Standard Model Theory

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Plan

I will highlight here a few broad directions with substantial recent progress but still in need for improvements
(NB: this is a personal selection, not an exhaustive list)

The keyword: precision

Why do we care about precise theoretical predictions?

Precision theory

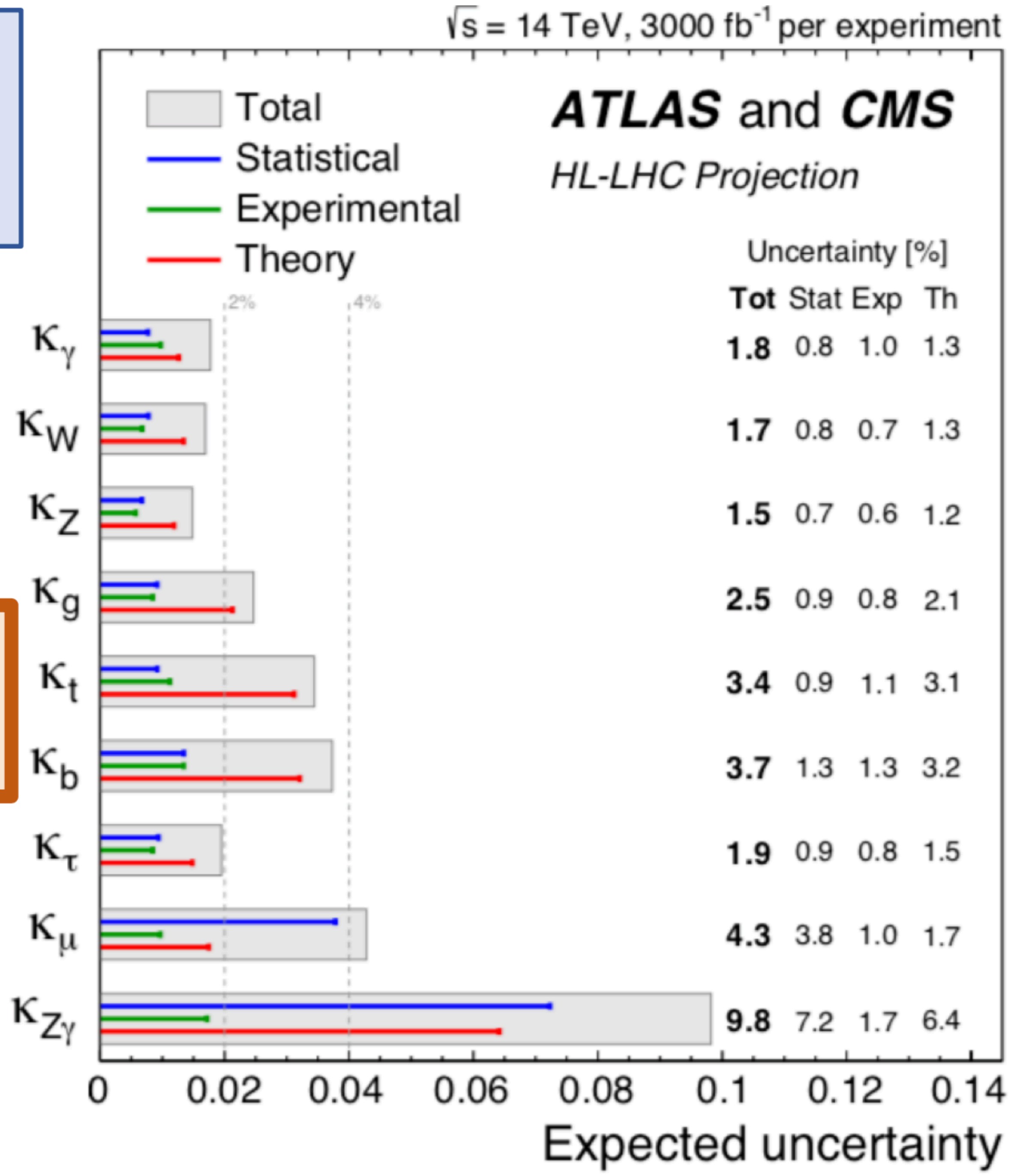
- LHC already collected around 150 fb^{-1} at 13 TeV. No major energy increase foreseen in the next 20 years
- Up to now, collected **only 5%** of the full expected dataset (3 ab^{-1})
- The reach of many precision tests will increase considerably
- Processes with a tiny cross section will benefit incredibly from the increase in luminosity + expect improvements in search techniques that are background limited
- Possible discoveries at the LHC might be indirect ones
  ⇒ precision as tool for indirect discoveries

Given the detailed projections from the experiments substantial further progress will be needed from theory calculations if these are not to become a limiting factor in interpreting a wide range of High-Luminosity LHC (HL-LHC) data

One example (out of many)

Higgs couplings after HL-LHC

Largest contribution to the uncertainty from theory

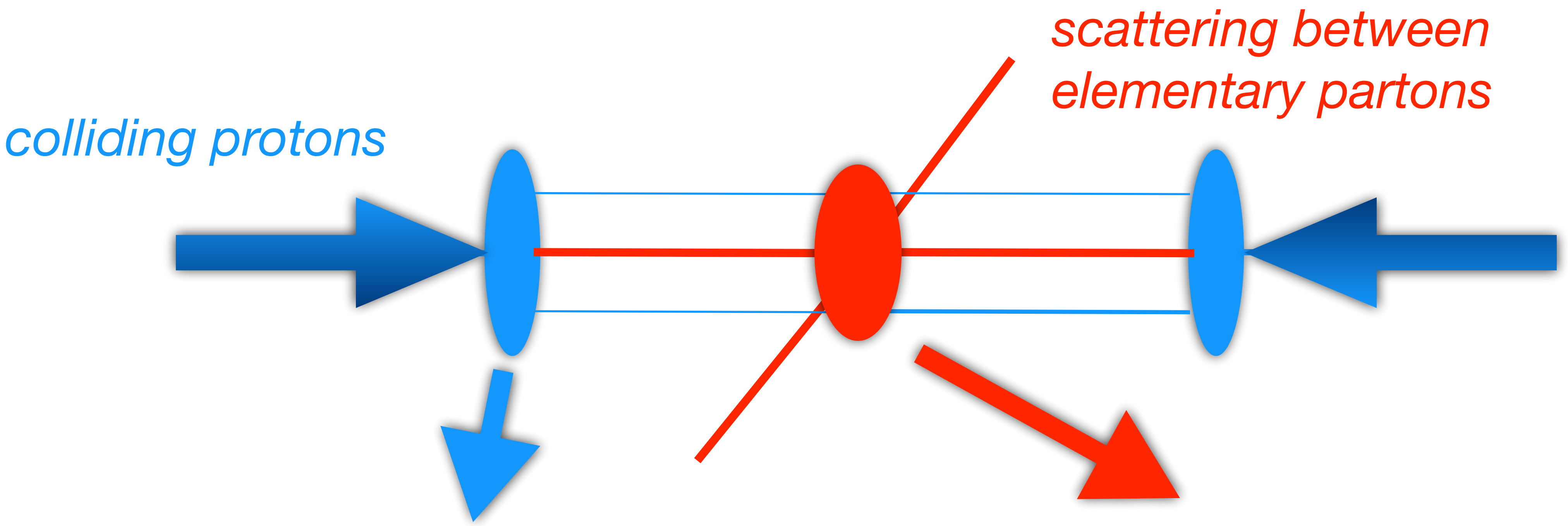


Uncertainty [%]

	Tot	Stat	Exp	Th
κ_γ	**1.8**	0.8	1.0	1.3
κ_W	**1.7**	0.8	0.7	1.3
κ_Z	**1.5**	0.7	0.6	1.2
κ_g	**2.5**	0.9	0.8	2.1
κ_t	**3.4**	0.9	1.1	3.1
κ_b	**3.7**	1.3	1.3	3.2
κ_τ	**1.9**	0.9	0.8	1.5
κ_μ	**4.3**	3.8	1.0	1.7
$\kappa_{Z\gamma}$	**9.8**	7.2	1.7	6.4

⇒ see talk by H. Abramowicz

Precision through perturbation



colliding protons

scattering between elementary partons

Parton distribution functions (PDFs): extracted from data at one scale, evolution is perturbative

Perturbative cross section: Expansion in the coupling constant (LO, NLO, NNLO ...)

$$\frac{d\sigma_{\text{pp}\to\text{hadrons}}}{dX} = \sum_{a,b}\int dx_1 dx_2 f_a(x_1,\mu_F) f_b(x_2,\mu_F) \times \frac{d\hat{\sigma}_{\text{ab}\to\text{partons}}(\alpha_s(\mu_R),\mu_R,\mu_F)}{dX} + \mathcal{O}\left(\frac{\Lambda^n_{\text{QCD}}}{Q^n}\right)$$

Perturbation in a nutshell

Leading order (LO):

adapted from M. Wiesemann

Perturbation in a nutshell

Leading order (LO):

Next-to-Leading order (NLO):

adapted from M. Wiesemann

Perturbation in a nutshell

Leading order (LO):

Next-to-Leading order (NLO):

NNLO:

adapted from M. Wiesemann

Perturbation in a nutshell

Leading order (LO):

Next-to-Leading order (NLO):

NNLO:

…

All-orders?

adapted from M. Wiesemann

Perturbation in a nutshell

Leading order (LO):

Next-to-Leading order (NLO):

NNLO:

Experimental data:

adapted from M. Wiesemann

Perturbation in a nutshell

Take-home messags:

1. Assessing how reliable a perturbative approximation is a very hard task. The assignment of a robust theoretical uncertainty is crucial to claim deviations
   Conventionally: renormalization/factorization scale variation around the "physical scale", look at convergence, see later
2. While perturbation theory relies on theoretical ground, decades of experience in data/theory comparison is incredibly valuable

Known at N^{3}LO

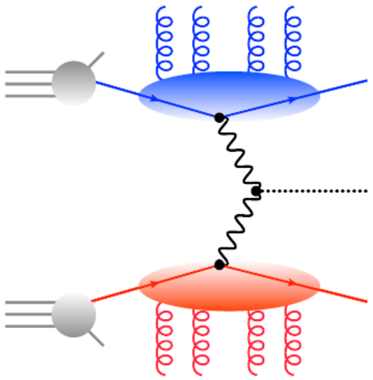
1. Inclusive Higgs production in the large-m$_t$ approximation

$$\sigma = 48.58\text{pb}^{+2.22\text{pb}(4.56\%)}_{-3.27\text{pb}(-6.72\%)}\,\text{theory} \pm 1.56\text{pb}(3.2\%)(\text{PDF} + \alpha_s)$$

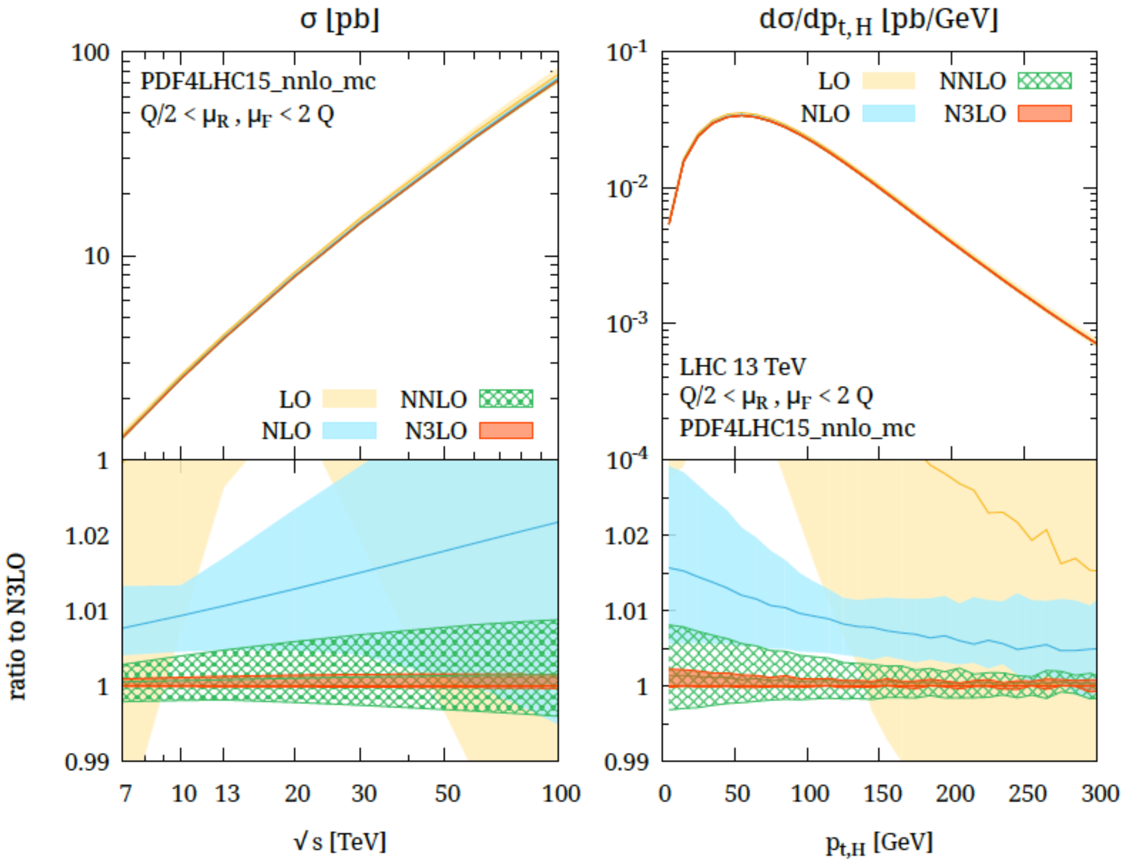
Anastasiou et al. 1602.00695
Mistlberger 1802.00833

2. Inclusive Vector Boson Fusion Higgs cross-section (DIS approx.)

Dreyer & Karlberg 1606.00840



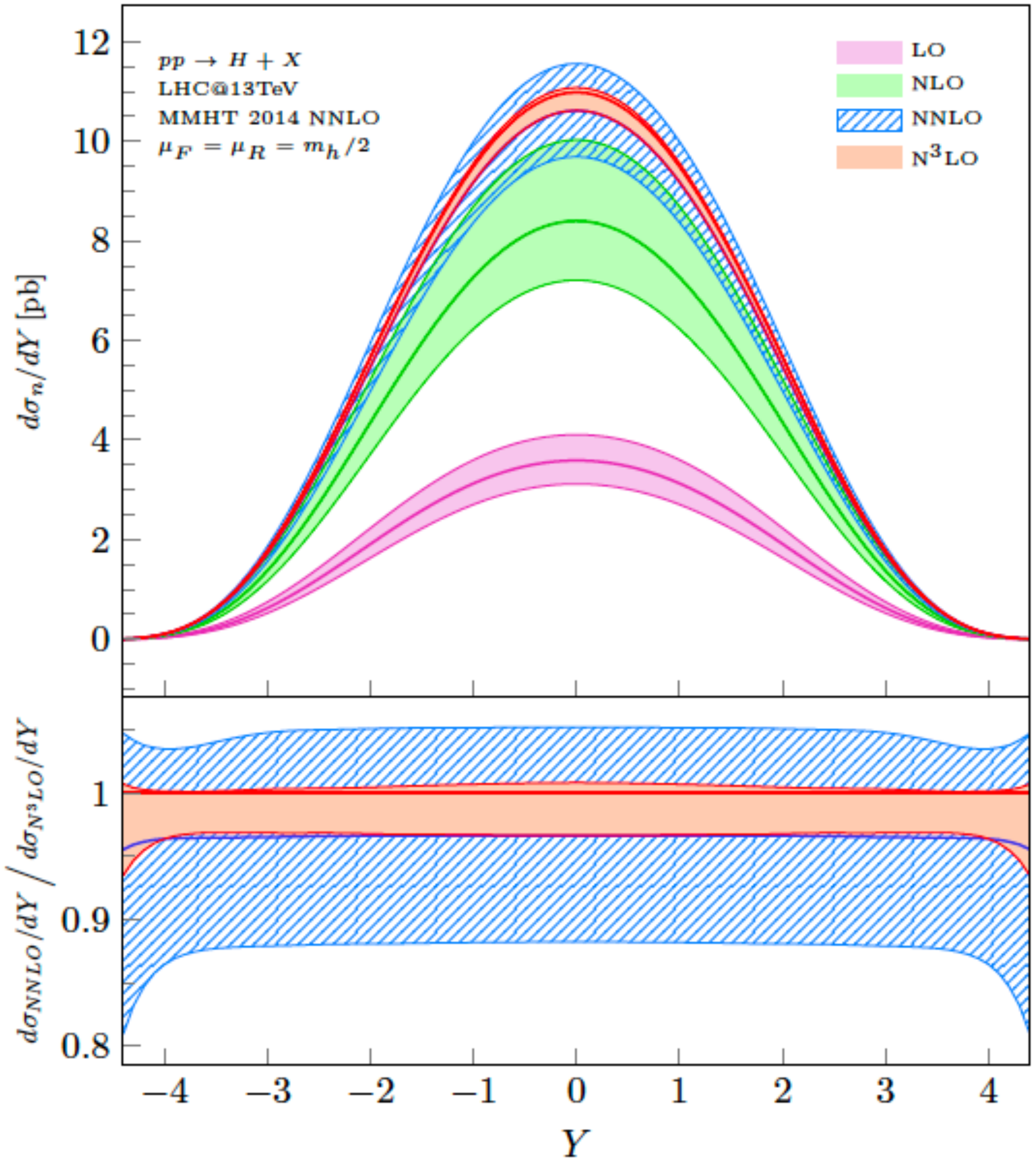
NB: NNLO non-factorizable effects sub-percent
Liu et al. 1906.10899



New at N^{3}LO

New at N^{3}LO:
Higgs rapidity (using a threshold expansion)

⇒Remarkable stability of perturbative expansion



Dulat, Mistlberger, Pelloni 1810.09462

N^3LO: future prospects?

