Max-Planck-Institut für Physik
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Higher-order calculations: Status and prospects

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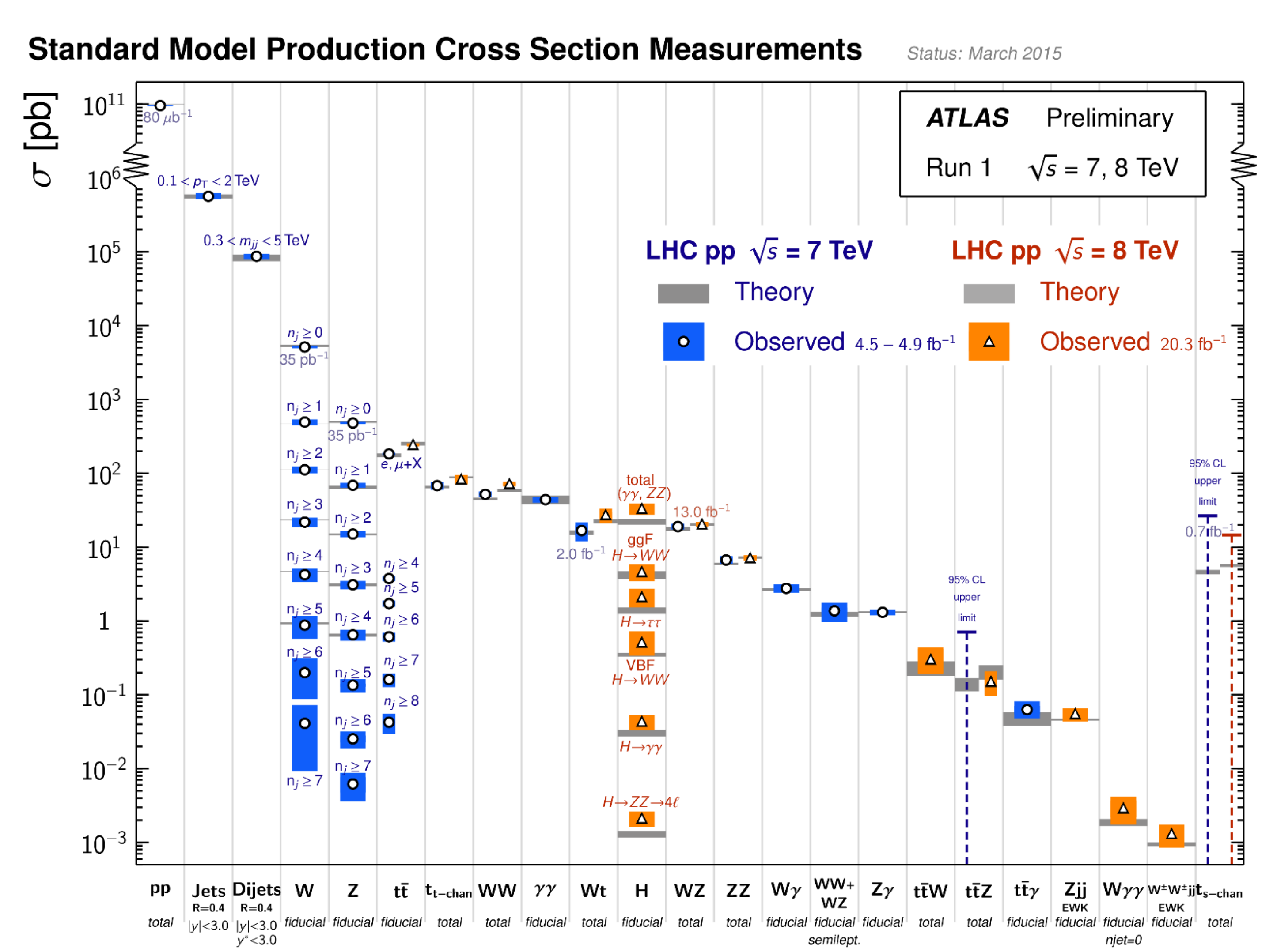
Recent developments in fixed order QCD

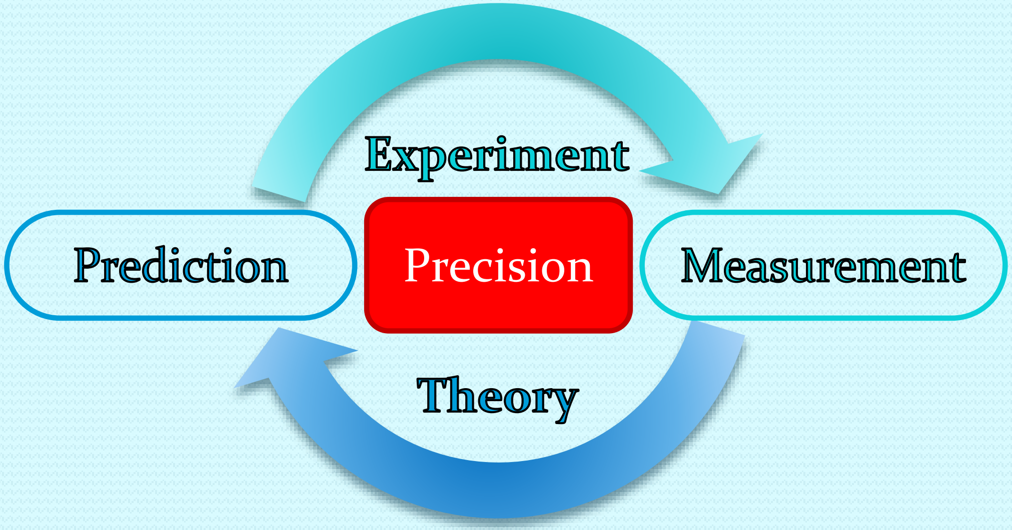
Introduction



Accompanying text on ATLAS TWiki:

Summary of several Standard Model total and fiducial production cross section measurements, corrected for leptonic branching fractions, compared to the corresponding theoretical expectations. All theoretical expectations were calculated at NLO or higher [...]

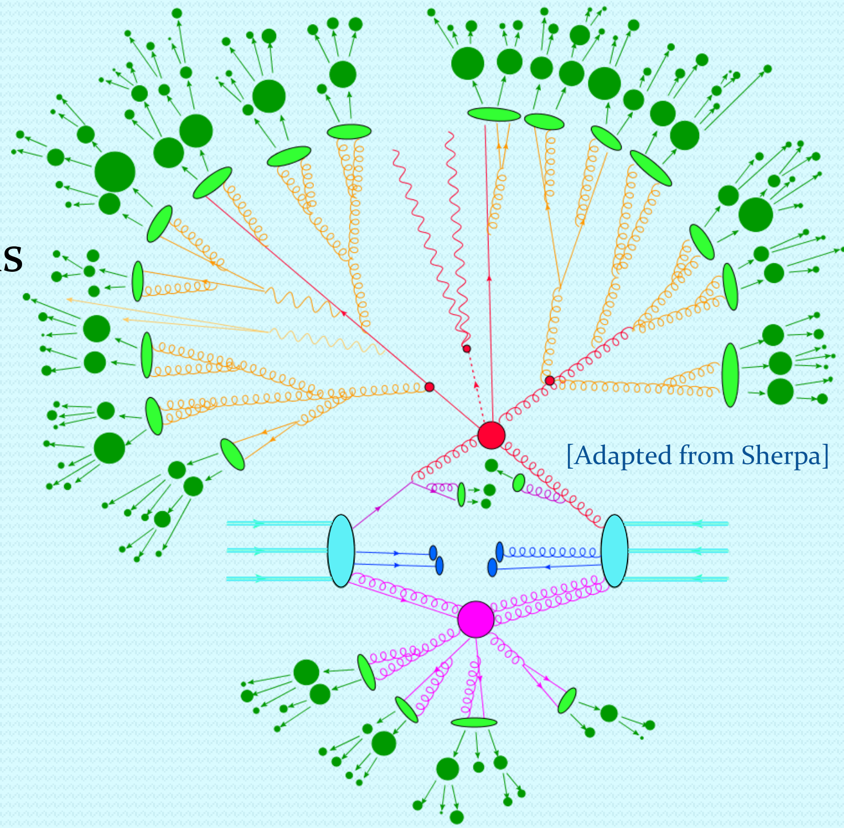
Introduction



- Precise measurements encourage and stimulate increasingly precise theoretical predictions:
  - New (automated) tools for computation of amplitudes
  - New NLO / NNLO computations in QCD/EW and mixed
  - New resummation results matched to fixed order
  - New/ upgraded shower Monte Carlo codes
  - Matching of (N)NLO+PS / merging multiplicities
  - Updated and more accurate input: PDFs, α_s, ...

