Higgs plus 1 jet at NNLO

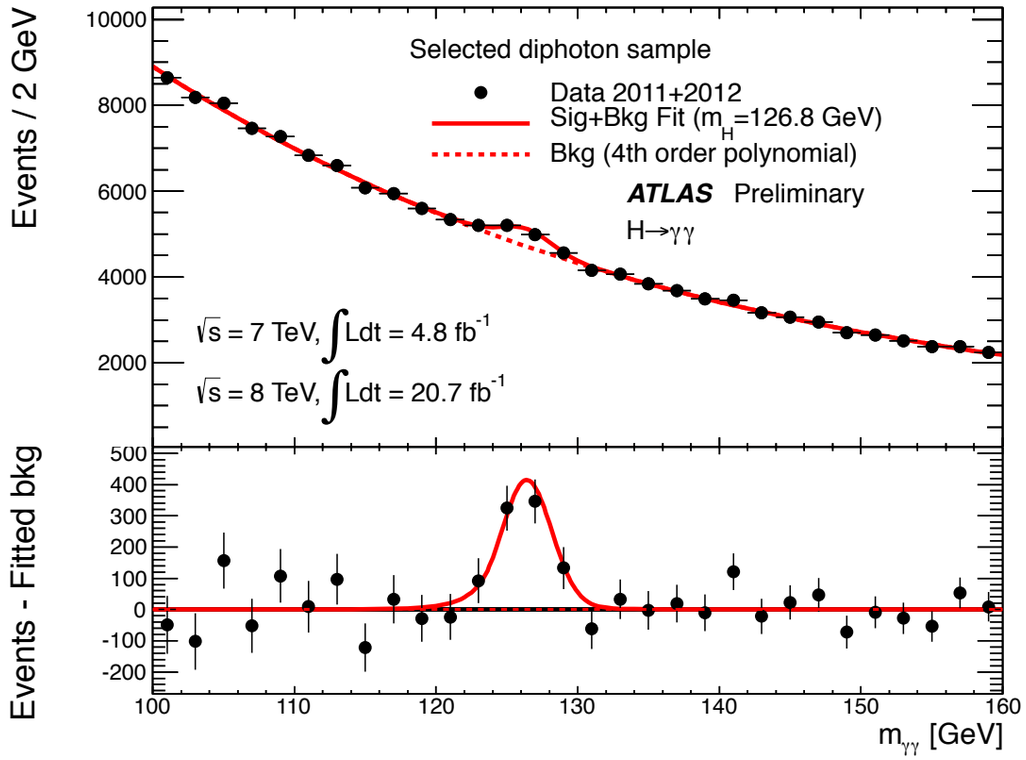
Fabrizio Caola, JHU

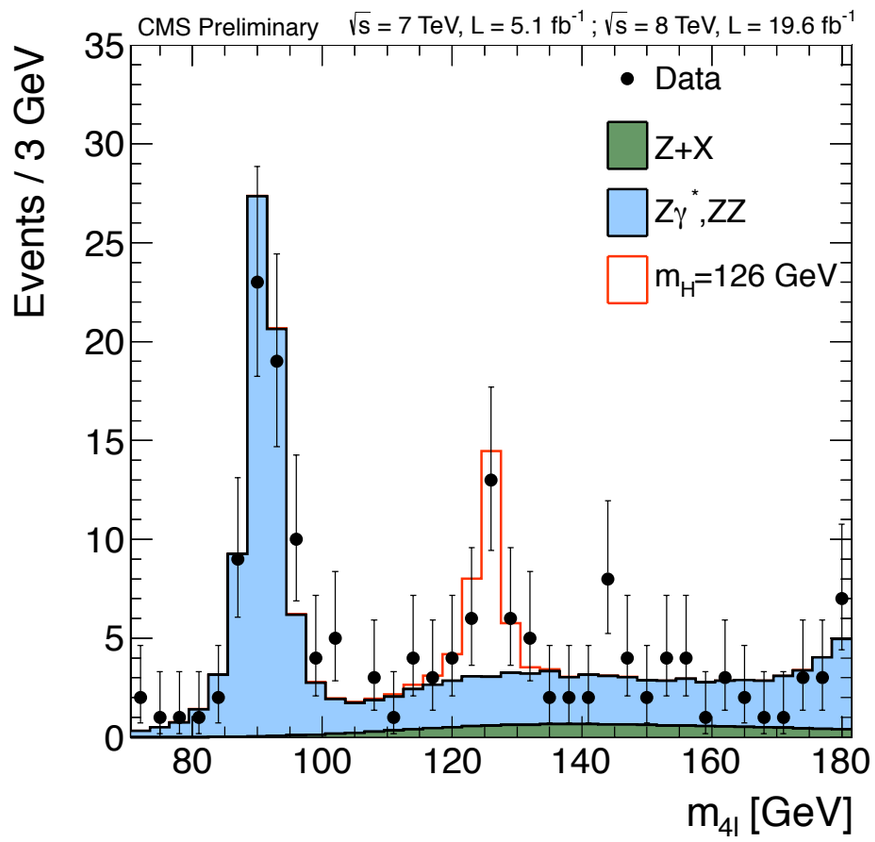
with K. Melnikov (JHU); R. Boughezal, F. Petriello, M. Schulze (ANL/Northwestern)

