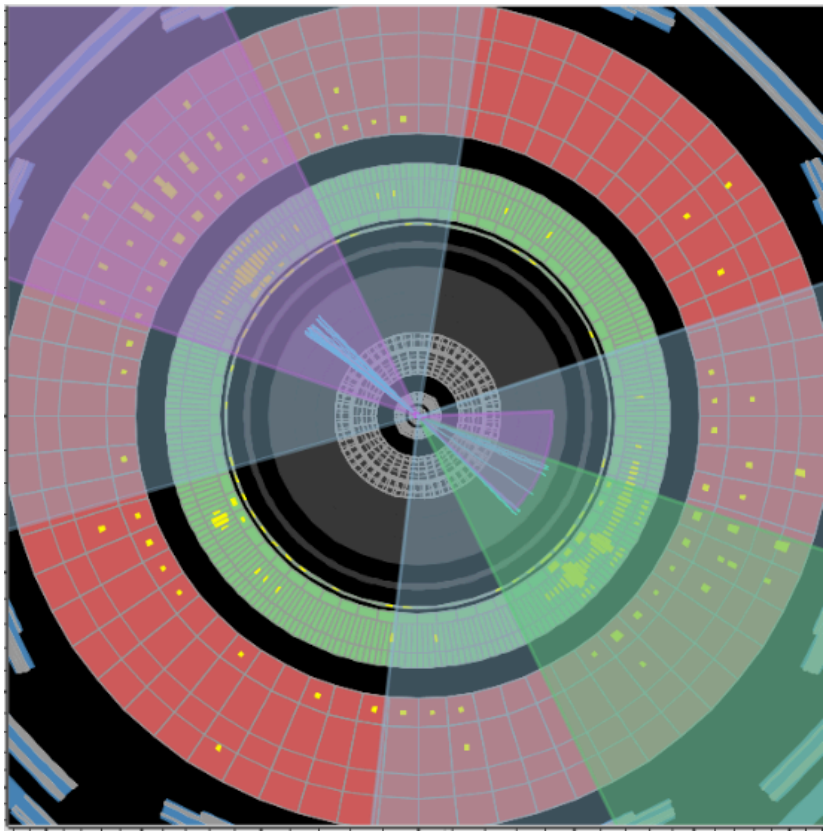


Highlights of Top Quark Production Measurements at ATLAS

Pekka K. Sinervo, C.M., FRSC
University of Toronto

Representing the ATLAS Collaboration

Talk at QCD@LHC, Buffalo, NY
July 2019

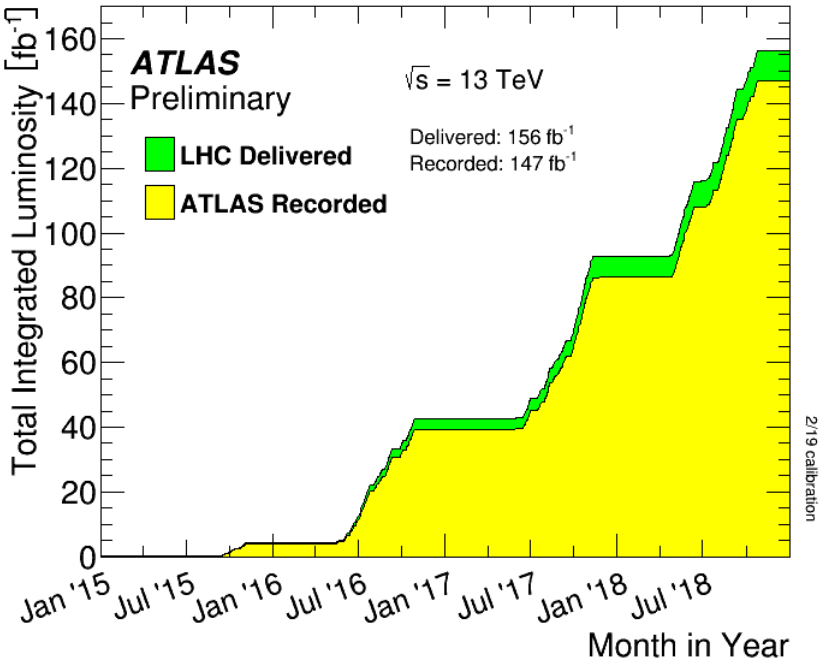
Why Top Quarks?

Heaviest known particle, only "bare" quark

- High statistics allows both **precision measurement** and search for **new physics**.
- $t\bar{t}$ complex final state – but **not too complex –** fostering:
  - Theoretical and experimental **advancements**
  - Fine details not yet completely understood: **NNLO** calculations still rather new / not matched to PS, $t\bar{t}$/tW/WbWb **interference** effects, …

See, e.g., M Grazzini's Plenary Talk

LHC and ATLAS



Exceptional machine & detector performance

Only a very small fraction of the total LHC + HL-LHC luminosity collected/analyzed so far!

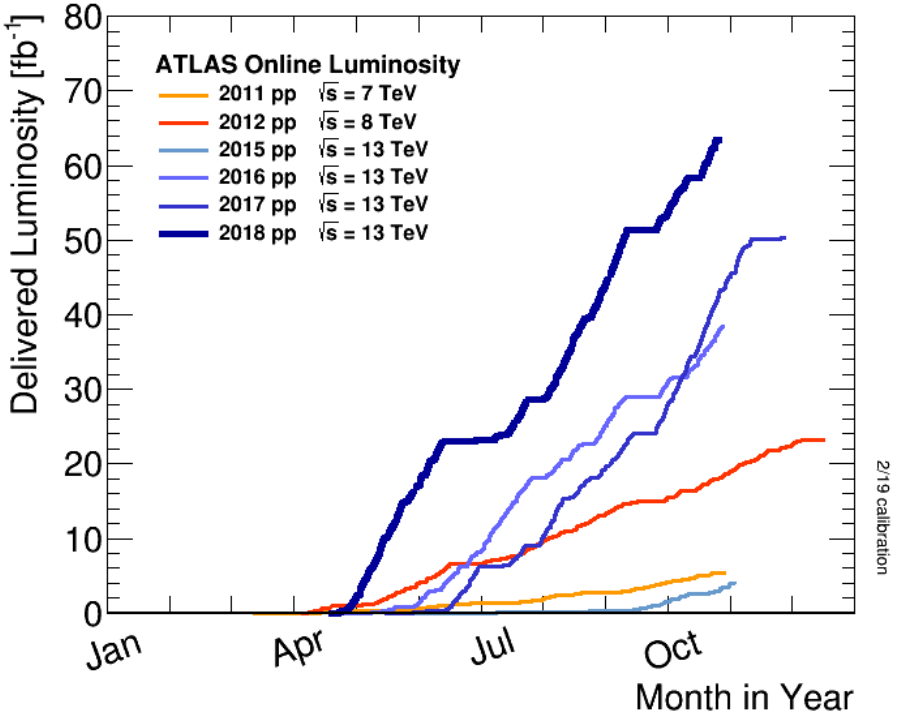
~150 fb^{-1} at √s = 13 TeV collected in Run 2

$$N = \mathcal{L} \cdot \sigma_{t\bar{t}}$$

$$\sigma_{t\bar{t}} \sim 830\,\mathrm{pb}$$

$$\mathcal{L} \sim 15 \times 10^{33}\,\mathrm{cm}^{2}\mathrm{s}^{-1}$$

~750 tt̄ pairs produced per minute



Focus today:

Couplings

Production cross-section(s)
Differential measurements
Single top
Associated production

Searches

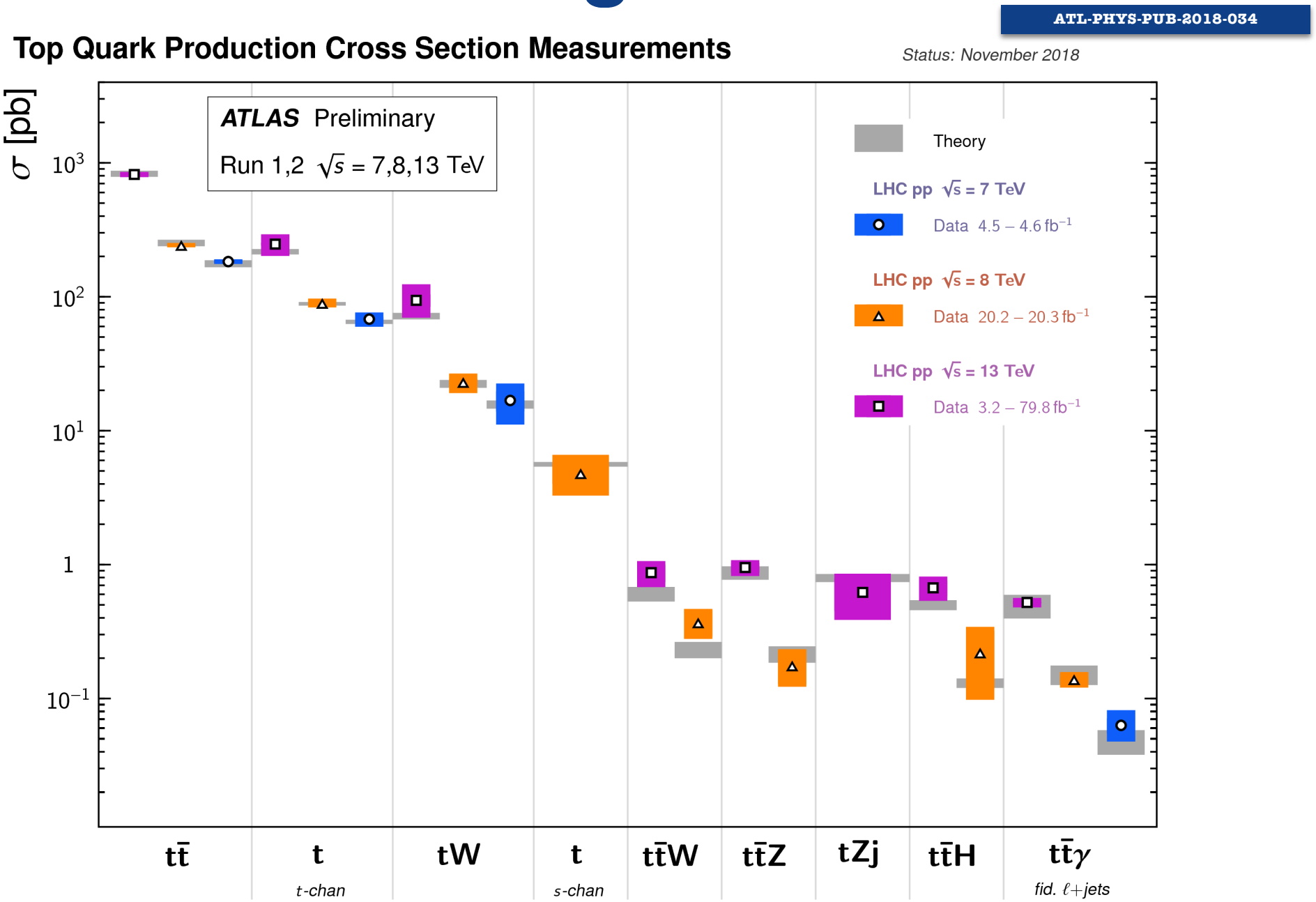
Resonant production (Z', g_{KK})
Vector-Like Quarks (VLQ)

Other topics covered in various talks
e.g., ATLAS+CMS results, Robert Vallance

Cross-Section

“Can you count how many top quarks are produced?”

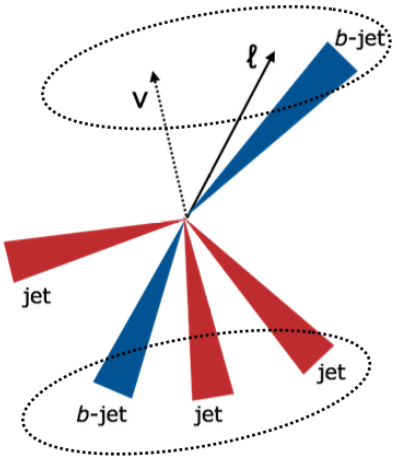
The "Big Picture"



Comparison with theory

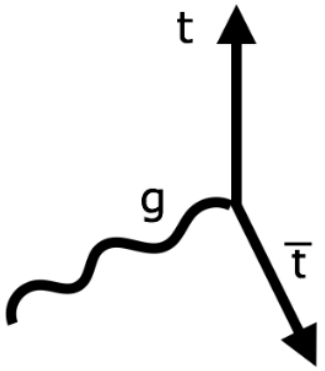
Fiducial phase-space

- Similar kinematic reconstruction at detector- and particle-level objects
- Reduce extrapolation uncertainty
- Endpoint of the theoretical prediction

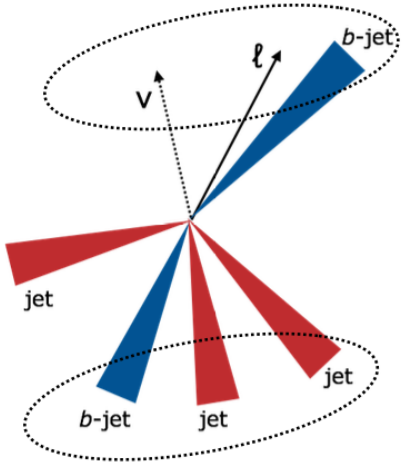


Full phase-space

- **NNLO+NNLL (+EKW)** accuracy only available by asking favourite theorists, often slow turnaround
- Larger **extrapolation** to low-p_T, high-η
- Observables must be **infrared safe**

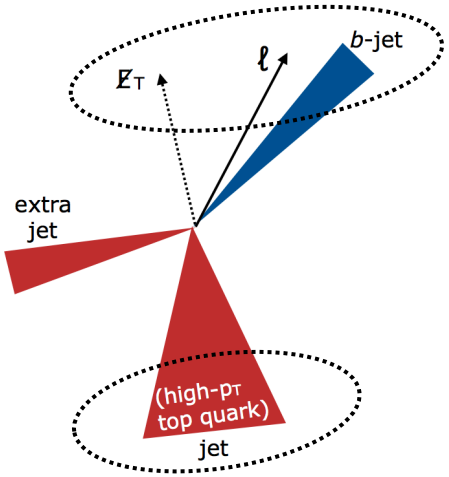


Kinematic reconstruction



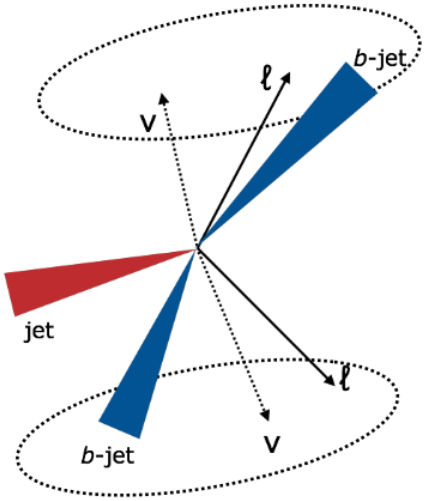
Single lepton resolved - PseudoTop

- Mass constraints (m_W, m_t) and b-tagging information to reconstruct decay chain



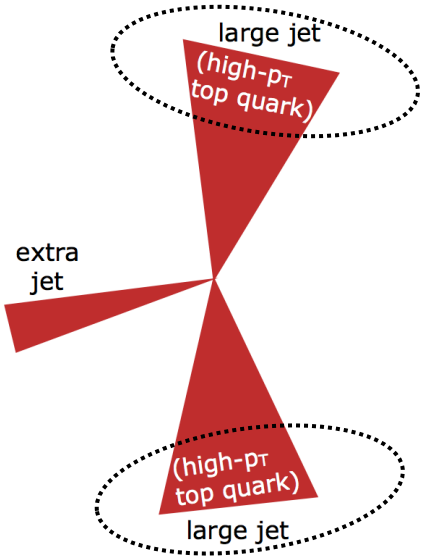
Single lepton boosted

- Kinematic constrains to reconstruct $t \to \ell\nu b$
- Hadronic top = large-*R* trimmed jet



Dilepton Neutrino weighting

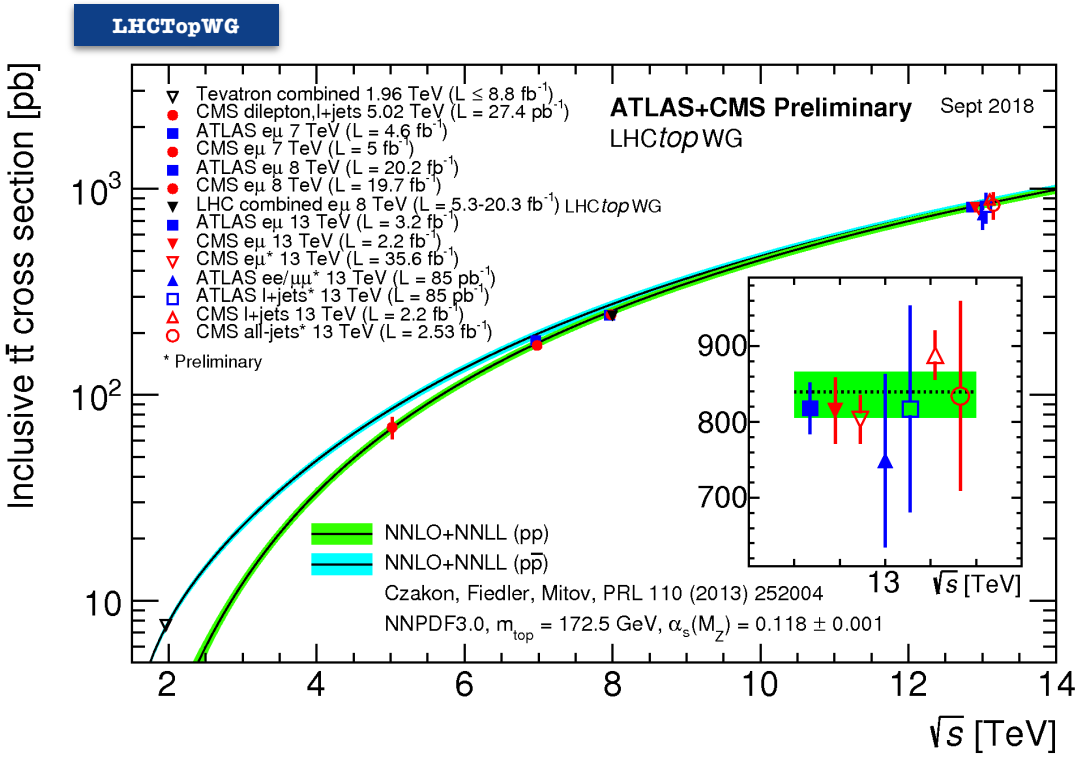
- Kinematic constrains to find optimal longitudinal component of the two neutrinos' momenta [Phys. Lett. B, 752 (2016) 18-26]
- Extra jet may also be photon, $b\bar{b}$ pair

