# QCD (Theory)

P. Nason, INFN, Sez. of Milano Bicocca

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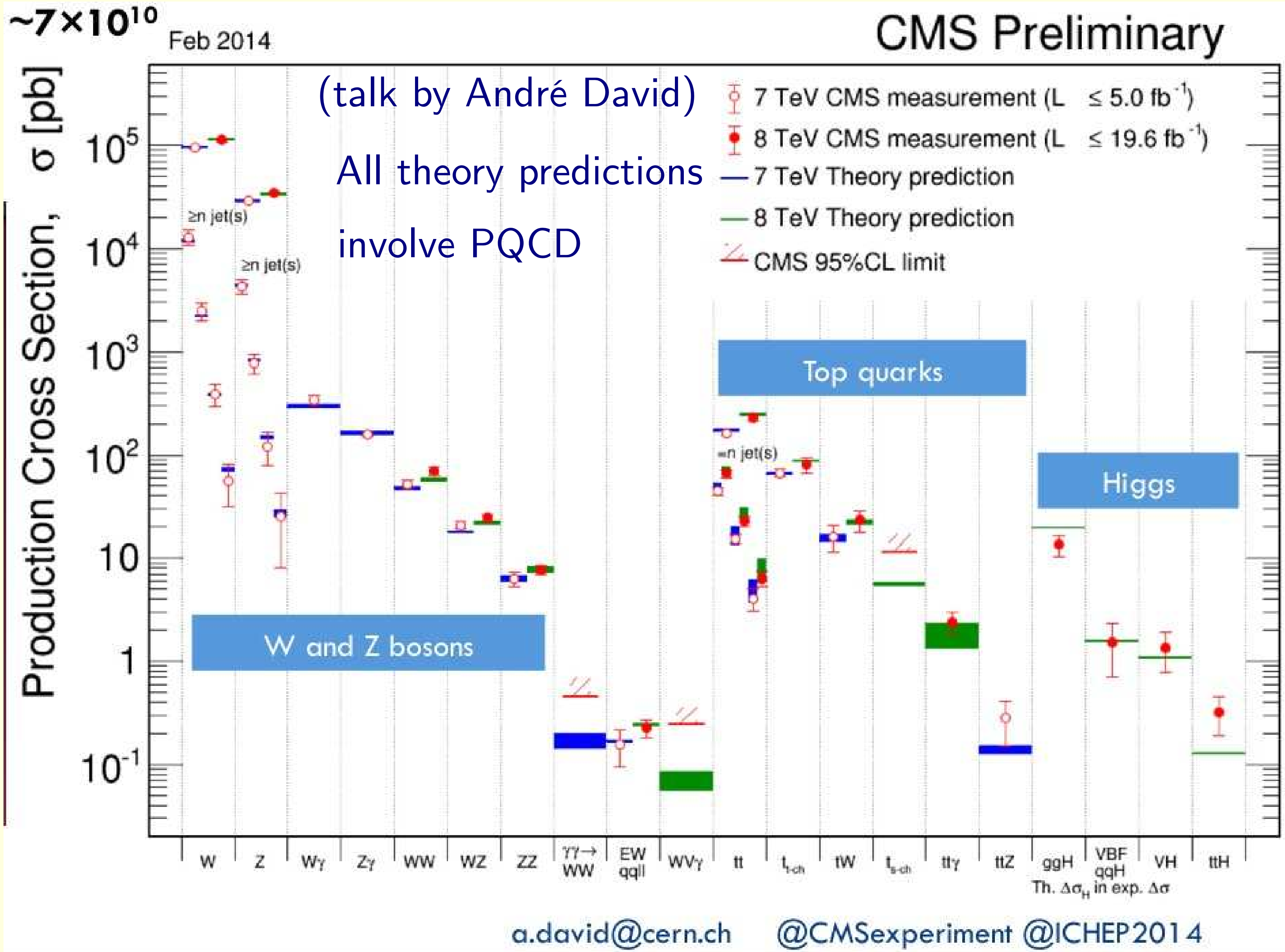
# QCD: strong interaction theory

- Weakly coupled at short distances, strongly coupled at large distances
  Perturbation theory predictive for observables insensitive to large distance dynamics (i.e. infrared finite observables).
- Large body of tests of PQCD predictions, as heritage from LEP, Tevatron and HERA.
- No major areas of discrepancies with data

Today: less emphasis on QCD tests, more emphasis on predicting and modeling collider processes

(talk by André David)

All theory predictions involve PQCD



# Areas of developement

- Development of fully automated techniques for NLO calculations (see Badger's talk), roughly in the past 10 years, currently progressing with several collaborating and competing research groups.
- The development of techniques for combining Fixed Order calculations with parton shower generators (`MC@NLO`, `POWHEG`, etc., see Re's talk)
- The sudden appearence of a number of new NNLO results since a little more than a year (see also Duhr's talk)
- The first glimpse at an NNNLO calculation few months ago
- Analytic resummation for observables with jet vetos, (see Monni's talk)
- Work on jet substructure, to enhance our discriminating ability to search for new phenomena at the LHC (see Cacciari's talk)
- Work on PDF's determination

Several collaborating/competing groups working in all these areas. It is impossible to review all of the recent progress here (my apologies for all what I left out).

My choice of topics:

# Plan of the talk

- Progress in NNNLO calculations: soft-virtual Higgs production at NNNLO
- Progress in NNLO
- Matching Fixed Order calculation with Parton Showers (FO+PS): from NLO+PS to NNLO+PS generators
- Progress in resummation and jets: analytic results for jet subtructure

# Gluon fusion threshold Higgs production at NNNLO

Anastasiou,Duhr,Dulat,Furlan,Gehrmann,Herzog,Mistlberger, March 2014)

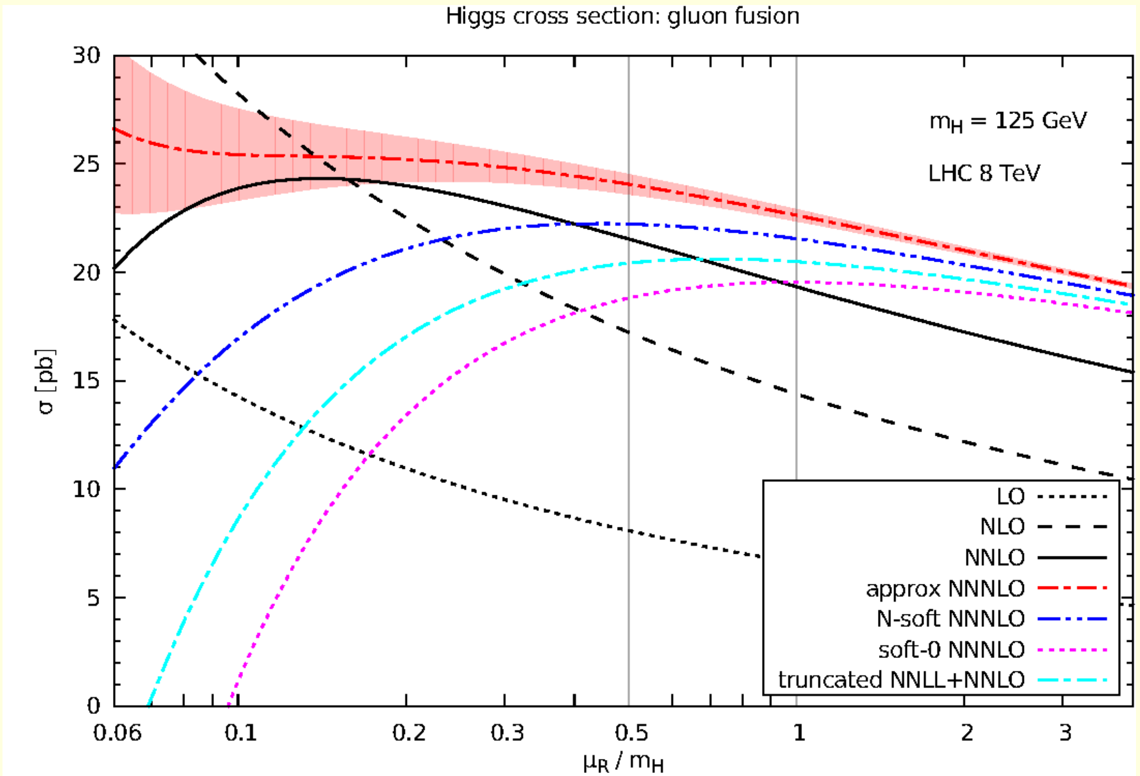
$$\hat{\sigma}_{ij}(m_{\rm H}^2, \hat{s}) = \frac{\pi C(\mu^2)^2}{8v^2} \sum_{k=0}^{\infty} \left(\frac{\alpha_s}{\pi}\right)^k \eta_{ij}^{(k)}(z)$$

where $C/4v$ is the effective ${\rm H}gg$ coupling, $z = m_{\rm H}^2/\hat{s}$. New result:

$$\begin{aligned} \eta^{(3)}(z) \;=\; & \delta(1-z)\, 1124.308887\ldots + \left[\frac{1}{1-z}\right]_+ 1466.478272\ldots - \left[\frac{\log(1-z)}{1-z}\right]_+ 6062.08673\ldots \\ & + \left[\frac{\log^2(1-z)}{1-z}\right]_+ 7116.015302\ldots - \left[\frac{\log^3(1-z)}{1-z}\right]_+ 1824.362531\ldots \\ & - \left[\frac{\log^4(1-z)}{1-z}\right]_+ 230 + \left[\frac{\log^5(1-z)}{1-z}\right]_+ 216 + \mathcal{O}(1-z) \end{aligned}$$

Offspins: soft contribution to $\delta(1-z)$ term is in fact universal; extended to Drell-Yan (Ahmed,Mahakhud,Rana,Ravindran, Apr. 2014) and to generic processes with colourless final state (Catani,Cieri,de Florian,Ferrera,Grazzini, May 2014)

Not yet full NNNLO result; approximate results based upon it:




Plot: Bonvini,Ball,Forte, Marzani,Ridolfi,2014

Soft-0 NNNLO, $z$ space (Anastasiou,Duhr,...)

