Tools for Higgs Physics at Run-II Status and Discussion

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15th April 2015, First Annual Meeting of ITN HiggsTools

outline

- most of what follows is from a (CMS) **user perspective**
  - lists will be incomplete
  - please help me in adding pieces of information!

- there's a broad spectrum of new N(N)LO event generators, **suitable for most of the first data taking physics programme** (Moriond 2016)

- requests to **improve the precision** in specific cases

- for exclusive final states, **the statistical uncertainty** — and all the statistically related experimental uncertainties — **will rapidly decrease in 2016**

- **in these slides**
  - some example cases from the Run1 analyses
  - my personal toy box of generators
  - some additional items for discussion

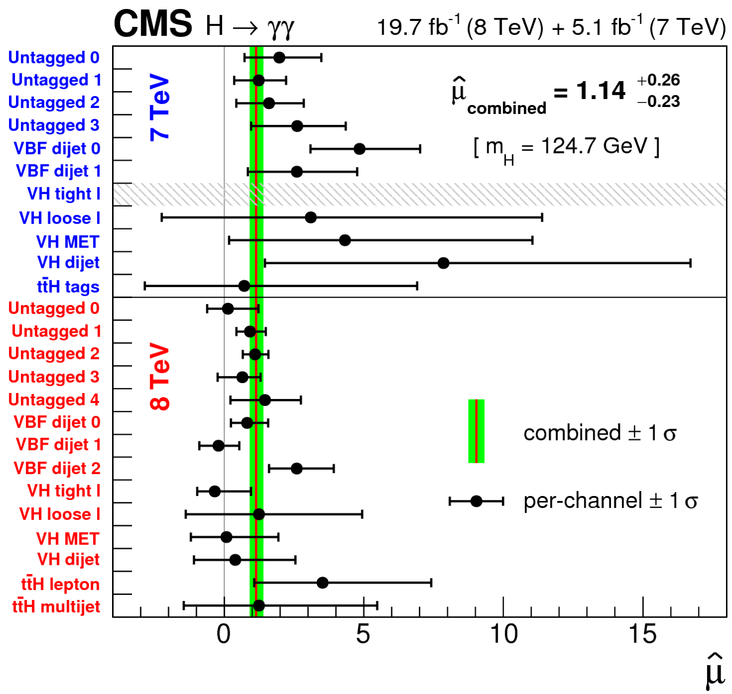
the H→γγ final state

arXiv:1407.0558

- Search for a resonance peaking over a falling background
- Mass is measured to be 124.70 ± 0.34 GeV = **124.70 ± 0.31 stat ± 0.15 syst GeV**,
- Best-fit signal strength is $1.14^{+0.26}_{-0.23}$ = **1.14 + 0.21 stat $^{+0.09}_{-0.05}$ sys $^{+0.13}_{-0.09}$ theo**.

inclusive measurement

Source of uncertainty	Uncertainty in $\hat{\mu}$
Production cross sect. and branching frac.	0.11
Shower shape modelling (Section 9)	0.06
Energy scale and resolution	0.02
Other	0.04
All syst. uncert. in the signal model	0.13
Statistical	0.21
Total	0.25



categories

Process	$\hat{\mu}$	Uncertainty: total	stat	systematic: theo	systematic: exp
ggH	$1.12^{+0.37}_{-0.32}$	0.34	0.30	0.13	0.09
VBF	$1.58^{+0.77}_{-0.68}$	0.73	0.69	0.20	0.15
VH	$-0.16^{+1.16}_{-0.79}$	0.97	0.97	0.08	
$t\bar{t}H$	$2.69^{+2.51}_{-1.81}$	2.2	2.1	0.4	

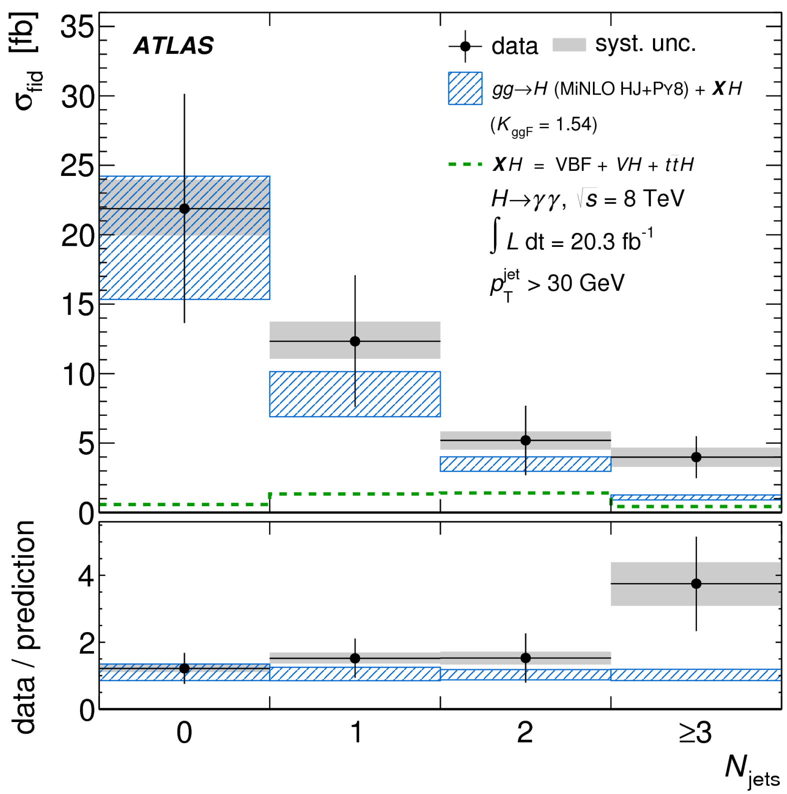
- for **exclusive final states** non-negligible theo. uncertainties
- in the **VBF case**, the jet counting and CJV uncertainty (on the gluon-fusion contamination also!) play a big role

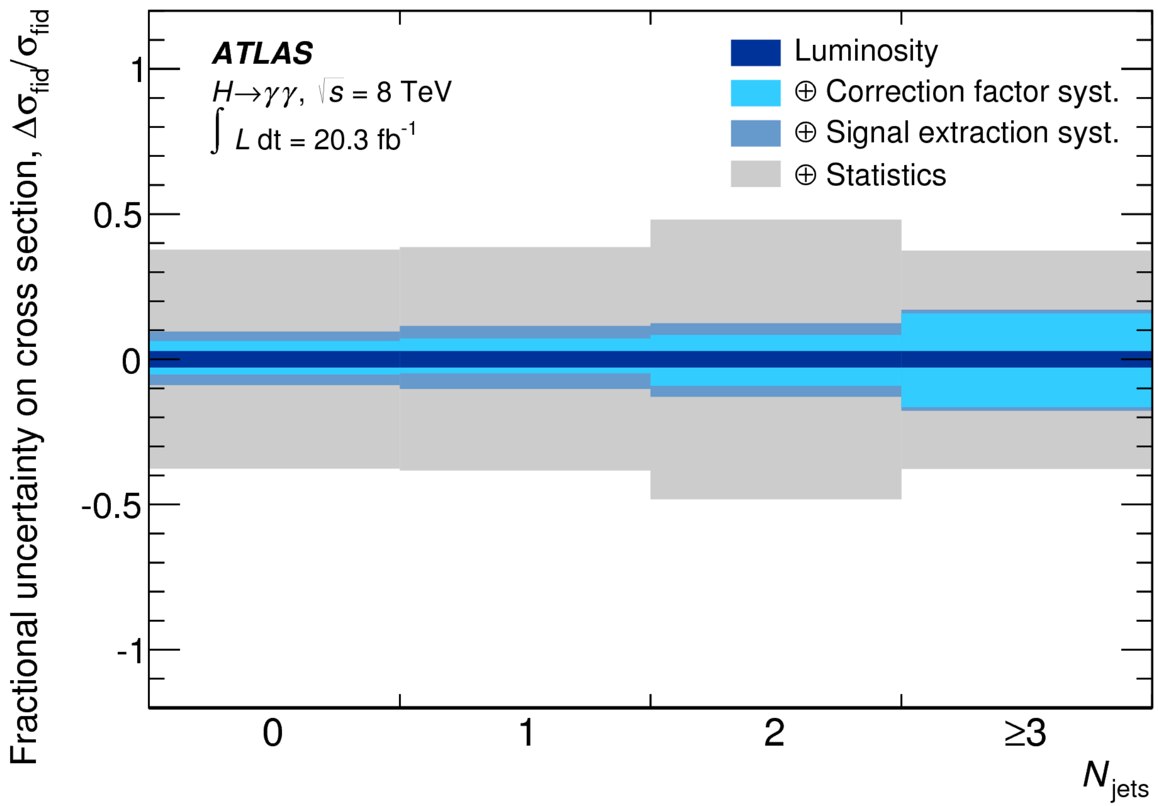
differential measurements

arXiv:1407.4222

- cross-section theoretical uncertainties: **scale and pdf** variations
- correction factor (unfolding) uncertainties:
  - **comparison among several** fully **simulated samples** (Powheg-Herwig, Minlo HJ, Minlo HJJ, Sherpa and Powheg-Pythia sample with MPI turned off)
  - **increased or decreased contributions from the VBF, VH and ttH** production within the measurement uncertainties

$$\sigma_i = \frac{\nu_i^{\mathrm{sig}}}{c_i \int L\mathrm{d}t}$$





the H→WW final state

arXiv:1312.5353

- also in the WW case, the **uncertainty on the jet counting** plays a large role

yield uncertainties

Source	H → WW	$q\bar{q}$ → WW	gg → WW	Non-Z resonant WZ/ZZ	$V\gamma^{(*)}$
Luminosity	2.2–2.6	—	—	2.2–2.6	2.2–2.6
Lepton efficiency	3.5	3.5	3.5	3.5	3.5
Lepton momentum scale	2.0	2.0	2.0	2.0	2.0
$\vec{E}_T^{miss}$ resolution	2.0	2.0	2.0	2.0	1.0
Jet counting categorization	7–20	—	5.5	5.5	5.5
Signal cross section	5–15	—	—	—	—
$q\bar{q} \to WW$ normalization	—	10	—	—	—
$gg \to WW$ normalization	—	—	30	—	—
WZ/ZZ cross section	—	—	—	4.0	—
$t\bar{t}$ + tW normalization	—	—	—	—	—
$Z/\gamma^* \to \ell\ell$ normalization	—	—	—	—	—
W + jets normalization	—	—	—	—	—
MC statistics	1.0	1.0	1.0	4.0	20

- the choice of the generator used to **model the main bkg shape (WW)** brings some differences as well

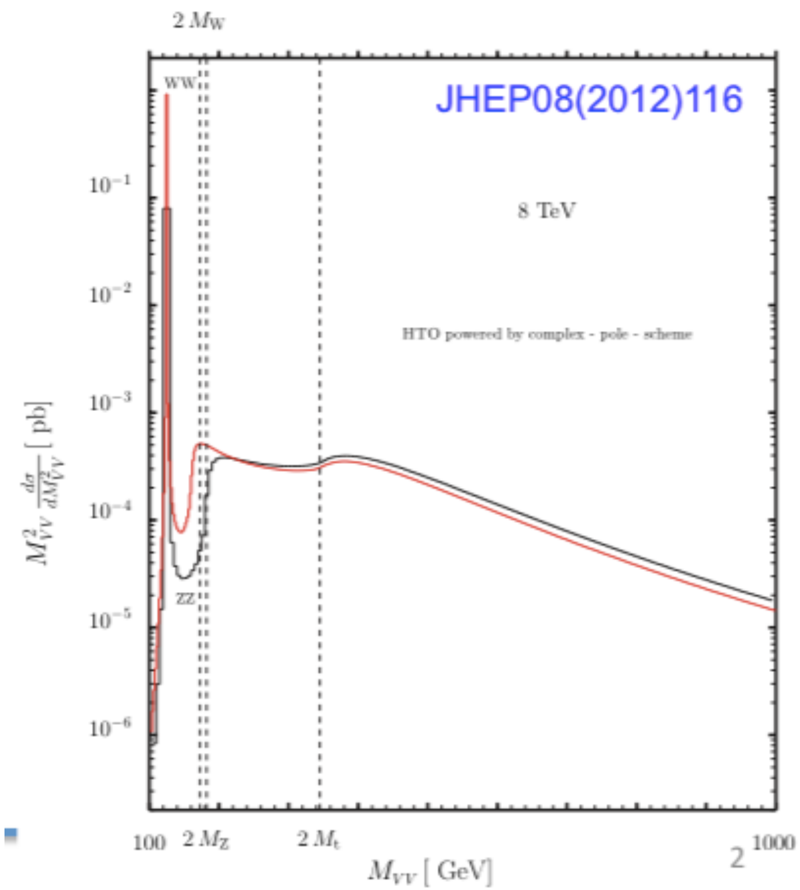
effect on the result of the WW samples choice

