Challenges for precision QCD at the LHC

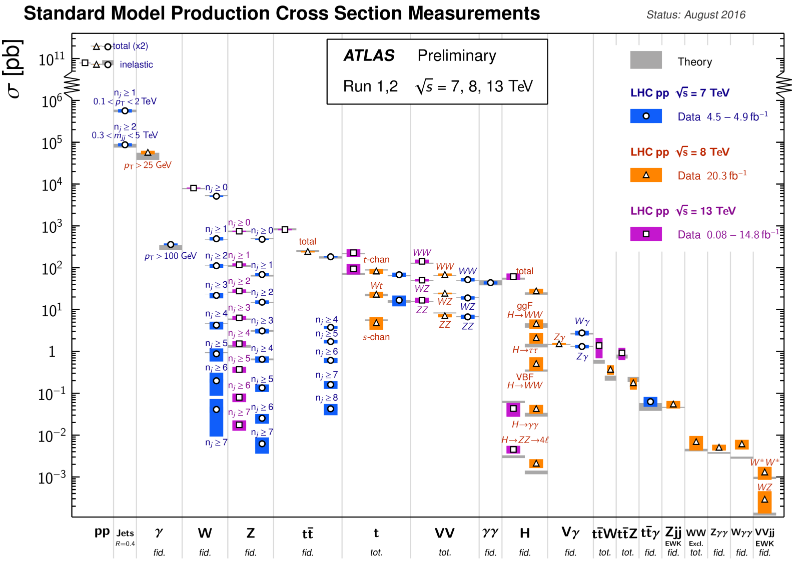
Emanuele Re

CERN & LAPTh Annecy

GDR QCD

IPN Orsay, 9 November 2016

SM at the LHC



Standard Model Production Cross Section Measurements
Status: August 2016
ATLAS Preliminary
Run 1,2 √s = 7, 8, 13 TeV
Theory
LHC pp √s = 7 TeV
Data 4.5 – 4.9 fb⁻¹
LHC pp √s = 8 TeV
Data 20.3 fb⁻¹
LHC pp √s = 13 TeV
Data 0.08 – 14.8 fb⁻¹
σ [pb]
total (x2)
inelastic
pp
Jets R=0.4 fid.
γ fid.
W fid.
Z fid.
tt̄ fid.
t tot.
VV tot.
γγ fid.
H fid.
Vγ fid.
tt̄W tot.
tt̄Z tot.
tt̄γ fid.
Zjj EWK fid.
WW Excl. tot.
Zγγ fid.
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SM at the LHC

LHC is a discovery machine

- optimize as much as possible our knowledge of the SM to make the most out of this experiment (particularly so if no BSM smoking-gun discovery)

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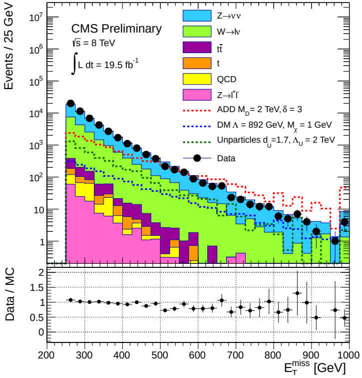
  . detect small deviations from SM backgrounds



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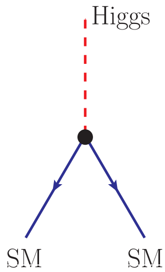

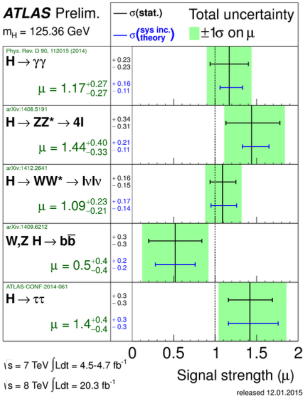

- accurate measurement of Higgs couplings
- extraction of SM parameters

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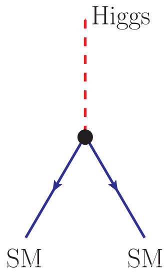

