High precision study for boosted Higgs at LHC

Second China High Precision HEP Workshop

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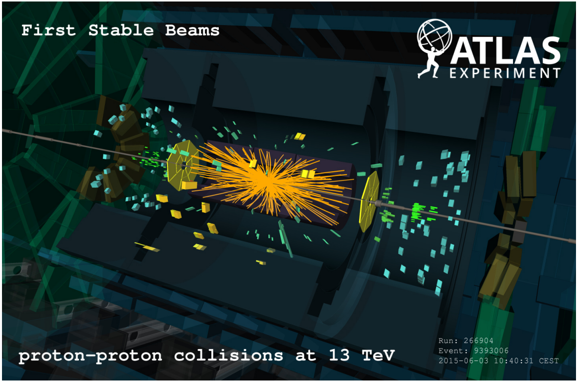
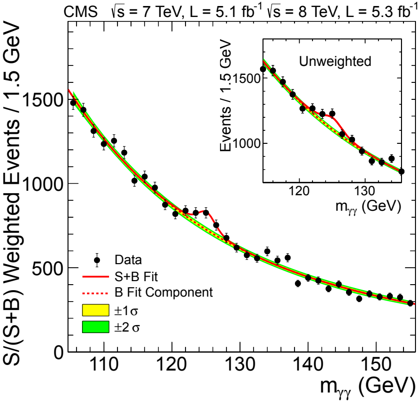
Typical Event at LHC

- Large production rate for Standard Model processes
  - jets
  - top quark pairs
  - vector bosons
- Allow high precision measurement
  - masses $(m_T, m_H \cdots)$
  - couplings (SM, EFT, BSM)
  - parton distributions
  - differential cross sections
- Strong constrain for both SM and BSM

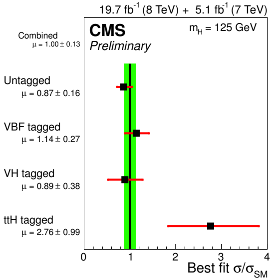


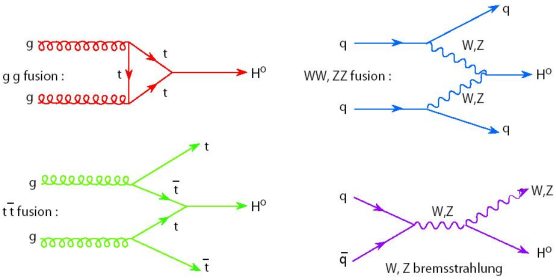
Milestone Achievement →New Scalar @ 125 GeV

- 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 ($N^3LO + NNLL$)

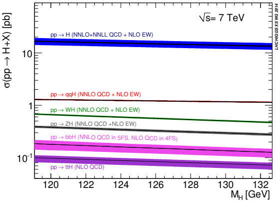


Higgs Boson Discovery → Precision Physics

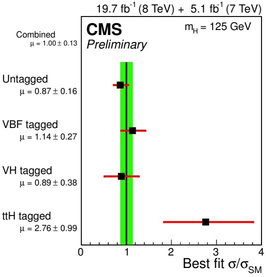


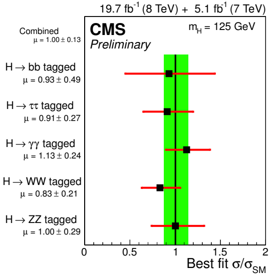


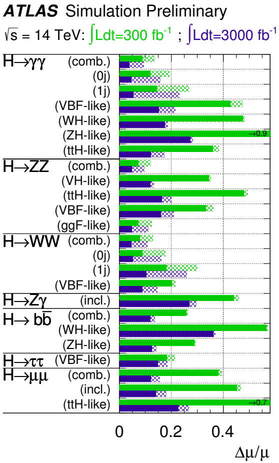
- Higgs discovery requires sophisticated theory predictions
  - higher-order perturbative calculations
  - resummation program
  - reliable non-perturbative tools (PDFs, PS, Jet ...)
- BSM effects are well hidden → more precise study of Higgs couplings



Higgs Boson Discovery → Precision Physics







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New Level of Precision Physics: Boosted Higgs

- Boosted Higgs is common phenomenon at LHC
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- Improve signal/ background ratio for different jet multiplicities
  - V boosted Higgs from $p\bar{p} \to V + H$
  - Jet boosted Higgs from $gg \to t\bar{t} + H$
  - Jet boosted Higgs from $pp \to H + jets$

