Loops and Multi-legs: Theory

Physics at TeV Colliders, Les Houches

2nd June 2015

Overview

Experiments always need smaller theory errors!

- LH wish-list 2013 - How well did we do?
  - New techniques for IR subtraction
  - New methods for multi-loop integrals
  - Many new predictions for $2 \rightarrow 2$ scattering processes
  - automated QCD+EW corrections
- Automated NLO is hard at work: NLO+PS, ME merging at NLO etc.

LH13 wishlist : Higgs and related

Process	State of the Art	Desired
H	dσ @ NNLO QCD (expansion in $1/m_{\mathrm{t}}$) full m_t/m_{b} dependence @ NLO QCD and @ NLO EW NNLO+PS, in the $m_t \to \infty$ limit	dσ @ NNNLO QCD (infinite-m_{t} limit) full $m_{\mathrm{t}}/m_{\mathrm{b}}$ dependence @ NNLO QCD and @ NNLO QCD+EW NNLO+PS with finite top quark mass effects
H + j	dσ @ NNLO QCD (g only) and finite-quark-mass effects @ LO QCD and LO EW	dσ @ NNLO QCD (infinite-m_{t} limit) and finite-quark-mass effects @ NLO QCD and NLO EW
H + 2j	σ_{tot}(VBF) @ NNLO(DIS) QCD dσ(VBF) @ NLO EW dσ(gg) @ NLO QCD (infinite-m_{t} limit) and finite-quark-mass effects @ LO QCD	dσ(VBF) @ NNLO QCD + NLO EW dσ(gg) @ NNLO QCD (infinite-m_{t} limit) and finite-quark-mass effects @ NLO QCD and NLO EW
H + V	dσ @ NNLO QCD dσ @ NLO EW σ_{tot}(gg) @ NLO QCD (infinite-m_{t} limit)	with $\mathrm{H} \to \mathrm{b\bar{b}}$ @ same accuracy dσ(gg) @ NLO QCD with full $m_{\mathrm{t}}/m_{\mathrm{b}}$ dependence
tH and $\mathrm{\bar{t}}$H	dσ(stable top) @ LO QCD	dσ(top decays) @ NLO QCD and NLO EW
$\mathrm{t\bar{t}}$H	dσ(stable tops) @ NLO QCD	dσ(top decays) @ NLO QCD and NLO EW
gg $\to$ HH	dσ @ NLO QCD (leading m_{t} dependence) dσ @ NNLO QCD (infinite-m_{t} limit)	dσ @ NLO QCD with full $m_{\mathrm{t}}/m_{\mathrm{b}}$ dependence

LH13 wishlist : Higgs and related

Anastasiou, Duhr, Dulat, Herzog, Mistlberger 1503.06056

Hamilton, Nason, Re, Zanderighi 1309.0017
Hamilton, Nason, Zanderighi 1501.04637

Boughezhal, Focke, Giele, Liu, Petriello 1505.03893

Boughezhal, Caola, Melnikov, Petriello, Schulze 1504.07922

gg only : Chen, Glover, Gehrmann, Jaquier 1408.5325

		Desired
	m_t) D and @ NLO EW NNLO+PS, in the $m_t \to \infty$ limit	$d\sigma$ @ NNNLO QCD (infinite-m_t limit) full m_t/m_b dependence @ NNLO QCD and @ NNLO QCD+EW NNLO+PS with finite top quark mass effects
H + j	$d\sigma$ @ NNLO QCD (g only)	$d\sigma$ @ NNLO QCD (infinite-m_t limit) and finite-quark-mass effects @ NLO QCD and NLO EW
	$d\sigma(gg)$ @ NLO QCD (infinite-m_t limit) QCD	$d\sigma$(VBF) @ NNLO QCD + NLO EW $d\sigma(gg)$ @ NNLO QCD (infinite-m_t limit) and finite-quark-mass effects @ NLO QCD and NLO EW
	mit)	with $H \to b\bar{b}$ @ same accuracy $d\sigma(gg)$ @ NLO QCD with full m_t/m_b dependence
		$d\sigma$(top decays) @ NLO QCD and NLO EW
		$d\sigma$(top decays) @ NLO QCD and NLO EW
	dence) $d\sigma$ @ NNLO QCD (infinite-m_t limit)	$d\sigma$ @ NLO QCD with full m_t/m_b dependence

