Top quark measurements with the ATLAS detector

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On behalf of the ATLAS collaboration

Why the top quark?

- In the SM it's the only quark:

  1. With a natural mass:

$$m_{top} = y_t v/\sqrt{2} \approx 173 \text{ GeV} \Rightarrow y_t \approx 1$$

  - Top quark interacts strongly with the Higgs sector - special role in EWSB?

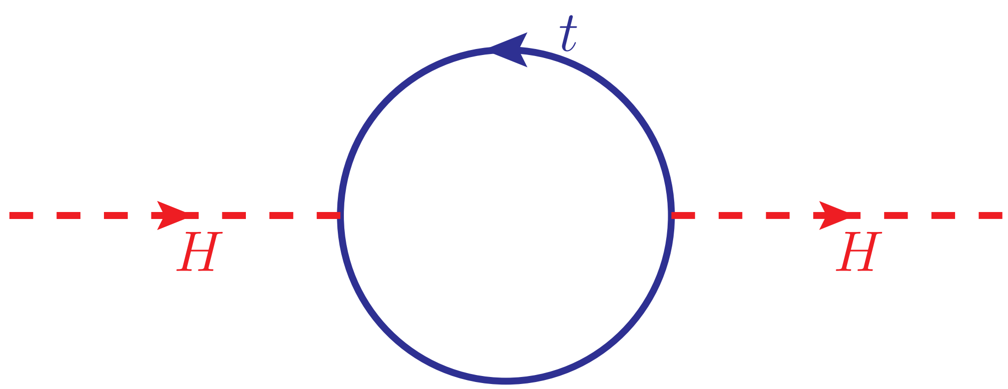
  2. That decays before hadronizing:

$$\tau_{had} \approx 2 \times 10^{-24} s$$
$$\tau_{top} \approx 5 \times 10^{-25} s$$

- Copious production rate at the LHC allows for precise tests of QCD involving multiple scales (pT(top), m(top), m(b)).

Why the top quark?

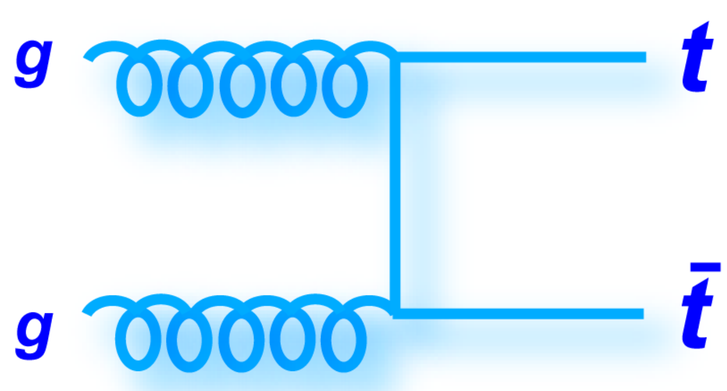
- Corrections to the Higgs mass in the SM depend on the top mass:



- Assume new physics enters at some high scale:
  - In effective theory approach: $$\Delta m_H^t \sim -\frac{3}{8\pi^2} y_t \Lambda^2$$
  - For less than 90% cancellation: $$\Lambda < 3\ TeV$$
- Top quark could be the place we see new physics.

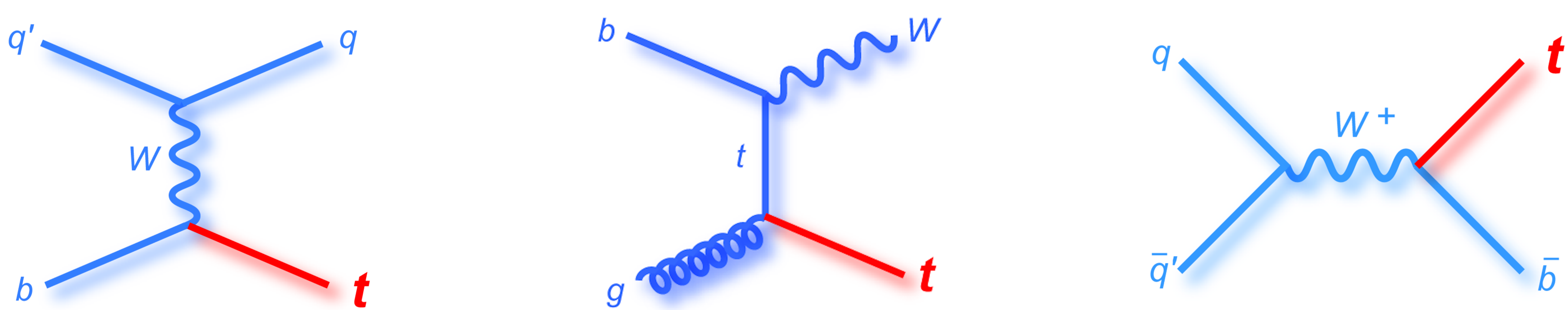
Top production at the LHC

- Top pair production:



- $\sigma(t\bar{t})$: test QCD predictions
- Clean sample: properties measurements

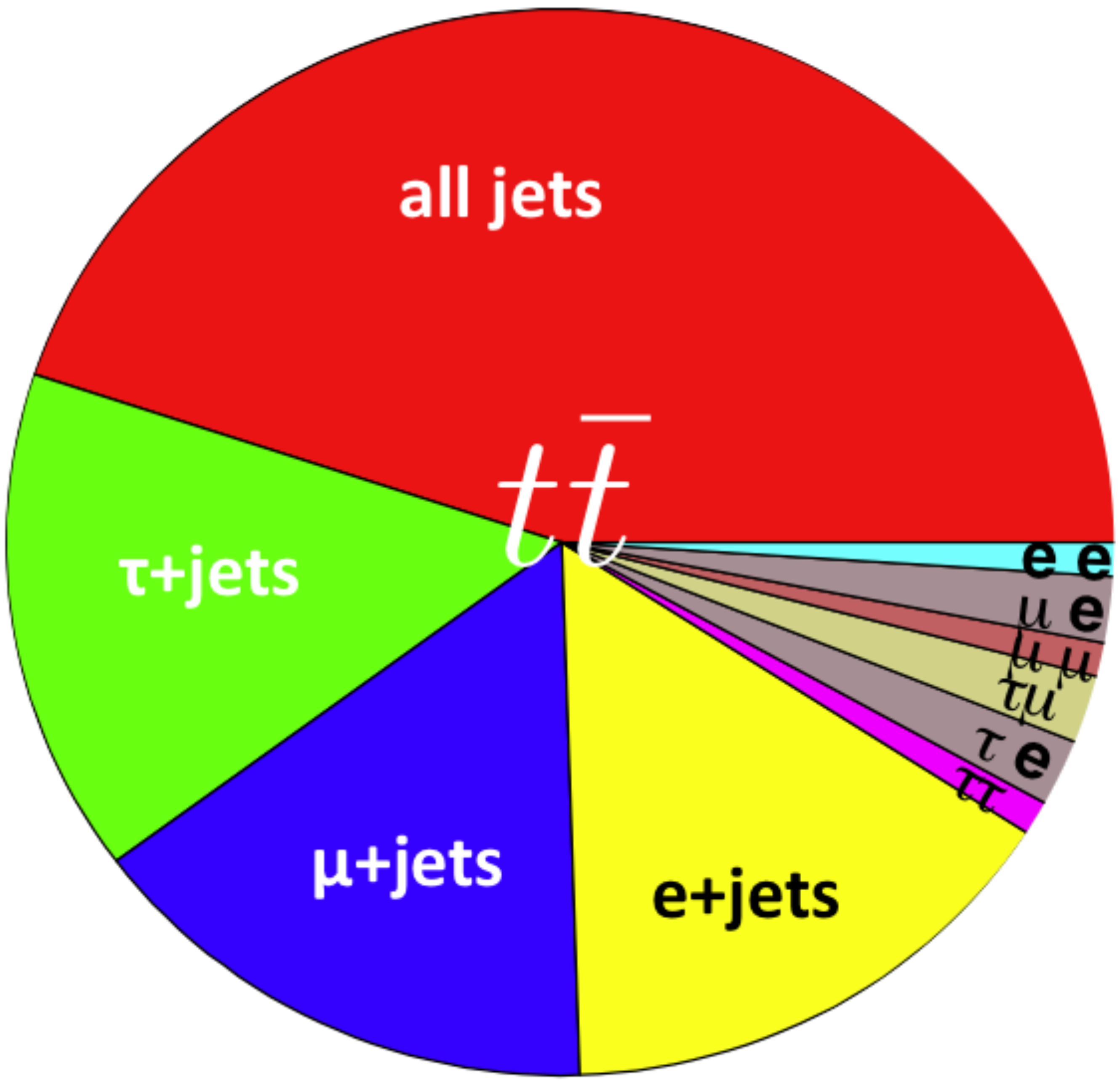
- Single top production:



- EW process: probe Wtb vertex

Top decay modes

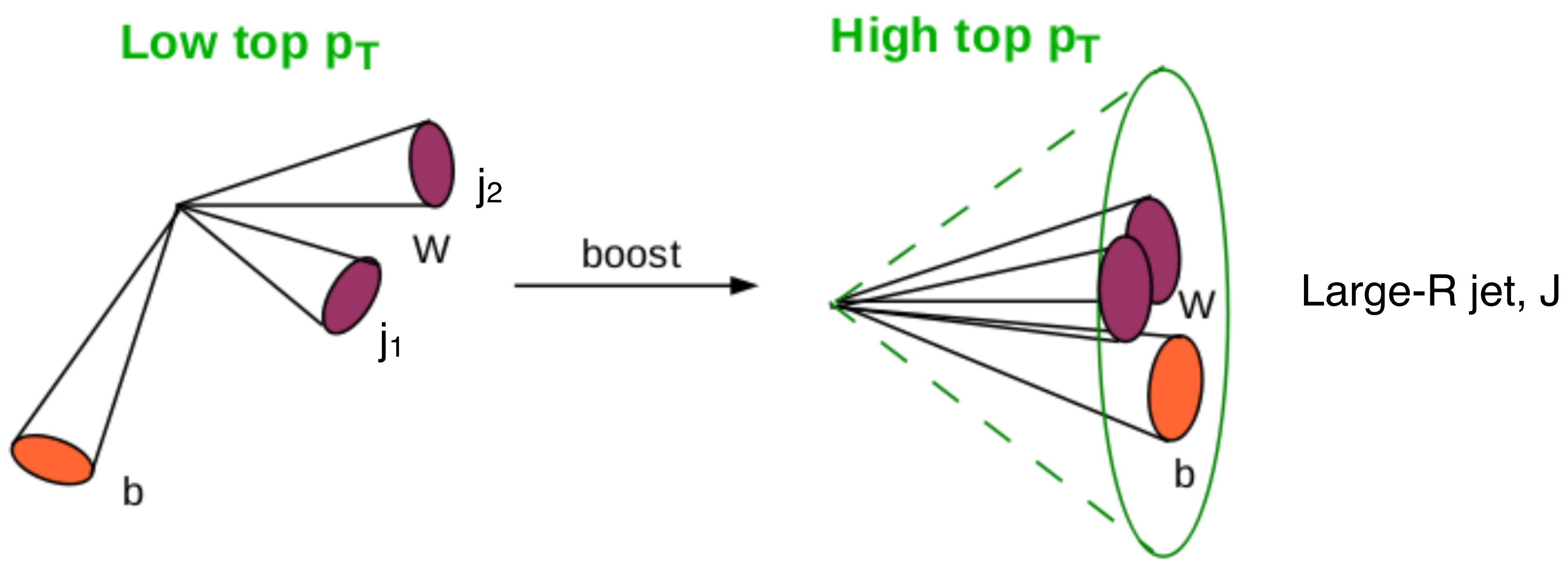
- SM top decays ~100% to $W^{\pm}b$.
- Final states dictated by W boson decays.



- All hadronic:
  - 2 b-jets + 4 q-jets
  - High Br
  - Large multijet background
- Lepton-plus-jets:
  - e / μ + ν + 2 b-jets + 2 q-jets
  - Good Br
  - Manageable backgrounds
- Di-lepton:
  - ee / μμ / eμ + νν + 2 b-jets
  - Small Br
  - Small backgrounds

Reconstructing top quarks

- Must reconstruct top from decay products.
- Now dedicated algorithms for high p_T top quarks:



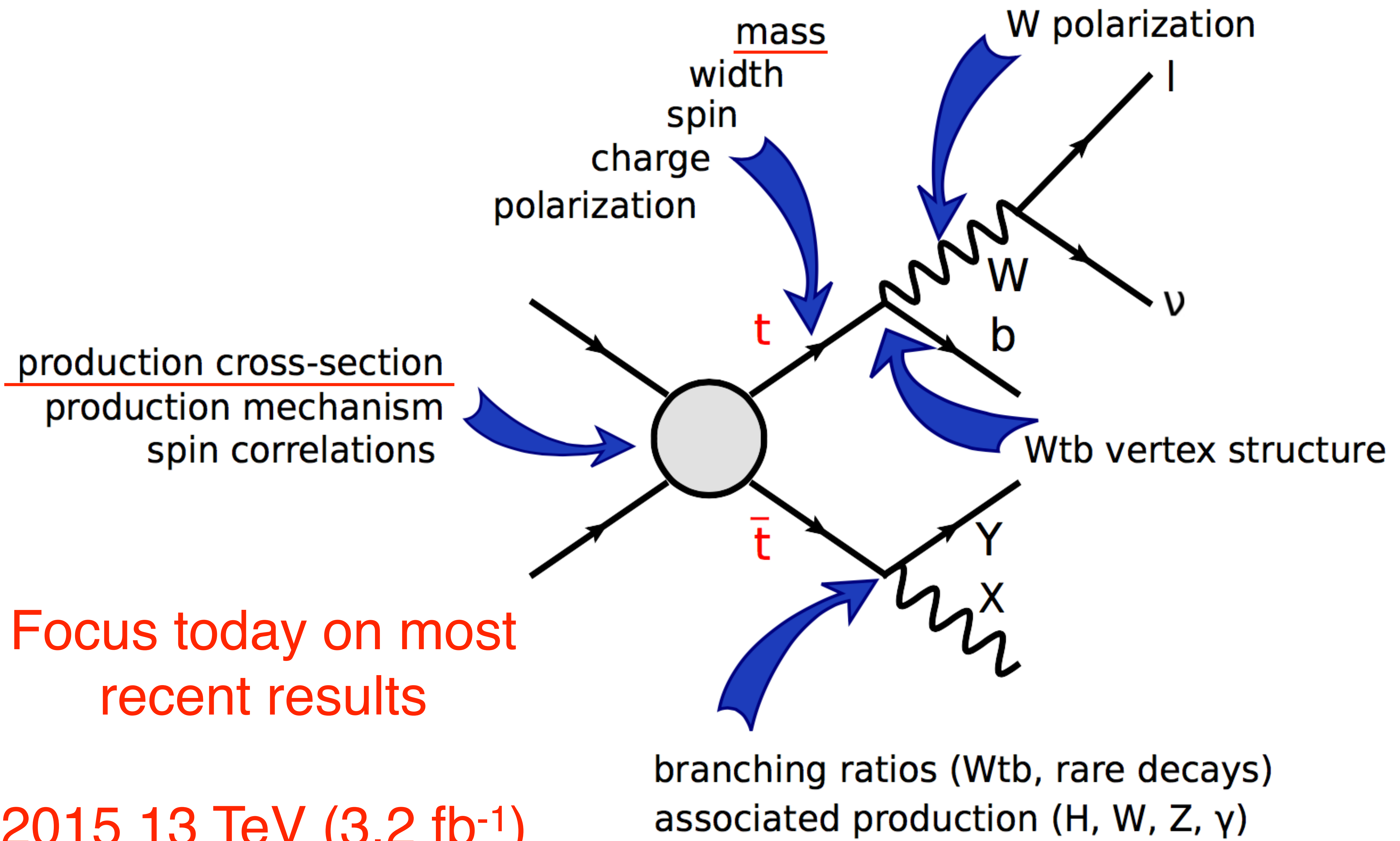
$\underline{t} = \underline{j}_1 + \underline{j}_2 + \underline{b}$

$\underline{t} = \underline{J}$

Use mass constraints to resolve combinatorics:
$m(\underline{j}_1 + \underline{j}_2) \sim m(W)$
$m(\underline{j}_1 + \underline{j}_2 + \underline{b}) \sim m(t)$

Use 'top-tagging' to look for structure within J and m(J) ~ m(t)

Top quark measurements



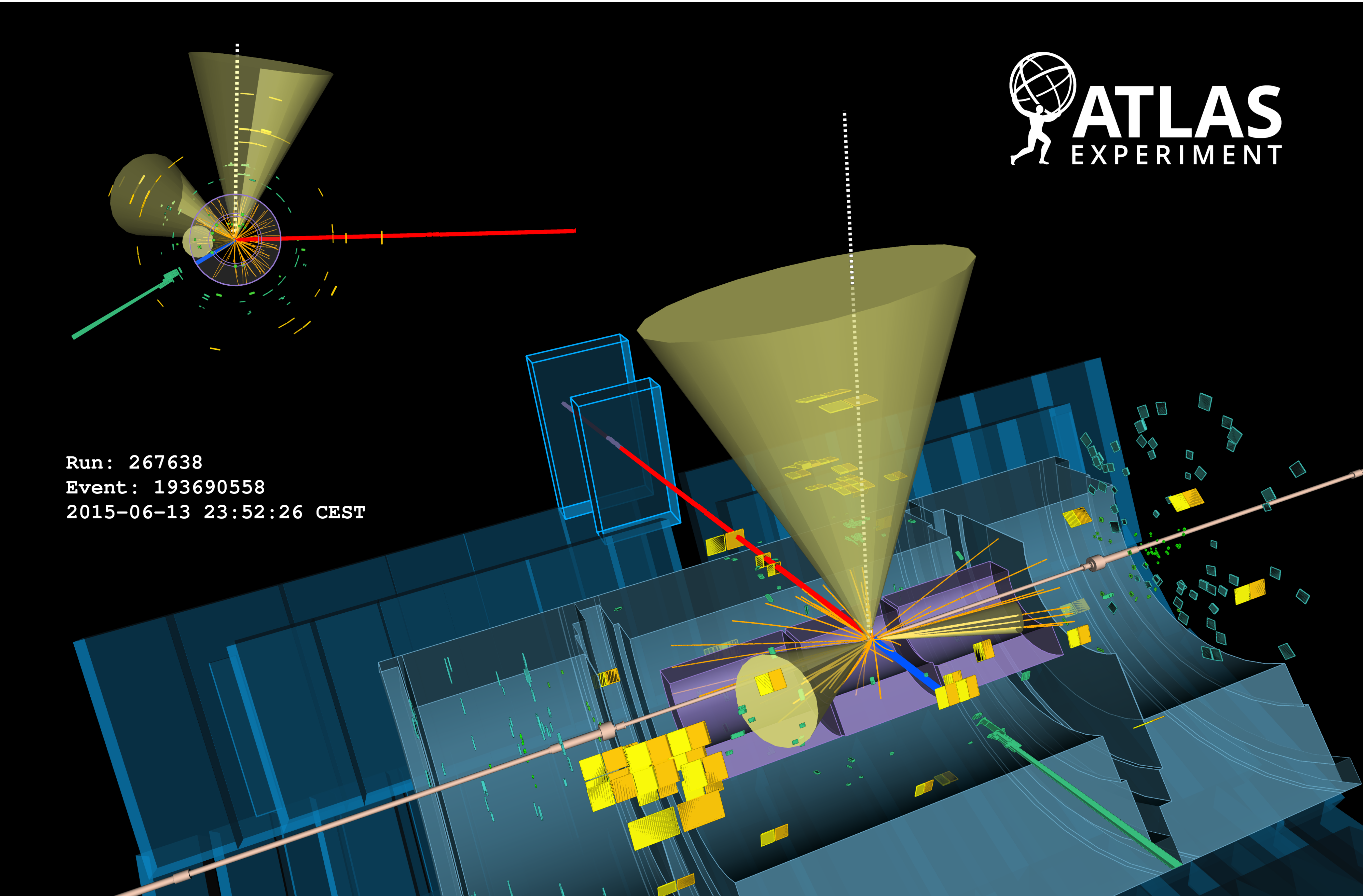
Focus today on most recent results

2015 13 TeV (3.2 fb^{-1})
2012 8 TeV (20 fb^{-1})