In the two cases where N^3LO results are known, the series shows a remarkable convergence and stability:

- it will be interesting to see whether the same pattern holds for Drell-Yan production and other processes
- it will be interesting to see how stable the picture is with realistic LHC fiducial cuts

⇒ see talk by C. Duhr

Core processes at N^3LO

Experimental precision of core 2→1 and 2 → 2 processes likely to approach 1% precision over a substantial range of phase-space

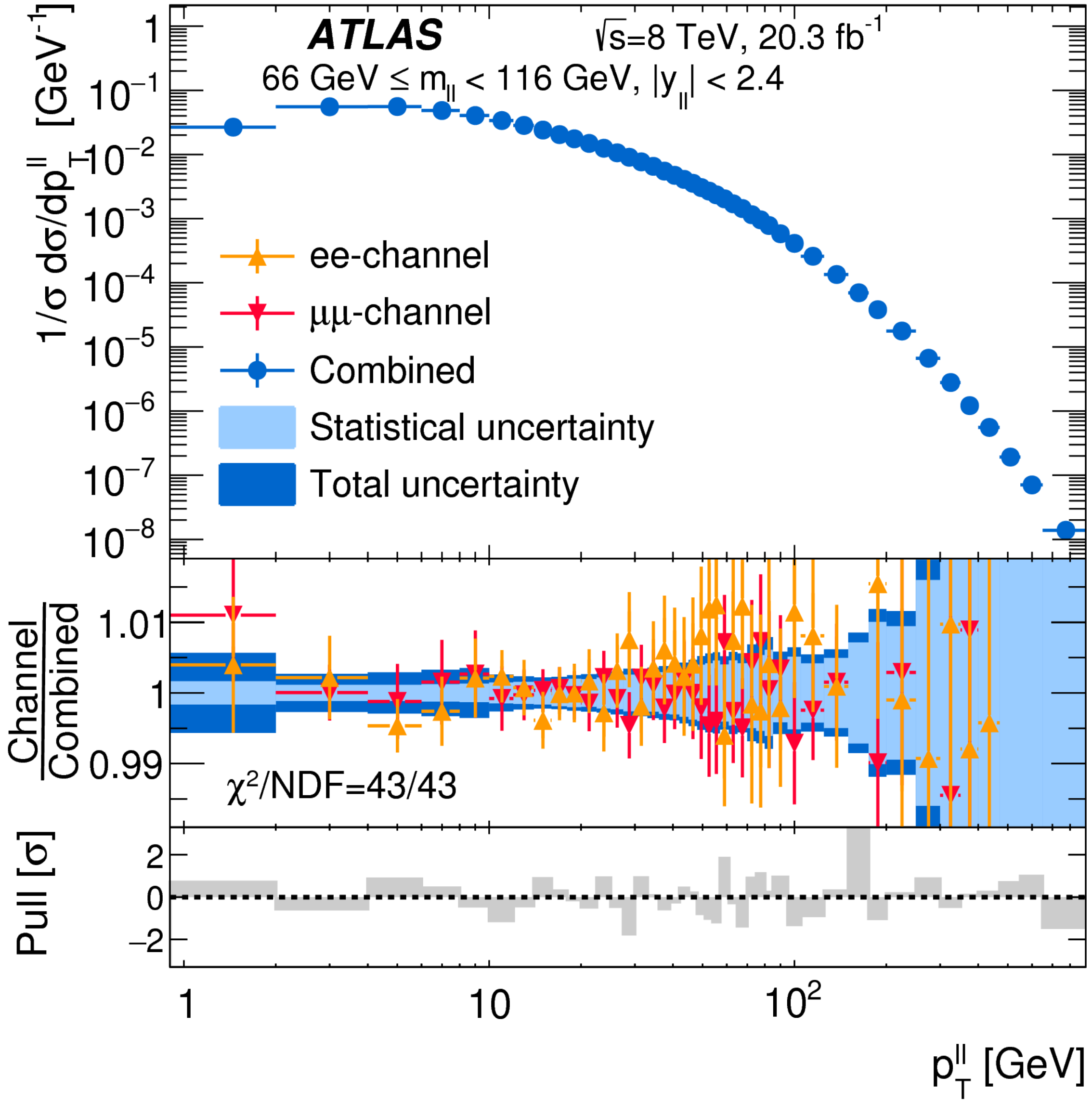
NNLO predictions do not normally reach 1% precision
⇒ strong case for seeking

N^3LO accuracy, also in the PDF extraction

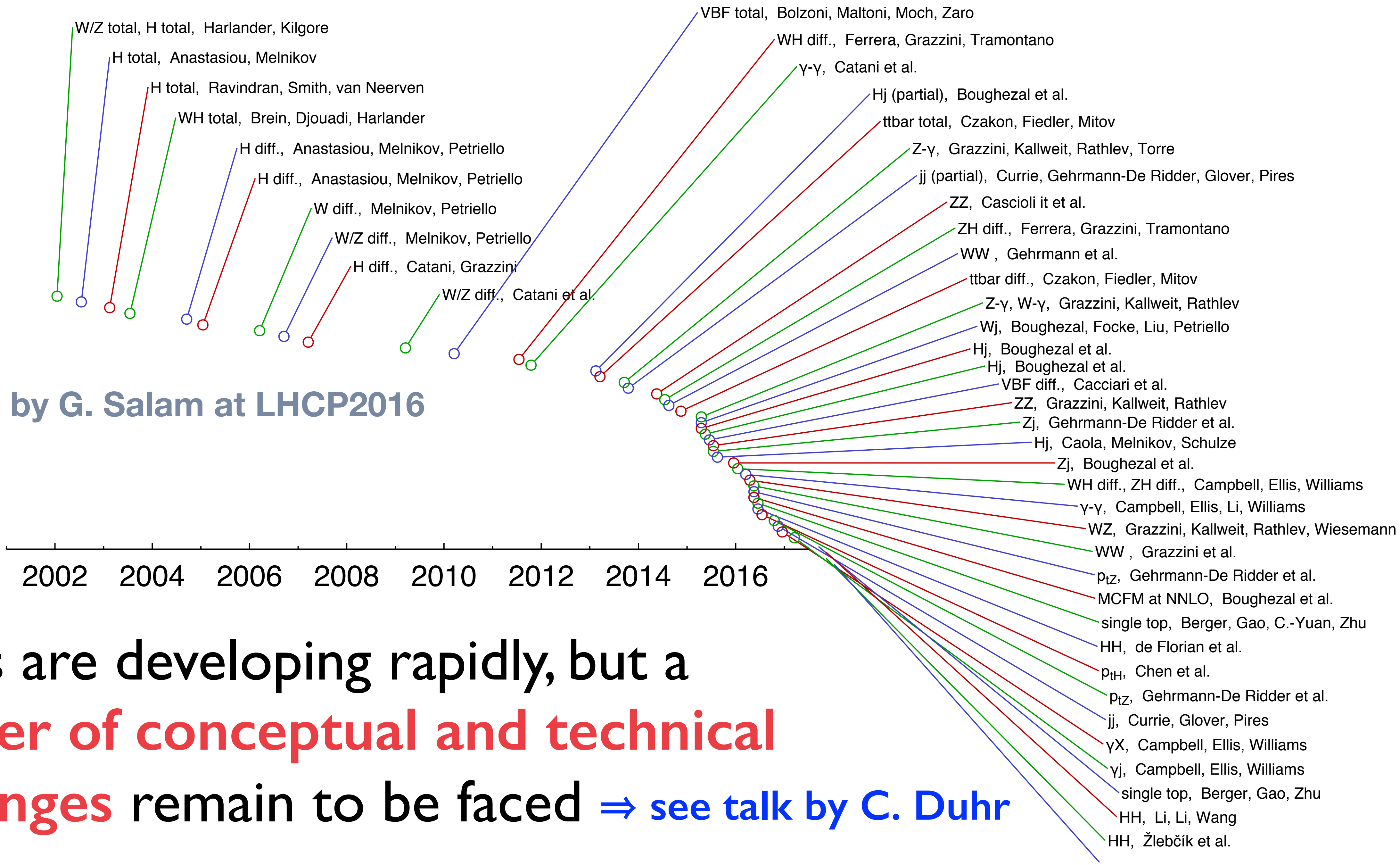
Example:

$$\sigma_Z/\sigma_{ZZ} = O(100) \quad \mathcal{L}_{\rm HL}/\mathcal{L}_{\rm RunI} = O(100)$$

⇒ permille statistical error in ZZ at HL-LHC



Status of NNLO



Talk given by G. Salam at LHCP2016

Things are developing rapidly, but a **number of conceptual and technical challenges** remain to be faced ⇒ **see talk by C. Duhr**

Status of NNLO

Talk given by G. Salam at LHCP2016

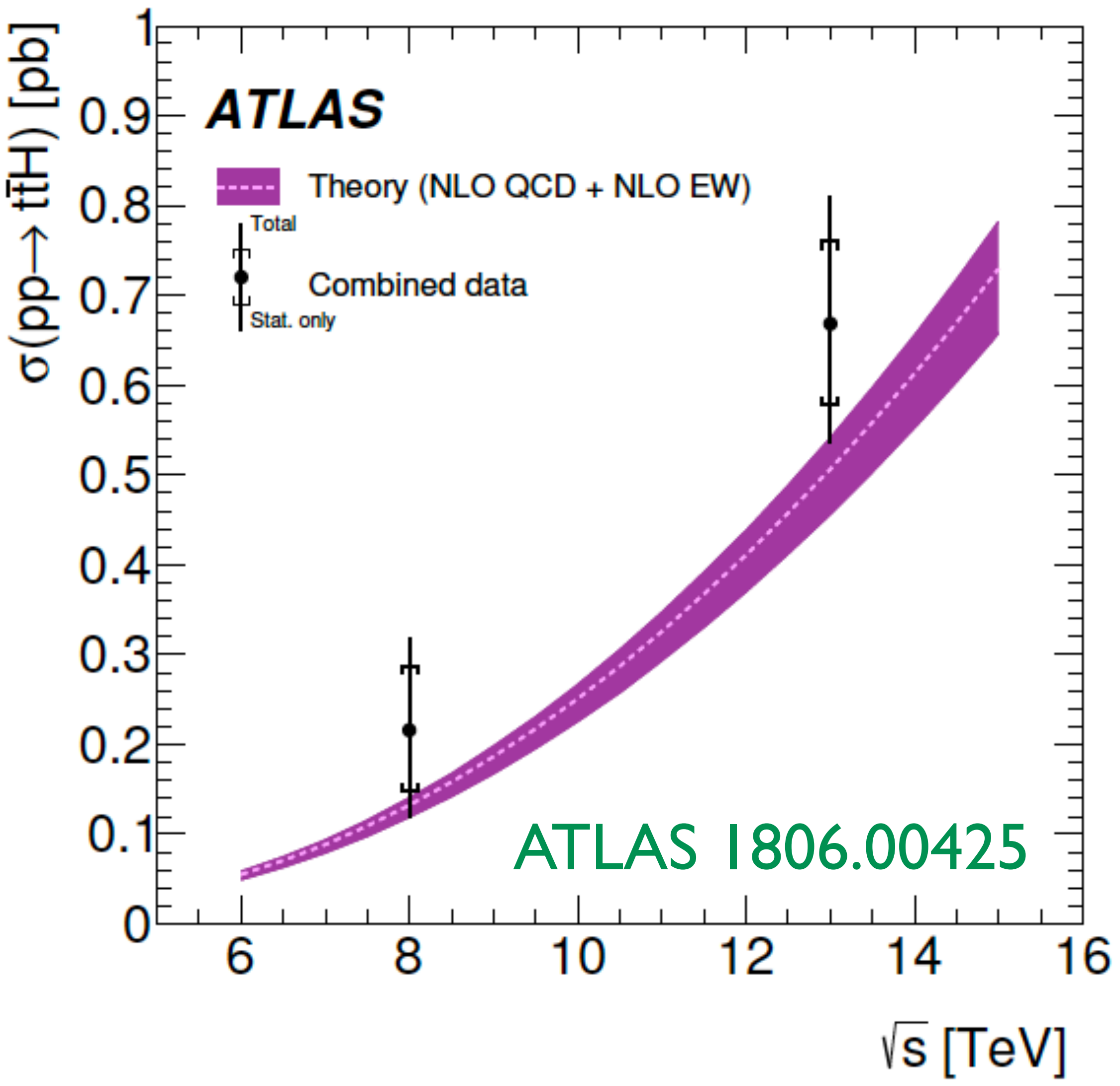
☑ Every SM 2→2 process known at NNLO

☐ No full 2→3 process known at NNLO

Things are developing rapidly, but a **number of conceptual and technical challenges** remain to be faced ⇒ **see talk by C. Duhr**

NNLO for 2→3

A number of crucial processes involving a 2→3 structure beyond today's state-of-the-art for NNLO calculations (e.g. 3-jet, ttH, ttV, H+2jets, …)



ATLAS 1806.00425

Example:
ttH expected to have 2% statistical precision at the end of the HL-LHC. Without NNLO QCD and NLO electroweak (EW) calculations such an experimental precision cannot be fully exploited

Five-particle 2-loop amplitudes

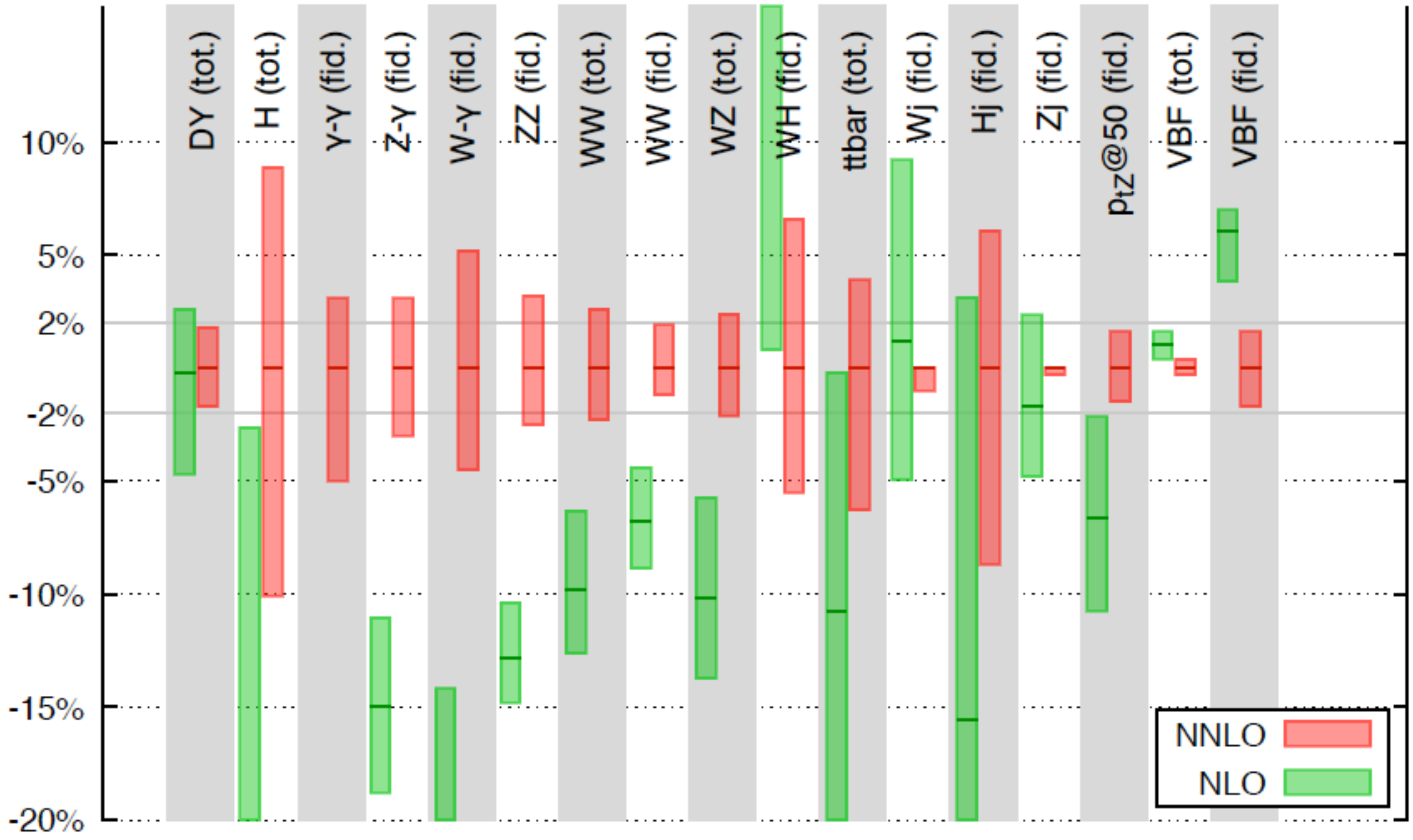
- **All QCD amplitudes in the planar limit are known analytically** [Abreu, Dormans, Febres Cordero, Ita, Page '18] Previous numerical [Badger, Brønnum-Hansen, Hartanto, Peraro '17][Abreu, Cordero, Ita, Page, Zeng '17] [Abreu, Cordero, Ita, Page, Sotnikov '18][Badger, Brønnum-Hansen, Gehrmann, Hartanto, Henn, Lo Presti, Peraro '18] and analytical results [Gehrmann, Henn, Lo Presti '15][Dunbar, Perkins '16] [Badger, Brønnum-Hansen, Hartanto, Peraro '18] in the planar approximation

- **Full-color $\mathcal{N} = 4$ super-Yang-Mills and $\mathcal{N} = 8$ supergravity amplitudes** (at symbol level) [D.C., Gehrmann, Henn, Wasser, Zhang, Zoia '18 '19][Abreu, Dixon, Herrmann, Page, Zeng '18 '19]

- **Full-color five-gluon all-plus helicity amplitude** [Badger, D.C., Gehrmann, Heinrich, Henn, Peraro, Wasser, Zhang, Zoia '19]
  $\Longrightarrow$ Very first complete analytic two-loop five-particle amplitude!

