Call for MC&Tools for RUN-2

Review on experimental needs for (N)NLO MC and Tools for RUN-2

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on behalf of the ATLAS and CMS collaborations

Introduction

- (almost) all Higgs results from Run 1 are **statistically limited**
- **Run-2 [2015-2018]**
  - x5 more luminosity [100/fb]
  - x2 increase in Higgs cross section (8 —> 13 TeV)

x10 more Higgs

—> the statistical uncertainty — and all the statistically related experimental uncertainties — will rapidly decrease!

- **Increasingly precise predictions** for Higgs signal and backgrounds
  - improved analytical calculations of inclusive and differential cross sections
  - Broad spectrum of (N)NLO event generators available in the past few years

—> ATLAS/CMS gearing up to use them in Run 2

In these slides:

- how theoretical predictions affected Run 1 results
- selected still-open topics of discussion

Not exhaustive list!

ATLAS + CMS combination: signal strength

CDS record 2053103

SM signal yields in all channels scaled by same global signal strength mu assuming SM ratios of production cross-sections and decay rates

$$\mu_i^f = \frac{\sigma_i \cdot \mathrm{BR}^f}{(\sigma_i)_{\mathrm{SM}} \cdot (\mathrm{BR}^f)_{\mathrm{SM}}} = \mu_i \times \mu^f$$

	Best-fit μ	Uncertainty				
		Total	Stat	Expt	Thbgd	Thsig
ATLAS and CMS (meas.)	1.09	$^{+0.11}_{-0.10}$	$^{+0.07}_{-0.07}$	$^{+0.04}_{-0.04}$	$^{+0.03}_{-0.03}$	$^{+0.07}_{-0.06}$
ATLAS and CMS (exp.)	–	$^{+0.11}_{-0.10}$	$^{+0.07}_{-0.07}$	$^{+0.04}_{-0.04}$	$^{+0.03}_{-0.03}$	$^{+0.06}_{-0.06}$

Most precise result at the expense of the largest assumptions

signal theoretical uncertainties same size as statistical uncertainty
—> in Run 2, statistical uncertainty will decrease quickly

Profile likelihood formalism for (systematic) uncertainties

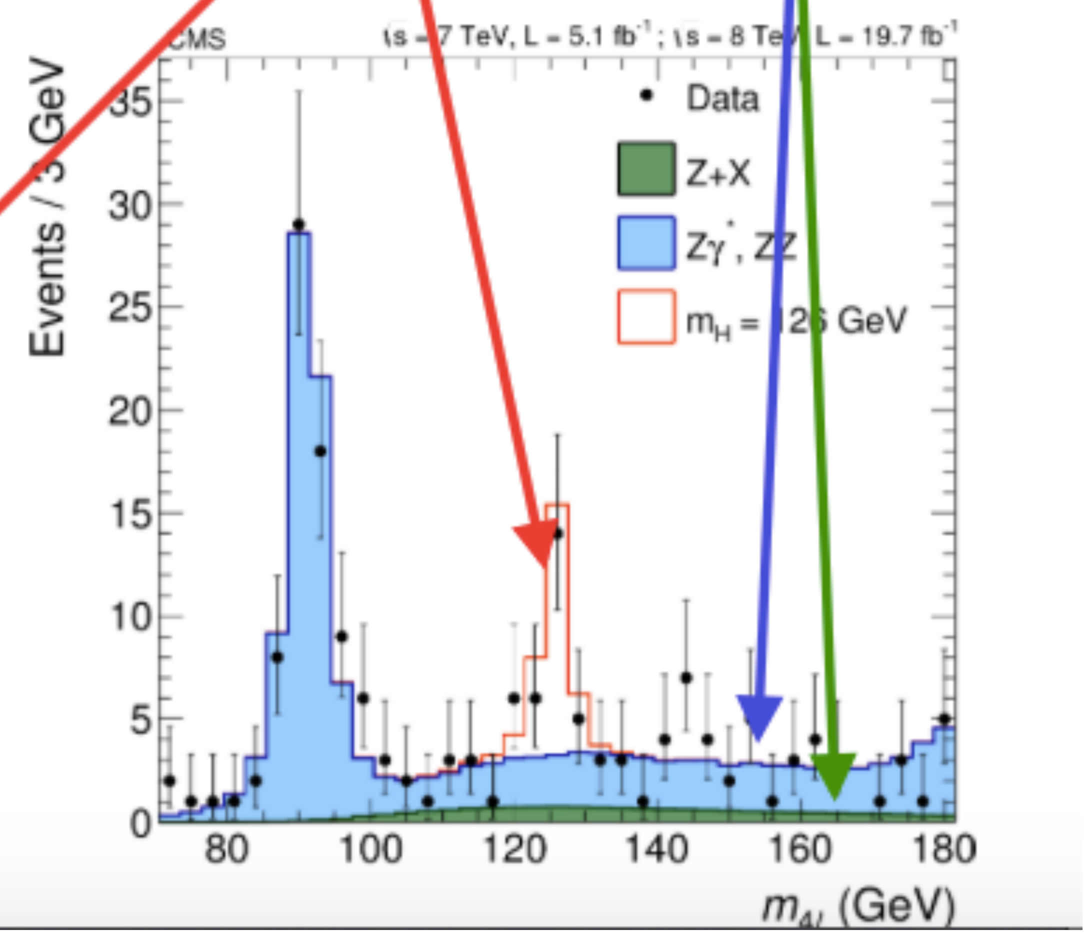
- Build likelihood function for *each* signal, control region of the data

i→H→f *Background*

$$L(\vec{N}\,|\,\vec{\mu}_i,\vec{\mu}_f,\vec{\theta}) = \prod_{k=0,nbins} Poisson\left(N_k\,|\sum_{i,f}\mu_i\cdot\mu^f\cdot S^f_{i,k}(\vec{\theta}) + \sum_m B_m(\vec{\theta}))\right)$$

Inclusive SM cross-section
Acceptance (from MC)
Efficiency (from MC)
Higgs BR
Luminosity

$$\mathcal{L}(k)\times\left\{\sigma_i^{\mathrm{SM}}\times A_i^f(k)\times\varepsilon_i^f(k)\times \mathrm{BR}^f_{\mathrm{SM}}\right\}$$



Profile likelihood formalism for (systematic) uncertainties

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Inclusive SM cross-section

Acceptance (from MC)

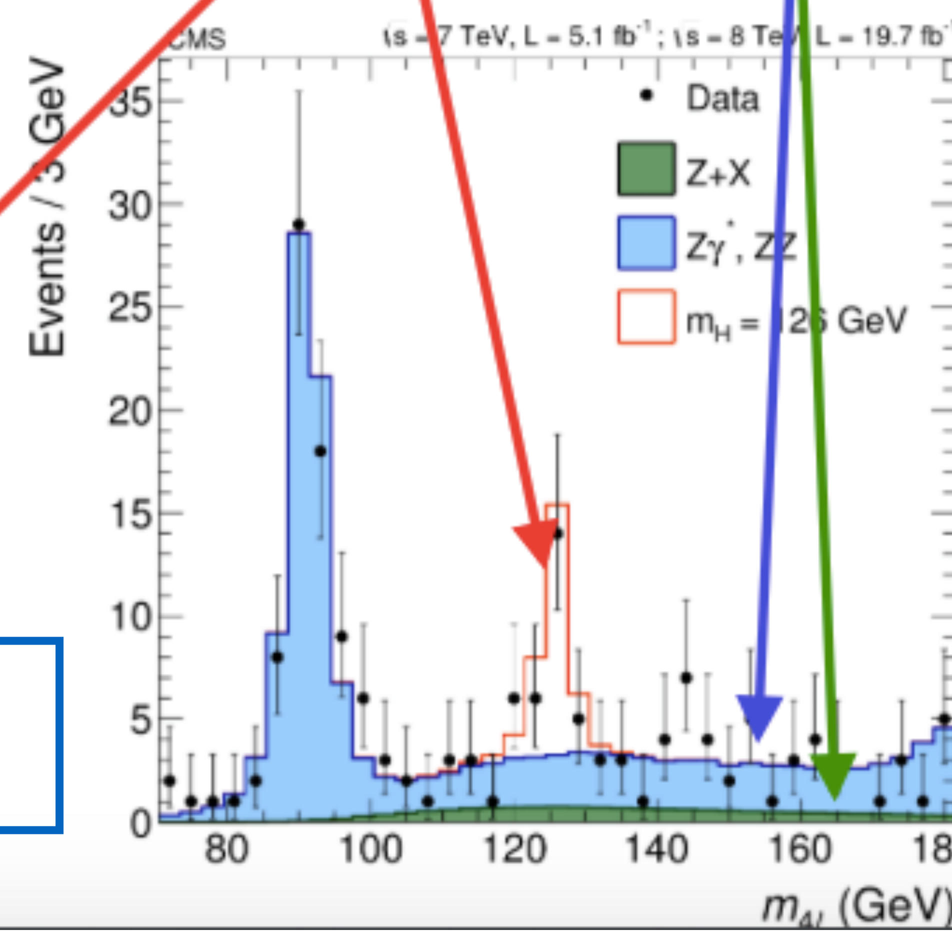
Efficiency (from MC)

Higgs BR

Luminosity

$$\mathcal{L}(k) \times \left\{ \sigma_i^{SM} \times A_i^f(k) \times \varepsilon_i^f(k) \times BR^f_{SM} \right\}$$

affected by theory uncertainties on
inclusive SM cross sections and BR



Profile likelihood formalism for (systematic) uncertainties

Assume SM Higgs boson for acceptance & efficiency

Production process	Event generator	
	ATLAS	CMS
ggF *	POWHEG [30–34]	POWHEG
VBF	POWHEG	POWHEG
WH	PYTHIA8 [35]	PYTHIA6.4 [36]
ZH ($qq \to ZH$ or $gg \to ZH$)	PYTHIA8	PYTHIA6.4
$ggZH$ ($gg \to ZH$)	POWHEG	See text
ttH	POWHEL [44]	PYTHIA6.4
tHq ($qb \to tHq$)	MADGRAPH [46]	aMC@NLO [29]
tHW ($gb \to tHW$)	aMC@NLO	aMC@NLO
bbH	PYTHIA8	PYTHIA6, aMC@NLO

(*) Higgs p_T distribution of ggF production reweighted to match HiRes 2.1calculation (includes NNLO and NNLL QCD corrections)

- Build likelih… data

…kground

$L(\vec{N} \mid \vec{\mu}_i, \vec{\mu}$ … $B_m(\vec{\theta}))$

Inclusive …

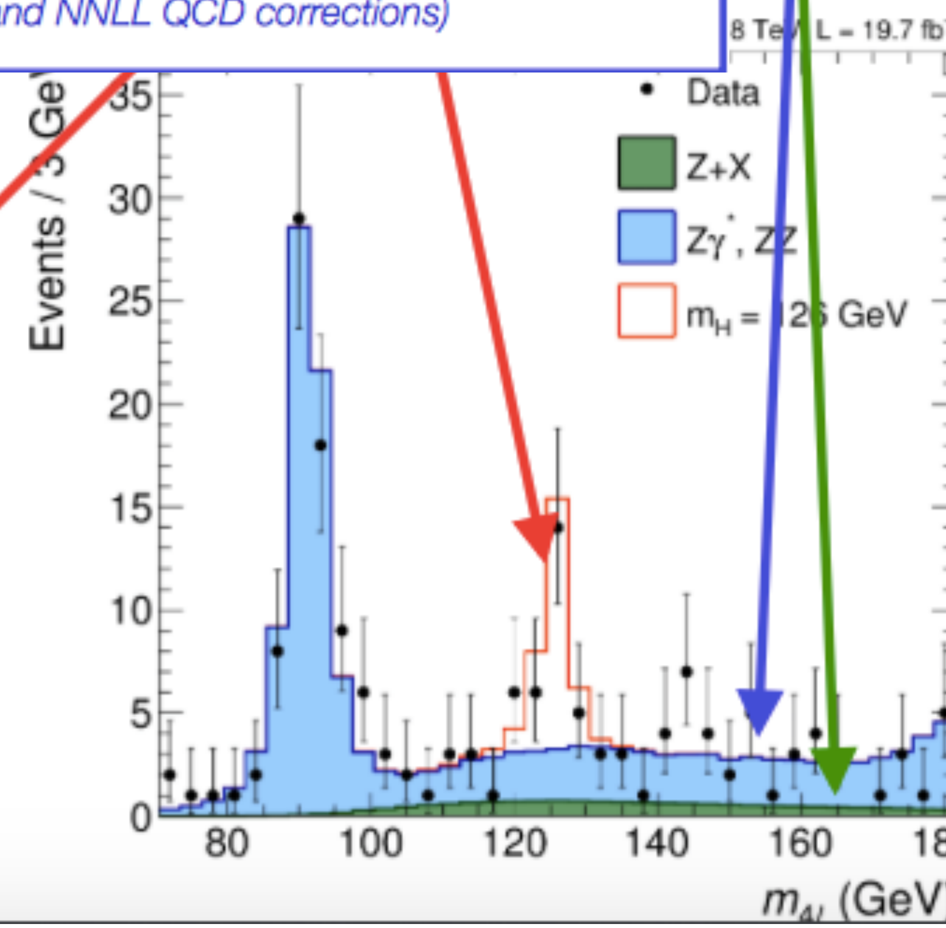
Acceptance (from MC)

Efficiency (from MC)

Higgs BR

Luminosity

$$\mathcal{L}(k) \times \{\sigma_i^{SM} \times \boxed{A_i^f(k) \times \varepsilon_i^f(k)} \times BR_{SM}^f\}$$



Profile likelihood formalism for (systematic) uncertainties

- Build likelihood function for *each* signal, control region of the data

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Inclusive SM cross-section

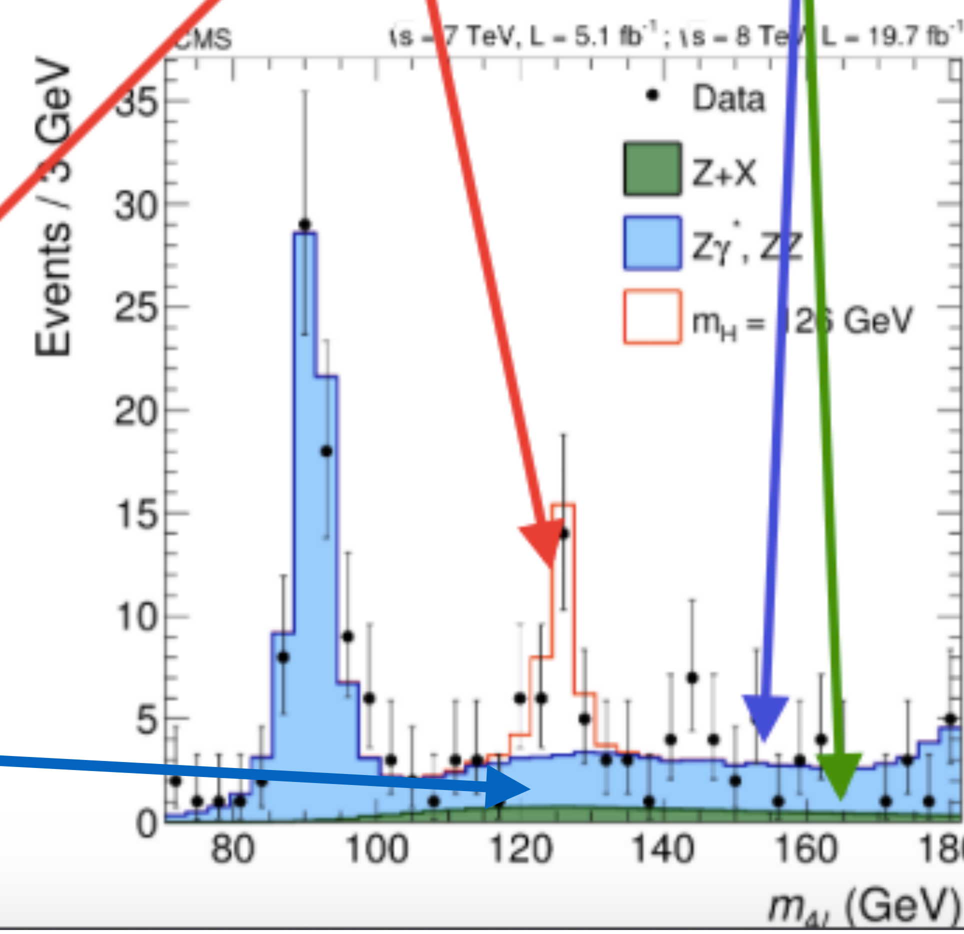
Acceptance (from MC)

Efficiency (from MC)

Higgs BR

Luminosity

$$\mathcal{L}(k) \times \{\sigma_i^{\mathrm{SM}} \times A_i^f(k) \times \varepsilon_i^f(k) \times \mathrm{BR}^f_{\mathrm{SM}}\}$$



Backgrounds are mostly data-driven, except WW, ZZ and tt+h.f./V+h.f.

