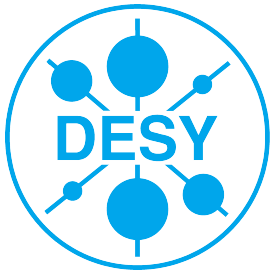
Top Physics in Run II: Experimental Perspective

Reinhild Yvonne Peters

The University of Manchester, also at DESY



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Introduction

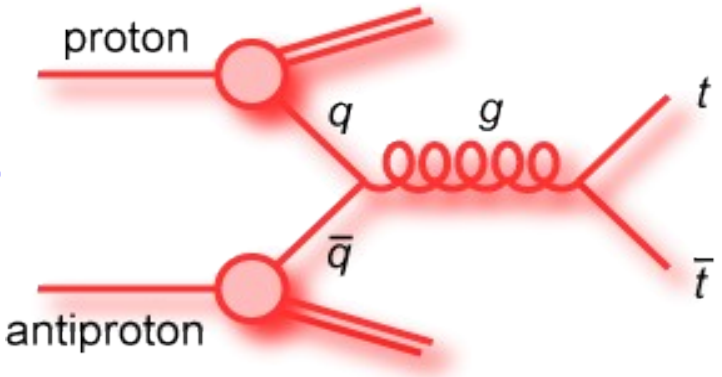
The Top Quark

- Heaviest known elementary particle:
  $m_t = \sim 173\,GeV$

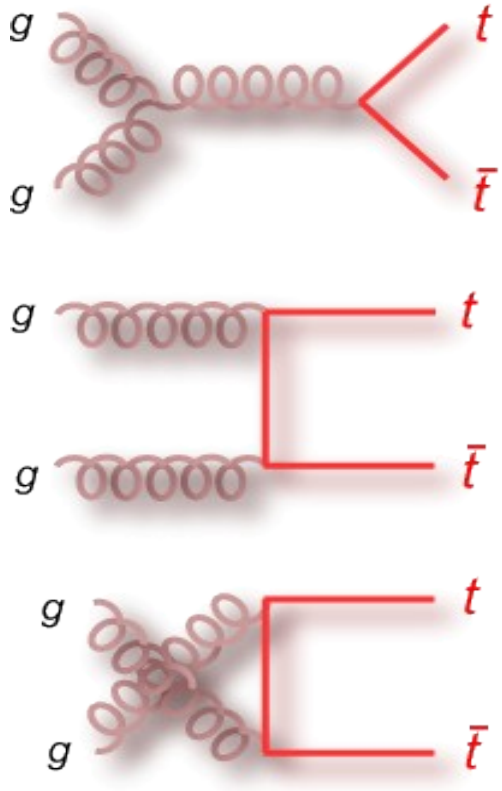
- Standard Model:
  - Single or pair production
  - Electric charge +2/3 e
  - Short lifetime 0.5×10^{-24}s
    - Bare quark - no hadronization
  - ~100% decay into Wb
  - Large coupling to SM Higgs boson

Top Quark Pair Production

At the Tevatron:



85%



+ 15%

At LHC:

14 TeV: 10% + 90%

7 TeV: 30% + 70%

Cross Sections:

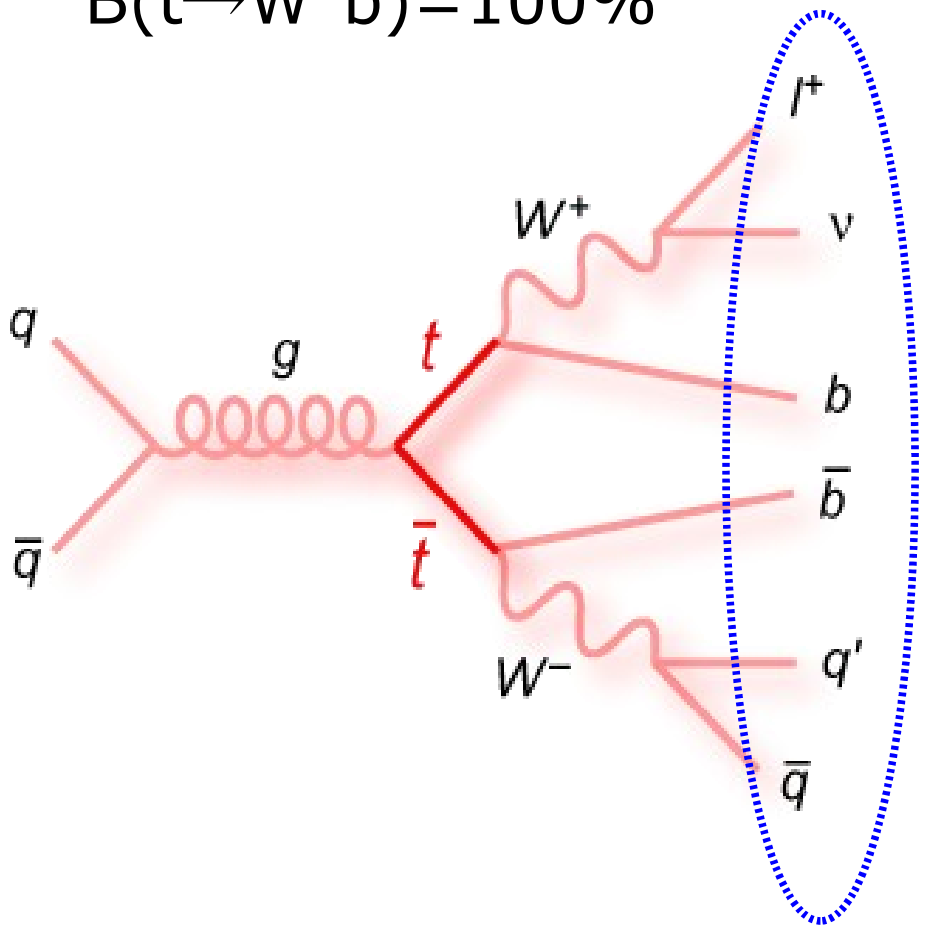
Collider	Cross section [pb]
Tevatron (1.96 TeV)	$7.35^{+0.23}_{-0.27}$
LHC (7 TeV)	$177.3^{+10.1}_{-10.8}$
LHC (8 TeV)	$252.9^{+13.3}_{-14.5}$
LHC (13 TeV)	$831.8^{+40.3}_{-45.6}$