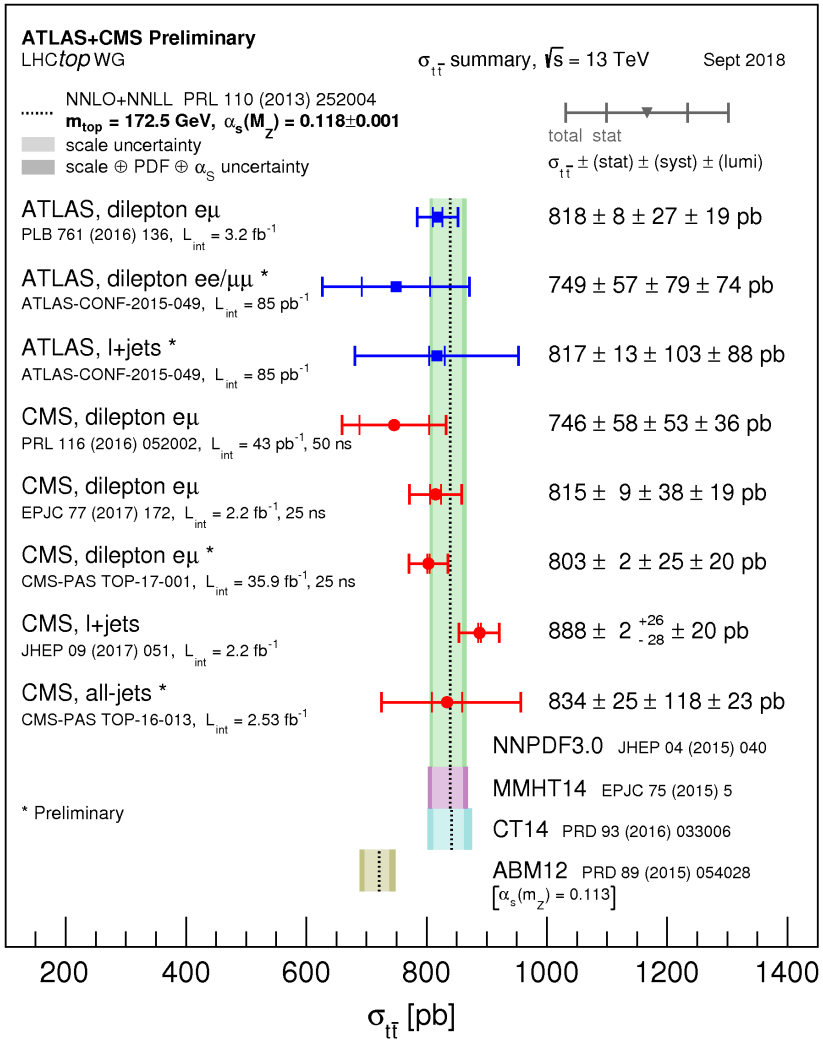


All-hadronic boosted

- Top quark candidates = 2 leading large-*R* trimmed massive jets (*b*- and *top*-tagged)

tt total xs (QCD)





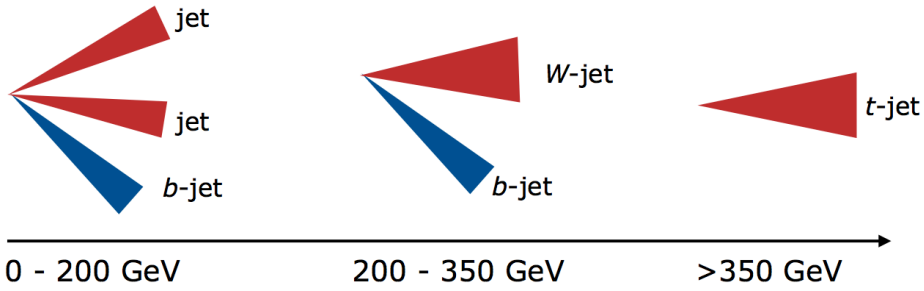
Inclusive cross-section in very good agreement with NNLO+NNLL calculations

Δσ(exp) ≲ Δσ(th)

Possible deviations still allowed:

- small corners of the phase-space
- differential cross-sections
- associated production

Top Quark p_T



- Different $\mathbf{p_T}$ regimes lead to different **reconstruction** techniques [0, ~1 TeV]
- Sensitive to **final state radiation**
- Very precise low-p_T differential cross-sections indicate **disagreement** with increasing p_T

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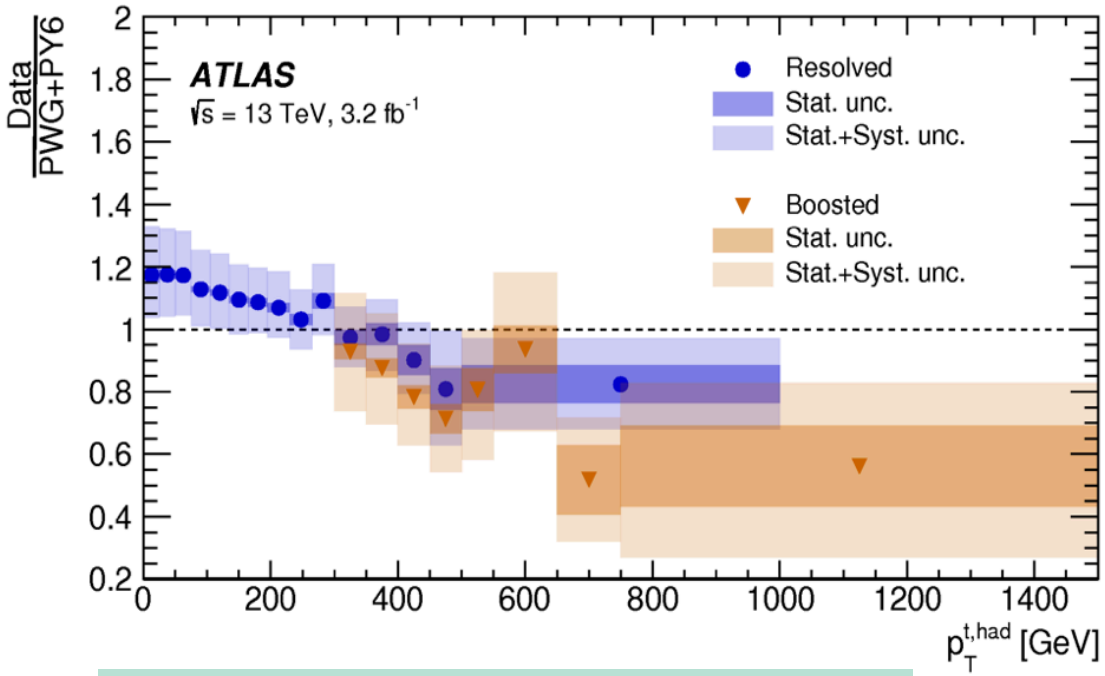

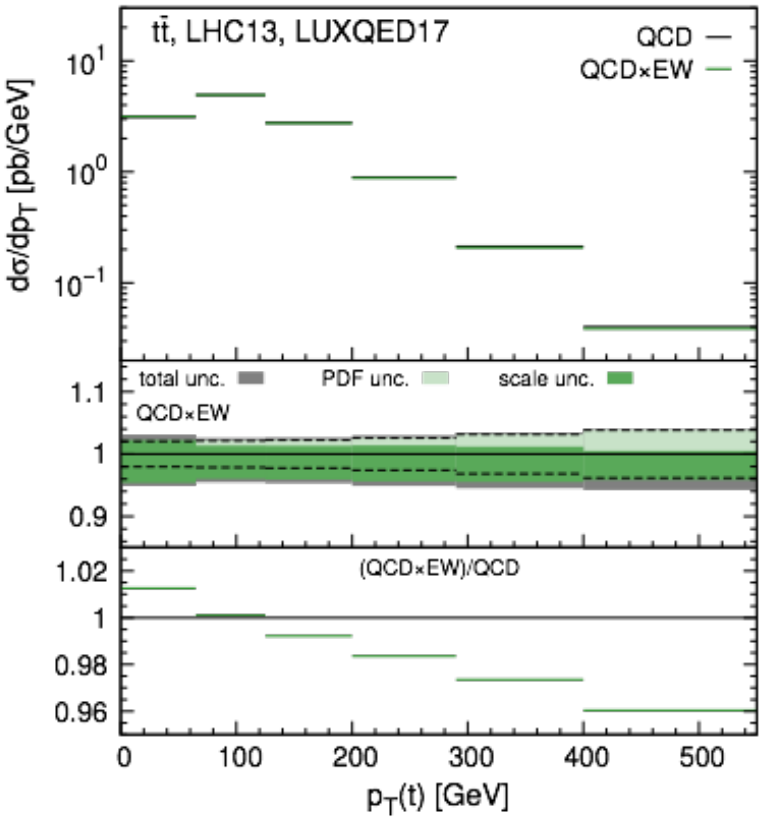

Resolved and boosted channel "overlap"
Indications that NNLO QCD + NLO EW corrections are important!

Top Quark p_T

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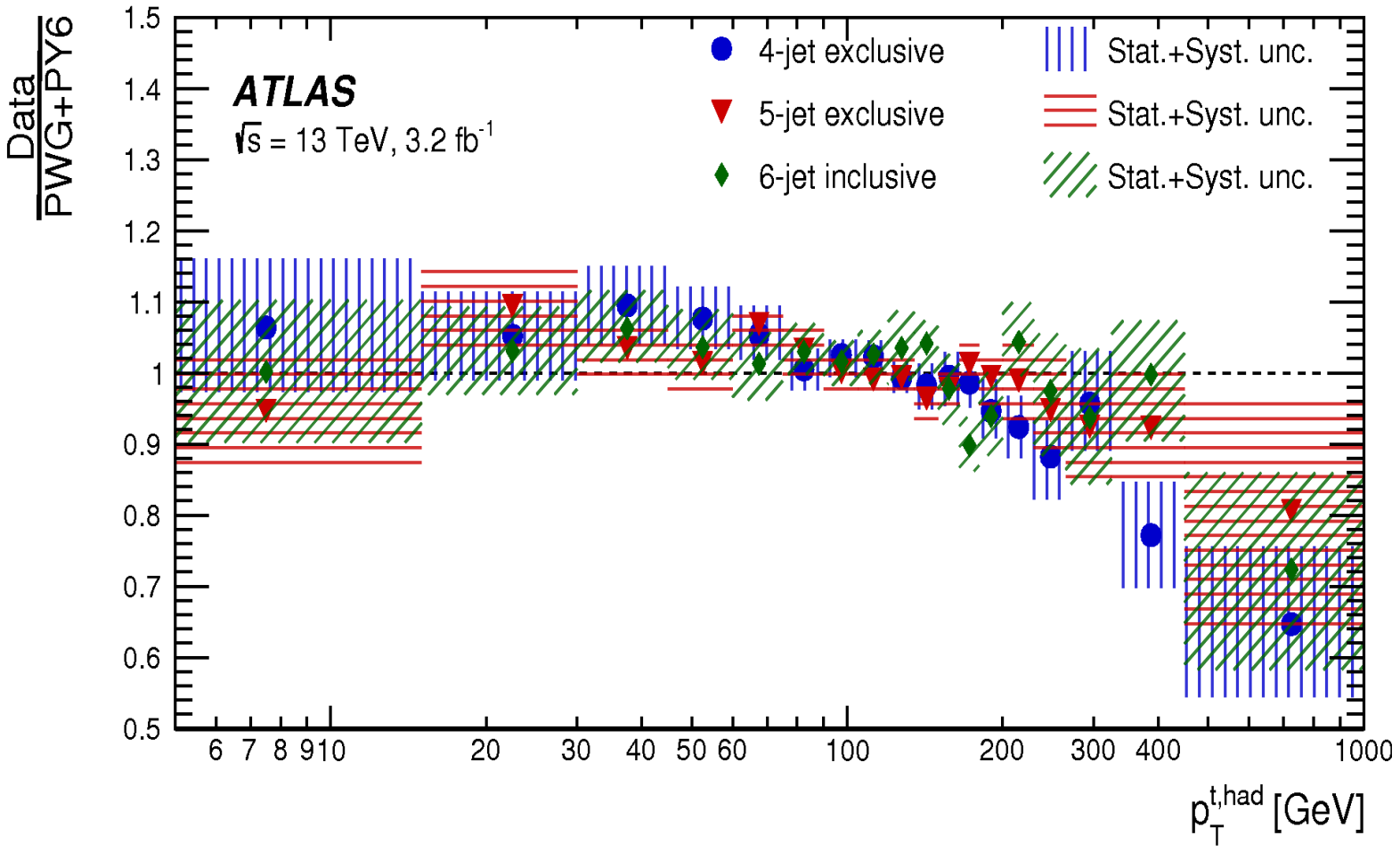
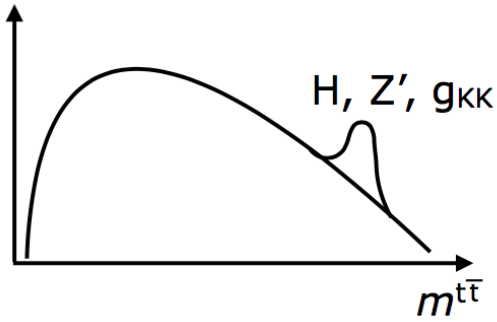
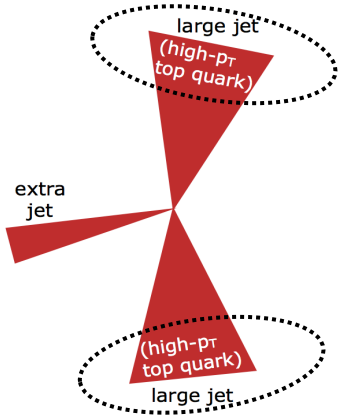


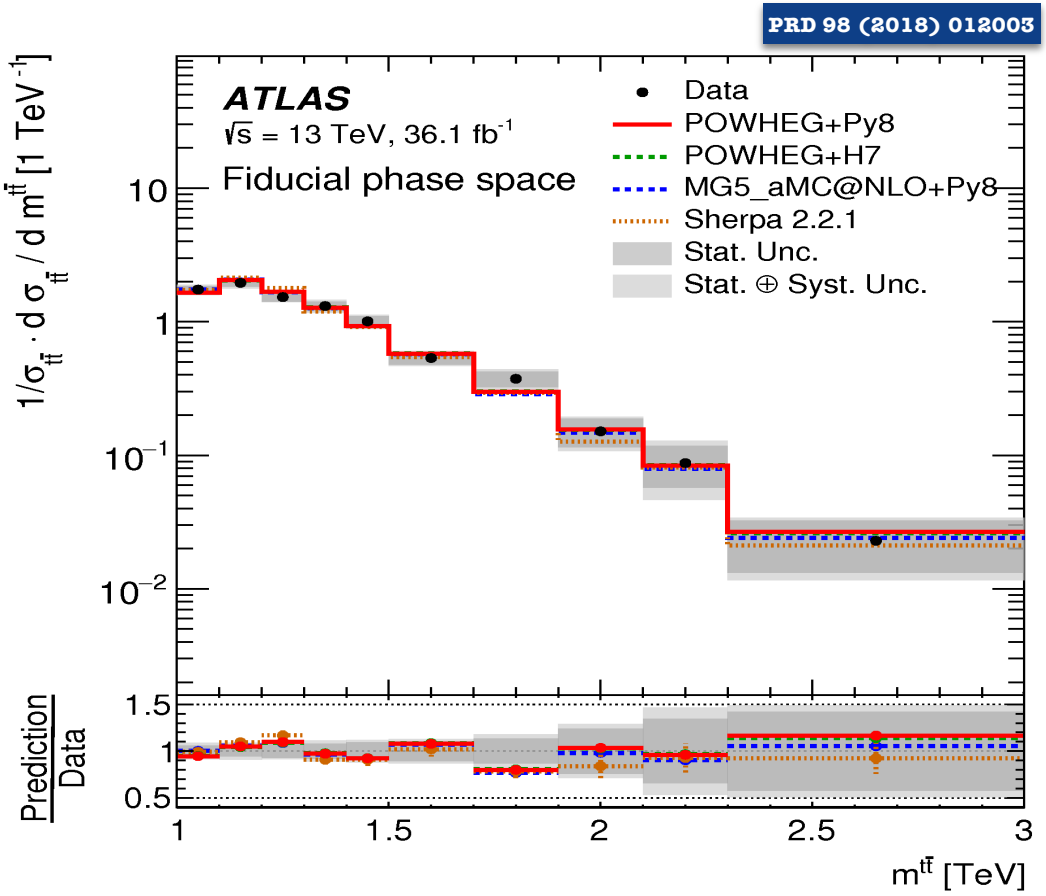
- Poorest data/PP6 agreement in $t\bar{t}$ ($\ell\nu$2j2b)+ 0j
- Improved agreement with additional jets

tt invariant mass





All-hadronic Boosted

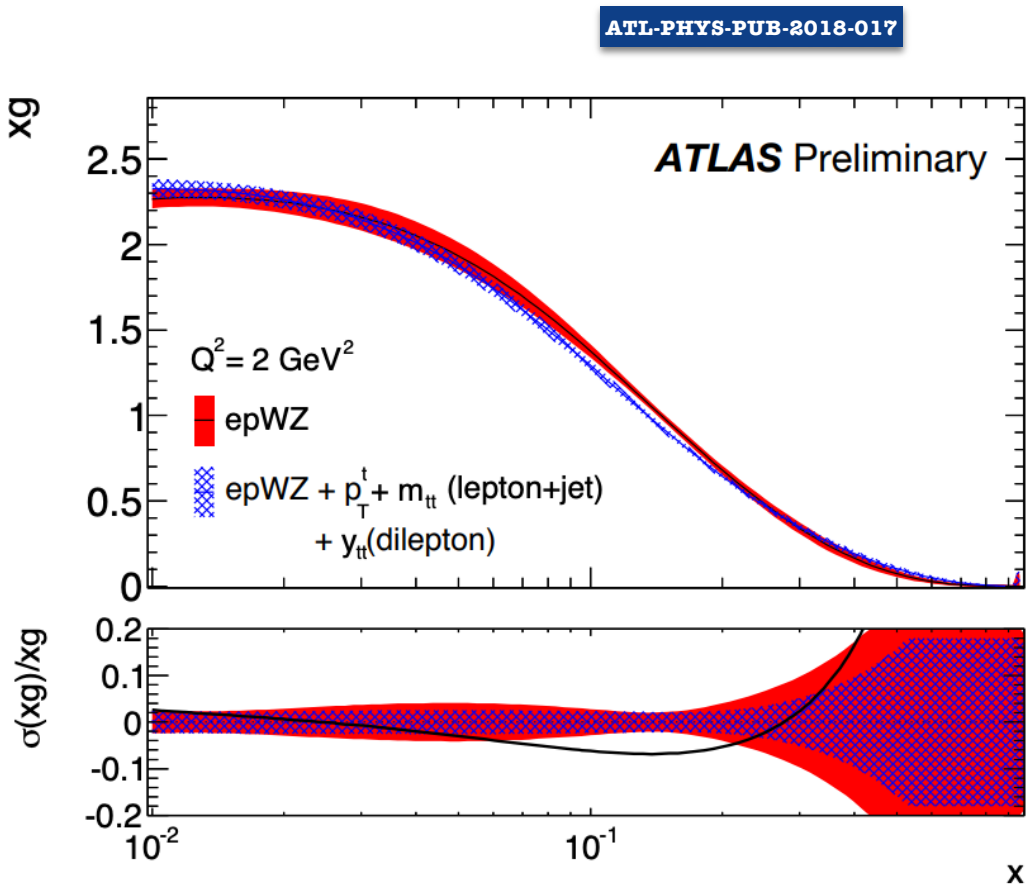


- Consistent with QCD prediction, no hint of BSM particles
- All-Hadronic boosted best m^{tt} resolution for mass > 1 TeV

