Recent results with boosted top

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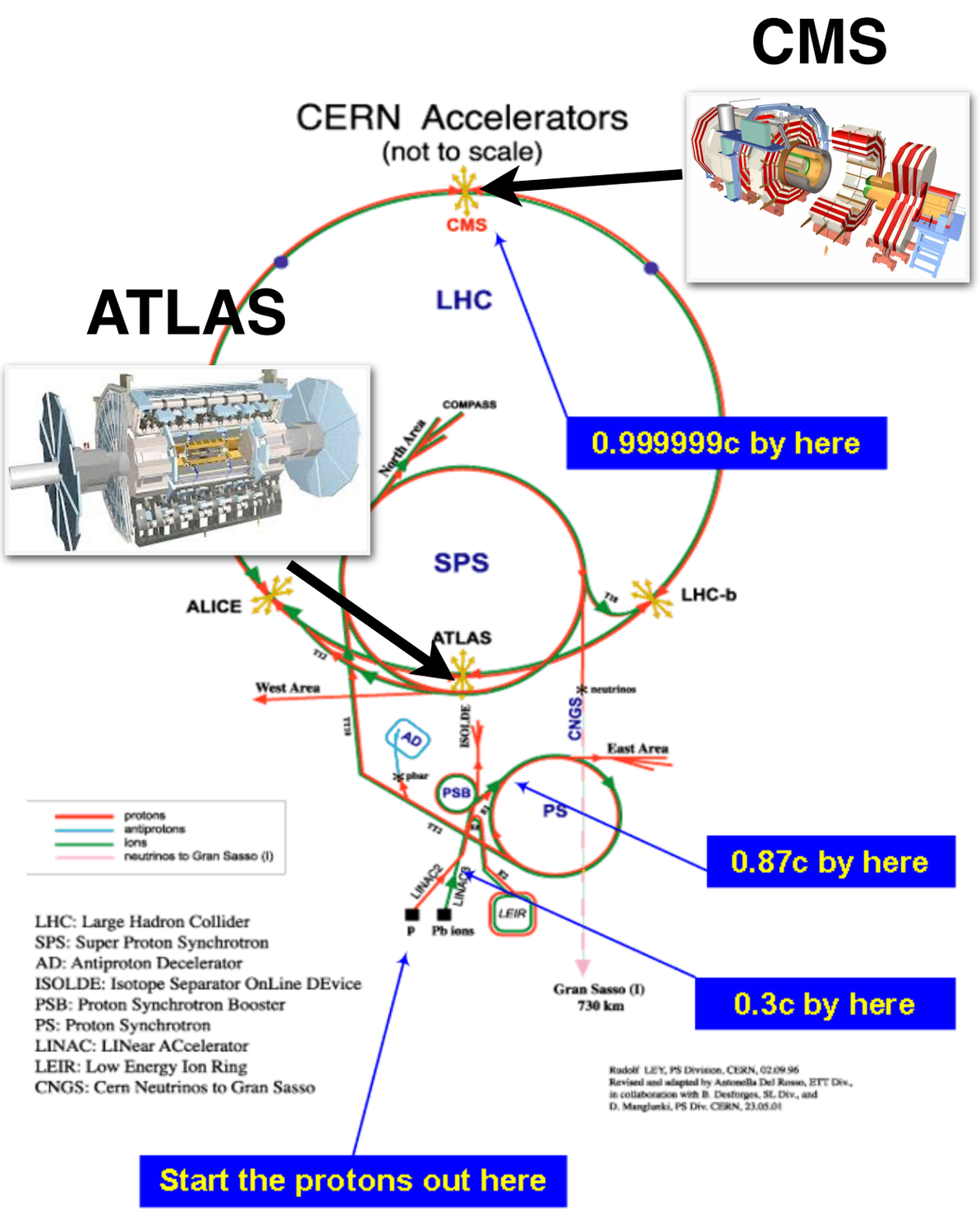
On behalf of the ATLAS and CMS collaborations

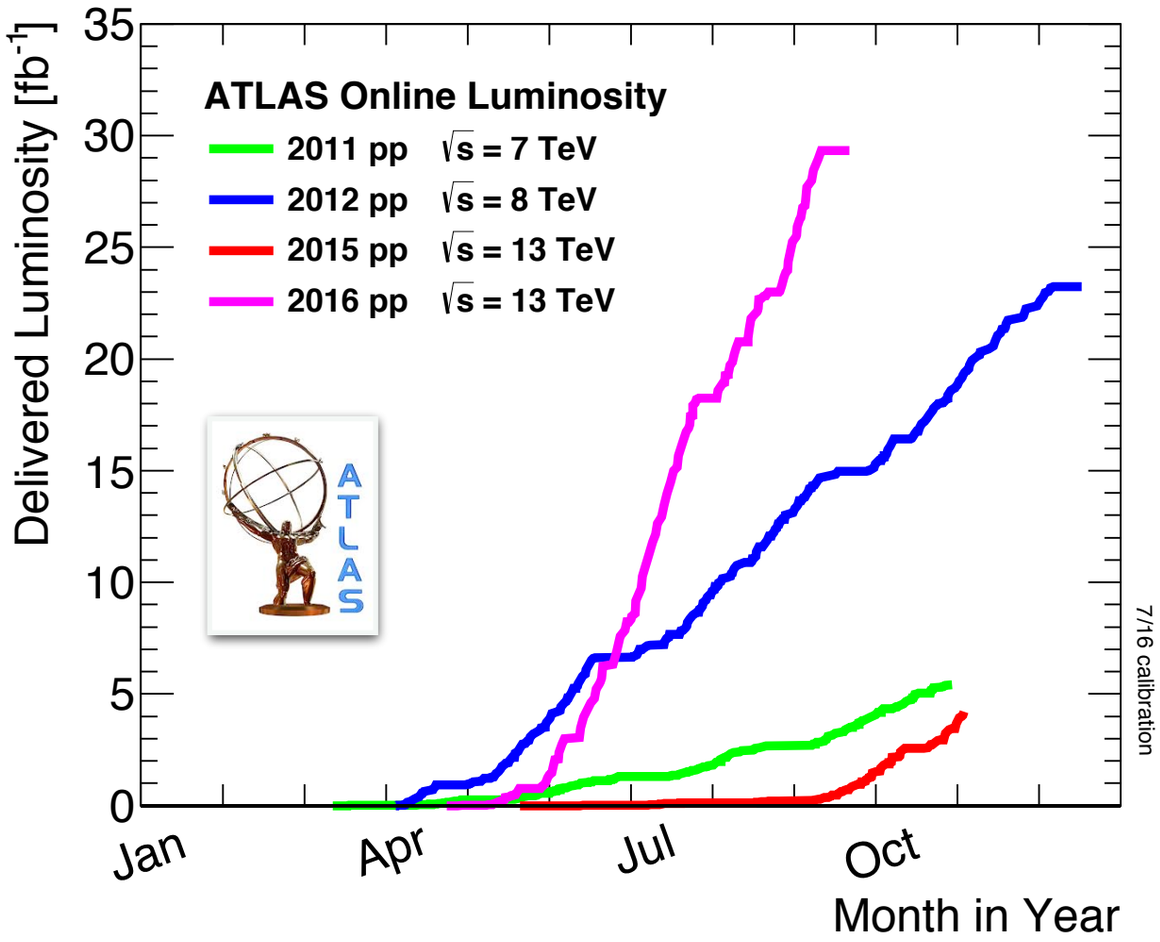
OLOMOUC, CZECH REPUBLIC
9th International Workshop on Top Quark Physics
19 - 23 September 2016

Outline

- motivation & challenges
- measurements with boosted top quarks
  - differential cross sections for top pair production @ 8 & 13 TeV
  - top properties
- searches with boosted top quarks
  - new heavy particles decaying to top pairs

Large Hadron Collider

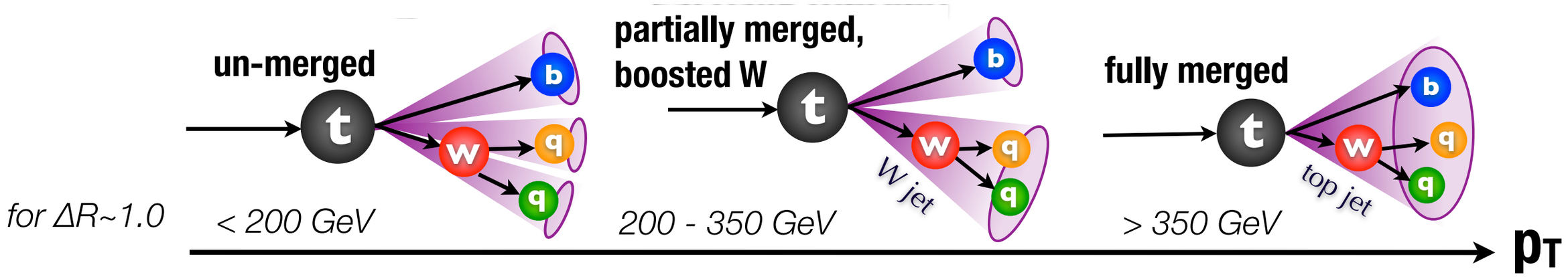




- **superb LHC performance**
  - large dataset at 8 TeV in Run I
  - Run II started very promising (2015)
  - ***2016 dataset beyond expectations!***

Why boosted tops?

- **LHC is a top factory**
  - high centre-of-mass energy combined with large datasets
  - access to previously unaccessible corners of phase space
  - differential measurements are feasible
    - confront the theory predictions and constrain fundamental QCD parameters
- **new physics may manifest in final states with high p_T (boosted) top quarks**
- **challenge: reconstruction of boosted top quarks**
  - appear as a large-radius jet
  - rule of thumb: $p_T \sim 2M/R$



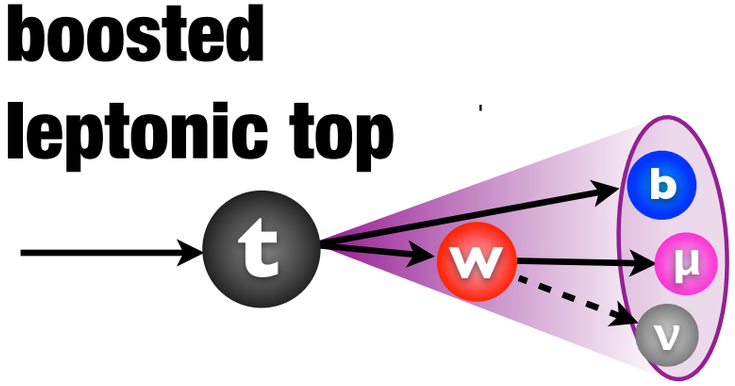
Challenges

- **discriminate boosted tops from ordinary QCD jets**
  - reconstruct large-radius jets (anti-k_T or Cambridge-Aachen algorithms)
  - exploit substructure properties
  - established techniques and new ideas (area of active development !)