automated NLO
e.g. aMC@NLO_MG5

finite top mass corrections at NNLO still challenging

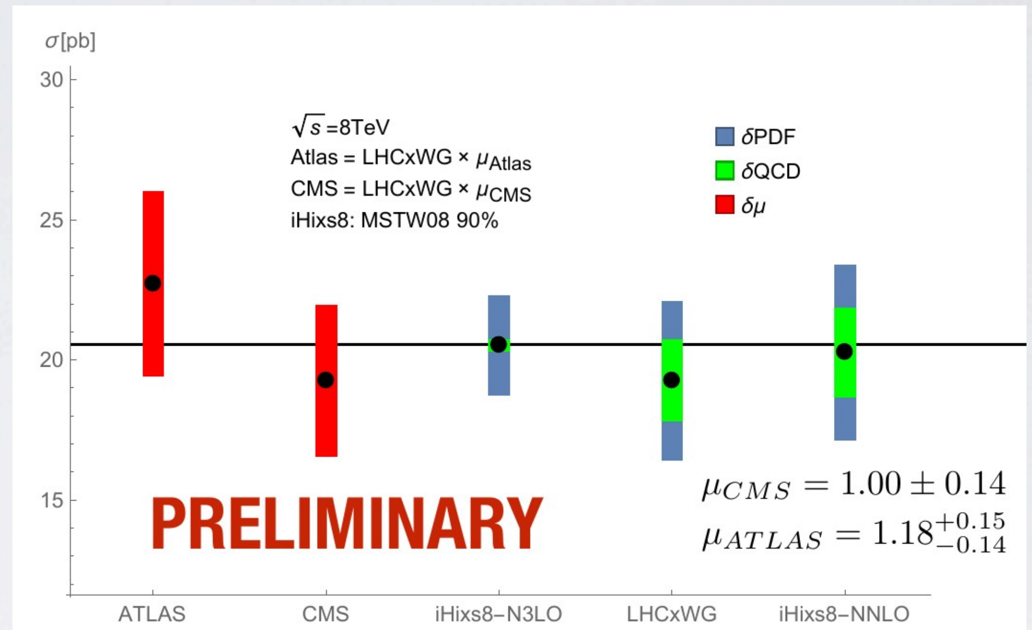
Precise Higgs predictions

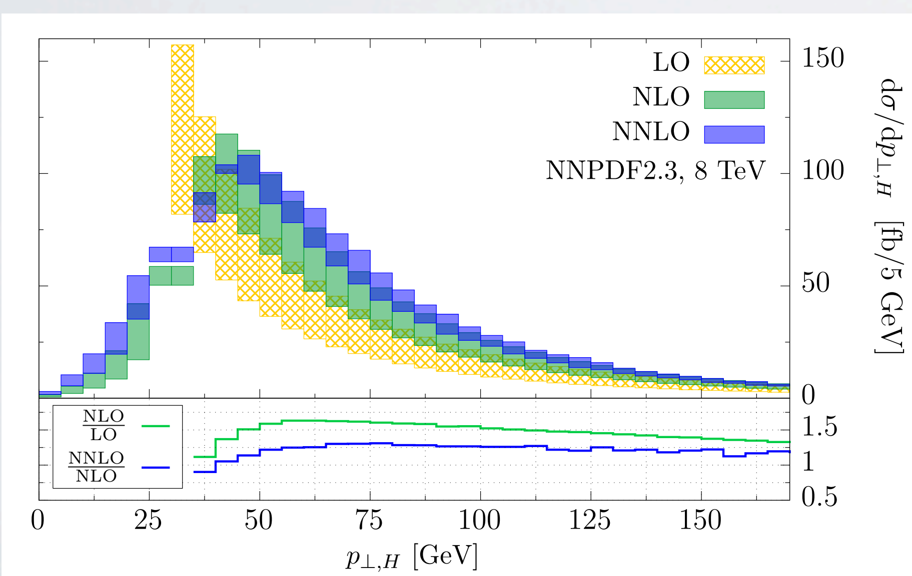
inclusive N^3LO

scale var. ~ 3-5%

PDF error dominates

[e.g. Herzog, PSR15 Kraków]

