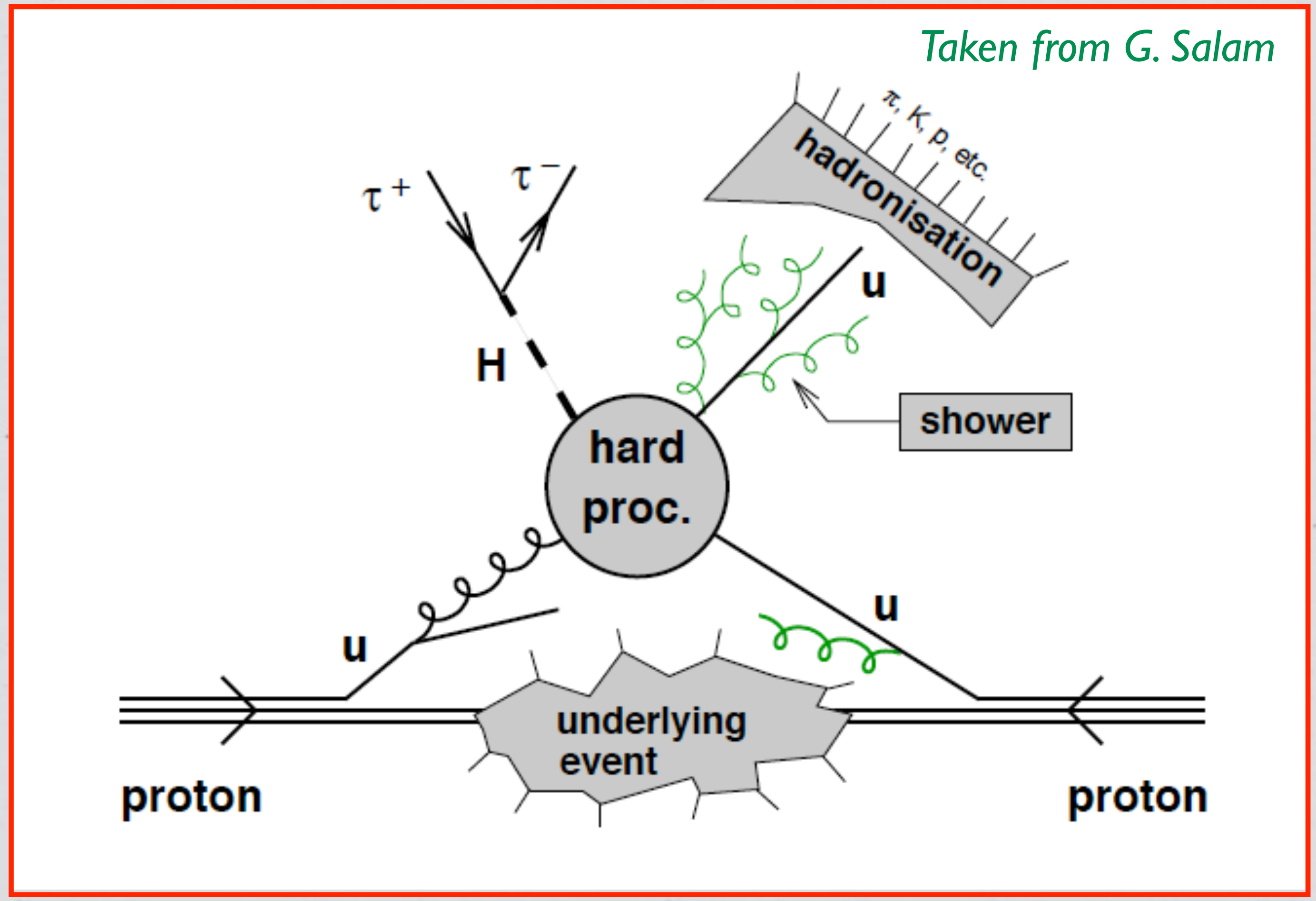
HIGHER ORDER CORRECTIONS

Status and perspectives

Giulia Zanderighi
University of Oxford & STFC

25th Rencontres de Blois 2013 on Particle Physics and Cosmology

This talk



This talk: focus only on the high-energy perturbative scattering process

To obtain hadron-level predictions need also: convolution with parton distribution functions and modeling of hadronization/underlying event

I will review a personal selection of recent highlights – apologies in advance for possible omissions

Higher orders

- At high energy QCD is perturbative, i.e. precision is achieved by computing higher order terms in the expansion in the (small) QCD coupling constant α_s
- Three main types of perturbative approximations
  - ✓ fixed order expansions (LO, NLO, NNLO …)
  - ✓ analytic resummations (exact log counting LL, NLL, NNLL …)
  - ✓ numerical resummations through Monte Carlo simulations
- Calculations have complementary benefits/drawback. Effort towards combining them to always obtain the most accurate predictions

Fixed order expansions

Rely on the idea of the an order-by-order expansion in the small coupling

$$\sigma = \sigma_0(1 + c_1\alpha_s + c_2\alpha_s^2 + \dots)$$

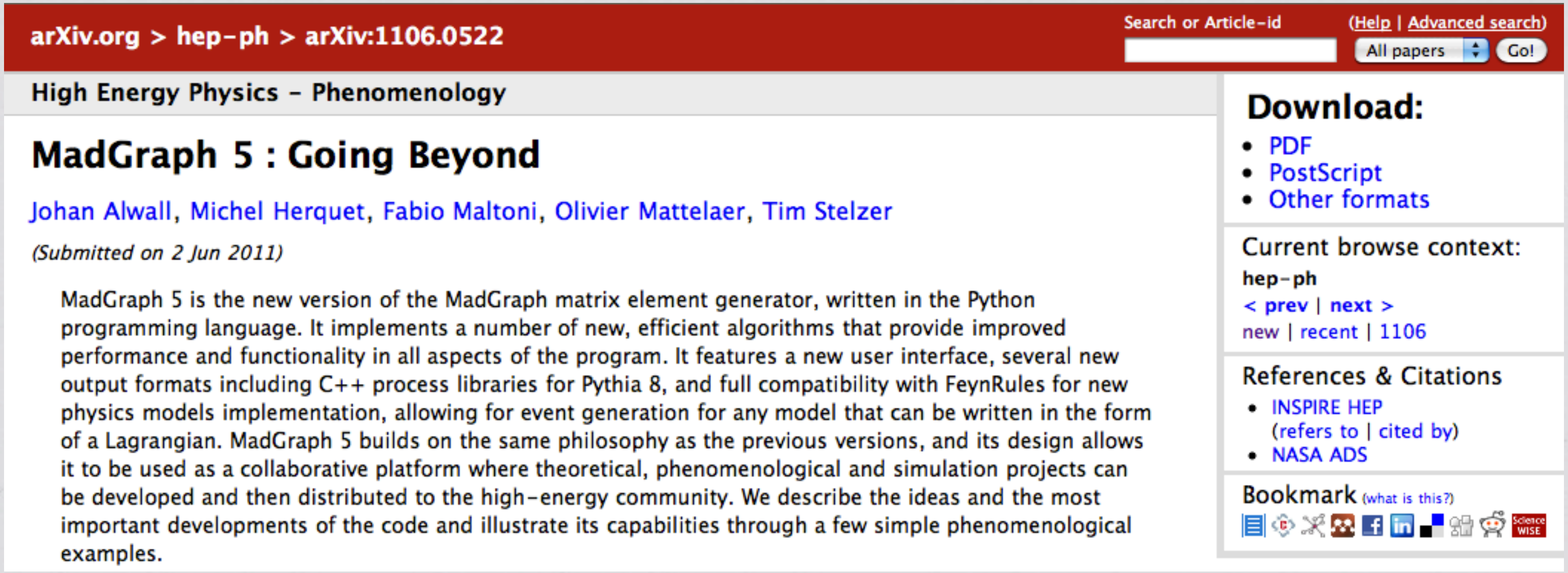
LO NLO NNLO ...

Sounds very simple but

- the calculation of perturbative coefficients very hard especially if many particles are involved
- the series is well-behaved if $c_1 \sim c_2 \sim \dots \sim 1$ -- but we will see that at hadron colliders this is often not the case

Leading Order

Today's standard set by Madgraph5



arXiv.org > hep-ph > arXiv:1106.0522

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All papers Go!

High Energy Physics – Phenomenology

MadGraph 5 : Going Beyond

Johan Alwall, Michel Herquet, Fabio Maltoni, Olivier Mattelaer, Tim Stelzer

(Submitted on 2 Jun 2011)

MadGraph 5 is the new version of the MadGraph matrix element generator, written in the Python programming language. It implements a number of new, efficient algorithms that provide improved performance and functionality in all aspects of the program. It features a new user interface, several new output formats including C++ process libraries for Pythia 8, and full compatibility with FeynRules for new physics models implementation, allowing for event generation for any model that can be written in the form of a Lagrangian. MadGraph 5 builds on the same philosophy as the previous versions, and its design allows it to be used as a collaborative platform where theoretical, phenomenological and simulation projects can be developed and then distributed to the high-energy community. We describe the ideas and the most important developments of the code and illustrate its capabilities through a few simple phenomenological examples.

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References & Citations

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Bookmark (what is this?)

- constant progress in extending flexibility and BSM support and in more efficient matrix element calculations (no Feynman diagrams)
- widely used to explore new ground, yet limited precision

Other popular code include Alpgen, CompHep, Sherpa ...

Next-to-leading order

Approaches make use of theoretical breakthrough ideas in the calculation of virtual amplitudes that started in 2004 (following pioneering ideas of the '90)

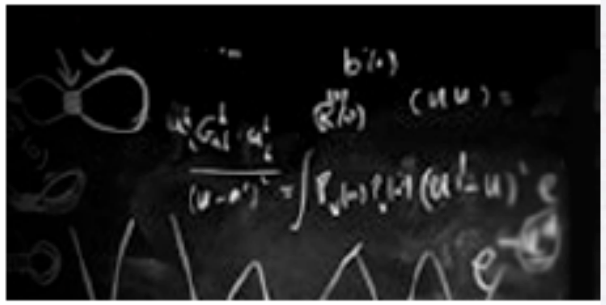
OPP algorithm, generalized unitarity, loops from trees, recursion relations, open loops ... [...]

The improved understanding on how to compute virtual amplitudes made it possible to compute many new processes at NLO ⇒ the **NLO revolution**

Today two major directions

- ✓ more processes: towards a full automation of NLO calculations with codes like Helac, GoSam or MadLoop
- ✓ more legs: e.g. Blackhat focuses on pure n jets or W/Z + n jets -- pushing the frontier of n

The Kavli Institute for Theoretical Physics
University of California, Santa Barbara



HOME DIRECTORY FOR SCIENTISTS TALKS NEWS EVENTS VISITOR INFO OUTREACH CONTACT HELP May 23, 2013

KITP Program: Collider Physics (Jan 12 - Apr 2, 2004)
Coordinators: Z. Bern, J. Huston, Z. Kunszt, K. Melnikov

Alekhin, Sergey	Haber, Howard	Nagy, Zoltan
Anastasiou, Charalampos	Hagiwara, Kaoru	Oleari, Carlo
Baur, Ulrich	Harlander, Robert	Peskin, Michael
Becher, Thomas	Heinrich, Gudrun	Petriello, Frank
Beneke, Martin	Hewett, Joanne	Puchwein, Martin
Berger, E.	Hollik, Wolfgang	Rainwater, David
Bern, Zvi	Huston, Joey	Reina, Laura
Bethke, Siggi	Kilgore, William	Richardson, Peter
Binoth, Thomas	Kniehl, Bernd	Rizzo, Tom
Bluemlein, Johannes	Kosower, David	Signer, Adrian
Campbell, John	Krauss, Frank	Sjostrand, Torbjorn
Czarnecki, Andrej	Kribs, Graham	Skands, Peter
de Florian, Daniel	Kuehn, Johann	Slusarczyk, Maciej
De Freitas, Abilio	Kulesza, Anna	Soper, Davison
Del Duca, Vittorio	Kunszt, Zoltan	Stirling, James
Dixon, Lance	Lykken, Joe	Strassler, Matthew
Ellis, Keith	Maltoni, Fabio	Tollefson, Kirsten
Ellis, Stephen	Mangano, Michelangelo	Tung, Wu-Ki
Field, Rick	Marchesini, Giuseppe	Wackeroth, Doreen
Gary, William	Marciano, Bill	Was, Zbigniew
Gehrmann, Aude	Mastrolia, Pierpaolo	Witten, Edward
Gehrmann, Thomas	Melnikov, Kirill	Yuan, C.-P.
Giele, Walter	Mitov, Alexander	Zanderighi, Giulia
Glover, Nigel	Moch, Sven-Olaf	Zeppenfeld, Dieter
Grazzini, Massimiliano	Mrenna, Steve	Zielinski, Marek

The event that marked the beginning of the “NLO revolution”:

