Top quark physics at the LHC

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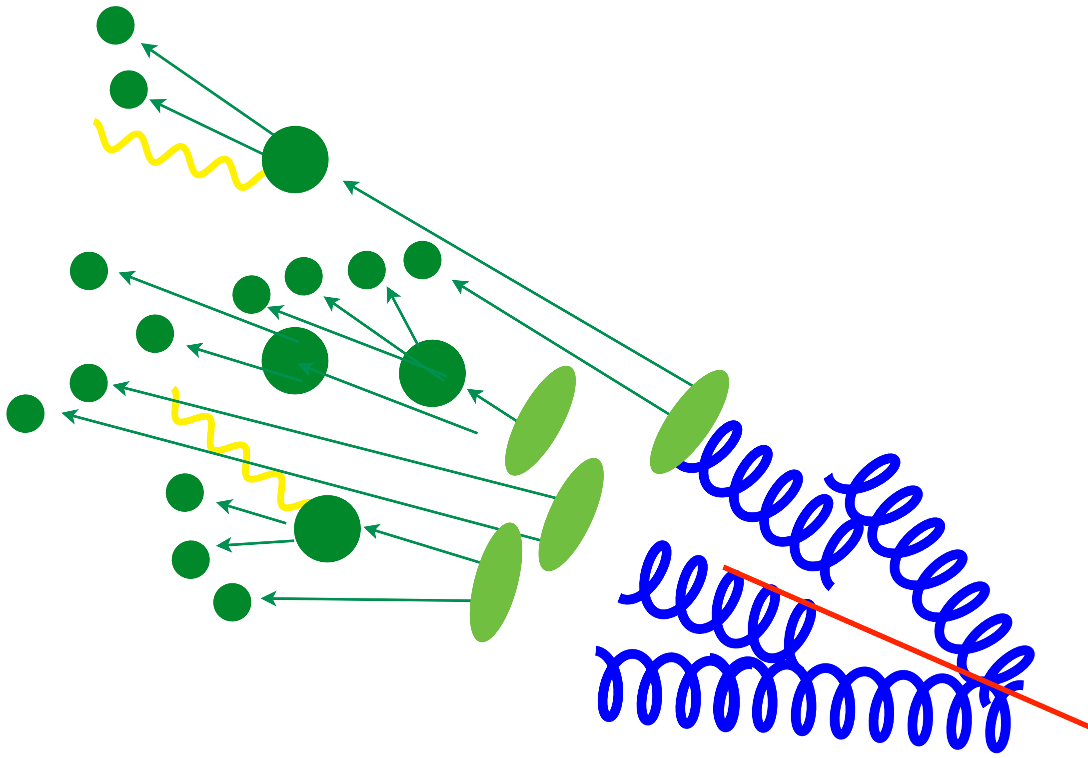
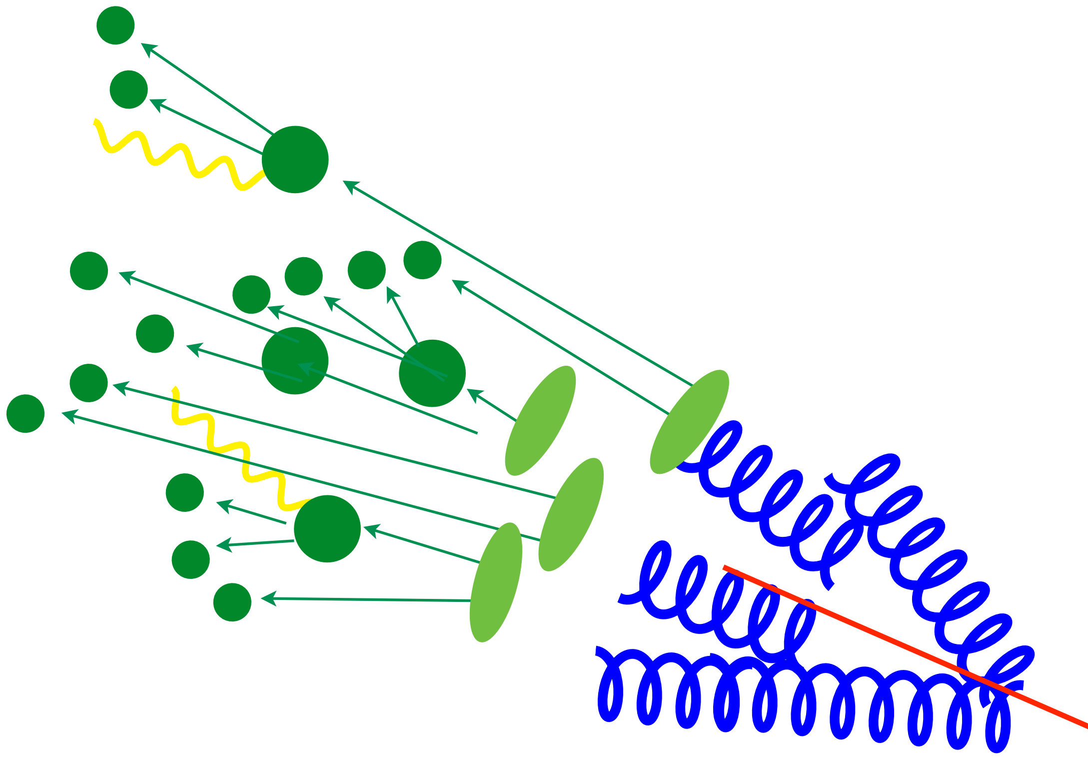
CTEQ school 2019



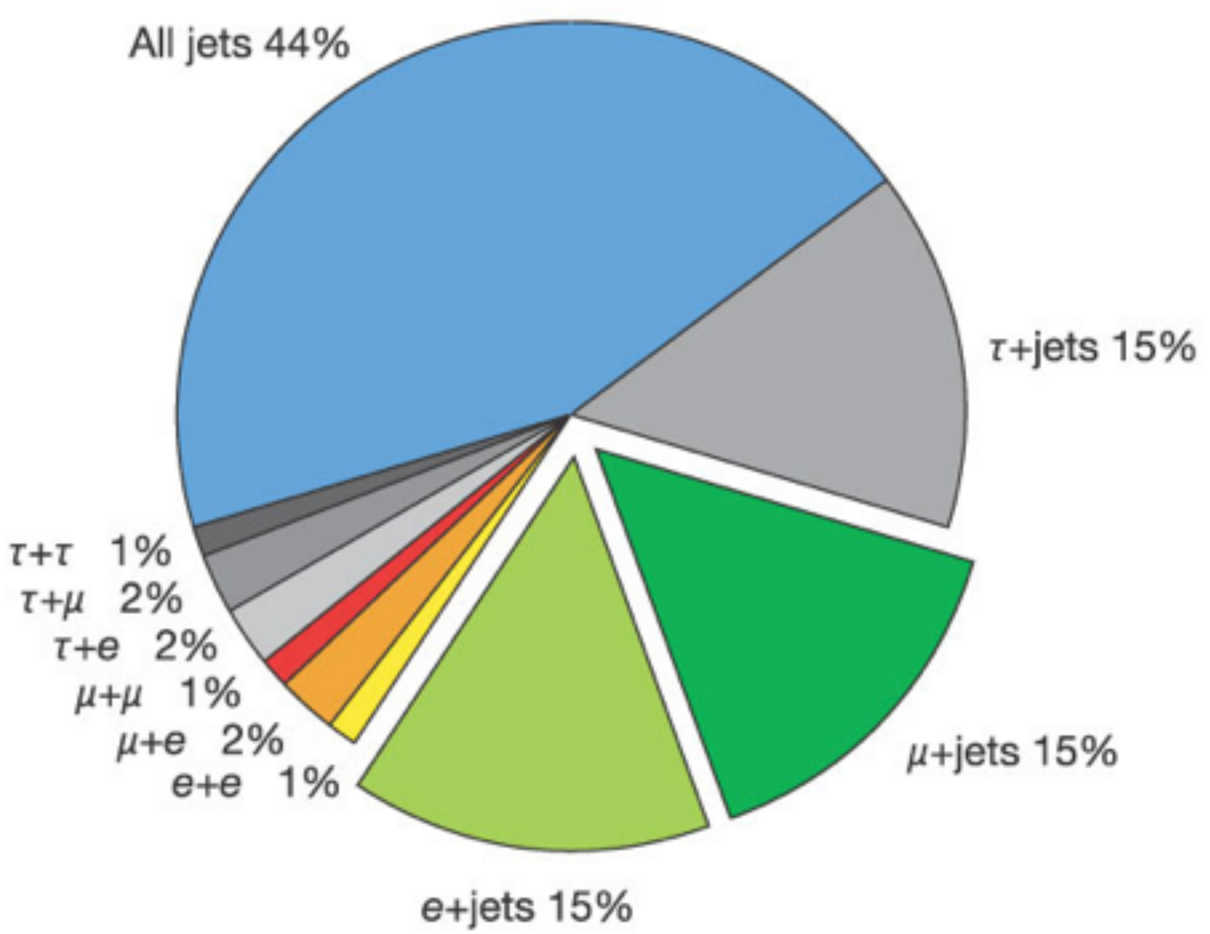
Outline

- Top quark mass
- Top quark properties
  - Jet pull
- Single top
  - Interference with di-top
- BSM with top quarks
  - stops in SUSY

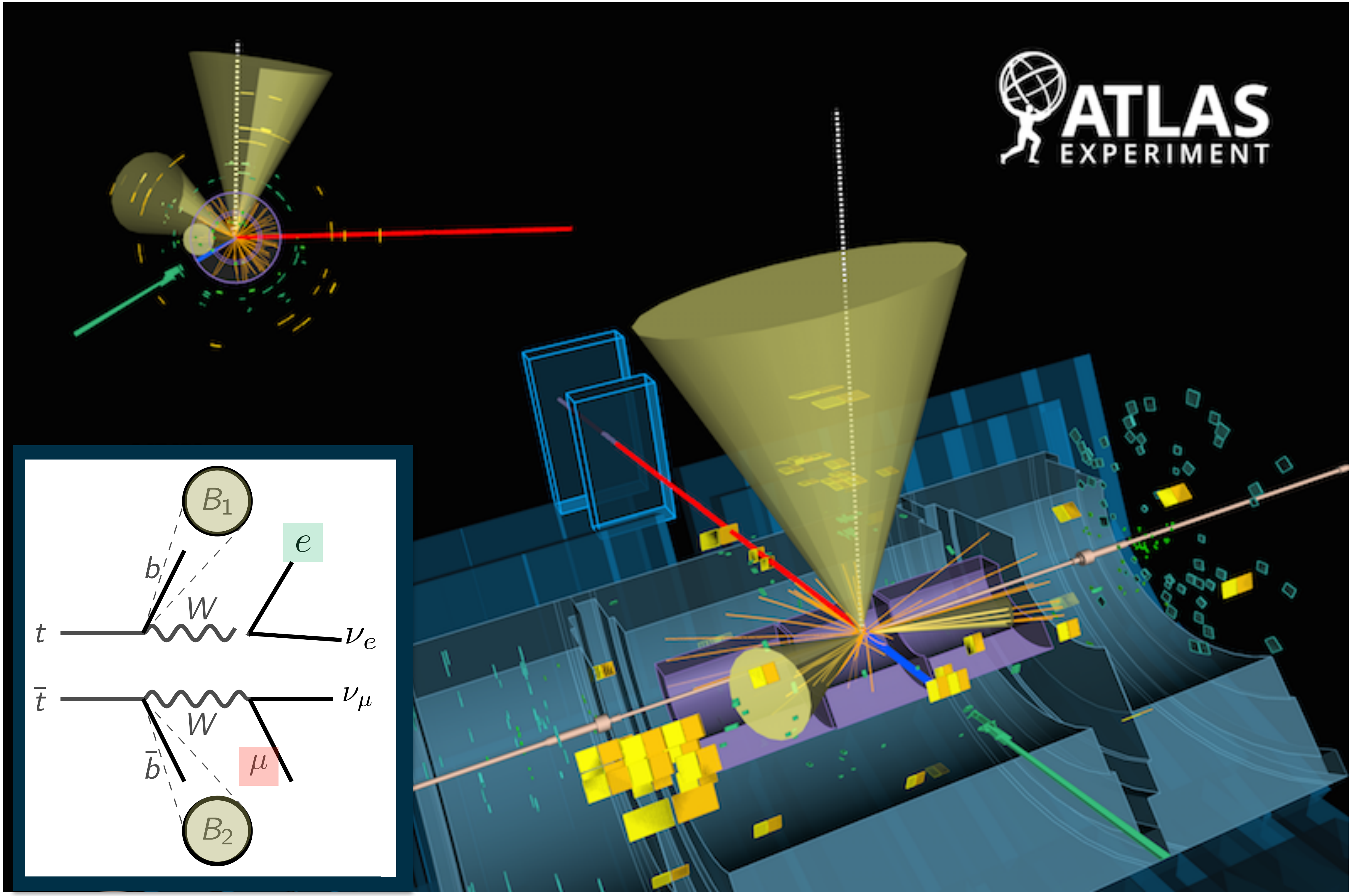


Why is the top quark special?

- Very heavy (mass ~ 175 GeV)
  - Decays ~100% of the time to bW (W on-shell)
  - Quadratic contributions to Higgs boson mass
- Short lived (lifetime ~ few 10^{-25} s)
  - ~Doesn't form hadrons

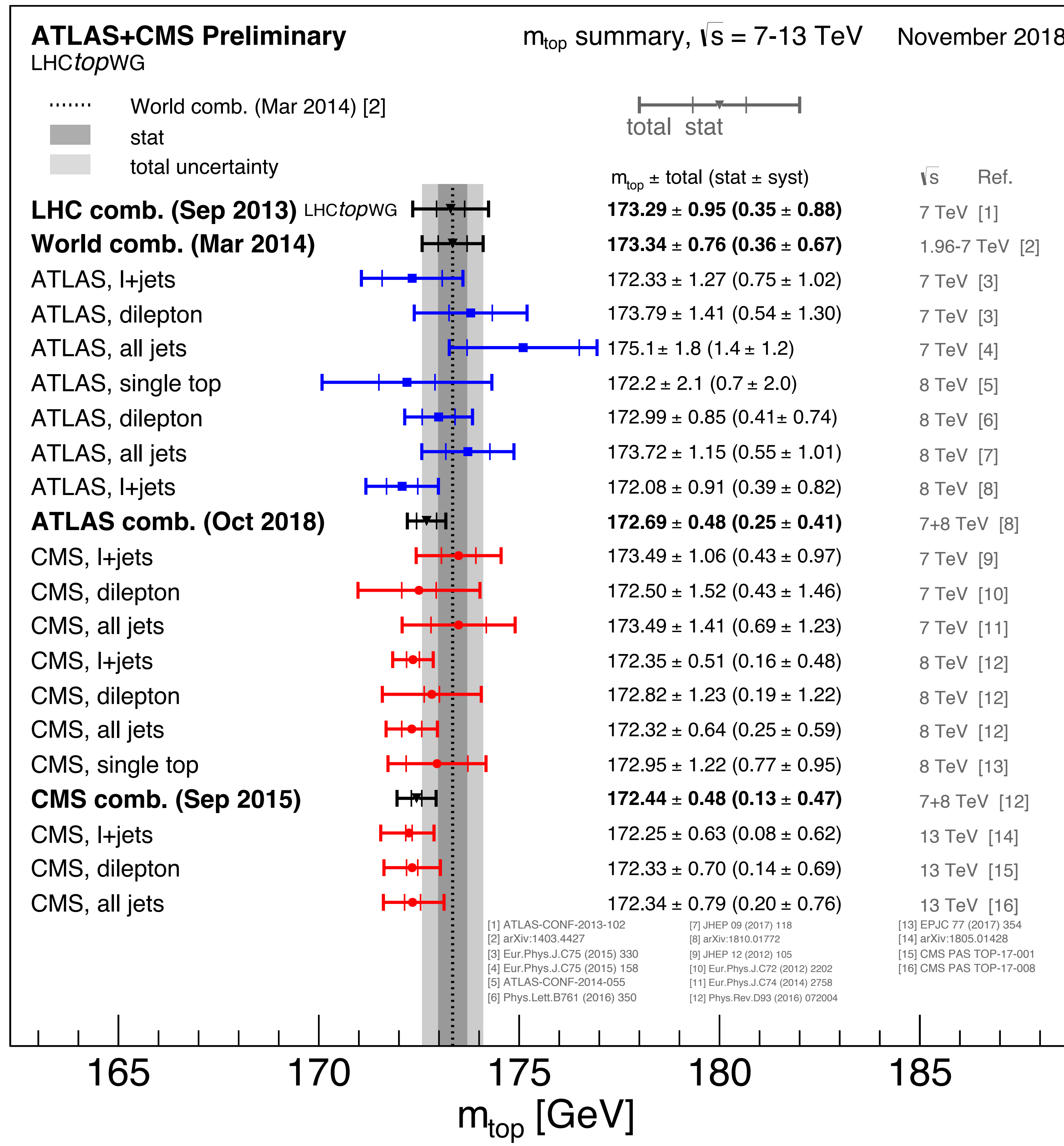


Identifying top quark final states

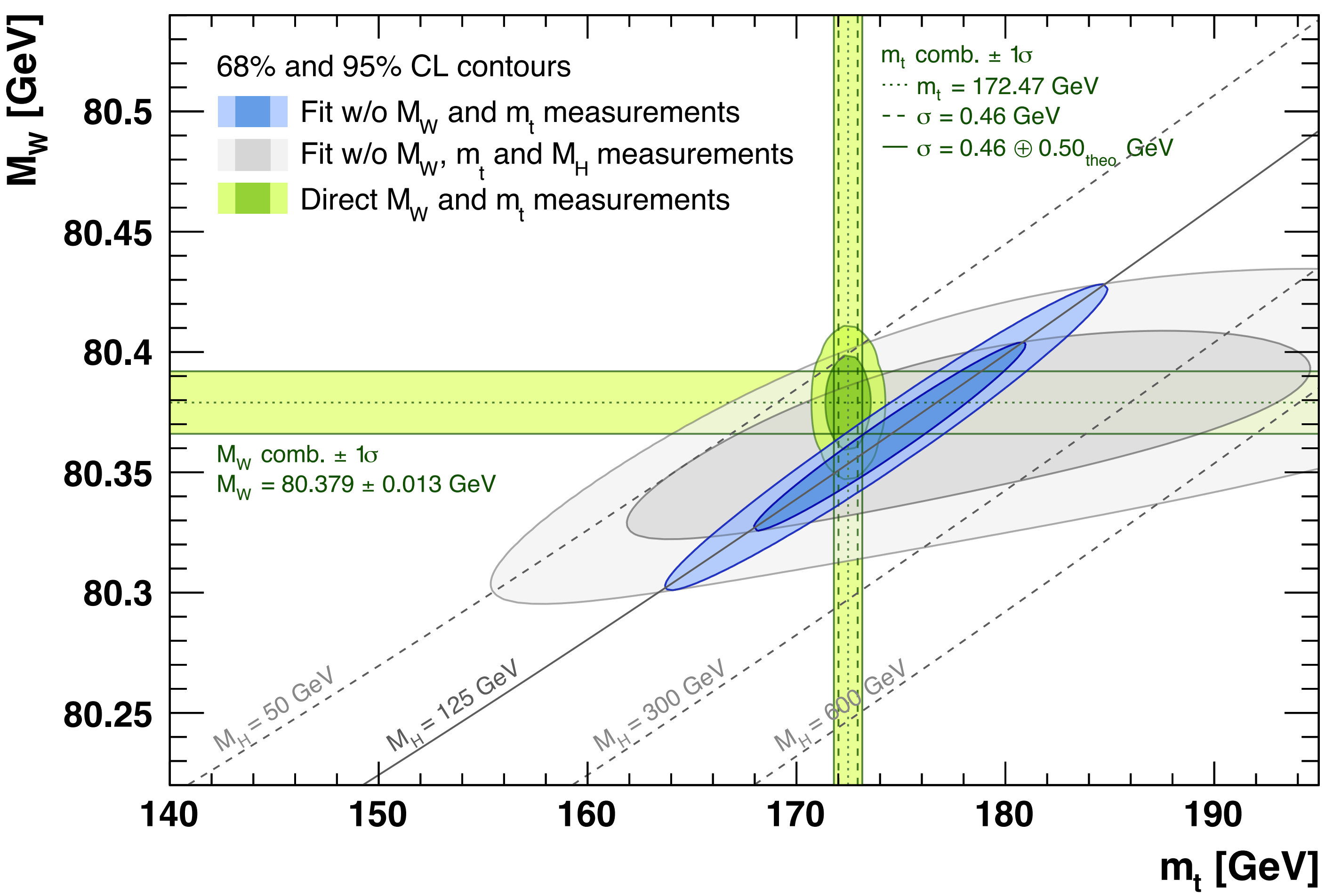


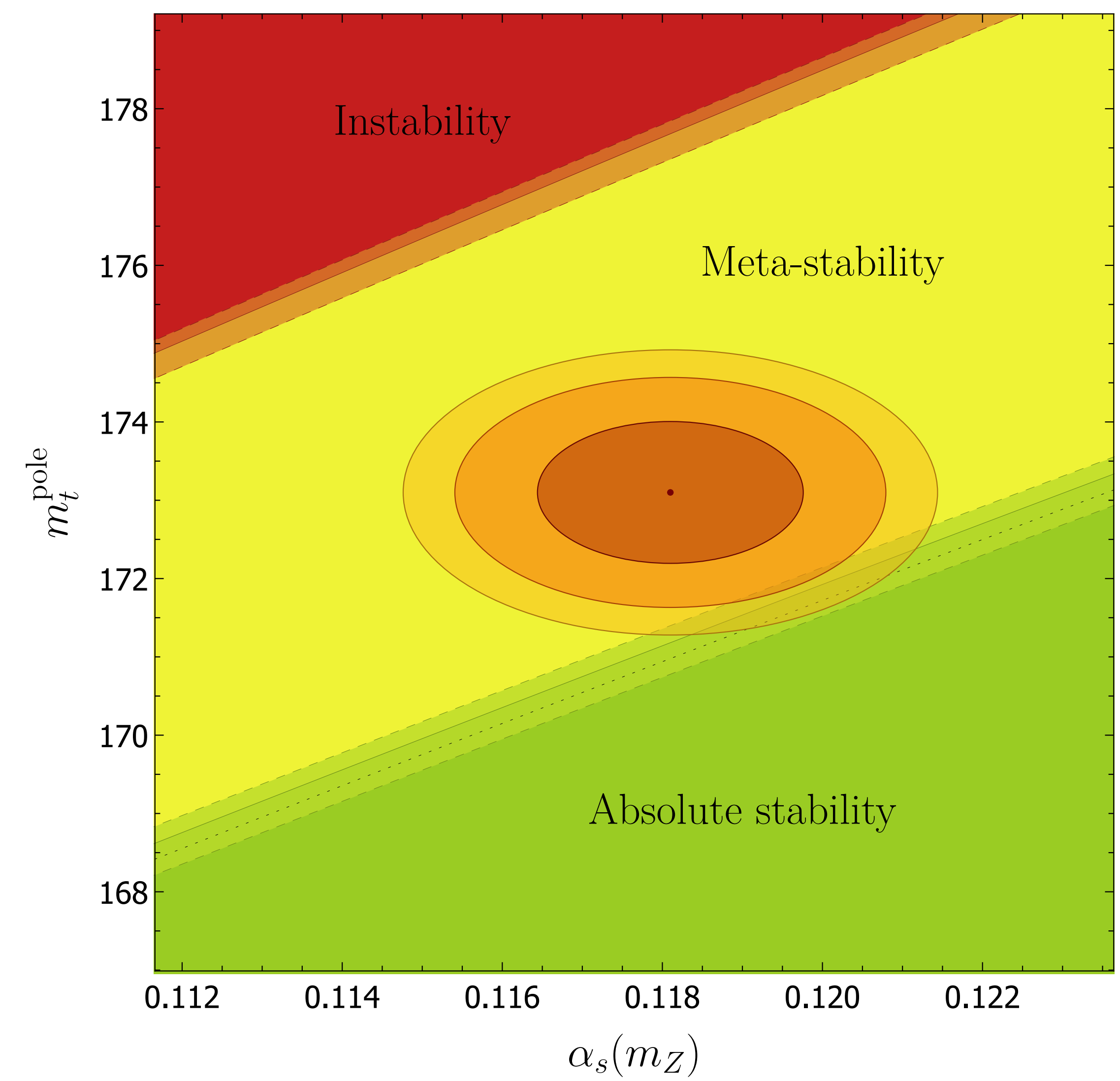
Top quark mass

- MC mass methods
  - m_{jjj} in semi-leptonic
  - m_{bl} / m_{T2} in di-leptonic
  - Spectra of decay products (e.g. J/ψ)
  - …
- Pole mass methods
  - top cross section
  - top jet mass
  - …



Top quark mass



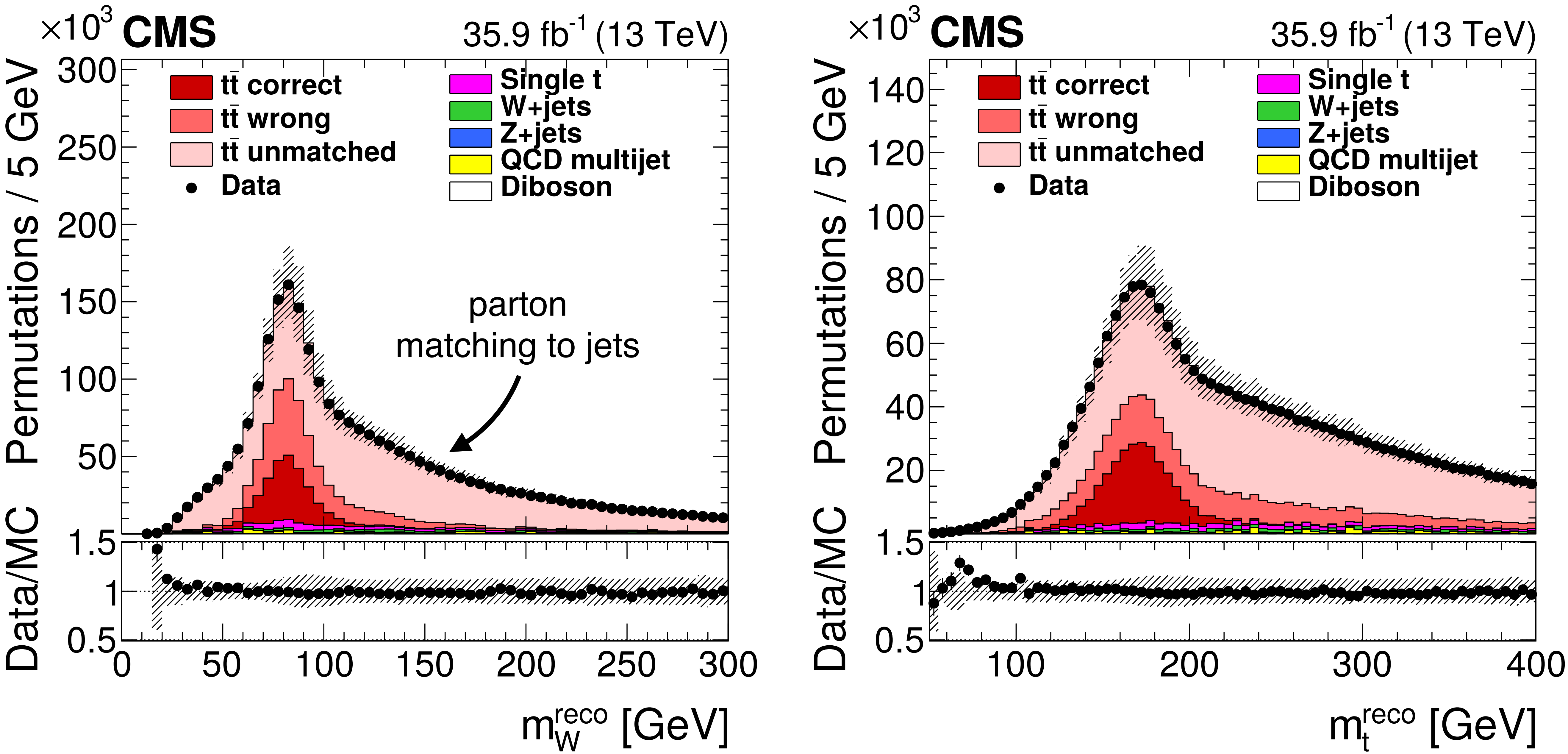


consistency of Standard Model

(unique input from hadron collider)

