SM: Loops and Multi-legs
Theoretical Introduction

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Joey Huston

NLO - the new standard

- ✓ A lot of progress, and the "best" solution is still to emerge. In the meantime, there are public codes with NLO capability that could only be dreamed of a few years ago.
- ✓ see http://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=212260 for more details.

SHERPA

Process	BlackHat	GoSam	OpenLoops
jets	≤ 3	—	≤ 4
γ+jets	≤ 3	≤ 2	≤ 3
$\gamma\gamma$+jets	≤ 2	—	≤ 2
V+jets	≤ 4	≤ 3	≤ 3
$V + b\bar{b}$+jets	—	≤ 1	≤ 1
VV'+jets	≤ 2	≤ 2	≤ 2
$V\gamma$+jets	—	≤ 2	≤ 2
$W^{\pm}W^{\pm}qq$	—	0	0
$VV'V''$	—	—	≤ 1
$t\bar{t}$+jets	—	≤ 1	≤ 1
$t\bar{t} + V$+jets	—	—	≤ 1
$tb^{\dagger}$	—	—	≤ 1
$tj^{\dagger}$	—	—	≤ 1
$tW^{\dagger}$	—	—	≤ 1
h+jets	≤ 2	≤ 2	—
WBF: hqq'	—	—	≤ 1
VH	—	—	≤ 1
$t\bar{t}h$	—	—	0
$gg \to 4\ell$	—	0	0

NLO – the new standard

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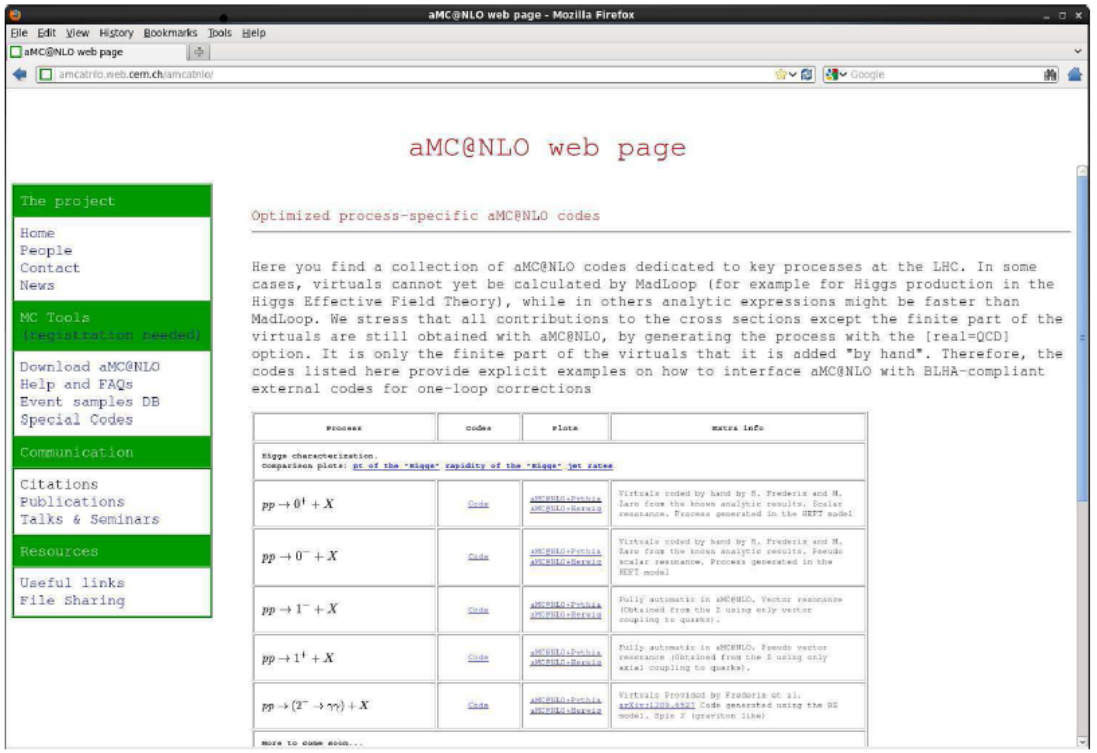

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VH	—	—	≤ 1
$t\bar{t}h$	—	—	0
$gg \to 4\ell$	—	0	0

Multileg codes

- Many competing codes with different strengths and approaches and complementary results
- Highest multiplicity @ NLO
  - BlackHat +SHERPA (pp → W + 5 jets)
  - NJET + SHERPA (pp → 5 jets)
  -
- Broadest applicability @ NLO
  - GoSam + SHERPA/MADGRAPH
  - OpenLoops + SHERPA
  -
- Resummation of high energy logs
  - HEJ

Special mention:
- HELAC/CutTools
- Rocket
- MADLOOPS+MADGRAPH
- RECOLA

BlackHat

Daniel Maître

with Z. Bern, L. Dixon, F. Febres Cordero, S. Höche, H. Ita,

D. Kosower, K. Ozeren

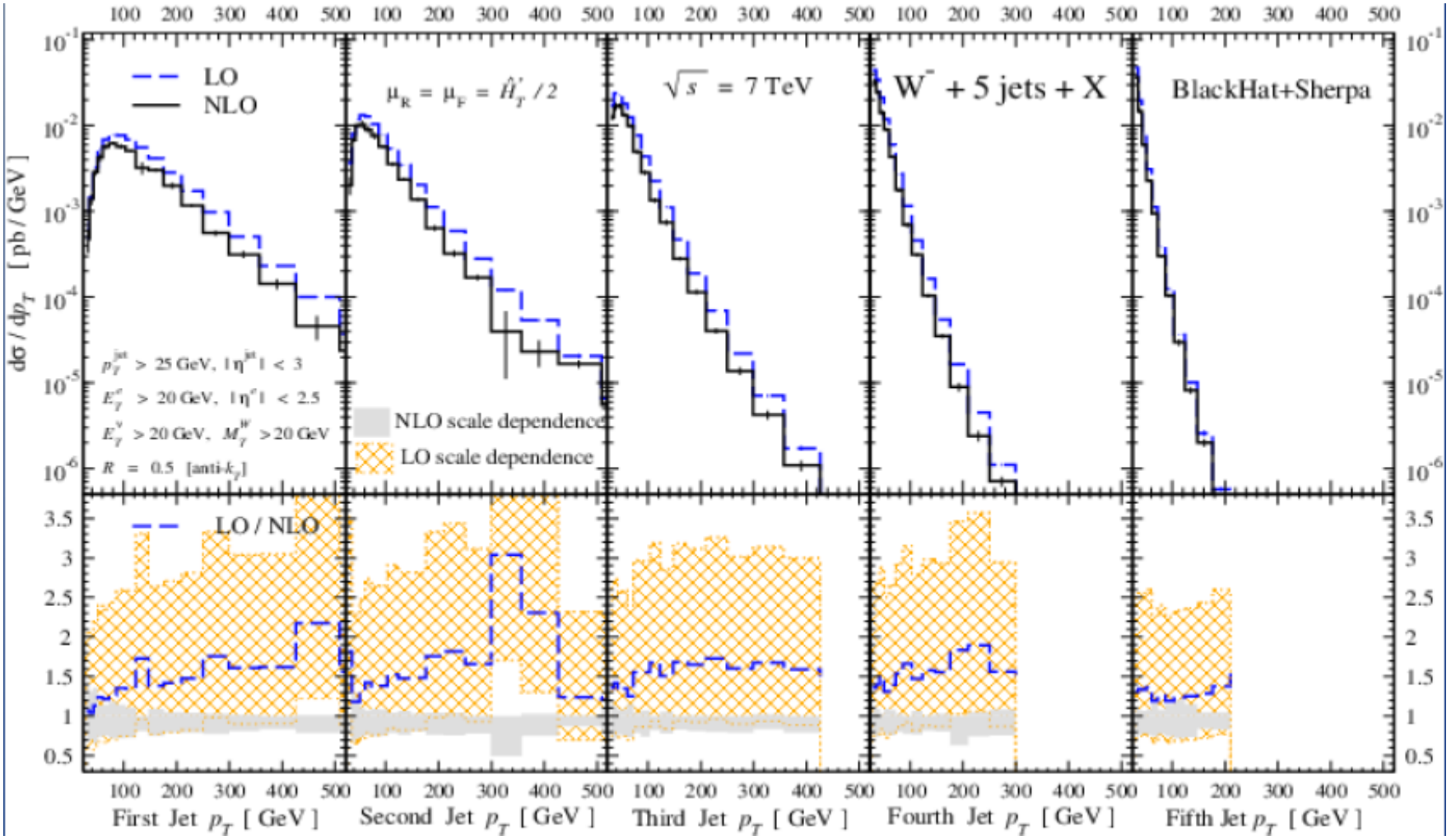
- BlackHat Capabilities:

  Virtual matrix elements for

  - **W + <=5 jets**
  - **Z + <= 4 jets**
  - **Pure QCD <=4 jets**
  - **Photon + <=3 jets**
  -
  -

BlackHat: most recent development

- W+5 jets with Sherpa arXiv:1304.1253

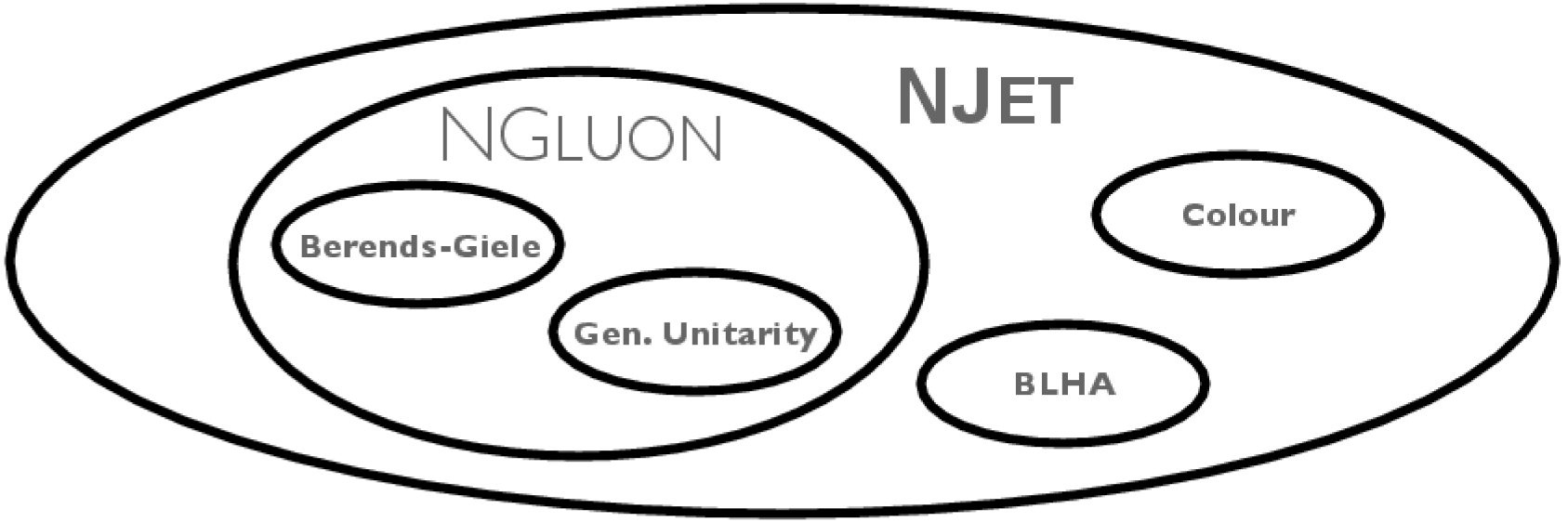


BlackHat at Les Houches

- BLHA second version
- Ntuples for 8 TeV
- Comparison with HEJ
- ...

- People in Les Houches: **Daniel Maître**

NJET



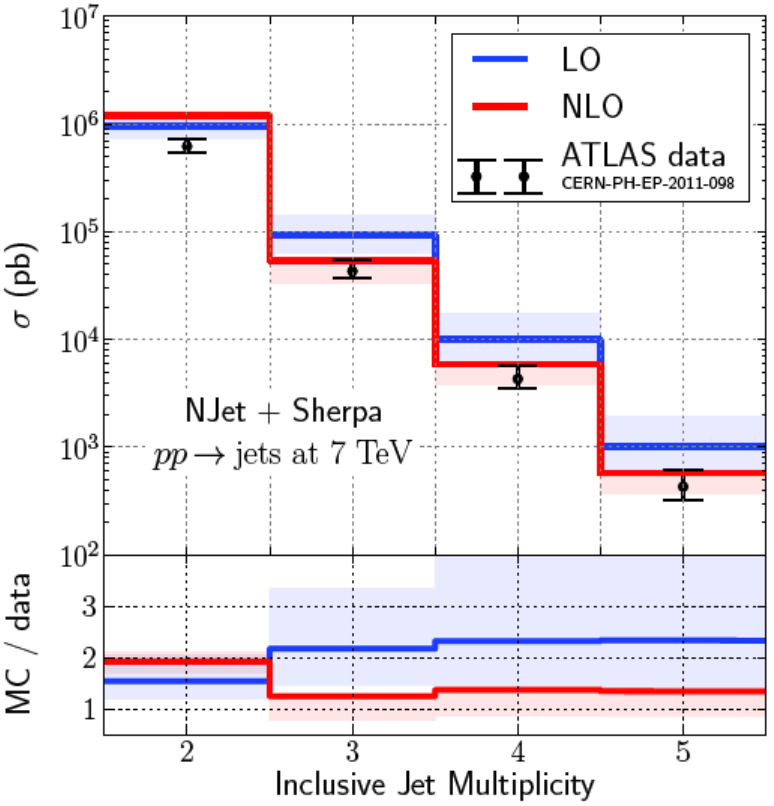
NJet for full colour pp → ≤ 5j arXiv:1209.0100

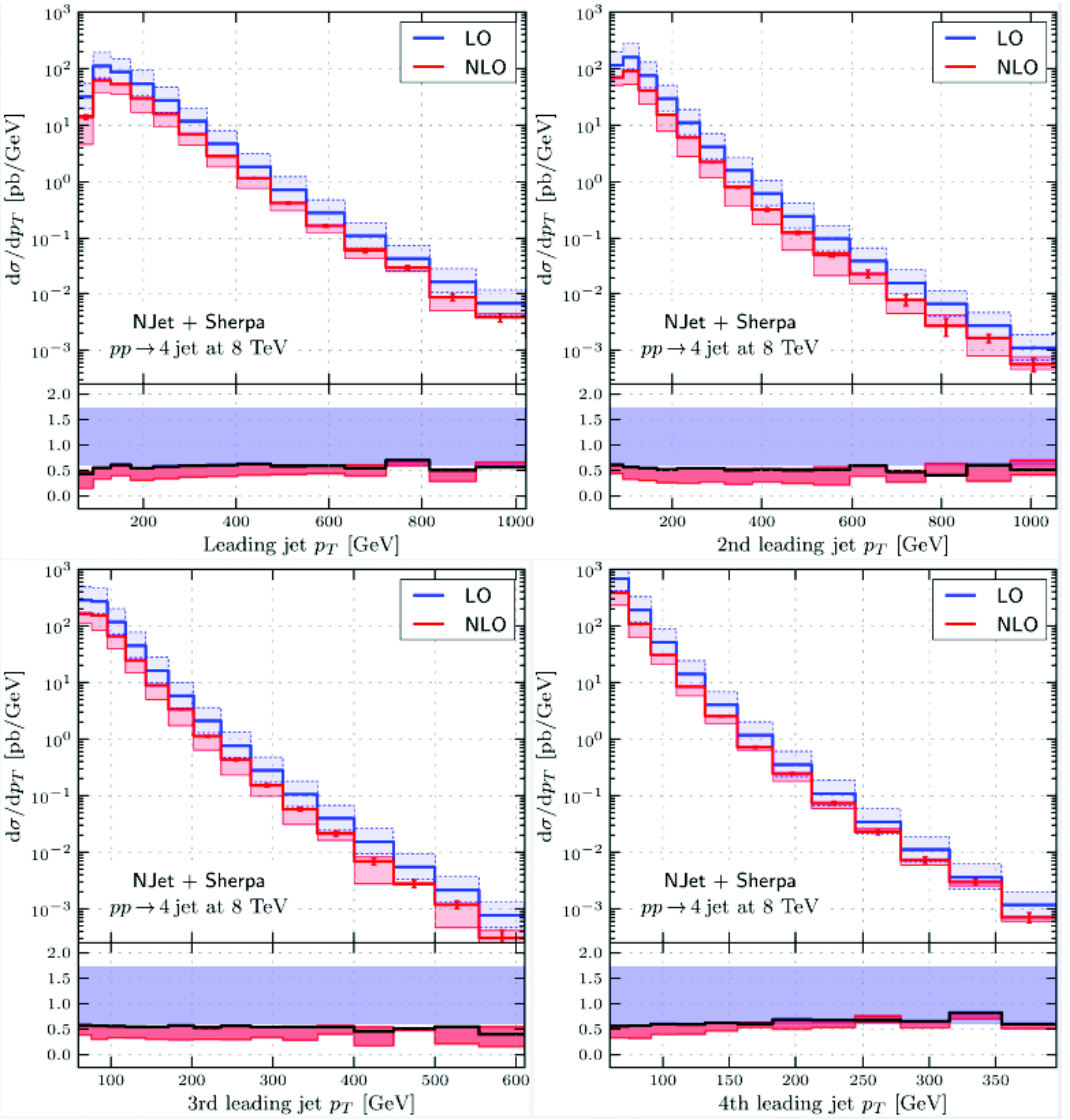
- uses NGluon for multi-parton primitive amplitudes
- Accuracy estimates via BLHA
- Public C++ code from http://www.bitbucket.org/njet/njet

