Higgs production: yields and kinematical distributions

Emanuele Re

CERN & LAPTh Annecy

Theorie LHC France workshop

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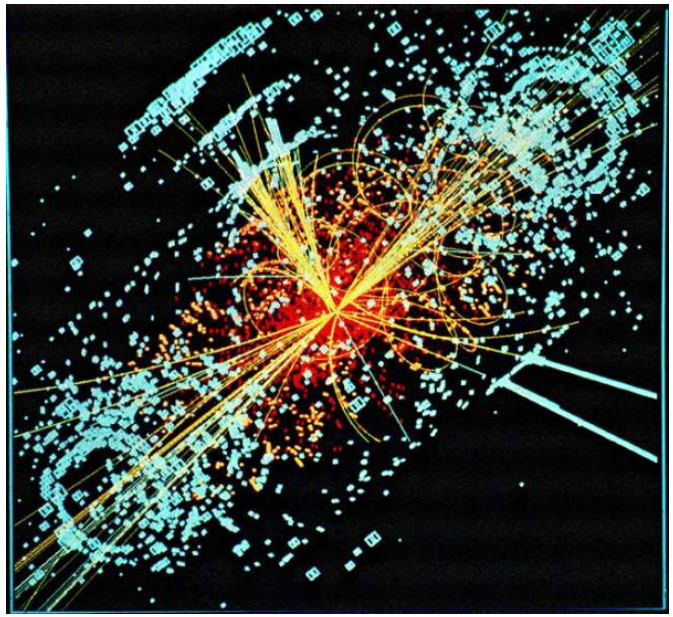
outline

- precision in Higgs physics is (and will be) an important topic in Run II and beyond

- this talk: biased selection of recent theoretical results relevant for Higgs phenomenology:

1. total cross sections
2. differential distributions (at fixed-order and matched with resummation)
3. Monte Carlo tools



disclaimer:
. by no means this talk is fully comprehensive (for instance, EW effects not covered)
. I will focus mostly on gluon-fusion and VBF processes
. apologies in advance for leaving out important results

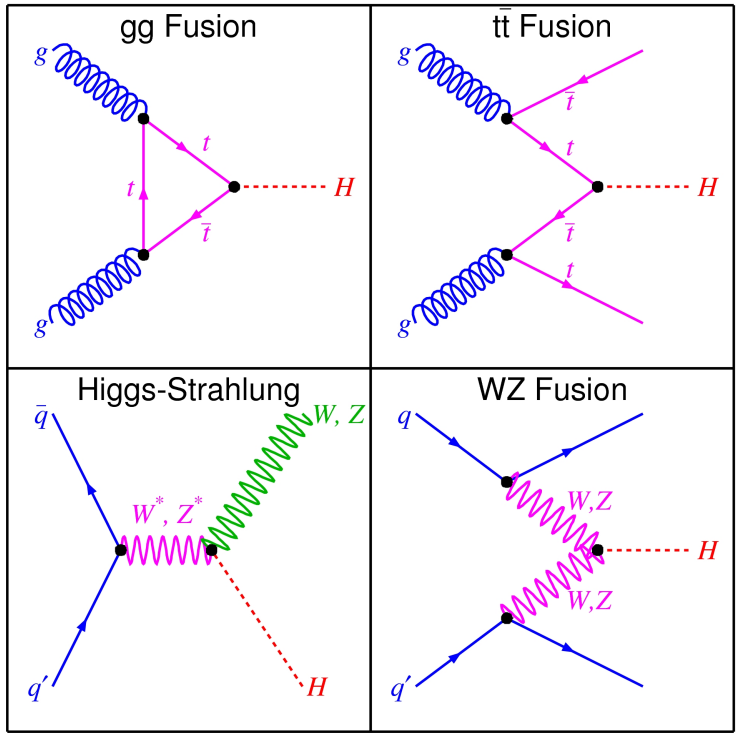
Higgs production at the LHC: cross-sections

gluon-fusion

- total: N3LO (+N3LL)
- differential: NNLO

$t\bar{t}H$

- total: NLO (+ NNLL)
- differential: NLO



VH

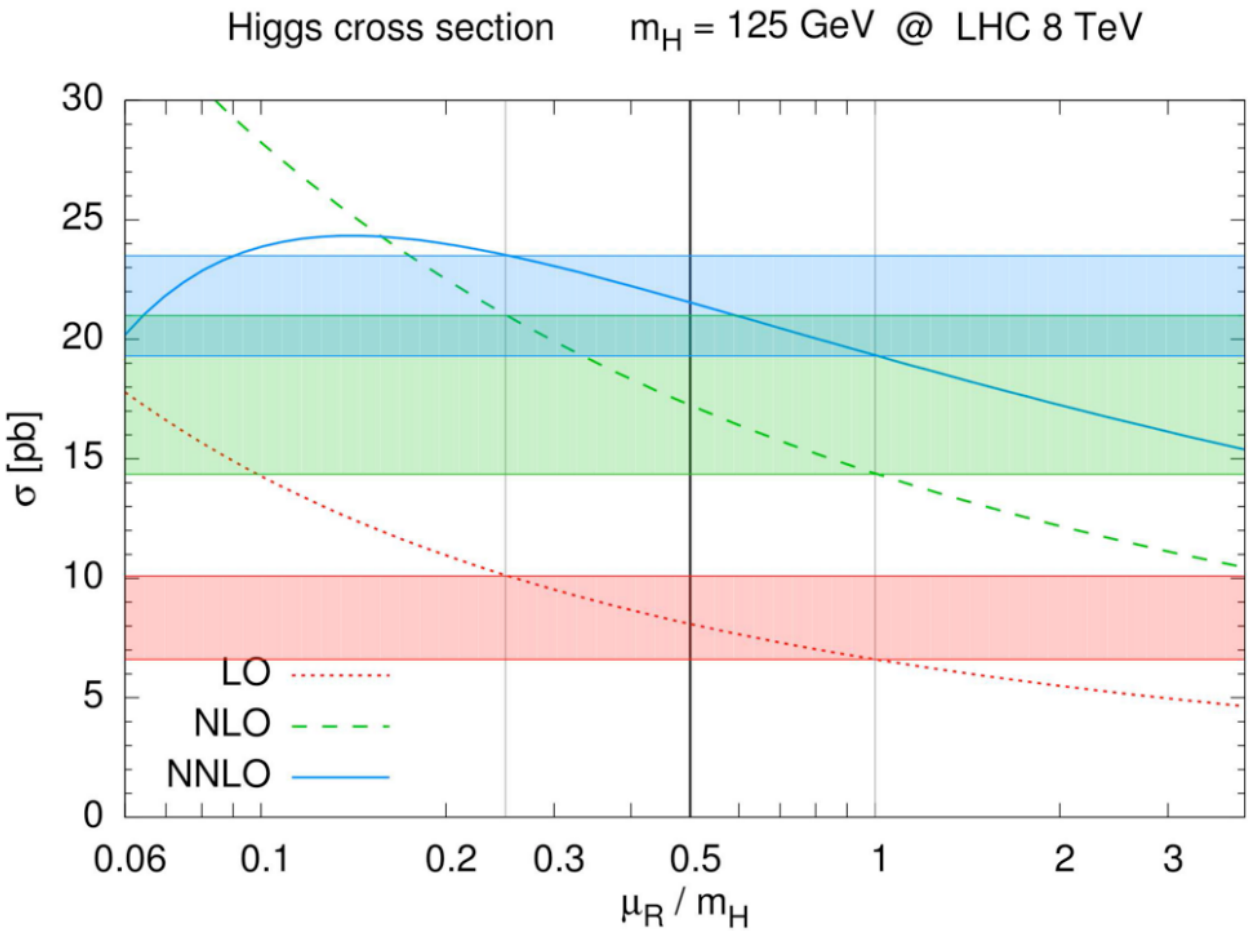
- total: NNLO
- differential: NNLO

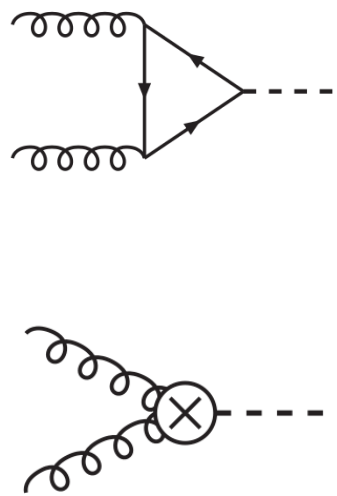
vector-boson fusion

- total: N3LO
- differential: NNLO

the Higgs cross section

- to measure Higgs properties, need to know Higgs production cross section
  - $gg \to H$ is the dominant production mechanism at the LHC
- known at NLO [Dawson; Djouadi et al.] and NNLO [Harlander,Kilgore; Anastasiou,Melnikov; Ravindran et al.]





- perturbative series: converges very slowly
- large perturbative uncertainties (estimated by scale variation)

gluon-fusion Higgs production at N3LO

- the $gg \to H$ cross section is now know at N3LO !