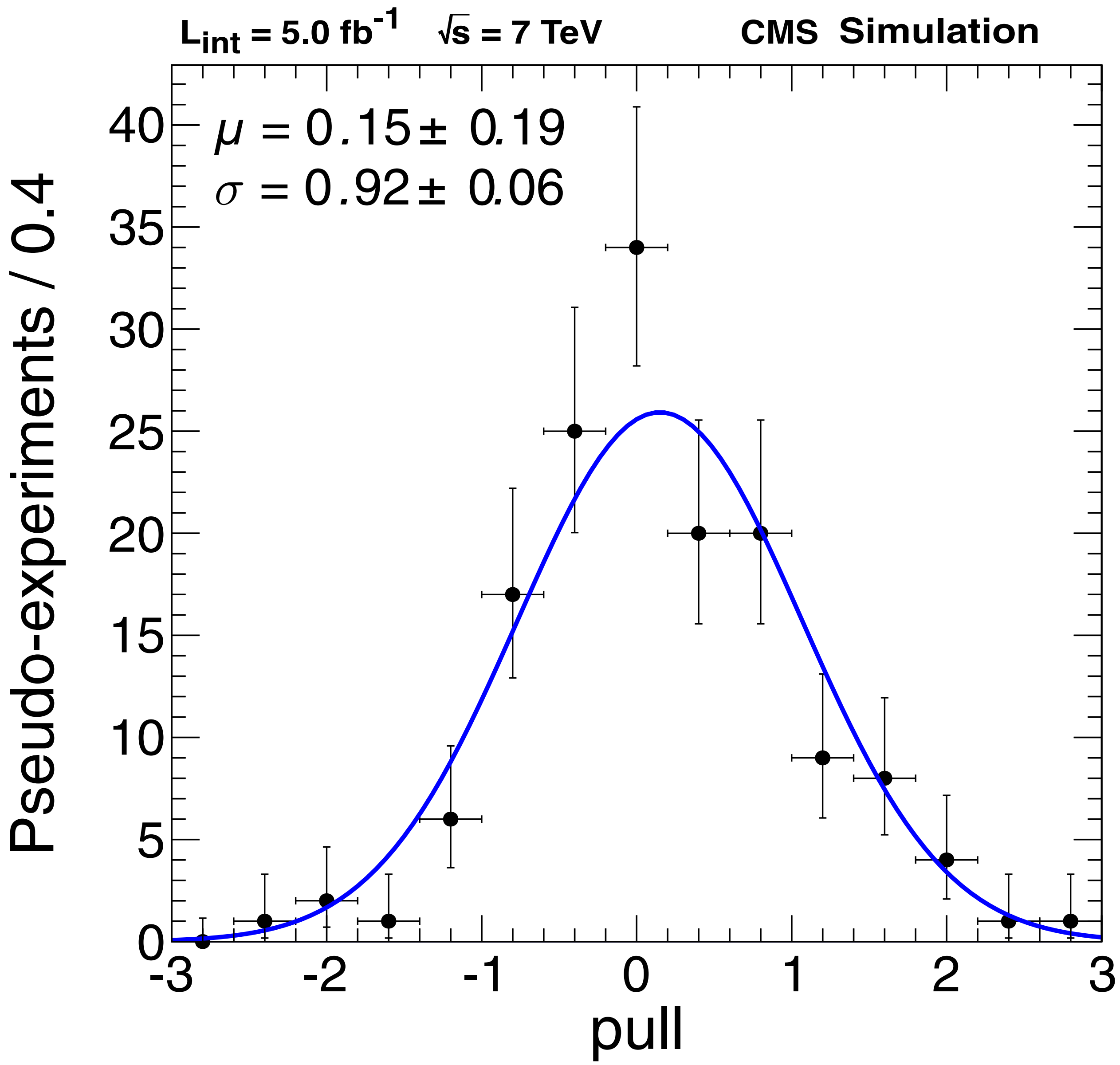
lifetime of the universe

Top quark mass: lepton + jets

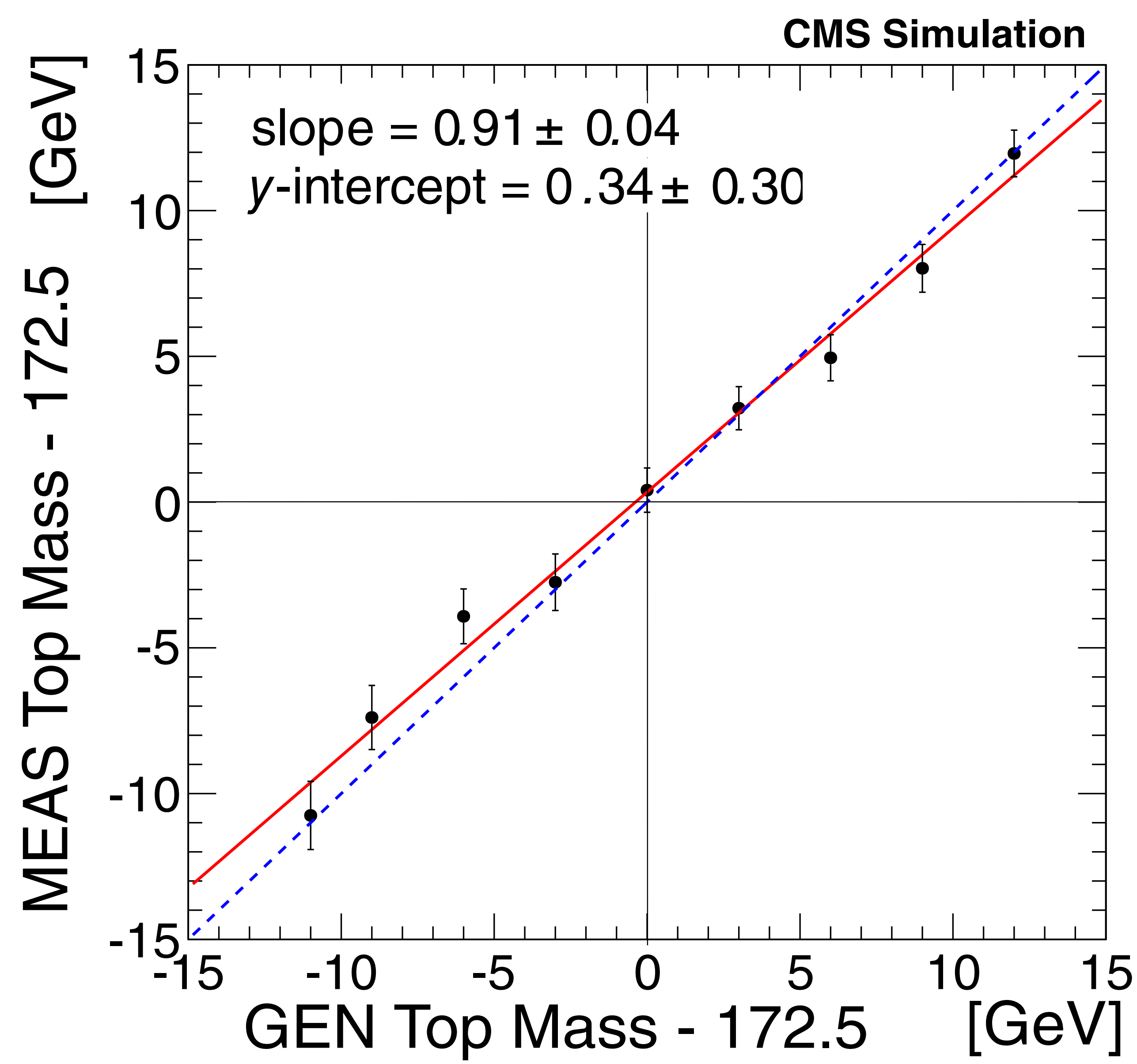


Use templates to fit m_{jjb}, constrain jet energy with fit to m_{jj}

Top quark mass: lepton + jets



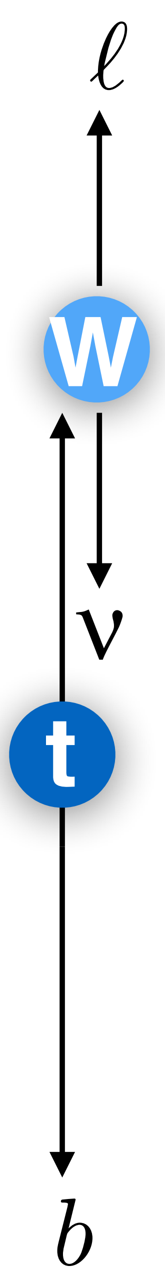
(measured - true)/uncertainty



Remember: $\langle c \times x \rangle = c \times \langle x \rangle$

$\sigma(c \times x) = c \times \sigma(x)$

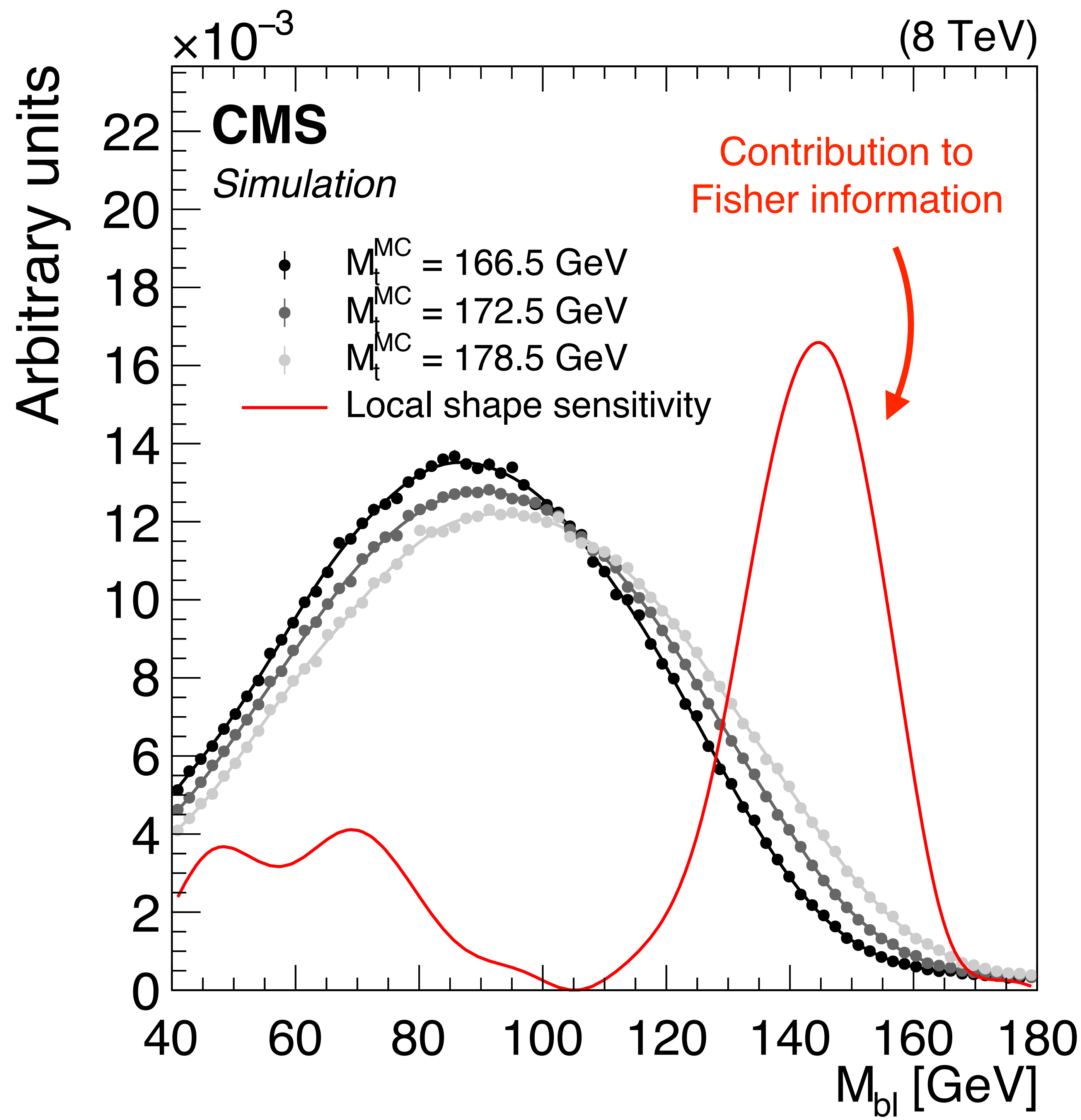
Top quark mass: dilepton



Neutrinos reduce the sensitivity (+ lower stats to begin with), but less background.

$$m_{b\ell}^{\max} = \sqrt{m_t^2 - m_W^2}$$

(can you derive this? easiest to use the W rest frame)



MC-template-based top quark mass

Warning: the "kinematic mass", aka MC mass is not the pole mass (or any well-defined mass in QFT)

There is a O(1) GeV ambiguity between the quantity we measure (which is MC-dependent) and the top quark mass in the Standard Model.

	2D approach	
	δm_t^{2D} [GeV]	δJSF^{2D} [%]
Experimental uncertainties		
Method calibration	0.05	<0.1
JEC (quad. sum)	0.13	0.2
– InterCalibration	(−0.02)	(<0.1)
– MPFInSitu	(−0.01)	(<0.1)
– Uncorrelated	(−0.13)	(+0.2)
Jet energy resolution	−0.08	+0.1
b tagging	+0.03	<0.1
…		

…

Underlying event	−0.10 ± 0.08	+0.1
Early resonance decays	−0.22 ± 0.09	+0.8
Color reconnection	+0.34 ± 0.09	−0.1
Total systematic	**0.72**	**1.0**
Statistical (expected)	0.09	0.1
Total (expected)	**0.72**	**1.0**

Alternative approaches

How would you measure the mass?

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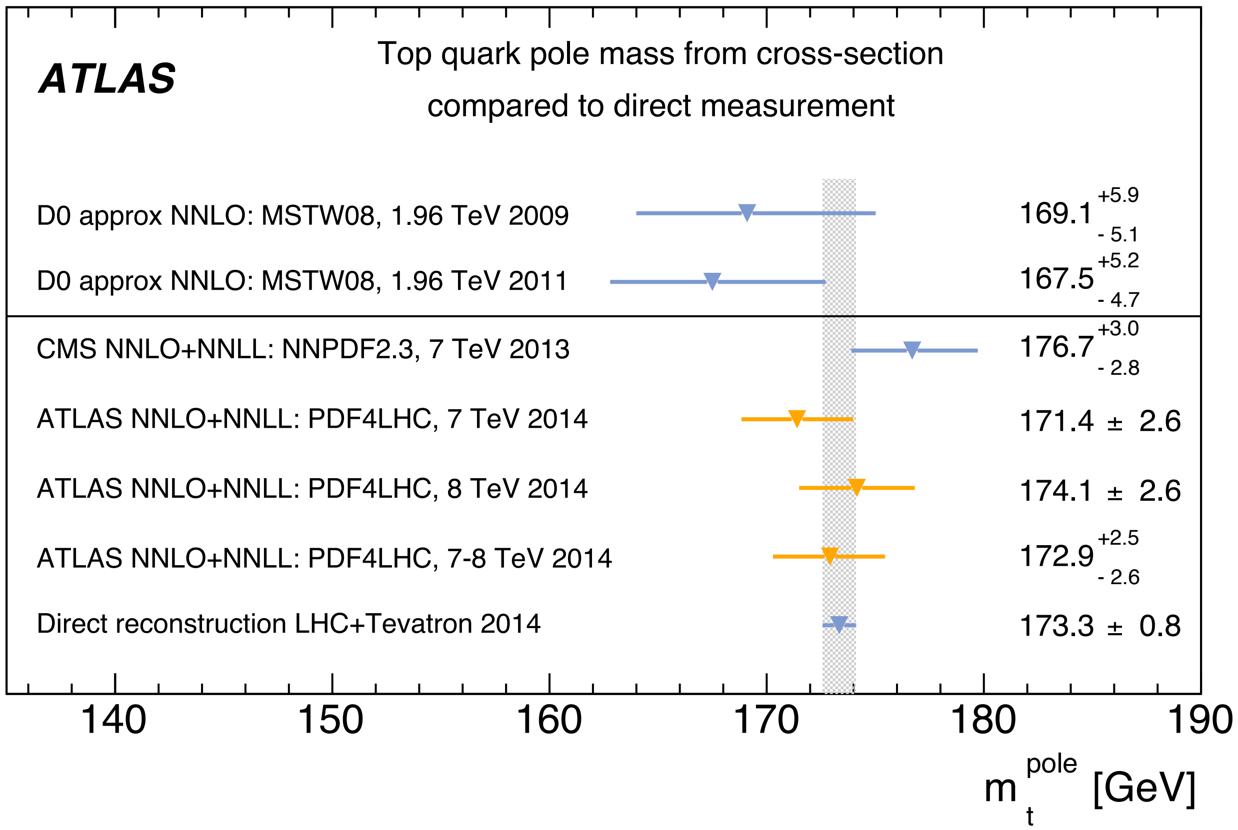
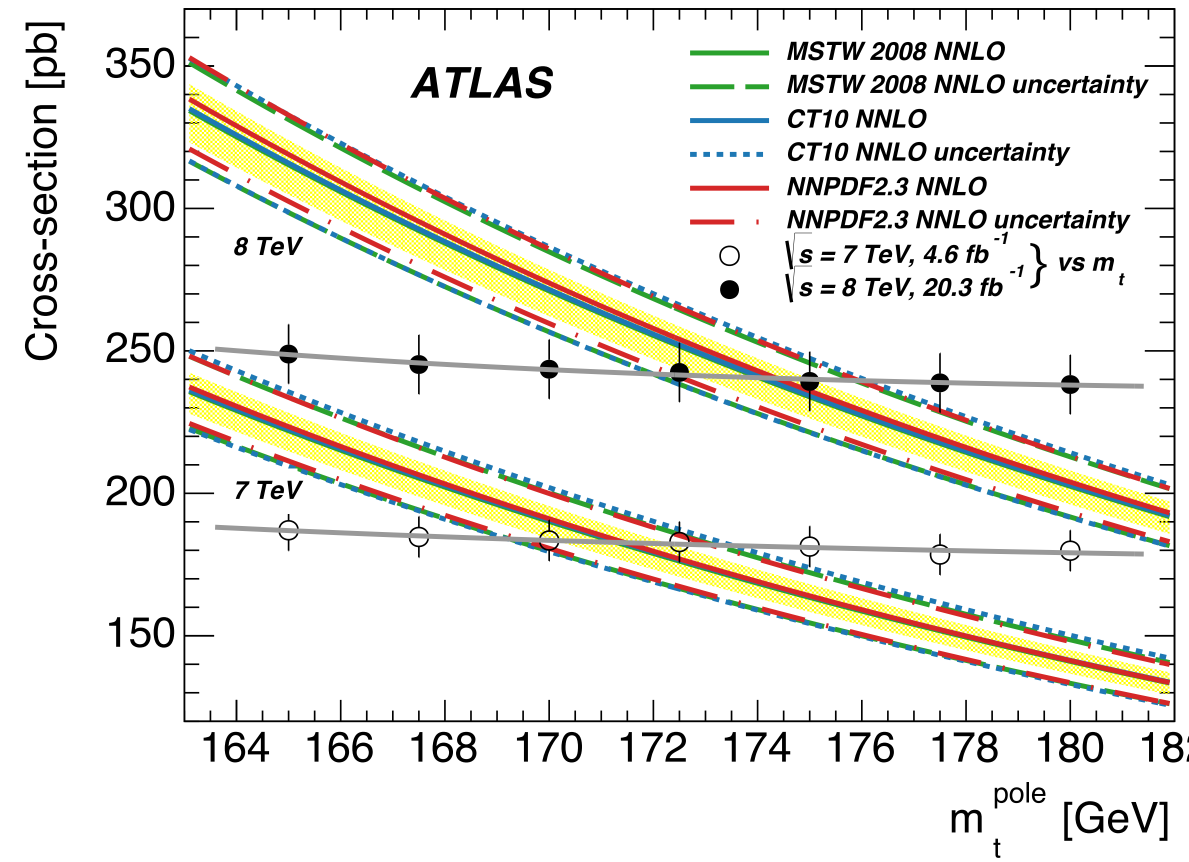
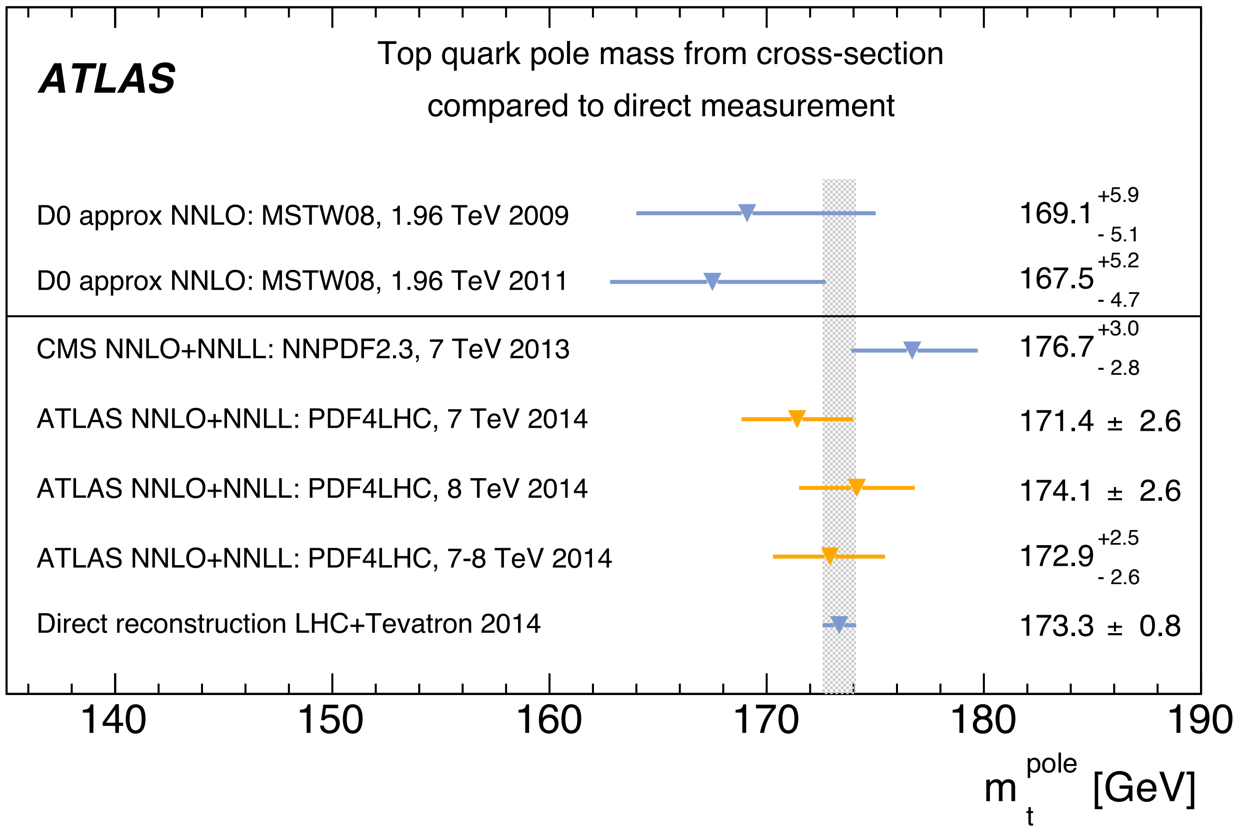


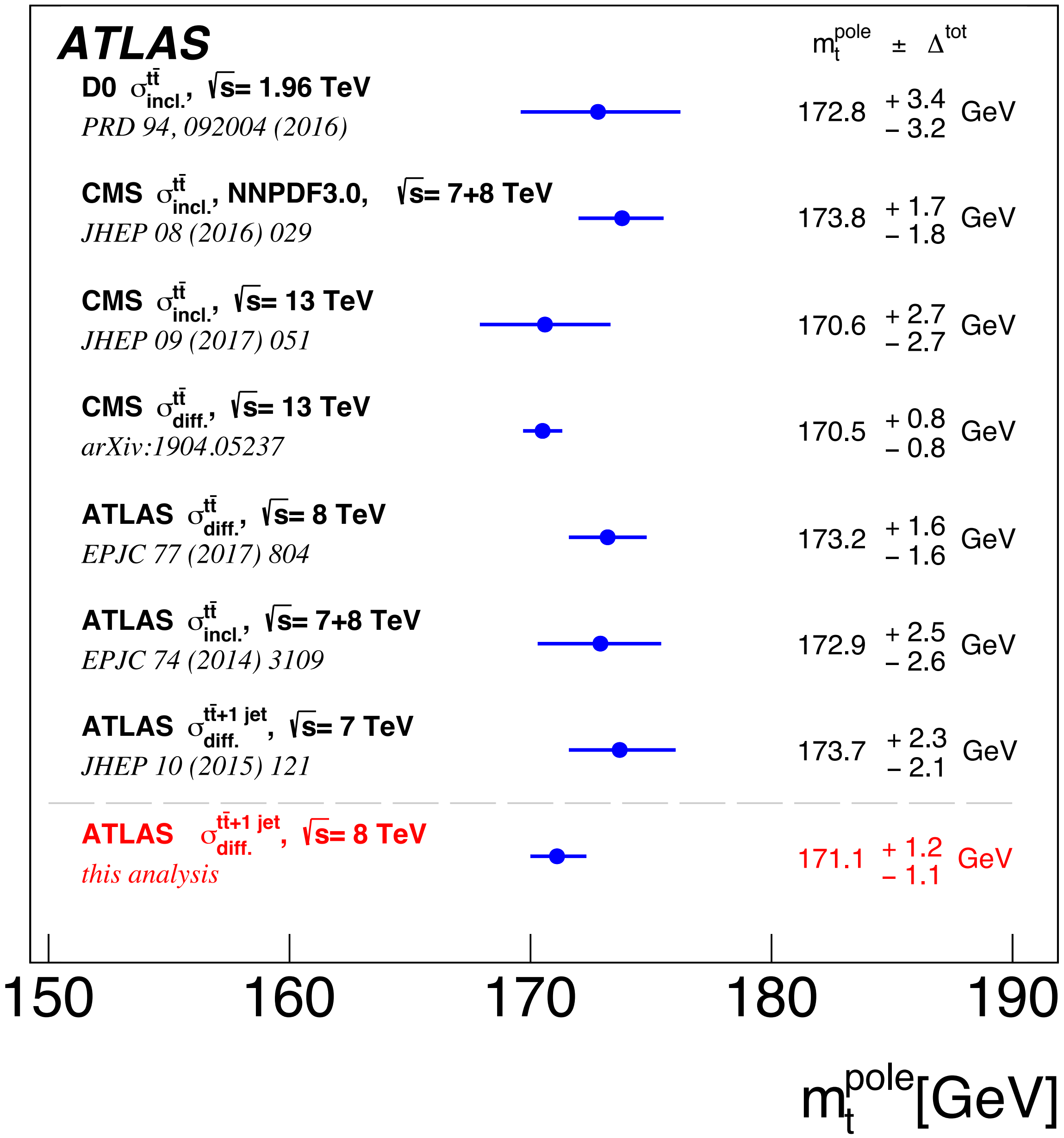


One possibility is to use the inclusive cross-section.
This is the safest approach, but least sensitive.
Would be nice to have a energy scan in e^+e^-!

Alternative approaches

How would you measure the mass?



