High precision top quark physics at the LHC

latest experimental results and theory challenges in top-quark physics

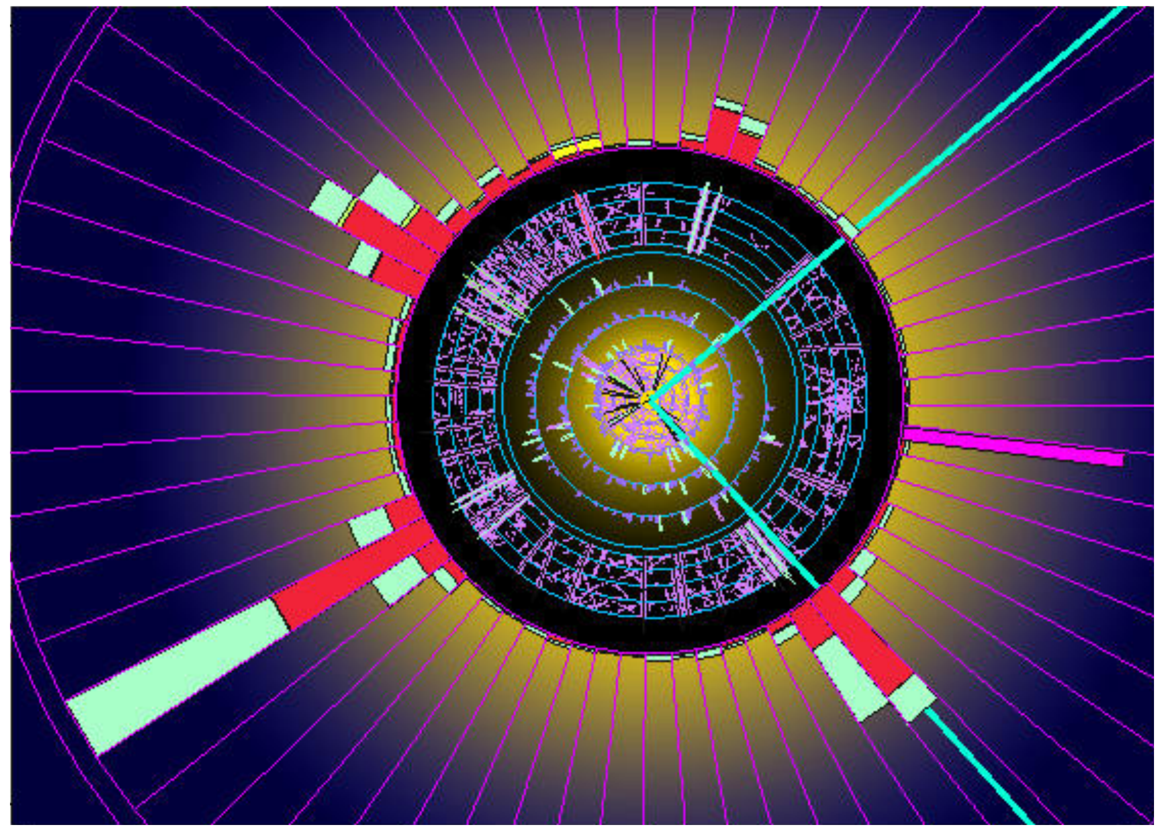
Frédéric Déliot
CEA-Saclay

LAL
26 June 2018

The top quark history

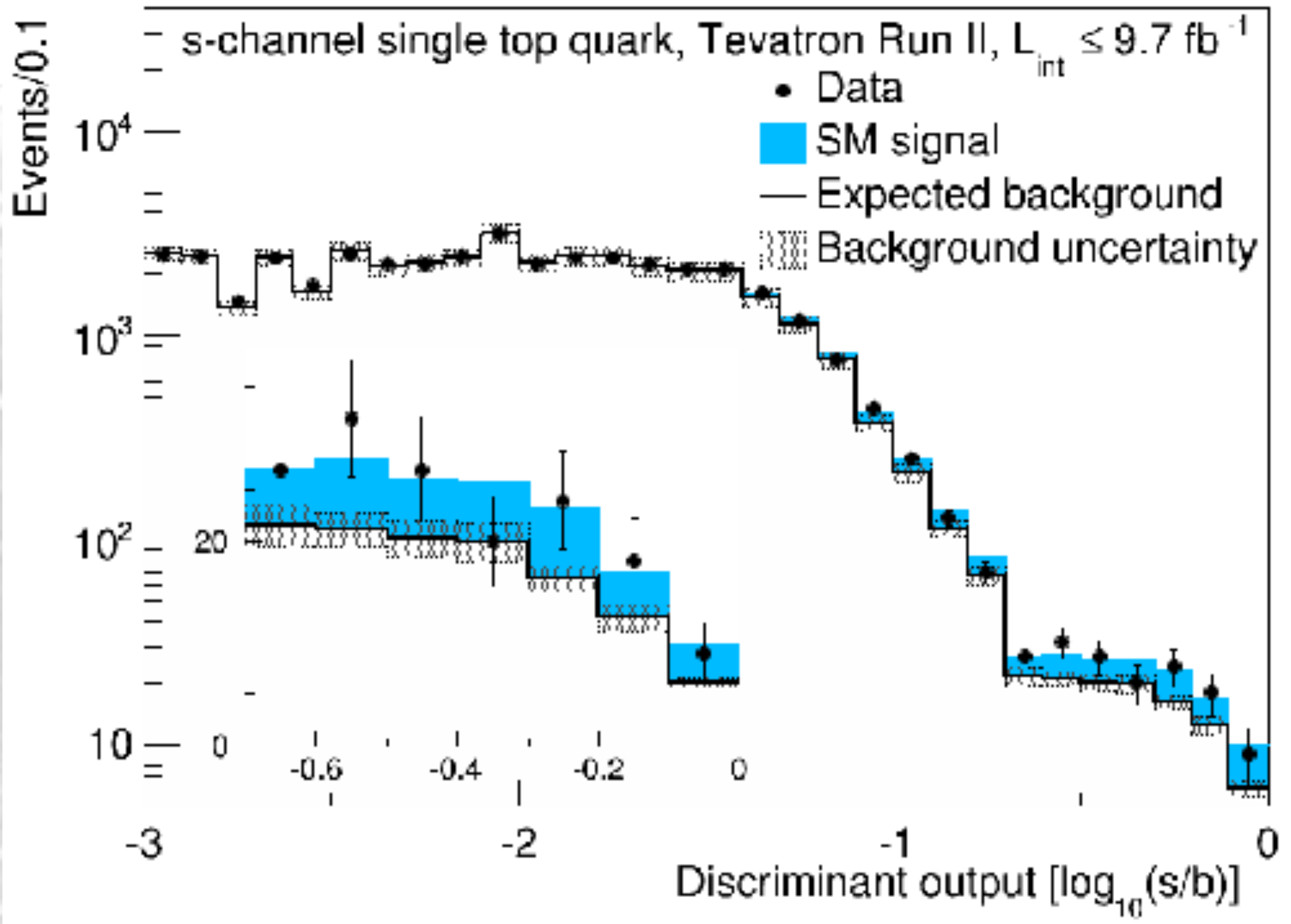
- the pre-LHC area
  - expected to complete the 3rd quark family after the discovery of the b in 1977
  - discovered in 1995 during the Run I of the Tevatron
    - constrain from the electroweak fit (1994): Mtop = 178 ± 21 GeV

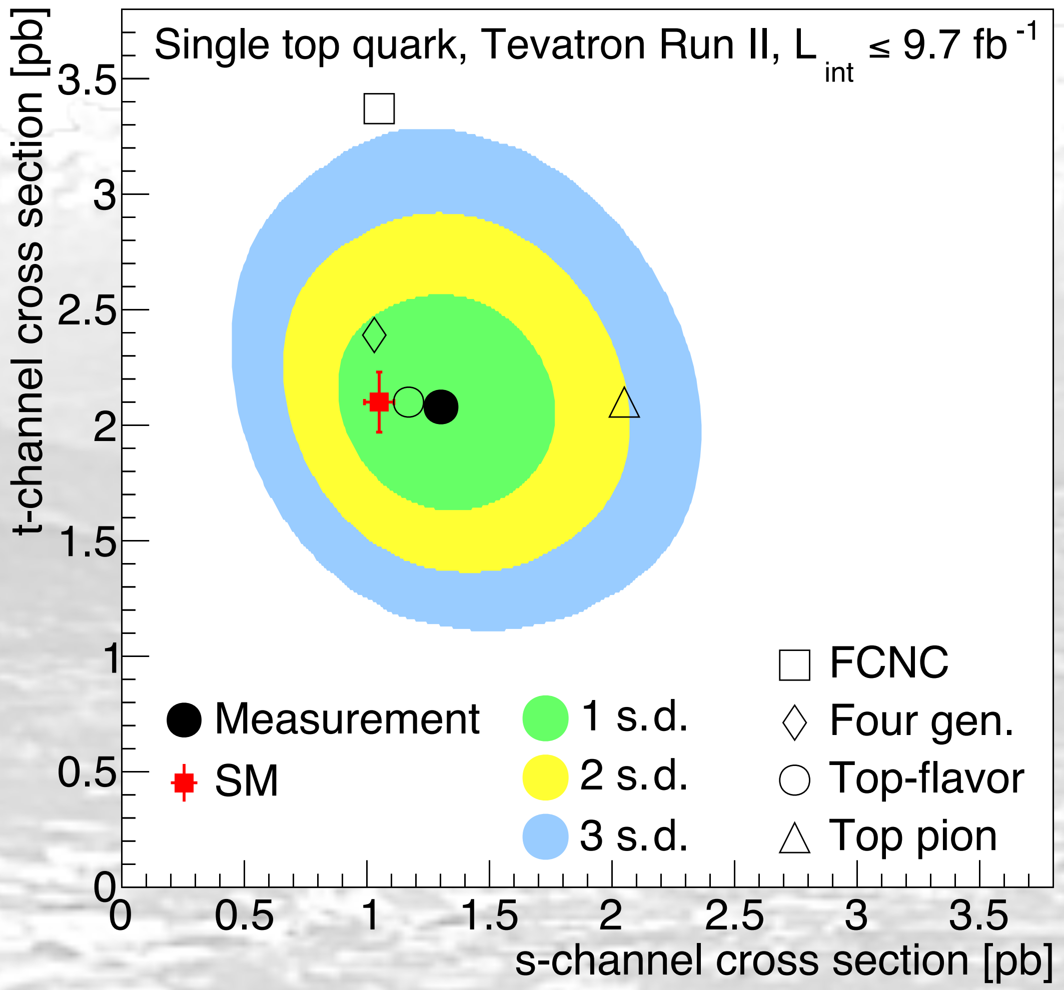
  - Tevatron Run II (2002-2011) √s = 1.96 TeV, L≈10 fb^{-1}
    - first measurements of its properties in all decay channels
    - discovery of single top production (2009) using multivariate techniques
    - D0+CDF combination: discovery of s-channel single top production (2014)
      - SM cross section: ~ 1 pb



PRL74, 2422 (1995), PRL74, 2626 (1995)

PRL 112, 231803 (2014)

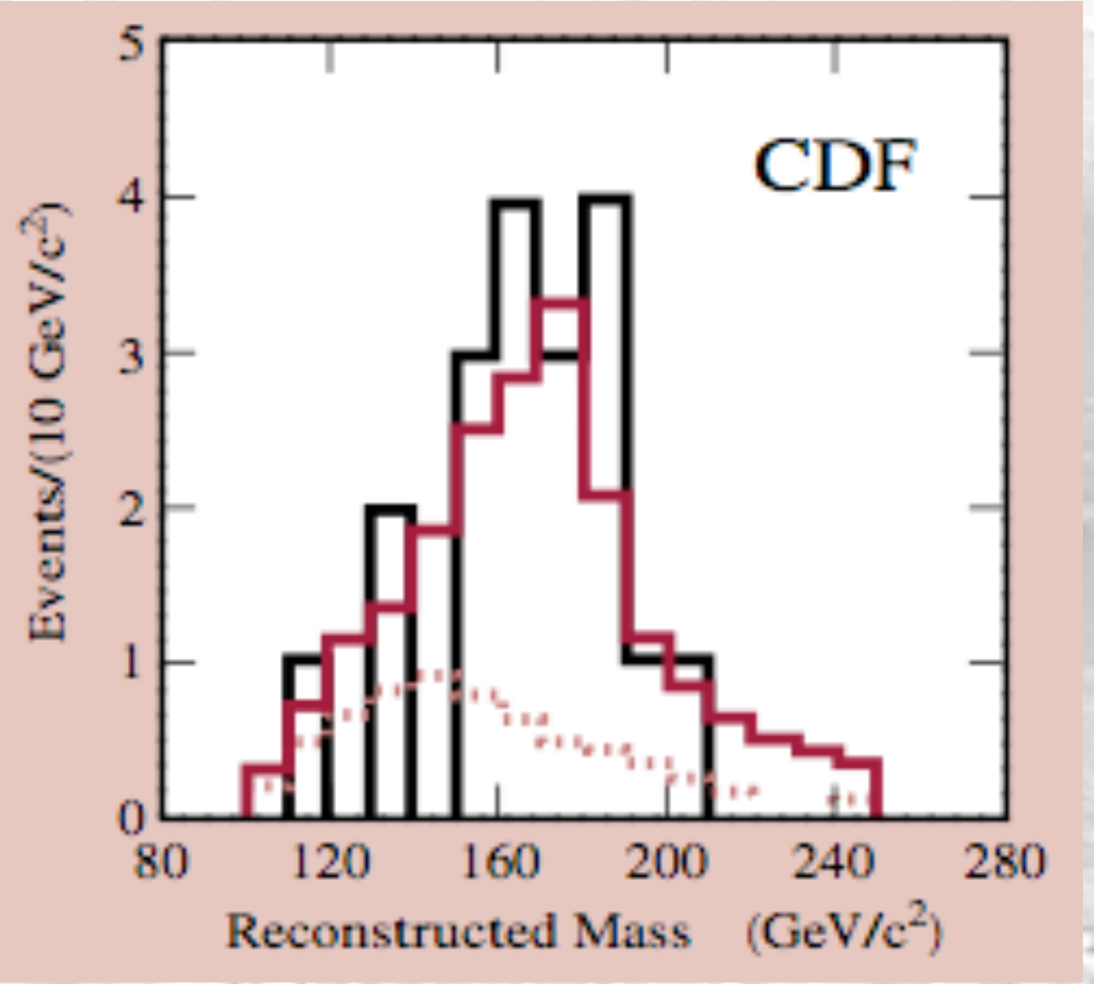




CDF: 67 pb^{-1} , 4.8 σ

M_{top} = 176 ± 13 GeV

$\sigma_{t\bar{t}} = 6.8^{+3.6}_{-2.4}$ pb



Why is the top quark so special ?

- The heaviest known elementary particle
  - 40x heavier than its isospin partner
  - coupling to the Higgs boson close to 1: special role in the electroweak symmetry breaking ?
    - the only quark with natural mass

  - this is the only quark that decays before hadronizing and before spin-flipping
    - unique opportunity to observe a bare quark
  - window to physics beyond the standard model

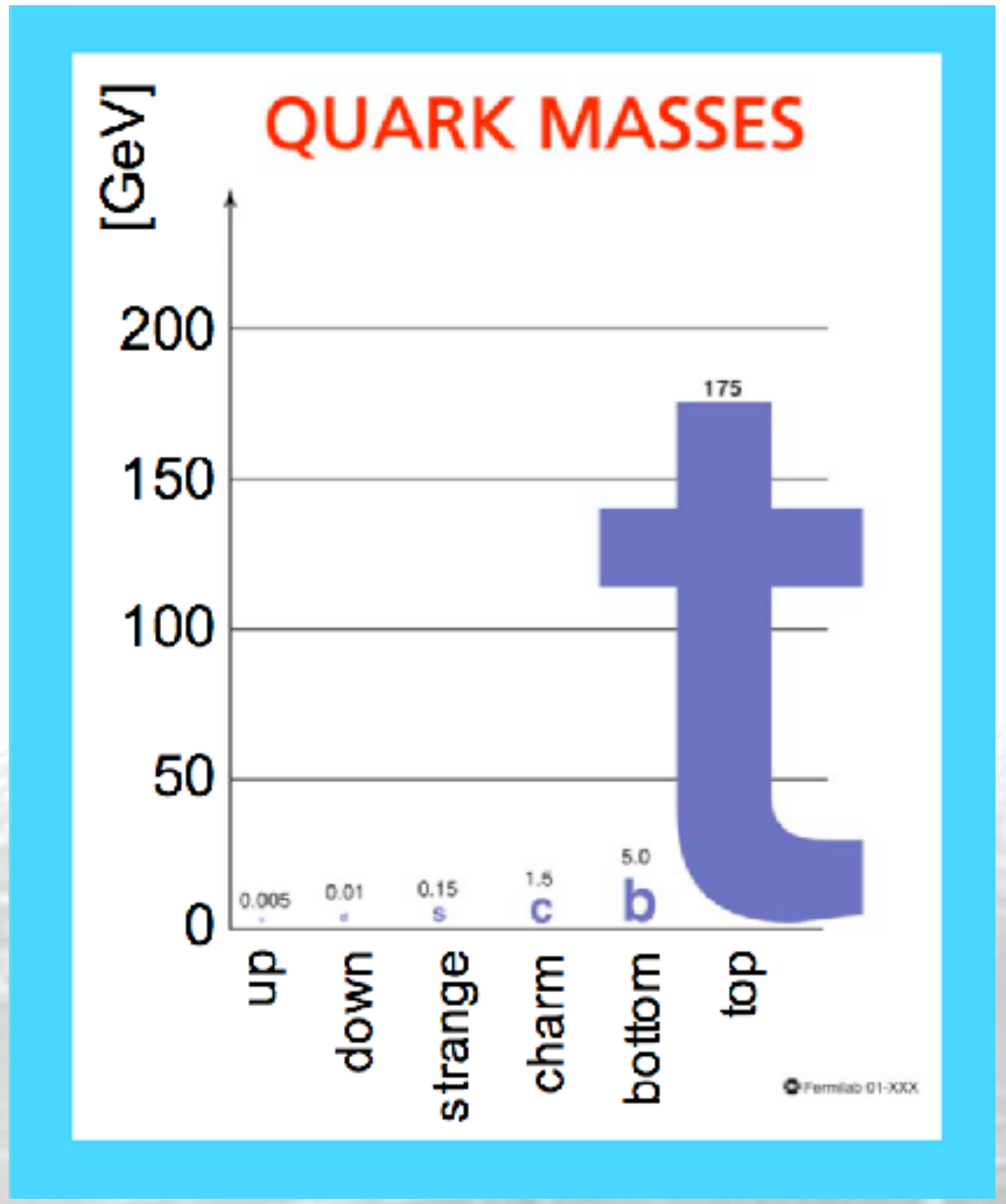
- Need to understand its properties with high precision

$$\mathcal{L}_{\mathrm{Yukawa}} = -\boxed{\lambda_t}\,\overline{\psi_{Lt}}\,\Phi\,\psi_{Rt}$$

$$\lambda_t \approx 1$$

$$m_t >> m_b$$

$$\tau \approx 5.10^{-25}\mathrm{s} << \Lambda_{\mathrm{QCD}}^{-1}$$



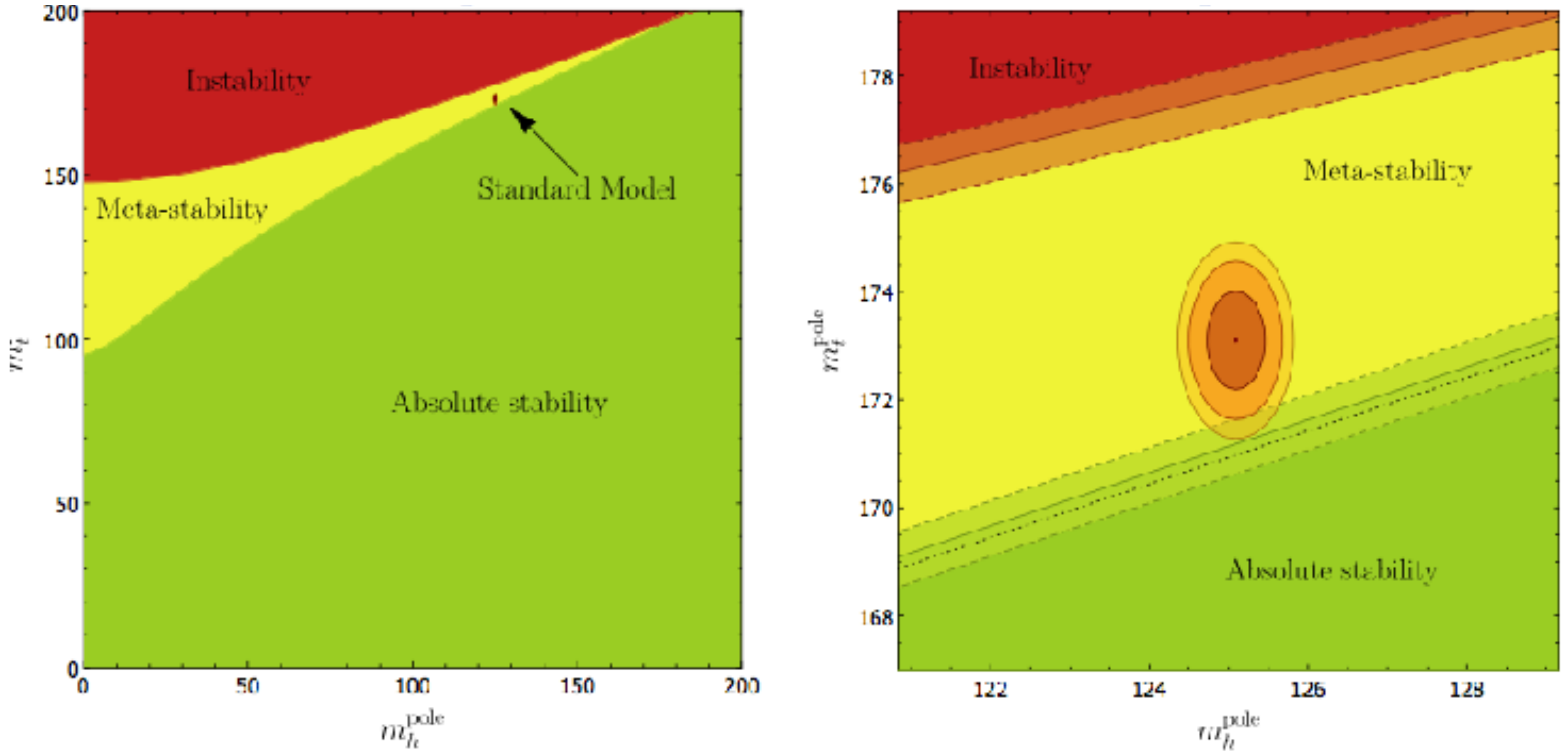
Why do we care about precision in top quark physics ?

- stability of the Standard Model vacuum
  - this is the only quark that drastically affects the stability of the Higgs mass
    - naturalness argument: BSM top partners should be light

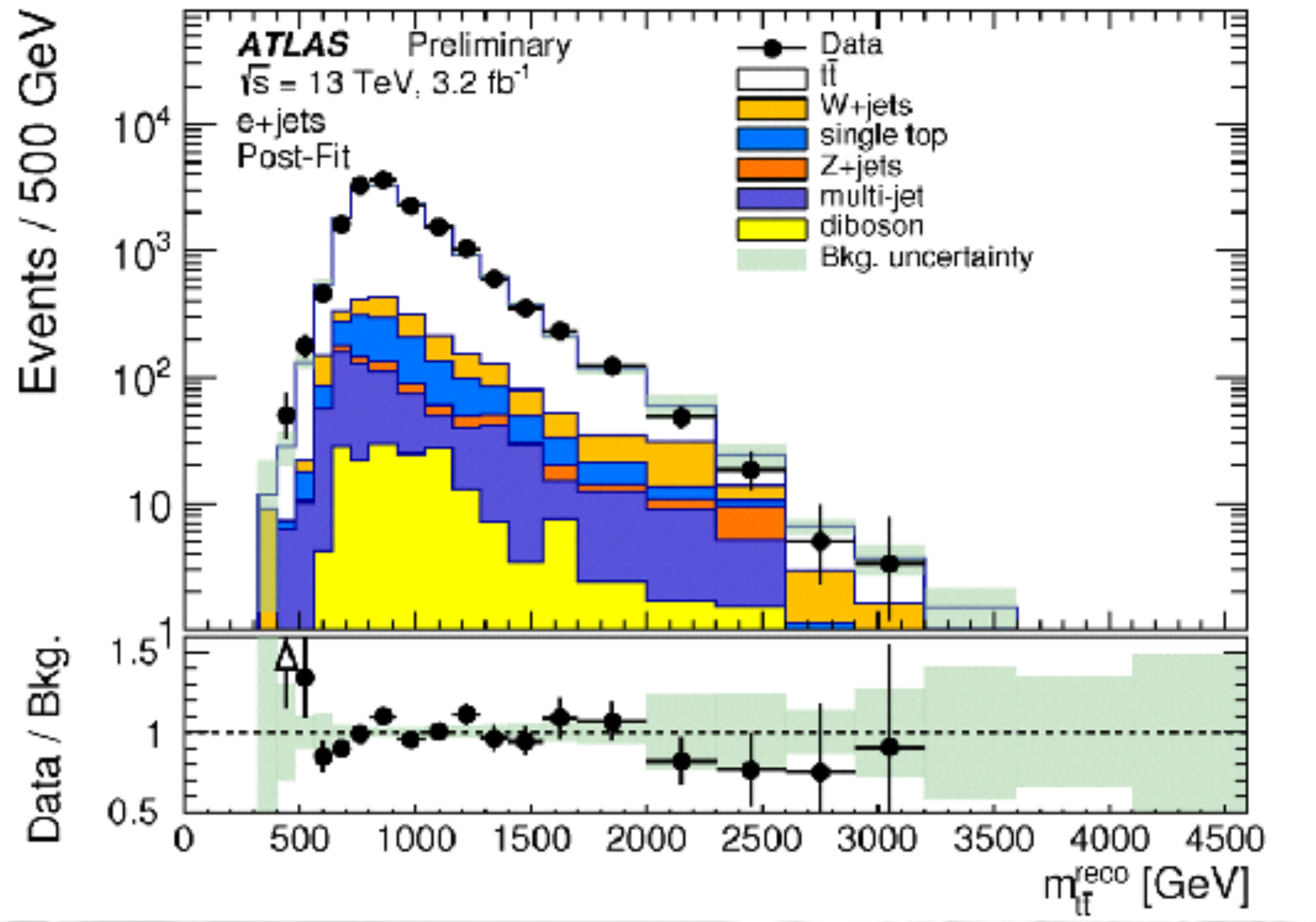
- Background to new physics search:
  - $t\bar{t}$ spectrum, top pt, $t\bar{t}$ + MET (dark matter search), single top …

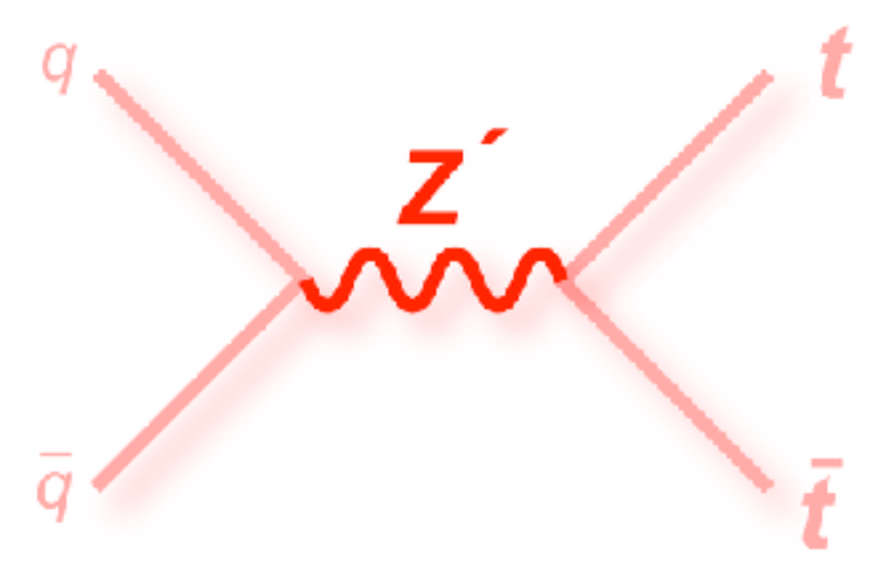
- Deviation from predictions:
  - indirect detection of new particles, anomalous couplings, …

Andreassen, Frost, Schwartz, arXiv:1707.08124

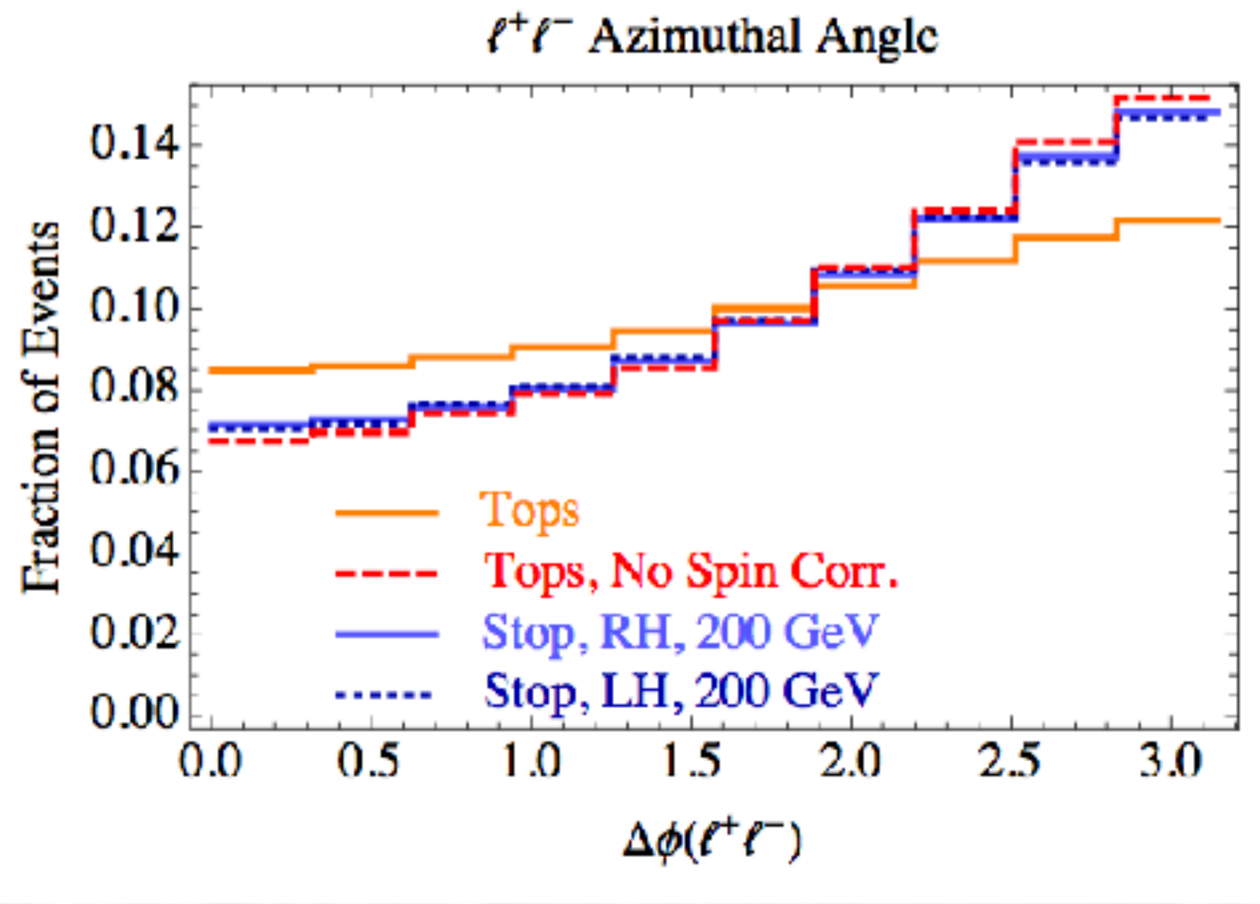


ATLAS-CONF-2016-014



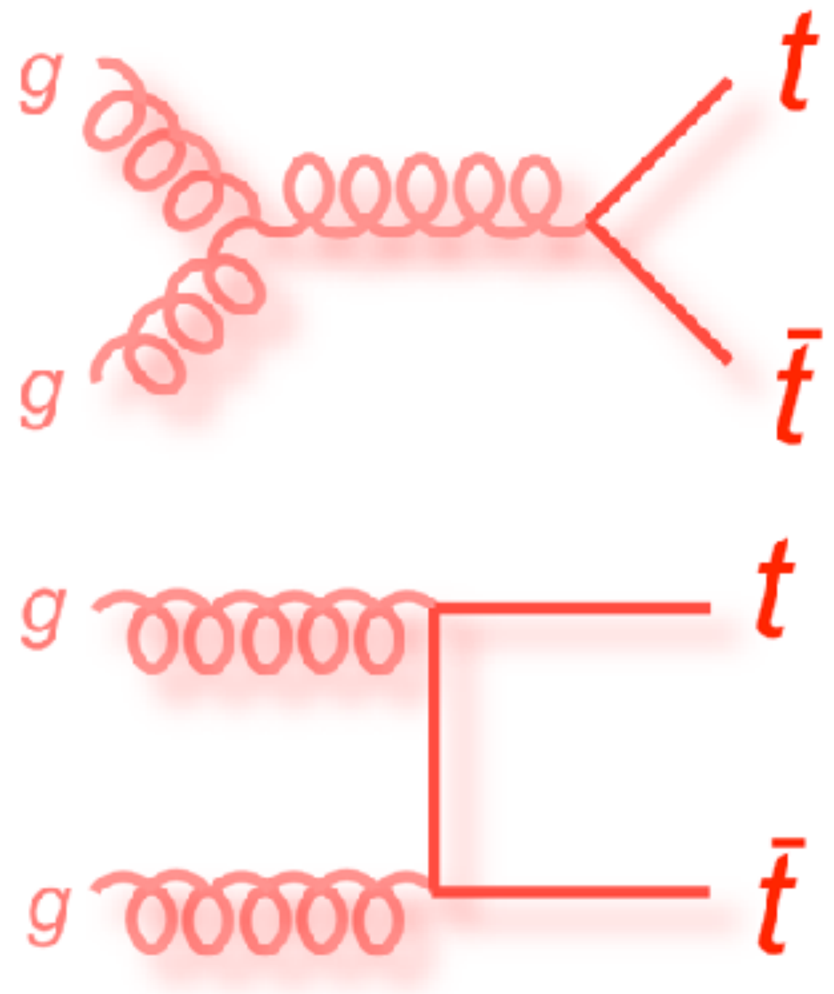


Han, Katz, Krohn, Reece, JHEP 1208, 083 (2012)

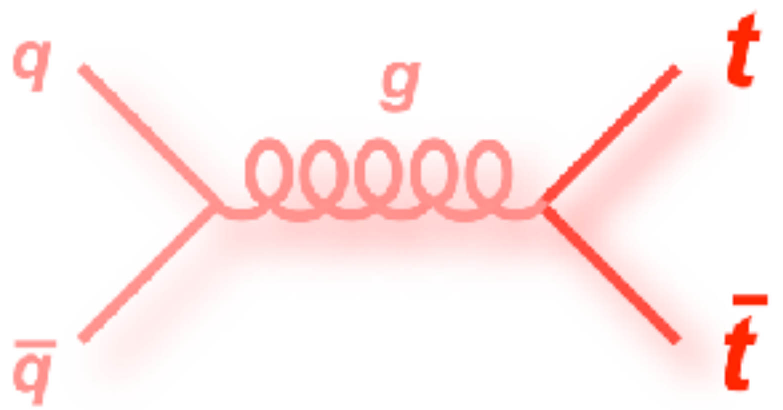


Producing and identifying the top quark

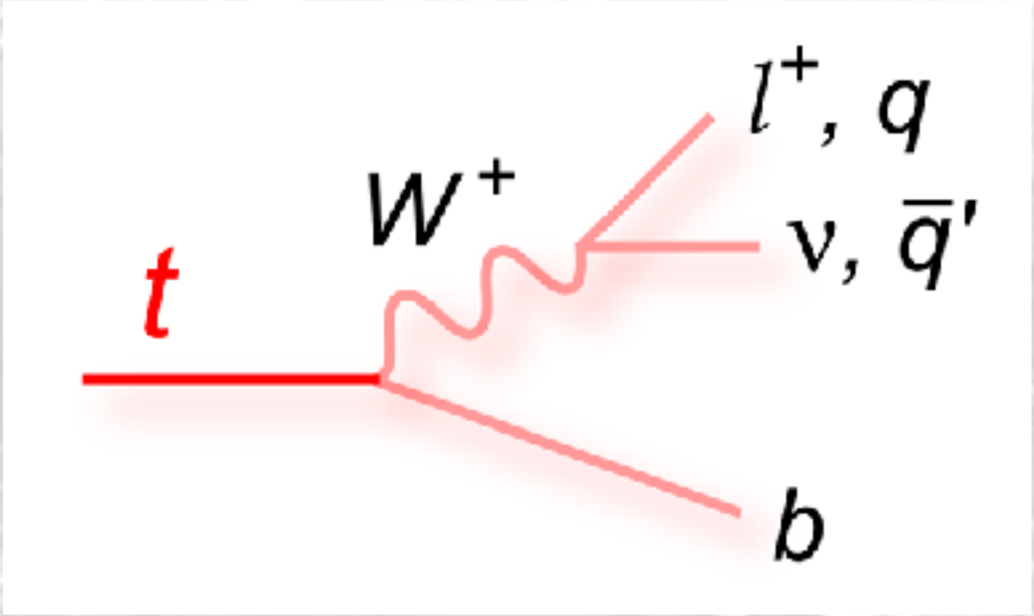
~ 90% @ LHC

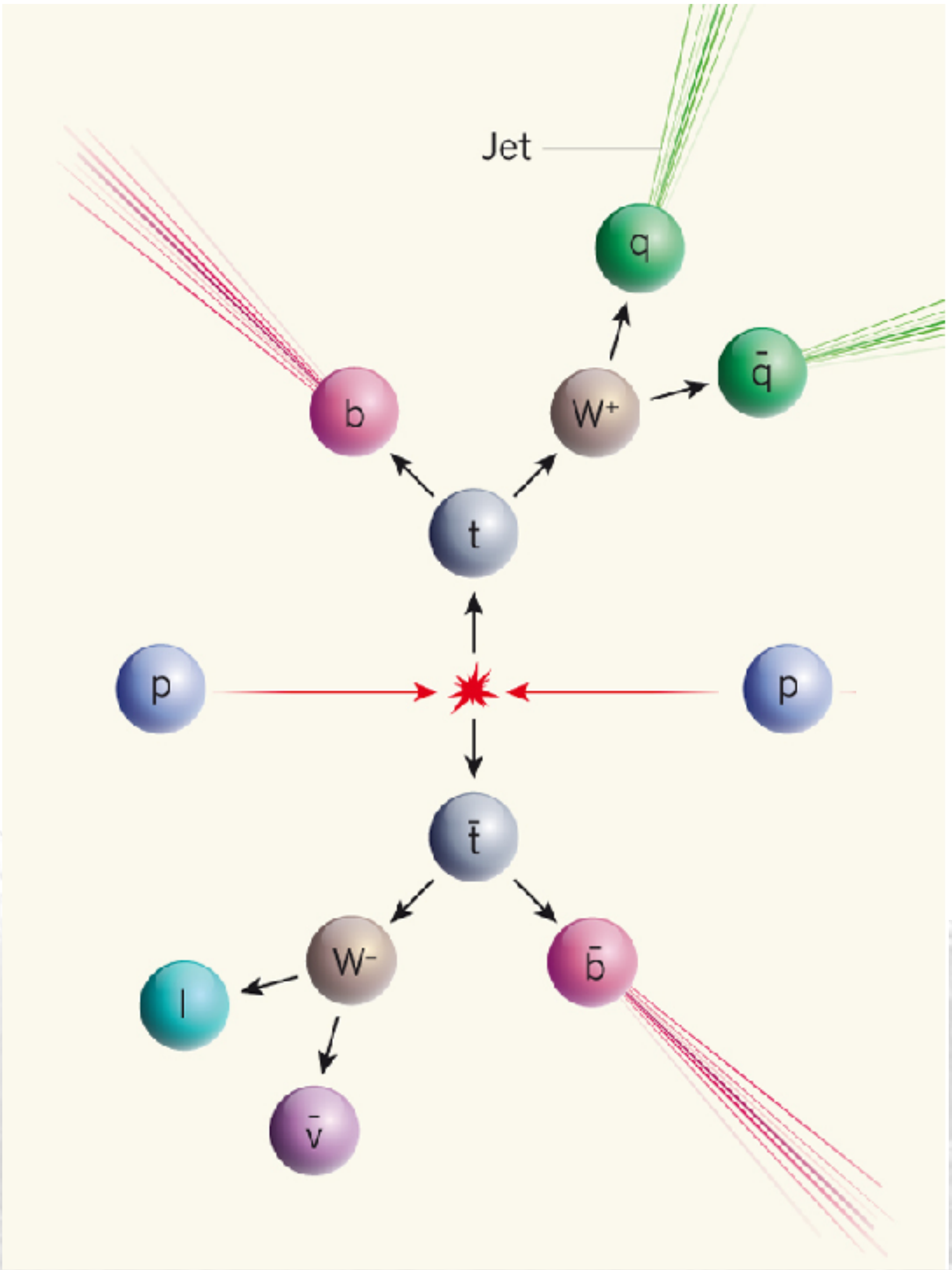


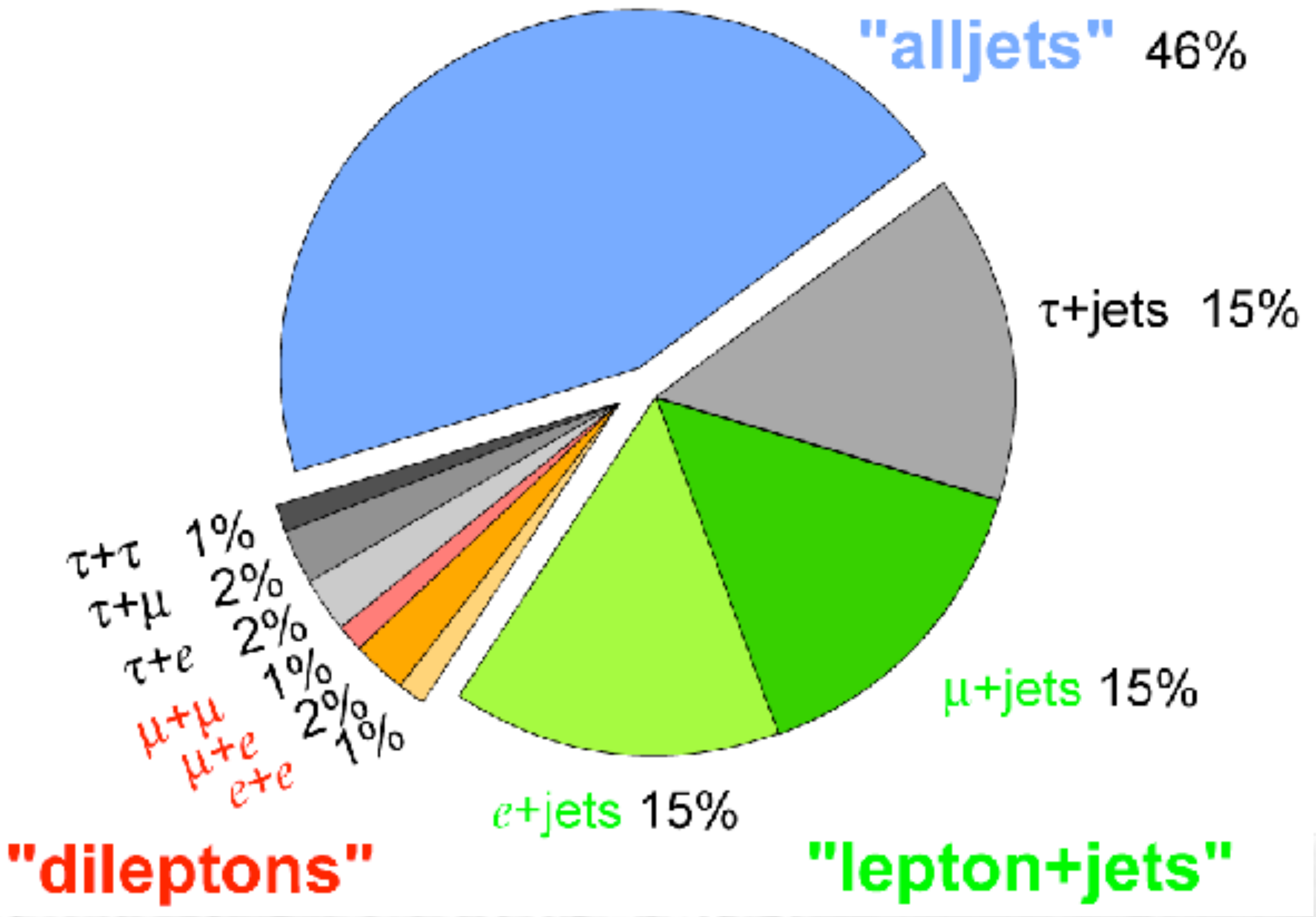
~ 10% @ LHC



~ 100% in the Standard Model





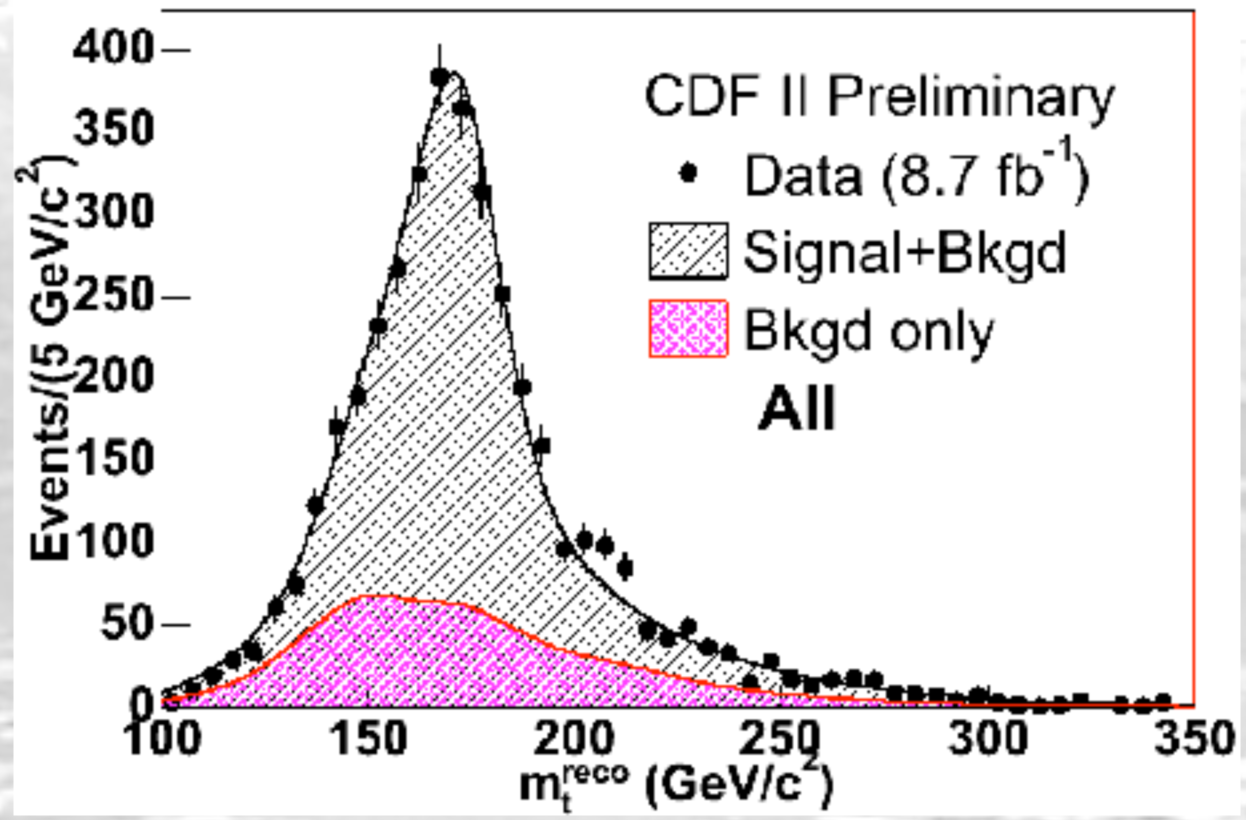


The LHC: a top quark factory

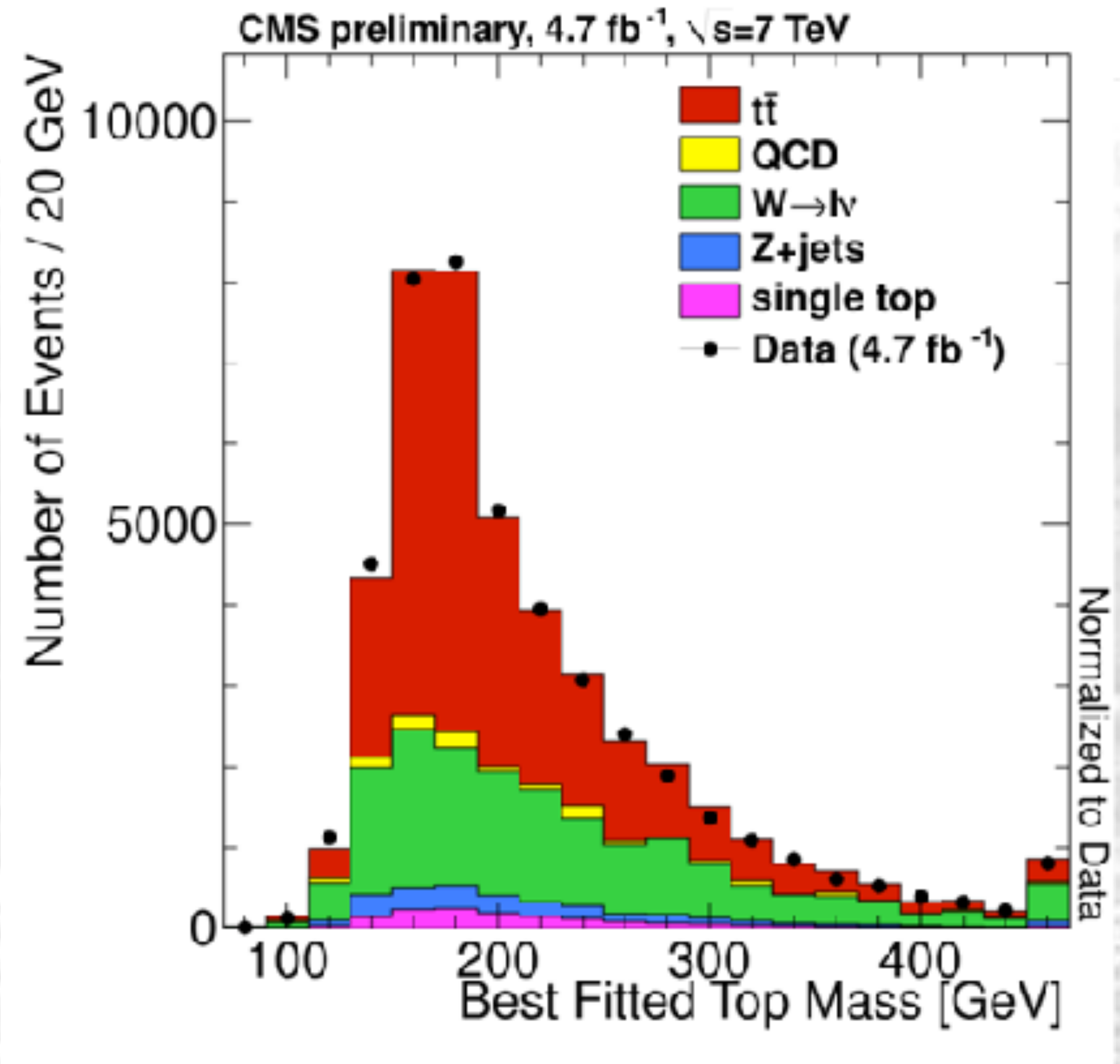
	Tevatron 1.96 TeV	**LHC 7 TeV**	**LHC 8 TeV**	**LHC 13 TeV**
$t\bar{t}$ theory cross section (NNLO+NNLL)	7.16±0.22 pb	177±11 pb	253±13 pb	831±49 pb
$t\bar{t}$ events after selection cuts (lepton+jets)	4.5 kevts (9.7 fb^{-1})	24 kevts (4.6 fb^{-1})	166 kevts (20.3 fb^{-1})	1200 kevts (30 fb^{-1})
$t+\bar{t}$ theory cross section (NLO)	3.46±0.18 pb	63±2.7 pb	85±3.5 pb	217± 8.3 pb
t-channel events after selection cuts (before discriminant cut)	100 evts (9.7 fb^{-1})	5 kevts (4.6 fb^{-1})	17 kevts (20.2 fb^{-1})	70 kevts (30 fb^{-1})