M. Czakon et al. arXiv:1112.5675

Final States in $t\bar{t}$

$t\bar{t} \rightarrow W^+bW^-\bar{b}$: Final states are classified according to W decay

$B(t \rightarrow W^+b)=100\%$

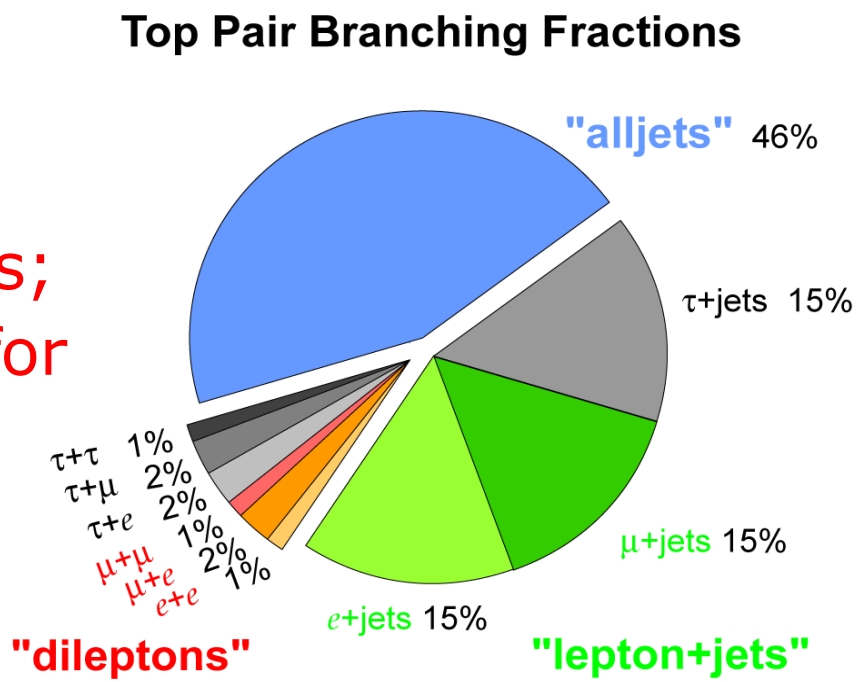


Final States in $t\bar{t}$

$t\bar{t} \rightarrow W^+bW^-\bar{b}$: Final states are classified according to W decay

$B(t \rightarrow W^+b) = 100\%$

pure hadronic:
≥6 jets (2 b-jets)

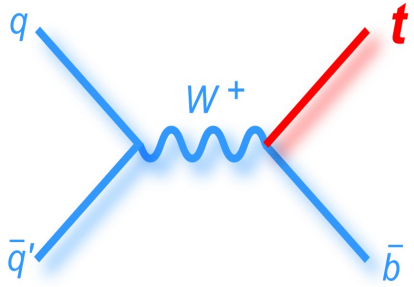


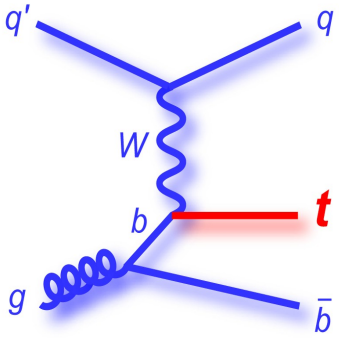
dilepton:
2 isolated leptons;
High missing E_T for neutrinos;
2 b-jets

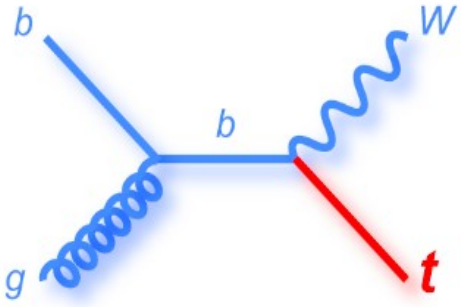
lepton+jets:
1 isolated lepton;
Missing E_T for neutrino;
≥4 jets (2 b-jets)

Single top Production

- Via electroweak interaction
  - Test of EW couplings
  - Probe for new physics
- Direct probe of Wtb interaction
- Direct measurement of CKM matrix element $|V_{tb}|$
- Challenging: background looks similar to signal