Badger, Biedermann, Uwer, Yundin

Applications with NJET+SHERPA

- Preliminary results for pp → 5j arXiv:1209.0100





c.f. BLACKHAT arXiv:1112.3940

NJET at Les Houches

- Discuss extensions and future of BLHA interface
- Validating and comparing NLO tools (pp → W+3j?)
  - NLO with different MCs e.g. Sherpa, MC@NLO, ...
  - Performance of integration strategies e.g. Leading Colour, helicity sampling etc.
  - Real Radiation for high multiplicity, FKS vs. Catani-Seymour?

- People in Les Houches: **Simon Badger, Valery Yundin**

GoSam

G. Cullen, H. van Deurzen, N. Greiner, G.Heinrich, G. Luisoni, P. Mastrolia, E. Mirabella, G. Ossola, T. Peraro, J. Reichel, J. Schlenk, J. F. von Soden-Fraunhofen, F. Tramontano

http://gosam.hepforge.org

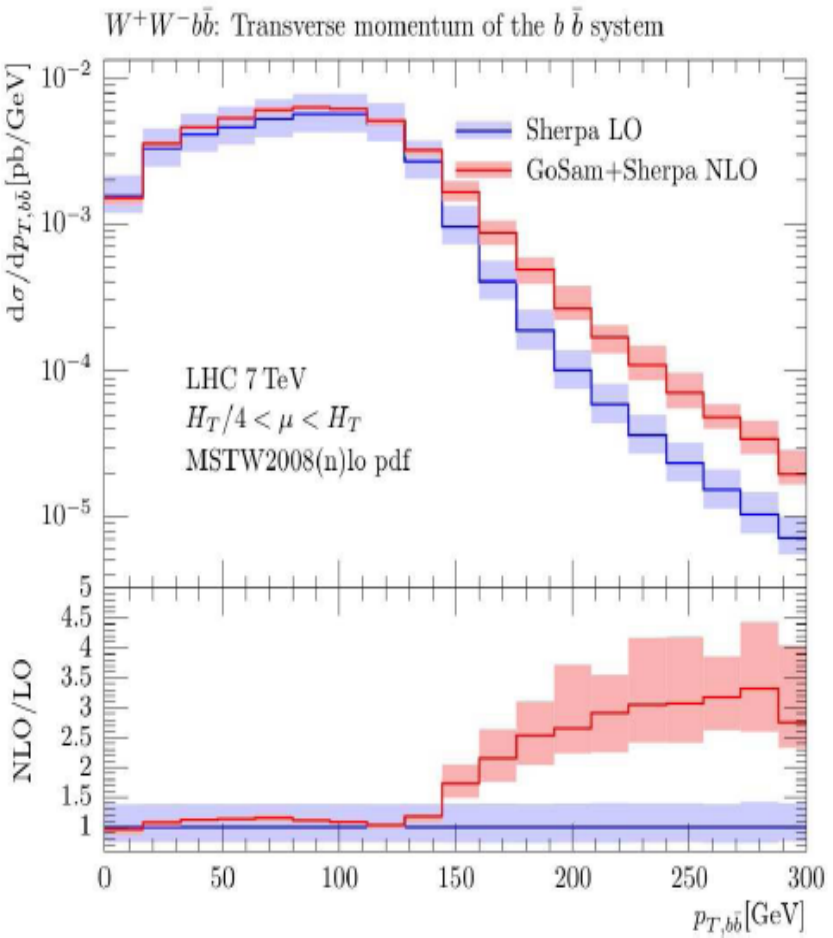
- GoSam status:
  - QCD fully automated
  - massive internal/external particles, also complex masses
  - can also do EW, BSM
  - (import of model les in UFO (Universal FeynRules Output) or LANHEP format)
  - rational part for free (no need for additional Feynman rules)
  - support for effective vertices/spin-two particles
- GoSam code development: version 2.0 coming out this year
  - more compact code, much faster runtimes
  - extended features, easier installation

Interfacing GoSam: examples

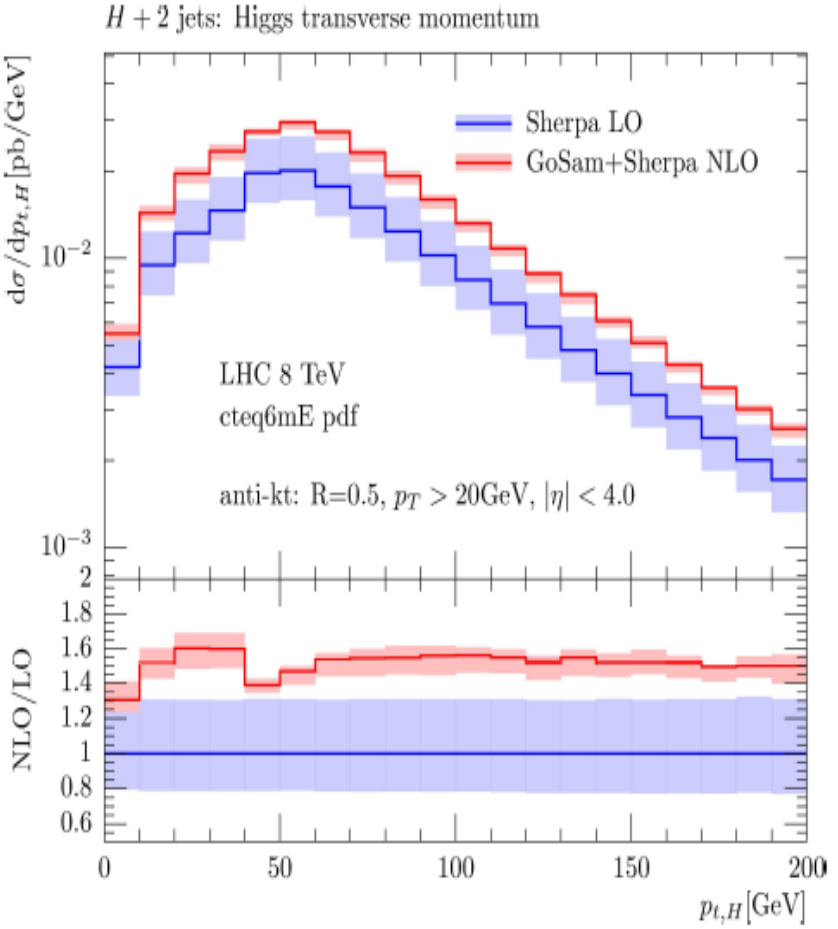
Gosam	Monte Carlo program
$b\bar{b}b\bar{b}$	x
W^+W^- +2 jets (including massive top)	x
$\tilde{\chi}_1^0\tilde{\chi}_1^0$+jet (SUSY QCD corr.)	x
$\gamma\gamma$+jet	x
$W^+W^-\ b\bar{b}$ (full off-shell effects)	x
H+0,1,2 jets (gluon fusion)	x
$W^{\pm}\,(\to e\nu_e) + 0, 1, 2, 3\,\text{jets}$	x
$Z/\gamma^*\,(\to e^+e^-) + 0, 1, 2\,\text{jets}$	x
$W^{\pm}\,(\to e\nu_e) + b\bar{b}$ (massive b's)	x
$W^+\,(\to \mu^+\nu_\mu) + W^-\,(\to e^-\bar{\nu}_e)$	x
$W^+\,(\to \mu^+\nu_\mu) + W^+\,(\to e^+\nu_e) + 2\,\text{jets}$	x
$t\bar{t} + 0, 1\,\text{jets}$	x
$t\bar{t}\,H + 0, 1\,\text{jets}$	x
$H\,V$+0,1 jet (V=W,Z + decay)	x

x: MadDipole/MadGraph/Madevent, x: Sherpa, x: Powheg Box

Interfacing GoSam: examples



$W^+W^-\,b\bar{b}$



H+2 jets

GoSam at Les Houches

- update of BLHA: achieve an Accord by the end of the workshop and possibly start implementing and validating it on a specific example
- discuss with experimentalists about projects (e.g. on prompt photons, Higgs property measurements, EW corrections, anomalous couplings, multi-leg NLO + shower matching)