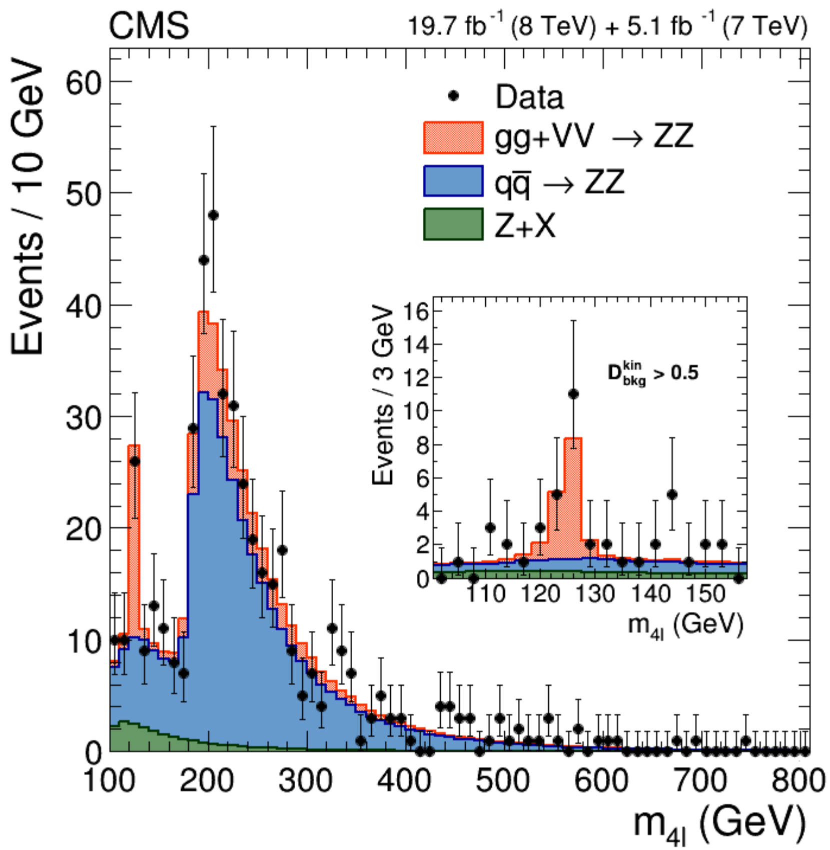
$q\bar{q} \to WW$ generator	95% CL limits on σ/σ_{SM} expected / observed	Significance expected / observed	σ/σ_{SM} observed
MADGRAPH (default)	0.4 / 1.2	5.2 / 4.0 sd	0.76 ± 0.21
MC@NLO	0.4 / 1.2	5.3 / 4.2 sd	0.82 ± 0.24
POWHEG	0.4 / 1.2	5.1 / 3.9 sd	0.74 ± 0.21

the off-shell H→ZZ analysis

arXiv:1405.3455

- measure the Higgs XS off-shell and extract the width by comparing to the on-shell XS
  - **on-shell**: H > ZZ peak, ggZZ and qqZZ backgrounds
  - **off-shell**: qqZZ, H > ZZ tail, ggZZ and its interference with Higgs
- enhance signal over background with matrix-element based discriminants (e.g. MELA)
- so far this is basically a counting experiment (precision on rates matters)
- a limit is observed on the total width of Γ_H < 22 MeV at a 95% CL, which is **5.4 times the expected value in the SM**.





the analysis systematics

arXiv:1503.01060

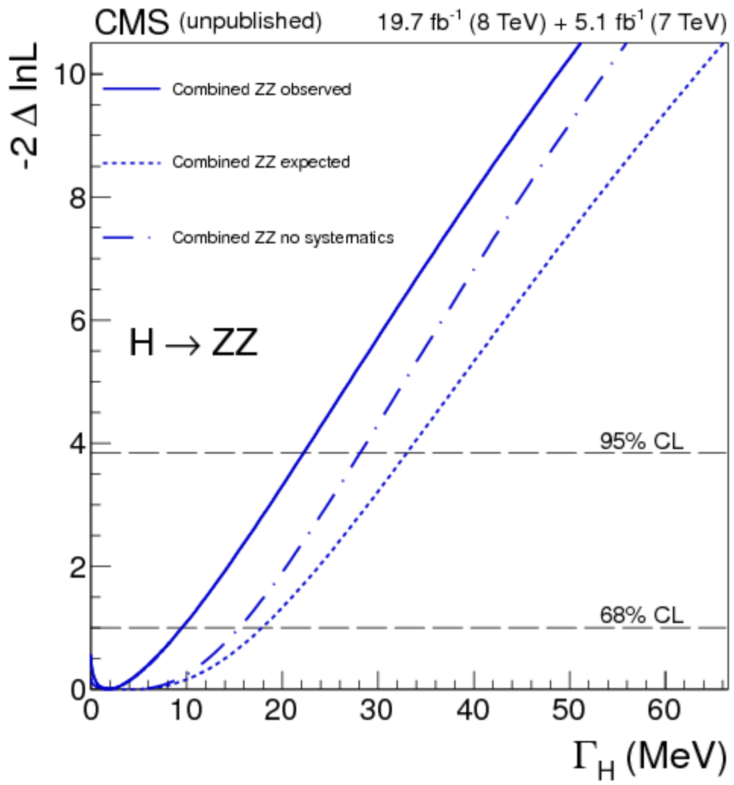
- **better precision in the off-shell region** (NNLO qqZZ, NLO ggZZ, NLO qqZZ EWK) would be beneficial

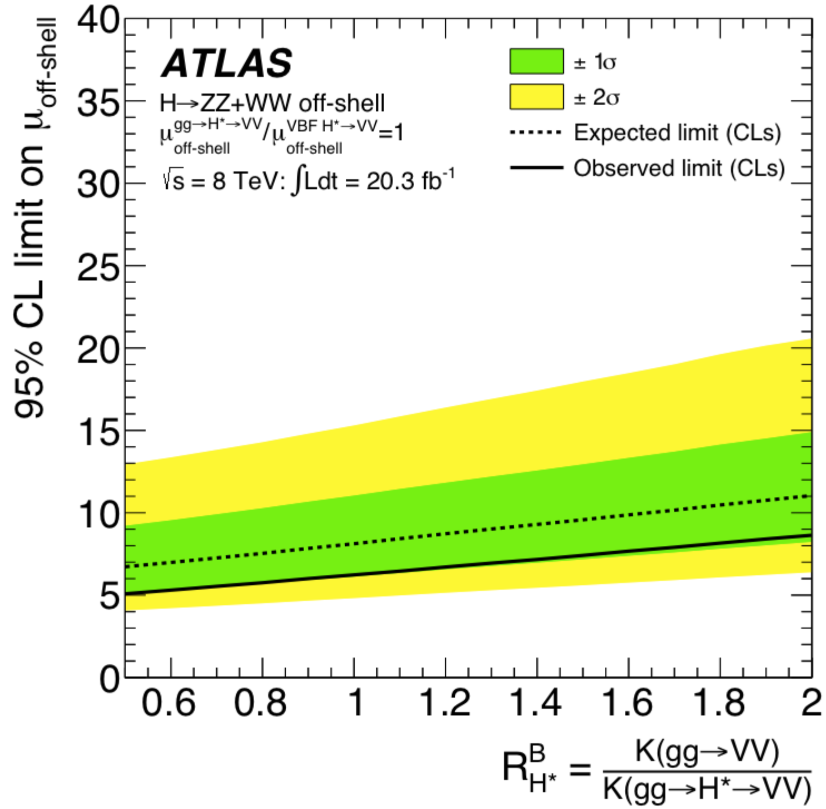
CMS

Theory uncertainties	
pdf, gluon-gluon initial state	6-11
pdf, quark-quark initial state	3.3-7.6
QCD scale, gluon-gluon initial state (ggZZ)	7+shape
QCD scale, quark-quark initial state (qqVV)	5.8-8.5+shape
$gg \to ZZ$ k-factor uncertainty	10
Underlying event and parton shower	6

ATLAS

OS higher orders gg > H > VV	20-30%
OS scale gg > H > VV	10-20%
gg > VV interference	30%
gg > VV uncorr. interference	30%
OS > VV QCD scale and PDF	5-10%



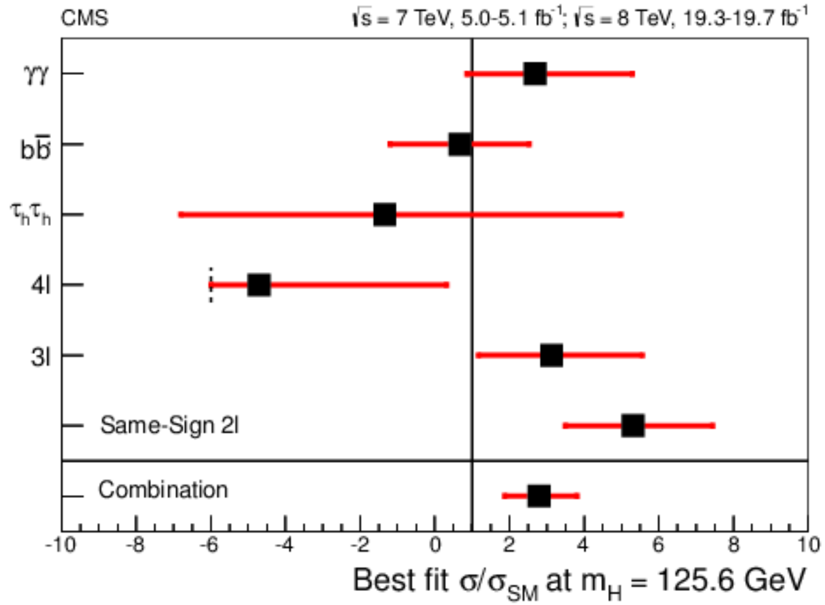


scaling QCD scale factor from signal to background

the exclusive ttH channel

arXiv:1408.1682

- very **low statistics**, spread out across several final states
- **LO signal** production
- **several backgrounds** from multi-boson + jets, ttbar + jets
- contamination from **ggH+many jets** in the γγ final state, known with PS precision
- large increase of XS expected for 13 TeV, the **statistical uncertainty will decrease quickly**



Source	Rate uncertainty		Shape
	Signal	Backgrounds	
NLO scales and PDF	9.7–14.8%	3.4–14.7%	No
MC modeling	2.3–5.1%	0.9–16.8%	Yes
Top quark p_T	—	1.4–6.9%	Yes
Additional hf uncertainty (H → hadrons)	—	50%	No
H contamination (H → photons)	36.7–41.2%		No
WZ (ZZ) uncertainty (H → leptons)	—	22% (19%)	No

- moving to **NLO generation for 13 TeV** data analysis, merging 0 and 1 jets
- the **ttW background** is estimated from simulation, NLO by now
- the **ttγγ and ttγ backgrounds** need better understanding

high mass higgs-like bosons

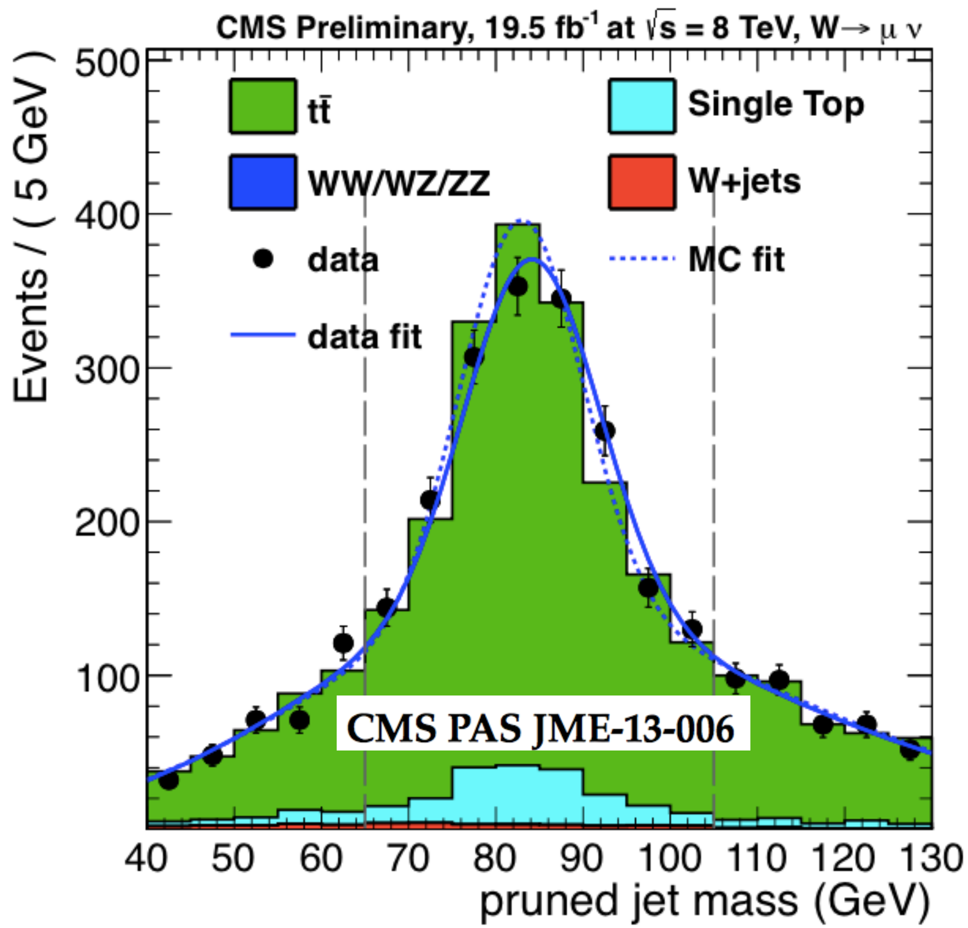
arXiv:1504.00936

- search for **high mass additional Higgs-like resonances** (VV decay channels)
  - proper treatment of **interference**
  - analysis performed **inclusively and after VBF requirements**
  - high mass means **boosted V regime**
- the **W-tagging uncertainty** comes from residual disagreement between data and MC in the fat jet tagging (half stats, half simulation)

signal uncertainties

Syst. uncertainty	ggH	VBF	ggH	VBF
Luminosity	2.6%	2.6%	2.6%	2.6%
PDF gg	9.1%*	-	-	9.1%*
PDF qq	-	5%*	-	5%*
ggH0In	26%	-	-	-
ggH2In	6%	-	19%	-
Int ggH	10%	-	10%	-
Int vbfH	-	10%	-	10%
Trigger eff.	1%	1%	1%	1%
Lepton eff.	2%	2%	2%	2%
B-Tagging	0.5%*	0.2%*	0.5%*	0.2%*
W-Tagging	9.3%	9.3%	9.3%	9.3%
Lepton Scale	2.1%*	1.5%*	3.5%*	1.8%*
Jet Scale (JES)	3.9%*	4.4%*	5.0%*	4.5%*
Jet Res (JER)	2.5%*	3.5%*	8.0%*	10.6%*