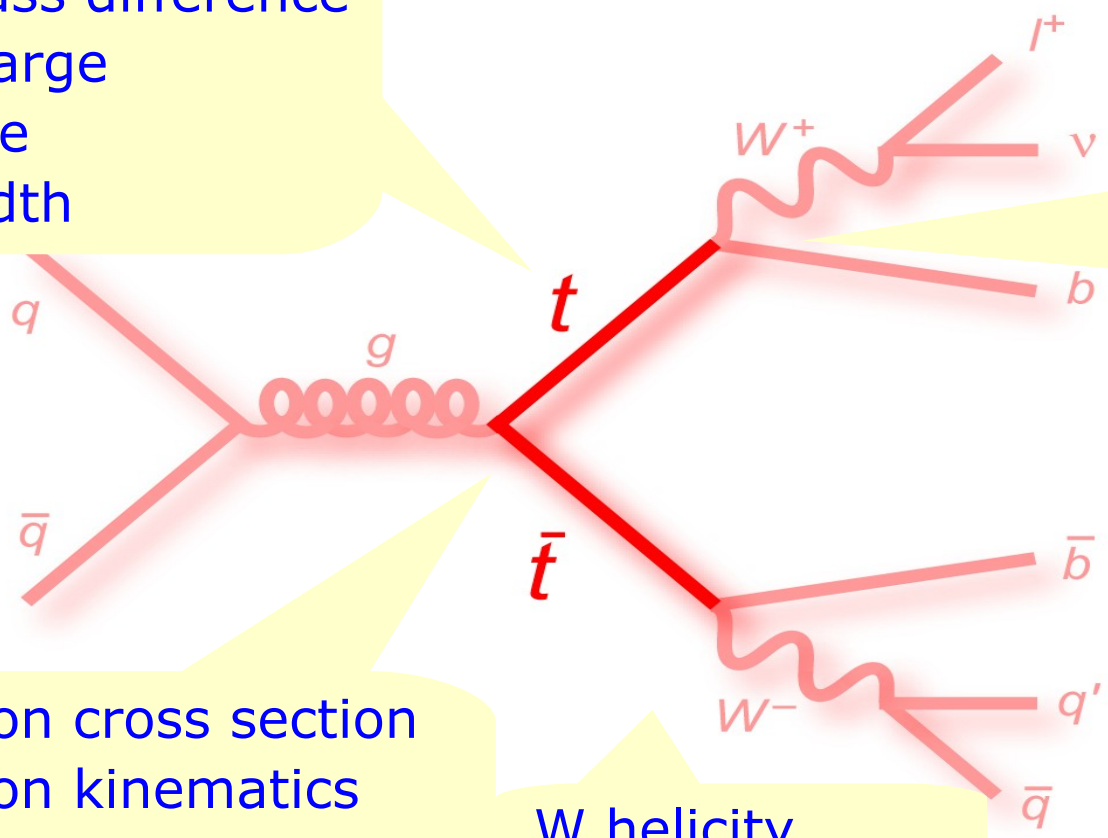


Collider	s-channel: σ_{tb}	t-channel: σ_{tbq}	Wt-channel: σ_{tW}
Tevatron: $p\bar{p}$ (1.96TeV)	1.04 pb	2.26 pb	0.28 pb
LHC: pp (7TeV)	4.3 pb	63.9 pb	15.7 pb
LHC: pp (8TeV)	5.2 pb	84.7 pb	22.4 pb
LHC: pp (13TeV)	10.3 pb	216.99 pb	71.7 pb

Status

Top Studies: Overview

Top mass
Top mass difference
Top charge
Lifetime
Top width



Branching ratios
$|V_{tb}|$
Anomalous coupling
New/Rare decays

Production cross section
Production kinematics
Production via resonance
New particles