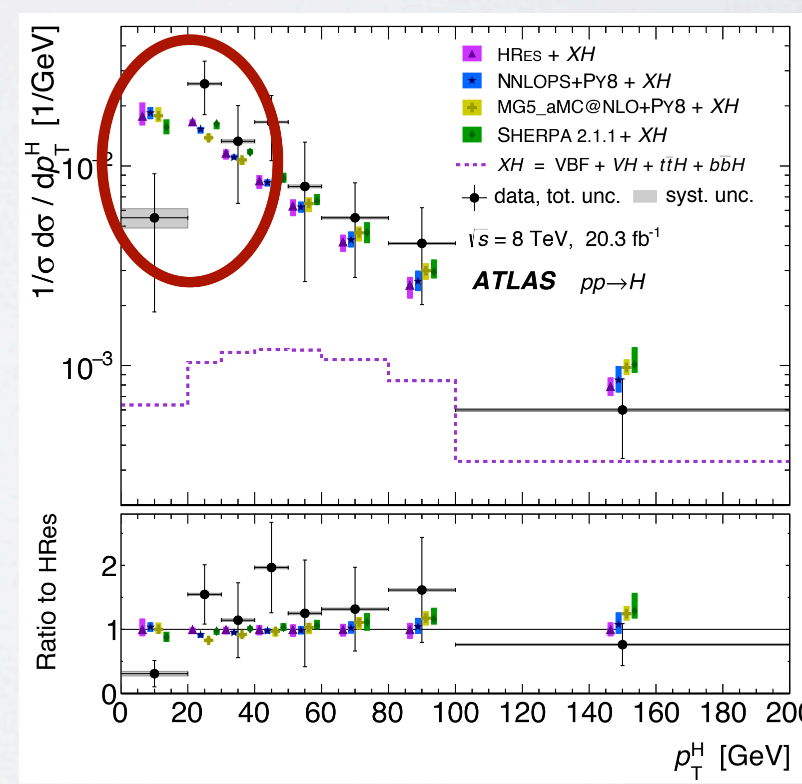




scale var. ~ 8%

PDF error ~ 5%

Boughezhal et al. 1504.07922



differential NNLO H+1j

LH13 wishlist : top and jets

Process	State of the Art	Desired
$t\bar{t}$	σ_{tot}(stable tops) @ NNLO QCD $d\sigma$(top decays) @ NLO QCD $d\sigma$(stable tops) @ NLO EW	$d\sigma$(top decays) @ NNLO QCD + NLO EW
$t\bar{t} + j(j)$	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(NWA top decays) @ NNLO QCD + NLO EW
$t\bar{t} + Z$	$d\sigma$(stable tops) @ NLO QCD	$d\sigma$(top decays) @ NLO QCD + NLO EW
single-top	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(NWA top decays) @ NNLO QCD + NLO EW
dijet	$d\sigma$ @ NNLO QCD (g only) $d\sigma$ @ NLO EW (weak)	$d\sigma$ @ NNLO QCD + NLO EW
3j	$d\sigma$ @ NLO QCD	$d\sigma$ @ NNLO QCD + NLO EW
$\gamma + j$	$d\sigma$ @ NLO QCD $d\sigma$ @ NLO EW	$d\sigma$ @ NNLO QCD + NLO EW