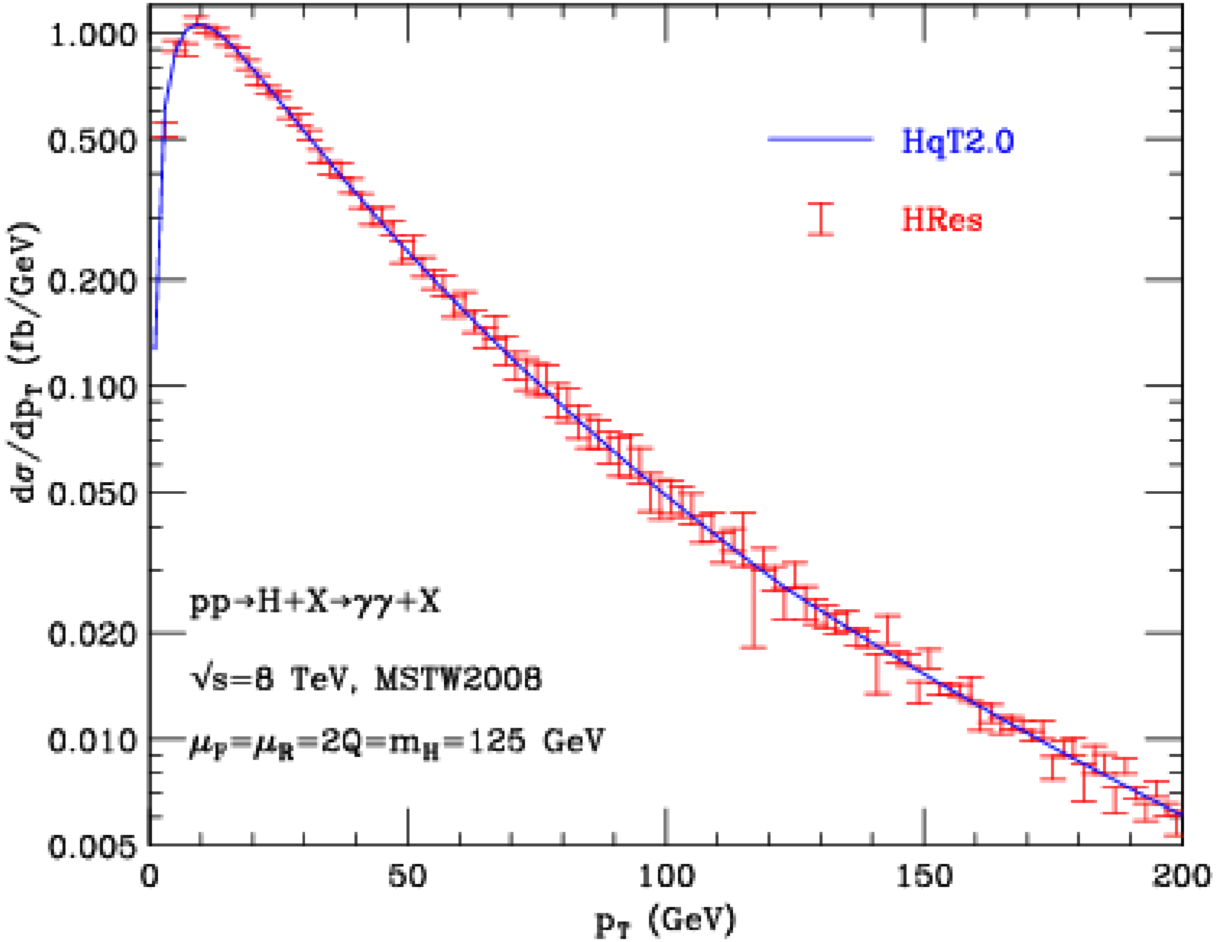
CMS PAS HIG-14-008



the Higgs p_T spectrum at NNLL + NNLO

D. de Florian, G. Ferrera, D. Tommasini, M. Grazzini (2011)

- HRes combines the NNLO calculation in HNNLO with the small p_T-resummation implemented in HqT
- Three decay channels of the Higgs boson implemented: $H \to \gamma\gamma$, $H \to WW \to l\nu l\nu$ and $H \to 4l$



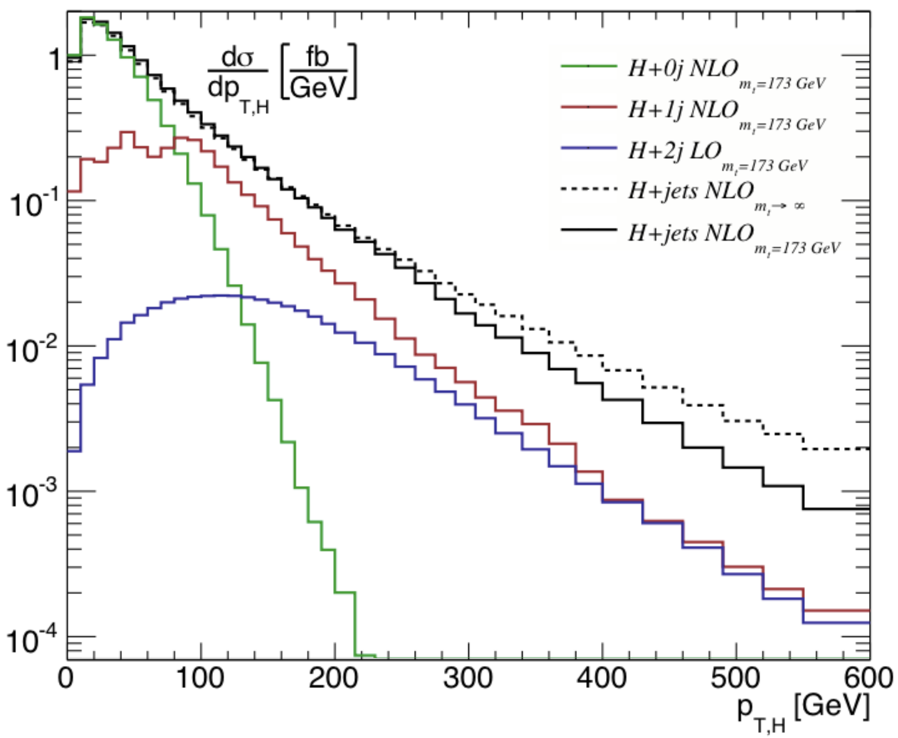
Hayk Sargsyan

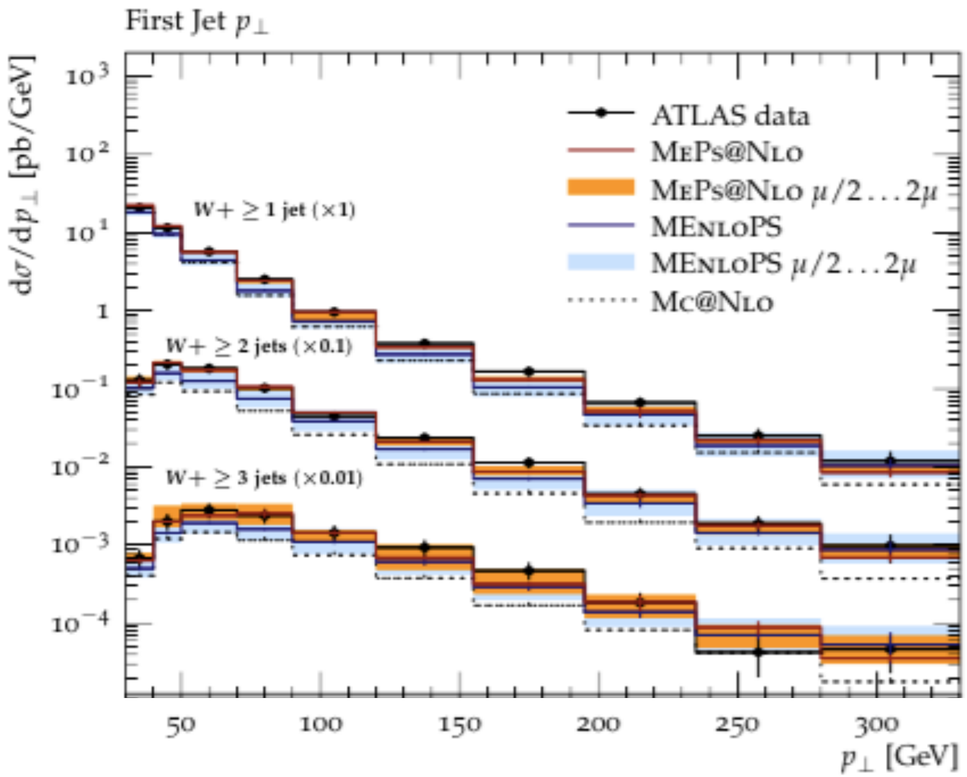
- heavy quark masses included as well

Sherpa

https://sherpa.hepforge.org

- **multi-purpose MC event generator** for the Simulation of High-Energy Reactions of PArticles in collisions
- **multi-jet merging at NLO**
  - basic idea: **towers of MEs** with increasing jet multiplicity (at NLO)
  - combine them into one sample, **remove overlap/double-counting maintaining NLO and LL** accuracy of ME and PS
  - can be further **supplemented with LO simulations**
- **finite quark masses** included in the calculations

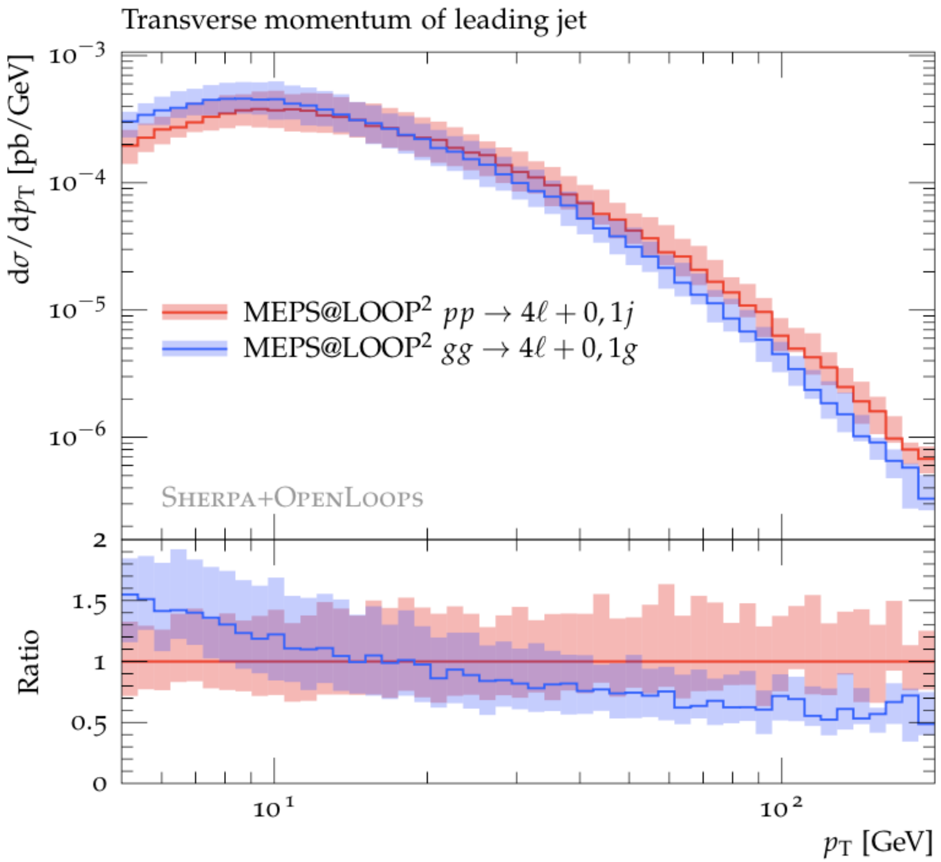




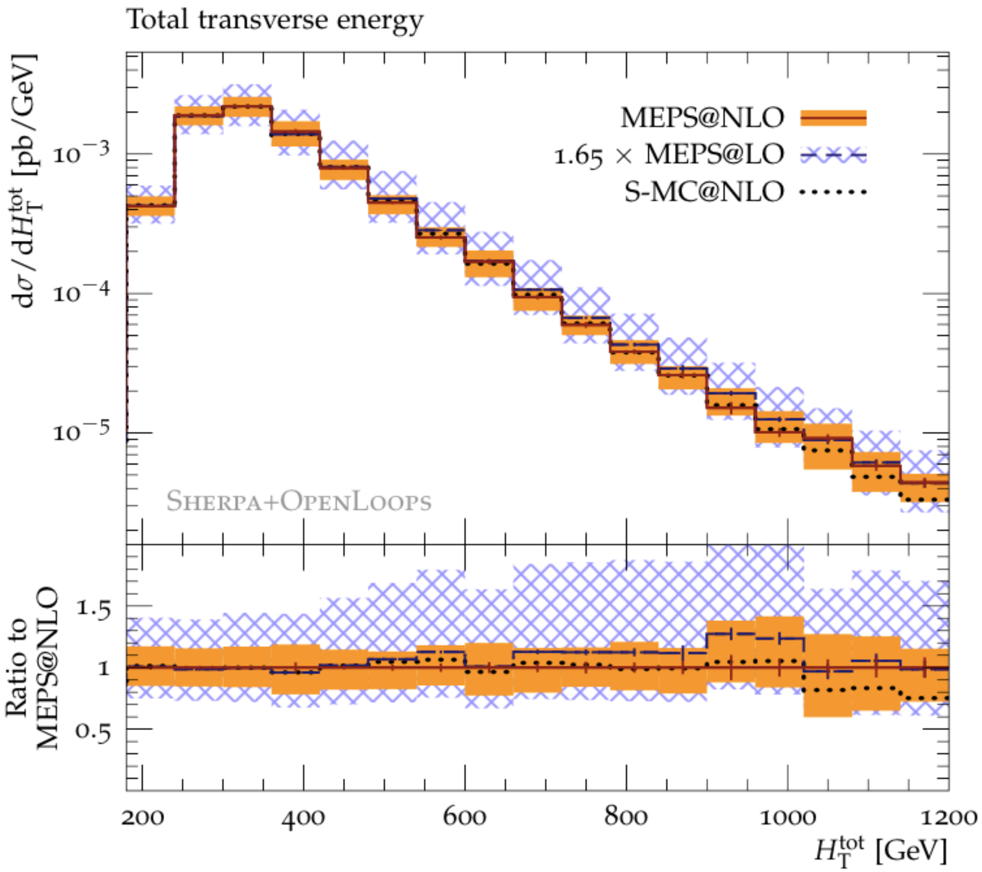
backgrounds to the SM Higgs process

- **backgrounds description** as relevant as signal one for precision measurements
- **W^+W^- + 0,1 jets at NLO**: main background to H > WW searches
- **ttbar + jets at NLO**: crucial for ttH analyses