  [Anastasiou,Duhr,Dulat,Herzog,Mistlberger (+Furlan,Gehrmann) '14-'15]

gluon-fusion Higgs production at N3LO

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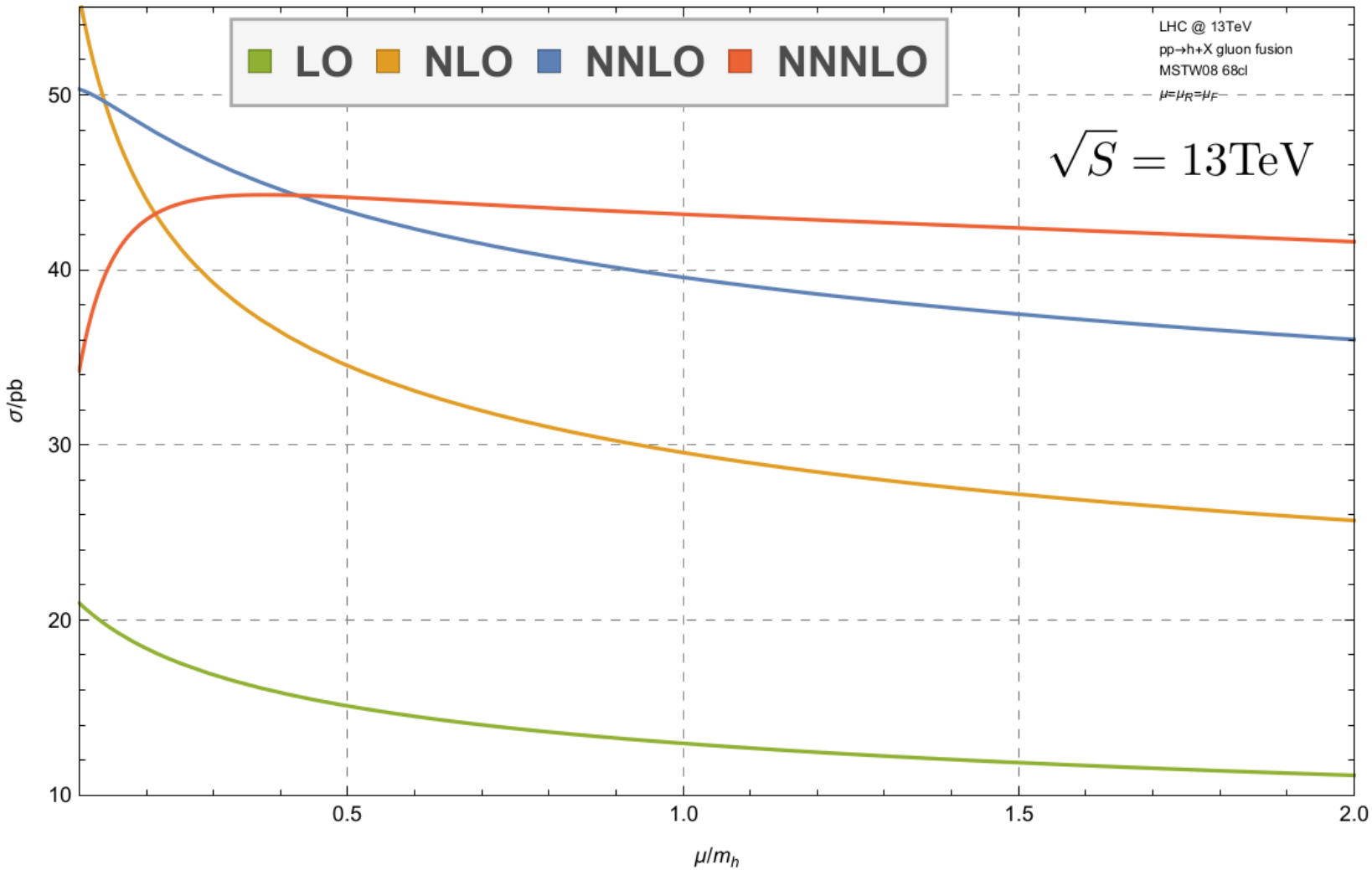
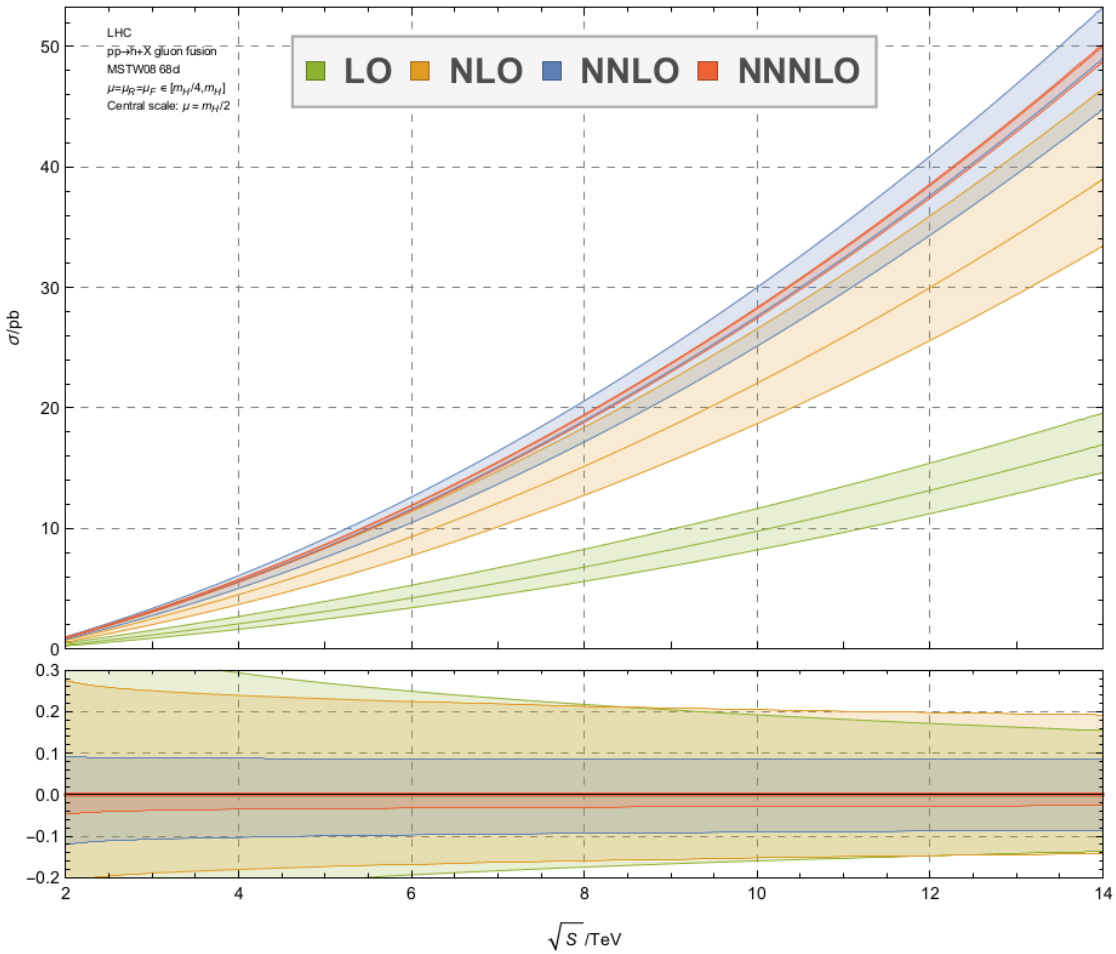


- N3LO result: exact soft-virtual + expansion around threshold [$N \simeq 30$]

$$\frac{\hat{\sigma}_{ij}(z)}{z} = \hat{\sigma}^{\text{SV}}\delta_{ig}\delta_{jg} + \sum_{N=0}^{\infty} \hat{\sigma}_{ij}^{(N)}(1-z)^N \quad \text{where} \quad z = m_H^2/\hat{s}$$

gluon-fusion Higgs production at N3LO

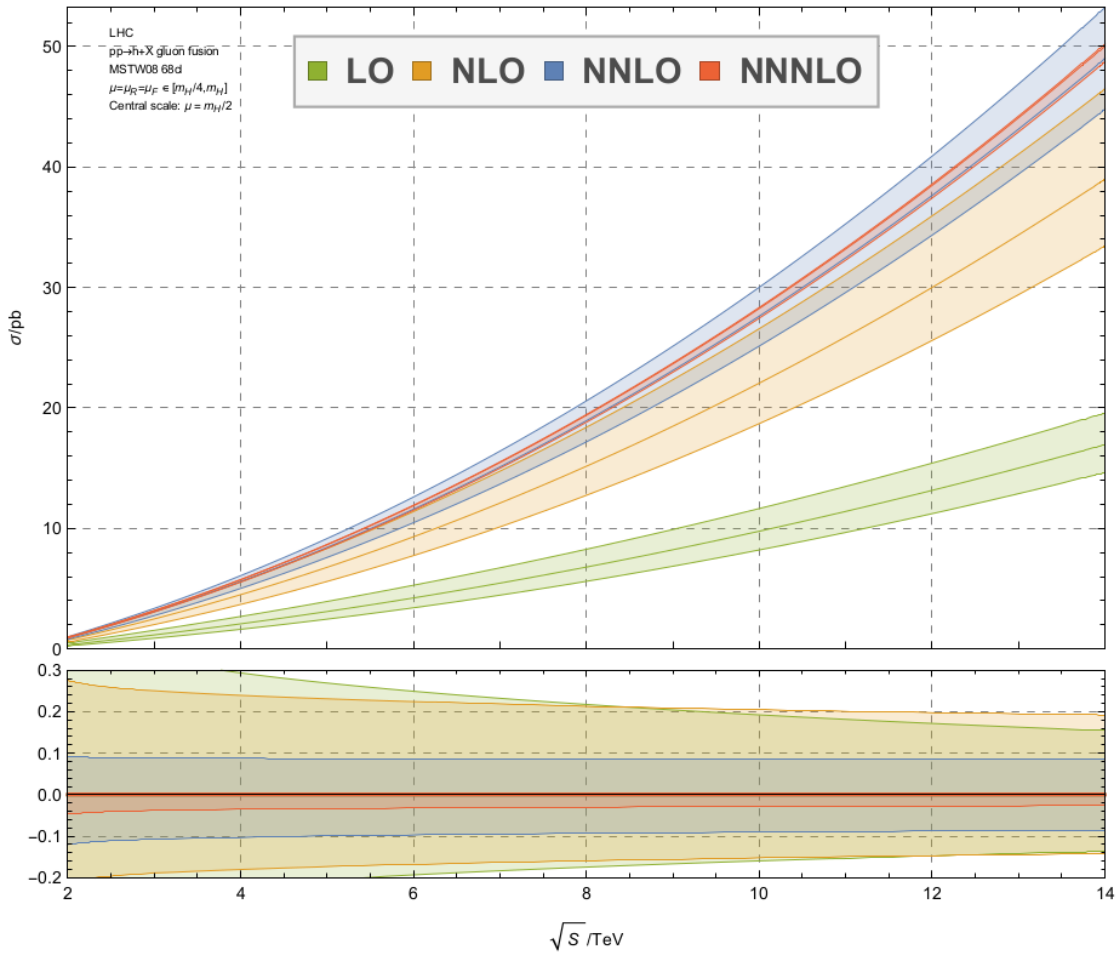
[Anastasiou,Duhr,Dulat,Herzog,Mistlberger (+Furlan,Gehrmann) '14-'15]



