Progressi teorici nei calcoli di Modello Standard e strumenti di generazione MC

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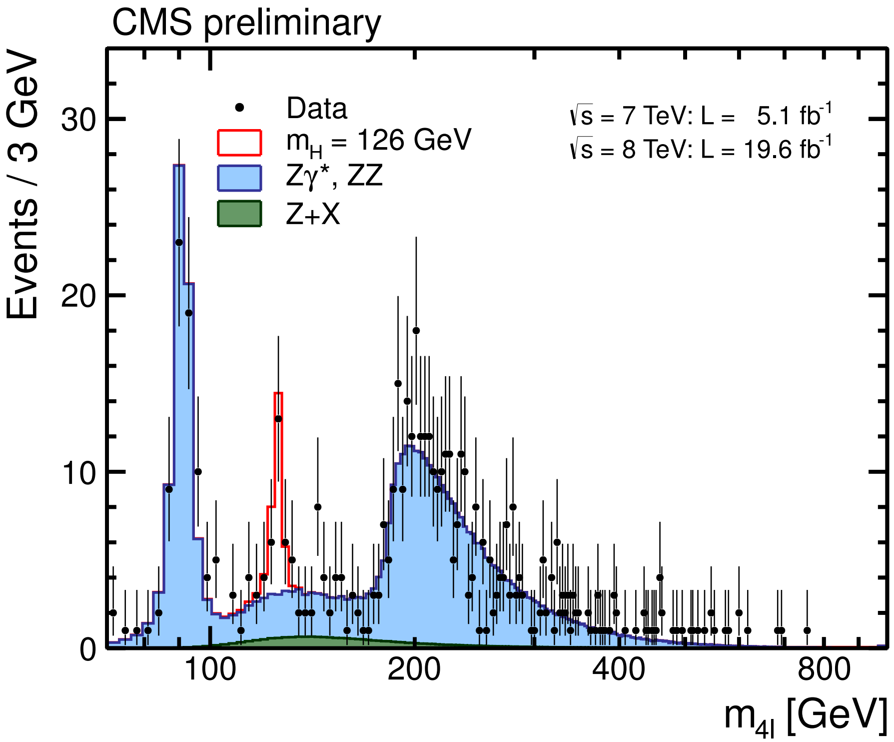
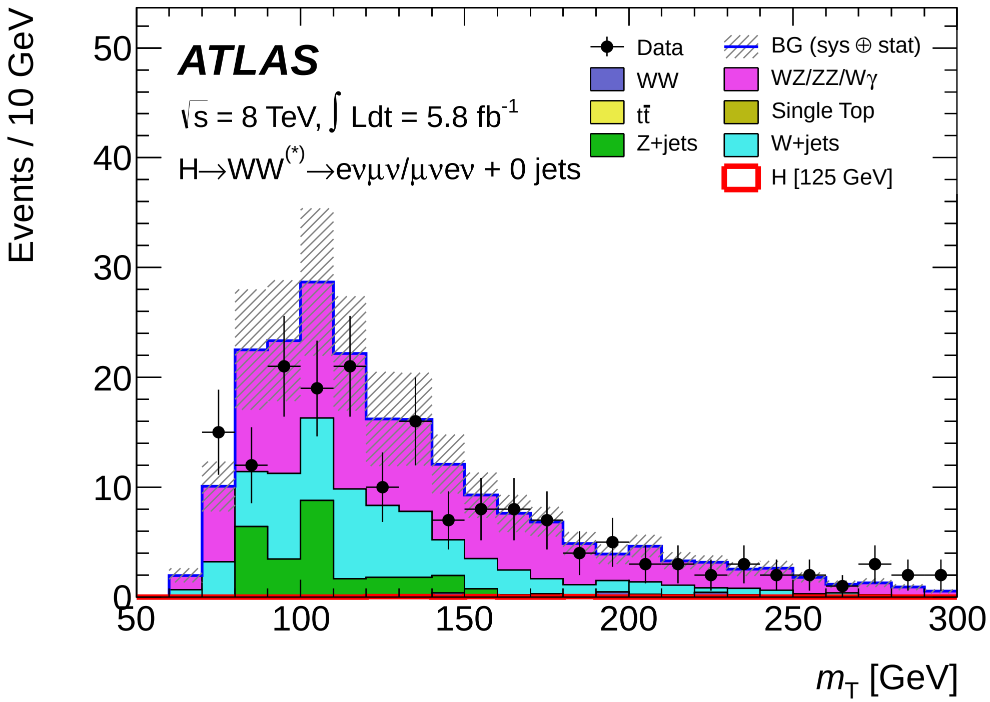
- NLO status and progresses
- NNLO status and progresses
- Partonic Monte Carlo tools at LO
- NLO + parton shower programs
- Merging samples
  - merging scale
  - MiNLO
- Conclusions and outlooks

Introduction





Background directly measured from data. Theory needed only for parameter extraction (normalization, acceptance…)

Background normalization and shapes should be known very well. Interplay among the best theoretical predictions (via MC) and data.

We are at a stage where the experimental community needs and asks for new tools for higher precision description of the data.

Les Houches wishlist

- The recent development of one-loop technologies has lead to several accomplishments: NLO QCD predictions are now available for the major collider processes, making rich phenomenology possible.
  - multiple jets (up to 4)
  - a gauge boson and up to 5 (!) jets
  - multiple gauge bosons in association with up to 2 jets (up to VV + 2 jets)
  - top quarks in association with jets (up to 2) and gauge bosons (W, Z, γ)
  - Higgs boson in association with up to 2 jets
- EW wishlist?

Process ($V \in \{Z, W, \gamma\}$)	Comments
Calculations completed since Les Houches 2005	
1. $pp \to VV$ jet	WW jet completed by Dittmaier/Kallweit/Uwer [27, 28]; Campbell/Ellis/Zanderighi [29]. ZZ jet completed by Binoth/Gleisberg/Karg/Kauer/Sanguinetti [30] WZ jet,$W\gamma$ jet completed by Campanario et al. [31, 32]
2. $pp \to$ Higgs+2 jets	NLO QCD to the gg channel completed by Campbell/Ellis/Zanderighi [33]; NLO QCD+EW to the VBF channel completed by Ciccolini/Denner/Dittmaier [34, 35] Interference QCD-EW in VBF channel [36, 37]
3. $pp \to VVV$	ZZZ completed by Lazopoulos/Melnikov/Petriello [38] and WWZ by Hankele/Zeppenfeld [39], see also Binoth/Ossola/Papadopoulos/Pittau [40] VBFNLO [41, 42] meanwhile also contains $WWW, ZZW, ZZZ, WW\gamma, ZZ\gamma, WZ\gamma, W\gamma\gamma, Z\gamma\gamma$, $\gamma\gamma\gamma, W\gamma\gamma j$ [43, 44, 45, 46, 47, 21]
4. $pp \to t\bar{t}b\bar{b}$	relevant for $t\bar{t}H$, computed by Bredenstein/Denner/Dittmaier/Pozzorini [48, 49] and Bevilacqua/Czakon/Papadopoulos/Pittau/Worek [50]
5. $pp \to V$+3 jets	W+3 jets calculated by the Blackhat/Sherpa [51] and Rocket [52] collaborations Z+3jets by Blackhat/Sherpa [53]
Calculations remaining from Les Houches 2005	
6. $pp \to t\bar{t}$+2jets	relevant for $t\bar{t}H$, computed by Bevilacqua/Czakon/Papadopoulos/Worek [54, 55]
7. $pp \to VV\, b\bar{b}$,	Pozzorini et al.[25],Bevilacqua et al.[23]
8. $pp \to VV$+2jets	W^+W^++2jets [56], W^+W^-+2jets [57, 58], VBF contributions calculated by (Bozzi/)Jäger/Oleari/Zeppenfeld [59, 60, 61]
NLO calculations added to list in 2007	
9. $pp \to b\bar{b}b\bar{b}$	Binoth et al. [62, 63]
NLO calculations added to list in 2009	
10. $pp \to V+4$ jets	top pair production, various new physics signatures Blackhat/Sherpa: W+4jets [22], Z+4jets [20] see also HEJ [64] for $W + n$jets
11. $pp \to Wb\bar{b}j$	top, new physics signatures, Reina/Schutzmeier [11]
12. $pp \to t\bar{t}t\bar{t}$	various new physics signatures
also completed: $pp \to W\gamma\gamma$ jet $pp \to$ 4 jets	 Campanario/Englert/Rauch/Zeppenfeld [21] Blackhat/Sherpa [19]