LH13 wishlist : top and jets

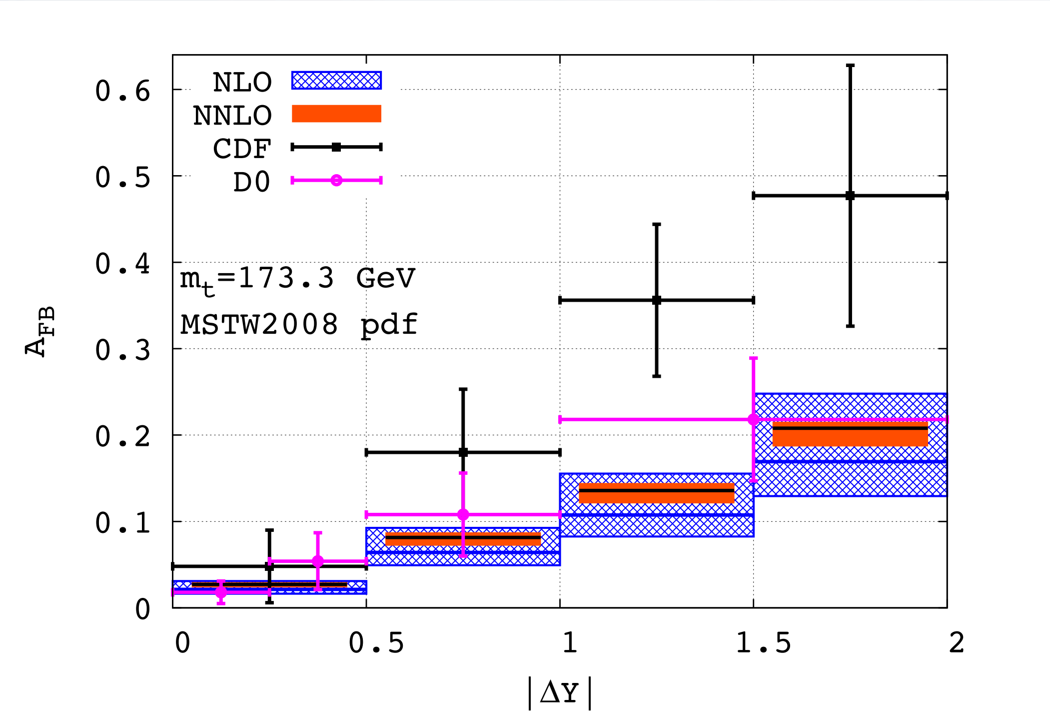
Process	State of the Art	Desired
	… QCD … D … V	dσ(top decays) @ NNLO QCD + NLO EW
	… LO QCD	dσ(NWA top decays) @ NNLO QCD + NLO EW
$t\bar{t} + Z$	dσ(stable tops) @ NLO QCD	dσ(top decays) @ NLO QCD + NLO EW
	… NLO QCD	dσ(NWA top decays) @ NNLO QCD + NLO EW
	… y) dσ @ NLO EW (weak)	dσ @ NNLO QCD + NLO EW
3j	dσ @ NLO QCD	dσ @ NNLO QCD + NLO EW
$\gamma + j$	dσ @ NLO QCD	dσ @ NNLO QCD + NLO EW

differential for Tevatron (qq):
Czakon, Fiedler, Mitov 1411.3007

t-channel:
Brucherseifer, Caola, Melnikov
1404.7116

Currie, Gehrmann, Gehrmann, Glover,
Pires 15xx.xxxxx

Precision Top and jets



Czakon, Fiedler, Mitov 1411.3007

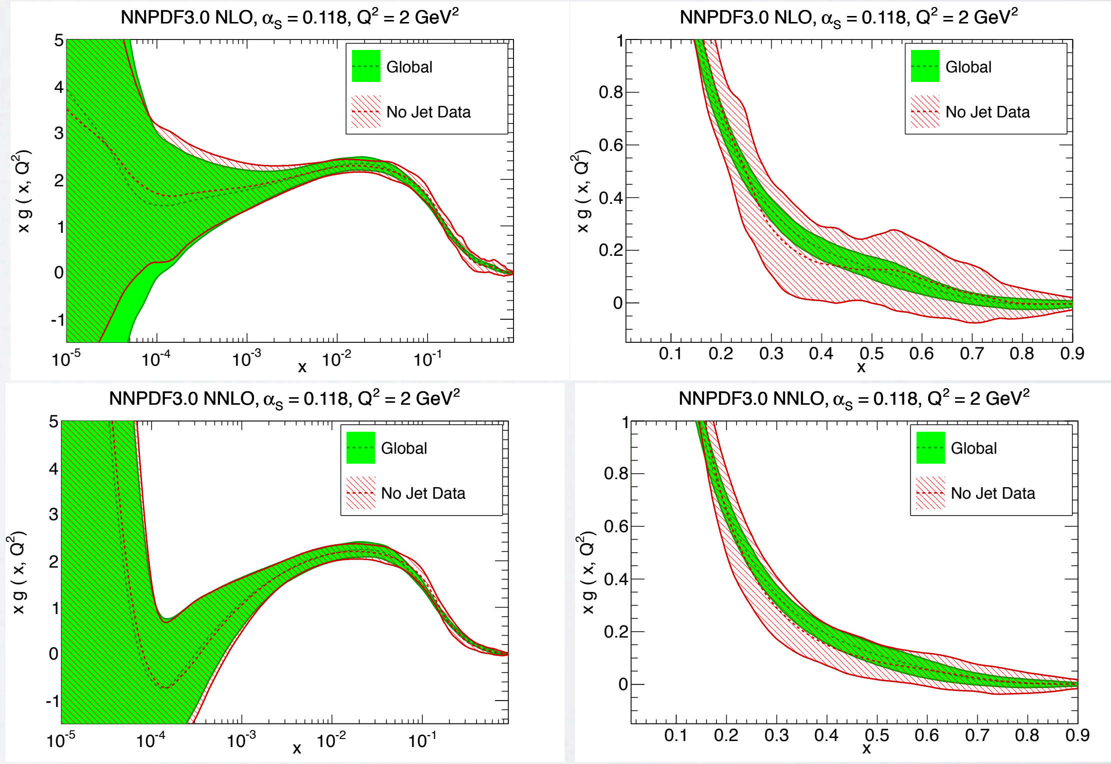
better agreement between theory and data for A_{FB} at Tevatron

