Top quark physics – status and prospects

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SWHEPPS 2016 meeting, Aigerisee, 8/6/16

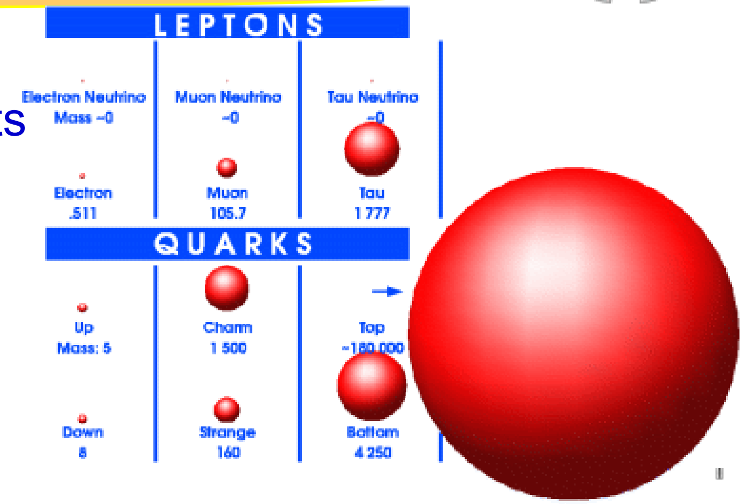
- Overview of top quark physics after LHC run-1, with first run-2 results
  - Top-pair (tT) production, including tT+X
  - Single top production
  - Top quark mass
  - Selected top quark properties .. e.g. rare decays
  - Outlook for LHC run-2 and beyond
- Current ‘state of the art’ and prospects for improvement
  - Rather selective – show ‘example’ measurements from ATLAS and CMS
  - Not covering searches for BSM physics involving top quarks in the final state
- Full details of all results:
  - ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
  - CMS: http://cms-results.web.cern.ch/cms-results/public-results/publications/TOP/index.html

Introduction

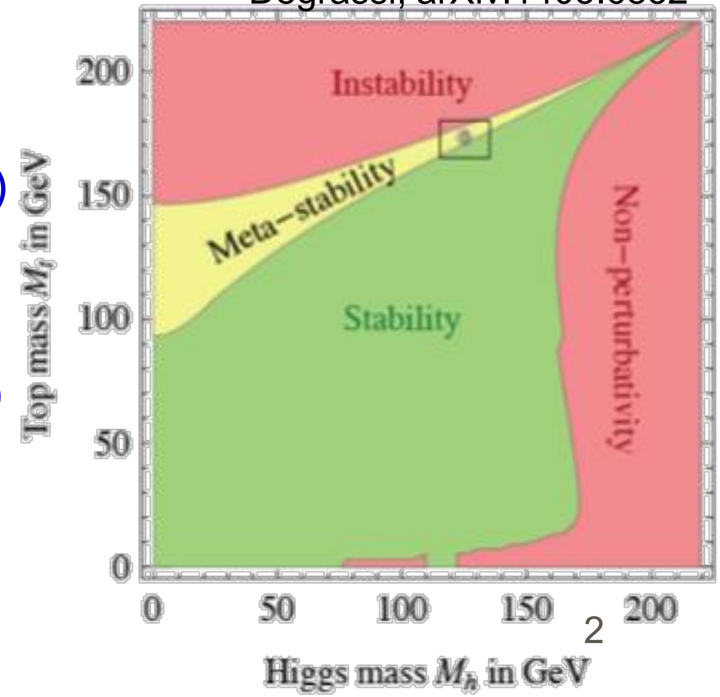
- Why is top quark physics interesting?
  - Top quark fits into the 3-generations of quark doublets
- But it is very heavy – 40x bottom quark
  - Same mass scale as W, Z and Higgs bosons – connection to EW symmetry breaking?
  - Now we know m_H=125 GeV, top Yukawa coupling is almost exactly 1… coincidence?

$$y_t = \sqrt{2} m_t / v \simeq 1$$

    - SM could be valid up to Plank scale, meta-stable?
- Top decays quickly, as a bare quark: $t \rightarrow Wb$
  - Lifetime of ~10^{-25} s too short to form hadrons (10^{-24} s)
    - Also shorter than spin de-correlation time (10^{-21} s)
- Heaviest particle in SM, copiously produced
  - Cross-section 0.2-0.8 nb at LHC energies (7-13 TeV)
  - Laboratory for QCD studies at highest energies
  - Important background and/or decay mode for BSM searches involving new heavy states

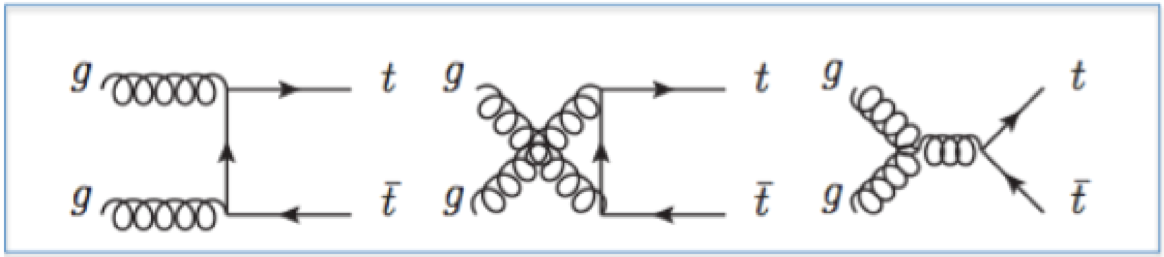


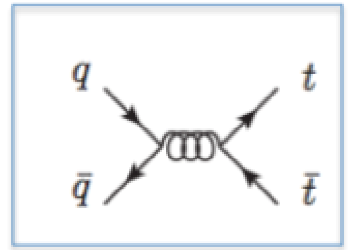
Degrassi, arXiv:1405.6852



Top-pair phenomenology

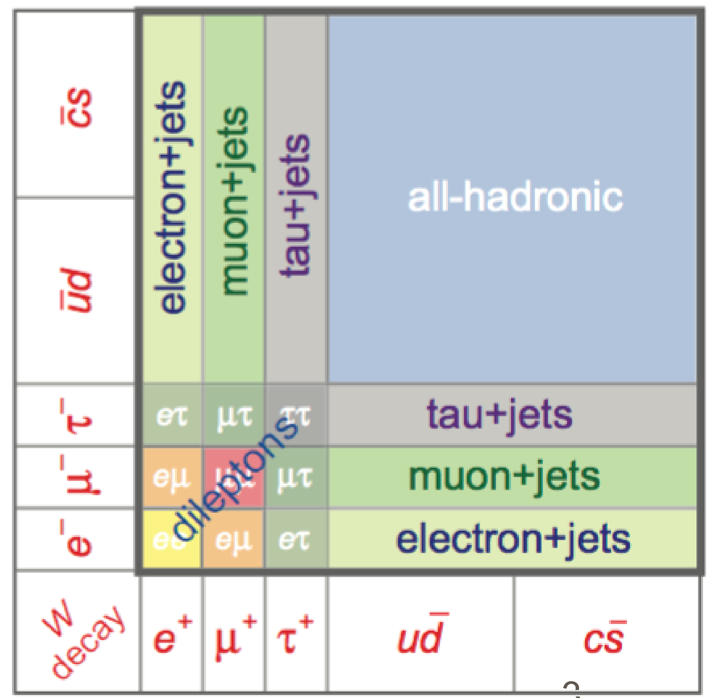
- Main production process: top-pair via gg or qqbar:





LO diagrams
NLO, NNLO also important

  - Cross-section ~250 pb @ 8 TeV, 830 pb @ 13 TeV
    - c.f. 7 pb in p-pbar production at Tevatron
- BR(t→Wb)=99.8%, signatures depend on W decay
  - Dilepton channels (ee$\nu\nu$bb, $\mu\mu\nu\nu$bb, e$\mu\nu\mu$bb) are cleanest, but only a few % of ttbar events
    - Especially eμ, free of background from Z→ee/$\mu\mu$
  - Lepton+jets (30%) e/μ ν bbqq
    - Significant background from W+jets, single top, multijet
  - All-hadronic (46%): bbqqqq
    - Challenging final state – hard to trigger, multijet b/g
  - Remainder: states involving at least one tau decay



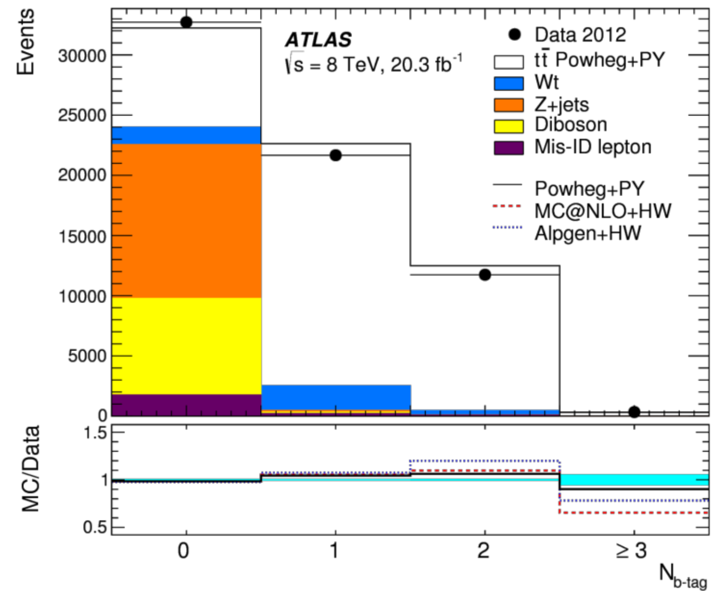
Top-pair cross-section measurements

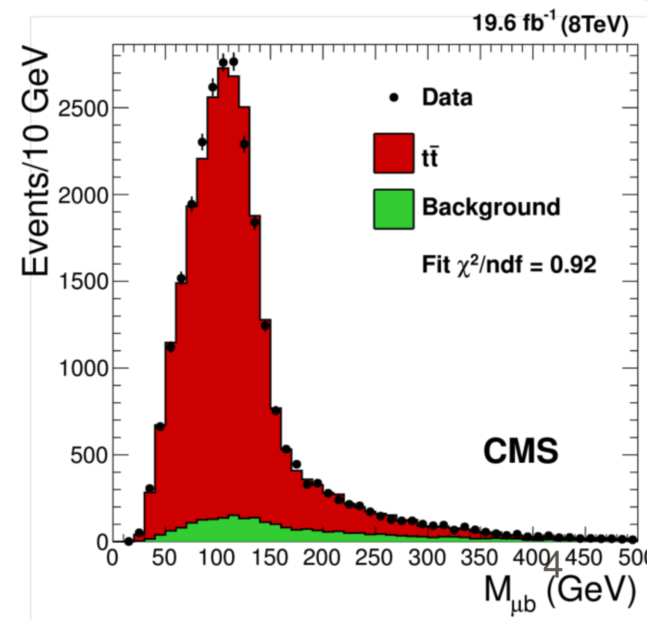
- Cleanest measurement from dileptons ($e\mu$)
  - Final states with 1 (2) b-jets ~90% (97%) pure tT
  - ATLAS double tag method to reduce systematics