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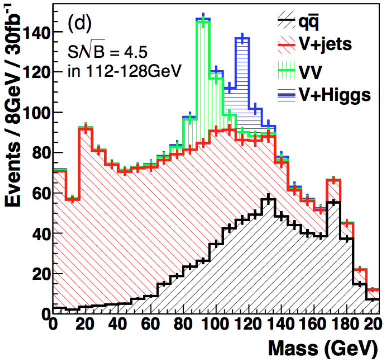
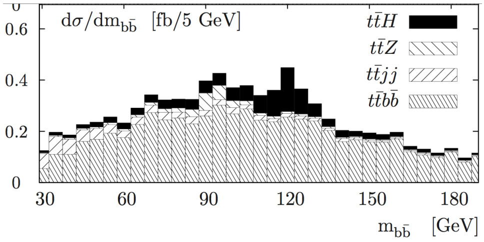
  - Jet boosted Higgs from $pp \to H + jets$
- Exclusive contribution to n-jet bins for Jet veto analysis in Higgs production

New Level of Precision Physics: Boosted Higgs

- Reduced signal/ background ratio from Higgs associated production channels
  - V boosted Higgs from $p\bar{p} \to V + H$
    - Select events with $p_T^H > 200 GeV$
  - Jet boosted Higgs form $gg \to t\bar{t} + H$
    - Select events with $p_T^H > 200 GeV$
    - Compare double and triple b-taggings to prevent Jet overlap



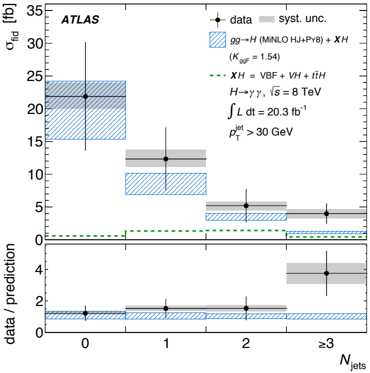


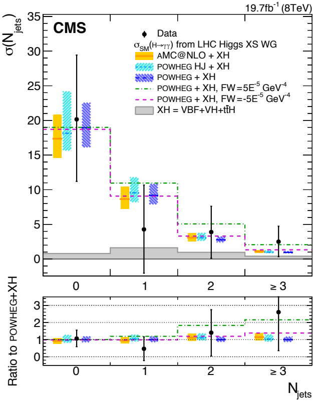
Plehn, Salam, Spannowsky 2009

Butterworth, Davison, Rubin, Salam 2008

New Level of Precision Physics: Boosted Higgs

- ATLAS and CMS both started the measurement for boosted Higgs

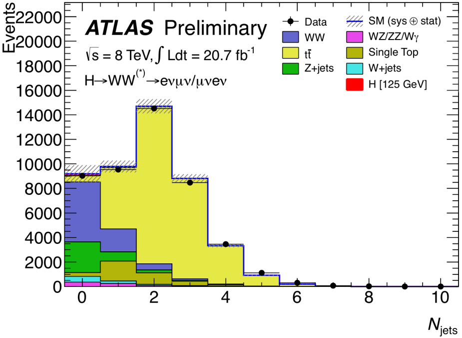


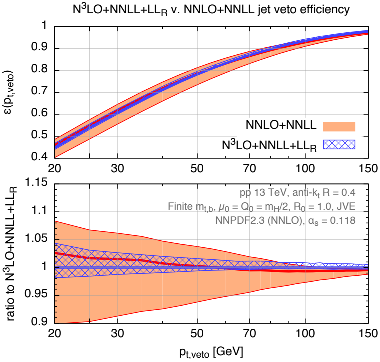


- $pp \to H \to \gamma\gamma$ jet-bin analyses
  - Different experimental accuracy in each bin
  - Large theory/exp disagreement at high jet multiplicity

New Level of Precision Physics: Boosted Higgs

- $pp \to H \to WW^{(*)}$ jet-bin analyses



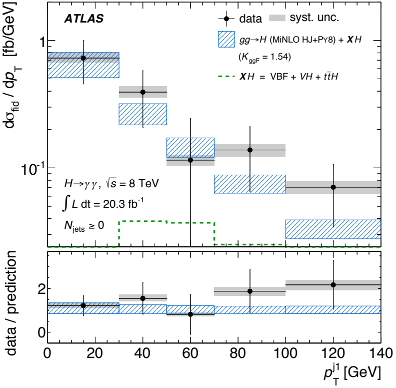


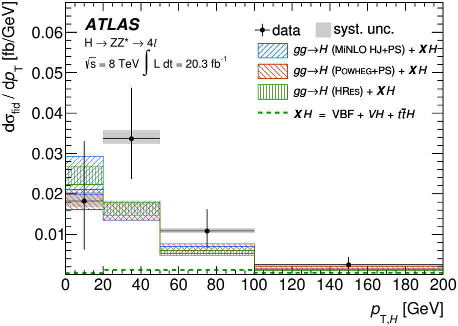
Banfi, Caola et al (15)