- LHC focus: new energy, precision and rare/new processes

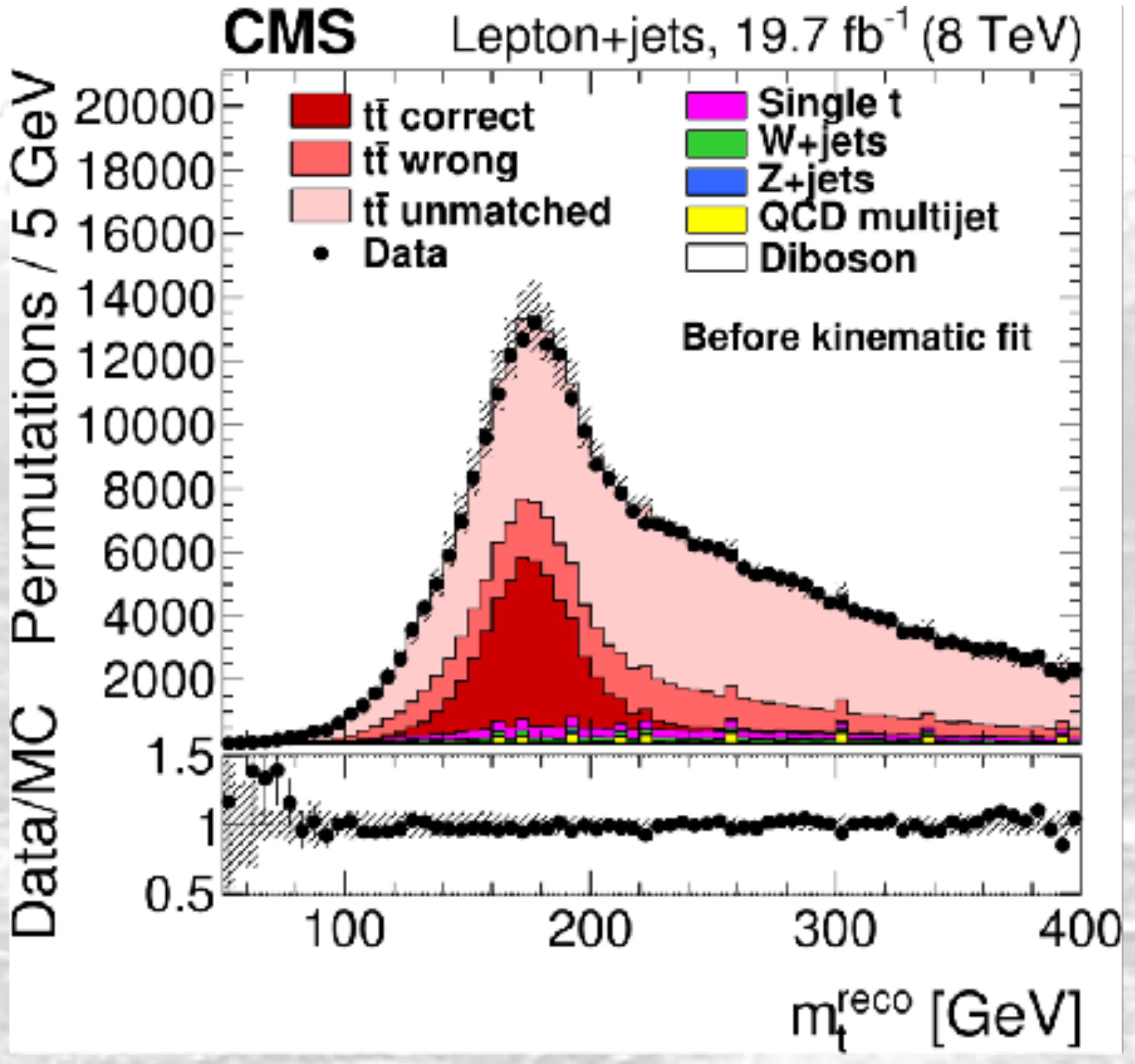
Tevatron Run II



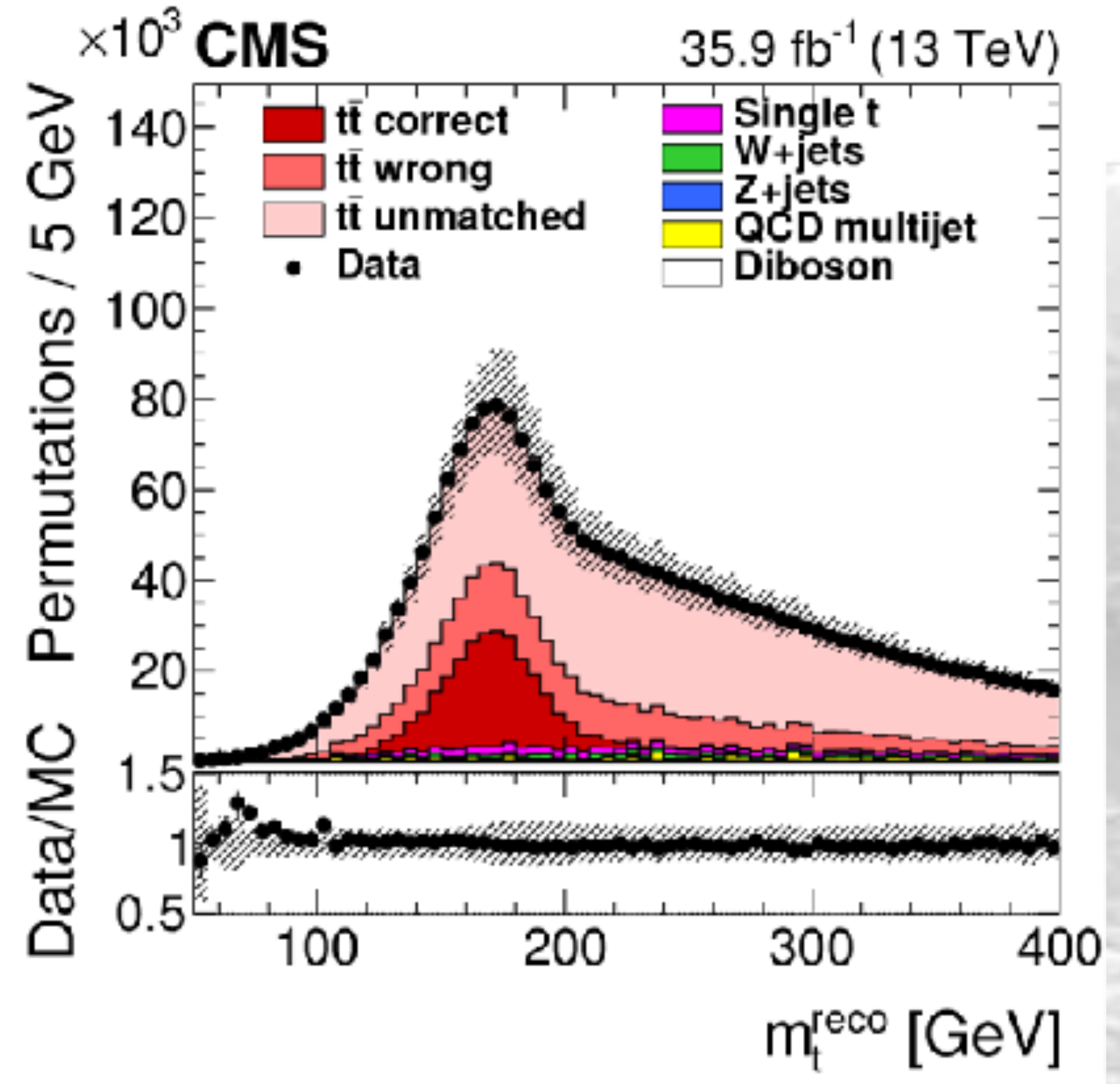
LHC 7 TeV



LHC 8 TeV

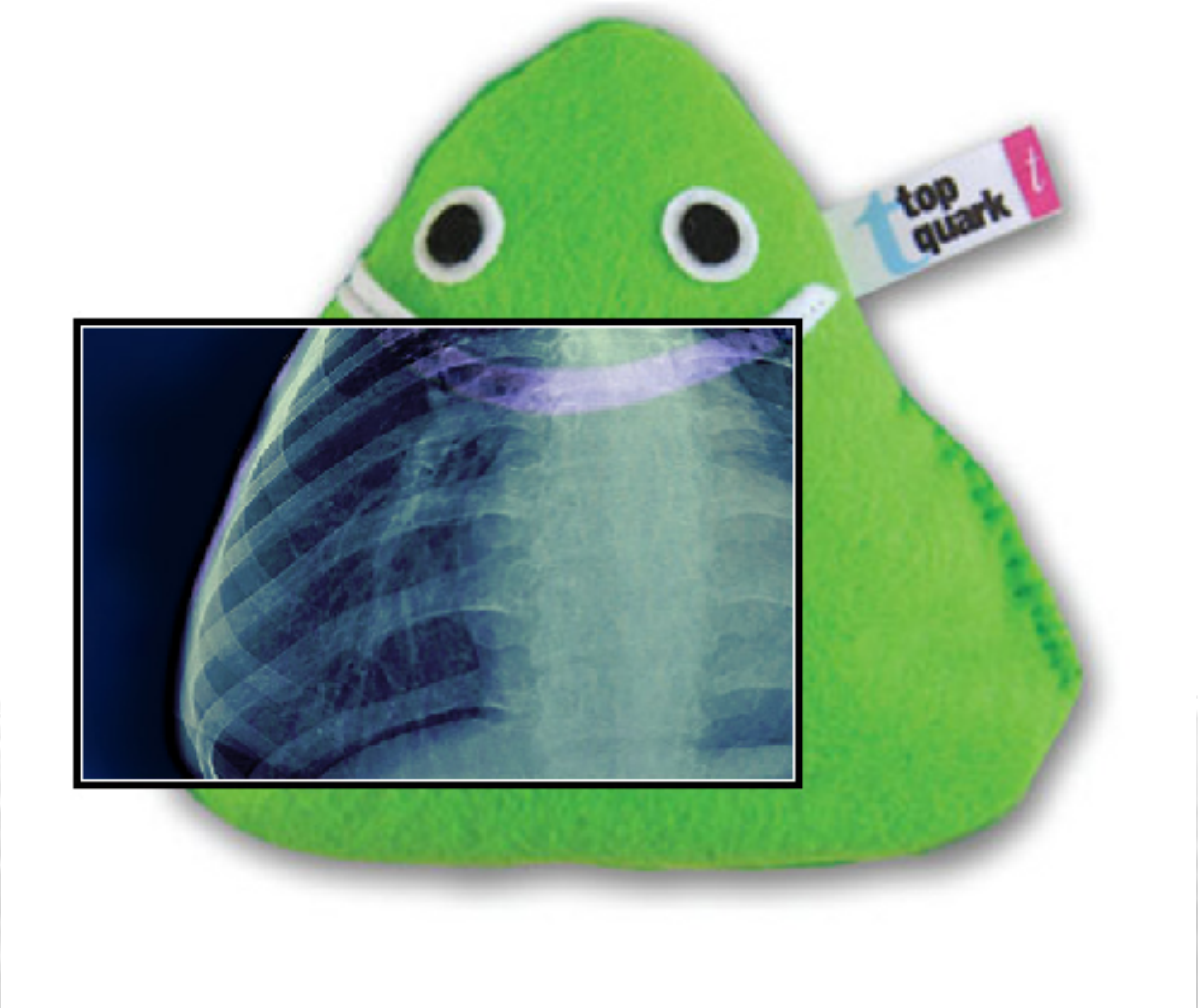


LHC 13 TeV



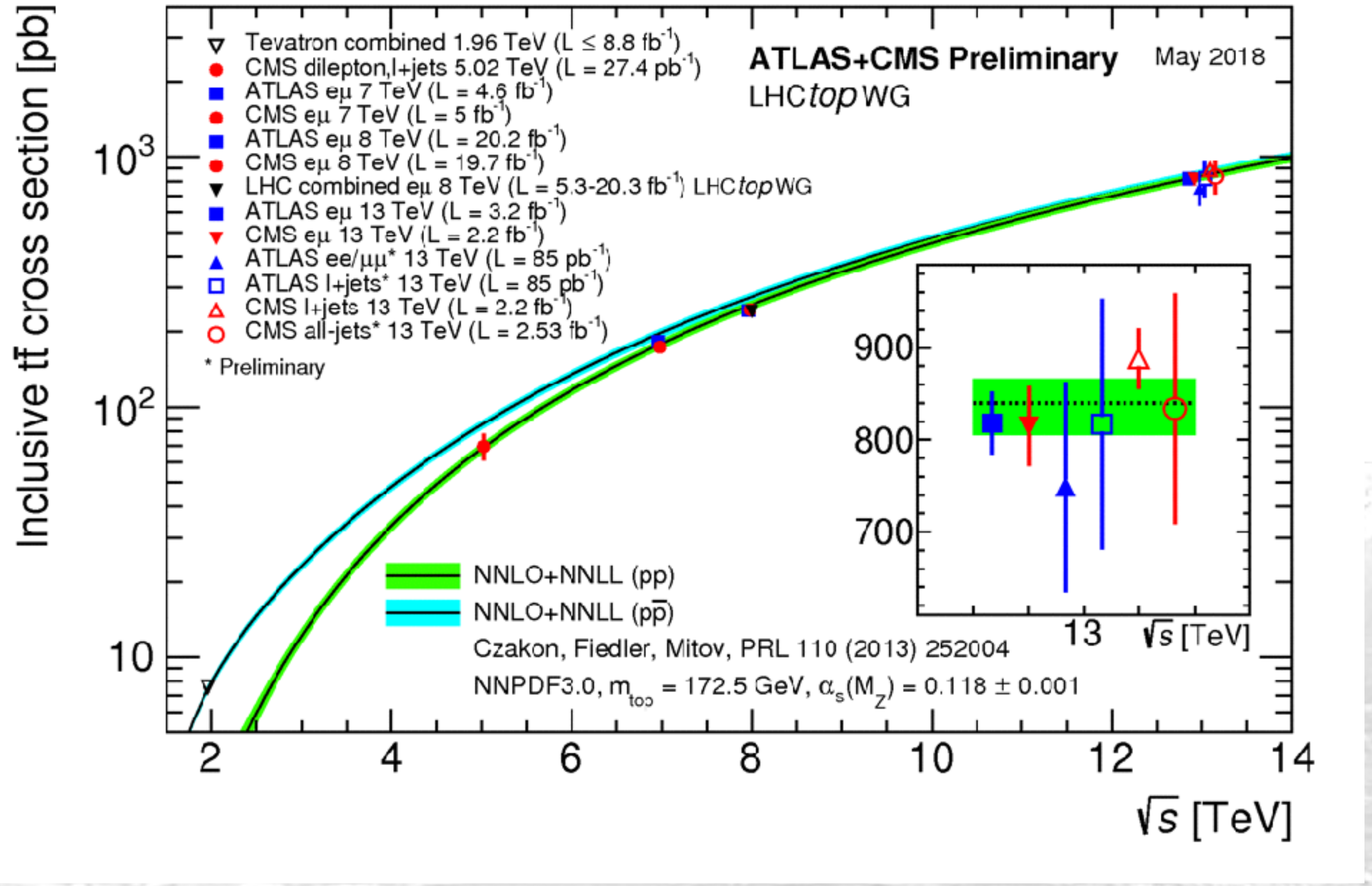
Outline

- $t\bar{t}$ cross section
  - latest inclusive and differential measurements
  - status of the theoretical predictions
  - improving the modelling
- single top cross section
  - latest inclusive and differential measurements
- top quark mass
  - latest experimental direct and alternative measurements
  - latest discussions on the mass definition and on the theoretical uncertainties
- top quark couplings
  - latest experimental measurements
  - the Effective Field Theory (EFT) approach

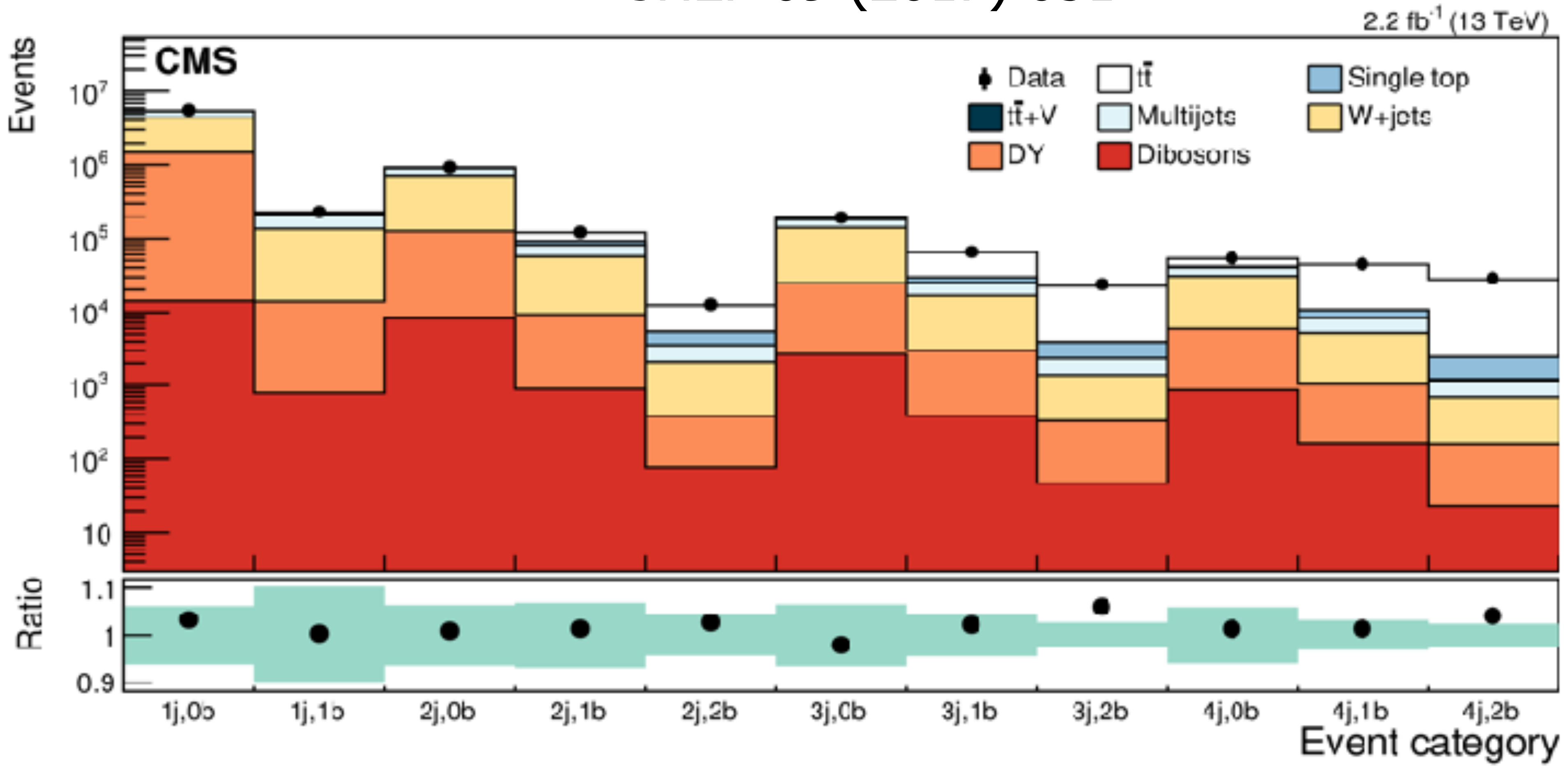


Inclusive $t\bar{t}$ cross section

- inclusive measurements
  - benchmark to control the selection and the background evaluation
  - precision ~ 4 % (at the level of the theory uncertainties)



JHEP 09 (2017) 051



$$\sigma_{t\bar{t}} = 888 \pm 2\,(\text{stat})^{+26}_{-28}\,(\text{syst}) \pm 20\,(\text{lumi})\ \text{pb}$$

Δσ/σ = 3.8 %

Limited by the systematic uncertainty on the background normalisation and on the object efficiencies

ATLAS eμ channel, PLB 761 (2016) 136

$$\sigma_{t\bar{t}} = 818 \pm 8\ (\text{stat}) \pm 27\ (\text{syst}) \pm 19\ (\text{lumi}) \pm 12\ (\text{beam})\ \text{pb}$$

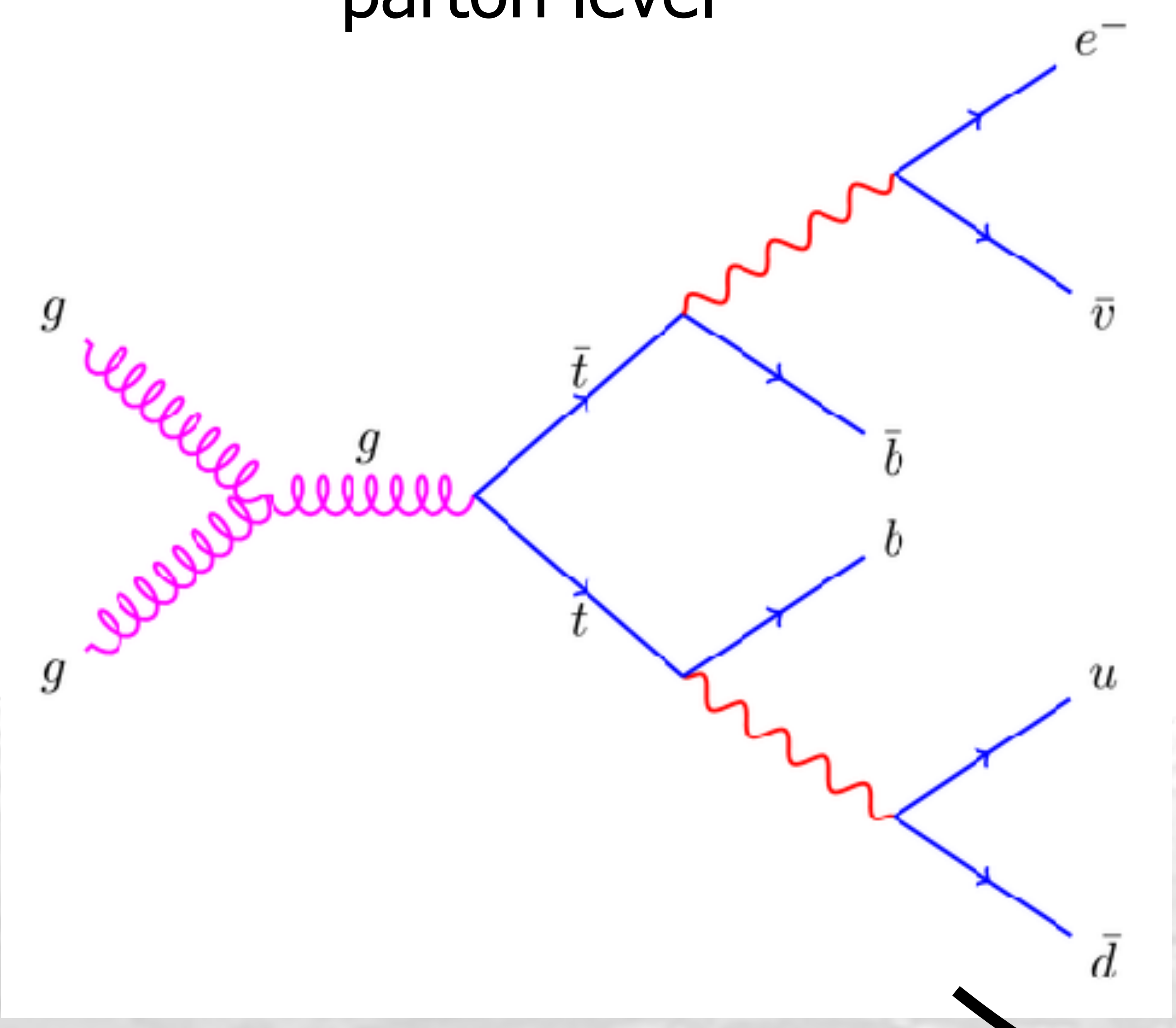
Δσ/σ = 4.4 %

Limited by the systematic uncertainty on the $t\bar{t}$ modeling

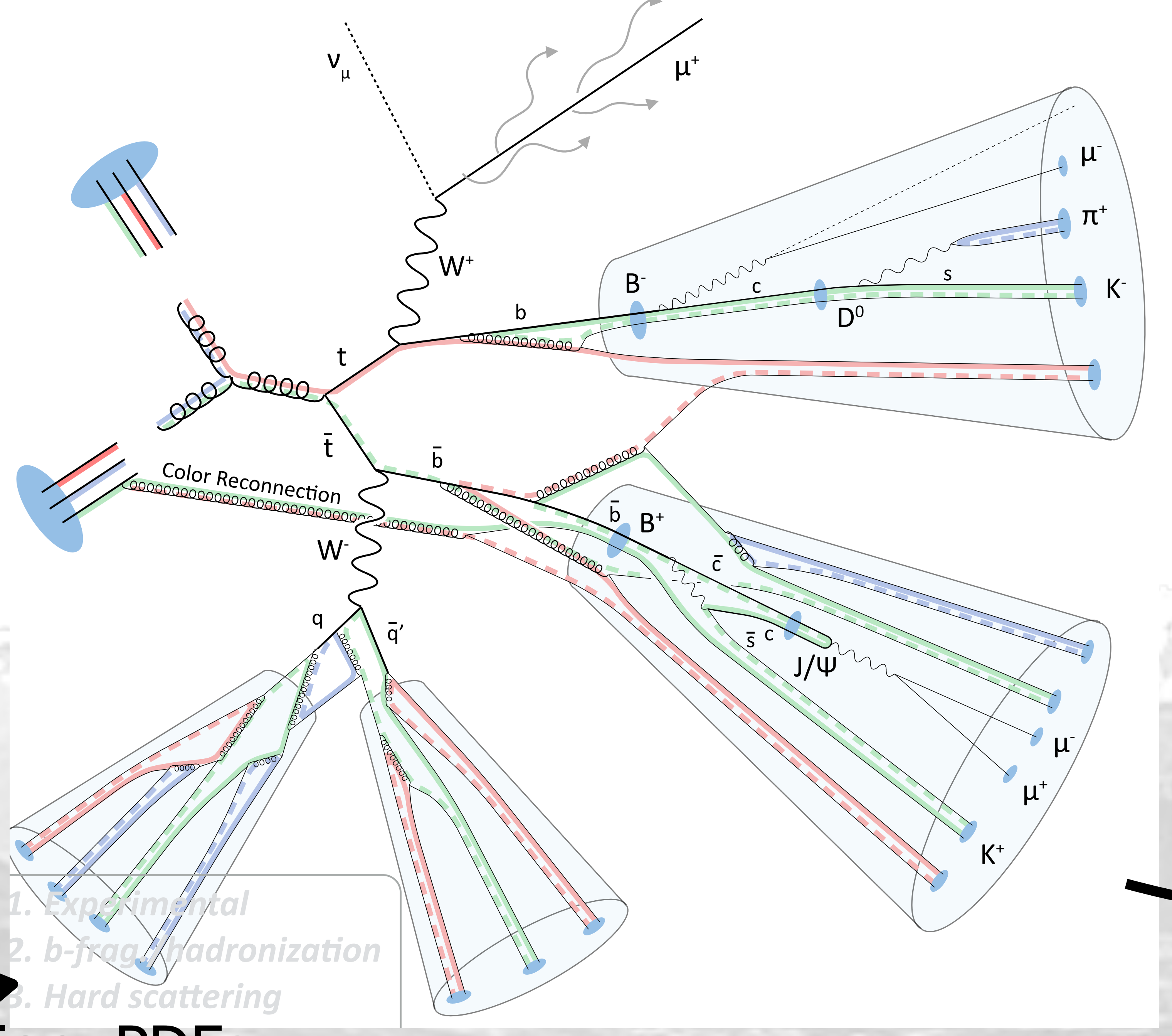
Differential $t\bar{t}$ cross section

- Differential measurements: allowed by the large $t\bar{t}$ statistics
  - essential to control the background for new physics search and the $t\bar{t}$ theory modelling
  - allow to relate state-of-the art theory calculations, MC generators and experiment
    - correction for acceptance and detector effects: particle level in fiducial phase space, parton level extrapolated to the full phase space

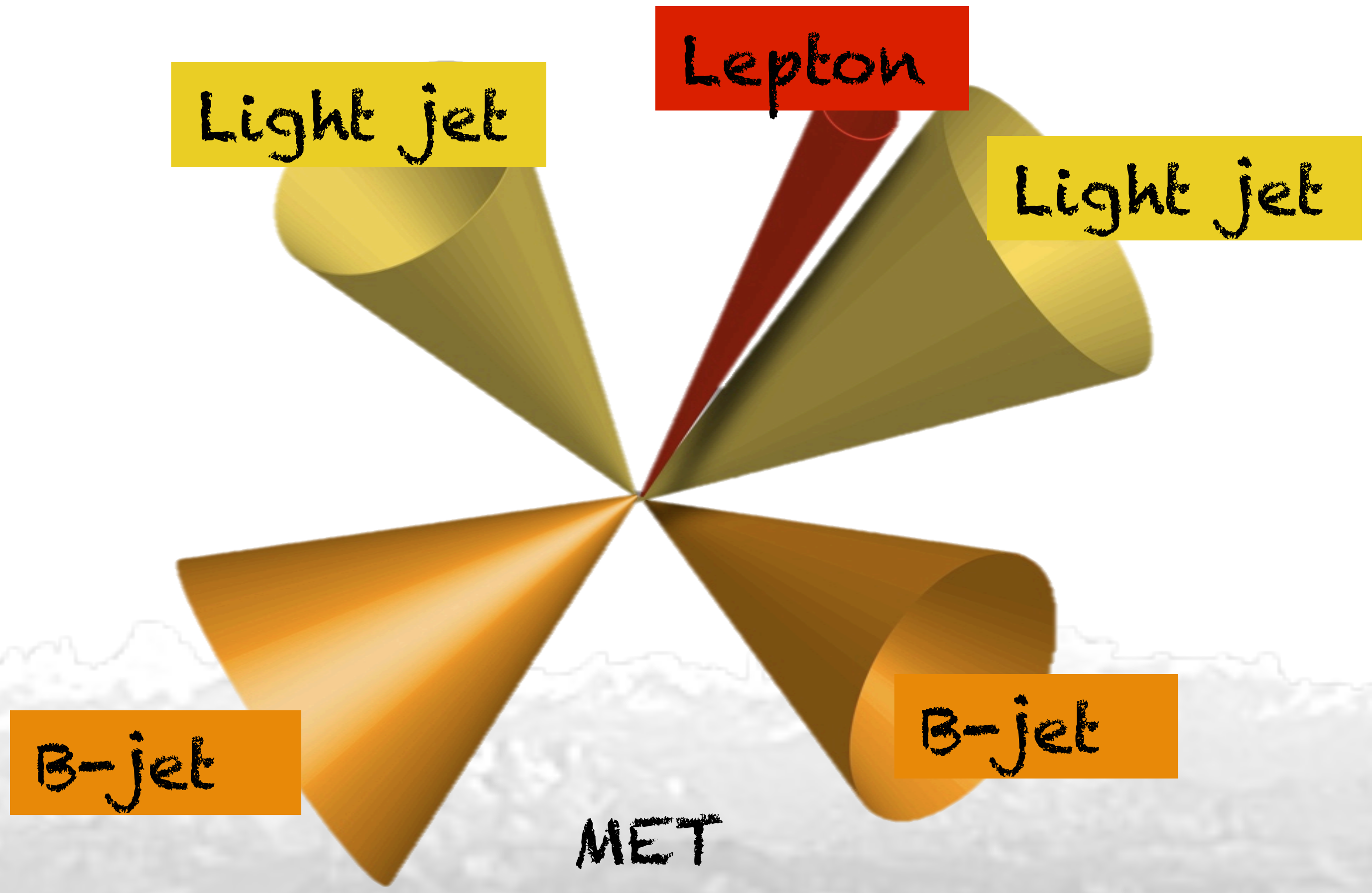
parton level



particle level



reconstruction level



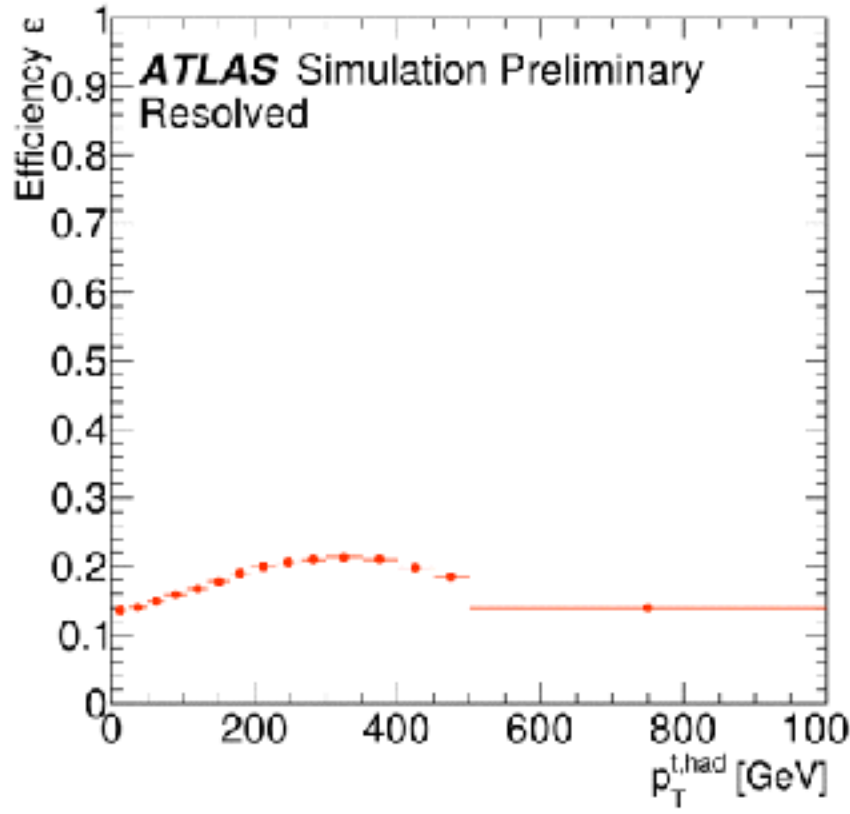
fragmentation, parton shower, hadronisation, PDFs,…

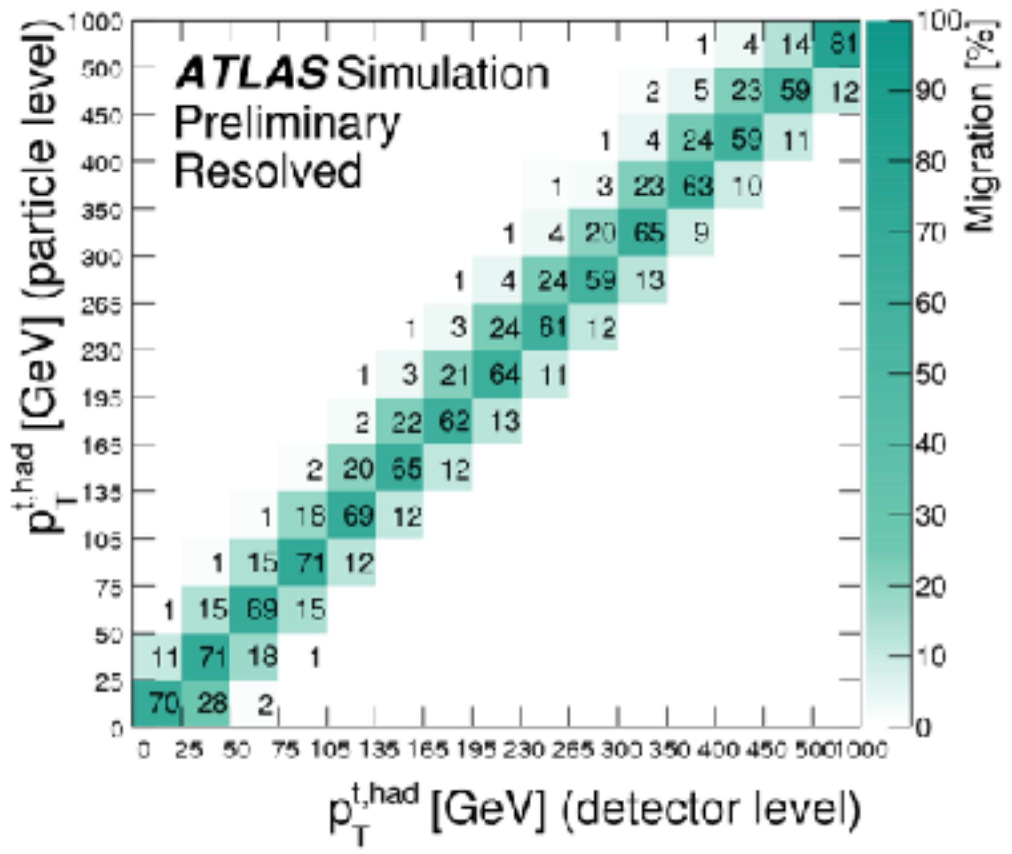
interactions in the detector

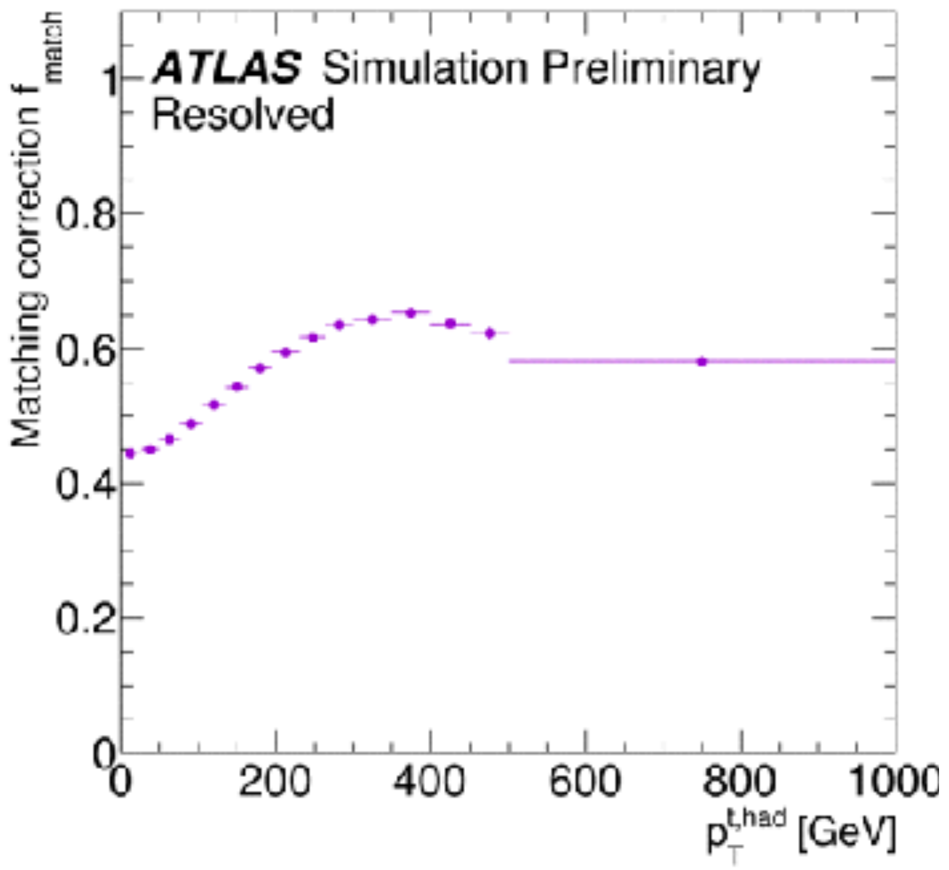
unfolding

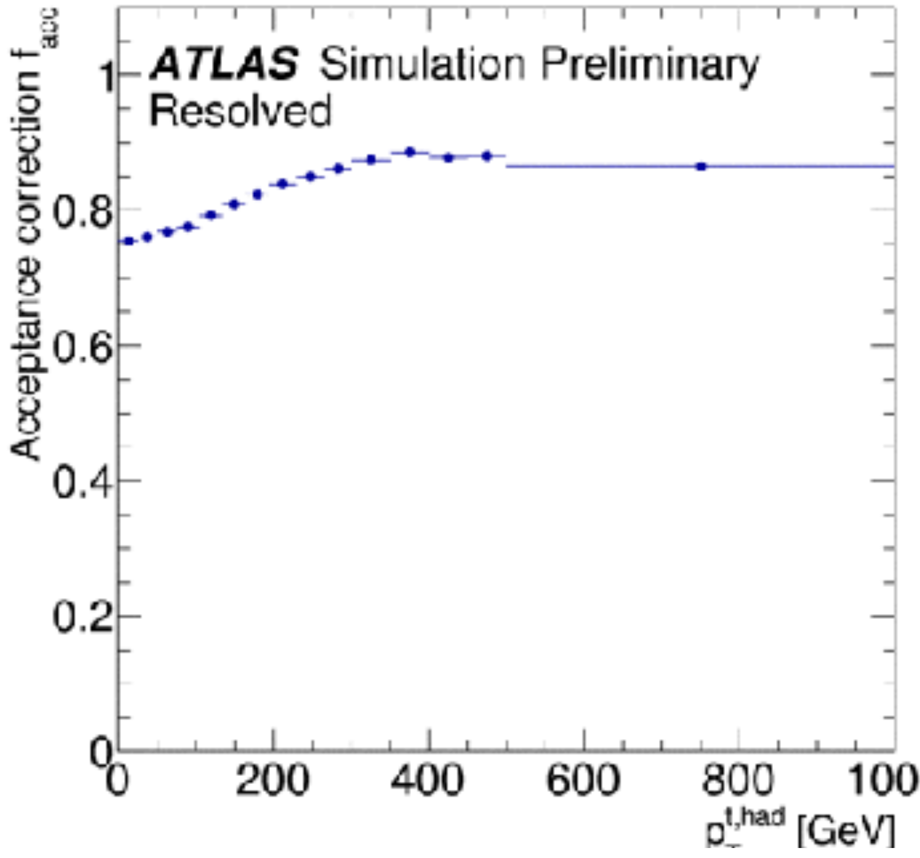
Unfolding principle

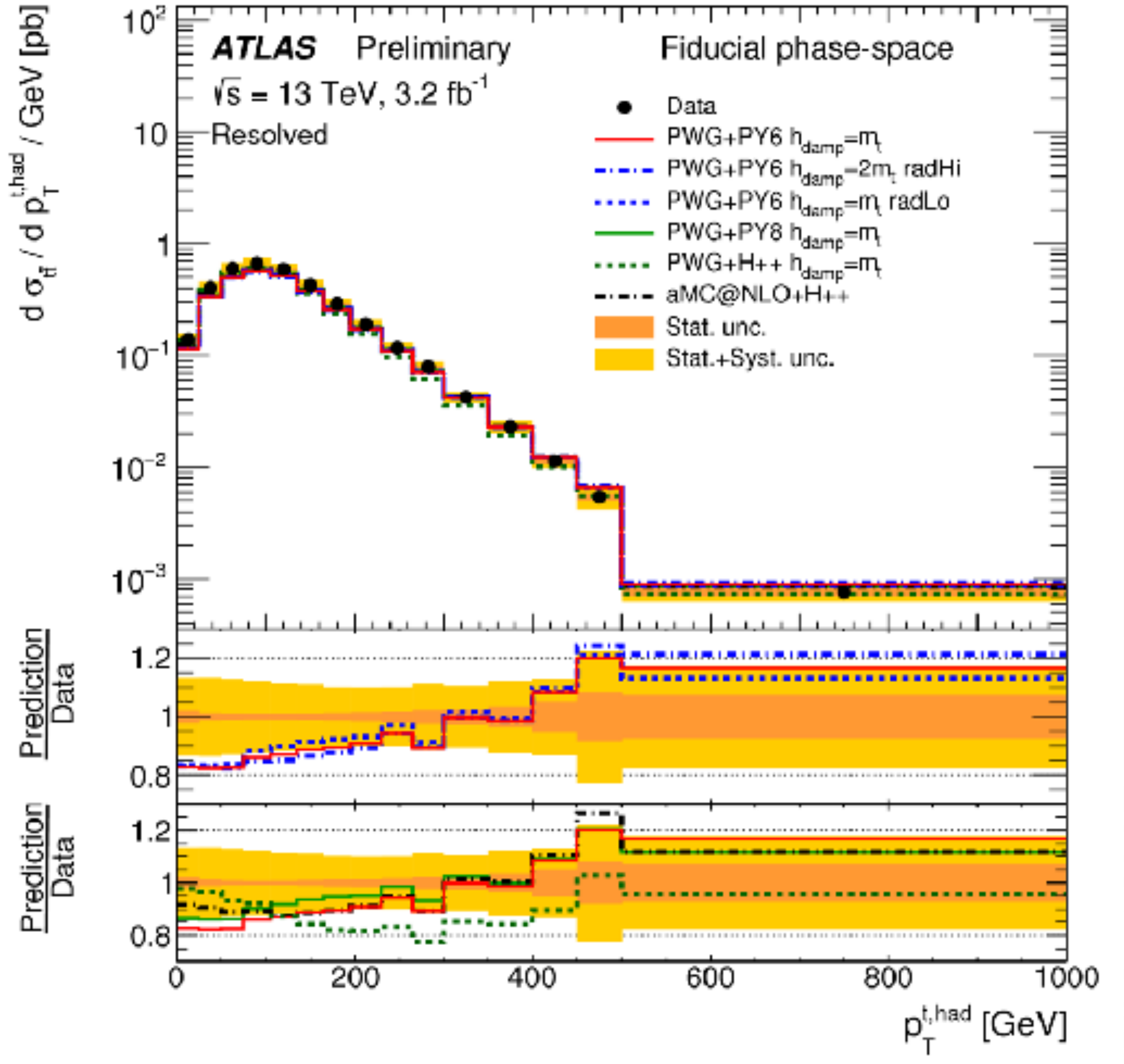
$$\frac{d\sigma^{\mathrm{fid}}}{dX^i} \equiv \frac{1}{\mathcal{L}\cdot\Delta X^i}\cdot\frac{1}{\epsilon^i}\cdot\sum_j \mathcal{M}^{-1}_{ij}\cdot f^j_{\mathrm{match}}\cdot f^j_{\mathrm{acc}}\cdot\left(N^j_{\mathrm{reco}}-N^j_{\mathrm{bg}}\right)$$

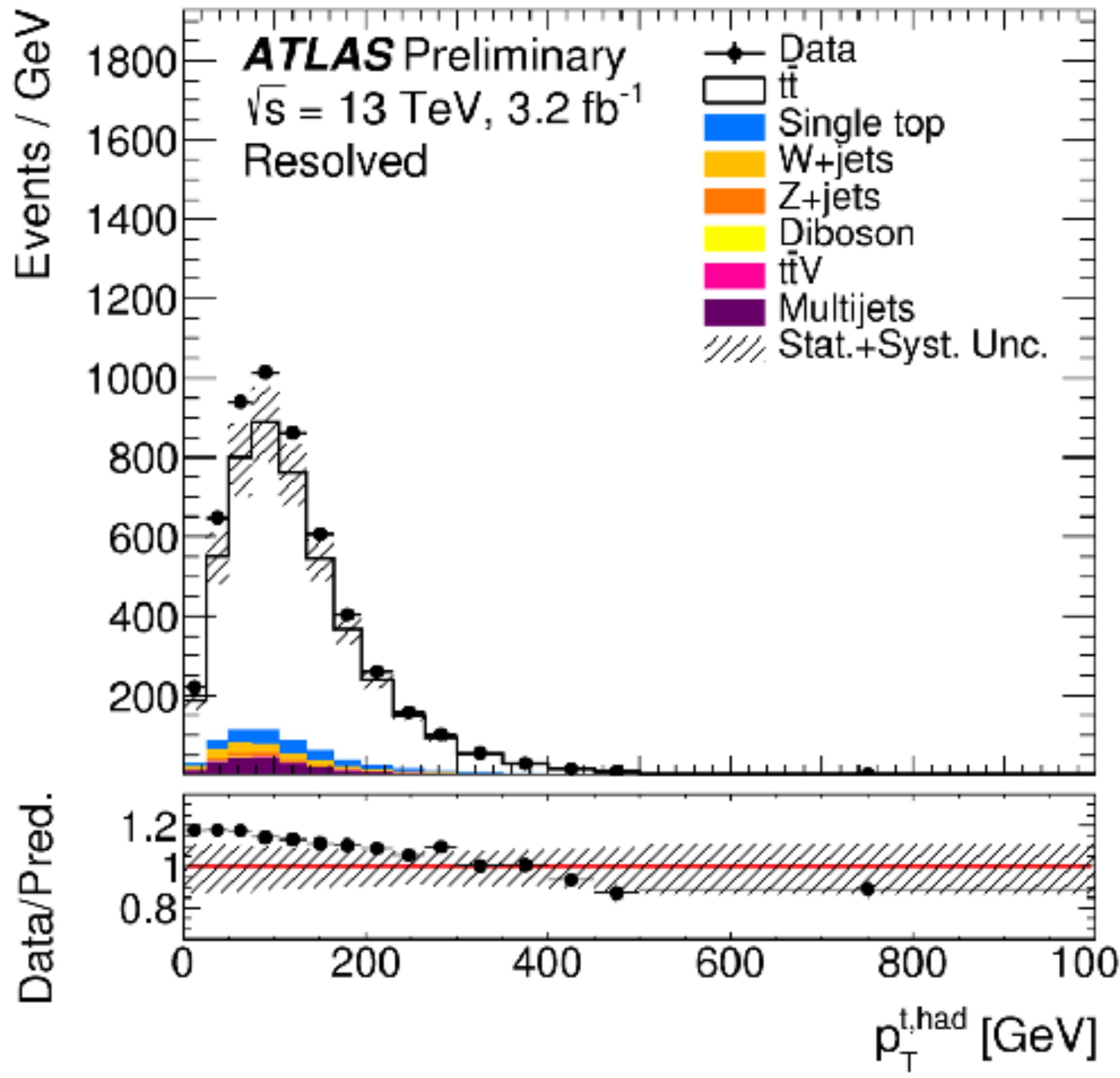






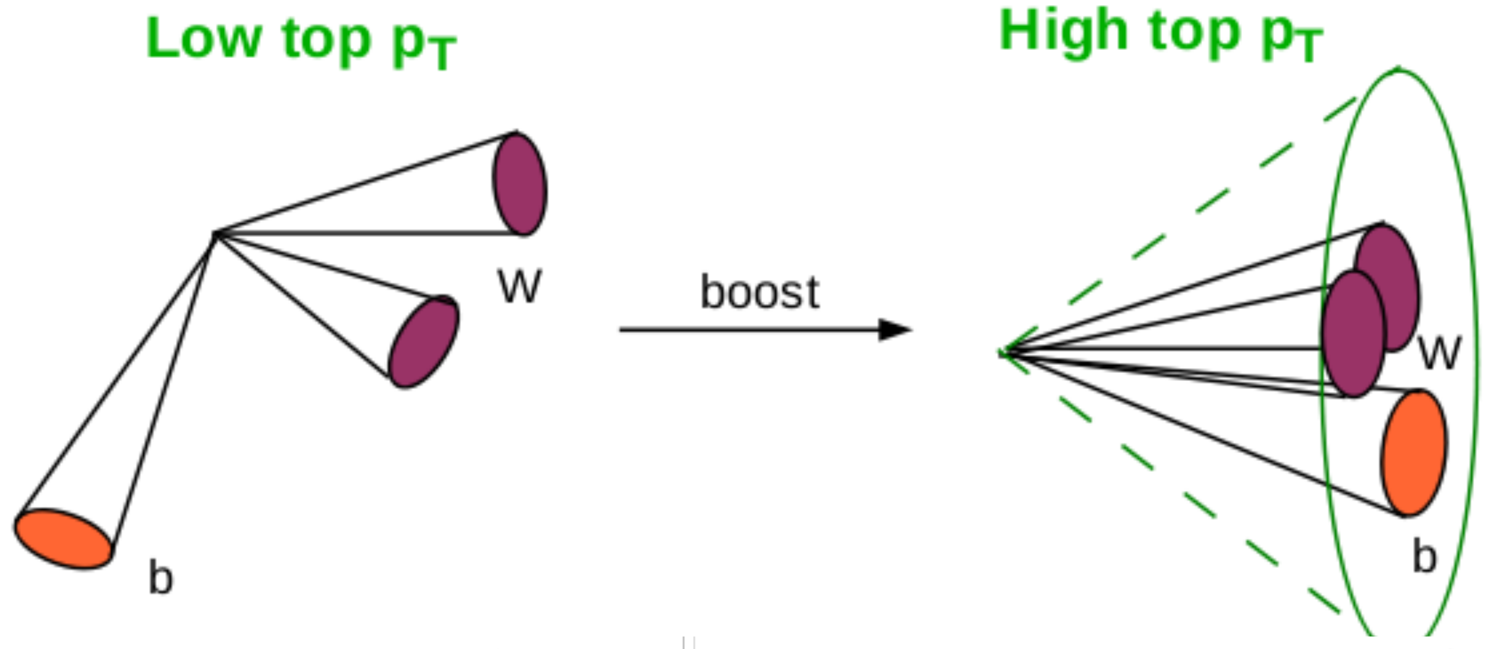


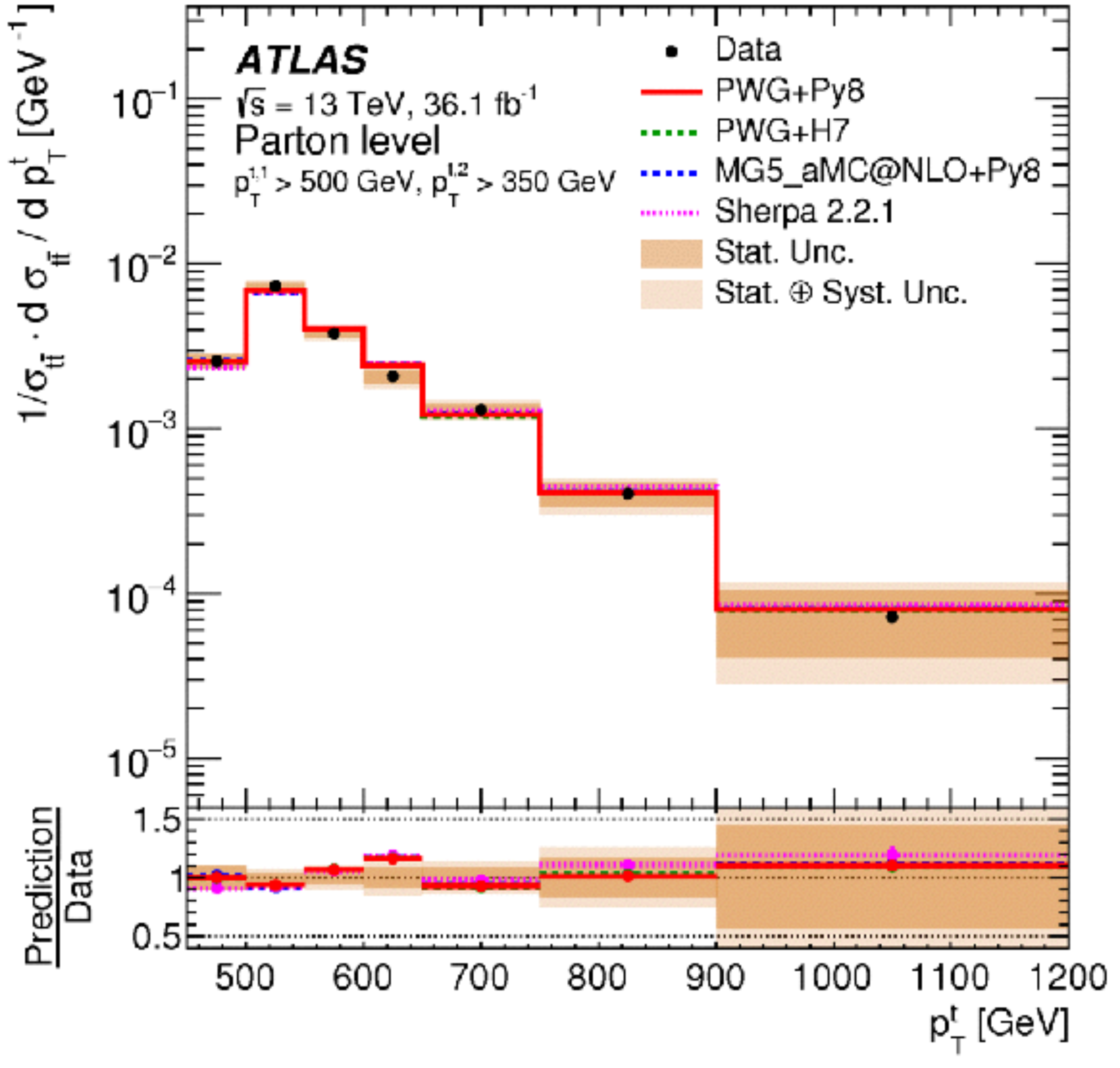


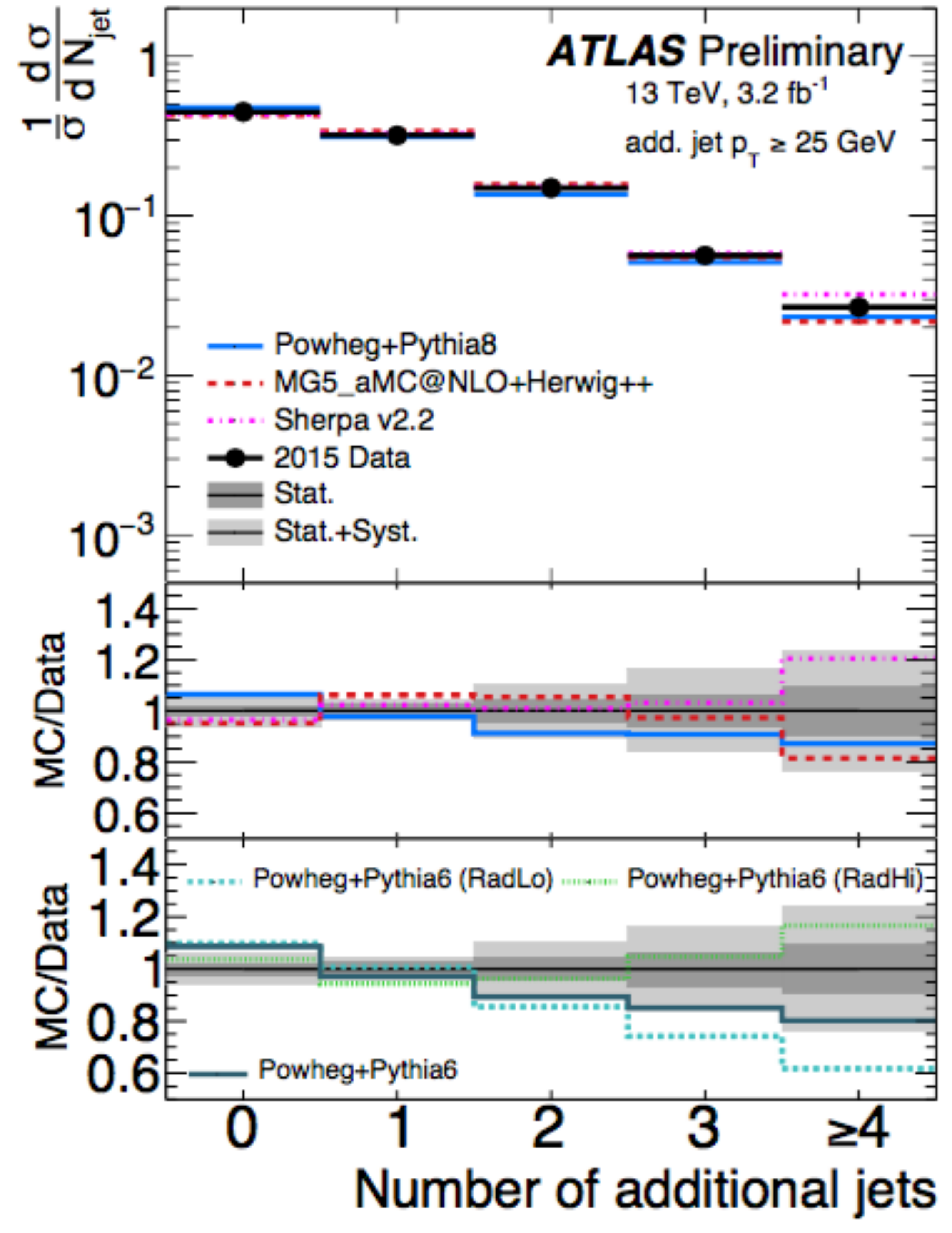


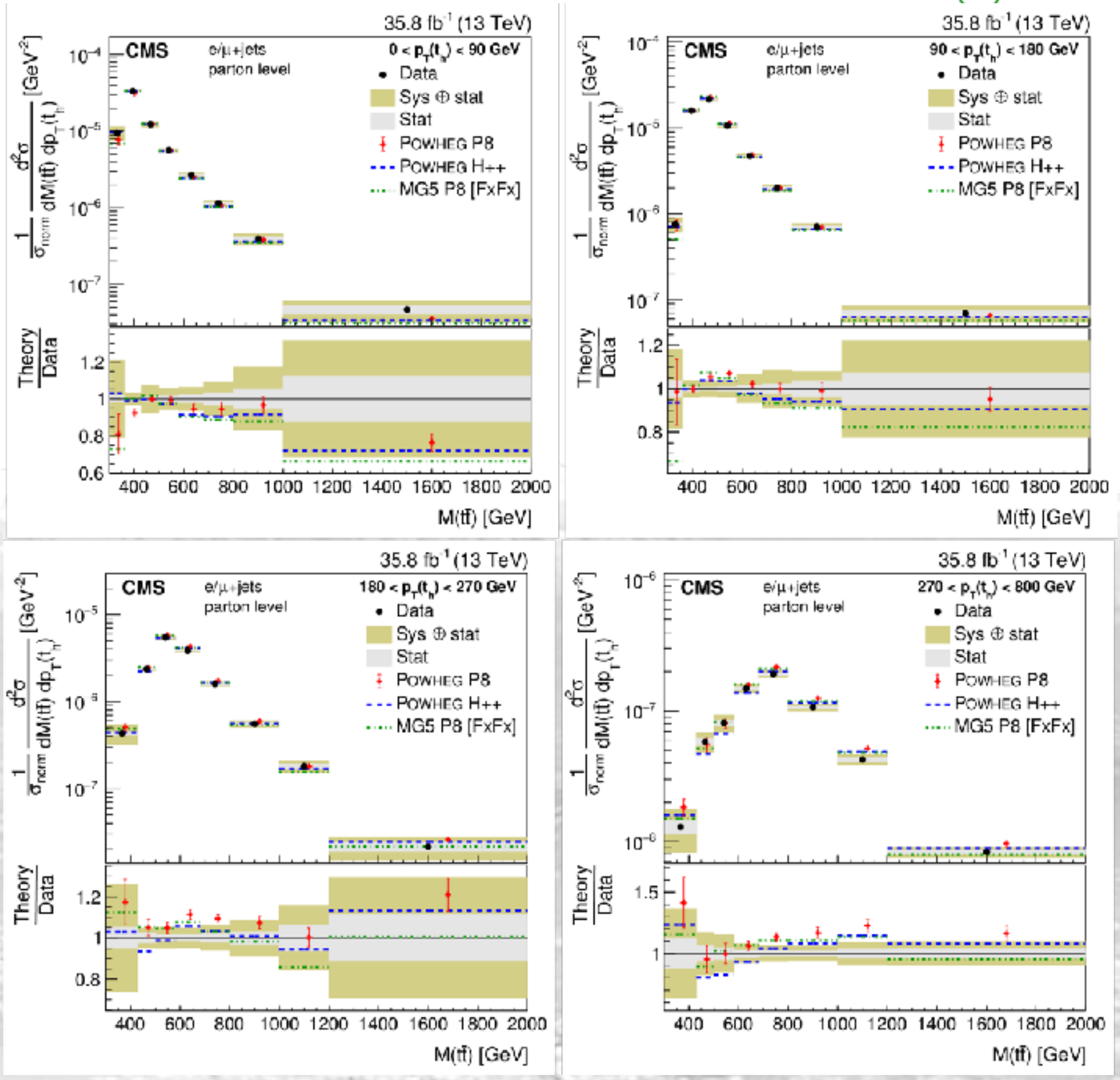
Differential $t\bar{t}$ cross section results

- Measurements in all decay channels
  - several observables sensitive to different effects (matrix element, radiation, hadronisation)
  - study the top at high momentum (boosted top)
  - double differential cross section measurements: better constrain MC by disentangling different effects, tighter constrain on PDF fit
  - $t\bar{t}$ with additional jets: constrain modelling of radiation