N-soft NNNLO $N$ space (Moch,Vogt,2005; De Florian,Grazzini,2012)

approx NNNLO $N$ space
$N$ analyticity constraints
high energy limit
(Bonvini etal,2013)

Large spread in different approaches. Ongoing debate on whether $N$ space or $z$ space approaches is preferable (reaching a consensus on that may narrow the spread of predictions).

Towards NNNLO:

- 3-loop virtual
  R. Lee, A. Smirnov, and V. Smirnov (2010)
  Baikov, Chetyrkin, A.V.Smirnov, V.A.Smirnov,Steinhauser (2009)
  Gehrmann,Glover,Huber,Ikizlerli,Studerus, 2010
- Contributions associated with Collinear-Ultraviolet counterterms
  S. Buehler and A. Lazopoulos (2013)
  A. Pak, M. Rogal and M. Steinhauser (2011)
  C. Anastasiou, S. Buehler, C. Duhr and F. Herzog (2012)
  M. Hoeschele, J. Hoff, A. Pak, M. Steinhauser and T. Ueda (2013)
- Two loop soft current:
  C. Duhr and T. Gehrmann (2013)
  Y. Li and H. X. Zhu (2013)
- Real-virtual (square of 1 loop correction in Higgs + 1 parton production)
  Anastasiou,Duhr,Dulat,Herzog,Mistlberger, Nov. 2013
  Kilgore, Feb. 2014

As with NNLO calculations, large collaborative effort;

# NNLO benchmarks

- Drell-Yan at NNLO, van Neerven, 1990
- Total $\sigma$ in gluon fusion Higgs production, Harlander,Kilgore 2001; Anastasiou,Melnikov 2002; Ravindran,Smith,Van Neerven 2003;
- Higgs differential distributions: Anastasiou,Melnikov,Petriello 2004; Catani,Grazzini 2007;
- $e^+e^- \to 3\,\mathrm{jets}$, A.Ghermann-De Ridder,T.Gehrmann,Glover,Heinrich, Jul.07;
- $WH$, $ZH$ production, total $\sigma$: Brein,Djouadi,Harlander 2004; differential $\sigma$: Ferrera,Grazzini,Tramontano 2011
- $\gamma\gamma$ production, Catani,Cieri,de Florian,Ferrera,Grazzini 2011;
- $H + j$, Boughezal,Caola,Melnikov,Petriello,Schulze Feb. 2013
- $t\bar{t}$ production, total $\sigma$: Czakon,Fieder,Mitov, Mar. 2013
- inclusive jets :Currie,Gehrmann,Glover,Gehrmann-de Ridder,Pires, 2013
- $Z/W+\gamma$, Grazzini,Kallweit,Rathlev,Torre, 2013,2014
- $ZZ$ production, Cascioli,Gehrmann,Grazzini,Kallweit,Maierhöfer, Manteuffel,Pozzorini,Rathlev,Tancredi,Weihs, May 2014
- t-channel single top, Bruscherseifer,Caola,Melnikov, Apr. 2014

# NNLO

Theoretical work carried out in several years by different teams.
Two loop, massless $2 \to 2$ amplitudes ($\gamma\gamma$, dijets), computed by
Anastasiou,Glover,Oleari,Tejeda-Yeomans 2000-2002.
12 more years to get the full result!

Much more difficult with massive particles (for $VV$ production):
Caola,Henn,Melnikov,Smirnov, Apr. 2014;
Gehrmann,Manteuffel,Tancredi,Weihs, Apr. 2014;

2-loop integrals for $2 \to 2$ processes seem to be feasible today
(recent groundbreaking technique found by Henn, 2013)

2-loop graphs is not the whole story: add square of 1-loop graphs (double virtual) 1-loop graphs with 1 real emission (real-virtual) and 2 real emission graphs, canceling out all IR divergences for IR safe observables.

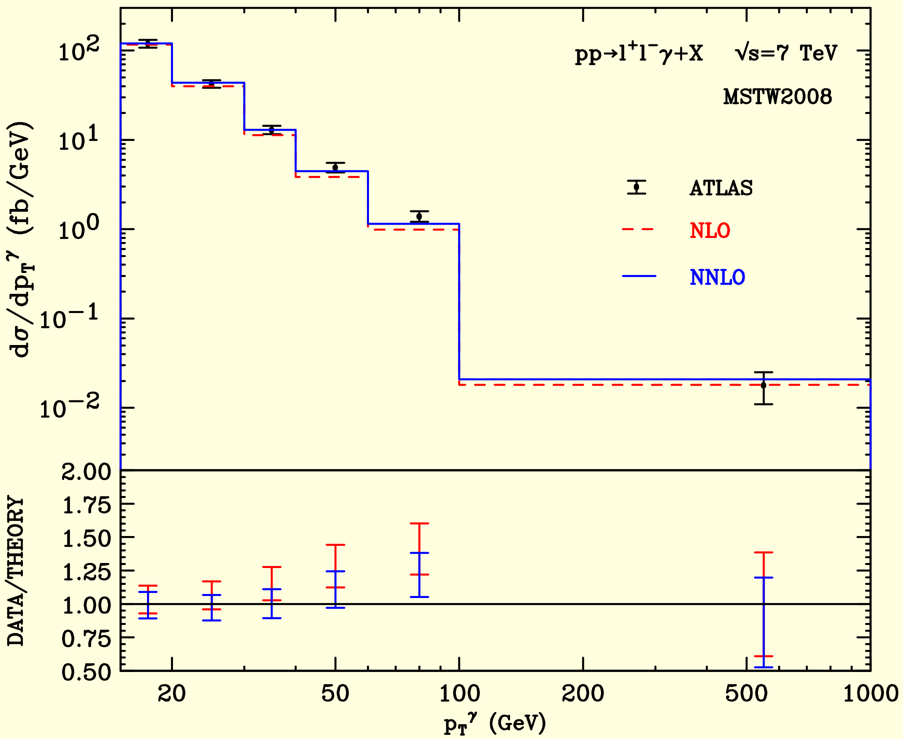
# NNLO

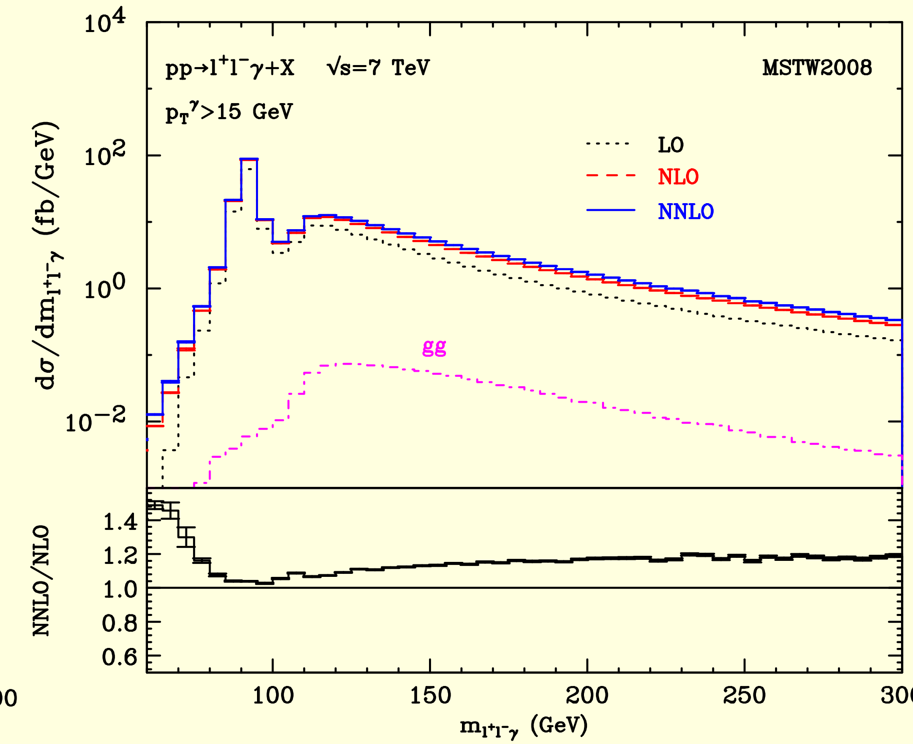
Current techniques for implementing the cancellation:

- $q_T$ subtraction (Catani,Grazzini 2007), only suitable for processes with (Born level) colour neutral massive system in the final state: gluon fusion Higgs production, Drell Yan, $\gamma\gamma$, $WH$, $ZH$, $ZZ$, etc.
- Antenna subtraction (Gehrmann,Gehrmann-DeRidder,Glover) has been used for $e^+e^- \to 3\,\mathrm{jets}$, dijets, and is being used in an effort to compute fully differential $t\bar{t}$ production at NNLO (Abelof,Gehrmann-de Ridder,Maierhofer,Pozzorini, Apr. 2014)
- SecToR Improved Phase sPacE for real Radiation, Czakon 2010, Boughezal,Melnikov,Petriello 2011, extension of FKS to NNLO, used in $t\bar{t}$ production, $H+j$, t-channel single top.
- other method: Bolzoni,Del Duca,Somogyi,Trosczanyi 2005-2013

The message: NNLO calculations of $2 \to 2$ processes become now feasible.

