NNLO QCD corrections to Higgs boson production at LHC

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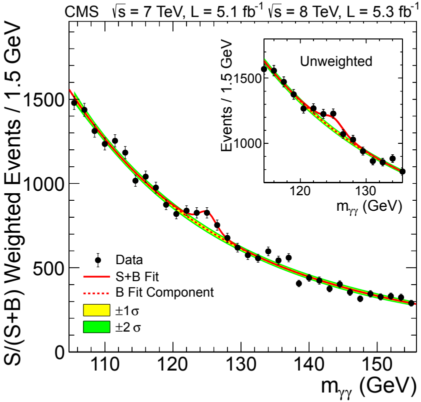
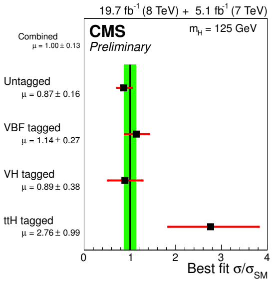
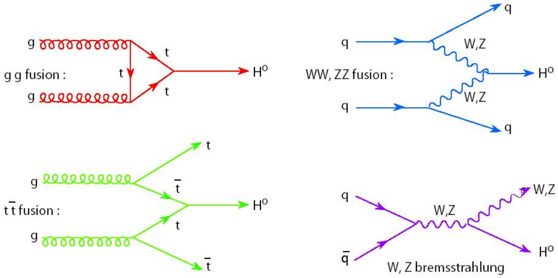
Higgs Boson Discovery → Precision Physics

- Theory is not crucial for direct discovery
- However is needed to interpret discovery as due to the production and decay of a Standard Model Scalar-like particle
- Indirect determination of spin and CP properties
- Currently the most accurately studied process involving QCD $(N^3LO + NNLL)$

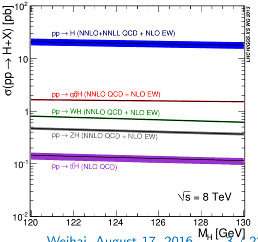


Higgs Boson Discovery → Precision Physics



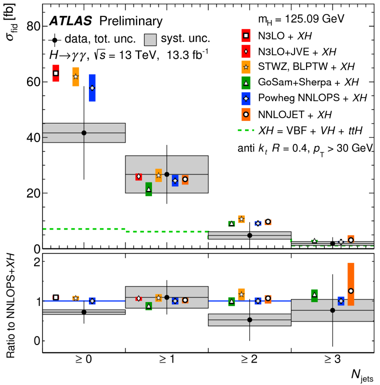


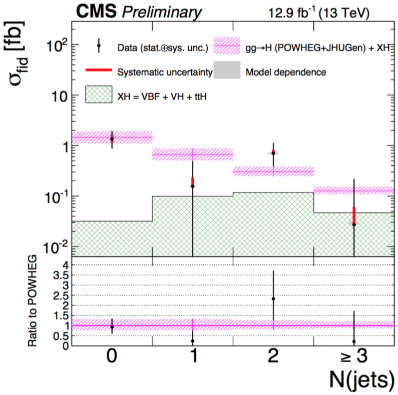
- Higgs discovery requires sophisticated theory predictions
  - higher-order perturbative calculations
  - resummation program
  - reliable non-perturbative tools (PDFs, PS, Jet ...)
- BSM effects are well hidden → more precise study of Higgs couplings



Boosted Higgs : Challenge & Opportunity

- $pp \to H \to \gamma\gamma$ jet-bin analyses
- $pp \to H \to ZZ^*$ jet-bin analyses