- Various selection rules in experiment to distinguish signal from background
- Need to study the precise theory involving those selection rules (e.g. jet veto cut)
  - N^3LO H production result is not enough for 0-jet bin: $\sigma_0 = \sigma_{tot} - \sigma_{\geq 1}$
  - Unertainty is reduced by improving $\sigma_{\geq 1}$(same α_s order: $H@N^3LO$, $HJ@NNLO$)

New Level of Precision Physics: Boosted Higgs

- Differential cross section in for boosted Higgs





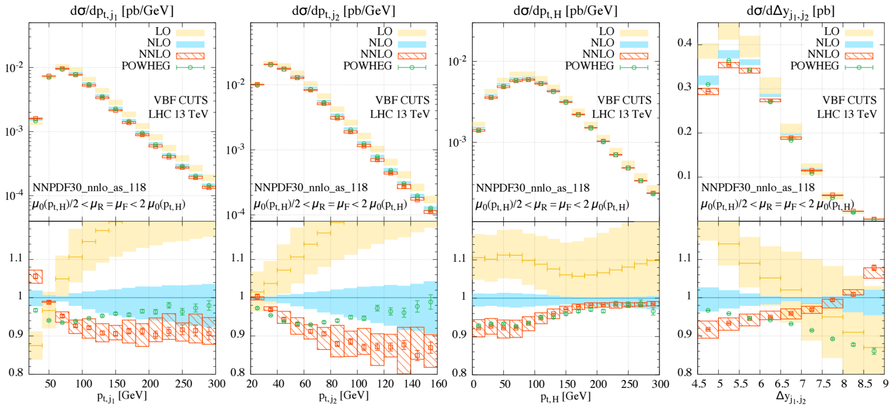
- Differential corss sections contain detailed properties of Higgs (event shape, forward/backward symmetry, $\cdots$)
- Large prediction error could be dominated by missing higher orders
- Request for more precise differential predictions

State-of-the-art Predictions for Boosted Higgs on LHC

- 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
- 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: see J. Wang's talk
- $t\bar{t}$ fusion channel (jet boosted, colour charged current)
  - H+$t\bar{t}$ approximate NNLO: A. Broggio, A. Ferroglia et al 15

State-of-the-art Predictions for Boosted Higgs on LHC

- pp → VBF → H + 2 jets

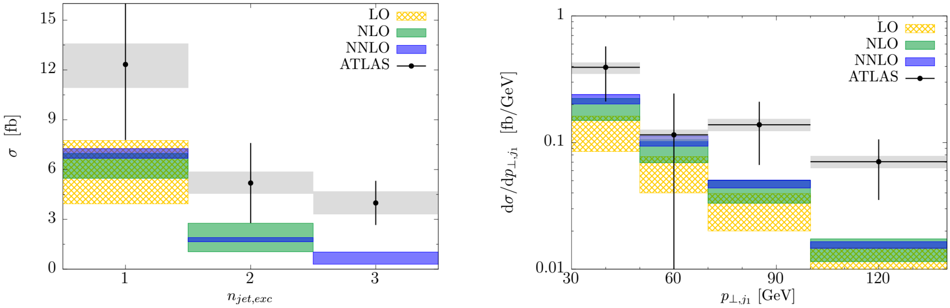


M. Cacciari, F. A. Dreyer et al 15

- Realistic collider VBF cuts: $p_t^j > 25GeV$; $|y_j| < 4.5$; $\Delta y_{j_1,j_2} > 4.5$ etc
- Improved scale variation
- Different distribution shape for NNLO

State-of-the-art Predictions for Boosted Higgs on LHC

- pp $\rightarrow$ H + jet (EFT)



F. Caola, K. Melnikov, M. Schulze 15

- Improved scale variation
- Relatively uniform k factor for NNLO/NLO (show later)
- Similar cuts used in ATLAS however has tension when comparing with data

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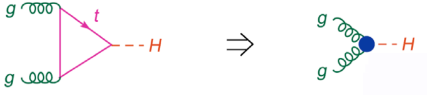
Higgs+jet building blocks

- 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)

