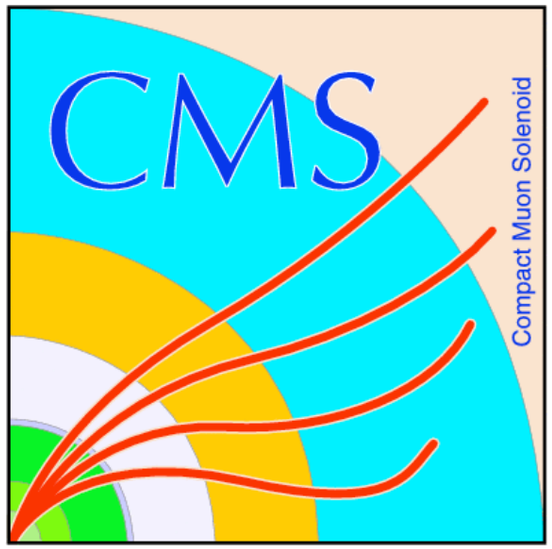
Stating the Case for Top at the LHC



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for the ATLAS and CMS collaborations
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Thanks to: Martine Bosman, Claudio Campagnari, Tim Christiansen, Richard Hawkings

The end of top physics?

You just heard a presentation on the great work done by the Tevatron experiments to understand the nature of the top quark:

- Top mass measured to 1.3 GeV (= 0.75%!), giving significant constraints on allowed SM Higgs mass
- Quantum numbers (spin, charge, couplings) consistent with SM predictions
- Meaningful limits on non-SM decays and production mechanisms
- No sign of heavy particles decaying to top
- Recent observation of electroweak single-top production demonstrates V_{tb} consistent with indirect measurements, and implementation of sophisticated data-analysis techniques

In short, the Tevatron has delivered all that was promised for top-quark physics, if not more. So why even consider working on this "boring" SM physics at the LHC?

Because top is the gateway to the physics of the next energy scale!

Why top at the LHC?

Top is a well-understood SM particle:

- Use it to commission experiments by showing that we can detect and measure all top decay products in a challenging event environment.

Top will be used to re-establish the SM at 14 (or 10) TeV:

- Can we believe any observations of new physics until we have established that the "old" physics works at the new energy scale?

Top will be characterized to exquisite detail with huge datasets

- LHC is truly a top factory, even more than Tevatron
- Deviations from SM expectations could indicate new physics

Top is still the heaviest observed elementary particle

- Decays unlike any other quark (real W, decay before hadronization)
- Could decay to non-SM particles, or vice-versa

Top is a significant background to a variety of new-physics signals

- Must be understood and controlled to get to the new physics

From $\sqrt{s}$ = 2 to 14 TeV

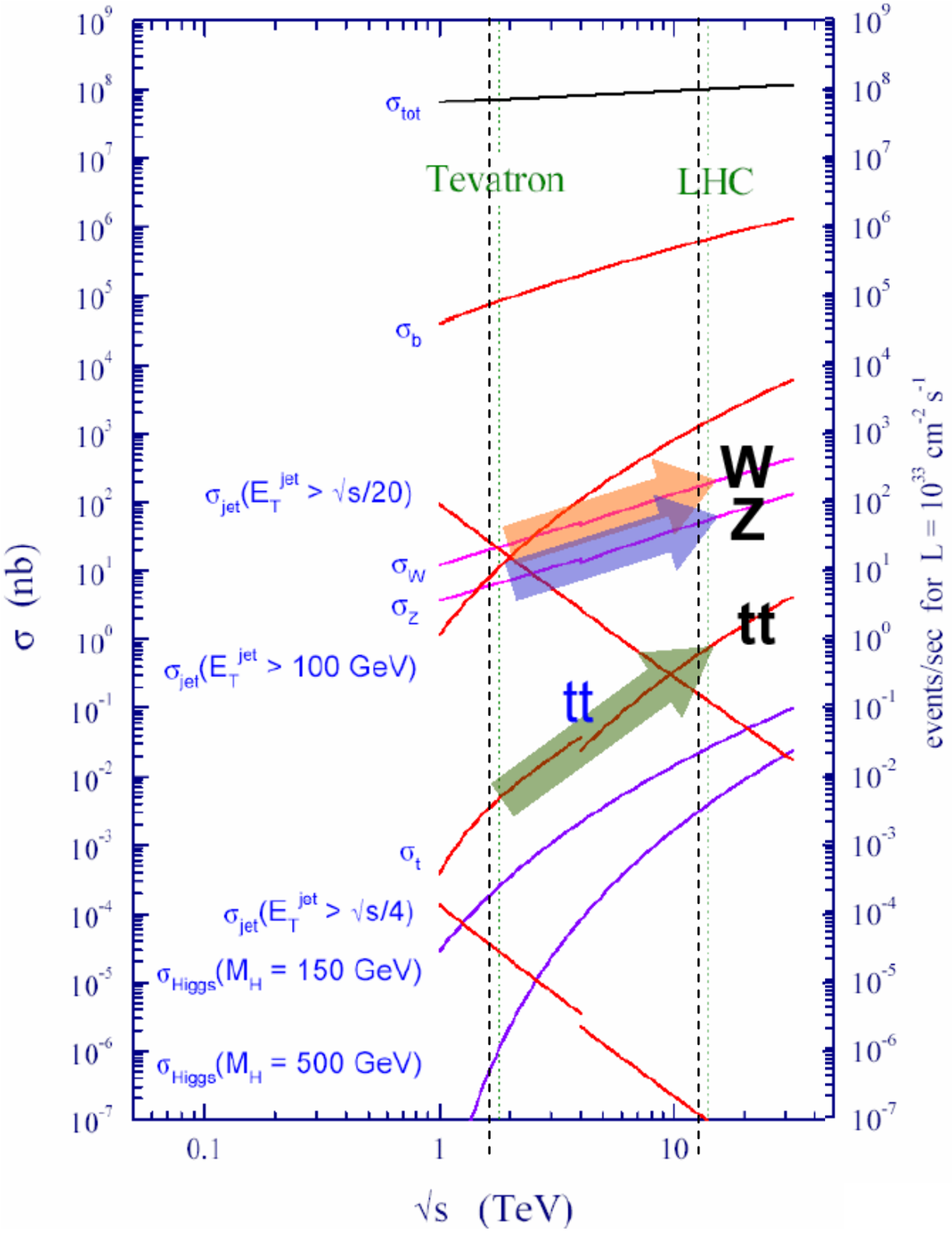
$\sigma(t\bar{t})$ 100x greater at LHC than Tevatron:

- "Low luminosity" (10^{33} $cm^{-2}s^{-1}$) gives 10^7 tt/year (1 Hz rate!)
- $\sigma(t\bar{t})/\sigma(W)$ larger at LHC too

One "nominal" year of LHC data yields datasets only dreamed of at Tevatron, with reduced physics backgrounds.

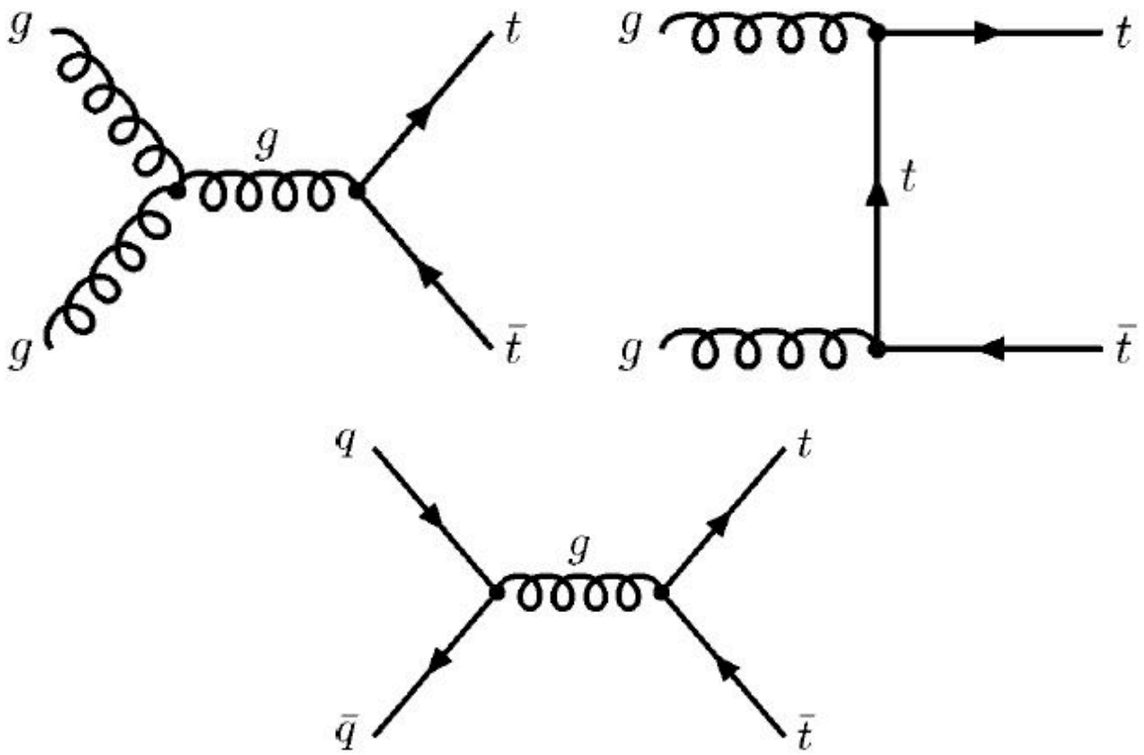
But:

- "Pileup" background will make precision studies difficult
- Need to understand instrumental background rate
- First year will be at $\sqrt{s}$=10 TeV, not 14 TeV (comments at end)



