Hard QCD for the LHC: status and perspectives

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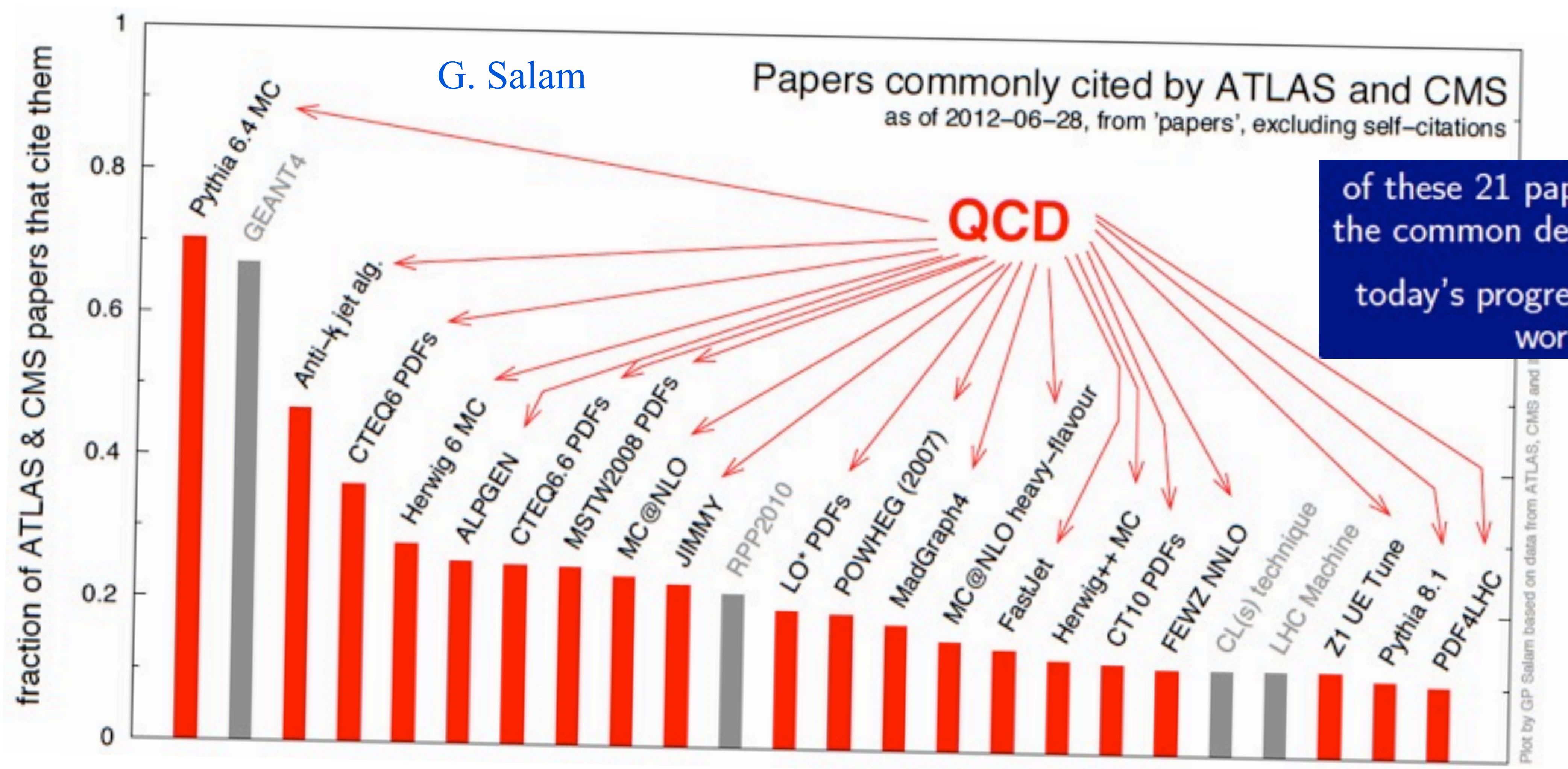
Why do we care about QCD

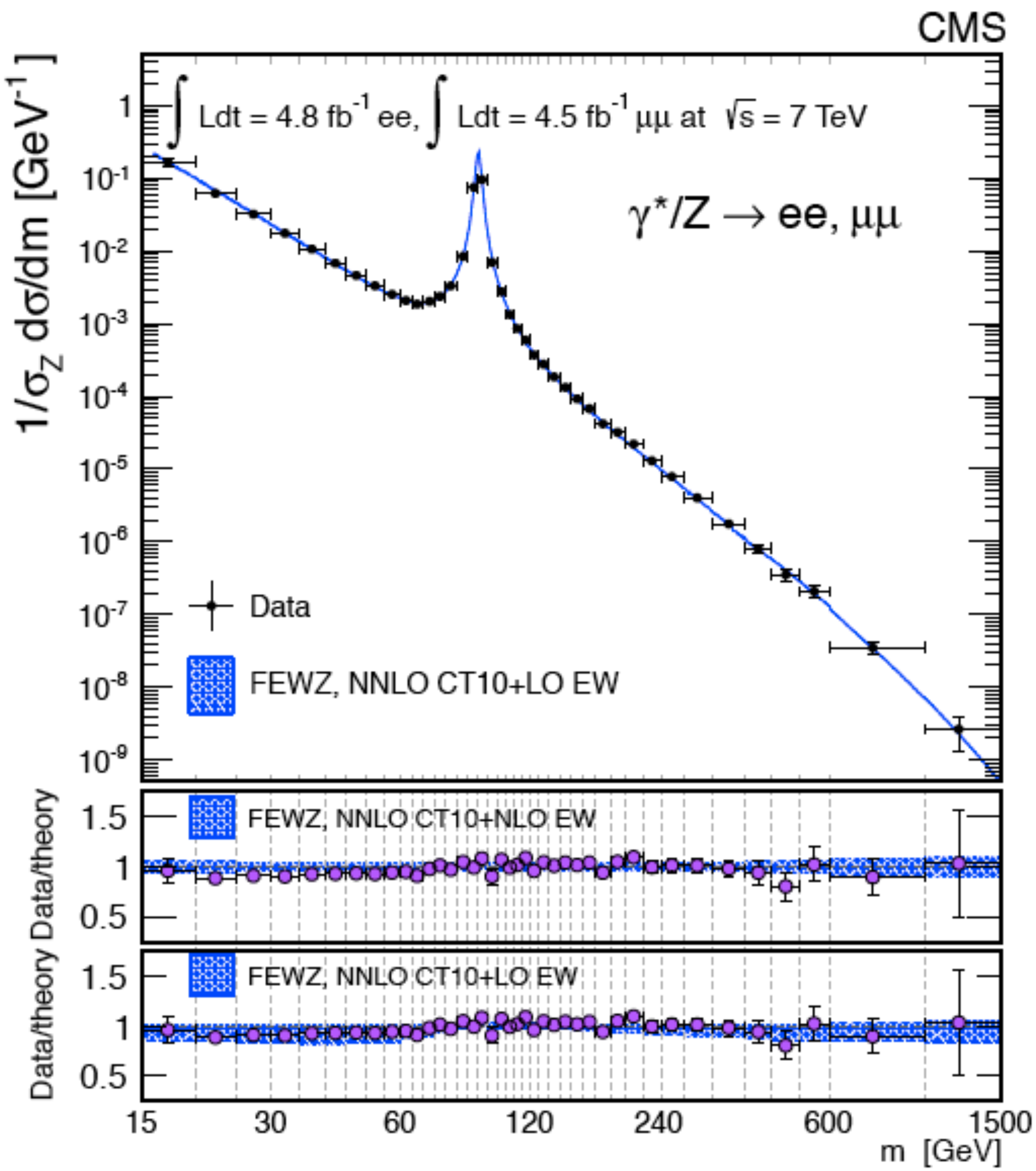


of these 21 papers, 19 are QCD: the common denominator at LHC

today's progress = tomorrow's workhorse

No real understanding of LHC physics is possible without sophisticated QCD calculations!

QCD Today



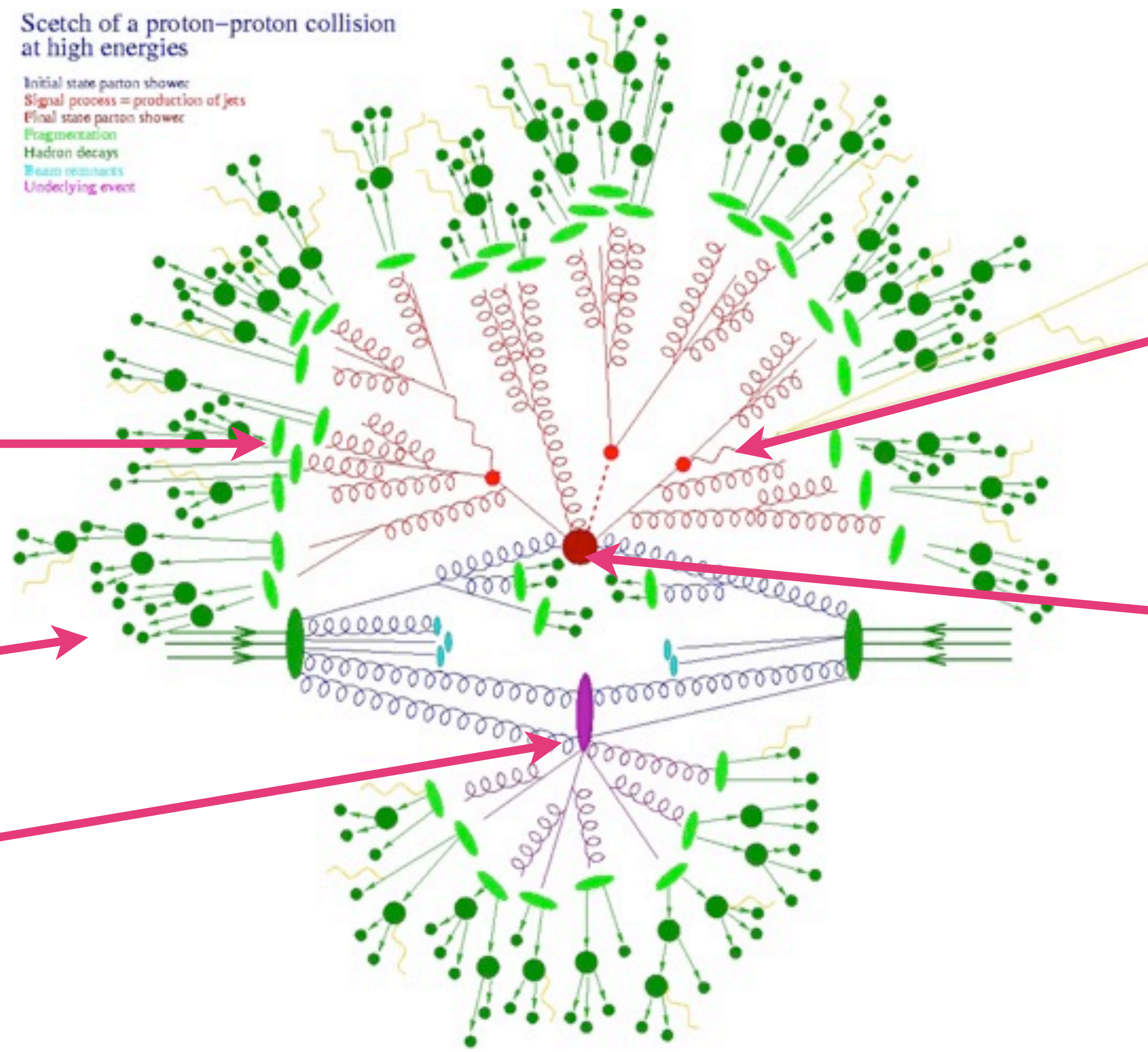
- NLO+parton shower tools now standard tools used in analyses
- NNLO QCD, sometimes with NLO EW combined, are becoming available for more and more channels
- Several global NNLO PDF extractions with robust errors now available

Outline

- The NLO frontier: methods, tools, highlights
- Merging fixed order results with parton showers
- Jet vetoes and analytic resummation
- The NNLO frontier: where we stand right now
- Summary and outlook

Hadronic Collisions at the LHC

- From a theorist's perspective, the challenge is dealing with QCD



$$\sigma_{h_1 h_2 \to X} = \int dx_1 dx_2 \underbrace{f_{h_1/i}(x_1; \overbrace{\mu_F^2}^{\text{factorization scale}}) f_{h_1/j}(x_2; \mu_F^2)}_{PDFs} \underbrace{\sigma_{ij \to X}(x_1, x_2, \mu_F^2, \{q_k\})}_{\text{partonic cross section}} + \underbrace{\mathcal{O}\left(\frac{\Lambda_{QCD}}{Q}\right)^n}_{\text{power corrections}}$$

NLO Predictions

- They provide the first reliable prediction (correct shape and normalization, accounts for effects of extra radiation, smaller scale dependence)

$$\sigma^{NLO}_{(m)} = \int_{\Phi_m} \left[\mathrm{d}\sigma^{Born} + \mathrm{d}\sigma^{V} + \int_{\Phi_1} \mathrm{d}\sigma^{S} \right] + \int_{\Phi_{m+1}} \left[\mathrm{d}\sigma^{R} - \mathrm{d}\sigma^{S} \right]$$

- Amazing recent progress with multiple codes and two major directions:

☑ more processes: towards full automation of NLO calculations with codes like GoSam, Helac-NLO, OpenLoops, MadGraph/aMC@NLO

☑ more legs: e.g. Blackhat focuses on pure n-jets or W/Z+ n-jets, pushing the frontier of n (currently n=5)

Enabling Tools

- NLO precision frontier has become a mature field. One-loop amplitudes can be calculated by many codes:
  - Blackhat (Bern, Dixon, Febres Cordero, Hoeche, Ita, Kosower, Maitre, Ozeren)
  - CutTools (Ossola, Papadopoulos, Pittau)
  - GoSam (Cullen, Greiner, Heinrich, Luisoni, Mastrolia, Ossola, Reiter, Tramontano)
  - MadLoop/aMC@NLO (Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Pittau, Stelzer, Torrielli, Zaro)
  - NJET (Badger, Biedermann, Uwer, Yundin)
  - OpenLoops (Cascioli, Maierhoefer, Pozzorini)

