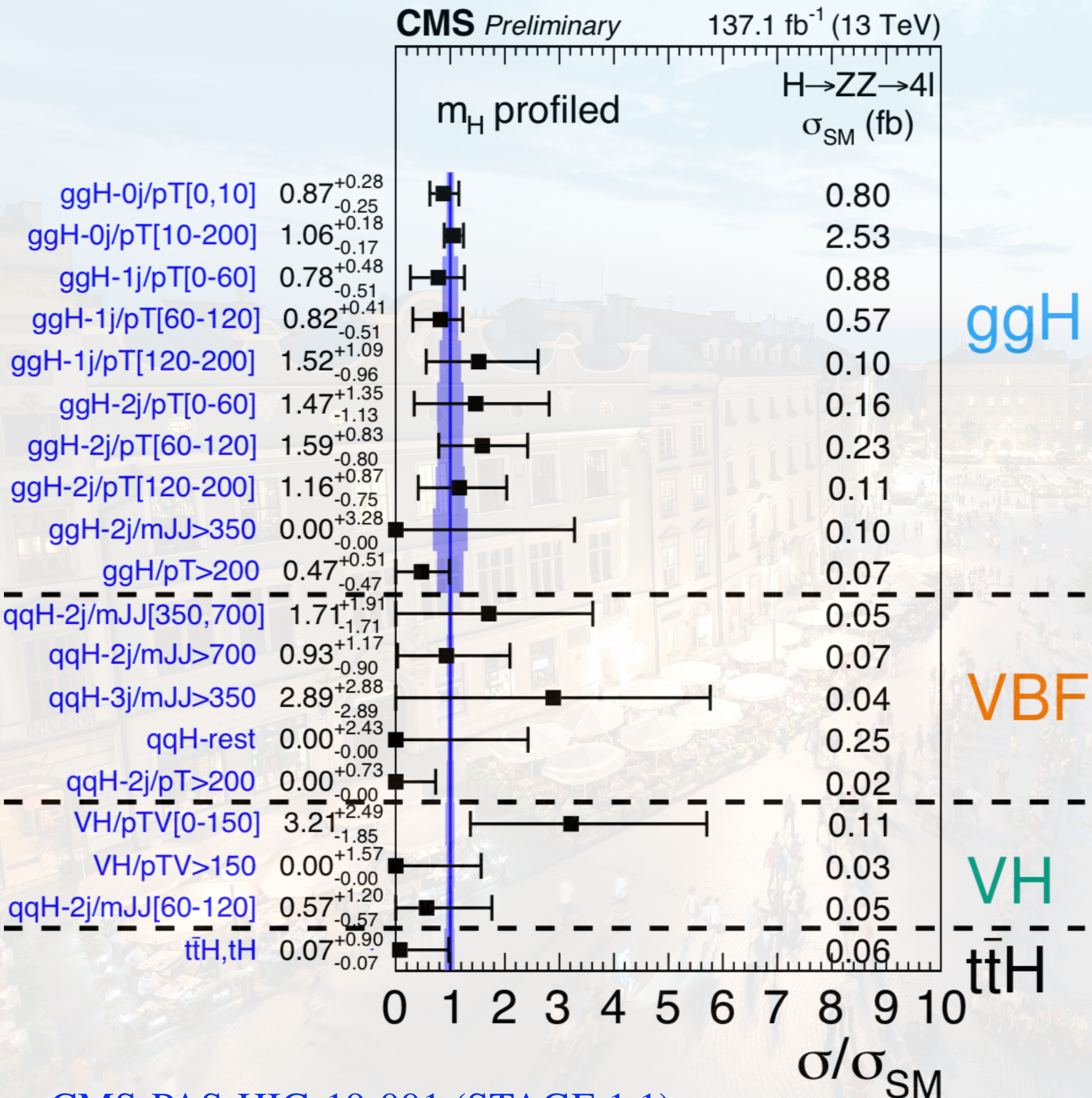




- Typical differential observables for Higgs (+jet) are:

$$\frac{d\sigma}{dp_T^H} \quad \frac{d\sigma}{d|y^H|} \quad \frac{d\sigma}{dp_T^{j1}} \quad \frac{d\sigma}{dN_{jets}}$$

- Inclusive decay observables are reconstructed from individual decay channel
- Combined results with ±20-40% uncertainties (EPS2019)
(ATLAS 1805.10197, CMS 1812.06504, ATLAS-CONF-2019-032)
- Breakdown in production channels through Simplified Template Cross Section (STXS)
- All Higgs production and decay channels contribute
- Complexity increase from Stage $0 \to 1 \to 1.1 \to \cdots \to 2$

# SUCCESS OF LHC HIGGS EXPERIMENTS




CMS-PAS-HIG-19-001 (STAGE 1.1)

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  $$\frac{d\sigma}{dp_T^H} \quad \frac{d\sigma}{d|y^H|} \quad \frac{d\sigma}{dp_T^{j1}} \quad \frac{d\sigma}{dN_{jets}}$$
- Inclusive decay observables are reconstructed from individual decay channel
- Combined results with ±30-50% uncertainties (ATLAS 1805.10197, CMS 1812.06504, ATLAS-CONF-2019-032)
- Breakdown in production channels through Simplified Template Cross Section (STXS)
- All Higgs production and decay channels contribute
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# QCD IMPROVED PARTON MODEL

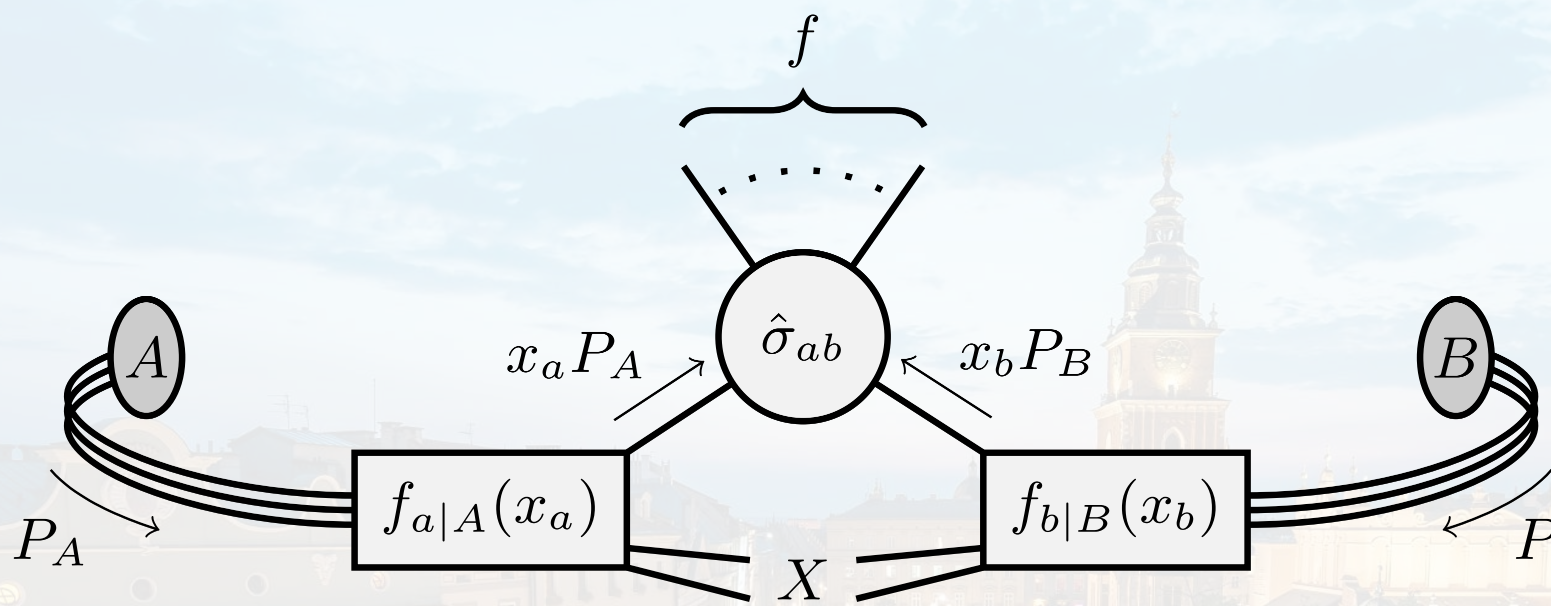


*Figure by A. Huss*

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

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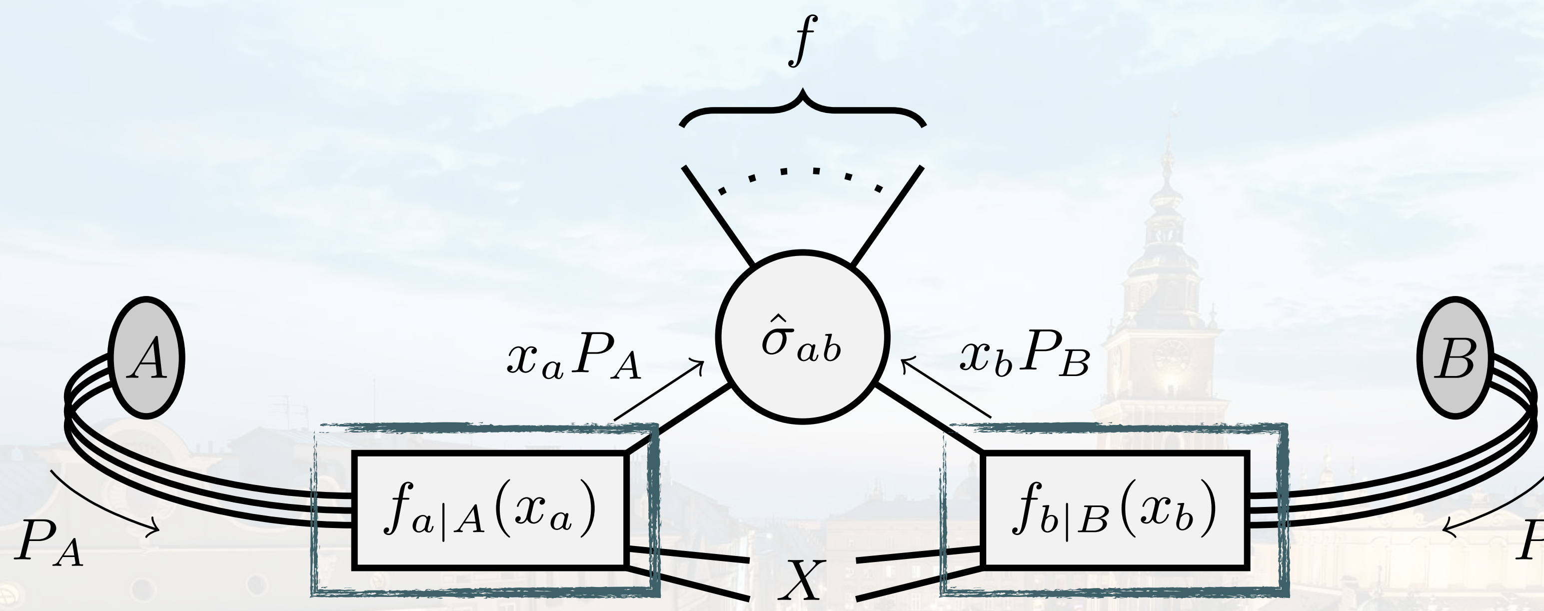


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**parton distribution functions**
*(systematically, improvable)*
$\sim$1 to 3 % at the LHC

Stefano's Talk

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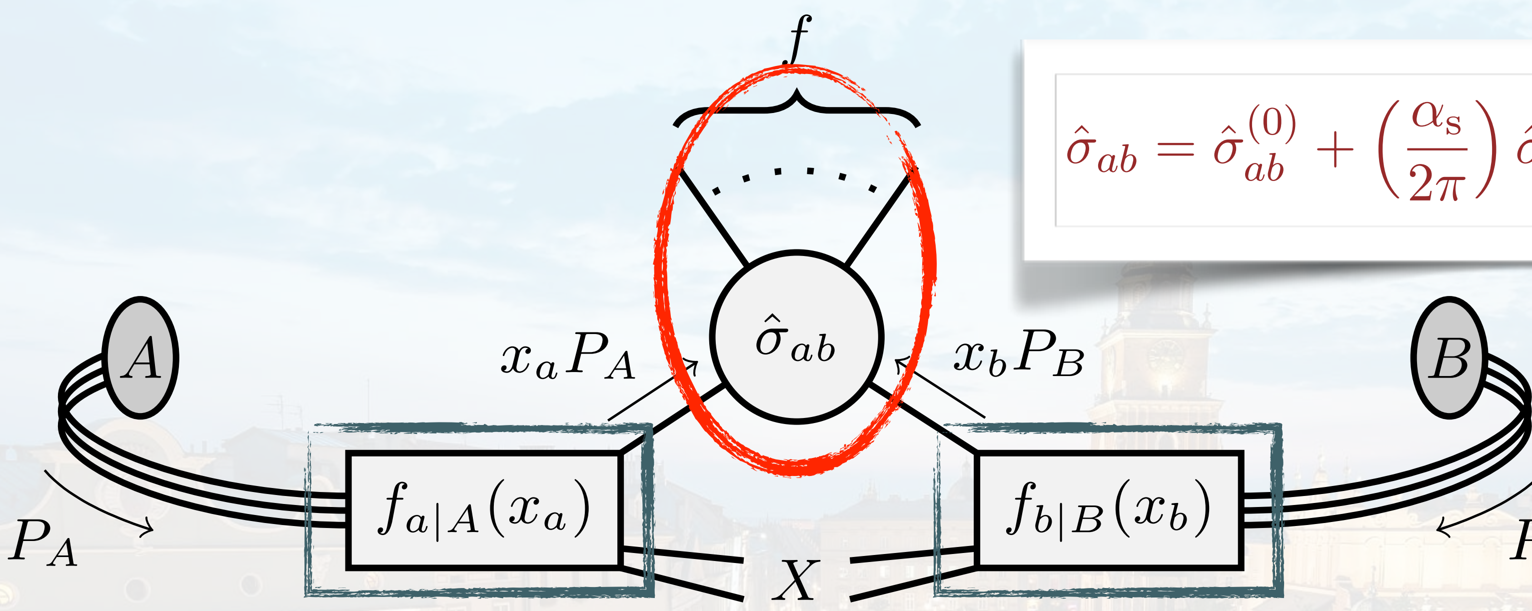


$$\hat{\sigma}_{ab} = \hat{\sigma}^{(0)}_{ab} + \left(\frac{\alpha_s}{2\pi}\right)\hat{\sigma}^{(1)}_{ab} + \left(\frac{\alpha_s}{2\pi}\right)^2\hat{\sigma}^{(2)}_{ab} + \dots$$

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**hard scattering**
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$\sim$10 % level!

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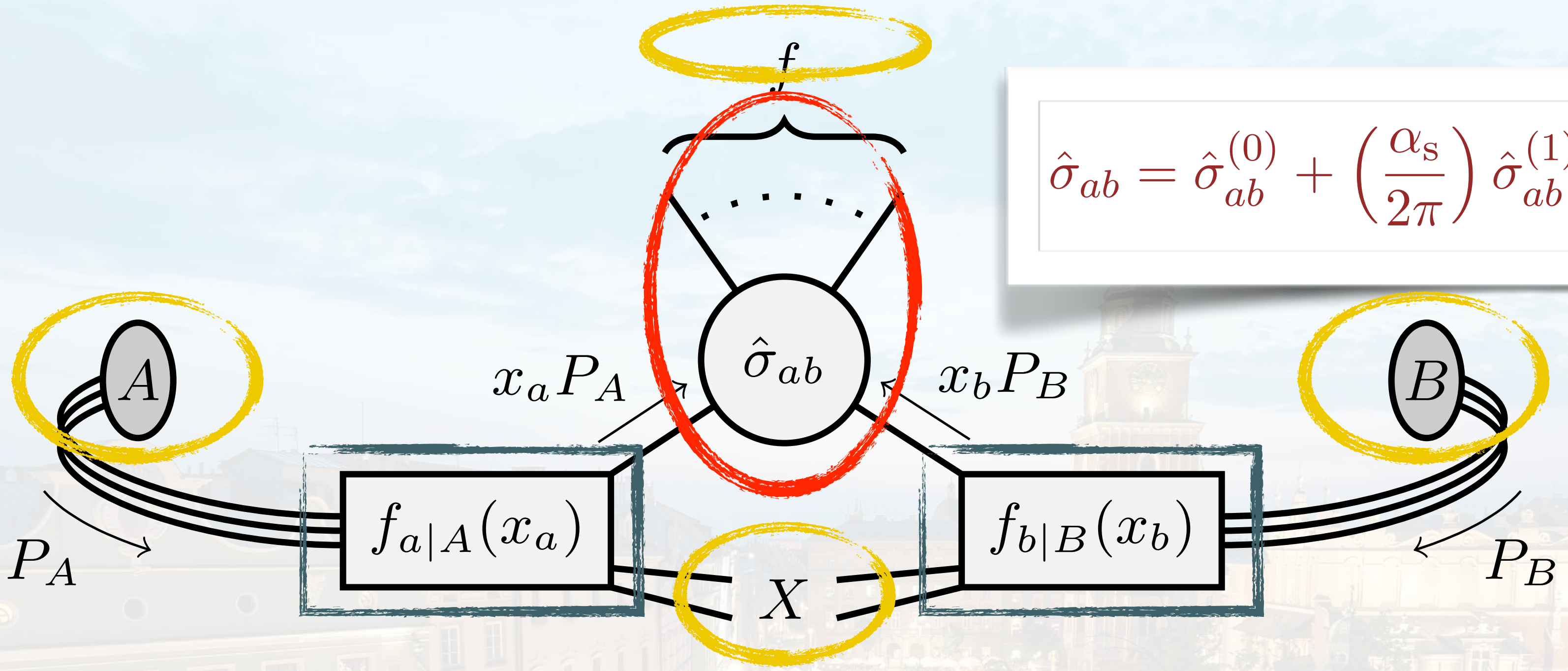


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**non-perturbative effects**
*(no good understanding)*
~ few %?

