$t\bar{t}$ +jets in ATLAS

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(on behalf of the ATLAS collaboration)

Jet Vetoes and Multiplicity Observables
19-21 September 2016, Durham

Motivation

LHC is a top factory:

$\sqrt{s}$	σ_{tt} [pb] *	L [fb^{-1}]	Number of top events
7 TeV (2011)	174	4.6	0.8 M
8 TeV (2012)	248	20.3	5 M
13 TeV (2015)	816	3.2	2.6 M

*Czakon, Fiedler, Mitov [PRL 110, 252004]

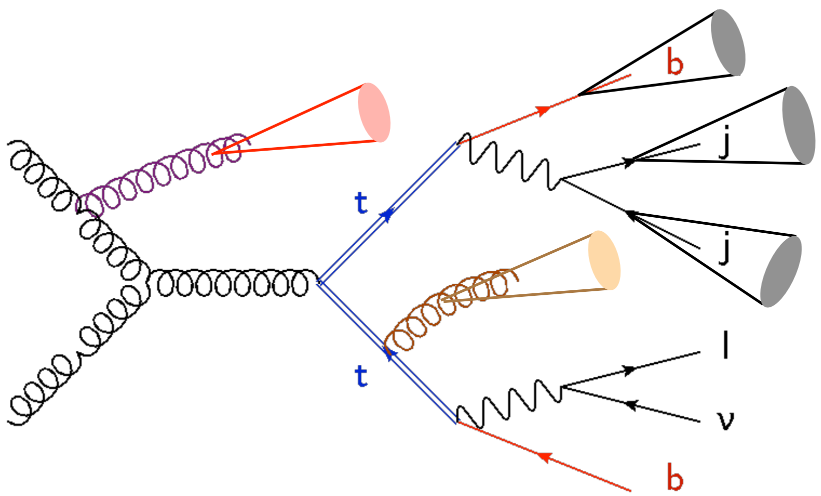
⇒ **precision measurements, understand top modeling**
(differential cross-section, additional jets production, heavy flavor, ...)

⇒ **reduce systematic uncertainties** in precision measurements (MC tuning)

⇒ **control top background** in other measurements/searches (ttH, SUSY, ...)

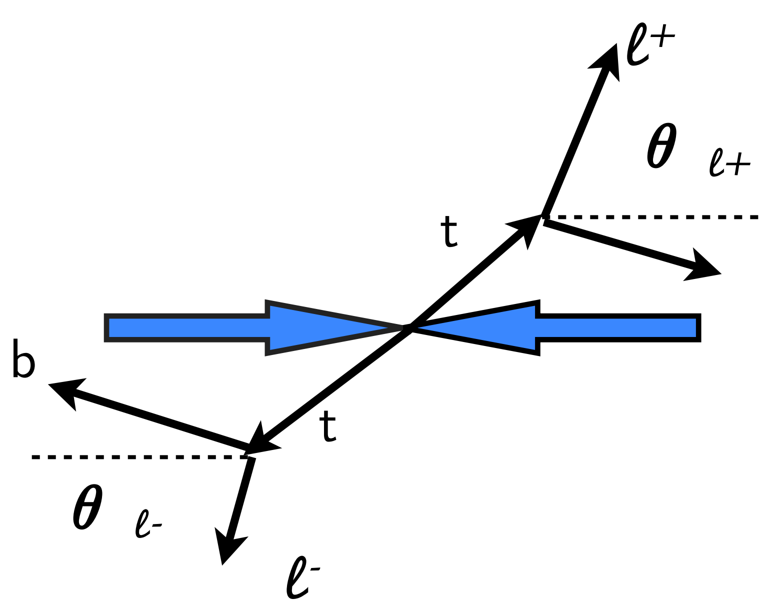
Some examples from measurements...

Top mass



- **ISR jets** can be mis-identified as jet from top decay
- **FSR** affects kinematics of top decay products
- **modeling of QCD radiation**: one of the dominant uncertainties: **30% of total systematic**

Spin correlation

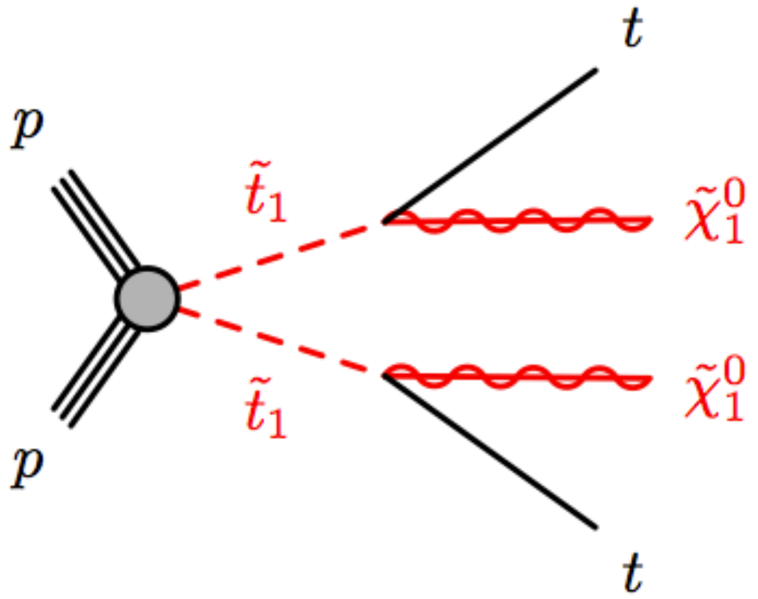


- extra radiation affecting the angle between leptons, jets
- **30-40% of total systematic**

arXiv: 1407.4314 , 1412.4742

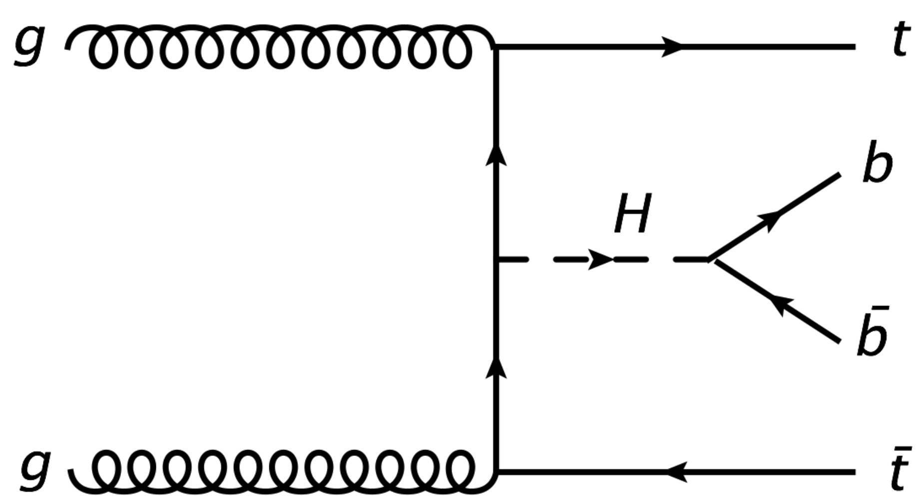
Some examples from searches...

SUSY



- signature based searches: leptons + jets + MET (same as top production)
- tt+jets is the **dominant background for many of the SUSY searches**

ttH(bb)



- **ttbb modeling** one of the main challenges of this search - also **the dominant systematic**

Overview

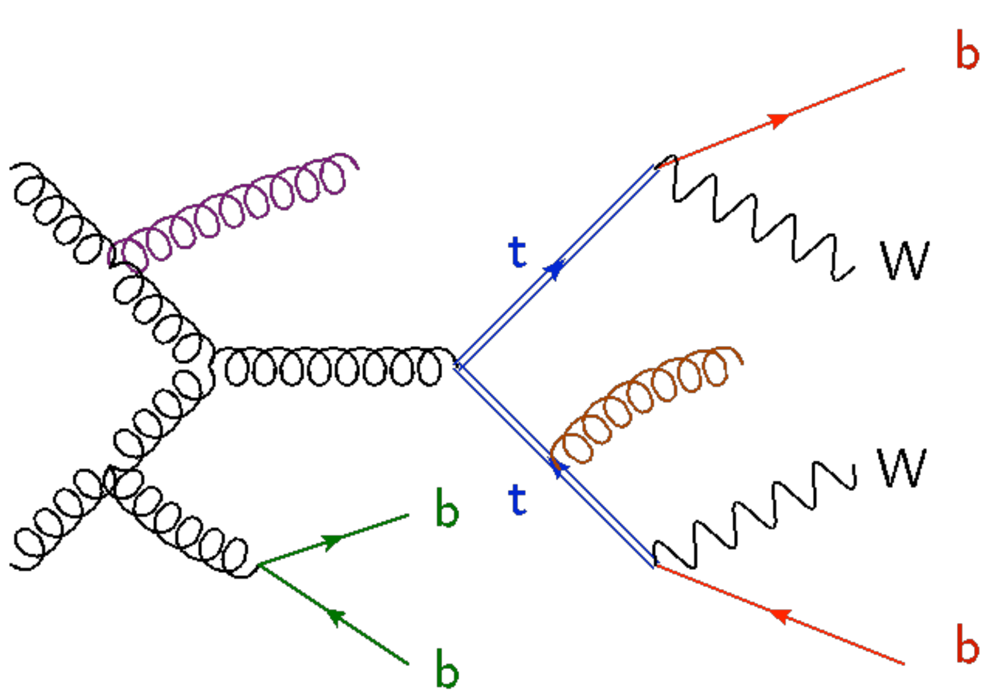
Measure jets produced in association with at top-antitop pair

Measurements

- **multiplicity and p_T spectrum** of additional jet activity (ISR, FSR) in top events
- **gap fraction**
- tt + **heavy flavor**

