Boosted top quarks measurements at the LHC

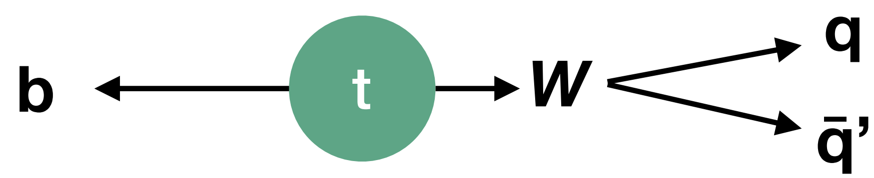
Riccardo Di Sipio, University of Toronto,
On behalf of the ATLAS and CMS collaborations

@rdisipio #topquark

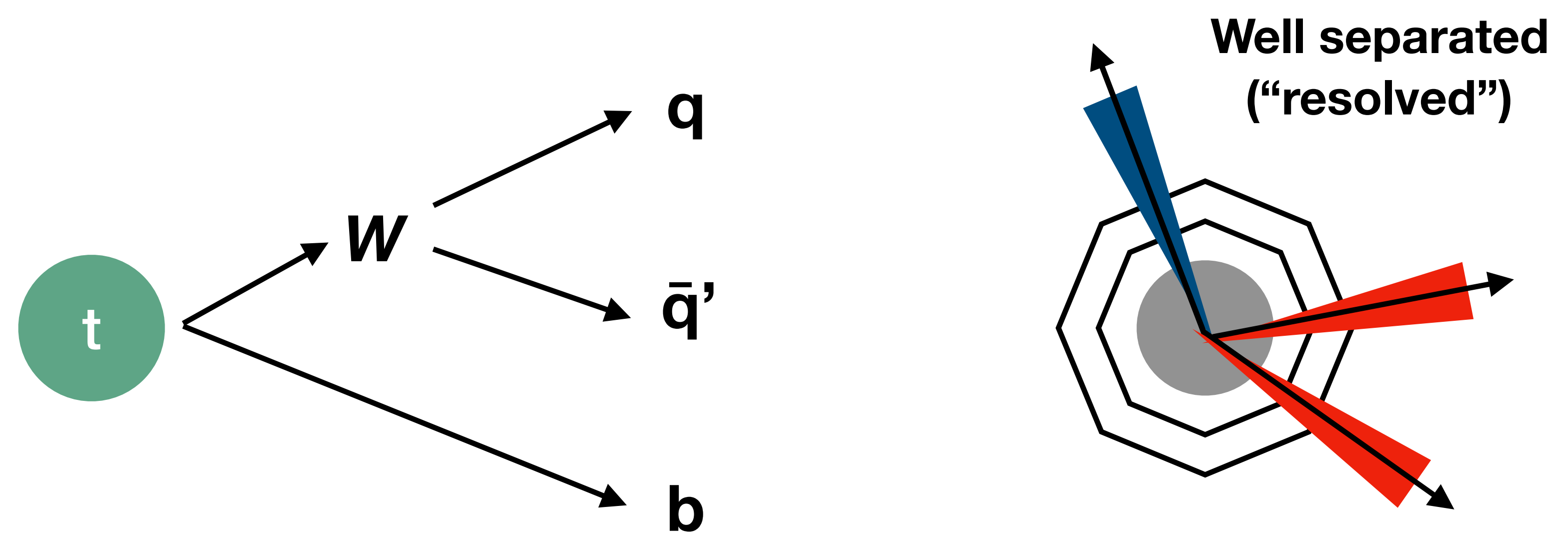
http://disipio.wordpress.com

What is a boosted top?

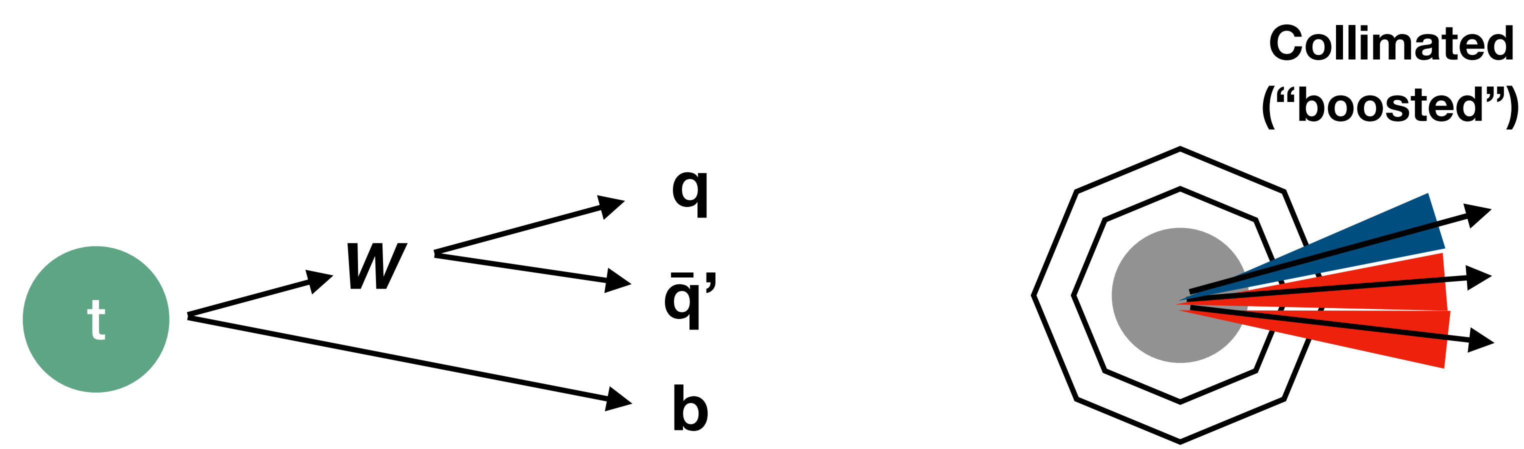
Top quark rest frame



Lab frame Low momentum

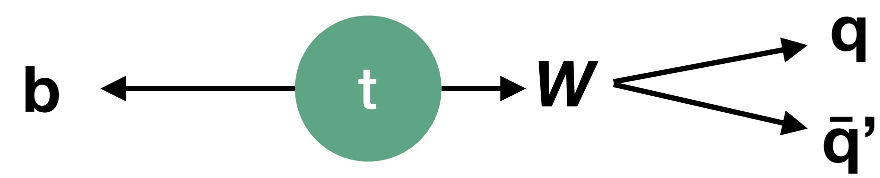


Lab frame High momentum

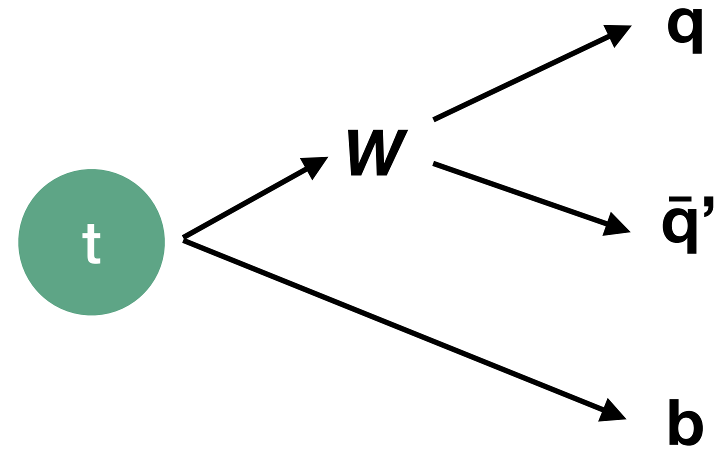


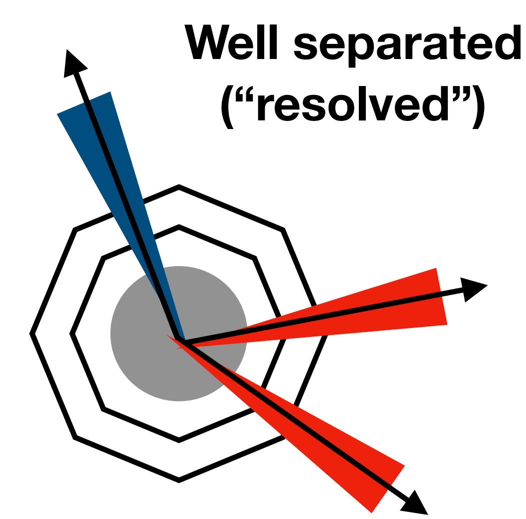
What is a boosted top?

Top quark rest frame

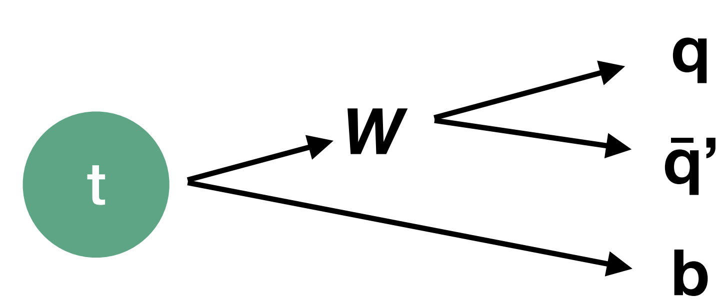


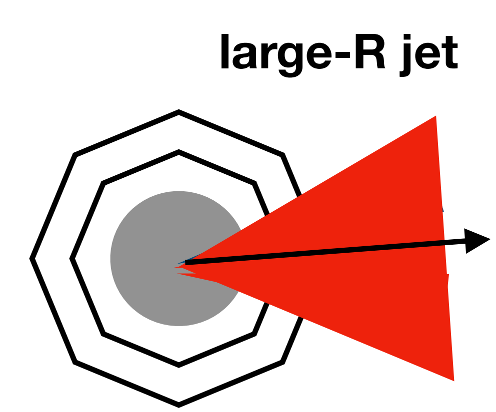
Lab frame Low momentum





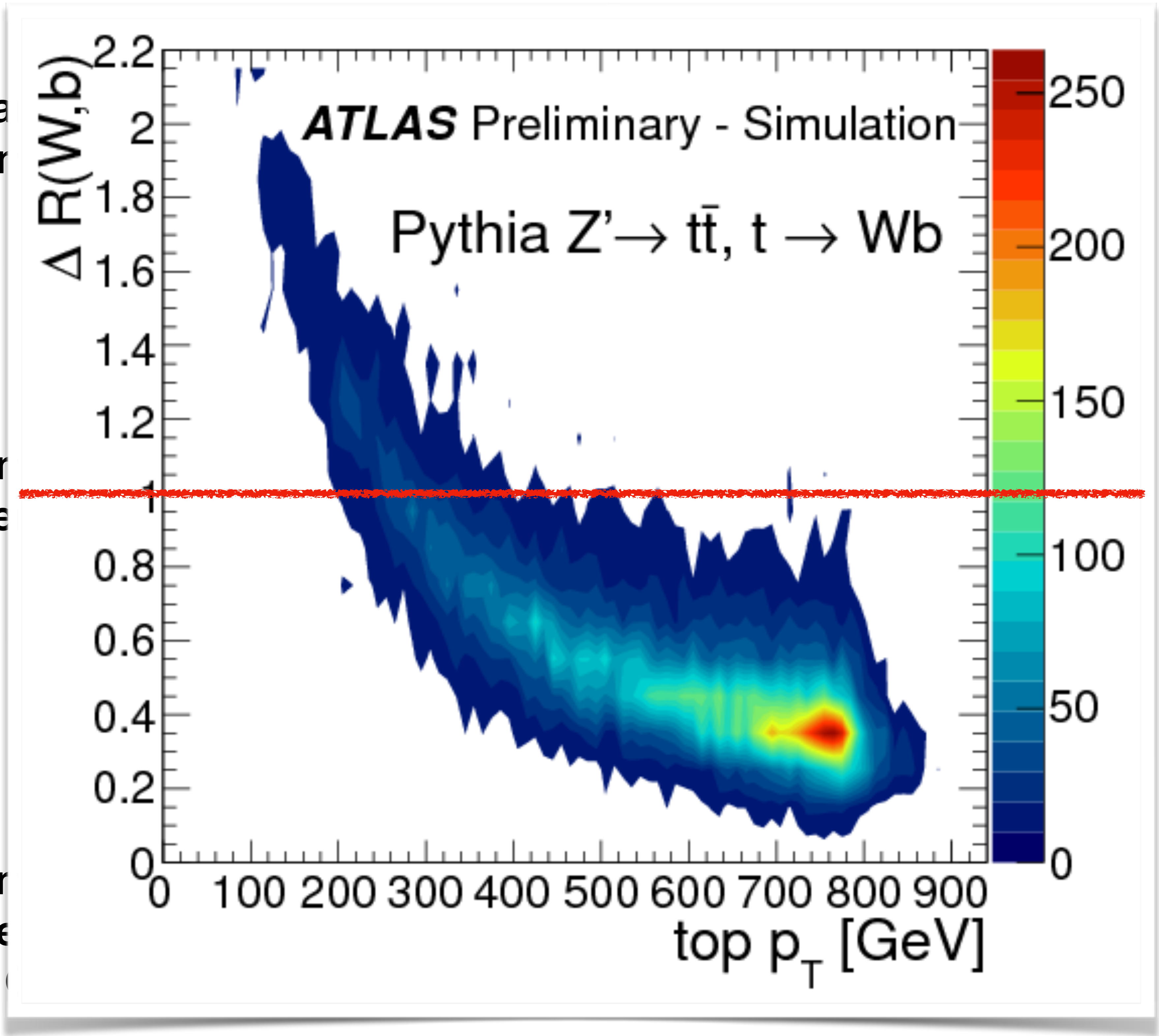
Lab frame High momentum (pT ≳ 350 GeV)



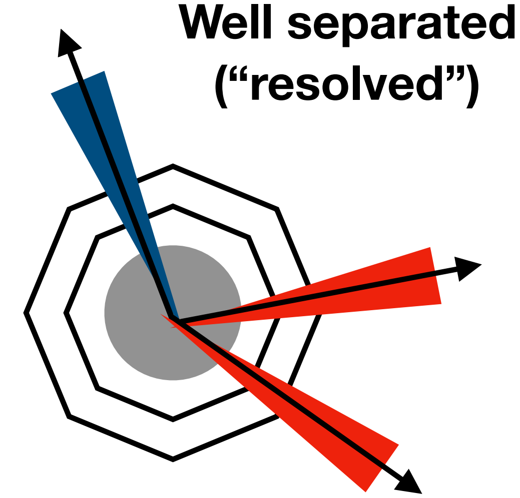


What is a boosted top?

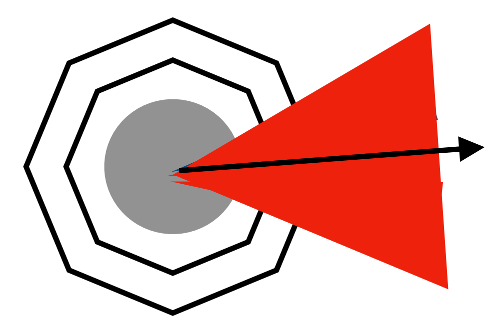
Top qua
rest frar



Lab frar
Low mome

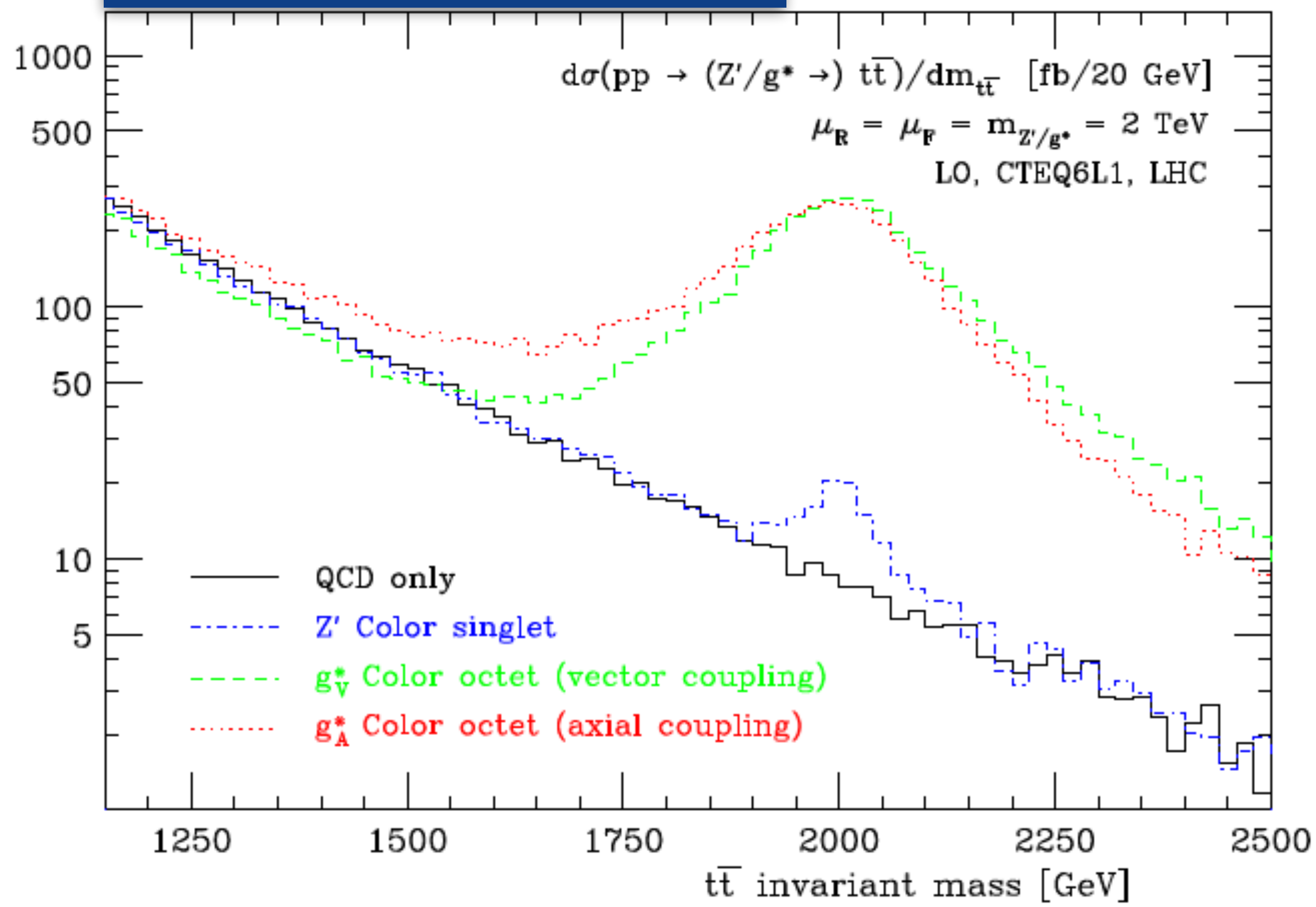


Lab frar
High mome
(pT ≳ 350



Why boosted tops?