Motivation: QCD at the LHC

- QCD is omnipresent at LHC:
  - PDF
  - Hard scattering and loop corrections
  - Parton Shower
  - Hadronization
  - Non Perturbative phenomena



[Adapted from Sherpa]

Motivation: QCD at the LHC

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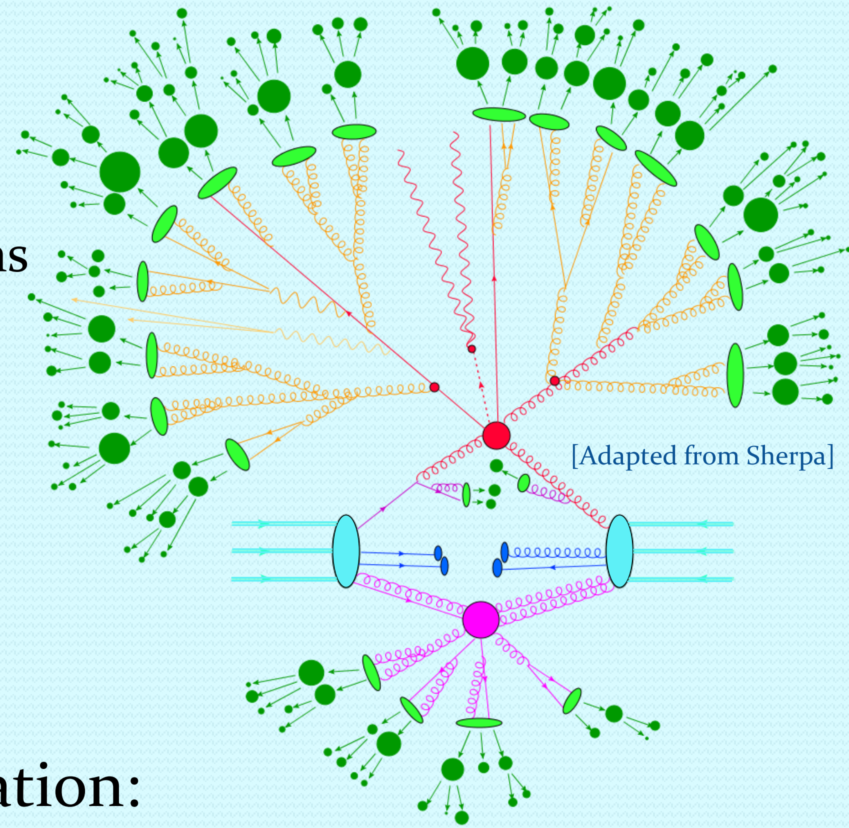


[Adapted from Sherpa]

- Structure of fixed order computation:

$$\sigma_{h_1 h_2 \to X} = \sum_{a,b} \int_0^1 dx_1 dx_2\, f_{h_1/a}(x_1, \mu_F^2)\, f_{h_2/b}(x_2, \mu_F^2) \times \hat{\sigma}_{a,b\to X}\left(x_1, x_2, \alpha_s(\mu_R^2), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2}\right) \left[+\mathcal{O}\left(\frac{1}{Q^2}\right)\right]$$

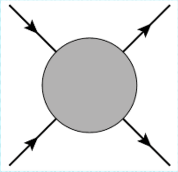
PDFs | partonic cross section | power corrections

Fixed Order Calculations

- Partonic cross section: for hard processes computed as series exp. in the strong coupling α_s

$$\hat{\sigma}_{a,b\to X} = \sigma_0$$

LO

- LO: 

Predicts only the order of magnitude:
- ➢ scale in coupling is not defined
- ➢ 1 parton ⟷ 1 jet

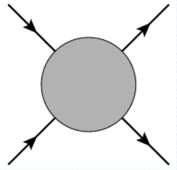
Fixed Order Calculations

- Partonic cross section: for hard processes computed as series exp. in the strong coupling α_s

$$\hat{\sigma}_{a,b\to X} = \sigma_0 + \alpha_s \sigma_1$$

LO | NLO

- LO:



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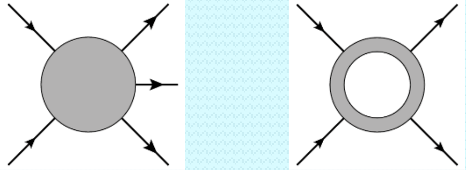
- NLO:



First reliable predictions:
➢ scale choices can ben made
➢ first description of jet substructure

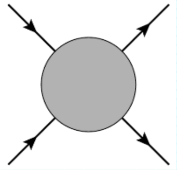
Fixed Order Calculations

- Partonic cross section: for hard processes computed as series exp. in the strong coupling α_s

$$\hat{\sigma}_{a,b\to X} = \sigma_0 + \alpha_s\sigma_1 + \alpha_s^2\sigma_2 + \alpha_s^3\sigma_3 + \mathcal{O}(\alpha_s^4)$$

LO	NLO	NNLO	N^{3}LO

- LO:



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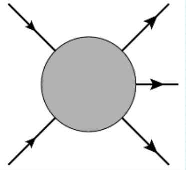

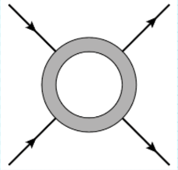

First reliable predictions:
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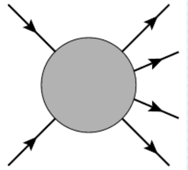
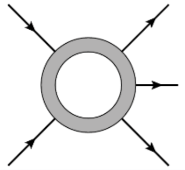
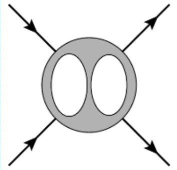
- NNLO:





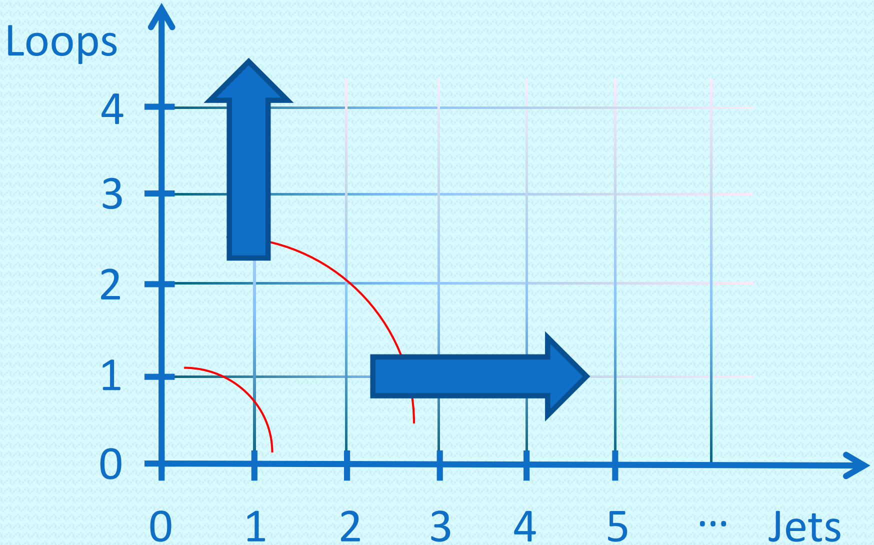


Possible to quantify uncertainties:
➢ convergence can be checked
➢ richer jet substructure

Loops vs Legs

- Growth of complexity in fixed order computations:

Complexity ~ # loops + # legs (+ # scales)



→ additional legs: hard

→ additional loops: very hard
  - loop integrals often unknown and tough

→ at 1 loop problem in principle solved
  - challenge are additional legs

⚠ NLO is not always 1 loop!
  - Especially for Higgs physics many relevant loop-induced processes

Computing power and smart ideas are the key for progress!

NLO and Automation

- Ingredients for NLO computation:

$$\hat{\sigma}^{\rm NLO}_{a,b\to X} = \int_{{\rm d}\Phi_m} {\rm d}\sigma_{\rm Born} + \int_{{\rm d}\Phi_{m+1}} \left({\rm d}\sigma^{\rm R}_{\rm NLO} - {\rm d}\sigma^{\rm S}_{\rm NLO}\right) + \int_{{\rm d}\Phi_m} \left[\int_{{\rm d}\Phi_1} {\rm d}\sigma^{\rm S}_{\rm NLO} + {\rm d}\sigma^{V}_{\rm NLO}\right]$$

  - In past decade the computation of the different ingredients was automatized and assembled into codes which allow for an automatic computation of fully differential NLO cross sections (at least up to 2 $\longrightarrow$ 4)

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Monte Carlo

Tree amplitudes
Subtraction scheme
Phase space integral

BLHA or ad hoc

One Loop Program

Virtual amplitude

➡ Problem is <u>*in principle*</u> solved!
(technical issue related to computational power arise beyond 2 $\longrightarrow$ 4)

➡ Very lively field with several different solutions.

➡ Many new results, often already interfaced with shower and merged
IMPOSSIBLE TO MENTION ALL NEW NLO RESULTS HERE!

NLO and Automation

Monte Carlo

- Tree amplitudes
- Subtraction scheme
- Phase space integral

BLHA or ad hoc

One Loop Program

- Virtual amplitude

Geneva	[Alioli et al.]
Helac-NLO (also loop)	[Bevilacqua et al.]
Herwig++/Matchbox	[Bellm et al.]
MadGraph5_aMC@NLO	[Alwall et al.]
Powheg	[Alioli et al.]
Sherpa	[Gleisberg et al.]
MCFM	[Campbell et al.]