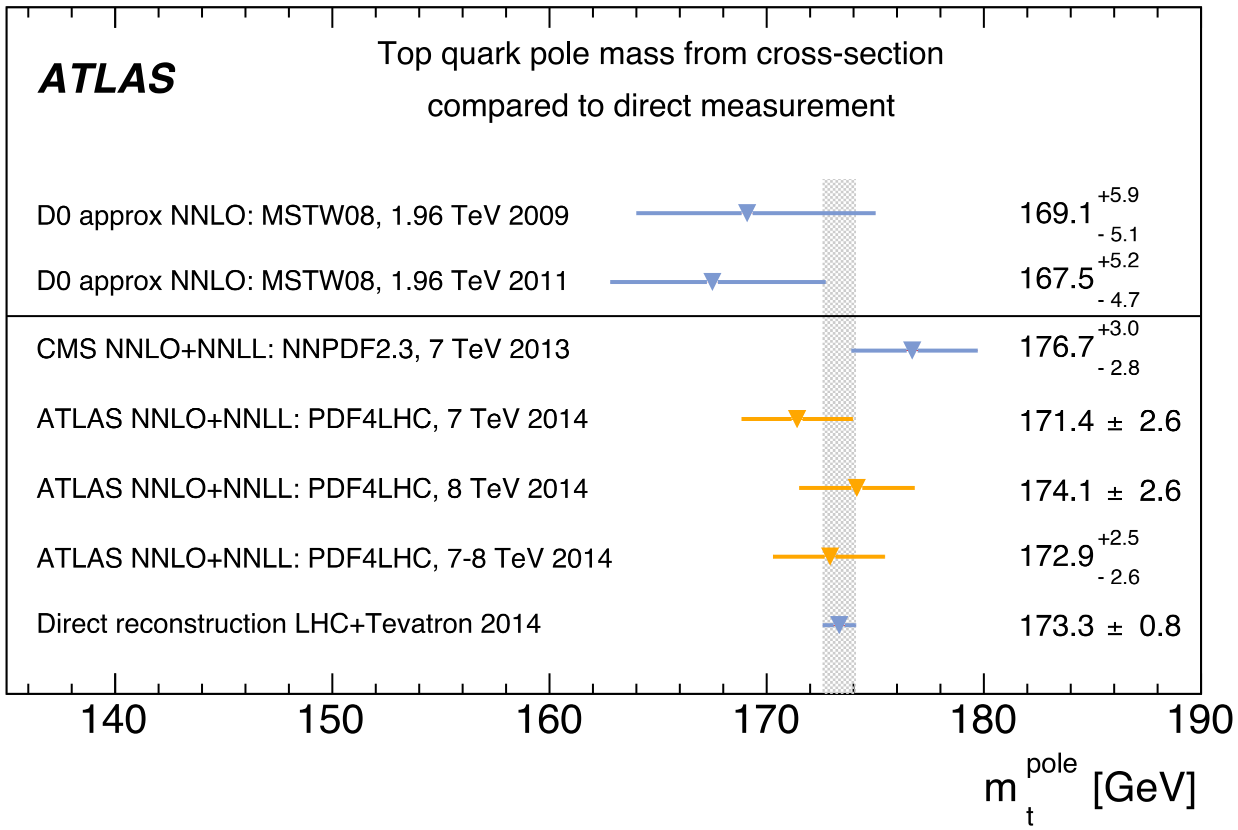


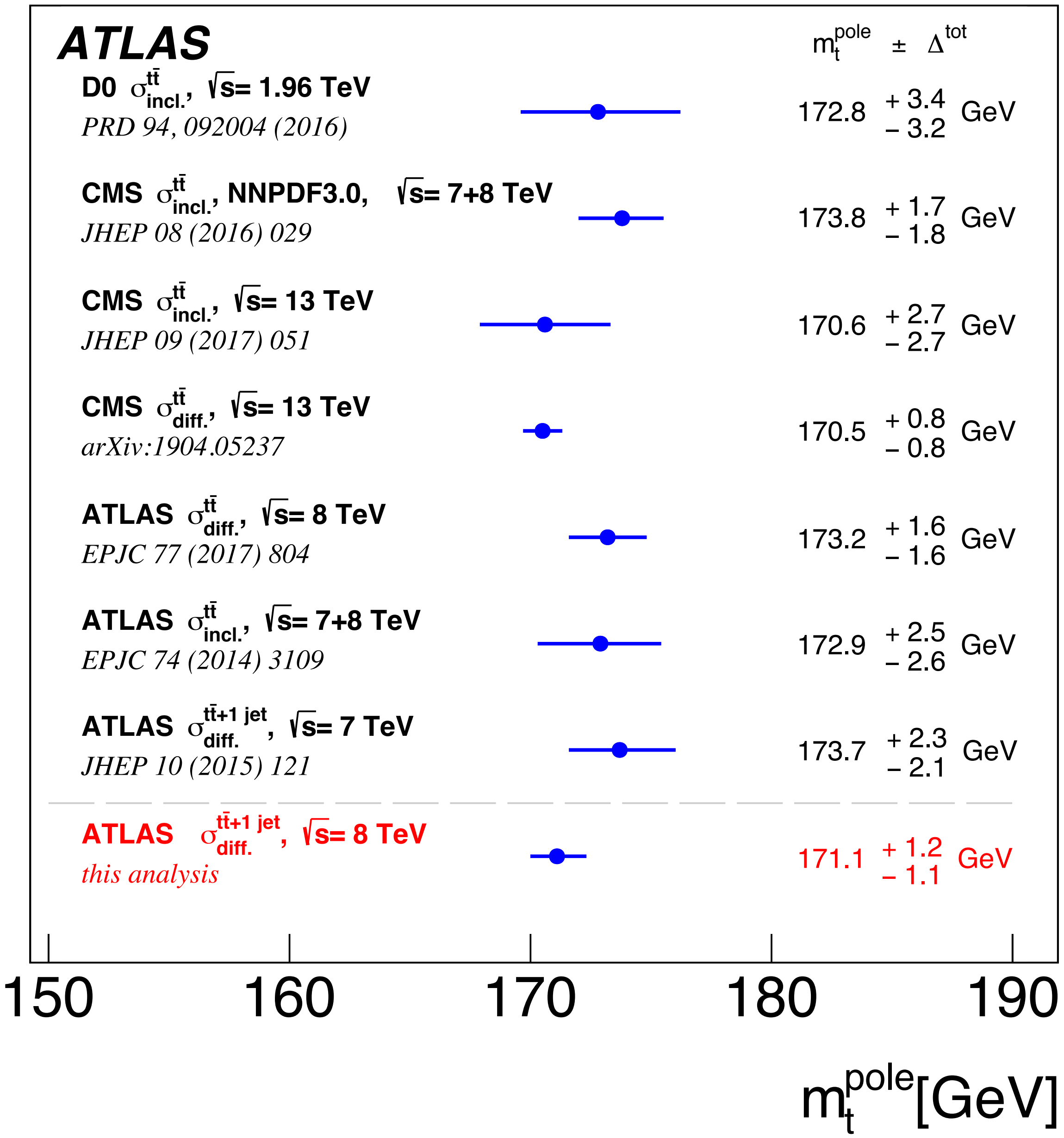
Another possibility is to use **differential cross-sections**. These require **unfolding to parton level** in order to compare with calculations*.

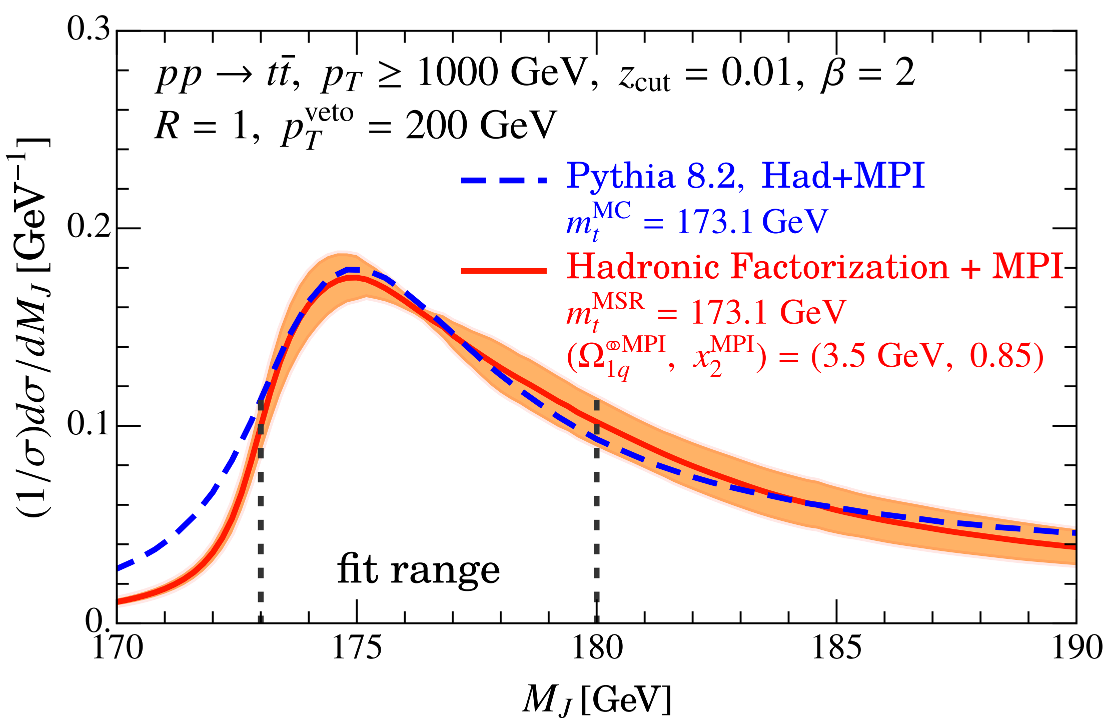
*also true for the inclusive cross section, but less sensitive.

Alternative approaches

How would you measure the mass?



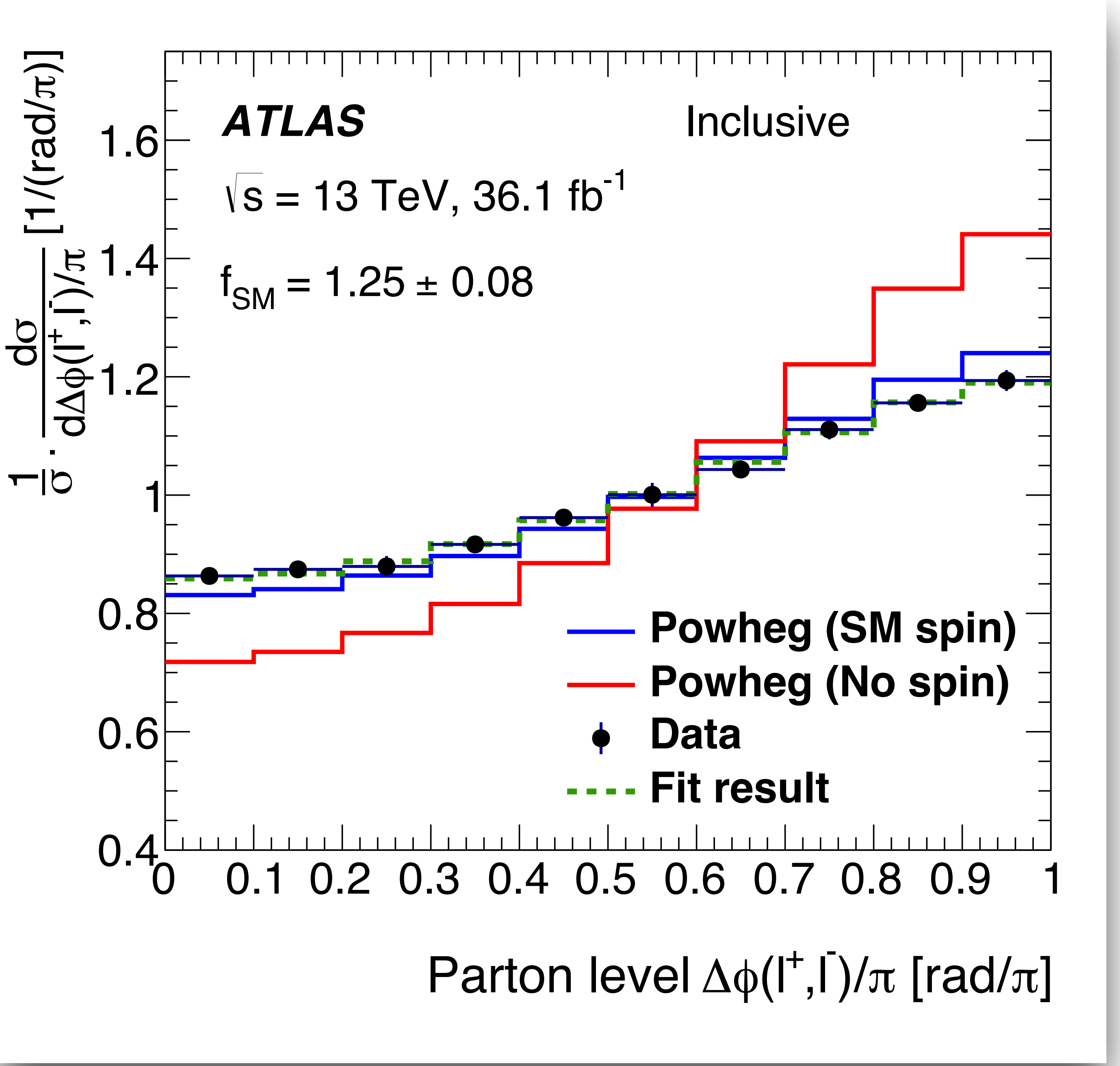




What about combining theoretical soundness
+ kinematic shape + jet substructure ??

Beyond the mass

The top quark has many interesting properties that can be measured at the LHC.



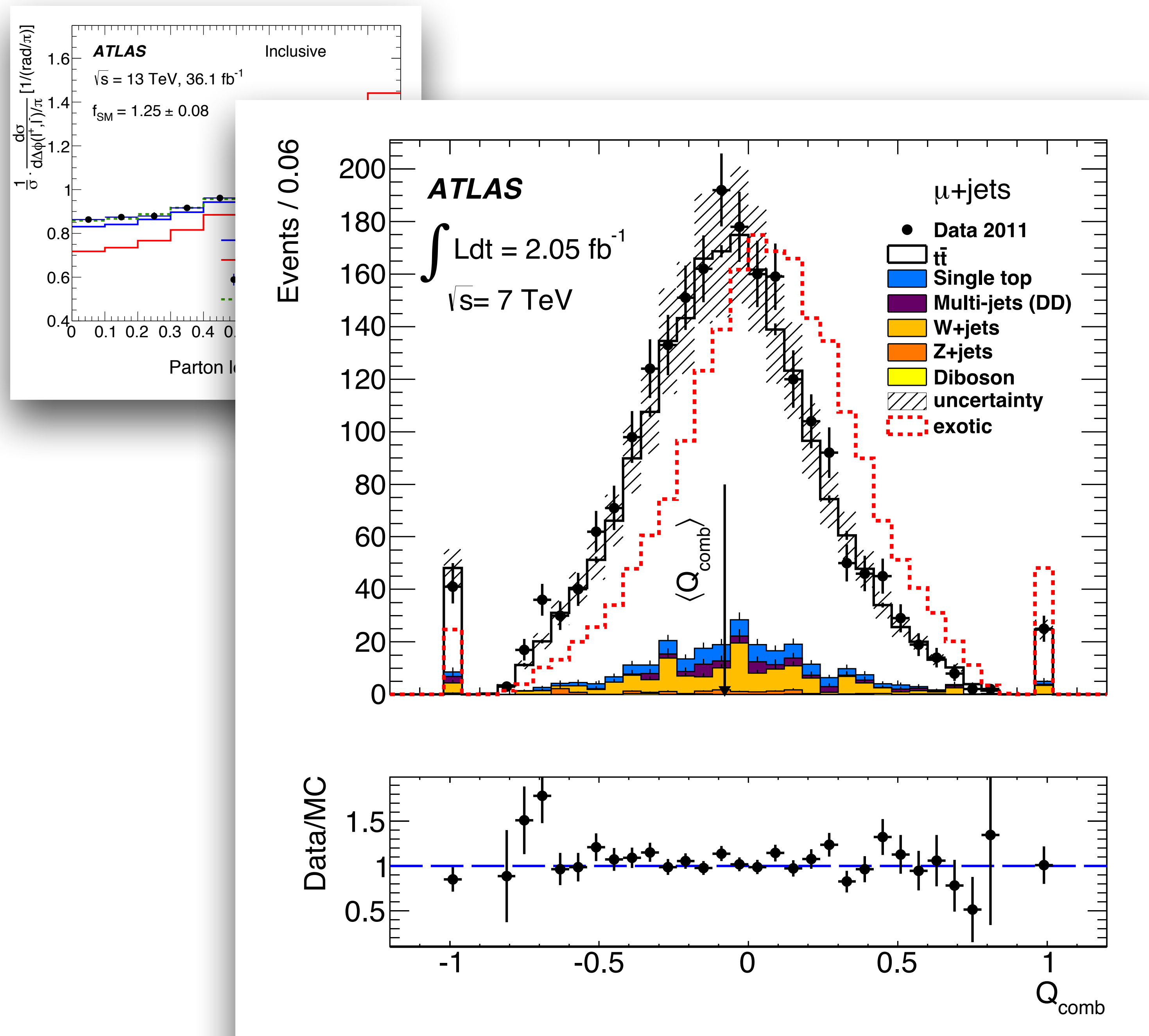
Spin correlations via angular correlations in dilepton events

(BSM may add an uncorrelated component - more on that later)

Unfolded to parton level

Beyond the mass

The top quark has many interesting properties that can be measured at the LHC.

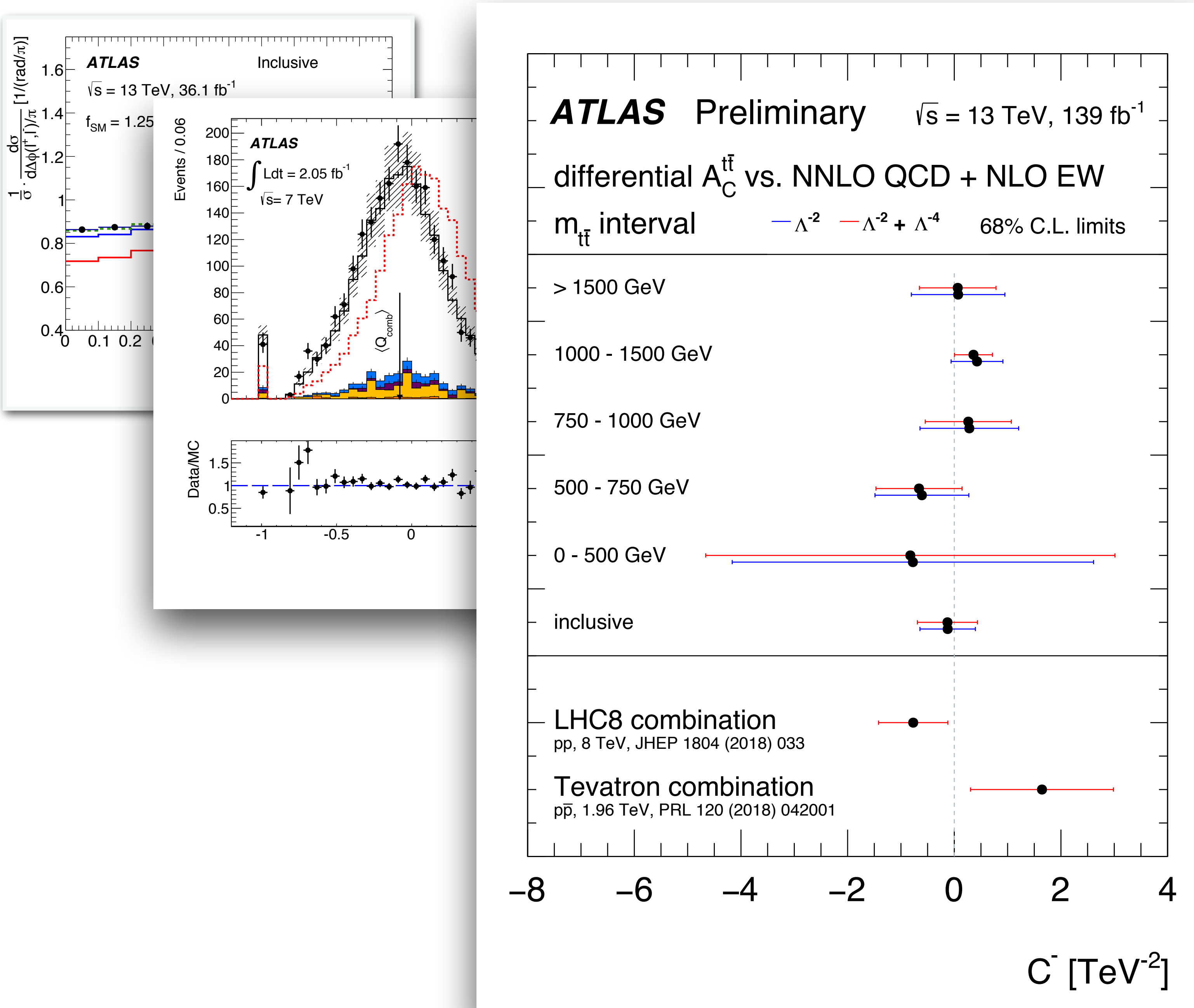


We are quite sure of the charge now, but early in the LHC, it was fashionable to rule out exotic electric charges.

(requires methods for estimating the “jet charge”)

Beyond the mass

The top quark has many interesting properties that can be measured at the LHC.



The Tevatron observed an excess in the forward-backward asymmetry (now ~gone)

This spurred a big program to probe the “charge asymmetry”

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

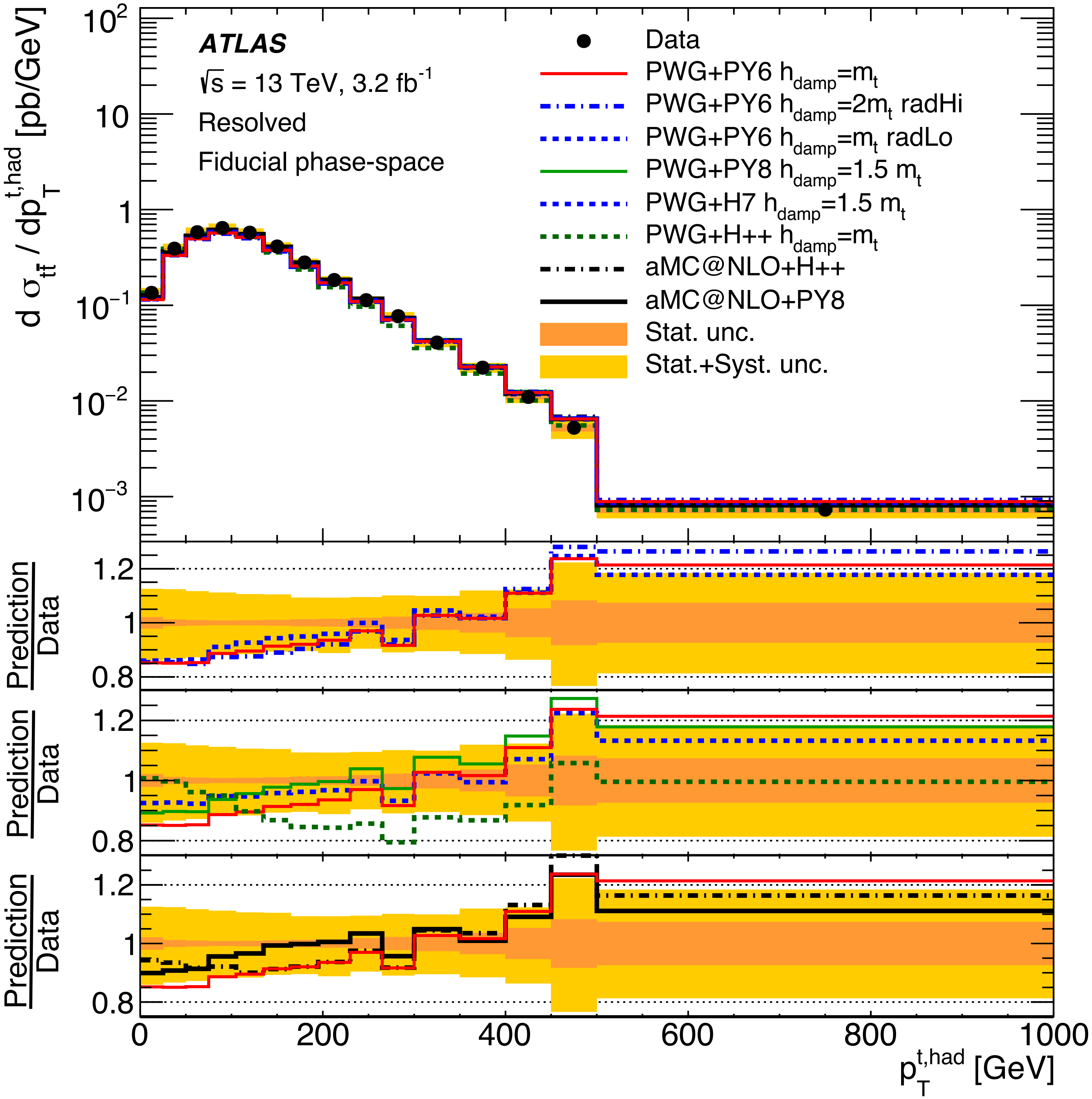
Which is much less sensitive than the Tevatron because we are gg dominated.

Top p_T

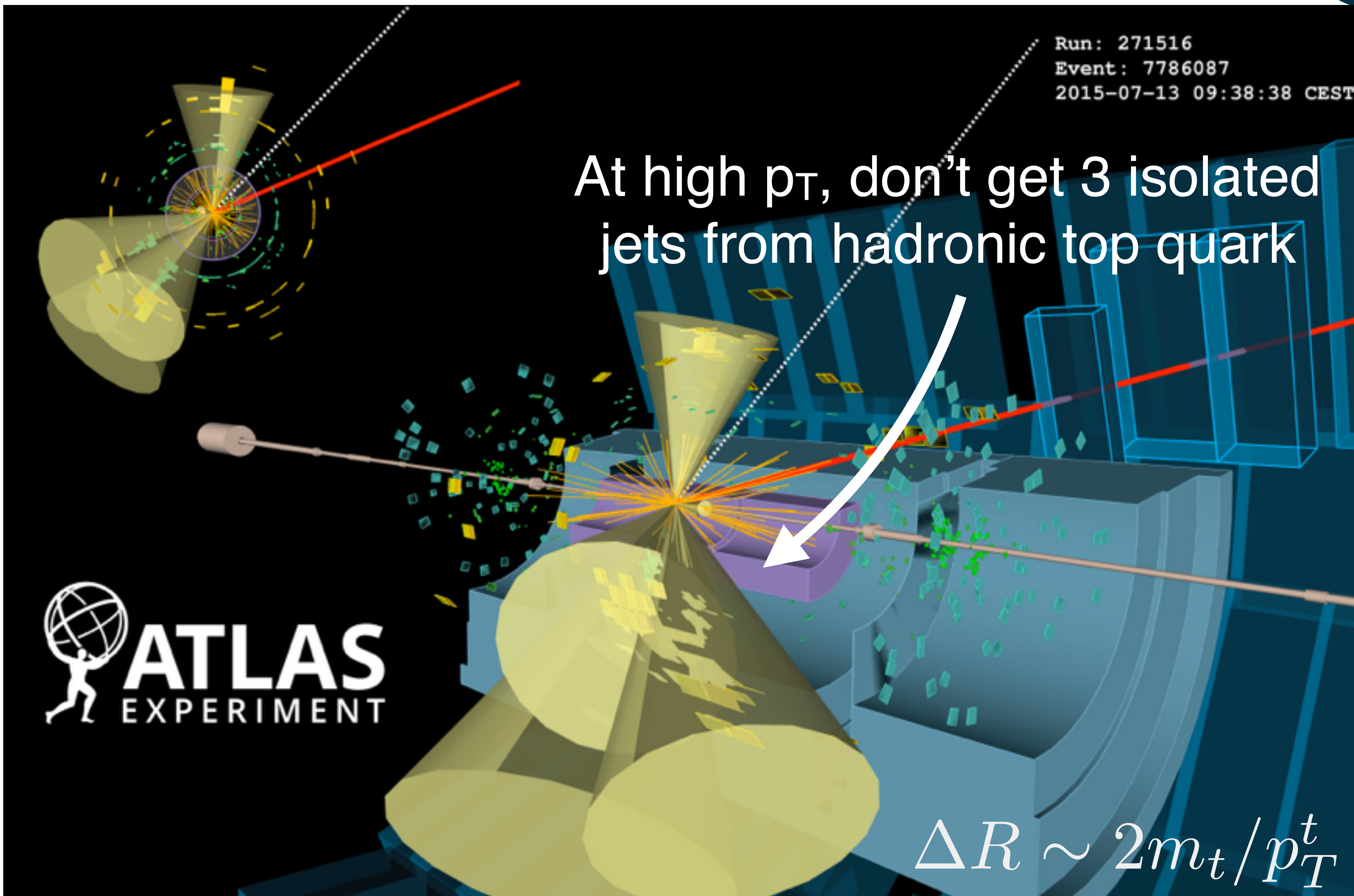
As top-quark pair production is a background for many searches, it is important to study the kinematic tails.

Long-standing observation that the spectrum is harder in simulation than data.

This seems to be partially accounted for at NNLO, but full story still under investigation.

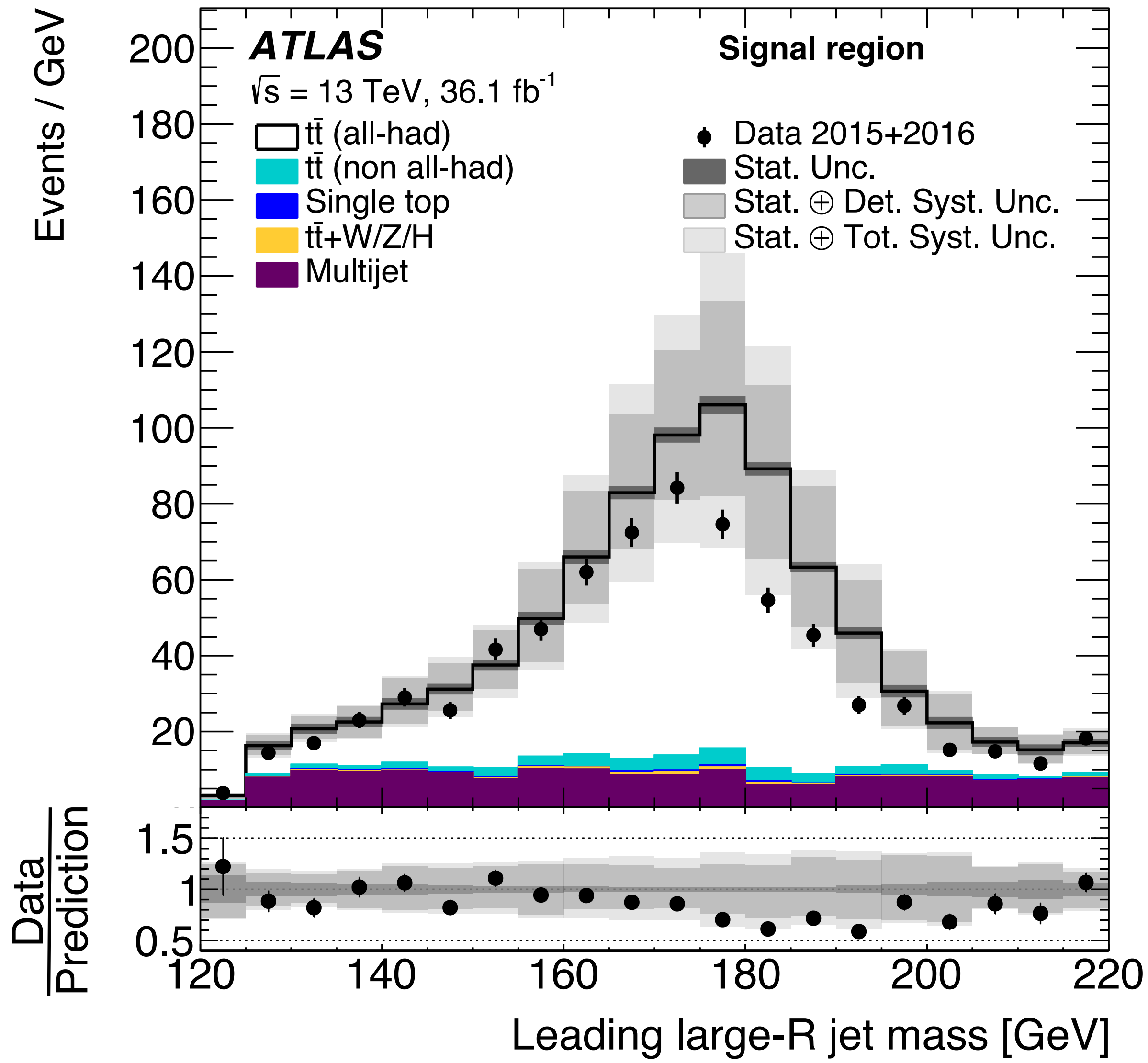


Boosted top quarks



(where does this come from?)