- **mitigate pileup contamination**
  - grooming methods to remove irrelevant soft particles
  - reject tracks/particles from pileup vertices

- **identify leptons within the boosted top**
  - non-isolated leptons in leptonic decays

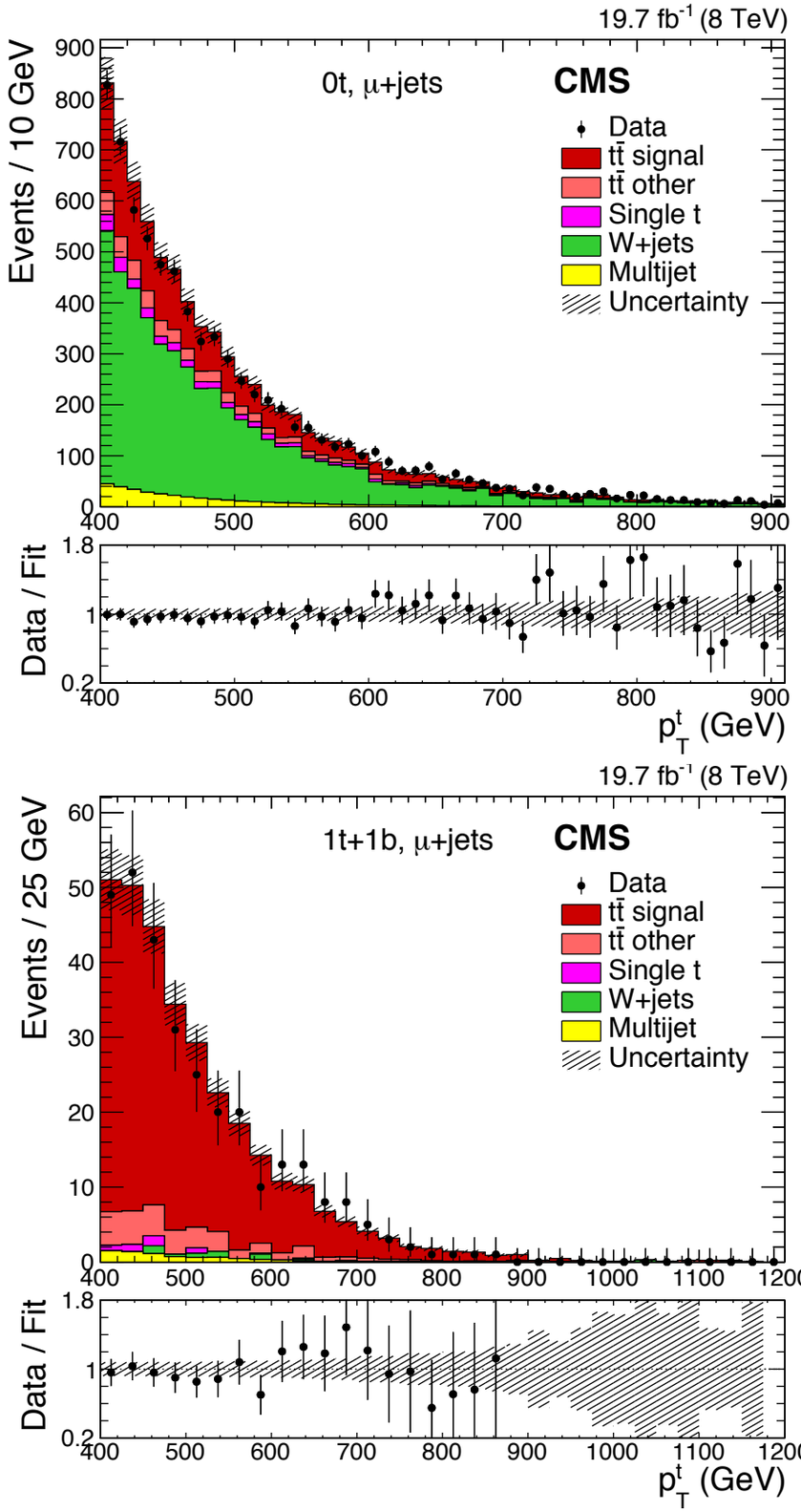
- **tag b-jets within the boosted top**
  - subjet b tagging with dedicated algorithms



details in J. Caudron's talk
"Boosted top: new algorithms and perspectives"

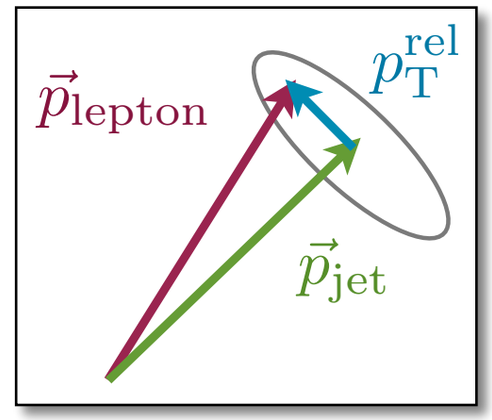
Precision measurements

Pair production of top quarks @ 8 TeV



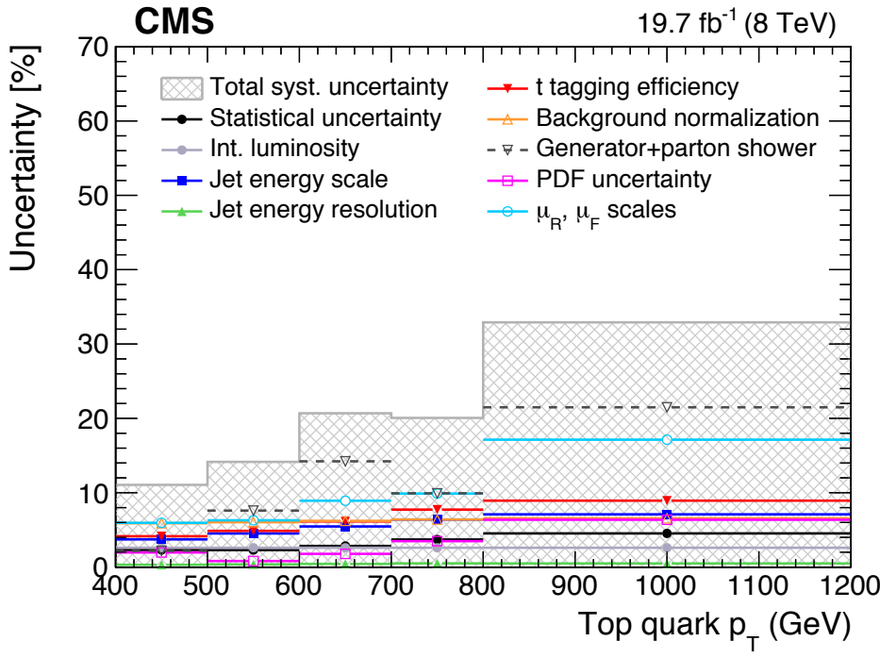
- **CMS measurement @ 8 TeV**
  - semileptonic decay
    - leptonic top triggers the event
  - inclusive & differential vs hadronic top kinematic variables (p_T, y)
    - for top $p_T > 400$ GeV
    - detector, particle, & parton level

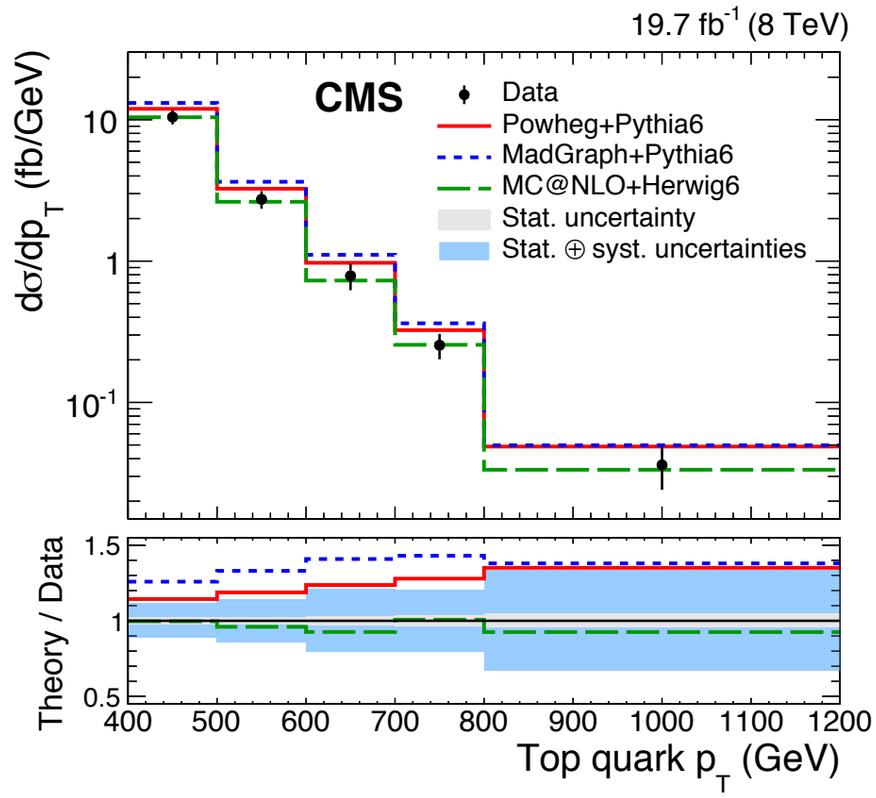
- **reconstruction**
  - small-R jets (AK5)
  - large-R jets (CA8)
  - leptons (μ, e)
    - $p_T > 45$ (μ), 35 (e) GeV
    - ΔR(l, small-R jet) > 0.5 II $p_T^{rel} > 25$ GeV
  - top tagging: *CMS top tagger*



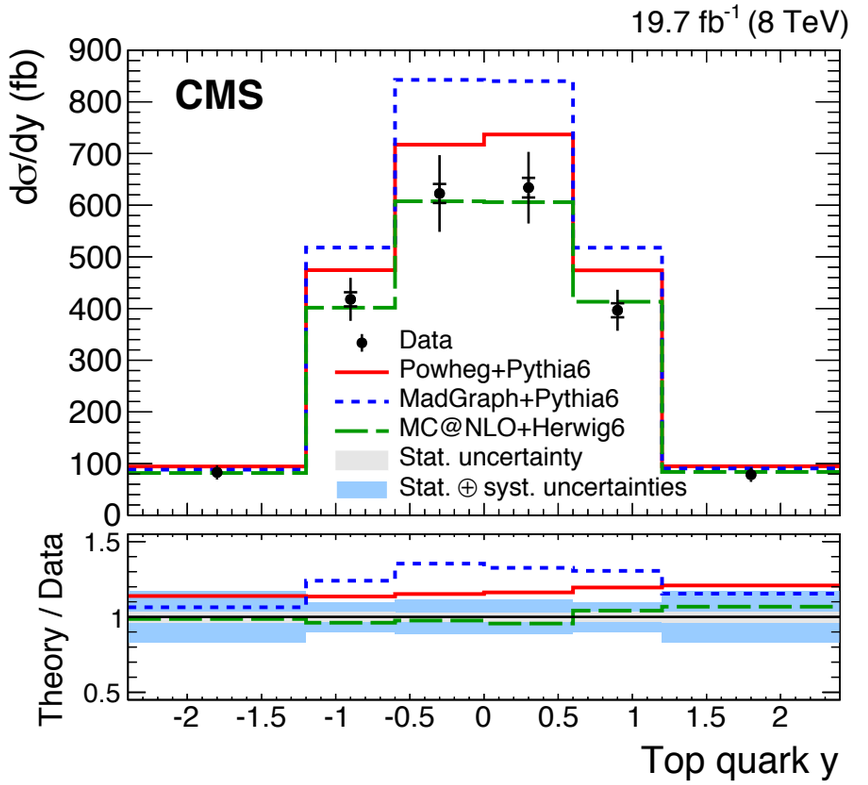
arXiv:1605.00116
(accepted by PRD)

Pair production of top quarks @ 8 TeV





- **signal extraction**
  - maximum likelihood fit in 3 categories based on top and b tags
- **unfolding to particle & parton level**
  - separately in electron and muon channels
  - SVD in RooUnfold
- **results**
  - integrated cross section overestimated by ~14%, but consistent within uncertainties
  - significant differences between MC models in the description of the differential cross section

