Jet-bin cross-sections

[the fixed order part of the story]

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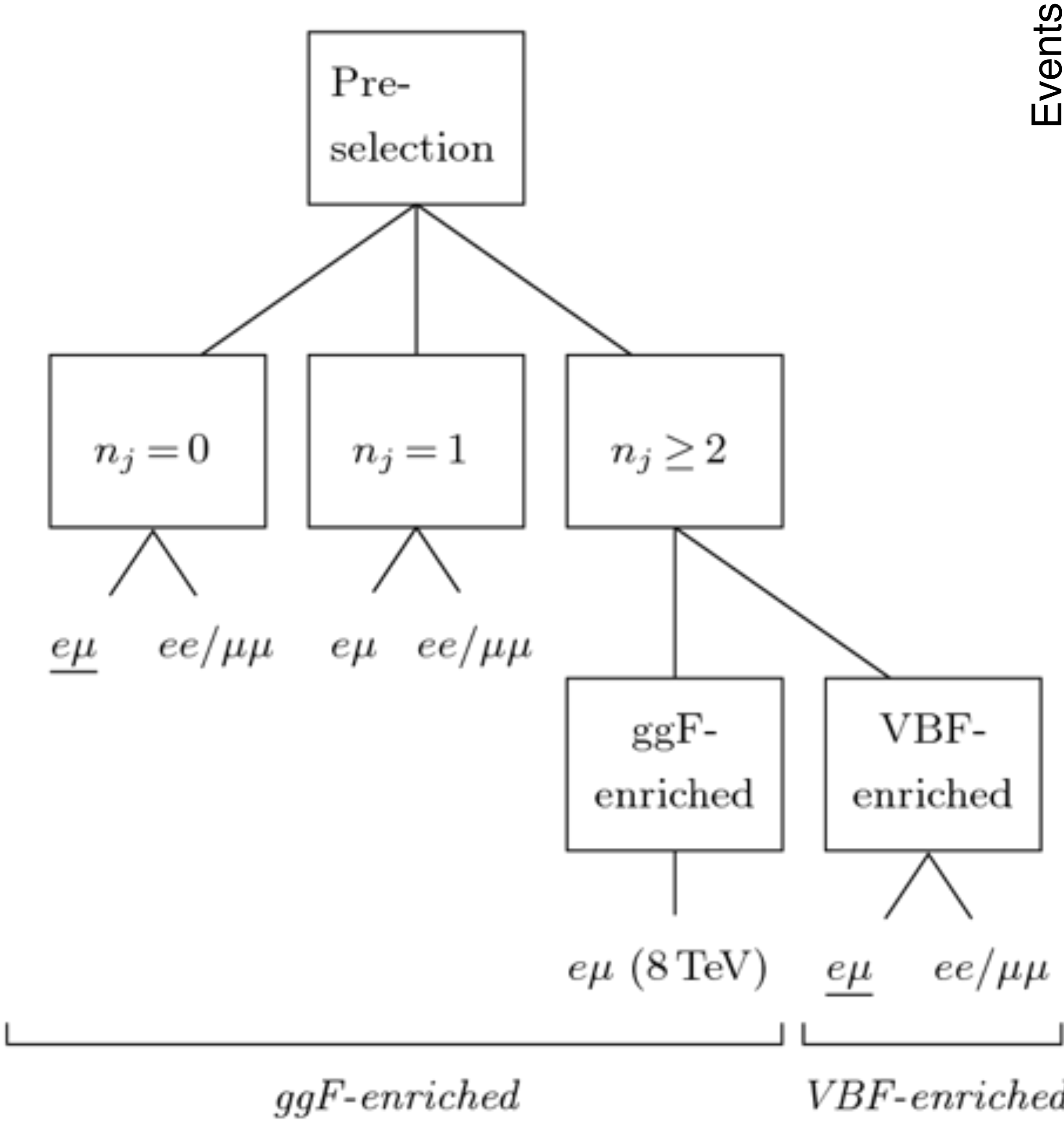
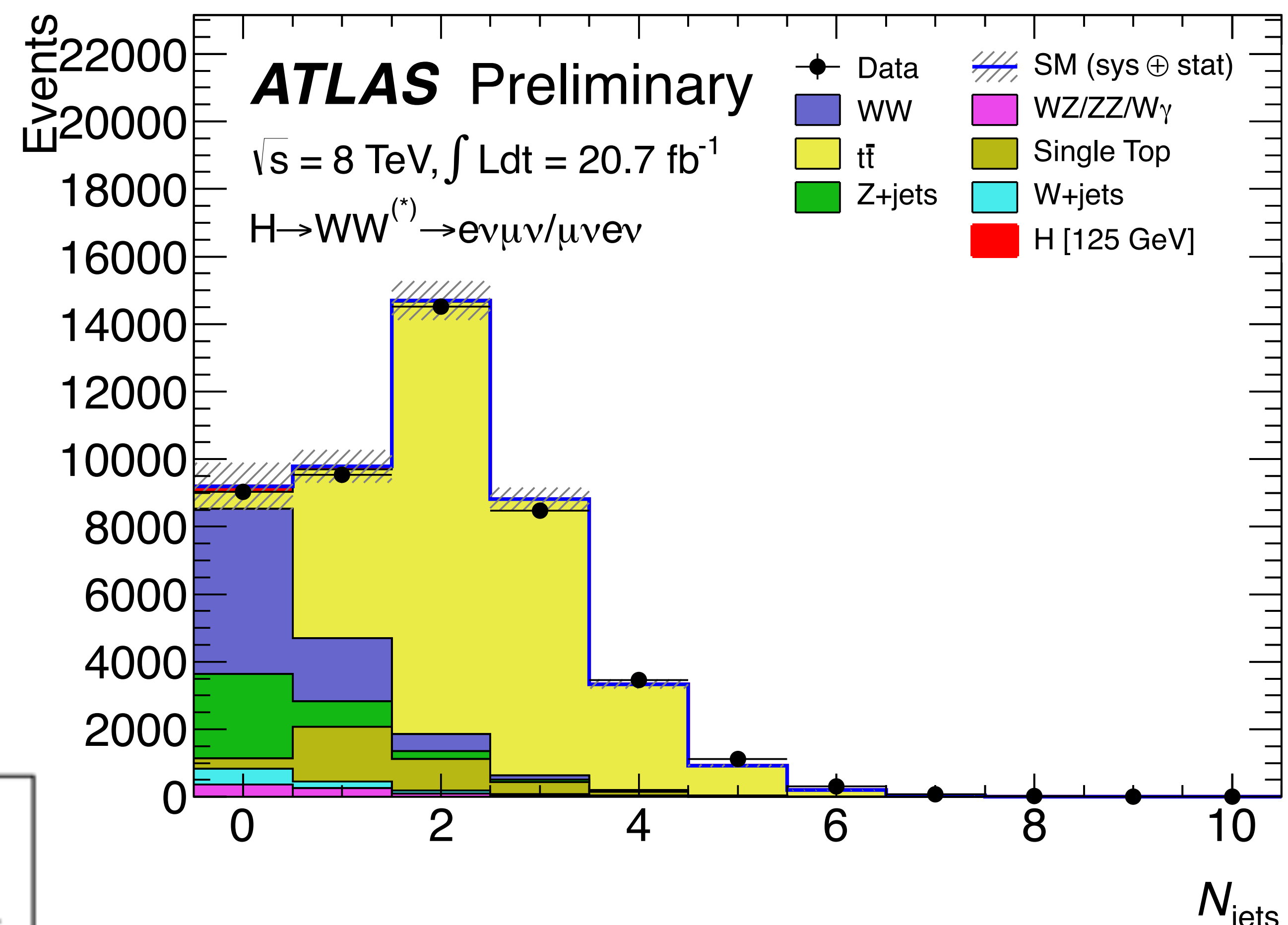
Jet-bin cross sections: why do we care

Experimental analyses for pp →H →WW (similar for ττ):
binned according to jet multiplicity (different systematics)

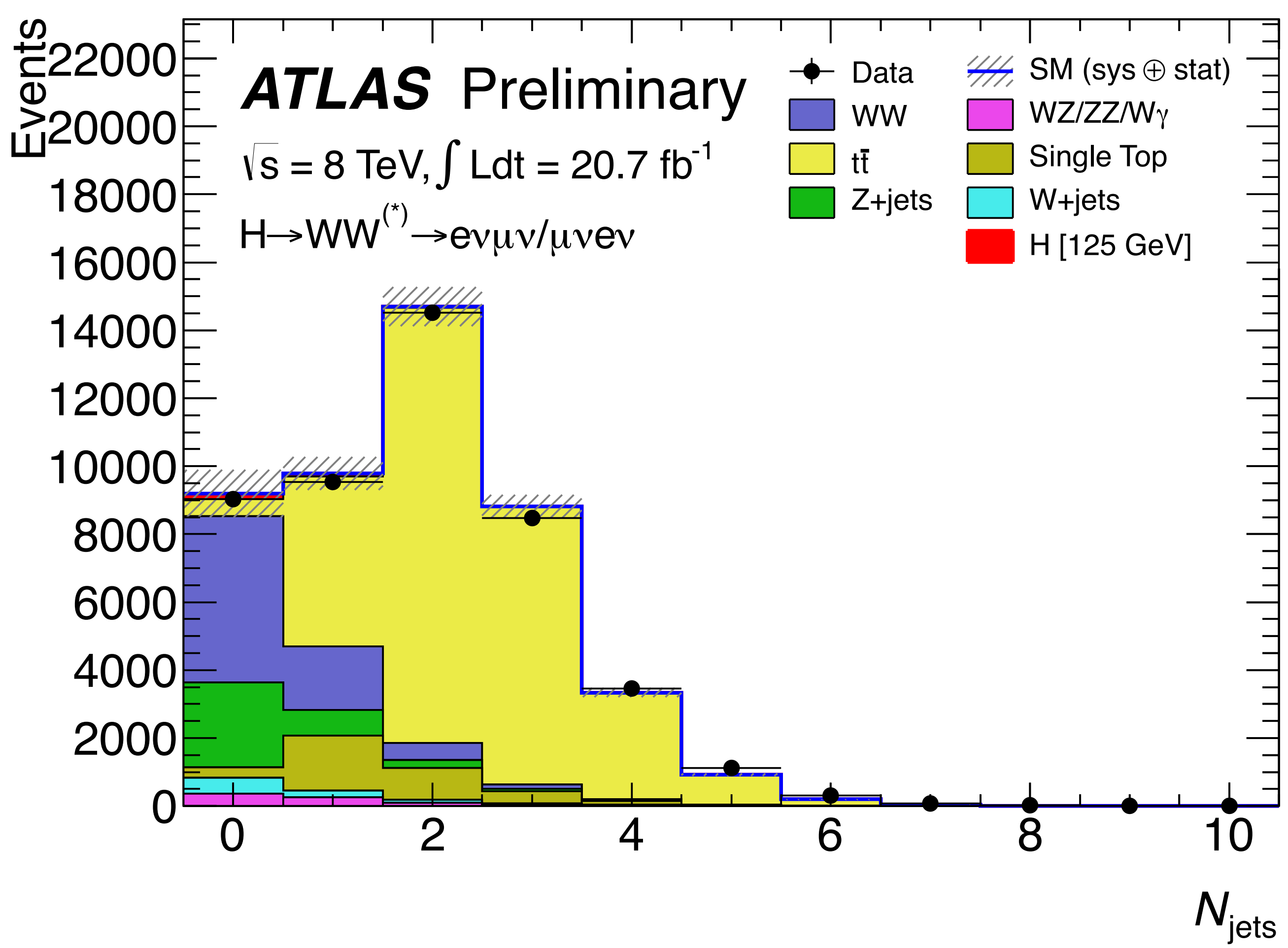




NEEDED TO IMPROVE SENSITIVITY

Jet-bin cross sections: the general picture

Experimental analyses for $pp \to H \to WW$ (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