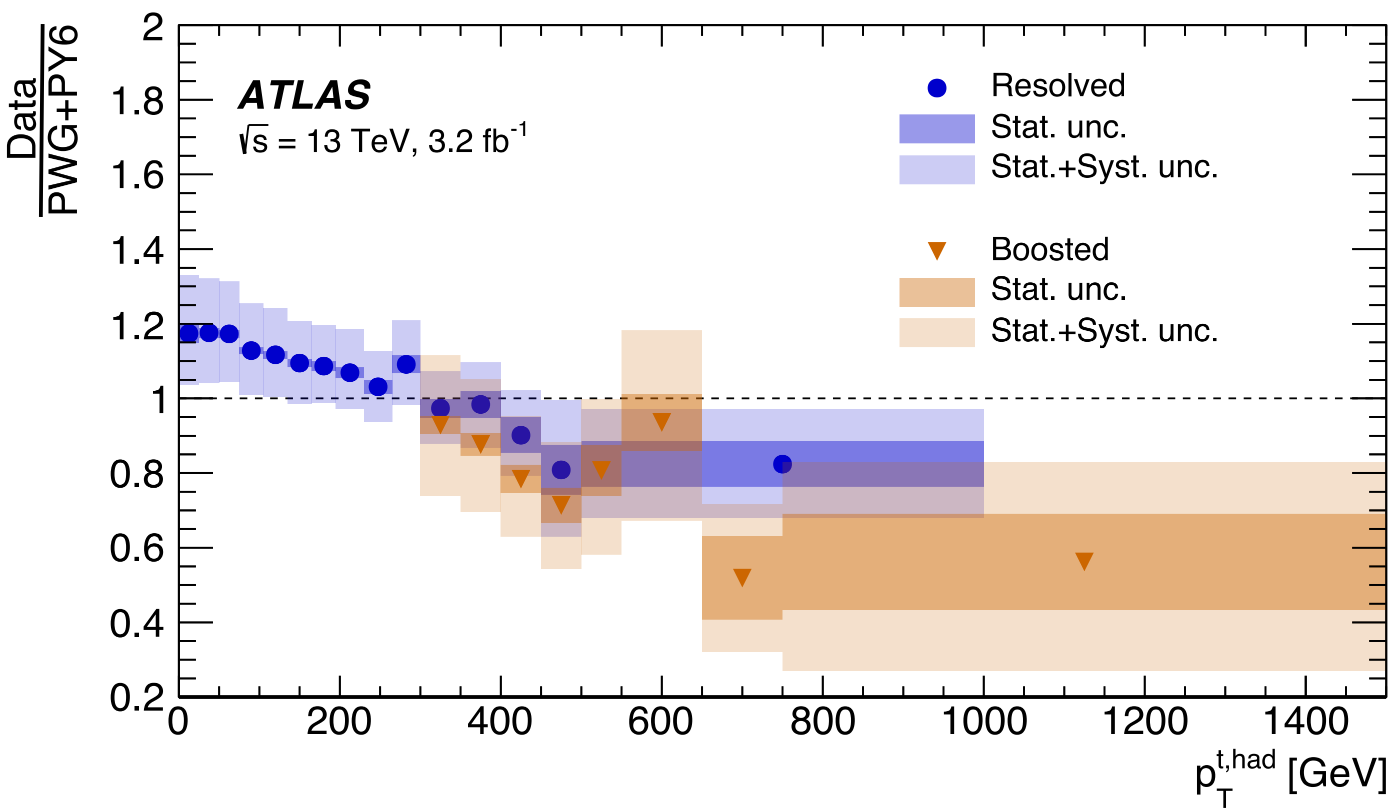
Boosted top quarks



In the "boosted" regime, need to use large(r)-radius jets

These jets have a 3-prong substructure and mass ~ m_t

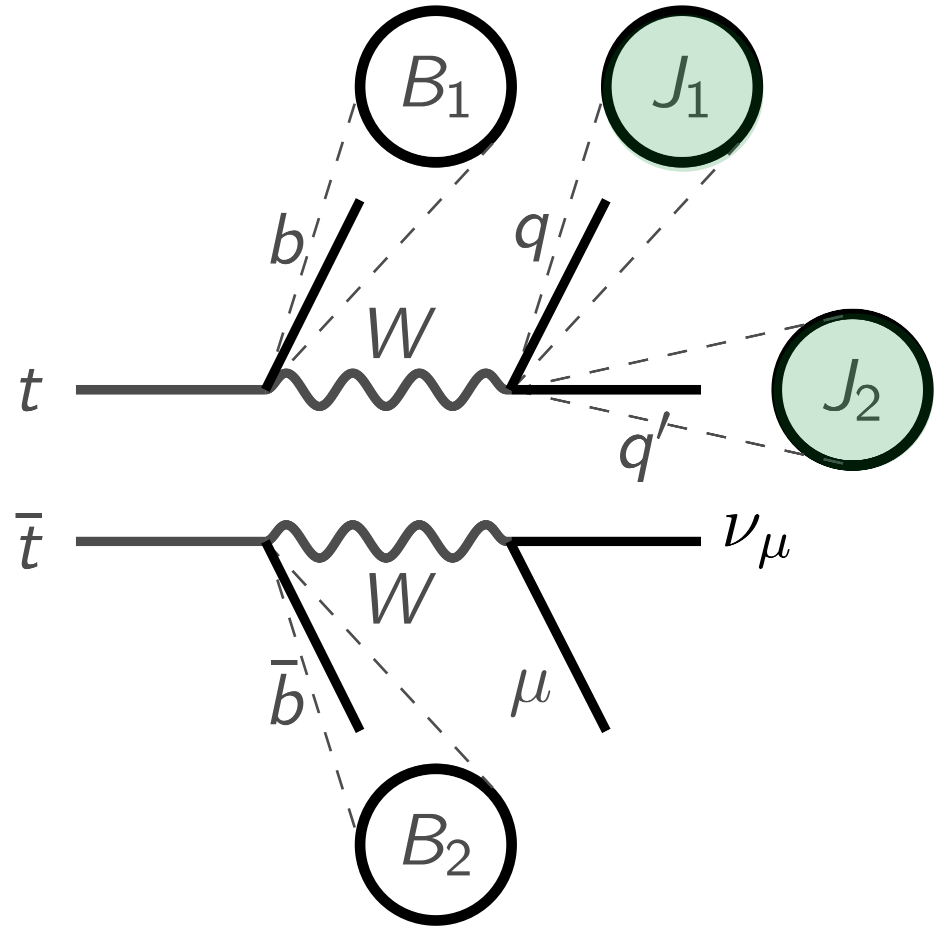
Jet substructure tagging is therefore important part for SM measurements, not just BSM searches!



Tops as a source of color singlets

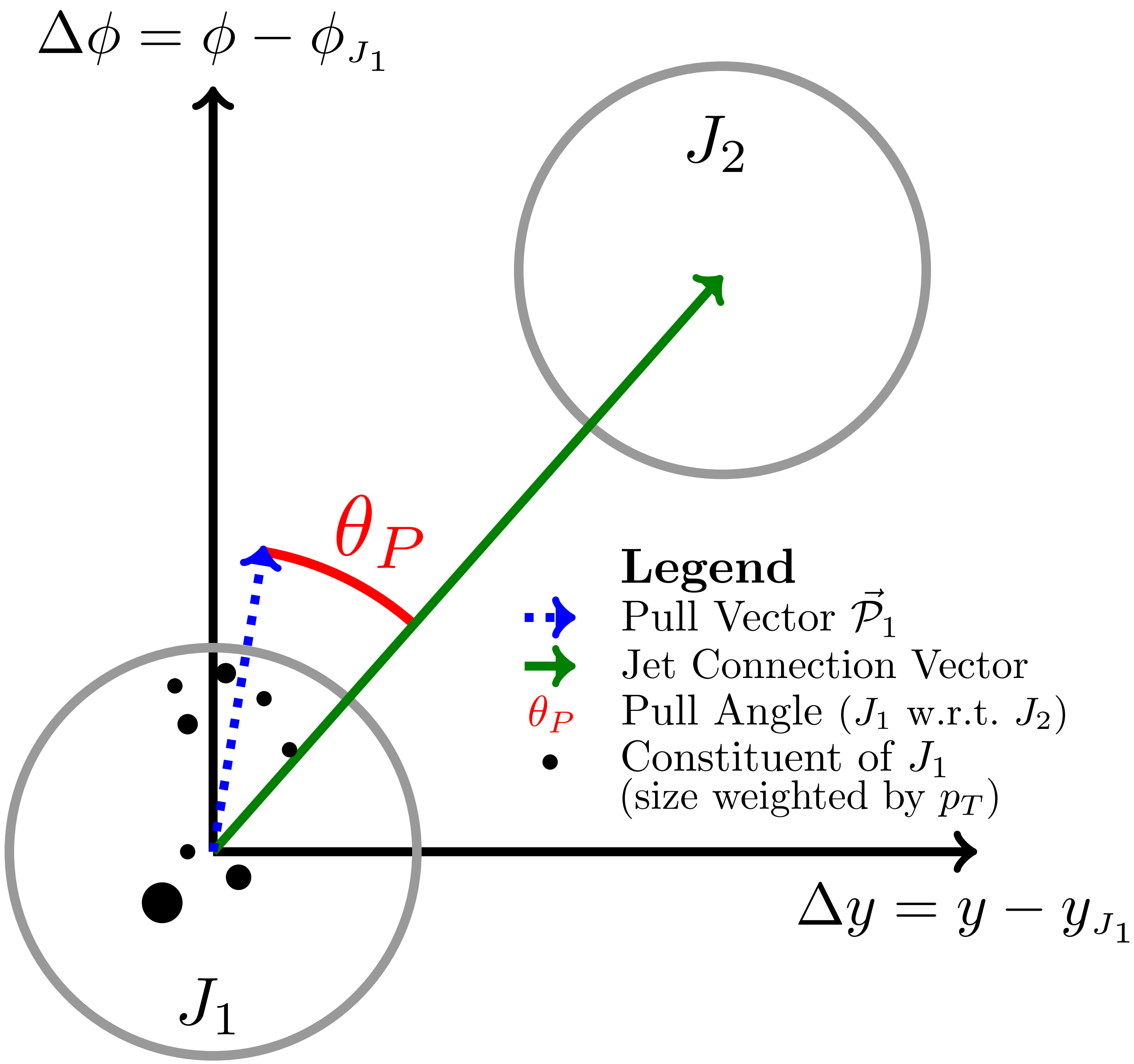
As the W bosons produced from top quarks are on-shell, top quark pairs offer unique LEP-like laboratory for QCD studies.

One can identify ('tag') events using the leptonic W decay and the study ('probe') the structure of the hadronic W decay.



Tops as a source of “singlet jets”

The only way to get a clean sample of jet originating from a singlet decay (since LEP)



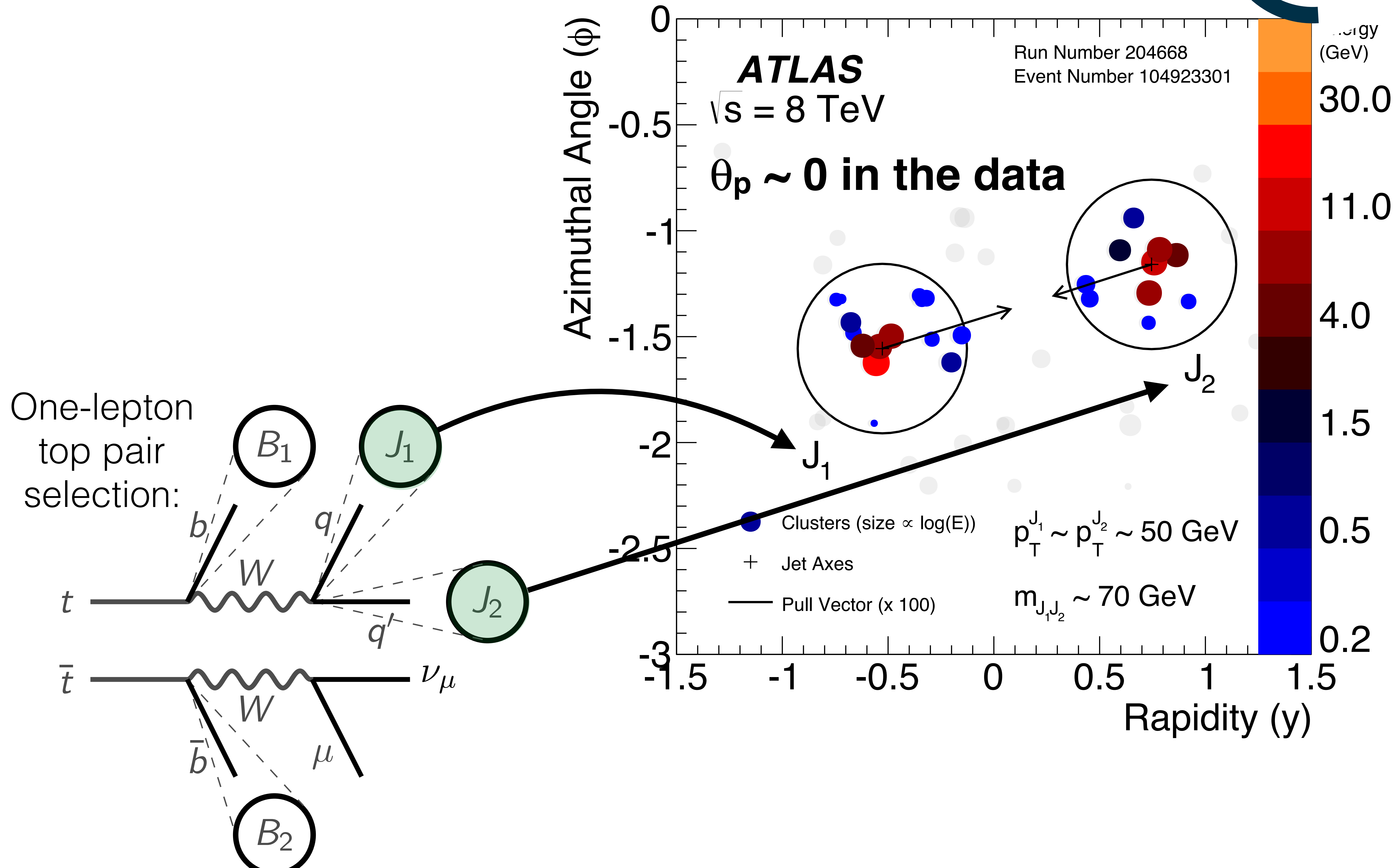
Step 1: How singlet-like is it?

Tool: Jet superstructure - the interplay between jet substructure and global radiation / kinematics.

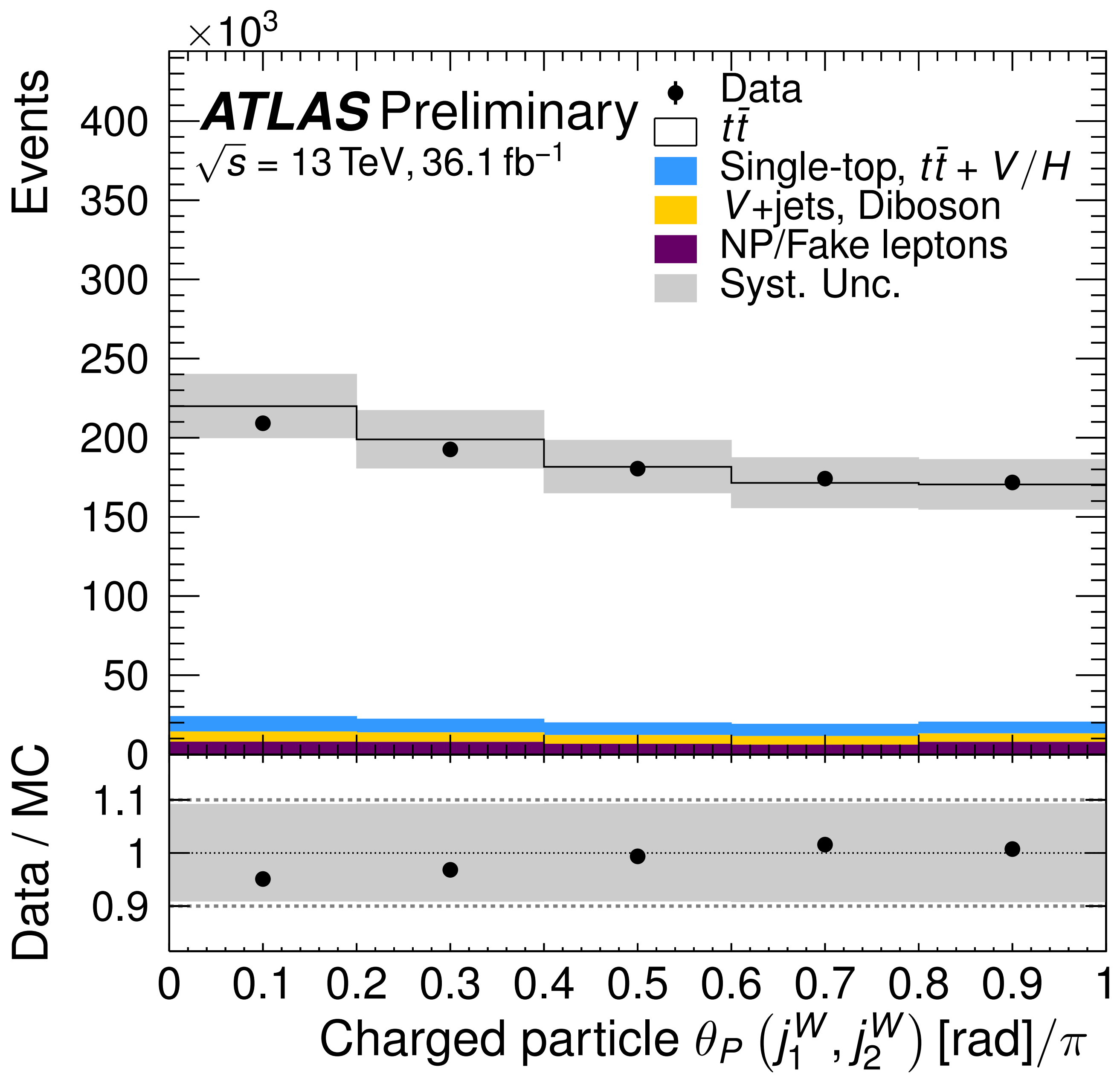
$$\vec{\mathcal{P}}(J) = \sum_{i \in J} \frac{\left|\vec{\Delta r}_i\right| \cdot p_{\mathrm{T}}^i}{p_{\mathrm{T}}^J} \vec{\Delta r}_i$$

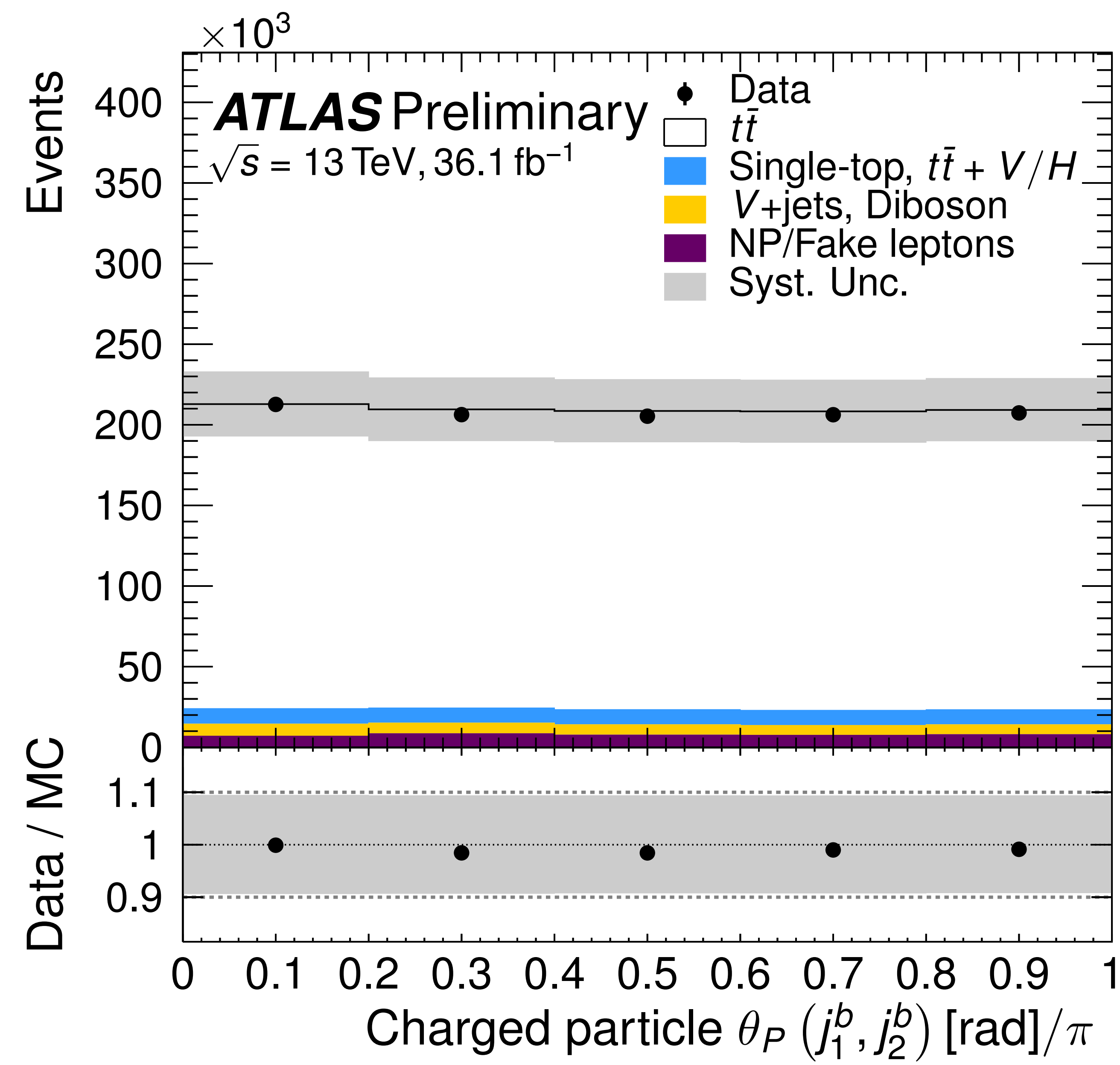
Question: how much does the radiation from one jet lean towards the other?

Hadronic Correlations: Jet Superstructure



Hadronic Correlations: Jet Superstructure

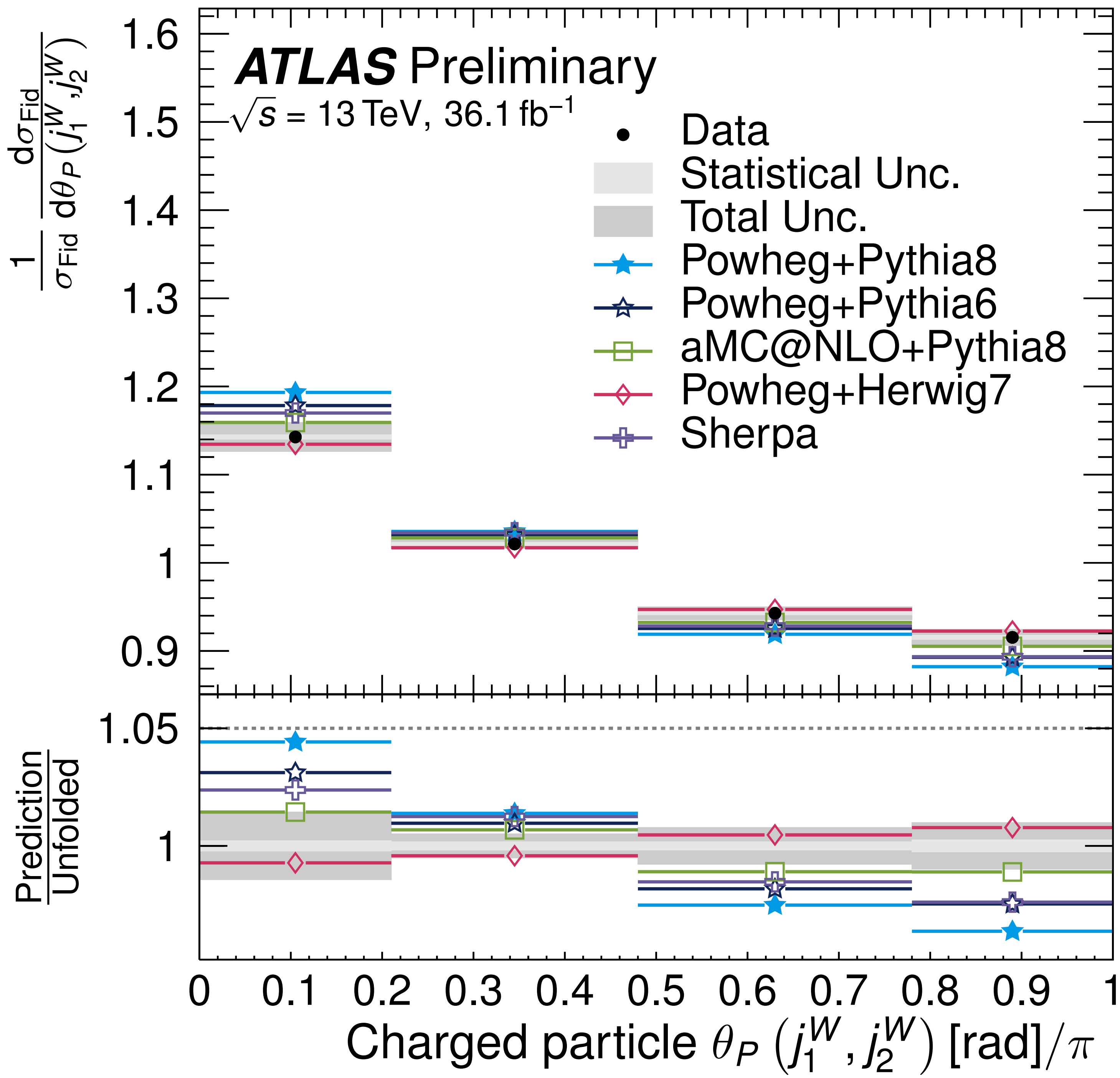




peak at 0 - W daughters are “connected”

no peak - b’s are not connected

Jet Pull for MC Tuning

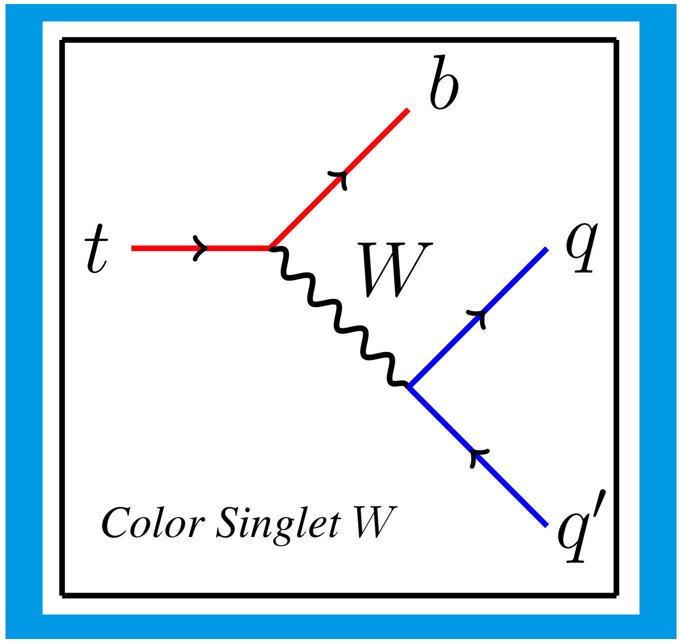


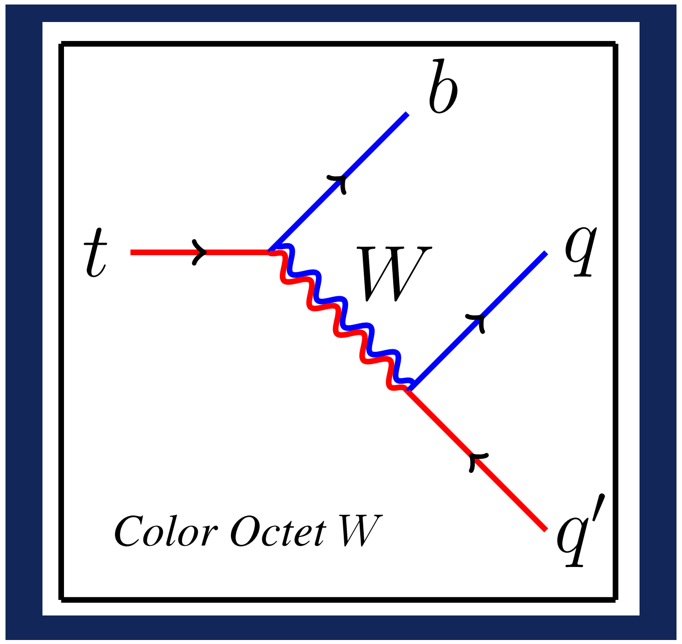
Challenging measurement, but we can reach to the 1%-level for precision.