W^+W^-+jets



$t\bar{t}$ + jets

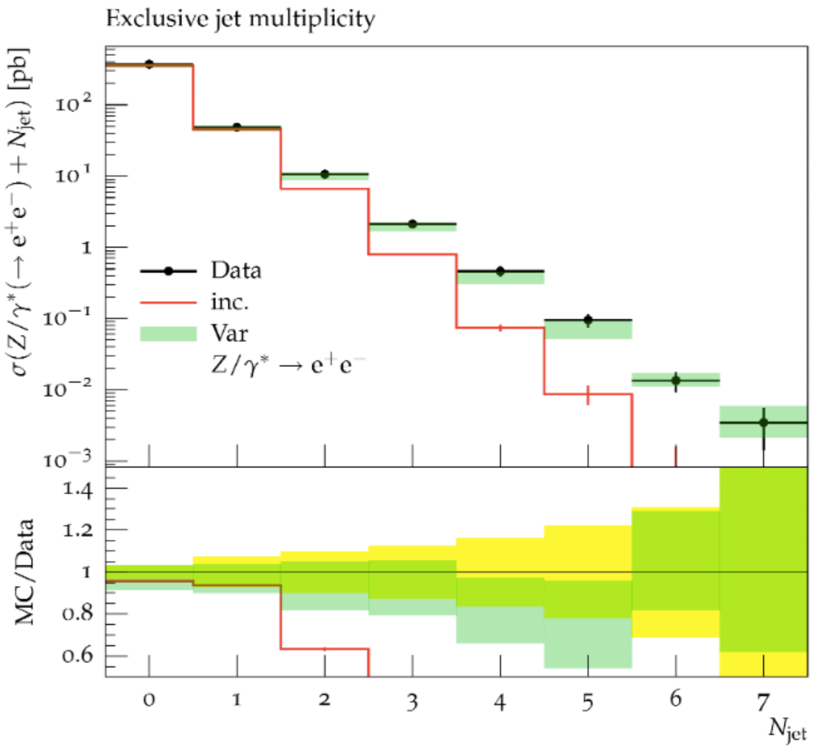


madgraph5_aMC@NLO (mg5nlo)

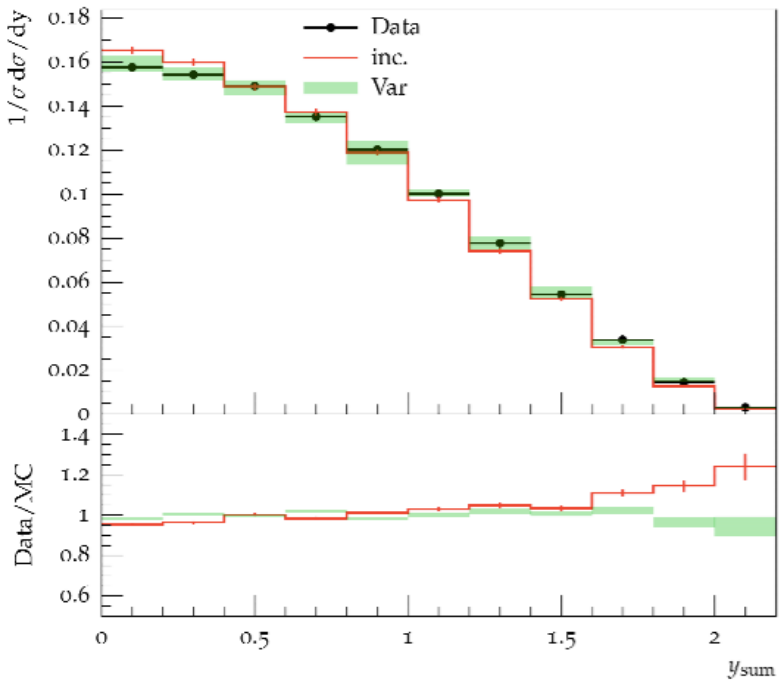
arXiv:1405.0301

- **automated** calculation
  - given a Lagrangian, transform it in a **set of rules used in computations**
  - **NLO specific information** calculation automated as well (1406.3030)
- **NLO matching** to Pythia8, Herwig++, Pythia6(Q2), Herwig6, and Pythia6(pT , ISR only)
- Scale and PDF uncertainties without recomputation
- **NLO multi-parton merging** fully automated, with both FxFx and UNLOPS (the latter for Pythia8 shower only)
- Loop-induced processes

1209.6215, 1211.7278



ATLAS Z+jets analysis

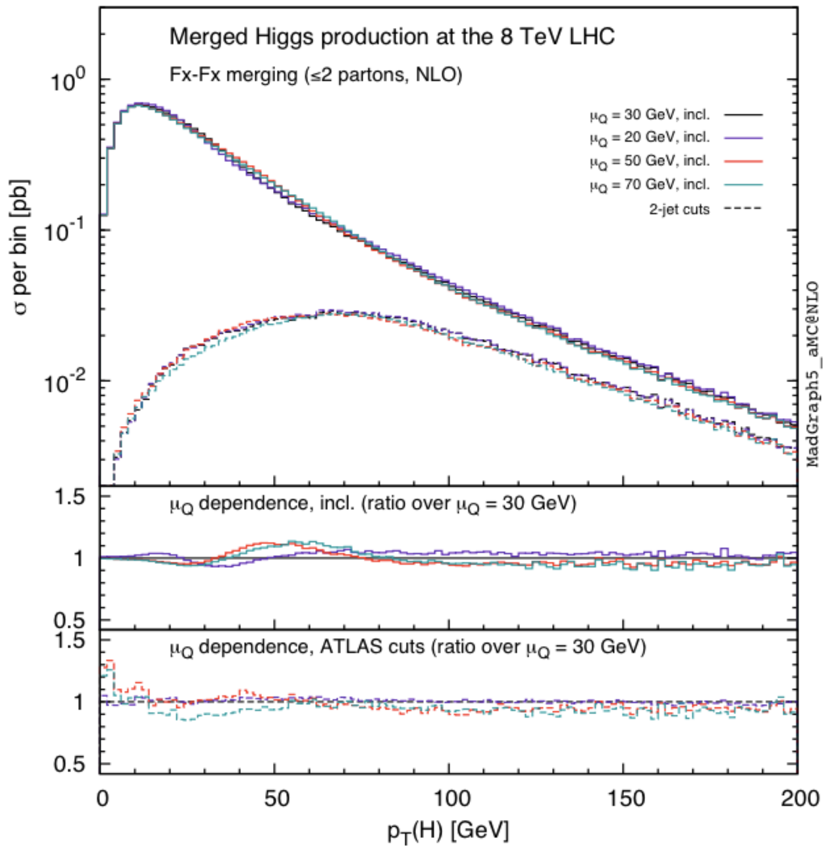


CMS Z+jets analysis

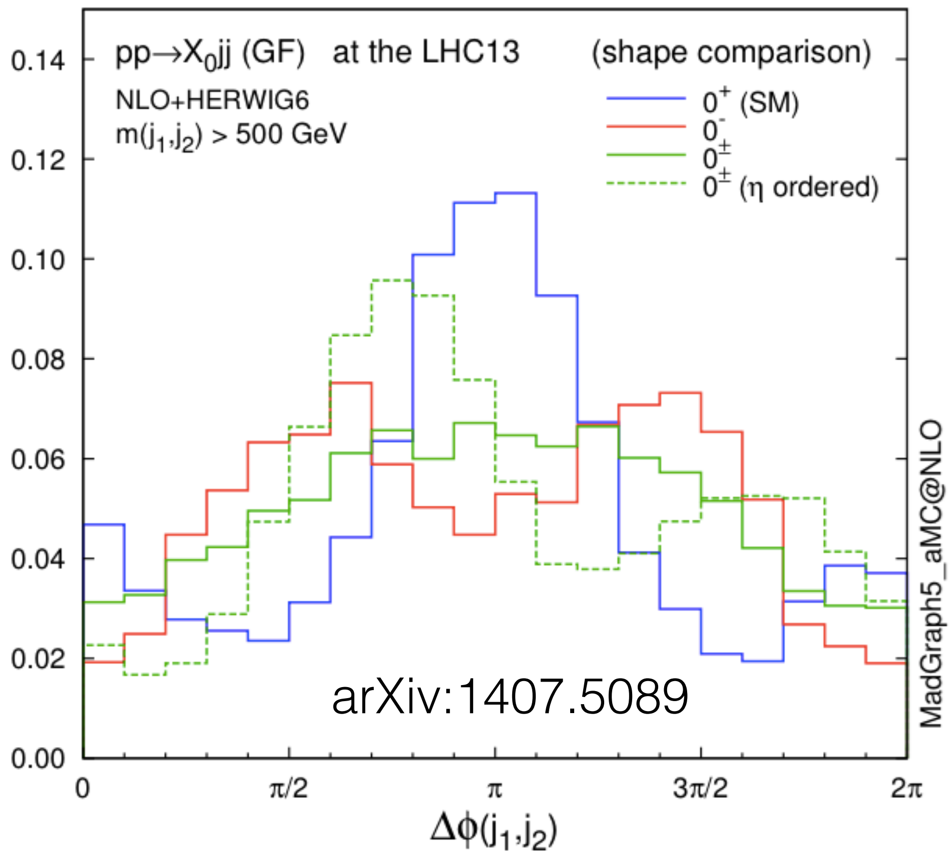
Higgs boson production in madgraph5_aMC@NLO

- different **jet multiplicities can be merged**
- **NLO automatisation** is very powerful in particular for BSM models
- examples: H with various J^P configurations, HH in SM, gg → HH in 2HDM, weak corrections to ttH, $X_{0\pm}$, bbH, EFT models, …
- **uncertainties** related to merging and matching scales are under study

SM Higgs boson

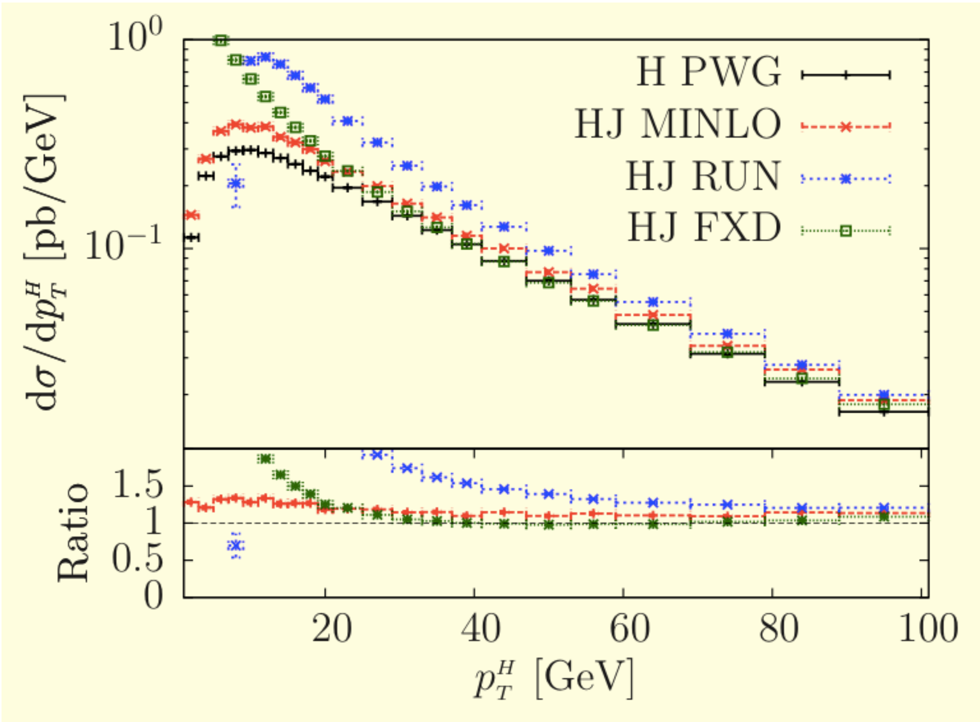


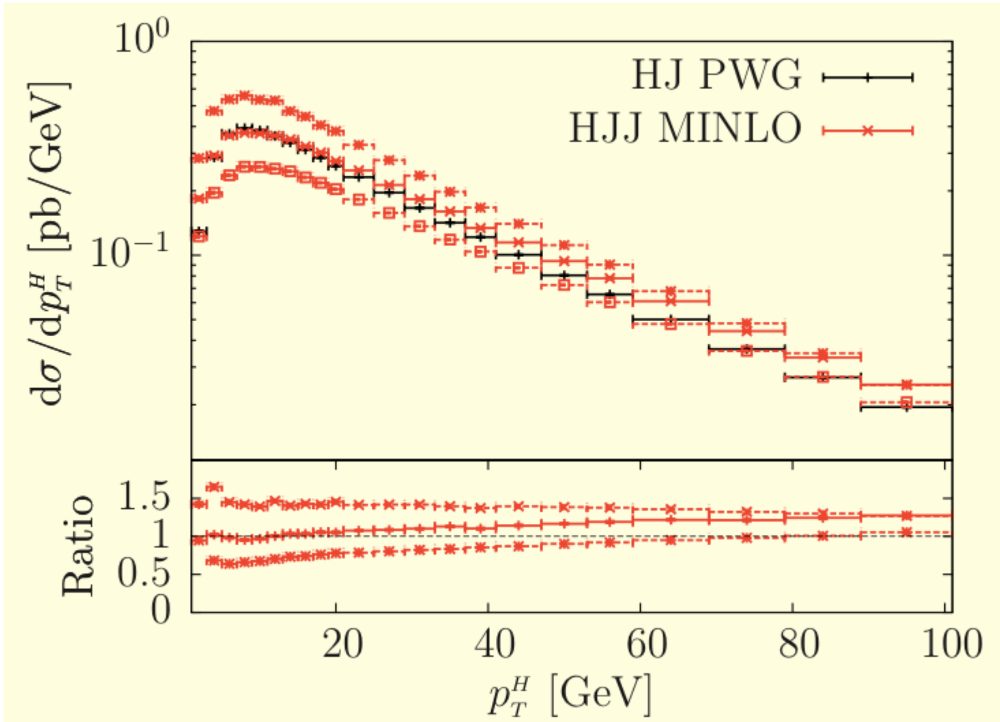
ggH generation, with several CP states of the H boson