Fredrerix & Maltoni, JHEP 01 (2009) 047



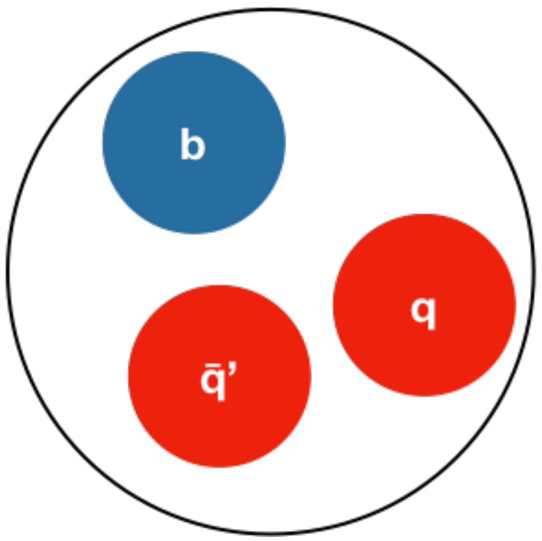
Top quark plays a special role in many models for New Physics

Additional vector bosons Z', W' (narrow resonances)
String-inspired resonances G_{KK}, g_{KK} (broad resonances)
Supersymmetric scalar top ($\tilde{t}$)
Other BSM particles (vector-like quarks)

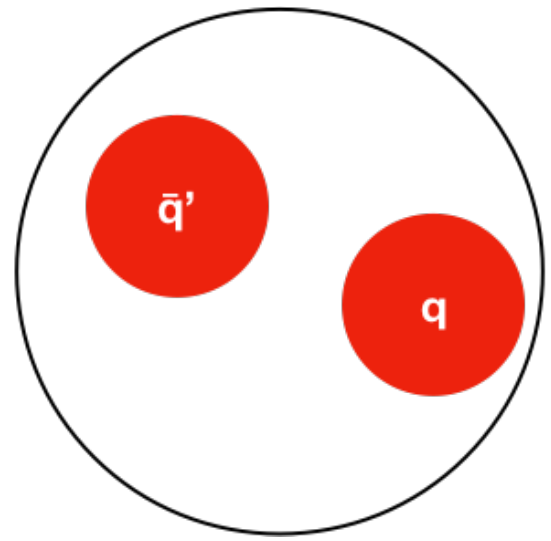
Rule of thumb:

Large mass of new particle → Large momentum of decay products → Boosted Top quarks!

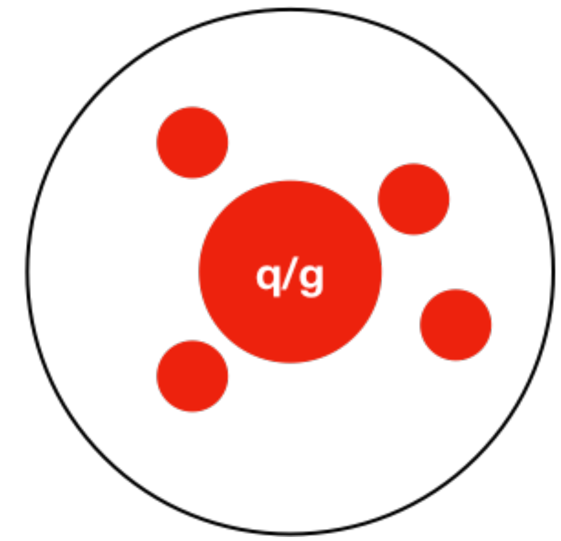
Detecting top quarks



Top quark
Three-prong topology



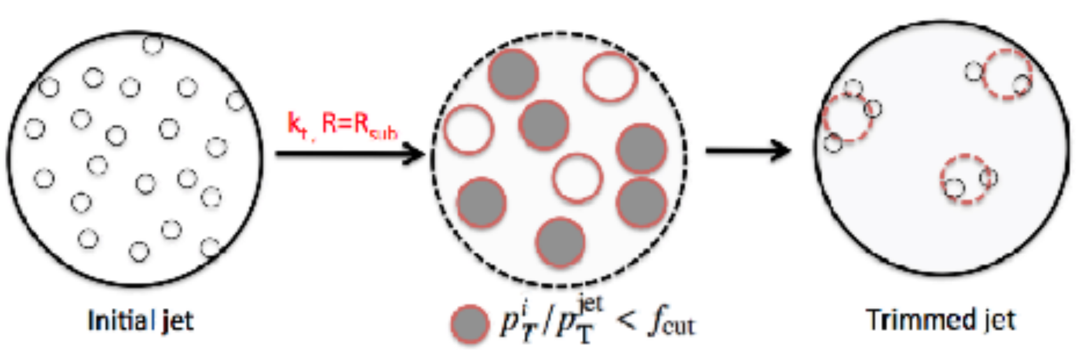
W boson
Two-prong topology

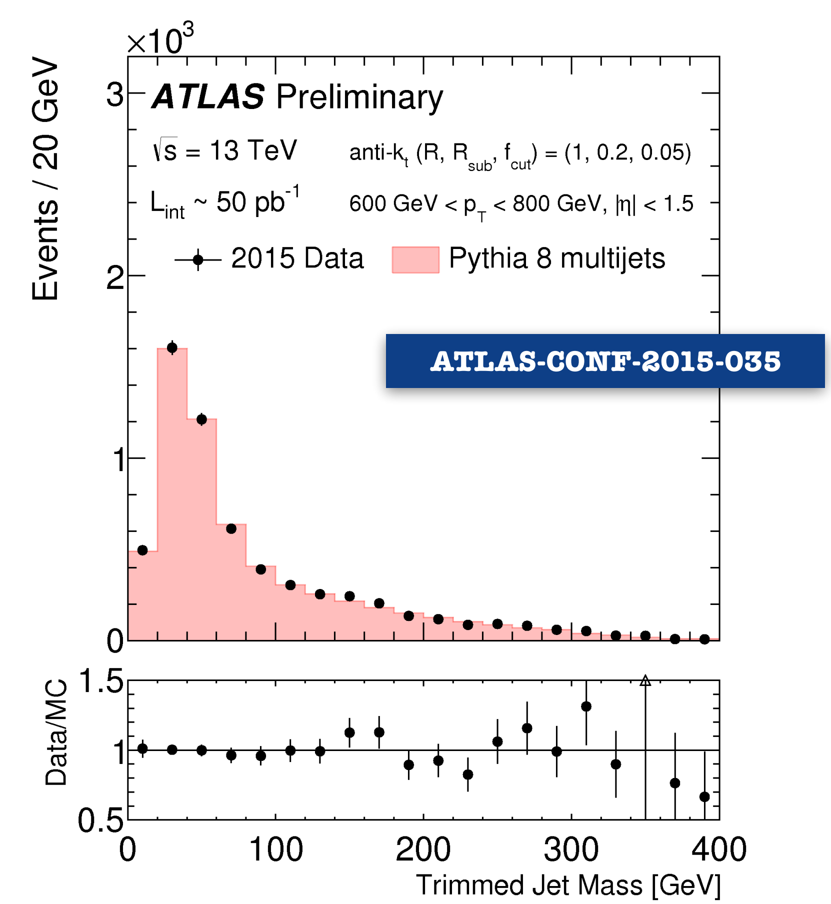


Quark/gluon
Axial topology

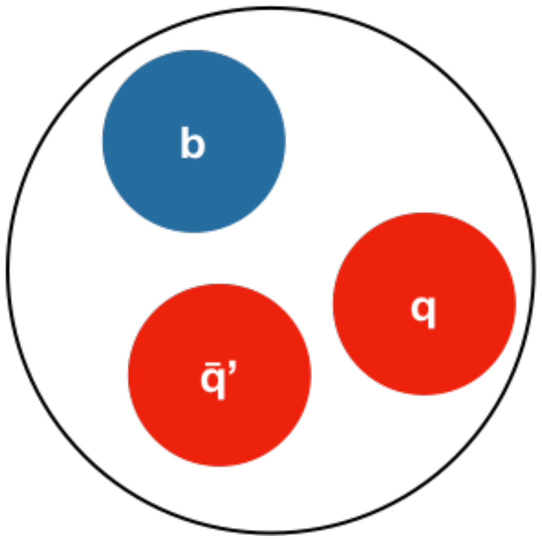
Trimming Thaler et al., JHEP 1002:084,2010

Removes pileup by discarding R=0.2 subjets with pT < 5% pT(J)





Detecting top quarks

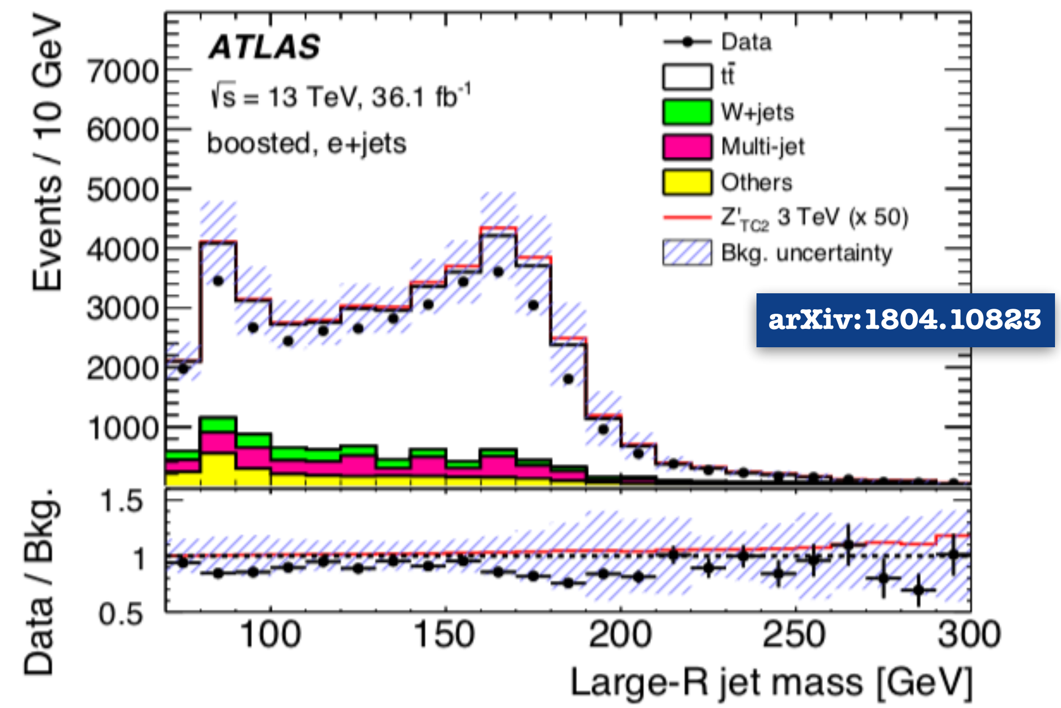


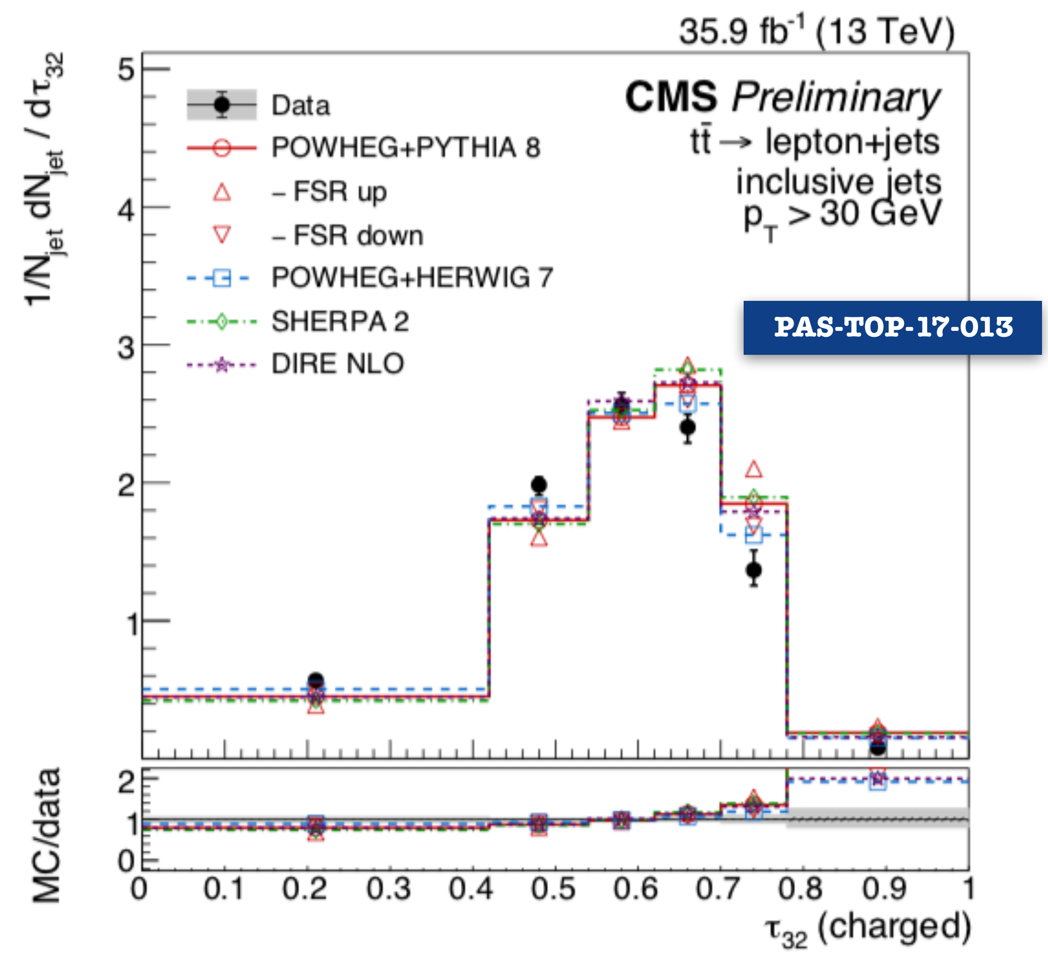
Jet Mass
Expected to peak
around resonance mass
(t~173 GeV; W~80.4 GeV)

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

- N-subjettiness ratio τ_{32}
- Splitting scale $\sqrt{d_{12}}$
- Soft drop mass, multiplicity n_{SD}
- Energy correlation functions $C_N^{(\beta)}$

Typical simple tagger:
Apply **cut** on **substructure** variable
as a function of jet **kinematic** variables (p_T, y, m)