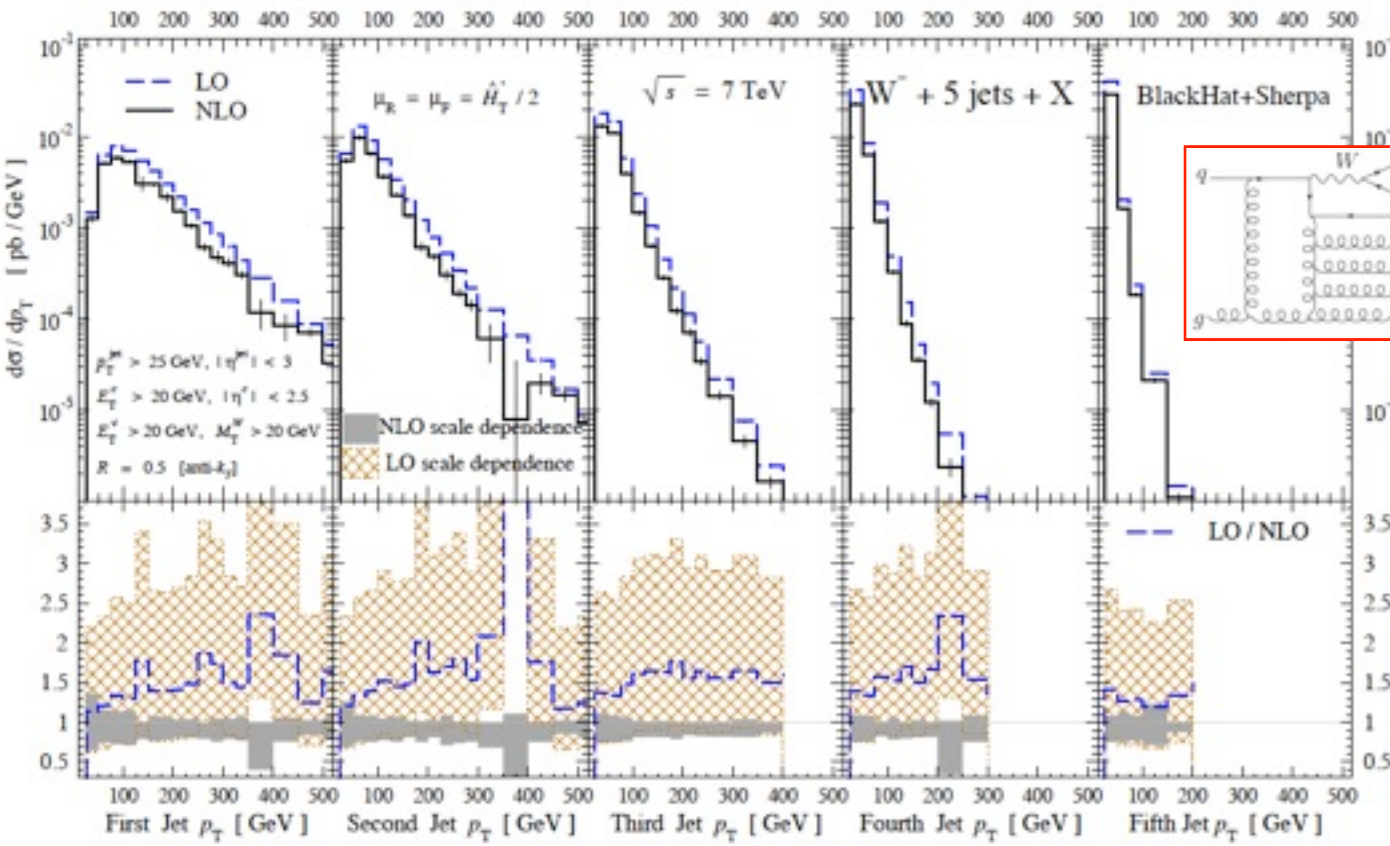
- Real radiation, subtraction terms and phase space integration:
  - HelacNLO (Bevilacqua et al)
  - Madgraph/MadEvent (Maltoni et al)
  - MCFM (Campbell, Ellis, Williams)
  - Sherpa (Krauss et al)

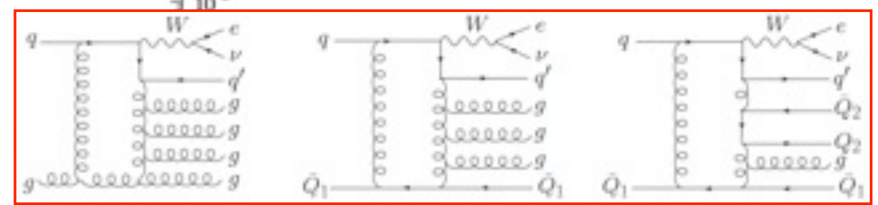
Many Results ...

- Successfully used the tools for many challenging calculations:
  - multiple jets (currently up to 4) (Blackhat + Sherpa: Bern et al; NJet: Badger et al)
  - gauge bosons and up to 5 jets (Blackhat + Sherpa: Bern et al)
  - Higgs with a top quark pair and 1 jet (GoSam+Sherpa+MadEvent: van Deurzen et al)
  - Higgs and up to 3 jets (GoSam+Sherpa+MadEvent: Cullen et al)
  - two gauge bosons with up to 2 jets (Melia et al; VBFNLO: Campanario et al)
  - three gauge bosons (VBFNLO: Bozzi et al)
  - top quarks with jets (up to 2) (Denner, Dittmaier, Kallweit, Pozzorini; Bevilacqua, Czakon, Papadopoulos, Worek)
  - top quarks with a gauge boson (Lazopoulos, Melnikov, Petriello; Melnikov, Schulze, Scharf; HelacNLO:Kardos et al; MCFM: Campbell, Ellis)

Can only show some highlights in the next slides.....

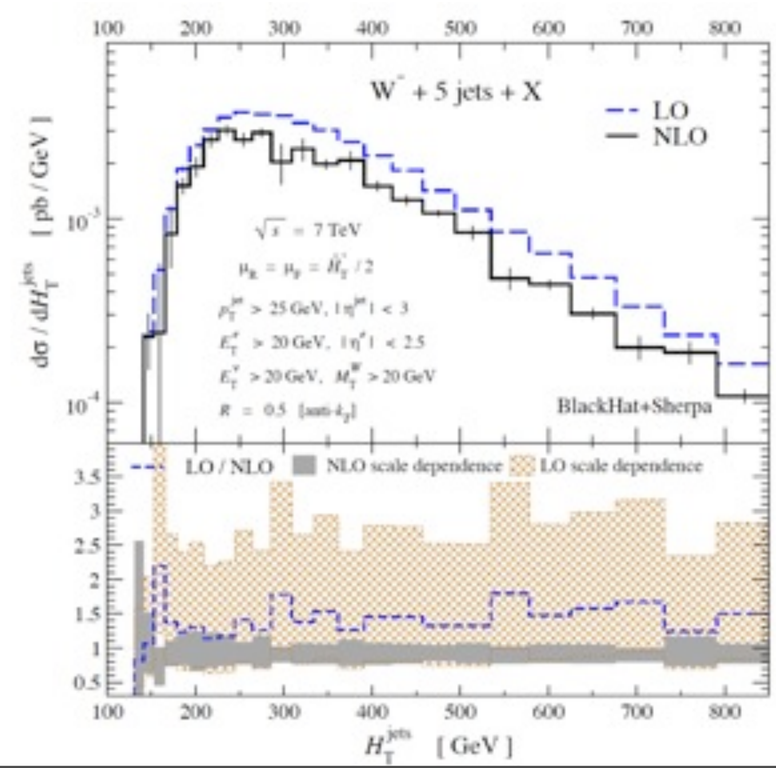
NLO highlights: W+5jets





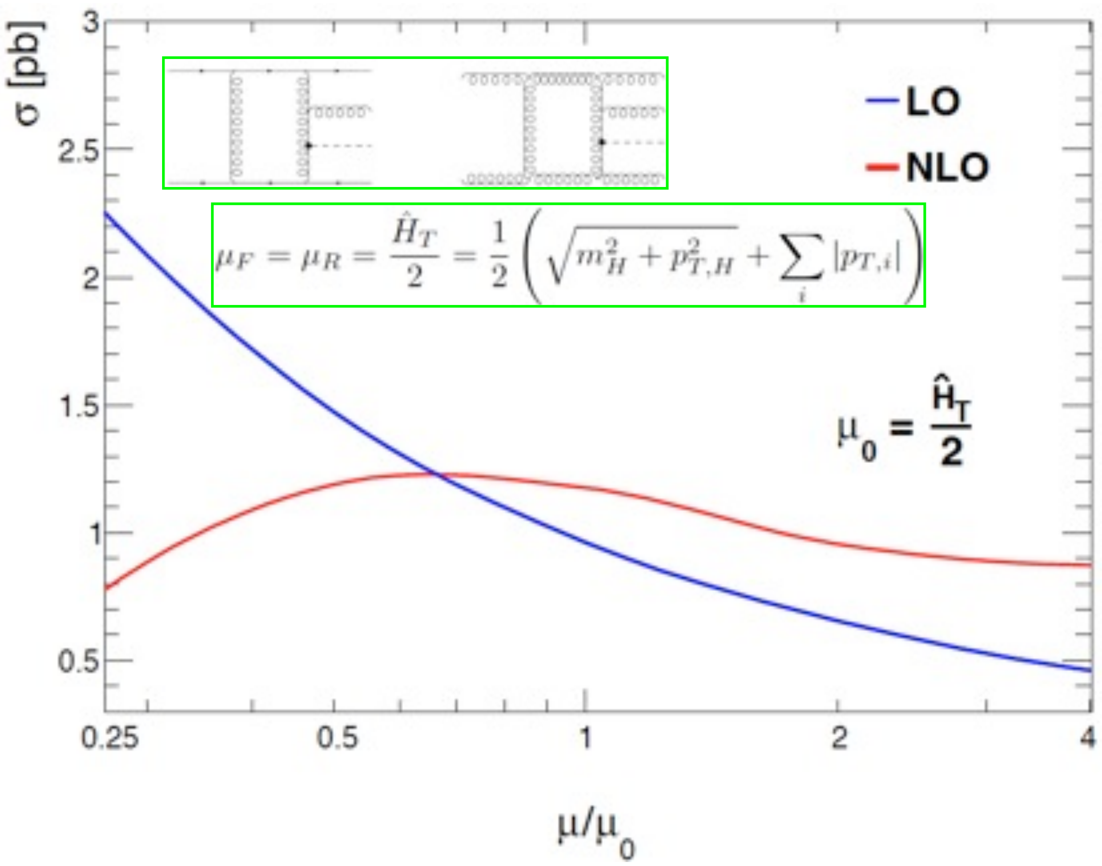
Bern, Dixon, Febres Cordero, Hoeche, Ita, Kosower, Maitre, Ozeren (2013)

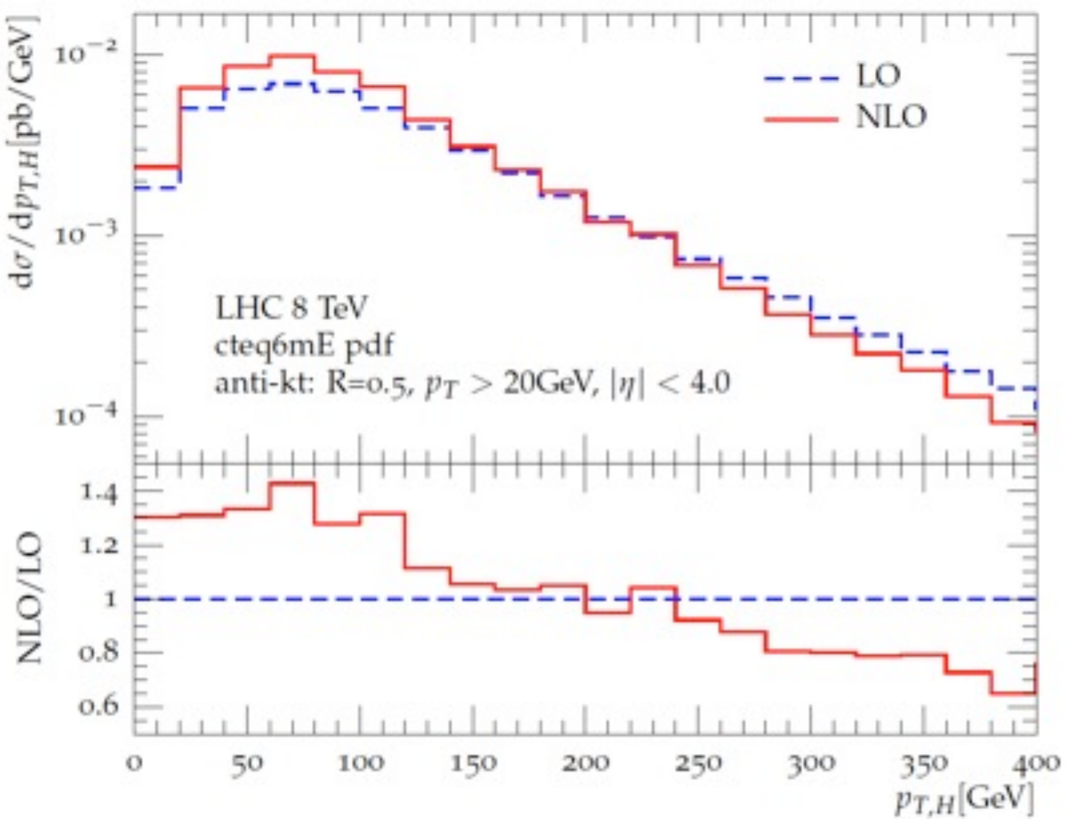
- First 2 $\longrightarrow$ 6 NLO calculation at a hadron collider using Blackhat + Sherpa
  - Dynamical scale choice: $\mu_R = \mu_F = \hat{H}'_T/2$ $\quad \hat{H}'_T \equiv \sum_m p^m_T + E^W_T$
  - scale variation: $\mu/2 \ldots 2\,\mu$
  - reduced scale dependence at NLO
  - Ratio of NLO/LO constant over full kinematic range