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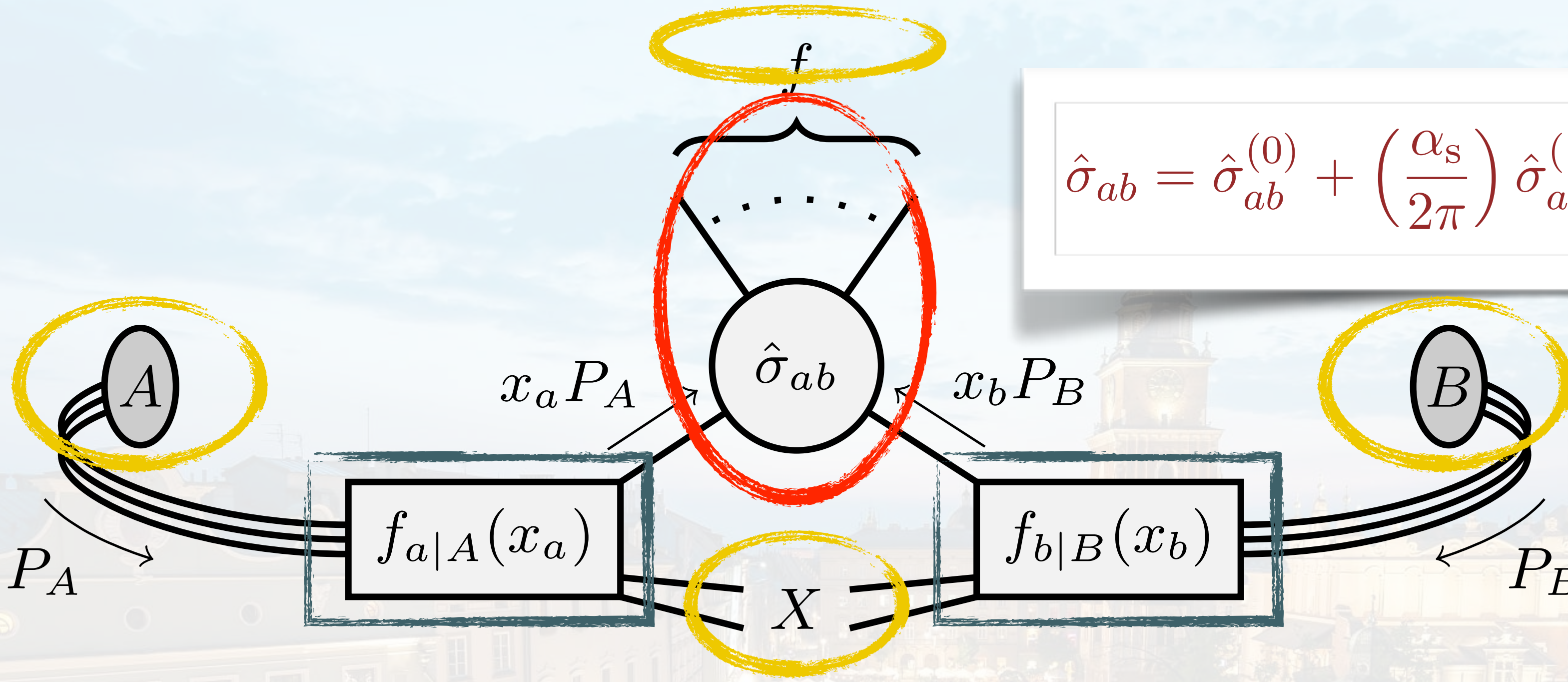


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~10 % level!

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~ few %?

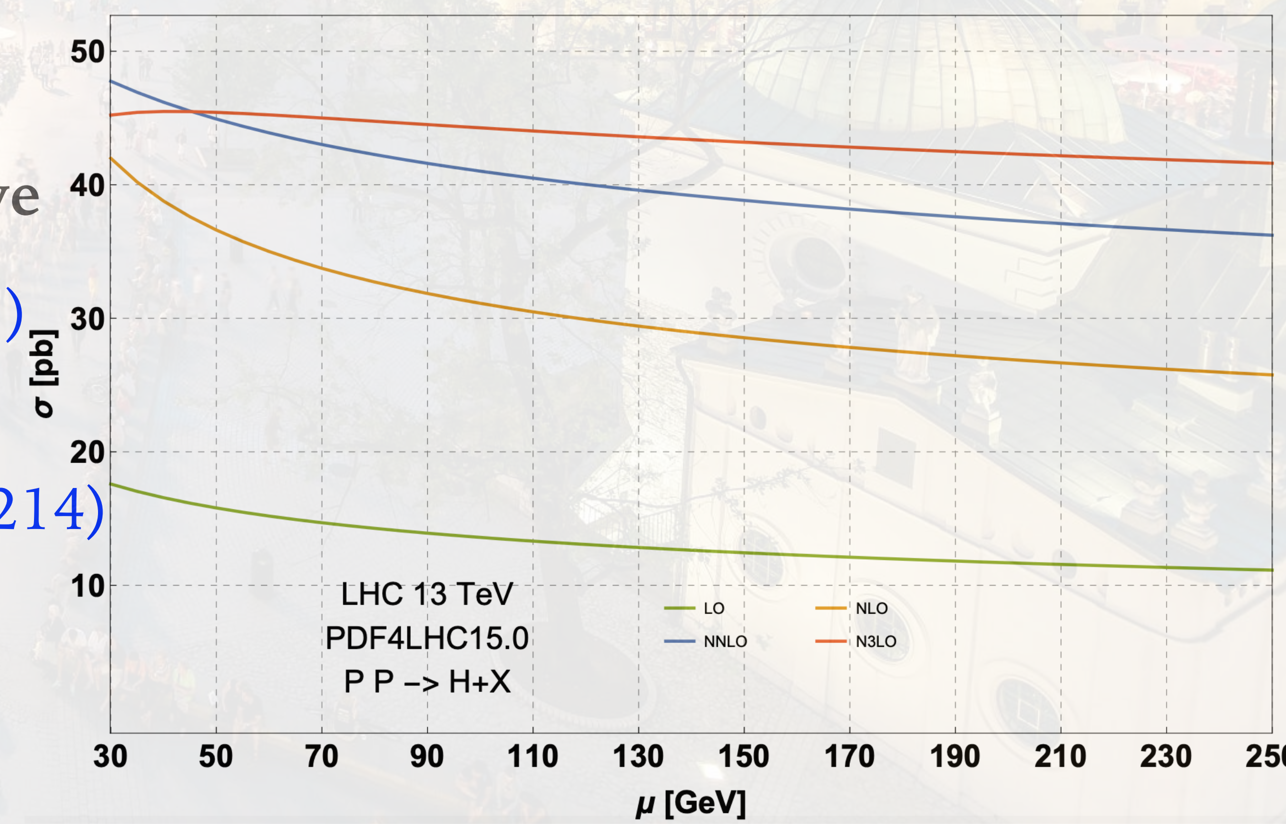
Parton Shower algorithms
for scale evolution
Simon's talk

# SUCCESS OF HIGGS THEORY (GLUON FUSION)

$$
\begin{aligned}
\sigma_{PP\to H+X} &= 16.00\text{ pb} & (+32.87\%) & \quad \text{LO, rEFT}\\
&+ 20.84\text{ pb} & (+42.82\%) & \quad \text{NLO, rEFT}\\
&+ 9.56\text{ pb} & (+19.64\%) & \quad \text{NNLO, rEFT}\\
&+ 1.62\text{ pb} & (+3.32\%) & \quad \text{N}^3\text{LO, rEFT}\\
&- 2.07\text{ pb} & (-4.25\%) & \quad \text{(t,b,c) corr. to exact NLO}\\
&+ 0.34\text{ pb} & (+0.70\%) & \quad 1/m_t \text{ corr. to NNLO}\\
&+ 2.37\text{ pb} & (+4.87\%) & \quad \text{EWK corr.}\\
&= 48.67\text{ pb}\,.
\end{aligned}
$$

$$
\begin{aligned}
\delta(\text{theory}) &= {}^{+0.13pb}_{-1.20pb} & \left({}^{+0.28\%}_{-2.50\%}\right) & \quad \delta(\text{scale})\\
&+ \pm 0.56pb & (\pm 1.16\%) & \quad \delta(\text{PDF-TH})\\
&+ \pm 0.49pb & (\pm 1.00\%) & \quad \delta(\text{EWK})\\
&+ \pm 0.41pb & (\pm 0.85\%) & \quad \delta(\text{t,b,c})\\
&+ \pm 0.49pb & (\pm 1.00\%) & \quad \delta(1/m_t)\\
&= {}^{+2.08pb}_{-3.16pb} & \left({}^{+4.28\%}_{-6.5\%}\right)\,, &\\
\delta(\text{PDF}) &= \pm 0.89\text{pb} & (\pm 1.85\%)\,, &\\
\delta(\alpha_S) &= {}^{+1.25pb}_{-1.26pb} & \left({}^{+2.59\%}_{-2.62\%}\right)\,. &
\end{aligned}
$$

- Total cross section with N3LO QCD corrections in heavy top limit (HTL) (Mistlberger 1802.00833)
- QCD scale variation reduced significantly
- Public in iHixs2 code (Dulat et al. 1802.00827)
- Uncertainty dominant by QCD (± 4%) (Anastasiou et al. 1602.00695)
- Three short boards of accuracy: QCD scale, PDF, $\alpha_s$

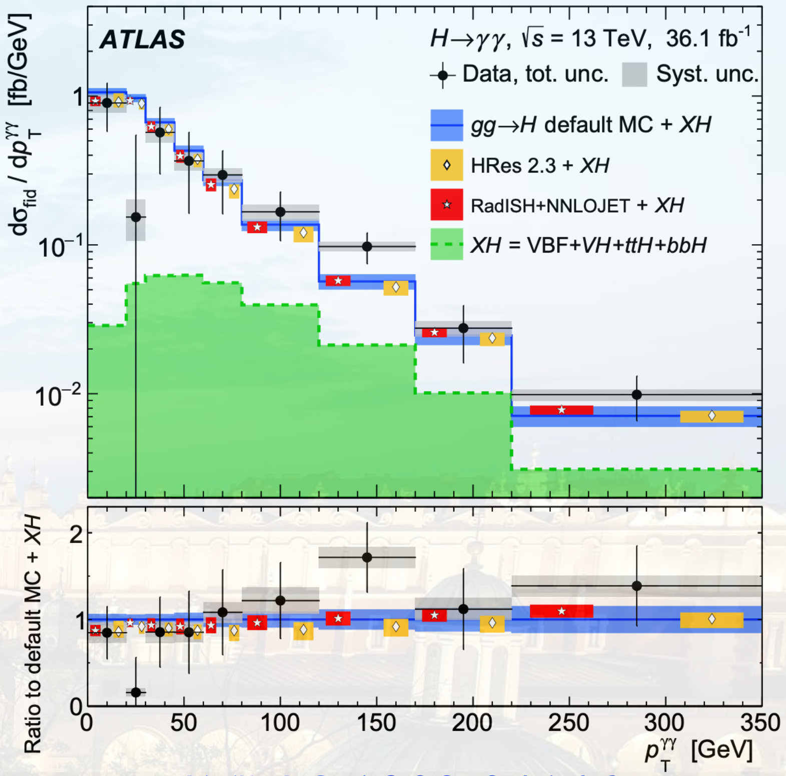



**Need to attack on many fronts to further improve**

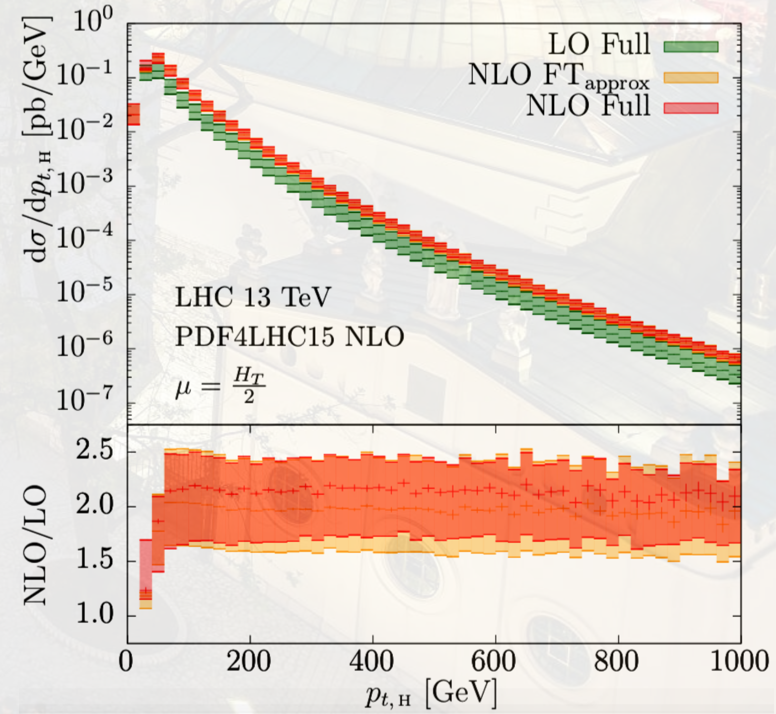
- Towards N3LO PDFs (Britzger et al. 1906.05303)
- Top quark mass dependence (Davies et al. 1906.00982, Davies et al 1911.10214)
- Bottom quark fusion at N3LO (Duhr, Dulat, Mistlberger 1904.09990)
- EWK corrections (1801.10403, 1811.11211) …

# SUCCESS OF HIGGS THEORY (GLUON FUSION)

- Differential predictions advance to new revolution
  - HpT (HTL) at NNLO+N3LL accuracy (details later)
    - Robust NNLO calculation at small pT
    - Resummation in two factorisation schemes
  - yH (HTL) at N3LO accuracy (details later)
    - Two methods with approximation in good agreement
    - New revolution to differential N3LO accuracy
  - H+J (full SM) at NLO accuracy (boosted pT region)
  - Still many aspects to improve:
    - Very time consuming at small pT (~ 7M CPU h)
    - Application with decay fiducial cuts
    - Light quark interference affects shape of distribution (Caola, Lindert et al. 1804.07632)




ATLAS 1802.04146




More details in Fabrizio's talk

Jones et al. 1802.00349

# SUCCESS OF HIGGS THEORY (VECTOR BOSON FUSION)

- Differential NNLO corrections to VBF-2J production and NLO corrections to VBF-3J production using structure function approach (Cruz-Martinez et al. 1802.02445)
- Uncovered error in earlier NNLO calculation stemming from VBF-3J piece (now fixed) (Cacciari, Dreyer et al. 1506.02660) (Jager, Schissler et al. 1405.6950)

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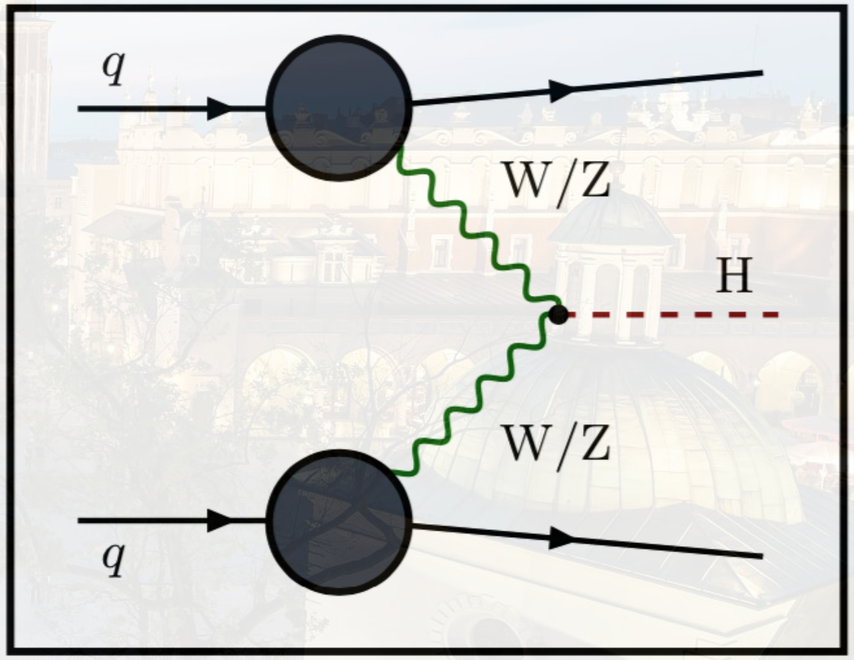


- NNLO cross section is -4% compared to NLO (VBF cuts)
- Scale variation now reduced to ± 3%
- Non-factorizable contribution estimated to be small (< 1%) (Liu, Melnikov et al. 1906.10899)
- Inclusive cross section at N3LO (Dreyer et al. 1606.00840)

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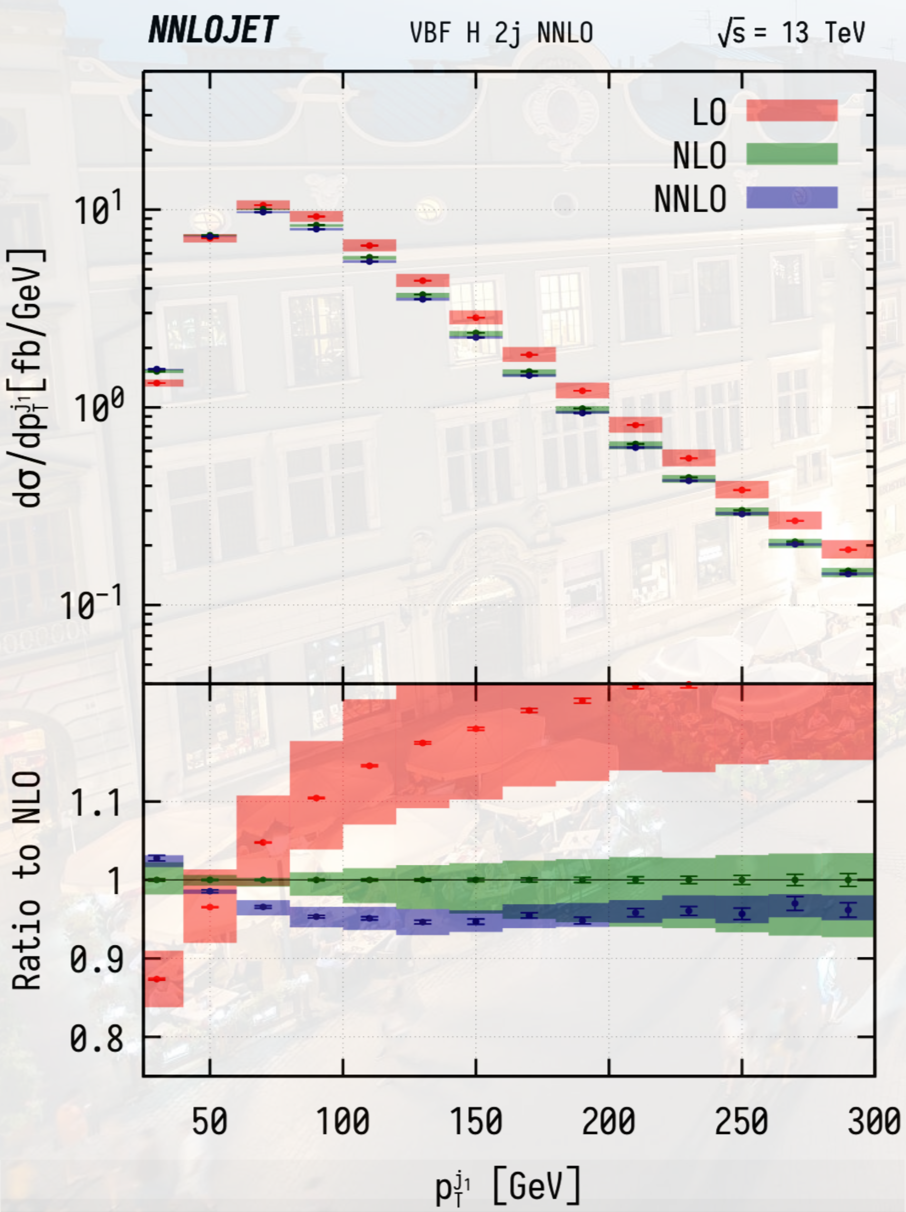