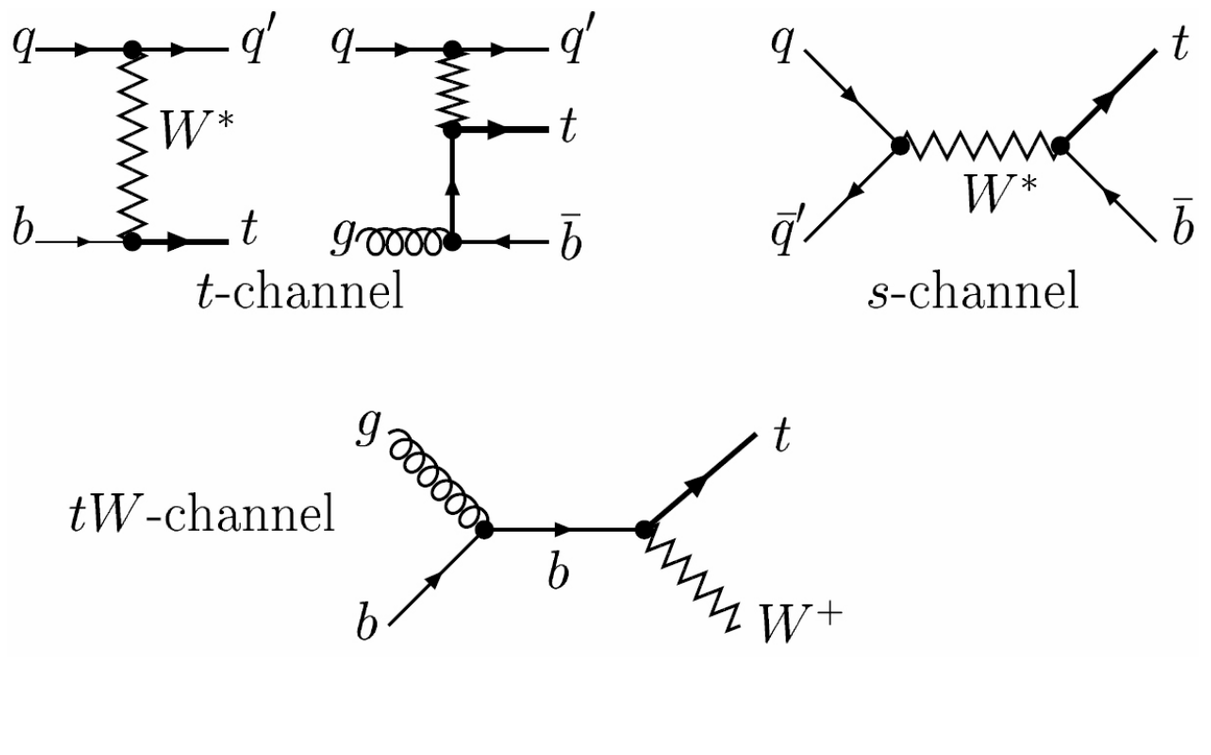
LHC production mechanisms

Strong $t\bar{t}$ pair production



$\sigma(t\bar{t}) = 830 \pm 100$ pb
at 14 TeV, 87% $gg \rightarrow t\bar{t}$
Gluonic production = more QCD radiation

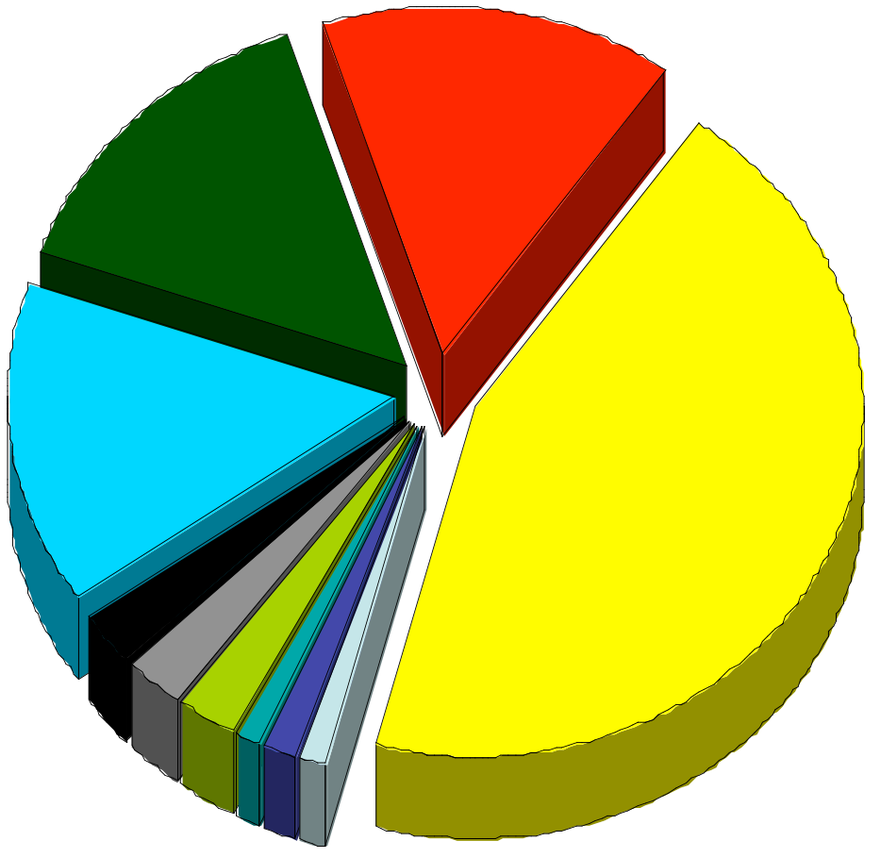
Electroweak single-t production

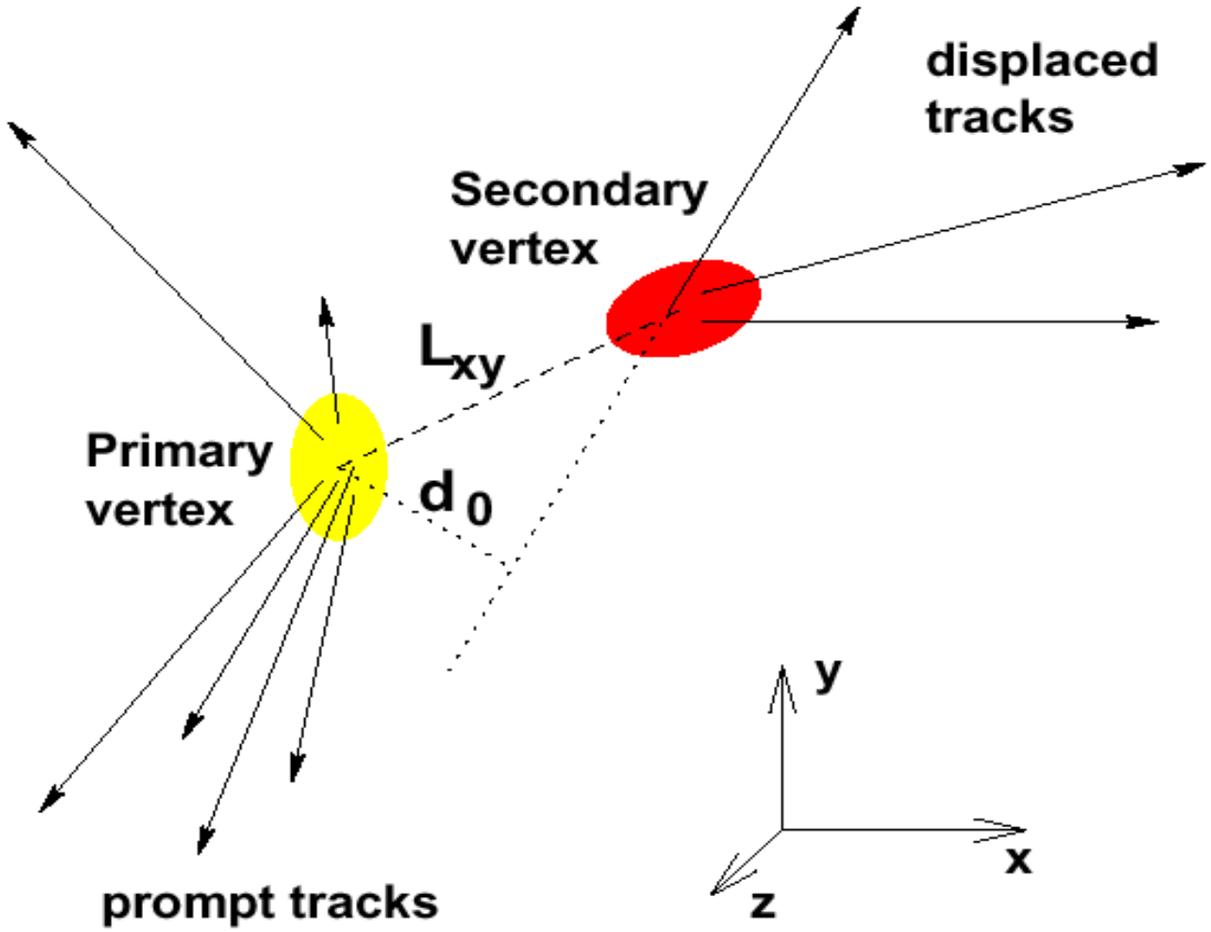


$\sigma(t) \approx 320$ pb at 14 TeV,
t-channel dominates,
more significant background to tt than at Tevatron

$t\bar{t}$ decay signatures

Each top decays $t \rightarrow Wb$; $W \rightarrow l\nu$ = 1/3, $W \rightarrow q\bar{q}$ = 2/3





2 W's in final state:
dilepton (~5%),
lepton plus jets (~44%),
all-hadronic (44%) modes

2 b's in final state:
displaced vertices,
lepton-enriched jets

$t\bar{t}$ signal and backgrounds

"Typical" $t\bar{t}$ event will have every possible object in it:

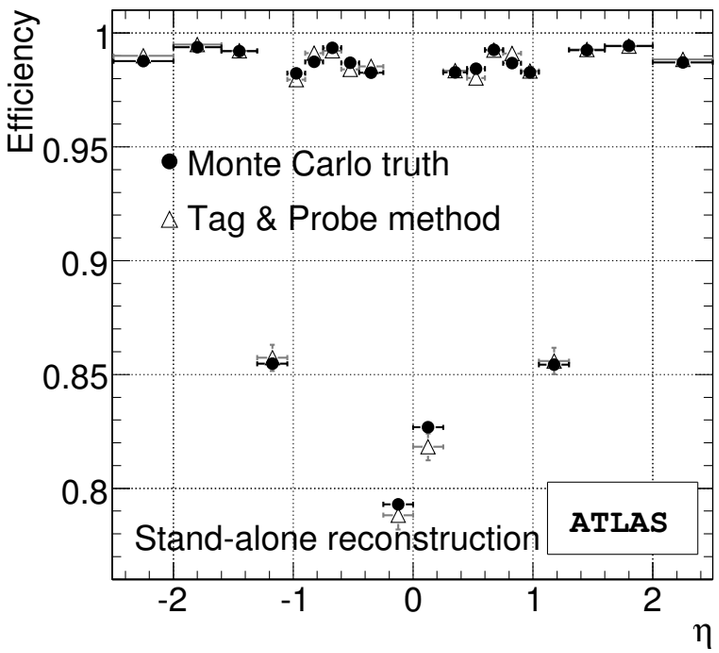
- One or two high-momentum leptons
- Missing energy due to neutrino in leptonic W decay(s)
- High-energy light-quark jets from hadronic W decay(s)
- High-energy b-quark jets

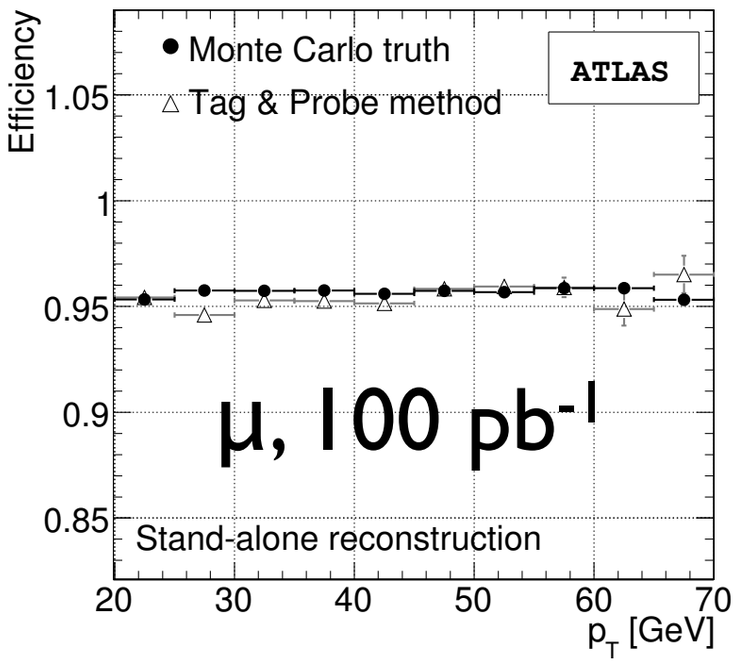
Need to exploit full capabilities of detector: lepton ID, missing energy resolution, jet energy scale, b-tagging,....