Selection	N_{obs}	N_{bkg}	N_{sig}	N_{WW}	N_{VV}	$N_{t\bar{t}}$	N_t	N_{Z/γ^*}	N_{W+jets}
$N_{jet} = 1$	9527	9460 ± 40	97 ± 1	1660 ± 10	270 ± 10	4980 ± 30	1600 ± 20	760 ± 20	195 ± 5
$N_{b\text{-}jet} = 0$	4320	4240 ± 30	85 ± 1	1460 ± 10	220 ± 10	1270 ± 10	460 ± 10	670 ± 10	160 ± 4
$Z \to \tau\tau$ veto	4138	4020 ± 30	84 ± 1	1420 ± 10	220 ± 10	1220 ± 10	440 ± 10	580 ± 10	155 ± 4
$m_{\ell\ell} < 50$	886	830 ± 10	63 ± 1	270 ± 4	69 ± 5	216 ± 6	80 ± 4	149 ± 5	46 ± 2
$\|\Delta\phi_{\ell\ell}\| < 1.8$	728	650 ± 10	59 ± 1	250 ± 4	60 ± 4	204 ± 6	76 ± 4	28 ± 3	34 ± 2

Jet-bin cross sections: not so nice objects…

The problem with jet-binned cross sections: large logs

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

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

Although not huge, these logs are not small:

in the Higgs case, for $p_T \sim 30$ GeV: O(40%) correction.

This issue on top of the already large Higgs K-factor

NEED HIGH F.O. AND LOG ACCURACY FOR RELIABLE RESULTS

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.

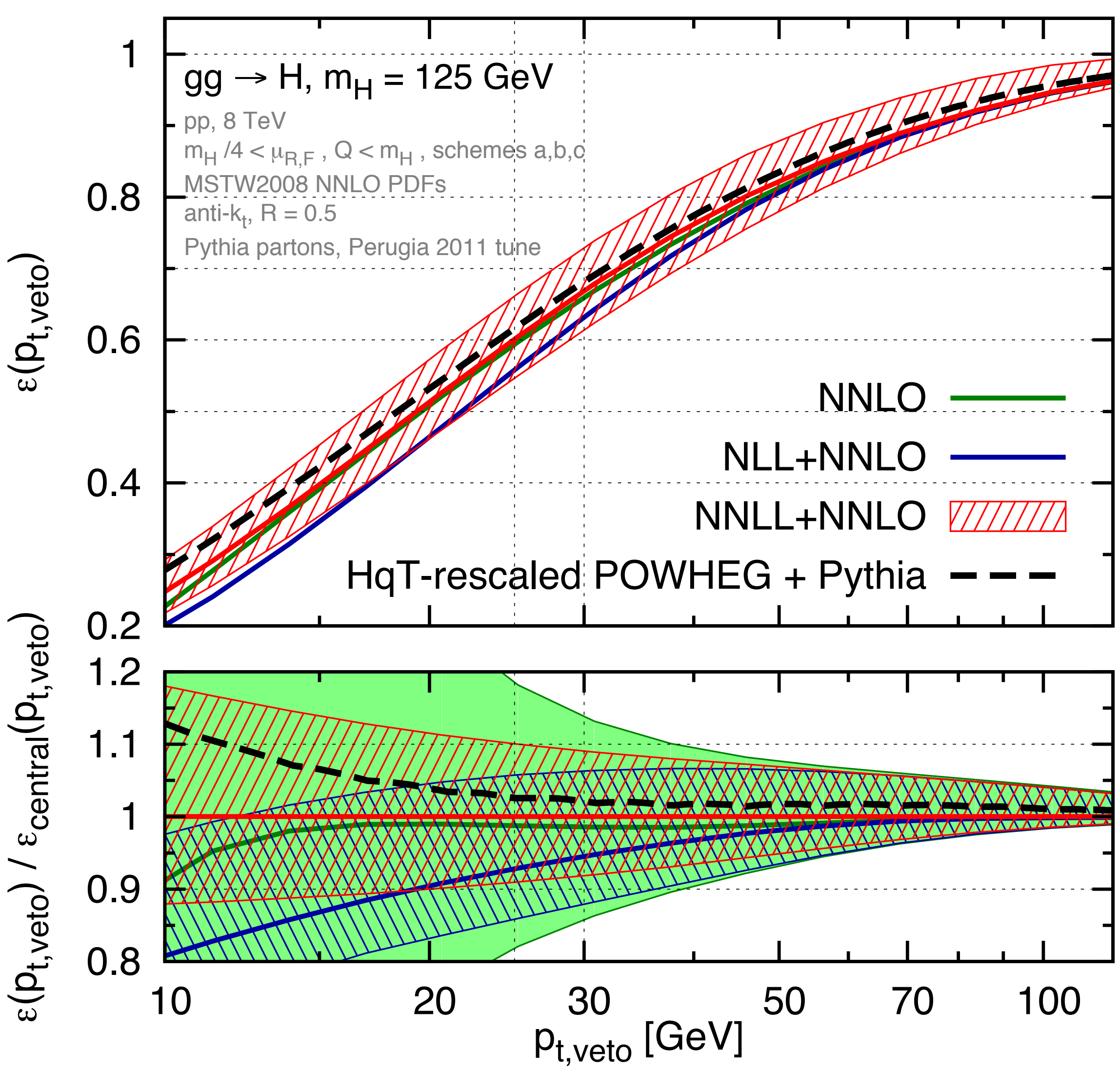
A PRAGMATIC APPROACH:

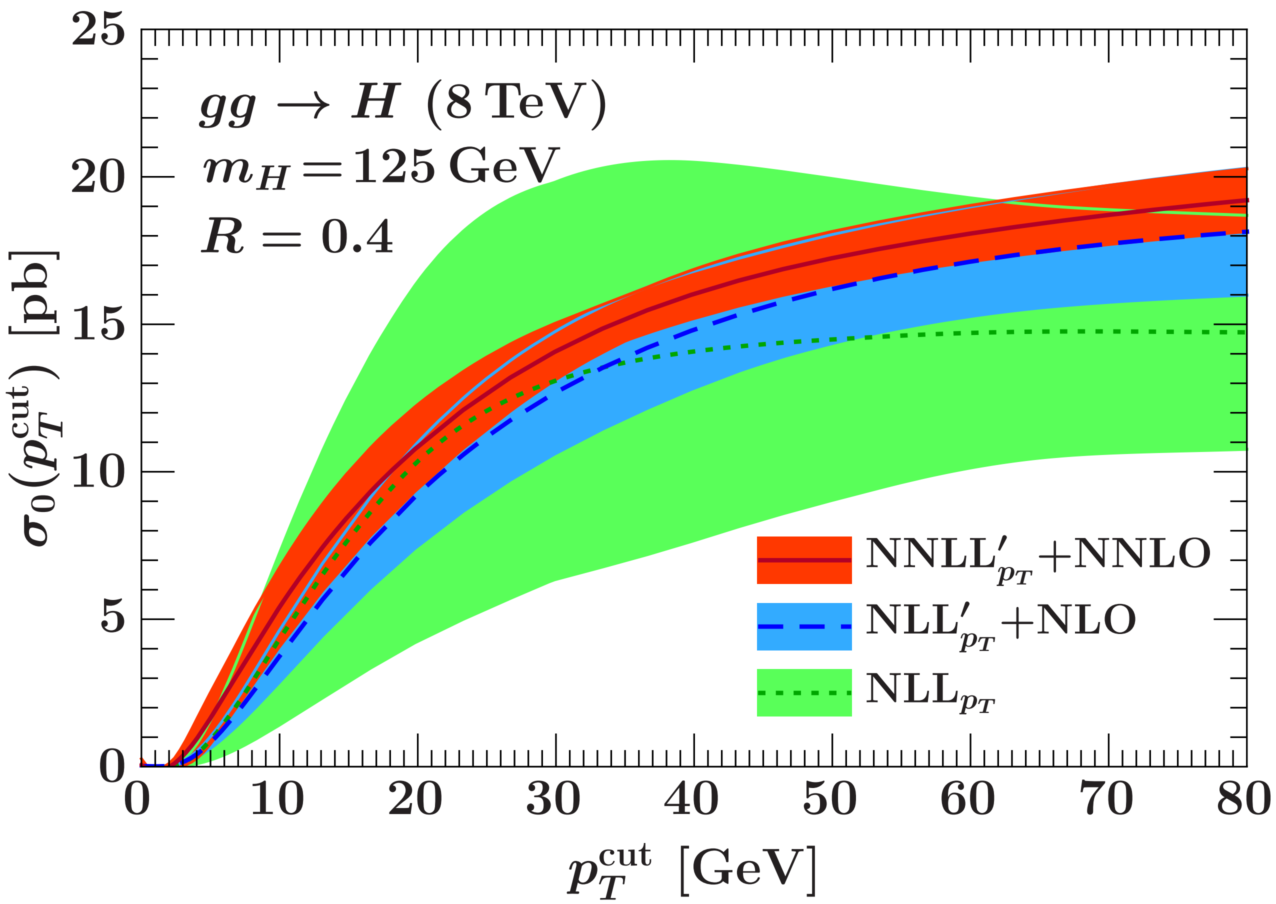
- Small p_T: resum these logs (-> later talks)
- High p_T: compute higher order corrections (-> this talk)
- Combine the two approaches

The resumption part of the story: recap

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)]