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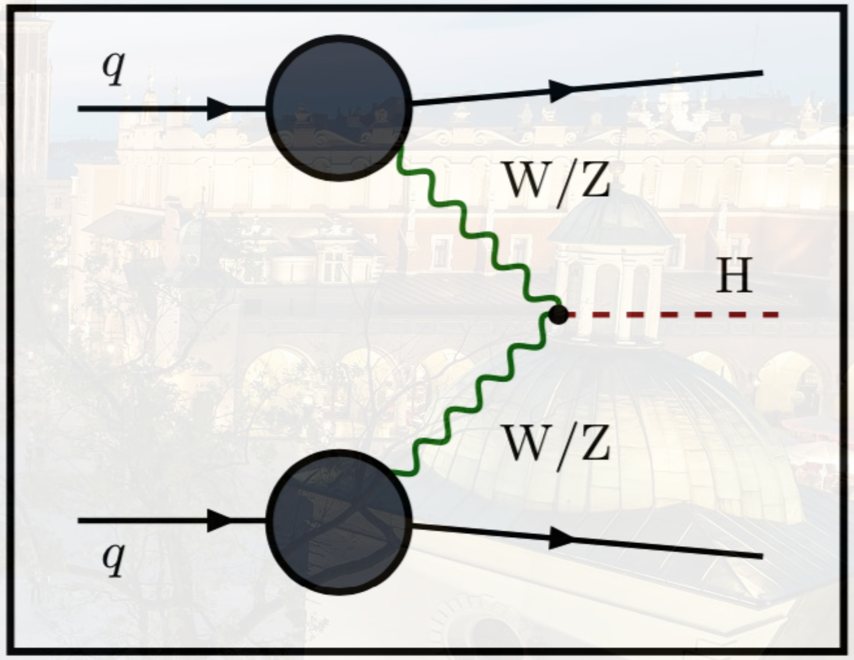


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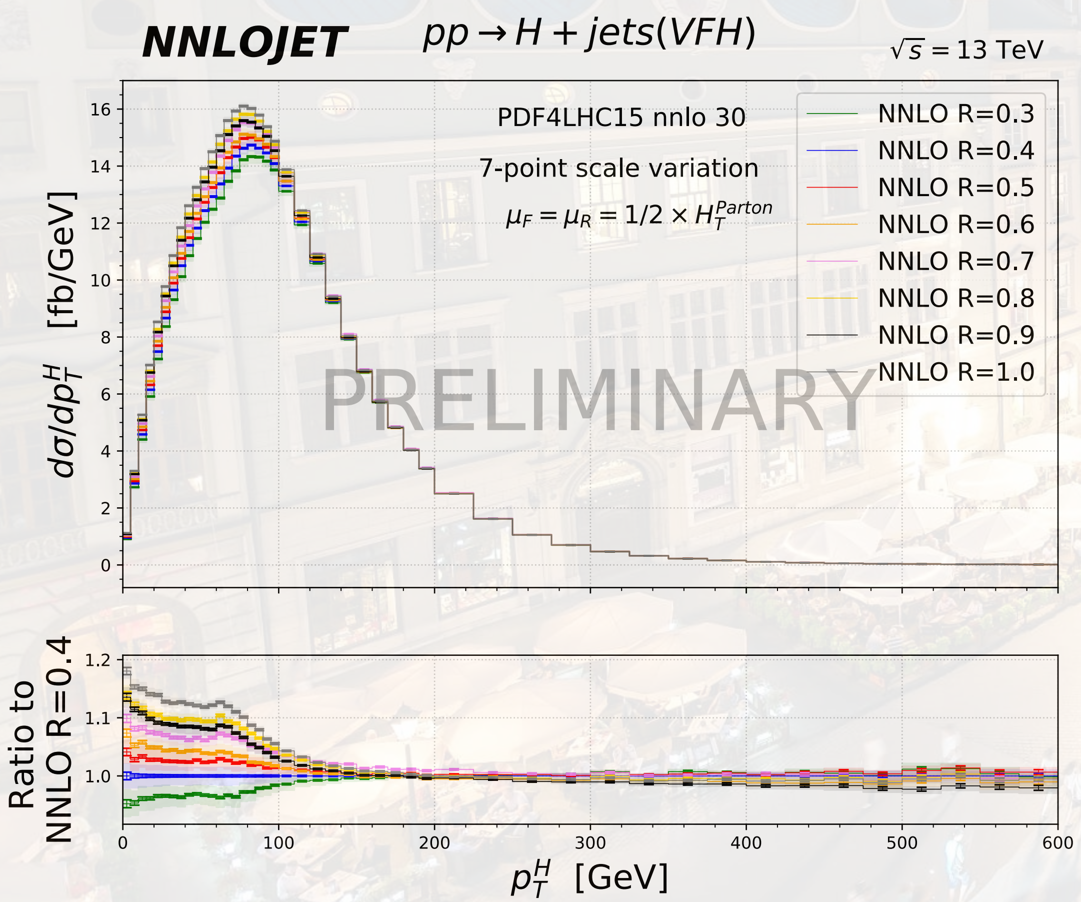


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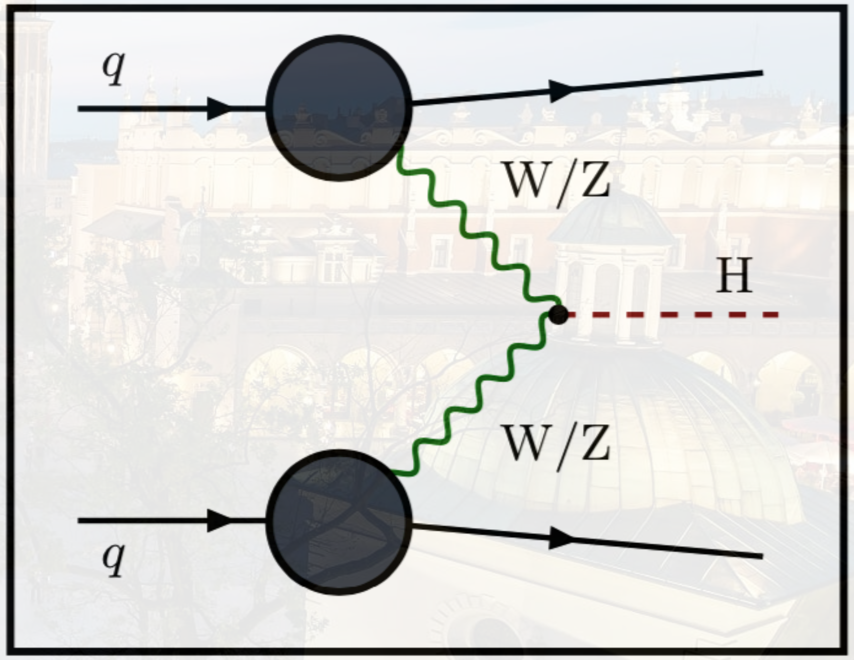


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Les Houches 19

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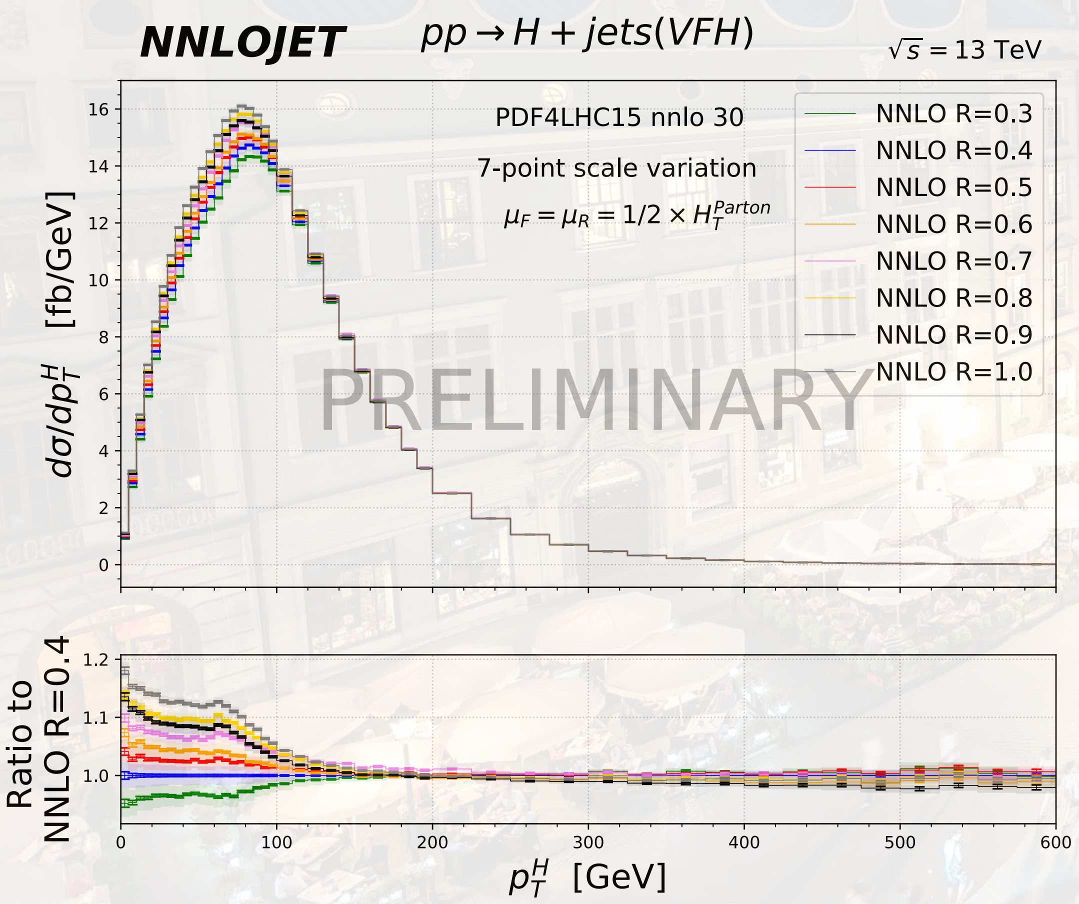


Les Houches 19

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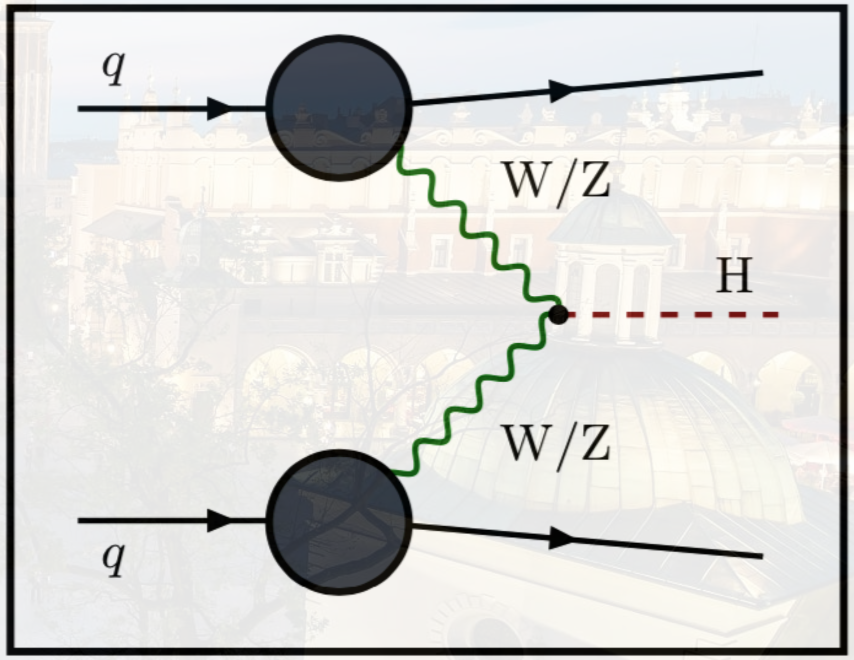


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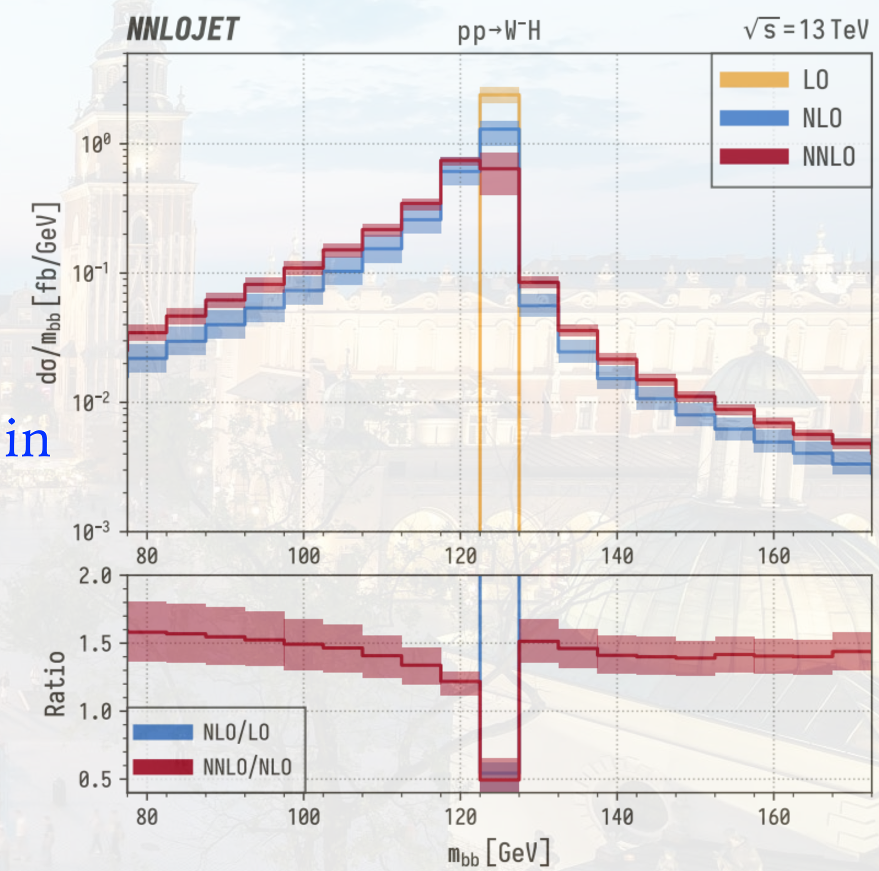
- Inclusive cross section at N3LO (Dreyer et al. 1606.00840)

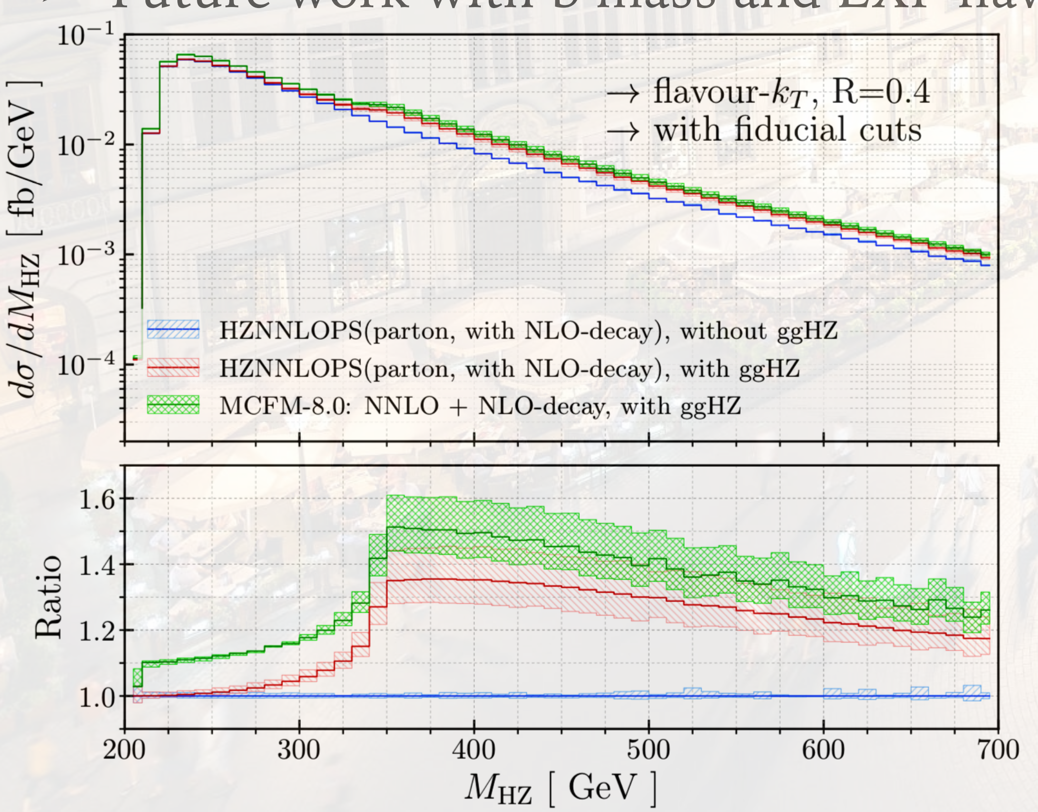
# SUCCESS OF HIGGS THEORY (VH)

- Current precision with NNLO QCD corrections in both production and decay to process $pp \to W(l\nu) + H(b\bar{b})$ with narrow width approximation and massless b quark (Ferrera et al. 1705.10304), (Caola et al. 1712.06954),(Gauld, Majer et al. 1907.05836)
  - NNLO corrects NLO $H \to b\bar{b}$ decay in both below and above Higgs mass threshold regions
  - Further including b quark mass up to NNLO (Werner et al.1805.06658), (Arnd et al. 1911.11524)
  - N3LO $H \to b\bar{b}$ decay now available (Mondini, Schiavi, Williams 1904.08960 )
  - Future work with b mass and EXP flavour kT jet