Tuning

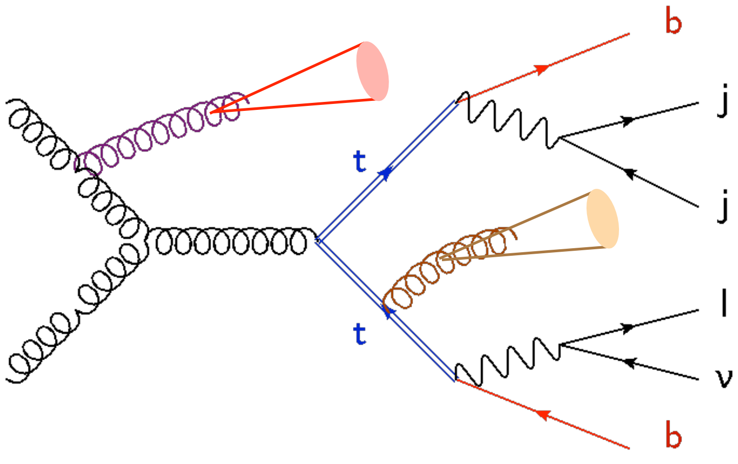
- "global"
- top-specific

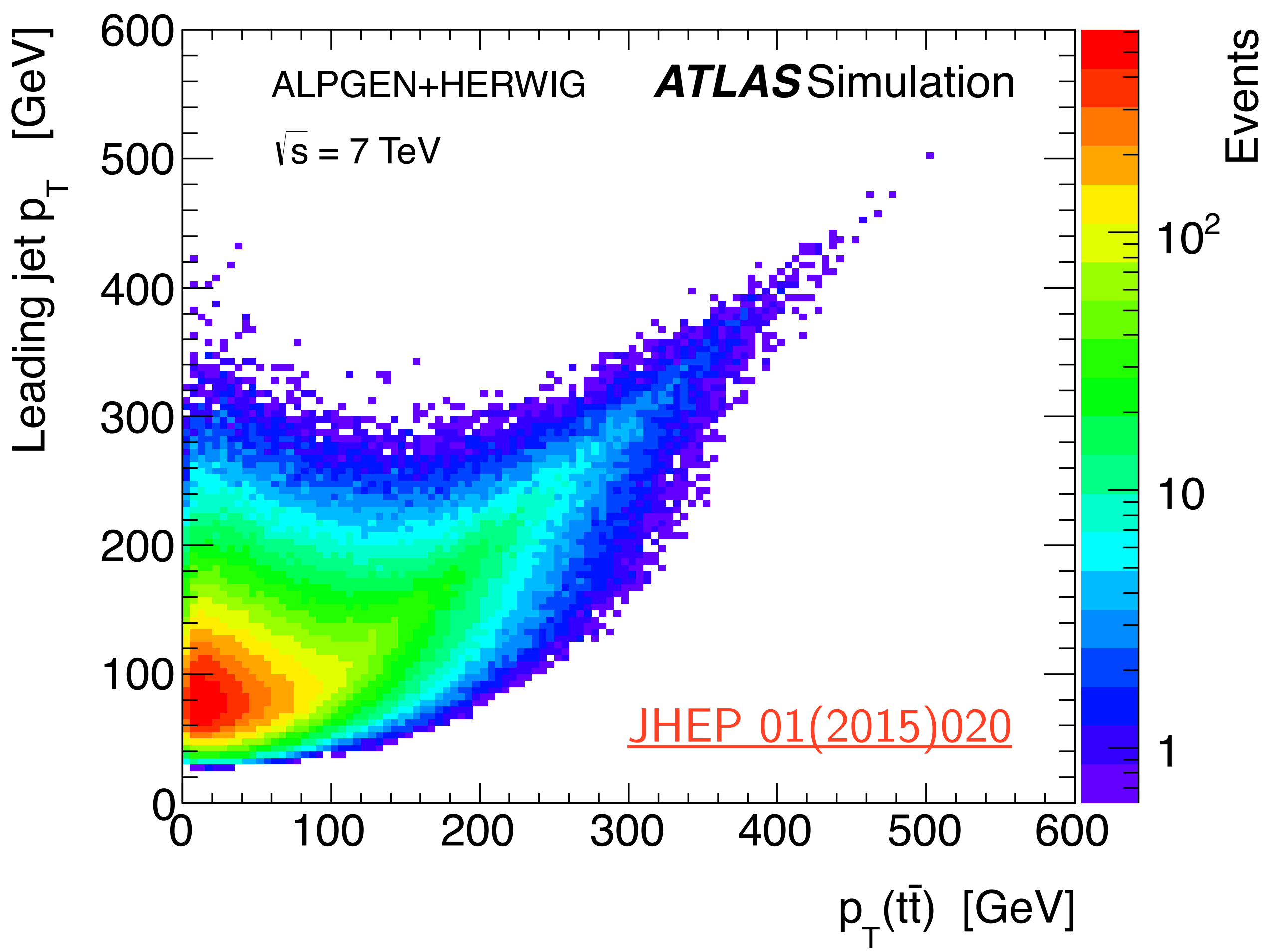


The measurements: generalities

Jet multiplicity & p_T spectrum

- jet multiplicity, p_T spectrum $\Rightarrow$ check predictions of **NLO, multi-leg generators and PS**
- probe **ME+PS matching and merging schemes**

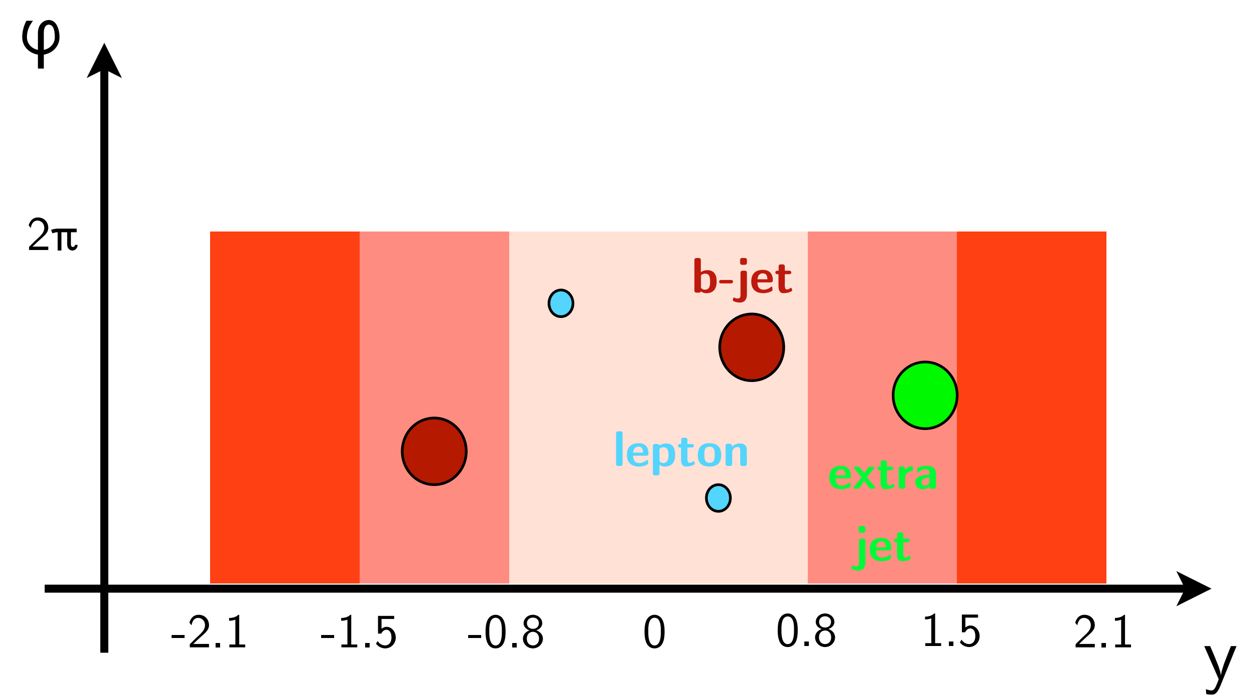




- **leading jet p_T spectrum** strongly correlated with $p_T(tt) \Rightarrow$ **complementary to differential cross-section** measurement

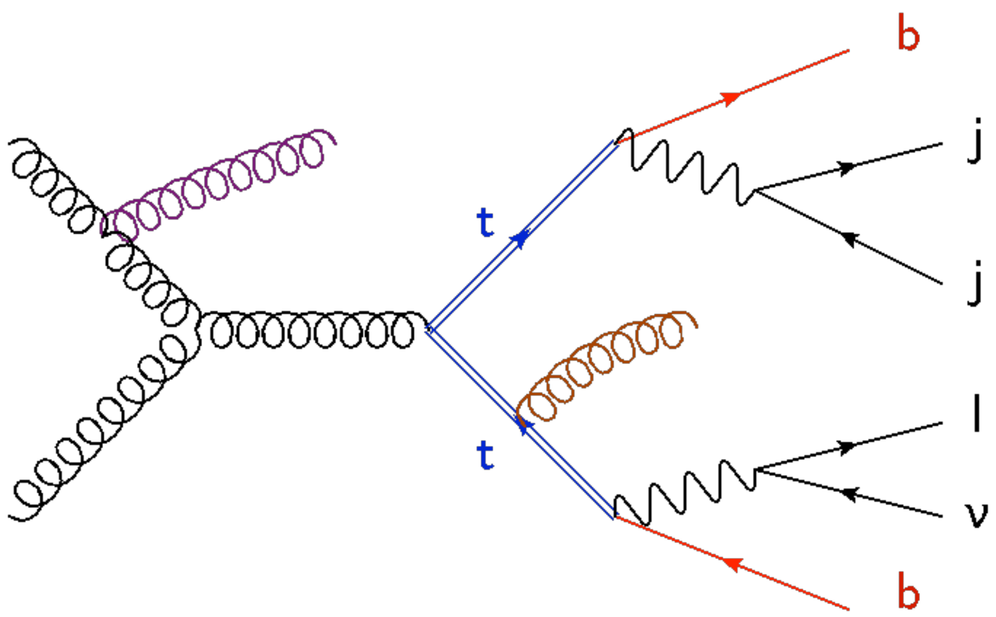
Gap fraction

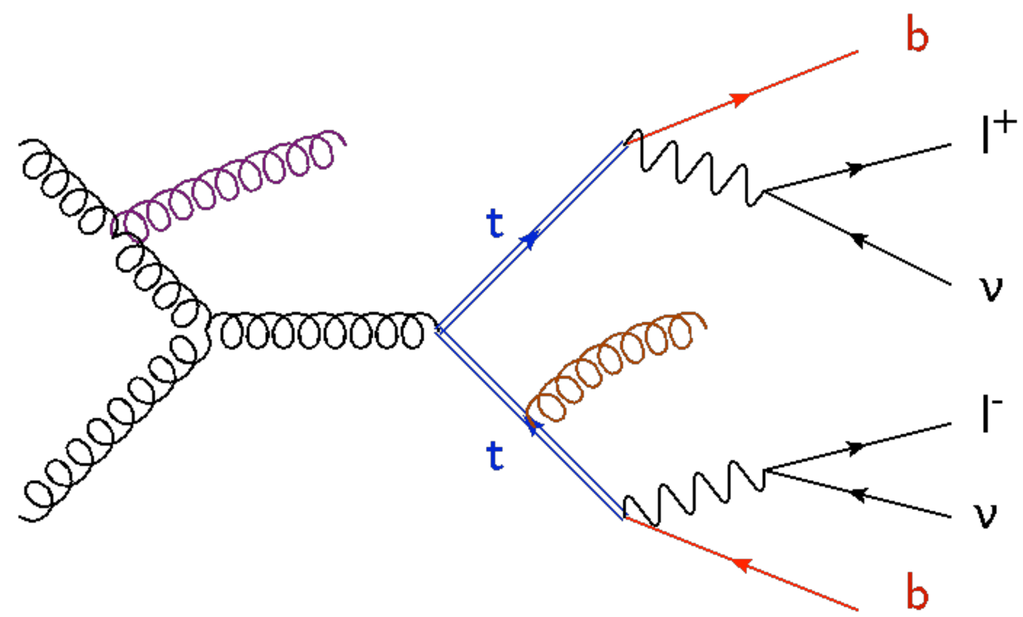
- measure ratio of events without extra jets in different rapidity intervals
- **sensitive to parton shower paremeters, ME+PS matching, α_s**
- differential in: jet veto scale Q, rapidity
- **ratio ⇒ cancellation of uncertainties**



$$f(Q_0) = \frac{\sigma(Q_0)}{\sigma} = \frac{\sigma(\text{no jet with } p_T > Q_0)}{\sigma}$$