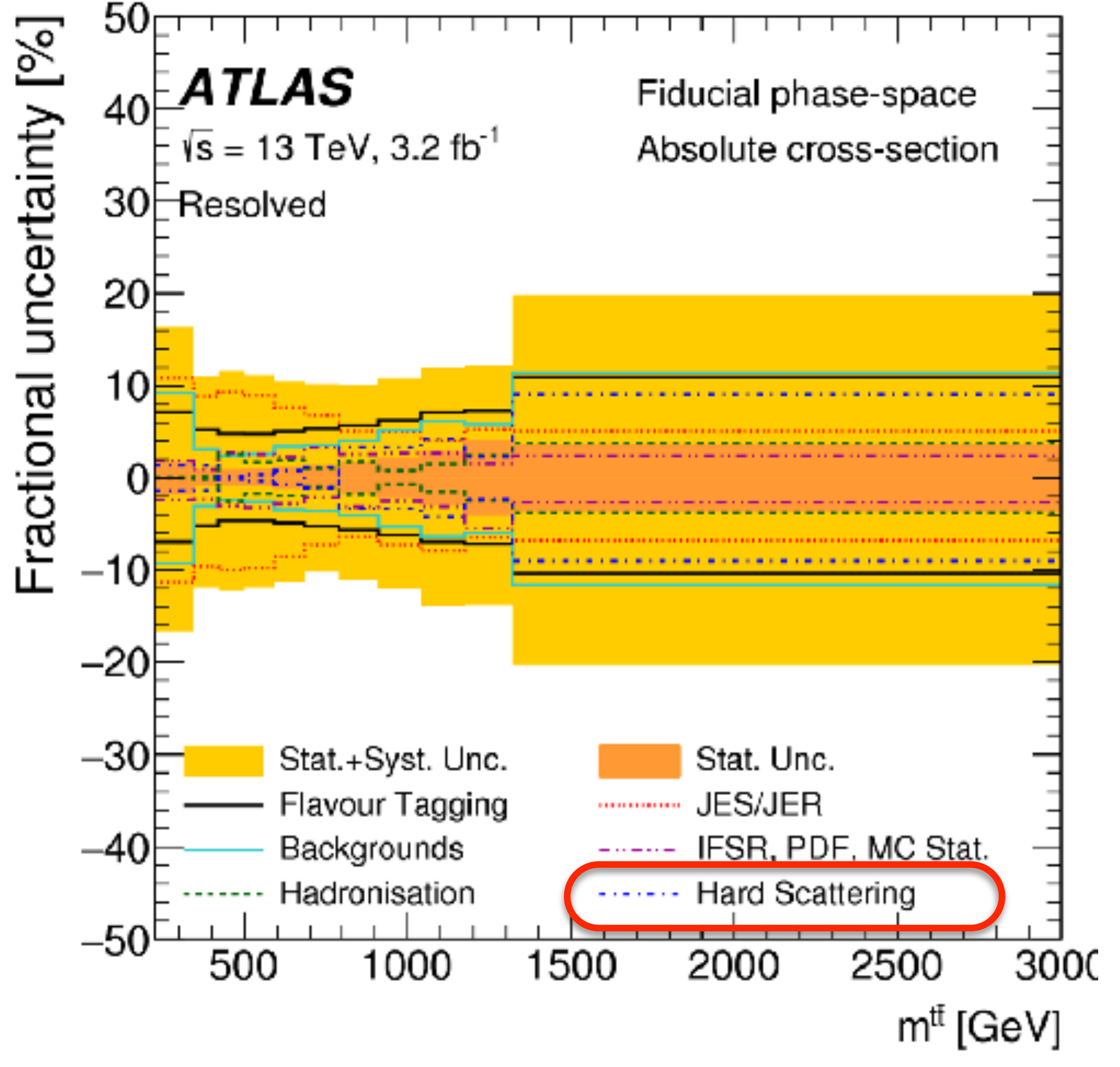


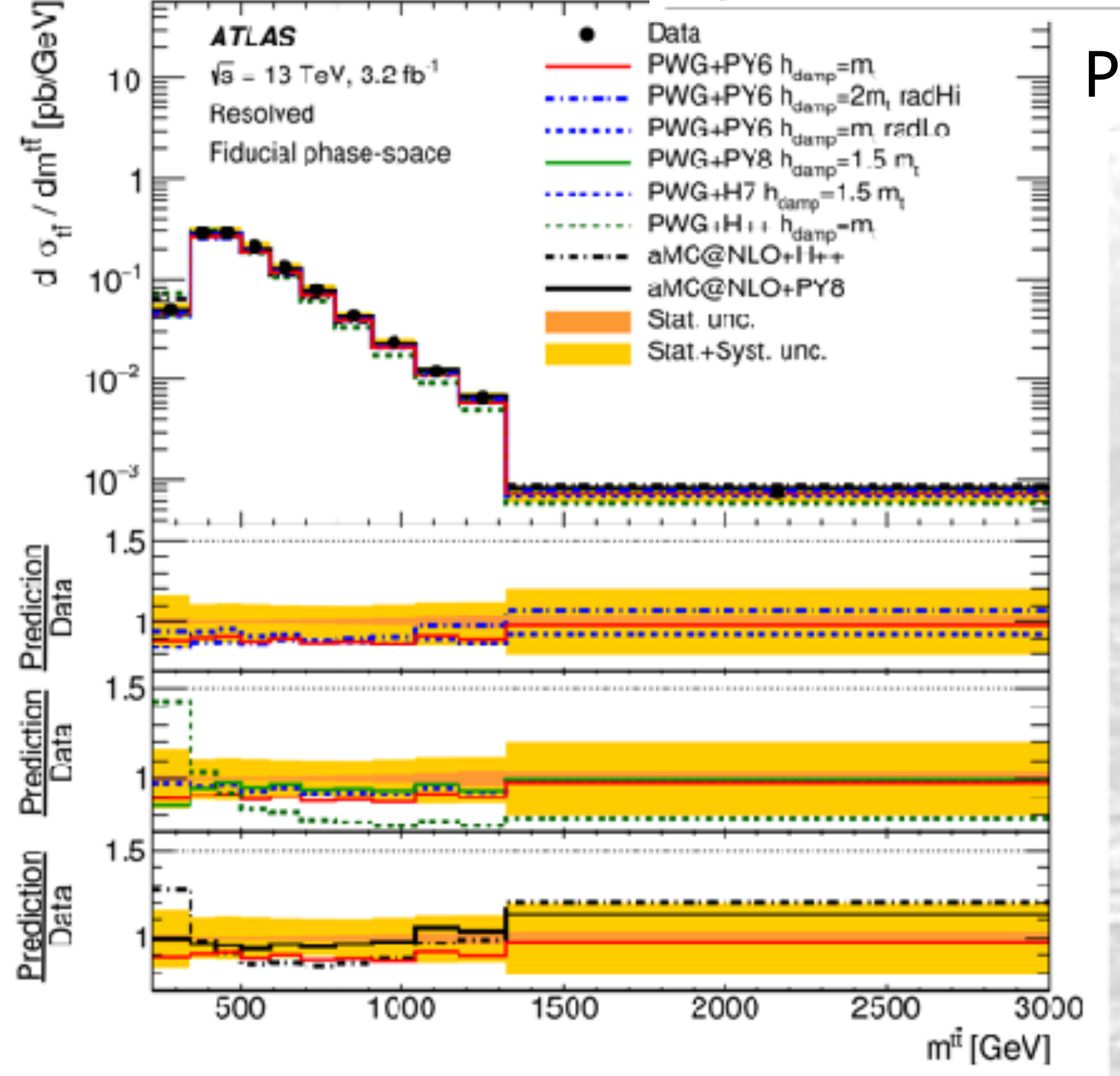


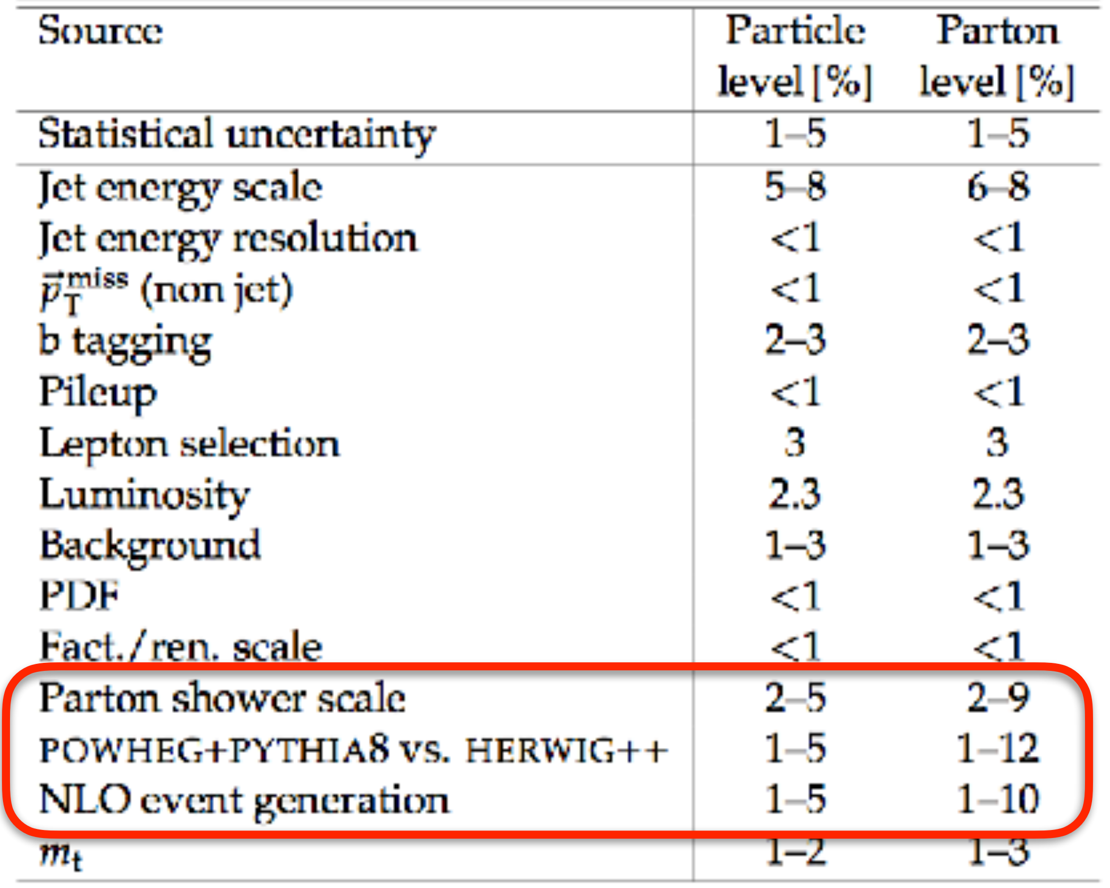
Precision $t\bar{t}$ differential cross section measurements

- $t\bar{t}$ kinematics start to be precisely studied
  - parton, particle levels, fiducial phase space, inclusive and exclusive final states
  - still ~ 15% uncertainty in the tails
  - reasonable agreement with the prediction (except for some variables)
- 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'

JHEP 11, 191 (2017)



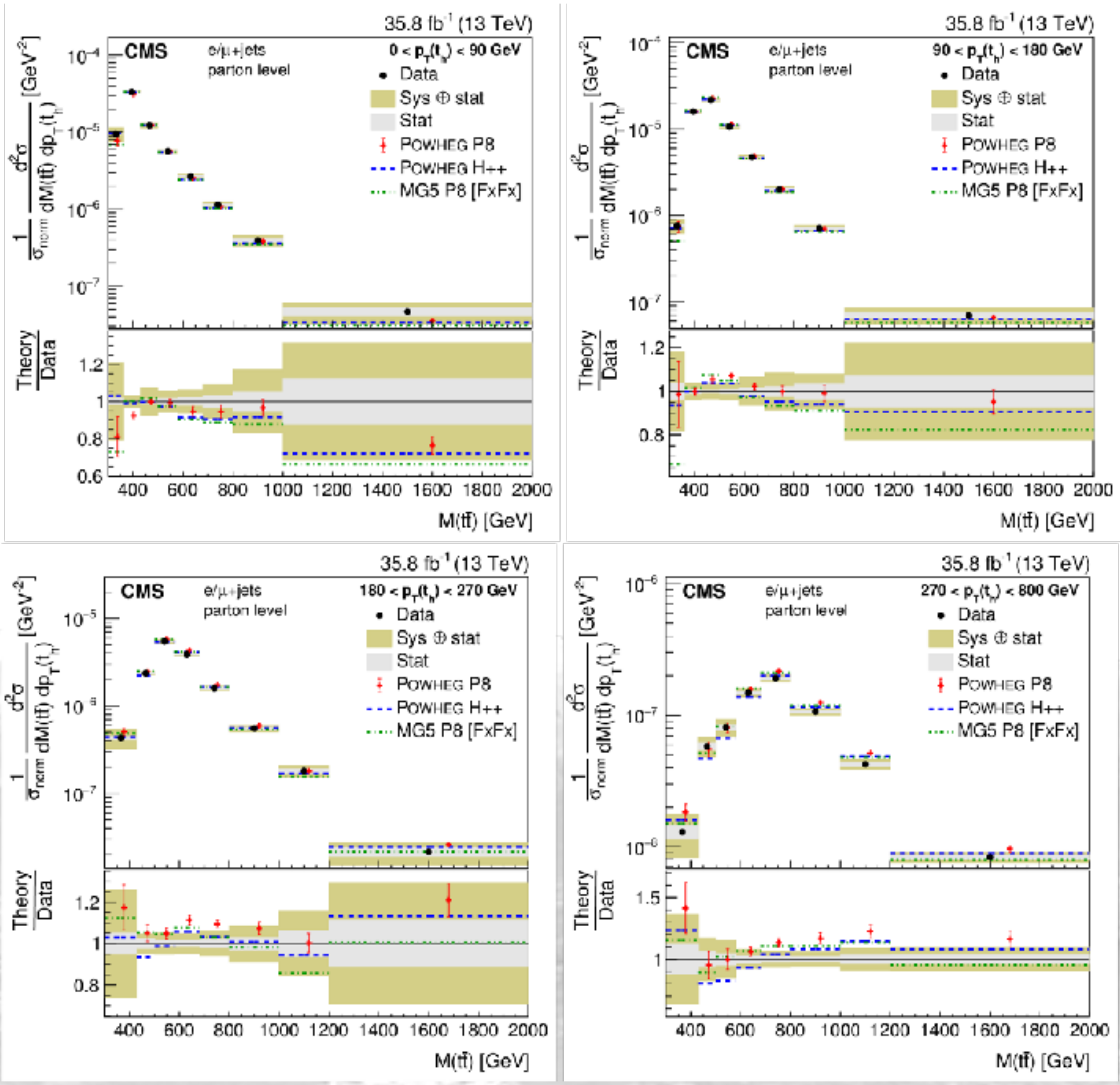




Source	Particle level [%]	Parton level [%]
Statistical uncertainty	1–5	1–5
Jet energy scale	5–8	6–8
Jet energy resolution	<1	<1
$\vec{p}_T^{miss}$ (non jet)	<1	<1
b tagging	2–3	2–3
Pileup	<1	<1
Lepton selection	3	3
Luminosity	2.3	2.3
Background	1–3	1–3
PDF	<1	<1
Fact./ren. scale	<1	<1
Parton shower scale	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)

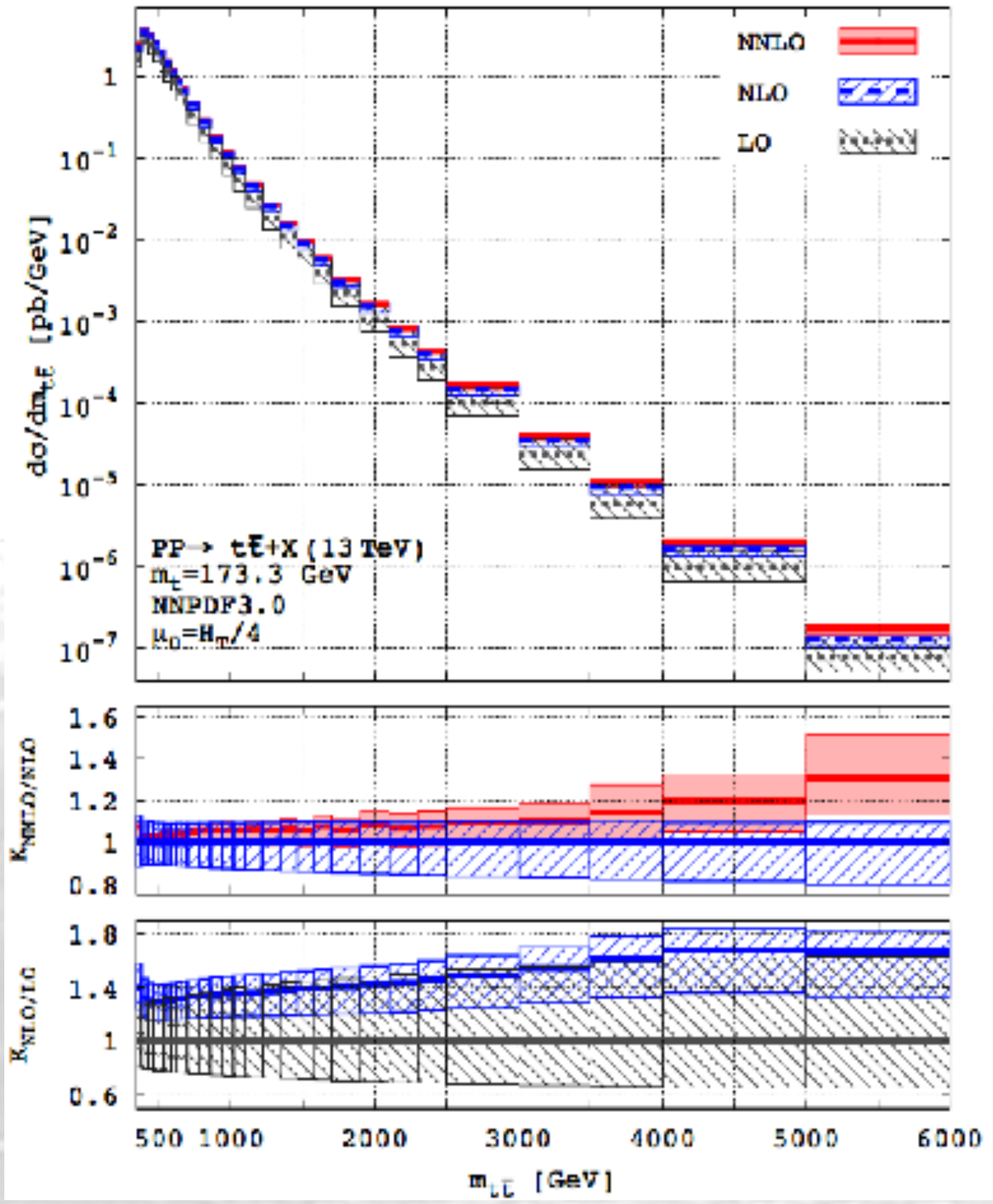
arXiv:1803.08856



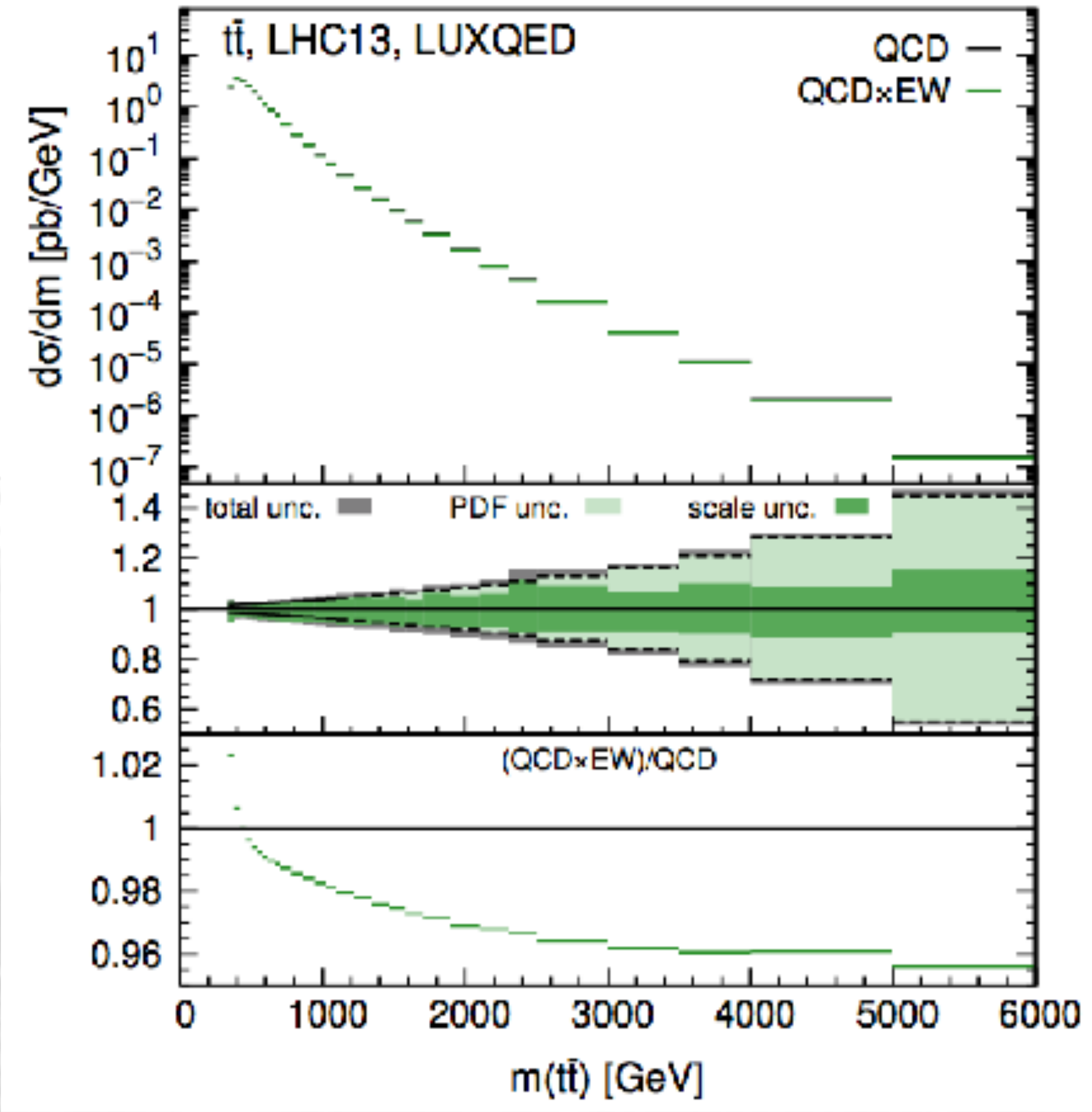
$t\bar{t}$ differential cross section predictions

- 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

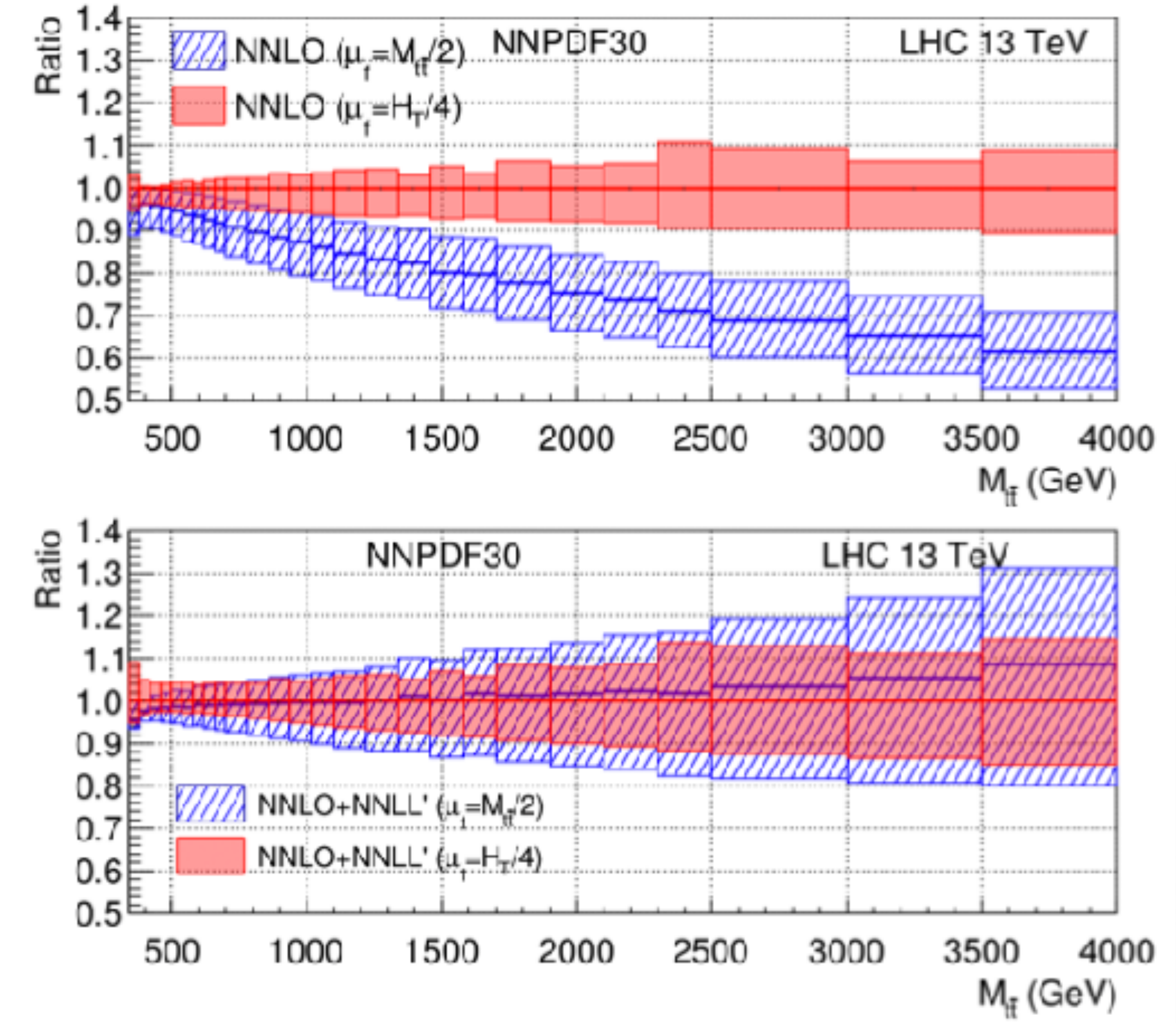
Czakon, Heymes, Mitov, JHEP 1704, 071 (2017)



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



Czakon et al., in preparation



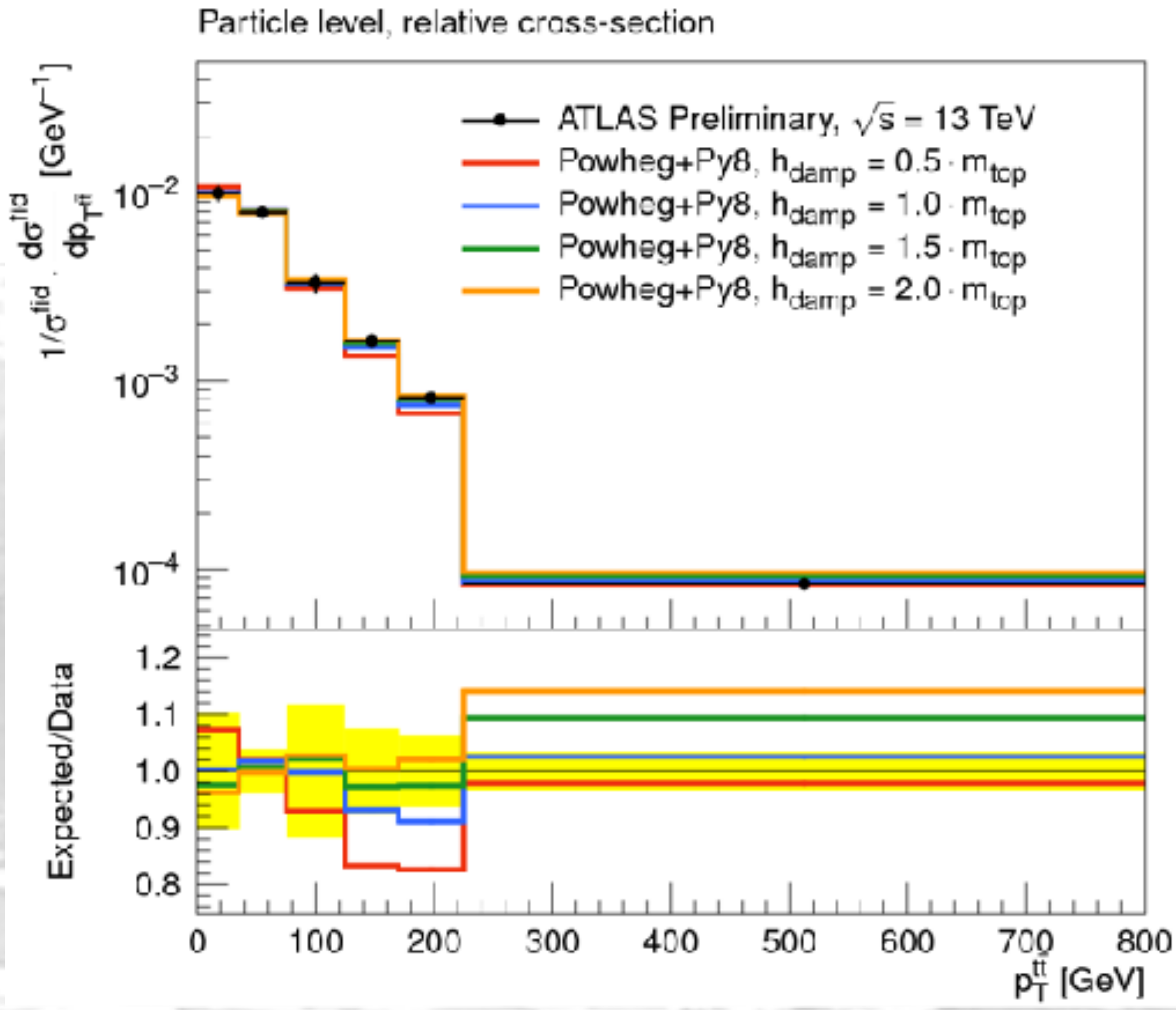
Large future applications for LHC data (PDF global fit, …)
Need to be compared with experimental measurements and implemented in public tools (on-going)
Further work on going to move from predictions with stable top (narrow width approximation, off-shell effects)

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

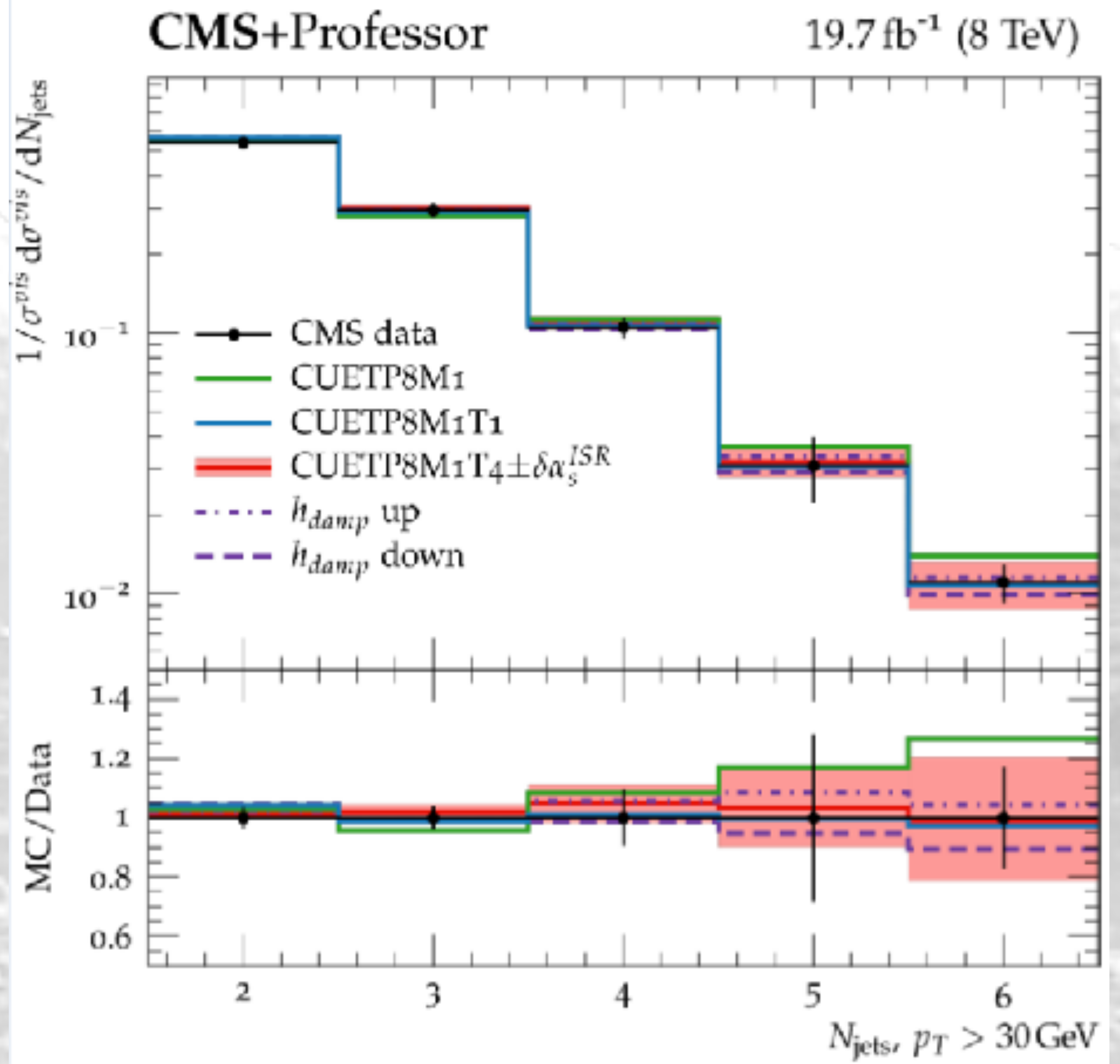
- baseline $t\bar{t}$ MC in both ATLAS and CMS: Powheg+Pythia8
  - optimisation of the central parameters (hdamp, alphaS): just looking at the varied distributions or using the Professor toolkit
  - reach setup with consistent parameters

ATL-PHYS-PUB-2016-020



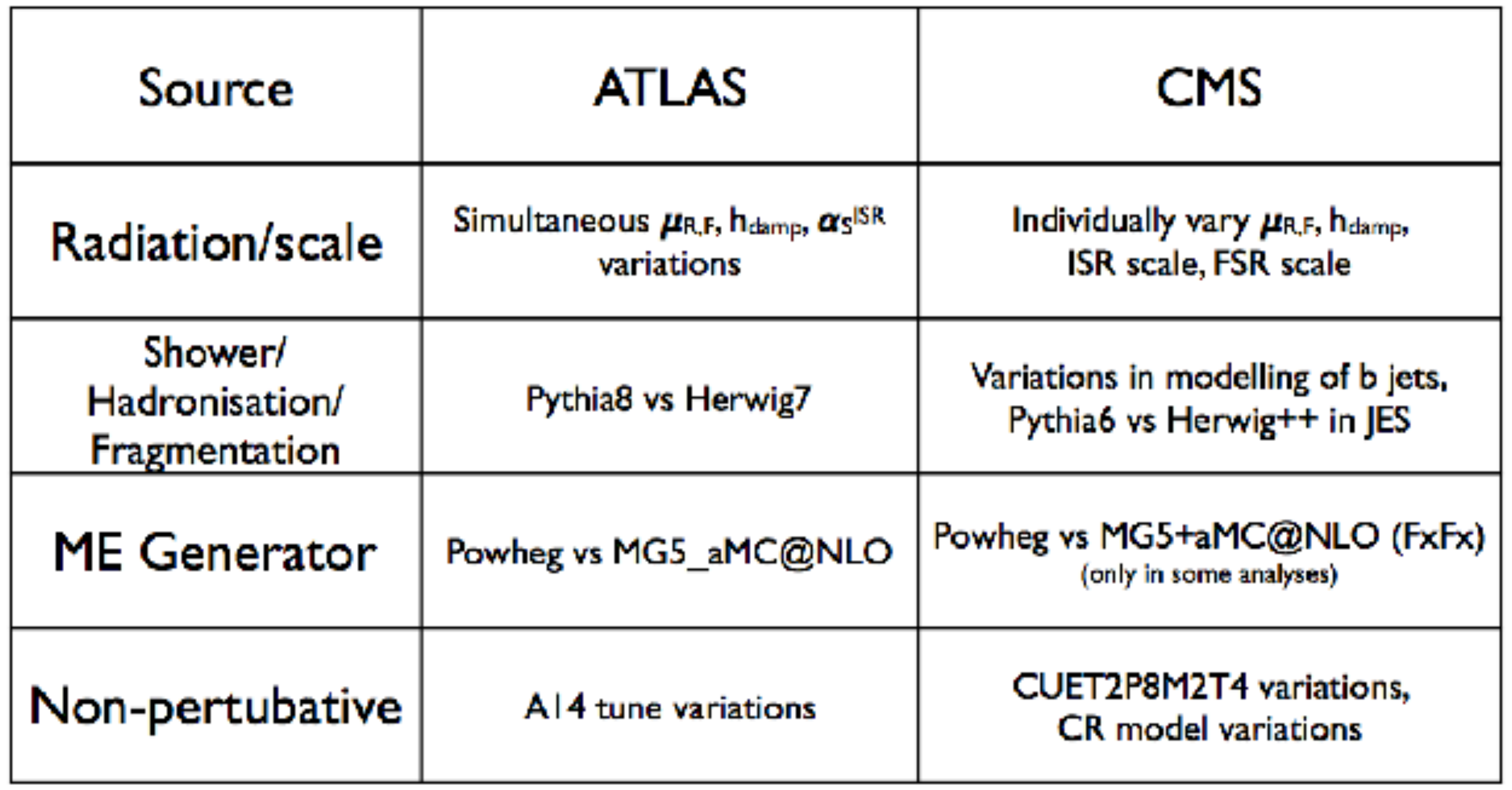
CMS-PAS-TOP-16-021

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



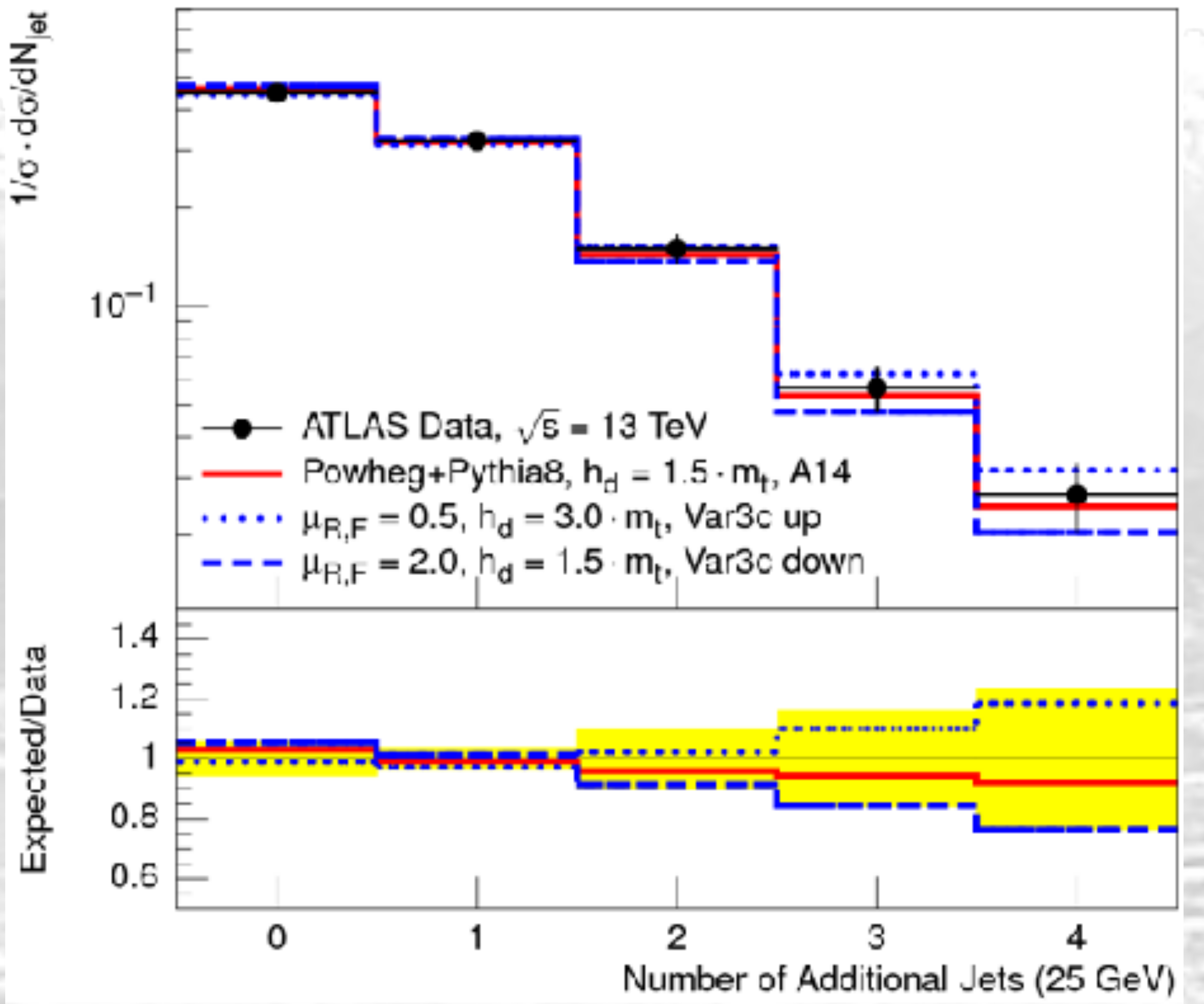
Top modelling and tuning (2)

- 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
- 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, …
  - more involved generators: NLO multileg $t\bar{t}$+0,1,2j @NLO
  - essential to have measurements in the top sector to constrain the models : underline event, colour reconnection, Wt-$t\bar{t}$ interference, $t\bar{t}$+heavy flavour

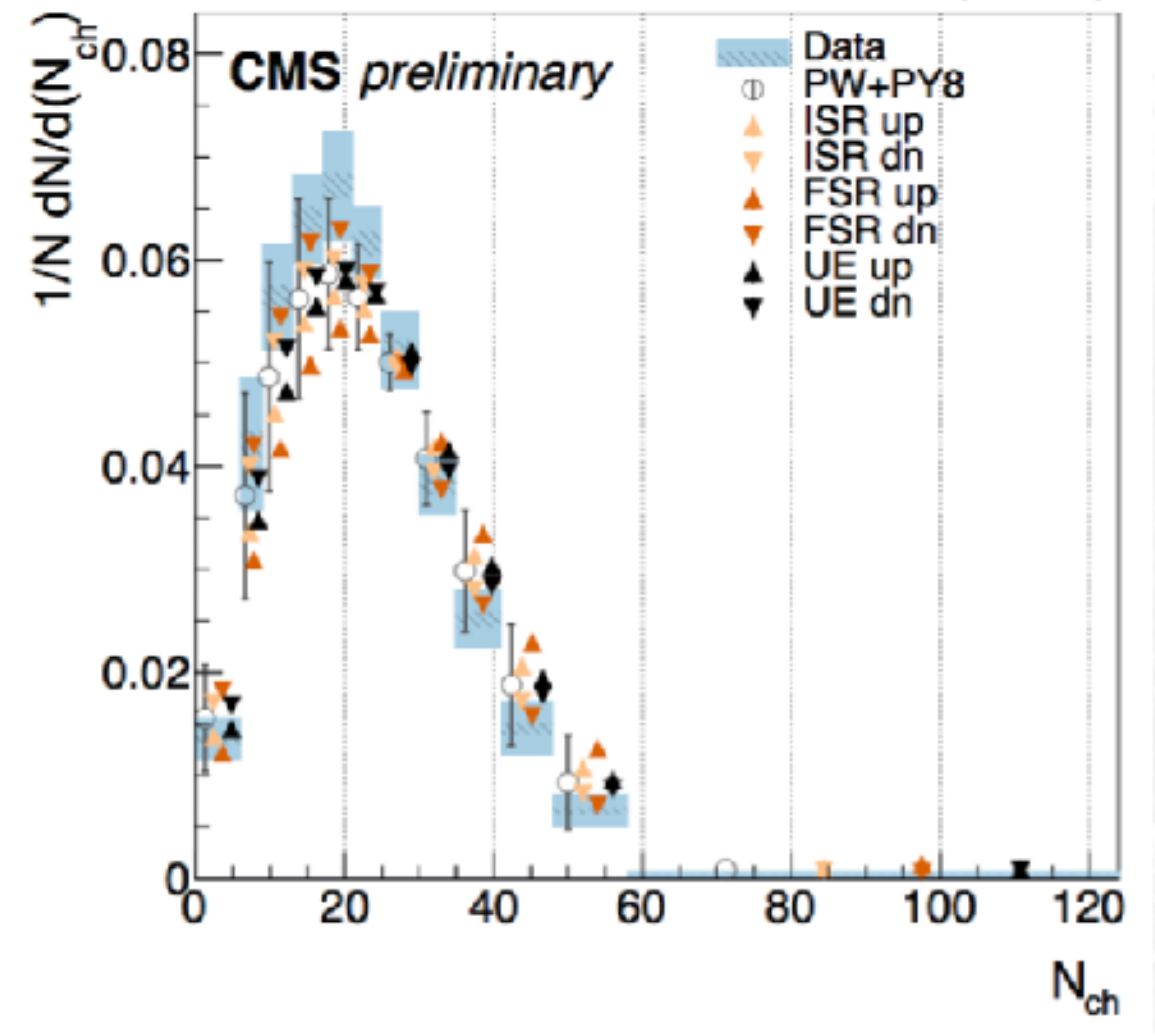


Source	ATLAS	CMS
Radiation/scale	Simultaneous $\mu_{R,F}$, h_{damp}, α_s^{ISR} variations	Individually vary $\mu_{R,F}$, h_{damp}, ISR scale, FSR scale
Shower/ Hadronisation/ Fragmentation	Pythia8 vs Herwig7	Variations in modelling of b jets, Pythia6 vs Herwig++ in JES
ME Generator	Powheg vs MG5_aMC@NLO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

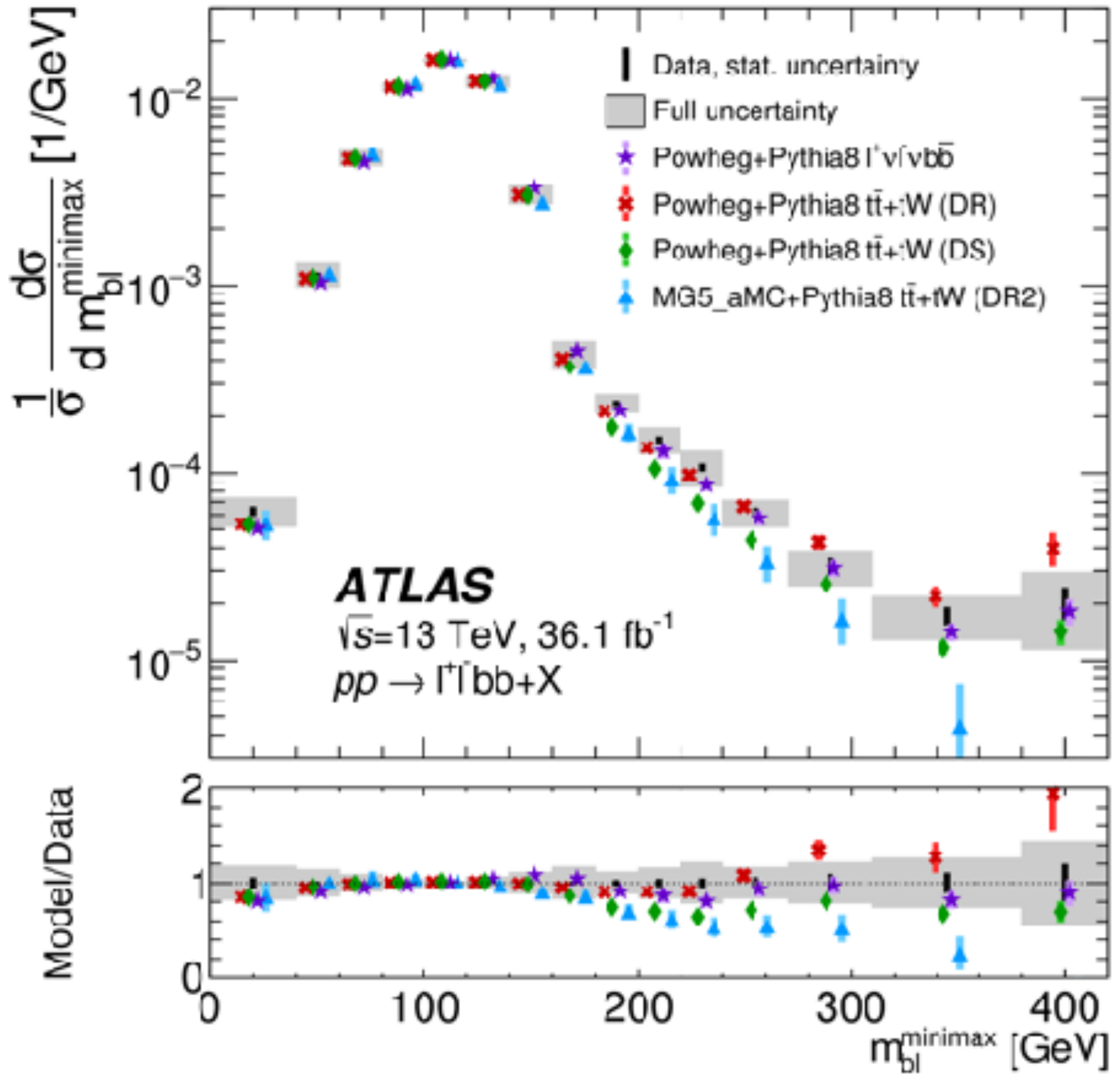
ATL-PHYS-PUB-2017-007



CMS PAS TOP-17-015

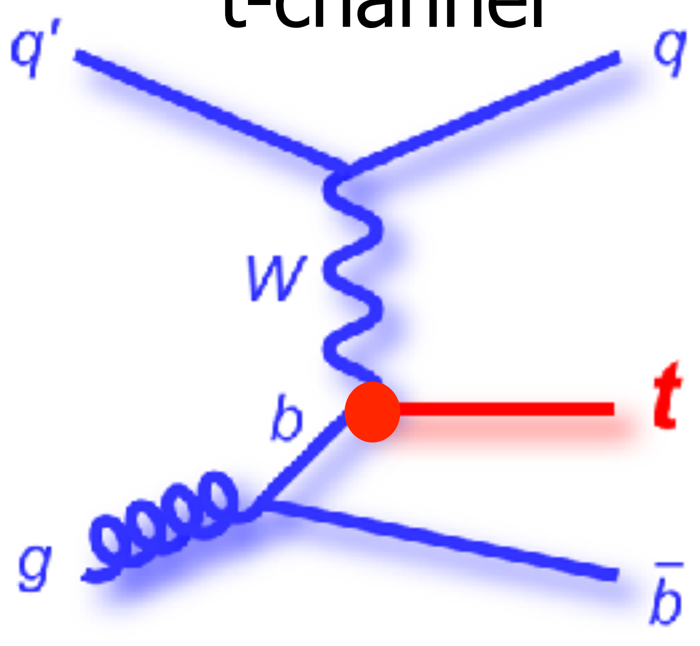


arXiv:1806.04667

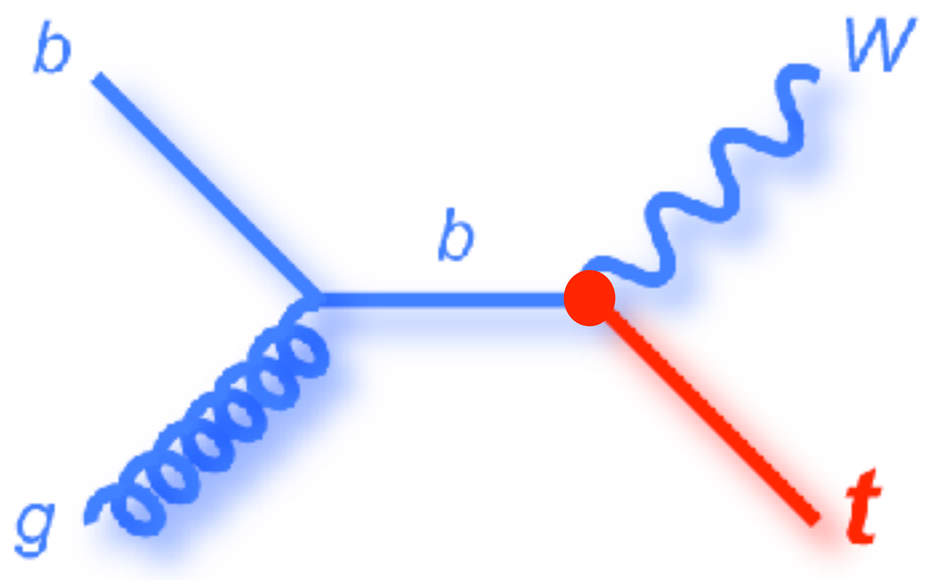


Single top production

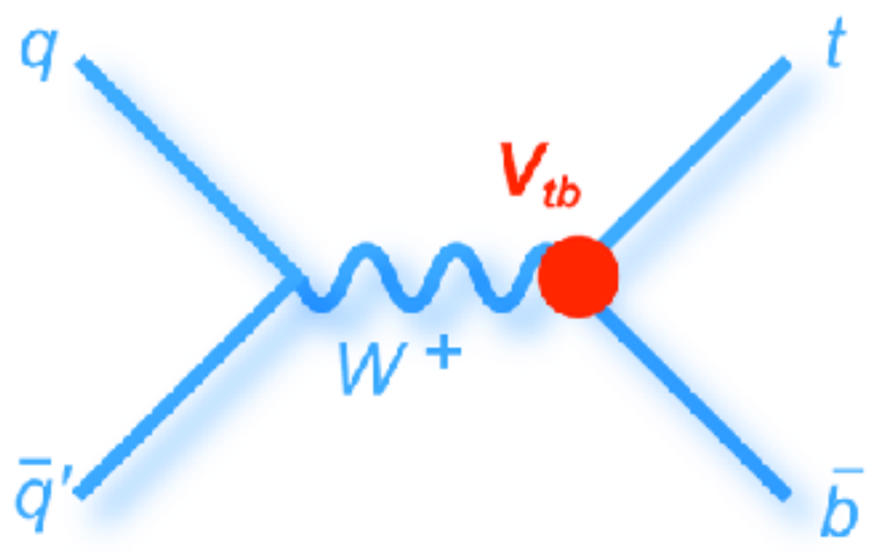
t-channel



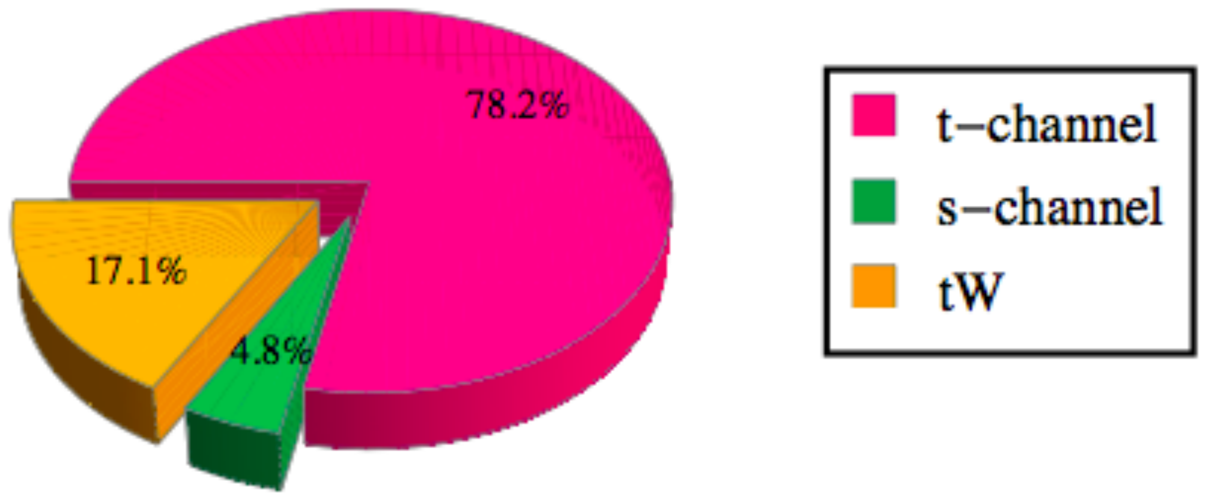
tW-channel



s-channel

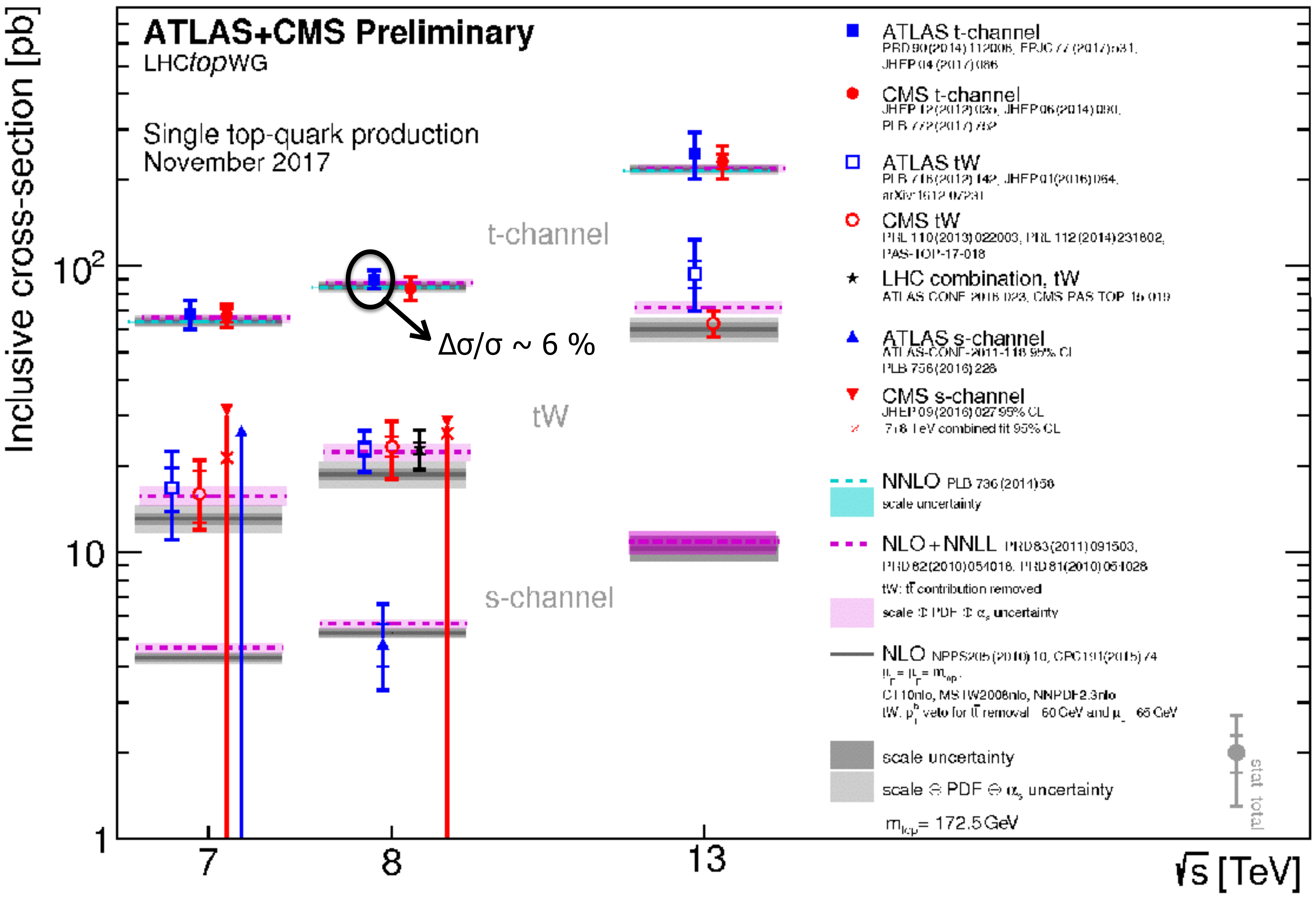


at the LHC



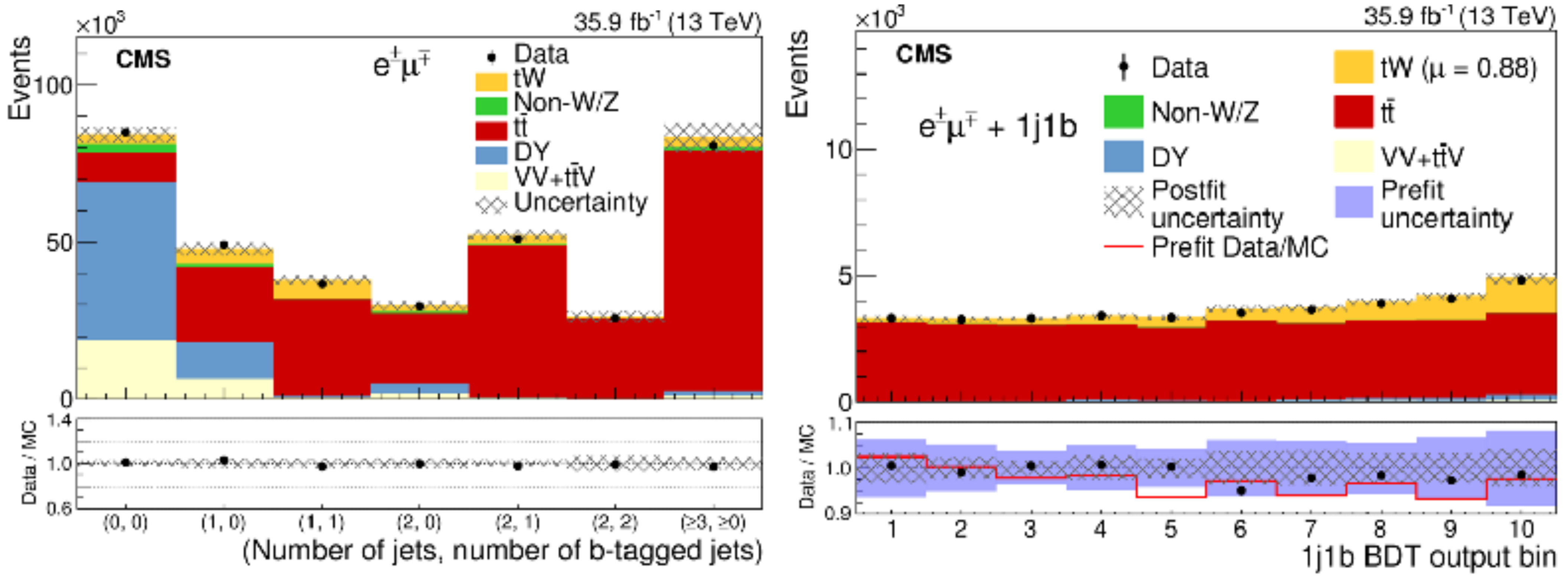
- the LHC quests
  - establish the single top signals at all energies
  - achieve precision measurements
  - move from inclusive to differential measurements