μ_{ggF} versus μ_{VBF}

- exclusive final states very limited by statistical uncertainty
- theory uncertainties in exclusive regions are larger

ATLAS, H->WW, PhysRevD.92.012006

Source	Observed $\mu = 1.09$ Error +	Error −	Plot of error (scaled by 100)	Observed $\mu_{ggF} = 1.02$ Error +	Error −	Plot of error (scaled by 100)	Observed $\mu_{VBF} = 1.27$ Error +	Error −	Plot of error (scaled by 100)
Data statistics	0.16	0.15		0.19	0.19		0.44	0.40	
Signal regions	0.12	0.12		0.14	0.14		0.38	0.35	
Profiled control regions	0.10	0.10		0.12	0.12		0.21	0.18	
Profiled signal regions	-	-	-	0.03	0.03		0.09	0.08	
MC statistics	0.04	0.04		0.06	0.06		0.05	0.05	
Theoretical systematics	0.15	0.12		0.19	0.16		0.22	0.15	
Signal $H \to WW^*$ $\mathcal{B}$	0.05	0.04		0.05	0.03		0.07	0.04	
Signal ggF cross section	0.09	0.07		0.13	0.09		0.03	0.03	
Signal ggF acceptance	0.05	0.04		0.06	0.05		0.07	0.07	
Signal VBF cross section	0.01	0.01		-	-	-	0.07	0.04	
Signal VBF acceptance	0.02	0.01		-	-	-	0.15	0.08	
Background WW	0.06	0.06		0.08	0.08		0.07	0.07	
Background top quark	0.03	0.03		0.04	0.04		0.06	0.06	
Background misid. factor	0.05	0.05		0.06	0.06		0.02	0.02	
Others	0.02	0.02		0.02	0.02		0.03	0.03	
Experimental systematics	0.07	0.06		0.08	0.08		0.18	0.14	
Integrated luminosity	0.03	0.03		0.03	0.02		0.05	0.03	
Total	0.23	0.21		0.29	0.26		0.53	0.45	
			-30 -15 0 15 30			-30 -15 0 15 30			-60 -30 0 30 60

$\Delta\mu(\text{stat})/\mu_{VBF} = 34\%$

$\Delta\mu(\text{ThSig})/\mu_{VBF} = 17\%$

Generic parameterisations of experimental results

CDS record 2053103

- **k-framework**, using ratios of coupling modifiers

$$\sigma_i \cdot \mathrm{BR}^f = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_{\mathrm{H}}}, \qquad \kappa_j^2 = \sigma_j / \sigma_j^{\mathrm{SM}} \ \text{ or } \ \kappa_j^2 = \Gamma^j / \Gamma^j_{\mathrm{SM}}.$$

affected by same theoretical uncertainties as signal strength

- Most **generic model** is ratio of cross sections and branching ratios

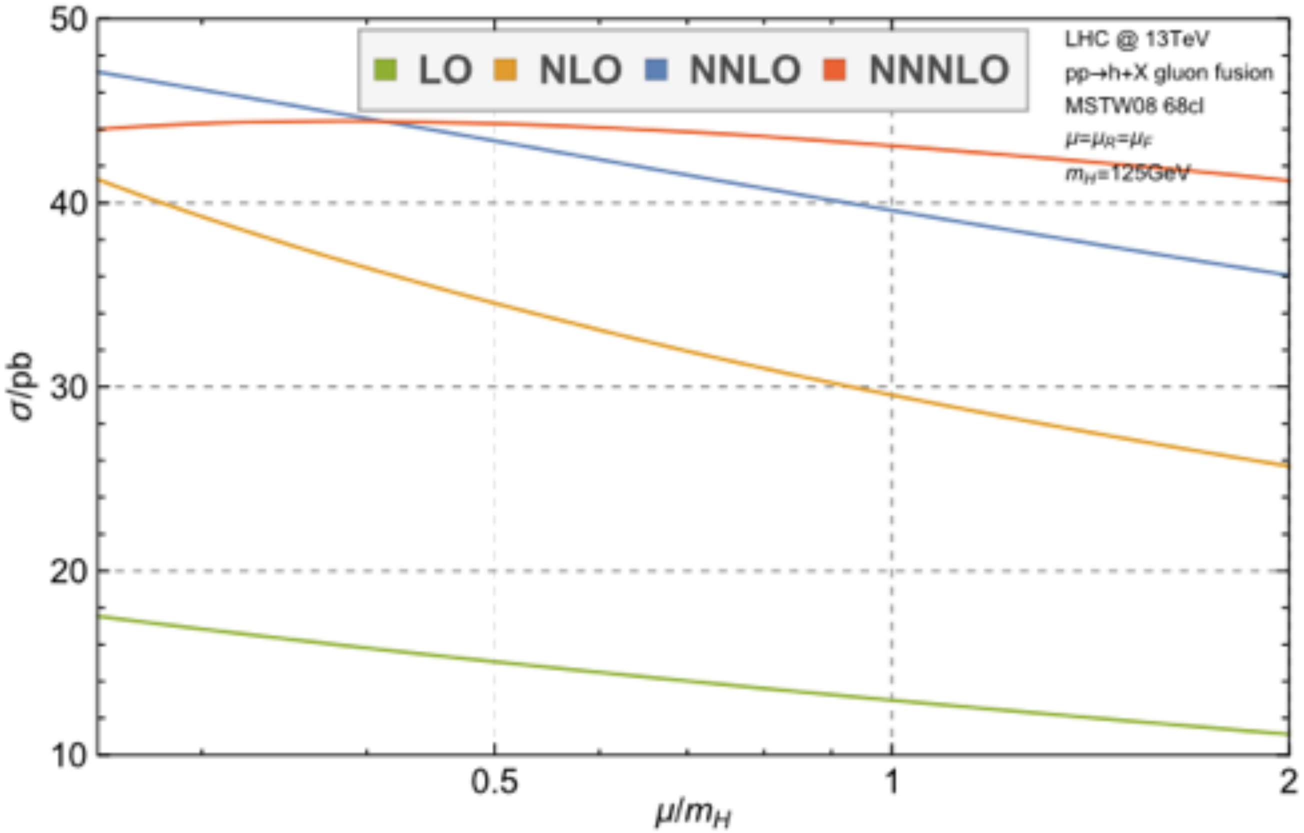
$$\sigma_i \cdot \mathrm{BR}^f = \sigma(gg \to H \to ZZ) \times \left(\frac{\sigma_i}{\sigma_{ggF}}\right) \times \left(\frac{\mathrm{BR}^f}{\mathrm{BR}^{ZZ}}\right),$$

- ratios of cross sections and of BR independent of theoretical predictions on inclusive cross section and BR

- theoretical uncertainties still affect acceptance (jet-bin migration, PS/UE)

Recent progress: highlights

C. Anastasiou et al., PRL 114 (2015) 212001



ggH N3LO calculation

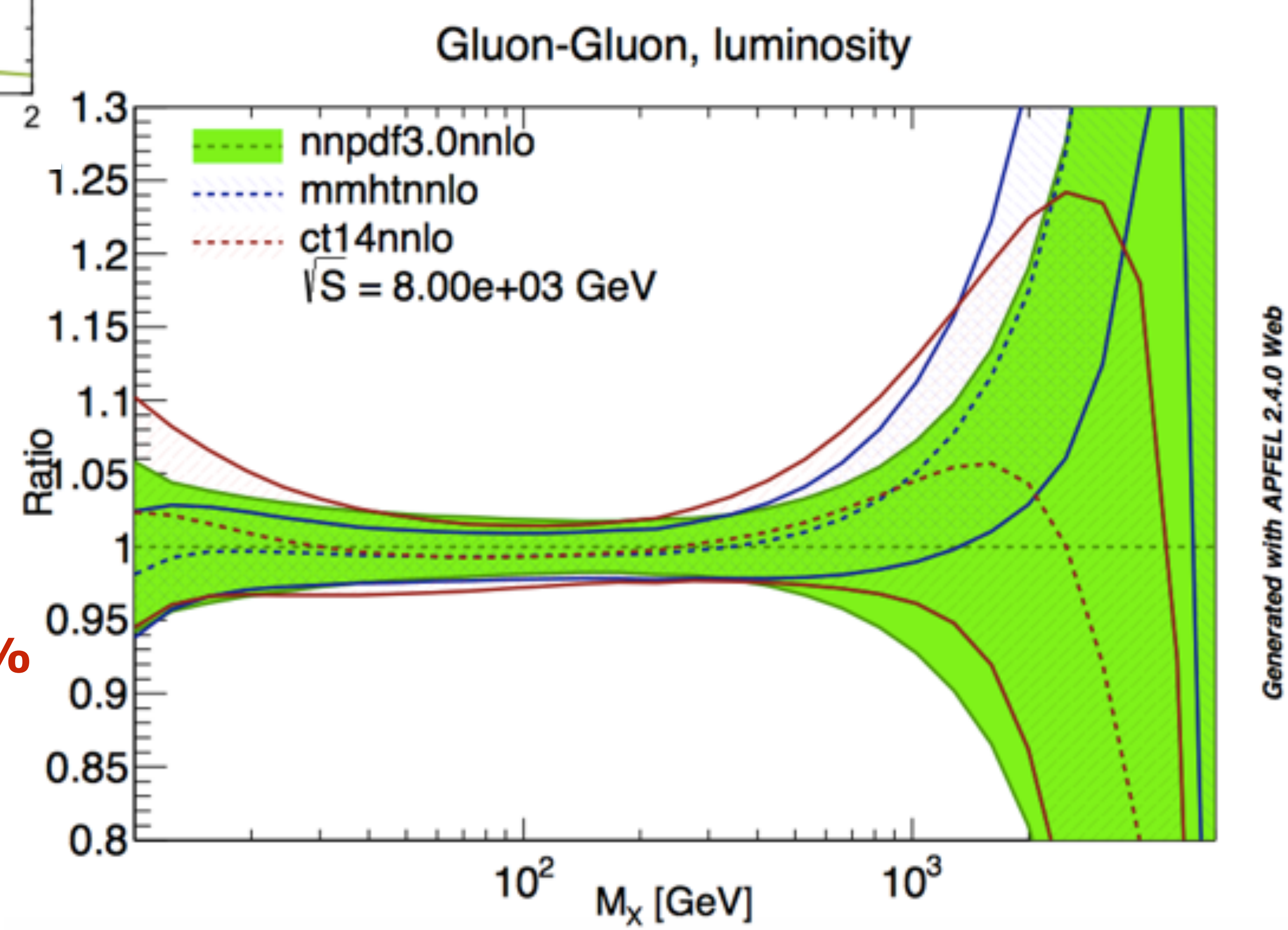
$\sigma(gg \rightarrow H)^{N3LO} = 19.47^{+0.32\%}_{-2.99\%}$
$[\mu = m_H/2]$

- QCD scale uncertainty reduced from 8% to 2%

S. Forte, 10th LHC Higgs XS WG

Major updates for all PDFs fits

improved agreement for gluon luminosity
PDF uncertainty on gg —> H* down to 2%



ggH modelling

- no NNLO QCD + NLO EWK MC generator yet!

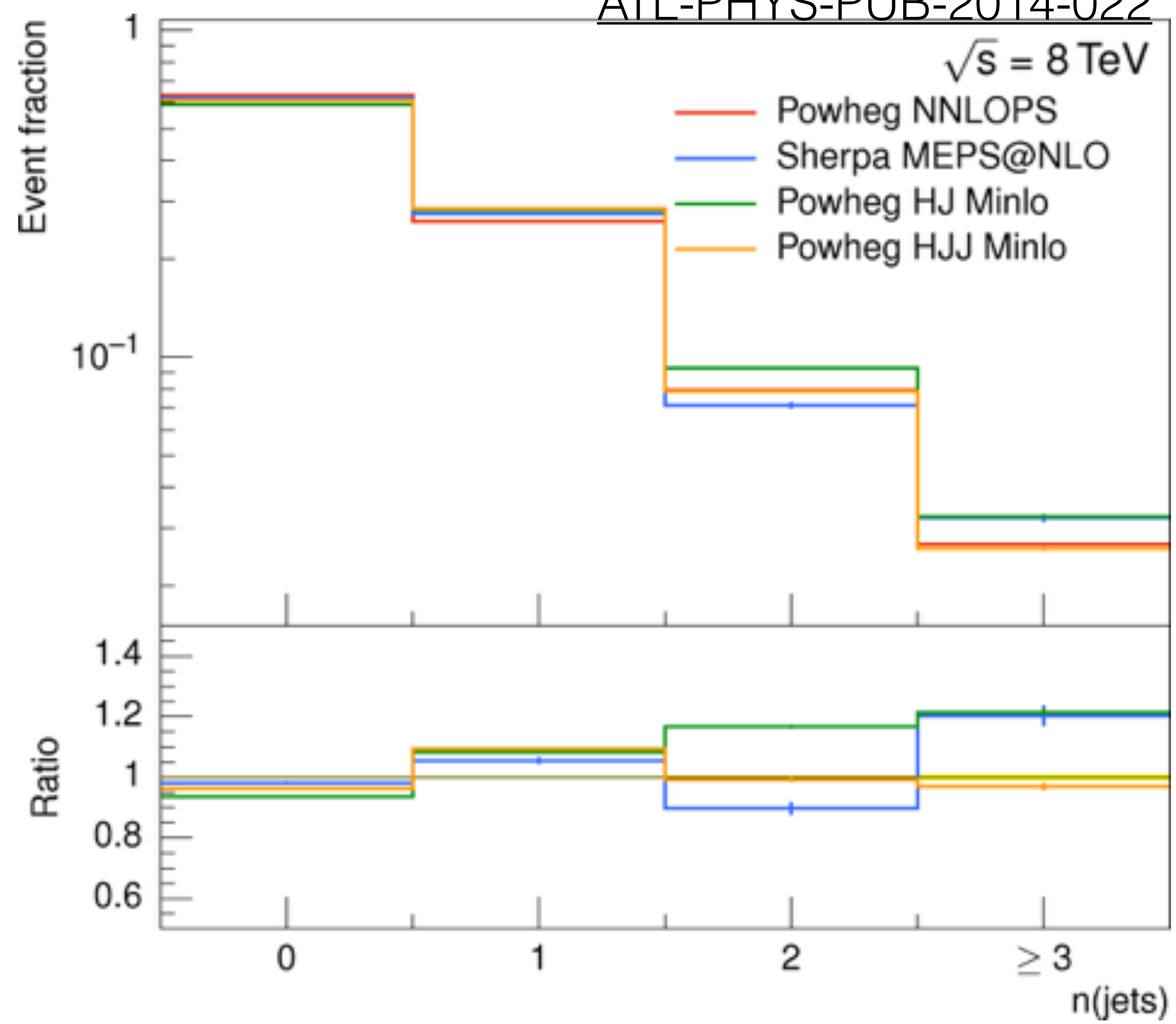
- HJ MiNLO promoted to NNLO+PS generator by **reweighting the events** with the factor