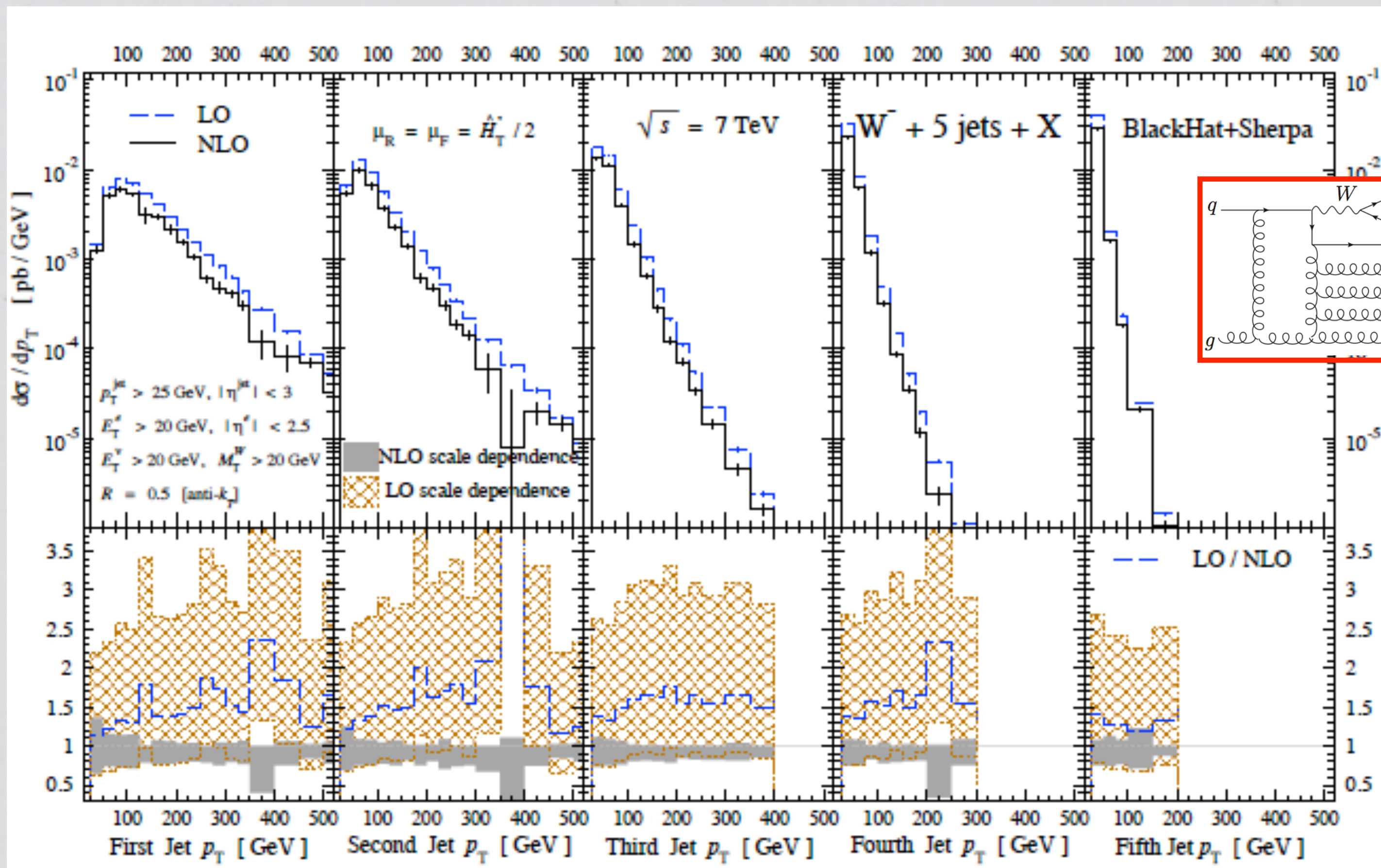
KITP conference on Collider Physics in ’04

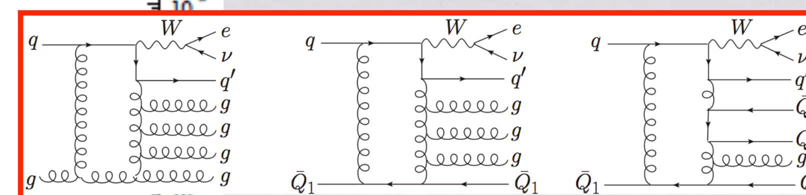
Most of the big players were there.

After almost ten years targets reached ... ?

If you ask me: the answer is yes!
e.g. Les Houches NLO wishlists are now closed chapters [ttbb, tttt, WWbb, bbbb, WWjj, W/Z+3j,W/Z+4j,W+5, 4j ...], still only few public codes

NLO highlight: W+5jets





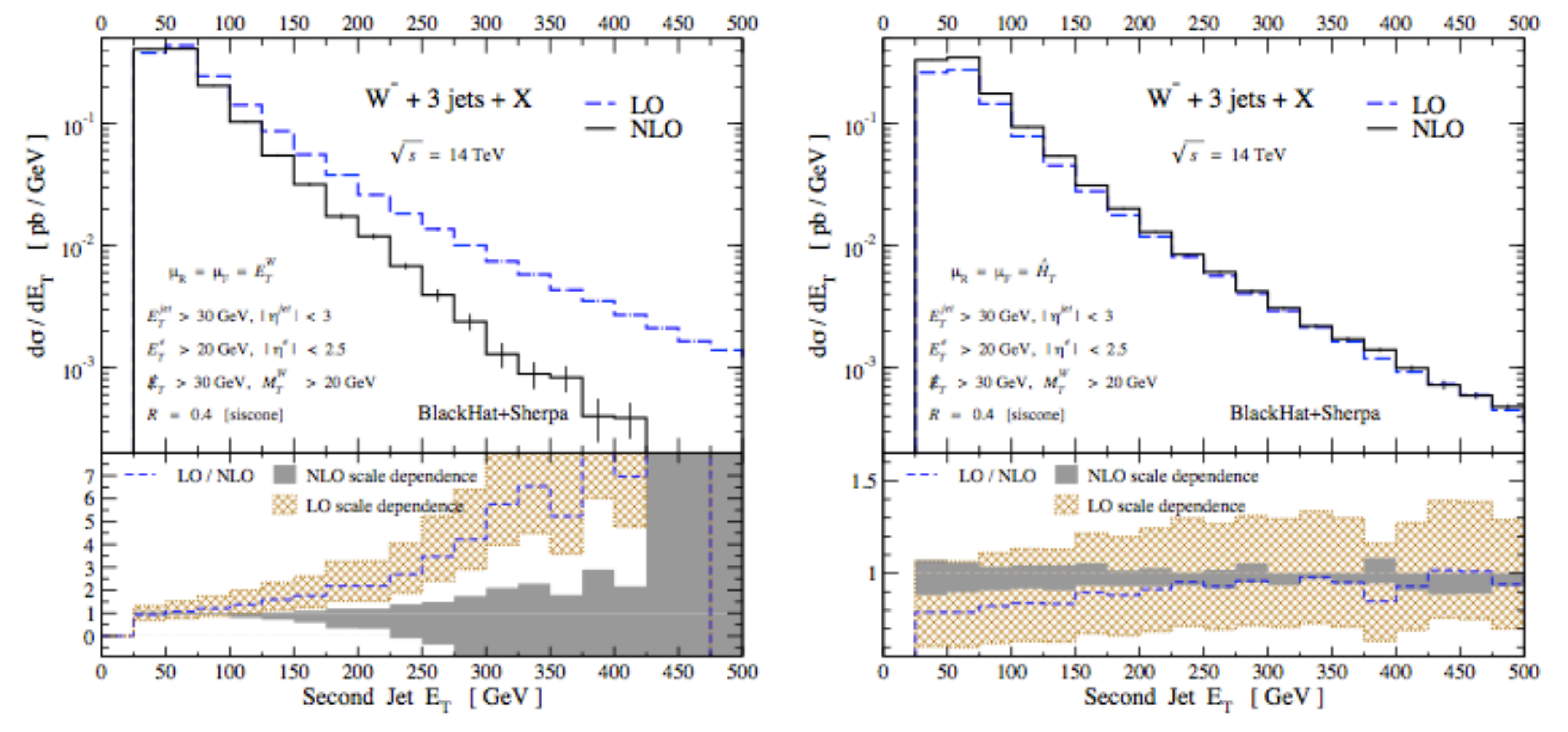
Bern et al. 1304.1253

Tremendous achievement. Three issues remain (in all pure NLO calculations)

1. scale choice (factorization and renormalization)
2. merging to parton shower + hadronization
3. NLO calculation fails in Sudakov regions (related to point 2. but not only)

NLO: scale choice

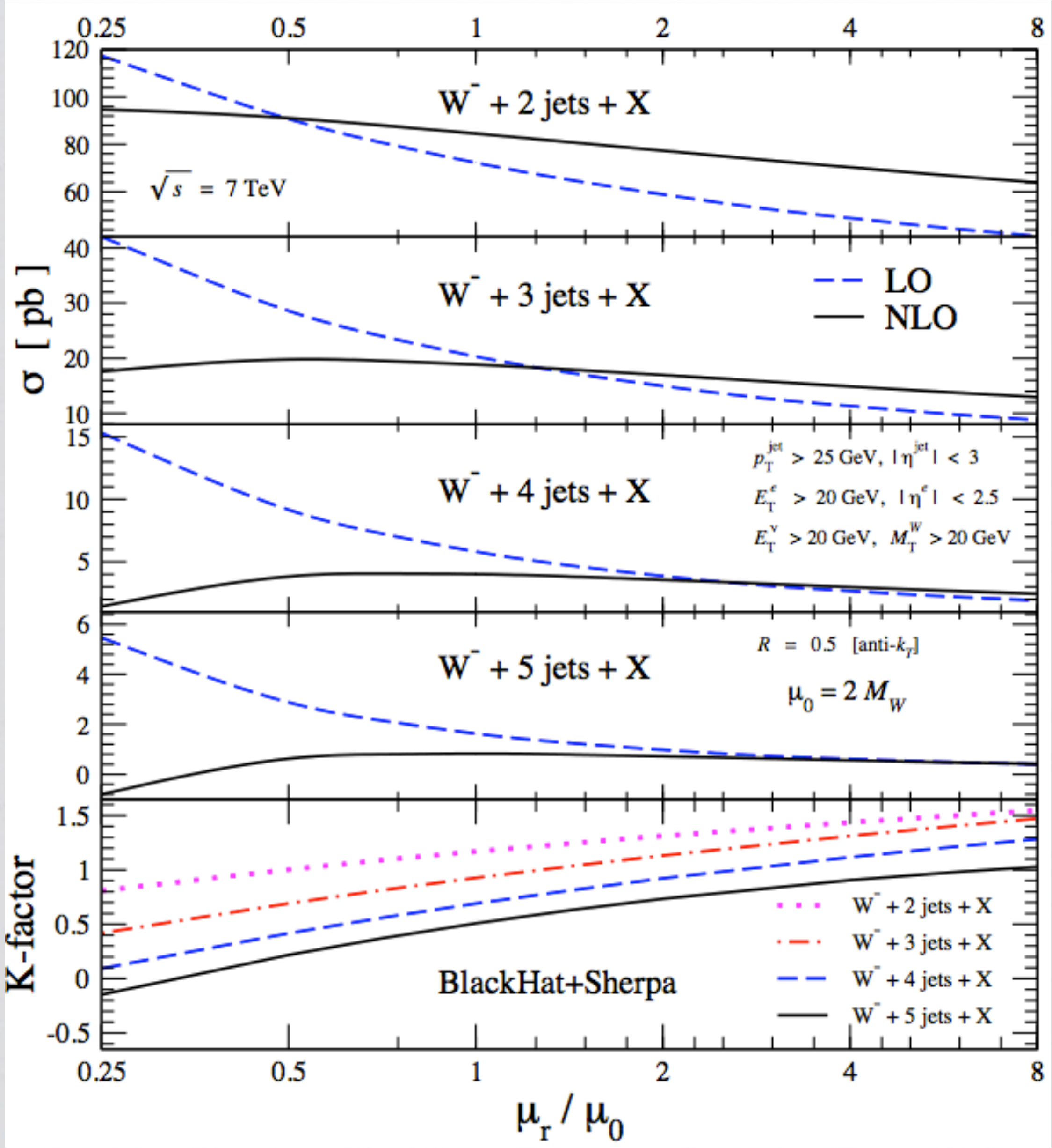
Scale choice: example of W+3 jets (problem more severe with more jets)



... large logarithms can appear in some distributions, invalidating even an NLO prediction.

Bern et al. 0907.1984

NLO: scale choice



Bern et al. 1304.1253

- K-factor very scale dependent (because of LO)
- NLO residual scale dependence large (pattern not driven by α_s-running)
- NLO negative at reasonable scales

$$K = \frac{NLO}{LO}$$

MiNLO

Hamilton et al. 1304.1253

If NLO calculations are implemented in POWHEG/MC@NLO and upgraded with MiNLO (Multi scale Improved NLO) all 3 issues are addressed

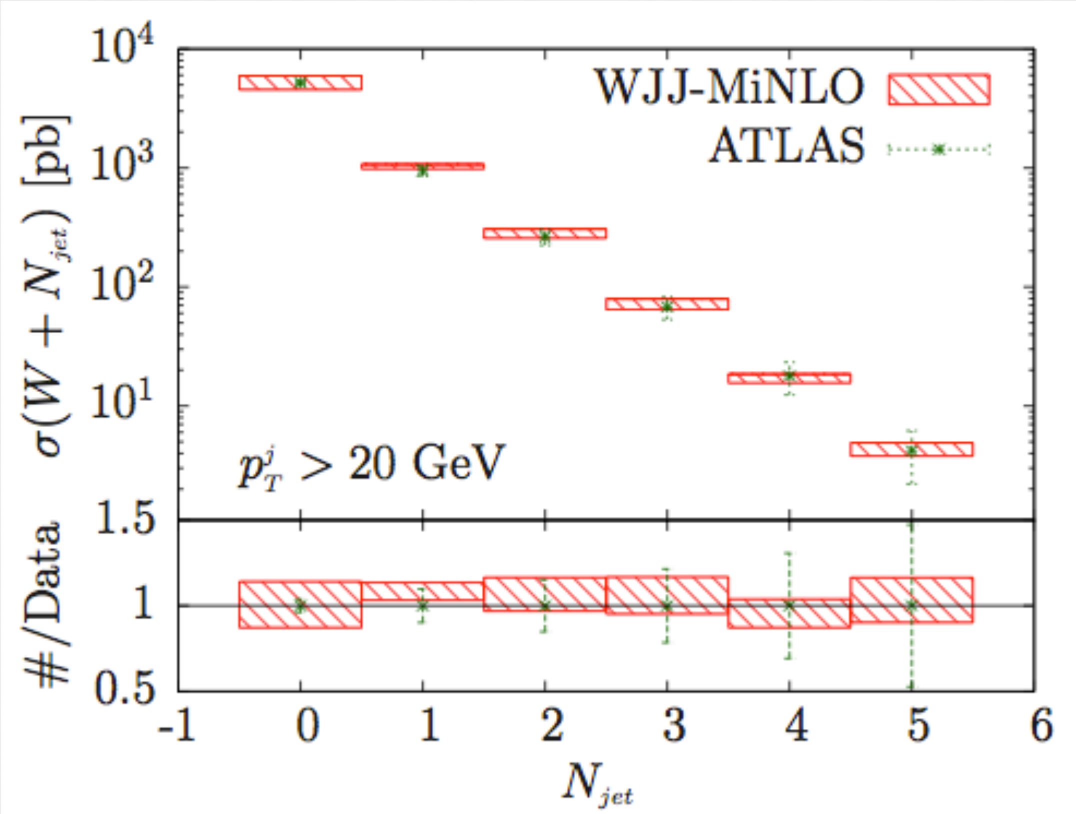
1. scale choice (factorization and renormalization): chosen as in the CKKW approach (i.e. reconstruct most like branching history and assign local transverse momentum scales at vertices)