- People in Les Houches: **Gudrun Heinrich, Gionata Luisoni, Johann von Soden-Fraunhofen**

OpenLoops

- Tools
  - Loop integrals: Collier [Denner, Dittmaier, Hofer]
  - 1-loop amplitudes: OpenLoops [Cascioli, Maierhofer, Pozzorini]
- Features and strengths of OpenLoops+Collier
  - NLO QCD for any 2 → 2, 3, 4, (5) SM process with complex masses, off-shell effects
  - fast code generation, compact code
  - fast loop amplitudes (thanks to open-loops algorithm)
  - high numerical stability (thanks to Denner-Dittmaier reduction)

OpenLoops

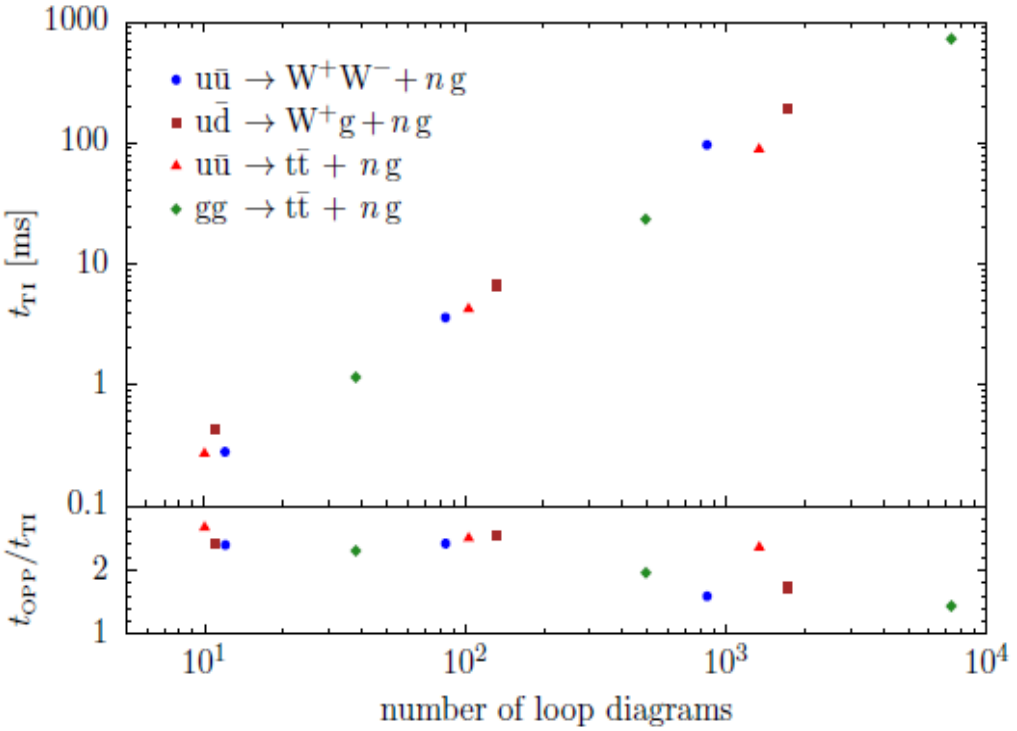
- Process library 1.0 (to be published in 2013, already available to ATLAS/CMS MCWGs)
  - many SM processes with (multi) bosons, photons, jets, heavy quarks, Higgs

W/Z	γ	jets	HQ pairs	single-top	Higgs
$V+3j$	$\gamma+3j$	$3(4)j$	$t\bar{t}+1j$	$tb+1j$	$(H+2j)$
$VV+2j$	$\gamma\gamma+1(2)j$		$t\bar{t}V+0(1)j$	$t+1(2)j$	$VH+1j$
$gg \to VV+1j$	$V\gamma+2j$		$b\bar{b}V+0(1)j$	$tW+0(1)j$	$t\bar{t}H$
$VVV+1j$					$qq \to Hqq+0(1)j$

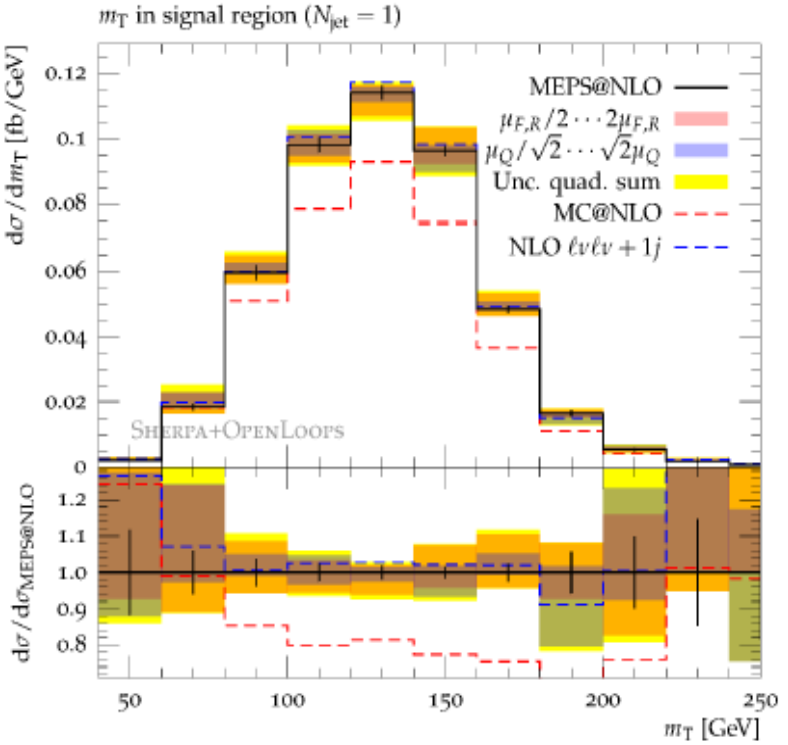
lower jet multiplicities implicitly understood

OpenLoops applications

Breaking 1-loop multi-leg speed bottleneck



Thorough modelling of nontrivial background



CPU cost grows linearly and remains low up to O(10^4) loop diagrams

Irreducible eμ+0,1 jets bkg to H → WW analysis: off-shell resonances with complex masses, interferences, loop-induced gg-contributions, jet vetoes/bins . . .

OpenLoops at Les Houches

- **leptons+neutrinos+jets** final states: theory simulations, applications to experimental analysis (with Sherpa, experimentalists)
- **heavy-flavour final states** (e.g. ttH(bb) signal and backgrounds): theory simulations, applications to experimental analysis (with Sherpa, experimentalists)
- technical aspects of **tensor-integral reduction** (with S. Dittmaier)
- systematic approaches to interface Collier+OpenLoops+Sherpa to experimental analyses (ATLAS/CMS MC generation, analysis groups)

- People in Les Houches: **Fabio Cascioli** (3-12 June)

  Stefano Pozzorini (10-12 June)