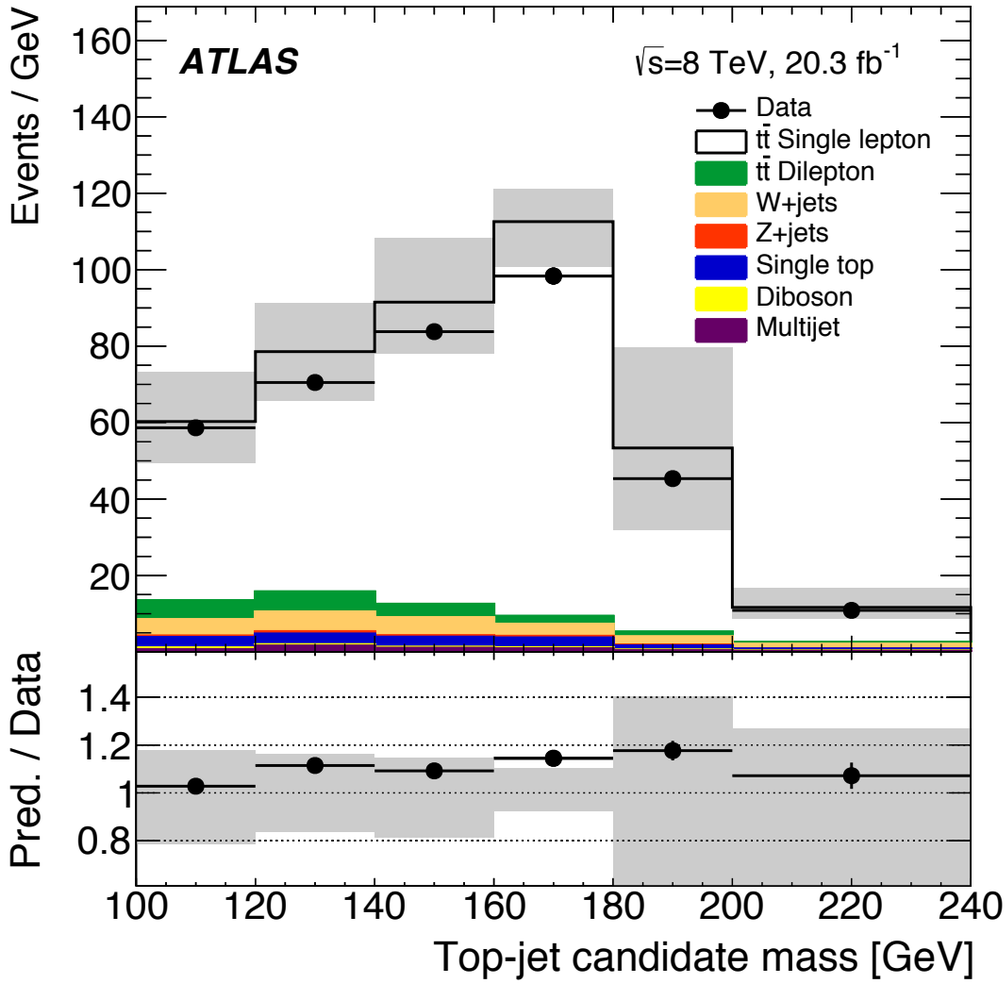


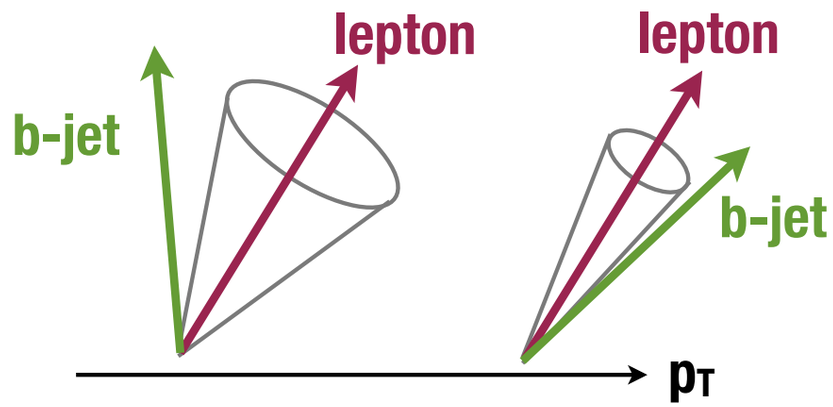
Pair production of top quarks @ 8 TeV

- **ATLAS measurement @ 8 TeV**
  - semileptonic decay
    - leptonic top triggers the event
  - differential vs hadronic top p_T
    - for top $p_T > 300$ GeV
    - detector, particle, & parton level

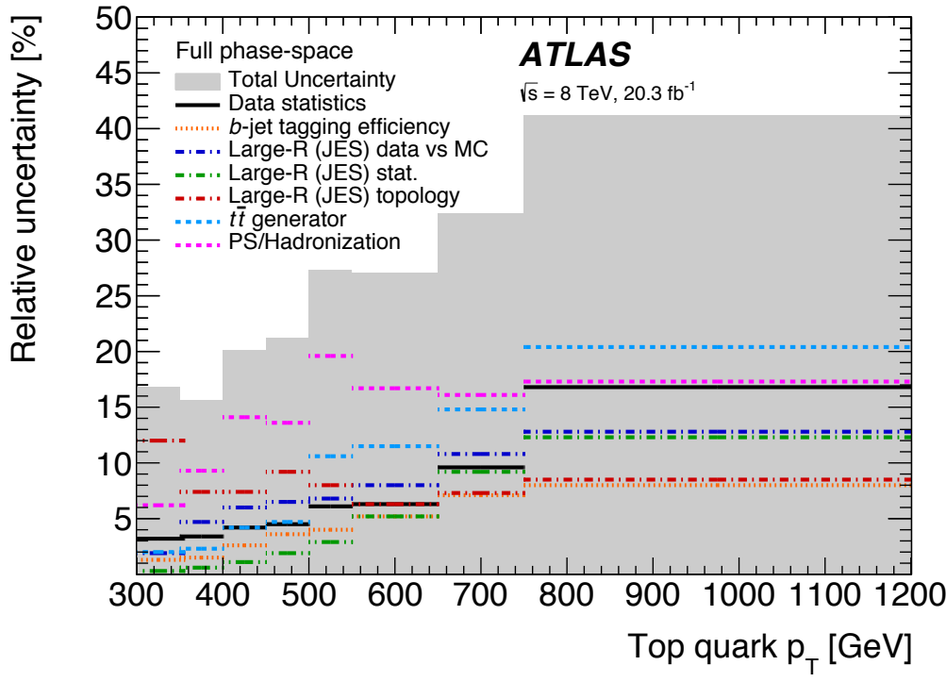
- **reconstruction**
  - small-R jets (AK4)
  - large-R jets (AK10)
    - trimming ($R_{sub} = 0.3$ & $f_{cut} = 0.05$)
  - leptons (μ, e)
    - $p_T > 25$ GeV
    - mini-isolation
  - top tagging: k_t splitting scale & jet mass

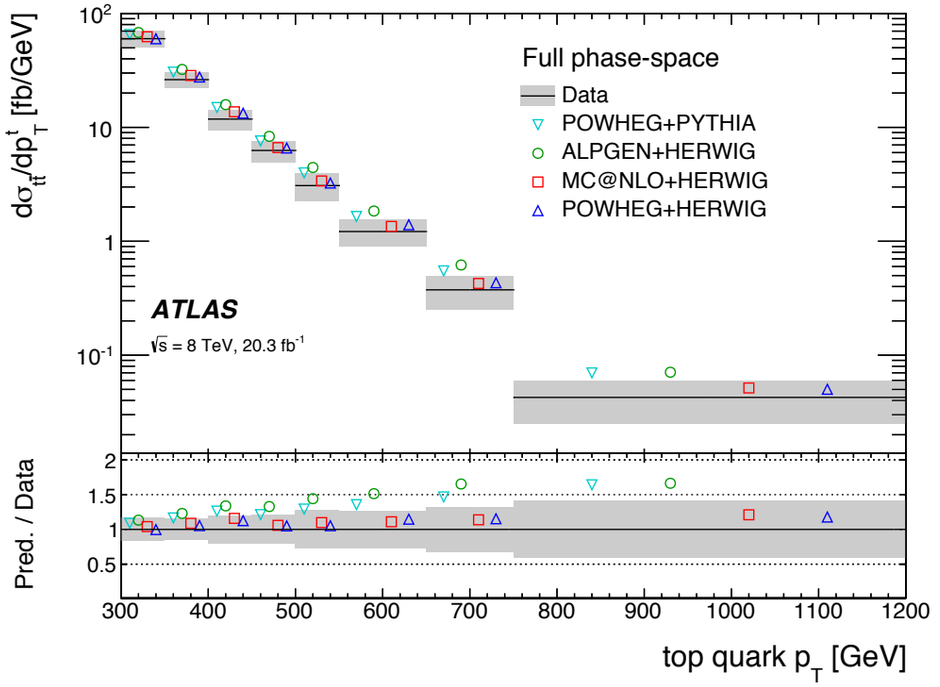
PRD 93 (2016) 032009



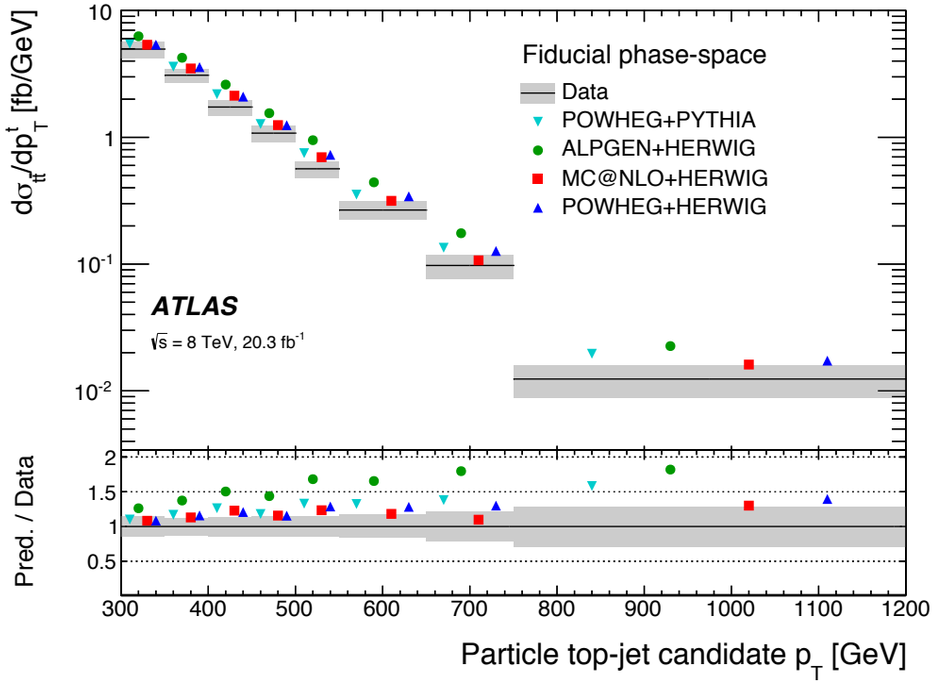


Pair production of top quarks @ 8 TeV





- **signal extraction**
  - background estimated with data-driven methods
- **unfolding to particle & parton level**
  - electron and muon channels combined at detector level, before unfolding
  - SVD
- **results**
  - all generators predict a harder top p_T spectrum
    - difference increases with top p_T
  - predictions are consistent with data within the uncertainties (correlated vs top p_T)



Differential cross section vs top mass @ 8 TeV

- **CMS measurement @ 8 TeV**
  - semileptonic decay
  - differential vs hadronic top mass
    - unfolded to parton level
  - normalized cross section used to check the sensitivity to the top mass (feasibility study)

