HIGH PRECISION PHENOMENOLOGY OF THE HIGGS BOSON

HUMBOLDT-UNIVERSITÄT ZU BERLIN AND DESY SEMINAR

Universität Zürich[UZH]

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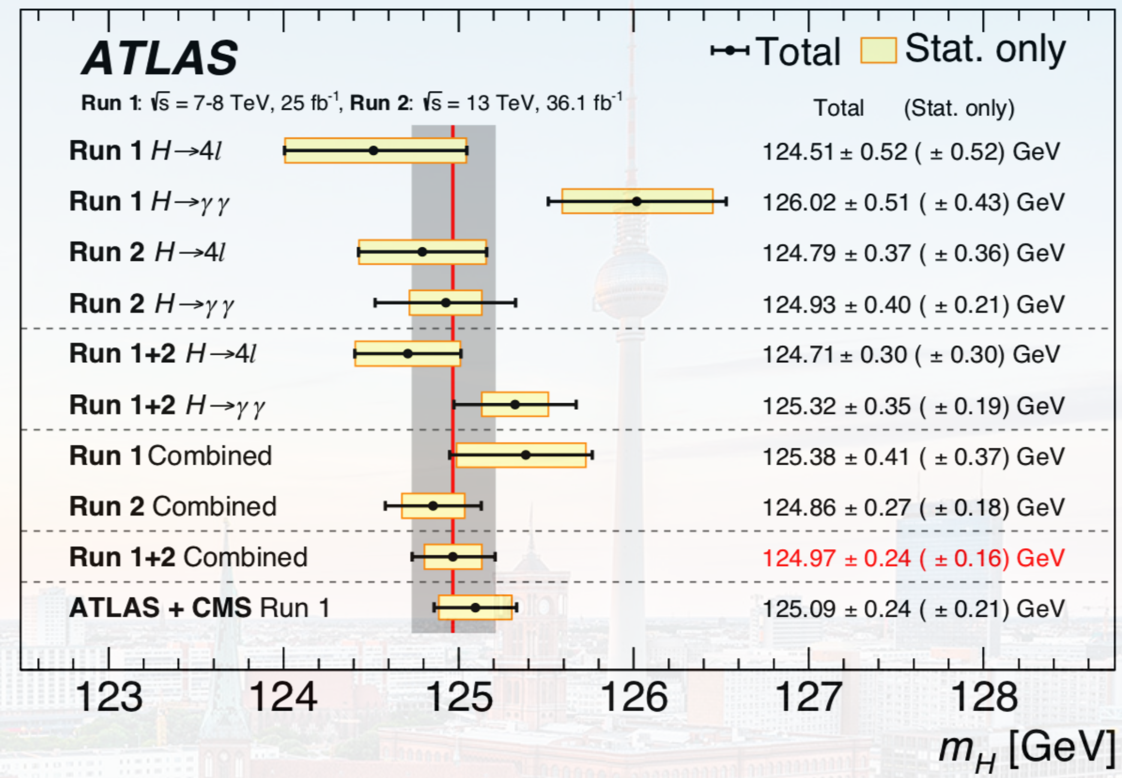
OUTLINE

- **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?
- **Precision QCD calculations in the past, present and future**
  - Roadmap of NNLO
  - Roadmap of N3LO
- **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 & 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
  - HH signal with 10 times SM exclusion limit
- Goal for the future: explore full potential of the LHC
  - Differential in production and decay channels
  - Projection to HL-LHC (estimate challenge)
  - Accelerate searches of new physics



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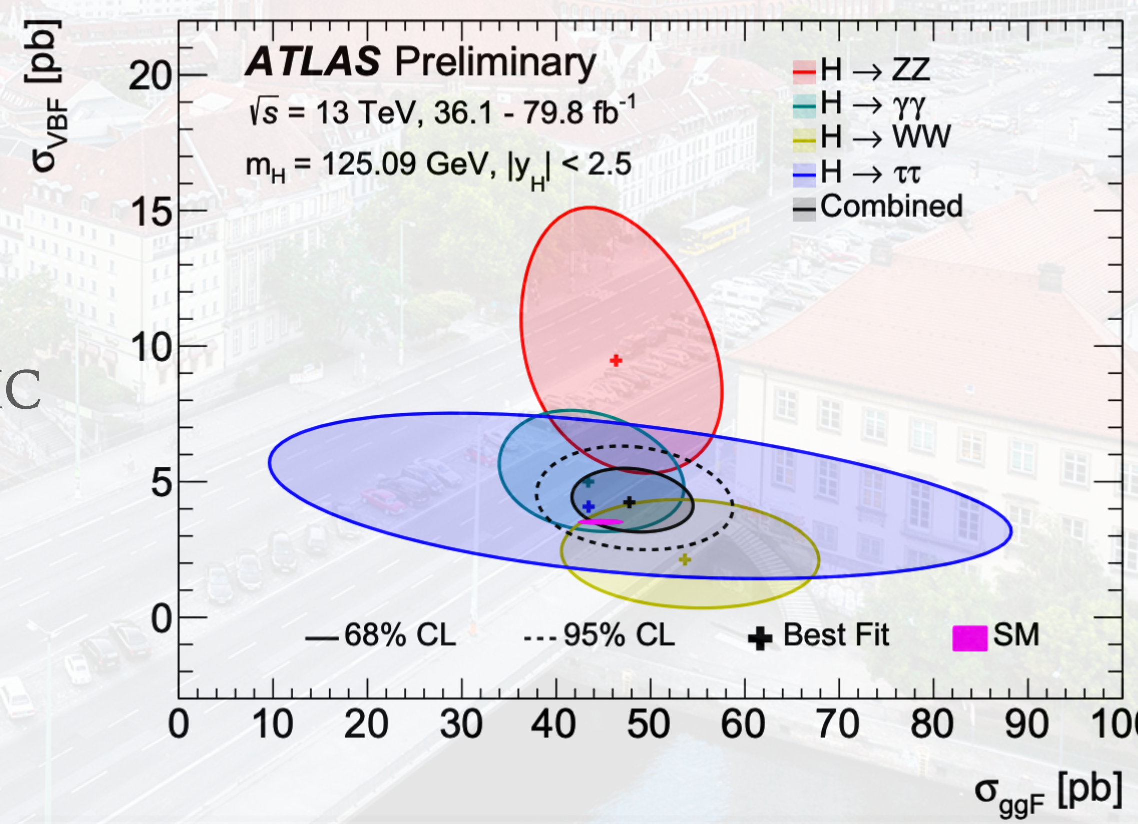
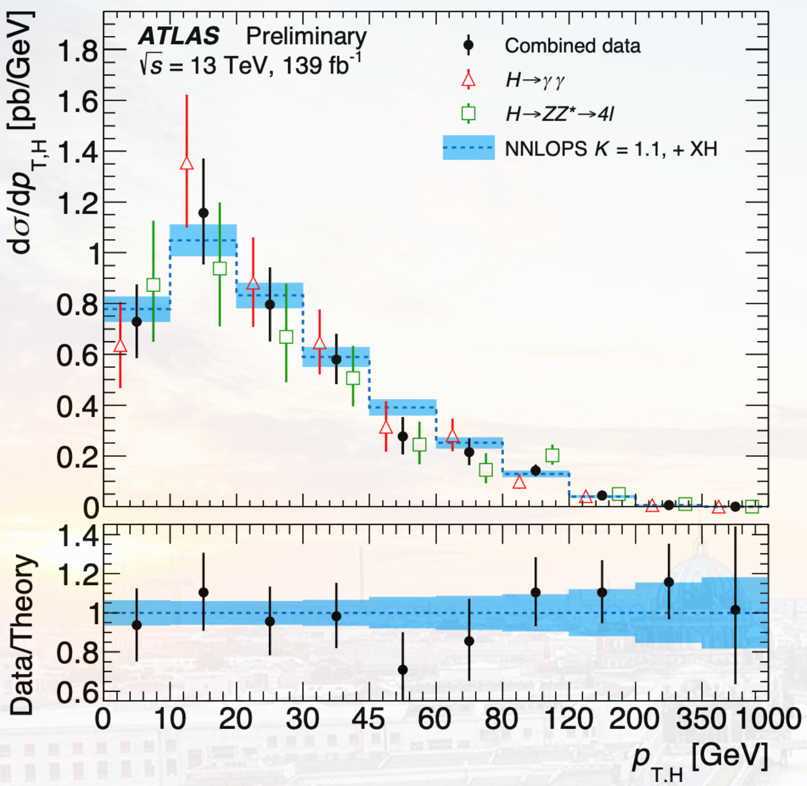
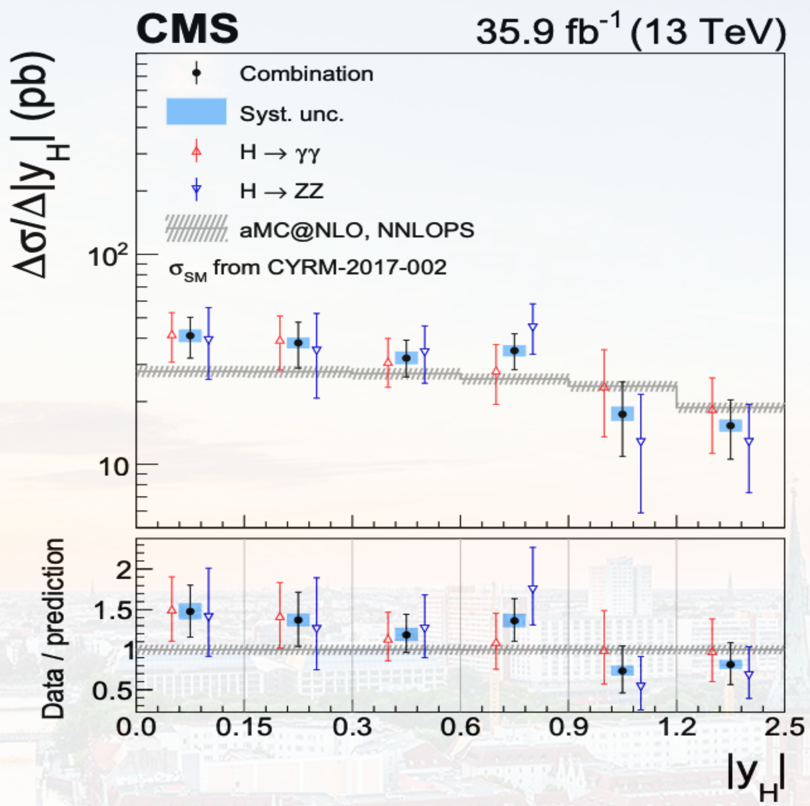
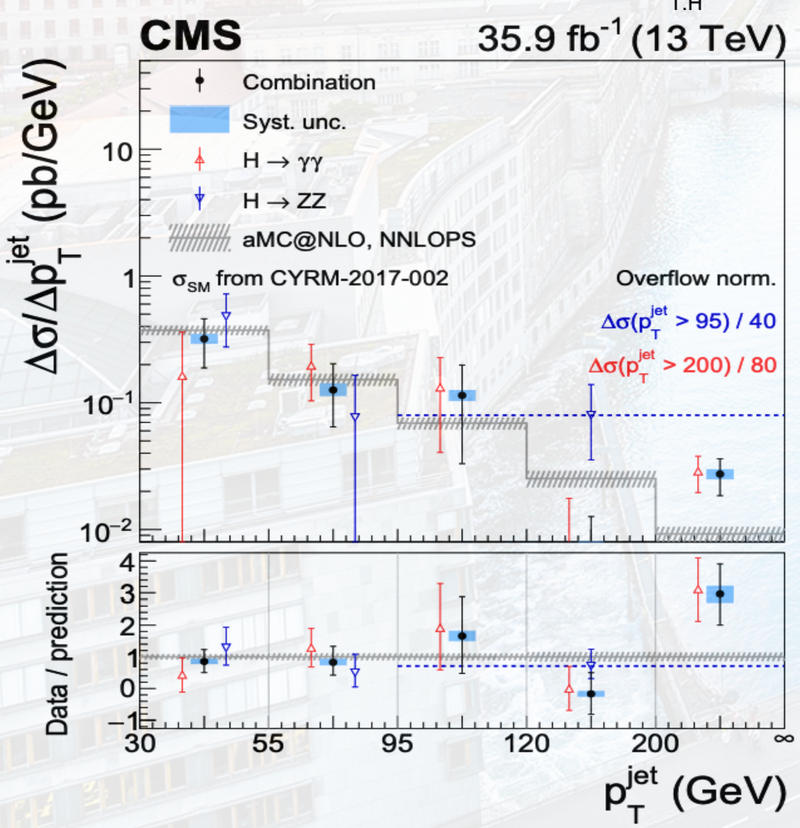


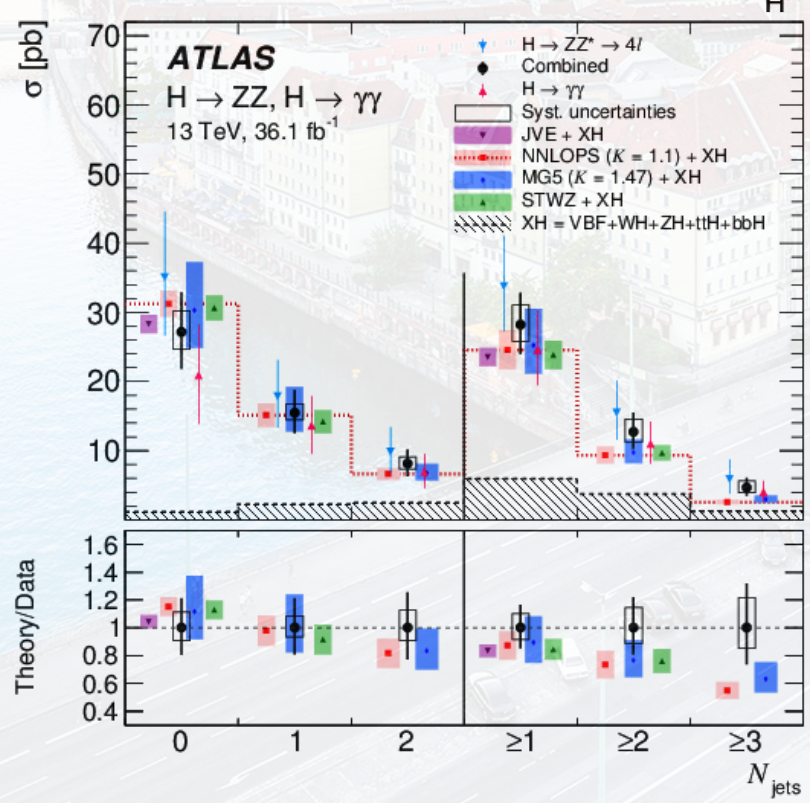
ATLAS-CONF-2018-031

SUCCESS OF LHC HIGGS EXPERIMENTS



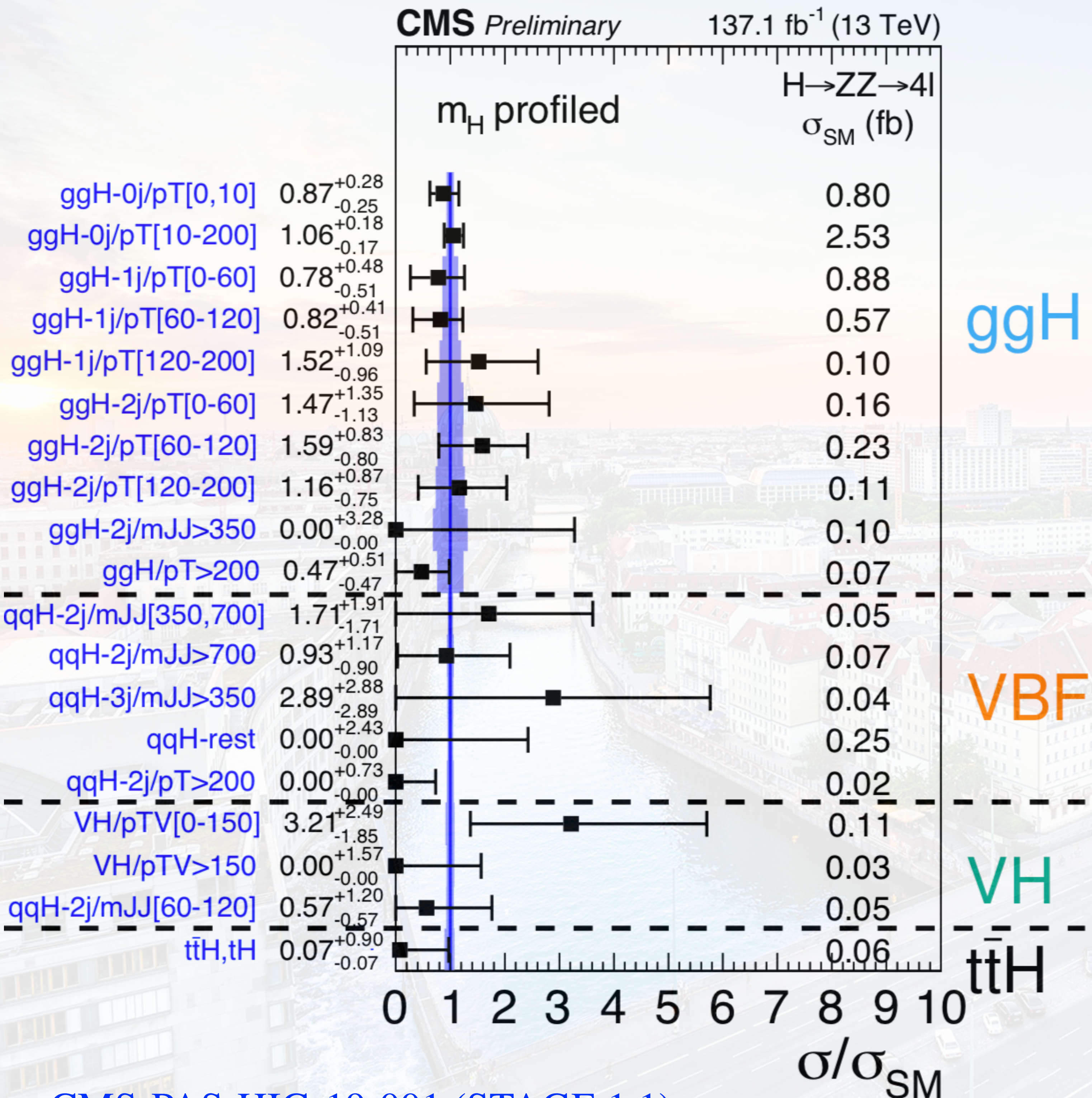






- Typical differential observables for Higgs (+jet) are:
$$\frac{d\sigma}{dp_T^H} \quad \frac{d\sigma}{d|y^H|} \quad \frac{d\sigma}{dp_T^{j1}} \quad \frac{d\sigma}{dN_{jets}}$$
- Inclusive decay observables are reconstructed from individual decay channel
- Combined results with ±20-40% uncertainties (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
$$0 \rightarrow 1 \rightarrow 1.1 \rightarrow \cdots \rightarrow 2$$

