Higgs+jet at NNLO QCD:

Fiducial cross sections for the LHC

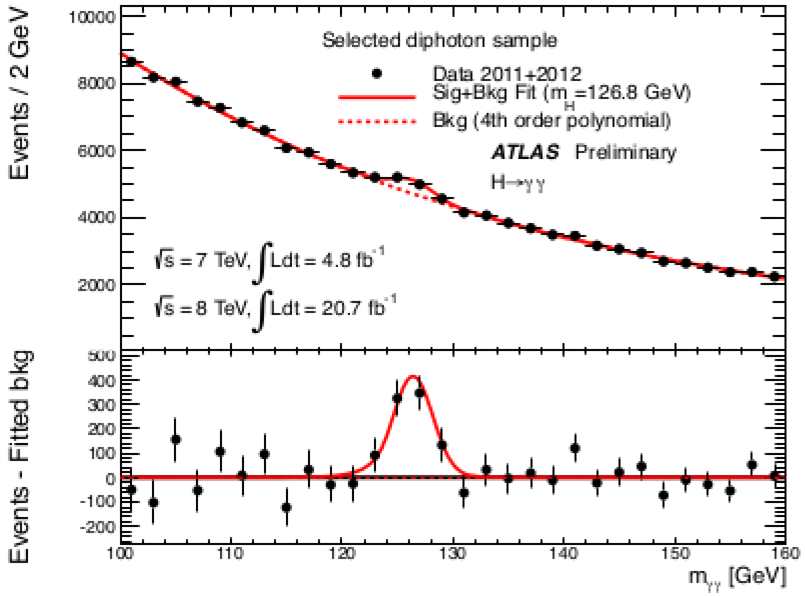
Markus Schulze

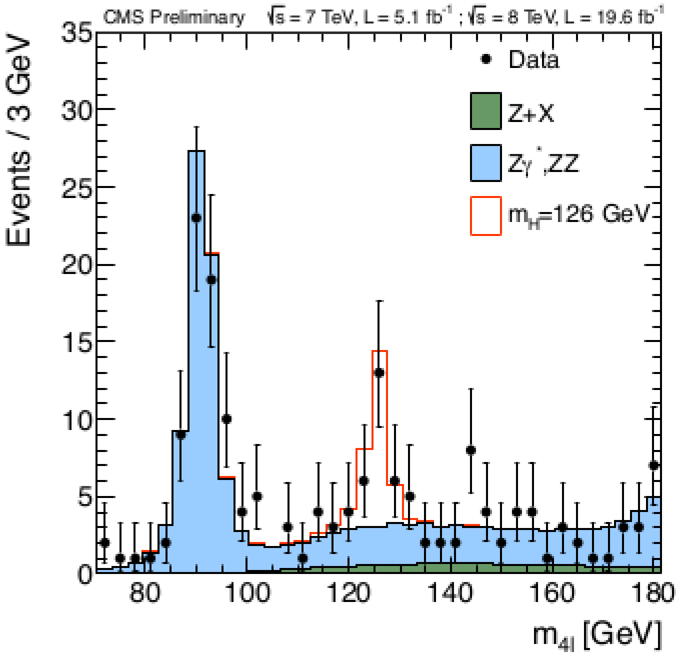
JHEP 1306 (2013) 072;

Phys. Rev. Lett. 115 (2015)8, 082003;

arXiv: 1508.02684 [hep-ph].

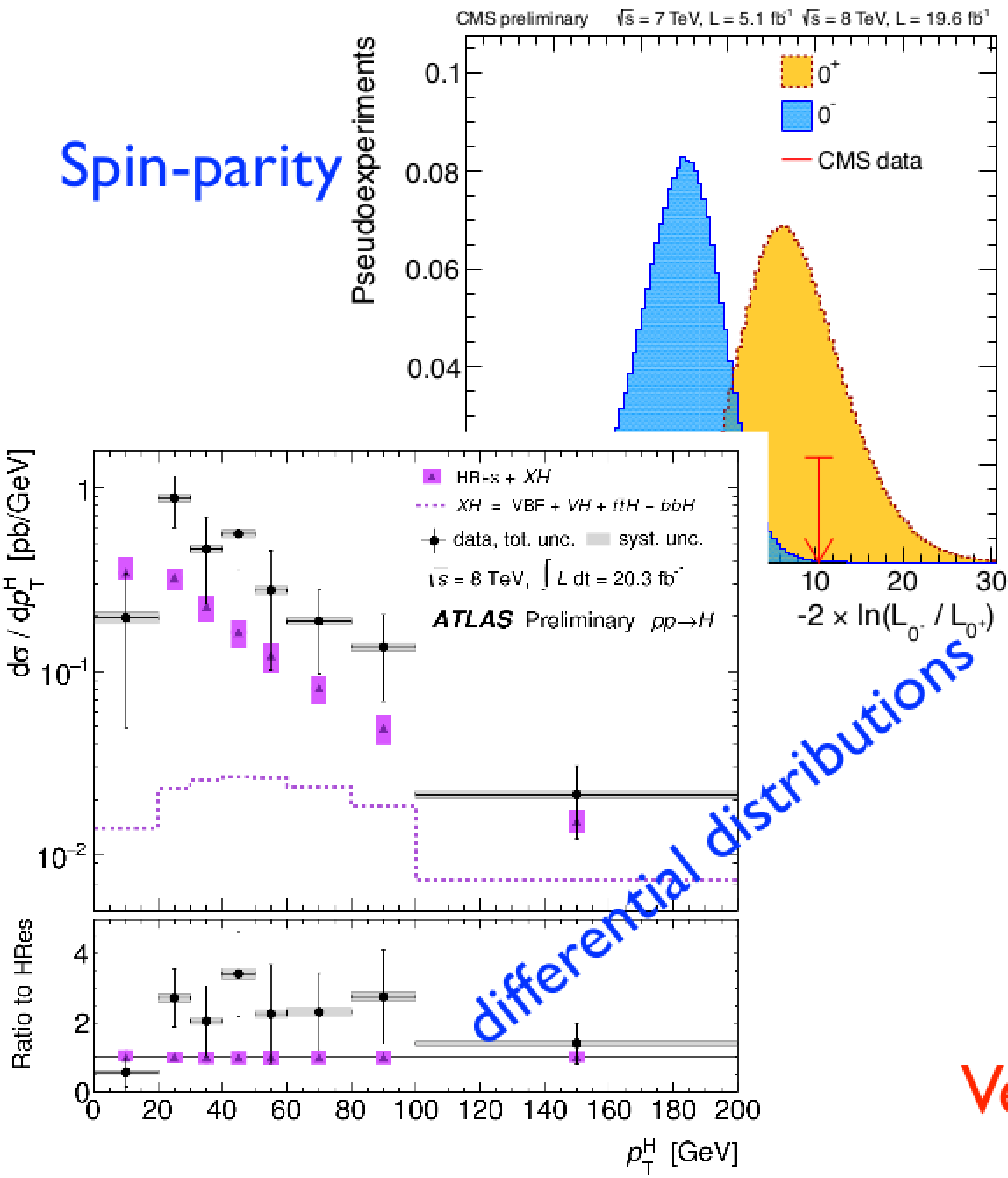
The legacy of run-I



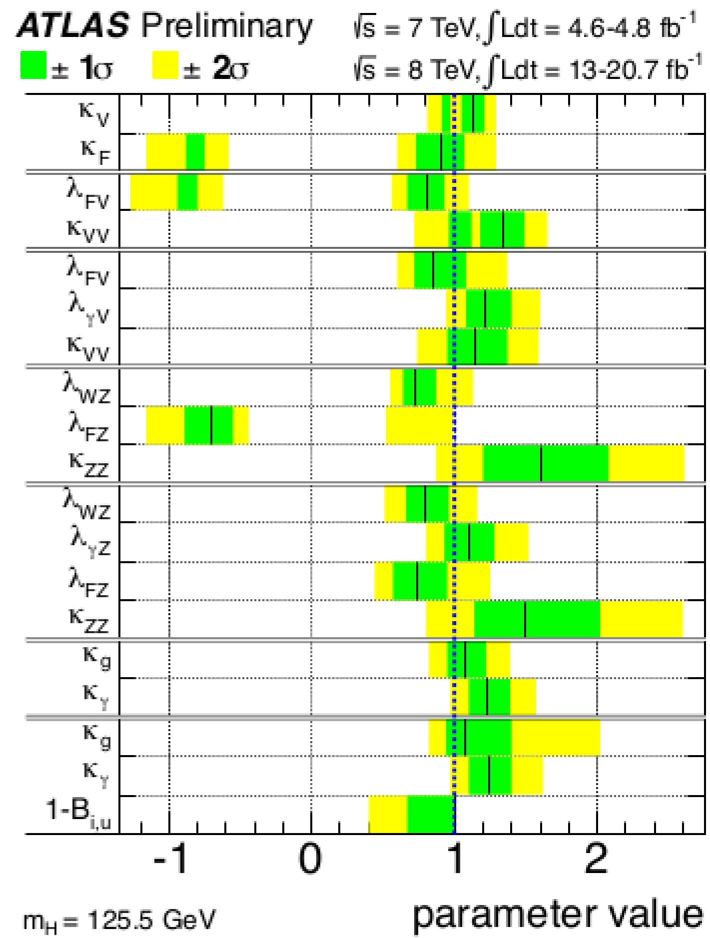


The legacy of run-I

Spin-parity



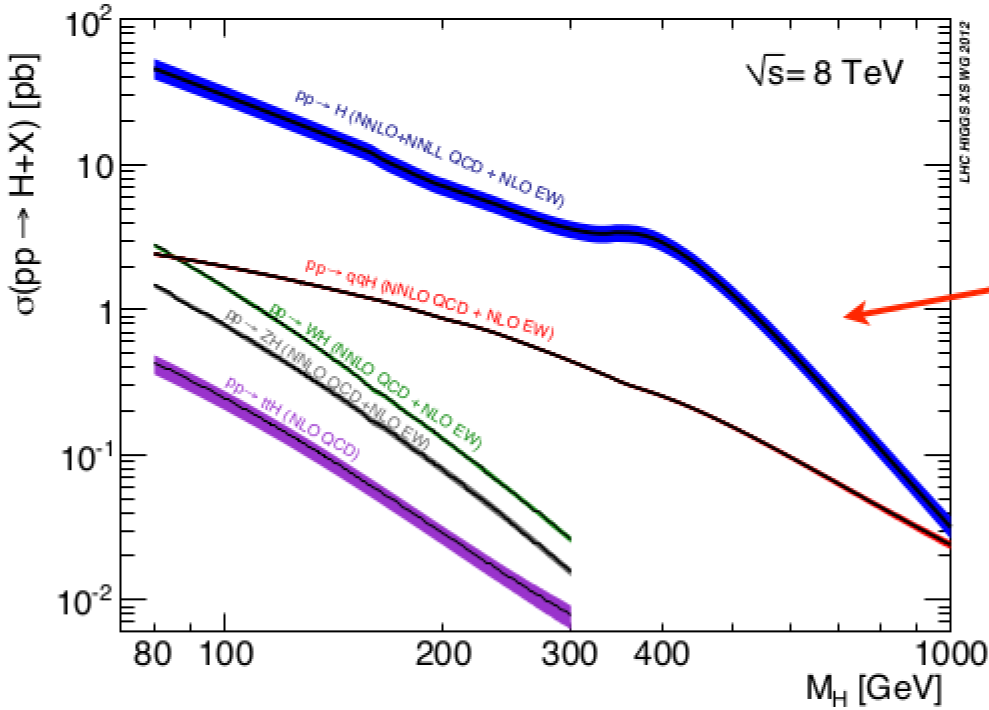
differential distributions



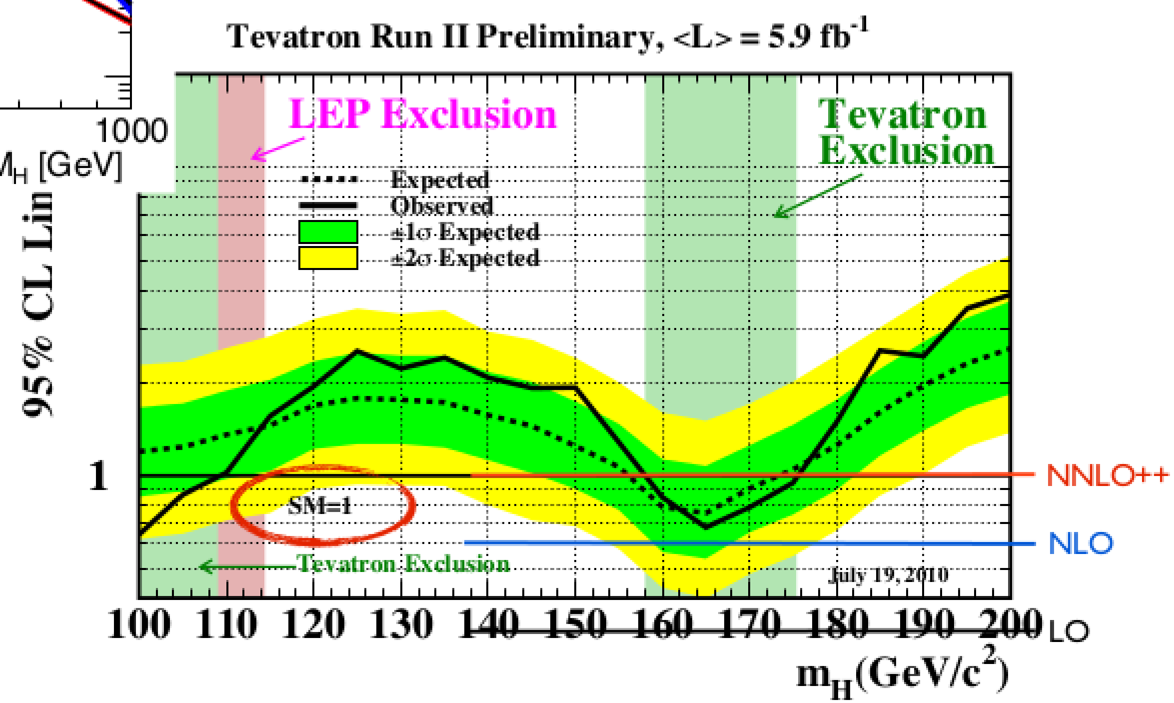
(SM) fit to couplings

Very SM like...

The legacy of run-I

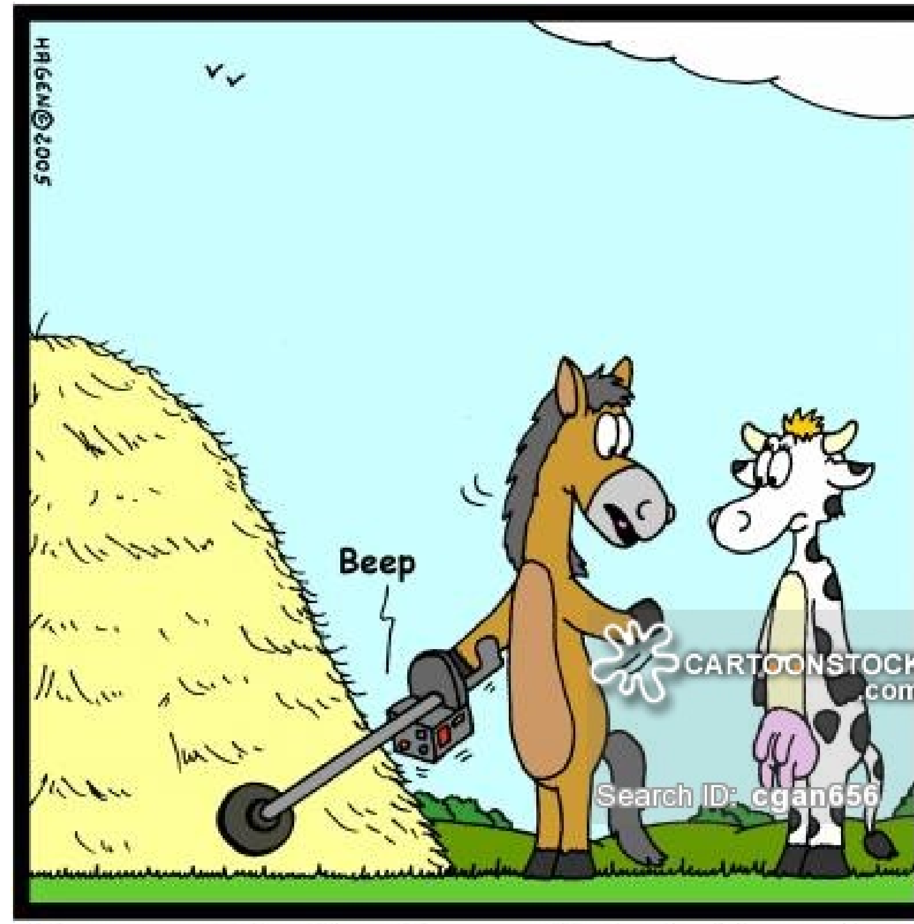


- Higher-order perturbative computations
- Resummation program
- Reliable tools (PS, PDFs...)



[Harlander, "First three years of the LHC"]

The legacy of run-I



You were right: There's a needle in this haystack...

The discovery and first characterization of the Higgs boson went extremely fast, thanks to remarkable efforts in the experimental and theoretical community.

