Towards high precision top quark physics

challenges in top physics and theory bottlenecks to achieve high precision measurements

Frédéric Déliot
CEA-Saclay

53rd Rencontres de Moriond Electroweak
10-17 March 2018

Disclaimer

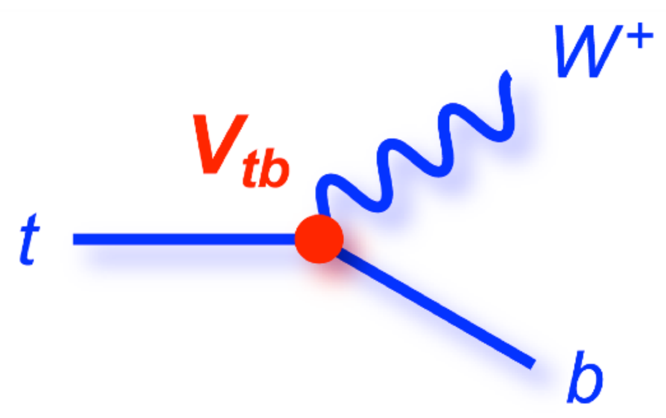
I am not a theorist so all the following is my biased view from an experimental side

- sources and acknowledgements
  - recent phenomenological papers (references on the following slides)
  - latest ATLAS and CMS results
  - presentations at the Top2017 conference
  - presentations at the Heavy Flavour Production @ LHC conference
  - LHCtopWG open meetings

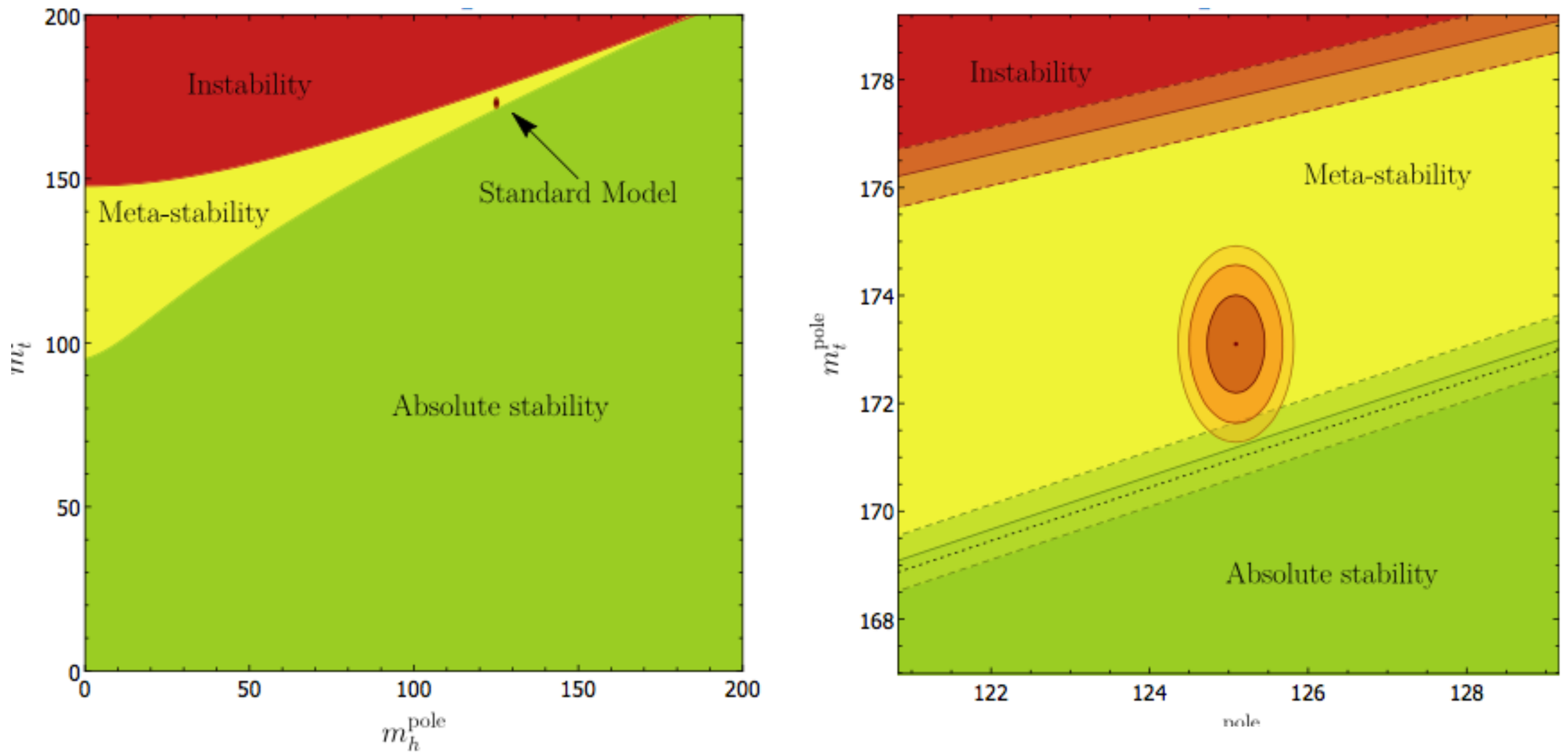
  - thanks to: Maria Aldaya Martin, Lydia Fayard, Rebeca Gonzalez Suarez, Reinhard Schwienhorst, Lisa Shabalina

Why do we care about precision in top quark physics ?

- the top quark is special
  - this is the only quark with natural mass:
    - $y_t \approx 1$, strongly interacts with the Higgs sector
  - this is the only quark that decays before hadronizing and before spin-flipping
  - this is the only quark that drastically affects the stability of the Higgs mass
    - naturalness argument: BSM top partners should be light



Andreassen, Frost, Schwartz, arXiv:1707.08124

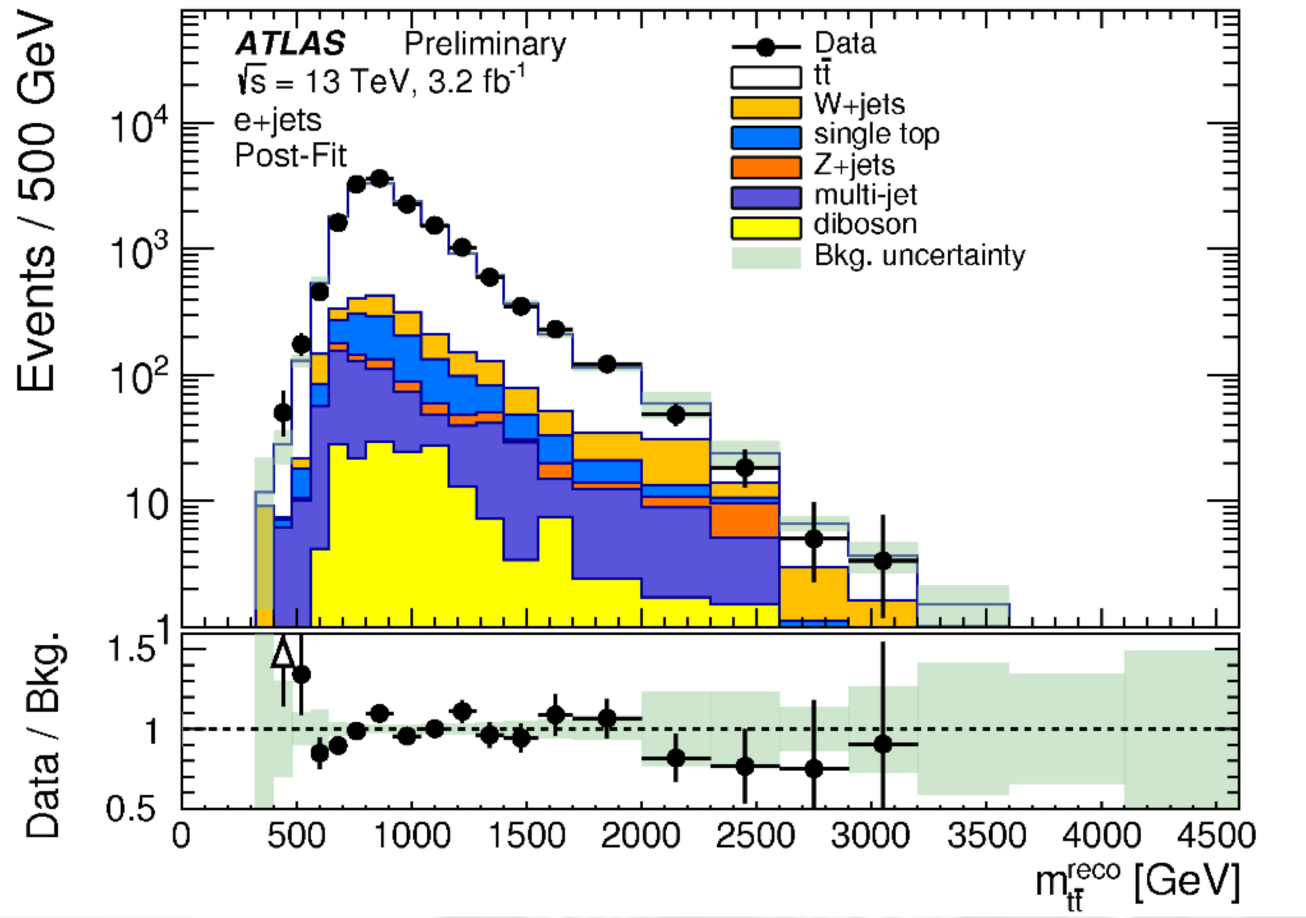


- Need for precision in the top quark sector
  - background to BSM search: $t\bar{t}$ spectrum, top pt, $t\bar{t}$ + MET (dark matter search), single top …
  - deviation from predictions: indirect detection of new particles, anomalous couplings, …

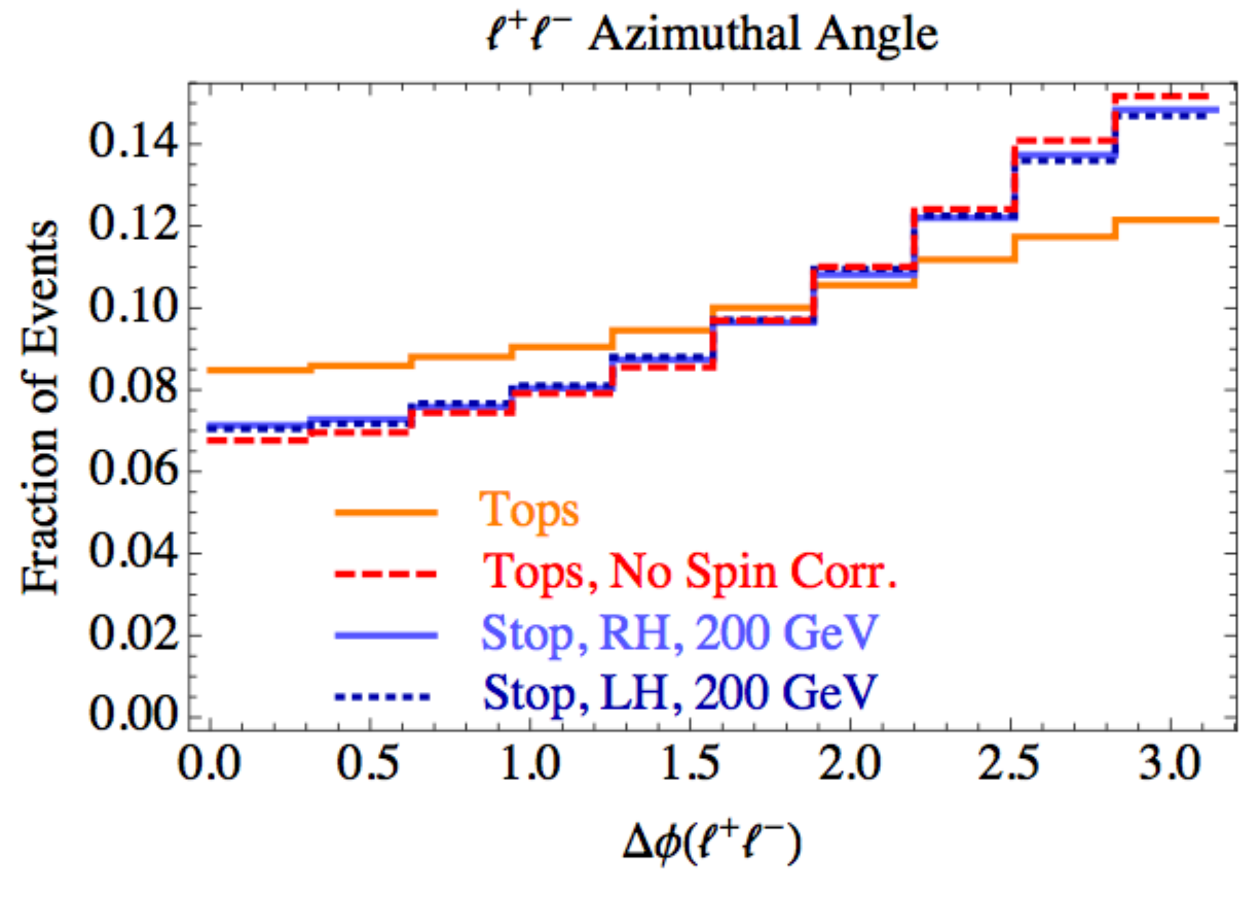
$$\tau_{\text{SM}} = \left(\frac{\Gamma}{V}\right)^{-1/4} = 10^{139^{+102}_{-51}} \text{ years}$$

$\Delta m_t < 250$ MeV to rule out absolute stability

ATLAS-CONF-2016-014



Han, Katz, Krohn, Reece, JHEP 1208, 083 (2012)

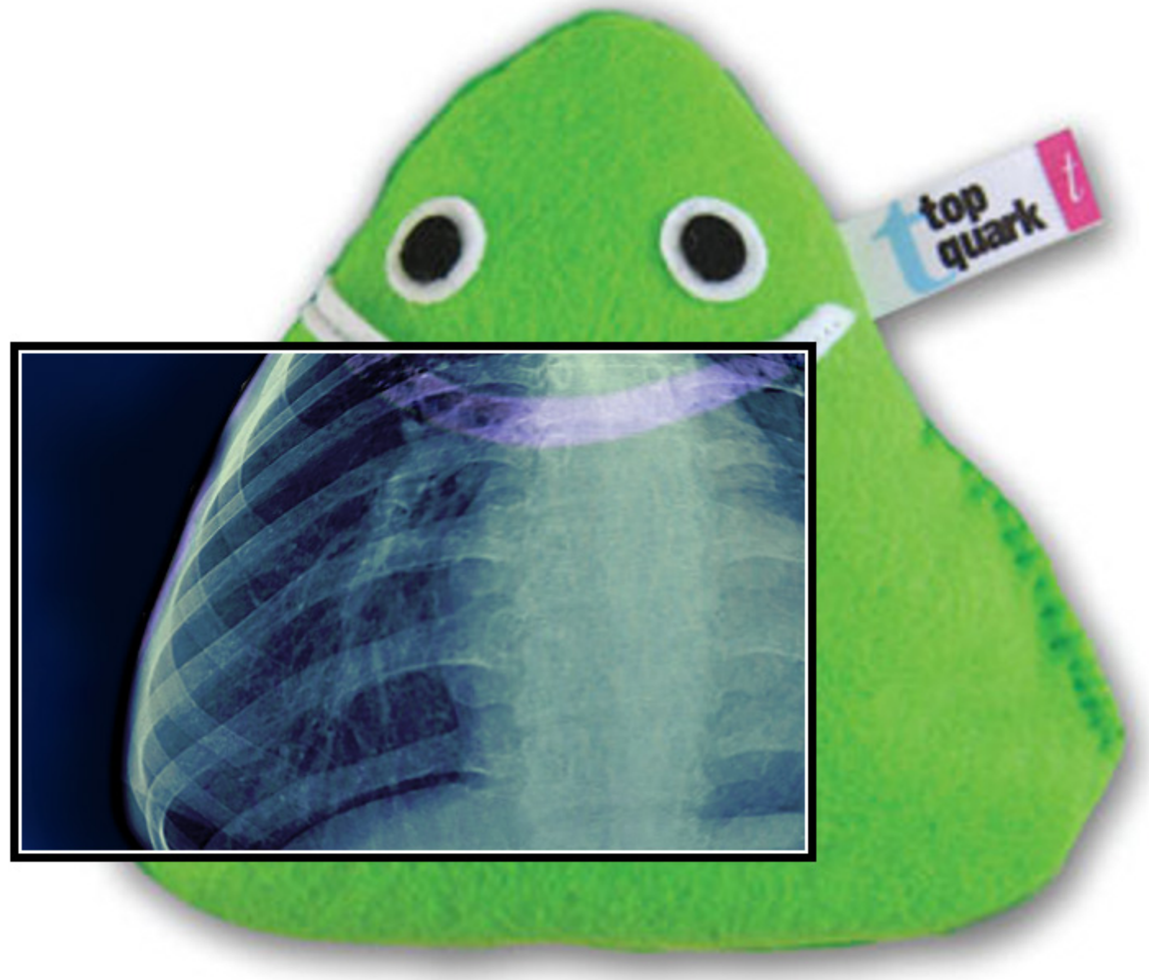


Outline

- $t\bar{t}$ differential cross section
  - latest theoretical predictions
  - the top pt saga
  - improving the modelling

- top quark mass
  - latest discussions on the mass definition and on the theoretical uncertainties

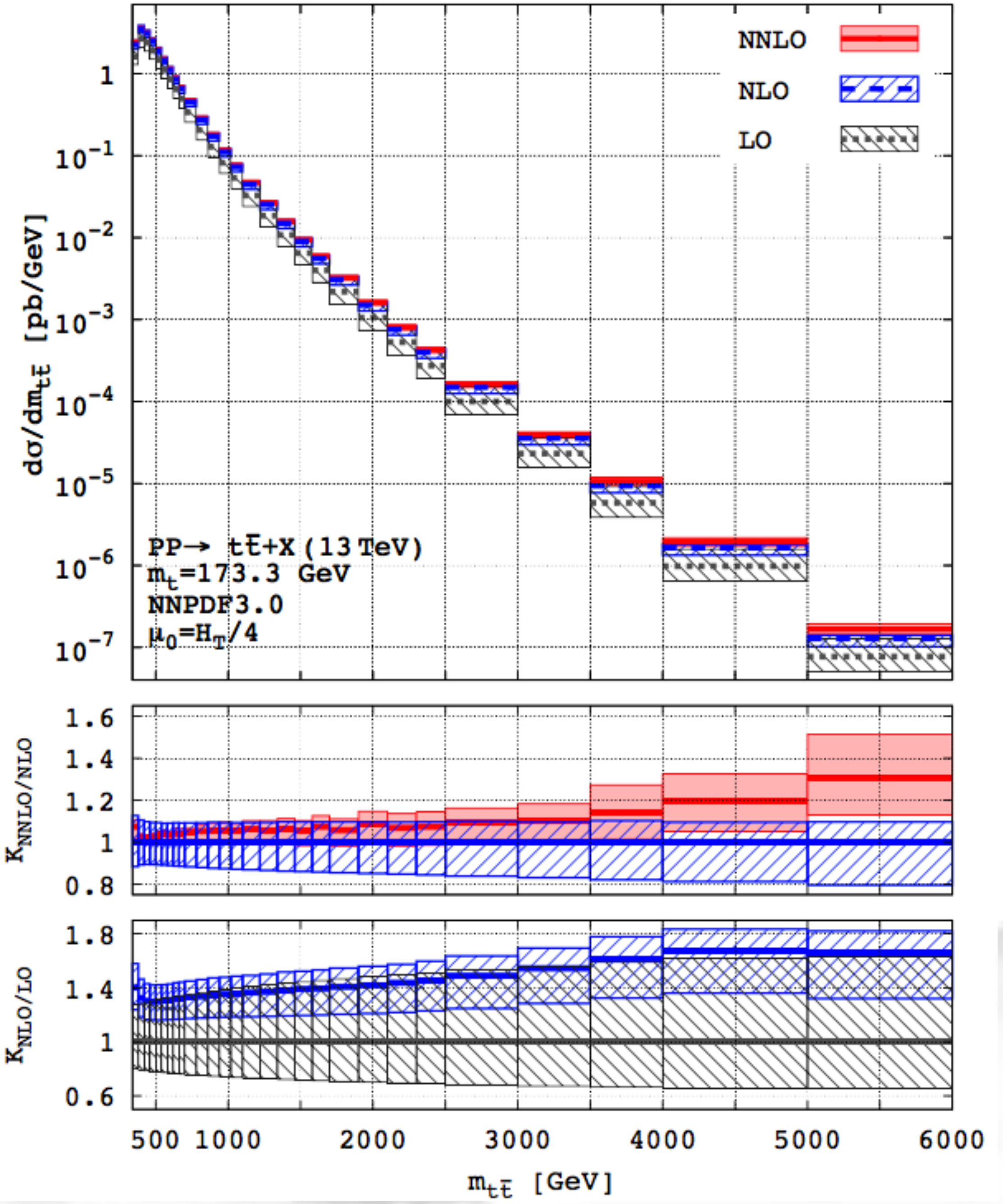
- top quark couplings
  - the Effective Field Theory (EFT) approach



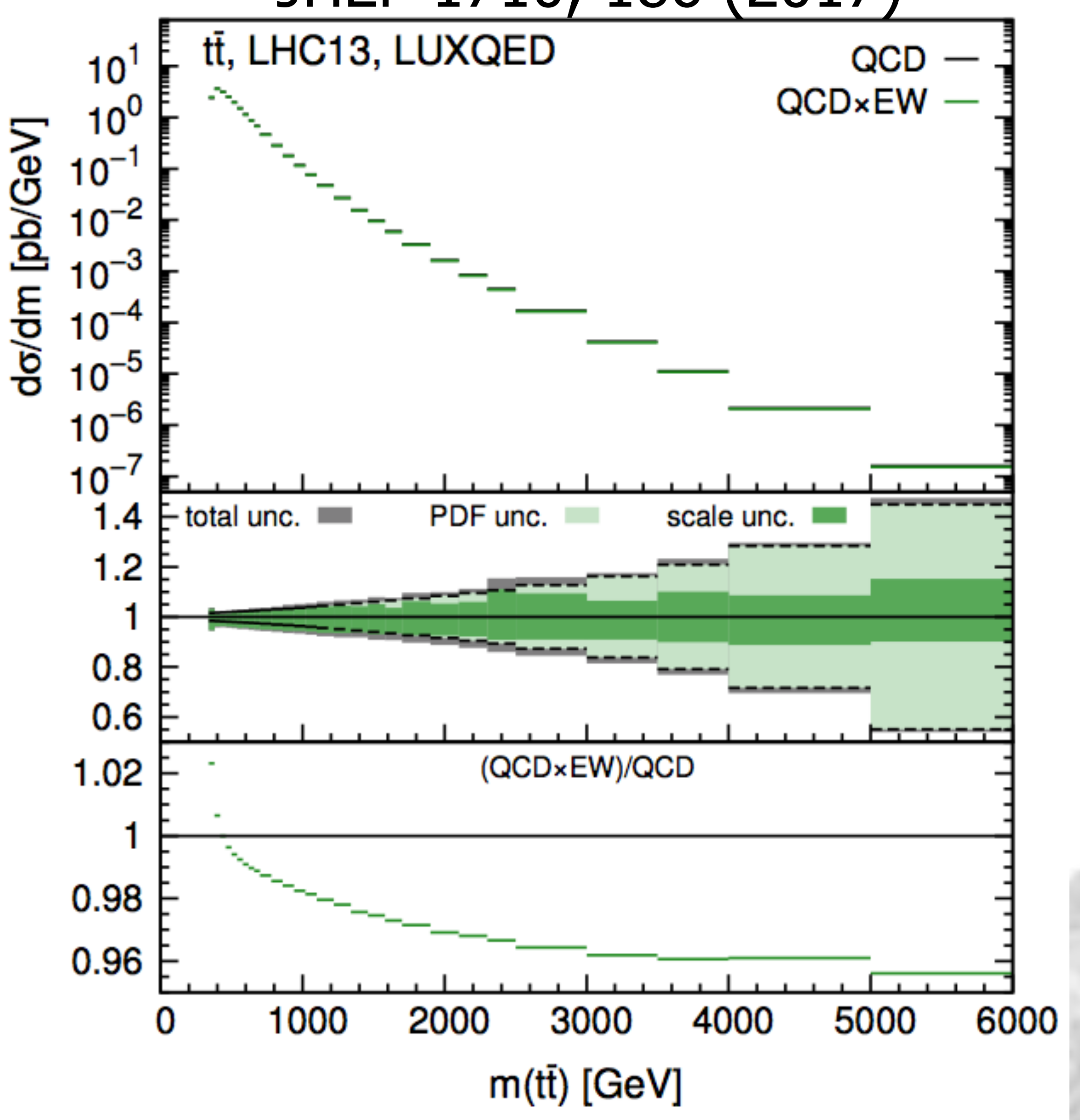
$t\bar{t}$ differential cross section predictions