SUCCESS OF LHC HIGGS EXPERIMENTS



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

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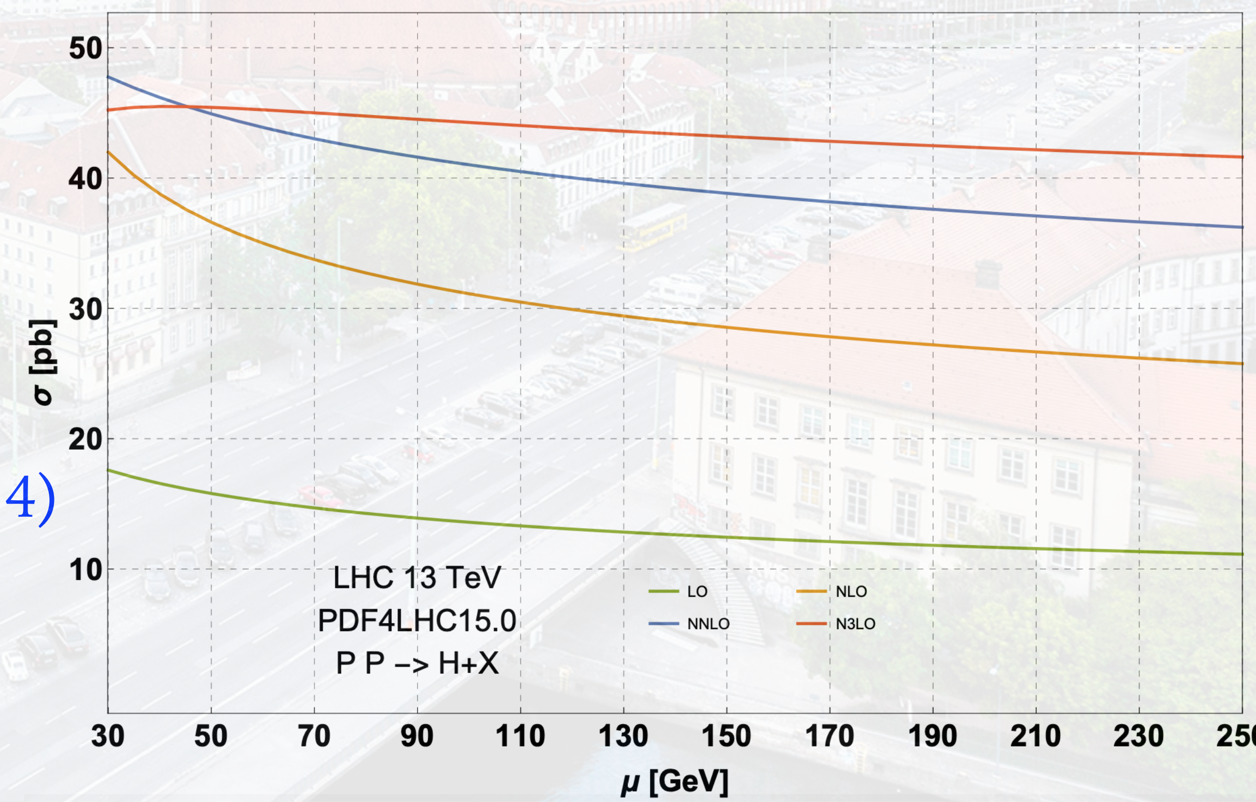
  $$\frac{d\sigma}{dp_T^H} \quad \frac{d\sigma}{d|y^H|} \quad \frac{d\sigma}{dp_T^{j1}} \quad \frac{d\sigma}{dN_{jets}}$$
- Inclusive decay observables are reconstructed from individual decay channel
- Combined results with $\pm$30-50% uncertainties (ATLAS 1805.10197, CMS 1812.06504, ATLAS-CONF-2019-032)
- Breakdown in production channels through Simplified Template Cross Section (STXS)
- All Higgs production and decay channels contribute
- Complexity increase from Stage
  $$0 \to 1 \to 1.1 \to \cdots \to 2$$

SUCCESS OF HIGGS THEORY (GLUON FUSION)

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

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

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

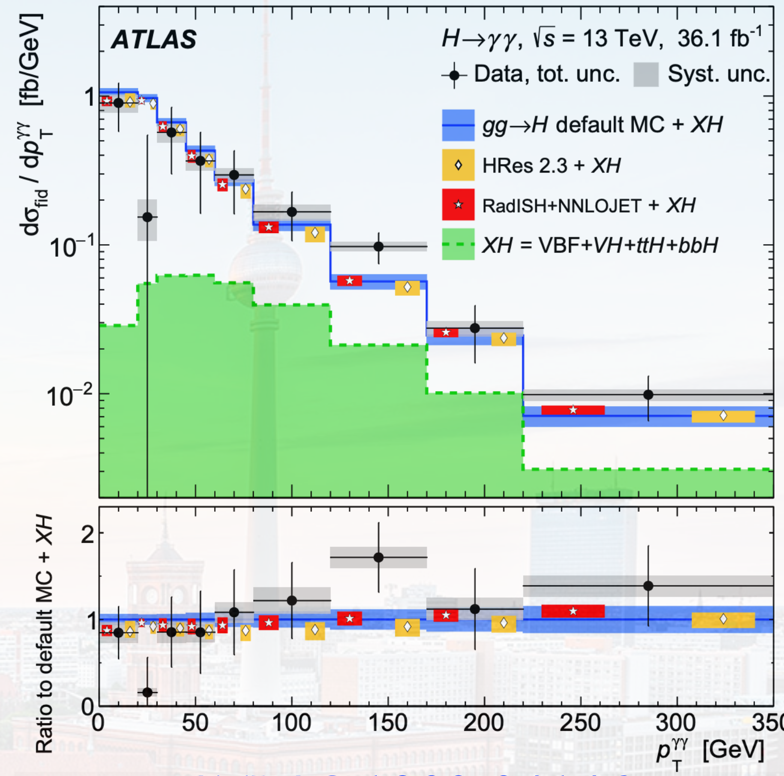


Need to attack on many fronts to further improve

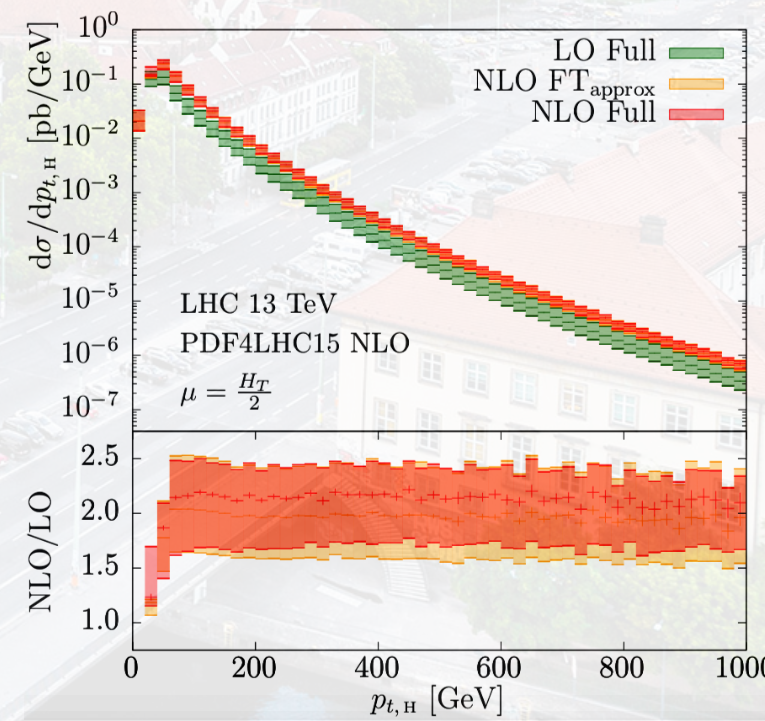
- Towards N3LO PDFs (Britzger et al. 1906.05303)
- Top quark mass dependence (Davies et al. 1906.00982, Davies et al 1911.10214)
- Bottom quark fusion at N3LO (Duhr, Dulat, Mistlberger 1904.09990)
- EWK corrections (1801.10403, 1811.11211) …

SUCCESS OF HIGGS THEORY (GLUON FUSION)

- Differential predictions advance to new precision
  - 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
    - Towards fully 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
    - Join with parton shower beyond LO and LL



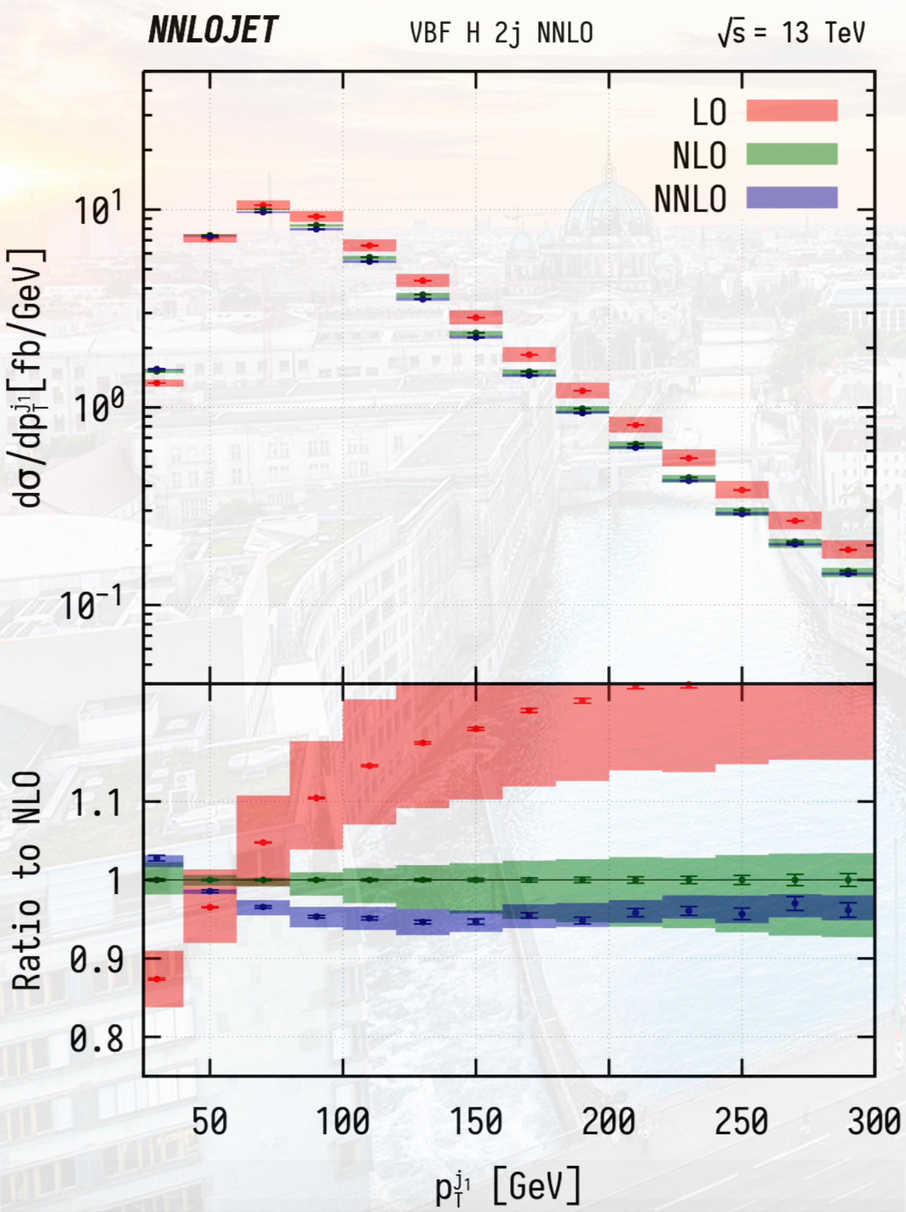
ATLAS 1802.04146



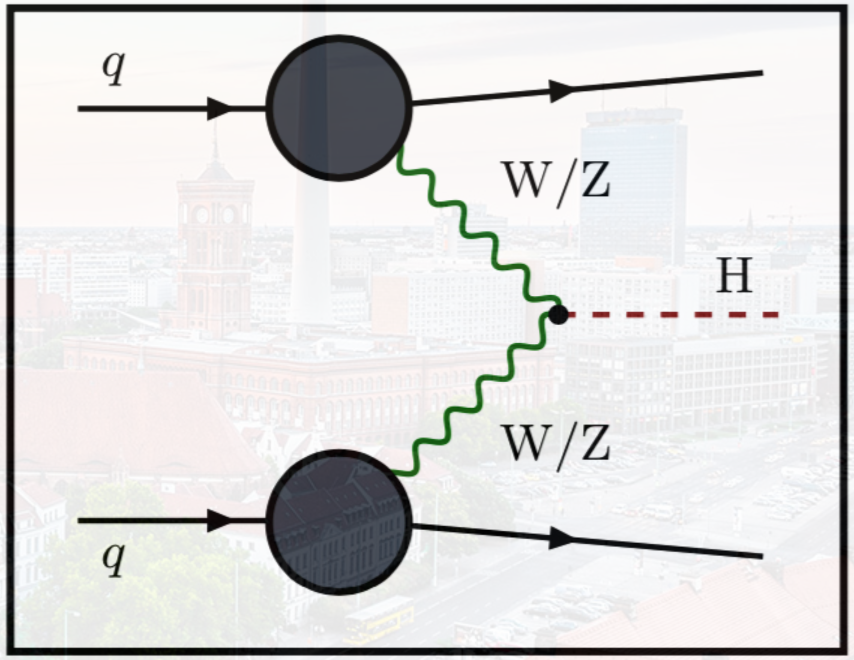
Jones et al. 1802.00349

SUCCESS OF HIGGS THEORY (VECTOR BOSON FUSION)

- Differential NNLO corrections to VBFH-2J production and NLO corrections to VBFH-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)