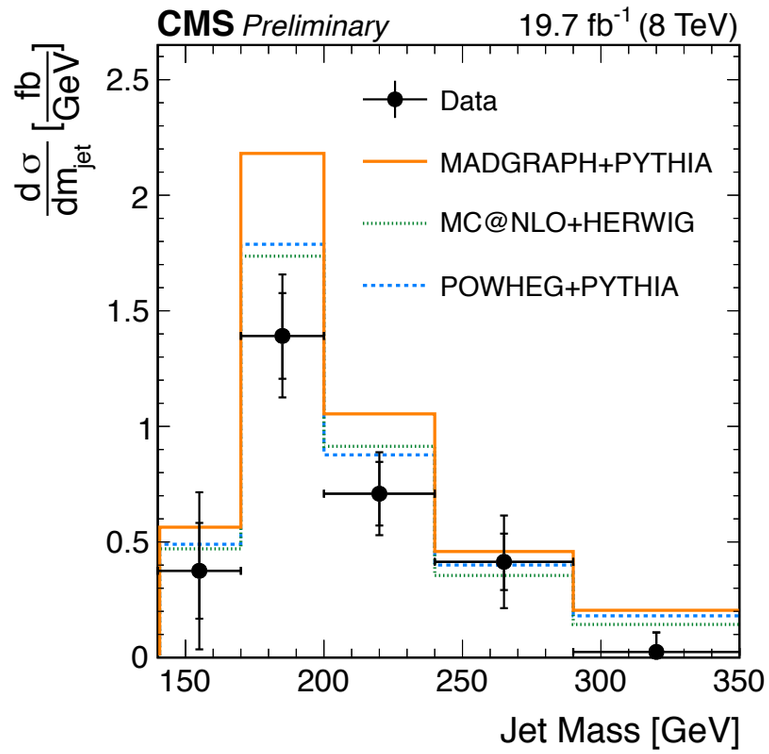
theory

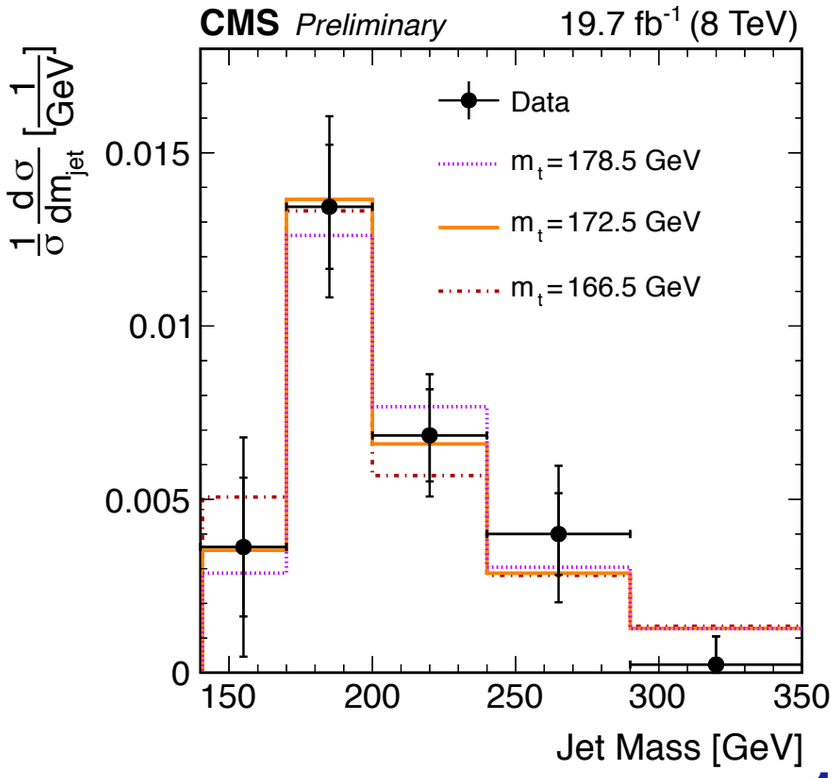
$m_t = 171.8 \pm 5.4 \pm 3.0 \pm 5.5 \pm 4.6$ GeV

stat syst model

- **reconstruction**
  - small-R jets (AK5)
  - large-R jets (CA12)
  - leptons (μ, e)
    - $p_T > 45$ GeV
    - $\Delta R(l, \text{small-R jet}) > 0.5$ II $p_T^{rel} > 25$ GeV

CMS-PAS-TOP-15-015

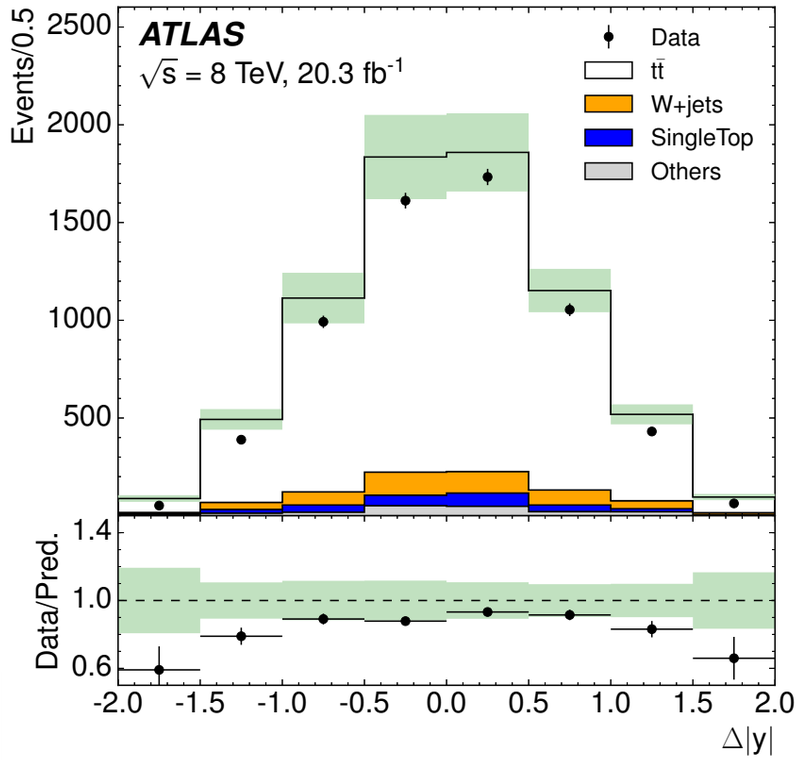




Charge asymmetry @ 8 TeV

PLB 756 (2016) 52

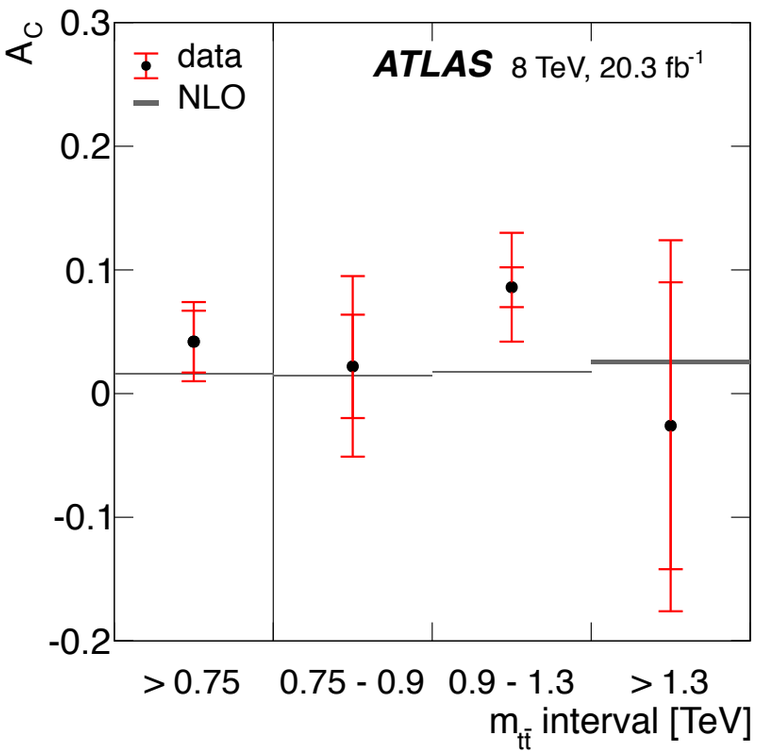
- **ATLAS measurement @ 8 TeV**
  - charge asymmetry caused by momentum differences (valence vs sea) in quark-antiquark initial states
    - largely diluted by gluonic initial states
    - SM prediction ~1% but sensitive to new physics
  - semileptonic decay
  - distribution of $\Delta|y| = |y_{top}| - |y_{antitop}|$
    - unfolded to parton level



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

- **reconstruction**
  - small-R jets (AK4)
  - large-R jets (AK10)
    - trimming ($R_{sub} = 0.3$ & $f_{cut} = 0.05$)
  - leptons (μ, e)
    - mini-isolation
    - leptonic top from lepton + MET
  - top tagging: k_t splitting scale & jet mass

details in M. Naseri's talk
"Asymmetry measurements in ttbar"

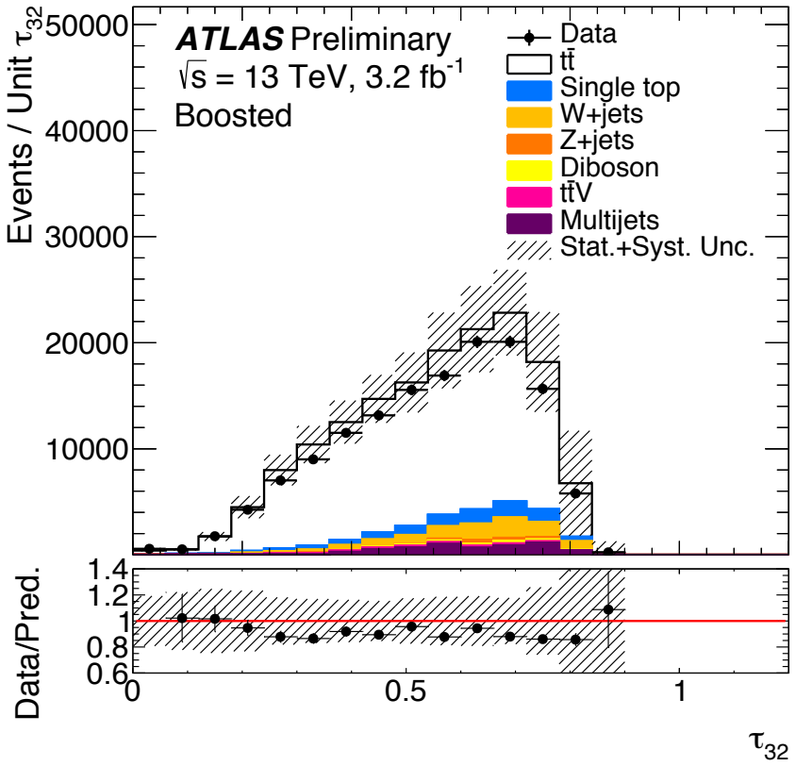


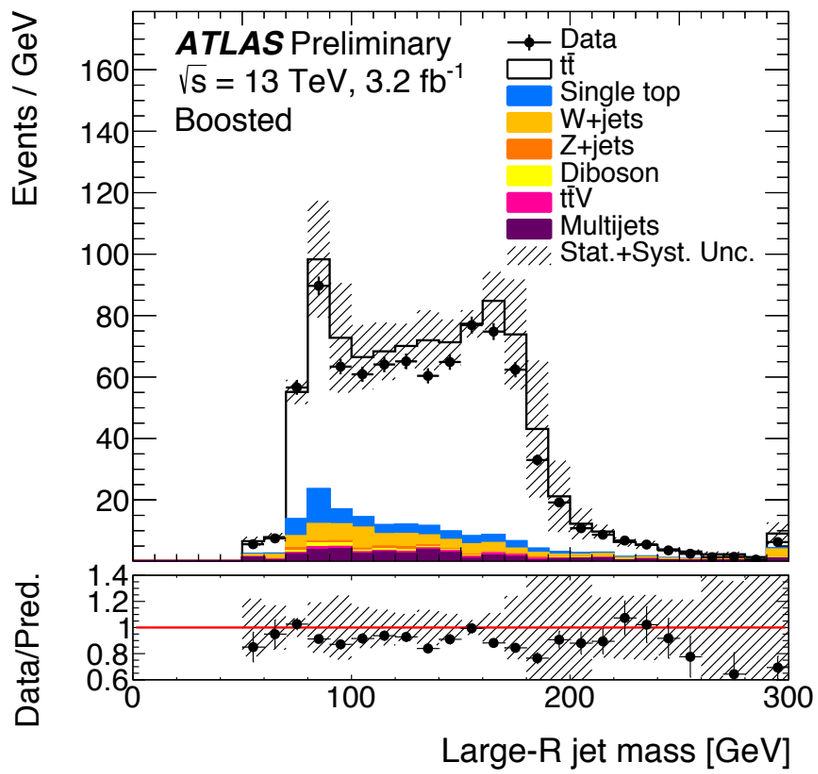
Pair production of top quarks @ 13 TeV

- **ATLAS measurement @ 13 TeV**
  - semileptonic decay
    - leptonic top triggers the event
  - differential vs hadronic top kinematic variables (p_T, y) and ttbar system
    - for top $p_T > 300$ GeV
    - particle level