⇒ **see talk by D. Chicherin**

Does NLO scale uncertainty account for the size of NNLO?



For many processes NNLO scale band is ~±2%
But only in 3/17 cases is NNLO (central) within NLO scale band…

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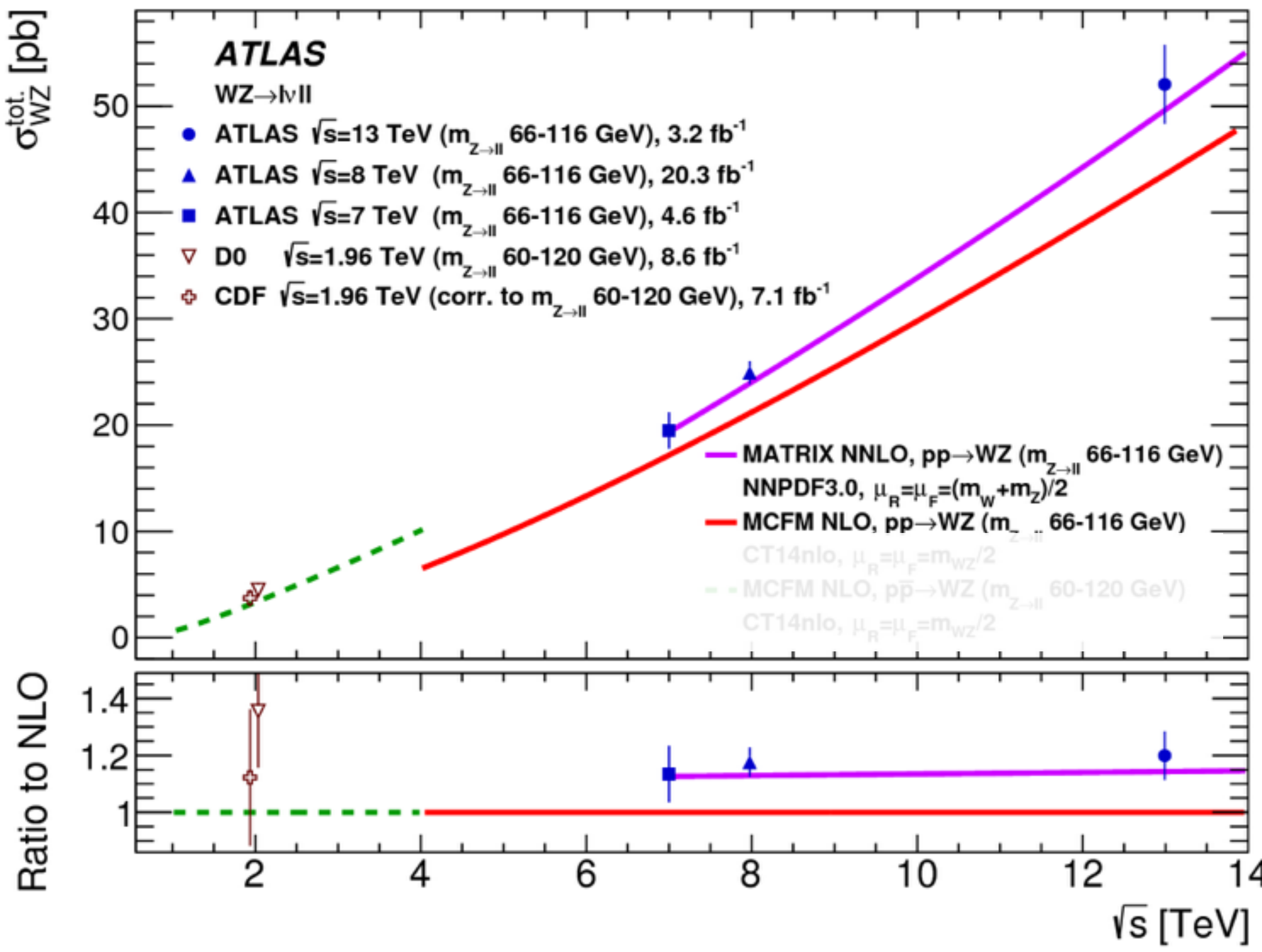
NNLO for diboson production



NNLO

NLO

Clear NLO not enough to describe current LHC data

Same conclusion in all measurements examined so far

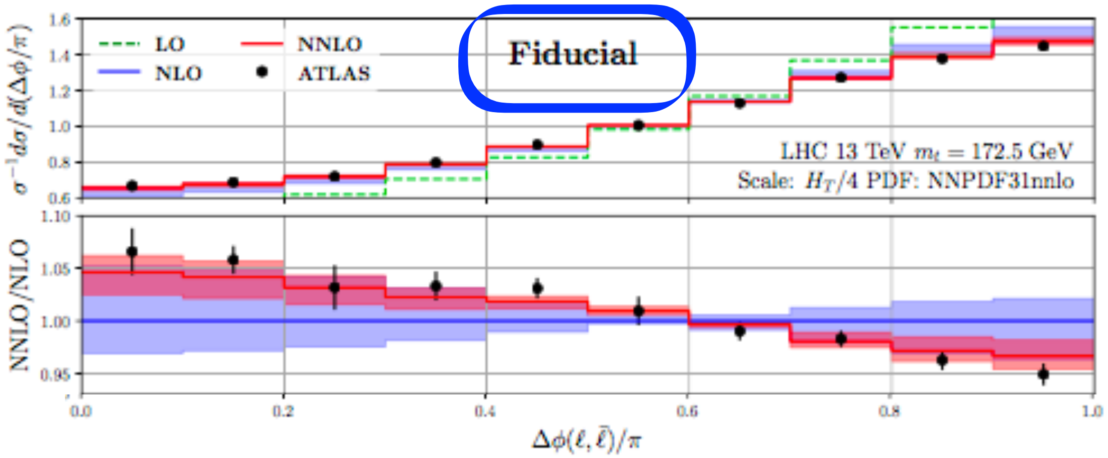
Top@NNLO: spin correlation

ATLAS reported a 3.2σ deviation in the azimuthal angle between between leptons in fully leptonic top-decay mode

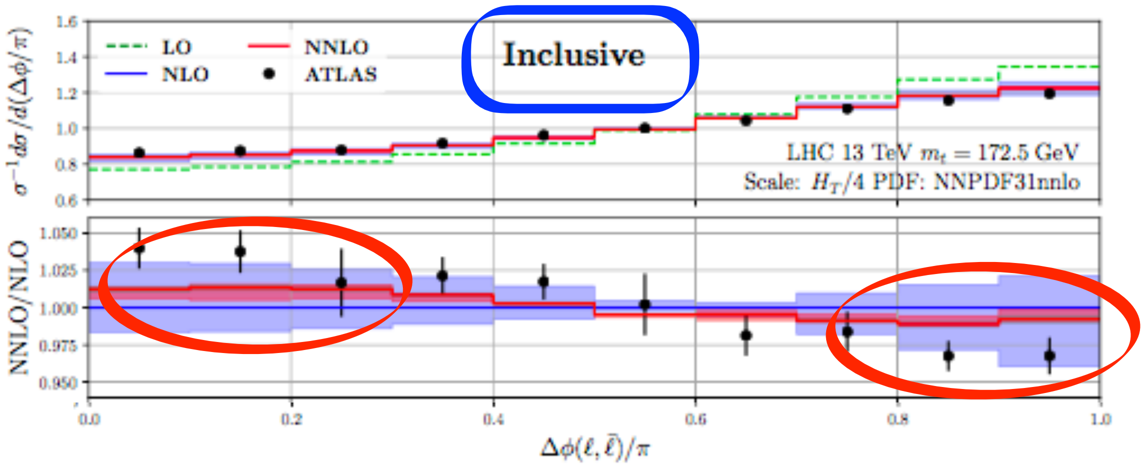
ATLAS-CONF-2018-027

NNLO calculation including spin correlation

Behring et al. 1901.05407



Fiducial level: good agreement NNLO & data



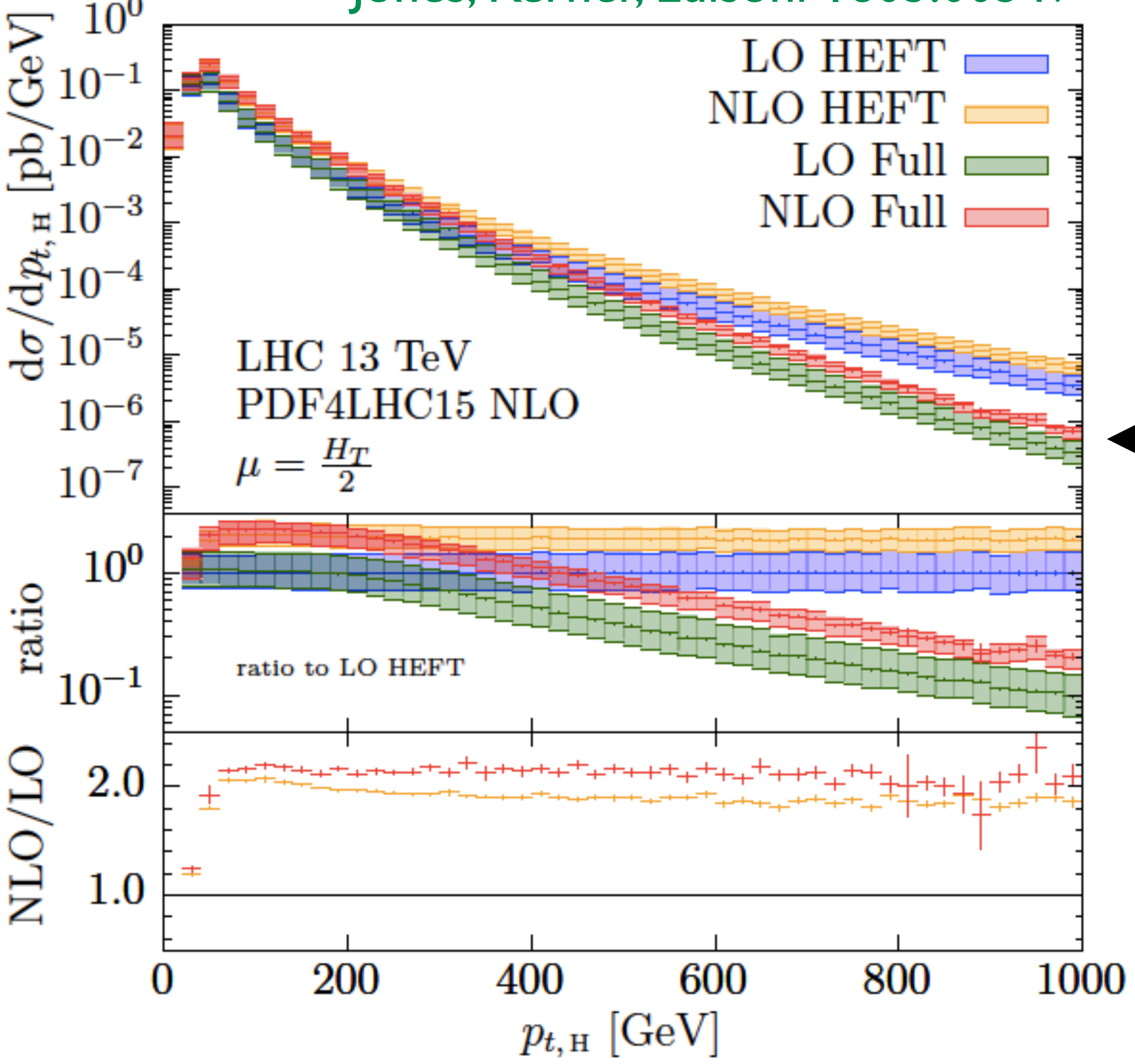
Inclusive level: less good agreement, mostly likely due to generators used in extrapolation

[EW effects tiny, see Frederix et al. 1804.10071]

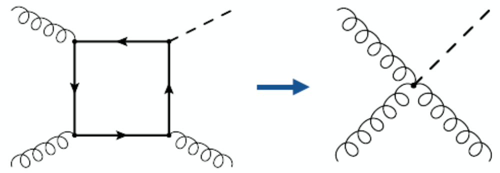
Reminiscent of discrepancy in inclusive WW cross-section reported a few years ago

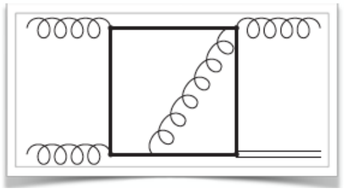
H+jet@NLO with top mass

Jones, Kerner, Luisoni 1803.00349



HEFT: $m_t \to \infty$ limit





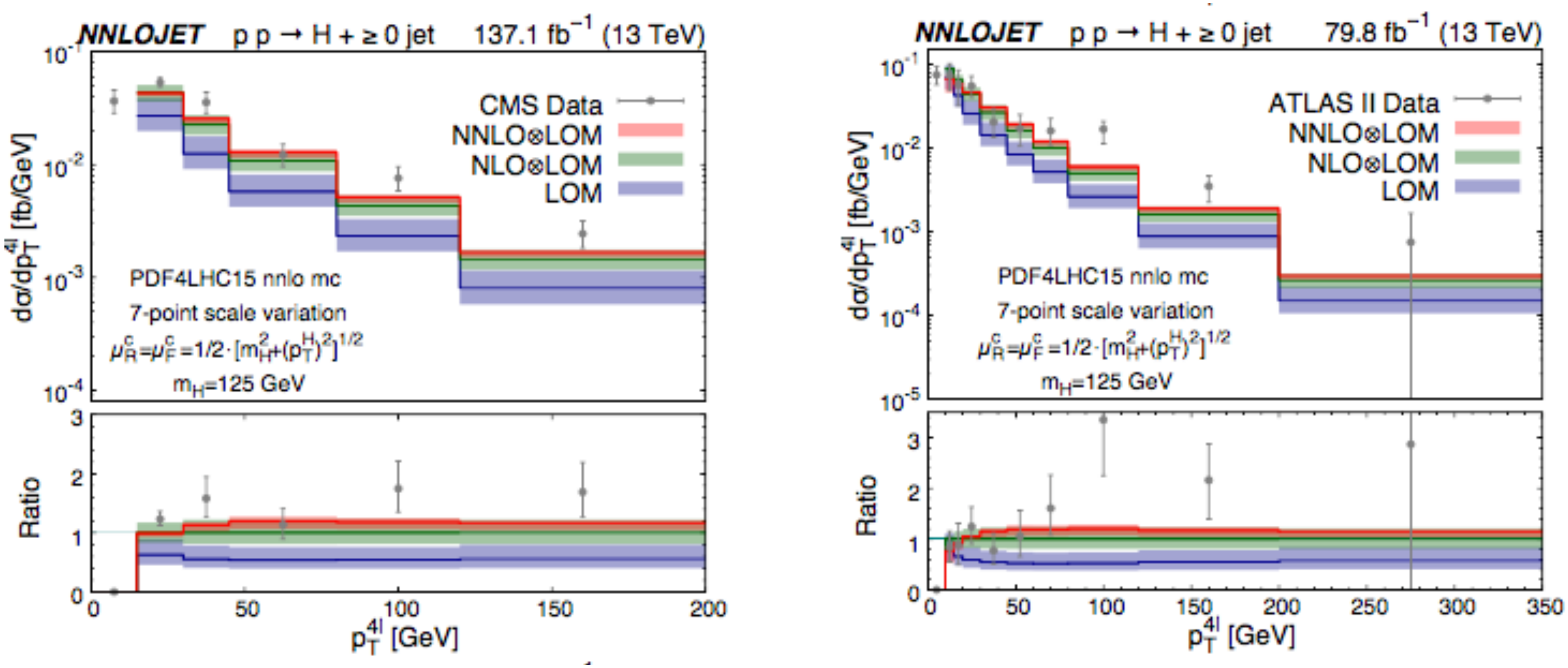
NLO loop-induced: different scaling behaviour at large p_T

- large p_T sensitive to BSM
- settles a longstanding question about uncertainties due to unknown top-mass effects

H(→4l)+jet @ NNLO

Chen, Gehrmann, Glover, Huss 1905.13738

Good agreement with ATLAS and CMS data (within their larger errors)



<u>ATLAS lepton isolation:</u> removal of non-isolated jet

<u>CMS lepton isolation:</u> removal of non-isolated lepton → worse convergence of acceptance at fixed-order

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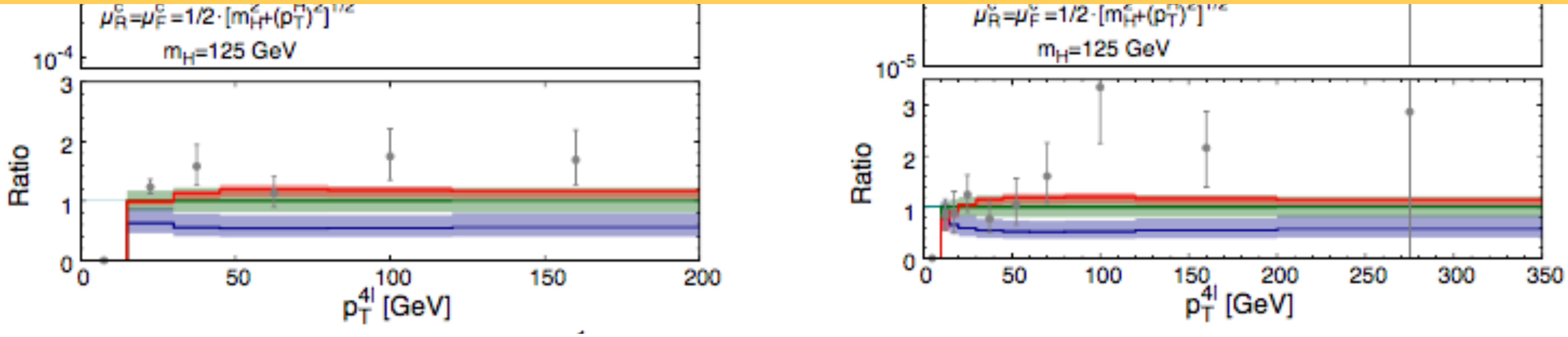
Example illustrates that theoretical calculations are up to the task of providing useful input (e.g. choice of isolation requirements, cuts, etc.)