Inclusive single top cross section



$\Delta\sigma/\sigma$ ~ 6 %

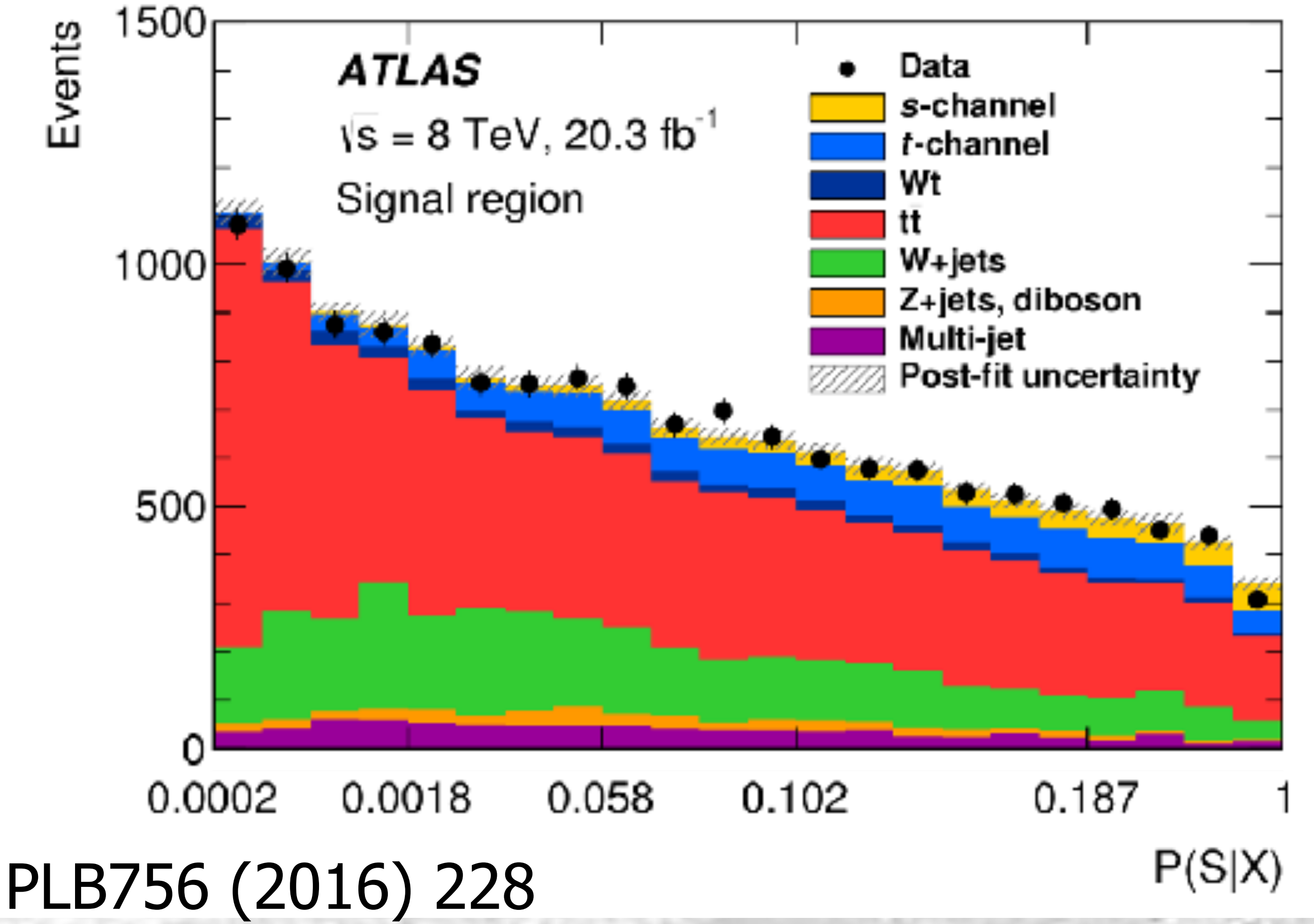
arXiv:1805.07399



$$\sigma_{tW} = 63.1 \pm 1.8\,(\text{stat}) \pm 6.4\,(\text{syst}) \pm 2.1\,(\text{lumi})\ \text{pb}$$

$\Delta\sigma/\sigma$ = 11 %
(theory prediction ~ 5%)

Evidence for s-channel production at LHC

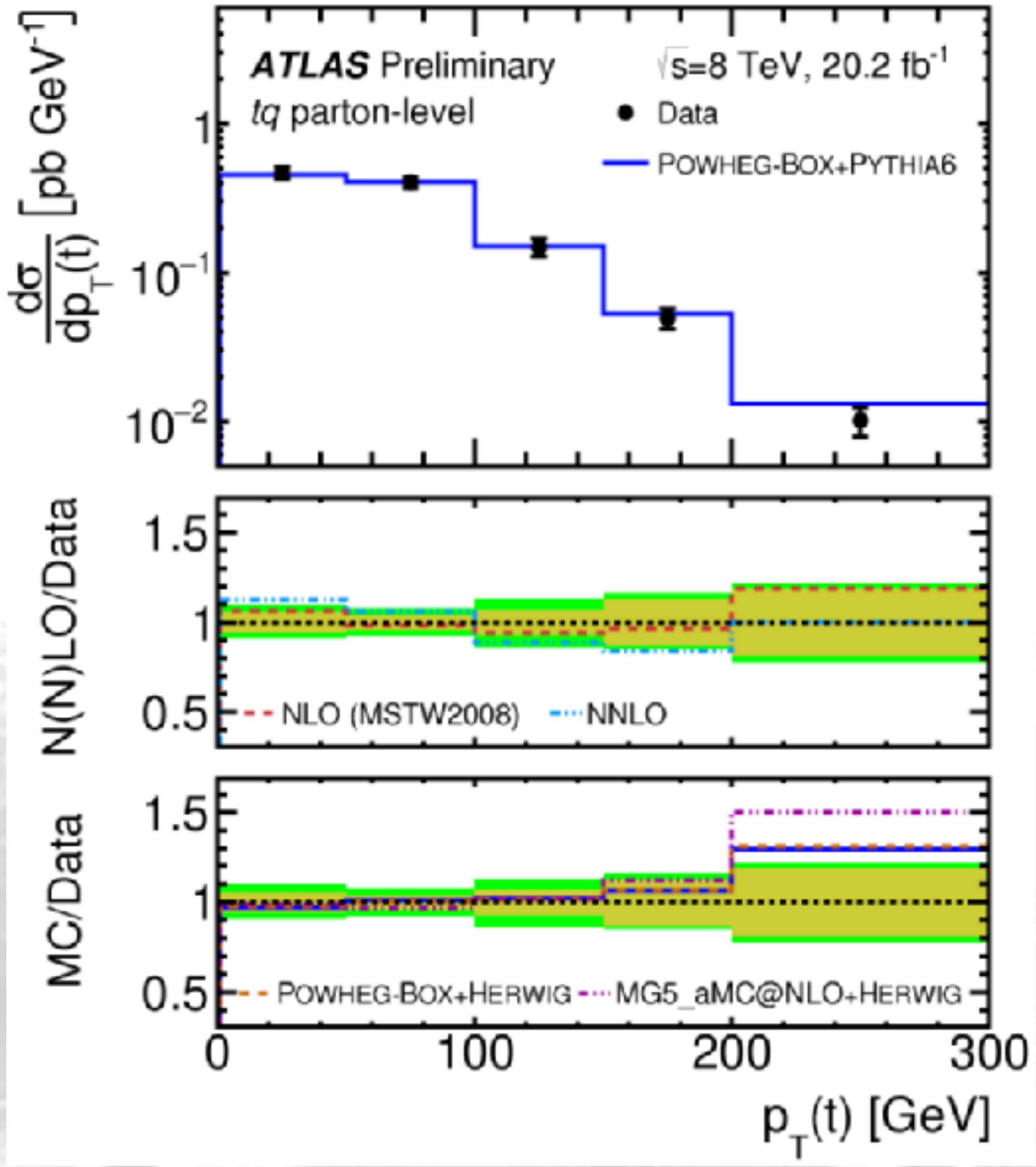


PLB756 (2016) 228

Differential single top cross section

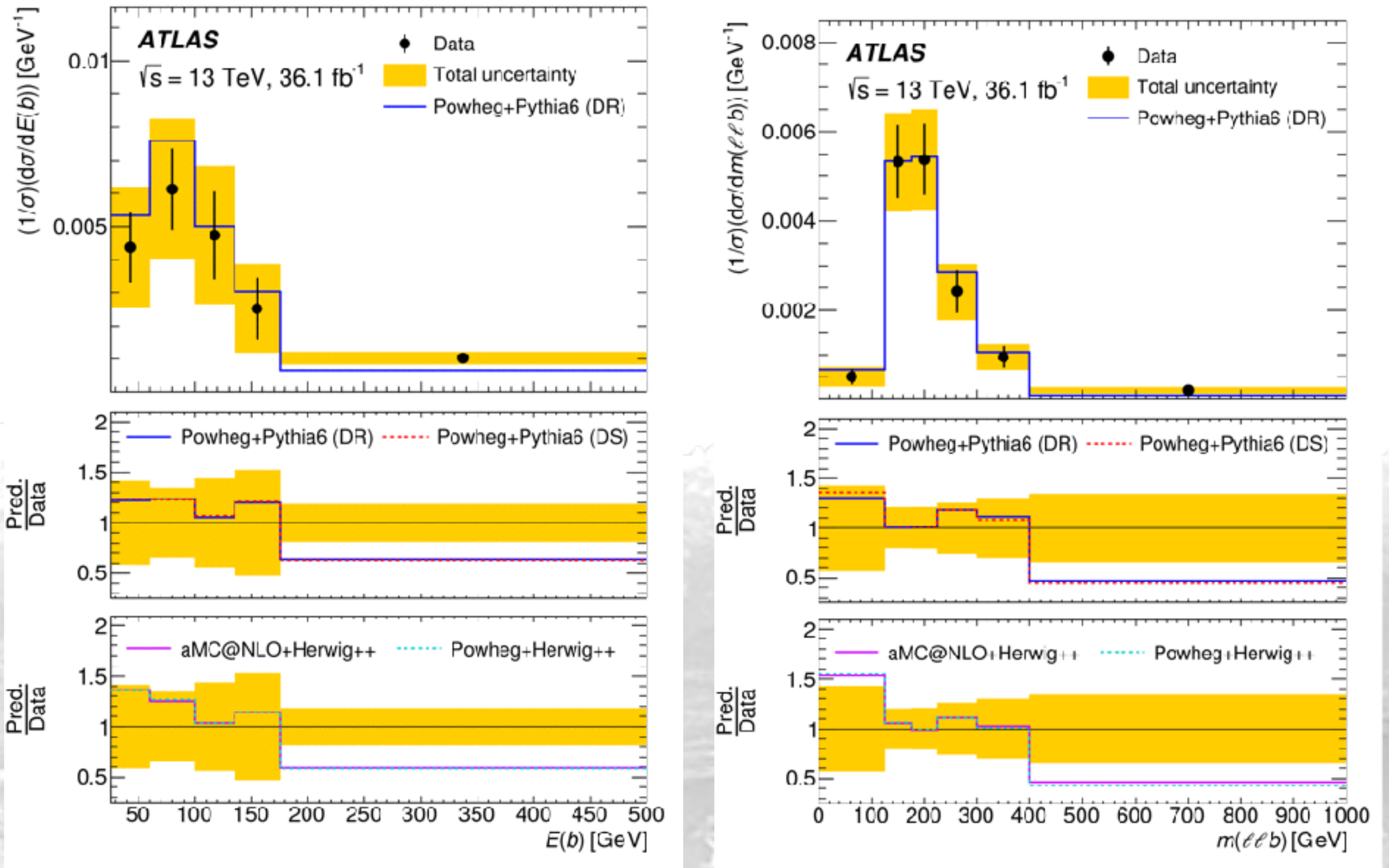
- start to be able to go differential in single top also:
  - expect to be able to use these measurements to also improve the simulation tuning

t-channel



EPJC 77 (2017) 531

tW-channel



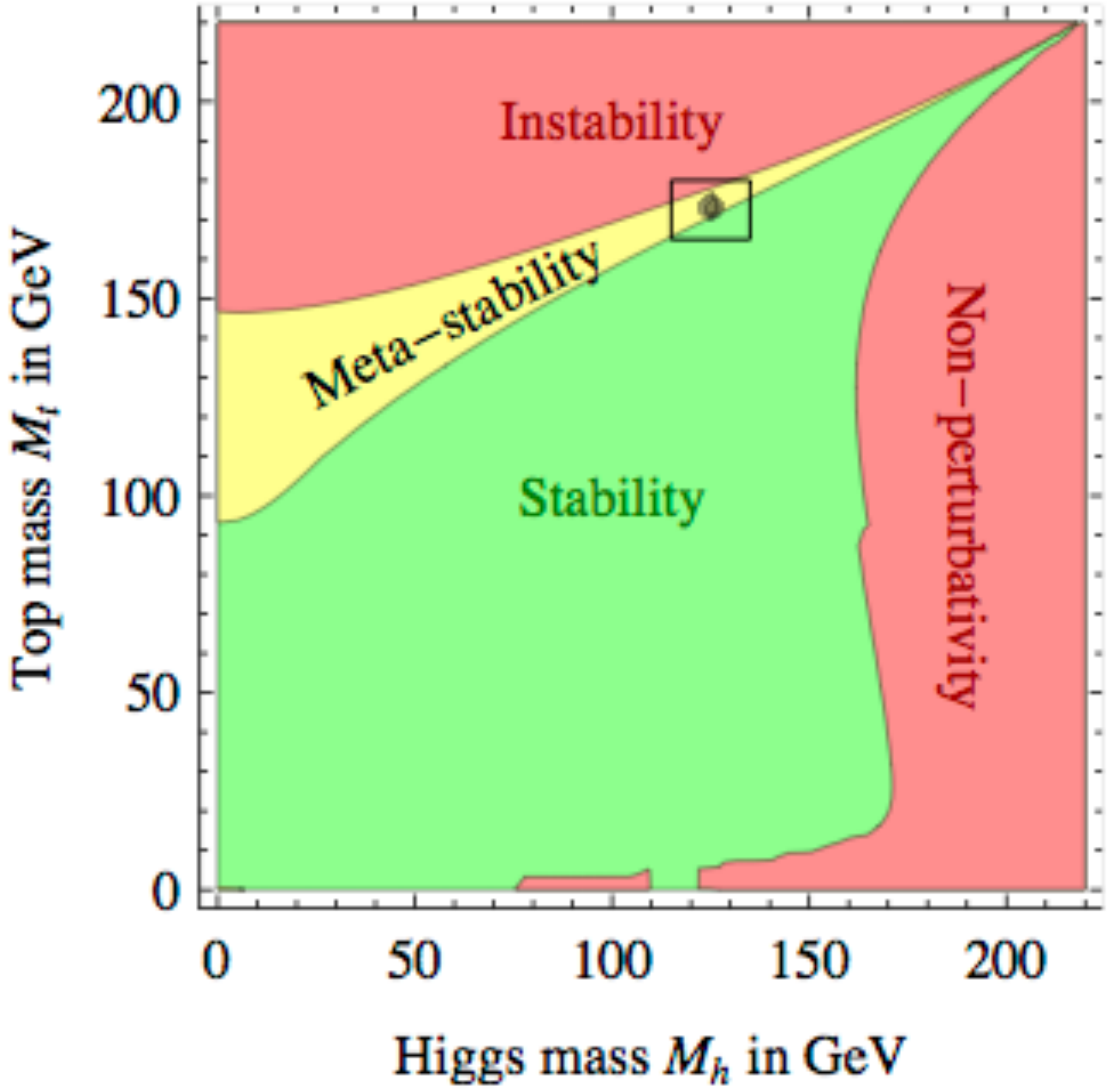
EPJC 78 (2018) 186

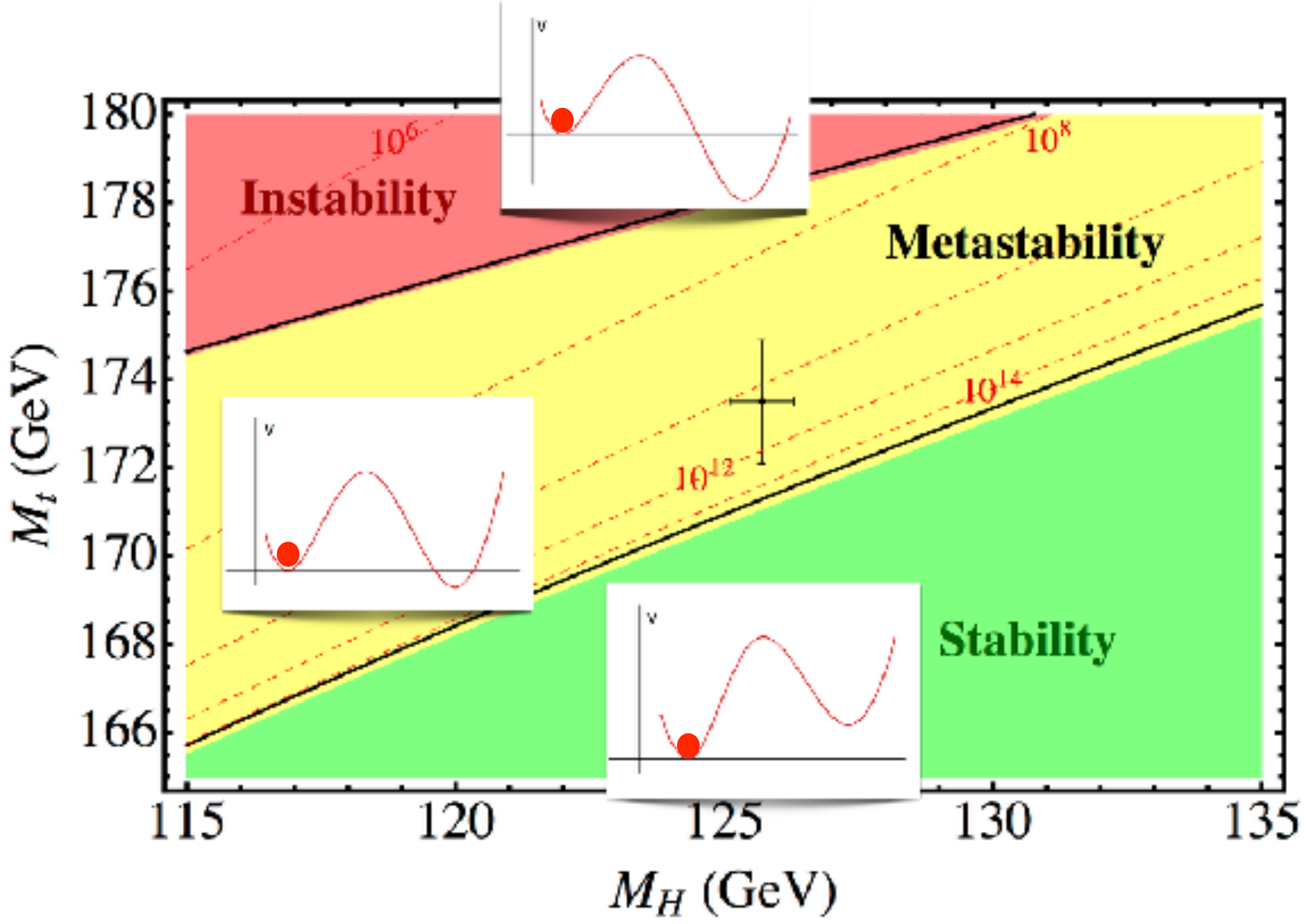
The top quark mass

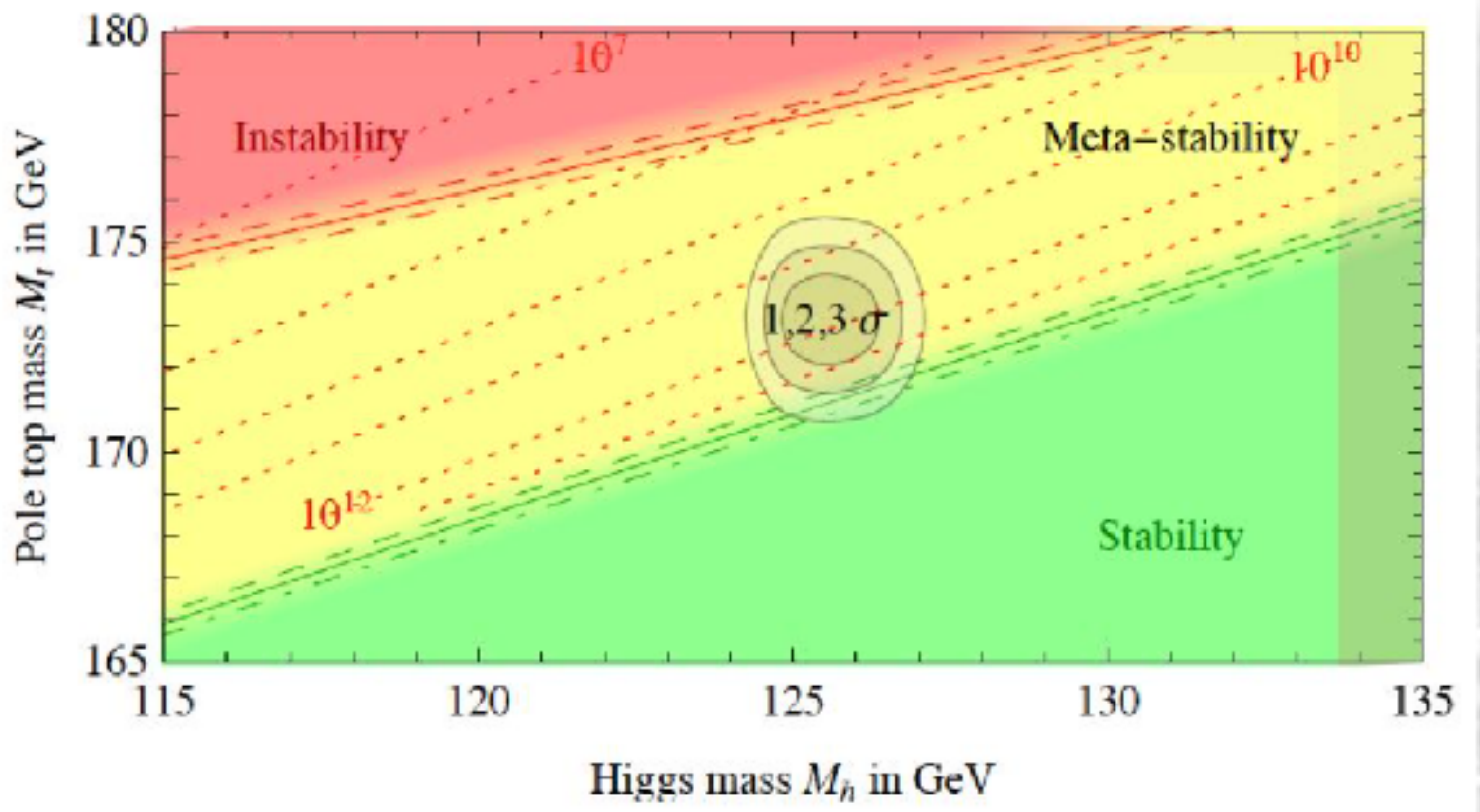
- Why do you need to precisely measure the top quark mass ?
  - compare direct measurements with electroweak fit (consistency of the Standard Model)
  - stability of the electroweak vacuum (Higgs boson quartic coupling almost vanishing at the Planck scale)
  - heaviest fermion: large contributions in radiative corrections

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

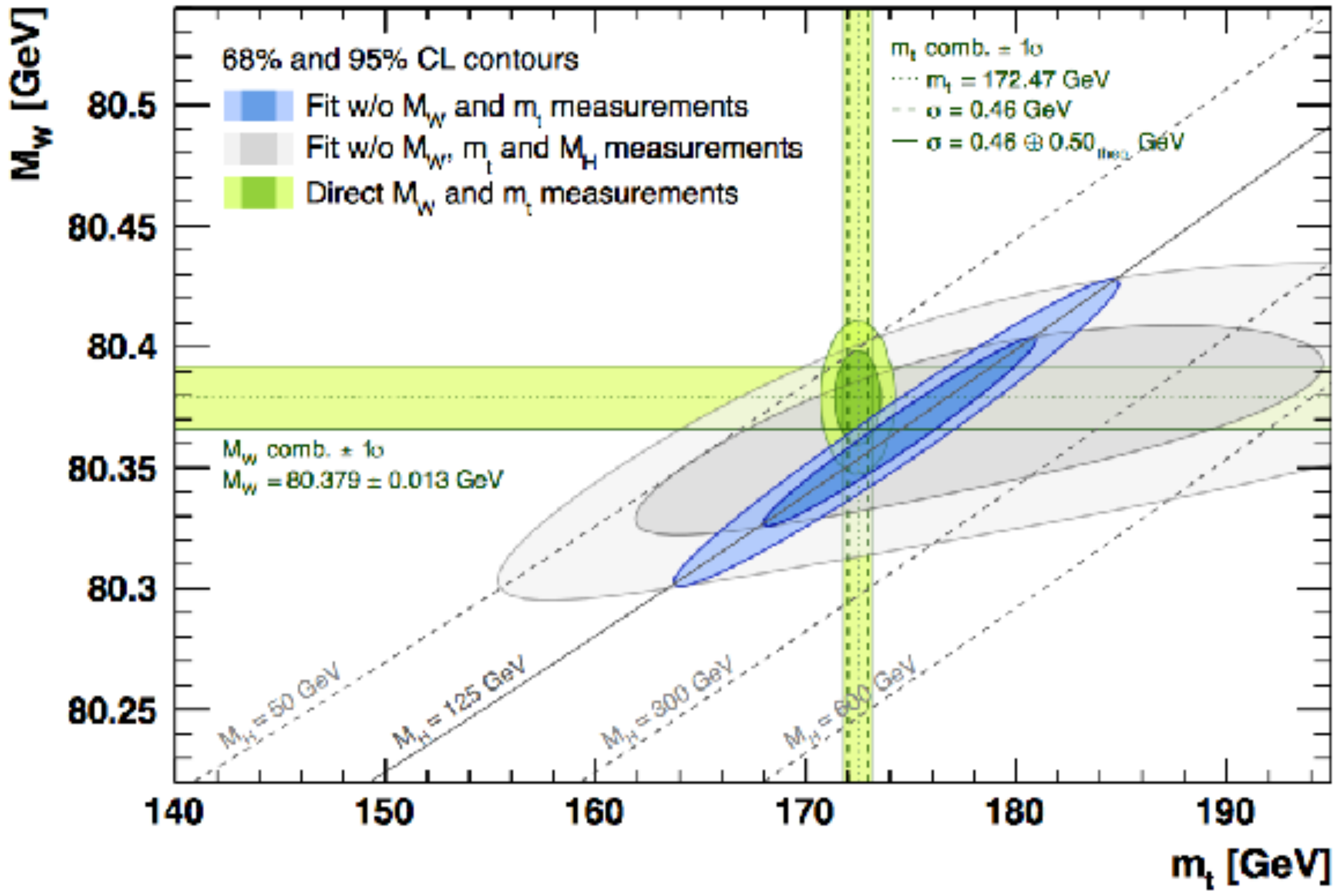
Δ m_t < 250 MeV to rule out absolute stability



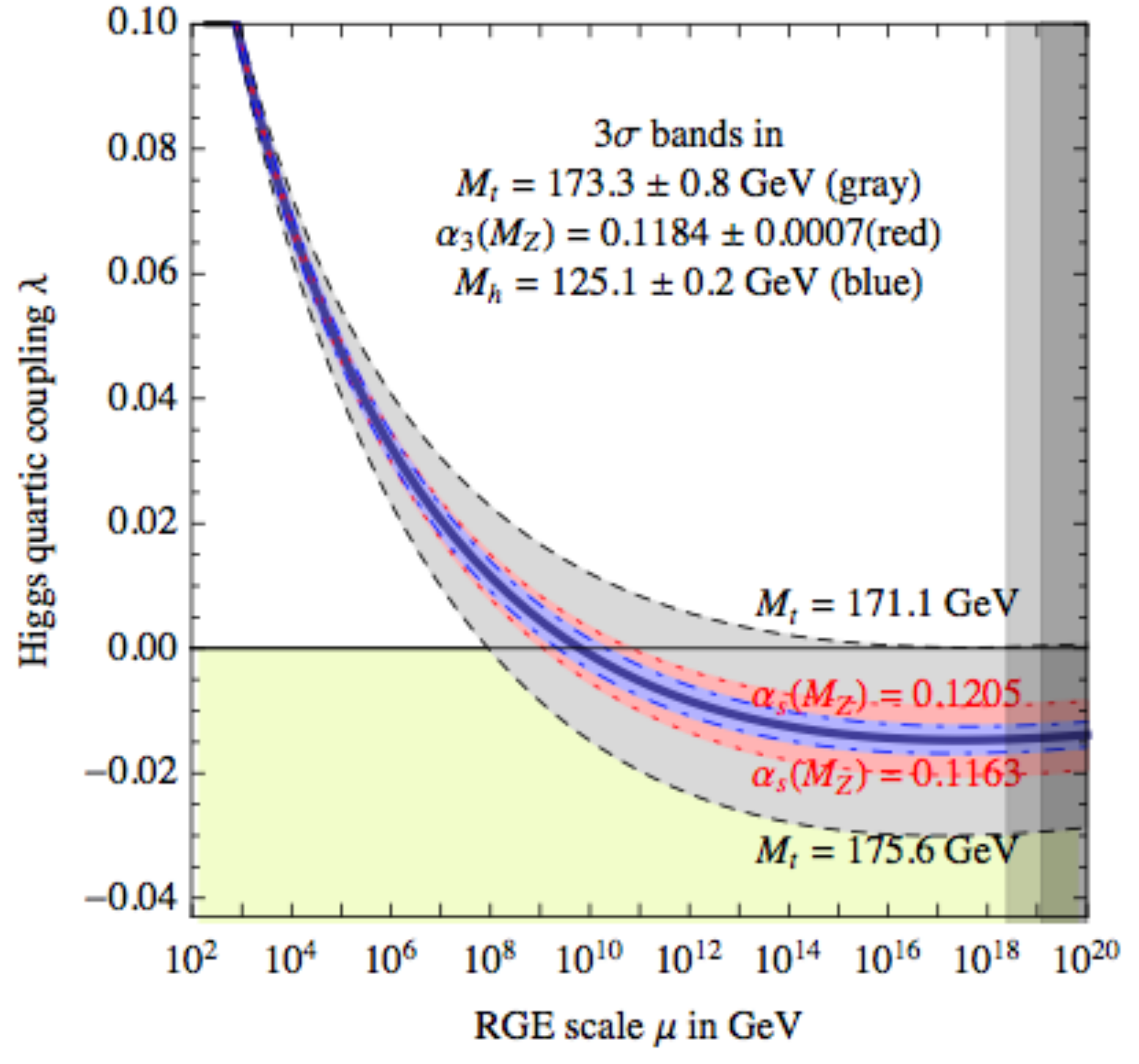




GFitter group, arXiv:1803.01853

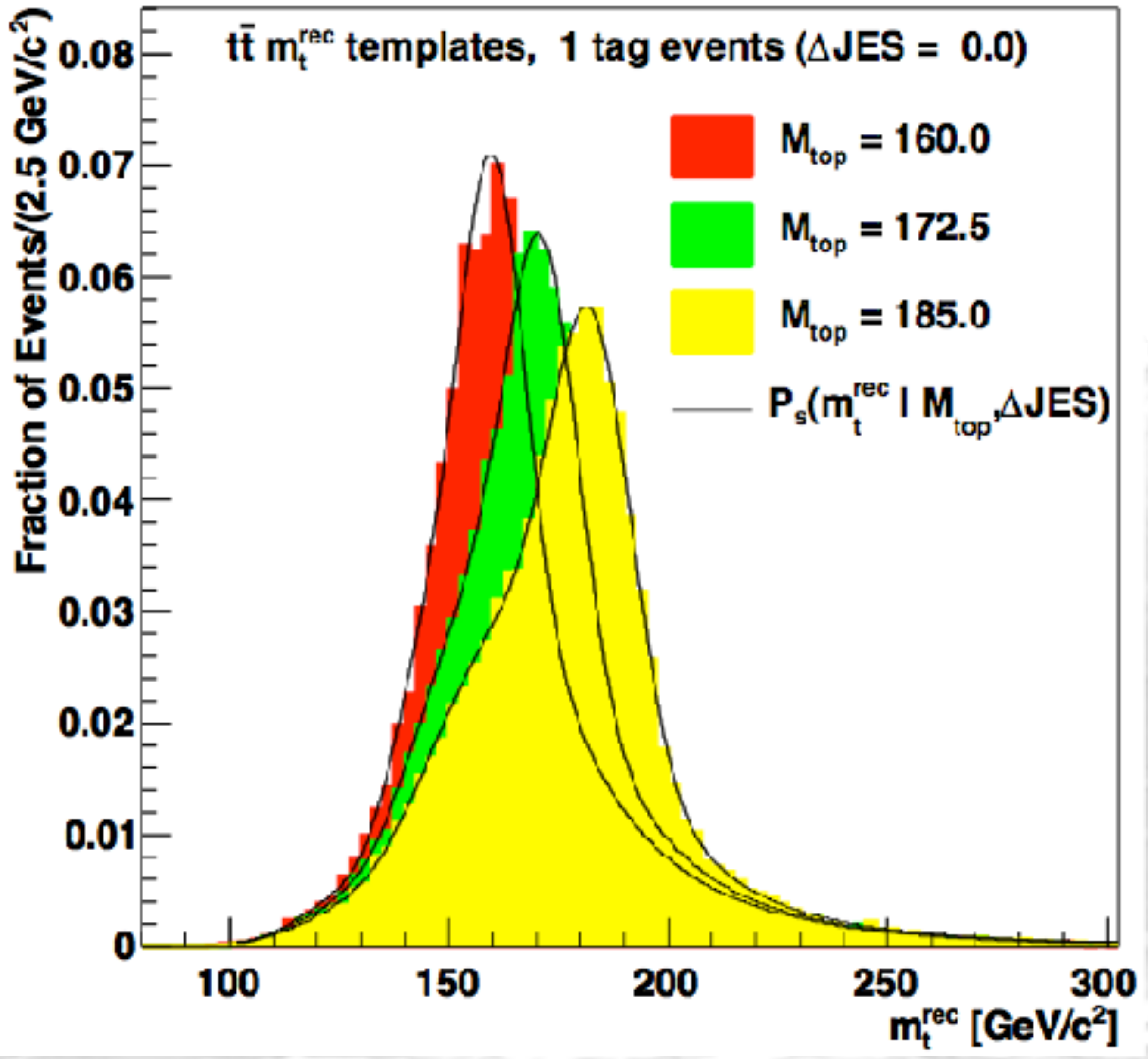


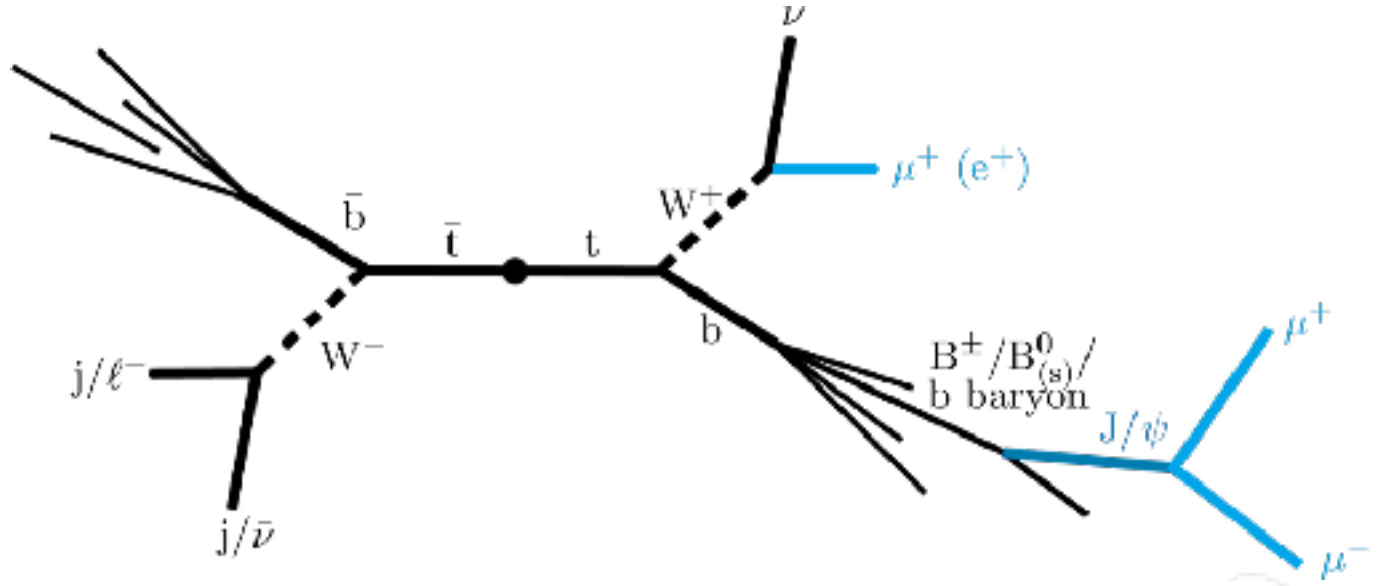
Buttazzo et al., JHEP 1312, 089 (2013)

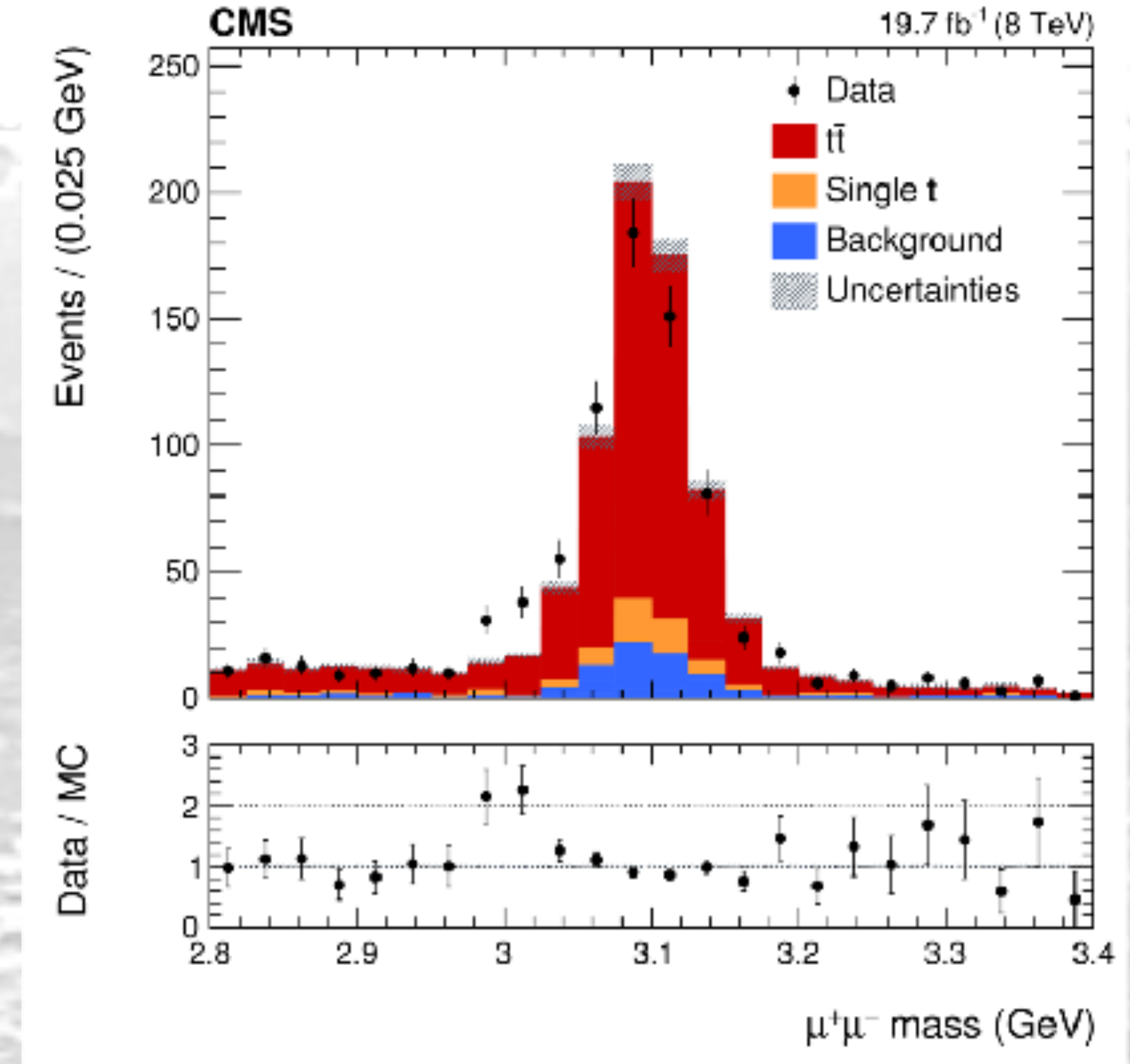


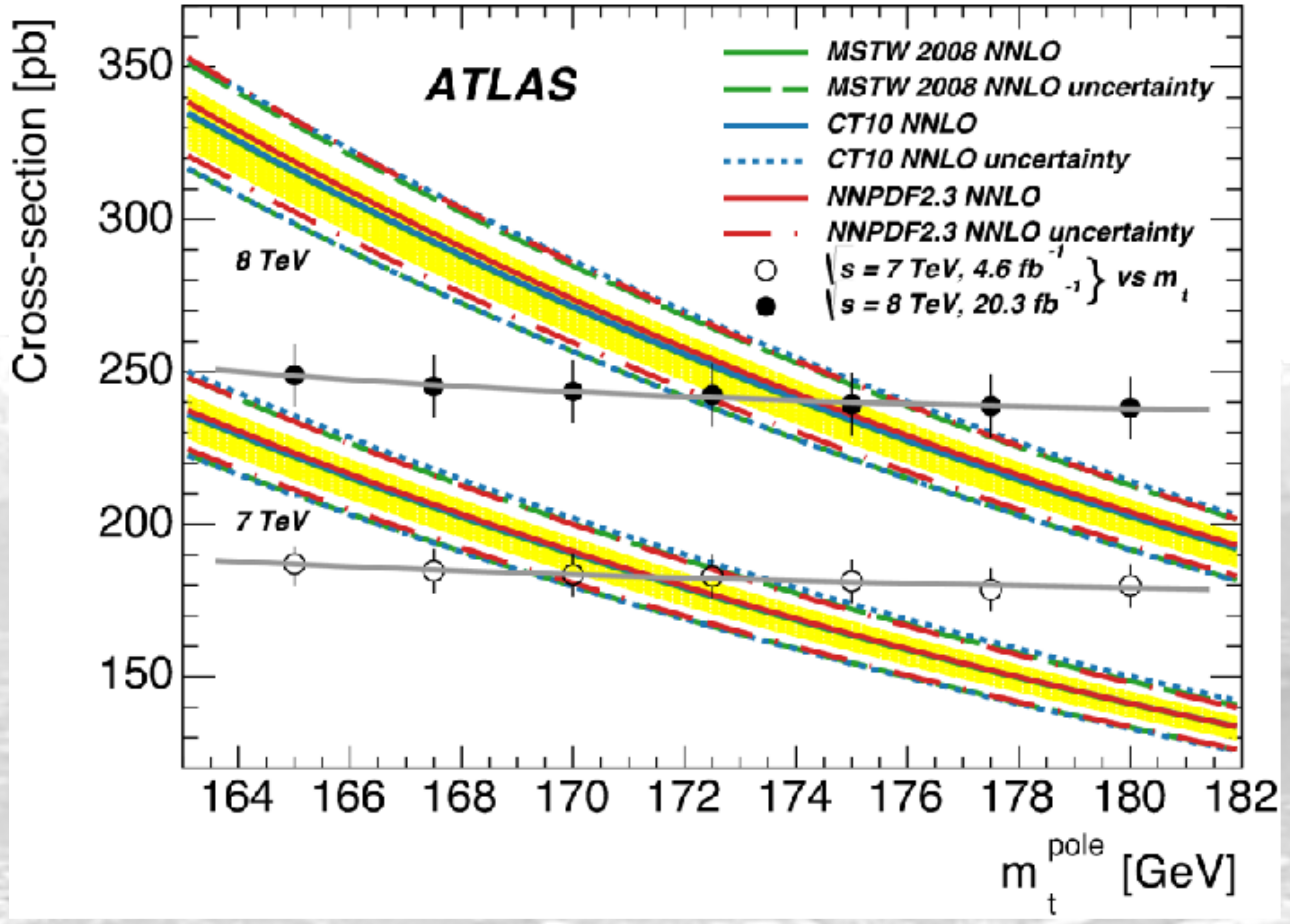
How to measure the top quark mass ?

- direct methods
  - standard methods: use template method by comparing an observable in data with MC generated with different masses
- alternative methods
  - using partial decay products (with less sensitivity to specific systematics) or different observables
  - using the cross section or the top kinematics: less input from simulation or different sensitivity to systematics or well defined renormalization scheme but currently less precise than the direct ones





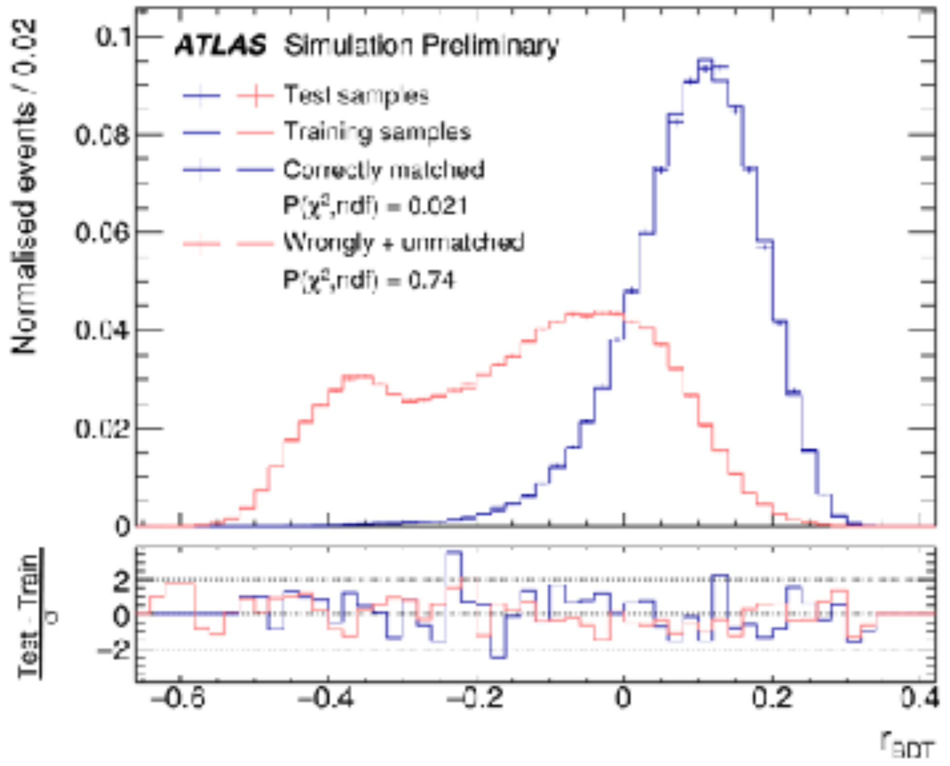


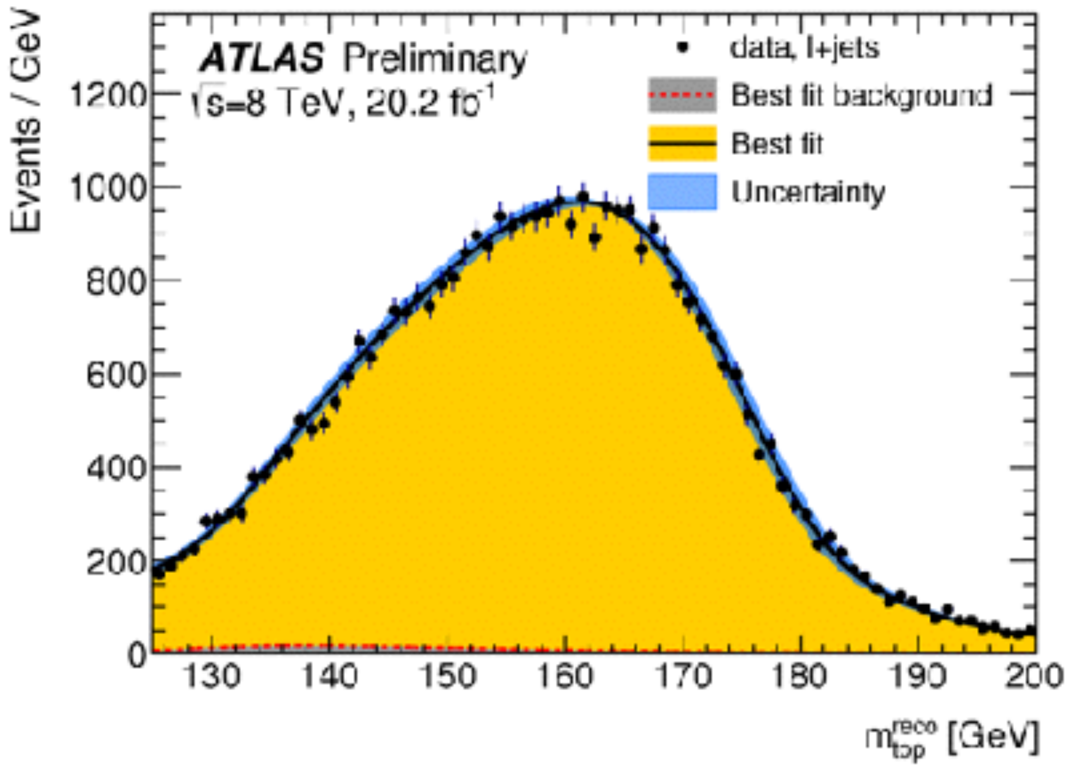


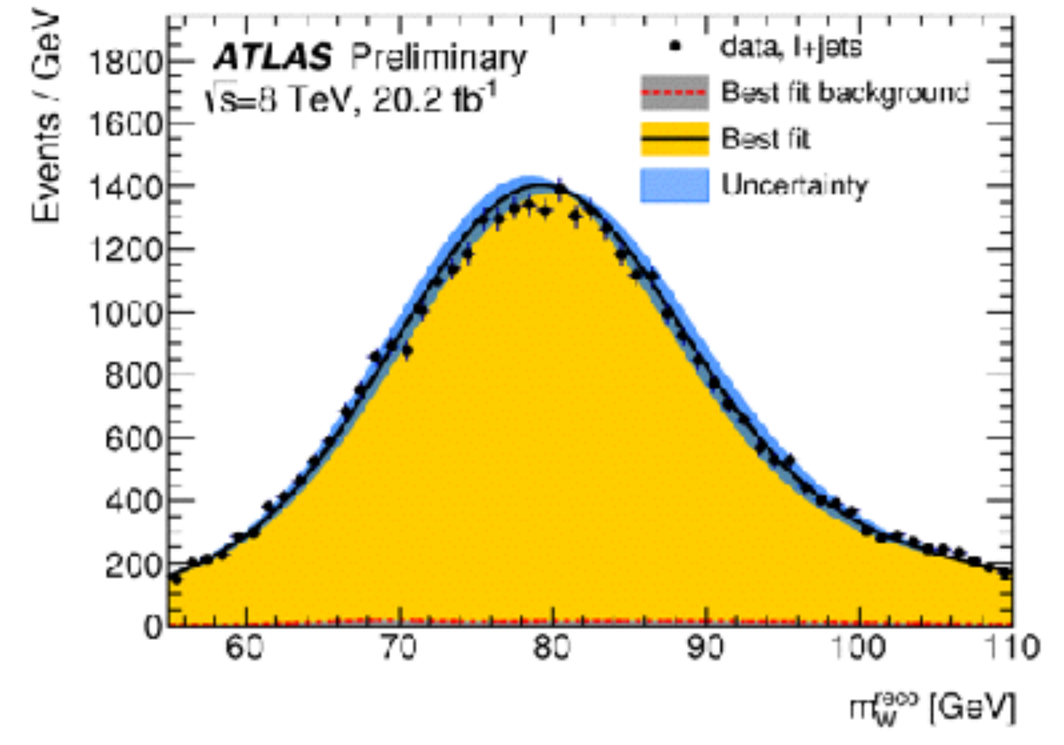
Direct top quark mass measurements

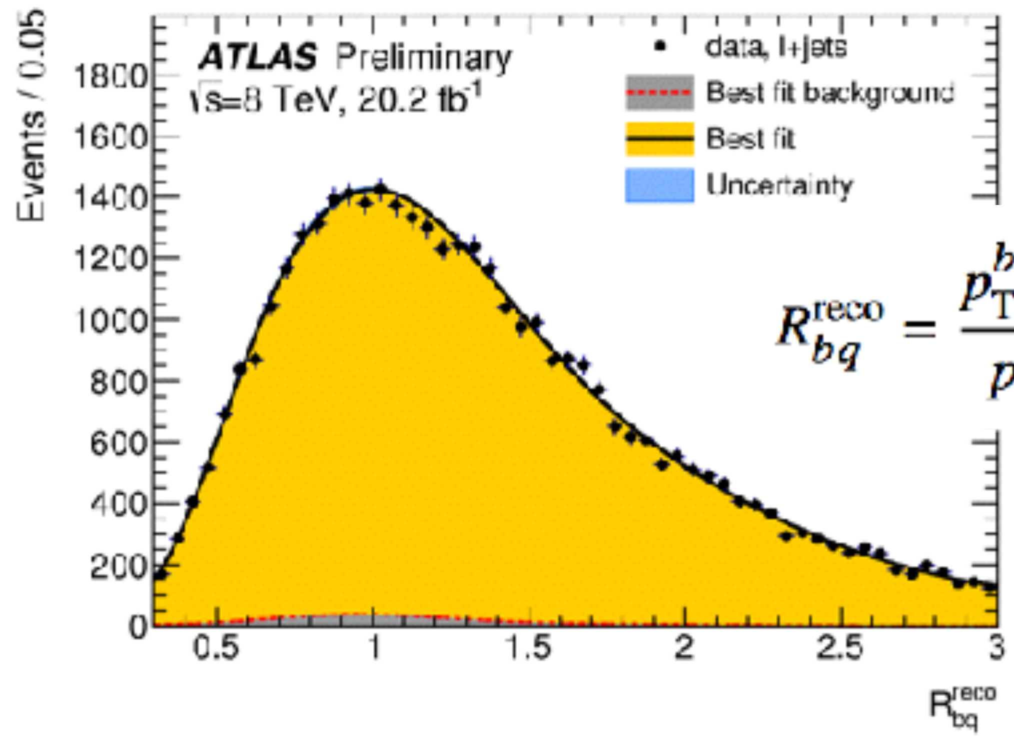
- analysis strategy
  - reconstruct the $t\bar{t}$ kinematics
  - perform likelihood fit with one or several parameters to constrain the jet energy scale (based on template or ideogram)
    - keep best permutation (after BDT selection) or all (weighted by their probability)