Blackhat	[Bern et al.]
GoSam	[Cullen et al.]
MadLoop	[Hirschi et al.]
NJet	[Badger, Biedermann, Uwer, Yundin]
OpenLoops	[Cascioli, Lindert, Maierhöfer, Pozzorini]
Recola	[Actis, Denner, Hofer, Scharf, Uccirati]

Loop reduction codes

Collier	[Denner, Dittmaier, Hofer]
Cuttools	[Ossola, Papadopoulos, Pittau]
Golem95	[Binoth, Guillet, Heinrich, Pilon, Reiter, Soden-Fraunhofen]
Ninja	[Mastrolia, Mirabella, Peraro]
Samurai	[v. Deurzen, Mastrolia, Ossola, Reiter, Tramontano]

Loop integral libraries

OneLOop	[v. Hameren]
QCDLoop	[Ellis, Zanderighi]
FF	[v. Oldenborgh]

Several can be used for EW too!! [More on EW in talk by S. Pozzorini]

Automated NLO QCD: MadGraph5_aMC@NLO

- Example:

[Alwall et al., 1405.0301]

	Process Higgs pair production	Syntax	Cross section (pb) LO 13 TeV		NLO 13 TeV	
h.1	$pp \to HH$ (Loop improved)	`p p > h h`	$1.772 \pm 0.006 \cdot 10^{-2}$	$^{+29.5\%}_{-21.4\%}$ $^{+2.1\%}_{-2.6\%}$	$2.763 \pm 0.008 \cdot 10^{-2}$	$^{+11.4\%}_{-11.8\%}$ $^{+2.1\%}_{-2.6\%}$
h.2	$pp \to HHjj$ (VBF)	`p p > h h j j $$ w+ w- z`	$6.503 \pm 0.019 \cdot 10^{-4}$	$^{+7.2\%}_{-6.4\%}$ $^{+2.3\%}_{-1.6\%}$	$6.820 \pm 0.026 \cdot 10^{-4}$	$^{+0.8\%}_{-1.0\%}$ $^{+2.4\%}_{-1.7\%}$
h.3	$pp \to HHW^{\pm}$	`p p > h h wpm`	$4.303 \pm 0.005 \cdot 10^{-4}$	$^{+0.9\%}_{-1.3\%}$ $^{+2.0\%}_{-1.5\%}$	$5.002 \pm 0.014 \cdot 10^{-4}$	$^{+1.5\%}_{-1.2\%}$ $^{+2.0\%}_{-1.6\%}$
h.4*	$pp \to HHW^{\pm}j$	`p p > h h wpm j`	$1.922 \pm 0.002 \cdot 10^{-4}$	$^{+14.2\%}_{-11.7\%}$ $^{+1.5\%}_{-1.1\%}$	$2.218 \pm 0.009 \cdot 10^{-4}$	$^{+2.7\%}_{-3.3\%}$ $^{+1.6\%}_{-1.1\%}$
h.5*	$pp \to HHW^{\pm}\gamma$	`p p > h h wpm a`	$1.952 \pm 0.004 \cdot 10^{-6}$	$^{+3.0\%}_{-3.0\%}$ $^{+2.2\%}_{-1.6\%}$	$2.347 \pm 0.007 \cdot 10^{-6}$	$^{+2.4\%}_{-2.0\%}$ $^{+2.1\%}_{-1.6\%}$
h.6	$pp \to HHZ$	`p p > h h z`	$2.701 \pm 0.007 \cdot 10^{-4}$	$^{+0.9\%}_{-1.3\%}$ $^{+2.0\%}_{-1.5\%}$	$3.130 \pm 0.008 \cdot 10^{-4}$	$^{+1.6\%}_{-1.2\%}$ $^{+2.0\%}_{-1.5\%}$
h.7*	$pp \to HHZj$	`p p > h h z j`	$1.211 \pm 0.001 \cdot 10^{-4}$	$^{+14.1\%}_{-11.7\%}$ $^{+1.4\%}_{-1.1\%}$	$1.394 \pm 0.006 \cdot 10^{-4}$	$^{+2.7\%}_{-3.2\%}$ $^{+1.5\%}_{-1.1\%}$
h.8*	$pp \to HHZ\gamma$	`p p > h h z a`	$1.397 \pm 0.003 \cdot 10^{-6}$	$^{+2.4\%}_{-2.5\%}$ $^{+2.2\%}_{-1.7\%}$	$1.604 \pm 0.005 \cdot 10^{-6}$	$^{+1.7\%}_{-1.4\%}$ $^{+2.3\%}_{-1.7\%}$
h.9*	$pp \to HHZZ$	`p p > h h z z`	$2.309 \pm 0.005 \cdot 10^{-6}$	$^{+3.9\%}_{-3.8\%}$ $^{+2.2\%}_{-1.7\%}$	$2.754 \pm 0.009 \cdot 10^{-6}$	$^{+2.3\%}_{-2.0\%}$ $^{+2.3\%}_{-1.7\%}$
h.10*	$pp \to HHZW^{\pm}$	`p p > h h z wpm`	$3.708 \pm 0.013 \cdot 10^{-6}$	$^{+4.8\%}_{-4.5\%}$ $^{+2.3\%}_{-1.7\%}$	$4.904 \pm 0.029 \cdot 10^{-6}$	$^{+3.7\%}_{-3.2\%}$ $^{+2.2\%}_{-1.6\%}$
h.11*	$pp \to HHW^+W^-$ (4f)	`p p > h h w+ w-`	$7.524 \pm 0.070 \cdot 10^{-6}$	$^{+3.5\%}_{-3.4\%}$ $^{+2.3\%}_{-1.7\%}$	$9.268 \pm 0.030 \cdot 10^{-6}$	$^{+2.3\%}_{-2.1\%}$ $^{+2.3\%}_{-1.7\%}$
h.12	$pp \to HHt\bar{t}$	`p p > h h t t~`	$6.756 \pm 0.007 \cdot 10^{-4}$	$^{+30.2\%}_{-21.6\%}$ $^{+1.8\%}_{-1.8\%}$	$7.301 \pm 0.024 \cdot 10^{-4}$	$^{+1.4\%}_{-5.7\%}$ $^{+2.2\%}_{-2.3\%}$
h.13	$pp \to HHtj$	`p p > h h tt j`	$1.844 \pm 0.008 \cdot 10^{-5}$	$^{+0.0\%}_{-0.6\%}$ $^{+1.8\%}_{-1.8\%}$	$2.444 \pm 0.009 \cdot 10^{-5}$	$^{+4.5\%}_{-3.1\%}$ $^{+2.8\%}_{-3.0\%}$
h.14*	$pp \to HHb\bar{b}$	`p p > h h b b~`	$7.849 \pm 0.022 \cdot 10^{-8}$	$^{+34.3\%}_{-23.9\%}$ $^{+3.1\%}_{-3.7\%}$	$1.084 \pm 0.012 \cdot 10^{-7}$	$^{+7.4\%}_{-10.8\%}$ $^{+3.1\%}_{-3.7\%}$

  - Sample from a list of NLO QCD cross sections for 172 processes

→ Focus on phenomenological analysis and it's relevance!

- Since recently able to handle also loop-induced processes:

	Process Single boson + jets	Syntax	Cross section (pb) $\sqrt{s} = 13$ TeV	$\Delta_{\hat{\mu}}$	Δ_{PDF}	Ref.
a.1	$pp \to H$	`p p > h [QCD]`	17.79 ± 0.060	$^{+31.3\%}_{-23.1\%}$	$^{+0.5\%}_{-0.9\%}$	[47]
a.2	$pp \to Hj$	`p p > h j [QCD]`	12.86 ± 0.030	$^{+42.3\%}_{-27.7\%}$	$^{+0.6\%}_{-0.9\%}$	[47]
a.3	$pp \to Hjj$	`p p > h j j QED=1 [QCD]`	6.175 ± 0.020	$^{+61.8\%}_{-35.6\%}$	$^{+0.7\%}_{-0.9\%}$	[47]

[Hirschi, Mattelaer, 1507.0002]

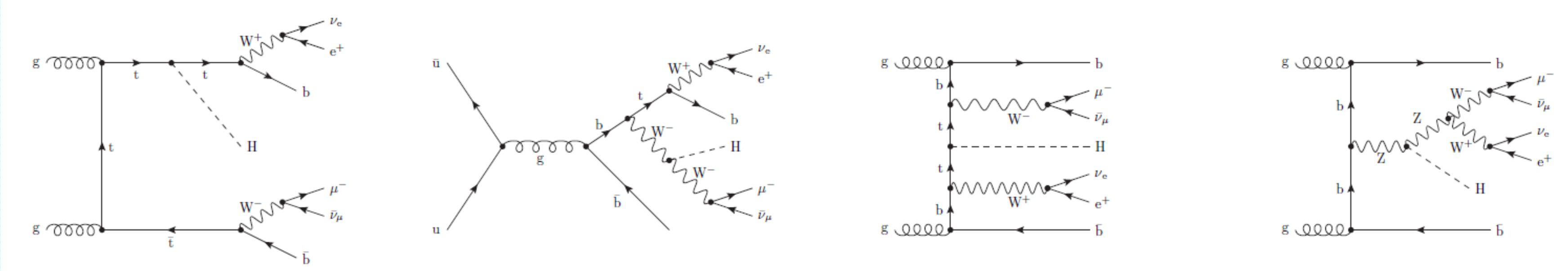
  - Possibility to choose OLP: MadLoop or GoSam

[Van Deurzen, Frederix, Hirschi, GL, Mastrolia, Ossola, in preparation]

NLO QCD results for $HW^+W^-b\bar{b}$

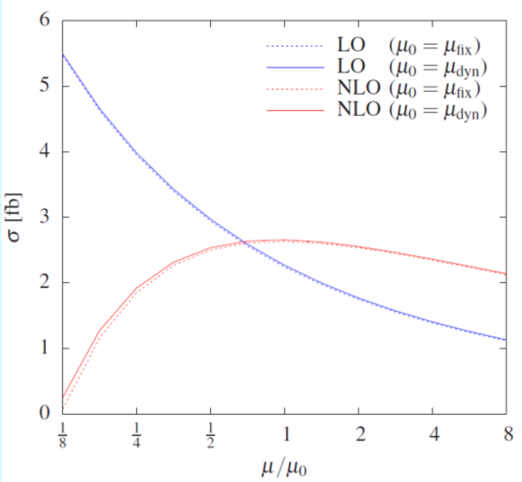
[Denner, Feger, 1506.07448]