Run-II

Higgs physics: search for small deviations

A closer look to small effects

Double Higgs production and the Higgs self-coupling

[Grigo, Hoff et al (2013); de Florian, Mazzitelli (2013); Dolan, Englert et al (2013)]

New ways to measure Higgs properties

- ttH coupling [Campbell, Ellis et al; Curtin, Galloway et al (2013)]
- Higgs interferometry [Dixon and Siu (2003); Martin; Kauer, Passarino (2013)]
- Higgs to J/ϒγ and the Hcc coupling [Bodwin, Petriello et al. (2013)]
- Γ_H from mass-shift in H->γγ [Dixon, Li (2013)]
- Γ_H from H->ZZ off-shell production [FC, Melnikov (2013)]

"No boson left behind": high-mass Higgs searches

- the Higgs boson line-shape [Goria et al. (2011), Franzosi et al. (2012)]
- signal-background interference at LO [Campbell, Ellis, Williams (2011); Kauer, Passarino (2012)] and beyond [Bonvini, FC et al. (2013)]

Higgs physics: search for small deviations

Push collider phenomenology to the boundaries

To the edge of pQCD: N^3LO

[Anastasiou, Duhr, Dulat, Herzog, Mistlberger (2015)]

Going exclusive: cope with jet-bin analysis, gg/VBF separation…

- H+3j @ NLO [Cullen et al, GoSam+MadDipole/MadEvent+Sherpa (2013)]
- resumming jet vetoes [Banfi et al.; Stewart, Tackmann et al. (2013); Liu and Petriello (2013); Boughezal et al (2014); Becher et al (2014)]
- HIGGS+JET @ NNLO

Always improving our tools:

- beyond $m_t \to \infty$, $m_b \to 0$ [Harlander et al, (2012); Grazzini, Sargsyan (2013)]
- PS matching @ NNLO [Hamilton et al, (2013), Hoeche et al (2014)]

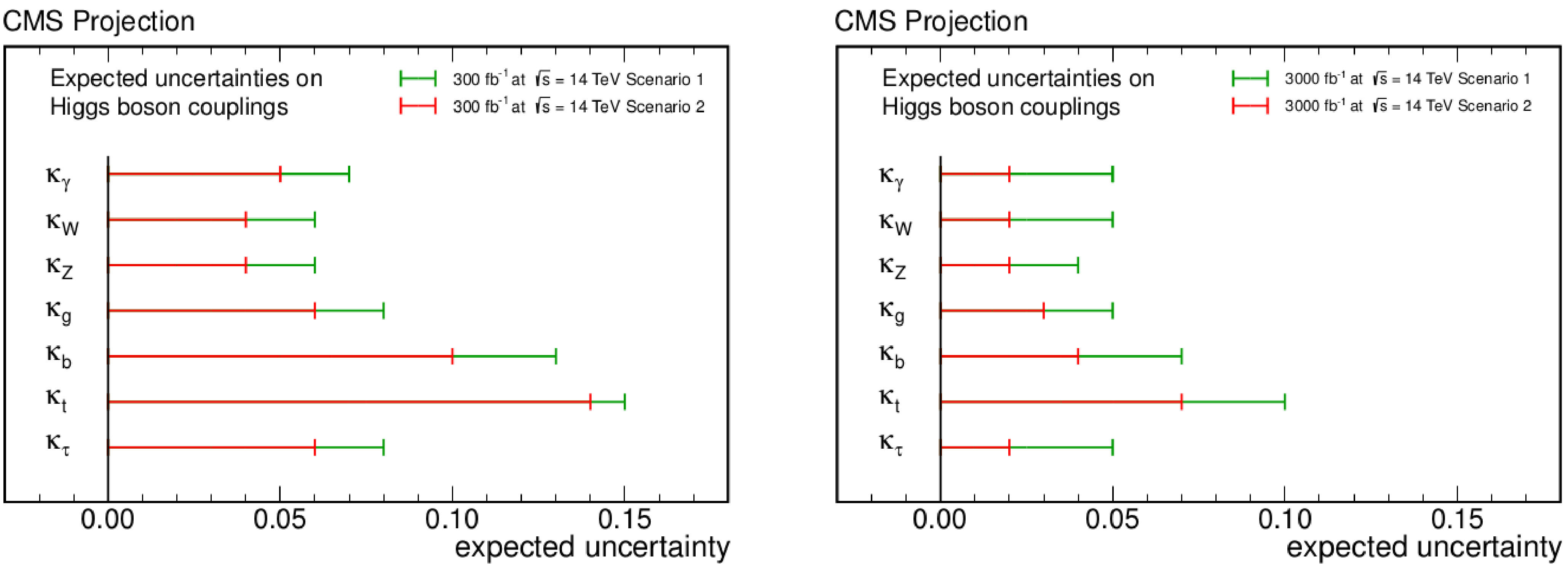
Run-II

[Dawson et al., Snowmass Higgs WG Report]

Table 1-8. *Generic size of Higgs coupling modifications from the Standard Model values when all new particles are* $M \sim 1$ *TeV and mixing angles satisfy precision electroweak fits. The Decoupling MSSM numbers assume* $\tan\beta = 3.2$ *and a stop mass of* 1 *TeV with* $X_t = 0$ *for the* κ_γ *prediction.*

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

Run-II



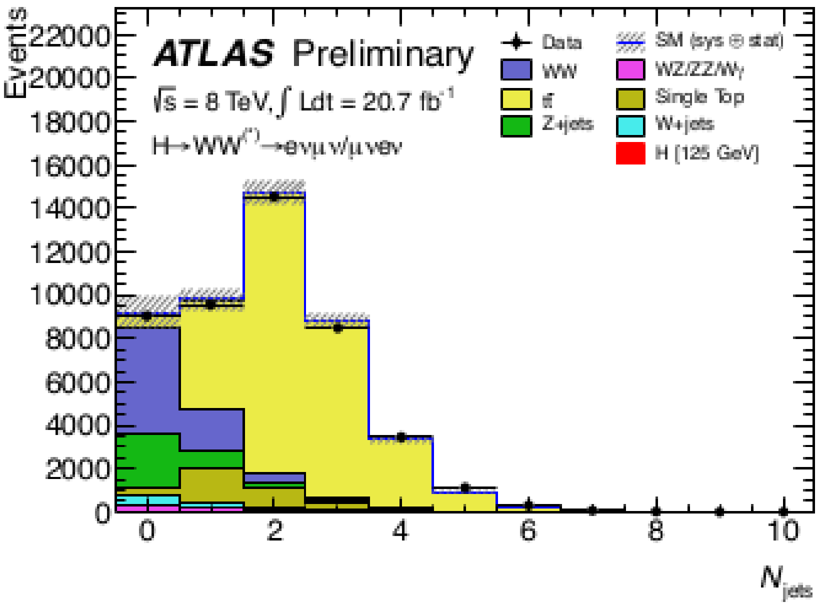
Scenario I: assume current theory uncertainties

Scenario II: ½ x theory uncertainties, 1/sqrt(10) x other systematics

H+jet

Higgs plus jet: jet-binned cross-sections

Experimental analyses for pp $\rightarrow$ H $\rightarrow$ WW (similar for $\tau\tau$): binned according to jet multiplicity (different systematics)



- Signal/background ratio for H+1, H+2 jets: $\sim 10\%$
- Significance in the H+1jet bin smaller, but not much smaller, than significance in the H+0 jet bin
- LARGE THEORY ERROR

Jet-bin cross sections: what to do

The problem with jet-binned cross sections: large logs

$$\sigma_{inc} = \sigma_0 + \sigma_1 + \ldots$$

$$-\frac{\alpha_s}{\pi} 2C_A \ln^2 \frac{p_T}{m_H}$$

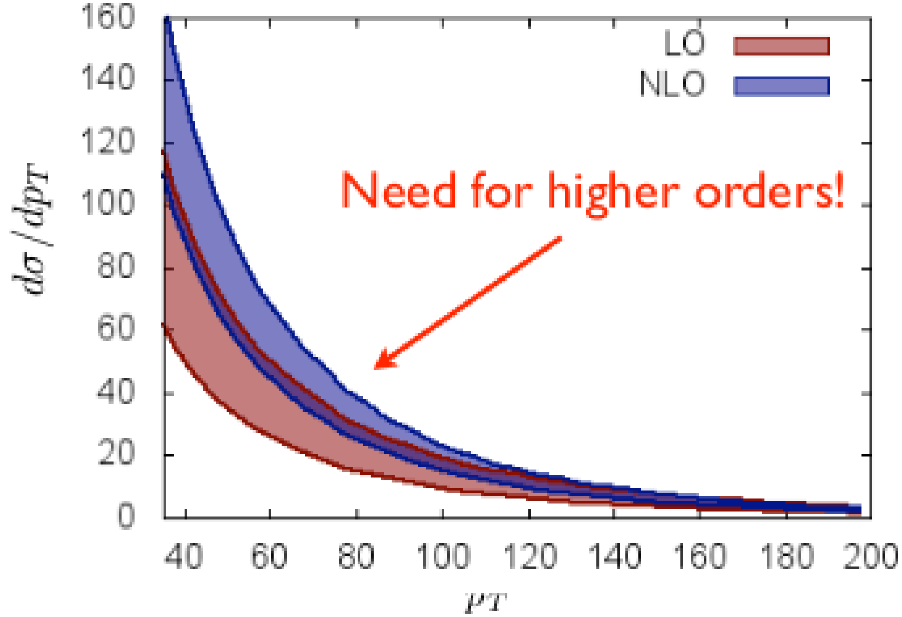
$$\frac{\alpha_s}{\pi} 2C_A \ln^2 \frac{p_T}{m_H}$$

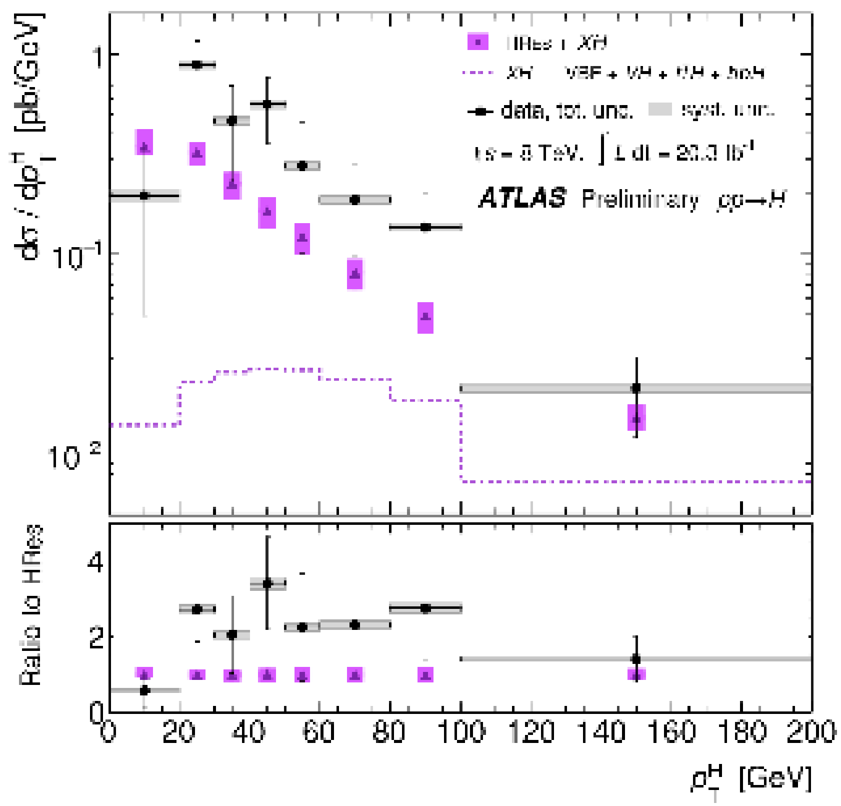
For $p_T \sim 30$ GeV: O(40%) correction.

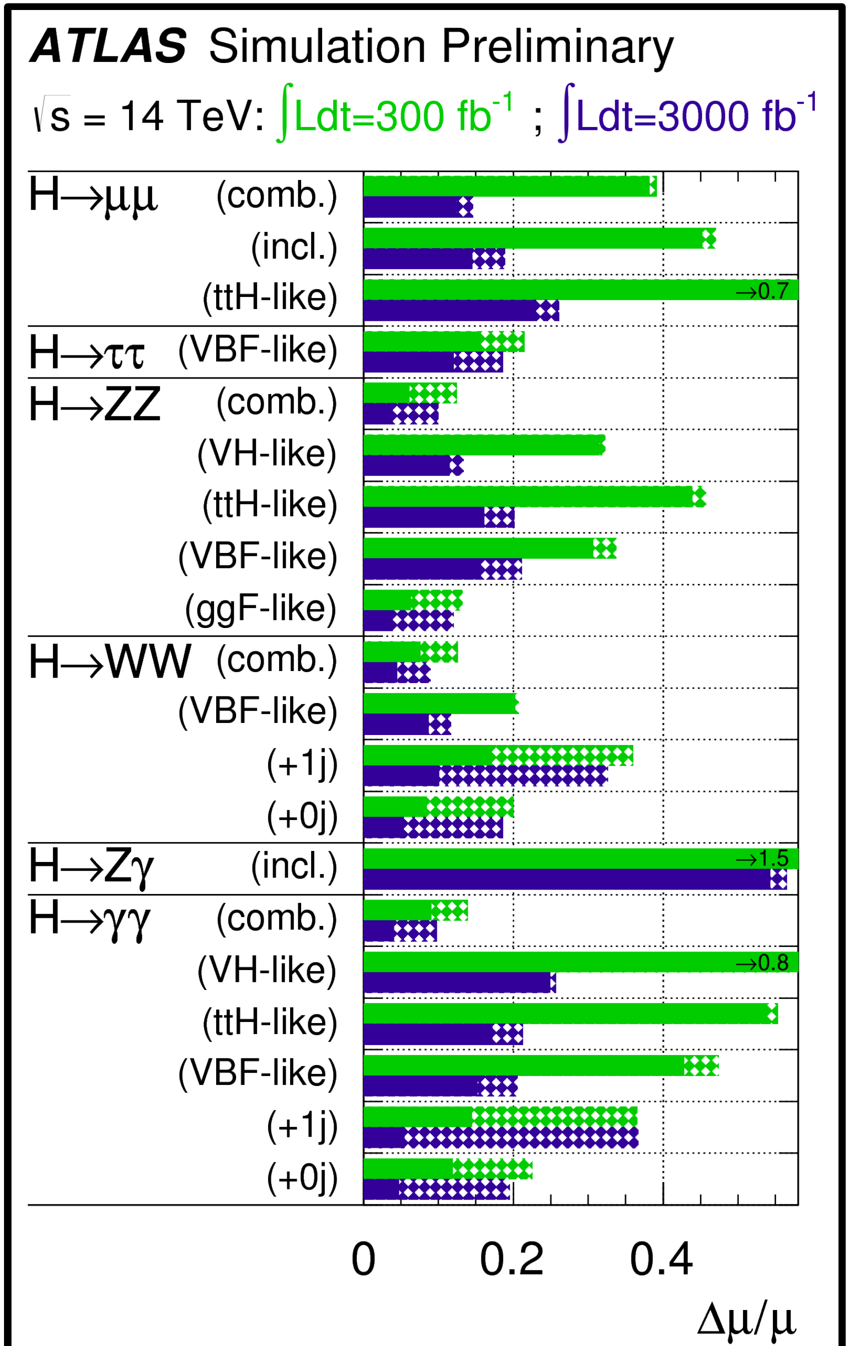
A PRAGMATIC APPROACH:

- Small p_T: resum these logs
- High p_T: compute higher order corrections
- Combine the two approaches