LHC distributions on the way

faster/more efficient code in development

jets at NNLO expected to have important impact on the gluon PDF

NNPDF3.0 approx. NNLO di-jets only



LH13 wishlist : EW gauge bosons

Process	State of the Art	Desired
V	$d\sigma$(lept. V decay) @ NNLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNNLO QCD and @ NNLO QCD+EW NNLO+PS
V + j(j)	$d\sigma$(lept. V decay) @ NLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNLO QCD + NLO EW
VV'	$d\sigma$(V decays) @ NLO QCD $d\sigma$(on-shell V decays) @ NLO EW	$d\sigma$(decaying off-shell V) @ NNLO QCD + NLO EW
$gg \to VV$	$d\sigma$(V decays) @ LO QCD	$d\sigma$(V decays) @ NLO QCD
$V\gamma$	$d\sigma$(V decay) @ NLO QCD $d\sigma$(PA, V decay) @ NLO EW	$d\sigma$(V decay) @ NNLO QCD + NLO EW
$Vb\bar{b}$	$d\sigma$(lept. V decay) @ NLO QCD massive b	$d\sigma$(lept. V decay) @ NNLO QCD + NLO EW, massless b
$VV'\gamma$	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW
$VV'V''$	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW
$VV' + j$	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW
$VV' + jj$	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW
$\gamma\gamma$	$d\sigma$ @ NNLO QCD + NLO EW	q_T resummation at NNLL matched to NNLO

LH13 wishlist : EW gauge bosons

Process	State of the Art	Desired
V	dσ(lept. V decay) @ NNLO QCD	dσ(lept. V decay) @ NNNLO QCD and @ NNLO QCD+EW NNLO+PS
V + j(j)	dσ(lept. V decay) @ NLO QCD NLO EW	dσ(lept. V decay) @ NNLO QCD + NLO EW
	QCD @ NLO EW	dσ(decaying off-shell V) @ NNLO QCD + NLO EW
gg → VV	dσ(V decays) @ LO QCD	dσ(V decays) @ NLO QCD
Vγ	dσ(V decay) @ NLO QCD dσ(PA, V decay) @ NLO EW	dσ(V decay) @ NNLO QCD +
		dσ(lept. V decay + NLO EW, ma
		dσ(V decays) @ NLO QCD +
		dσ(V decays) @ NLO QCD +
		dσ(V decays) @ NLO QCD + NLO EW
		dσ(V decays) @ NLO QCD + NLO EW
		q_T resummation at NNLL matched to NNLO