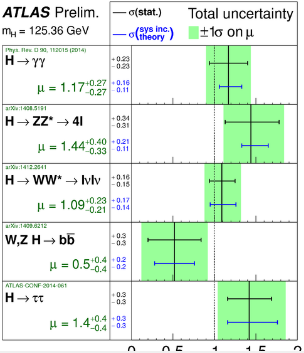

- accurate measurement of Higgs couplings
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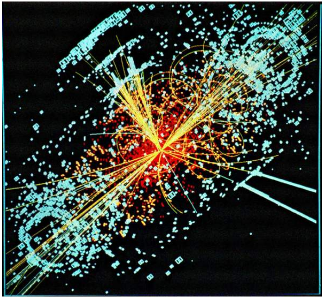
important also in presence of new discovery

outline

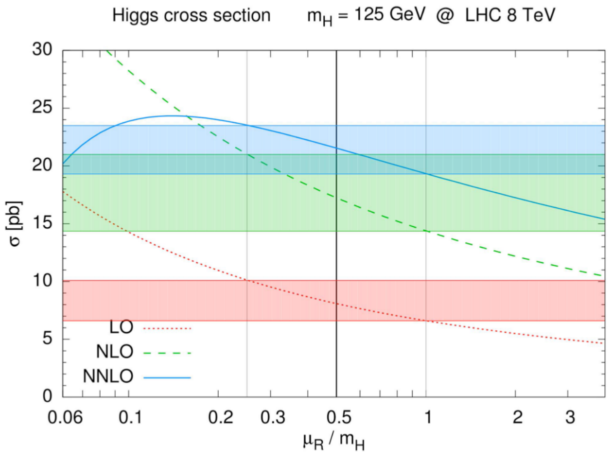
- selection of recent theoretical progress in “large p_T” perturbative QCD, relevant for precise predictions of SM processes

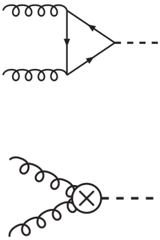
1. total cross sections
2. differential distributions (at fixed-order and matched with resummation)
3. Monte Carlo tools
4. PDFs



the inclusive 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]

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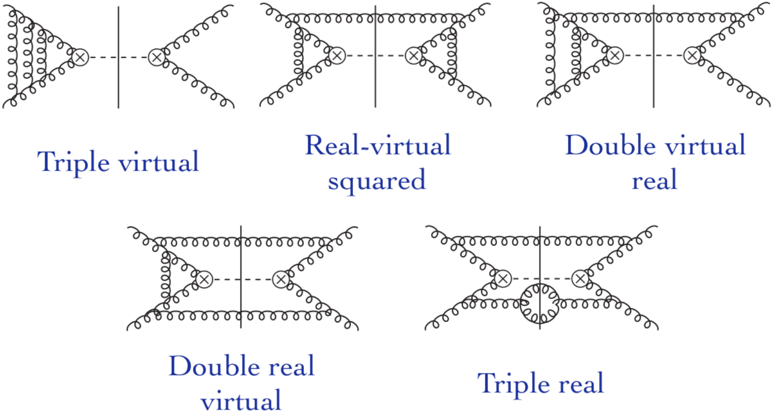

from C. Duhr talk at Higgs Hunting '15

gluon-fusion Higgs production at N3LO

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

	NNLO	N3LO
# diagrams	~ 1.000	~ 100.000
# integrals	~50.000	517.531.178
# masters	27	1.028