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

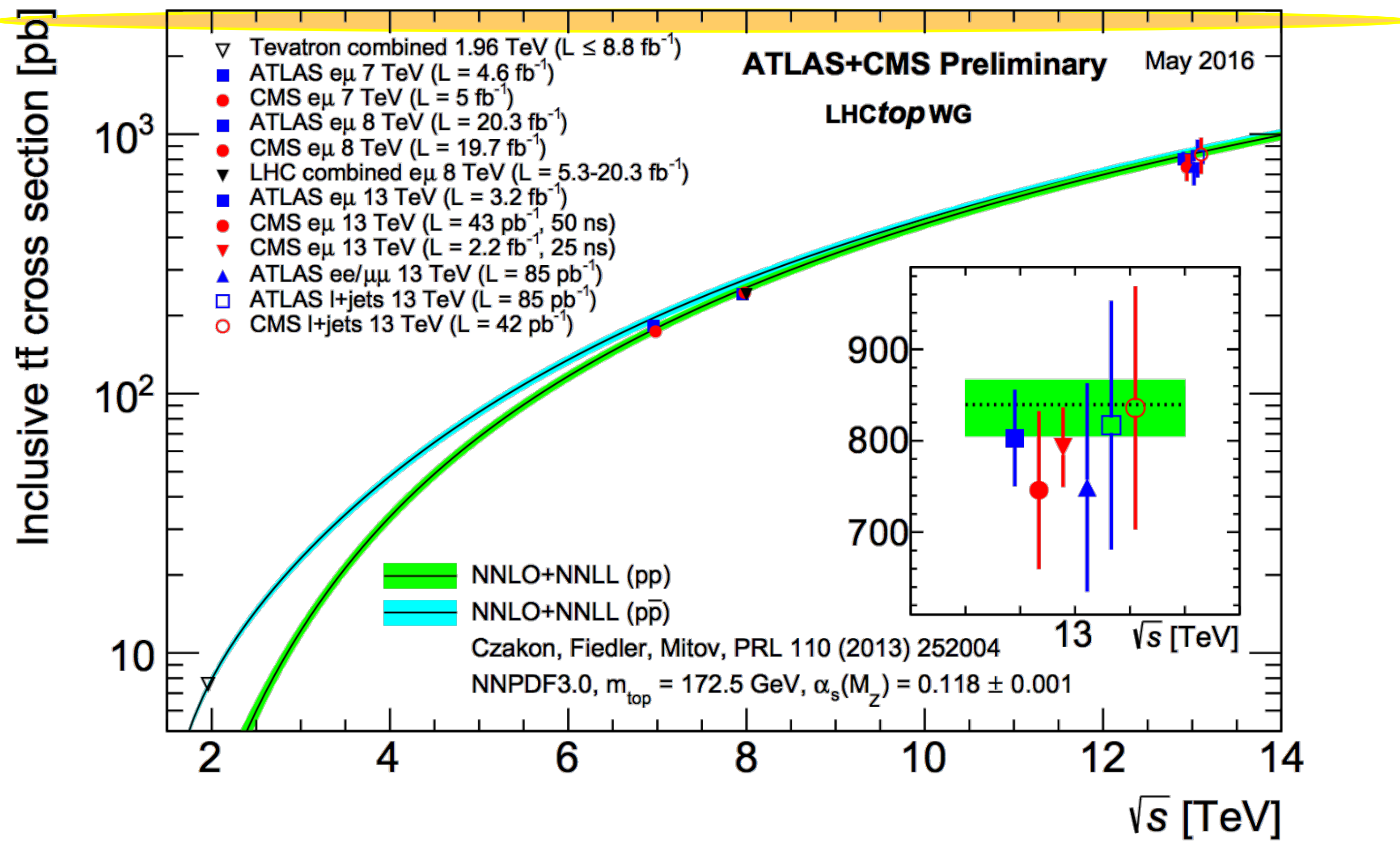
$$N_2 = L\sigma_{t\bar{t}}\ \epsilon_{e\mu} C_b {\epsilon_b}^2 + N_2^{\mathrm{bkg}}$$

    - Fit for cross-section σ and jet+b-tag efi ε_b
  - Experimental systematics ~2% (run-1), 3% (run-2)
    - Also integrated luminosity (~2%), LHC E_{beam} (1.7%)
  - Similar results from CMS, using a more complex profile likelihood fit with kinematic information
- Measurements in l+jets channel
  - e/μ, E_T^{miss}, >=4 jets, b-tagged jet requirements
  - E.g. CMS template fit to m(μ+b-jet) distribution
  - Total uncertainty of 6-7% (tT modelling, jet energies)
- Also measurements in all-hadronic channel, and in final states involving hadronic taus





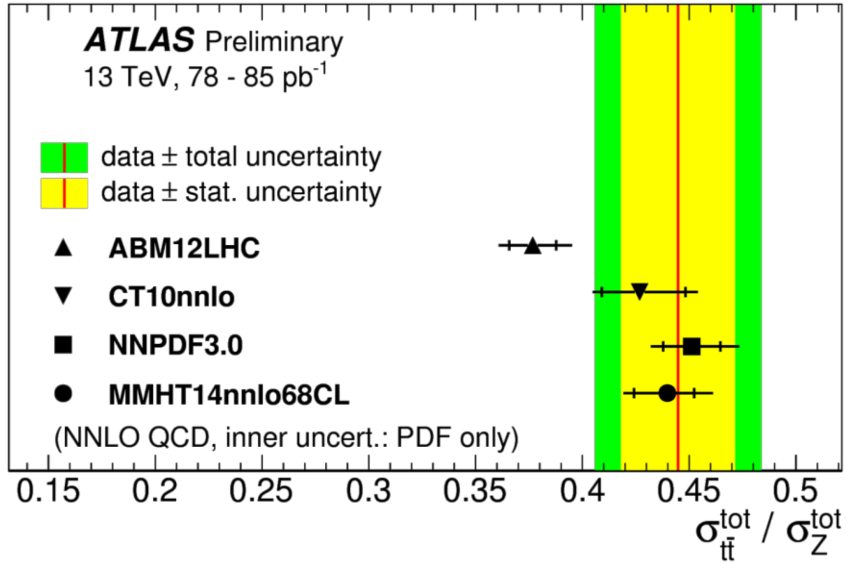
Top-pair production cross-section



- Agreement at Tevatron, LHC run-1 and now run-2 energies
  - Experimental precision (eμ) ~3-4% per expt. at 7-8 TeV, 6-7% so far at 13 TeV
    - Typically dominated by luminosity and ttbar modelling uncertanties
  - Theory NNLO+NNLL 4-5% PDFs, 3% scales, ∓3% for ±1 GeV on top mass
    - Some modest improvements may be possible – average experiments, updated PDFs

Cross-section ratios, and top quark mass

- Cross-section ratios reduce uncertainties
  - E.g. $R_{t\bar{t}/Z} = \frac{\sigma_{t\bar{t}}}{0.5\left(\sigma_{Z\to ee} + \sigma_{Z\to\mu\mu}\right)}$
  - ATLAS ±9% measurement with early 2015 data (limited by statistics and tT modelling)
  - Constrain PDFs – typically high-x gluon
  - To come: Double ratios combining different processes and beam energies
- Predicted cross-section depends on m_t
  - The **pole** mass – theoretically well-defined
    - Check consistency with direct measurements, for different PDF assumptions

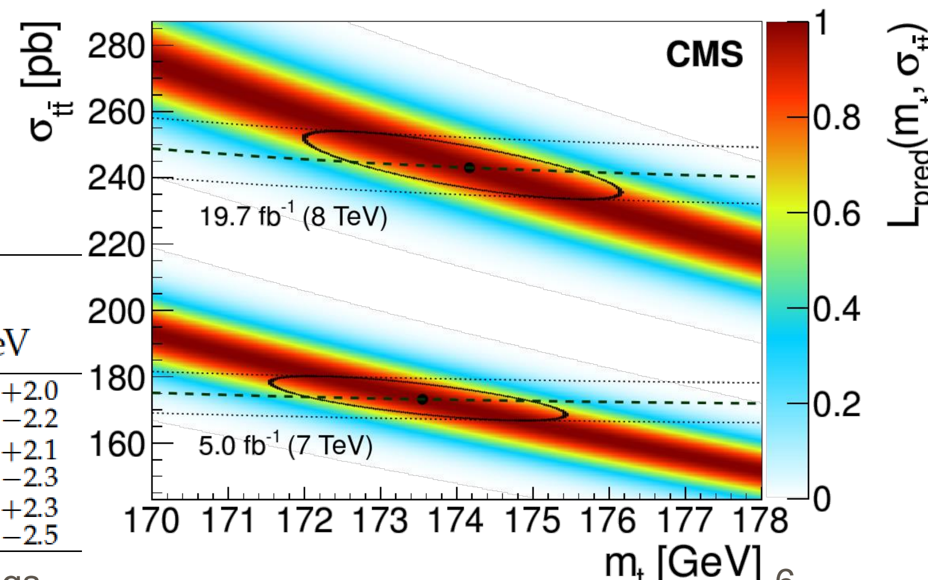


ATLAS: PDF4LHC envelope
7+8 TeV combined

$$m_t^{\mathrm{pole}} = 172.9^{+2.5}_{-2.6}\ \mathrm{GeV}$$

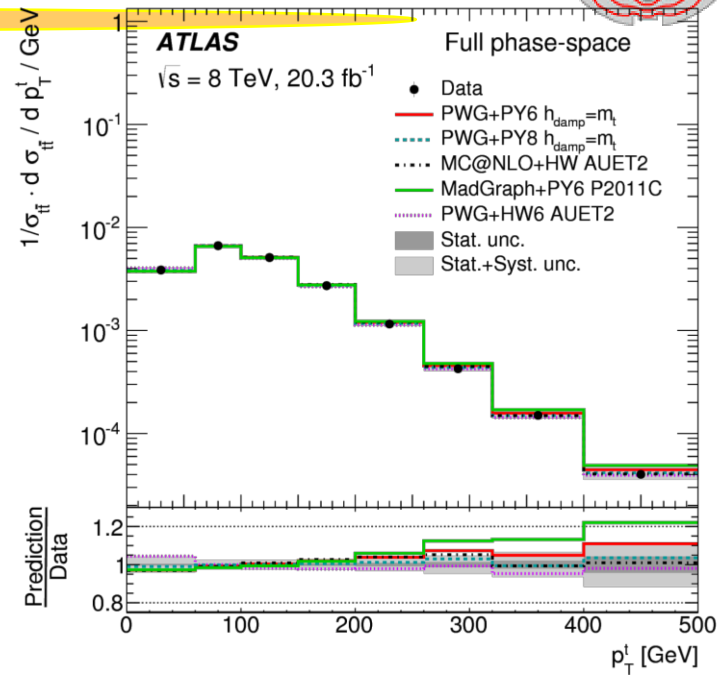
CMS: single PDFs m_t [GeV]

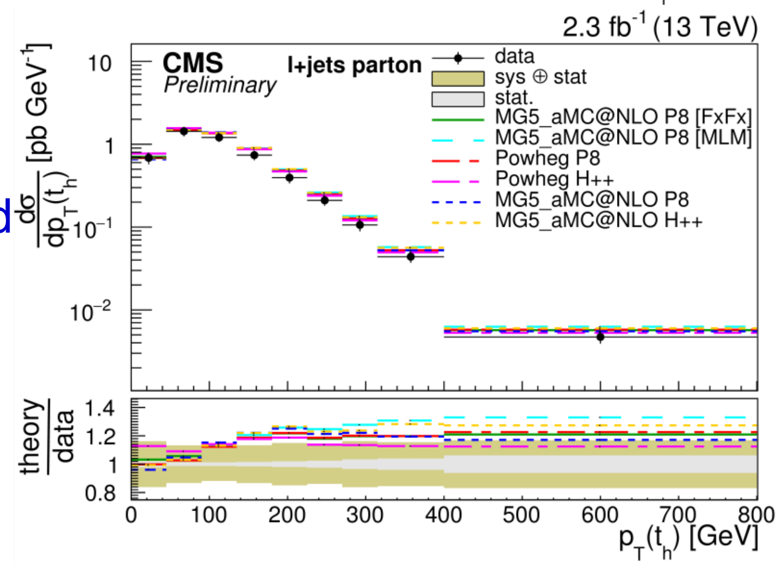
	7 TeV	8 TeV
NNPDF3.0	$173.5^{+1.9}_{-2.0}$	$174.2^{+2.0}_{-2.2}$
MMHT2014	$173.9^{+2.0}_{-2.1}$	$174.4^{+2.1}_{-2.3}$
CT14	$174.1^{+2.2}_{-2.4}$	$174.6^{+2.3}_{-2.5}$