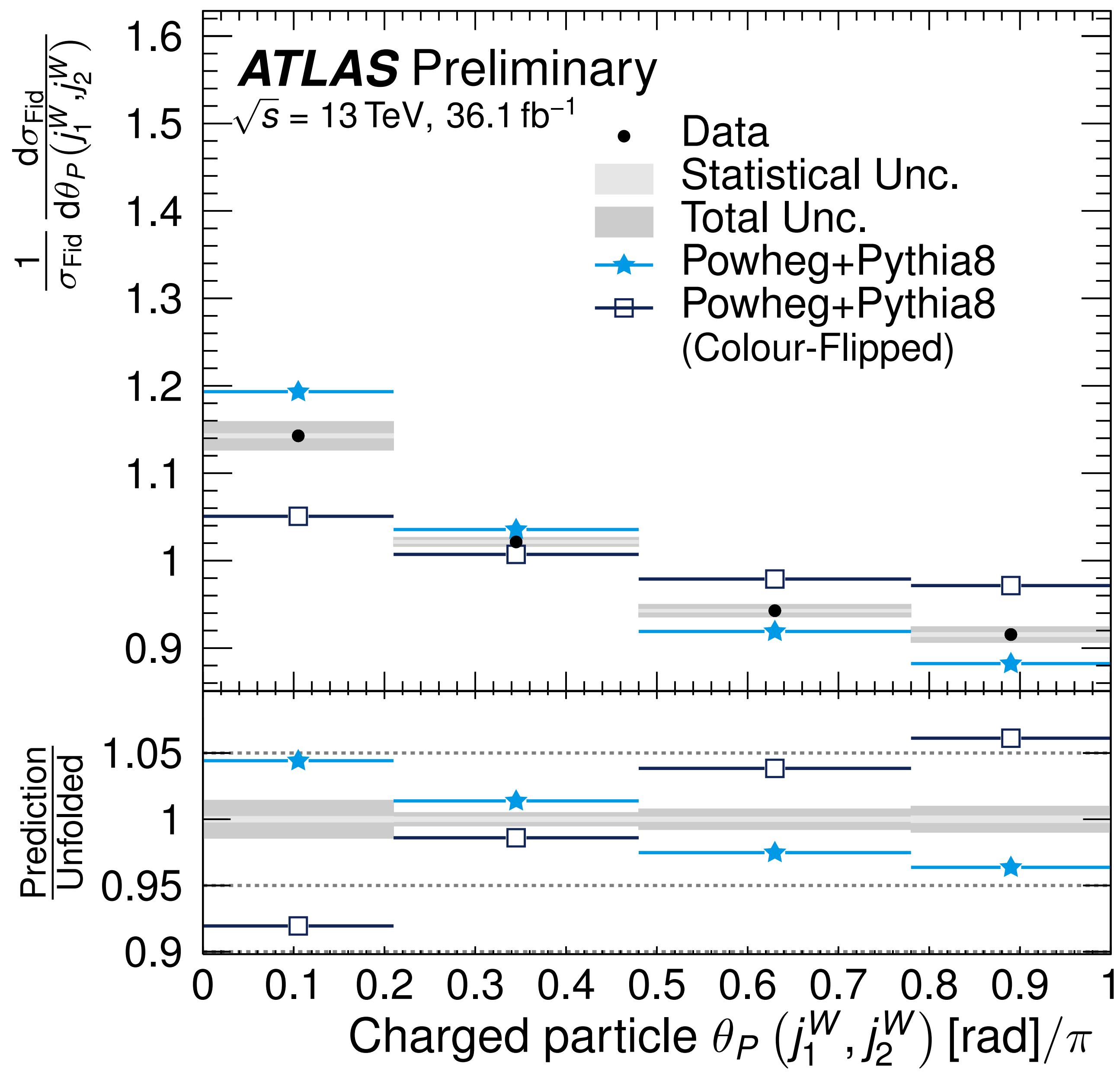
Interestingly, there is a rather large spread in the MC predictions.

(useful for tuning!)

Jet Pull: Much more to learn!





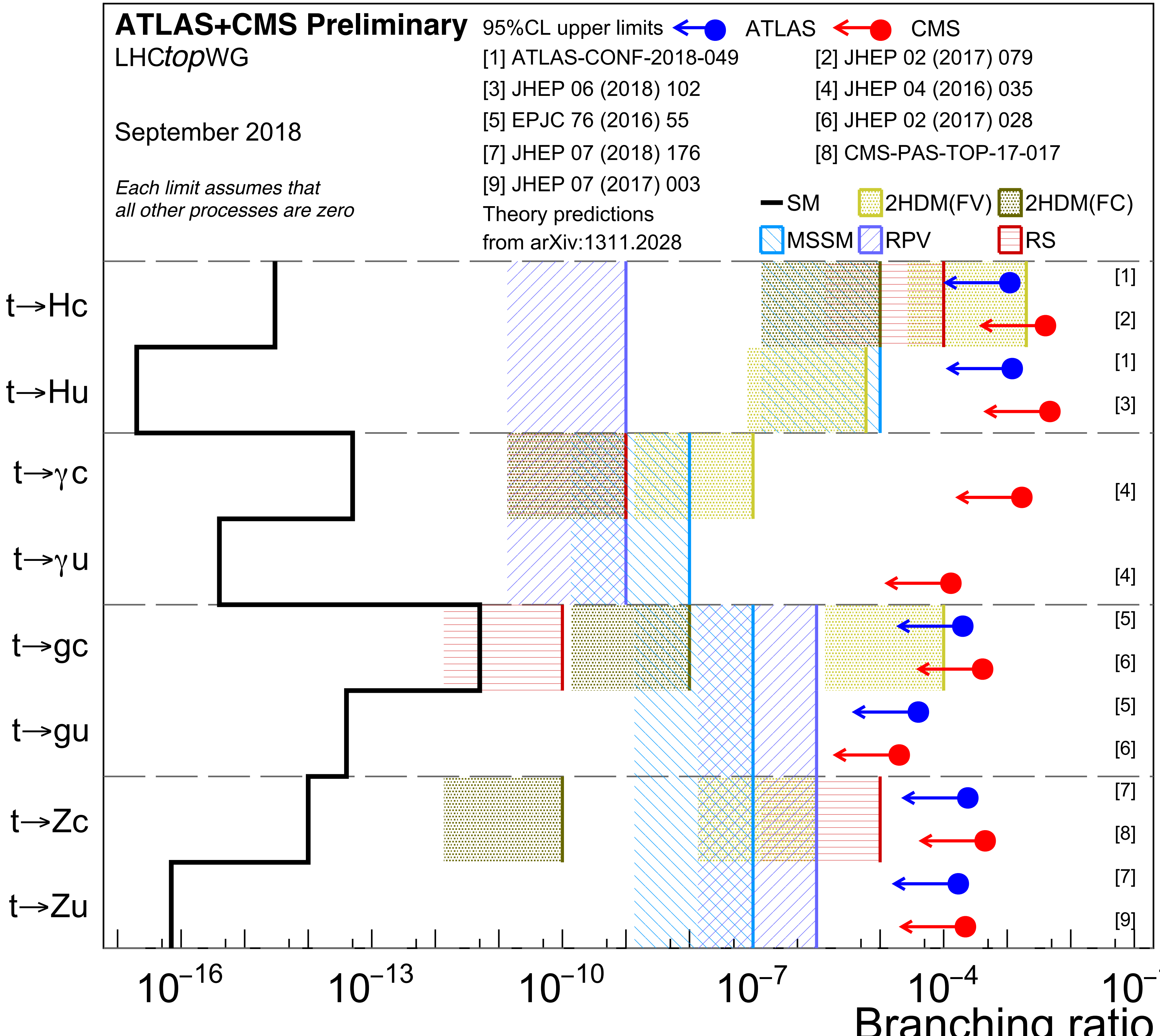


An important message: if we artificially make W's in Pythia octet-like, then we only marginally prefer the singlet.

clearly there is something we can learn for here!

How do we know the W is not an octet?

Back to top properties: decays



top decays to anything other than Wb are (highly) suppressed in the Standard Model.

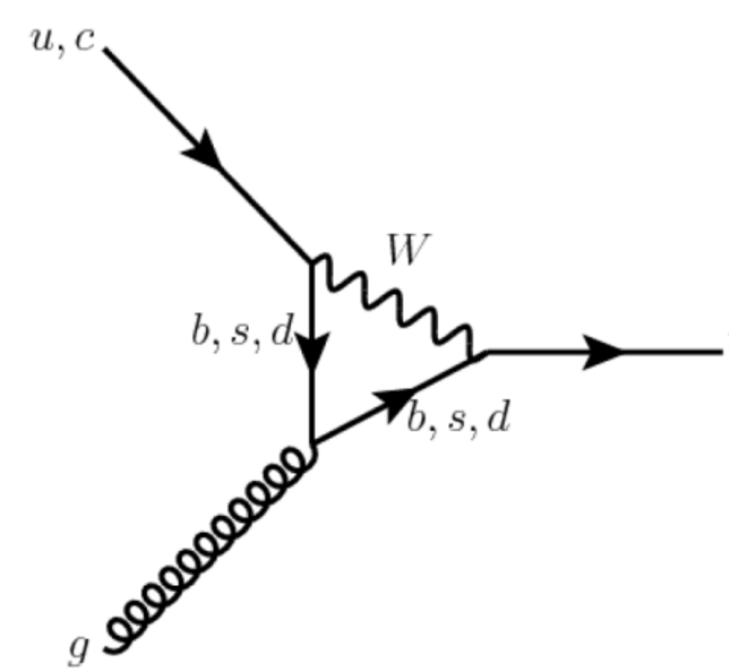
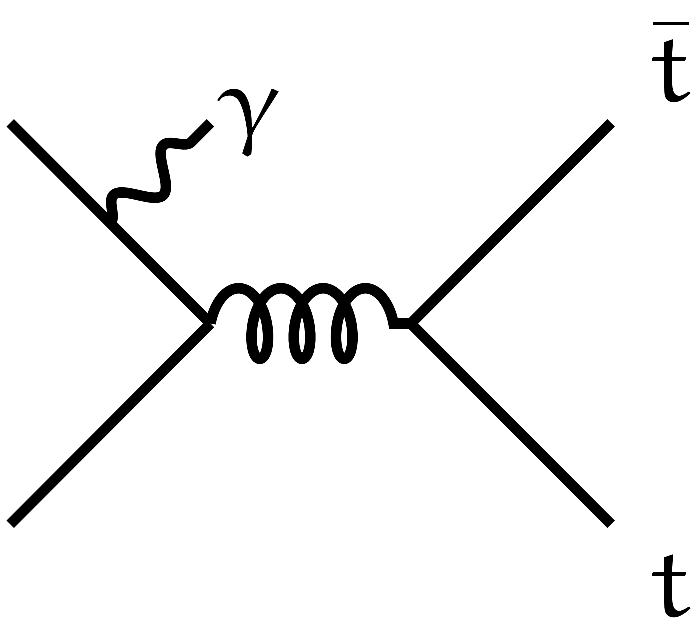


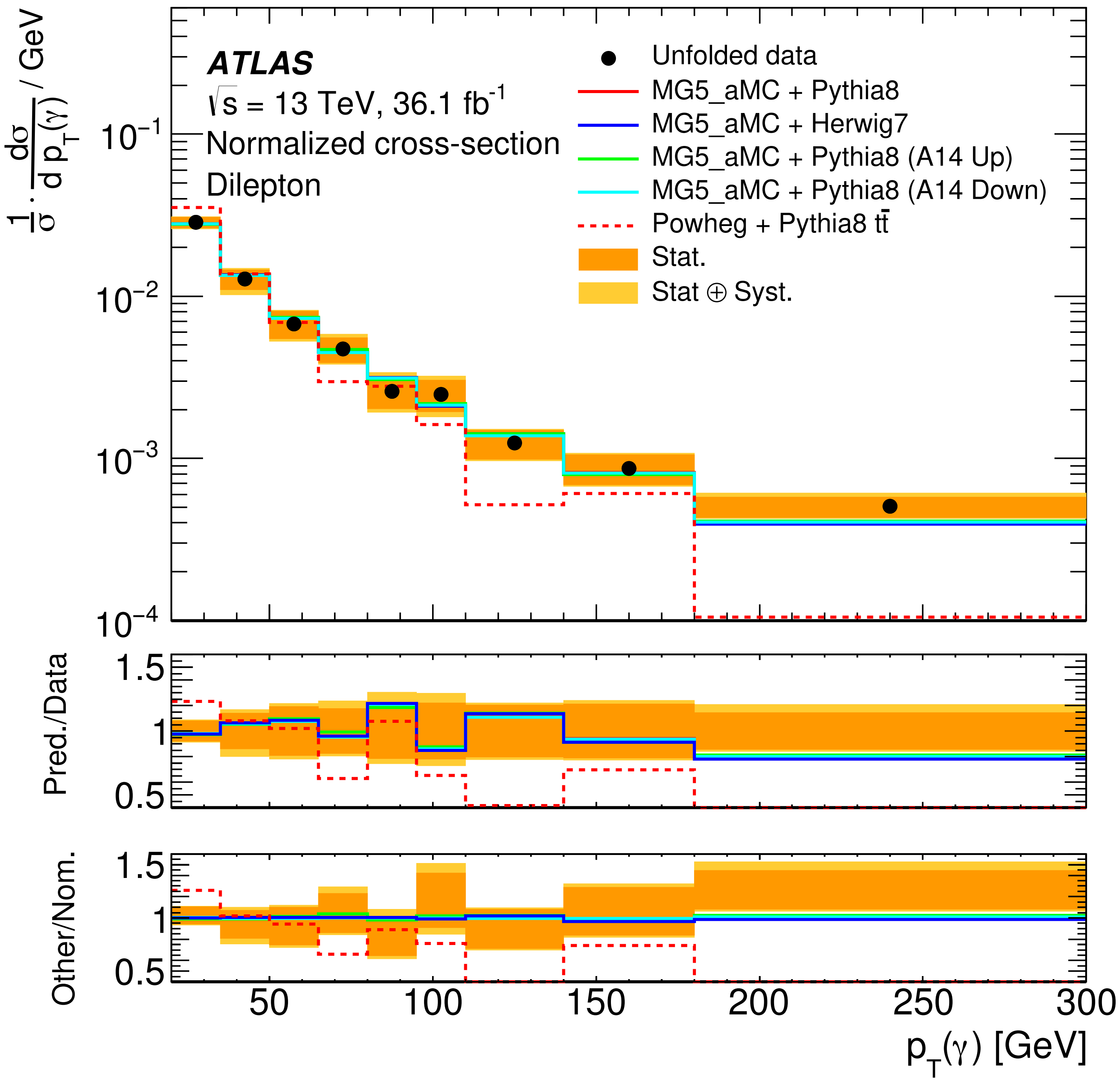
Diagram credit: Markus Cristinziani, Top 2013

Associated production: photons

Dominated by qq production

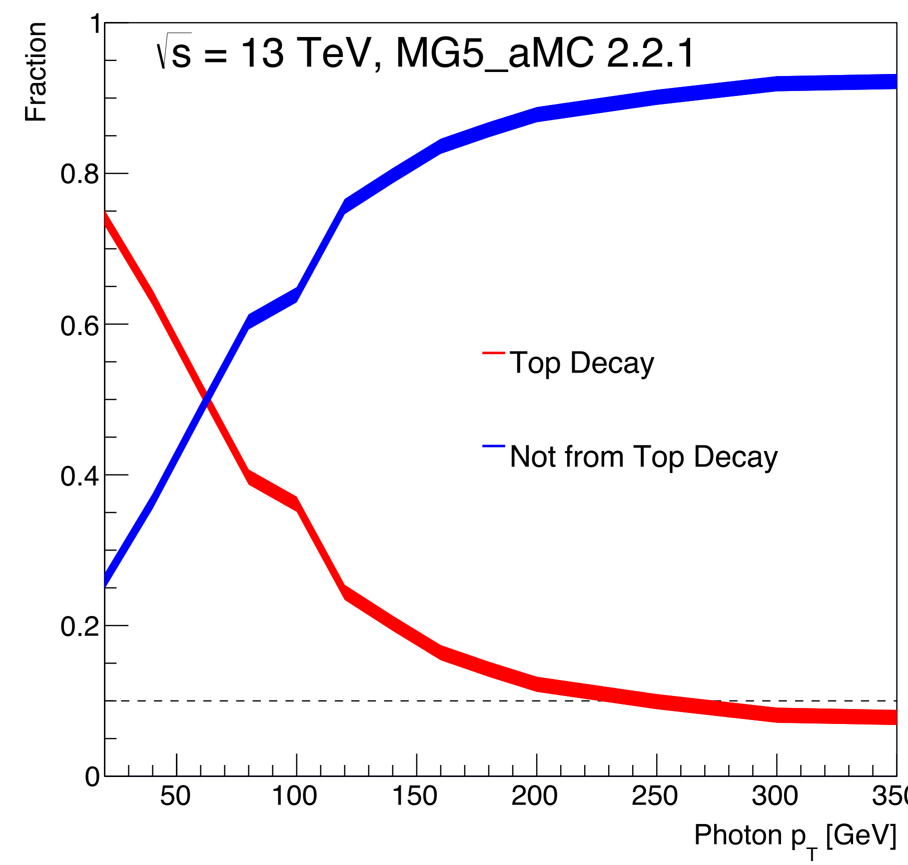
Powerful tool for EFT, etc.

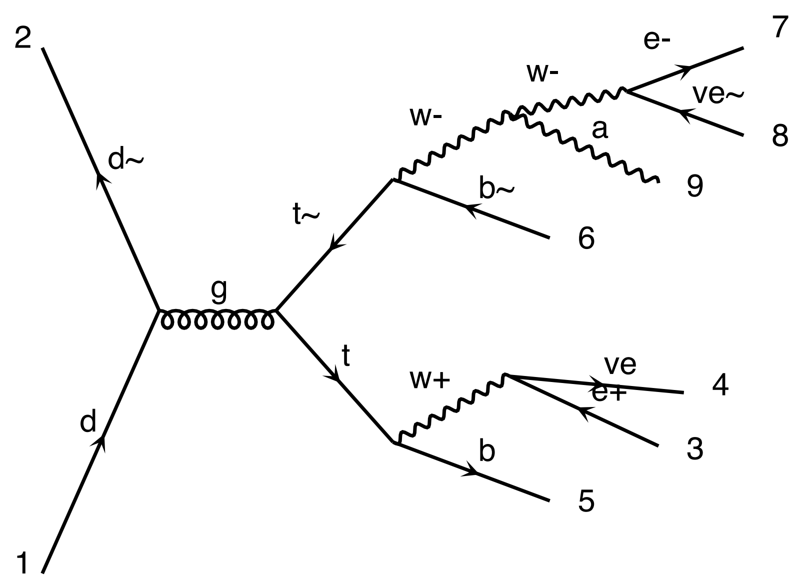


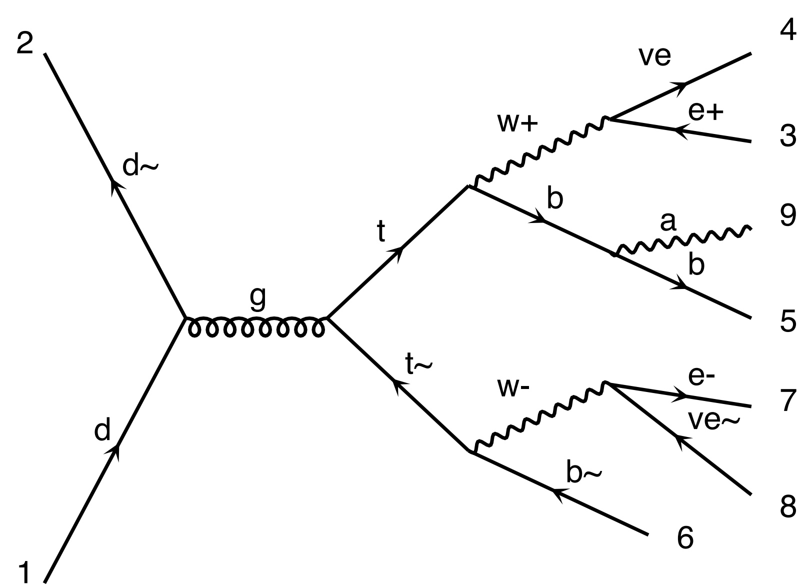


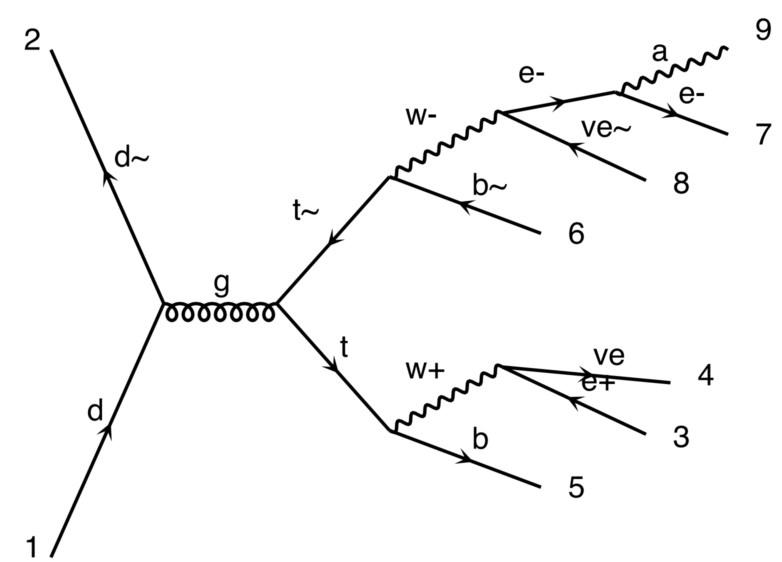
Associated production: photons

Warning: any electrically charged object can radiate a photon!



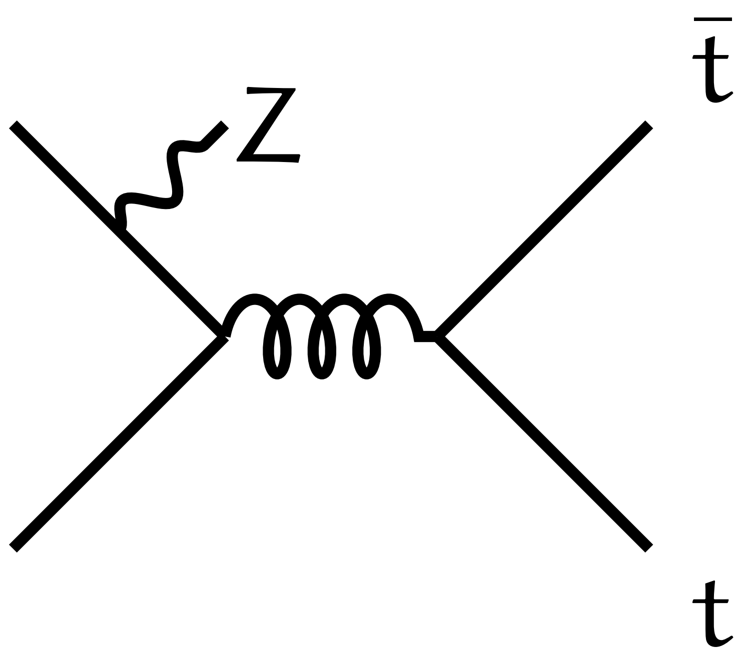


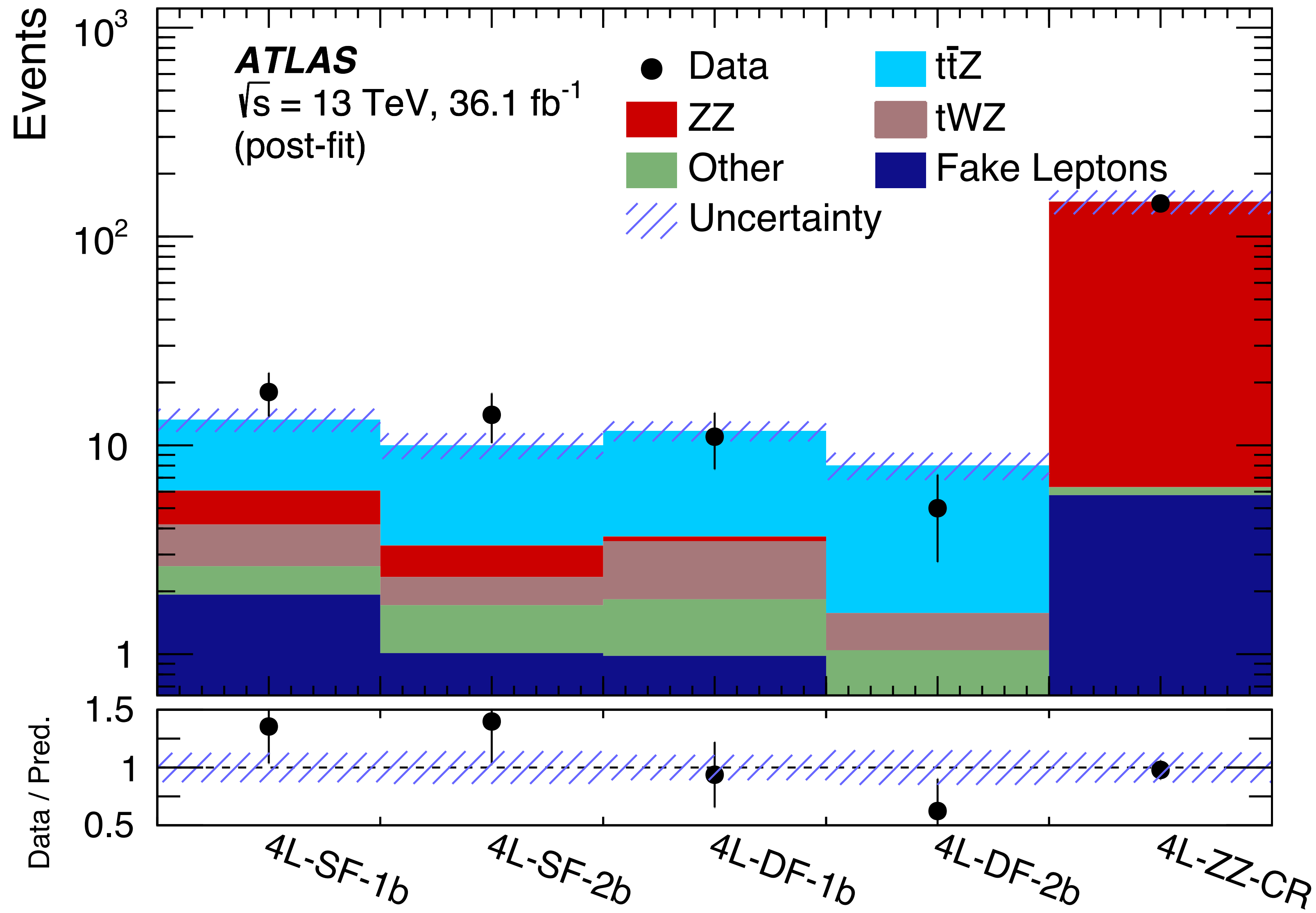




Associated production: W/Z

Powerful probe for EFTs

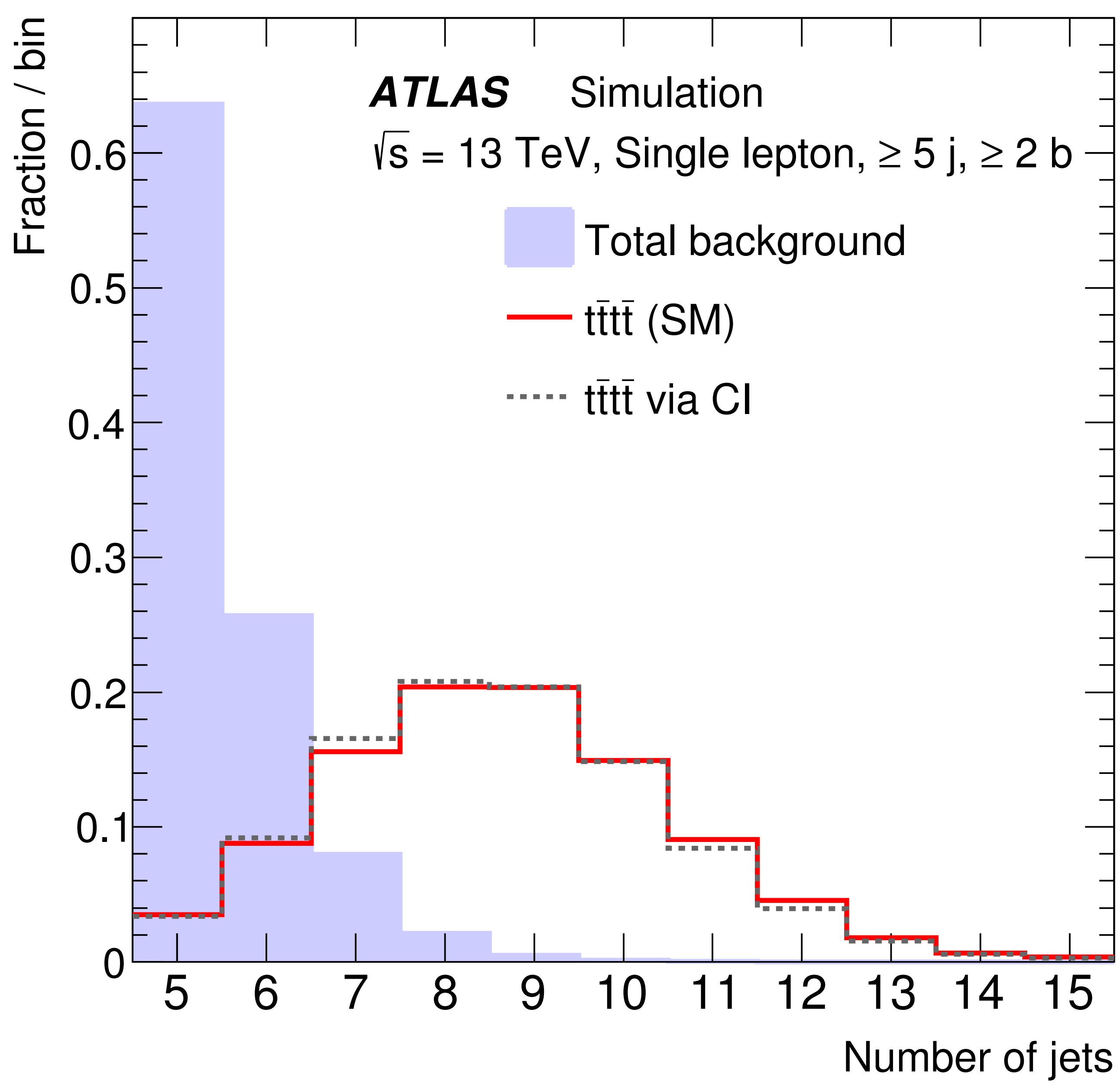


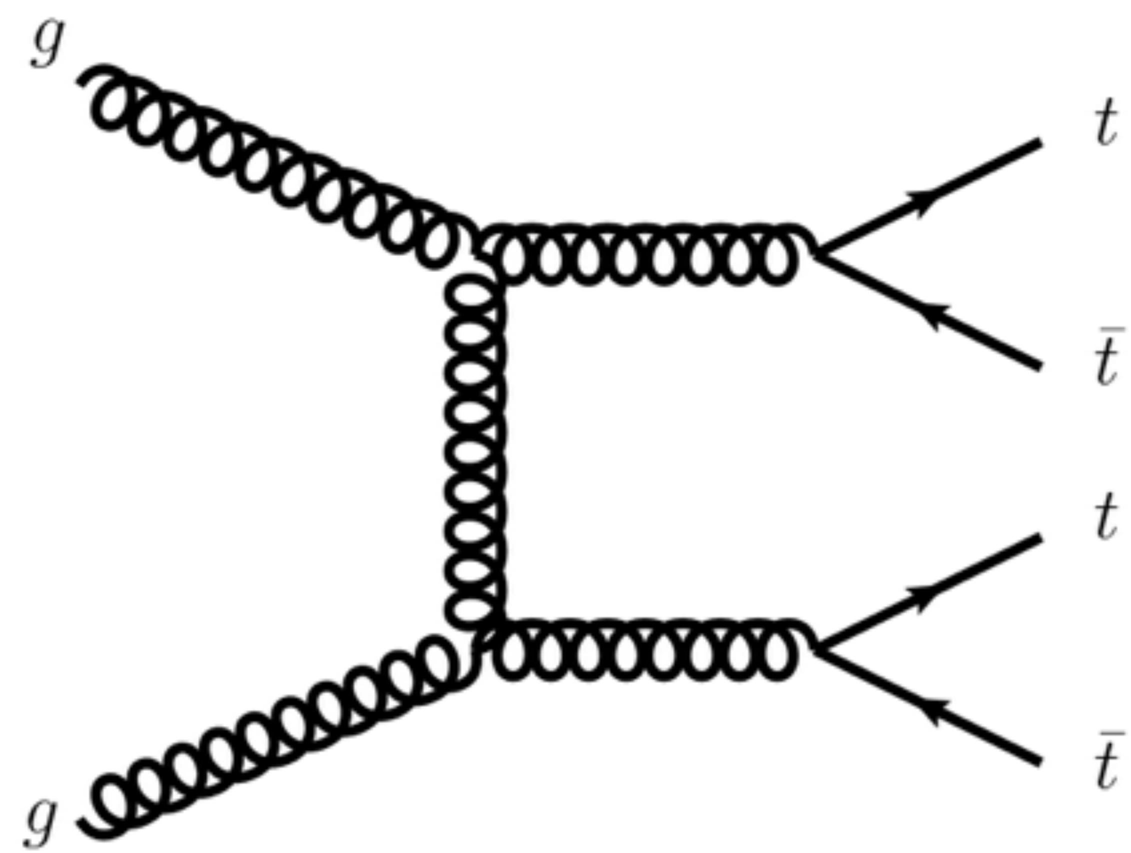


Also a significant background for BSM (both for same-sign lepton searches and for top + MET (Z -> νν))