Double real virtual

Triple real

from C. Duhr talk at Higgs Hunting '15

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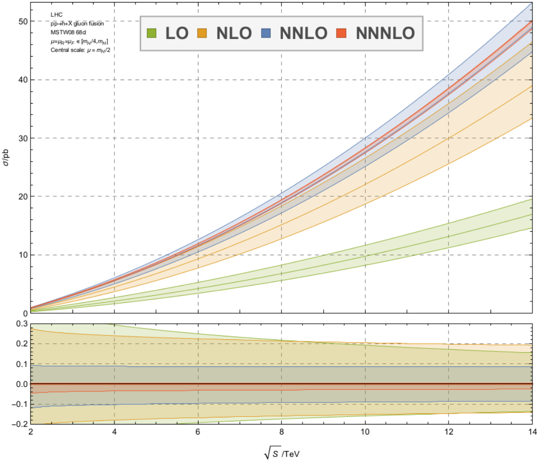

- N3LO result: perturbative uncertainties massively reduced [± 2 %]

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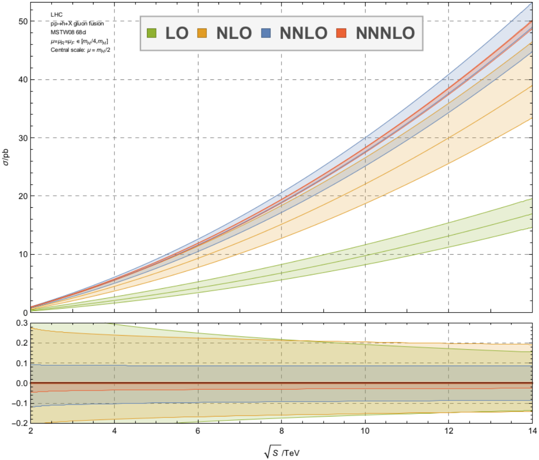

- N3LO result: perturbative uncertainties massively reduced [± 2 %]
- consider residual effects: $(1/m_t)$, threshold resummation , missing N3LO PDFs , PDFs+α_S , EW effects...

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

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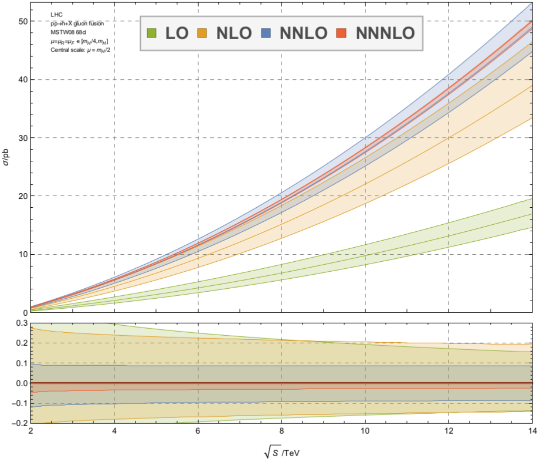

- N3LO result: perturbative uncertainties massively reduced [± 2 %]
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- next challenge: Higgs rapidity at N3LO

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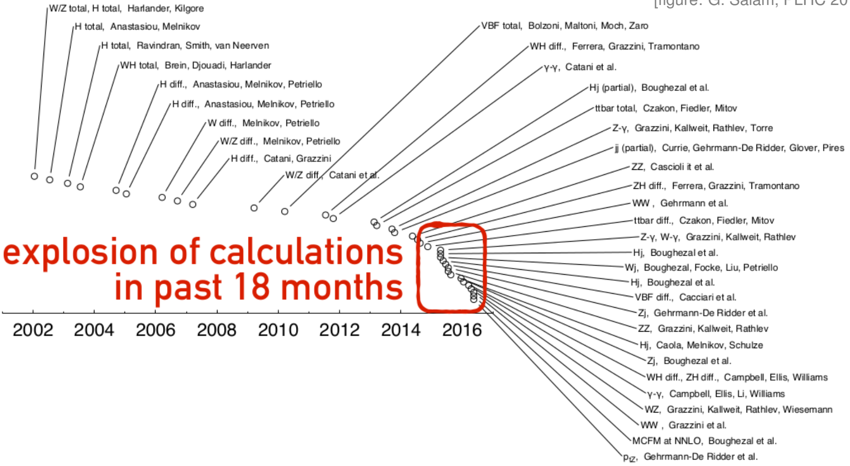
differential distributions