arXiv: 1302.6216

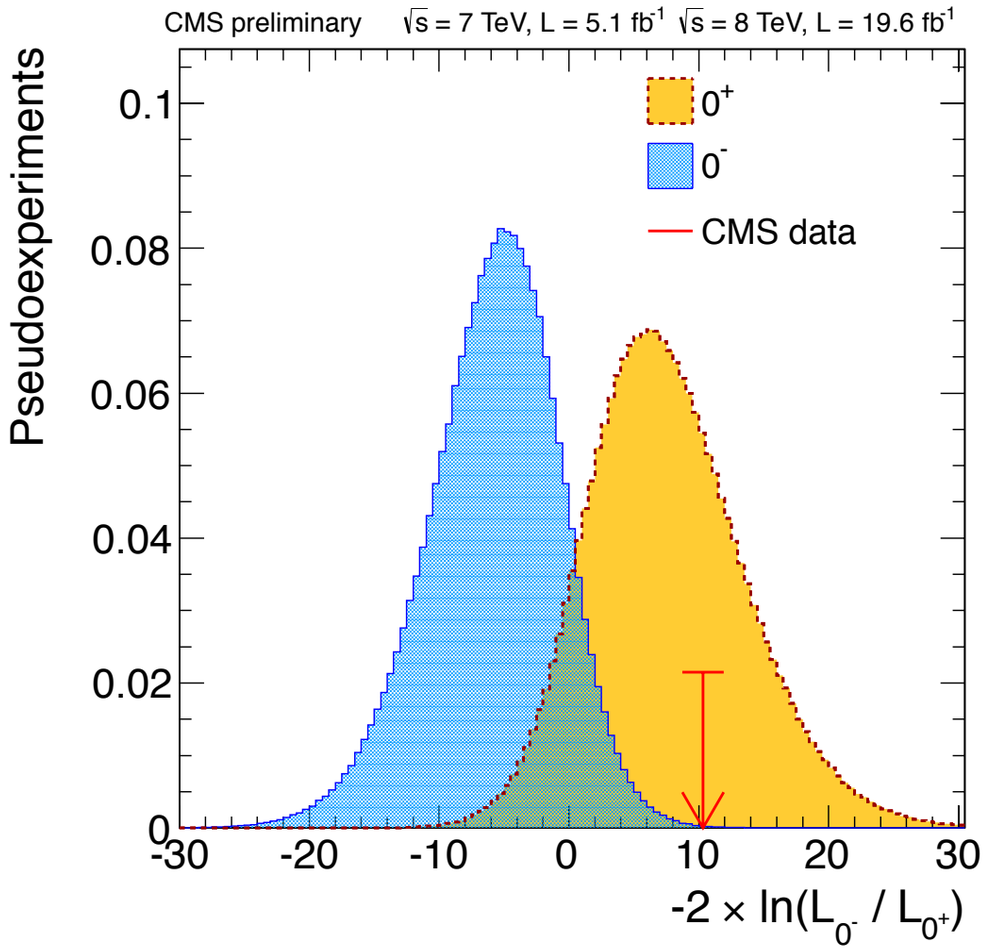
EPS, JULY 18TH 2013

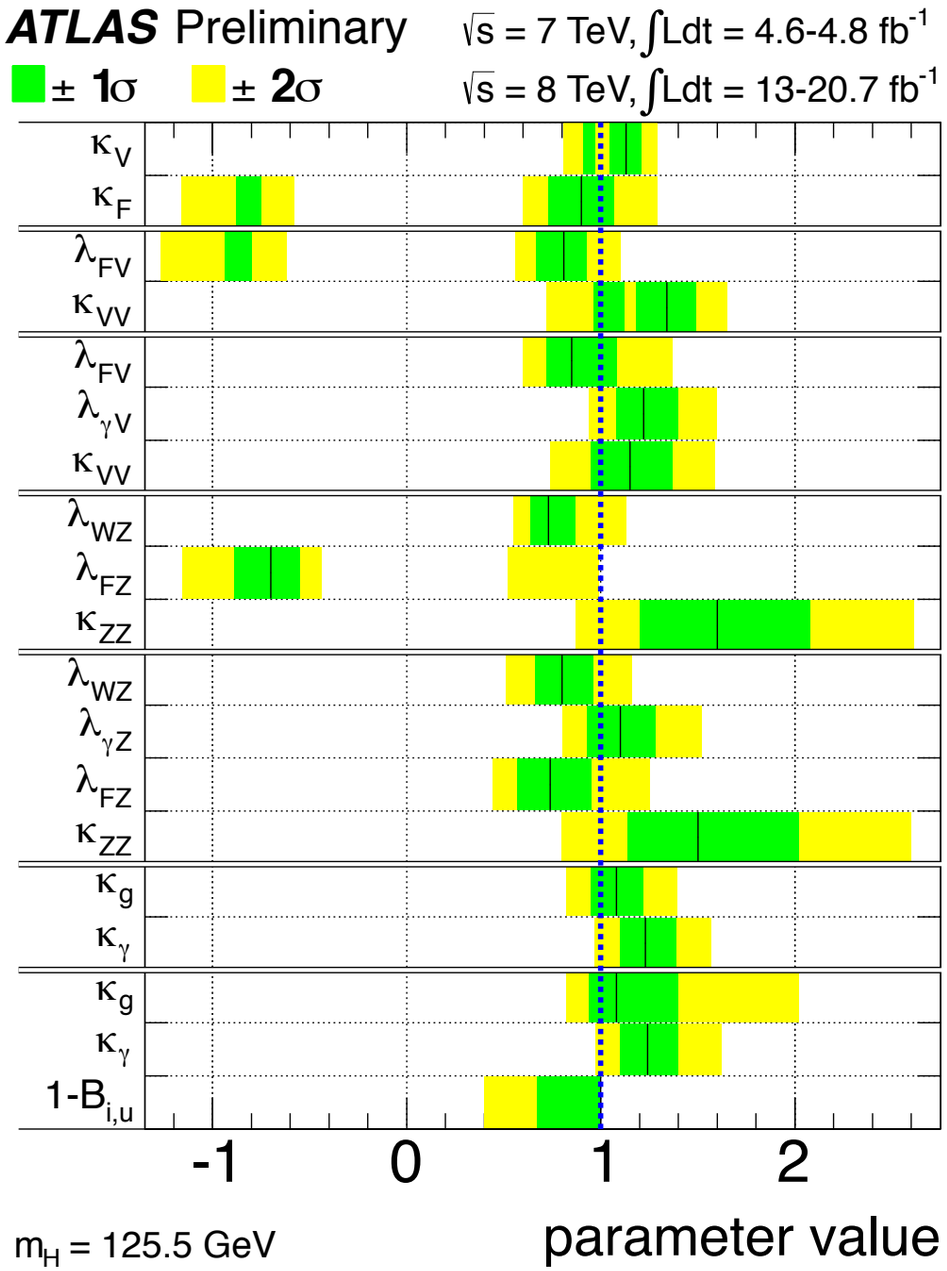
The Higgs Boson: from discovery...





The Higgs Boson: ... to precision measurements





So far: very SM-like

Good control of theoretical predictions is required to search for small deviations

The Higgs Cross Section: what do we know

Gluon fusion: $\sim 10\%$

- NNLO QCD (inclusive and differential)
- NLO EW
- QCD resummations
- approximate NNNLO
- mixed QCD-EW
- 1/mt,mb corrections
- H+1j, H+2j @ NLO

VBF: $\sim 1\%$

- NNLO QCD (inclusive only)
- NLO EW
- VBF+1j @ NLO

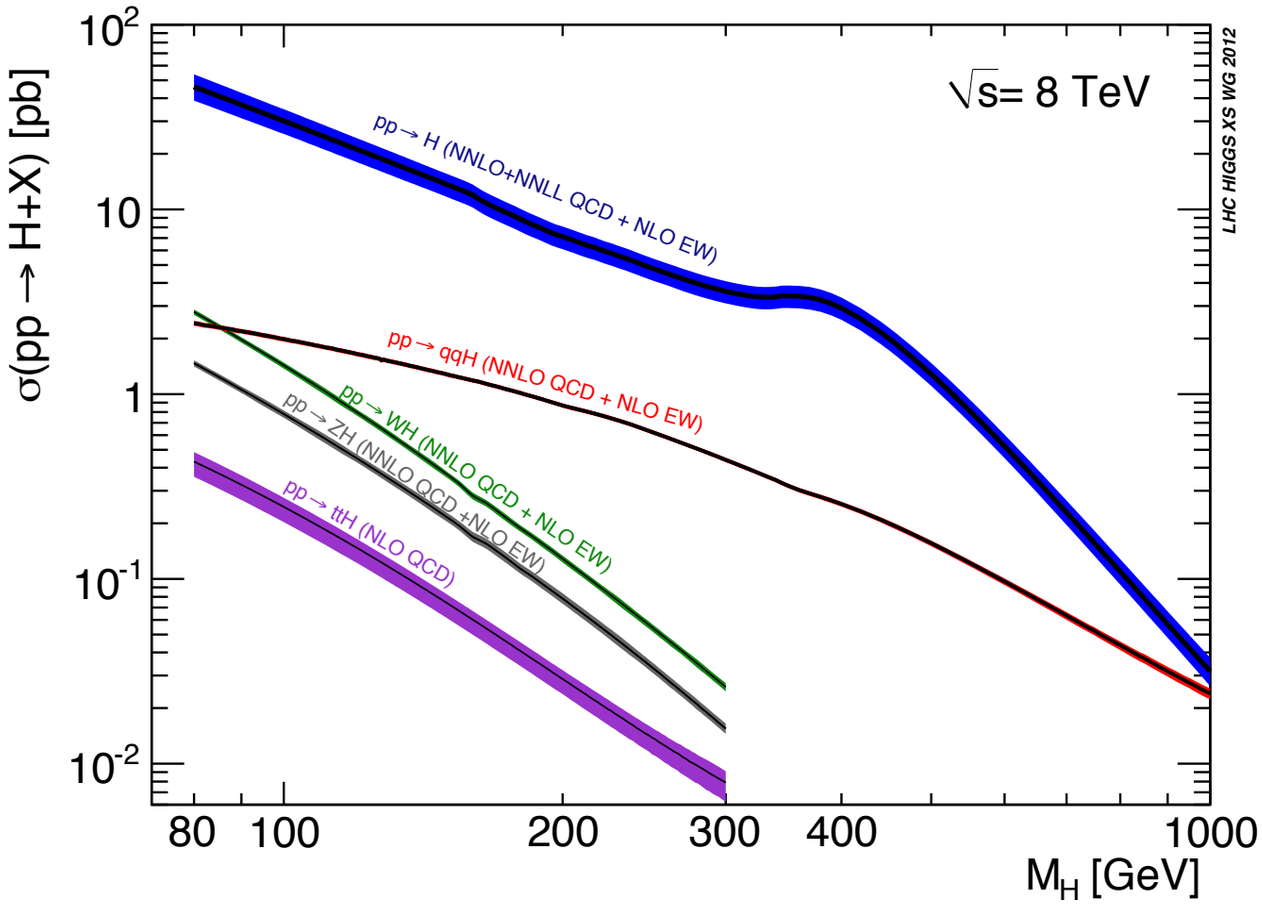
Higgs-Strahlung: $\sim 1\%$

- NNLO QCD (differential)
- NLO EW
- VH+1j @ NLO

ttH: $\sim 10\%$

- NLO QCD, including PS matching

+ PDFs + MC tools + ...