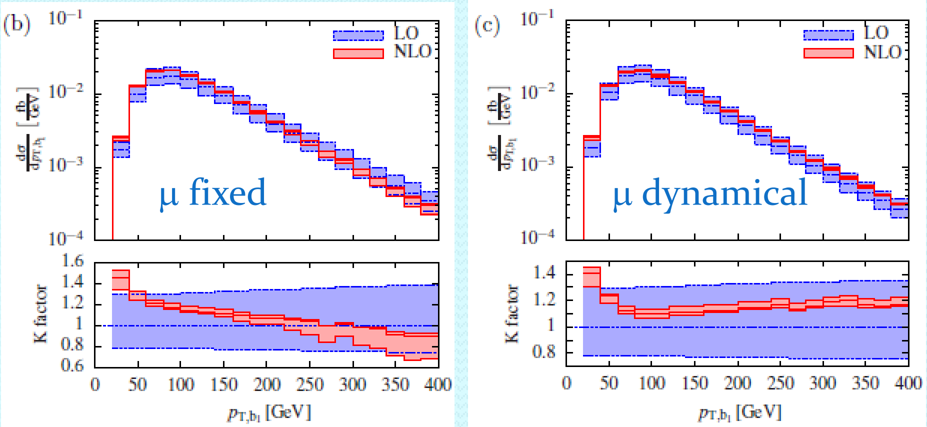
- Includes all Higgs production contributions (from t and W):
  (no b quarks in initial state)



- Computed using Recola, Collier and inhouse multi-channel MC
- Fixed and dynamical scale: $\mu_R = \mu_F = m_t + \frac{1}{2} M_H = 236\,\text{GeV}$

$\mu_R = \mu_F = (m_{t,T} m_{\bar{t},T} m_{H,T})^{1/3}$ $\quad m_T = \sqrt{m^2 + p_T^2}$



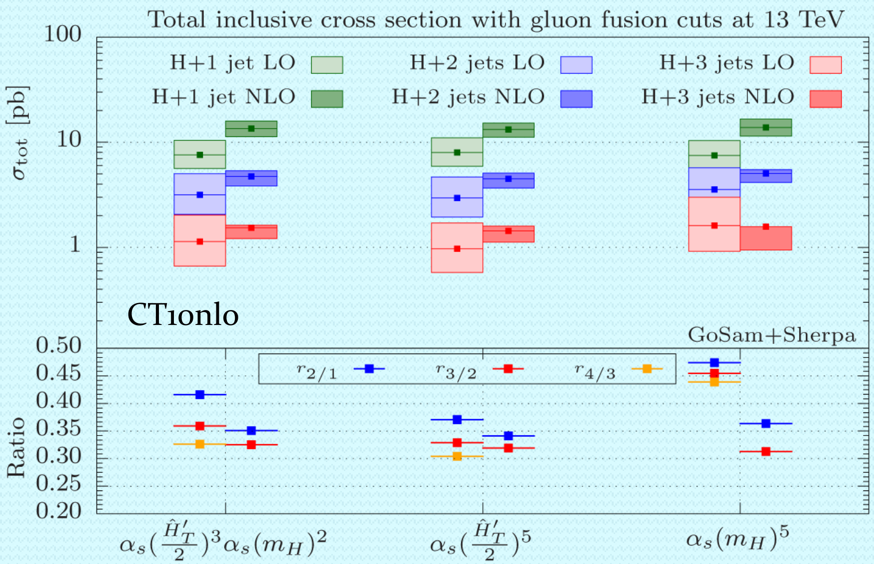


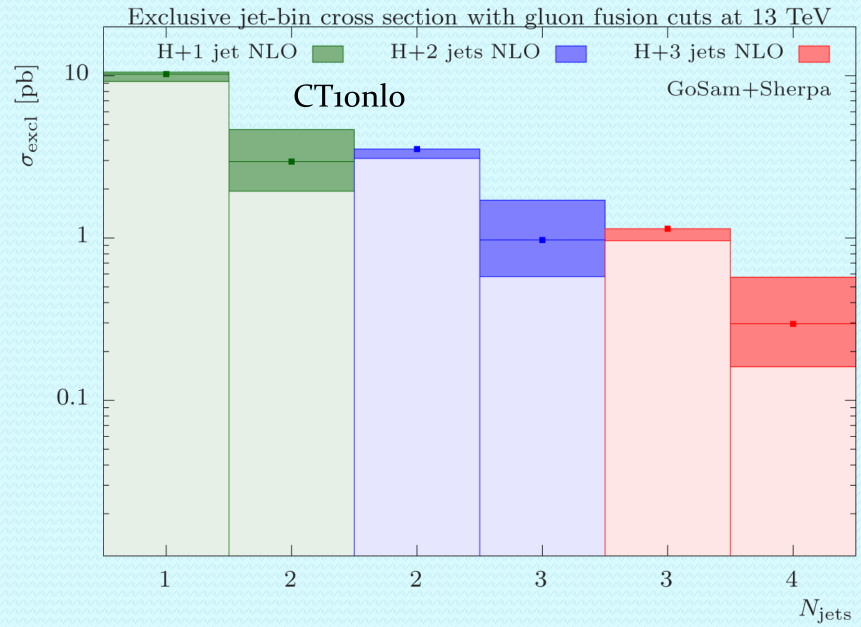
NLO QCD results for H+3j in GGF

[Cullen et al., 1307.4737; Greiner et al., 1506.01016]

- Phenomenological analysis via generation of ROOT Ntuple files: 8 and 13 TeV
  - Plan is to store them at CERN: soon publicly available
  - Flexible for **scale**, **PDF**, **jet-algorithm/radius**, **cuts**, **jet-tagging** variation

- XS with GGF cuts: anti-kt $p_T > 30$ GeV, $|\eta| < 4.4$





- $r_{3/2}$ ratio very stable --> extrapolate?
- possibility to compare ratios between different hard processes

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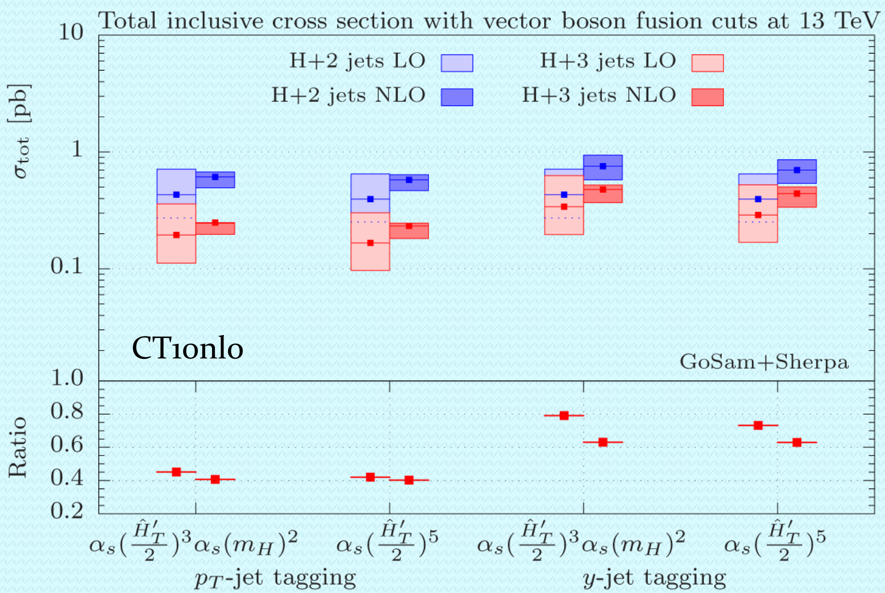
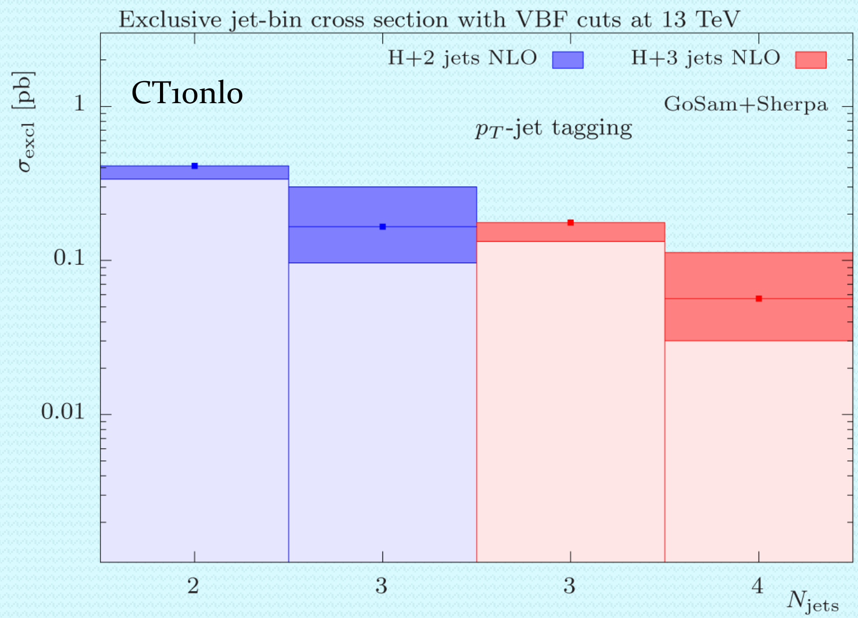
- XS with VBF cuts: anti-kt $p_T > 30$ GeV, $|\eta| < 4.4$ and $m_{j_1 j_2} > 400$ GeV, $|\Delta y_{j_1,j_2}| > 2.8$