Top pair production measurements

13 TeV

Dilepton top-pair event



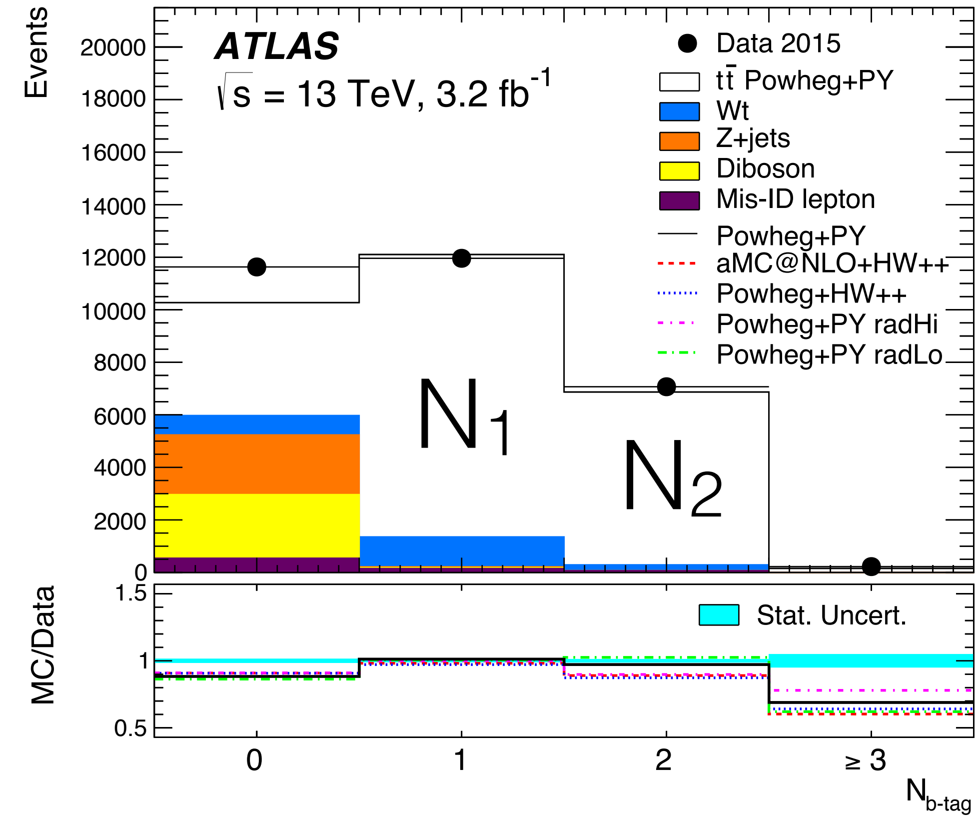
13 TeV

Inclusive cross-section

- Use clean eμ+2b+2ν to measure inclusive cross-section.
- Cross-section and b-jet reconstruction efficiency extracted from number of events with 1 or 2 b-jets:

$$N_1 = L\,\sigma_{t\bar{t}}\,\epsilon_{e\mu}\,2\epsilon_b(1 - C_b\,\epsilon_b) + N_1^{\mathrm{bkg}}$$
$$N_2 = L\,\sigma_{t\bar{t}}\,\epsilon_{e\mu}\,C_b\,\epsilon_b^2 + N_2^{\mathrm{bkg}}$$

- Systematics associated with jets & MC modelling significantly reduced.
- Remaining systematics dominated by luminosity & MC modelling.



$$\sigma_{SM}(t\bar{t}) = 832^{+40}_{-46}\ \mathrm{pb}$$

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

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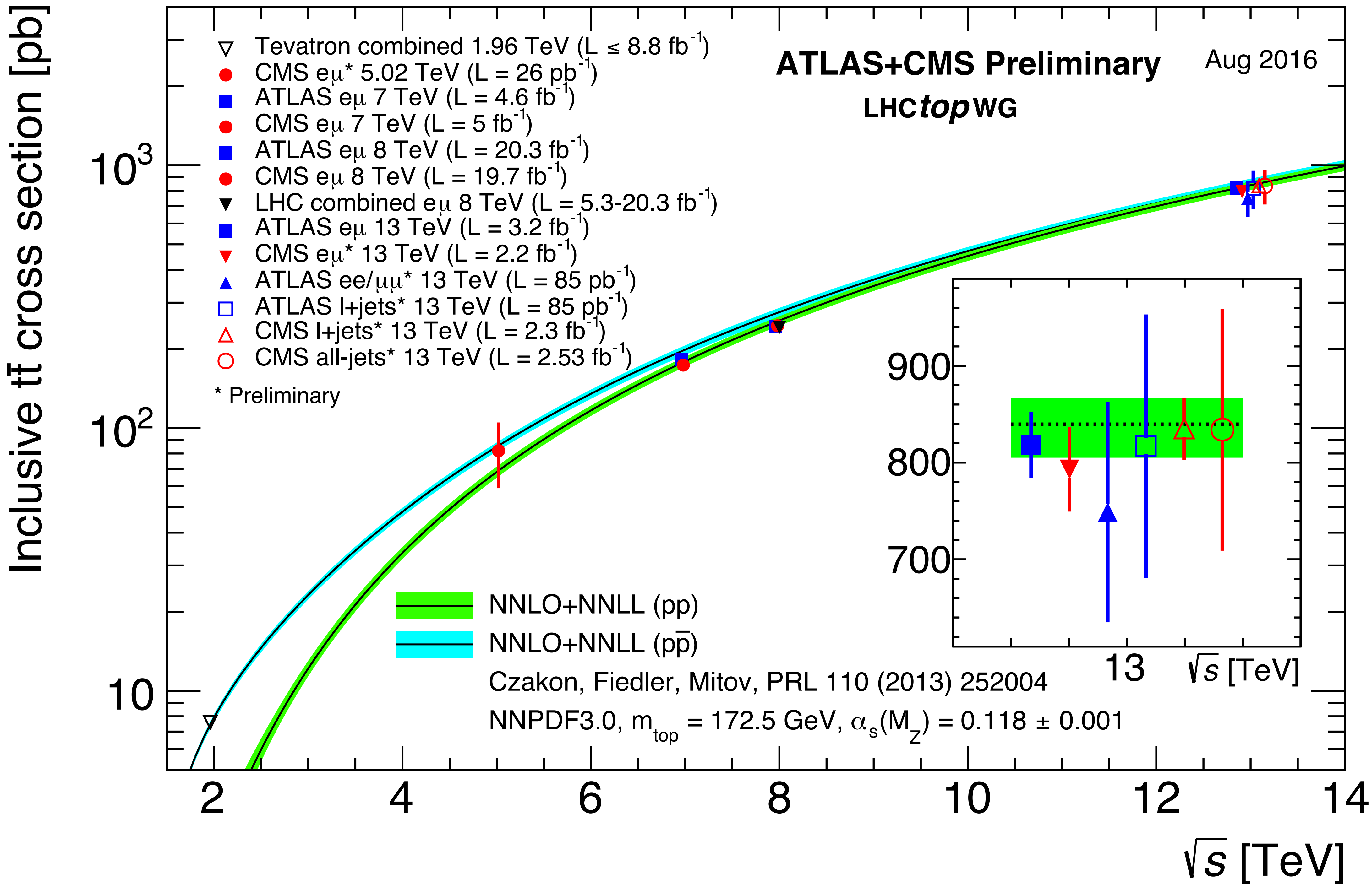
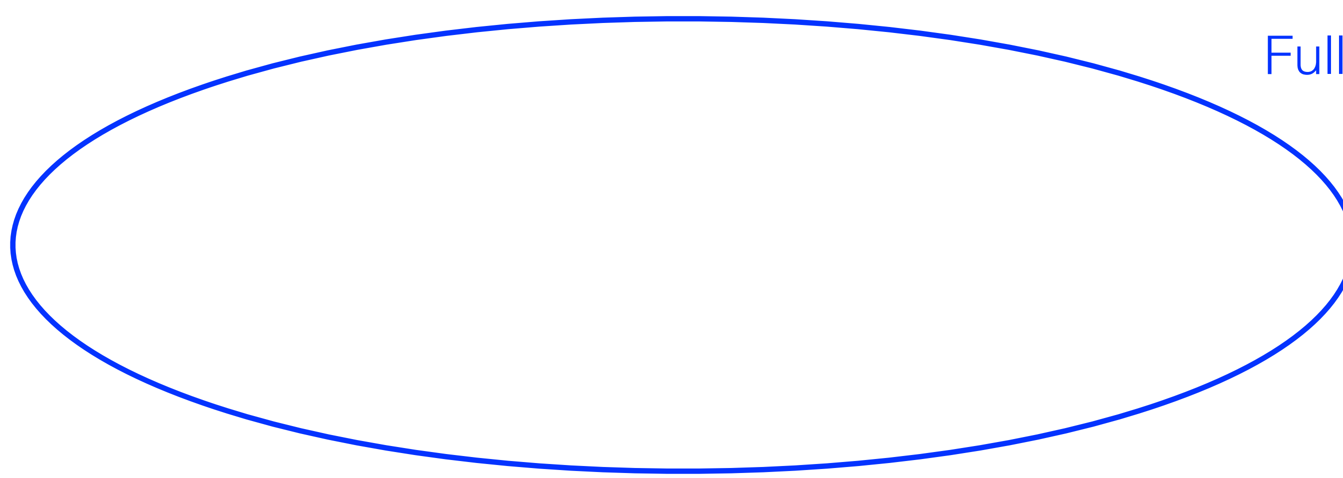
Inclusive cross-section



- Agreement with SM predictions across energy range probed.

Differential cross-sections

- Explore kinematics of top pair events:
  - Probe QCD up to TeV scale (high pT tops).
  - Deviations due to new physics?
- Define measurements at two levels:
  - Parton-level: define ‘parton-tops’ directly before decay.
    - Compare to state-of-the-art QCD predictions for stable tops (NNLO).
    - Need MC to extrapolate from jets & leptons to parton-level, often in full phase-space.



Full phase space: all top-quark pair events produced in collisions

Differential cross-sections

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  - Probe QCD up to TeV scale (high pT tops).
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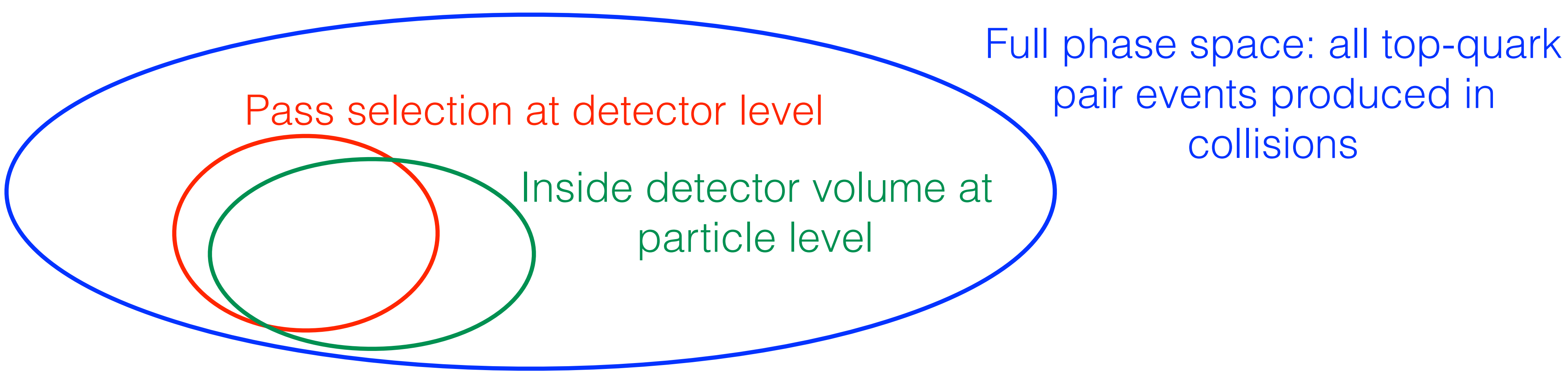
Differential cross-sections

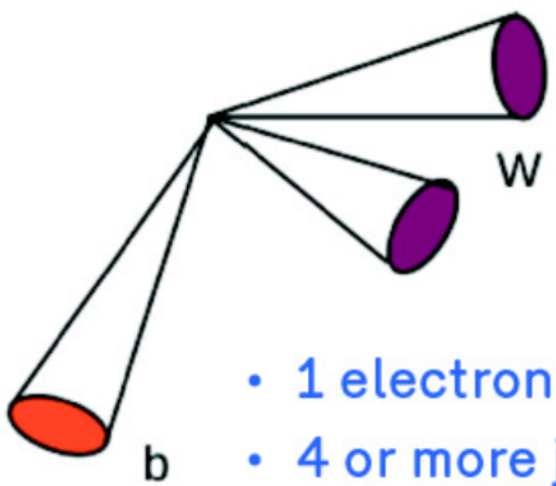
- Explore kinematics of top pair events:
  - Probe QCD up to TeV scale (high pT tops).
  - Deviations due to new physics?
- Define measurements at two levels:
  - Particle-level: build ‘pseudo-tops’ from stable particles.
    - Close connection to particles observed in detector.
    - Reduced dependence on MC for measurement: smaller uncertainties.
    - Compare to MC models (hadron-level predictions).



Differential cross-sections

- Differential cross-section measurement in resolved and boosted lepton-plus-jets events:

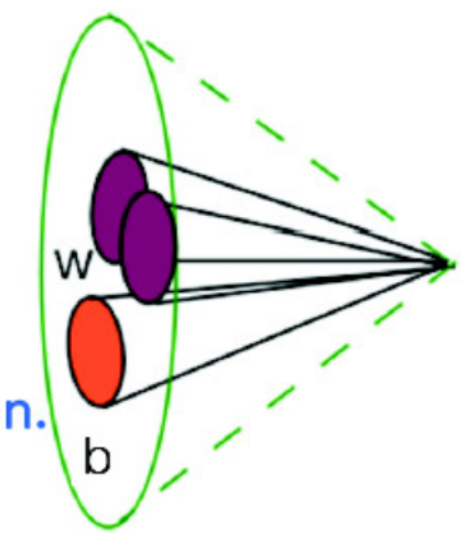
Resolved Top



- 1 electron or muon
- 4 or more jets (at least 2 b-tagged)
- Hadronic and leptonic top reconstruction.

Boosted Top

- 1 electron or muon.
- 1 or more small-R jets
- 1 top-tagged large-R jet
- MET > 20 GeV
- MET + $m_T(W)$ > 60 GeV
- Hadronic top reconstruction. $p_T(t)$ > 300 GeV
- Either small-R and large-R jets b-tagged (77% eff.).