Channels





single lepton channel:

- signature: 2 b-jets from top decay + 2 extra jets from W decay (**4 jets @ LO**)
- single isolated lepton + MET
- **higher statistics**, lower background than all-hadronic
- additional jets can't be unambiguously defined (no reconstruction of top candidate)

di-lepton channel:

- signature: 2 b-jets from top decay (**2 jets @ LO**)
- two isolated leptons + MET
- **low background**
- **additional jets can be identified** without top reconstruction

eμ channel:

- **highest purity**

Reconstruction & event selections

Common object selection

- electrons: $E_T > 25$ GeV, $|\eta| < 2.47$ excluding $1.37 < |\eta| < 1.52$
- muons: $p_T > 25$ GeV, $|\eta| < 2.5$
- jets: anti-kT R=0.4, pt > 25 GeV, $|\eta| < 2.5$
  - lepton-jet isolation: $\Delta R > 0.4$
- b-tagging:
  - multi-variate tagger using information from impact parameter, secondary vertex reconstruction and b-decay topology
  - different training for 7, 8, 13 TeV

Channel-specific event selection

single lepton channel:

- $m_T(W) > 35$ GeV
- MET > 30 GeV

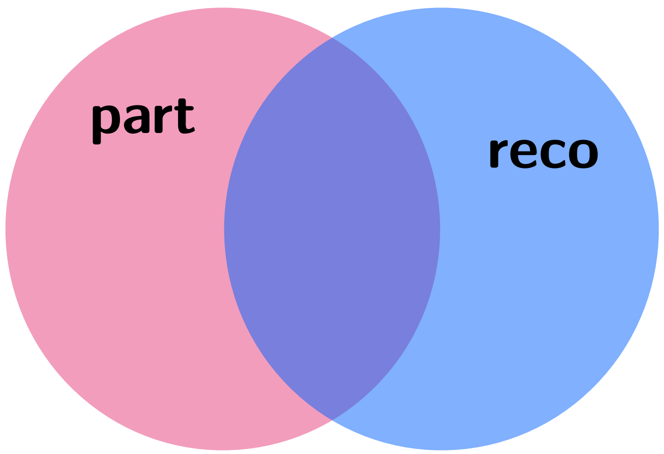
di-lepton channel:

- opposite sign leptons
- $|m_{ll}-m_Z| > 10$ GeV , $m_{ll} > 15$ (40) GeV

Fiducial volume definition

Goal

- define a **reference phase space** that is close to the region where the detector functions with high efficiency
- **minimize extrapolations** which cannot be experimentally constrained



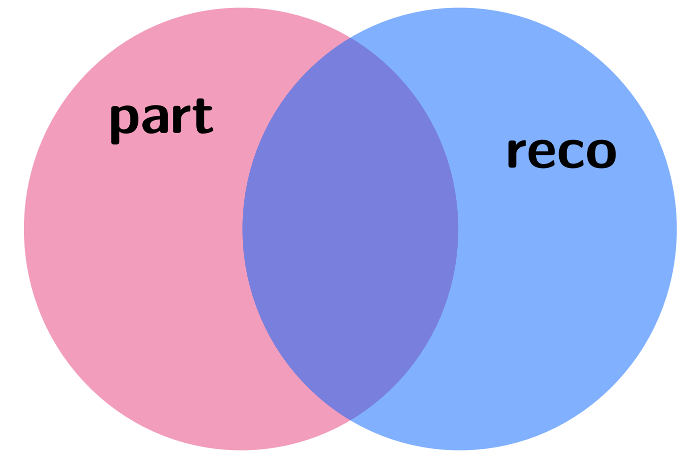
Definition

- use stable particles (lifetime > 30 ps)
- leptons: not coming from hadron decays, dressed with photons within a cone of $\Delta R = 0.1$
- same p_T and η cuts for all objects as the ones used for reconstruction (for electrons one extrapolates over $1.37 < |\eta| < 1.52$)
- b-tagging: ghost association of B hadrons with $p_T > 5$ GeV with jets

Definitions developed after series of workshops involving top and SM groups as well as theorists

Unfolding

- extract particle-level spectrum from measured reco-level
- for p_T unfolding reco-jets are matched ($\Delta R < 0.35$) to particle jets after ordering in p_T or b-tagging score
- correct for detector effects:
  - pass part & not reco: $\mathbf{f}_{\mathbf{part!reco}}$
  - pass reco & not part: $\mathbf{f}_{\mathbf{reco!part}}$
  - acceptance effects (b-tag, trigger, lepton): $\mathbf{f}_{\mathbf{accpt}}$
  - migration across bins: $\mathbf{M}$, $\mathbf{f}_{\mathbf{misassign}}$



$$N^i_{\text{part}} = f^i_{\text{part!reco}} \cdot \sum_j M^{\text{part},i}_{\text{reco},j} \cdot f^j_{\text{misassign}} \cdot f^j_{\text{reco!part}} \cdot f^j_{\text{accpt}} \cdot (N^j_{\text{reco}} - N^j_{\text{bgnd}})$$

The measurements: specifics

Jet multiplicity @ 8 TeV - di-lepton eμ

arXiv:1606.09490

Goal:

- repeat previous jet multiplicity, p_T and gap fraction measurements utilizing εμ top-cross-section measurement (Eur.Phys.J. C74 (2014) 3109)

Interlude about the eμ top cross-section measurement:

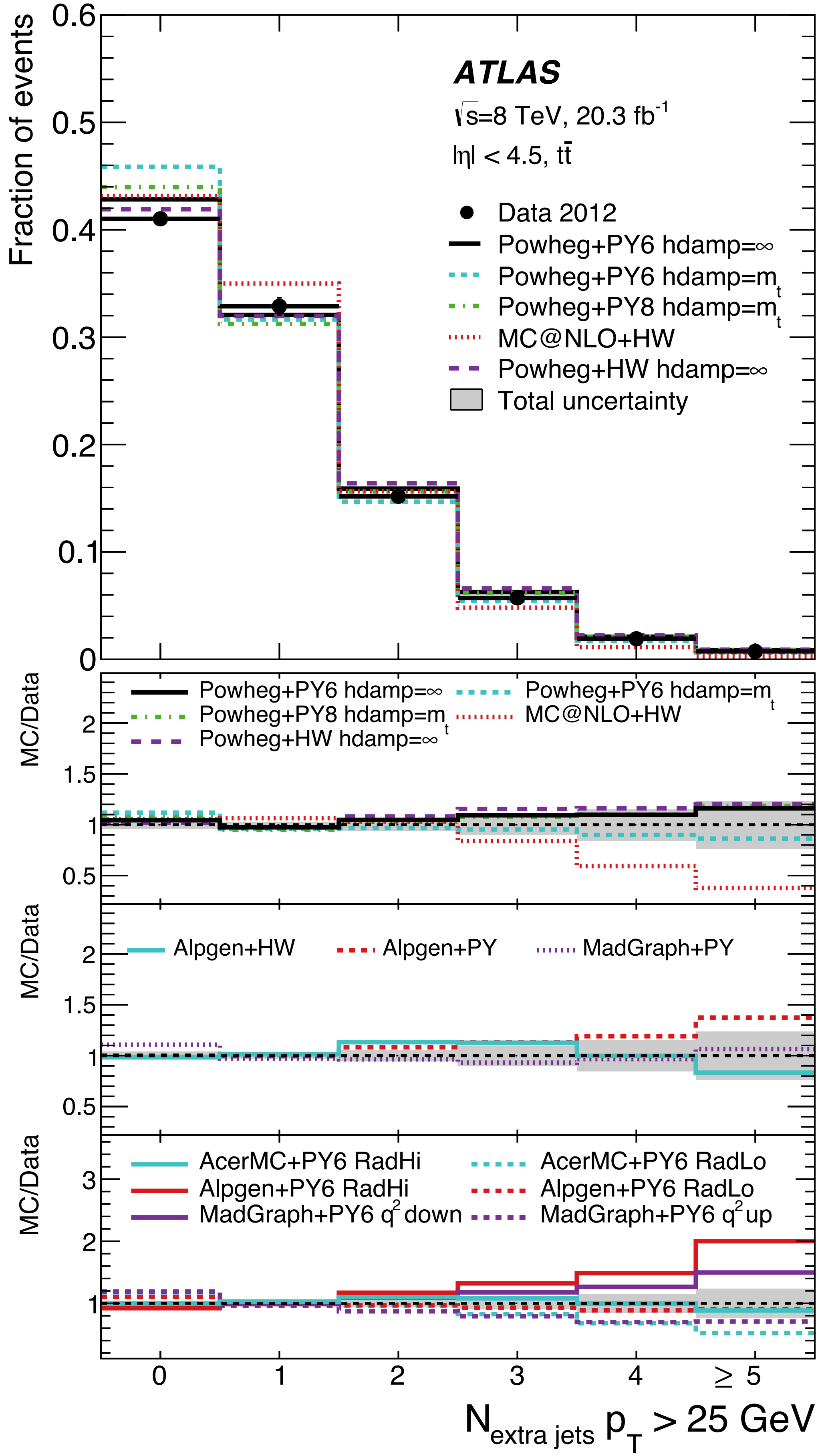
- most precise measurement of the top cross-section
- uncertainty slightly smaller than NNLO+NNLL prediction

$$N_1 = L \cdot \sigma_{t\bar{t}} \cdot \epsilon_{e\mu} \cdot 2\epsilon_b(1 - C_b\epsilon_b) + N_1^{\mathrm{bg}}$$

$$N_2 = L \cdot \sigma_{t\bar{t}} \cdot \epsilon_{e\mu} \cdot C_b \cdot {\epsilon_b}^2 + N_2^{\mathrm{bg}}$$

- based on in-situ measurement of b-tagging efficiency to reduce uncertainties
- Events with at least 2 b-jets have very high signal purity: $> 96\%$