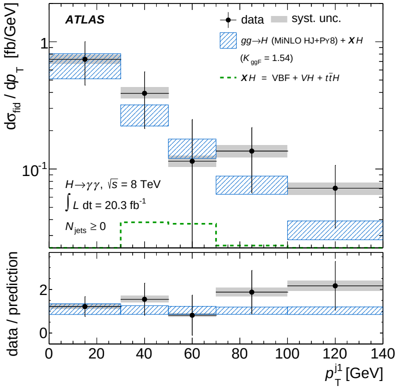


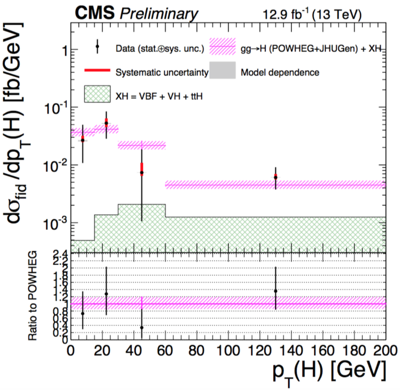


- Different Signal/Background ratio for each bin
- Large theory error in high jet multiplicity
- Different experimental challenge in parameter space

Boosted Higgs : Challenge & Opportunity

- Higgs + jets: Differential cross section in LHC





- Differential corss sections contain detailed properties of Higgs (event shape, forward/backward symmetry, $\cdots$)
- Large prediction error dominate by missing higher orders
- Request for more precise differential predictions especially for BSM study (more details in Lilin Yang's talk)

Cutting Edge Predictions for Higgs Boson Production

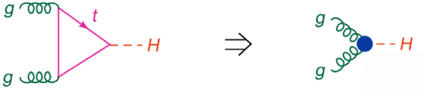
- Higgs production (ggH EFT): (more details in Lilin Yang's talk)
  - Fully inclusive N^3LO pp$\rightarrow$ H
    Anastasiou, Duhr et al (15)
  - Theoretical uncertainty $\sim 5\%$
  - Jet veto differential cross section from $N^3LO + NNLL + LL(R)$
    Banfi, Caola, et al (15)
- Boosted Higgs final states: jet-bin analysis, differential cross section
  - ggF channel (jet boosted, colour charged current)
    - H + 2 jets NLO (EFT): H. van Deurzen, N. Greiner et al 13
    - H + 3 jets NLO (EFT): G. Cullen, H. van Deurzen et al 13
    - H + jet $NNLO$(EFT): R. Boughezal et al 13; XC et al 14; F. Caola et al 15
    - H + H $NNLO$ (EFT) D. de Florian, J. Mazzitelli 14
    - H + jet LO (Full mt): S. Dawson 90's
    - H + H NLO (Full mt): S. Borowka, N. Greiner, G. Heinrich et al 16

Cutting Edge Predictions for Higgs boson

- Boosted Higgs final states: jet-bin analysis, differential cross section
  - VBF channel (jet boosted, colour neutral current)
    - H+2 jets NNLO (Fully inclusive): P. Bolzoni, F. Maltoni 10
    - HH+2 jets NNLO (Fully inclusive): Liu-Sheng Ling et al 14
    - H+2 jets NNLO (Fully differential): M. Cacciari, F. A. Dreyer et al 15
  - VH channel (V boosted, colour charged current)
    - ZH NNLO: G. Ferrera, M. Grazzini, F. Tramontano 14
    - WH NNLO: G. Ferrera, M. Grazzini, F. Tramontano 13
    - WHH NNLO: J. Wang, et al (in progress)
  - $t\bar{t}$ fusion channel (jet boosted, colour charged current)
    - H+$t\bar{t}$ approximate NNLO: A. Broggio, A. Ferroglia et al 15
- Improving above tools:
  - Finite m_t, m_b correction
    Harlander et al, (12); Grazzini, Sargsyan (13); XC, J. Cruz-Martinez et al, (16)
  - Parton shower (PS) matching @ NNLO Hamilton, Nason et al (13)
  - Modern PDF form LHC Run II Ball, Bertone et al (14)

Higgs+jet building blocks

- Higgs production via gluon fusion through a quark loop. In the heavy Top mass limit, we have the effective interaction



- The effective dimension five term in Lagrangian Wilczek, Shifman et al (70's)