Powheg MiNLO

- **merging without merging scales**, for processes of production of a massive colourless system in association with one jet (H, Z, W, H+Z)
- Extension to **NLO** of CKKW (Catani,Krauss,Kuhn,Webber,2001)
- The scale matching the PS is set to the last clustering scale for Born and Virtual contributions, and to the second last clustering scale for the Real (i.e. is **not an externally imposed scale**)





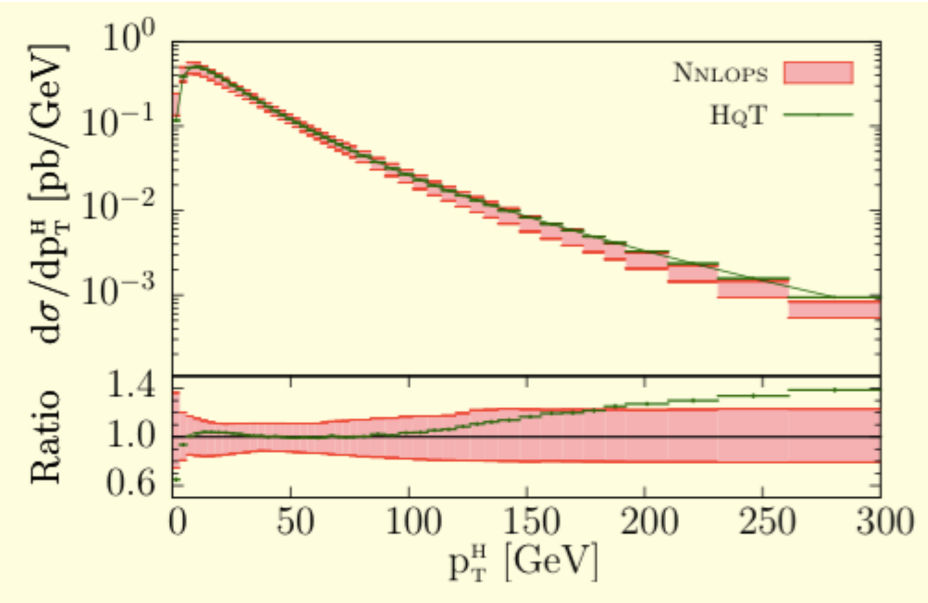
Hamilton,Nason,Zanderighi 2013,
Luisoni,Nason,Oleari,Tramontano 2013
Karlberg,Re,Zanderighi 2014

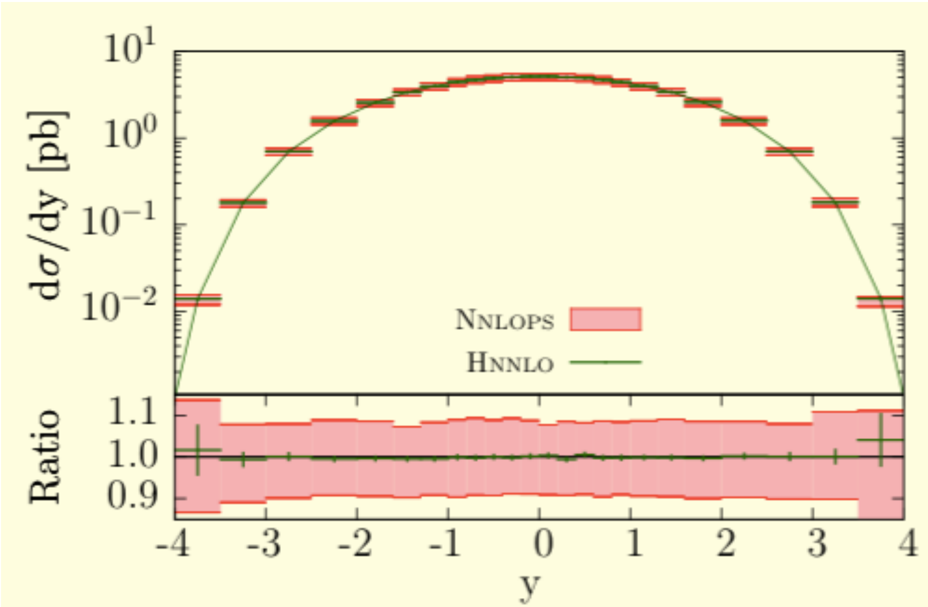
MiNLO and NNLO+PS

- extend the MiNLO framework in such a way that a **true NNLO+PS generator is built**, without the use of any matching scales
- In the example of Higgs production: the MiNLO HJ generator can be promoted to a NNLO +PS generator by simply **reweighting the events** with the factor:

$$\frac{d\sigma^{(\mathrm{NNLO})}}{dy_{\mathrm{H}}} \Big/ \frac{d\sigma^{(\mathrm{HJ})}}{dy_{\mathrm{H}}} = 1 + \mathcal{O}(\alpha_S^2)$$

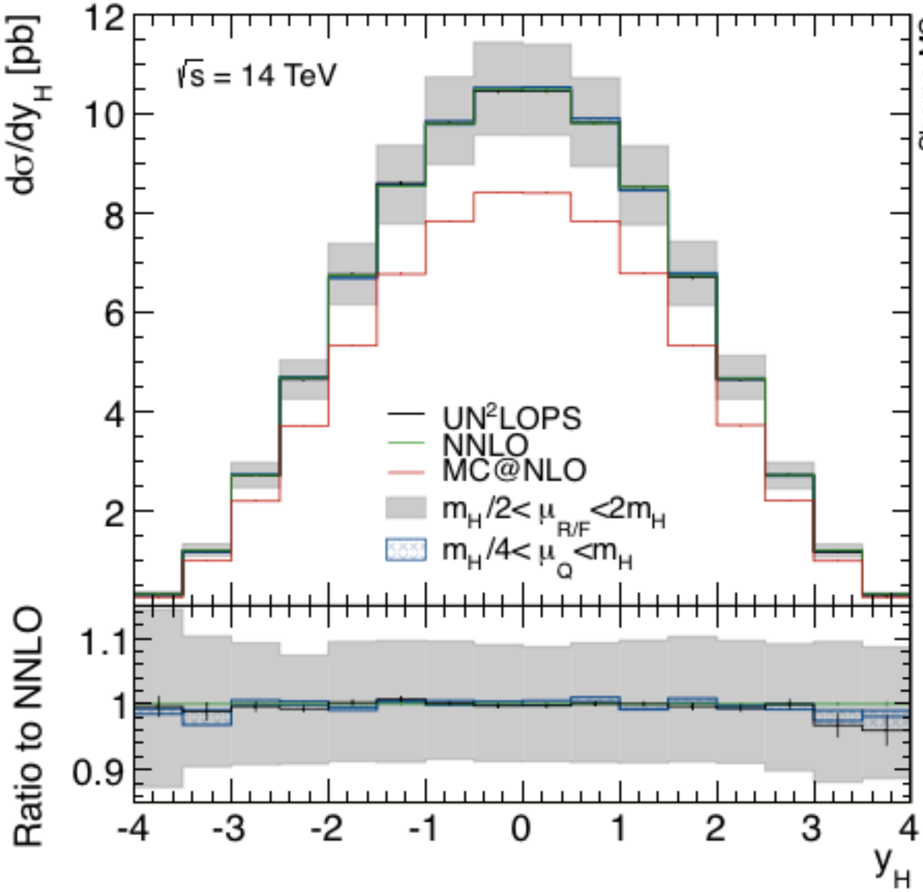
- **Intrinsic uncertainty**: in which region of phase space the reweighting is done
- so far applied to HJ and Drell-Yan, **extension to all processes** under development

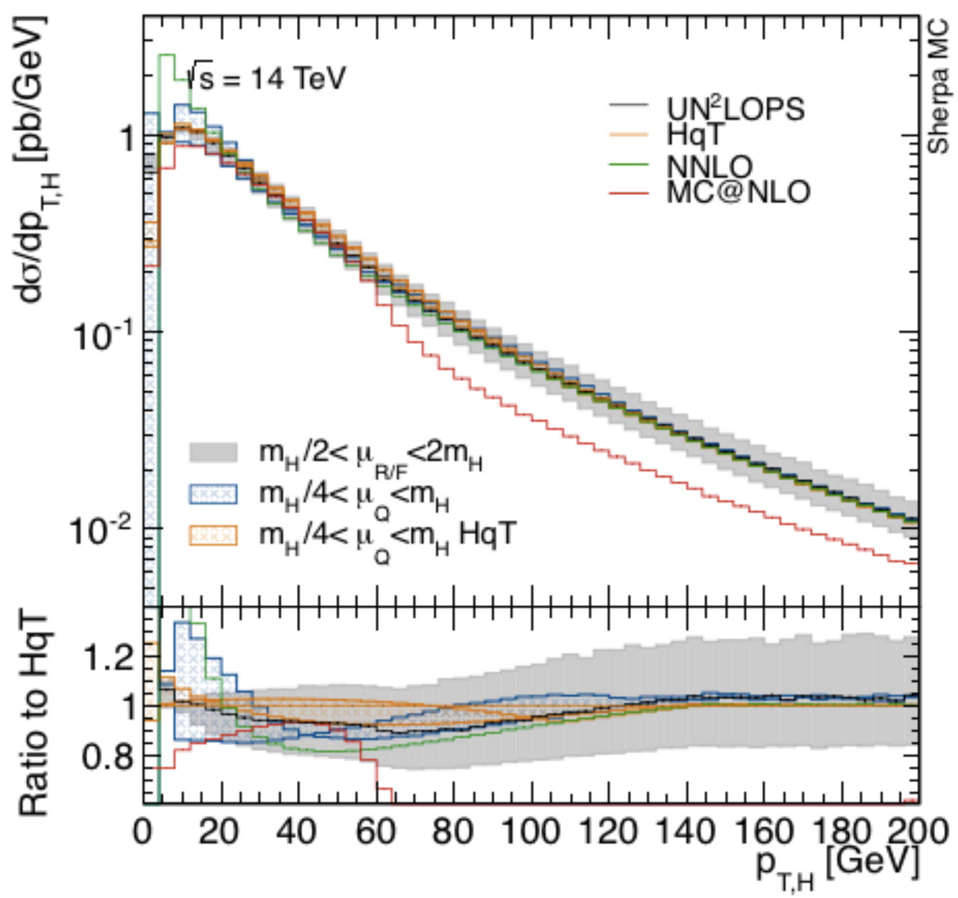




Pythia8 and UNLOPS

- the UNLOPS scheme is implemented in Pythia8
- adds the **parton shower** and performs **matching and merging of QCD NLO** samples
- matched to the **powheg-box** output as well
- introducing UN²LOPS scheme for matching **NNLO calculations**

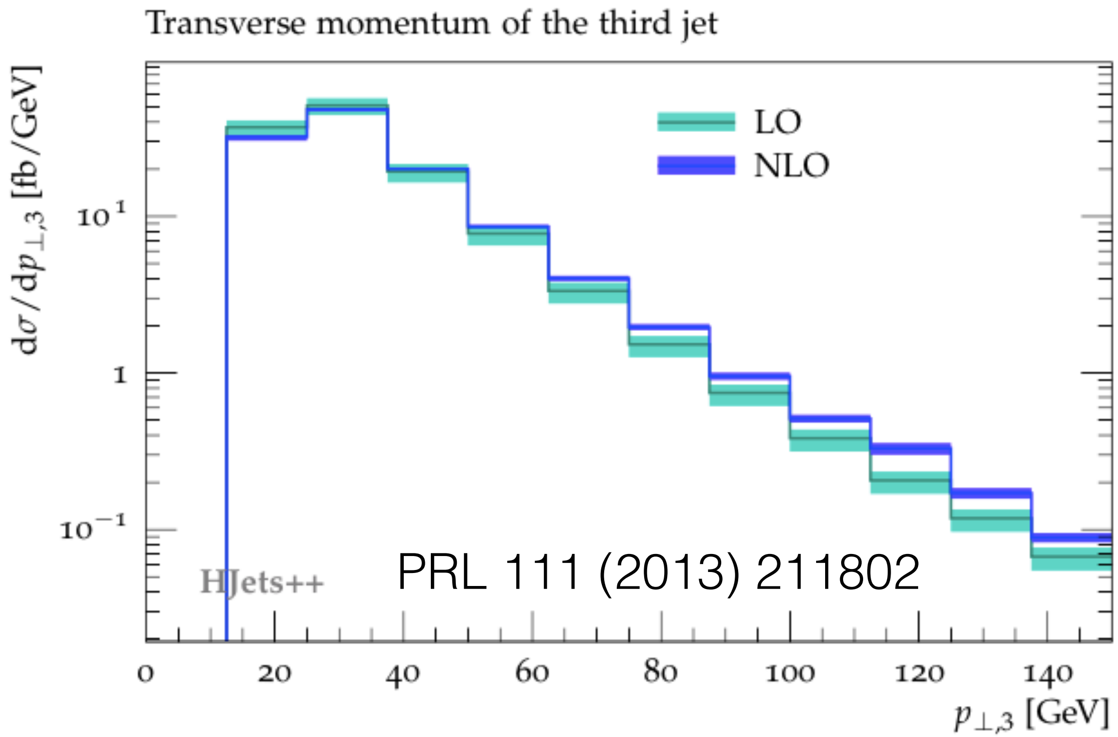




arXiv:1407.3773

Herwig++ and ThePEG

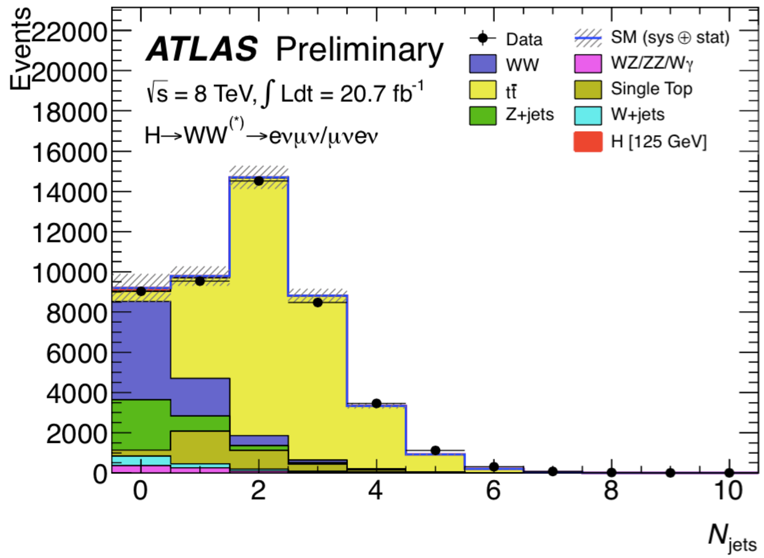
- Toolkit for High Energy Physics Event Generation
- **Current release**: Dedicated approaches to NLO matching
- Various Higgs processes and backgrounds available: gg ➞ h, VBF, VH, VV.
  - Including NLO matched Higgs to $Q\bar{Q}$ decays.
  - hh available at LO with full mass dependence
- **Herwig++ 3.0 faces change in paradigm**: Automated NLO × Two showers × Two matching algorithms.
- **Concerning the Higgs simulation** HJets++ will be released along with Herwig++ 3.0 ➞ EW Higgs plus jets production at NLO QCD