- State of the art
  - differential NNLO QCD for $t\bar{t}$ production (JHEP 1704, 071 (2017)) now also including the $t\bar{t}$ charge asymmetry
    - crucial to use dynamic scale (renormalisation and factorisation scales that vary event by event)
    - leading uncertainty: PDF
  - NLO EW corrections (JHEP 1710, 186 (2017))
    - EW corrections could have a large impact in tails of distributions (-4% for $m_{t\bar{t}}$, up to -25% for top pt)
  - Next-to-Next-Leading Log (NNLL) resummation
    - reduce scale uncertainty and the dependence due to the scale choice

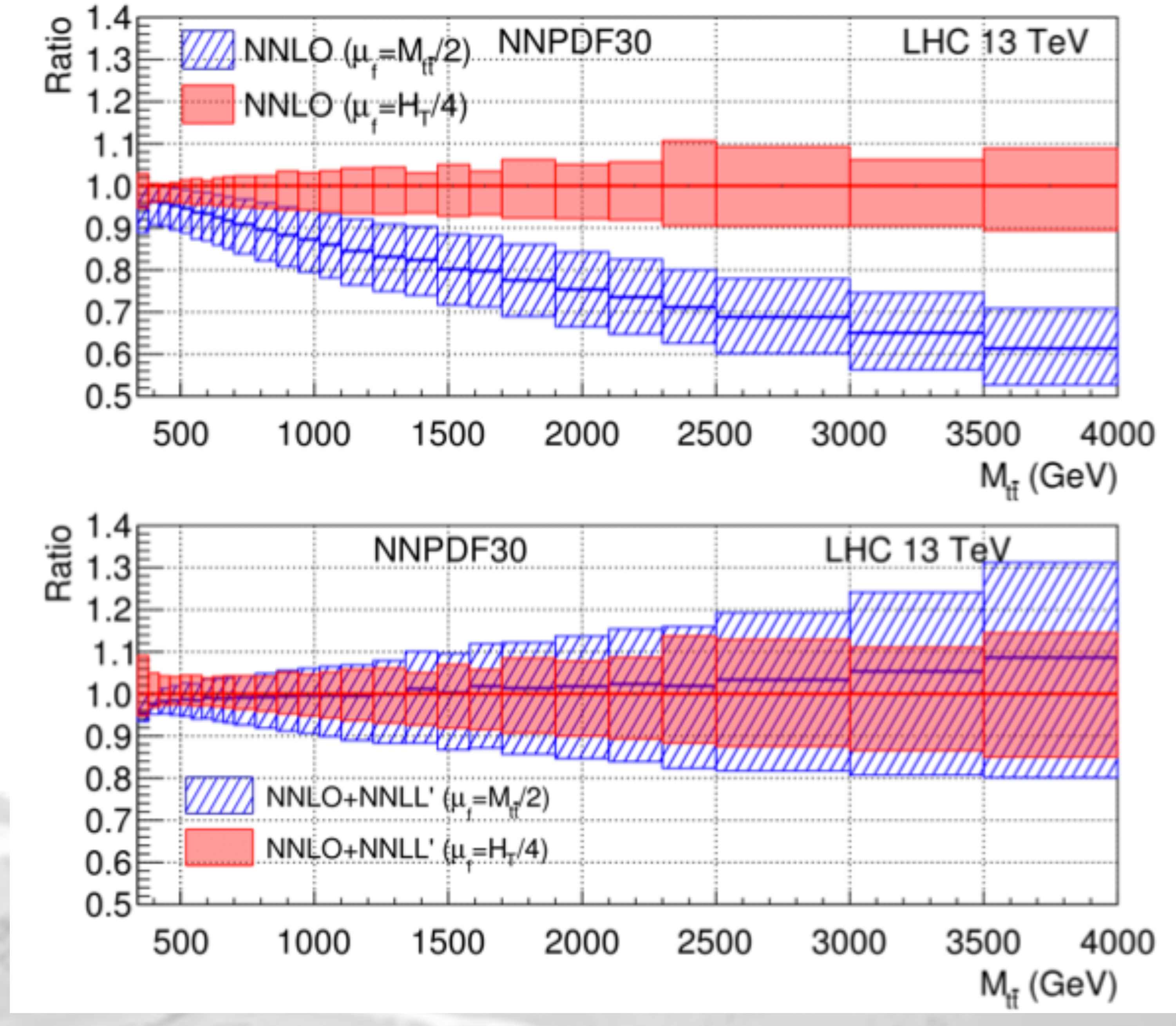
Czakon, Heymes, Mitov, JHEP 1704, 071 (2017)



Czakon, Heymes, Mitov, Pagani, Tsinikos, Zaro
JHEP 1710, 186 (2017)



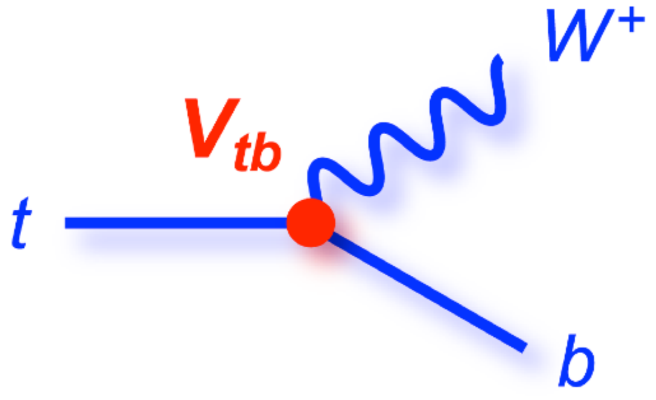
Czakon et al., in preparation



Large future applications for LHC data (PDF global fit, …)
Need to be compared with experimental measurements and implemented in public tools (on-going)

$t\bar{t}$ predictions: moving away from stable tops

- top quark always detected through its decay products
  - measurements compared with MC with different shower and decay treatments: difficult to assess the related theoretical uncertainties
  - precision top quark physics requires predictions that include the top decays (mass from leptonic decay products, direct measurement of the top width …):
    - NLO corrections to decay usually change normalization and shape

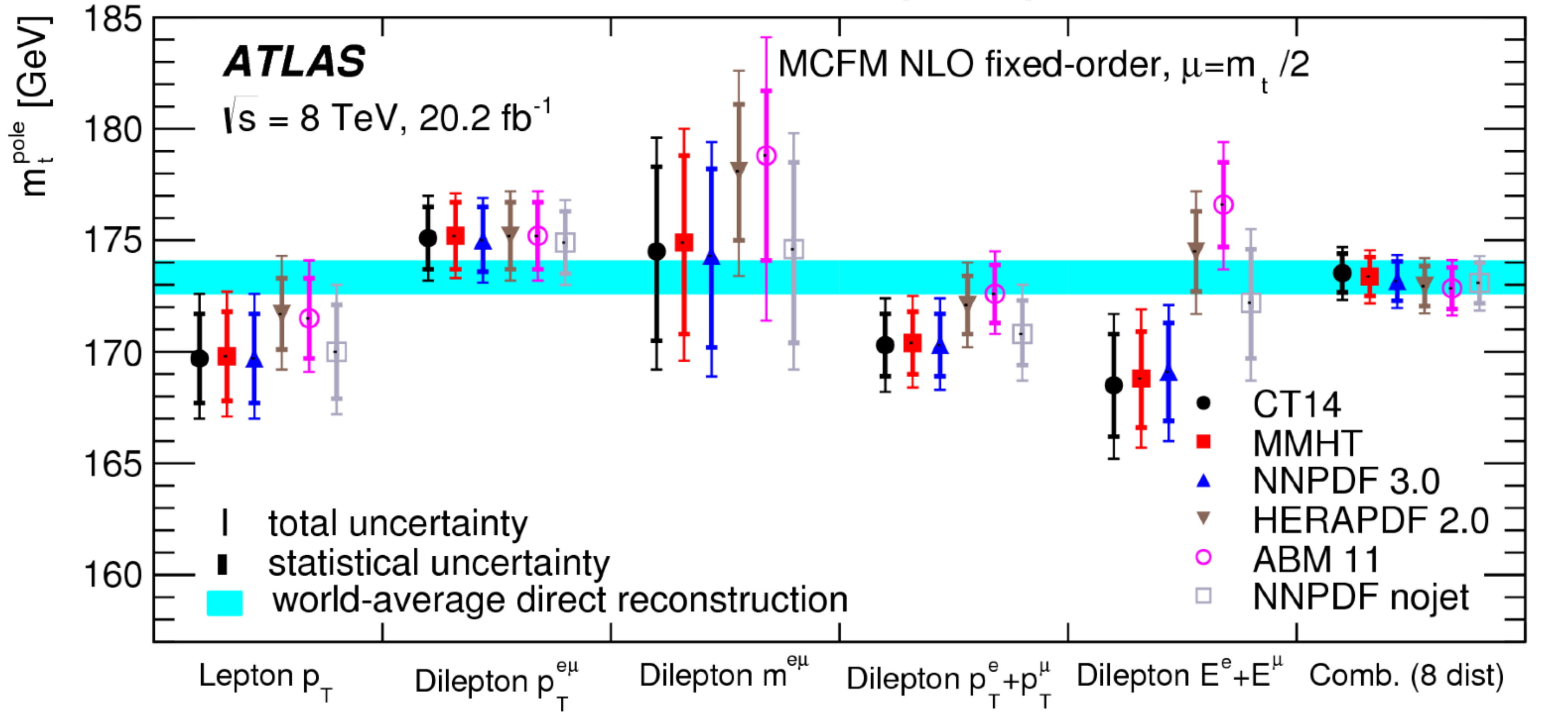


mass from leptonic decay products

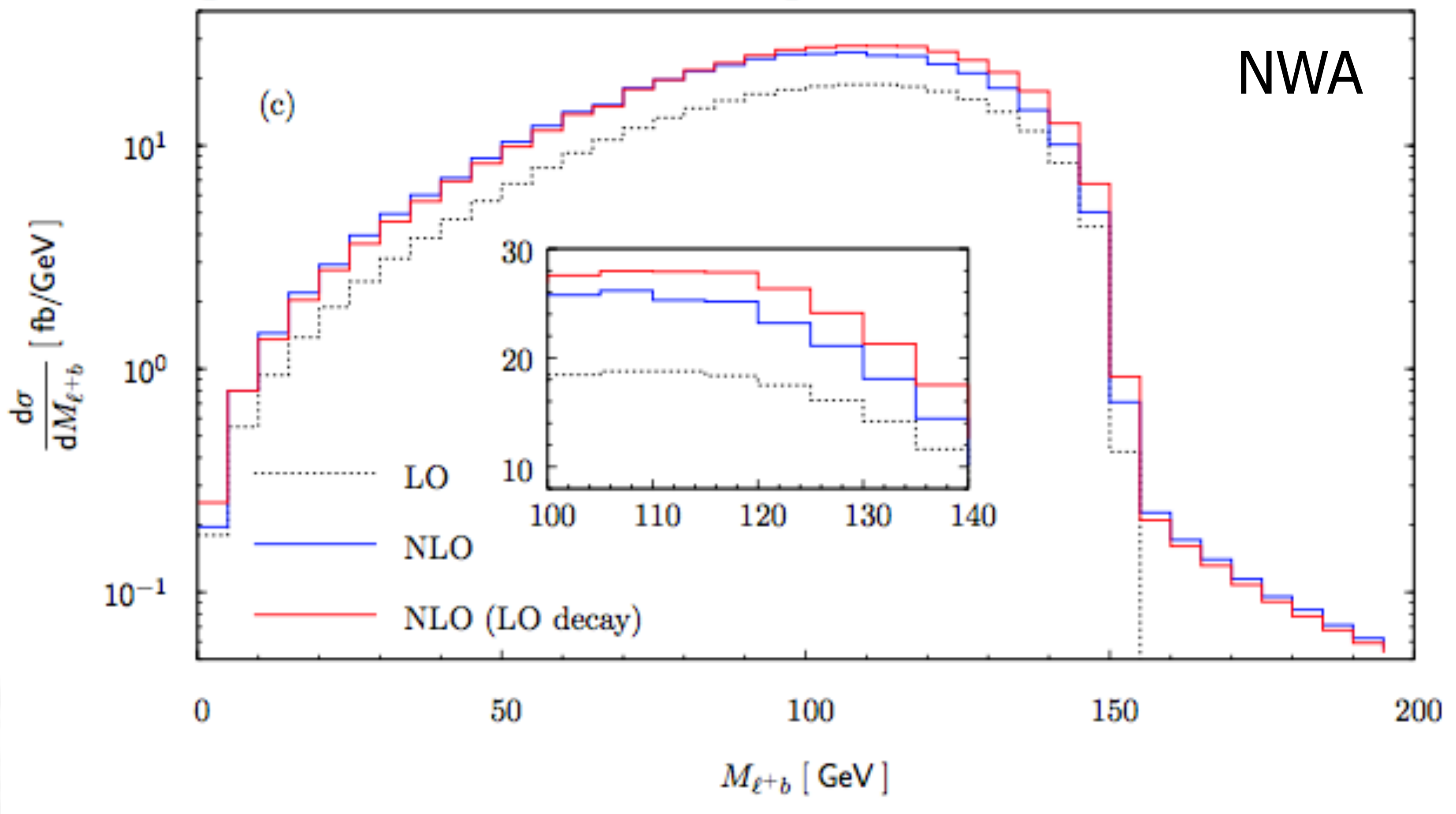
$$m_t^{\text{pole}} = 173.2 \pm 0.9 \pm 0.8 \pm 1.2\ \text{GeV}$$

different QCD scales

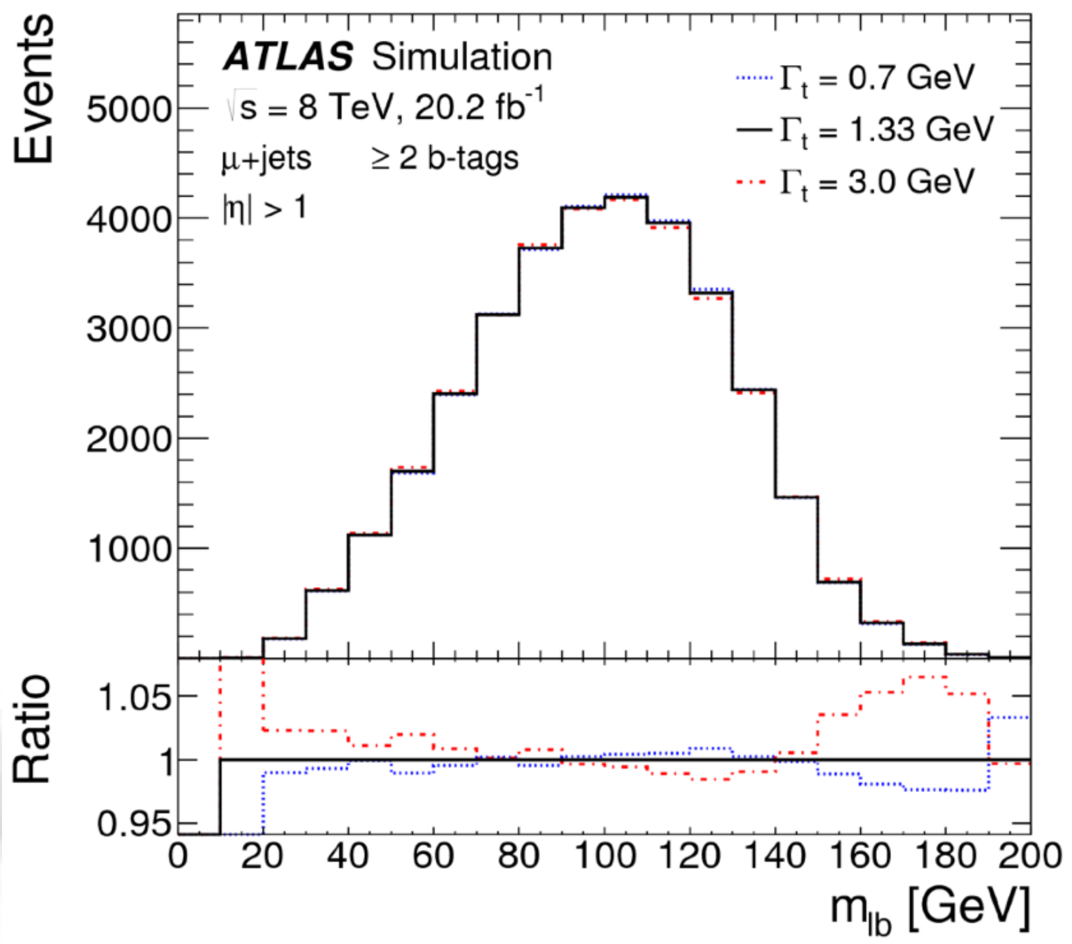
EPJC 77, 804 (2017)



Melnikov, Schulze, JHEP 0908, 049 (2009)



EPJC 78, 129 (2018)

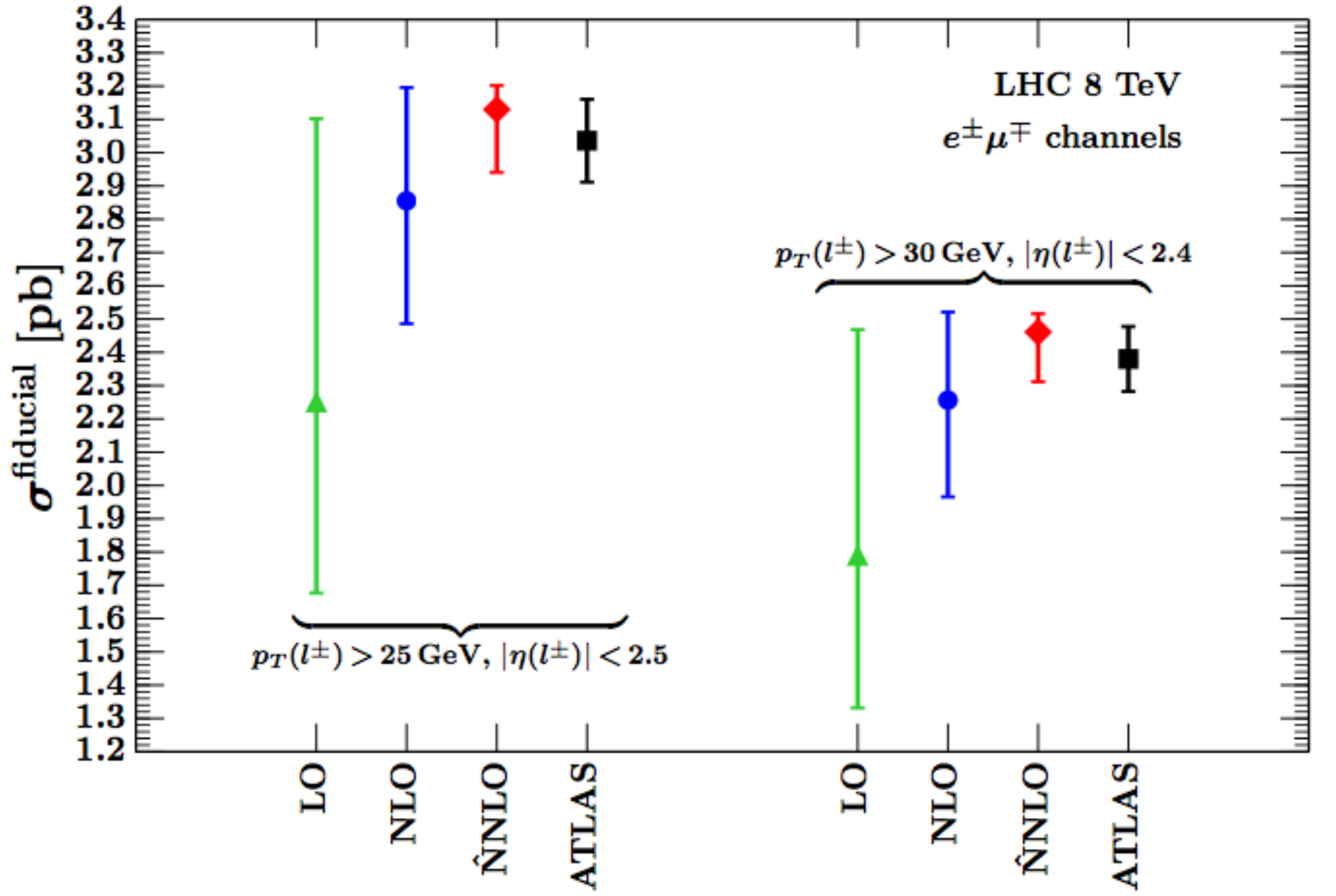


$t\bar{t}$ predictions: moving away from stable tops (2)