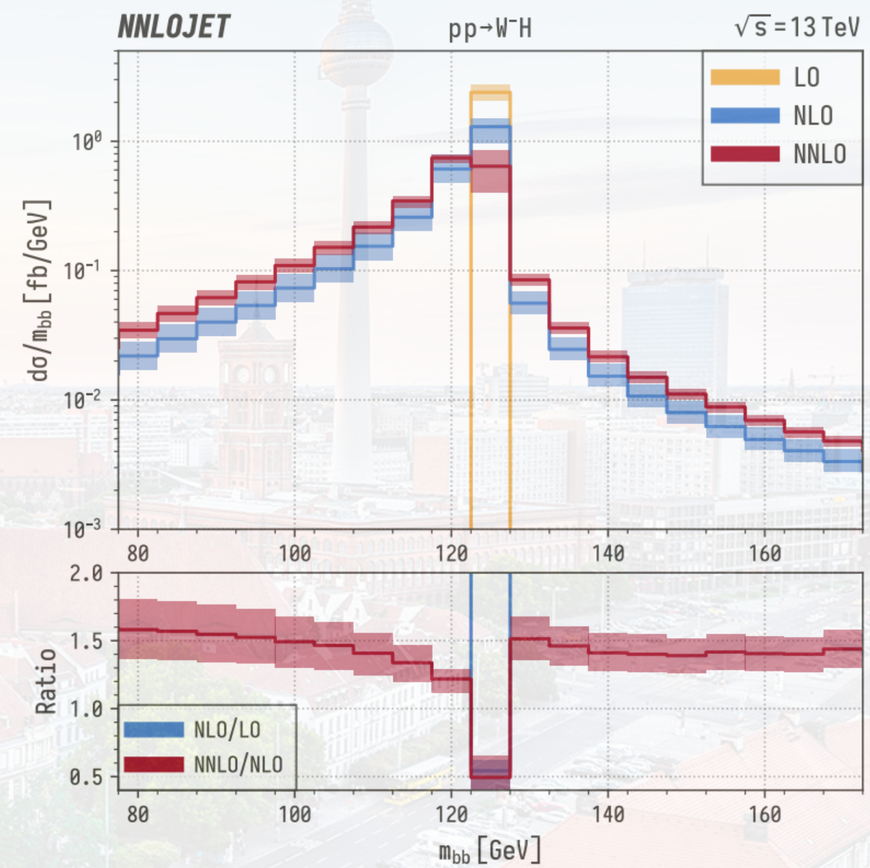
DIS⊗DIS



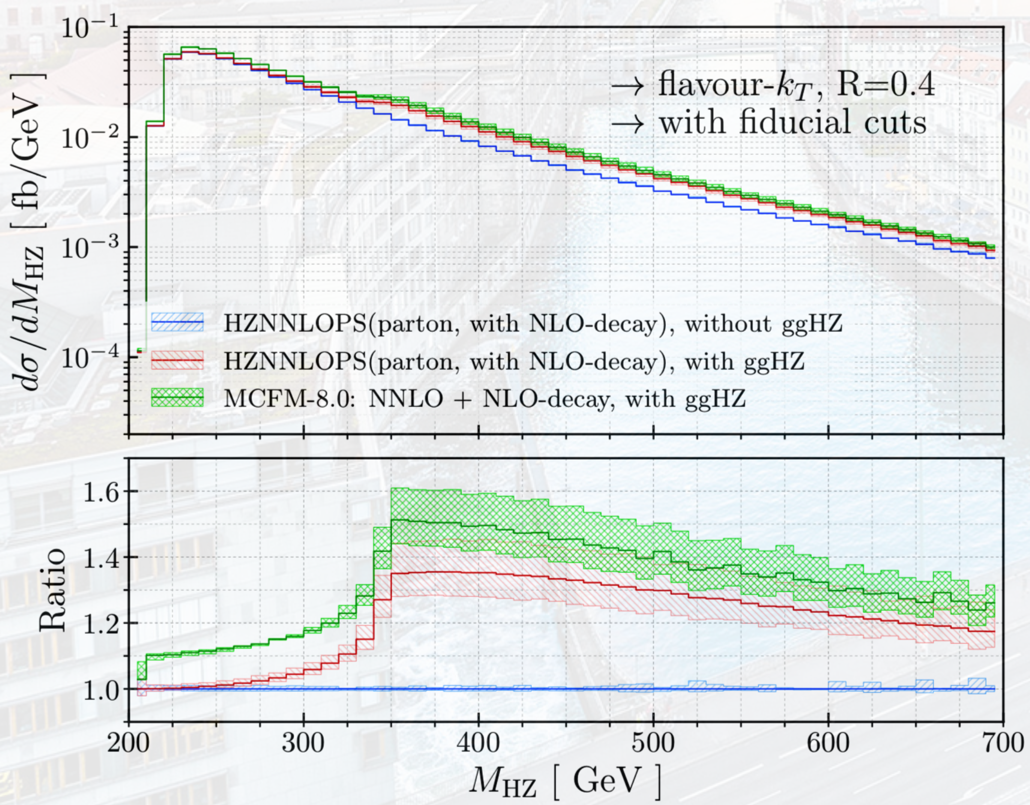
- NNLO cross section is -4% compared to NLO (VBF cuts)
- Scale variation now reduced to ± 3%
- Large overlap in fiducial volume with gluon fusion H+2J
- More studies on jet radius and "VFH-cut" via LH19
- Inclusive cross section at N3LO (Dreyer et al. 1606.00840)

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
  - New interference at NNLO from $H \to gg$
  - N3LO $H \to b\bar{b}$ decay now available (Mondini, Schiavi, Williams 1904.08960)
  - Future work with b mass and EXP flavour kT jet



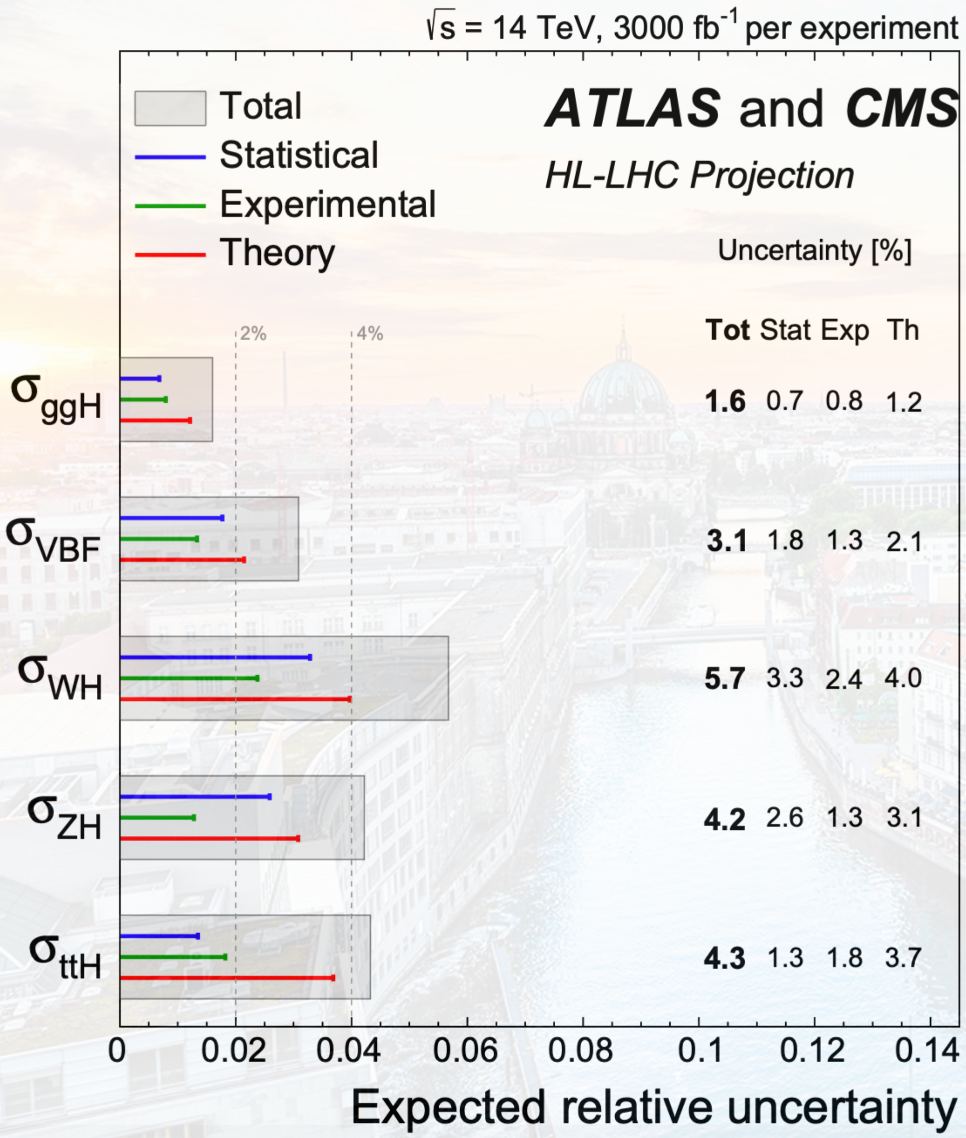
Gauld, Majer et al. 1907.05836



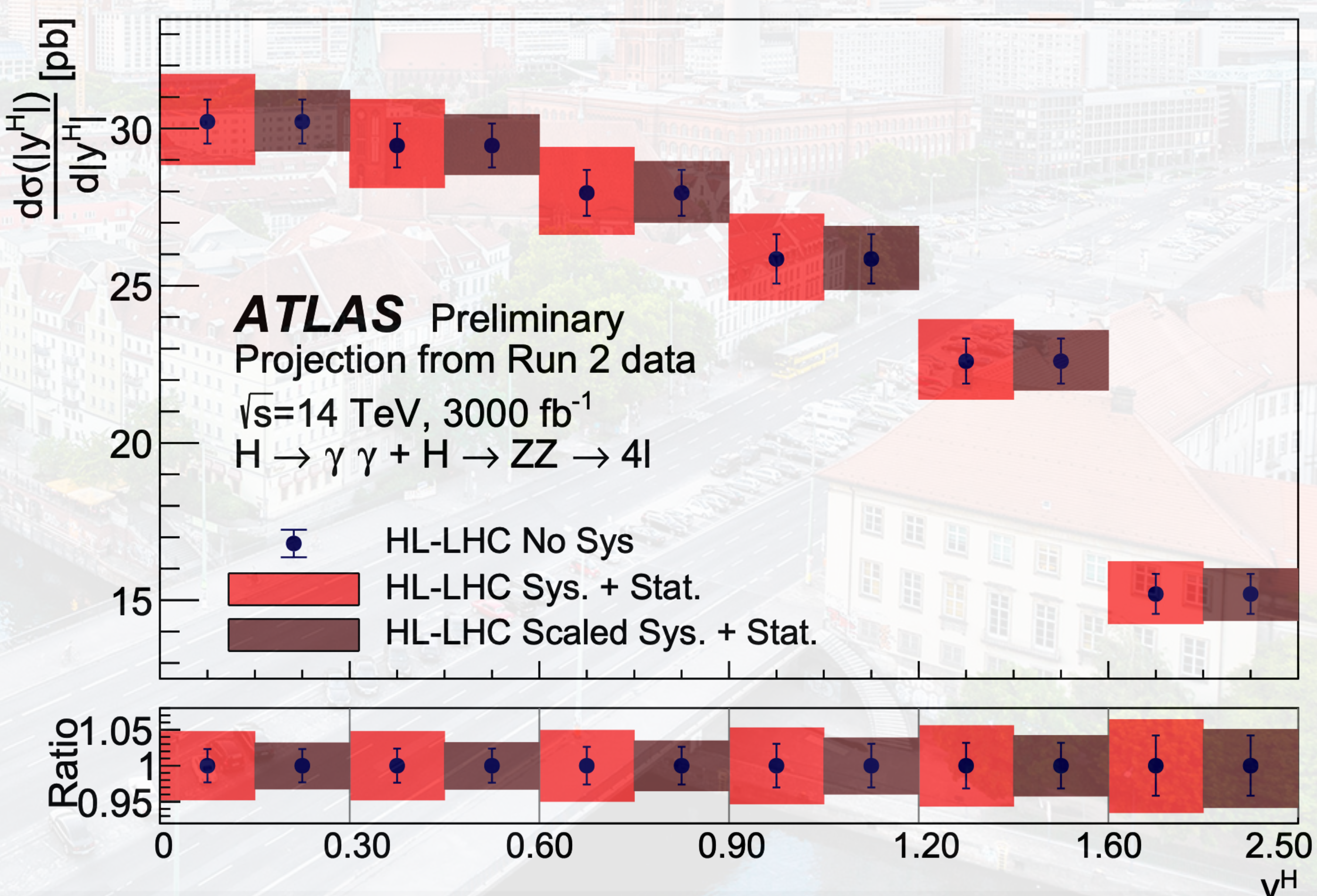
- NNLOPS accurate $pp \to Z(l^+l^-) + H(b\bar{b})$ (Astill, Bizoń et al. 1804.08141)
- Sizeable impact of loop induced $gg \to Z(l^+l^-) + H(b\bar{b})$ above top mass threshold (1-loop^2 at LO)
- NLO corrections includes interference with qg and $q\bar{q}$ channels (need two-loop massive top for a through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



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

WG2 report on HL-LHC 1902.00134

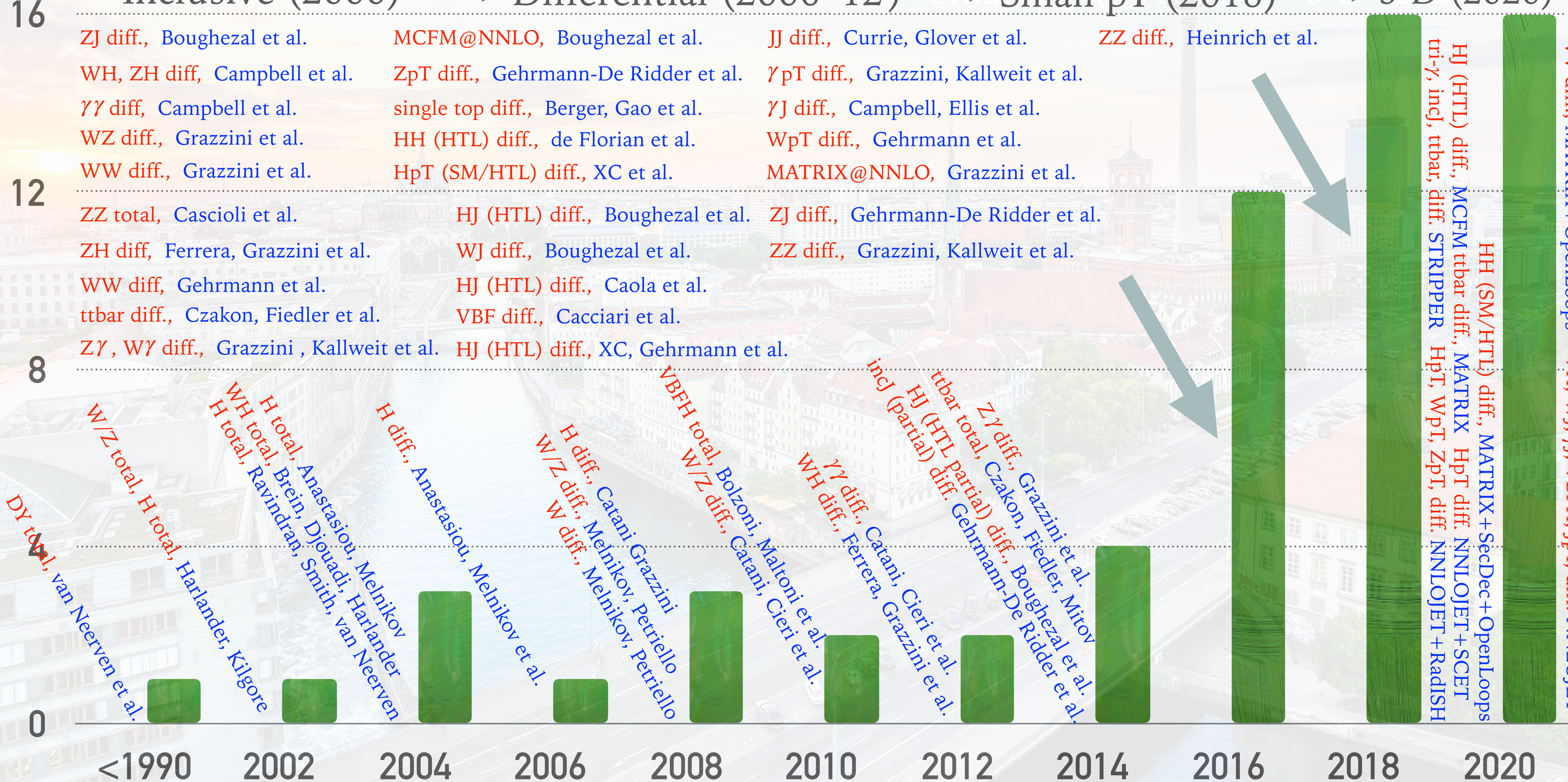
WG2 report on HL-LHC 1902.00134

(A DETOUR)

PRECISION QCD CALCULATIONS IN THE PAST, PRESENT AND FUTURE

THE STANDARD NNLO @ LHC

- LHC processes at NNLO QCD accuracy (include secondary confirmations)
  - One colourless (2000) ⟶ Two colourless (2004) ⟶ One or two Colourful (2014)
  - QCD+QED
  - Inclusive (2000) ⟶ Differential (2006-12) ⟶ Small pT (2018) ⟶ 3-D (2020)



THE STANDARD NNLO @ LHC IN NEXT 5 YEARS

- LHC processes at NNLO QCD accuracy
  - $2 \to 2$ is well developed, $2 \to 3$ available for limited topology (VBFH-2J, $\gamma\gamma\gamma$). More differential observables in coming years.
  - Rapid progress in the calculations of 2-loop-5-point amplitudes.

    LC 5-gluon: all-plus (Badger et al 1507.08797) (Gehrmann et al 1511.05409), one-plus (Badger et al 1811.11699), all-helicities (Abreu et al 1712.03946, 1812.04586), LC 5-parton: all-helicities (Abreu et al 1809.09067, 1904.00945), FC 5-gluon: all-plus (Badger et al 1905.03733) FC 5-parton: all master integrals (Chicherin et al 1812.11160), LC W+4-parton (Hartanto et al 1906.11862)
  - $\gamma\gamma\gamma$ production from STRIPPER (Chawdhry, Czakon et al 1911.00479)
    (excluding small contributions from 2-loop non-planner and internal quark loop)
    γ+JJ, $\gamma\gamma$+J, JJJ etc. productions in coming years and desire for $t\bar{t}H$
    (bottleneck is the 2-loop AMP but approximations like in $\gamma\gamma\gamma$ might be acceptable)
  - Towards "NNLO revolution" (performance matters)
    - Automation of two-loop matrix elements. SecDec, OpenLoops2
    - Automation of removing IR divergence. STRIPPER, nested-soft-collinear, etc.
- Equally important input resolving NNLO accuracy: top mass effects, $\alpha\alpha_s$ mixing, flavours of jets, resummation corrections, non-perturbative effects etc.