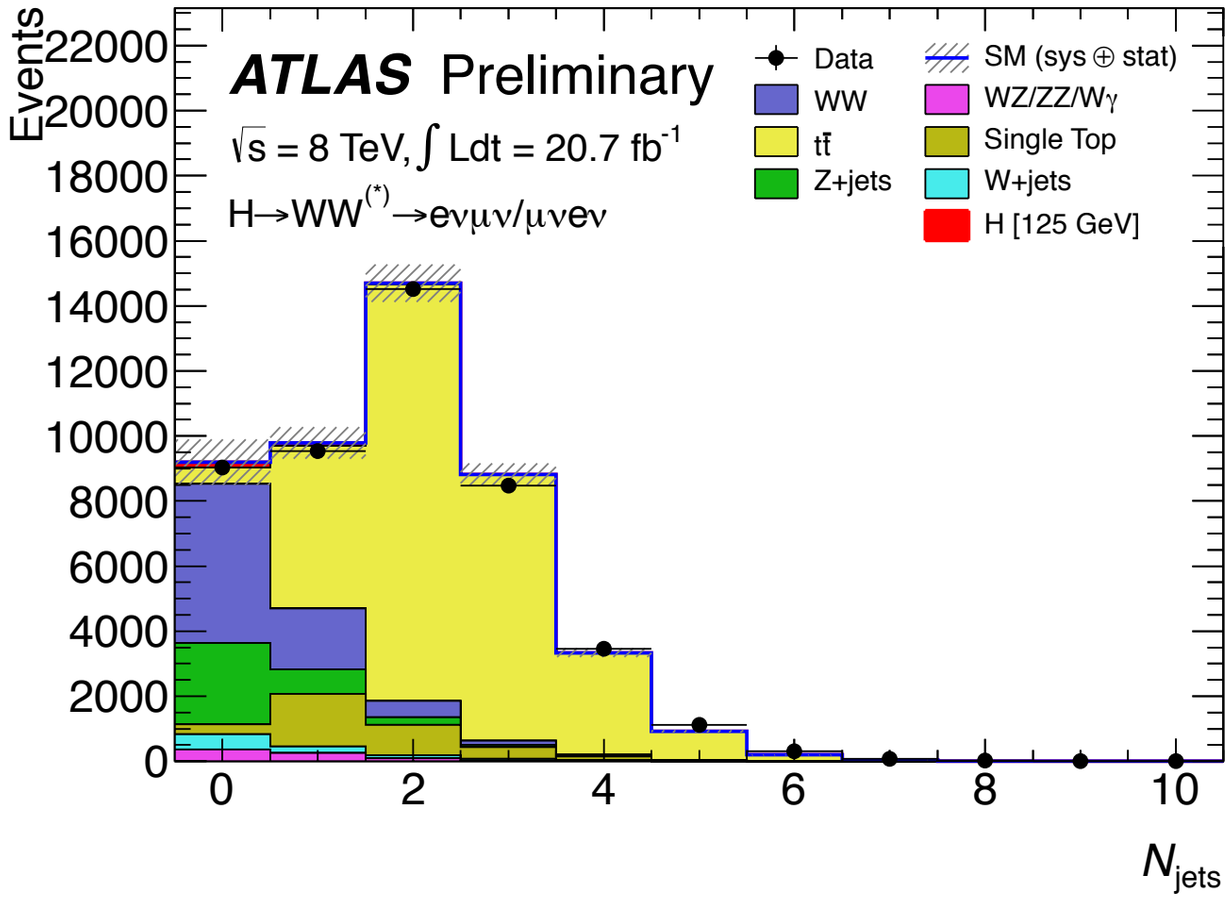


Very good theoretical control

Is it Enough?

Higgs plus jet: need for improvement

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

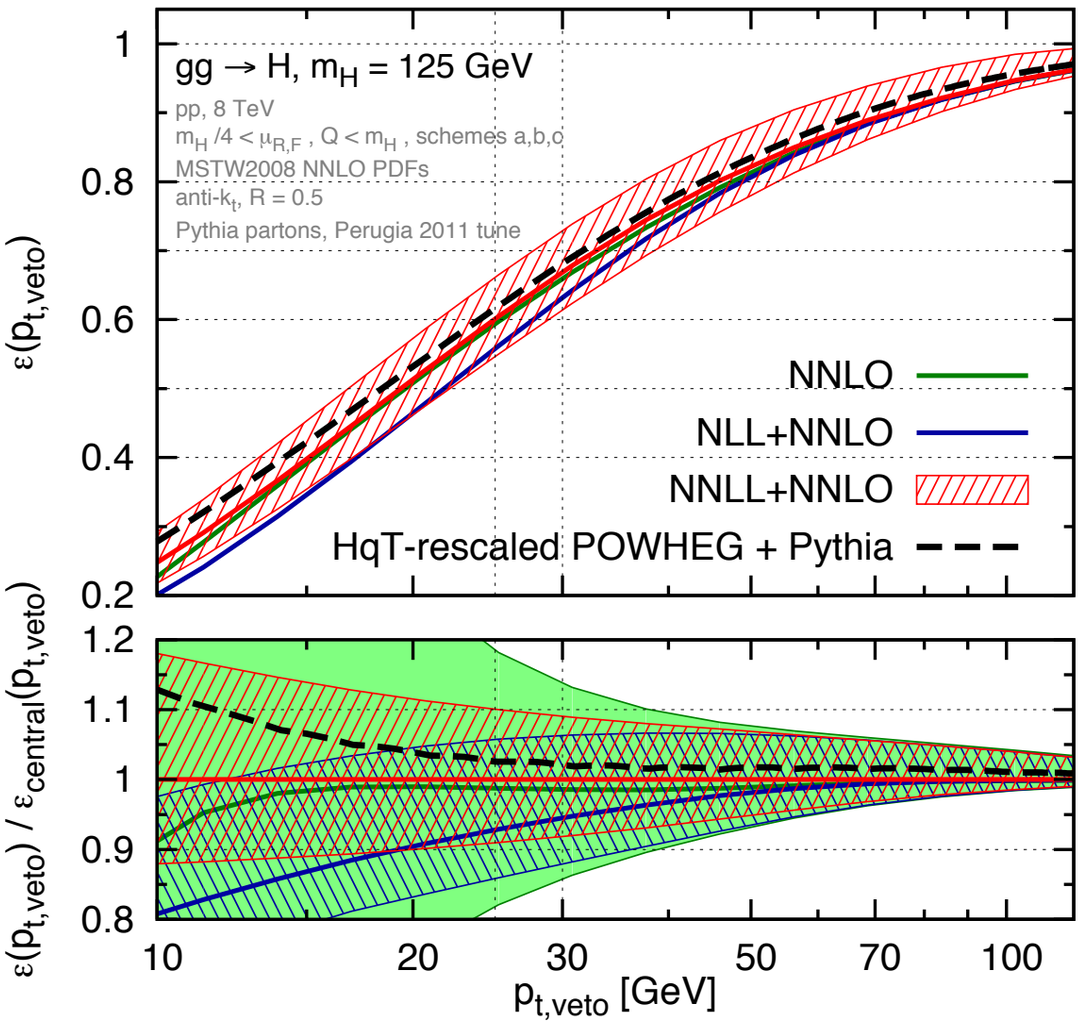


- Signal/background ratio for H+1, H+2 jets: $\sim 10\%$
- Significance in the H+1 jet bin smaller, but not much smaller, than significance in the H+0 jet bin
- LARGE THEORY ERROR