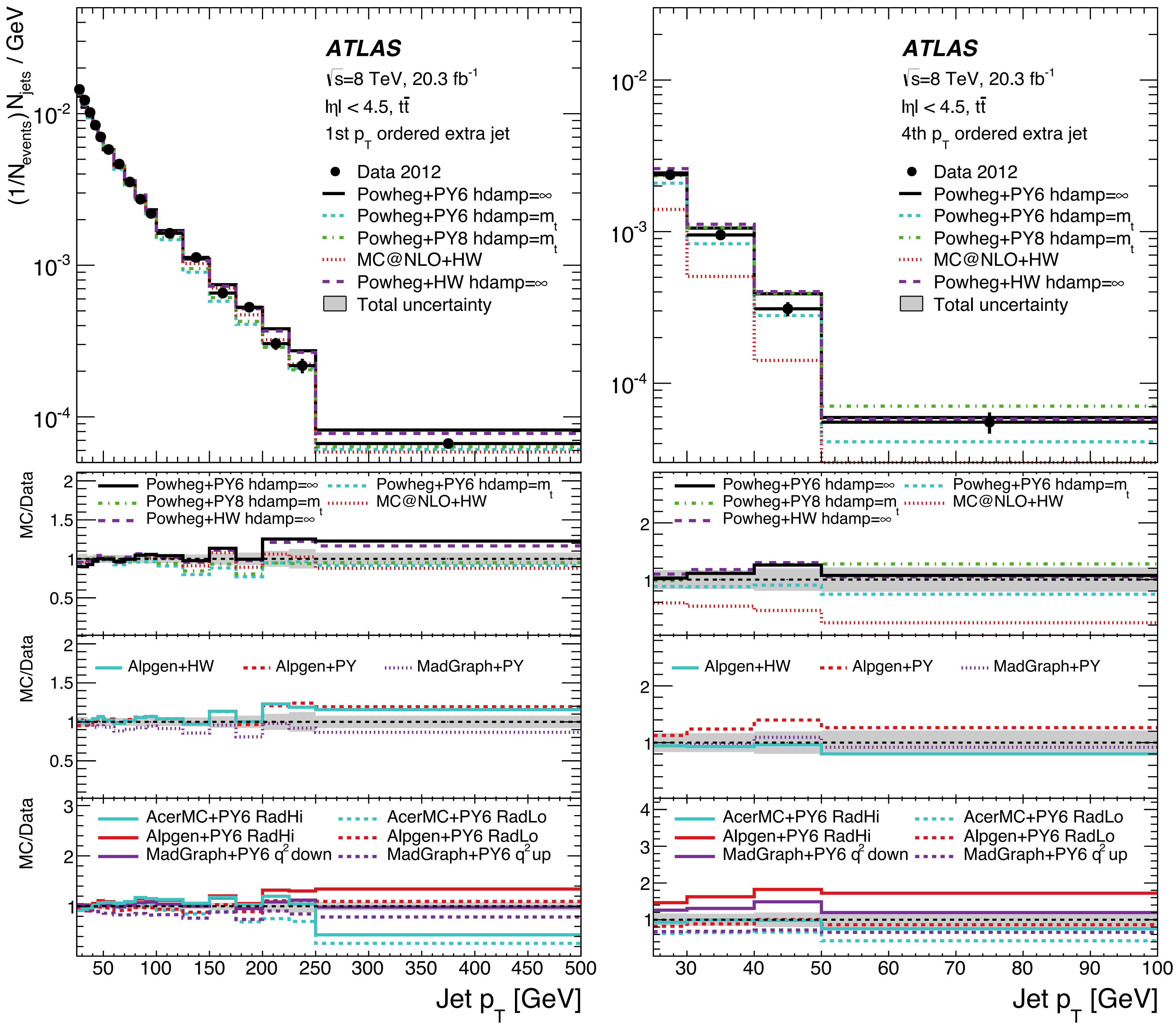
Jet multiplicity @ 8 TeV - di-lepton eμ



arXiv:1606.09490

- uncertainty significantly reduced with respect to 7 TeV measurement
- measurement compared against wider variety of MC predictions
- same features as 7 TeV measurement
  - **MC@NLO+Herwig doesn't describe the high jet multiplicity** tail
  - data prefer **lower values of α_s**

Jet multiplicity @ 8 TeV - di-lepton eμ



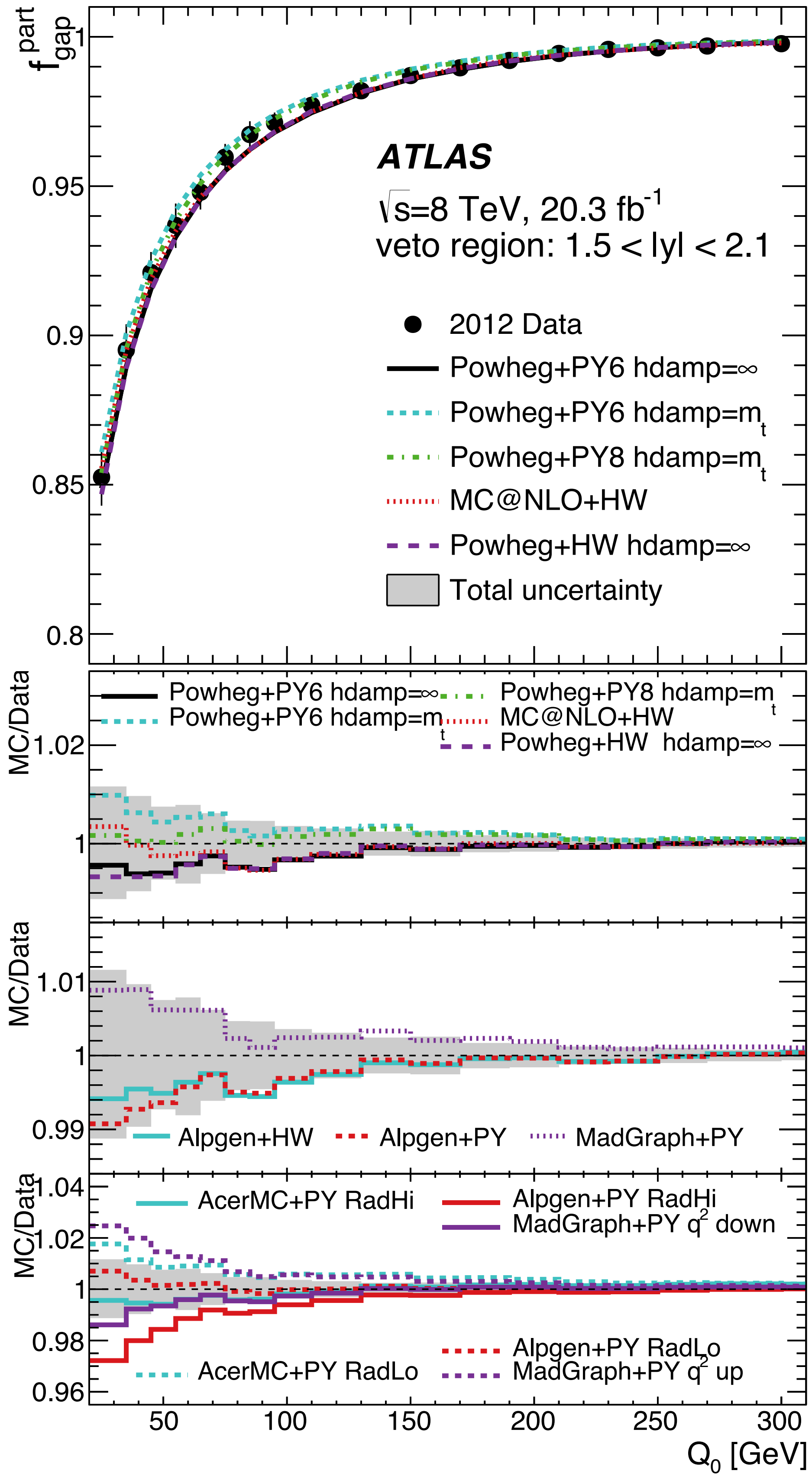
arXiv:1606.09490

- features seen in jet multiplicity spectrum can be explained by looking at the p_T spectra
- setting with **radiation damping** ($h_{damp}=m_{top}$) **preferred** over setting with no damping