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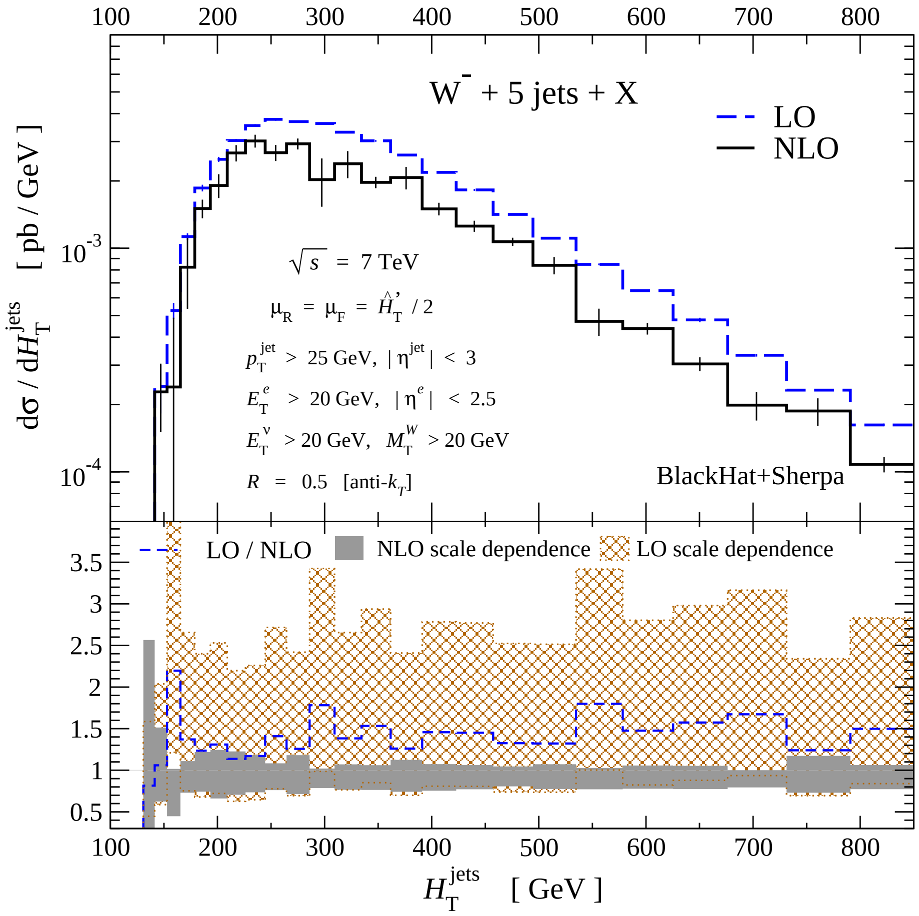
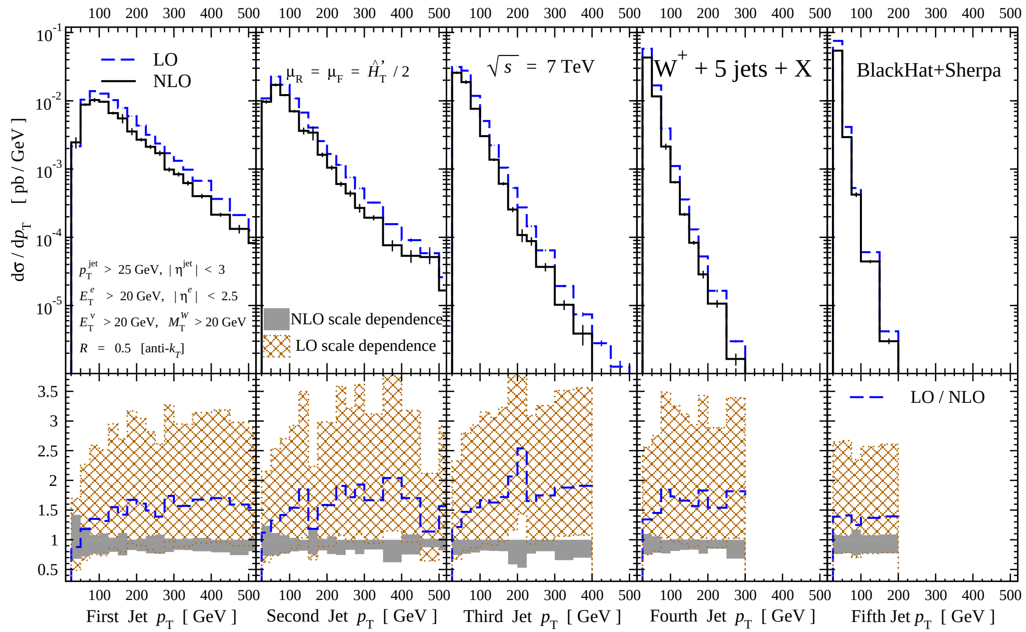
Table 1: The updated experimenter's wishlist for LHC processes

NLO most complicated: W + 5 jets

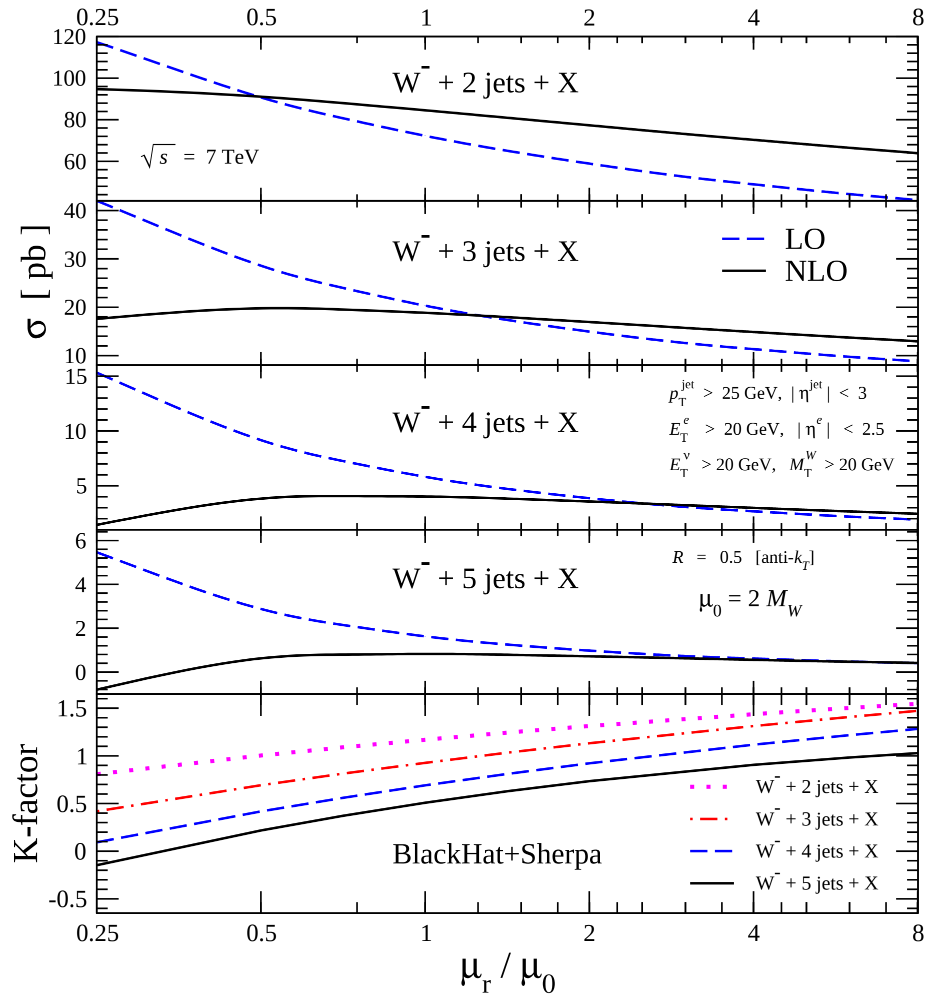




BlackHat + Sherpa collaboration

Bern, Dixon, Febres Cordero, Hoeche, Ita, Kosower, Maître, Ozeren, arXiv:1304.1253

NLO most complicated: W + 5 jets



- Reduced scale dependence
- NLO corrections are not always positive: need “appropriate” scale choice

Towards full automation

Paramount progresses in the automatic calculation of virtual corrections

- HELAC-NLO, a computer framework that allows for a complete evaluation of QCD NLO corrections [Bevilacqua, Czakon, Garzelli, van Hameren, Kardos, Papadopoulos, Pittau, Worek, arXiv:1110.1499]
- GoSam, a program for automated one-loop calculations, from Golem + Samurai [Cullen, Greiner, Heinrich, Luisoni, Mastrolia, Ossola, Reiter, Tramontano, arXiv:1111.6534 + collaborators]
- OpenLoops [Cascioli, Maierhofer, Pozzorini, arXiv:1111.5206]
- MadLoop [Hirschi, Frederix, Frixione, Garzelli, Maltoni, Pittau, arXiv:1103.0621]
- BlackHat, program for calculating one-loop amplitudes [Berger, Bern, Dixon, Febres Cordero, Forde, Ita, Kosower, Maître, arXiv:0807.3705 + collaborators]
- NGluon, one-loop multi-gluon amplitudes [Badger, Biedermann, Uwer, arXiv:1011.2900]
- Recola, recursive calculation of one-loop amplitudes in the SM. Automatic NLO generator for full SM (including EW corrections) [Actis, Denner, Hofer, Scharf, Uccirati, arXiv:1211.6316]
- ...