Differential cross-section measurements

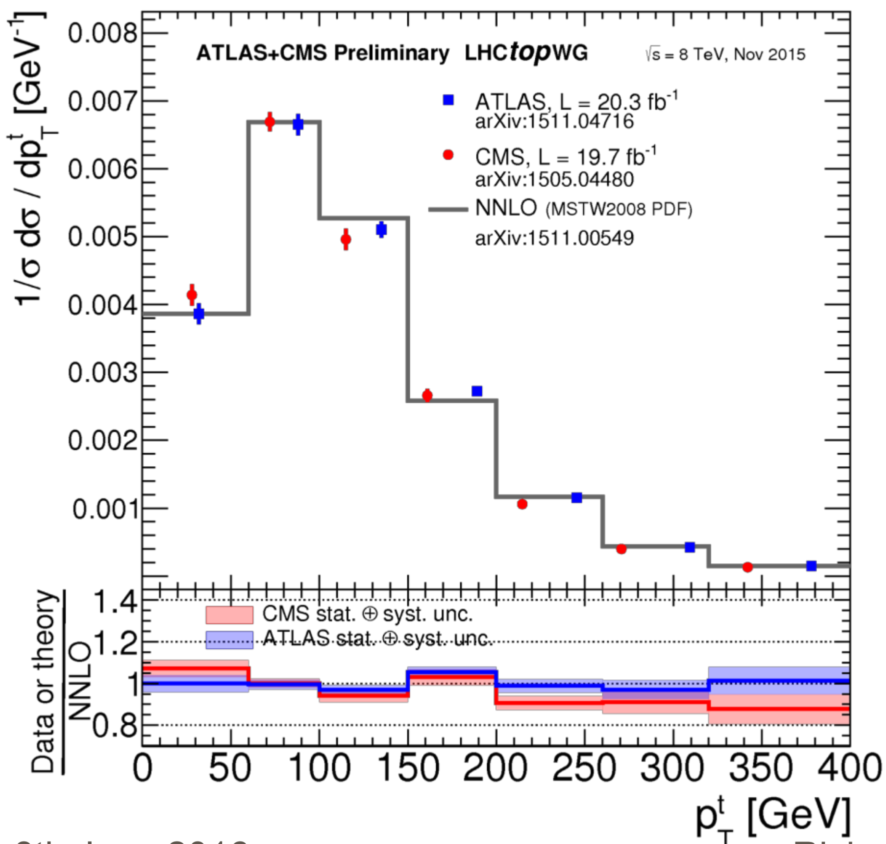
- Measure normalised differential cross-sections
  - As functions of p_T(t), p_T(tT), m(tT), y(tT) etc.
  - Requires full reconstruction of tT system kinematics
    - l+jets final state generally better – only one neutrino
    - Dilepton can also be used with approximations
  - Correct for resolution effects using unfolding
  - Aim to measure a **fiducial** cross-section corresponding to detector acceptance
  - Or correct to full phase space – model dependent
- Measurements at 7, 8 and now 13 TeV
  - Probe detailed description of tT kinematics in MC
  - NLO and LO generators (e.g. Powheg, MC@NLO, MadGraph, Alpgen)+parton shower generally good
    - Important input for parameter tuning
  - But persistent problems in describing p_T(t)
    - Also impacts estimates of top backgrounds in many searches (particularly SUSY)

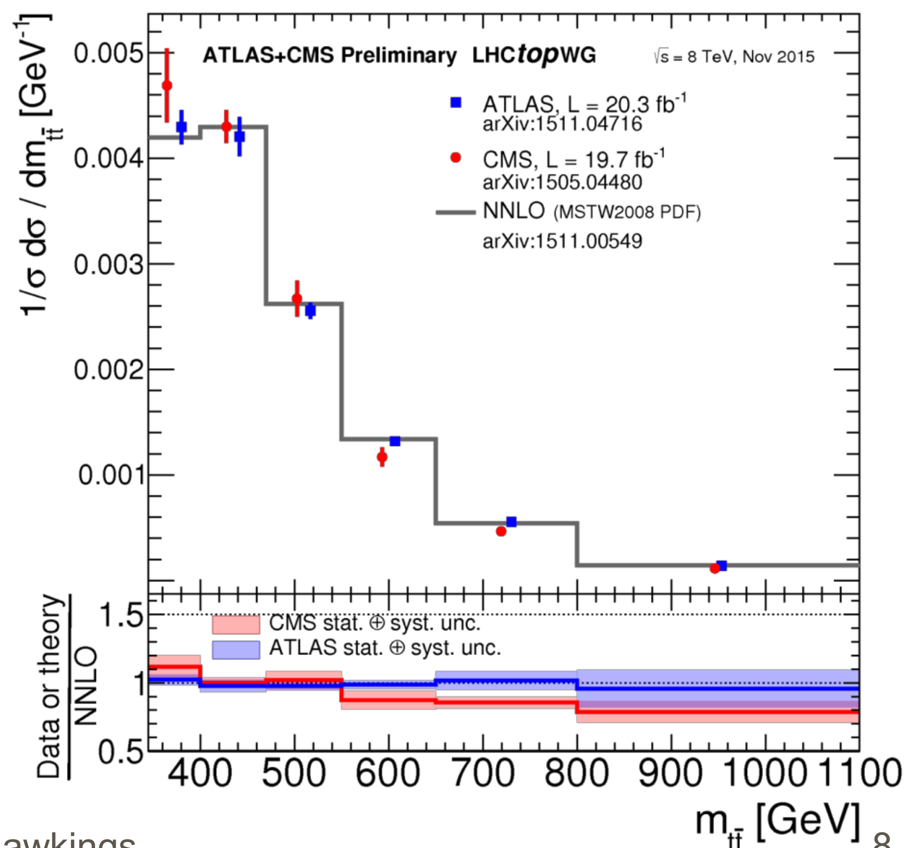




Comparison with NNLO predictions

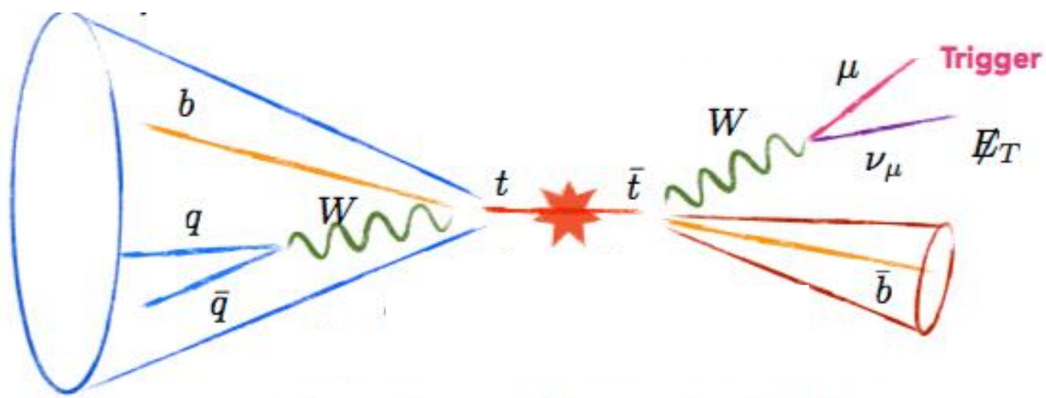
- Recent progress in calculating top differential distributions at NNLO
    - E.g. Czakon, Haymes, Mitov, PRL 116 082003 (arXiv:1511.00549)
  - Better agreement for $p_T(t)$, not quite so good for m(tT)
  - Cannot yet incorporate these predictions into full MCs, except by reweighting



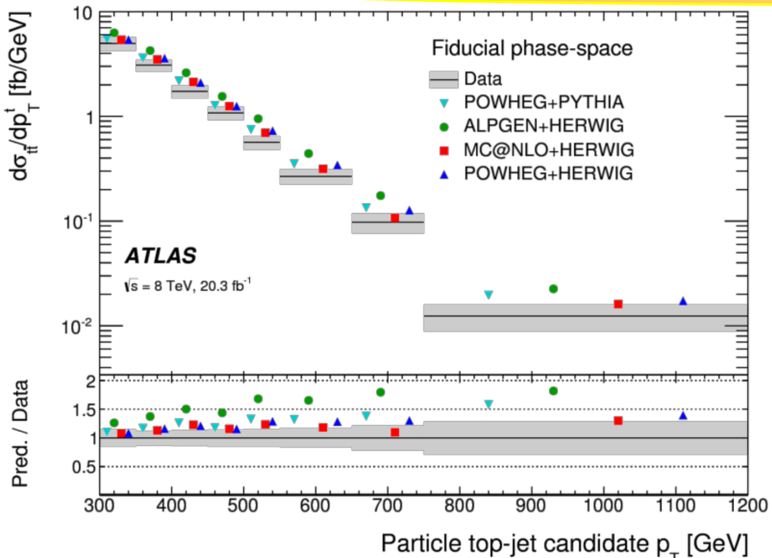


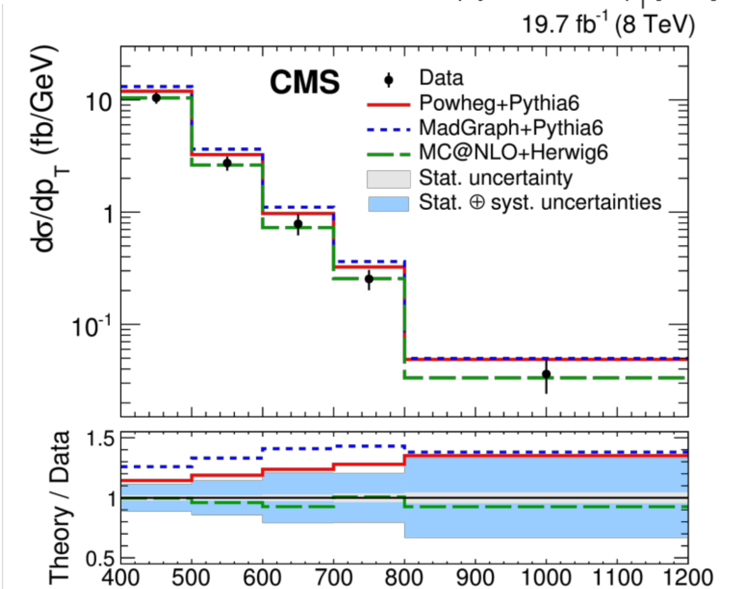
Boosted topologies

- At high m(tT) / p_T(t), top decays are **boosted**
  - 3 jets (bqq) from hadronic top start to merge
  - Use jet substructure techniques to reconstruct a a large R (R=1.0), high p_T, high mass jet
    - Apply substructure selections to resolve internal jet structure (subjets, splitting scale)



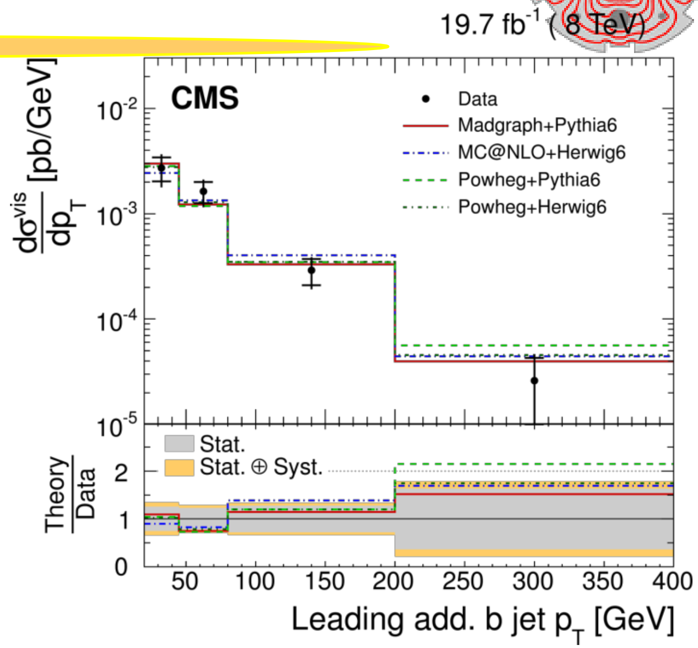
  - Unfolding techniques as for resolved selection
- Again, most MCs predict harder p_T spectrum
  - Important to improve modelling in this regime for searches exploiting jet substructure