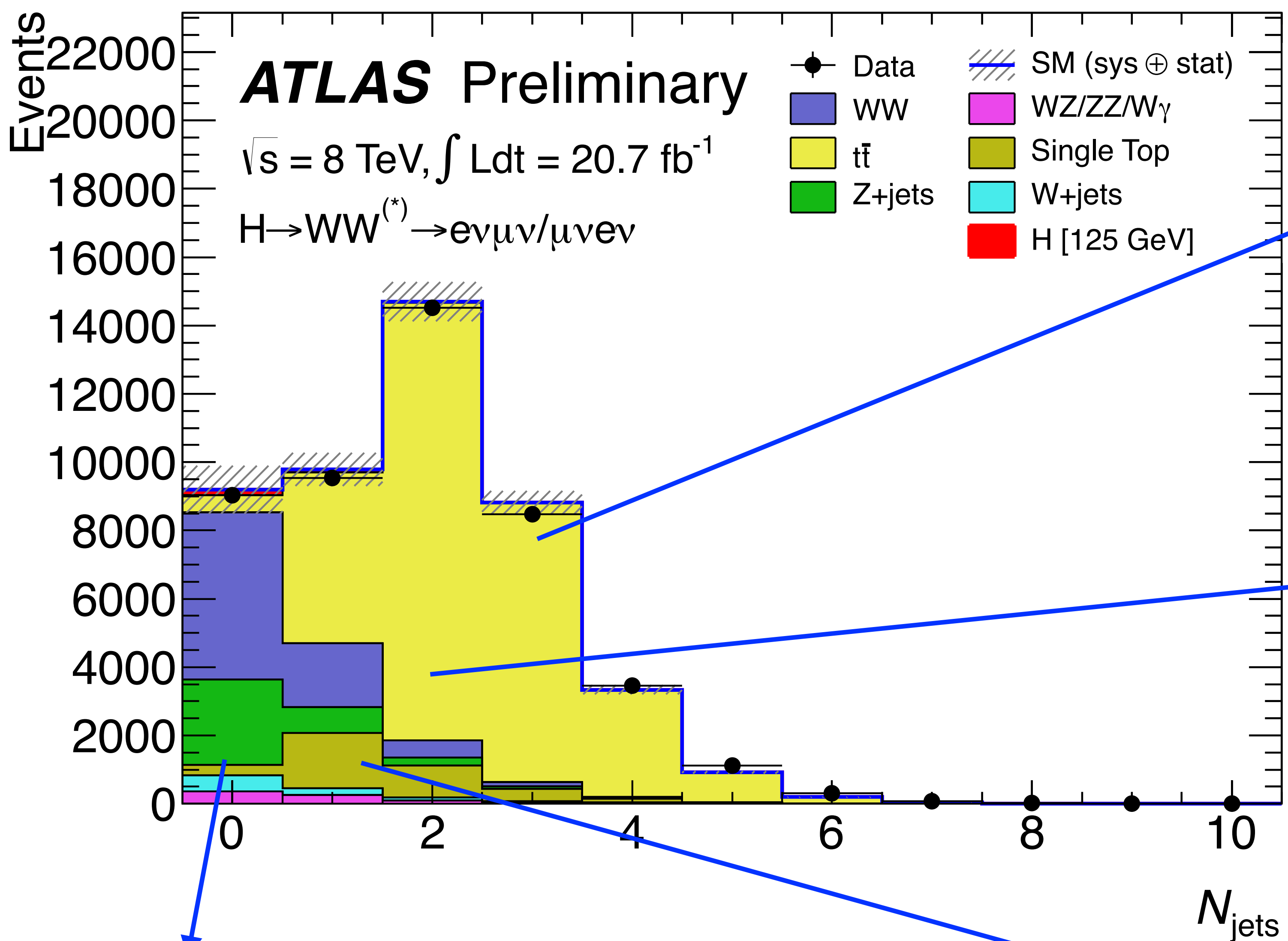




- Logs more or less under control
- Improvement will come from h.o. matching

Expect a transition for $p_T \sim 30$ GeV

The f.o. part of the story: where do we stand



3-jet bin: NLO QCD
[see Valery's talk]

2-jet bin: NLO QCD
- ~ 15-20% K-factor
- ~ 20% scale uncertainty

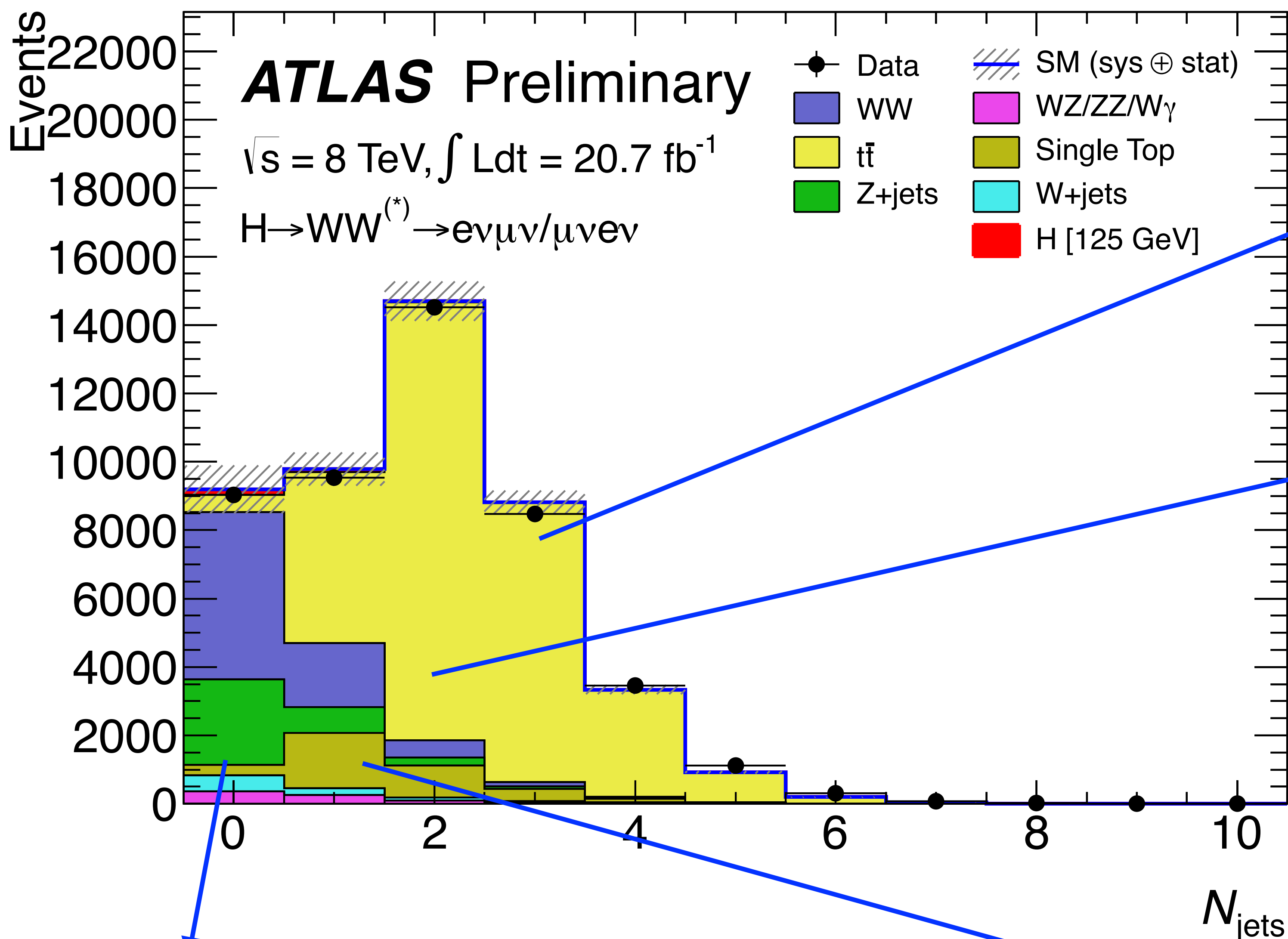
1-jet bin: NLO QCD
- large yield
- large ~40% K-factor,
- ~30% scale uncertainty

0-jet bin:
NNLO QCD, finite m_q effects
- largest yield
- ~15% accuracy

(0,1,2: matched/Merged with PS, and LO finite m_q effects)

The f.o. part of the story: what do we aim at

[in the not-so-distant future, hopefully]



3-jet bin: NLO QCD

2-jet bin: NLO QCD

1-jet bin: NLO QCD
NNLO, NLO with finite m_t

0-jet bin: NNLO QCD,
N^{3}LO [see e.g. Babis' talk at last HXSWG]

('+PS' ideally, at least at NLO)

Higgs plus jet: need for improvement

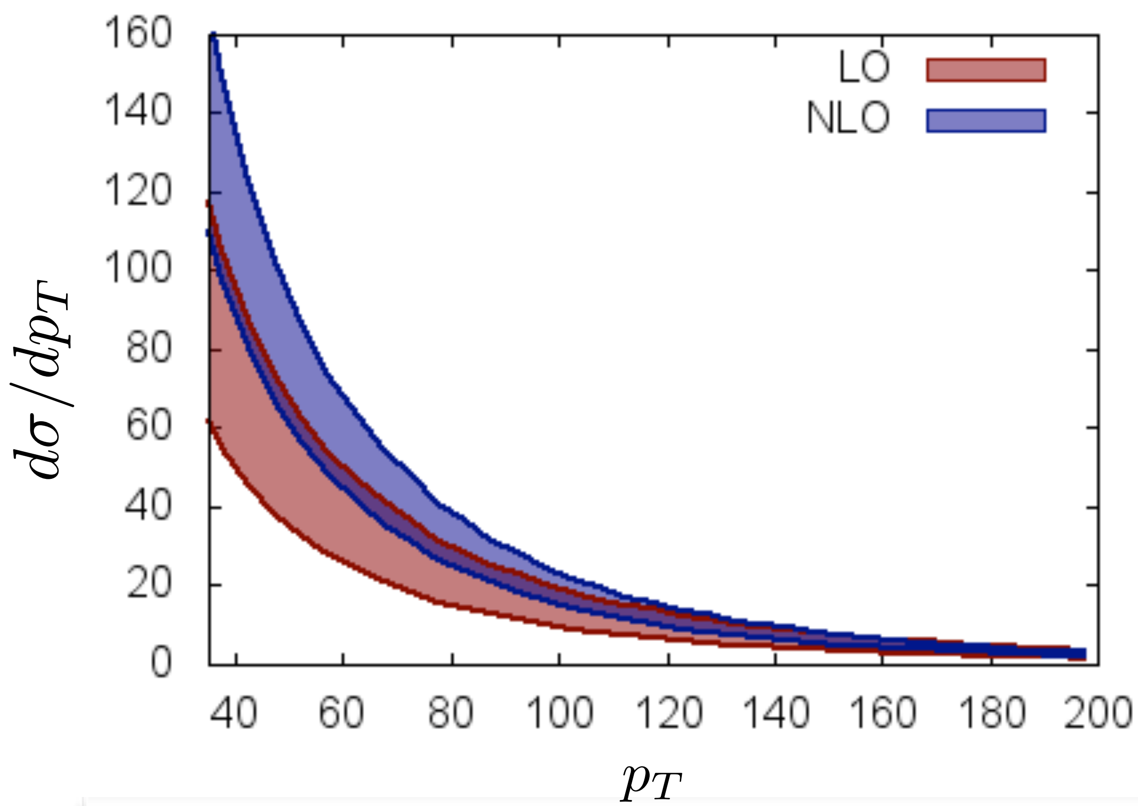
H+1 jet @ NLO: large NLO K-factor and large theoretical uncertainty

Source (1-jet)	Signal (%)	Bkg. (%)
1-jet incl. ggF signal ren./fact. scale	27	0
2-jet incl. ggF signal ren./fact. scale	15	0
Missing transverse momentum	8	3
W+jets fake factor	0	7
b-tagging efficiency	0	7
Parton distribution functions	7	1

ATLAS

$$\sigma_{\rm LO} = 4.1^{+2.1}_{-1.3}\ {\rm pb}$$

$$\sigma_{\rm NLO} = 5.8^{+1.4}_{-1.1}\ {\rm pb}$$



Need for higher orders!