# NNLO, $Z\gamma$ production

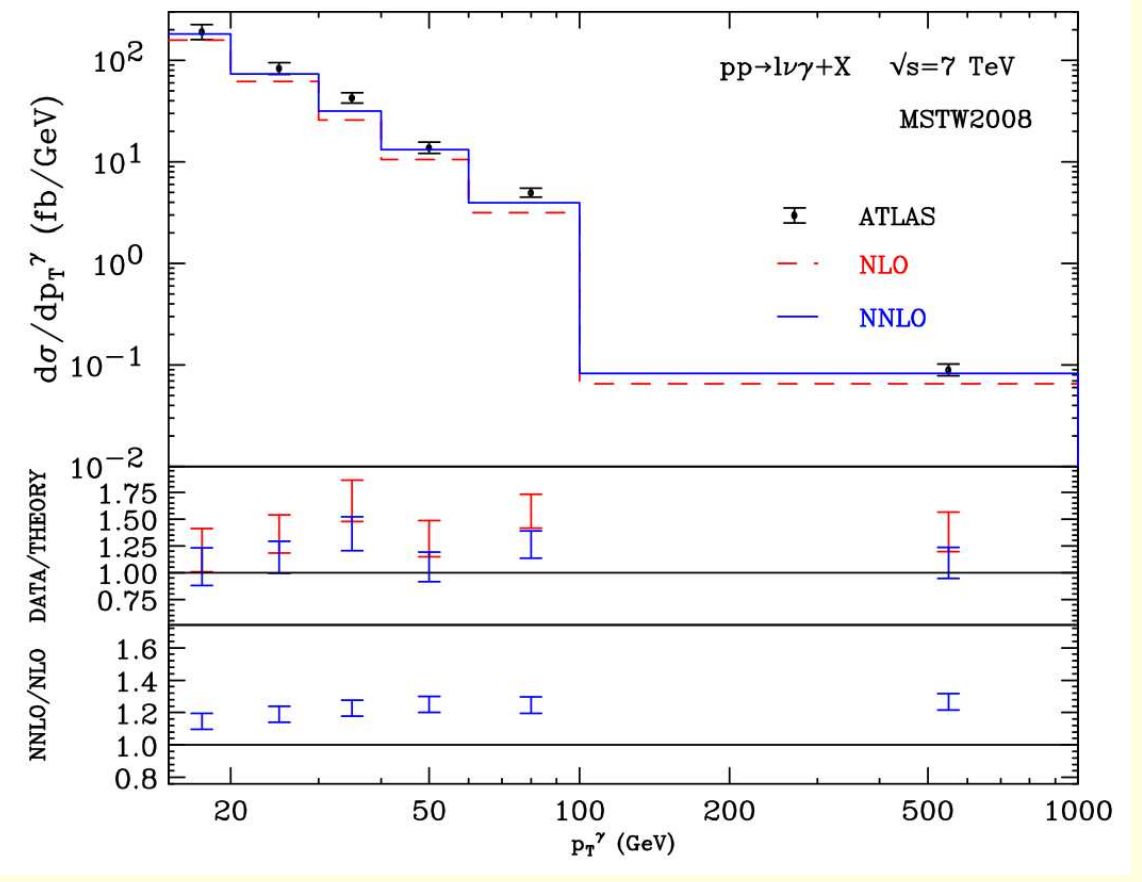



$Z\gamma$ production at NNLO, Grazzini etal, April 2014.
Reasonable pattern of LO, NLO, NNLO corrections.
ATLAS data favours slightly NNLO result.

# NNLO, $W\gamma$ production

Cascioli etal, in preparation
NNLO corrections needed
to reach reasonable agreement
with ATLAS data.

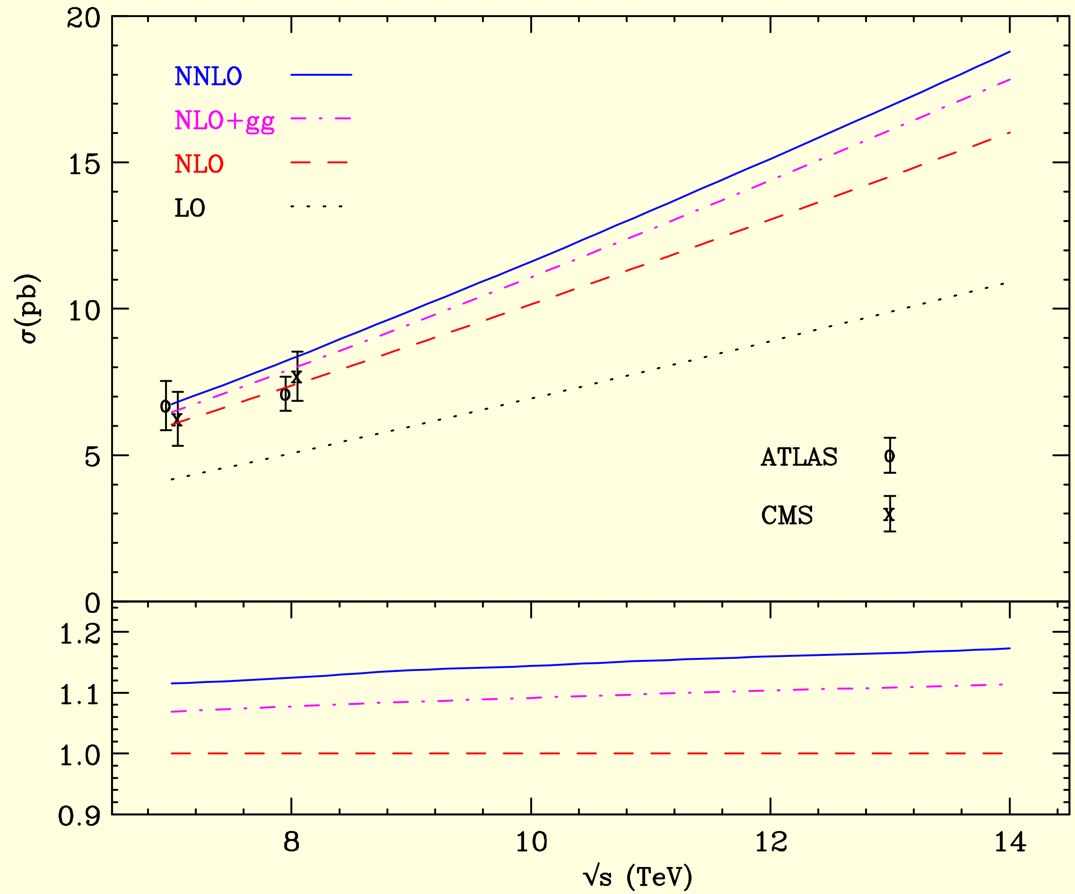


# NNLO, $ZZ$ production

Cascioli etal, May 2014

Reasonable pattern of LO, NLO and NNLO corrections.

The $gg$ contribution was known to give an important contribution to the NNLO corrections because of the size of the $gg$ luminosity

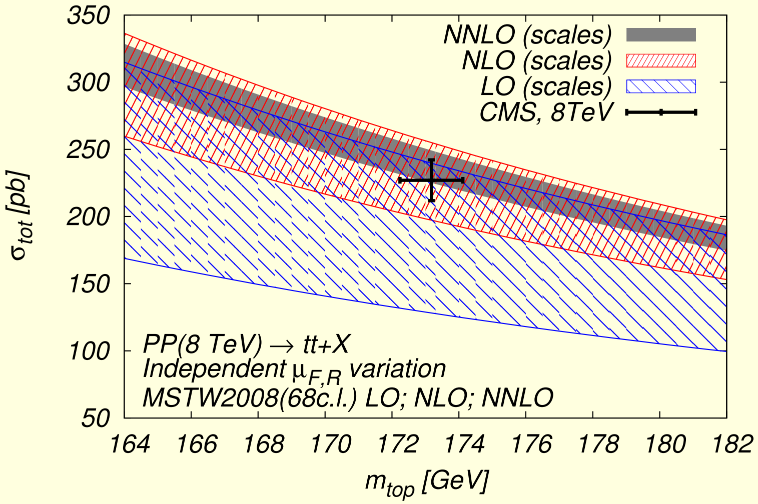


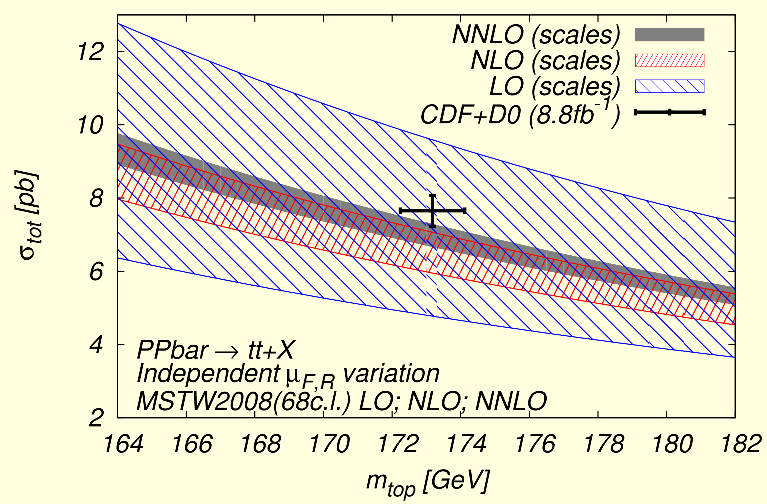

$WW$ will probably come soon: CMS/ATLAS have an eccess there ...