Collection of "handmade" NLO processes

Being dedicated codes, they have the advantage that they are very fast, if com[pared to the automatic-generated ones

- MCFM, Campbell, Ellis, Williams
  `http://mcfm.fnal.gov/`
- VBFNLO, Arnold, Bellm, Bozzi, Campanario, Englert, Feigl, Frank, Figy, Jager, Kerner, Kubocz, C.O., Palmer, Rauch, Rzehak, Schissler, Schlimpert, Spannowsky, Zeppenfeld, arXiv:1207.4975
  `http://www-itp.physik.uni-karlsruhe.de/~vbfnloweb/`
- ...

ProcId	Process	Bsm
120	$p\overset{(-)}{p} \to Z\,jj \to \ell^+\ell^-\,jj$	
121	$p\overset{(-)}{p} \to Z\,jj \to \nu_\ell\bar{\nu}_\ell\,jj$	
130	$p\overset{(-)}{p} \to W^+\,jj \to \ell^+\nu_\ell\,jj$	} anomalous couplings (120–150)
140	$p\overset{(-)}{p} \to W^-\,jj \to \ell^-\bar{\nu}_\ell\,jj$	
150	$p\overset{(-)}{p} \to \gamma\,jj$	
191	$p\overset{(-)}{p} \to S_2\,jj \to \gamma\gamma\,jj$	only spin-2 resonant production
200	$p\overset{(-)}{p} \to W^+W^-\,jj \to \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}\,jj$	anomalous couplings, Kaluza-Klein & spin-2 models
210	$p\overset{(-)}{p} \to ZZ\,jj \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-\,jj$	
211	$p\overset{(-)}{p} \to ZZ\,jj \to \ell_1^+\ell_1^-\nu_{\ell_2}\bar{\nu}_{\ell_2}\,jj$	
220	$p\overset{(-)}{p} \to W^+Z\,jj \to \ell_1^+\nu_{\ell_1}\ell_2^+\ell_2^-\,jj$	} Kaluza-Klein models, spin-2 models (210–230)
230	$p\overset{(-)}{p} \to W^-Z\,jj \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^+\ell_2^-\,jj$	
250	$p\overset{(-)}{p} \to W^+W^+\,jj \to \ell_1^+\nu_{\ell_1}\ell_2^+\nu_{\ell_2}\,jj$	
260	$p\overset{(-)}{p} \to W^-W^-\,jj \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}\,jj$	
300	$p\overset{(-)}{p} \to W^+W^- \to \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}$	anomalous VVV and HVV couplings
310	$p\overset{(-)}{p} \to W^+Z \to \ell_1^+\nu_{\ell_1}\ell_2^+\ell_2^-$	} anomalous VVV couplings (310–320)
320	$p\overset{(-)}{p} \to W^-Z \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^+\ell_2^-$	
330	$p\overset{(-)}{p} \to ZZ \to \ell_1^-\ell_1^+\ell_2^-\ell_2^+$	anomalous HVV couplings
340	$p\overset{(-)}{p} \to W^+\gamma \to \ell_1^+\nu_{\ell_1}\gamma$	} anomalous VVV couplings (340–350)
350	$p\overset{(-)}{p} \to W^-\gamma \to \ell_1^-\bar{\nu}_{\ell_1}\gamma$	
360	$p\overset{(-)}{p} \to Z\gamma \to \ell_1^-\ell_1^+\gamma$	} anomalous HVV couplings (360–370)
370	$p\overset{(-)}{p} \to \gamma\gamma$	

Existing calculations

process	NLO QCD	NLO PS matching	loop induced gg contribution	NLO EW
$\gamma\gamma$	✓, NNLO	✓	✓	
$V\gamma$	✓		✓	PA
Vj	✓	✓	OS	✓
VV	✓	✓	✓	OS/PA+HEA
$\gamma\gamma\gamma$	✓			
γjj	VBF			
$V\gamma\gamma$	✓			
$V\gamma$j	✓		OS	
Vjj	VBF	✓		
VVj	✓		OS	
$VV\gamma$	✓			
VVV	✓			
VVjj	VBF,(✓)	(✓)		

OS = on-shell approximation

VBF= vector-boson-fusion part

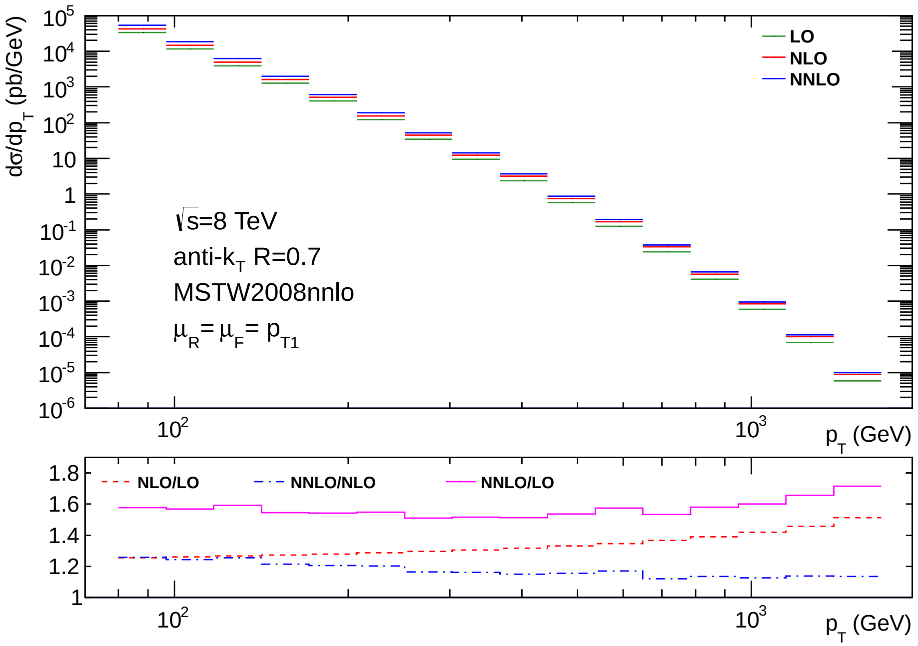
(✓): partial results or specific processes