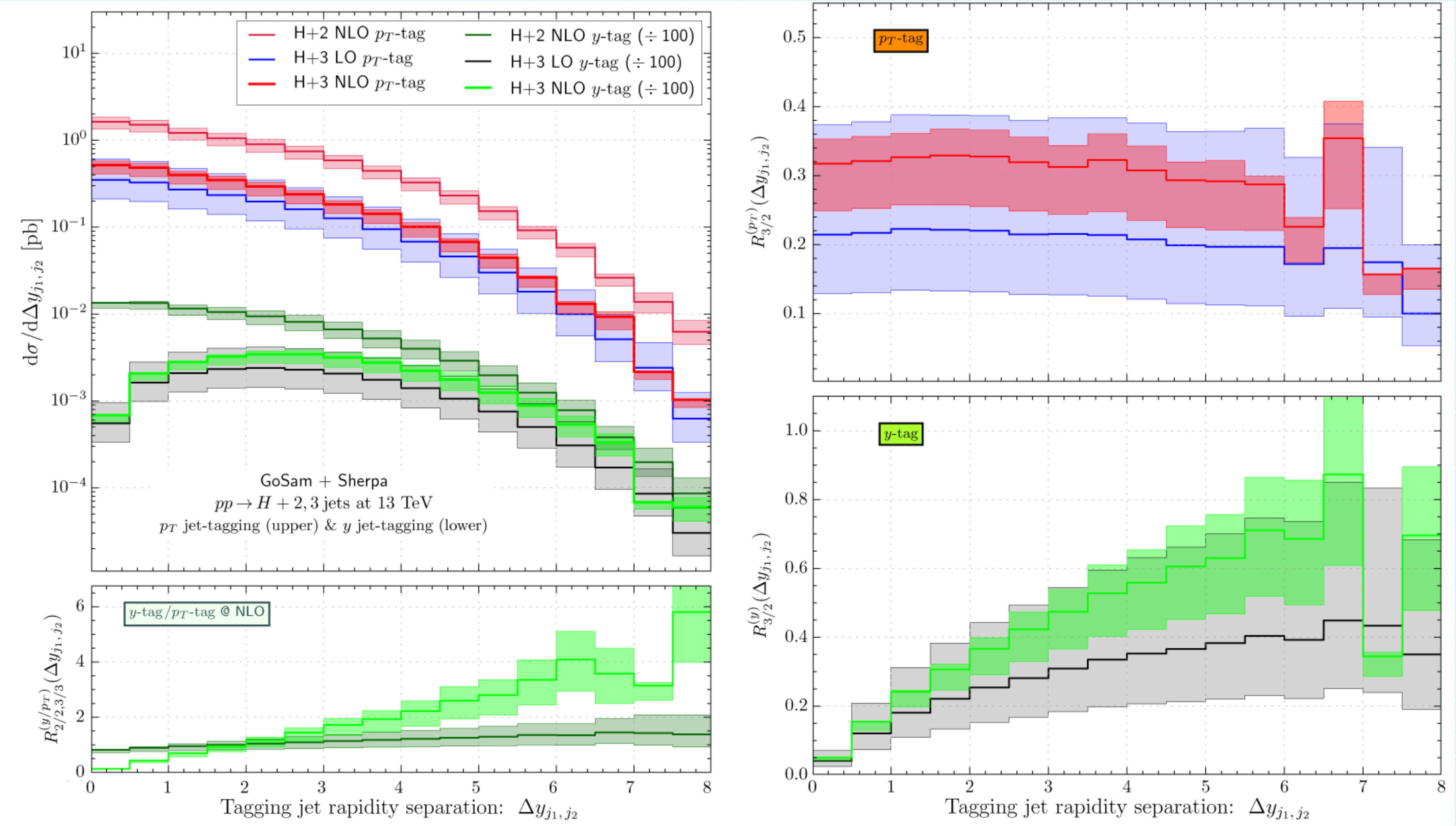




- VBF cuts enhance real radiation contribution (y-tagging even more)
  - larger portion of total XS described with LO accuracy if using H+2j @ NLO only

➢ H+3j NLO needed for accurate 3 jet prediction and exclusive H+2j XS

NLO QCD results for H+3j in GGF



- NLO H+3 jets results get closer to high energy behaviour

NNLO computations

- New frontier: many very recent developments in techniques and tools:

$$\begin{aligned}\hat{\sigma}^{\mathrm{NNLO}}_{a,b\to X} = \hat{\sigma}^{\mathrm{NLO}}_{a,b\to X} &+ \int_{\mathrm{d}\Phi_{m+2}} \left(\mathrm{d}\sigma^{\mathrm{R}}_{\mathrm{NNLO}} - \mathrm{d}\sigma^{\mathrm{S}}_{\mathrm{NNLO}}\right) + \int_{\mathrm{d}\Phi_{m+2}} \mathrm{d}\sigma^{\mathrm{S}}_{\mathrm{NNLO}} \\ &+ \int_{\mathrm{d}\Phi_{m+1}} \left(\mathrm{d}\sigma^{\mathrm{V},1}_{\mathrm{NNLO}} - \mathrm{d}\sigma^{\mathrm{VS},1}_{\mathrm{NNLO}}\right) + \int_{\mathrm{d}\Phi_{m+1}} \mathrm{d}\sigma^{\mathrm{VS},1}_{\mathrm{NNLO}} \\ &+ \int_{\mathrm{d}\Phi_{m}} \mathrm{d}\sigma^{\mathrm{V},2}_{\mathrm{NNLO}}.\end{aligned}$$

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$$\hat{\sigma}^{\text{NNLO}}_{a,b\to X} = \hat{\sigma}^{\text{NLO}}_{a,b\to X} + \int_{d\Phi_{m+2}} \left(d\sigma^{\text{R}}_{\text{NNLO}} - d\sigma^{\text{S}}_{\text{NNLO}}\right) + \int_{d\Phi_{m+2}} d\sigma^{\text{S}}_{\text{NNLO}} + \int_{d\Phi_{m+1}} \left(d\sigma^{\text{V},1}_{\text{NNLO}} - d\sigma^{\text{VS},1}_{\text{NNLO}}\right) + \int_{d\Phi_{m+1}} d\sigma^{\text{VS},1}_{\text{NNLO}} + \int_{d\Phi_{m}} d\sigma^{\text{V},2}_{\text{NNLO}}.$$

- 2 loops contribution
  - Several developments in higher loop computation
    - integrand level reduction
    - differential equations
    - sector decomposition
    - non-linear transformations
  - Many relevant 2-loop amplitudes and many people contribute to the huge process!

    [Anastasiou, Bern, Bonciani, Badger, Borowka, Caola, Czakon, Del Duca, Dixon, Frellesvig, Gehrmann, Glover, Heinrich, Henn, Jaquier, Kosower, Koukoutsakis, von Manteuffel, Mastrolia, Melnikov, Moriello, Ossola, Petriello, Remiddi, Smirnov, Smirnov, Tancredi, Tejeda-Yeomans, Weinzierl, …]

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  - 1 loop interference
    - Automated 1-loop amplitude generators adapted to compute this contribution
      - OpenLoops: used e.g. for top-antitop, ZZ, WW, Zγ, Wγ

        [Abelof et al., 1404.6493, Cascioli et al., 1405.2219, Gehrmann et al., 1408.5243, Grazzini et al., 1504.01330]

      - GoSam: used e.g. for top-antitop in e^+e^-

        [Gao, Zhu, 1410.3165]

NNLO computations

- New frontier: many very recent developments in techniques and tools:

$$\hat{\sigma}^{\mathrm{NNLO}}_{a,b\to X} = \hat{\sigma}^{\mathrm{NLO}}_{a,b\to X} + \int_{\mathrm{d}\Phi_{m+2}} \left(\mathrm{d}\sigma^{\mathrm{R}}_{\mathrm{NNLO}} - \mathrm{d}\sigma^{\mathrm{S}}_{\mathrm{NNLO}}\right) + \int_{\mathrm{d}\Phi_{m+2}} \mathrm{d}\sigma^{\mathrm{S}}_{\mathrm{NNLO}} + \int_{\mathrm{d}\Phi_{m+1}} \left(\mathrm{d}\sigma^{\mathrm{V},1}_{\mathrm{NNLO}} - \mathrm{d}\sigma^{\mathrm{VS},1}_{\mathrm{NNLO}}\right) + \int_{\mathrm{d}\Phi_{m+1}} \mathrm{d}\sigma^{\mathrm{VS},1}_{\mathrm{NNLO}} + \int_{\mathrm{d}\Phi_{m}} \mathrm{d}\sigma^{\mathrm{V},2}_{\mathrm{NNLO}}.$$

  - subtraction scheme:
    - Sector decomposition [Binoth, Heinrich, hep-ph/0004013; Anastasiou et al., hep-ph/0311311]
    - Antenna subtraction [Gehrmann De-Ridder, Gehrmann, Glover, hep-ph/0505111, […]]
    - Colorful subtraction [Somogy, Trocsanyi, hep-ph/0609042, […]; Del Duca et al., 1501.07226]
    - Subtraction & sector decomposition [Czakon, 1005.0274; Boughezal, Melnikov, Petriello, 1111.7041]
    - q_T subtraction [Catani, Grazzini, hep-ph/0703012; Bonciani et al., 1508.03585]
    - N-Jettiness [Boughezal et al., 1504.02131 and 1505.03893; Gaunt et al., 1505.04794]
    - Born projection (used for VBF) [Cacciari et al., 1506.02660]

NNLO results

- Many new NNLO results for processes where very precise predictions are needed:

$e^+e^- \to 3\,\text{jets}$ [Gehrmann De-Ridder et al. 0711.4711; Weinzierl 0904.1077]

NEW $pp \to 2\,\text{jets}$ (gluon channel) [Gehrmann De-Ridder et al. 1301.7310; Currie et al., 1310.3993]

$pp \to W,\, Z$ [Anastasiou et al., hep-ph/0312266; Melnikov et al., hep-ph/0604182; Catani et al., 0903.2120]

$pp \to H$ (Now at N³LO) [see also talks by A. Vicini and K. Melnikov] [Anastasiou et al., hep-ph/0501130; Grazzini, 0801.3232]