NEED NNLO FOR H+JET(S) TO FIX THESE ISSUES

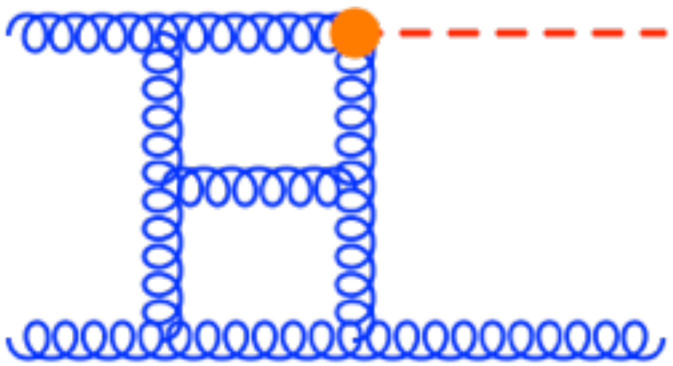
Higgs plus 1 jet at NNLO

Anatomy of a NNLO computation

- For a long time, the problem of NNLO computations was how to consistently extract IR singularity from double-real emission/real-virtual emission
- This problem has now been solved both in theory (antenna subtraction, sector decomposition+FKS, semi-analytic subtraction) and in practice. Colorful 2->2 has been achieved (top-pair, dijet, single-top,…)
- Now the problematic part is computing two-loop amplitudes. State of the art:
  - Numerically: 2->2 with 1 extra mass-parameter (tt)
  - Analytically: 2->2 with two external mass scales (VV*)

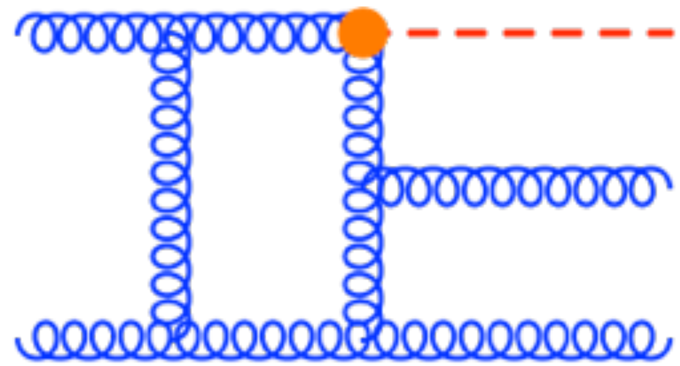
H+J: building blocks

VV



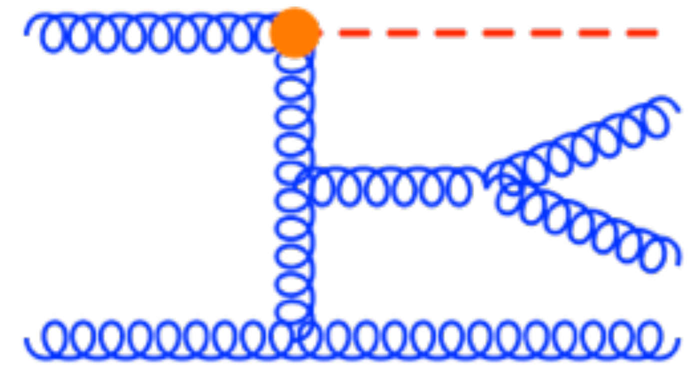
[Gehrmann et al. (2011)]

RV



[Badger et al. (2011)]

RR



[Del Duca et al., Dixon et al. (2004)]

$$\int \left[\frac{\mathrm{vv}_4}{\epsilon^4} + \frac{\mathrm{vv}_3}{\epsilon^3} + \frac{\mathrm{vv}_2}{\epsilon^2} + \frac{\mathrm{vv}_1}{\epsilon} + \mathrm{vv}_0\right] d\phi_2$$

$$\int \left[\frac{\mathrm{rv}_2}{\epsilon^2} + \frac{\mathrm{rv}_1}{\epsilon} + \mathrm{rv}_0\right] d\phi_3$$

$$\int \left[\mathrm{rr}_0\right] d\phi_4$$

Problematic part is to extract implicit IR poles from RV and RR in a FULLY-DIFFERENTIAL way, i.e. without doing the PS integration

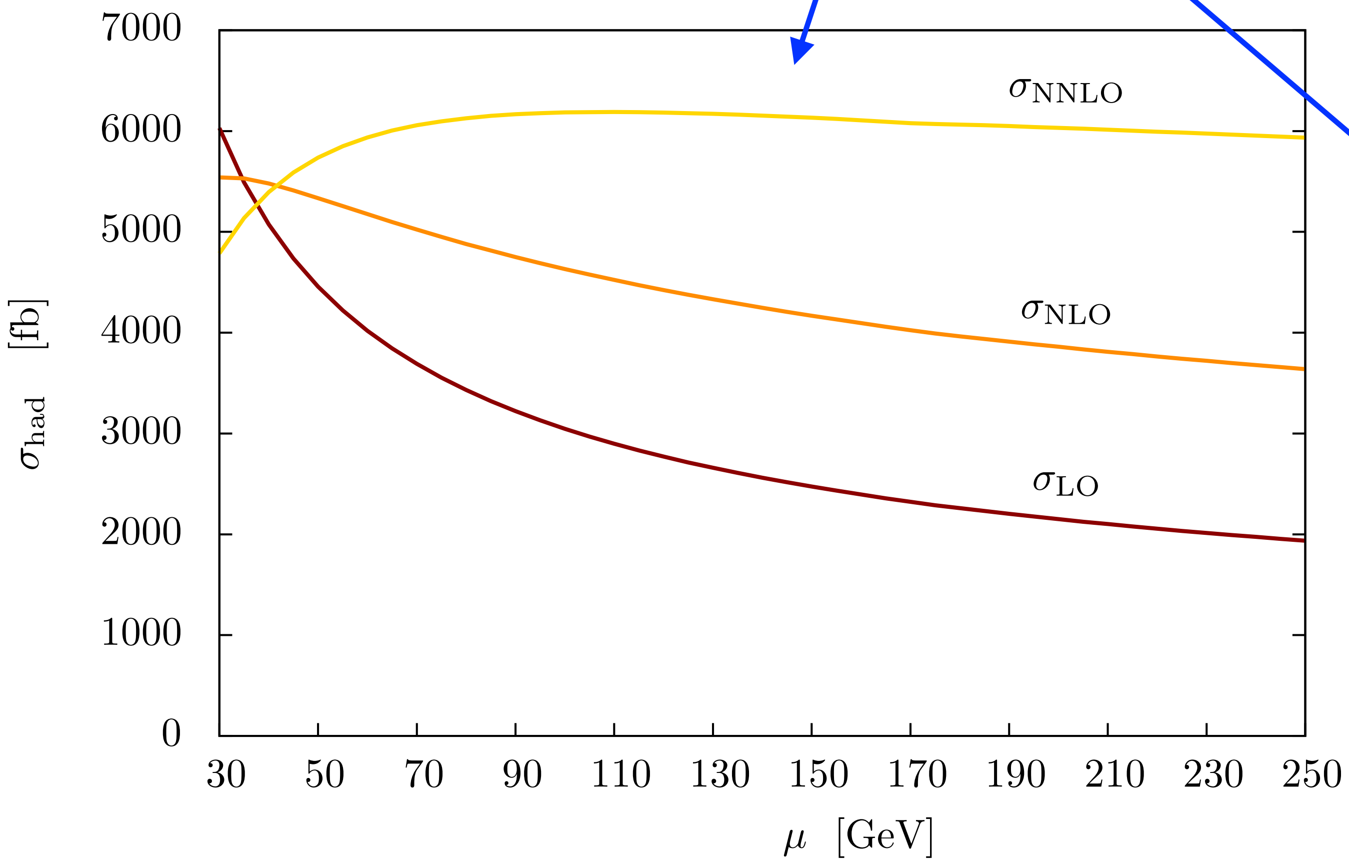
OUR APPROACH: SECTOR DECOMPOSITION + FKS

[Czakon (2010), Boughezal, Melnikov, Petriello (2011); Czakon, Heymes (2014)]

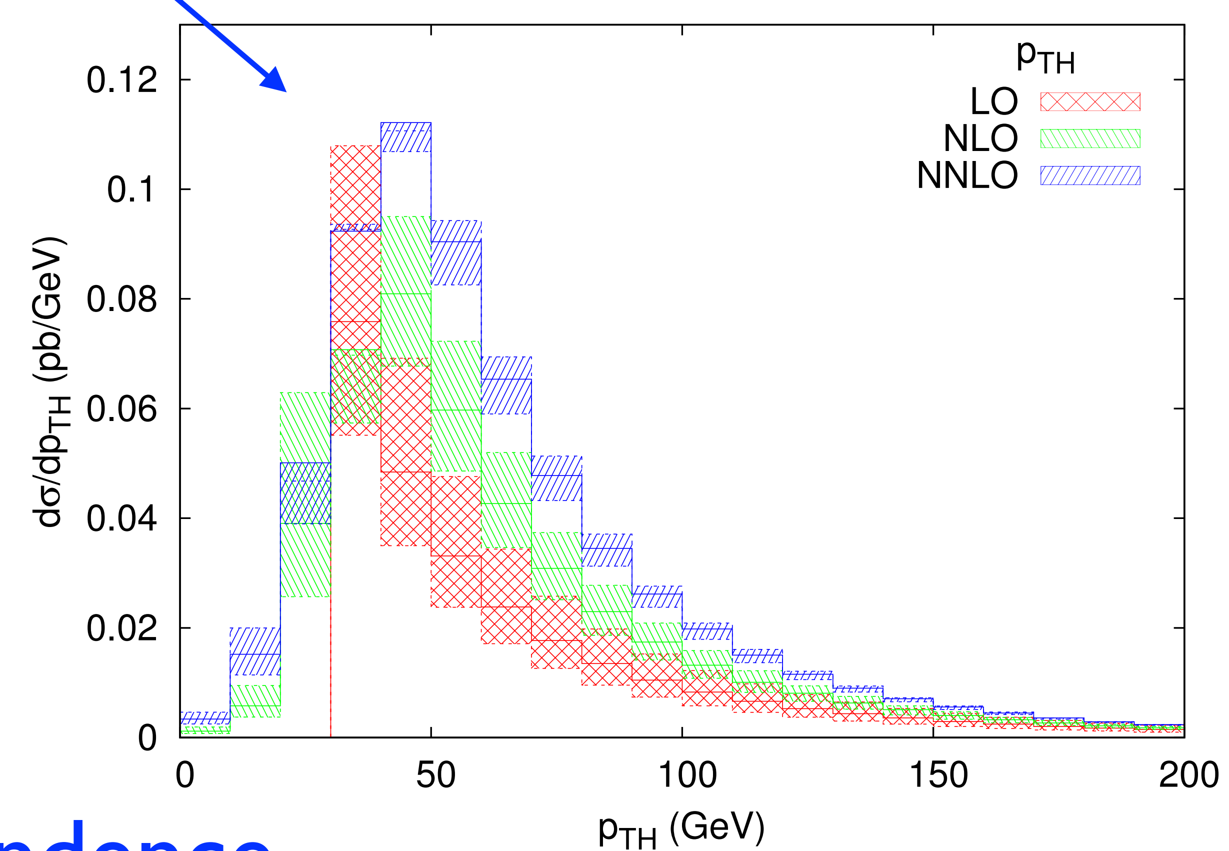
H+J@NNLO: where do we stand

Two groups are computing it -> cross-checks

- Boughezal, FC, Melnikov, Petriello, Schulze
- X. Chen, Gehrmann, Glover, Jaquier