[figure: G. Salam, PLHC 2016]



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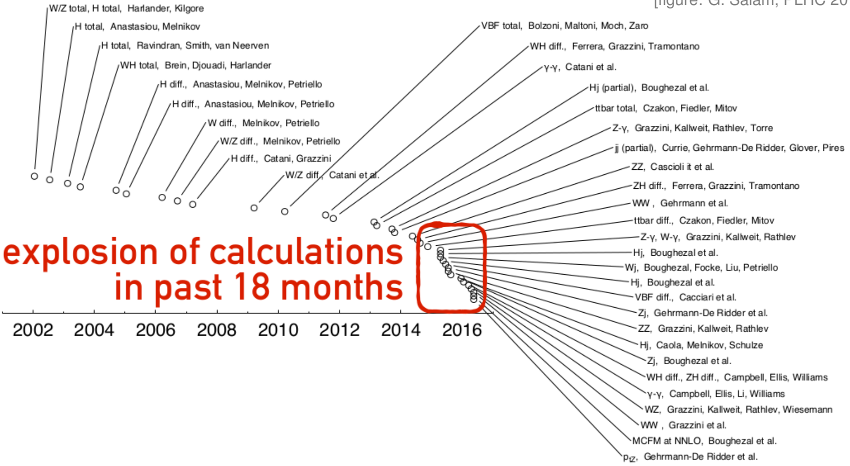

“NNLO revolution”

- NNLO computations, matched with resummation when needed, are becoming the new standard

fully differential NNLO

- differential distributions essential to compare EX (after cuts) and TH
- last 3 years: huge progress in computing $2 \to 2$ LHC processes at NNLO in QCD

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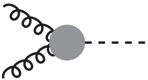
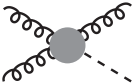
matrix elements

- 2-loops $2 \to 2$ amplitudes $\sim$ known for years



$\#$ loops: $0 \quad 1 \quad 2$



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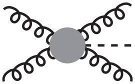

$\#$ loops: 0

subtraction scheme

- $\mathcal{O}(\alpha_s^2)$ matrix-elements live in different phase spaces

$\Downarrow$

- numerical algorithm to combine them: cancellation of IR divergences for a generic observable

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- q_T-subtraction [Catani,Grazzini '07]
- sector-improved residue subtraction [Czakon '10, Boughezal et al. '11]
- antenna subtraction [Gehrmann et al.]
- colorful NNLO [Somogy et al.]
- N-jettiness subtraction [Boughezal et al., Gaunt et al. '15]
- "projection to Born" [Cacciari et al. '15]

☞ NNLO QCD at the LHC: [V / H / VV / VH] [top-pair / single-top] [VBF H] [Vj / Hj / dijets]

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☞ first partial results for 2-loops $2 \to 3$

- $gg \to ggg$, planar, all + helicities

[Badger et al. ’13-’15, Gehrmann,Henn et al. ’15]