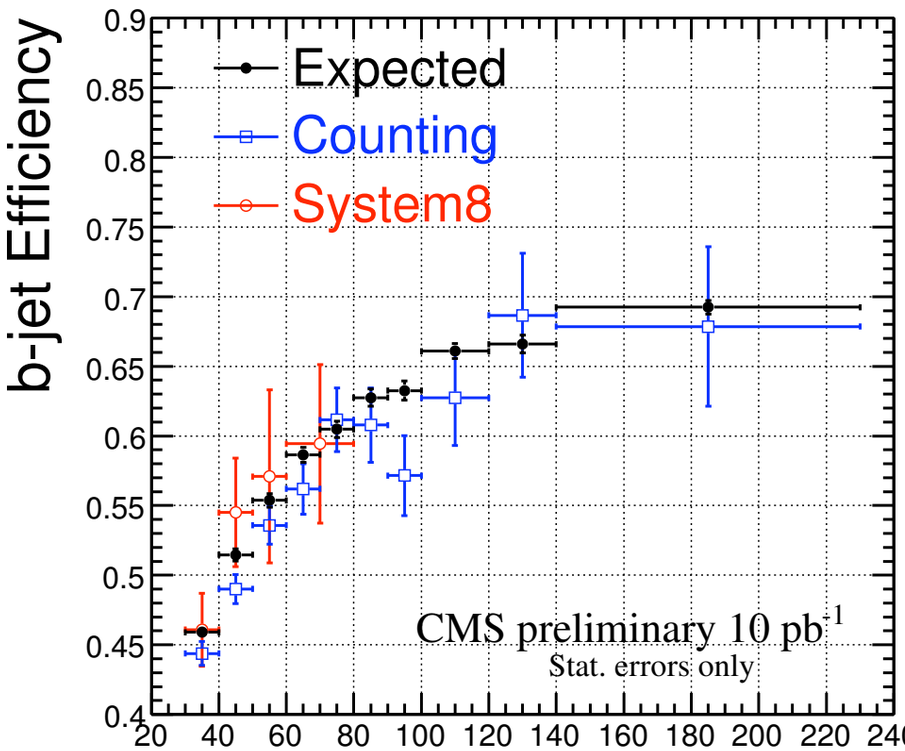
Backgrounds to top:

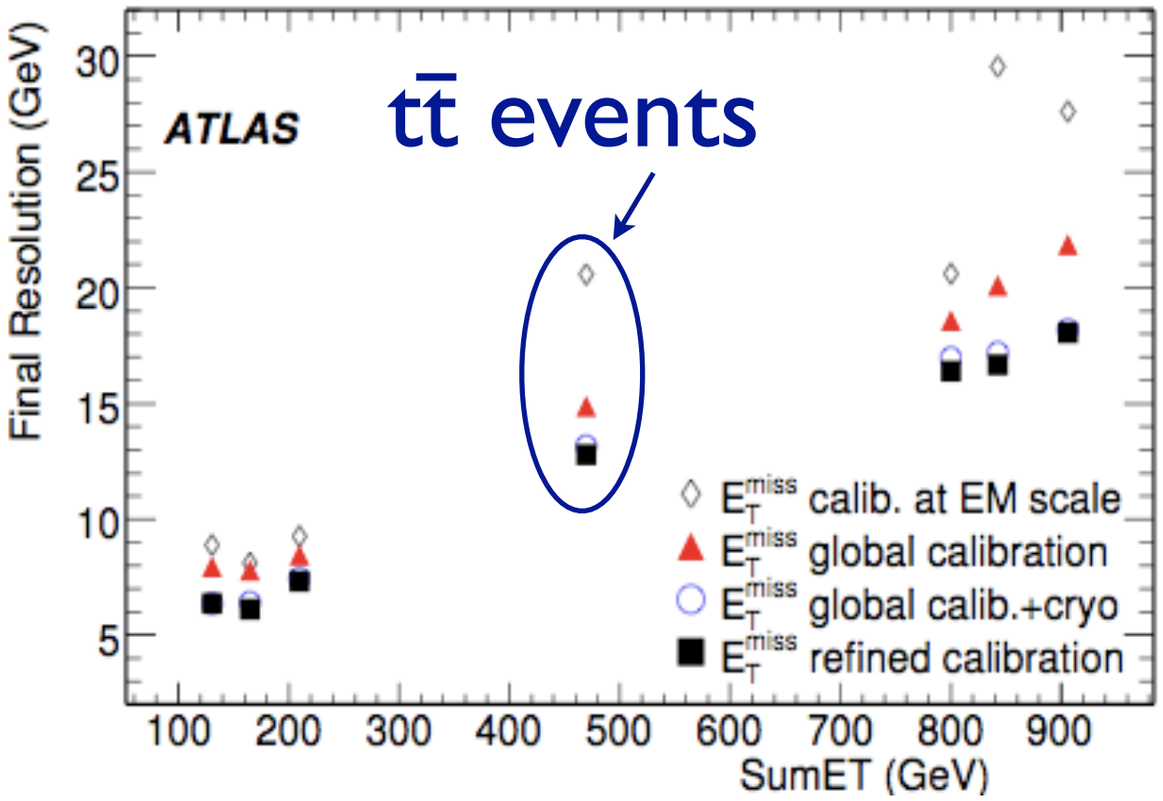
- W+multijet production -- hard to simulate, esp. heavy-flavor content
  - $\sigma(t\bar{t})/\sigma(W)$ larger than Tevatron, but $\sigma(t\bar{t})/\sigma(W+4\text{ jets})$ isn't!
- Multijets with "leptons" not from W's -- even harder to simulate
  - Real leptons from b decay (dominant?) and fake/non-prompt leptons
- Z+multijet and dibosons are backgrounds for dilepton channel
- Single top can't be ignored

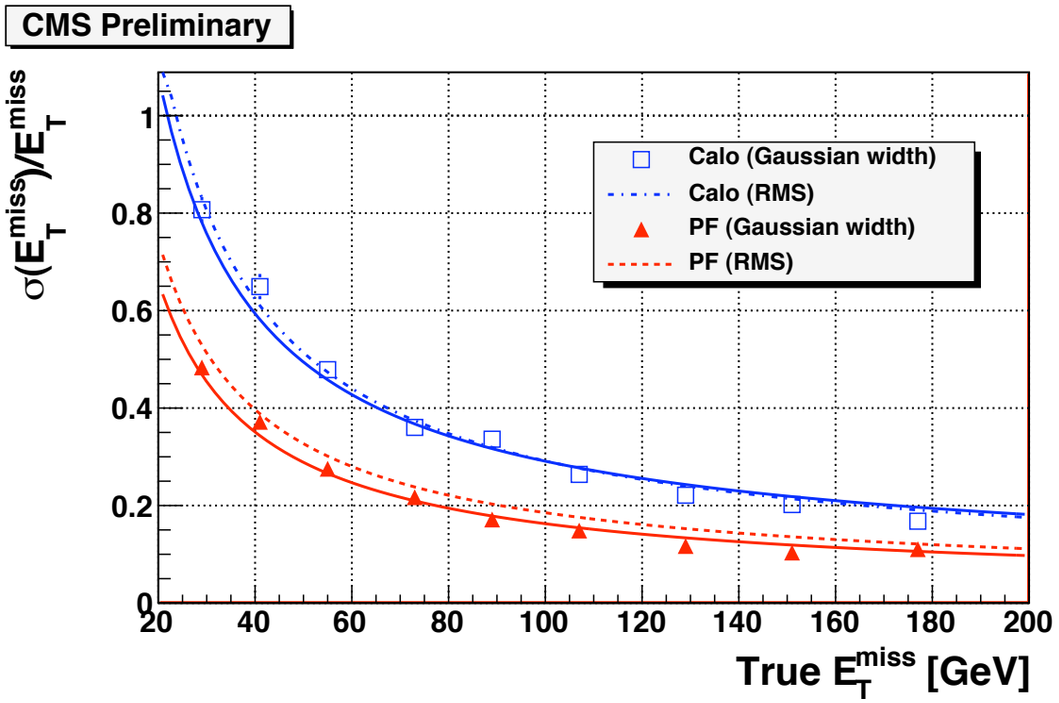
Getting ready for top: object reconstruction











Getting to the top

With first reconstruction tools in place and large $\sigma(t\bar{t})$, should be able to observe a top signal fairly quickly.

- But it will take a while to fully understand the detector and the data!

First thing to do: measure $\sigma(t\bar{t})$, to demonstrate consistency with SM predictions, and to establish a sample of $t\bar{t}$ events for study.