More details in Bizon's Talk



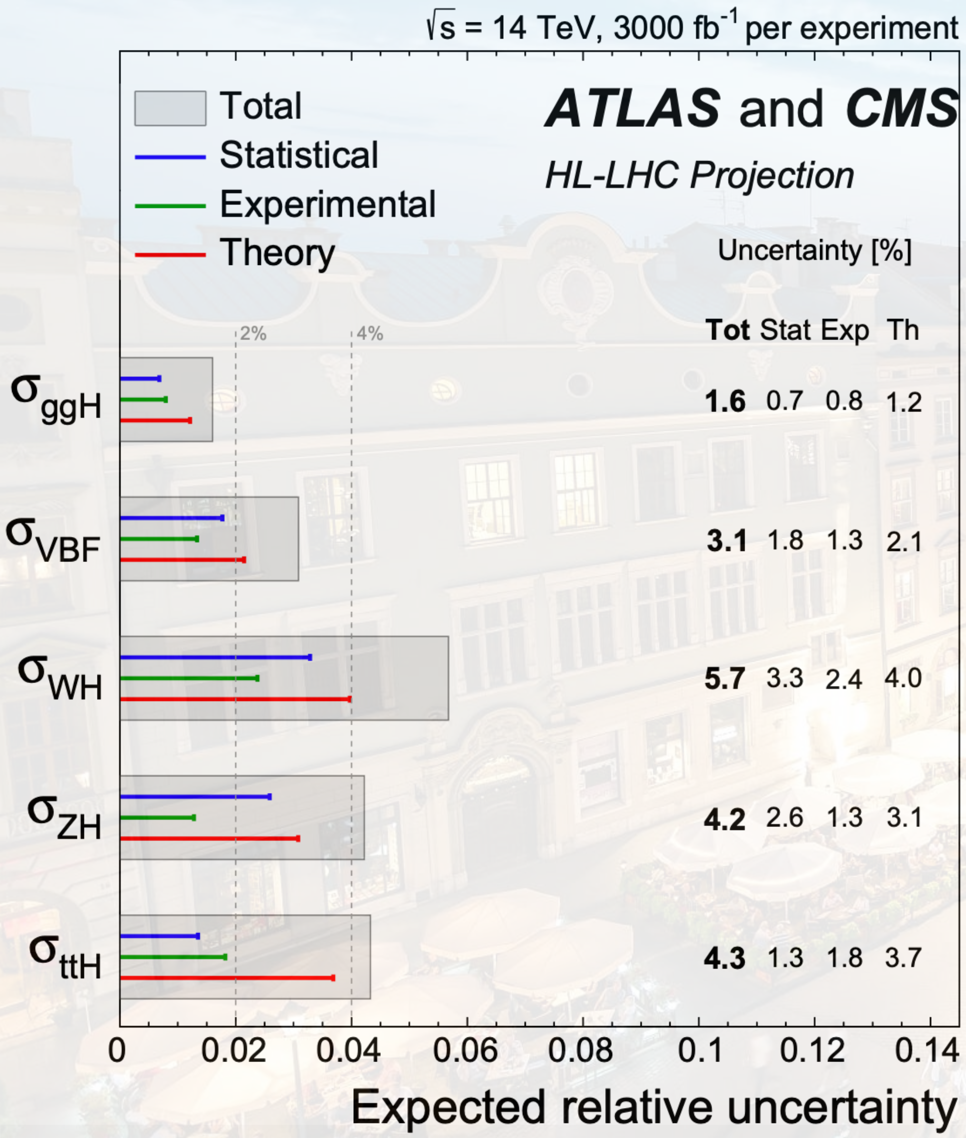

Gauld, Majer et al. 1907.05836



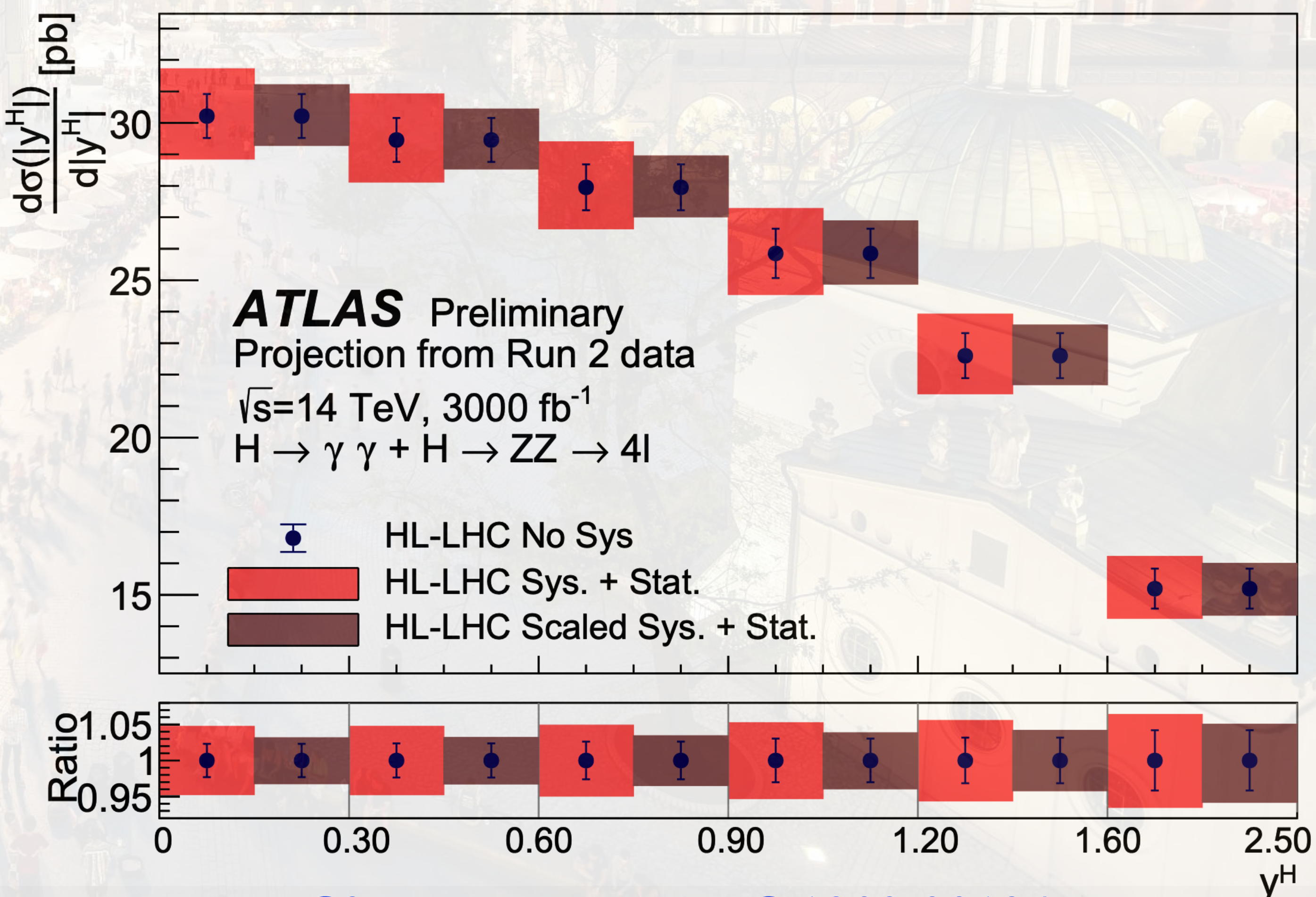

- NNLOPS accurate $pp \to Z(l^+l^-) + H(b\bar{b})$ (Astill, Bizoń et al. 1804.08141)
- Sizeable impact of loop induced $gg \to Z(l^+l^-) + H(b\bar{b})$ above top mass threshold (1-loop$^2$ at LO)
- NLO corrections includes interference with $qg$ and $q\bar{q}$ channels (need two-loop massive top for a through study)

# CHALLENGE FROM HL-LHC PROJECTION (20 YEARS)

- Is it precise enough? Not yet according to HL-LHC Projections!
  - Theory complexity scales up exponentially, EXP error scales down by $1/\sqrt{\mathscr{L}}$




- Differential observables (S2) HL-LHC projections: yH ± 3% HpT ± 5% (more details in this talk)
- Theory need consistent upgrade to reduce PDF and $\alpha_s$ uncertainties




- HL-LHC expects ± 1.6% in two decades
- Current N3LO has ± 4% for QCD alone!

WG2 report on HL-LHC 1902.00134

WG2 report on HL-LHC 1902.00134

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* NNLOJET: A multiprocess parton level event generator at O(alpha_s^3)*
*                                                              *
****************************************************************
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X. Chen, J. Cruz-Martinez, J. Currie, R. Gauld, A. Gehrmann-De Ridder, T. Gehrmann, E.W.N. Glover, M. Höfer, A. Huss, I. Majer, J. Mo, T. Morgan, J. Niehues, J. Pires, R. Schürmann, D. Walker, J. Whitehead

| LHC Higgs Production channels | | |
|---|---|---|
| $H+J$ $(ggF)$ | NNLO HTL$\otimes$ LO SM | 1408.5325, 1607,08817, 1805.00736, 1805.05916 |
| $H$ $(ggF)$ | N3LO HTL (approx.) | 1807.11501 |
| $H+JJ$ $(VBF)$ | NNLO | 1802.02445 |
| $H+V$ $(VH)$ | NNLO | 1907.05836 |

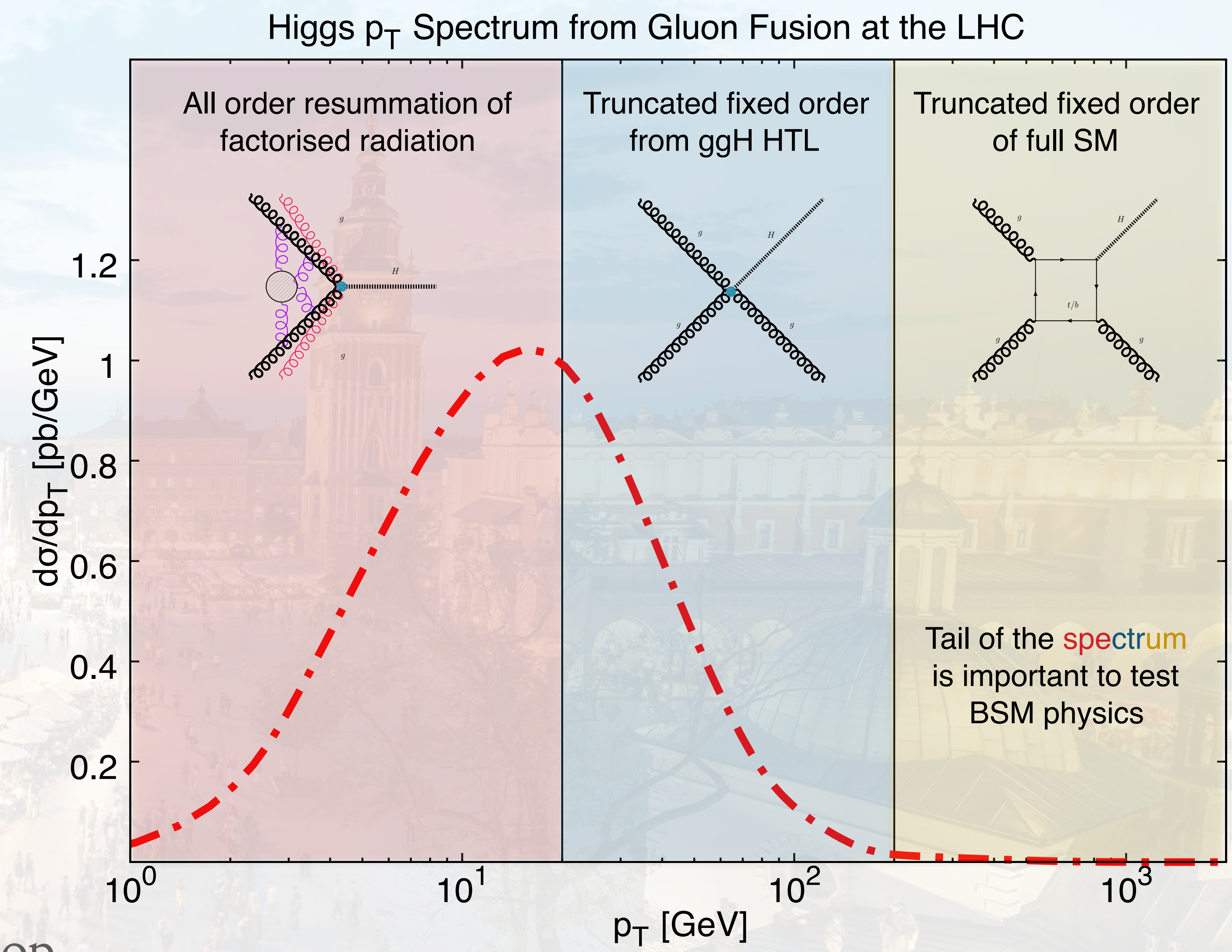
| Higgs Decay channels | | |
|---|---|---|
| $b\bar{b}$ | NNLO | b-tagging |
| $WW^* \to 2l2\nu$ | LO | Lepton isolation |
| $\tau^+\tau^-$ | LO | Massive final states |
| $ZZ^* \to 4l$ | LO | Lepton isolation |
| $\gamma\gamma$ | LO | Photon isolation |
| $Z(\to 2l)\gamma$ | LO | Photon + lepton iso. |

- Parton level event generator with NNLO antenna subtraction method
- NNLOJET provides many cutting-edge predictions of the Higgs boson phenomenology.
- ggF, VBF and VH channels are linked with various decay channels.
- Identification of EW and QCD final states using EXP algorithms.

# HIGGS TRANSVERSE MOMENTUM DISTRIBUTION IN FULL SPECTRUM

# HIGGS TRANSVERSE MOMENTUM SPECTRUM

- Higgs pT spectrum tests SM in various aspects
- Small pT region (< 20 GeV):
  - Singular log terms spoil any reliable fixed order predictions $\ln^k(m_H^2/p_T^2)/p_T^2$
  - Resummation of log terms and match to fixed order: $d\sigma^{FO} \ominus d\sigma^{S} \oplus d\sigma^{R}$
- Medium pT region (20 ~ 200 GeV):
  - Reliable with heavy top limit (HTL)
  - Current best precision is H+J NNLO HTL
- Boosted pT region (> 200 GeV)
  - Energy scale resolve mass effect of quark loop
  - Best ggF precision is H+J at NLO SM
  - VBF, VH and ttH channels equally important
- Many other effects involved: top-bottom interference, heavy quark Yukawa couplings, resummation of logs involving quark mass etc.



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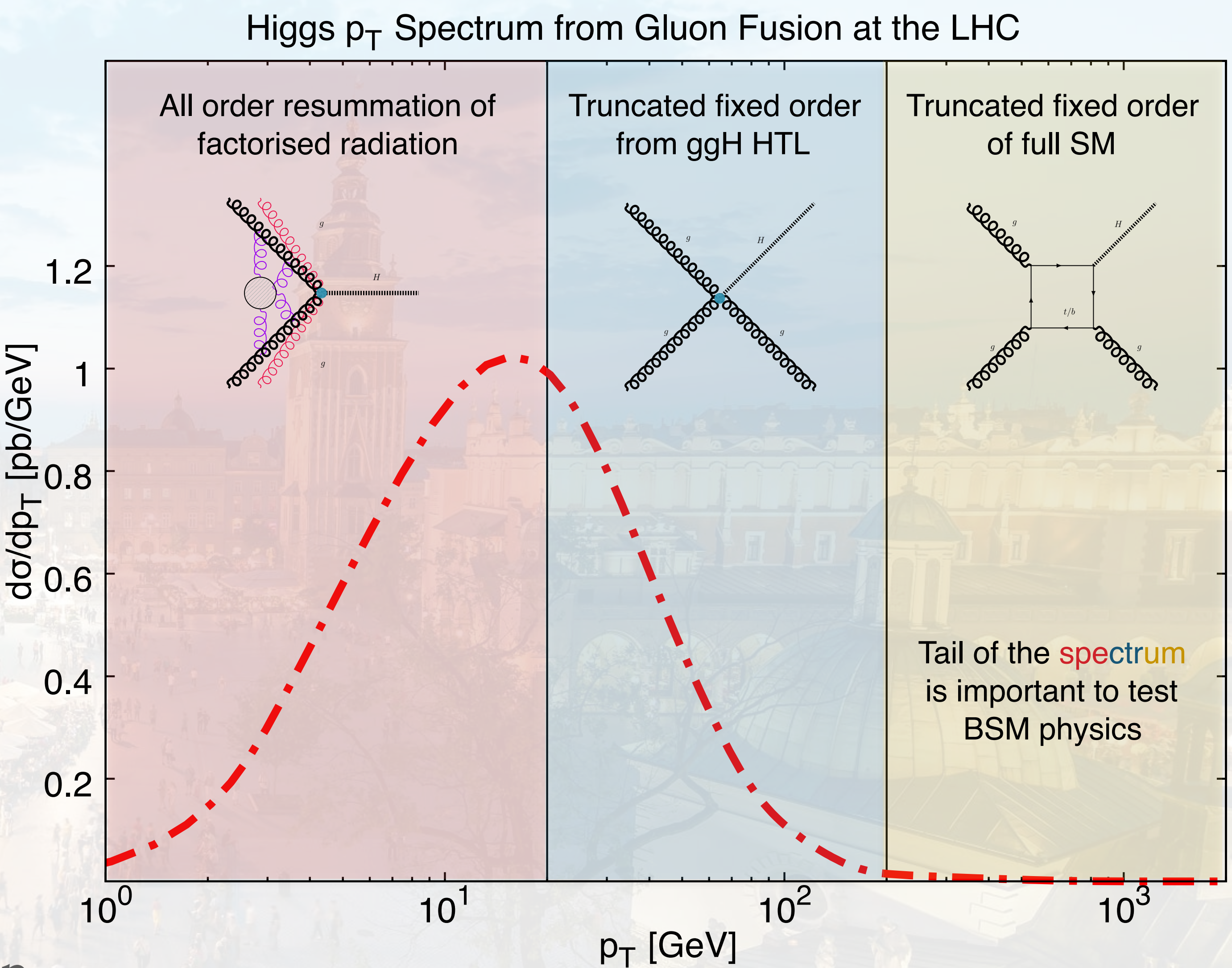
- Small pT region (< 20 GeV):
  - Singular log terms spoil any reliable fixed order predictions $\ln^k(m_H^2/p_T^2)/p_T^2$
  - Resummation of log terms and match to fixed order: $d\sigma^{FO} \ominus d\sigma^{S} \oplus d\sigma^{R}$
- Medium pT region (20 ~ 200 GeV):
  - Reliable with heavy top limit (HTL)
  - Current best precision is H+J NNLO HTL
- Boosted pT region (> 200 GeV)
  - Energy scale resolve mass effect of quark loop
  - Best ggF precision is H+J at NLO SM
  - VBF, VH and ttH channels equally important
- **Many other effects involved**: top-bottom interference, heavy quark Yukawa couplings, resummation of logs involving quark mass etc.




Will separately discuss the pheno in each HpT region next

# HIGGS TRANSVERSE MOMENTUM AT MEDIUM PT

- H+J Computed at NNLO QCD (HTL) by 4 groups using 3 methods
  - Antenna subtraction (NNLOJET) XC, Gehrmann, Glover et al. (1408.5325, 1607.08817)
  - Sector improved subtraction (STRIPPER) Boughezal, Caola et al. (1302.6216, 1504.07922)
  - N-Jettiness (BFGLP and MCFM) Boughezal, Focke et al. (1505.03893) Campbell et al. (1906.01020)

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- It was the battle ground for the first LHC process with single jet + colourless @ NNLO
  - Long-standing discrepancy between N-Jettiness and other methods

| | $\sigma^{EFT}_{H(\to\gamma\gamma)+\geq 1jet,\mathrm{NNLO}}$ | $\sigma^{EFT}_{H+\geq 1jet,\mathrm{NNLO}}$ | $\sigma^{EFT}_{H+\geq 1jet,\mathrm{NNLO}}$ |
|---|---|---|---|
| **NNLOJET** | $9.44^{+0.59}_{-0.85}$ fb | $16.8^{+0.9}_{-1.5}$ pb | $5.81^{+0.51}_{-0.62}$ pb |
| **STRIPPER** | $9.45^{+0.58}_{-0.82}$ fb | - | - |
| **STRIPPER** | - | $16.7^{+1.0}_{--}$ pb | - |
| **BFGLP** | - | - | $5.5^{+0.3}_{-0.4}$ pb |

XC, Gehrmann, Glover et al. (1408.5325, 1607.08817)

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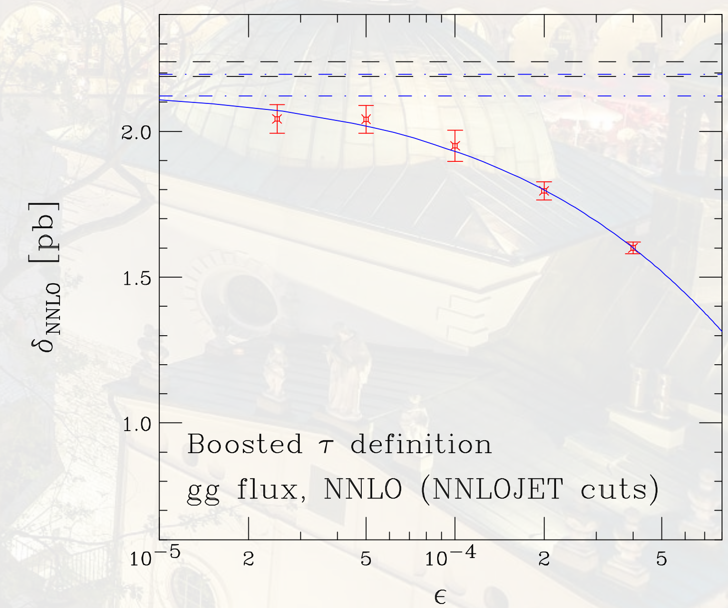


  - Finally resolved with MCFM revisit study last year
    - Jettiness cut 20 times smaller than in BFGLP
    - Extrapolate to zero (~5% @ NNLO)
    - Desire sub-leading power correction at NNLO

$$\sigma_{NNLO}(\mathrm{NNLOJET}) = 16.73 \pm 0.05\,^{+1.00}_{-1.51}\,\mathrm{pb}$$
$$\sigma_{NNLO}(\mathrm{MCFM, fit}) = 16.71 \pm 0.05\,^{+1.03}_{-1.52}\,\mathrm{pb}$$

Campbell et al. (1906.01020)

# HIGGS TRANSVERSE MOMENTUM AT SMALL PT

- FO break down, where is the problem come from?
  - Take $d\sigma^H_{NLO}$ as example:

$$A^0_{2gH}(\hat{g},\hat{g},H) + A^0_{3gH}(\hat{g},\hat{g},g,H) - F^0_3(\hat{g},g,\hat{g})A^0_{2gH}(\tilde{\hat{g}},\tilde{\hat{g}},\tilde{H}) + A^1_{2gH}(\hat{g},\hat{g},H) + \mathcal{F}^0_3(\hat{g},\hat{g})A^0_{2gH}(\tilde{\hat{g}},\tilde{\hat{g}},\tilde{H})$$

$\delta(p^H_T)$    $p^H_T$    $\delta(p^H_T)$    $\delta(p^H_T)$    $\delta(p^H_T)$

  - Finite $p^H_T$ region has no IR regulator $\longrightarrow$ fixed order predictions break down
- How to make reliable predictions of $d\sigma/dp^H_T$ at 1 GeV?
  - Use QCD factorisation to distinguish radiations from Born kinematics.

$$d\sigma = \sigma_{LO} \otimes H \otimes B \otimes B \otimes S \otimes J$$

  - Replace IR subtraction by IR renormalisation (IR poles removed).
  - Find and solve RGE of factorised functions to include all order effects.