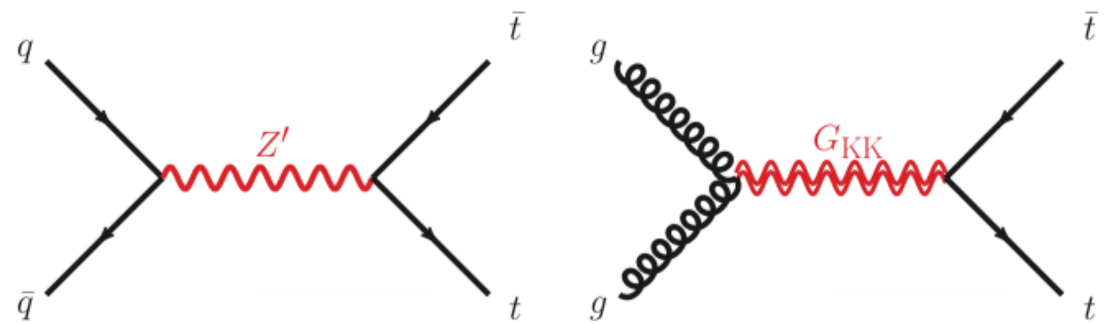


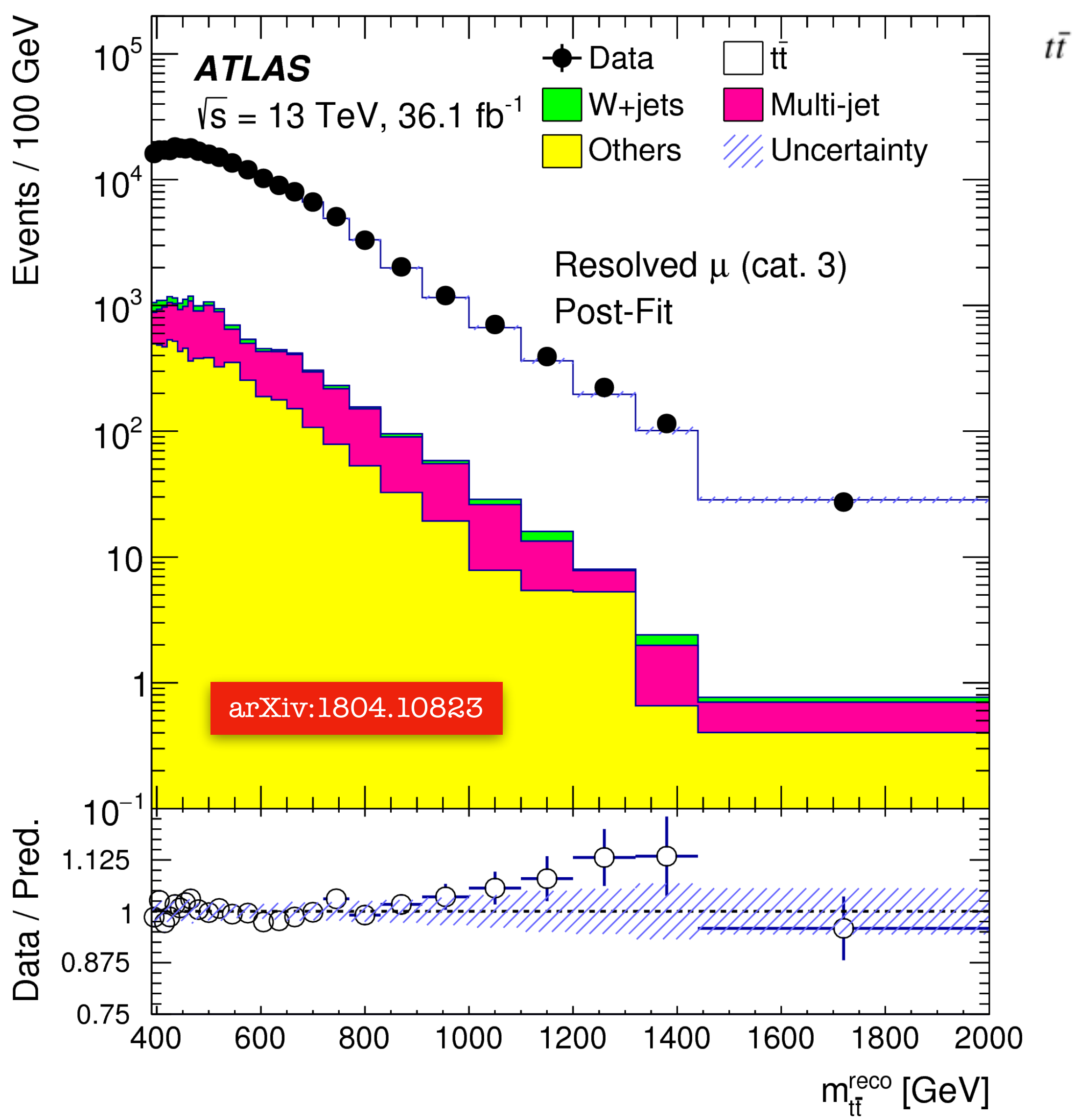
Searches with boosted tops

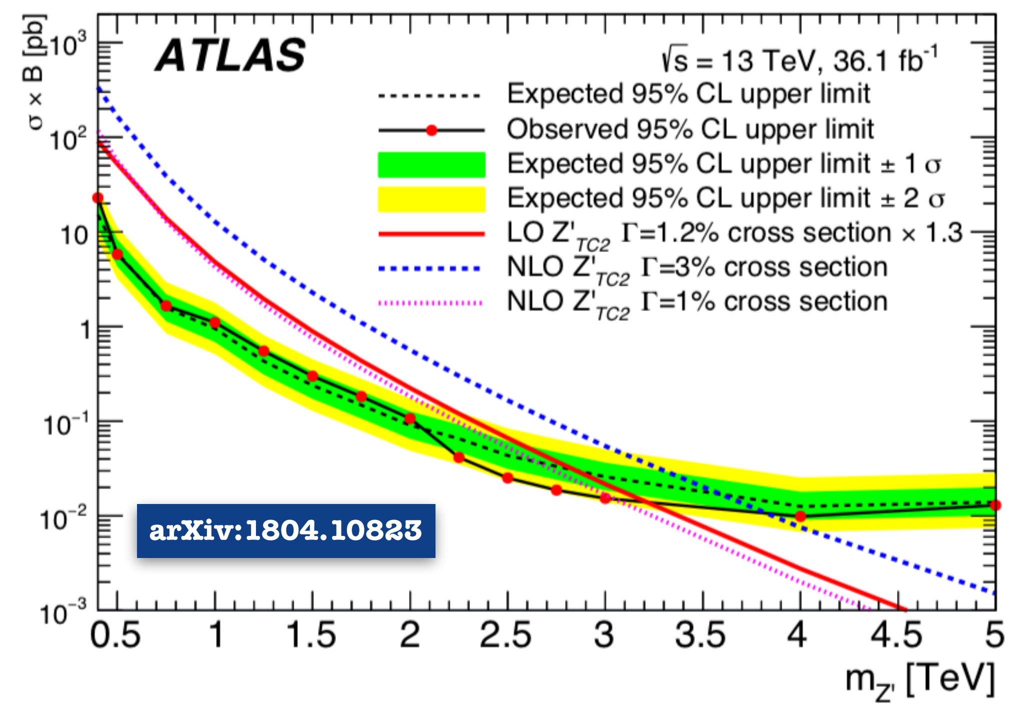
X→tt Resonances

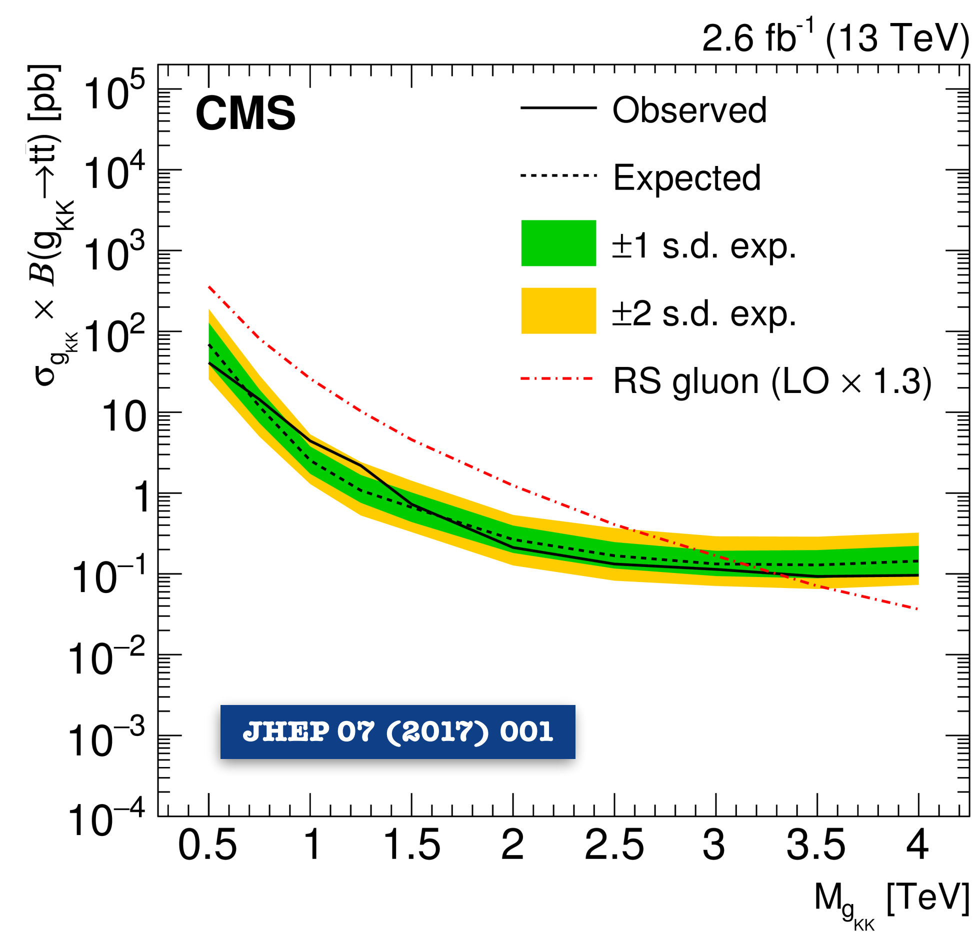
Look for bumps in $t\bar{t}$ invariant mass:

Narrow resonance **Broad resonance**



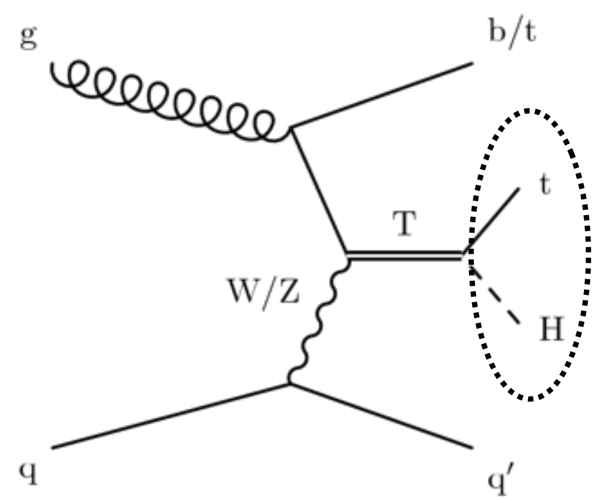


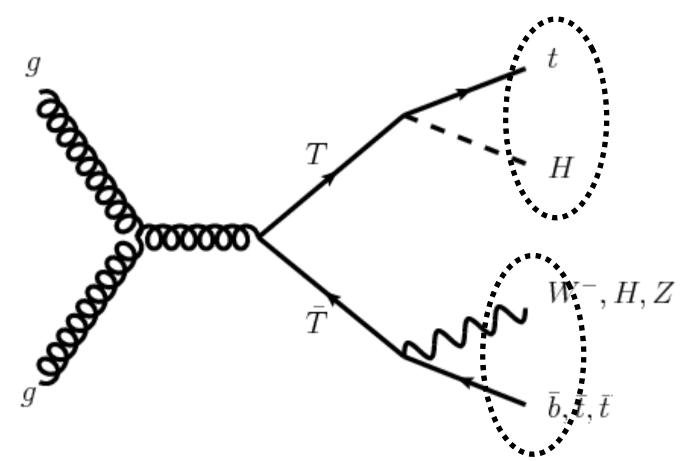


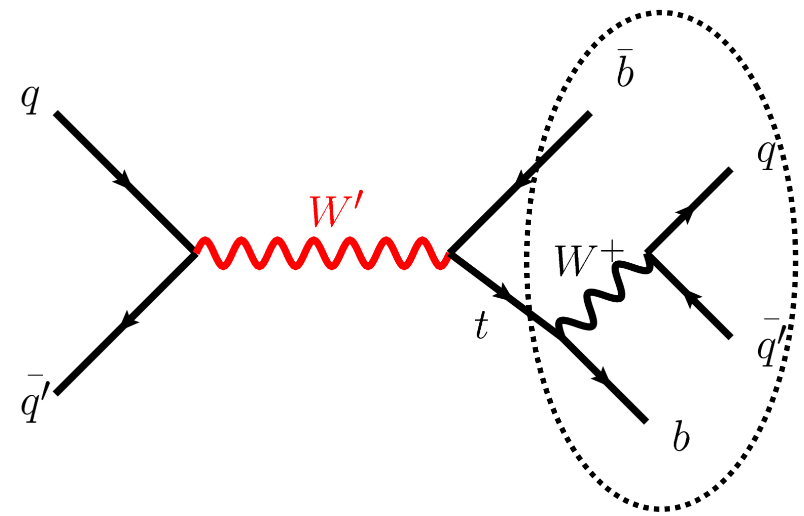


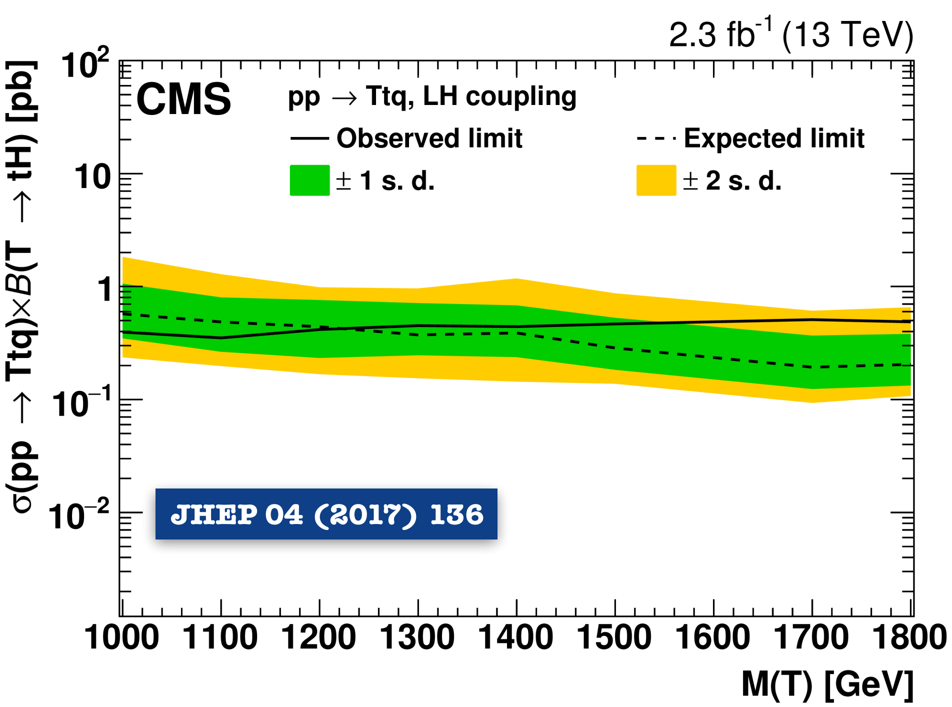
X→tb,TZ,tH Resonances

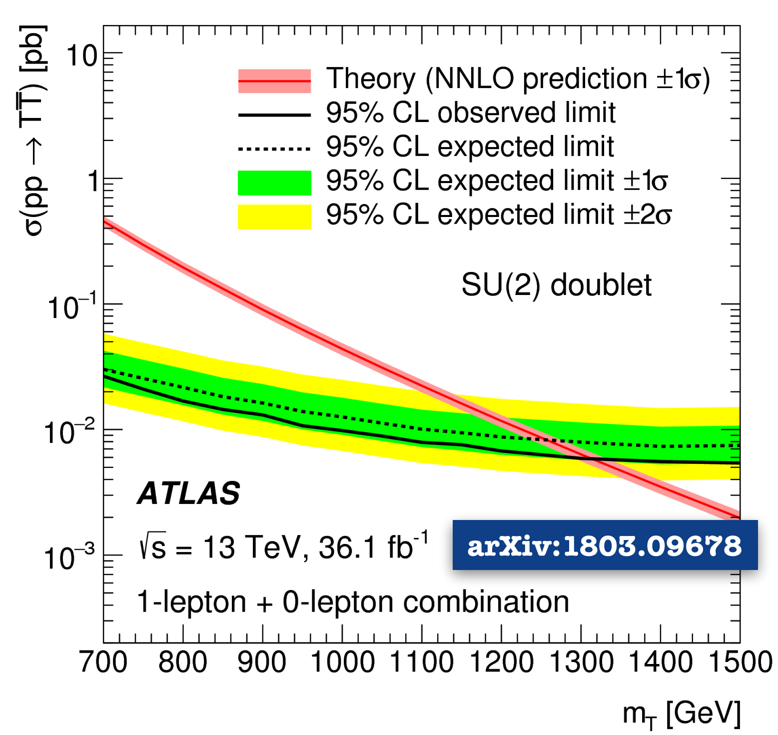
- Look for bumps in (t,b) or (t,H) invariant mass spectrum
- **Vector-Like Quarks (VLQ)**: quarks with vector-like interactions with other particles.
- **W'$_R$** and **W'$_L$**: additional gauge bosons, mediator of a new charged vector current