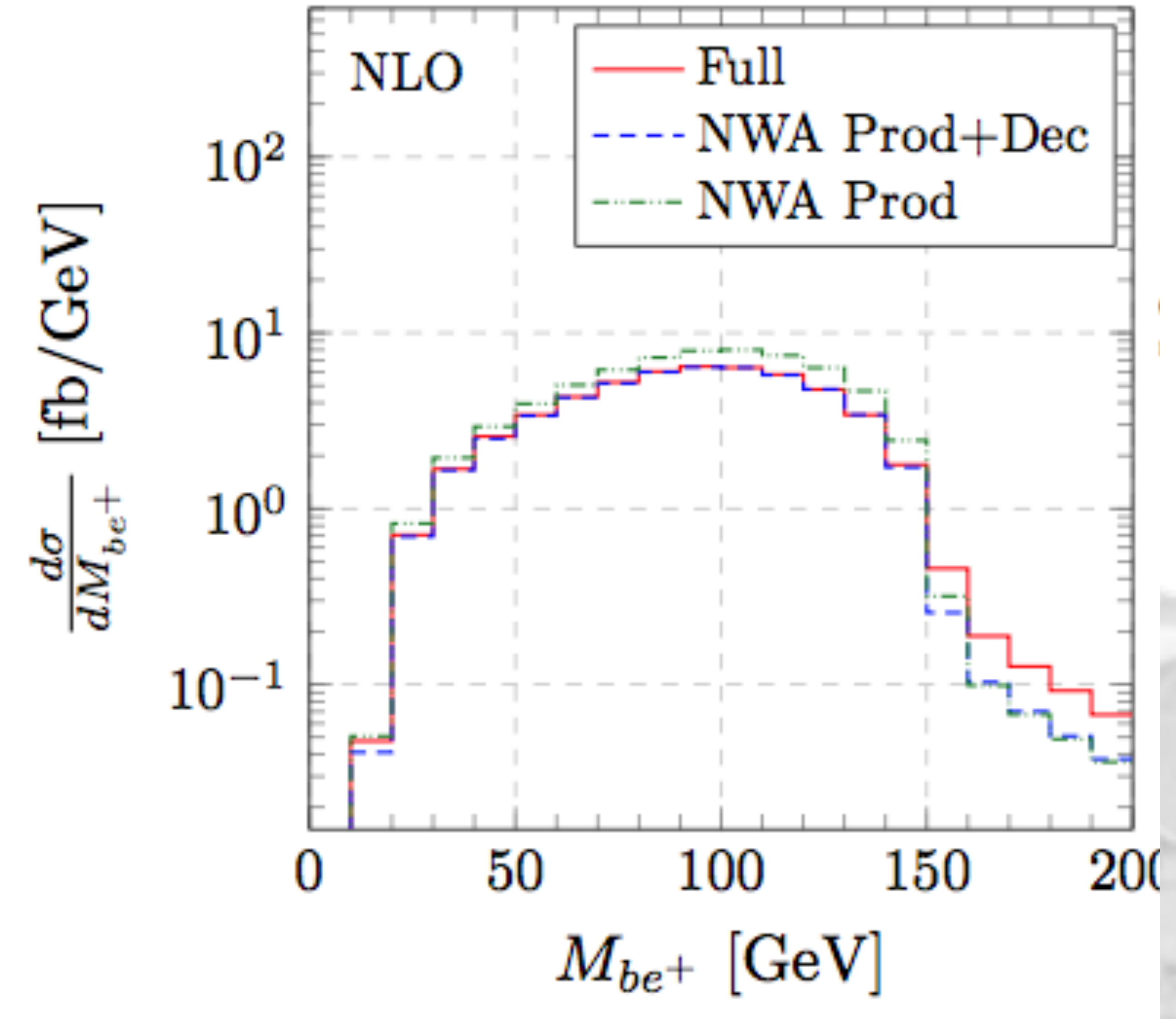
- two approaches
  - narrow-width approximation NWA (factorisation of the production and decay, on-shell top): good approximation for large class of observables
    - usually good performances, exact NNLO not yet available
  - off-shell treatment: off-shell and non-resonant effects small for large class of observables but crucial for some phase space regions
    - NLO corrections to eμbb and eμbbj

- including parton showers
  - off-shell, NLO corrections to resonant and non-resonant contributions implemented in POWHEG (bb4l): see discussion on the mass

Gao, Papanastasiou, PRD96 051501 (2017)
approx NNLO, NWA



Bevilaqua, Hartando, Krauss, Schulze, Worek,
in preparation



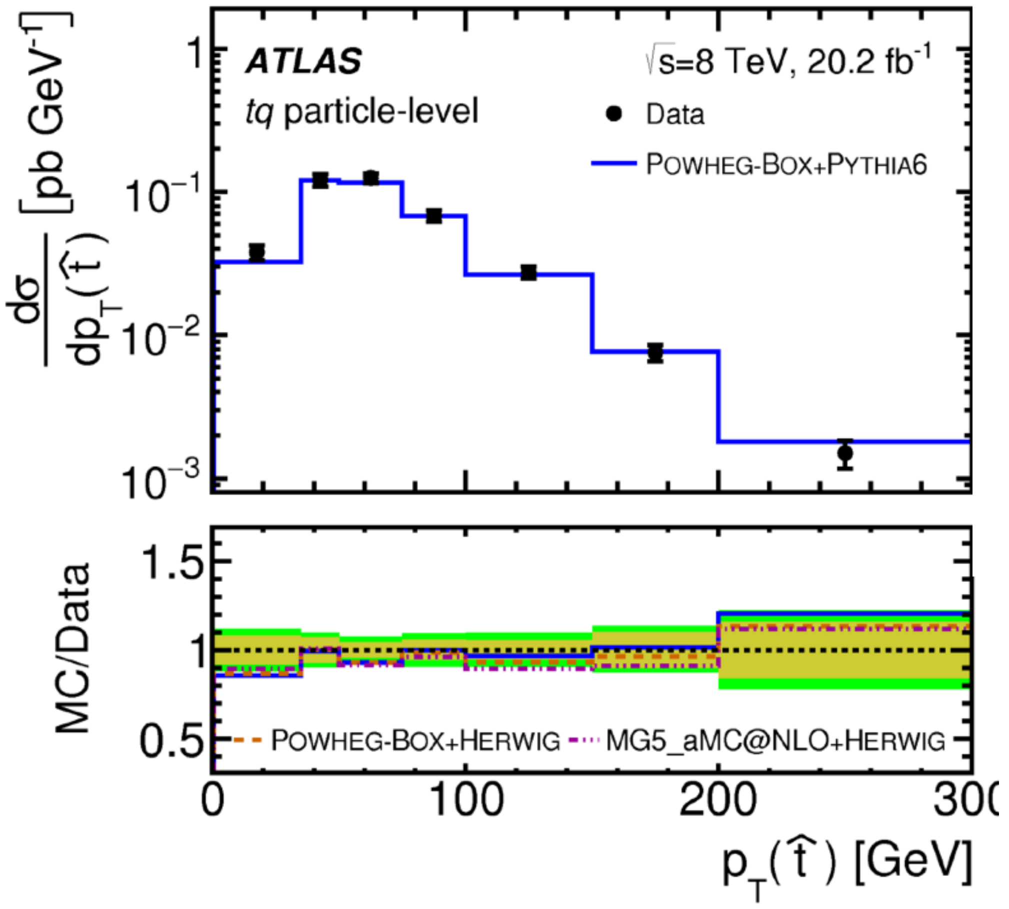
The top pt saga

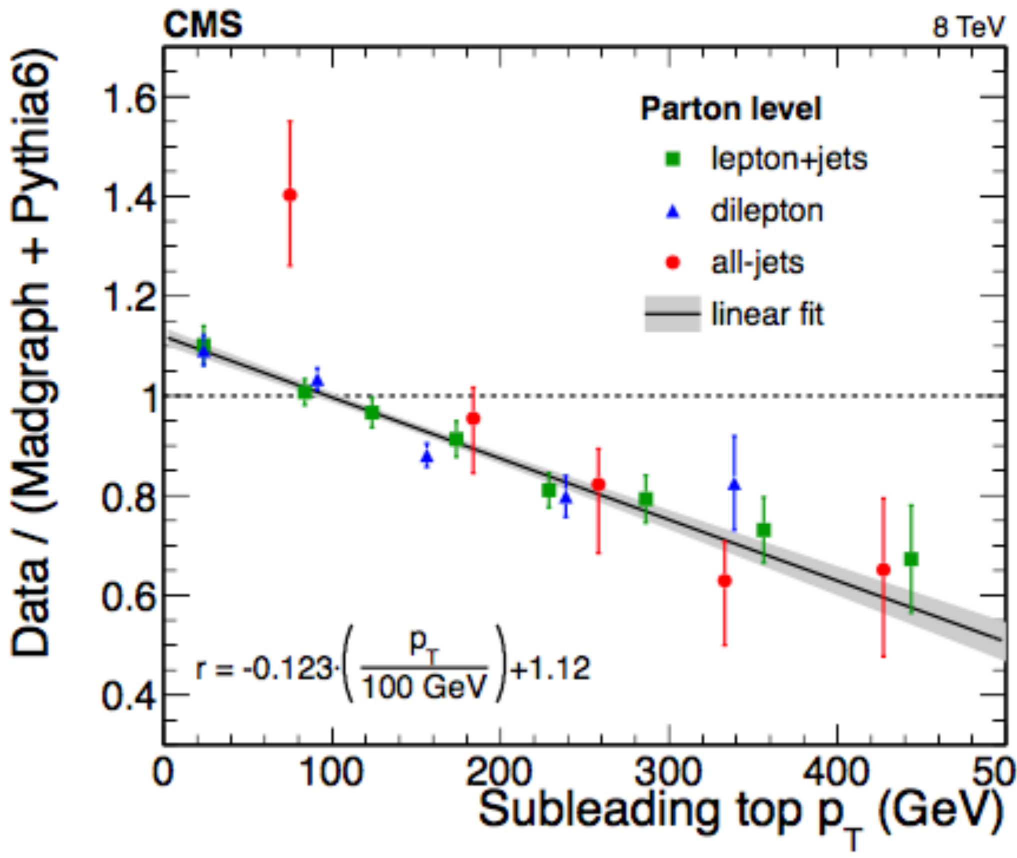
- one of the important observables to be well modelled
  - influence the kinematics of the top decay products (lepton pt, b-jet pt, … and then global variable like Ht)
  - define the collimation of the top decay products

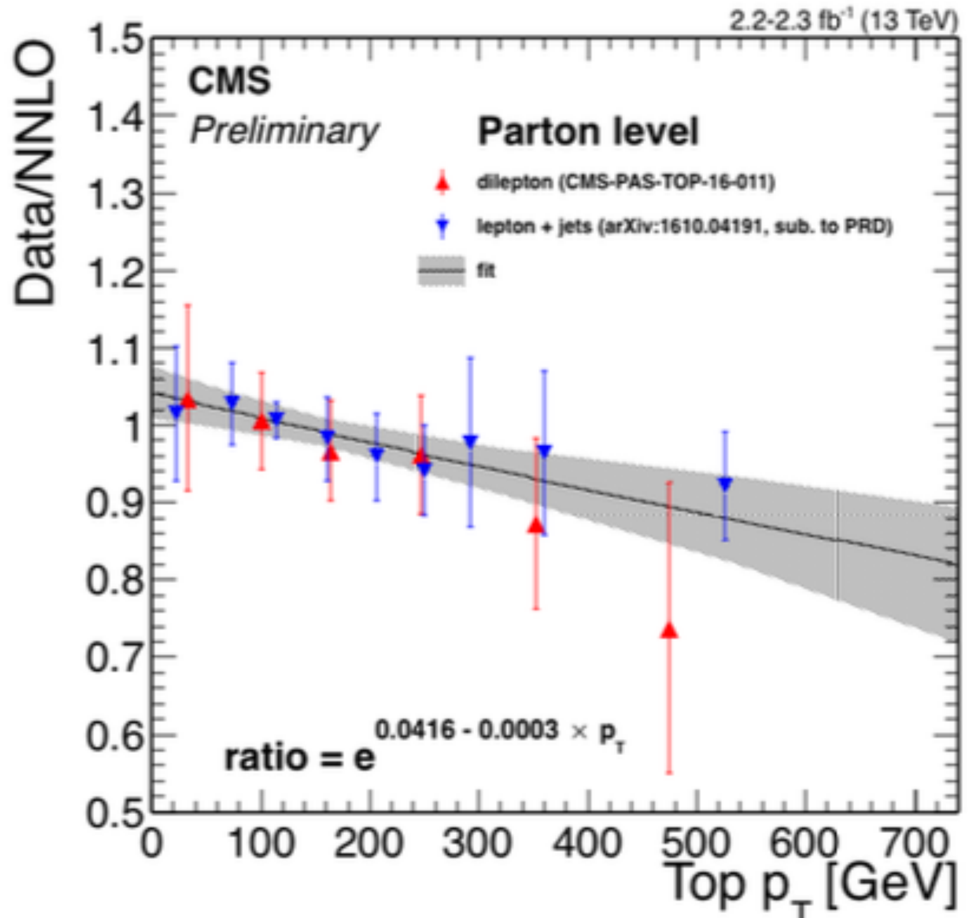
- measured at parton and particle level at all LHC energies
  - top pt seems always softer in data than in MC (seen by both ATLAS and CMS), disagreement seen both in 1D and 2D measurements
  - leading top pt agrees better with data than subleading top pt, boosted all-had top pt looks OK
  - NNLO+NNLL better agreement
  - would the addition EW corrections close the issue ?

  - to be continued …

EPJC 77, 531 (2017)
single top t-channel

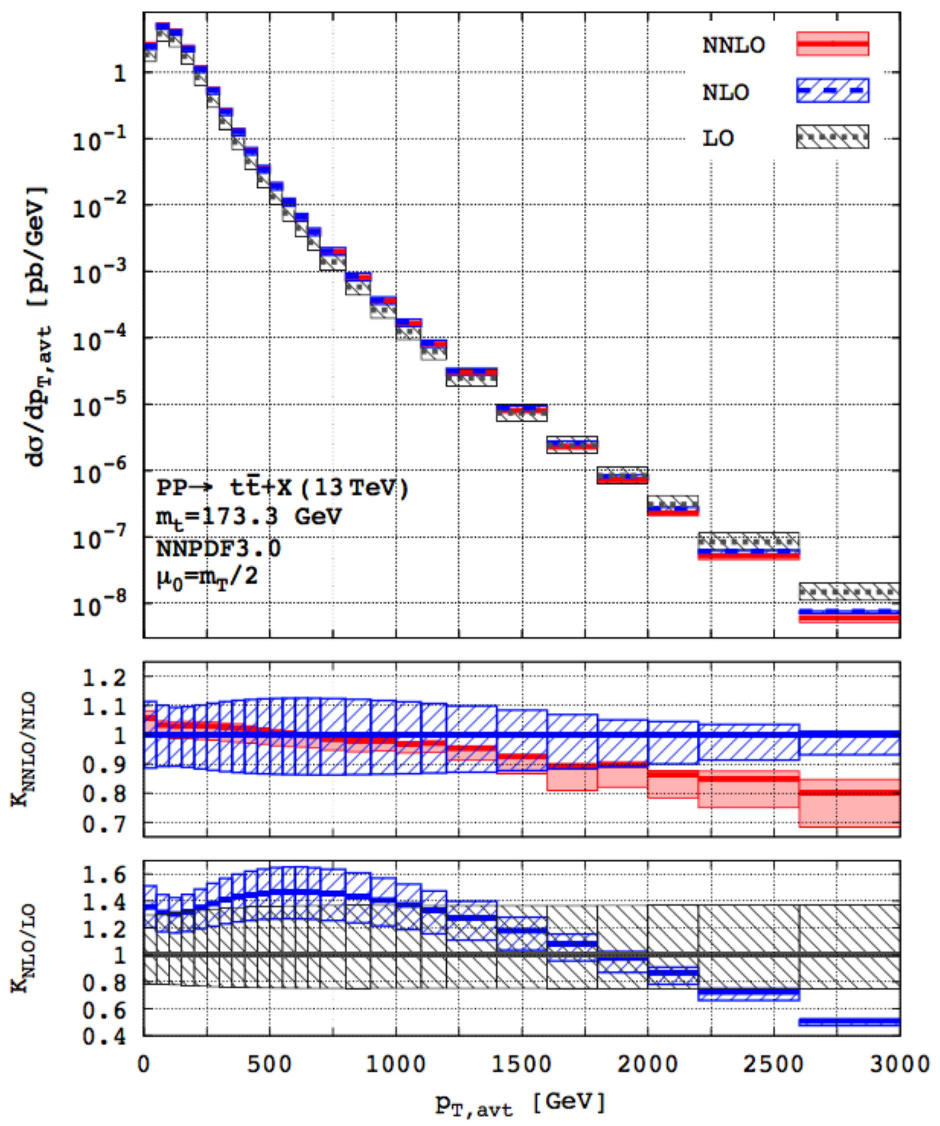


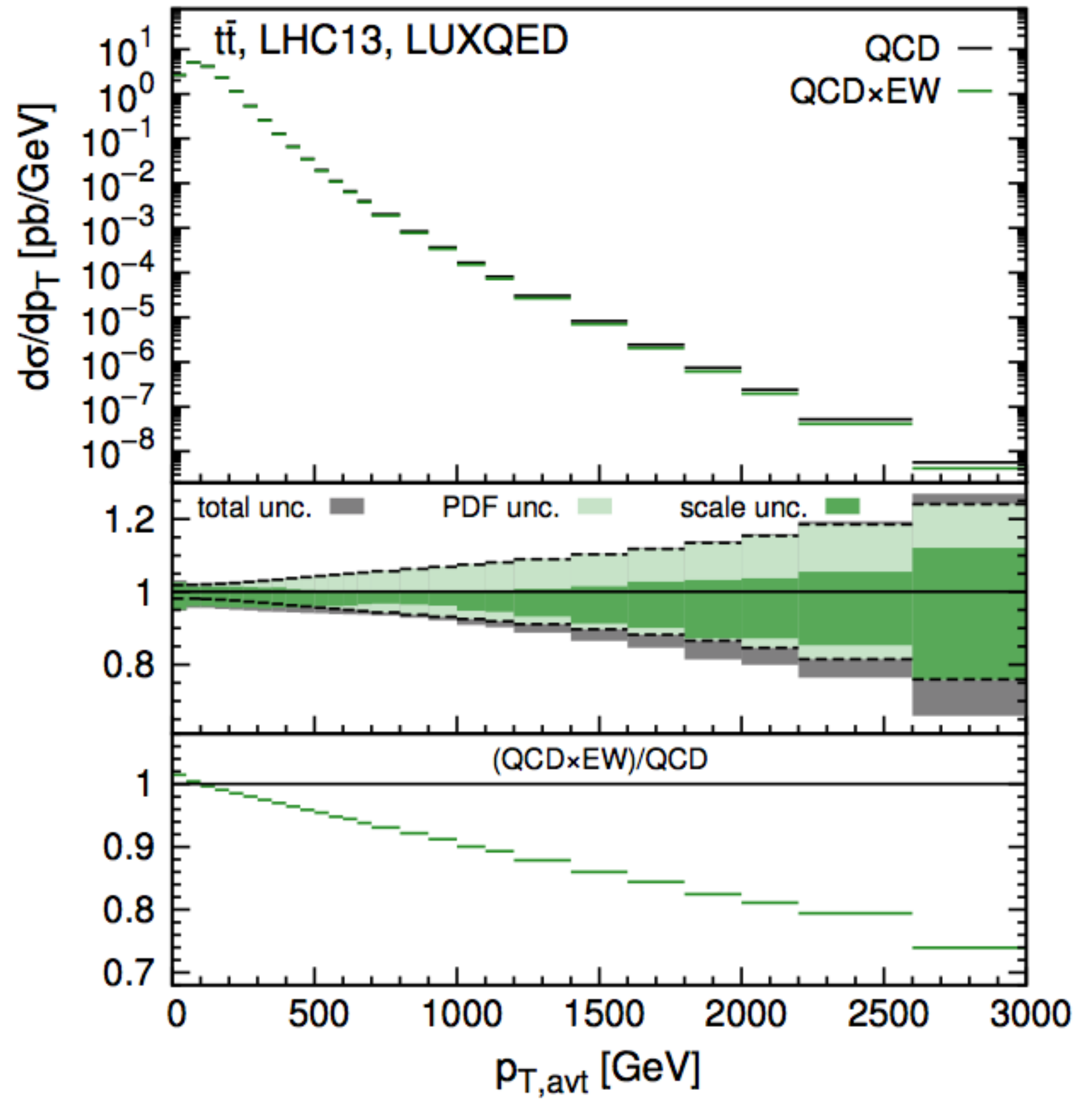


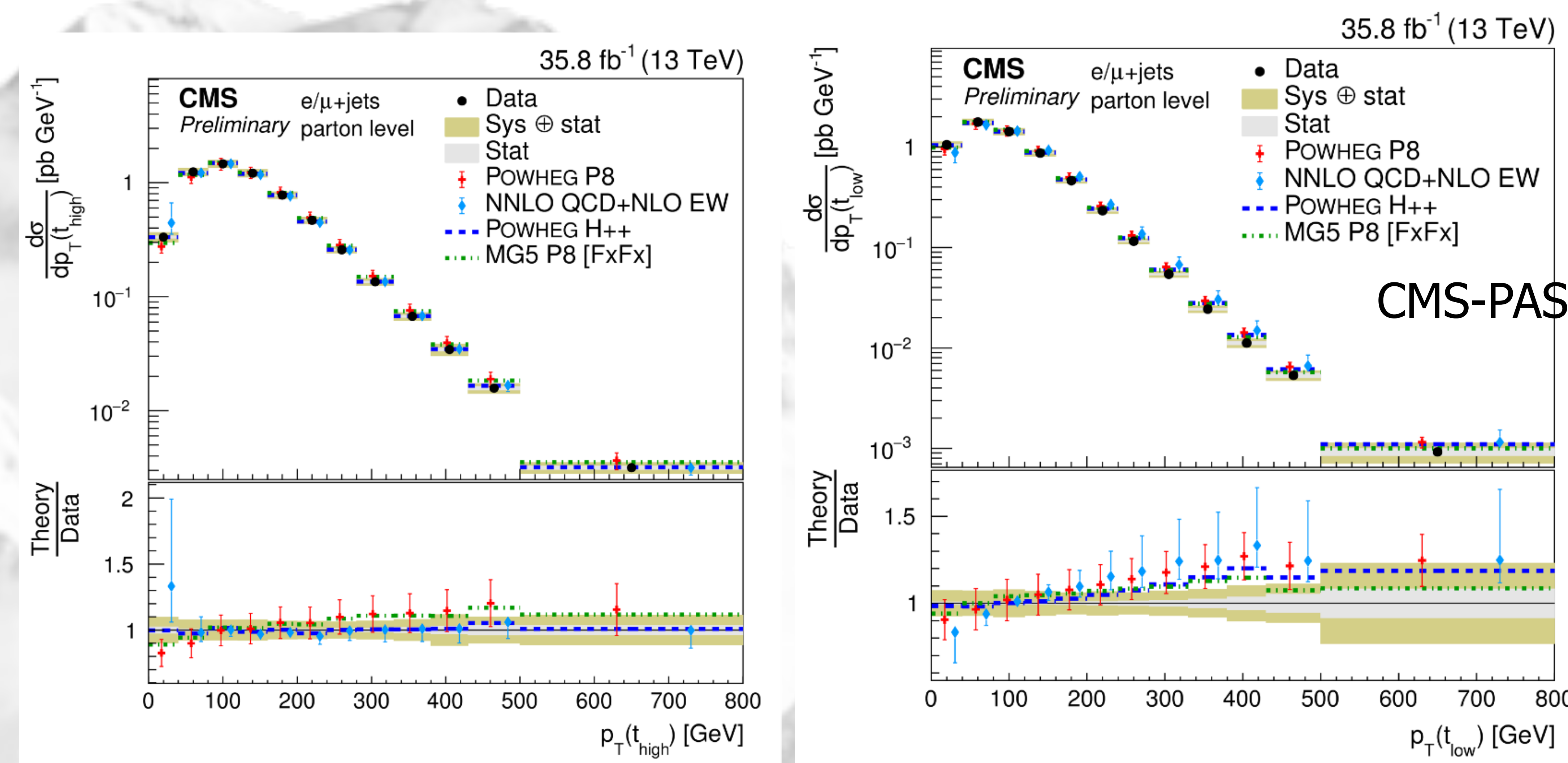


Czakon, Heymes, Mitov,
JHEP 1704, 071 (2017)

Czakon et al.
JHEP 1710, 186 (2017)