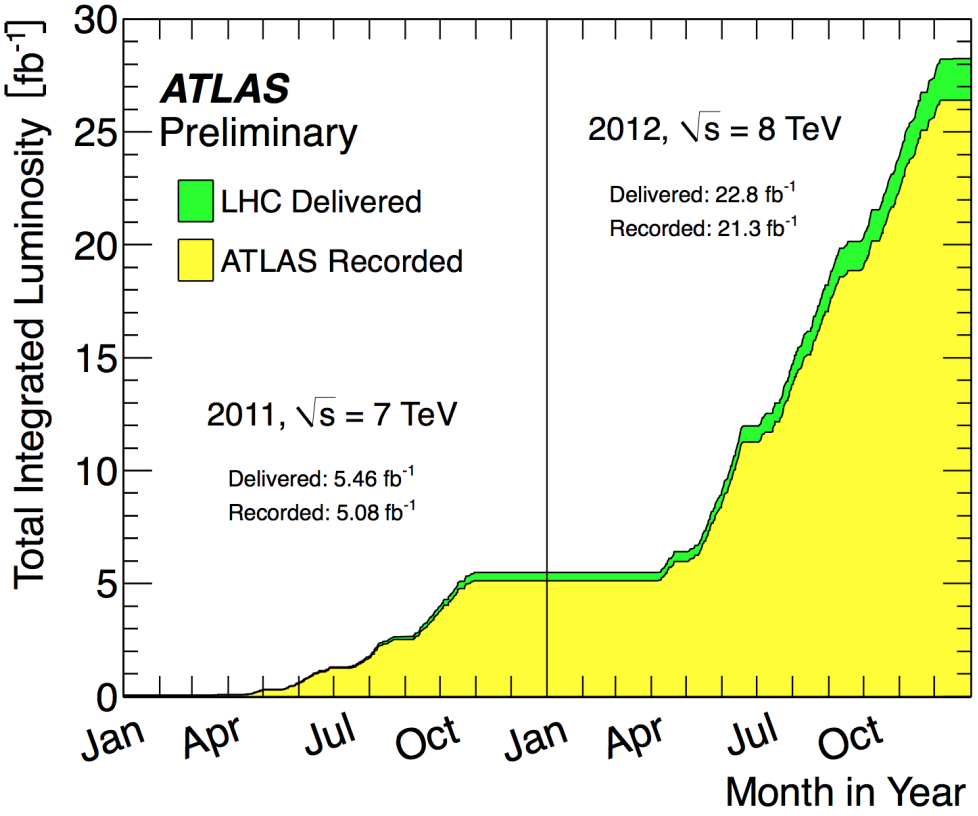
W helicity

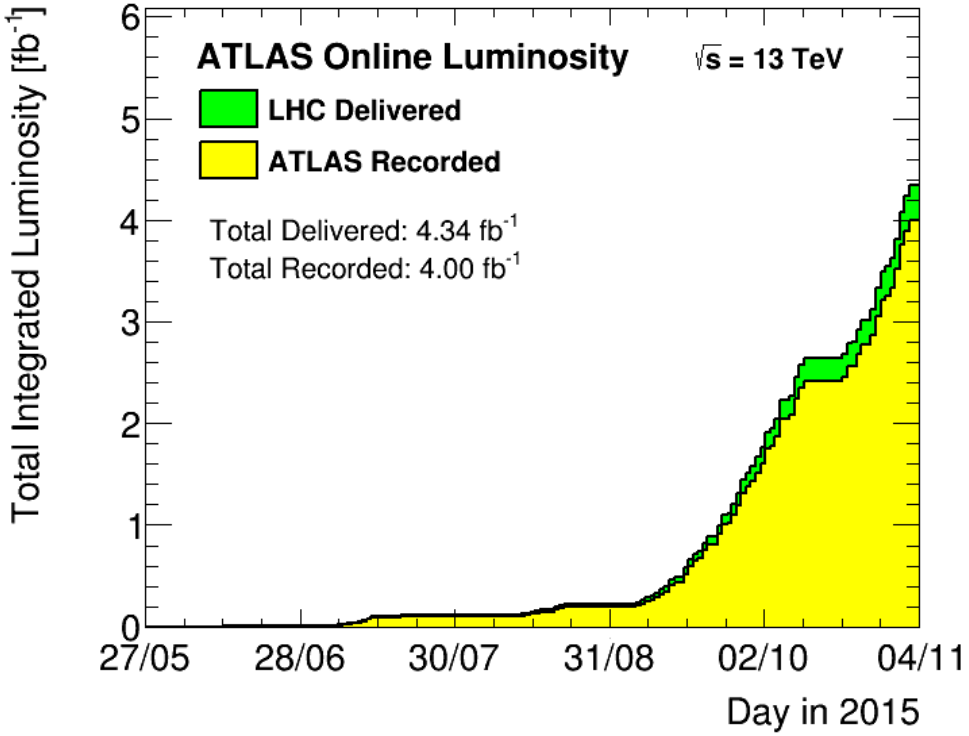
Spin correlation
Charge asymmetry
Color Flow