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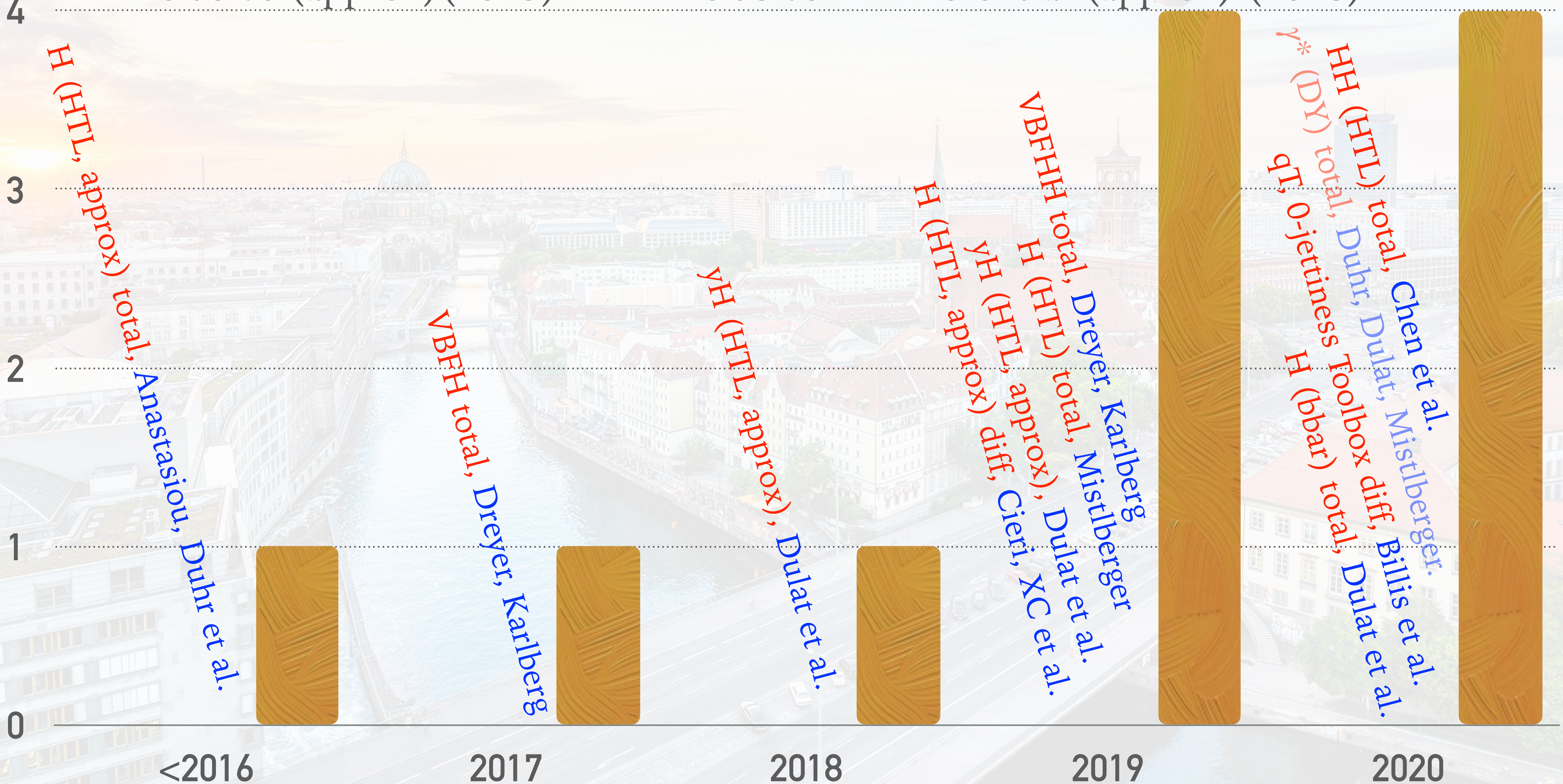
THE CUTTING-EDGE N3LO @ LHC

- LHC processes at N3LO accuracy (include secondary confirmation)
  - N3LO at 2015 was like the early stage of NNLO in 2000's.
  - Inclusive (approx) (2015) ⟶ Inclusive + Differential (approx) (2018)



TOWARDS FULLY DIFFERENTIAL N3LO PRECISION ?

- Several cutting edge N3LO differential calculations available recently:
  - $ep \to ep$: fully differential one-jet DIS (Currie, Gehrmann, Glover et al. 1803.09973)
  - $gg \to H$: in HTL with approximation of N3LO beam function (Cieri, XC et al. 1807.11501)
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- More N3LO processes could be available based on established NNLO works for LHC:
  - VBFH: using N3LO structure function (1606.00840) + NNLO two-jet DIS (1703.05977)
  - DY: N3LO qT and 0-jettiness toolbox (1909.00811) + NNLO Z+J at small qT (1805.05916)
  - W: N3LO qT and 0-jettiness toolbox (1909.00811) + NNLO W+J at small qT (1905.05171)
- However, can we call it N3LO precision? (unsolved issues at NNLO)
  - PDFs fitted at NNLO evolution but with limited NNLO hard coefficients (DIS, p_T^Z, $t\bar{t}$)
  - $\delta(\alpha_s) \sim \pm 2.6\,\%$ and δ(PDF-TH) $\sim \pm 1.16\,\%$ (missing higher order uncertainty) for $\sigma^{H,tot}_{N^3LO}$
  - Non-perturbative effects fitted at NLOPS accuracy (Underlying events, γ fragmentation etc.)

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HIGGS PRODUCTION AND DECAY PROCESSES IN NNLOJET

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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 limited decay channels.
- Identification of EW and QCD final states using EXP algorithms.

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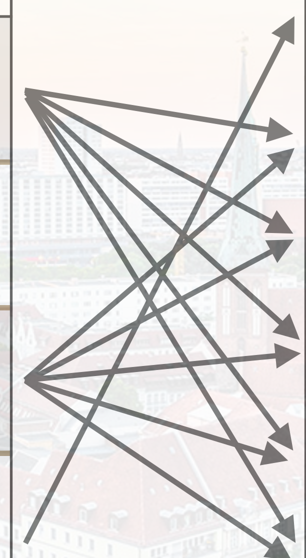
X. Chen, J. Cruz-Martinez, J. Currie, R. Gauld, A. Gehrmann-De Ridder, T. Gehrmann, E.W.N. Glover, M. Höfer, A. Huss, I. Majer, J. Mo, T. Morgan, J. Niehues, J. Pires, R. Schürmann, D. Walker, J. Whitehead

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



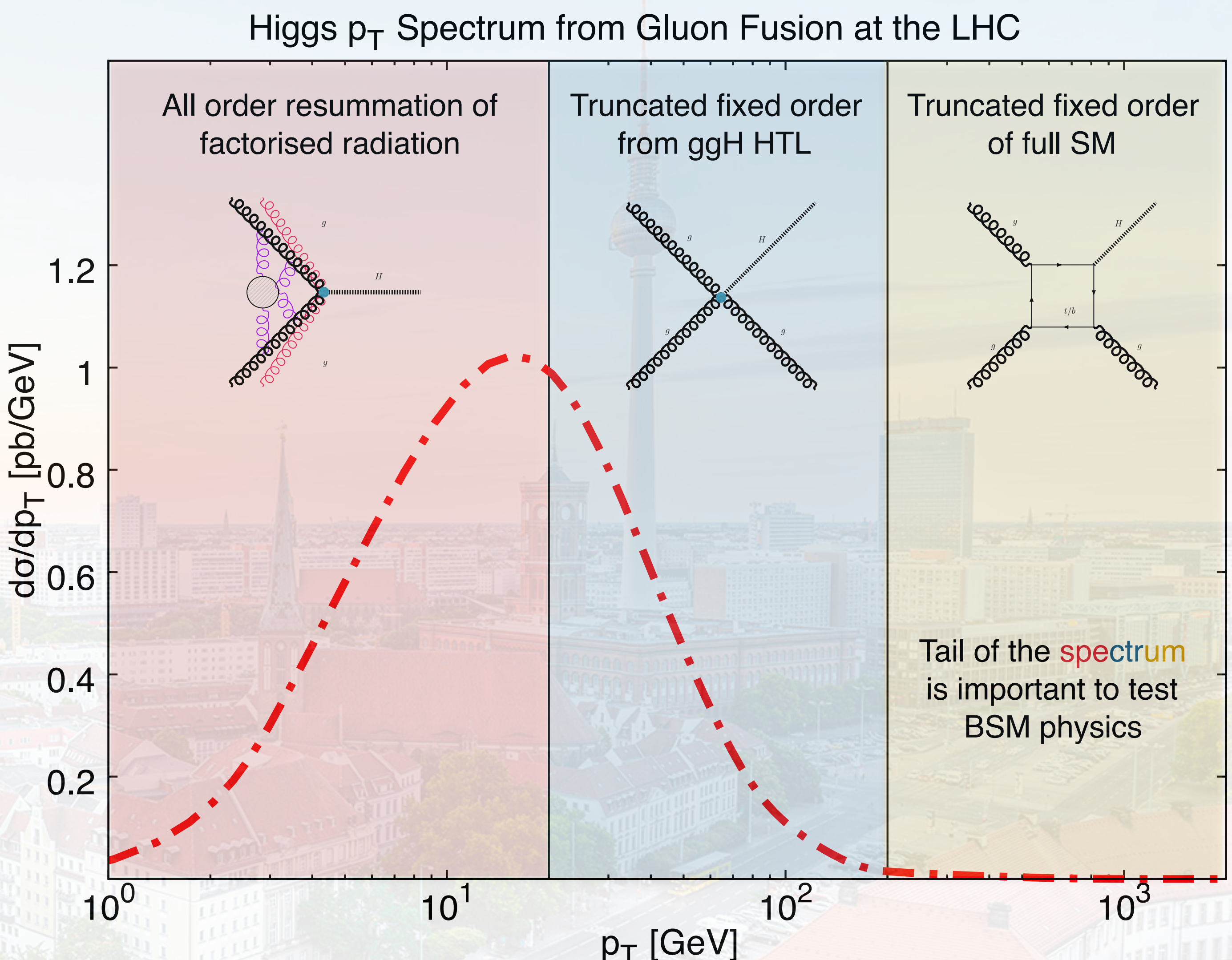
Higgs Decay channels		
$b\bar{b}$	NNLO	b-tagging
$WW^* \to 2l2\nu$	LO	Lepton isolation
$\tau^+\tau^-$	LO	Massive final states
$ZZ^* \to 4l$	LO	Lepton isolation
$\gamma\gamma$	LO	Photon isolation
$Z(\to 2l)\gamma$	LO	Photon + lepton iso.

- 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 or EFT)
  - 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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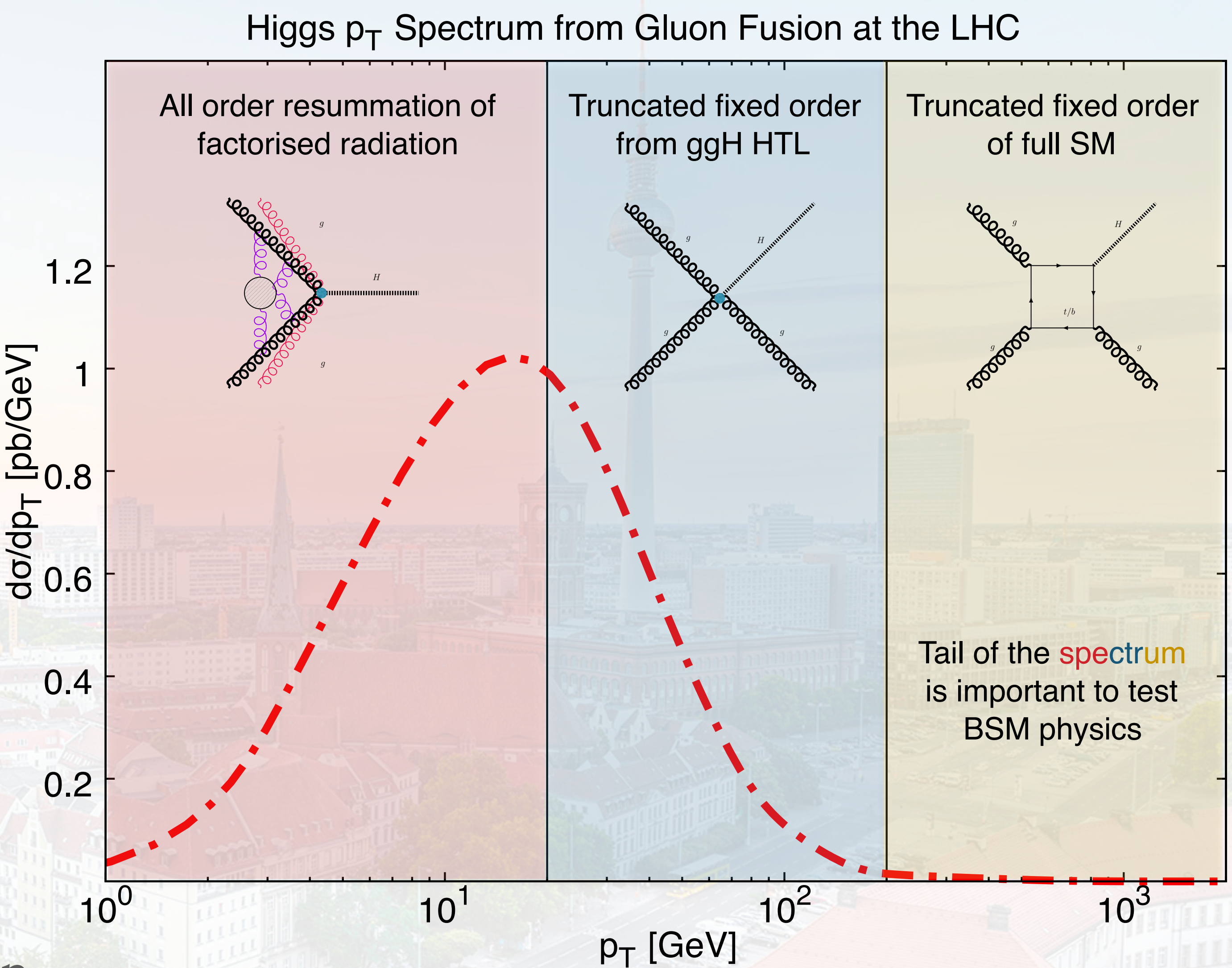


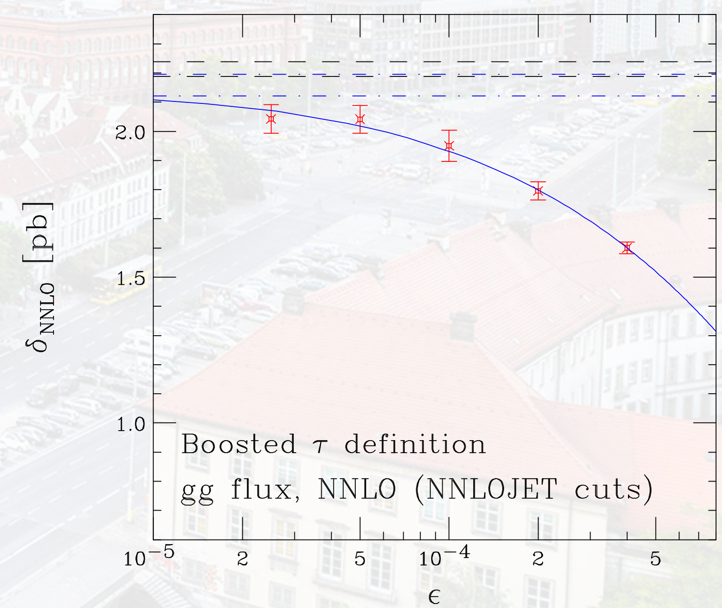
Will separately discuss the pheno in each HpT region next

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, Schulze et al. (1302.6216, 1504.07922)
  - N-Jettiness (BFGLP and MCFM) Boughezal, Focke et al. (1505.03893) Campbell et al. (1906.01020)
- 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)