# NNLO, $t\bar{t}$ and single top

Czakon, Fiedler, Mitov, 2013

Plot from Czakon, Fiedler, Mitov, Rojo 2013




Brucherseifer Caola Melnikov Apr. 2014

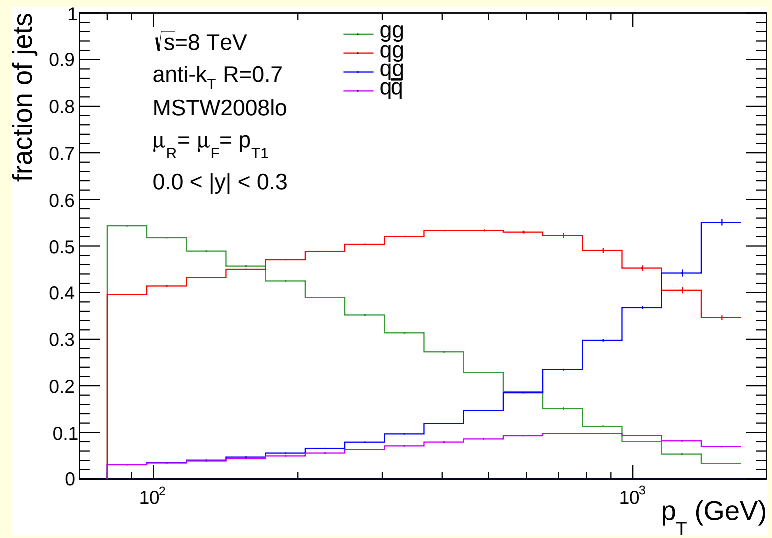
t-channel single top

| $p_\perp$ | $\sigma_{\rm LO}$, pb | $\sigma_{\rm NLO}$, pb | $\delta_{\rm NLO}$ | $\sigma_{\rm NNLO}$, pb | $\delta_{\rm NNLO}$ |
|---|---|---|---|---|---|
| 0 GeV | $53.8^{+3.0}_{-4.3}$ | $55.1^{+1.6}_{-0.9}$ | $+2.4\%$ | $54.2^{+0.5}_{-0.2}$ | $-1.6\%$ |
| 20 GeV | $46.6^{+2.5}_{-3.7}$ | $48.9^{+1.2}_{-0.5}$ | $+4.9\%$ | $48.3^{+0.3}_{-0.02}$ | $-1.2\%$ |
| 40 GeV | $33.4^{+1.7}_{-2.5}$ | $36.5^{+0.6}_{-0.03}$ | $+9.3\%$ | $36.5^{+0.1}_{+0.1}$ | $-0.1\%$ |
| 60 GeV | $22.0^{+1.0}_{-1.5}$ | $25.0^{+0.2}_{+0.3}$ | $+13.6\%$ | $25.4^{-0.1}_{+0.2}$ | $+1.6\%$ |

# Inclusive jets at NNLO

$gg$ (green), $qg$ (red) and $qq$ (blue) dominant at the LHC in different kinematic regions.

$gg$ and $q\bar{q}$ important at the Tevatron

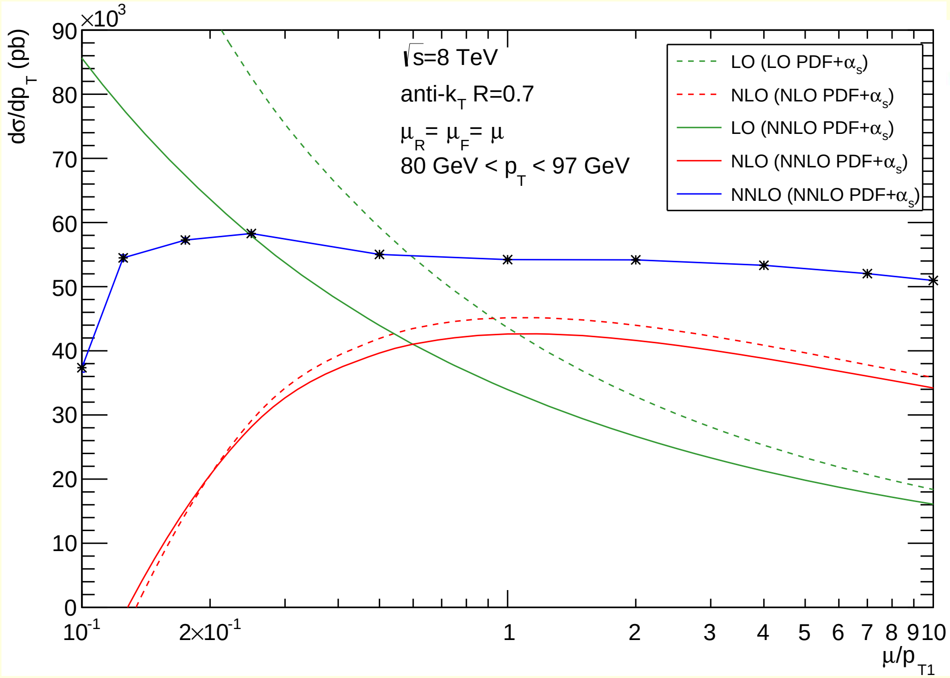


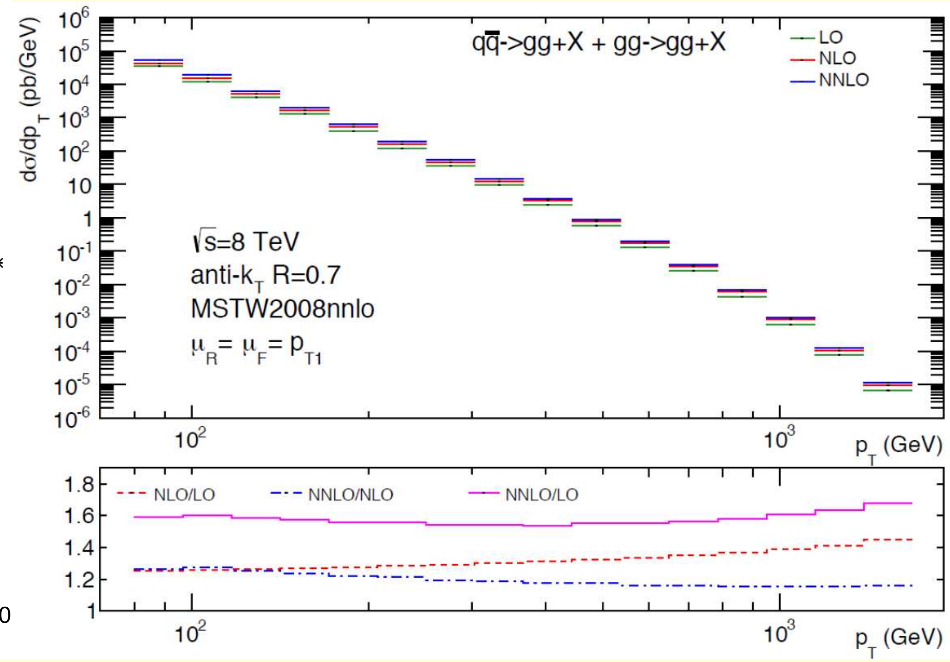

- $gg \rightarrow gg$

  Gehrmann, Gehrmann-de Ridder,Glover,Pires, Jan. 2013

  Currie, Gehrmann-de Ridder, Glover,Pires, Dec. 2013 (full colour)

- $q\bar{q} \rightarrow gg$ available, other processes in progress




- $qg$ component still missing
- Worry: NNLO same size as NLO correction up to 200 GeV jets; non-overlapping scale variation bands
- Wait for full result ...

# NNLO summary

- Large effort of the theoretical community, started about 15 years ago, is beginning to deliver. Several differential cross sections for important, complex LHC processes have become available in 2013, 2014.
- It looks like all $2 \to 2$ processes are becoming feasible at NNLO
- The value of NNLO results cannot be understated. In view of the often large NLO correction for hadronic processes, the NNLO result can give us confidence that we are not dealing with asymptotic expansions that are diverging already at the first term.

# Fixed Order and Showers

Parton Shower Monte Carlo fully simulate hadronic production processes by merging together a QCD component (the Shower itself) and a model for hadron formation. The QCD component is typically given in the collinear approximation.

In the past 10 years, considerable effort has gone in building NLO-improved PS generators (NLO+PS) using the results of Fixed Order, NLO calculations.

Methods like `MC@NLO` and `POWHEG` allow to combine fixed order NLO calculation with existing parton shower generators like `PYTHIA` and `HERWIG`.

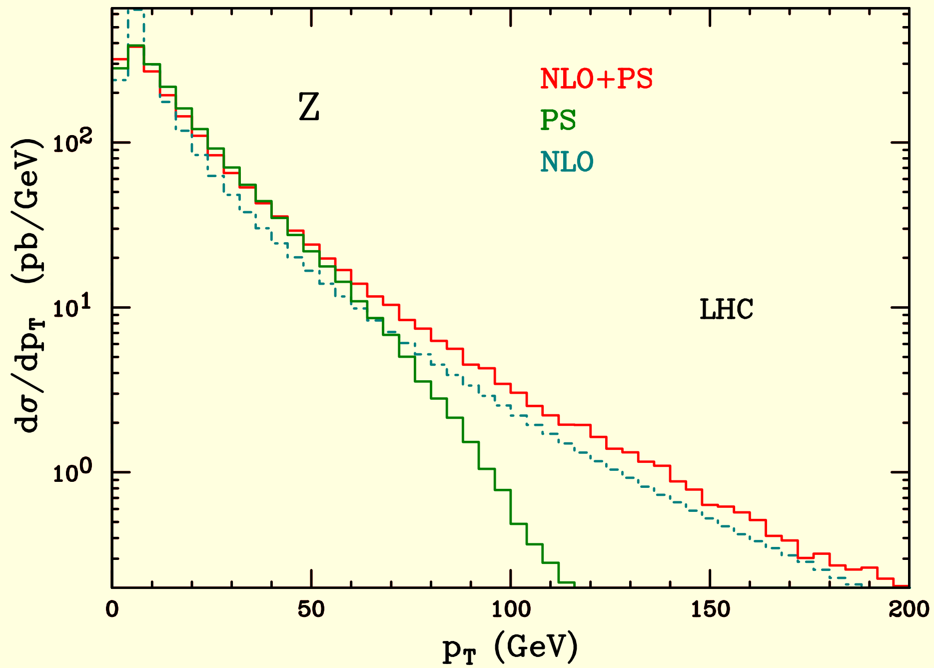
In view of the recent progress with NNLO calculation, the extension to NNLO+PS is under study.