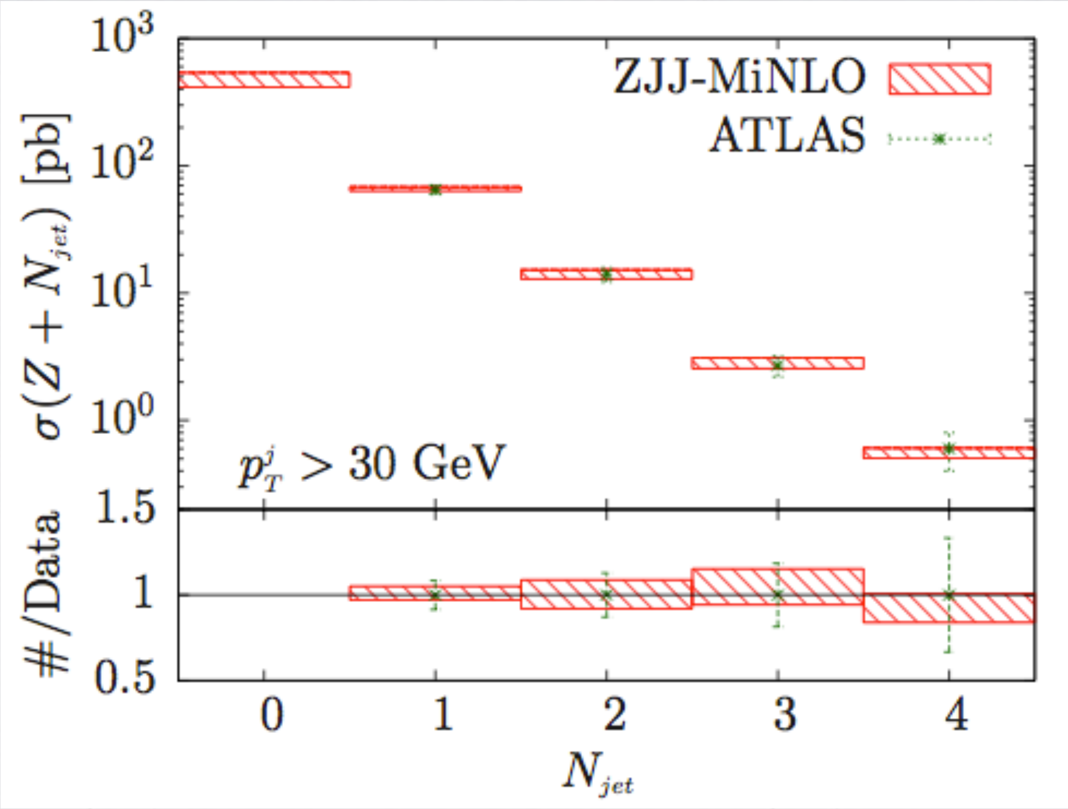
2. merging to parton shower + hadronization: solved by standard POWHEG/MC@NLO approaches

   Frixione and Webber '02; Nason '04

3. NLO calculation fail in Sudakov regions: add Sudakov form factors such that NLO vanishes rather than diverge in Sudakov regions

MiNLO: V+jets





Campbell et al. 1303.5447

Results out of the box versus ATLAS data for 0,1… 5 jets

To note: predictions are NLO accurate only in the 2-jet bin.

Does one catch the bulk of the NLO corrections anyhow?

For 1 jet the answer is yes. Still more experience is needed

NNLO status

The last decade saw an enormous number of new results at NLO. But at NLO theory error often already larger then experimental one.
What is the progress at NNLO at hadron colliders?

Status in 2010:

- inclusive NNLO results for Higgs and Drell-Yan known since many years (1990, 2002-2004)

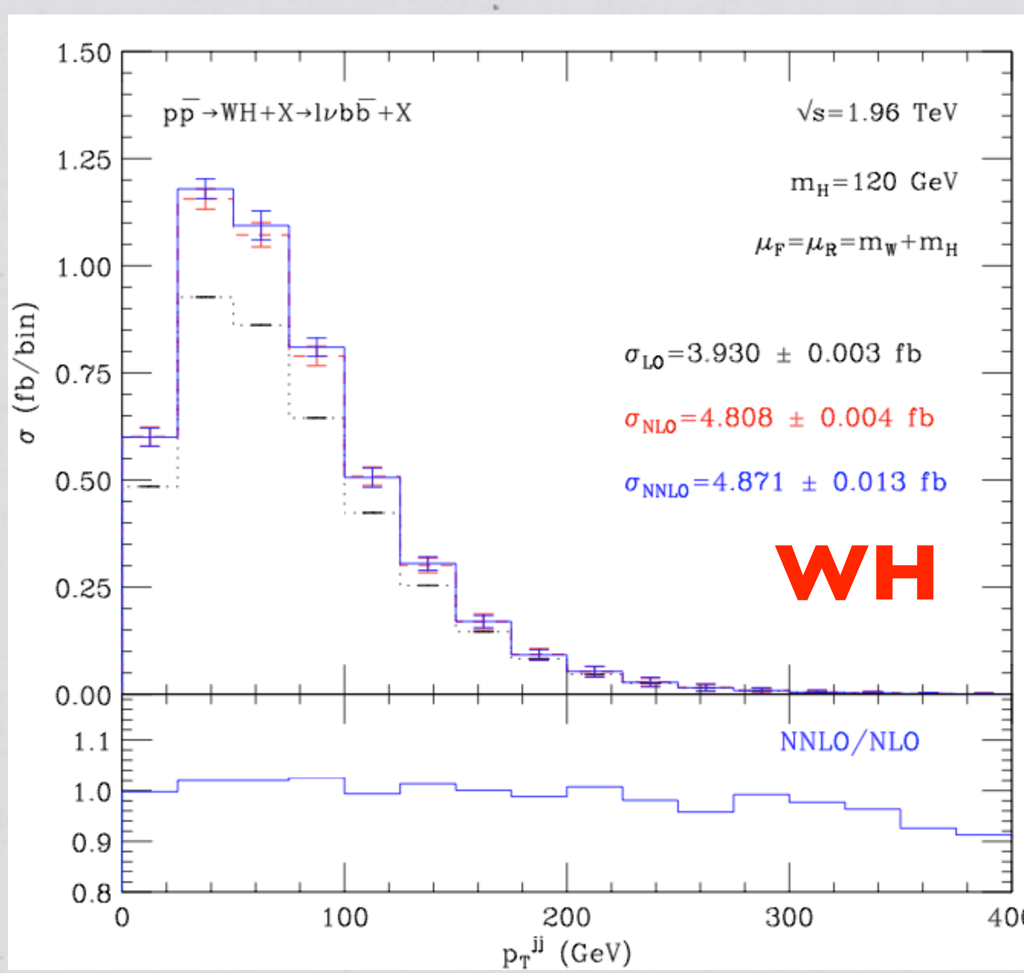
  [...]
- technical improvements, optimization, fully exclusive with decay corrections to those processes

  [...]
- technical progress in terms of calculating new amplitudes ($2 \to 2$) and in techniques to cancel (overlapping) divergences

  [...]

But only since very recently also lots of interesting phenomenological results for a variety of $2 \to 2$ processes

NNLO highlights: associated VH

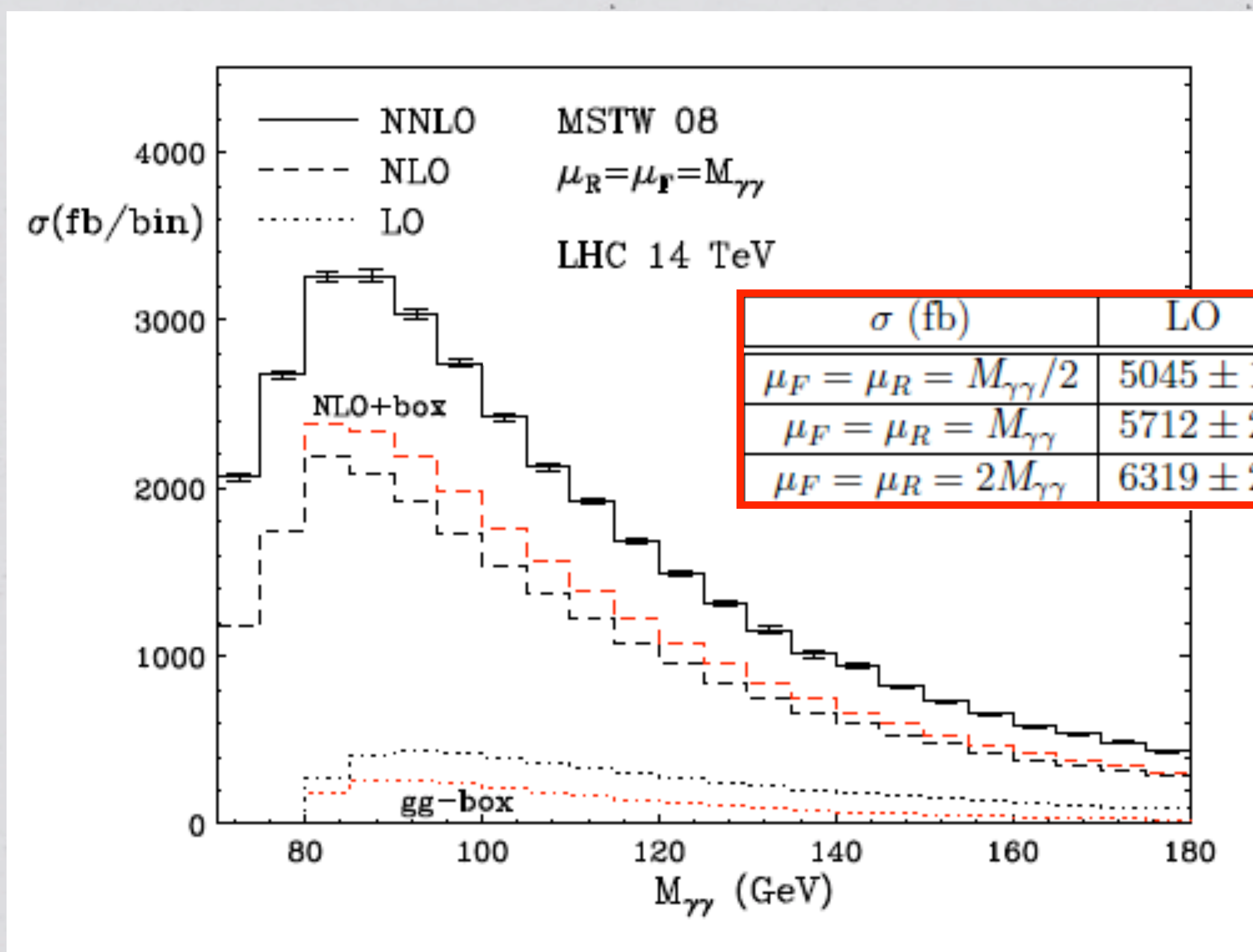


Ferrera et al. 1107.1164

⇒ fully differential

⇒ good convergence of PT

NNLO highlights: $\gamma\gamma$



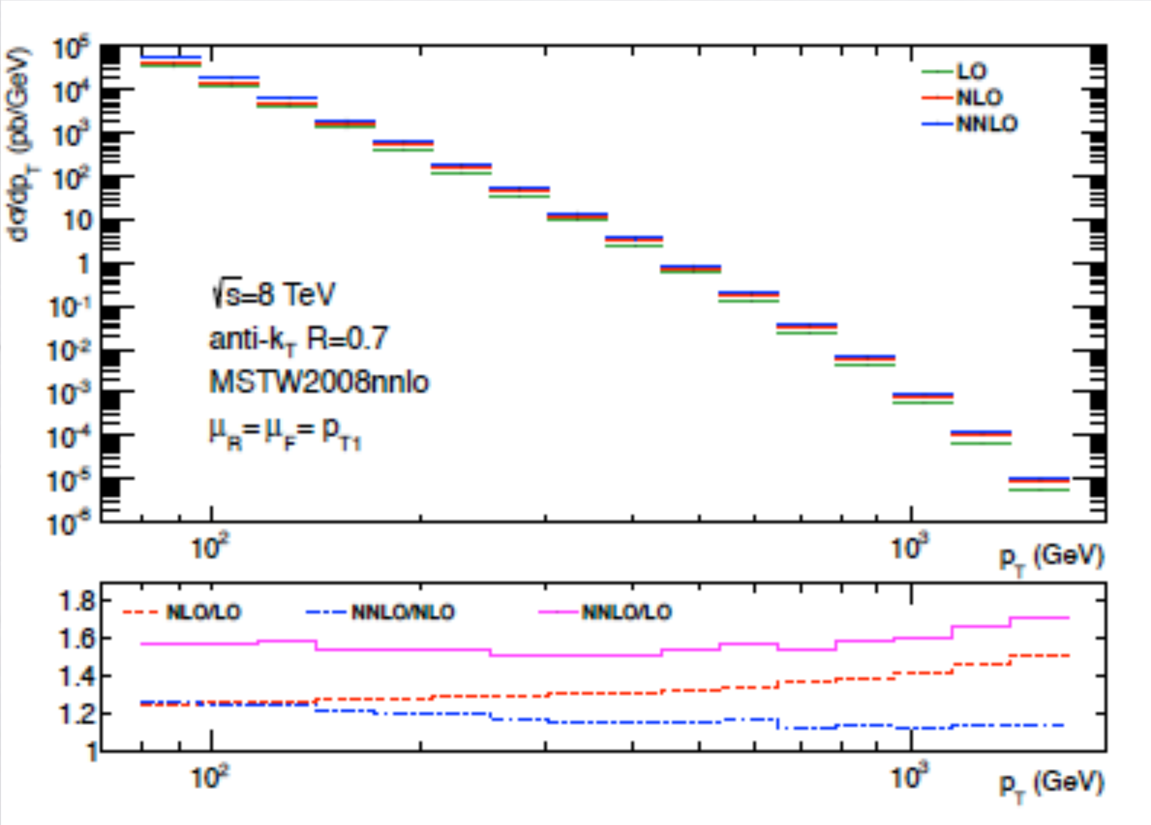
σ (fb)	LO	NLO	NNLO
$\mu_F = \mu_R = M_{\gamma\gamma}/2$	5045 ± 1	26581 ± 23	45588 ± 97
$\mu_F = \mu_R = M_{\gamma\gamma}$	5712 ± 2	26402 ± 25	43315 ± 54
$\mu_F = \mu_R = 2M_{\gamma\gamma}$	6319 ± 2	26045 ± 24	41794 ± 77