$$p_T(t), |y(t)|, p_T(t\bar{t}), m(t\bar{t}), |y(t\bar{t})|$$

13 TeV

Resolved lepton-plus-jets event

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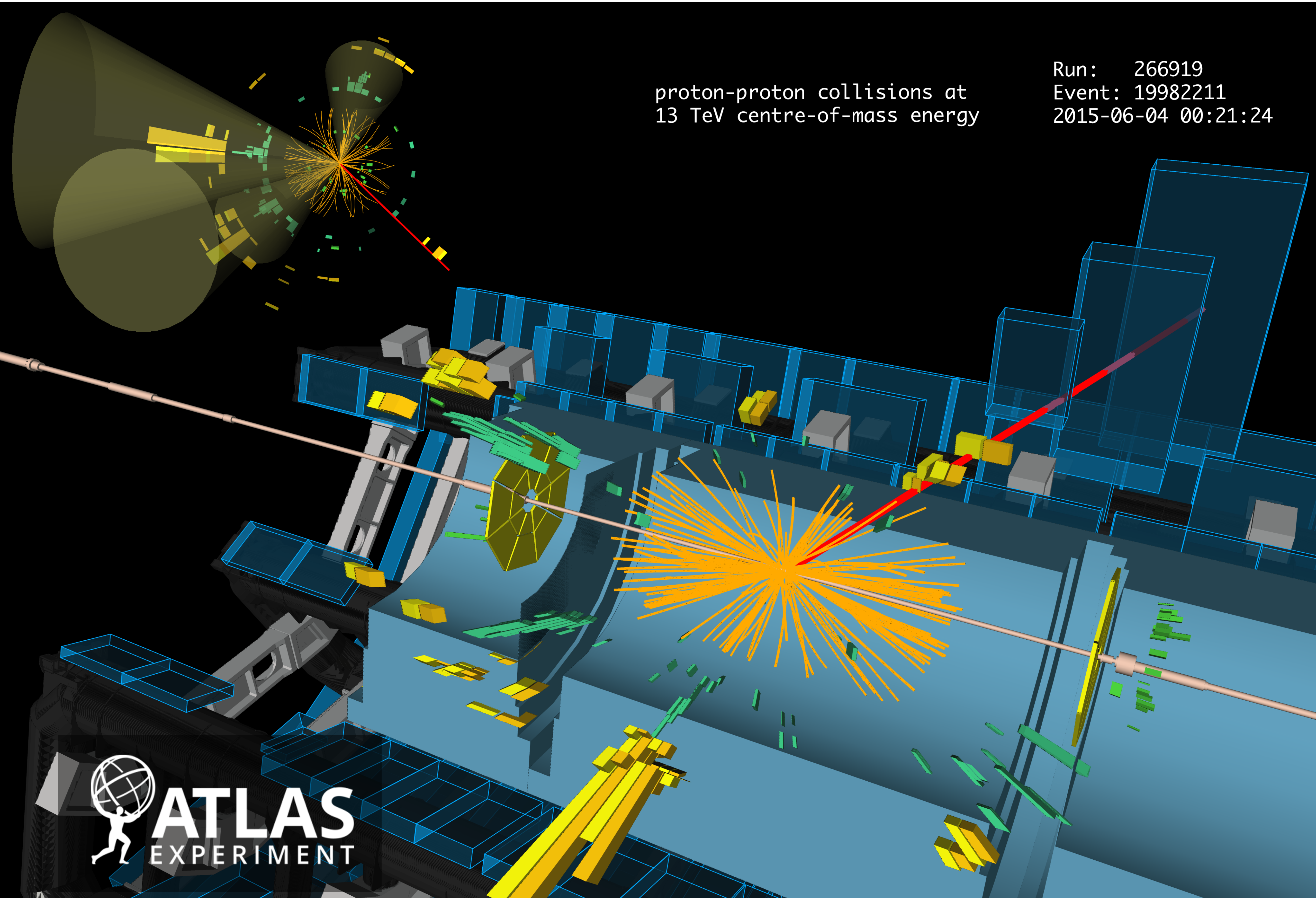
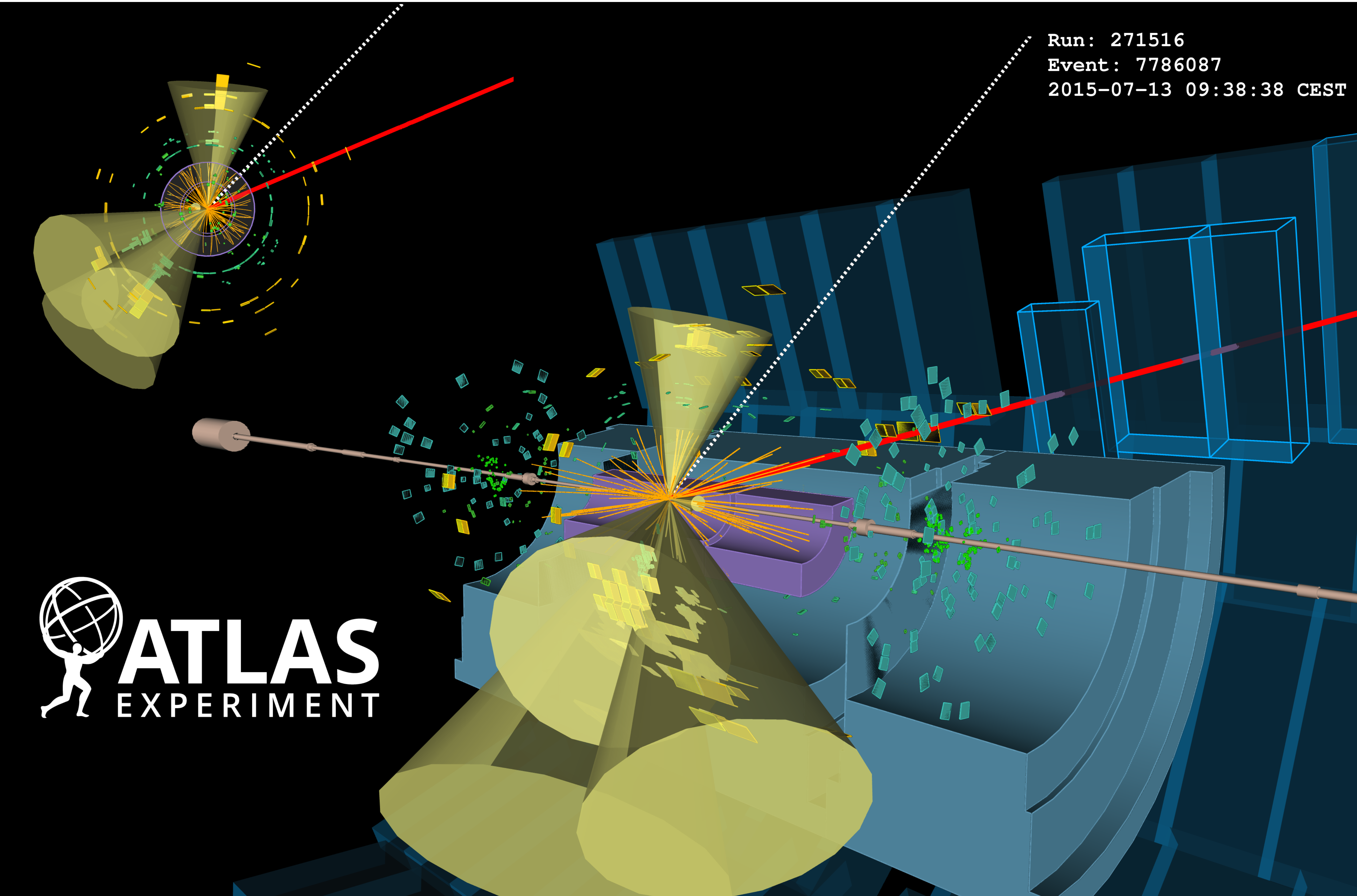


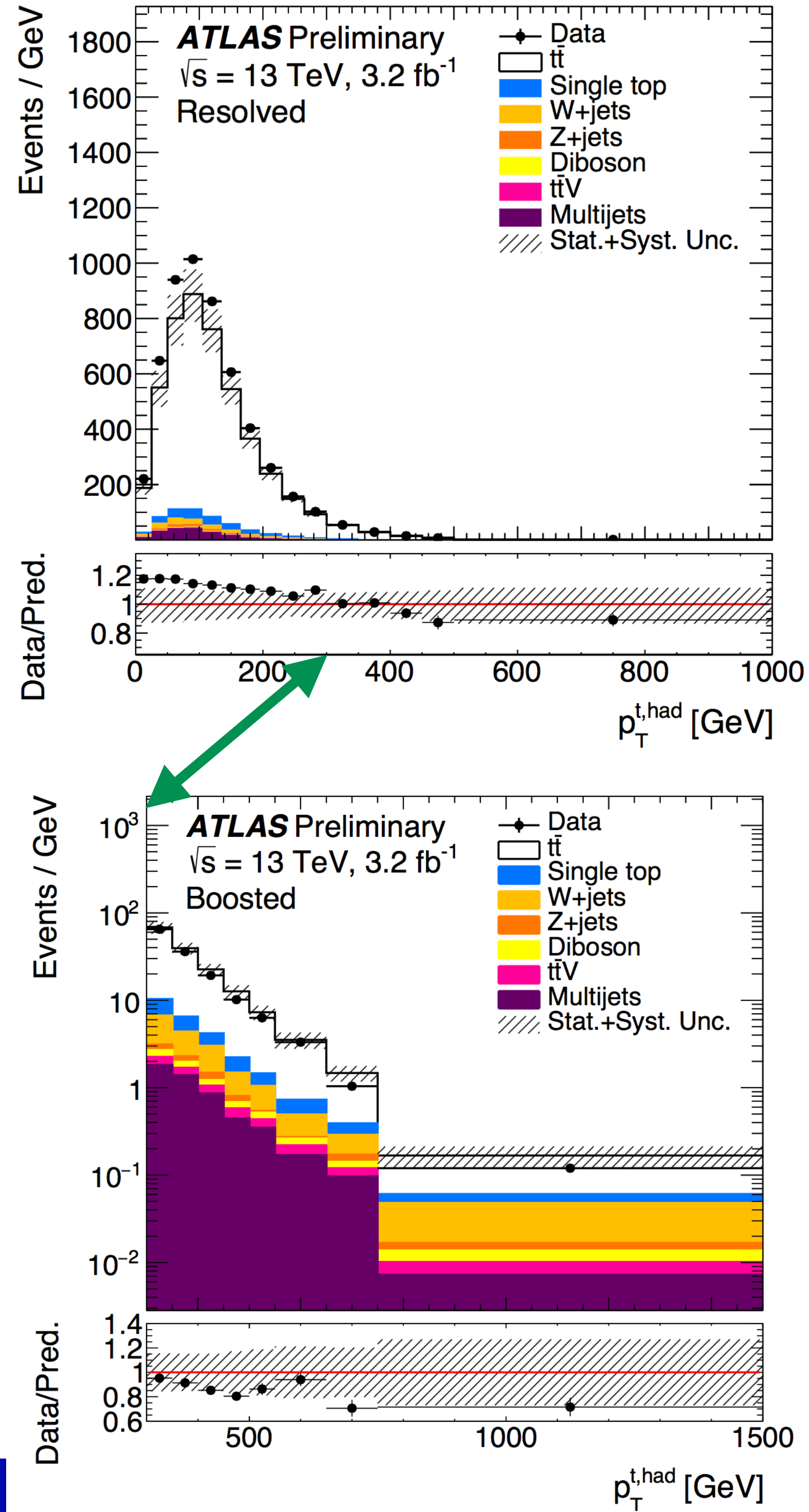
13 TeV

Boosted lepton-plus-jets event



Differential cross-sections

- Top pT, reconstructed in the detector:



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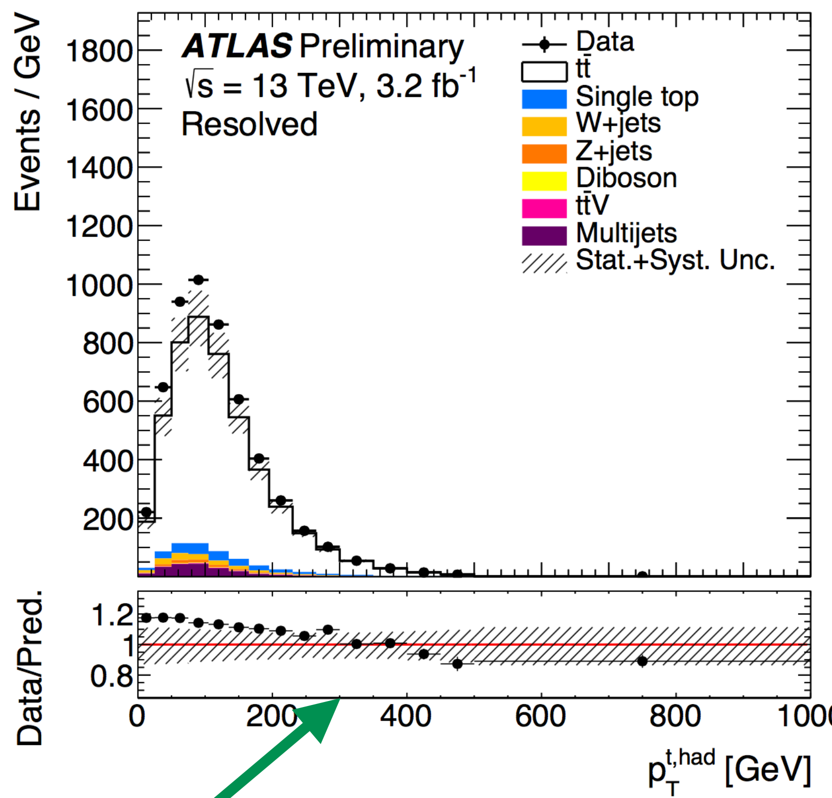
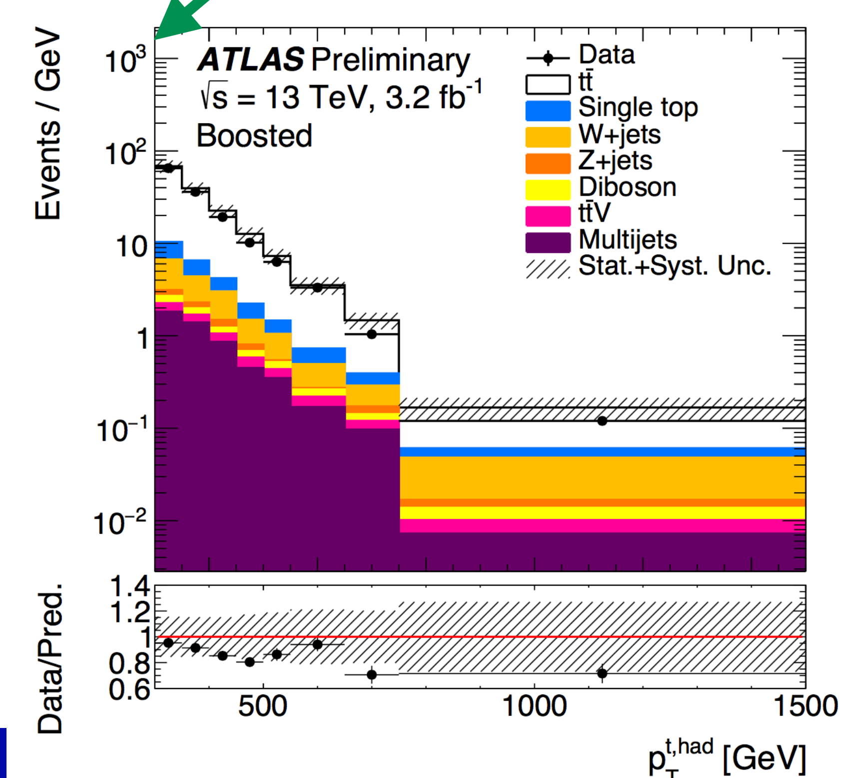
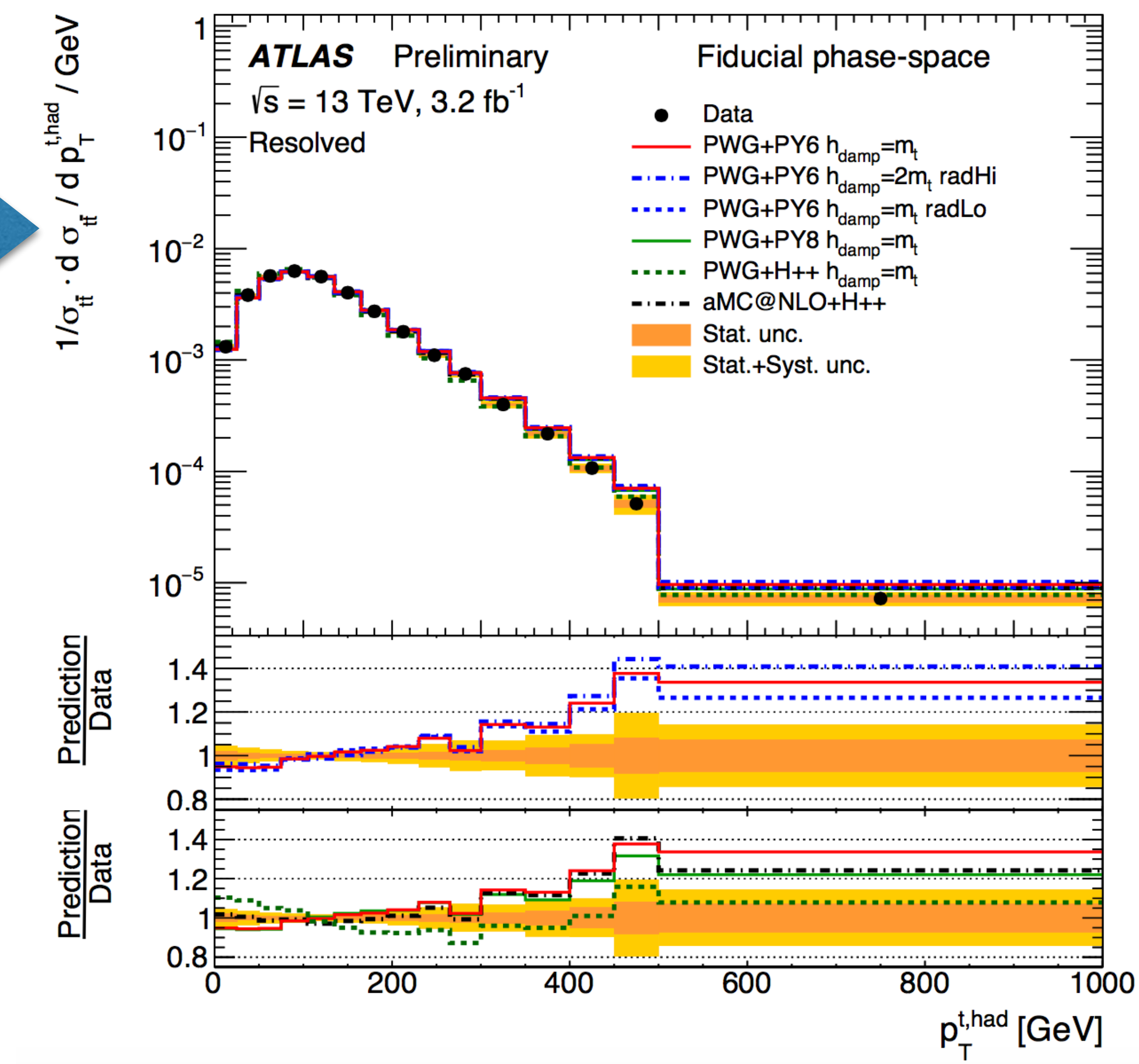
13 TeV

Differential cross-sections

- Top pT, correct for detector effects (resolution, efficiency):