# Why NLO+PS

PS alone fails at large $p_T$;
(Only approximate there)

NLO alone fails at small $p_T$;
(NLO corrections diverge,
needs all order resummation
of singular contributions)

NLO+PS works in both regions;



# NLO and NLO+PS

- MadGraph5_aMC@NLO, Alwall etal, 2011, May 2014 (first release), automates all steps of the calculation in the same code: generation of real and virtual amplitudes, calculation of LO and NLO cross section, matched to a shower using the MC@NLO scheme.
- GoSam, Cullen etal, Apr. 2014, automatic generation of virtual amplitudes.
- Recola, Actis,Denner,Hofer,Scharf,Uccirati, 2013, automatic generation of virtual amplitudes.
- Open Loops, Cascioli,Maierhöfer,Pozzorini, 2012, automatic generation of virtual amplitudes.
- Black Hat, Bern etal, 2008, one loop amplitudes for $W + n\,\mathrm{jets}$, with $n$ up to 5.
- POWHEG BOX, Alioli,Oleari,Re,P.N. 2010, automatic NLO calculation, NLO+PS generation using the POWHEG method.
- Helac-NLO, PowHel, Bevilacqua etal., altomated generation of amplitudes, NLO calculation and NLO+PS generation using the POWHEG method.
- Sherpa, Hoëche etal, implements a framework for NLO calculation and for NLO+PS generation
- MatchBox, NLO+PS within Herwig++ (Gieseke etal)

new developments: "merged" NLO+PS generators

# NLO+PS "merging" and NNLO+PS

Illustration in the framework of Higgs production in gluon fusion.
LO cross section: $\alpha_s^2$, NLO: $\alpha_s^3$, NNLO: $\alpha_s^4$. Compare:

- The NLO+PS generators for $H$, $H+1j$: `H`, `HJ`
- A "merged" $H, H+1j$ generator: `H-HJ`
- An NNLO+PS $H$ generator: `NNH`

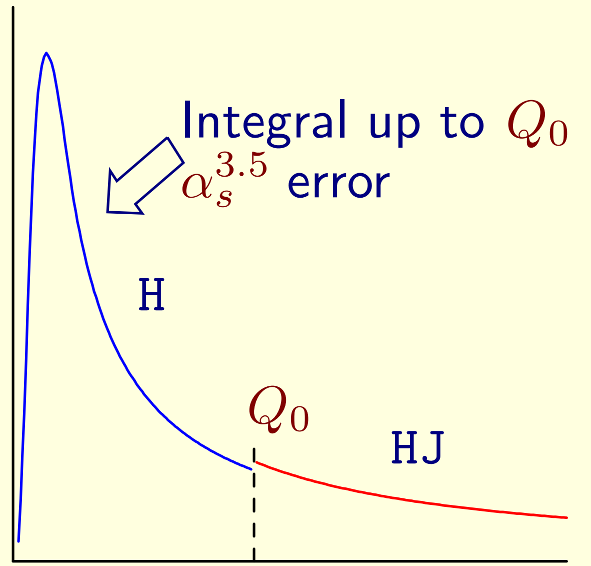
| | Inclusive Higgs | Higgs+1 jet | Higgs+2 jet |
|---|---|---|---|
| `H` | NLO, $\mathcal{O}(\alpha_s^2+\alpha_s^3)$ | LO, $\mathcal{O}(\alpha_s^3)$ | collinear limit |
| `HJ` | none | NLO, $\mathcal{O}(\alpha_s^3+\alpha_s^4)$ | LO, $\mathcal{O}(\alpha_s^4)$ |
| `H-HJ` | NLO, $\mathcal{O}(\alpha_s^2+\alpha_s^3)$ | NLO, $\mathcal{O}(\alpha_s^3+\alpha_s^4)$ | LO, $\mathcal{O}(\alpha_s^4)$ |
| `NNH` | NNLO, $\mathcal{O}(\alpha_s^2+\alpha_s^3+\alpha_s^4)$ | NLO, $\mathcal{O}(\alpha_s^3+\alpha_s^4)$ | LO, $\mathcal{O}(\alpha_s^4)$ |

`H-HJ` gets the best out of `H` and `HJ`. If improved for the inclusive Higgs observables can reach NNLO accuracy.

The real challenge is to set up an NLO+PS merged generator.

Why is it difficult? Naive approach:

- Start with the H and HJ generator
- Introduce a separation scale: $\Lambda_{\rm QCD} \ll Q_0 \ll M_H$
- Use H for $p_T^H < Q_0$
- Use HJ for $p_T^H > Q_0$




The Sudakov peak is at $\alpha_s L^2 \approx 1$ ($L = \log M_H/p_T^H$). Even if the Sudakov form factor is accurate at the NLL level in the H generator, missing NNLL terms of order $\alpha_s^2 \times \alpha_s^2 L \approx \alpha_s^{3.5}$ spoil NLO accuracy, that requires $\alpha_s^2$ neglected terms.

The only way out seems to require $\alpha_s^2 L \approx \alpha_s^2$, i.e. $Q_0 \approx M_H$!!

Current merging approaches differ in the way they address (or don't address) the above problem:

- SHERPA, [Hoeche, Krauss, Schonherr, Siegert, 2012], traditional merging with matching scales.
- aMC@NLO, [Frederix, Frixione, 2012], traditional merging with matching scales; scales kept high to avoid above problems.
- [Platzer, arXiv:1211.5467], [Lönnblad, Prestel, 2012], force unitarity by subtracting appropriate terms.
- GENEVA, [Alioli, Bauer, Berggren, Hornig, Tackmann, Vermilion, Walsh, Zuberi, 2012], increase precision in LL resummation to reach accurate matching.
- MiNLO, [Hamilton,Oleari,Zanderighi,P.N. 2012], merging without matching scales, improve accuracy of Sudakov form factor.
- Vincia [Hartgring,Laenen,Skands, Sept. 2013], NLO+PS method with antenna showers

Given an H-HJ merged generator (accurate at order $\alpha_s^3$ for fully inclusive quantities, and at order $\alpha_s^4$ for Higgs plus one jet observables), it is easy to prove that NNLO accuracy can be achieved as follows:

- Generate events with the NLO+PS merged generator
- Reweight the event cross section as a function of $y_{\mathrm{H}}$ with the factor

$$\frac{\frac{\mathrm{d}\sigma^{\mathrm{NNLO}}}{\mathrm{d}\,y_{\mathrm{H}}}}{\frac{\mathrm{d}\sigma^{\mathtt{H-HJ}}}{\mathrm{d}\,y_{\mathrm{H}}}}$$

  so that the Higgs rapidity distribution becomes NNLO accurate

In order for the proof to work, it is essential that

$$\frac{\frac{d\sigma^{\rm NNLO}}{d\,y_{\rm H}}}{\frac{d\sigma^{\tt H-HJ}}{d\,y_{\rm H}}} = \frac{\sigma^{(0)}_{\rm NNLO} + \alpha_s \sigma^{(1)}_{\rm NNLO} + \alpha_s^2 \sigma^{(2)}_{\rm NNLO}}{\sigma^{(0)}_{\tt H-HJ} + \alpha_s \sigma^{(1)}_{\tt H-HJ}} = 1 + \mathcal{O}(\alpha_s^2)$$

i.e. that $d\sigma_{\tt H-HJ}/dy_{\rm H}$ is NLO accurate.

If the ratio was $1+\mathcal{O}(\alpha_s)$, distributions like the Higgs transverse momentum, that have the expansion:

$$\frac{d\sigma}{dp_t} = \alpha_s^3 \frac{d\sigma^{(3)}}{dp_t} + \alpha_s^4 \frac{d\sigma^{(3)}}{dp_t}$$

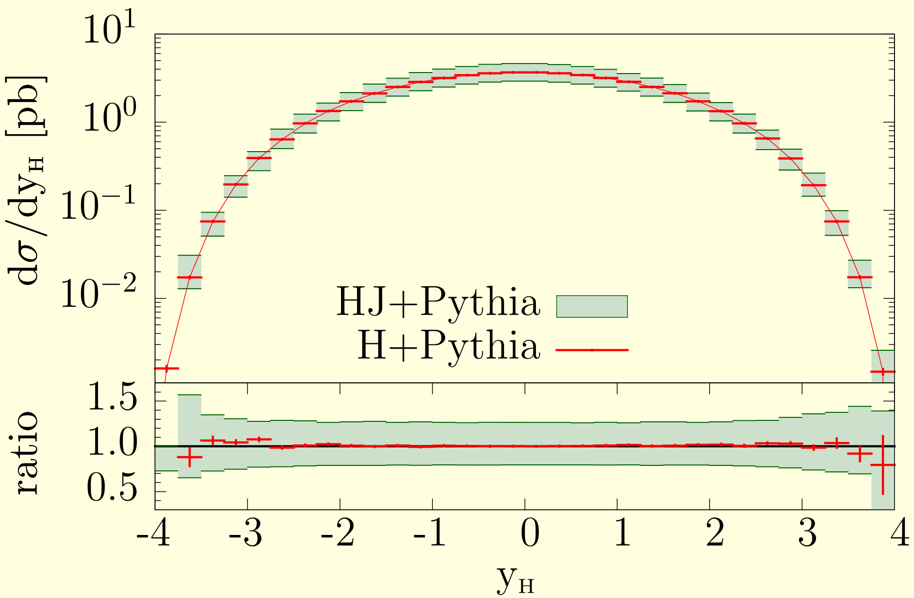
so that by reweighting:

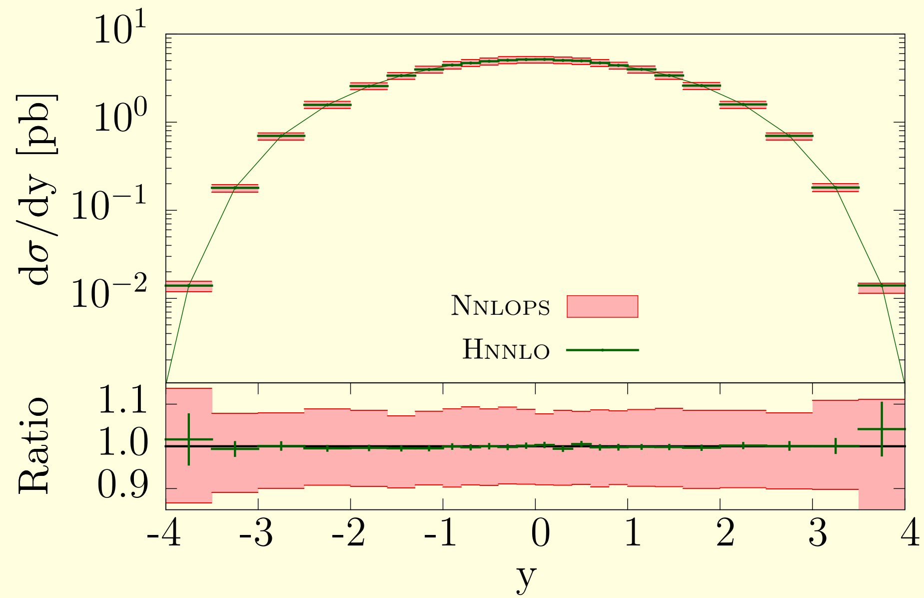
$$(1+\mathcal{O}(\alpha_s)) \times \frac{d\sigma}{dp_t} = \alpha_s^3 \frac{d\sigma^{(3)}}{dp_t} + \alpha_s^4 \frac{d\sigma^{(3)}}{dp_t} + \underbrace{\alpha_s^3 \frac{d\sigma^{(3)}}{dp_t} \times \mathcal{O}(\alpha_s)}_{\mathcal{O}(\alpha_s^4)}$$

we get spurious terms of order $\alpha_s^4$, spoiling its $\alpha_s^4$ accuracy.