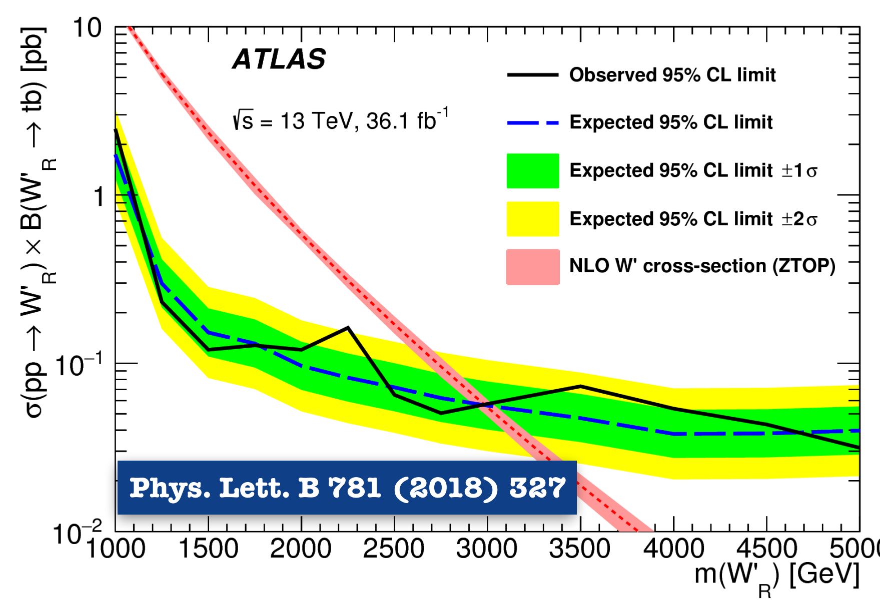






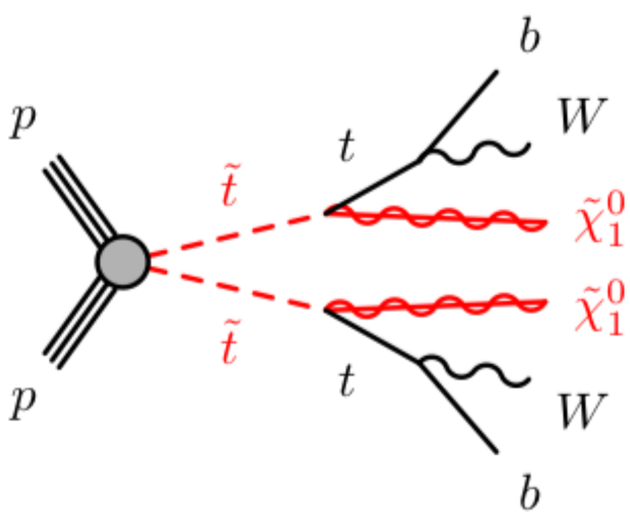




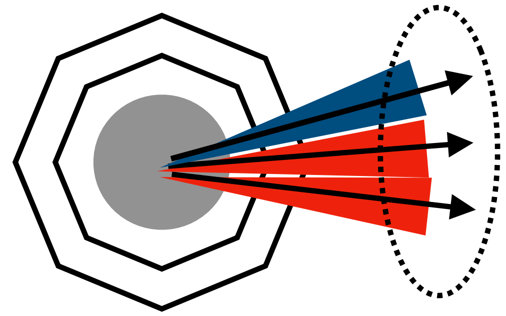


JHEP 12(2017)085

Supersymmetric Scalar Tops

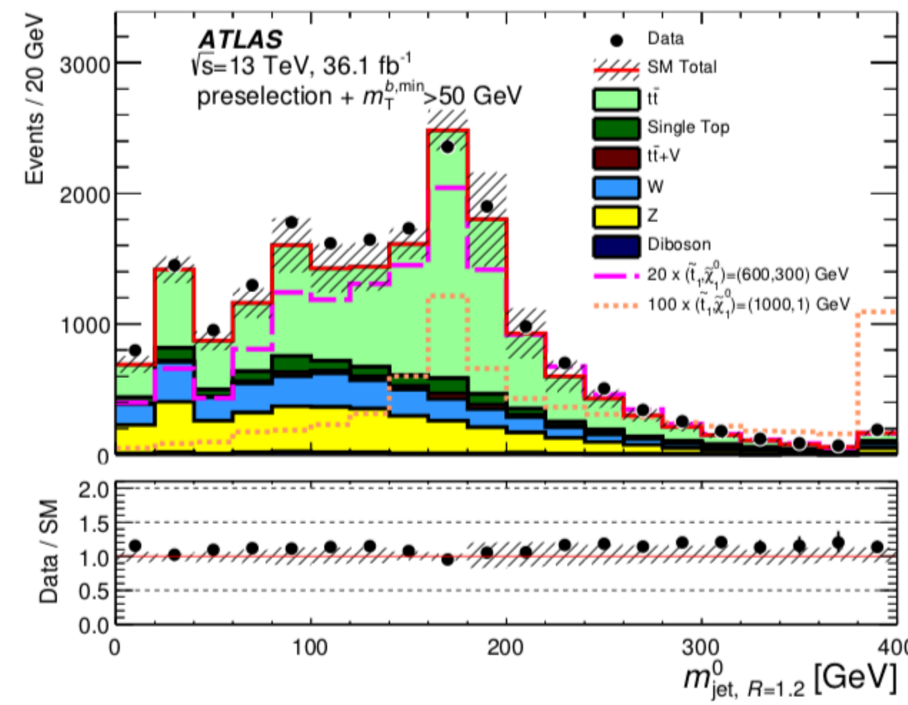


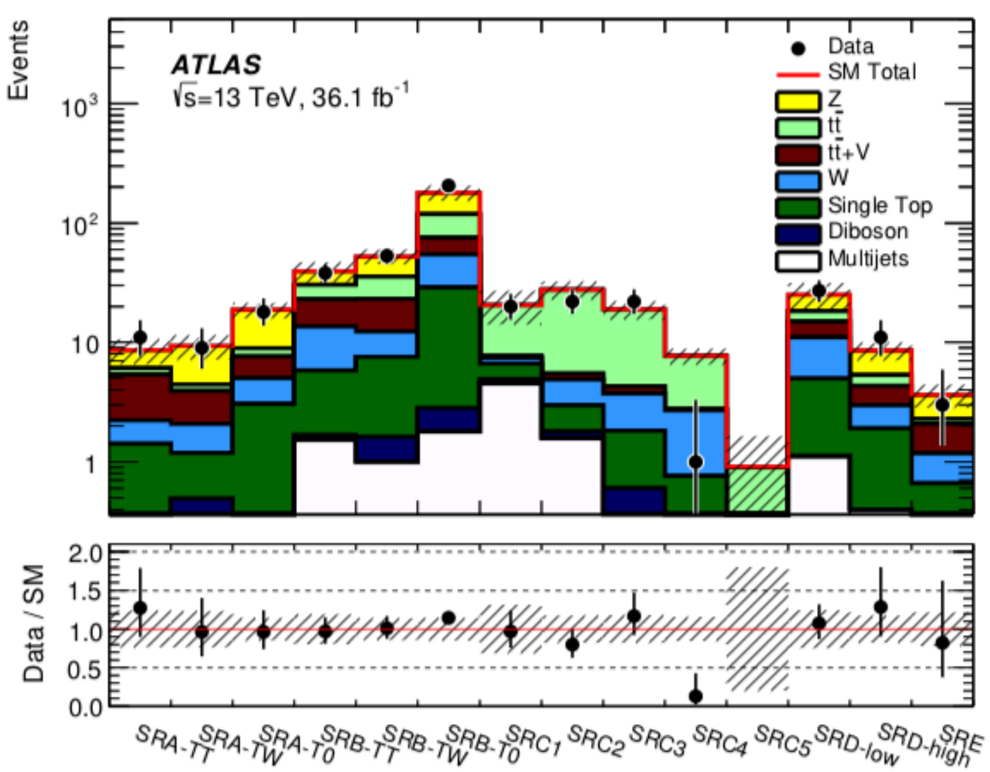
(a) $\tilde{t}_1 \to t^{(*)} \tilde{\chi}_1^0$



Reclustered R=1.2 jet

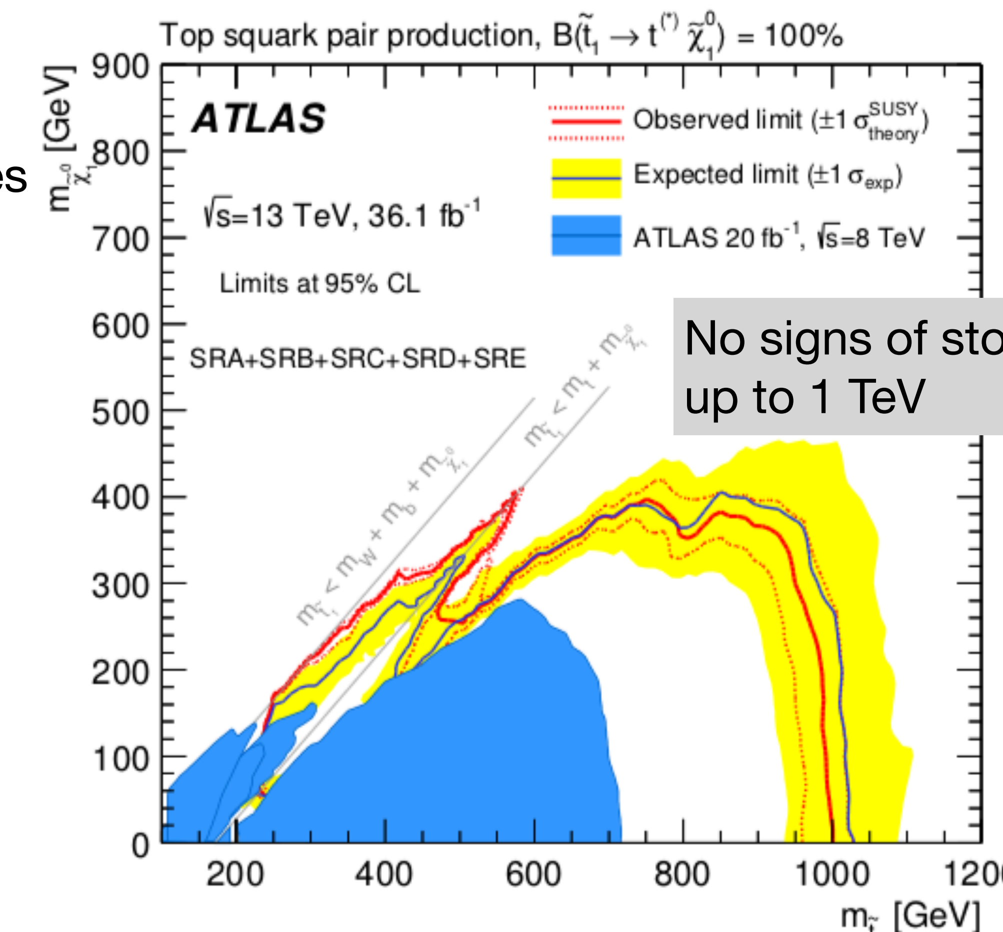
heavy stops almost produced at rest,
low momentum → unusually large jet radius





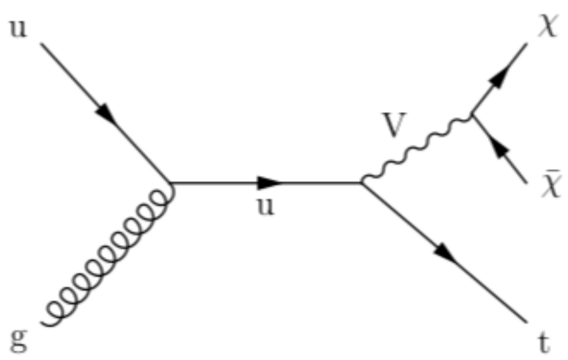
Signal xs depends on stop and neutralino masses