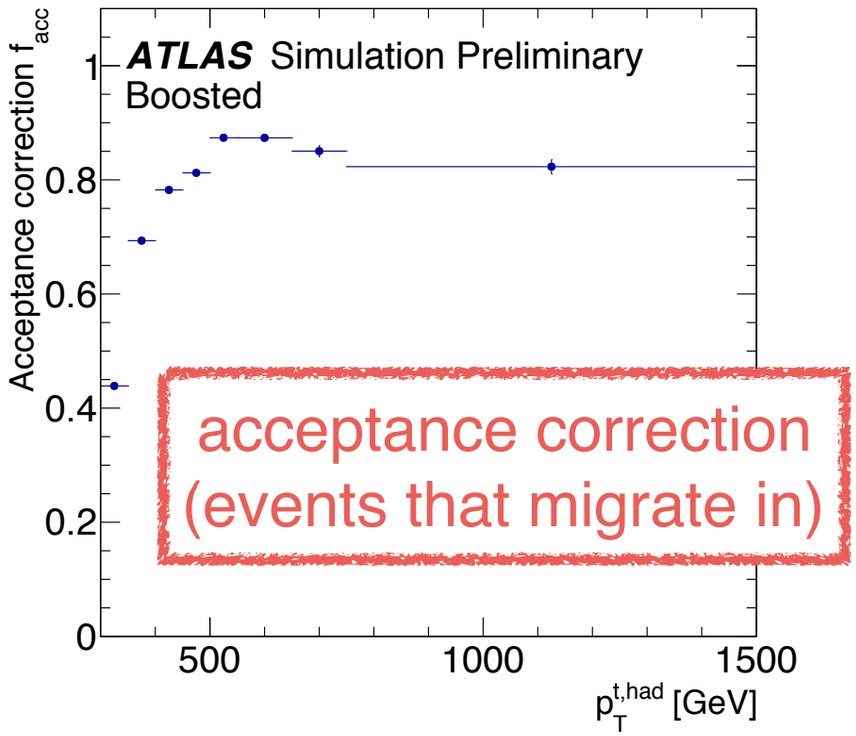
- **reconstruction**
  - small-R jets (AK4)
  - large-R jets (AK10)
    - trimming ($R_{sub} = 0.3$ & $f_{cut} = 0.05$)
  - leptons (μ, e)
    - $p_T > 25$ GeV
    - mini-isolation
  - top tagging: N-subjettiness ratio τ_{32} + hard subjets + mass compatible with a top quark
  - resolved & boosted selections (non exclusive)

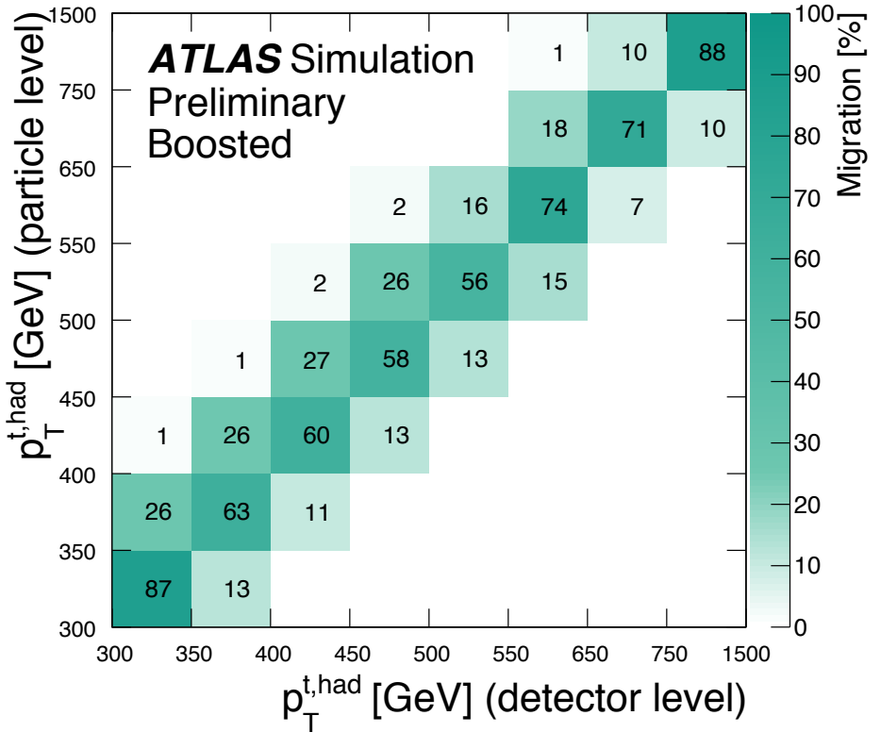
ATLAS-CONF-2016-040

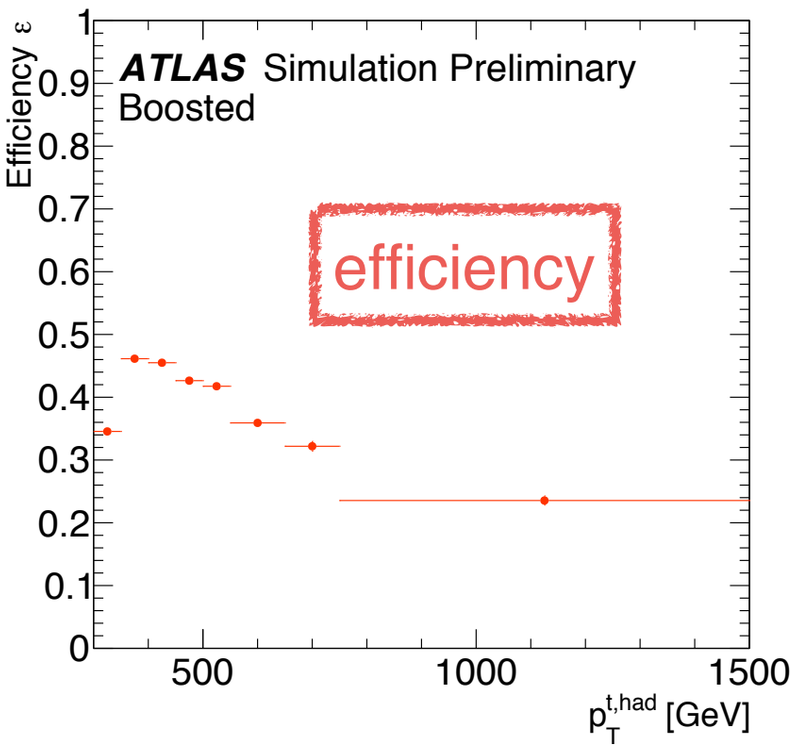




Pair production of top quarks @ 13 TeV



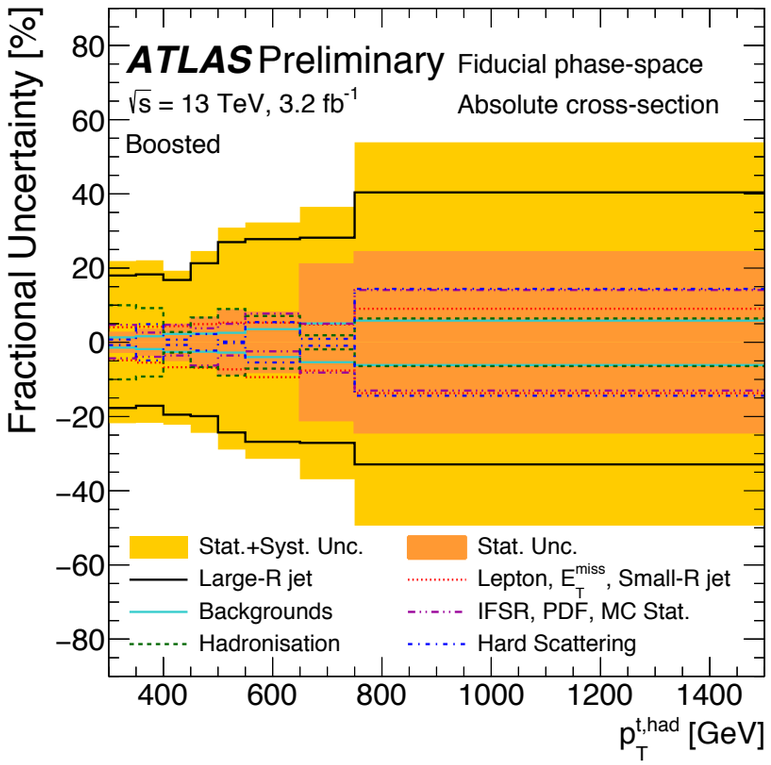


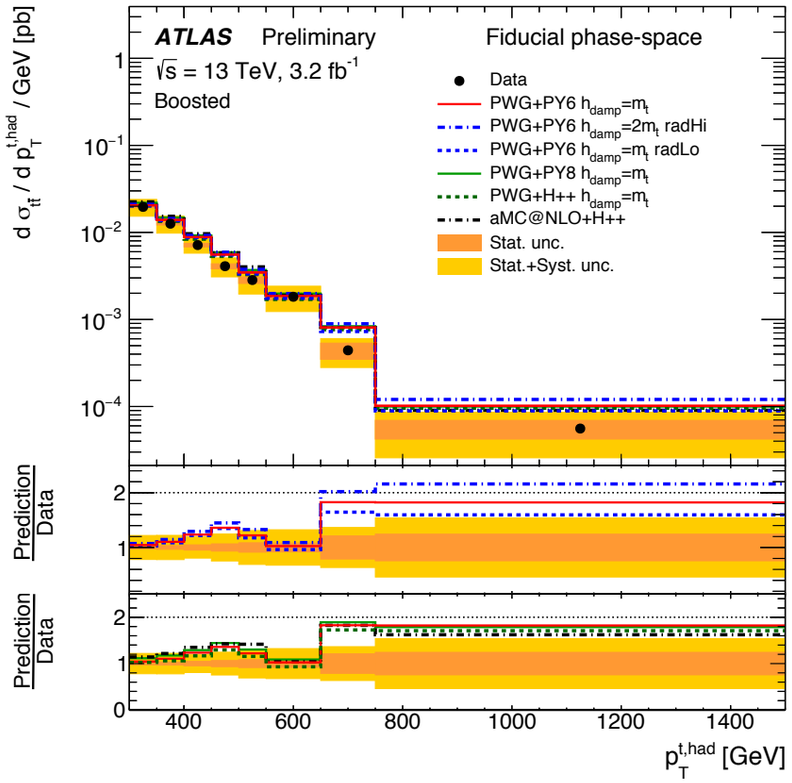


$$\frac{\mathrm{d}\sigma^{\mathrm{fid}}}{\mathrm{d}X^i} \equiv \frac{1}{\mathcal{L}\cdot\Delta X^i}\cdot\frac{1}{\epsilon^i}\cdot\sum_j \mathcal{M}_{ij}^{-1}\cdot f_{\mathrm{match}}^j\cdot f_{\mathrm{acc}}^j\cdot\left(N_{\mathrm{reco}}^j - N_{\mathrm{bg}}^j\right)$$

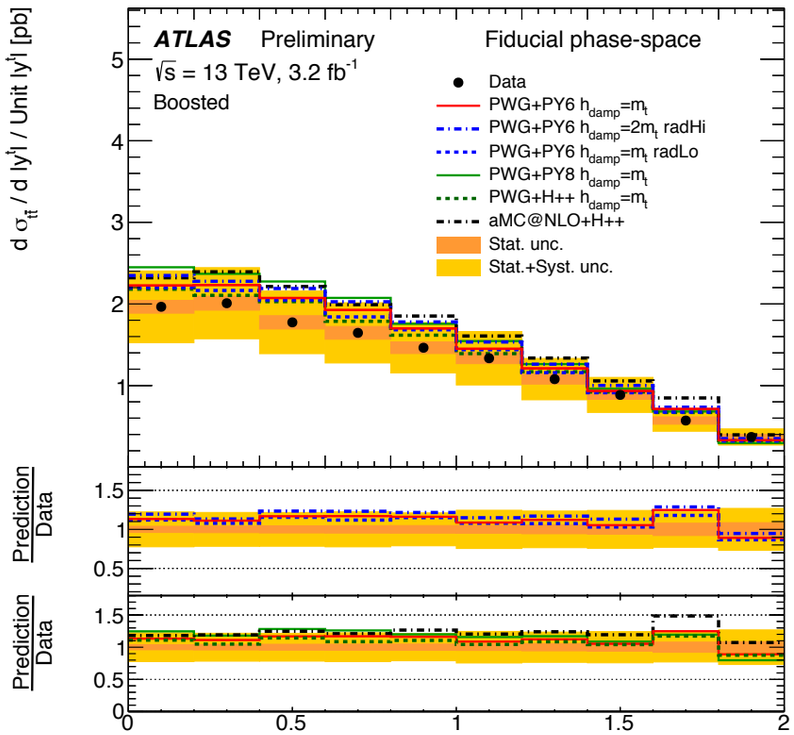
- **signal extraction**
  - background estimated with data-driven methods
- **unfolding to particle level**
  - electron and muon channels combined at detector level, before unfolding
  - d' Agostini iterative method