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Example illustrates that theoretical calculations are up to the task of providing useful input (e.g. choice of isolation requirements, cuts, etc.)

But example also illustrates shortcomings of NNLO calculations, where only 4 leptons from the Higgs decay are present

ATLAS

CMS lepton isolation: removal of non-isolated lepton → worse convergence of acceptance at fixed-order

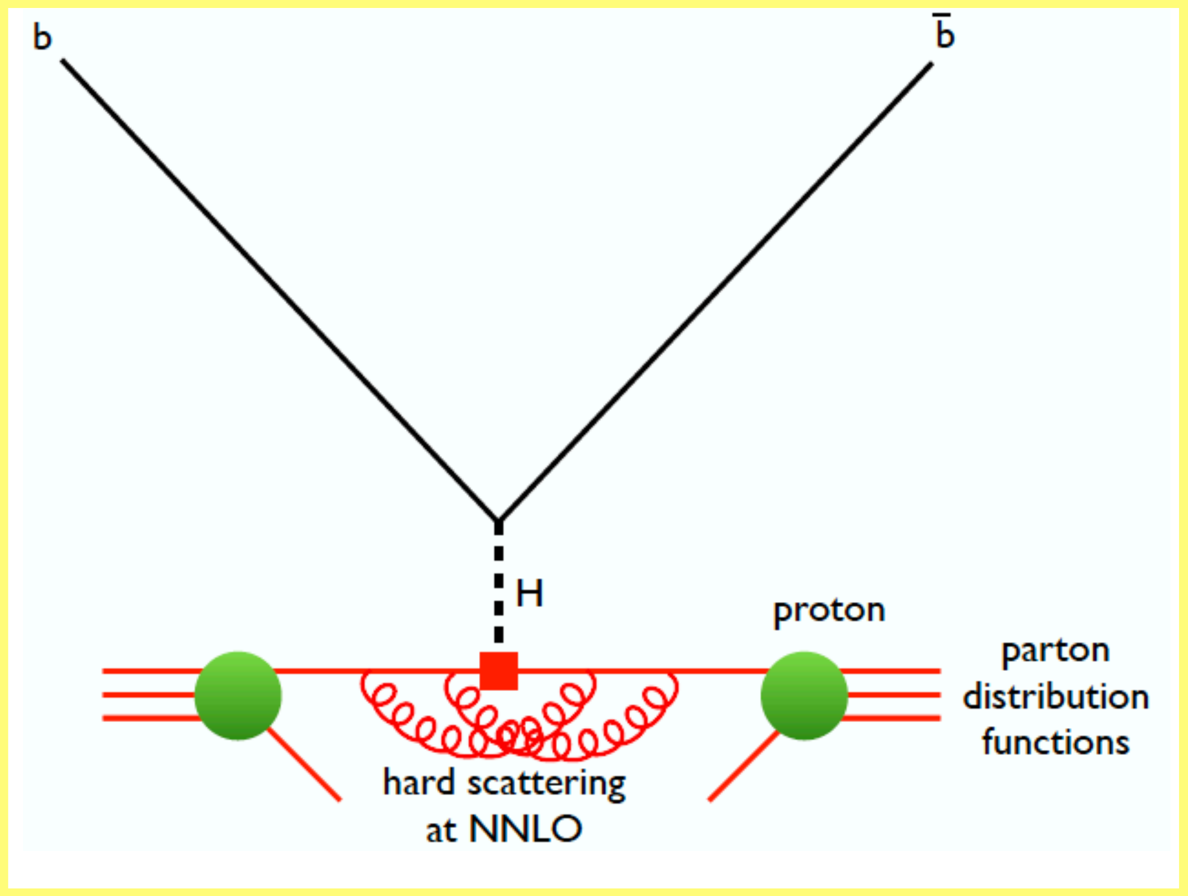
NNLO or PS ?

NNLO:

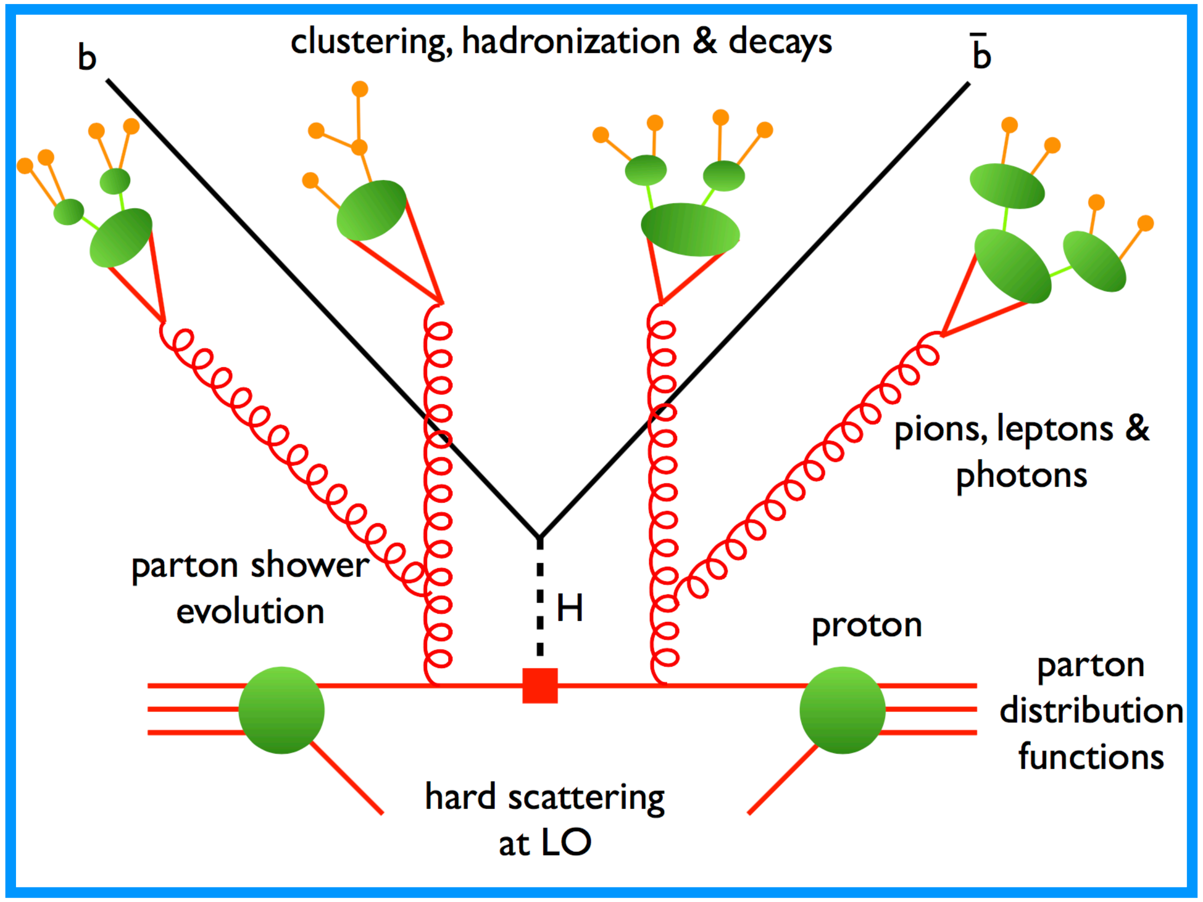
good perturbative accuracy, accurate inclusive cross-sections, but limited to low multiplicity and parton level only

Parton shower (PS):

less accurate, but realistic description, including multi-parton interactions, resummation, hadronization effects



?



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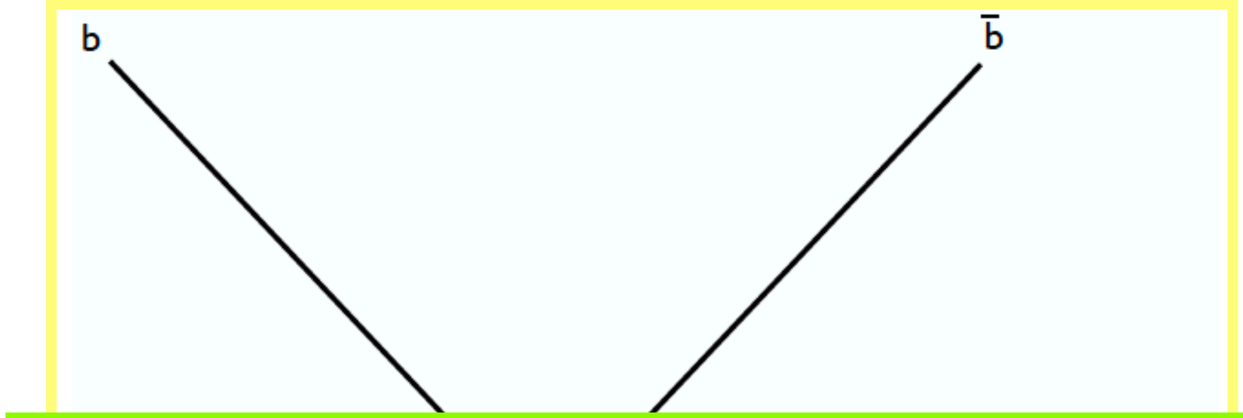
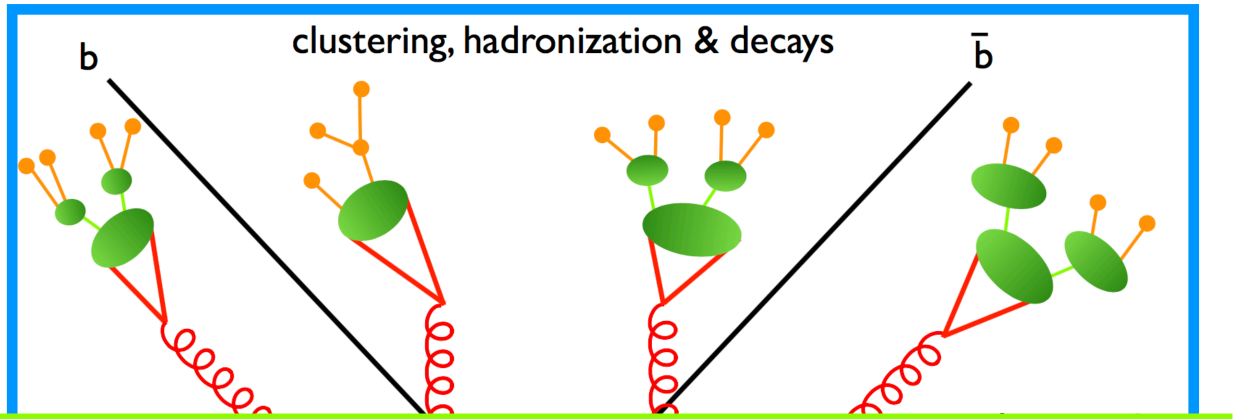




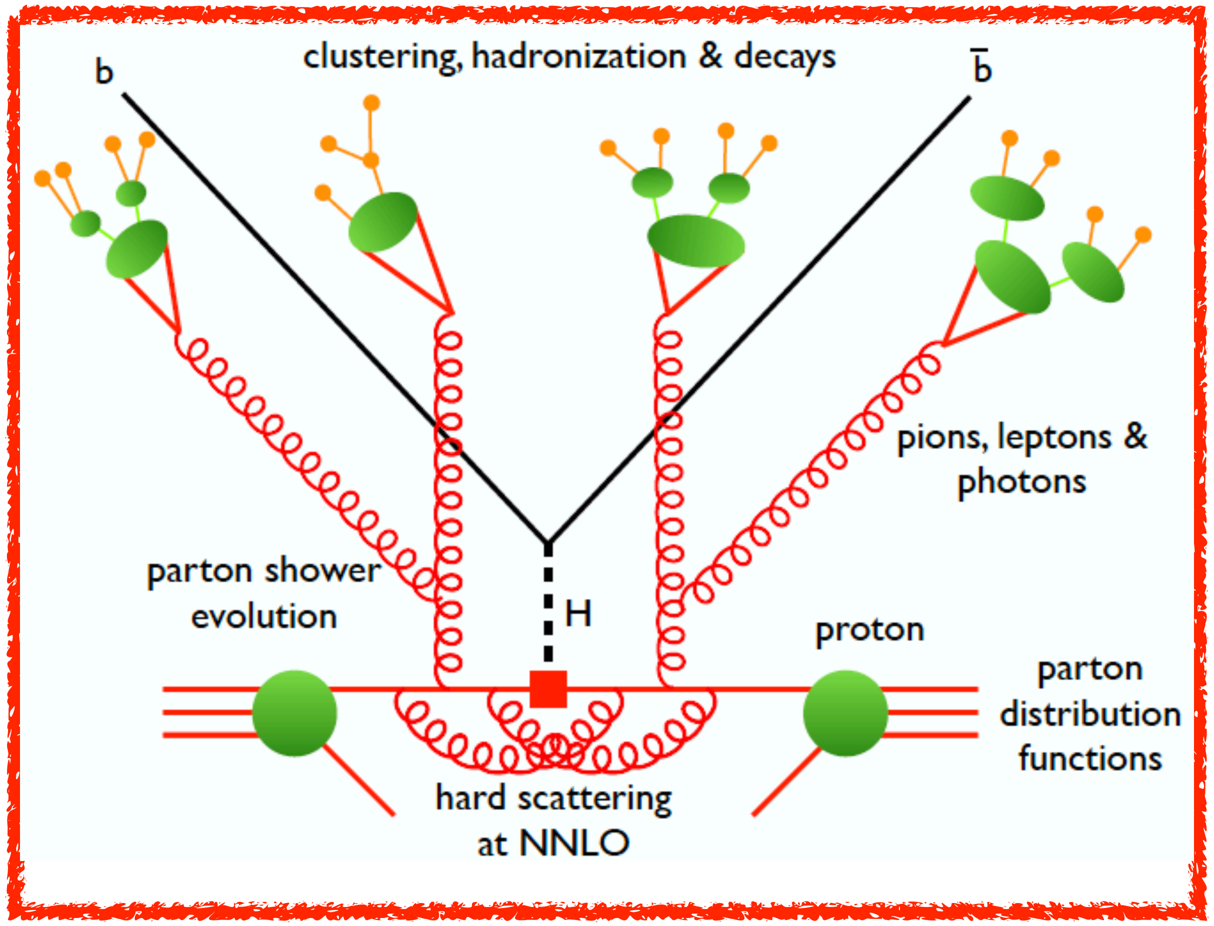
Matching of NLO & PS achieved in seminal papers about 15 years ago

Nason hep-ph/0409146; Frixione & Webber hep-ph/0204244

Today: NLOPS codes (MC@NLO, POWHEG, Sherpa) well-established and used in all advanced LHC analyses

NNLOPS

Matching of NNLO and PS (NNLOPS) is a must to have the best perturbative accuracy with a realistic description of final state



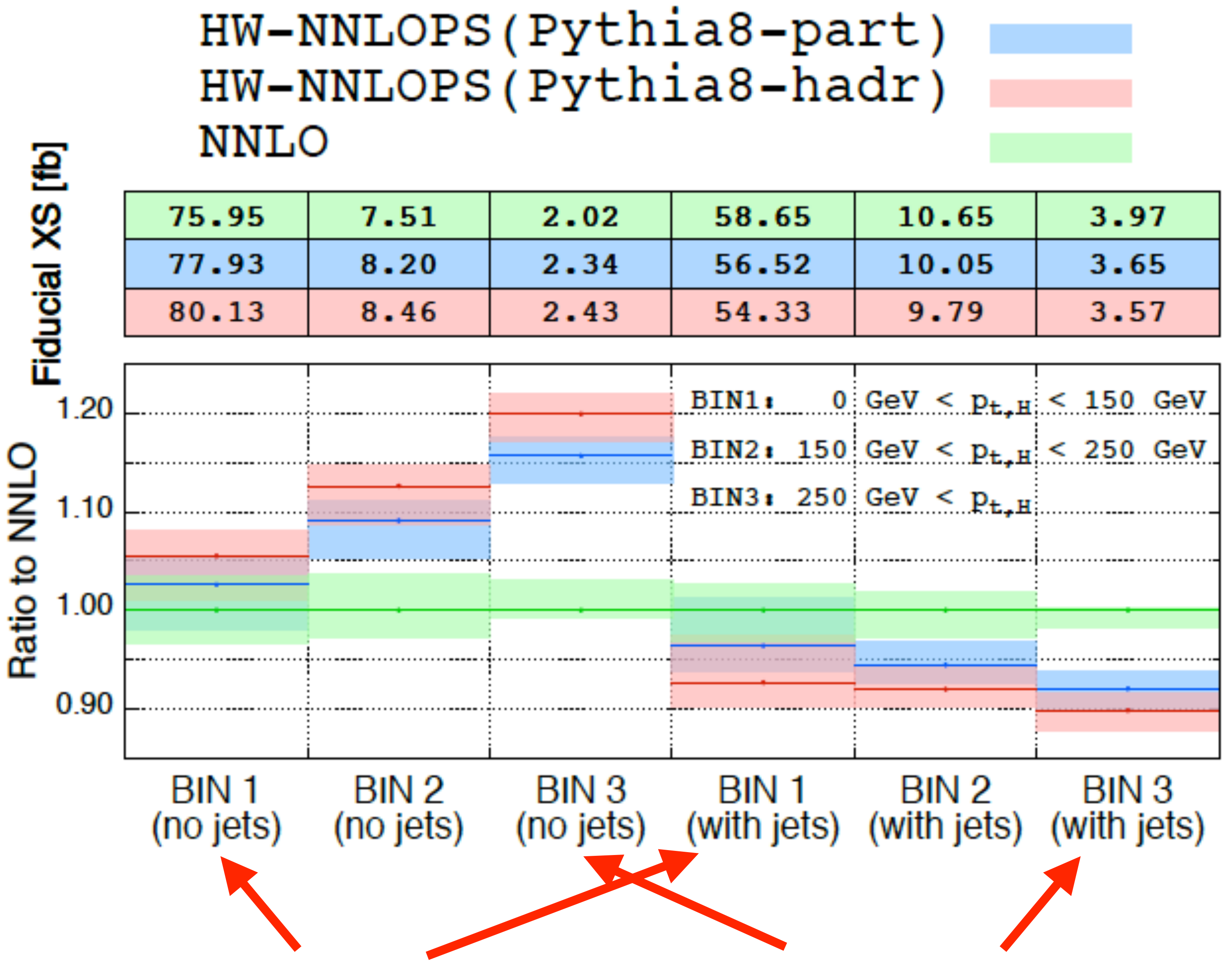
NNLOPS: currently three methods exist (UNNLOPS, Geneva, MiNLO) but very hard to extend to generic 2 → 2 processes. *New approaches/ideas required?*