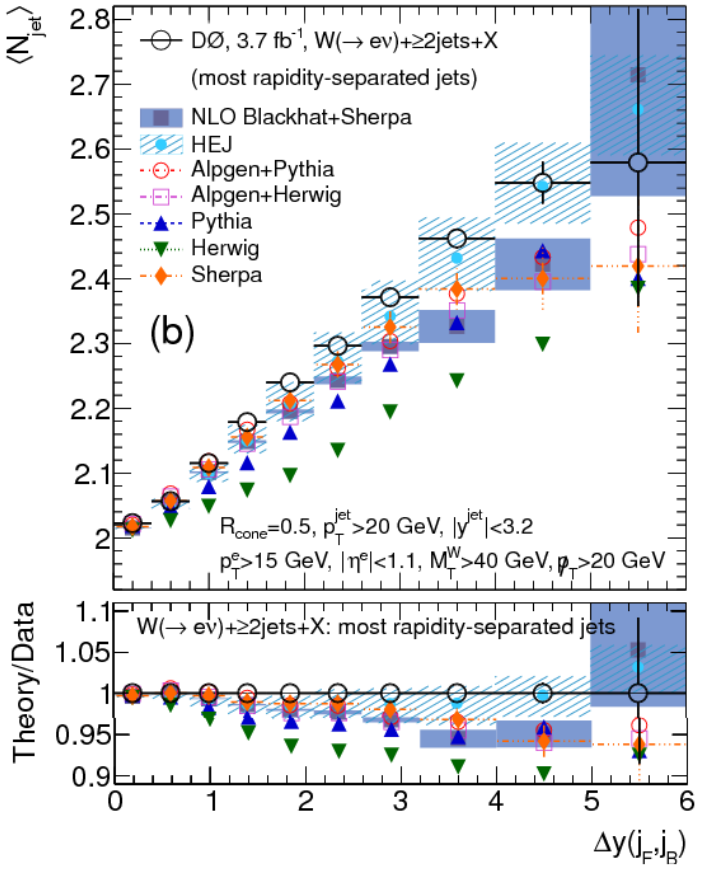
High Energy Jets

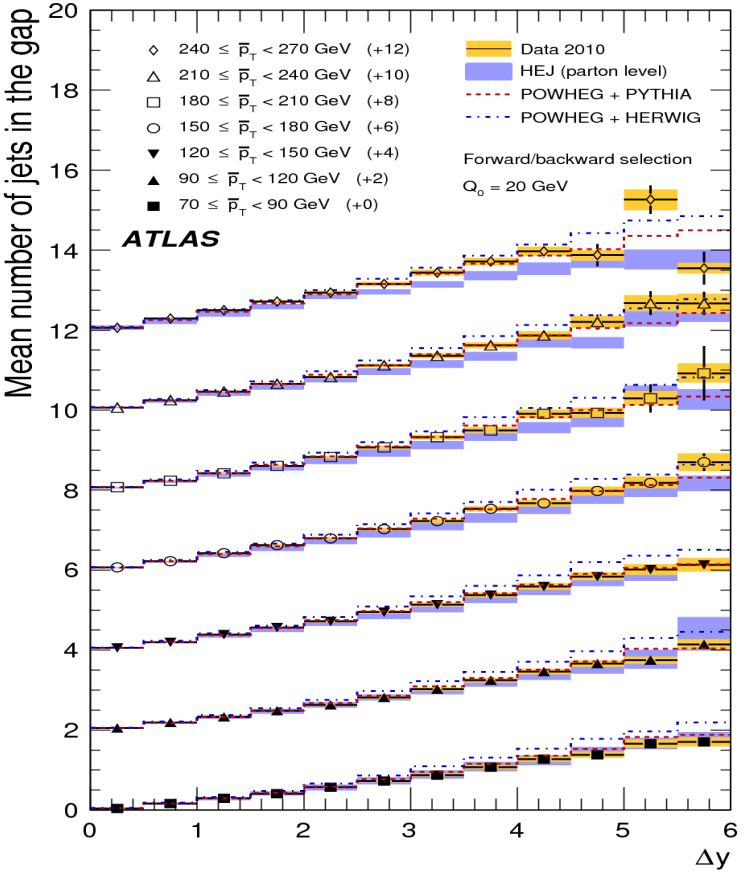
- **HEJ** calculates the leading **real and virtual** corrections to **wide-**angle QCD emissions to all orders in the coupling (and with high-multiplicity tree-level ME corrections)
- Production of **multiple jets**, also when of similar transverse momentum (i.e. no strong pt ordering required)
- **Fully flexible** partonic MC implementation

  publicly available at http://cern.ch/hej
- (LH event files, rivet analyses, LHAPDF,...)
- See arXiv: 0908.2786, 1101.5394, 1206.6763

High Energy Jets

- Speciality: The dominant radiative corrections at **large invariant mass** or **large rapidity intervals** of jets (very relevant for H+dijets)





HEJ at Les Houches

- Comparisons between W+jets and H+jets with NLO for LHC and beyond (with Snowmass)
- Discuss strategies for Hjj gluon fusion suppression, and for extracting CP properties of Higgs-gluon coupling
- Further strategies for stress-testing theoretical descriptions in difficult (but important) regions of phase space
- Progress towards HEJ+NLO

- People in Les Houches: **Jeppe Andersen, Jenni Smillie**

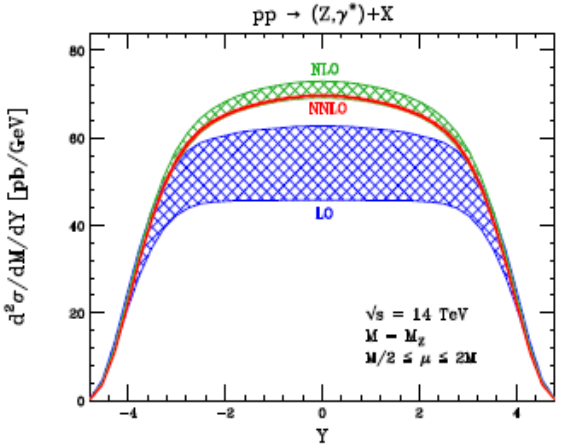
NNLO calculations for $2 \to 2$ processes

$$\mathrm{d}\sigma = \sum_{i,j} \int \frac{d\xi_1}{\xi_1} \frac{d\xi_2}{\xi_2} f_i(\xi_1, \mu_F^2) f_j(\xi_2, \mu_F^2) \mathrm{d}\hat{\sigma}_{ij}(\alpha_s(\mu_R), \mu_R, \mu_F)$$

$$\mathrm{d}\hat{\sigma}_{ij} = \mathrm{d}\hat{\sigma}_{ij}^{LO} + \left(\frac{\alpha_s(\mu_R)}{2\pi}\right) \mathrm{d}\hat{\sigma}_{ij}^{NLO} + \left(\frac{\alpha_s(\mu_R)}{2\pi}\right)^2 \mathrm{d}\hat{\sigma}_{ij}^{NNLO} + \mathcal{O}(\alpha_s^3)$$

Processes of interest

- ✓ $pp \to 2$ jets
- ✓ $pp \to \gamma$+jets
- ✓ $pp \to \gamma\gamma$
- ✓ $pp \to V$+jet
- ✓ $pp \to t\bar{t}$
- ✓ $pp \to VV$
- ✓ $pp \to H$+jet
- ✓ $\ldots$



Massively reduced theoretical error

Anastasiou, Dixon, Melnikov, Petriello (04)

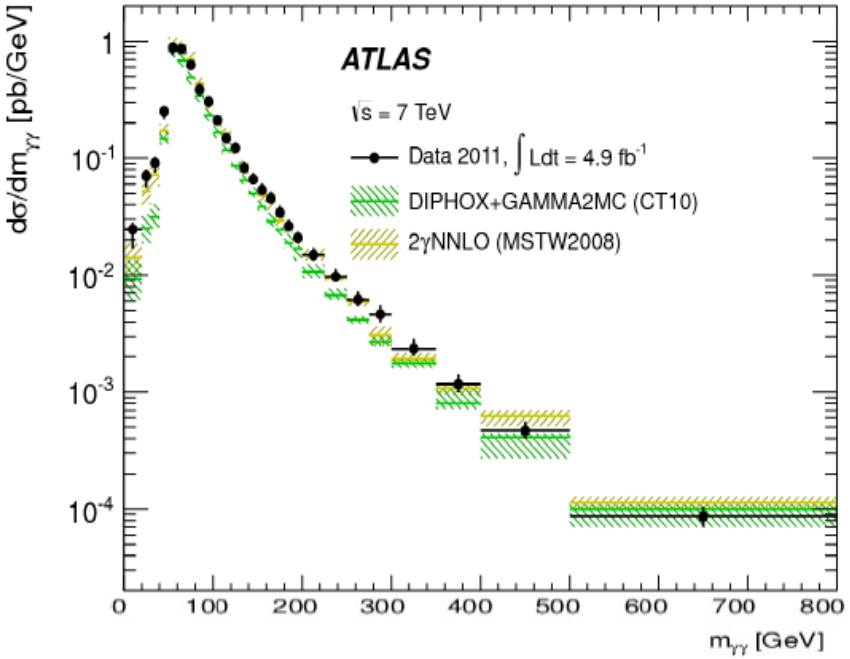
Diphoton production at NNLO (2γNNLO)