ATLAS-CONF-2017-071



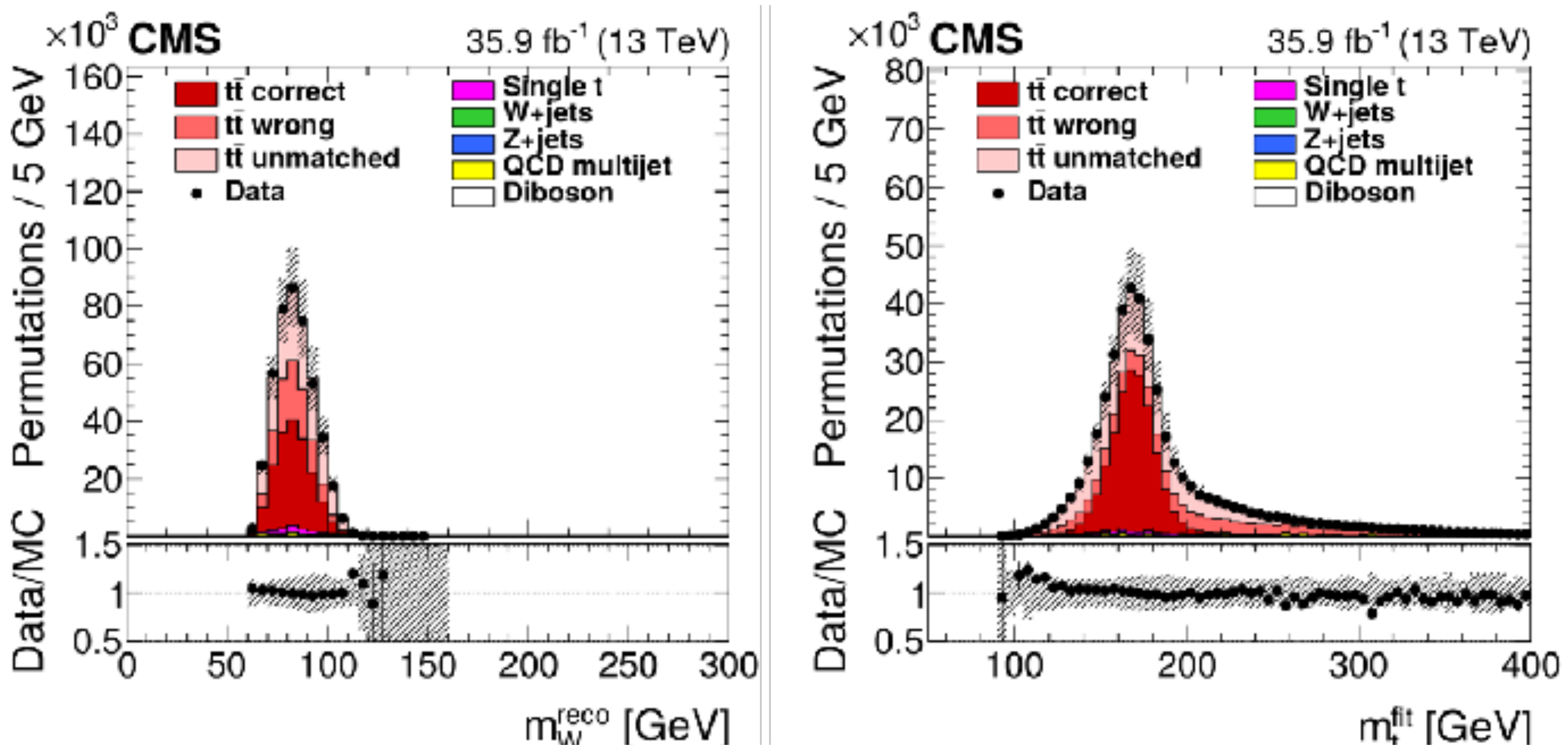






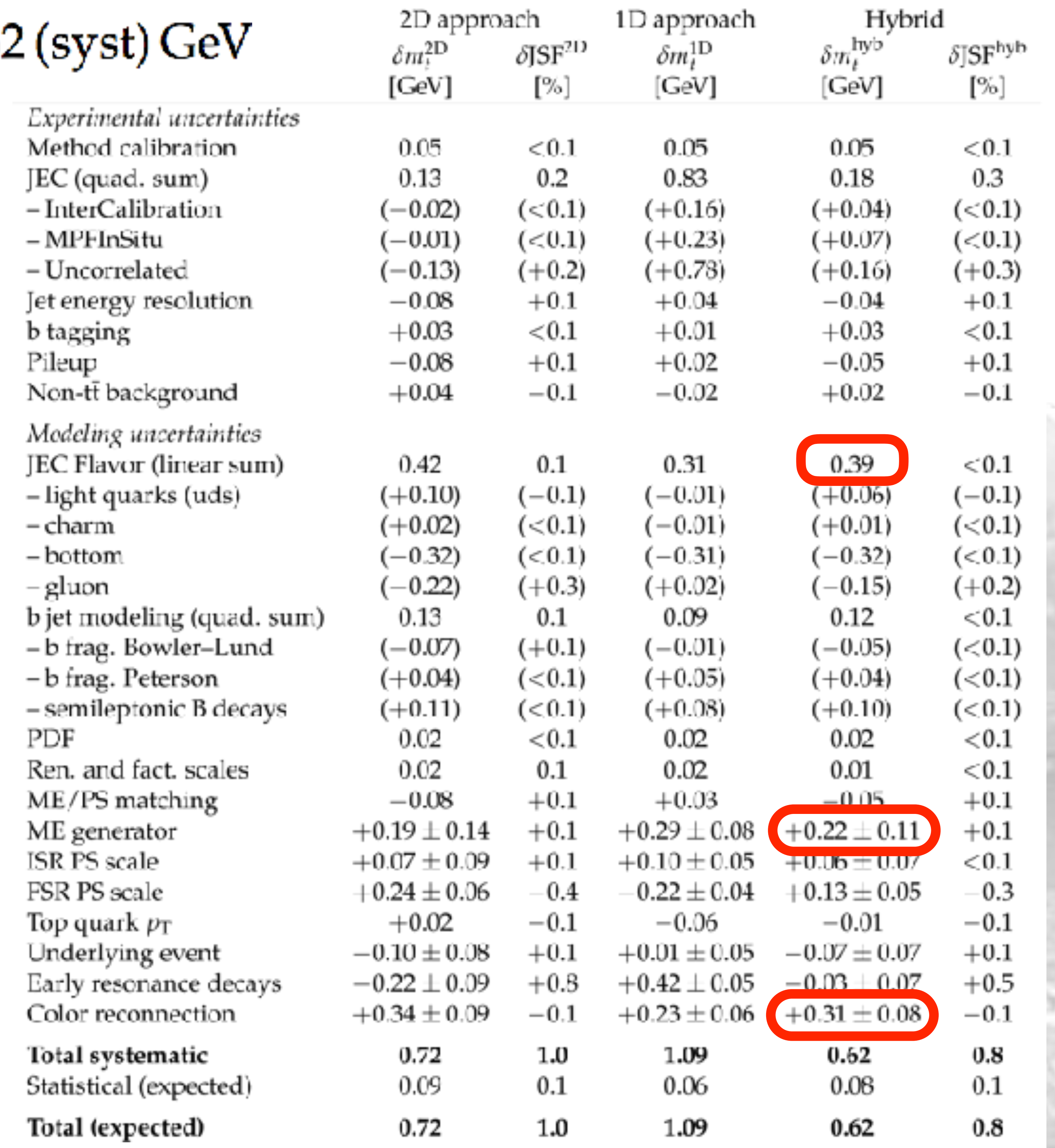
$$R_{bq}^{reco} = \frac{p_T^{b_{had}} + p_T^{b_{lep}}}{p_T^{q_1} + p_T^{q_2}}$$

$$m_{top} = 172.08 \pm 0.39\,(\text{stat}) \pm 0.82\,(\text{syst})\ \text{GeV}$$



$$172.25 \pm 0.08\,(\text{stat+JSF}) \pm 0.62\,(\text{syst})\ \text{GeV}$$

arXiv:1805.01428



	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	<0.1	0.05	0.05	<0.1
JEC (quad. sum)	0.13	0.2	0.83	0.18	0.3
– InterCalibration	(−0.02)	(<0.1)	(+0.16)	(+0.04)	(<0.1)
– MPFInSitu	(−0.01)	(<0.1)	(+0.23)	(+0.07)	(<0.1)
– Uncorrelated	(−0.13)	(+0.2)	(+0.78)	(+0.16)	(+0.3)
Jet energy resolution	−0.08	+0.1	+0.04	−0.04	+0.1
b tagging	+0.03	<0.1	+0.01	+0.03	<0.1
Pileup	−0.08	+0.1	+0.02	−0.05	+0.1
Non-$t\bar{t}$ background	+0.04	−0.1	−0.02	+0.02	−0.1
Modeling uncertainties					
JEC Flavor (linear sum)	0.42	0.1	0.31	0.39	<0.1
– light quarks (uds)	(+0.10)	(−0.1)	(−0.01)	(+0.06)	(−0.1)
– charm	(+0.02)	(<0.1)	(−0.01)	(+0.01)	(<0.1)
– bottom	(−0.32)	(<0.1)	(−0.31)	(−0.32)	(<0.1)
– gluon	(−0.22)	(+0.3)	(+0.02)	(−0.15)	(+0.2)
b jet modeling (quad. sum)	0.13	0.1	0.09	0.12	<0.1
– b frag. Bowler–Lund	(−0.07)	(+0.1)	(−0.01)	(−0.05)	(<0.1)
– b frag. Peterson	(+0.04)	(<0.1)	(+0.05)	(+0.04)	(<0.1)
– semileptonic B decays	(+0.11)	(<0.1)	(+0.08)	(+0.10)	(<0.1)
PDF	0.02	<0.1	0.02	0.02	<0.1
Ren. and fact. scales	0.02	0.1	0.02	0.01	<0.1
ME/PS matching	−0.08	+0.1	+0.03	−0.05	+0.1
ME generator	+0.19 ± 0.14	+0.1	+0.29 ± 0.08	+0.22 ± 0.11	+0.1
ISR PS scale	+0.07 ± 0.09	+0.1	+0.10 ± 0.05	+0.06 ± 0.07	<0.1
FSR PS scale	+0.24 ± 0.06	−0.4	+0.22 ± 0.04	+0.13 ± 0.05	−0.3
Top quark p_T	+0.02	−0.1	−0.06	−0.01	−0.1
Underlying event	−0.10 ± 0.08	+0.1	+0.01 ± 0.05	−0.07 ± 0.07	+0.1
Early resonance decays	−0.22 ± 0.09	+0.8	+0.42 ± 0.05	−0.03 ± 0.07	+0.5
Color reconnection	+0.34 ± 0.09	−0.1	+0.23 ± 0.06	+0.31 ± 0.08	−0.1
Total systematic	**0.72**	**1.0**	**1.09**	**0.62**	**0.8**
Statistical (expected)	0.09	0.1	0.06	0.08	0.1
Total (expected)	**0.72**	**1.0**	**1.09**	**0.62**	**0.8**

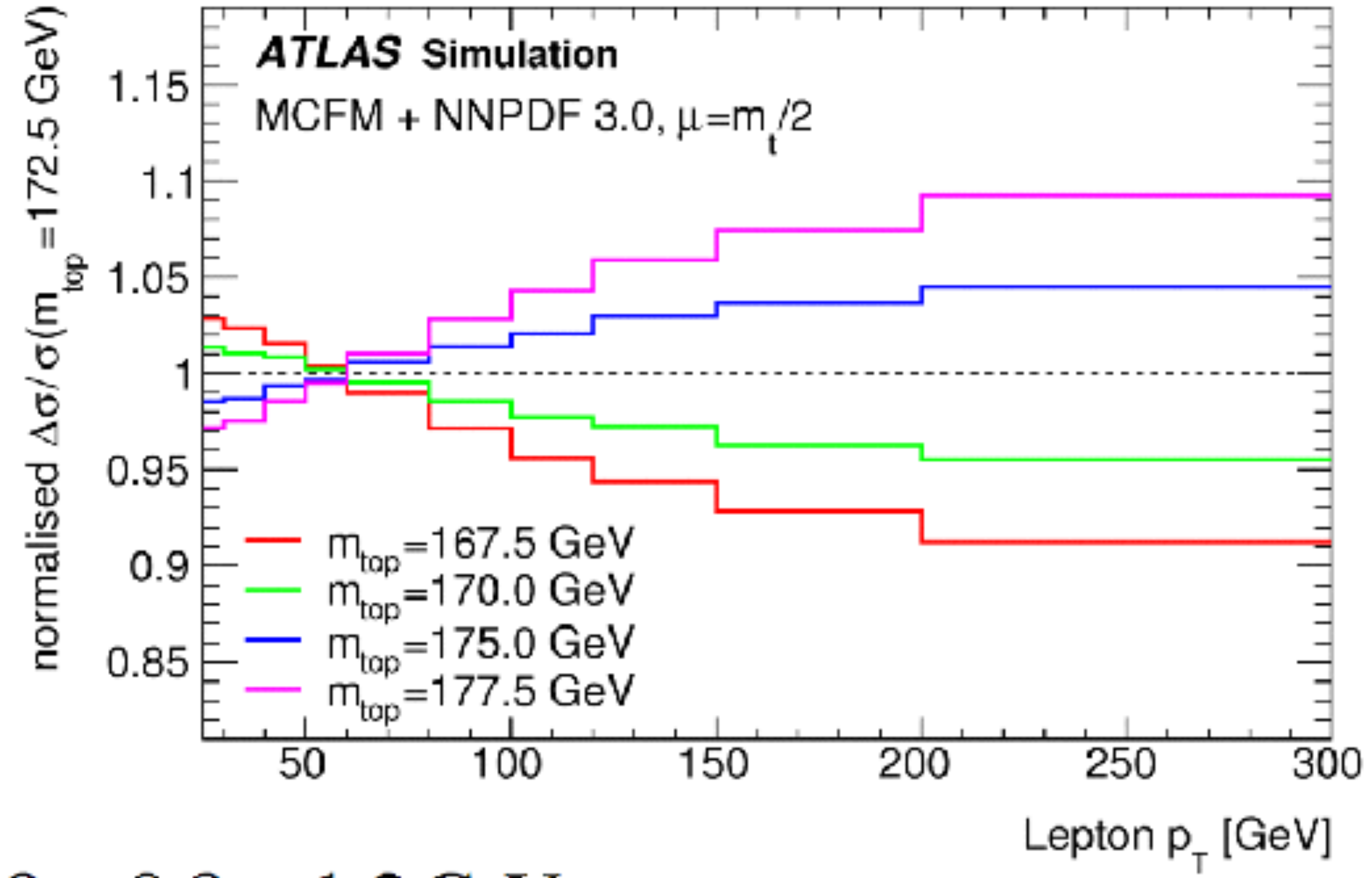
Examples of alternative top quark mass measurements

- can use total or differential cross section

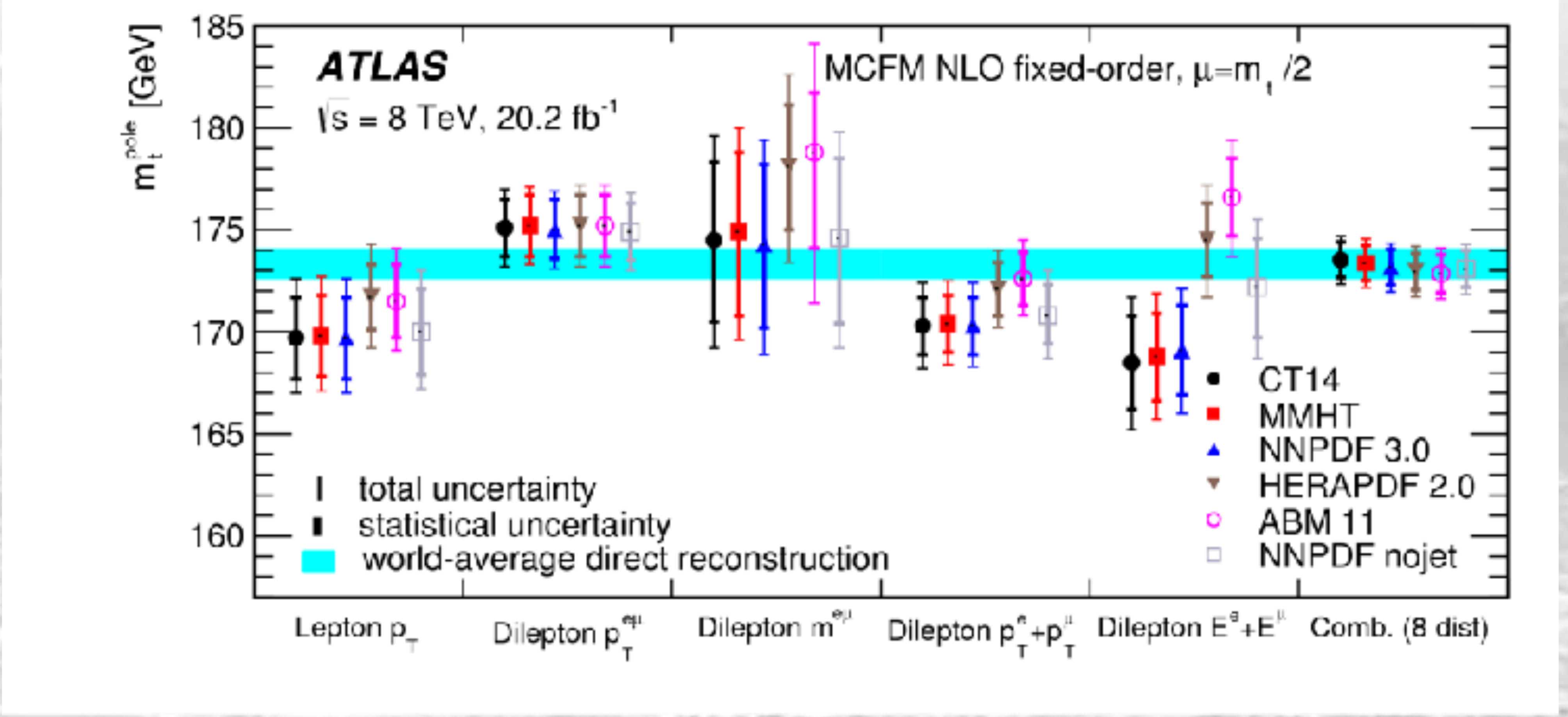
  - from $t\bar{t}$+1jet unfolded distribution: $\mathcal{R}(m_t^{\text{pole}},\rho_s) = \frac{1}{\sigma_{t\bar{t}+1\text{-jet}}}\frac{d\sigma_{t\bar{t}+1\text{-jet}}}{d\rho_s}(m_t^{\text{pole}},\rho_s)$ $\rho_s = \frac{2\cdot m_0}{\sqrt{s_{t\bar{t}+\text{jet}}}}$

  - from unfolded dilepton differential distributions
    - Simultaneous fit to MCFM templates in all 8 dilepton differential distributions (p_T, rapidities and $\Delta\Phi$)
      - PDF constrained by rapidities, scale by opening angle, p_T and E best m_t sensitivity
      - largest error from scale variations, would benefit from NNLO predictions with top decays

EPJC 77 (2017) 804

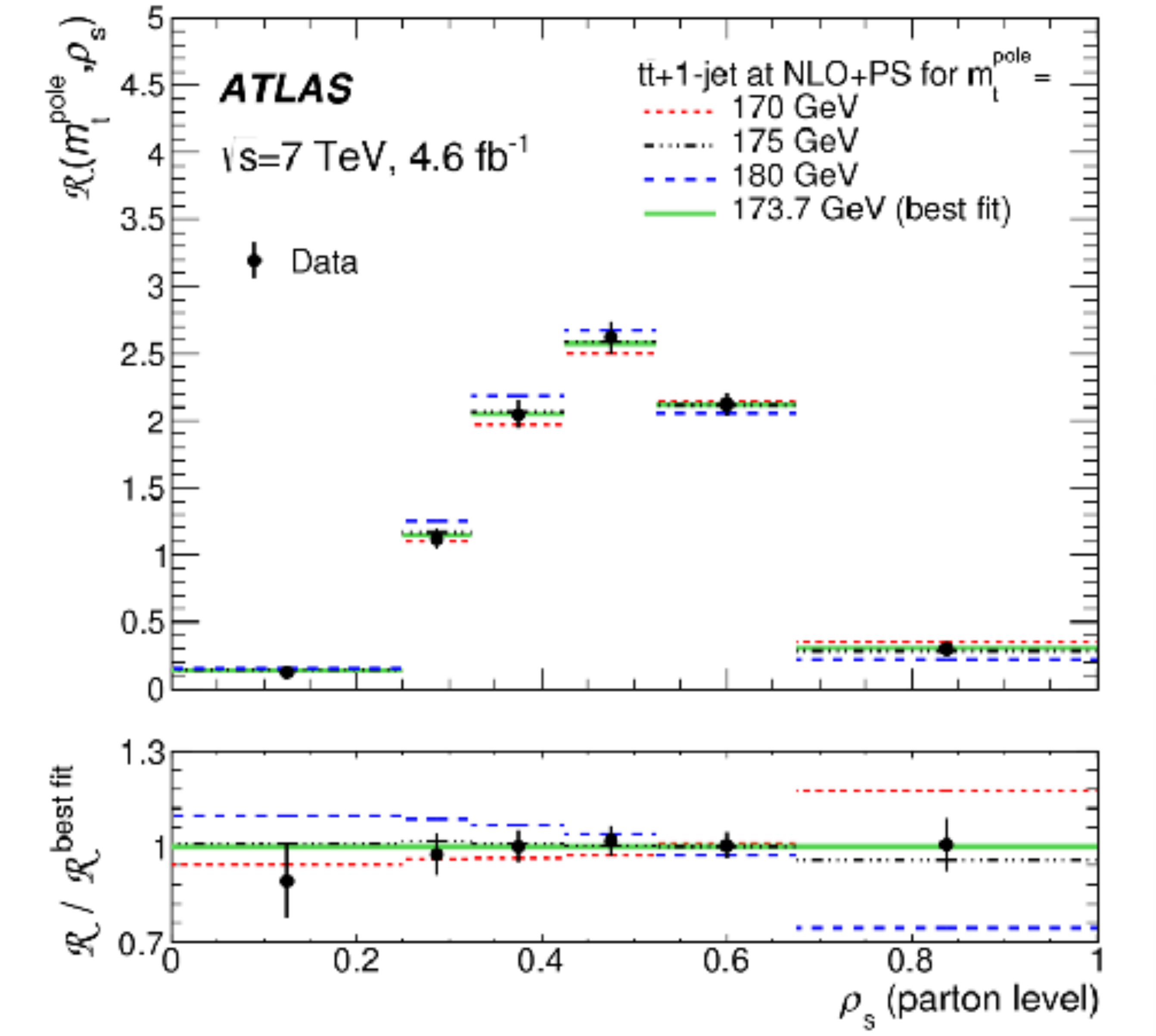


$$m_t^{\text{pole}} = 173.2 \pm 0.9 \pm 0.8 \pm 1.2\,\text{GeV}$$



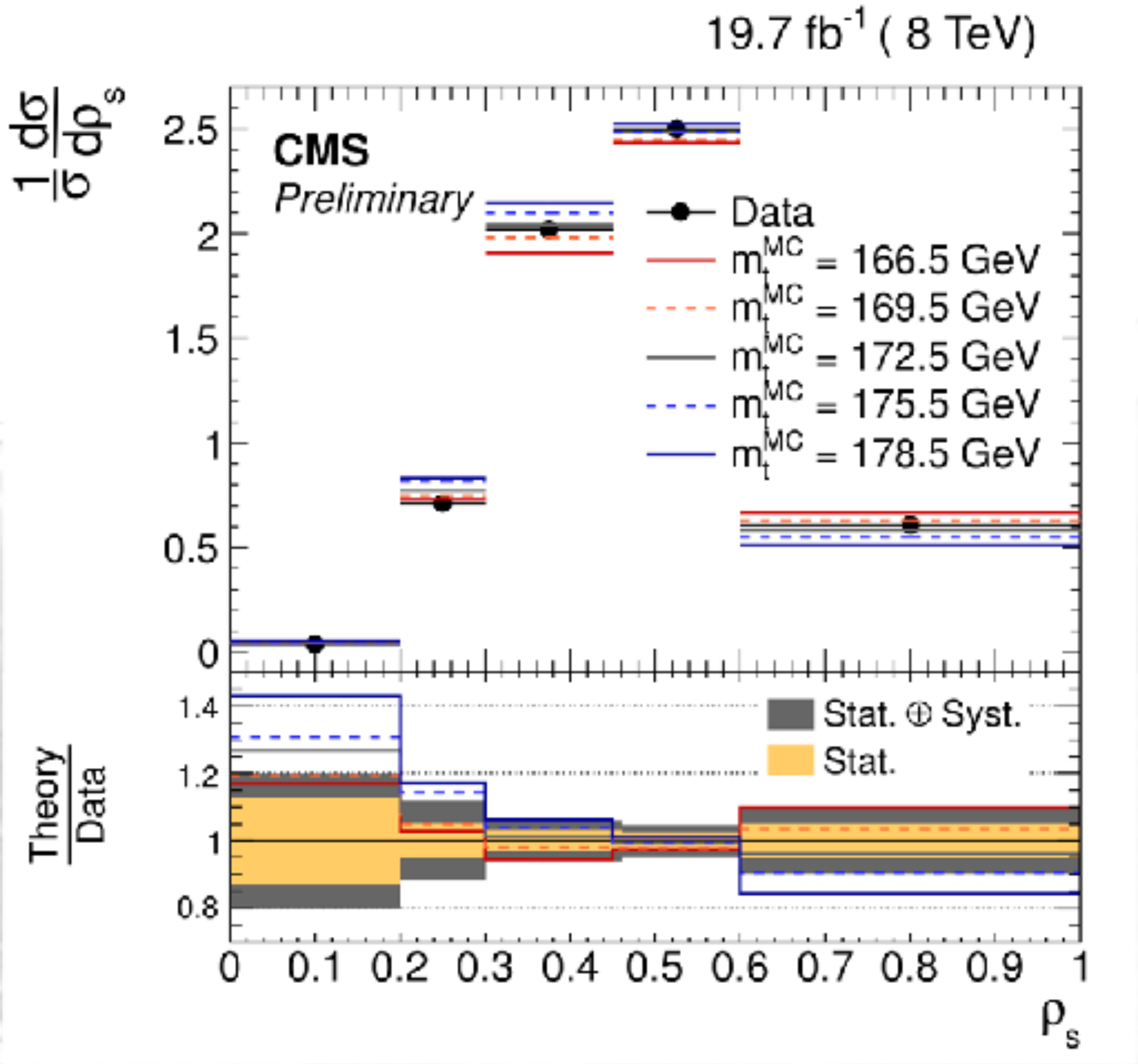
JHEP 10 (2015) 121

$$m_t^{\text{pole}} = 173.7 \pm 1.5\,(\text{stat.}) \pm 1.4\,(\text{syst.})\,^{+1.0}_{-0.5}\,(\text{theory})\ \text{GeV}$$



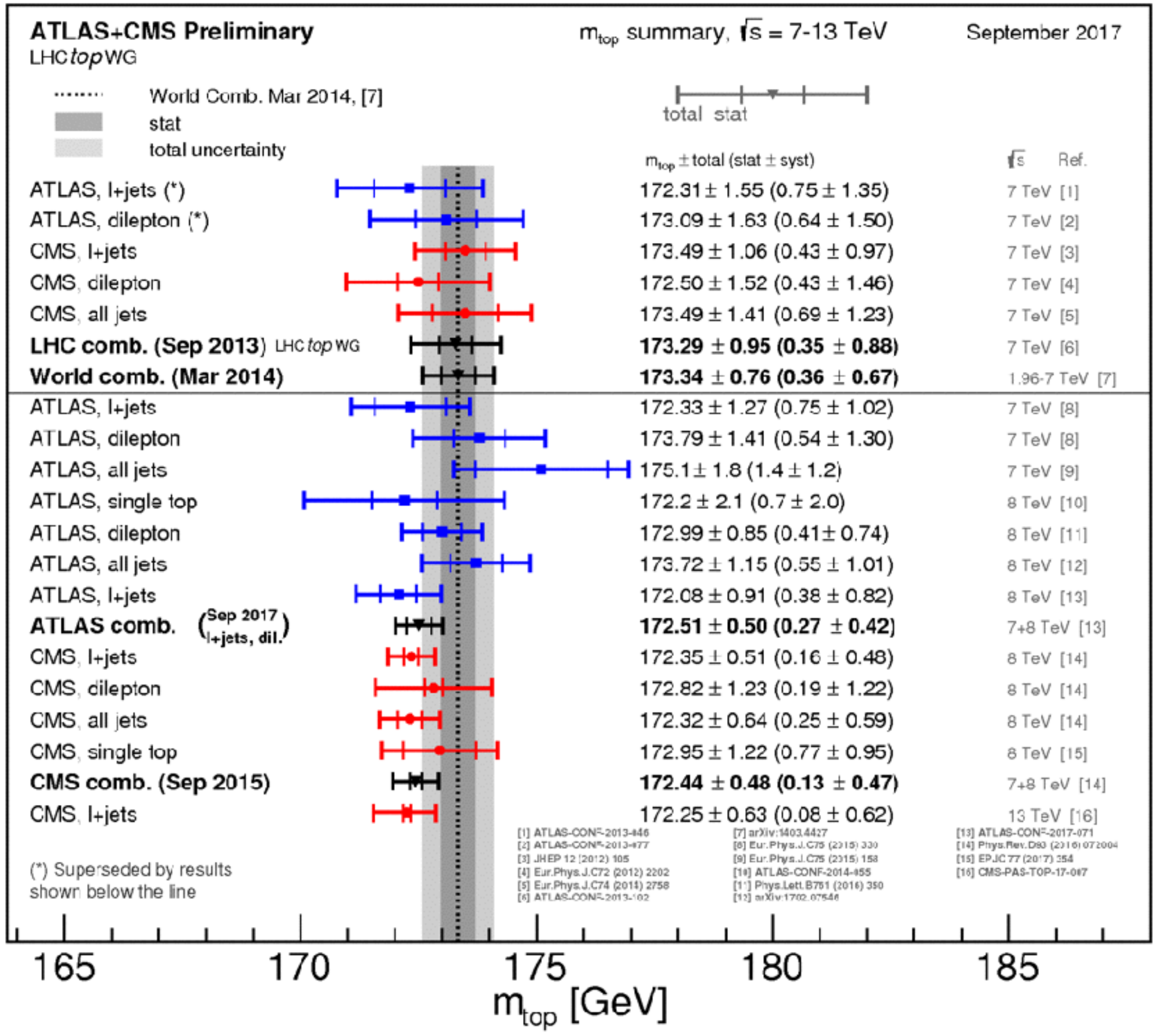
CMS-PAS-TOP-13-006

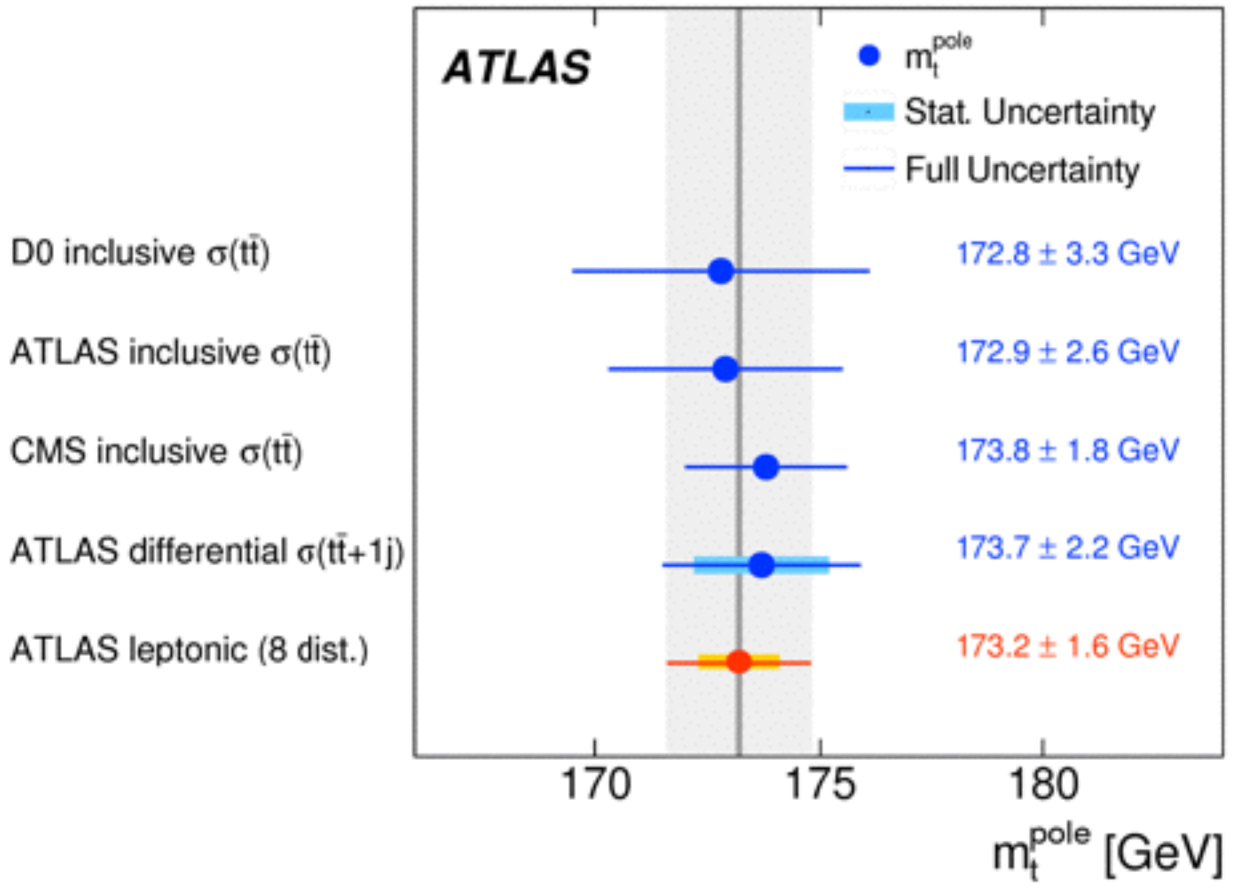
$$169.9 \pm 1.1\,(\text{stat})\,^{+2.5}_{-3.1}\,(\text{syst})\,^{+3.6}_{-1.6}\,(\text{theo})\ \text{GeV}$$

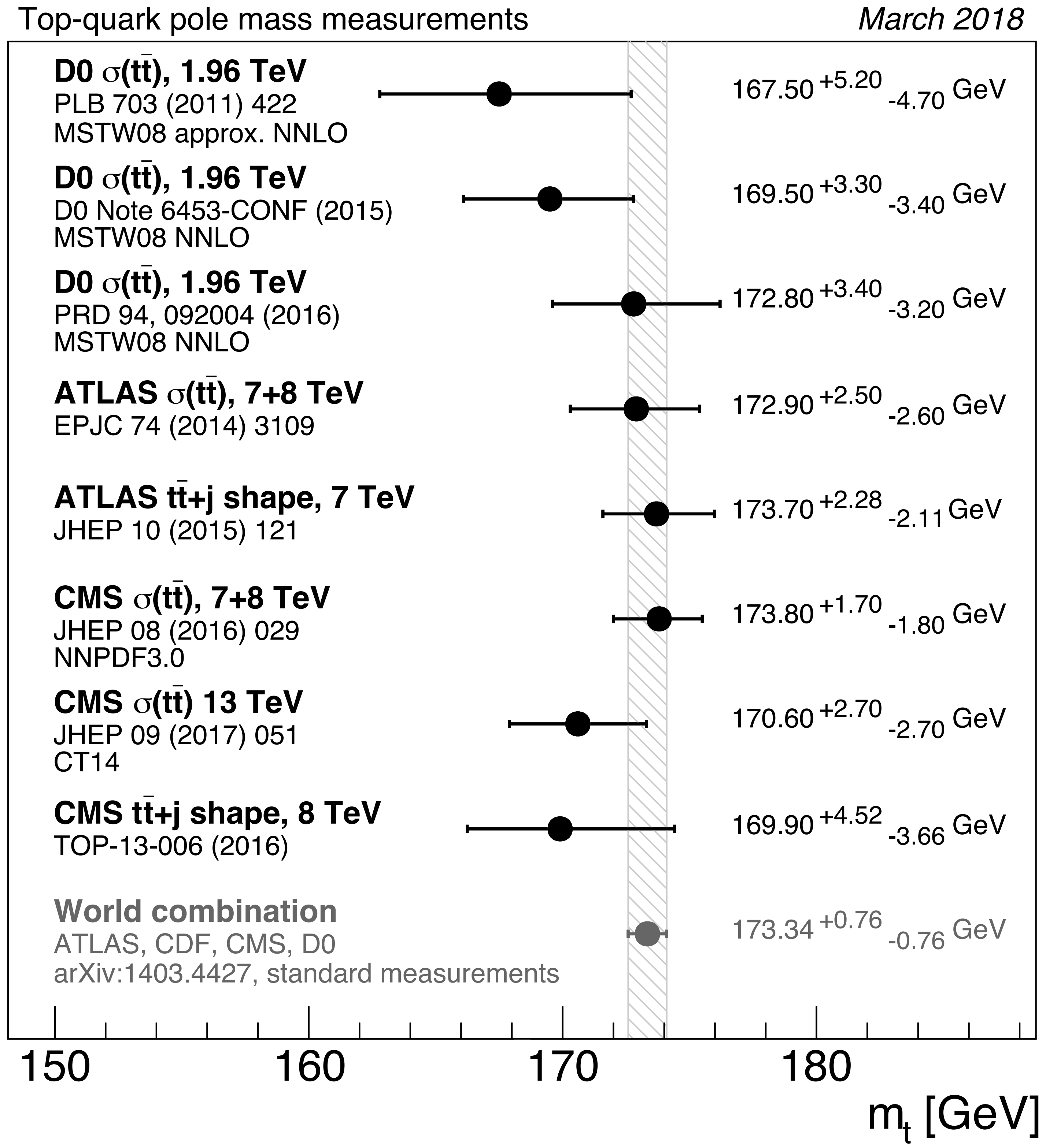


Summary of the top mass measurements

ATLAS combination: m_t = 172.51 ± 0.50 GeV
CMS combination: m_t = 172.44 ± 0.48 GeV

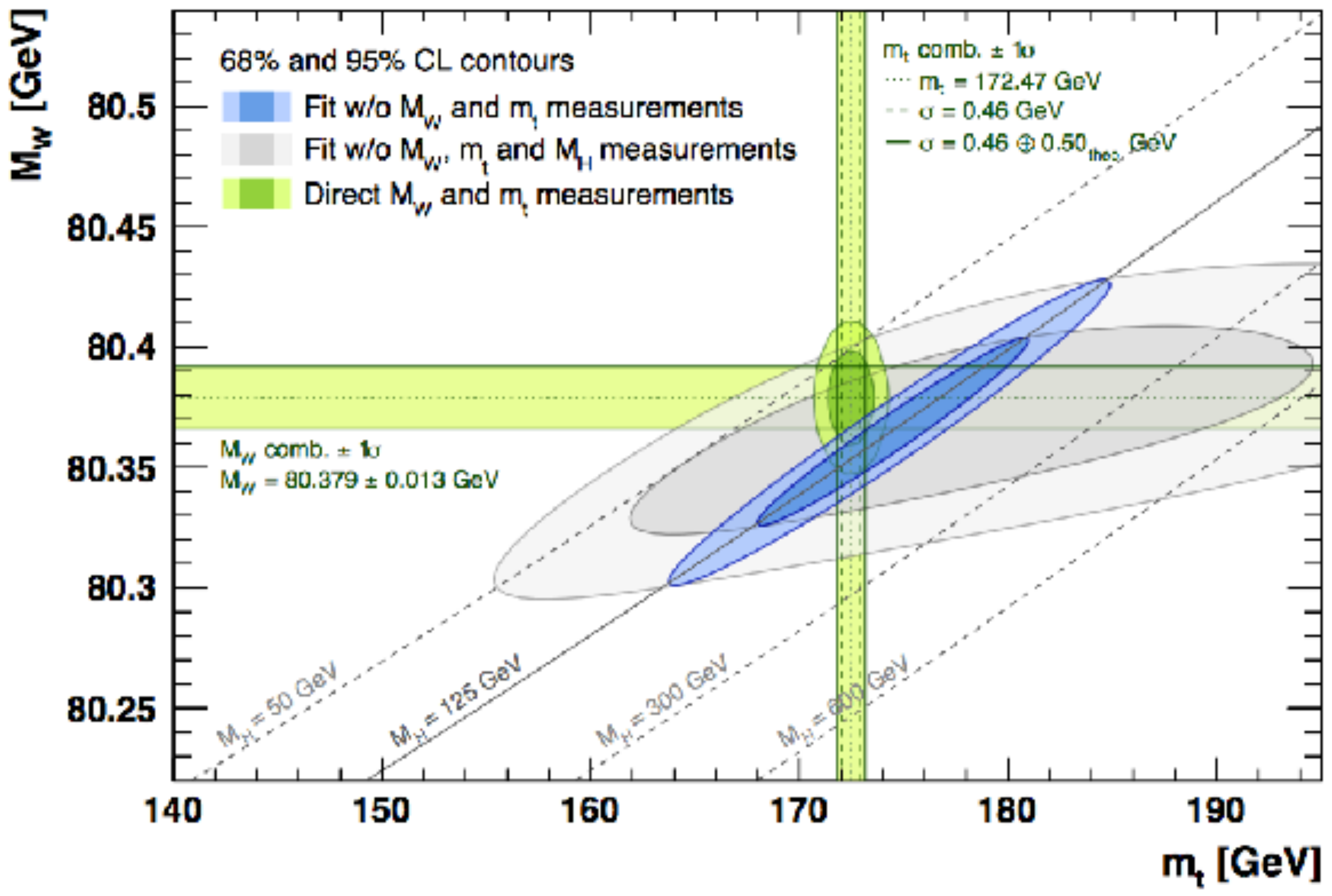






Which top quark mass do we measure ?

- 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.



GFitter group, arXiv:1803.01853

- 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

The top quark mass definition

- the renormalon ambiguity

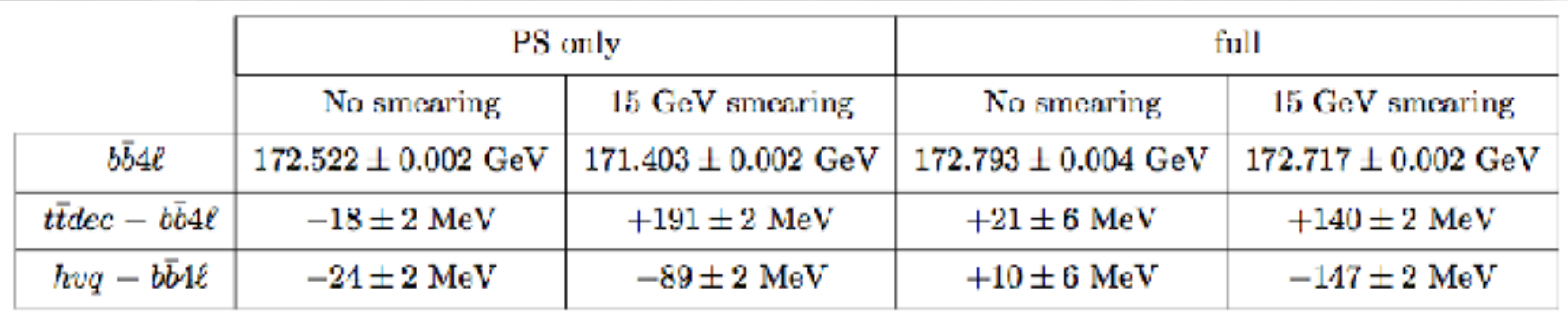
  - ultimate precision due to the irreducible ambiguity of the pole mass (order of the hadronic scale)
  - recent calculations: better estimate of this ambiguity (depending some choice in the procedure):
    - 110 MeV (Beneke, Marquard, Steinhauser, Nason, PLB775, 63 (2017))
    - 250 MeV (Hoang, Lepenik, 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

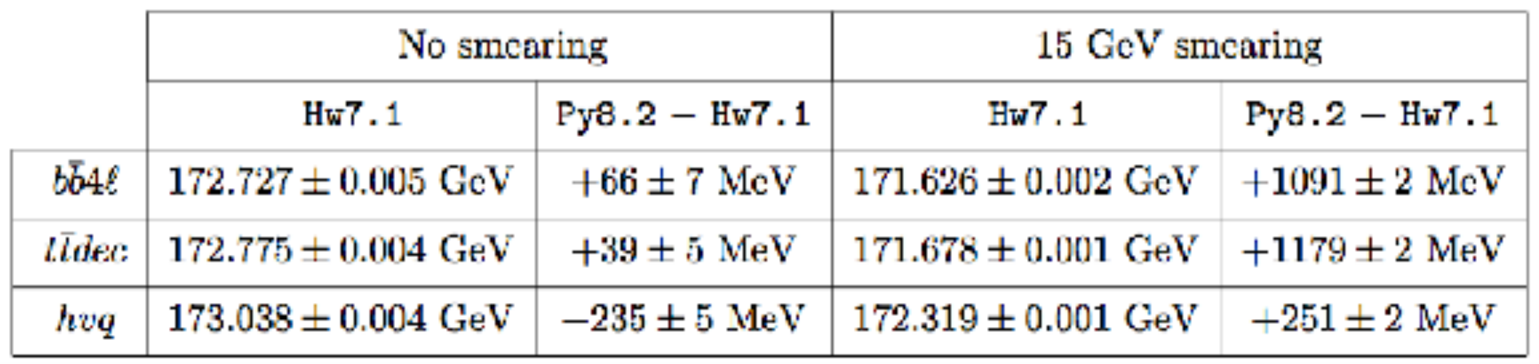
  - calibration of the mass in the MC in boosted $t\bar{t}$ in e^+e^- annihilation using SCET
    - currently not available for pp collision
    - probably depend on the MC (currently developed for Pythia8)
  - NLO+PS generator studies:
    - compare hvq (NLO only in production, on-shell), ttdec (NLO in 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

Ravasio, Jezo, Nason, Oleari, arXiv:1801.03944

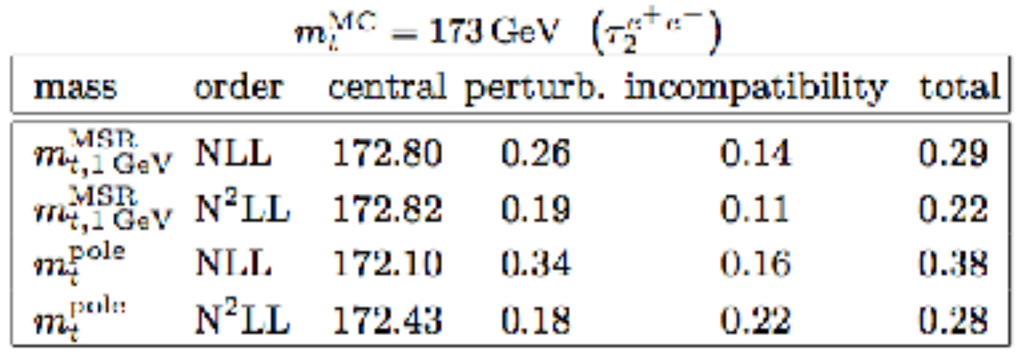


	PS only		full	
	No smearing	15 GeV smearing	No smearing	15 GeV smearing
$b\bar{b}4\ell$	172.522 ± 0.002 GeV	171.403 ± 0.002 GeV	172.793 ± 0.004 GeV	172.717 ± 0.002 GeV
$t\bar{t}dec - b\bar{b}4\ell$	-18 ± 2 MeV	$+191 \pm 2$ MeV	$+21 \pm 6$ MeV	$+140 \pm 2$ MeV
$hvq - b\bar{b}4\ell$	-24 ± 2 MeV	-89 ± 2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



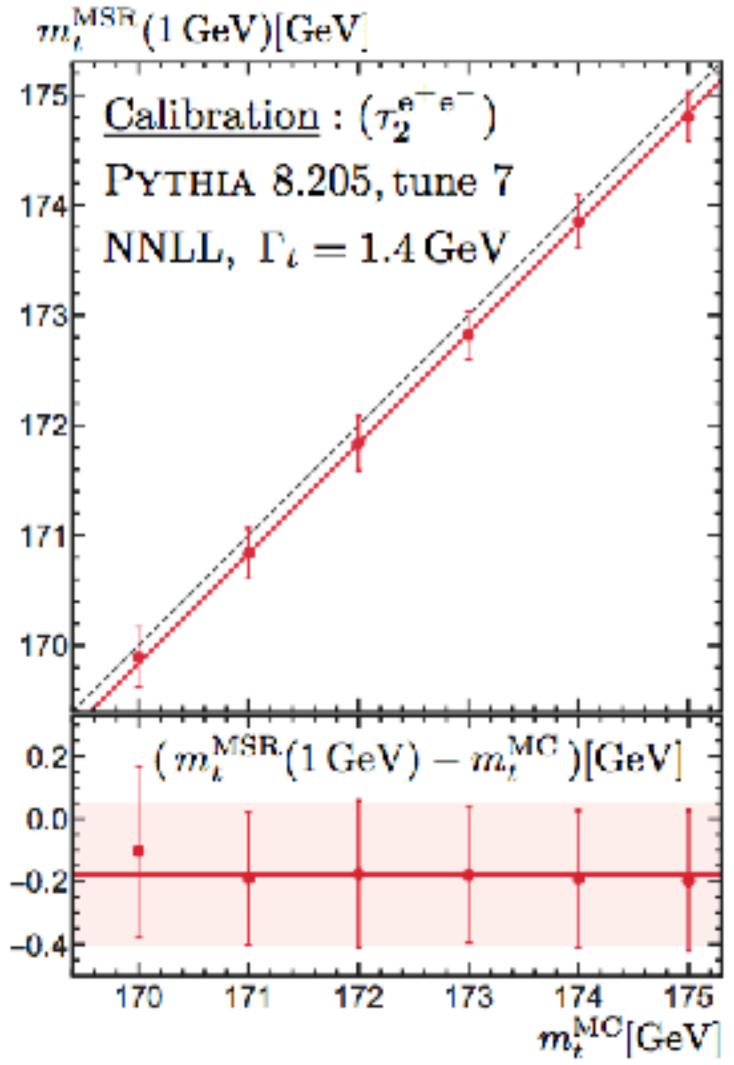
	No smearing		15 GeV smearing	
	Hw7.1	Py8.2 − Hw7.1	Hw7.1	Py8.2 − Hw7.1
$b\bar{b}4\ell$	172.727 ± 0.005 GeV	$+66 \pm 7$ MeV	171.626 ± 0.002 GeV	$+1091 \pm 2$ MeV
$t\bar{t}dec$	172.775 ± 0.004 GeV	$+39 \pm 5$ MeV	171.678 ± 0.001 GeV	$+1179 \pm 2$ MeV
hvq	173.038 ± 0.004 GeV	-235 ± 5 MeV	172.319 ± 0.001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

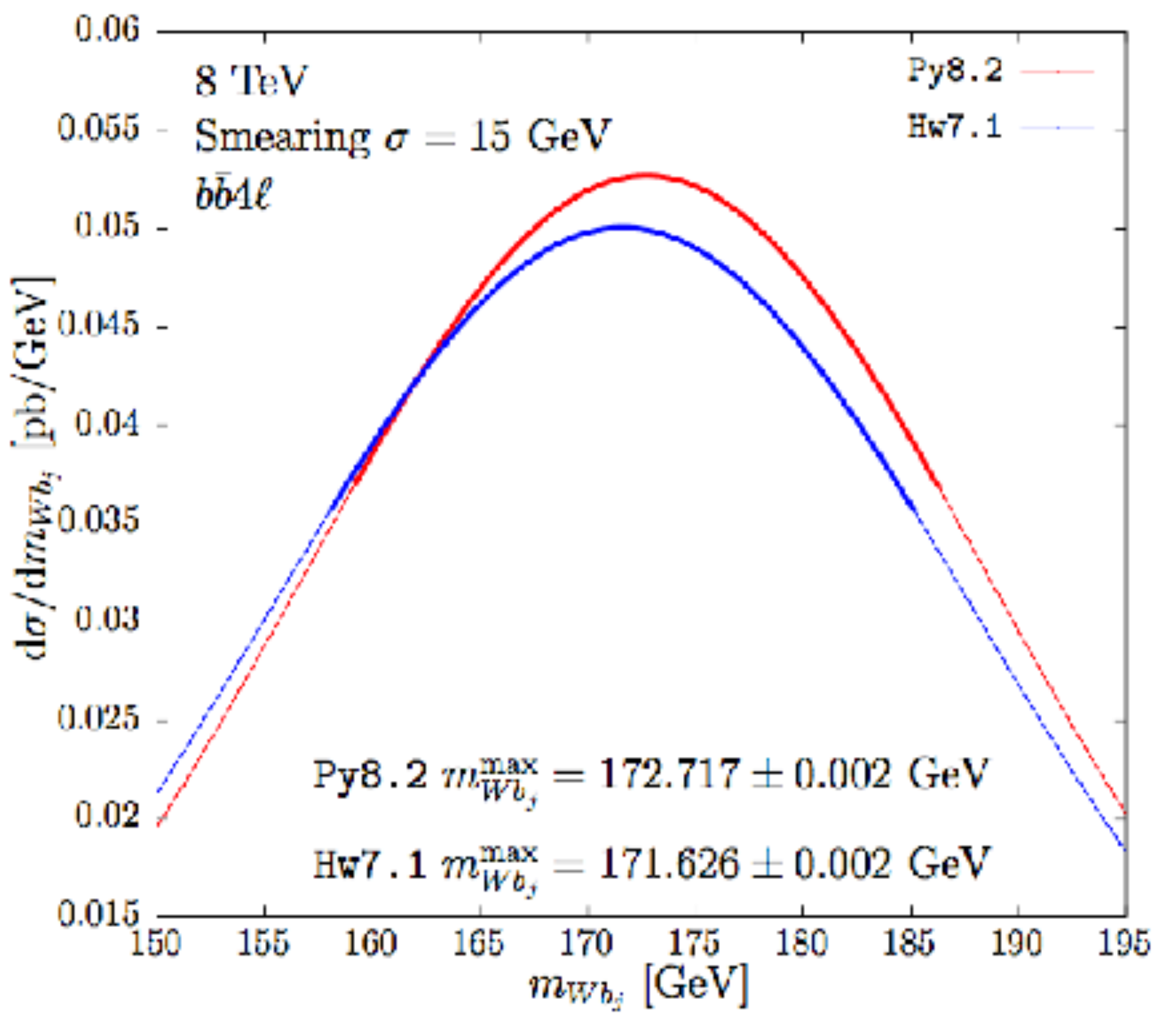
Butenschoen et al. PRL117. 232001 (2016)



$m_t^{MC} = 173$ 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
$m_{t,1\,\mathrm{GeV}}^{\mathrm{MSR}}$	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}	N^2LL	172.43	0.18	0.22	0.28

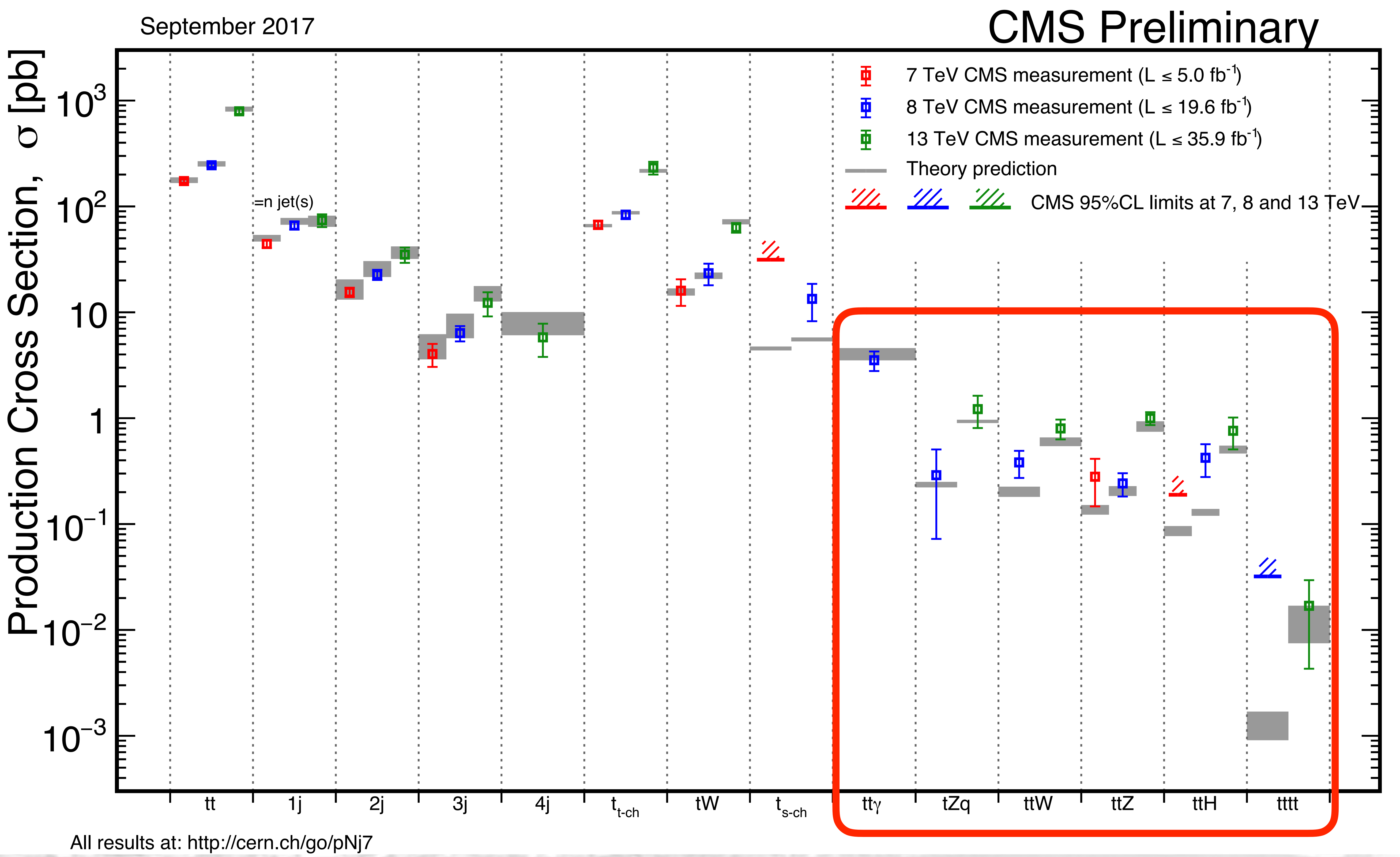




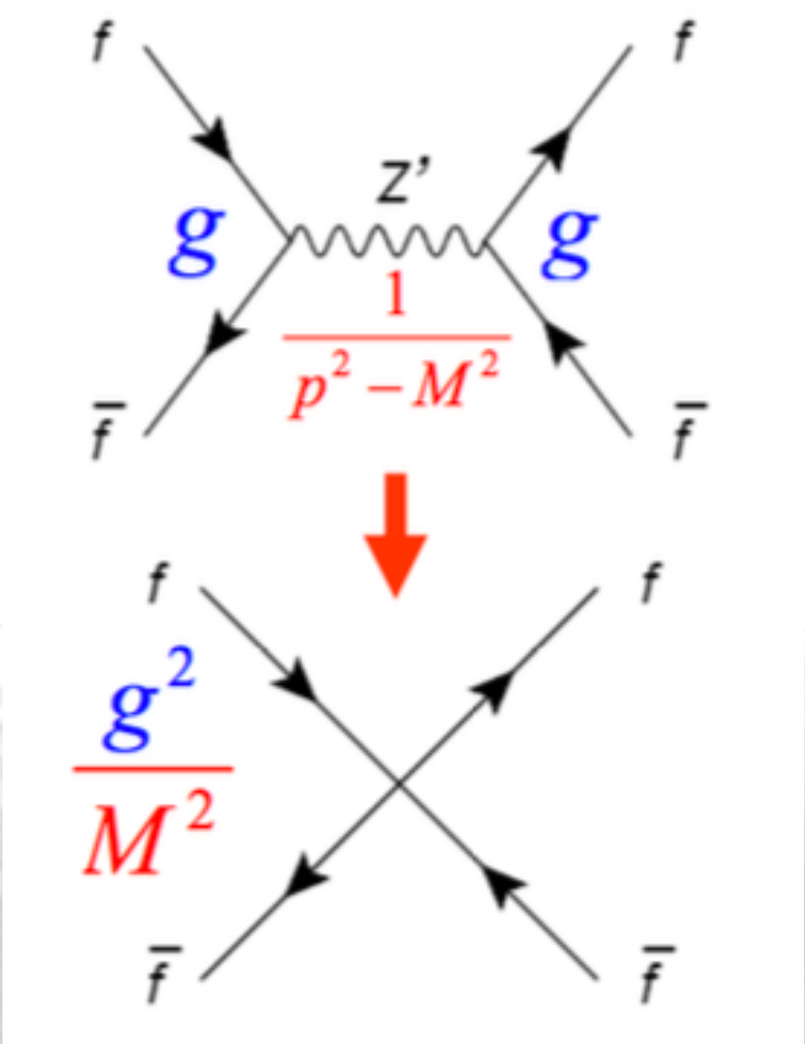
Top quark couplings: towards rare processes