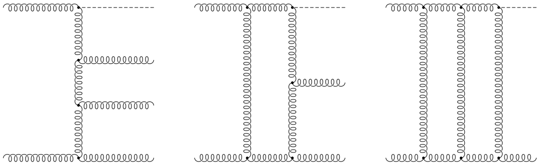
$$\mathcal{L}_H^{int} = \frac{C}{2} H \, \mathrm{Tr} G_{\mu\nu} G^{\mu\nu} \qquad C = \frac{\alpha_s}{6\pi V}(1 + \mathcal{O}(\alpha_s))$$

  - 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)

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

Higgs+jet building blocks



- tree level 2→3+H amplitudes Del Duca, Frizzo, Maltoni (Feynman); XC, Nigel (BCFW);
  - Implicit divergency in P.S.
- 1-loop 2→2+H amplitudes Berger, Del Duca, Dixon; Badger, Glover, Mastrolia, Williams; Badger, Ellis
  - Implicit divergency in P.S. as well as explcit poles up to ϵ^{-2}
- 2-loop 2→1+H amplitudes Gehrmann, Jaquier, Glover, Koukoutsakis
  - Explicit poles up to ϵ^{-4}
- 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 the subtraction method
- 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 Antenna Subtraction Method

Gehrmann-De Ridder, Gehrmann, Glover 05

- Subtraction terms constructed from antenna functions (from ME)
- Each antenna has two specified hard radiators + 1 or 2 unresolved patrons

$$X_3^0(i,j,k) \sim \frac{|\mathcal{M}^0_{ijk}|^2}{|\mathcal{M}^0_{IL}|^2}$$

$$X_4^0(i,j,k,l) \sim \frac{|\mathcal{M}^0_{ijkl}|^2}{|\mathcal{M}^0_{IL}|^2}$$

$$X_3^1(i,j,k) \sim \frac{|\mathcal{M}^1_{ijk}|^2}{|\mathcal{M}^0_{IK}|^2} - X^0_{ijk}\frac{|\mathcal{M}^1_{IK}|^2}{|\mathcal{M}^0_{IK}|^2}$$

- Momentum mappings give the P.S. for reduced ME

$d\Phi_{H+3} \to d\Phi_{H+2}$
$d\Phi_{H+3} \to d\Phi_{H+1}$
$d\Phi_{H+2} \to d\Phi_{H+1}$

- Integrated antenna functions all known and contain explicit poles
- Explicit pole cancellation between integrated antenna functions and loop calculations is analytical

Antenna Subtraction Method

- Antenna function form physical matrix elements

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

Gehrmann-De Ridder, Gehrmann, Glover, 05

- Complete set of Antenna tool box

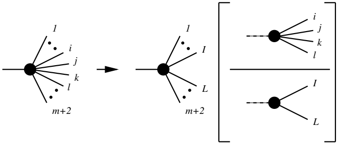
$$phase\ config. \otimes type \otimes parton\ types$$
$$[FF, IF, II] \otimes [X_3^0, X_4^0, X_3^1] \otimes [A \sim H]$$

- All antenna functions are analytically integrable
  - 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)

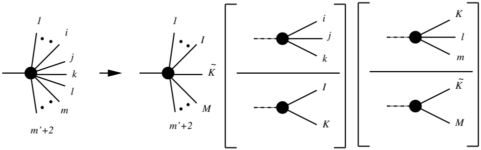
Antenna subtraction for double real emission (RR)

$$d\hat{\sigma}^S_{NNLO} \sim X^0_3|\mathcal{M}^0_{n+1}|^2 + X^0_4|\mathcal{M}^0_n|^2 + X^0_3 X^0_3|\mathcal{M}^0_n|^2 + X^0_3|\mathcal{M}^0_n|^2 soft$$

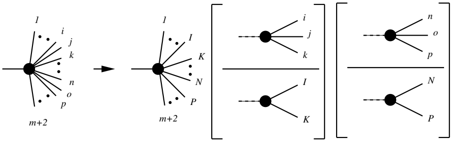
- Three possible colour ordering of double unresolved particles



(a) colour connected $X^0_4 \otimes |\mathcal{M}^0_n|^2$



(b) colour almost connected $X^0_3 \otimes X^0_3 \otimes |\mathcal{M}^0_n|^2$



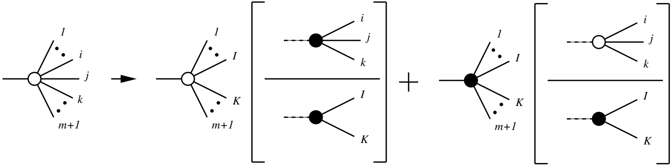
(c) colour not connected $X^0_3 \otimes X^0_3 \otimes |\mathcal{M}^0_n|^2$