CMS-PAS-TOP-17-002

Precision $t\bar{t}$ differential cross section measurements

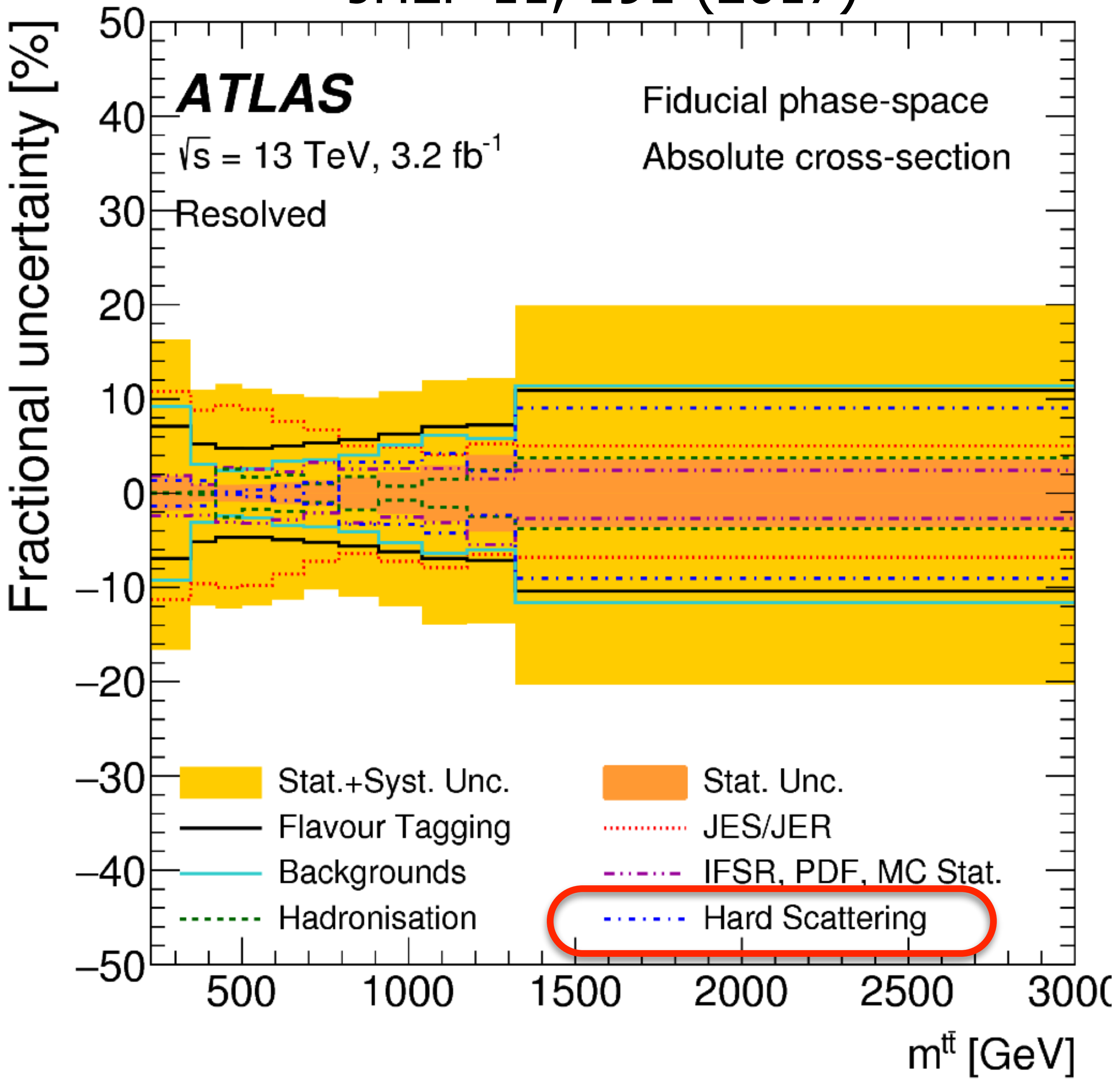
- $t\bar{t}$ kinematics start to be precisely studied
  - parton, particle levels, fiducial phase space, inclusive and exclusive final states
  - still ~ 15% uncertainty in the tails

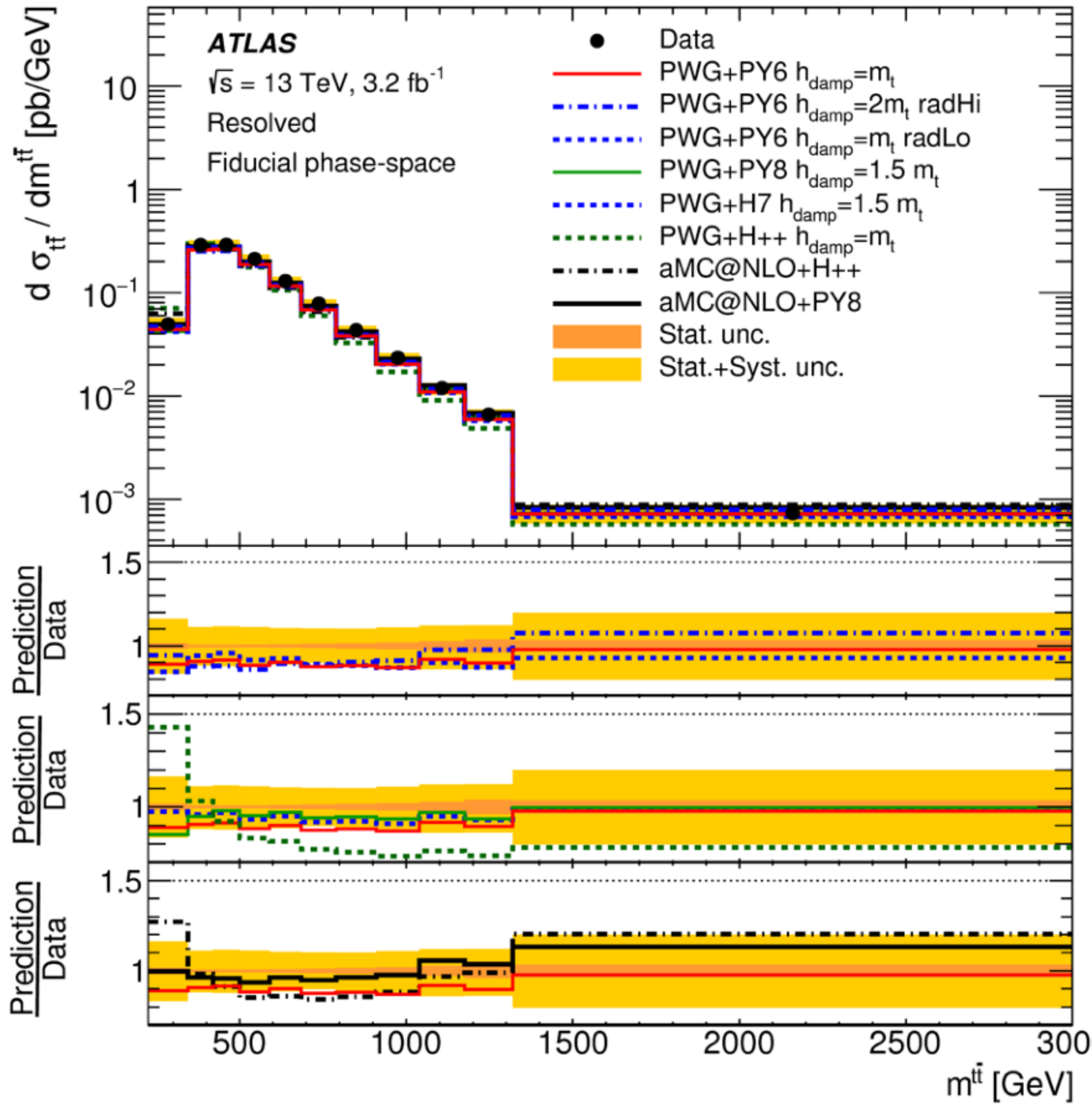
- how to go further ?
  - 2D (3D?) differential measurements
  - improve modelling uncertainties
  - more extreme phase space regions
  - still discussion on how to define what is called `parton level'

Source	Particle level [%]	Parton level [%]
Statistical uncertainty	1–5	1–5
Jet energy scale	5–8	6–8
Jet energy resolution	<1	<1
$\vec{p}_T^{\,miss}$ (non jet)	<1	<1
b tagging	2–3	2–3
Pileup	<1	<1
Lepton selection	3	3
Luminosity	2.3	2.3
Background	1–3	1–3
PDF	<1	<1
Fact./ren. scale	<1	<1
Parton shower scale	2–5	2–9
POWHEG+PYTHIA8 vs. HERWIG++	1–5	1–12
NLO event generation	1–5	1–10
m_t	1–2	1–3

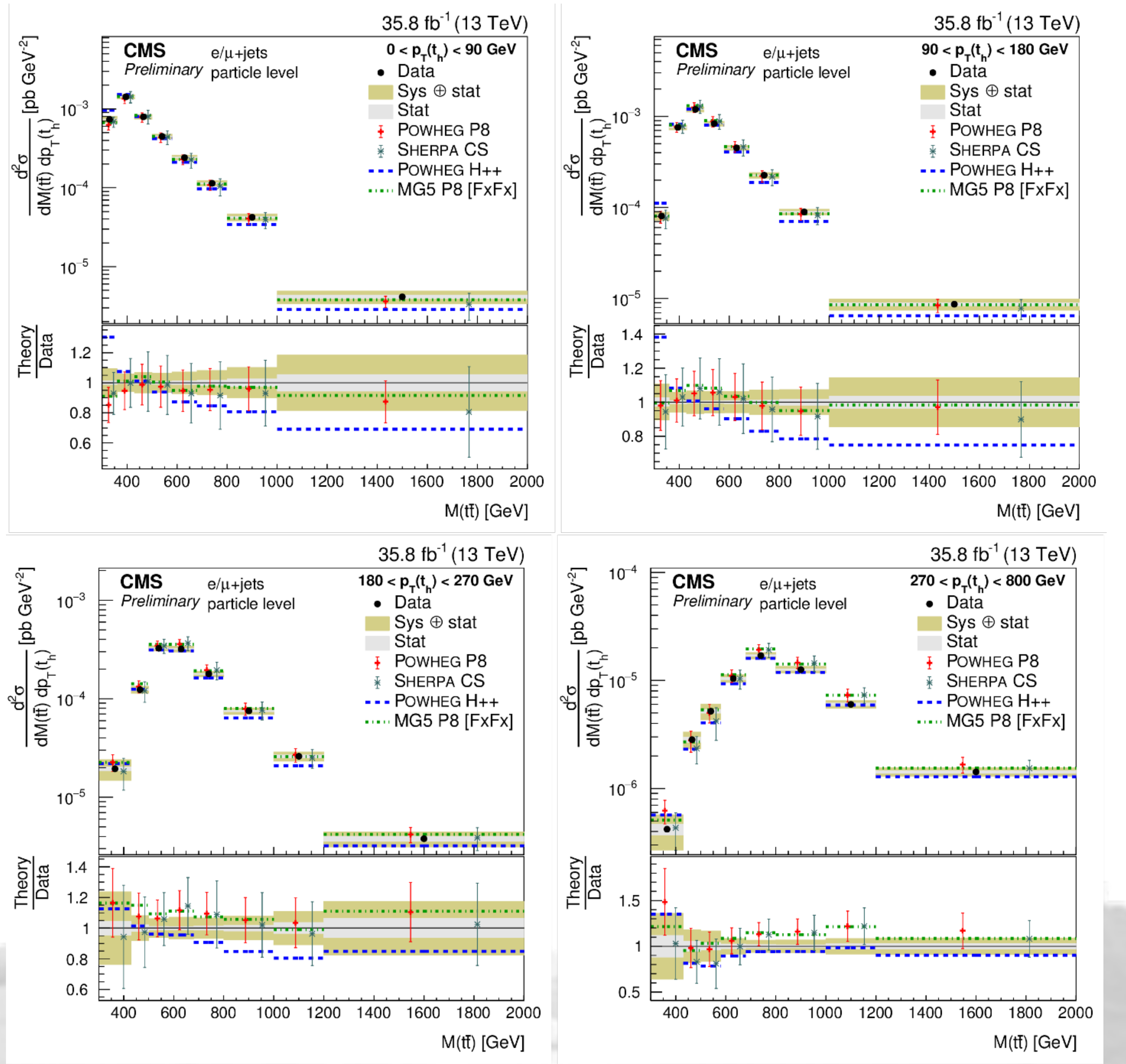
PRD95, 092001 (2017)

JHEP 11, 191 (2017)





CMS-PAS-TOP-17-002

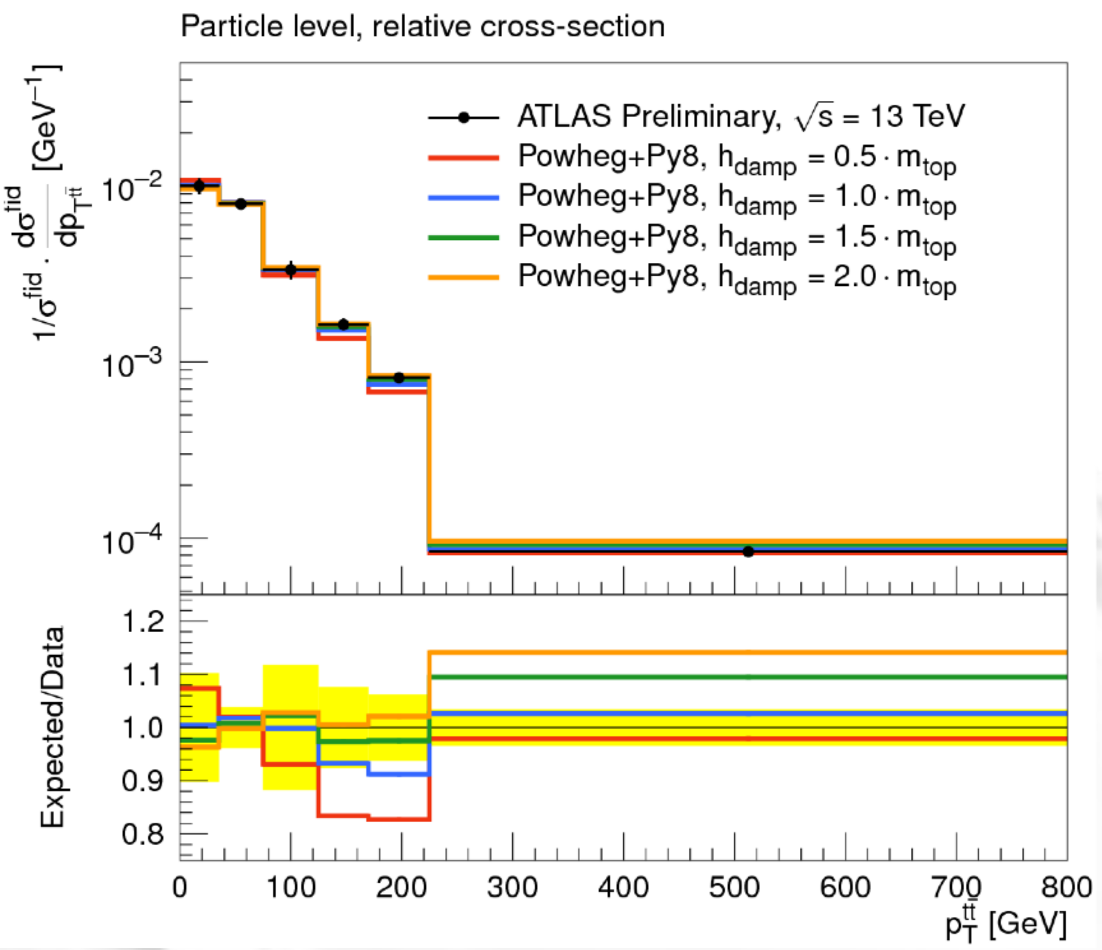


Top modelling and tuning

- MC generator setups
  - need to choose MC parameters/models that cannot be obtained from first principles: adjust/tune them on data
  - need to determine uncertainties related to these choices
- baseline $t\bar{t}$ MC in both ATLAS and CMS: Powheg+Pythia8
  - optimisation of the central parameters (hdamp, alphaS): just looking at the varied distributions or using the Professor toolkit
  - reach setup with consistent parameters
- assessment of the modelling systematics
  - factorisation approach of the different physical effects: radiation, showering, hadronization, matrix element generator, underlying event and colour reconnection
  - parameter variations so that it ‘brakets’ the data
  - currently no uniformed approaches between ATLAS and CMS

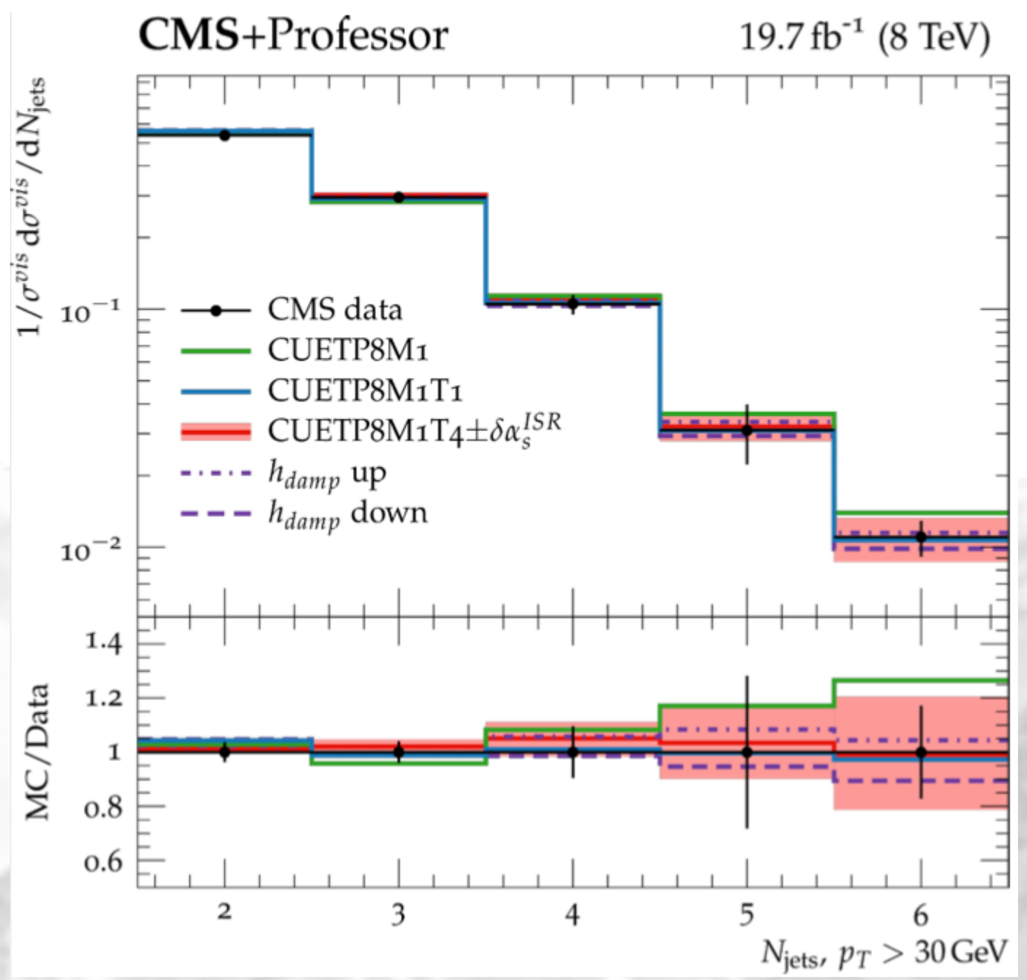
Source	ATLAS	CMS
Radiation/scale	Simultaneous $\mu_{R,F}$, h_{damp}, α_S^{ISR} variations	Individually vary $\mu_{R,F}$, h_{damp}, ISR scale, FSR scale
Shower/ Hadronisation/ Fragmentation	Pythia8 vs Herwig7	Variations in modelling of b jets, Pythia6 vs Herwig++ in JES
ME Generator	Powheg vs MG5_aMC@NLO	Powheg vs MG5+aMC@NLO (FxFx) (only in some analyses)
Non-pertubative	A14 tune variations	CUET2P8M2T4 variations, CR model variations