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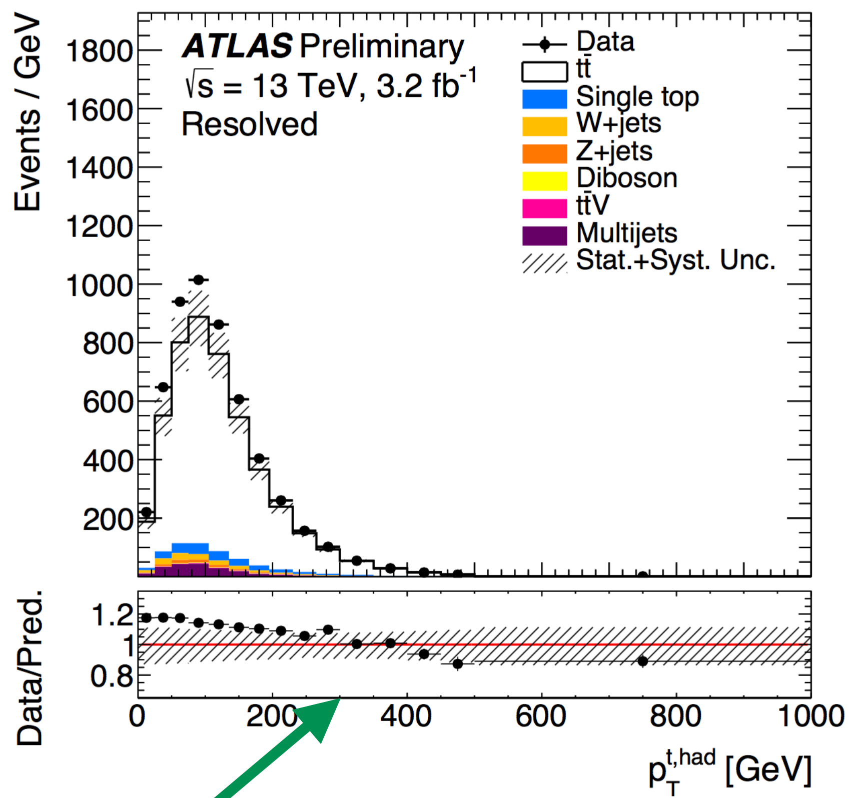
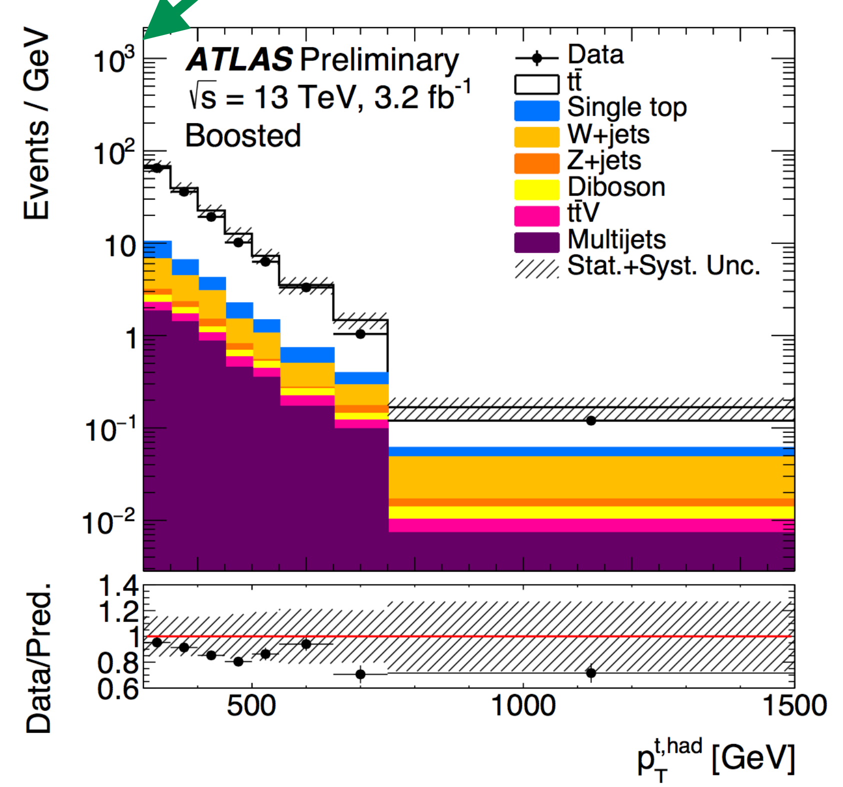
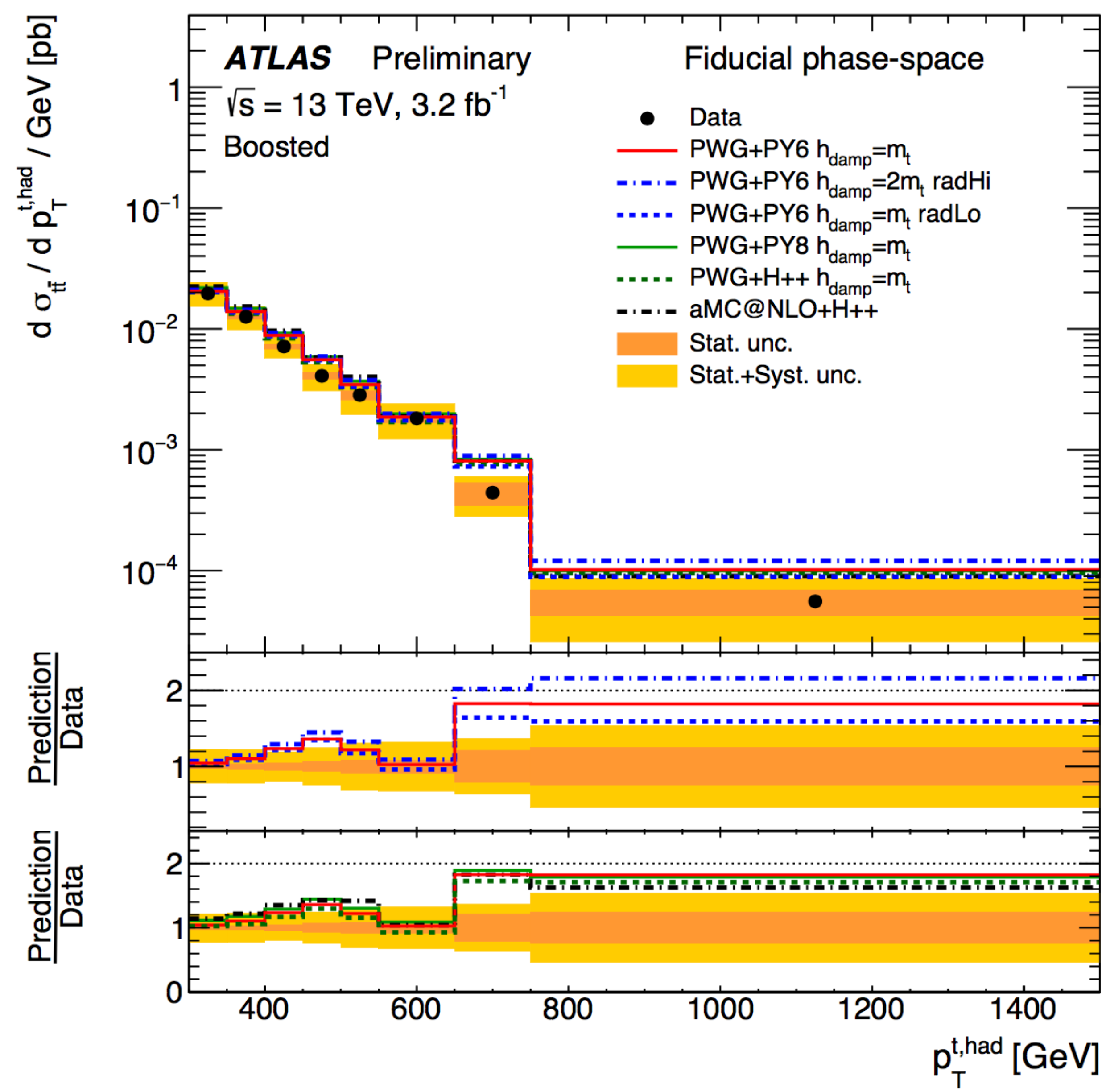
Differential cross-sections

- Top pT, correct for detector effects (resolution, efficiency):







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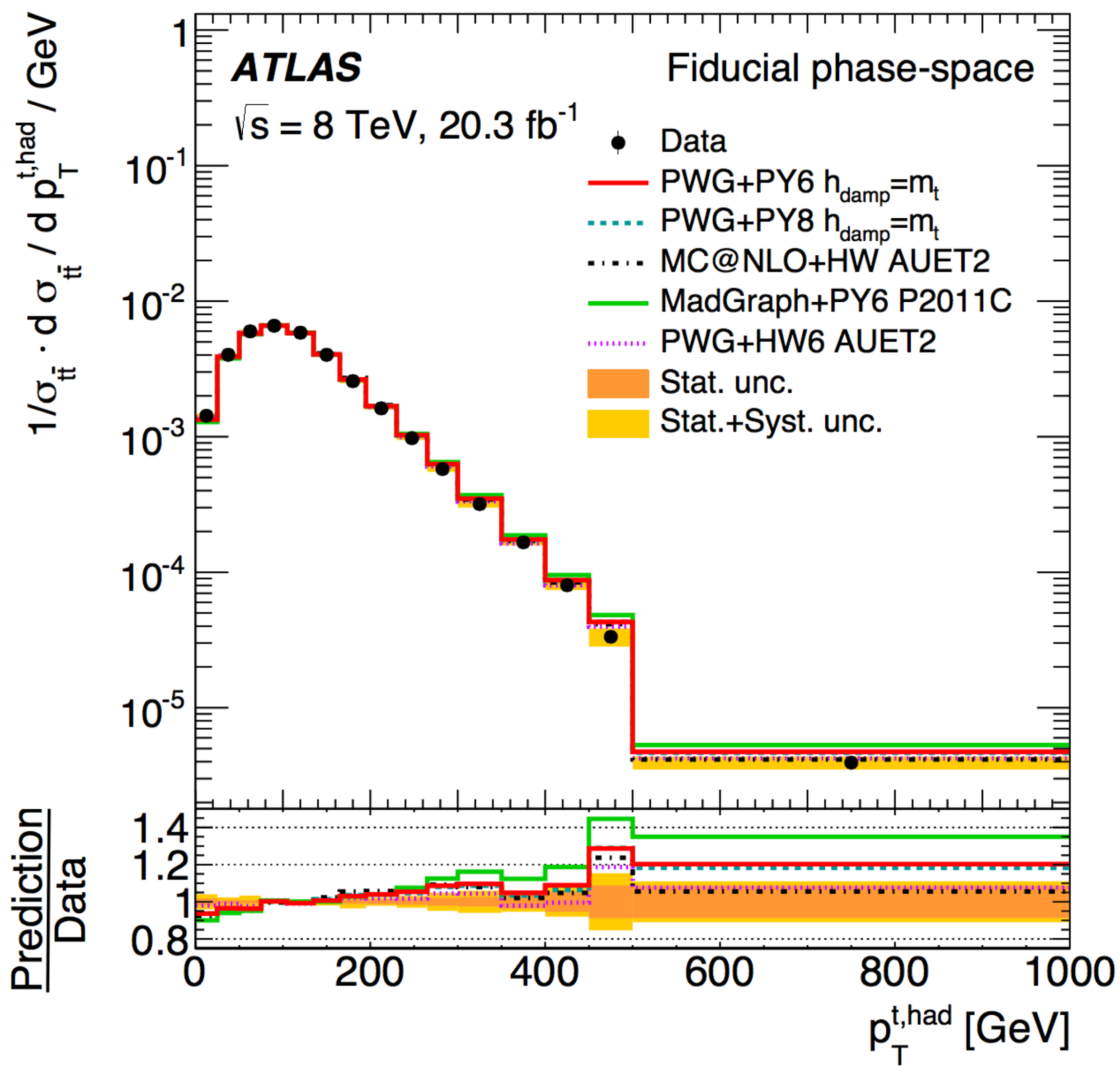
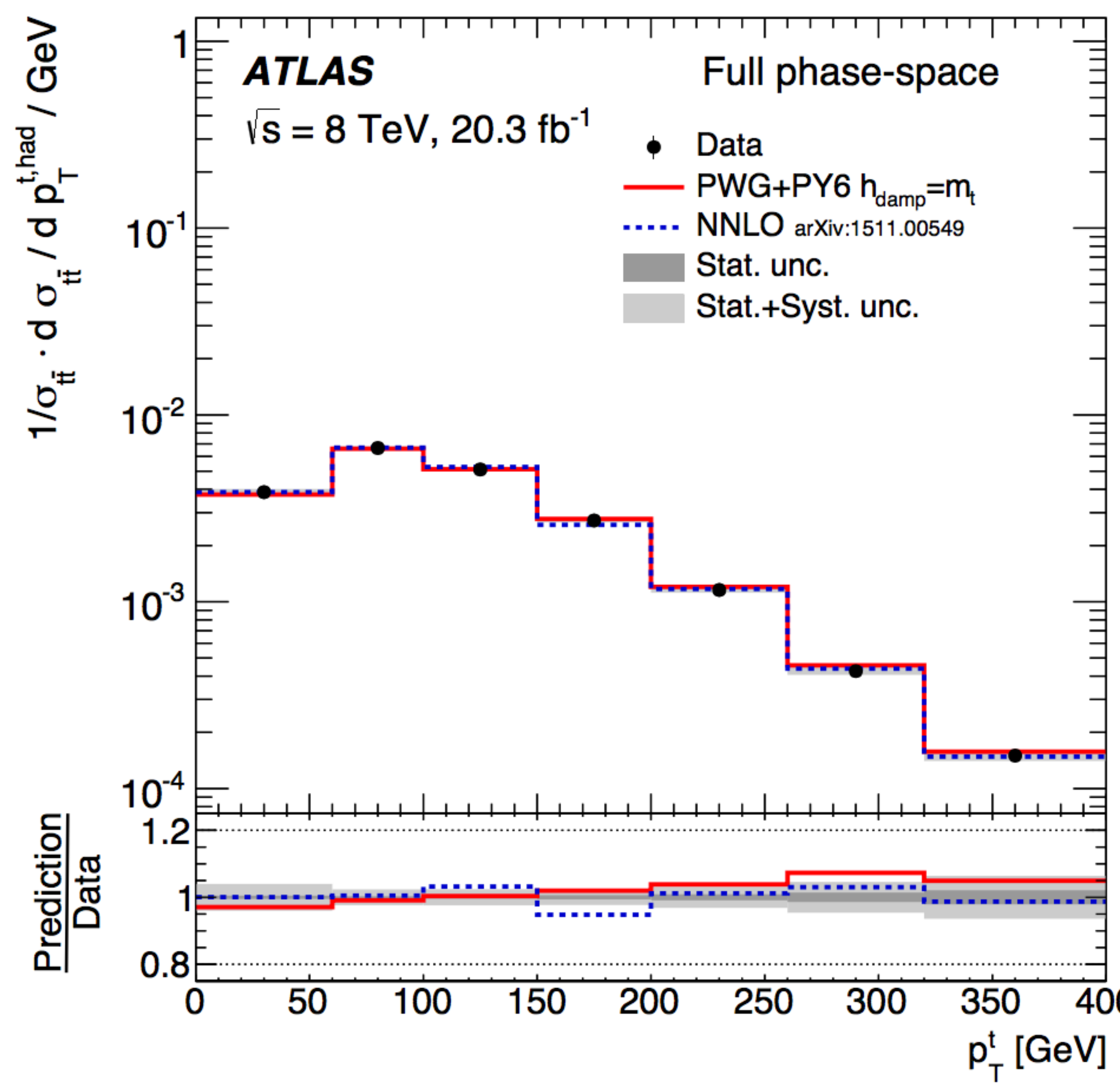
8 TeV

Differential cross-sections

- Same trend for top pT seen at 8 TeV:





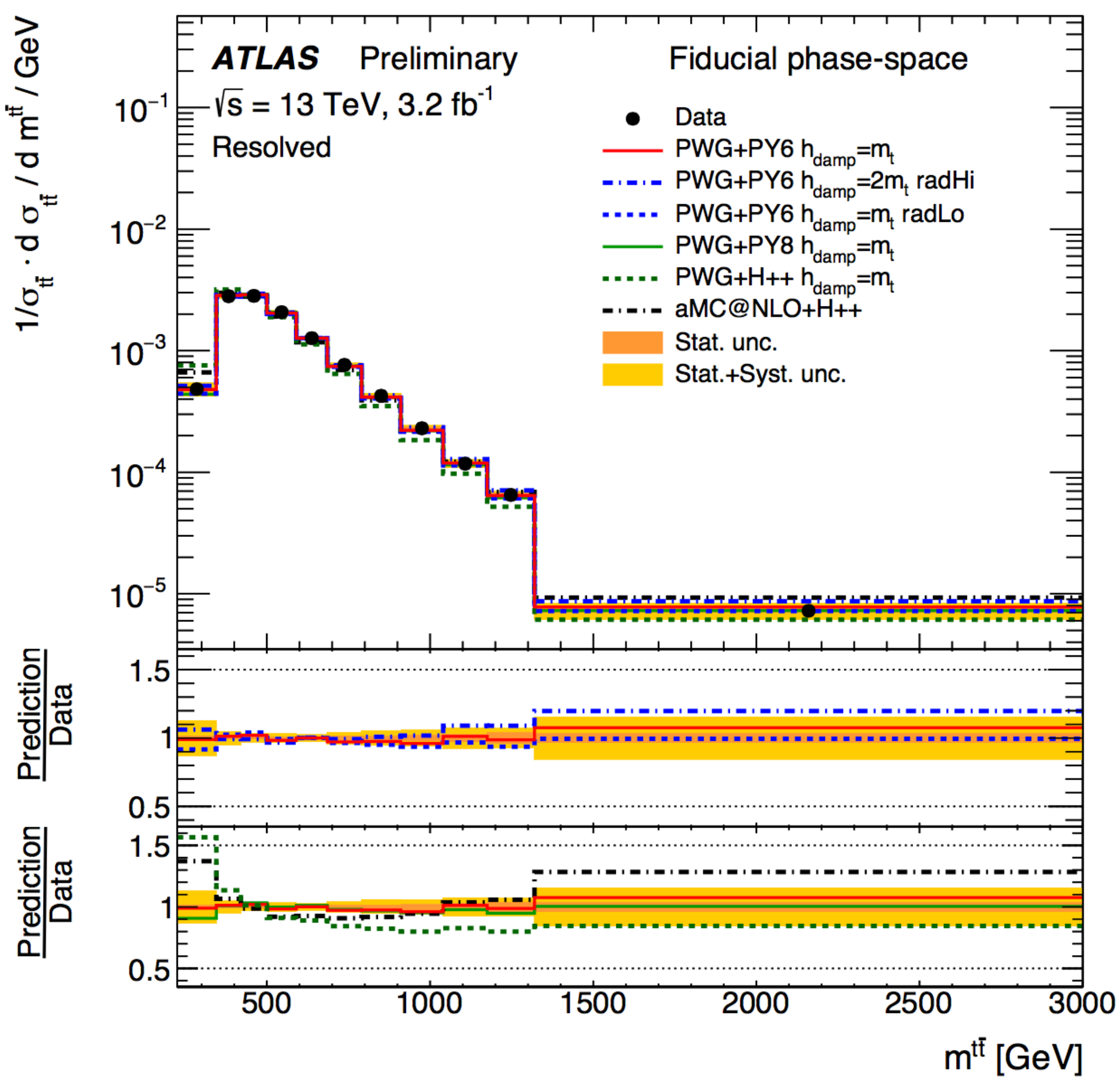
- Agreement improved when using NNLO predictions.

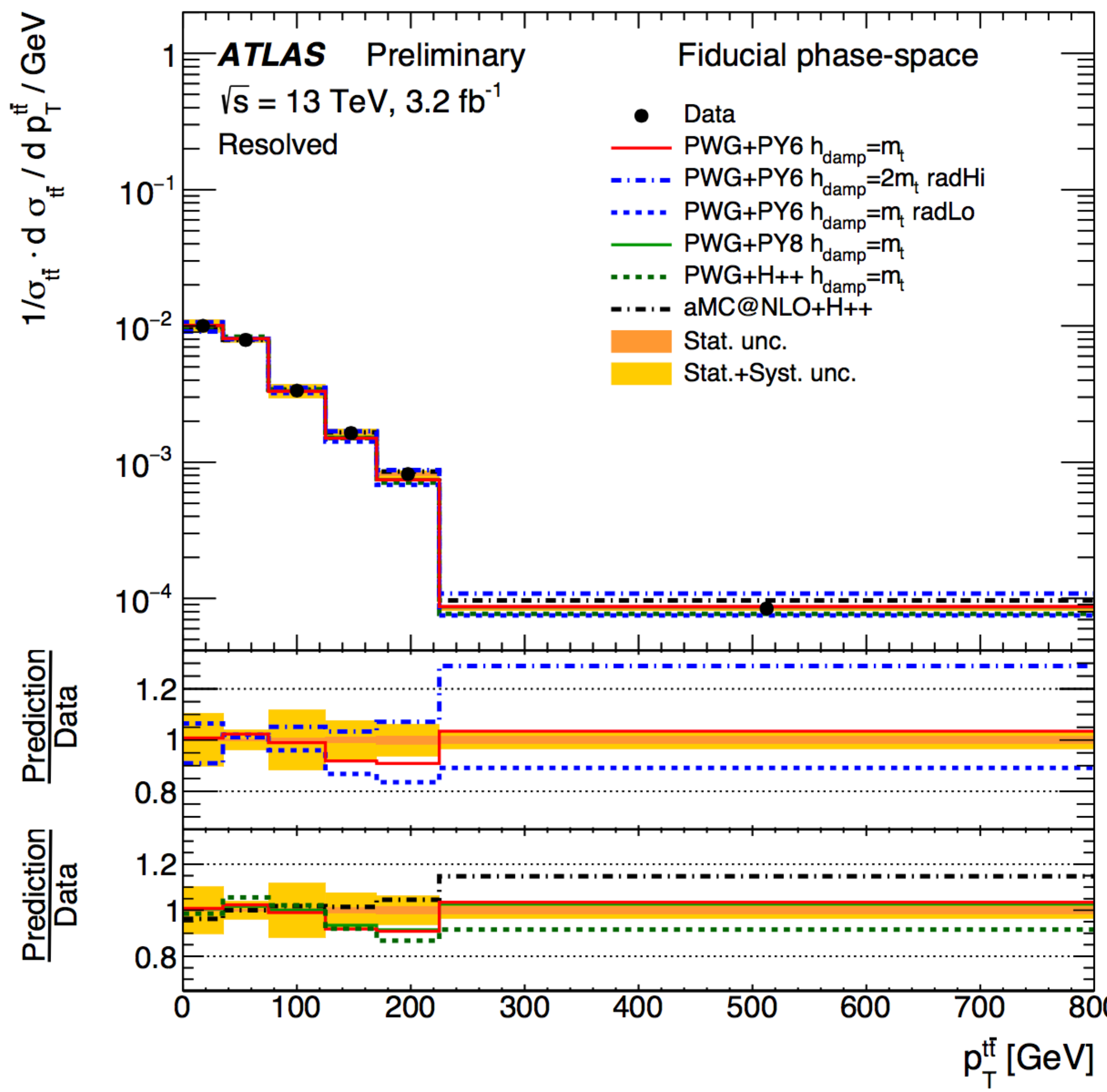
arXiv:1511.04716

13 TeV

Differential cross-sections

- Invariant mass & pT of top-quark pair system:





- (No bump at 750 GeV!)