- N3LO result: perturbative uncertainties drastically reduced [± 2 %]
- consider residual effects: $(1/m_t)$, threshold resummation , missing N3LO PDFs , PDFs+α_S , EW effects...

gluon-fusion Higgs production at N3LO

[Anastasiou,Duhr,Dulat,Furlan,Gehrmann,Herzog,Lazopoulos,Mistlberger '16]



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$$\sigma = 48.58\,\text{pb}^{+2.22\,\text{pb}\,(+4.56\%)}_{-3.27\,\text{pb}\,(-6.72\%)}\ (\text{theory}) \pm 1.56\,\text{pb}\,(3.20\%)\ (\text{PDF}+\alpha_s)\,.$$

gluon-fusion Higgs production at N3LO

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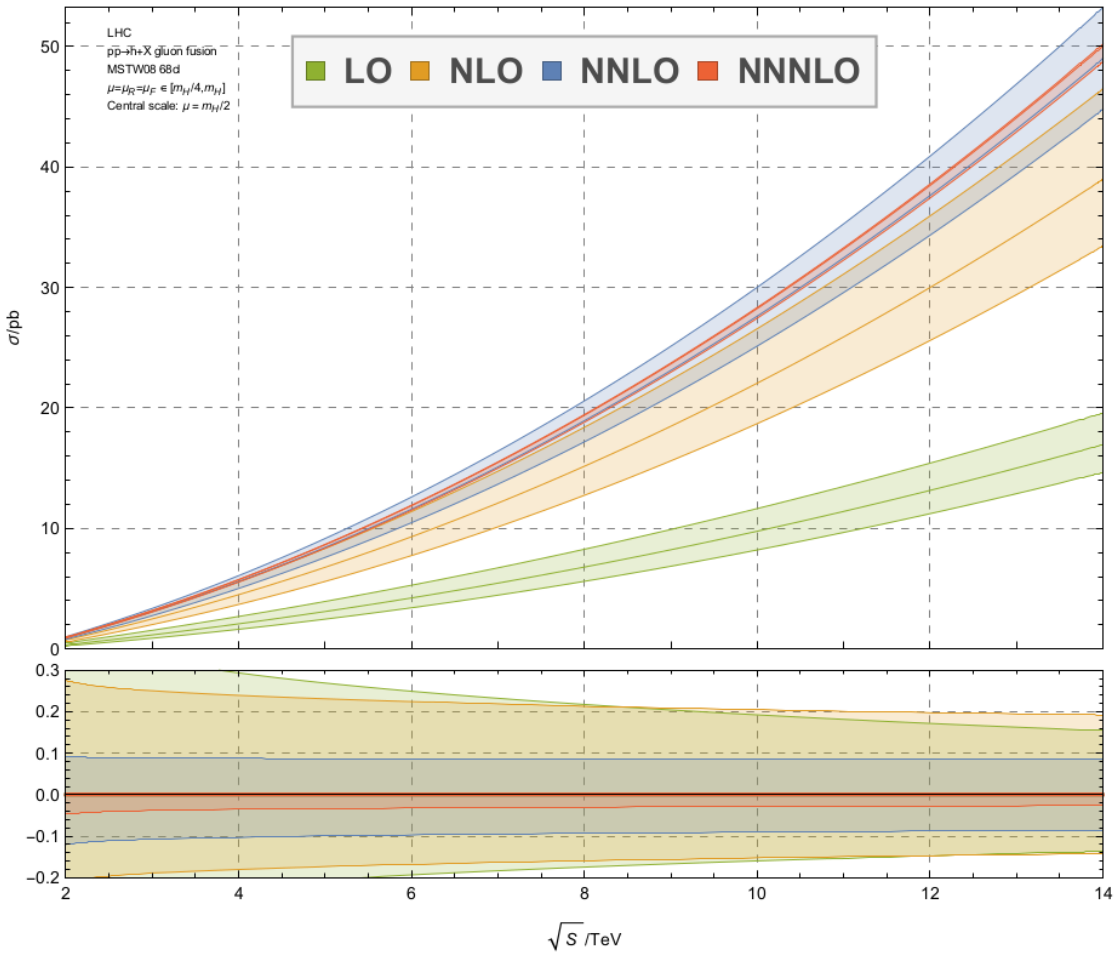

- N3LO result: perturbative uncertainties drastically reduced [± 2 %]
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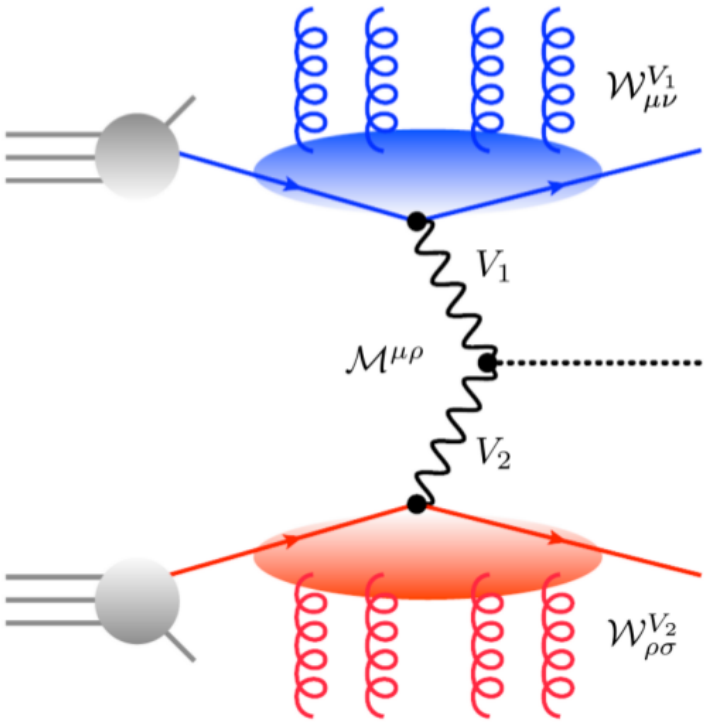
δ(scale)	δ(trunc)	δ(PDF-TH)	δ(EW)	$\delta(t,b,c)$	$\delta(1/m_t)$
$^{+0.10\text{ pb}}_{-1.15\text{ pb}}$	± 0.18 pb	± 0.56 pb	± 0.49 pb	± 0.40 pb	± 0.49 pb
$^{+0.21\%}_{-2.37\%}$	$\pm 0.37\%$	$\pm 1.16\%$	$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$

VBF (inclusive) Higgs production at N3LO

- the vector-boson fusion cross section is now also know at N3LO !

[Dreyer,Karlberg '16]



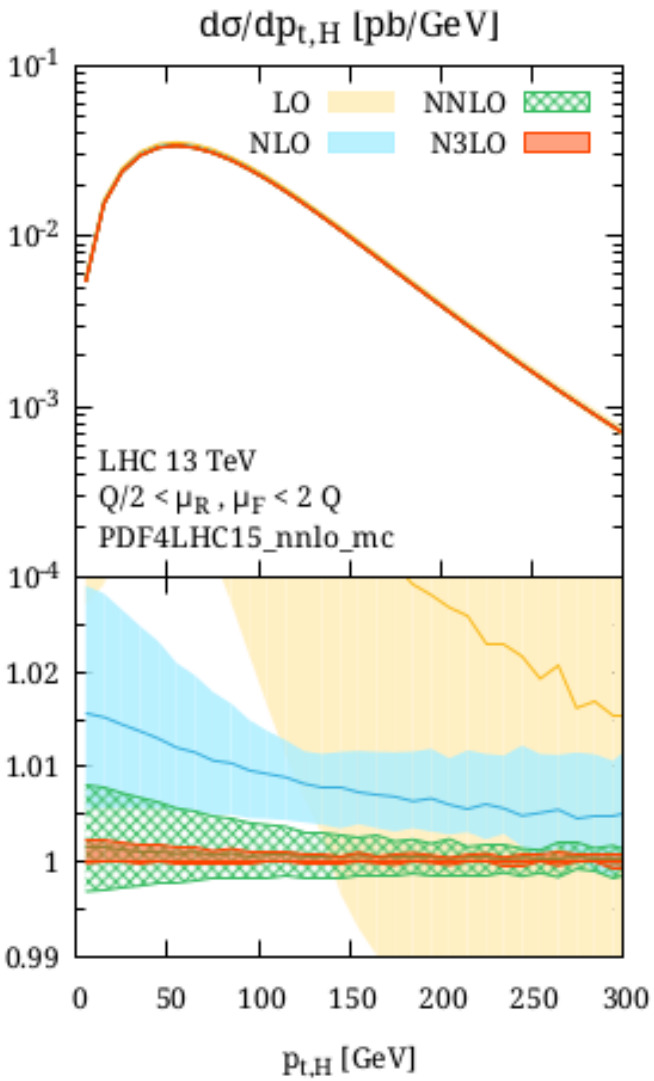
. "structure function approach:
VBF $\simeq$ DIS $\times$ DIS