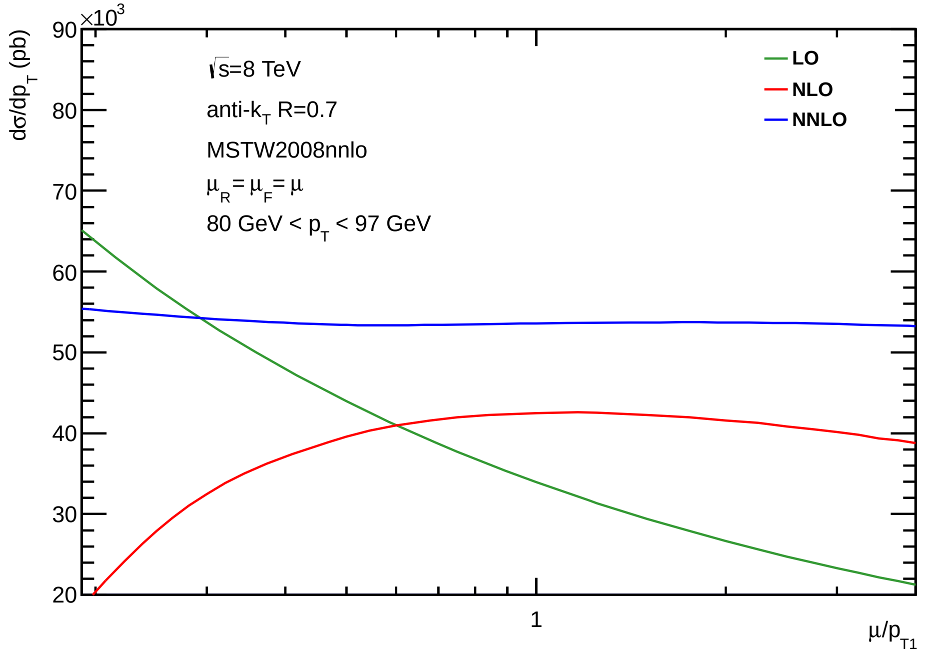
PA = pole approximation

HEA= high-energy approximation

⇒ much work to be done, in particular on EW side

$gg \to 2$ jets at NNLO



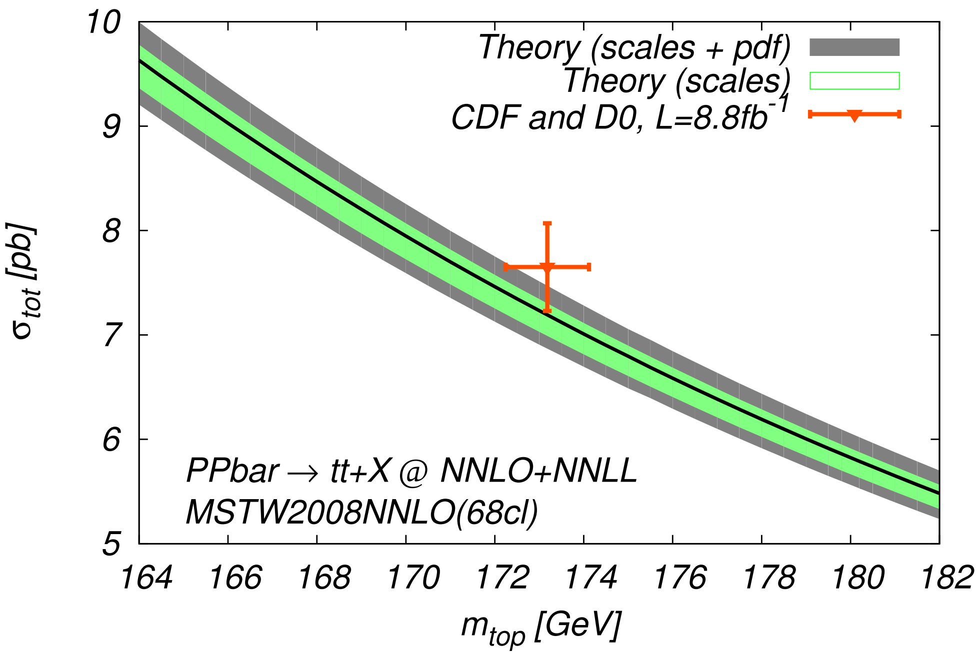


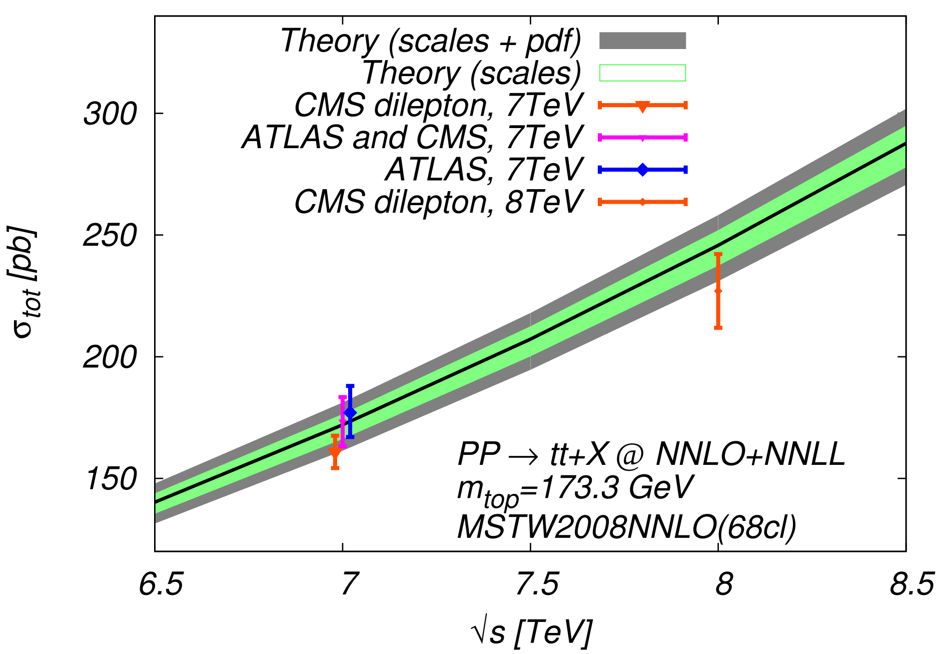
Fully differential, leading color only. A proof of concept that $pp \to 2$ jets can be done

Gehrmann-De Ridder, Gehrmann, Glover, Pires, arxiv:1301.7310

- NNLO/NLO K-factor $\approx 20\%$, quite independent of $p_{\rm T}$ value
- Very small residual scale dependence ($< 1\%$)

$t\bar{t}$ at NNLO



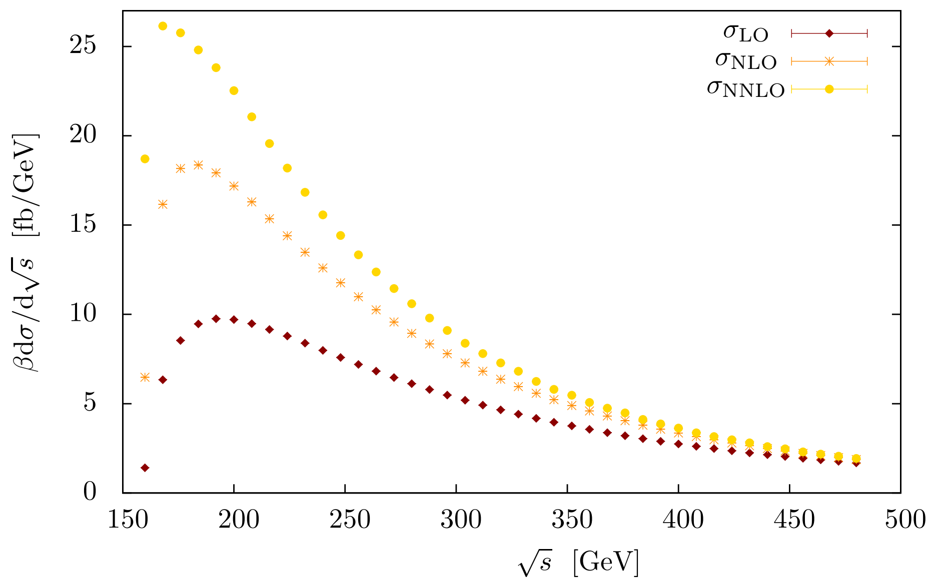


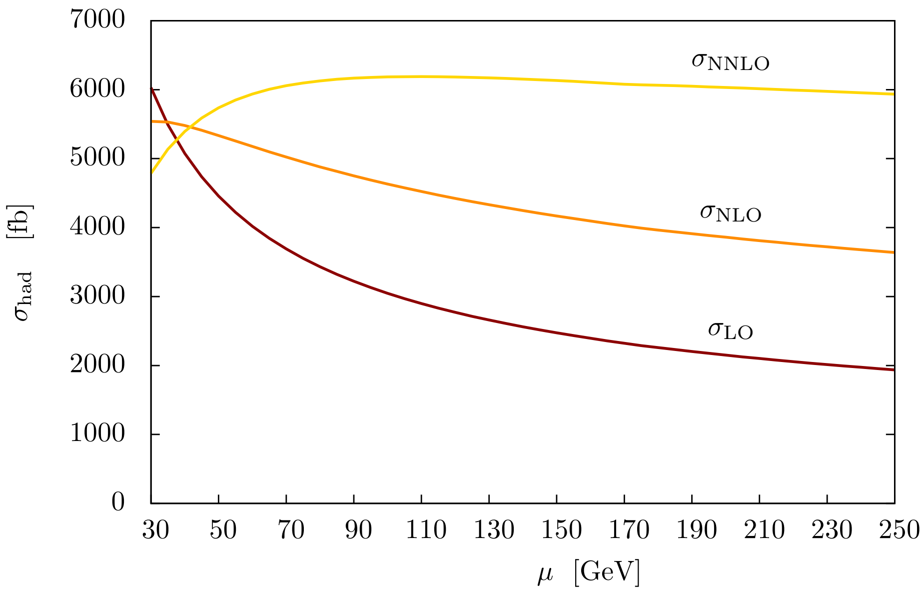
Total inclusive cross section at NNLO: first NNLO calculation with massive fermions.