Antenna subtraction for real emission at loop level (RV)

$$d\hat{\sigma}^{T}_{NNLO} \sim J_2^{(1)}|\mathcal{M}^0_{n+1}|^2 + X_3^0|\mathcal{M}^1_n|^2 + X_3^1|\mathcal{M}^0_n|^2 + J_2^{(1)}X_3^0|\mathcal{M}^0_n|^2$$

Currie, Glover, Wells (13)

- Only single unresolved limit



(d) Loop level: $X_3^0|\mathcal{M}^1_n|^2 + X_3^1|\mathcal{M}^0_n|^2$

$$J_2^{(1)} = \int X_3^0 d\Phi_{FF,IF,II} + M.F._{IF,II}$$

$$Poles\left(J_{2,ij}^{(1)}\right) = Poles\left(I_{ij}^{(1)}(\epsilon, s_{ij})\right)$$

Antenna subtraction for two-loop level (VV)

- Double virtual level only have explicitly poles and no parton become unresolved
- Collect all leftover subtraction terms (integrated) in $d\hat{\sigma}^U_{NNLO}$

$$
\begin{aligned}
d\hat{\sigma}^U_{NNLO} \sim\ & J_2^{(1)}(|\mathcal{M}_n^1|^2 - \frac{\beta_0}{\epsilon}|\mathcal{M}_n^0|^2) \\
& - \frac{1}{2} J_2^{(1)} \otimes J_2^{(1)} |\mathcal{M}_n^0|^2 \\
& + J_2^{(2)} |\mathcal{M}_n^0|^2
\end{aligned}
$$

Currie, Glover, Wells (13)

$$
pole\{d\hat{\sigma}^{VV}_{NNLO}\} \sim pole\left\{ I_{ij}^{(1)} \otimes |\mathcal{M}_n^1|^2 - (\frac{1}{2} I_{ij}^{(1)} \otimes I_{ij}^{(1)} + \frac{\beta_0}{\epsilon} I_{ij}^{(1)} - I_{ij}^{(2)}) |\mathcal{M}_n^0|^2 \right\}
$$

S. Catani (98)

- VV pole cancellation analytically checked with FORM
- Master code (.map) $\rightarrow$ (.frm) (.f) (.tex)