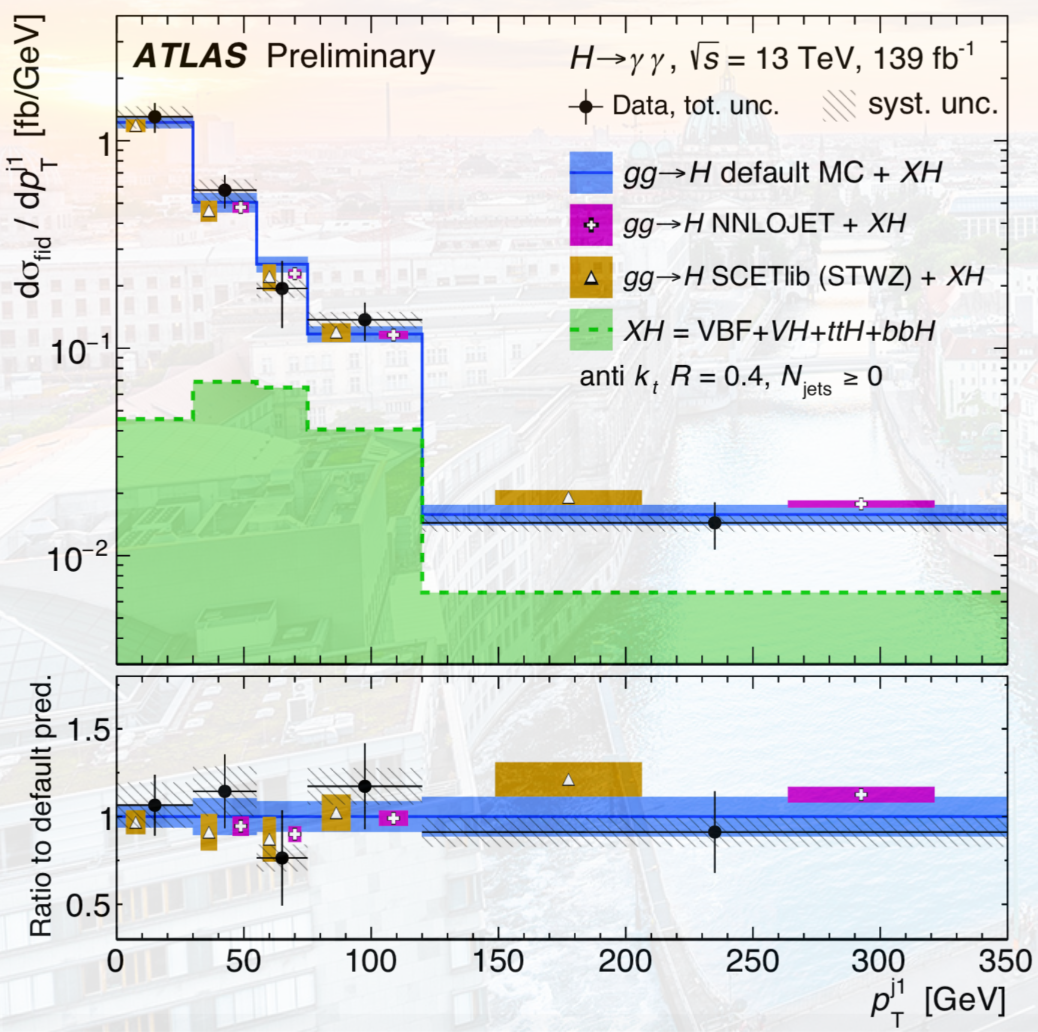
- Finally resolved with MCFM revisit study in this year
  - Jettiness cut 20 times smaller than in BFGLP
  - Extrapolate to zero (~5% @ NNLO)
  - Desire sub-leading power correction at NNLO

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

Campbell et al. (1906.01020)

HIGGS TRANSVERSE MOMENTUM AT **MEDIUM PT**

- Fiducial cross section for H+J now known at NNLO QCD for:
  - $H \to \gamma\gamma$ Caola, Melnikov, Schulze (1508.02684), XC, Gehrmann, Glover et al. (1607.08817)
  - $H \to WW^* \to 2l2\nu$ Caola, Melnikov, Schulze (1508.02684)
  - $H \to ZZ^* \to 4l$ XC, Gehrmann, Glover, Huss (1905.13738)



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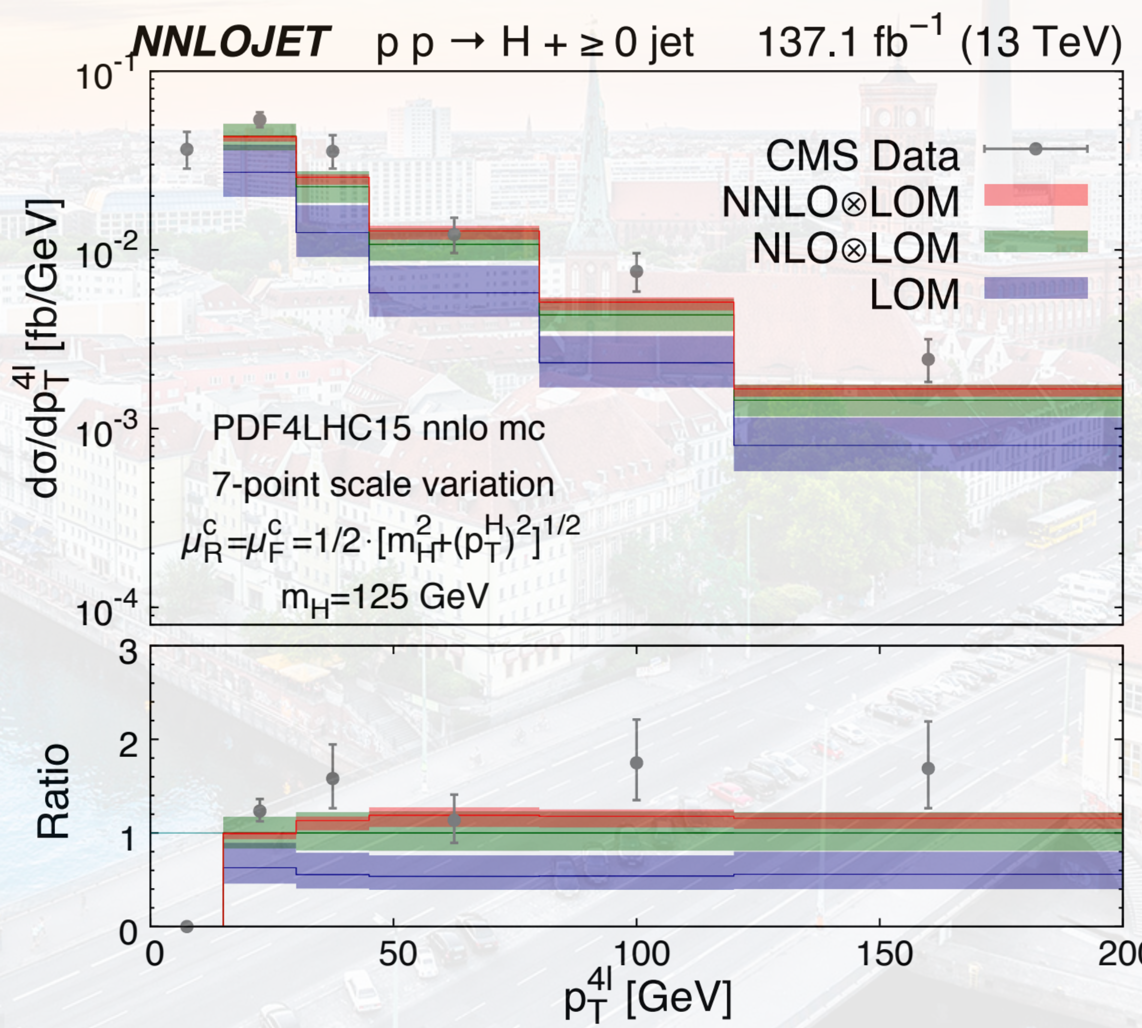

XC, Gehrmann, Glover, Huss (1905.13738)

Exact EXP fiducial region with:

- Photon isolation
- Lepton isolation
- Jet identification
- Top mass @ LO

Good agreement!

HIGGS TRANSVERSE MOMENTUM AT SMALL PT

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

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

$\delta(p_T^H)$ $\quad p_T^H \quad$ $\delta(p_T^H)$ $\quad$ $\delta(p_T^H)$ $\quad$ $\delta(p_T^H)$

  - Finite p_T^H region has no IR regulator $\longrightarrow$ fixed order predictions break down
- How to make reliable predictions of $d\sigma/dp_T^H$ 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.

HIGGS TRANSVERSE MOMENTUM AT SMALL PT

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$$\downarrow \quad \downarrow \quad \downarrow \quad \downarrow \quad \downarrow$$

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

  - Finite p^H_T region has no IR regulator $\longrightarrow$ fixed order predictions break down
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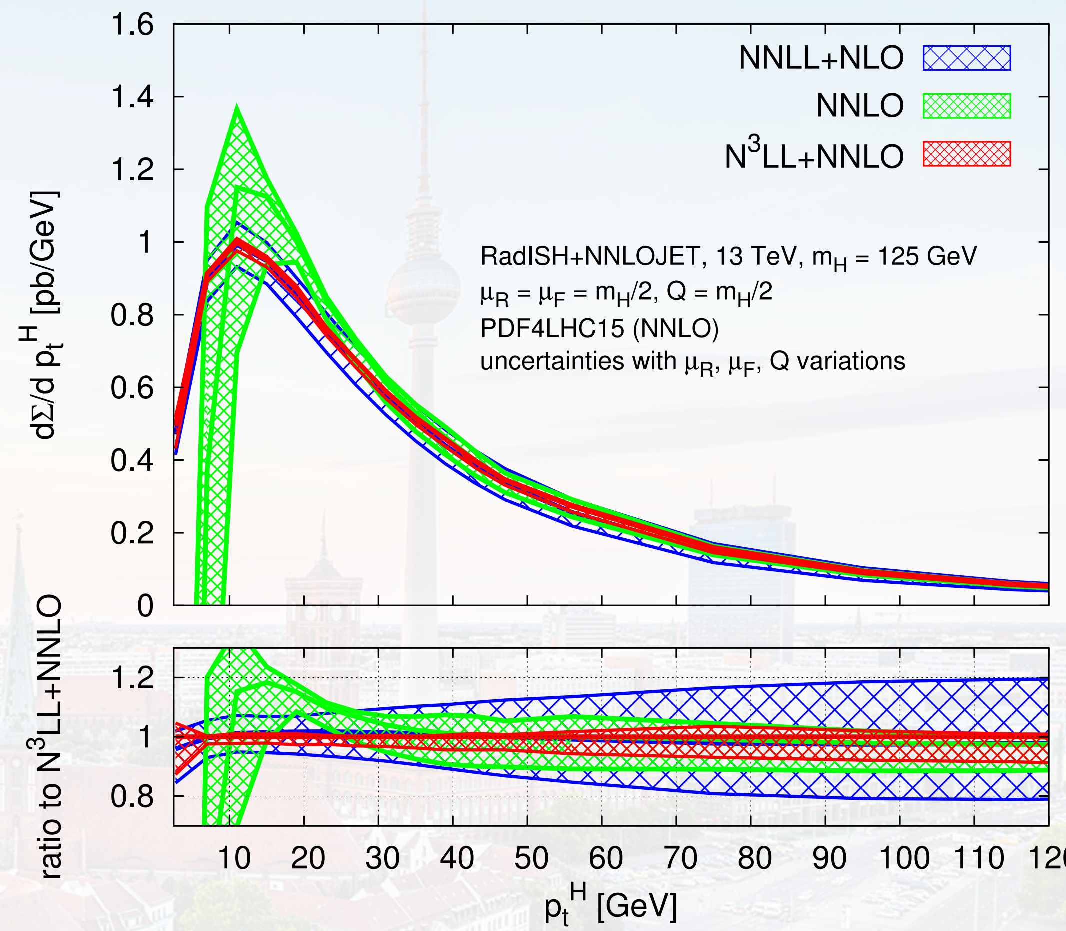
$$d\sigma = \sigma_{LO} \otimes H \otimes B \otimes B \otimes S \otimes J$$

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

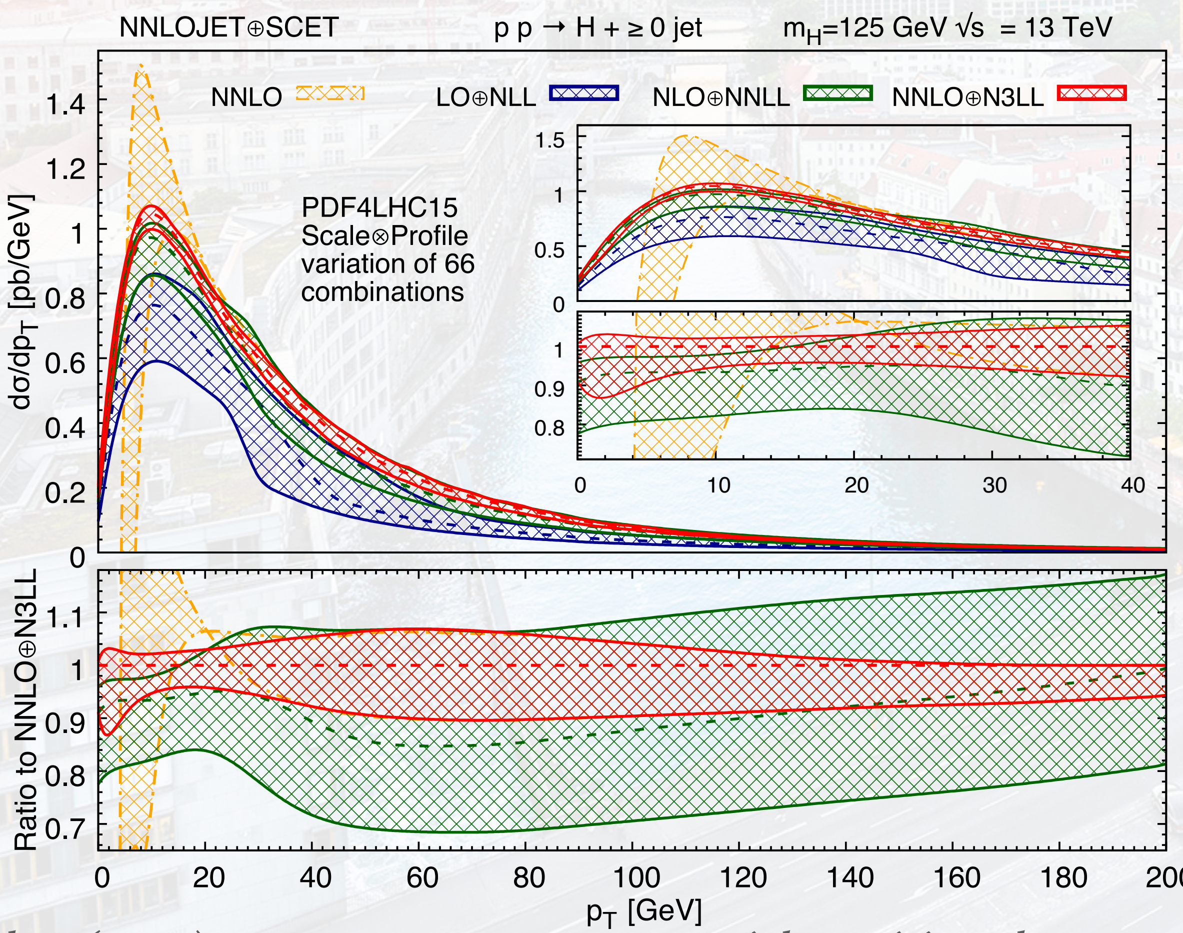
HIGGS TRANSVERSE MOMENTUM SPECTRUM (SMALL+MEDIUM)