Hoeche, Li,Prestel [UNNLOPS]
Astill, Bizon, Hamilton, Karlberg, Nason, Re, GZ [MiNLO]
Alioli, Bauer, Berggren, Guns, Tackmann, Walsh [Geneva]

NNLOPS

Example: associated HW production with cuts used by HXSWG

- PS and hadronization cause migration between jet-bins
- Difficult to reach high accuracy in jet-binned observables



	BIN 1 (no jets)	BIN 2 (no jets)	BIN 3 (no jets)	BIN 1 (with jets)	BIN 2 (with jets)	BIN 3 (with jets)
🟩	75.95	7.51	2.02	58.65	10.65	3.97
🟦	77.93	8.20	2.34	56.52	10.05	3.65
🟥	80.13	8.46	2.43	54.33	9.79	3.57

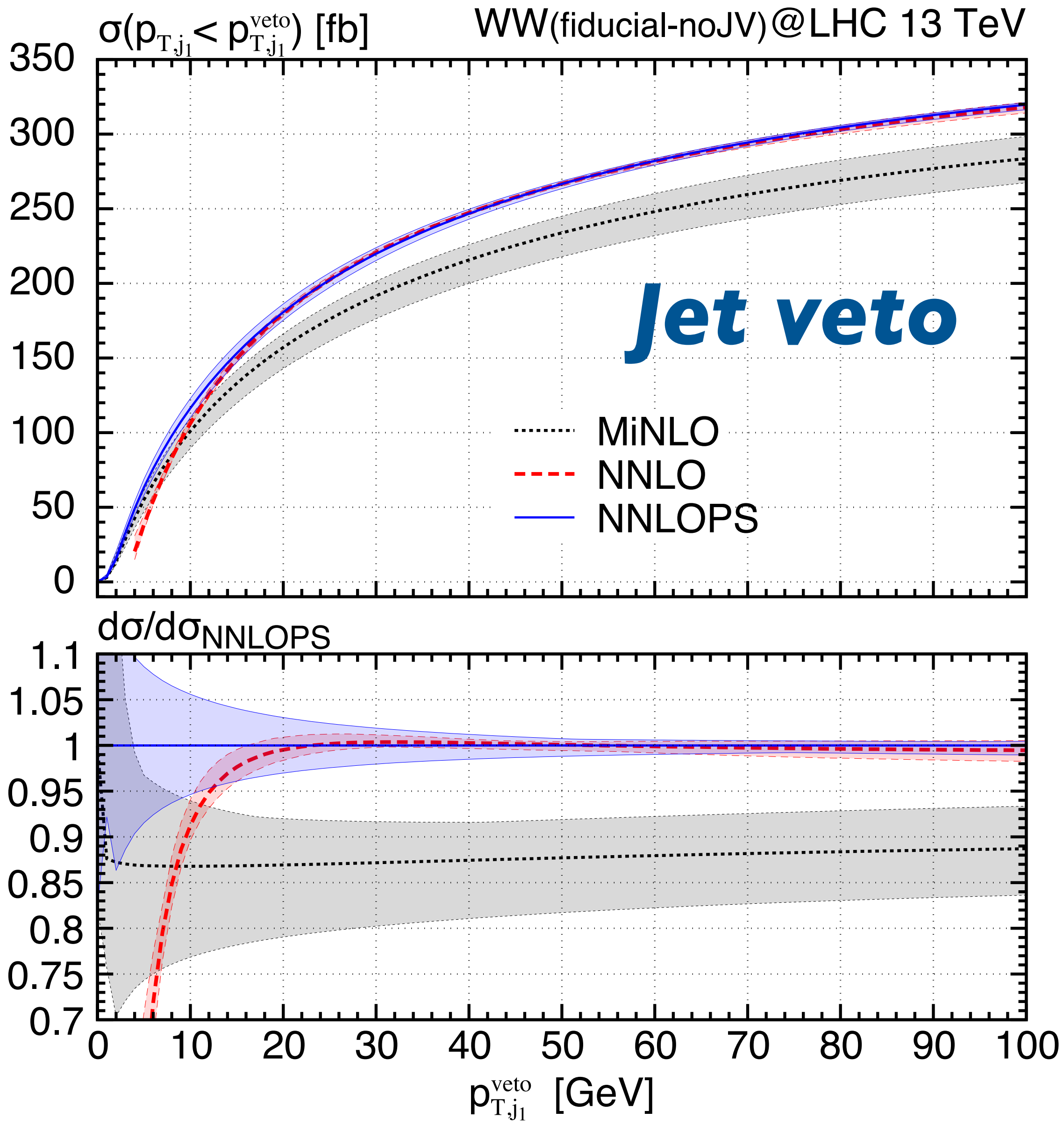
Bizon et al. 1603.01620

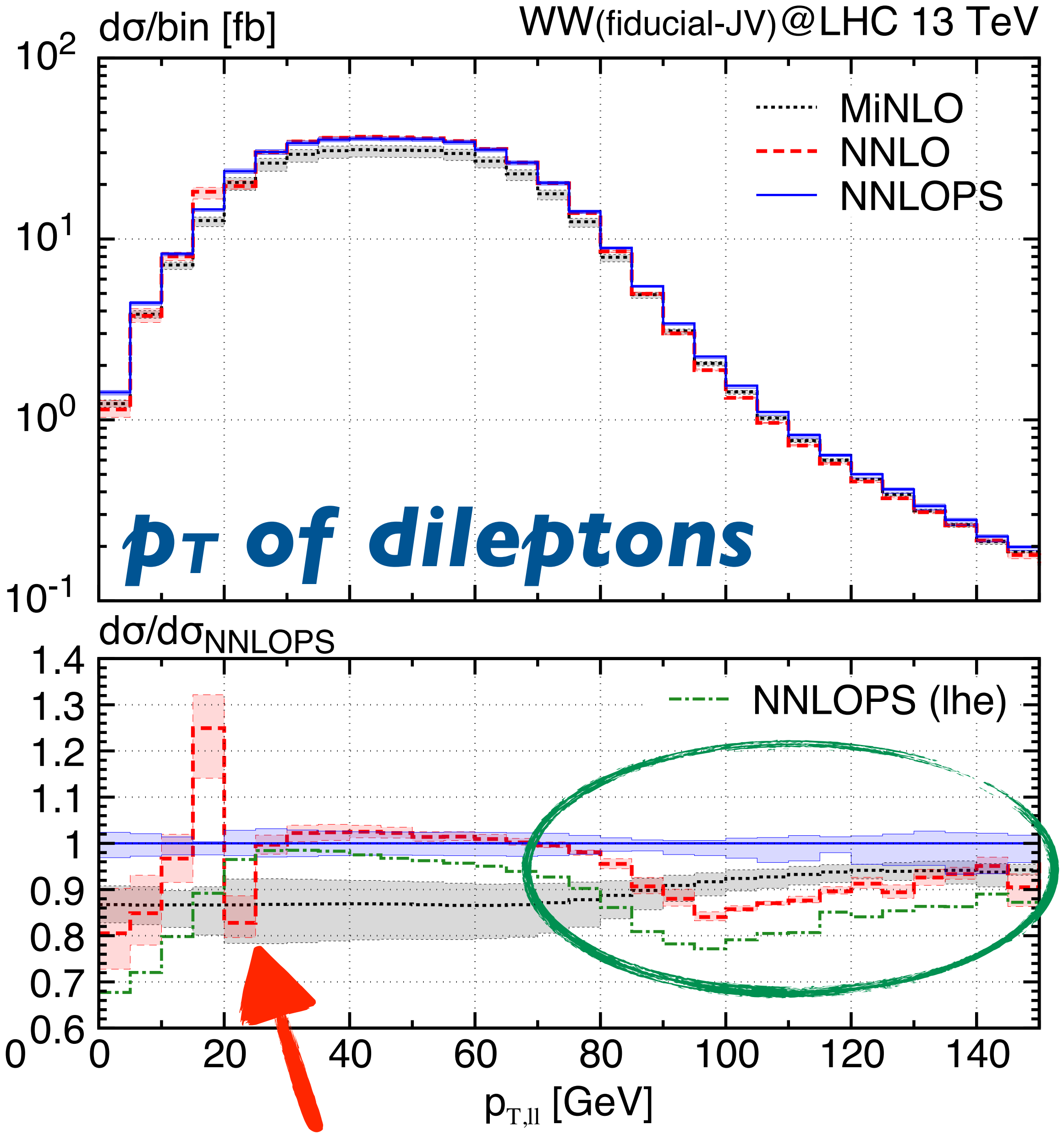
Low p_T

Boosted

NNLOPS for WW

Re, Wiesemann, GZ 1805.09857





→ **NNLOPS physical down to $p_T = 0$**

→ **NNLOPS cures perturbative instabilities (p_T^{miss} cut)**

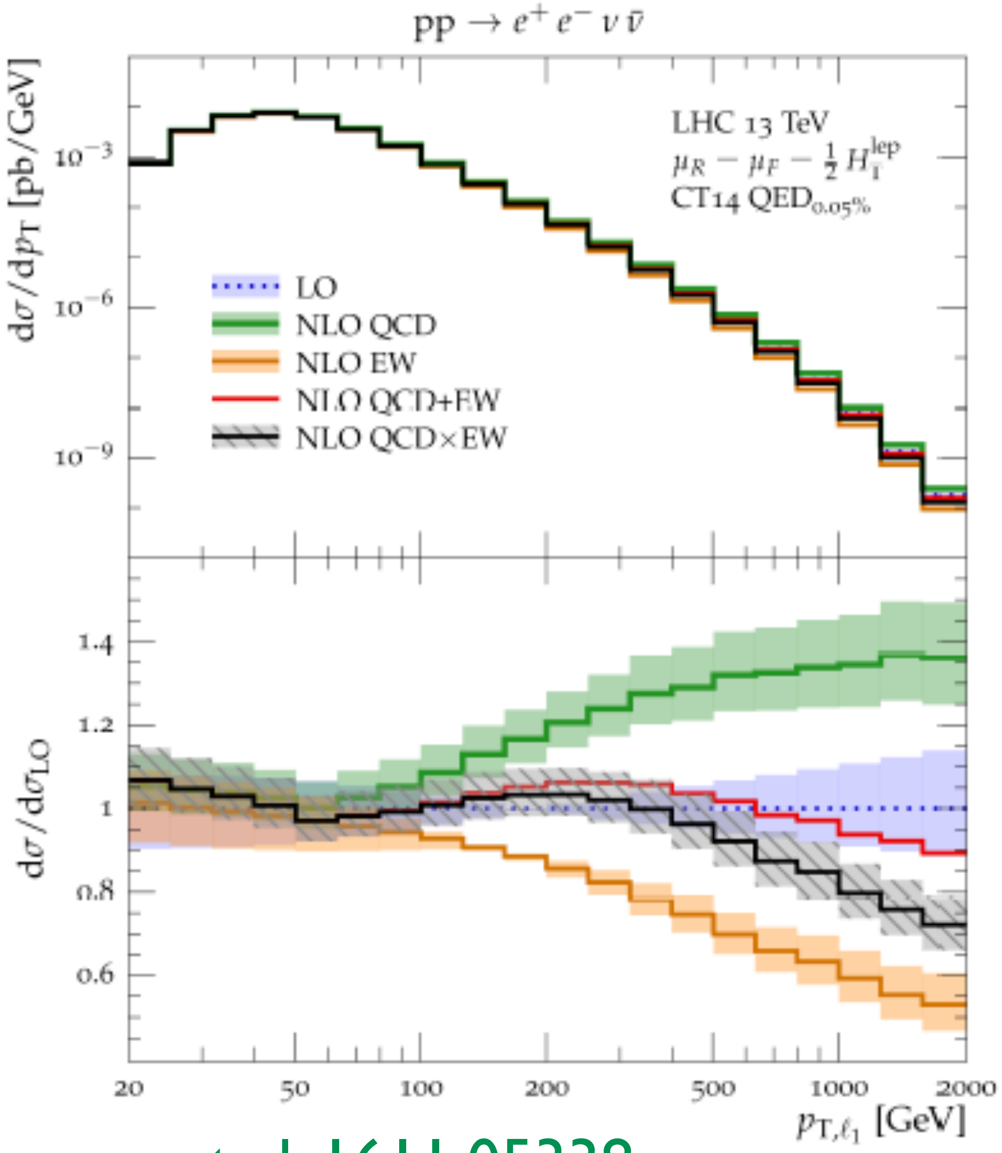
→ **NNLOPS induces additional shape effects**

EW effects & accuracy at high p_T

Understanding logarithmically enhanced EW effects at high p_T, also in relevant background processes, will be crucial to fully exploit future data

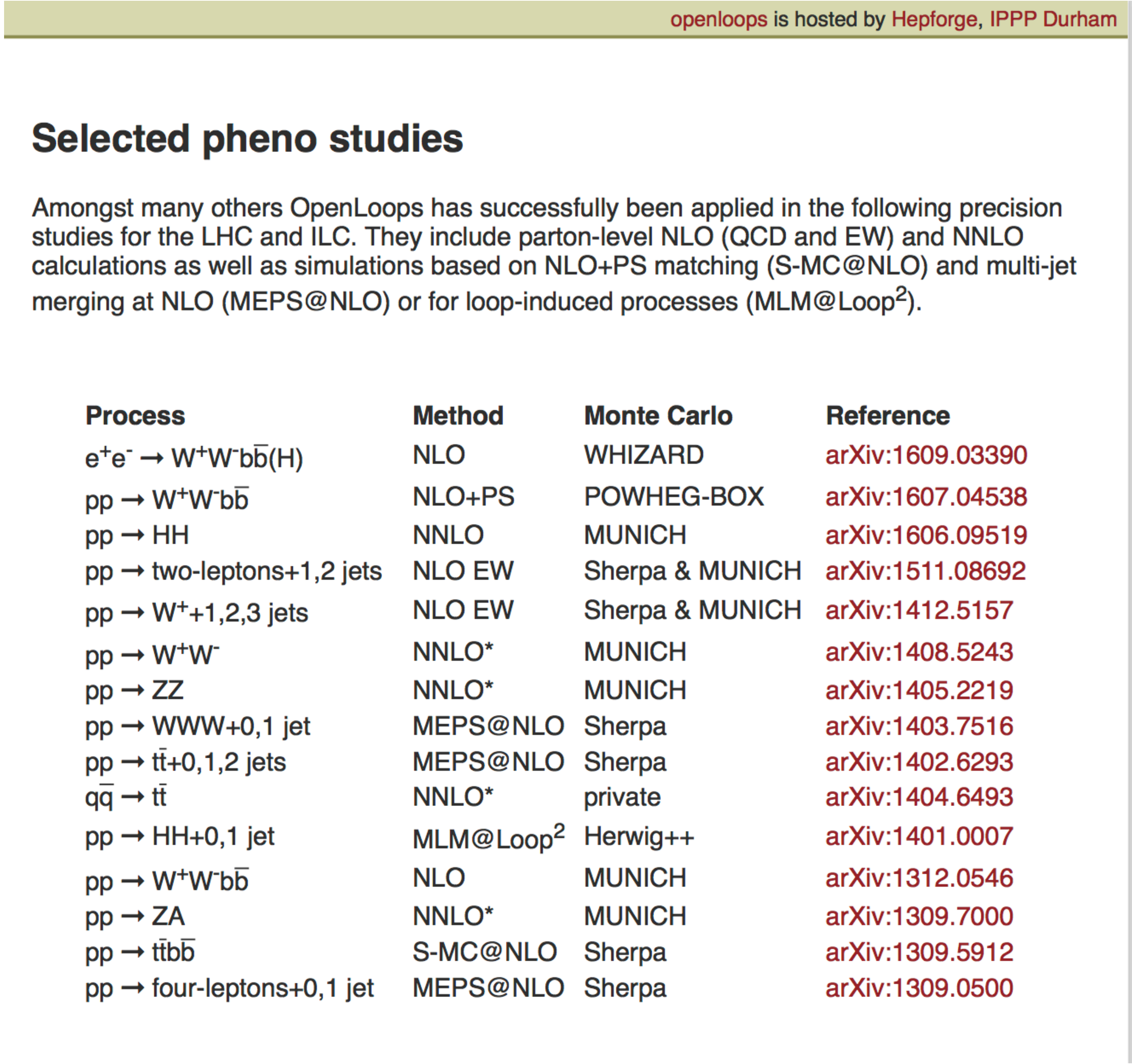
Plot also highlights importance of genuine mixed QCD+EW effects — combining corrections multiplicatively or additively leads to large ambiguities

Examples:
Two most important examples are high-p_T Higgs production and dark matter searches



Biedermann et al. 1611.05338

Public codes



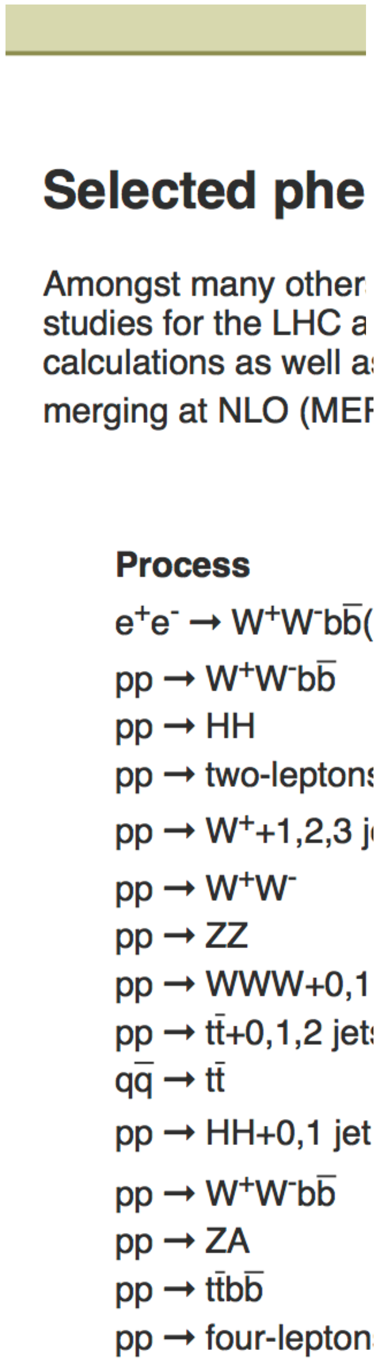
openloops is hosted by Hepforge, IPPP Durham

Selected pheno studies

Amongst many others OpenLoops has successfully been applied in the following precision studies for the LHC and ILC. They include parton-level NLO (QCD and EW) and NNLO calculations as well as simulations based on NLO+PS matching (S-MC@NLO) and multi-jet merging at NLO (MEPS@NLO) or for loop-induced processes (MLM@Loop^2).