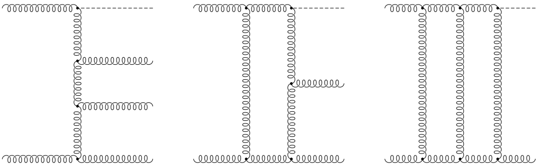
$$\mathcal{L}_H^{int} = \frac{C}{2} H \,\mathrm{Tr} G_{\mu\nu} G^{\mu\nu} \qquad C = \frac{\alpha_s}{6\pi V}(1 + \mathcal{O}(\alpha_s))$$

  - Less than 1% theoretical uncertainty in pure Higgs production Harlander, Mantler et al (10)
  - EFT approximation breaks down in high P_T region in Higgs + jets final states Harlander, Neumann et al (12)

- Effective dimension six operators for new physics effects Dawson et al (14); Ghosha et al (14)

$$O_g = \Phi^\dagger \Phi G^a_{\mu\nu} G^{\mu\nu a} \qquad O_{3g} = f^{abc} G^{a\mu}_{\nu} G^{b\nu}_{\rho} G^{c\rho}_{\mu} \qquad \cdots$$

Higgs+jet building blocks



- tree level 2→3+H amplitudes Del Duca, Frizzo, Maltoni; (use BCFW) Chen;
  - Implicit divergency in P.S. (IR)
- 1-loop 2→2+H amplitudes Berger, Del Duca, Dixon; Badger, Glover, Mastrolia, Williams; Badger, Ellis
  - Implicit divergency in P.S. (IR) as well as explcit poles up to ϵ^{-2} (UV)
- 2-loop 2→1+H amplitudes Gehrmann, Jaquier, Glover, Koukoutsakis
  - Explicit poles up to ϵ^{-4} (UV)
- Analytic results with spinor-helicity formalism (Stable IR limit for RR and RV)

Parton Level Cross Section Structure at NNLO

$$
\begin{aligned}
d\hat{\sigma}_{NNLO} &= \int [\langle \mathcal{M}^0 | \mathcal{M}^0 \rangle]_{H+5} d\Phi_{H+3} \\
&+ \int [\langle \mathcal{M}^0 | \mathcal{M}^1 \rangle + \langle \mathcal{M}^1 | \mathcal{M}^0 \rangle]_{H+4} d\Phi_{H+2} \\
&+ \int [\langle \mathcal{M}^1 | \mathcal{M}^1 \rangle + \langle \mathcal{M}^2 | \mathcal{M}^0 \rangle + \langle \mathcal{M}^0 | \mathcal{M}^2 \rangle]_{H+3} d\Phi_{H+1} \\
&= \int_{d\Phi_{H+3}} d\hat{\sigma}^{RR}_{NNLO} + \int_{d\Phi_{H+2}} d\hat{\sigma}^{RV}_{NNLO} + \int_{d\Phi_{H+1}} d\hat{\sigma}^{VV}_{NNLO}
\end{aligned}
$$

- $d\hat{\sigma}$ renormalised factorized parton level cross section
- Analytical integration of P.S. transforms IR divergence into explicit poles
- Challenge to extract implicit IR divergence from RR and RV without P.S. integration
  - Calculate RR and RV in separate parton level Monte Carlos
  - Collect finite contributions from RR and RV for differential cross-section analysis

NNLO Subtraction

$$
\begin{aligned}
d\hat{\sigma}_{NNLO} = & \int_{d\Phi_{H+3}} (d\hat{\sigma}^{RR}_{NNLO} - d\hat{\sigma}^{S}_{NNLO}) \\
& + \int_{d\Phi_{H+2}} (d\hat{\sigma}^{RV}_{NNLO} - d\hat{\sigma}^{T}_{NNLO}) \\
& + \int_{d\Phi_{H+1}} (d\hat{\sigma}^{VV}_{NNLO} - d\hat{\sigma}^{U}_{NNLO})
\end{aligned}
$$