- 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



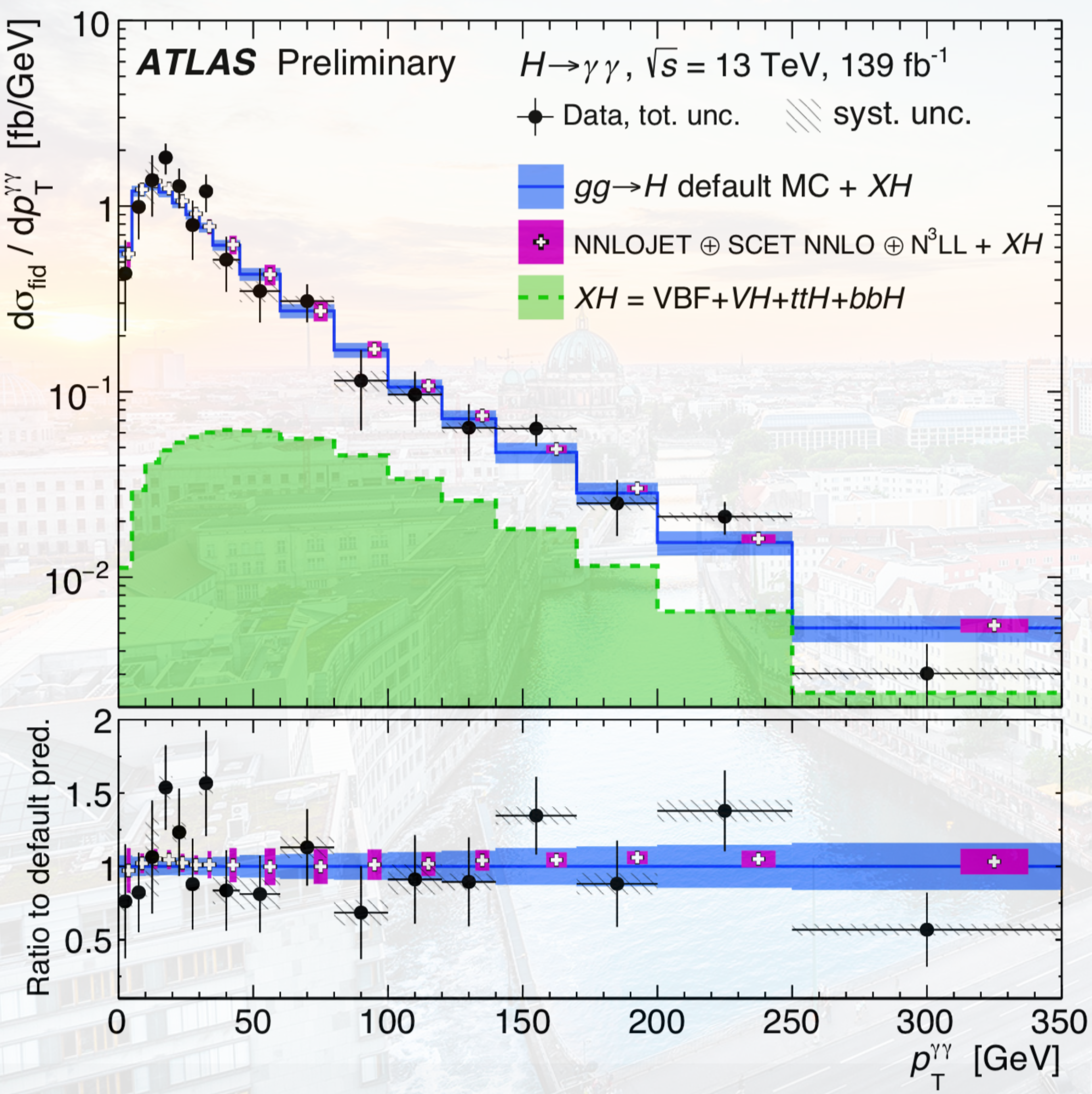
SCET+NNLOJET
1805.00736



- 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



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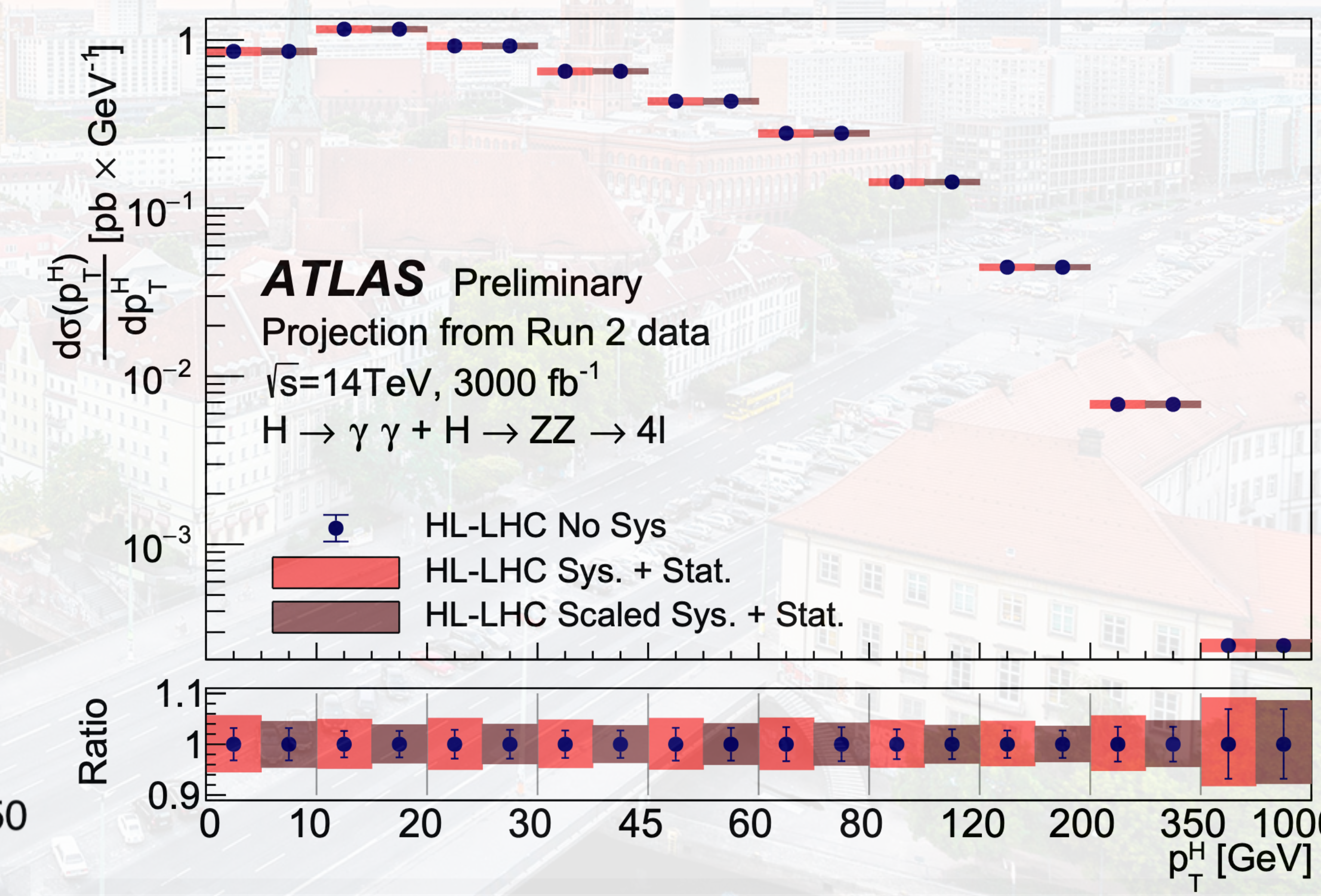
➤ SCET + NNLOJET at N3LL + NNLO

➤ Consistent with LHC full Run II data

➤ EXP uncertainty ± 40%, TH uncertainty ± 8%

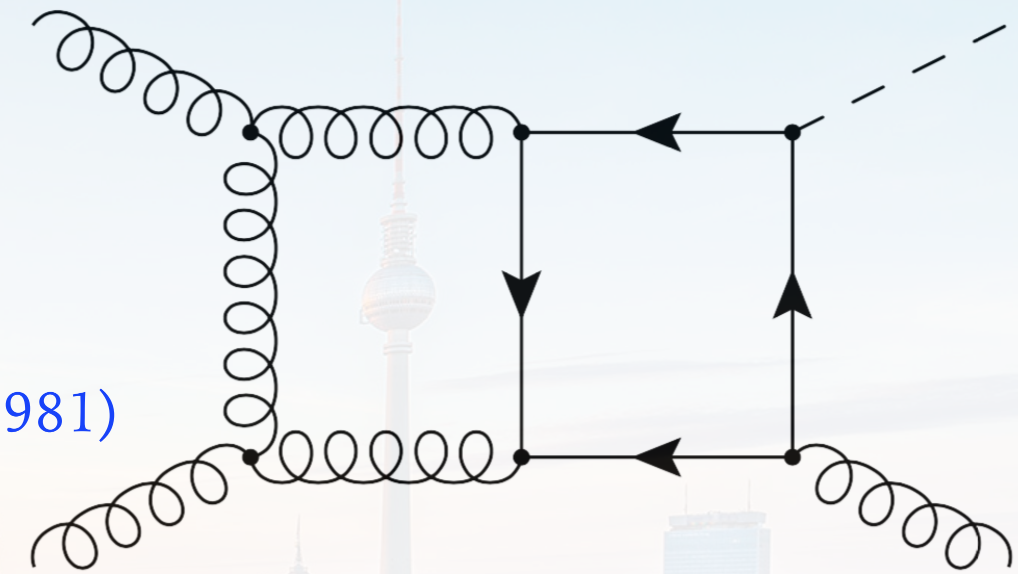
➤ Close to HL-LHC projection uncertainty ± 5% (S2)

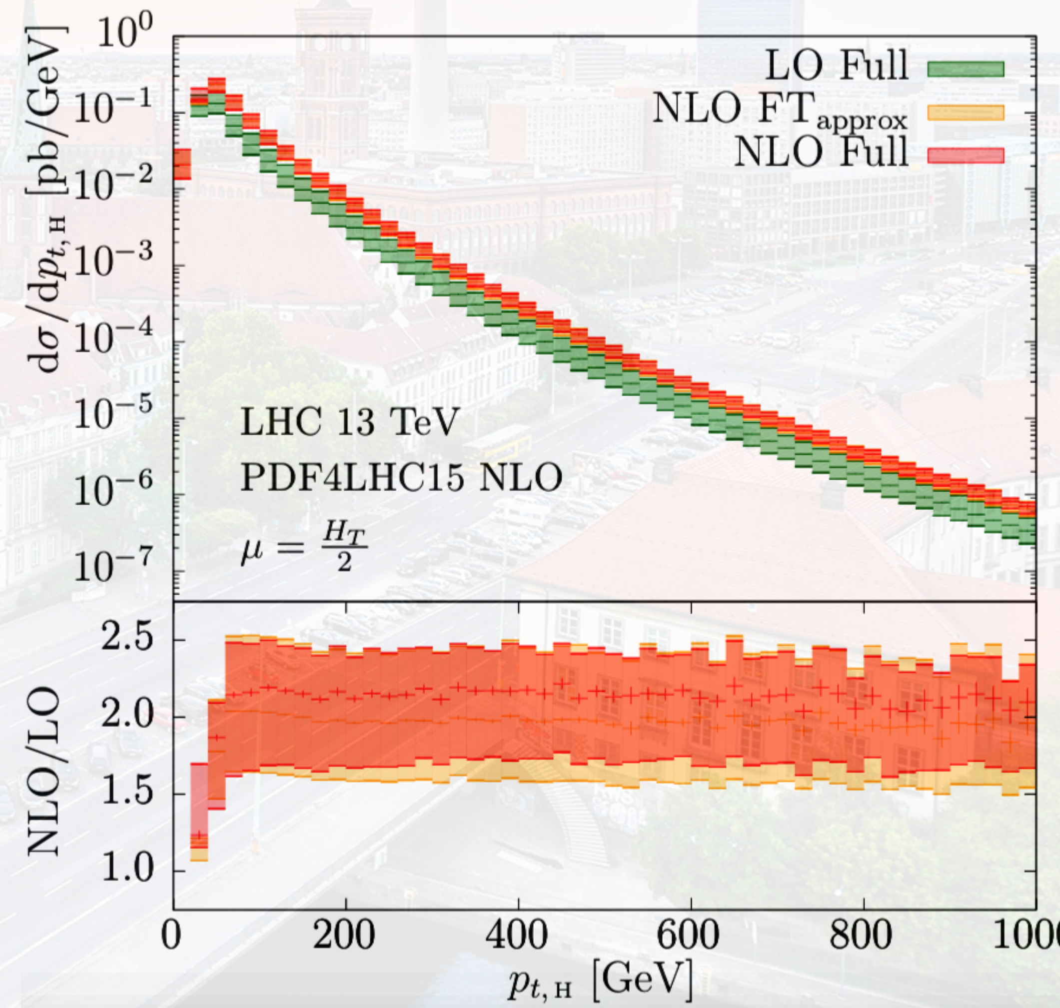


WG2 report on HL-LHC 1902.00134

HIGGS TRANSVERSE MOMENTUM AT BOOSTED REGION

- Expect HTL approximation fail for pT > 200 GeV
- Two approaches to include top mass effects
  - Expansion valid for $m_H^2, m_t^2 \ll |s| \sim |t| \sim |u|$
    Lindert, Kudashkin, et al (1703.03886); Neumann (1802.02981)
  - Exact results (numerical in SecDec)
    Jones, Kerner, Luisoni (1802.00349)
  - Joint effort in HH: exact numerical+expansion
    Davies, Heinrich, Jones, et al. (1907.06408)
- Large NLO/LO K-factor ~ 2
  - K-factor very similar to HTL
  - K-factor nearly flat at large pT
- **Several open questions.....**
  - Combination with NNLO HTL
  - Top-quark mass scheme uncertainty OS/MSbar
  - Numerical stability of P.S. at large pT

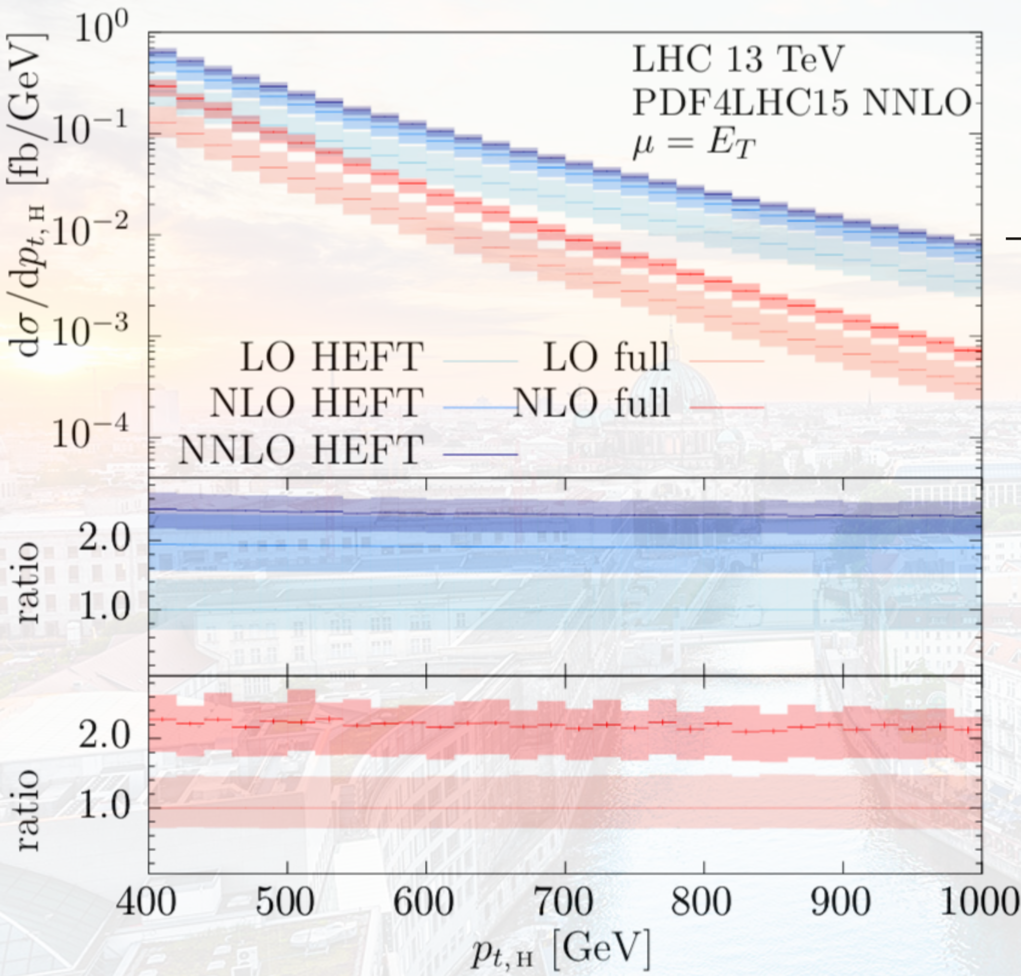




Jones, Kerner, Luisoni (1802.00349)

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

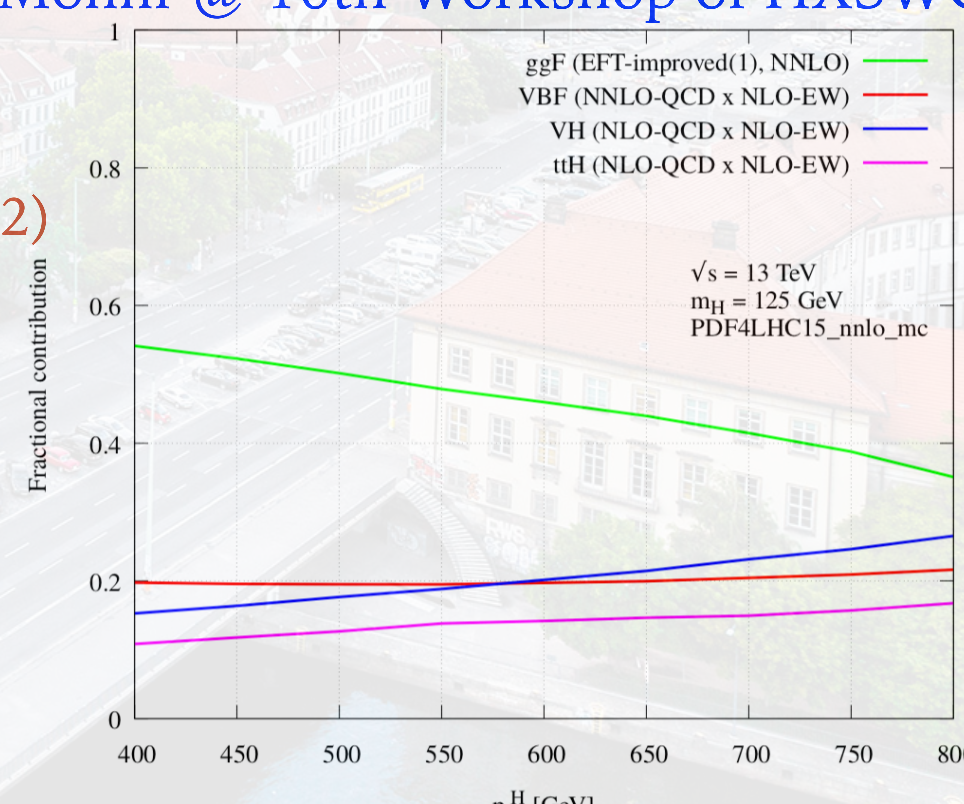


$$\Sigma^{\text{EFT-improved (1), NNLO}}(p_\perp^{\text{cut}}) = \frac{\Sigma^{\text{QCD, NLO}}(p_\perp^{\text{cut}})}{\Sigma^{\text{EFT, NLO}}(p_\perp^{\text{cut}})}\,\Sigma^{\text{EFT, NNLO}}(p_\perp^{\text{cut}})$$

p_T^{cut}	$\text{NNLO}^{\text{approximate}}_{\text{quad.unc.}}$ [fb]	HJ-MINLO [fb]	MG5_MC@NLO [fb]
400 GeV	$33.3^{+10.9\%}_{-12.9\%}$	$29^{+24\%}_{-21\%}$	$31.5^{+31\%}_{-25\%}$
430 GeV	$23.0^{+10.8\%}_{-12.8\%}$	-	$21.8^{+31\%}_{-25\%}$
450 GeV	$18.1^{+10.8\%}_{-12.8\%}$	$16.1^{+22\%}_{-21\%}$	$17.1^{+31\%}_{-25\%}$