NLO helps to motivate the scale choice

NLO highlights: H+3jets





GoSam: Cullen, van Deurzen, Greiner, Luisoni, Mastrolia, Mirabella, Ossola, Peraro, Tramontano

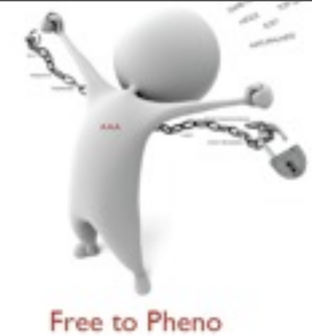
- Can be used to improve the theoretical prediction of the exclusive H+2jet bin

$$\sigma_2 = \sigma_{\geq 2} - \sigma_{\geq 3}$$

- NLO corrections affect the shape of the $P_{T,Higgs}$ distribution

- NLO corrections improve the scale dependence

MadGraph5_aMC@NLO



- Promises to provide NLO computations in any model with the press of a button

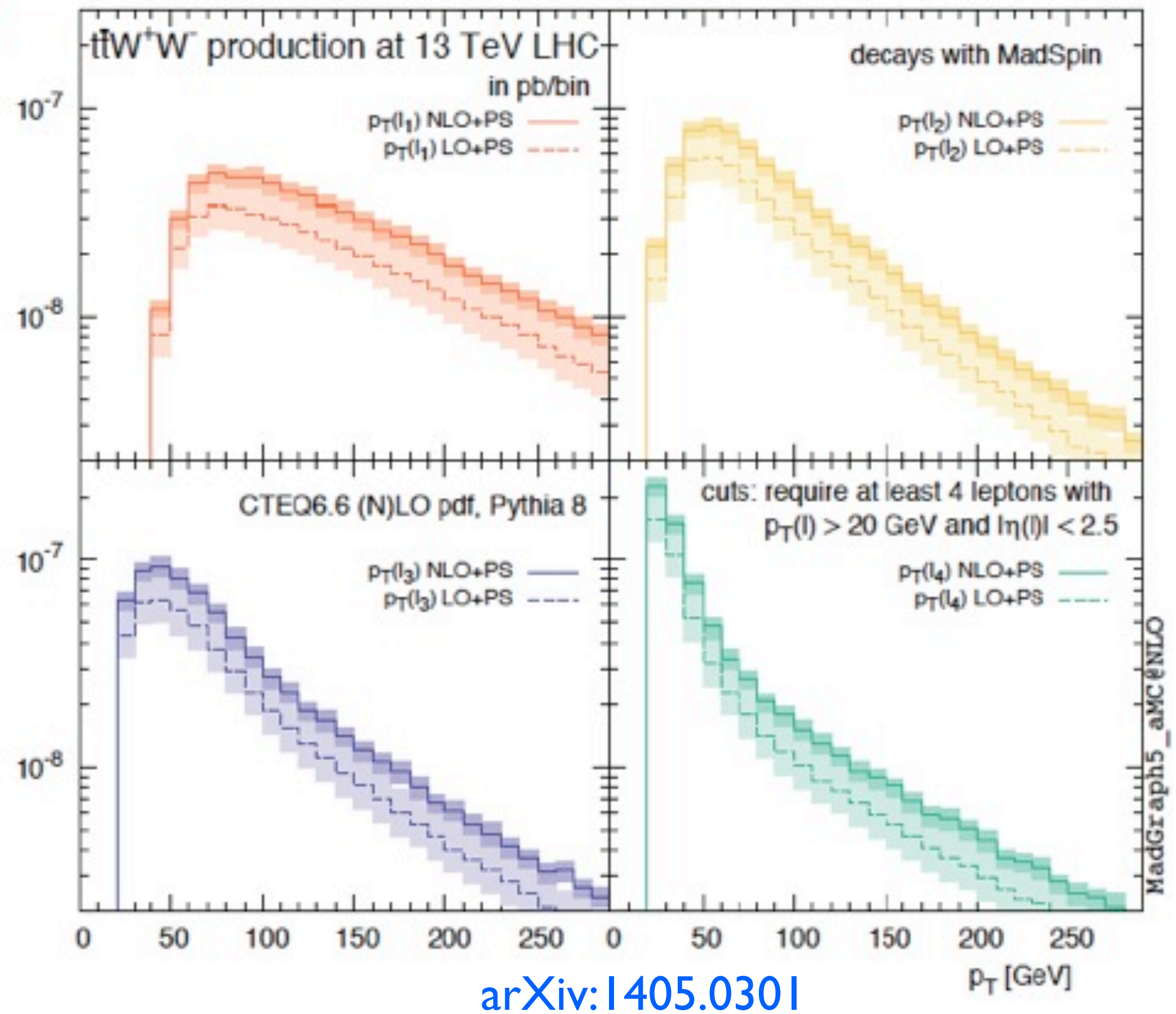
Suppose now you are interested in multi-lepton backgrounds to SUSY. You might want to check:

F. Maltoni, Physics at 100TeV collider workshop, SLAC 2014

```
./bin/mg5_aMC
> generate p p > t t~ W+ W- [QCD]
> output ttww
> launch
```

where heavy states can then be decayed by MadSpin keeping spin correlations.

Uncertainties from scale variation and pdfs **are automatically computed** (at no extra cost) and associated to each of the **unweighted events** (=any distribution will have the corresponding uncertainty band)



arXiv:1405.0301

Merging Fixed Order Results with Parton Showers

- Benefits of combining NLO+PS:
  - First hard emission correctly described by NLO
  - Virtual corrections get the correct normalization of the inclusive cross section
  - Resummation of soft+collinear radiation described by the parton shower

- Challenge: avoid double counting

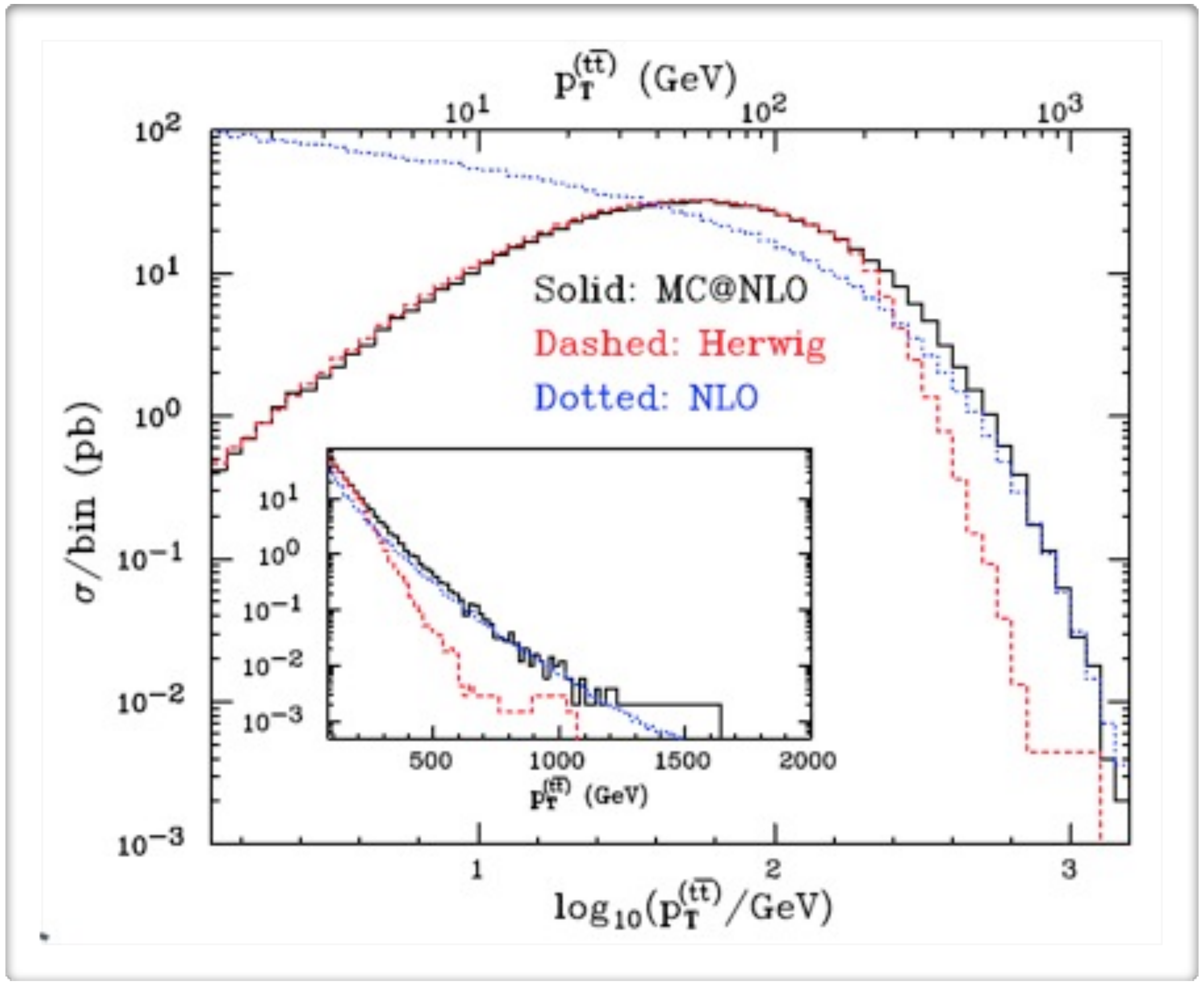
- Two established methods:

  - MC@NLO (Frixione, Webber)
  - POWHEG (Nason; Frixione, Nason, Oleari)

- Combines NLO accuracy for hard radiation with multiple soft emissions

  - High P_T described by NLO
  - Low P_T described by parton shower

- Many recent results of NLO predictions combined with parton shower

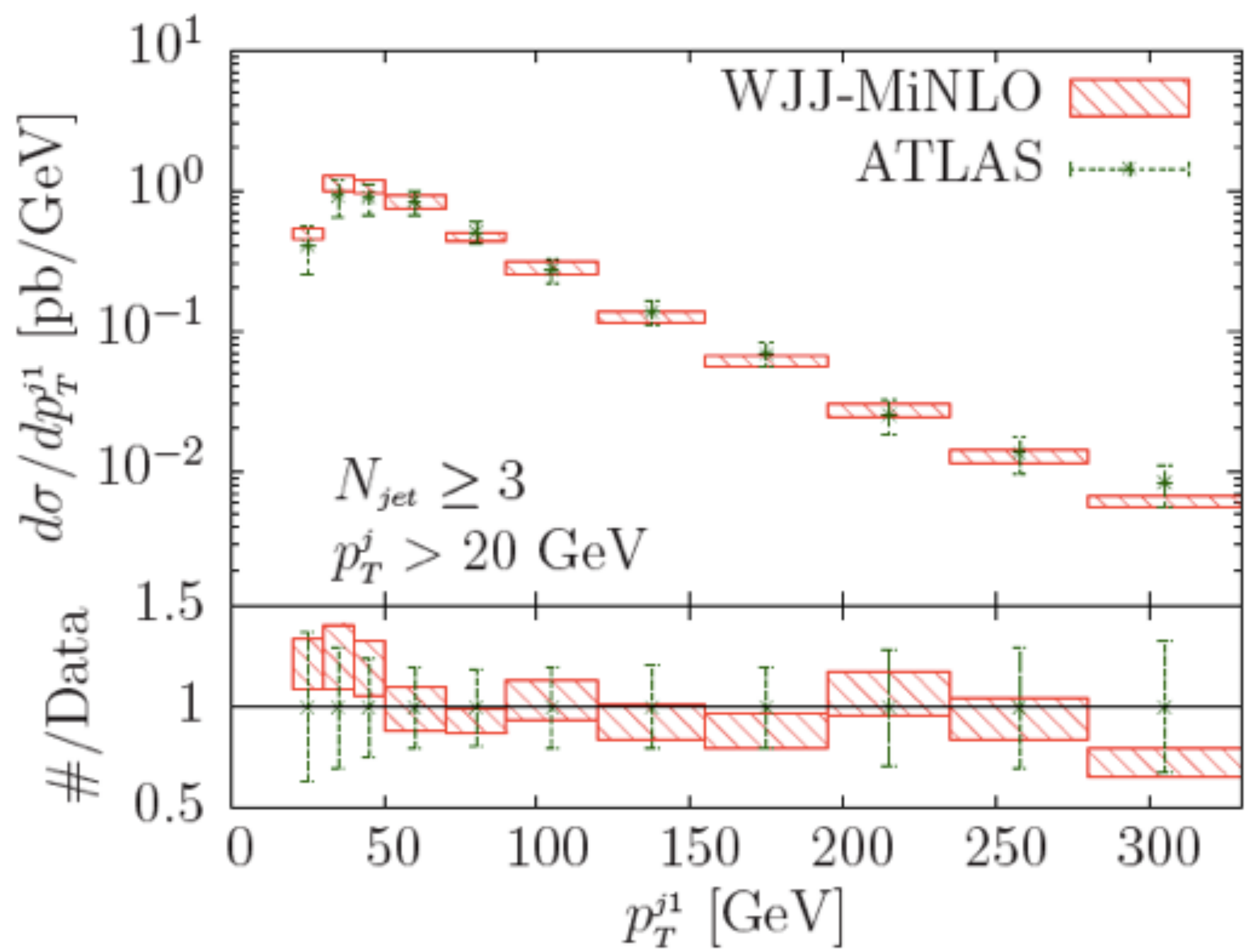


Top-quark pair production at Tevatron: P_T-distribution (Frixione, Nason, Webber)

Packing the POWHEG box

- The 'POWHEG box' method has been developed to allow any NLO calculations to be easily combined with a parton shower (Alioli, Nason, Oleari, Re (2010))
- Simulations with NLO+PS accuracy are becoming the standard, even for previously complex, multi-particle final states
- A recent example combining Vjj@NLO from MCFM: (Campbell, Ellis, Nason, Zanderighi (2013))