'PURE-GLUE' APPROXIMATION



- Large K-factor
- Non-trivial shapes
- (Much) better scale (in)dependence

H+J@NNLO: where do we stand

However, so far both results only for a pure-glue theory

[This Is Not the full gg-channel, pieces are missing]

- Pure glue:

$$\sigma_{\rm LO} = 2.8^{+1.4}_{-0.9}\ {\rm pb}$$

$$\sigma_{\rm NLO} = 4.4^{+0.8}_{-0.7}\ {\rm pb}$$

- Full QCD:

$$\sigma_{\rm LO} = 2.8^{+1.4}_{-0.9}\ [gg] + 1.3^{+0.6}_{-0.4}\ [qg] \qquad (+0.01\ [q\bar{q}])$$

$$\sigma_{\rm NLO} = 4.1^{+0.8}_{-0.8}\ [gg] + 1.7^{+0.5}_{-0.3}\ [qg] \qquad (+0.03\ [q\bar{q} + qq + qq'])$$

For REAL PHENOMENOLOGY, both the FULL GG and the QG channels must be computed at NNLO

H+J@NNLO: status

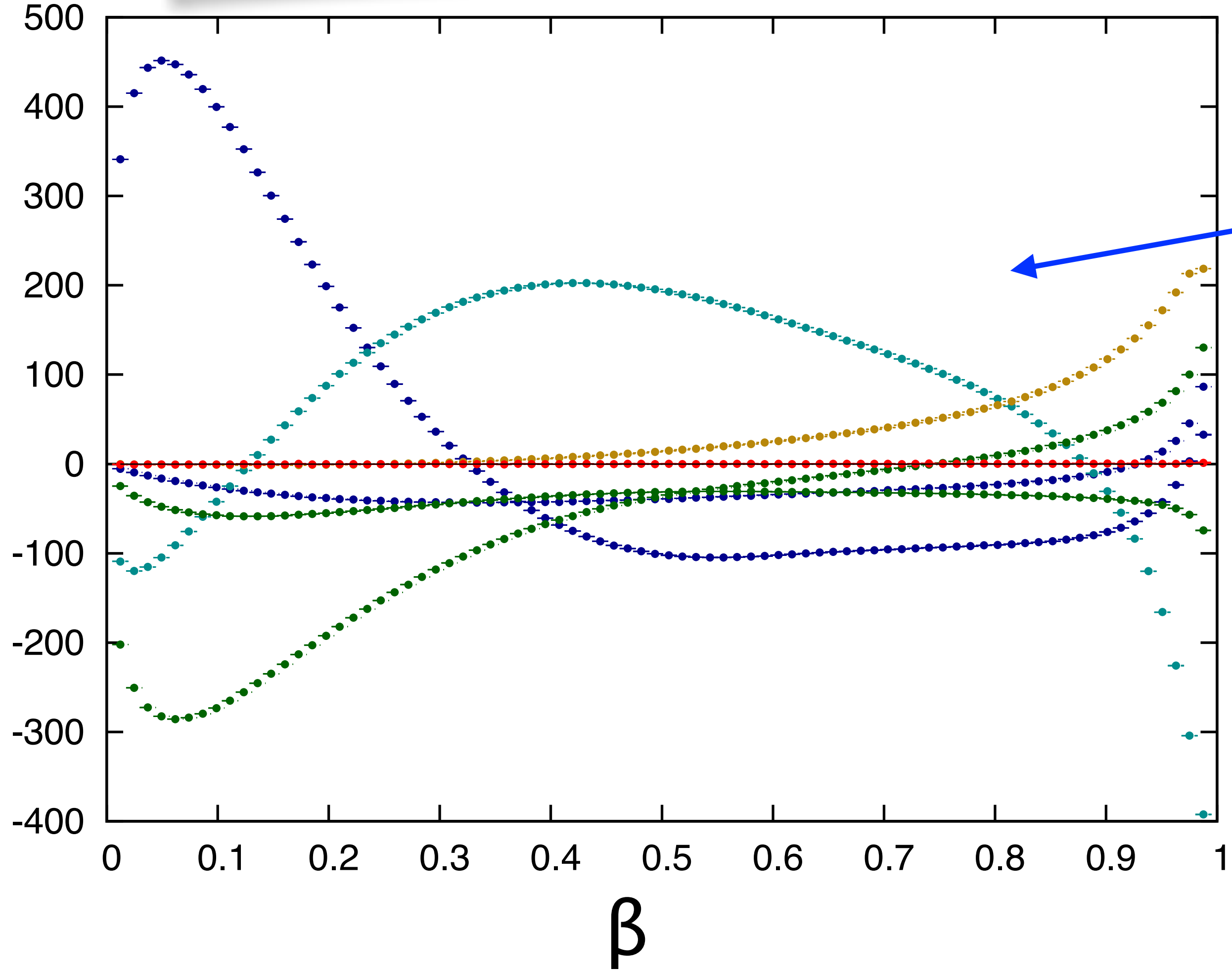
Both groups are actively working towards the full result

Our status/plans:

- internal consistency checks (numerical pole cancellation, RGE…) plus checks with existing results (all tree/loop amplitudes, H+2j@NLO…). Done
- preliminary results are there, but still not fully validated
- to be sure about the correctness of the computation, two completely independent implementations
  - close to independent validations for the total cross-section
  - still some validation work for differential distributions