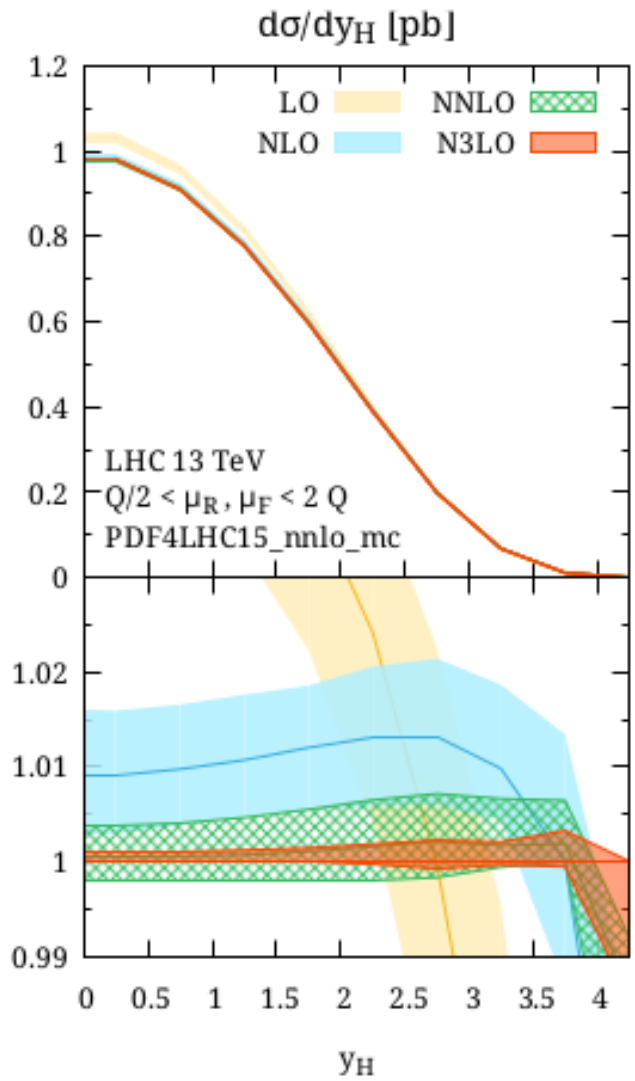
. DIS coefficient known at N3LO

. inclusive over radiation, but exclusive over Higgs distributions (Q_1 and Q_2 known)

VBF (inclusive) Higgs production at N3LO

[Dreyer,Karlberg '16]

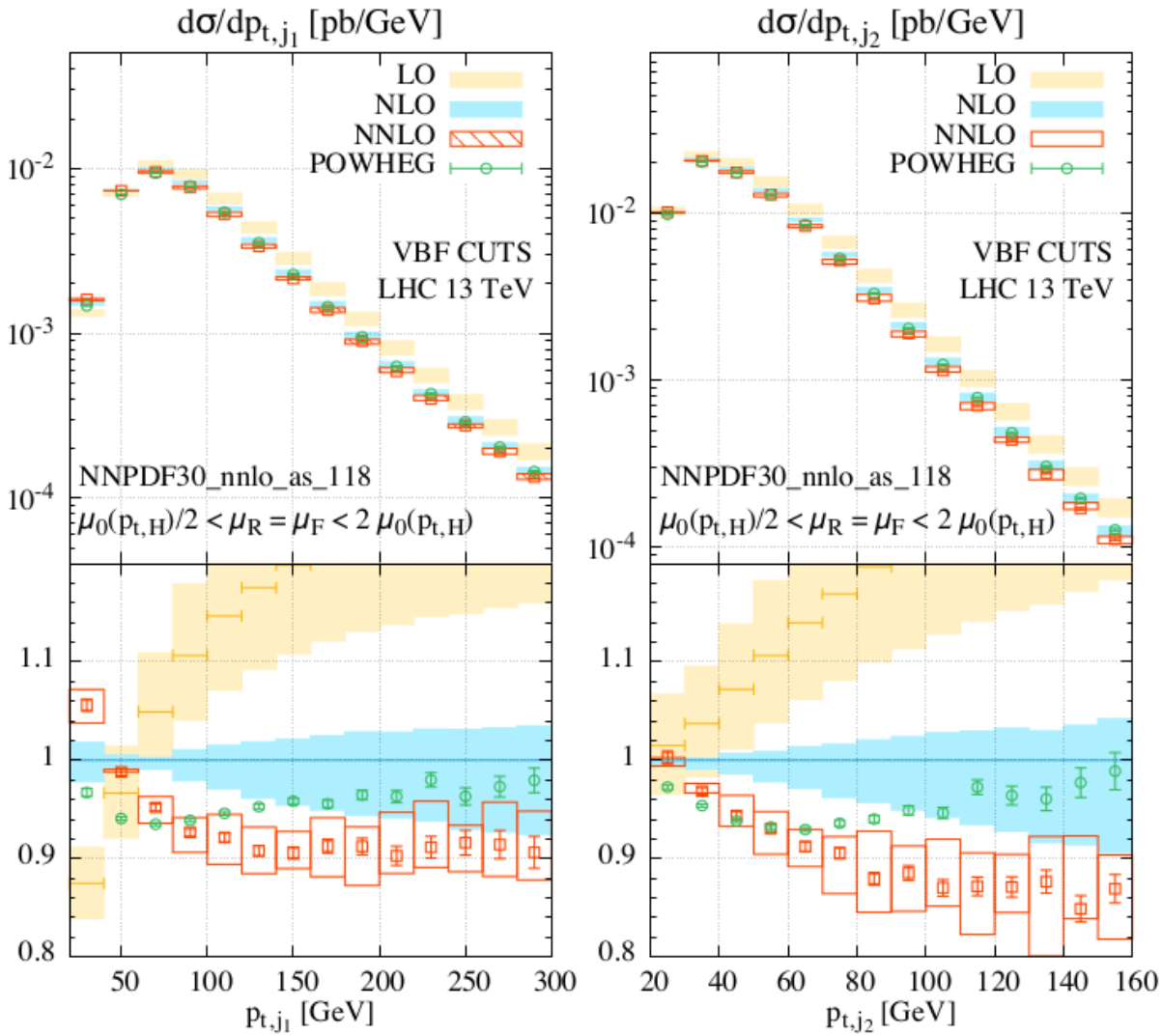




- in absence of VBF cuts, corrections are almost flat, and N3LO completely included in NNLO bands: "no" perturbative uncertainties left

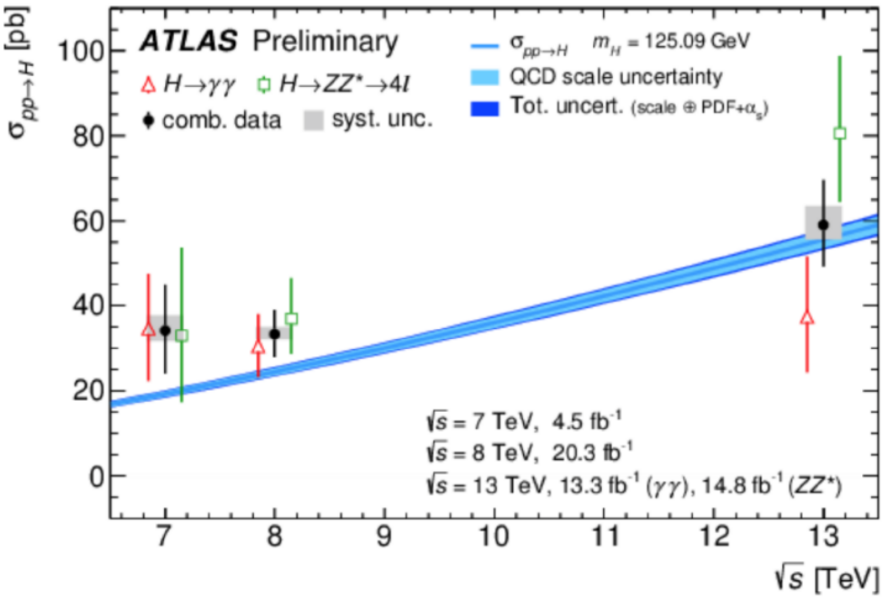
VBF exclusive Higgs production at NNLO

[Cacciari,Dreyer,Karlberg,Salam,Zanderighi '15]



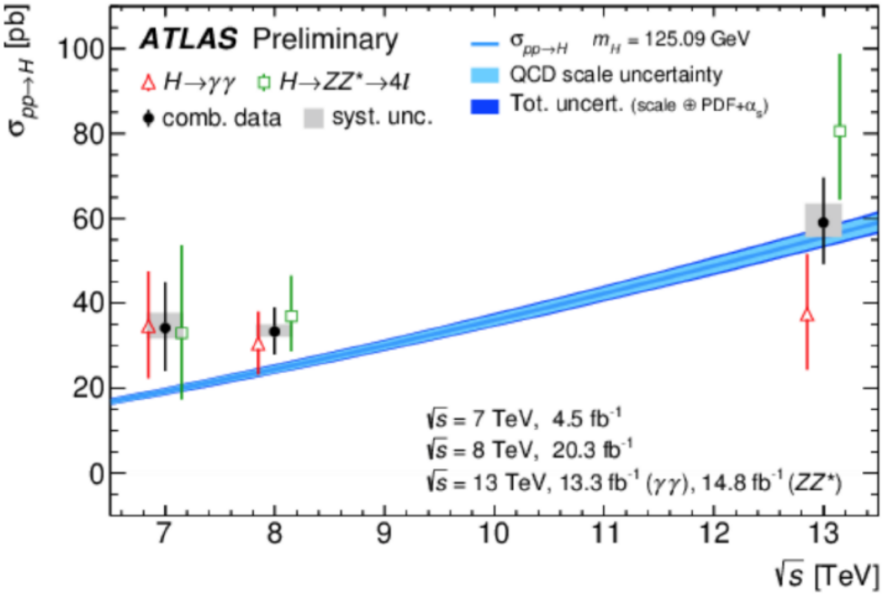
- with VBF cuts, corrections wrt NLO can be sizeable, up to 10-12 %
  - not always captured by NLO+PS