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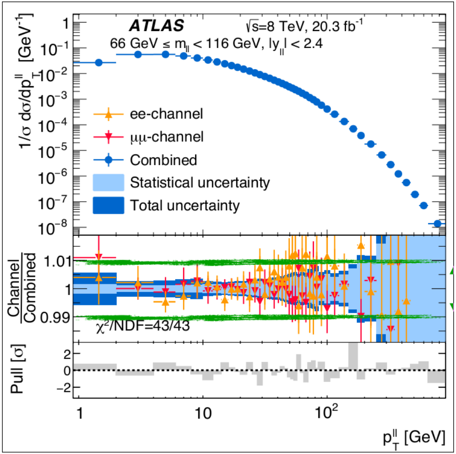
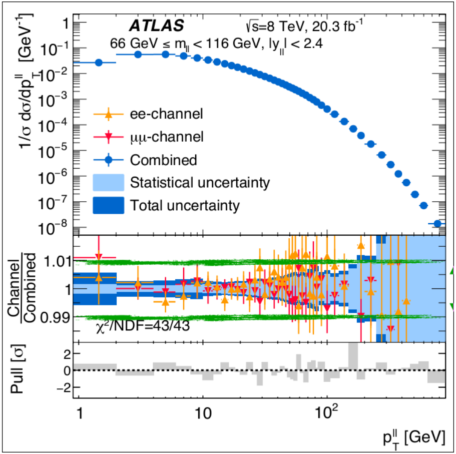
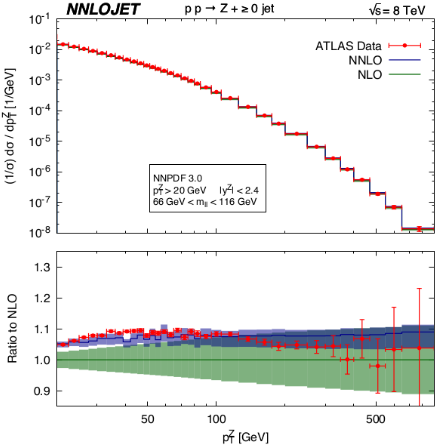


- the Z p_T spectrum is measured with less that 1% EX uncertainty
- NLO is definitely not enough

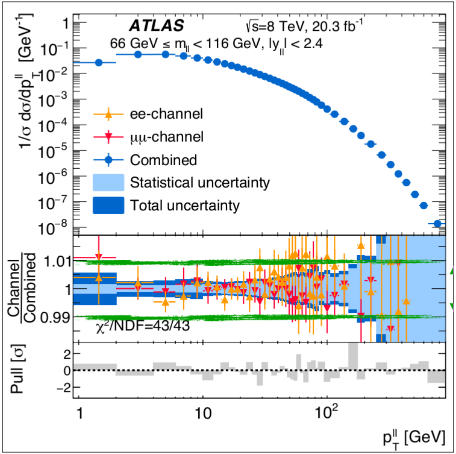
fully differential NNLO

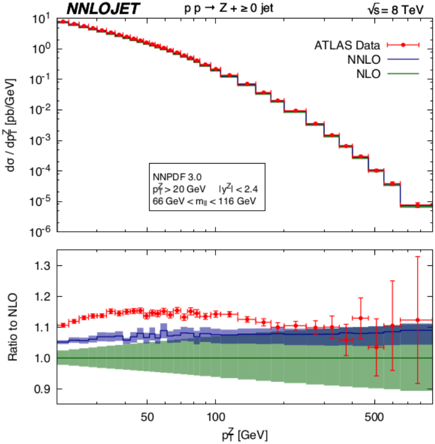




- NNLO available [Gehrmann-de Ridder et al. ’16, Boughezal et al. ’15]
- in perturbative region, normalized spectrum agrees very well with theory