Selection	N_{obs}	N_{bkg}	N_{sig}	N_{WW}	N_{VV}	$N_{t\bar{t}}$	N_t	N_{Z/γ^*}	$N_{W+\text{jets}}$
$N_{\text{jet}} = 1$	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
$\lvert\Delta\phi_{\ell\ell}\rvert < 1.8$	728	650 ± 10	59 ± 1	250 ± 4	60 ± 4	204 ± 6	76 ± 4	28 ± 3	34 ± 2

Higgs plus jet: need for improvement

0-jet bin: $\sigma_0 = \sigma_{\text{tot}} - \sigma_{\geq 1}$



Large uncertainties even after NNLL resummation

[Banfi et al. (2012); Tackmann et. al (2012-2013)]

1- and 2-jet bin

State of the art: NLO for H+1,2 jets

[see e.g. Campbell et al. (2012)]

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

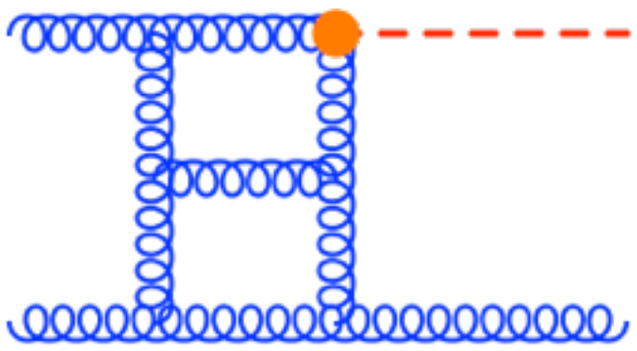
Large K-factors, error dominated by missing higher orders

UNCERTAINTY CAN BE REDUCED BY IMPROVING FIXED ORDER H+JETS PREDICTIONS

Higgs plus 1 jet at NNLO

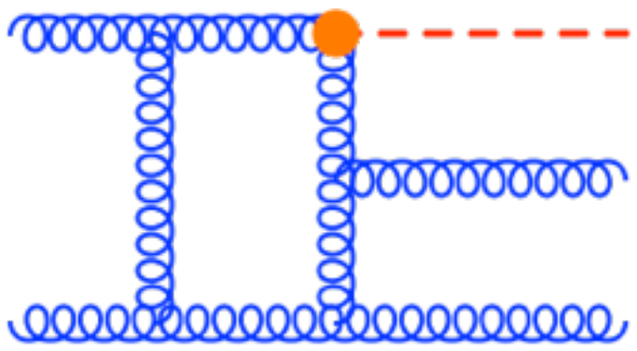
Anatomy of a NNLO computation

VV



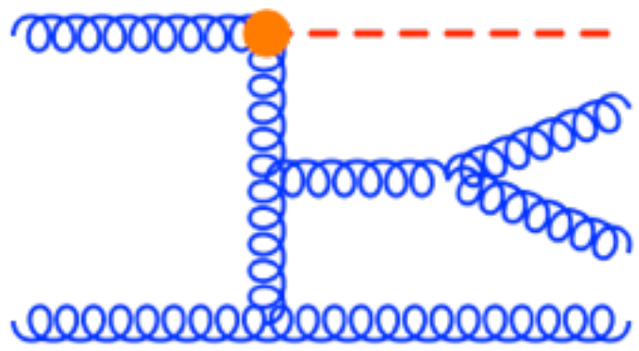
[Gehrmann et al. (2011)]

RV



[Badger et al. (2011)]

RR



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

Individual ingredients known for a while.

What prevented from doing the computation?

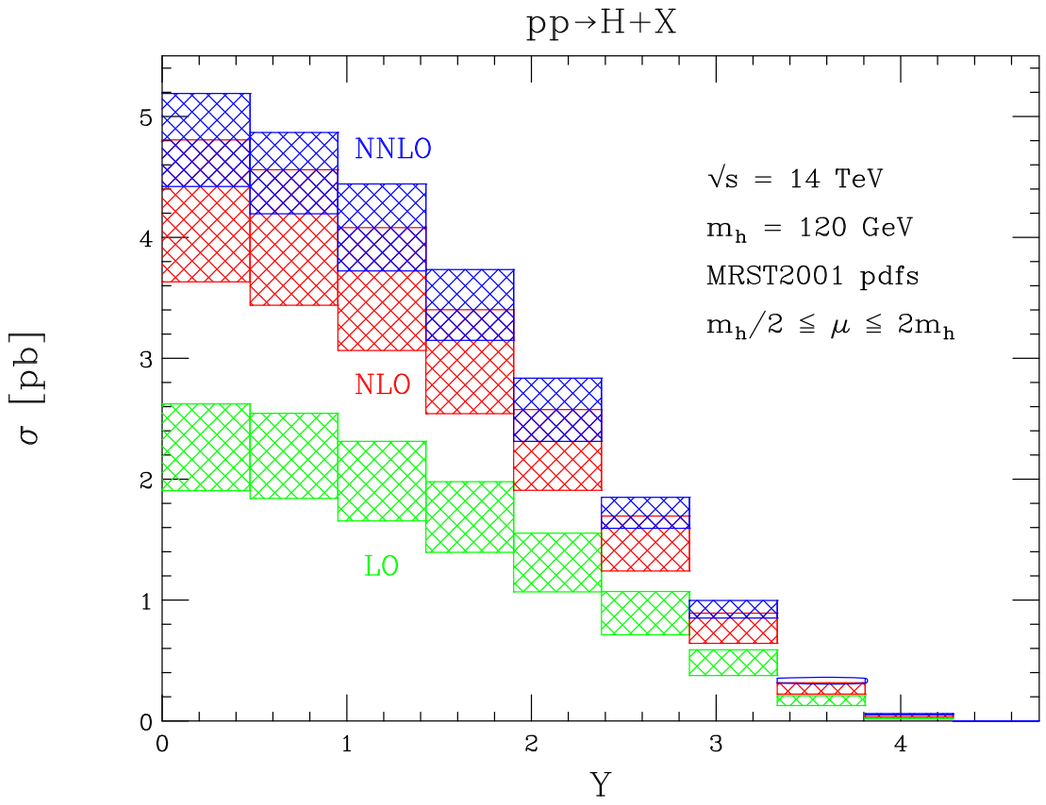
A (generic) procedure to extract IR poles from RV and RR was unknown until very recently

A successful strategy for simpler processes:

SECTOR DECOMPOSITION

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

Basic idea: CLEVER PARAMETRIZATION of the phase space which makes IR SINGULARITIES MANIFEST



Powerful tool for fully differential NNLO:

- dijet production at LEP
  [Anastasiou, Melnikov, Petriello (2004)]
- Higgs production at hadron colliders
  [Anastasiou, Melnikov, Petriello (2005)]
- DY production at hadron colliders
  [Melnikov, Petriello (2006)]