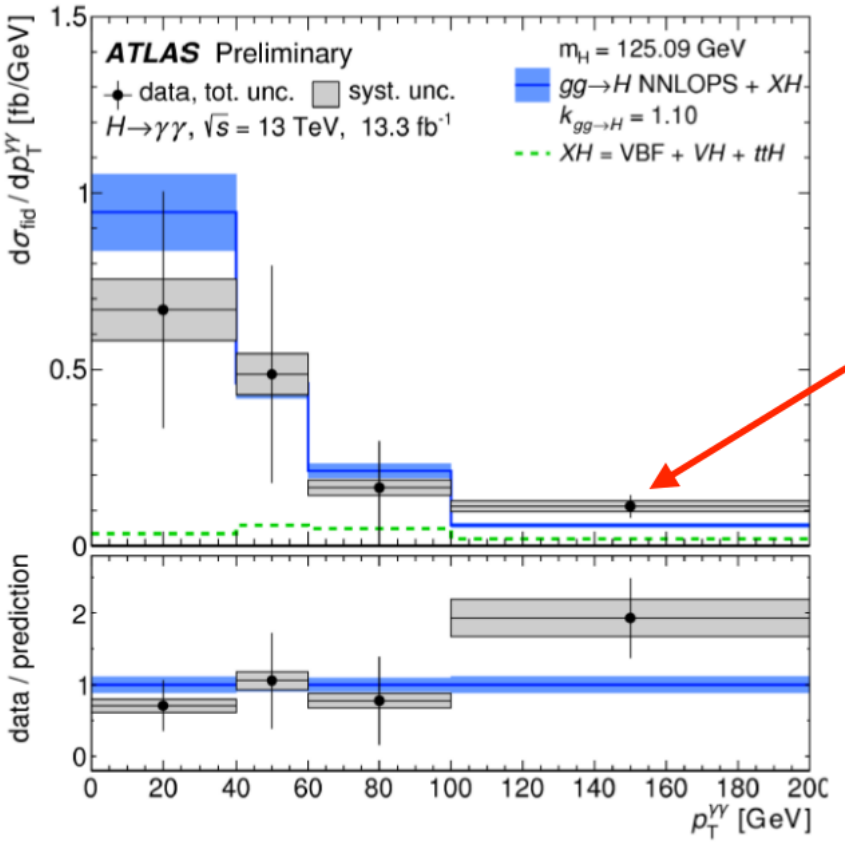
theory vs. data



- is theoretical accuracy high enough ?

theory vs. data

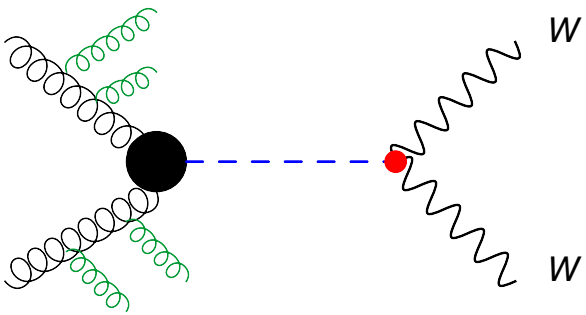


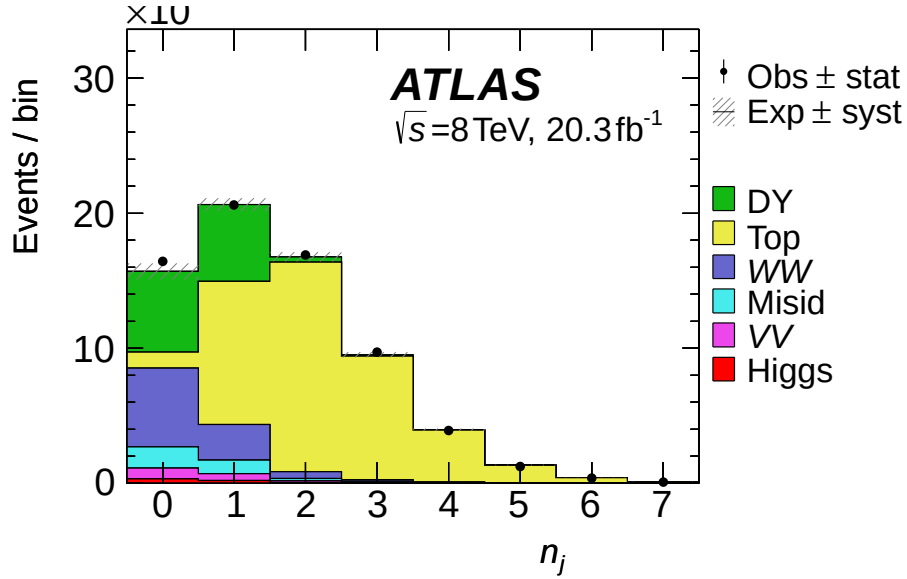


- is theoretical accuracy high enough ?
- what about differential distributions?
  - NNLO computations, matched with resummation when needed, are becoming the new standard !

the “zero-jet” cross section

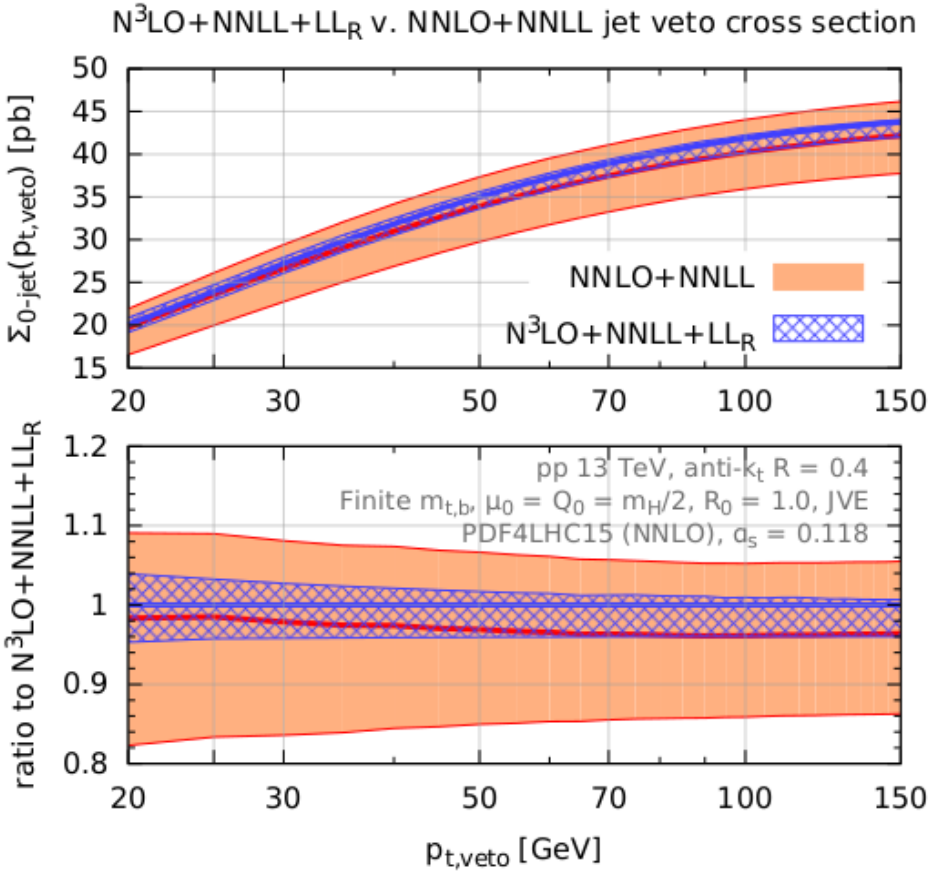
- jet-binned cross sections important to suppress backgrounds
  - for $H \to WW$ and $H \to \tau\tau$: jet veto at 25-30 GeV





the “zero-jet” cross section

- 0-jet x-section now known at N3LO + NNLL + $\mathrm{LL_R}$ [Banfi et al. ’15]



- NNLL resummation of $\log(m_H/p_{T,\text{veto}})$

  [Banfi et al. ’12 (+heavy quarks ’13)]
  [Becher et al. ’15; Stewart et al. ’13]

- N3LO and NNLO H+1 jet

  [Anastasiou et al. ’15]
  [Boughezal et al. ’15]