  - Provides a good description of the final-state kinematics over the entire range
  - Allows perturbative uncertainties, and parton-shower modeling uncertainties, to be simultaneously studied



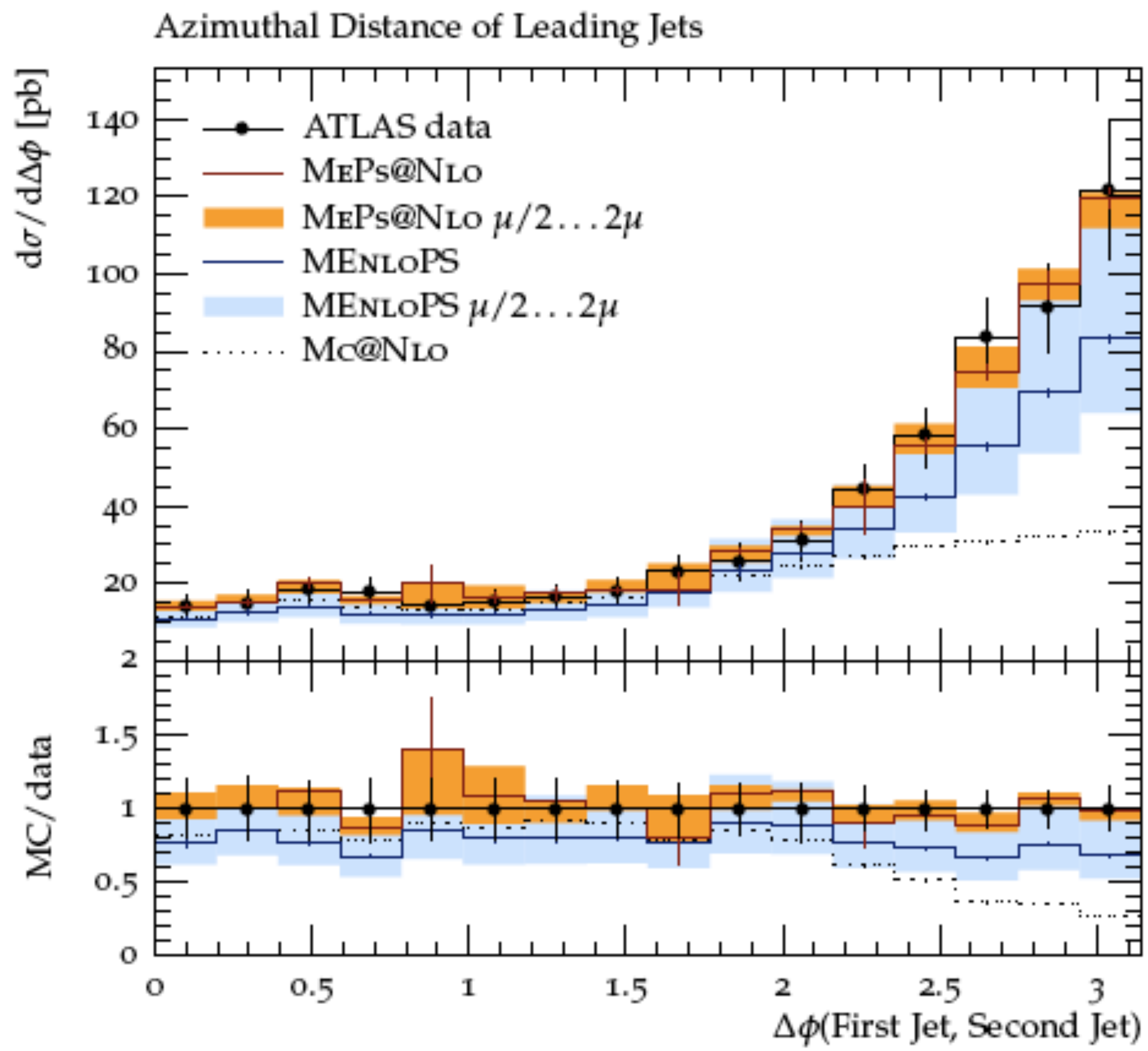
New directions in N^nLO+PS

- Efforts to combine NLO+PS for processes of differing jet multiplicity
- Very active field!

  - SHERPA (Hoeche, Krauss, Schoenherr, Siegert)
  - MINLO (Hamilton, Nason, Oleari, Zanderighi)
  - UNLOPS (Lonnblad, Prestel)
  - FxFx (Frixione, Frederix)

- Beginning attempts to combine NNLO with parton showers; stay tuned!

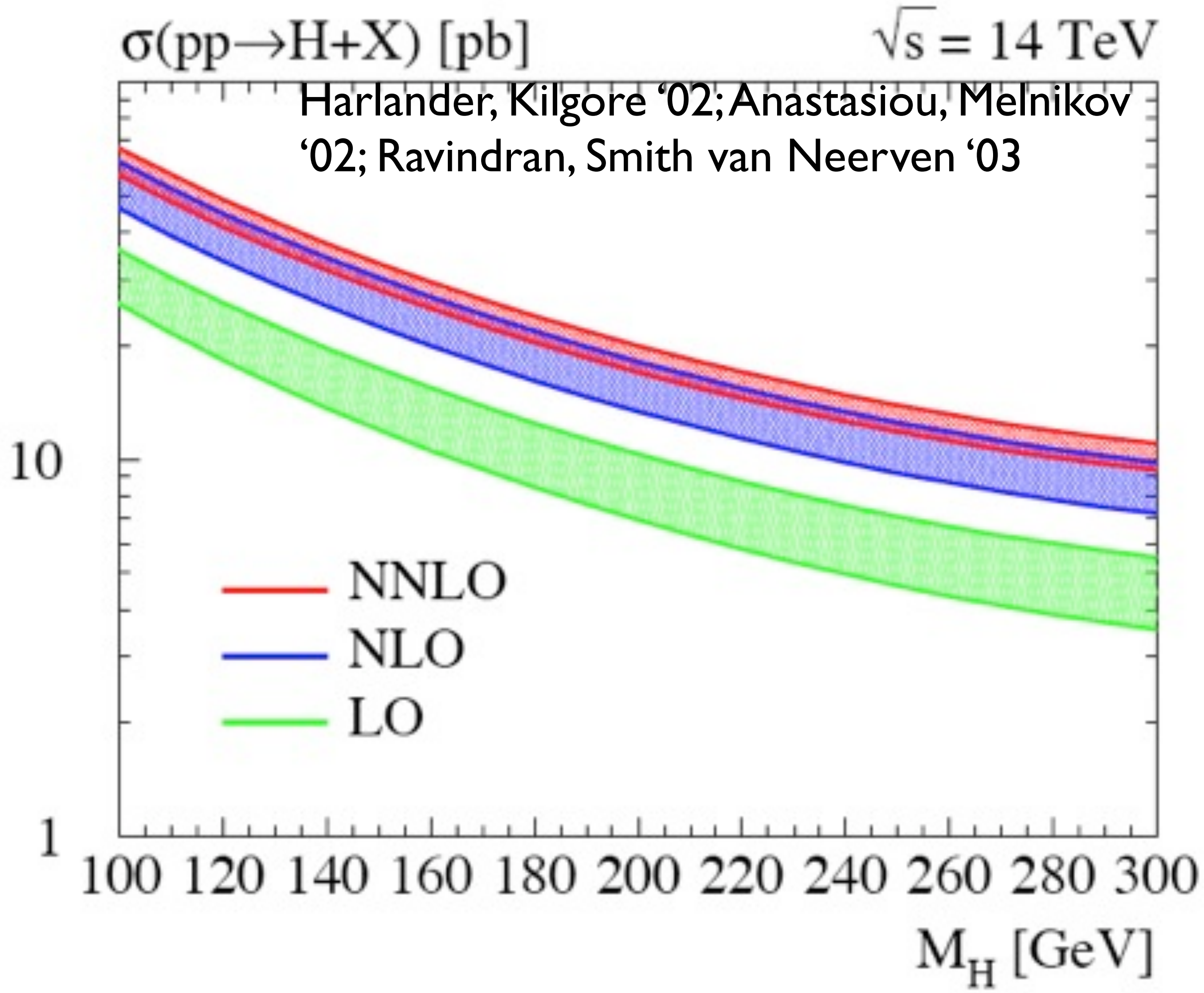
  - UNLOPS+SHERPA for Drell-Yan (Hoeche, Li, Prestel)
  - MINLO for Higgs production (Hamilton, Nason, Oleari, Zanderighi)
  - The GENEVA framework (Alioli, Bauer, Berggren, Tackmann, Walsh, Zuberi)



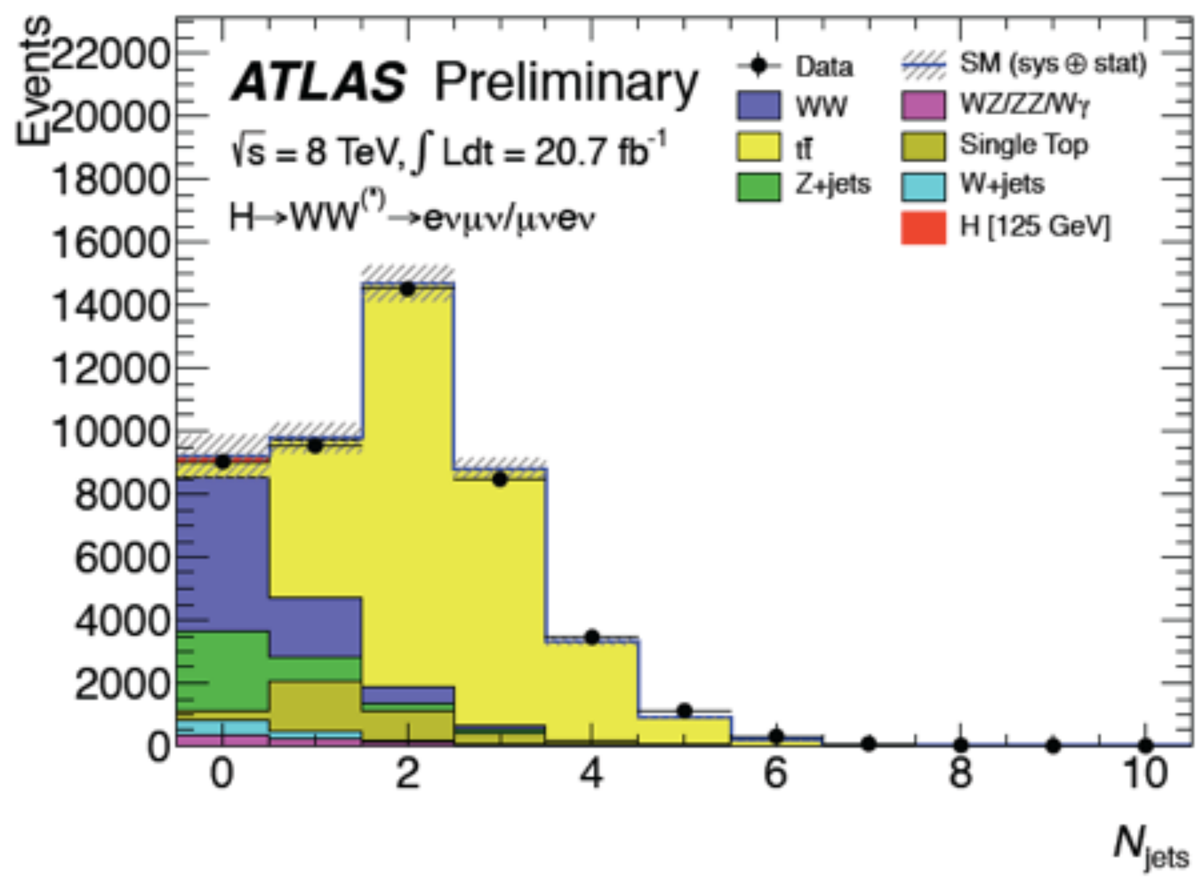
- MEPS@NLO example from Sherpa combines NLO W+0,1,2 jets into a single event sample
- Improvement over basic MC@NLO for W+0 jets for observables that probe jet proerties, such as azimuthal separations

How much is enough?

• Higgs production in gluon fusion offers an excellent example for the need of high precision predictions: two reasons for the dominance of theory uncertainties



Large fixed-order QCD corrections to Higgs production processes



Division into exclusive jet bins introduces large logarithms that must be resummed

• Progress on both fronts needed to improve Higgs-signal modeling for Run II of the LHC, as well as controlling PDFs and parametric uncertainties.