Pair production of top quarks @ 13 TeV





- **results**
  - no MC generator can describe all distributions
    - resolved and boosted selections alike
  - most significant tension in the top pT
    - cannot be accounted for by EWK corrections
    - NLO+PS models predict a harder spectrum
    - the agreement improves with NNLO calculations at parton level

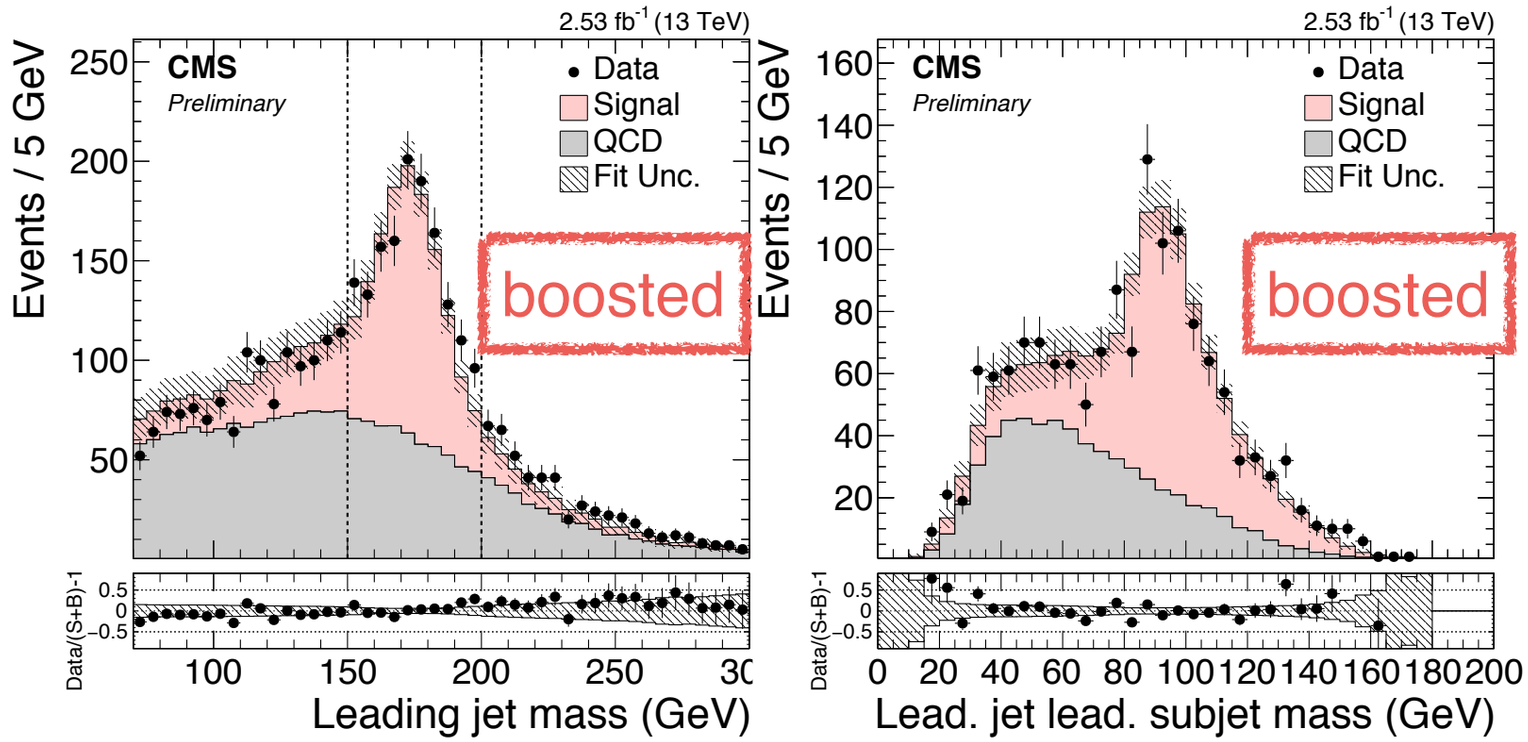


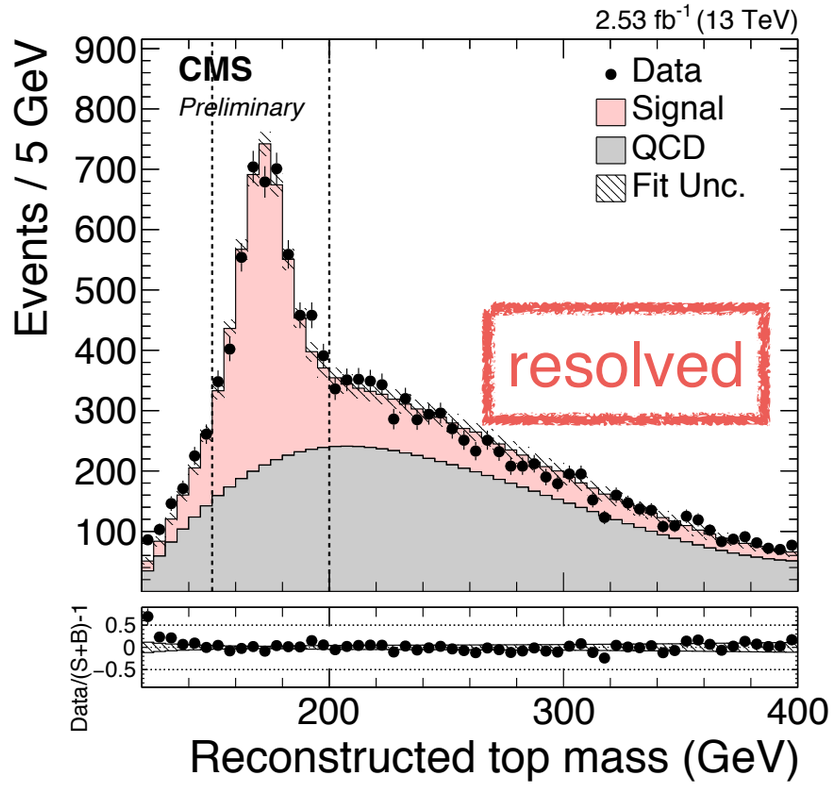
Pair production of top quarks @ 13 TeV

- **CMS measurement @ 13 TeV**
  - all-hadronic decay
    - large BR
    - efficiency increases with p_T
  - differential vs leading top p_T
    - for top p_T > 450 GeV
    - parton level

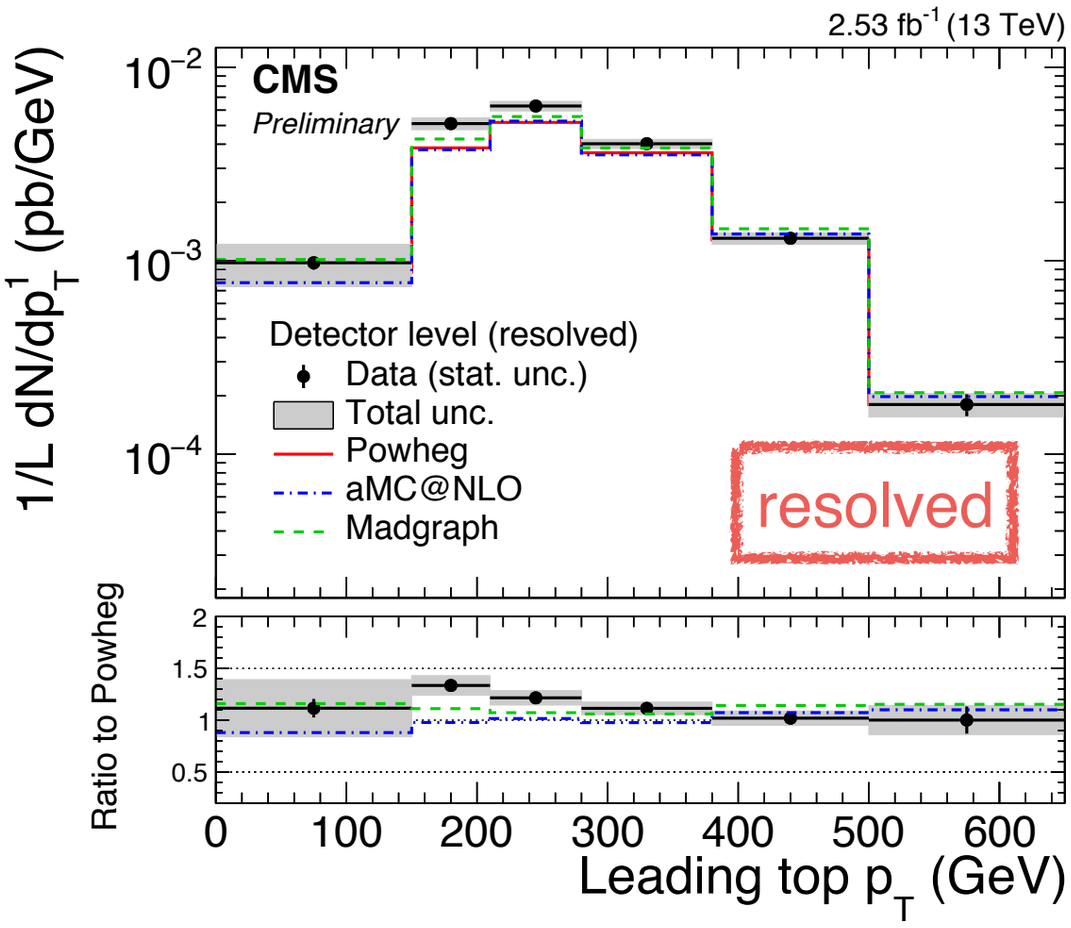
- **reconstruction**
  - small-R jets (AK4)
  - large-R jets (AK8)
    - soft-drop (β=0, identical to modified mass-drop tagger)
  - dedicated top pair tagging: *Fisher discriminant* using τ_{31} and τ_{32} of both jets
  - subjet b tagging
  - resolved & boosted selections (non exclusive)