Pier Monni @ 16th Workshop of HXSWG

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

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:

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

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

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

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

- 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)

HIGGS PRODUCTION AT N3LO (APPROXIMATED)

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

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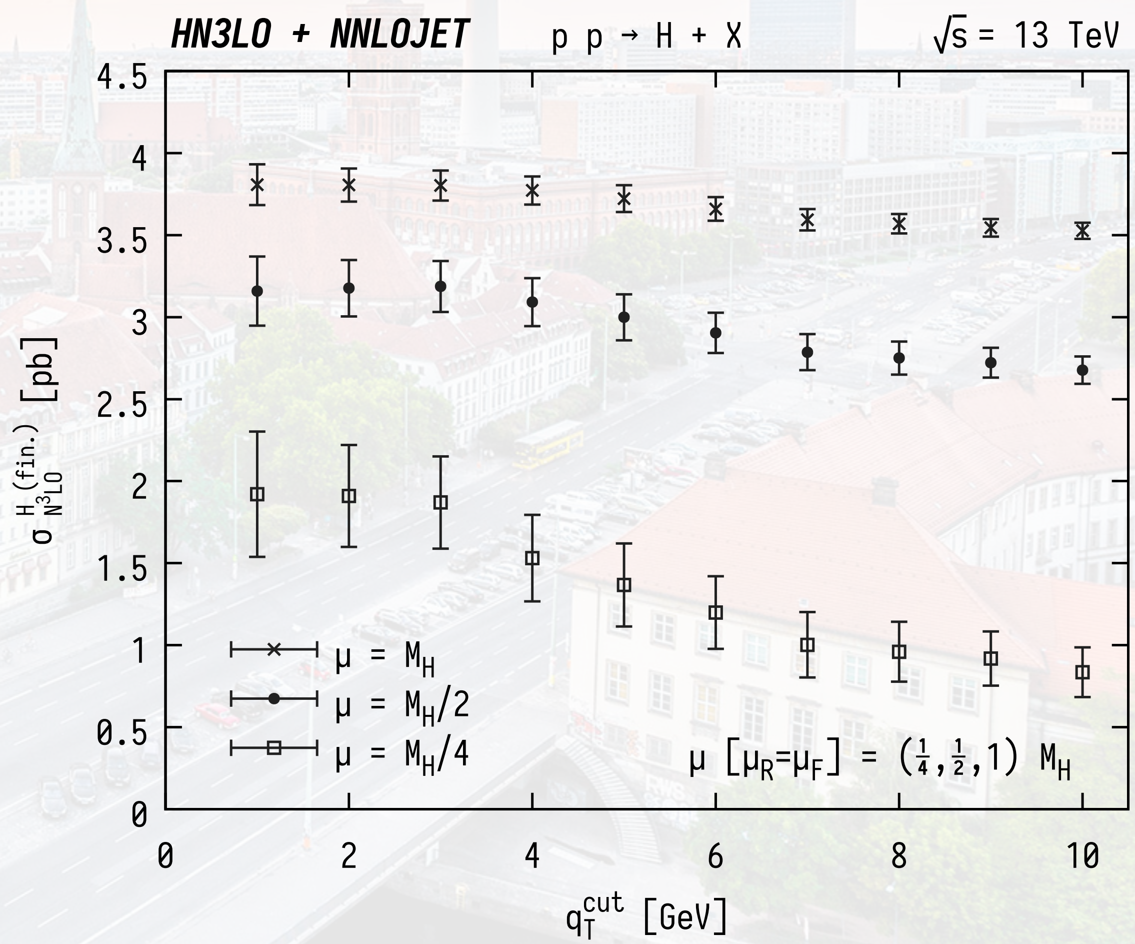

- Numerically abstract the C_{N3} coefficient using exact N3LO total cross section (1802.00833, 1802.00827)

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

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

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

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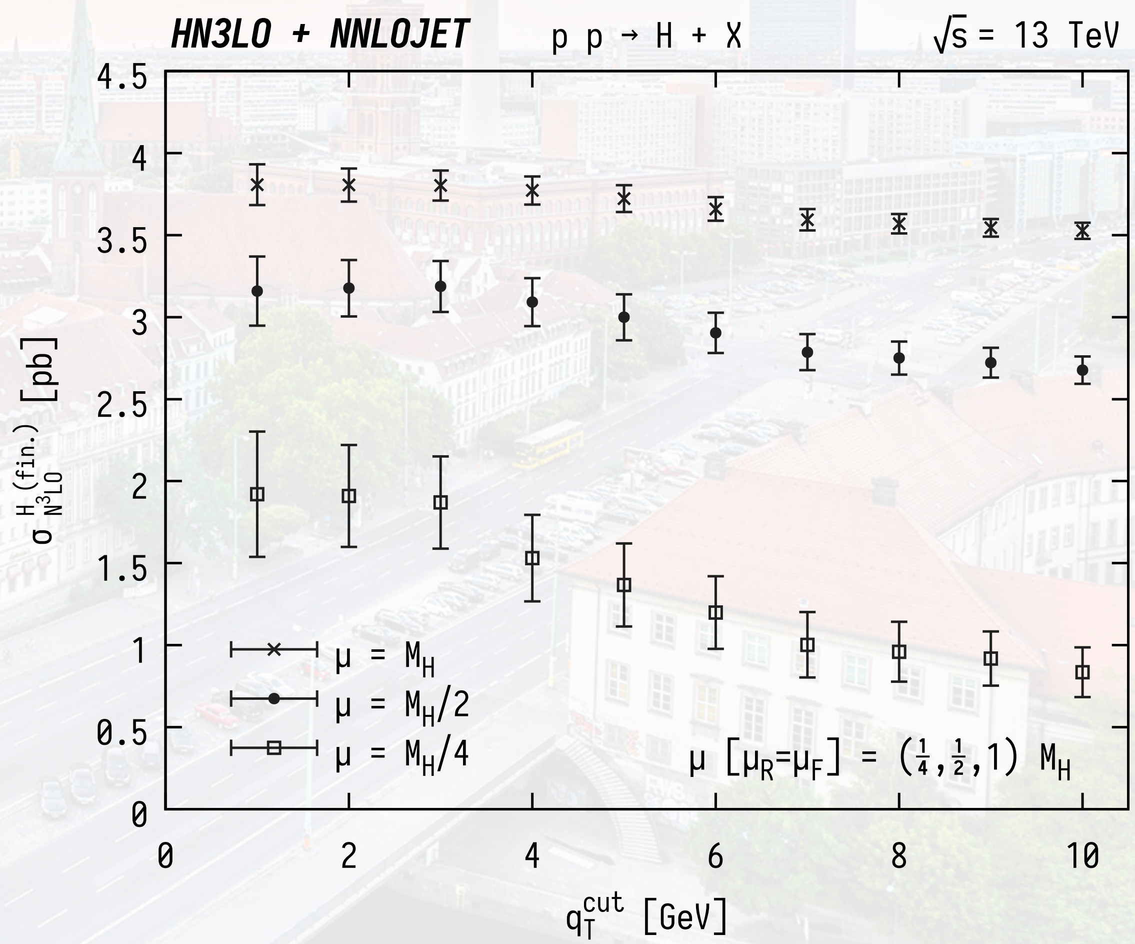
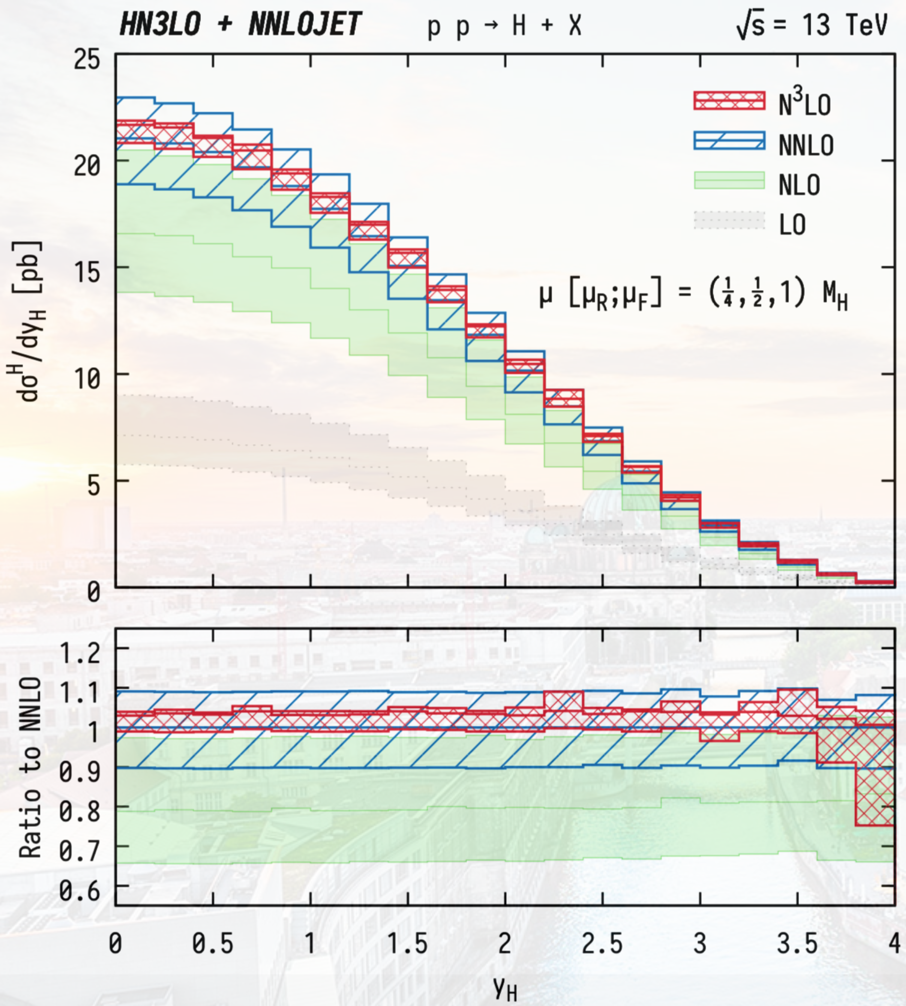


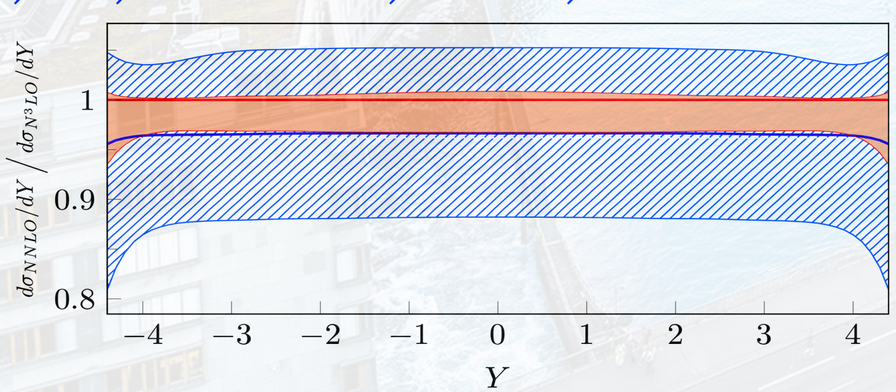
- Numerically abstract the C_{N3} coefficient using exact N3LO total cross section (1802.00833, 1802.00827).

HIGGS RAPIDITY DISTRIBUTIONS AT N3LO (APPROXIMATED)

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

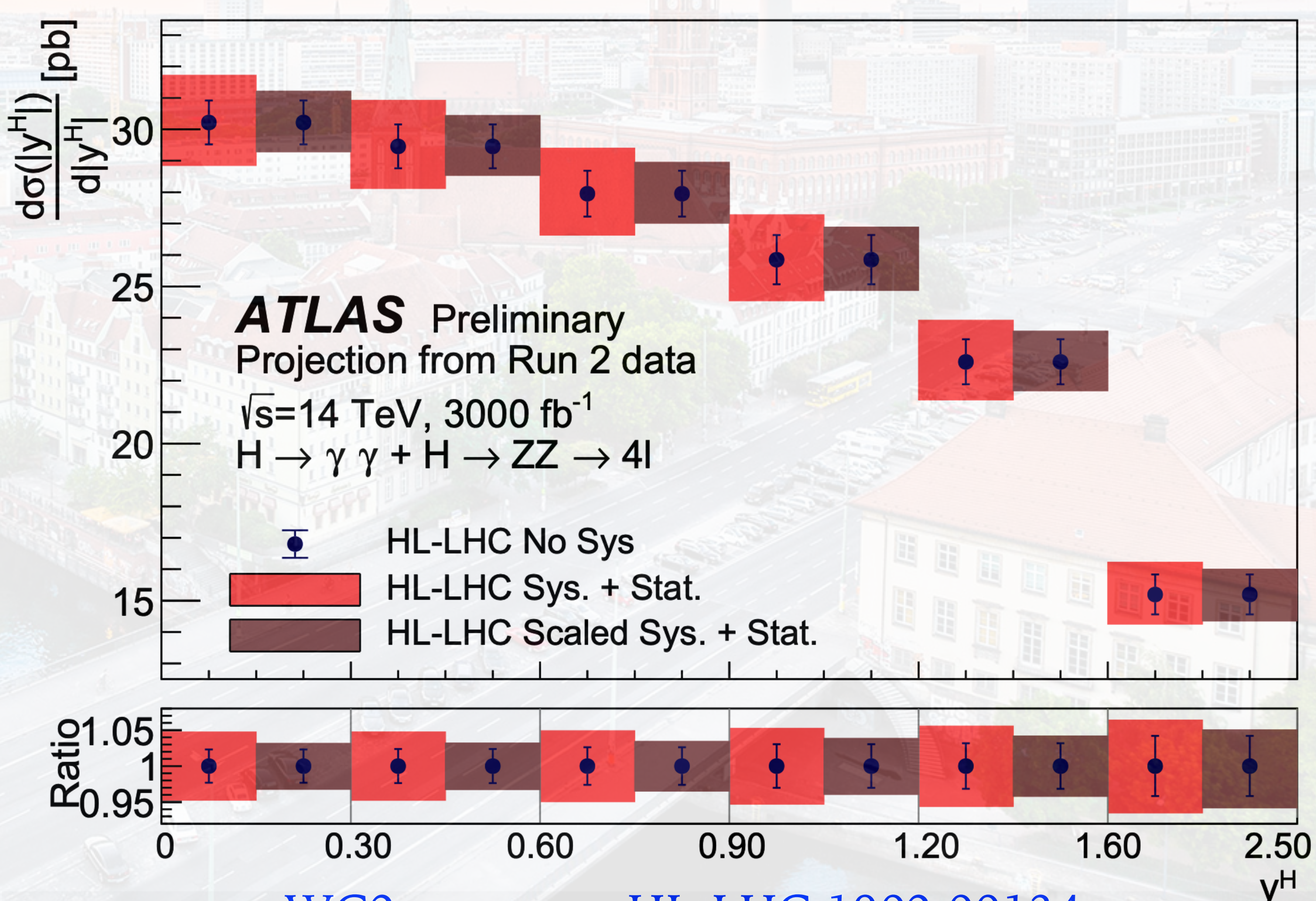


Cieri, XC, Gehrmann, Glover, Huss 1807.11501



Dulat, Mistlberger, Pelloni 1810.09462

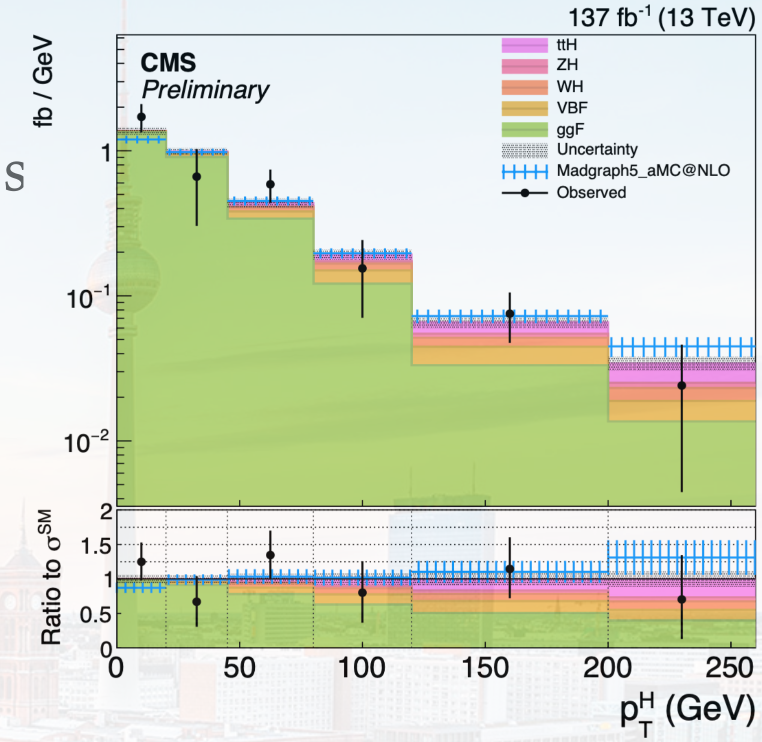
- Remarkably flat K-factor (as expected)
- QCD scale uncertainty reduced to $^{+1\%}_{-3\%}$
- Comparable to (S2) HL-LHC projections ± 3%
- Future upgrade to reduce PDF and α_s uncertainties