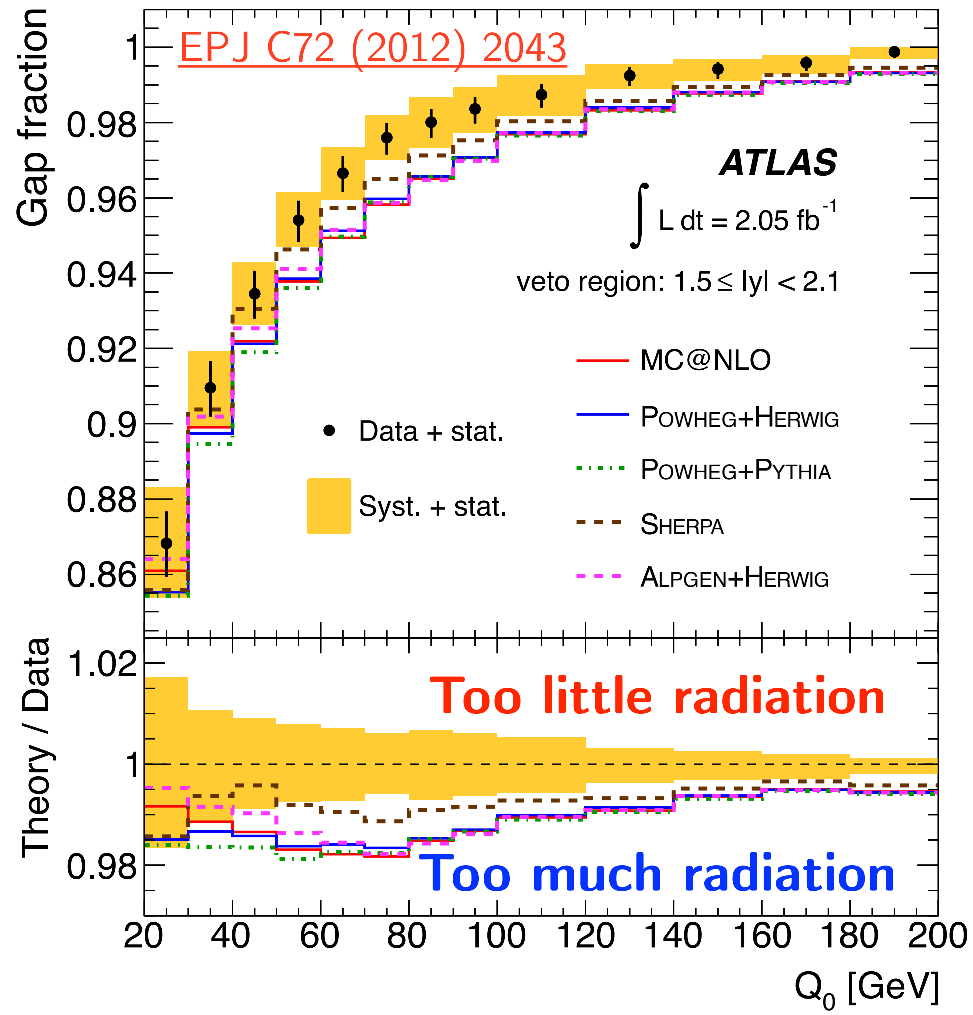
Gap fraction @ 8 TeV - di-lepton eμ

arXiv:1606.09490

8 TeV



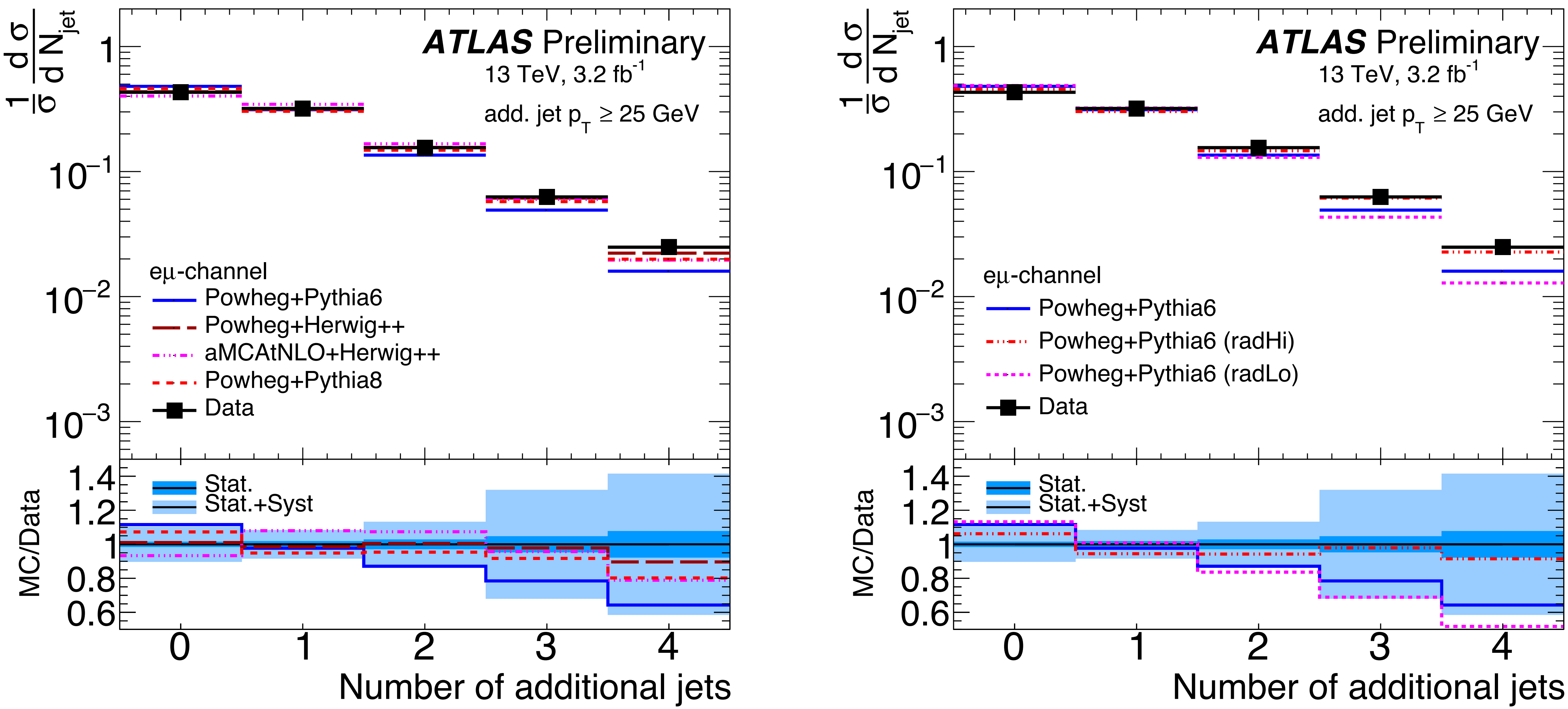
7 TeV



- MCs in better agreement with data in the forward region in the 8 TeV measurement
- more precise jet calibration in the forward region

Jet multiplicity @ 13 TeV - di-lepton ee+eμ+μμ

ATLAS-CONF-2015-065



- **New generators tested** (aMC@NLO) and **more PS** (Pythia8, Herwig++)
- All generators in good agreement with data
- **higher radiation preferred for Powheg+Pythia6** setup

Jet multiplicity @ 13 TeV - di-lepton ee+eμ+μμ

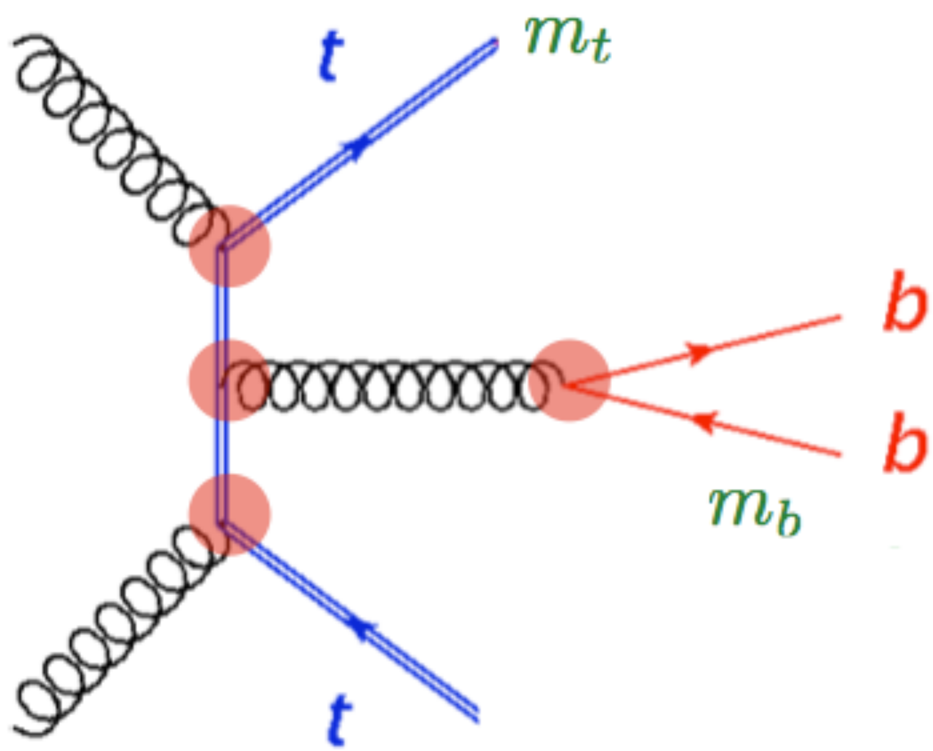
New

TOPQ-2015-17

- Plots to become available very soon
- Comparisons to **state of the art generators** including
  - Sherpa 2.2 and Powheg and MG5_aMC@NLO interfaced to
  - **Pythia 8, Herwig++, Herwig7**
- Powheg+**Herwig7** produces **too much extra radiation**
- Powheg+**Pythia8 too little radiation**
- **13 TeV data is not described very well by previous tunes**

ttbb @ 8 TeV

Eur. Phys. J. C (2016) 76:11



Why to measure ttbb:

- **dominant background** for ttH(bb), H^+ (tb), some SUSY searches
- **hard to calculate**: multi-scale process, α_s^4
  $\Rightarrow$ large uncertainties from scale choice
- sensitive to **modeling** aspects which are **poorly constrained** ($g \rightarrow bb$)

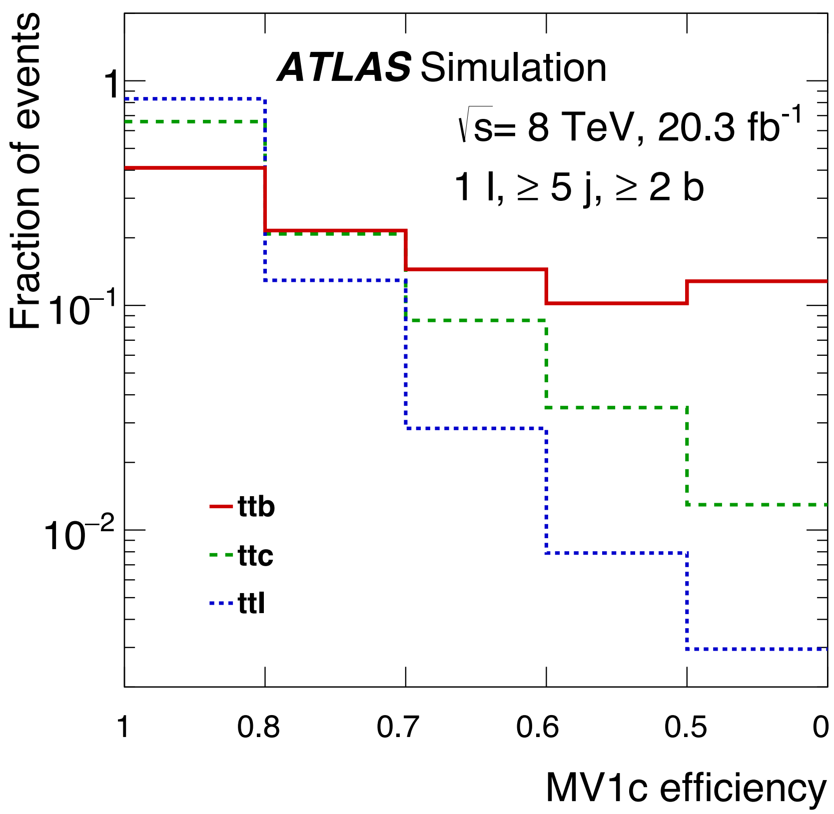
Measurements:

- 5 measurements:
  - tt+$\geq$ 1b: single-lepton & di-lepton
  - tt+$\geq$ 2b: di-lepton cut-and-count and fit
  - ttbb/ttjj