s-, t- and Wt-channel production, properties and searches in single top events

Data Samples

- LHC performed well



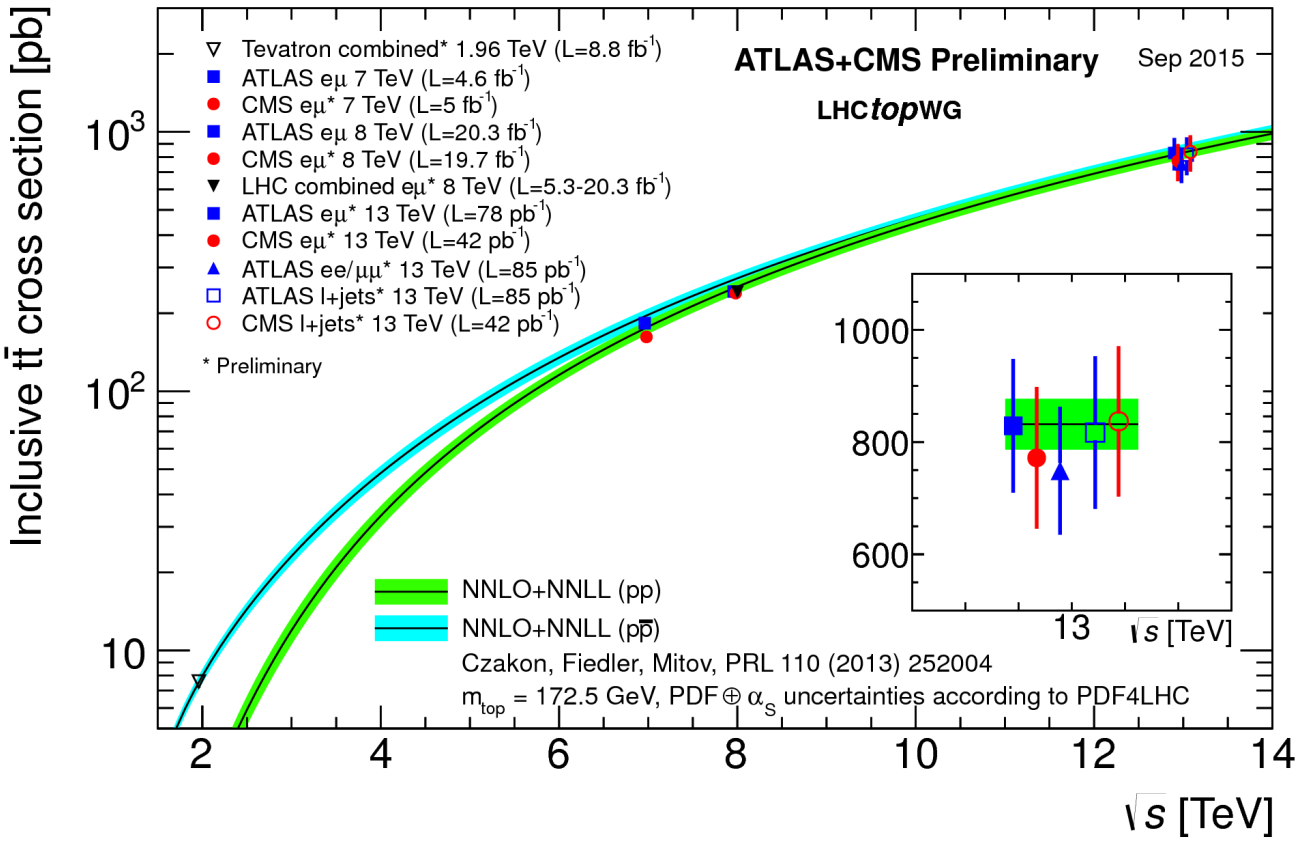


~5fb^{-1} of 7 TeV & ~20 fb^{-1} of 8 TeV on disk per experiment

2015: ~4fb^{-1} of 13 TeV data

Status

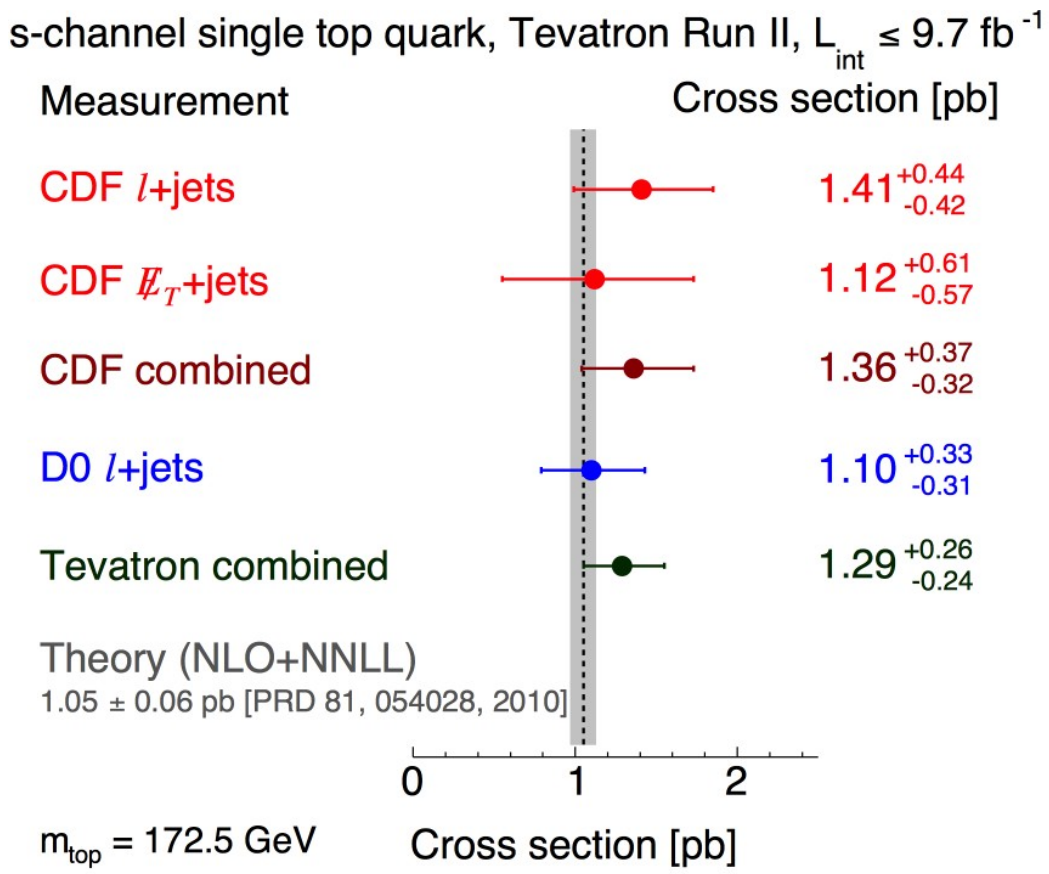
- Precision measurement of production cross section
  - At Tevatron and LHC
  - In single top and $t\bar{t}$ production

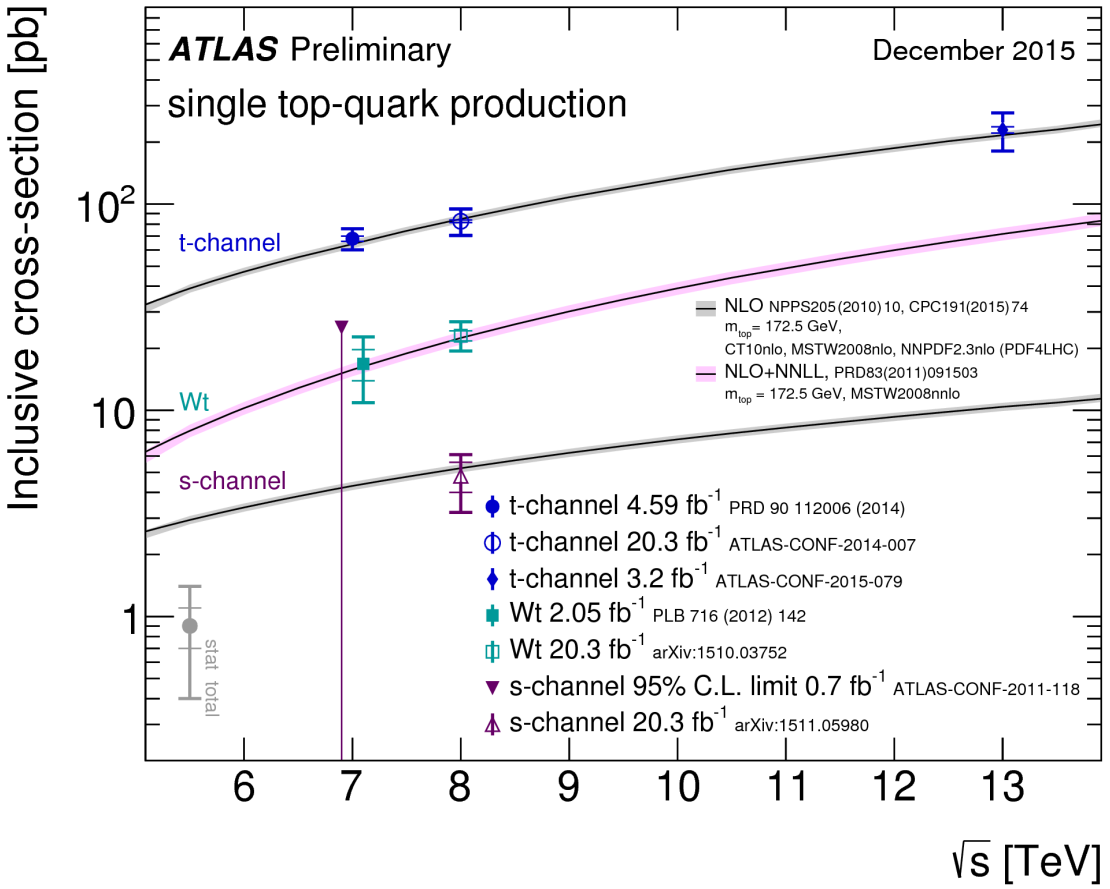


Experimental precision close to theory uncertainty!