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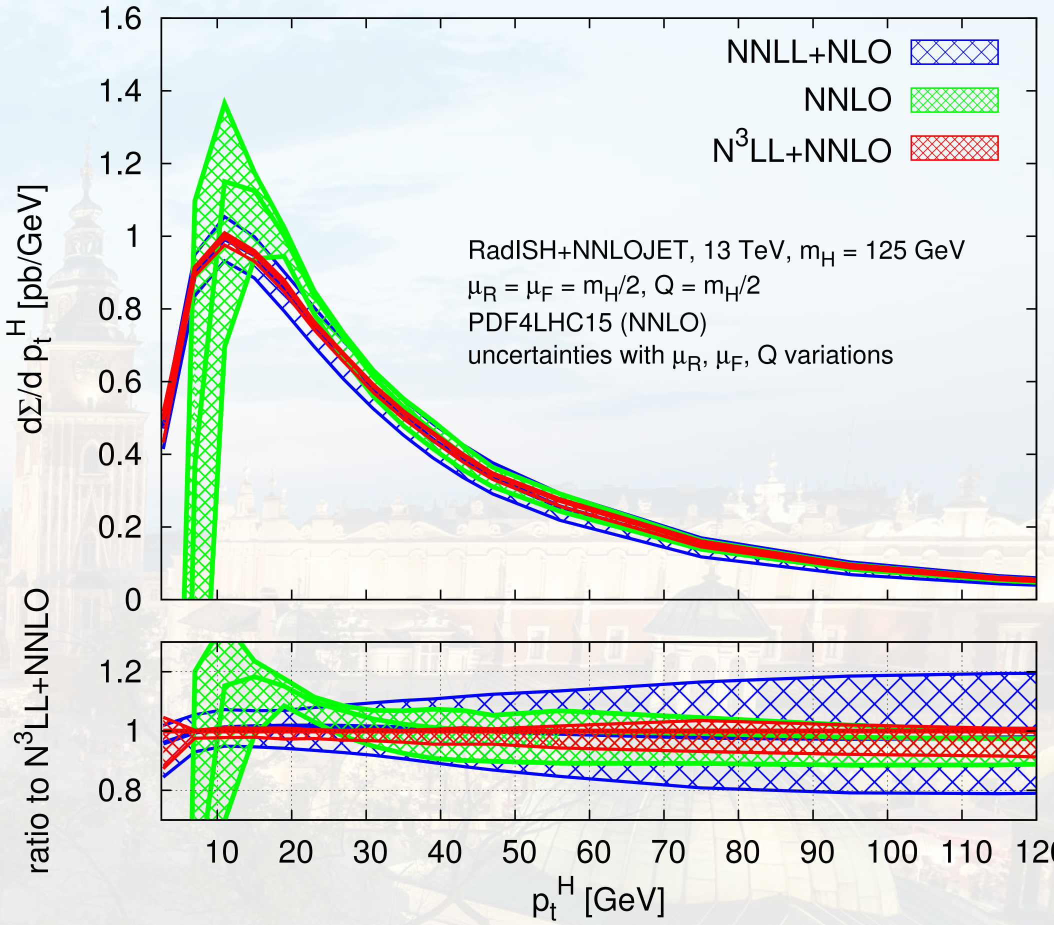
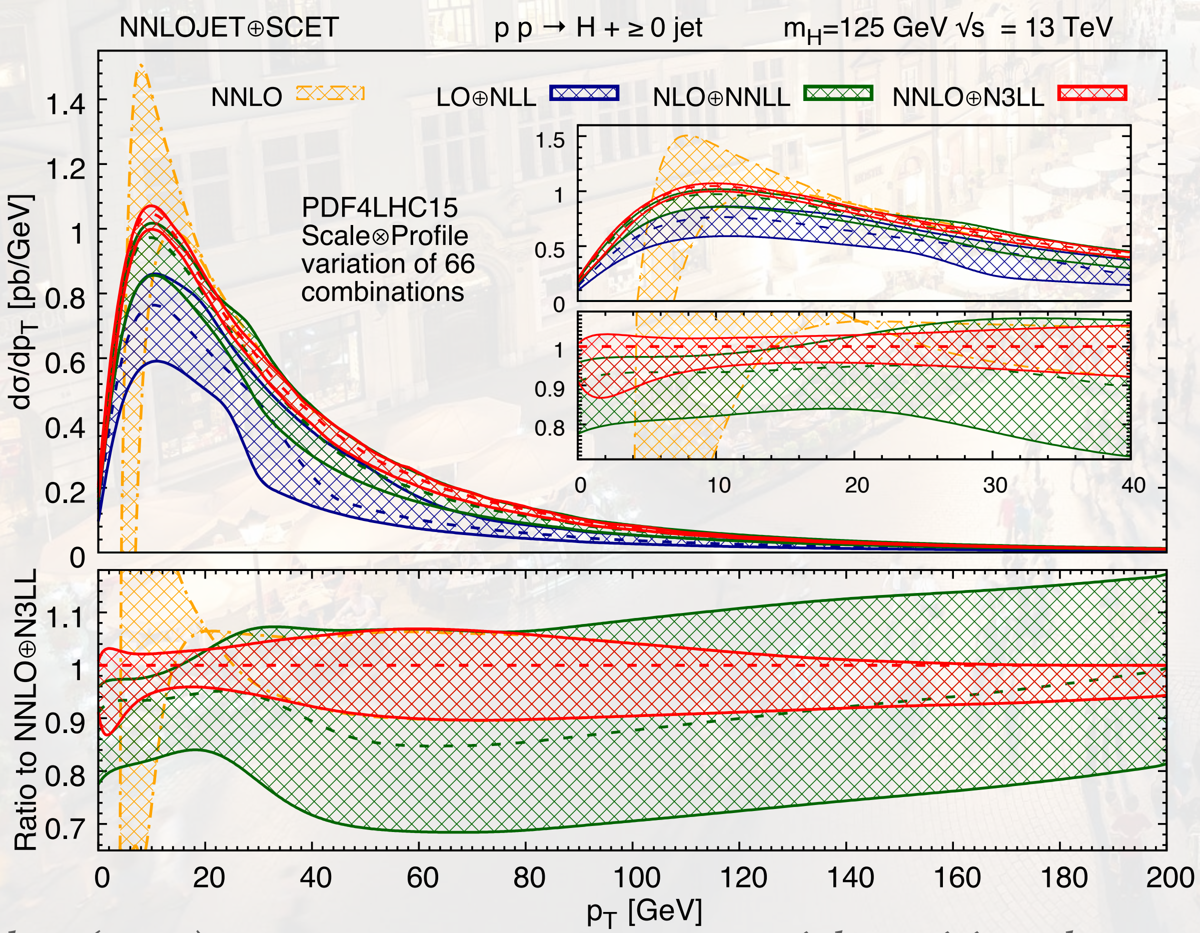
# HIGGS TRANSVERSE MOMENTUM SPECTRUM (SMALL+MEDIUM)

- NNLO + N3LL Resummation with SCET and RadISH
  - RadISH + NNLOJET at N3LL + NNLO
  - Multiplicative matching to NNLO total X.S.
  - Substantial regulation from NNLO+N3LL at the peak of spectrum
  - Scale variation reduced by 60% from NLO+NNLL to NNLO+N3LL

RadISH+NNLOJET 1805.05916



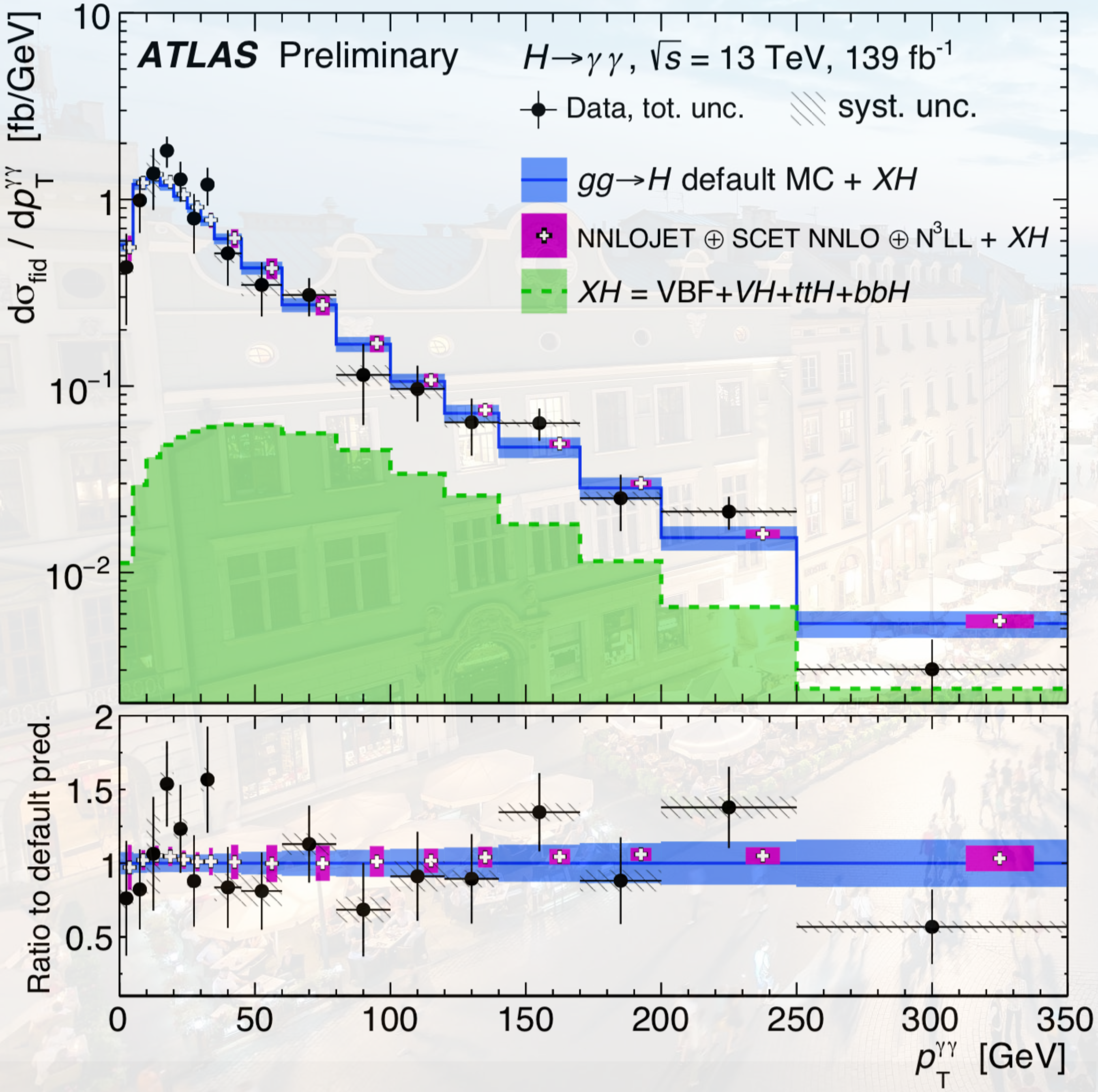

SCET+NNLOJET 1805.00736



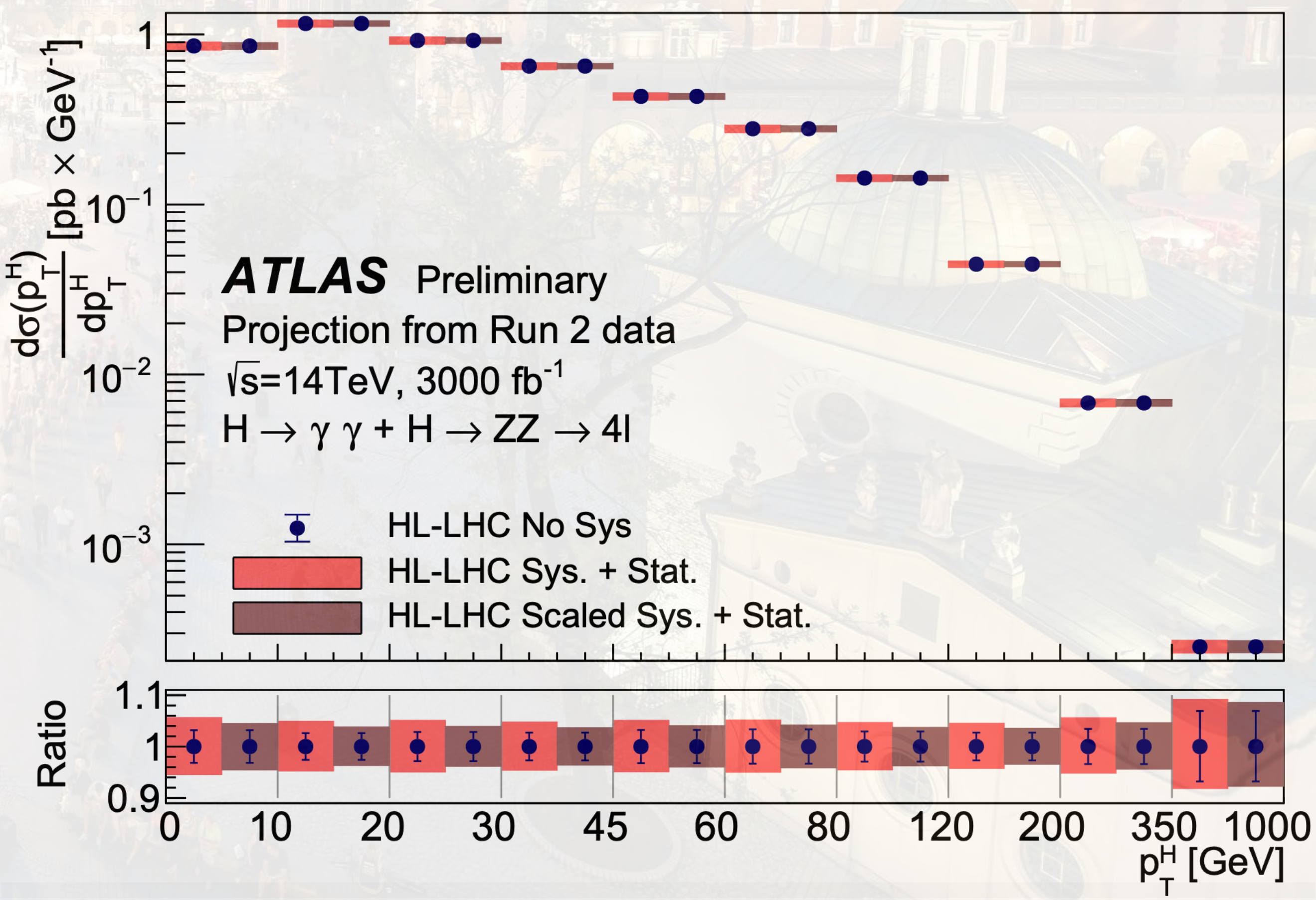

- SCET + NNLOJET at N3LL + NNLO
- Additive matching using profile functions
- Conservative uncertainty estimation involving 11 scale variation choices times 6 profile functions
- Noticeable deviation between NNLO and NNLO+N3LL starting from 30 GeV
- Future extension to include $m_t$ and $m_b$ effect

# HIGGS TRANSVERSE MOMENTUM SPECTRUM (SMALL+MEDIUM)

- ➤ Comparison with LHC data and HL-LHC projection



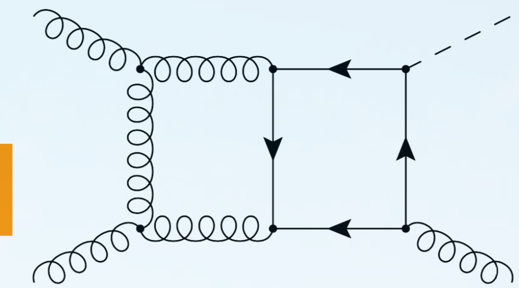

- ➤ SCET + NNLOJET at N3LL + NNLO
- ➤ Consistent with LHC full Run II data
- ➤ EXP uncertainty ± 40%, TH uncertainty ± 8%
- ➤ Close to HL-LHC projection uncertainty ± 5%(S2)