Karlberg, Re, Zanderighi arXiv:1407.2940

Boughezal, Focke, Giele, Liu, Petriello arXiv:1504.02131

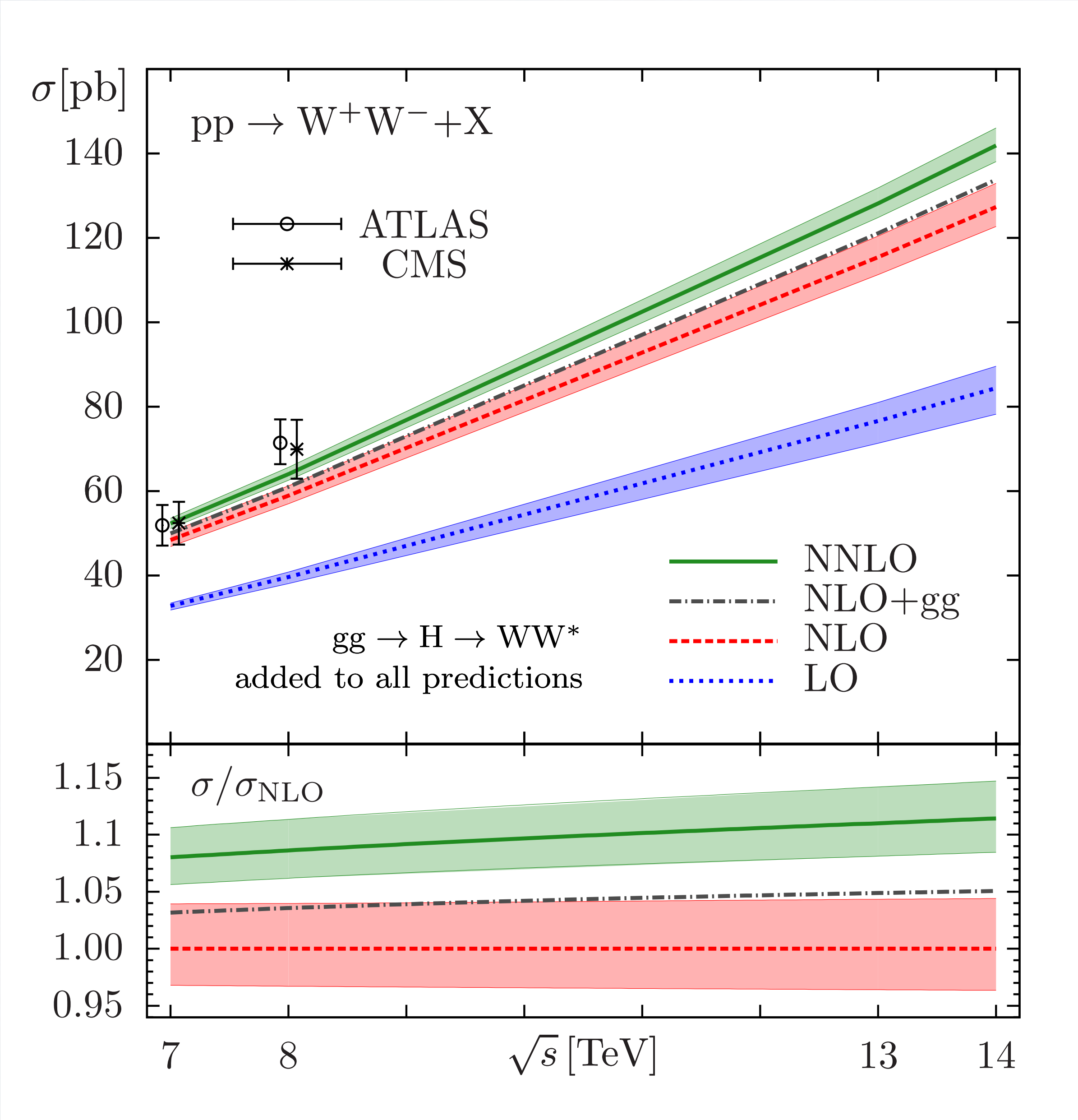
Cascoli, Grazzini, Kallweit, Rathlev, Gehrmann, Pozzorini, von Manteuffel, Maierhofer, Tancredi, Torre, Weihs

arXiv:1309.7000, 1405.2219, 1408.5243, 1504.01330

VV* amplitudes
Caola, Henn, Melnikov, Smirnov, Smirnov arXiv: 1408.6409, arXiv: 1503.08759

Cieri, Coradeschi, de Florian arXiv:1505.03162

pp → W⁺W⁻



NNLO inclusive in better agreement with ATLAS and CMS

[Gehrmann, Grazzini, Kallweit, Maierhöfer, von Manteuffel, Pozzorini, Rathlev, Tancredi 1408.5243]

discrepancies can also arise due to systematic errors when extrapolating fiducial results to inclusive ones

[Monni, Zanderighi 1410.4745]

NNLO methods

IR subtraction

Antenna [Glover et al.]

STRIPPER [Czakon]

qT [Catani, Grazzini]

N-Jettiness [Bougezhal et al.]

talk tomorrow from F. Petriello

CPU intensive

improving convergence
(locality, mis-binning)

multi-loop techniques

canonical differential equations [Henn (2013)]

direct integration [Panzer (2014)]

$pp \to VV^*$ [Caola et al. (2015)]

prospects for $2 \to 3$?
($pp \to 3j$ / $pp \to H+2j$)