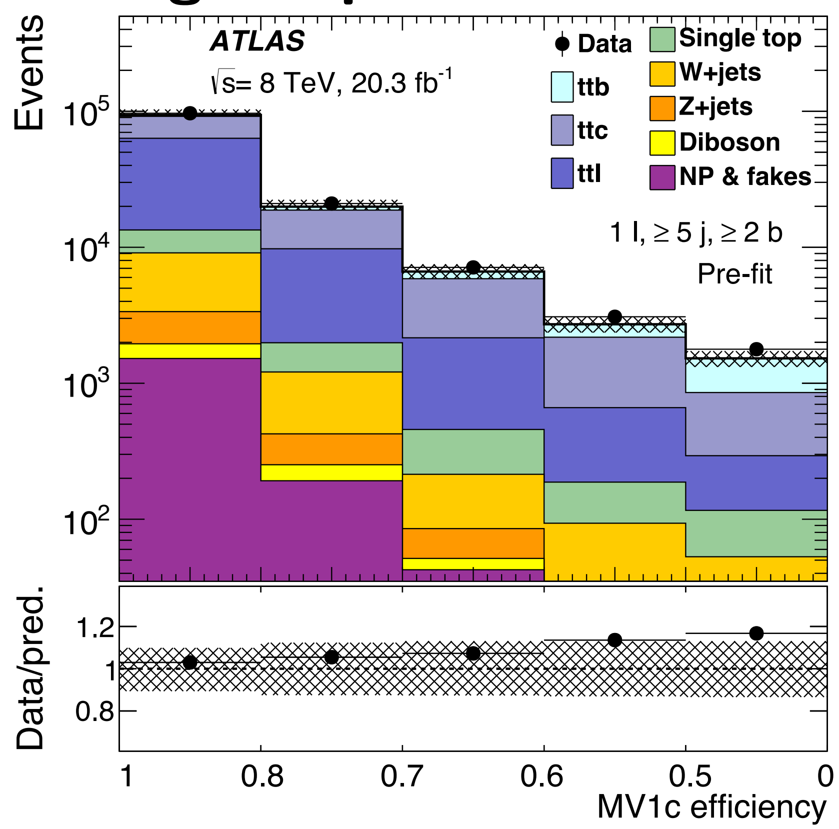
ttbb @ 8 TeV

Eur. Phys. J. C (2016) 76:11

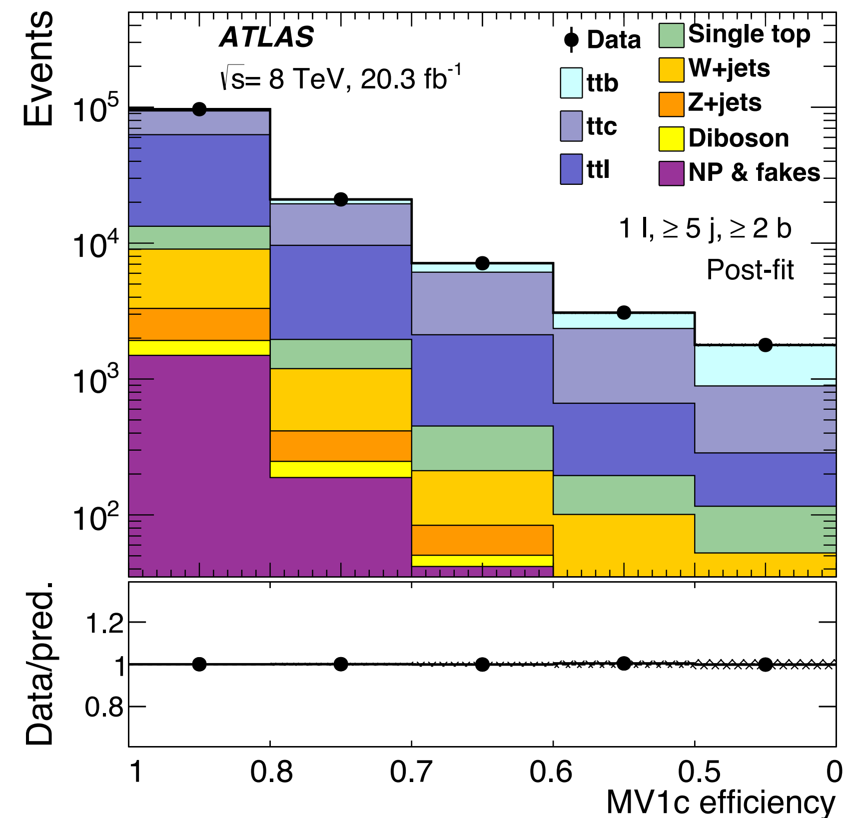
Discriminate signal/bg using b-tag score



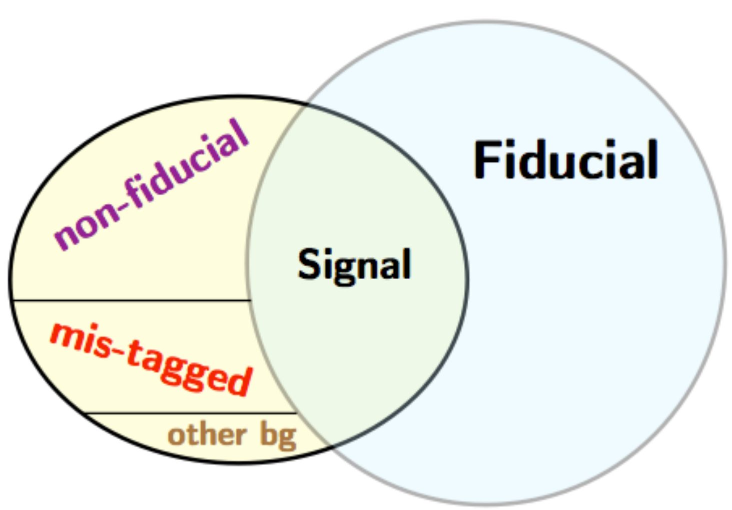
Fit data to MC signal/bg templates



Extract σ from best-fit value



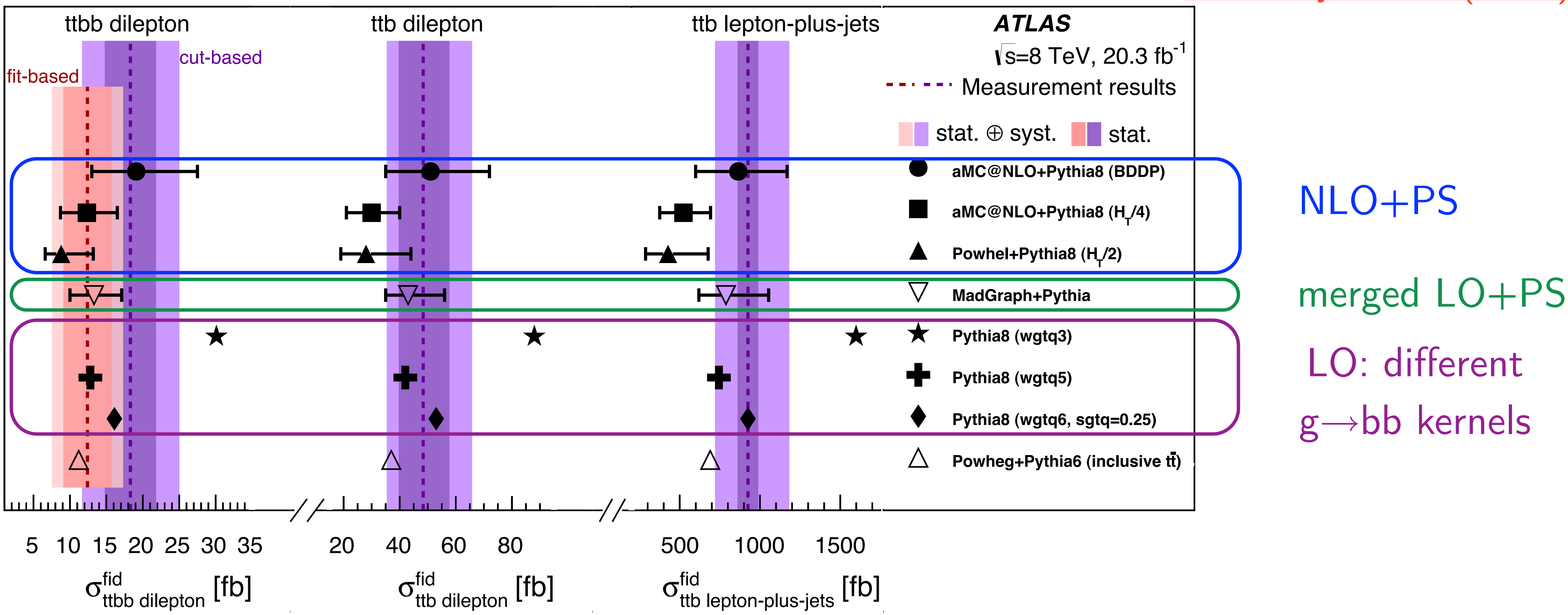
Cut-and-count

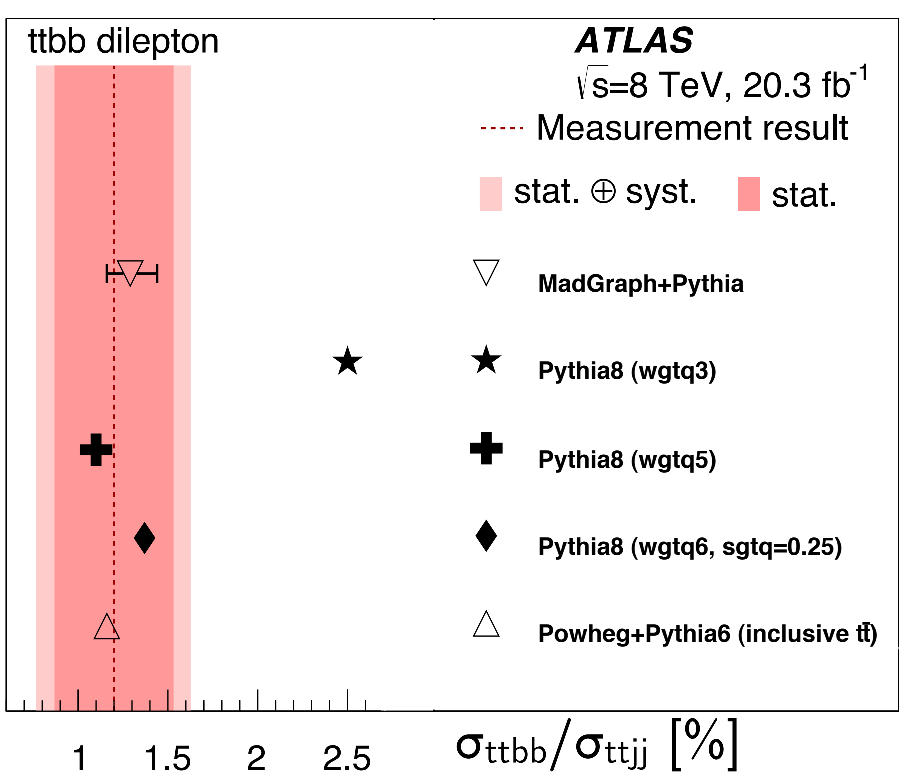


$$\sigma^{\text{fid}}_{t\bar{t}b\bar{b}} = \frac{\left(N^{\text{data}}_{4b} - N^{\text{mis-tagged}}_{t\bar{t}+\text{jets}} - N^{\text{non-}t\bar{t}+\text{jets}}_{\text{bg}}\right) f_{\text{sig}}}{\mathcal{L}\cdot\epsilon_{\text{fid}}}$$

ttbb @ 8 TeV

Eur. Phys. J. C (2016) 76:11





- Measurements generally agree with predictions within uncertainties
- **Data prefer** slightly **higher g→bb** rates
- Soft scales seem to perform better $\mu_{BDDP} = m_{top}^{1/2} (p_T(b) p_T(b))^{1/4}$
- **Sensitivity to g→bb description**: most extreme model disfavored

Tunes and modeling studies using tt measurements

several public notes on different aspects of top modeling:

- Top modeling at 13 TeV (ATL-PHYS-PUB-2016-004)
- Tuning of MG5_aMC@NLO+Pythia8 (ATL-PHYS-PUB-2015-048)
- Modeling of bottom and charged hadrons in top decays (ATL-PHYS-PUB-2014-008)
- Study of measurements constraining QCD radiation in top events (ATL-PHYS-PUB-2013-005)
- Study of ttcc with MG5_aMC@NLO (ATL-PHYS-PUB-2016-011)
- and many more