- LHC Run2 opened 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)
- 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

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

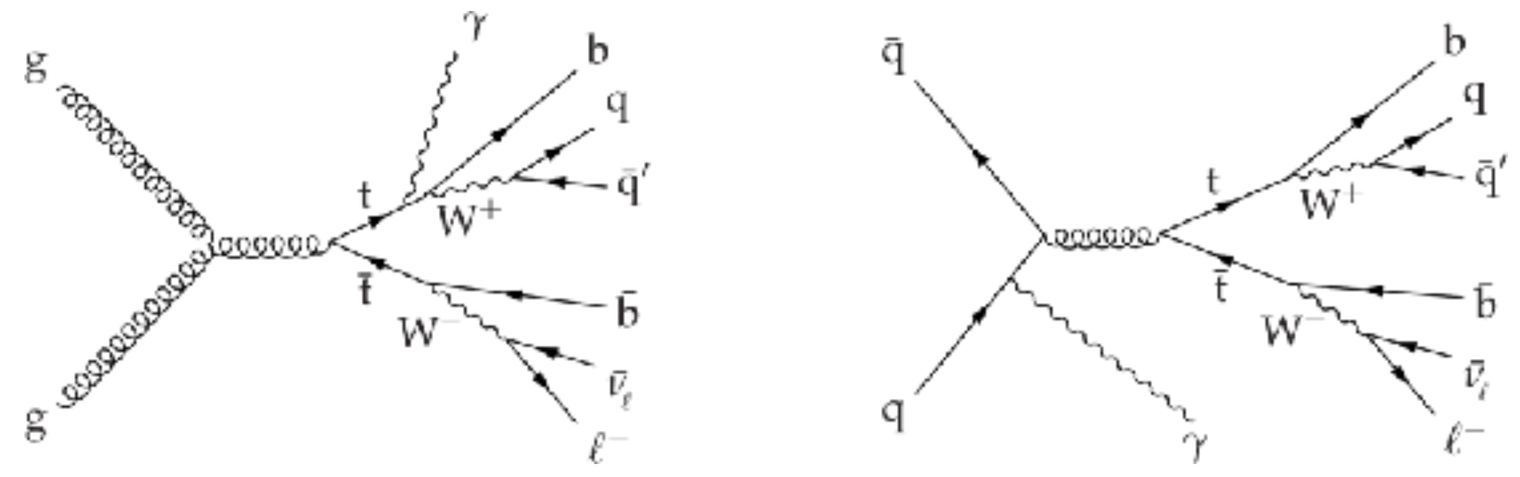


All results at: http://cern.ch/go/pNj7

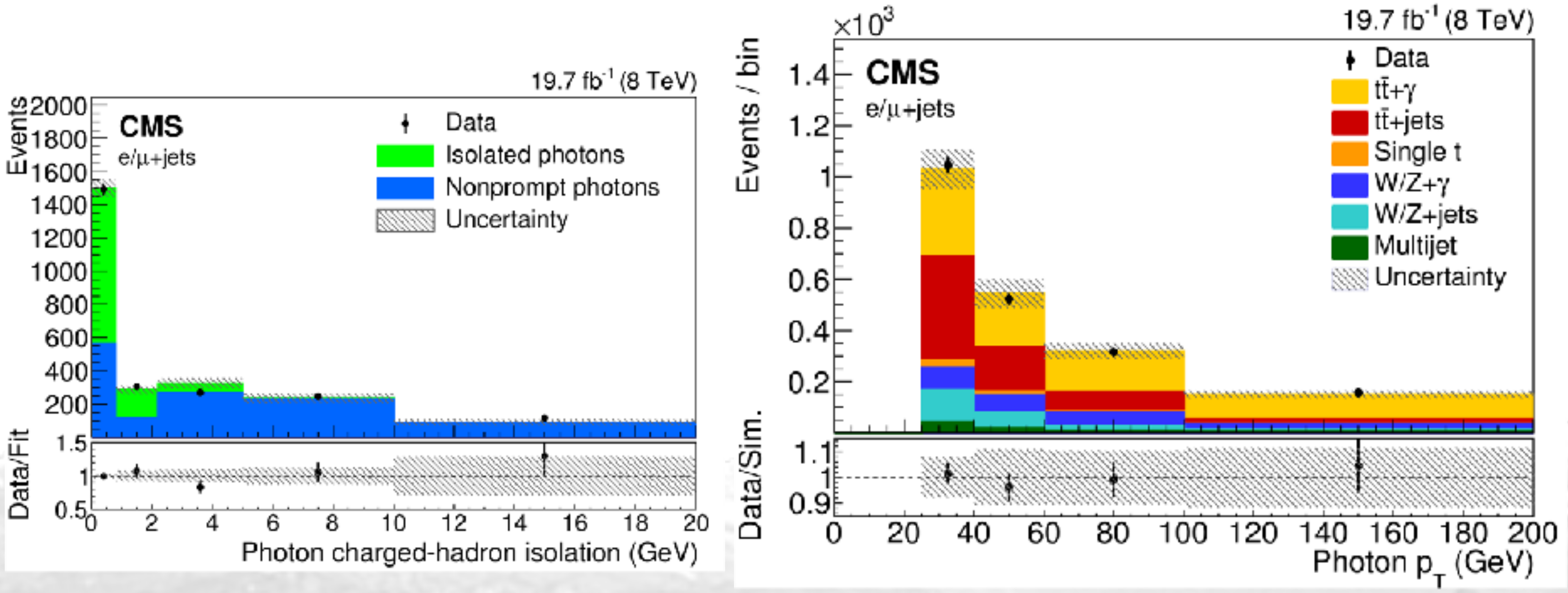


$t\bar{t}\gamma$ production

- cross section sensitive to radiative corrections and anomalous form factors
  - main background from events with a non-prompt or misidentified photon:
    - evaluated from data
  - cross section extracted in fiducial volume in agreement with the Standard Model prediction



JHEP 10 (2017) 006



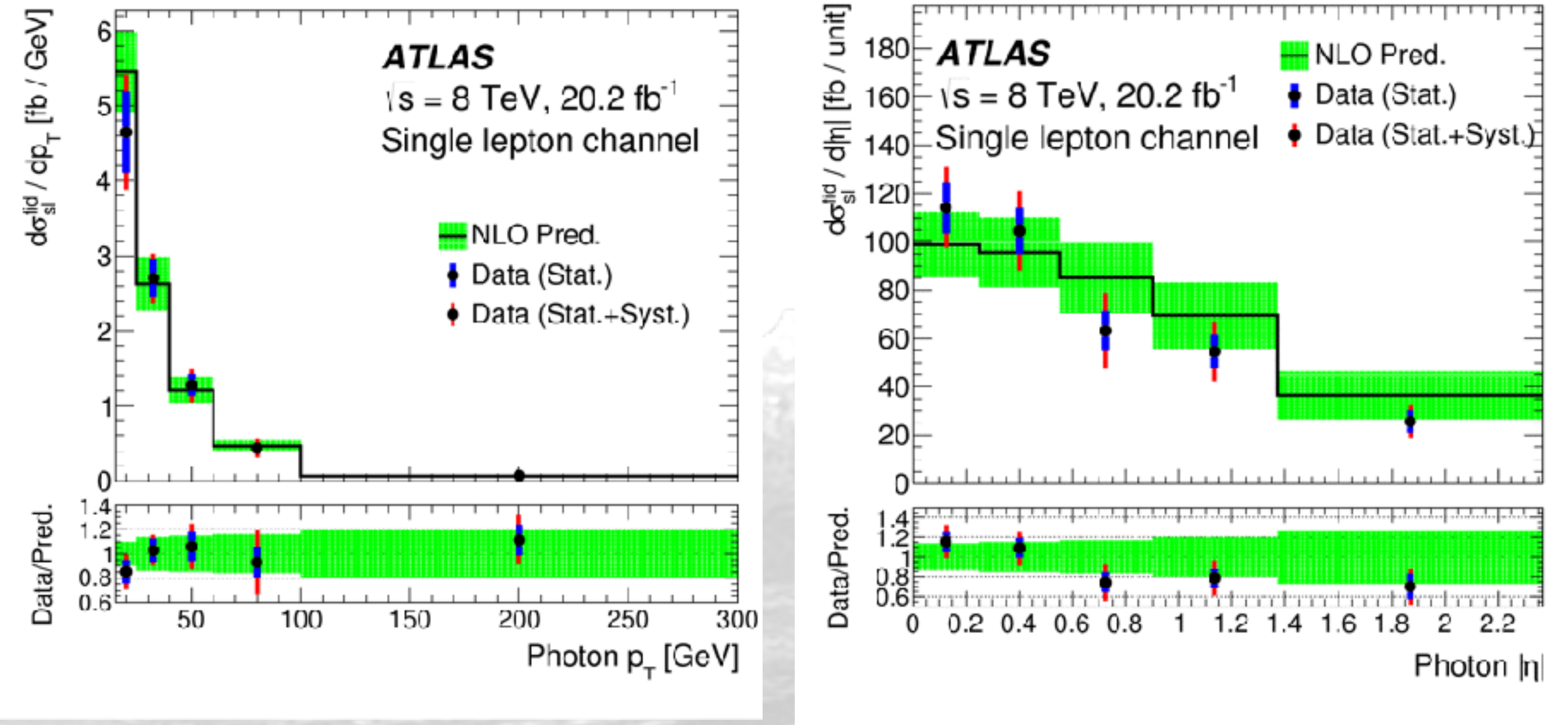
$$R = \frac{\sigma^{\text{fid}}_{t\bar{t}+\gamma}}{\sigma_{t\bar{t}}}$$

$$\sigma^{fid}_{tt+\gamma} = 127 \pm 27 \text{ fb}$$

$$R = (5.2 \pm 1.1) \times 10^{-4}$$

JHEP 11 (2017) 086

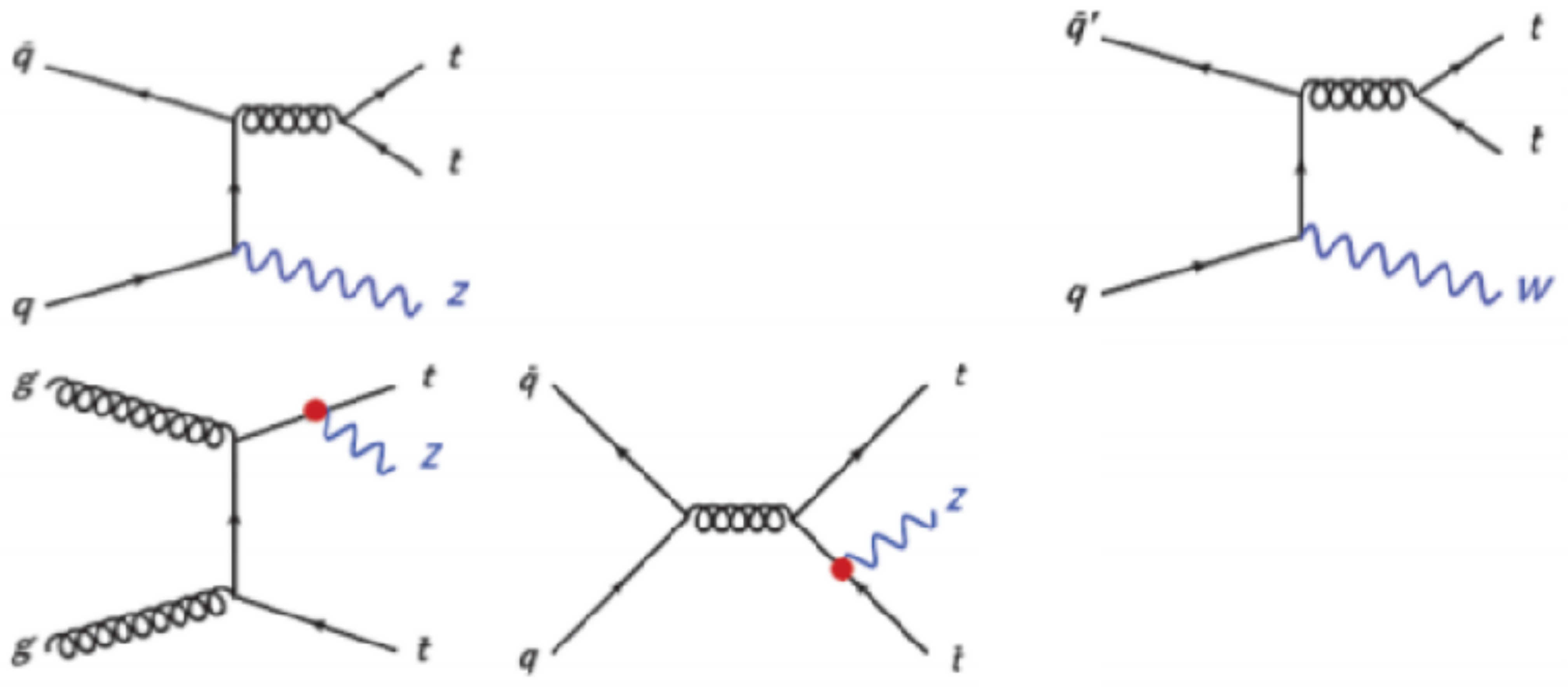
unfolded distributions at particle level



$$\sigma^{fid} = 139 \pm 18 \text{ fb}$$

$t\bar{t}$+W/Z production

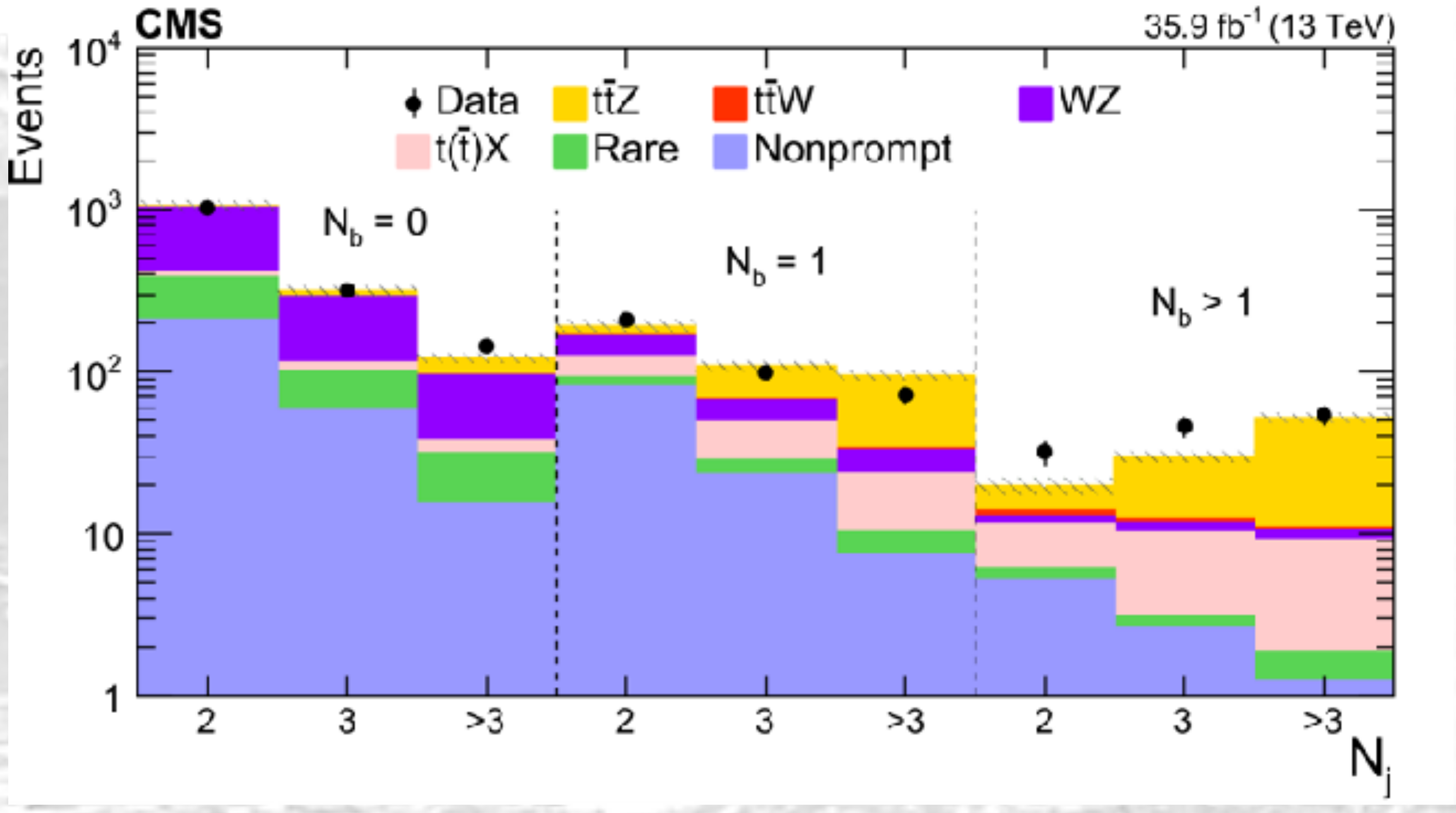
- cross section probes the t-Z coupling directly
  - t-W is produced by q-$\bar{q}$ annihilation (will lead to a tW-$\bar{t}$W asymmetry)



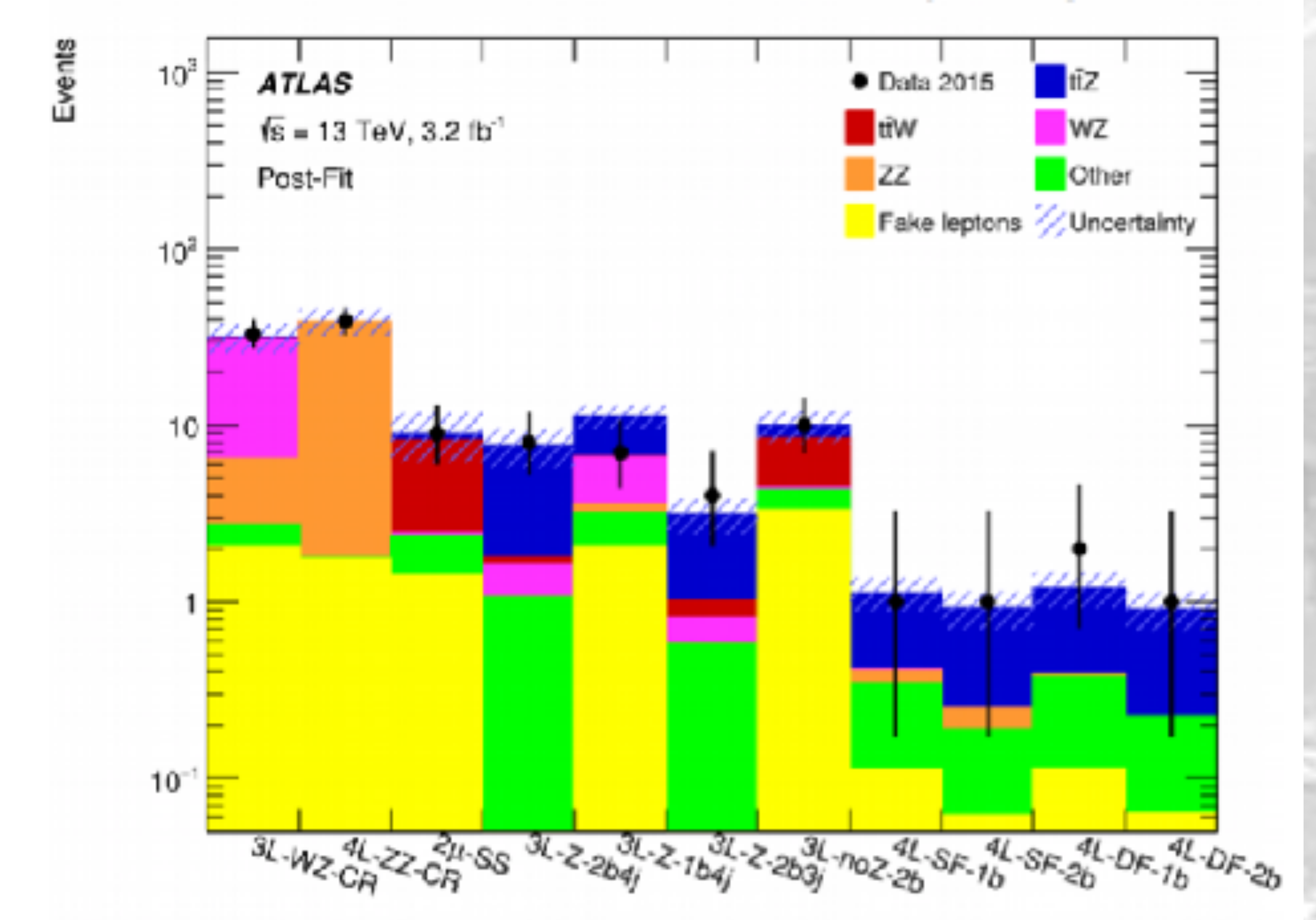
- measurement strategy
  - $t\bar{t}$Z: 3 lepton or 4 lepton channel
  - $t\bar{t}$W: 2 leptons with same sign
  - split by jet multiplicity
  - challenging background: fake/non-prompt leptons estimated using data
  - signal extracted using multivariate discriminant

- non-prompt background estimate
  - primary from $t\bar{t}$+semileptonic b-hadron decay or Z→ ll + misidentified lepton
  - estimated from data using a sample with loose isolated lepton (ratio method or matrix method)
    - lepton efficiency and fake rate measured in control samples

arXiv:1711.02547



EPJC 77 (2017) 40



$t\bar{t}$+W/Z production

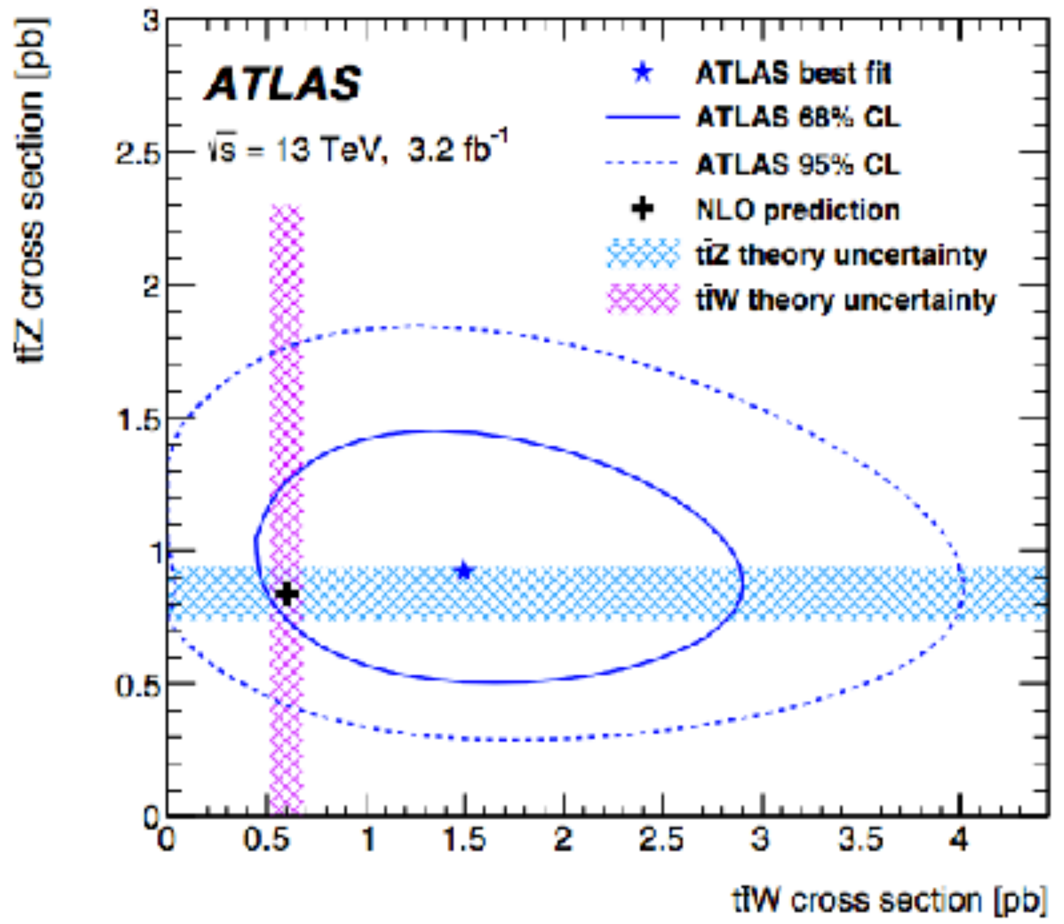
- signal extraction
  - $t\bar{t}Z$-$t\bar{t}W$: multidimensional likelihood fit to Njet and Nb
  - $t\bar{t}W$ (CMS): fit of the BDT discriminant
- limit on anomalous couplings
  - EFT: Constrains on Wilson coefficients for 8 dimension 6 operators
- the next steps are
  - go differential for all the processes
  - measure the properties of these new processes
  - measure multiple couplings simultaneously
  - use these handles to search for new physics

EPJC 77 (2017) 40

$\sigma(t\bar{t}Z) = 0.92 \pm 0.29$ (stat.) ± 0.10 (syst.) pb

$\sigma(t\bar{t}W) = 1.50 \pm 0.72$ (stat.) ± 0.33 (syst.) pb

ttZ: 3.9σ (3.4σ)
ttW: 2.2σ (1.0σ)

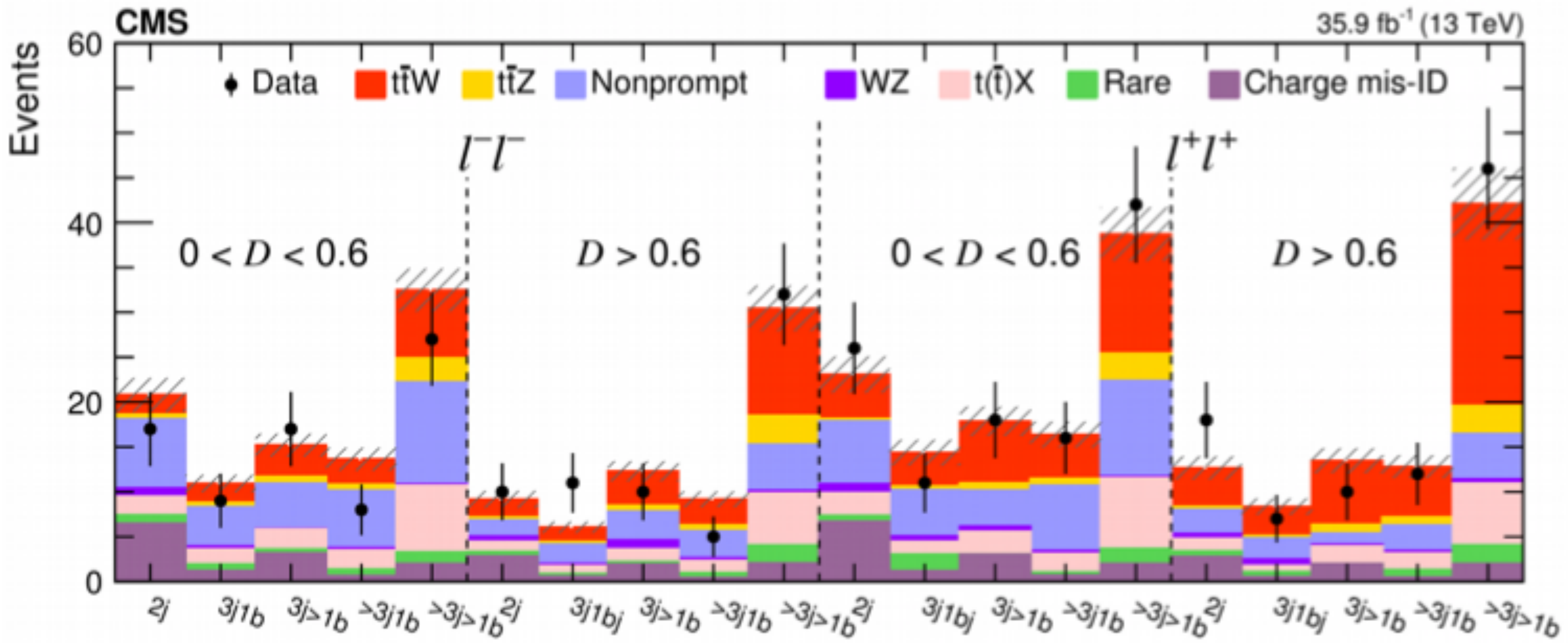


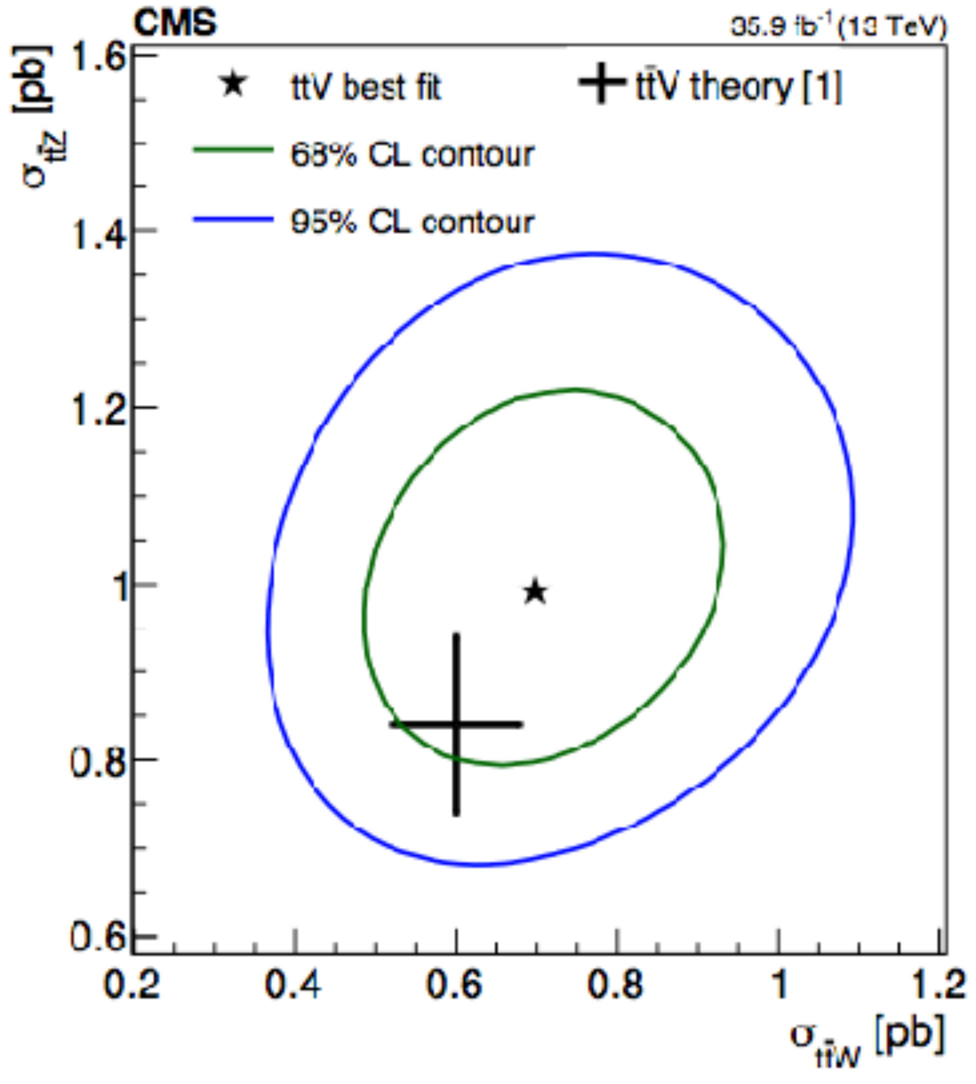
$$\sigma_{t\bar{t}Z} = 1.00^{+0.09}_{-0.08}(\text{stat.})^{+0.12}_{-0.10}(\text{sys.})\ \text{pb}$$

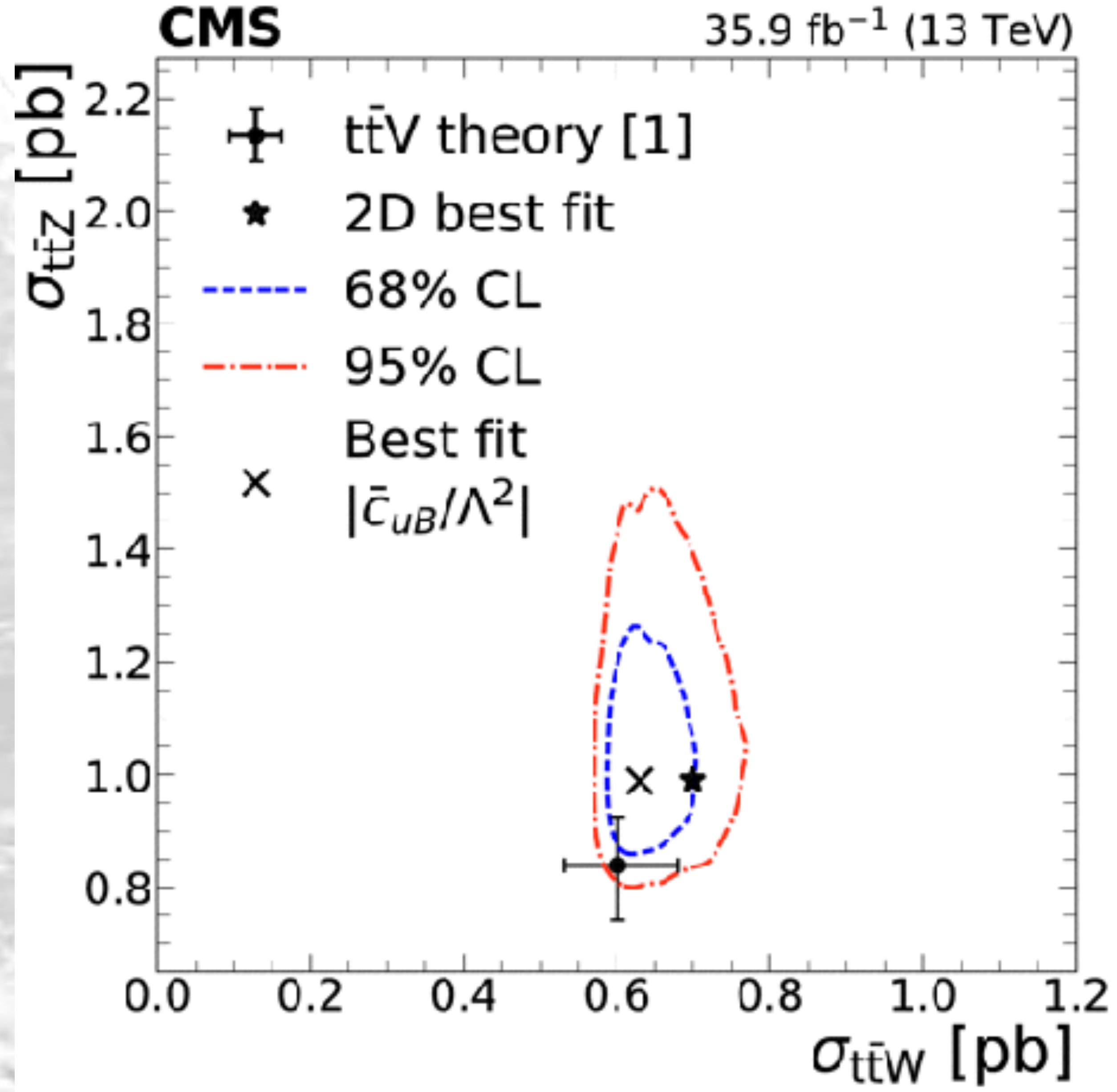
$$\sigma_{t\bar{t}W} = 0.80^{+0.12}_{-0.11}(\text{stat.})^{+0.13}_{-0.12}(\text{sys.})\ \text{pb}$$

ttZ: >5σ (>5σ)
ttW: 5.3σ (4.5σ)

arXiv:1711.02547



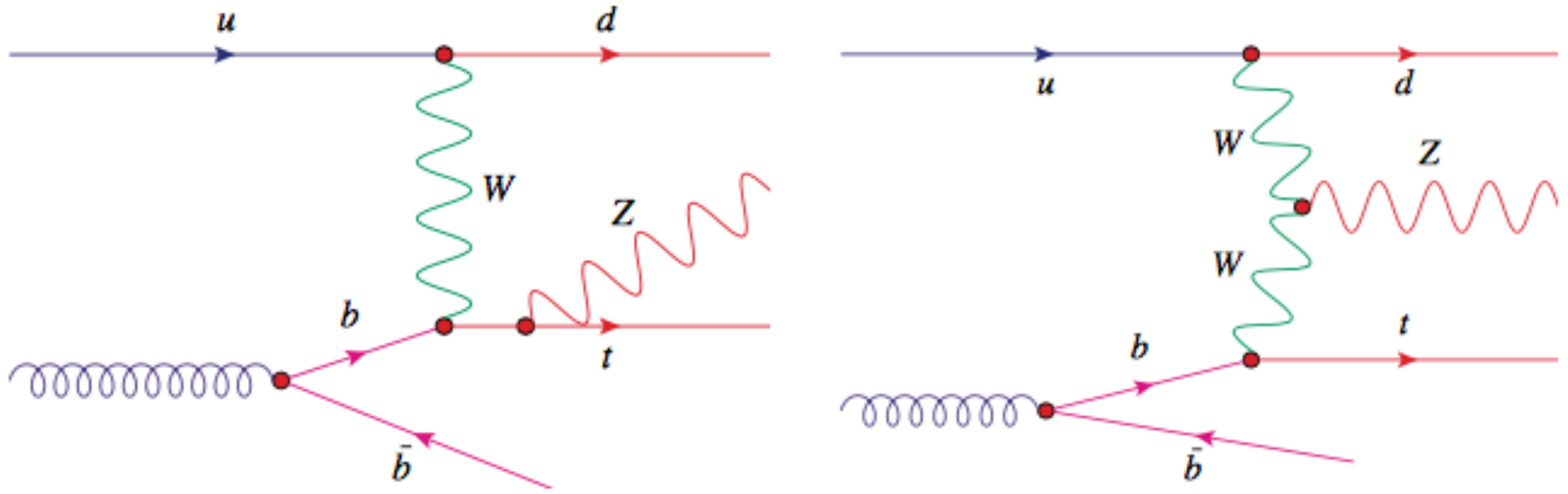




tZq production

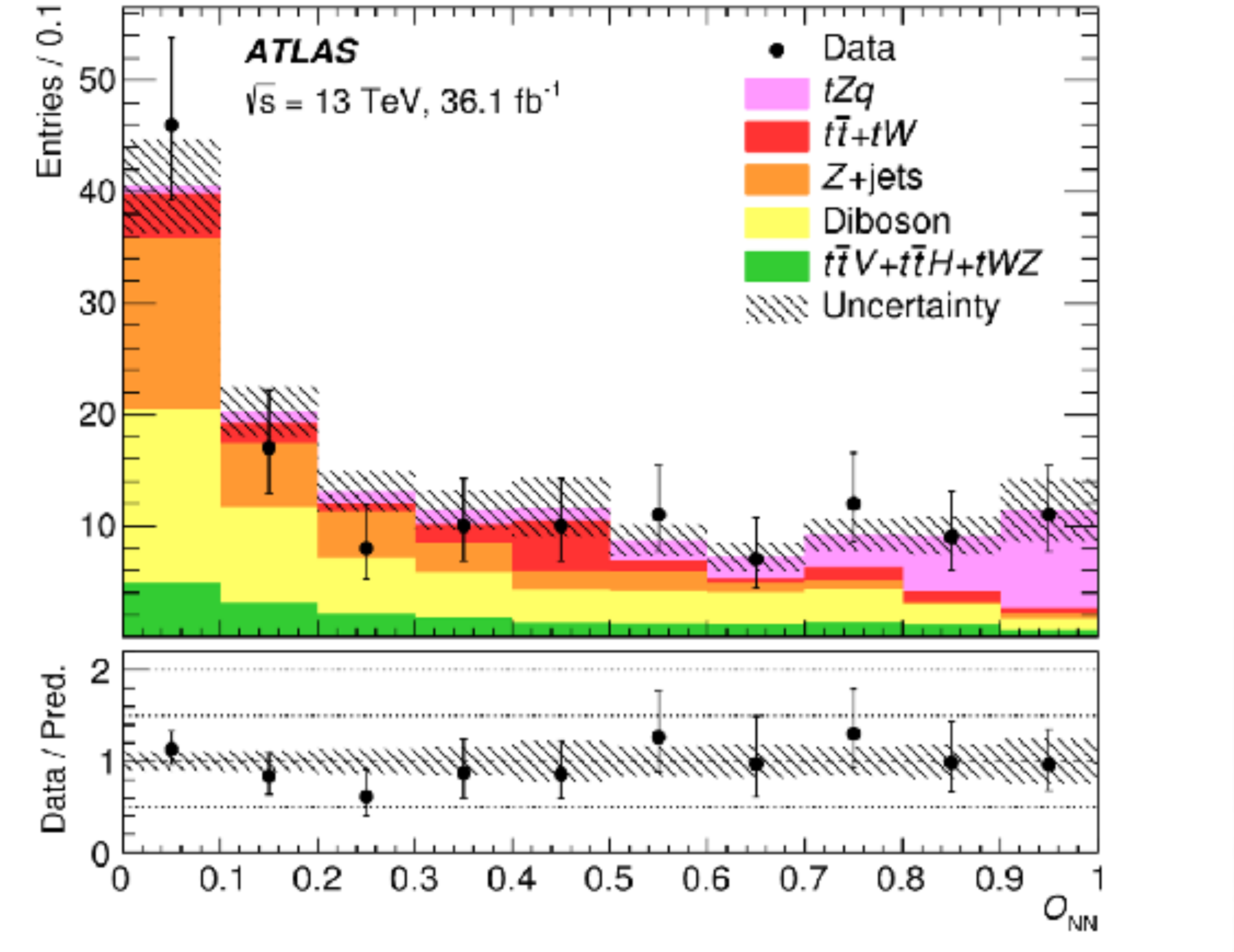
- cross section probes the t-Z coupling directly
  - also sensitive to the WWZ coupling

- measurement strategy
  - trilepton channel
  - main background: fake/non-prompt leptons (in $t\bar{t}$ or Drell-Yan)
    - estimation using data or MC corrected in control regions
  - signal extracted using multivariate discriminant



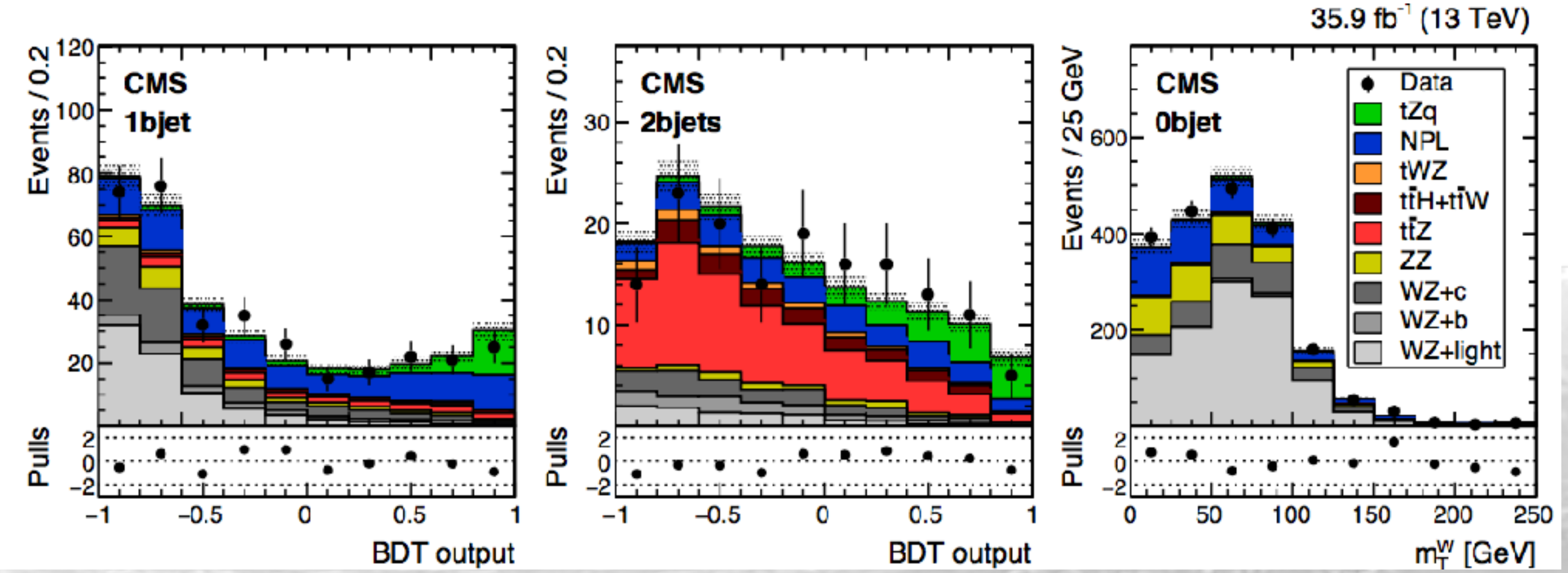
PLB 779 (2018) 358

Phys. Lett. B 780 (2018) 557



obs: 4.2 σ (exp: 5.4 σ)

Matrix element weight added as input to the BDT to increase separation simultaneous fit in 2 b-tag multiplicity regions

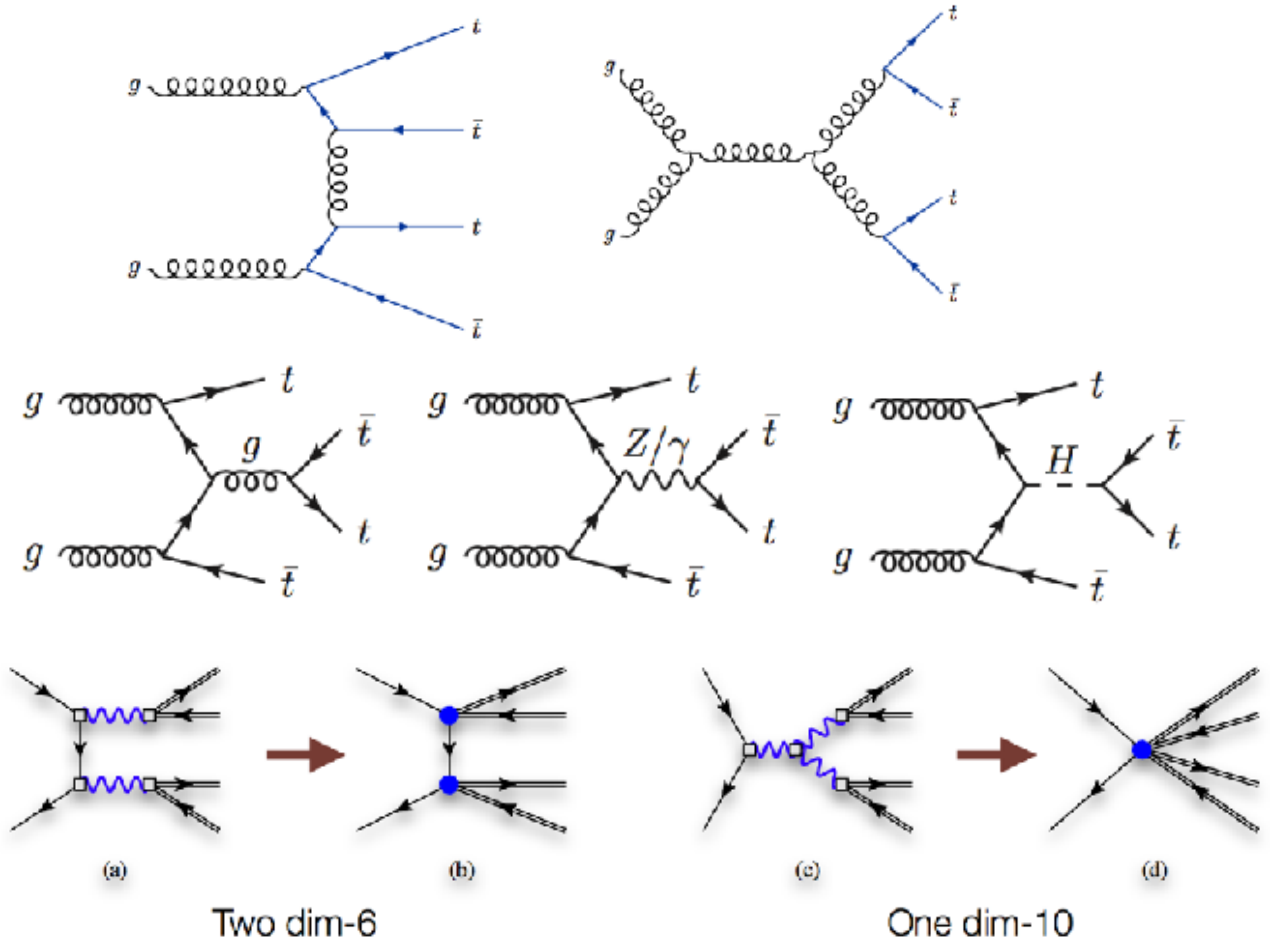


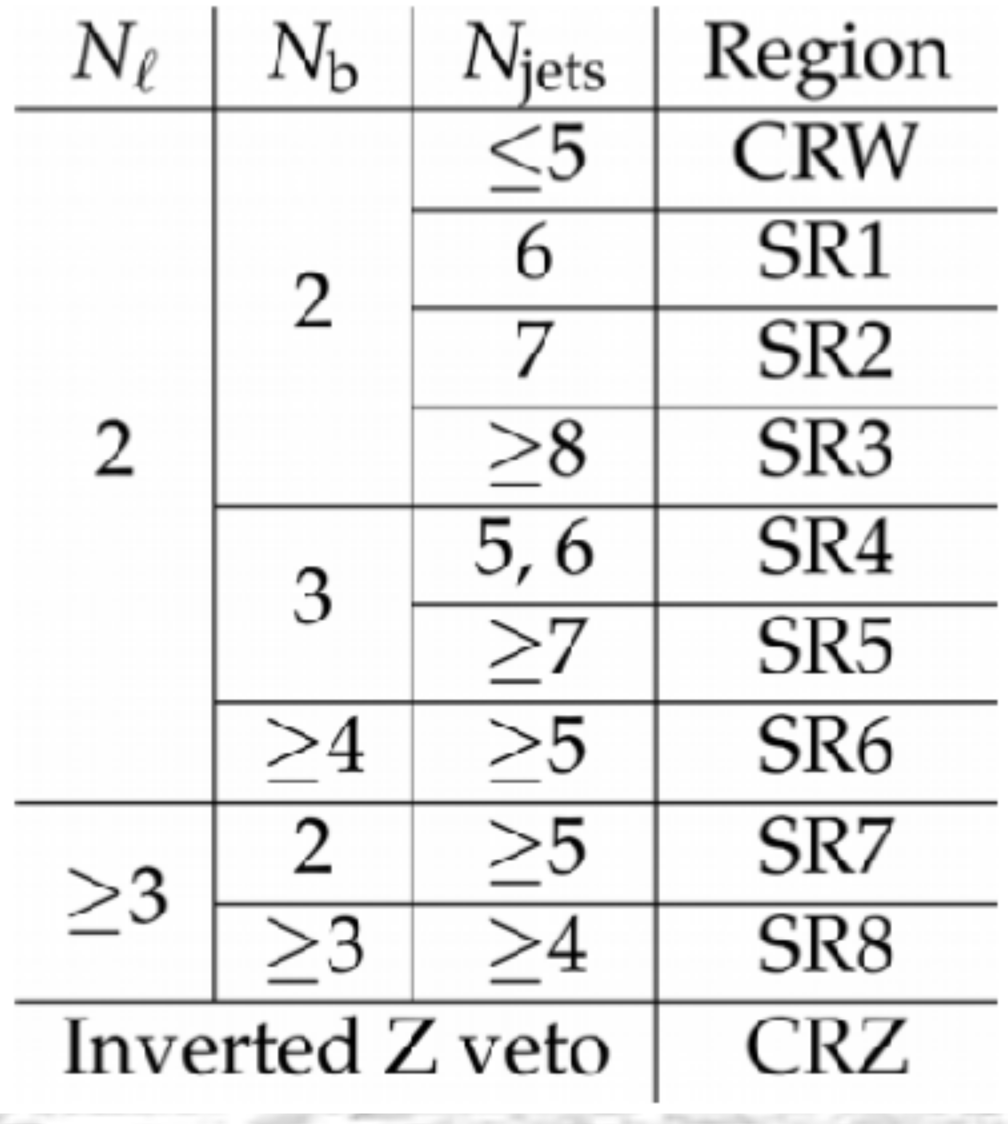
obs: 3.7 σ (exp: 3.1 σ)

4 top production

- very rare process
  - SM expected cross section: ~ 10 fb
  - not yet observed
  - very sensitive to New Physics: new resonances, e.g. color-octet/singlet vectors/ scalars, top compositeness, EFT: 4t operator is not constrained elsewhere

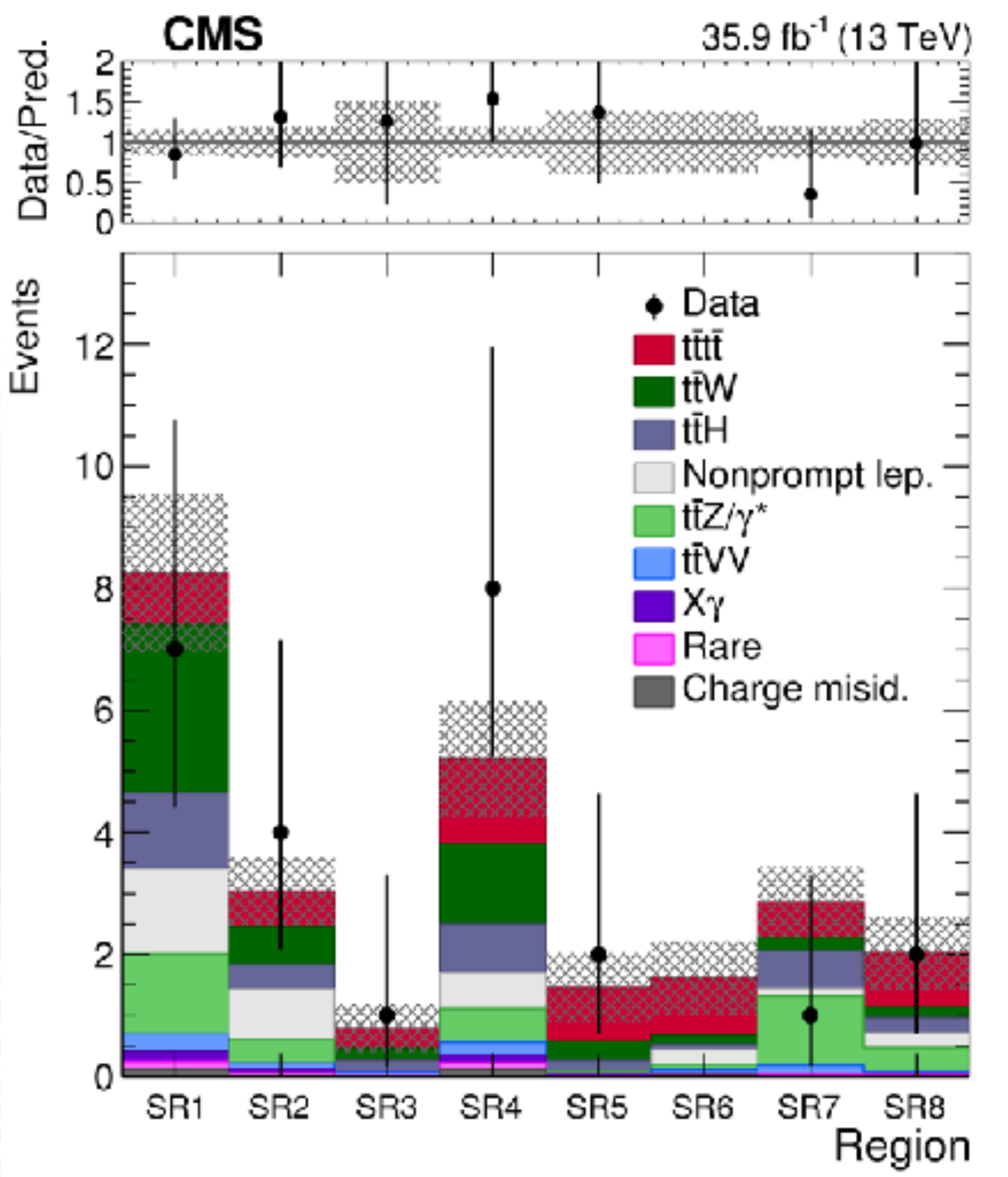
- analysis strategy
  - both ljets/OS and same-sign/multilepton channel
  - background:
    - multilepton: $t\bar{t}V$ and fake
    - ljets: $t\bar{t}+b\bar{b}$





N_ℓ	N_b	N_jets	Region
2	2	≤5	CRW
		6	SR1
		7	SR2
		≥8	SR3
	3	5, 6	SR4
		≥7	SR5
	≥4	≥5	SR6
≥3	2	≥5	SR7
	≥3	≥4	SR8
Inverted Z veto			CRZ