$pp \to t\,\bar{t}$ [latest updates in the talk by D. Heymes] [Czakon, Fiedler, Mitov, 1303.6254]

NEW $pp \to H + 1\,\text{jet}$ [see also talks by A. Vicini and K. Melnikov] [Boughezal et al., 1504.07922; Boughezal et al., 1505.03893; Melnikov et al., 1508.02684; Chen et al., 1408.5325]

NEW $pp \to Z + 1\,\text{jet}$ [Gehrmann De-Ridder, Gehrmann, Glover, Huss, Morgan, 1507.02850]

NEW $pp \to W + 1\,\text{jet}$ [Boughezal, Focke, Liu, Petriello, 1504.02131]

NEW $pp \to H\,V \quad (V = W/Z/\gamma)$ [Ferrera, Grazzini, Tramontano, 1407.4747, Ferrera, Grazzini, Tramontano, 1107.1164]

$pp \to H\,H$ [de Florian, Mazzitelli, 1309.6594]

$pp \to \gamma\,\gamma$ [Catani, Cieri, de Florian, Ferrera, Grazzini, 1110.2375]

NEW $pp \to W\,\gamma,\; Z\,\gamma$ [see talks by S. Kallweit and S. Pozzorini] Grazzini et al., 1309.7000; Grazzini et al., 1504.01330]

NEW $pp \to W\,W$ [see talks by S. Kallweit and S.Pozzorini] [Gehrmann et al., 1408.5243]

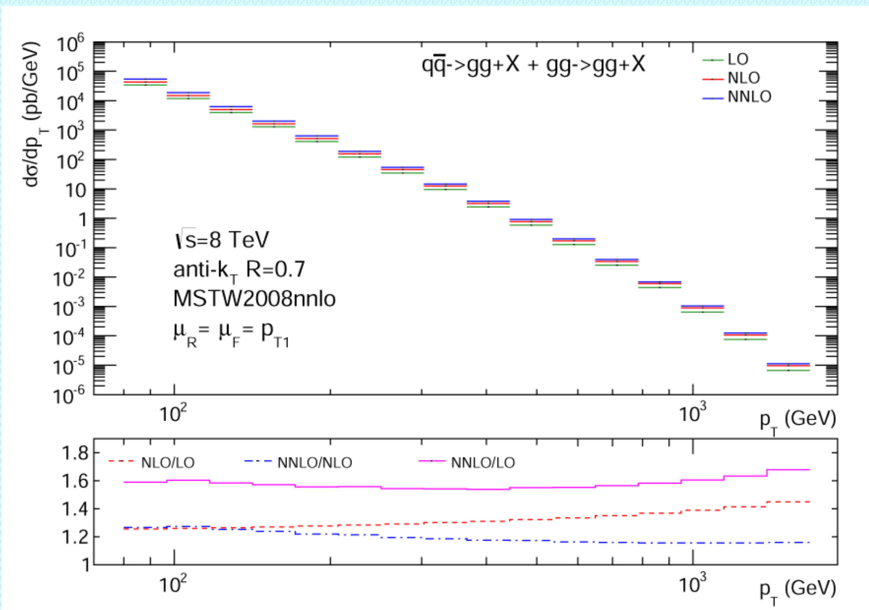
NEW $pp \to Z\,Z$ [see talks by S. Kallweit and S. Pozzorini] [Cascioli et al. 1405.2219; Grazzini, Kallweit, Rathlev, 1507.06257]

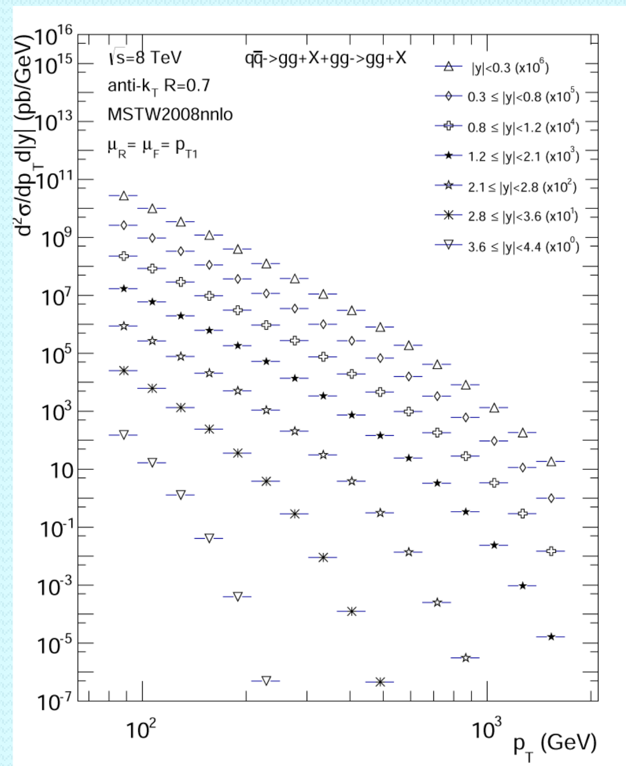
NEW $pp \to H + 2\,\text{jets} \quad (\text{VBF})$ [see also talk by K. Melnikov] [Cacciari et al., 1506.02660]

Dijet production at NNLO

[Currie, Gehrmann De-Ridder, Gehrmann, Glover, Pires, 1310.3993]

- Computed using antenna formalism
- Many IR divergencies due to large number of massless partons
- gg-channel completed in 2013 (other channel on the way)





- Inclusive jet cross section for p_T>80 ; |y|<4.4

- NNLO/NLO for qq--> gg channel alone is 5%

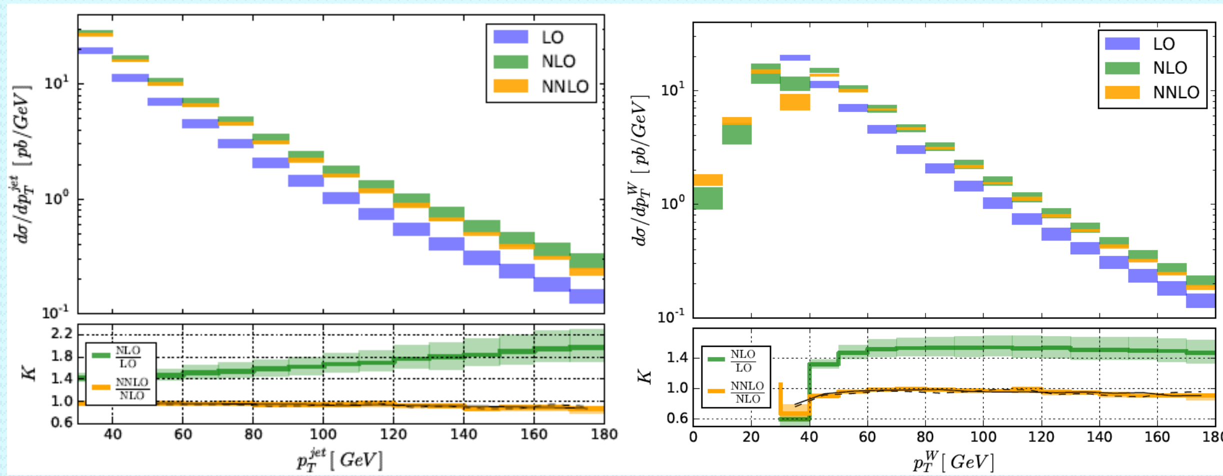
W/Z + 1 jet at NNLO

- **W+1 jet:** first application of N-Jettiness subtraction

[Boughezal et al., 1504.02131]

$p_T^{jet} > 30$ GeV, $\lvert\eta_{jet}\rvert < 2.4$	
Leading order:	533^{+39}_{-38} pb
Next-to-leading order:	797^{+63}_{-49} pb
Next-to-next-to-leading order:	787^{+0}_{-8} pb

- small (negative) NNLO corrections
- reduction of uncertainties
- relatively flat NNLO corrections

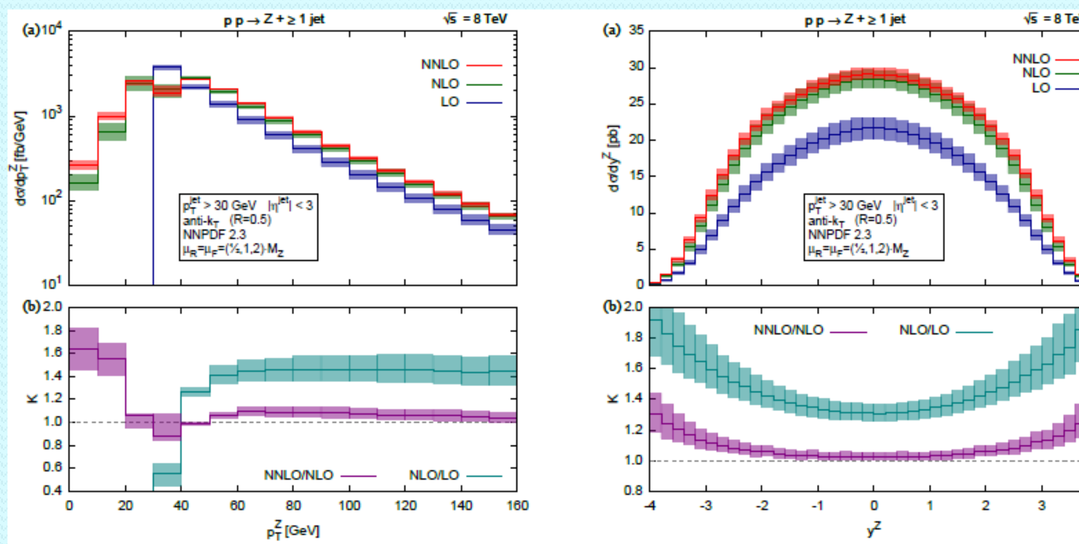


- **Z+1 jet:**

[Gehrmann De-Ridder et al., 1507.02850]