Czakon, Fiedler, Mitov, arXiv:1303.6254

Best NNLO+NNLL results compared to Tevatron and LHC data

HJ at NNLO





Exclusive $H + 1$ jet production. Only $gg \to Hj$ channel

Boughezal, Caola, Melnikov, Petriello, Schulze, arXiv:1302.6216

$p_T^{min} = 30$ GeV, $\quad m_H = 125$ GeV, $\quad \beta = \sqrt{1 - \frac{E_{th}^2}{s}}, \quad E_{th} = \sqrt{m_H^2 + p_T^2} + p_T = 158.55$ GeV

On the left, the total partonic cross section at NNLO at 8 TeV.

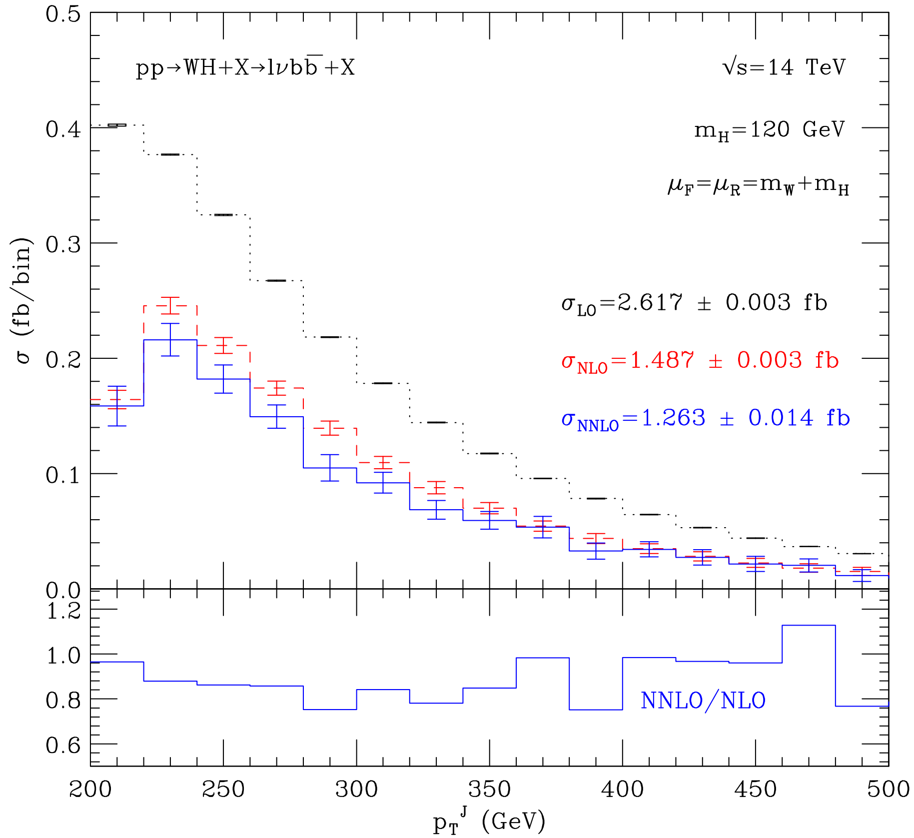
On the right, scale dependence of the “total” hadronic cross section (within cuts).

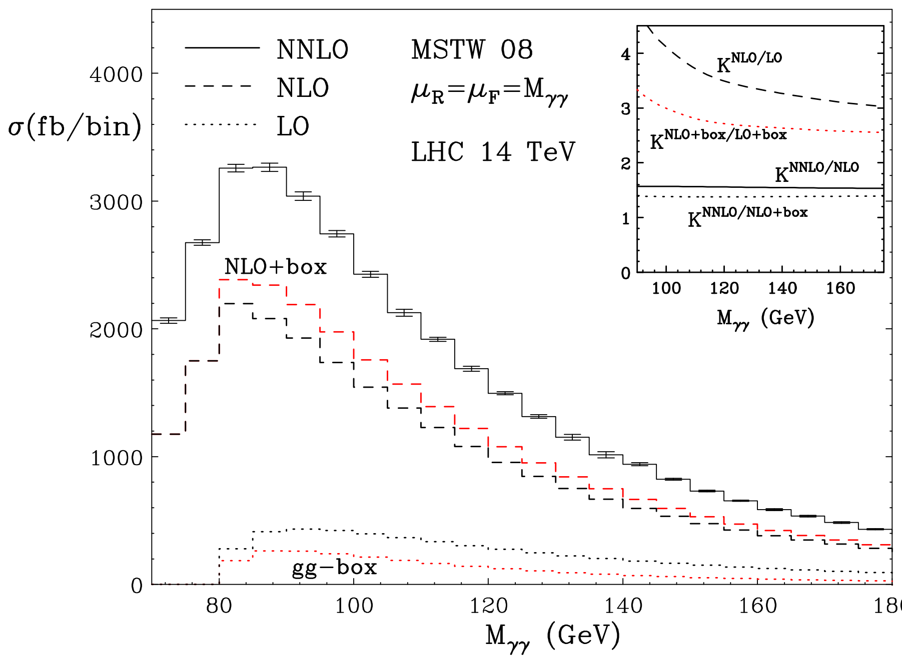
$$\sigma_{LO}(pp \to Hj) = 2713^{+1216}_{-776} \text{ fb}$$

$$\sigma_{NLO}(pp \to Hj) = 4377^{+760}_{-738} \text{ fb} \qquad \sigma_{NNLO}/\sigma_{NLO}(pp \to Hj) = 1.4$$

$$\sigma_{NNLO}(pp \to Hj) = 6177^{-204}_{+242} \text{ fb}$$

HW and $\gamma\gamma$ at NNLO





Left: fully exclusive HW production [Ferrera, Grazzini, Tramontano, arxiv:1107.1164]

Right: fully exclusive $\gamma\gamma$ production [Catani, Cieri, de Florian, Ferrera, Grazzini, arXiv:1110.2375]

Partonic MC tools at LO

- MadGraph 5/MadEvents: "software that allows you to generate amplitudes and events for any process in any mode". It is an automatic generator of amplitudes.
  Extended models to cope with BSM physics, interfaced to parton-shower codes (Pythia and Herwig), CKKW and MLM matching...

  Now it can generate not only LO amplitudes, but NLO ones too.
  Alwall, Demin, de Visscher, Frederix, Maltoni, Plehn, Rainwater, Stelzer, arXiv:0706.2334 + collaborators

  `http://madgraph.phys.ucl.ac.be`

- ALPGEN: several processes with high jet-multiplicity (formally can run up to 12 jets)
  Barzè, Mangano, Moretti, Piccinini, Pittau, Polosa ...

  `http://alpgen.web.cern.ch/alpgen/`

- ...

NLO+PS Monte Carlo programs

- MC@NLO: Frixione, Webber
- POWHEG BOX: Alioli, Nason, C.O., Re. It benefits now of two interfaces: one to Madgraph 4, for the automatic generation of the Born, spin- and color-correlated amplitudes and real diagrams, and the other to GoSam, for the automatic generation of the virtual amplitude.
  New features: event reweighting, photon shower, MiNLO, some BSM processes, resonances, parallelization...
  `http://powhegbox.mib.infn.it`
- Sherpa: Hoeche, Hoeth, Krauss, Schoenherr, Schumann, Siegert, Zapp. It has interfaces to several automatic virtual-amplitude generators (Blackhat/GoSam/NJET/OpenLoops/Collier) and it is based in an automated MC@NLO-style merging scheme
  New features: merging samples, some BSM, tunes for hadronisation and UE available...
  `www.sherpa-mc.de`
- aMC@NLO: Alwall, Hirschi, Frederix, Frixione, Maltoni, Mattelaer, Pittau, Torrielli, Zaro...
  It uses MadGraph5, MadLoop and MadFKS to generate automatically its own NLO amplitudes.
  New features: merging samples (FxFx), reweighting, BSM...
  `http://amcatnlo.cern.ch`

Merging samples at NLO

✓ Several codes provide NLO + Parton Shower results for the production of color-neutral object ($H/W/Z$, that we call B) plus 0, 1 and 2 jets

✓ Events produced with these Monte Carlo programs overlap in their population of the phase space, but the relative accuracies of each one in the various regions is complementary:

- the `B` generator
  - NLO accurate for inclusive boson distribution
  - LO accurate in the description of the hard radiation
- the `BJ` generator
  - NLO accurate for boson plus one jet distributions
  - LO accurate in the description of two jets
- ...