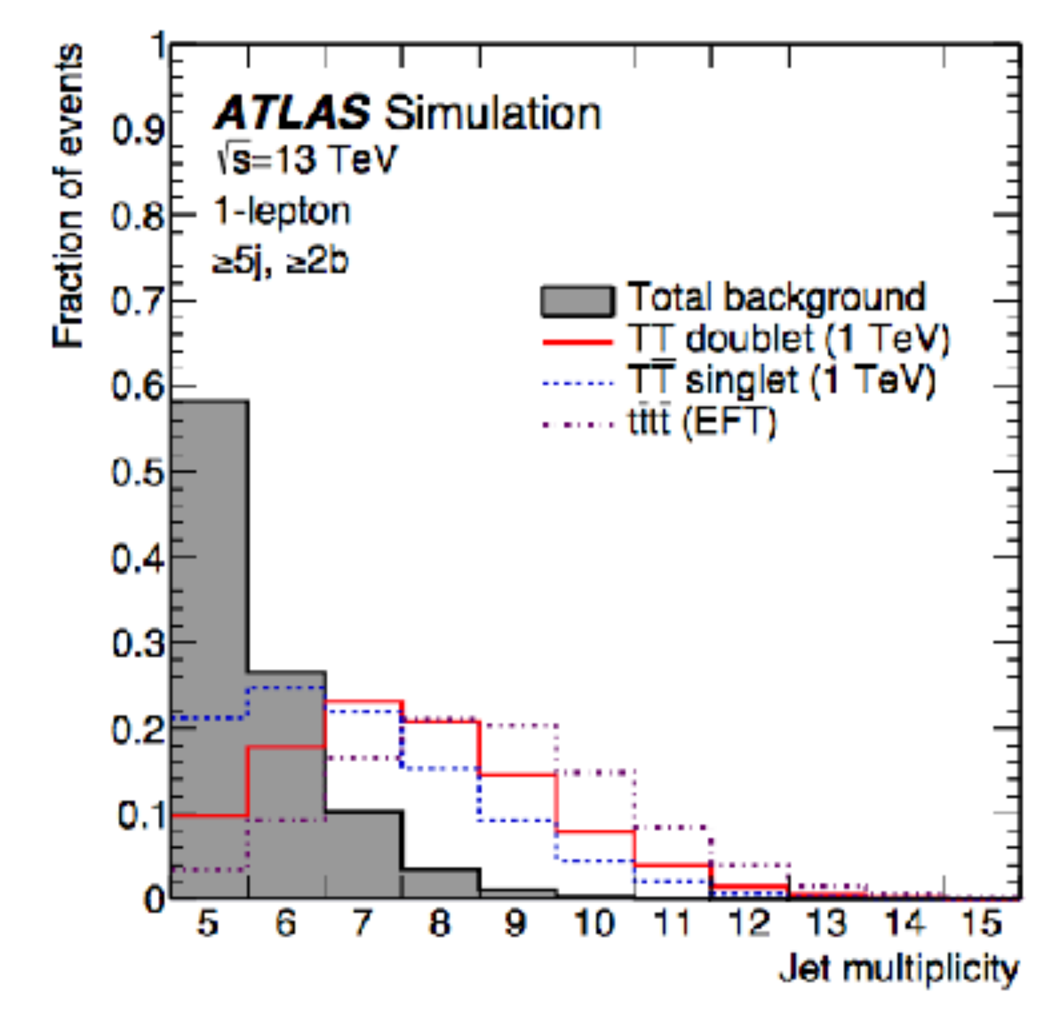
EPJC 78 (2018) 140



$$\sigma = 16.9^{+13.8}_{-11.4}\ \mathrm{fb}$$

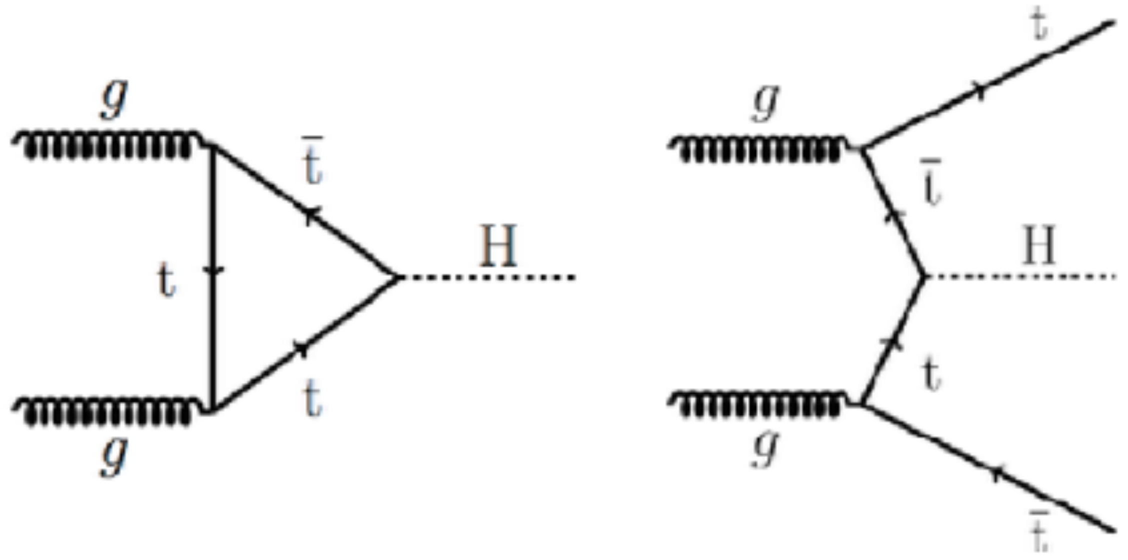
upper limit: 4x σ_{4t} SM

arXiv:1803.09678

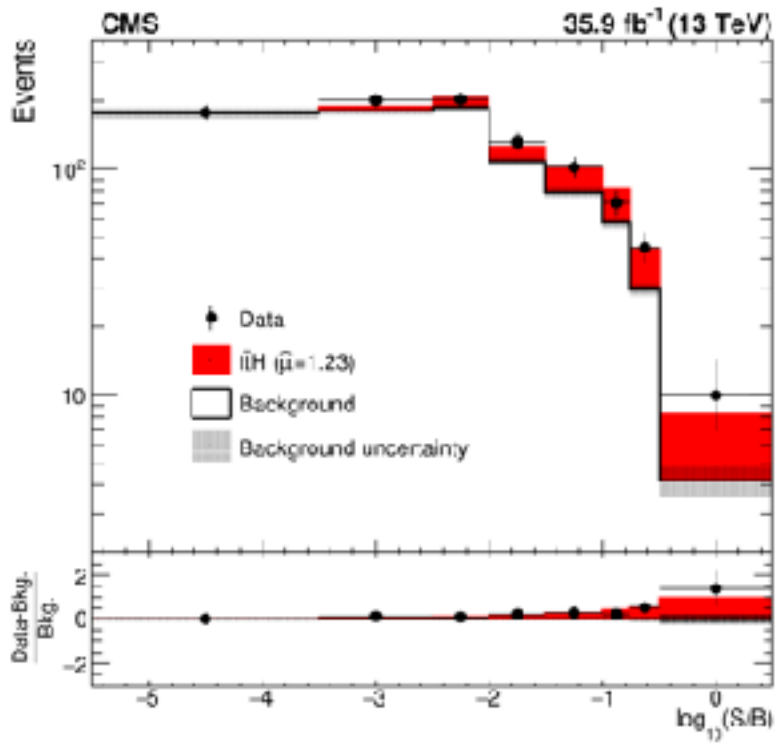


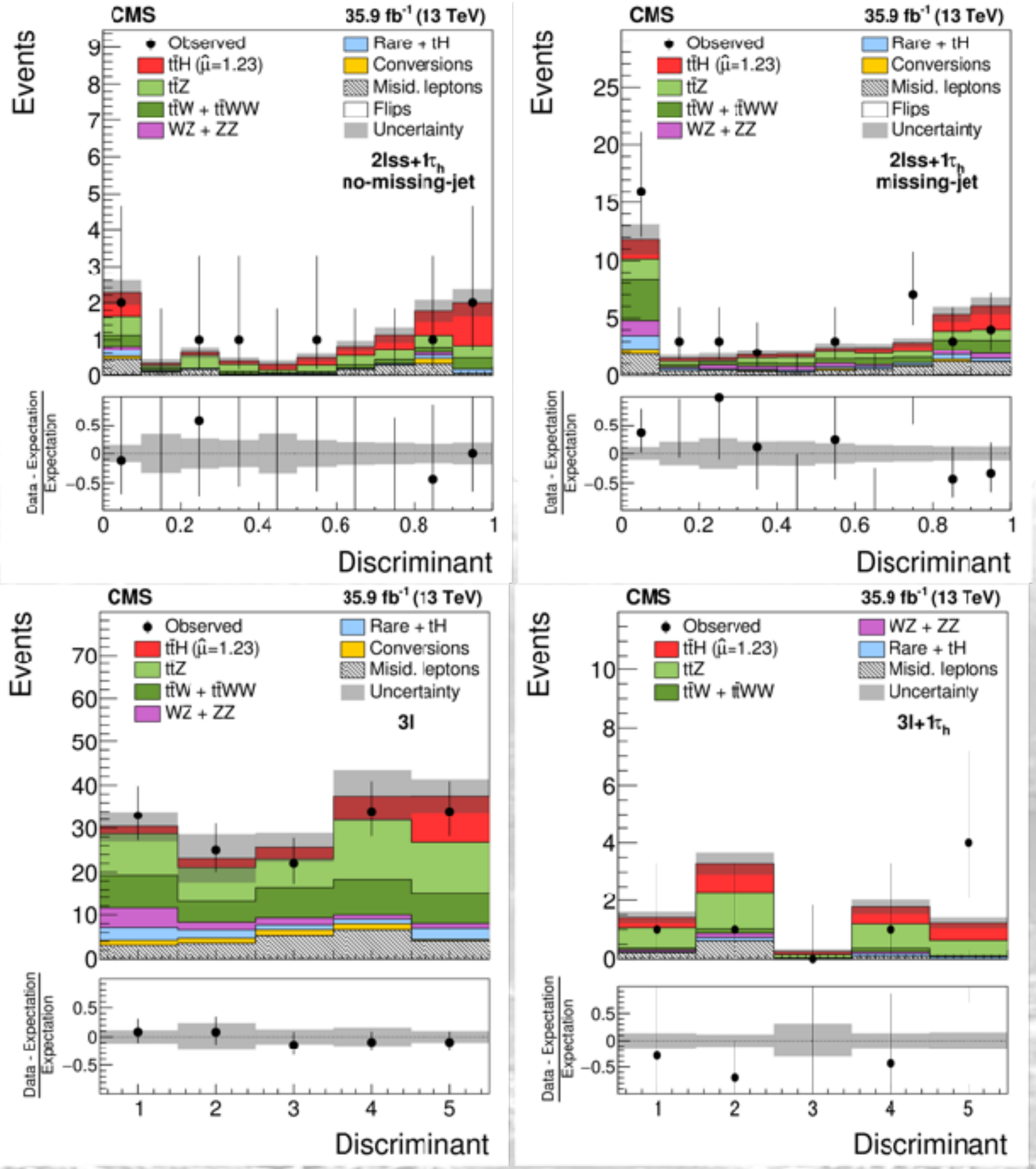
top-Higgs coupling

- the top quark has the strongest coupling to the Higgs boson
  - crucial to measure this coupling directly
  - accessible directly by the $t\bar{t}H$ cross section ($\sigma \sim 510$ fb @ 13 TeV)
- analysis strategy: try to measure all Higgs decay channels
  - $t\bar{t}$ + b-jets ($H \rightarrow b\bar{b}$): large branching ratio, but large background
  - $t\bar{t}$ + leptons ($H \rightarrow WW^*, ZZ^*, \tau\tau$): lower rate, low SM backgrounds
  - $t\bar{t} + \gamma\gamma$ ($H \rightarrow \gamma\gamma$): very clean final state, but small rate
- leptonic final states
  - channels: 2ℓSS, 3ℓ, 4ℓ, $1\ell+2\tau_{had}$, $2\ell\text{SS}+1\tau_{had}$, $2\ell\text{OS}+1\tau_{had}$, $3\ell+1\tau_{had}$
  - main backgrounds: ttV, VV, non-prompt/fake leptons in $t\bar{t}$
  - split by lepton flavour, charge and b-jet multiplicity
  - signal extraction using multivariate discriminant



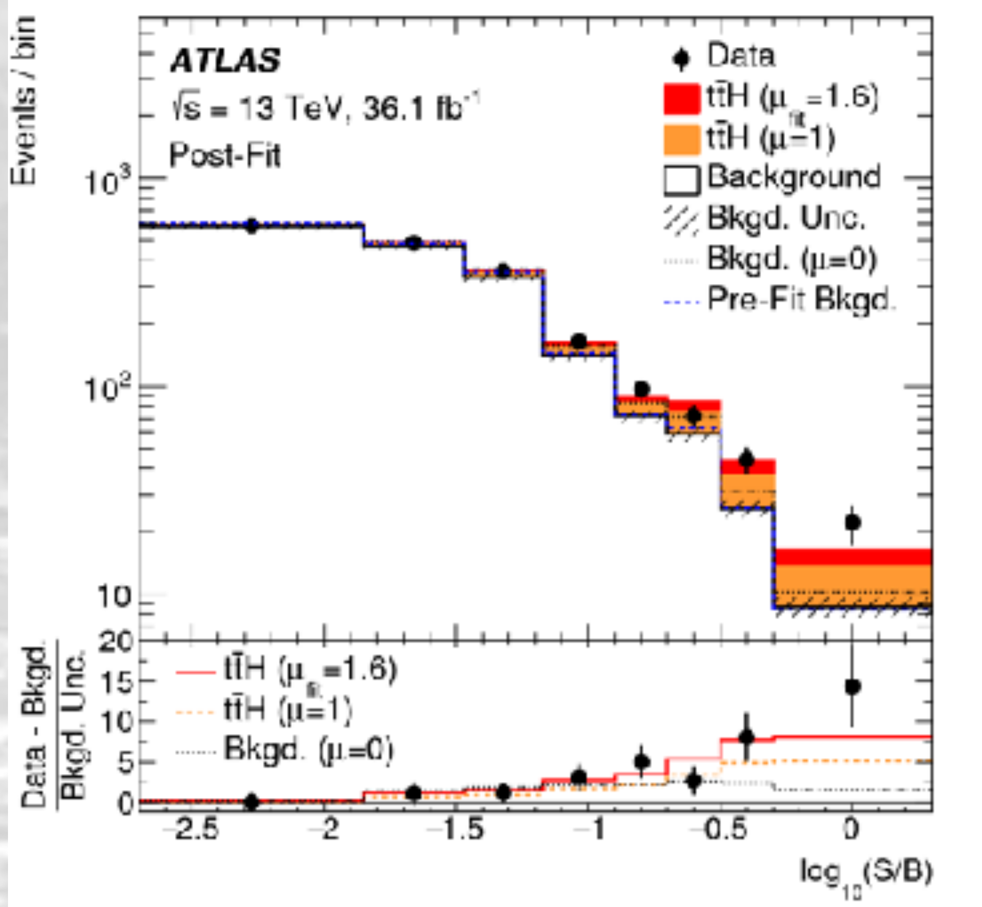
arXiv:1803.05485

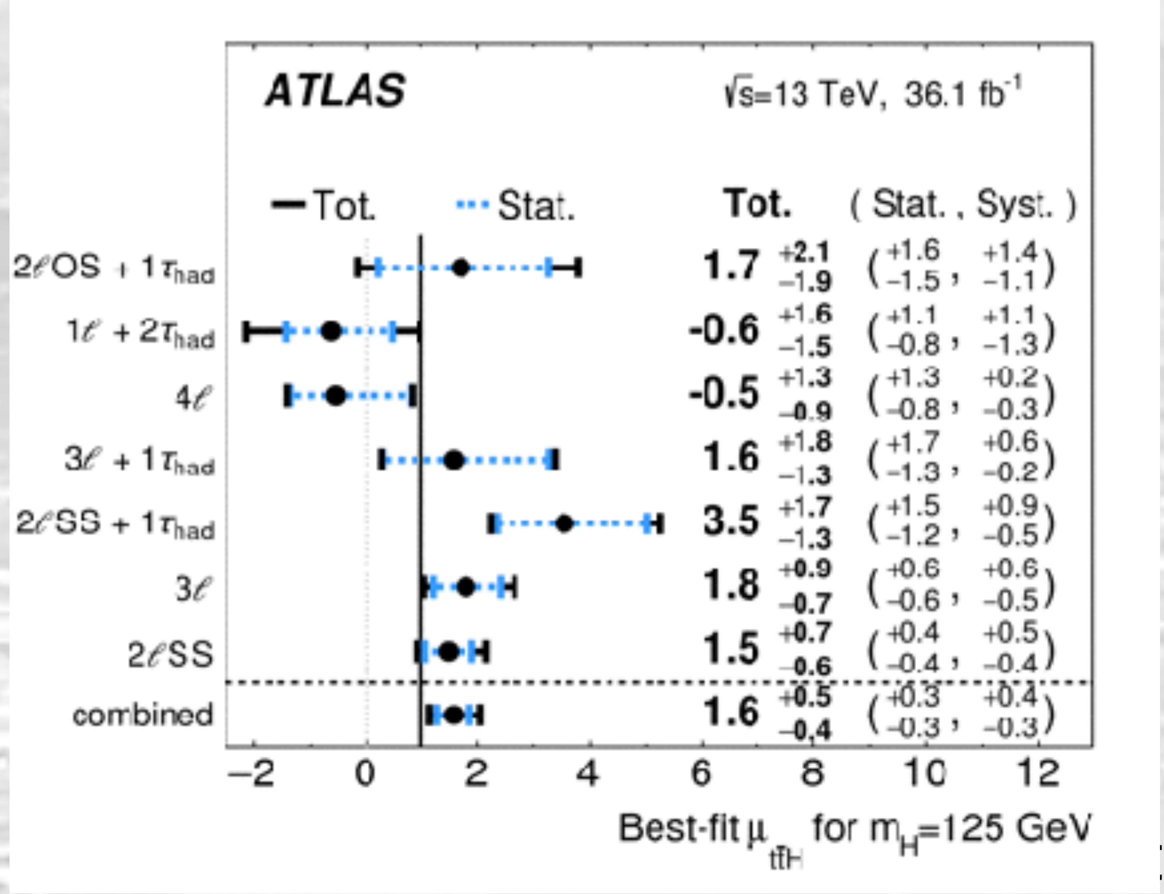




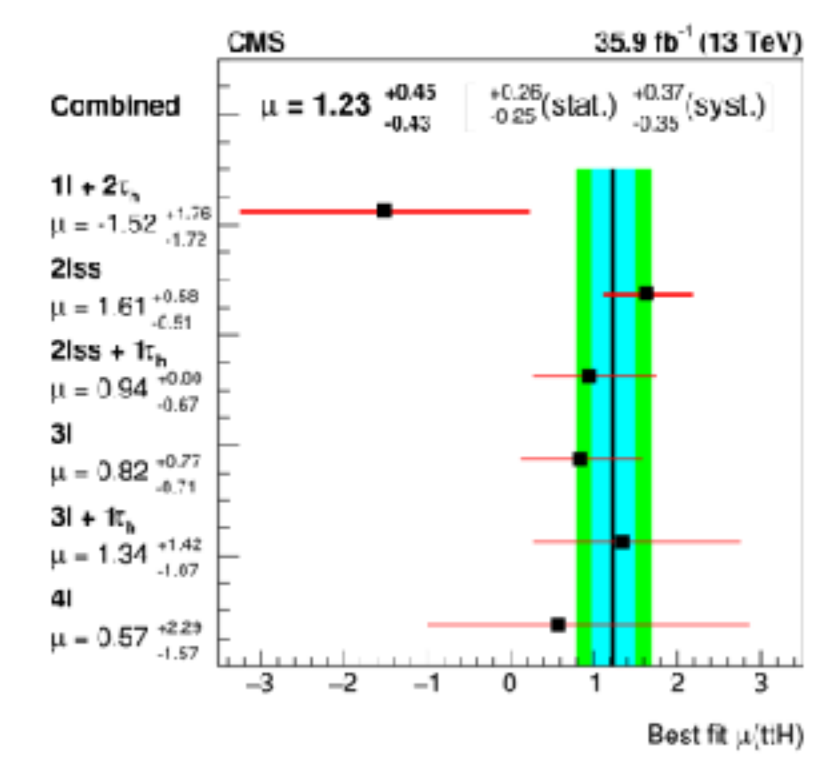
PRD 97 (2018) 072003

evidence for ttH: 4.1σ (2.8σ exp)



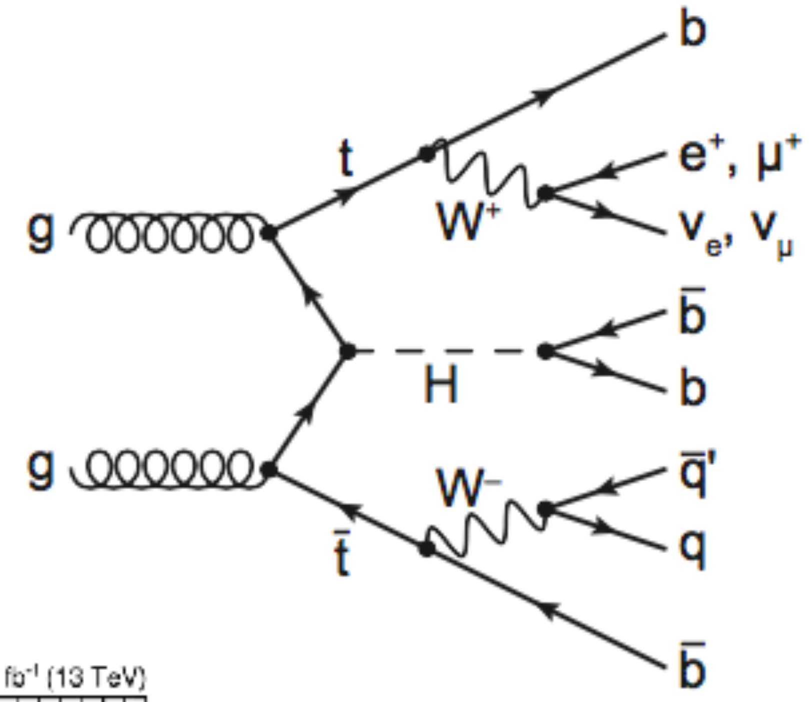


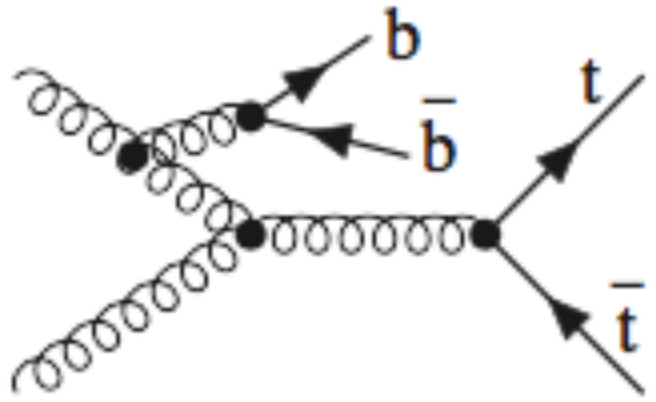
evidence for ttH: 3.2σ (2.8σ exp)



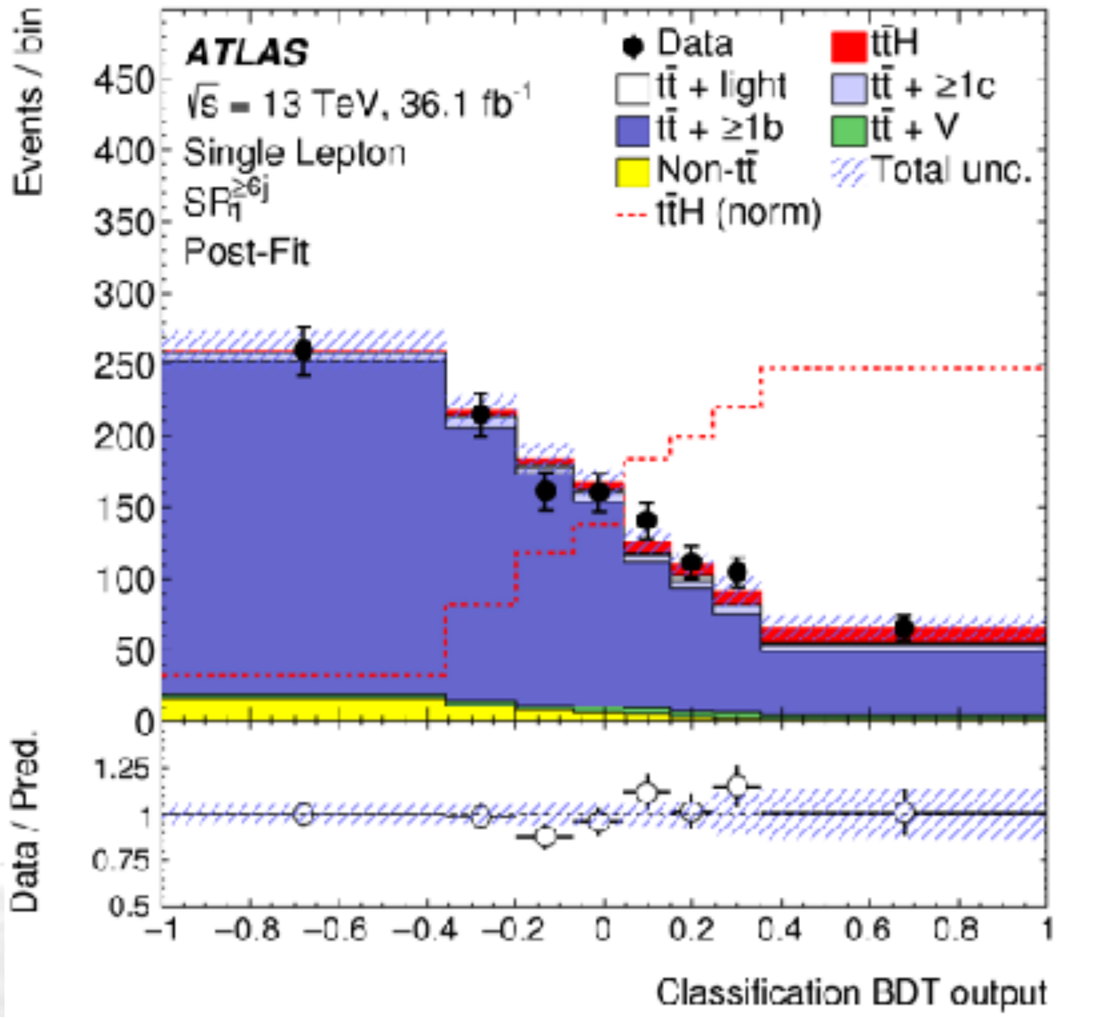
top-Higgs coupling in the $t\bar{t}$+b-jets channel

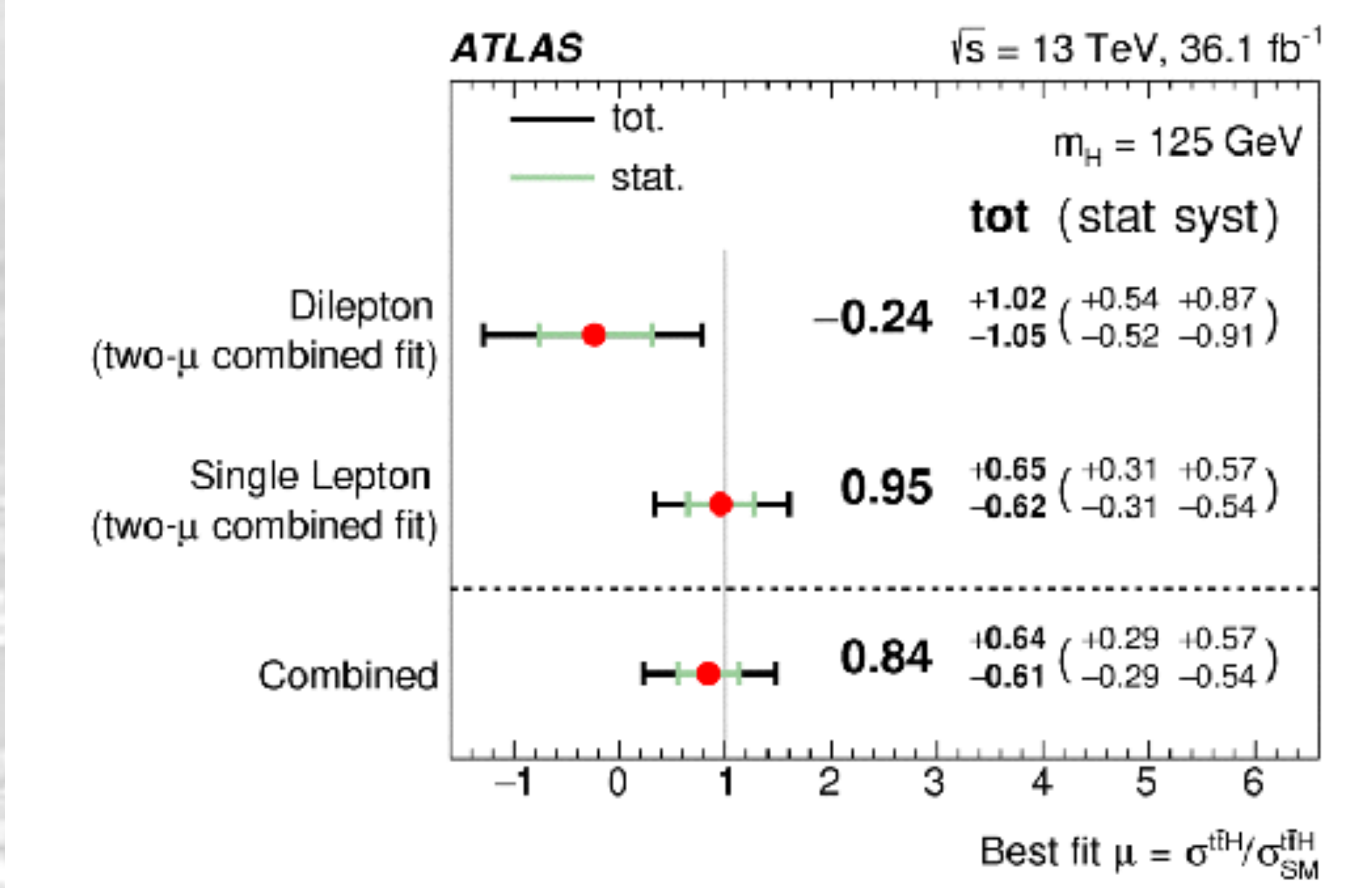
- $t\bar{t}$+H($b\bar{b}$) final state
  - channels: 1ℓ or 2ℓ + ≥4 jets, ≥3 b-tag
  - challenging because of combinatorics and $t\bar{t}$+heavy flavour background
  - heavily rely on multivariate discriminants
  - systematics are dominant (modelling of $t\bar{t}b\bar{b}$), constrained by data

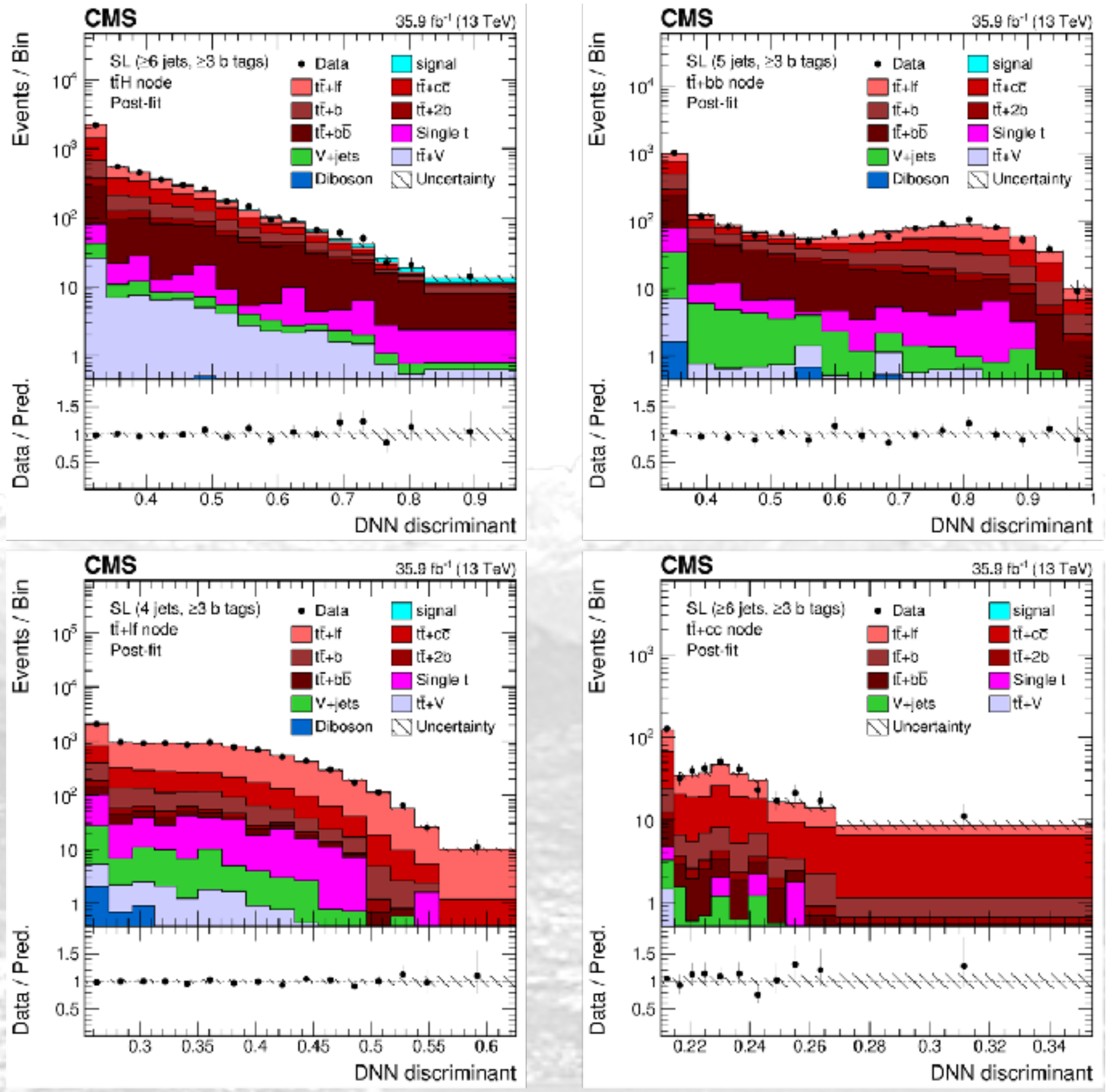


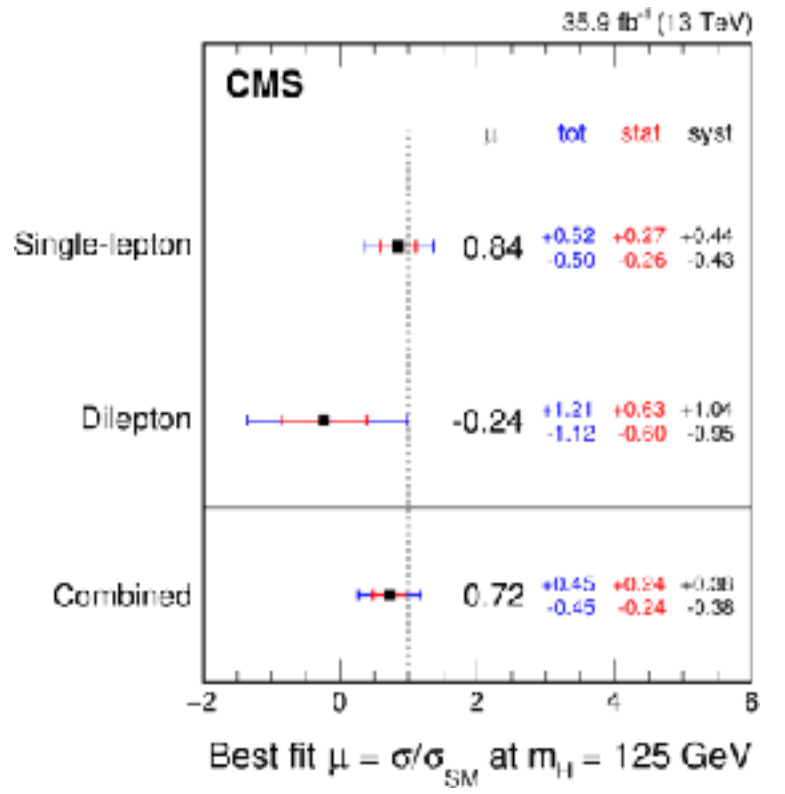


PRD97 (2018) 072016

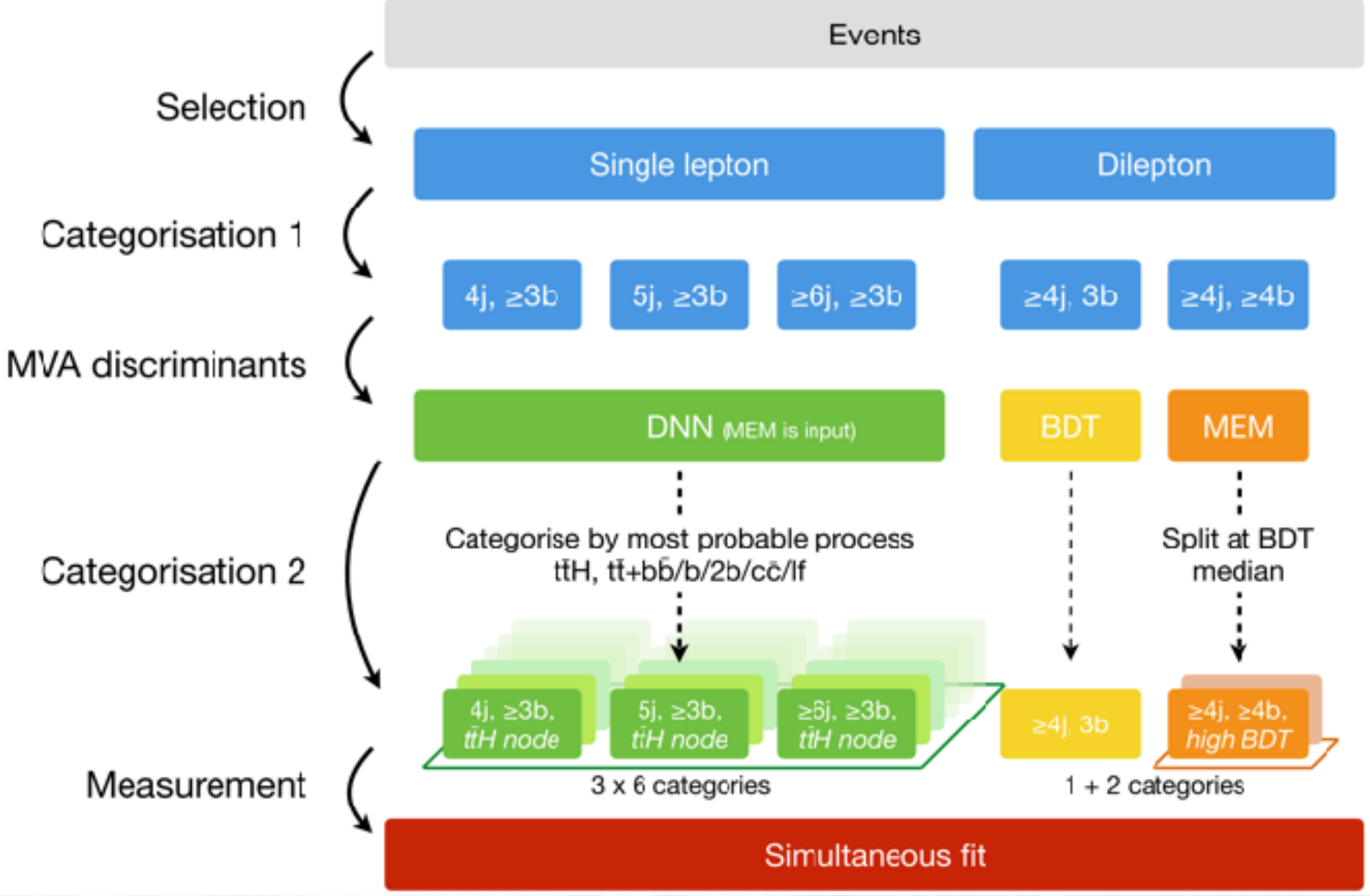








arXiv:1804.03682



Events

Selection

Single lepton | Dilepton

Categorisation 1

4j, ≥3b | 5j, ≥3b | ≥6j, ≥3b | ≥4j, 3b | ≥4j, ≥4b

MVA discriminants

DNN (MEM is input) | BDT | MEM

Categorisation 2

Categorise by most probable process tt̄H, tt̄+bb̄/b/2b/cc̄/lf

Split at BDT median

4j, ≥3b, ttH node | 5j, ≥3b, ttH node | ≥6j, ≥3b, ttH node | ≥4j, 3b | ≥4j, ≥4b, high BDT

3 x 6 categories

1 + 2 categories

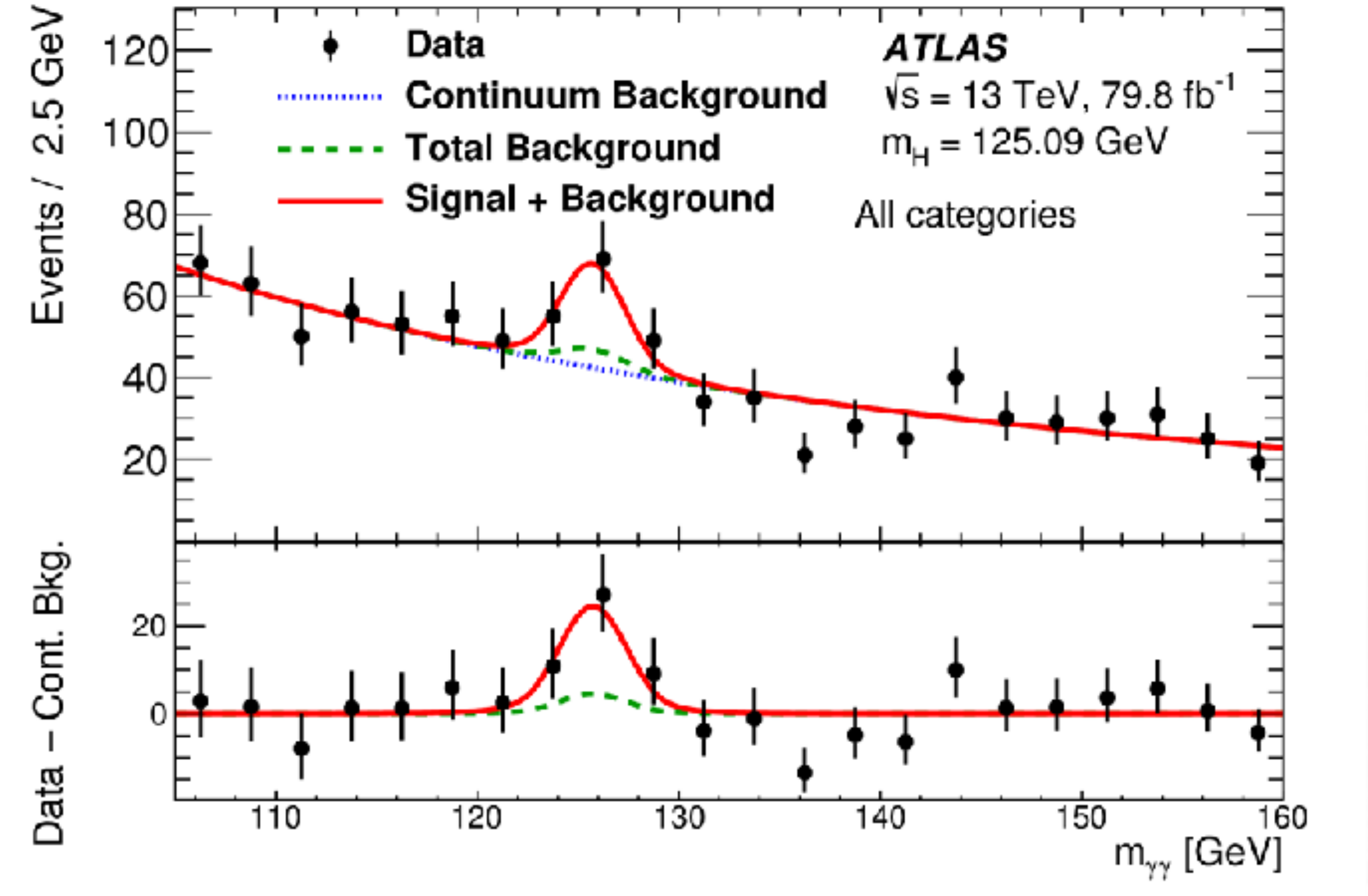
Measurement

Simultaneous fit

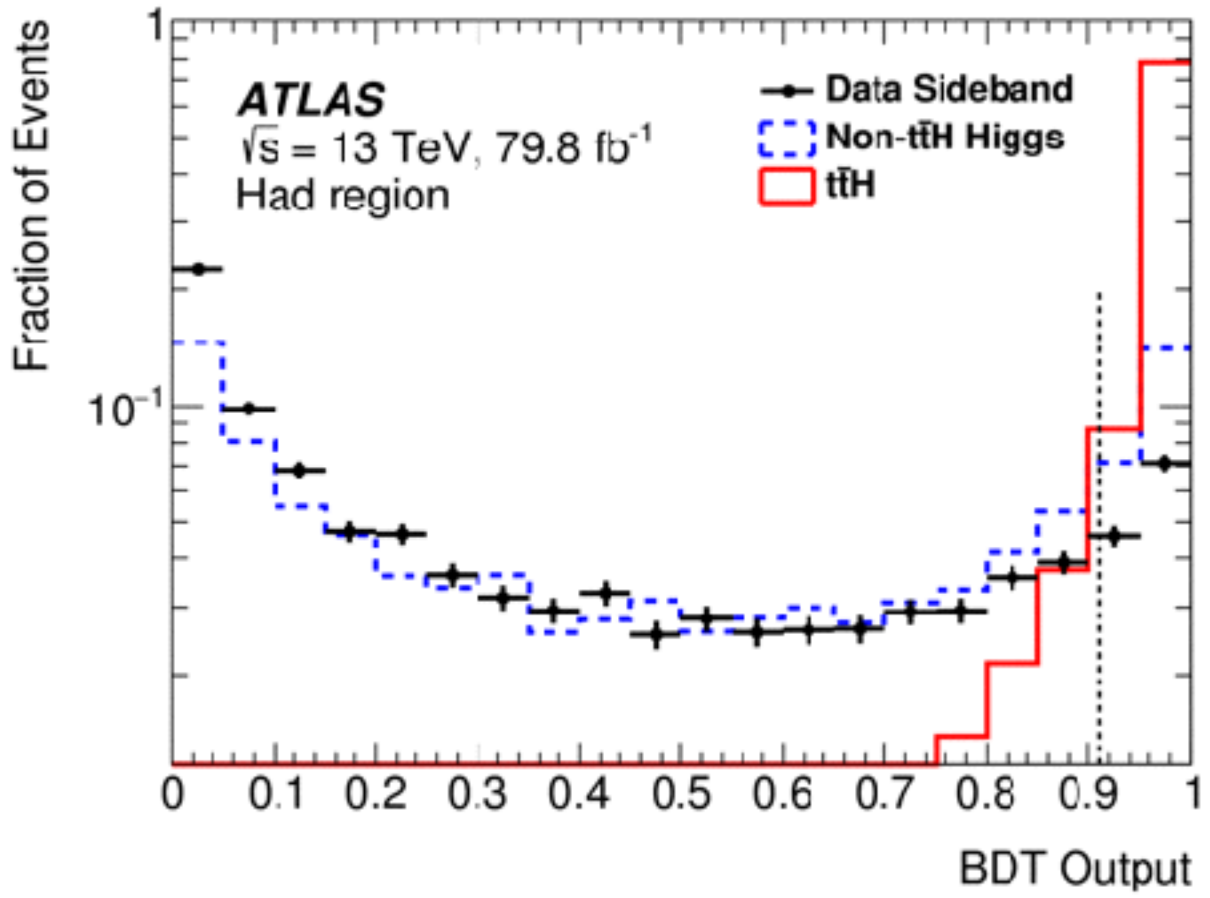
top-Higgs coupling in the γγ channel

arXiv:1806.00425

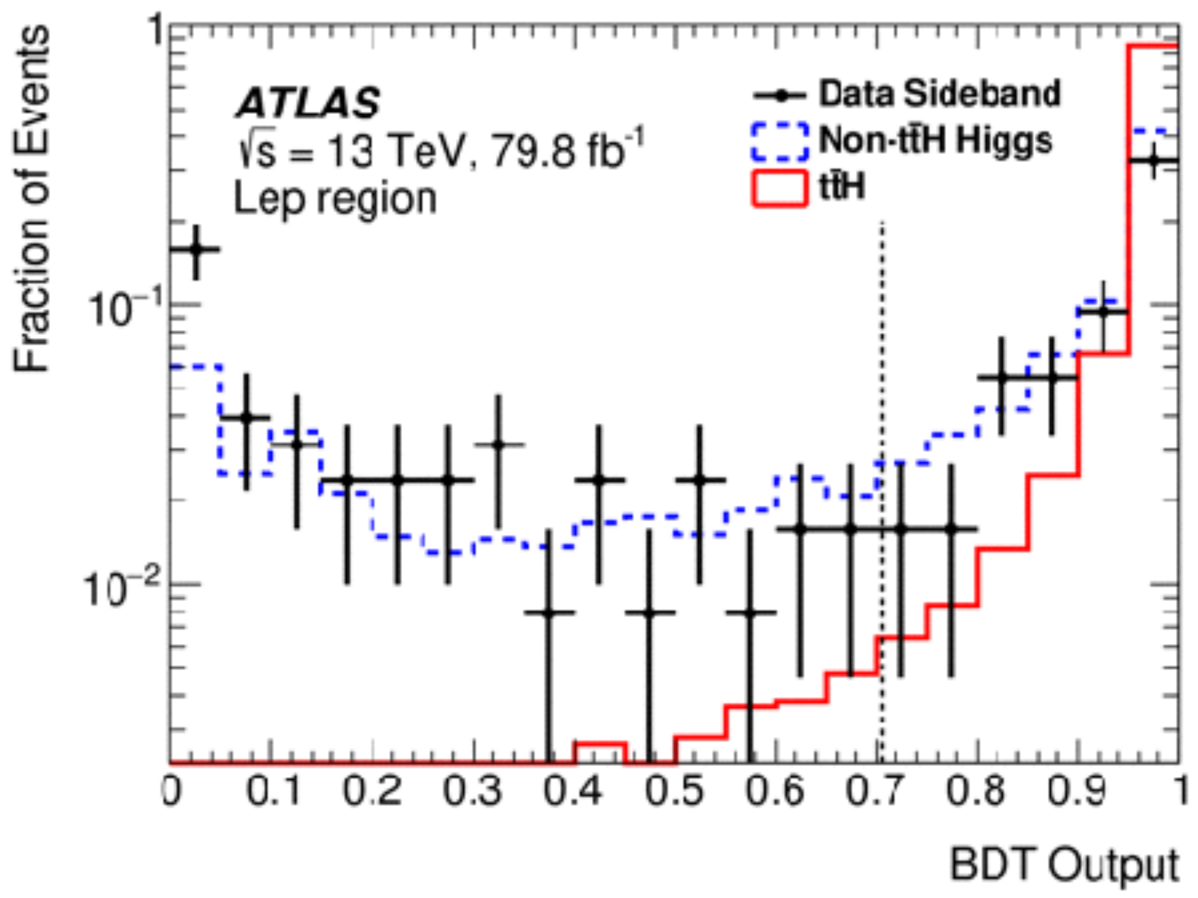
- ATLAS analysis of the $t\bar{t}$+H(γγ) final state
  - 79.8 fb^{-1}
  - 2 isolated photons, $p_T/m_{\gamma\gamma} > 0.35\text{-}0.25$
  - at least 1 jet (p_T>25 GeV) which is b-tagged
  - BDT to discriminant between signal and background (lepton or hadronic decay of the top)



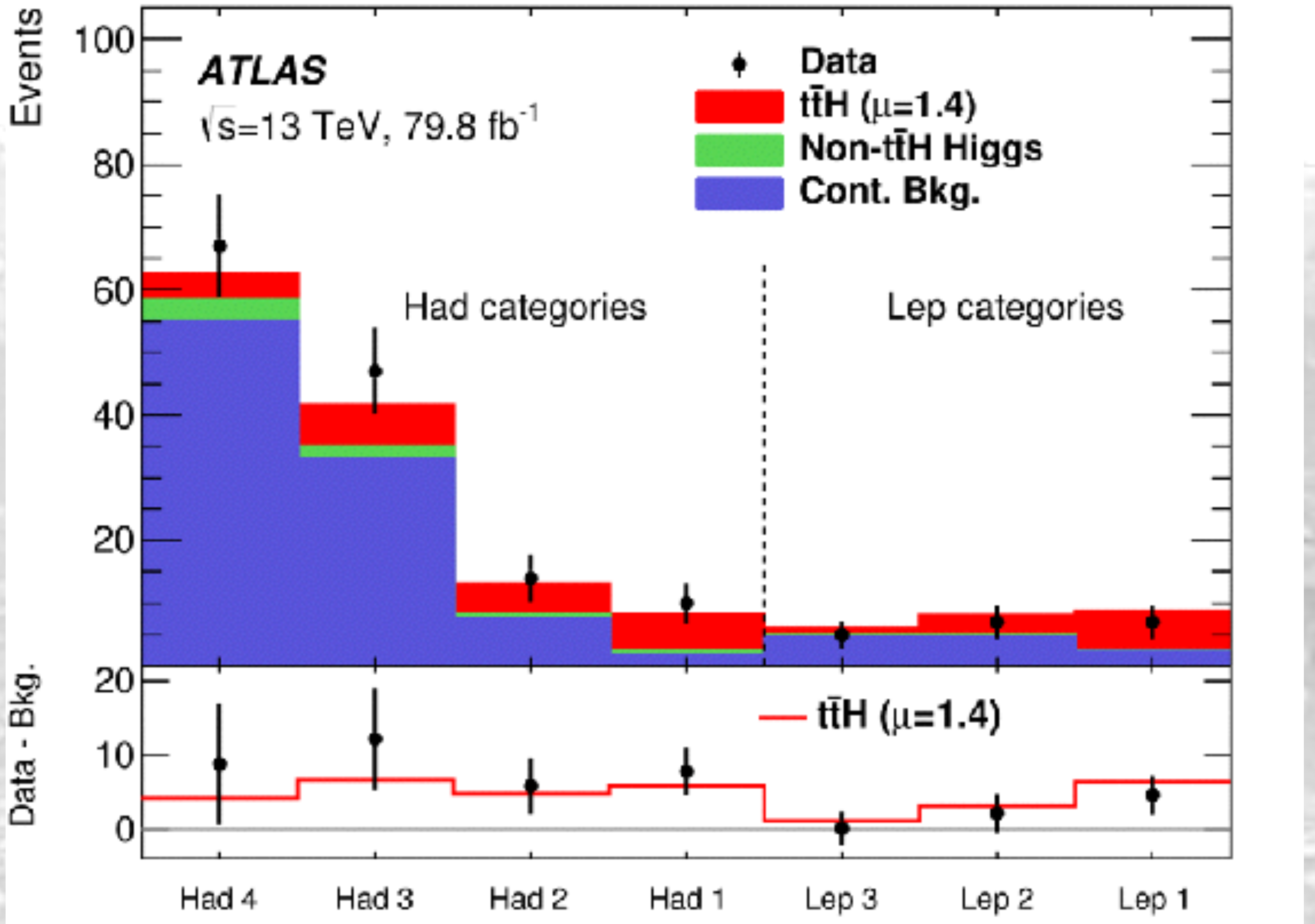
hadronic channel



leptonic channel

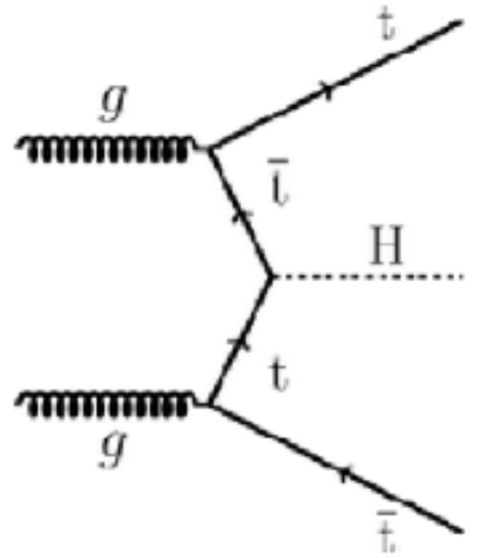


yields in different BDT bins

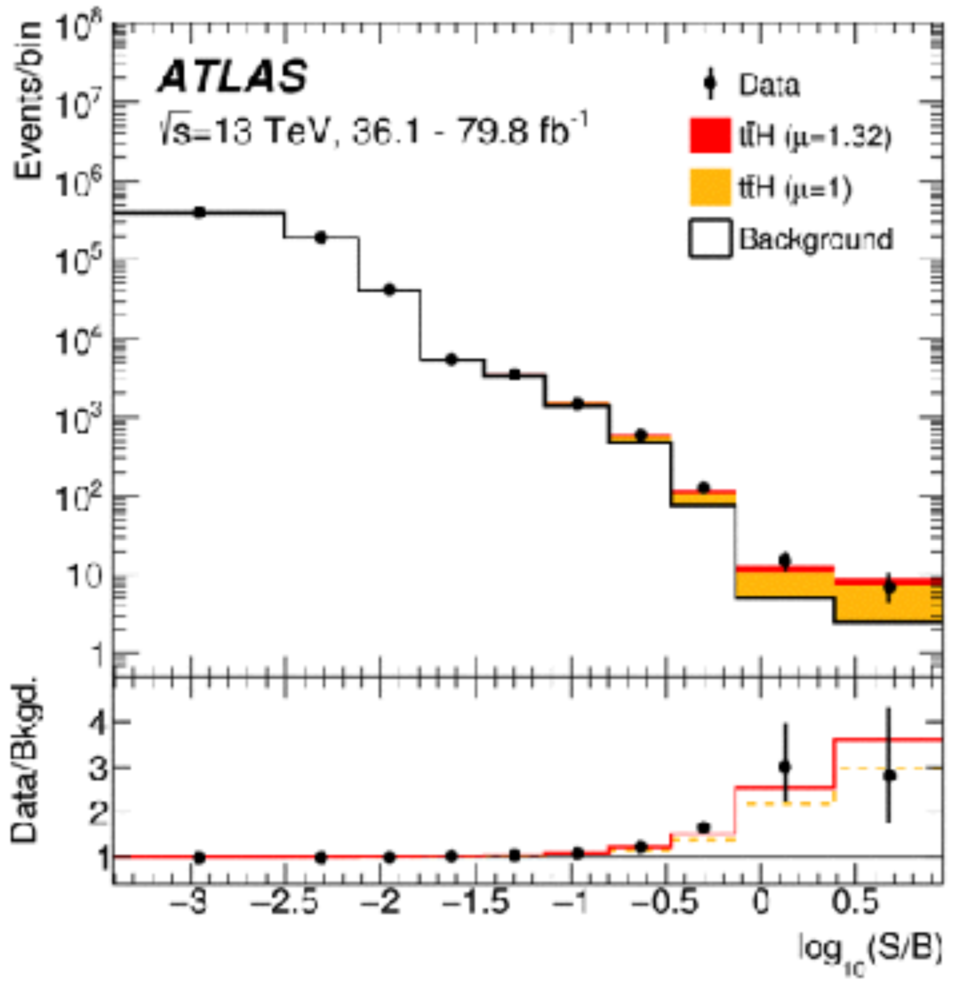


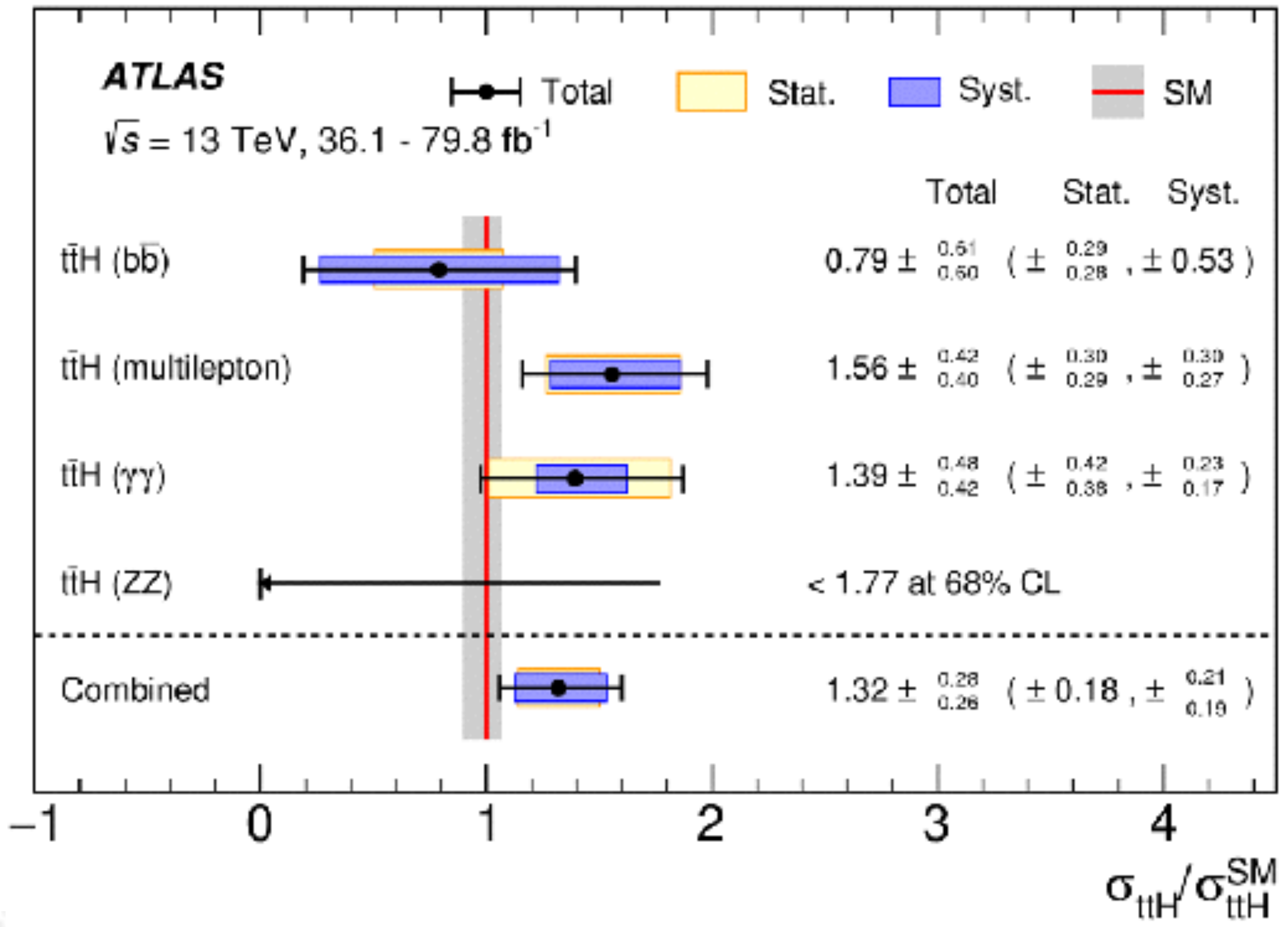
$t\bar{t}H$ combination

- combining all the channels
  - including $t\bar{t}$+H(γγ) and $t\bar{t}$+H(4ℓ)
  - Run 1 + Run 2