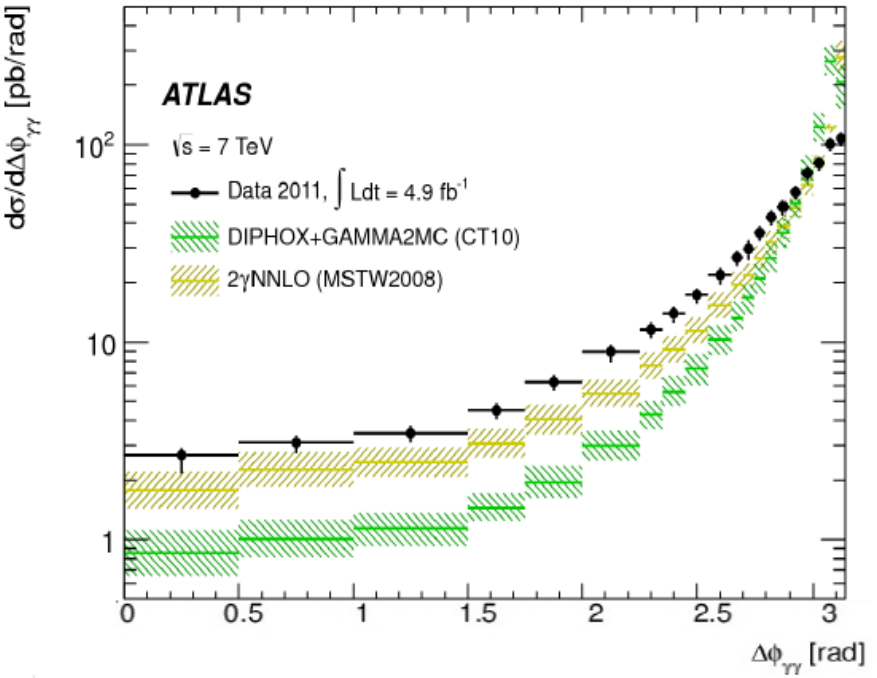
Catani, Cieri, de Florian, Ferrera, Grazzini

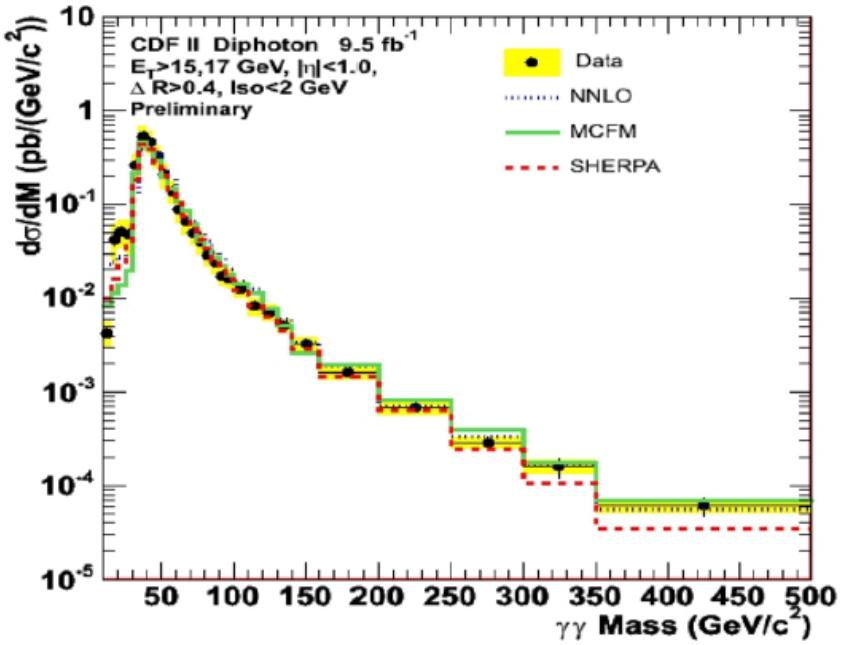
arXiv:1110.2375

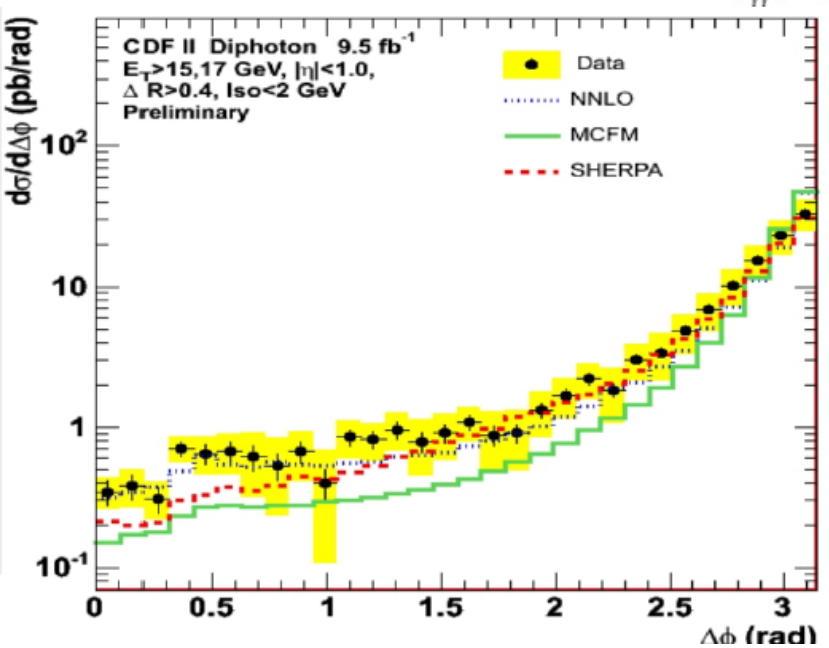
- First exclusive NNLO in pp collisions with two final state particles
- Fully exclusive NNLO description (direct contribution) for $pp \to \gamma\gamma$
- No fragmentation contribution → Frixione Isolation

2γNNLO results

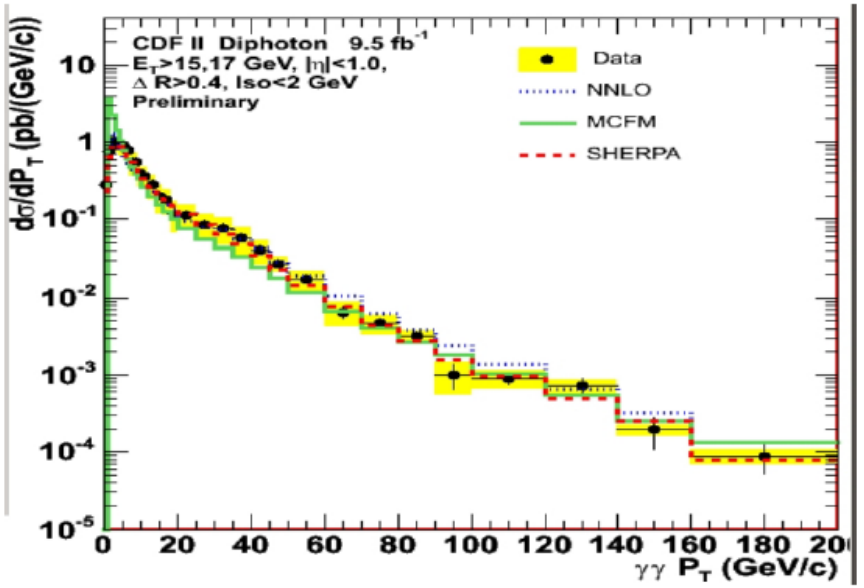


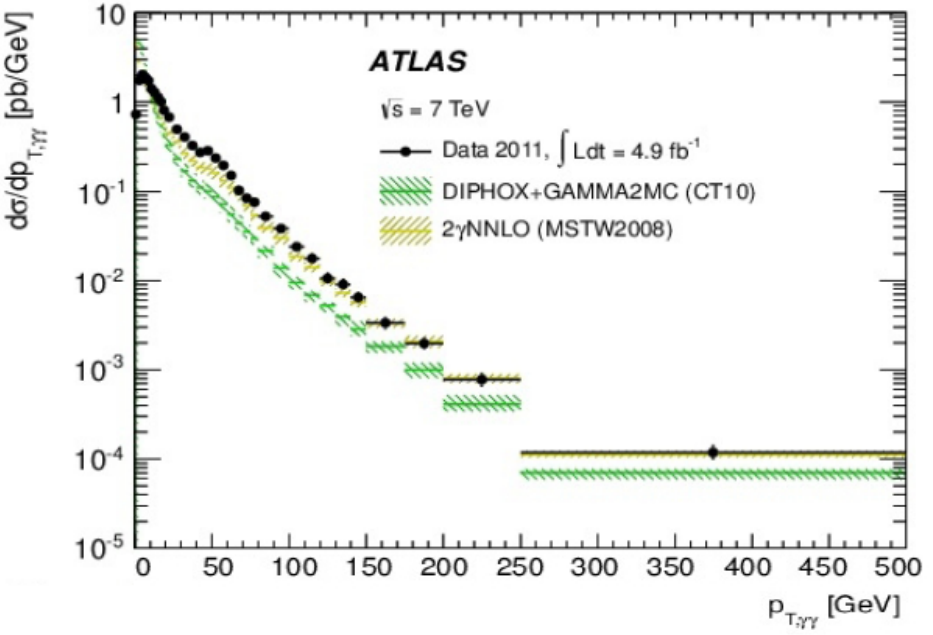






2γNNLO results





- Reduction of discrepancies between NLO description and data
- Sizeable NNLO corrections to the γγ mass distribution in kinematical regions related to Higgs boson searches