multi-scale integrals still unknown

unknown functions for integrals with internal masses

automated NNLO subtractions

Czakon, PSR15 Kraków

Collection of matrix elements required

$$\langle \mathcal{M}_n^{(0)} | \mathcal{M}_n^{(0)} \rangle, \quad \langle \mathcal{M}_n^{(0)} | \mathbf{T}_i \cdot \mathbf{T}_j | \mathcal{M}_n^{(0)} \rangle, \quad \langle \mathcal{M}_n^{(0)} | \lambda_i \rangle \langle \lambda'_i | \mathcal{M}_n^{(0)} \rangle,$$
$$\langle \mathcal{M}_n^{(0)} | \{ \mathbf{T}_i \cdot \mathbf{T}_j, \mathbf{T}_k \cdot \mathbf{T}_l \} | \mathcal{M}_n^{(0)} \rangle, \quad \langle \mathcal{M}_n^{(0)} | f^{abc} T_i^a T_j^b T_k^c | \mathcal{M}_n^{(0)} \rangle,$$
$$\langle \mathcal{M}_n^{(0)} | \mathbf{T}_i \cdot \mathbf{T}_j | \lambda_k \rangle \langle \lambda'_k | \mathcal{M}_n^{(0)} \rangle, \quad \langle \mathcal{M}_n^{(0)} | \lambda_i \lambda_j \rangle \langle \lambda'_i \lambda'_j | \mathcal{M}_n^{(0)} \rangle,$$
$$\langle \mathcal{M}_{n+1}^{(0)} | \mathcal{M}_{n+1}^{(0)} \rangle, \quad \langle \mathcal{M}_{n+1}^{(0)} | \mathbf{T}_i \cdot \mathbf{T}_j | \mathcal{M}_{n+1}^{(0)} \rangle, \quad \langle \mathcal{M}_{n+1}^{(0)} | \lambda_i \rangle \langle \lambda'_i | \mathcal{M}_{n+1}^{(0)} \rangle,$$
$$\langle \mathcal{M}_{n+2}^{(0)} | \mathcal{M}_{n+2}^{(0)} \rangle, \quad \langle \mathcal{M}_n^{(0)} | \mathcal{M}_n^{(1)} \rangle, \quad \langle \mathcal{M}_n^{(0)} | \mathbf{T}_i \cdot \mathbf{T}_j | \mathcal{M}_n^{(1)} \rangle,$$
$$\langle \mathcal{M}_n^{(0)} | \lambda_i \rangle \langle \lambda'_i | \mathcal{M}_n^{(1)} \rangle, \quad \langle \mathcal{M}_{n+1}^{(0)} | \mathcal{M}_{n+1}^{(1)} \rangle,$$
$$\langle \mathcal{M}_n^{(1)} | \mathcal{M}_n^{(1)} \rangle, \quad \langle \mathcal{M}_n^{(0)} | \mathcal{M}_n^{(2)} \rangle.$$

BLHA accord should be able to provide these matrix elements in the near future

rather simple extension - should make it's standardised

STRIPPER implementation: Czakon, Heymes, van Hameren (work in progress)

similar efforts with Antenna subtraction

one-loop codes are able to provide the necessary ingredients but precision and speed are more important

NLO EW+QCD

aMC@NLO_MADGRAPH5

RECOLA OPENLOOPS

GOSAM

automated EW+QCD

$pp \to Z + 3j$ (EW Sudakov's)[Chiesa, Montagnia , Barzè, Moretti, Nicrosini, Piccinni, Tramontano 1305.6837]

$pp \to t\bar{t}H$ [Yu Zhang et al. 1407.1110][Frixione et al. 1407.0823]

$pp \to Z + 2j$ [Denner, Hofer, Scharf, Uccirati 1411.0916]

$pp \to W + \gamma$ [Denner, Dittmaier, Hecht, Pasold 1412.7412]

$pp \to W + \leq 3j$ [Kallweit, Lindert, Maierhöfer, Pozzorini, Schönherr 1412.5157]

QCD x EW for Drell-Yan [Dittmaier, Huss, Schwinn 1403.3216]

[w/ interleaved QED/QCD shower Barzè et al. 1202.0465, 1302.4606, 1408.5766]