- Subtraction terms mimic the divergent behaviour of matrix elements
- Each bracket is finite
- Calculations in d dimension for explicit pole cancellation
- The construction of red terms and the treatment of P.S. depends on different subtraction schemes
- pp→H+J processes: color particles in both initial and final states

- Consistency requirement:

$$
0 = \int_{d\Phi_{H+3}} d\hat{\sigma}^{S}_{NNLO} + \int_{d\Phi_{H+2}} d\hat{\sigma}^{T}_{NNLO} + \int_{d\Phi_{H+1}} d\hat{\sigma}^{U}_{NNLO}
$$

NNLO subtraction scheme

- NNLO subtraction schemes are usually inspired by NLO techniques
  - FKS $\rightarrow$ Sector Improved Decomposition (STRIPPER) (M.Czakon 10; Boughezal et al 11)
  - q_T subtraction + FKS $\rightarrow$ N-jettiness (J.R.Gaunt et al 15; Boughezal, et al 15)
  - Antenna function (X_3^0) $\rightarrow$ Antenna function (X_3^1,X_4^0) (T.Gehrmann et al 05)
  - q_T subtraction (S.Catani, M.Grazzini 07), Colourful subtraction (Del Duca, Trocsanyi et al 05), Born projection (Cacciari, Dreyer et al 15) $\cdots$
- Each NNLO subtraction scheme has its advantanges and disadvantages

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	Analytic	Local	FS colour	IS colour	Automated
Antenna	✔	✔	✔	✔	✘
STRIPPER	✘	✔	✔	✔	✘
N-jettiness	✔	✘	✔	✔	✘
Colourful	✔	✔	✔	✘	✘
q_T	✔	✘	✘	✔	✔
Born Projection	✔	✔	✔	✔	✘

Antenna Subtraction at NNLO

- Antenna function form physical matrix elements (from 2005)

$$A,\ \widetilde{A},\ B,\ C\ \sim\ \gamma^* \to q\bar{q}\ + partons\ (hard\ quark - antiquark\ pair)$$
$$D,\ E,\ \widetilde{E}\ \sim\ \widetilde{\mathcal{X}} \to \tilde{g}\ + partons\ (hard\ quark - gluon\ pair)$$
$$F,\ G,\ \widetilde{G},\ H\ \sim\ H \to\ partons\ (hard\ gluon - gluon\ pair)$$

A.Gehrmann-De Ridder, T.Gehrmann, N.Glover, 05

- Complete set of Antenna tool box (NNLO)

$$phase\ config. \otimes type \otimes parton\ types$$
$$[FF, IF, II] \otimes [X_3^0, X_4^0, X_3^1] \otimes [A \sim H]$$

- All antenna functions are analytically integrable (from 2012)
  - Final-Final $\mathcal{X}_3^0$, $\mathcal{X}_4^0$ and $\mathcal{X}_3^1$ Gehrmann-De Ridder, Gehrmann, Glover (05)
  - Initial-Final $\mathcal{X}_3^0$, $\mathcal{X}_4^0$ and $\mathcal{X}_3^1$ Daleo, Gehrmann, Gehrmann-De Ridder, Luisoni, Maitre (06,09,12)
  - Initial-Initial $\mathcal{X}_3^0$, $\mathcal{X}_4^0$ and $\mathcal{X}_3^1$ Boughezal, Daleo, Gehrmann-De Ridder, Gehrmann, Maitre, Monni, Ritzmann (10,11,12)

NNLOJET: NNLO tool with Antenna subtraction

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                 /    /    / /__/ /_/ / // / _/  / /
                /_/|_/_/|_/____/\____/\___/___/ /_/

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*                                                                     *
* NNLOJET: A multiprocess parton level event generator at O(alpha_s^3)*
*                                                                     *
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XC, J. Cruz-Martinez, J. Currie, A. Gehrmann-De Ridder, T. Gehrmann, N. Glover, A. Huss, M. Jaquier, T. Morgan, J. Niehues, J. Pires