ATLAS-CONF-2019-029

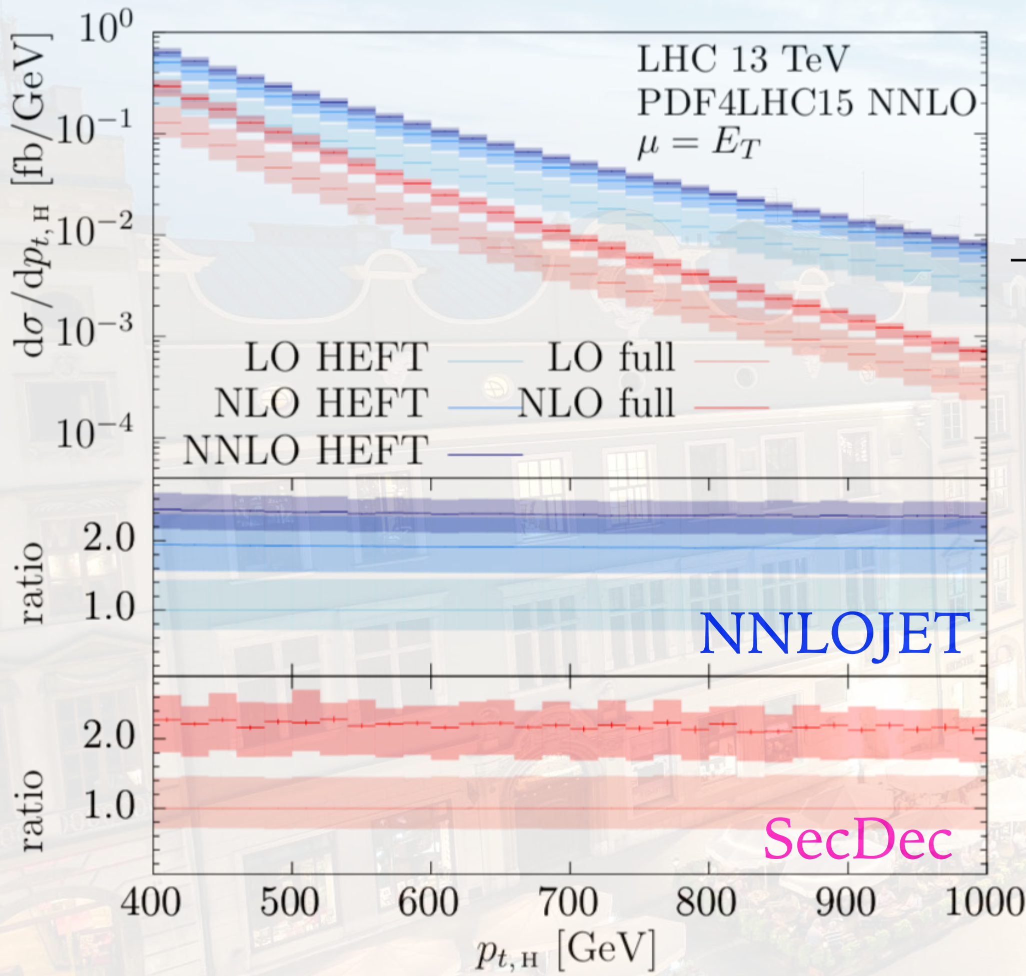
WG2 report on HL-LHC 1902.00134

# HIGGS TRANSVERSE MOMENTUM AT BOOSTED REGION



- Extension to NNLO HTL/NLO SM combined distributions in boosted region: Rescale NLO SM by $K^{HTL}_{NNLO}$ with the assumption of similar SM/HTL K-factors

Jones, Kerner, Luisoni (1802.00349)




$$\Sigma^{\text{EFT-improved (1), NNLO}}(p_\perp^{\text{cut}}) = \frac{\Sigma^{\text{QCD, NLO}}(p_\perp^{\text{cut}})}{\Sigma^{\text{EFT, NLO}}(p_\perp^{\text{cut}})}\,\Sigma^{\text{EFT, NNLO}}(p_\perp^{\text{cut}})$$

| $p_T^{\text{cut}}$ | $\text{NNLO}^{\text{approximate}}_{\text{quad.unc.}}$ [fb] | HJ-MINLO [fb] | MG5_MC@NLO [fb] |
|---|---|---|---|
| 400 GeV | $33.3^{+10.9\%}_{-12.9\%}$ | $29^{+24\%}_{-21\%}$ | $31.5^{+31\%}_{-25\%}$ |
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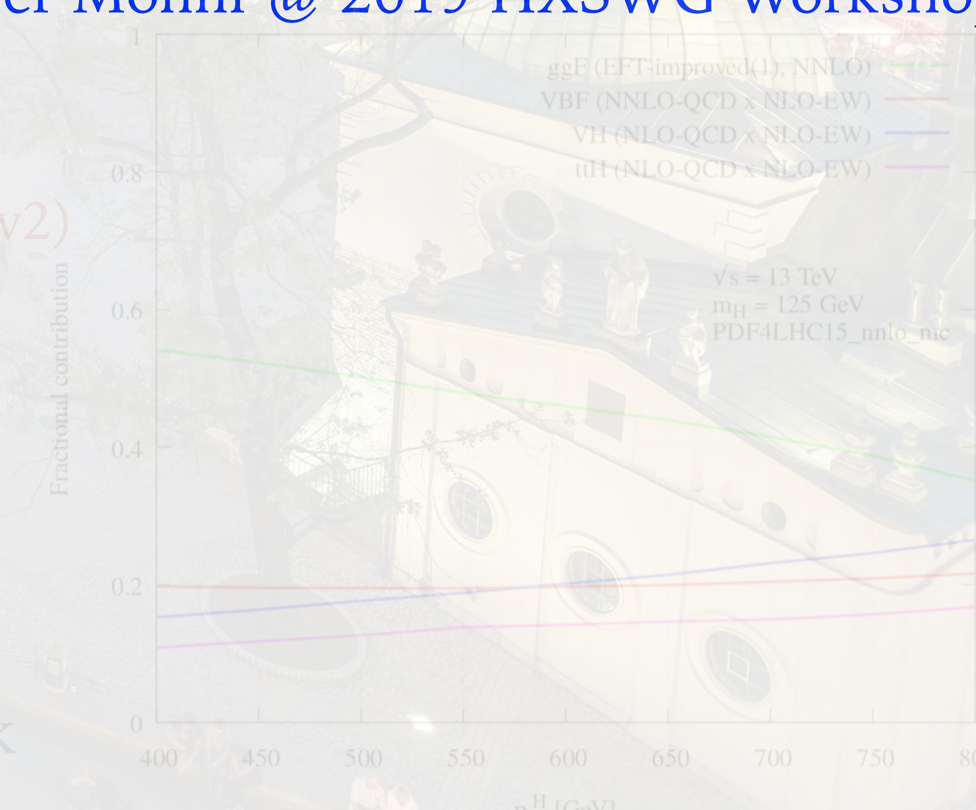
Pier Monni @ 2019 HXSWG Workshop

Coming soon in the LHCHXSWG-2019-002(v2)

- Considerable contribution from VH, VBF and ttH
- Need state-of-the-art precision from all channels
- Sensitive to BSM models ~ new generation of quark



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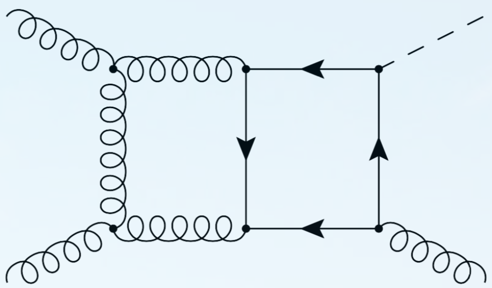

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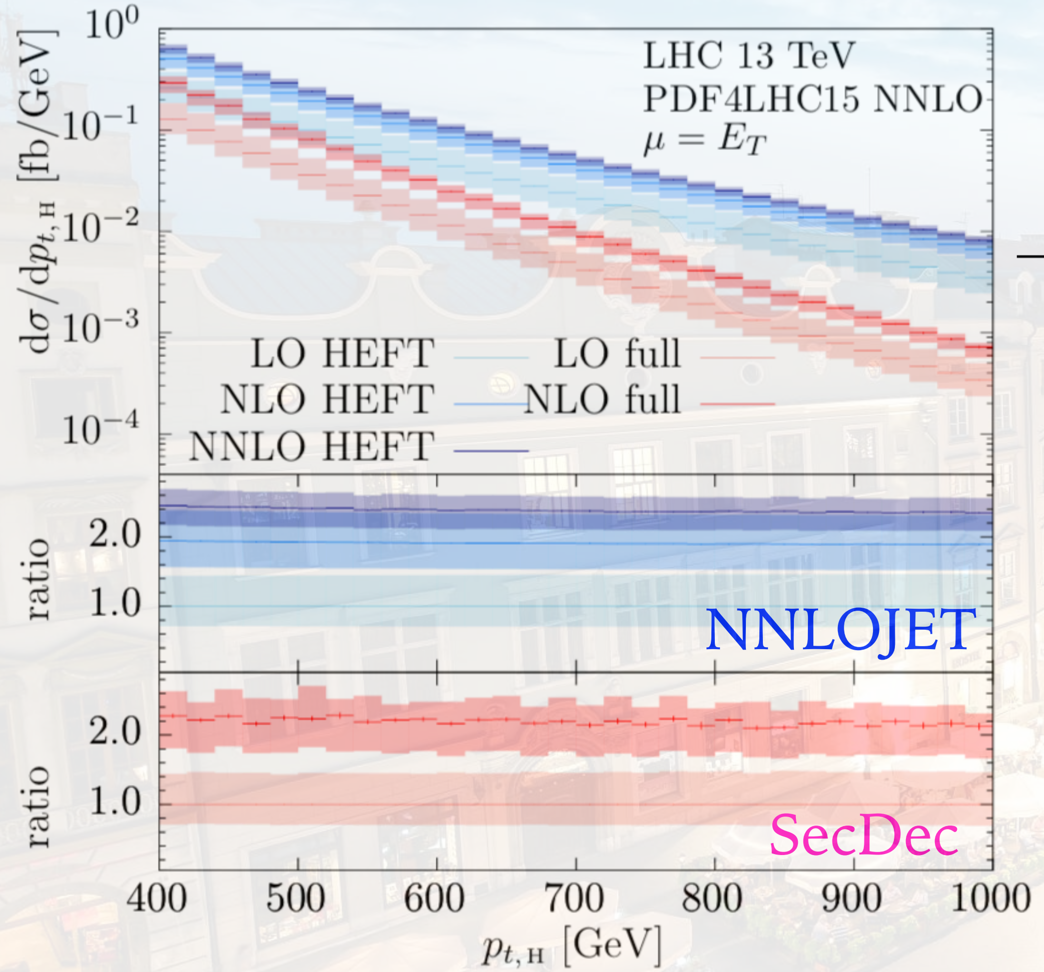


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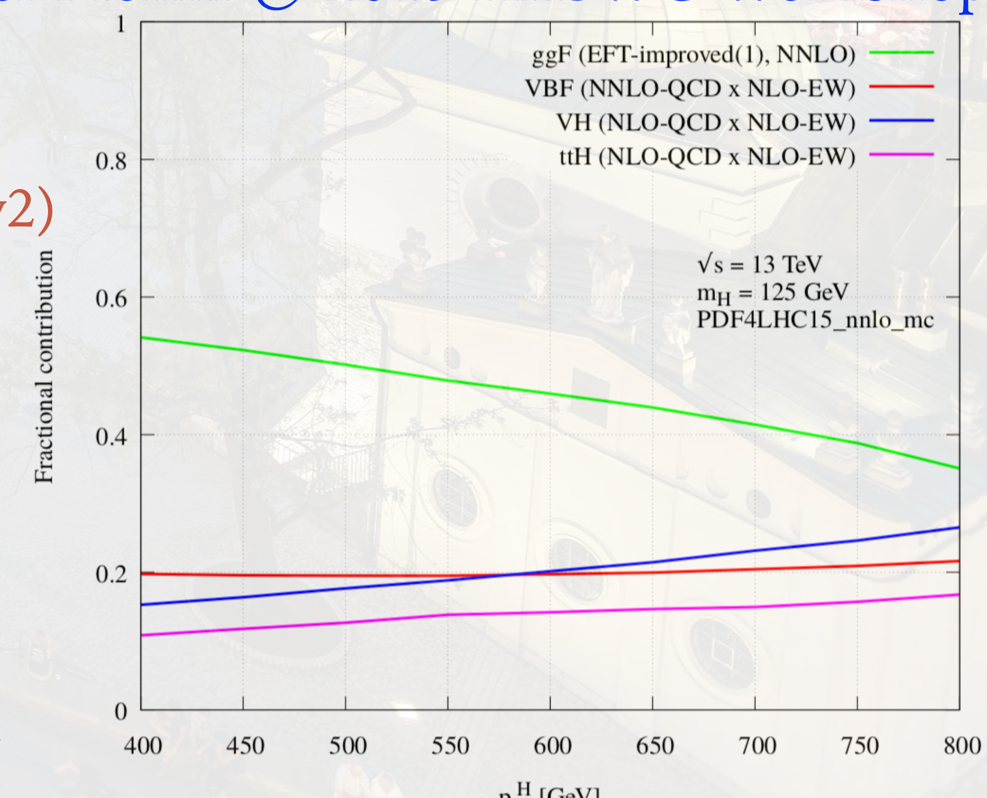


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# HIGGS RAPIDITY DISTRIBUTION AT N3LO

# HIGGS PRODUCTION AT N3LO (APPROXIMATED)

- Extend qT-subtraction method to N3LO (Cieri, XC et al. 1807.11501).
  In qT (CSS) factorisation to Higgs production at N3LO:

$$\frac{d\sigma}{dp_T^2 dy} = \frac{m_H^2}{s}\sigma^H_{LO}\int_0^{+\infty} db \frac{b}{2} J_0(bp_T) S_g(m_H, b) \sum_{a_1,a_2}\int_{x_1}^1 \frac{dz_1}{z_1}\int_{x_2}^1 \frac{dz_2}{z_2}\left[HC_1C_2\right]_{gg:a_1a_2}\prod_{i=1,2} f_{a_i/h_i}(x_i/z_i, b_0^2/b^2)$$

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

- Apply $q_T^{cut}$ to factorise full N3LO into two parts.

$$d\sigma^H_{N^3LO} = \mathcal{H}^H_{N^3LO} \otimes d\sigma^H_{LO}\Big|_{\delta(p_T)} + \left[d\sigma^{H+jet}_{NNLO} - d\sigma^{H\,CT}_{N^3LO}\right]_{p_T > q_T^{cut}}$$

- Above $q_T^{cut}$, recycle H+jet at NNLO from NNLOJET with qT counter terms (CT) to regulate IR divergence.
- Below $q_T^{cut}$, factorise real radiations from hard coefficient functions at $\delta(p_T)$ in HN3LO package.
- Most of the factorised components of $\delta(p_T)$ contribution are known analytically at N3LO.
- We use a constant $C_{N3}\delta_{ga}\delta_{gb}(1-z)$ to approximate the unknown pieces.
- Numerically abstract the $C_{N3}$ coefficient using exact N3LO total cross section (1802.00833, 1802.00827).

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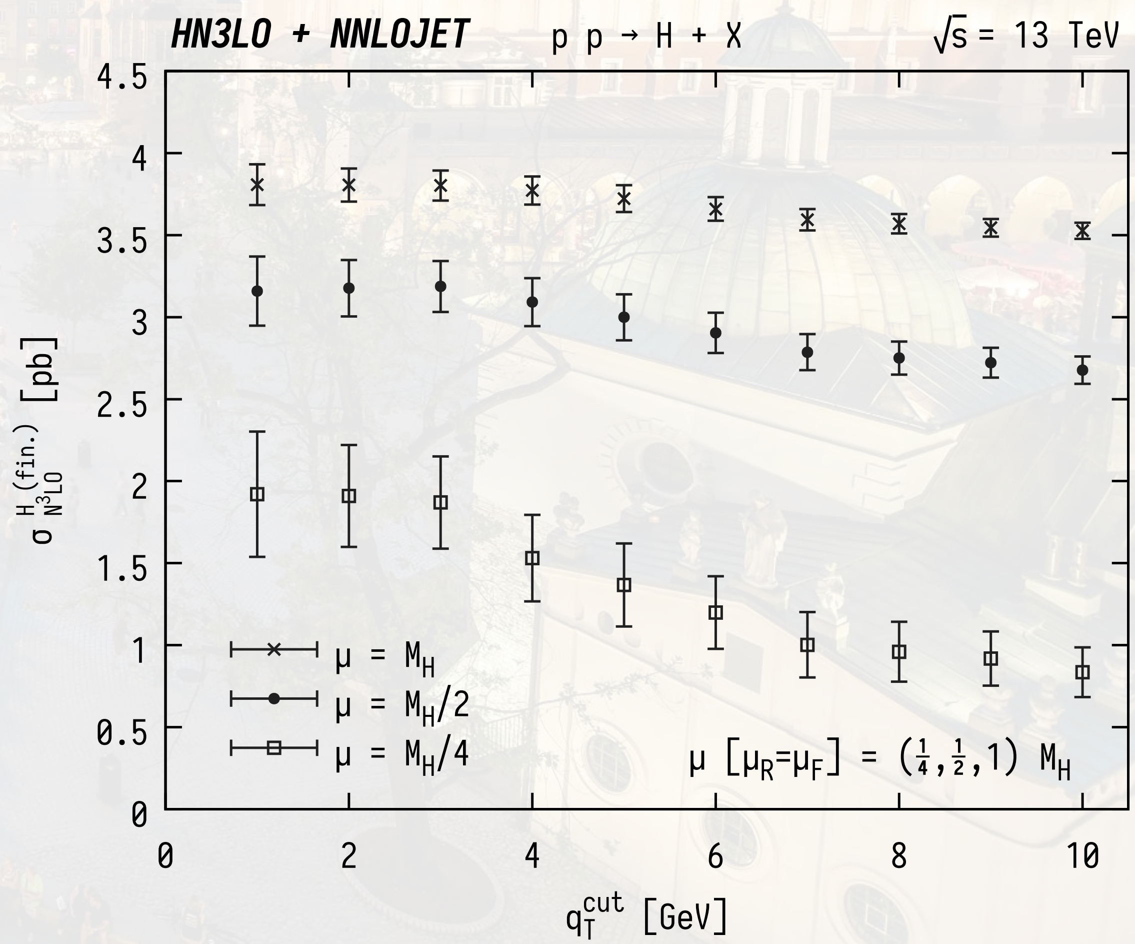


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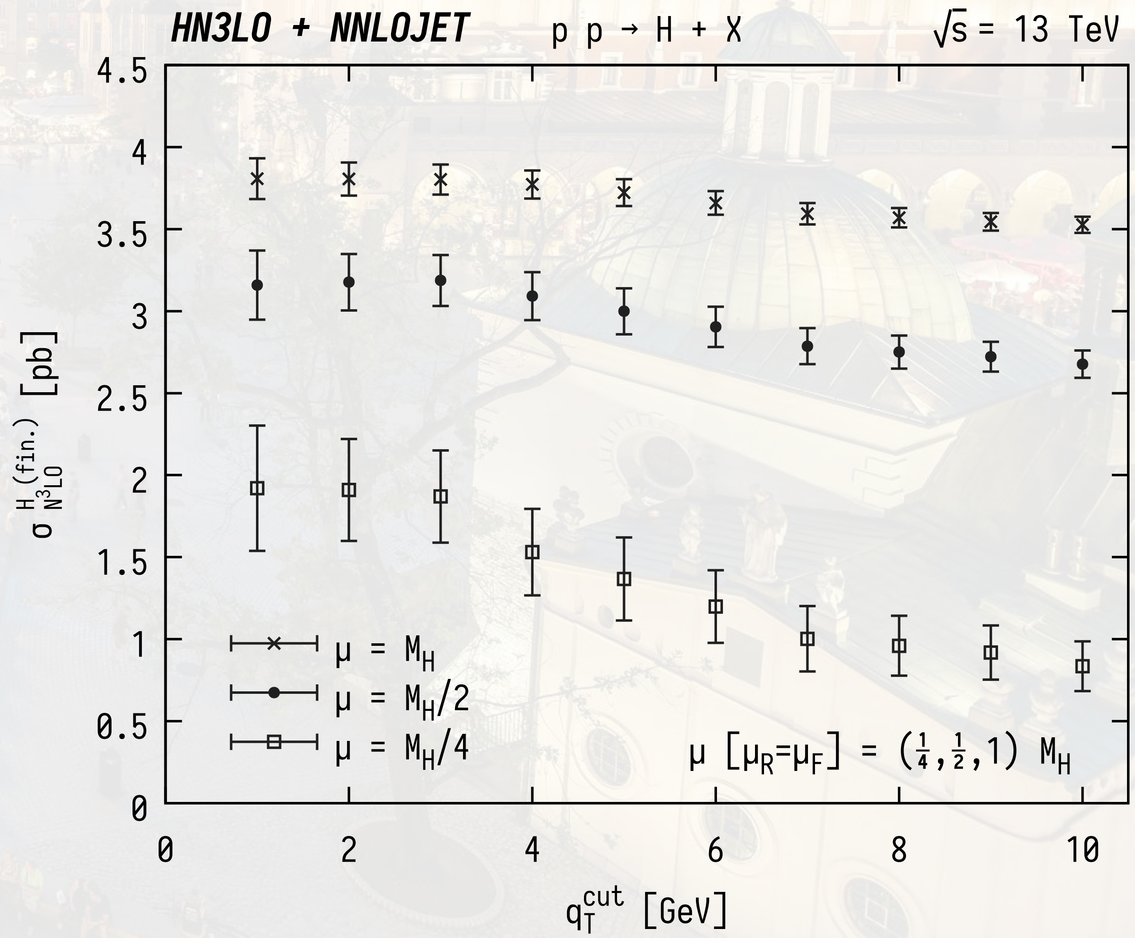