# First result on Higgs production at NNLO+PS:

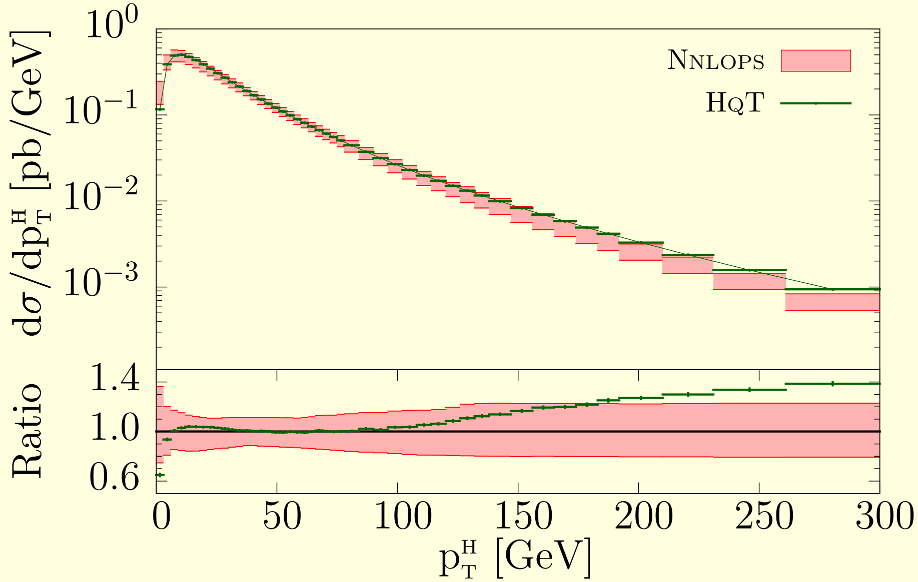
Zanderighi,Hamilton,Re,P.N. Aug. 2013, reweighting `MiNLO` generator from Zanderighi,Hamilton,Oleari,P.N. 2012

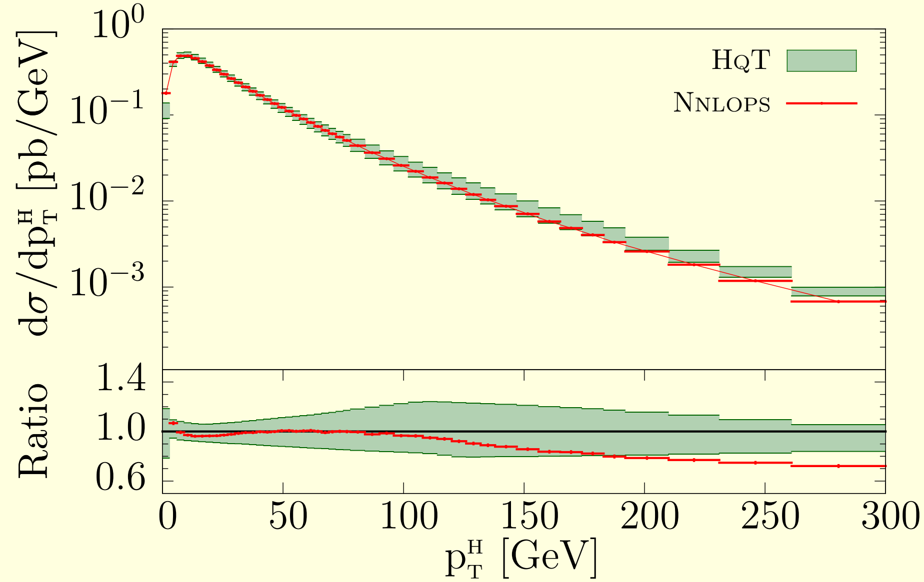



Accuracy: (left) `H-HJ` MiNLO: ∼30%, (right) NNLO+PS:∼10%

# Higgs transverse momentum comparison to HqT

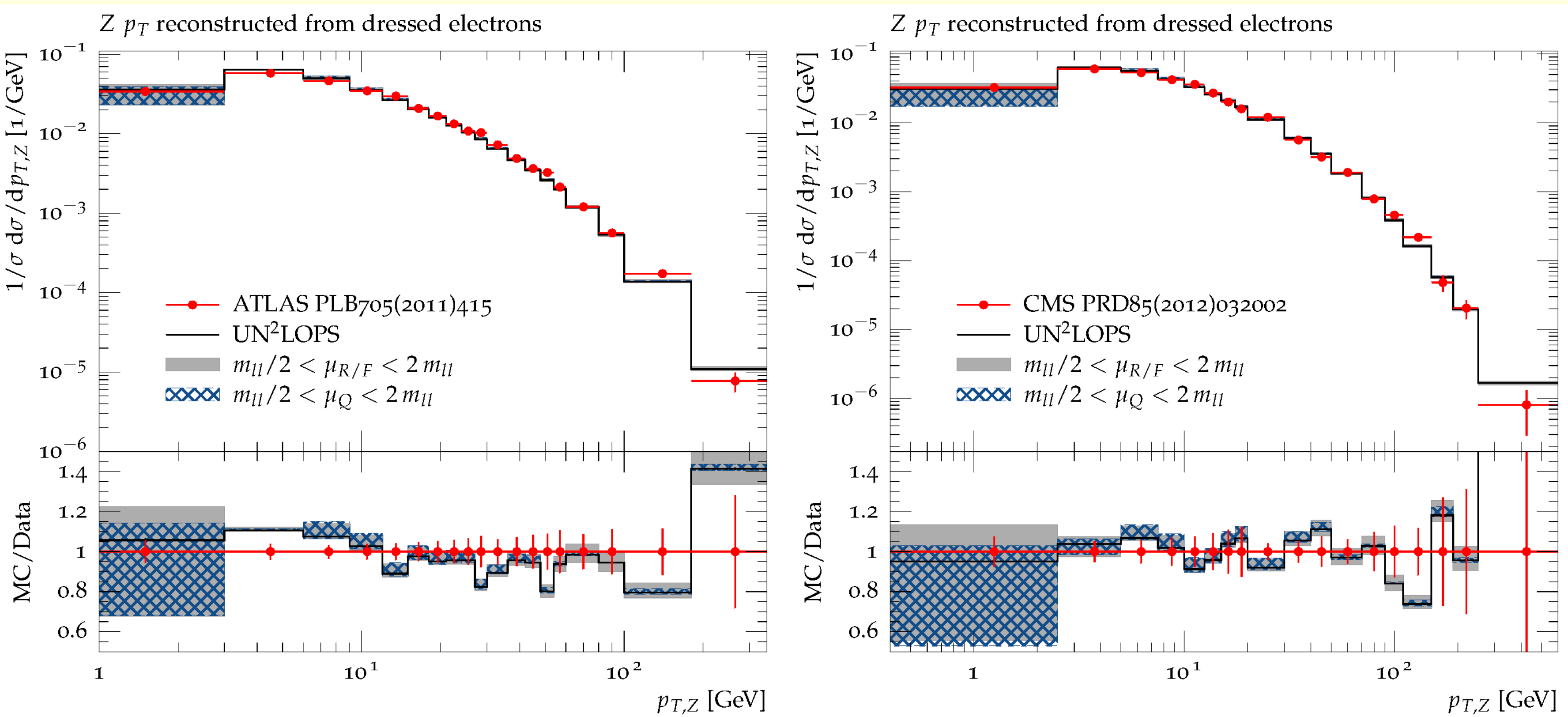



- HqT: dedicated program for NNLO+NNLL calculation of $\mathrm{d}\sigma^{\mathrm{H}}/\mathrm{d}p_{\mathrm{T}}$, Bozzi,Catani,De Florian,Ferrera,Grazzini,Tommasini
- Good agreement at small/moderate $p_{\mathrm{T}}$
- Large $p_{\mathrm{T}}$: it will be interesting to compare to $H+1j$ NNLO calculation by Boughezal,Caola,Melnikov,Petriello,Schulze Feb. 2013
- Approach valid in all production processes of colourless massive systems