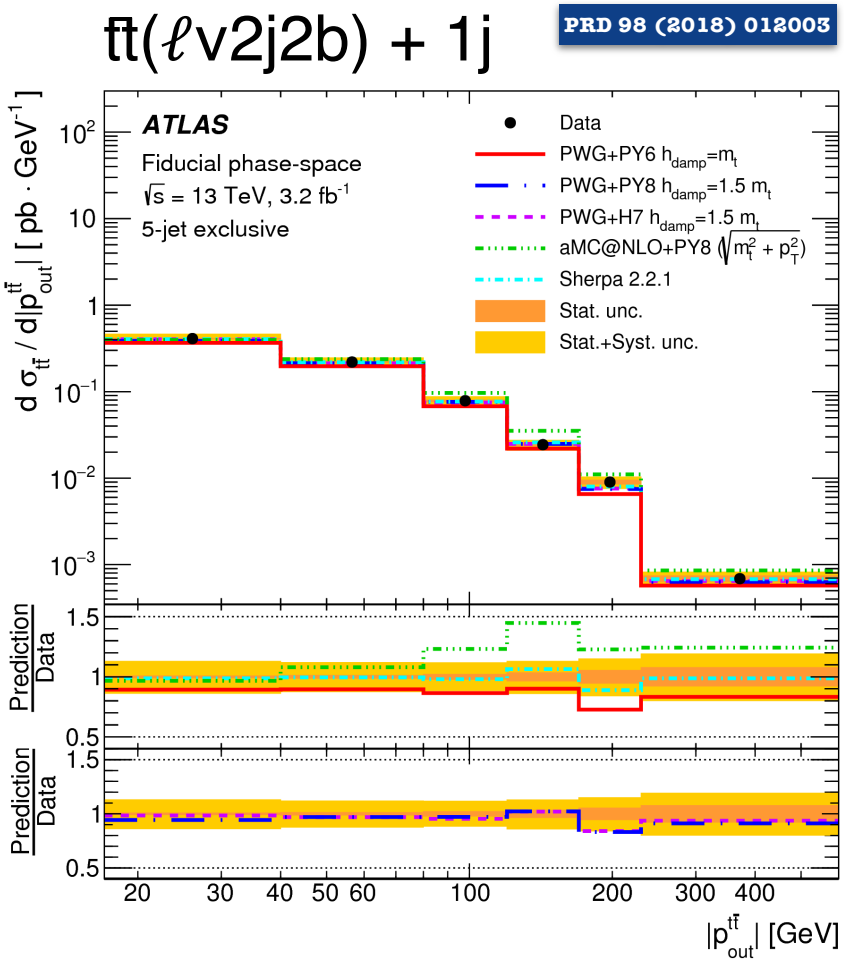
PDF Fit

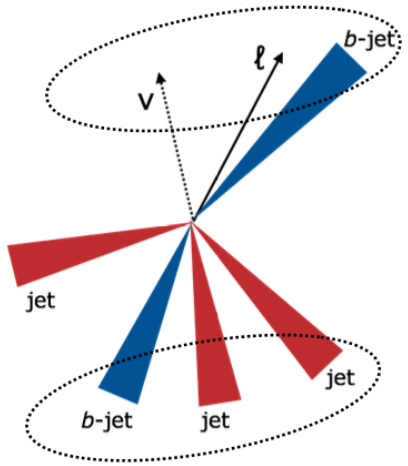
ATLASepWZtop18:

- NNLO pQCD fit using
  - ATLAS differential cross-sections at 7 TeV (W, Z/γ*) and 8 TeV ($t\bar{t}$ p_T, m_{tt} single lepton, y_{tt} dilepton)
  - HERA $e^{\pm}p$ data
- Good fit to data when p_T^t and m^{tt} used separately
  - Pull opposite ways >> decorrelation
  - Effect due to **IFSR** modelling systematic.
  - No significant impact on the shape of gluon PDF
- Impact of top diffxs: harder PDF, reduced high-x gluon uncertainty

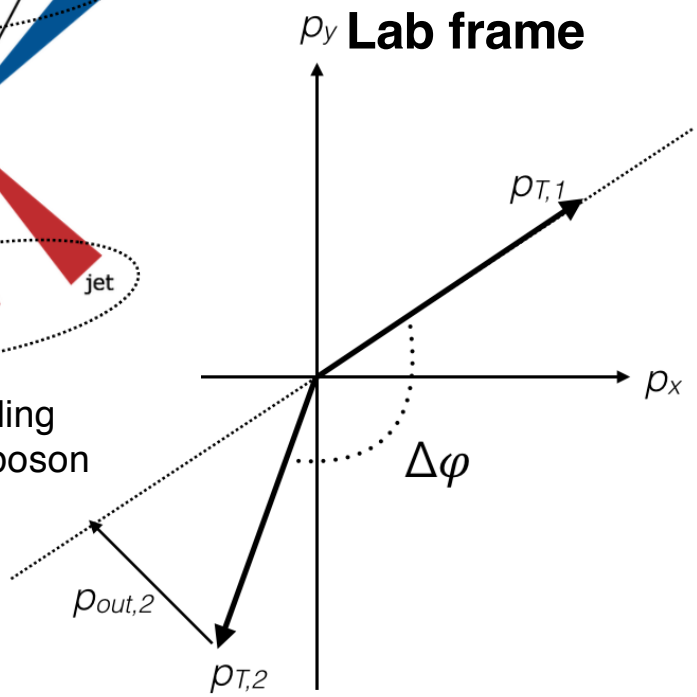


Extra radiation





tt system recoiling against extra jet/boson

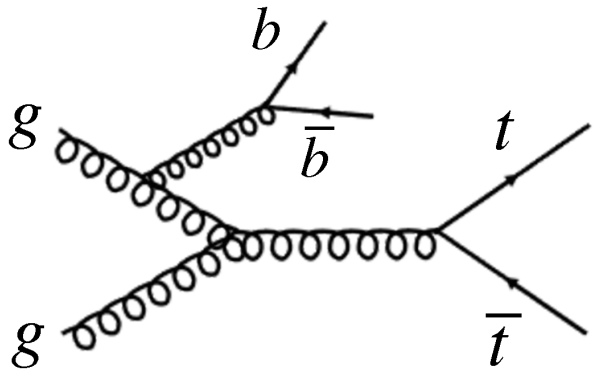


"out-of-plane" momentum (correlated with p_T^{tt} and $\Delta\phi^{tt}$)

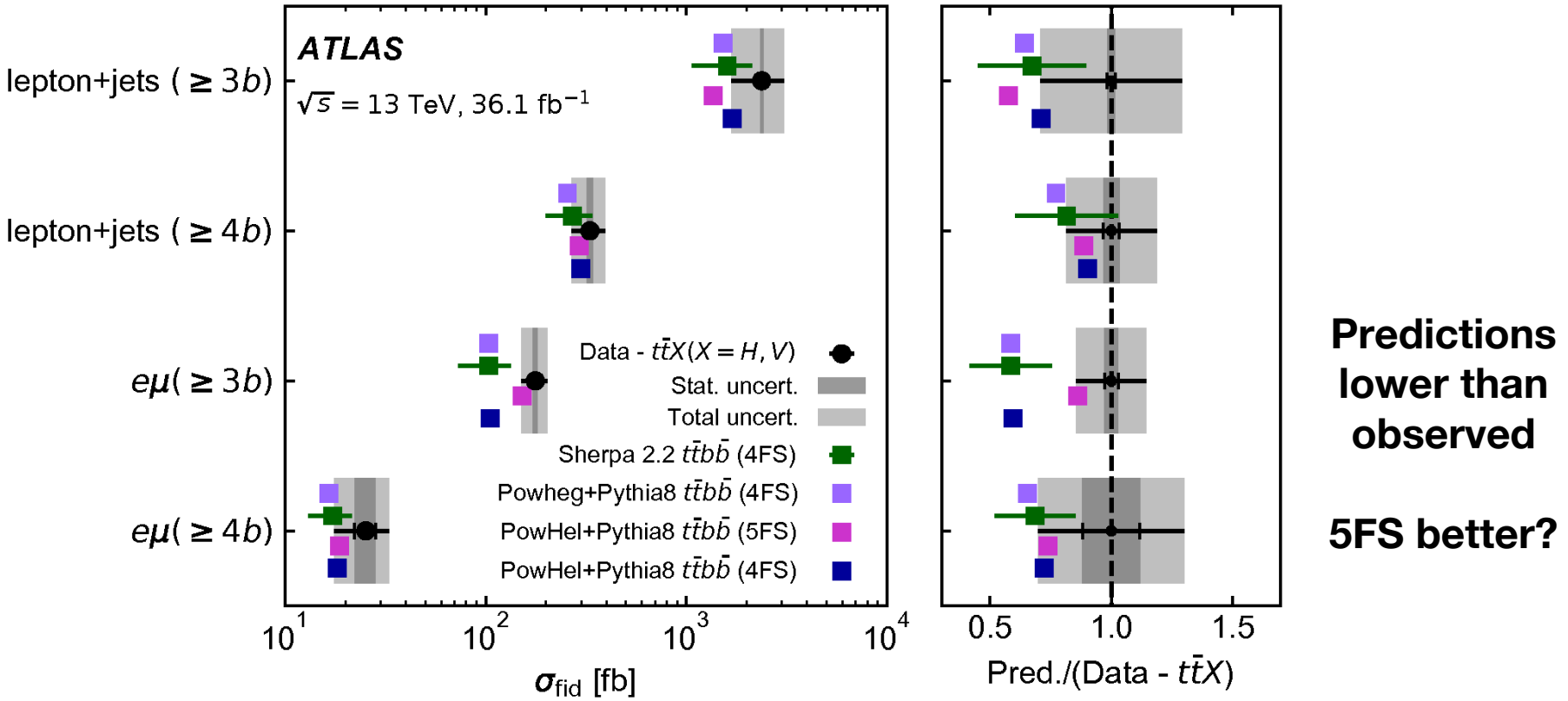
- Additional radiation (esp ISR) test NLO, NNLO calculations
- Very useful for MC tuning

Extra radiation (HF)

- Associated emission of tt̄ + bb̄ heavy flavour complicated process!
- Crucial background to tt+Higgs



JHEP 04 (2019) 046



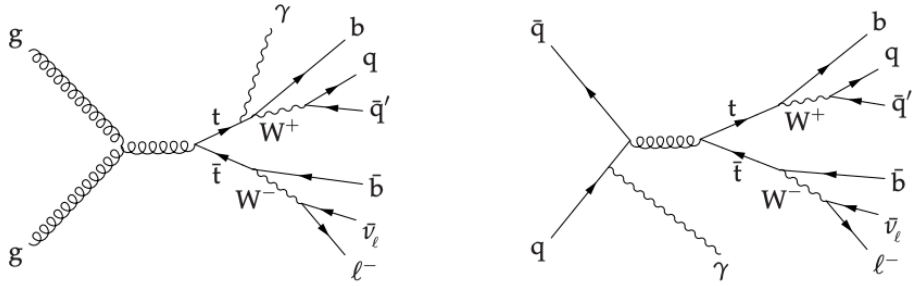
Predictions lower than observed

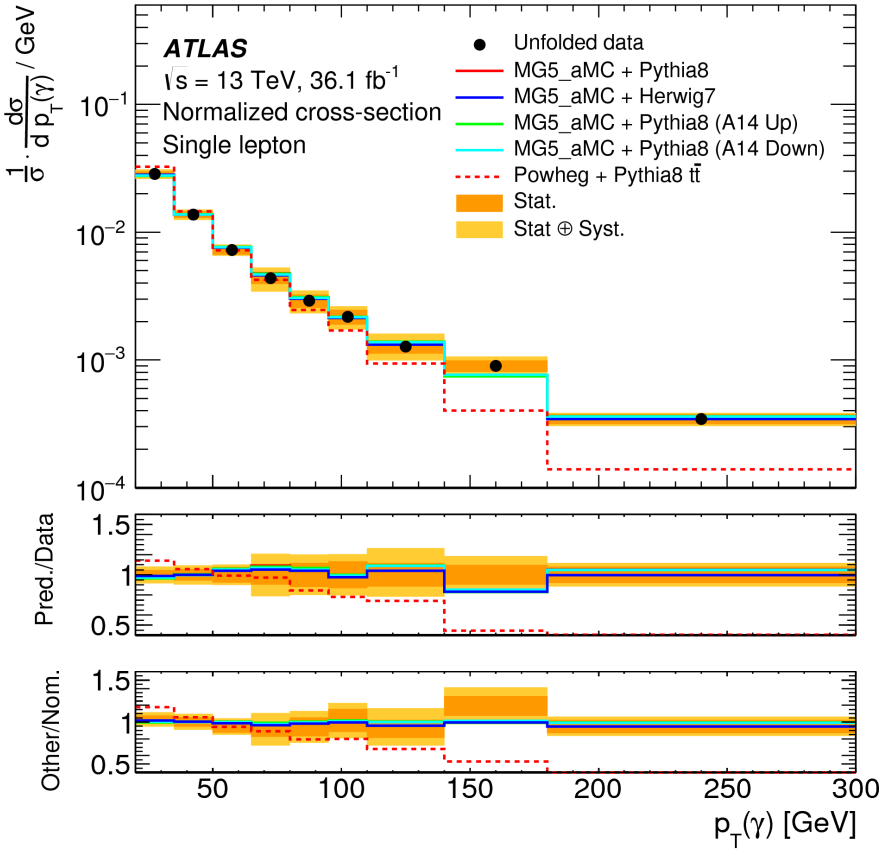
5FS better?

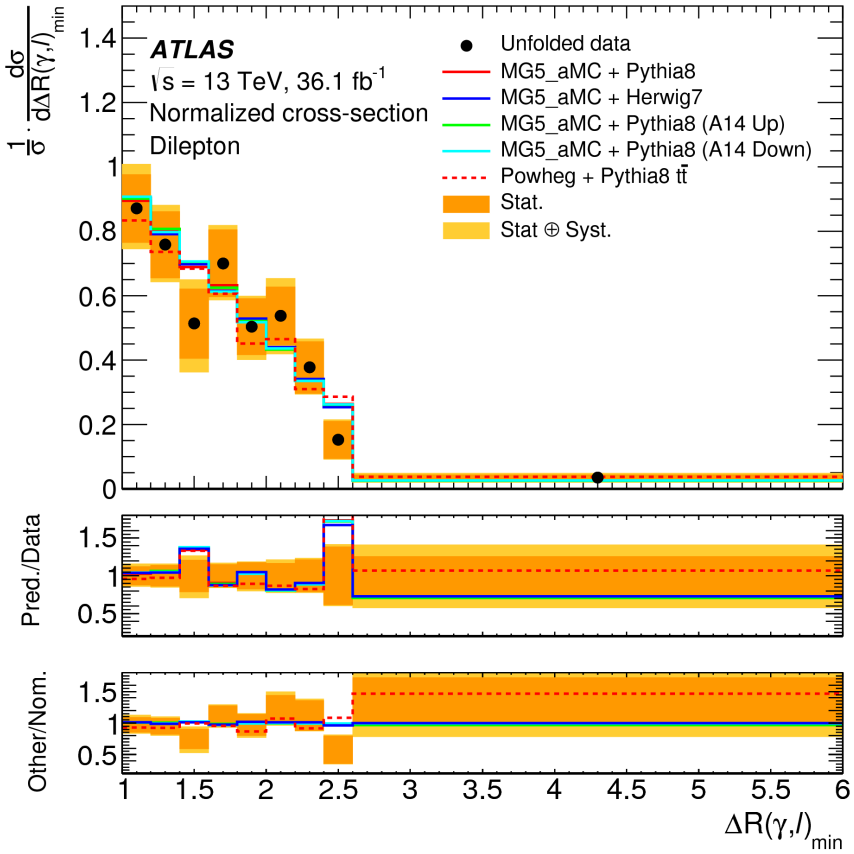
Extra radiation (γ)

EPJC 79 (2019) 382

- Top quarks have EM charge, emit light!
- But also quarks in the initial state…
- Probes compositeness: t* →tγ

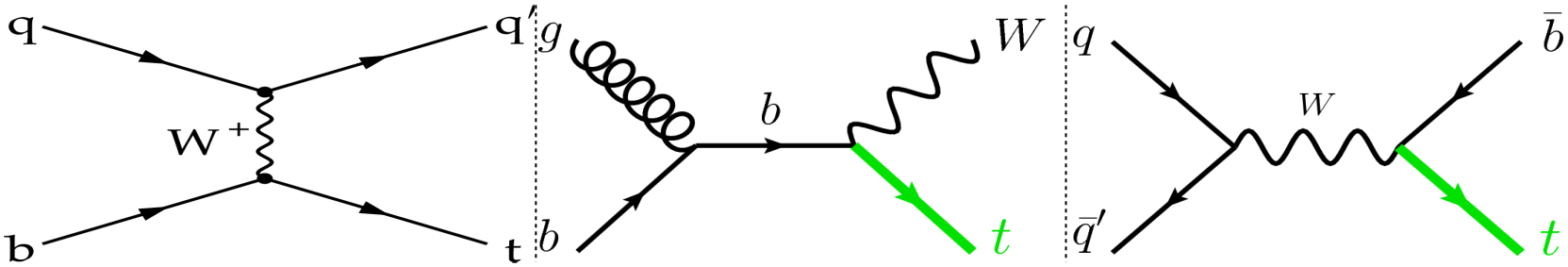






Single top (EWK)