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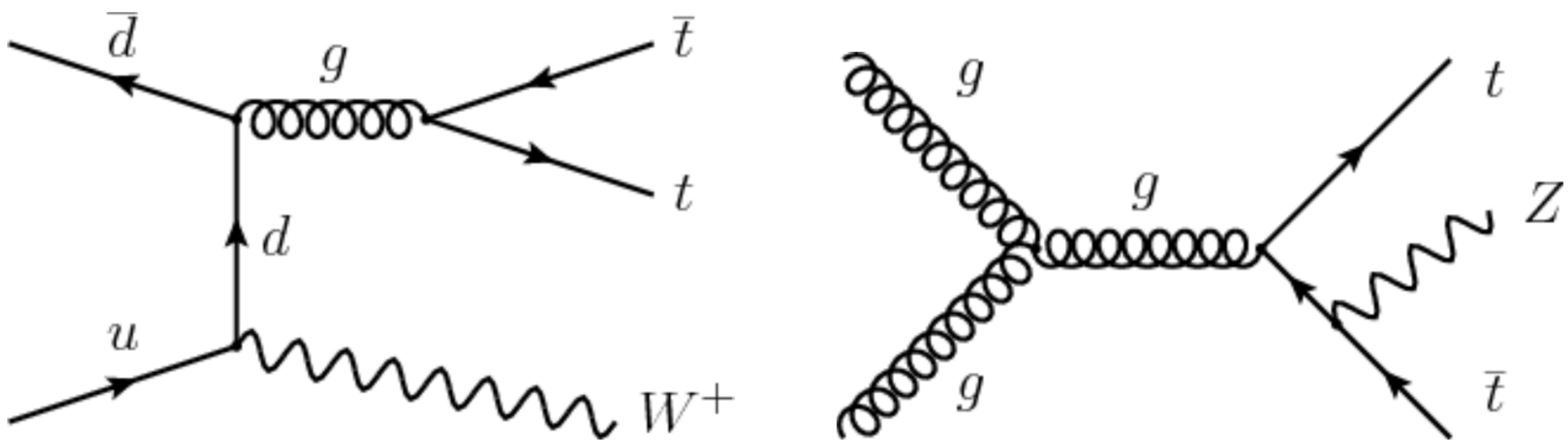
ttV Production

- Large datasets give access to rare tt+W and tt+Z processes.
  - ttZ: Direct probe of top-Z coupling (new physics?).
  - ttW: Important background to new physics searches.

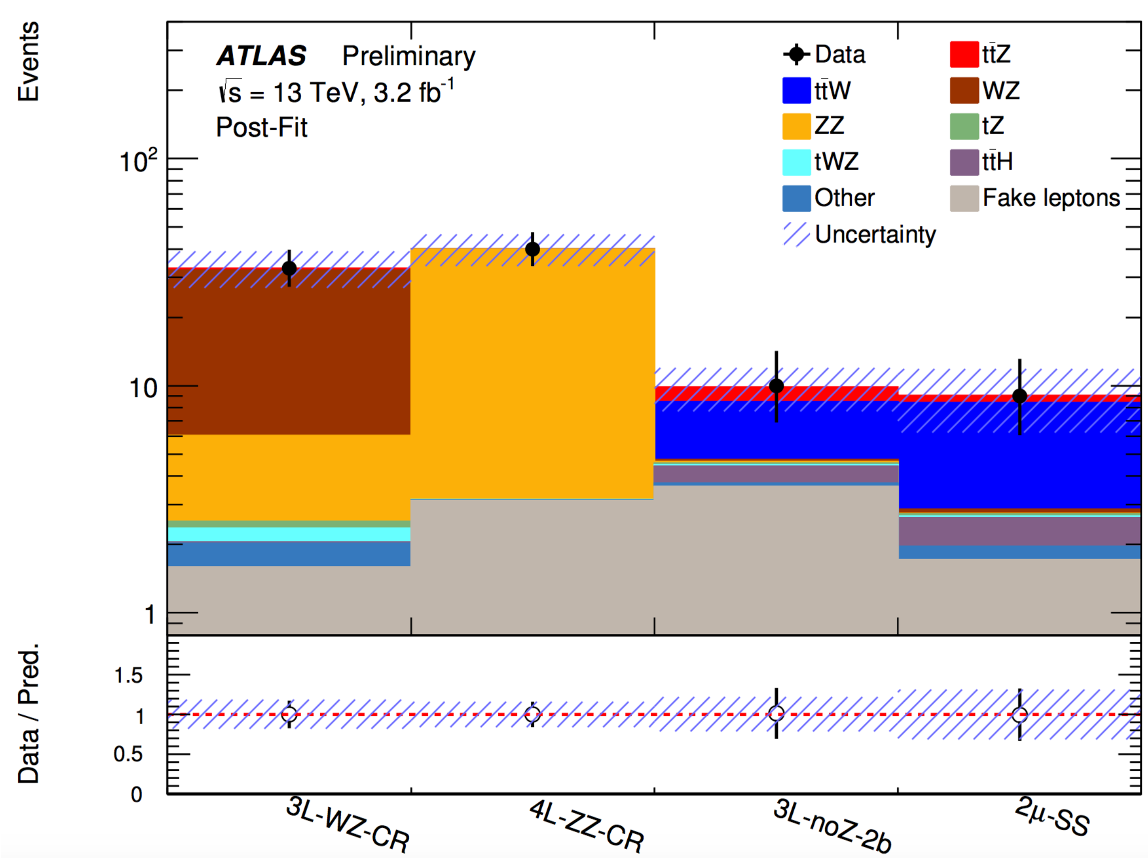


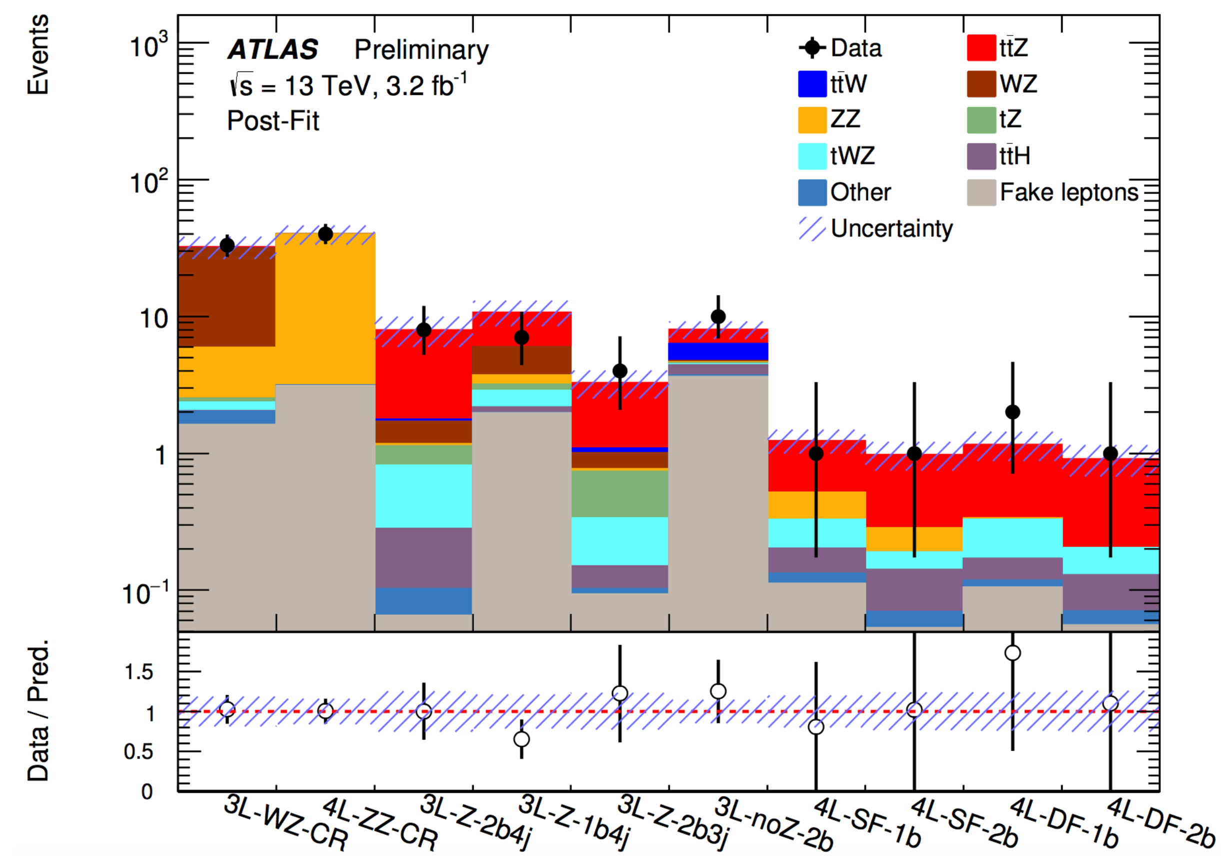
- Use multi-lepton final states to reduce background:
  - 2 same-sign charge leptons, 3 or 4 lepton final states.

13 TeV

ttV Production

- 2 same-sign charge leptons, 3 or 4 lepton final states.
    - Split selected events according to lepton-pairings & number of b-jets.
    - Use control regions to constrain WZ & ZZ backgrounds.





$$\sigma(t\bar{t}W) = 1.4 \pm 0.8 \text{ pb}$$
$$\sigma_{\rm SM}(t\bar{t}W) = 0.57 \pm 0.06 \text{ pb}$$

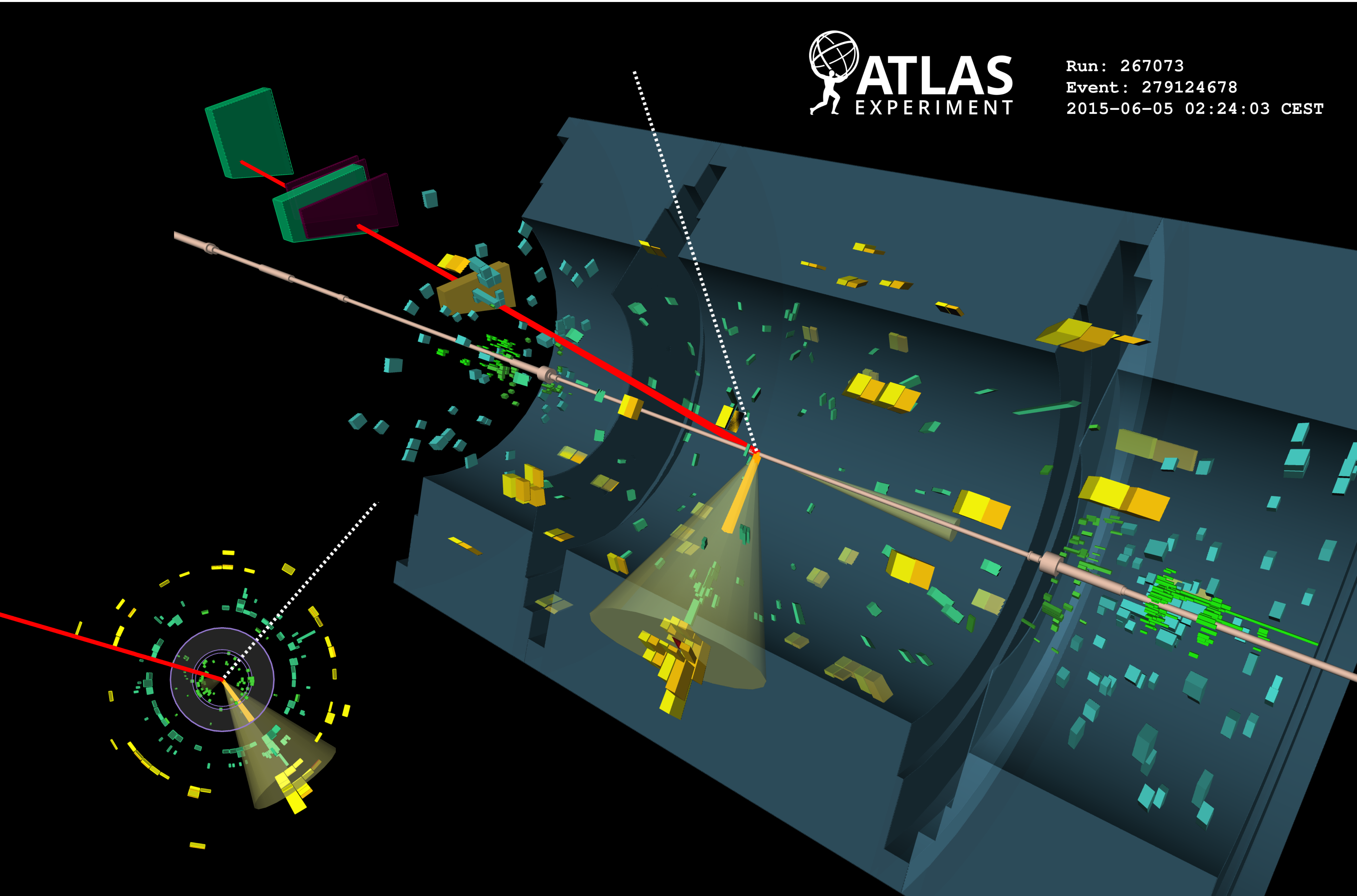
$$\sigma(t\bar{t}Z) = 0.9 \pm 0.3 \text{ pb}$$
$$\sigma_{\rm SM}(t\bar{t}Z) = 0.76 \pm 0.08 \text{ pb}$$

- Statistics limited - big scope improvements with 2016 dataset.

Single top production measurements

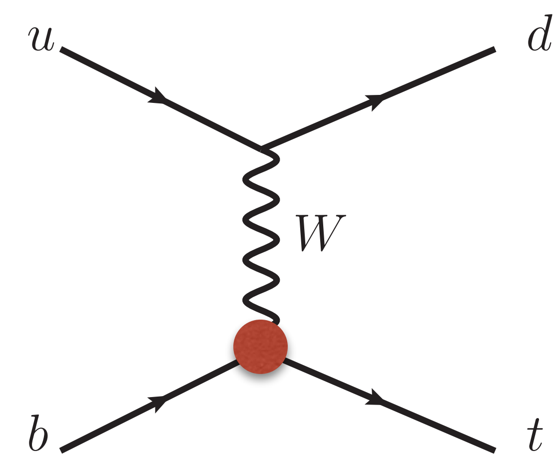
13 TeV

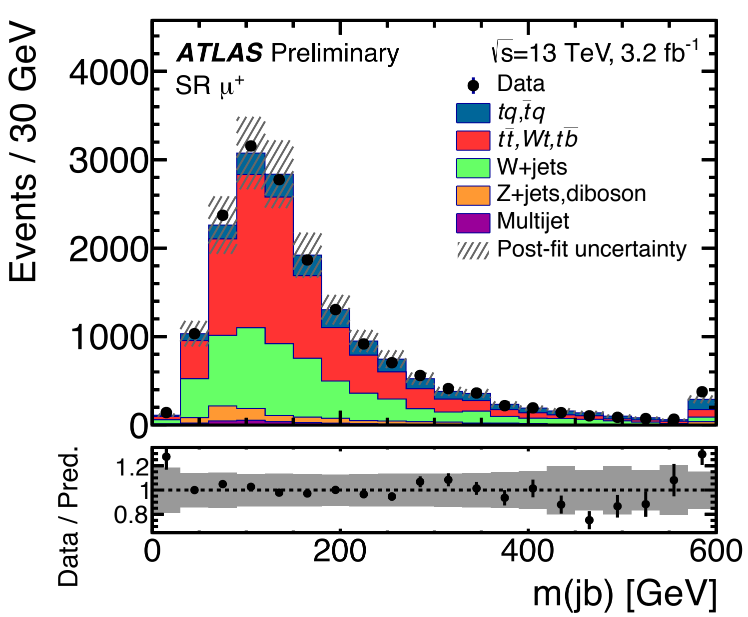
t-channel event

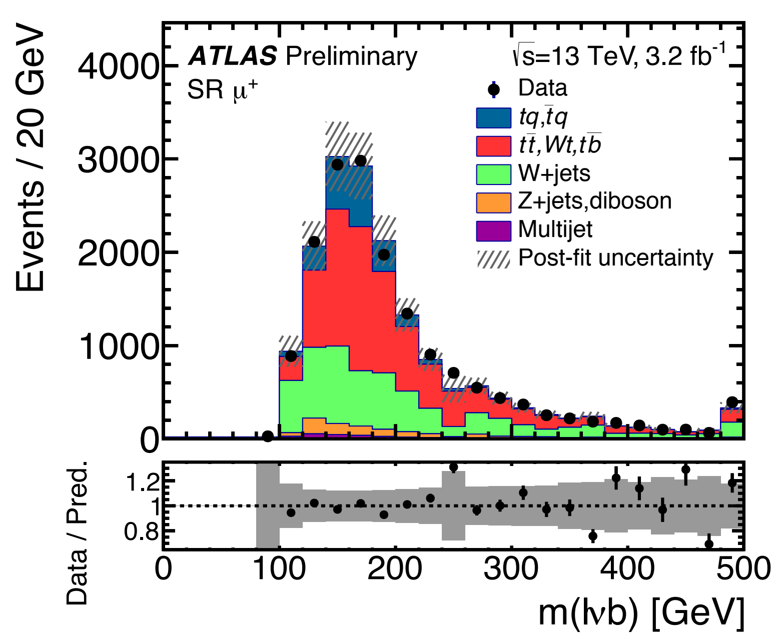


t-channel cross-section

- Largest single-top production mode, directly sensitive to Wtb coupling.
- Select events with 1 muon, 2 jets (1 b-jet) and missing transverse momentum.
- Significant backgrounds from top-quark pair and W+jets production.
- Combine multiple variables together in Neural Network to separate signal from background.