- Deviations from expected rates, kinematic distributions, etc. could be early hints of new physics!
- Shake down event reconstruction in busy event environment

So, keep things simple for early top-quark measurements:

- Simple "square" cuts on object p_T's
- Set relatively high thresholds on object p_T's to hold down multijet background
- Possible to make some early measurements without
  - requiring b-tagged jets
  - requiring large missing energy

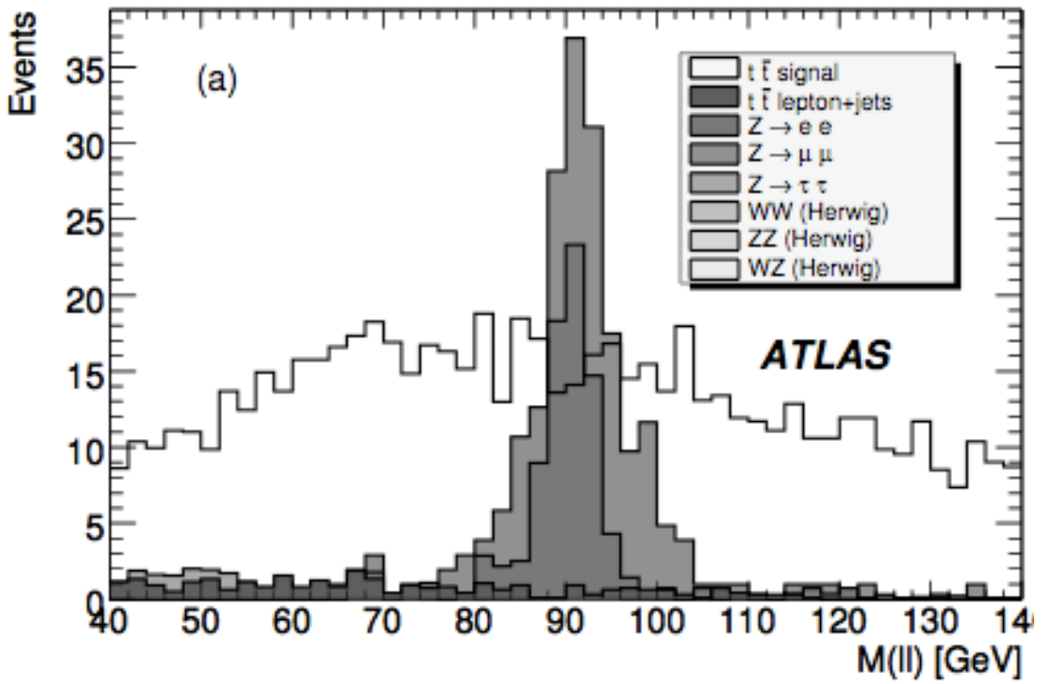
Early σ(tt̄): dileptons

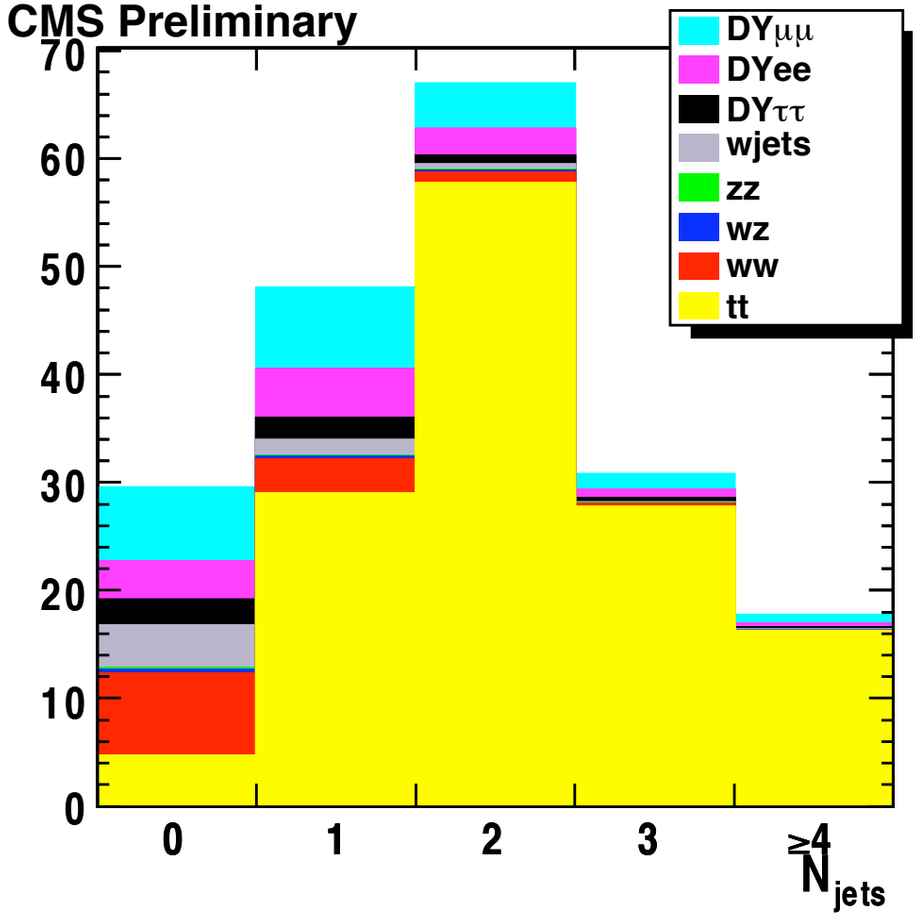
Lowest-rate tt̄ signal, but the cleanest:

- Can observe a signal without b tags, require missing energy + ≥2 jets
- Dominant Z+jets background eliminated with dilepton mass cut
- Remaining backgrounds are DY+jets, dibosons, W+jets

Expectations:

- CMS: O(10%) statistical uncertainty with 10 pb^{-1}
- ATLAS: ~5% statistical uncertainty with 100 pb^{-1}
- Should be the tt̄ "re-discovery" channel



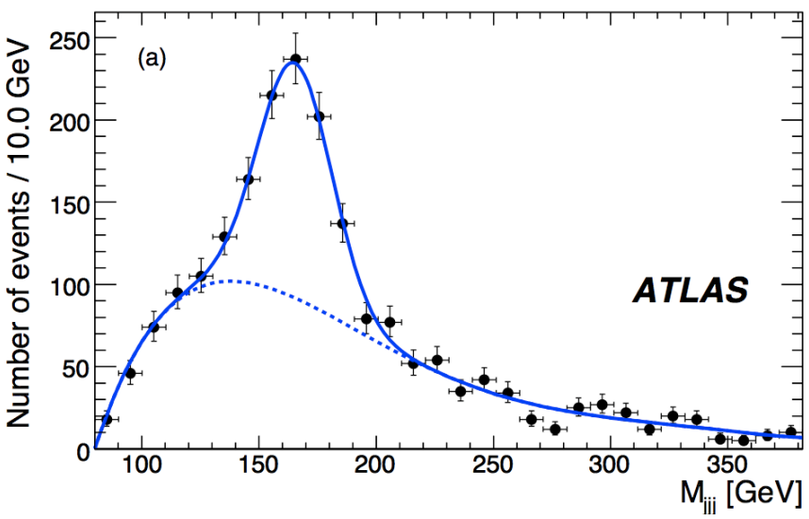


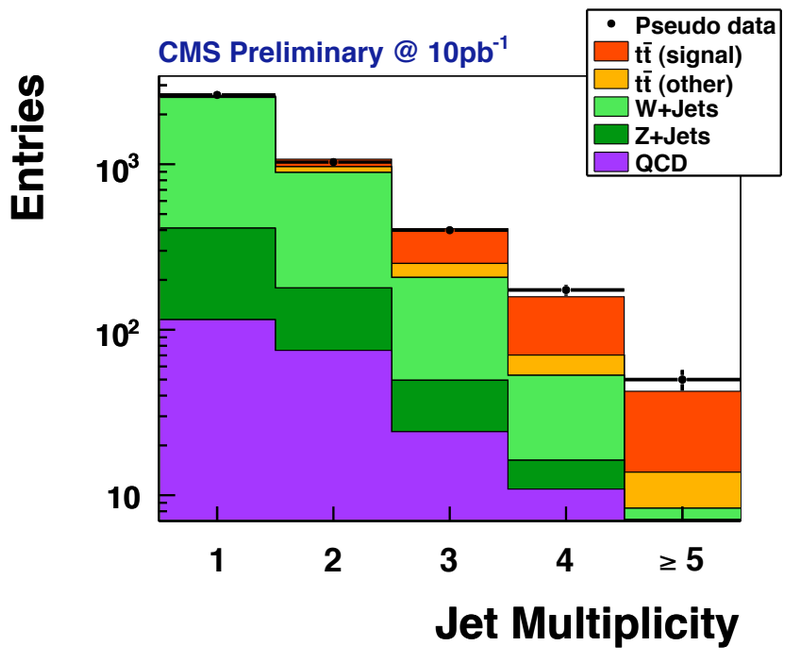
Early σ(tt̄): lepton + jets

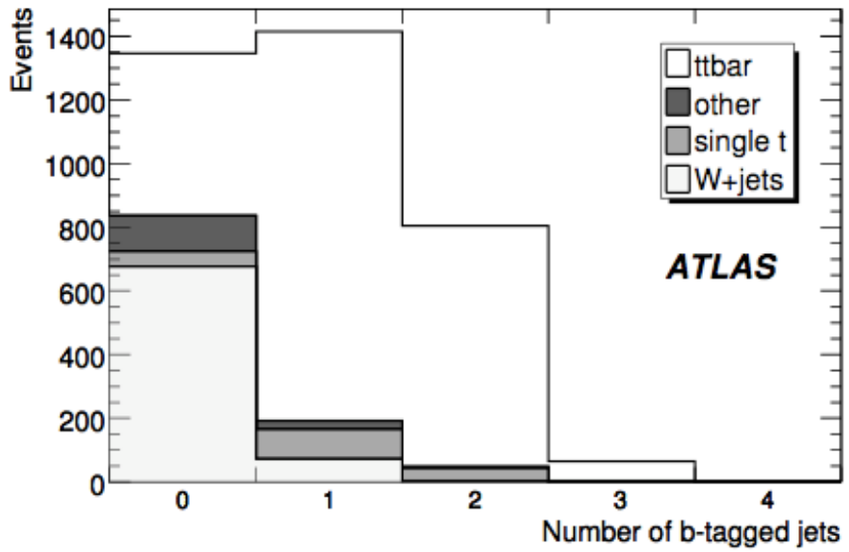
Select events with lepton and four jets; don't have to require b tags (or even missing energy) to find a signal in early data.

- But estimating backgrounds, especially W+jets, is a challenge
- Use kinematic distributions to separate, e.g. three-jet invariant mass
  - Still has dependences on modeling, jet energy scale....
- CMS: expect ~130 μ+jets signal events on ~80 background in 10 pb^{-1}
- ATLAS: 5σ statistical sensitivity at ~20 pb^{-1}

S/B is much increased by requiring b-tag, once it is available







Top for getting ready: b-tagging efficiency

Once top is re-found, we can use it to understand the detectors. Example:

A now-classic Tevatron measurement: measure $R = B(t \to Wb)/B(t \to Wq)$ by counting number of b-tagged jets in $t\bar{t}$ events.

- $R < 1$ → fewer b jets/$t\bar{t}$ event → fewer b-tagged jets
- Need to know the tagging efficiency: can't know whether a particular jet is not tagged because it is not a b, or because of inefficiency

But, can turn this around and measure the tagging efficiency.