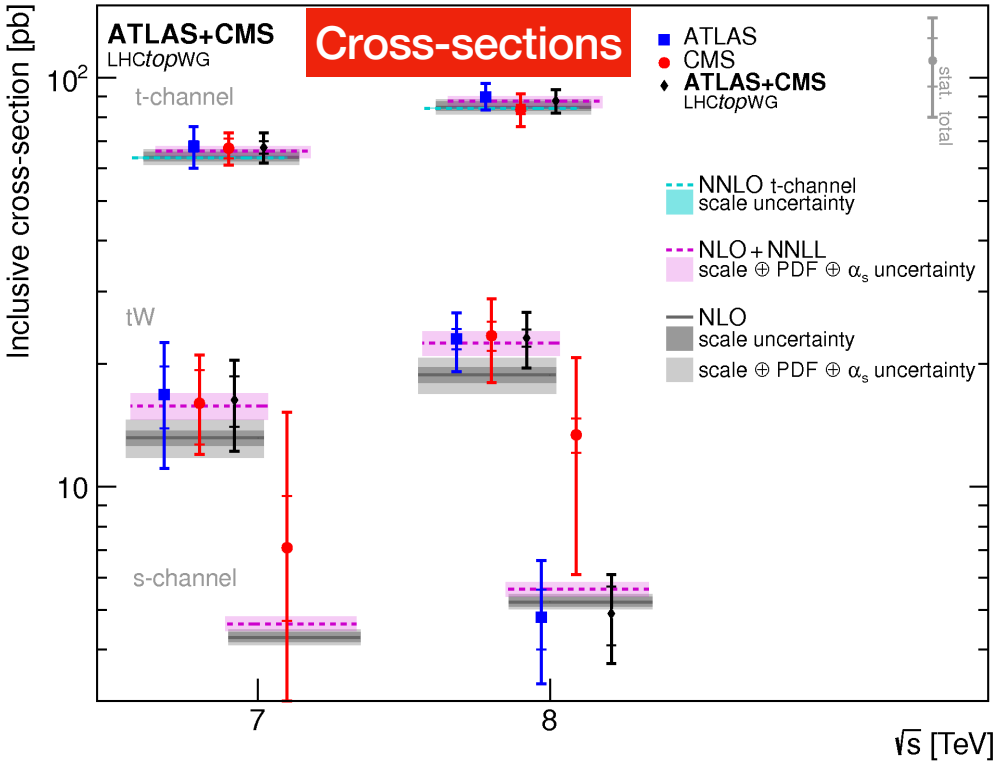
arXiv:1902.07158

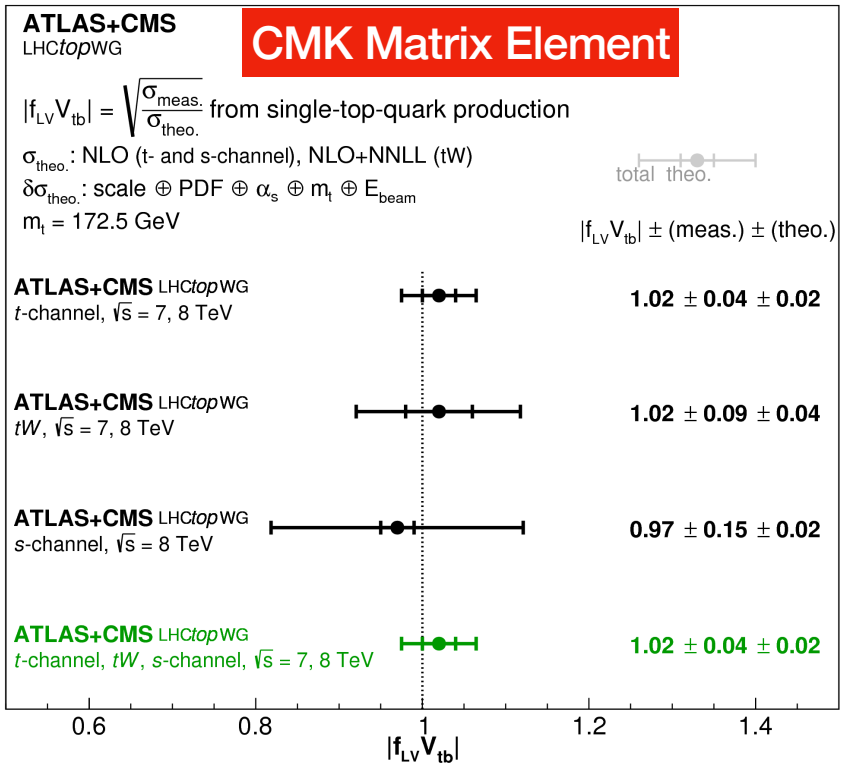


t-channel
Most abundant,
Constrains PDF

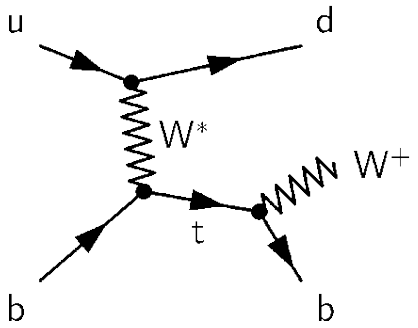
tW-channel
Interference with $t\bar{t}$

s-channel
Small cross-section,
BSM resonances?



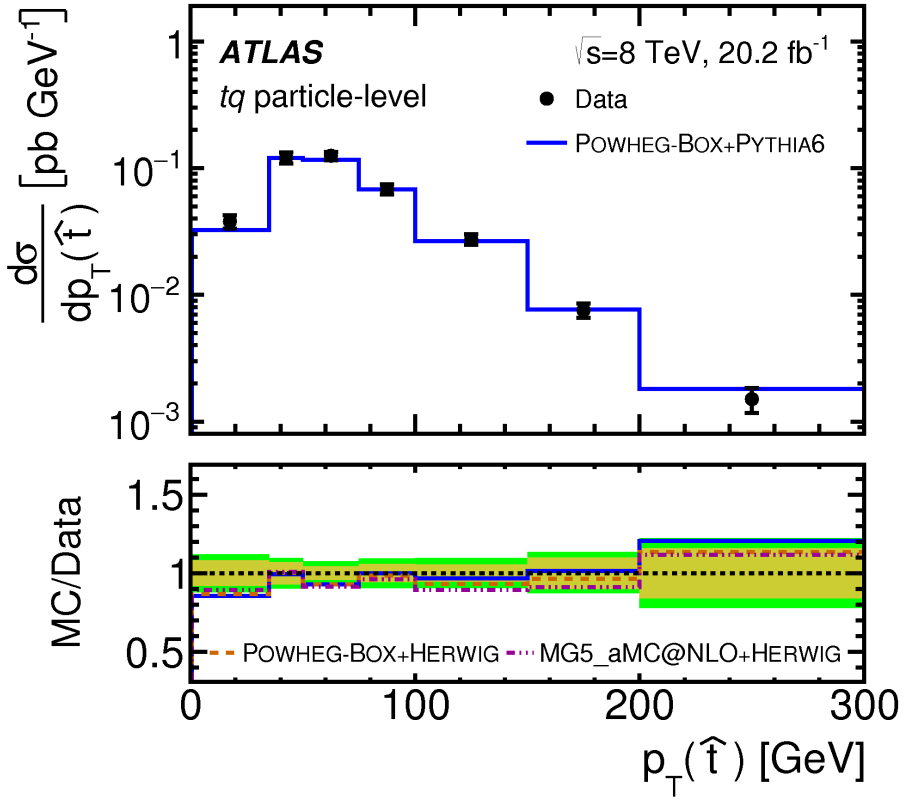


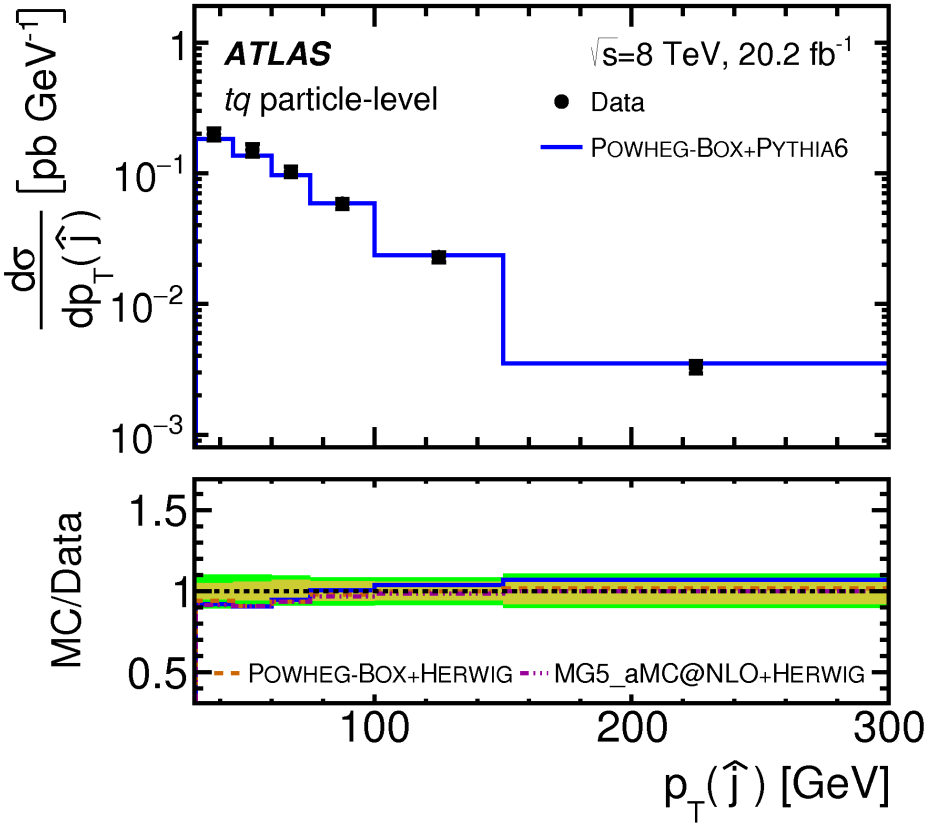
t-channel



- Have measured unfolded differential cross-sections
- Some differences in MC modelling as well?

Eur. Phys. J. C 77 (2017) 531

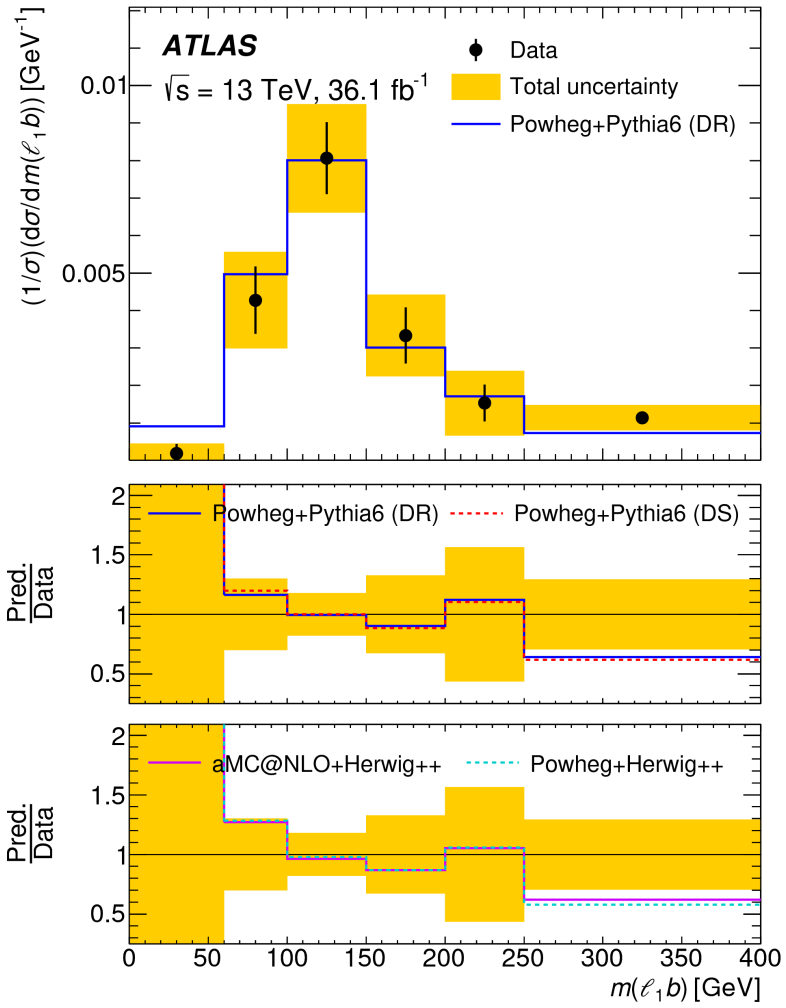




Single top + W/Z

tWb

Eur. Phys. J. C 78 (2018) 186

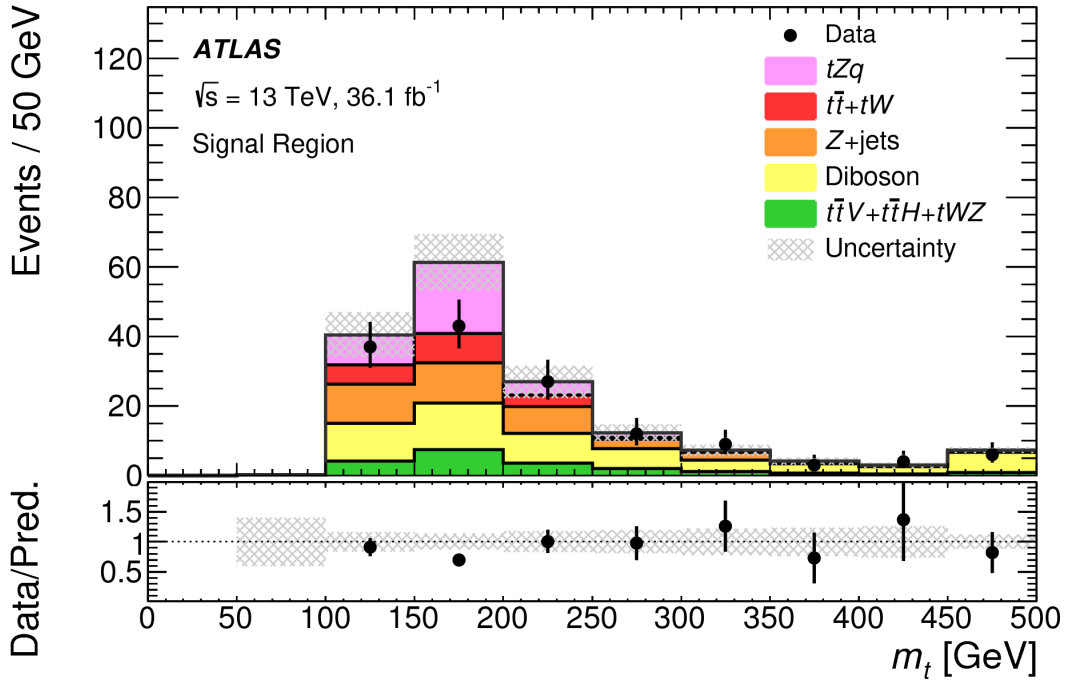


Associated production with W/Z established

- *tW* differential cross-sections
- tZq @ 4.2σ evidence (CMS >5σ, 77 fb^{-1})

tZq

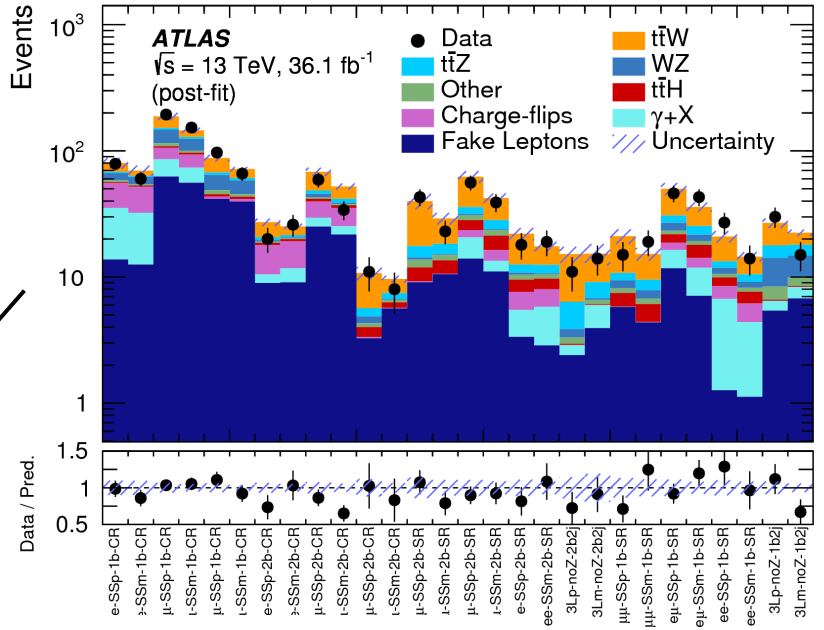
Phys. Lett. B 780 (2018) 557

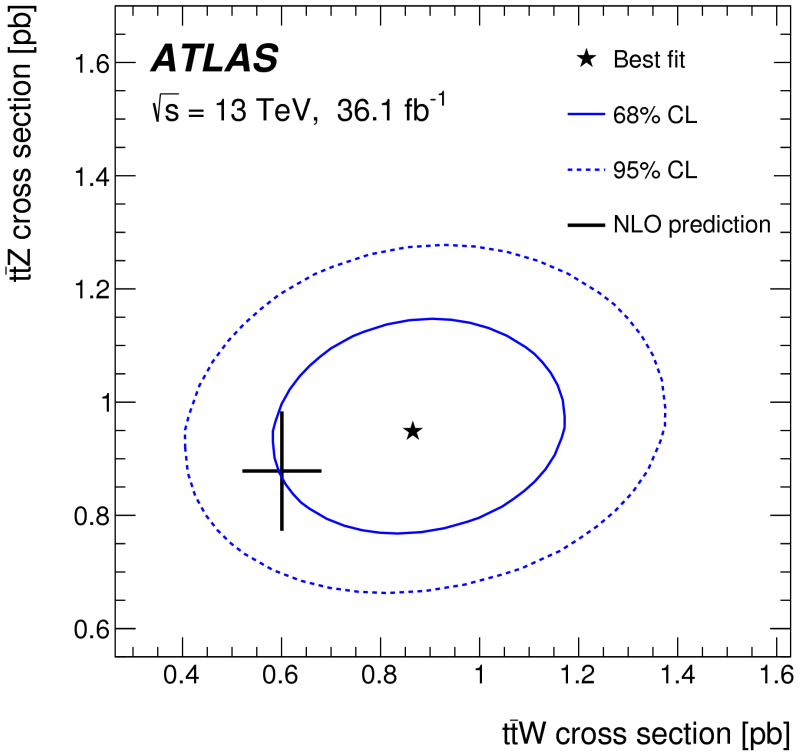


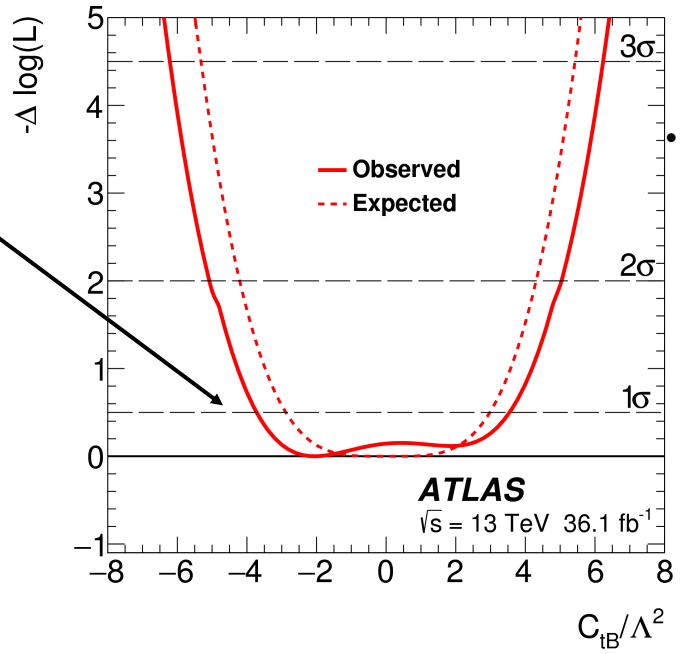
tt+W/Z

PRD 99 (2019) 072009

- Many final states with 2–4 leptons
- Observed cross-sections in agreement with SM