- jet-radius logarithms

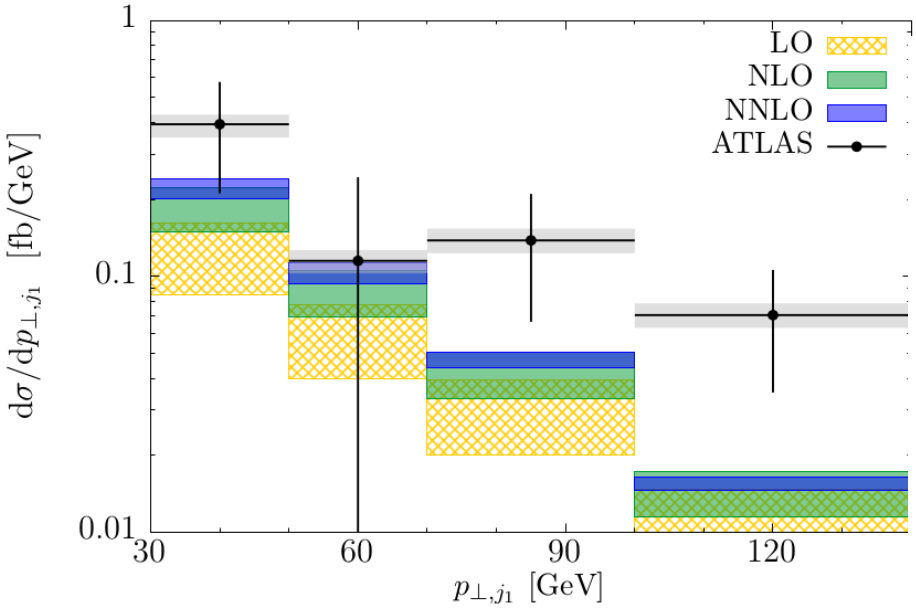
  [Dasgupta et al. ’14]

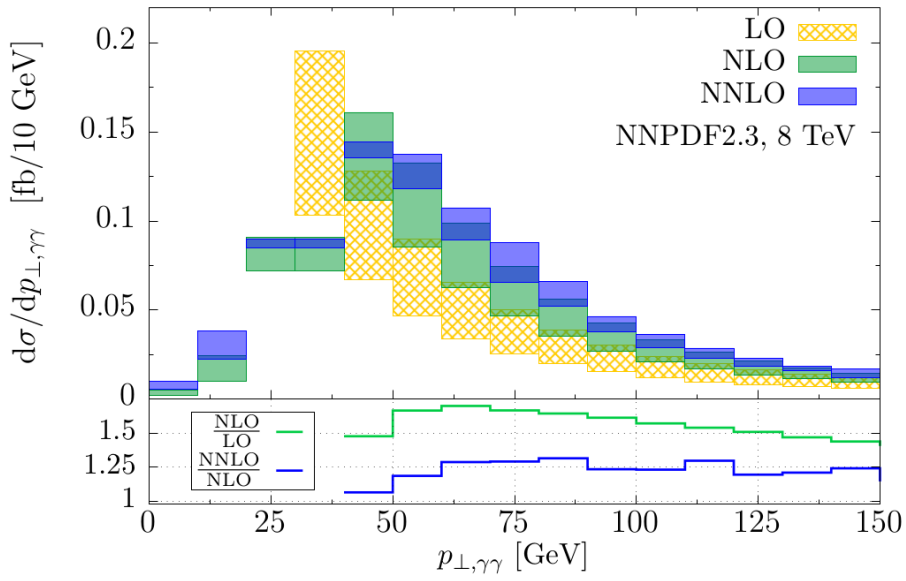
- impact of N3LO: +2%; impact of resummation: +2% (not shown in plot above)
- final perturbative uncertainty: ~ 4 %

Higgs + 1 jet cross section

- gluon induced $\Rightarrow$ large fractions of events have at least 1 jet
  - at 13 TeV: $\sigma(p_{T,j} > 30 \text{ GeV}) \simeq 40\% \ \sigma_{tot}$
  - several measurements available, more to come!
- known at NNLO (in the HEFT)

[Boughezal,Caola et al. '15; Boughezal et al. '15; Chen et al. '16]





- NNLO corrections are important, and improve data/theory agreement

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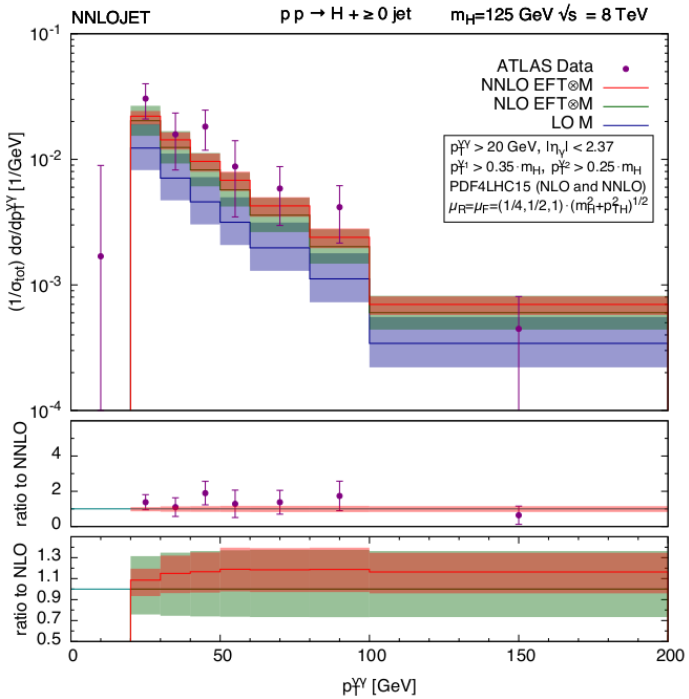

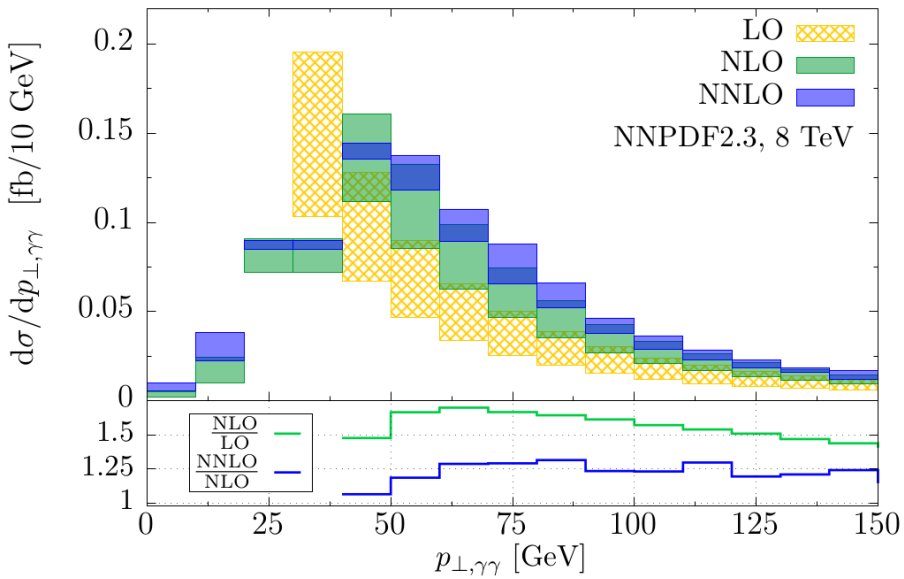

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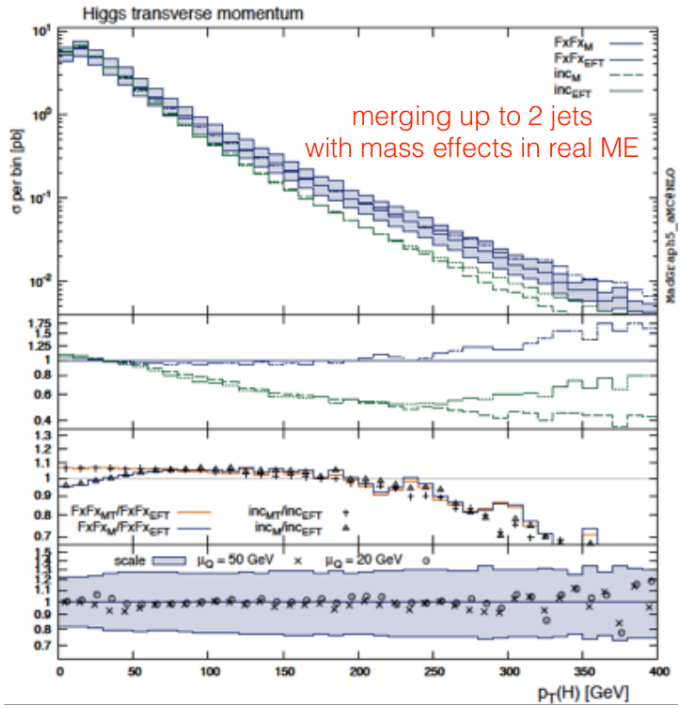
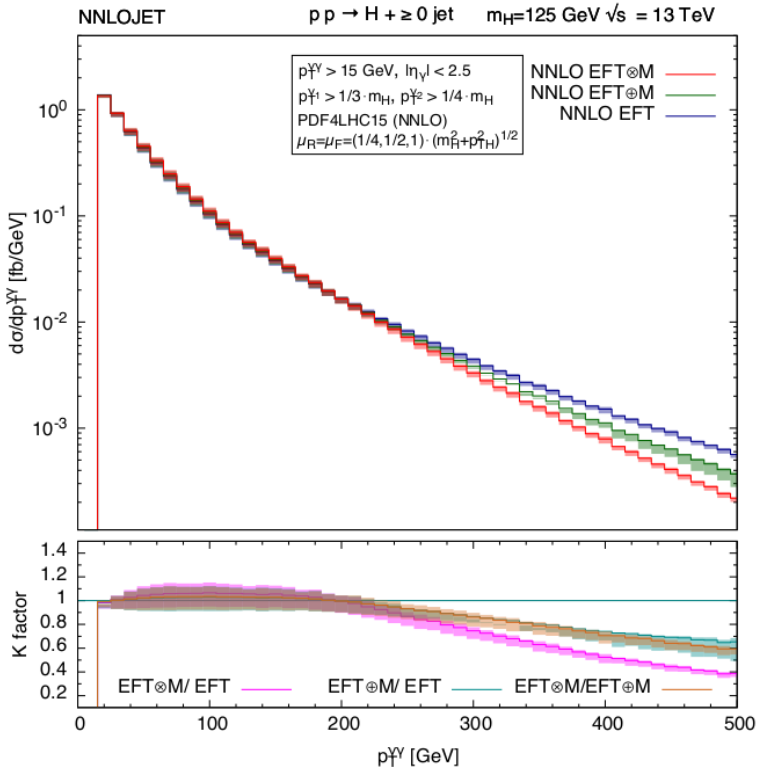
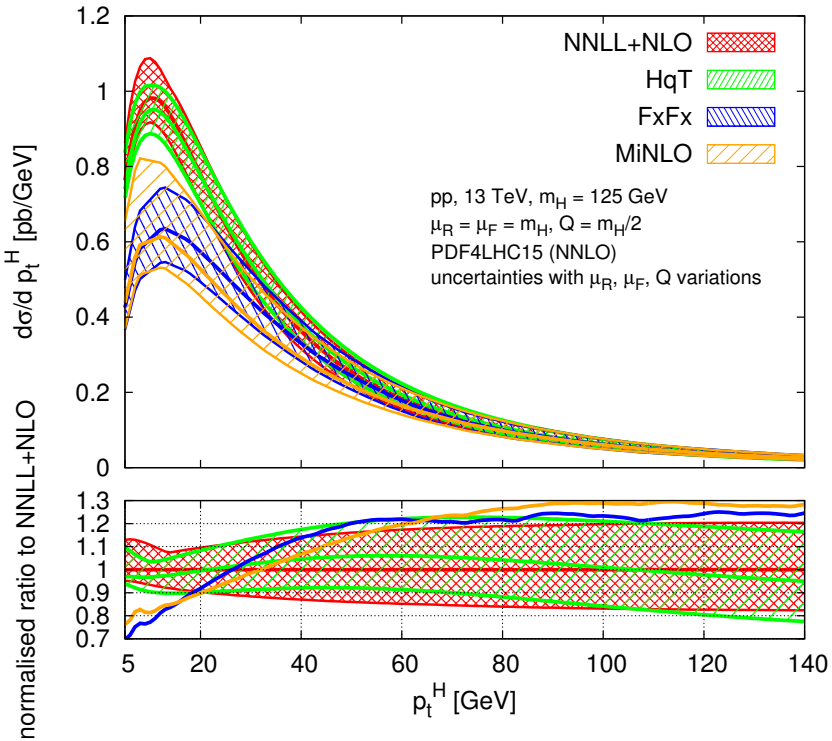