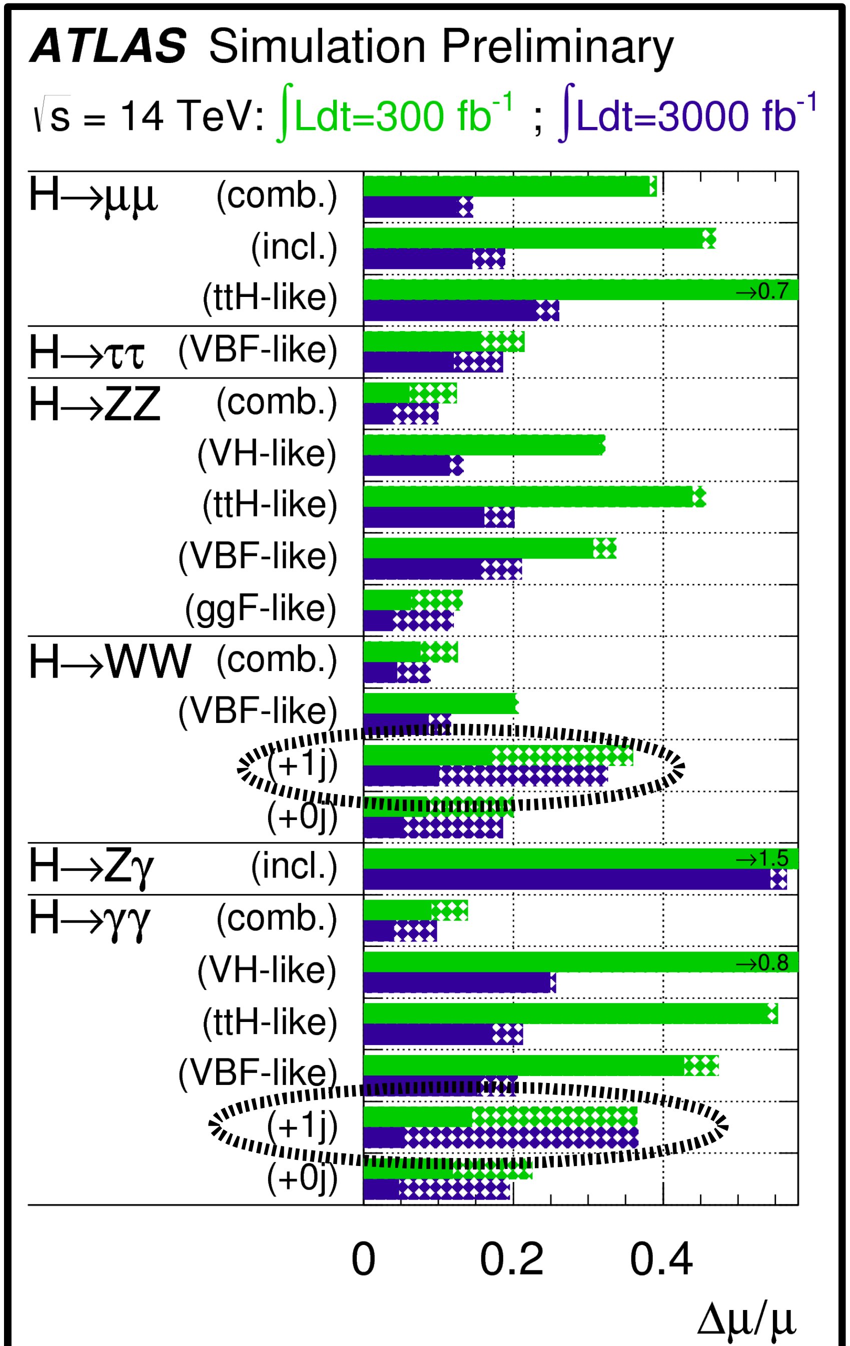
H+jet at NNLO QCD





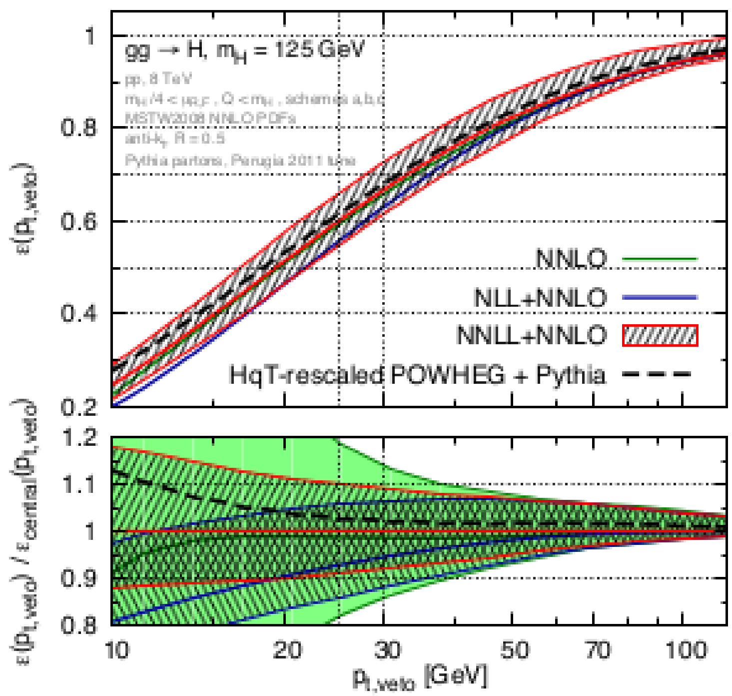

ATLAS Simulation Preliminary
√s = 14 TeV: ∫Ldt=300 fb-1 ; ∫Ldt=3000 fb-1
H→μμ (comb.)
(incl.)
(ttH-like)
→0.7
H→ττ (VBF-like)
H→ZZ (comb.)
(VH-like)
(ttH-like)
(VBF-like)
(ggF-like)
H→WW (comb.)
(VBF-like)
(+1j)
(+0j)
H→Zγ (incl.)
→1.5
H→γγ (comb.)
(VH-like)
→0.8
(ttH-like)
(VBF-like)
(+1j)
(+0j)
0
0.2
0.4
Δμ/μ

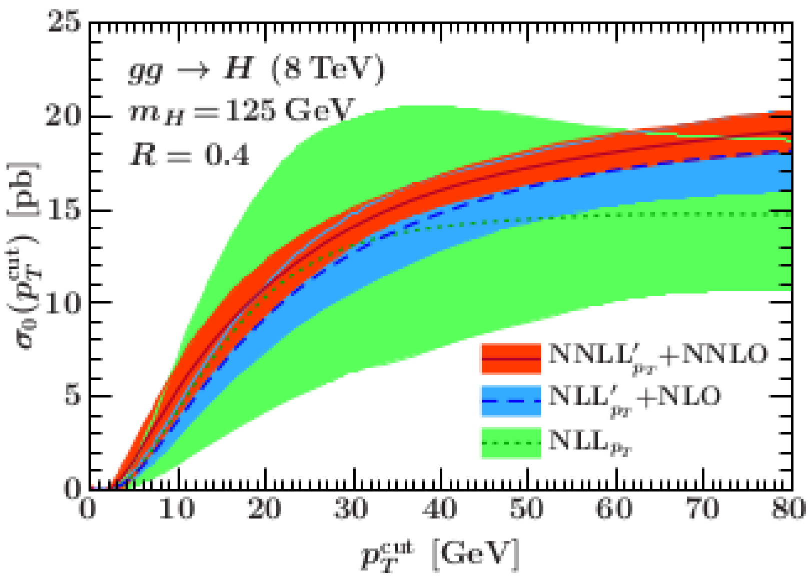
H+jet at NNLO QCD



Jet (veto) resummation approach: very good shape

[Banfi et al.; Stewart, Tackmann et al. (2013); Liu and Petriello (2013); Boughezal et al (2014); Becher et al (2014); Dasgupta, Dreyer, Salam, Soyez(2015)]



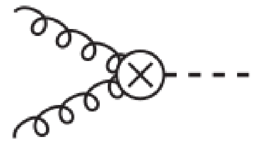


- Logs more or less under control
- Improvement will come from h.o. matching

Expect a transition for $p_T \sim 30$ GeV

- NNLO QCD predictions for *H*+jet have been achieved in the *Higgs Effective Theory*

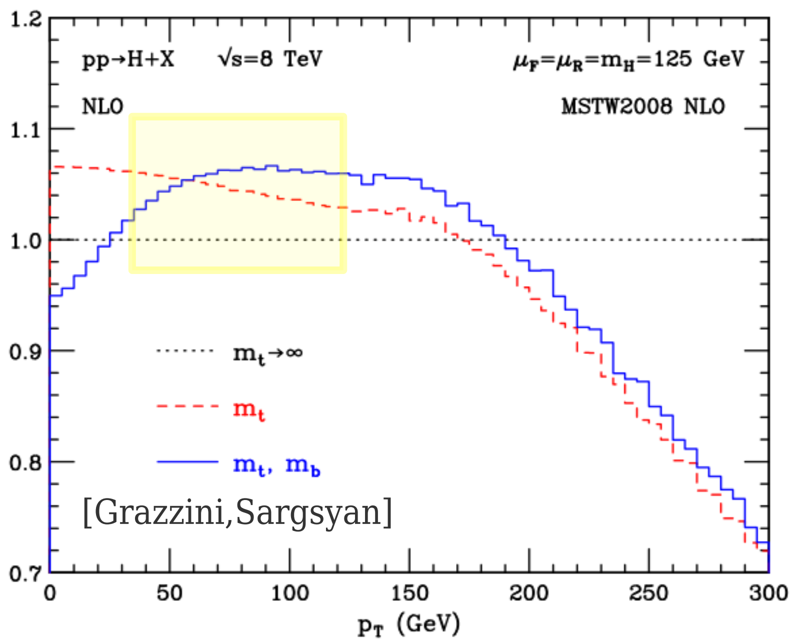
$$\mathcal{L} = \mathcal{L}_{QCD,5} - \frac{1}{4v} C_1 \, H \, G^a_{\mu\nu} \, G_a^{\mu\nu}$$



[Boughezal,Caola,Melnikov,Petriello,M.S.], [Chen,Gehrmann,Glover,Jaquier], [Boughezal,Focke,Giele,Liu,Petriello]

- Finite quark mass effects have been studied

[Harlander, Ozeren; Pak, Rogal, Steinhauser; Ball, Del Duca, Marzani, Forte, Vicini; Harlander, Mantler, Marzani, Ozeren]



→ within p_T=30–120 GeV

O(2-7%) effect, almost flat correction

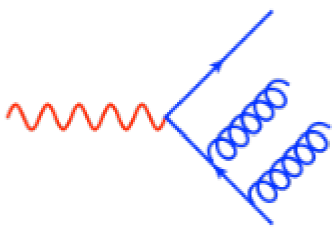
Blackboard:

- Partonic channels
- Anatomy of a NNLO correction
- Shopping list
- FKS-improved sector decomposition

NNLO: same spirit, new problems to solve

Overlapping divergences ⟶ SECTOR DECOMPOSITION

[Binoth, Heinrich; Anastasiou, Melnikov, Petriello (2004)]



$$|M|^2 \sim \frac{1}{s_{ijk}} = \frac{1}{s_{ij}+s_{ik}+s_{jk}}$$

$$\int |M|^2 d\Phi \sim \int \frac{dx_1 dx_2}{x_1^{1+\epsilon} x_2^{1+\epsilon} (x_1+x_2)^{\epsilon}} F(\vec{x};\{y\})\{dy\}$$

- **Sector I:** $x_1 > x_2 \to x_2 = z x_1$

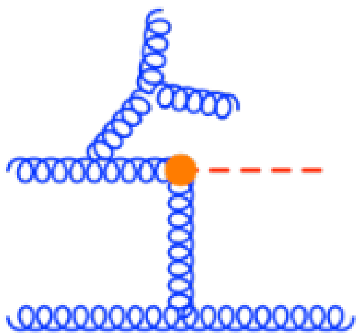
$$\int |M|^2 d\Phi \sim \int \frac{dx_1 dz}{x_1^{1+3\epsilon} z^{1+\epsilon} (1+z)^{\epsilon}} F(\vec{x};\{y\})\{dy\}$$

- **Sector II:** $x_1 < x_2 \to x_1 = t x_2$

$$\int |M|^2 d\Phi \sim \int \frac{dt dx_2}{t^{1+\epsilon} x_2^{1+3\epsilon} (1+t)^{\epsilon}} F(\vec{x};\{y\})\{dy\}$$

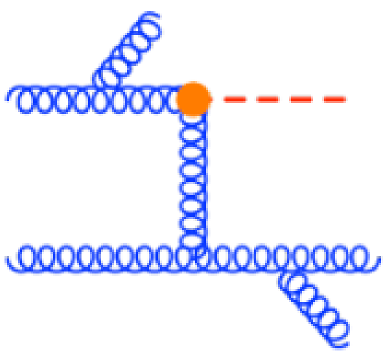
Higgs plus jet: singularity structure

Much more complicated singularity structure. Collinear:

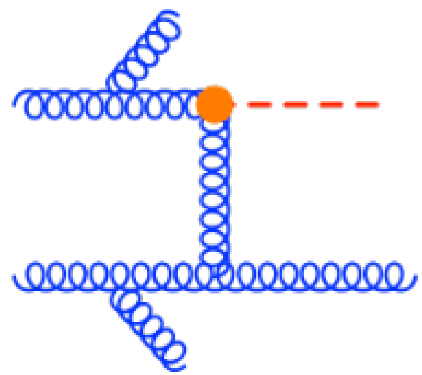


$$\sim \frac{P_{ggg} \otimes |M_j|^2}{s_{igg}}, \quad \frac{P_{gg} \otimes |M_{jj}|^2}{s_{gg}}$$

x3



x2,



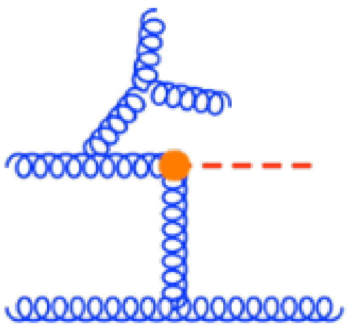
$$\sim \frac{P_{gg} P_{gg} \otimes |M_j|^2}{s_{ig} s_{jg}}$$

Potential troubles: $s_{1g}, s_{2g}, s_{3g}, s_{gg}, s_{1gg}, s_{2gg}, s_{3gg}$ and combinations

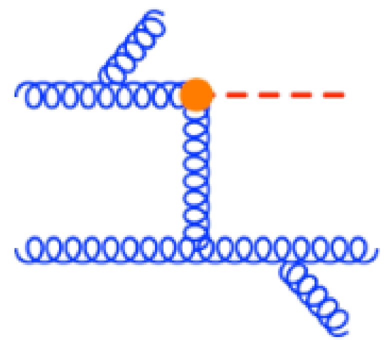
Finding a 'good' global parametrization is (very) hard

Sector-improved subtraction scheme [Czakon (2010)]

HOWEVER: collinear sing. cannot occur all together



Troubles:
s_{igg}, s_{gg} only



Troubles:
s_{ig}, s_{jg} only

Can we make use of it, i.e.
can we single out different collinear directions?

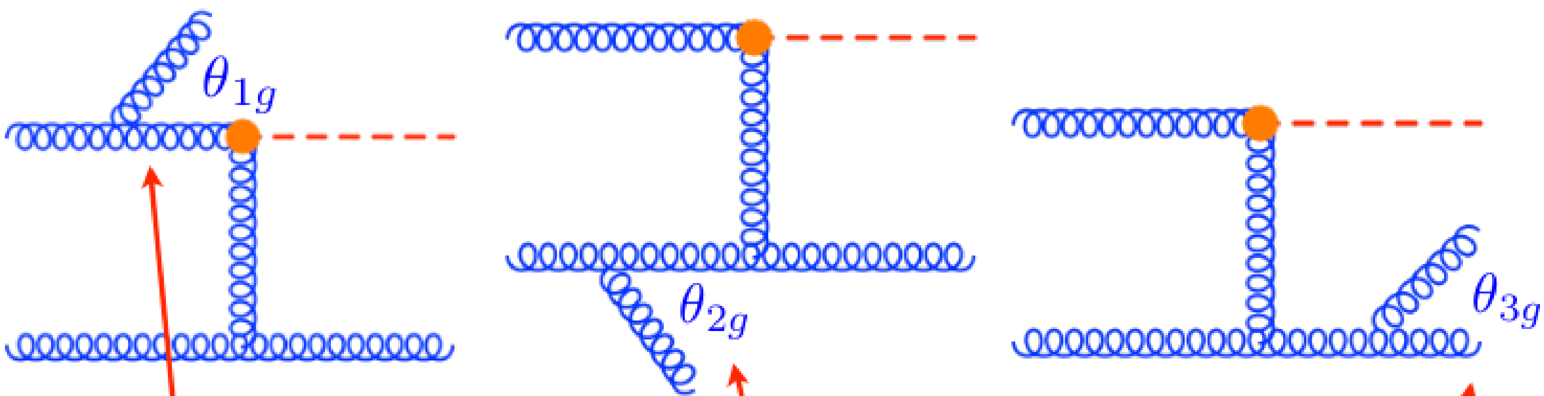
YES, just use the Frixione-Kunszt-Signer (FKS) partitioning
[Czakon (2010)]

$$1 = \sum \Delta^{g_1||i, g_2||j}$$

$$\Delta_s^{g_1||i, g_2||j} \to 0 \text{ when } g_1||p_l,\ g_2||p_m,\ l \neq i,\ m \neq j$$

FKS redux

Again the NLO case [Frixione, Kunszt, Signer (1995)]



$$\rho_i = 1 - \cos\theta_{ig}$$

$$1 = \frac{\rho_2\rho_3 + \rho_1\rho_3 + \rho_1\rho_2}{\rho_2\rho_3 + \rho_1\rho_3 + \rho_1\rho_2}$$

$$\int |M|^2 \cdot 1 \; d\phi_3 =$$

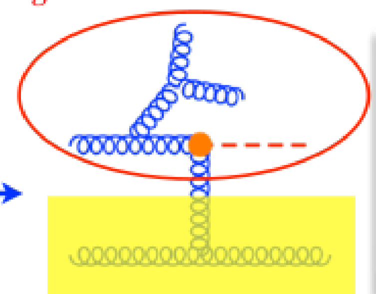
$$\int \frac{|M|^2 \rho_2\rho_3 \; d\phi_3}{\rho_2\rho_3 + \rho_1\rho_3 + \rho_1\rho_2} + \int \frac{|M|^2 \rho_1\rho_3 \; d\phi_3}{\rho_2\rho_3 + \rho_1\rho_3 + \rho_1\rho_2} + \int \frac{|M|^2 \rho_1\rho_2 \; d\phi_3}{\rho_2\rho_3 + \rho_1\rho_3 + \rho_1\rho_2}$$