Combining fixed-order and analytic resummation

- Parton showers resum leading logarithms (LL) and partial next-to-leading logarithms (NLL) in phase-space regions dominated by soft+collinear radiation
- For many important processes we require resummation to NNLL and beyond matched to high-precision fixed-order

Source **ATLAS**	$N_{jet}=0$	$N_{jet}=1$	$N_{jet}\geq 2$
Theoretical uncertainties on total signal yield (%)			
QCD scale for ggF, $N_{jet}\geq 0$	+13	-	-
QCD scale for ggF, $N_{jet}\geq 1$	+10	−27	-
QCD scale for ggF, $N_{jet}\geq 2$	-	−15	+4
QCD scale for ggF, $N_{jet}\geq 3$	-	-	+4
Parton shower and underlying event	+3	−10	±5
QCD scale (acceptance)	+4	+4	±3
Experimental uncertainties on total signal yield (%)			
Jet energy scale and resolution	5	2	6
Uncertainties on total background yield (%)			
WW transfer factors (theory)	±1	±2	±4
Jet energy scale and resolution	2	3	7
b-tagging efficiency	-	+7	+2
f_{recoil} efficiency	±4	±2	-

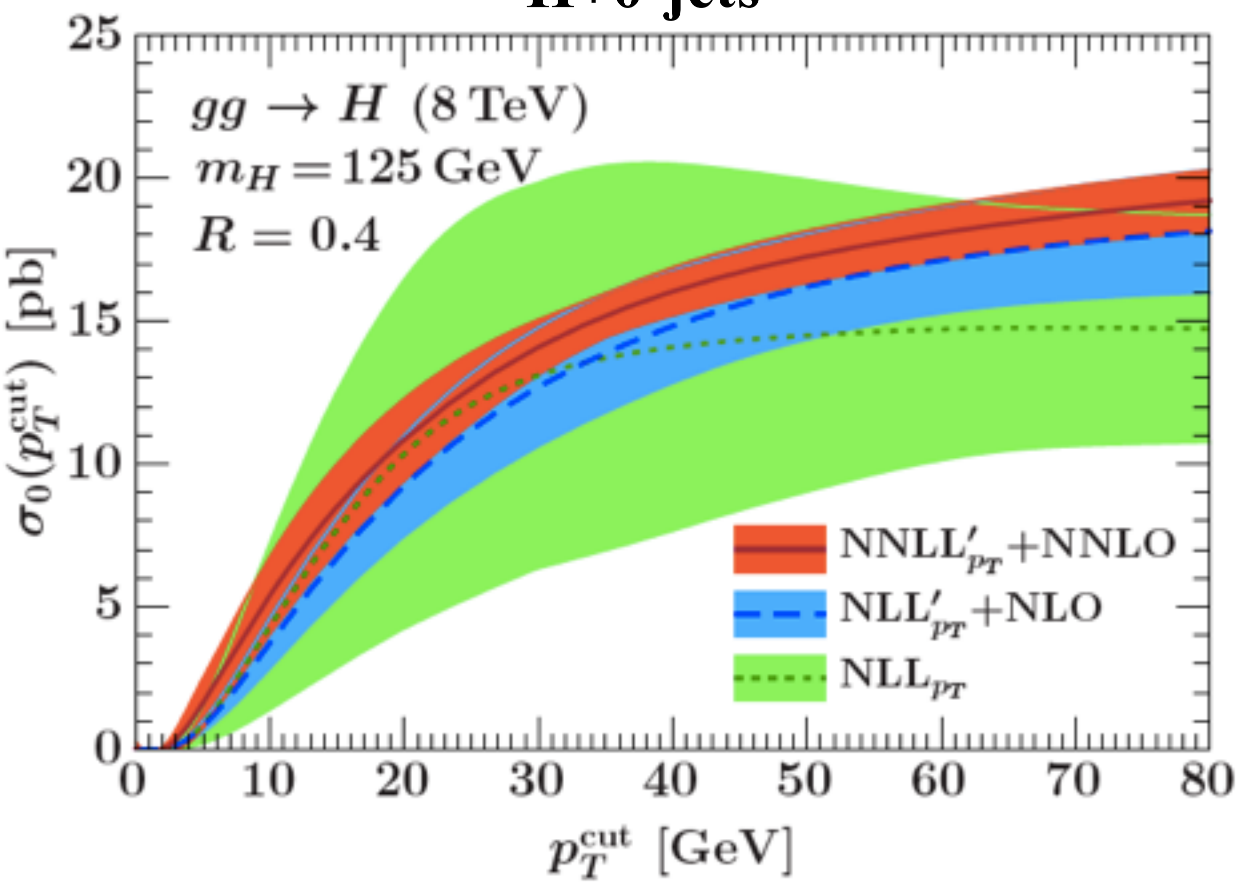
- An example of recent importance is the use of jet vetoes in Higgs measurements in the WW channel
- This introduces large uncertainties coming from large terms $\ln(m_H/p_{veto})$ in the perturbative expansion
- Uncertainties currently handled at fixed-order using the Stewart-Tackmann prescription (2011)
- We want to resum these terms; they are a large source of systematic uncertainty in this channel!

Resummation of jet-veto logarithms

- Resummation of jet-veto logarithms in Higgs physics is a very active area recently

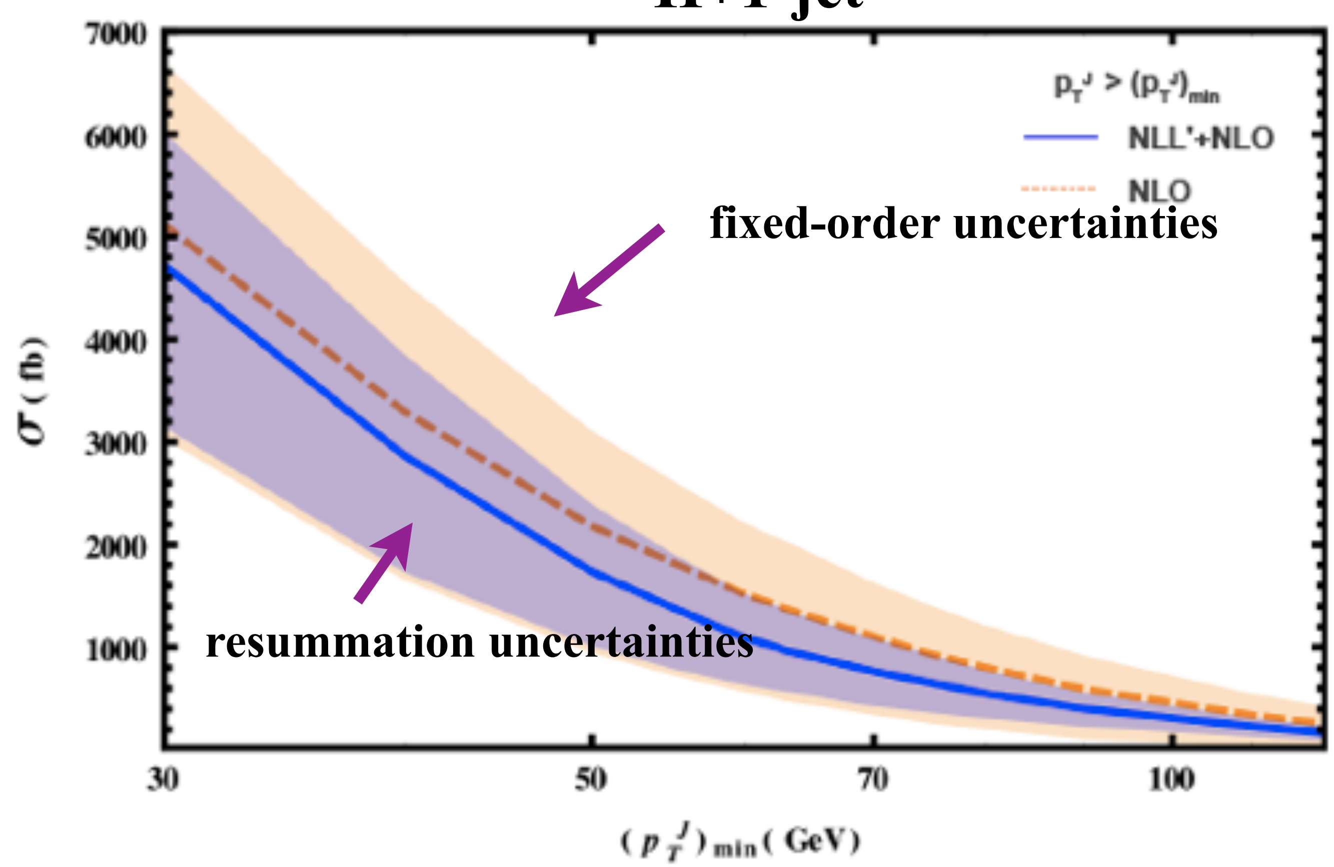
- H+0-jets in gluon fusion (Banfi, Monni, Salam, Zanderighi; Becher, Neubert; Stewart, Tackmann, Walsh, Zuberi)
- H+1-jet in gluon fusion (Liu, Petriello)
- Combination of the 0+1-jet bins (R.B., Liu, Petriello, Tackmann, Walsh)
- Associated VH production with a jet veto (Li,Liu)

H+0-jets



Stewart, Tackmann, Walsh, Zuberi (2013)

H+1-jet

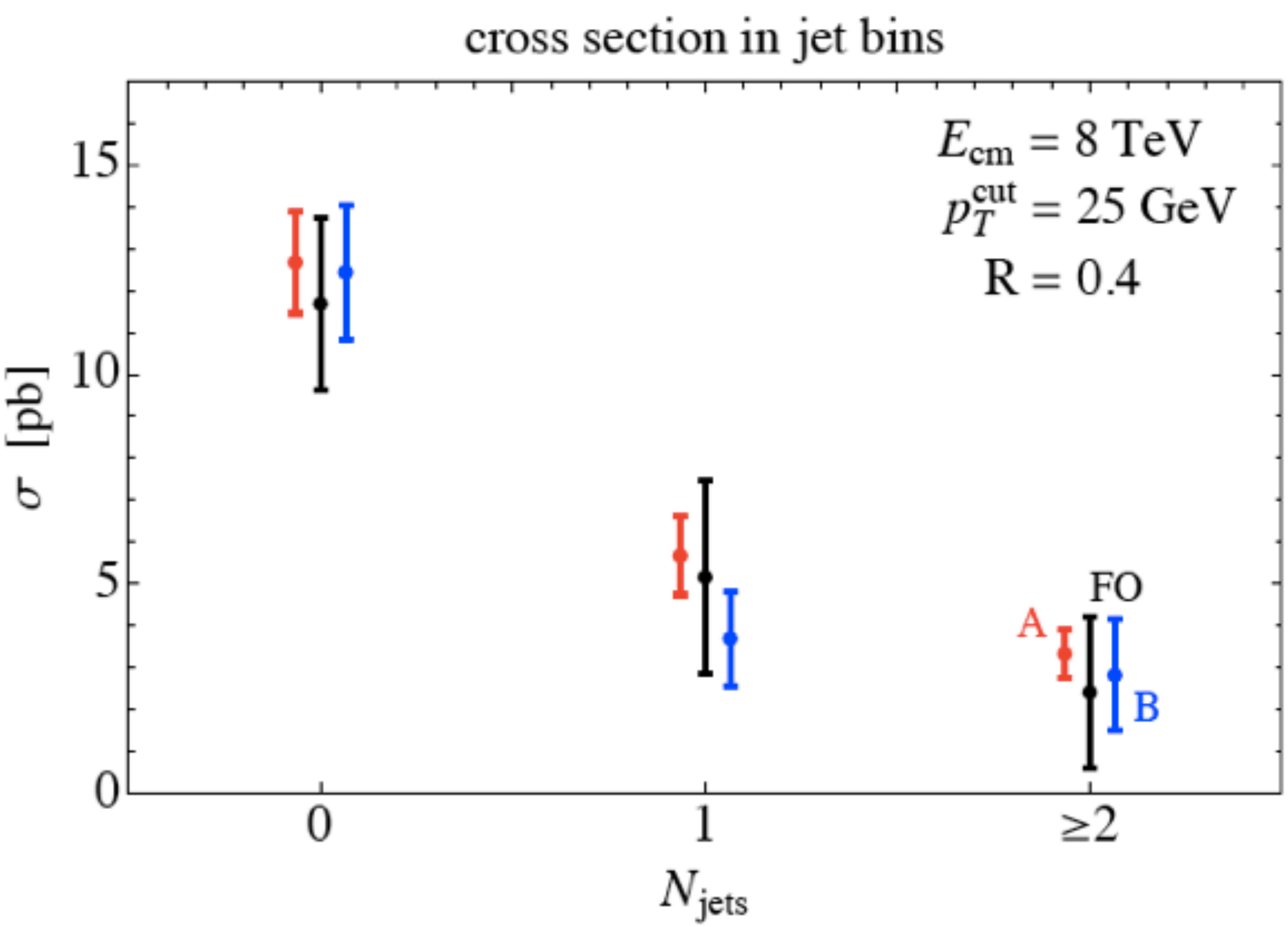


Liu, Petriello (2013)

Resummation of jet-veto logarithms

- Can combine the resummation of the zero-jet and one-jet bins into a complete resummation of the global logarithms affecting the Higgs signal in gluon fusion

R.B., Liu, Petriello, Tackmann, Walsh (2013)



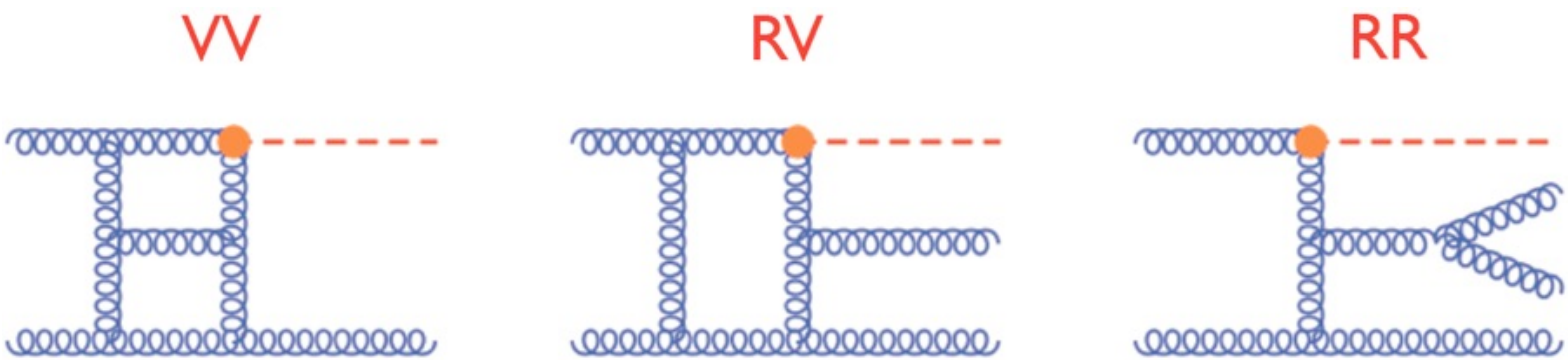
- Greatly reduced uncertainties in all three bins used in the analysis
- Provided complete covariance matrix for experimental use
- Can translate into a reduced uncertainty in the signal-strength extraction:

$$(\Delta\mu/\mu)_{old} = 13.3\%$$
$$(\Delta\mu/\mu)_{new} = 6.9\%$$

- Nearly a factor of 2 reduction in the theory uncertainty affecting the WW channel!