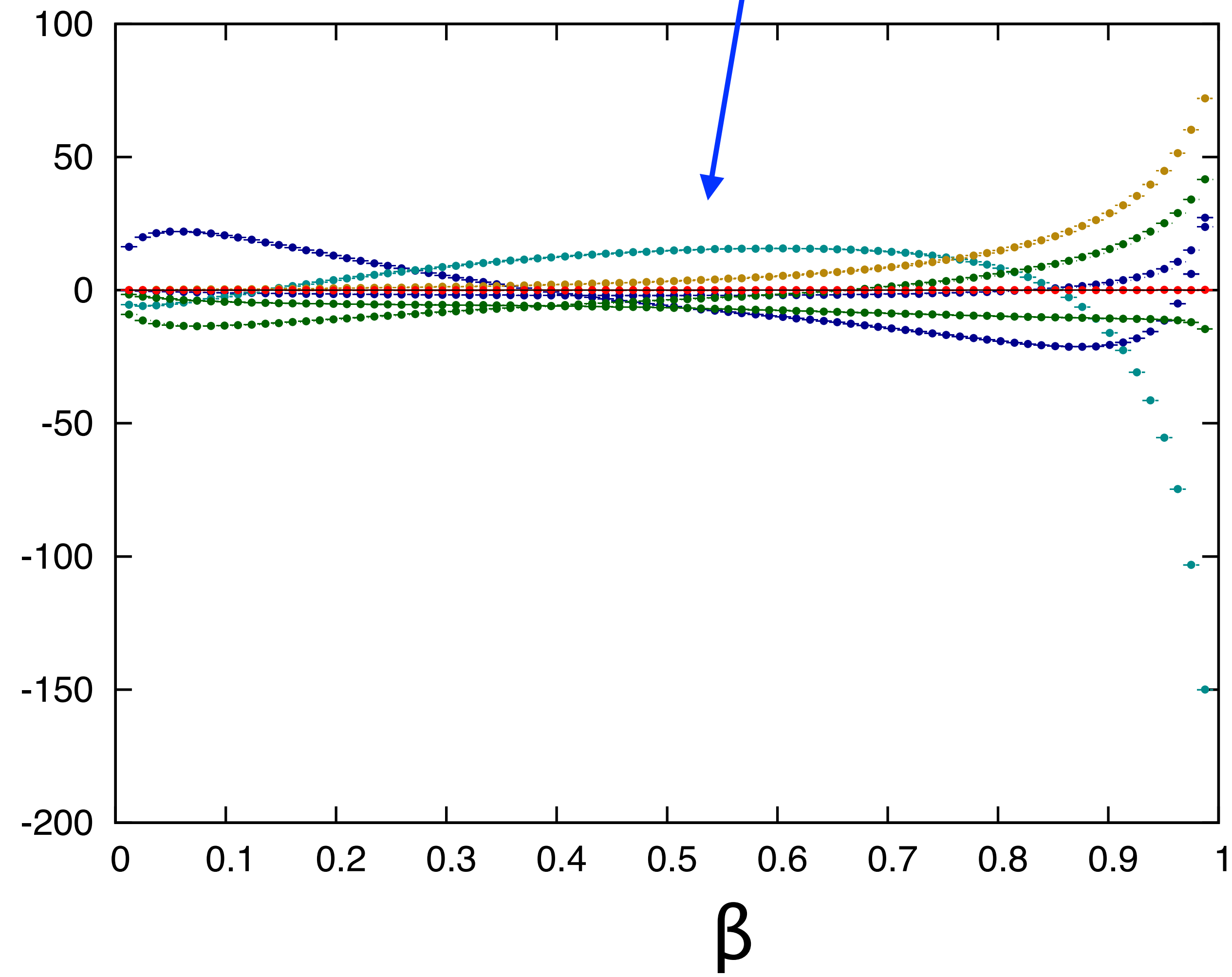
Some checks: cancellation of 1/ε poles

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



gg

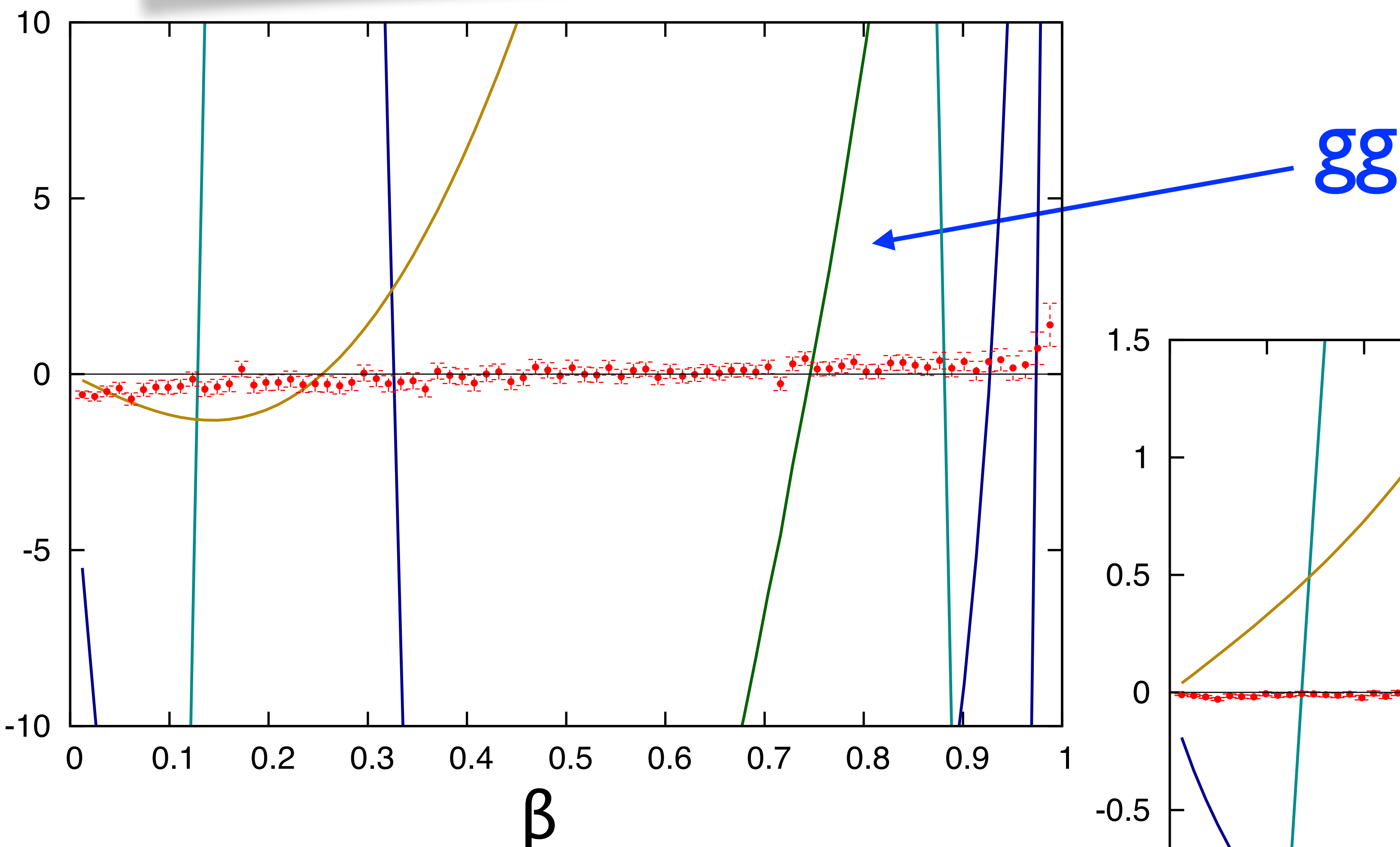
qg

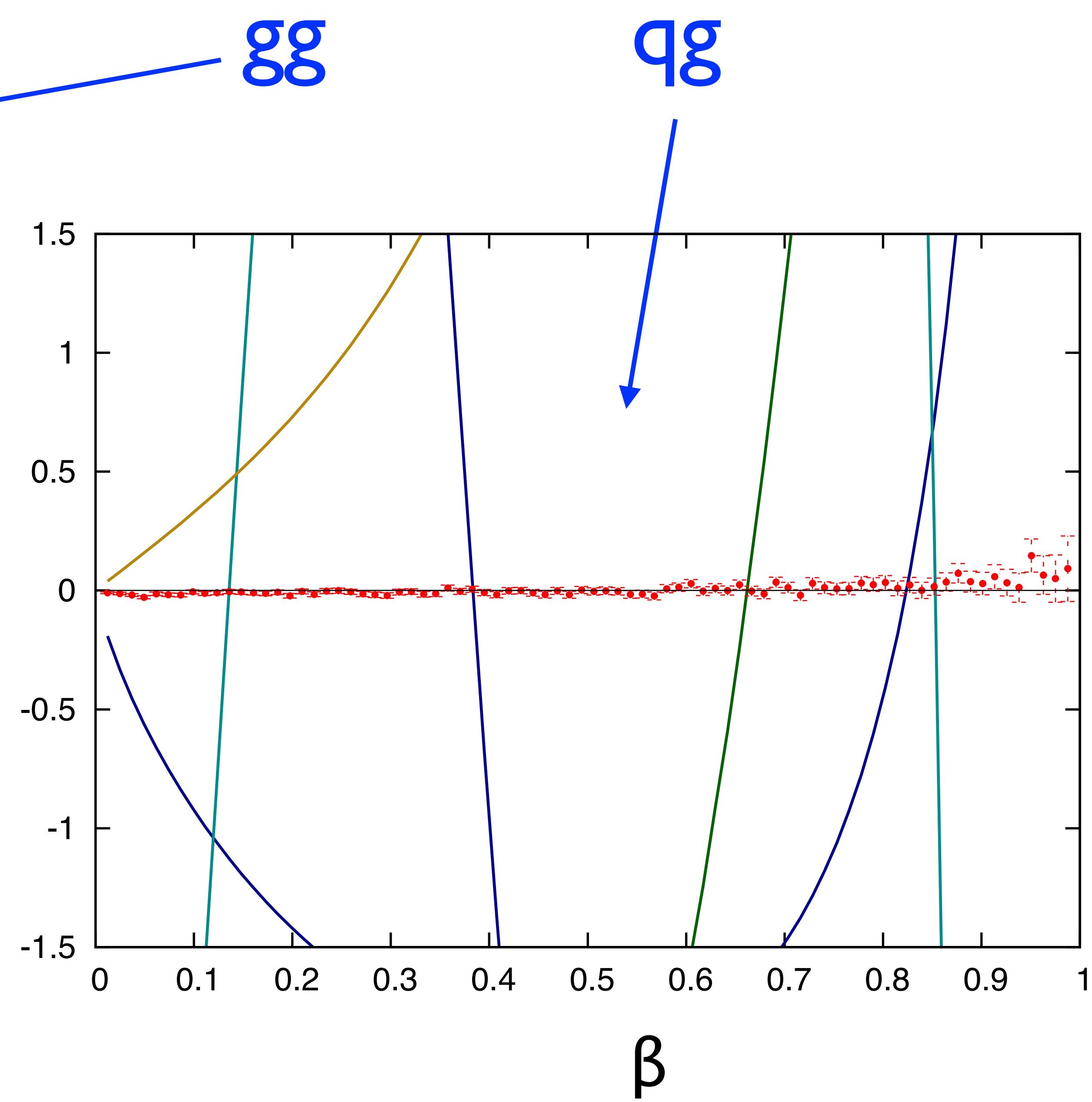


$$\beta = \sqrt{1 - \frac{s_{th}}{\hat{s}}}$$

Some checks: cancellation of 1/ε poles

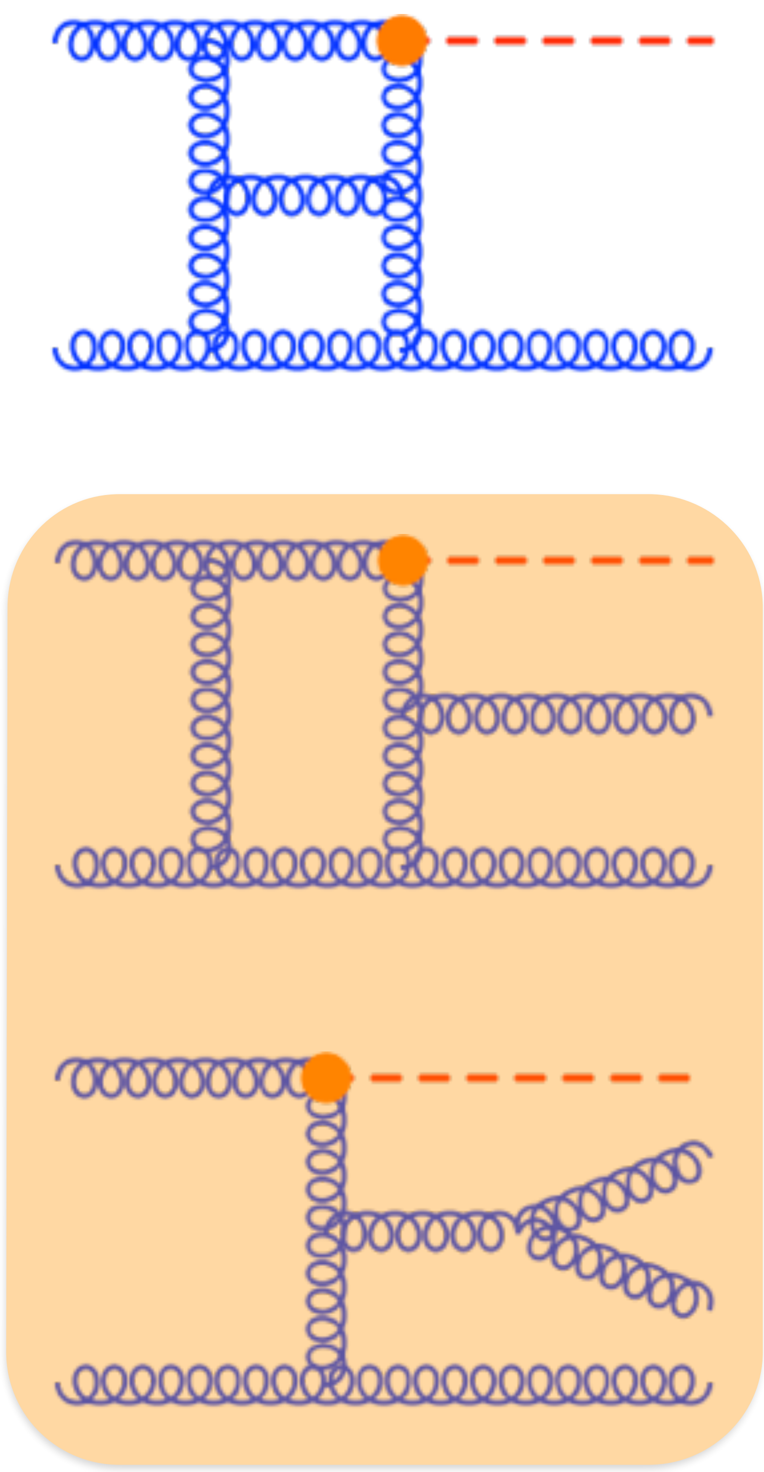
NUMERICAL CANCELLATION between
renormalization and coll. couterterms, RR, RV, VV