NNLOJET: NNLO tool with Antenna subtraction

```
      _  ___  ____   ____    ___________
     / |/ / |/ / /  / __ \__ / / __/_  __/
    /    /    / /__/ /_/ / // / _/  / /
   /_/|_/_/|_/____/\____/\___/___/ /_/

**********************************************************************
*                                                                    *
* 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
- ✓ ...

NNLOJET: application in $pp \to H + \geq 1jet$

- $pp \to H + \geq 1jet$
  - Higgs production via gluon fusion in EFT
  - Precise study for p_t^H distribution (Boosted Higgs)
  - Current large disgreement in $\gamma\gamma Jet$ final states
- One of the first NNLO processes done with three different subtraction formalisms
  - pp $\to$ H + J Antenna subtraction. XC, Gehrmann, Glover and Jaquier 1408.5325, 1604.04085
  - pp $\to$ H + J Sector Improved Decomposition subtraction (without quark-quark channel). Boughezal, Caola, Melnikov, Petriello, Schulze 1302.6216, 1504.07922, 1508.02684
  - pp $\to$ H + J N-jettiness subtraction. Boughezal, Focke, Giele, Liu, Petriello 1505.03893
  - Important crosscheck - to appear in LHCHXSWG YR4 report ggF chapter

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  - Current large disgreement in $\gamma\gamma Jet$ final states
- One of the first NNLO processes done with three different subtraction formalisms
  - pp $\to$ H + J Antenna subtraction. XC, Gehrmann, Glover and Jaquier 1408.5325, 1604.04085
  - pp $\to$ H + J Sector Improved Decomposition subtraction (without quark-quark channel). Boughezal, Caola, Melnikov, Petriello, Schulze 1302.6216, 1504.07922, 1508.02684
  - pp $\to$ H + J N-jettiness subtraction. Boughezal, Focke, Giele, Liu, Petriello 1505.03893
  - Important crosscheck - to appear in LHCHXSWG YR4 report ggF chapter
- Published results with ATLAS cuts (1407.4222v2):
  - ATLAS: $\sigma^{\text{fid}}_{H+\geq 1j \to \gamma\gamma+\geq 1j}(8\text{ TeV}) = 21.5 \pm 5.3(\text{stat.}) \pm^{2.4}_{2.2}(\text{syst.}) \pm 0.6(\text{lumi})$ fb
  - NNLOJET: $\sigma^{\text{fid}}_{NNLO} = 9.4^{+0.65}_{-0.89}$ fb $(\mu_R = \mu_F = m_H, 0.5 \times m_H, 2 \times m_H)$

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

  - Sector Improved Decomposition:

$$\sigma^{\text{fid}}_{LO} = 5.42^{+2.32}_{-1.49}\text{ fb},\ \sigma^{\text{fid}}_{NLO} = 7.98^{+1.76}_{-1.46}\text{ fb},\ \sigma^{\text{fid}}_{NNLO(\not{qq})} = 9.45^{+0.58}_{-0.82}\text{ fb}$$

NNLOJET: application in $pp \to H+ \geq 1jet$

- Improve with new setup (preliminary):
    - Include full m_t, m_b, m_c dependence at LO:
    - Apply modern PDF set: PDF4LHC15_nnlo (was NNPDF2.3)
    - Apply identical photon isolation algorithm as ATLAS (85% $\sim$ 95% efficiency)

$$\sigma_{LO}^{\text{fid}(m_q)} = 4.19^{+1.78}_{-1.17} \text{ fb}, \ \sigma_{NLO}^{\text{fid}(m_q@LO)} = 7.72^{+1.7}_{-1.45} \text{ fb}, \ \sigma_{NNLO}^{\text{fid}(m_q@LO)} = 9.19^{+0.71}_{-0.96} \text{ fb}$$

$p_\perp^{jet} > 30$ GeV, $|\eta_{jet}| < 4.4$
$p_\perp^{\gamma_1} > 0.35 \cdot m_H$, $p_\perp^{\gamma_2} > 0.25 \cdot m_H$
$|\eta_\gamma| < 2.37$
anti-k_T (R=0.4)
PDF4LHC15
$\mu_R = \mu_F = (0.5,1,2) \cdot (m_H^2 + p_{TH}^2)^{1/2}$

ATLAS fiducial cut

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ATLAS fiducial cut

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

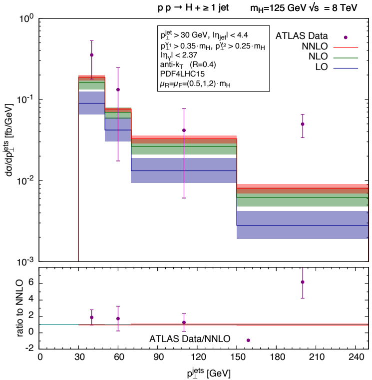
CMS fiducial cut

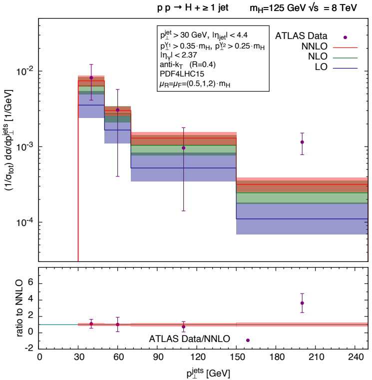
- Published CMS data with very different cut (photon isolation efficiency 63%) (1508.07819):
  - CMS: $\sigma^{\text{fid}}_{H+\geq 1j \to \gamma\gamma+\geq 1j}$(8 TeV) $= 10.7 \pm 7.7$(comb.) fb (hepData not available)