Sector-improved subtraction scheme

Sector decomposition + FKS

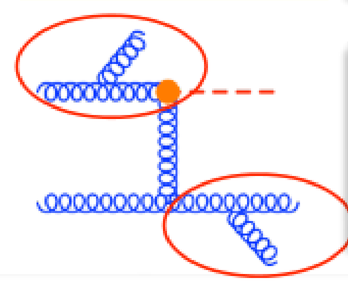
$$\int |M|^2 d\phi = \sum_s \int |M|^2 d\phi \Delta_s^{g_1||i,g_2||j}$$

$$\int |M|^2 d\phi \Delta^{g_1||1,g_2||1} \longrightarrow$$



Single collinear direction
~ parametrization of
ggH, DY, e^+e^- → dijets

$$\int |M|^2 d\phi \Delta^{g_1||1,g_2||3} \longrightarrow$$



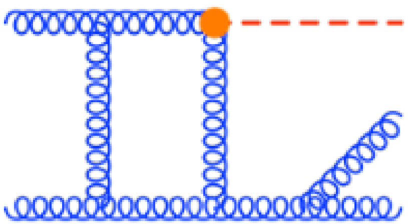
Two (~uncorrelated) dir.
~ NLO^2

No matter how complicated the process is,
it can be reduced to the sum of individual contributions. For each of them, we know a sector decomposition-friendly PS parametrization
[Czakon (2010)]

Sector-improved subtraction and H+j

Worked-out details for RV: [Boughezal, Melnikov, Petriello (2011)]

(Although we need a slight generalization)



Three collinear partitions
(same of NLO)

Phase-space is simple (same of NLO), but amplitudes have non trivial branch-cuts

$$\mathrm{RV}_i = \int \{dy\} \frac{dx_1}{x_1^{1+2\epsilon}} \frac{dx_2}{x_2^{1+\epsilon}} \left(F_{i,1} + (x_1^2 x_2)^{-\epsilon} F_{i,2} + x_1^{-2\epsilon} F_{i,3}\right) =$$

$$= \int \{dy\} \left[\frac{A}{\epsilon^4} + \frac{B}{\epsilon^3} + \frac{C}{\epsilon^2} + \frac{D}{\epsilon} + E\right]$$

Complexity

```
schulze@XPS14:~/temp/HJET/Sectors$ ls
inc                          sector_nlo_r_coll_43_gg.f90   sector_nnlo_al_42_52_1_qg.f90  sector_nnlo_rn_gg.f90          sector_nnlo_rr_42_52_5_qg.f90
sector_lo_gg.f90             sector_nlo_r_coll_43_qg.f90   sector_nnlo_al_42_52_2_gg.f90  sector_nnlo_rn_nlor_41_gg.f90  sector_nnlo_rr_42_53_gg.f90
sector_lo_gq.f90             sector_nlo_rn_gg.f90          sector_nnlo_al_42_52_2_qg.f90  sector_nnlo_rn_nlor_41_qg.f90  sector_nnlo_rr_42_53_qg.f90
sector_lo_qg.f90             sector_nlo_rn_gq.f90          sector_nnlo_al_42_52_3_gg.f90  sector_nnlo_rn_nlor_42_gg.f90  sector_nnlo_rr_43_51_gg.f90
sector_lo_qqb.f90            sector_nlo_rn_qg.f90          sector_nnlo_al_42_52_3_qg.f90  sector_nnlo_rn_nlor_42_qg.f90  sector_nnlo_rr_43_51_qg.f90
sector_nlo_cv_gg.f90         sector_nlo_rn_qqb.f90         sector_nnlo_al_42_52_4_gg.f90  sector_nnlo_rn_nlor_43_gg.f90  sector_nnlo_rr_43_52_gg.f90
sector_nlo_cv_gq.f90         sector_nlo_r_soft_41_gg.f90   sector_nnlo_al_42_52_4_qg.f90  sector_nnlo_rn_nlor_43_qg.f90  sector_nnlo_rr_43_52_qg.f90
sector_nlo_cv_qg.f90         sector_nlo_r_soft_41_qg.f90   sector_nnlo_al_42_52_5_gg.f90  sector_nnlo_rn_qg.f90          sector_nnlo_rr_43_53_1_gg.f90
sector_nlo_cv_qqb.f90        sector_nlo_r_soft_42_gg.f90   sector_nnlo_al_42_52_5_qg.f90  sector_nnlo_rr_41_51_1_gg.f90  sector_nnlo_rr_43_53_1_qg.f90
sector_nlo_cv_qq.f90         sector_nlo_r_soft_42_qg.f90   sector_nnlo_al_42_53_gg.f90    sector_nnlo_rr_41_51_1_qg.f90  sector_nnlo_rr_43_53_2_gg.f90
sector_nlo_cv_qr.f90         sector_nlo_r_soft_43_gg.f90   sector_nnlo_al_42_53_qg.f90    sector_nnlo_rr_41_51_2_gg.f90  sector_nnlo_rr_43_53_2_qg.f90
sector_nlo_r_41_gg.f90       sector_nlo_r_soft_43_qg.f90   sector_nnlo_al_43_51_gg.f90    sector_nnlo_rr_41_51_2_qg.f90  sector_nnlo_rr_43_53_3_gg.f90
sector_nlo_r_41_gq.f90       sector_nlo_v_gg.f90           sector_nnlo_al_43_51_qg.f90    sector_nnlo_rr_41_51_3_gg.f90  sector_nnlo_rr_43_53_3_qg.f90
sector_nlo_r_41_qg.f90       sector_nlo_v_gq.f90           sector_nnlo_al_43_52_gg.f90    sector_nnlo_rr_41_51_3_qg.f90  sector_nnlo_rr_43_53_4_gg.f90
sector_nlo_r_41_qqb.f90      sector_nlo_v_qg.f90           sector_nnlo_al_43_52_qg.f90    sector_nnlo_rr_41_51_4_gg.f90  sector_nnlo_rr_43_53_4_qg.f90
sector_nlo_r_41_qq.f90       sector_nlo_v_qqb.f90          sector_nnlo_al_43_53_1_gg.f90  sector_nnlo_rr_41_51_4_qg.f90  sector_nnlo_rr_43_53_5_gg.f90
sector_nlo_r_41_qr.f90       sector_nnlo_al_41_51_1_gg.f90 sector_nnlo_al_43_53_1_qg.f90  sector_nnlo_rr_41_51_5_gg.f90  sector_nnlo_rr_43_53_5_qg.f90
sector_nlo_r_42_gg.f90       sector_nnlo_al_41_51_1_qg.f90 sector_nnlo_al_43_53_2_gg.f90  sector_nnlo_rr_41_51_5_qg.f90  sector_nnlo_rv_41_gg.f90
sector_nlo_r_42_gq.f90       sector_nnlo_al_41_51_2_gg.f90 sector_nnlo_al_43_53_2_qg.f90  sector_nnlo_rr_41_52_gg.f90    sector_nnlo_rv_41_qg.f90
sector_nlo_r_42_qg.f90       sector_nnlo_al_41_51_2_qg.f90 sector_nnlo_al_43_53_3_gg.f90  sector_nnlo_rr_41_52_qg.f90    sector_nnlo_rv_41_soft_gg.f90
sector_nlo_r_42_qqb.f90      sector_nnlo_al_41_51_3_gg.f90 sector_nnlo_al_43_53_3_qg.f90  sector_nnlo_rr_41_53_gg.f90    sector_nnlo_rv_41_soft_qg.f90
sector_nlo_r_42_qq.f90       sector_nnlo_al_41_51_3_qg.f90 sector_nnlo_al_43_53_4_gg.f90  sector_nnlo_rr_41_53_qg.f90    sector_nnlo_rv_42_gg.f90
sector_nlo_r_42_qr.f90       sector_nnlo_al_41_51_4_gg.f90 sector_nnlo_al_43_53_4_qg.f90  sector_nnlo_rr_42_51_gg.f90    sector_nnlo_rv_42_qg.f90
sector_nlo_r_43_gg.f90       sector_nnlo_al_41_51_4_qg.f90 sector_nnlo_al_43_53_5_gg.f90  sector_nnlo_rr_42_51_qg.f90    sector_nnlo_rv_42_soft_gg.f90
sector_nlo_r_43_gq.f90       sector_nnlo_al_41_51_5_gg.f90 sector_nnlo_al_43_53_5_qg.f90  sector_nnlo_rr_42_52_1_gg.f90  sector_nnlo_rv_42_soft_qg.f90
sector_nlo_r_43_qg.f90       sector_nnlo_al_41_51_5_qg.f90 sector_nnlo_cv_gg.f90          sector_nnlo_rr_42_52_1_qg.f90  sector_nnlo_rv_43_gg.f90
sector_nlo_r_43_qqb.f90      sector_nnlo_al_41_52_gg.f90   sector_nnlo_cv_nlor_41_gg.f90  sector_nnlo_rr_42_52_2_gg.f90  sector_nnlo_rv_43_qg.f90
sector_nlo_r_43_qq.f90       sector_nnlo_al_41_52_qg.f90   sector_nnlo_cv_nlor_41_qg.f90  sector_nnlo_rr_42_52_2_qg.f90  sector_nnlo_rv_43_soft_gg.f90
sector_nlo_r_43_qr.f90       sector_nnlo_al_41_53_gg.f90   sector_nnlo_cv_nlor_42_gg.f90  sector_nnlo_rr_42_52_3_gg.f90  sector_nnlo_rv_43_soft_qg.f90
sector_nlo_r_coll_41_gg.f90  sector_nnlo_al_41_53_qg.f90   sector_nnlo_cv_nlor_42_qg.f90  sector_nnlo_rr_42_52_3_qg.f90  sector_nnlo_vv.f90
sector_nlo_r_coll_41_qg.f90  sector_nnlo_al_42_51_gg.f90   sector_nnlo_cv_nlor_43_gg.f90  sector_nnlo_rr_42_52_4_gg.f90
sector_nlo_r_coll_42_gg.f90  sector_nnlo_al_42_51_qg.f90   sector_nnlo_cv_nlor_43_qg.f90  sector_nnlo_rr_42_52_4_qg.f90
sector_nlo_r_coll_42_qg.f90  sector_nnlo_al_42_52_1_gg.f90 sector_nnlo_cv_qg.f90          sector_nnlo_rr_42_52_5_gg.f90
schulze@XPS14:~/temp/HJET/Sectors$
```

sectors at NNLO:

RR: 13(gg)+21(qg),
5D: 13(gg)+21(qg),
RV: 2(gg)+3(qg),

pdf ren.: 5(gg)+6(qg),
UV ren.: 4(gg)+4(qg),
2-loops: 1(gg)+1(qg)

Complexity

```
schulze@XPS14:~/temp/HJET/Sectors$ ls
inc                       sector_nlo_r_coll_43_gg.f90  sector_nnlo_al_42_52_1_qg.f90  sector_nnlo_rn_gg.f90            sector_nnlo_rr_42_52_5_qg.f90
sector_lo_gg.f90          sector_nlo_r_coll_43_qg.f90  sector_nnlo_al_42_52_2_gg.f90  sector_nnlo_rn_nlor_41_gg.f90    sector_nnlo_rr_42_53_gg.f90
sector_lo_gq.f90          sector_nlo_rn_gg.f90         sector_nnlo_al_42_52_2_qg.f90  sector_nnlo_rn_nlor_41_qg.f90    sector_nnlo_rr_42_53_qg.f90
sector_lo_qg.f90          sector_nlo_rn_gq.f90         sector_nnlo_al_42_52_3_gg.f90  sector_nnlo_rn_nlor_42_gg.f90    sector_nnlo_rr_43_51_gg.f90
sector_lo_qqb.f90         sector_nlo_rn_qg.f90         sector_nnlo_al_42_52_3_qg.f90  sector_nnlo_rn_nlor_42_qg.f90    sector_nnlo_rr_43_51_qg.f90
sector_nlo_cv_gg.f90      sector_nlo                                                                                    gg.f90
sector_nlo_cv_gq.f90      sector_nlo                                                                                    qg.f90
sector_nlo_cv_qg.f90      sector_nlo                                                                                    1_gg.f90
sector_nlo_cv_qqb.f90     sector_nlo                                                                                    1_qg.f90
sector_nlo_cv_qq.f90      sector_nlo                                                                                    2_gg.f90
sector_nlo_cv_qr.f90      sector_nlo                                                                                    2_qg.f90
sector_nlo_r_41_gg.f90    sector_nlo                                                                                    3_gg.f90
sector_nlo_r_41_gq.f90    sector_nlo                                                                                    3_qg.f90
sector_nlo_r_41_qg.f90    sector_nlo                                                                                    4_gg.f90
sector_nlo_r_41_qqb.f90   sector_nlo                                                                                    4_qg.f90
sector_nlo_r_41_qq.f90    sector_nlo                                                                                    5_gg.f90
sector_nlo_r_41_qr.f90    sector_nnlo                                                                                   5_qg.f90
sector_nlo_r_42_gg.f90    sector_nnlo                                                                                   f90
sector_nlo_r_42_gq.f90    sector_nnlo                                                                                   f90
sector_nlo_r_42_qg.f90    sector_nnlo                                                                                   t_gg.f90
sector_nlo_r_42_qqb.f90   sector_nnlo                                                                                   t_qg.f90
sector_nlo_r_42_qq.f90    sector_nnlo                                                                                   f90
sector_nlo_r_42_qr.f90    sector_nnlo                                                                                   f90
sector_nlo_r_43_gg.f90    sector_nnlo                                                                                   t_gg.f90
sector_nlo_r_43_gq.f90    sector_nnlo                                                                                   t_qg.f90
sector_nlo_r_43_qg.f90    sector_nnlo                                                                                   f90
sector_nlo_r_43_qqb.f90   sector_nnlo                                                                                   f90
sector_nlo_r_43_qq.f90    sector_nnlo                                                                                   t_gg.f90
sector_nlo_r_43_qr.f90    sector_nnlo                                                                                   t_qg.f90
sector_nlo_r_coll_41_gg.f90  sector_nnlo
sector_nlo_r_coll_41_qg.f90  sector_nnlo
sector_nlo_r_coll_42_gg.f90  sector_nnlo
sector_nlo_r_coll_42_qg.f90  sector_nnlo
schulze@XPS14:~/temp/HJET/Sectors$
```

```fortran
!DEC$ if (_withgg.eq.1)
subroutine gg_jjjh_tree(p,res)
  real(dp), intent(in) :: p(4,6)
  real(dp), intent(out) :: res
  real(dp) :: me2gg,me2nf,me2nf_4,me2nf_5,me2nf_6
  real(dp) :: sprod(5,5)
  complex(dp) :: za(5,5),zb(5,5)

  call spinoru(5,(/-p(:,1),-p(:,2),p(:,3),p(:,4),p(:,5)/),za,zb,sprod)

  !-- ggg
  call me2_ggggg_tree(1,2,3,4,5,za,zb,sprod,me2gg)

  !DEC$ if (_withnf.eq.1)
  call me2_qbqggg_tree(4,5,1,2,3,za,zb,sprod,me2nf_4) !-- gqq
  call me2_qbqggg_tree(3,5,1,2,4,za,zb,sprod,me2nf_5) !-- qgq
  call me2_qbqggg_tree(3,4,1,2,5,za,zb,sprod,me2nf_6) !-- qqg
  me2nf = me2nf_4 * _tagmsq4 + me2nf_5 * _tagmsq5 + me2nf_6 * _tagmsq6
  !DEC$ else
  me2nf = zero
  !DEC$ endif

  res = (_tagmsq1 * me2gg + twonf * me2nf)*avegg

end subroutine gg_jjjh_tree
!DEC$ endif
```

se

RR: 13(gg)+21(qg), pdf ren.: 5(gg)+6(qg),
5D: 13(gg)+21(qg), UV ren.: 4(gg)+4(qg),
RV: 2(gg)+3(qg), 2-loops: 1(gg)+1(qg)

Complexity

```
!----- generating angular variabels
!---   parametrization of the harder gluon in the CMS
cos3 = 1.0_dp - 2.0_dp*x7
sin3 = sqrt(abs(1.0_dp - cos3**2))
phi3 = twopi*x8

!----- gluon 5
cos5 = 1.0_dp - two*x3                    ! -- lab frame
sin5 = sqrt(abs(1.0_dp - cos5**2))
phi5 = twopi*x6
phi53 = phi5+phi3

!----- gluon 4 , lab frame
cos4 = -1.0_dp + two*x4
sin4 = sqrt(abs(1.0_dp) - cos4**2)
phi4 = twopi*x5
phi43 = phi4+phi3

xmax = 1.0_dp
if (x1.eq.0.0_dp) then
   param = 2.0_dp
else
   param = (1.0_dp - x1)/x1/(1.0_dp - beta2*x1*eta45)
endif
if (param.lt.1.0_dp) xmax = param

Eg5 = emaxlocal*x1*x2*xmax
Eg4 = emaxlocal*x1

p(:,4) = Eg4*(/one,n4(1),n4(2),n4(3)/)
p(:,5) = Eg5*(/one,n5(1),n5(2),n5(3)/)

p(:,1) = sqrts/two*(/one,zero,zero,one/)
p(:,2) = sqrts/two*(/one,zero,zero,-one/)

Q(:) = p(:,1) + p(:,2) - p(:,5) - p(:,4)
Q2 = scr(Q,Q)
Eg3 = (Q2- mh**2)/two/(sqrts - Eg4*(one-sc3(n3,n4)) &
    - Eg5*(one-sc3(n3,n5)) )
p(:,3) = Eg3*(/one,sin3*cos(phi3),sin3*sin(phi3),cos3/)
```

```
x1=buff+onet*real(yRnd(1),dp)
x2=buff+onet*real(yRnd(2),dp)
x3=buff+onet*real(yRnd(3),dp)
x4=buff+onet*real(yRnd(4),dp)
x5=buff+onet*sin(pi*real(yRnd(5),kind=dp)/two)**2
xx(1) = x5
xx(2:4+ndim_dc)=buff+onet*real(yRnd(6:8+ndim_dc),dp)


if (x1*x2*x3*x4 .lt. cbuff) return


!DEC$ if(_withpdf.ge.1)
 xa = buff+onet*real(yRnd(9+ndim_dc),dp)
 xb = buff+onet*real(yRnd(10+ndim_dc),dp)
!DEC$ else
 xa = one
 xb = one
!DEC$ endif
```