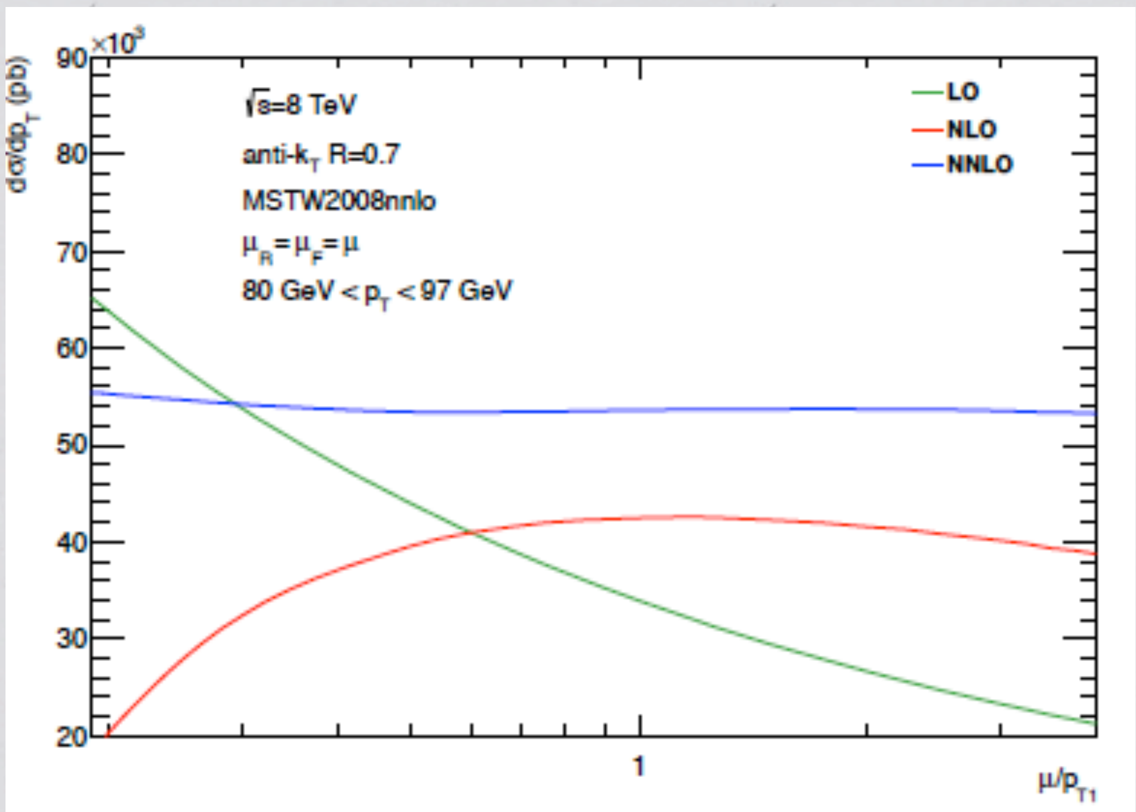
Catani et al. 1110.2375

$\Rightarrow$ no good convergence of PT (asymmetric cuts + new channels)
[similar to gg $\rightarrow$ H]

NNLO highlights: dijets

gluon only contribution, leading color





Gehrmann et al. 1301.7310

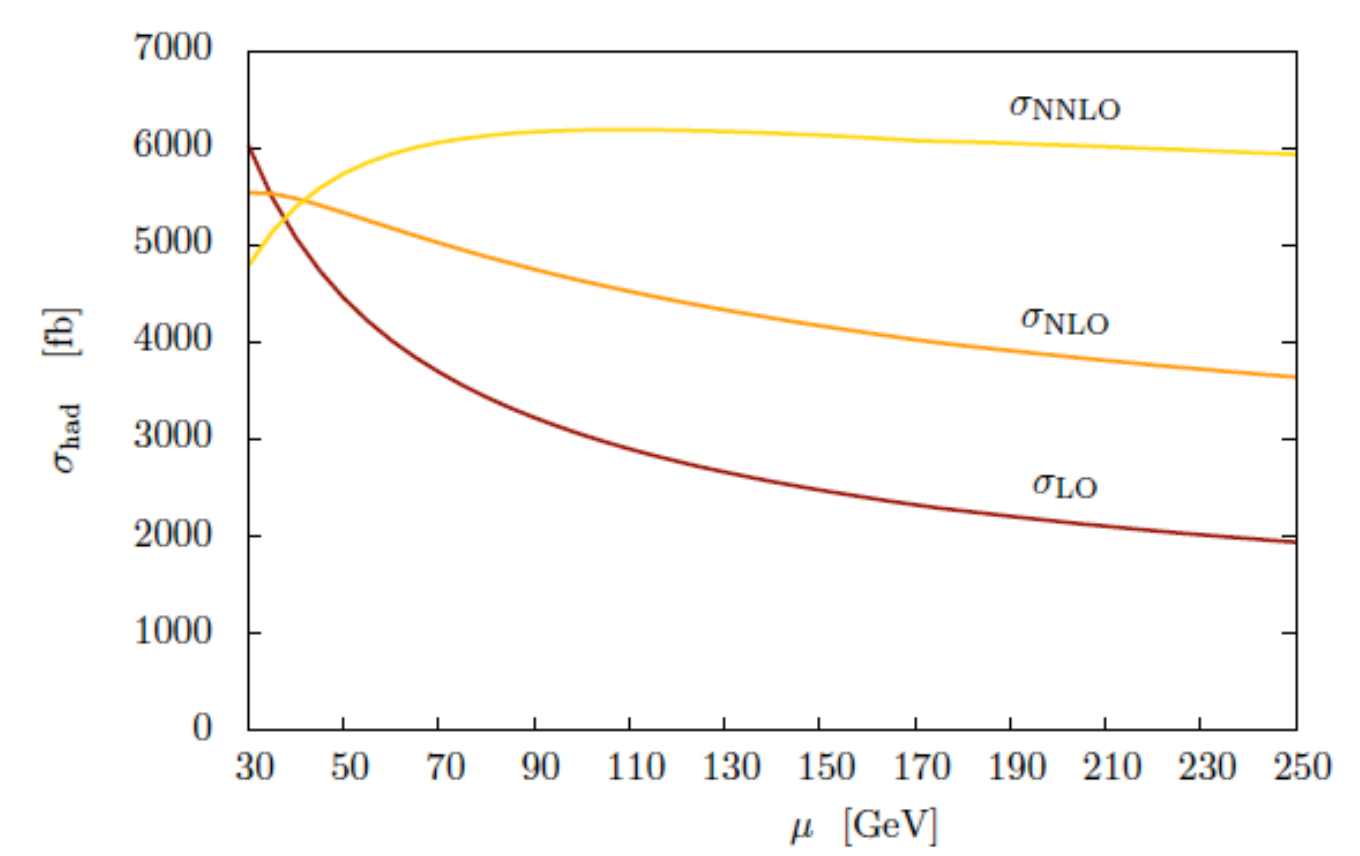
$\Rightarrow$ no good convergence of PT [similar to $gg \to H$, $pp \to \gamma\gamma$]

Does this pattern survive once the full NNLO calculation is completed?

NNLO highlights: H+jet

Boughezal et al. 1302.6216

Gluon fusion contribution to H+1jet

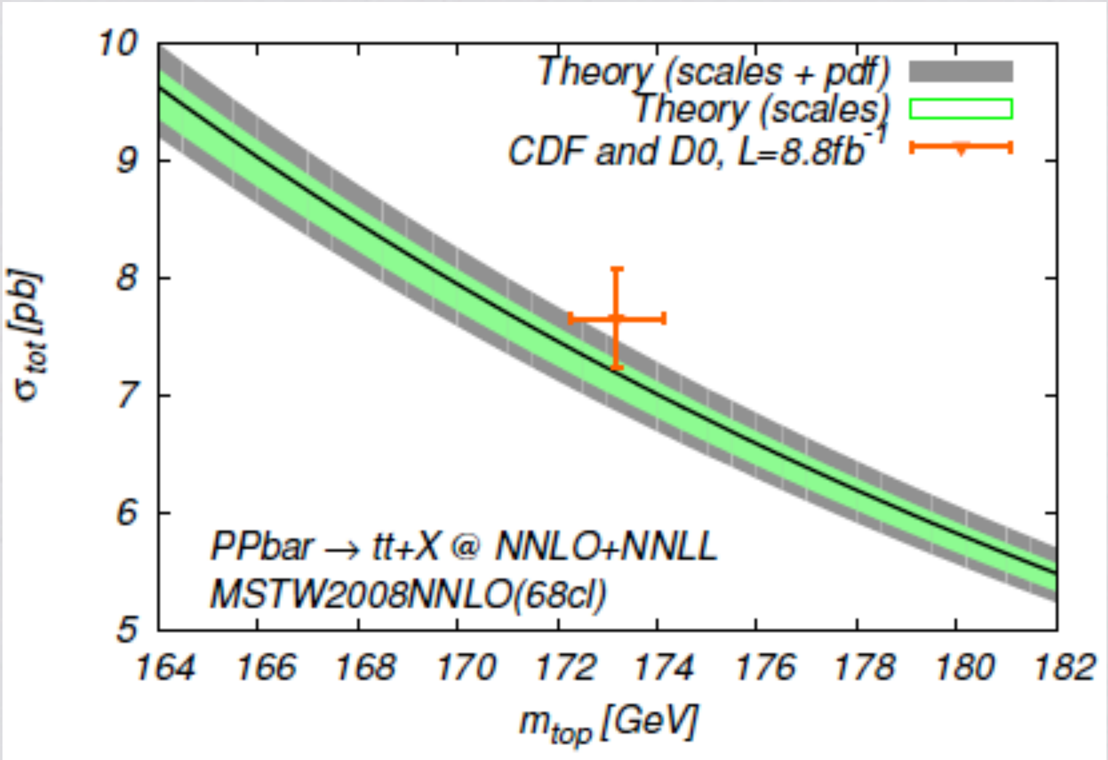


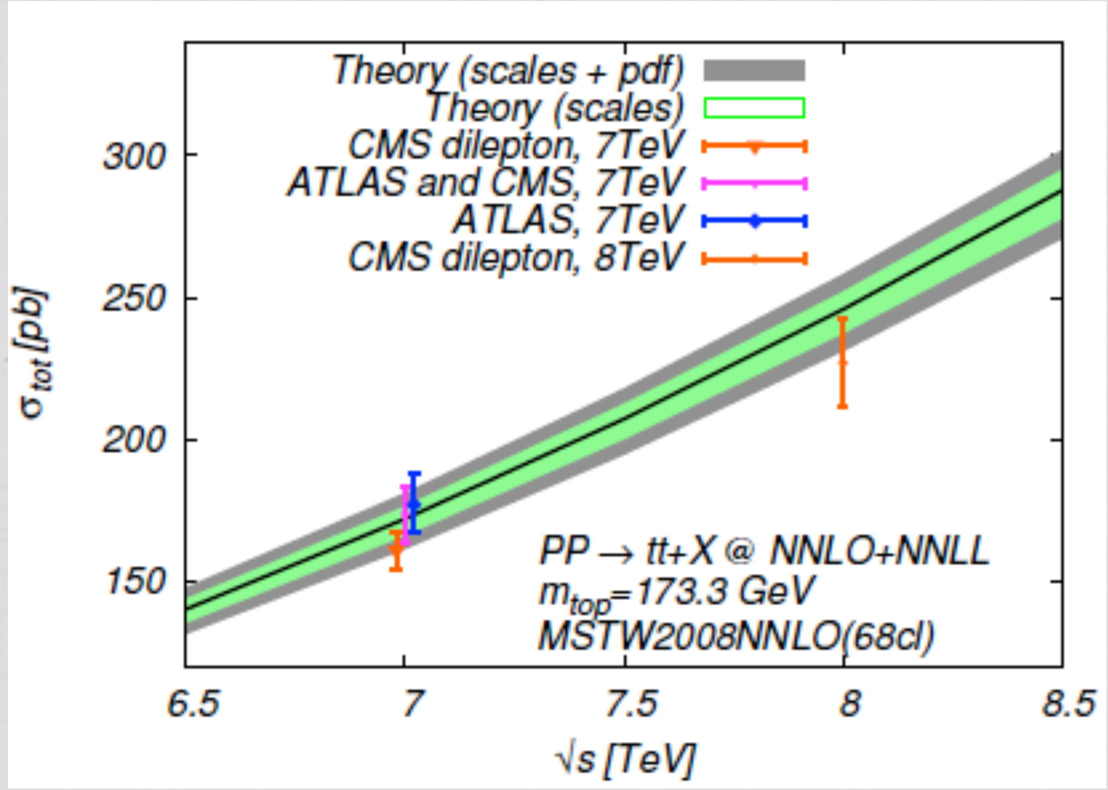
⇒ no good convergence of PT [similar to $gg \to H$, $pp \to \gamma\gamma$, $pp \to$ dijets]

Does this pattern survive once the full NNLO calculation is completed?