ATL-PHYS-PUB-2016-020

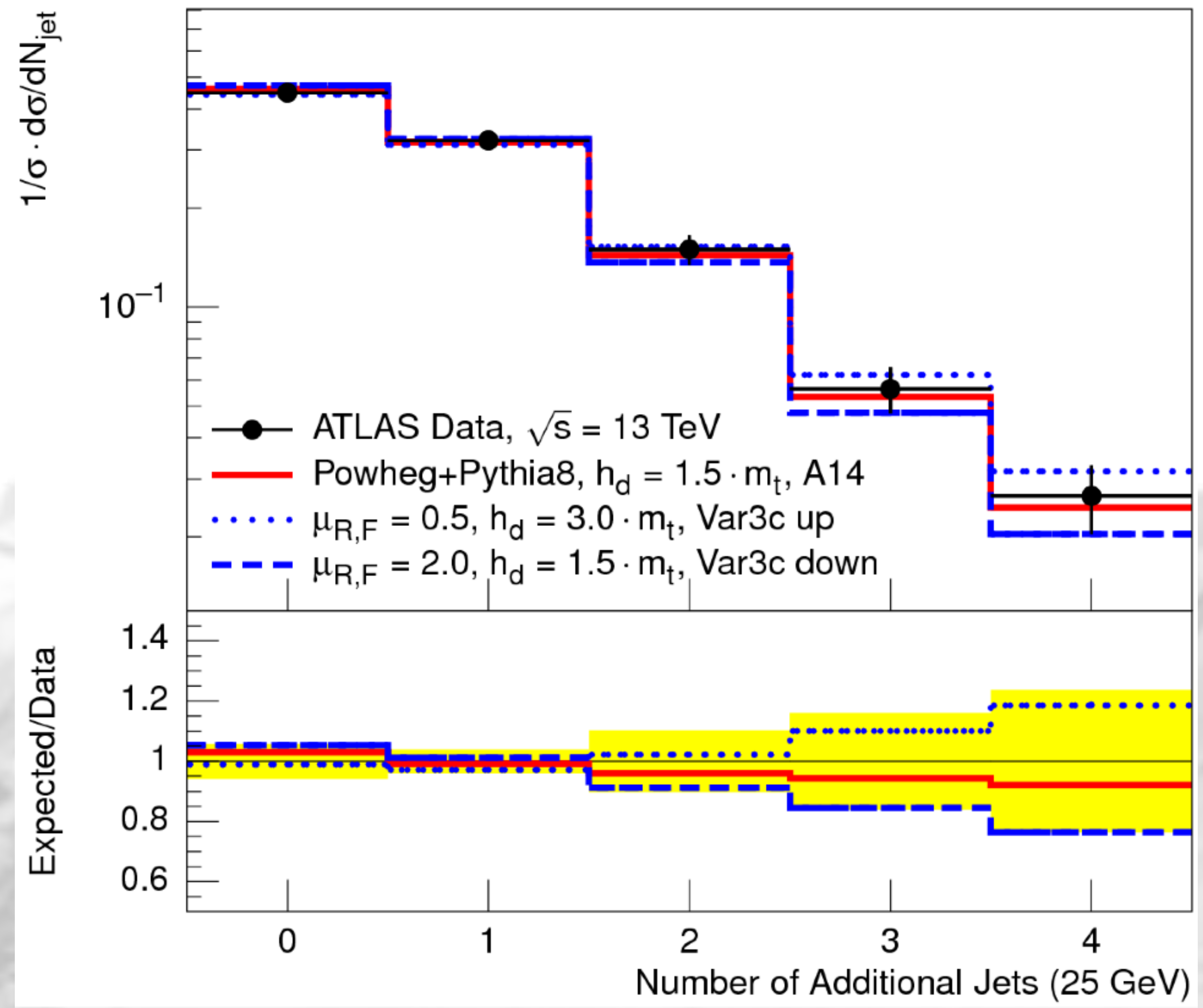


CMS-PAS-TOP-16-021

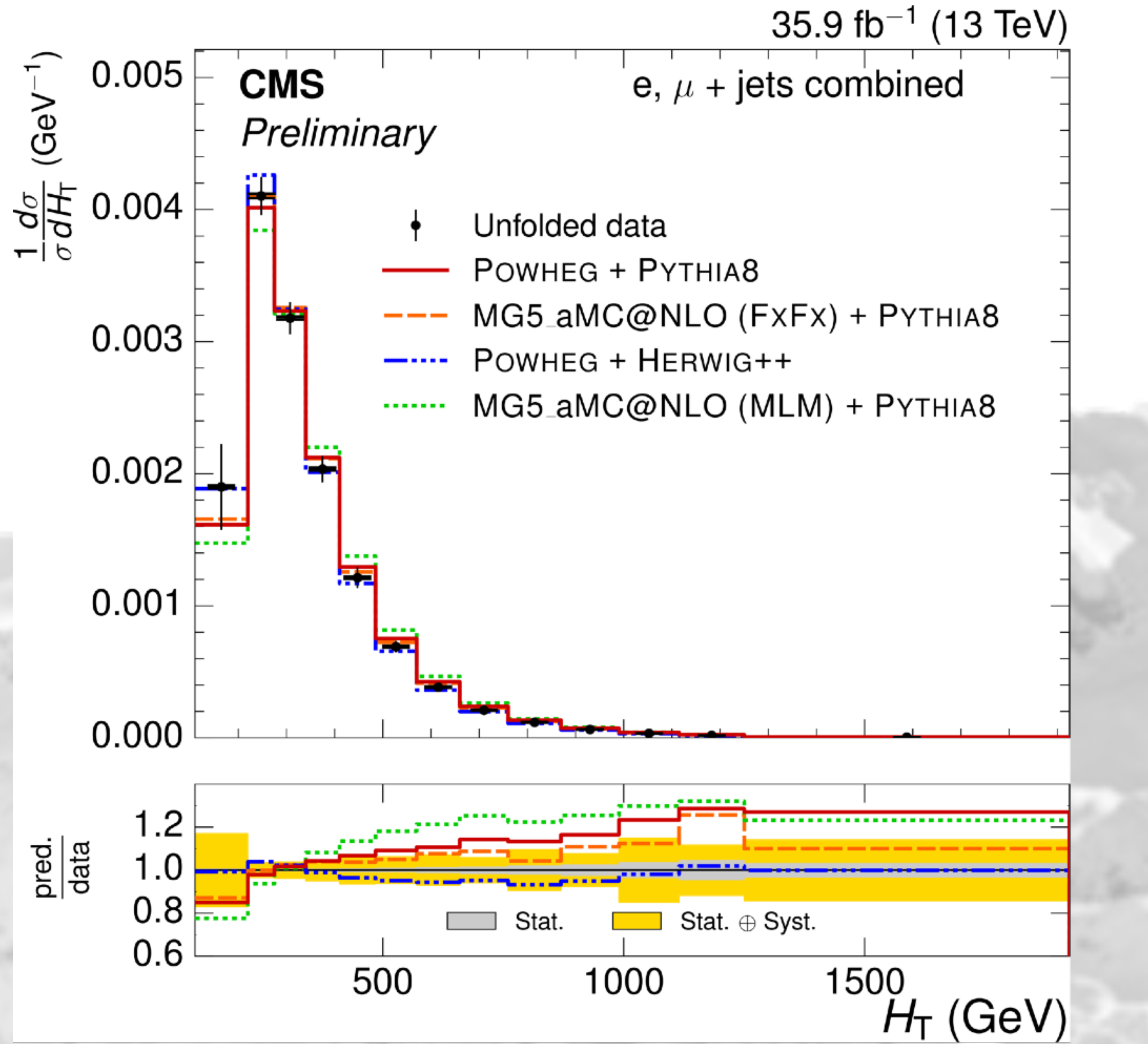
$h_{damp} = 1.581^{+0.658}_{-0.585} \times m_t, \quad \alpha_s^{ISR} = 0.1108^{+0.0145}_{-0.0142}$



ATL-PHYS-PUB-2017-007



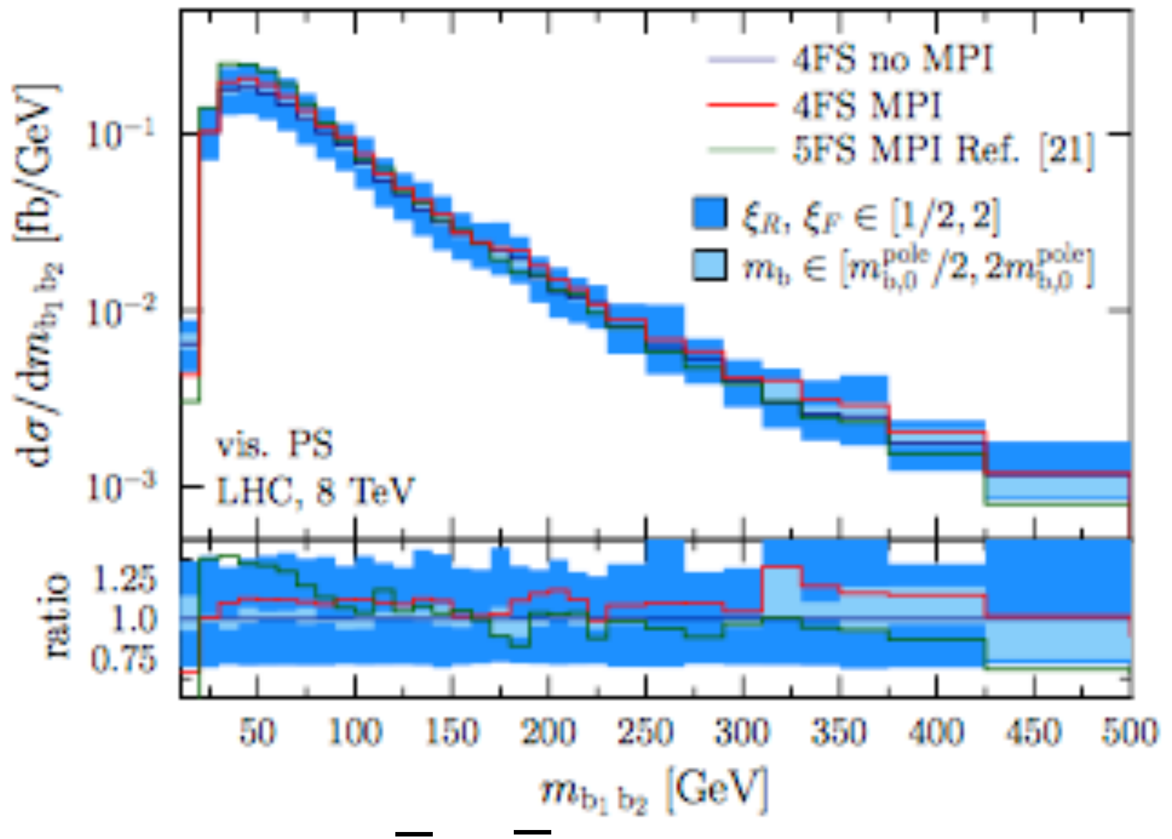
CMS-PAS-TOP-16-014



Going forward for top modelling

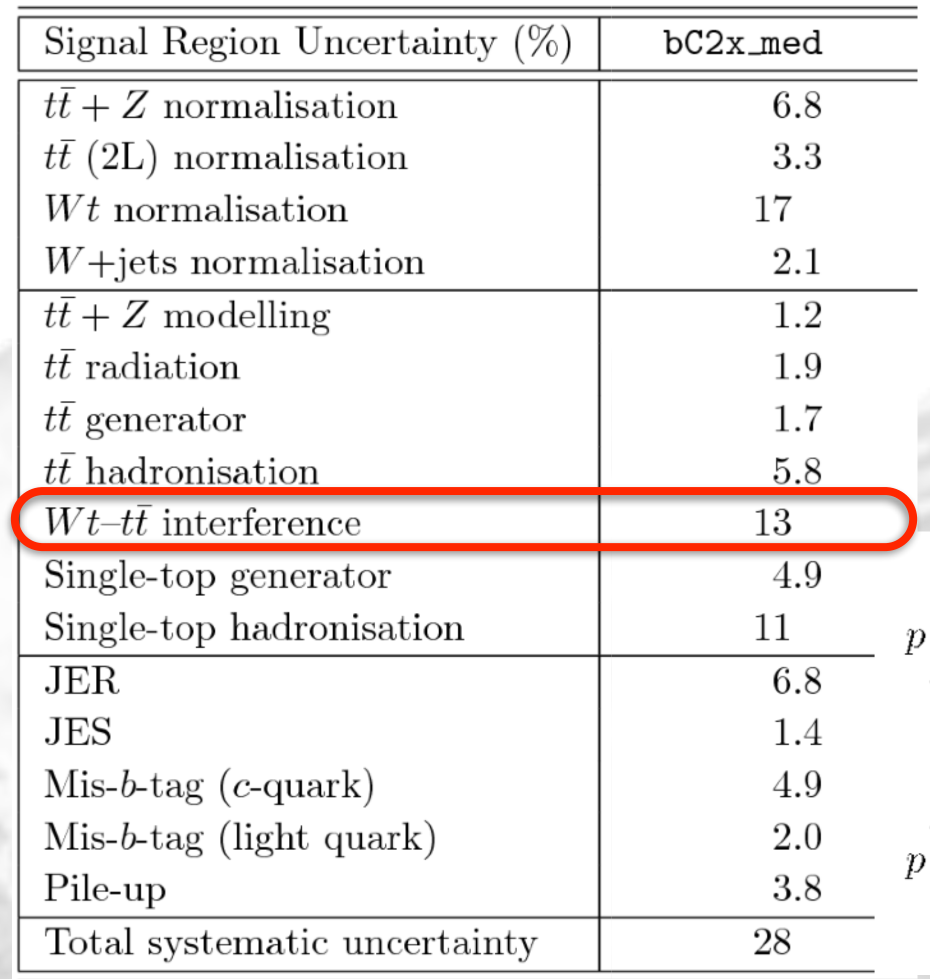
- more involved generators: NLO multileg $t\bar{t}$+0,1,2j @NLO
  - better underlying theory model of production of additional jets
  - MG5_aMC@NLO+Pythia8 [FxFx] or Sherpa : would need further tuning
- $t\bar{t}$+heavy flavour modelling: essential for ttH(bb) and searches with multiple b's
  - challenging for MC (several scales and massive quarks)
  - 5 Flavour (mb=0) vs 4 Flavour $t\bar{t}+b\bar{b}$ predictions, new 4F $t\bar{t}+b\bar{b}$ NLO+PS, need MC tuning
- further desirable steps
  - define all modelling uncertainties within one single generator (Herwig7 or Sherpa):
    - for instance Herwig7 allows to switch between Powheg and MC@NLO matching, between angular- and dipole-ordered showers, …
  - essential to have measurements in the top sector to constrain the models : colour reconnection, Wt-$t\bar{t}$ interference, $t\bar{t}$+heavy flavour
- question to keep in mind
  - how much should we tune the MC to data (overtuning, predictivity)

arXiv:1709.06915

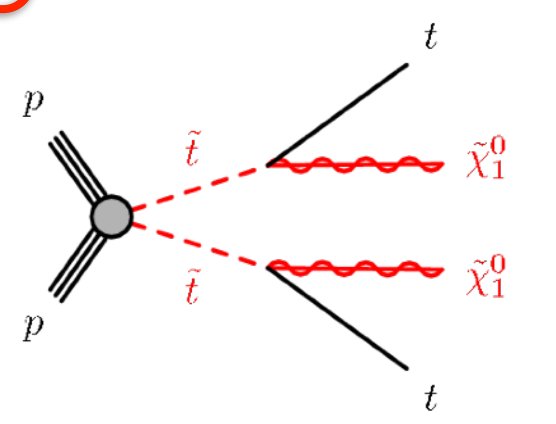


$t\bar{t}+b\bar{b}$ in Powhel

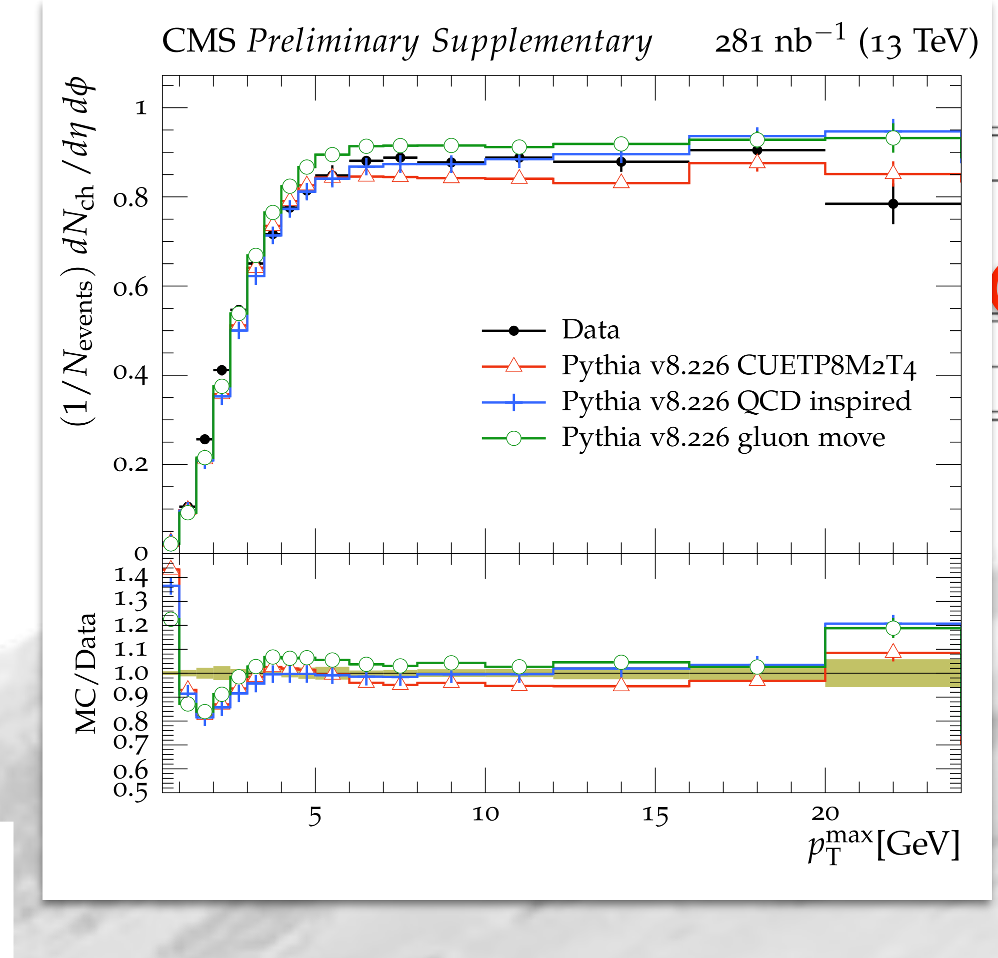
arXiv:1711.11520

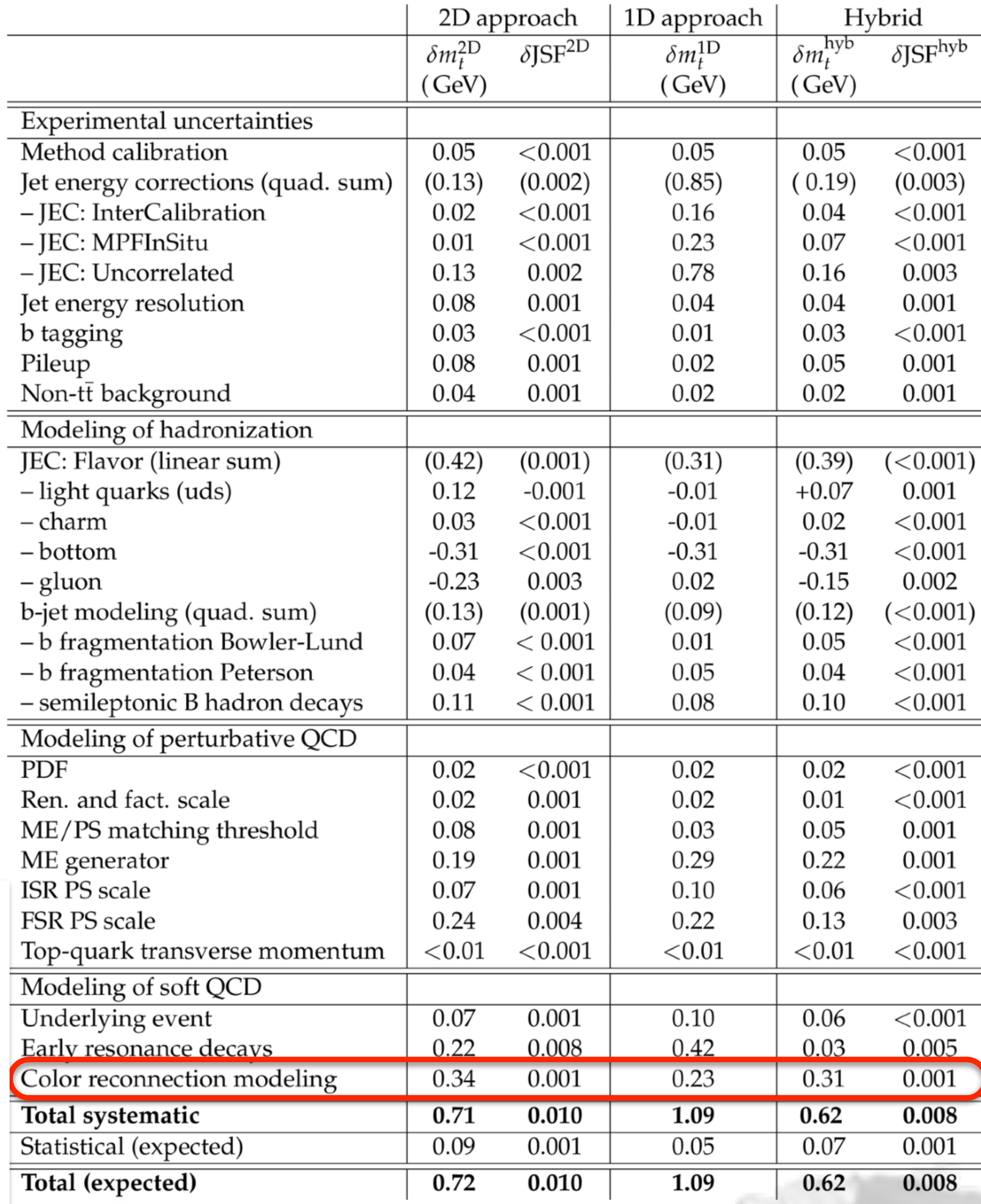


Signal Region Uncertainty (%)	bC2x_med
$t\bar{t}+Z$ normalisation	6.8
$t\bar{t}$ (2L) normalisation	3.3
Wt normalisation	17
W+jets normalisation	2.1
$t\bar{t}+Z$ modelling	1.2
$t\bar{t}$ radiation	1.9
$t\bar{t}$ generator	1.7
$t\bar{t}$ hadronisation	5.8
Wt–$t\bar{t}$ interference	13
Single-top generator	4.9
Single-top hadronisation	11
JER	6.8
JES	1.4
Mis-b-tag (c-quark)	4.9
Mis-b-tag (light quark)	2.0
Pile-up	3.8
Total systematic uncertainty	28



CMS-PAS-TOP-17-007





	2D approach		1D approach	Hybrid	
	δm_t^{2D} (GeV)	δJSF^{2D}	δm_t^{1D} (GeV)	δm_t^{hyb} (GeV)	δJSF^{hyb}
Experimental uncertainties					
Method calibration	0.05	<0.001	0.05	0.05	<0.001
Jet energy corrections (quad. sum)	(0.13)	(0.002)	(0.85)	(0.19)	(0.003)
– JEC: InterCalibration	0.02	<0.001	0.16	0.04	<0.001
– JEC: MPFInSitu	0.01	<0.001	0.23	0.07	<0.001
– JEC: Uncorrelated	0.13	0.002	0.78	0.16	0.003
Jet energy resolution	0.08	0.001	0.04	0.04	0.001
b tagging	0.03	<0.001	0.01	0.03	<0.001
Pileup	0.08	0.001	0.02	0.05	0.001
Non-$t\bar{t}$ background	0.04	0.001	0.02	0.02	0.001
Modeling of hadronization					
JEC: Flavor (linear sum)	(0.42)	(0.001)	(0.31)	(0.39)	(<0.001)
– light quarks (uds)	0.12	-0.001	-0.01	+0.07	0.001
– charm	0.03	<0.001	-0.01	0.02	<0.001
– bottom	-0.31	<0.001	-0.31	-0.31	<0.001
– gluon	-0.23	0.003	0.02	-0.15	0.002
b-jet modeling (quad. sum)	(0.13)	(0.001)	(0.09)	(0.12)	(<0.001)
– b fragmentation Bowler-Lund	0.07	< 0.001	0.01	0.05	<0.001
– b fragmentation Peterson	0.04	< 0.001	0.05	0.04	<0.001
– semileptonic B hadron decays	0.11	< 0.001	0.08	0.10	<0.001
Modeling of perturbative QCD					
PDF	0.02	<0.001	0.02	0.02	<0.001
Ren. and fact. scale	0.02	0.001	0.02	0.01	<0.001
ME/PS matching threshold	0.08	0.001	0.03	0.05	0.001
ME generator	0.19	0.001	0.29	0.22	0.001
ISR PS scale	0.07	0.001	0.10	0.06	<0.001
FSR PS scale	0.24	0.004	0.22	0.13	0.003
Top-quark transverse momentum	<0.01	<0.001	<0.01	<0.01	<0.001
Modeling of soft QCD					
Underlying event	0.07	0.001	0.10	0.06	<0.001
Early resonance decays	0.22	0.008	0.42	0.03	0.005
Color reconnection modeling	0.34	0.001	0.23	0.31	0.001
Total systematic	**0.71**	**0.010**	**1.09**	**0.62**	**0.008**
Statistical (expected)	0.09	0.001	0.05	0.07	0.001
Total (expected)	**0.72**	**0.010**	**1.09**	**0.62**	**0.008**

13 TeV lepton+jets mass
CMS-PAS-TOP-17-007

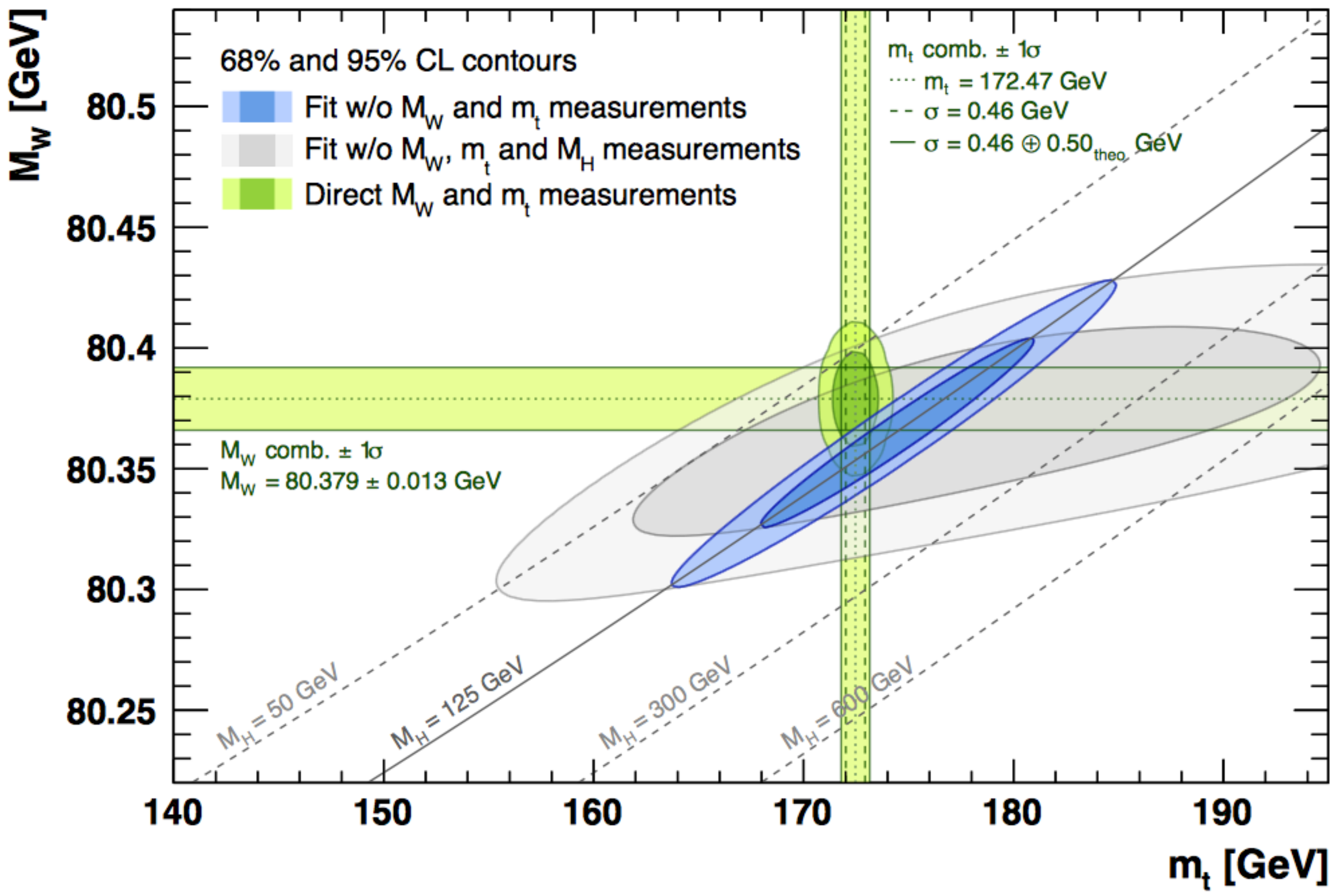
The top quark mass

- precision determination of the top quark mass
  - compare direct measurements with electroweak fit
  - stability of the electroweak vacuum (Higgs boson quartic coupling almost vanishing at the Planck scale)
  - how precisely can it be measured at hadron collider ?