Process	**Method**	**Monte Carlo**	**Reference**
$e^+e^- \to W^+W^-b\bar{b}(H)$	NLO	WHIZARD	arXiv:1609.03390
$pp \to W^+W^-b\bar{b}$	NLO+PS	POWHEG-BOX	arXiv:1607.04538
$pp \to HH$	NNLO	MUNICH	arXiv:1606.09519
$pp \to$ two-leptons+1,2 jets	NLO EW	Sherpa & MUNICH	arXiv:1511.08692
$pp \to W^+$+1,2,3 jets	NLO EW	Sherpa & MUNICH	arXiv:1412.5157
$pp \to W^+W^-$	NNLO*	MUNICH	arXiv:1408.5243
$pp \to ZZ$	NNLO*	MUNICH	arXiv:1405.2219
$pp \to WWW$+0,1 jet	MEPS@NLO	Sherpa	arXiv:1403.7516
$pp \to t\bar{t}$+0,1,2 jets	MEPS@NLO	Sherpa	arXiv:1402.6293
$q\bar{q} \to t\bar{t}$	NNLO*	private	arXiv:1404.6493
$pp \to HH$+0,1 jet	MLM@Loop^2	Herwig++	arXiv:1401.0007
$pp \to W^+W^-b\bar{b}$	NLO	MUNICH	arXiv:1312.0546
$pp \to ZA$	NNLO*	MUNICH	arXiv:1309.7000
$pp \to t\bar{t}b\bar{b}$	S-MC@NLO	Sherpa	arXiv:1309.5912
$pp \to$ four-leptons+0,1 jet	MEPS@NLO	Sherpa	arXiv:1309.0500

Public codes

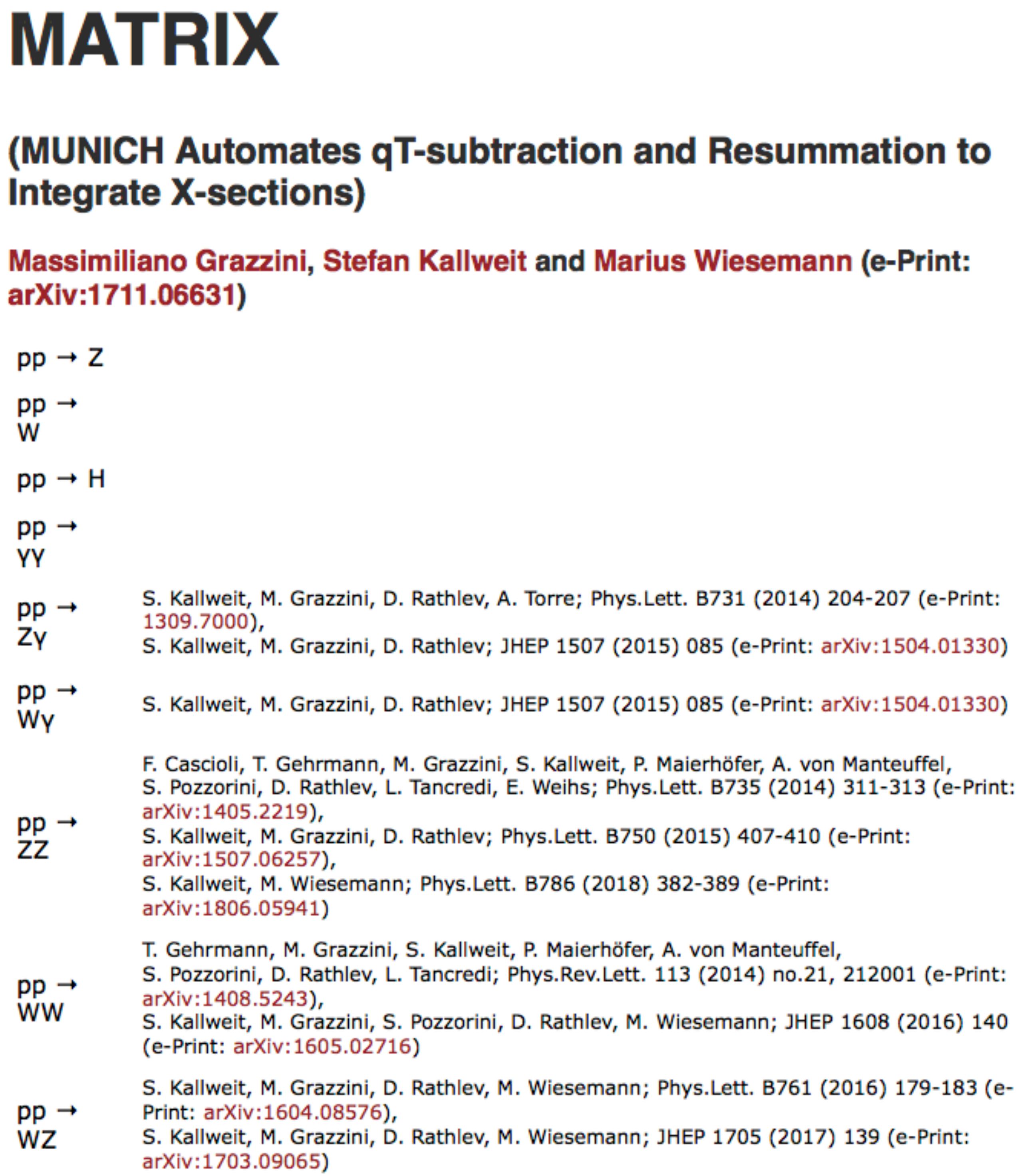


Selected phe

Amongst many other
studies for the LHC a
calculations as well a
merging at NLO (MEF

Process

$e^+e^- \to W^+W^-b\bar{b}($
$pp \to W^+W^-b\bar{b}$
$pp \to HH$
$pp \to$ two-leptons
$pp \to W^+$+1,2,3 j
$pp \to W^+W^-$
$pp \to ZZ$
$pp \to$ WWW+0,1
$pp \to t\bar{t}$+0,1,2 jet
$q\bar{q} \to t\bar{t}$
$pp \to$ HH+0,1 jet
$pp \to W^+W^-b\bar{b}$
$pp \to ZA$
$pp \to t\bar{t}b\bar{b}$
$pp \to$ four-lepton



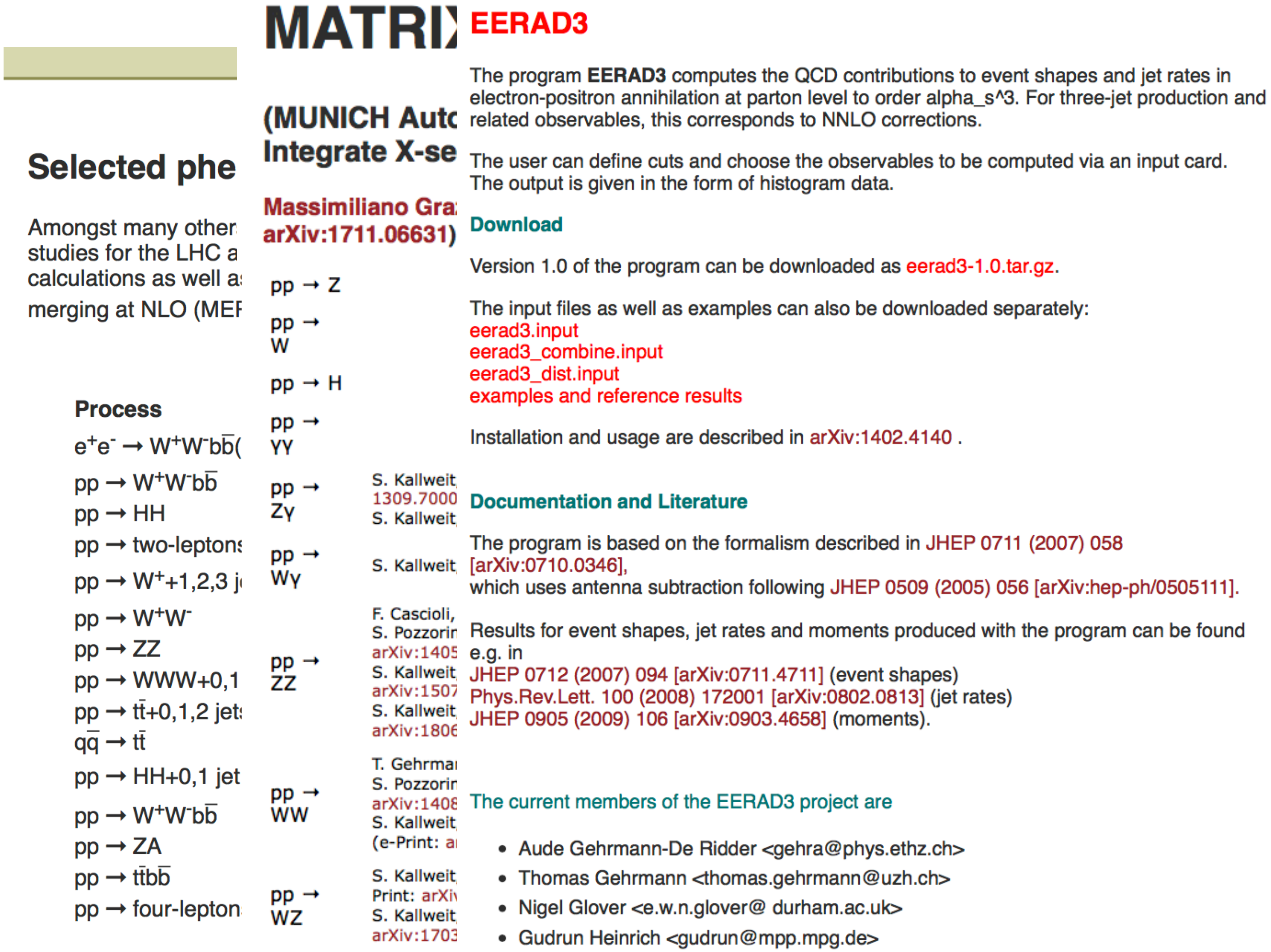
MATRIX

(MUNICH Automates qT-subtraction and Resummation to Integrate X-sections)

Massimiliano Grazzini, Stefan Kallweit and Marius Wiesemann (e-Print: arXiv:1711.06631)

$pp \to Z$	
$pp \to W$	
$pp \to H$	
$pp \to \gamma\gamma$	
$pp \to Z\gamma$	S. Kallweit, M. Grazzini, D. Rathlev, A. Torre; Phys.Lett. B731 (2014) 204-207 (e-Print: 1309.7000), S. Kallweit, M. Grazzini, D. Rathlev; JHEP 1507 (2015) 085 (e-Print: arXiv:1504.01330)
$pp \to W\gamma$	S. Kallweit, M. Grazzini, D. Rathlev; JHEP 1507 (2015) 085 (e-Print: arXiv:1504.01330)
$pp \to ZZ$	F. Cascioli, T. Gehrmann, M. Grazzini, S. Kallweit, P. Maierhöfer, A. von Manteuffel, S. Pozzorini, D. Rathlev, L. Tancredi, E. Weihs; Phys.Lett. B735 (2014) 311-313 (e-Print: arXiv:1405.2219), S. Kallweit, M. Grazzini, D. Rathlev; Phys.Lett. B750 (2015) 407-410 (e-Print: arXiv:1507.06257), S. Kallweit, M. Wiesemann; Phys.Lett. B786 (2018) 382-389 (e-Print: arXiv:1806.05941)
$pp \to WW$	T. Gehrmann, M. Grazzini, S. Kallweit, P. Maierhöfer, A. von Manteuffel, S. Pozzorini, D. Rathlev, L. Tancredi; Phys.Rev.Lett. 113 (2014) no.21, 212001 (e-Print: arXiv:1408.5243), S. Kallweit, M. Grazzini, S. Pozzorini, D. Rathlev, M. Wiesemann; JHEP 1608 (2016) 140 (e-Print: arXiv:1605.02716)
$pp \to WZ$	S. Kallweit, M. Grazzini, D. Rathlev, M. Wiesemann; Phys.Lett. B761 (2016) 179-183 (e-Print: arXiv:1604.08576), S. Kallweit, M. Grazzini, D. Rathlev, M. Wiesemann; JHEP 1705 (2017) 139 (e-Print: arXiv:1703.09065)

Public codes



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Amongst many other studies for the LHC a calculations as well a merging at NLO (MEF

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arXiv:1711.06631)

$pp \to Z$

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$pp \to Z\gamma$ — S. Kallweit, 1309.7000 S. Kallweit,

$pp \to W\gamma$ — S. Kallweit,

$pp \to ZZ$ — F. Cascioli, S. Pozzorin arXiv:1405 S. Kallweit, arXiv:1507 S. Kallweit, arXiv:1806

$pp \to WW$ — T. Gehrmar S. Pozzorin arXiv:1408 S. Kallweit, (e-Print: ar

$pp \to WZ$ — S. Kallweit, Print: arXiv S. Kallweit, arXiv:1703

EERAD3

The program **EERAD3** computes the QCD contributions to event shapes and jet rates in electron-positron annihilation at parton level to order alpha_s^3. For three-jet production and related observables, this corresponds to NNLO corrections.

The user can define cuts and choose the observables to be computed via an input card. The output is given in the form of histogram data.

Download

Version 1.0 of the program can be downloaded as eerad3-1.0.tar.gz.

The input files as well as examples can also be downloaded separately:
eerad3.input
eerad3_combine.input
eerad3_dist.input
examples and reference results

Installation and usage are described in arXiv:1402.4140 .

Documentation and Literature

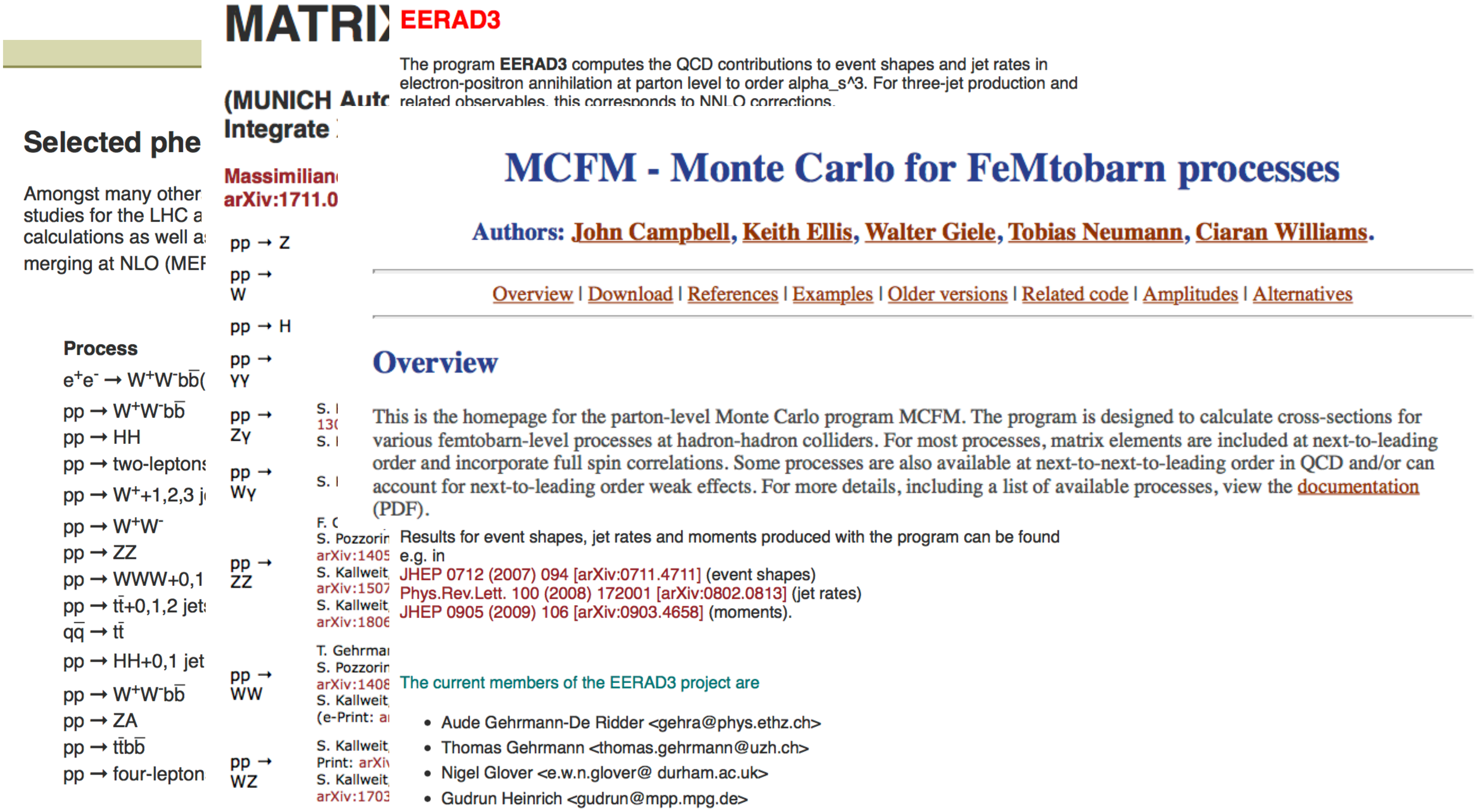
The program is based on the formalism described in JHEP 0711 (2007) 058 [arXiv:0710.0346],
which uses antenna subtraction following JHEP 0509 (2005) 056 [arXiv:hep-ph/0505111].