$$\sigma_{LO}^{\text{fid}(m_q)} = 4.19^{+1.81}_{-1.15}\ \text{fb},\ \sigma_{NLO}^{\text{fid}(m_q@LO)} = 8.03^{+1.84}_{-1.53}\ \text{fb},\ \sigma_{NNLO}^{\text{fid}(m_q@LO)} = 9.81^{+0.8}_{-1.06}\ \text{fb}$$

NNLOJET: application in $pp \to H + \geq 1jet$

- Differential cross section comparison



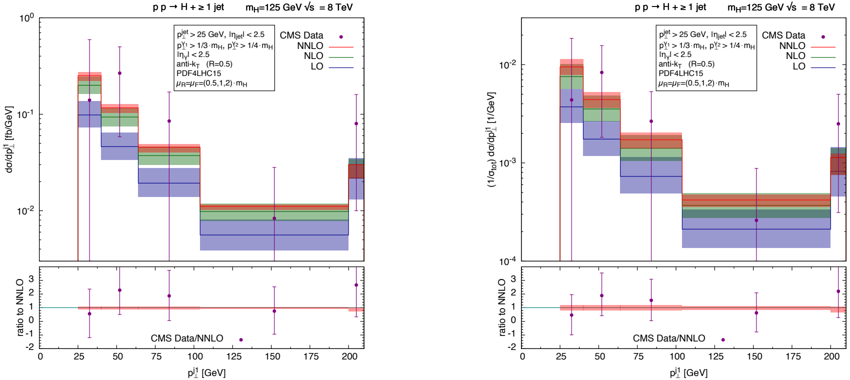


XC, Cruz-Martinez, Gehrmann, Glover and Jaquier (Preliminary)

- Tension in the total cross section help us better understand the distributions
- In general, normalising by σ^H_{tot} is to minimize the luminosity error
- Tension in the last bin above due to finite quark mass effects

NNLOJET: application in $pp \rightarrow H + \geq 1jet$

- Differential cross section comparison



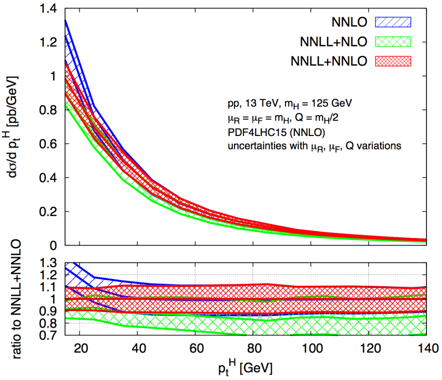
XC, Cruz-Martinez, Gehrmann, Glover and Jaquier (Preliminary)

- Differential distribution in the high p_T region is well controled
- Scale variation reduced drastically with NNLO
- NNLO corrections are essential $(\geq 25\%)$ in some bins

p_T^H study from $pp \to H+ \geq 0jet$

- Study Higgs p_T distributions with parton boosted Higgs at NNLO+NNLL

- 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 (see Huaxing Zhu's talk)



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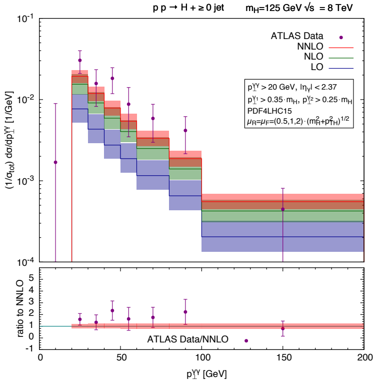
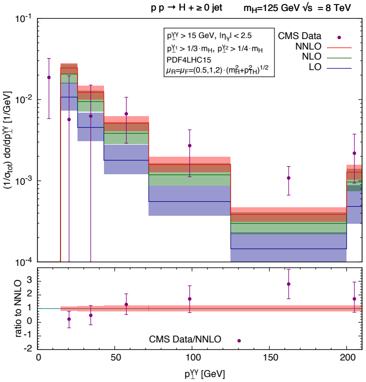
NNLOJET: application in $pp \to H + \geq 0jet$

- Higgs p_T distributions with parton boosted Higgs at NNLO





XC, Cruz-Martinez, Gehrmann, Glover and Jaquier (Preliminary)

- Differential distribution in full p_T region is well controled
- Scale variation reduced drastically with NNLO
- NNLO corrections are subtential and towards the right direction

Summary & Outlook

- Summary
  - Boosted properties of Higgs is an interesting field not yet well understood
    - Boosted Higgs is very common on LHC and reveal more details of understanding of SM
    - Precise QCD calculations are essential for such study at LHC
    - Resolve theory/experiment disagreement requires more inputs on both sides
  - Future work
    - To compare with ATLAS and CMS data in $H \to ZZ(WW)$ decay channel
    - The dominant Higgs decay channel $H \to b\bar{b}$ is more complicated
    - Implementation/collaboration on NNLO VBF channel

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THANK YOU!

Back Up Slides

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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- Each NNLO subtraction scheme has its advantanges and disadvantages

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

NNLOJET: NNLO tool with Antenna subtraction

NNLOJET: NNLO tool with Antenna subtraction

- Matrix elements
  - Use known tree, one-loop, two-loop ME directly (fast evaluation)
  - Automation not yet available $\rightarrow$ interface with automated tools
  - Constrained by limited two-loop ME
  - Test numerical stability of known tree and one-loop ME
    (Internal cancellation of terms with high divergent order)

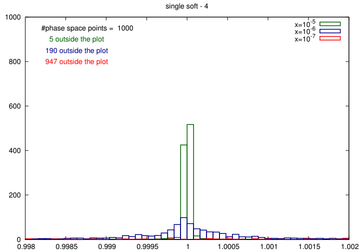

Figure: $|M_H^1(gggg)|^2$ unstable

$\rightarrow$

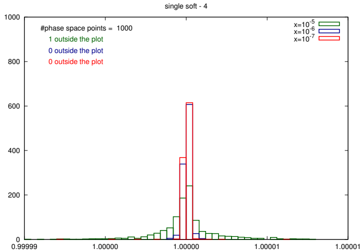

Figure: $|M_H^1(gggg)|^2$ stable

- Subtraction terms (semi-automated)
- Uniformed structure (user friendly)

NNLOJET: NNLO tool with Antenna subtraction

- Matrix elements
- Subtraction terms (semi-automated)
  - Analytical construction for process with different legs
  - Fast application for process with same complexity: $pp \to H + Jet$ directly application to $pp \to V + Jet$
  - Maple $\to$ (Form) $\to$ Fortran (auto-generation)