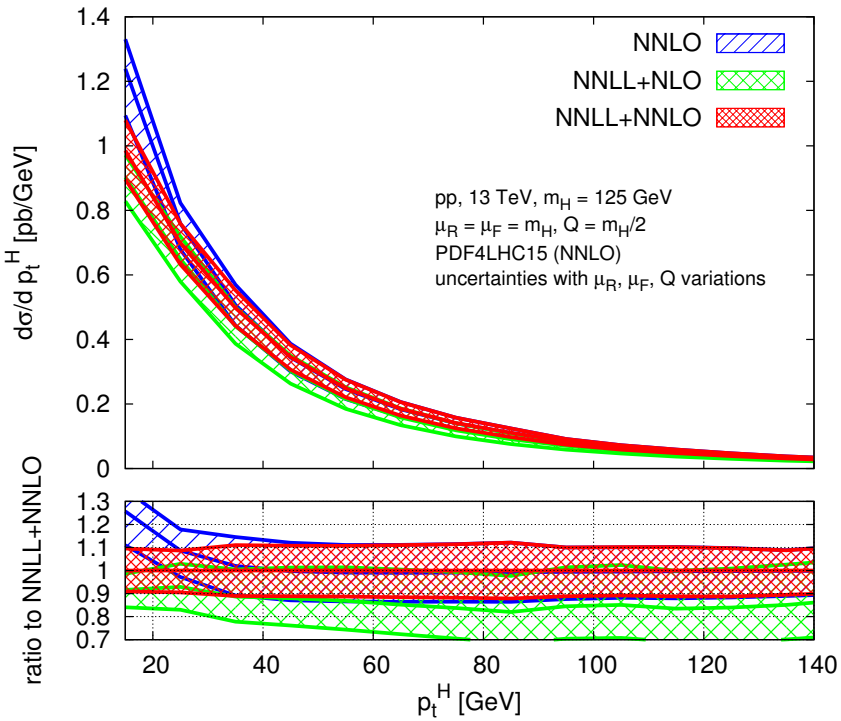


- exact mass effects important at high p_T:
  - differential NLO HEFT + LO exact masses up to H+3 jets [Greiner et al. '15-'16]
  - NLOPS merging up to 2 jets [Buschmann et al. '14; Frederix et al. '16]

the Higgs transverse momentum distribution

- Sudakov resummation at NLO+NNLL (NNLO inclusive) available in various approaches [Bozzi,Catani et al.; Becher et al.]
- matching at NNLO+NNLL (N3LO inclusive) now available [Monni,ER,Torrielli '16]





- new method to resum directly in direct space, validated against previous results
- resummation: sizeable below 30 GeV
- medium-high p_T, matching to differential NNLO matters (as expected): + 10 %

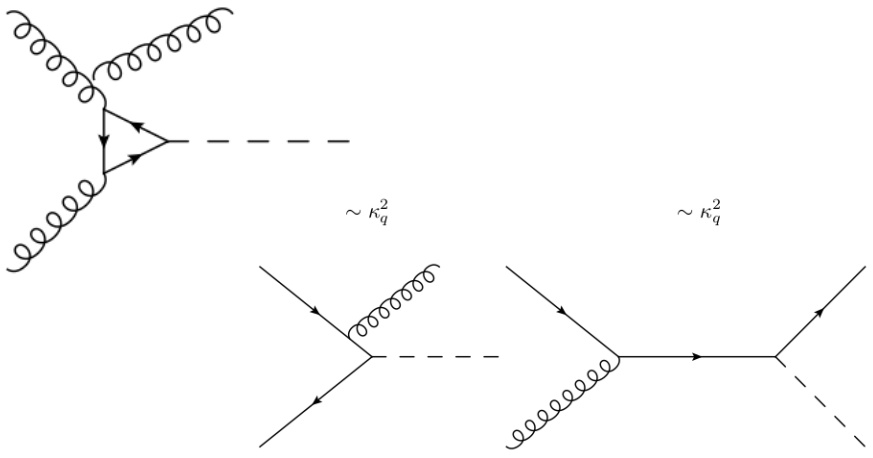
light-Yukawa from Higgs p_T

- several methods have been proposed to constrain the light Yukawa couplings
  [exclusive decays (Bodwin et al.; Kagan et al.; Koenig,Neubert), recasting $Vh(\to b\bar{b})$ (Perez et al.; Delaunay et al.), hc (Brivio et al.), width, global fit]

light-Yukawa from Higgs p_T

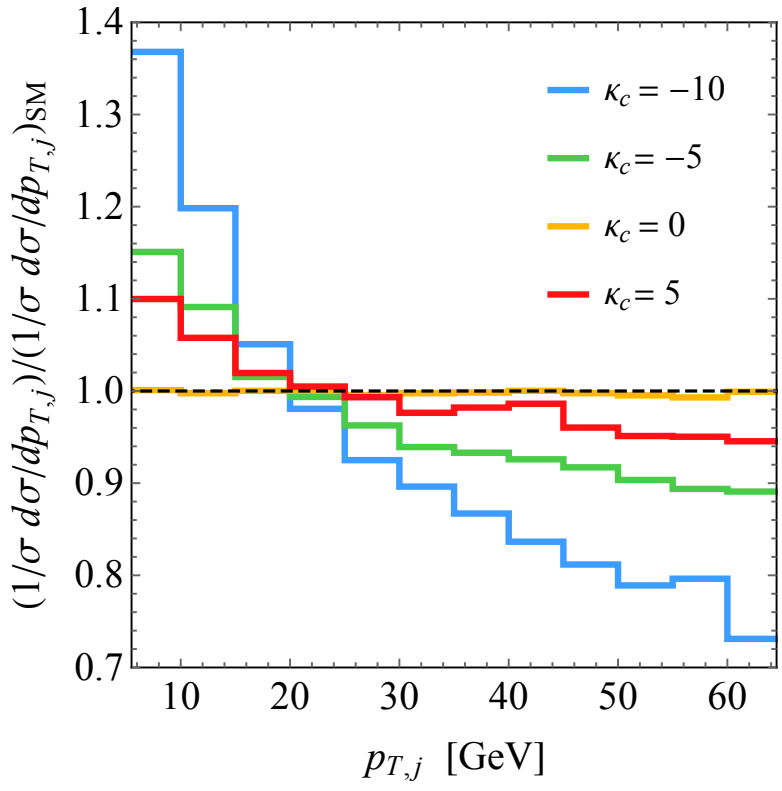
- several methods have been proposed to constrain the light Yukawa couplings
- bounds can also be inferred comparing data and theory for differential distributions [Bishara,Haisch,Monni,ER '16; Soreq et al. '16]
  - $gg \to H + j$: bottom and charm mass effects important at low to intermediate $p_{T,H}$
  - interplay with quark-initiated processes

$$\sim \kappa_q \frac{m_q^2}{m_h^2} \ln^2\left(\frac{p_\perp^2}{m_q^2}\right) \text{ (interference w/ top)}$$



$\kappa_c \in [-16, 18]$ [LHC Run I]

$\kappa_c \in [-1.4, 3.8]$ [LHC Run II (300 fb^{-1})]



- using $p_{T,H}$, EX uncertainty expected not to be a limiting factor
  - improving theory $\Rightarrow$ better bound!