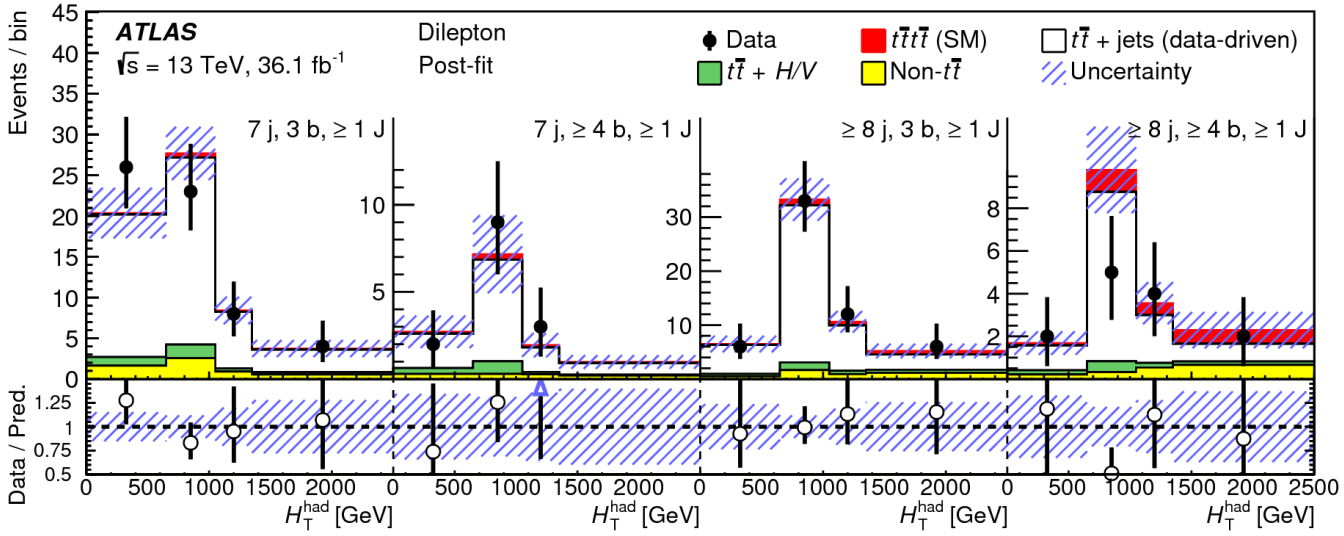


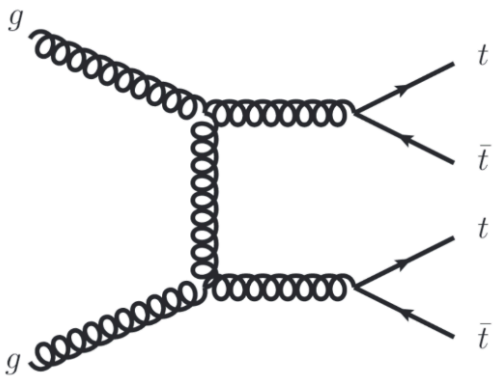


- Limits set to EFT O_6 Wilson coefficients

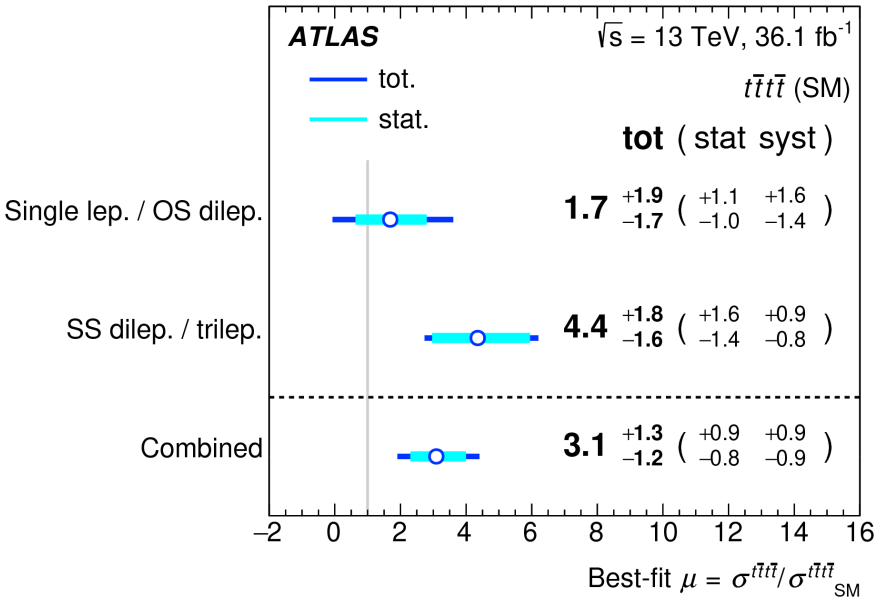
tt+tt

Phys. Rev. D 99 (2019) 052009





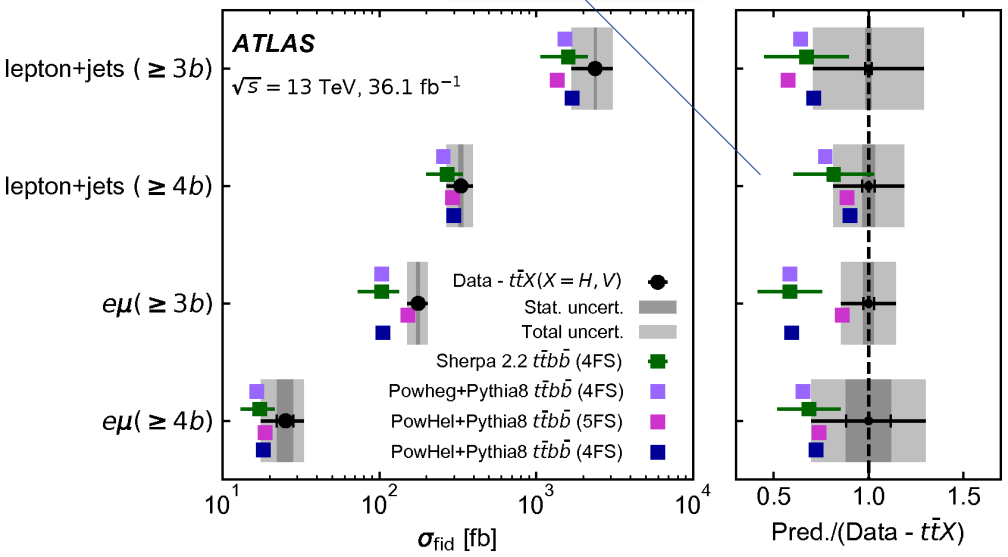
- Very small SM cross-section, but enhanced in many BSM models
- Background to tt+H, very complicated final state



Total cross-sections

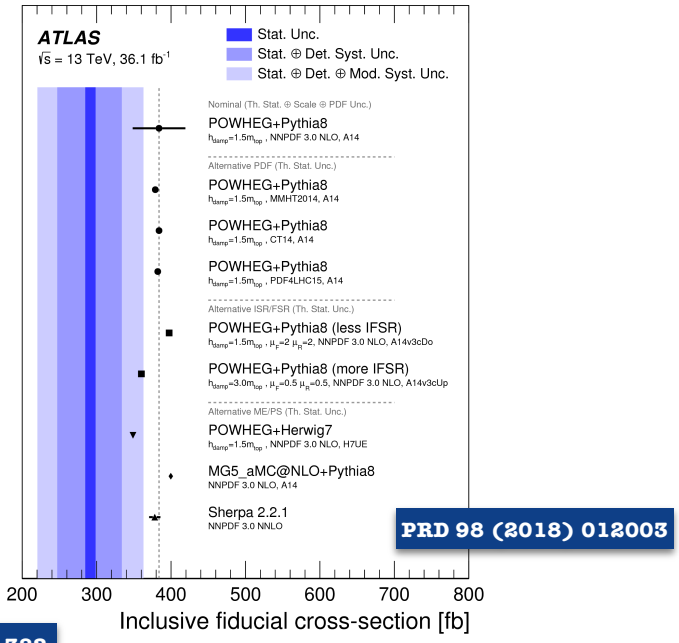
tt + h.f.

JHEP 04 (2019) 046



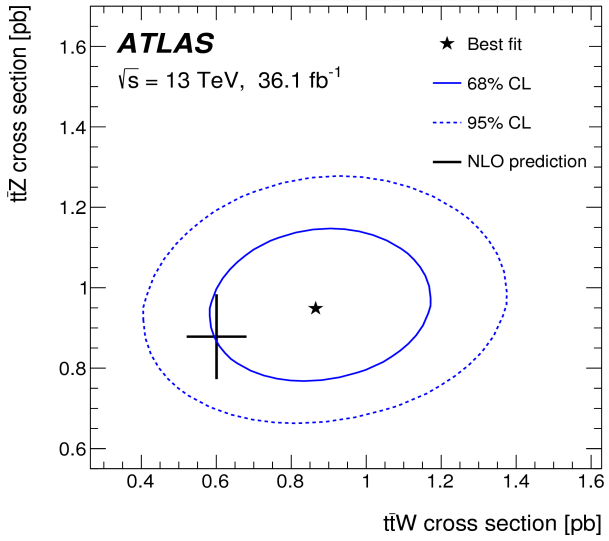
All-hadronic ($p_{T,1}$>500 GeV, $p_{T,2}$>350 GeV)

PRD 98 (2018) 012003



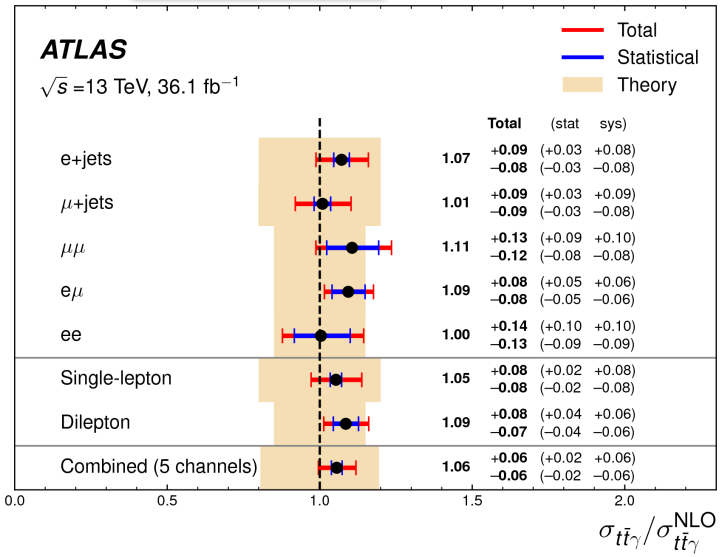
tt + W/Z

PRD 99 (2019) 072009



tt + γ

EPJC 79 (2019) 382



Search for New Physics

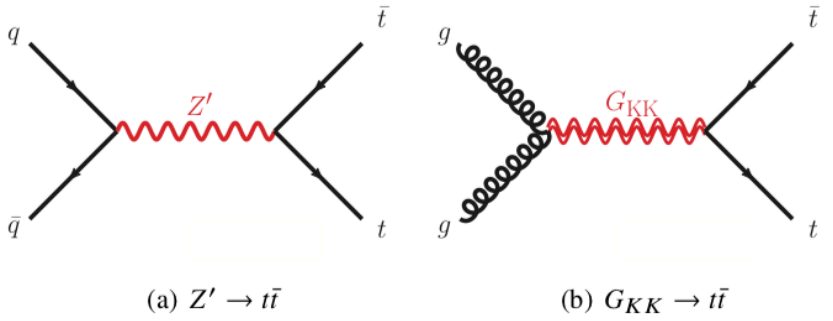
“So what else is there?”

X→ tt̄ Resonances

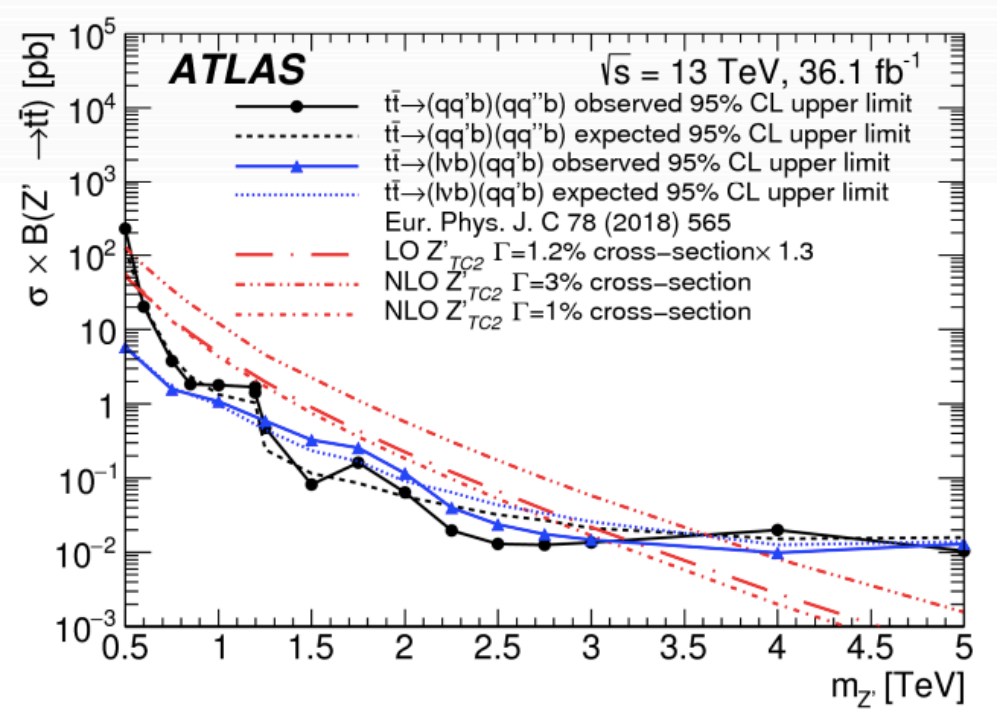
arXiv:1804.10823

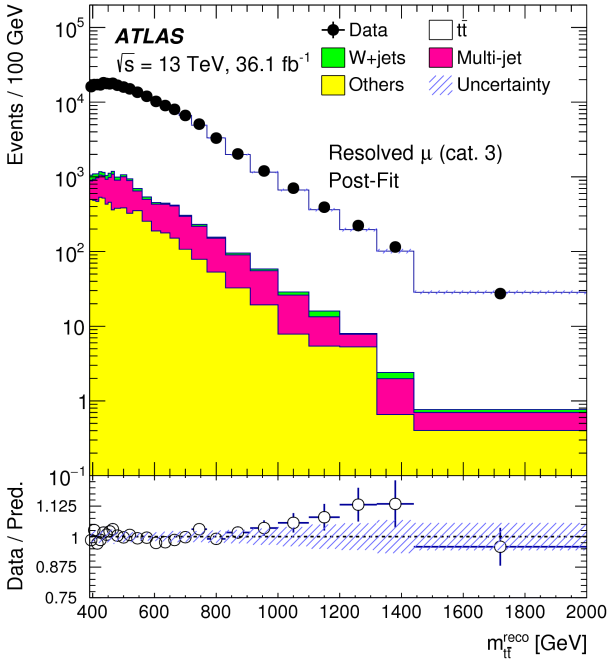
Look for bumps in tt̄ invariant mass:

Narrow resonance Broad resonance



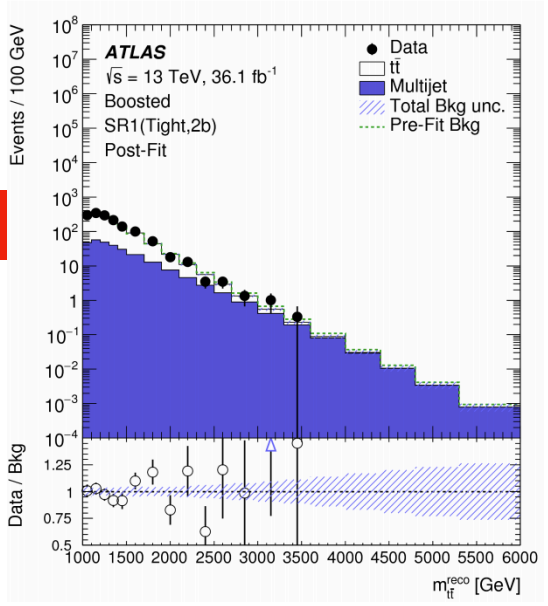
(a) $Z' \to t\bar{t}$ (b) $G_{KK} \to t\bar{t}$