NNLO highlights: top pair

First full NNLO calculation with colored particles in the initial and final state. Paves the way to a number of other calculations





Czakon et al. 1303.6254
[+ previous refs...]

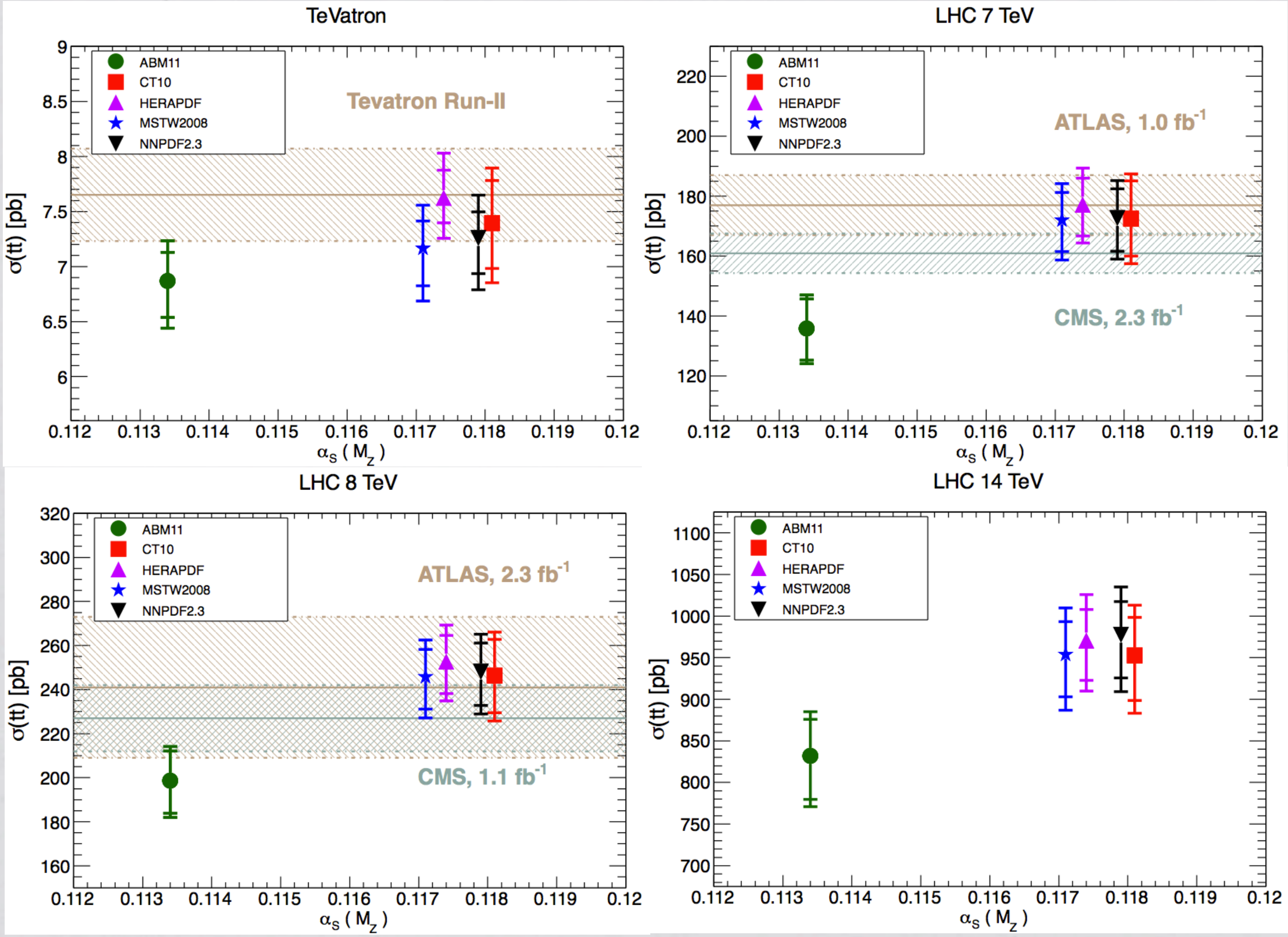
Theory uncertainty from missing higher orders: reduced from 9% at NLO+NNLL to 3% at NNLL+NNLO

Top pair: first phenomenology

Czakon et al. 1303.7215

Best predictions obtained by combining NNLO+NNLL

✓ comparison to data



Top pair: first phenomenology

Czakon et al. 1303.7215

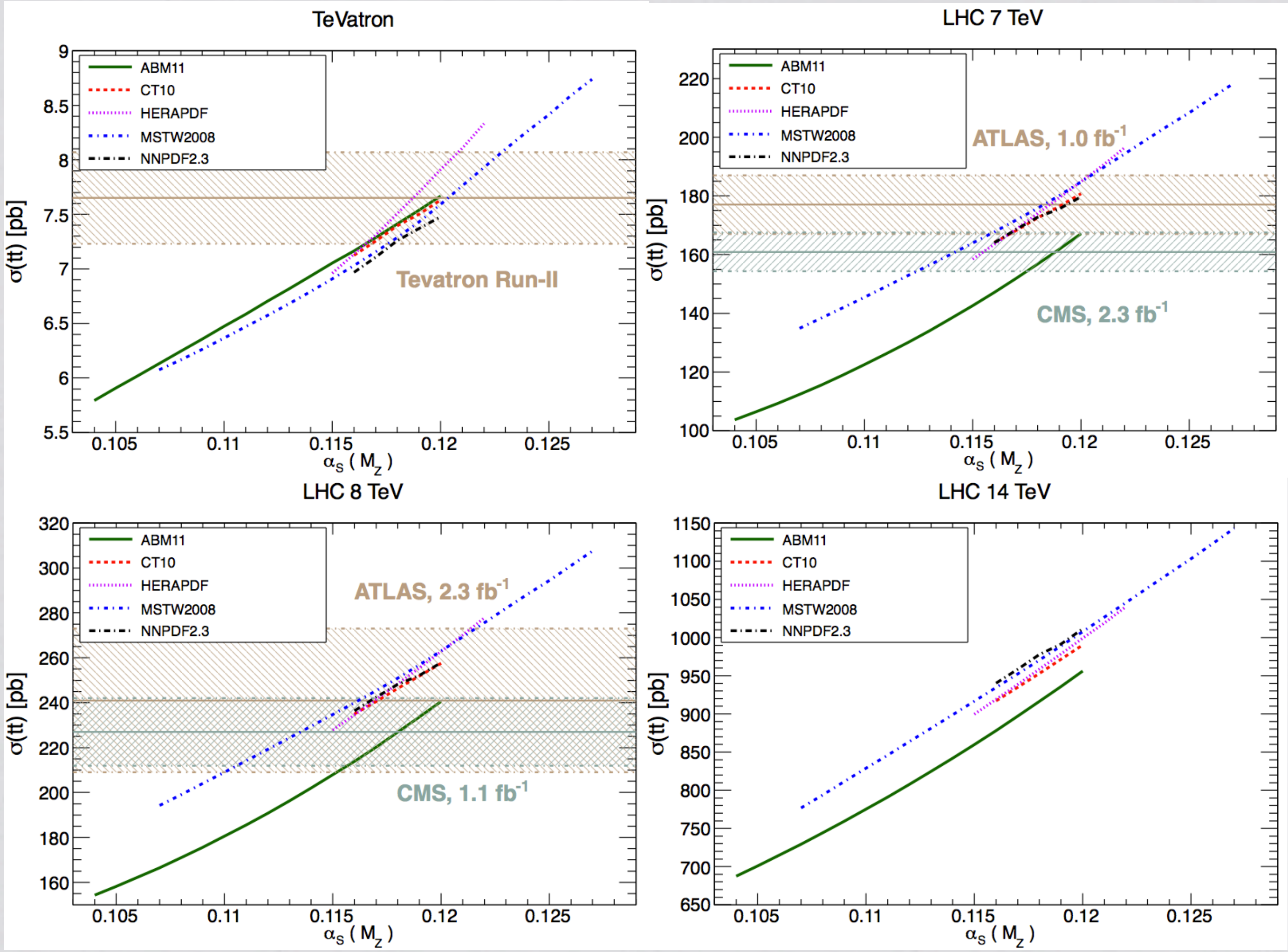
Best predictions obtained by combining NNLO+NNLL

✓ comparison to data

✓ dependence on α_s

$\delta\alpha_s = 0.001$ means $\delta\sigma$

- 0.13 pb [TEV]
- 4 pb [LHC7]
- 6 pb [LHC8]
- 20 pb [LHC14]



Top pair: first phenomenology

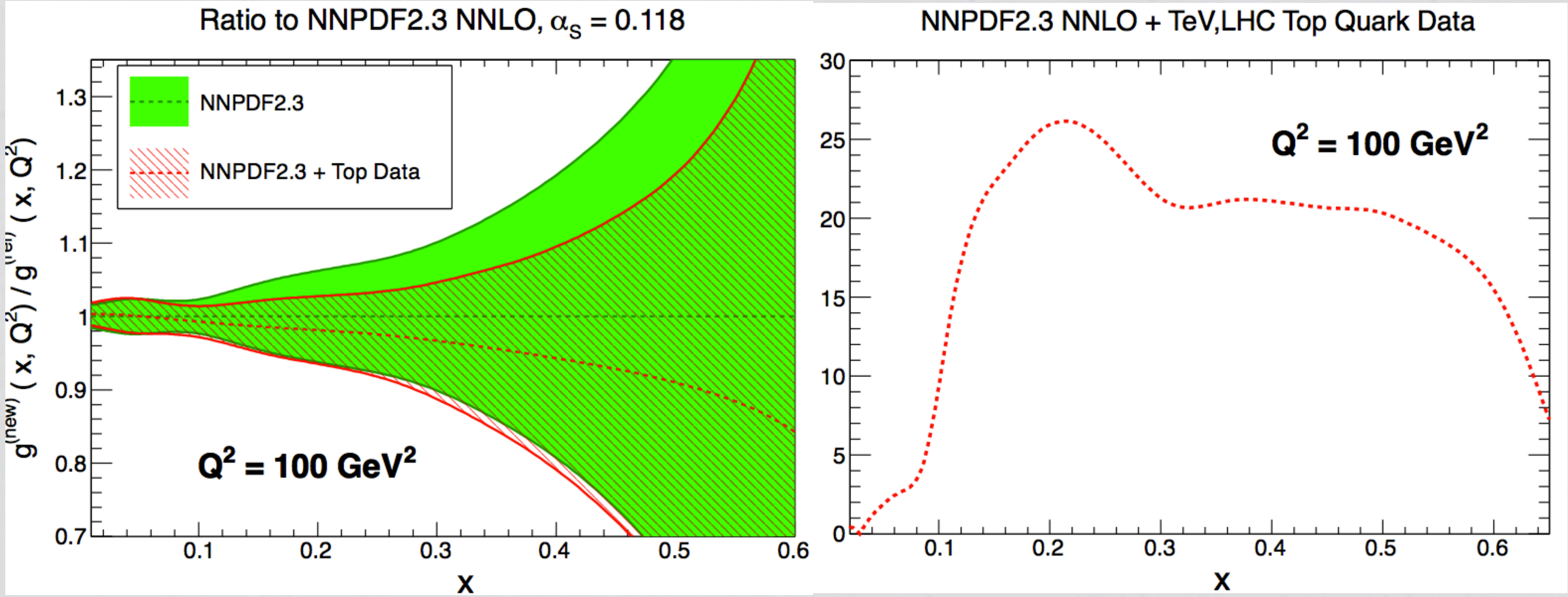
Czakon et al. 1303.7215

Best predictions obtained by combining NNLO+NNLL

✓ comparison to data

✓ dependence on α_s

✓ impact on gluon pdf



important new benchmark for pdf fits

Note: LHC data starts to be included in PDF fits

Top pair: first phenomenology

Czakon et al. 1303.7215

Best predictions obtained by combining NNLO+NNLL

✓ comparison to data

✓ dependence on α_s

✓ impact on gluon pdf

✓ constraint m_t

w.o. δm_t with δm_t

Collider	σ_{tt} (pb)	$\delta_{\mathrm{PDF+scales}+\alpha_s}$ (pb)	δ_{tot} (pb)
Tevatron	7.258	$^{+0.267}_{-0.352}$ $\left(^{+3.7\%}_{-4.9\%}\right)$	$^{+0.390}_{-0.469}$ $\left(^{+5.4\%}_{-6.5\%}\right)$
LHC 7 TeV	172.7	$^{+10.4}_{-11.8}$ $\left(^{+6.0\%}_{-6.8\%}\right)$	$^{+12.5}_{-13.7}$ $\left(^{+7.2\%}_{-8.0\%}\right)$
LHC 8 TeV	248.1	$^{+14.0}_{-16.2}$ $\left(^{+5.6\%}_{-6.5\%}\right)$	$^{+17.1}_{-19.1}$ $\left(^{+6.9\%}_{-7.7\%}\right)$
LHC 14 TeV	977.5	$^{+44.1}_{-55.8}$ $\left(^{+4.5\%}_{-5.7\%}\right)$	$^{+57.4}_{-68.5}$ $\left(^{+5.9\%}_{-7.0\%}\right)$