Results for event shapes, jet rates and moments produced with the program can be found e.g. in
JHEP 0712 (2007) 094 [arXiv:0711.4711] (event shapes)
Phys.Rev.Lett. 100 (2008) 172001 [arXiv:0802.0813] (jet rates)
JHEP 0905 (2009) 106 [arXiv:0903.4658] (moments).

The current members of the EERAD3 project are

- Aude Gehrmann-De Ridder <gehra@phys.ethz.ch>
- Thomas Gehrmann <thomas.gehrmann@uzh.ch>
- Nigel Glover <e.w.n.glover@ durham.ac.uk>
- Gudrun Heinrich <gudrun@mpp.mpg.de>

Public codes



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arXiv:1703

MCFM - Monte Carlo for FeMtobarn processes

Authors: John Campbell, Keith Ellis, Walter Giele, Tobias Neumann, Ciaran Williams.

Overview | Download | References | Examples | Older versions | Related code | Amplitudes | Alternatives

Overview

This is the homepage for the parton-level Monte Carlo program MCFM. The program is designed to calculate cross-sections for various femtobarn-level processes at hadron-hadron colliders. For most processes, matrix elements are included at next-to-leading order and incorporate full spin correlations. Some processes are also available at next-to-next-to-leading order in QCD and/or can account for next-to-leading order weak effects. For more details, including a list of available processes, view the documentation (PDF).

Results for event shapes, jet rates and moments produced with the program can be found e.g. in
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Homepage of the POWHEG BOX 14/07/2019, 10:12

The POWHEG BOX

Project

The POWHEG BOX is a general computer framework for implementing NLO calculations in shower Monte Carlo programs according to the POWHEG method. It is also a library, where previously included processes are made available to the users. It can be interfaced with all modern shower Monte Carlo programs that support the Les Houches Interface for User Generated Processes.

Available Processes

- Single vector-boson production with decay, S. Alioli, P. Nason, C. Oleari and E. Re, *JHEP* **0807** (2008) 060, arXiv:0805.4802 [paper]

POWHEG-BOX/W
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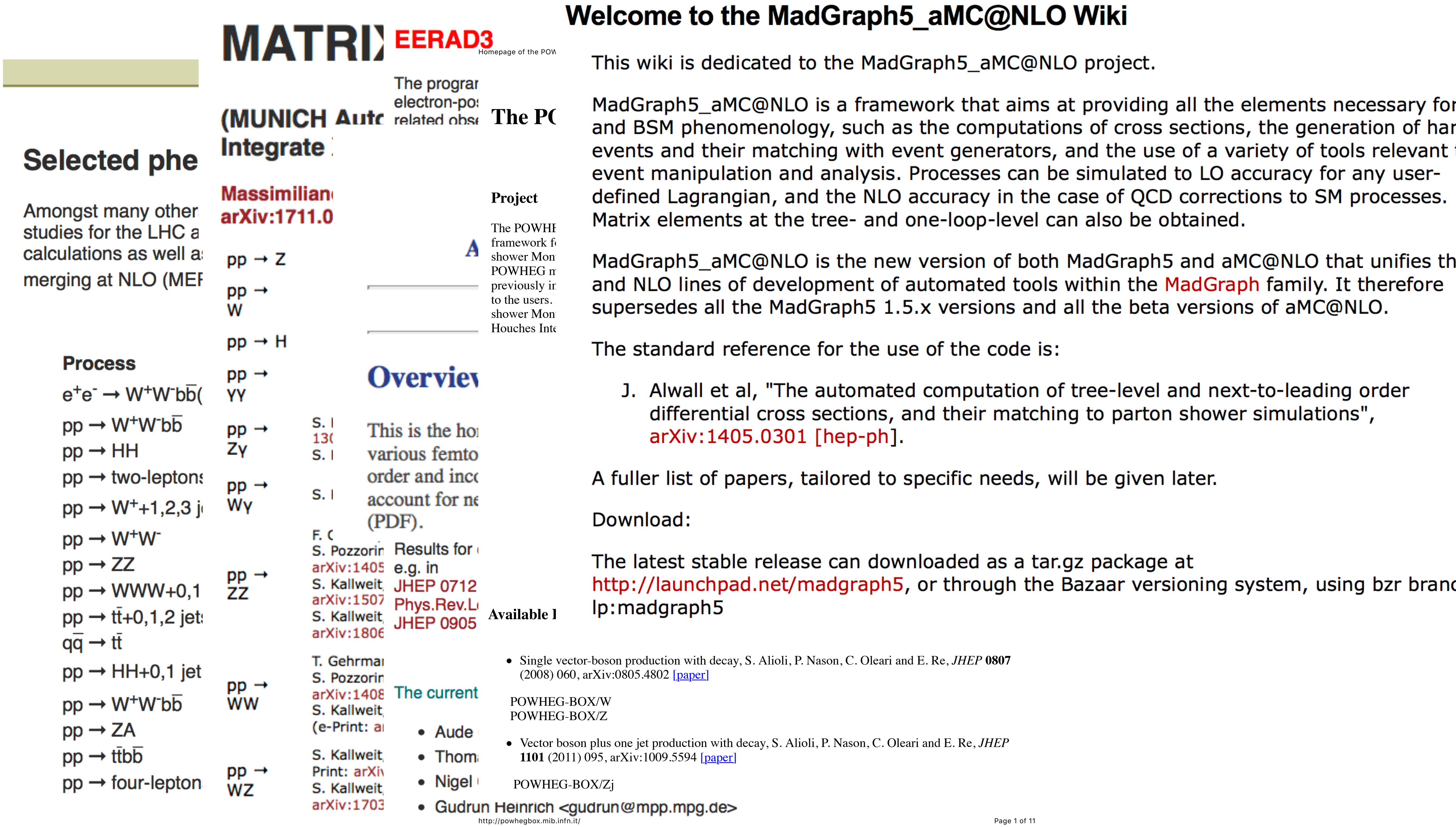
POWHEG-BOX/Zj

http://powhegbox.mib.infn.it/ Page 1 of 11

Public codes



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Homepage of the POW

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Page 1 of 11

Welcome to the MadGraph5_aMC@NLO Wiki

This wiki is dedicated to the MadGraph5_aMC@NLO project.

MadGraph5_aMC@NLO is a framework that aims at providing all the elements necessary for and BSM phenomenology, such as the computations of cross sections, the generation of har events and their matching with event generators, and the use of a variety of tools relevant event manipulation and analysis. Processes can be simulated to LO accuracy for any user-defined Lagrangian, and the NLO accuracy in the case of QCD corrections to SM processes. Matrix elements at the tree- and one-loop-level can also be obtained.

MadGraph5_aMC@NLO is the new version of both MadGraph5 and aMC@NLO that unifies th and NLO lines of development of automated tools within the MadGraph family. It therefore supersedes all the MadGraph5 1.5.x versions and all the beta versions of aMC@NLO.

The standard reference for the use of the code is:

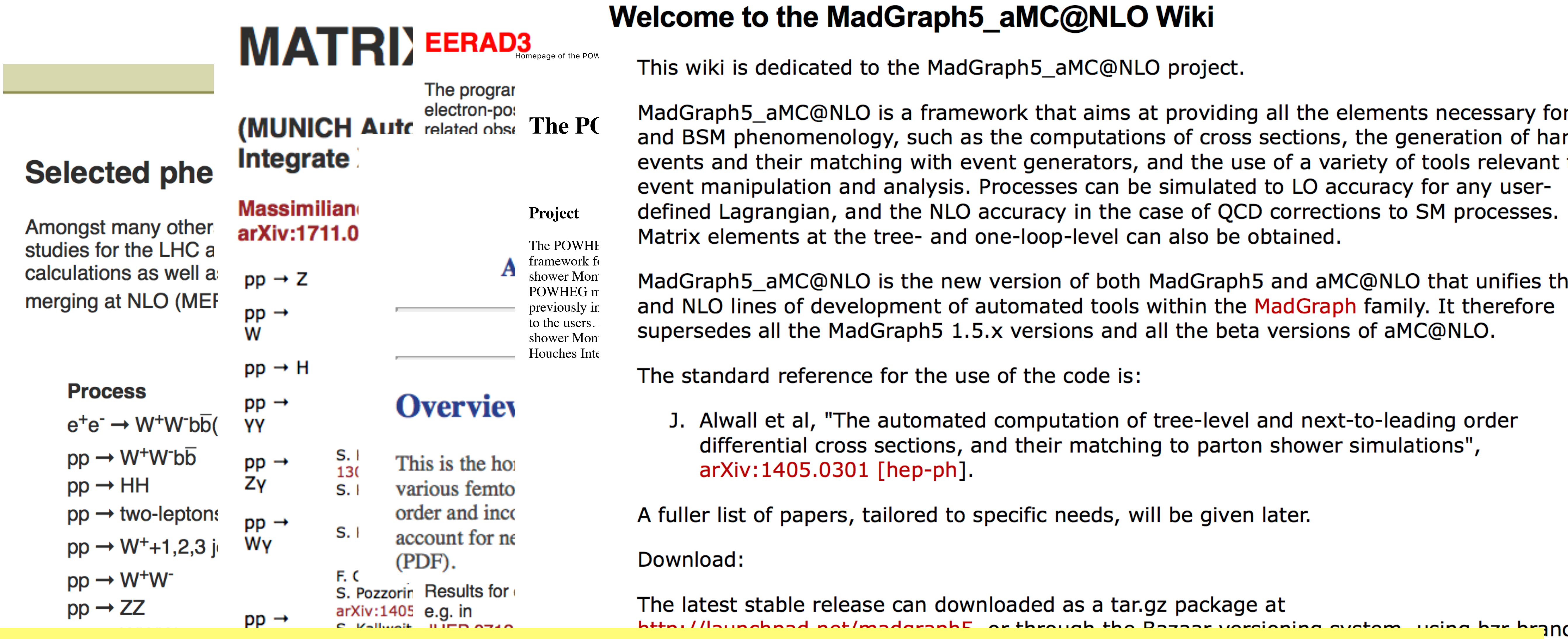
J. Alwall et al, "The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations", arXiv:1405.0301 [hep-ph].

A fuller list of papers, tailored to specific needs, will be given later.

Download:

The latest stable release can downloaded as a tar.gz package at http://launchpad.net/madgraph5, or through the Bazaar versioning system, using bzr branc lp:madgraph5

Public codes



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EERAD3

Homepage of the POW

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+ many more codes with (semi) automated implementation of NLO, NNLO, NLO-EW, NLO-BSM

Top mass

Top-mass determination is a very challenging theoretical problem

No consensus in the theory community on a number of points

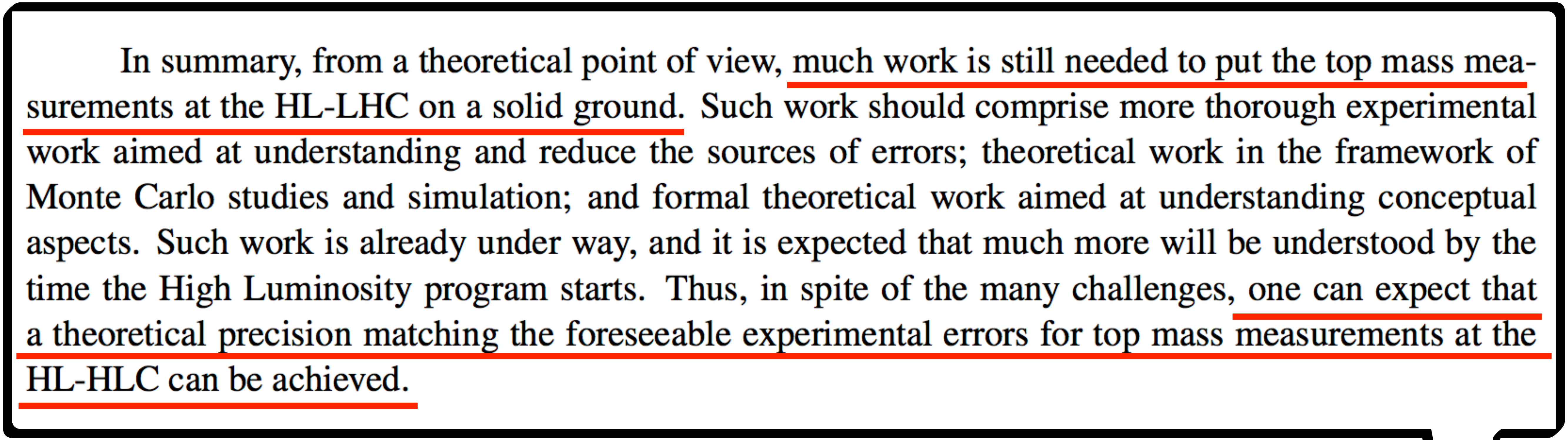
- Optimal observables?
- Effect of cutoff in Monte Carlo?
- Linear power corrections?
- Which mass is better when?
- Impact of width?
- What type of infrared sensitivity?

Progress in understanding differences and reaching consensus

HE-LHC Working Group report 1902.04070

Analytic progress in understanding power corrections: Ravasio, Nason, Oleari 1810.10931

Top mass



In summary, from a theoretical point of view, much work is still needed to put the top mass measurements at the HL-LHC on a solid ground. Such work should comprise more thorough experimental work aimed at understanding and reduce the sources of errors; theoretical work in the framework of Monte Carlo studies and simulation; and formal theoretical work aimed at understanding conceptual aspects. Such work is already under way, and it is expected that much more will be understood by the time the High Luminosity program starts. Thus, in spite of the many challenges, one can expect that a theoretical precision matching the foreseeable experimental errors for top mass measurements at the HL-HLC can be achieved.

Progress in understanding differences and reaching consensus

HE-LHC Working Group report 1902.04070

Top mass

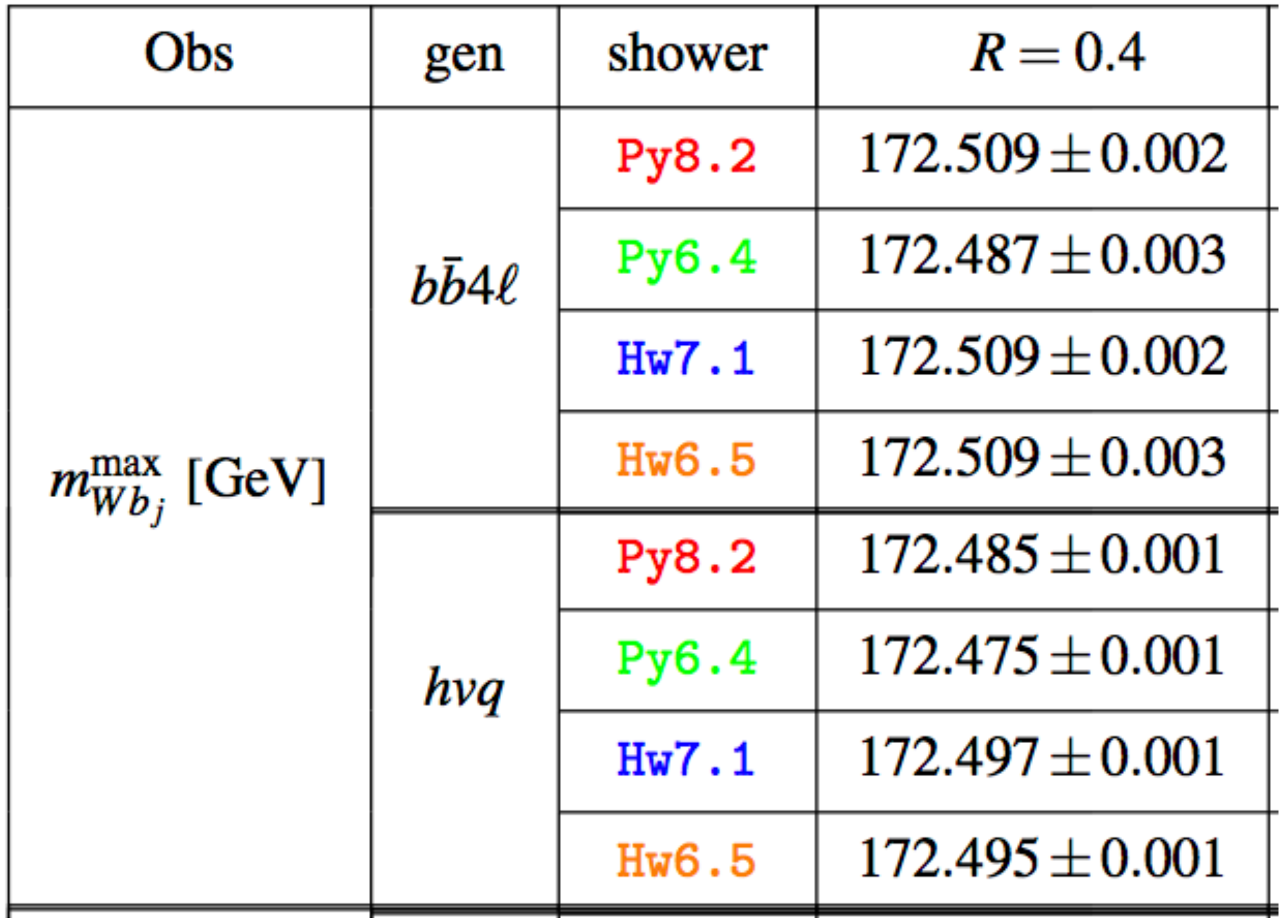
Realistic top-quark simulation: considerable theoretical progress in matching NLO & PS in a "resonance-aware" way