Associated production: many tops

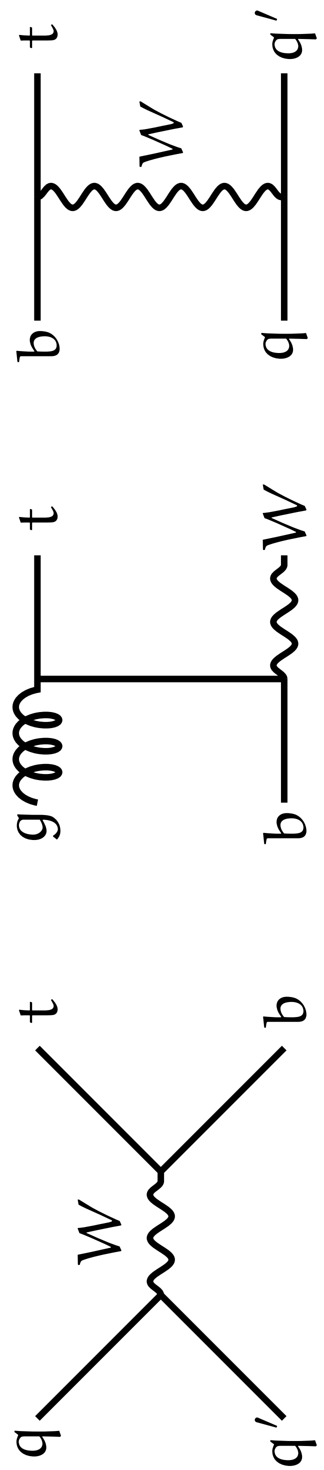
Another interesting probe of EFTs with a diversity of final states.





(current sensitivity is ~few x Standard Model prediction of ~10 fb)

Single top


t
q′
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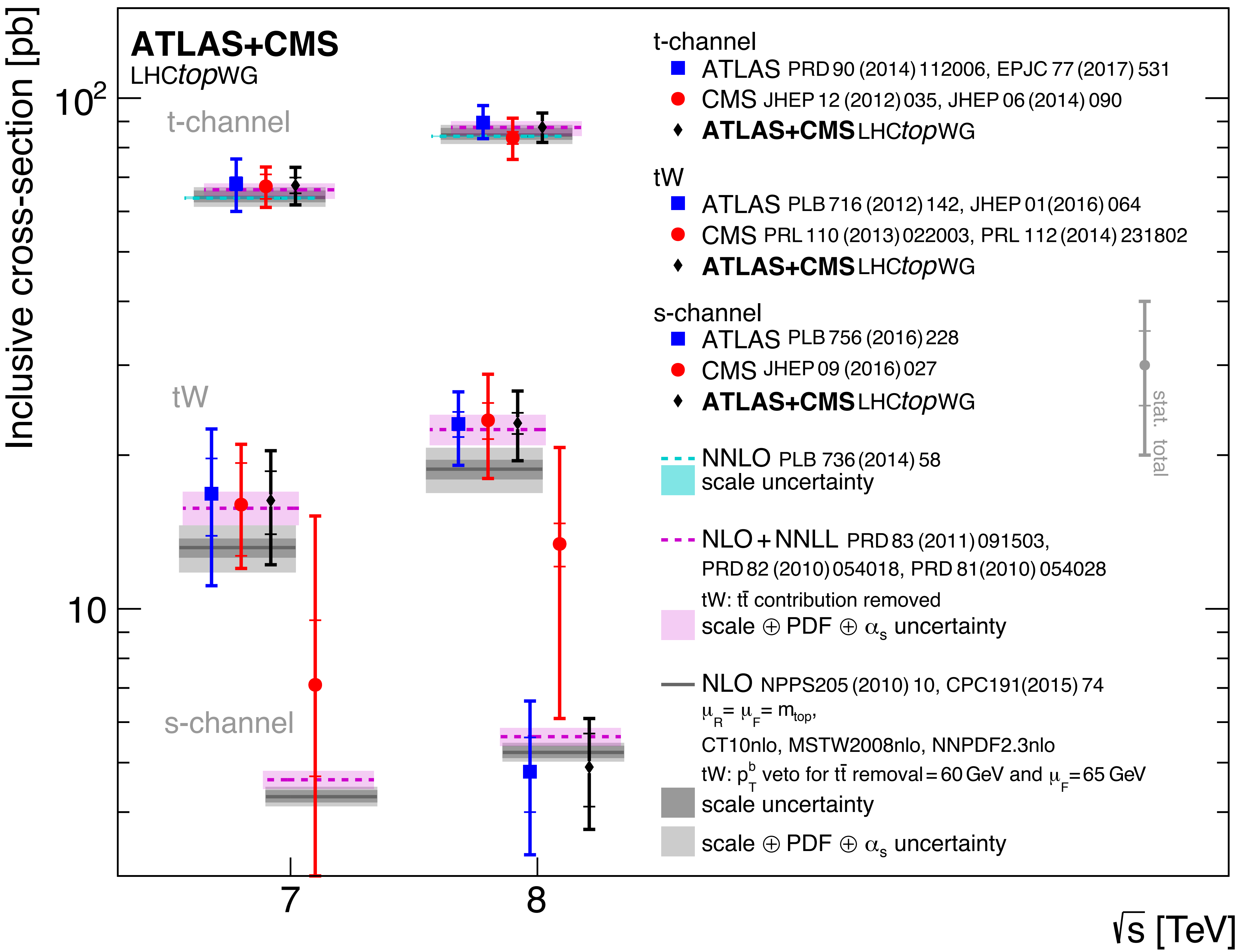
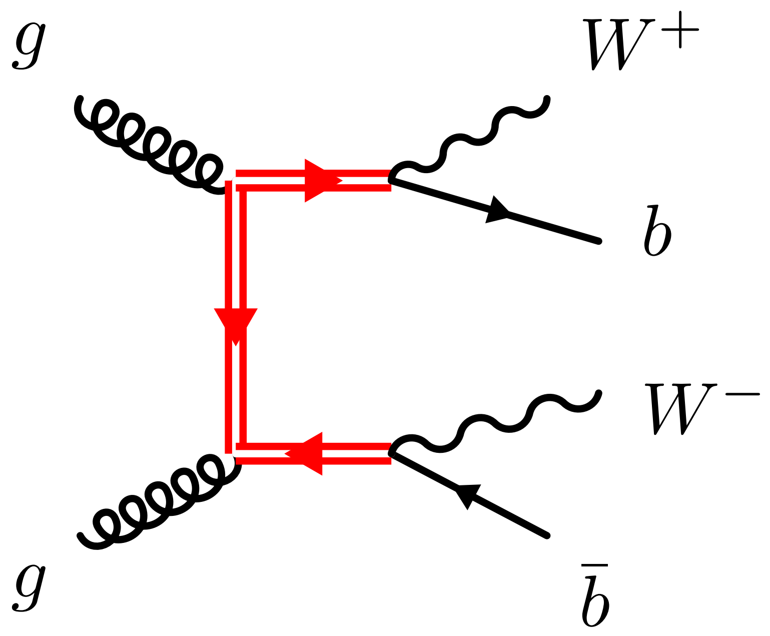
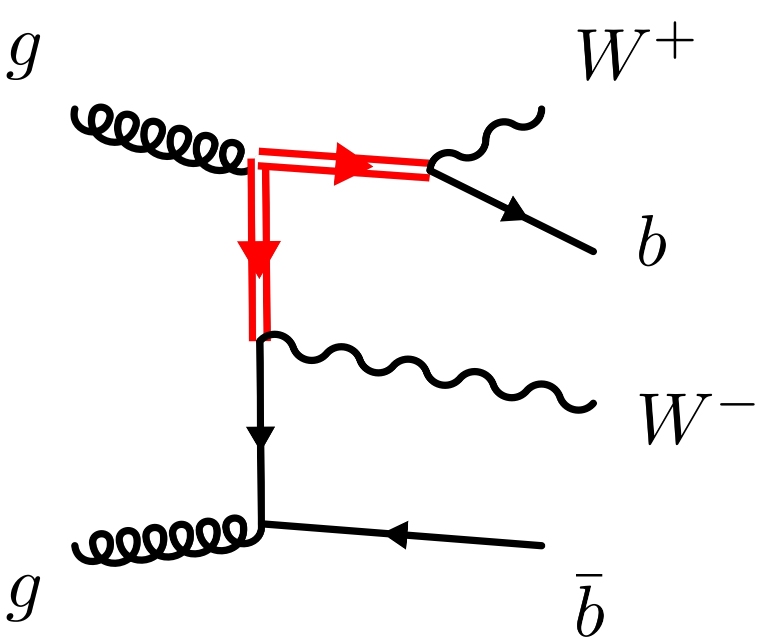

ATLAS+CMS
LHCtopWG
t-channel
tW
s-channel
Inclusive cross-section [pb]
10²
10
7
8
√s [TeV]
t-channel
ATLAS PRD 90 (2014) 112006, EPJC 77 (2017) 531
CMS JHEP 12 (2012) 035, JHEP 06 (2014) 090
ATLAS+CMS LHCtopWG
tW
ATLAS PLB 716 (2012) 142, JHEP 01(2016) 064
CMS PRL 110 (2013) 022003, PRL 112 (2014) 231802
ATLAS+CMS LHCtopWG
s-channel
ATLAS PLB 756 (2016) 228
CMS JHEP 09 (2016) 027
ATLAS+CMS LHCtopWG
stat. total
NNLO PLB 736 (2014) 58
scale uncertainty
NLO + NNLL PRD 83 (2011) 091503,
PRD 82 (2010) 054018, PRD 81(2010) 054028
tW: tt̄ contribution removed
scale ⊕ PDF ⊕ αs uncertainty
NLO NPPS205 (2010) 10, CPC191(2015) 74
μR = μF = mtop,
CT10nlo, MSTW2008nlo, NNPDF2.3nlo
tW: pTb veto for tt̄ removal = 60 GeV and μF = 65 GeV
scale uncertainty
scale ⊕ PDF ⊕ αs uncertainty

Interference with pair production



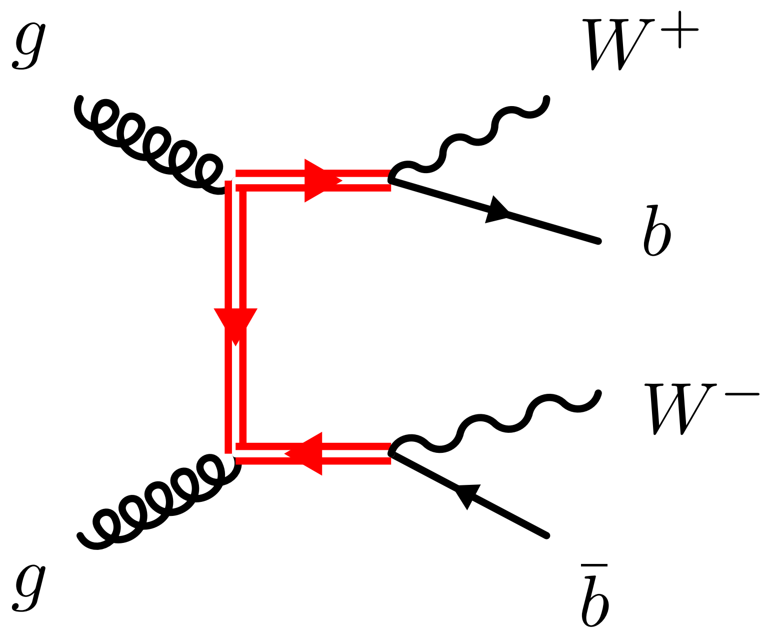


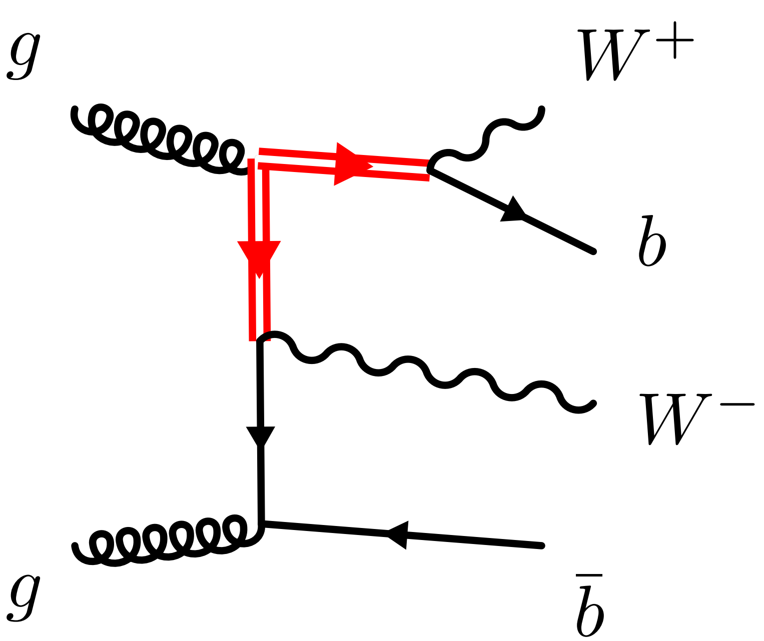
Many searches where top-pairs are a background are finding that Wtb is a significant residual background.

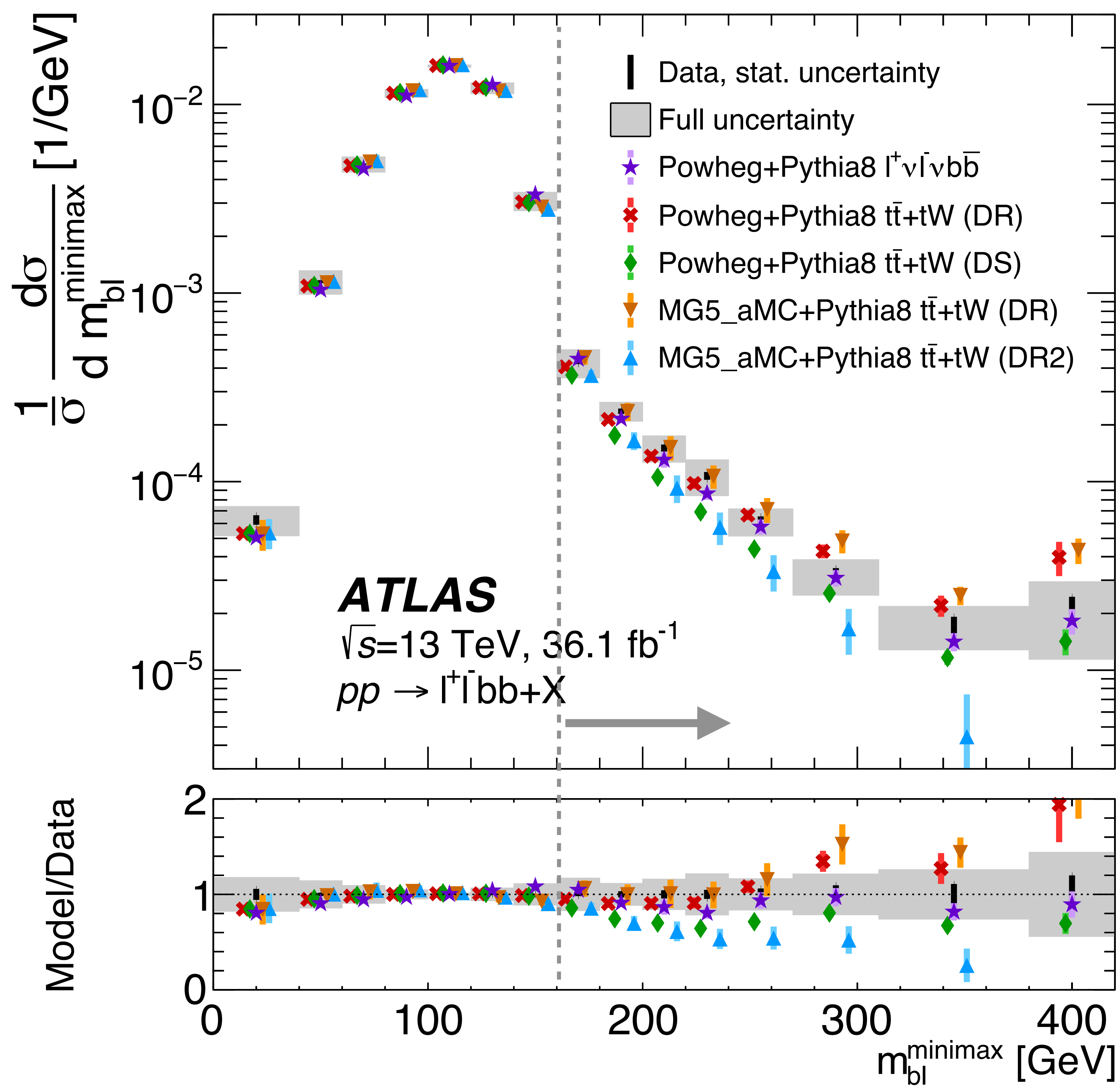
However, beyond leading order, single top and top pair production interfere!

This makes the modeling of this process complicated!

Interference with pair production

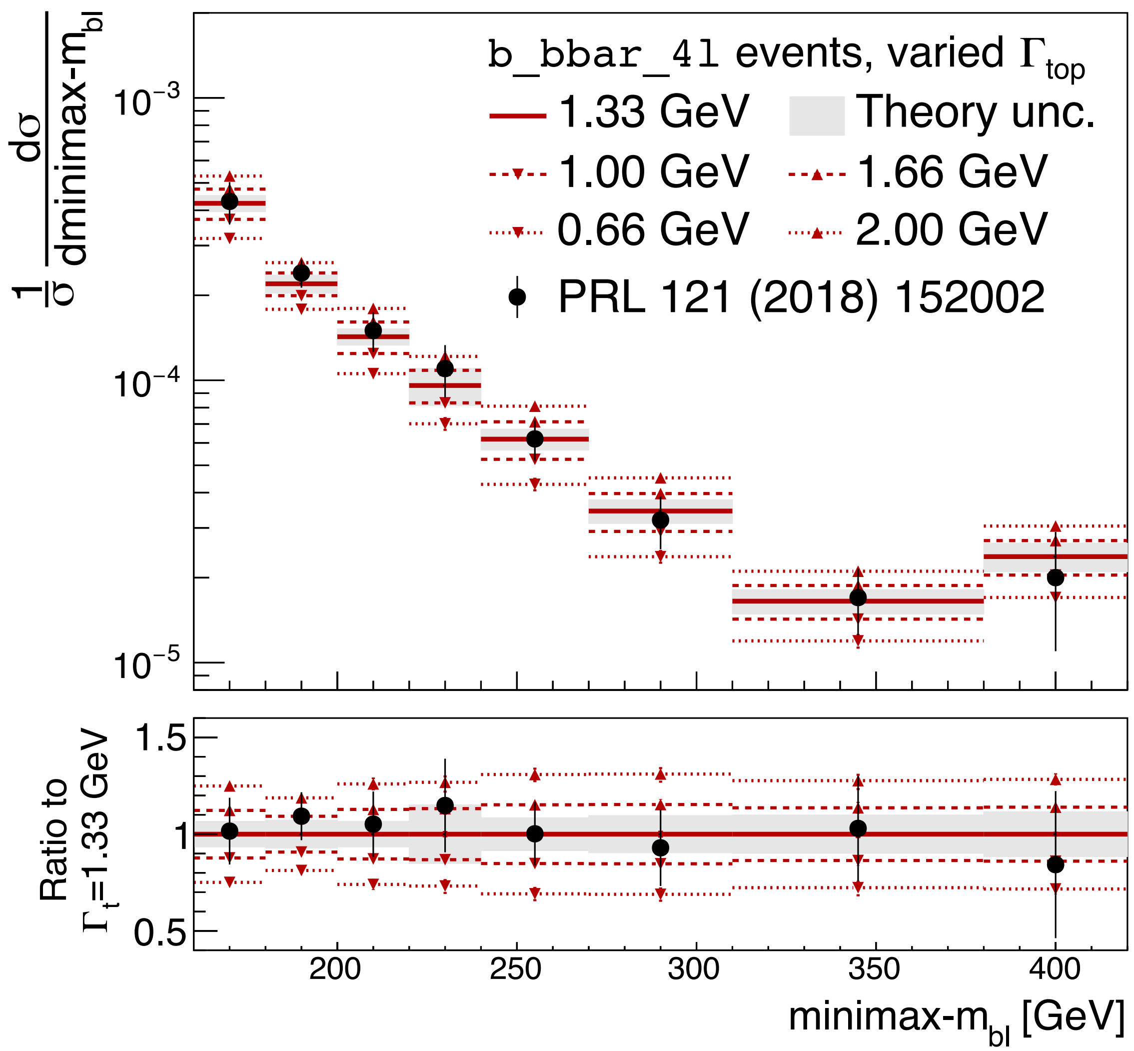






Interference-sensitive region

Top quark width

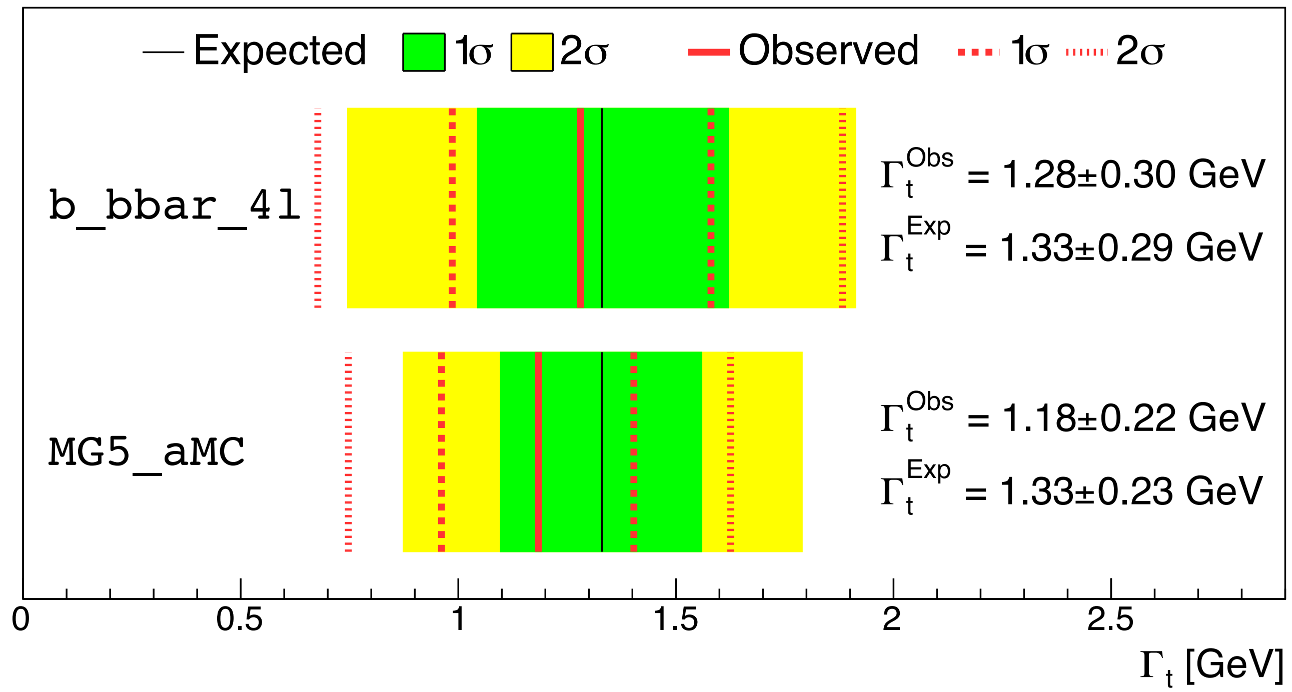


In fact, this region is rather sensitive to the top quark width!