- ✓ $pp \to H \to \gamma\gamma$ plus 0, 1, 2 jets
- ✓ $pp \to e^+e^-$ plus 0, 1 jets
- ✓ $pp \to$ dijets
- ✓ $ep \to 2(+1)$ jets
- ✓ $\ldots$

NNLOJET: application in $pp \rightarrow H + jet$

- $pp \rightarrow H + jet$
  - Higgs production via gluon fusion in EFT
  - Precise study for p_T^H distribution (Boosted Higgs with NNLO accuracy)
  - Excellent agreement in inclusive H($\gamma\gamma$)+Jet final states (RUN II data)
- One of the first NNLO processes done with three different subtraction schemes
  - pp $\rightarrow$ H + J Antenna subtraction. XC, Gehrmann, Glover and Jaquier 1408.5325, 1604.04085 [hep-ph]
  - pp $\rightarrow$ H + J Sector Improved Decomposition subtraction (without quark-quark channel). Boughezal, Caola, Melnikov, Petriello, Schulze 1302.6216, 1504.07922, 1508.02684 [hep-ph]
  - pp $\rightarrow$ H + J N-jettiness subtraction. Boughezal, Focke, Giele, Liu, Petriello 1505.03893 [hep-ph]

NNLOJET: application in $pp \to H + jet$

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- Important crosscheck
  - Comparison with ATLAS cuts (RUN I $H \to \gamma\gamma$ channel) (1407.4222v2):
    - NNLOJET: $\sigma^{\text{fid}}_{NNLO} = 9.4^{+0.65}_{-0.89}$ fb ($\mu_R = \mu_F = m_H, 0.5 \times m_H, 2 \times m_H$)

      $$\sigma^{\text{fid}}_{LO} = 5.42^{+2.32}_{-1.49}\text{ fb},\ \sigma^{\text{fid}}_{NLO} = 7.98^{+1.76}_{-1.46}\text{ fb},\ \sigma^{\text{fid}}_{NNLO(\not{q}\not{q})} = 9.44^{+0.59}_{-0.85}\text{ fb}$$
    - Sector Improved Decomposition (STRIPPER):

      $$\sigma^{\text{fid}}_{LO} = 5.42^{+2.32}_{-1.49}\text{ fb},\ \sigma^{\text{fid}}_{NLO} = 7.98^{+1.76}_{-1.46}\text{ fb},\ \sigma^{\text{fid}}_{NNLO(\not{q}\not{q})} = 9.45^{+0.58}_{-0.82}\text{ fb}$$
  - Comparison using LHCHXSWG recommend cuts (to appear in YR4 report):

    $$\sigma^{\text{fid},\text{NNLOJET}}_{NNLO(\not{q}\not{q})} = \sigma^{\text{fid},\text{STRIPPER}}_{NNLO(\not{q}\not{q})} = 17.6\text{ pb } (\mu_R = \mu_F = 1/2 m_H)$$

Comparison with ATLAS and CMS in RUN I ($H \to \gamma\gamma$)

- Simulation setup for fiducial cross section and differential cross section:
  - Include full m_t, m_b, m_c dependence at LO
  - Apply photon isolation algorithm:
    ATLAS (CMS) algorithm has 85% $\sim$ 95% (63%) signal efficiency
  - Use $\mu_R = \mu_F = 1/2\sqrt{m_H^2 + p_{TH}^2}$ as central scale

$p_T^{jet} > 30$ GeV, $|\eta_{jet}| < 4.4$
$p_T^{\gamma_1} > 0.35 \cdot m_H$, $p_T^{\gamma_2} > 0.25 \cdot m_H$
$|\eta_\gamma| < 2.37$
anti-k_T (R=0.4)
PDF4LHC15 (NLO and NNLO)
$\mu_R=\mu_F=(1/4,1/2,1)\cdot(m_H^2+p_{TH}^2)^{1/2}$