  40-55% effect over NLO
- NNLO very large away from back-to-back configuration (effectively NLO)
- At NNLO starts to reliably predict values of cross sections in all kinematical regions (with very few exceptions; e.g pTγγ → 0)

  All channels opened

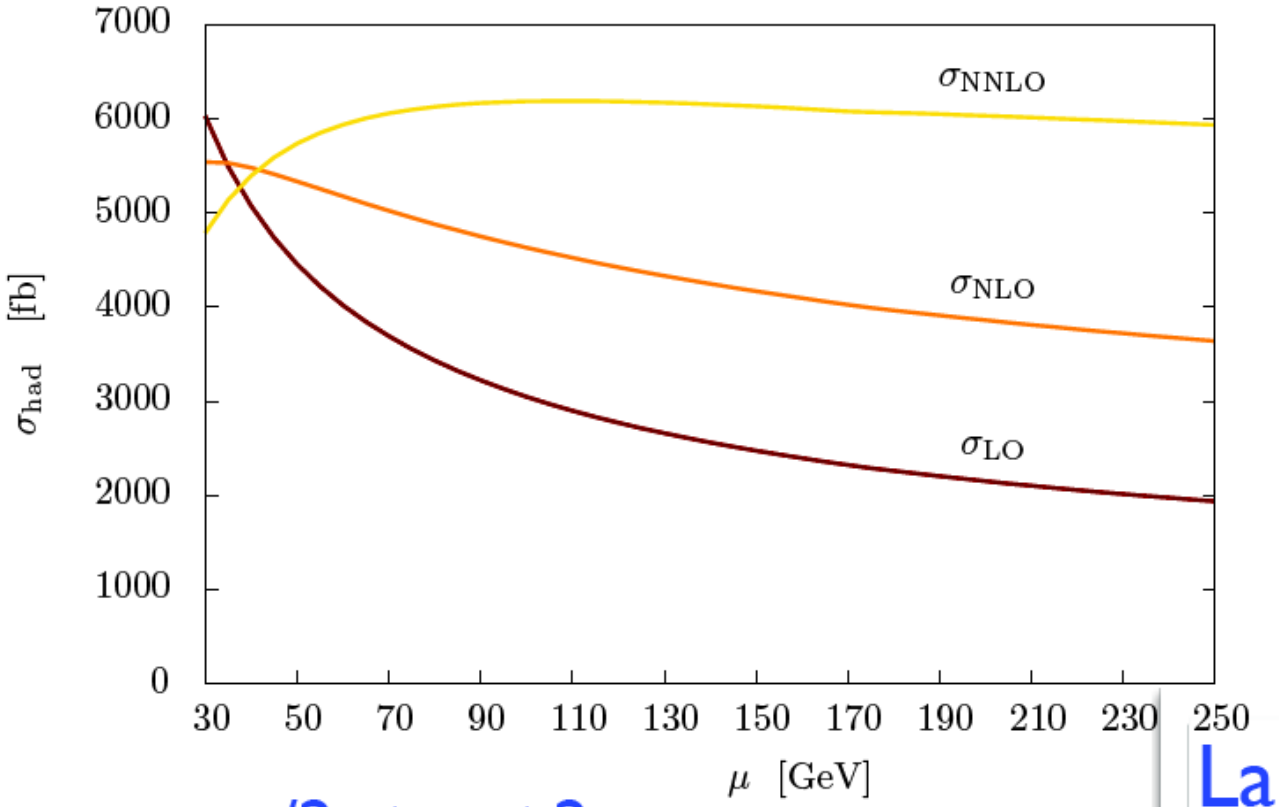
Higgs plus jet at NNLO

Boughezal, Caola, Melnikov, Petriello and Schulze

arXiv:1302.6216

- Current status:
  - total cross section in a gluon-only theory
  - Realistic jet algo, kT with R=0.5, pT > 30 GeV
  - Partonic cross-section profiled → very easy to study
  - scale and PDFs dependence
- Ongoing work:
  - run with ATLAS and CMS setup
  - qg channel, distributions (Higgs pT, leading jet pT, number of jets) [results by the end of the year?]

H+j @ NNLO (gg only)



Setup:

- m_H = 125 GeV
- NNPDF set
- kT algo, R=0.5, pT > 30 GeV

$m_H/2 < \mu < 2m_H$

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

Large K-factors

σ_{NLO}/σ_{LO} = 1.6

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

Significantly reduced O(4%) scale dependence

pp → di-jets (gluons only)

Setup:

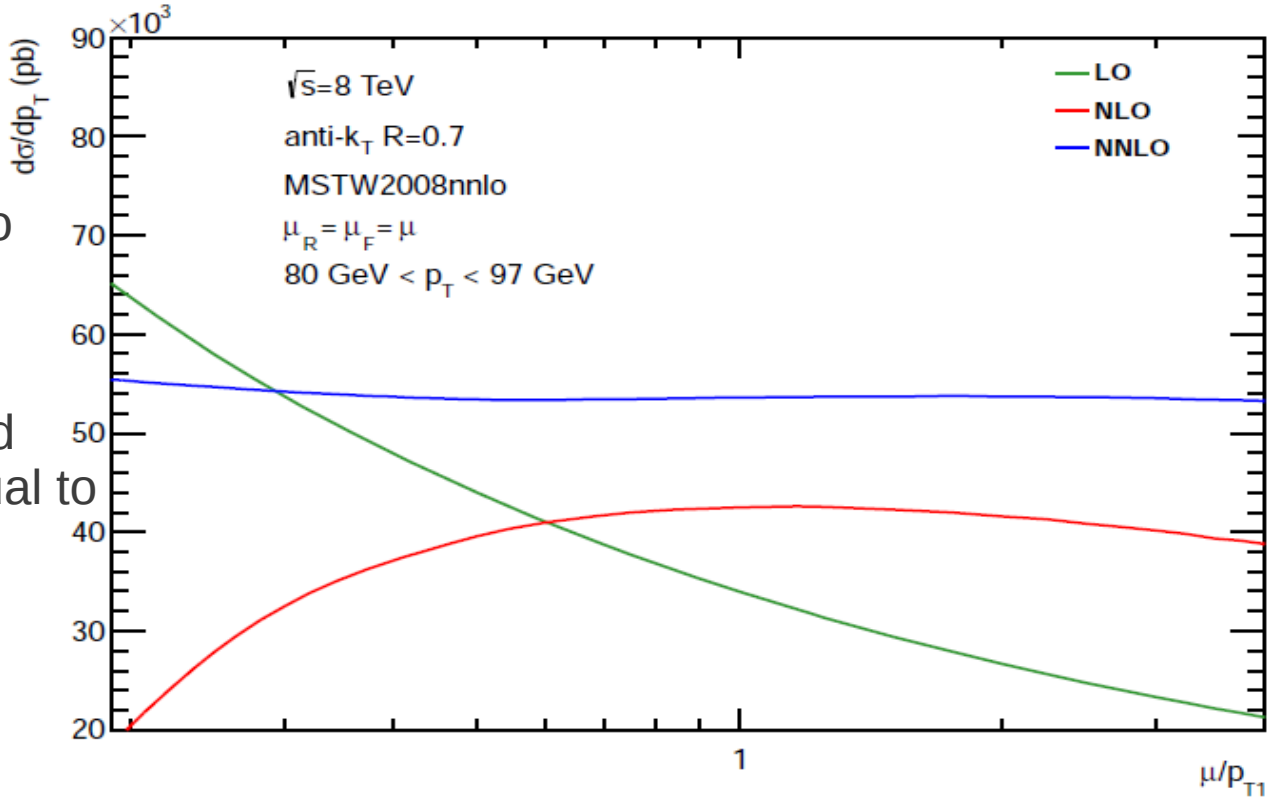
- jets identified with the anti-kT jet algorithm
- jets accepted at rapidities

  |y| < 4:4
- leading jet with transverse momentum pt > 80 GeV
- subsequent jets required to have at least pt > 60 GeV
- MSTW2008nnlo PDF
- dynamical factorization and renormalization scales equal to the leading jet pT

  (muR = muF = mu = pT1)