13 TeV

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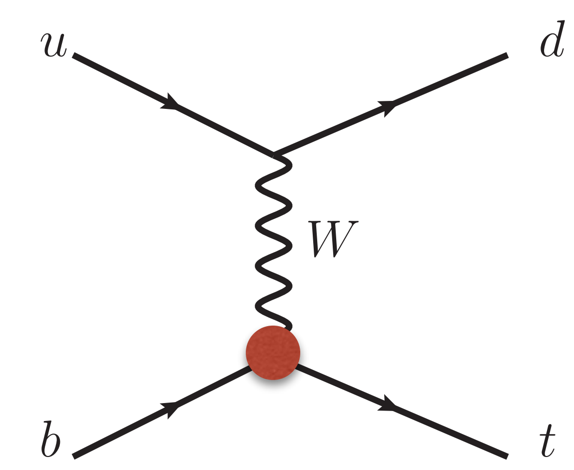

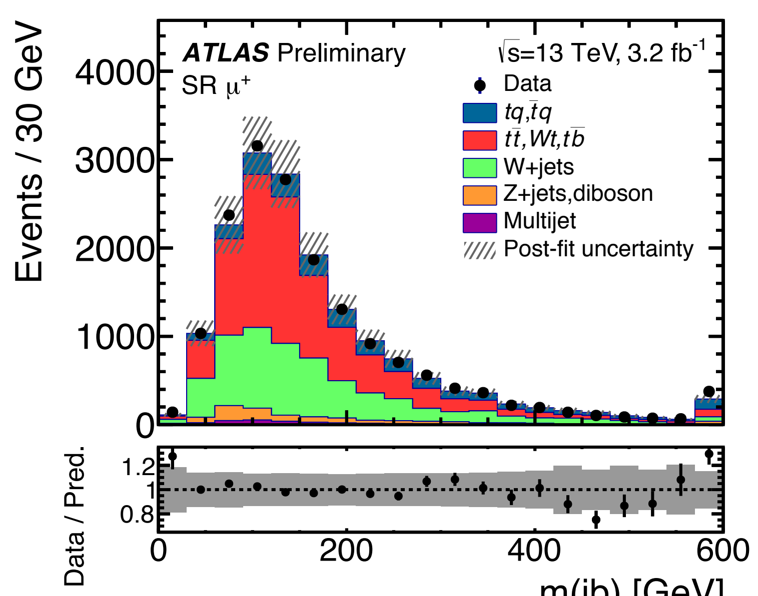

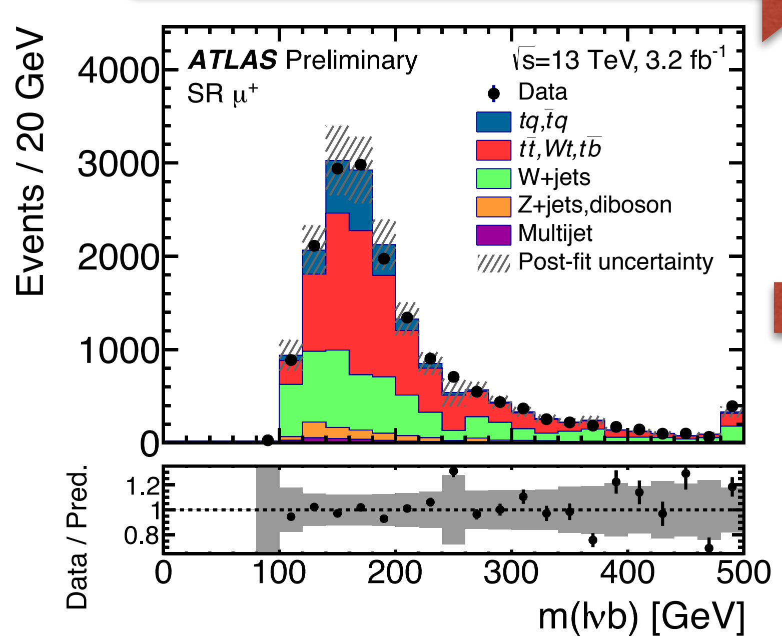

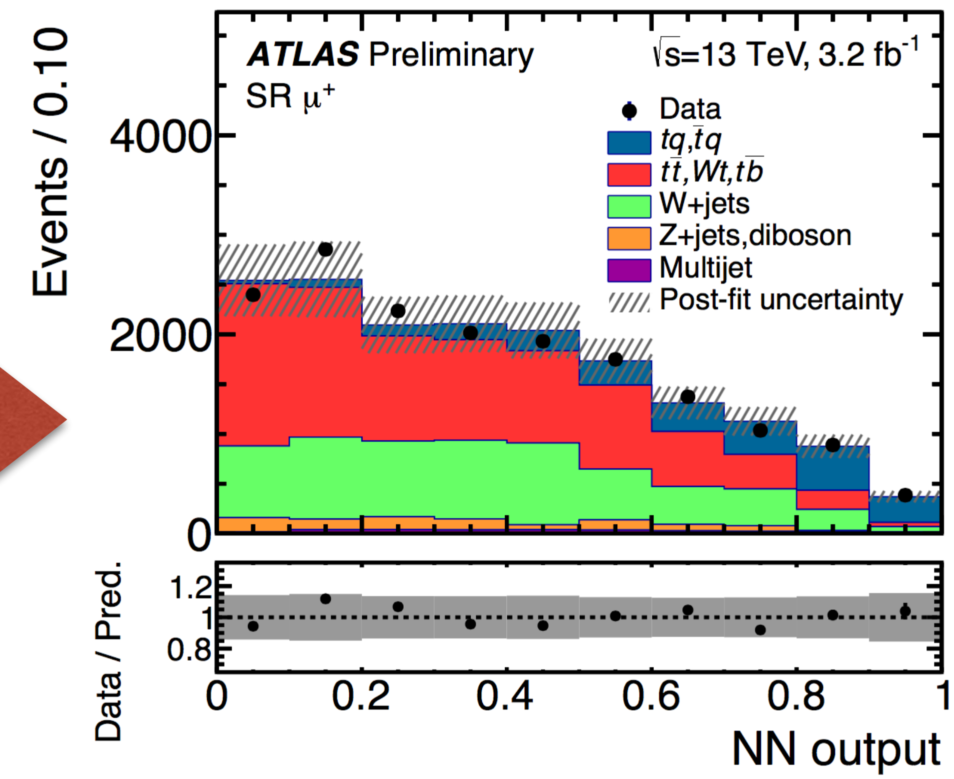

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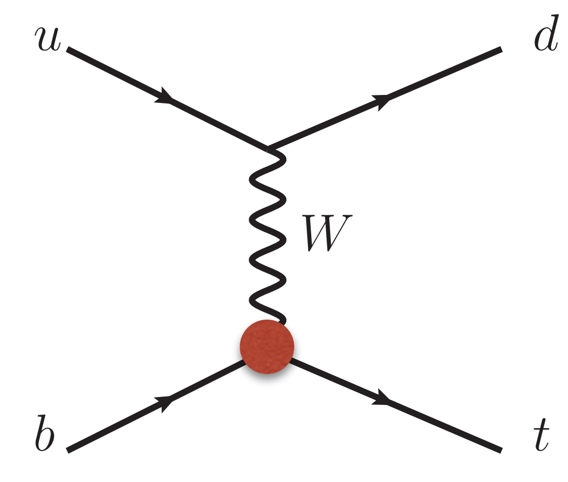
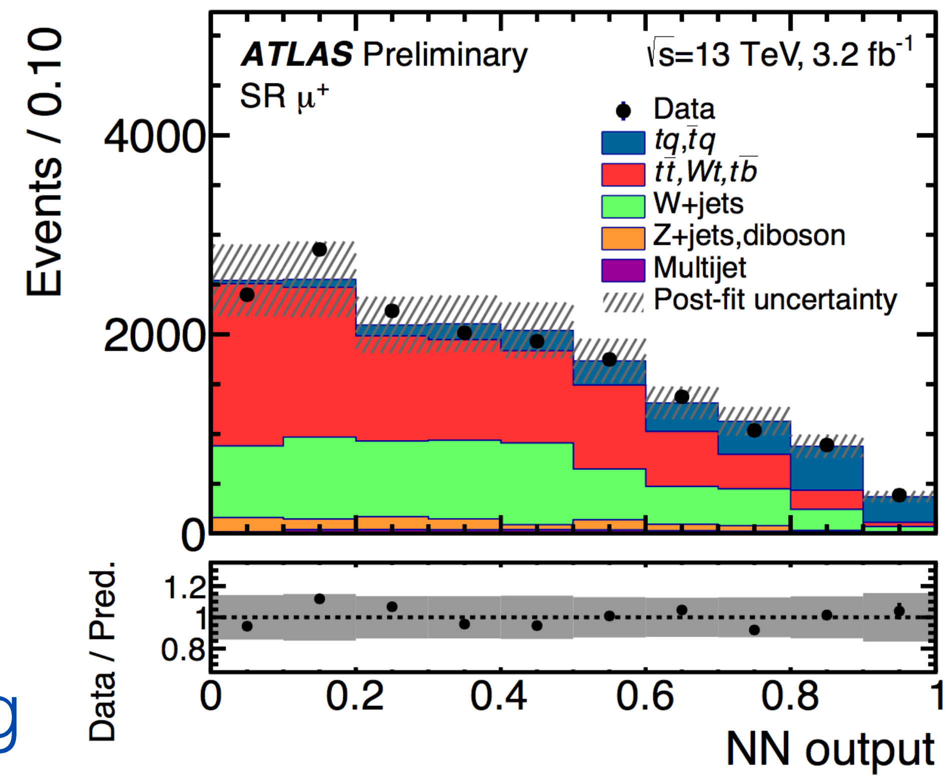


$$|f_{\rm LV} \cdot V_{tb}| = 1.03 \pm 0.11$$

$$\sigma(\bar{t}q) = 96 \pm 24 \text{ pb} \quad \sigma(tq) = 133 \pm 25 \text{ pb}$$

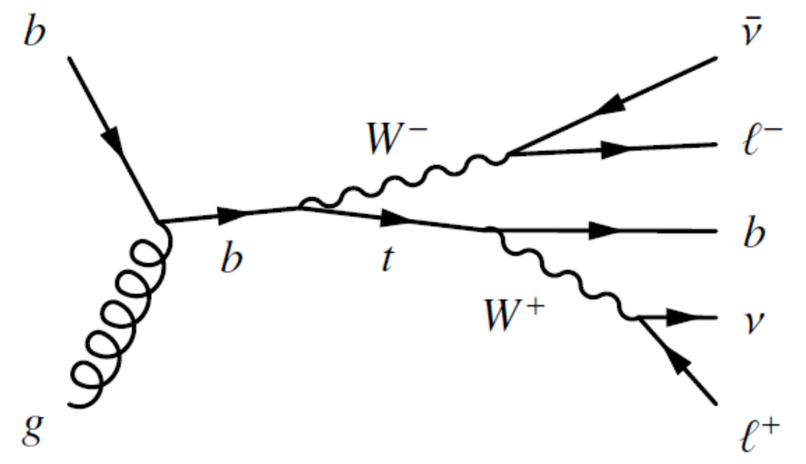
$$\sigma_{\rm SM}(\bar{t}q) = 81^{+4.1}_{-3.6} \text{ pb} \quad \sigma_{\rm SM}(tq) = 136^{+5.4}_{-4.6} \text{ pb}$$



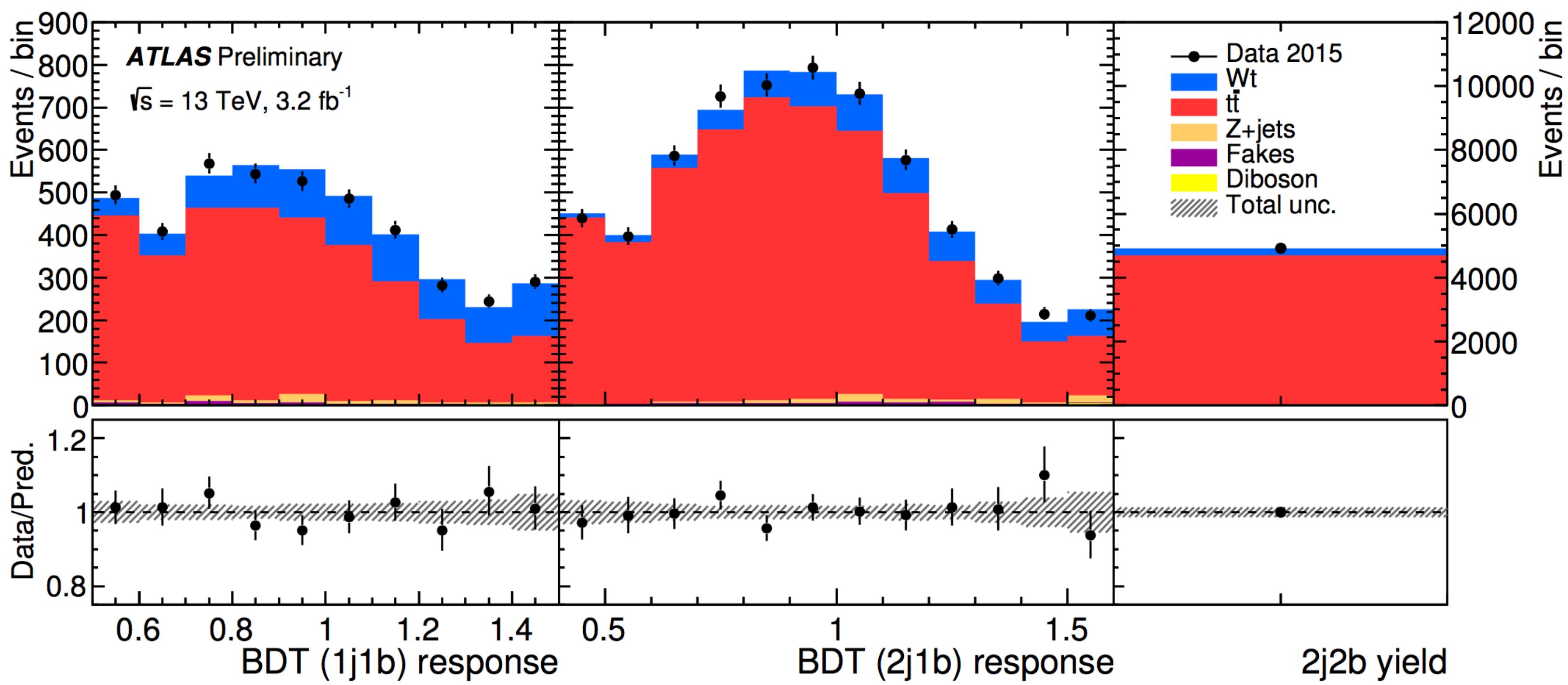
- Largest systematics: MC modelling & b-tagging

Wt cross-section

University of Glasgow



- Second largest production mode at LHC.
  - At NLO QCD, interferes with top-quark pair-production.
- Select events with an eμ pair and split by jet multiplicity:
  - 1b1j, 1b2j: signal regions; 2b2j: ttbar control region
- Combine multiple variables together in BDT to separate signal from ttbar background.

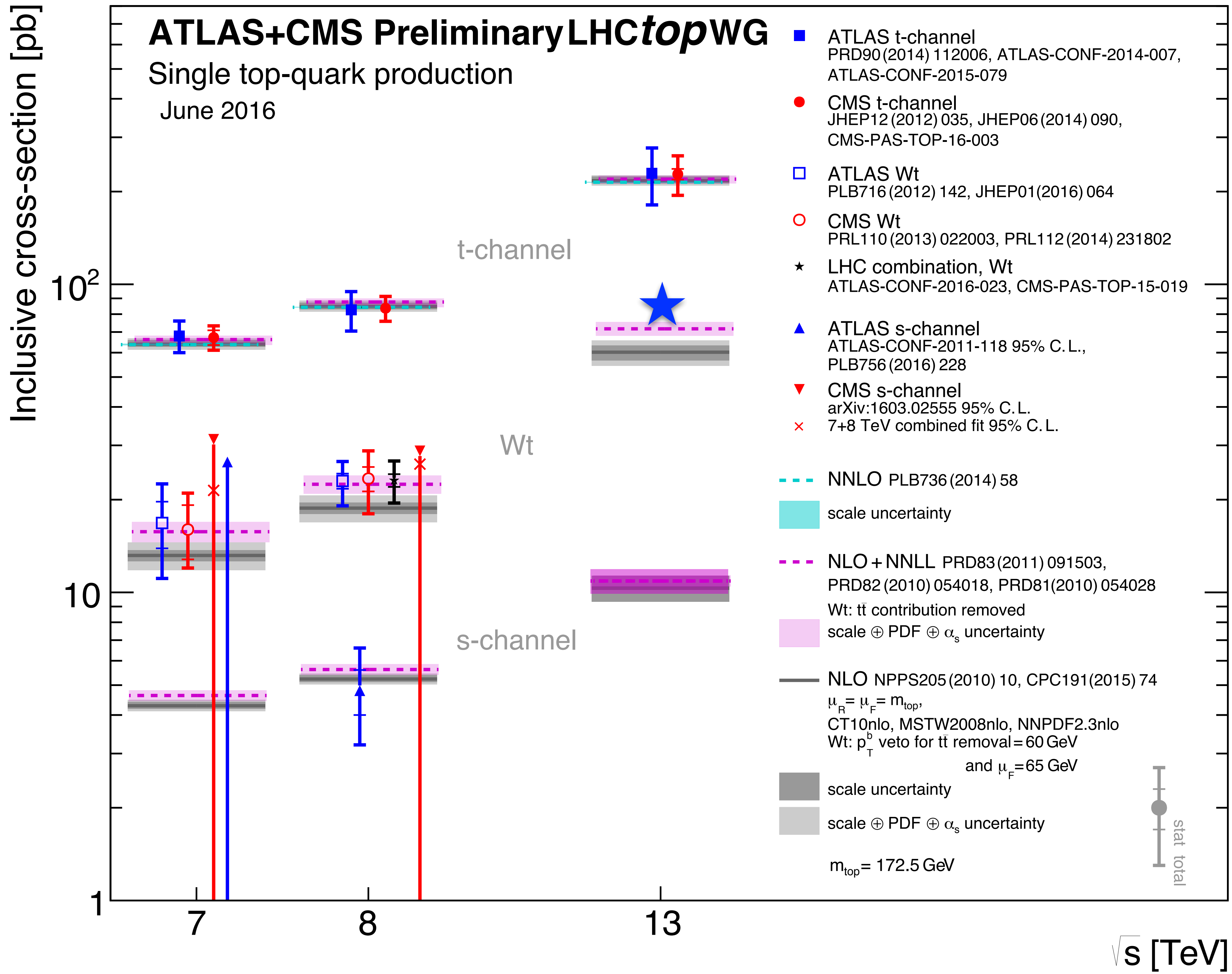


$$\sigma(Wt) = 94 \pm 10\ (\text{stat.})^{+28}_{-23}\ (\text{syst.})\ \text{pb}$$