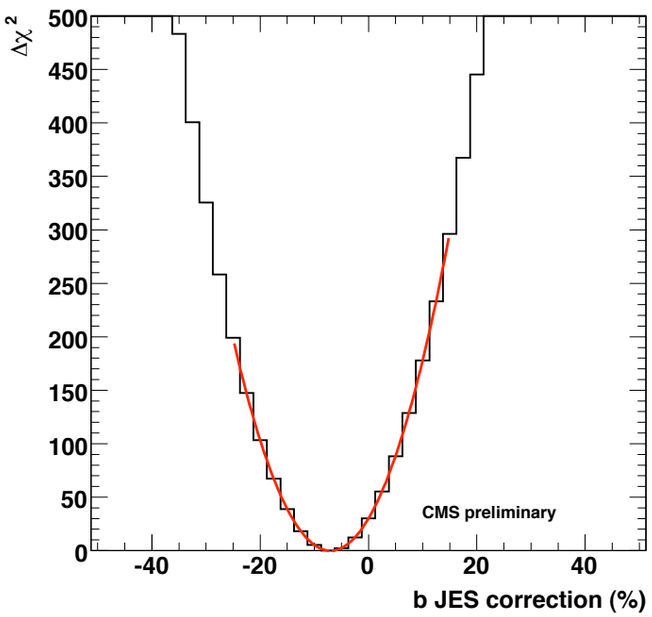
- Assume $R = 1$, and assume any deficit of tags (modulo acceptances etc.) is due to inefficiency.
- An in-situ measurement of b-tag efficiency!
- Large $\sigma(t\bar{t})$ gives enough statistics make this feasible.

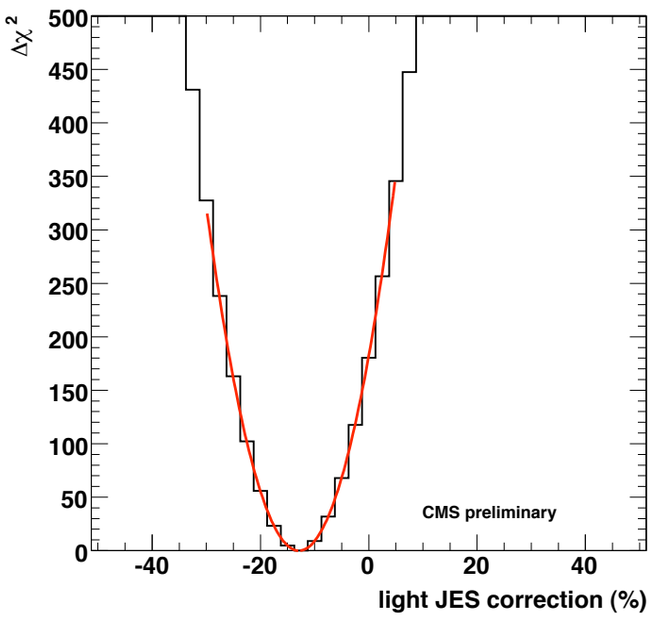
ATLAS: Expect ~5% uncertainty on b-tag efficiency with 100 pb^{-1} with this method.

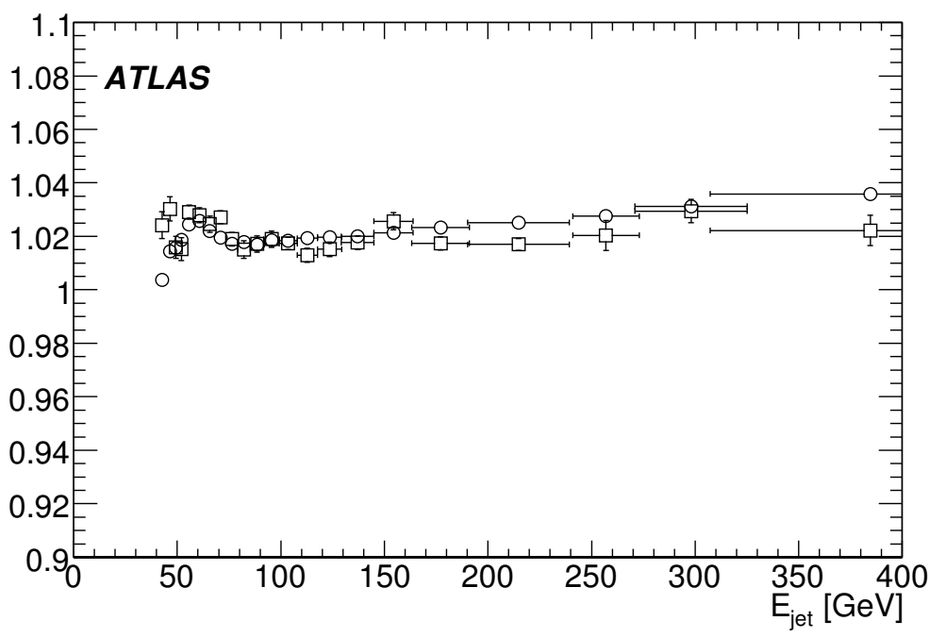
Top for getting ready: jet-energy scale

Absolute jet-energy scale is challenging, limiting systematic for top mass

But by applying a kinematic fit to $t \rightarrow Wb \rightarrow q\bar{q}b$ decays, with constraints to the world-average W and top masses, we can determine the jet-energy scale for both light-flavor and b jets.







CMS, 100 pb^{-1}

ATLAS, 10 fb^{-1}

0.1-1 fb^{-1} should be sufficient to achieve 1% precision on energy scale by this method.

After the beginning: single top

Many topics require more data than we will have in the first year of LHC.

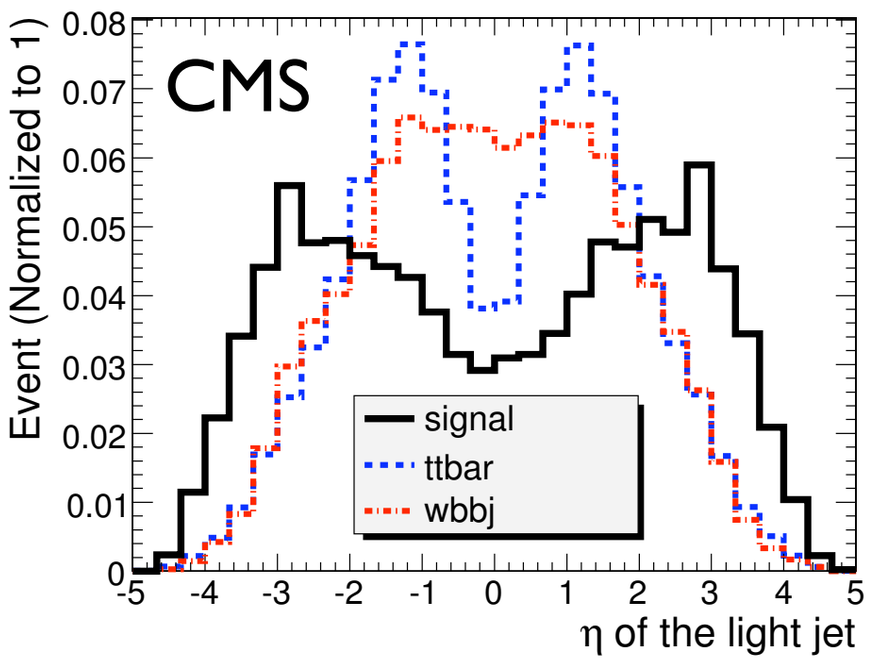
Single top: large cross section (~100x Tevatron), but large backgrounds too:

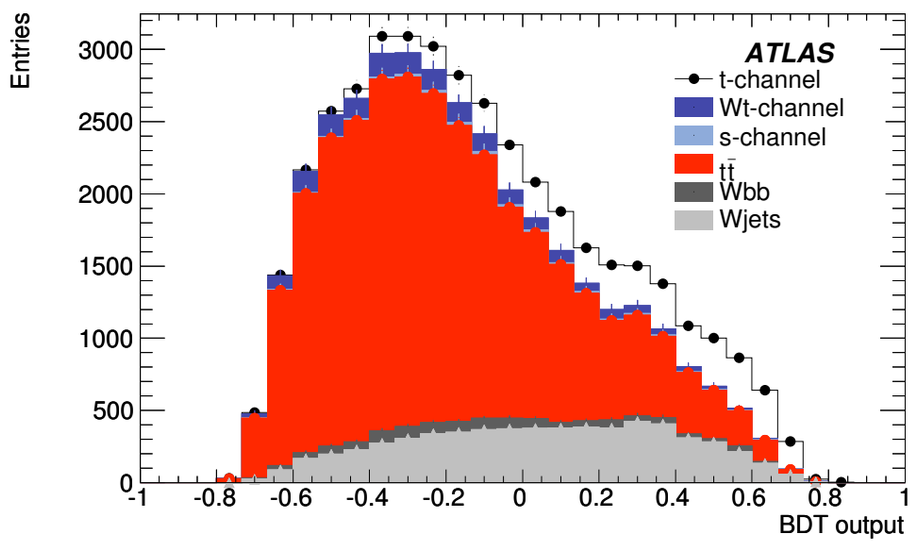
- Significant contamination from $t\bar{t}$ (x2.5 σ)
- Fewer jets in final state means more W+jets, multijet background

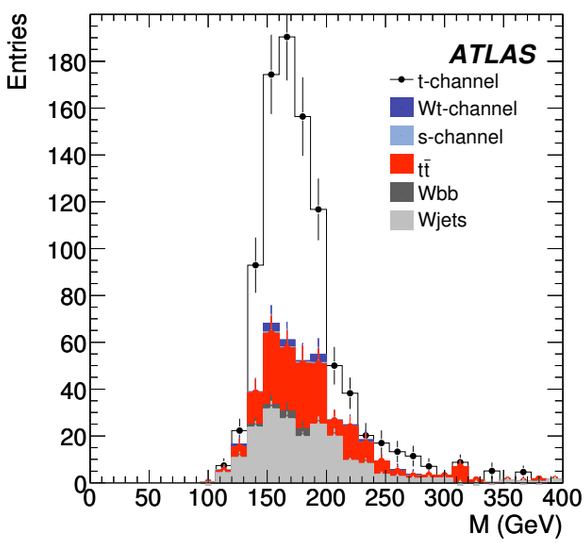
Best early opportunity is t-channel: largest σ, distinctive η distribution; use multivariate analysis for best S/B separation

Both experiments expect $\Delta\sigma/\sigma$ = 10% at 10 fb^{-1}; systematics dominated