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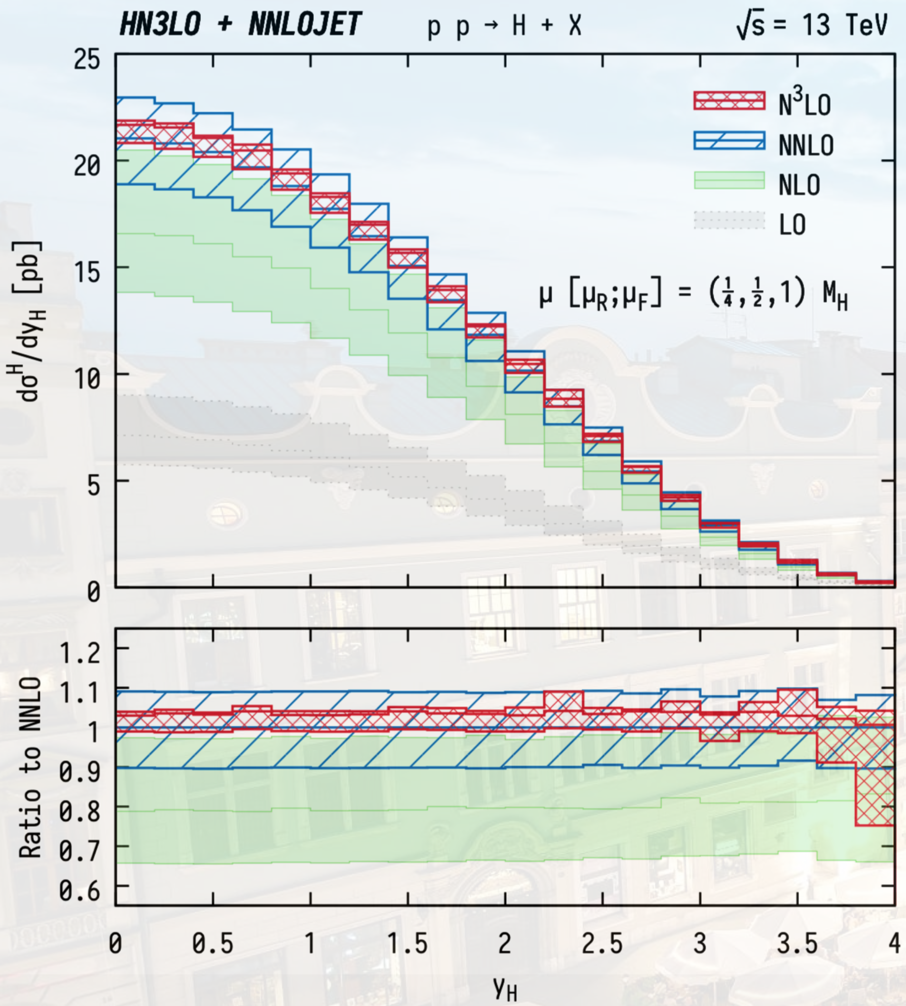
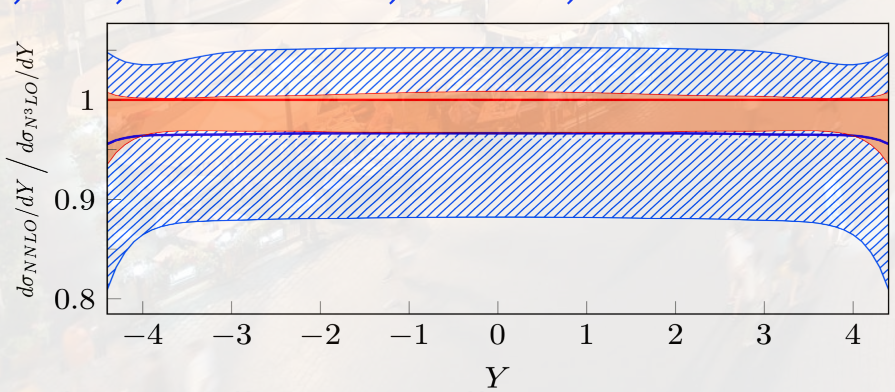
# HIGGS RAPIDITY DISTRIBUTIONS AT N3LO (APPROXIMATED)

- N3LO differential observables at the LHC from qT-subtraction and threshold expansion

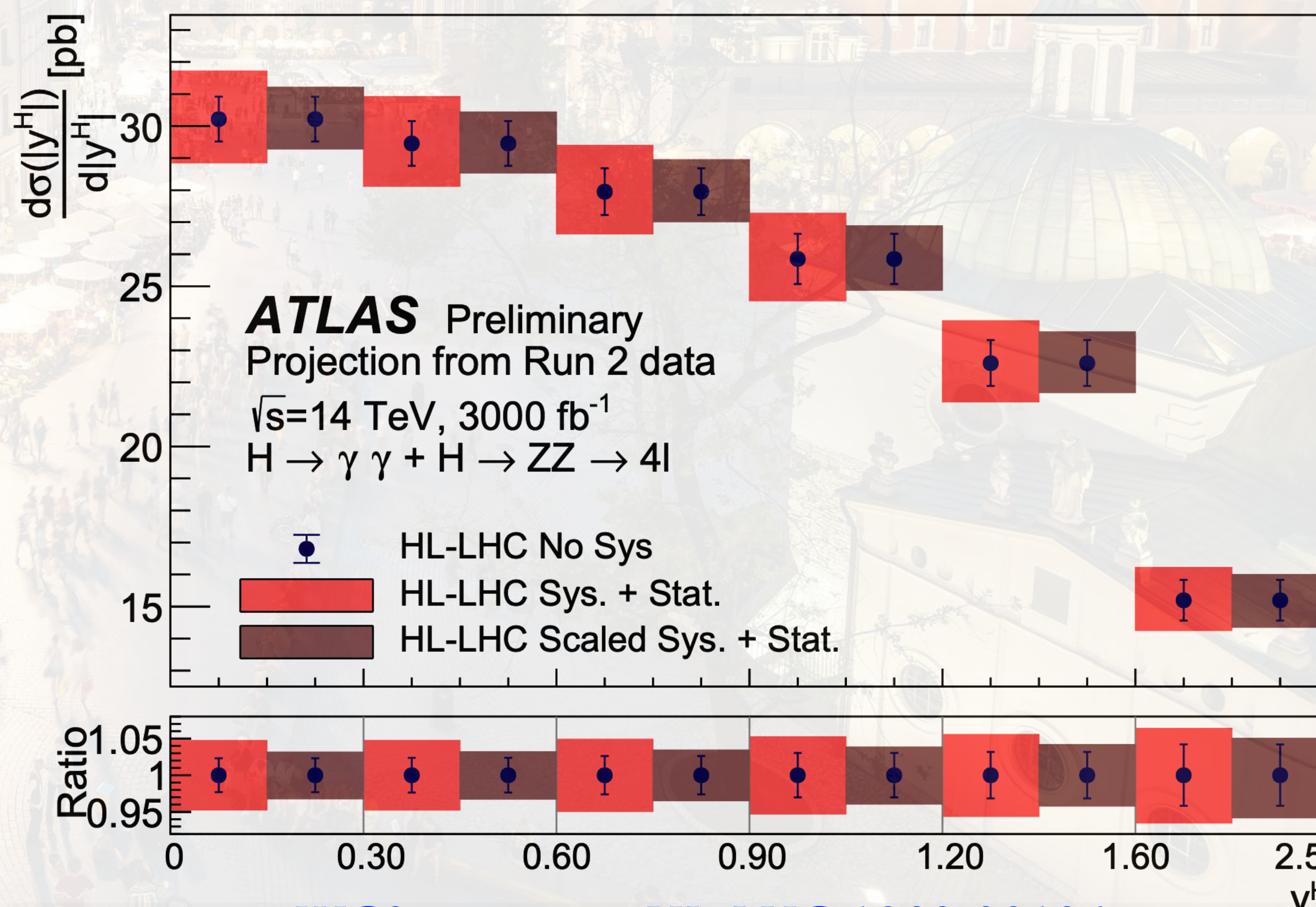



Cieri, XC, Gehrmann, Glover, Huss 1807.11501




Dulat, Mistlberger, Pelloni 1810.09462

- Remarkably flat K-factor (as expected)
- QCD scale uncertainty reduced to $^{+1\%}_{-3\%}$
- Comparable to (S2) HL-LHC projections ± 3%
- Future upgrade to reduce PDF and $\alpha_s$ uncertainties

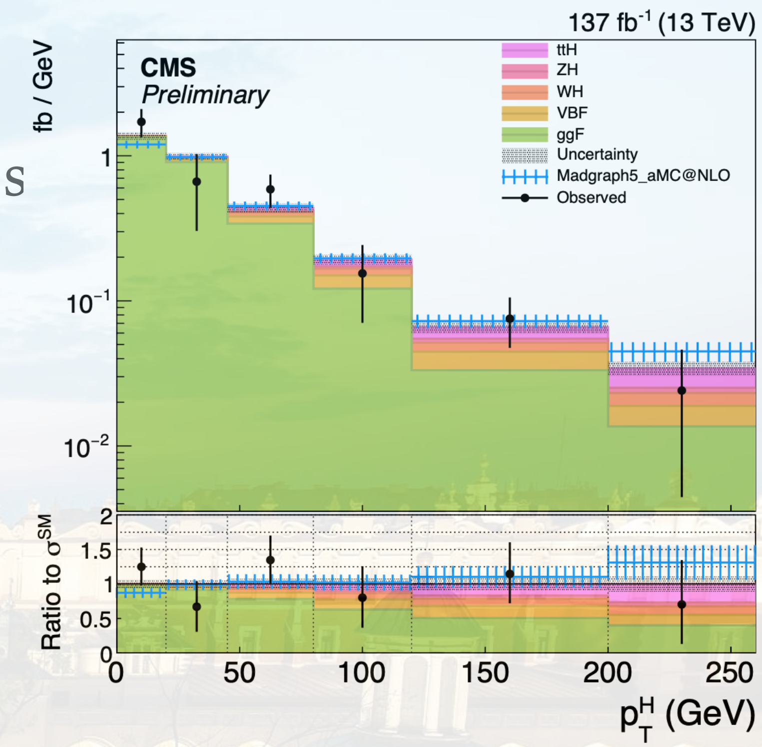



WG2 report on HL-LHC 1902.00134

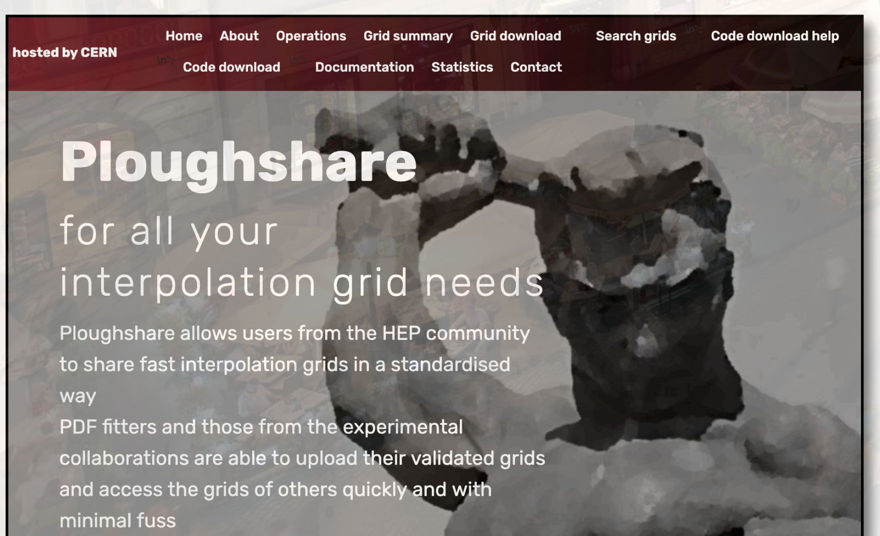
# FUTURE WORK

- Precision Higgs phenomenology
  - Compare and combine various production and decay channels
  - Top mass effects at large pT region (PbP, full SM at RR)
- High precision prediction in general
  - Provide NNLO grids for PDF fitting (APLLfast)
  - Make NNLOJET public (Yes it will happen)
  - DY and W production at full differential N3LO

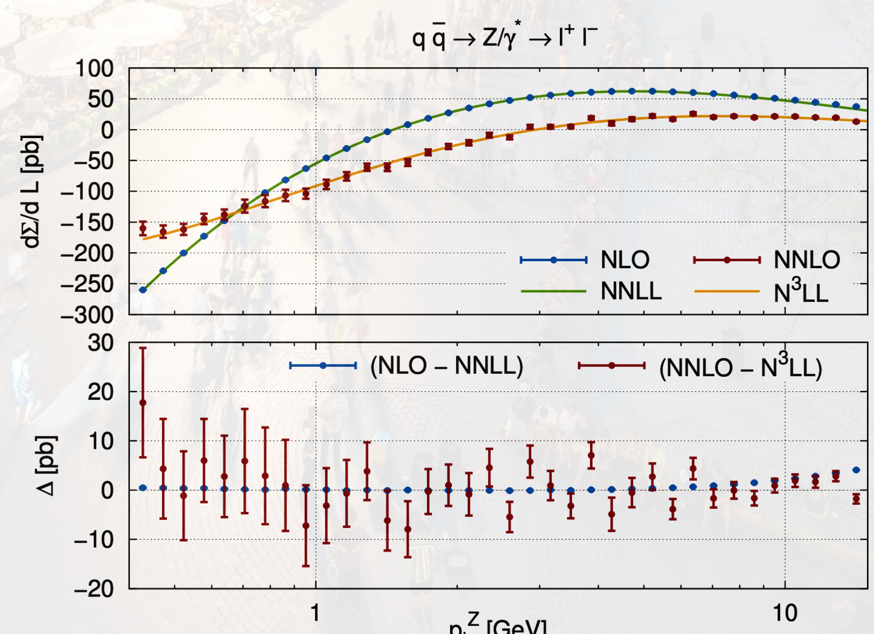
    Exact N3LO with quark beam functions recently available: Luo, Yang et al 1912.05778
  - NNLO corrections of 2 → 3 processes

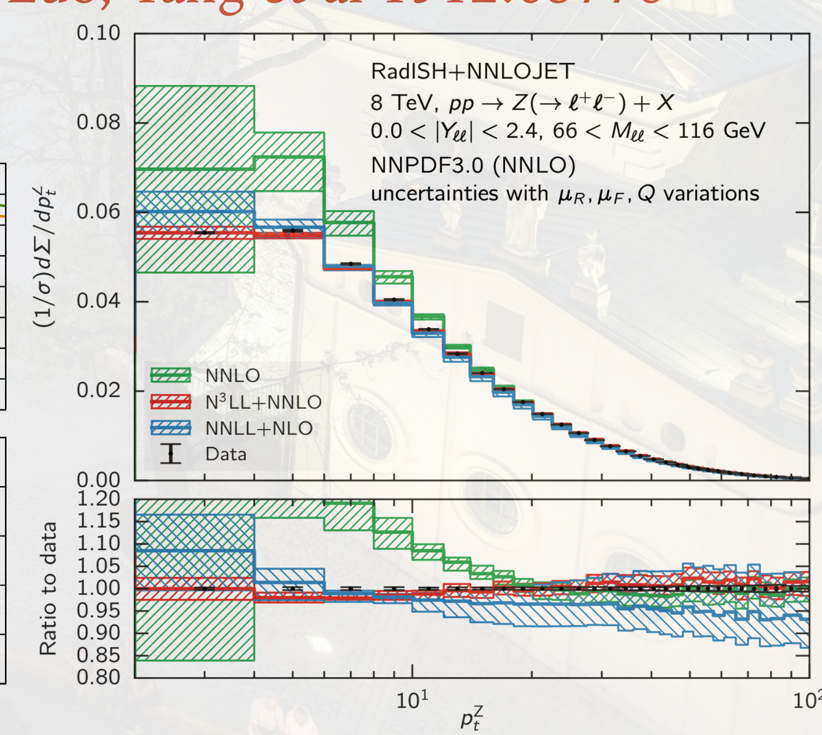



$H \to 2l2\nu$ (HIG-19-002-pas)




http://ploughshare.web.cern.ch




Bizoń, XC, et al. 1805.05916

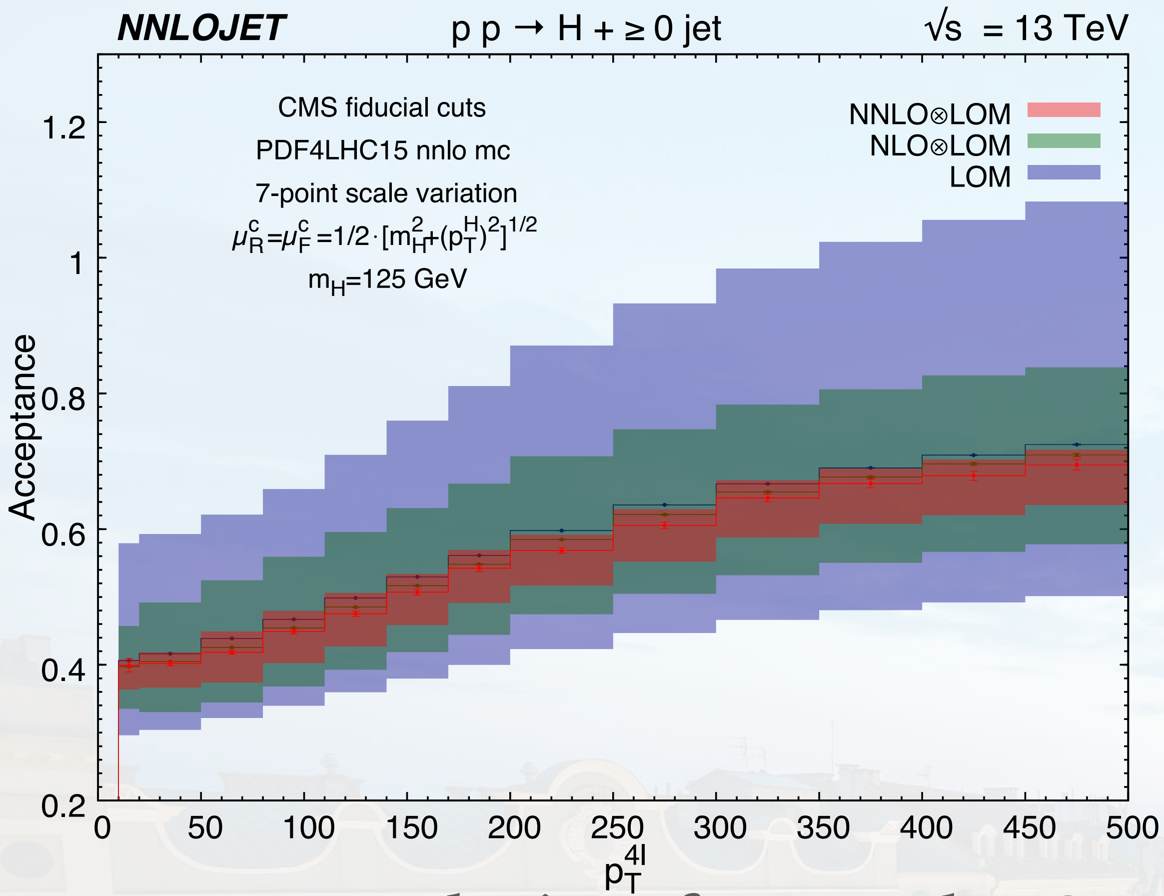
# SUMMARY

- High Energy Physics is advancing to precision study at a steady speed and Higgs phenomenology will benefit from it. (Targets set for HL-LHC)
- Higgs boson precision measurements focus on differential observables and distinguishing production and decay channels
- Higgs boson precision predictions focus on reducing uncertainties from all sources. Major factor still from QCD
- NNLO QCD is the new standard for Higgs production channels, more consistent update to PDF and $\alpha_s$ will be available in the future
- NNLO+N3LL and N3LO predictions are available for limited observables. With realistic projection of theory progresses, we can expect promising precisions at HL-LHC accuracy.
- Many important studies are desired in the future: quark mass, parton shower beyond LO and LL, $\alpha\alpha_s$ mixing, interference contributions etc.