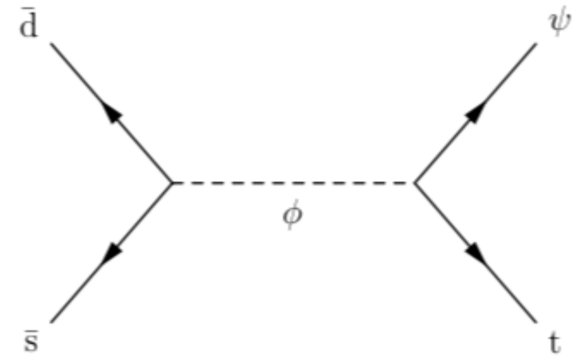
Set limits using simplified models



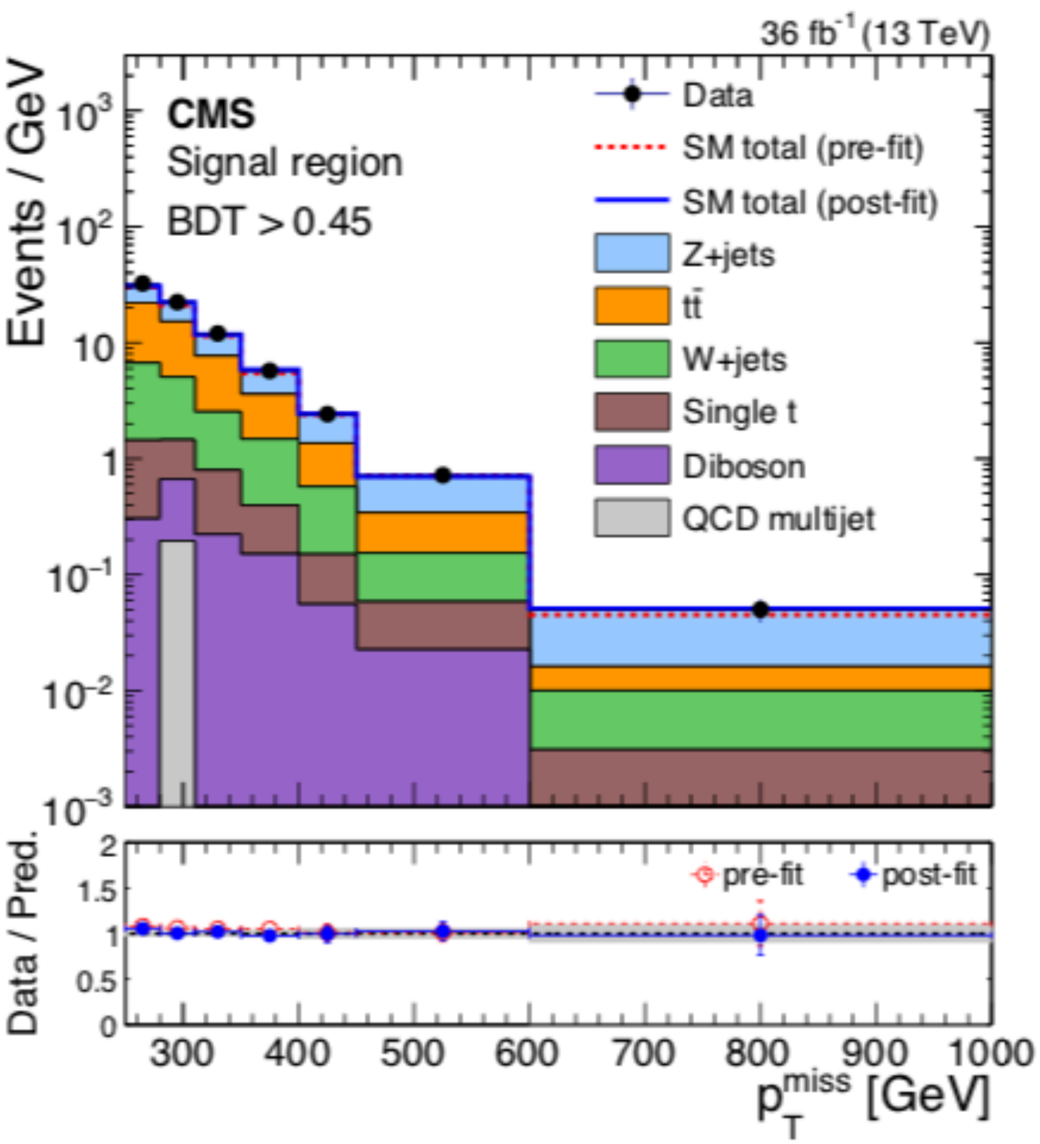
No signs of stops up to 1 TeV

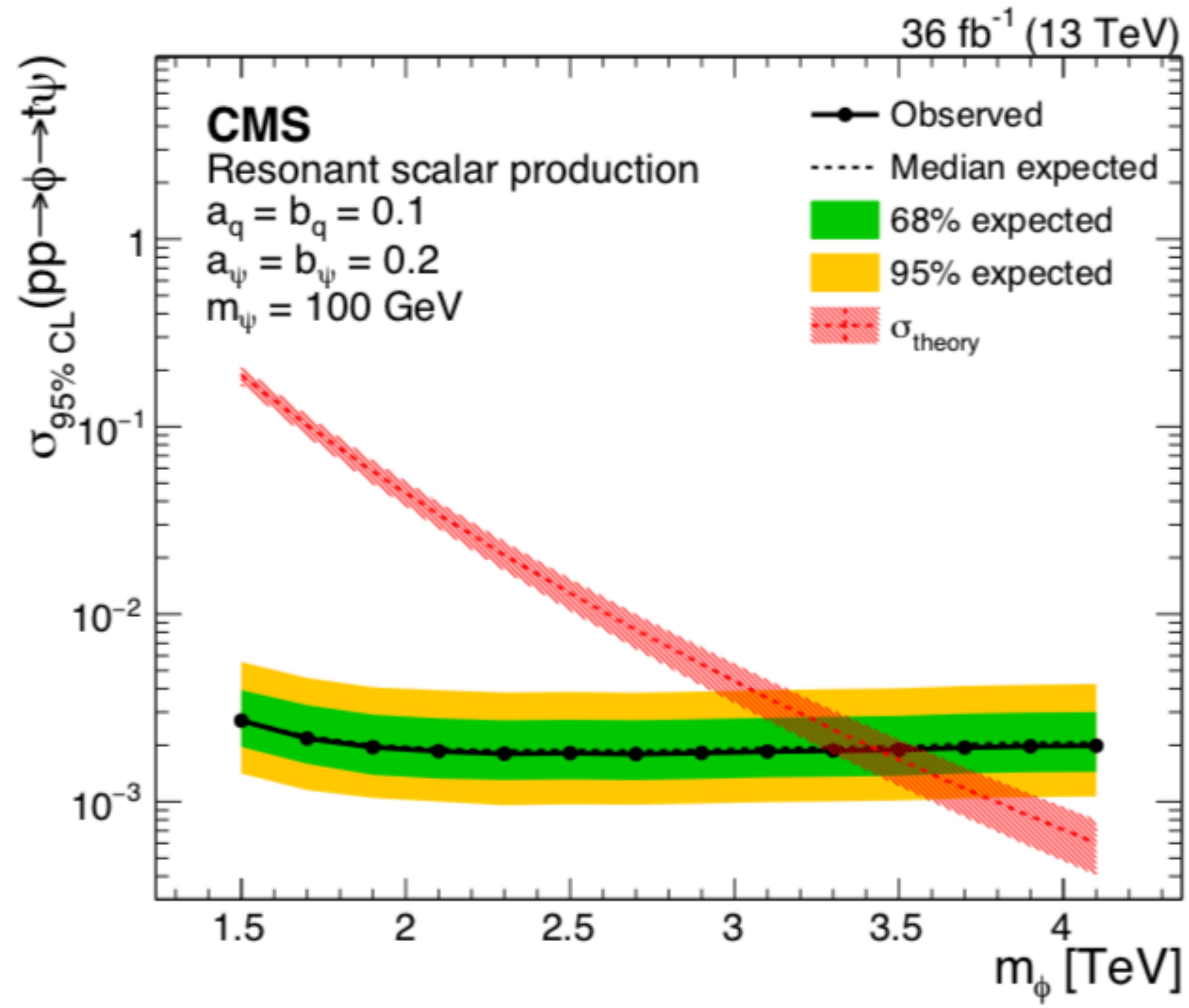
Recoiling Dark Matter





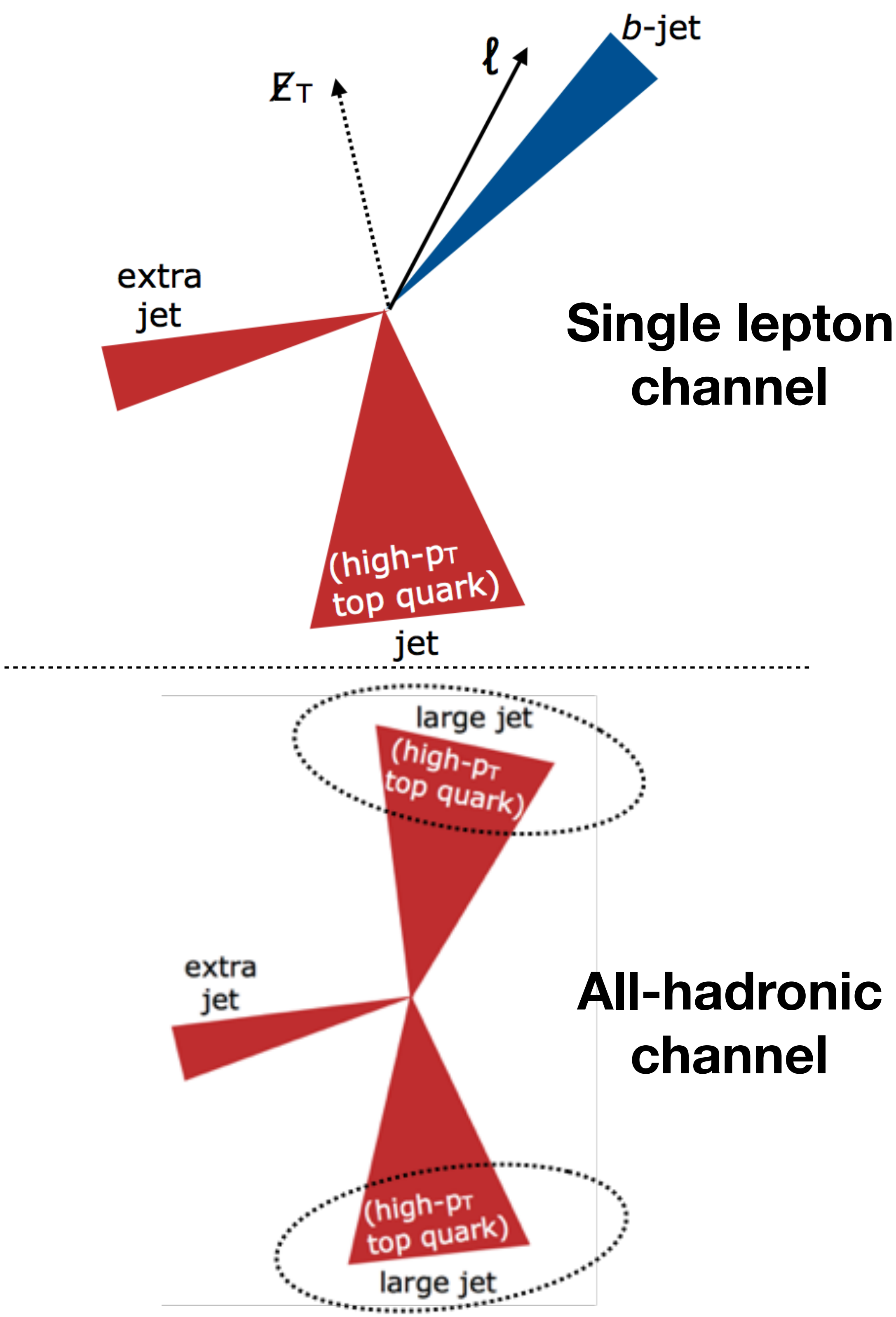
Very striking signature! Top + E_T^{miss}





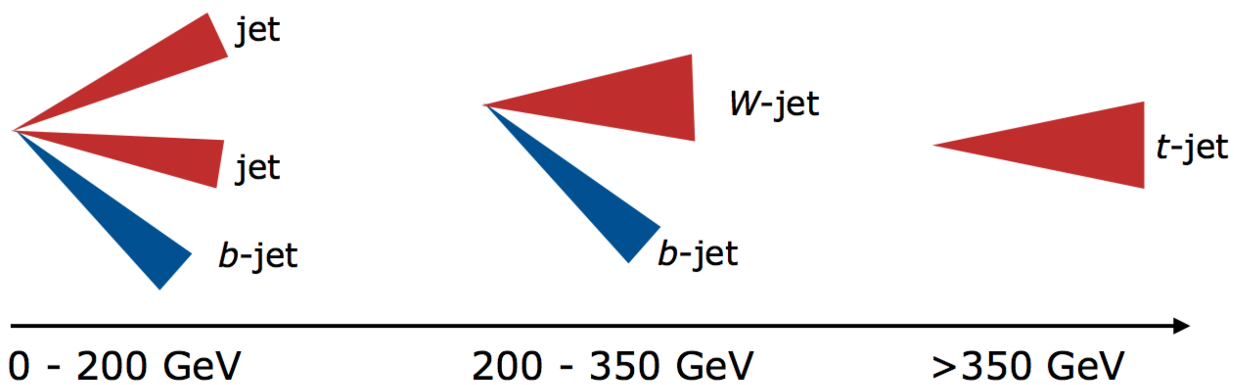
Precision measurements with boosted tops

Differential Cross-sections



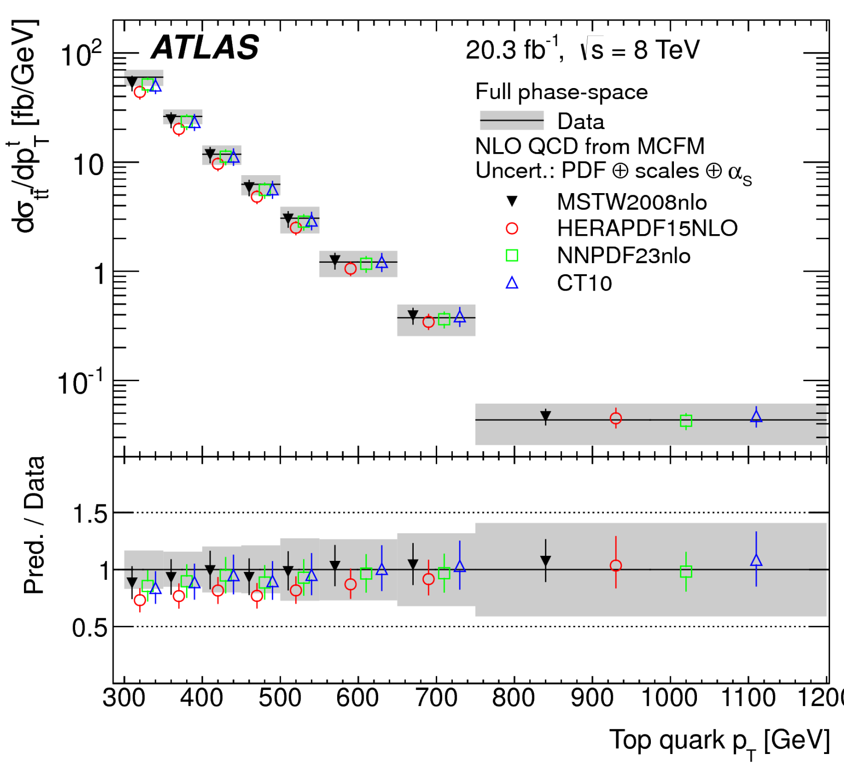
- Measurement of the production cross-section as a function of kinematic variables
  - Mostly central, back-to-back top quarks
  - Cross-section falls rapidly as a function of transverse momentum rapidity
- State-of-the art comparisons:
  - **Particle level**
    Monte Carlo **event generators** with next-to-leading order (**NLO**) accuracy
    ✓ Improve **tuning** of event generators
  - **Parton level**
    Fixed-order **calculation** with next-to-next-to-leading order (**NNLO**) accuracy
    ✓ Parton Distribution Functions (**PDF**) global fits

Top Transverse Momentum

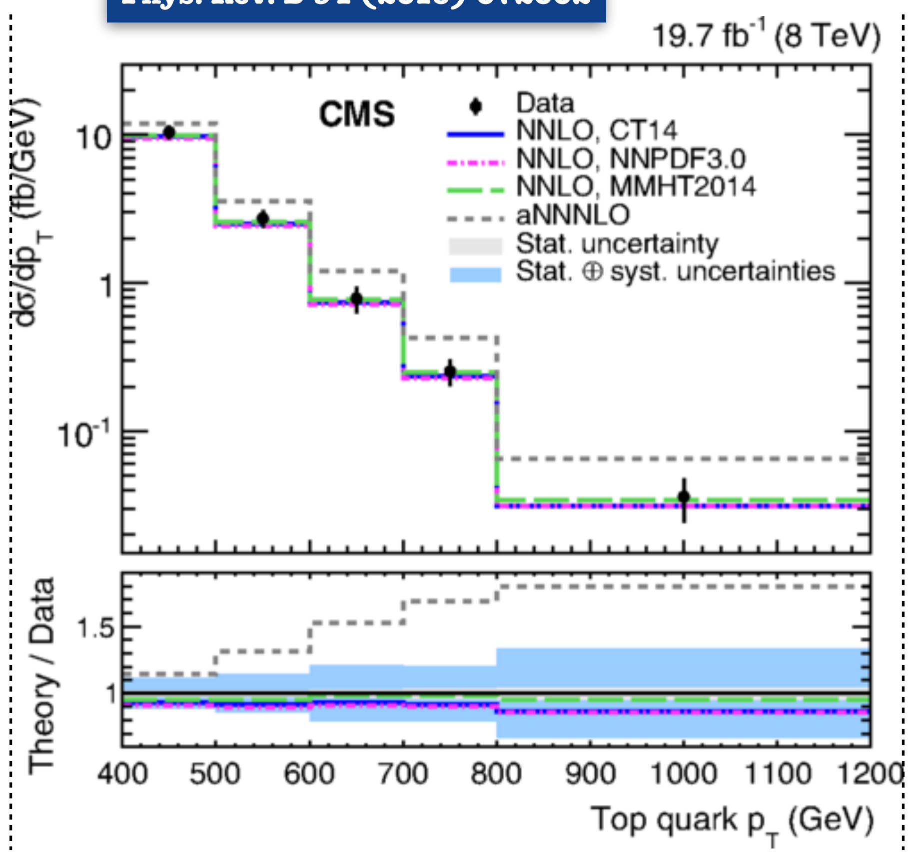


- Probably the **most important** observable
- Measurements up to ~1 TeV span different **kinematic** regimes and **reconstruction** techniques
- Sensitive to **final state radiation**
- Very precise low-p_T differential cross-sections indicate **disagreement** with increasing p_T