1e-10...1e-12

```
    !DEC$ if (_withhisto.eq.1)
    !DEC$ if (_withqp.eq.0)
#include './inc/rr_dc_m2_obs.f90'
    !DEC$ else
    if (x1*x2*x3*x4.lt.switchbuff_rr) then
#include './inc/rr_dc_m2_obs_qp.f90'
    else
#include './inc/rr_dc_m2_obs.f90'
    endif
    !DEC$ endif
    !DEC$ else
    !DEC$ if (_withqp.eq.0)
```

1e-7

H+jet at NNLO QCD

```
[maschulz@lxplus0094 cluster]$ cls
[maschulz@lxplus0094 cluster]$ ll
total 44M
-rwxr-xr-x. 1 maschulz t3 44M Jul 14 01:32 hjet
-rw-r--r--. 1 maschulz t3 795 Jul 14 01:32 hjet.cfg
-rwxr--r--. 1 maschulz t3 37K Jul 14 01:32 sub_pdf_nnlo.sh
[maschulz@lxplus0094 cluster]$ more sub_pdf_nnlo.sh
bsub -n 8,8 -C 1 -W 48:00 -q 2nd rr_41_51_1_epo_0_c10_mh_gg_11111100_NN_pdf.sh
sleep 1
bsub -n 8,8 -C 1 -W 48:00 -q 2nd rr_41_51_2_epo_0_c10_mh_gg_11111100_NN_pdf.sh
sleep 1
bsub -n 8,8 -C 1 -W 48:00 -q 2nd rr_41_51_3_epo_0_c10_mh_gg_11111100_NN_pdf.sh
sleep 1
bsub -n 8,8 -C 1 -W 48:00 -q 2nd rr_41_51_4_epo_0_c10_mh_gg_11111100_NN_pdf.sh
sleep 1
bsub -n 8,8 -C 1 -W 48:00 -q 2nd rr_41_51_5_epo_0_c10_mh_gg_11111100_NN_pdf.sh
sleep 1
bsub -n 8,8 -C 1 -W 48:00 -q 2nd rr_42_52_1_epo_0_c10_mh_gg_11111100_NN_pdf.sh
sleep 1
bsub -n 8,8 -C 1 -W 48:00 -q 2nd rr_42_52_2_epo_0_c10_mh_gg_11111100_NN_pdf.sh
sleep 1
bsub -n 8,8 -C 1 -W 48:00 -q 2nd rr_42_52_3_epo_0_c10_mh_gg_11111100_NN_pdf.sh
sleep 1
bsub -n 8,8 -C 1 -W 48:00 -q 2nd rr_42_52_4_epo_0_c10_mh_gg_11111100_NN_pdf.sh
sleep 1
bsub -n 8,8 -C 1 -W 48:00 -q 2nd rr_42_52_5_epo_0_c10_mh_gg_11111100_NN_pdf.sh
sleep 1
bsub -n 8,8 -C 1 -W 48:00 -q 2nd rr_43_53_1_epo_0_c10_mh_gg_11111100_NN_pdf.sh
sleep 1
bsub -n 8,8 -C 1 -W 48:00 -q 2nd rr_43_53_2_epo_0_c10_mh_gg_11111100_NN_pdf.sh
sleep 1
bsub -n 8,8 -C 1 -W 48:00 -q 2nd rr_43_53_3_epo_0_c10_mh_gg_11111100_NN_pdf.sh
sleep 1
bsub -n 8,8 -C 1 -W 48:00 -q 2nd rr_43_53_4_epo_0_c10_mh_gg_11111100_NN_pdf.sh
sleep 1
bsub -n 8,8 -C 1 -W 48:00 -q 2nd rr_43_53_5_epo_0_c10_mh_gg_11111100_NN_pdf.sh
sleep 1
bsub -n 8,8 -C 1 -W 48:00 -q 2nd rr_41_52_epo_0_c10_mh_gg_11111100_NN_pdf.sh
```

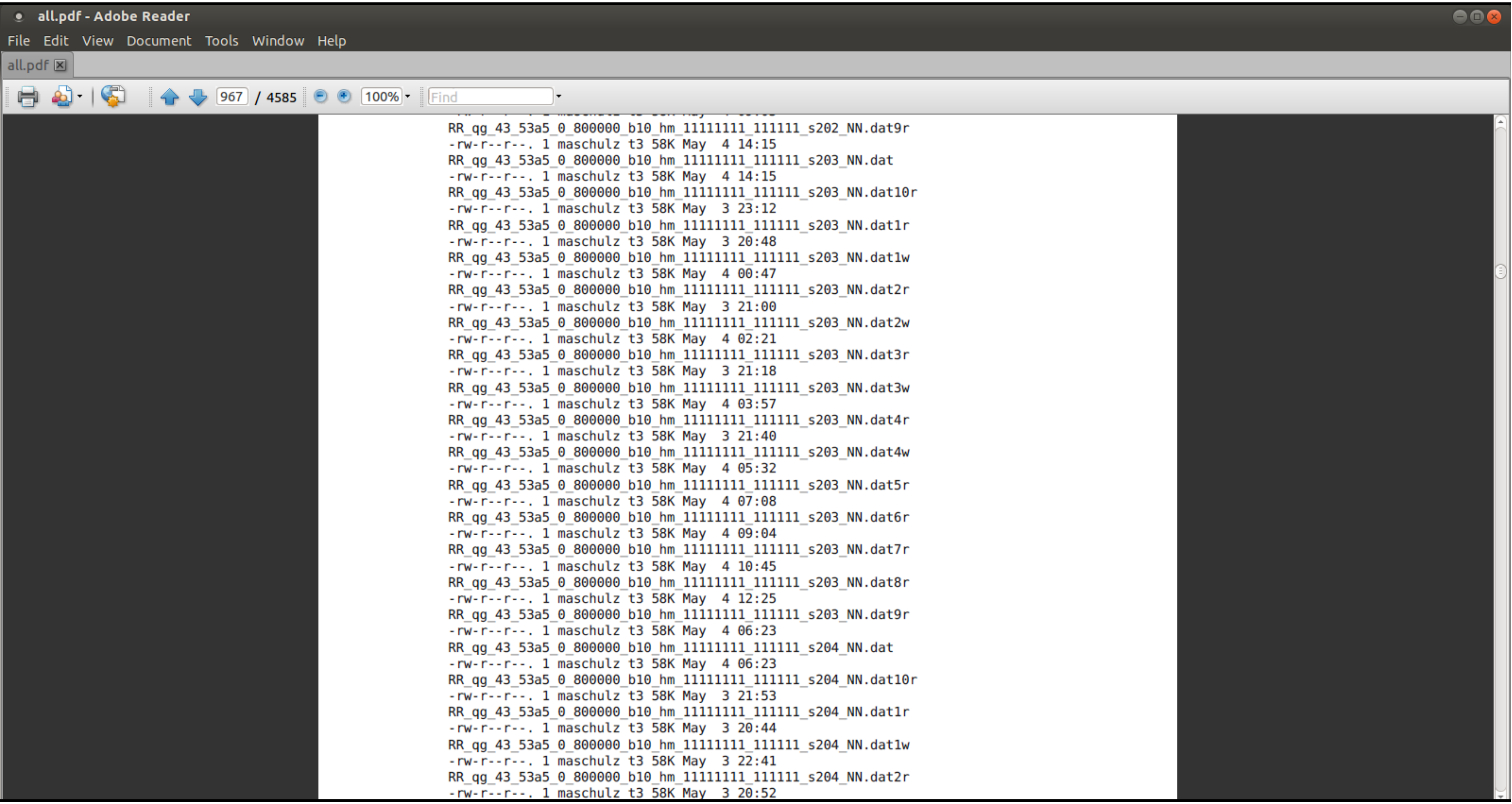
Run times:
(stable Higgs boson)

RR: ~36h / sector

RV: ~36h / sector

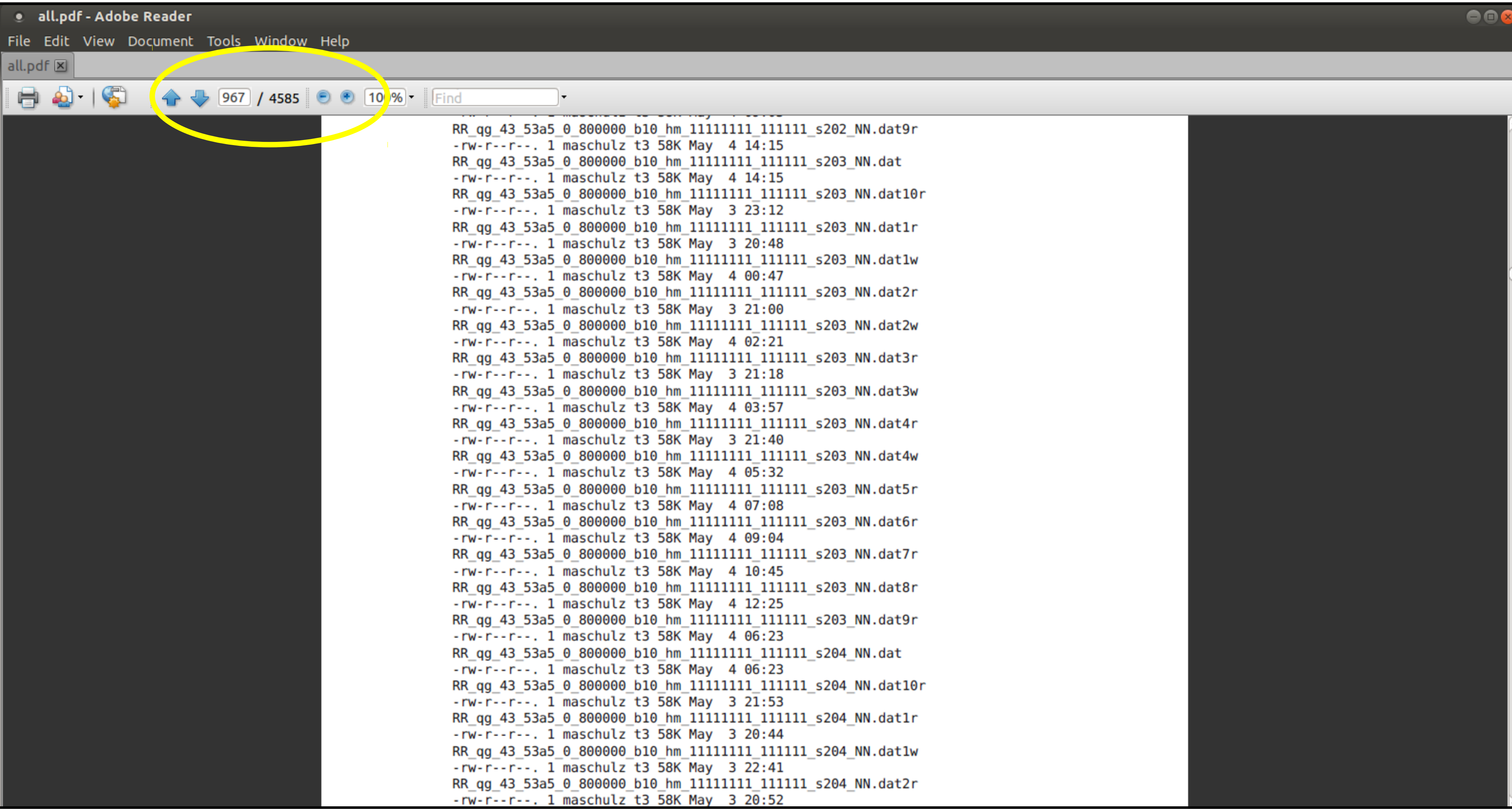
rest: negligible

H+jet at NNLO QCD




```
RR_qg_43_53a5_0_800000_b10_hm_11111111_111111_s202_NN.dat9r
-rw-r--r--. 1 maschulz t3 58K May  4 14:15
RR_qg_43_53a5_0_800000_b10_hm_11111111_111111_s203_NN.dat
-rw-r--r--. 1 maschulz t3 58K May  4 14:15
RR_qg_43_53a5_0_800000_b10_hm_11111111_111111_s203_NN.dat10r
-rw-r--r--. 1 maschulz t3 58K May  3 23:12
RR_qg_43_53a5_0_800000_b10_hm_11111111_111111_s203_NN.dat1r
-rw-r--r--. 1 maschulz t3 58K May  3 20:48
RR_qg_43_53a5_0_800000_b10_hm_11111111_111111_s203_NN.dat1w
-rw-r--r--. 1 maschulz t3 58K May  4 00:47
RR_qg_43_53a5_0_800000_b10_hm_11111111_111111_s203_NN.dat2r
-rw-r--r--. 1 maschulz t3 58K May  3 21:00
RR_qg_43_53a5_0_800000_b10_hm_11111111_111111_s203_NN.dat2w
-rw-r--r--. 1 maschulz t3 58K May  4 02:21
RR_qg_43_53a5_0_800000_b10_hm_11111111_111111_s203_NN.dat3r
-rw-r--r--. 1 maschulz t3 58K May  3 21:18
RR_qg_43_53a5_0_800000_b10_hm_11111111_111111_s203_NN.dat3w
-rw-r--r--. 1 maschulz t3 58K May  4 03:57
RR_qg_43_53a5_0_800000_b10_hm_11111111_111111_s203_NN.dat4r
-rw-r--r--. 1 maschulz t3 58K May  3 21:40
RR_qg_43_53a5_0_800000_b10_hm_11111111_111111_s203_NN.dat4w
-rw-r--r--. 1 maschulz t3 58K May  4 05:32
RR_qg_43_53a5_0_800000_b10_hm_11111111_111111_s203_NN.dat5r
-rw-r--r--. 1 maschulz t3 58K May  4 07:08
RR_qg_43_53a5_0_800000_b10_hm_11111111_111111_s203_NN.dat6r
-rw-r--r--. 1 maschulz t3 58K May  4 09:04
RR_qg_43_53a5_0_800000_b10_hm_11111111_111111_s203_NN.dat7r
-rw-r--r--. 1 maschulz t3 58K May  4 10:45
RR_qg_43_53a5_0_800000_b10_hm_11111111_111111_s203_NN.dat8r
-rw-r--r--. 1 maschulz t3 58K May  4 12:25
RR_qg_43_53a5_0_800000_b10_hm_11111111_111111_s203_NN.dat9r
-rw-r--r--. 1 maschulz t3 58K May  4 06:23
RR_qg_43_53a5_0_800000_b10_hm_11111111_111111_s204_NN.dat
-rw-r--r--. 1 maschulz t3 58K May  4 06:23
RR_qg_43_53a5_0_800000_b10_hm_11111111_111111_s204_NN.dat10r
-rw-r--r--. 1 maschulz t3 58K May  3 21:53
RR_qg_43_53a5_0_800000_b10_hm_11111111_111111_s204_NN.dat1r
-rw-r--r--. 1 maschulz t3 58K May  3 20:44
RR_qg_43_53a5_0_800000_b10_hm_11111111_111111_s204_NN.dat1w
-rw-r--r--. 1 maschulz t3 58K May  3 22:41
RR_qg_43_53a5_0_800000_b10_hm_11111111_111111_s204_NN.dat2r
-rw-r--r--. 1 maschulz t3 58K May  3 20:52
```