Rule of thumb: at the LHC

δm_t = 1 GeV $\Rightarrow$ $\delta\sigma/\sigma$ = 1-1.5%

Note: LHC data starts to be included in PDF fits

Top pair: first phenomenology

Czakon et al. 1303.7215

Best predictions obtained by combining NNLO+NNLL

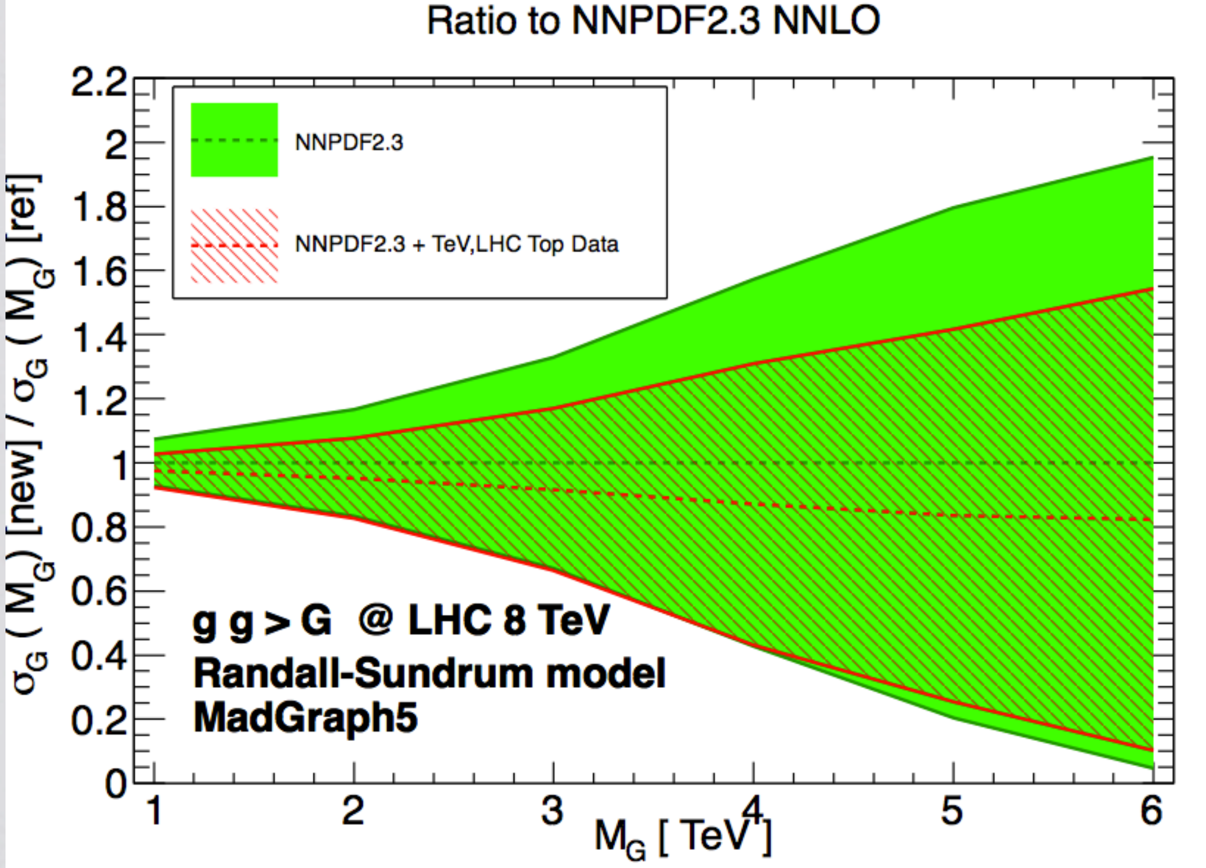
✓ comparison to data

✓ dependence on α_s

✓ impact on gluon pdf

✓ constraint m_t

✓ impact on BSM



Note: LHC data starts to be included in PDF fits

NNLO: open questions ...

What is the pattern that emerges at NNLO?

➡ NNLO seems often outside the NLO band

➡ NNLO corrections large

Is something missing? Should we change how we estimate theory uncertainties?

To remember: the use of scale variation to asses theory uncertainties has serious limitations (e.g. it does not work in conformal invariant theories, it has no value in QED where photon polarization effects can be resummed exactly ...). In QCD it often works well in practice and it is simple (when it fails we often know why). That is why it has become a standard, at LO and NLO

Completion of partial calculations and new calculations in the next few years will help gain more experience and a better theoretical understanding at NNLO.Useful insights also from analytic resummations

Beyond NNLO for H

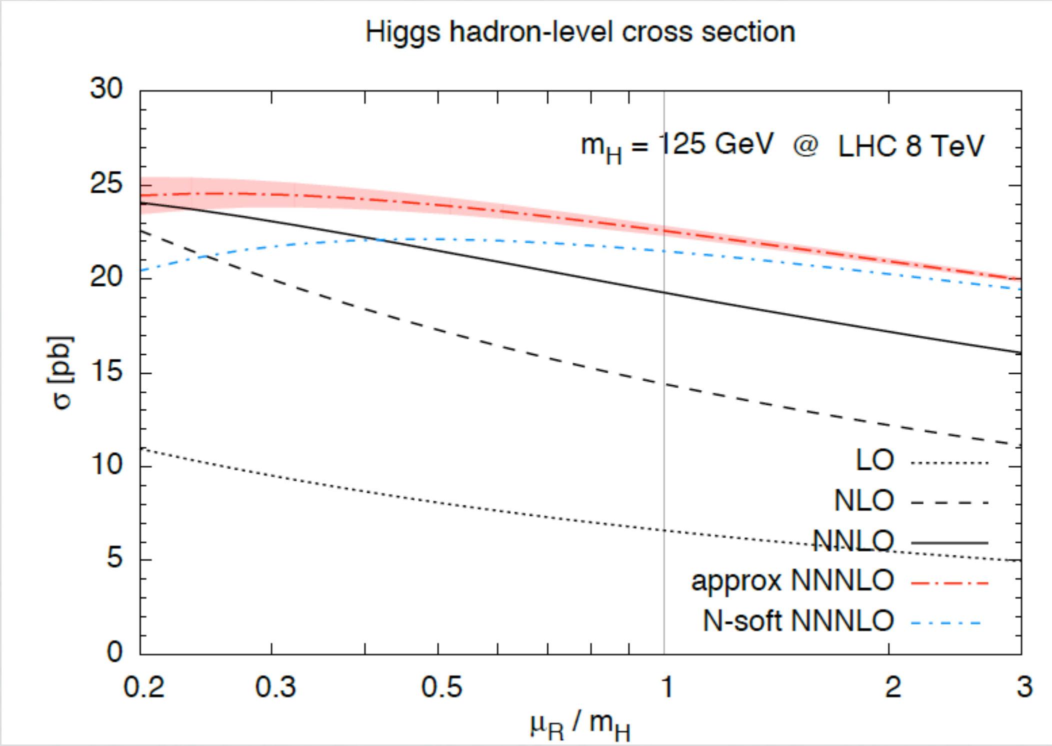
State of the art for Higgs transverse momentum distributions: NNLO +NNLL. Still residual theoretical uncertainty > 7-8%. Effort to go beyond

- expansion around threshold limit. Pioneering work towards first N^3LO

Anastasiou et al. 1302.4379

- approx N^3LO (from soft and high-energy resummation)

Ball et al. 1303.3590



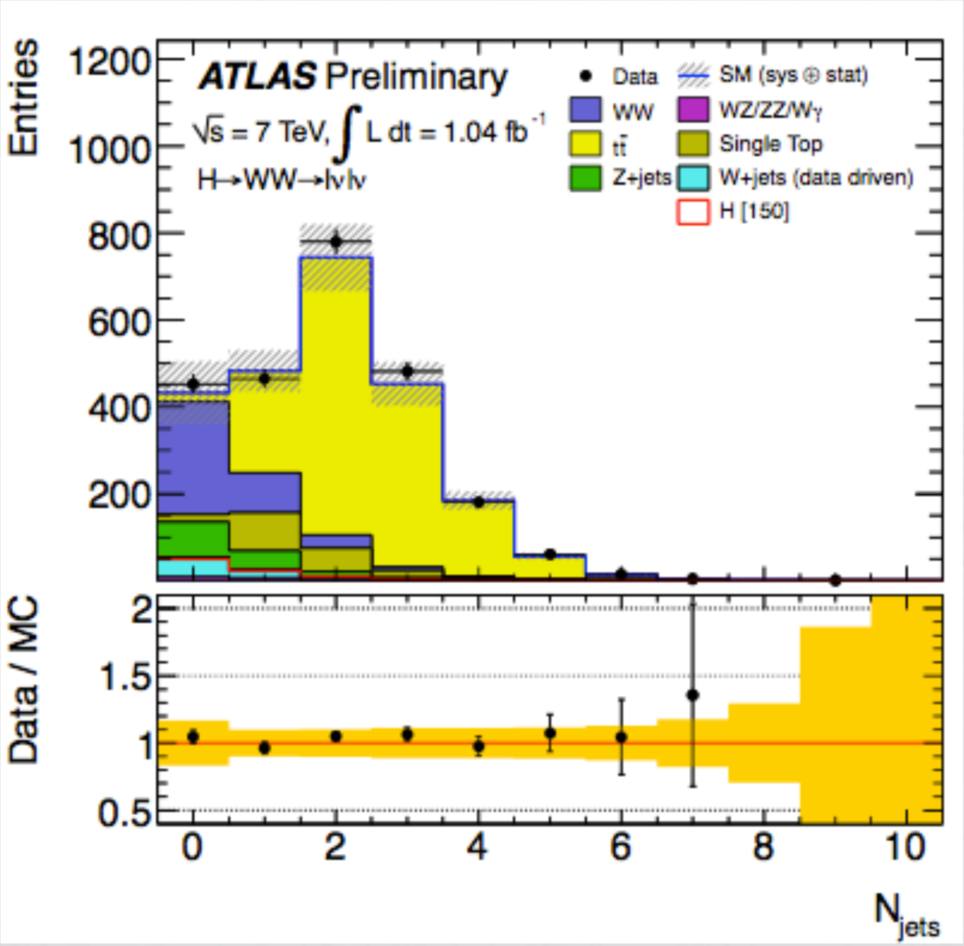
- approx N^3LO: sizable correction about 17% at M_H, beyond uncertainty band or about 7-8% at $M_H/2$, within uncertainty band
- overall reduction of uncertainty

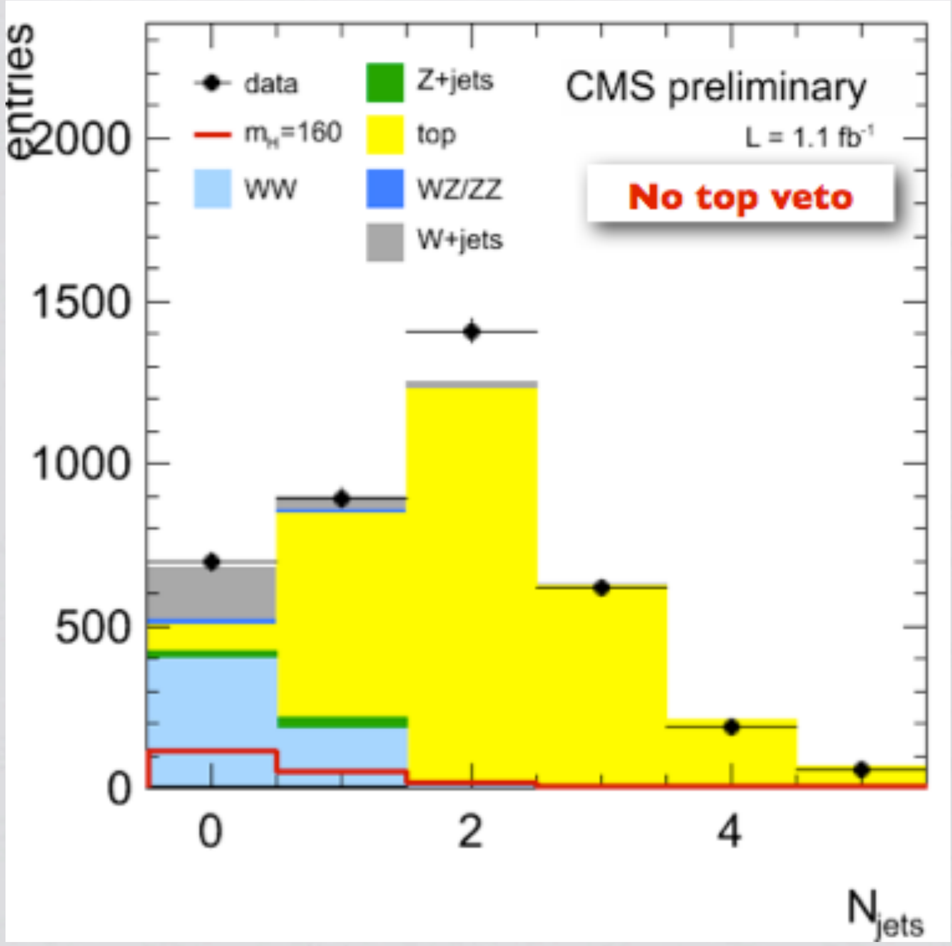
Beyond NNLO

When even NNLO is not enough … the example of the jet-veto

ATLAS/CMS study Higgs contributions in distinct jet-bins to optimize S/B.