ATLAS fiducial cut (1407.4222v2)

$p_T^{jet} > 25$ GeV, $|\eta_{jet}| < 2.5$
$p_T^{\gamma_1} > 1/3 \cdot m_H$, $p_T^{\gamma_2} > 1/4 \cdot m_H$
$|\eta_\gamma| < 2.5$
anti-k_T (R=0.5)
PDF4LHC15 (NLO and NNLO)
$\mu_R=\mu_F=(1/4,1/2,1)\cdot(m_H^2+p_{TH}^2)^{1/2}$

CMS fiducial cut (1508.07819)

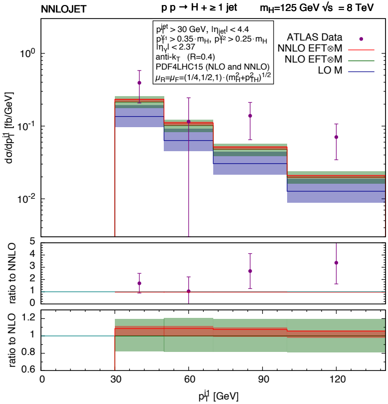
- Results for fiducial cross sections: (XC, Cruz-Martinez, Gehrmann, Glover and Jaquier, 1607.08817)
  - ATLAS: $\sigma^{\text{fid}}_{H+\geq 1j}(8\ \text{TeV}) = 21.5 \pm 5.3(\text{stat.}) \pm^{2.4}_{2.2}(\text{syst.}) \pm 0.6(\text{lumi})$ fb

    $\sigma_{LO}^{\text{fid}(m_q)} = 5.84^{+2.61}_{-1.69}$ fb, $\sigma_{NLO}^{\text{fid}(m_q@LO)} = 9.07^{+1.79}_{-1.66}$ fb, $\sigma_{NNLO}^{\text{fid}(m_q@LO)} = 9.74^{+0.63}_{-0.79}$ fb
  - CMS: $\sigma^{\text{fid}}_{H+\geq 1j\to\gamma\gamma+\geq 1j}(8\ \text{TeV}) = 10.7 \pm 7.7(\text{tot. unc.})$ fb

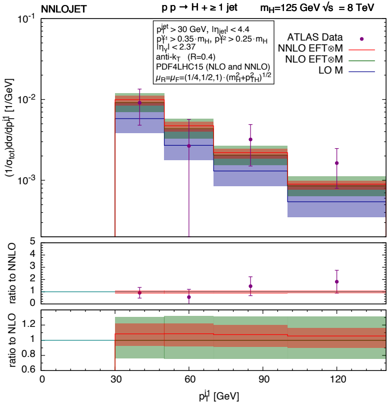
    $\sigma_{LO}^{\text{fid}(m_q)} = 5.84^{+2.54}_{-1.66}$ fb, $\sigma_{NLO}^{\text{fid}(m_q@LO)} = 9.54^{+2.08}_{-1.81}$ fb, $\sigma_{NNLO}^{\text{fid}(m_q@LO)} = 10.52^{+0.41}_{-0.95}$ fb

Comparison with ATLAS and CMS in RUN I ($H \to \gamma\gamma$)

- Differential cross section of p_T^{j1} in ATLAS (XC, Cruz-Martinez, Gehrmann, Glover and Jaquier, 1607.08817)