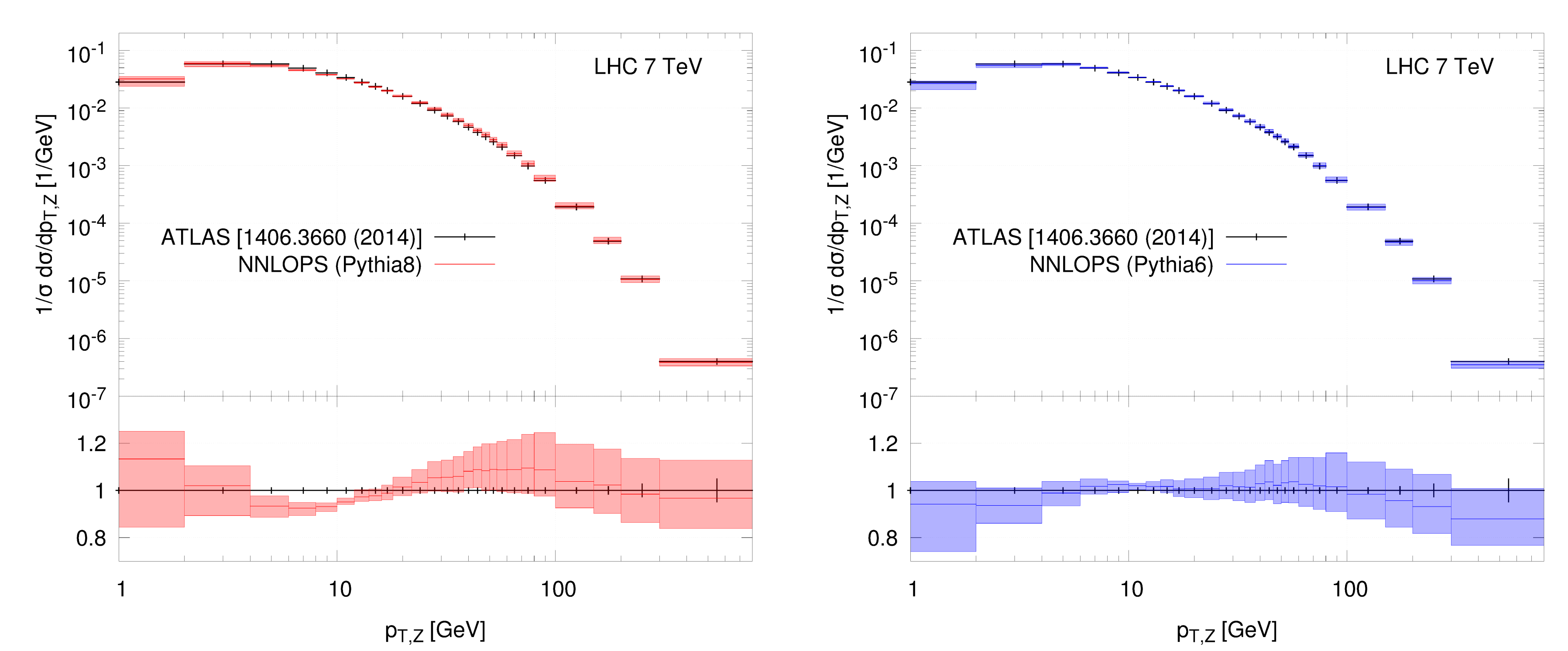
# Other methods:

NNLO+PS for Drell Yan pair production, Höche,Ye Li,Prestel, May 2014, based upon the UNLOPS merging method by Lönnblad, Prestel, 2012:



# Preliminary results on Drell-Yan NNLO+PS using the MiNLO Method:

Karlberg,Re,Zanderighi, in progress:



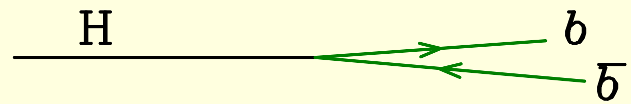

Monte Carlo tunes still play an important role.

# NNLO+PS summary and perspective

- First results have appeared for Higgs and Drell Yan type processes
- Application to other production processes with colour neutral final state should be feasible
- Different methods being pursued: `MiNLO`, `UNLOPS`, + general method within the Geneva theoretical framework
  Alioli,Bauer,Berggren,Tackmann,Walsh,Zuberi, Nov. 2013:

# Resummation and Jet substructure

Boosted, massive objects decaying into hadrons look like jets:




How do we distinguish them from QCD jets? Pioneering work: Seymour 1993; Since 2008 (Butterworth,Davison,Rubin,Salam) very active research direction, with >100 papers and its own dedicated conference (Boost2014)

Main handles for QCD jets substructure

- They tend to be asymmetric (soft emission is favoured)
- They are surrounded by more activity with respect to neutral objects (colour coherence inhibits large angle soft radiation)

Several techniques have been put forward to select out QCD jets, using jet substructure: mass-drop, pruning and trimming techniques, N subjettiness, template overlap, energy correlation functions, shower deconstruction, planar flow and several others

# (modified) Mass drop tagger

- Break the jet $j$ into two subjets $j_1, j_2$ with $m_1 > m_2$
- If there is a mass drop: $m_2 < \mu m$, and the splitting is not too asymmetric: $\min\left(p_{t,j_1}^2, p_{t,j_2}^2\right) \Delta R_{j_1 j_2}^2 / m^2 > y_{\rm cut}$ the jet $j$ is tagged; otherwise continue with the subjet with the largest $p_t^2 + m^2$.

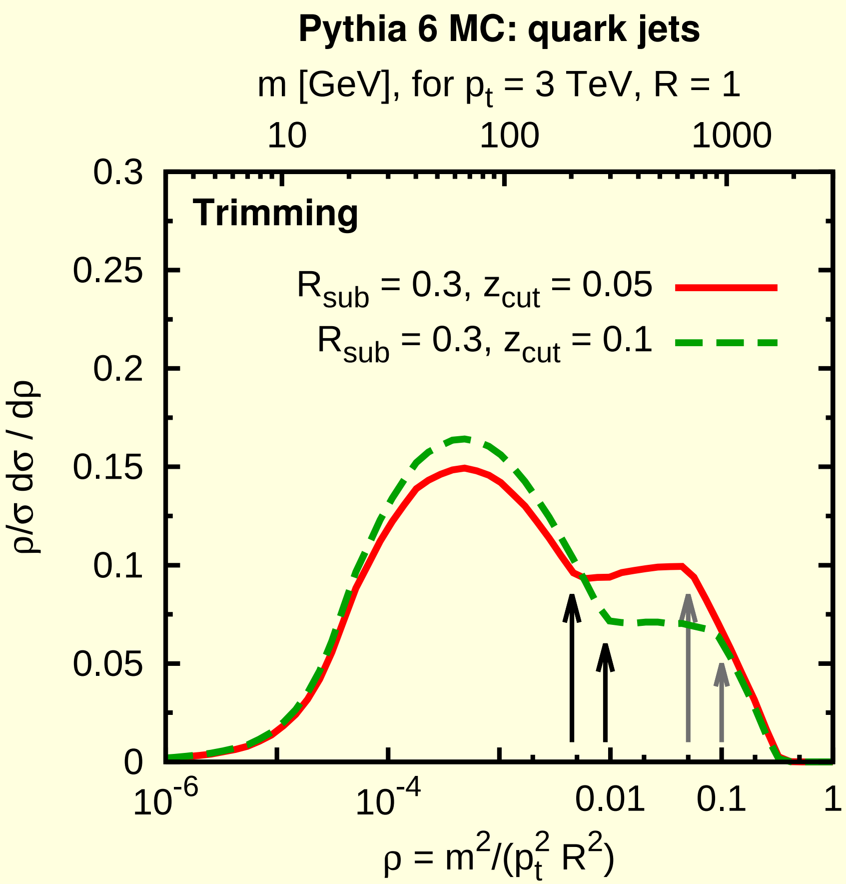
# Pruning, Trimming

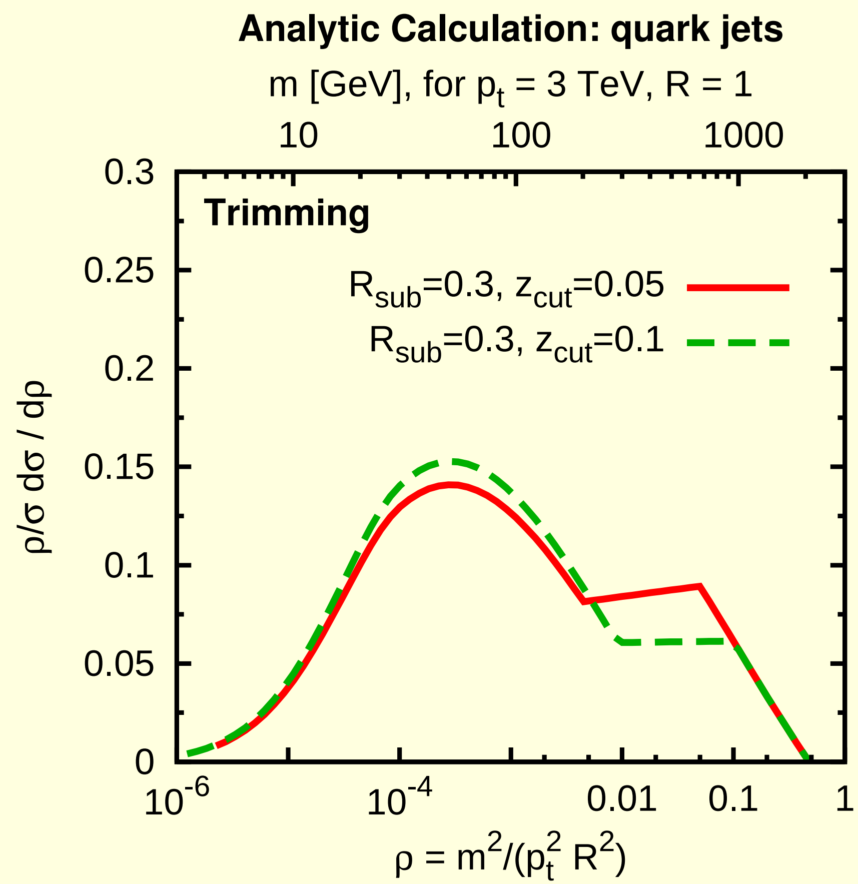
- Sets a radius $R$ ($R = m/p_t$ for pruning, fixed $R = R_{\rm trim}$ for trimming)
- Recluster the jet; if any two objects have distance larger than $R$, and $\min\left(p_{t,a}, p_{t,b}\right) < z_{\rm cut}\, p_{t,(a+b)}$ discard softer object

Easiest way to assess performance of jet taggers is using Monte Carlo's;
Hard to do with all parameters combination and for the whole range of kinematics and jet definitions.