NLO EW+QCD

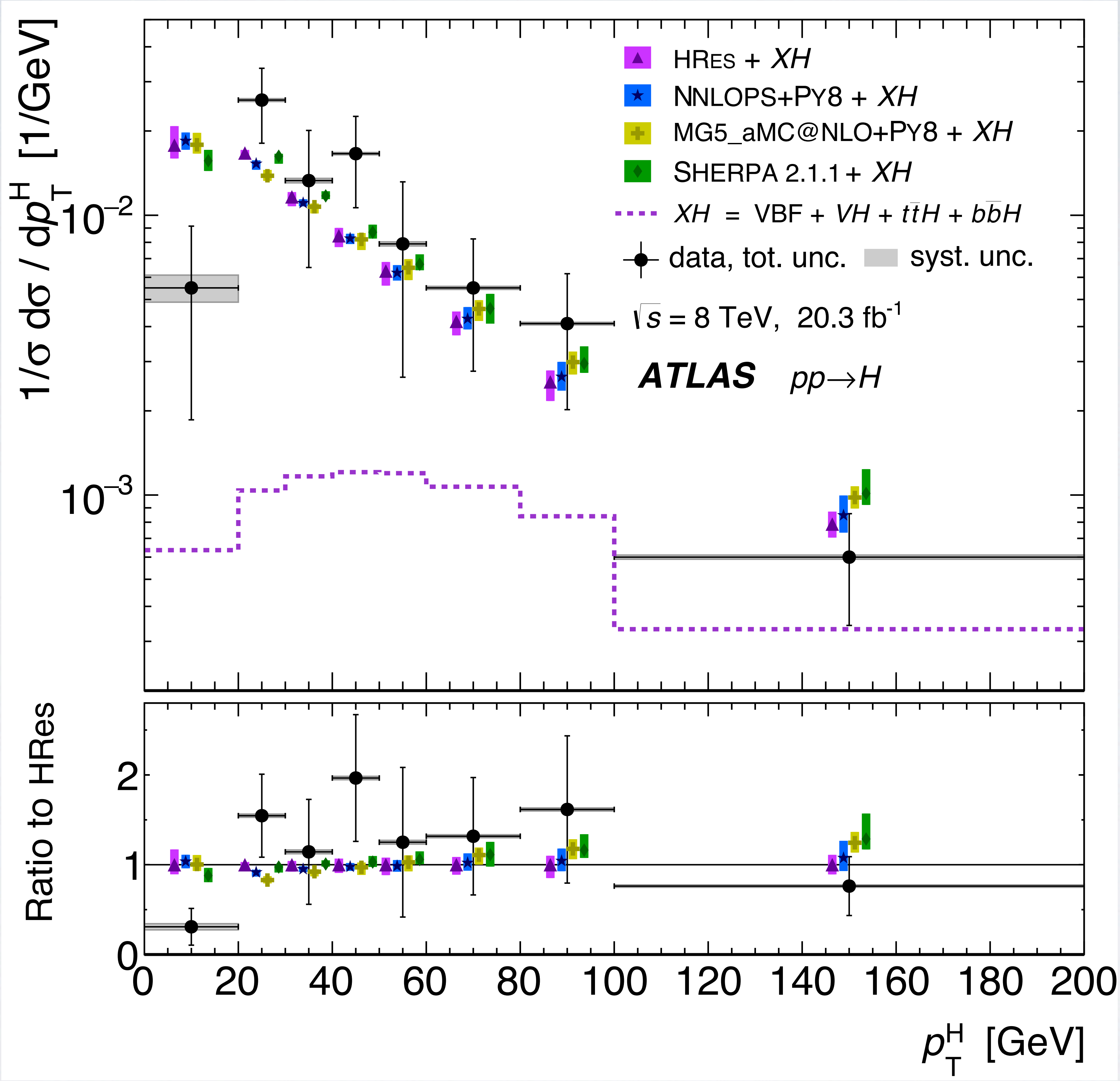
- improved QED PDFs [NNPDF2.3, other groups in progress]
  - impact of photon induced processes
  - uncertainties in photon PDFs

- better understanding of EW+QCD matching to parton shower?

- assessment/comparison of the current EW+QCD tools: are we providing the necessary predictions to the experiments?

Outlook

- Overall: good progress for NNLO and NLO+EW since 2013
- Further development of NNLO tools needed for widespread use in the experimental analyses [Ntuples, ApplGrid, Rivet,...]
- NNLO beyond 2 → 3 still needs a lot of work - projects are underway
  - bottleneck at NNLO now in double virtual corrections
- Comparisons between new fixed order NNLO and NLO MC techniques
  - understanding theoretical errors (NNLO vs merged NLO)
  - impact of re-summations (Parton showers/explicit re-summation)
  - dynamical scale choices (e.g. m_H vs H_T vs CKKW/MiNLO in H+j)



HRES + XH
NNLOPS+PY8 + XH
MG5_aMC@NLO+PY8 + XH
SHERPA 2.1.1 + XH
XH = VBF + VH + ttH + bbH
data, tot. unc.
syst. unc.
√s = 8 TeV, 20.3 fb-1
ATLAS pp→H
1/σ dσ / dpTH [1/GeV]
Ratio to HRes
pTH [GeV]