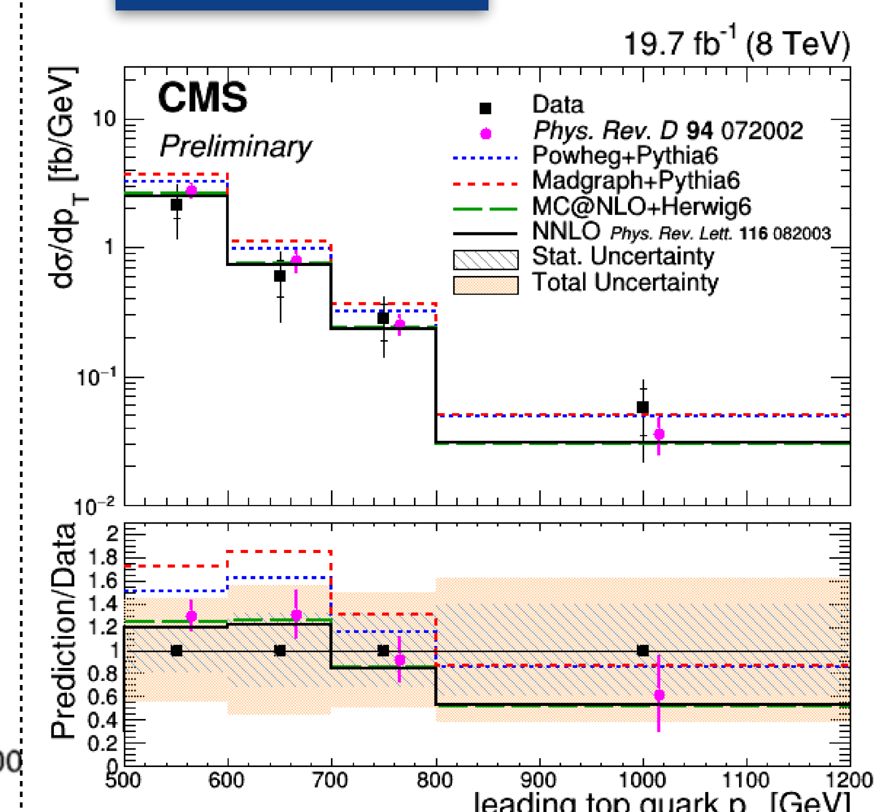
Phy. Rev. D 93 (2016) 032009



Phys. Rev. D 94 (2016) 072002



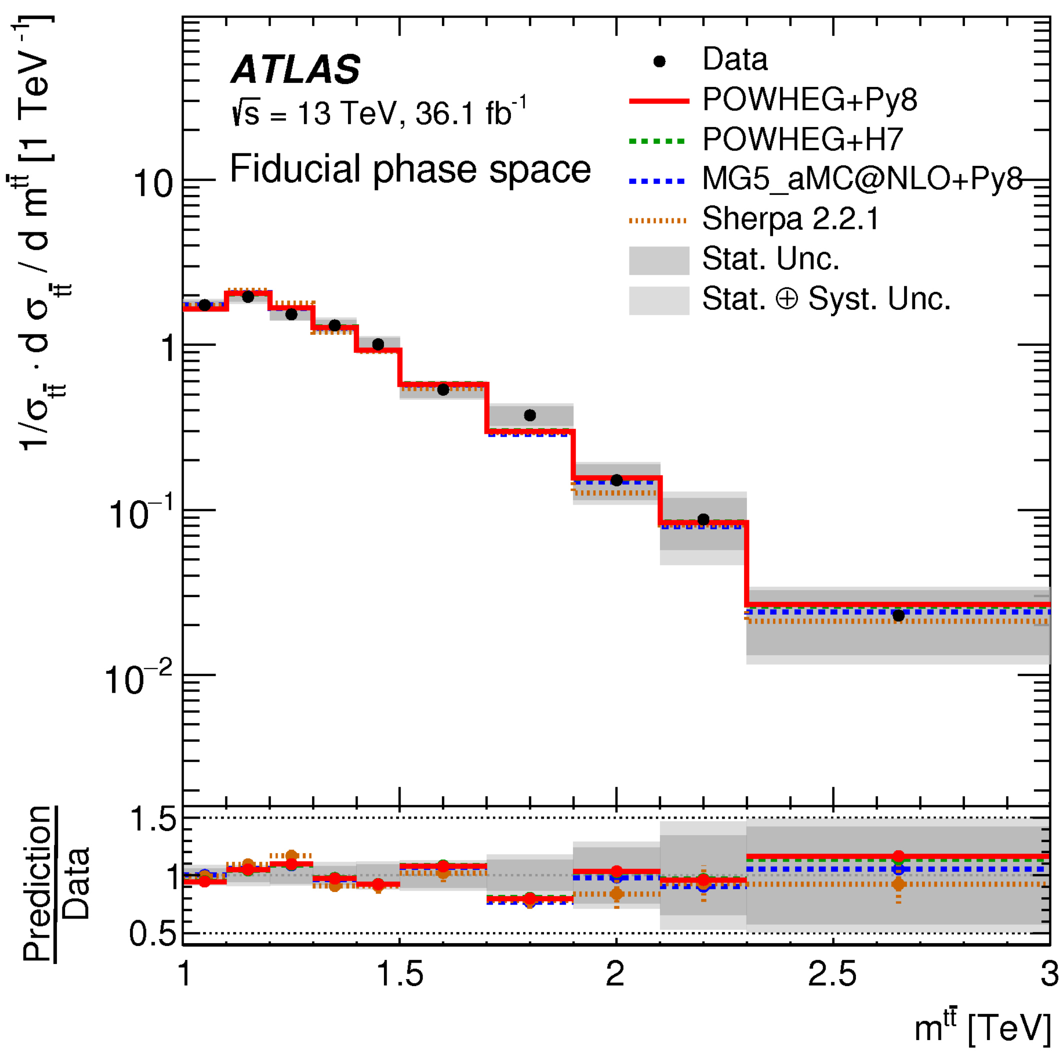
CMS-PAS-TOP-16-018



Top–antitop system

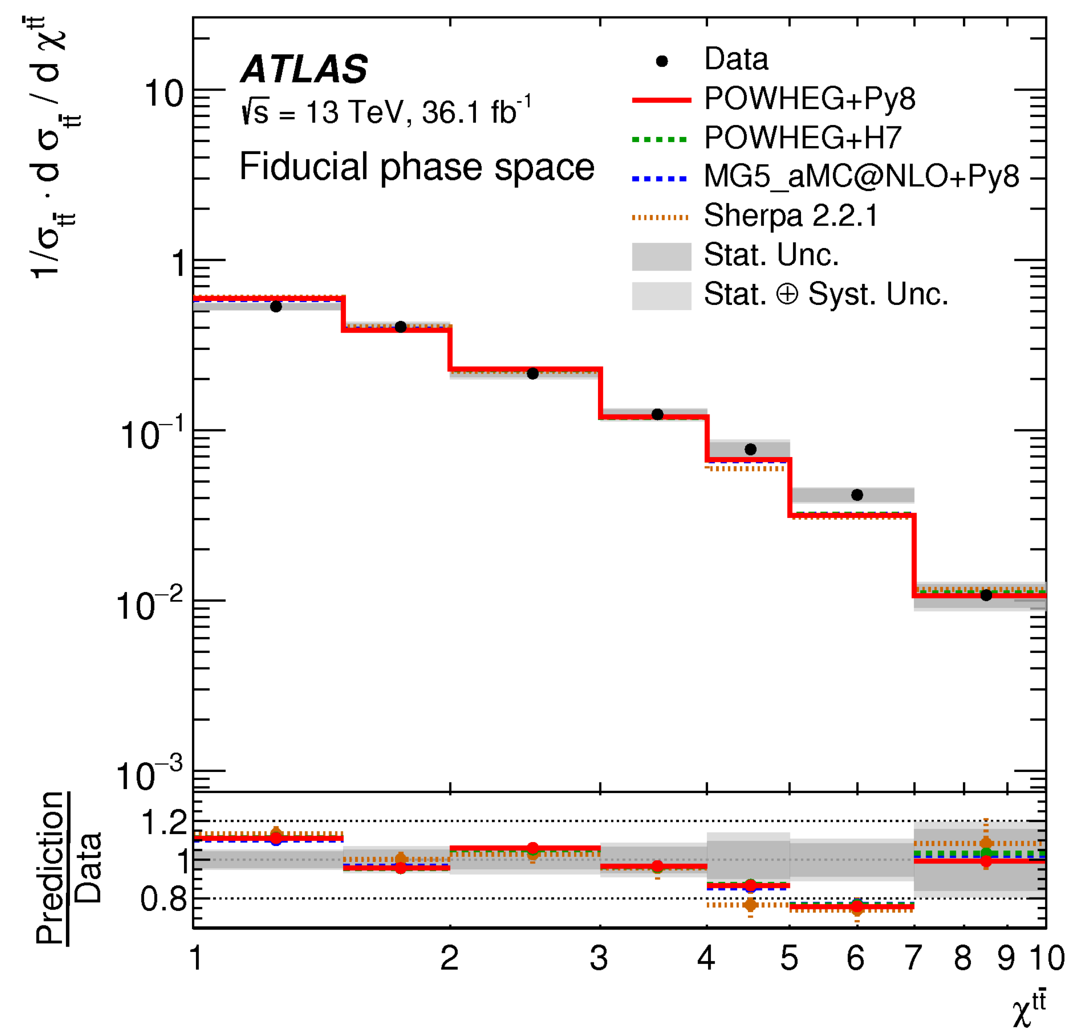
arXiv:1801.02052

Critical to describe SM tt production before claiming discovery of New Physics showing up in …



Invariant mass - resonances

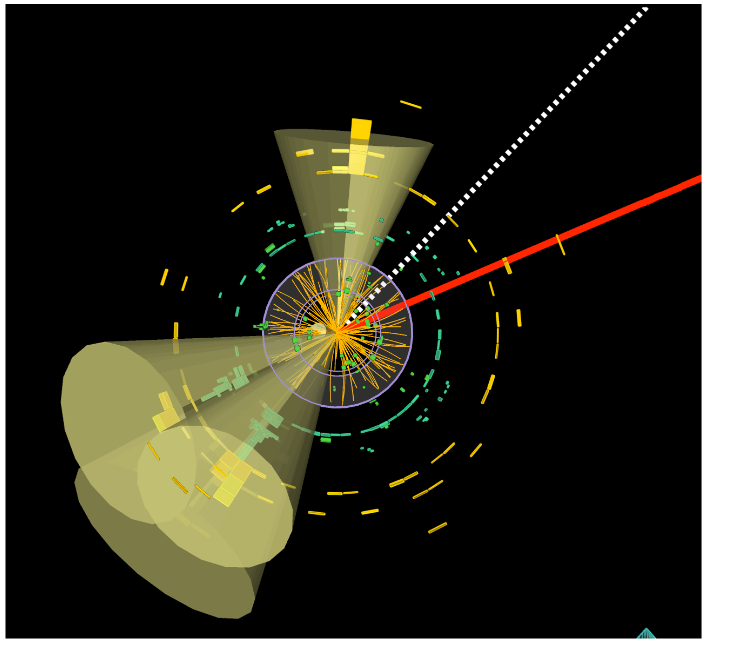
(tt̄ large background to searches!)



Angular production - virtual loops

(see also charge asymmetry in backup)

Conclusions



ATLAS and CMS collected data containing a large number of **high-momentum top-quark pairs**

Boosted top quarks currently deployed for **searches** and **precision** measurements

Boosted tops excellent probe for **high-mass** regions, where **new physics** likely to appear

Precision measurements **support** searches and help improving our **understanding** of the ***tt*** **production**

Backup Material

Glossary

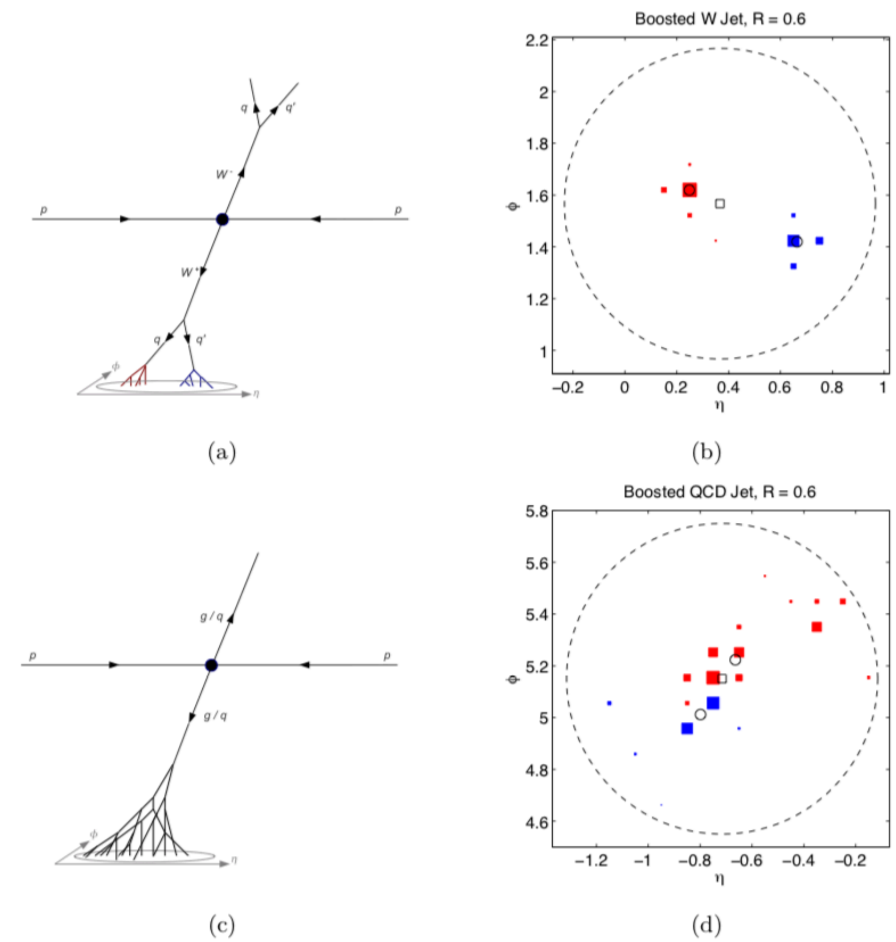
- **N-subjettiness** τ_N [JHEP03(2011)015] [JHEP02(2012)093]
  A measure of the likelihood that the distribution of jet constituents have *N* subjets.

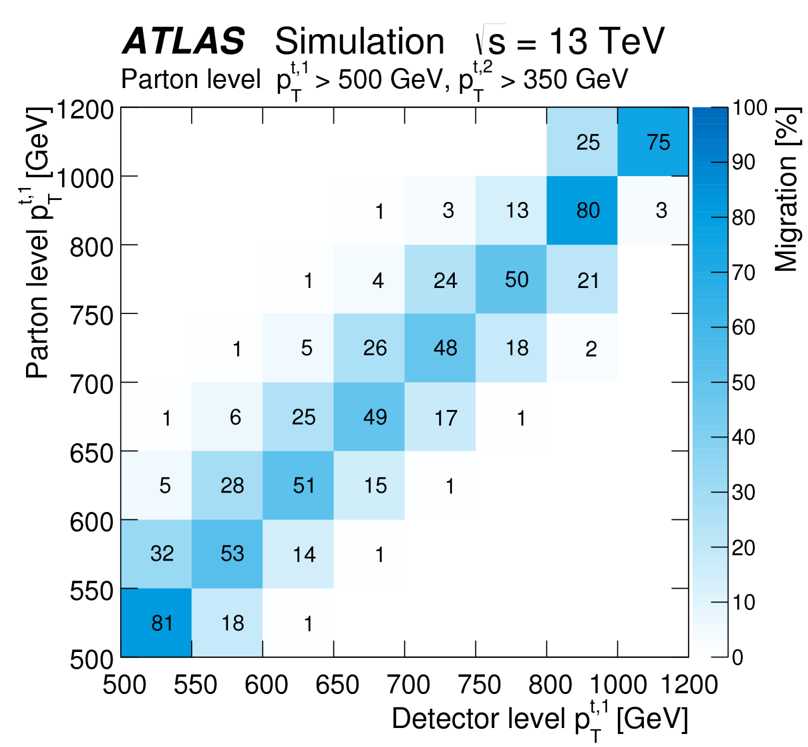
$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min\{\Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k}\}$$

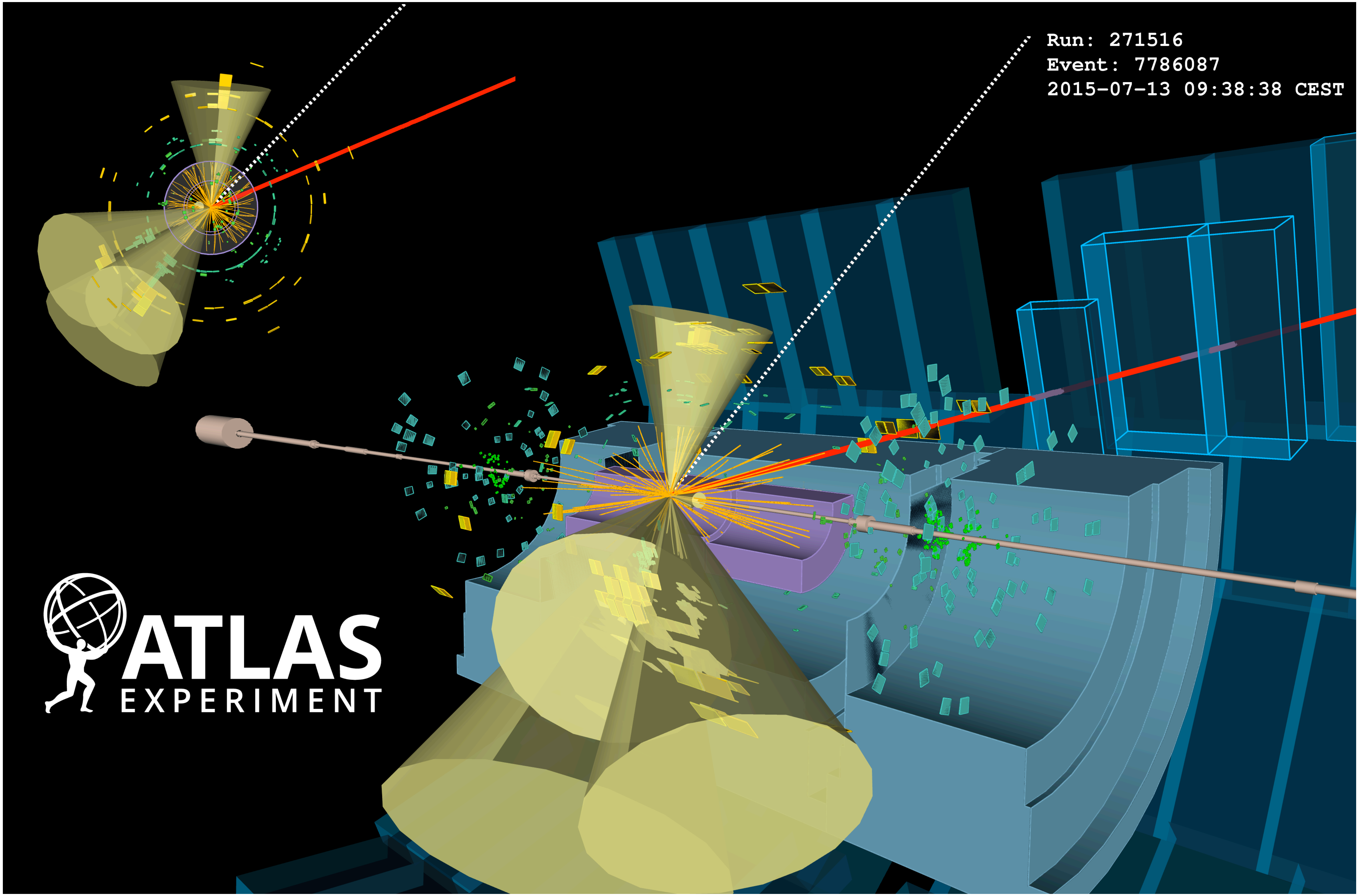
- **Subjettiness ratio** τ_{21}, τ_{32}, etc…
  Ratio of (N+1) / (N) subjettiness, i.e. a measure of the likelihood of a given jet to have (N+1) subjets rather than N

- **Unfolding**
  Technique to correct for detector effects (limited resolution, signal selection efficiency, geometric acceptance)

- **Migrations**
  Limited resolution and other effects tend to reconstruct a certain kinematic quantity (e.g. pT) with a different value compared to its “truth” value; a key part of the unfolding, migrations are encoded in a matrix that correlates a given observable before and after detector simulation