WG2 report on HL-LHC 1902.00134

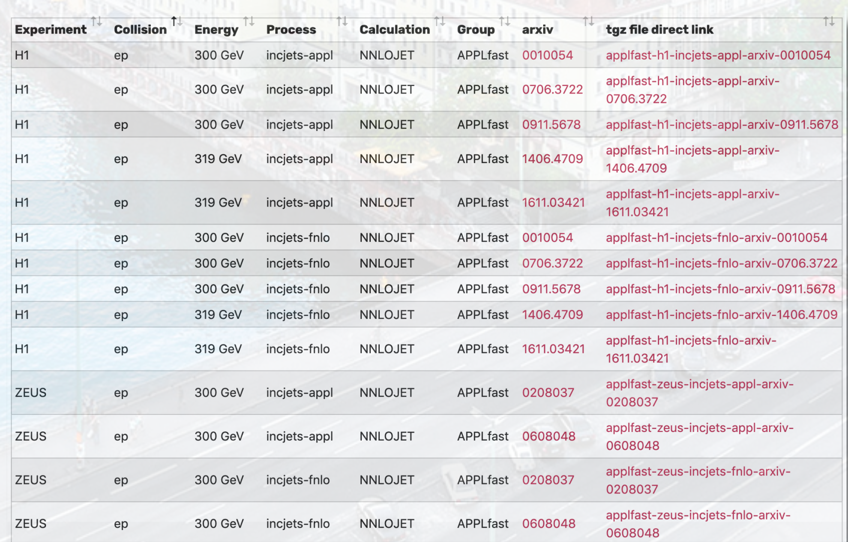
FUTURE WORK

- 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
  - NNLO corrections of γ+JJ, $\gamma\gamma$+J, JJJ productions



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

http://ploughshare.web.cern.ch



Experiment	Collision	Energy	Process	Calculation	Group	arxiv	tgz file direct link
H1	ep	300 GeV	incjets-appl	NNLOJET	APPLfast	0010054	applfast-h1-incjets-appl-arxiv-0010054
H1	ep	300 GeV	incjets-appl	NNLOJET	APPLfast	0706.3722	applfast-h1-incjets-appl-arxiv-0706.3722
H1	ep	300 GeV	incjets-appl	NNLOJET	APPLfast	0911.5678	applfast-h1-incjets-appl-arxiv-0911.5678
H1	ep	319 GeV	incjets-appl	NNLOJET	APPLfast	1406.4709	applfast-h1-incjets-appl-arxiv-1406.4709
H1	ep	319 GeV	incjets-appl	NNLOJET	APPLfast	1611.03421	applfast-h1-incjets-appl-arxiv-1611.03421
H1	ep	300 GeV	incjets-fnlo	NNLOJET	APPLfast	0010054	applfast-h1-incjets-fnlo-arxiv-0010054
H1	ep	300 GeV	incjets-fnlo	NNLOJET	APPLfast	0706.3722	applfast-h1-incjets-fnlo-arxiv-0706.3722
H1	ep	300 GeV	incjets-fnlo	NNLOJET	APPLfast	0911.5678	applfast-h1-incjets-fnlo-arxiv-0911.5678
H1	ep	319 GeV	incjets-fnlo	NNLOJET	APPLfast	1406.4709	applfast-h1-incjets-fnlo-arxiv-1406.4709
H1	ep	319 GeV	incjets-fnlo	NNLOJET	APPLfast	1611.03421	applfast-h1-incjets-fnlo-arxiv-1611.03421
ZEUS	ep	300 GeV	incjets-appl	NNLOJET	APPLfast	0208037	applfast-zeus-incjets-appl-arxiv-0208037
ZEUS	ep	300 GeV	incjets-appl	NNLOJET	APPLfast	0608048	applfast-zeus-incjets-appl-arxiv-0608048
ZEUS	ep	300 GeV	incjets-fnlo	NNLOJET	APPLfast	0208037	applfast-zeus-incjets-fnlo-arxiv-0208037
ZEUS	ep	300 GeV	incjets-fnlo	NNLOJET	APPLfast	0608048	applfast-zeus-incjets-fnlo-arxiv-0608048

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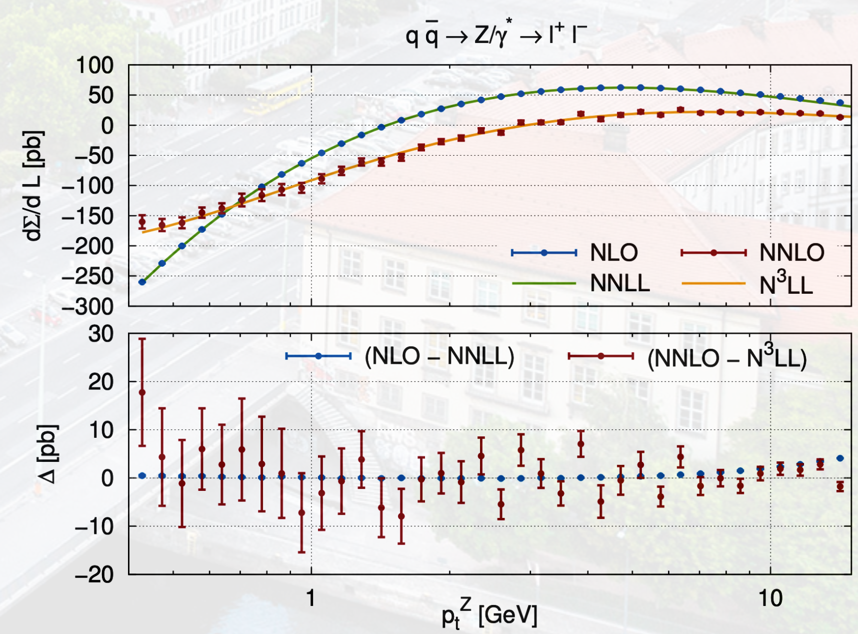


Bizoń, XC, et al. 1805.05916

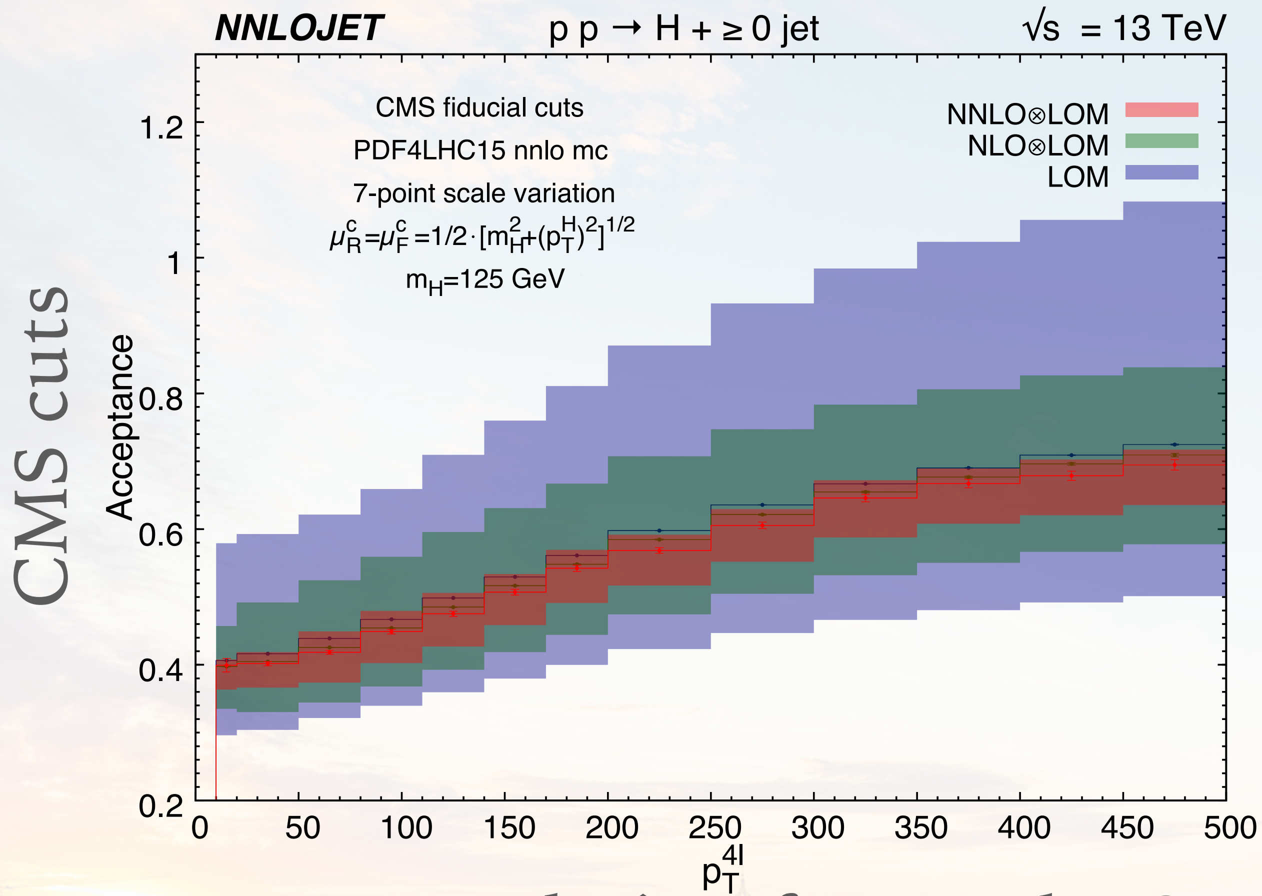
SUMMARY

- 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 α_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.

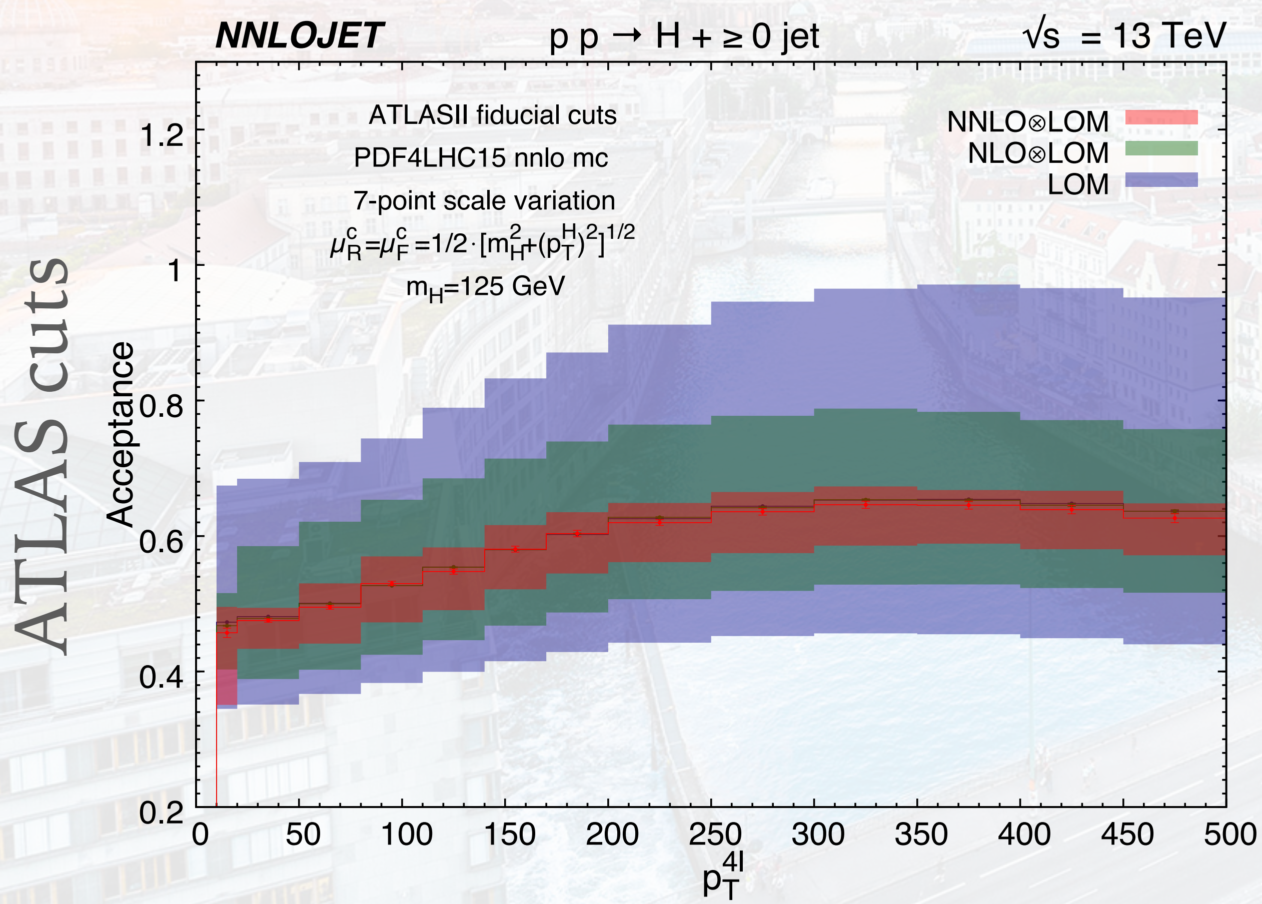
Thank You for your Attention

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)

ACCEPTANCE STUDY
$H \to ZZ^* \to 4l$



Acceptance deviate from each FO



Acceptance consistent for each FO

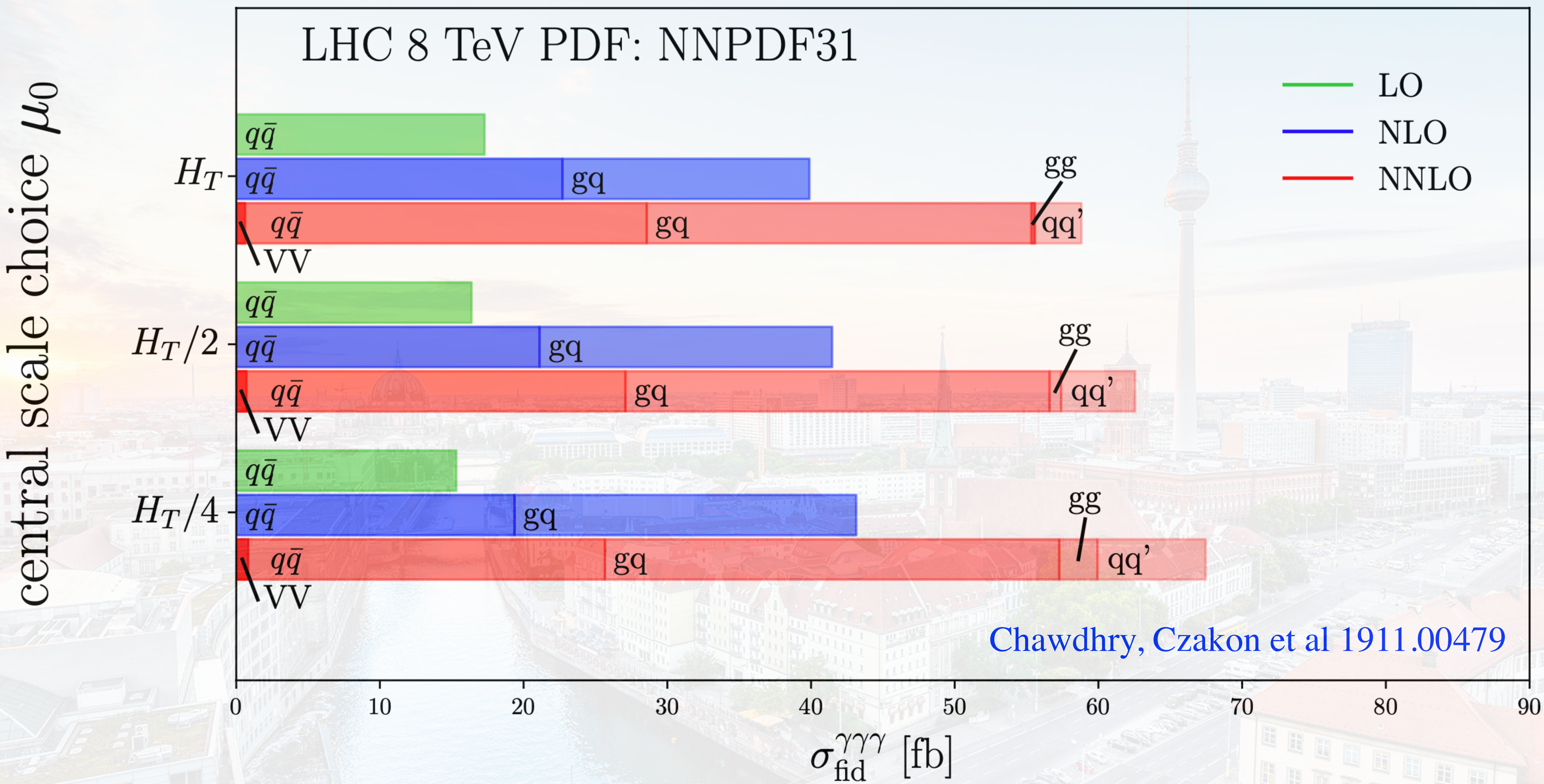
- CMS (1706.09936) and ATLAS (1708.02810) use different lepton isolation algorithm in $ZZ^* \to 4l$

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

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

APPROXIMATION IN $pp \rightarrow \gamma\gamma\gamma$ @NNLO



- Anatomy of higher-order corrections to the three-photon fiducial cross-section
- VV is the scale-independent part of the two-loop finite remainder (CL without quark loop)
- The missing contributions are expected to be similar or less than current VV