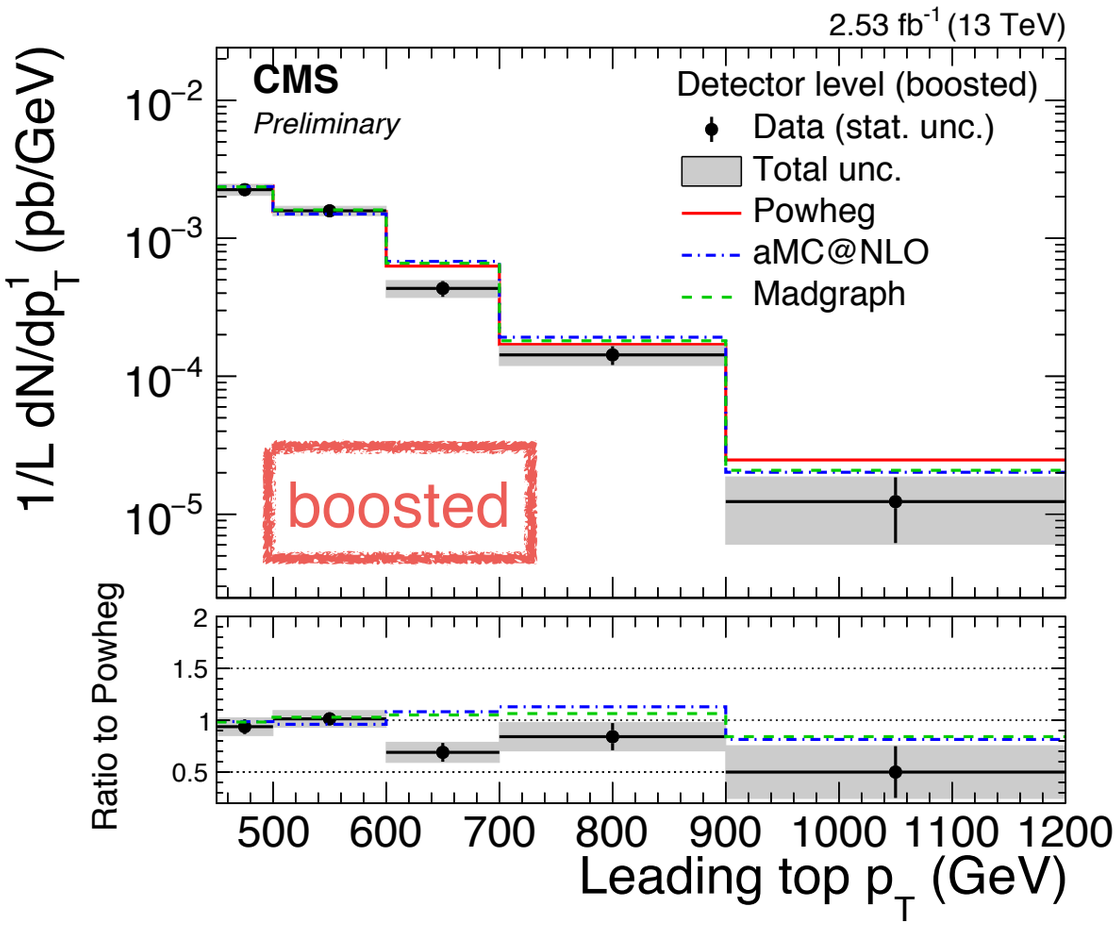
CMS-PAS-TOP-16-013





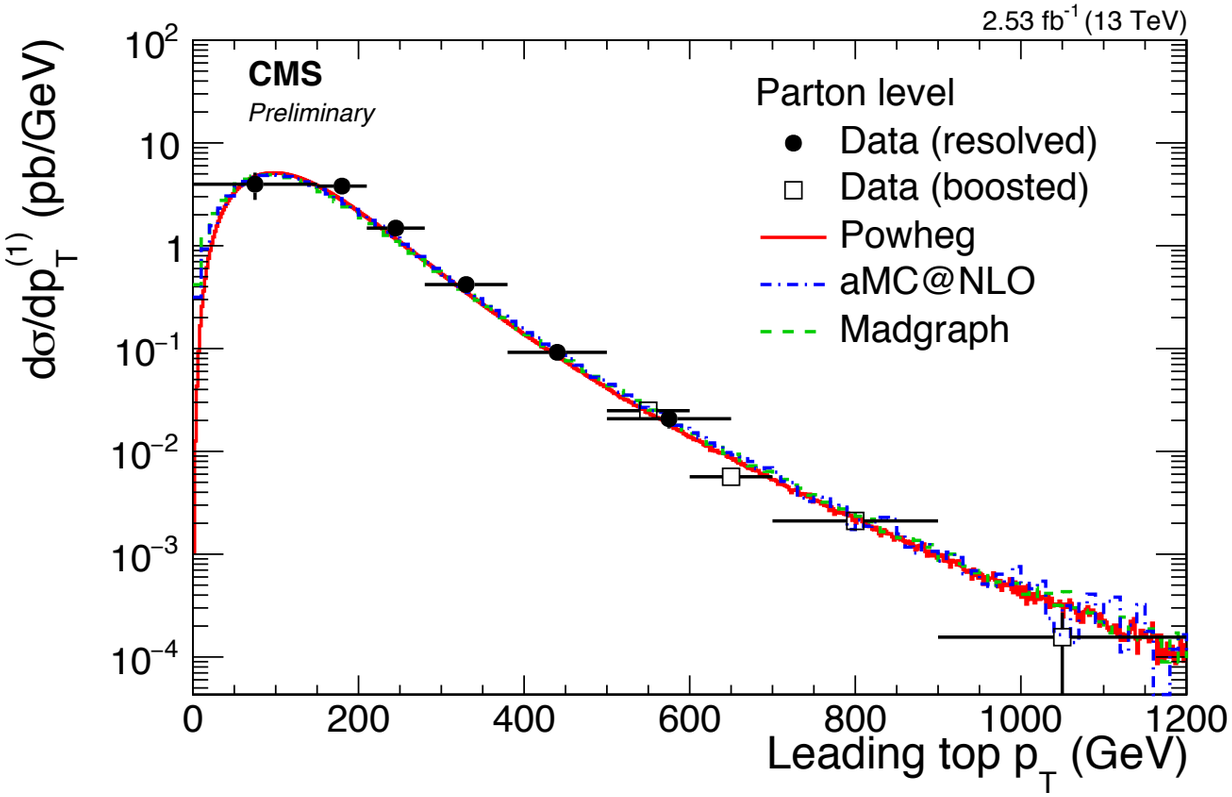
Pair production of top quarks @ 13 TeV

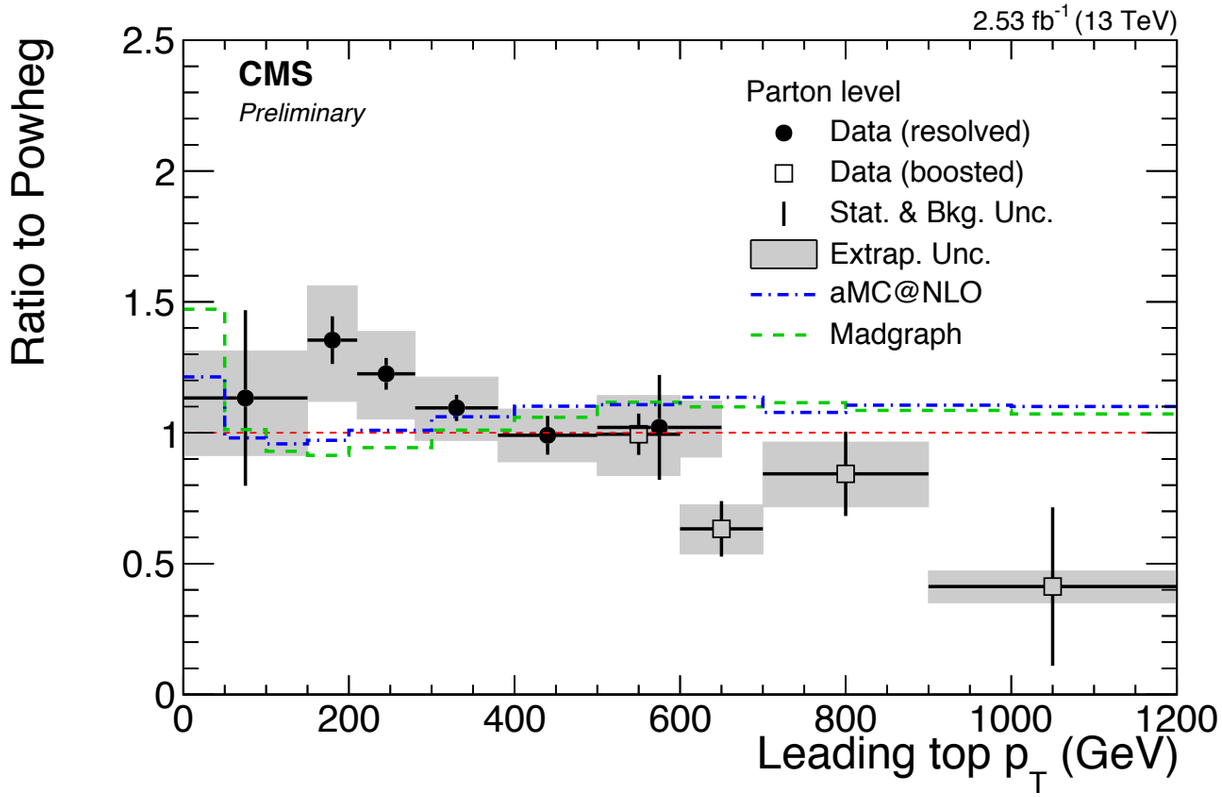




- **signal extration**
  - template fit to the data
  - data-driven background shape estimate
- **result at detector level**
  - resolved: systematics limited
  - boosted: statistics limited
  - MC generators do not describe the data
    - softer measured spectrum

Pair production of top quarks @ 13 TeV





- **unfolding to parton level**
  - d' Agostini iterative method

- **results**
  - agreement between the two selections in the overlapping region
  - all generators predict a harder top p_T spectrum
    - difference increases with top p_T

Searches for new physics

highlights from ttbar resonances

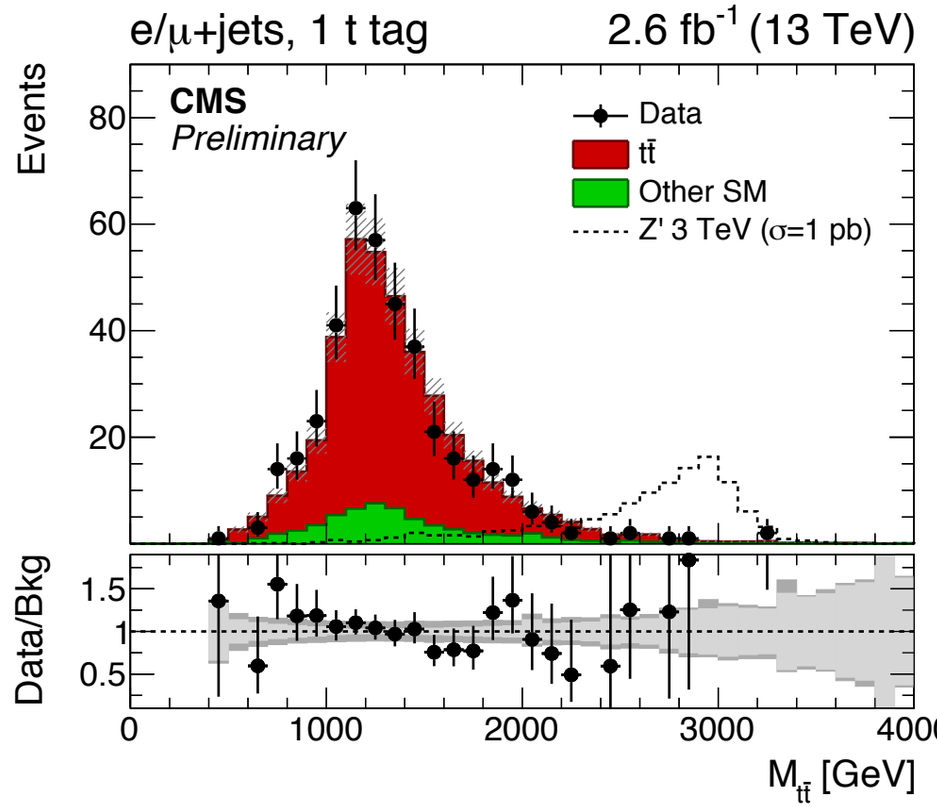
details in dedicated talks

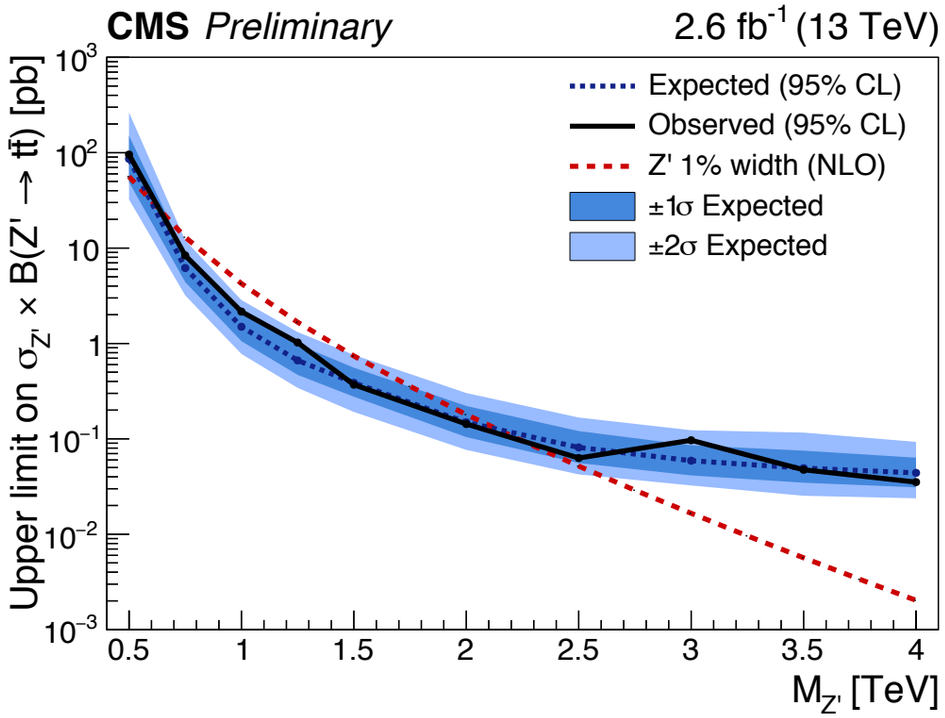
1. **M. Missiroli**: “Searches for ttbar resonances with the CMS detector at 13 TeV”
2. **K. Jones**: “Searches for new resonances decaying to top quarks”
3. **A. Barker**: “Searches for vector like quarks”
4. **A. Lipniacka**: “Searches for SUSY with top quarks”