Fixed Order Cross Sections @ NNLO

- Need the following ingredients for NNLO cross sections



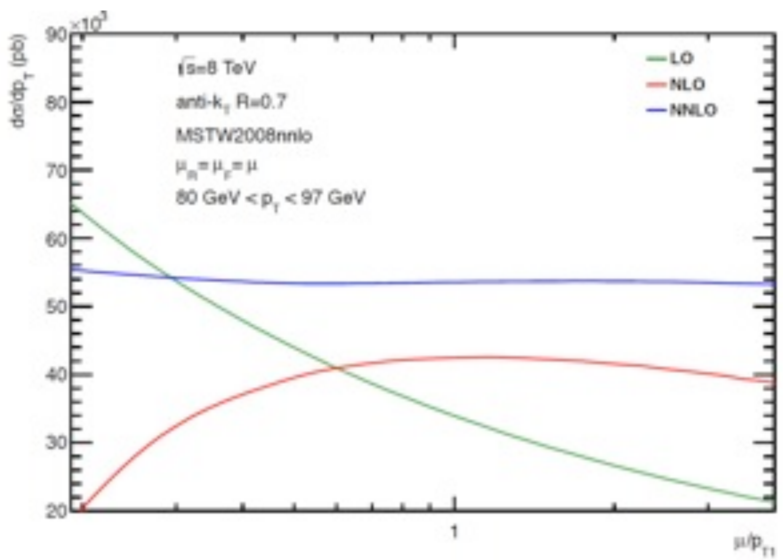
- IR singularities cancel in the sum of real and virtual corrections and mass factorization counterterms but only after phase space integration for real radiations

- Virtual corrections have explicit IR poles, whereas real corrections have implicit IR poles that need to be extracted.

- A generic procedure to extract IR singularities from RR and RV was unknown until very recently

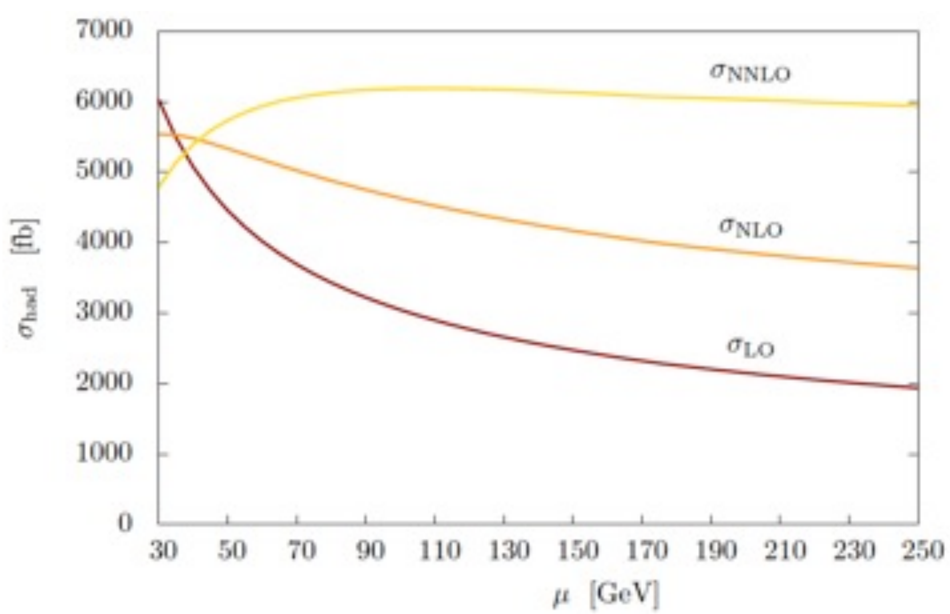
First NNLO Results

- First NNLO QCD corrections to processes with both colored initial and final states (2013)



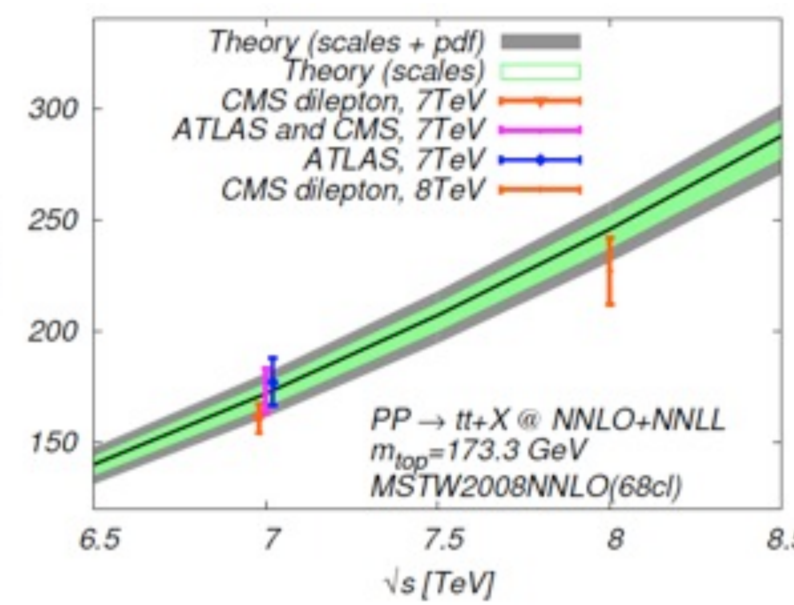
Gehrmann-de Ridder, Gehrmann, Glover, Pires

dijet: gg-channel



R.B., Caola, Melnikov, Petriello, Schulze

H+1j:gg-channel



Czakon, Fiedler, Mitov

ttbar: all-channels

Based on Antenna subtraction scheme

Based on sector-improved subtraction scheme

Methods for Real Radiation @ NNLO

- Sector decomposition (Binoth, Heinrich; Anastasiou, Melnikov, Petriello)
  - $pp \to H, pp \to V$ including decays

  (Anastasiou, Melnikov, Petriello; Buehler, Herzog, Lazopoulos, Mueller)

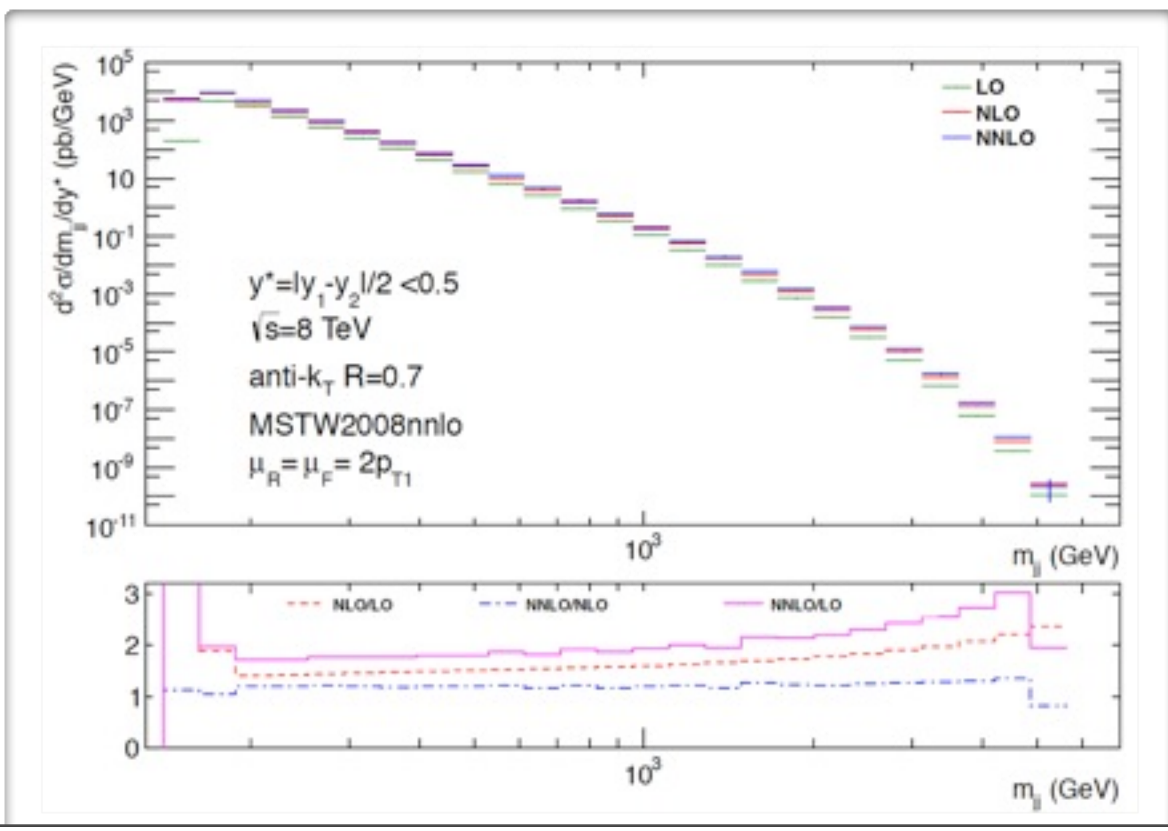
- Sector-improved subtraction schemes (Czakon; R.B, Melnikov, Petriello)
  - $pp \to t\bar{t}$ (Czakon)
  - $pp \to H + j$ (R.B., Caola, Melnikov, Petriello, Schulze)

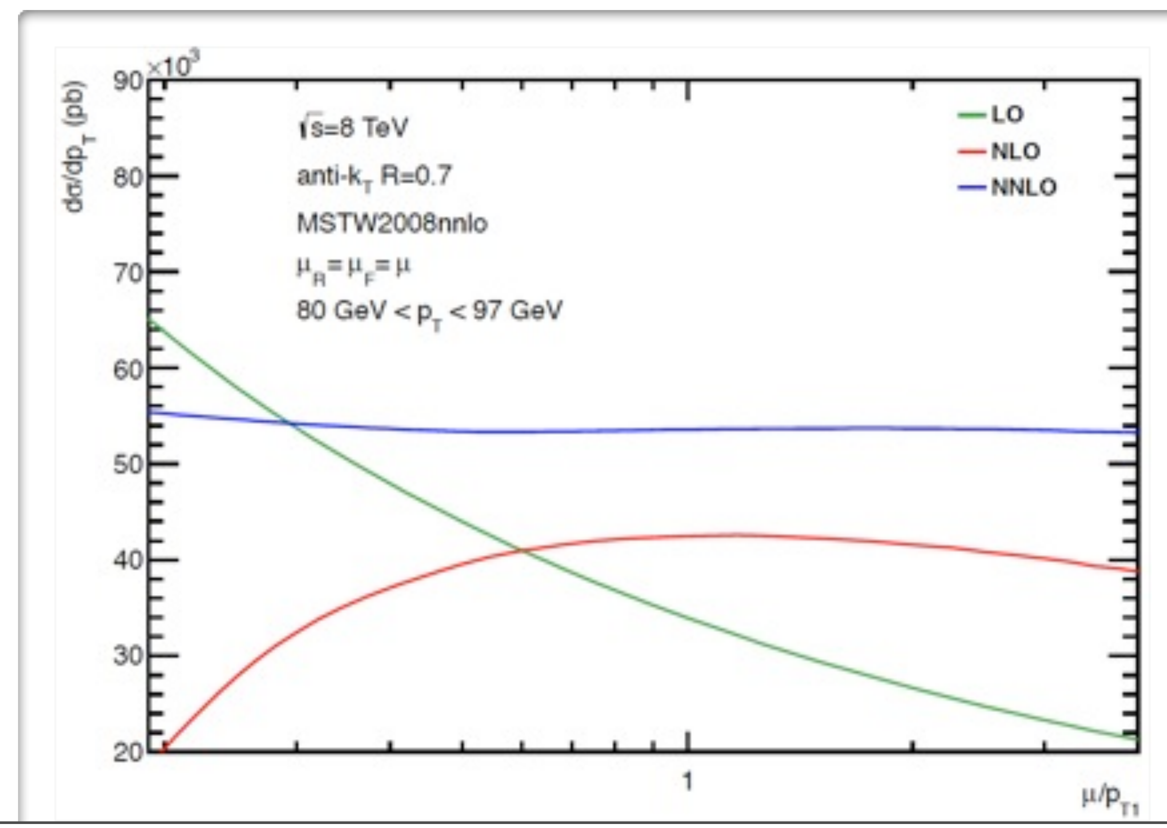
- Antenna subtraction (Gehrmann-De Ridder, Gehrmann, Glover)
  - $ee \to 3j$ (Gehrmann-De Ridder, Gehrmann, Glover, Heinrich; Weinzierl)
  - $pp \to jj$ (Gehrmann-de Ridder, Gehrmann, Glover, Pires)

- qT- subtraction (Catani, Grazzini)
  - $pp \to H, pp \to V, pp \to \gamma\gamma, pp \to VH, pp \to VV$

pp → 2jets @ NNLO (gg only)

- First results at NNLO available
  - gg → gg subprocess (Gehrmann-de Ridder, Gehrmann, Glover, Pires 2013)
  - Using antenna subtraction to extract IR singularities (analytic cancellation of poles)
- Inclusive jet P_T distribution
  - NNLO/NLO differential K-factor flat over the whole PT range
  - Dynamical scale choice: leading jet P_T
  - Stabilization of scale dependence at NNLO