A top-specific tune: ATTBAR

ATL-PHYS-PUB-2015-007

- 2 step tune:
  - Pythia 8 stand-alone (ATTBAR)
  - ATTBAR applied to NLO+PS (Powheg, MadGraph5_aMC@NLO) + further tuning of matching parameters
- Starting points:
  - Monash [Skands, Carazza, Rojo, Eur.Phys.J. C74 (2014) no.8, 3024]
  - 4C [Corke, Sjöstrand, JHEP 1103:032,2011]
- 7 TeV ATLAS data:
  - **tt gap fraction**, **additional jet pT and multiplicity**, jet shapes

Parameters tuned

ATL-PHYS-PUB-2015-007

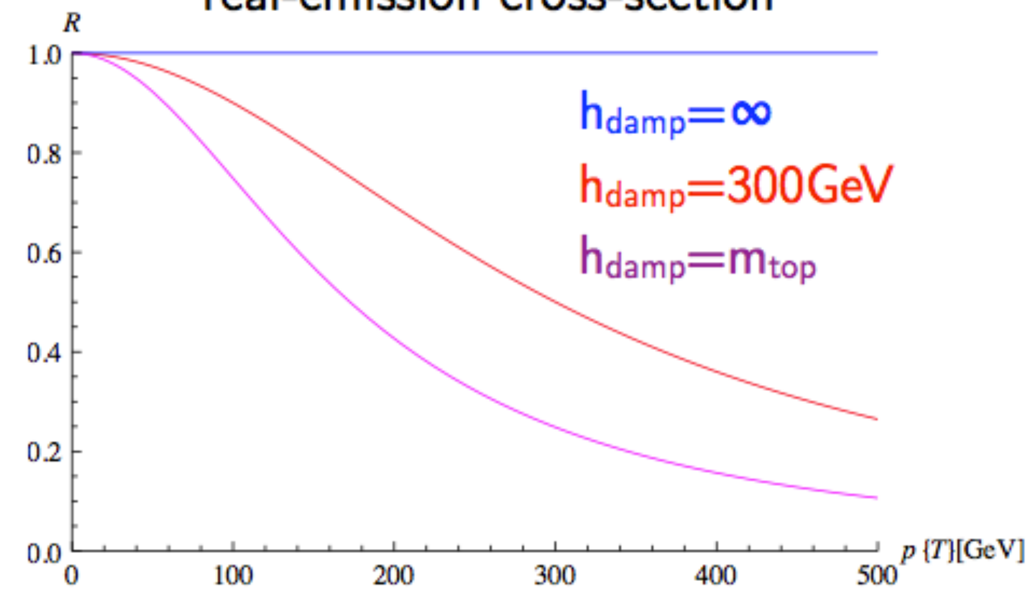
Parameters for ATTBAR tune

Parameter	PYTHIA8 setting	Variation range	4C	Monash
$\alpha_s^{\mathrm{ISR}}(m_Z)$	`SpaceShower:alphaSvalue`	0.110 – 0.140	0.137	0.1365
ISR damping	`SpaceShower:pTdampMatch`	1 (fixed)	0	0
$p_{\mathrm{T,damp}}^{\mathrm{ISR}}$	`SpaceShower:pTdampFudge`	0.8 – 1.8	-	-
$\alpha_s^{\mathrm{FSR}}(m_Z)$	`TimeShower:alphaSvalue`	0.110 – 0.150	0.1383	0.1365
$p_{\mathrm{T,min}}^{\mathrm{FSR}}$ [GeV]	`TimeShower:pTmin`	0.1 – 2.0	0.4	0.5

Parameters for NLO+PS tunes:

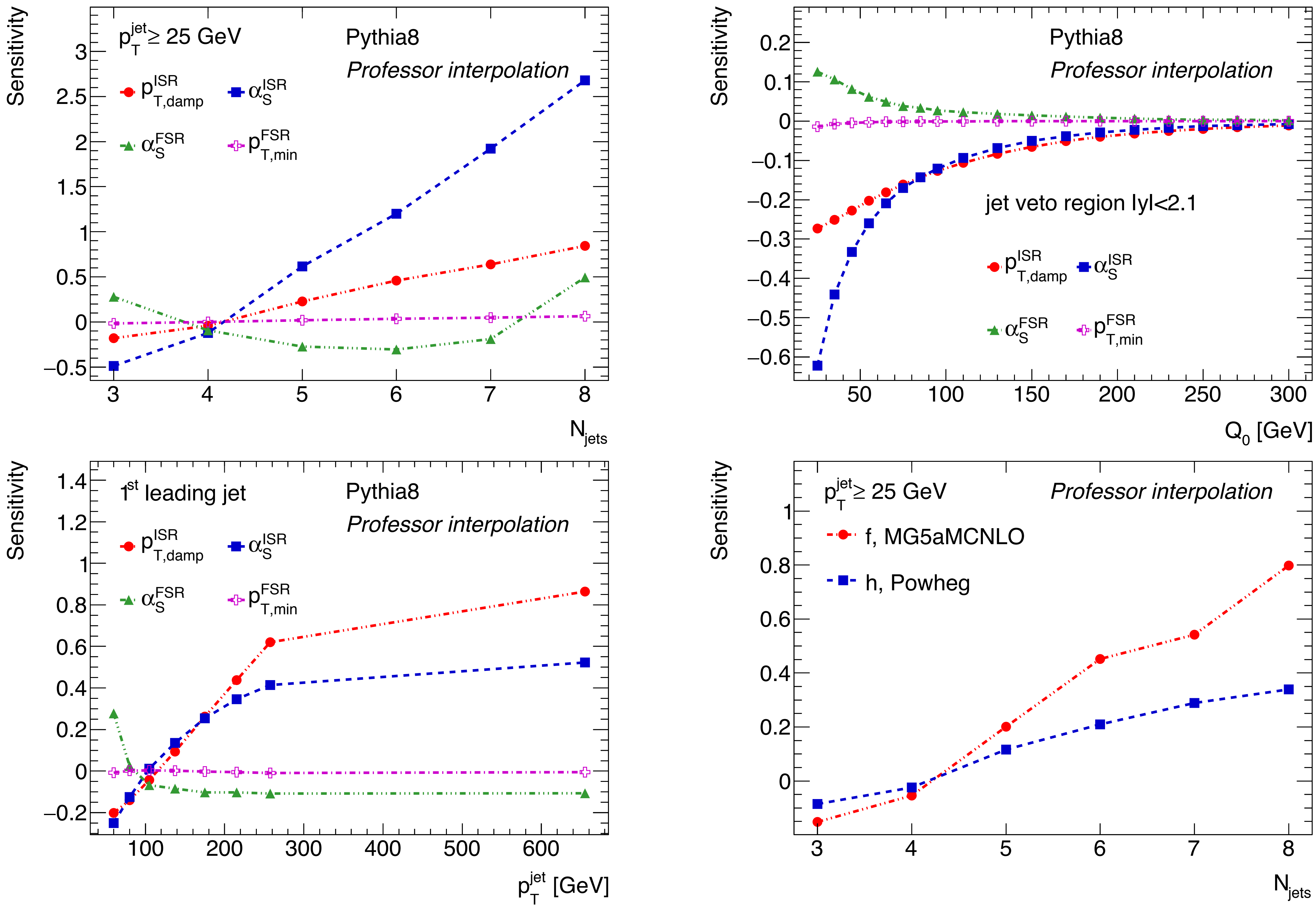
- h_{damp} Powheg: $R^s = R \cdot \frac{h_{\mathrm{damp}}^2}{h_{\mathrm{damp}}^2 + p_T^2}$
- starting scale of shower in MG5_aMC@NLO

R^s: shower approximation to real-emission cross-section



Sensitivity to tuned parameters

ATL-PHYS-PUB-2015-007



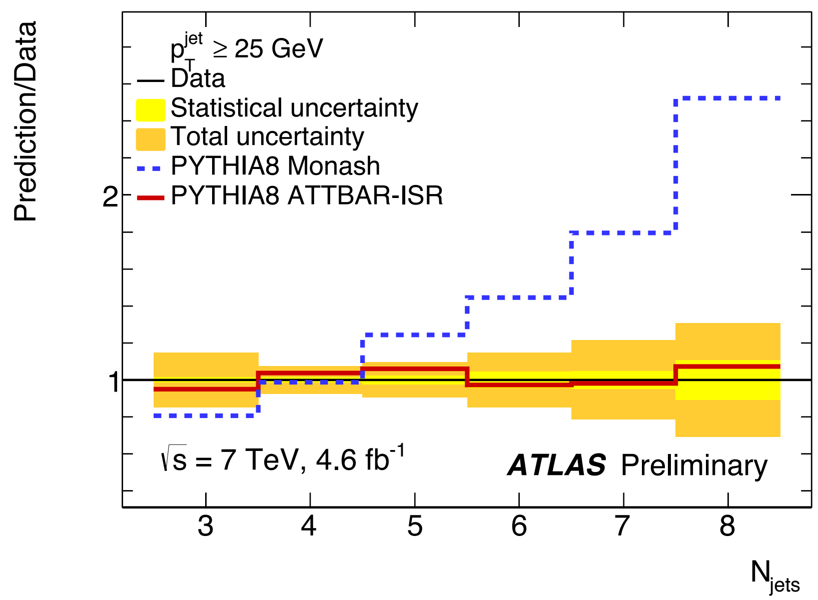
- Jet multiplicity and gap fraction **mostly sensitive to α_s choice for ISR** (also sensitive to hdamp choice)
- **Leading jet p_T also sensitive to damping scale**