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

Intrinsic uncertainty: in which region of phase space the reweighting is done

- A lot of progress and new tools:
  - automatic generation of NLO+PS processes
  - attention to non-accounted diagrams in NLO!
    gq/qq negligible (<few %) in NNLO inclusive
    but gq is 30% of H+1 jet NNLO
  - merging/matching multi-leg processes
    various schemes: POWHEG MiNLO,
    Fx-Fx aMC@NLO, SHERPA MEPS@NLO,
    PYTHIA8/UNLOPS, HW++/Matchbox

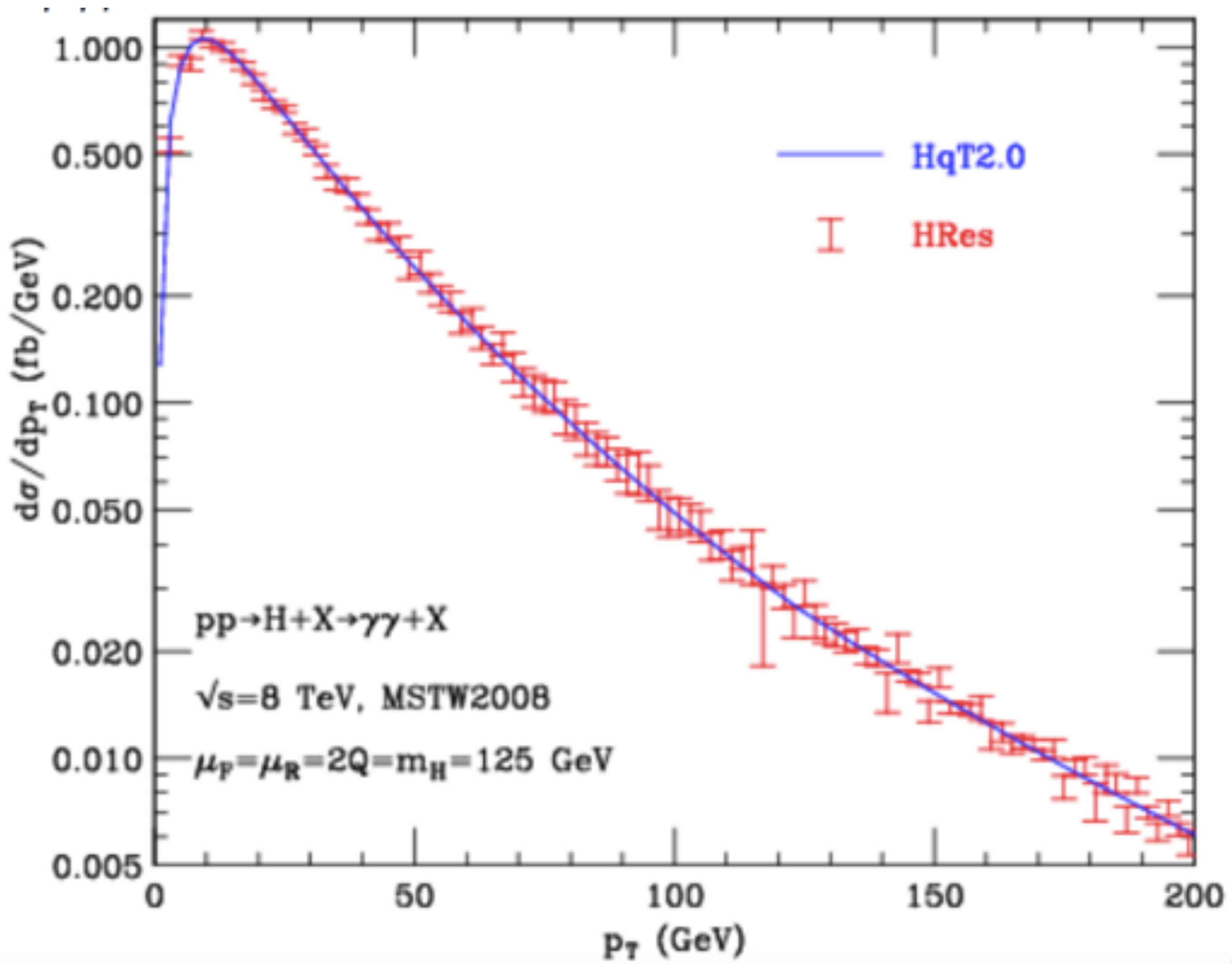
ATL-PHYS-PUB-2014-022



Q) Systematic comparison including uncertainties?

Higgs P_T

- HRes combines the NNLO calculation in HNNLO with the small pT-resummation implemented in HqT
- Three decay channels of the Higgs boson implemented: H—>ɣɣ, H—>WW —> *lvlv*, H—> 4l



arxiv:1306.4581

finite quark-mass effect included in v2.3

in Run1 POWHEG+PYTHIA reweighed to HRes(v2) NNLL+NNLO $p_T(H)$

Q) higher precision MCs for Run 2. Reweighting $p_T(H)$?

Jet binning

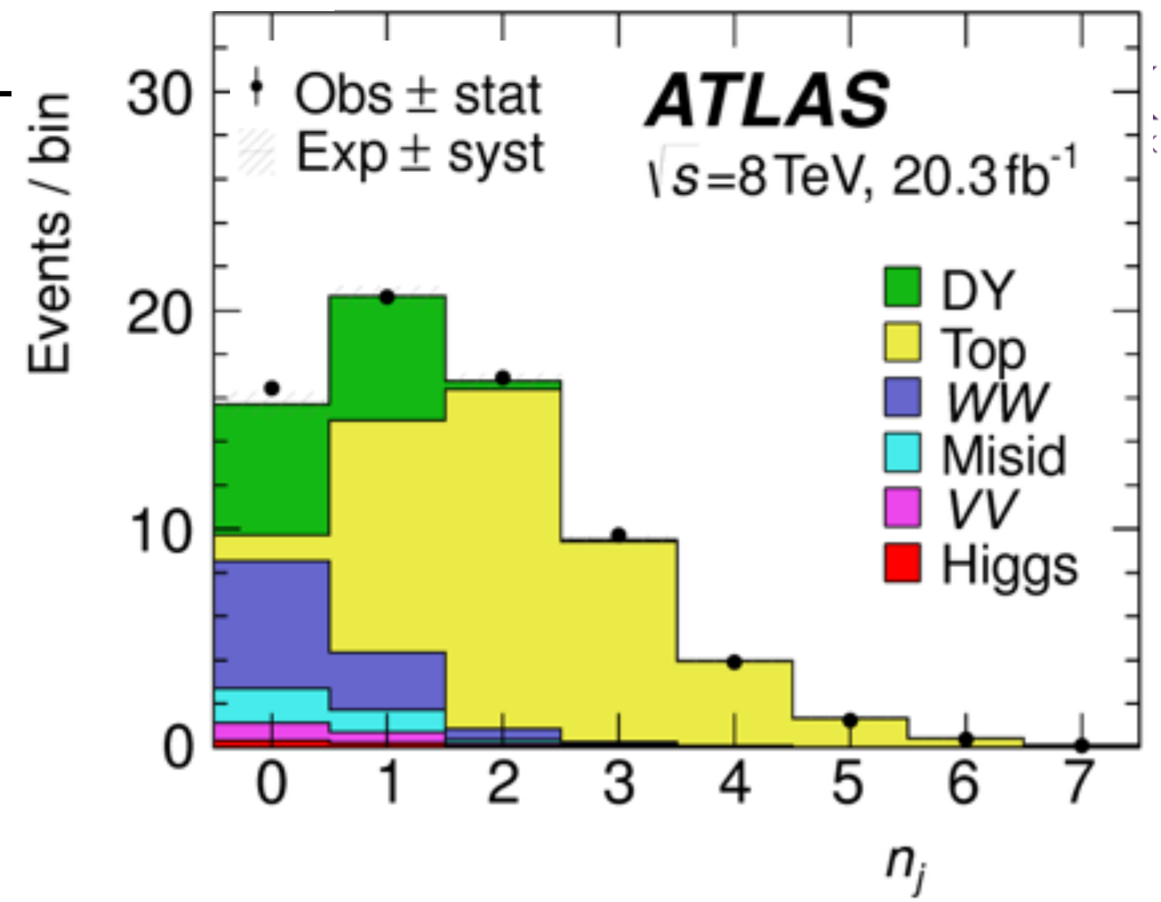
- improve S/B ratio in bin with different background compositions

- affected by **large** dependencies on QCD corrections

CMS, H ->WW: HIG-13-023 **yields 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
$\vec{E}_{\mathrm{T}}^{\mathrm{miss}}$ 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

x10[3] PhysRevD.92.012006



ATLAS, H->WW **yields uncertainties [%]**

	n	n	n
ST	18%	43%	70%
JVE	15%	27%	34%

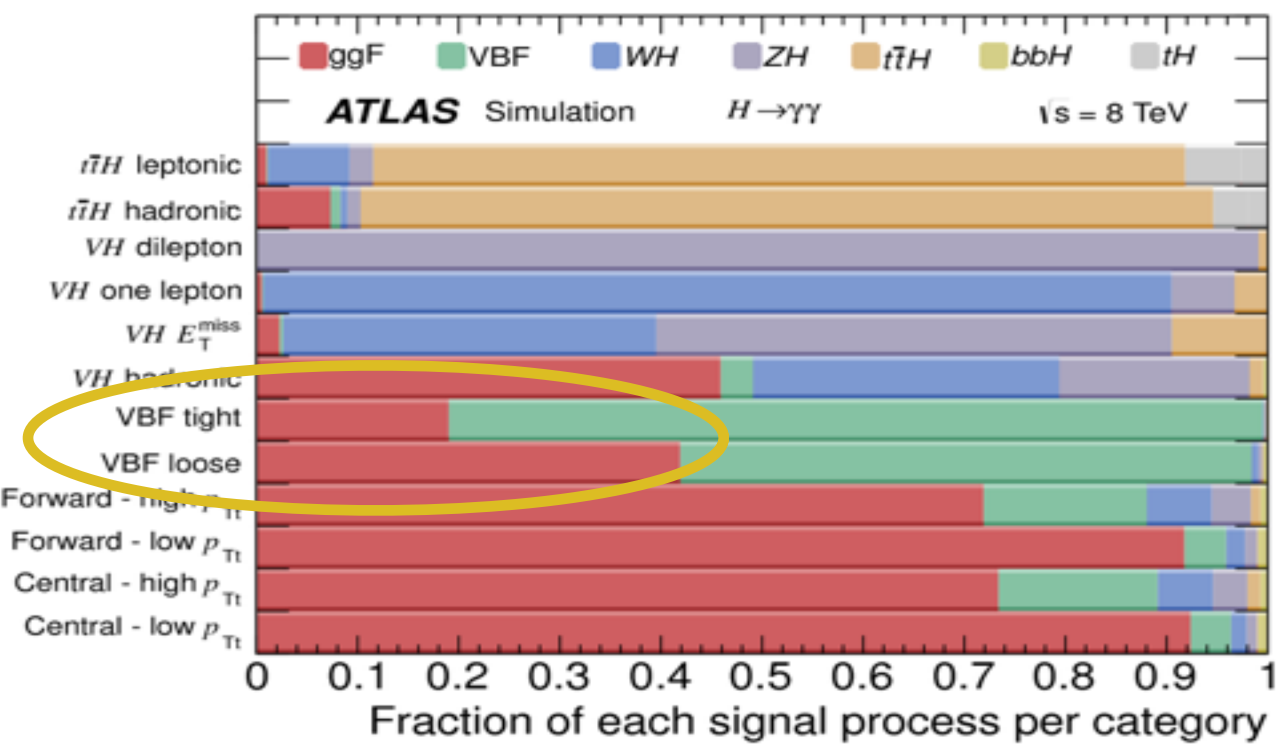
- various method to estimate effect of missing higher orders corrections to yields in jet-bins:
  - **Stewart-Tackman** [ST] [PRD 85 (2012) 034011]
  - **Jet-Veto efficiency** [JVE]: include resummed results [PRL 109 (2012) 202001]
  - **Updated ST** with 0,1-jet resume by Tackmann, Petriello et al [PRD 89 (2014) 074044]
  - other groups with SCET (soft-collinear effective theory), Neubert et al.[arXiv:1412.8408]

Q) correlation between N(jets) and p_T(H)?

Jet binning: H+2 jets

- veto third jet to isolate VBF H production
- signal/bkg separation increased by MVA based selection
  —> need precise event generations for ggH+jets, VBF+jets
- ggH background contamination in VBF region: ~ 30%
  reduction of theory uncertainty possible in the future (Gosam HJJJ at NLO)

H —> γγ



Source	Observed $\mu_{VBF} = 1.27$ Error +	−	Plot of error (scaled by 100)
Data statistics	0.44	0.40	
Signal regions	0.38	0.35	
Profiled control regions	0.21	0.18	
Profiled signal regions	0.09	0.08	
MC statistics	0.05	0.05	
Theoretical systematics	0.22	0.15	
Signal $H \rightarrow WW^* \mathcal{B}$	0.07	0.04	
Signal ggF cross section	0.03	0.03	
Signal ggF acceptance	0.07	0.07	
Signal VBF cross section	0.07	0.04	
Signal VBF acceptance	0.15	0.08	
Background WW	0.07	0.07	
Background top quark	0.06	0.06	
Background misid. factor	0.02	0.02	
Others	0.03	0.03	

- 30% unc on ggH yield due to CJV
- 50% unc on ggH yield due to QCD scale variations on BDT shape

Q)What EXPs should do for H+2-jet bin in RUN-2?