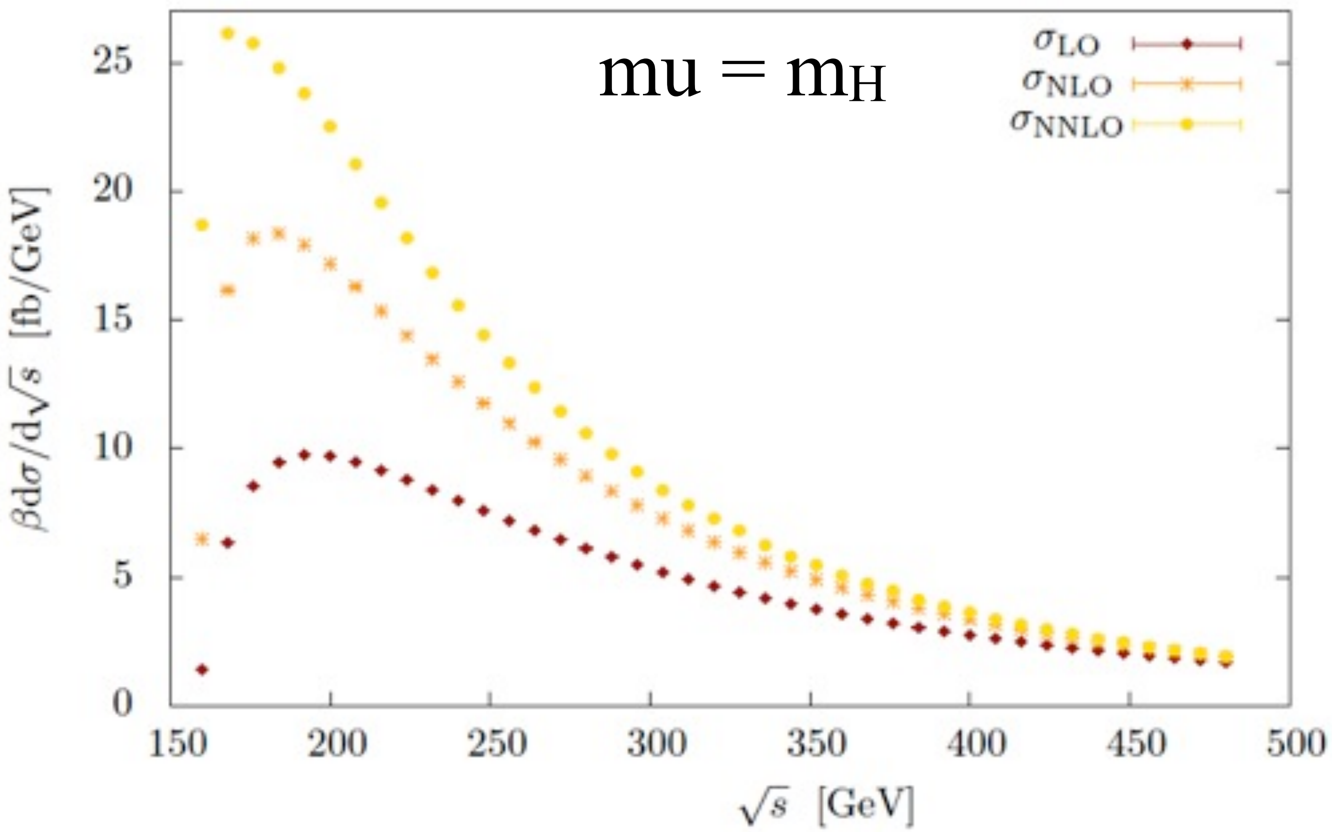


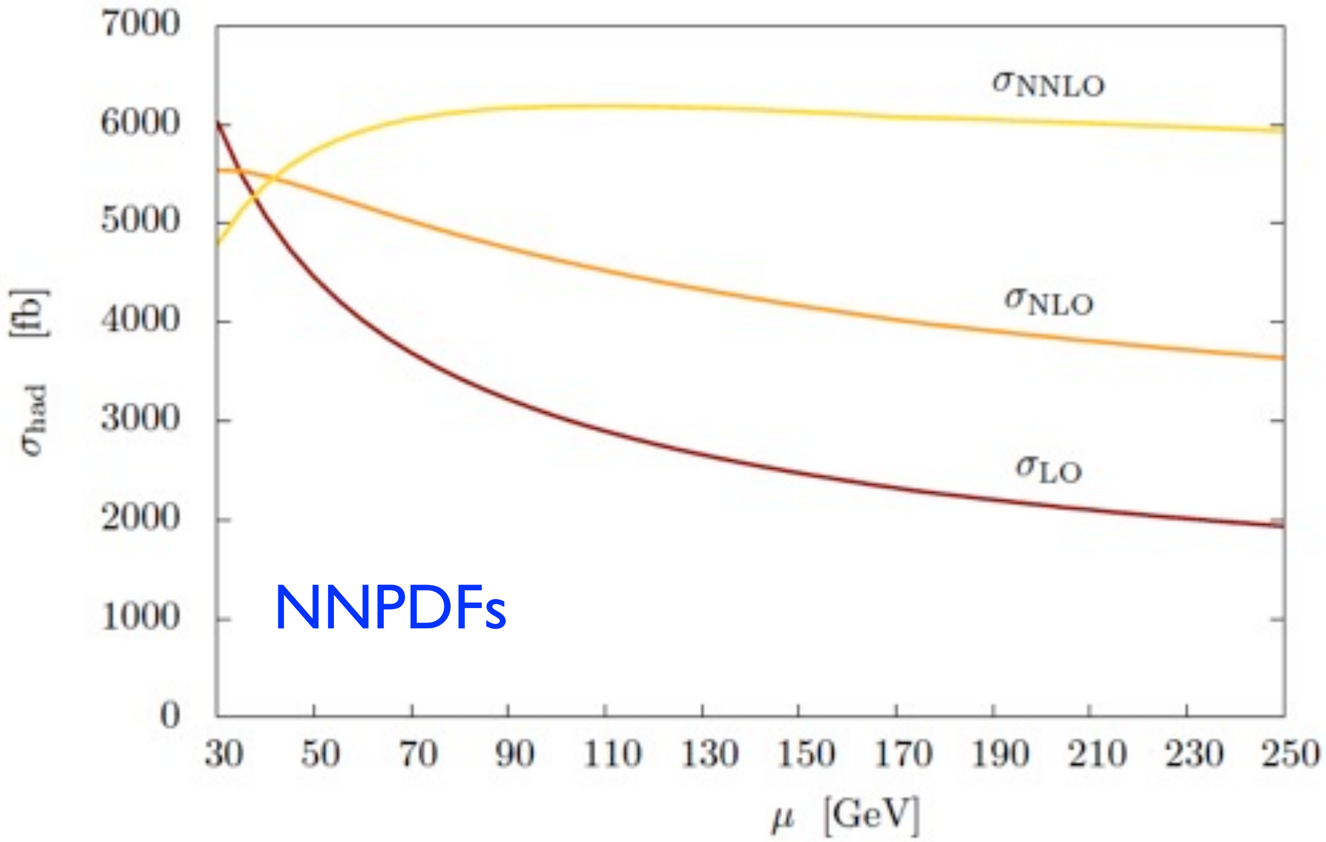


Higgs + jet @ NNLO (gg only)

- Large QCD corrections to Higgs+jet, need NNLO corrections !
- Uses sector-improved subtraction scheme for IR singularities

R.B., Caola, Melnikov, Petriello, Schulze (2013)





$\sigma_{NLO}/\sigma_{LO} = 1.6$, $\sigma_{NNLO}/\sigma_{NLO} = 1.3$

Large K-factor !

Significantly reduced scale dependence: O(4%) at NNLO instead of O(20%) at NLO

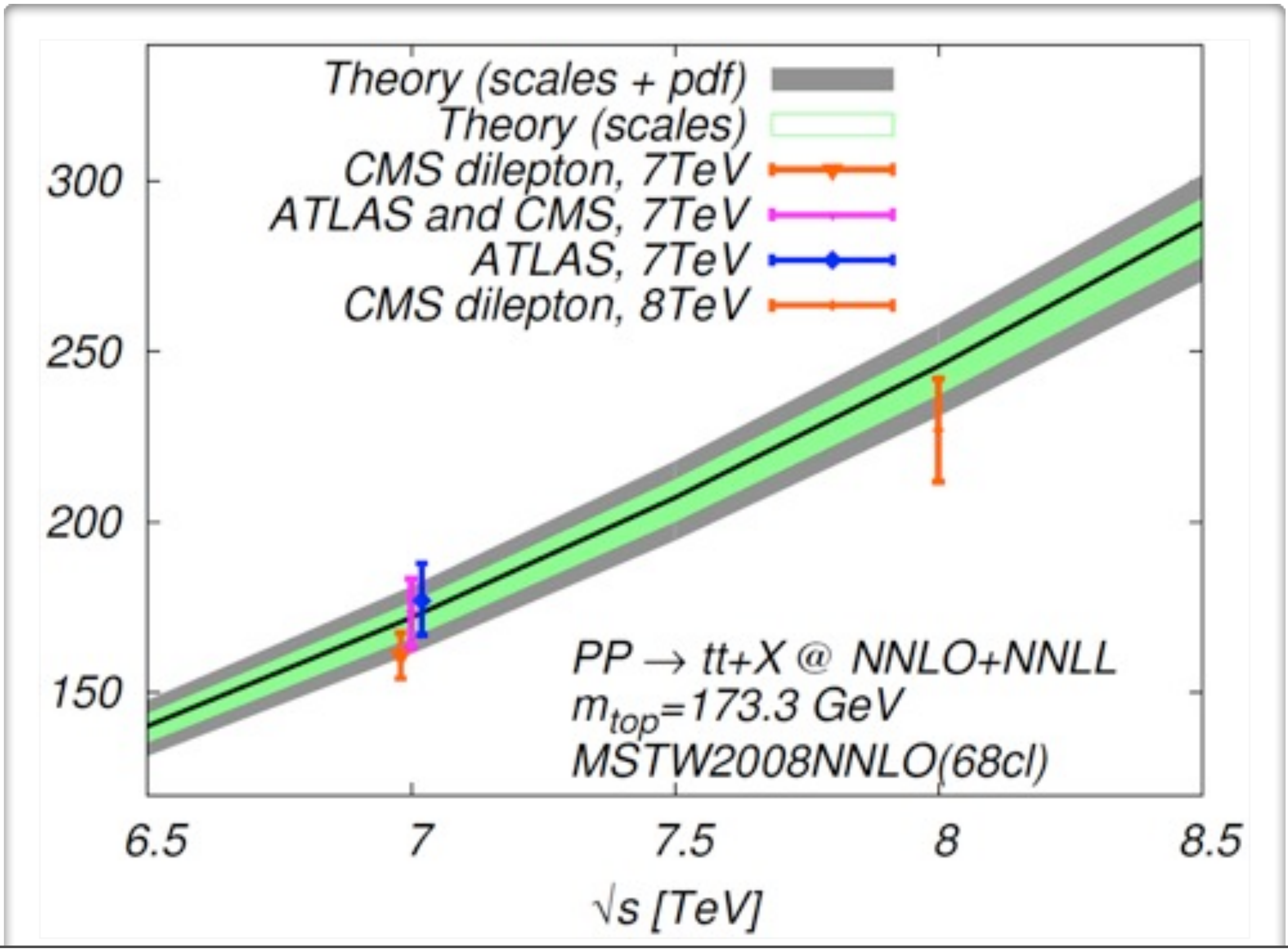
- gg-channel is the dominant one for phenomenological studies: at NLO gg (70%), qg (30%)
- quark channels necessary for achieving the relevant precision: ongoing work

R.B., Caola, Melnikov, Petriello, Schulze

ttbar @ NNLO

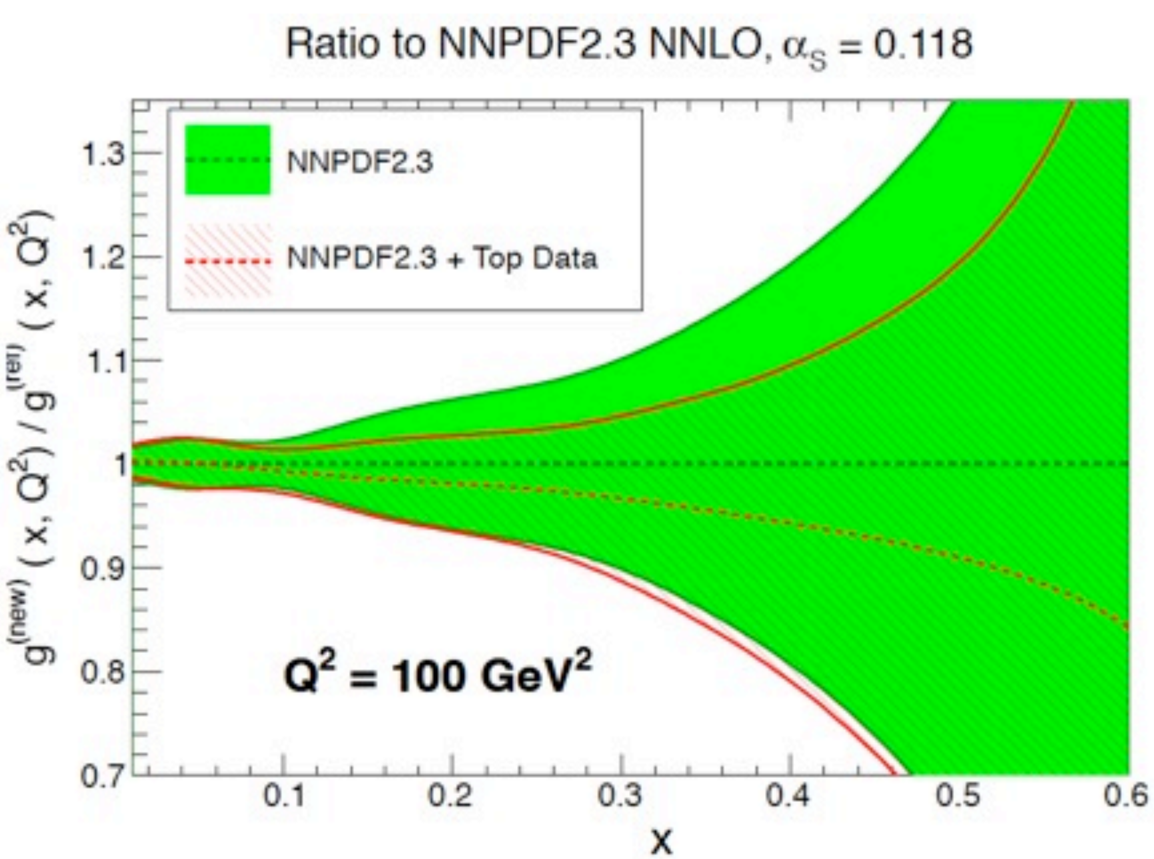
- Large production cross section at LHC: ~ 250 pb at 8 TeV
  - Expected experimental error ~5%
  - NLO+NLL predictions yield an uncertainty of ~10%
- Need NNLO precision for theory
- Results available for the complete total cross section (Czakon, Fiedler, Mitov 2013)