Resonances decaying to top quarks

- **CMS search @ 13 TeV**
  - semileptonic final state
- **object reconstruction**
  - small-R jets (AK4)
  - large-R jets (AK8)
    - soft-drop
  - lepton $p_T > 45$ GeV
    - mini-isolation
- **top tagging**
  - N-subjettiness ratio τ_{32} + large-R jet mass
- **results**
  - 3 categories based on top and b tags
  - search performed on the top pair mass
  - signal models: Z' (various widths), KK gluons
  - no excess observed !
    - same sensitivity as the 8 TeV dataset
    - great prospects with the 2016 dataset

CMS-PAS-B2G-15-002

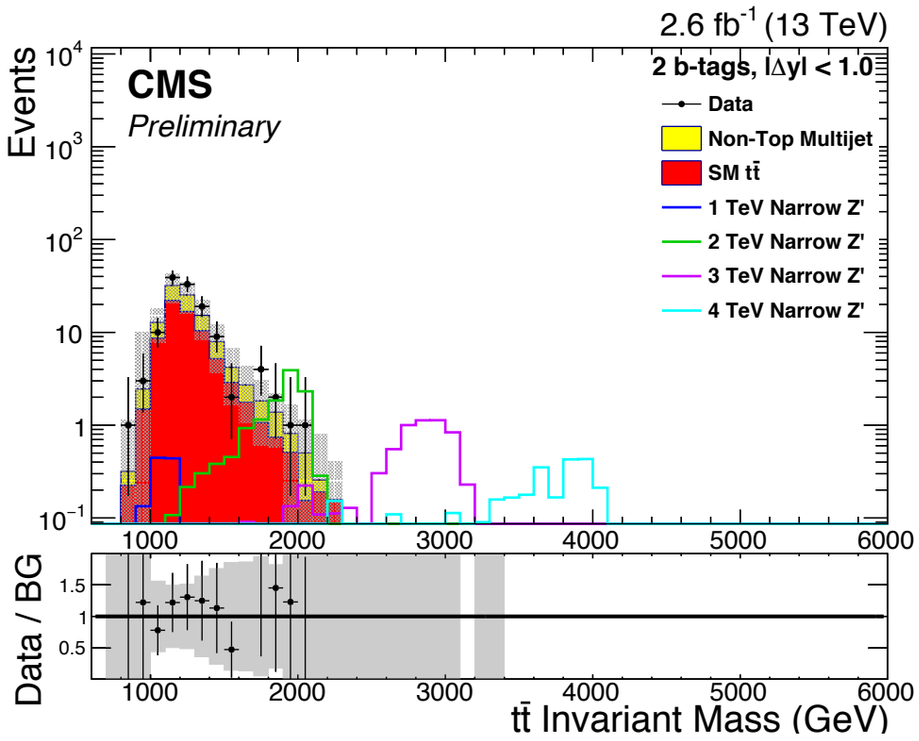


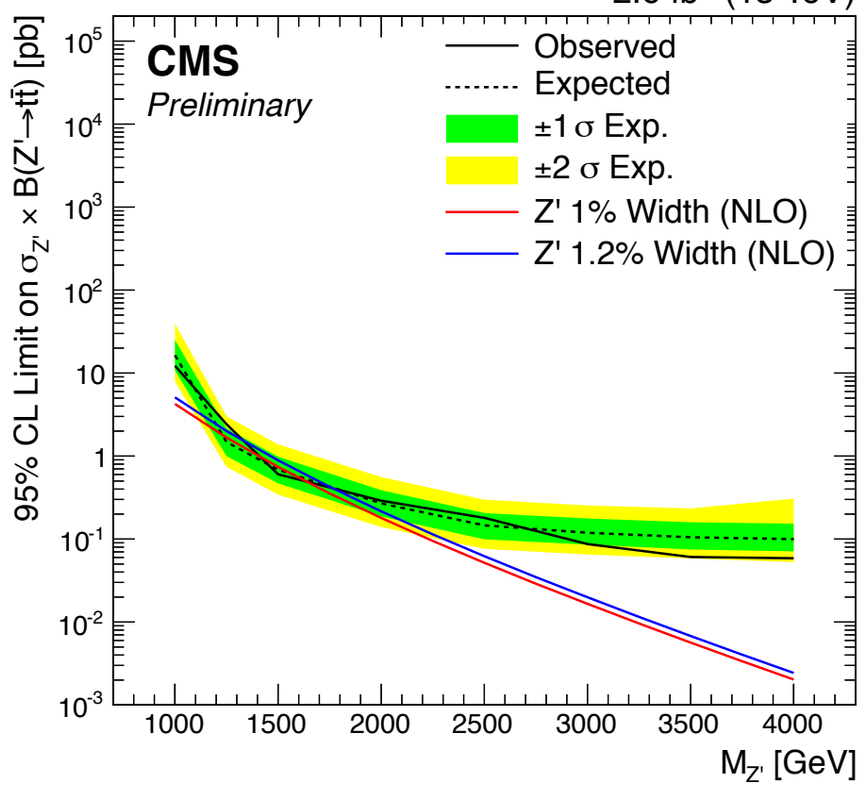


Resonances decaying to top quarks

- **CMS search @ 13 TeV**
  - all-hadronic final state
- **object reconstruction**
  - large-R jets (AK8)
    - soft-drop
- **top tagging**
  - N-subjettiness ratio τ_{32} + large-R jet mass
  - subjet b tagging
- **results**
  - 6 categories based on b tags and $|\Delta y|$
  - search performed on the top pair mass
  - signal models: Z' (various widths), RS gravitons
  - no excess observed !
    - same sensitivity as the 8 TeV dataset
    - great prospects with the 2016 dataset

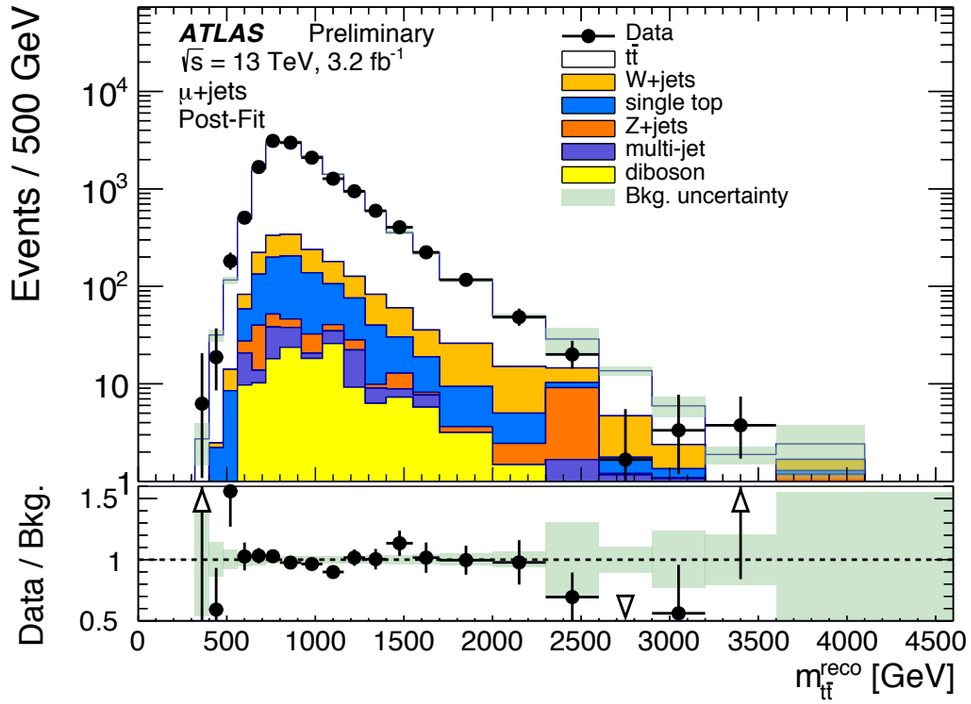
CMS-PAS-B2G-15-003

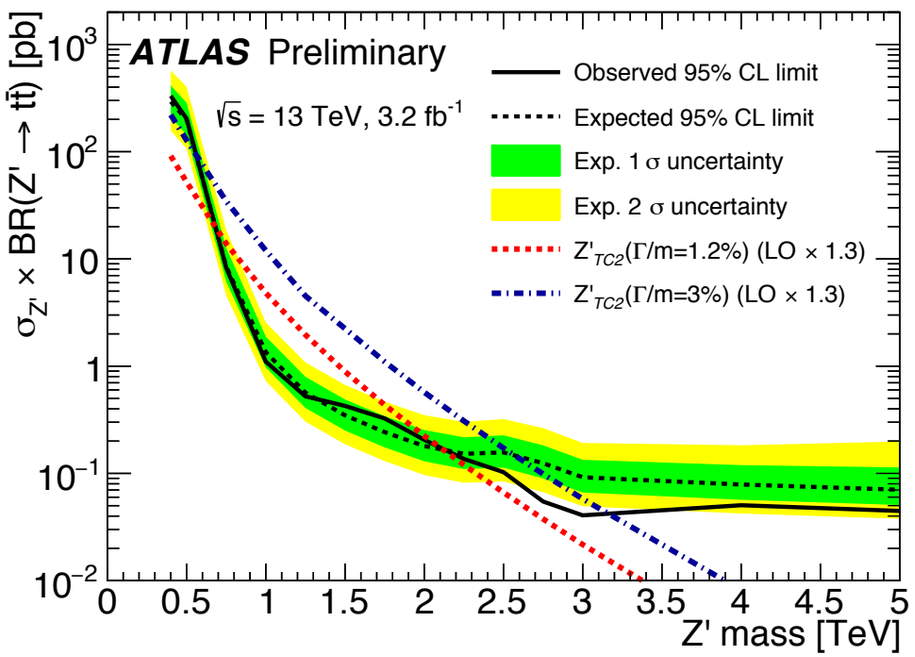




Resonances decaying to top quarks

- **ATLAS search @ 13 TeV**
  - semileptonic final state
- **object reconstruction**
  - small-R jets (AK4)
  - track jets (AK2)
  - large-R jets (AK10)
    - trimming (R_{sub} = 0.2 & f_{cut} = 0.05)
  - lepton p_T > 45 GeV
    - mini-isolation
- **top tagging**
  - N-subjettiness ratio τ_{32} + large-R jet mass
- **results**
  - search performed on the top pair mass with BUMPHUNTER
  - signal models: Z' (various widths)
  - no excess observed !





ATLAS-CONF-2016-014

Summary

- **copious production of high p_T top quarks at LHC**
  - high boost ⇒ collimated top decay products
  - identification of boosted tops with sophisticated reconstruction techniques
  - semileptonic and all-hadronic final states
  - ample statistics with the 2016 dataset (stay tuned for many new results !)
- **precision measurements**
  - differential cross sections vs various observables
  - top p_T spectrum measured beyond the TeV scale
  - general observation: NLO+PS generators predict much harder top p_T spectrum
  - boosted tops have been used to measure other properties, such as the top mass and the charge asymmetry
  - the 8 TeV and first 13 TeV analyses have made us wiser: ***over-conservatism*** *in systematic uncertainties is being reconsidered (room for more precise measurements with the 2016 dataset)*
- **new physics with boosted tops**
  - many searches are being performed in final states with high p_T tops
  - no hint so far but sensitivity is being pushed to much higher scale