BUT

Parametrization becomes challenging for more complicated processes

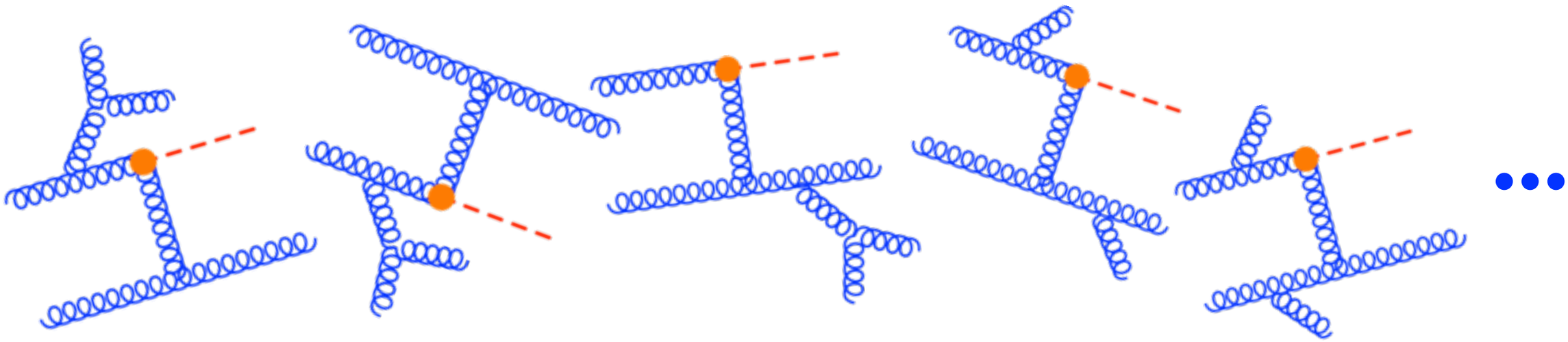
Parametrization known only for ONE COLLINEAR DIRECTION

As it is, highly process-dependent framework

Sector-improved subtraction scheme

[Czakon (2010)]

Combining sector decomposition and FKS partitioning makes extraction of singularities systematic and process-independent



- Basic NNLO building block: double unresolved configuration with two partons soft/collinear to hard directions

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[Czakon (2010)]

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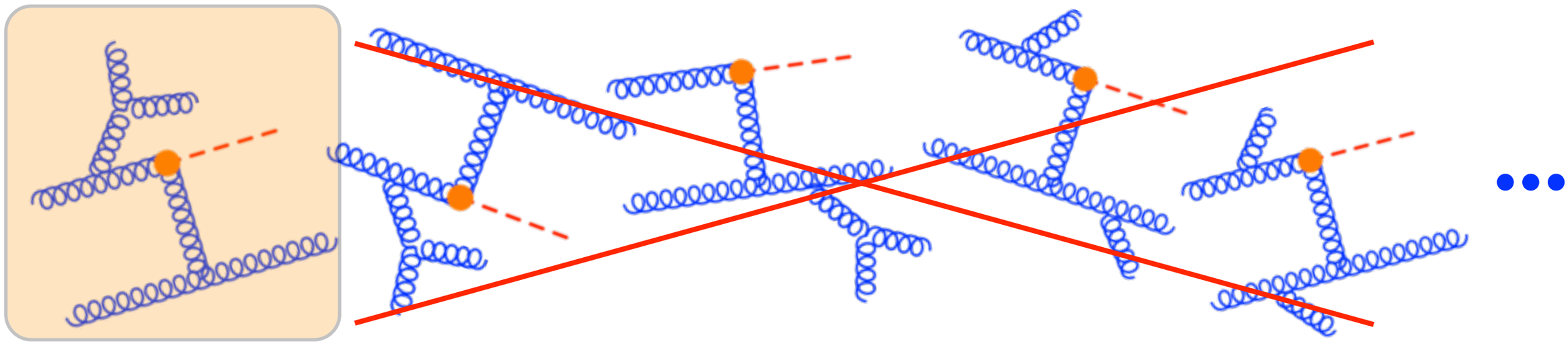

- Basic NNLO building block: double unresolved configuration with two partons soft/collinear to hard directions
- FKS: partition the phase space such that in each partition unresolved partons can be collinear only to a single hard direction (triple collinear),

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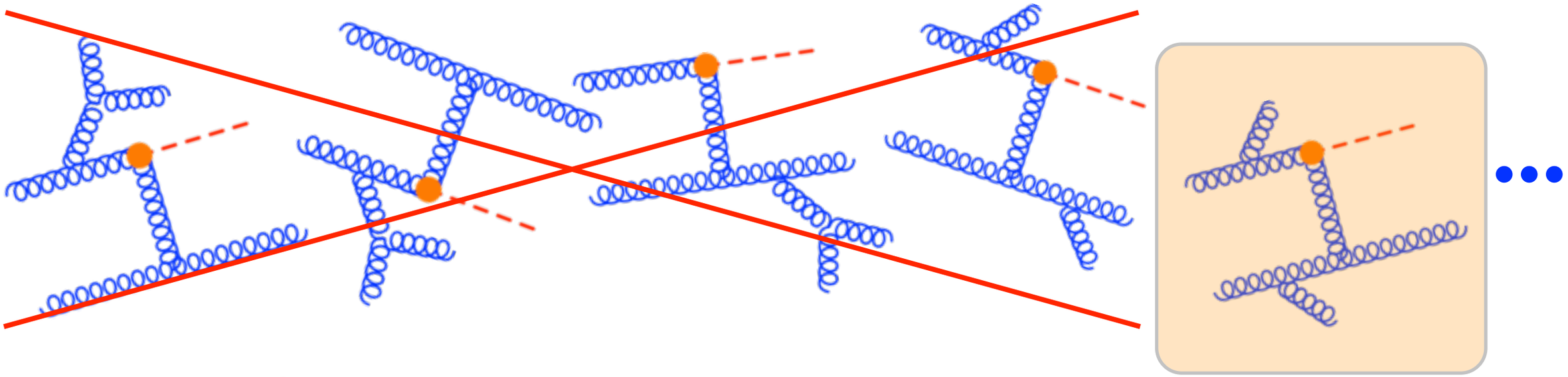


- Basic NNLO building block: double unresolved configuration with two partons soft/collinear to hard directions
- FKS: partition the phase space such that in each partition unresolved partons can be collinear only to a single hard direction (triple collinear), or a single pair of hard directions (double collinear)
- Use a local sector decomposition in each partition