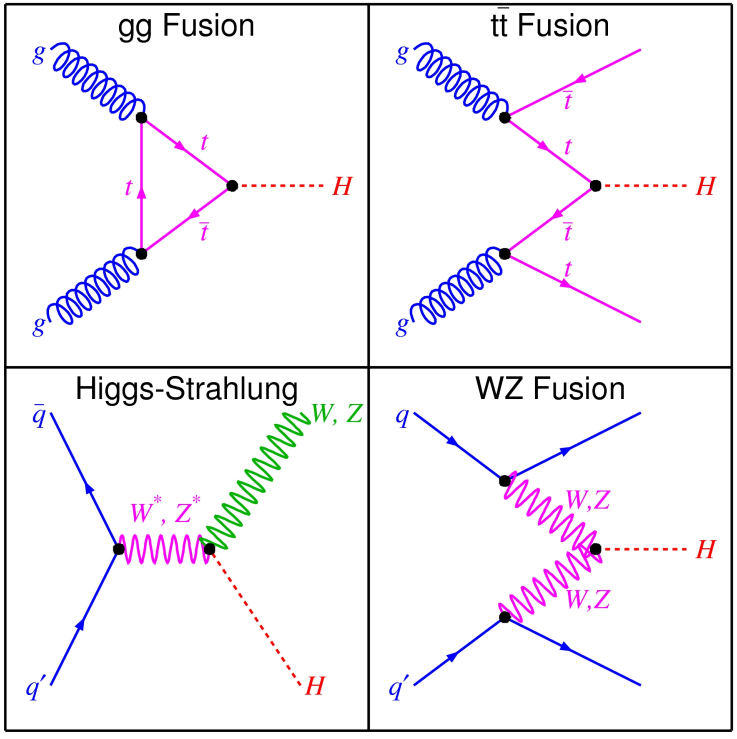
Higgs production at the LHC: MC generators

gluon-fusion

. NNLO + PS

$t\bar{t}H$

. NLO + PS



VH

. NNLO + PS

vector-boson fusion

. NLO + PS

MC generators for Higgs physics

- steady progress, mostly related to "NLO+PS merging", from which "NNLO+PS" can be achieved (for color-singlet production)

  . NNLOPS for $gg \to H$ available with 2 methods `MiNLO+Powheg, UN2LOPS`

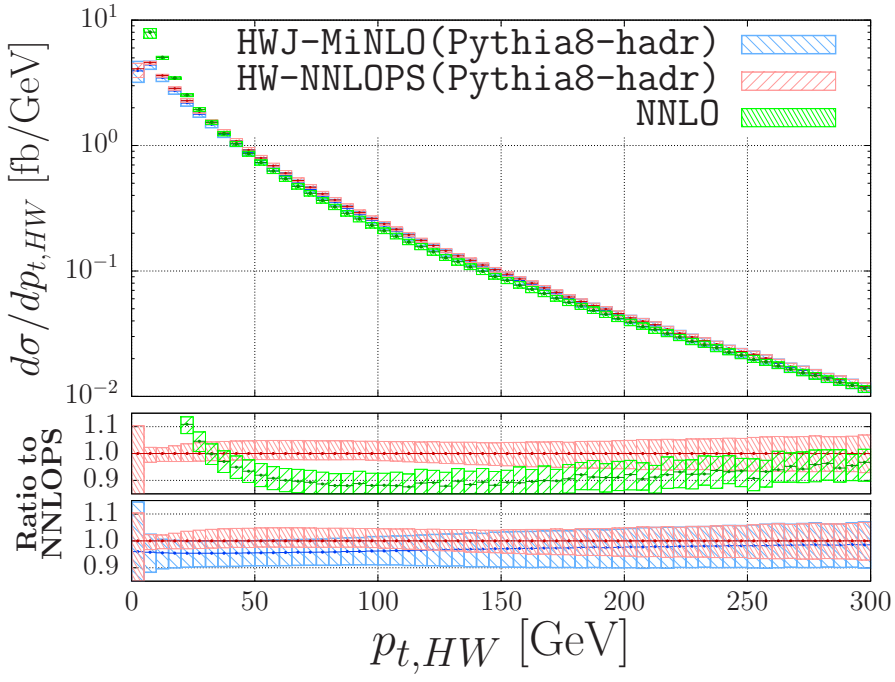
  [Hamilton et al. '13; Hoeche et al. '14]

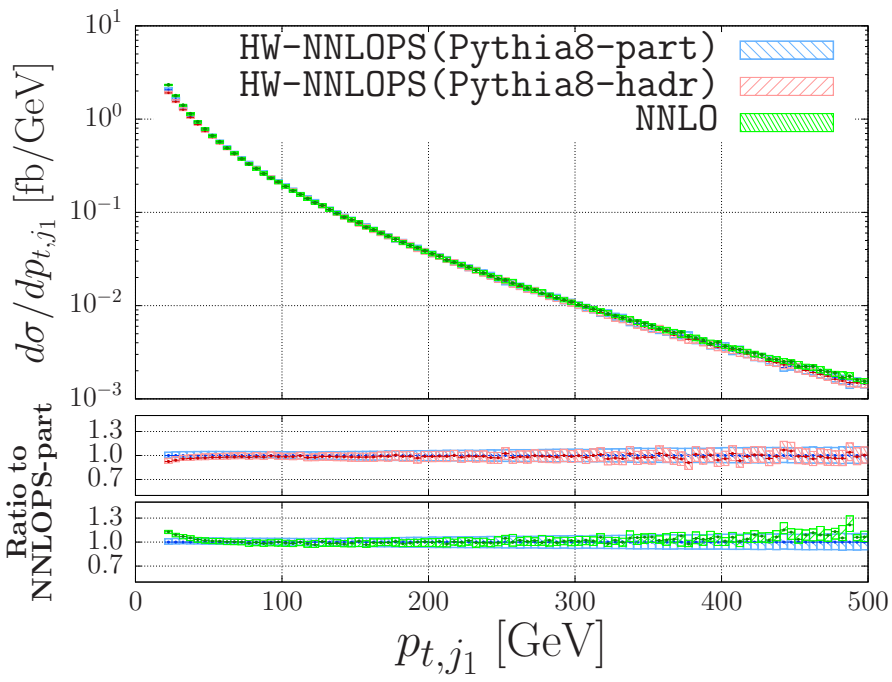
  . same accuracy in principle possible also with `Geneva` [Alioli et al.]

MC generators for Higgs physics

- steady progress, mostly related to "NLO+PS merging", from which "NNLO+PS" can be achieved (for color-singlet production)

. few months ago: $pp \to WH$ at NNLO+PS [Astill,Bizon,ER,Zanderighi '16]
  - should be possible to include NLO QCD corrections to H decay





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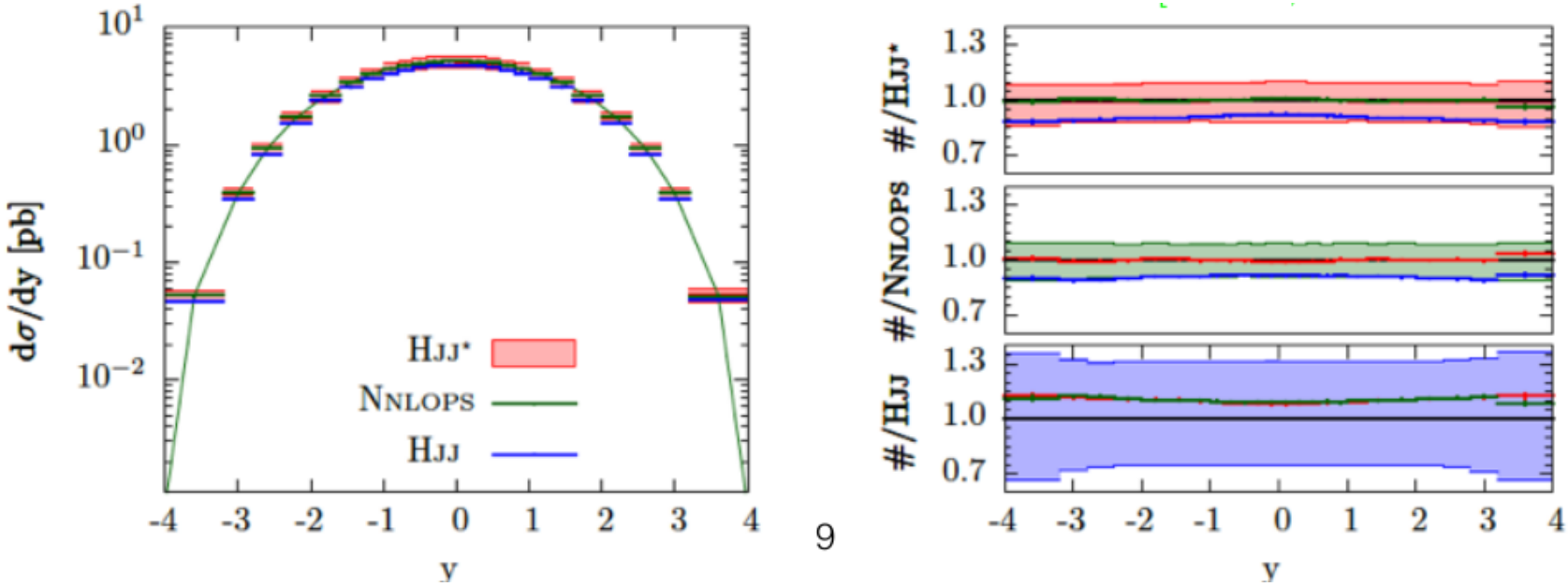
. important result (with `MiNLO`): H+jj @ NLO, H+j @ NLO and H @ NNLO
[Hamilton,Frederix '15]



9

conclusions

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...questions?