Fully Differential cross section: VBF

NNLO QCD correction to σ_{TOT} very small, well within NLO QCD scale unc O(3%)

Fully differential VBF Higgs cross section [Cacciari et all, PRL 115 (2015) 082002]

k(NNLO/NLO): 5%(1%) with (without) VBF cuts, outside of NLO band

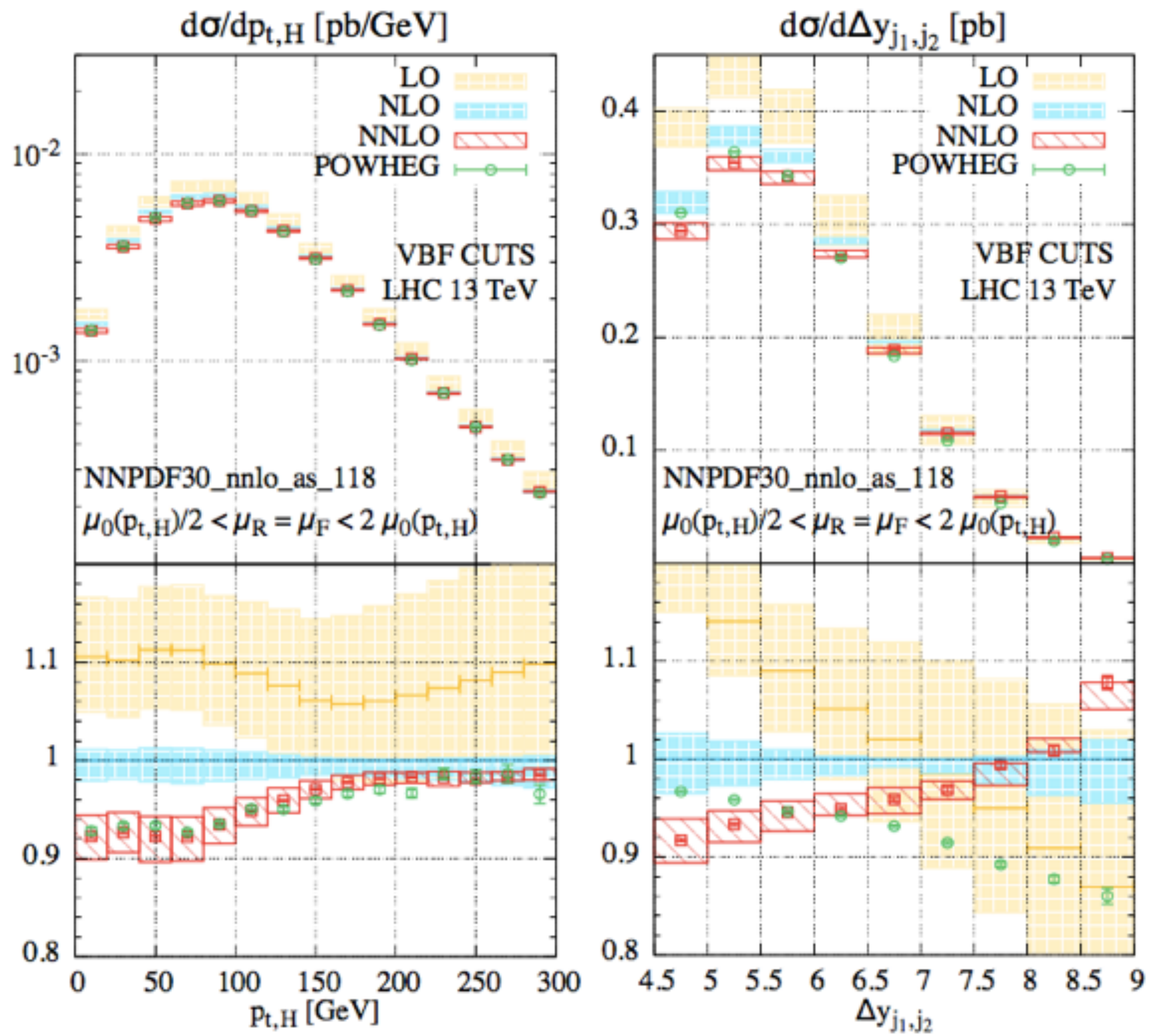
	$\sigma^{(\text{no cuts})}$ [pb]	$\sigma^{(\text{VBF cuts})}$ [pb]
LO	$4.032^{+0.057}_{-0.069}$	$0.957^{+0.066}_{-0.059}$
NLO	$3.929^{+0.024}_{-0.023}$	$0.876^{+0.008}_{-0.018}$
NNLO	$3.888^{+0.016}_{-0.012}$	$0.826^{+0.013}_{-0.014}$

LHC 13 TeV, anti-k_t R = 0.4
MH = 125 GeV,
NNPDF3.0_nnlo_as0118

$p_{t,j} > 25GeV \; |y_j| < 4.5$

$\Delta y_{j1,j2} > 4.5 \quad y_{j_1} y_{j_2} < 0$

$m_{j1,j2} > 600GeV$



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Fully differential VBF Higgs cross section [Cacciari et all,PRL 115 (2015) 082002]

k(NNLO/NLO): 5%(1%) with (without) VBF cuts, outside of NLO band

	$\sigma^{(\text{no cuts})}$	$^{(\text{VBF cuts})}$
LO	4.03	
NLO	3.92	
NNLO	3.88 -0.012	-0.014

Q) how to account for NNLO corrections to VBF in experimental analysis
Re-weight MC? Inflate theory uncertainty?

LHC 13 TeV, anti-k_t R = 0.4
MH = 125 GeV,
NNPDF3.0_nnlo_as0118

$p_{t,j} > 25 GeV \; |y_j| < 4.5$

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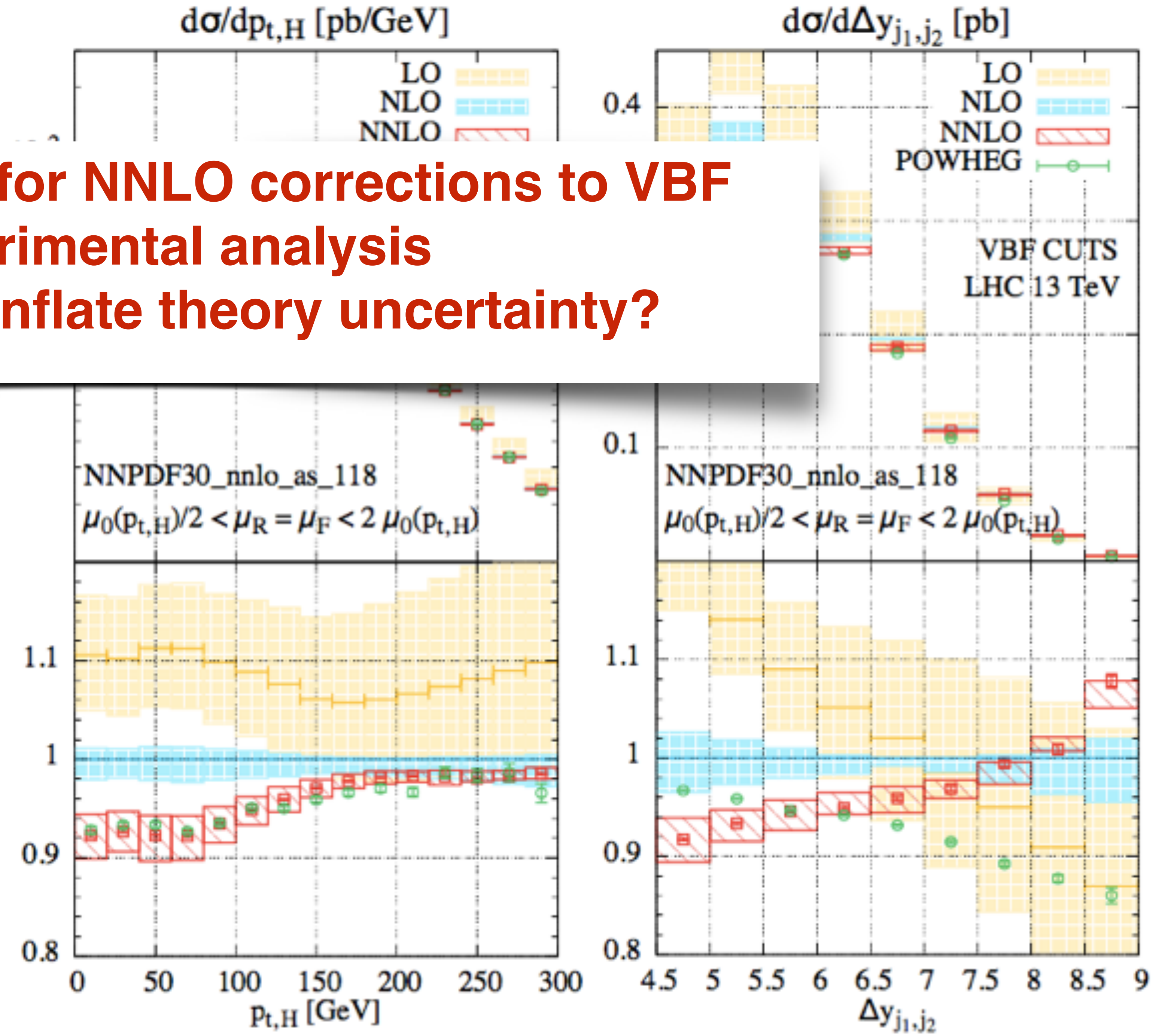


Fully Differential cross section: VBF

NNLO QCD correction to σ_{TOT} very small, well within NLO QCD scale unc O(3%)

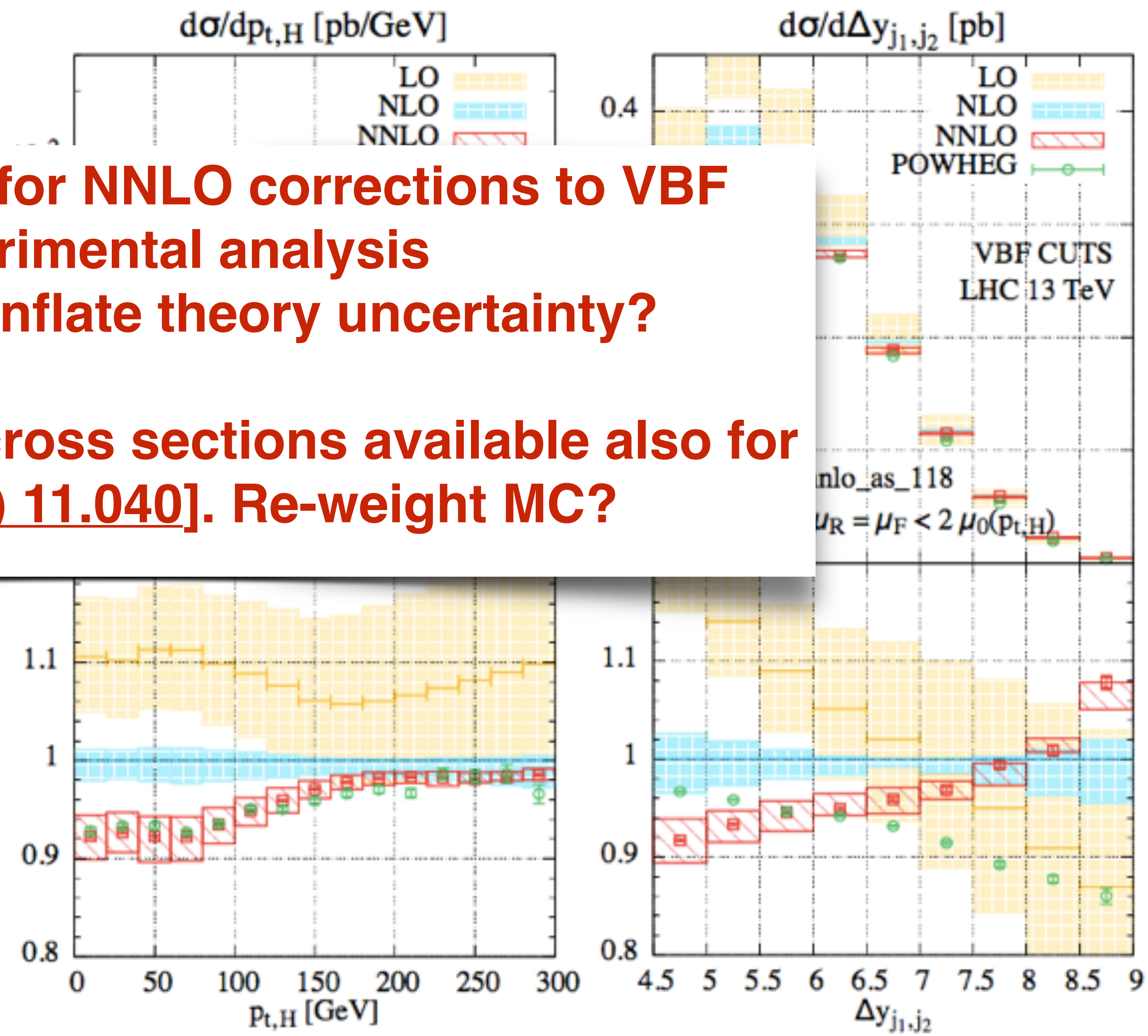
Fully differential VBF Higgs cross section [Cacciari et all,PRL 115 (2015) 082002]
k(NNLO/NLO): 5%(1%) with (without) VBF cuts, outside of NLO band

	$\sigma^{(\text{no}}$ [illegible]
LO	4.03
NLO	3.92
NNLO	3.88

Q) how to account for NNLO corrections to VBF in experimental analysis
Re-weight MC? Inflate theory uncertainty?

Q) NNLO differential cross sections available also for VH [PLB (2014) 11.040]. Re-weight MC?

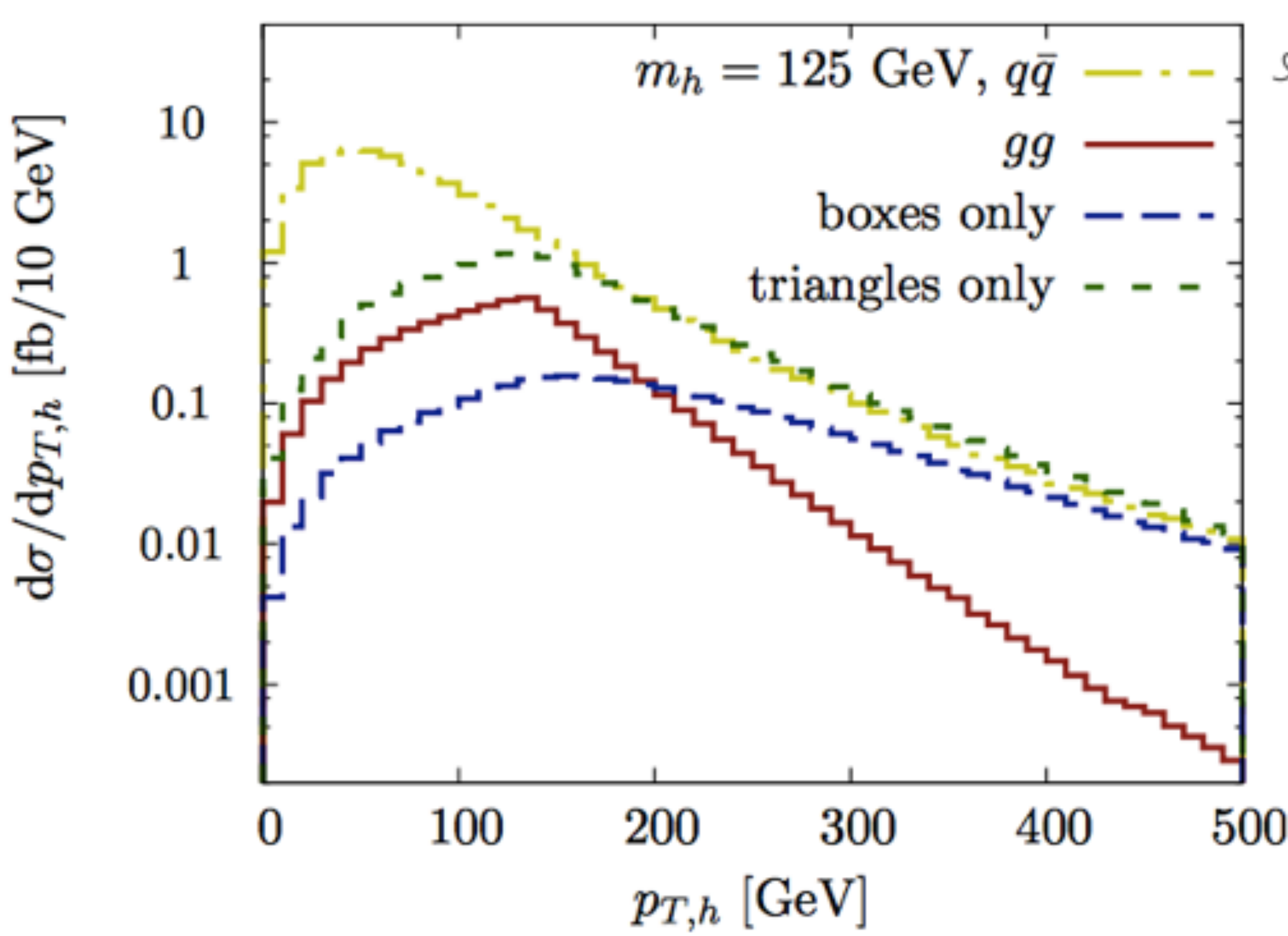
LHC 13 ...
MH = 125 GeV,
NNPDF3.0_nnlo_as0118
$p_{t,j} > 25GeV \ |y_j| < 4.5$
$\Delta y_{j1,j2} > 4.5 \quad y_{j_1} y_{j_2} < 0$
$m_{j1,j2} > 600GeV$