✓ Merging the `B`, `BJ`,... simulations means having an "output" that

- has NLO accuracy for inclusive boson distributions
- has NLO accuracy for boson plus one jet distributions
- ...

Merging with a scale

Merging with a scale means to

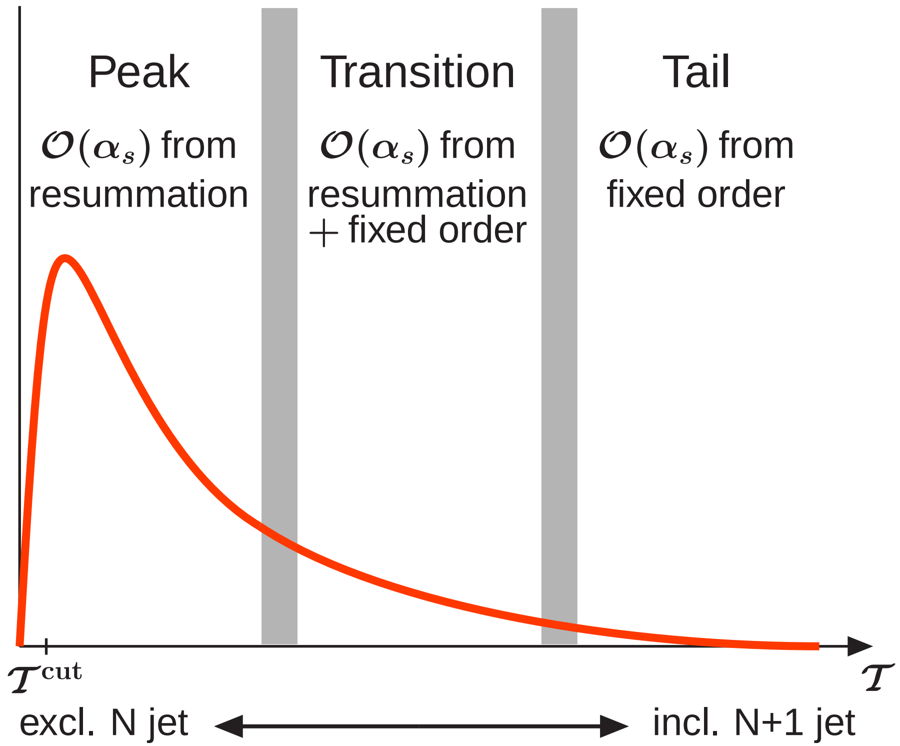
- separate the output of each simulation according to the jet multiplicity (need a jet-resolution scale, called merging scale), discarding events for which each generator does not possess NLO accuracy
- join events in an inclusive sample

In essence, each generator contributes a single exclusive jet-bin to the final inclusive sample, the magnitude of each bin being predominantly determined by the jet resolution scale used in performing the merging.

The merging scale is an unphysical parameter, and the dependence of the merged sample on this scale has to be mitigated as much as possible.

Merging with a scale

- if the merging scale is too low, the sample is dominated by the higher-multiplicity generators, that become unreliable as the Sudakov region is approached
- if it is too large, one describes relatively hard jets only with tree-level accuracy, or, even worse, with the parton-shower approximation.



Take W production for example and call $\mathcal{T}$ the jet-resolution variable, for example $p_{\rm T}^{\rm W}$

- in peek, need resummation
  - lowest order accuracy is LL
  - next-to-lowest requires at least NLL resummation
- in tail, need fixed order
  - lowest order accuracy is LO
  - next-to-lowest requires NLO

Merging with a scale

The introduction of a scale, a p_T^{cut} for example, gives rise to $\log(M_H/p_T^{cut})$ that can become large:

- some of the new NLO merging techniques attempt to resum these logarithmic corrections to all orders. This is what the GENEVA collaboration does [Alioli, Bauer, Berggren, Hornig, Tackmann, Vermilion, Walsh, Zuberi, arXiv:1211.7049]
- some tackle the problem by forcing unitarity on the approach, using suitable subtractions in order to restore NLO accuracy: Platzer, arXiv:1211.5467; Lönnblad and Prestel, arXiv:1211.7278
- some use merging scales which are not too low: Frederix, Frixione, arXiv:1209.6215 in aMC@NLO
- Sherpa too should have this problem [Hoeche, Krauss, Schonherr, Siegert, arXiv:1207.5030]

MiNLO+NLO

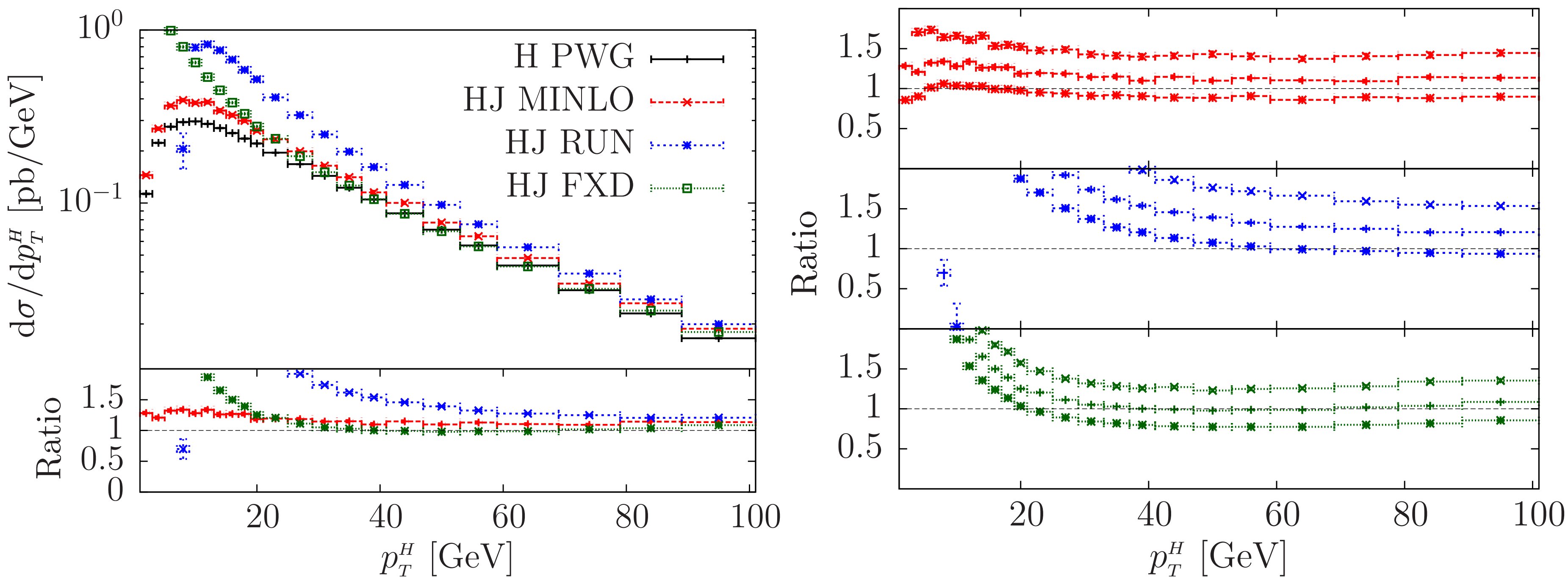
- ✓ MiNLO: Multi-scale improved NLO (Hamilton, Nason, Zanderighi, arXiv:1206.3572)
- ✓ The purpose of MiNLO is to improve the NLO computation of inclusive quantities when regions of the phase space with widely different scales are approached.
- ✓ The MiNLO procedure has been inspired by the CKKW method.
- ✓ The full result has formal NLO accuracy, therefore the scale variation around the central values is formally of NNLO order
- ✓ The accuracy and the smooth behavior near the Sudakov regions is comparable to that of the corresponding tree-level calculation in the adopted CKKW scheme
- ✓ The procedure is simple and easily implemented for any NLO parton level generator, requiring only minor work on top of the NLO calculation available.