$$\sigma_{SM}(Wt) = 71.7 \pm 3.8\ \text{pb}$$

13 TeV

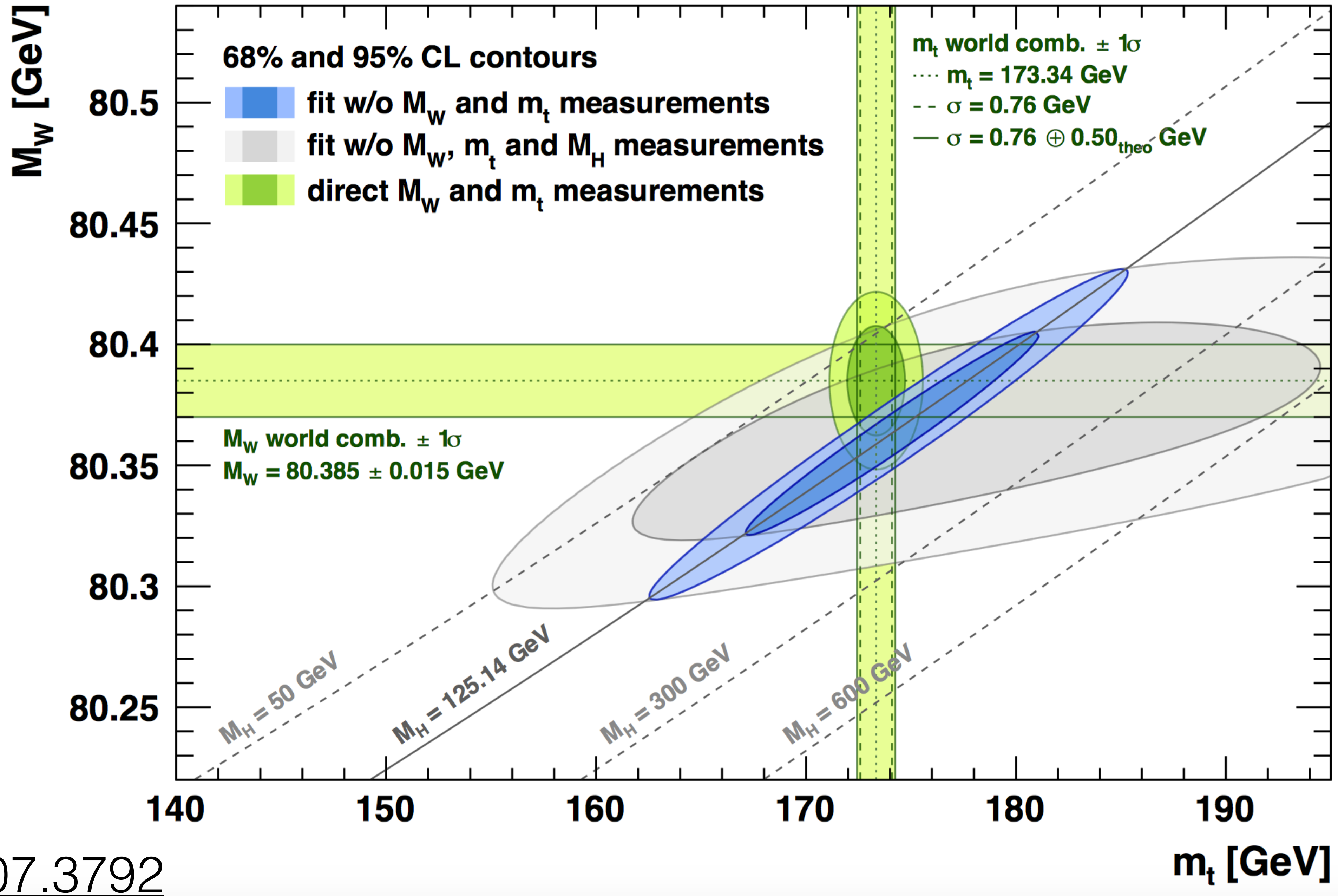
Single-top cross-sections



Top properties measurements

The top quark mass

- Top quark mass critical to understanding self-consistently of SM:

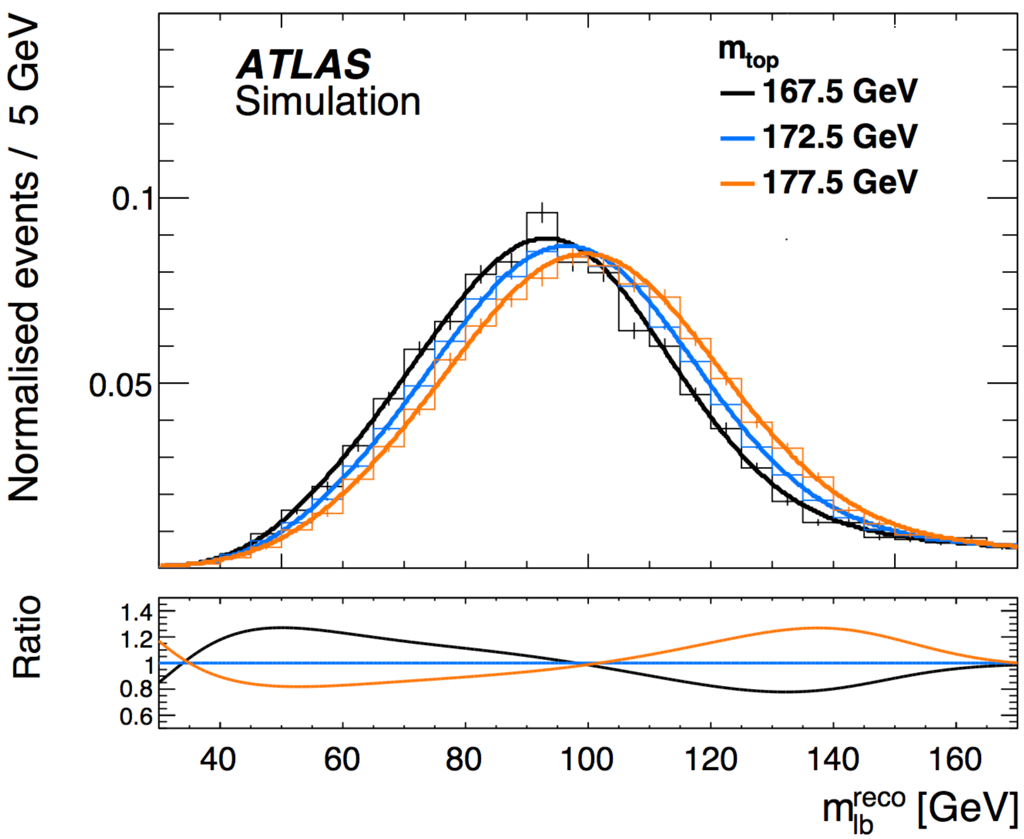


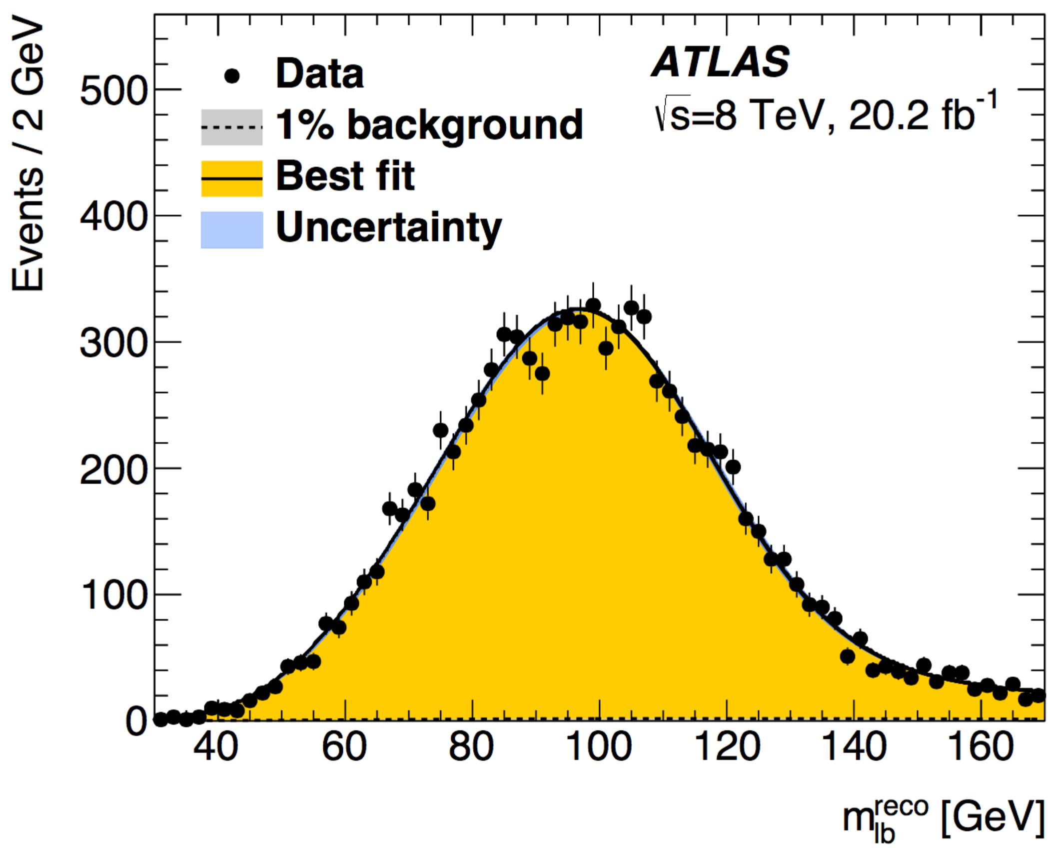
arXiv:1407.3792

8 TeV

The top quark mass

- Dilepton channel: two neutrinos in the final state, system is under-constrained.
  - Optimised selection on pT(lb) to reduce uncertainties.
  - Use m(lb) as top mass sensitive variable.





- Largest systematic uncertainties: JES, bJES, MC modelling.

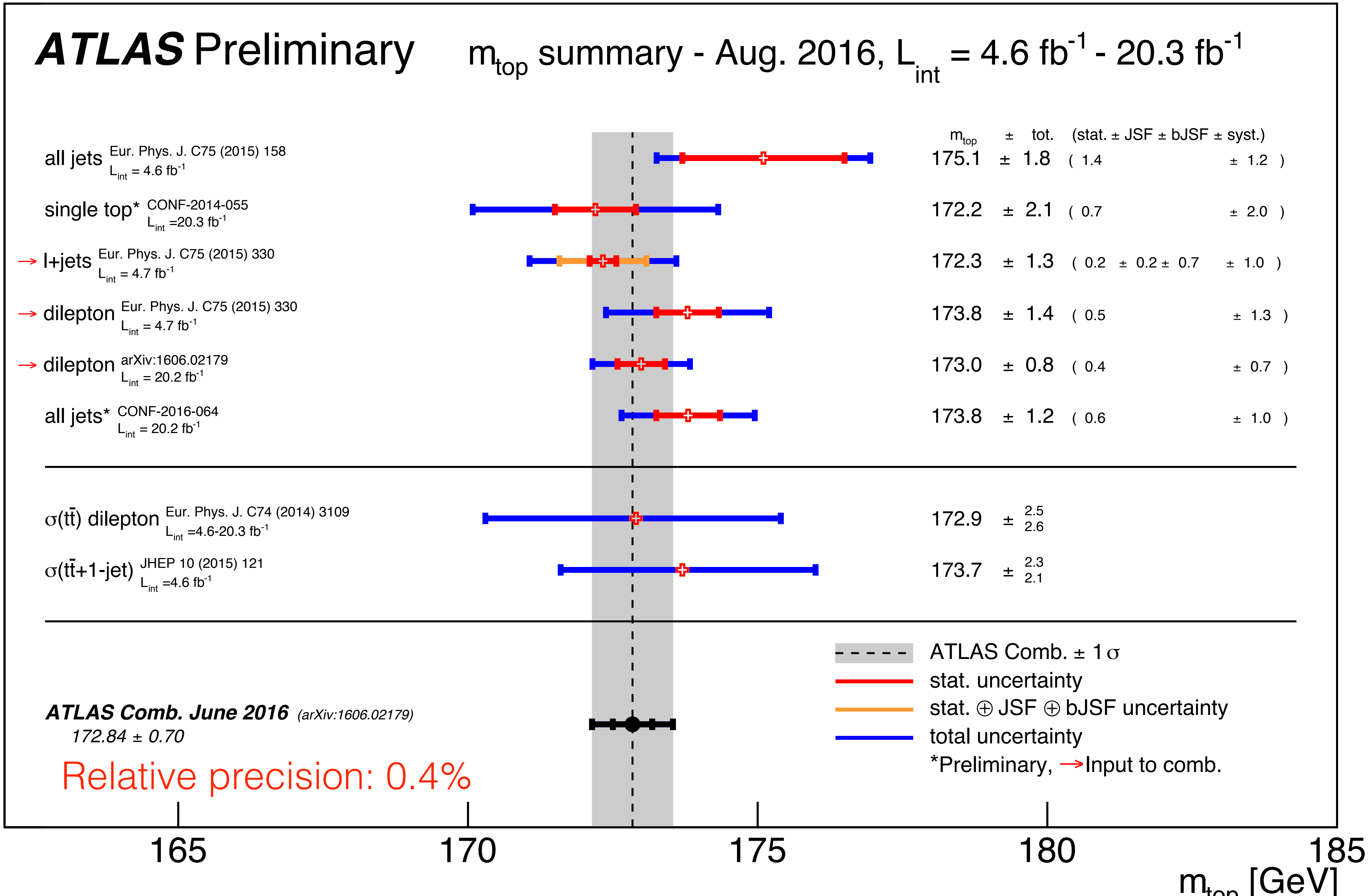
$$m_{top} = 172.99 \pm 0.41\ (\text{stat}) \pm 0.74\ (\text{syst})\ \text{GeV}$$

Most precise measurement in dilepton channel to date

arXiv:1606.02179

7+8 TeV

The top quark mass



Summary

- The top quark is (still) the heaviest fundamental particle.
  - Top sector could be linked to BSM physics.
  - Top quark allows us to study a ‘bare’ quark.
- First set of top measurements at 13 TeV, so far in good agreement with Standard Modal.
- No signs of new physics in top measurements yet - looking forward to results from 2016 data and beyond.

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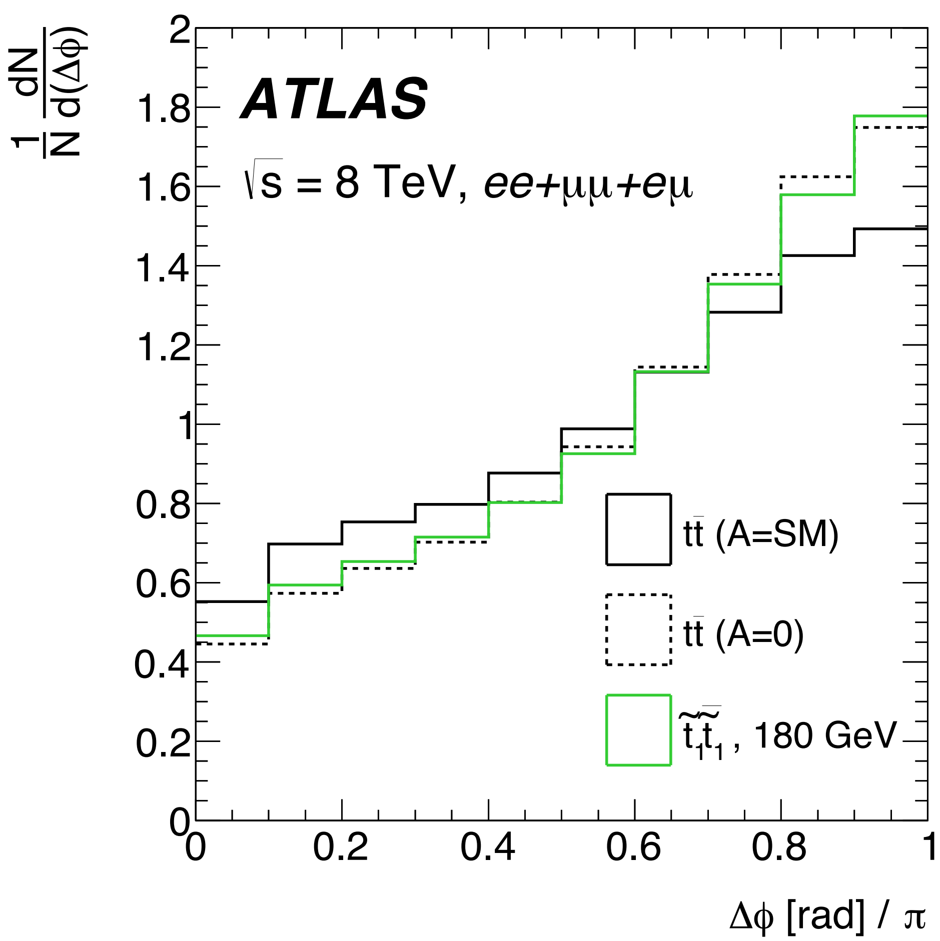
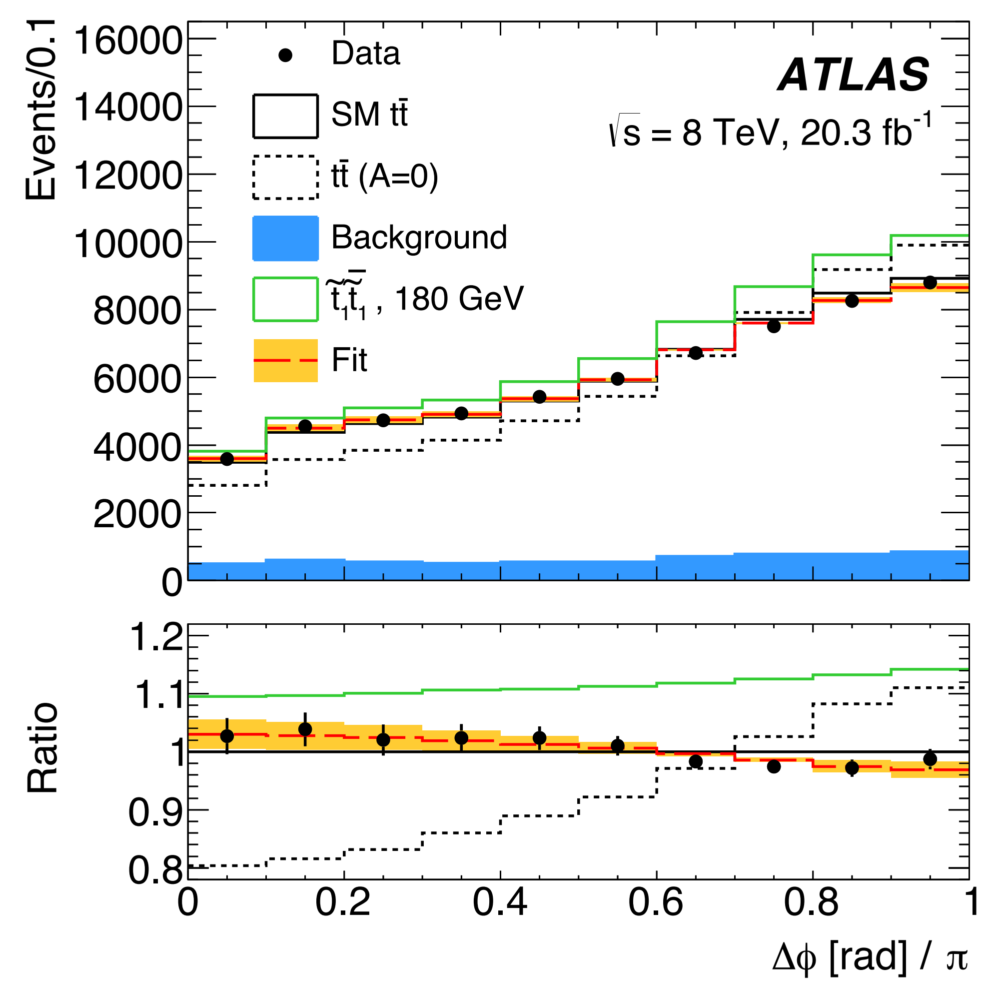
Backup