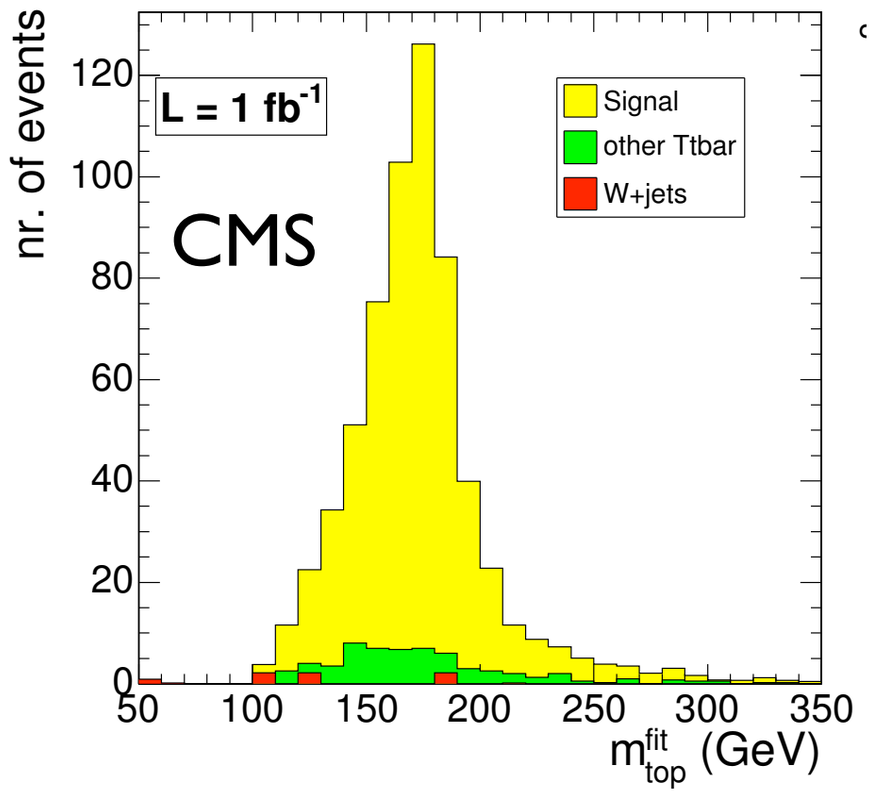
- $\Delta|V_{tb}|/|V_{tb}| = (\Delta\sigma/\sigma) / 2$

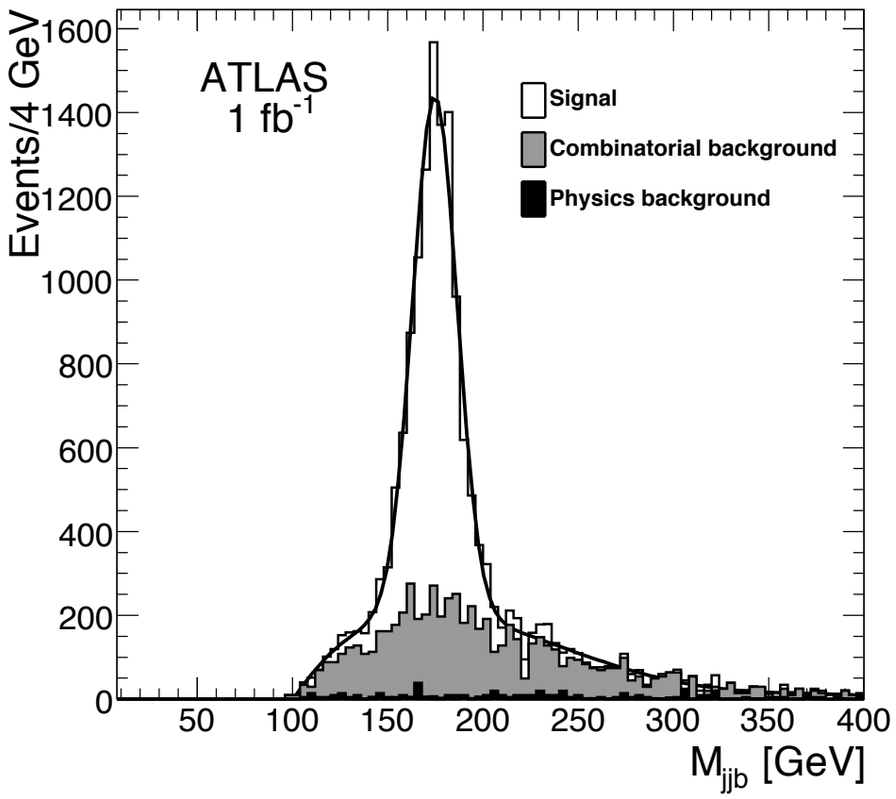






After the beginning: top mass





m_t still interesting at the LHC for constraining SM and new physics!

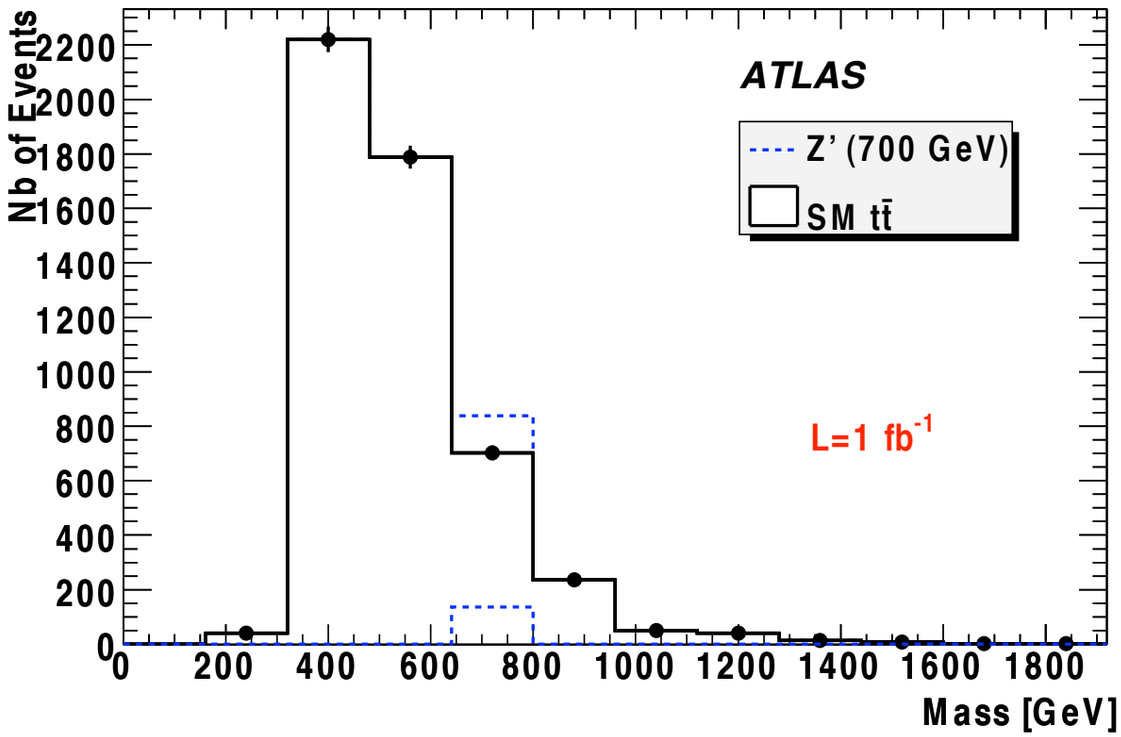
With 1 fb^{-1}, have 100's of events for a mass measurement with very small backgrounds

Systematics totally dominate: estimate from ATLAS (CMS similar):

Uncertainty	Value
light JES	0.2 GeV/%
b JES	0.7 GeV/%
ISR/FSR	~0.3 GeV
b fragmentation	≤ 0.1 GeV
background	negligible
method	0.1-0.2 GeV

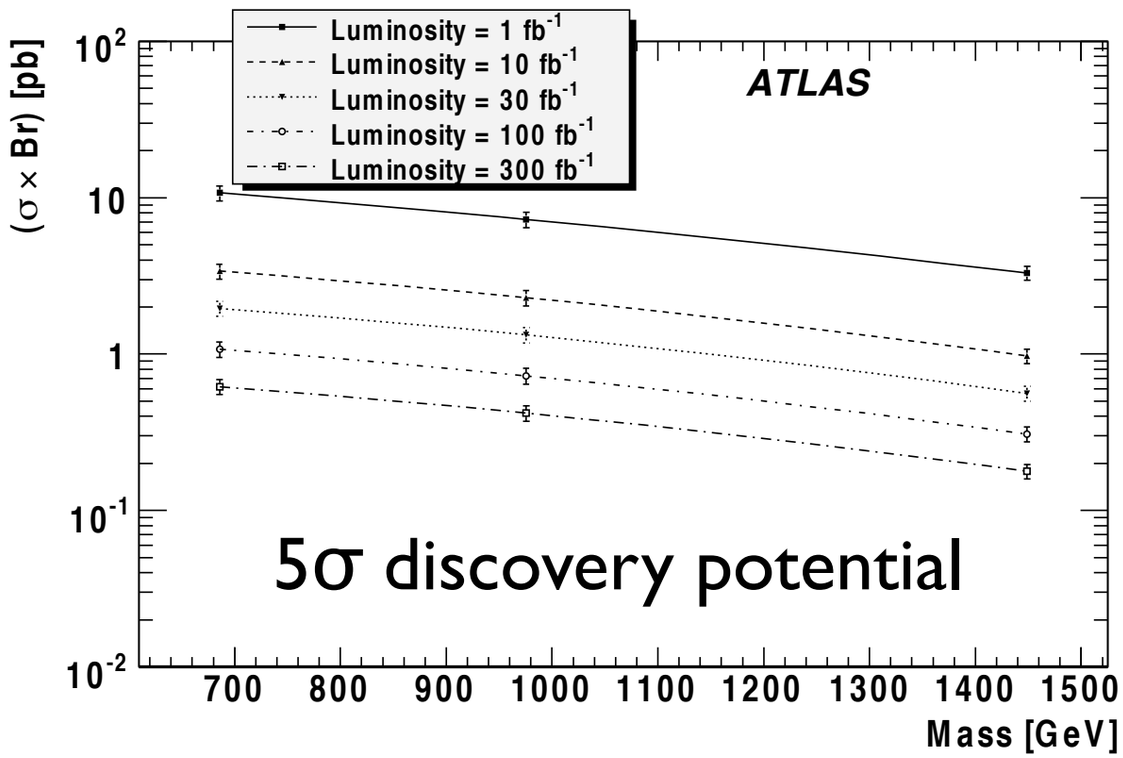
Total about 1 GeV...after JES uncertainties to O(1%), which will take time.