- using antenna subtraction
- large N_c approx. for dominan channel
- similar pattern as W+1 jet
- missing channel coming soon

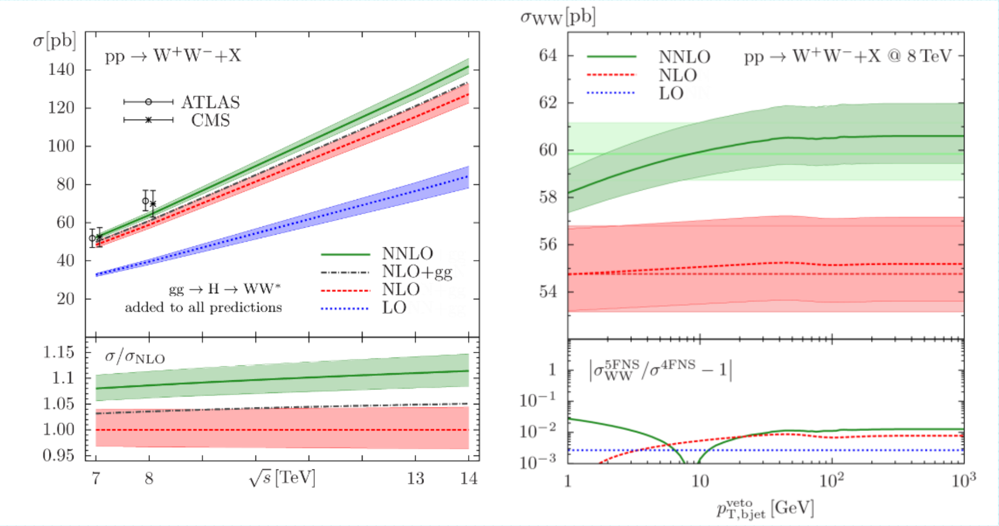
$$\sigma_{LO} = 103.6^{+7.7}_{-7.5} \text{ pb}$$
$$\sigma_{NLO} = 144.4^{+9.0}_{-7.2} \text{ pb}$$
$$\sigma_{NNLO} = 151.0^{+4.9}_{-3.6} \text{ pb}$$



VV production at NNLO [see also talks by S. Kallweit, S.Pozzorini]

[Gehrmann, Grazzini, Kallweit, Maierhöfer, von Manteuffel, Pozzorini, Rathlev, Tancredi, 1408.5243]

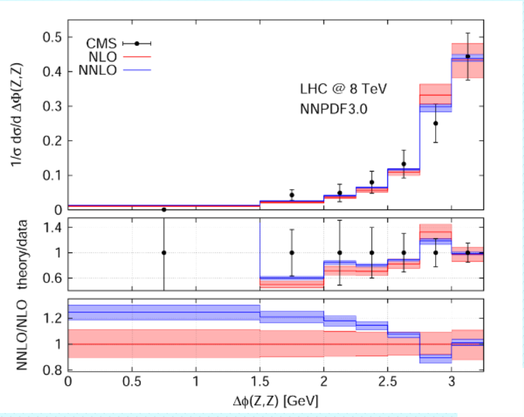
- WW: 4f and 5f scheme (scheme dep. is relevant source of uncertainty)
  - Introduction of b-jet veto is problematic (uncancelled collinear divergencies)
  - definition of 5FS by scaling properties of resonant contributions with Γ_t
  - decreases tension between predictions and data at 8 TeV



- ZZ: [Cascioli et al. 1405.2219; Grazzini, Kallweit, Rathlev, 1507.06257]
  - Computation with fiducial cuts of ATLAS and CMS in different channels

Channel	$\sigma_{\rm LO}$ (fb)	$\sigma_{\rm NLO}$ (fb)	$\sigma_{\rm NNLO}$ (fb)	$\sigma_{\rm exp}$ (fb)
$e^+e^-e^+e^-$	$3.547(1)^{+2.9\%}_{-3.9\%}$	$5.047(1)^{+2.8\%}_{-2.3\%}$	$5.79(2)^{+3.4\%}_{-2.6\%}$	$4.6^{+0.8}_{-0.7}({\rm stat})^{+0.4}_{-0.4}({\rm syst.})^{+0.1}_{-0.1}({\rm lumi.})$
$\mu^+\mu^-\mu^+\mu^-$				$5.0^{+0.6}_{-0.5}({\rm stat})^{+0.2}_{-0.2}({\rm syst.})^{+0.2}_{-0.2}({\rm lumi.})$
$e^+e^-\mu^+\mu^-$	$6.950(1)^{+2.9\%}_{-3.9\%}$	$9.864(2)^{+2.8\%}_{-2.3\%}$	$11.31(2)^{+3.2\%}_{-2.5\%}$	$11.1^{+1.0}_{-0.9}({\rm stat})^{+0.5}_{-0.5}({\rm syst.})^{+0.3}_{-0.3}({\rm lumi.})$

+ 15% (60% of which form gg)



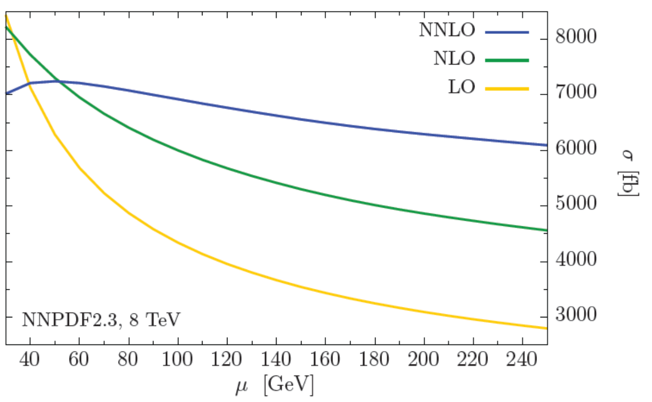
H + 1 jet at NNLO

[see also talk by K. Melnikov]

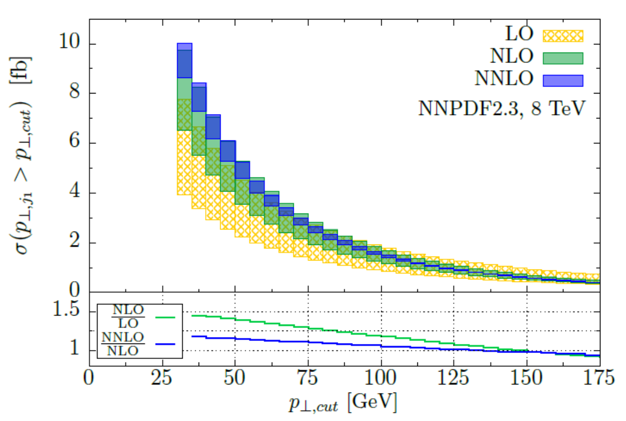
[Boughezal et al., 1504.07922; Boughezal et al., 1505.03893; Chen et al., 1408.5325]

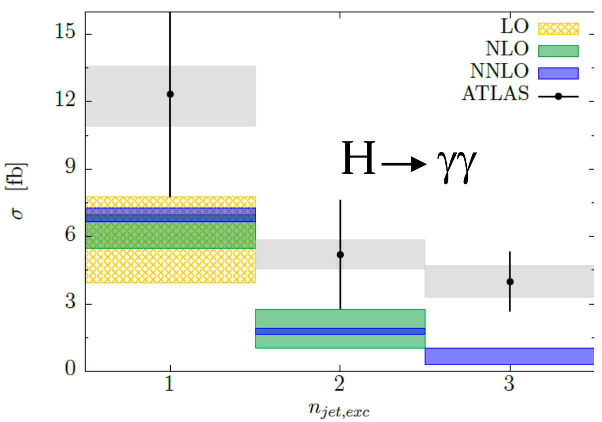
- Three different computations carried out with different subtraction schemes: antenna, subtraction and sector decomposition, N-Jettiness

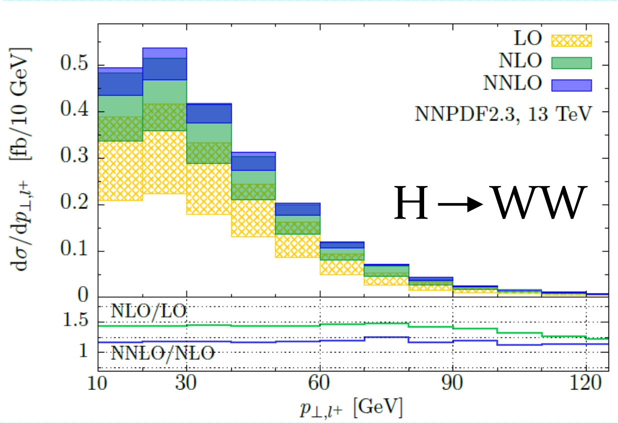
$p_T^{jet} > 30$ GeV, $\lvert Y^{jet}\rvert < 2.5$	
Leading order:	$3.1^{+1.3}_{-0.9}$ pb
Next-to-leading order:	$4.8^{+1.1}_{-0.9}$ pb
Next-to-next-to-leading order:	$5.5^{+0.3}_{-0.4}$ pb



- First results for fiducial cross section at 8 TeV: [Caola, Melnikov, Schulze, 1508.02684]