MiNLO+POWHEG

- ✓ The underlying Born kinematics is generated with a probability proportional to the NLO inclusive cross section ($\overline{B}$), at a given point in the Born phase space
- ✓ The radiation jet is already accompanied by its Sudakov form factor
- ✓ We can then improve the POWHEG formula by implementing MiNLO on the inclusive $\overline{B}$ function
- ✓ No merging scale needed!
- ✓ We get a sample of events that covers the whole p_{T} range without doing any merging at all.
- ✓ The MiNLO procedure has been implemented and made public in the POWHEG BOX and can be found at:

`svn://powhegbox.mib.infn.it/trunk/POWHEG-BOX`

MiNLO HJ



- H PWG: the (showered) *H* POWHEG BOX result
- RUN and FXD need a generation cut (or Born suppression factor) at small $p_{\mathrm{T}}^{\mathrm{H}}$. The MiNLO result is instead finite (up to a cut-off $\approx \Lambda_{\mathrm{QCD}}$)
- The MiNLO result at small $p_{\mathrm{T}}^{\mathrm{H}}$ is almost NLO accurate. More details later on.
- We get a result that is sensible also at low $p_{\mathrm{T}}^{\mathrm{H}}$, rather than divergent.

MiNLO+POWHEG

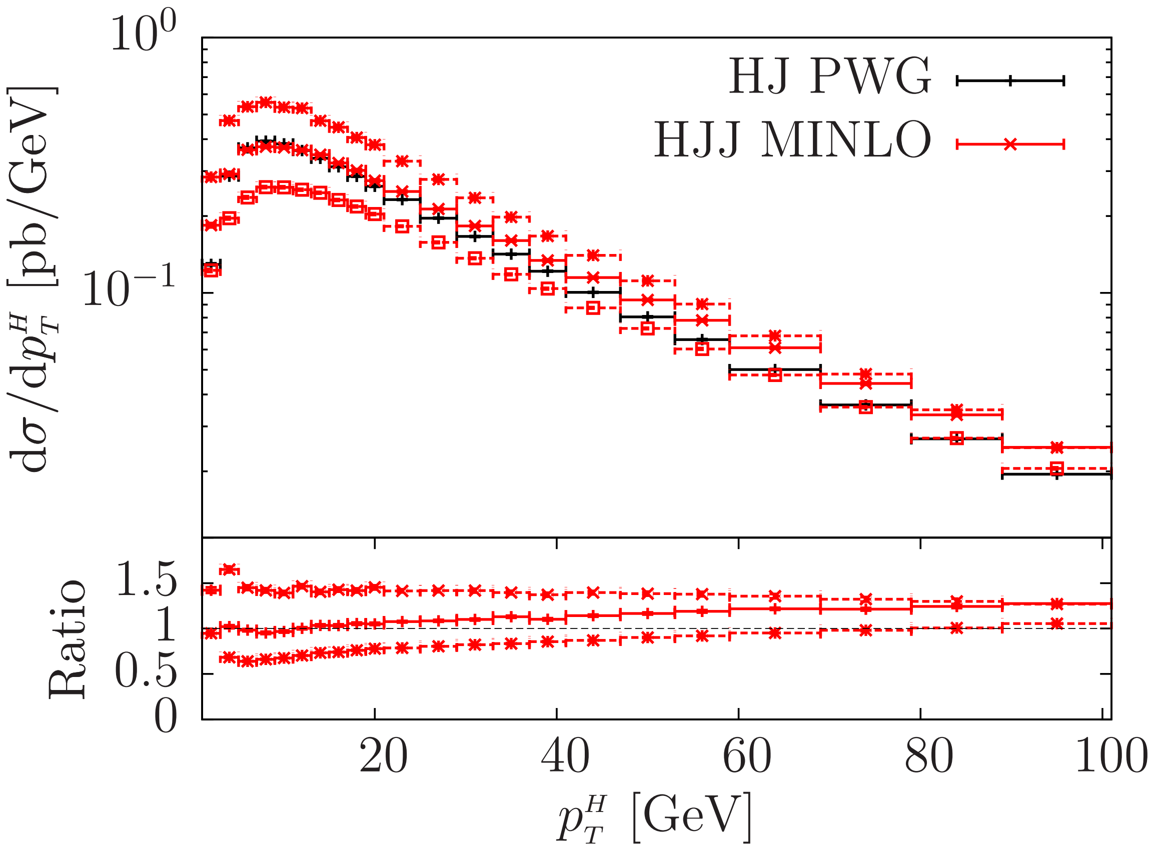
- ✓ The MiNLO approach improves the POWHEG implementations involving associated jet production, in the singular phase-space region.

- ✓ It provides a better match with the corresponding lower-multiplicity process.

  For example, $H+1$ jet matches H when approaching the zero-jet region and $H+2$ jets matches $H+1$ jet when approaching the one-jet region.
  See Hamilton, Nason, Zanderighi, arXiv:1206.3572 for more details.
  And Campbell, Ellis, Nason, Zanderighi, arXiv:1303.5447 for Wjj and Zjj production

- ✓ It turned out that the MiNLO approach eases considerably the construction of matched samples with different jet multiplicities (see FxFx in aMC@NLO).

MiNLO HJJ



- HJ PWG is obtained with MiNLO activated in POWHEG
- again very good agreement of the HJJ sample down to zero p_T^H
- scale-variation band by varying the renormalization and factorization scales by a factor of 2 up and down, around the reference scale

Accuracy of MiNLO+POWHEG in BJ

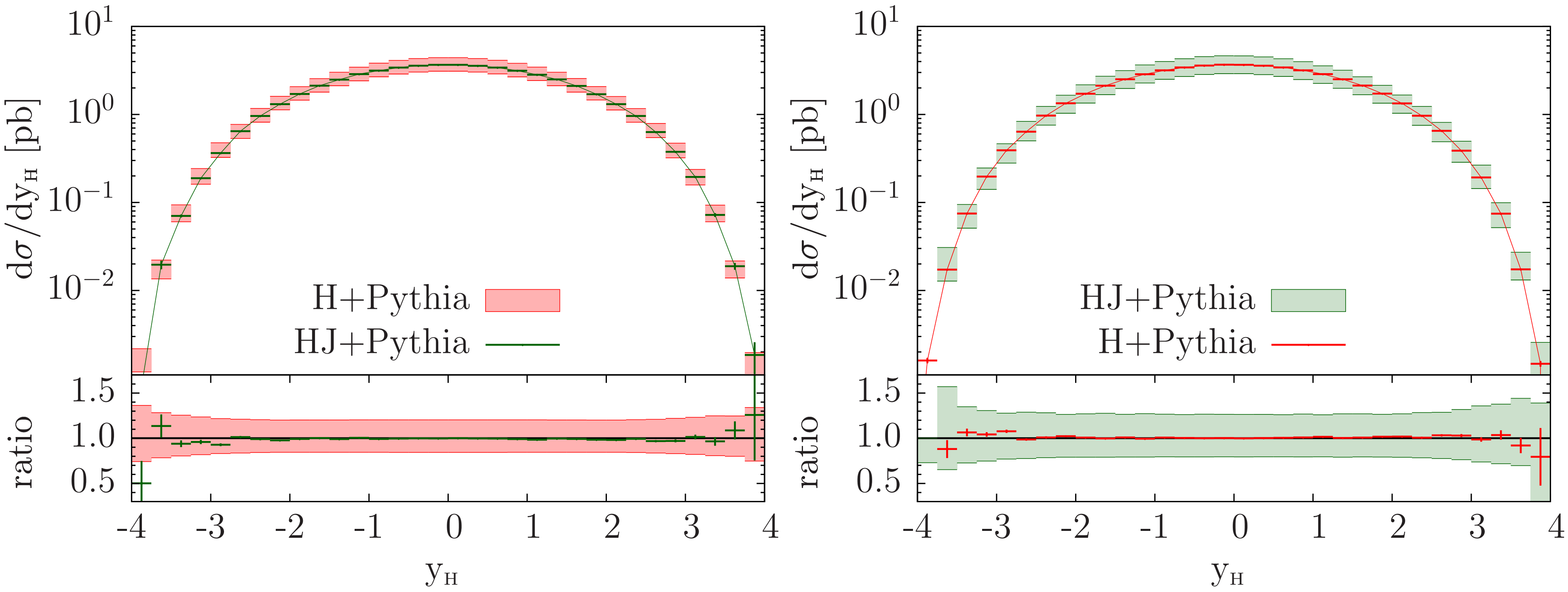
In a recent paper (Hamilton, Nason, C.O., Zanderighi, arXiv:1212.4504), we have investigated the accuracy of the BJ+MiNLO results. We have found that:

✓ It is possible to slightly modify the BJ+MiNLO procedure in a very simple way such that one can reach NLO accuracy for inclusive observables.