L+jets

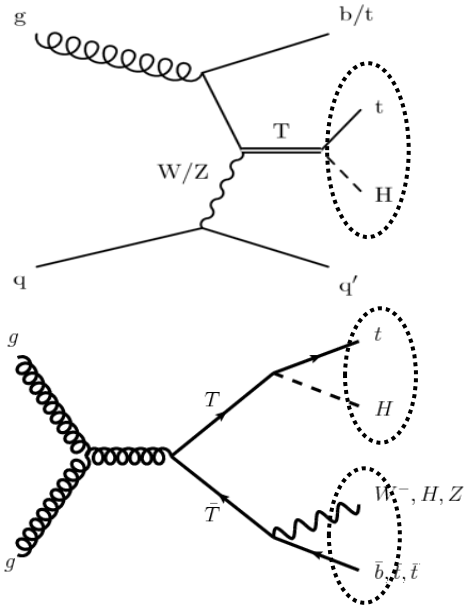
All-hadronic

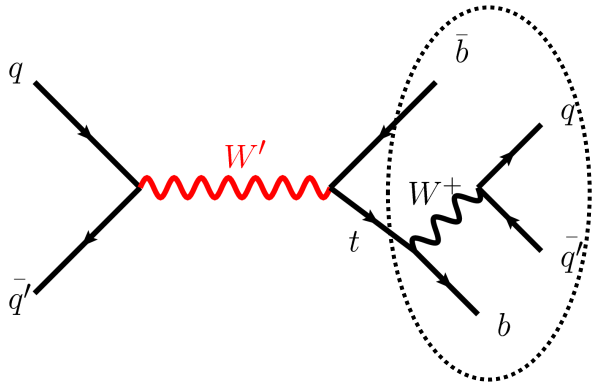


X→tb,TZ,tH Resonances

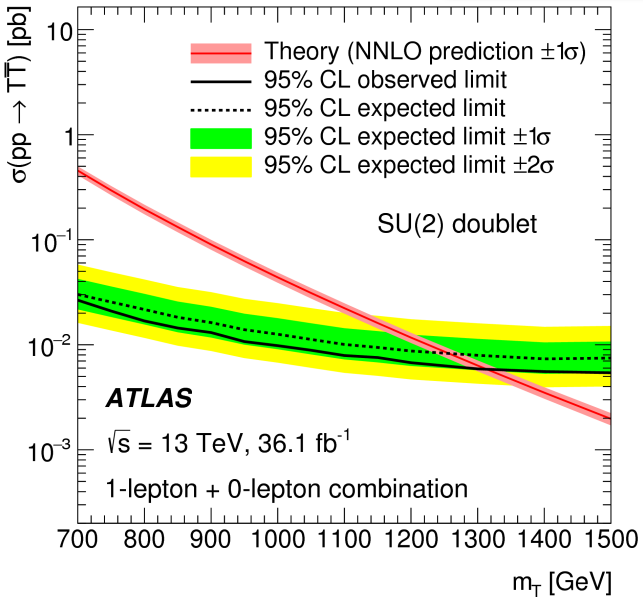
Look for bumps in (t,b) or (t,H) invariant mass spectrum

- **Vector-Like Quarks (VLQ)**: quarks with vector-like interactions
- **W'R** and **W'L**: additional gauge bosons





arXiv:1803.09678



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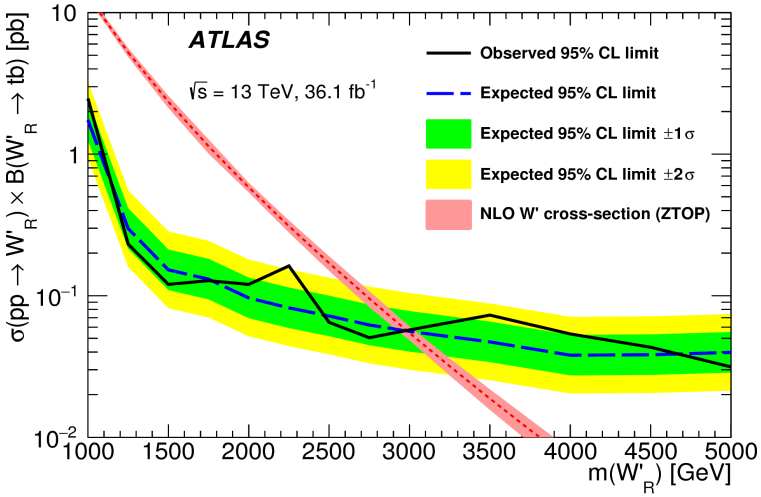


Conclusions

- Production cross-section measurements of increasing precision
  - Confirm Standard Model NLO predictions
  - ATLAS baseline **POWHEG + Pythia8** model in good agreement with data, but underwent significant tuning compared to other generators
- Hard-scattering and parton-shower **modelling** large source of **systematic** uncertainty
- Associated production measurements in agreement with theory
- “Tick-tock” approach to reduce modelling systematics works
- No evidence for new physics in top-quark final states, yet!

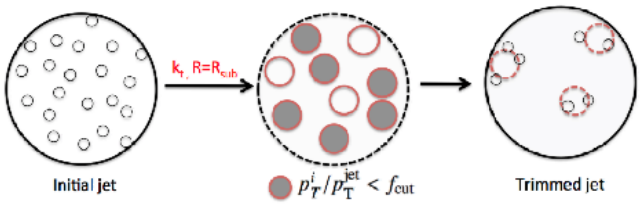
Backup

Top Tagging in a Nutshell

Apply **cut** on **substructure** variable(s) as a function of jet **kinematic** variables (p_T, y, m)

Key variables:

- Mass of the jet

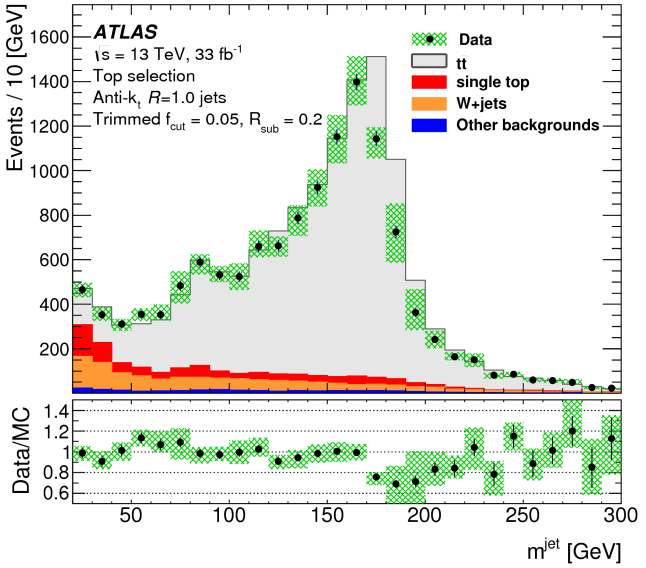


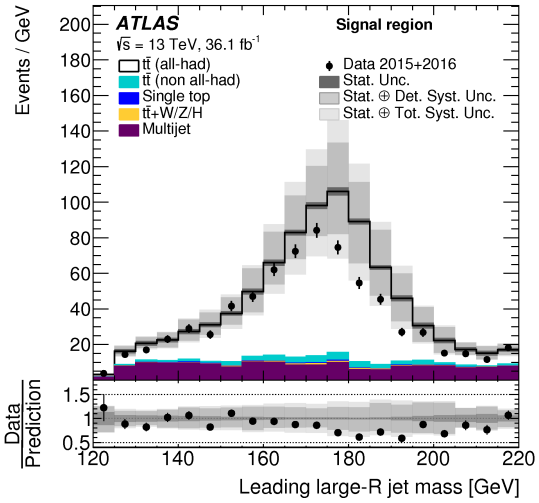
- Measures of internal substructure
- b-tagging of subjets

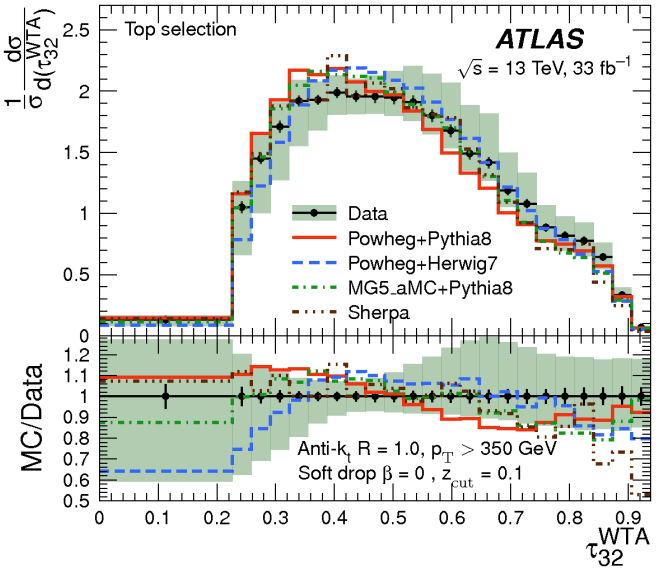
Results in clean $t\bar{t}$ samples

All-hadronic
($p_{T,1}$>500 GeV, $p_{T,2}$>350 GeV)

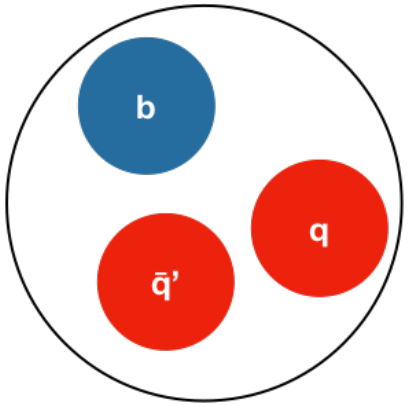
Boosted l+jets ($p_{T,1}$>350 GeV)



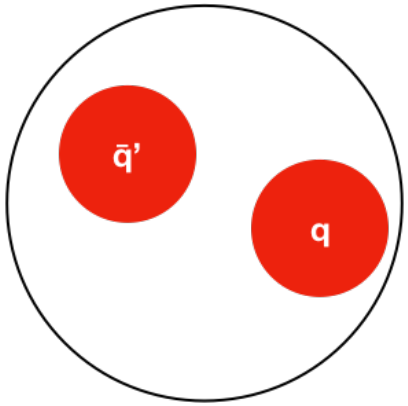




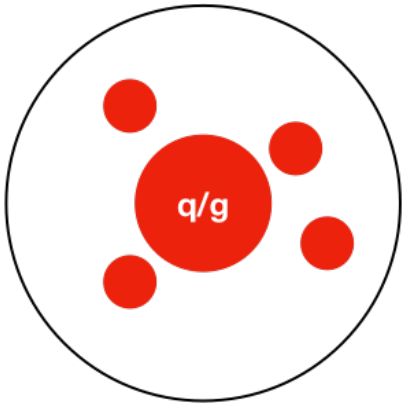
High-pT (Boosted) Tops



Top quark
Three-prong topology

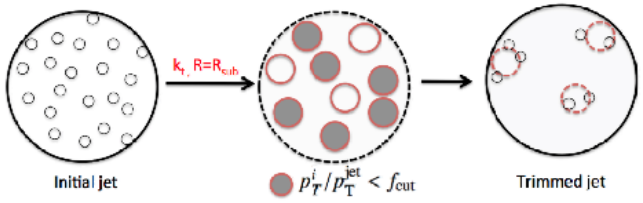


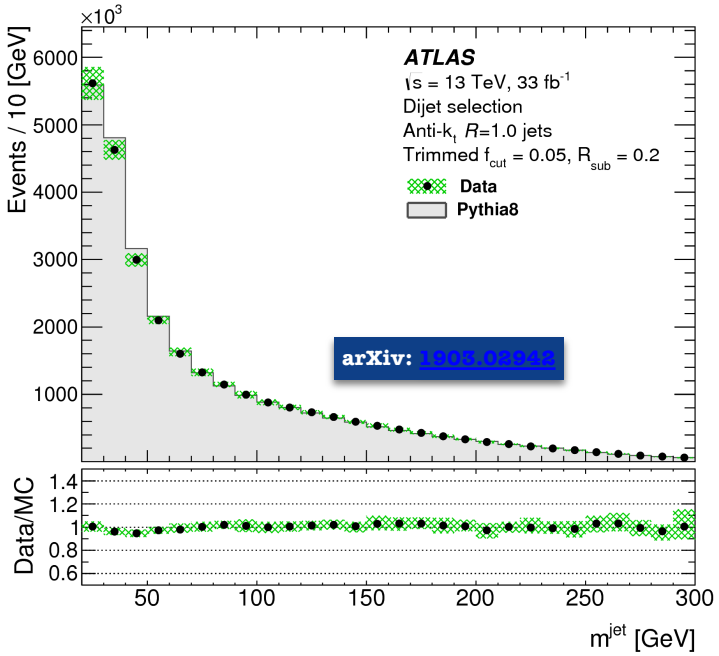
W boson
Two-prong topology



Quark/gluon
Axial topology

Trimming Thaler et al., JHEP 1002:084,2010
Removes pileup by discarding R=0.2 subjets with pT < 5% pT(J)

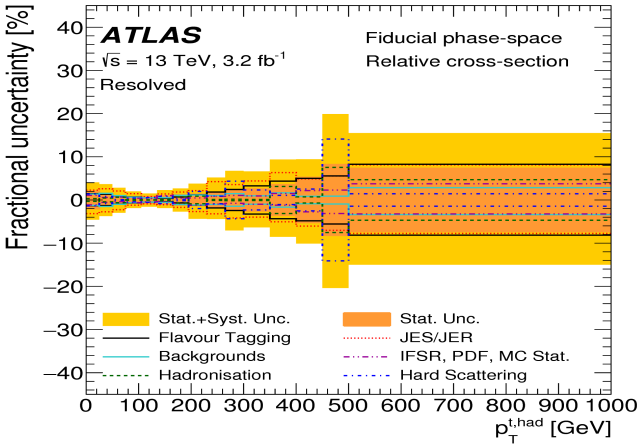




Substructure
Distribution in (η,ϕ,E) of calo clusters reflects underlying top quark decay

- *N*-subjettiness ratio τ_{32}
- Soft drop mass, n_{SD}
- ECF, $C_2^{(\beta)}$, $D_2^{(\beta)}$