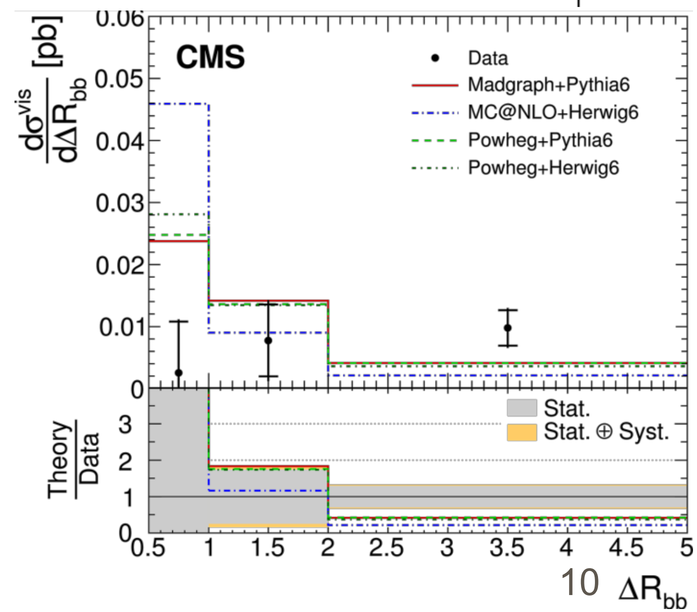




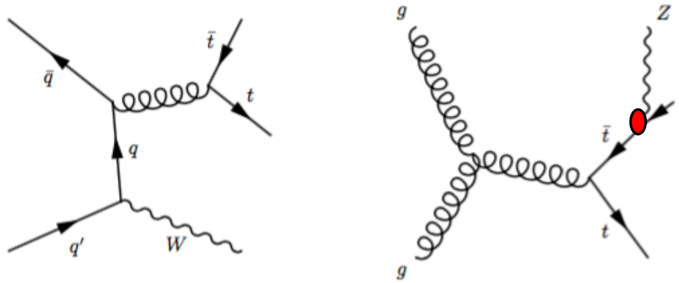
Top-pair + heavy flavour production

- Extensive studies of tT+extra jets
  - Generally well-modelled by NLO and LO multi-leg generators, with tuned parton shower parameters
  - Production of tT+extra b-jets particularly important
    - Irreducible background to ttH with H→bb
- Study cleanly with dileptonic tT with >=3 b-jets
  - Small statistics, e.g. O(100) events with >=4 b-tagged jets in 8 TeV data samples
    - Backgrounds from tT + mistaged light/c jets
  - Larger samples of tT+1 extra b-tagged jet
    - tT+g(→bb) in one jet, or 2[nd] b outside acceptance
- MC models with extra b-jets from parton shower
  - Typically underestimate rate for >=2 extra b-jets
  - PowHel NLO ttbb calculation does better
- Differential studies of m_{bb}, ΔR_{bb} for >=2 extra-b
  - Statistically-limited, MCs overestimate at low ΔR

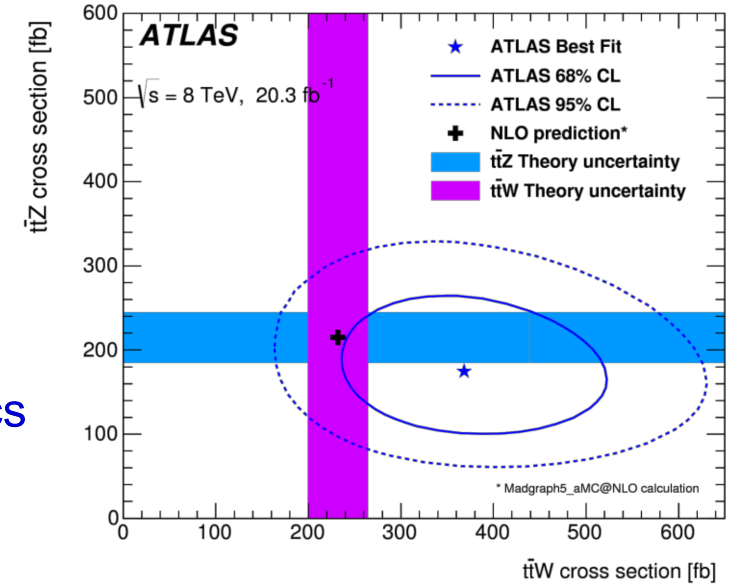




Top pair + vector boson production

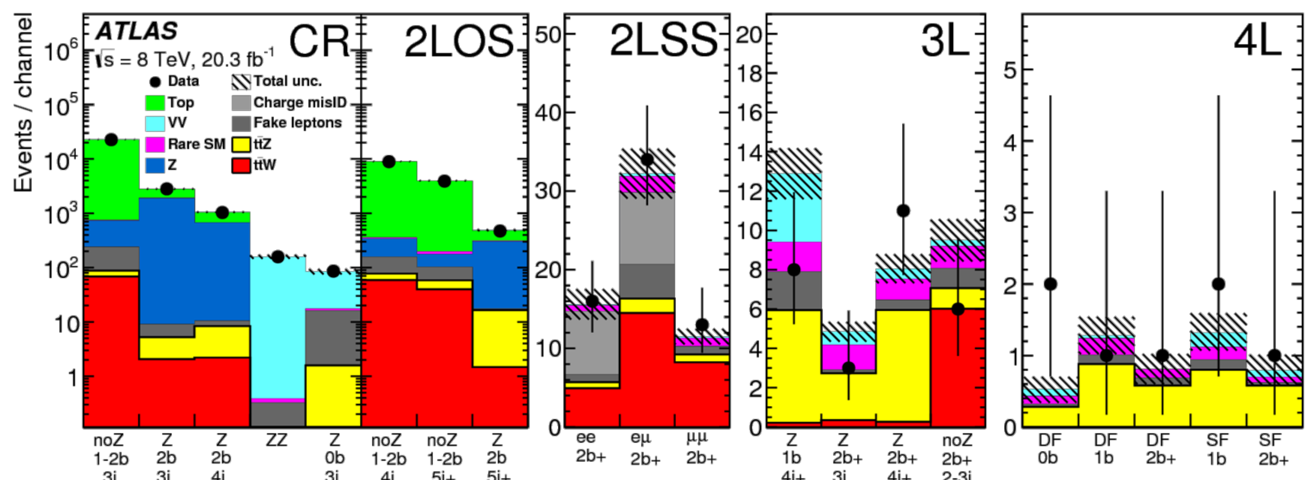


tZ coupling



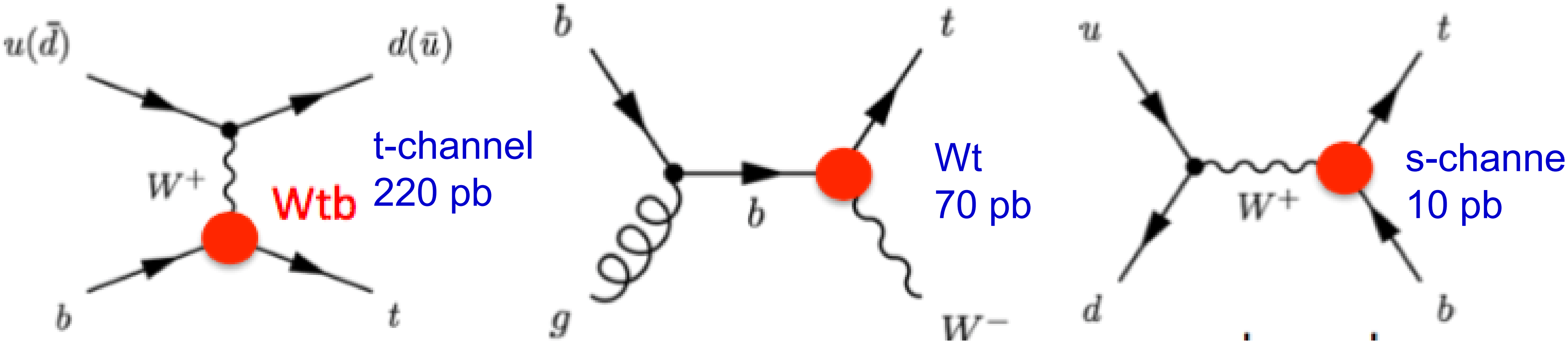
- ttbar+W and ttbar+Z: similar signatures
  - Final states with 2, 3, 4 leptons, (b) jets, low statistics
    - Significant contributions from 'fake' leptons
  - ATLAS 8 TeV: ttW: 5σ, ttZ: 4.2σ
  - CMS 8 TeV: ttW: 4.8σ, ttZ: 6.4σ

Process	$t\bar{t}$ decay	Boson decay	Channel	$Z \to \ell^+\ell^-$
$t\bar{t}W^\pm$	$(\ell^\pm \nu b)(q\bar{q}b)$	$\ell^\mp \nu$	OS dilepton	no
	$(\ell^\pm \nu b)(\ell^\mp \nu b)$	$q\bar{q}$	OS dilepton	no
	$(\ell^\pm \nu b)(q\bar{q}b)$	$\ell^\pm \nu$	SS dilepton	no
	$(\ell^\pm \nu b)(\ell^\mp \nu b)$	$\ell^\pm \nu$	Trilepton	no
$t\bar{t}Z$	$(\ell^\pm \nu b)(\ell^\mp \nu b)$	$q\bar{q}$	OS dilepton	no
	$(q\bar{q}b)(q\bar{q}b)$	$\ell^+\ell^-$	OS dilepton	yes
	$(\ell^\pm \nu b)(q\bar{q}b)$	$\ell^+\ell^-$	Trilepton	yes
	$(\ell^\pm \nu b)(\ell^\mp \nu b)$	$\ell^+\ell^-$	Tetralepton	yes



Single top production

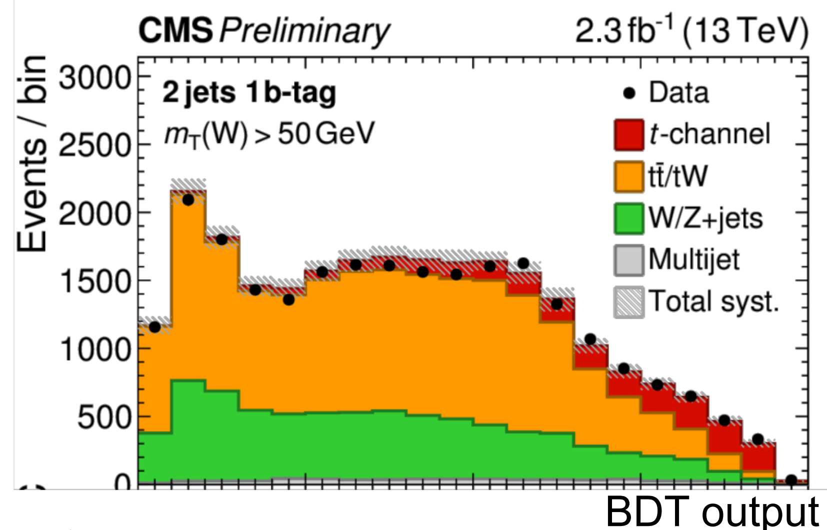
- Electroweak process involving the Wtb vertex – 3 sub-processes