Spin correlations

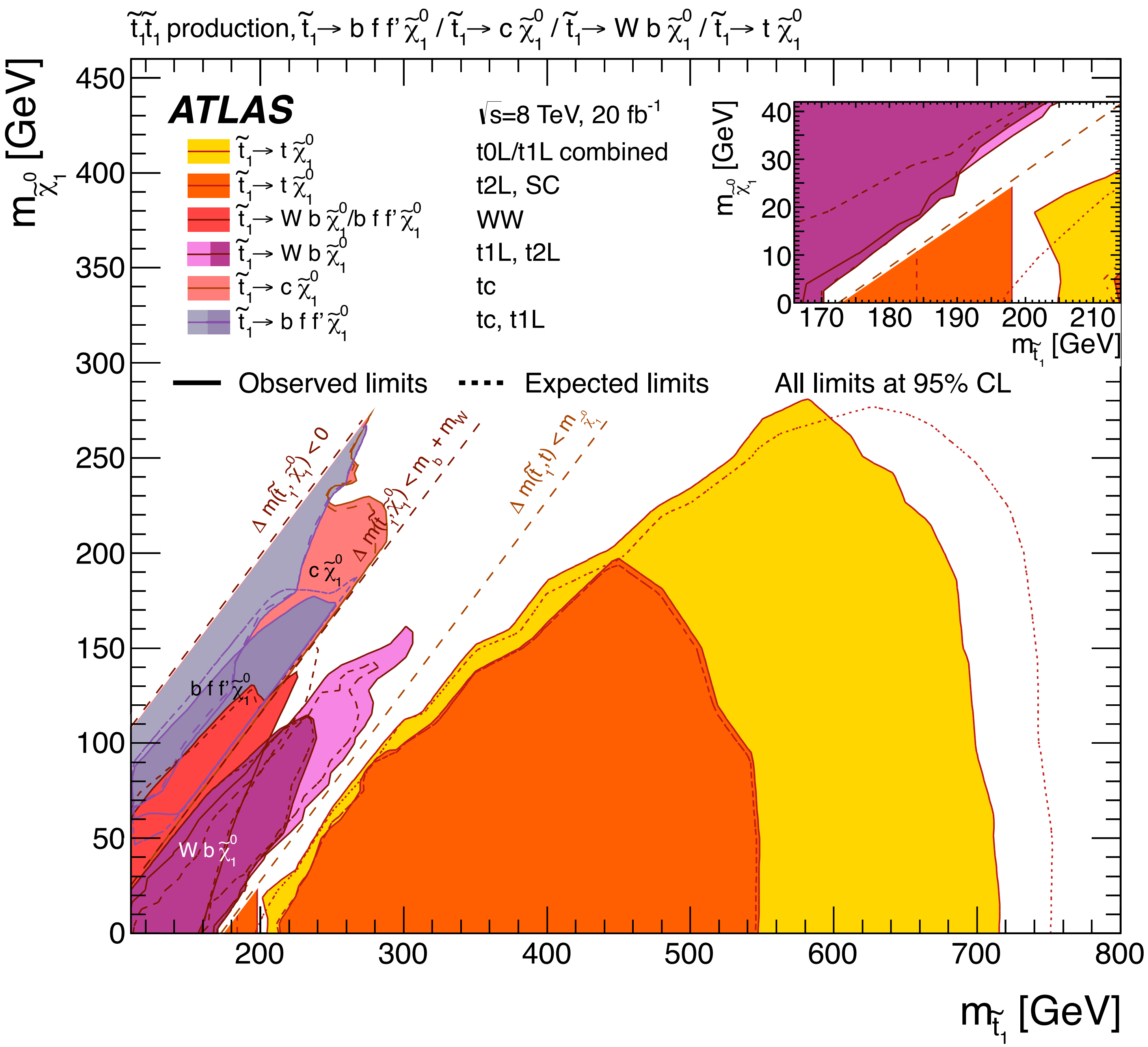
- Since top quark decays before hadronising, spin information is transferred to decay products.
- SM predicts a correlation between the spin directions of the top-quark in pair-production.
    - New physics (e.g. stop quarks) could alter the correlation.
- Observable in the $\Delta\phi$ distribution between the two leptons from the top decay.





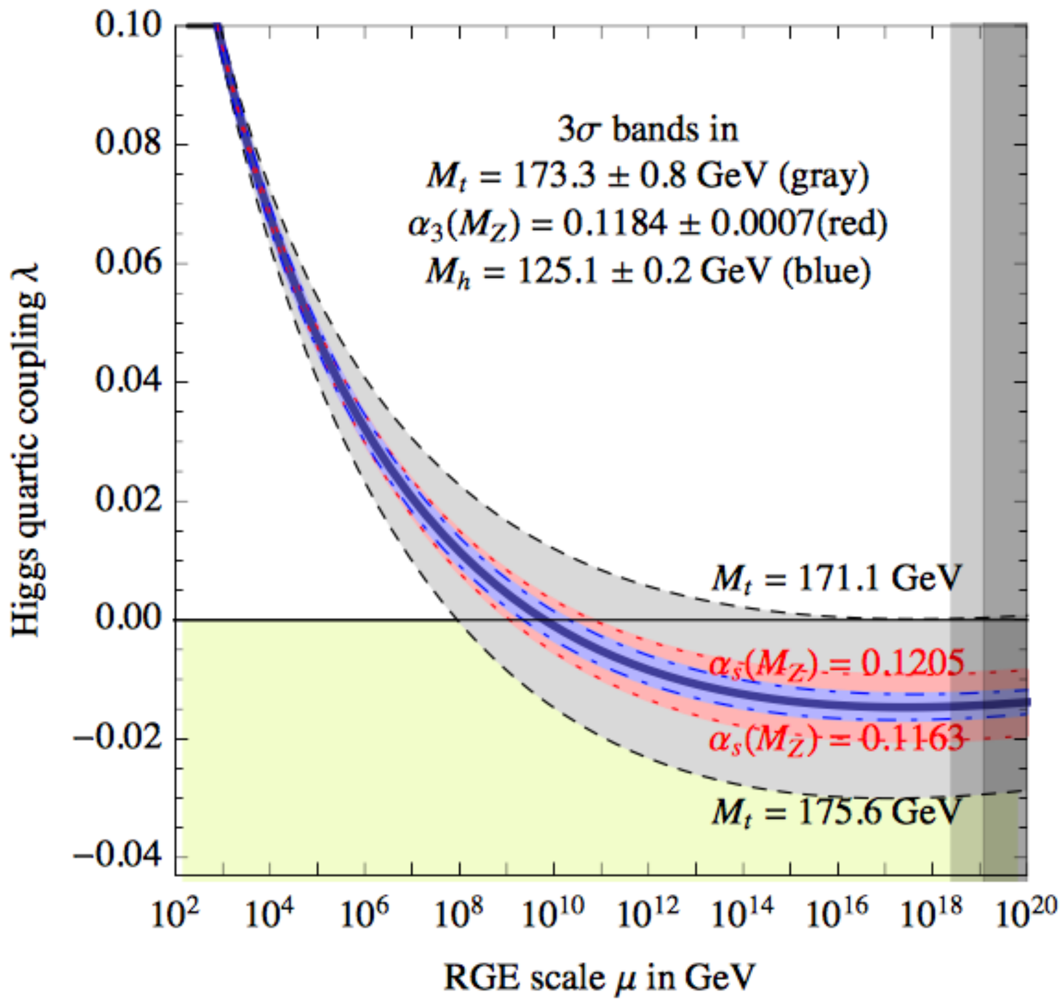
Spin correlations

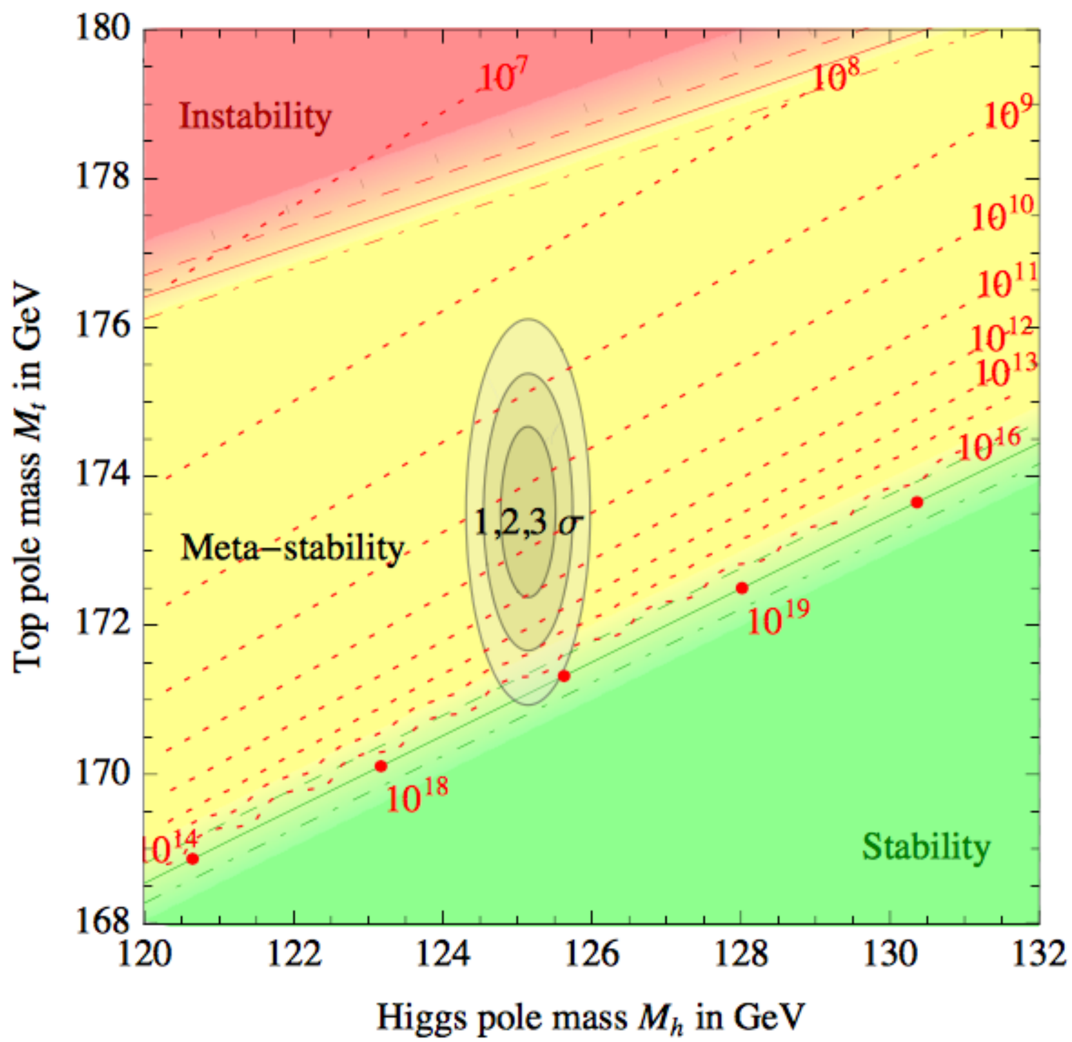
- Good agreement with SM. Use this measurement to set limits on stop quarks ('stealth stop'):



The top quark mass

- Top quark mass critical to understanding if SM is valid to high scales:

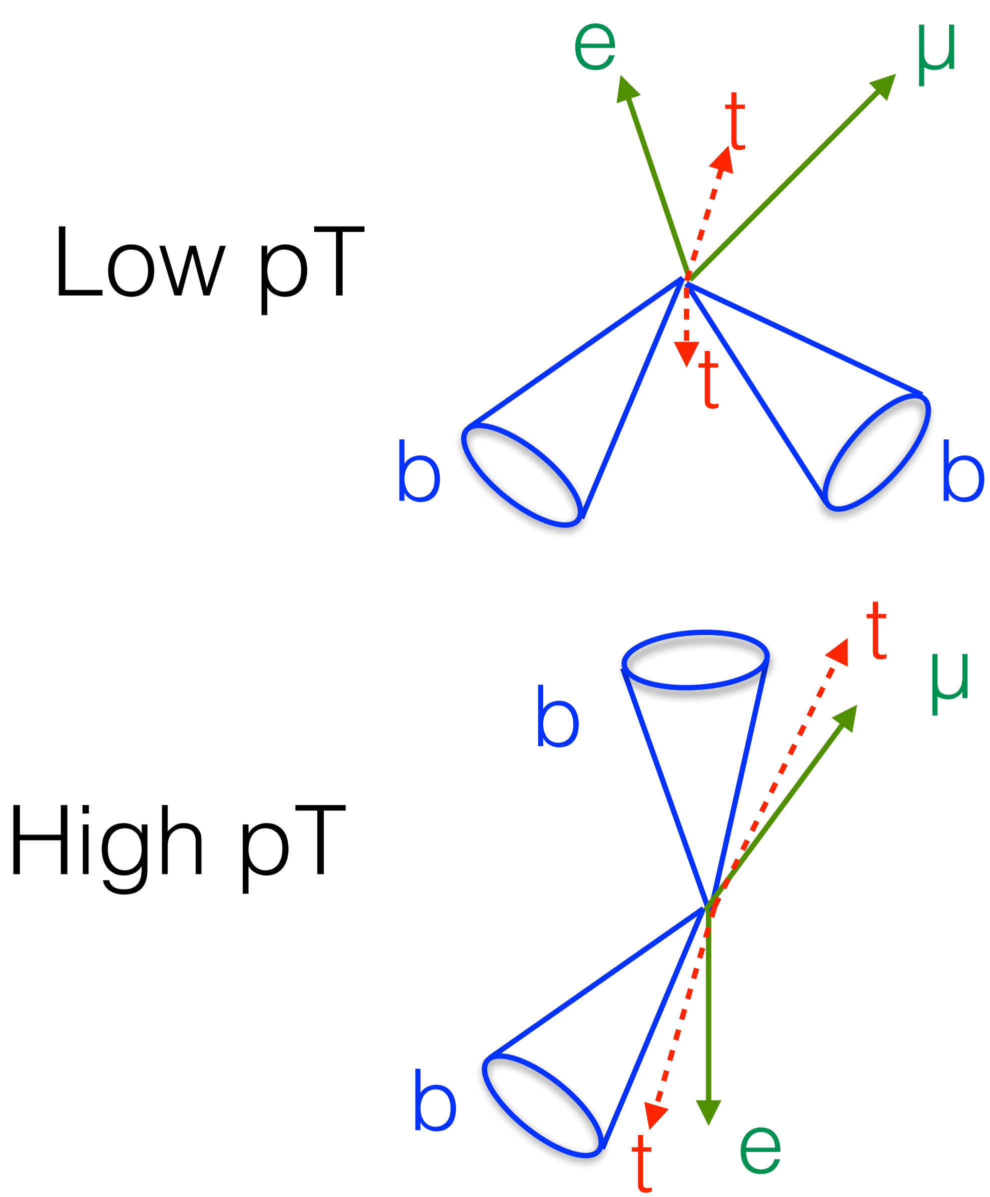


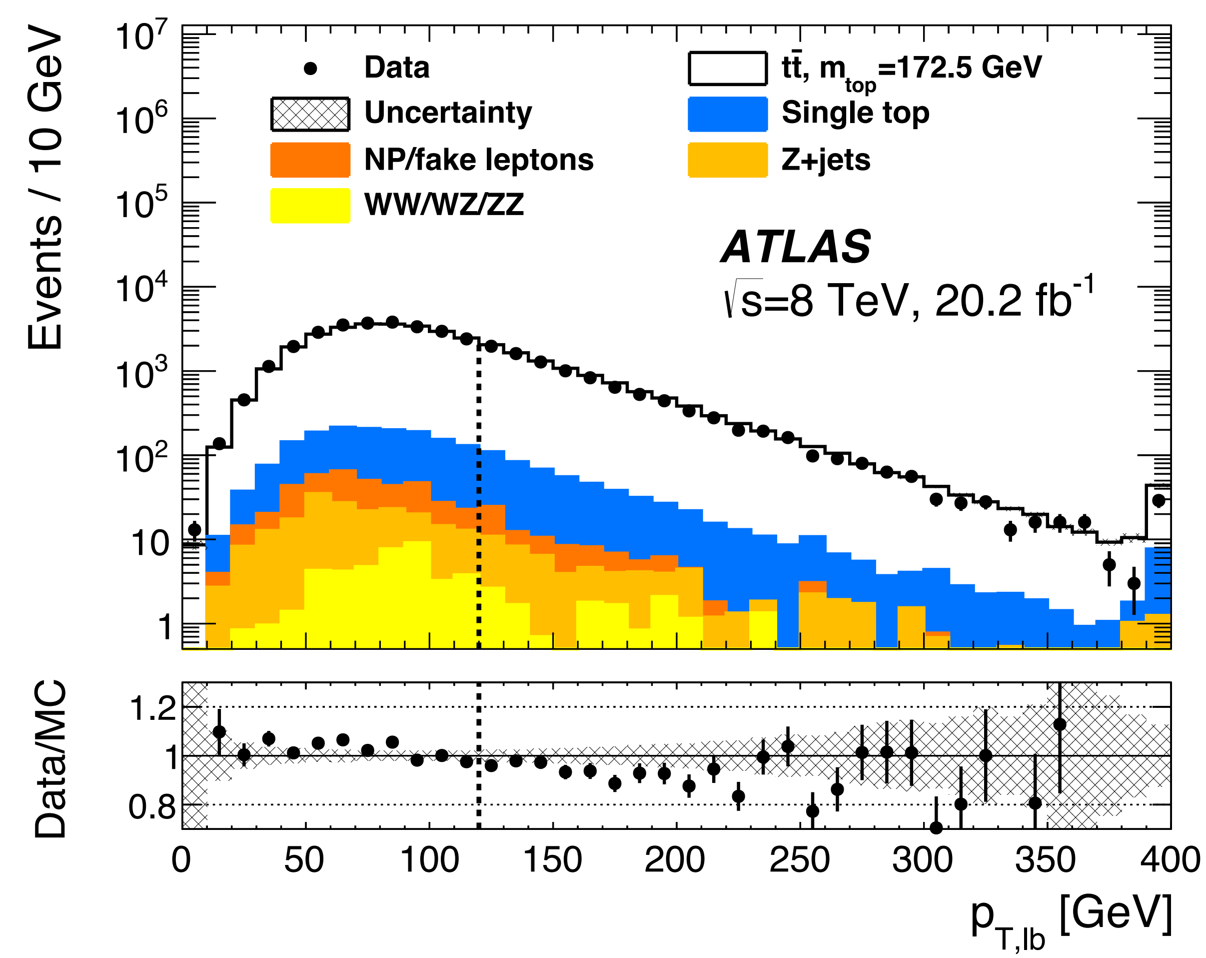


arXiv:1307.3536

The top quark mass

- New measurement in the dilepton channel at 8 TeV.
- Apply cut on pT(lb) - increases fraction of events where correct pairing of lepton & b are selected & reduces total uncertainty.





arXiv:1606.02179