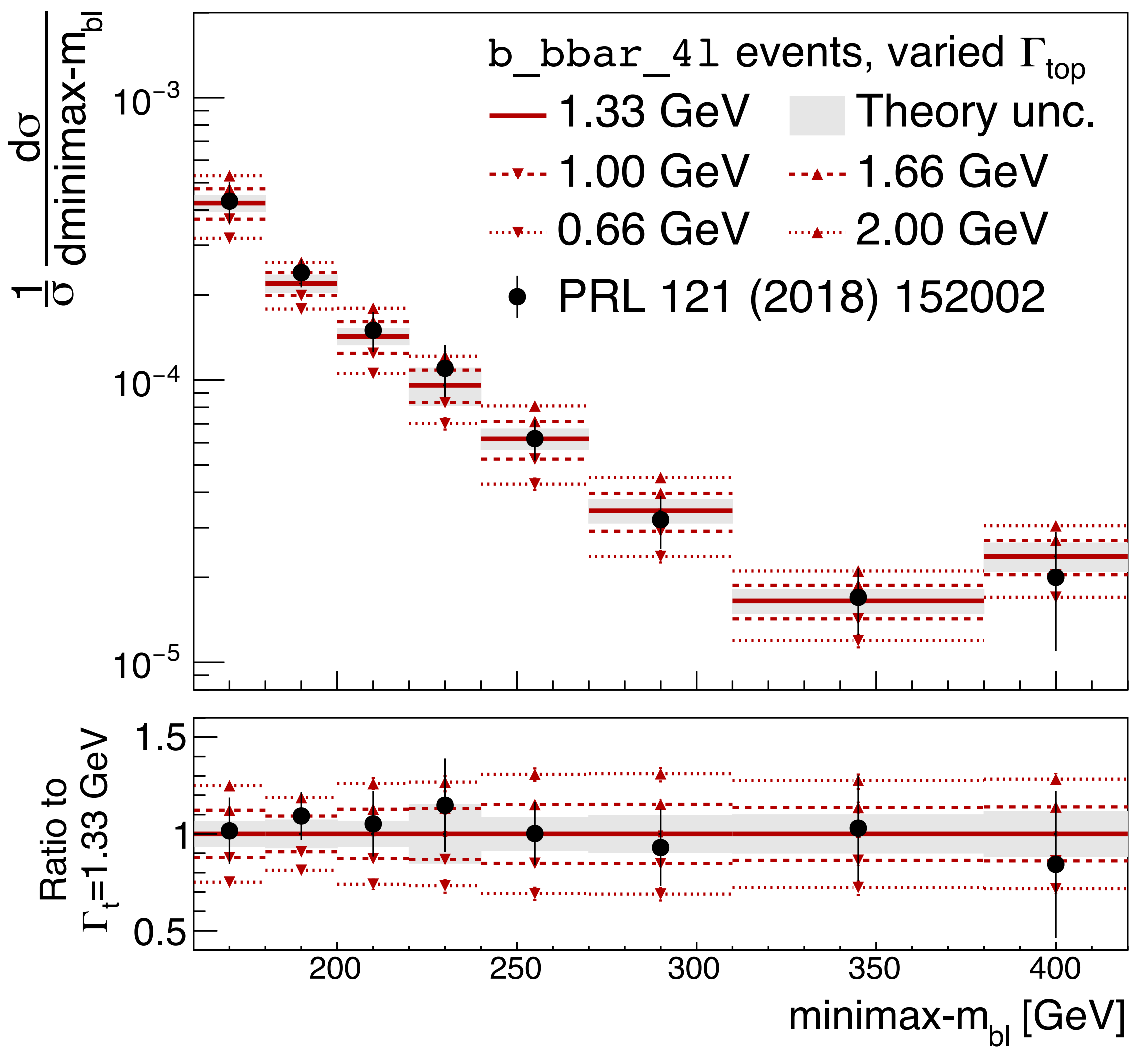
Stronger sensitivity than the peak region (traditional method)

(why?)

The top quark width is precisely known, but experimental precision is only ~20%



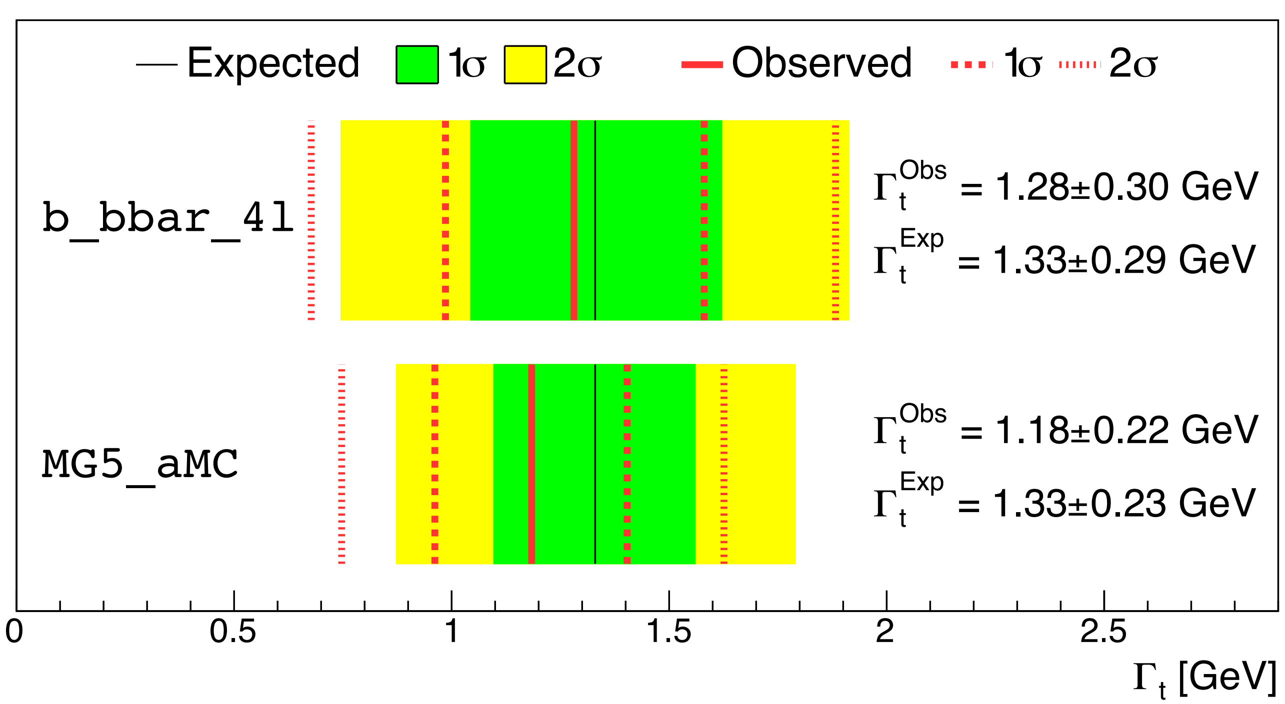
Top quark width



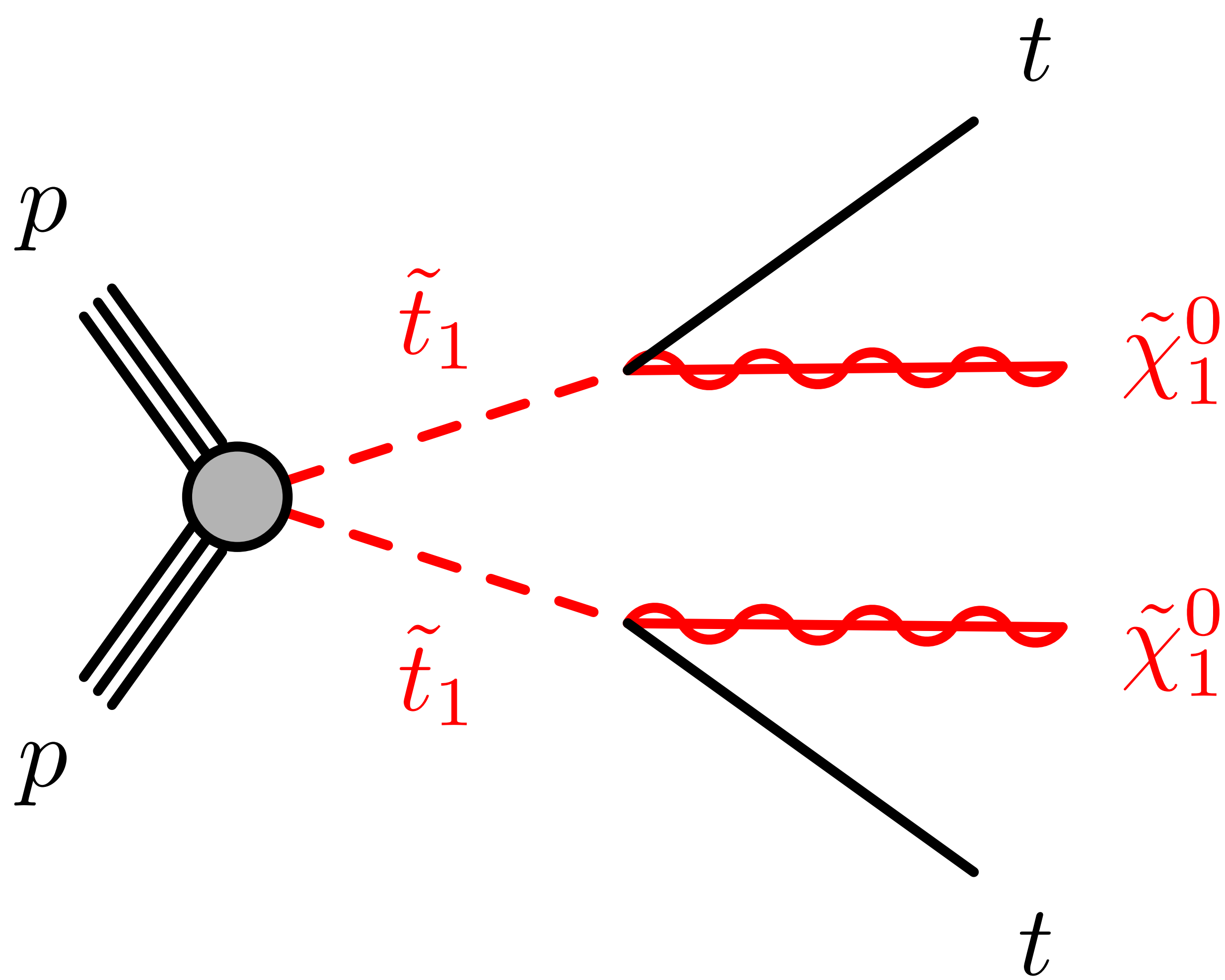
$$\mathcal{BR}(t \to \mathrm{BSM}) < \frac{\Gamma_{\mathrm{ext}}^{+95\%} - \Gamma_{t\to bW}^{\mathrm{SM}}}{\Gamma_{\mathrm{ext}}^{+95\%}}$$

One can use this to set model-independent limits on the BSM branching ratio.

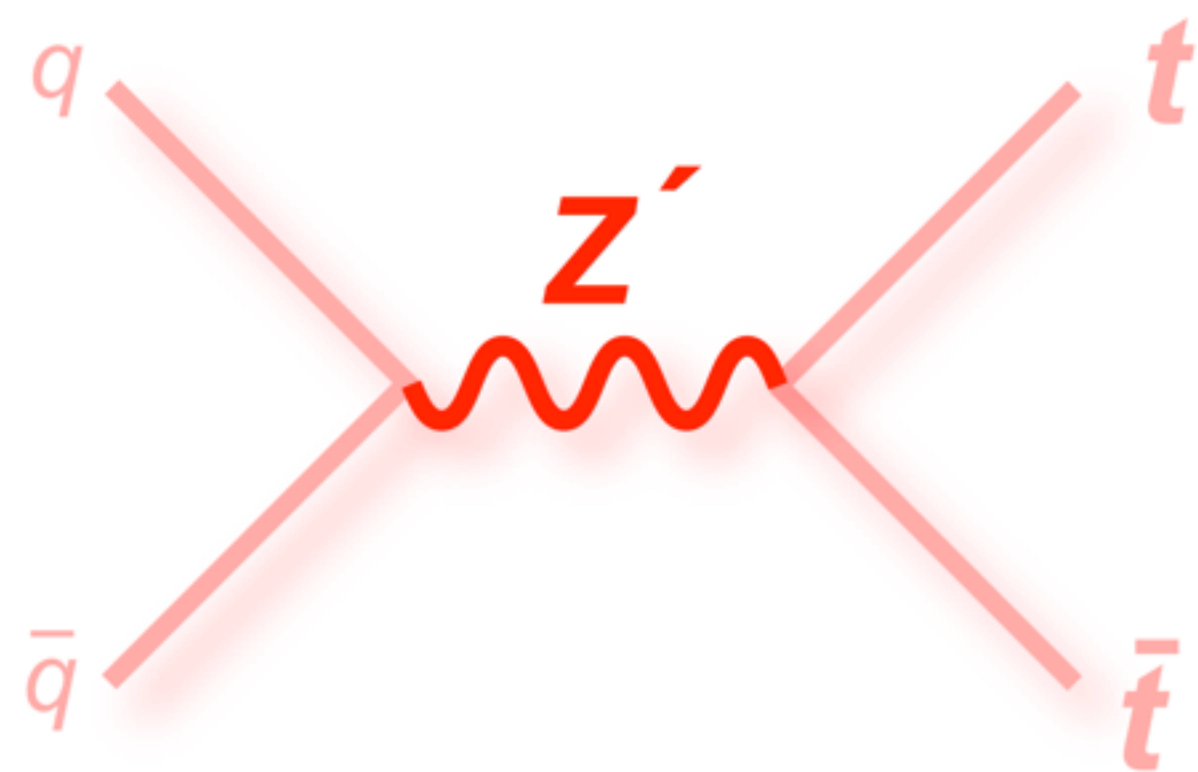
These are quite week compared to the FCNC results shown earlier!



Last topic: BSM with top quarks

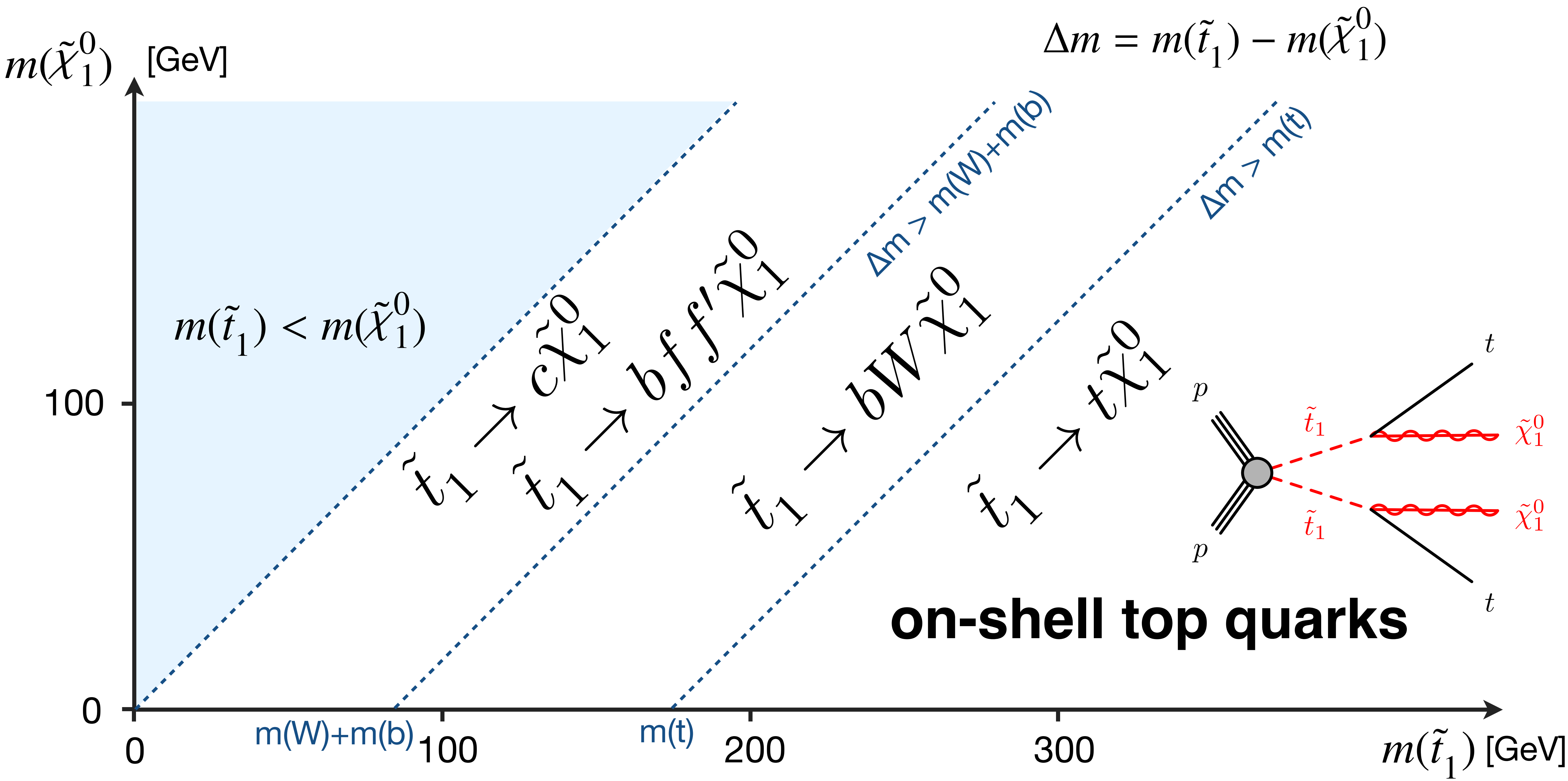


Top quarks feature prominently in many searches, either as the target or as the main background.



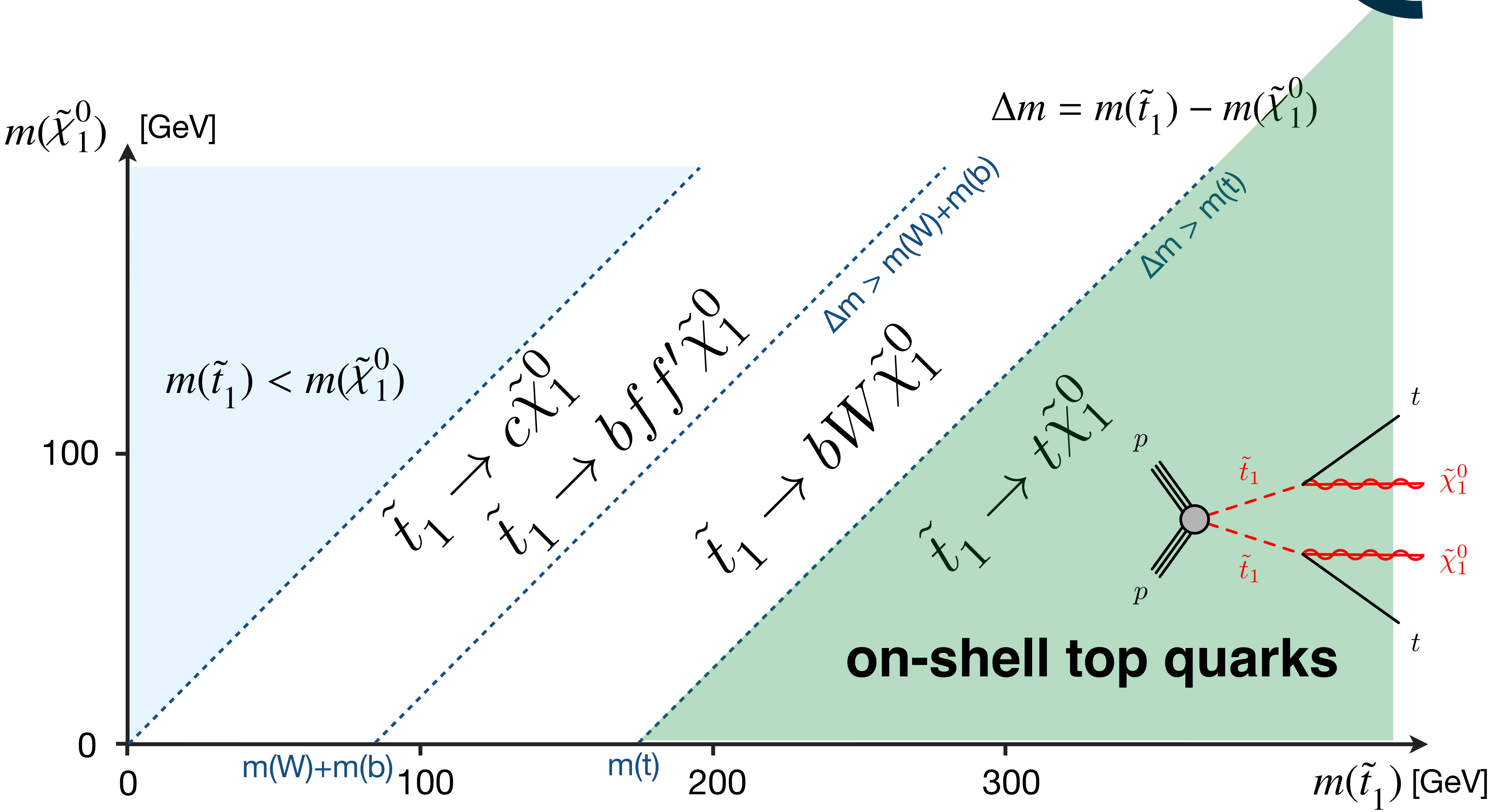
I'll briefly discuss the interplay between the stop search and SM top measurements.