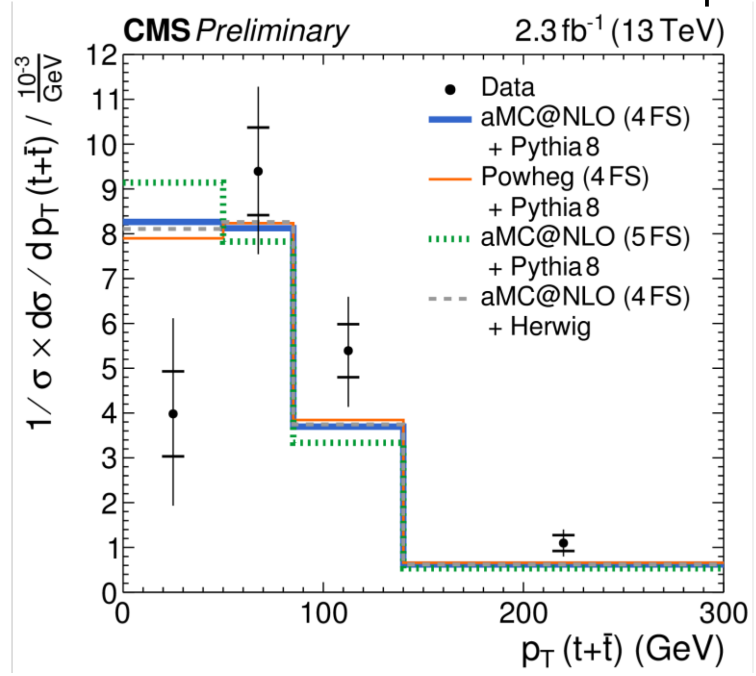


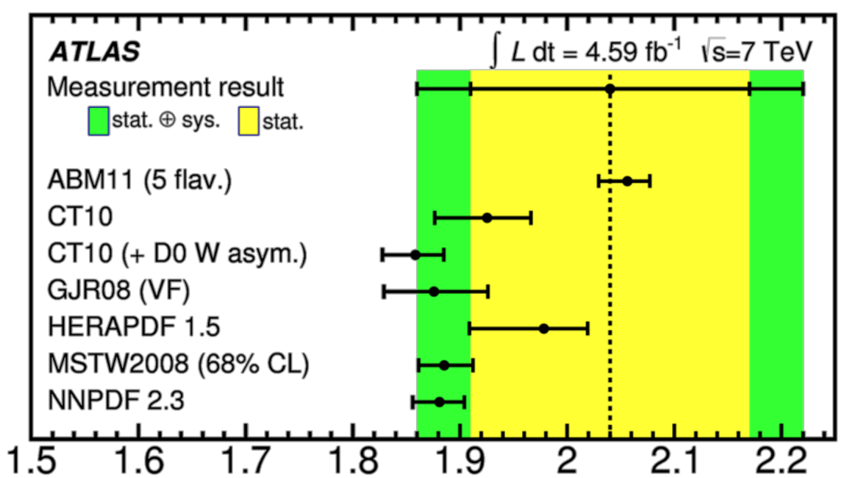
  - Cross-sections are proportional to $|V_{tb}|^2 \approx 1$ – can interpret as constraints on $|V_{tb}|$
    - Values given for $\sqrt{s}$=13 TeV
- Typically look for semileptonic decay of W: $t \rightarrow bl\nu$
  - t-channel: additional forward 'spectator' jet from the outgoing light quark
  - Wt-associated production: additional $W(\rightarrow l\nu)$ – like tT but with one fewer b-jet
    - Process interferes with tT production at NLO (Wtb→WWbb vs. tT→WWbb)
  - s-channel: $l\nu$+2 high p_T b-jets, low x-sec at LHC due to sea antiquark in initial state
- Significant backgrounds from top-pair production, and W/Z+(b) jets
  - Sophisticated analysis techniques (multivariate, matrix element) needed

t-channel single top

- Multivariate techniques based on e.g.
  - Light jet rapidity, m(lνb), angular information
  - Control regions with extra jets, non-b-tagged jets to constrain tT and W+jets contribution
- Achieve signal purities >50%
  - Start to measure differentially , e.g. p_T(t)
  - Results so far agree with MC predictions
- Ratio $R_t=\sigma(t)/\sigma(\text{t-bar})$ sensitive to u/d in proton
  - Many systematics cancel – R_t stat-dominated
    - Constrain PDFs with full run-1 and run-2 datasets

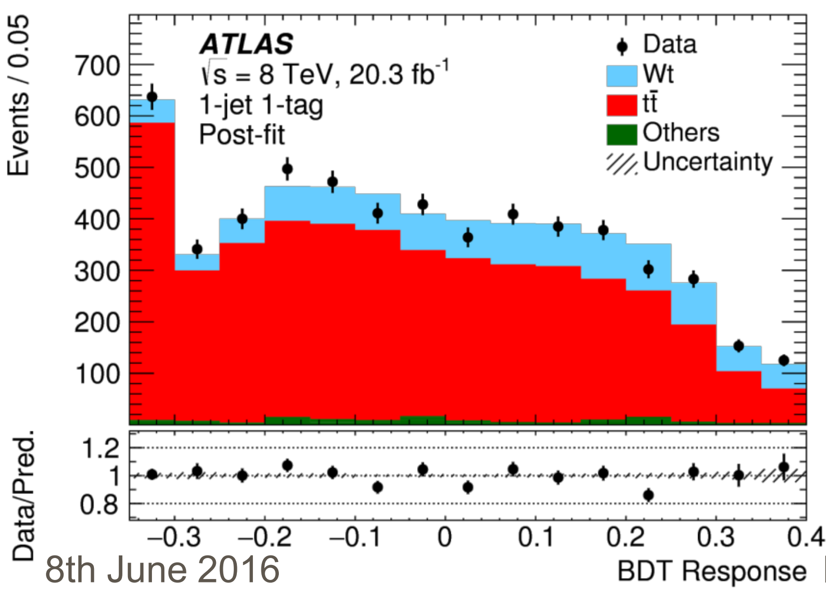


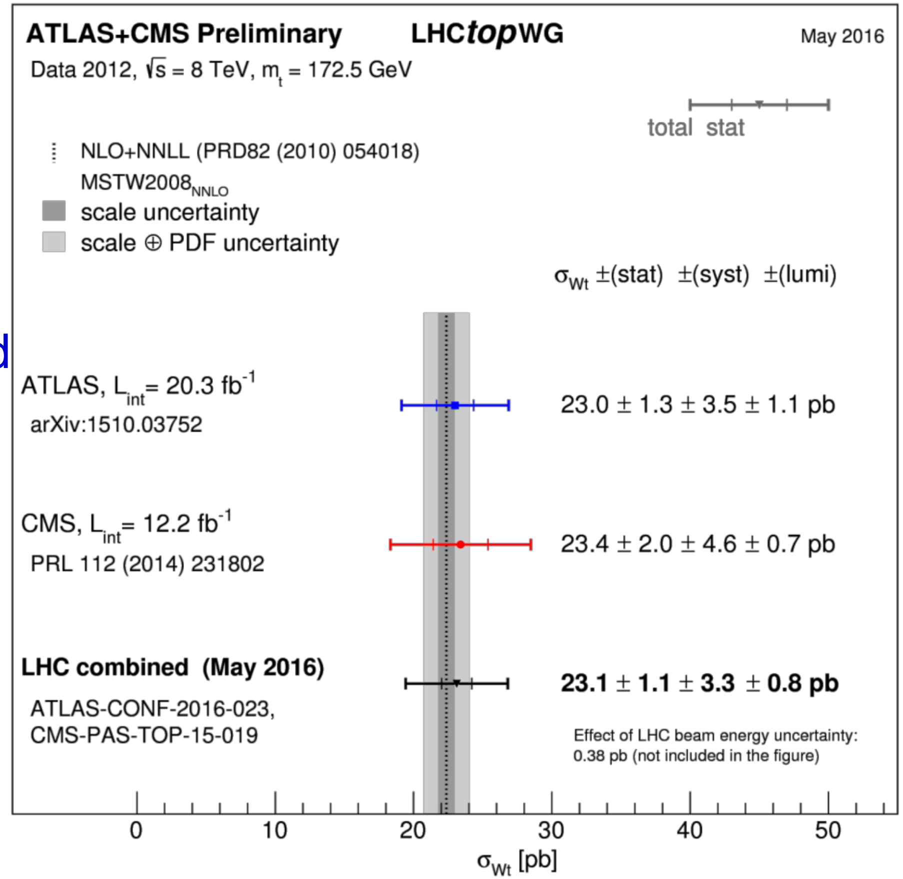




Wt associated production

- Signal concentrated in dilepton+1 b-tag jet
  - Combine multiple kinematic quantities in MVA to separate from tT with one 'missed' b-jet
  - Use 2-jet events with 1 or 2 b-tags to constraint the dominant top-pair background
  - Only limited signal purity can be achieved
    - Wt signal in ATLAS and CMS only fully established with 8 TeV datasets





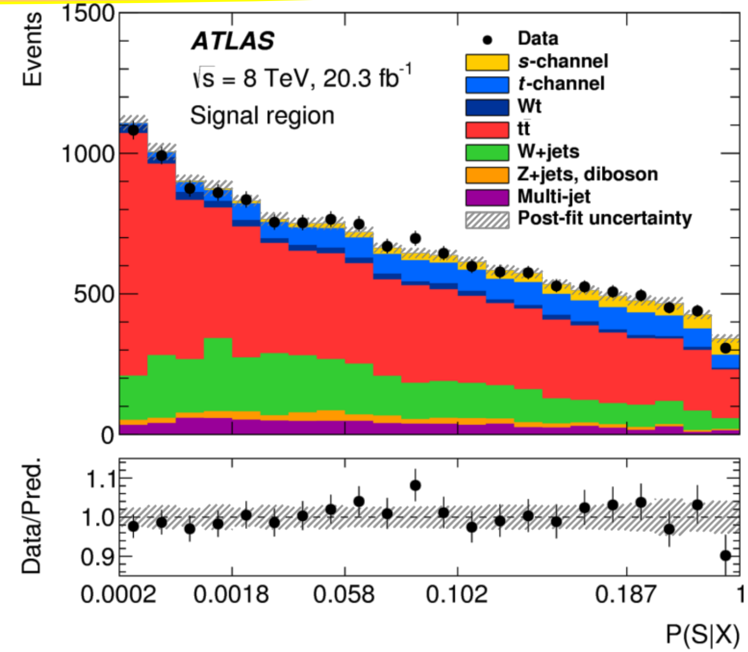
- Combined ATLAS+CMS 8 TeV result with precision of 16%
  - Agrees with NLO+NNLL prediction with 6% uncertainty

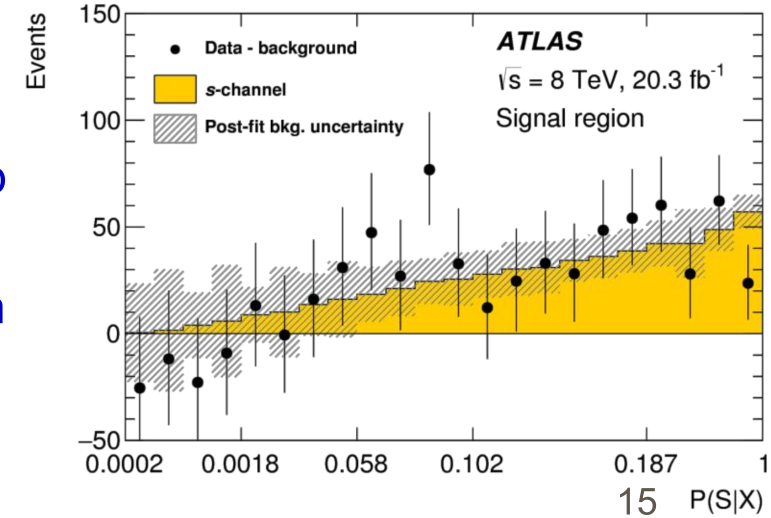
s-channel single top

- Small signal with e/μ, E_T^{miss}, 2 high p_T b-tagged jets
  - Veto on second lepton with p_T>5 GeV to reduce tT
  - Use 'matrix element' (ME) method to calculate per-event signal probability based on kinematics
    - Using theoretical ME for each signal and b/g process

$$P(S|X) = \frac{\sum_i \alpha_{S_i} \mathcal{P}(X|S_i)}{\sum_i \alpha_{S_i} \mathcal{P}(X|S_i) + \sum_j \alpha_{B_j} \mathcal{P}(X|B_j)}$$