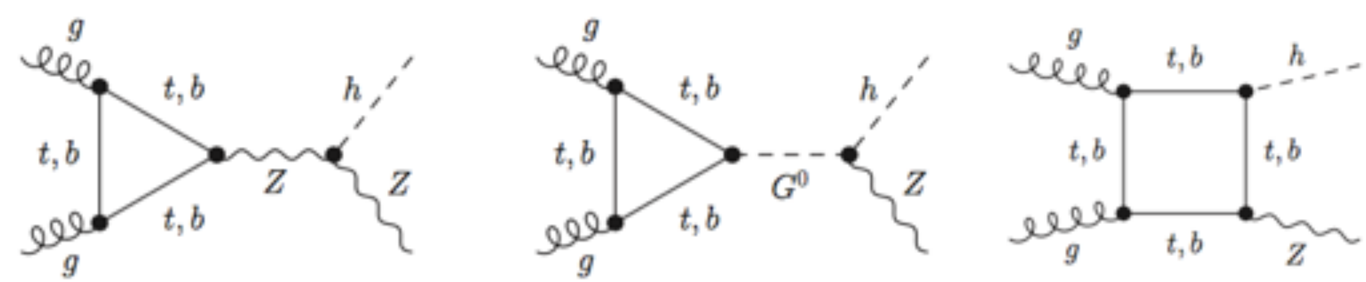


Gluon-initiated ZH production

- gg—>ZH contribution increase at high p_T(H)
  most sensitive region
- only LO generators available during Run 1
- k(NLO/LO) ~ 2   **Q) pT dependency?**

http://arxiv.org/pdf/1310.4828.pdf





ATLAS/CMS VH—>bb analysis [in combination]
QCD scale unc on gg->ZH yields: 50%

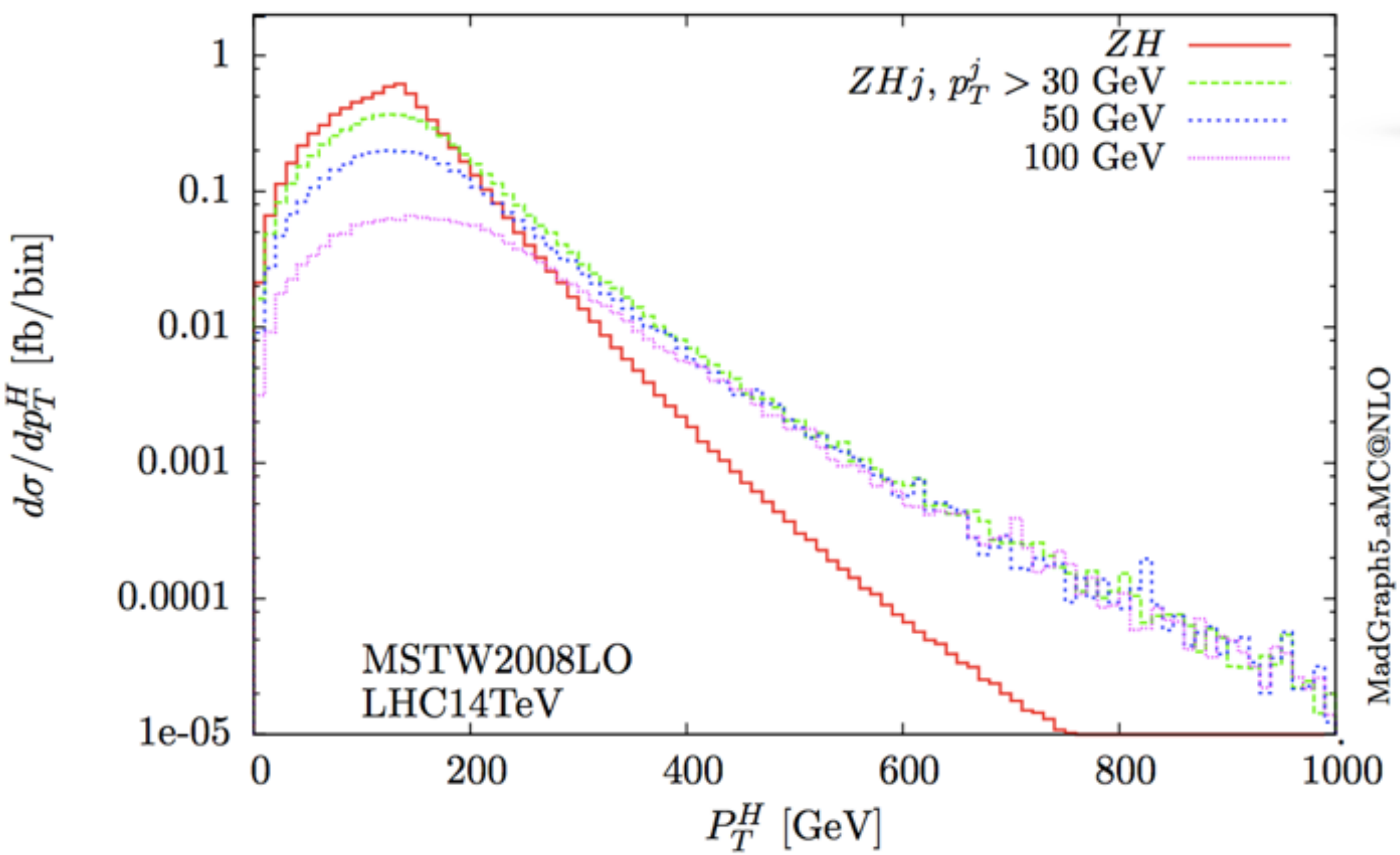
σ(gg—>ZH)/σ(qq—>ZH) x2 larger at 13TeV!

Gluon-initiated ZH production

- LO gg—> ZHj and gg—> ZH available in aMC@NLO/POWHEG/SHERPA
- MLM merged ZHj and ZH: more accurate prediction of the kinematics (reduce shower uncertainty)

Q) NLO gg —> ZH MC?

B. Hespel, F. Maltoni, E. Vrynidou arxiv:1503.01656



include exact top-mass dependency

Background Modelling: H —>WW

- Precise knowledge of background also crucial
- Modelling of continuum WW background one of the largest sources of theory unc

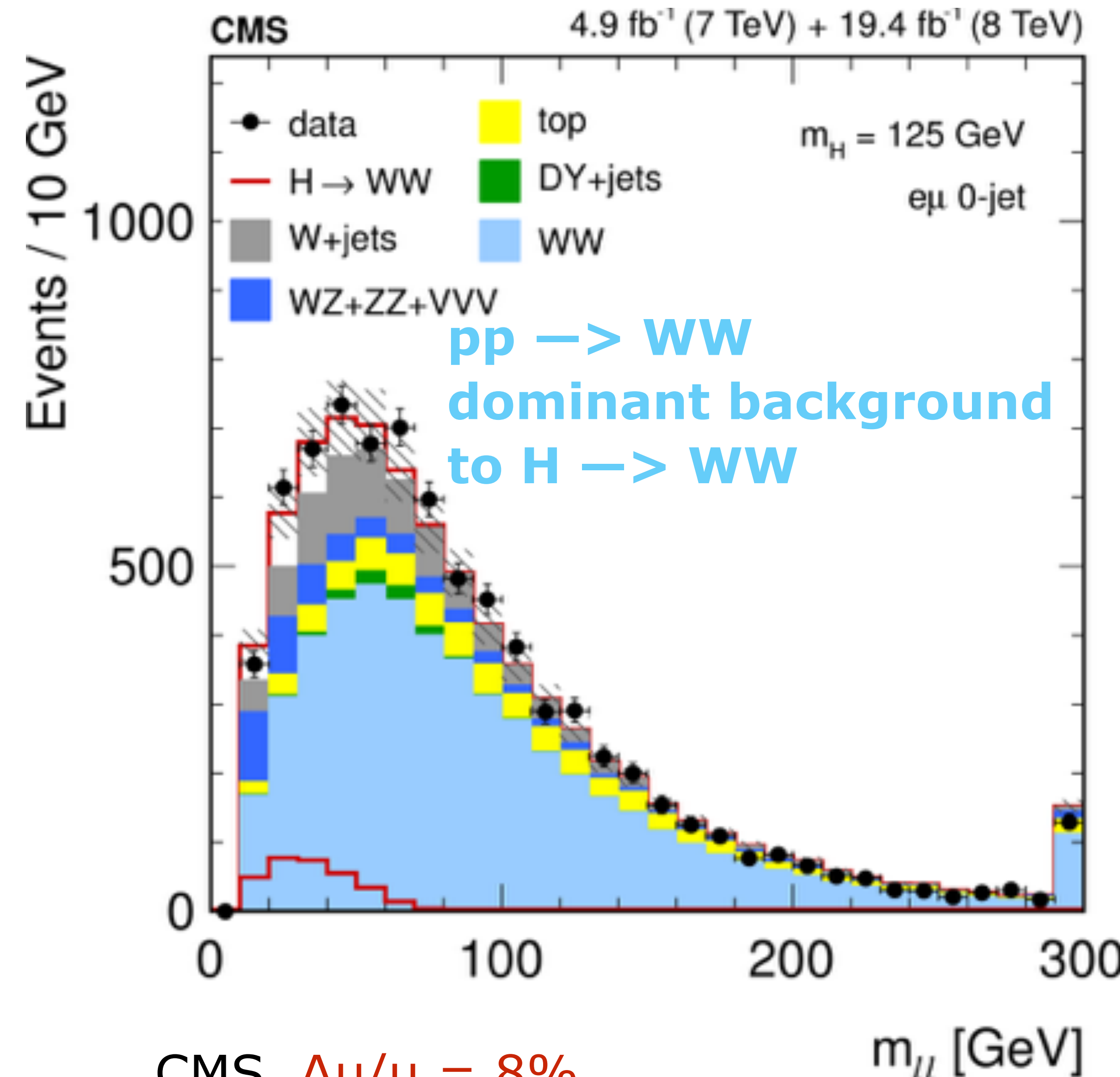
ATLAS, H—>WW,PhysRevD.92.012006

WW	**[NLO]**
$q\bar{q} \to WW$ and $qg \to WW$	POWHEG+PYTHIA6

Source	Observed $\mu = 1.09$ Error +	−	Plot of error (scaled by 100)
Data statistics	0.16	0.15	
Signal regions	0.12	0.12	
Profiled control regions	0.10	0.10	
Profiled signal regions	-	-	-
MC statistics	0.04	0.04	
Theoretical systematics	0.15	0.12	
Signal $H \to WW^* \mathcal{B}$	0.05	0.04	
Signal ggF cross section	0.09	0.07	
Signal ggF acceptance	0.05	0.04	
Signal VBF cross section	0.01	0.01	
Signal VBF acceptance	0.02	0.01	
Background *WW*	0.06	0.06	
Background top quark	0.03	0.03	
Background misid. factor	0.05	0.05	
Others	0.02	0.02	

uncertainty on WW extrapolation factors (QCD, PDF, UE)

CMS, H—>WW
J. High Energy Phys. 01 (2014) 096



CMS, $\Delta\mu/\mu$ = 8%

$q\bar{q} \to WW$ generator **[LO]**	σ/σ_{SM} observed
MADGRAPH (default)	0.76 ± 0.21
MC@NLO	0.82 ± 0.24
POWHEG	0.74 ± 0.21

Background Modelling: Di-boson

- NNLO QCD pp—> WW/ZZ/Wg/Zg calculations by M. Grazzini et al

  NNLO correction at 9-12% for pp—>WW (gg—>WW contributes to 35% at NNLO)

  NNLO correction at 12-17% for pp—>ZZ (gg—>ZZ contributes to 58-62% at NNLO)

  Final goal is to have a public program [MATRIX] that can deal with all pp—>VV processes, including leptonic decay and off-shell effect, and fully differential. Not available yet.

- but no NNLO+PS MC exist yet!

Q) Apply NNLO QCD correction (as a function of 4l invariant mass) with exp cuts?

- Full NLO EW corrections for WW and ZZ production are complete now.

  as important as NNLO QCD

Q) Assume factorization of NNLO QCD and NLO EW?
EW K-factors included via reweighting distributions?

Background Modelling: heavy flavour

- tt+bb/tt+cc: non-reducible background to ttH->bb

H.F. cross section not very well known
inclusive t-tbar pT distribution [NLO+PS] re-weighted to 7TeV data

Source	Rate uncertainty	Shape	Process		
			$t\bar{t}$H	$t\bar{t}$+jets	Others
Theoretical uncertainties					
Top p_T modelling	3–8%	Yes		✓	
μ_R/μ_F variations	2–25%	Yes		✓	
$t\bar{t}$+$b\bar{b}$ normalisation	50%	No		✓	
$t\bar{t}$+b normalisation	50%	No		✓	
$t\bar{t}$+$c\bar{c}$ normalisation	50%	No		✓	
Signal cross section	7%	No	✓		
Background cross sections	2–20%	No		✓	✓
PDF	3–9%	No	✓	✓	✓
Statistical uncertainty (bin-by-bin)	4–30%	Yes	✓	✓	✓

CMS, ttH: arxiv:1502.02485.pdf
yields uncertainties [%]
[t-tbar+0,1,2p LO MadGraph 5.1.3]

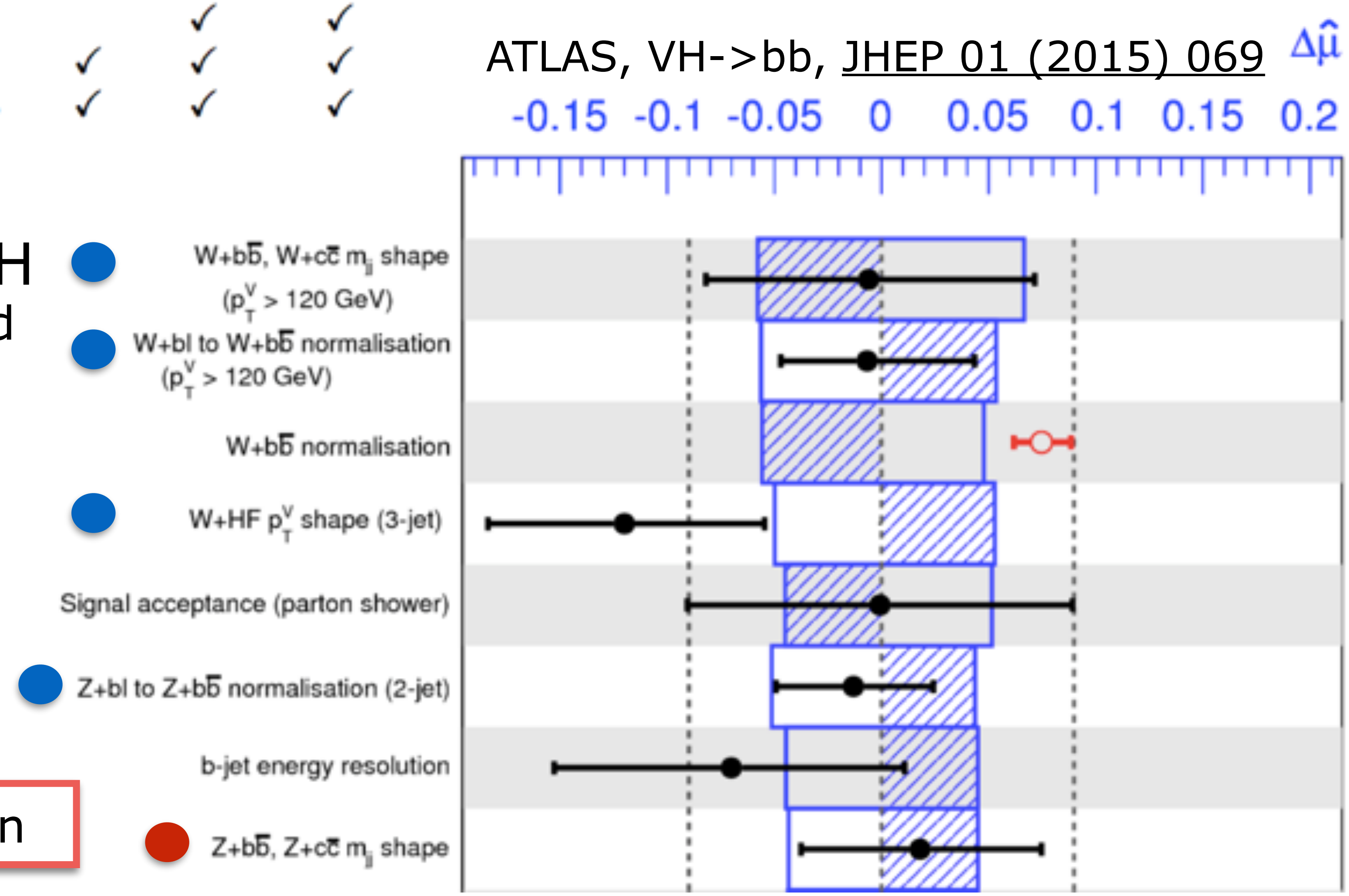
NLO merged predictions available now!