Jezo, Nason 1509.09071

<u>Two main conclusions:</u>

- Best observable remains the reconstructed top invariant mass (not lepton observables or $E_{b,max}$)
- Residual theoretical uncertainty of O(200 MeV) if no smearing to account for experimental uncertainties is performed and small R is used (R=0.4-0.5)

$E_{b,max}$ → Agashe et al. 1903.03445
Leptonic obs. → Frixione, Mitov 1407.2763



Obs	gen	shower	$R = 0.4$
$m_{Wb_j}^{\max}$ [GeV]	$b\bar{b}4\ell$	`Py8.2`	172.509 ± 0.002
		`Py6.4`	172.487 ± 0.003
		`Hw7.1`	172.509 ± 0.002
		`Hw6.5`	172.509 ± 0.003
	hvq	`Py8.2`	172.485 ± 0.001
		`Py6.4`	172.475 ± 0.001
		`Hw7.1`	172.497 ± 0.001
		`Hw6.5`	172.495 ± 0.001

Ravasio et al. 1906.09166

Resummations

Current status: in several cases, the accuracy of all-order resummed predictions pushed to NNLL or even N^3LL, properly matched to fixed order

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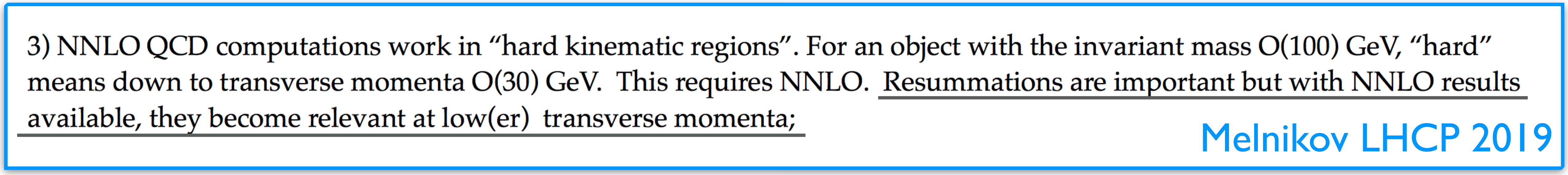
- On one side, once an accurate fixed order result is available, the impact of the resummation is limited to regions of low transverse momenta, see e.g.



3) NNLO QCD computations work in "hard kinematic regions". For an object with the invariant mass O(100) GeV, "hard" means down to transverse momenta O(30) GeV. This requires NNLO. Resummations are important but with NNLO results available, they become relevant at low(er) transverse momenta;

Melnikov LHCP 2019

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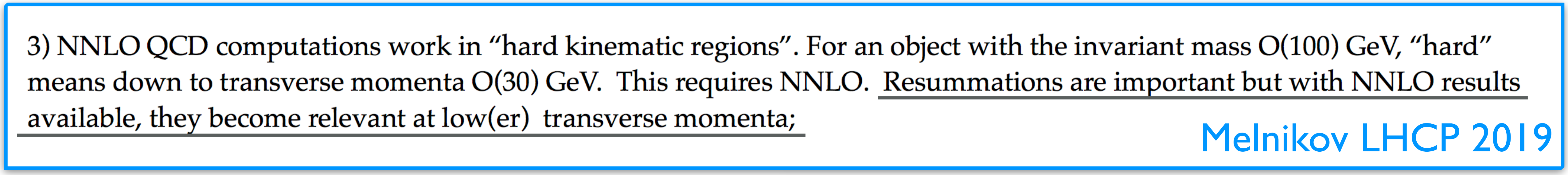

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- On the other side, resummed predictions are often inclusive and do not allow for fiducial cuts. This limits the applicability of resummed calculations

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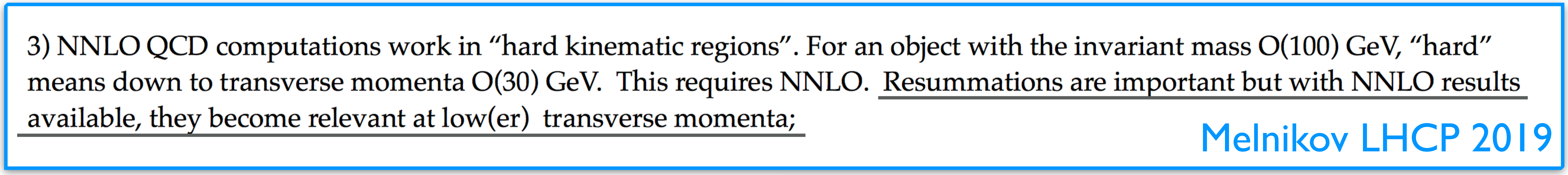

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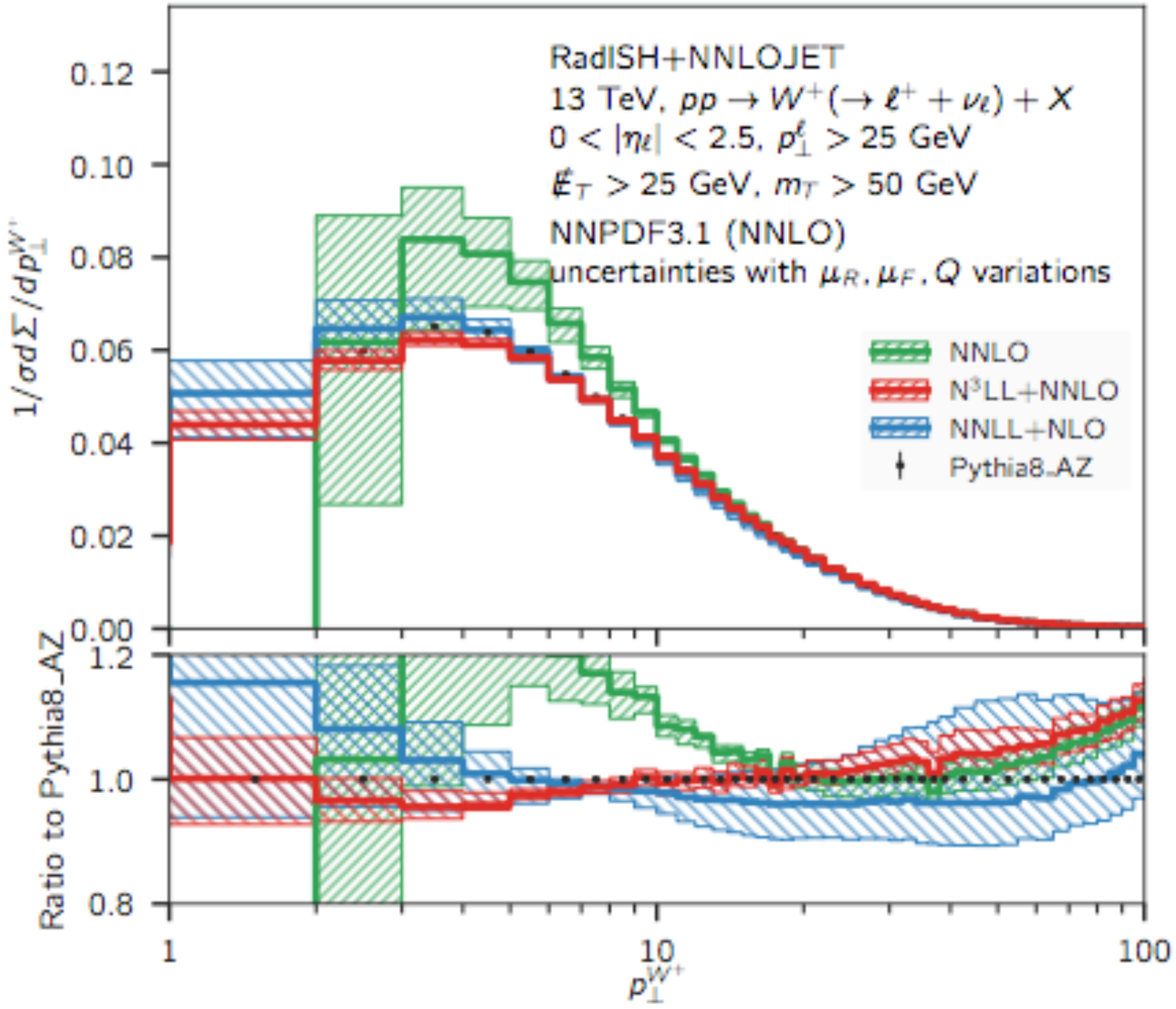
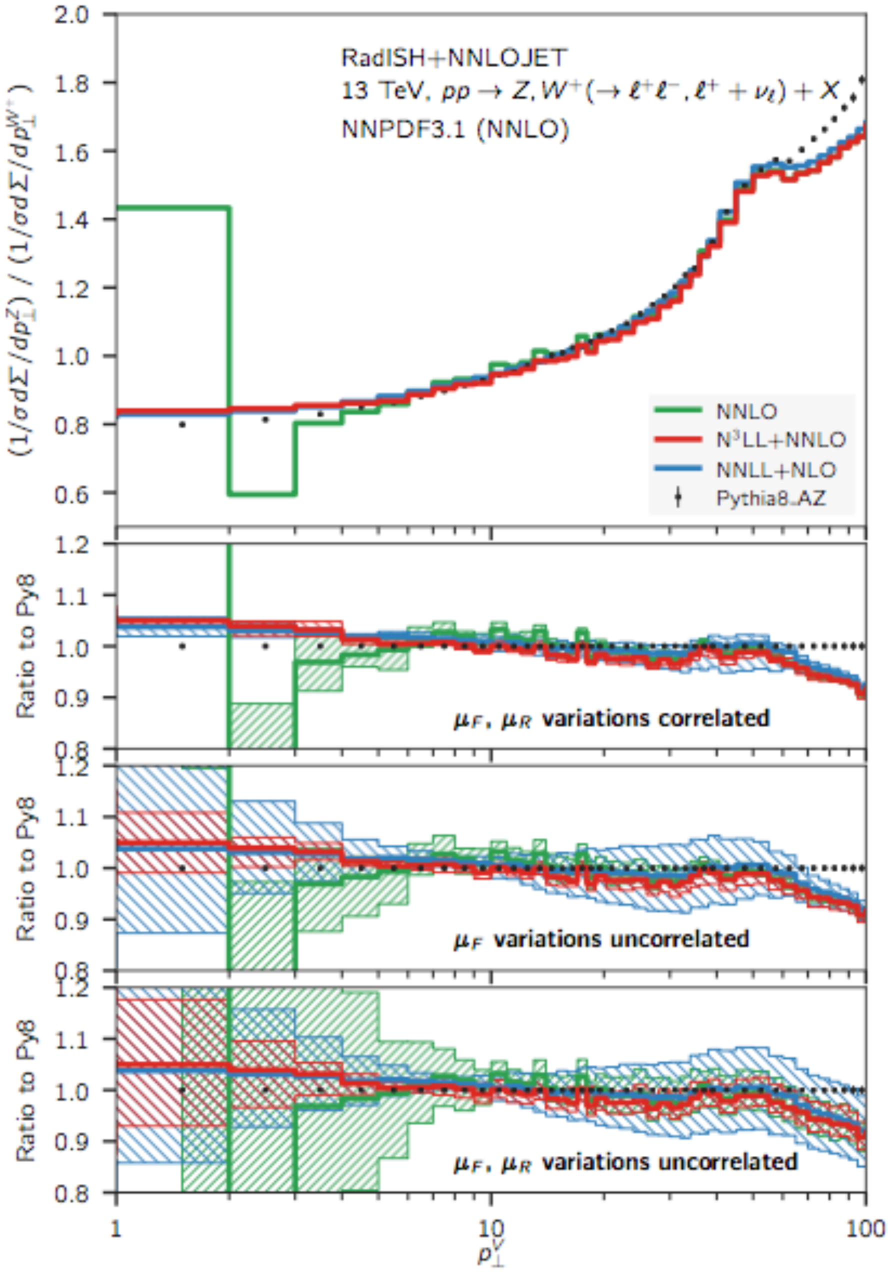
Both points seem to imply that resummations are not quite that useful. I want to argue that this is not true.

Resummations

<u>Selected example:</u> transverse momentum spectrum of weak bosons at $N^3LL+NNLO$ with fiducial cuts

Bizon et al. 1905.05171

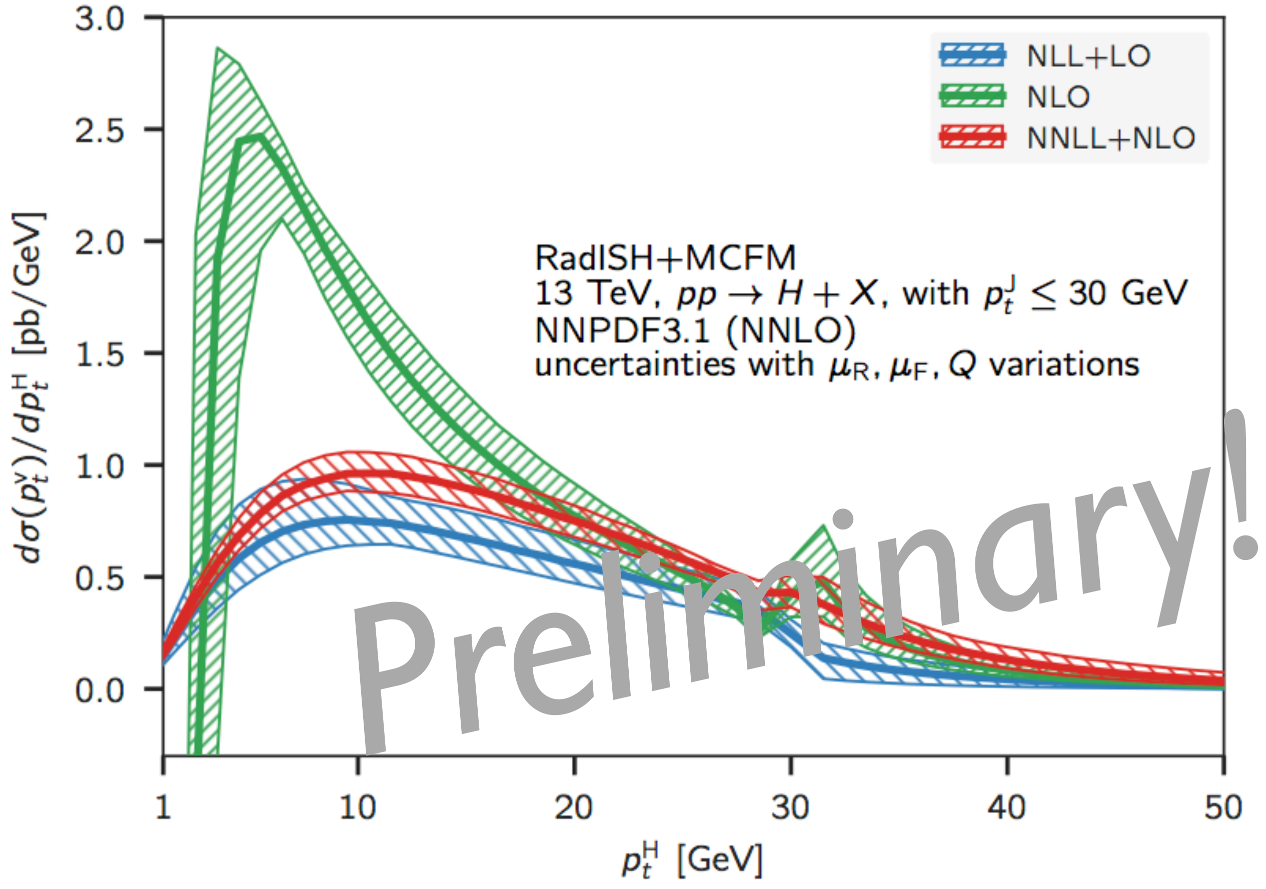




Joint resummations

Even if the hard scale is of O(100 GeV), fiducial cuts can push all the kinematics at low transverse momentum values, e.g. for Higgs production the bulk of the cross section lies well below 30 GeV

Double differential resummed predictions, e.g. NNLL resummed predictions for the Higgs transverse momentum with a veto on jets



Monni et al. '19

Reminder: jet-veto is required in the WW decay channel to suppress top background

Other joint resummmations

Increasing interest in resummations in more exclusive regions

• $p_{T,H}$ and small-x	Laenen et al. hep-ph/0010080; Kulesza et al. hep-ph/0309264 Lustermans et 1605.027400; Muselli et al. 1701.01464
• $p_{T,H}$ and large-x	Marzani 1511.06039; Forte and Muselli 1511.05561
• small-x and large-x	Bonvini and Marzani 1802.07758
• $p_{T,H}$ and jet-radius	Banfi et al. 1511.02886
• $p_{T,V}$ and 0-jettiness	Lustermans et al. 1901.03331
• 2 angularities	Larkoski et al. 1501.4458; Procura et al. 1806.10622

Resummations no longer limited to inclusive observables

⇒ closer connection between resummed predictions and measurements

Conclusions

- Precision QCD crucial to enhance sensitivity in the search for physics beyond the SM
- Theoretical calculations are reaching an impressive level of sophistication
- I presented a selection of recent new theoretical results
  - ➡ N^{3}LO, NNLO, automated EW, NLO+EW, loop-induded, NNLOPS, (joint) resummations, heavy-flavour effects, …
- Lots of room and need for improvements in various areas
- Precision is *not* just about computing one more order in perturbation theory, it is really a multilateral challenge