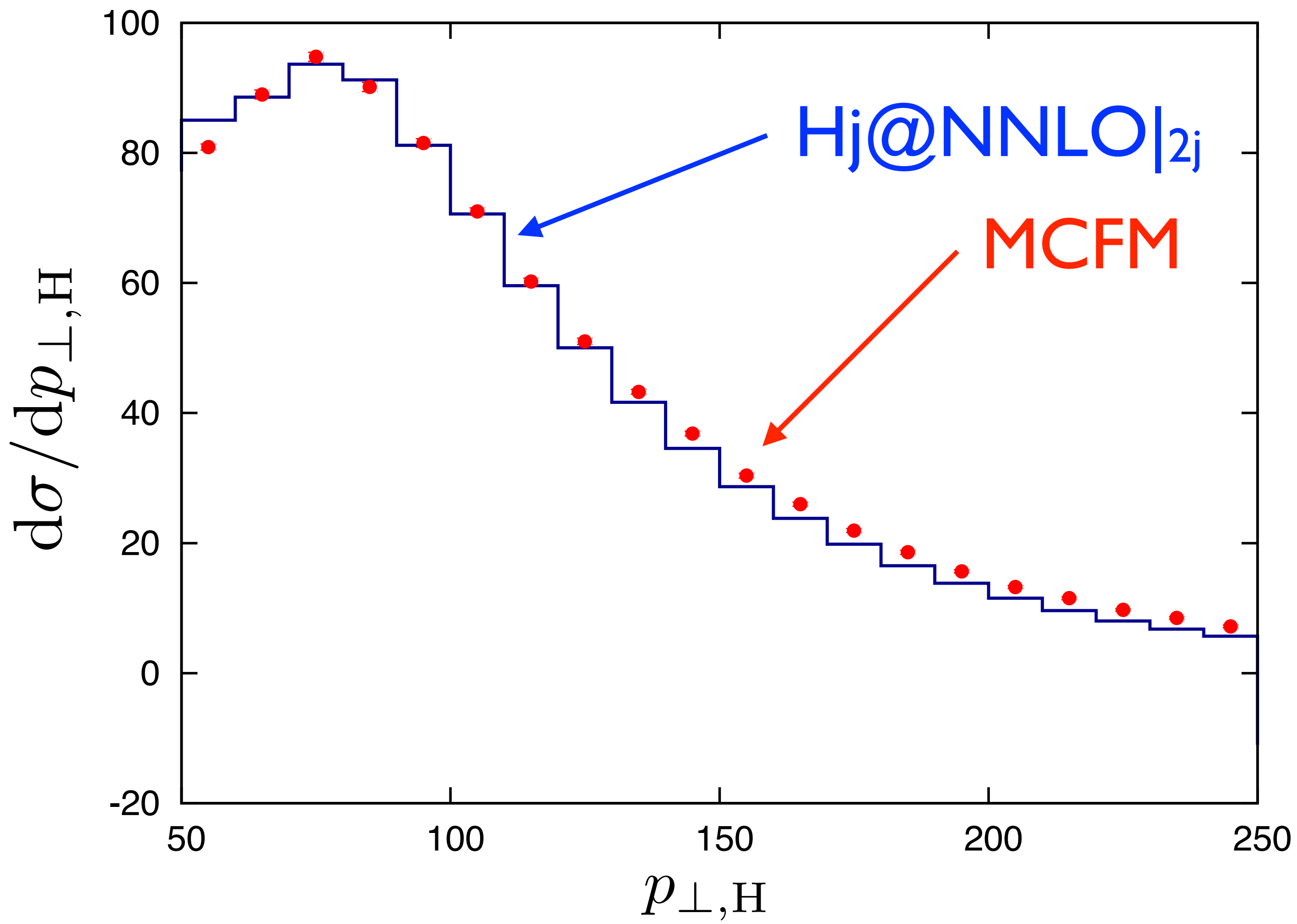


Better than per mill
cancellation at 1/ε

Some checks: p_T spectrum in the 2-jet bin



H+j @NNLO ∈ H+jj@NLO

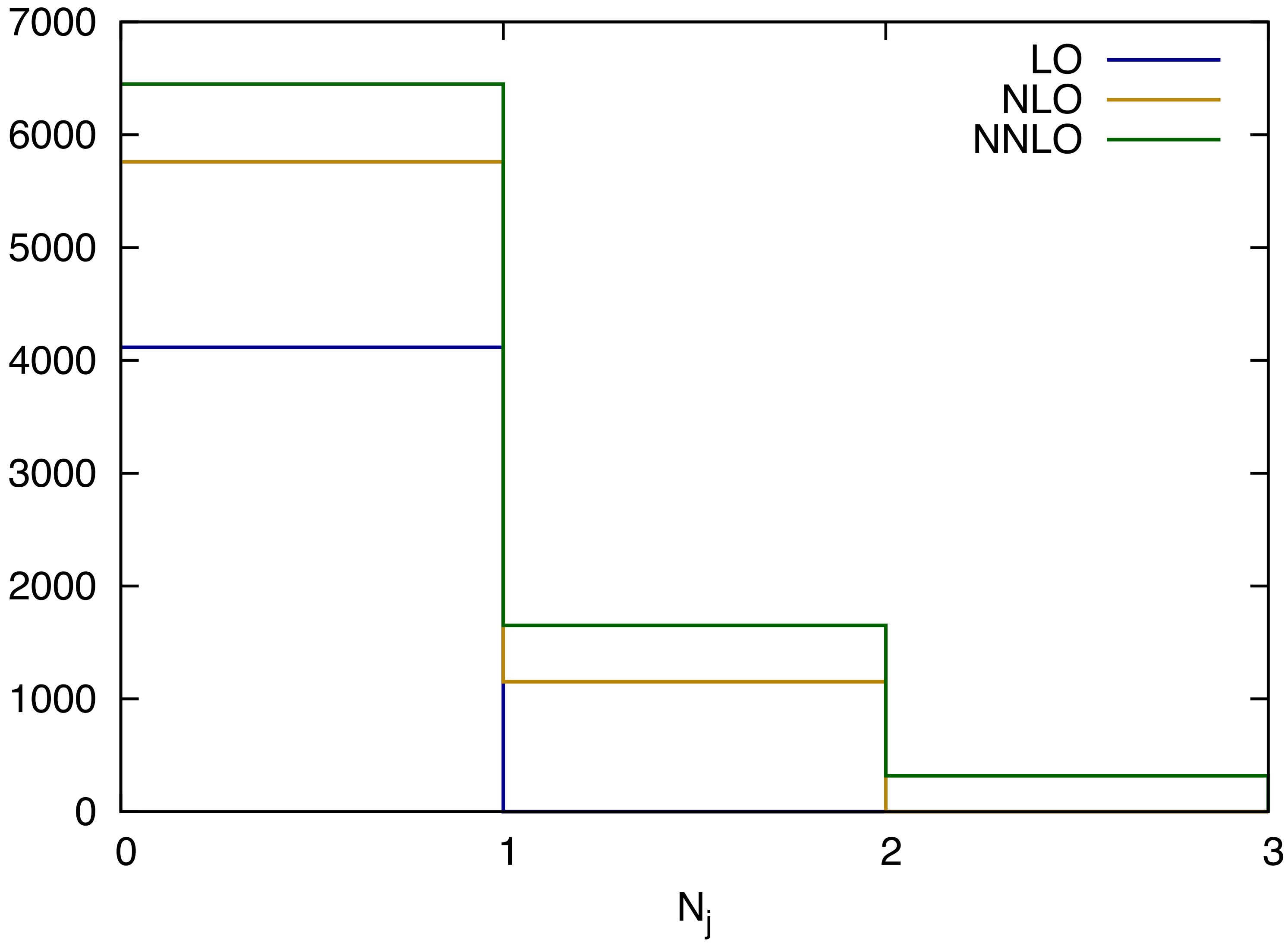


Good agreement with MCFM

H+jet@NNLO, preliminary results

Inclusive jet bins

[LHC8, MSTW2008, p_T=30 R=0.5 anti-KT, μ=m_H=125 GeV]

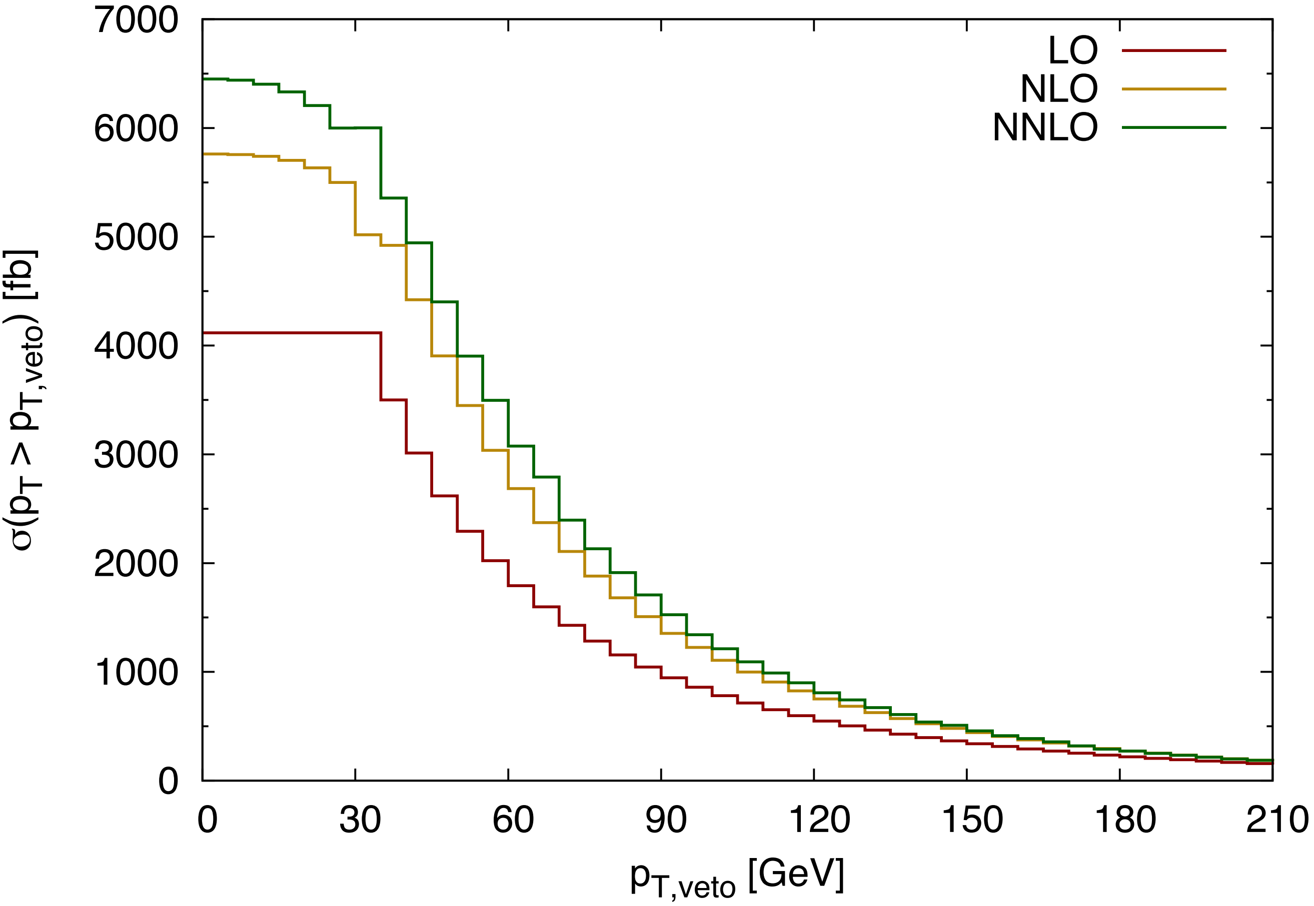


- Large K-factor, but smaller than for pure-glue (expected)
- K-factor somewhat larger in the 1-jet bin
- Reduced O(7%) scale variation (no PDF error for now)
- Better perturbative convergence for smaller scales