Top for BSM: $t\bar{t}$ resonances



New resonances or gauge bosons strongly coupled to top could give resonances in the $t\bar{t}$ invariant mass distribution

ATLAS: search for generic narrow resonance in lepton + jets events; primary background is continuum $t\bar{t}$ production



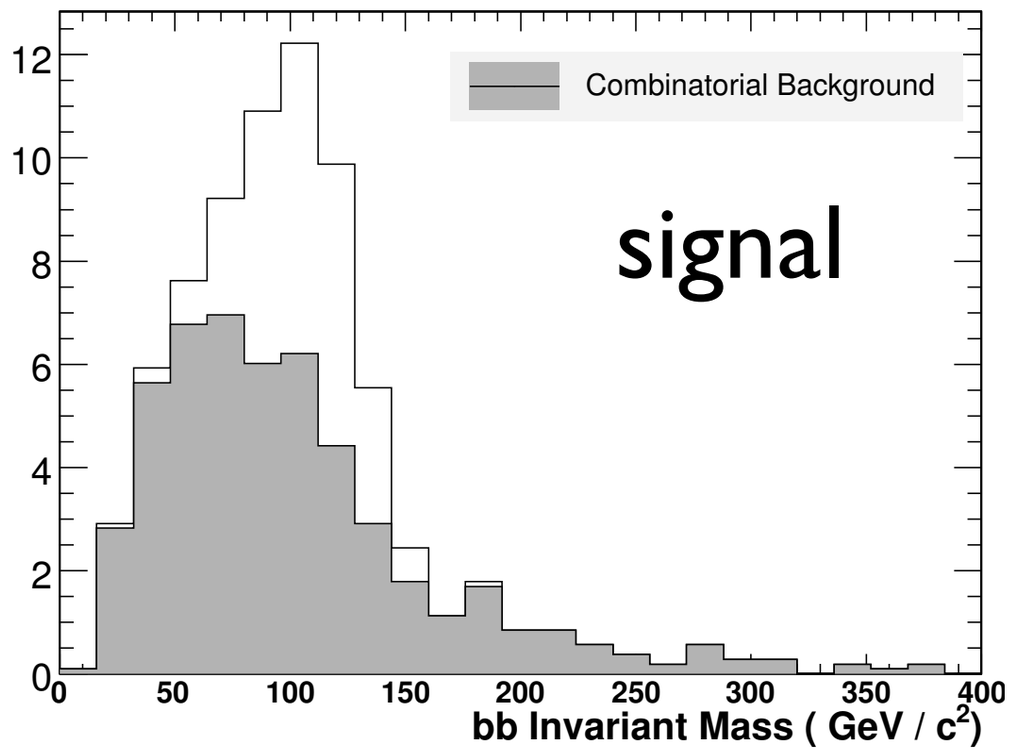
Could observe a 700 GeV $Z' \rightarrow t\bar{t}$ with 1 fb^{-1}, with current expectations for mass resolution

Analysis limited to M < 2 TeV, at which point top decay products are highly collimated ("t-jets")

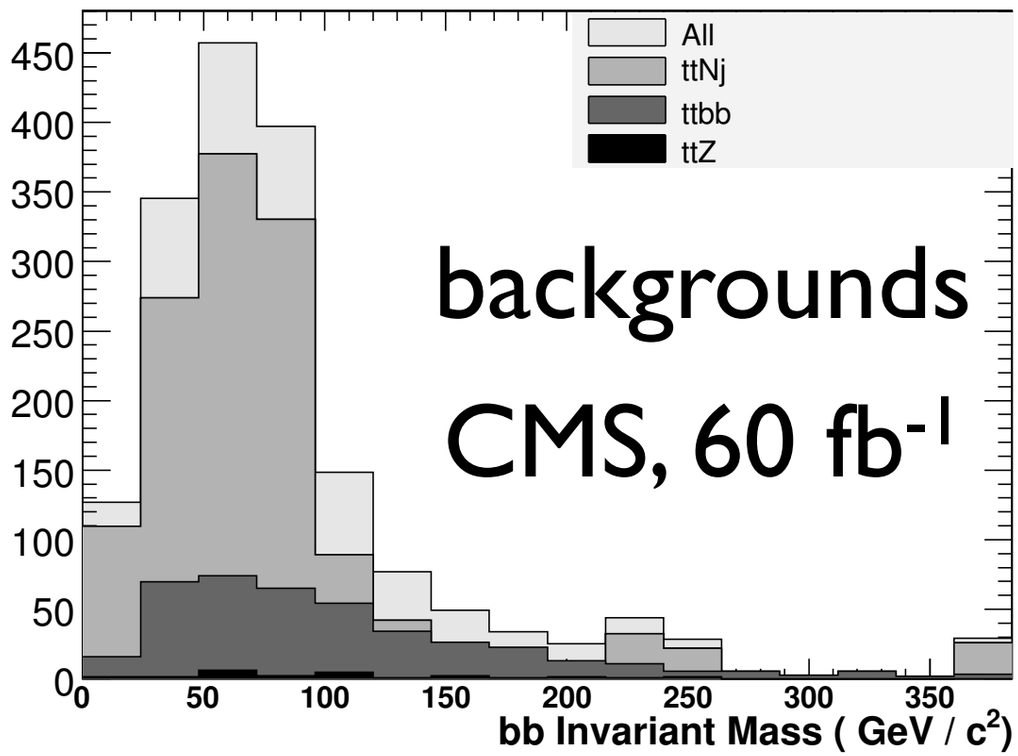
Top for BSM: $t\bar{t}H$ search

With $H \rightarrow bb$ dominant for $m_H < 135$ GeV, direct production almost impossible to observe. Instead, try radiative $t\bar{t}H$.

Significant backgrounds from tt with QCD radiation, all other backgrounds negligible. CMS: Even in cleanest l+jets channel, S/B ≃ 0.09 at best.

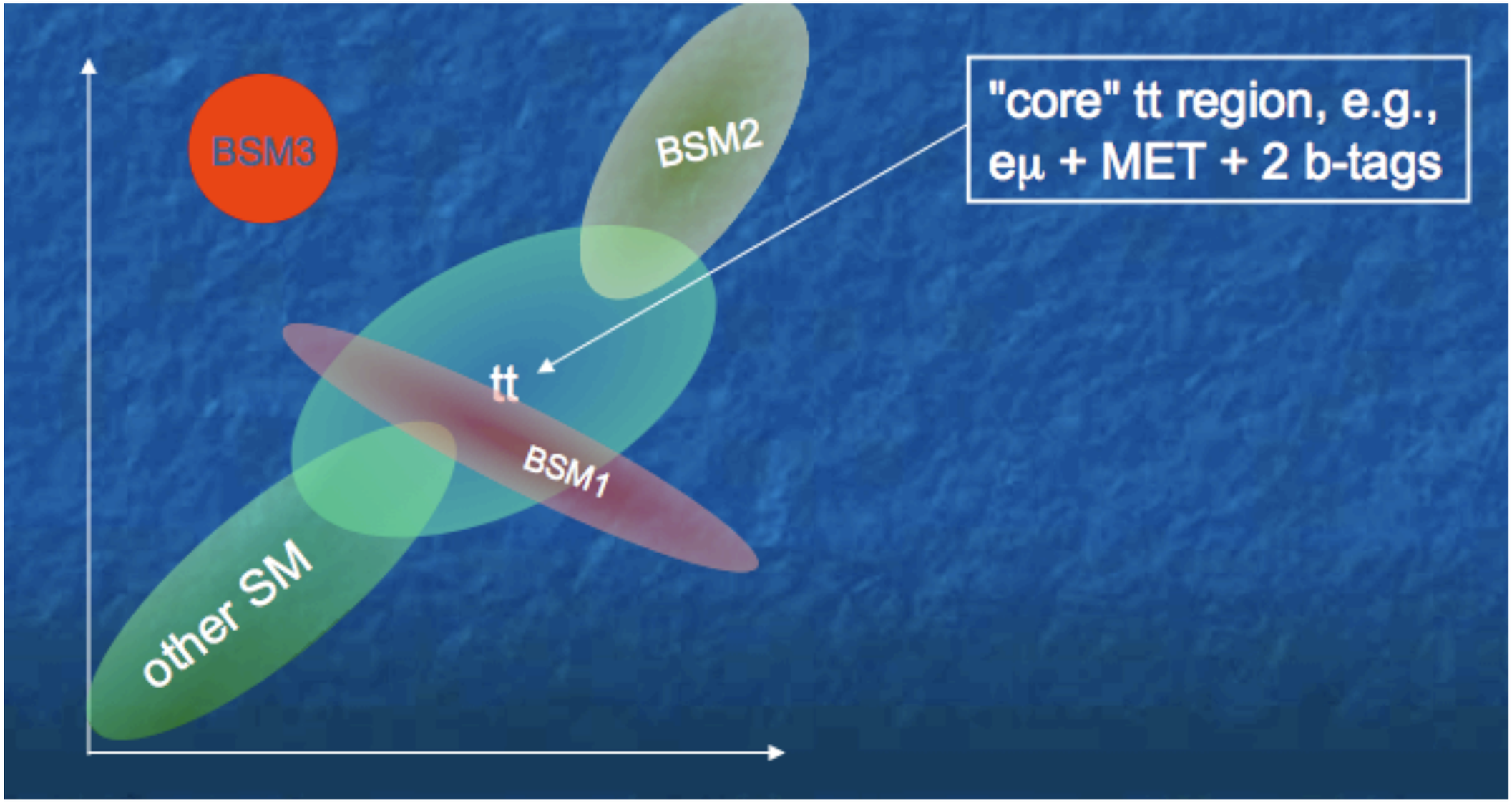


Will be very challenging, even with as much as 60 fb^{-1}!



Top against BSM

We don't know where BSM physics might show up:



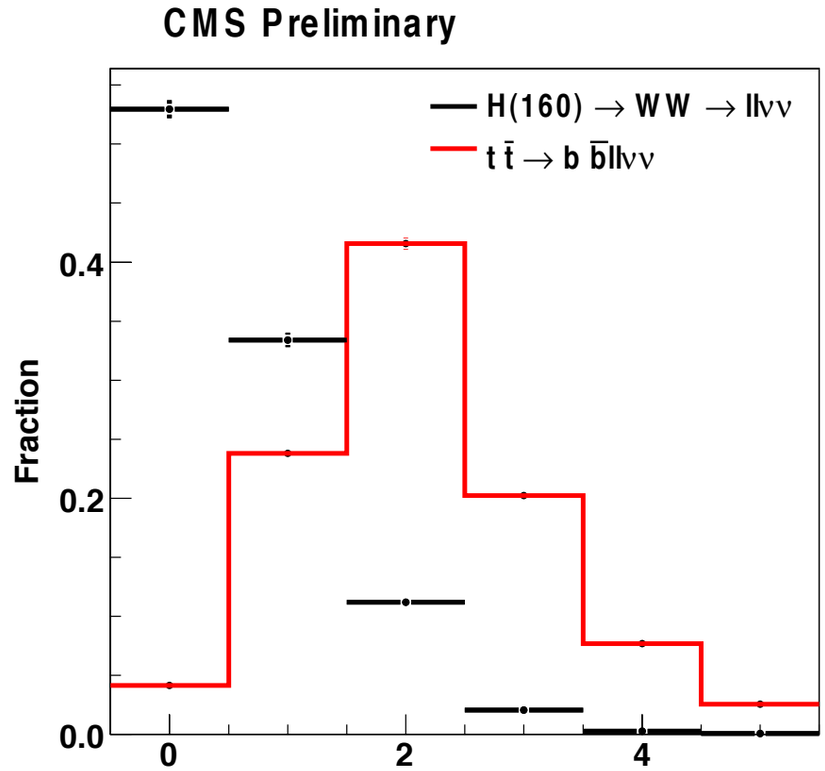
If the new physics lives in a region that overlaps where top lives, then we must understand top well enough to separate it from the new physics. (And be on the lookout for BSM contamination in top samples!)