Status

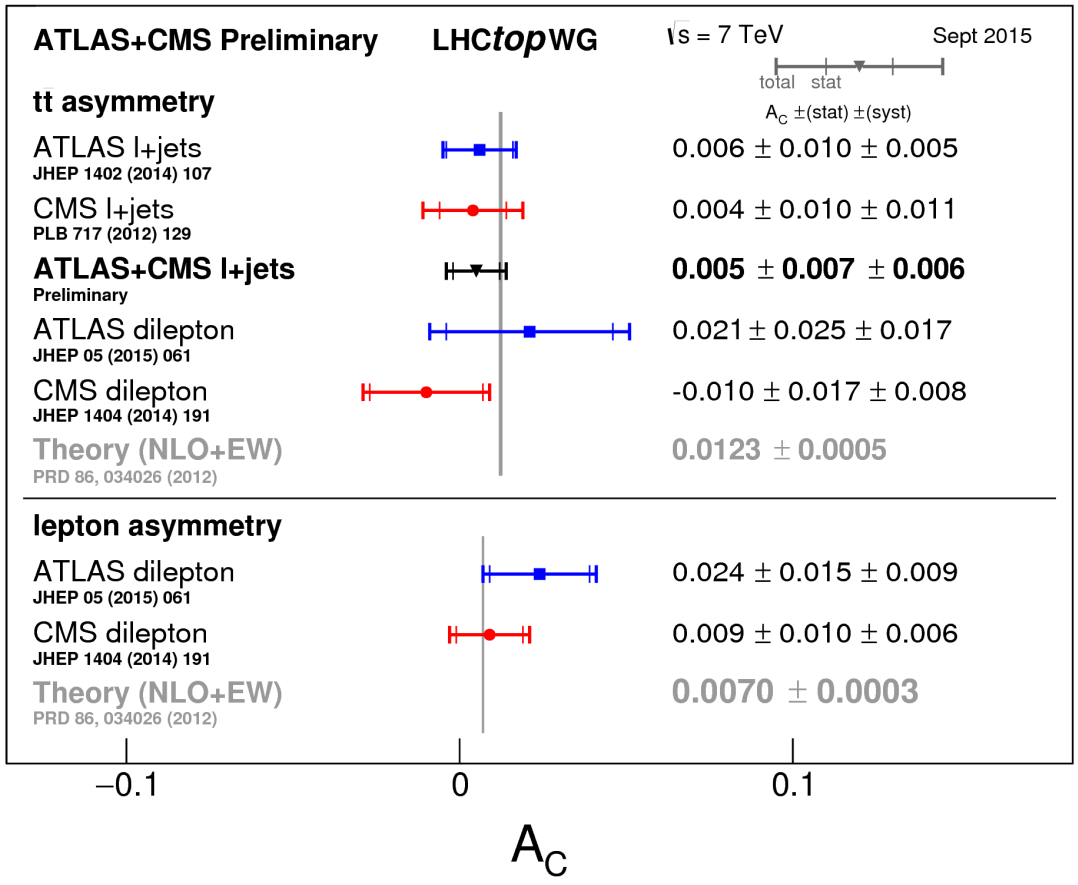
- Precision measurement of production
  - At Tevatron and LHC
  - In single top and $t\bar{t}$ production





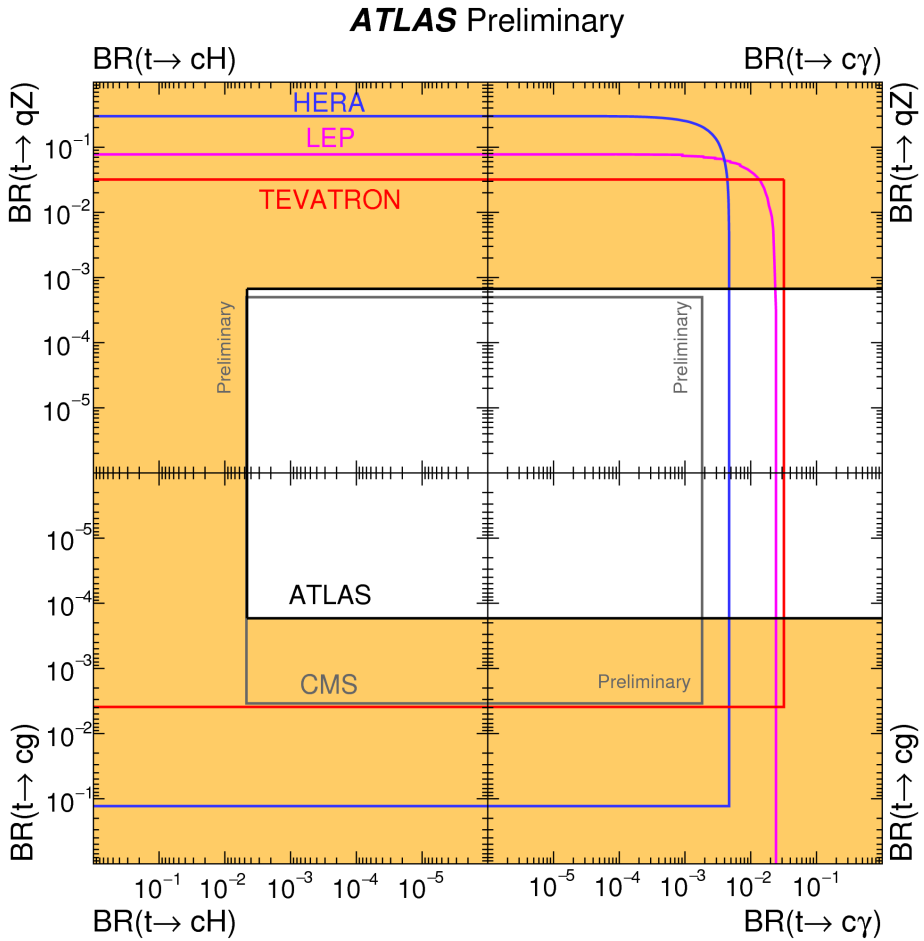
Status

- Precision measurement of production
  - At Tevatron and LHC
  - In single top and $t\bar{t}$ production
- Many properties measured precisely
  - From top quark mass to spin correlation, asymmetries, etc