H+jet at NNLO QCD




```
RR_qg_43_53a5_0_800000_b10_hm_11111111_111111_s202_NN.dat9r
-rw-r--r--. 1 maschulz t3 58K May  4 14:15
RR_qg_43_53a5_0_800000_b10_hm_11111111_111111_s203_NN.dat
-rw-r--r--. 1 maschulz t3 58K May  4 14:15
RR_qg_43_53a5_0_800000_b10_hm_11111111_111111_s203_NN.dat10r
-rw-r--r--. 1 maschulz t3 58K May  3 23:12
RR_qg_43_53a5_0_800000_b10_hm_11111111_111111_s203_NN.dat1r
-rw-r--r--. 1 maschulz t3 58K May  3 20:48
RR_qg_43_53a5_0_800000_b10_hm_11111111_111111_s203_NN.dat1w
-rw-r--r--. 1 maschulz t3 58K May  4 00:47
RR_qg_43_53a5_0_800000_b10_hm_11111111_111111_s203_NN.dat2r
-rw-r--r--. 1 maschulz t3 58K May  3 21:00
RR_qg_43_53a5_0_800000_b10_hm_11111111_111111_s203_NN.dat2w
-rw-r--r--. 1 maschulz t3 58K May  4 02:21
RR_qg_43_53a5_0_800000_b10_hm_11111111_111111_s203_NN.dat3r
-rw-r--r--. 1 maschulz t3 58K May  3 21:18
RR_qg_43_53a5_0_800000_b10_hm_11111111_111111_s203_NN.dat3w
-rw-r--r--. 1 maschulz t3 58K May  4 03:57
RR_qg_43_53a5_0_800000_b10_hm_11111111_111111_s203_NN.dat4r
-rw-r--r--. 1 maschulz t3 58K May  3 21:40
RR_qg_43_53a5_0_800000_b10_hm_11111111_111111_s203_NN.dat4w
-rw-r--r--. 1 maschulz t3 58K May  4 05:32
RR_qg_43_53a5_0_800000_b10_hm_11111111_111111_s203_NN.dat5r
-rw-r--r--. 1 maschulz t3 58K May  4 07:08
RR_qg_43_53a5_0_800000_b10_hm_11111111_111111_s203_NN.dat6r
-rw-r--r--. 1 maschulz t3 58K May  4 09:04
RR_qg_43_53a5_0_800000_b10_hm_11111111_111111_s203_NN.dat7r
-rw-r--r--. 1 maschulz t3 58K May  4 10:45
RR_qg_43_53a5_0_800000_b10_hm_11111111_111111_s203_NN.dat8r
-rw-r--r--. 1 maschulz t3 58K May  4 12:25
RR_qg_43_53a5_0_800000_b10_hm_11111111_111111_s203_NN.dat9r
-rw-r--r--. 1 maschulz t3 58K May  4 06:23
RR_qg_43_53a5_0_800000_b10_hm_11111111_111111_s204_NN.dat
-rw-r--r--. 1 maschulz t3 58K May  4 06:23
RR_qg_43_53a5_0_800000_b10_hm_11111111_111111_s204_NN.dat10r
-rw-r--r--. 1 maschulz t3 58K May  3 21:53
RR_qg_43_53a5_0_800000_b10_hm_11111111_111111_s204_NN.dat1r
-rw-r--r--. 1 maschulz t3 58K May  3 20:44
RR_qg_43_53a5_0_800000_b10_hm_11111111_111111_s204_NN.dat1w
-rw-r--r--. 1 maschulz t3 58K May  3 22:41
RR_qg_43_53a5_0_800000_b10_hm_11111111_111111_s204_NN.dat2r
-rw-r--r--. 1 maschulz t3 58K May  3 20:52
```

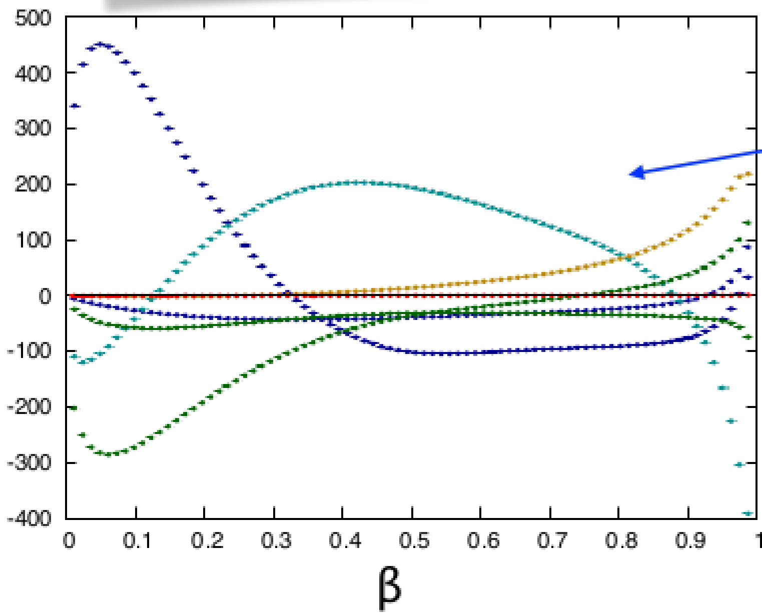
Cross checks

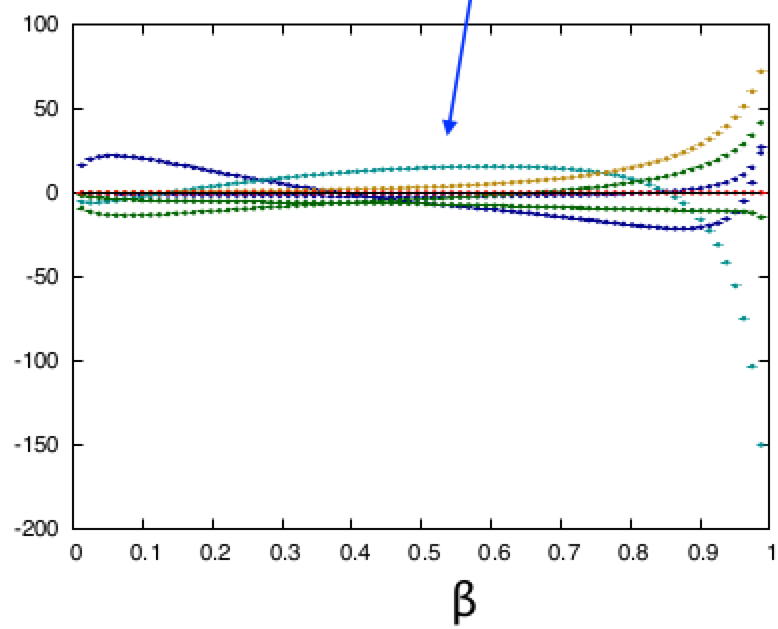
- Two independent calculations and implementations: point-wise comparisons and integrated sectors for 80 different points in sqrt(shat)
- Cancellation of 1/eps^4,3,2,1 poles for total cross section and histograms
- Soft/collinear limit checks, point-wise cancellation and scaling behavior
- Analytic integration of some soft and collinear limits in RV
- Point-wise checks of 4-dim. LO matrix elements with Madgraph
- NLO 1- and 2-jet cross section/histograms checked against MCFM
- eps-dim. amplitudes checked against “brute-force” analytic calculation
- Checks of phase-space volume, D-dim. rotation invariance, FKS partitioning
- Independence on variation of technical cut-offs
- Implementation of 2-loop amplitude numerically checked against PETER [Becher *et al.*]
- Explicit scale variation checked against RGE predictions
- ...
- Confirmation by [Boughezal,Focke,Giele,Liu,Petriello] using n-jetiness + MCFM

Cross checks

cancellation of 1/ε poles

NUMERICAL CANCELLATION between
renormalization and coll. couterterms, RR, RV, VV



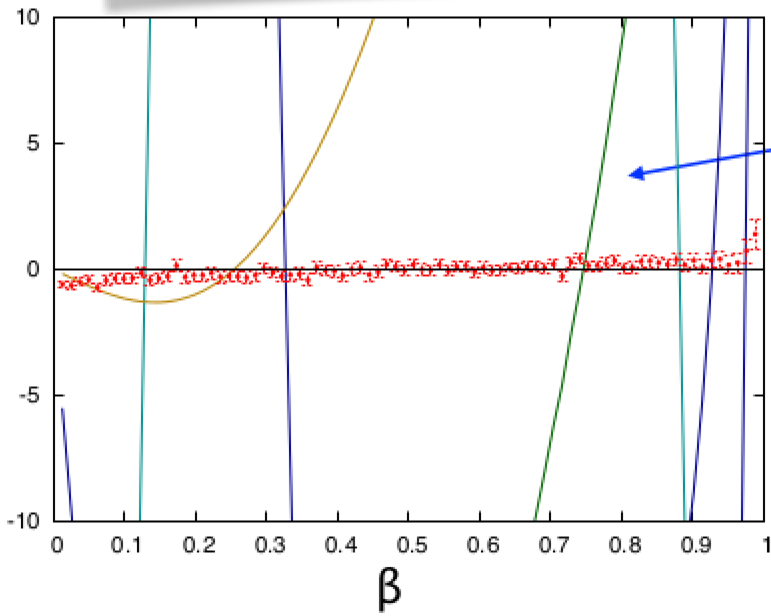


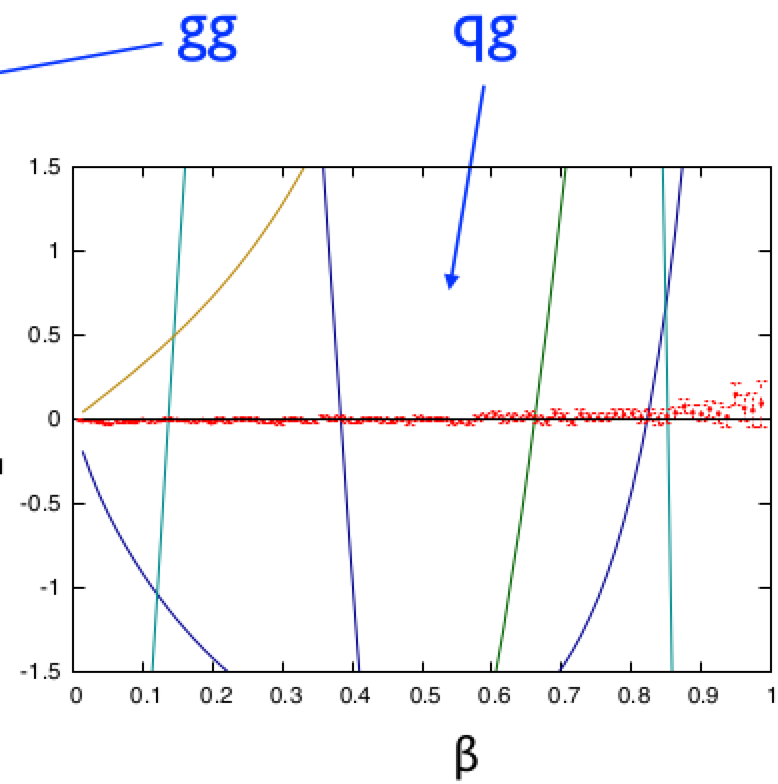
$$\beta = \sqrt{1 - \frac{s_{th}}{\hat{s}}}$$

Cross checks

cancellation of 1/ε poles

NUMERICAL CANCELLATION between
renormalization and coll. couterterms, RR, RV, VV



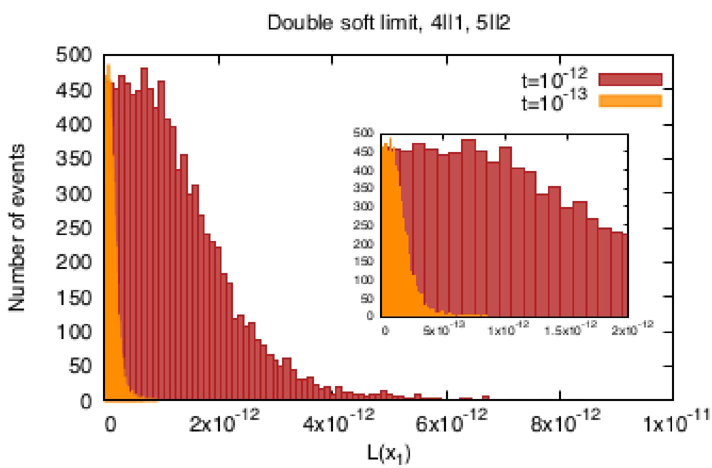


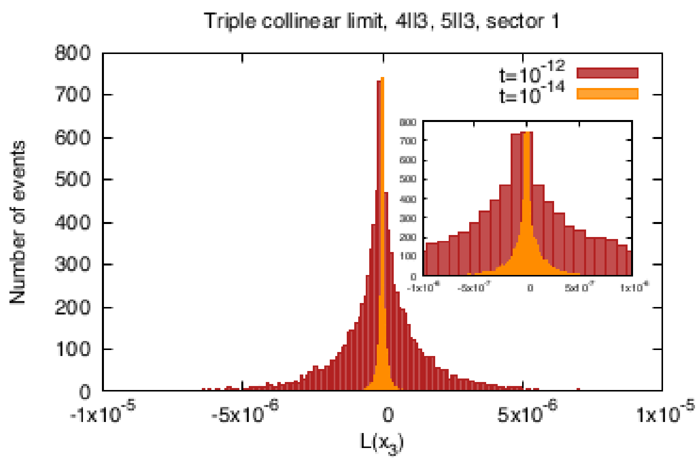
Better than per mill
cancellation at 1/ε

Cross checks

limits and scaling

Subtraction terms should match the full amplitude in singular limits





Soft limits:

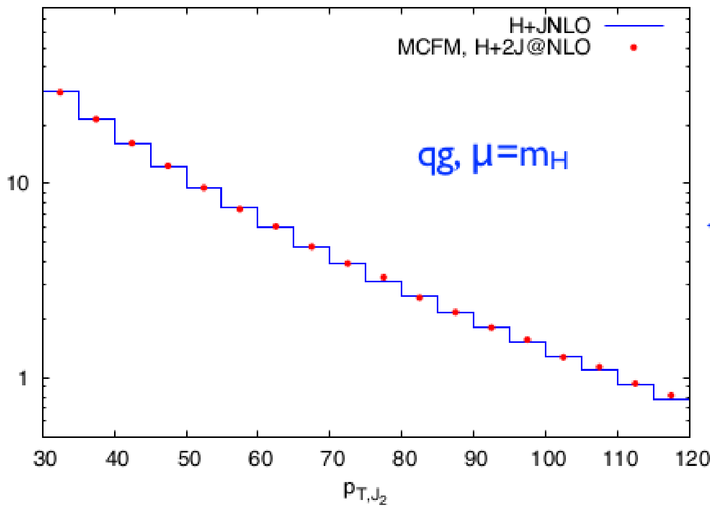
$$\lim_{x_1 \to 0} 1 - F(x_1)/F(0) \sim x_1$$

Collinear limits:

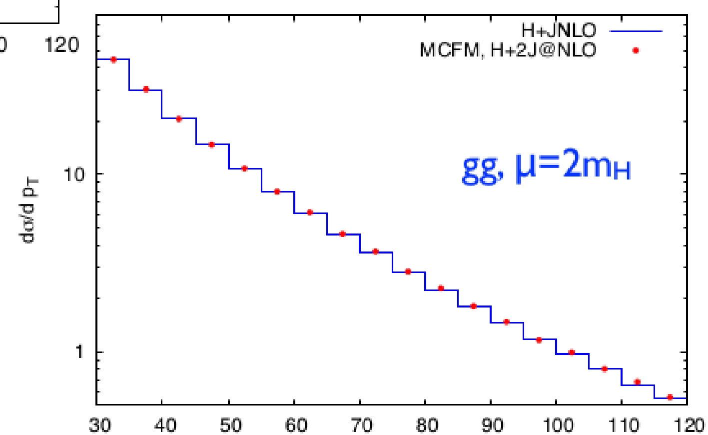
$$\lim_{x_2 \to 0} 1 - F(x_2)/F(0) \sim \sqrt{x_2}$$

Cross checks

H+2j@NLO for ≥2-jet observables



$$\frac{d\sigma}{dp_{T,J_2}}$$



Very good agreement with MCFM, channel by channel, with different settings

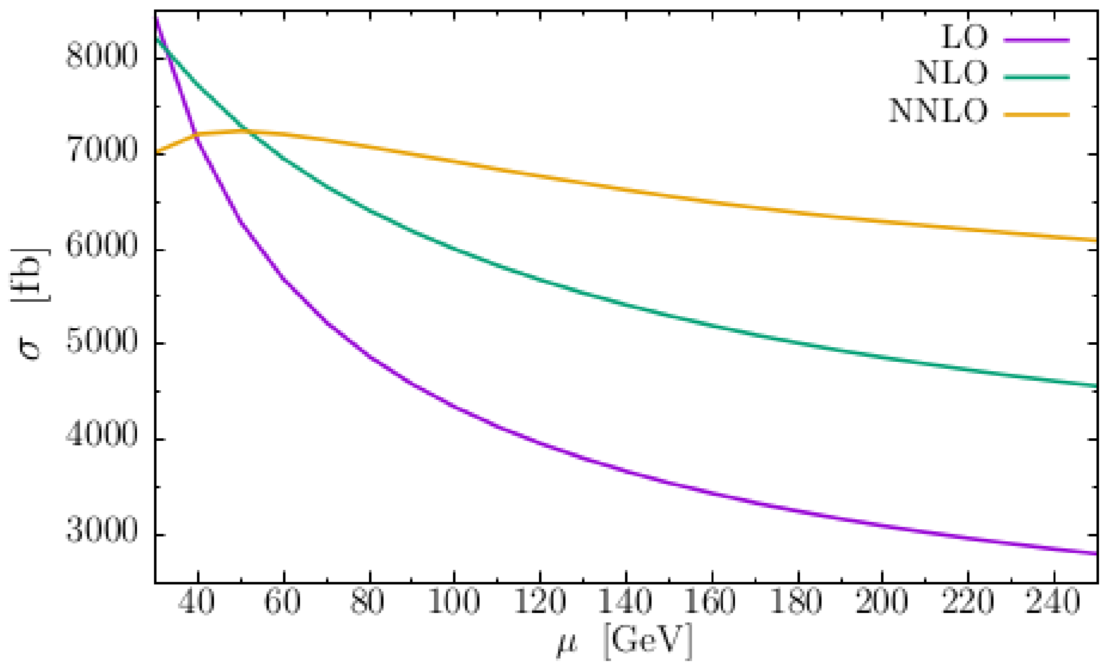
σ_{JJ}^{NLO}	best prediction		gg and qg-only	
	us	MCFM	us	MCFM
$\mu = m_H/2$	$2021.4 \pm 3.7 \cdot 10^{-01}$	$2027.1 \pm 6.2 \cdot 10^{+00}$	$1940.4 \pm 3.7 \cdot 10^{-01}$	1938.0
$\mu = m_H$	$1710.1 \pm 2.1 \cdot 10^{-01}$	$1712.0 \pm 3.3 \cdot 10^{+00}$	$1659.5 \pm 2.1 \cdot 10^{-01}$	1656.3
$\mu = 2m_H$	$1349.6 \pm 1.6 \cdot 10^{-01}$	$1356.1 \pm 2.1 \cdot 10^{+00}$	$1315.9 \pm 1.6 \cdot 10^{-01}$	1317.2