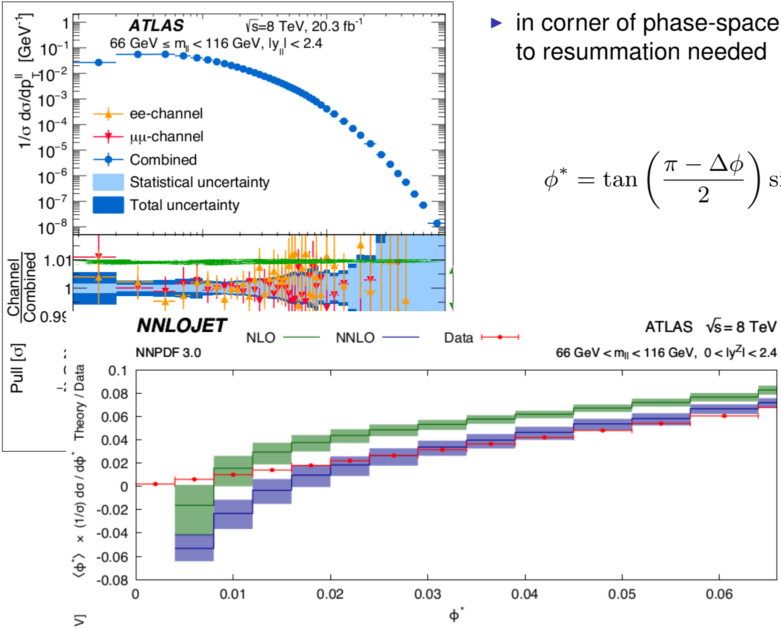
fully differential NNLO





- NNLO available [Gehrmann-de Ridder et al. ’16, Boughezal et al. ’15]
- in perturbative region, normalized spectrum agrees very well with theory
- absolute rate: not so well

fully differential NNLO



- in corner of phase-space, matching to resummation needed

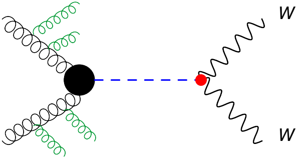
$$\phi^* = \tan\left(\frac{\pi - \Delta\phi}{2}\right)\sin\theta^*$$

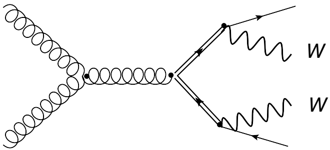
fixed-order + resummation

- jet-substructure methods very powerful as SM/BSM discriminators
  - especially to have a solid understanding of them, analytic resummation needed

  [→ talk by L. Schunk]

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





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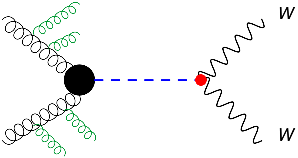
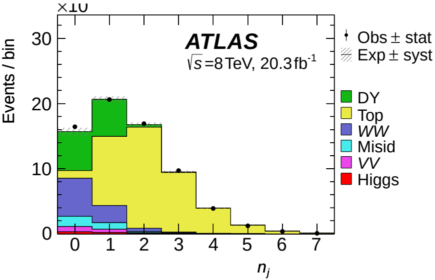
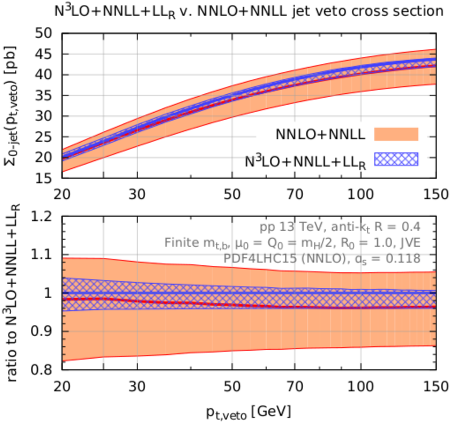




fixed-order + resummation

- 0-jet x-section now known at N3LO + NNLL + 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]

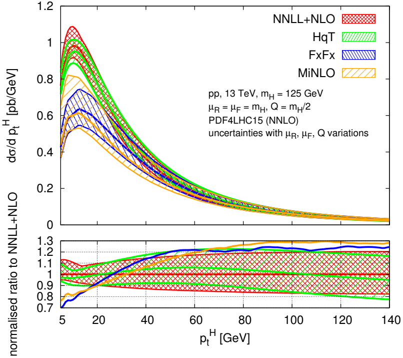
- jet-radius logarithms

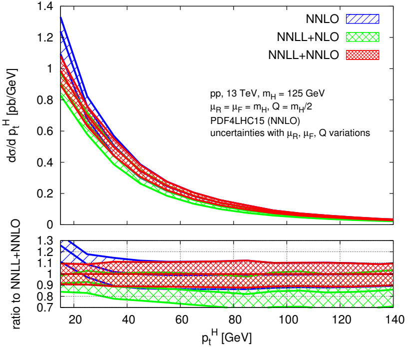
  [Dasgupta et al. '14]