Status

- Precision measurement of production
  - At Tevatron and LHC
  - In single top and $t\bar{t}$ production
- Many properties measured precisely
  - From top quark mass to spin correlation, asymmetries, etc
- Sensitive searches performed
  - For all kind of new physics



Let's look at

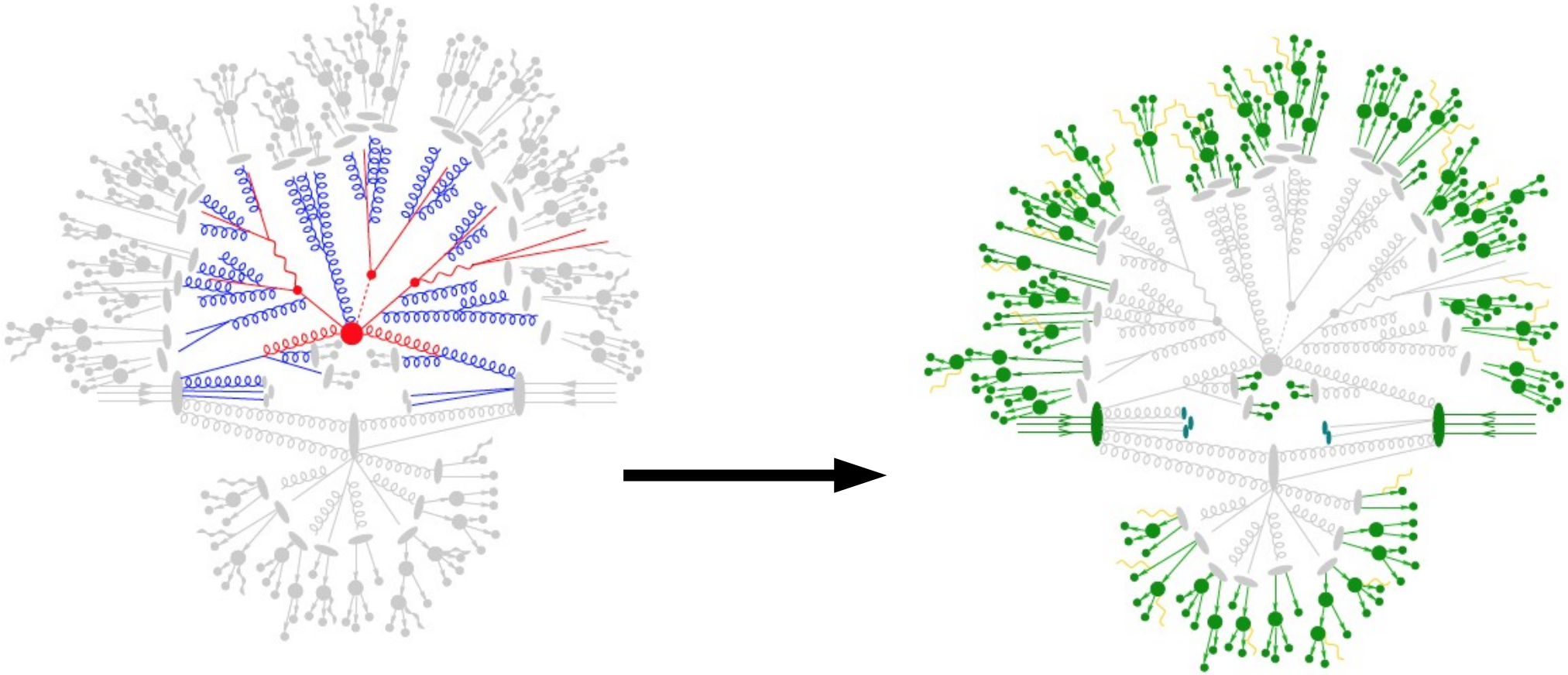
- 4 selected topics:
  - The runner-up: Differential distributions
    - High available statistics enables precision tests of kinematics
  - The evergreen: Top quark mass
    - Precise methods → high precision results
  - The star for Run II: $t\bar{t}H$
    - Important to measure coupling of heaviest elementary fermion to heaviest elementary boson!
  - The sandpit: top events as laboratory to test new tools.
    Example: colour flow and boosting algorithms
    - Increase sensitivity to new physics

Hot Topic 1: Differential Distributions

- Differential distributions:
  - Test of higher-order QCD calculations
  - Generic test of SM → test for new physics
- Also important to tune MC
  - Reduction of systematic uncertainties for many analyses
    - Due to large amount of data: many analyses are limited by systematic uncertainties!
- Main challenge:
  - Make distributions comparable to theory: correct detector effects
  - Distributions defined with "true" particles

Differential

- Also various differential and fiducial measurements now possible!
- General issue: parton versus particle level?