Phenomenology

Higgs plus Jet at NNLO: LHC8 results

Sample setup (any setup can be easily considered)

- EFT; anti-k_T, R=0.5, $p_{T,cut}$ = 30 GeV
- NNPDF23 parton sets, $\mu = m_H$=125 GeV



$$\sigma_{\rm LO} = 3.9^{+1.7}_{-1.1}\ \rm pb$$

$$\sigma_{\rm NLO} = 5.6^{+1.3}_{-1.1}\ \rm pb$$

$$\sigma_{\rm NNLO} = 6.7^{+0.5}_{-0.6}\ \rm pb$$

$$K^{m_H}_{\rm NNLO} \sim 20\%,\ K^{m_H/2}_{\rm NNLO} \sim 4\%$$

$$\delta^{\rm PDF4LHC}_{\rm PDF} \sim 5\%$$

Sizable corrections, significantly reduced scale uncertainty

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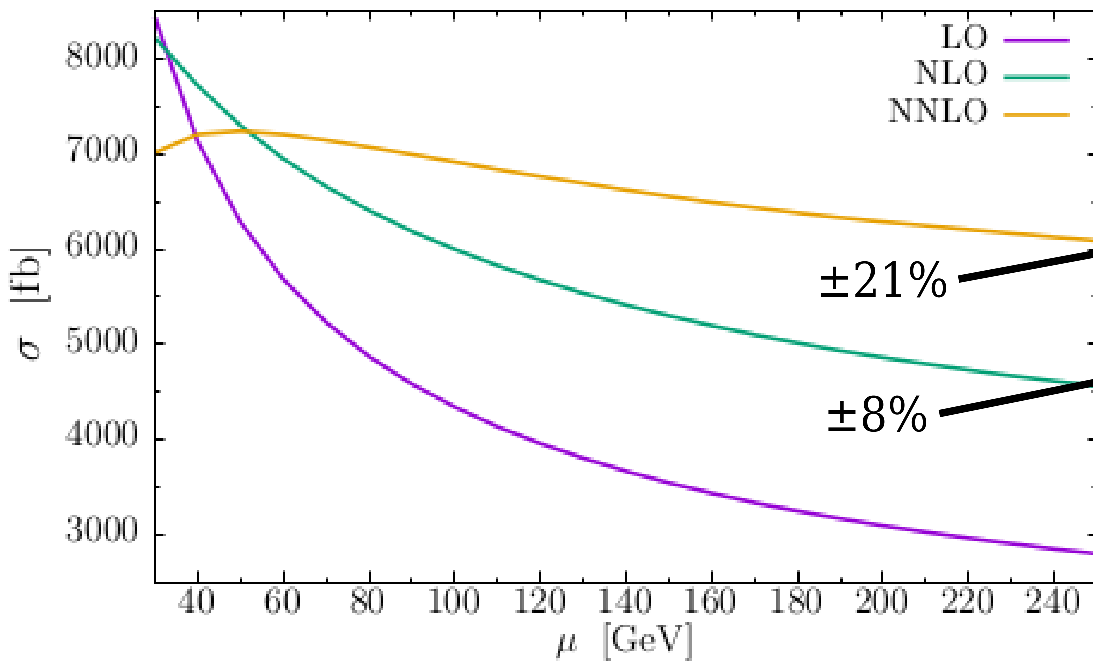

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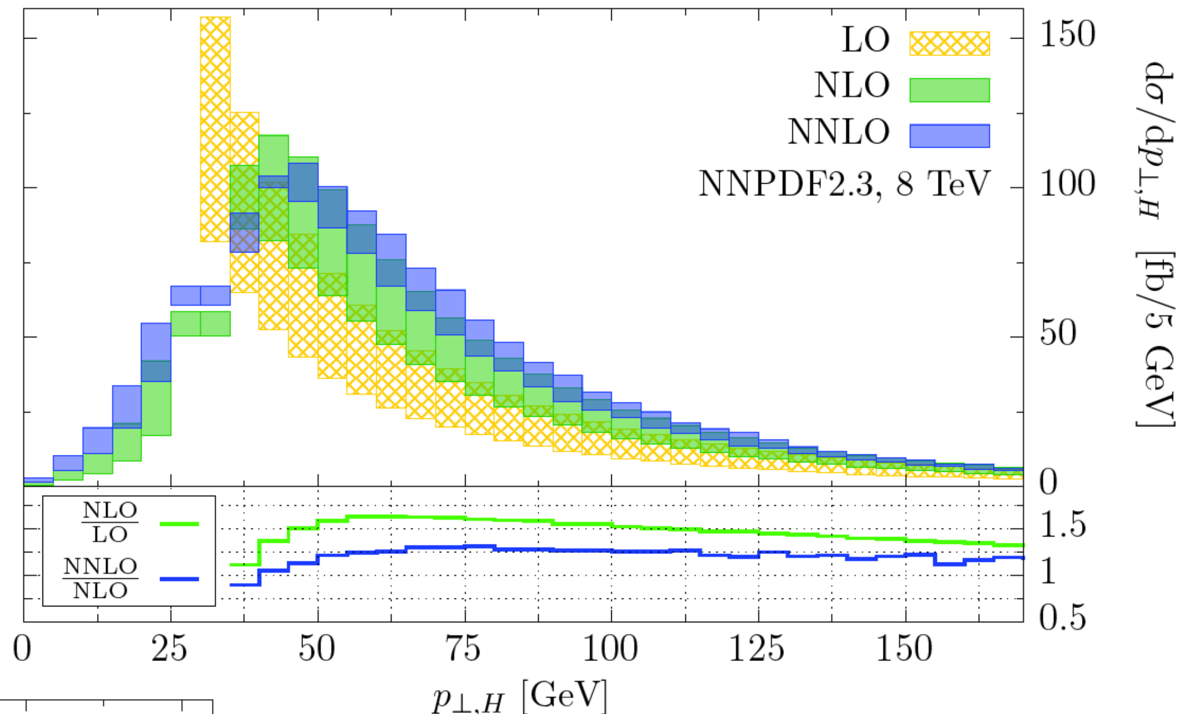
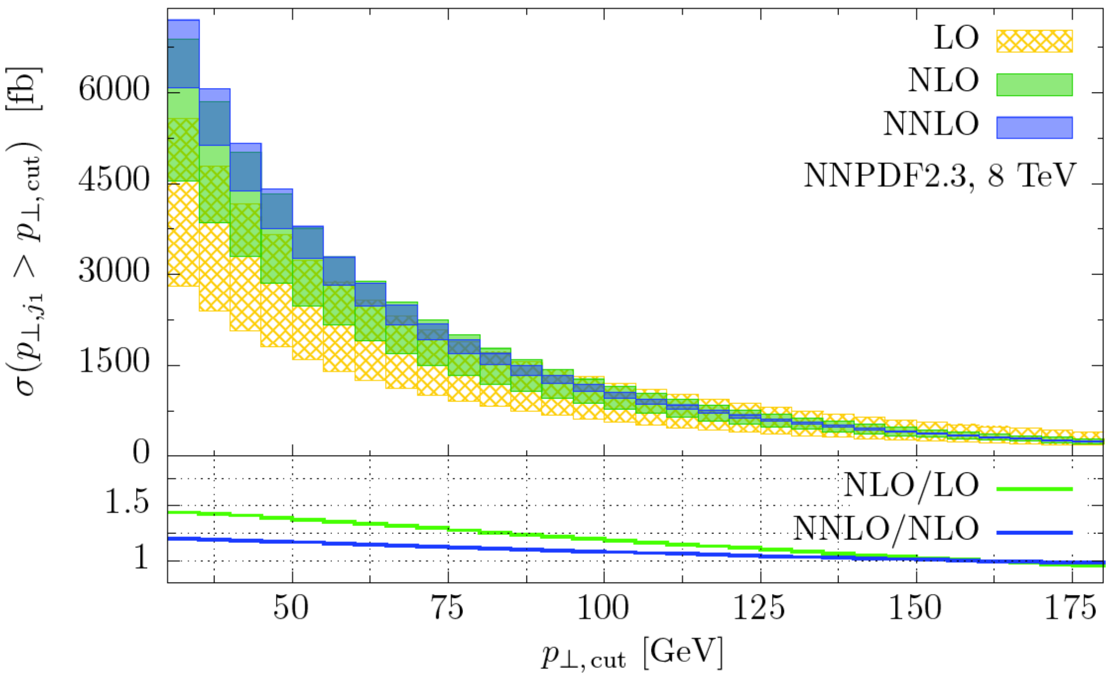
H+jet at NNLO QCD

Phys. Rev. Lett. 115 (2015)8, 082003;

- reasonable convergence also for kinematic distributions
- reduced shape changes at NNLO





- investigating the p_T(jet)-cut dependence suggests that pert. theory is reliable at 30 GeV

NEW

Fiducial volume cross sections

arXiv: 1508.02684 [hep-ph]

pp → H+j → γγ +j

closely following ATLAS 8 TeV analysis; JHEP 1409, 112 (2014)

anti-$k_\perp$ algorithm

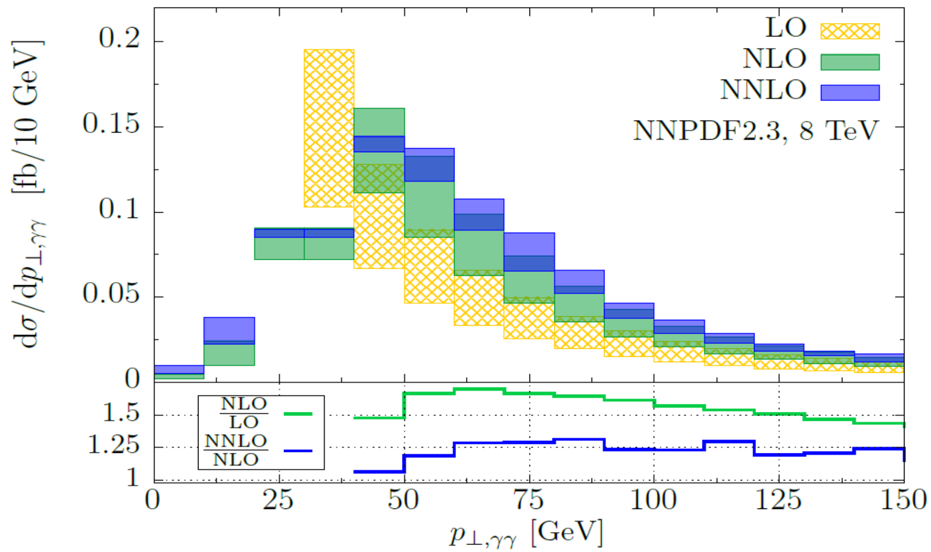
$\Delta R = 0.4$ and $p_{\perp,j} > 30$ GeV

$-4.4 < y_j < 4.4$

$p_{\perp,\gamma_1} > \max(25 \text{ GeV}, 0.35\, m_{\gamma\gamma})$

$p_{\perp,\gamma_2} > \max(25 \text{ GeV}, 0.25\, m_{\gamma\gamma})$

$|y_\gamma| < 2.37, \ \Delta R_{\gamma j} > 0.4$



$$\sigma^{\rm fid}_{\rm LO} = 5.43^{+2.32}_{-1.49} \text{ fb}, \quad \sigma^{\rm fid}_{\rm NLO} = 7.98^{+1.76}_{-1.46} \text{ fb}, \quad \sigma^{\rm fid}_{\rm NNLO} = 9.45^{+0.58}_{-0.82} \text{ fb},$$

- selection criteria do not spoil perturbation series

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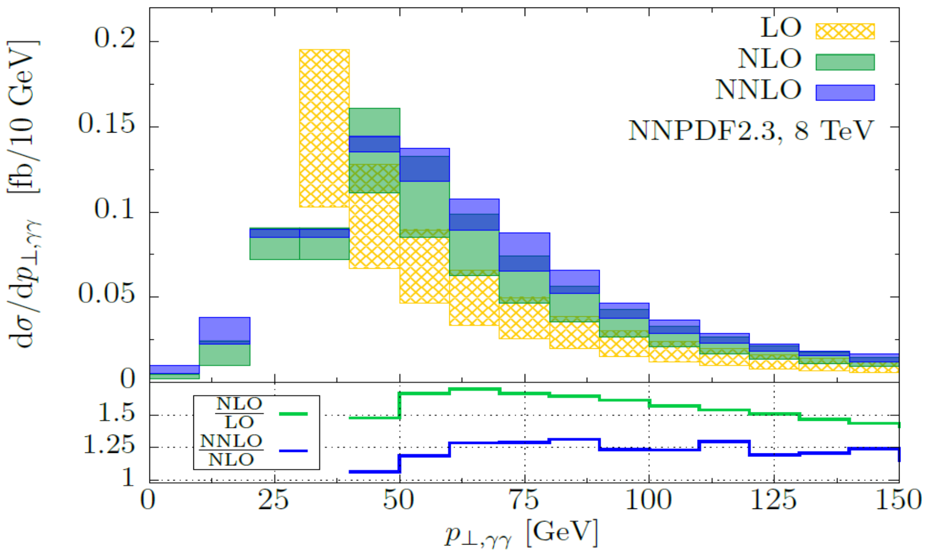
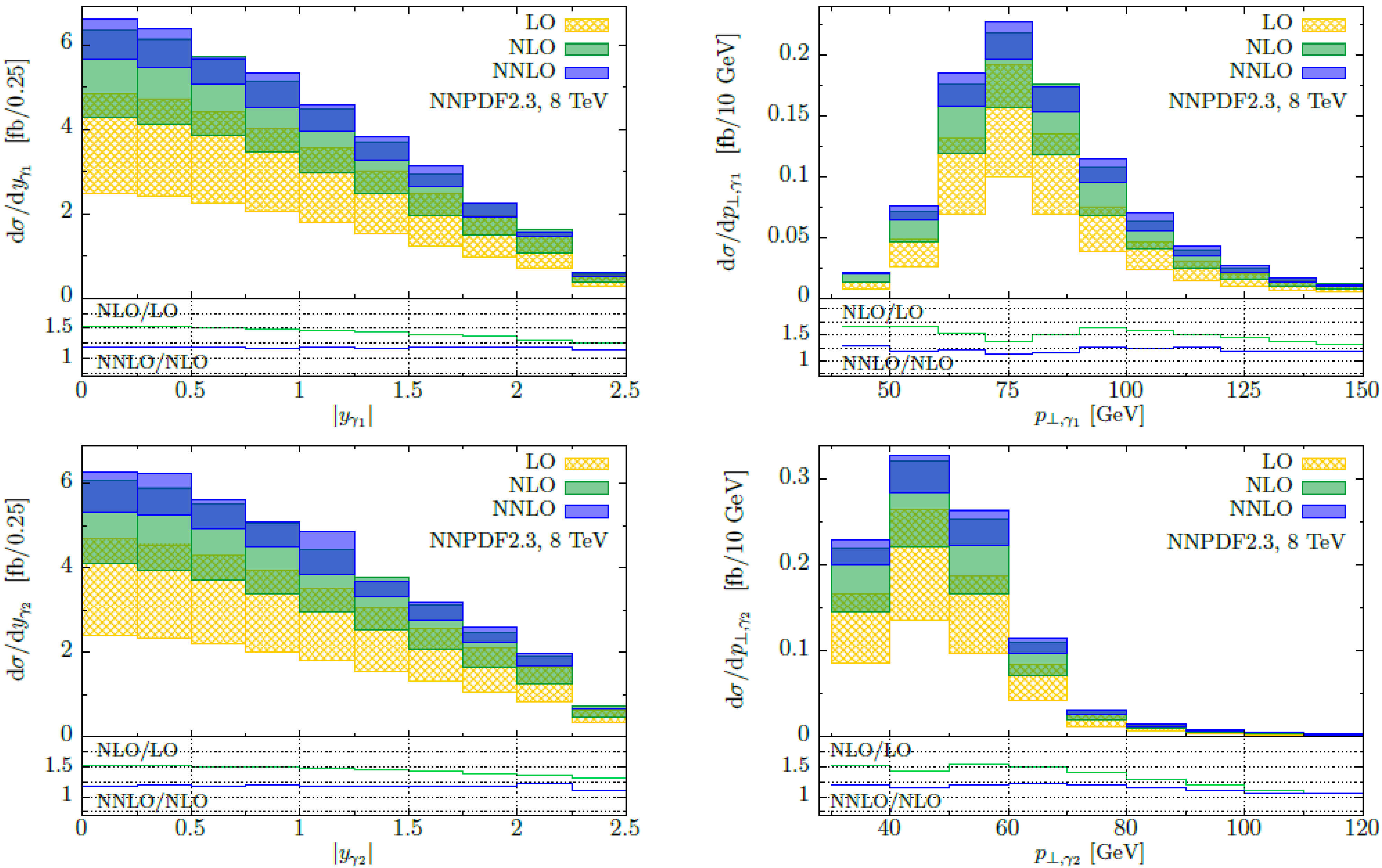