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

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 %

MC generators

☞ NLO+PS has become the standard: by using the MC@NLO and POWHEG methods, NLO QCD results can be matched to Parton Showers (Pythia8, Herwig7, Sherpa)

$$\Downarrow$$

- fully automated for SM, getting closer and closer for BSM
- improved description of phase-space regions where large soft/collinear logarithms arise
- available to a wide EXP community

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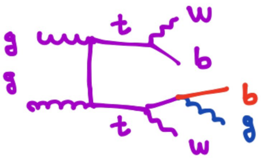

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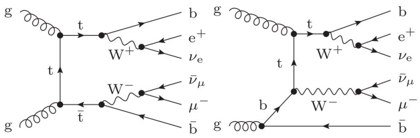

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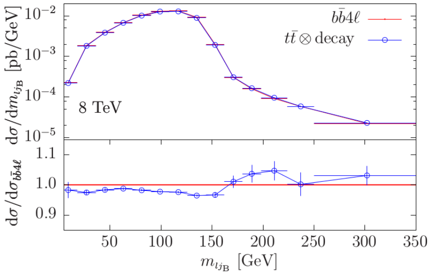

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- $W^+W^-b\bar{b}$ @ NLOPS now available

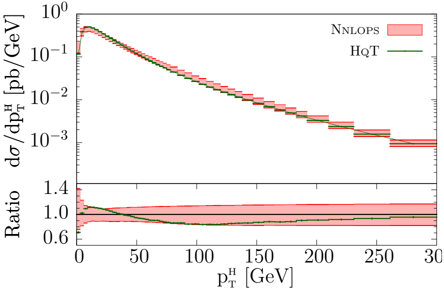
[Jezo et al, '16]

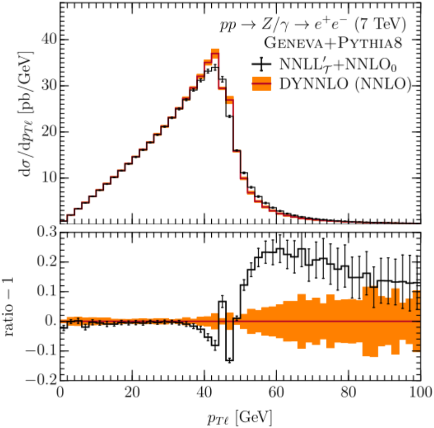
MC generators

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

. NNLOPS available with 3 methods `MiNLO+Powheg, UN2LOPS, Geneva`

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





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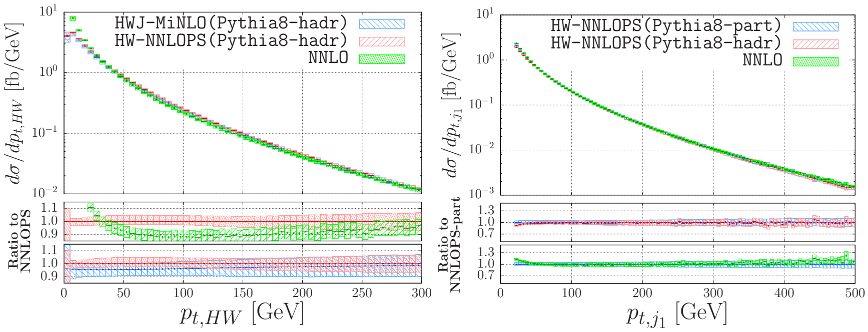
. few months ago: $pp \to WH$ at NNLO+PS [Astill,Bizon,ER,Zanderighi ’16]
- should be possible to include NLO QCD corrections to H decay