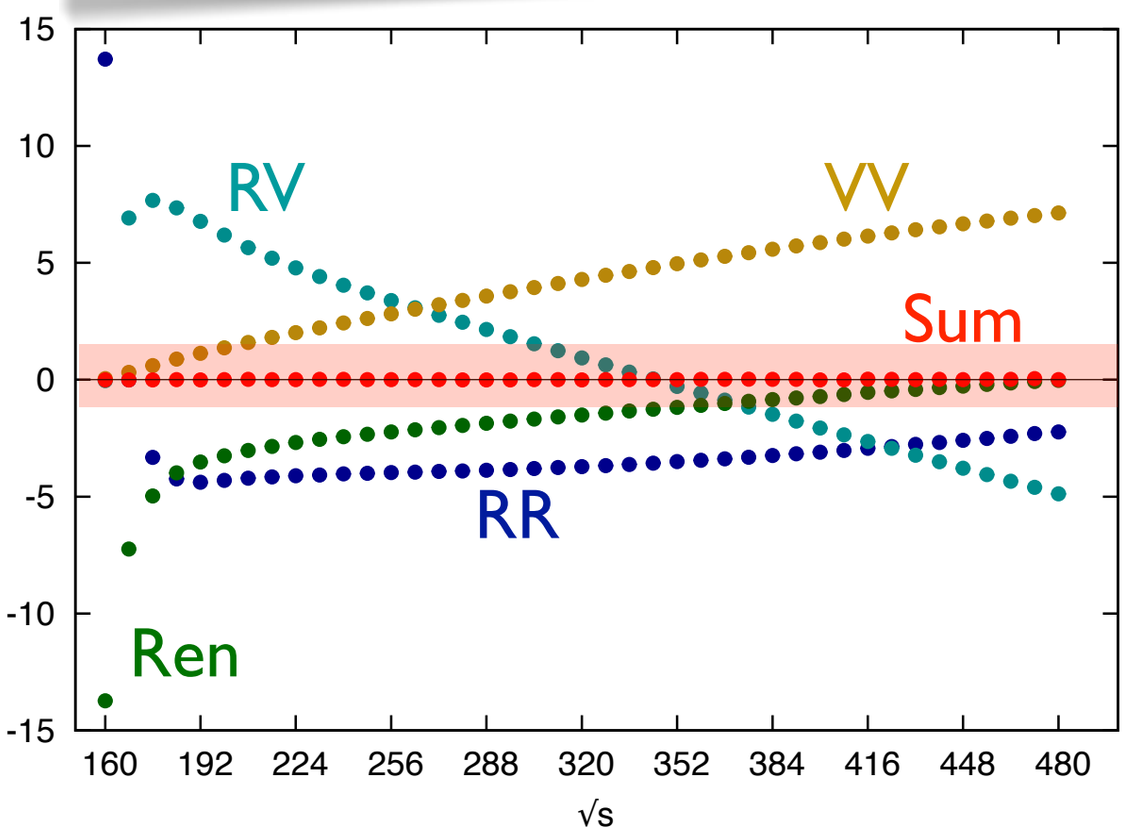
Bonus: parametrization in terms of energy/angles ⟶
physical singularities related to known eikonals/splitting functions

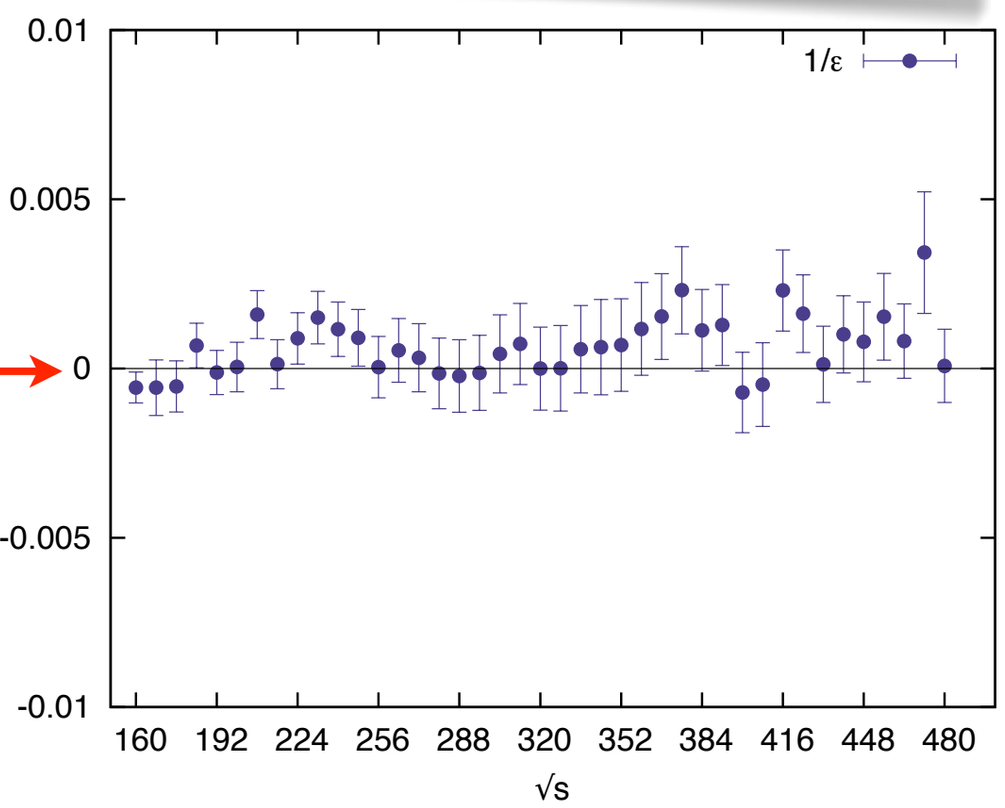
Higgs plus 1 jet at NNLO: results (gg only)

Checks

Two entirely independent computations (JHU/ANL-Northwestern)

NUMERICAL CANCELLATION OF INFRARED POLES
between different contributions:
renormalization and coll. couterterms, RR, RV, VV