0-jet bin prominent role: dominant signal and reduced top-background

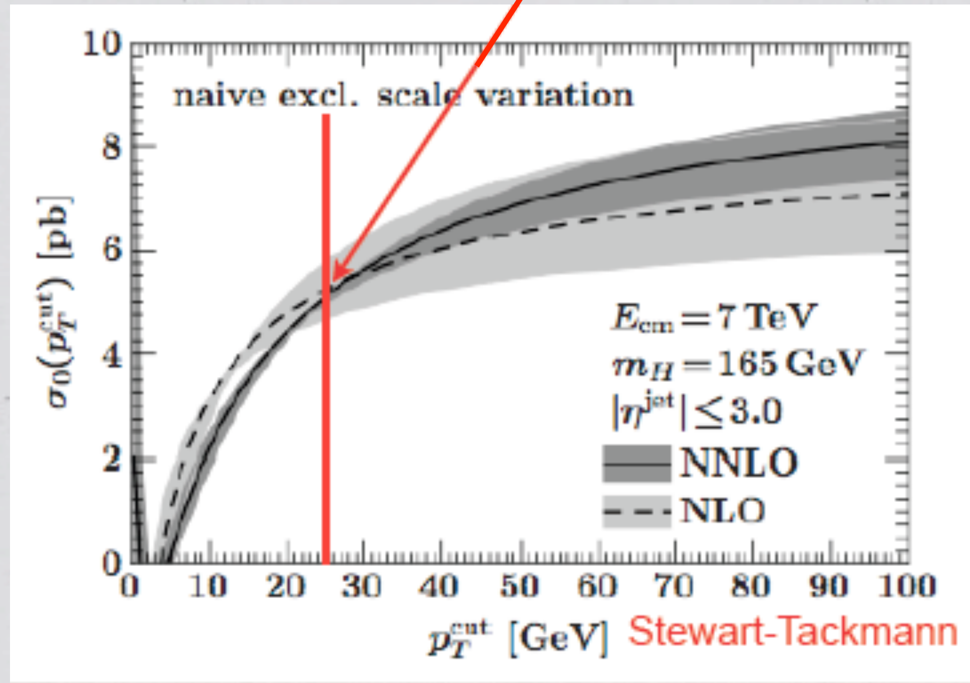




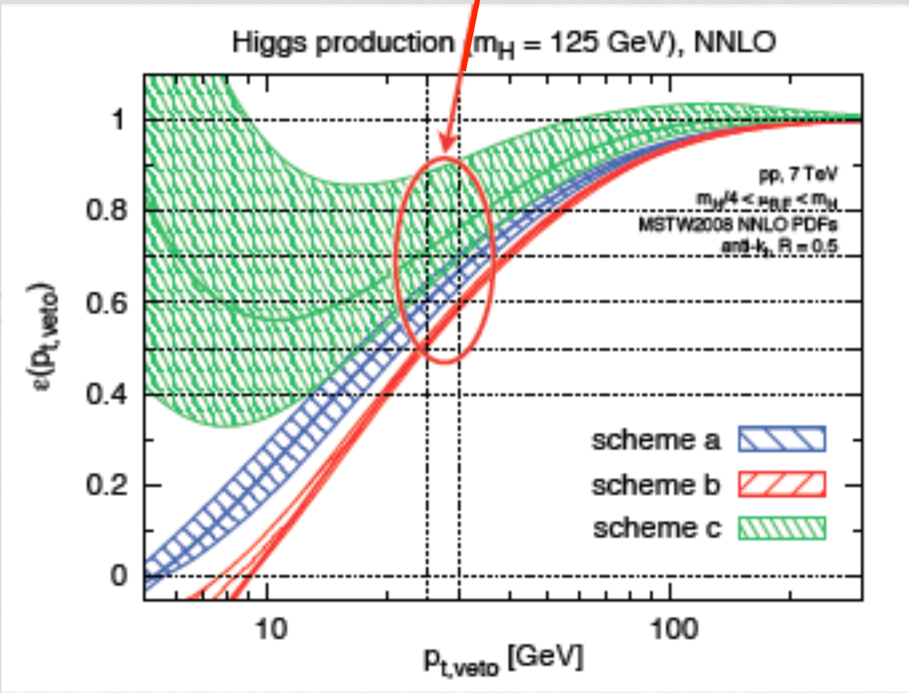
Beyond NNLO

But predictions for vetoed cross-sections difficult. Two ways to look at the problem:

cross-section uncertainty vanishes



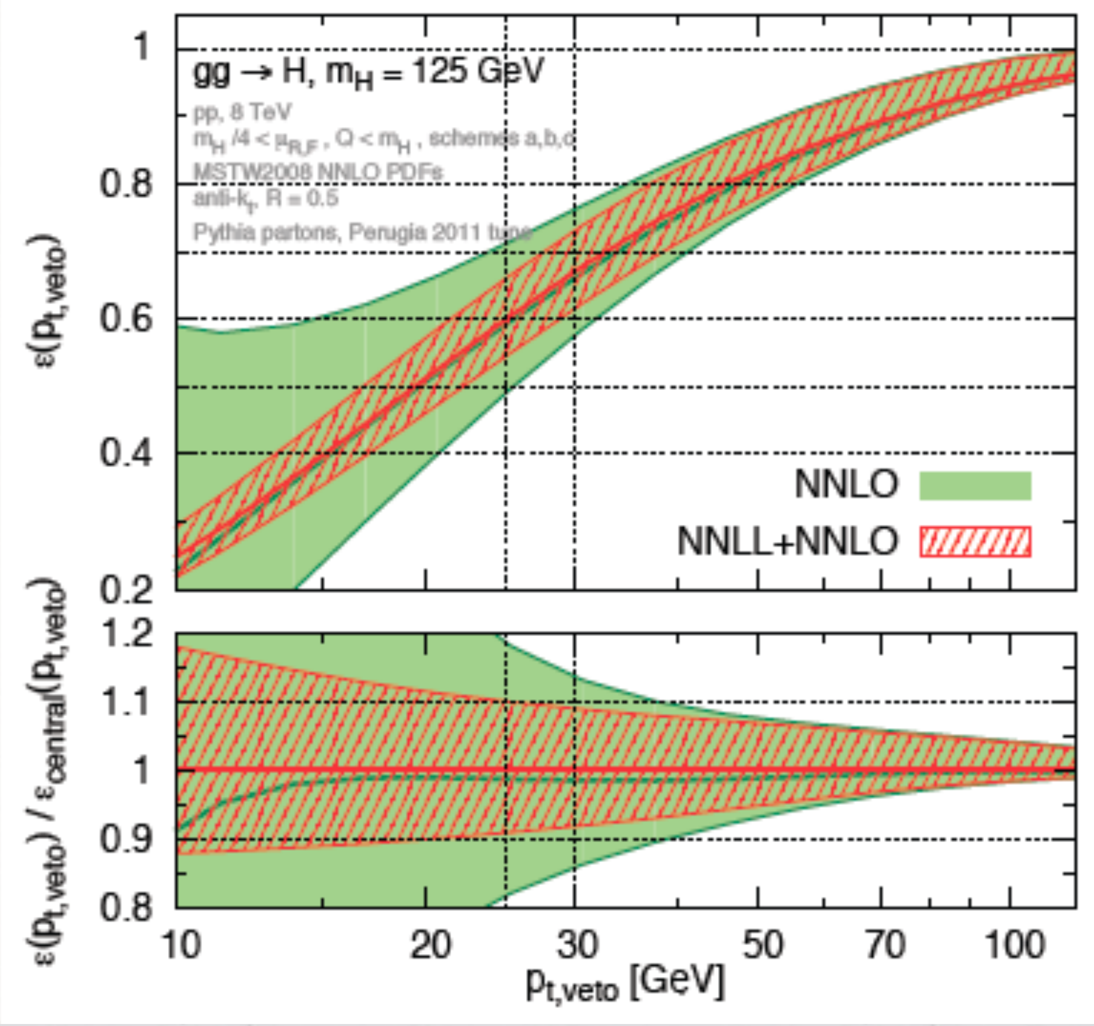
efficiency blows up



Reduction of theory uncertainty possible via a NNLL resummation of large logarithms of $p_{t,veto}/M_H$.

Jet veto at NNLO+NNLL

Banfi et al. 1206.4998; also Becher&Neubert 1205.3806; Tackmann, Walsh, Zuberi in preparation



- Reduction of theory uncertainty at NNLL+NNLO
- Further reduction of uncertainty possible with larger jet-radius
- Resummation for H+1jet also interesting

Liu&Petriello 1210.1906

NNLO+parton shower

Progress in NLO calculations went hand in hand with the development of NLO combined with parton shower corrections in tools like

MC@NLO (➠ aMC@NLO), POWHEG (➠ POWHEG BOX) or Sherpa

Best of both worlds: combine precision of NLO with realistic events that can be processed through detector simulations

These tools are essential for most ATLAS/CMS studies

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What about NNLO+PS ?

At the moment various NNLO results appeared but NO NNLO+PS

First ideas towards NNLO+PS (but no practical implementation yet)

Hamilton et al. 1212.4504

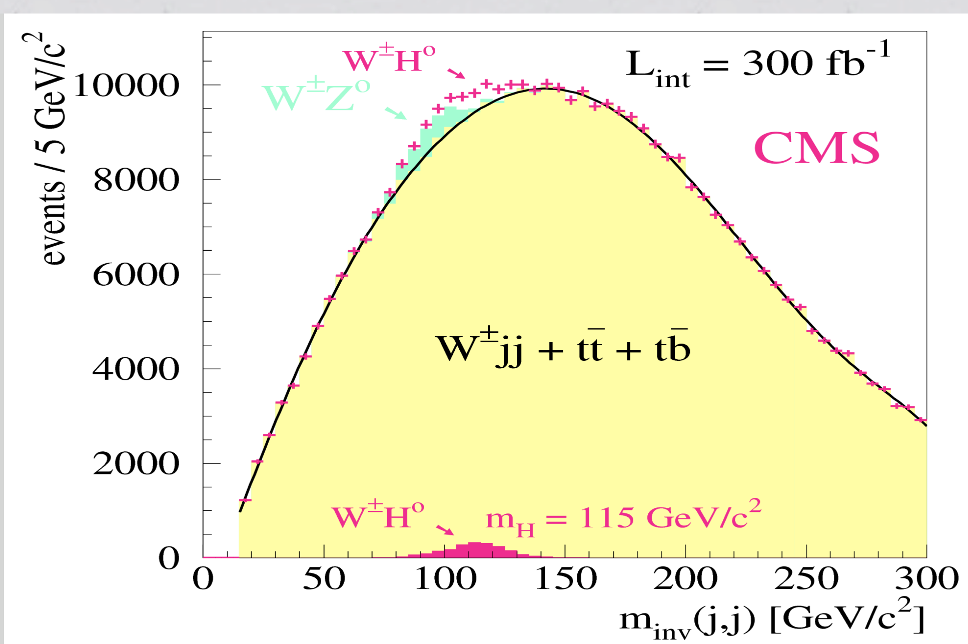
A novel field

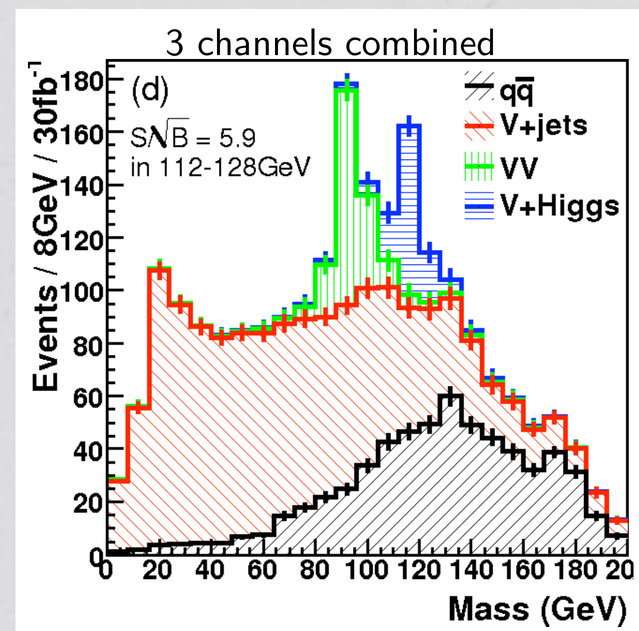
Pioneering work: jet-substructure in WW scattering

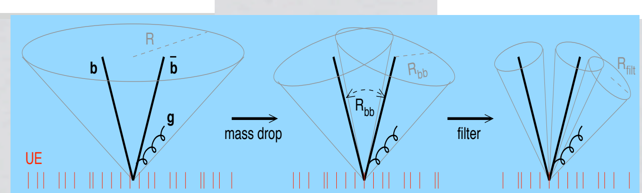
Butterworth et al. hep-ph/0201098

A lot of activity since '08 (focus on development of infrared-safe jet-algorithms, SISCone + anti-k_t born, jet-area for pile-up subtraction, quality measures ...)

The poster boy: associated WH with $H \rightarrow bb$ as a new Higgs search channel







Butterworth et al. 0802.2470

Jet substructure today

Very active field today

- many processes reanalyzed using boosted kinematics + jet substructure
- even new nomenclature [filtering, trimming, pruning, mass tagger …]
- regular conferences/writeups, e.g. 1012.5412, 1201.0008, …

Overall situation:

many "difficult" processes like VH, ttH, … can be rescued with

- boosted cuts ($\Rightarrow$ fat jets)
- jet algorithms tuned to find the structure one is looking for

i.e. if you know the mass and the decay mode, it is "easy" to design an optimal search strategy. Of course, blind searches are more difficult

ttH without jet substructure

With boosted technique throw away more than 99% of data. Is this really the best one can do ? It does sort of seem unnatural ...

ttH without jet substructure

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One alternative: Matrix Element Method (MEM), i.e. assign probabilities to competing hypothesis (e.g. B vs S+B) given a sample of events using a weight given by the matrix element for each event

ttH without jet substructure

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Per se simple approach, but lots of challenges when dealing with complex final states (combinatorics, complicated backgrounds ...)