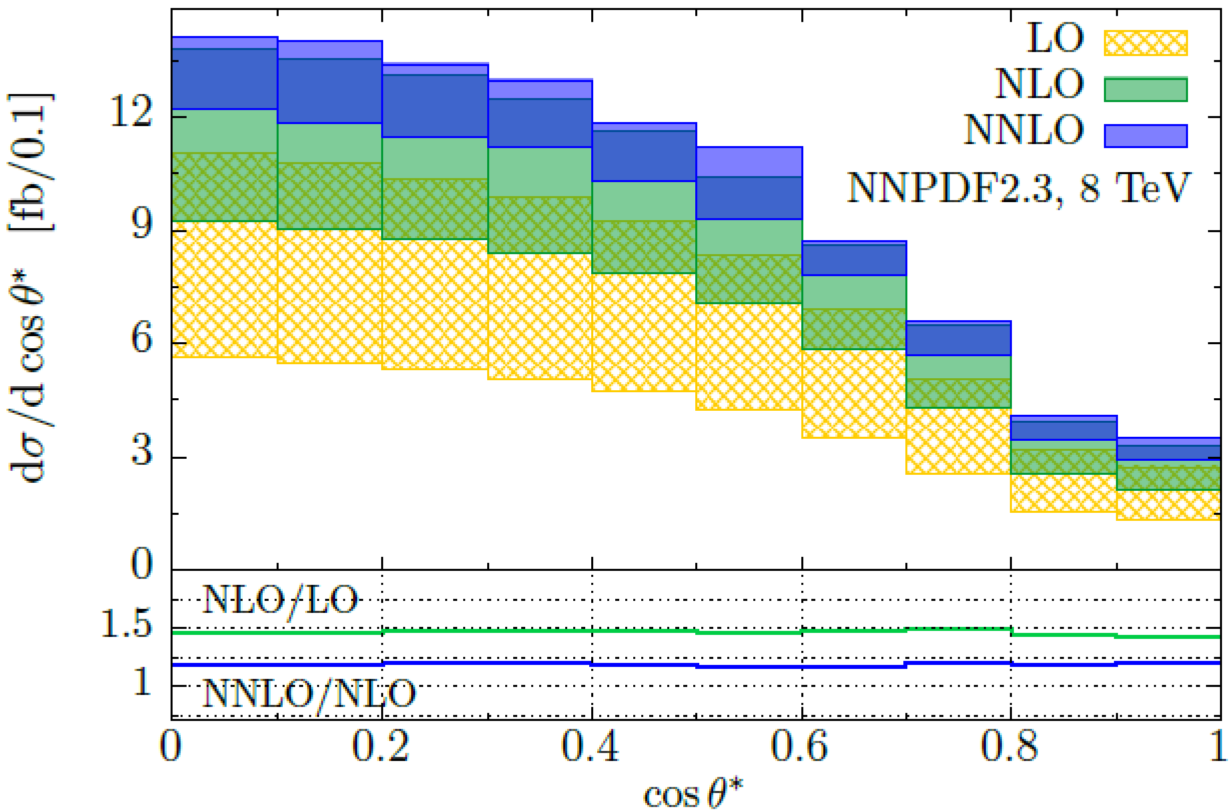
acceptance $A = \dfrac{\sigma_{\text{cuts}}}{\sigma_{\text{tot}}}$

$$A_{\text{LO}} = 0.594(4), \quad A_{\text{NLO}} = 0.614(3), \quad A_{\text{NNLO}} = 0.614(4).$$

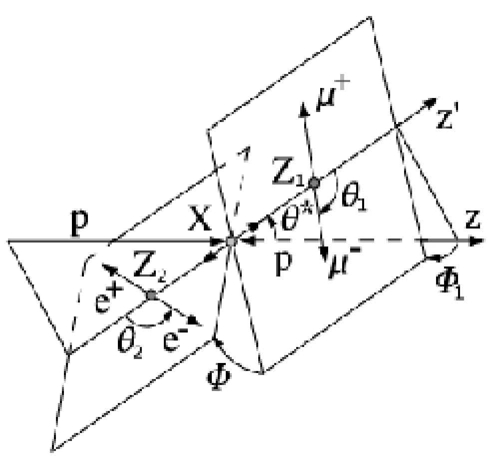
- acceptance is predicted reliably at NLO

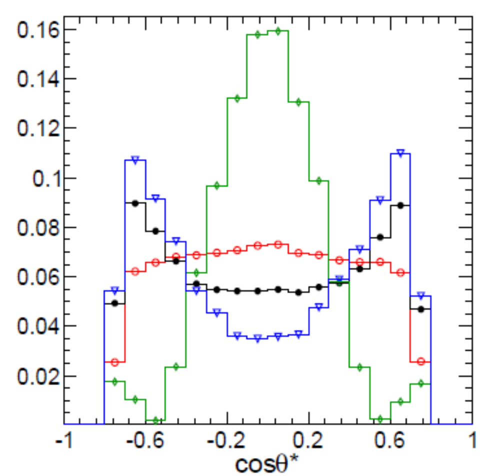
H+jet at NNLO QCD





- Photon decay angles in the *Collins-Soper* reference frame is important for studying the spin-parity properties of the Higgs
- We find flat corrections

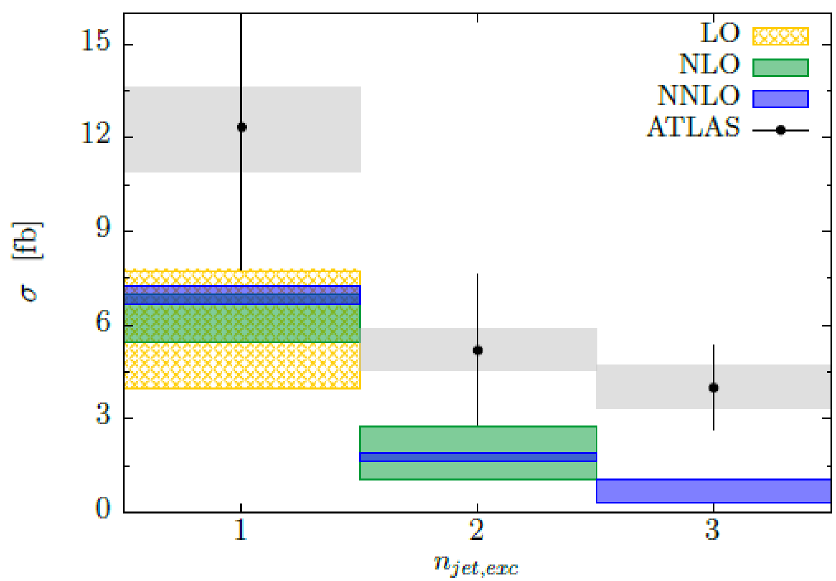


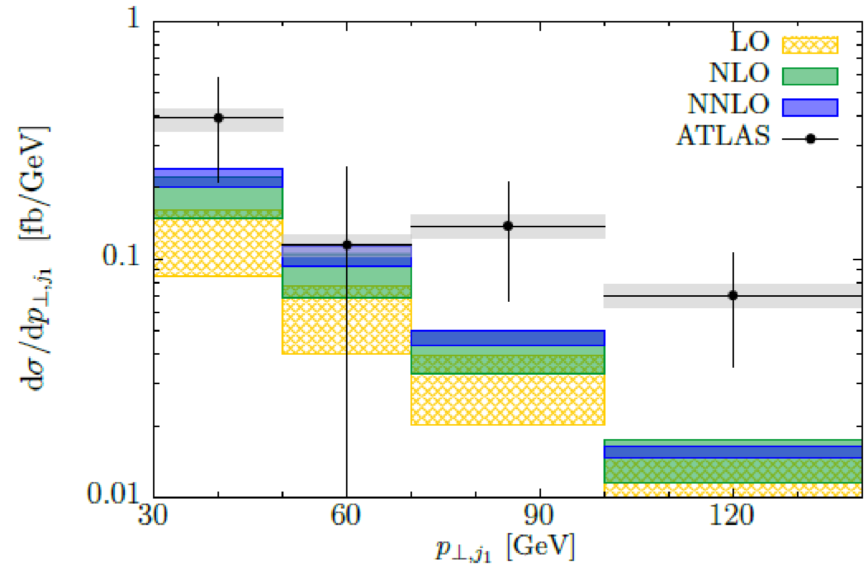


- Comparison with data

$$\sigma^{\text{fid}}_{\text{NNLO}} = 9.45^{+0.58}_{-0.82}\ \text{fb},$$

$$\sigma^{\text{fid}}_{H+j}(8\ \text{TeV}) = 21.5 \pm 5.3(\text{stat.}) \pm^{2.4}_{2.2}(\text{syst.}) \pm 0.6(\text{lumi})\ \text{fb}.$$





- Central value by ATLAS is higher by a factor 2.1−2.5
- This difference translates to approximately 2.4 standard deviations
- This mismatch is larger than in incl. Higgs production (factor 1.4)

NEW

Fiducial volume cross sections

arXiv: 1508.02684 [hep-ph]

pp → H+j → WW+j → 4l +j

closely following CMS 8 TeV analysis; JHEP1401,096 (2014)

anti-$k_\perp$ algorithm

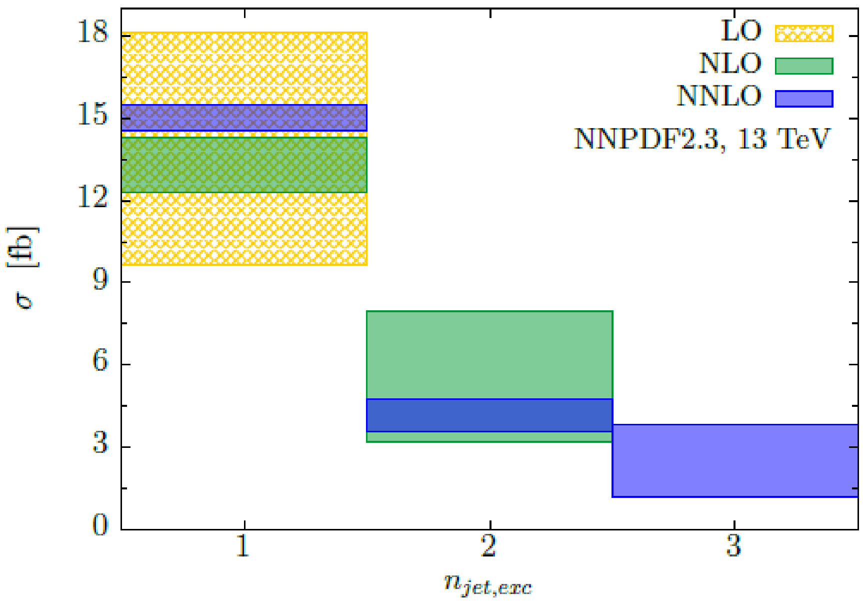
$\Delta R = 0.4$ and $p_{\perp,j} > 30$ GeV

$-4.7 < y_j < 4.7$

$p_{\perp,l} > 20$ GeV $\quad E_{\perp,\mathrm{miss}} > 20$ GeV.

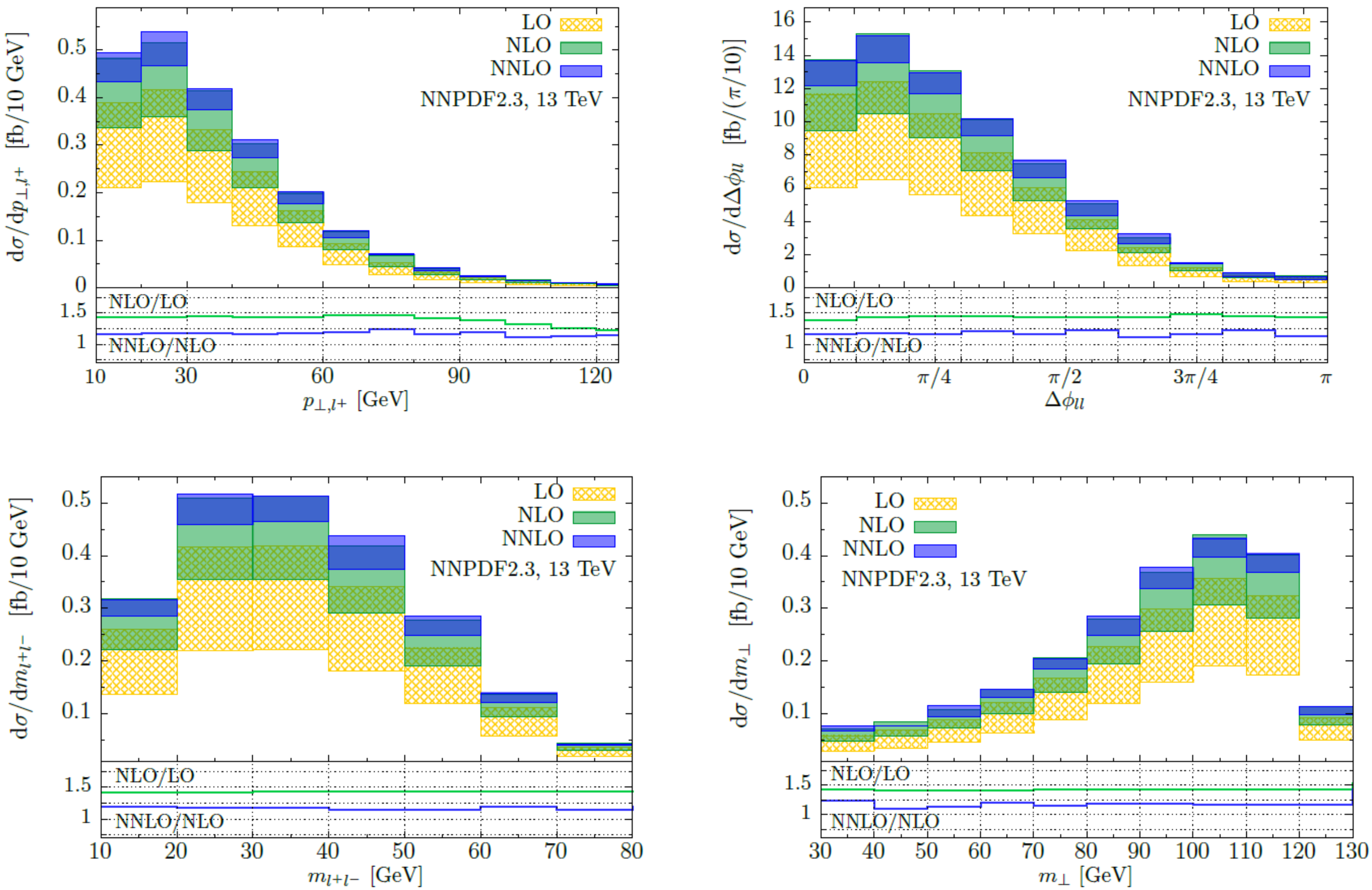
$m_{ll} > 12$ GeV; $p_{\perp,ll} > 30$ GeV

$m_\perp = \sqrt{2p_{\perp,ll}E_{\perp,\mathrm{miss}}(1 - \cos\Delta\phi_{ll,\mathrm{miss}})} > 30$ GeV



$$\sigma^{\mathrm{fid}}_{\mathrm{LO}} = 13.0^{+5.1}_{-3.4}\ \mathrm{fb}, \quad \sigma^{\mathrm{fid}}_{\mathrm{NLO}} = 18.6^{+3.7}_{-3.1}\ \mathrm{fb}, \quad \sigma^{\mathrm{fid}}_{\mathrm{NNLO}} = 21.9^{+0.9}_{-1.7}\ \mathrm{fb}.$$

H+jet at NNLO QCD



- ratio of cross sections:

  many experimental & theoretical uncertainties cancel

$$R_{WW/\gamma\gamma} = \frac{\sigma_{H+j}^{WW\to e^+\mu^-\nu\bar{\nu},13\ \mathrm{TeV}}}{\sigma_{H+j}^{\gamma\gamma,8\ \mathrm{TeV}}} = 2.39^{-0.06}_{+0.04}, \quad 2.33^{-0.04}_{+0.05}, \quad 2.32^{-0.04}_{+0.02},$$

- we are able to predict R with the precision of *better than 2%*

SUMMARY:

- We have completed a full NNLO QCD computation for $pp \to$ Higgs+jet
- We predict differential distributions in the fiducial detector volume, accounting for the main decay channels of the Higgs boson
- NNLO corrections are moderate (~20%) for the total cross section and differential distributions (even in the case of selection cuts)
- We find no indication that perturbative QCD breaks down and requires resummation for the jet cut as low as 30 GeV
- Scale variation + pdf variation suggests an uncertainty of <10% (less than half of the NLO prediction) and even better for ratios of cross sections