Absolute distribution for ATLAS RUN I

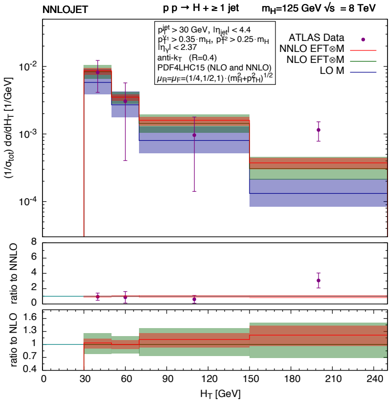


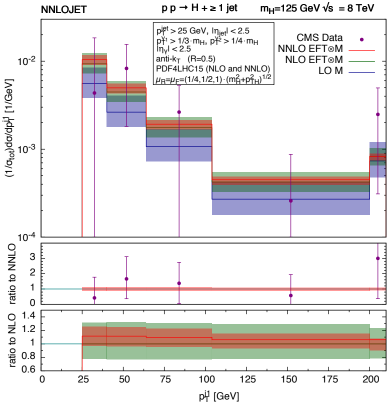
Normalised distribution for ATLAS RUN I

- Tension in the total cross section help us better understand the distributions
- In general, normalising by σ_{tot}^{H} is to minimize the luminosity error
- NLO and NNLO predictions are re-weighted by $d\sigma_{LO}^{Full}/d\sigma_{LO}^{EFT}$

Comparison with ATLAS and CMS in RUN I ($H \to \gamma\gamma$)

- Differential cross section of p_T^{j1} in CMS (right) and H_T in ATLAS (left)





Normalised distribution for ATLAS RUN I

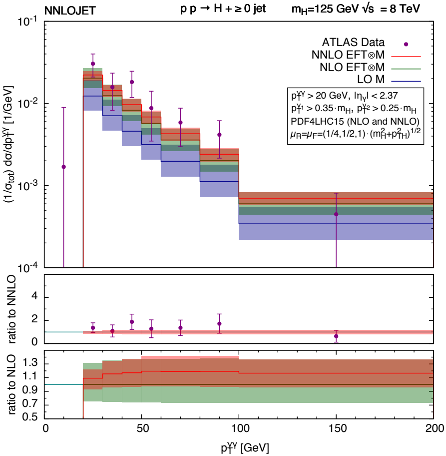
Normalised distribution for CMS RUN I

- Normalised NNLO distributions correctly predict the shape
- NNLO contributions could potentially change the distribution shape of NLO
- Essential NNLO corrections for about $\sim 15\%$ and reduced theory uncertainties

Comparison with ATLAS and CMS in RUN I ($H \to \gamma\gamma$)

- Study Higgs p_T distributions with parton boosted Higgs at NNLO

- Loose/remove the requirment of jet to study more inclusive P.S. for Higgs
- Still require a p_T^H cut to keep the integral finite
- No jet algorithm applied
- Large log terms related to the p_T^H cut will appear
- Require resummation especially in the small p_T region ($p_T < 40$ GeV) P. F. Monni, E. Re, P. Torrielli 16



Normalised distribution for ATLAS RUN I

Comparison with ATLAS in RUN II ($H \to \gamma\gamma$)

- Simulation setup for fiducial cross section and differential cross section:
  - Fiducial setup and data taken from ICHEP (ATLAS-CONF-2016-067)
  - Similar setup as in RUN I but with $\sqrt{s} = 13$ TeV
  - Exclude the endcap wheel region for photon identification ($1.37 < |\eta| < 1.52$)
  - Slightly different photon isolation algorithm ($< 1\%$ effect, not applied)
  - Improved sampling efficiency $\to$ 50% faster for a complete NNLO computation

Comparison with ATLAS in RUN II ($H \to \gamma\gamma$)