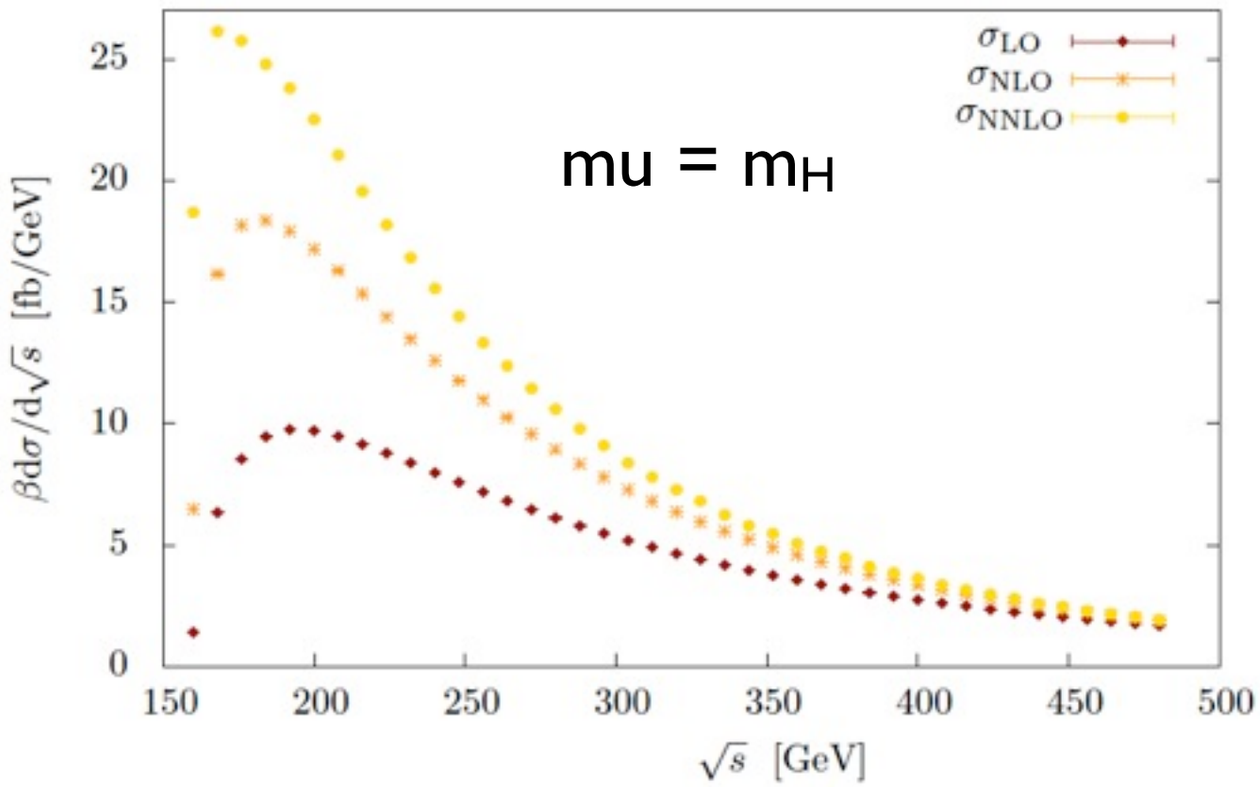


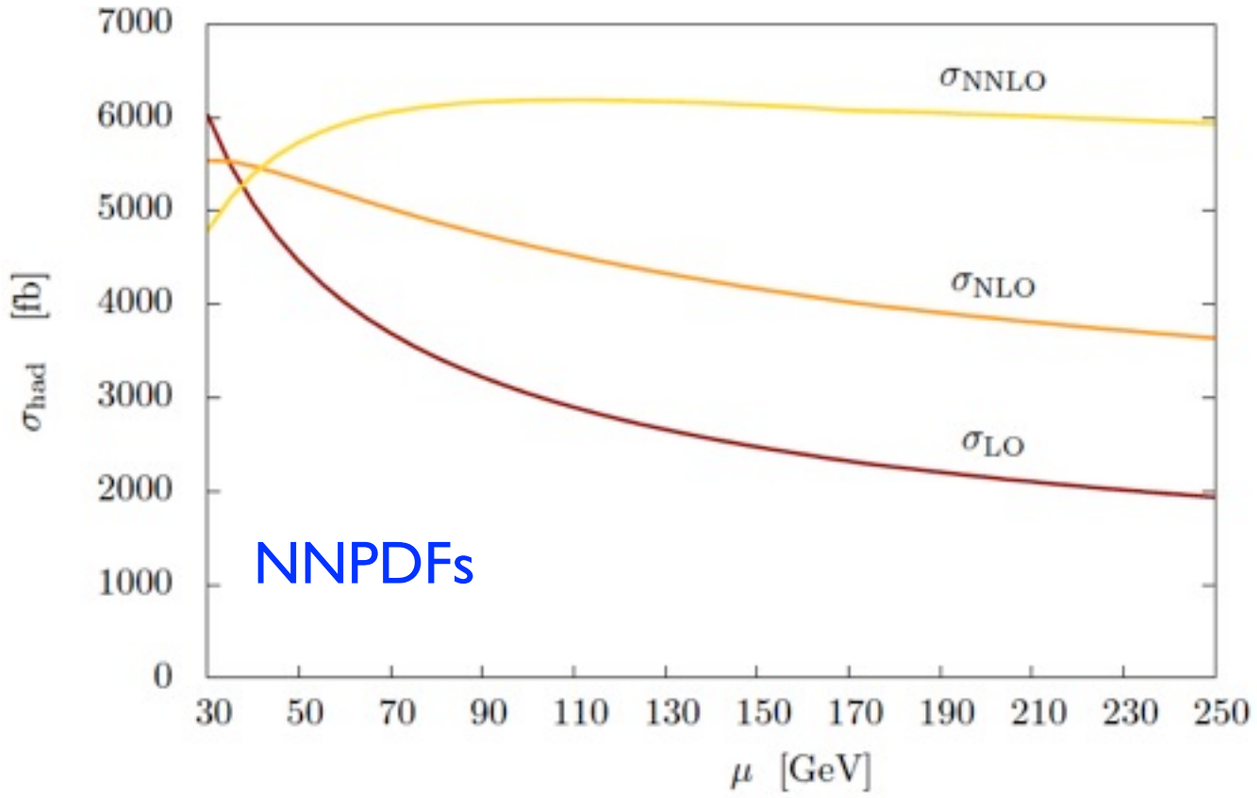


$1/\epsilon$ poles, summing individual contributions

(Higher poles: even better cancellation)

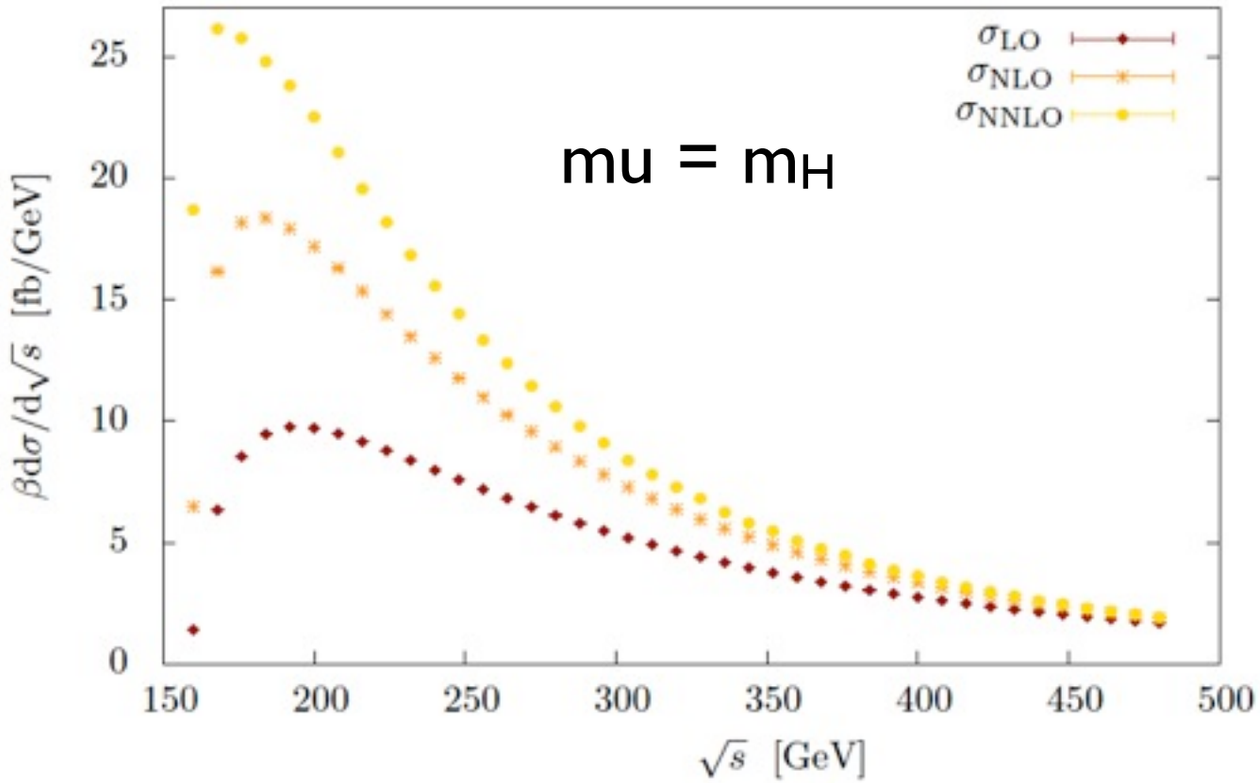
H+j @ NNLO (gg only)