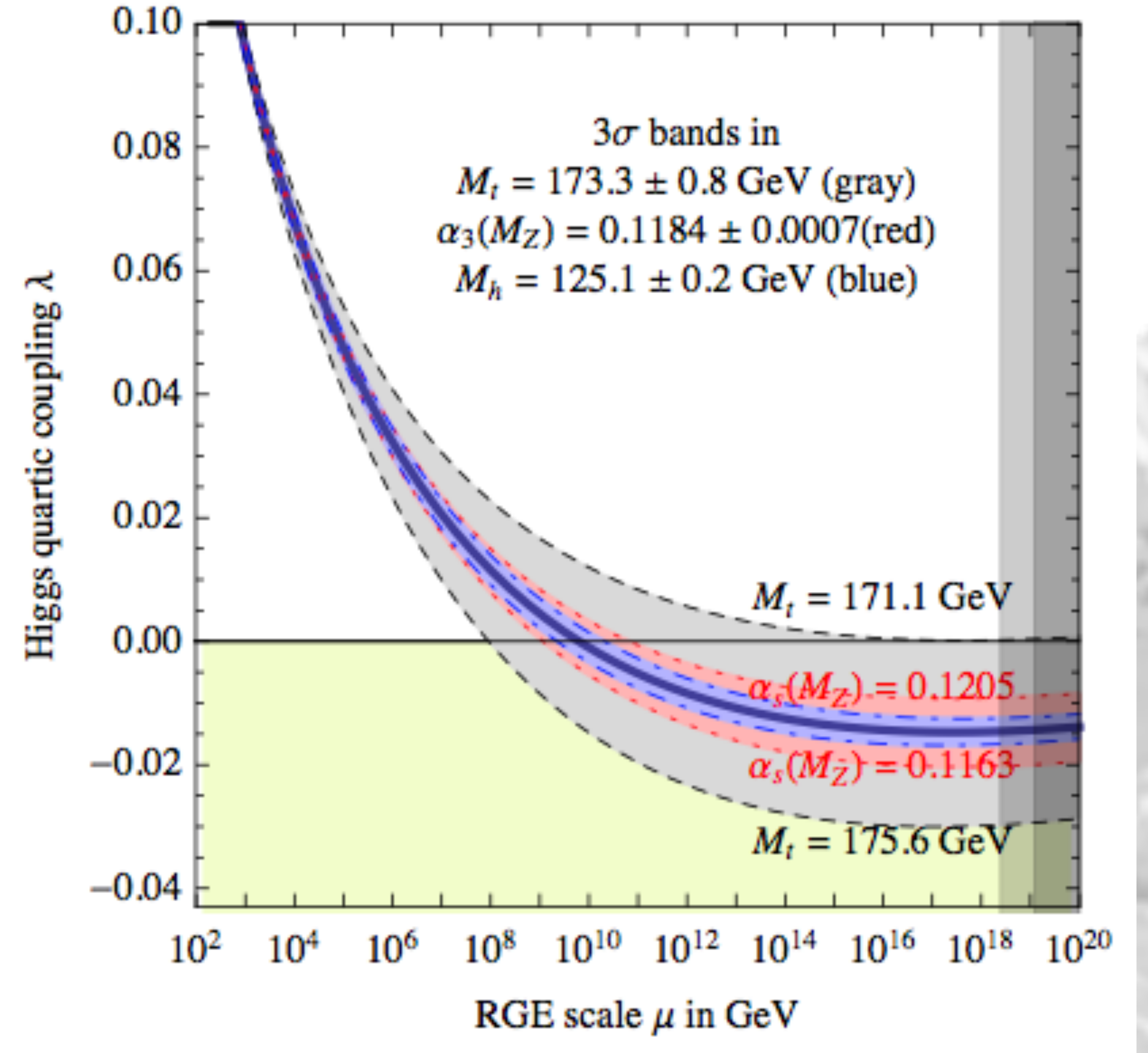
- top quark mass definition
  - top quark is coloured: can’t be unambiguously associated with its decay products
  - standard measurements: mass extracted from a fit to the measured distributions, affected by theoretical errors (related to how well the distributions are modelled)
  - alternative measurements: mass extraction using methods that have less/other theory errors. Currently less precise than standard measurements.

- arguments raised against standard mass measurements (Nason, arXiv:1712.02796)
  - difficult to relate the mass measured using MC to well defined theoretical parameter because of non-perturbative effects
    - do we need to interpret the measured mass with a mass in other scheme (MSR scheme with a scale R = 1 GeV) ?
  - the pole mass scheme is a poor choice because it suffers from the intrinsic renormalon ambiguity

GFitter group, arXiv:1803.01853



Buttazzo et al., JHEP 1312, 089 (2013)



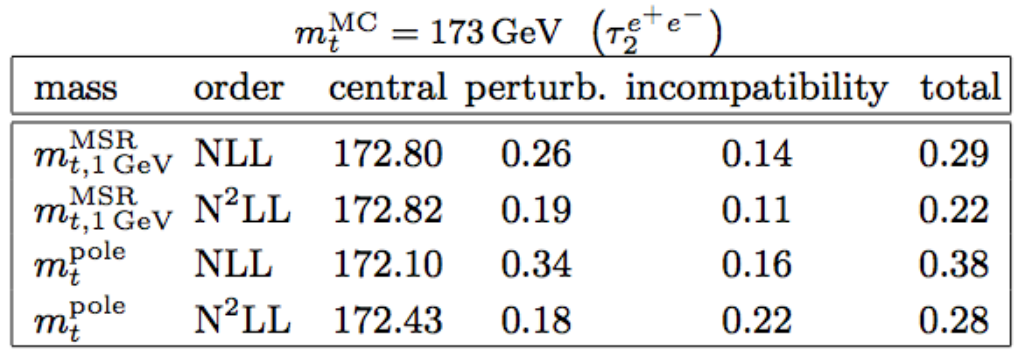
The top quark mass (2)

- the renormalon ambiguity
  - ultimate precision due to the irreducible ambiguity of the pole mass (order of the hadronic scale)
  - recent calculations: better estimate of this ambiguity (depending some choice in the procedure):
    - 110 MeV (Beneke, Marquard, Steinhauser, Nason, PLB775, 63 (2017))
    - 250 MeV (Hoang, Lepenik, Preisser, JHEP 1709, 099 (2017))
  - in all cases this ambiguity seems much smaller than the current experimental precision: ie. the pole mass is still a usable scheme

- estimate the non-perturbative effects
  - calibration of the mass in the MC in boosted $t\bar{t}$ in e^+e^- annihilation using SCET
    - currently not available for pp collision
    - probably depend on the MC (currently developed for Pythia8)
  - NLO+PS generator studies:
    - compare hvq (NLO only in production, on-shell), ttdec (NLO in production and decay, off shell via reweighting), bb4l (full NLO with offshell effects)
    - in particular look at the m(W-bj) peak including some simple smearing
    - very modest change for the different setups, except between Pythia8 and Herwig7

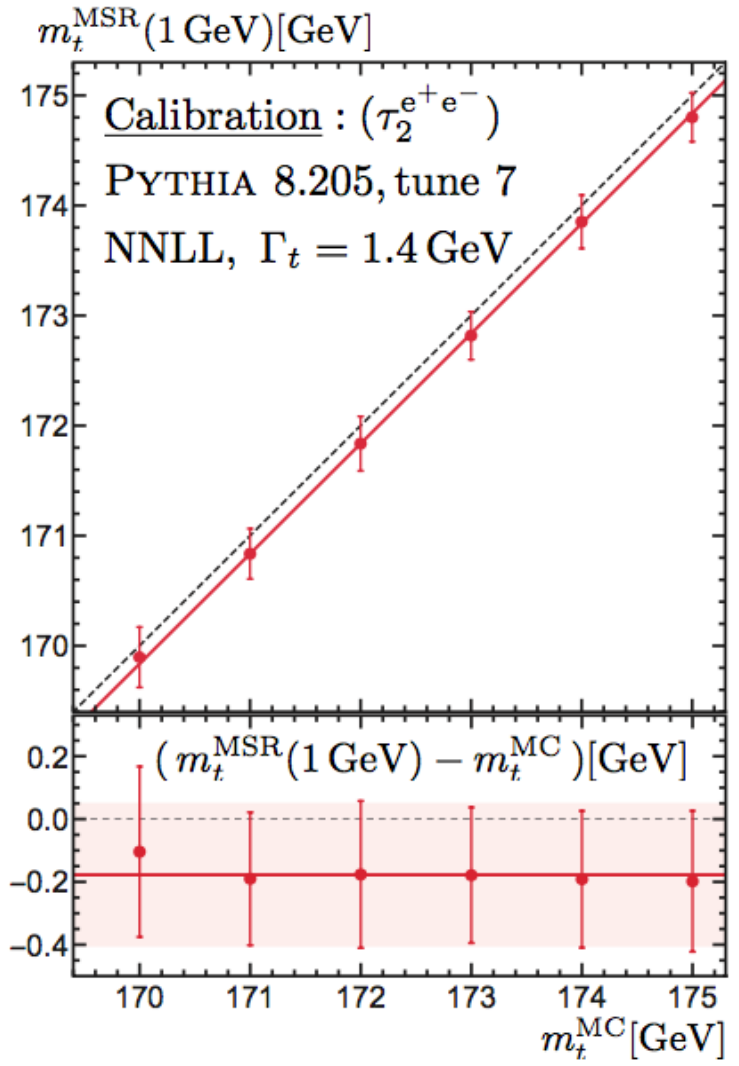
the debate seems to be nailed down to quantify the uncertainties on how the MC implement effects that are power suppressed

Butenschoen et al. PRL117. 232001 (2016)

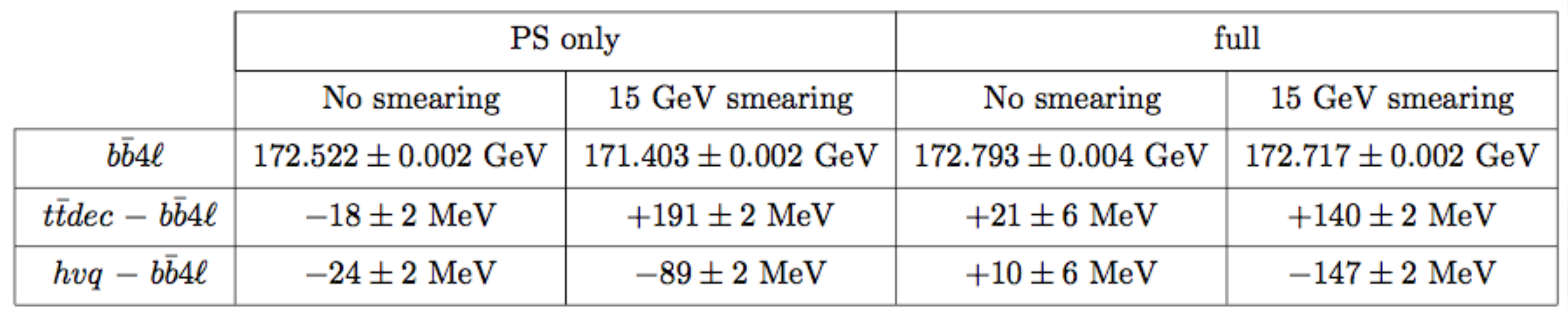


$m_t^{\mathrm{MC}} = 173\,\mathrm{GeV}\ \ (\tau_2^{e^+e^-})$

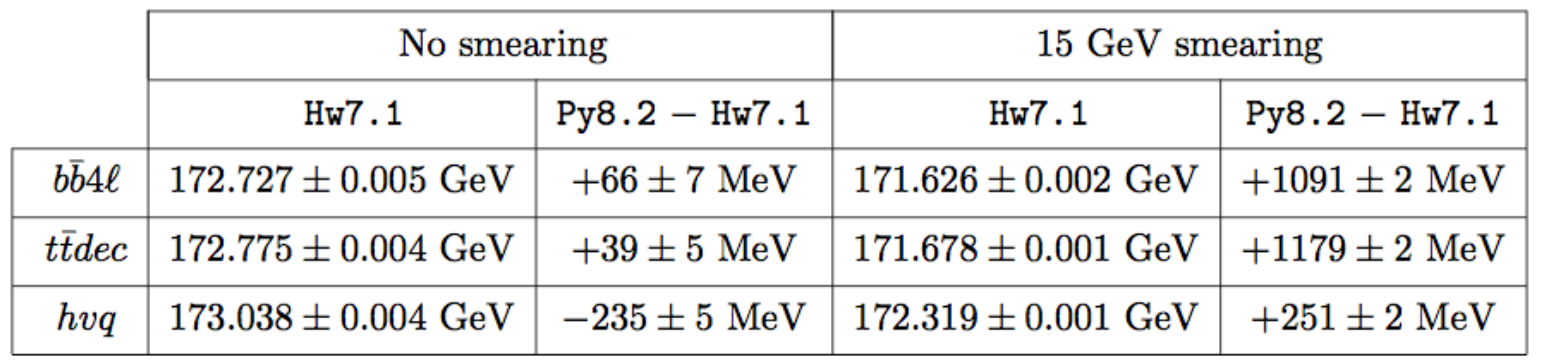
mass	order	central	perturb.	incompatibility	total
$m_{t,1\,\mathrm{GeV}}^{\mathrm{MSR}}$	NLL	172.80	0.26	0.14	0.29
$m_{t,1\,\mathrm{GeV}}^{\mathrm{MSR}}$	$\mathrm{N^2LL}$	172.82	0.19	0.11	0.22
m_t^{pole}	NLL	172.10	0.34	0.16	0.38
m_t^{pole}	$\mathrm{N^2LL}$	172.43	0.18	0.22	0.28



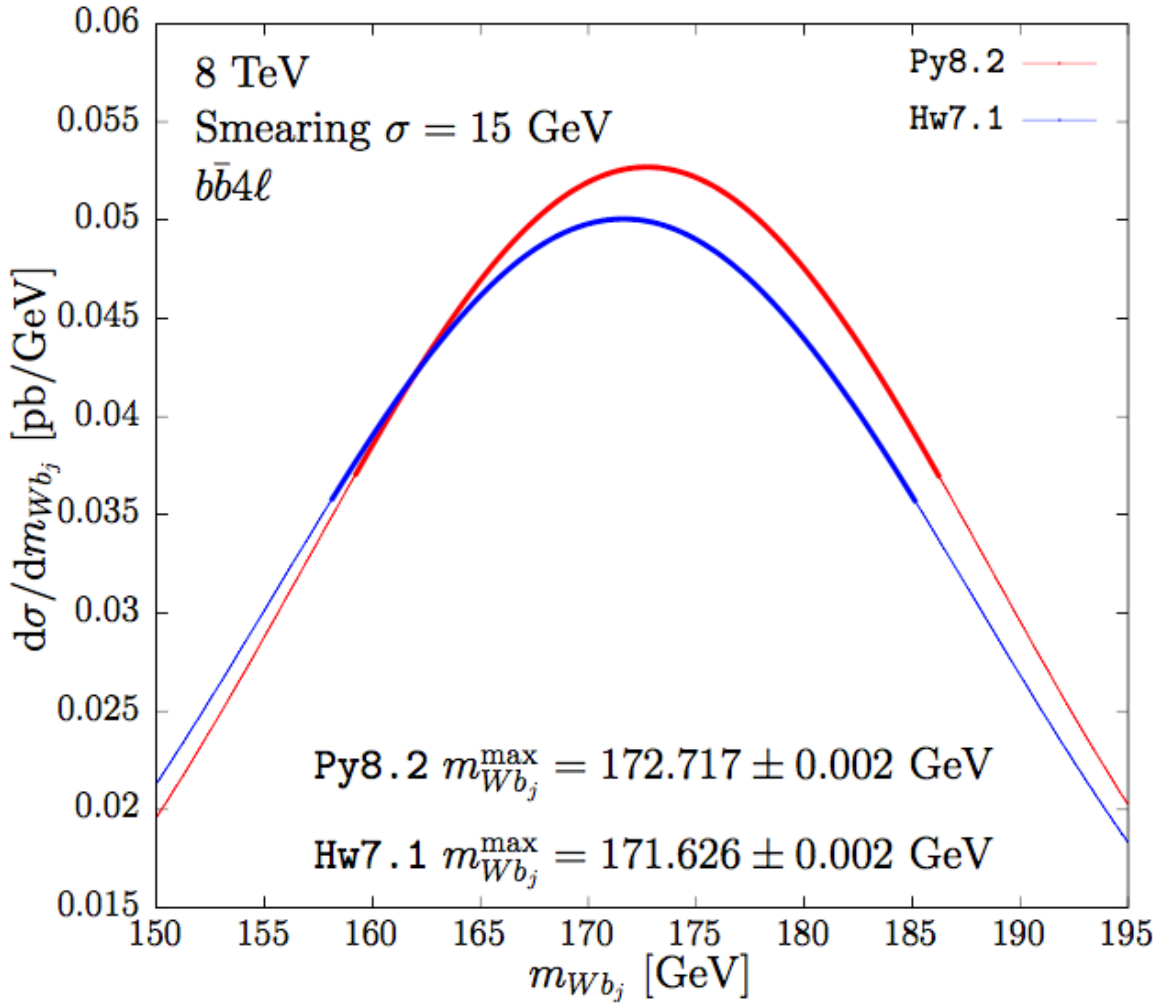
Ravasio, Jezo, Nason, Oleari, arXiv:1801.03944



	PS only		full	
	No smearing	15 GeV smearing	No smearing	15 GeV smearing
$b\bar{b}4\ell$	172.522 ± 0.002 GeV	171.403 ± 0.002 GeV	172.793 ± 0.004 GeV	172.717 ± 0.002 GeV
$t\bar{t}dec - b\bar{b}4\ell$	-18 ± 2 MeV	$+191 \pm 2$ MeV	$+21 \pm 6$ MeV	$+140 \pm 2$ MeV
$hvq - b\bar{b}4\ell$	-24 ± 2 MeV	-89 ± 2 MeV	$+10 \pm 6$ MeV	-147 ± 2 MeV



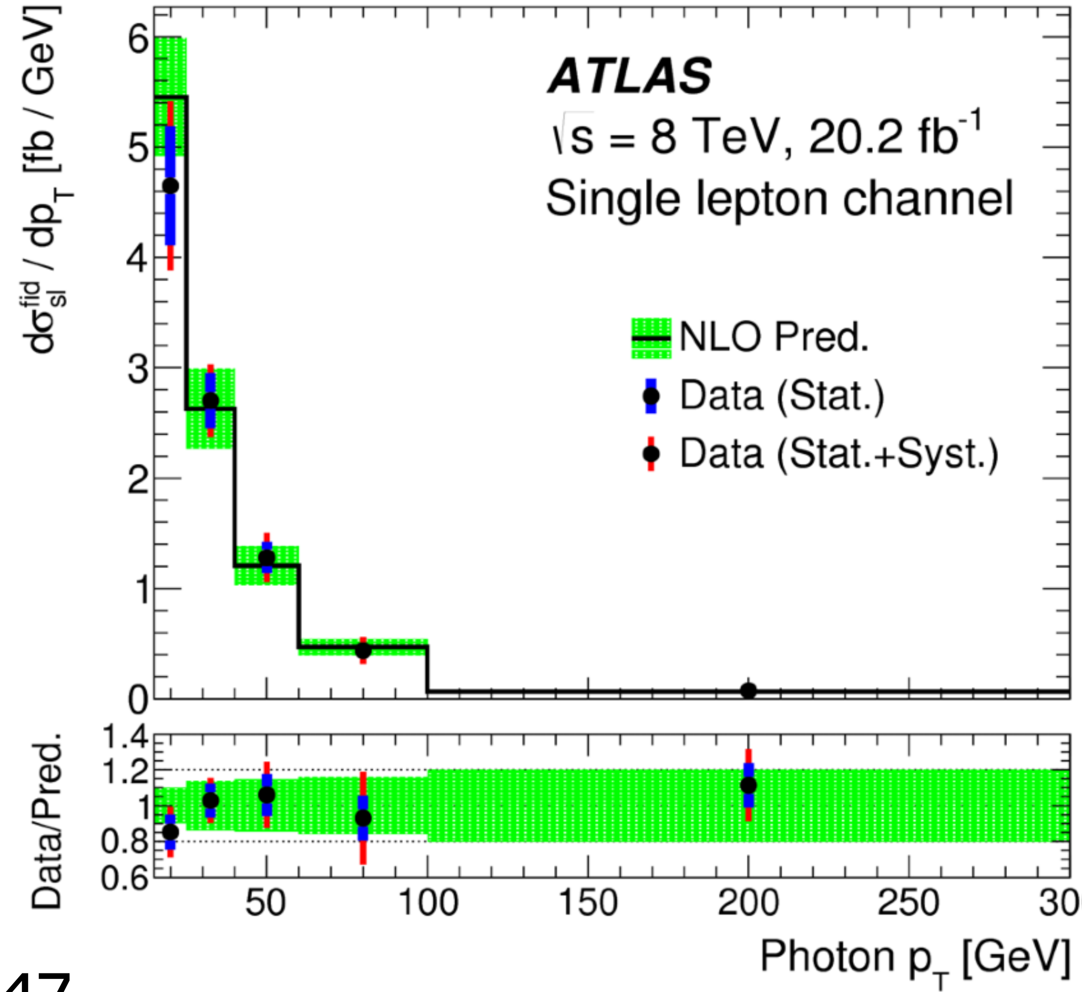
	No smearing		15 GeV smearing	
	`Hw7.1`	`Py8.2 – Hw7.1`	`Hw7.1`	`Py8.2 – Hw7.1`
$b\bar{b}4\ell$	172.727 ± 0.005 GeV	$+66 \pm 7$ MeV	171.626 ± 0.002 GeV	$+1091 \pm 2$ MeV
$t\bar{t}dec$	172.775 ± 0.004 GeV	$+39 \pm 5$ MeV	171.678 ± 0.001 GeV	$+1179 \pm 2$ MeV
hvq	173.038 ± 0.004 GeV	-235 ± 5 MeV	172.319 ± 0.001 GeV	$+251 \pm 2$ MeV