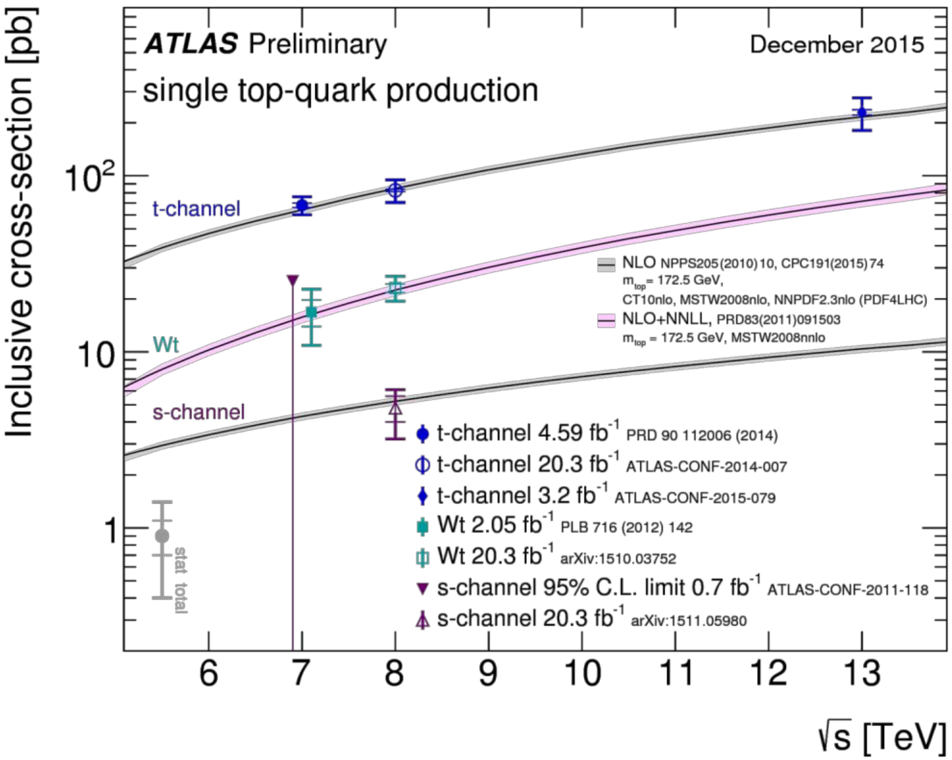
  - Fit P(S|X) dstribution in selected sample
    - Lepton charge used to increase W+jets discrimination
    - Validation in W+jets and tT dominated regions
- Results in 3.2σ signal, c.f. expected 3.9σ
  - Cross-section measurement of 4.8±0.8+1.8-1.6 pb
    - Consistent with theoretical prediction of 5.6±0.2 pb
  - Improvement over previous BDT-based analysis on same data sample (5.0±4.3 pb)

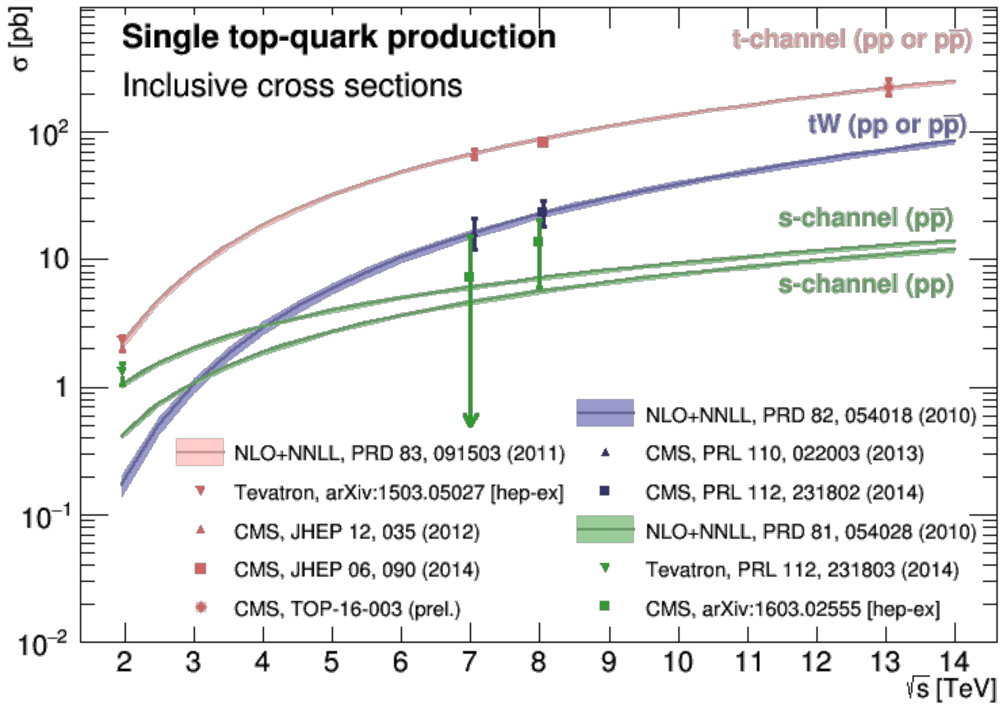




Summary of single top production

- Measurements from 7, 8 TeV; first measurements from 13 TeV

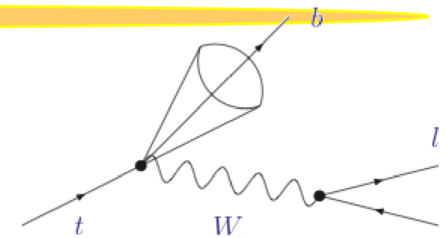


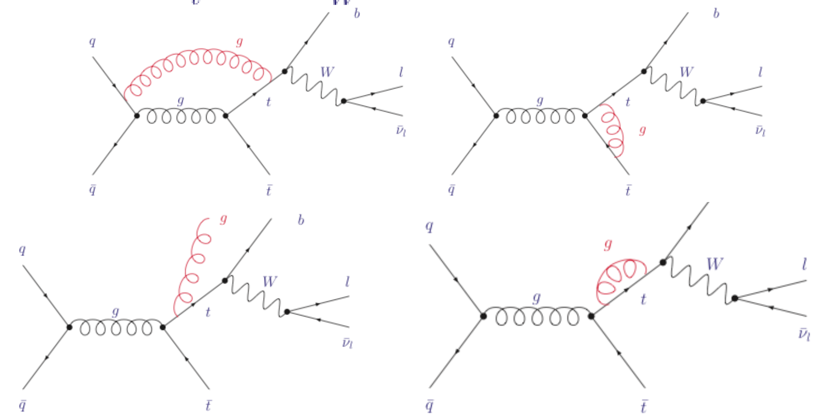


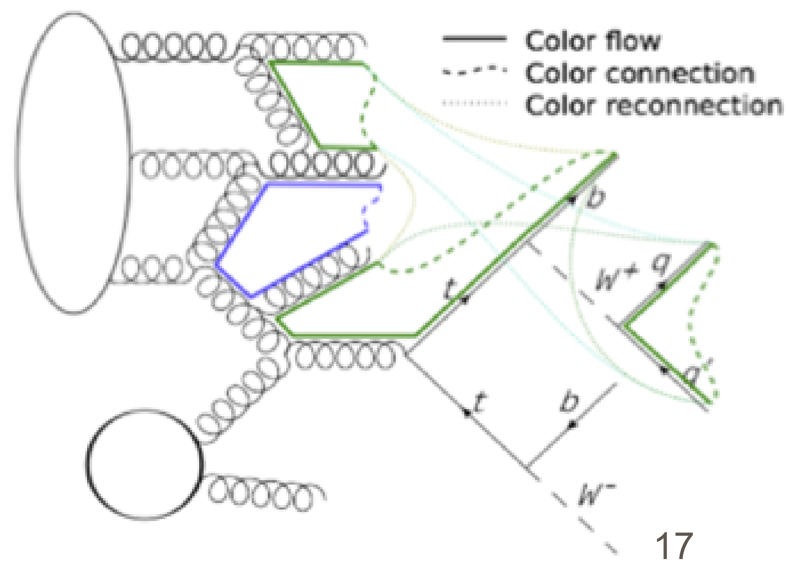
- Measurements in agreement with NLO+NNLL predictions
  - Experimental precision of 9-14% for t-channel, worse for Wt and s-channel
    - Theoretical precision ~5%
  - Room for improvement with larger run-2 datasets, more differential measurements

Top quark mass – what are we measuring?

- Measuring mass of a coloured particle
  - Experimentally, $\sqrt{(E^2-p^2)}$ from final state particles (leptons, jets, E_T^{miss})
- But there are radiative corrections …
  - In principle accounted for in the NLO generators and the parton shower
  - Top quark-self energy corrections
- Colour reconnection to rest of the event
  - Only phenomenological models (UE data)
- Need the **pole mass** for electroweak fit
  - Corresponding to propagation of free particle
    - But suffering from renormalon ambiguity
  - Expect O(1 GeV) difference between pole mass and MC mass definitions
  - But ~10 GeV difference to short-distance masses like MS-bar scheme
- Experimental precision now ~0.5 GeV …

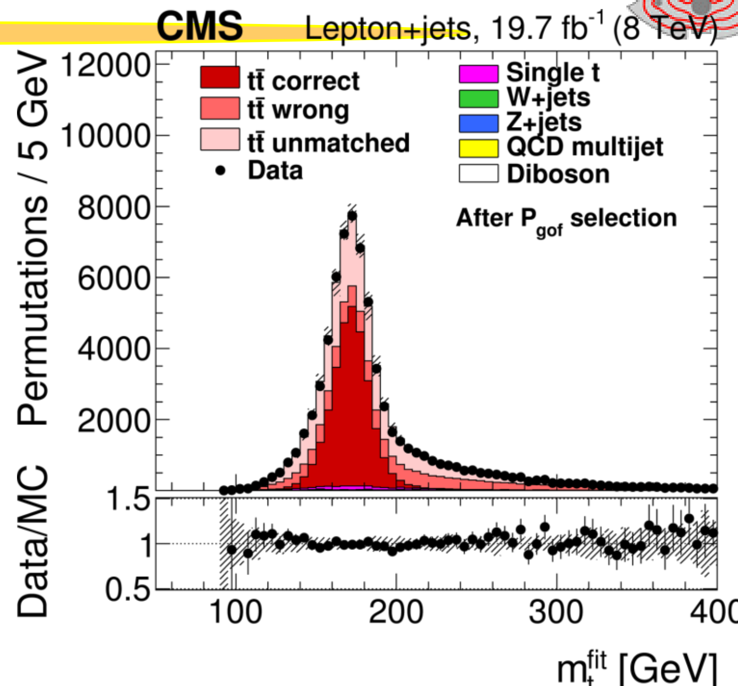


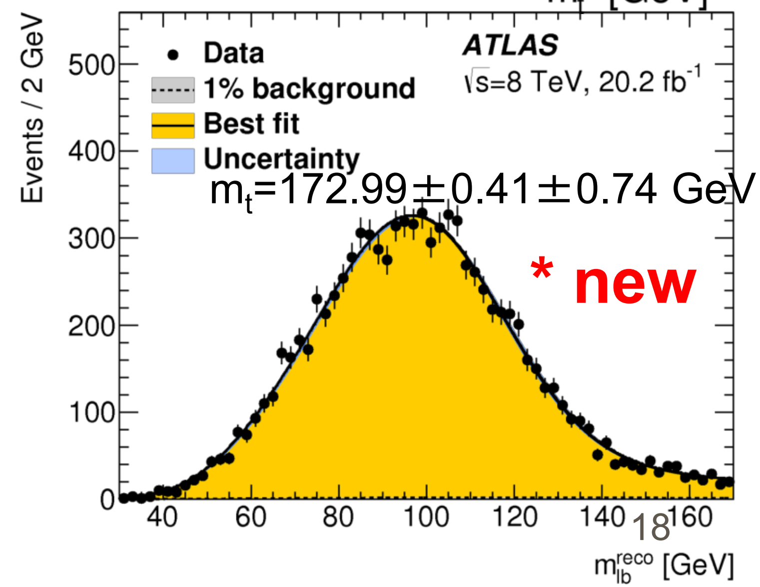




Measurements via direct reconstruction

- Most precise measurements from l+jets
  - Require b-tagged jets, kinematic fits to choose or weight jet combinations (goodness of fit)
  - W→qq decay allows jet energy scale to be constrained **in situ** using known m_W (2D fit)
    - Various techniques to combine this with external input on jet energy scale (from γ+jet, Z+jet etc)
    - ATLAS also constrains b-jet scale in situ (3D fit)
  - Precision limited by jet energy scale (incl. b)
- Dilepton measurement – two neutrinos
  - CMS uses AMWT technique to weight solutions of the tT system kinematics
  - ATLAS uses fit to m(lb) – still sensitive to m_t
  - Precision limited by b JES and tT modelling
- All-hadronic channel – also useful results
  - Large combinatoric background, constrain JES with W decays