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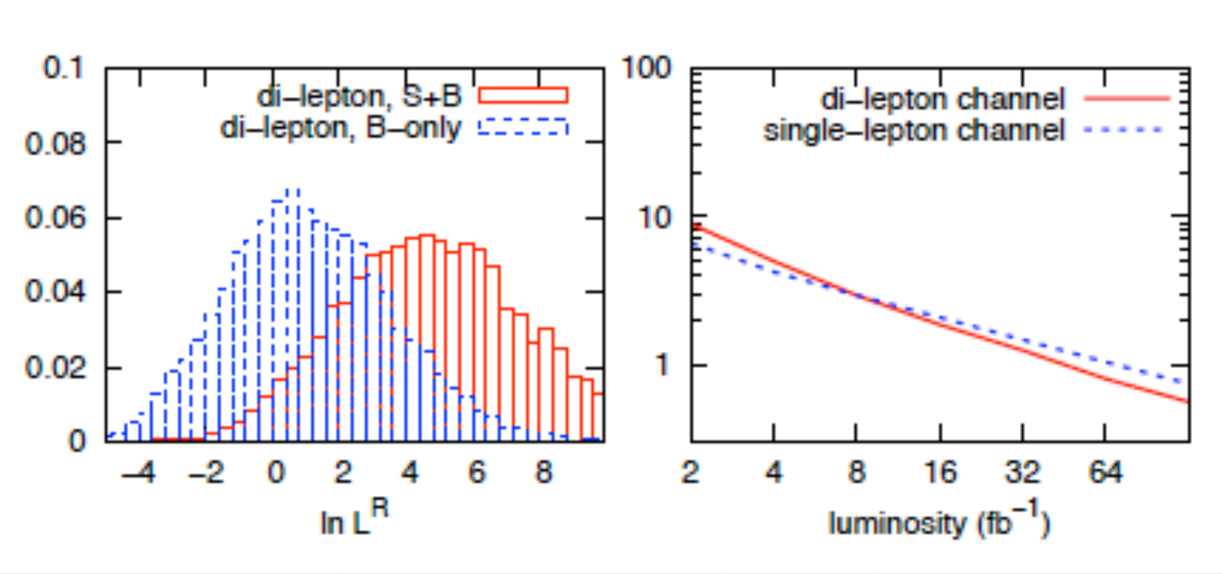
Per se simple approach, but lots of challenges when dealing with complex final states (combinatorics, complicated backgrounds ...)

Applied to a complicated process only recently. Promising results.

Artoisenet et al. 1304.6414



ttH without jet substructure

With boosted technique throw away more than 99% of data. Is this really the best one can do ? It does sort of seem unnatural ...

One alternative: Matrix Element Method (MEM), i.e. assign probabilities to competing hypothesis (e.g. B vs S+B) given a sample of events using a weight given by the matrix element for each event

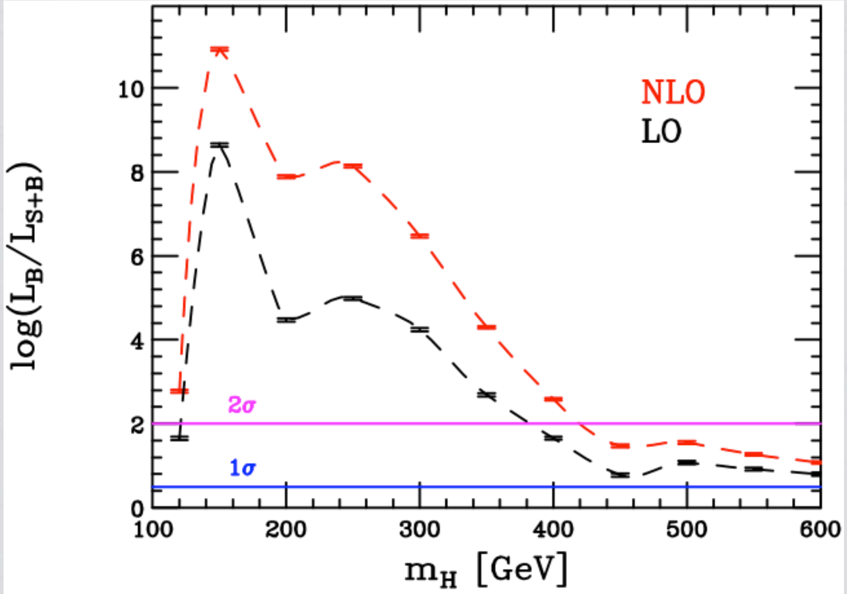
Per se simple approach, but lots of challenges when dealing with complex final states (combinatorics, complicated backgrounds ...)

Applied to a complicated process only recently. Promising results.

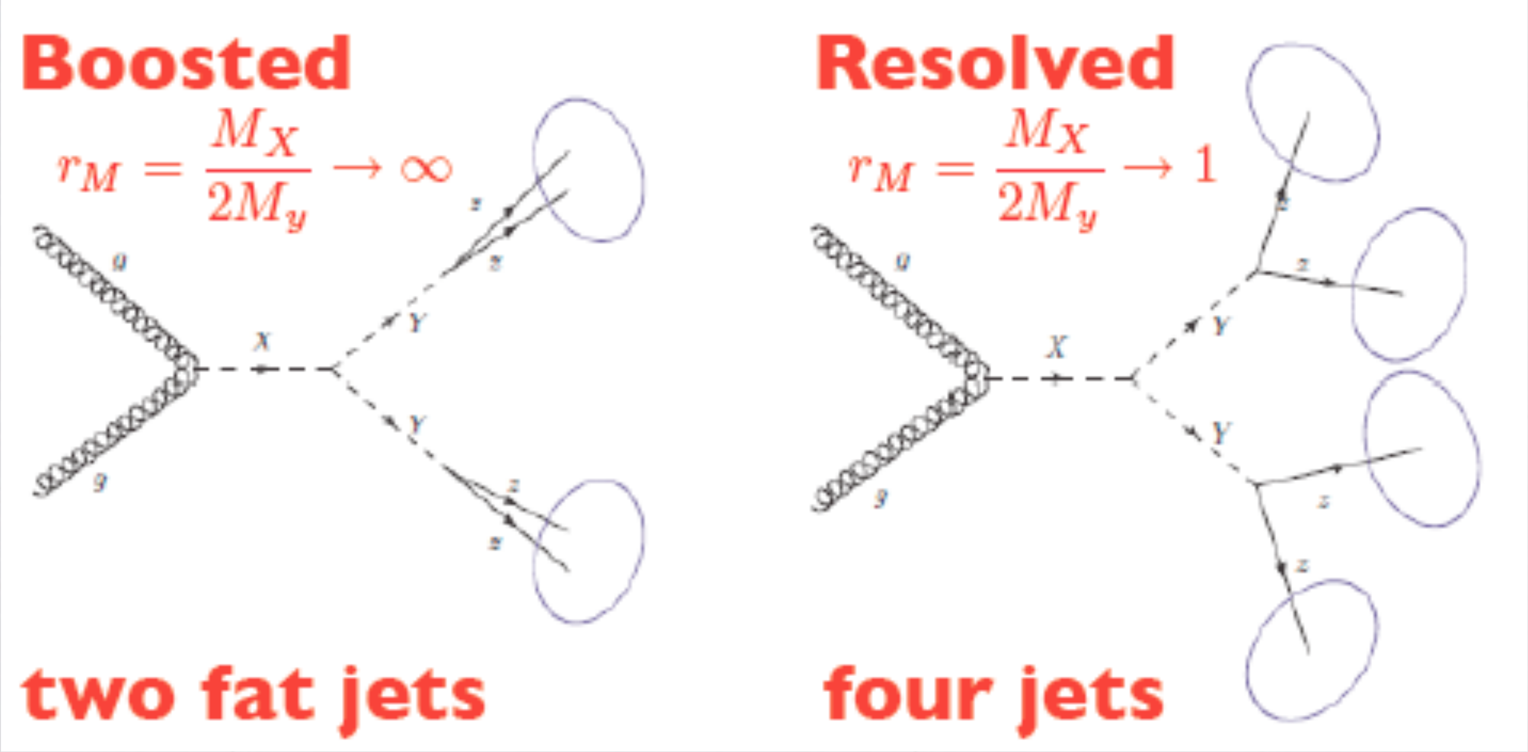
Artoisenet et al. 1304.6414

Also possible at NLO

see e.g. Campbell et al. 1204.4424 & 1301.7086



News in jet substructure

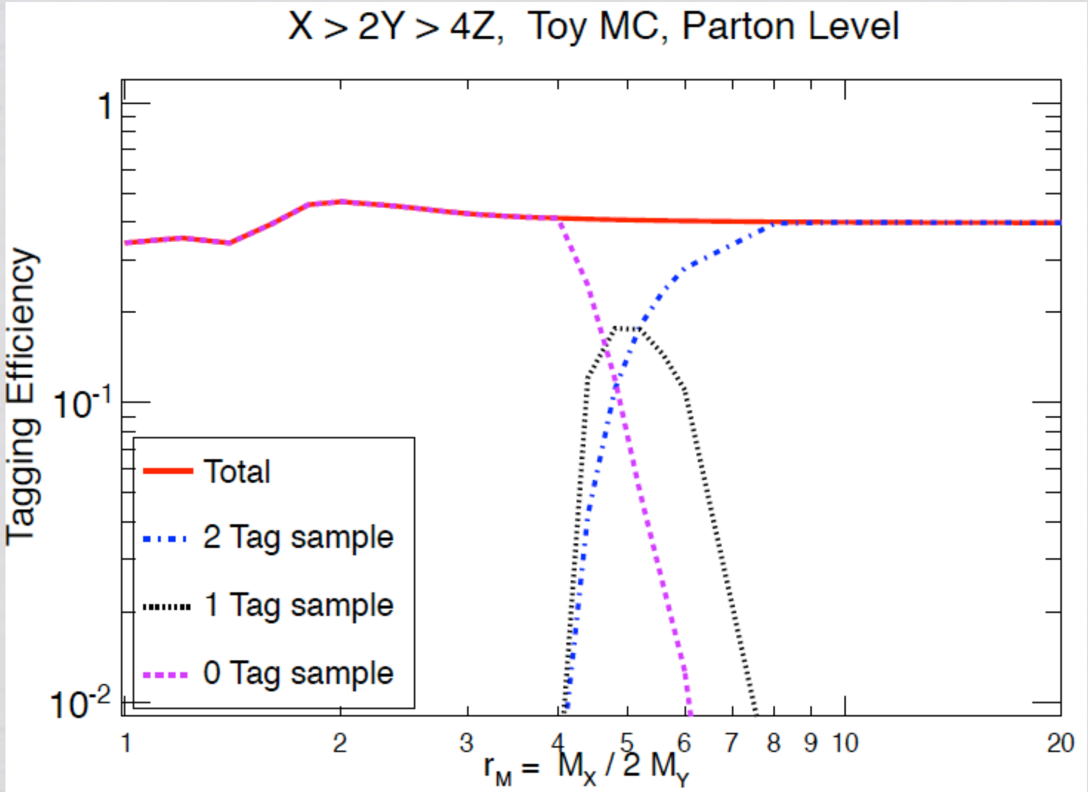


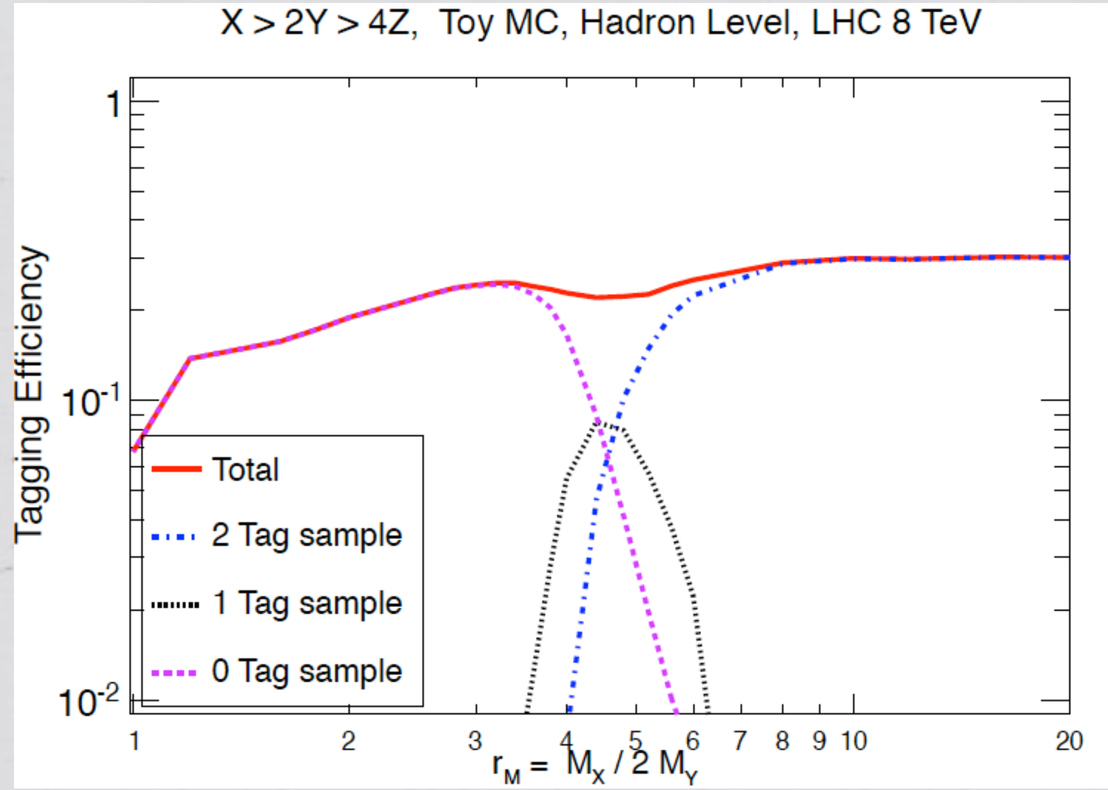
Different r_M benefit from different search strategies, but r_M not known a priori

Use a combined strategy that simultaneously explores all regimes. Idea is to exploit the fact that one knows at least the topology of what one is looking for

Gouvevitch et al. 1303.6636

News in jet substructure





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Gouvevitzh et al. 1303.6636

Conclusions

Recent tremendous progress in higher order calculations

- NLO: two goals achieved
  - automation
  - more legs
- NNLO for more generic processes is the new frontier
  - many new results for 2 to 2 (some to be completed), more to come soon
  - lots of lessons learnt at NLO, not much experience yet at NNLO
  - more results + better theoretical understanding will guide us further
- use insight from higher order calculations also to find better ways to look at data (MEM methods, better jet algorithms, boosted methods ...)

Concrete, successful effort to fulfill the needs of our experimental friends