Top couplings

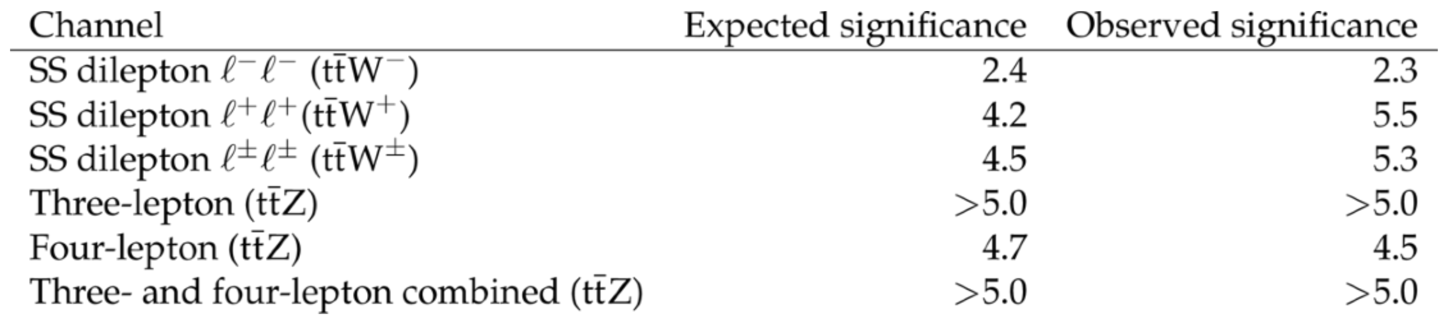
- the LHC Run2 opens a new area for top production with gauge bosons
  - whole list of new processes that were never observed before: ttγ, ttV, tZq, ttH (probe new couplings)
  - many of the current measurements have still large statistical uncertainties and mainly currently focussed at the inclusive cross sections (complex final states)
  - the next steps are:
    - go differential for all the processes
    - measure the properties of these new processes
    - measure multiple couplings simultaneously
    - use these handles to search for new physics

JHEP11, 086 (2017)



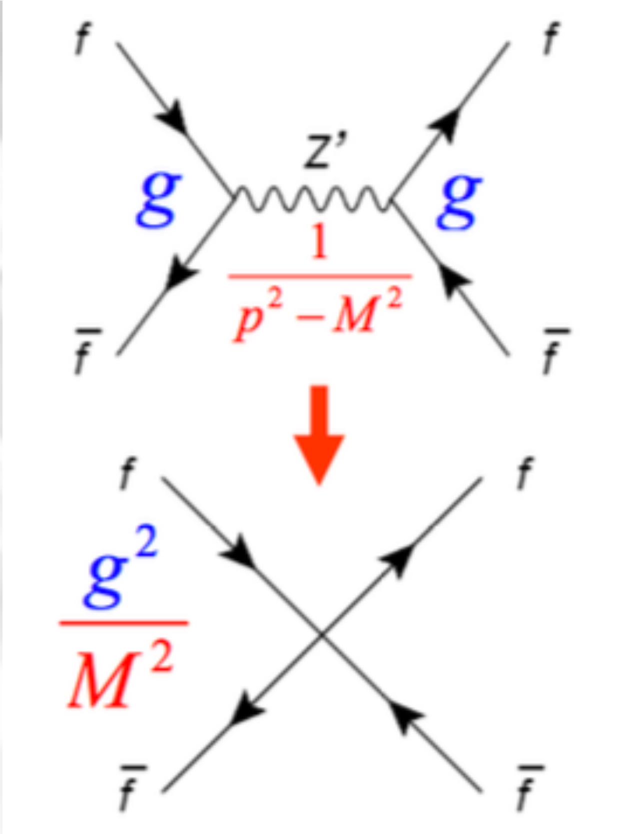
- search for modified couplings through effective field theory
  - non resonant model independent BSM search
  - SM measurements are searches for deviations from the dim=4 SM predictions

arXiv:1711.02547

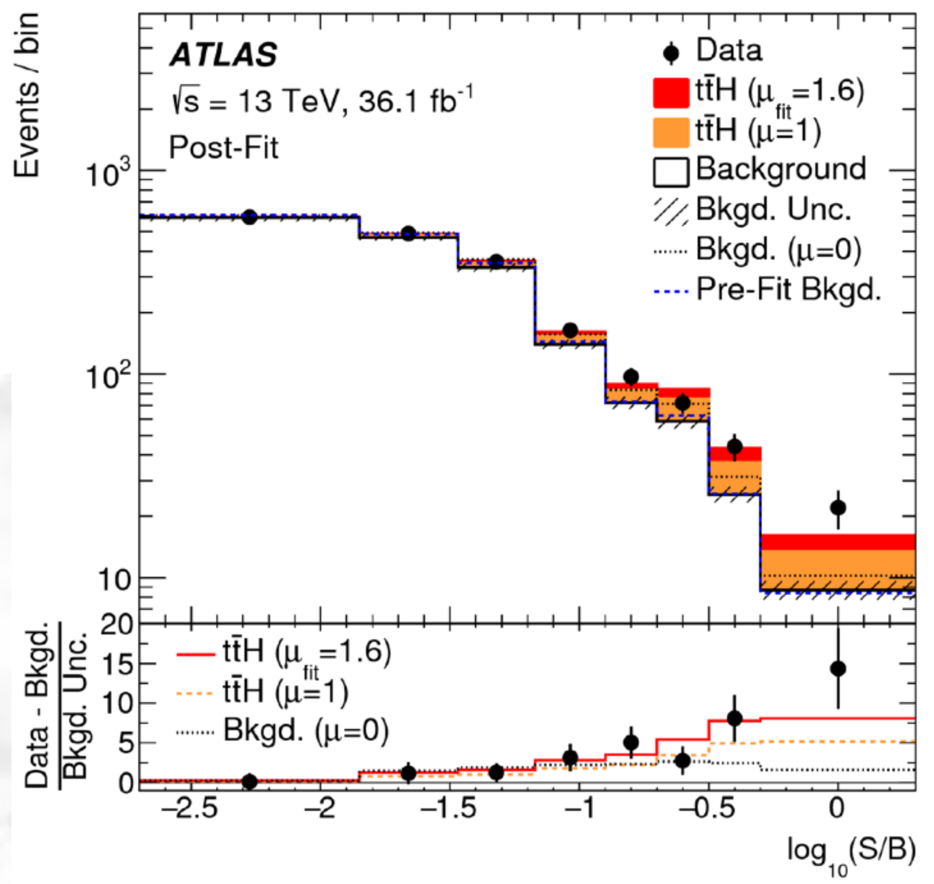


Channel	Expected significance	Observed significance
SS dilepton $\ell^-\ell^-$ ($t\bar{t}W^-$)	2.4	2.3
SS dilepton $\ell^+\ell^+$ ($t\bar{t}W^+$)	4.2	5.5
SS dilepton $\ell^\pm\ell^\pm$ ($t\bar{t}W^\pm$)	4.5	5.3
Three-lepton ($t\bar{t}Z$)	>5.0	>5.0
Four-lepton ($t\bar{t}Z$)	4.7	4.5
Three- and four-lepton combined ($t\bar{t}Z$)	>5.0	>5.0

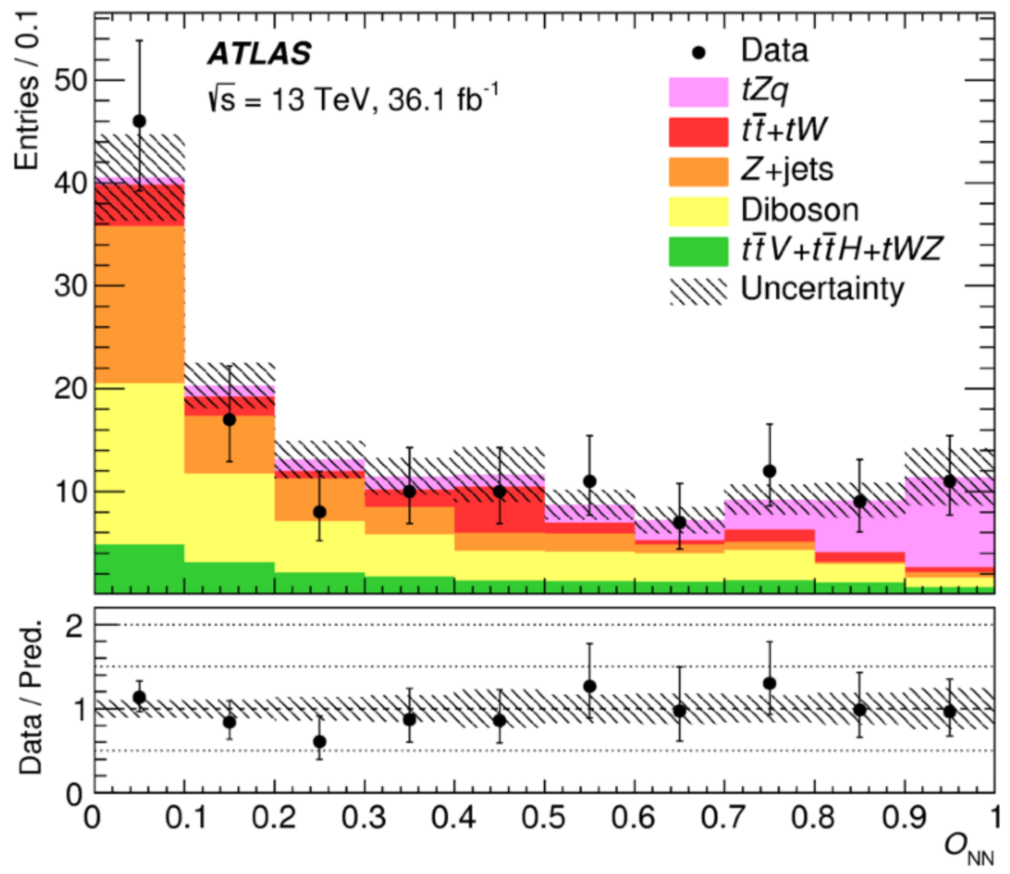
$$\mathcal{L}_{SM}^{(6)} = \mathcal{L}_{SM}^{(4)} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \ldots$$

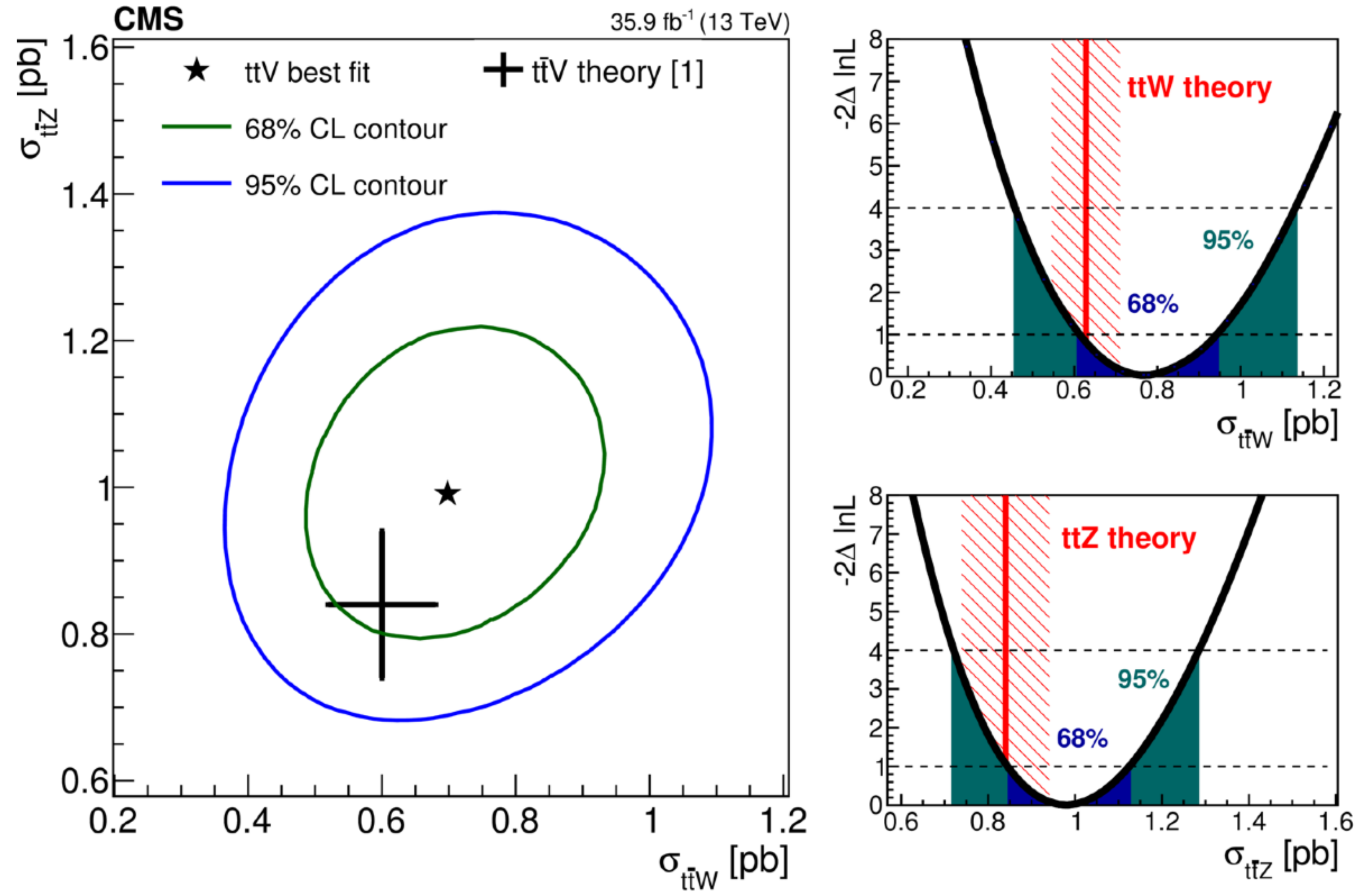


arXiv:1712.08891



arXiv:1710.03659

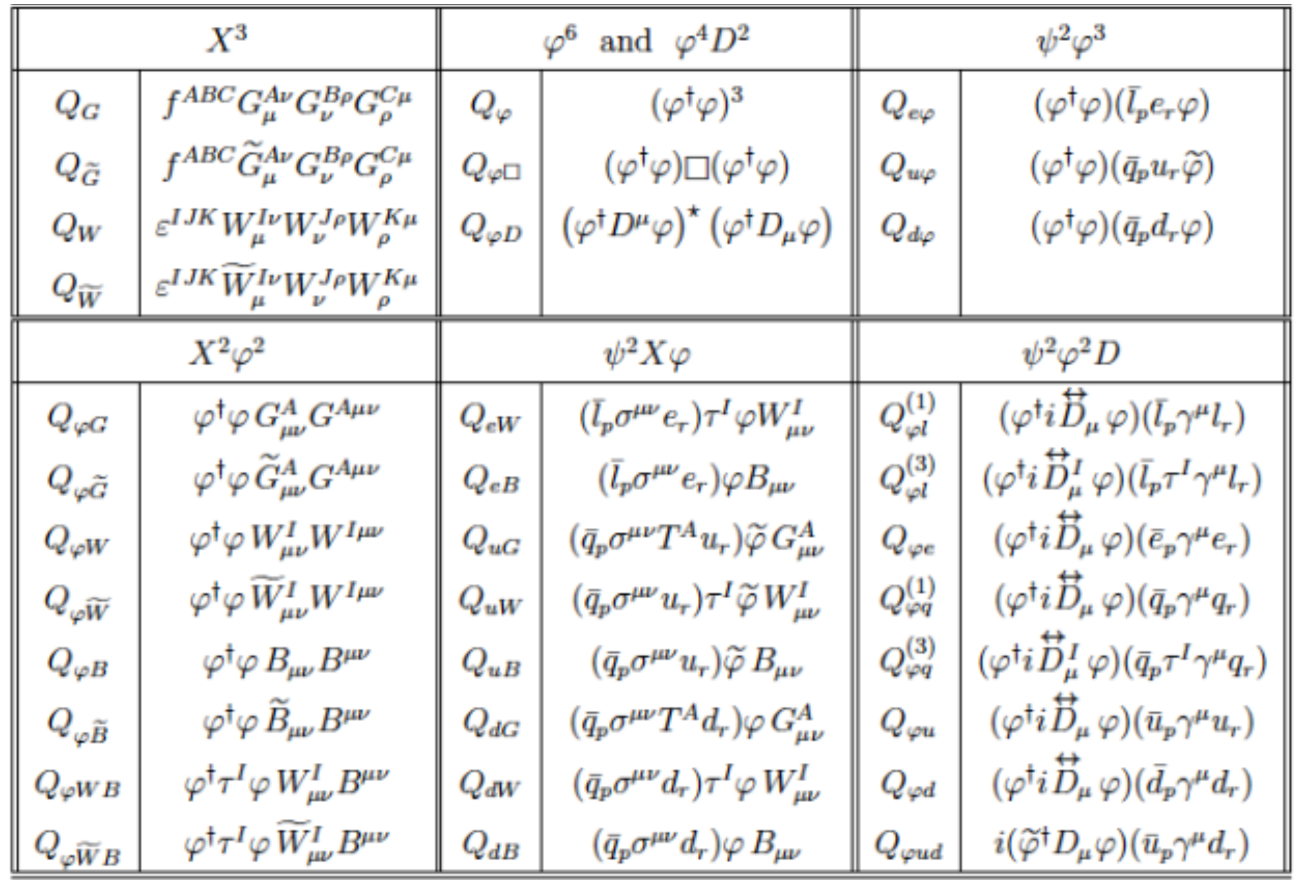




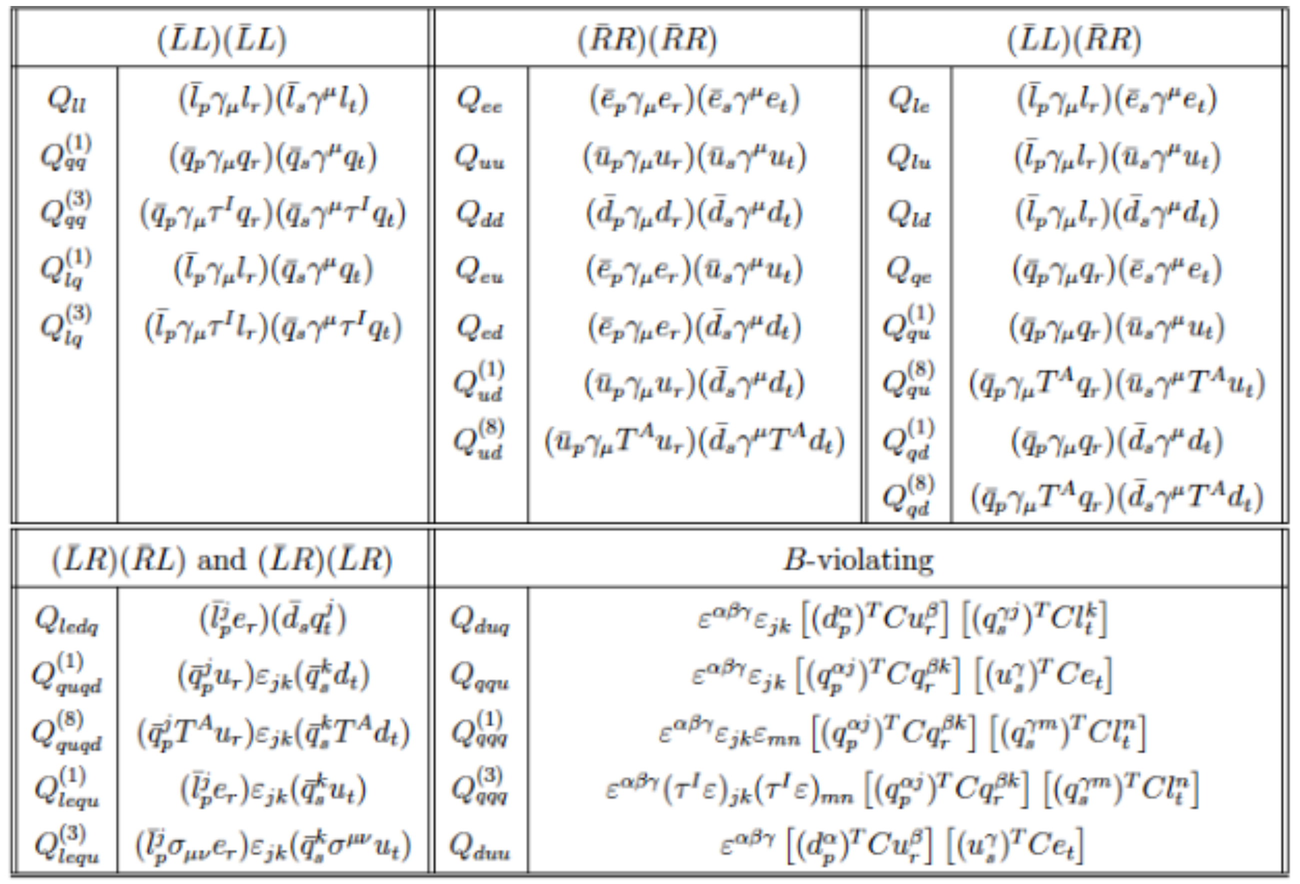
EFT in top physics

- attractive approach
  - can compute perturbation and renormalisation
  - possibility of global strategy (33 anomalous operators affecting production and decay)
  - sequential approach: study the sensitivity of the observables to the anomalous couplings, consider only couplings with sizeable effects

Buchmuller & Wyler NPB268, 621 (1986)
Grzadkowski et al, JHEP10, 085 (2010)