# *Thank You for your Attention*

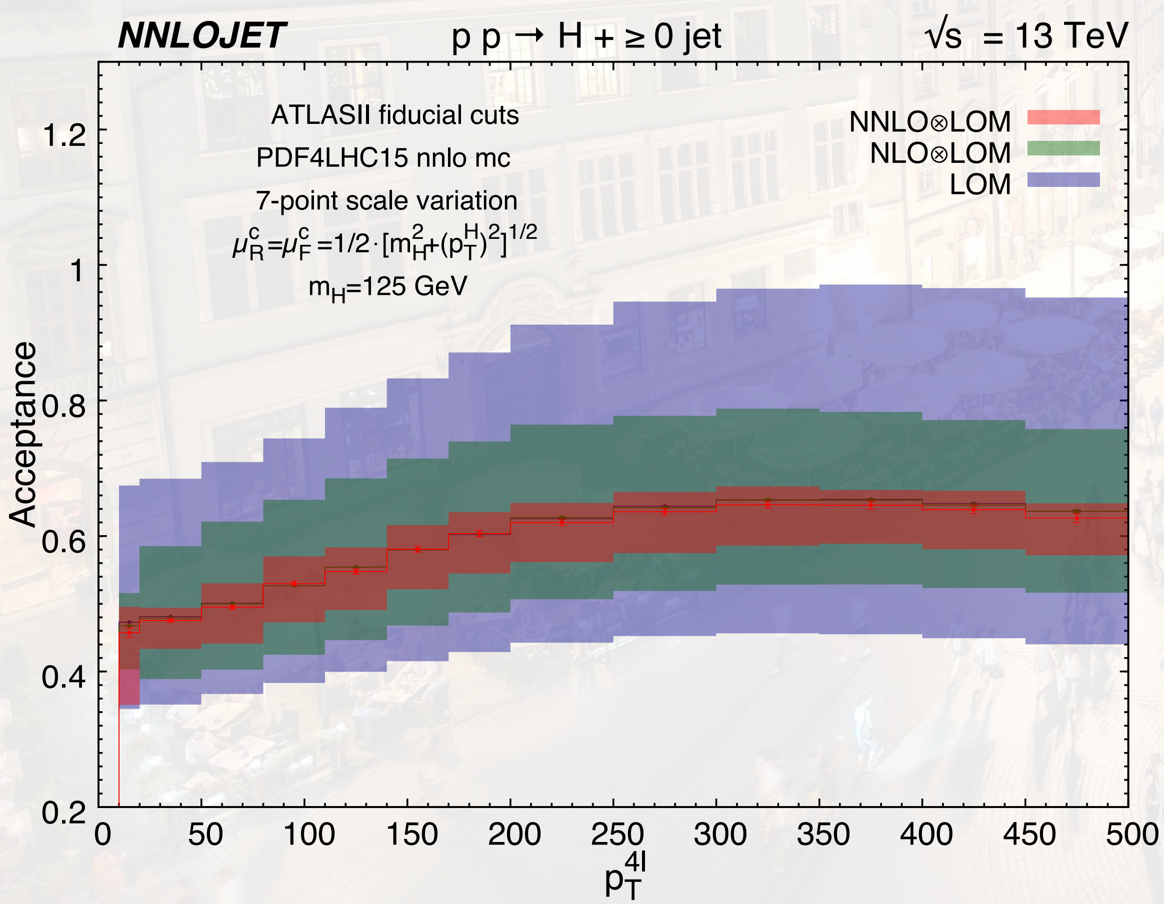
| Total time (int. dimension Of the tree level) | LO | NLO | NNLO |
|---|---|---|---|
| H | 1 min (3) | 30 min (6) | 300h (9) |
| H—>di-photon | 1 min (3) | 40 min (6) | 400h (9) |
| H—>4l (2e2mu, 4e, 4mu require at least two separate runs) | 2~3 min (9) | 2h (12) | 1000h (15) |
| H+j | 3 min (6) | 1.5h (9) | 70000h (12) |
| H—>di-photon + jet | 4 min (6) | 2h (9) | 90000h (12) |
| H—>4l (2e2mu, 4e, 4mu require at least two separate runs)+jet | 20 min (12) | 10h (15) | 600000h (18) |
| H_qT | 20 min (6) | 5h (9) | 7000000h (12) |

CMS cuts




**Acceptance deviate from each FO**

ATLAS cuts




**Acceptance consistent for each FO**

# ACCEPTANCE STUDY

## $H \to ZZ^* \to 4l$

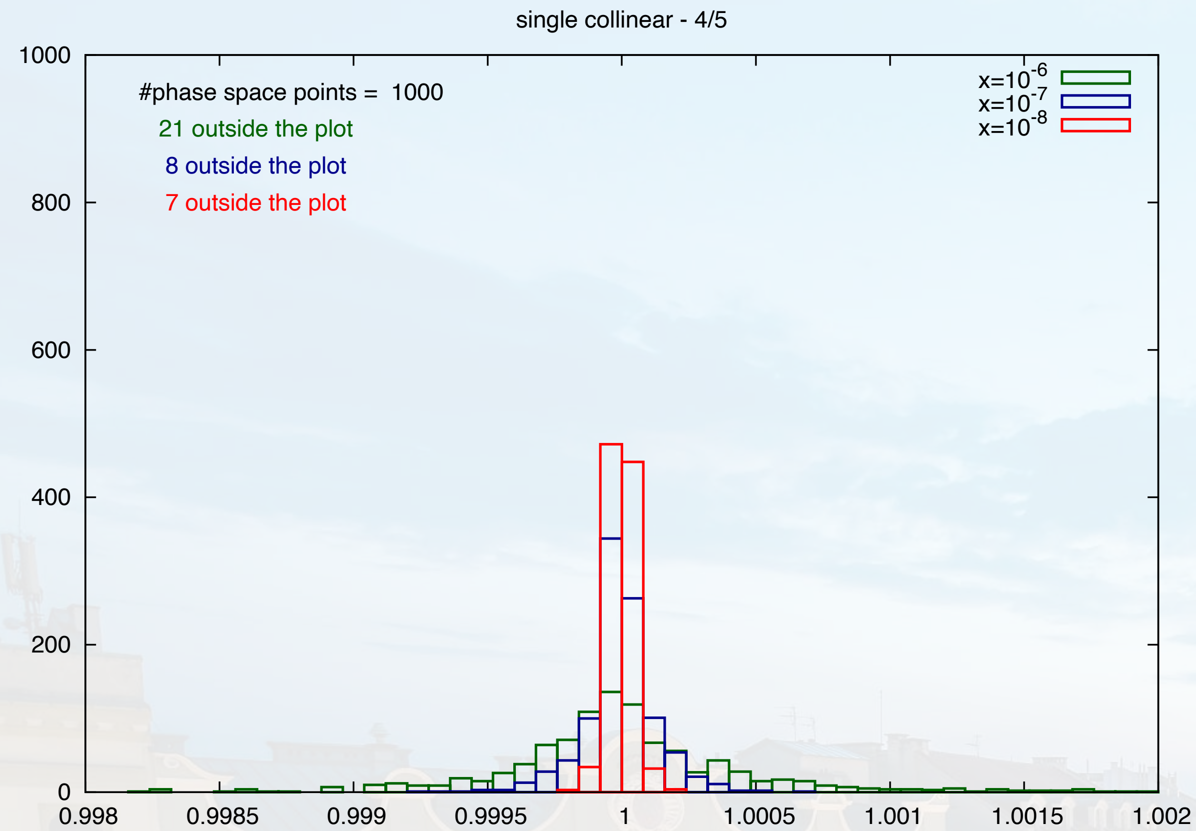
- CMS (1706.09936) and ATLAS (1708.02810) use different lepton isolation algorithm in $ZZ^* \to 4l$

| Fiducial Cuts | CMS | ATLAS |
|---|---|---|
| Lepton Isolation | | |
| Cone size $R^l$ | 0.3 | — |
| $\sum p_T^i/p_T^l\ (i \in R^l)$ | $< 35\%$ | — |
| $\Delta R^{SF(DF)}(l_i, l_j)$ | $> 0.02$ | $> 0.1(0.2)$ |
| Jet Definition (anti-kT with R=0.4) | | |
| $p_T^{jets}$ (GeV) | $> 30$ | $> 30$ |
| $\lvert y^{jets}\rvert$ | $< 2.5$ | $< 4.4$ |
| $\Delta R(jet, e(\mu))$ | — | $> 0.2(0.1)$ |

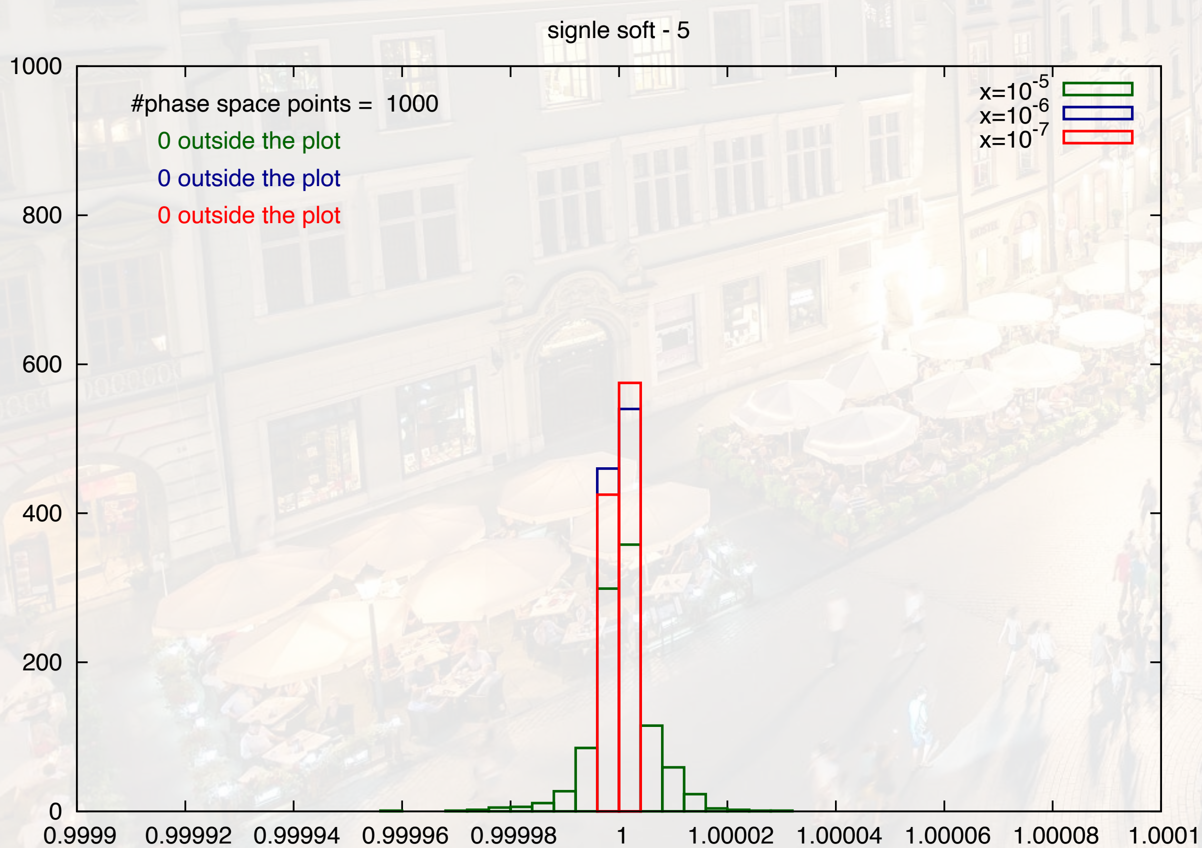
- Fixed order study of acceptance reveals detailed structures

$$A_{FO}(\mathcal{O}) = \frac{d\sigma_{FO}^{H(\to ZZ^*\to 4l)+jet}/d\mathcal{O}}{d\sigma_{FO}^{H+jet}/d\mathcal{O} \times (BR_{2e2\mu} + BR_{4\mu} + BR_{4e})}$$

# TEST NUMERICAL STABILITY OF MATRIX ELEMENTS




**Single collinear limit 4//5 with $x \sim 10^{-8}$**



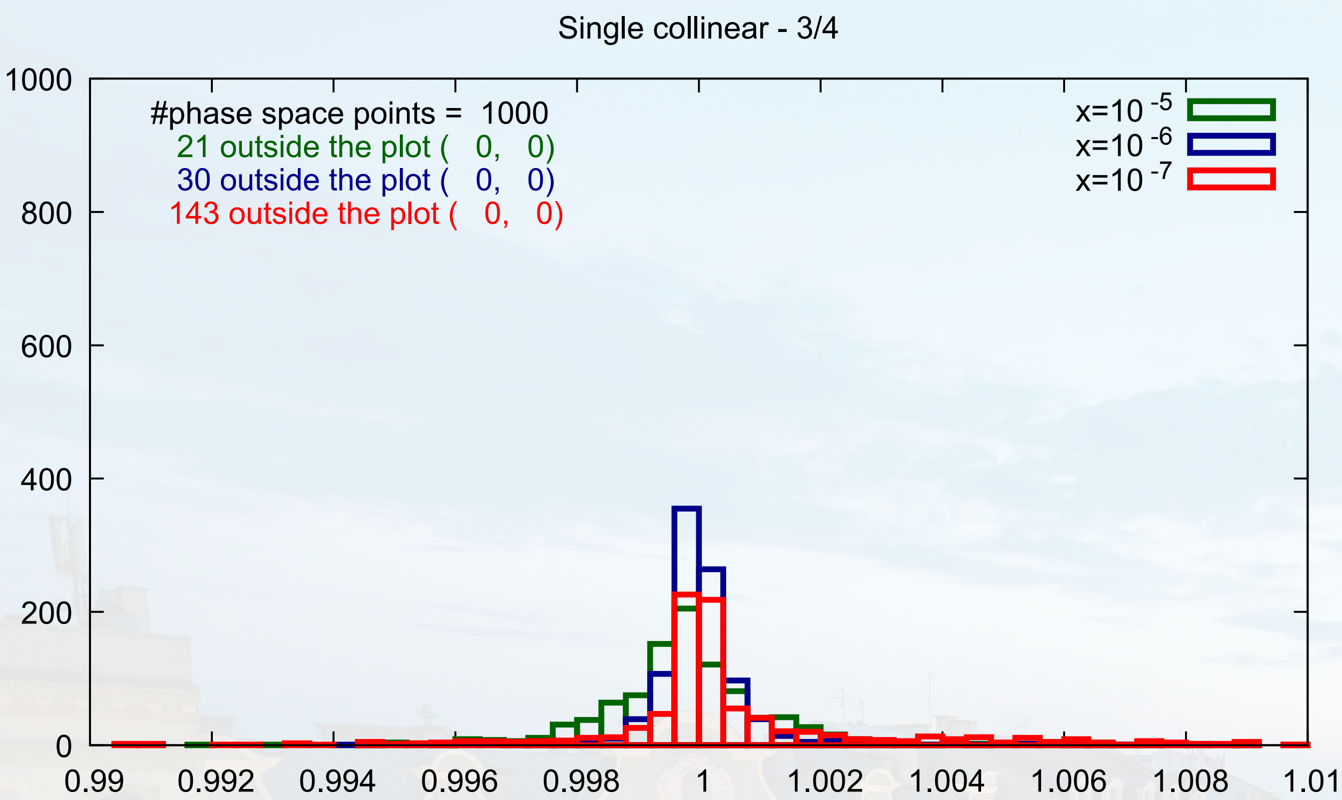

**Single soft limit $5 \to 0$ with $x \sim 10^{-7}$**

- Construct antenna subtraction terms (ATS) to mimic unresolved limits of matrix elements (ME)
- Test function (tree level): $R = \dfrac{ME^0}{AST^0}$
- R ~ the horizontal axis (centre at one near the unresolved region)
- Number of P.S. points in each bin ~ the vertical axis
- Controlling singular region correctly will achieve spike plots
- For example: $p_1 + p_2 \to p_3 + p_4 + p_5$

Single collinear limit: $x = \dfrac{s_{45}}{s}, \quad x \sim 10^{-8}$

Single soft limit: $xs = s_{35} + s_{45}, \quad x \sim 10^{-7}$

# TEST NUMERICAL STABILITY OF MATRIX ELEMENTS




**Single collinear limit 3//4 with** $x \sim 10^{-6}$


**Single soft limit** $4 \to 0$ **with** $x \sim 10^{-3}$

- Ideally we would like to use ME from automated tools
- However, not many of them are numerical stable in IR singular regions
- OpenLoops2 is one of the best auto-tools optimised in IR singular regions
- However for a loop-induced process:

  $g_1 + g_2 \to \gamma + \gamma + g_3 + g_4$
- Test function (loop induced):

$$R = \frac{ME^1}{AST^1}$$

- We observe spikes break down at

  single collinear limit: $x \sim 10^{-7}$

  single soft limit: $x \sim 10^{-4}$