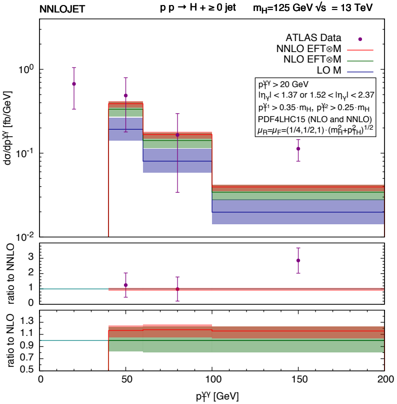
- Simulation setup for fiducial cross section and differential cross section:
  - Fiducial setup and data taken from ICHEP (ATLAS-CONF-2016-067)
  - Similar setup as in RUN I but with $\sqrt{s} = 13$ TeV
  - Exclude the endcap wheel region for photon identification ($1.37 < |\eta| < 1.52$)
  - Slightly different photon isolation algorithm ($< 1\%$ effect, not applied)
  - Improved sampling efficiency $\to$ 50% faster for a complete NNLO computation
- Preliminary: results for fiducial cross sections: (XC, Cruz-Martinez, Gehrmann, Glover and Jaquier to JHEP)
  - ATLAS: $\sigma^{\text{fid}}_{H+\geq 1j}(13\text{ TeV}) = 26.75 \pm^{10.6}_{10.7}$ (tot. unc.) fb
  - NNLOJET:

$$\sigma^{\text{fid}(m_q)}_{LO} = 14.43^{+5.64}_{-3.83} \text{ fb}$$
$$\sigma^{\text{fid}(m_q@LO)}_{NLO} = 21.77^{+3.96}_{-3.62} \text{ fb}$$
$$\sigma^{\text{fid}(m_q@LO)}_{NNLO} = 23.21^{+0.62}_{-1.67} \text{ fb}$$

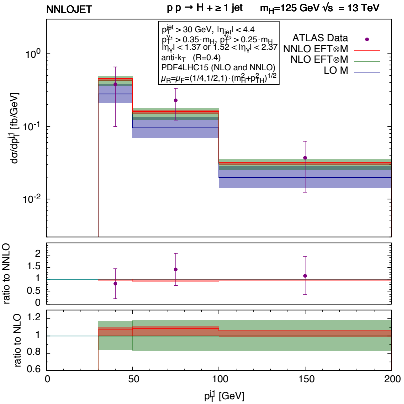
  - Tension in the fiducial cross section comparison from RUN I resolves in RUN II
  - Finite quark mass effects at NLO are likely to give positive corrections to fiducial cross sections (currently not yet available)

Comparison with ATLAS in RUN II ($H \to \gamma\gamma$)

- Preliminary: differential cross section of p_T^{j1} (right) and p_T^H (left) in ATLAS
  (XC, Cruz-Martinez, Gehrmann, Glover and Jaquier to JHEP)



Absolute distribution for ATLAS RUN II



Absolute distribution for ATLAS RUN II

- ATLAS data with limited statistics already show good agreement
- Establish a solid setup for precise comparison (shape, normalisation etc.)

Summary & Outlook

- Summary
  - Strong motivation for precise QCD studies
    - LHC RUN II data is getting more and more precise
    - SM prediction entering NNLO era
  - Boosted properties of Higgs is an interesting field not yet well understood
    - Boosted Higgs is very common on LHC and reveal more details of the SM
    - Precise QCD calculations are essential for such study at LHC
    - Simulations for LHC RUN II data at NNLO accuracy show promising agreement
  - Future work
    - To compare with ATLAS and CMS data in $H \to ZZ(WW)$ decay channel
    - Finite quark mass effects @ NLO are challenging but important
    - Implementation/collaboration on NNLO VBF channel (2-jet bin)

Summary & Outlook

- Summary
  - Strong motivation for precise QCD studies
    - LHC RUN II data is getting more and more precise
    - SM prediction entering NNLO era
  - Boosted properties of Higgs is an interesting field not yet well understood
    - Boosted Higgs is very common on LHC and reveal more details of the SM
    - Precise QCD calculations are essential for such study at LHC
    - Simulations for LHC RUN II data at NNLO accuracy show promising agreement
  - Future work
    - To compare with ATLAS and CMS data in $H \to ZZ(WW)$ decay channel
    - Finite quark mass effects @ NLO are challenging but important
    - Implementation/collaboration on NNLO VBF channel (2-jet bin)

THANK YOU!