Analytic understanding needed: Dasgupta,Fregoso,Marzani,Salam,Powling 2013

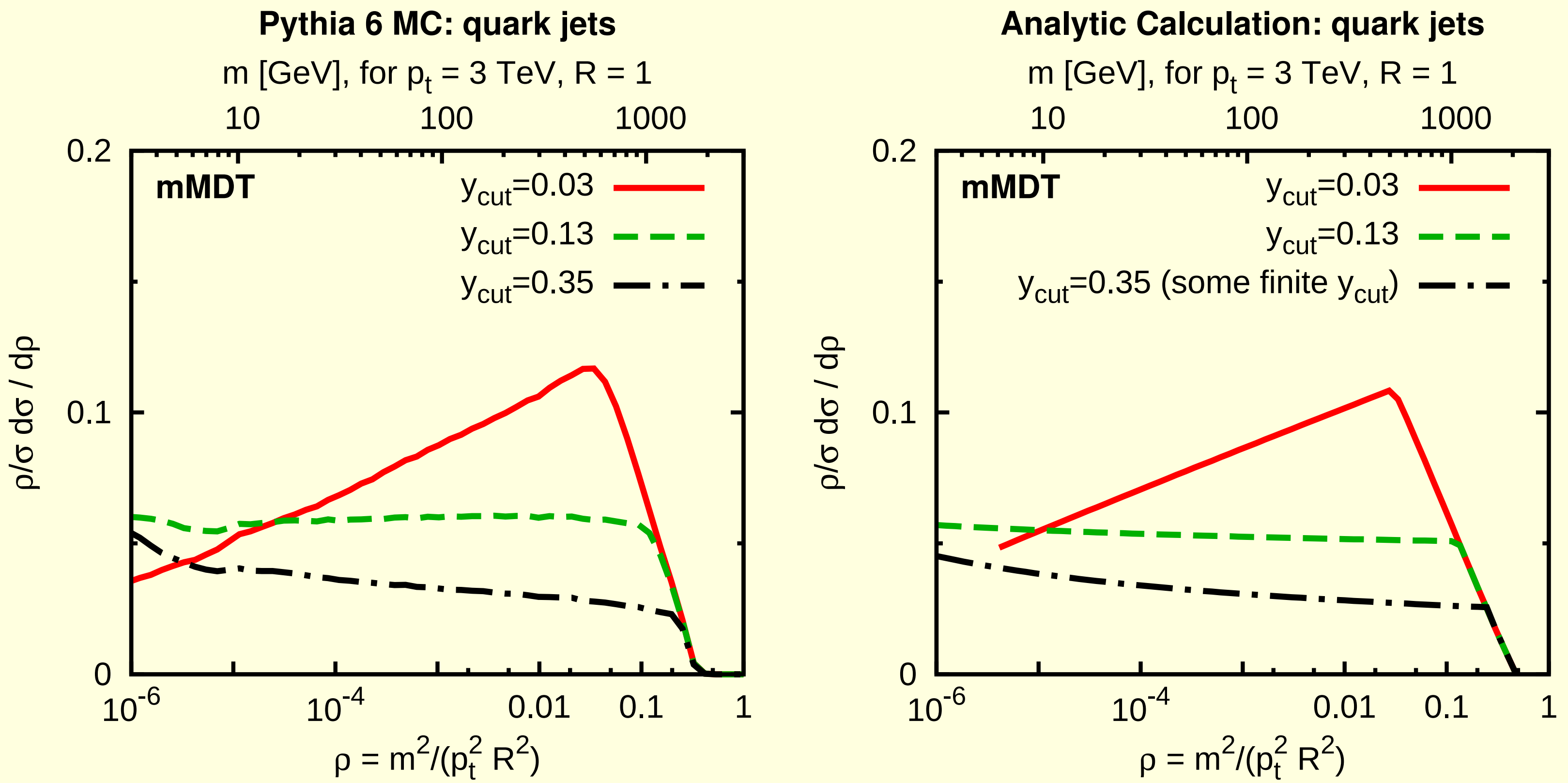
# Trimming




$$\frac{\rho}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\rho} = \rho\frac{\partial}{\partial\rho}\exp\left[-C_F\frac{\alpha_s}{2\pi}\left(-\frac{3}{2}\ln\frac{1}{\rho} + \theta(\rho - z)\,\ln^2\frac{1}{\rho} + \theta(z-\rho)2\ln\frac{z}{\rho}\,\ln\frac{1}{z} + \theta(zr^2-\rho)\ln^2\frac{zr^2}{\rho}\right)\right]$$

# Modified Mass Drop




$$\frac{\rho}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\rho} = \rho\frac{\partial}{\partial\rho}\exp\left[-C_F\frac{\alpha_s}{2\pi}\left(\ln\frac{1}{y_{\mathrm{cut}}}\ln\frac{1}{\rho} - \frac{3}{4}\ln\frac{1}{\rho}\right)\right], \qquad \rho < y$$

mMDT has single log structure! Many advantages ...

Notice:

- mMDT was found by improving the analytic properties of the MDT tagger; it is nearly impossible to do this by running a Shower Monte Carlo
- Analytic result can check the behaviour of Shower Monte Carlo's
- A standard for new algorithms has been set. Besides running a shower, its analytic properties should be studied (as an example: soft drop declustering, Larkoski, Marzani, Soyez,Thaler, van Tilburg, 2014)

# Conclusions

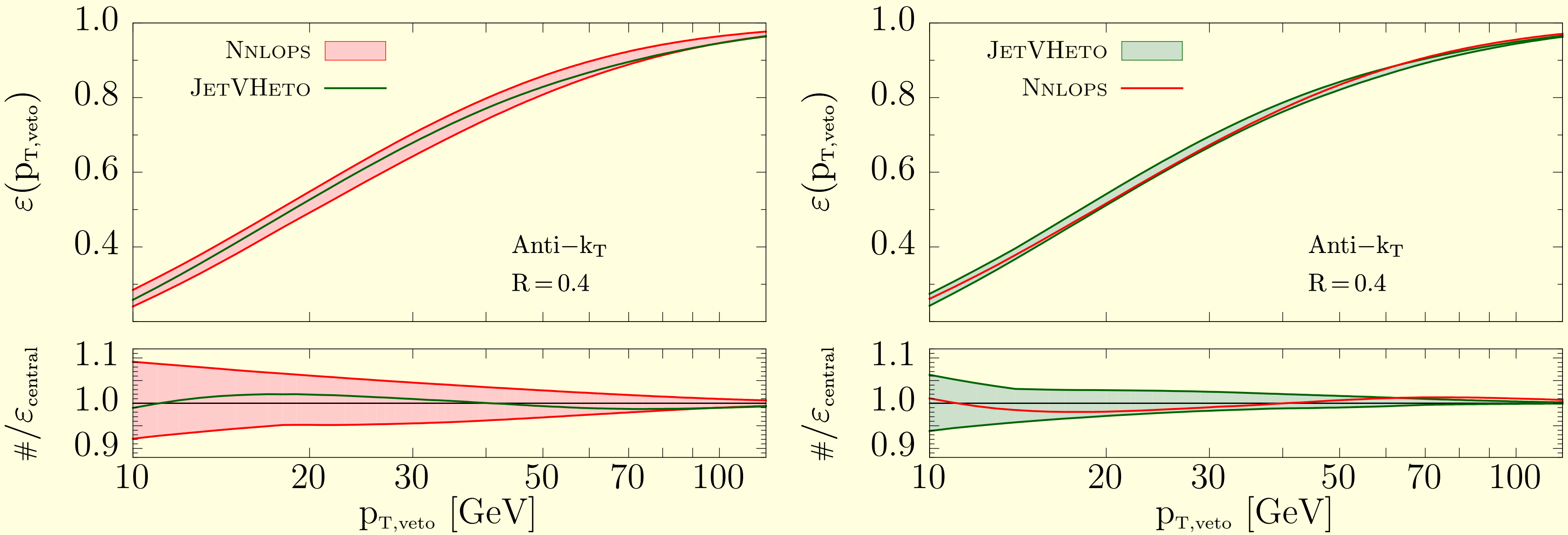
QCD is currently undergoing enormous progress, in fixed order calculations, soft gluon resummation and Shower algorithms, mostly dedicated to collider (LHC) physics. Highlights:

- NNLO is coming! $2 \to 2$ processes have become calculable at NNLO, with several results for important (complex) processes already available.
- NNLO improved parton shower generator are feasible; available for some simple processes of interest. Several tecniques are being studied.
- Not all QCD progress means very involved multiloop calculations. Novel results in the analytic understanding of jet substructure.

# Backup

# Soft gluon resummation

Besides using PS generators, resummation can also be performed analytically for specific observables. An important one: Jet veto in Higgs production:




JetVHeto: dedicated NNLO+NNLL, Banfi,Salam,Monni,Zanderighi 2012

Recent progress: Becher, Neubert, Rothen, June 2013; Stewart, Tackmann, Walsh,Zuberi, July 2013; Boughezal, Liu,Petriello,Tackmann, Walsh, Dec. 2013; Banfi,Monni,Zanderighi, Aug. 2013.

# Why Soft gluon resummation

Isn't FO+PS enough? FO+PS generators do perform soft gluon resummation, but the resummation accuracy is very limited.
Resummation involves exponentiated corrections of the form

$$\exp\left[\, L(c_0^{\rm LL}\, a + c_1^{\rm LL} a^2 + \ldots) + (c_0^{\rm NLL}\, a + c_1^{\rm NLL} a^2 + \ldots) + \alpha_s (c_0^{\rm NNLL}\, a + c_1^{\rm NNLL} a^2 + \ldots)\right]$$

where $L$ is the large (kinematic) log, and $a = \alpha_s L$.

- PS models can only do the LL contribution, and (part of) the NLL contribution right.
- In PS models it is difficult to estimate the theoretical uncertainties from missing higher order resummation towers
- hard to gain insight in the resummation properties of observables

Analytic resummation can reach NNLL accuracy, and can add understanding of the resummation properties of the observables.
For particularly importand observables, the effort of a dedicated analyticresummation calculation is thus justified.