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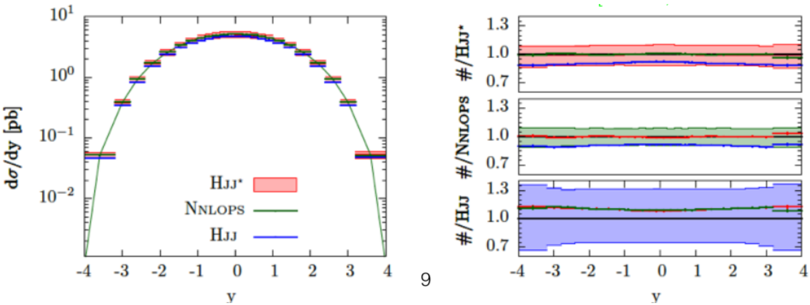
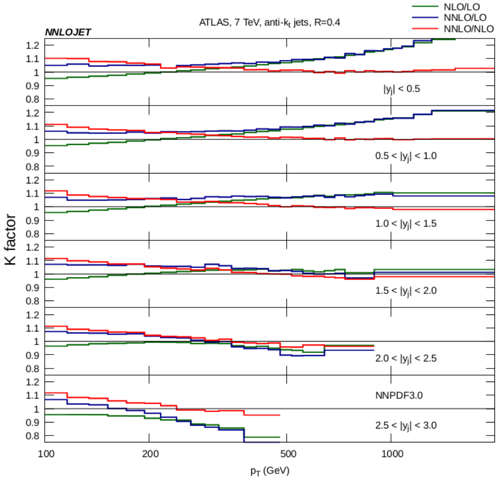
. important result (with `MiNLO`): H+jj @ NLO, H+j @ NLO and H @ NNLO

[Hamilton,Frederix '15]



PDFs



- long-awaited NNLO jet computation now available [Currie et al. '16]

conclusions

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  - the experimental precision already requires very accurate computations
    - interesting in their own
    - relevant for direct & indirect searches for new Physics

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- current status:
  - all backgrounds and many signals known at NLO+PS
  - almost all $2 \to 2$ NNLO fully differential computations performed
  - NNLO+PS for simple processes achieved
  - $gg \to$ and VBF Higgs cross sections known at N^{3}LO
  - subleading log-resummation: jet-vetoes, jet-shapes, jet substructures
  - PDFs (and α_S) will be known better and better (data driven + new ideas)

conclusions

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  - the experimental precision already requires very accurate computations
    - interesting in their own
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thank you for your attention !

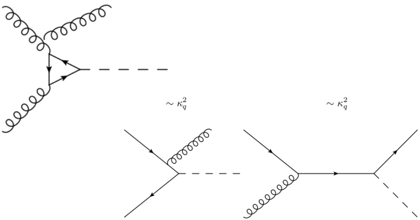
light-Yukawa from Higgs p_T

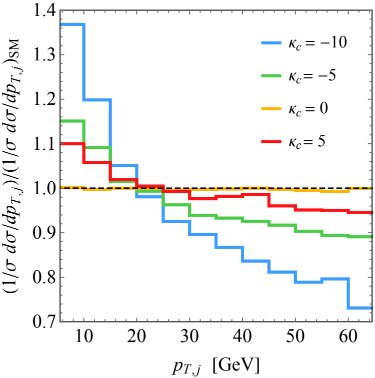
- several methods have been proposed to constrain the light Yukawa couplings
  [exclusive decays (Bodwin et al.; Kagan et al.; Koenig,Neubert), recasting $Vh(\to b\bar{b})$ (Perez et al.; Delaunay et al.), hc (Brivio et al.), width, global fit]

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

$\sim \kappa_q \frac{m_q^2}{m_h^2} \ln^2\left(\frac{p_\perp^2}{m_q^2}\right)$ (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!