✓ This means that we can generate a single sample that

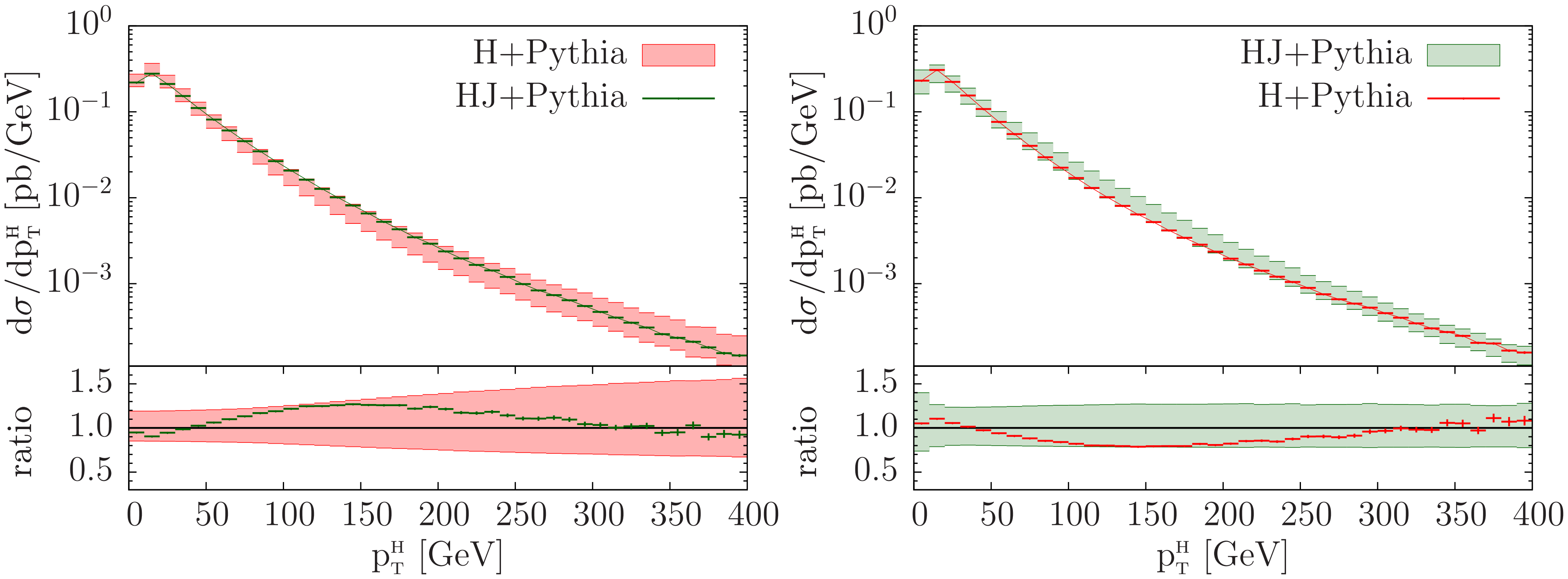
- is NLO accurate in the description of inclusive B distributions (typically the rapidity of the boson)
- is NLO accurate in the description of inclusive $B + 1$ jet distributions (typically the transverse momentum of the boson or of the leading jet)

HJ-MiNLO-NEW



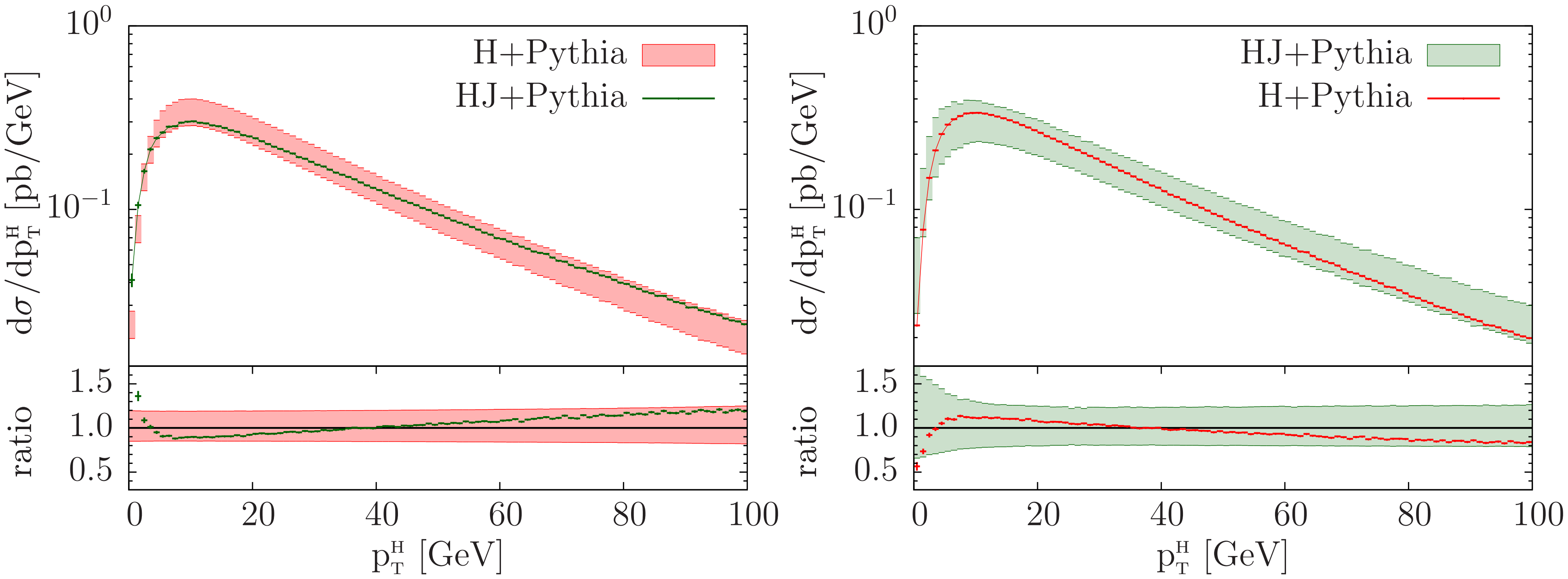
- $m_{\rm H} = 125$ GeV, LHC @ 8 TeV, `hfact` = $m_{\rm H}/1.2$
- envelope of the scale-variation bands obtained by varying the scale factor parameters by a factor of 2

HJ-MiNLO-NEW



- central values of the H and HJ-MiNLO generator in very good agreement
- the HJ-MiNLO generator has a smaller scale-variation band: the HJ-MiNLO generator achieves NLO accuracy for one-jet inclusive distributions, while the H generator is only tree-level accurate.

HJ-MiNLO-NEW



- the scale uncertainty band of HJ-MiNLO widens at small transverse momentum
  - approaching of the strong coupling regime
  - for $p_T^H < m_H$, the H result does not show a realistic scale uncertainty (S-type events)
- difference in shape in the very small transverse-momentum region, due to different NNLL and non-singular contributions in the two Sudakov form factors.

Conclusions and outlooks

- ✓ The past few years have seen the development of many new techniques for the efficient and, sometimes, automatic calculation of NLO and NNLO differential cross sections
- ✓ At the same time, new shower Monte Carlo programs at NLO have appeared on the market allowing for better simulation of hadronic events
- ✓ Several NLO + parton shower experts are now dealing with the issue of merging samples of different multiplicity
- ✓ The MiNLO approach allows for such a merging without the use of a merging scale. In addition, for the production of a colorless system B $(= V, H, VH \ldots) +$ 1 jet, an improved version of MiNLO can reach NLO accuracy both for inclusive distributions of the B system and for inclusive distributions of the $B + 1$ jet
- ✓ In addition, with the new BJ-MiNLO generators, it is actually possible to construct a NNLO+PS generator, by a simply reweighting procedure.

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Chiedo venia a tutti coloro che non ho citato o che ho impropriamente citato. L'argomento era vasto e riassumere lo stato attuale in un talk breve non è stato facile. O almeno non lo è stato per me.