Top against BSM: H→WW→llνν

$t\bar{t}$ →llννbb is a background; require missing energy but veto events with central jets.

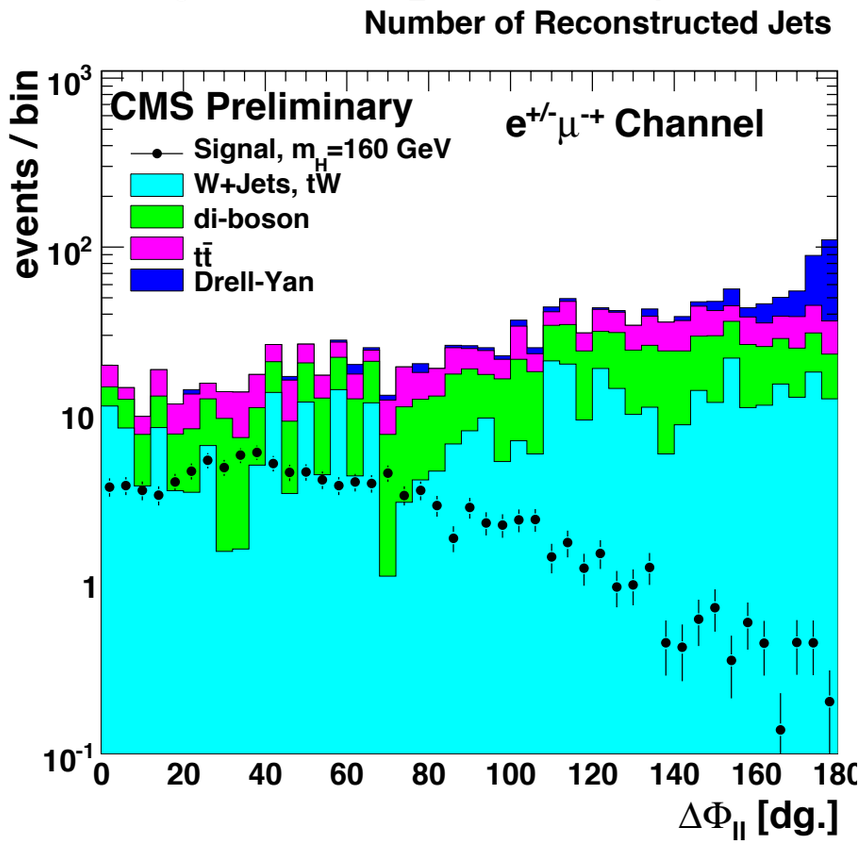
CMS: in 1 fb^{-1}, expect

- 72.6 ± 6.0 H→WW events
  - (for m_H = 160 GeV -- excluded!!)
- 39.7 ± 6.0 WW events
- 17.3 ± 3.1 $t\bar{t}$ events

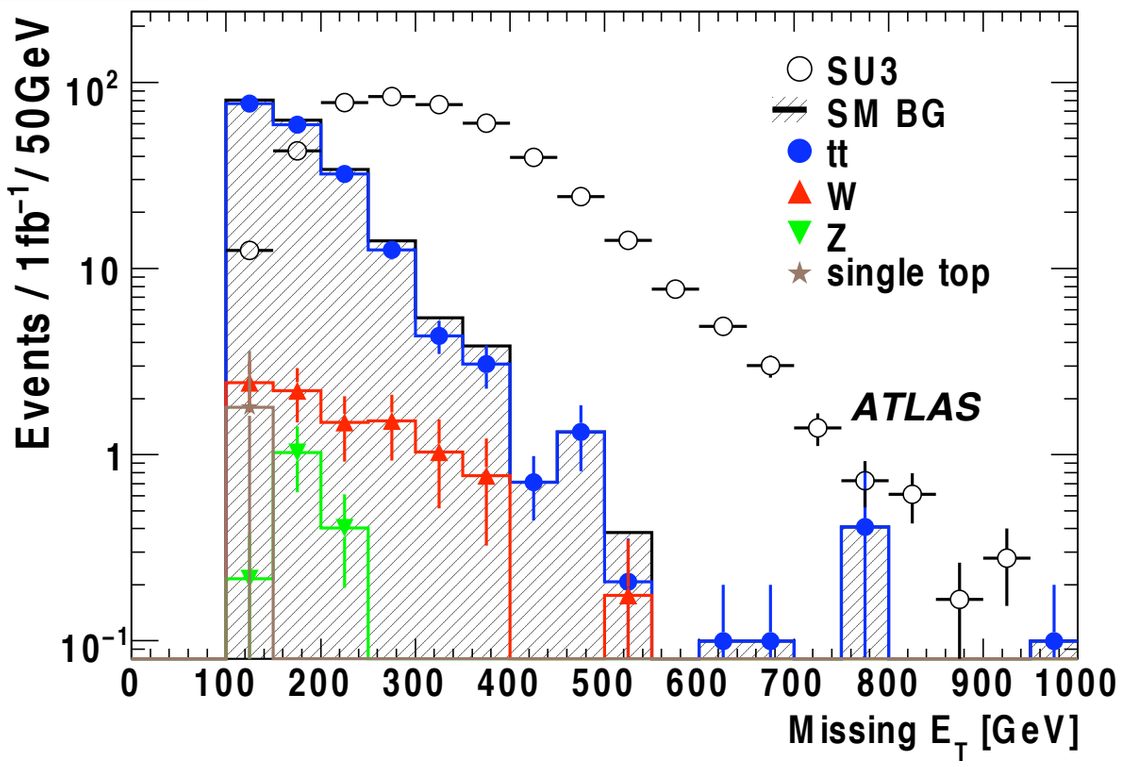


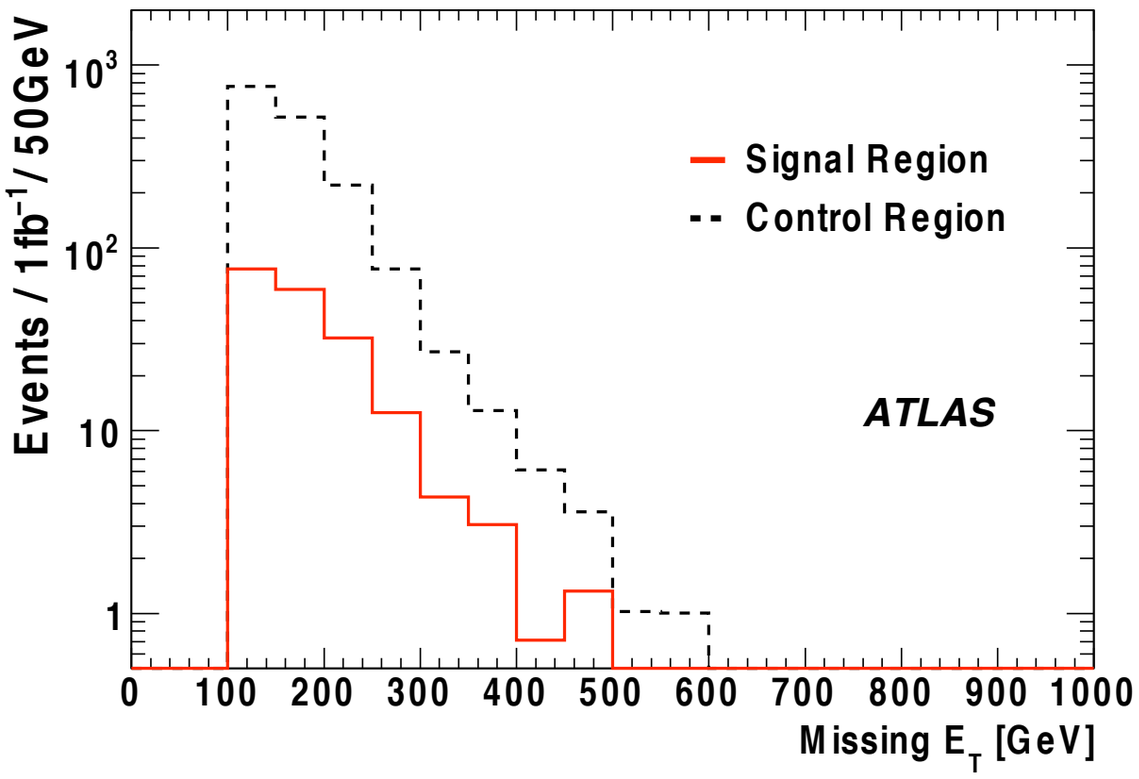
Set normalization of $t\bar{t}$ by selecting complementary $t\bar{t}$-enriched sample (drop jet veto, require two b-tagged jets), and relying on MC for scaling into signal sample.

Requires good (and early) understanding of missing energy, b-tagging, jet energy scale -- all things that we can study in the $t\bar{t}$ sample.



Top against BSM: Low-mass SUSY





ATLAS: SUSY search in l + jets + missing energy topology has significant SM background, dominated by $t\bar{t}$

Require lepton-missing energy transverse mass > 100 GeV; use M_T < 100 GeV as $t\bar{t}$ control sample

- Missing energy in control sample is good model for signal sample

Normalize rate in signal sample using signal/control ratio from simulation; ~15% uncertainty

Only believable if a $t\bar{t}$ signal can be established in this topology first!

LHC in 2009-2010

In the coming year, $\sqrt{s}$ = 10 TeV, not 14 TeV:

- $t\bar{t}$ cross section smaller by factor of ~2.3
- W cross section smaller by factor of ~1.4 (but W+jets?)
- But still should be able to measure $\sigma(t\bar{t})$ with ~10% uncertainty with 30-40 pb^{-1} of analyzable data

Long LHC run, starting in September with a short December holiday break, and then run through winter into summer:

- Great news for the experiments that we will have beam for so long!
- Estimated delivered integrated luminosity is 300 pb^{-1}
- Should still be more than enough data to shake down the detector, develop analysis procedures, and begin to do top physics.

It's not the 10 fb^{-1} at $\sqrt{s}$ = 14 TeV year that we may have imagined, but still more than enough to be one of the most exciting years of a scientific lifetime.

Outlook

Top can be "re-discovered" in early LHC data:

- Reconstruction tools are in place
- Observable signal within the upcoming first year of data

Once established, top will be an essential tool

- for verifying the SM at the highest energies yet
- for commissioning the detectors
- for demonstrating that we understand how to do LHC physics

And then, top will be crucial for discovering new physics:

- Look for new-physics effects in regular top analyses
- Use top as a probe for new physics
- Carefully understand/control top as a background to new physics

As interesting as the first ~15 years of the top quark have been, the most interesting times may yet lie ahead of us!