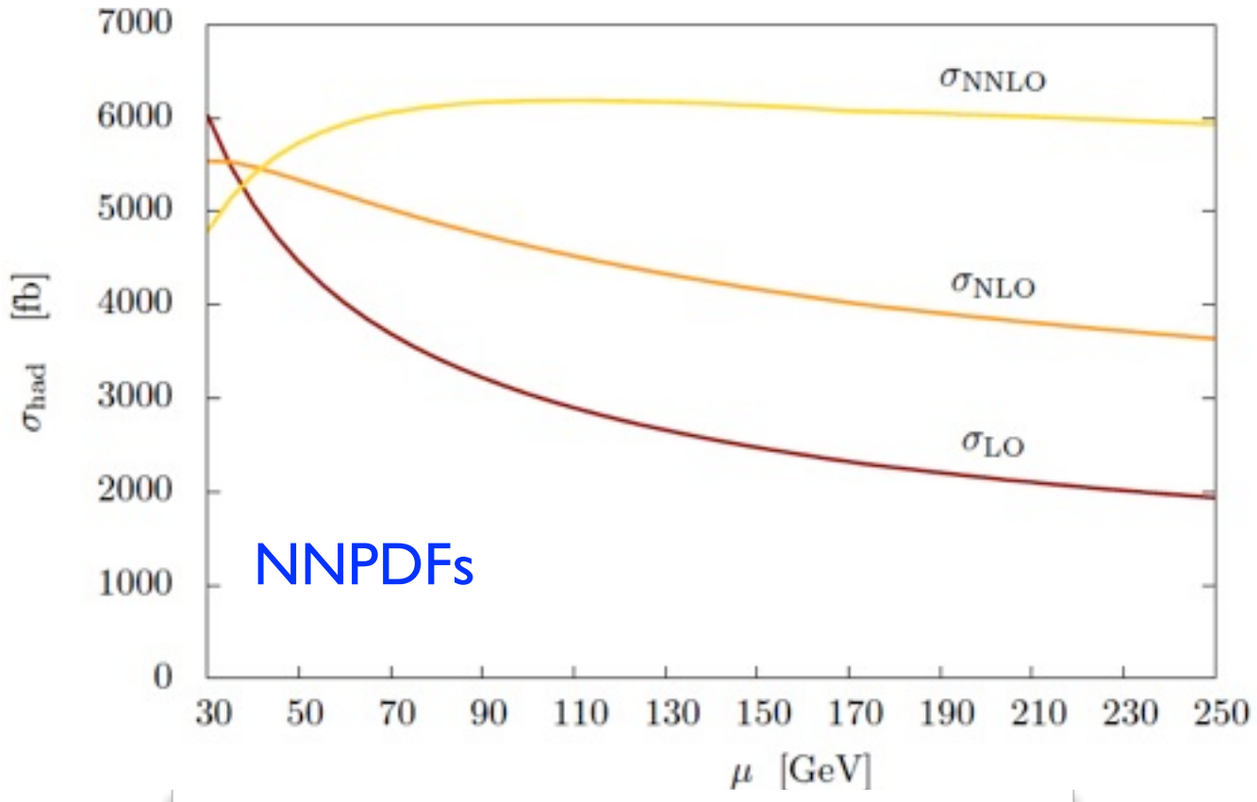




- Partonic cross section for gg → Hj @ LO, NLO, NNLO
- Realistic jet algorithm, k_T with R=0.5, p_T > 30 GeV
- Hadronic cross-section pp → Hj using latest NNPDF sets
- Scale variation in the range $m_H/2 < \mu < 2\ m_H$, m_H = 125 GeV

H+j @ NNLO (gg only)





$$\sigma_{\rm LO}(pp \to Hj) = 2713^{+1216}_{-776}\ \text{fb},$$
$$\sigma_{\rm NLO}(pp \to Hj) = 4377^{+760}_{-738}\ \text{fb},$$
$$\sigma_{\rm NNLO}(pp \to Hj) = 6177^{-204}_{+242}\ \text{fb}.$$

Large K-factors

σ_{NLO}/σ_{LO} = 1.6

$\sigma_{NNLO}/\sigma_{NLO}$ = 1.3

Significantly reduced O(4%) scale dependence

Conclusions

- We presented results for H+1j @ NNLO (gg only)
- Result urgently needed to reduce theoretical uncertainties in jet-bin based analyses
- gg channel: ~ 70% of the full result (NLO), and corrections to other channels expected to be smaller (color charges)
- Result already useful for preliminary phenomenological studies
- Large O(30%) NNLO/NLO K-factor
- Improved scale variation: 30% (NLO) → 4% (NNLO)
- PDFs uncertainty: 1-2%

Conclusions

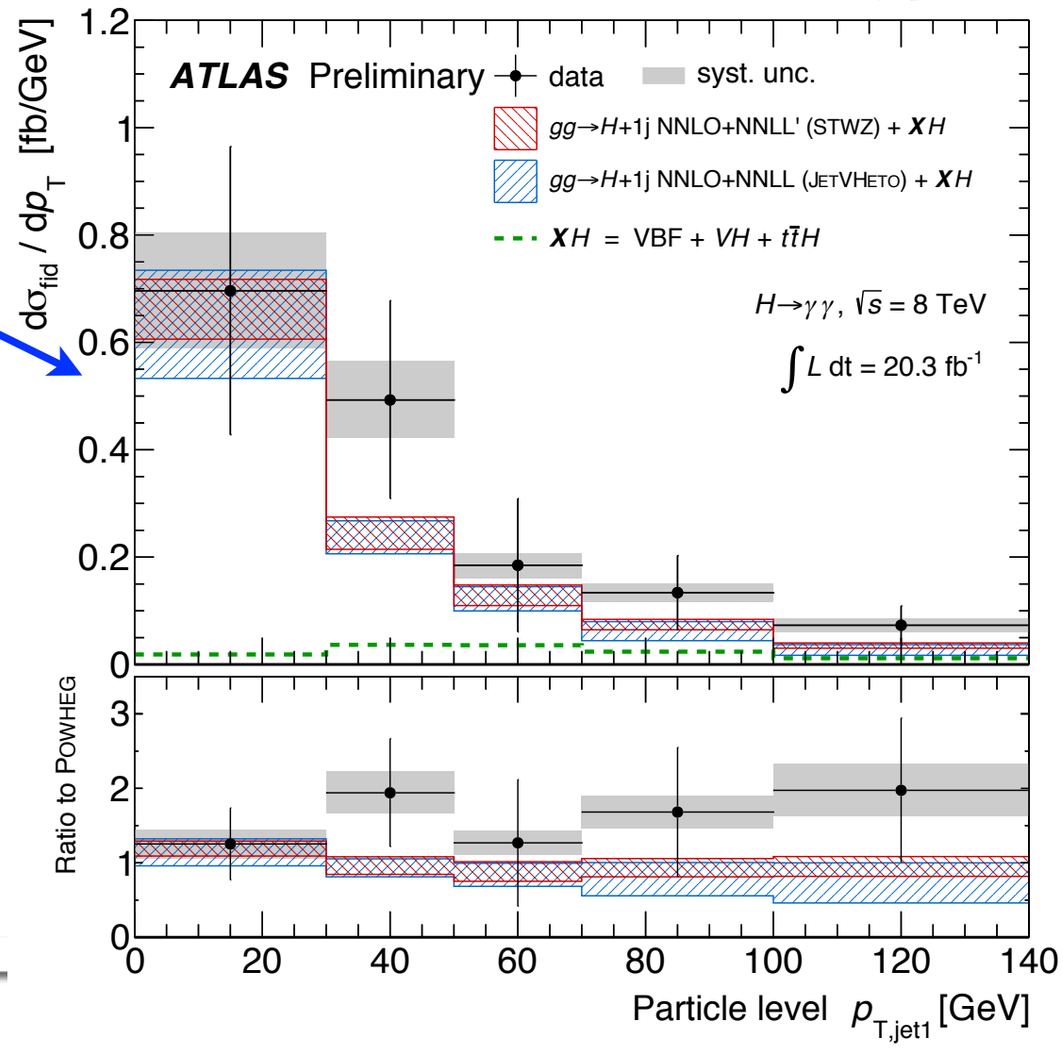
- One of the first NNLO QCD results for 2→2 processes whose existence depends on a jet algorithm [dijet: Gehrmann et al.]
- Prototype of a generic NNLO computation
  - most generic singularity structure (initial, final and mixed collinear singularities)
  - large number of diagrams, but compact results with spinor-helicity techniques
  - all technical complications are present (spin correlations...)
- Robust test of the theoretical framework
  - [Czakon (2010)], [Boughezal, Melnikov, Petriello (2011)]
  - Very similar to the framework used for the computation of the NNLO ttbar cross section [Czakon, Mitov et al.]

Outlook

- Include quark-gluon channel, for reliable phenomenology
  - reliable results in the 1-jet bin
  - more precise description of jet-vetoed cross section
  - genuine NNLO analysis of the Higgs p_T spectrum

(see J.B. Devivie's talk this morning)

- Include Higgs decays (trivial)
- Compute differential distributions
  - already done within this framework for top decay and charmless b-decay [Brucherseifer, FC, Melnikov (2013)]
- Run with ATLAS/CMS setup



Thank you for your attention!