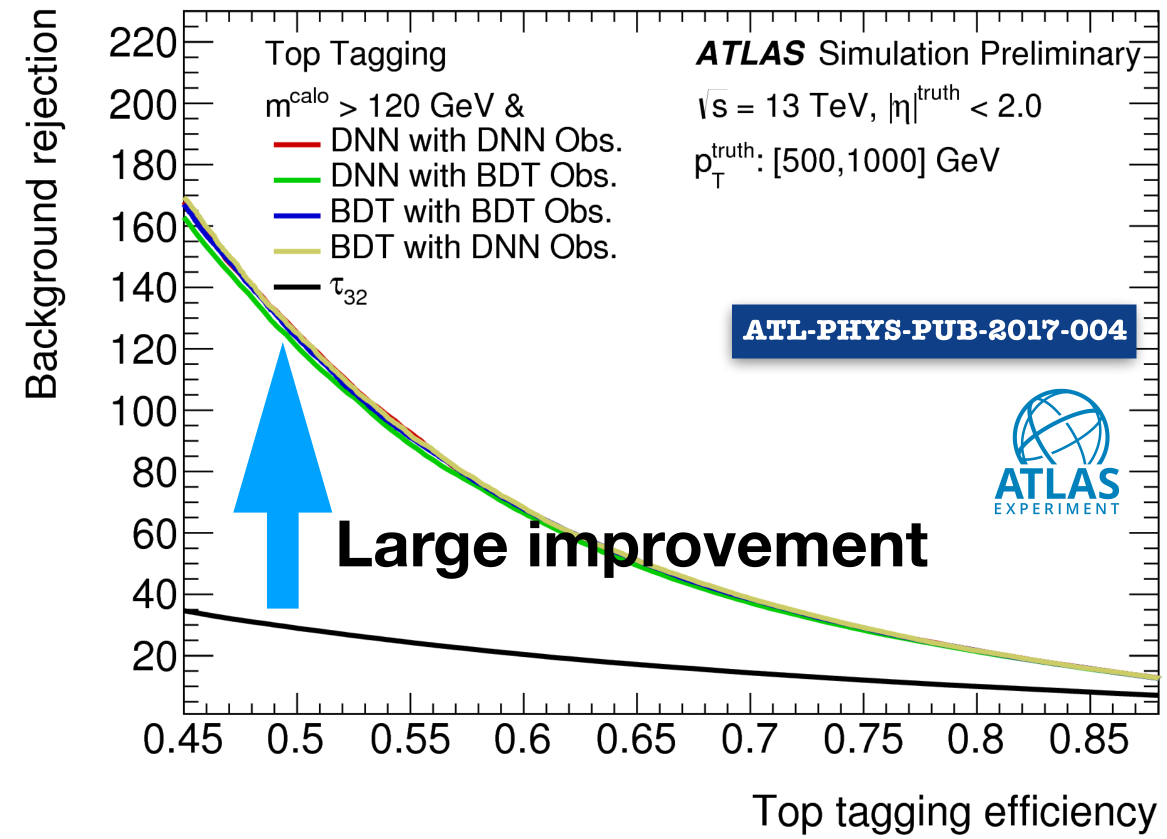

Run: 271516
Event: 7786087
2015-07-13 09:38:38 CEST
ATLAS
EXPERIMENT

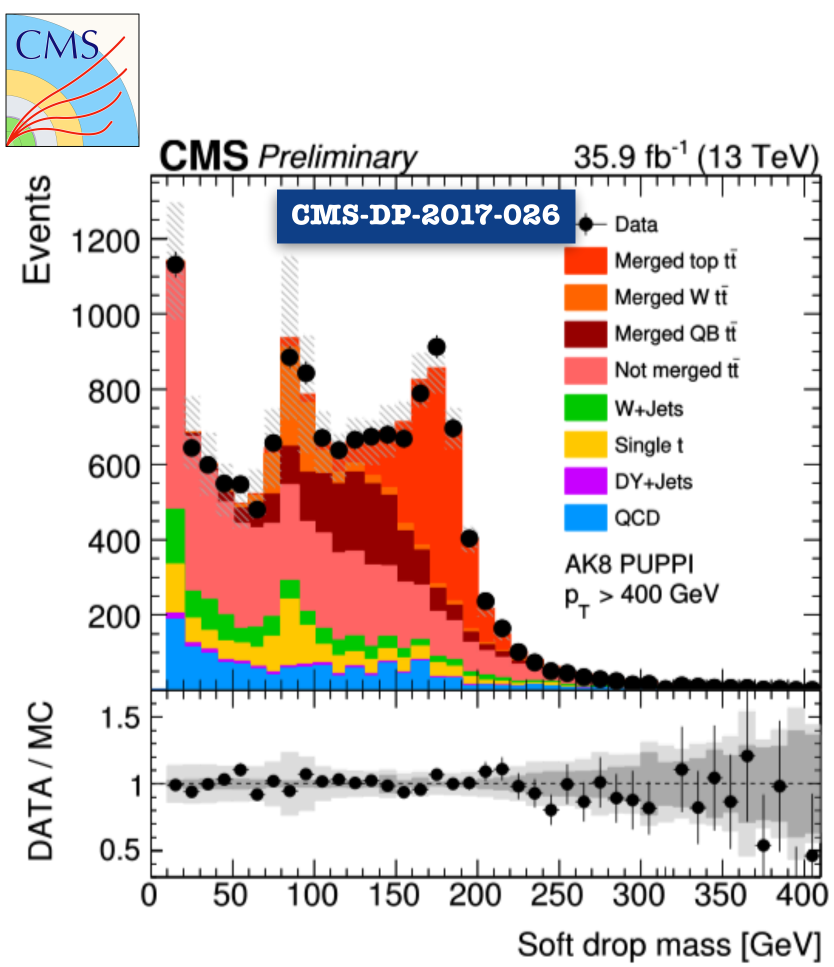
Advanced Experimental Taggers

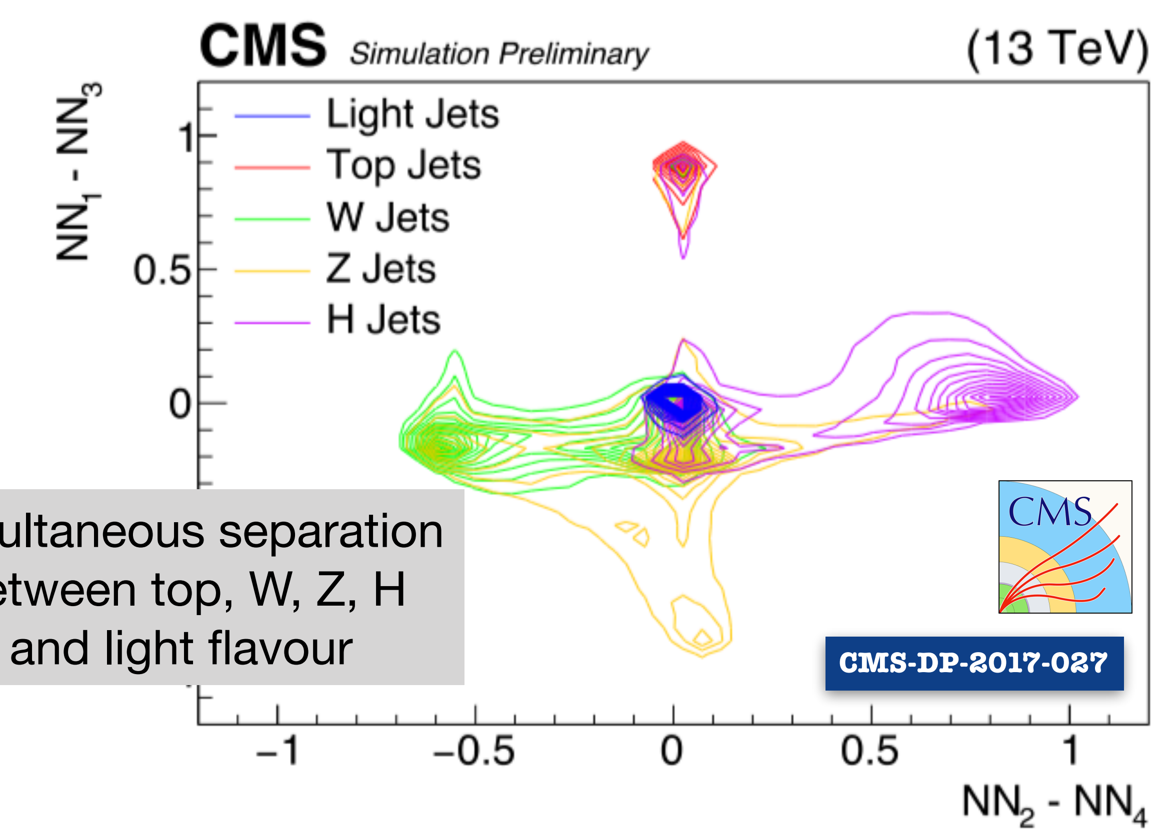
MVA tagger

Use substructure variables to train BDT, DNN classifiers

Observable	Top Tagging Observable Groups 1	2	3	4	5	6	7 (BDT)
ECF_1				∘		∘	∘
ECF_2				∘		∘	
ECF_3				∘		∘	∘
C_2					∘	∘	∘
D_2					∘	∘	∘
τ_1		∘	∘	∘	∘	∘	
τ_2		∘	∘	∘	∘	∘	∘
τ_3		∘	∘	∘	∘	∘	
τ_{21}	∘		∘		∘	∘	∘
τ_{32}	∘		∘		∘	∘	∘
$\sqrt{d_{12}}$	∘	∘	∘	∘	∘	∘	∘
$\sqrt{d_{23}}$	∘	∘	∘	∘	∘	∘	∘
Q_w	∘	∘	∘	∘	∘	∘	∘

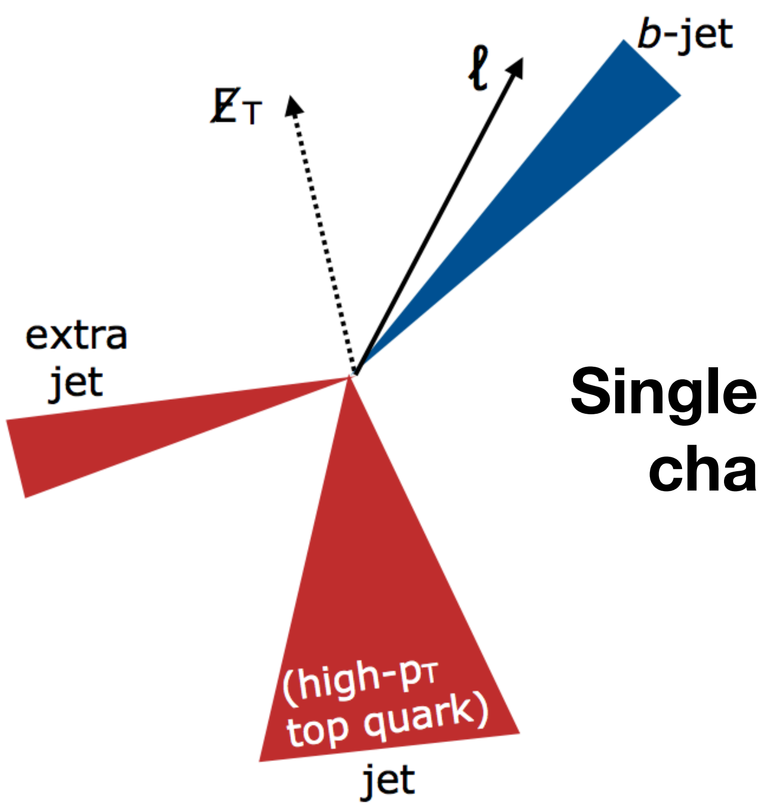




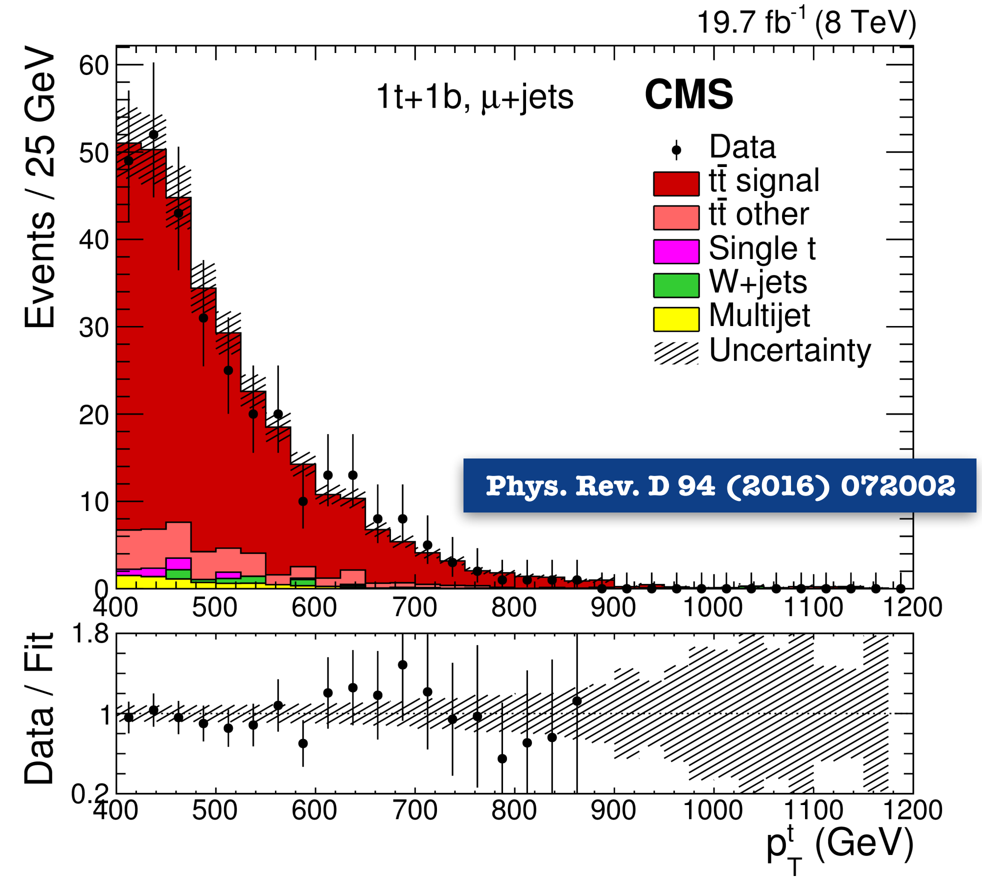


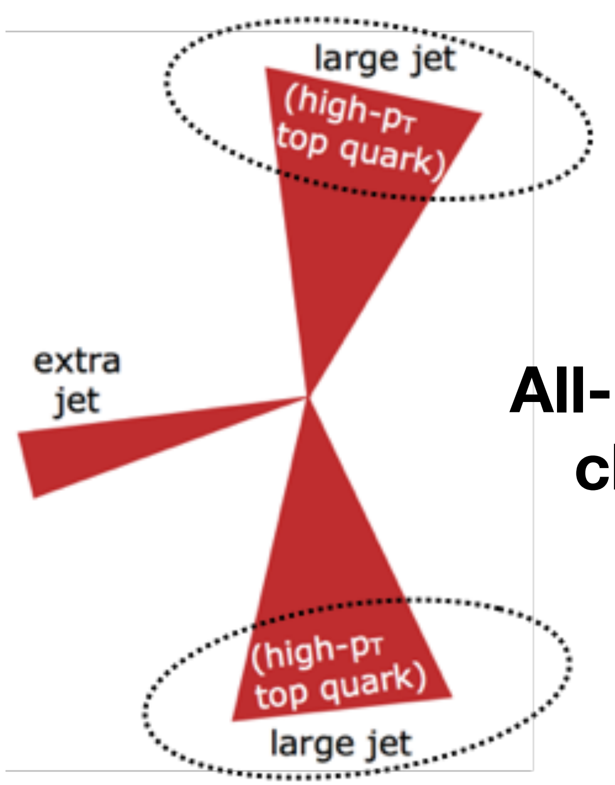
Simultaneous separation between top, W, Z, H and light flavour

Differential Cross-sections

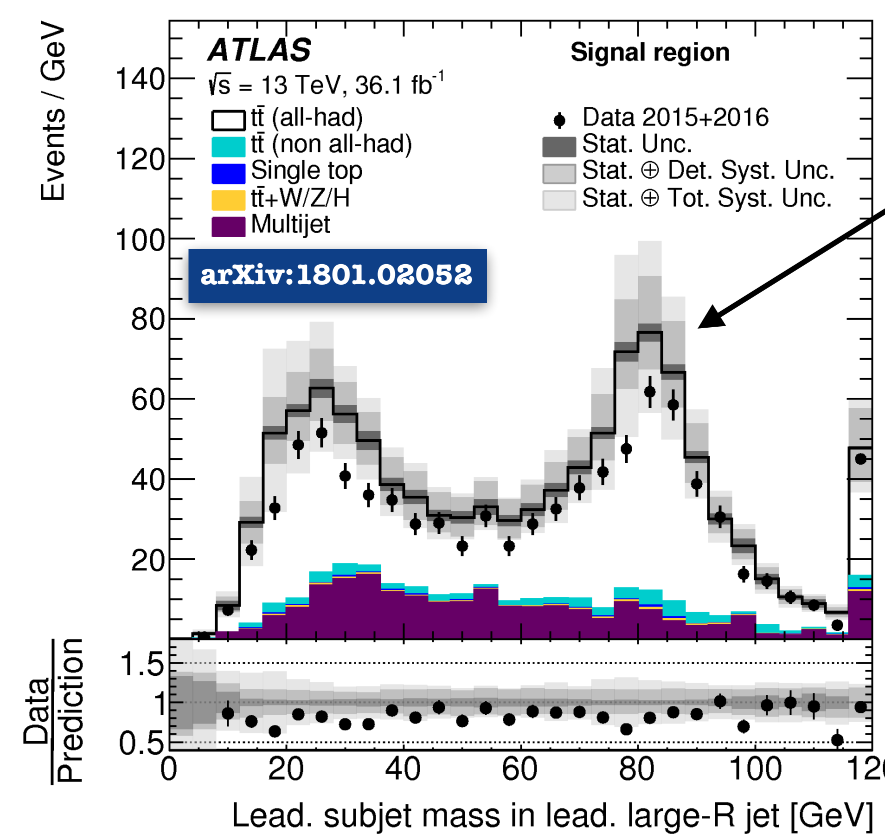


Single lepton channel

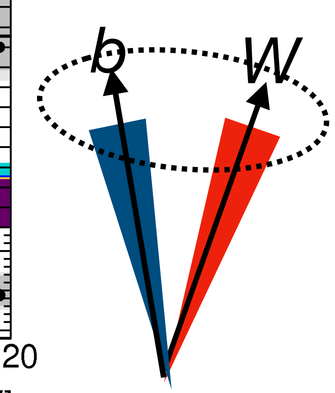




All-hadronic channel



Boosted *W* mass peak inside large-*R* jet



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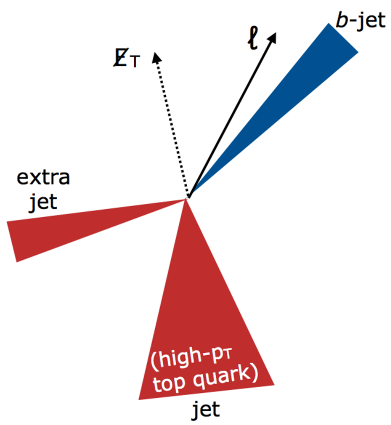
Top transverse momentum