- V+h.f.: major background to VH
  modelled with SHERPA LO V+p merged (massive b- and c-)

shape comparison between different generator for V+h.f.

data/MC comparisons in b-jet tag region

ATLAS, VH->bb, JHEP 01 (2015) 069



Differential cross section

Most model-independent way to present experimental results

$$\sigma_i = \frac{N_i^{data} - N_i^{bkg}}{c_i \int L dt}$$

i: bin of observable

Theoretical uncertainties have limited impact on differential cross section:

uncertainty on σ	**Baseline**	**Njets >=3**	**VBF-enhanced**
Signal extraction (stat)	±22	±33	±34
Jet energy scale/resolution		+15, -13	+12, -11
Theoretical modelling	+3.3, -1.0	+6.3, -4.9	+2.2,-3.2

Perfect laboratory to test SM predictions and indirectly constrain new physics

- with increasing stat, need highly accurate theoretical predictions to compare to
- need **predictions able to describe complicated fiducial volumes** (include decay modes)

Caola et al, arxiv:1508.02684

ATLAS (H—> γγ) $\sigma^{\rm fid}_{H+j}(8\ {\rm TeV}) = 21.5 \pm 5.3({\rm stat.}) \pm^{2.4}_{2.2}\ ({\rm syst.}) \pm 0.6({\rm lumi})\ {\rm fb}.$

H+1jet NNLO prediction $\sigma^{\rm fid}_{\rm NNLO} = 9.45^{+0.58}_{-0.82}\ {\rm fb}$

Fiducial Volume:
2 isolated photons, |η| < 2.37
$p_T/m_{\gamma\gamma}$ > 0.35 (0.25)
≥1 jet: p_T > 30 GeV, |y| < 4.4.

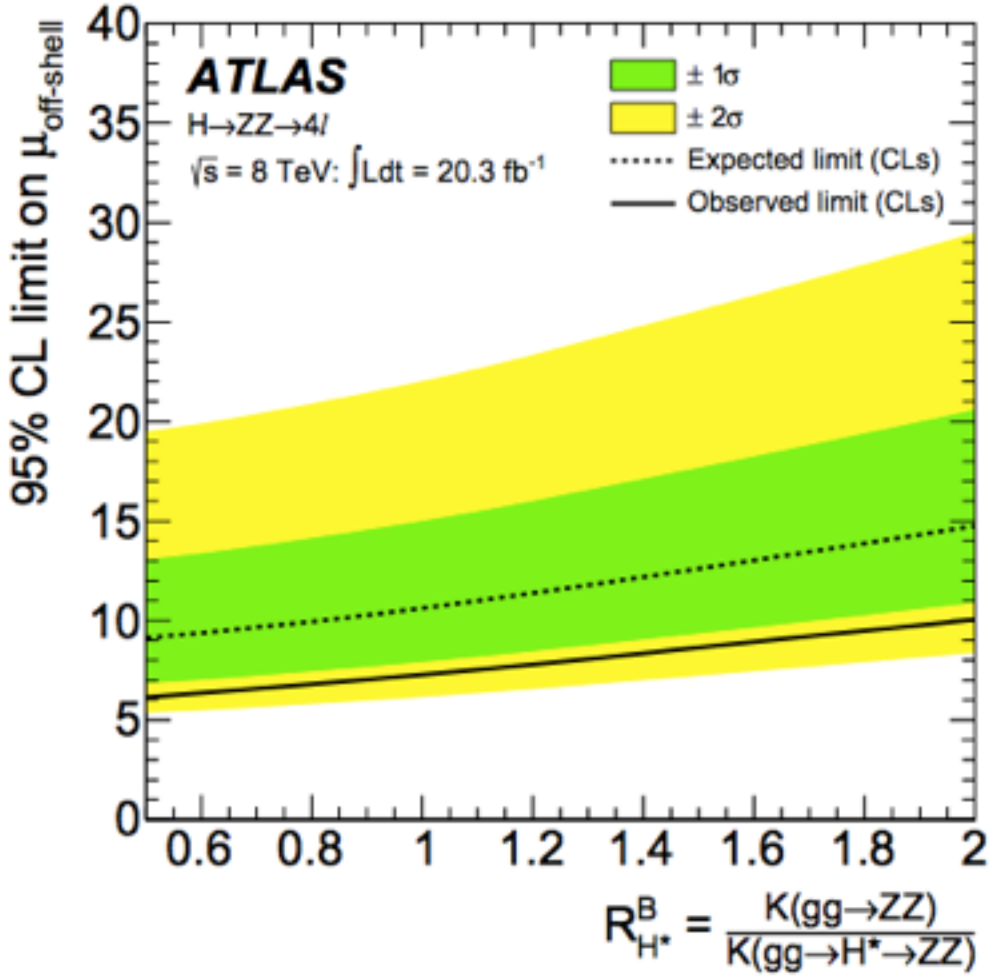
Interference in off-shell H—>VV analyses

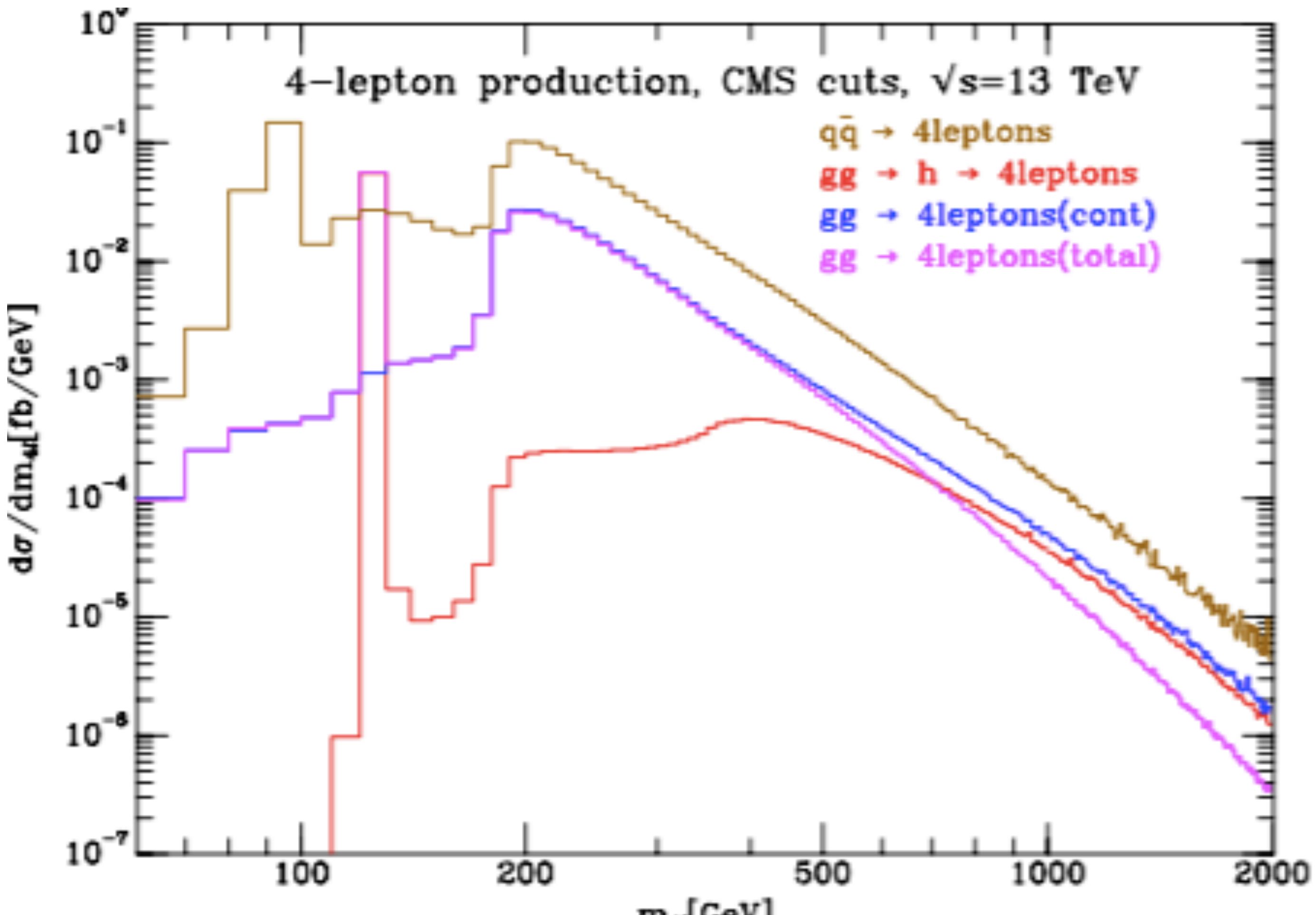
- Off-shell, gg —> H* —> VV and gg —> VV continuum interference is large
  - no interference effect for on-shell [Kauer, Passarino, JHEP 08 (2012) 116]

- gg —> VV known only at LO, as well as interference term [gg2VV and MCFM]
  gg—>H*—>VV also modelled at LO, NNLO k-factors as a function of m(VV) applied

$$K^{H^*}(m_{VV}) = \sigma^{NNLO}_{gg\to H^*\to VV}/\sigma^{LO}_{gg\to H^*\to VV}$$

k-factor for background un-known:
CMS: $k_{continuum} = k_{signal}$ [Phys. Lett. B 736 (2014) 64]
ATLAS: results as a function unknown $k_{continuum}/k_{signal}$ [Eur. Phys. J. C (2015) 75:335]





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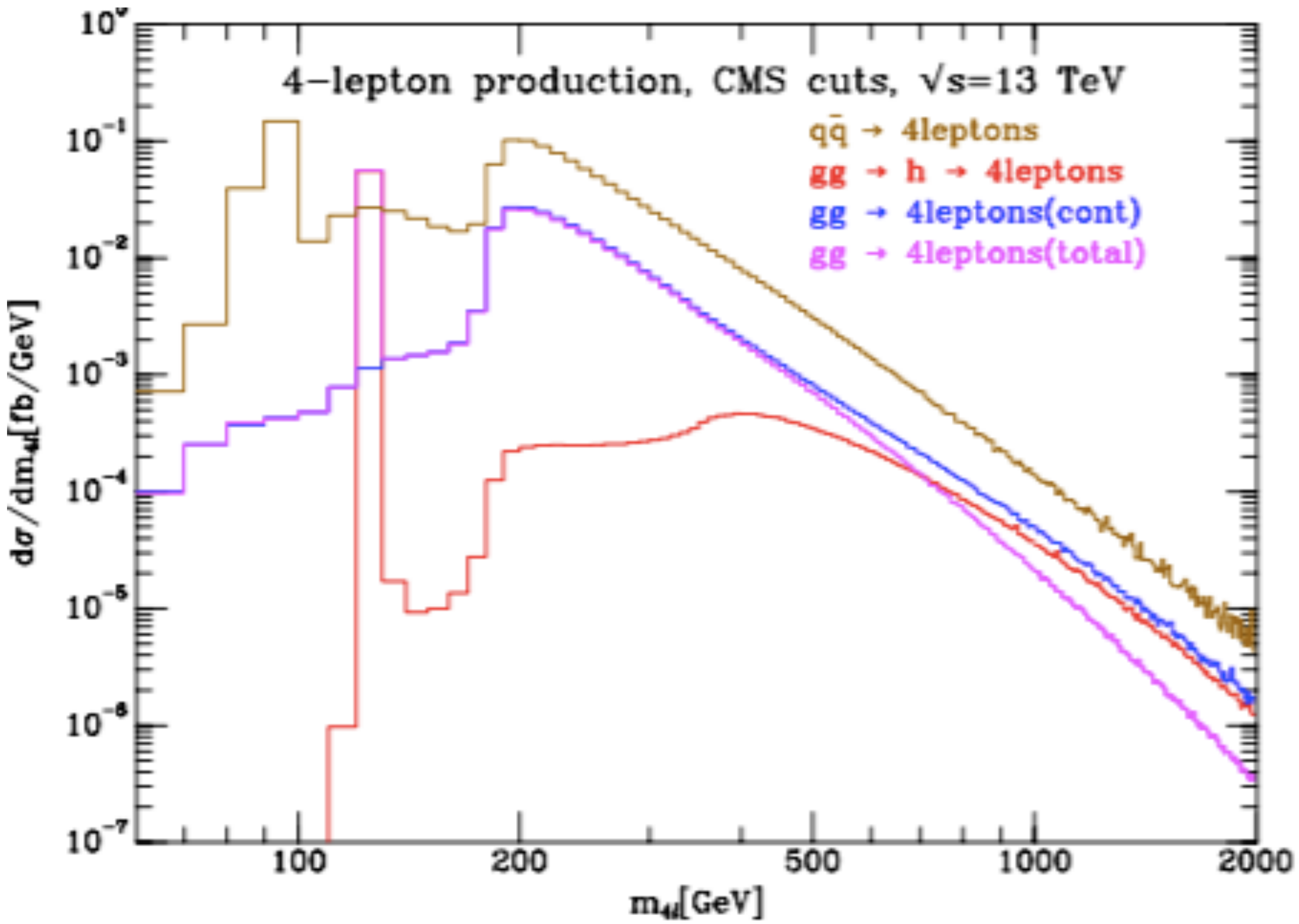
- Off-shell region useful to set constraints on the H width

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH}g^2_{HZZ}}{m_H\Gamma_H} \qquad \sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH}g^2_{HZZ}}{(2m_Z)^2}$$