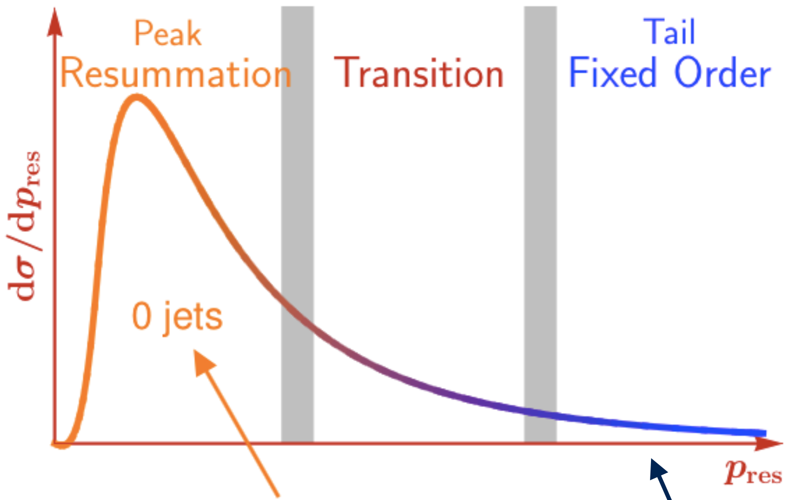


third hardest jet
EWK H + 3jets
generation with
NLO QCD
precision

the binning in number of jets

- **improve S/B ratio** in bins with different bkg compositions
- **isolate VBF H production** (the ggH one is a contamination in this case)
- analysis selection based on MVA tools, hence need of **precise events generation** for ggH + jets, VBFH (+jets), main backgrounds
- **systematic uncertainties related to jet binning** have to be treated properly





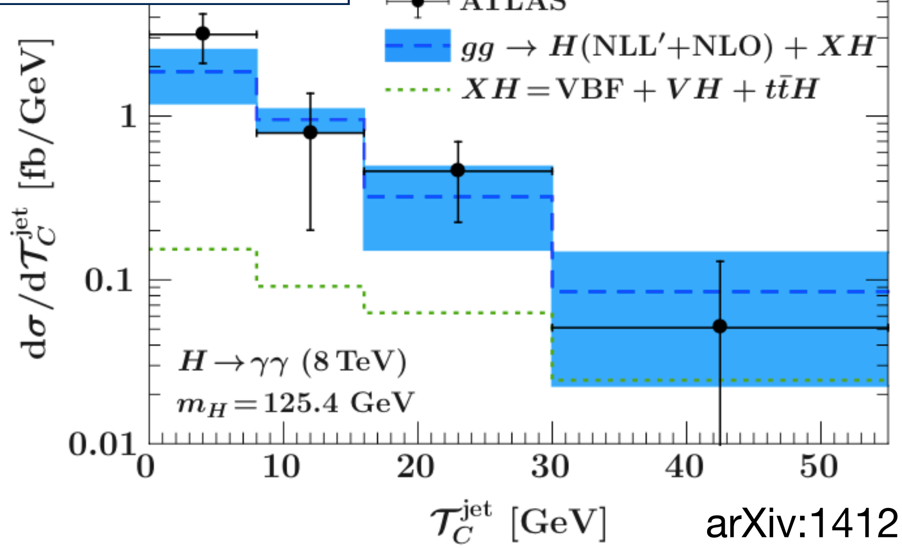
Stewart-Tackmann, JVE, yield and migration uncertainties.

higher order calculations

1308.4634, 1206.4998

- **new jet-veto variables** dependent on *y* that can be resummed at the same level of p_{Tj}

$$\mathcal{T}_{fj} = p_{Tj}\, f(y_j)$$

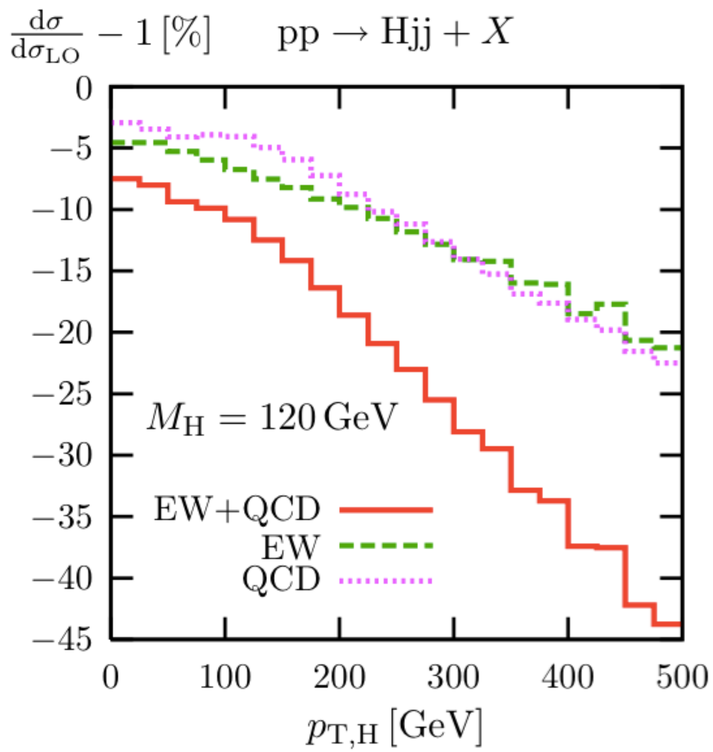


arXiv:1412.4792

EWK corrections

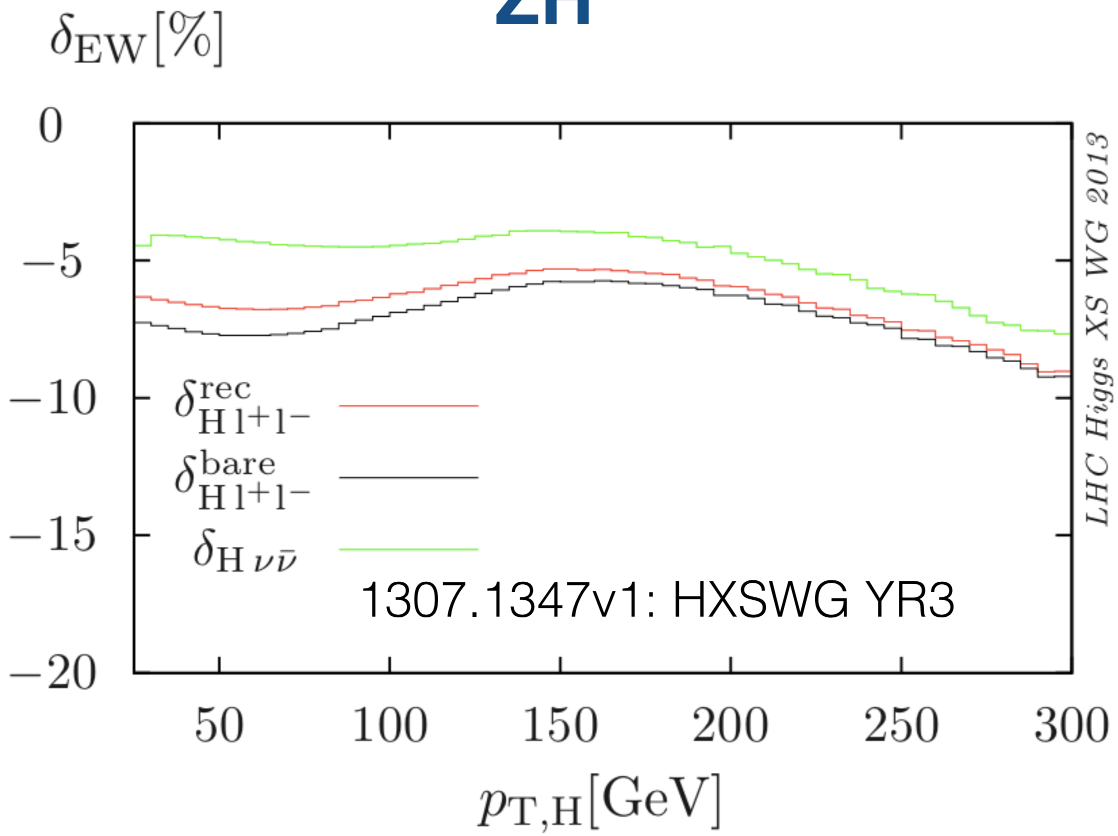
- **differential predictions** in form of histograms
- EW corrections **at percent level** (5-10% in VBF H i.e. comparable to QCD ones)
- Relative EW corrections rather **independent of** PDF, QCD scale and collider energy
- assume **approximate factorisation** of corrections:
- use **differential reweighting event by event**
- **HAWK, VBFNLO** implement QCD and EWK corrections

VBF H



[Ciccolini, Denner, Dittmaier [arXiv:0710.4749]]

ZH



1307.1347v1: HXSWG YR3

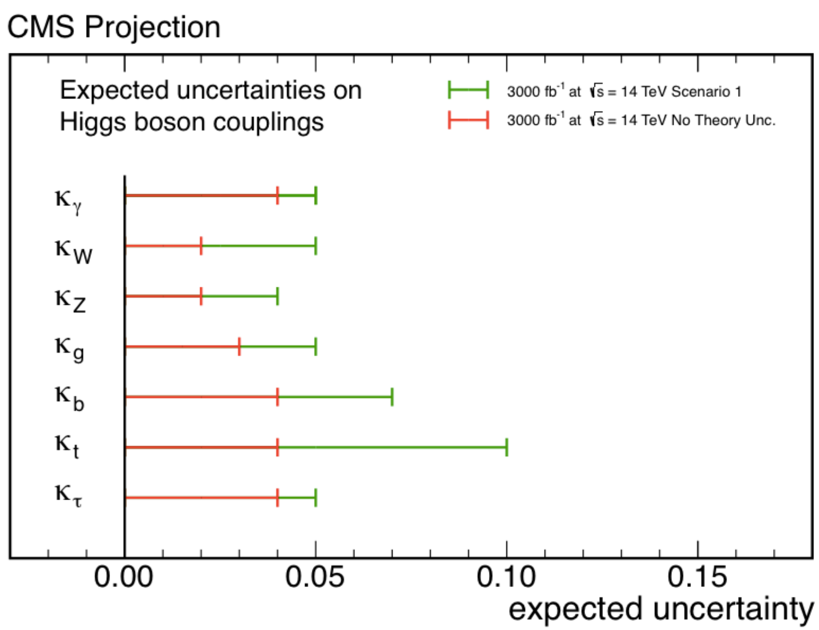
a (not complete) toy box

	0-jet	1-jet	2-jet	3-jet	4-jet	5-jet	finite
powheg gg H	NLO	LO	PS				X
NNLOPS gg H	NNLO	NLO	LO	PS			X
minlo' gg HJ	NLO	NLO	LO	PS			
minlo gg HJJ	approx LO	approx LO	NLO	LO	PS		
mg5nlo gg H	NLO	NLO	NLO	LO	PS		
powheg VBF H	-	-	NLO	LO	PS		
mg5nlo VBF H	-	-	NLO	LO	PS		
powheg VBF HJ	-	-	-	NLO	LO	PS	
mg5nlo VBF HJ	-	-	-	NLO	LO	PS	
powheg pp > VH	NLO	LO	PS				
minlo pp > VHJ	NLO	NLO	LO	PS			
powheg gg > ZH	LO	PS					
mg5nlo pp > VH	NLO	NLO	maybe NLO	PS			
powheg tt H	NLO	LO	PS				
mg5nlo tt H	NLO	NLO	maybe NLO	PS			
mg5nlo bb H	NLO	LO	PS				
sherpa gg H	NLO	NLO	NLO	NLO?	LO?	PS	
sherpa gg H + interf.	NLO	LO	LO	PS			X
sherpa tt H	NLO	NLO	LO	LO	PS		
sherpa VBF H	-	-	NLO	LO	LO	PS	
sherpa VH, H > VV	NLO	NLO	LO	PS			

BSM effective field theory

- leit motiv: indirectly **access new physics through precise measurements**
- **implementations in event generators** exist based on FeynRules
  - Madgraph5, Sherpa, Powheg
  - MCFM, gg2VV, MC@NLO
  - eHDECAY for the Higgs decay
- Use of Run2 requires **MC at NLO**!
  - NLO tools (MCFM/POWHEG and MC@NLO) under study
  - improved uncertainties, to match the reduced statistical uncertainty in data