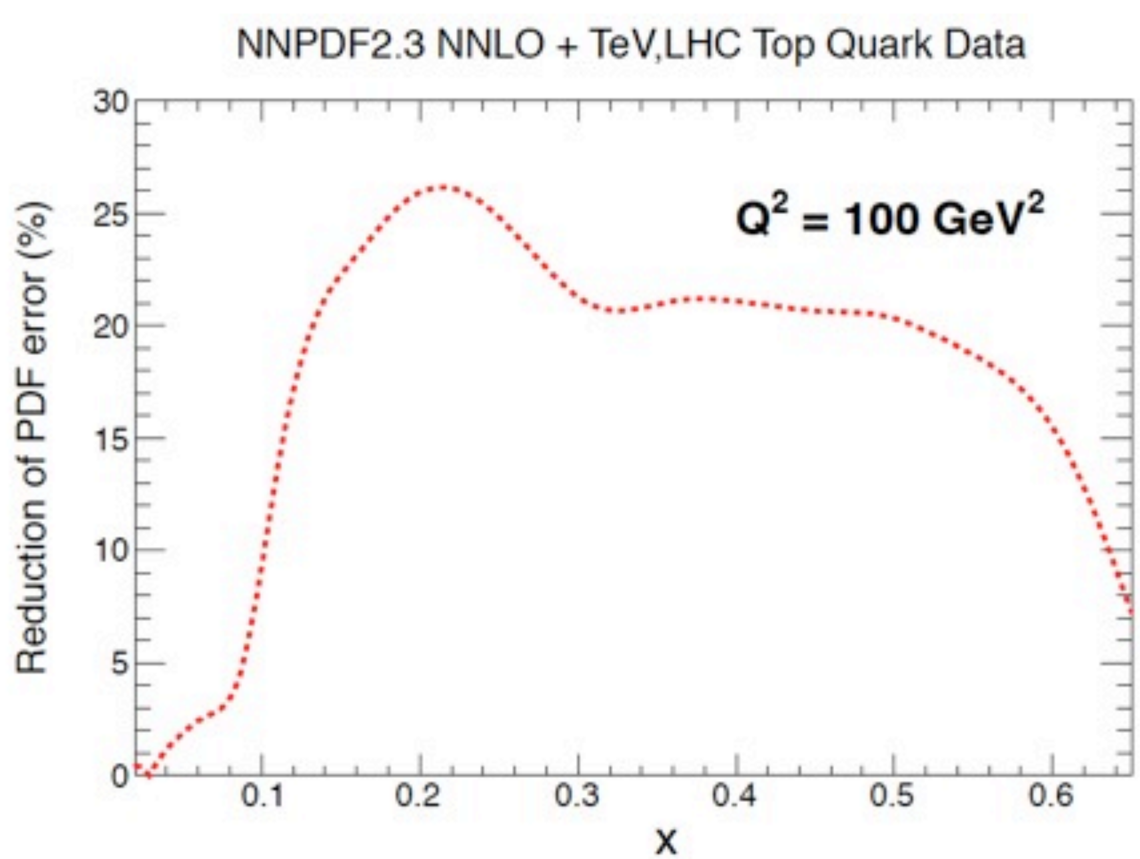
  - Based on sector-improved subtraction scheme for IR singularities
  - Comparable theoretical and experimental uncertainties
  - Differential distributions in progress



ttbar @ NNLO and the PDFs

- Impact on determination of parton distributions
  - Top production at LHC mainly from qg and gg processes
  - Total cross section sensitive to gluon distributions
  - NNLO cross section included into NNLO PDF fits (Czakon, Mangano, Mitov, Rojo 2013)
  - Uncertainty on gluons reduced at large x

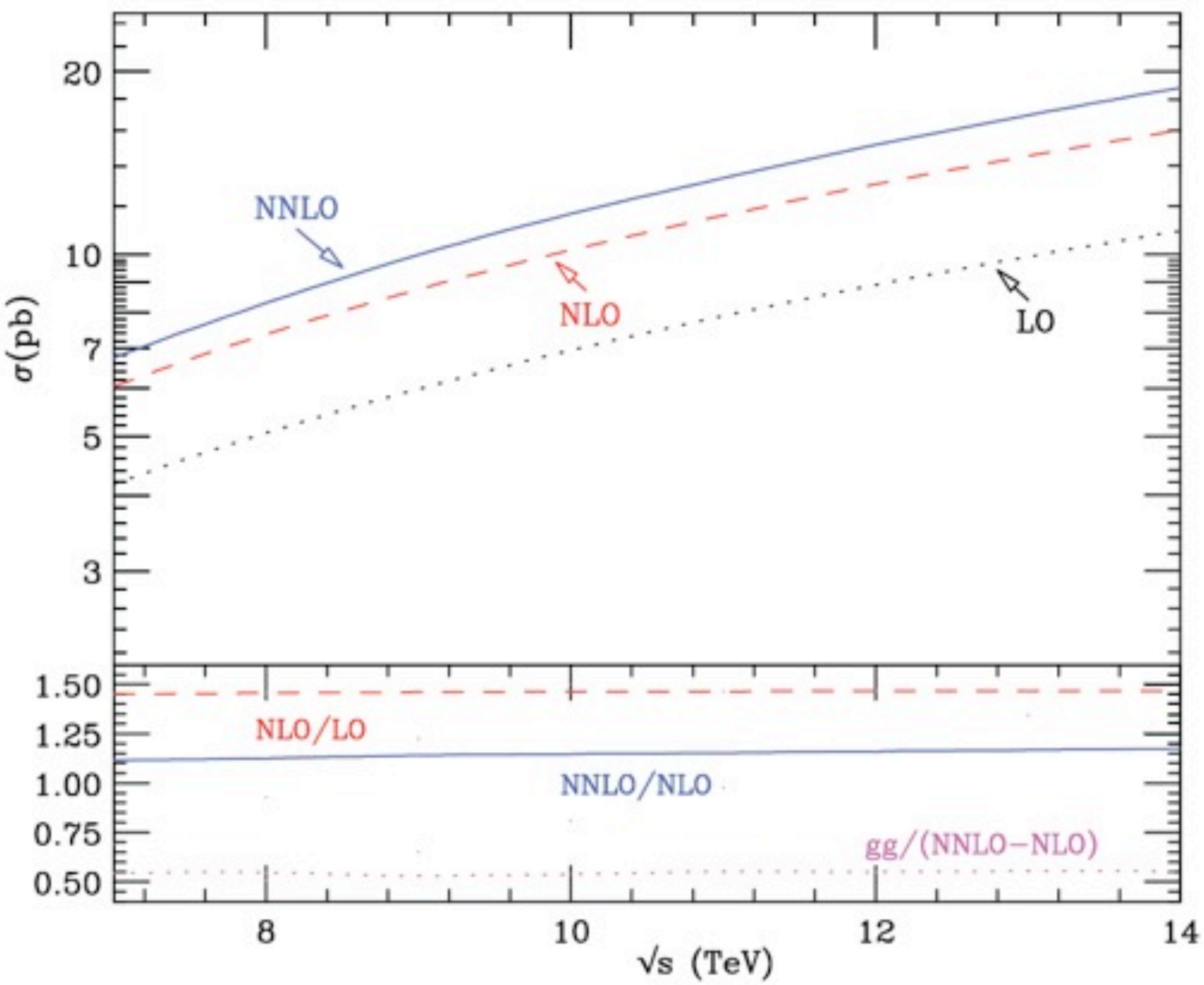




pp→ZZ + X @ NNLO

- Inclusive cross section for on-shell ZZ pair production is now available at NNLO

Cascioli, Gehrmann, Grazzini, Kallweit, Maierhoefer, von Manteuffel, Pozzorini, Rathlev, Tancredi, Weihs



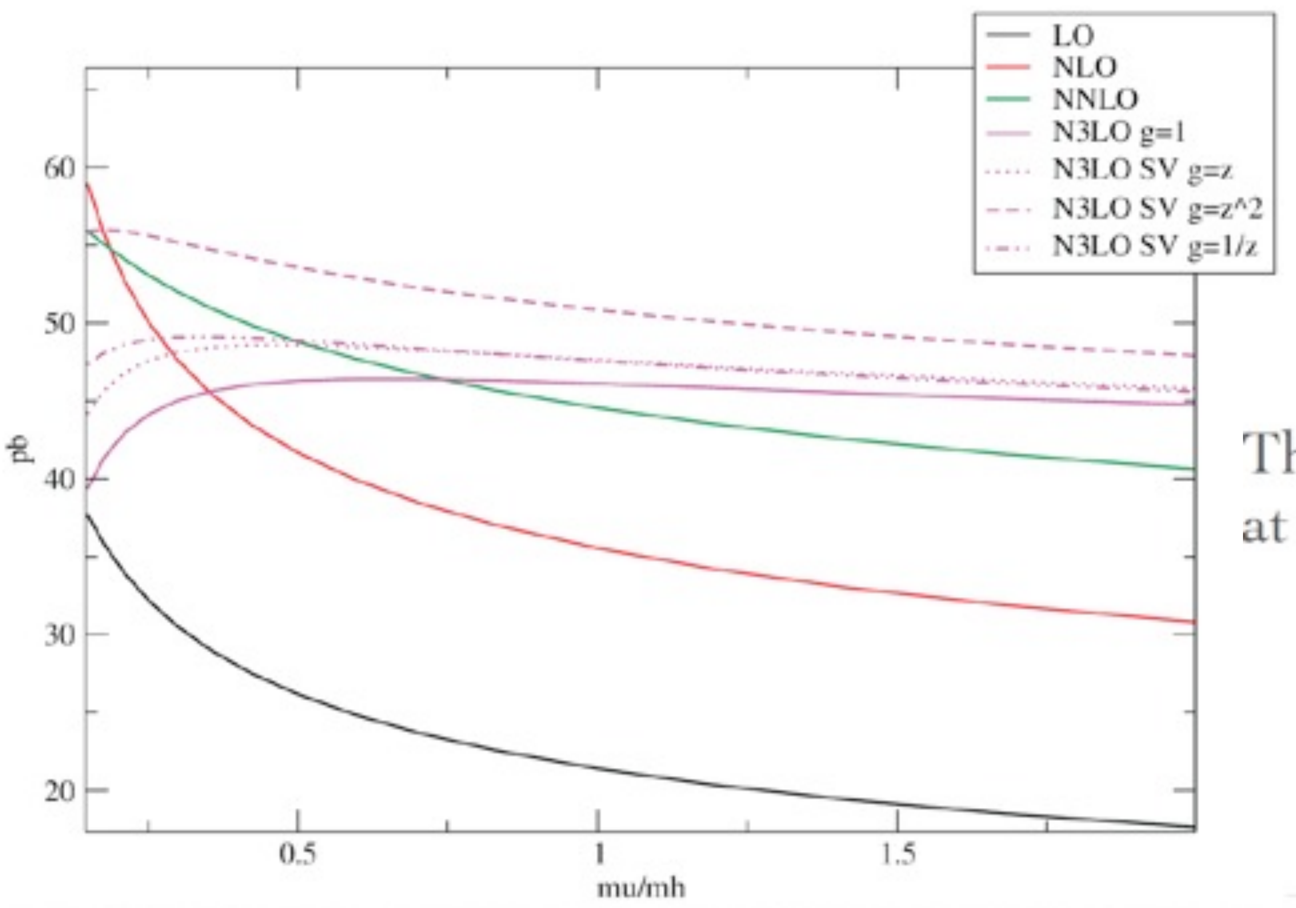
- NNLO corrections increase NLO result by 12%-17% when $\sqrt{s}$ varies from $7-14$ TeV
- Loop-induced gluon fusion (gg) contribution provides 60% of the total NNLO effect
- Scale uncertainty remains at 3% when going from NLO to NNLO
- Scale uncertainty computed by varying muF and muR independently with

$$\frac{1}{2}m_Z < \mu_F, \mu_R < 2\,m_Z; \frac{1}{2} < \frac{\mu_F}{\mu_R} < 2$$

- Uses qT subtraction for the IR singularities

Soft+Virtual exact N^{3}LO results for the inclusive cross section

• gg → H at N^{3}LO: needed to reduce the NNLO uncertainty to help extract the Higgs properties (Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Mistlberger)



• Uses threshold expansion in z
$\mathbf{z = m^2/s}$ where $\mathbf{z \sim 1}$ near threshold

$$\hat{\sigma}(z) = \boxed{\sigma_{-1}} + \sigma_0 + (1-z)\,\sigma_1 + \mathcal{O}(1-z)^2$$

The soft-virtual term receives contributions from a 'pole' at $z \sim 1$:

$$(1-z)^{-1+n\epsilon} = \frac{\delta(1-z)}{n\,\epsilon} + \left[\frac{1}{1-z}\right]_+ + n\epsilon\left[\frac{\log(1-z)}{1-z}\right]_+ + \mathcal{O}(\epsilon^2)$$

New — Moch, Vogt

• Work in progress to determine the subleading terms at threshold

• Other partial and approximate results are available: Li, von Manteuffel, Schabinger, Xing Zhu; Kilgore; Bonvini, Forte, Marzani, Ridolfi; Buehler, Lazopoulos; Hoeschele, Hoff, Ball, Pak, Steinhauser, Ueda

Summary and Outlook

• The need for precise and reliable description of signals and backgrounds for LHC Run II has led to several remarkable achievements.

• NLO is now a mature field, multi-particle processes that used to be unthinkable are now feasible, with a high level of automation. Current state-of-the-art is matched fixed order results with parton showers to facilitate comparison with data.

• New understanding of analytic resummation in the presence of final-state jet algorithms, with important applications to Higgs predictions.

• Remarkable progress on the NNLO frontier, with various methods to get the predictions. Calculations are still on a process-by-process level due to the complexity. Merging with parton showers has already started.

• Future directions:
  - Matching of different multiplicities at NLO with parton showers
  - Development of powerful new mathematical techniques for NNLO virtual corrections