BSM with top quarks

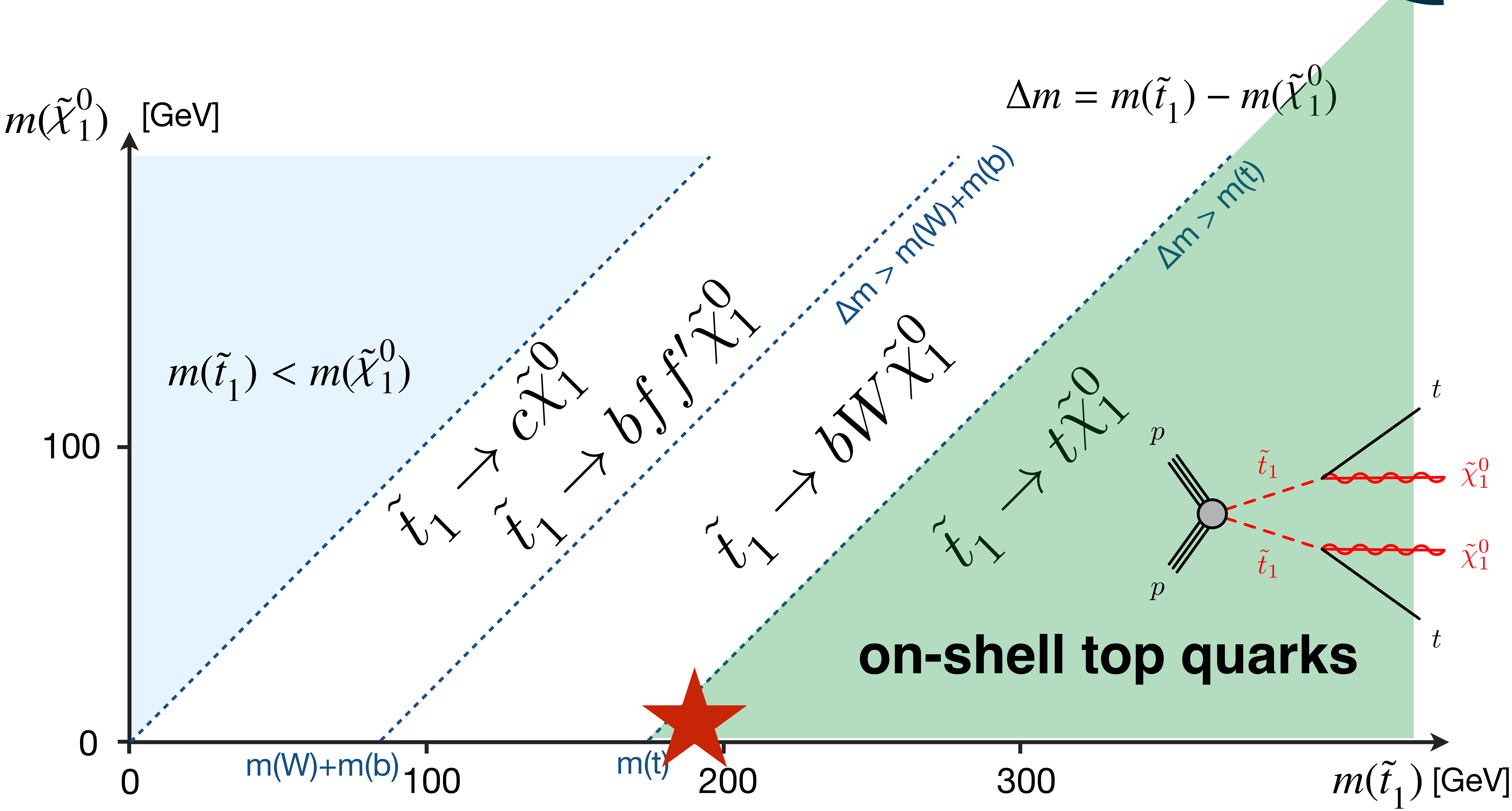


I won't motivate why SUSY/stops - see ***Beyond SM*** tomorrow

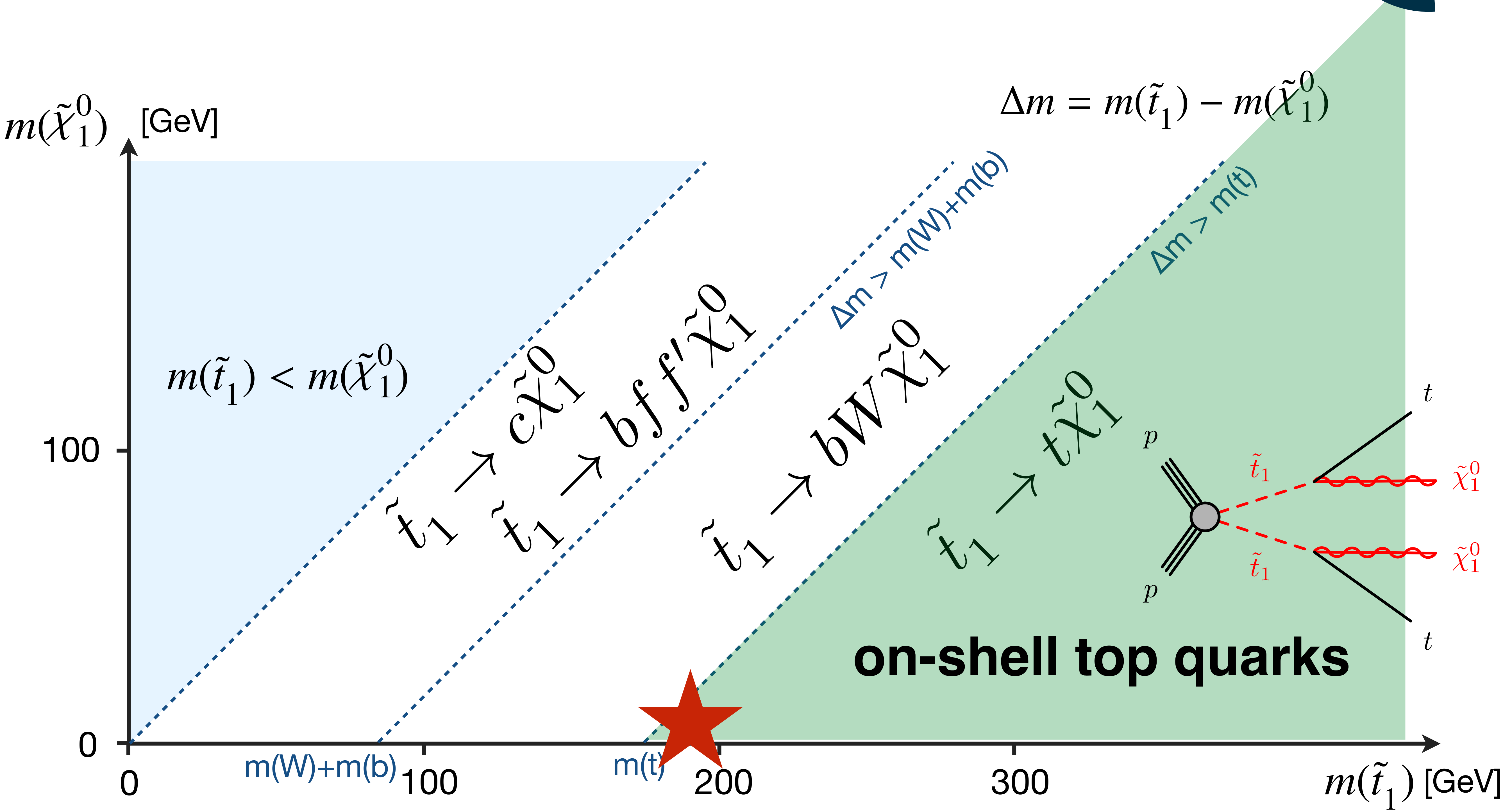
BSM with top quarks



BSM with top quarks

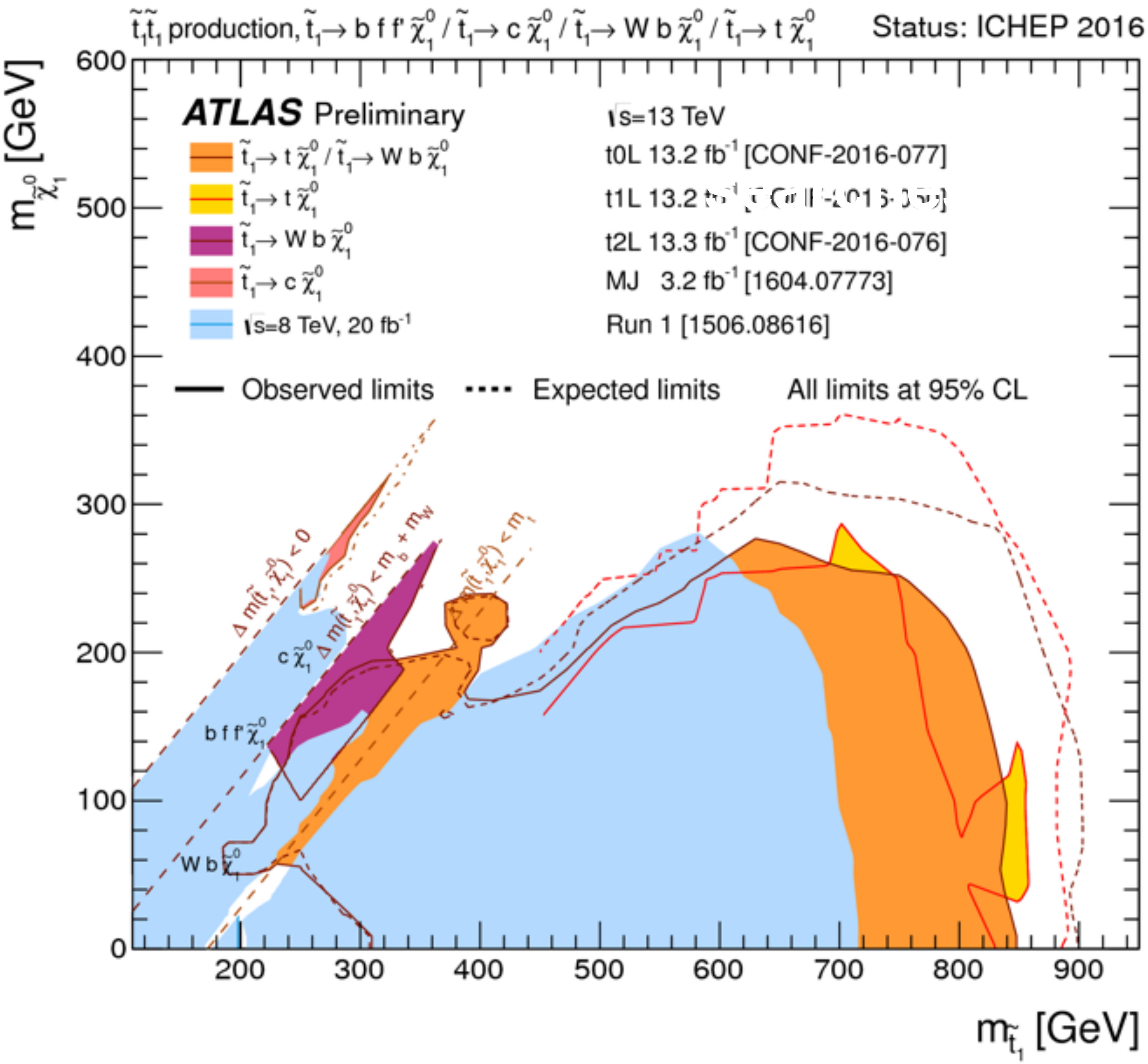


BSM with top quarks

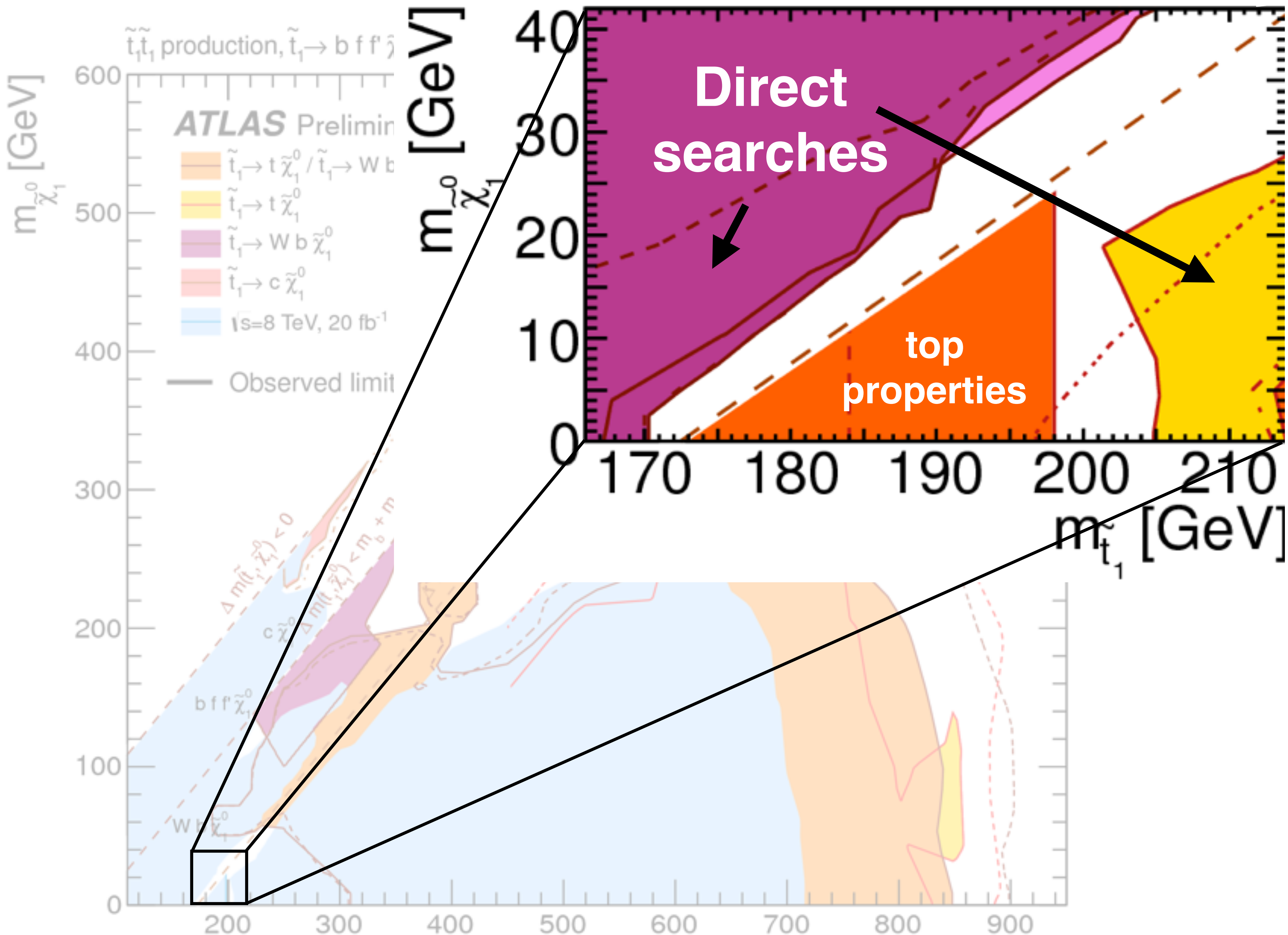


In this “stealth” region, the neutralinos have little momentum.

BSM with top quarks



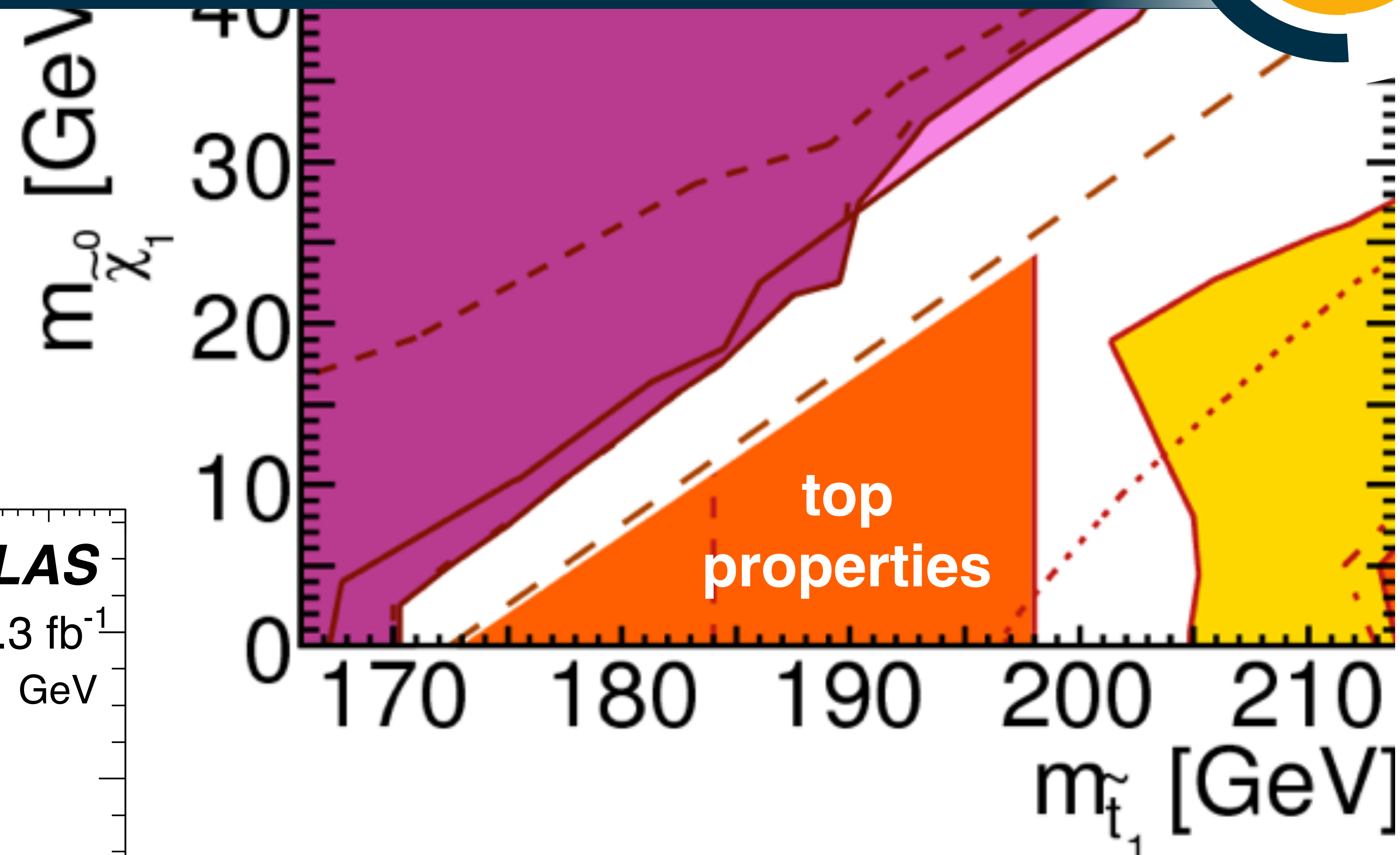
Stop ~ top

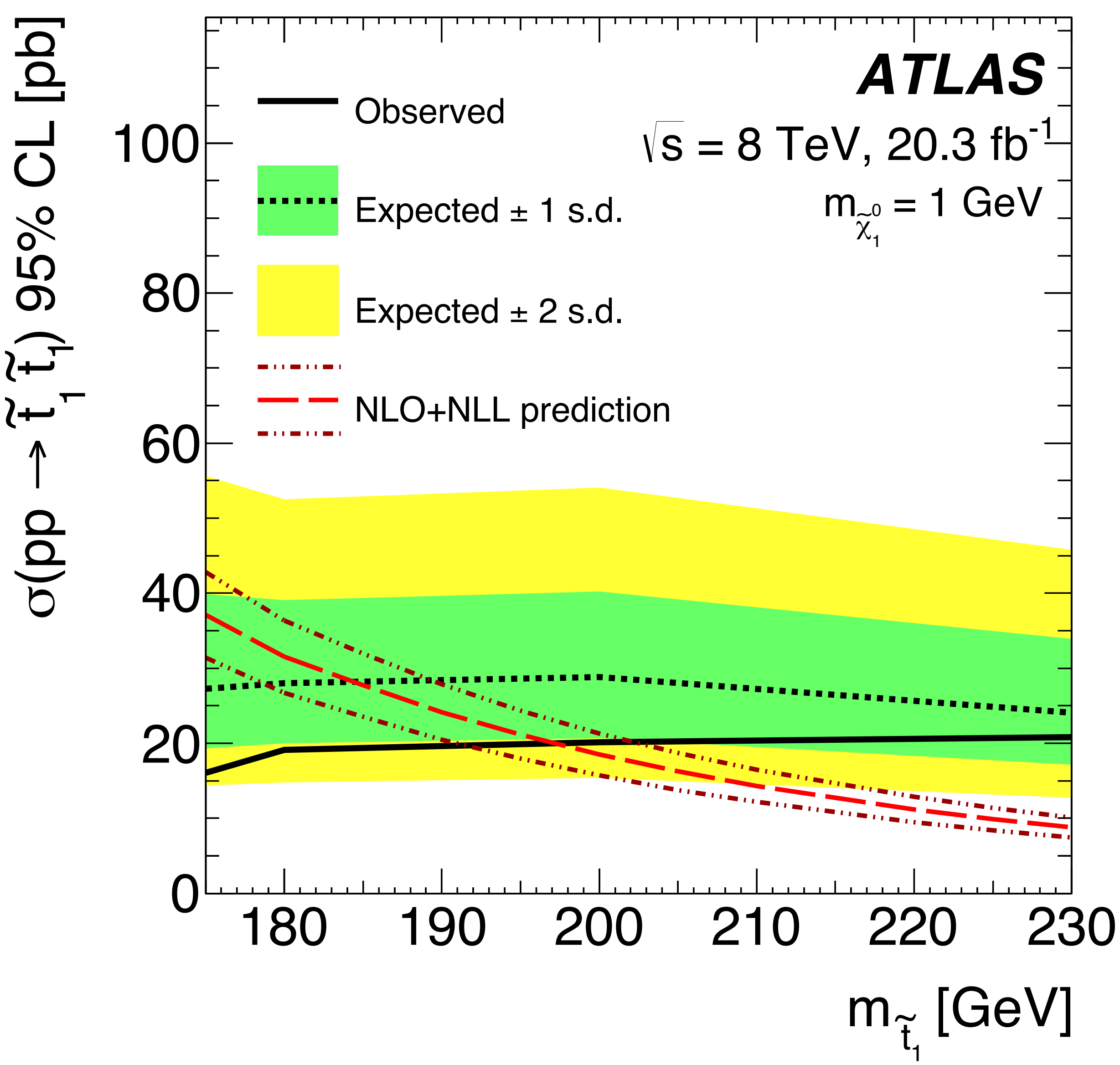


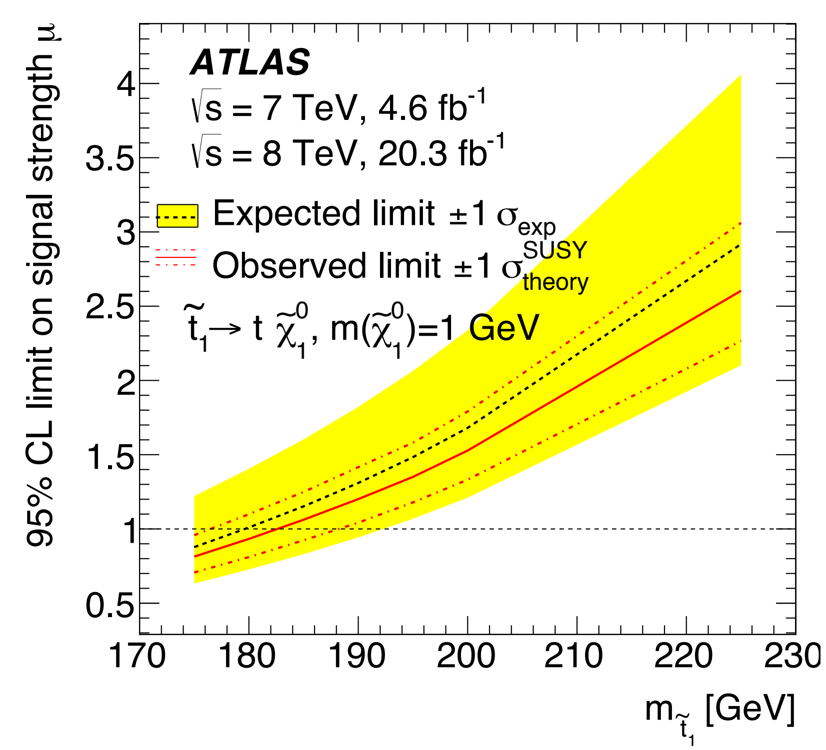
$\tilde{t}_1\tilde{t}_1$ production, $\tilde{t}_1 \rightarrow b f f' \tilde{\chi}$
ATLAS Prelimin
$\tilde{t}_1 \rightarrow t \tilde{\chi}^0_1$ / $\tilde{t}_1 \rightarrow W b$
$\tilde{t}_1 \rightarrow t \tilde{\chi}^0_1$
$\tilde{t}_1 \rightarrow W b \tilde{\chi}^0_1$
$\tilde{t}_1 \rightarrow c \tilde{\chi}^0_1$
$\sqrt{s}$=8 TeV, 20 fb^{-1}
Observed limit
$m_{\tilde{\chi}^0_1}$ [GeV]
$m_{\tilde{t}_1}$ [GeV]
Direct searches
top properties

Stop ~ top

spin correlations measurement

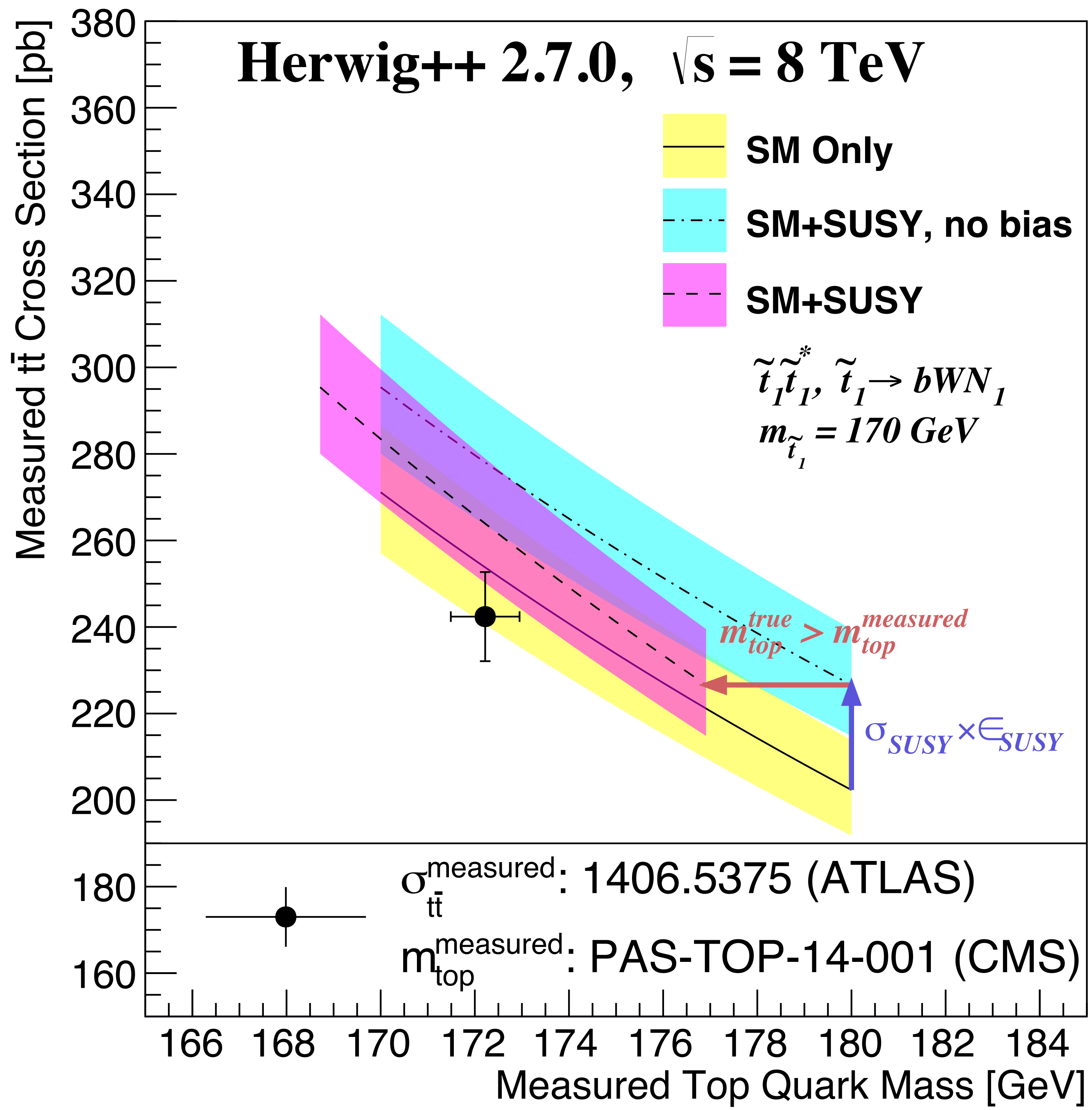






Top cross-section measurement

Warning: sneaky light stop



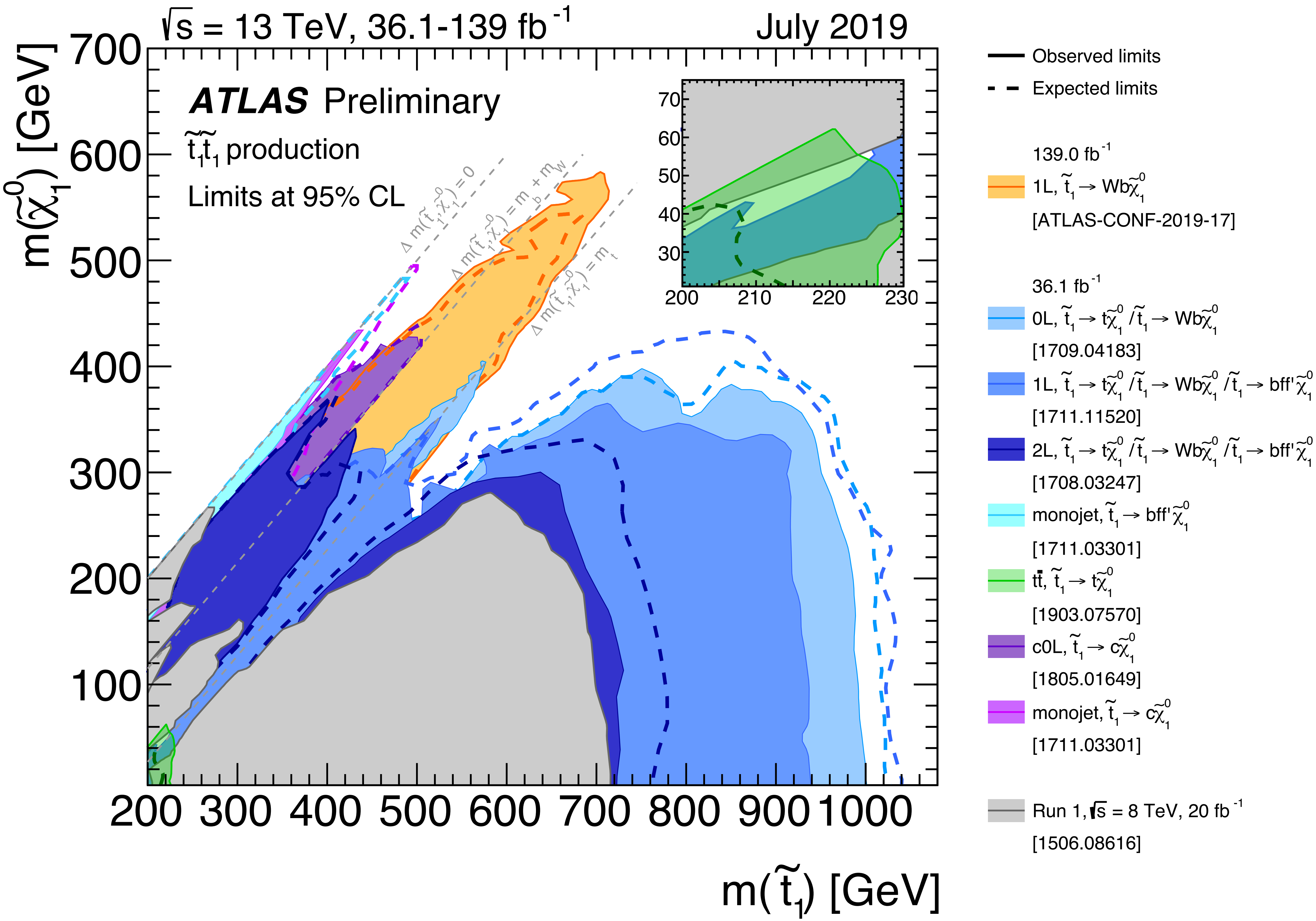
*it is always low because m(blv) or m(bjj) are always less for the stop than the top.

A light stop could introduce a bias in the top mass measurement.

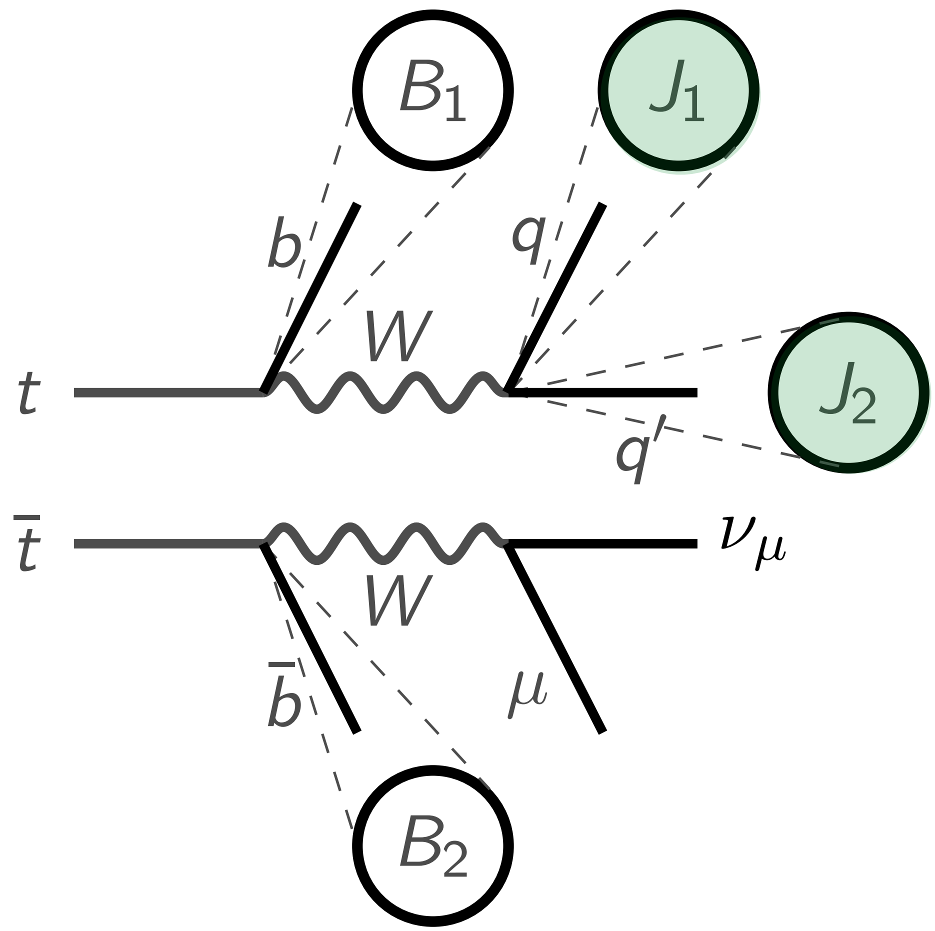
If **we measure the mass too low***, we will predict too high a ttbar cross-section.

The **added cross-section from the stop** can then be hidden!

Status today

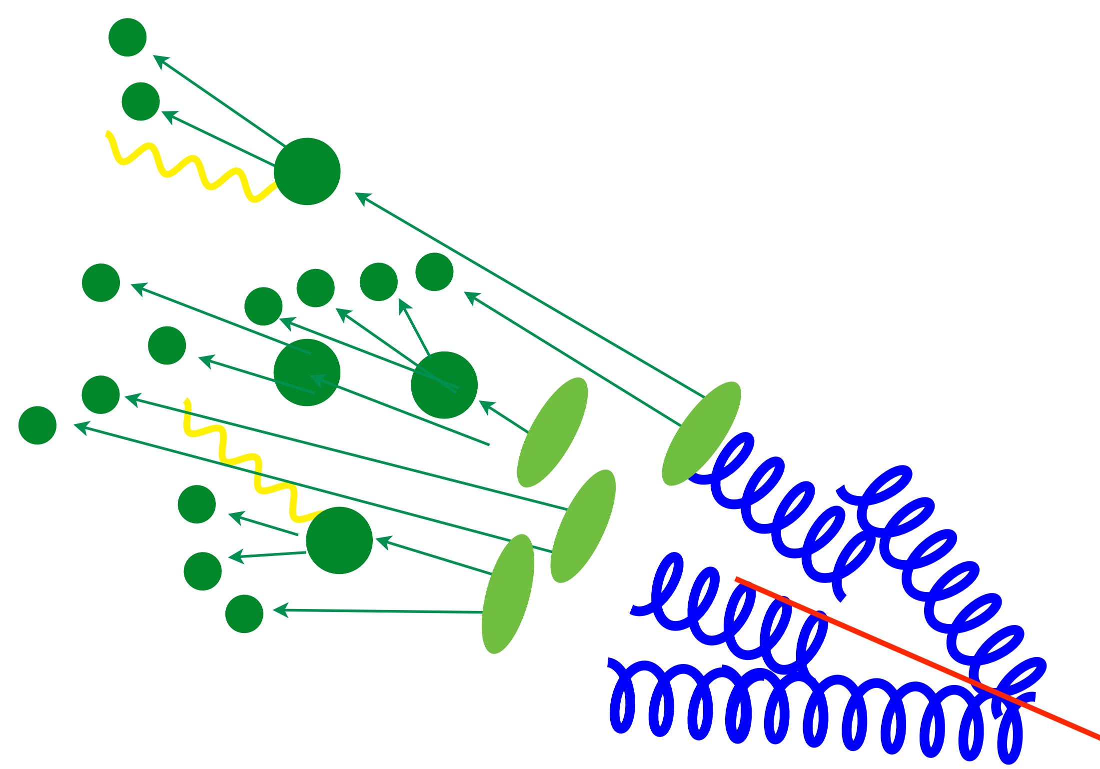


Summary and overview



The top quark is unique in the Standard Model.

Many of its properties are being studied for precision at the LHC for the first time.



In many ways, it produces the most BSM-like phenomenology and by studying it more detail, we can learn about QCD as well as prepare for the unknown.

Questions?