```
A5g0HXS.map:
#####################################
-F40(1,i,2,k)*A3g0H([1],[2],j,H)*JET11(j)*a31
+ggF30II(1,i,2)*ggF30II([1],k,[2])*A3g0H([[1]],[[2]],j,H)*JET11(j)*a32
+ggF30II(1,k,2)*ggF30II([1],i,[2])*A3g0H([[1]],[[2]],j,H)*JET11(j)*a33
```

```
autoA5g0HXS.f:
#####################################
*  {i4 = k3, i6 = k4, i7 = k5, [i1] = k1, [i2] = k2}
      call pmap7to5II(i1,i2,i3,i5,i4,i6,i7,k1,k2,k3,k4,k5,ipass)
      call ecuts_vj(5,ipass)
      if(ipass.eq.1)then
        jpass(31)=1
        call getqcdnorm(ix,partons(31,:),facnorm(31,:))
        wt(31)=-1d0*FullF40(i1,i3,i2,i5,7)*A3g0H(k1,k2,k3,k4,k5)
        call bino(1,partons(31,:),-relfac*wt(31)*facnorm(31,:),5)
      endif
```

- Uniformed structure (user friendly)

NNLOJET: NNLO tool with Antenna subtraction

- Matrix elements
- Subtraction terms (semi-automated)
- Uniformed structure (user friendly)
  - Automated link between LO, NLO and NNLO

```
jet.map:
#####################################
LO:=[                              RR:=[
[A4g0,[g,g,g,g],1],                [A6g0,[g,g,g,g,g,g],1],
[B2g0,[qb,g,g,q],1/nc],            [At6g0,[g,g,g,g,g,g],-1/nc**2],
[Bt2g0,[qb,gt,gt,q],-1/nc**3],     [B4g0,[qb,g,g,g,g,q],1/nc],
[C0g0,[qb,Q,Qb,q],1/nc**2],        [Bt4g0,[qb,g,g,g,g,q],-1/nc**3],
[D0g0,[qb,q,qb,q],-1/nc**3]        [Btt4g0,[qb,g,g,g,g,q],(nc**2+1)/nc**5]
]:                                 ]:
```

```
qcdnormjet.f:
#####################################
c -- double real
      case(171)
         factor=2d0*1d0/24d0*facRR          ! g g -> g g g g     A6g0
      case(172)
         factor=-1d0/nc**2*2d0*1d0/24d0*facRR   ! g g -> g g g g At6g0
      case(173)
         factor=1d0/nc*1d0/24d0*facRR       ! q qb -> g g g g    B4g0
      case(174)
```

  - Optmised integration: azimuthal averaging, dynamic scale, double differential XS

NNLOJET: NNLO tool with Antenna subtraction

- Matrix elements
- Subtraction terms (semi-automated)
- Uniformed structure (user friendly)
  - Automated link between LO, NLO and NNLO

```
sigRRHJ.f:
#####################################
c--- q qb to g g g ph1 ph2
      if(ip(88))then
        iproc = 88    nfB1 = 3     ip1 = 30    ip2 = -30
        call getqcdnorm(ix,partons,factor)
        kinwt = factor*(B3g0H(1,3,4,5,2,6,7)
     .                       +B3g0H(1,3,5,4,2,6,7)
     .                       +B3g0H(1,4,3,5,2,6,7)
     .                       +B3g0H(1,4,5,3,2,6,7)
     .                       +B3g0H(1,5,3,4,2,6,7)
     .                       +B3g0H(1,5,4,3,2,6,7))
```

```
sigSHJ.f:
#####################################
c--- q qb to g g g ph1 ph2
      if(ip(88))then
        iproc = 88    nfB1 = 3     ip1 = 30    ip2 = -30
        wt = qqbB3g0HS(1,3,4,5,2,6,7)
        wtsum = wtsum + wt
```

  - Optmised integration: azimuthal averaging, dynamic scale, double differential XS