CMS projections



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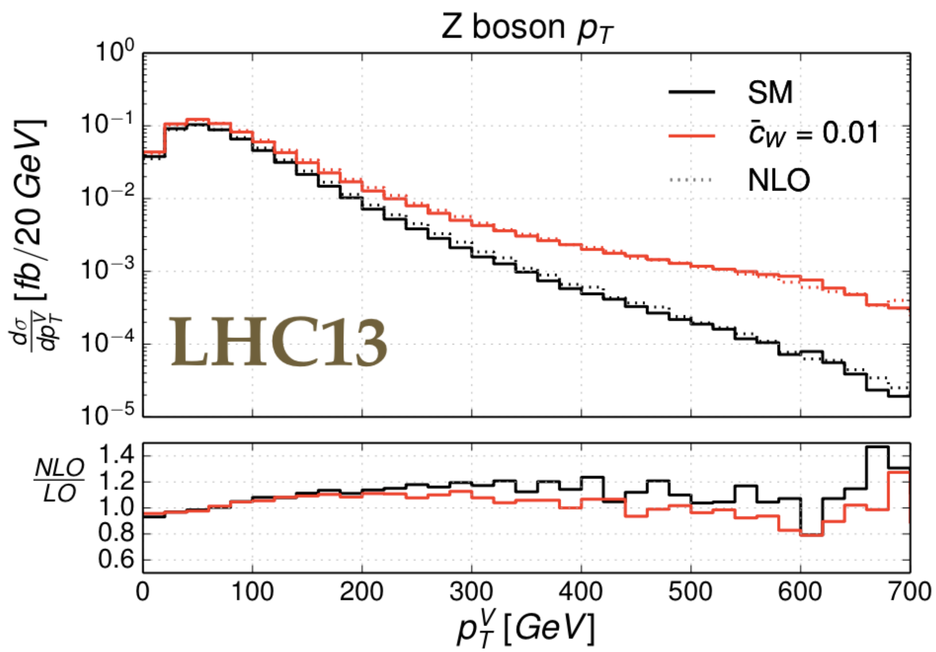
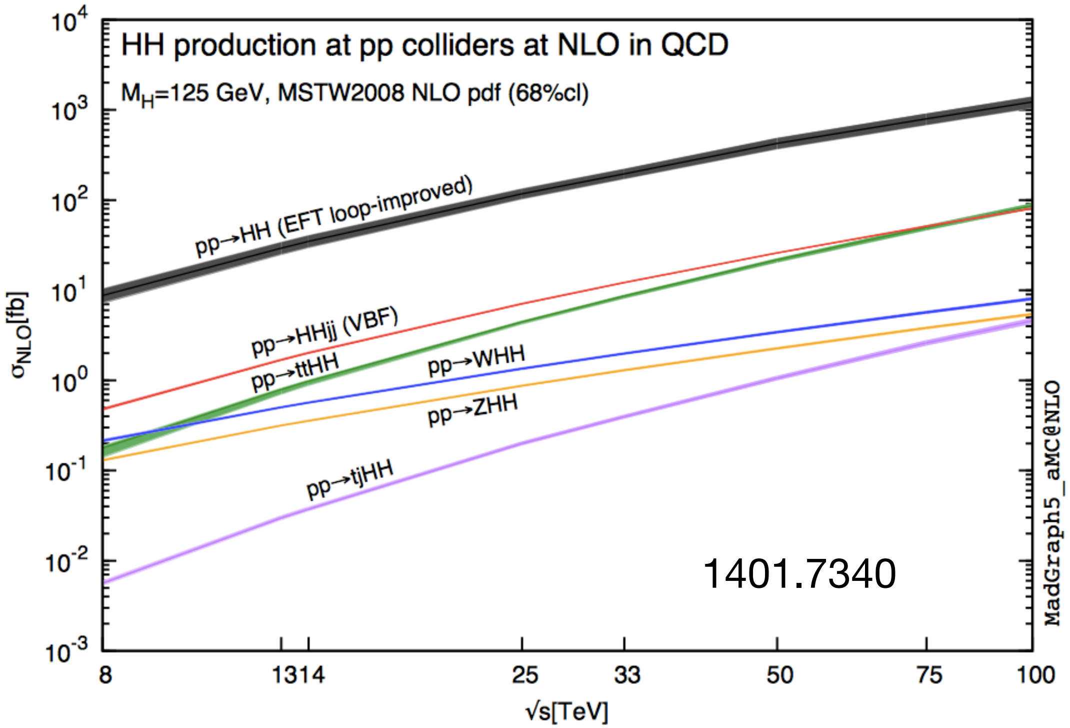
NLO MCFM & Powheg test

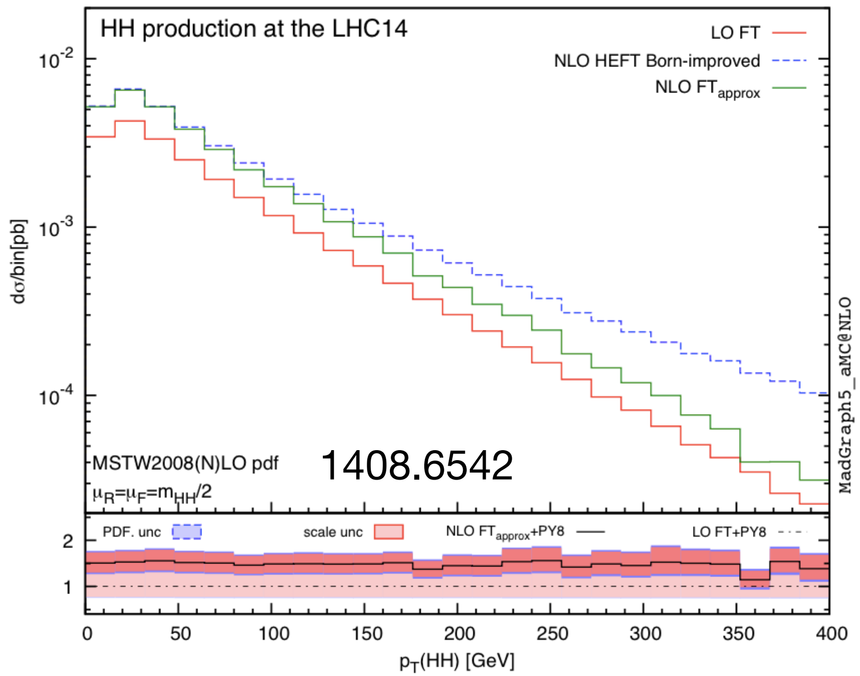


V. Sanz slides, december 2014

di-Higgs generation

- HPAIR matrix elements and mg5nlo for XS calculation
- mg5nlo, herwig++ for events generation
- LO + HEFT for **gluon fusion,** NLO for **other production mechanisms**
- top mass effects are relevant (10%), therefore a **full NLO calculation would be useful**

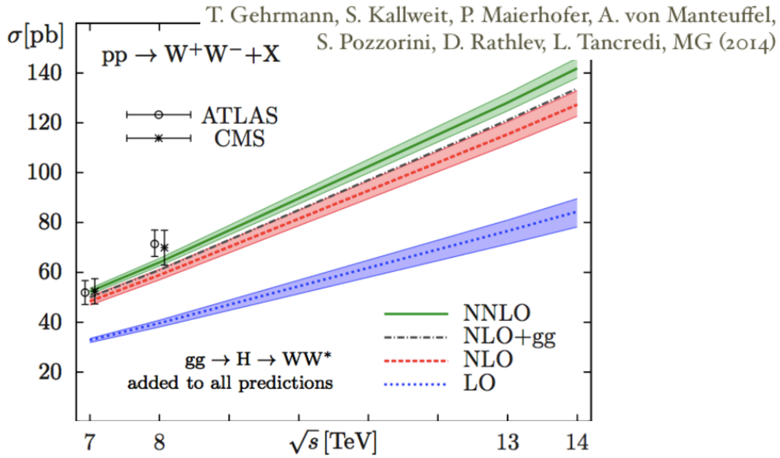


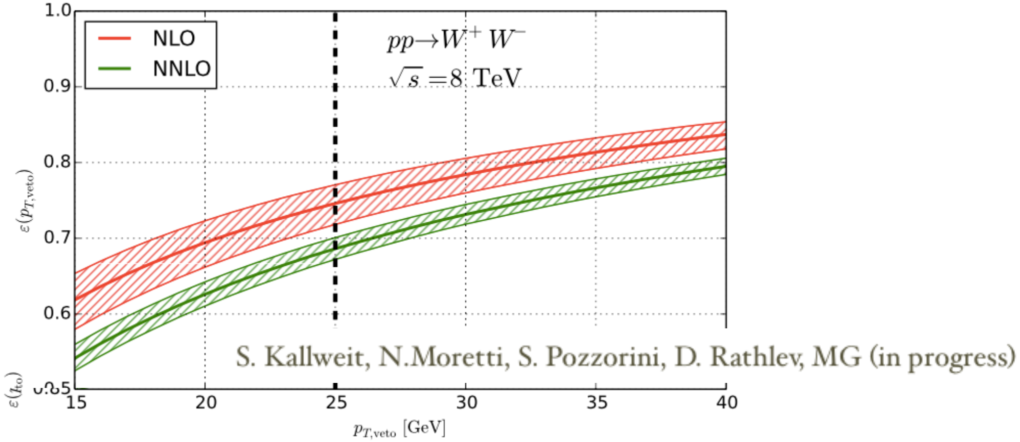


- **BSM** di-higgs available for the 2HDM case in mg5nlo via the NLOCT package (1406.3030)

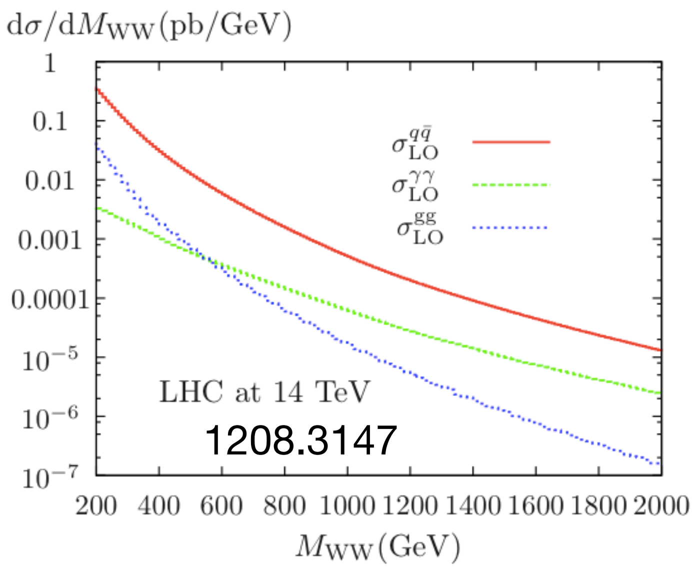
high precision WW background

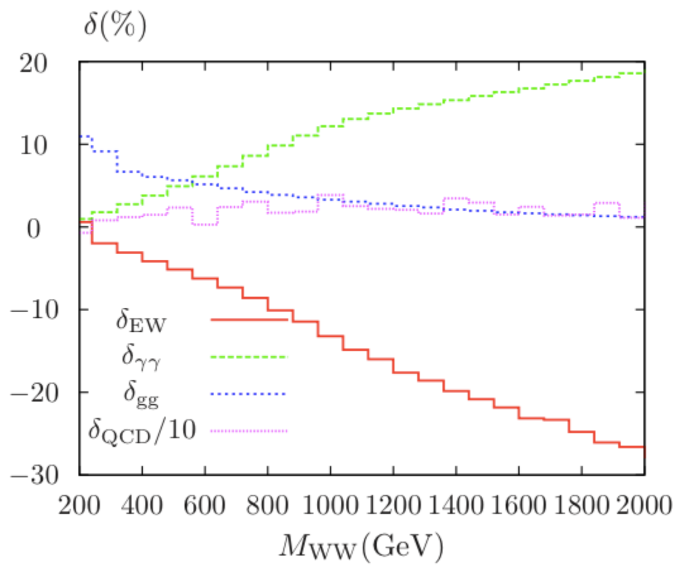
- crucial for the HWW analysis, where **the ttbar production is reduced with jet veto**
- high precision very important also for **higgs width determination** from off-shell measurement
- **NNLO QCD**: inclusive cross-section + fully diff w/ off-shell effects and W decay





- **NLO EWK**: ewk corrections + additional γγ-induced production

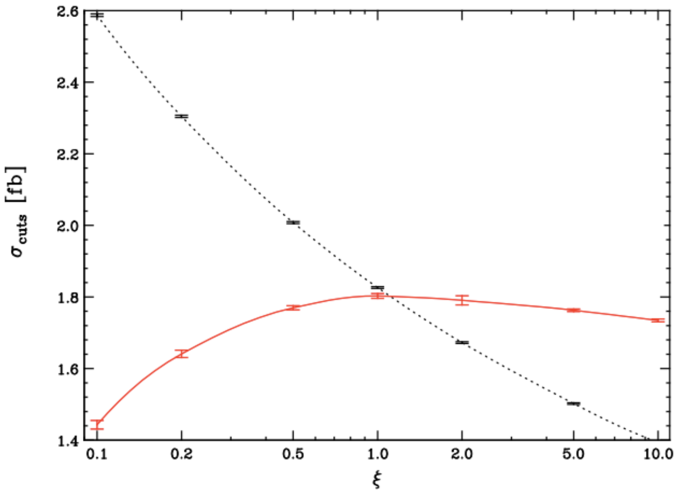




vector boson scattering

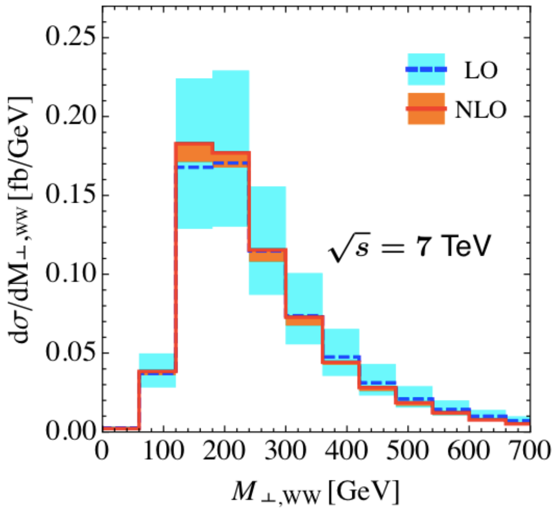
- the key to **understand the electroweak symmetry breaking** in the high energy regime
- after the Higgs boson discovery, the **BSM effects expected to be small**
- **exact LO** calculation and events generation known since long ago (0801.3359)
- **NLO** calculations: available for most of all the signals, for some of the bkg only
- **EWK** corrections: unknown, expected to be large
- resonant and non-resonant contributions included
- spin correlations in the decays included