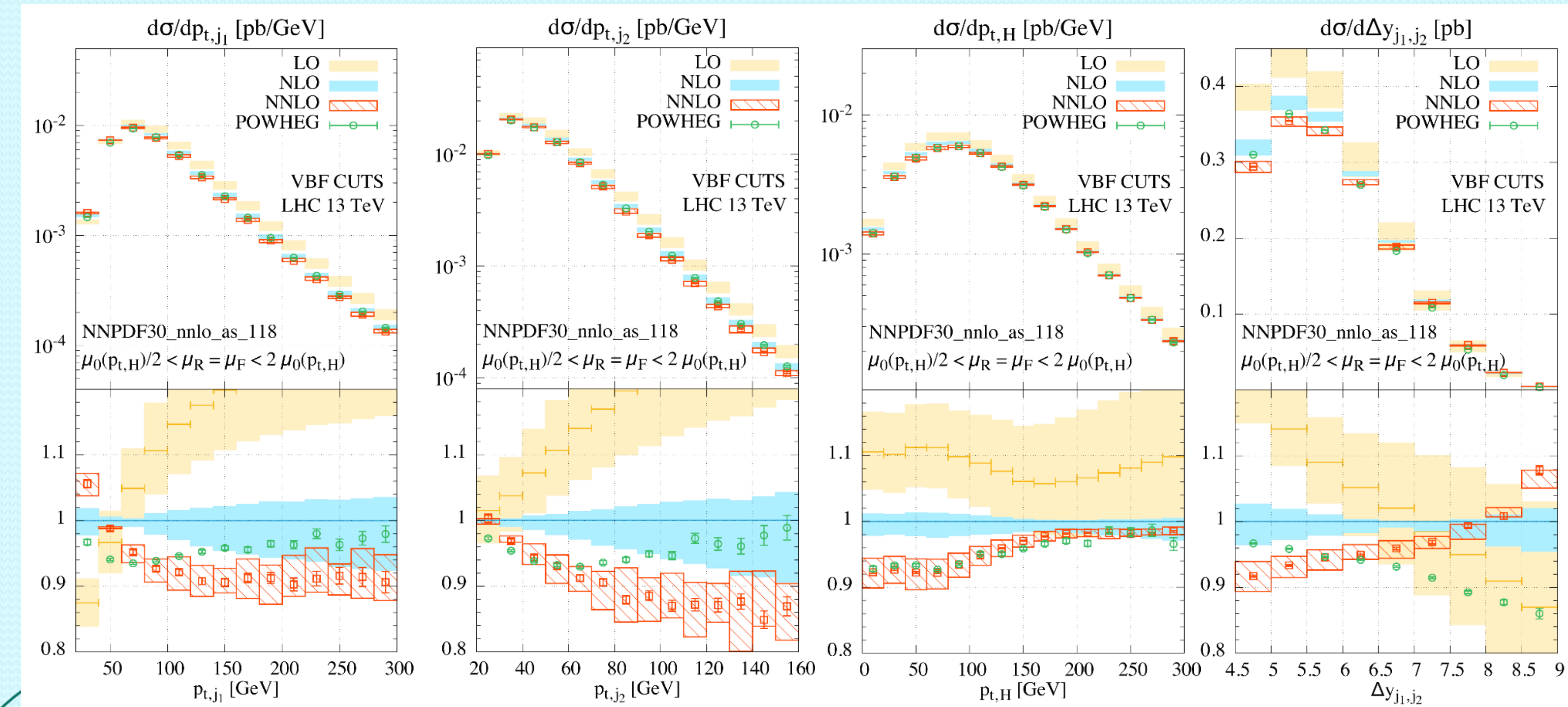


H+2 jets in VBF at NNLO

[Cacciari, Dreyer, Karlberg, Salam, Zanderighi, 1506.02660]
[see also talk by K. Melnikov]

- Computation performed in the structure-function approach
  - DIS structure function at NNLO
  - H+3 jets in VBF at NLO
  - projection to Born

	$\sigma^{(\text{no cuts})}$ [pb]	$\sigma^{(\text{VBF cuts})}$ [pb]
LO	$4.032^{+0.057}_{-0.069}$	$0.957^{+0.066}_{-0.059}$
NLO	$3.929^{+0.024}_{-0.023}$	$0.876^{+0.008}_{-0.018}$
NNLO	$3.888^{+0.016}_{-0.012}$	$0.826^{+0.013}_{-0.014}$

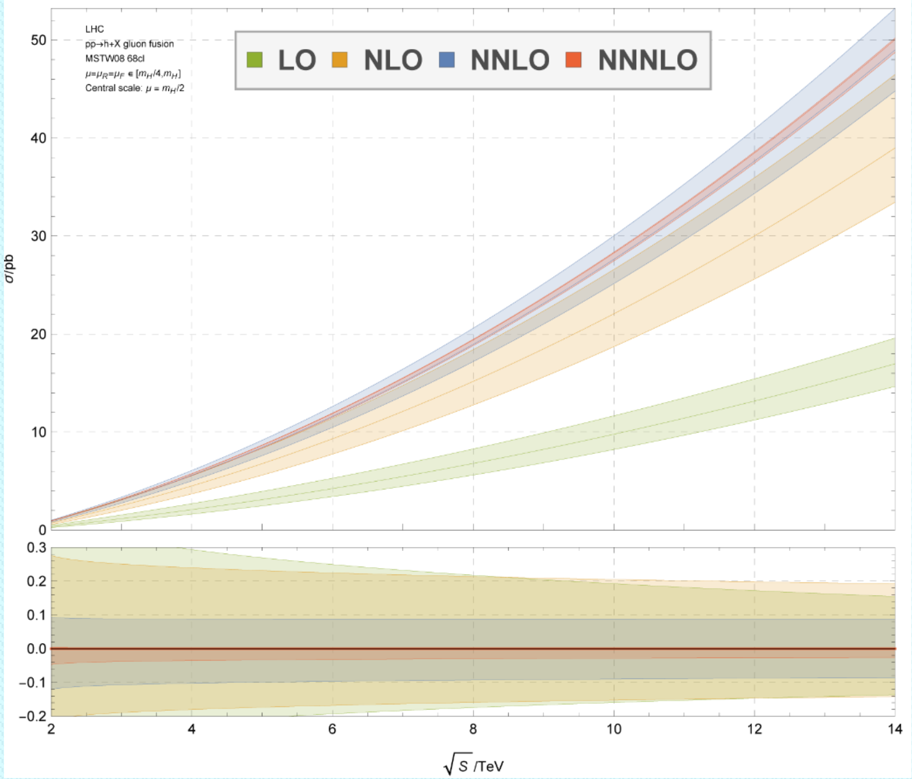


N^3LO inclusive Higgs production

[Anastasiou, Duhr, Dulat, Herzog, Mistlberger, 1503.06056]
[see also talks by A. Vicini and K. Melnikov]

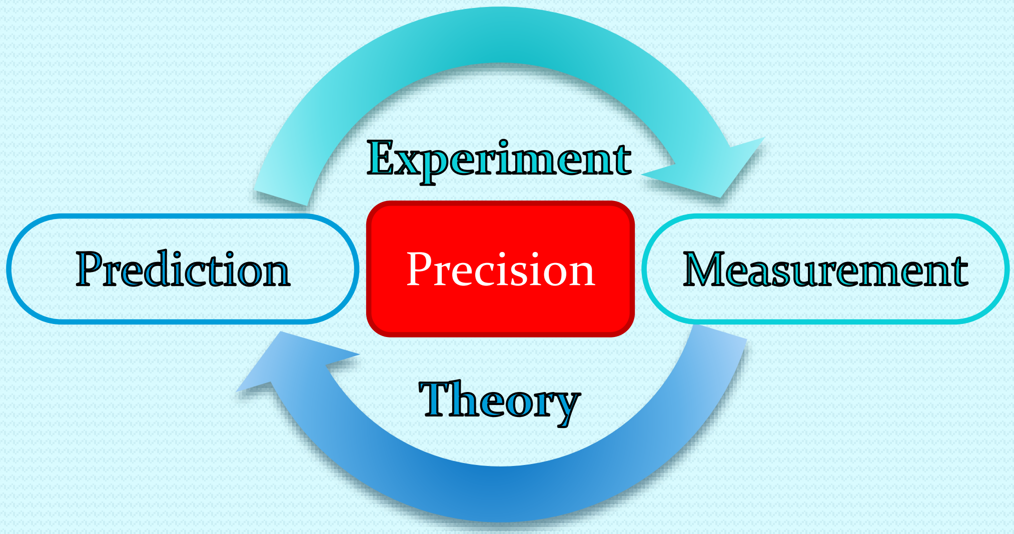
- First complete N^3LO computation in pp-collision
- Use infinite m_{top} limit

Stabilization of the scale dependence:



→ Together with NNLO H+1 jet computation allow to improve the exclusive 0-jet bin

Outlook



- Next steps
  - Computationally
    - even faster and reliable NLO (also beyond 2 → 4 for relevant processes)
    - 2-loop amplitudes for 2 → 3 : first results appeared recently [e.g. Badger et al., 1507.08797]
    - new flexible frameworks for NNLO computation: e.g. MATRIX [see talk of S.Kallweit]
    - 3 loops
    - ...
  - Phenomenologically
    - Detailed studies and comparison of different methods and approximations:
      full higher order - approximate computations
      fixed order + resummation - NLO+PS - NNLO+PS - NLO-merged+PS
    - reliable determination of uncertainties: α_s, PDFs
    - ...

Conclusions

- A decade ago higher order computations were a tough obstacles to face and cross

Conclusions

- A decade ago higher order computations were a tough obstacles to face and cross
- The need for precision led to developments in the last 10 years that allowed to bridge these obstacles and to face even harder ones
- The requirements for the LHC RUN II and the results it will deliver will push this even further!

Apologize for many further aspects and important work which I could not cover here!

Many thanks to M. Grazzini, P. Mastrolia, G.Ossola and J.Winter for inspiration and suggestions in preparing this review!