H+jet@NNLO, preliminary results

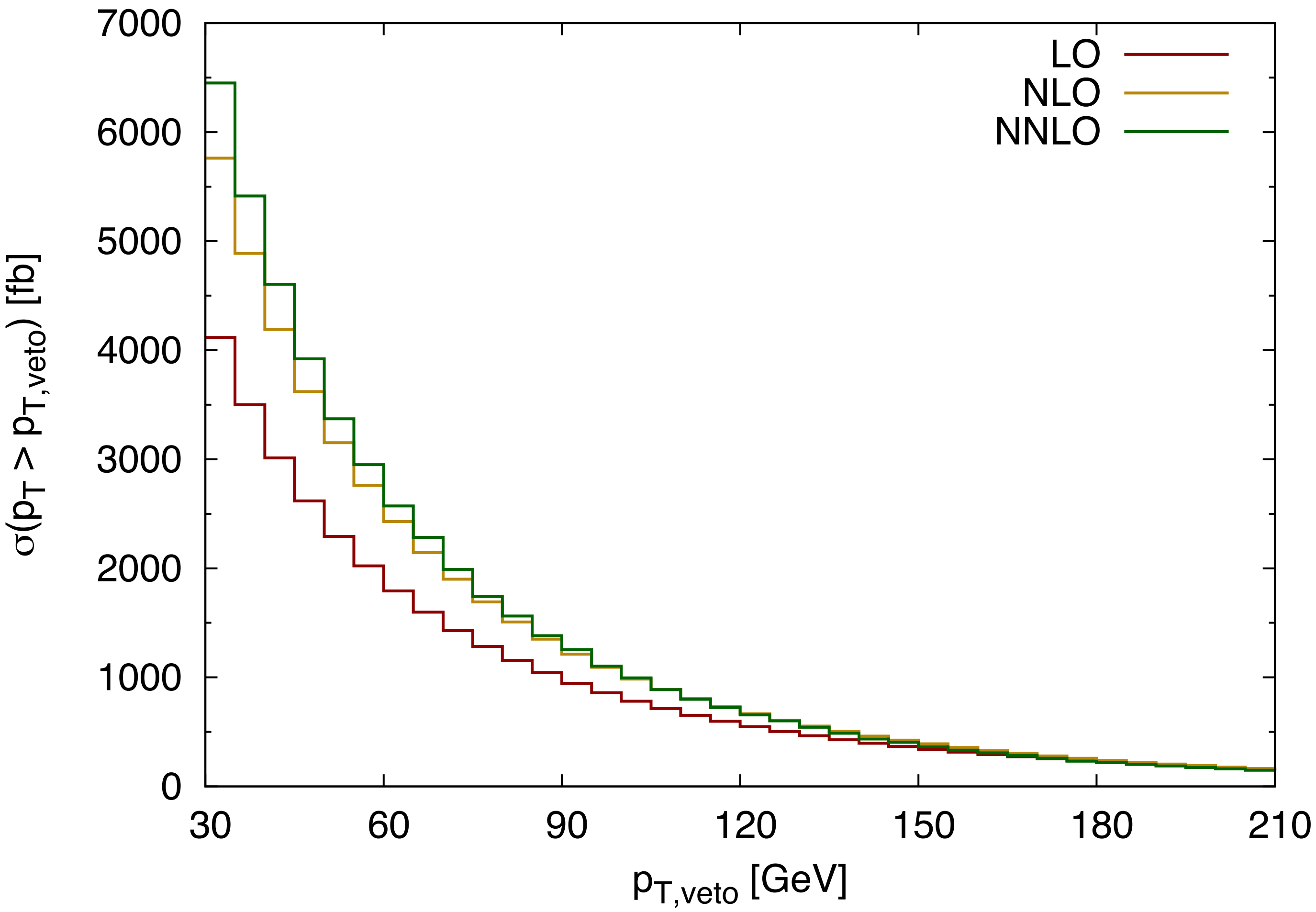
Higgs and leading jet cumulative p_T

[LHC8, MSTW2008, p_T=30 R=0.5 anti-KT, $\mu=m_H$=125 GeV]



Higgs

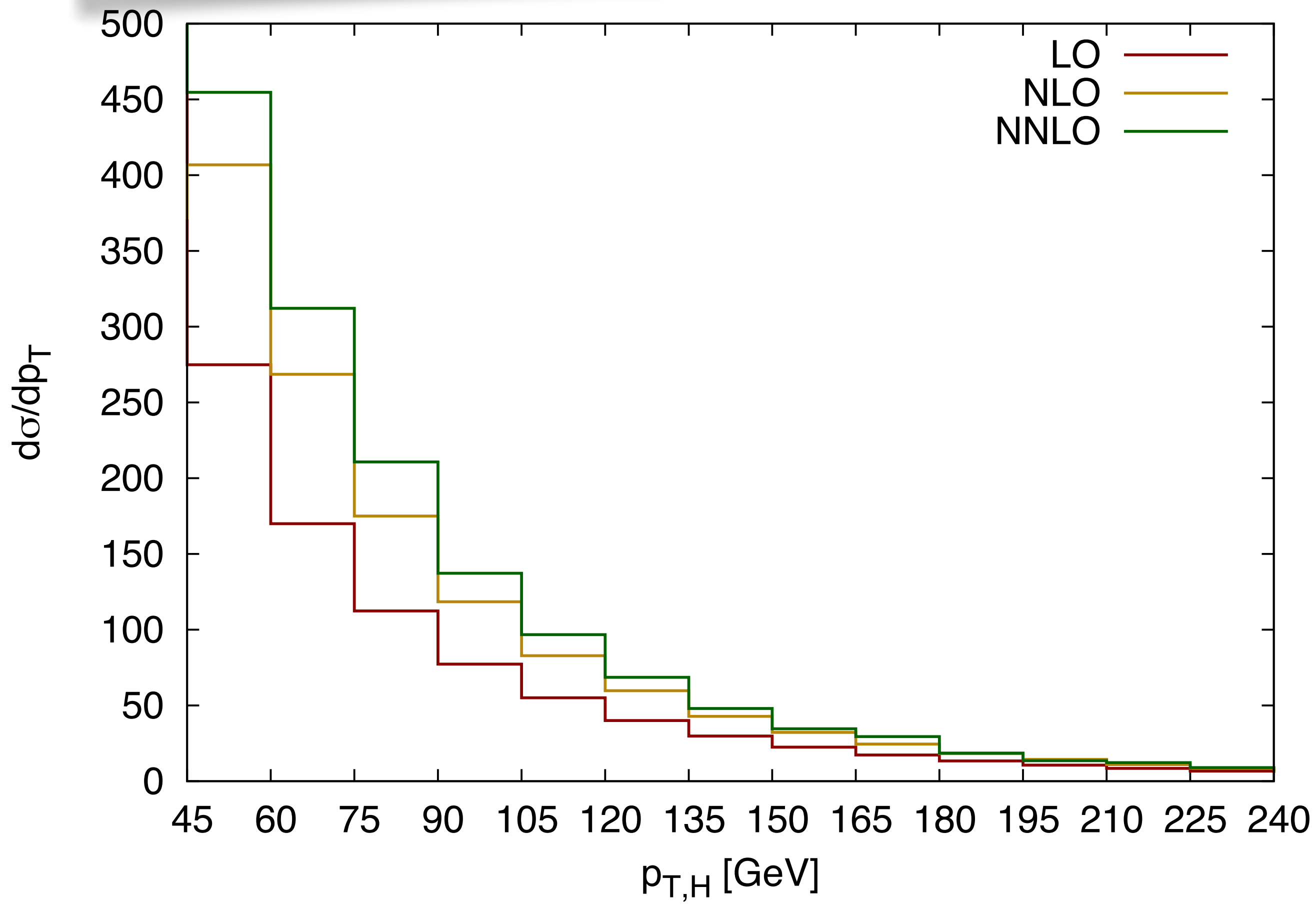
Leading-p_T jet



H+jet@NNLO, preliminary results

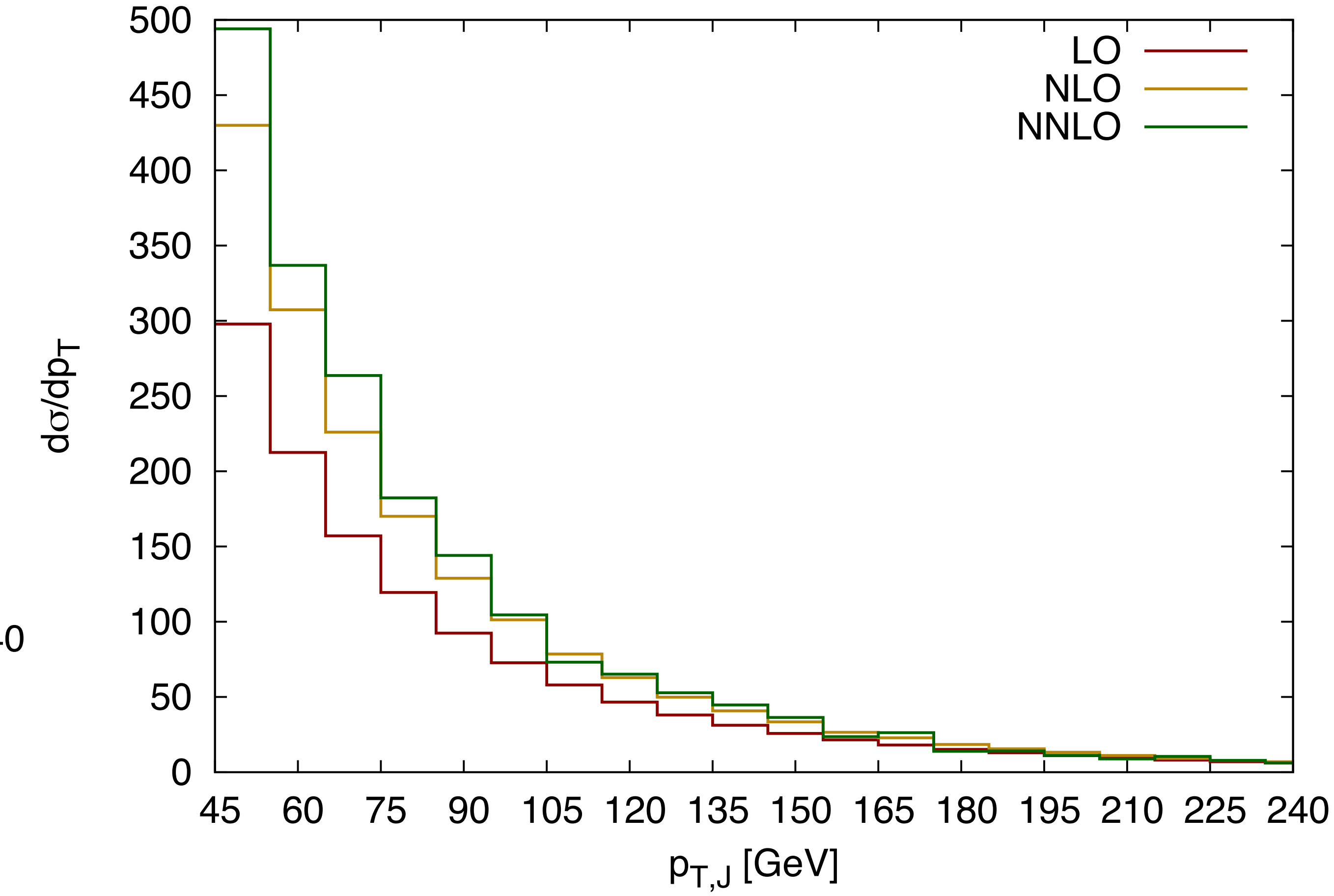
Higgs and leading jet p_T distribution

[LHC8, MSTW2008, p_T=30 R=0.5 anti-KT, μ=m_H=125 GeV]



Higgs

Leading-p_T jet



Larger corrections at small p_T

Conclusions

- Jet-binned predictions extremely important, but tricky
- Log resummation program must be carried out -> good shape
- To improve predictions: accurate f.o. computations -> NNLO
  - Orders of magnitude more complex than NLO
  - Recent progress made possible colorful 2->2
- H+J was one of the first computations done, and the only one done by 2 groups
  - So far, results not yet ready for real phenomenology
  - Computation of the full result well-underway (no new conceptual problems, but some work)
- When computation properly validated: phenomenology runs with exact ATLAS/CMS setup (fiducial volume, distributions…)

Thank you for
your attention!