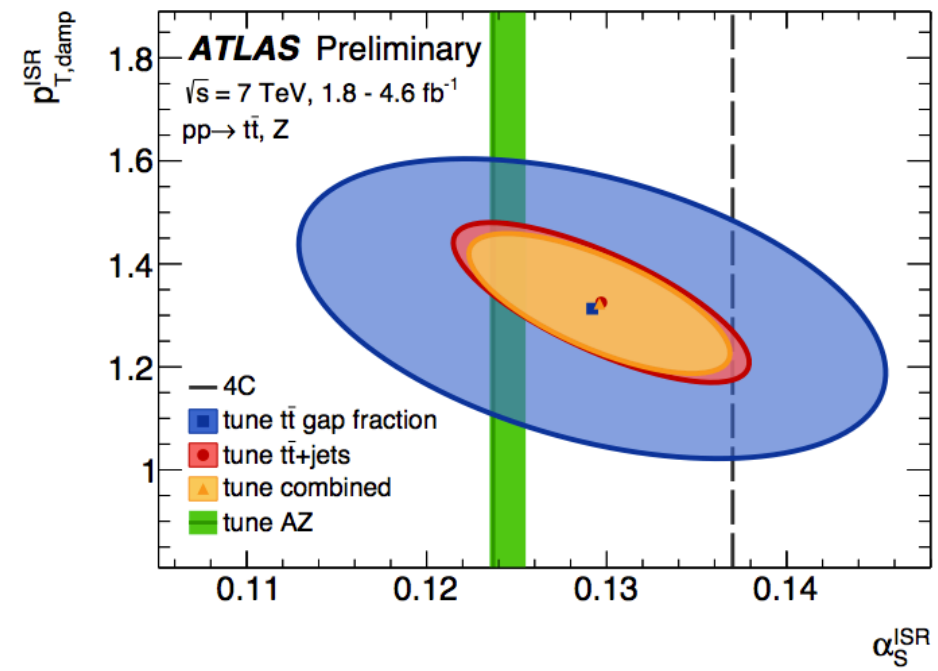
A more in-depth look: the ATTBAR tune

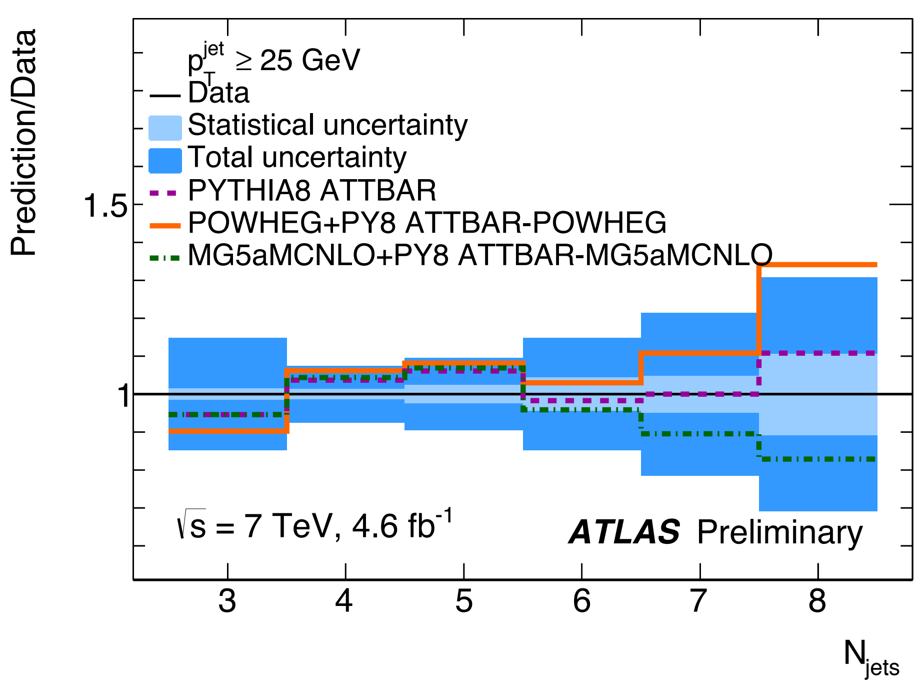
ATL-PHYS-PUB-2015-007

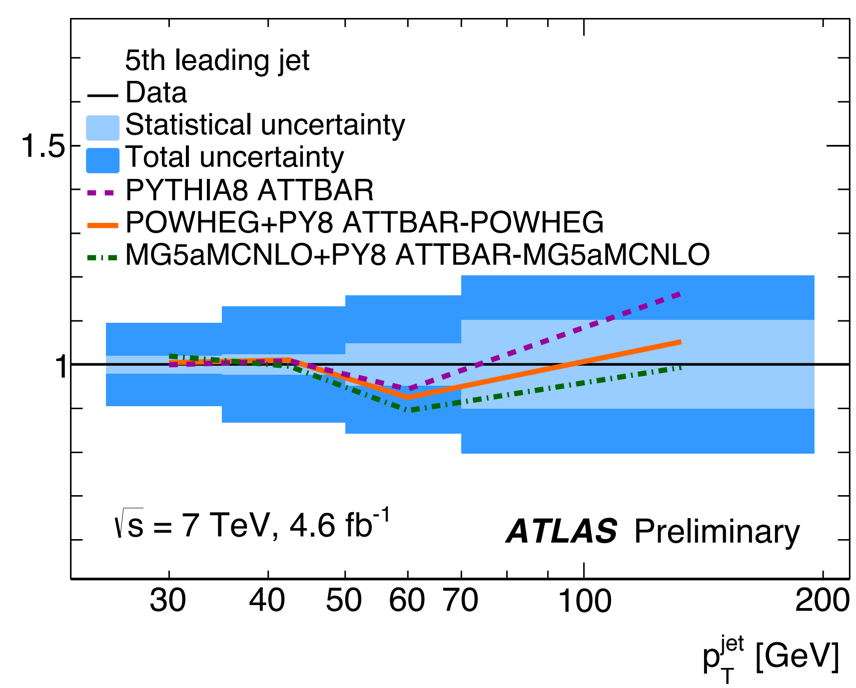
- **A top-specific tune can greatly improve the description of top observables**

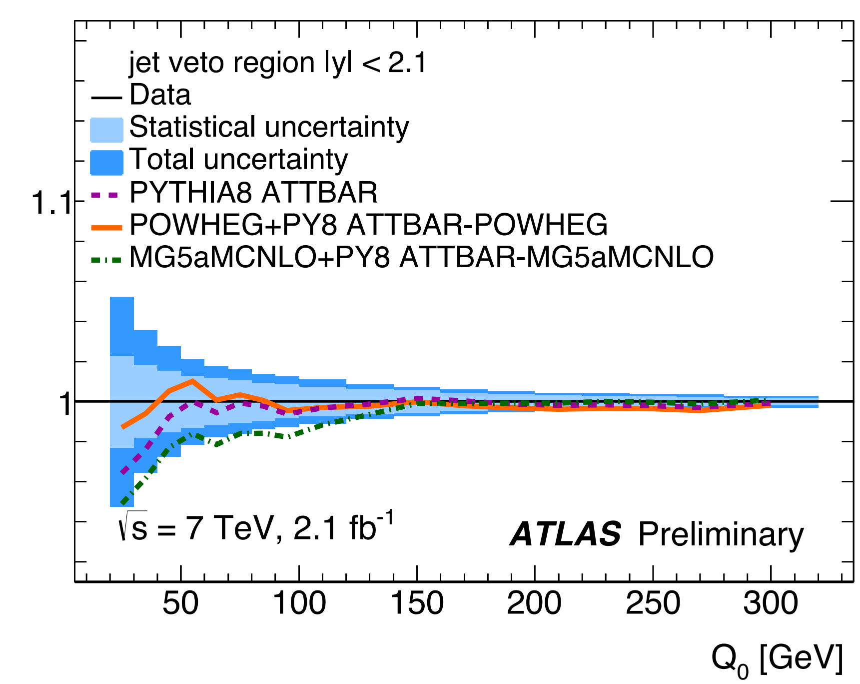
- After the tuning the LO and NLO+PS predictions agree with the measurements within errors







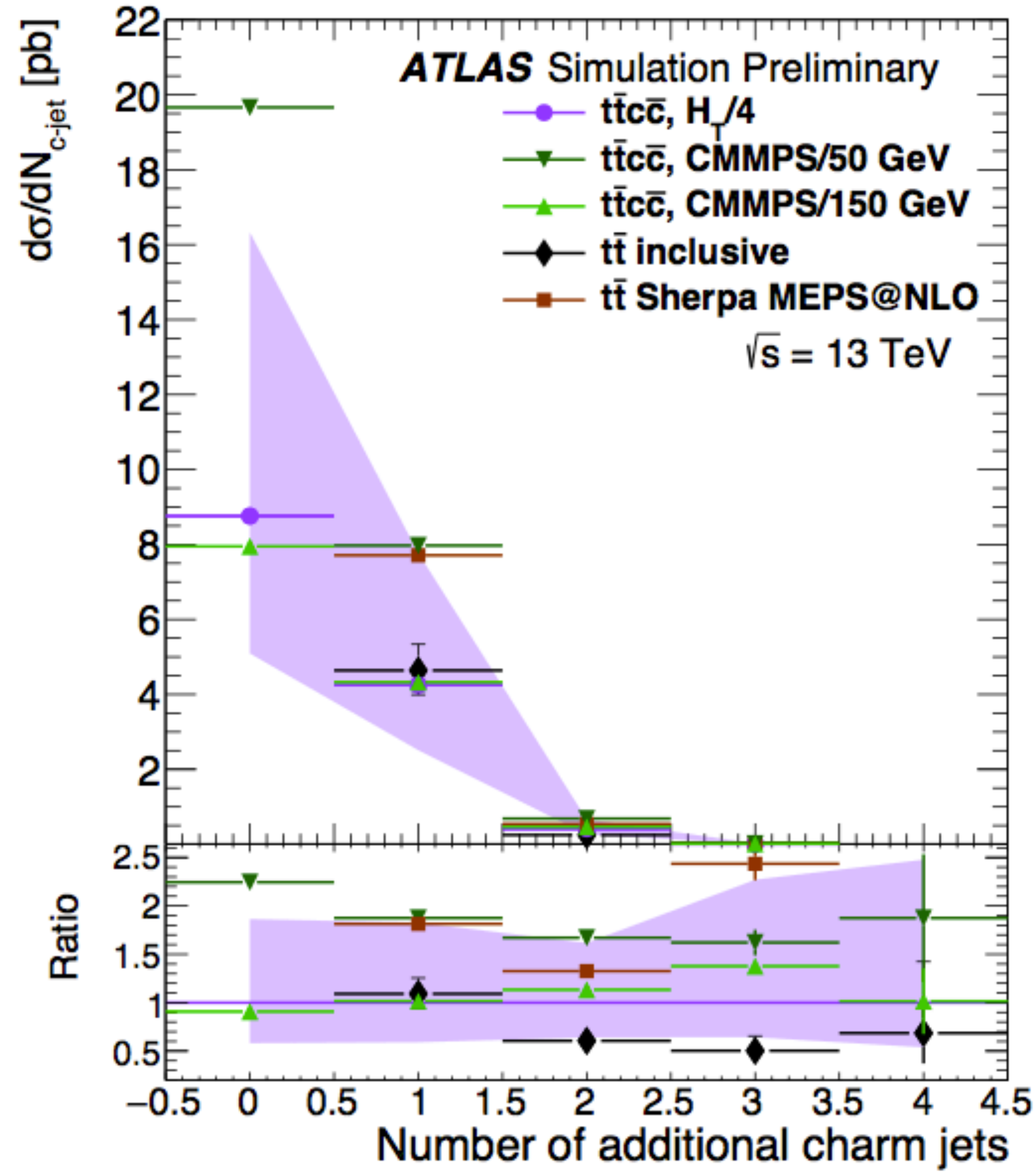




The wild west: ttcc

ATL-PHYS-PUB-2016-011

- MG5_aMC@NLO with several functional forms for the renormalization/factorization scale
- **Scale uncertainties 50-100%**
- **Generator predictions vary by a factor of 2** or more - beyond scale uncertainties



Conclusion

- rich program of measurements including tt+X in ATLAS

- lots of top quarks

  ⇒ precision measurements

  ⇒ **better understanding of top modeling**

  ⇒ **reduced systematics** / **better description of top bg**

- synergy between experiment & theory (e.g. Top LHC WG)

Thank you for your attention!