CMS:
unc on gg —> ZZ are the largest ones

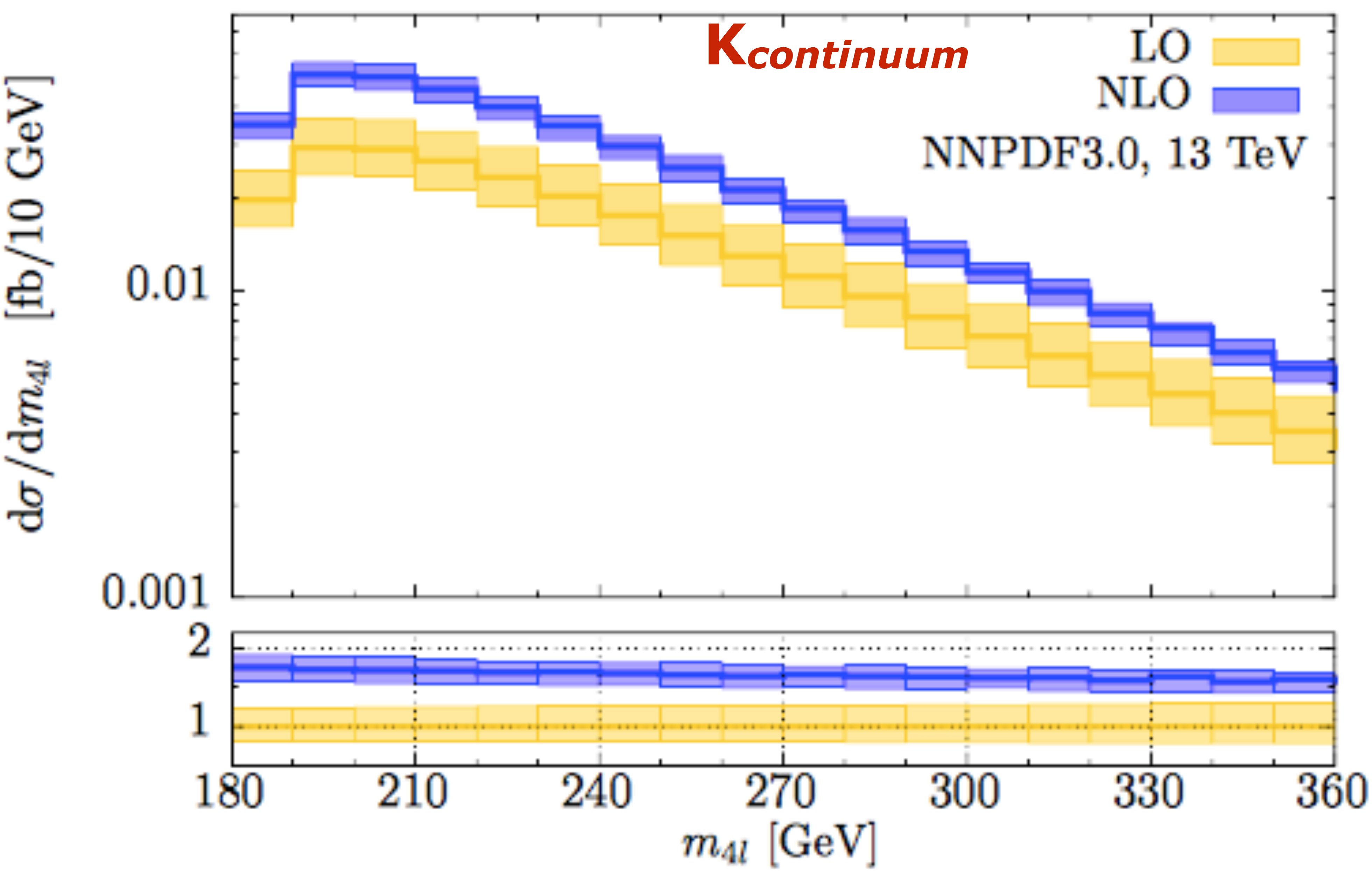
ATLAS:
unc on interference and K^H (m_{VV}) dominant ones on $\mu_{\text{off-shell}}$



gg —> ZZ production

new preprint, 22 Sept: http://arxiv.org/pdf/1509.06734.pdf [Caola et al]

- NLO QCD correction to gg —> ZZ:
  σ(gg—>ZZ) increases by O(50% – 100%)
  σ(pp—>ZZ) increases by O(6-8%), outside of QCD scale unc on recent NNLO QCD calculation [Grazzini et al, arxiv:1507.06257]



Summary

Not exhaustive list!

ggH:

- high precision MC generators
- Higgs pT re-weighting and correlation to N(jets)
- ggH+2jets in VBF region and CJV

VBF:

- NNLO corrections in complex phase space

VH:

- gg—>ZH NLO MC

Backgrounds:

- DiBoson: NNLO+PS MC
  inclusion of EWK corrections
  gg —> VV NLO MC
- improved predictions for tt+h.f. and V+jets/V+h.f.

Conclusion

- Statistical uncertainty will rapidly decrease in Run2
  —> need increasingly precise predictions

- In Run 2, more model-independent experimental results when possible (differential cross sections) but theory uncertainty will still affect coupling analyses

- Not only for signal, backgrounds prediction important too
  need to cover the backgrounds with the same systematic approach used for the signal

- Close connection between experiments and Higgs cross section working group is fundamental
  experiments will follow up very closely the phenomenological news

- Having common approaches in ATLAS/CMS very important
  —> need clear recommendations

Backup

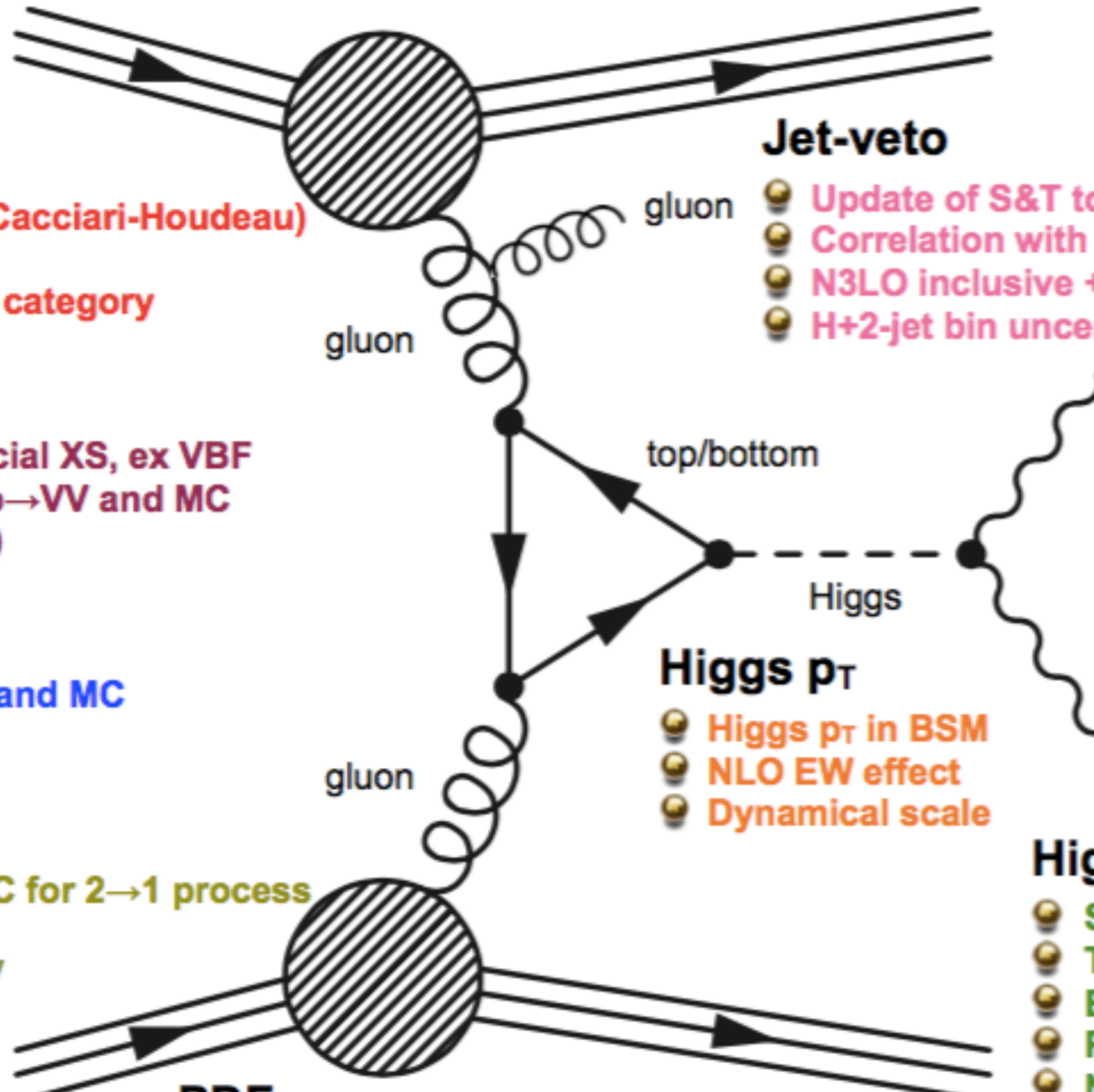
Leftover from RUN-1 and challenge for RUN-2

ggF
- N3NLO QCD correction
- Scale uncertainty prior (Cacciari-Houdeau)
- α_s uncertainty reduction
- Reduction of ggF in VBF category

Differential NNLO
- NNLO QCD effect in fiducial XS, ex VBF
- NNLO QCD + NLO EW pp→VV and MC (include offshell, ex Z*Z*)

Higgs Interferometry
- NLO QCD in gg→VV, ZH and MC
- Interferometry in VBF

(N)NLO MC
- NNLO QCD + NLO EW MC for 2→1 process
- H+0/1/2-jets (N)NLO MC
- H+3-jets NLO MC for CJV
- $\Delta\Phi_{jj}$ in H+2-jets MC



Jet-veto
- Update of S&T to JVE, new SCET approach
- Correlation with Higgs p_T
- N3LO inclusive + NNLO H+0/1-jet comb.
- H+2-jet bin uncertainty beyond NLO

Higgs p_T
- Higgs p_T in BSM
- NLO EW effect
- Dynamical scale

Higgs Decay
- Separation of THU and PU
- THU statistical prior
- BR update (ex H→bb)
- PU update (α_s, m_b, m_c, m_t)
- NLO EW differential (Prophecy4f/Hto4l)
- Dalitz decay common def.

PDF
- N3LO PDF
- PDF4LHC15 (LHAPDF) for XS and MC
- PDF correlation between Higgs and SM bkg.

Compiled by R. Tanaka, Sep. 2015

Processes

- Needs to survey detectable processes for Higgs production and decay for Run-2 and beyond!

- Tool development is also very important aspect

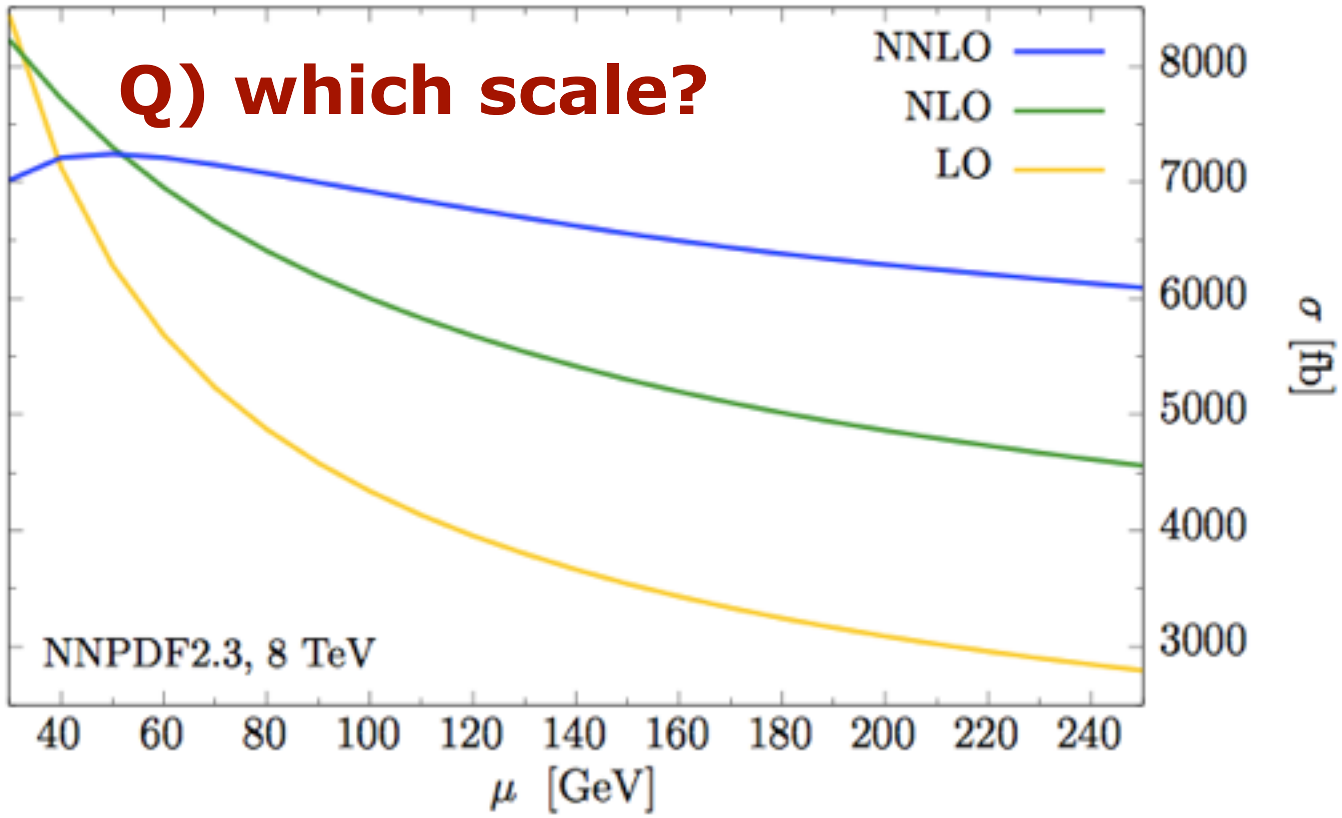
I. Main Production processes	[gg—>H, qqH, VH]
II. Associated Higgs production with heavy quarks	[bbH/ttH/ccH]
III. Associated production with heavy quarks	[tHq,WtH,btH,tH,bH]
IV. Higgs boson pair/triple production	[HH,qqHH,VHH,ttHH,tjHH,HHH]
V. Higgs production in association with gauge boson pairs	[VVH]
VI. Higgs production in association with gauge bosons and two jets	[qqVH]
VII. Guage boson scattering	[WW—>WW, WW—>HH, etc]
VIII. Rare process and decay	[qq—>Hγ, t—>cH, etc] [quarkonia J/Ψ(Y)+γ, γ/W/Z+P, etc]

Q) any other process?

NNLO H+1 jets

R. Boughezal, F. Caola, K.M., F. Petriello, M. Schulze [arXiv:1504.07922]

NNLO corrections increase H+jet production cross section by O(20%) and significantly reduce the scale dependence uncertainty



$$\sigma_{\mathrm{LO}} = 3.9^{+1.7}_{-1.1}\ \mathrm{pb}$$

$$\sigma_{\mathrm{NLO}} = 5.6^{+1.3}_{-1.1}\ \mathrm{pb}$$

$$\sigma_{\mathrm{NNLO}} = 6.7^{+0.5}_{-0.6}\ \mathrm{pb}$$

The cross sections for the anti-k_t algorithm with the jet transverse momentum cut of 30 GeV at the 8 TeV LHC.