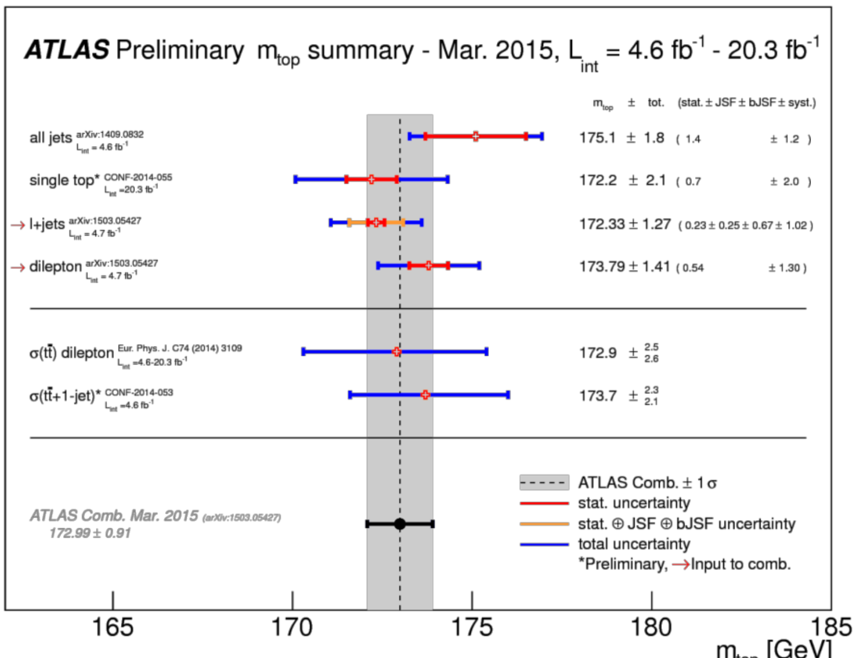


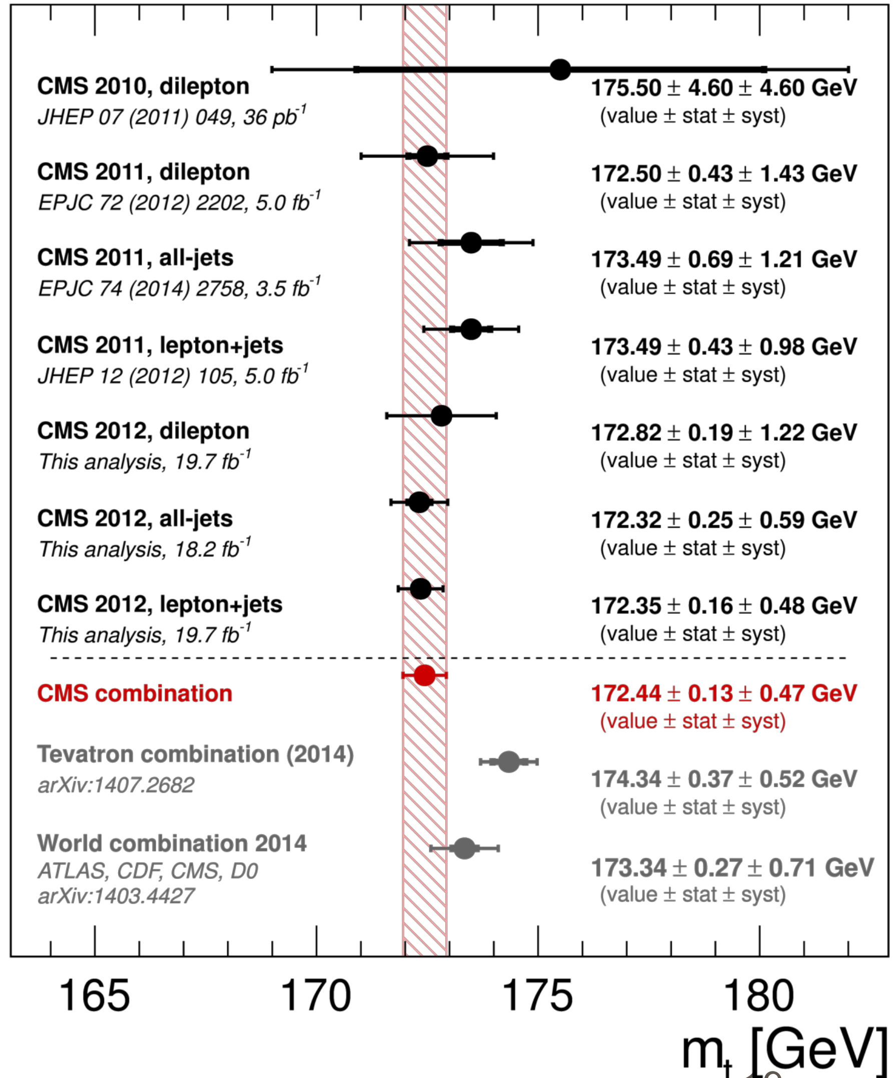


Direct top mass measurement results

- Impressive precision now reached
  - CMS (7+8 TeV): Δm/m=0.28% (0.5 GeV)
  - ATLAS (7+8 ll): Δm/m=0.40% (0.7 GeV)
  - Tevatron still competitive: 0.36% (0.6 GeV)
    - Some ‘tension’ between CMS and Tevatron
  - Very precise, but what do we measure?

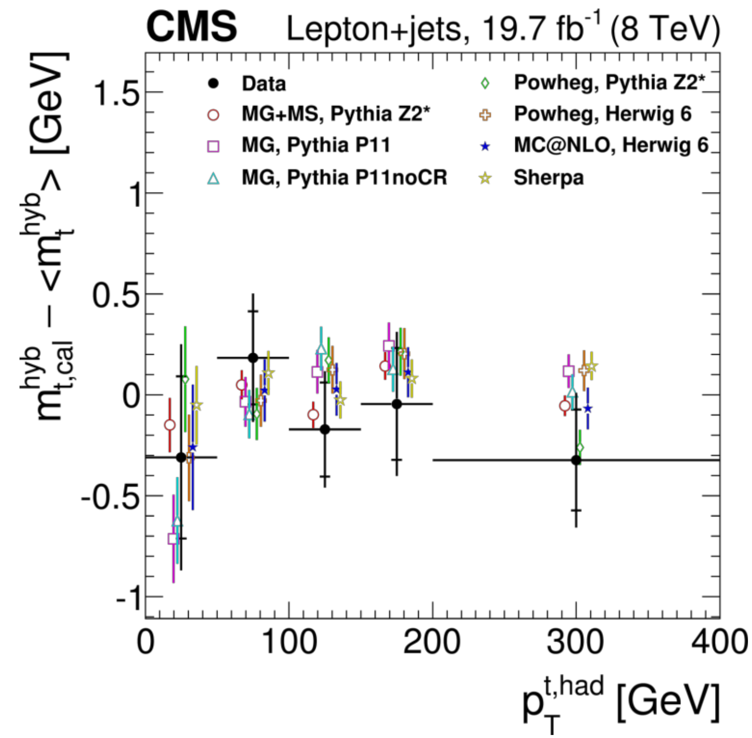
ATLAS new: 7 TeV+8 TeV ll: 172.84±0.34±0.61 GeV

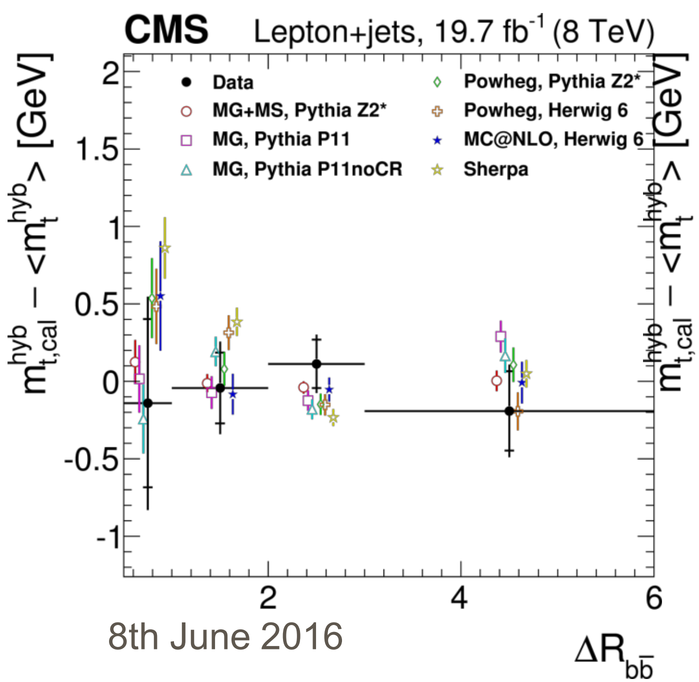


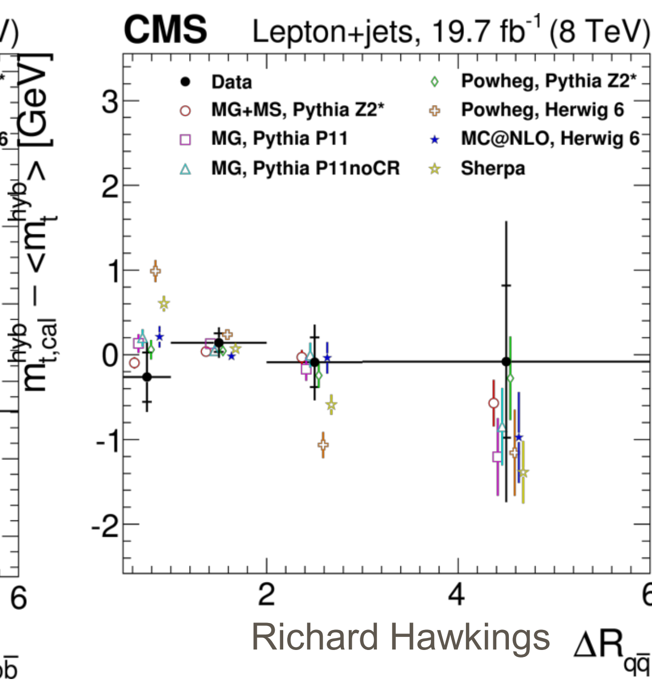


Probing QCD effects

- Study m_t vs. kinematic variables with 8 TeV data
  - Look at m_t - $<m_t>$ to look for biases which are not modelled by the MC generators
  - Top kinematics (e.g. $p_T(t)$) and variables which might be sensitive to colour reconnection
    - E.g. ΔR between jets
  - So far, no indications of mismodelling - important to continue with higher statistics at 13 TeV







Simulation	χ^2	Standard deviations
MG + PYTHIA 6 Z2*	17.55	0.10
MG + PYTHIA 6 P11	37.68	1.73
MG + PYTHIA 6 P11noCR	31.57	1.15
POWHEG + PYTHIA 6 Z2*	19.70	0.20
POWHEG + HERWIG 6	76.48	4.84
MC@NLO + HERWIG 6	20.47	0.24
SHERPA	46.79	2.56

Alternative mass measurements

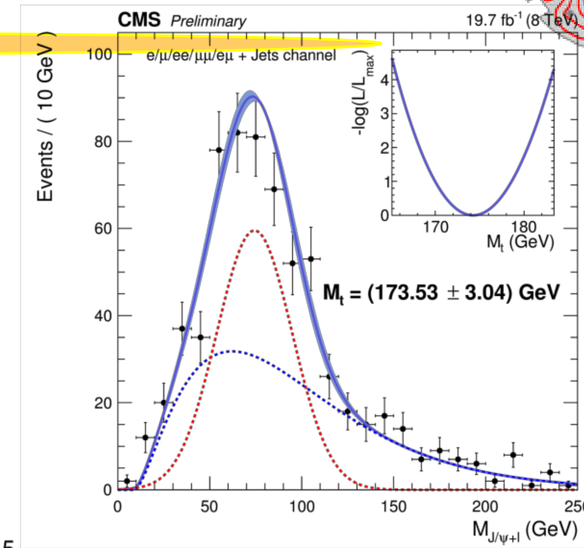
- Many other observables can be defined
  - Mass of J/ψ+l system in t→bW→J/ψ(→$\mu\mu$)+X + lν
  - Branching fraction 3 10^{-4} – need large sample
  - No jets used in selection – different systematics
  - Statistically limited: ±3 GeV with 20 fb^{-1} at 8 TeV
    - Systematics ~1 GeV, dominated by p_T(t) and b-decay modelling – promising for future
- Top mass from m(ttj) in tT+1 jet events
  - Diff. x-sec shape R(ρ_s) with ρ_s~1/m_{ttj} sensitive to m_t