Uncertainties: Top quark p_T



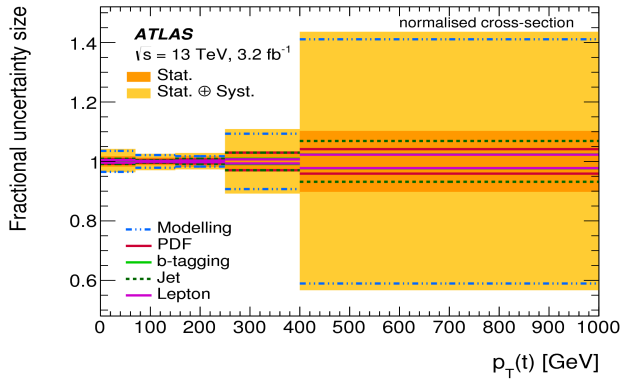
Single lepton + jets

Jet energy scale 5%

b-tagging < 5%

Background modelling (low pT) 2%

→ Signal modelling (high pT) 5%

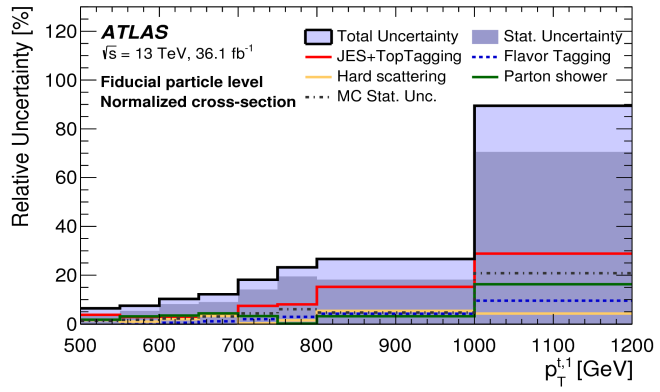


Dilepton

→ Signal modelling >10%

PDF 5%

b-tagging < 5%



All-hadronic

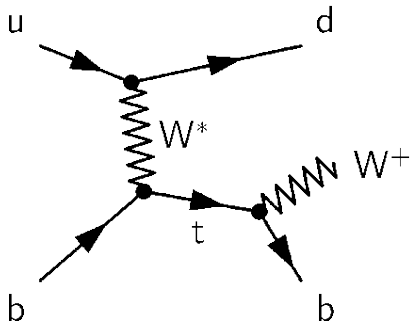
Jet energy scale 5%

Top-tagging 10%

b-tagging < 10%

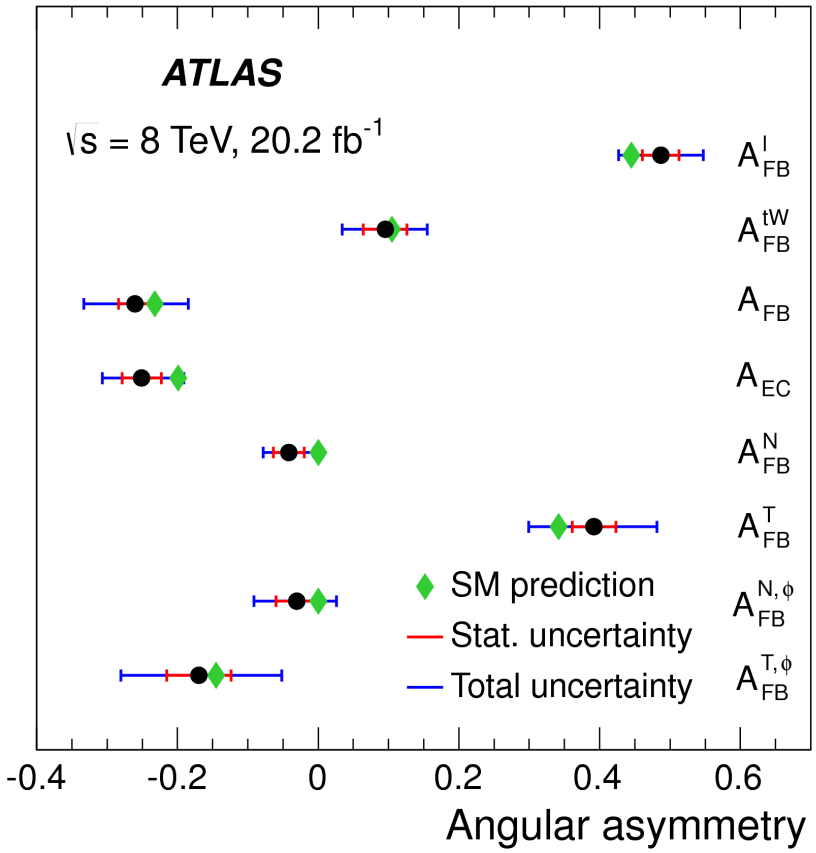
→ Signal modelling (ps/had) 15%

t-channel

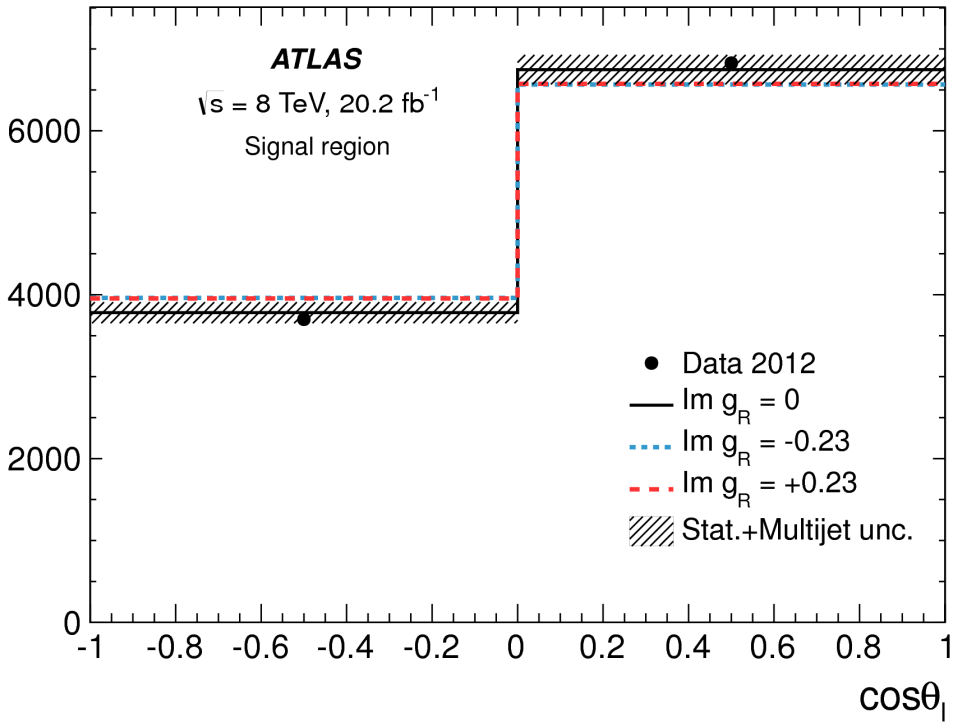


JHEP 04 (2017) 124

Polarization observables extracted from angular asymmetries



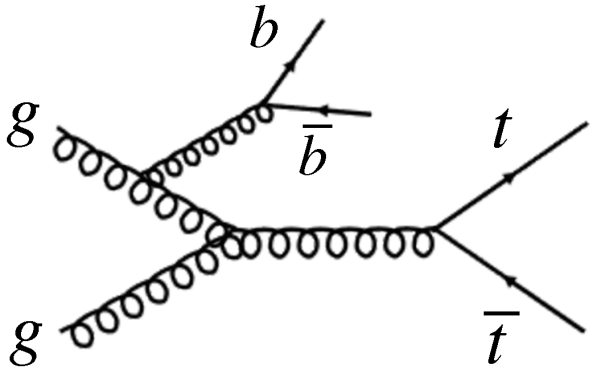
Set limits on anomalous couplings

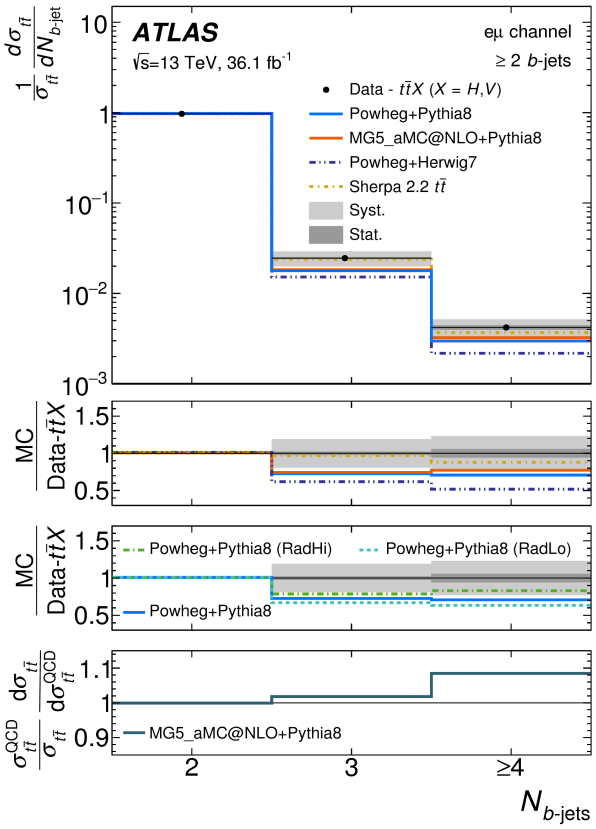


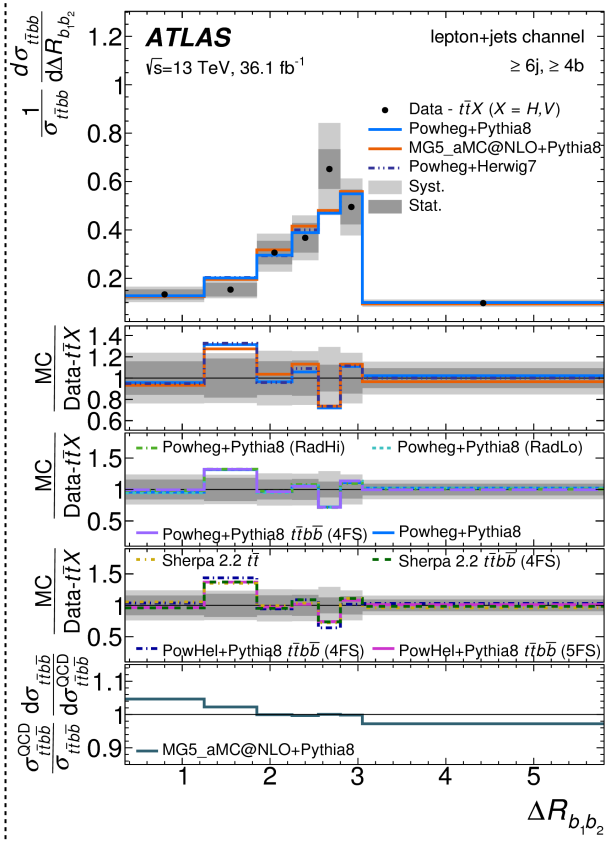
Extra radiation (HF)

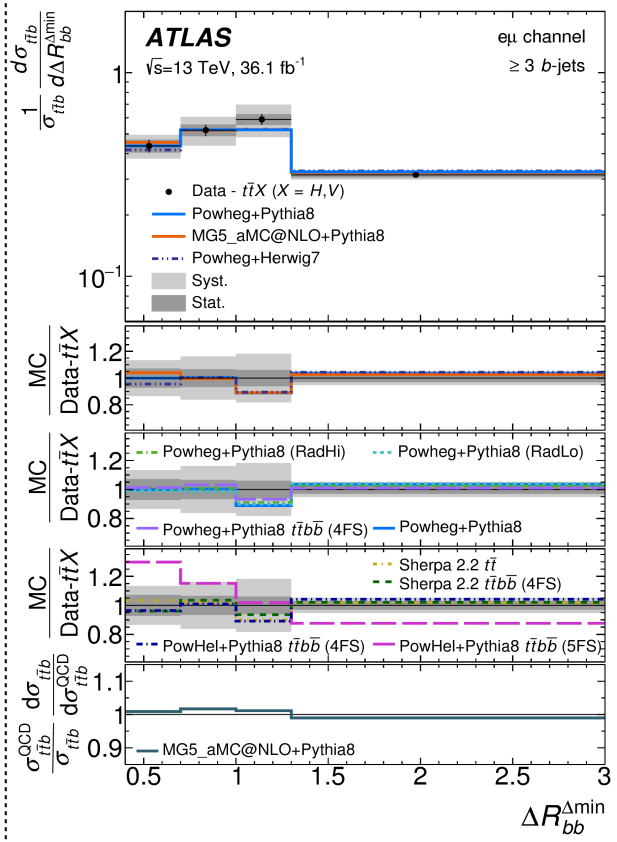
JHEP 04 (2019) 046

- Associated emission of tt̄ + bb̄ heavy flavour complicated process!
- Crucial background to tt+Higgs





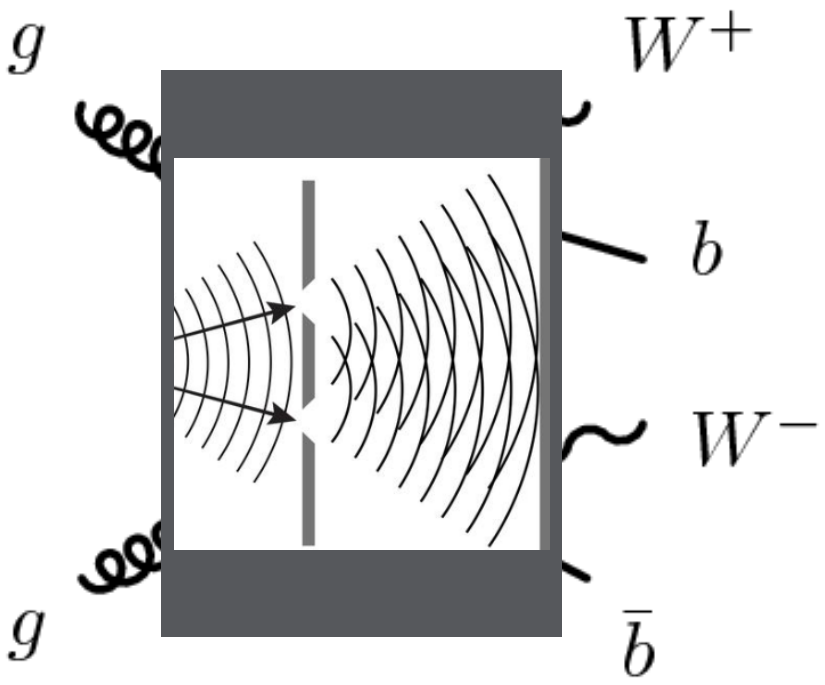




PRL 121 (2018) 152002

tt/tW interference

- Double slit experiment with top quarks!
- Doubly (tt) and singly (tWb) resonant productions have similar final states and thus interfere
- Interference “removed” with
  - “Traditional” methods
    - diagram removal (DR)
    - diagram subtraction (DS))
  - Fully-consistent treatment (POWHEG bb4l)



PRL 121 (2018) 152002

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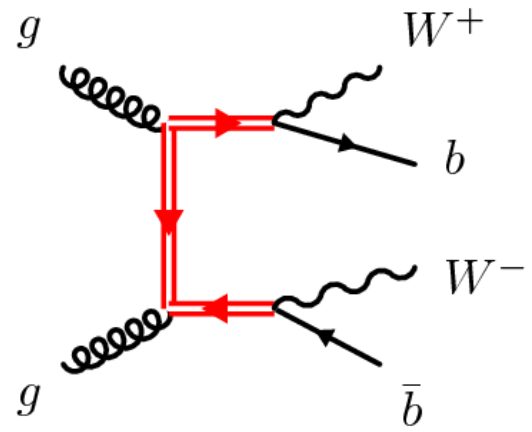
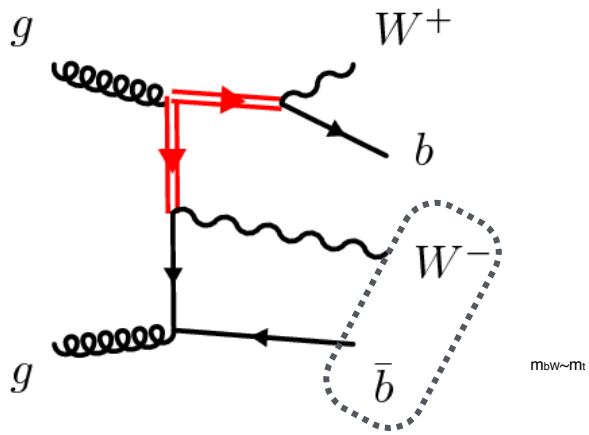
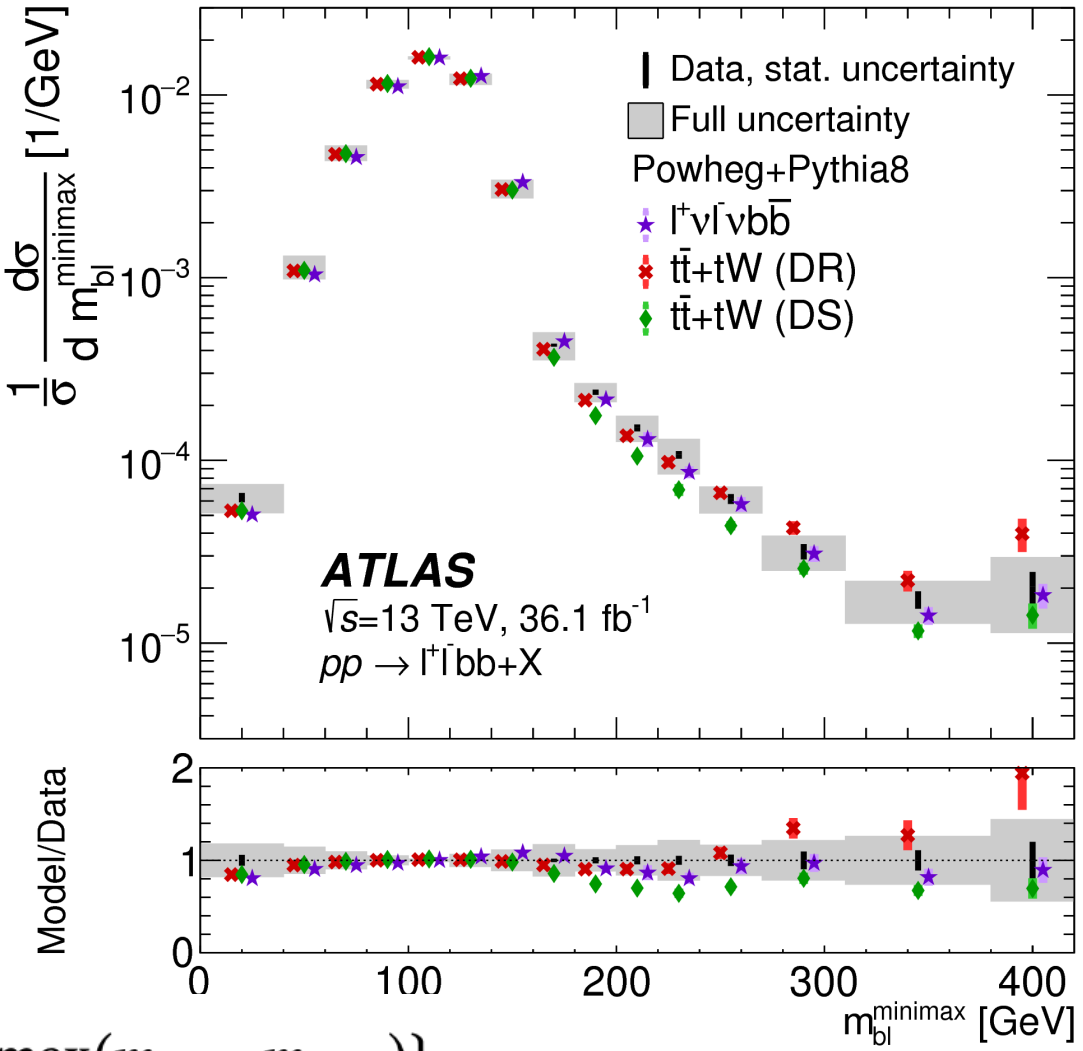




PRL 121 (2018) 152002

tt/tW interference

- Invariant mass (b,ℓ) characteristic distribution in presence of resonance
- $m_{b\ell}^{\text{minimax}}$ sensitive to interference effects in the tail
- Uncertainty small enough to constrain different treatments
  - Resonance-aware treatment in better agreement with data



$$m_{b\ell}^{\text{minimax}} \equiv \min\{\max(m_{b_1\ell_1}, m_{b_2\ell_2}), \max(m_{b_1\ell_2}, m_{b_2\ell_1})\}$$

$$m_{b\ell}^{\text{minimax}} < \sqrt{m_t^2 - m_W^2}$$

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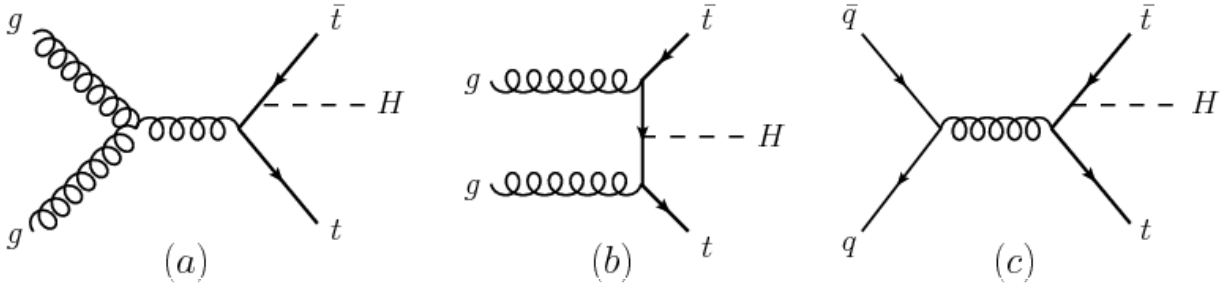
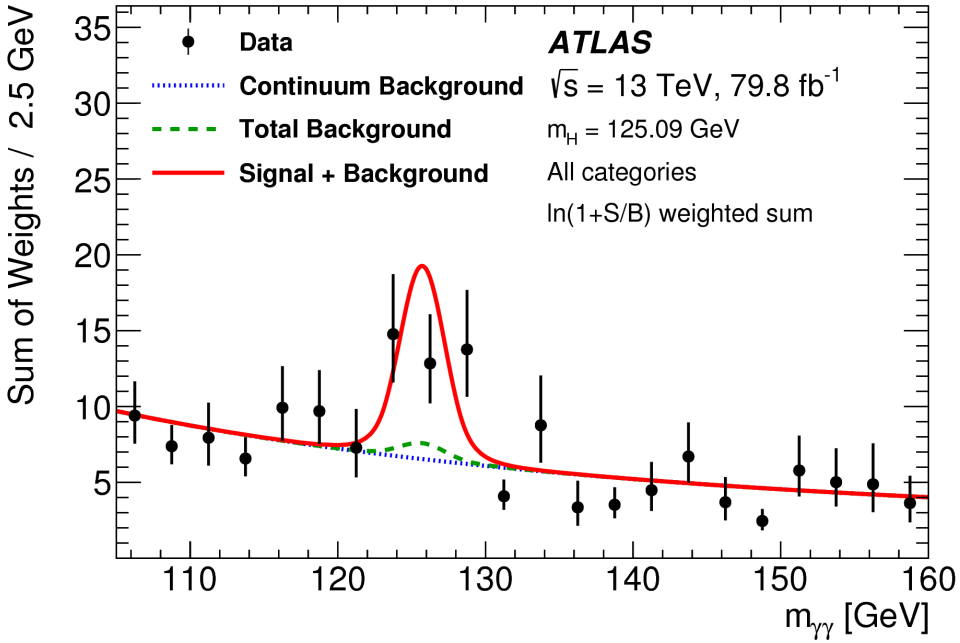
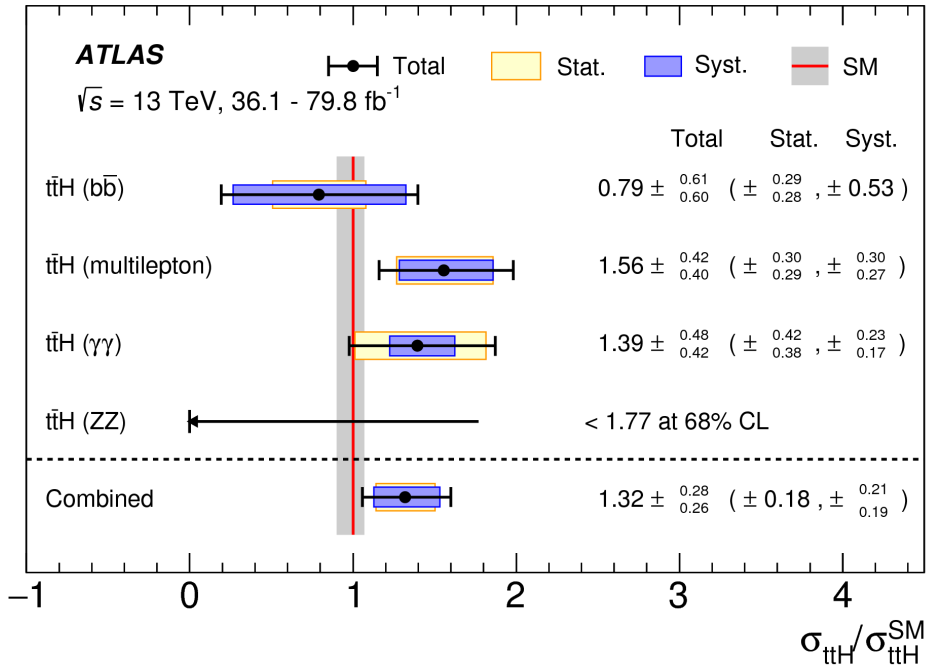
tt̄+H (or H+ tt̄?)