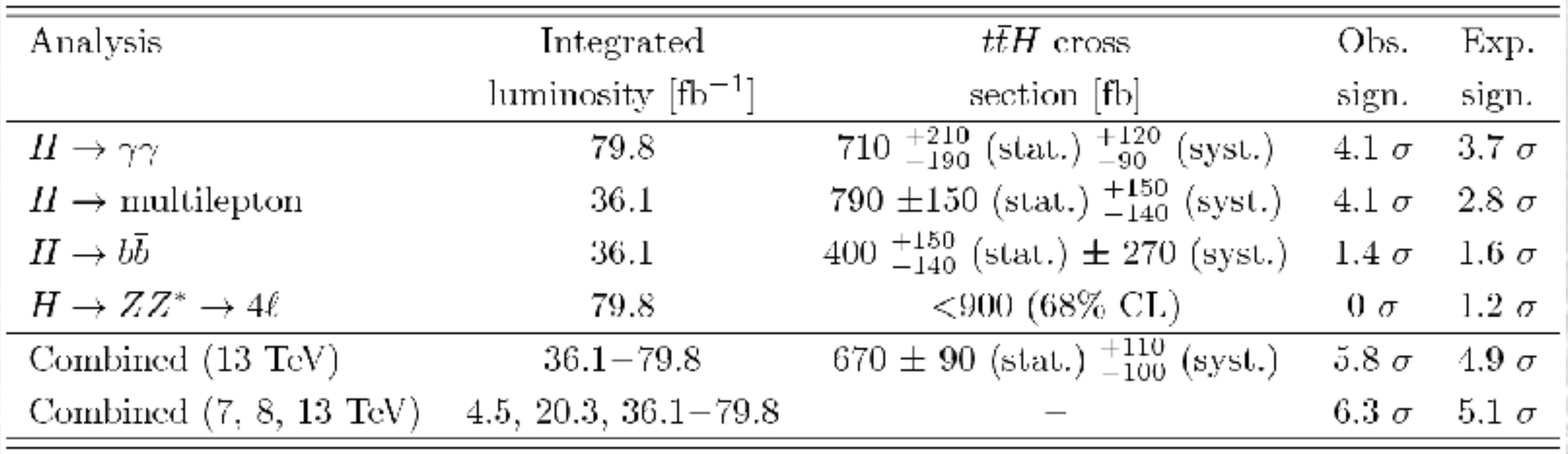
arXiv:1806.00425





	Total	Stat.	Syst.
$t\bar{t}H$ (bb)	$0.79 \pm ^{0.61}_{0.60}$	$\pm ^{0.29}_{0.28}$	± 0.53
$t\bar{t}H$ (multilepton)	$1.56 \pm ^{0.42}_{0.40}$	$\pm ^{0.30}_{0.29}$	$\pm ^{0.30}_{0.27}$
$t\bar{t}H$ (γγ)	$1.39 \pm ^{0.48}_{0.42}$	$\pm ^{0.42}_{0.38}$	$\pm ^{0.23}_{0.17}$
$t\bar{t}H$ (ZZ)	< 1.77 at 68% CL		
Combined	$1.32 \pm ^{0.28}_{0.26}$	± 0.18	$\pm ^{0.21}_{0.19}$

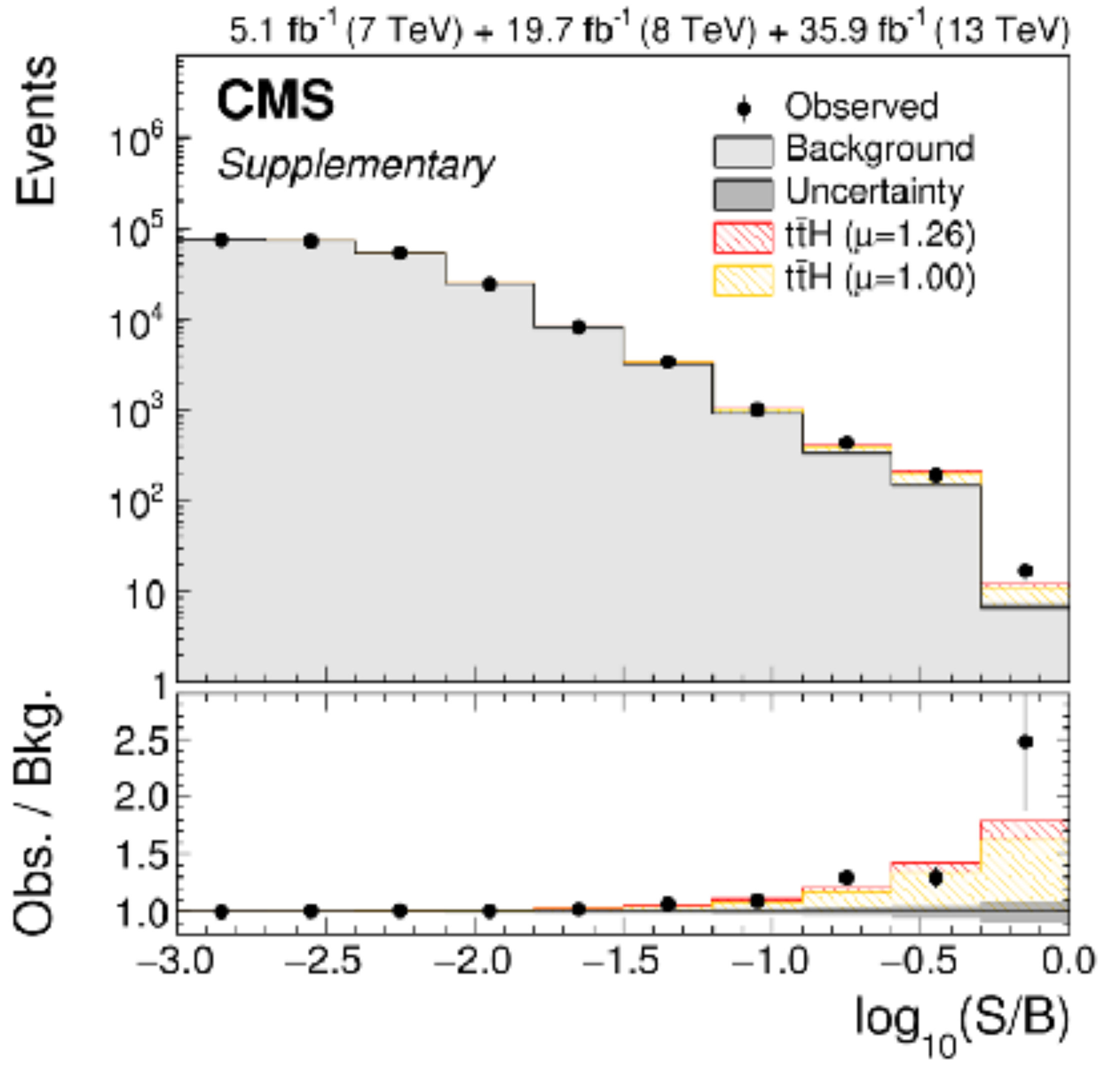
observation of ttH: 6.3σ (5.1σ exp)

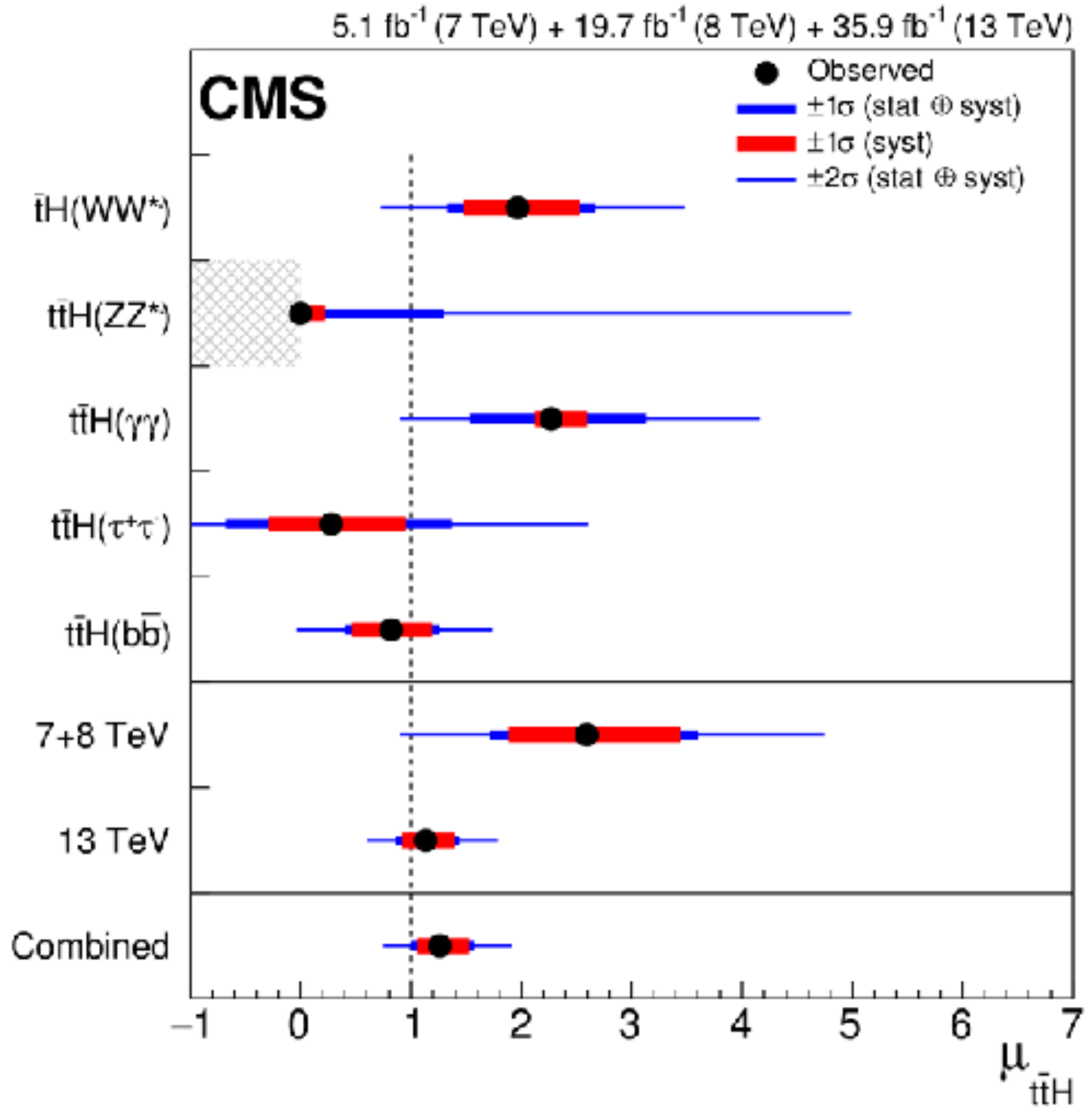


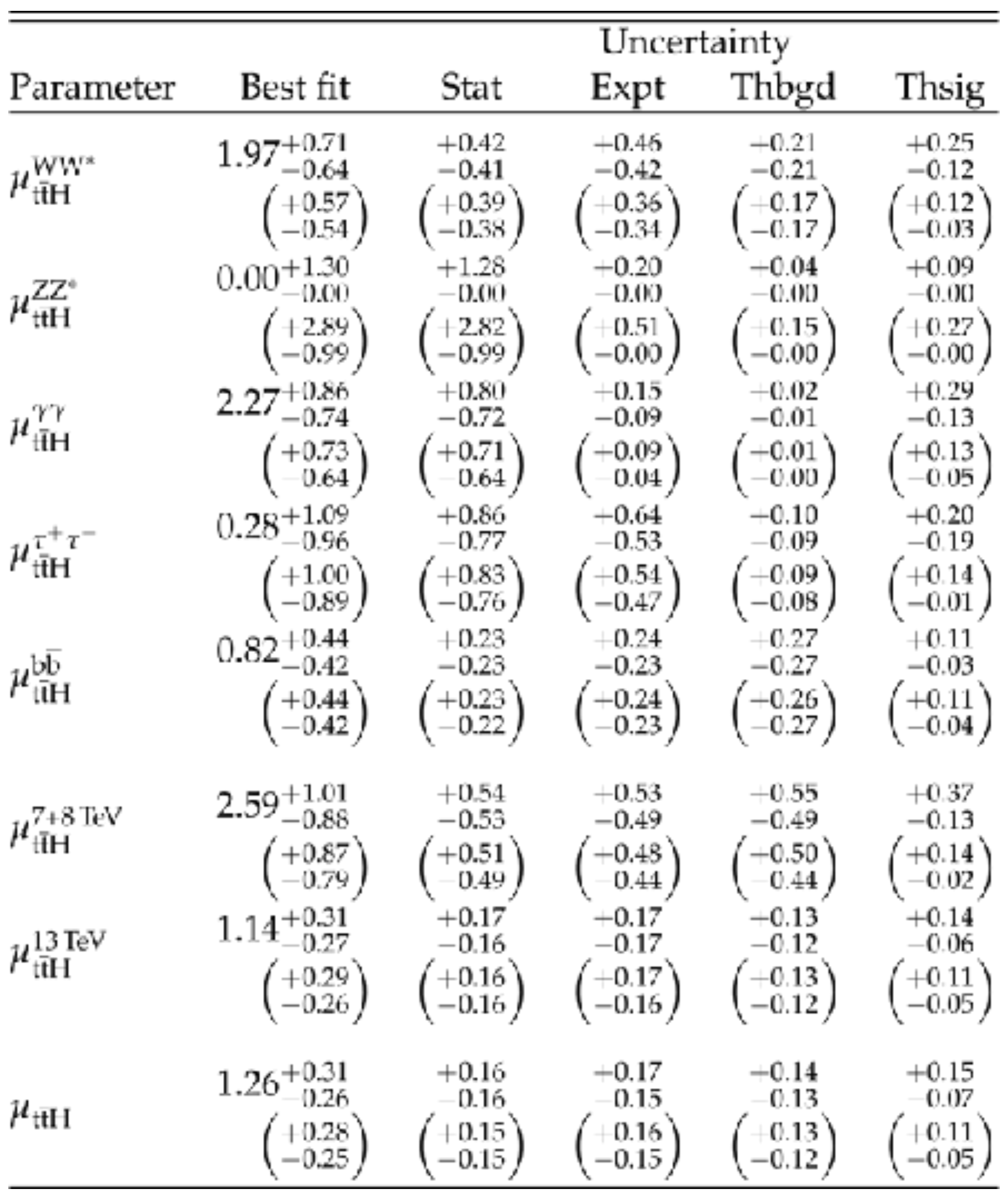
Analysis	Integrated luminosity [fb^{-1}]	$t\bar{t}H$ cross section [fb]	Obs. sign.	Exp. sign.
$H \to \gamma\gamma$	79.8	$710\ ^{+210}_{-190}$ (stat.) $^{+120}_{-90}$ (syst.)	4.1 σ	3.7 σ
$H \to$ multilepton	36.1	790 ± 150 (stat.) $^{+150}_{-140}$ (syst.)	4.1 σ	2.8 σ
$H \to b\bar{b}$	36.1	$400\ ^{+150}_{-140}$ (stat.) $\pm$ 270 (syst.)	1.4 σ	1.6 σ
$H \to ZZ^* \to 4\ell$	79.8	<900 (68% CL)	0 σ	1.2 σ
Combined (13 TeV)	36.1–79.8	670 ± 90 (stat.) $^{+110}_{-100}$ (syst.)	5.8 σ	4.9 σ
Combined (7, 8, 13 TeV)	4.5, 20.3, 36.1–79.8	–	6.3 σ	5.1 σ

arXiv:1804.02610

observation of ttH: 5.2σ (4.2σ exp)







Parameter	Best fit	Uncertainty Stat	 Expt	 Thbgd	 Thsig
$\mu^{WW^*}_{t\bar{t}H}$	$1.97^{+0.71}_{-0.64}$ $\left(^{+0.57}_{-0.54}\right)$	$^{+0.42}_{-0.41}$ $\left(^{+0.39}_{-0.38}\right)$	$^{+0.46}_{-0.42}$ $\left(^{+0.36}_{-0.34}\right)$	$^{+0.21}_{-0.21}$ $\left(^{+0.17}_{-0.17}\right)$	$^{+0.25}_{-0.12}$ $\left(^{+0.12}_{-0.03}\right)$
$\mu^{ZZ^*}_{t\bar{t}H}$	$0.00^{+1.30}_{-0.00}$ $\left(^{+2.89}_{-0.99}\right)$	$^{+1.28}_{-0.00}$ $\left(^{+2.82}_{-0.99}\right)$	$^{+0.20}_{-0.00}$ $\left(^{+0.51}_{-0.00}\right)$	$^{+0.04}_{-0.00}$ $\left(^{+0.15}_{-0.00}\right)$	$^{+0.09}_{-0.00}$ $\left(^{+0.27}_{-0.00}\right)$
$\mu^{\gamma\gamma}_{t\bar{t}H}$	$2.27^{+0.86}_{-0.74}$ $\left(^{+0.73}_{-0.64}\right)$	$^{+0.80}_{-0.72}$ $\left(^{+0.71}_{-0.64}\right)$	$^{+0.15}_{-0.09}$ $\left(^{+0.09}_{-0.04}\right)$	$^{+0.02}_{-0.01}$ $\left(^{+0.01}_{-0.00}\right)$	$^{+0.29}_{-0.13}$ $\left(^{+0.13}_{-0.05}\right)$
$\mu^{\tau^+\tau^-}_{t\bar{t}H}$	$0.28^{+1.09}_{-0.96}$ $\left(^{+1.00}_{-0.89}\right)$	$^{+0.86}_{-0.77}$ $\left(^{+0.83}_{-0.76}\right)$	$^{+0.64}_{-0.53}$ $\left(^{+0.54}_{-0.47}\right)$	$^{+0.10}_{-0.09}$ $\left(^{+0.09}_{-0.08}\right)$	$^{+0.20}_{-0.19}$ $\left(^{+0.14}_{-0.01}\right)$
$\mu^{b\bar{b}}_{t\bar{t}H}$	$0.82^{+0.44}_{-0.42}$ $\left(^{+0.44}_{-0.42}\right)$	$^{+0.23}_{-0.23}$ $\left(^{+0.23}_{-0.22}\right)$	$^{+0.24}_{-0.23}$ $\left(^{+0.24}_{-0.23}\right)$	$^{+0.27}_{-0.27}$ $\left(^{+0.26}_{-0.27}\right)$	$^{+0.11}_{-0.03}$ $\left(^{+0.11}_{-0.04}\right)$
$\mu^{7+8\,\mathrm{TeV}}_{t\bar{t}H}$	$2.59^{+1.01}_{-0.88}$ $\left(^{+0.87}_{-0.79}\right)$	$^{+0.54}_{-0.53}$ $\left(^{+0.51}_{-0.49}\right)$	$^{+0.53}_{-0.49}$ $\left(^{+0.48}_{-0.44}\right)$	$^{+0.55}_{-0.49}$ $\left(^{+0.50}_{-0.44}\right)$	$^{+0.37}_{-0.13}$ $\left(^{+0.14}_{-0.02}\right)$
$\mu^{13\,\mathrm{TeV}}_{t\bar{t}H}$	$1.14^{+0.31}_{-0.27}$ $\left(^{+0.29}_{-0.26}\right)$	$^{+0.17}_{-0.16}$ $\left(^{+0.16}_{-0.16}\right)$	$^{+0.17}_{-0.17}$ $\left(^{+0.17}_{-0.16}\right)$	$^{+0.13}_{-0.12}$ $\left(^{+0.13}_{-0.12}\right)$	$^{+0.14}_{-0.06}$ $\left(^{+0.11}_{-0.05}\right)$
$\mu_{t\bar{t}H}$	$1.26^{+0.31}_{-0.26}$ $\left(^{+0.28}_{-0.25}\right)$	$^{+0.16}_{-0.16}$ $\left(^{+0.15}_{-0.15}\right)$	$^{+0.17}_{-0.15}$ $\left(^{+0.16}_{-0.15}\right)$	$^{+0.14}_{-0.13}$ $\left(^{+0.13}_{-0.12}\right)$	$^{+0.15}_{-0.07}$ $\left(^{+0.11}_{-0.05}\right)$

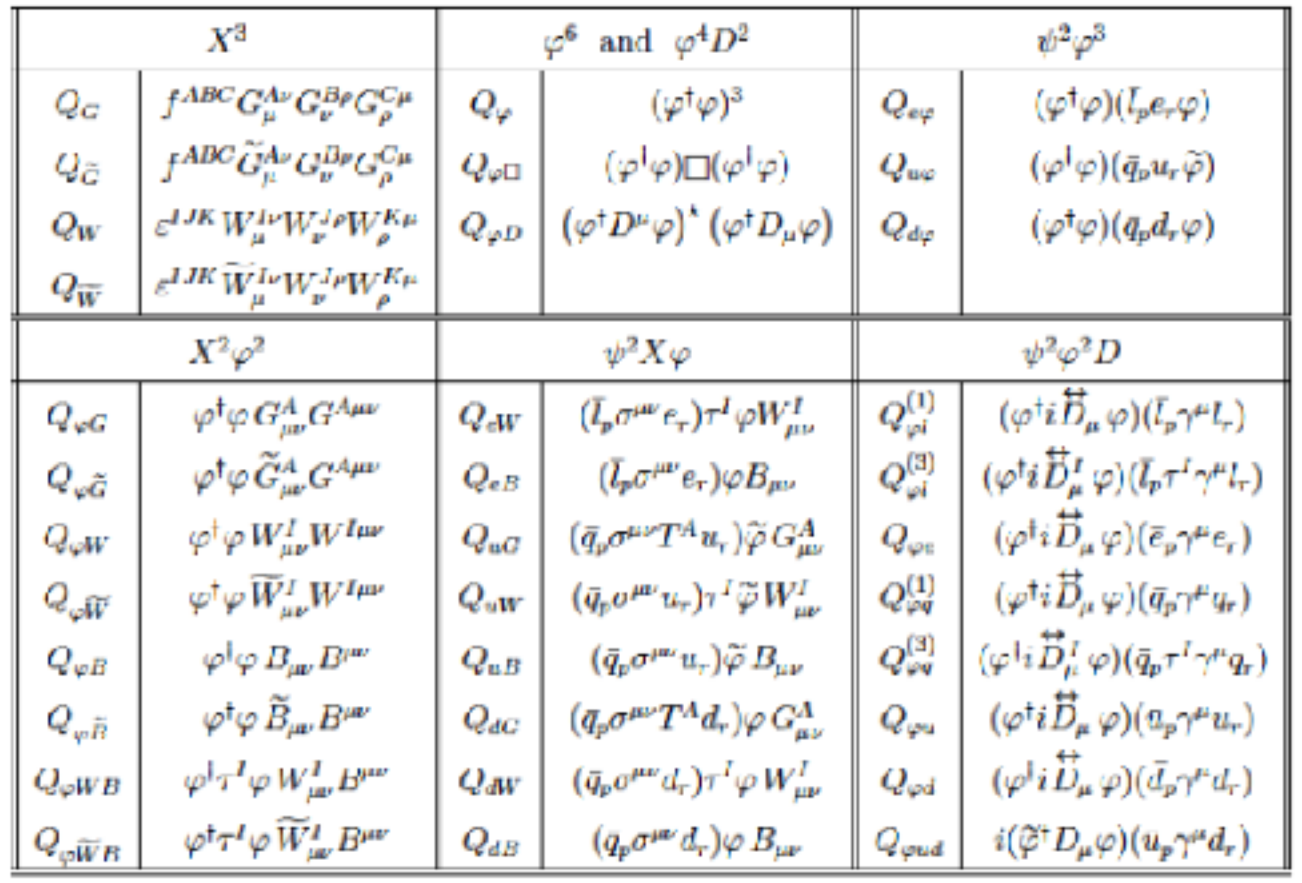
new physics in top couplings through EFT

- search for new physics in top couplings
  - using the Effective Field Theory approach

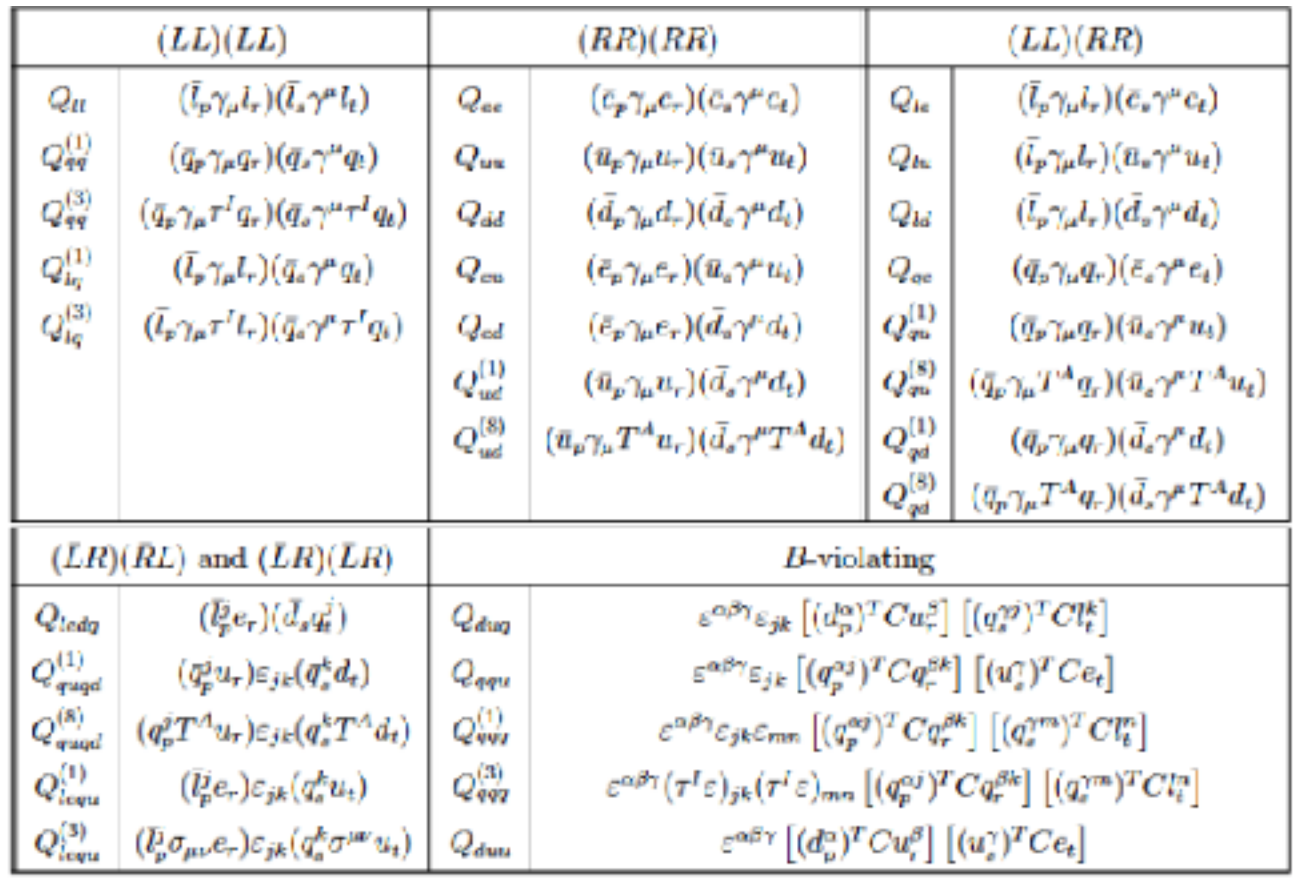
- attractive approach
  - can compute perturbation and renormalisation
  - possibility of global strategy (33 anomalous operators affecting production and decay)
  - sequential approach: study the sensitivity of the observables to the anomalous couplings, consider only couplings with sizeable effects

- first try of a global fit
  - input: inclusive and differential results for the $t\bar{t}$ and single top productions
  - SM at NLO/NNLO, EFT at LO

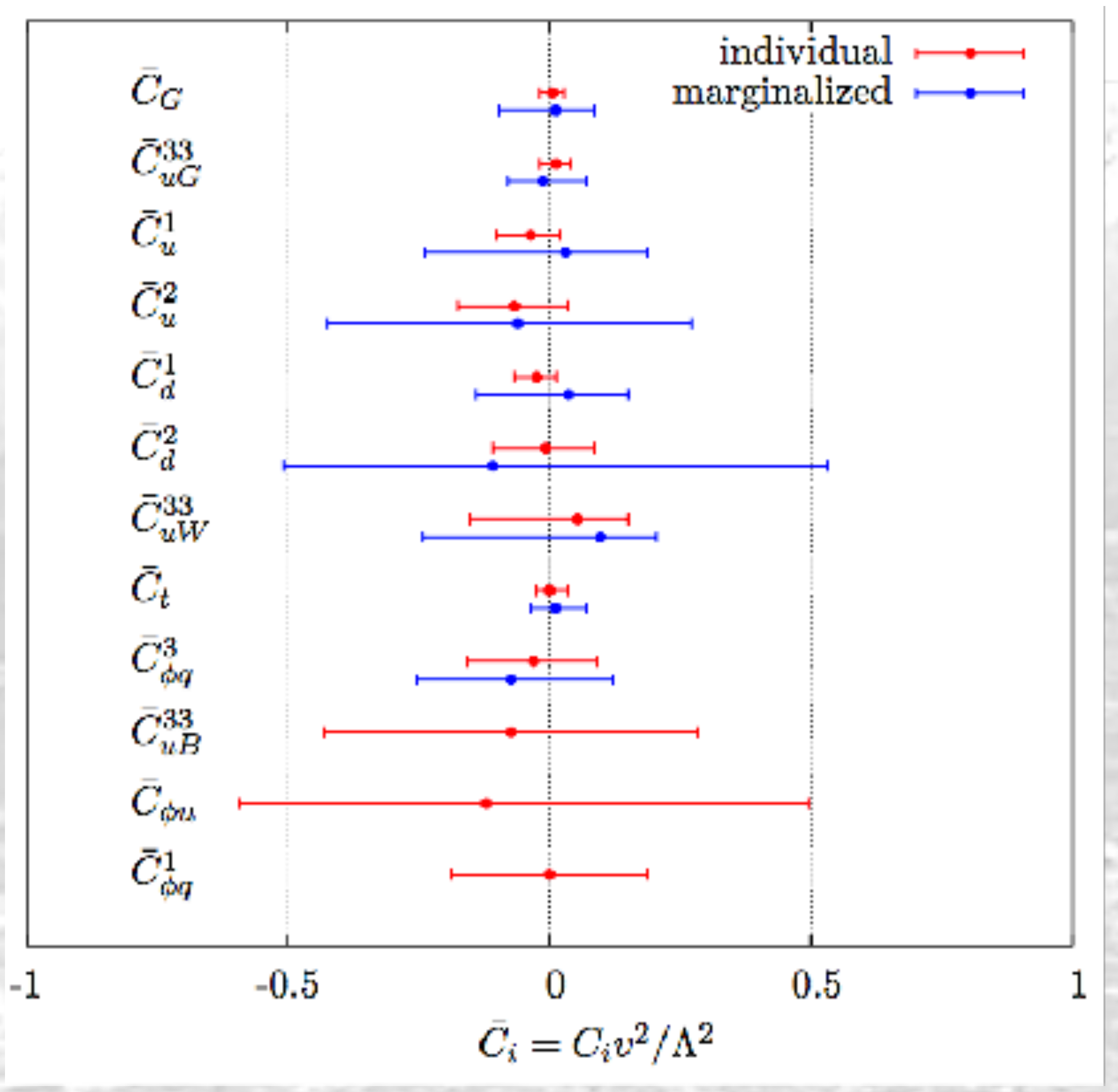
Buchmuller & Wyler NPB268, 621 (1986)
Grzadkowski et al, JHEP10, 085 (2010)



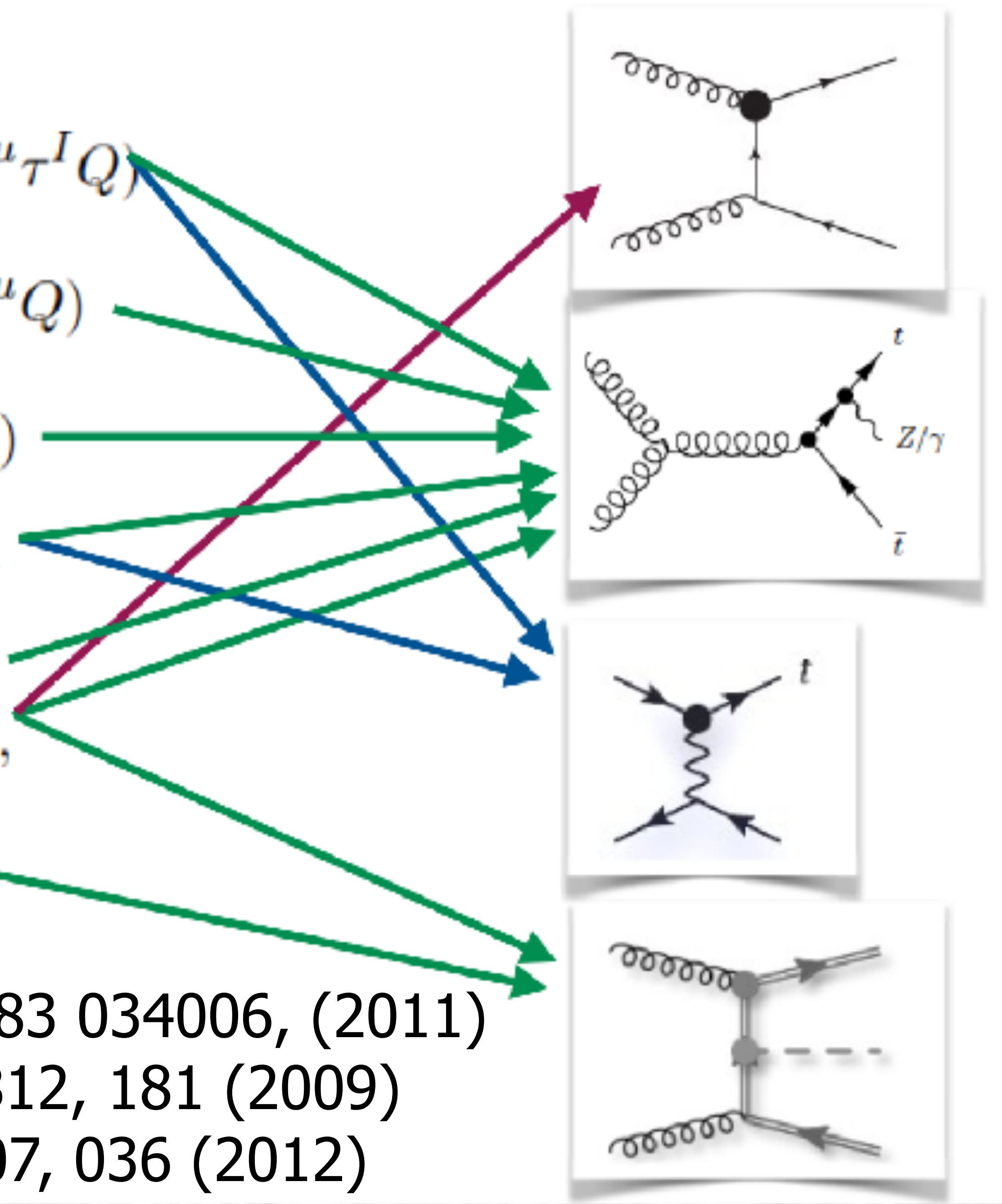
X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^\star (\varphi^\dagger D_\mu\varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	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}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$



$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
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}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$
$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$		



Buckley et al. JHEP04, 015 (2016)



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

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

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

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

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

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

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

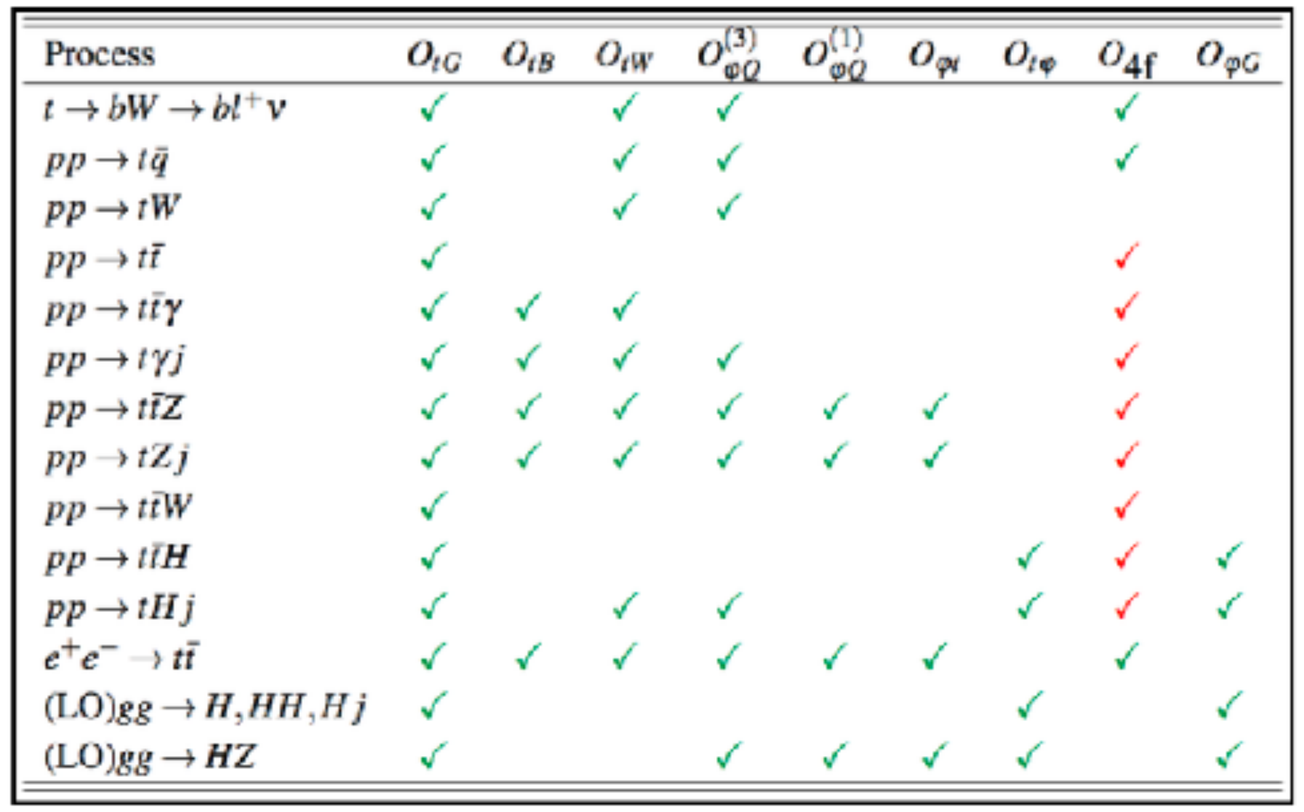
Zhang & Willenbrock, PRD83 034006, (2011)
Aguilar-Saavedra, NPB812, 181 (2009)
Degrande et al, JHEP07, 036 (2012)

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, …)
  - perform differential measurements

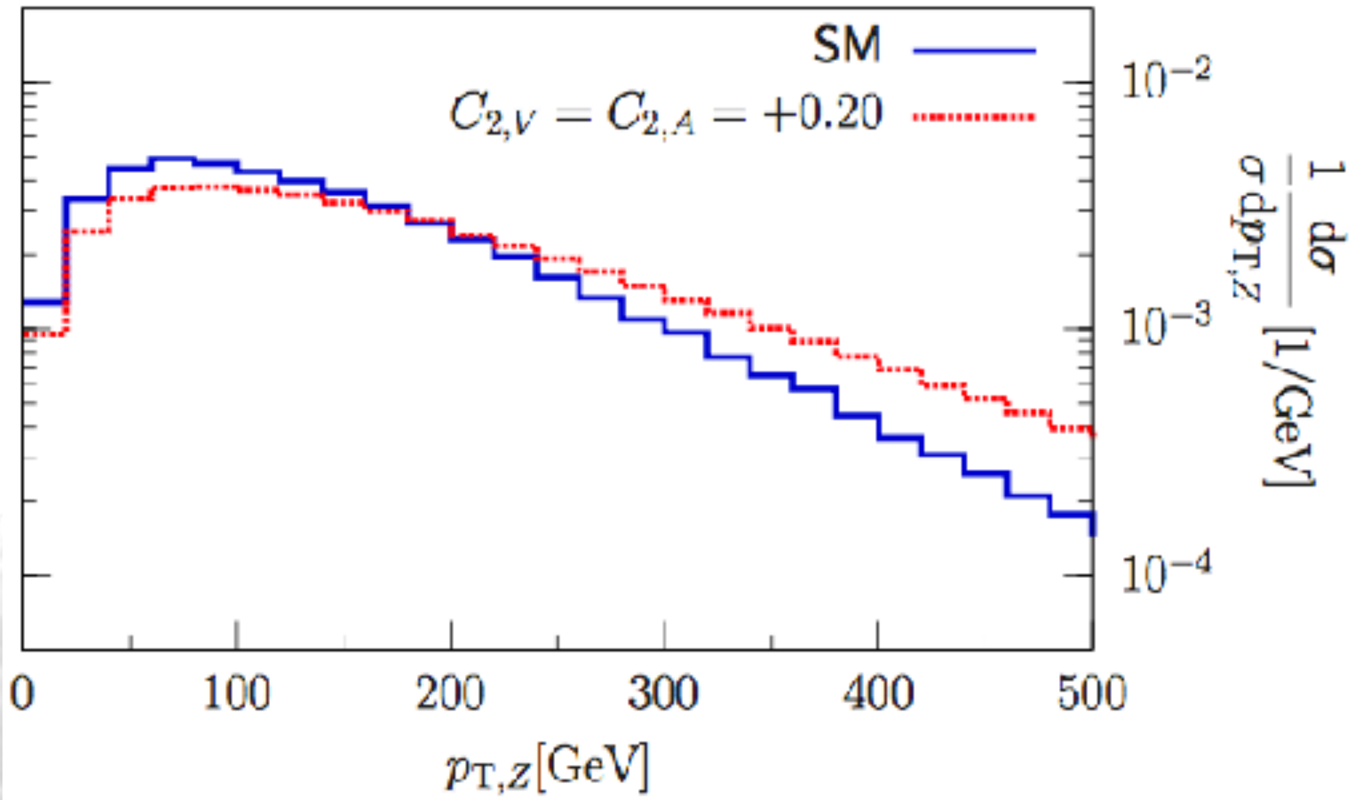
- generic guidelines under the LHCtopWG (arXiv:1802.07237)
  - recommended basis (Warsaw basis), LO
  - three different assumptions about BSM flavour structures considered
  - degrees of freedom: independent linear combination of operators that interfere with SM

- 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

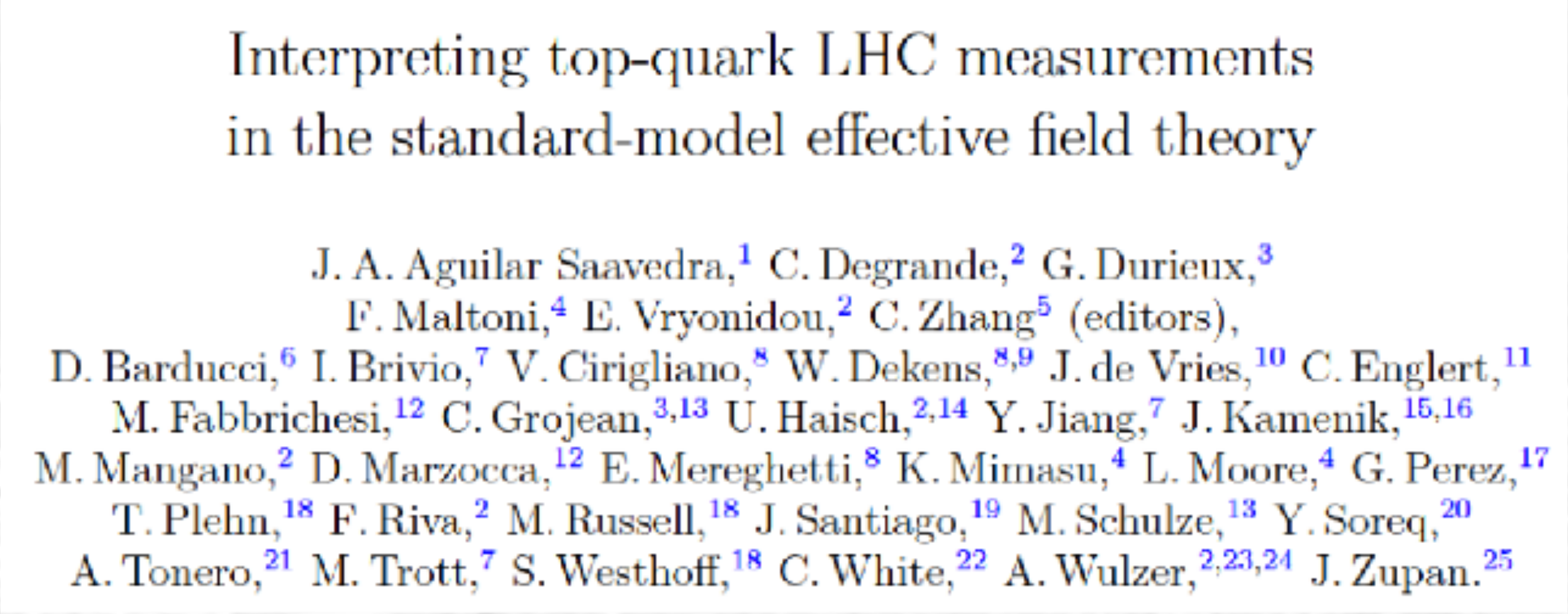


Process	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$	O_{4f}	$O_{\varphi G}$
$t\to bW\to bl^+\nu$	✓		✓	✓				✓	
$pp\to t\bar{q}$	✓		✓	✓				✓	
$pp\to tW$	✓		✓	✓					
$pp\to t\bar{t}$	✓							✓	
$pp\to t\bar{t}\gamma$	✓	✓	✓					✓	
$pp\to t\gamma j$	✓	✓	✓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

Rontsch & Schulze, JHEP08, 044 (2015)

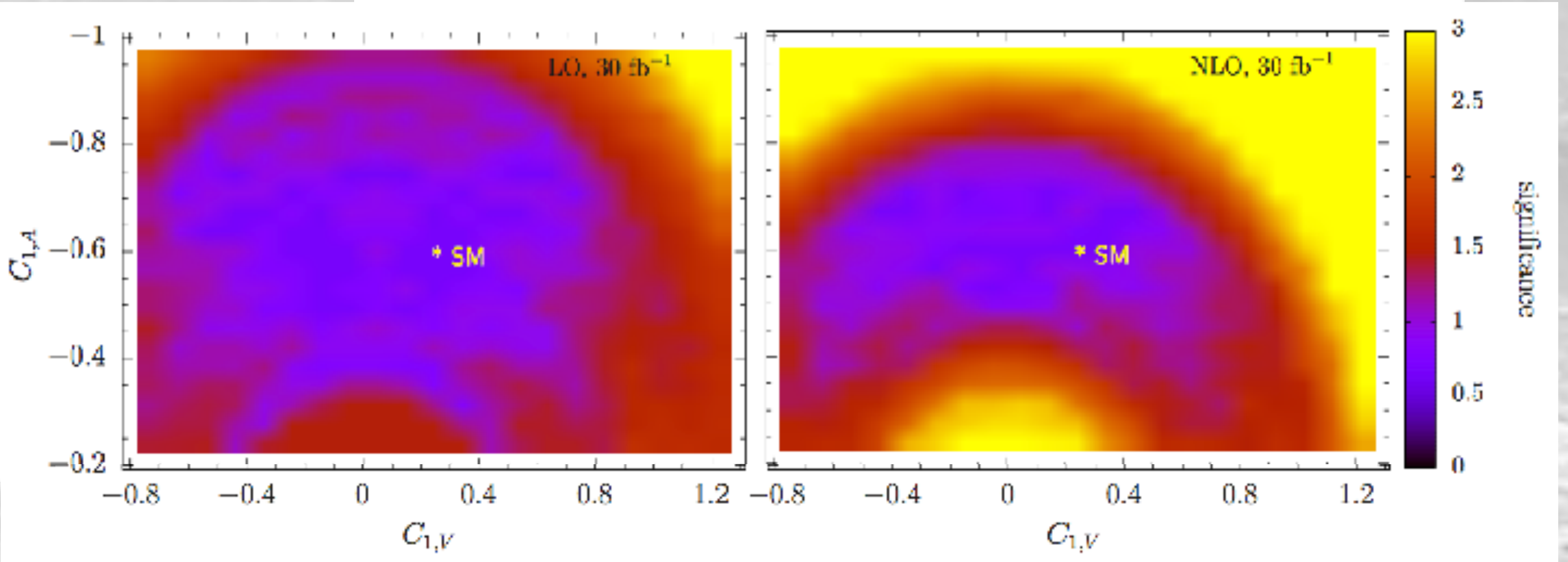


arXiv:1802.07237



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]

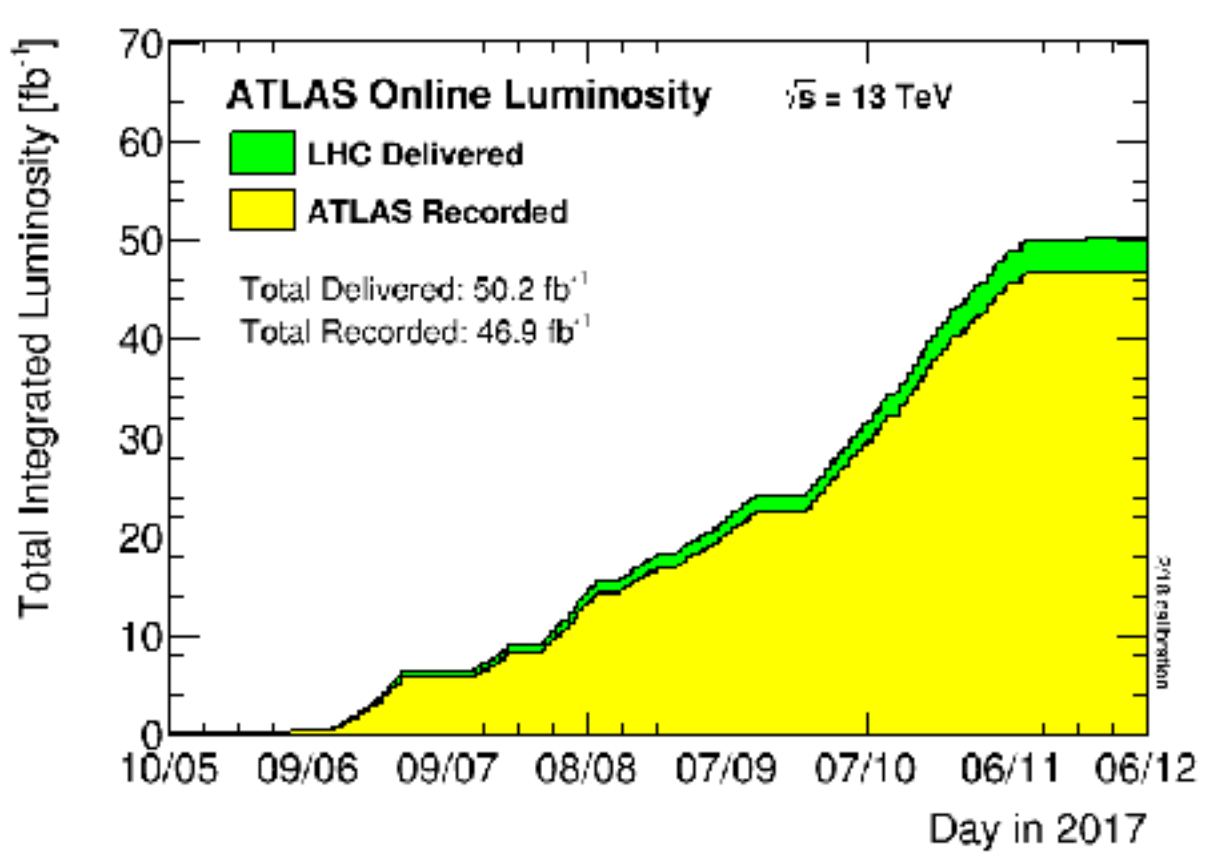


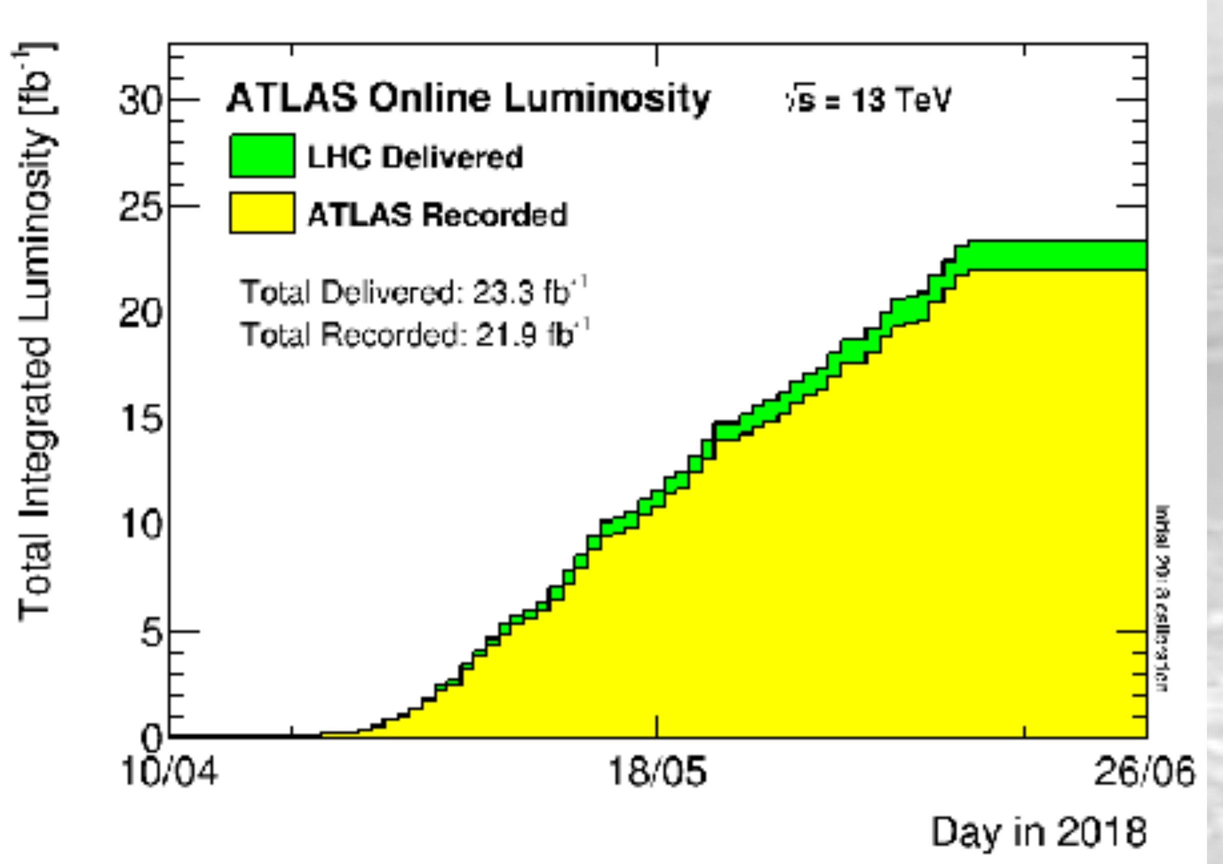
Conclusion

- with LHC Run 2, top quark physics is entering the high precision regime
  - multi-dimensional differential cross section measurements
    - a lot of recent theory developments to compare with, need now to be implemented in MC generators
    - important to perform dedicated measurements for MC tuning
  - top mass precision is now below 500 MeV
    - developing activities to measure it with alternative methods
  - top couplings to all bosons are starting to be explored
    - would need more statistics to look at differential distributions

- 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 with the full LHC Run 2 statistics and 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, …)





Thank you for your attention