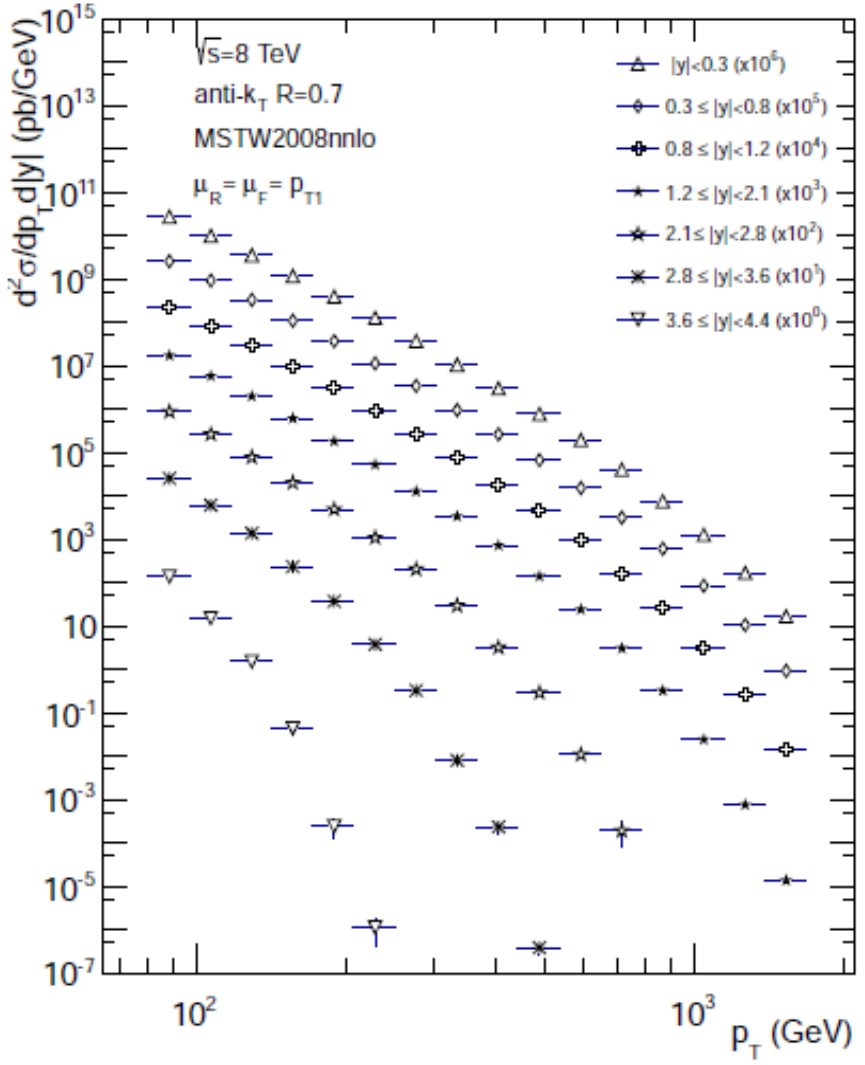
Gehrmann, Gehrmann-De Ridder, NG, Pires

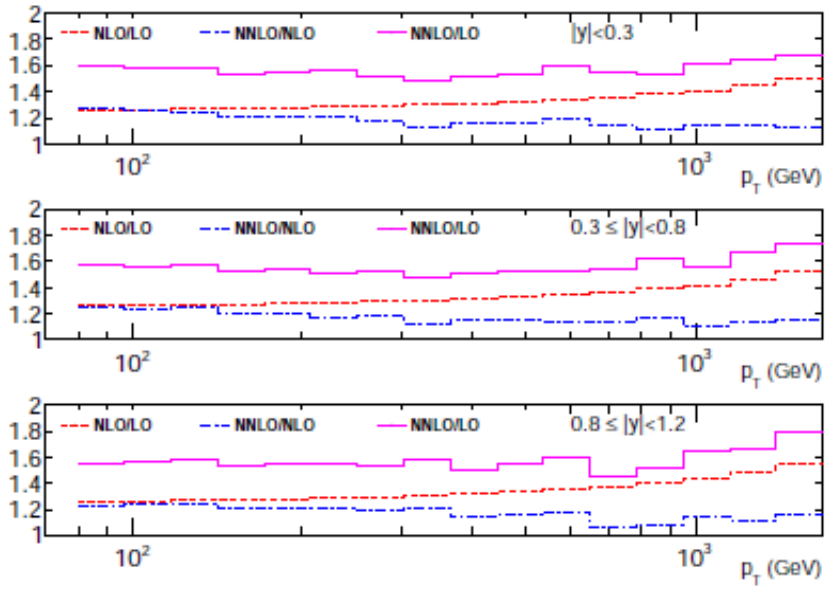
arXiv:1301.7310



pp → di-jets (gluons only)

- Double differential distribution R=0.7

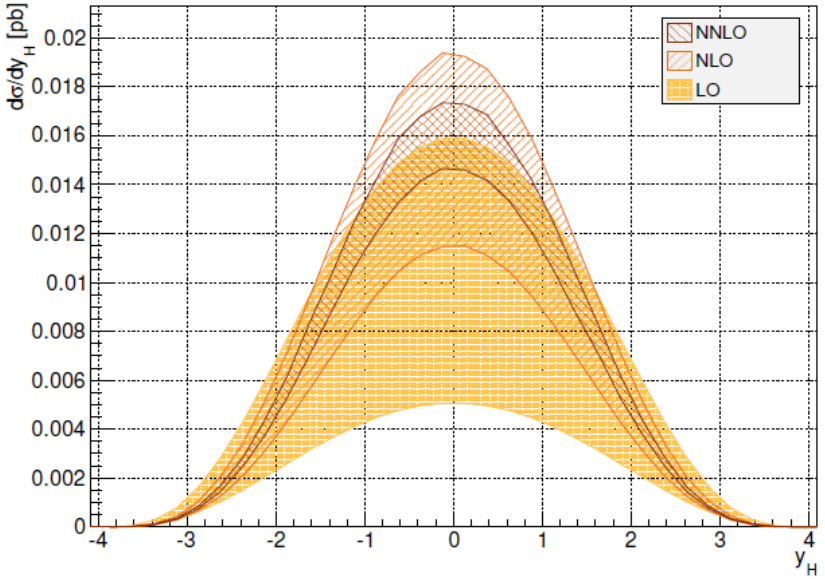




double differential k-factors

- NNLO result varies between 25% to 12% with respect to the NLO cross section
- similar behaviour between the rapidity slices

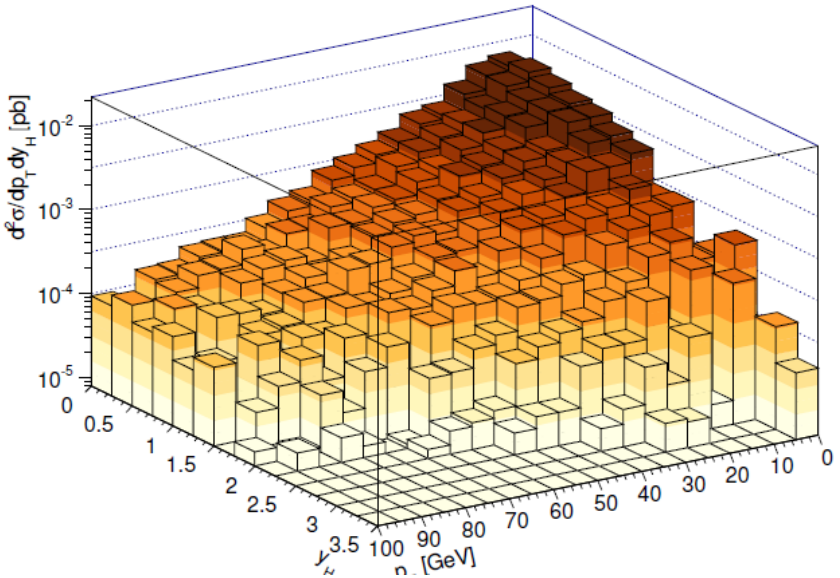
bb → H



Buehler, Herzog, Lazopoulos, Mueller arXiv:1204.4415

- bb->H rapidity distribution

  (m_h=125GeV, LHC@8TeV)



- bb->H double differential distribution in pT and rapidity

  (m_h=125GeV, LHC@8TeV)

NNLO to do in Les Houches

- Phenomenology:
  - A priority wish-list for NNLO from exp.
  - What is really needed? In which form?
  - Is speed / computing an issue?
  - NNLO for PDFs?
- Technical discussions / comparison of frameworks:
  - Recap: what can we do (in theory and in practice) and how well with our frameworks? Timescales?
  - Ideas to solve generic framework-independent issues (bin-to- bin fluctuations...)
  - clarify the strengths and weaknesses of each RR method in the market, especially in terms of:
    - extending to arbitrary processes (2->2, 2->3)
    - prospects for automatization (or at least “automatization”)
    - performance/numerical stability issues