- Probes Yukawa coupling (is the top quark the only "natural" quark?)
- Combination of H→bb̄,WW*,ττ,γγ,ZZ* >5σ

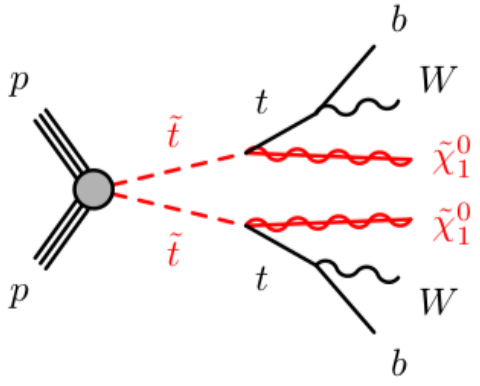




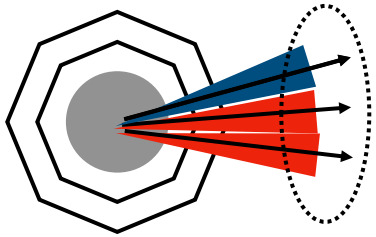


Supersymmetric Scalar Tops

JHEP 12(2017)085

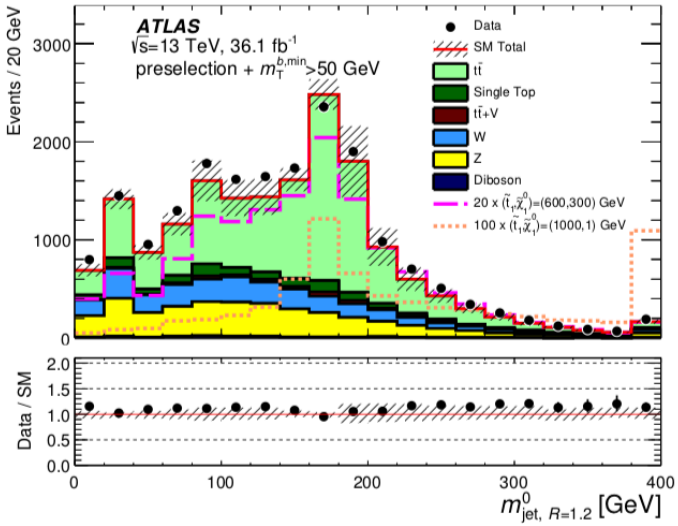


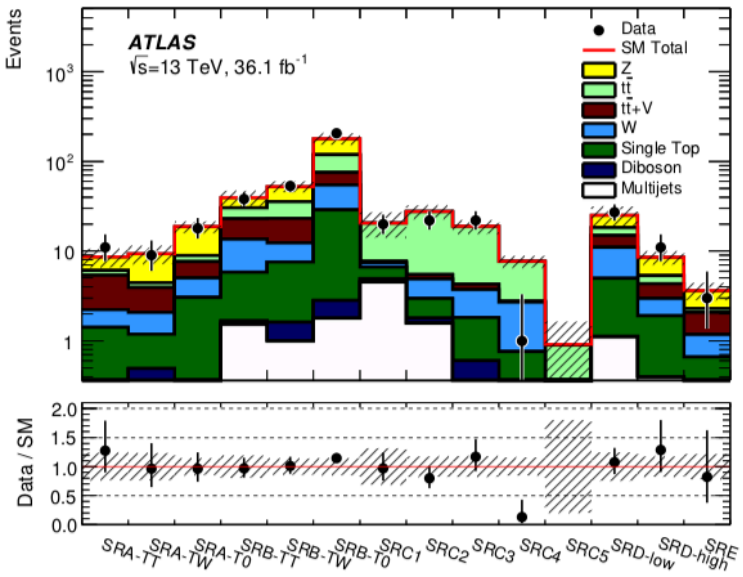
(a) $\tilde{t}_1 \to t^{(*)}\tilde{\chi}_1^0$



Reclustered R=1.2 jet

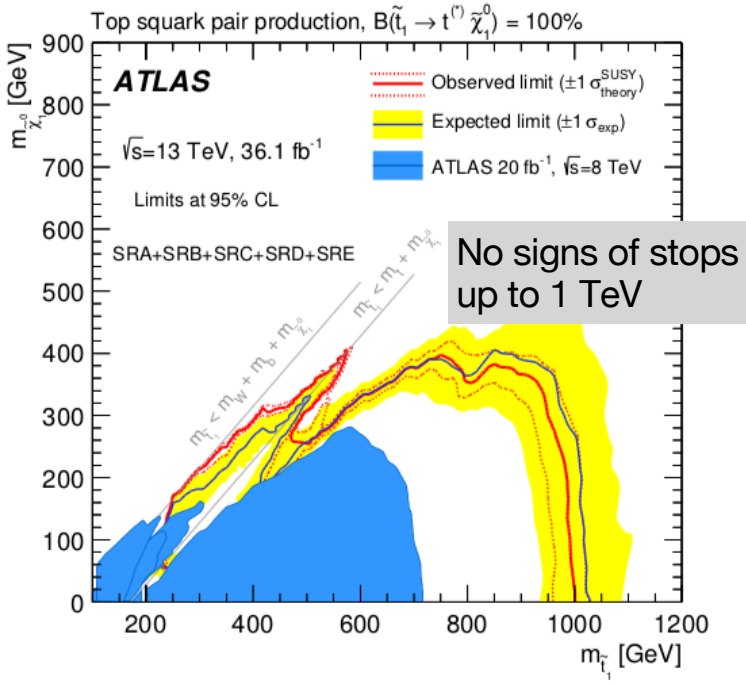
heavy stops almost produced at rest,
low momentum → unusually large jet radius





Signal xs depends on stop and neutralino masses

Set limits using simplified models

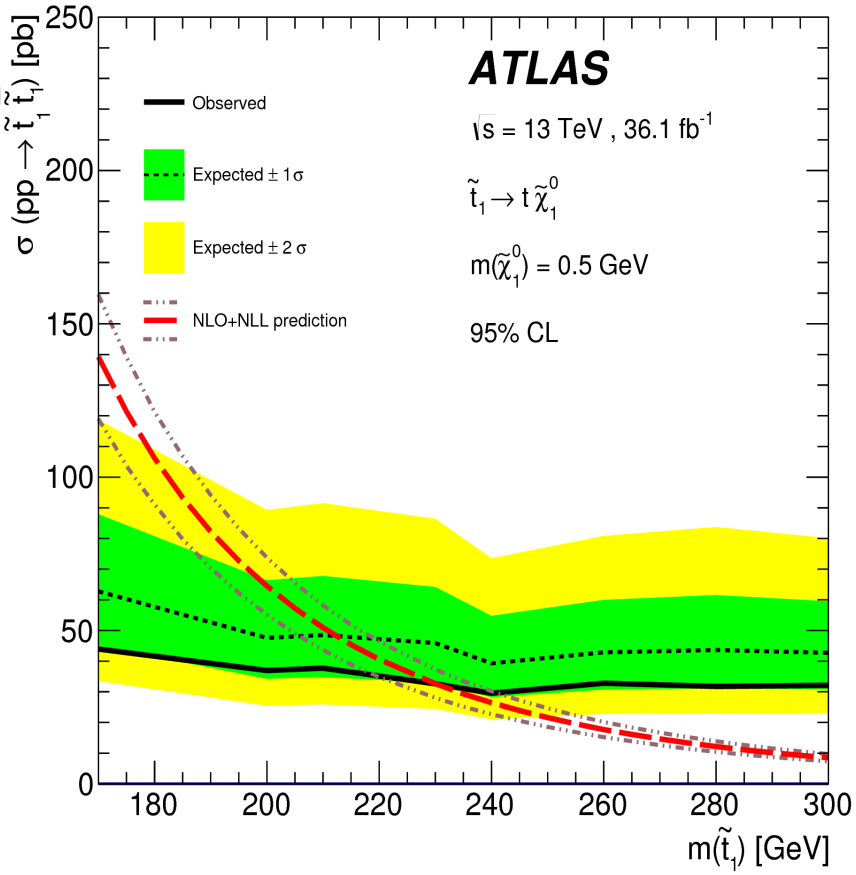


No signs of stops up to 1 TeV

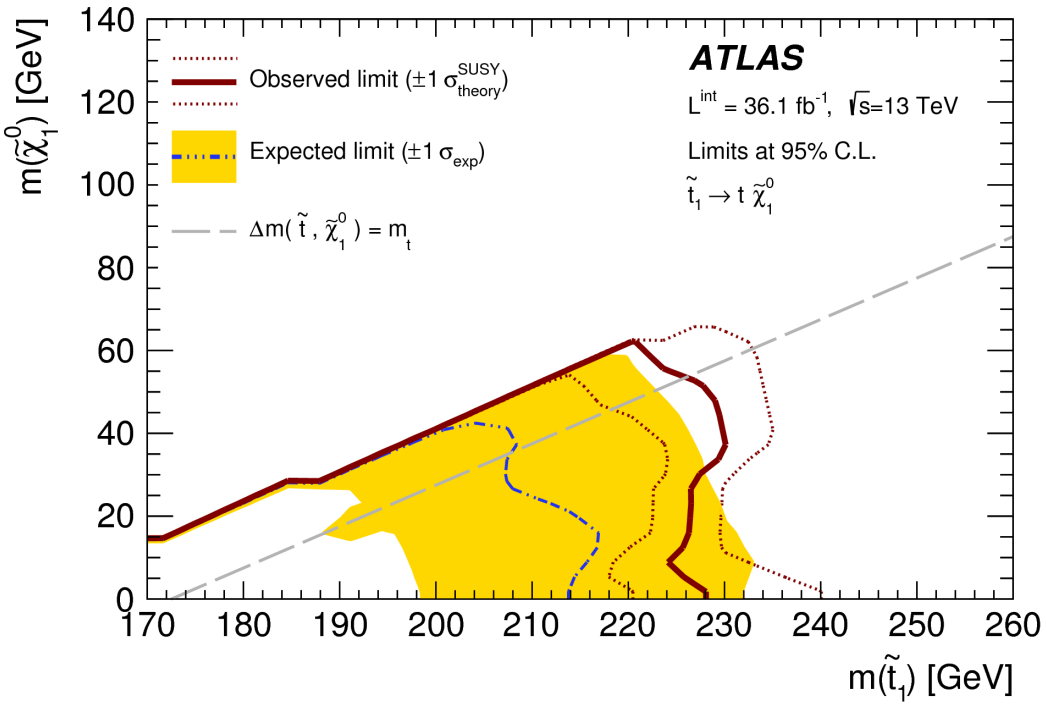
Stops from Spin Correlations

arXiv:1903.07570

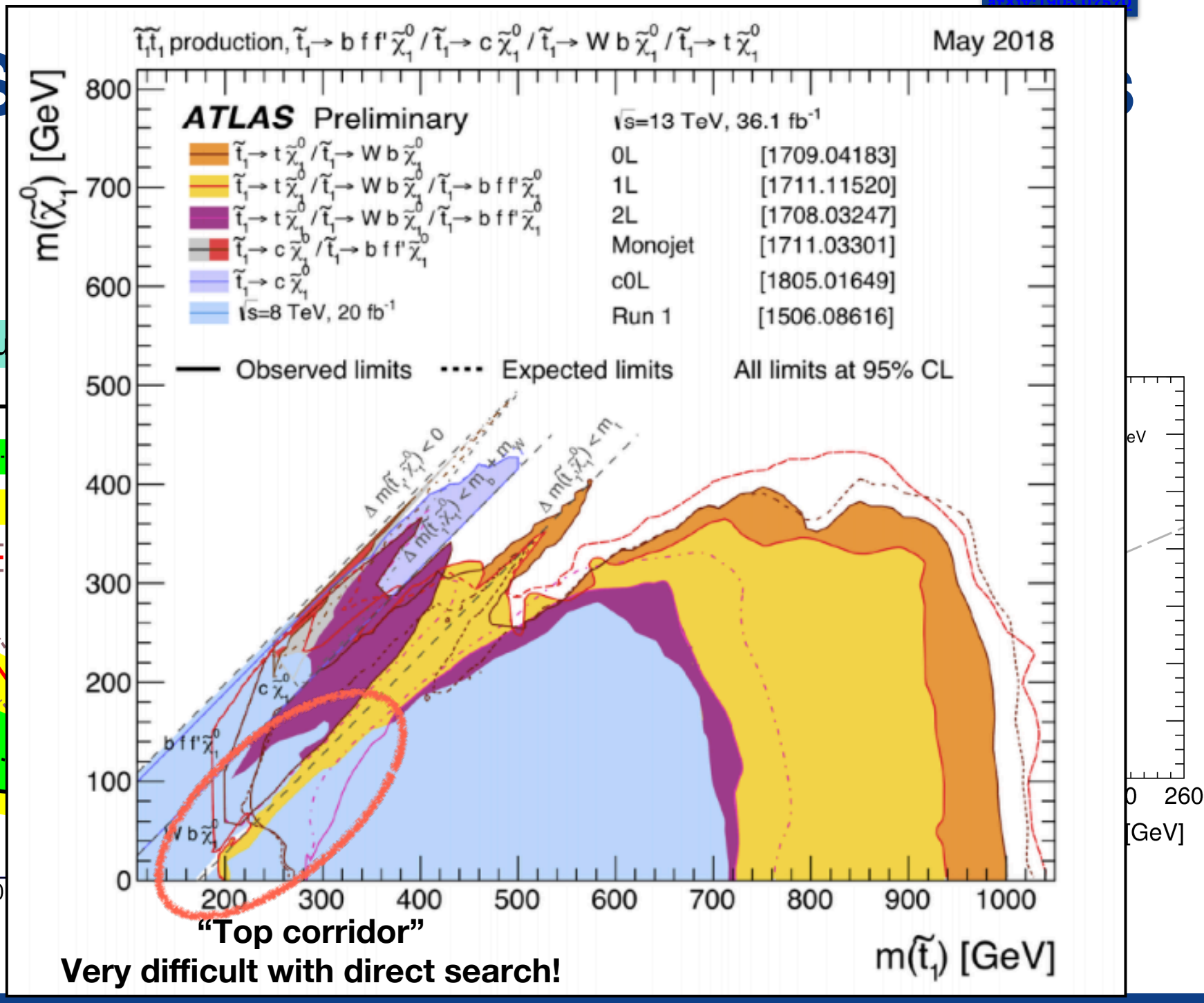
Assume 100% $\tilde{t} \rightarrow t\tilde{\chi}$, $m_{\tilde{\chi}} = 500$ GeV



Assume 100% $\tilde{t} \rightarrow t\tilde{\chi}$, scan $m_{\tilde{\chi}}$



"Searches never stop"

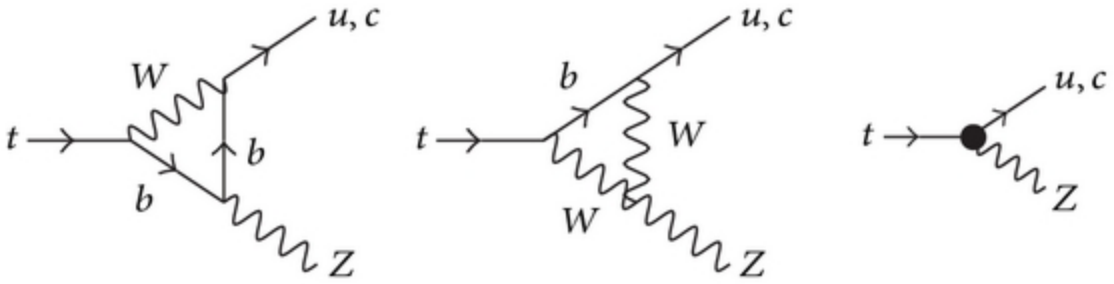


"Top corridor"

Very difficult with direct search!

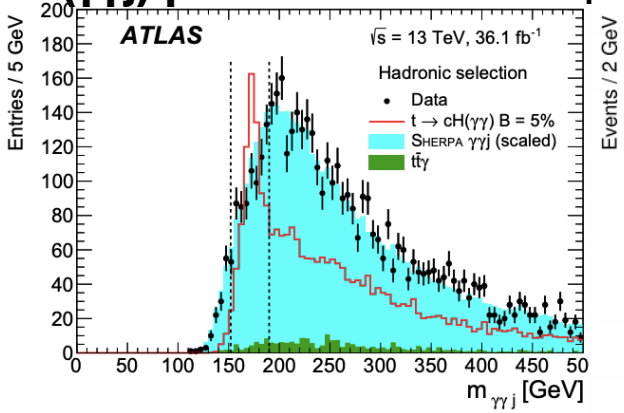
arXiv:1812.11568

FCNC



- Flavour-changing neutral currents strongly suppressed in the SM, but enhanced in some BSM scenarios
- Look for tt→WbHq (W→qq/ℓν,H→γγ/bb)

m(γγj) peaks close to m_{top}



No Higgs peak