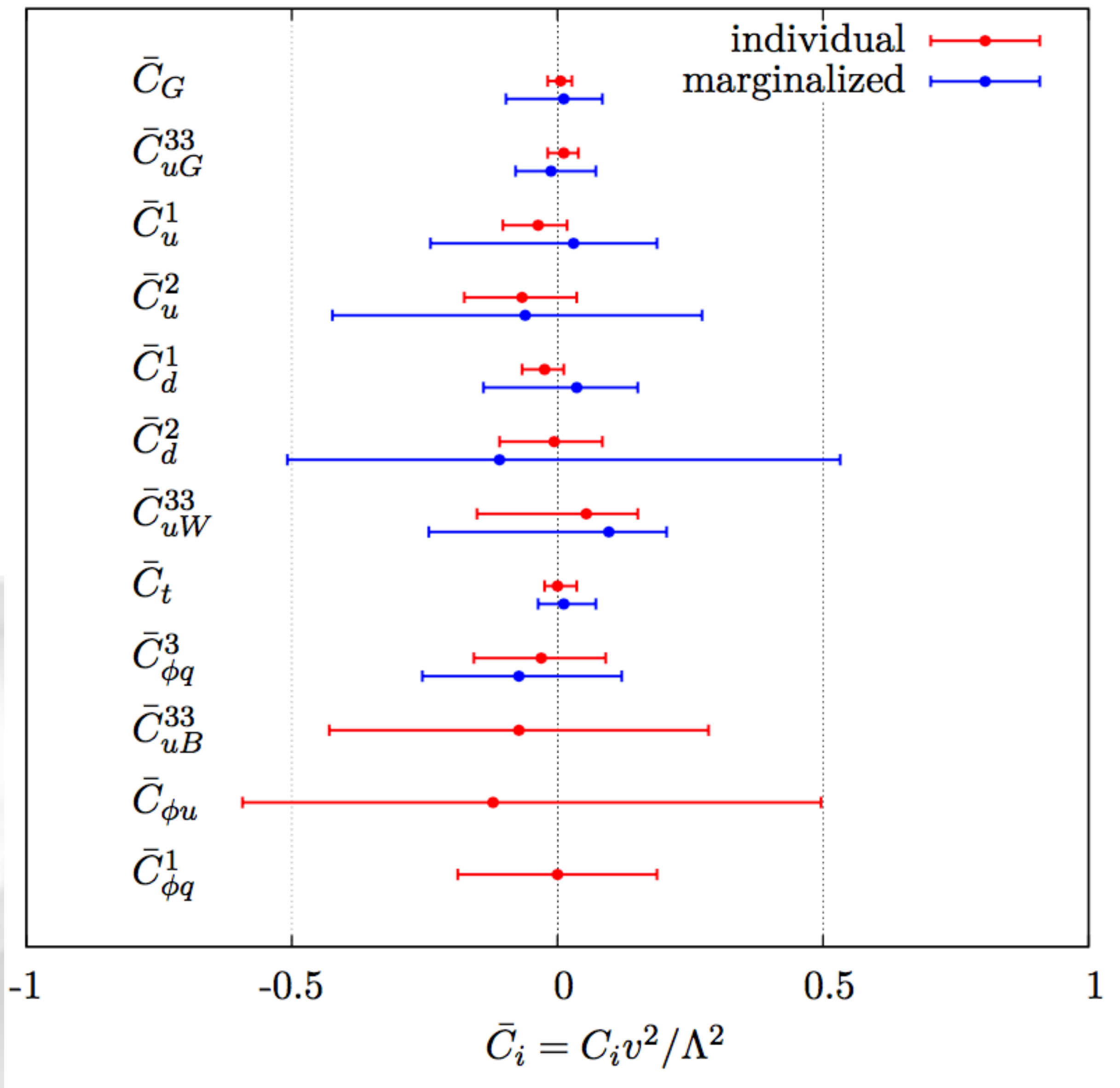


X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu \varphi)(\bar u_p \gamma^\mu d_r)$

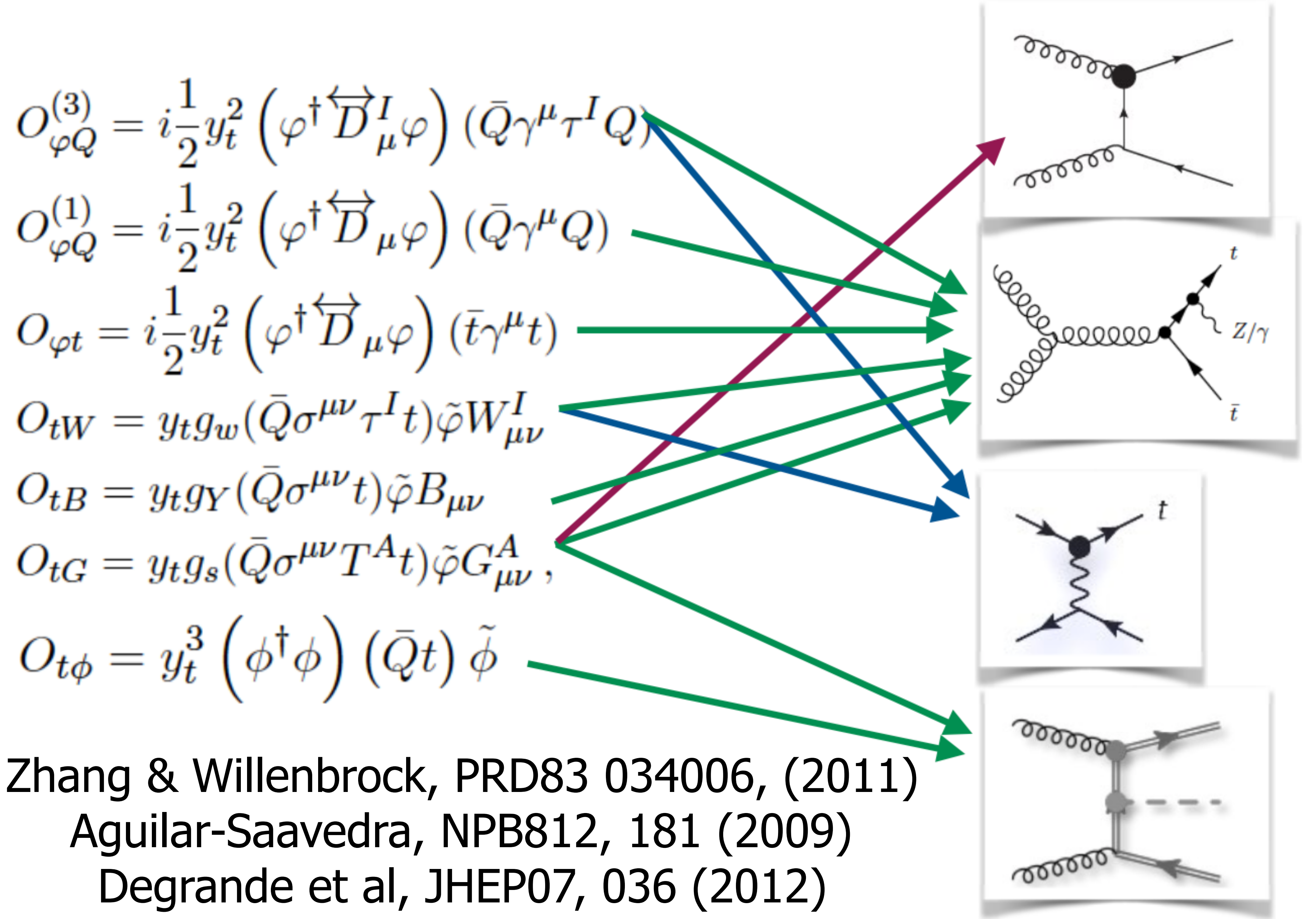


$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating			
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$		
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$		

- first try of a global fit
  - input: inclusive and differential results for the tt̄ and single top productions
  - SM at NLO/NNLO, EFT at LO



Buckley et al. JHEP04, 015 (2016)



$$O_{\varphi Q}^{(3)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar Q\gamma^\mu\tau^I Q)$$

$$O_{\varphi Q}^{(1)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar Q\gamma^\mu Q)$$

$$O_{\varphi t} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar t\gamma^\mu t)$$

$$O_{tW} = y_t g_w(\bar Q\sigma^{\mu\nu}\tau^I t)\tilde\varphi W^I_{\mu\nu}$$

$$O_{tB} = y_t g_Y(\bar Q\sigma^{\mu\nu} t)\tilde\varphi B_{\mu\nu}$$

$$O_{tG} = y_t g_s(\bar Q\sigma^{\mu\nu}T^A t)\tilde\varphi G^A_{\mu\nu}\,,$$

$$O_{t\phi} = y_t^3\left(\phi^\dagger\phi\right)(\bar Q t)\,\tilde\phi$$

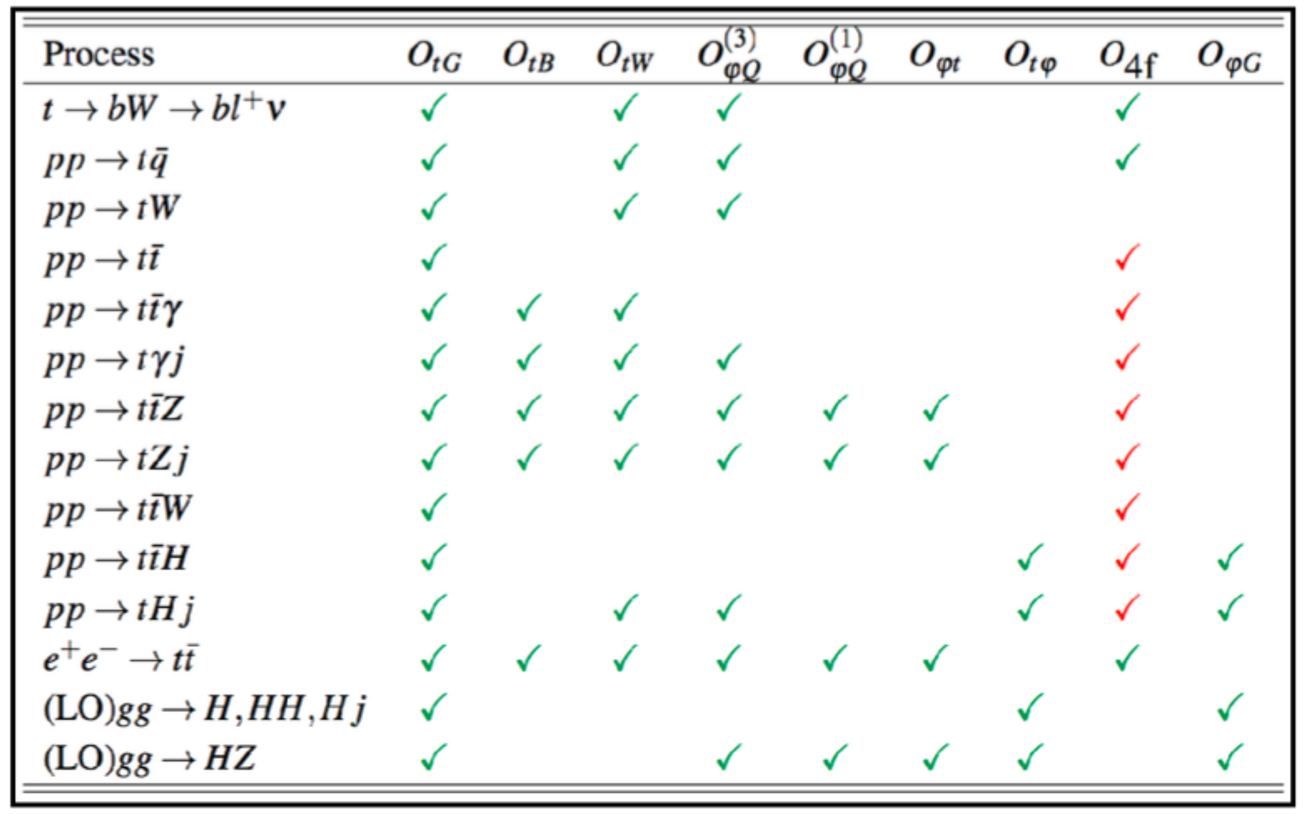
Zhang & Willenbrock, PRD83 034006, (2011)
Aguilar-Saavedra, NPB812, 181 (2009)
Degrande et al, JHEP07, 036 (2012)

Towards a global top EFT fit at the LHC

- next steps
  - add NLO EFT effects: more processes to consider together
  - include 4-fermion operators
  - add new measurements (tt+X, spin-sensitive observables, …)

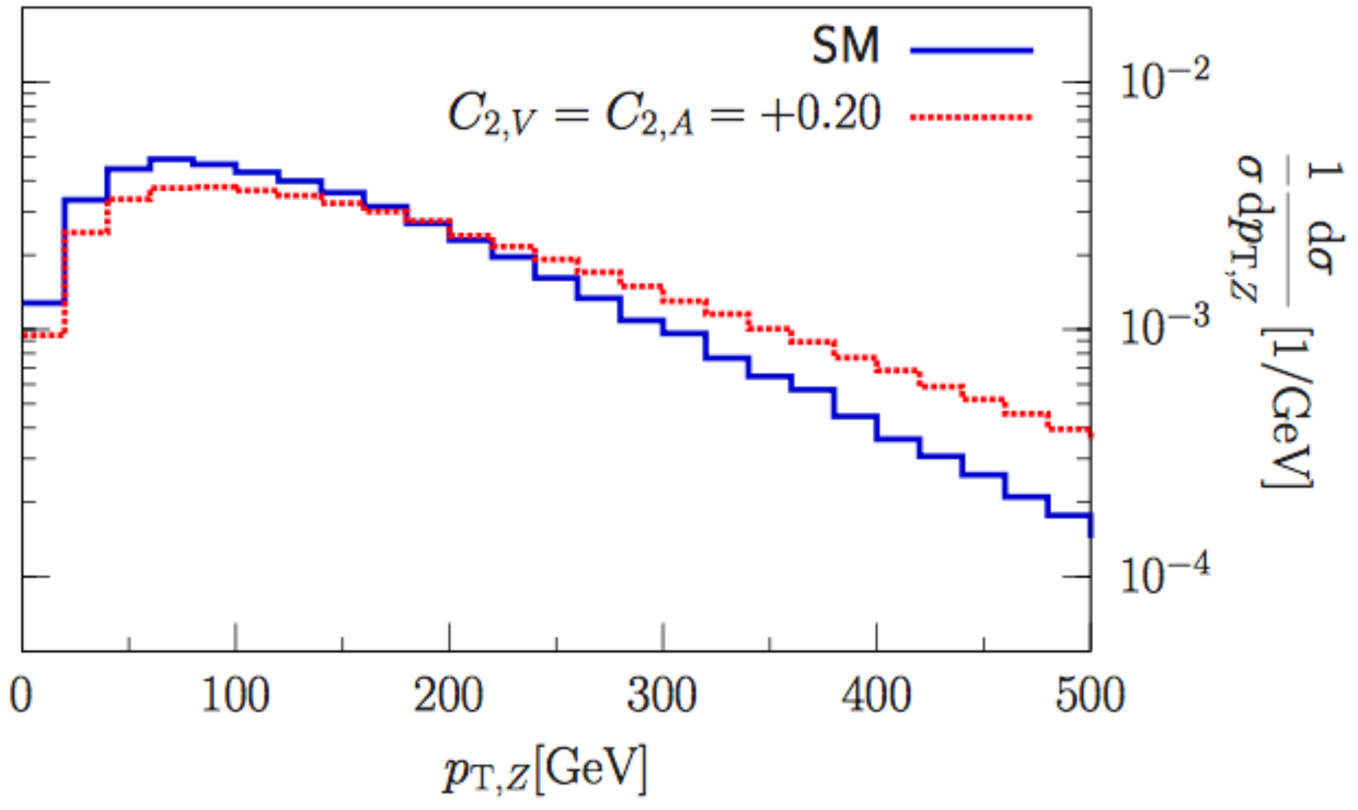
- generic guidelines under the LHCtopWG (arXiv:1802.07237)
  - recommended basis (Warsaw basis), LO
  - three different assumptions about BSM flavour structures considered
  - degrees of freedom: independent linear combination of operators that interfere with SM

- proposed example of EFT analysis strategy
  - define observable in a fiducial volume close to the detector one
  - unfold the measurement to particle level (check the unfolding validity when EFT contributes)
  - provide the statistical and systematics likelihoods, error breakdown and correlations
  - compute for the observables the linear and quadratic contributions of 6D operators and extract constraints on them

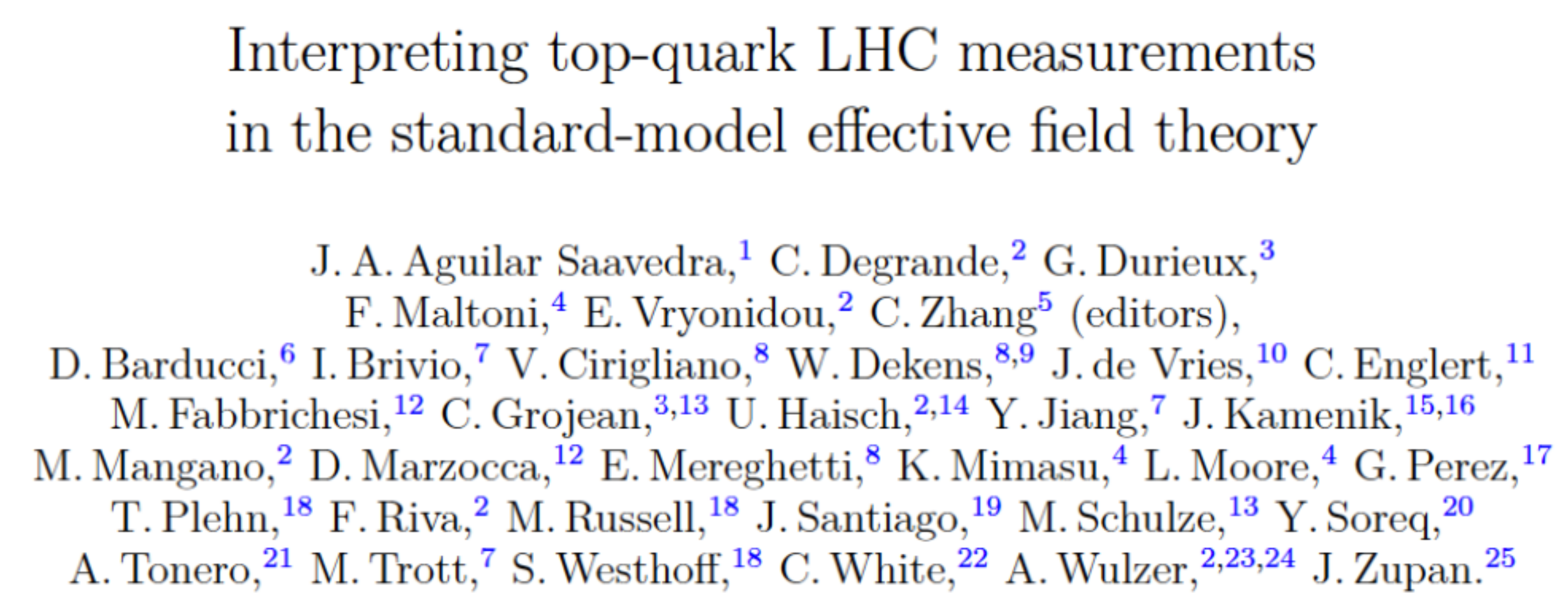


Process	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$	O_{4f}	$O_{\varphi G}$
$t \to bW \to bl^+\nu$	✓		✓	✓				✓	
$pp \to t\bar{q}$	✓		✓	✓				✓	
$pp \to tW$	✓		✓	✓					
$pp \to t\bar{t}$	✓							✓	
$pp \to t\bar{t}\gamma$	✓	✓	✓					✓	
$pp \to t\gamma j$	✓	✓	✓	✓				✓	
$pp \to t\bar{t}Z$	✓	✓	✓	✓	✓	✓		✓	
$pp \to tZj$	✓	✓	✓	✓	✓	✓		✓	
$pp \to t\bar{t}W$	✓							✓	
$pp \to t\bar{t}H$	✓						✓	✓	✓
$pp \to tHj$	✓		✓	✓			✓	✓	✓
$e^+e^- \to t\bar{t}$	✓	✓	✓	✓	✓	✓		✓	
(LO)$gg \to H,HH,Hj$	✓						✓		✓
(LO)$gg \to HZ$	✓			✓	✓	✓	✓		✓

Rontsch & Schulze, JHEP08, 044 (2015)

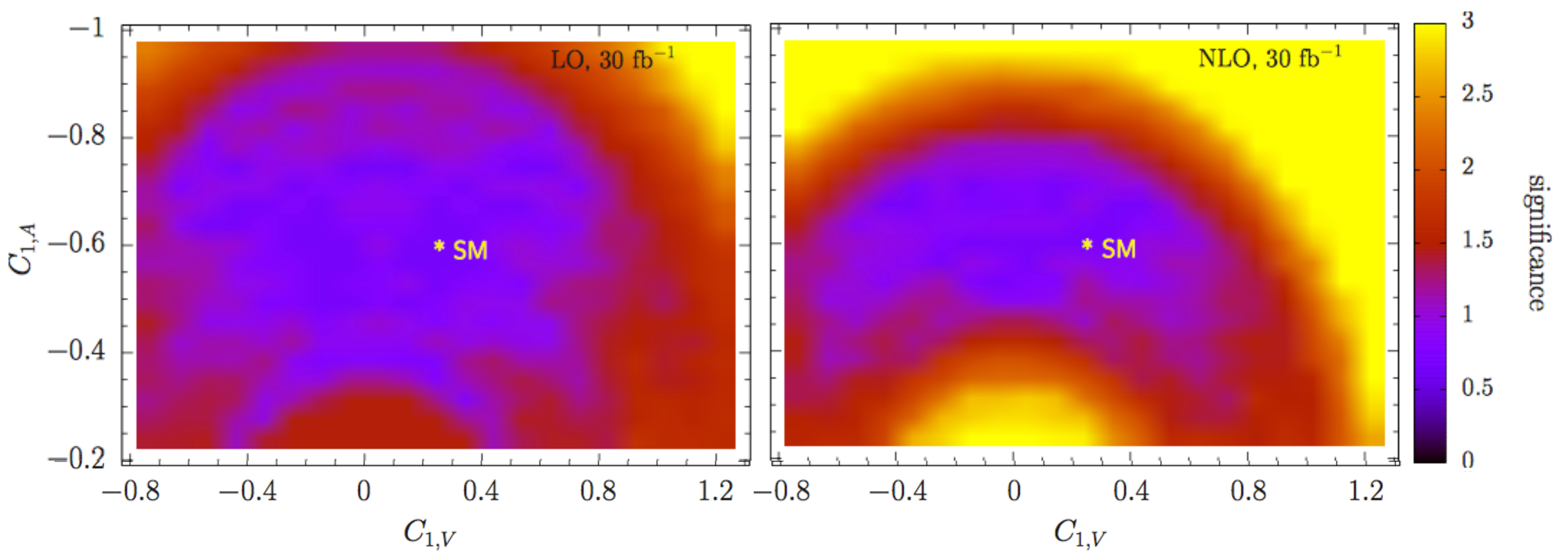


arXiv:1802.07237



Interpreting top-quark LHC measurements
in the standard-model effective field theory

J. A. Aguilar Saavedra,[1] C. Degrande,[2] G. Durieux,[3]
F. Maltoni,[4] E. Vryonidou,[2] C. Zhang[5] (editors),
D. Barducci,[6] I. Brivio,[7] V. Cirigliano,[8] W. Dekens,[8,9] J. de Vries,[10] C. Englert,[11]
M. Fabbrichesi,[12] C. Grojean,[3,13] U. Haisch,[2,14] Y. Jiang,[7] J. Kamenik,[15,16]
M. Mangano,[2] D. Marzocca,[12] E. Mereghetti,[8] K. Mimasu,[4] L. Moore,[4] G. Perez,[17]
T. Plehn,[18] F. Riva,[2] M. Russell,[18] J. Santiago,[19] M. Schulze,[13] Y. Soreq,[20]
A. Tonero,[21] M. Trott,[7] S. Westhoff,[18] C. White,[22] A. Wulzer,[2,23,24] J. Zupan.[25]



Conclusion

- by the end of Run 2 onwards, top quark physics will enter the high precision regime
  - multi-dimensional differential cross section measurements would benefit from high order predictions that include top decays and from improve modelling uncertainties
  - crucial to perform dedicated measurements for MC tuning

- latest theoretical computations would help when they are implemented in MC generators (with parton shower)
  - important for some experimental measurements
  - could help to assess the theoretical uncertainty on the measured top quark mass

- precision Standard Model measurements are searches for deviations from the SM Lagrangian
  - EFT provides a nice framework for these searches
  - a global EFT fit still requires further joint efforts between theorists and experimentalists
  - flavour physics (lepton universality, Vcb, …)

- great top quark physics perspectives ahead at the HL-LHC.
  New top HL-LHC perspectives by the end of this year
  - increase precision, specific space phase
  - boosted channels
  - rare processes (4tops, tZq, ttW asymmetries, …)