Using these results and the N3LO computation of the Higgs total cross section, one can find the fraction of Higgs boson events without detectable jet radiation —> reduce uncertainty on $\sigma_{0\text{-jet}}$

Can be compared with measured fiducial cross section from ATLAS

LHC13 efficiencies: 0- and 1-jet bin

[Many thanks to P. F. Monni and F. Dulat]

F. Caola, LHCHXSWG WG1 meeting, May 2015

0-jet bin

ord	$\sigma^{\text{f.o.}}_{0-\text{jet}}$ (JVE)	$\sigma^{\text{f.o.+NNLL}}_{0-\text{jet}}$ (JVE)	$\sigma^{\text{f.o.+NNLL}}_{0-\text{jet}}$ (scales)
NNLO	$26.2^{+4.0}_{-4.0}$ pb	$25.8^{+3.8}_{-3.8}$	$25.8^{+1.6}_{-1.6}$
N^3LO	$27.2^{+2.7}_{-2.7}$ pb	$27.2^{+1.4}_{-1.4}$	$27.2^{+0.9}_{-0.9}$

≥1-jet bin

ord	$\sigma^{\text{f.o.}}_{\geq 1-\text{jet}}$ (scales)	$\sigma^{\text{f.o.}}_{\geq 1-\text{jet}}$ (JVE)	$\sigma^{\text{f.o.+NNLL}}_{\geq 1-\text{jet}}$ (JVE)
NLO	$14.7^{+2.8}_{-2.8}$ pb	$14.7^{+3.4}_{-3.4}$	$15.1^{+2.7}_{-2.7}$
NNLO	$17.5^{+1.3}_{-1.3}$ pb	$17.5^{+2.6}_{-2.6}$	$17.5^{+1.1}_{-1.1}$

Preliminary

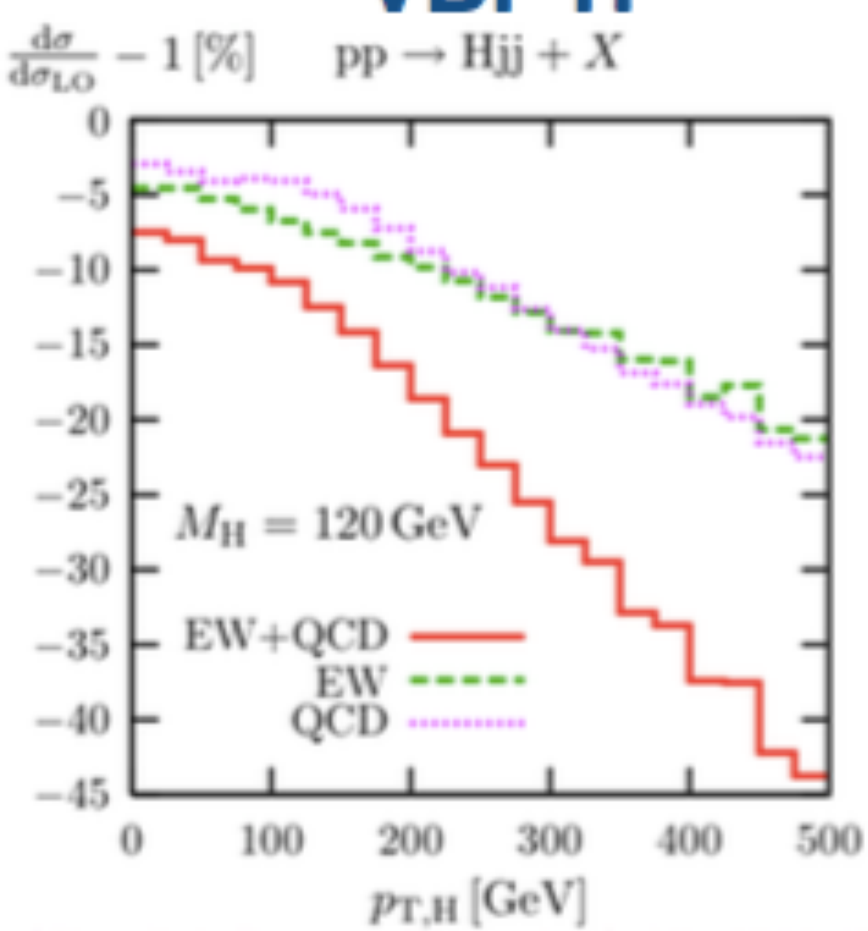
- Logs completely under control
  (logR: see [Dasgupta, Dreyer, Salam, Soyez (2015)])
- No breakdown of f.o. perturbation theory for $p_T \sim 30$ GeV
- Reliable error estimate from lower orders
- Logs help in reducing uncertainties
- Significant decrease of pert. uncertainty

25

EWK corrections

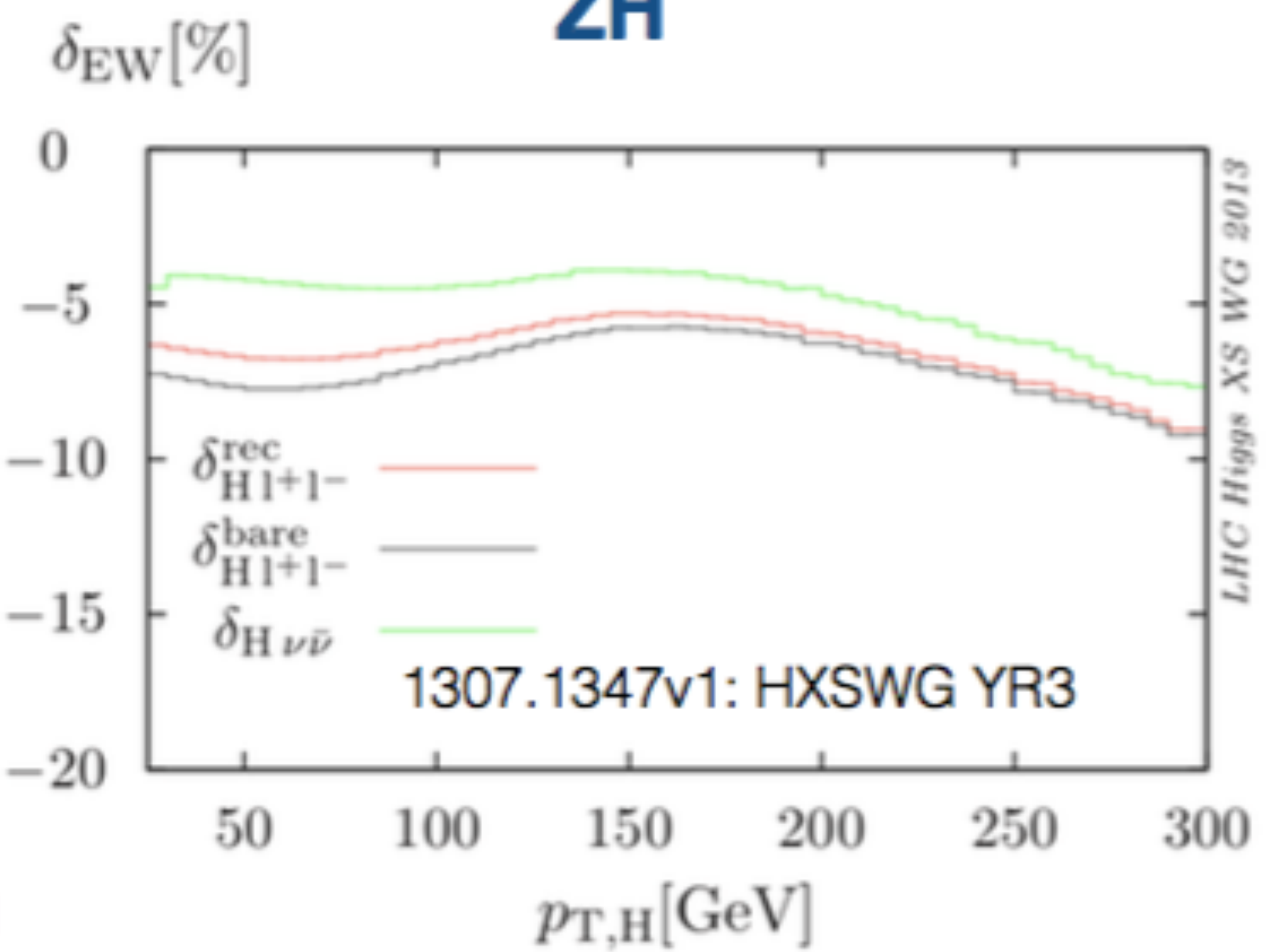
- differential predictions in form of histograms
- EW corrections at the percent level (5-10% VBF, comparable to QCD ones)
  - estimated with HAWK/VBFNLO
- Assume approximate factorisation of QCD and EWK corrections
- Accounted for via MC reweighting as a function of pT(H), prescription on twiki

VBF H



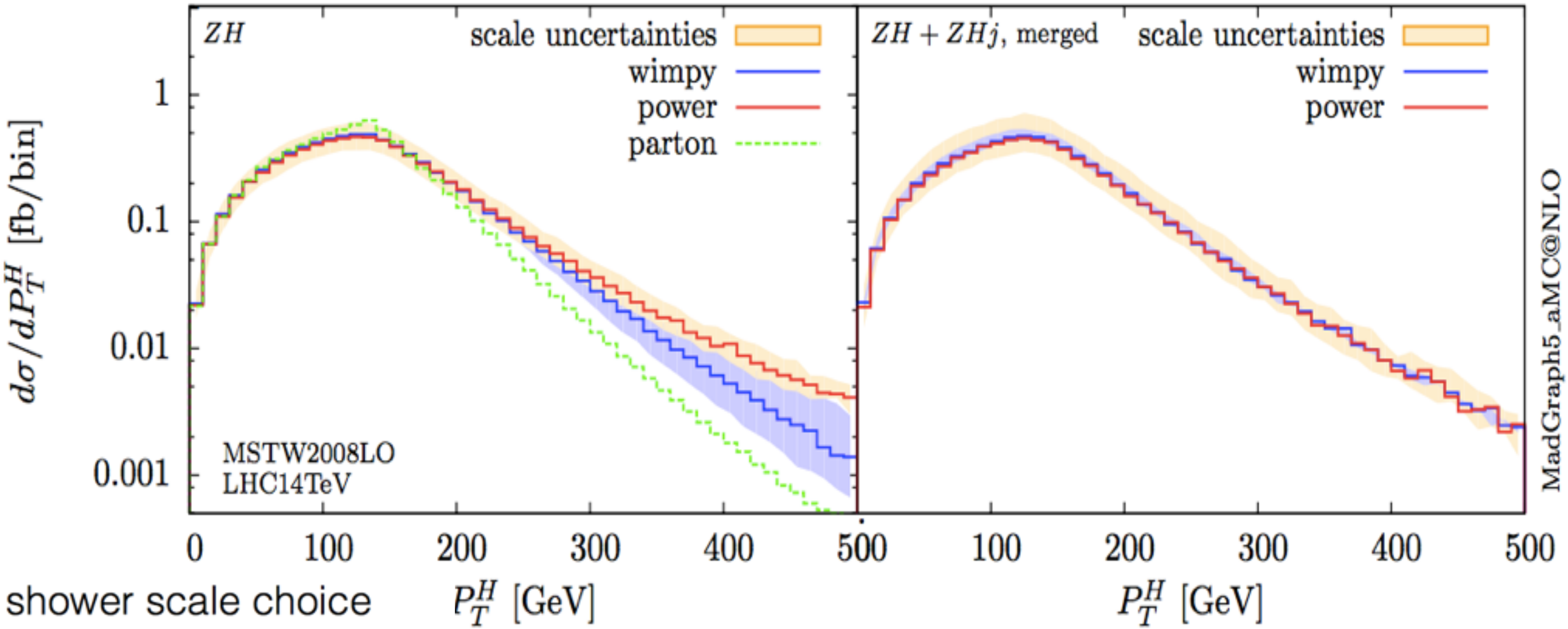
[Ciccolini, Denner, Dittmaier [arXiv:0710.4749]]

ZH



gg—>ZH: Better description by merging and matching

Merging-matching in MG5_aMC@NLO/Pythia8.2

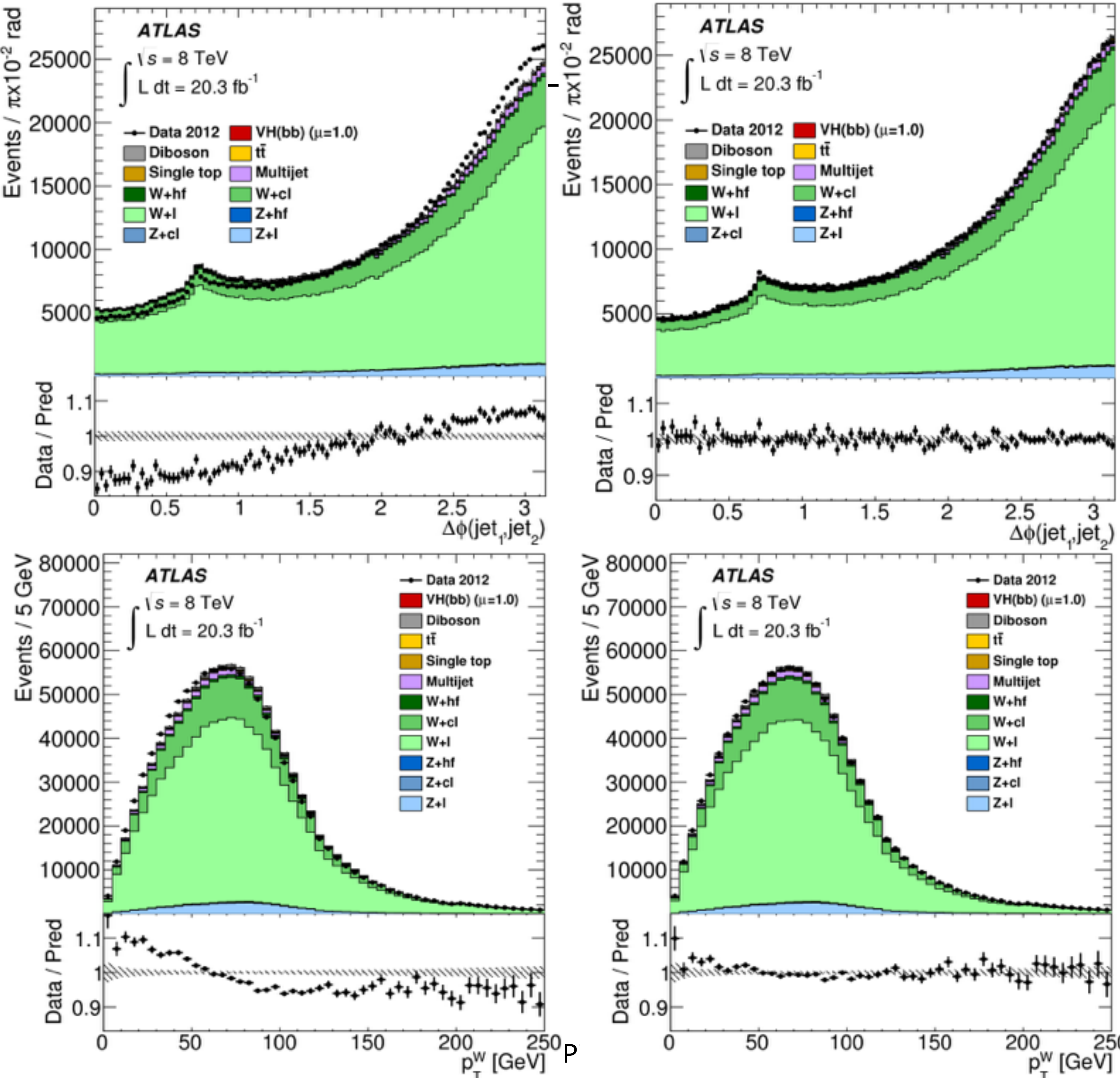


shower scale choice

- $\mu_f = m_{ZH}$ ‘wimpy-shower’
- $\sqrt{s}/2$ ‘power-shower’

Merged results: MLM
Shower-KT
QCut=30GeV

Shower-sensitive observable
Merged results:
Reduced shower uncertainty
More accurate prediction of the kinematics


ATLAS
$\sqrt{s}$ = 8 TeV
$\int$ L dt = 20.3 fb^{-1}
Data 2012
VH(bb) (μ=1.0)
Diboson
$t\bar{t}$
Single top
Multijet
W+hf
W+cl
W+l
Z+hf
Z+cl
Z+l
Events / πx10^{-2} rad
Data / Pred
Δφ(jet$_1$,jet$_2$)
Events / 5 GeV
p_T^W [GeV]

Pi