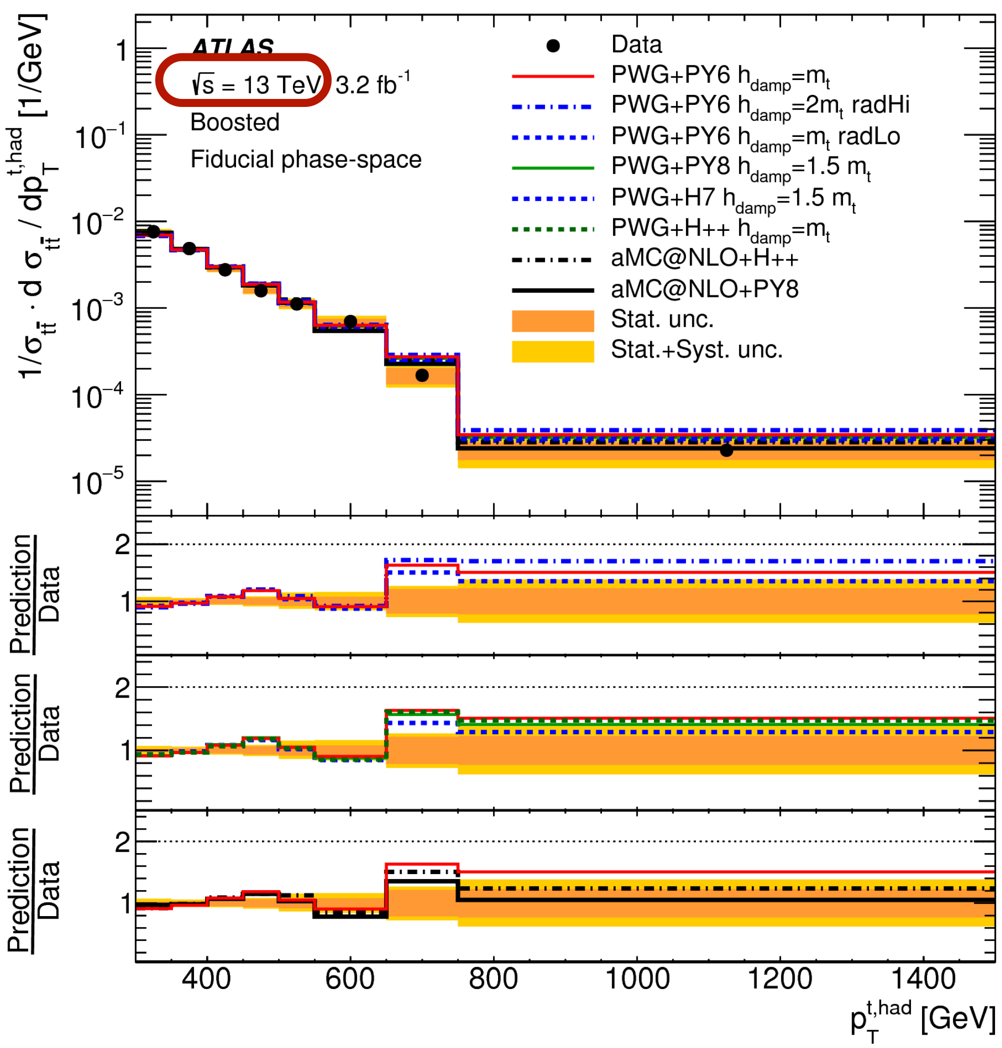


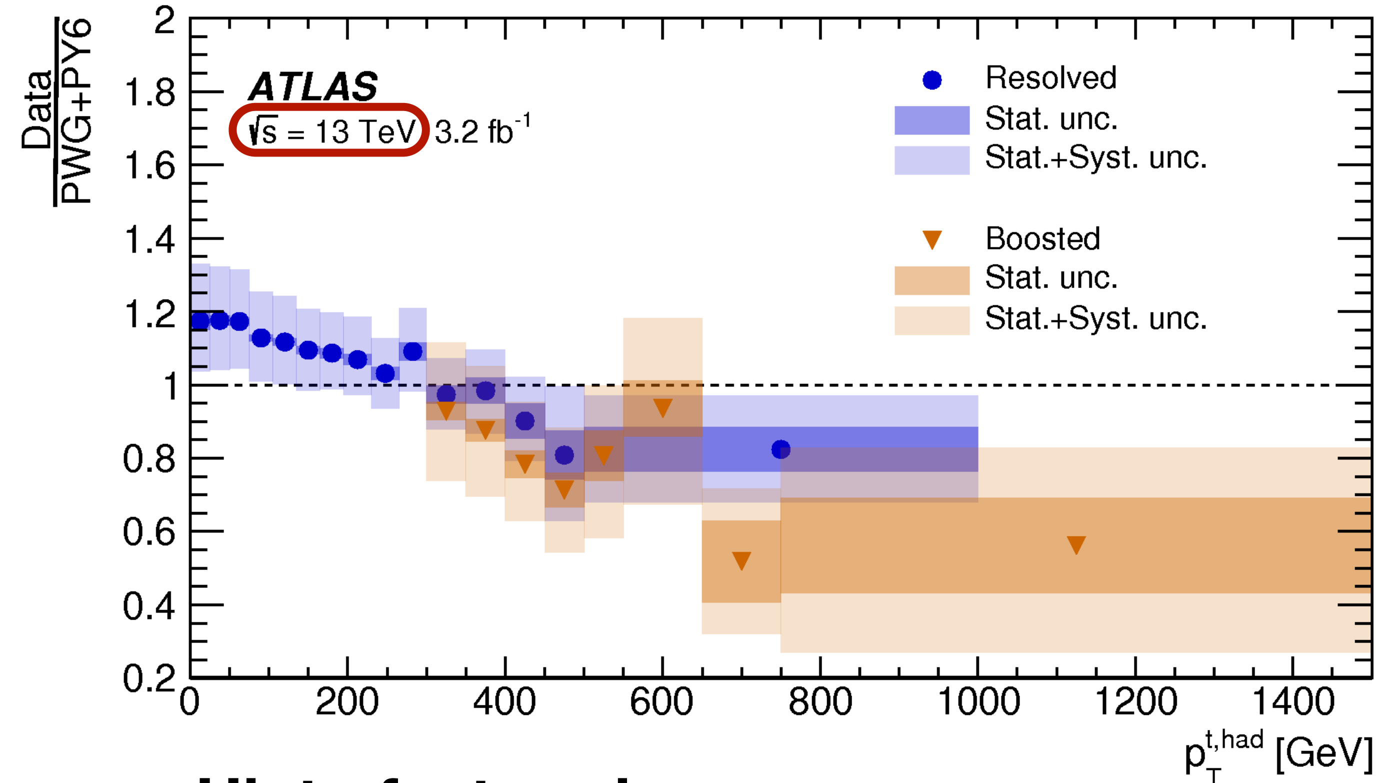
Single lepton

Hadronic top = large-R jet

Background determined using (mostly) MC simulations

High stats, syst dominated by signal modelling, large-R jet tagging and energy scale



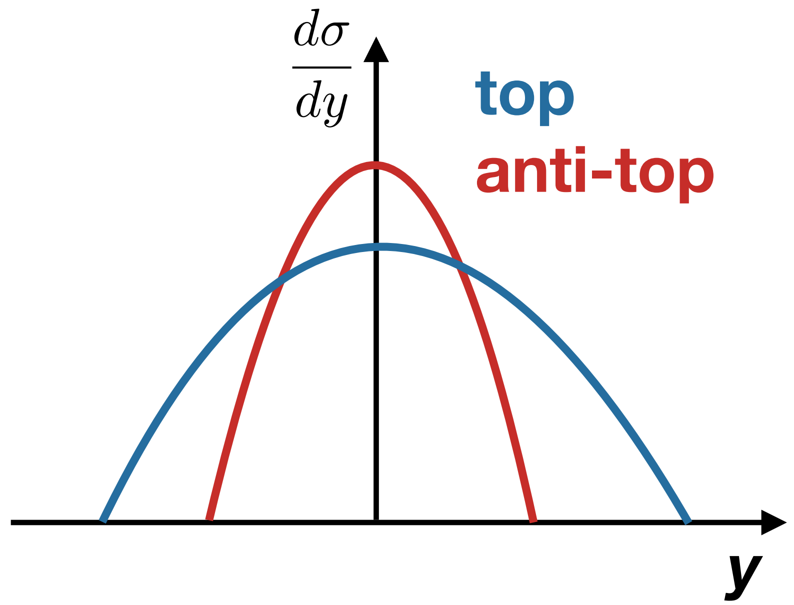


Hint of a trend:

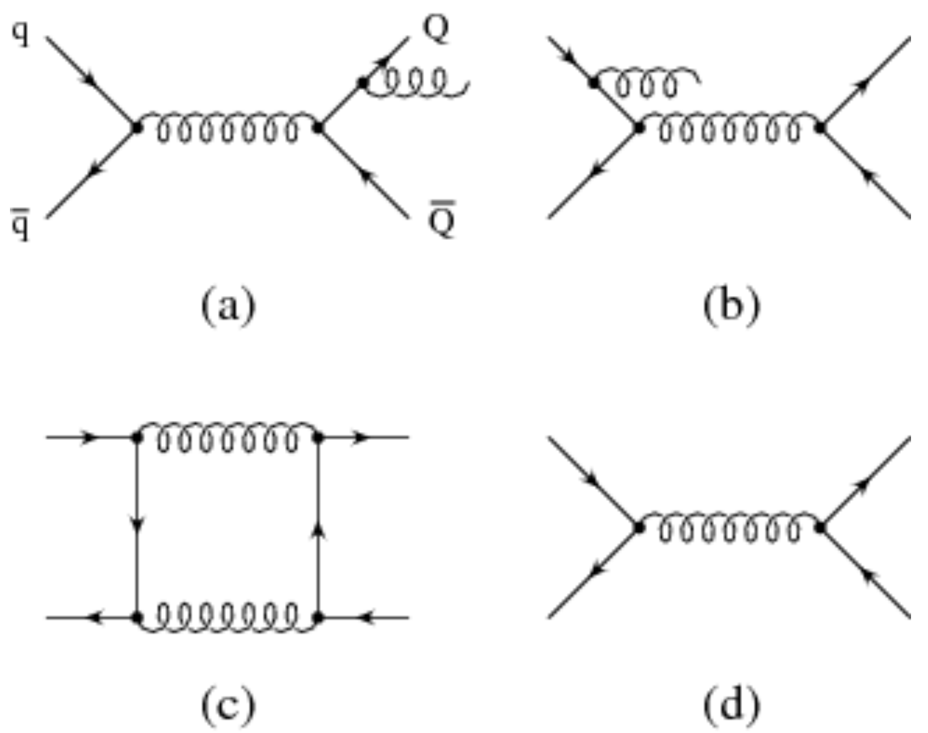
Top p_T softer than predicted at NLO

Higher-order QCD and EW corrections important at high-p_T

Charge Asymmetry



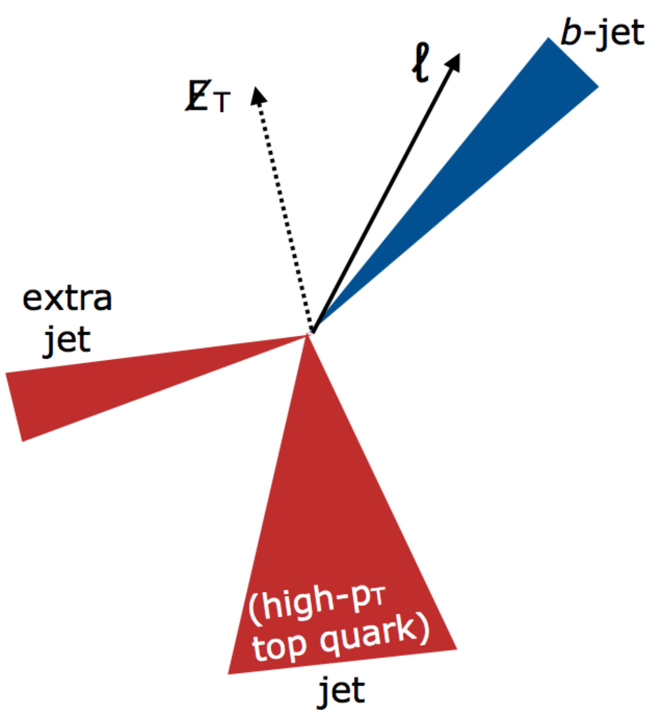
Top and anti-top production
Has different probability
As a function of rapidity

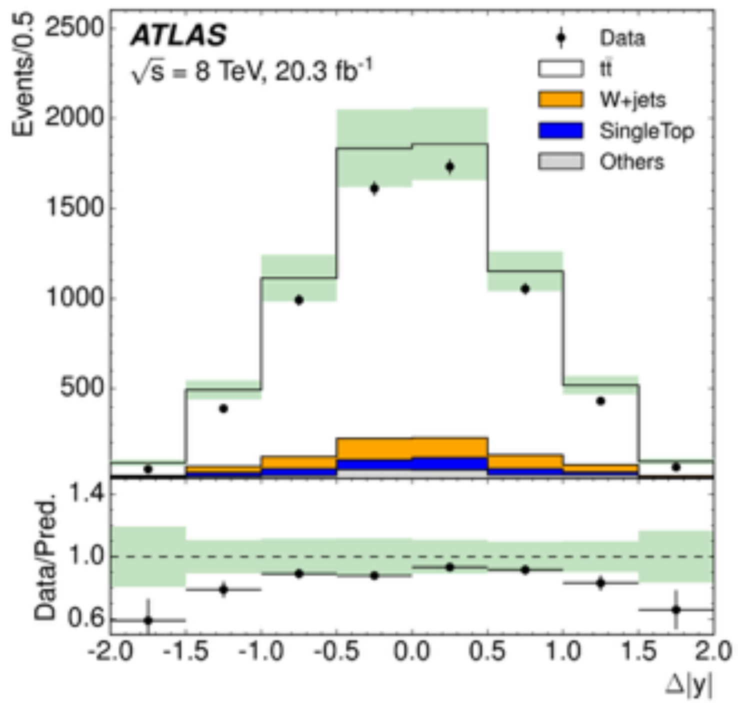


Small asymmetry predicted by
The Standard Model due to
Interference among LO and NLO $q\bar{q}$ diagrams

$$A_C = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0}$$

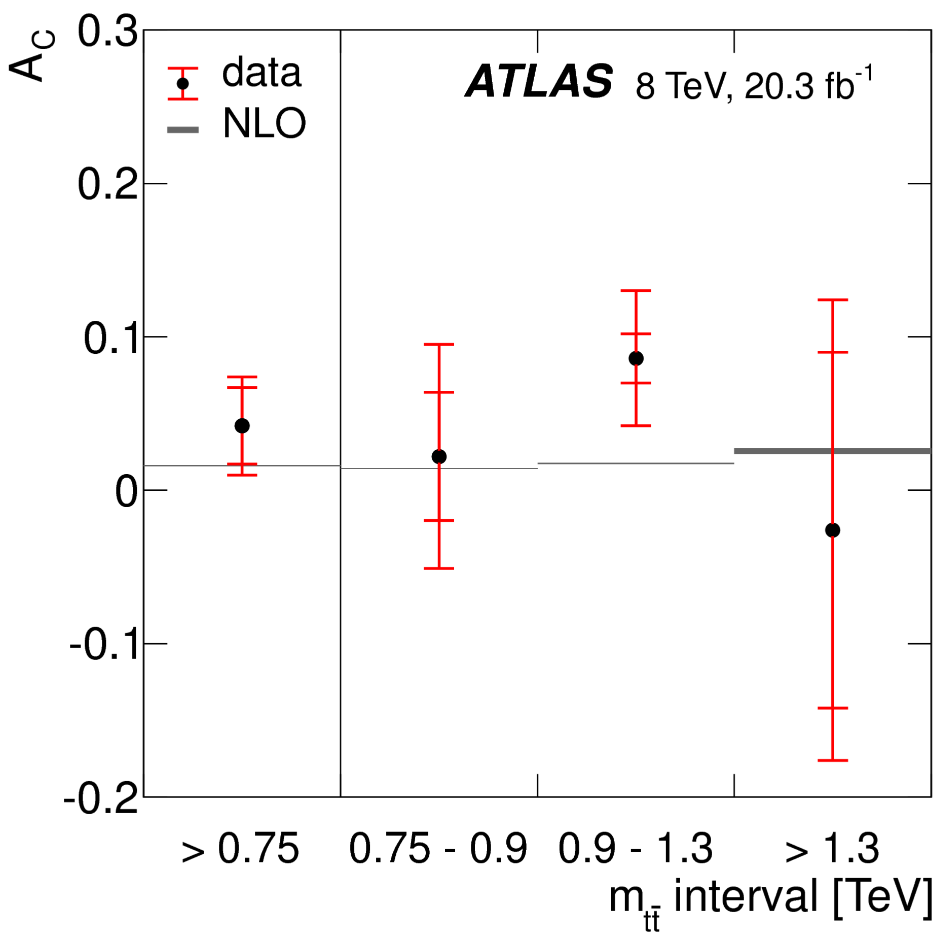
Charge Asymmetry





Event selected with
m^{tt} > 750 GeV
-2 < Δ|y| < 2

$$A_C = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$



Analysis limited by statistics and signal modelling systematics