JHEP 0607 (2006) 015

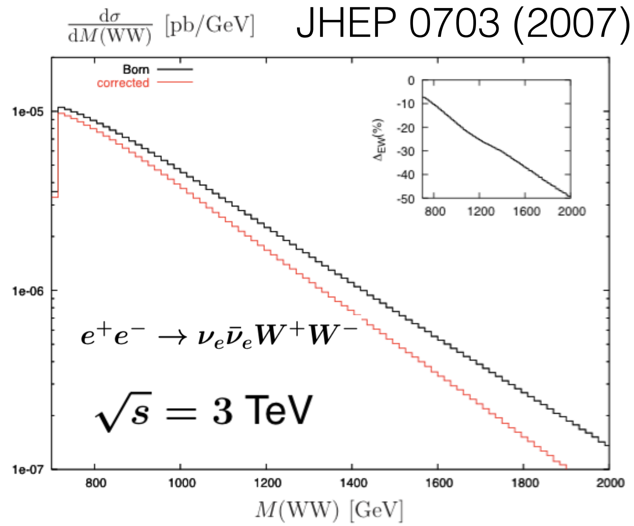


Oleari, Zeppenfeld, B.J. (2006)

Phys.Rev. D83 (2011) 114043



JHEP 0703 (2007) 078

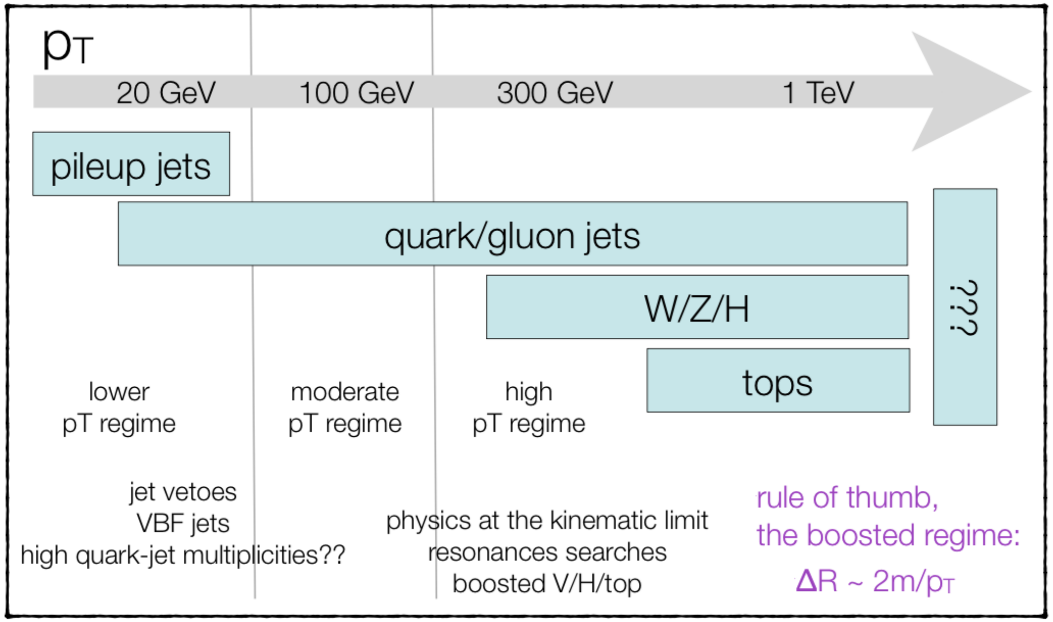


- **NLO QCD VBS HH** production available
- calculations with **additional jets**, merged to 0 jets, do not exist: relevant for CJV
- BSM parameterisations available
- **tri-boson production** might be important as well

If you ain't boostin', you ain't livin' (N.V. Tran)

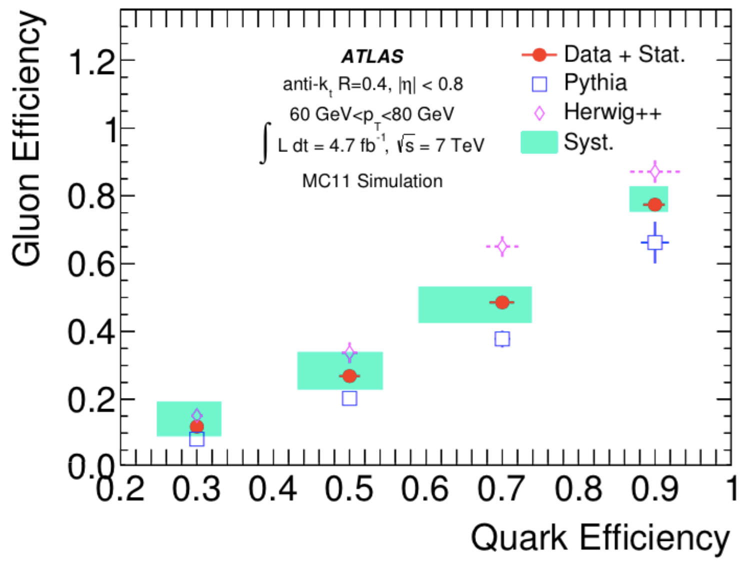
- extremely active field, (not only) for the high energy frontier
  - **increase signal statistics**
  - **extend discovery reach**

e.g.
- PU reduction
- q/g separation
- color flow



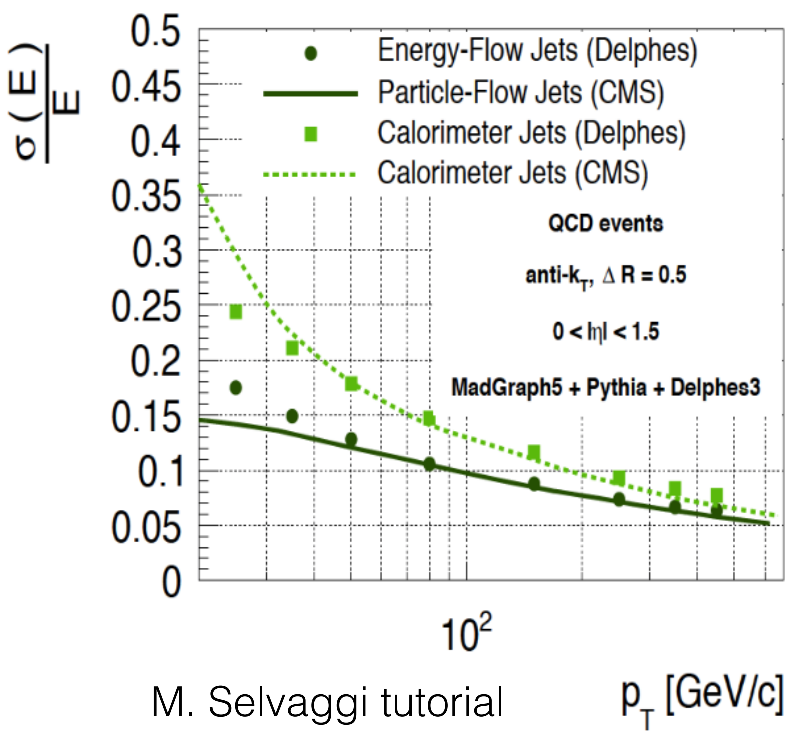
e.g.
- cleaning jets from PU and non-perturbative effects
- particle ID in boosted jets

- tools which **need a theoretical understanding**
- "If we see evidence of new physics how do we convince the world (and ourselves) that we're right and that its not a feature of the tagger" (E. Thompson)
- in contrast to what discussed before, **the showering and hadronisation scheme matter** here

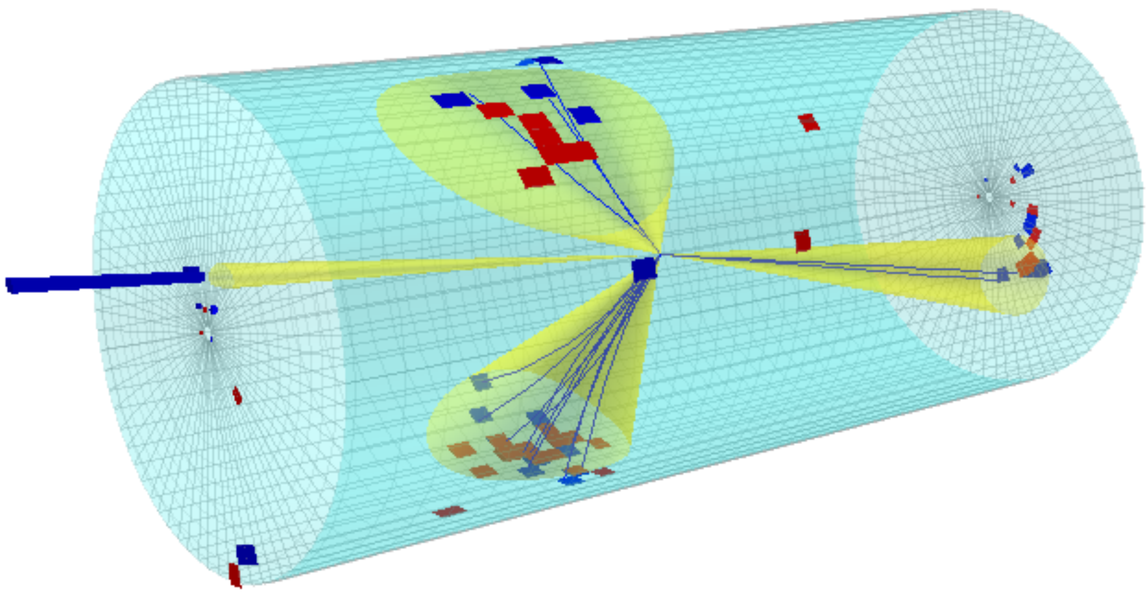


the Delphes tool

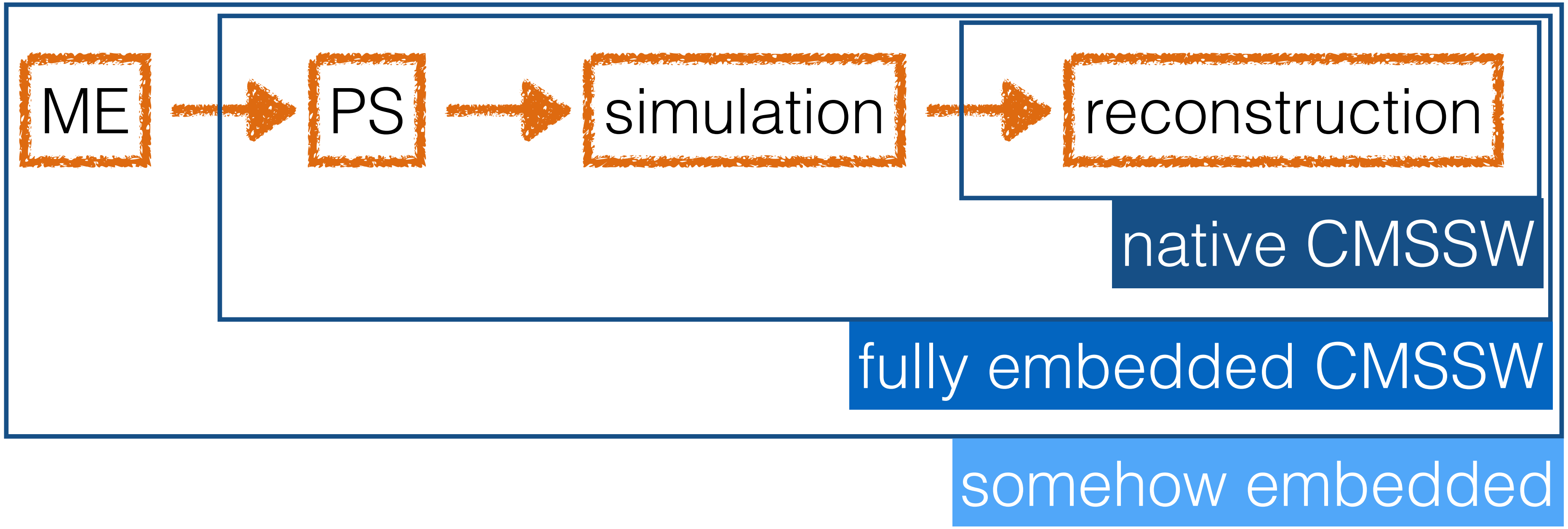
- **parametric simulation** particle-matter interaction
  - a lot of (reasonable) approximations
- realistic **models of detectors**
  - need a very close **interaction with the experiments**
  - easy to understand and modify C++ code
  - **detailed can be added or removed** depending on the analysis needs
- **preliminary physics studies** can be performed in short time (e.g SnowMass)
- can be used in parallel with full detector simulation
- impact of pile-up on isolation, jet structure, multiplicities ...



M. Selvaggi tutorial



technical aspects: generation in the CMS experiment



- 12 Billion events generated for run I
- **5 Billion events will generated in 2015** (at the speed of the order of 1 Billion events per month)
- the **integration in the CMSSW of generators** allows for a better control of parameters consistency and proper usage of the tools, and seamless running
- despite best efforts, there's a **delay** between the release of a code and its use
- a documented **versioning** of generation codes helps a lot in keeping track of the integration in the CMSSW releases
- (simpler is better)

conclusions

- there's a broad spectrum of new N(N)LO event generators, suitable for **most of the first data taking physics programme** (Moriond 2016)
- requests to improve the precision in **specific cases**
- **the statistical uncertainty** — and all the statistically related experimental uncertainties — **will rapidly decrease in 2016**

- experiments follow up very closely the phenomenological news
- they exploit more and more sophisticated data treatment

- the **close interaction** granted by HiggsTools (and the Higgs Cross Section Working Group) is extremely beneficial
- the envelope of all the available tools yields the **theoretical uncertainty** for the measurements, a common grounding is of paramount importance

- need of properly covering the **backgrounds** as well with the same systematic approach used for the signal