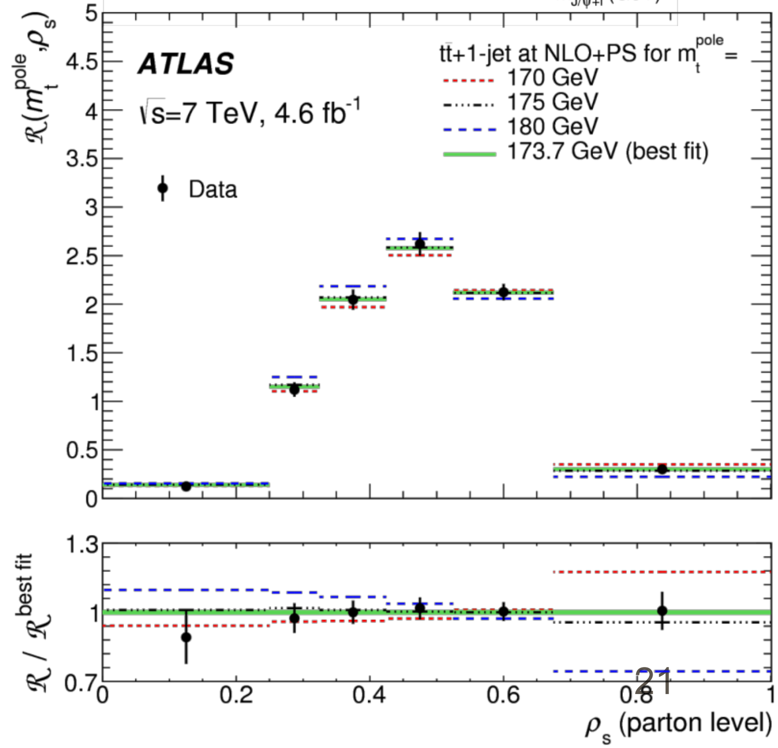
$$\mathcal{R}(m_t^{\text{pole}}, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1\text{-jet}}} \frac{d\sigma_{t\bar{t}+1\text{-jet}}}{d\rho_s}(m_t^{\text{pole}}, \rho_s), \quad \rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}+1\text{-jet}}}}$$

  - Mass m_t here corresponds to pole mass
  - Distribution predicted at NLO+PS accuracy, unfold experimental results

$$m_t^{\text{pole}} = 173.7 \pm 1.5\,(\text{stat.}) \pm 1.4\,(\text{syst.})^{+1.0}_{-0.5}\,(\text{theory})\ \text{GeV}$$

- Many other 'alternative' methods being pursued
  - None close to precision of direct reco ..yet





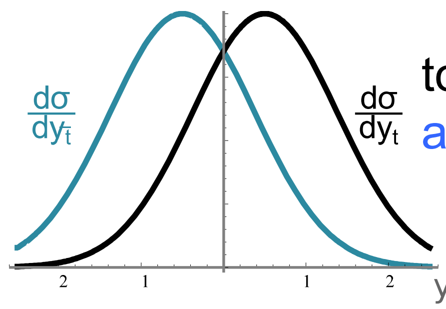
Top charge asymmetry

- q qbar→t tbar exhibits a small asymmetry
  - Zero at LO, but interference terms at NLO produce small positive asymmetry
    - Top quark follows direction of incoming q
  - Leads to ~10% forward-backward asymmetry at Tevatron (p-pbar)
    - Historical discrepancy with prediction …
  - LHC has symmetric pp, and ttbar production dominated by gg not q qbar
    - Top more fwd/bwd, anti-top central

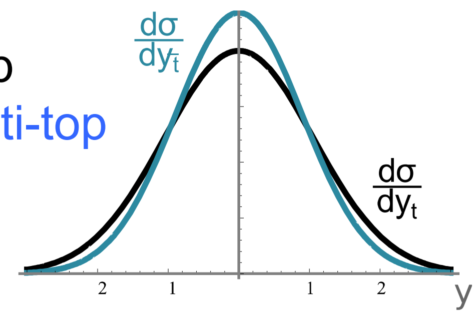
$$A_C = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)} \qquad \Delta|y| = |y_t| - |y_{\bar{t}}|$$

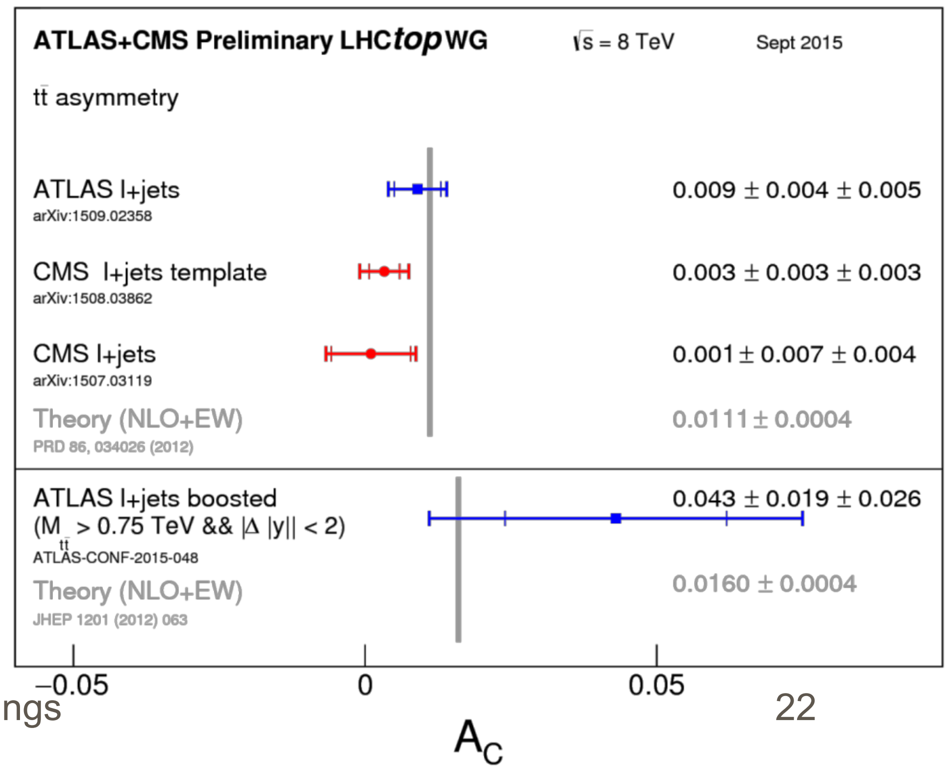
    - 1% asymmetry in SM
- Measurements in l+jets and dileptons
  - Precision ~0.5%, results agree with SM
- Also asymmetry in boosted topologies
  - More q-qbar, more sensitive to BSM

Tevatron (p-pbar)



LHC (pp)



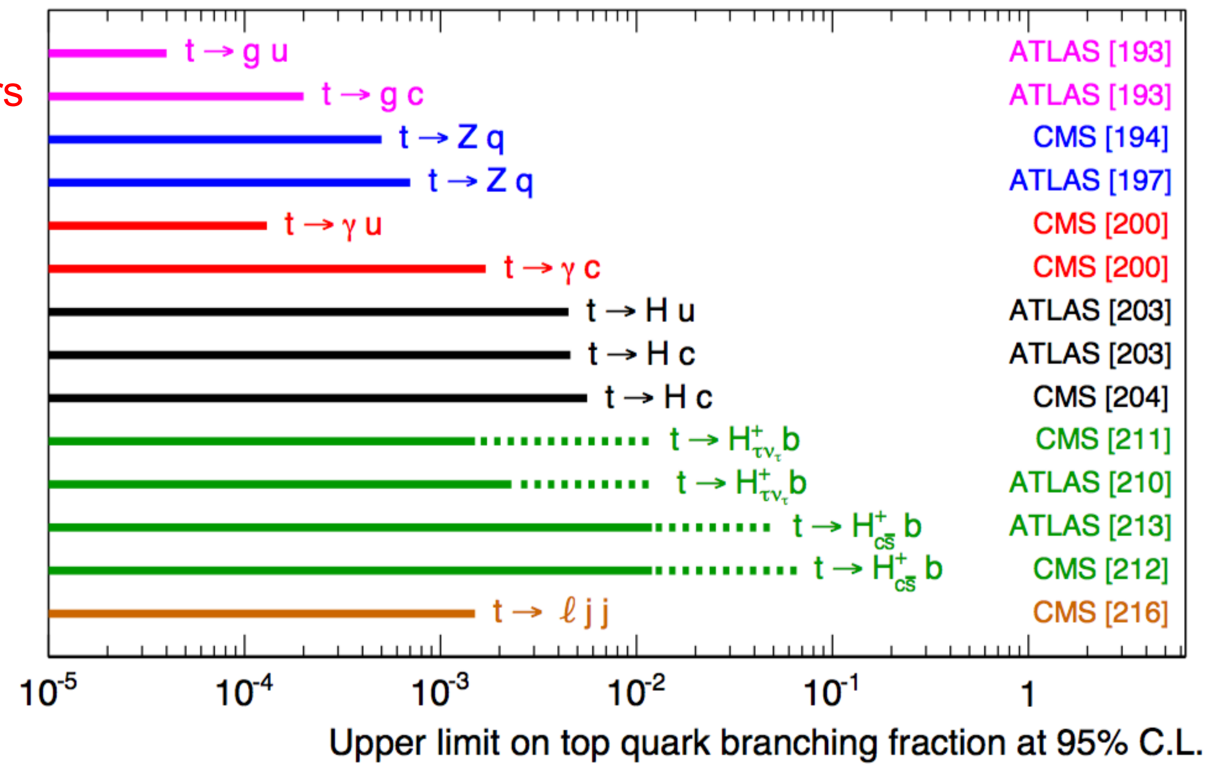


Exotic top decays

- FCNC: $t \to Zq$ by looking for $Z \to ll$ in top decays (3 lepton final state)
- $t \to gq$ impossible to see in decay, produces anomalous single top production: $qg \to t$
- $t \to \gamma q$: look for single top production in association with a photon
- $t \to Hq$: look for Higgs (various decay modes) produced in top-pair production
- $t \to H^+b$: look for enhancement of τ ($H^+ \to \tau\nu$), or qq peak with mass> m_W ($H^+ \to cs$)

- Only limits so far … will benefit from larger statistics of LHC run-2

Cristinziani & Mulders
arXiv:1606.00327



Summary – the story so far

- Precision top quark physics at LHC Run-1, with 100x Tevatron dataset
  - Detailed studies of tT production, inclusive and differential cross-sections
  - NNLO predictions are needed to match experimental precision (below ~5%)
    - Will need NNLO differential predictions, including top decays, to fully exploit new data
  - Single top t-channel differential measurements, Wt established, s-chan on the way
    - Start of precision physics with single tops, e.g. mass measurement
  - Associated production of W, Z, heavy flavour with tT becoming established
    - Important foundations for ttH associated production – a key goal for LHC run-2
  - Many top production/decay properties measured (e.g spin-corl, W polarisation)
    - No evidence for non-SM behaviour, or unexpected decay modes
  - Top mass measurements now overtaking Tevatron – but what do they mean?
    - Explore alternative measurement strategies, and expt./theory. collaboration to make progress

Summary – future prospects

- LHC run-2 has started, with 2-3 fb^{-1} in 2015, 20-30 fb^{-1} expected this year
  - Already seeing first 13 TeV x-sec measurements (tT, t-channel, tT+W/Z)
  - Hope for ~100 fb^{-1} before next LHC shutdown (LS2) – 15x more tops than run-1
- Full program of measurements ahead
  - With present techniques, many measurements will be systematically limited
    - Harsher environment (pileup) than run-1 – new ideas and analysis strategies will be needed to fully exploit this sample
  - At 13 TeV, boosted techniques (e.g. tagging top jets) will become more important
- Looking further ahead to HI-LHC: 1-3 ab^{-1} sample – another jump in statistics
  - Ultimate precision on top mass: ~0.3 GeV in well-defined scheme ?
  - Precise measurements of top couplings (g, γ, W, Z, H) – possible BSM contrib^{n}s
  - Extending reach of rare decay searches (e.g. FCNC)
  - Very challenging experimental environment for precision measurements, and large statistics in boosted topologies…
- Exciting challenges ahead in top physics...