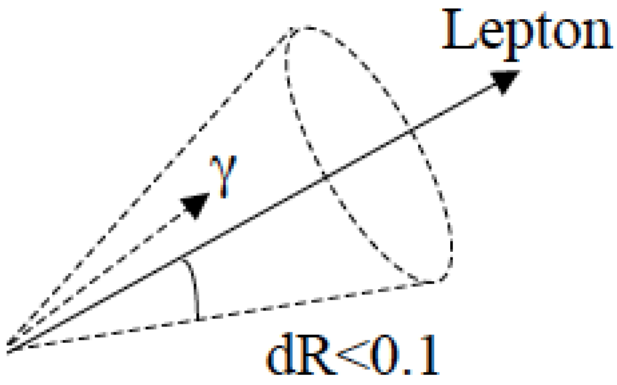


MC generator dependencies

Stable particles

Differential

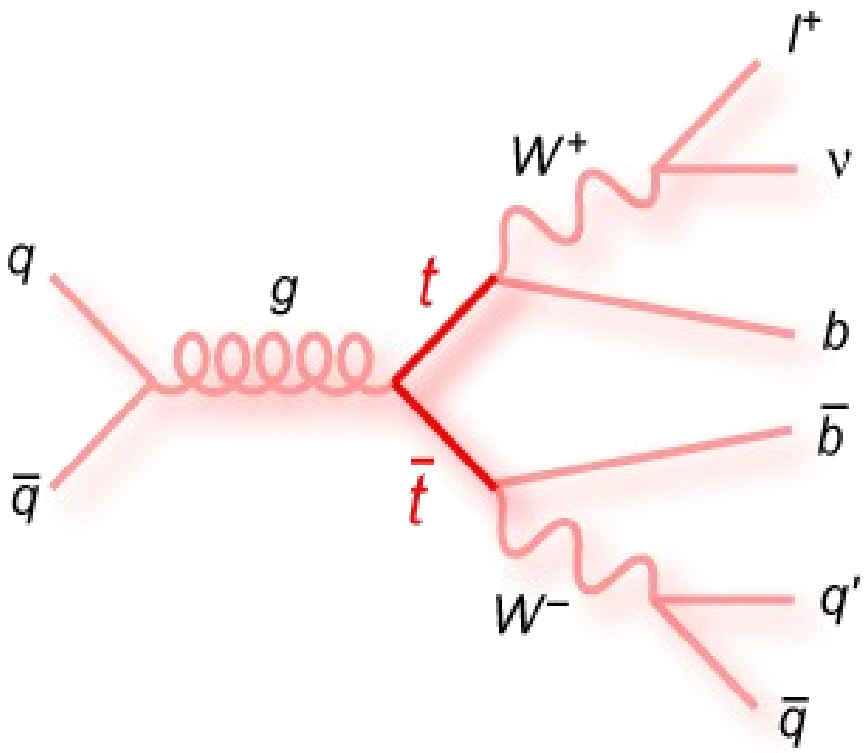
- Define "pseudo-tops" on particle level
  - In fiducial region
  - Easy to reproduce for theorists!



- Pseudo-top:
  - Use particles with mean lifetime > $3*10^{-11}$s
  - Leptons: use "dressed lepton":
    leptons are used together with photons in their vicinity
  - Jets: anti-kT with R=0.4 applied on stable particles (not leptons or neutrinos)
    - Presence of b-hadron with p_T>5GeV: jet is taken as a b-jet

Differential

- l+jets channel: selection



Exactly 1 lepton (e or μ)

e: p_T>25GeV, $|\eta|$<2.47 & !(1.37<$|\eta|$<1.52)

μ: p_T>25GeV, $|\eta|$<2.5

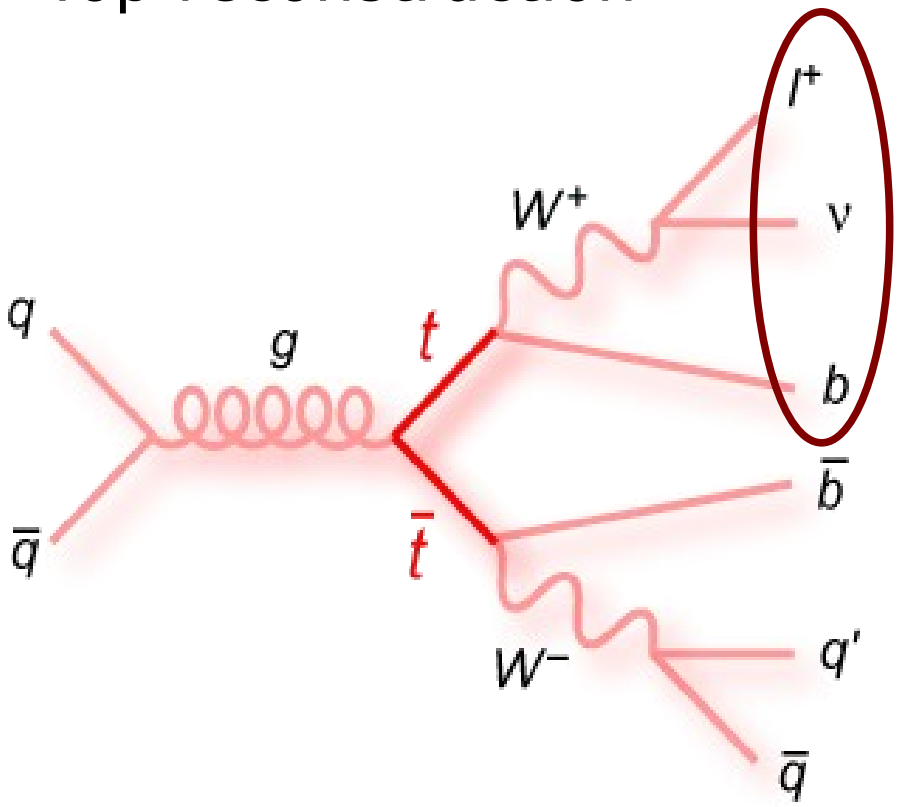
Missing p_T for neutrino ($\not{E}_T$): >30GeV

≥4 jets with p_T>25GeV; $|\eta|$<2.5

≥2 jets b-tagged

Differential

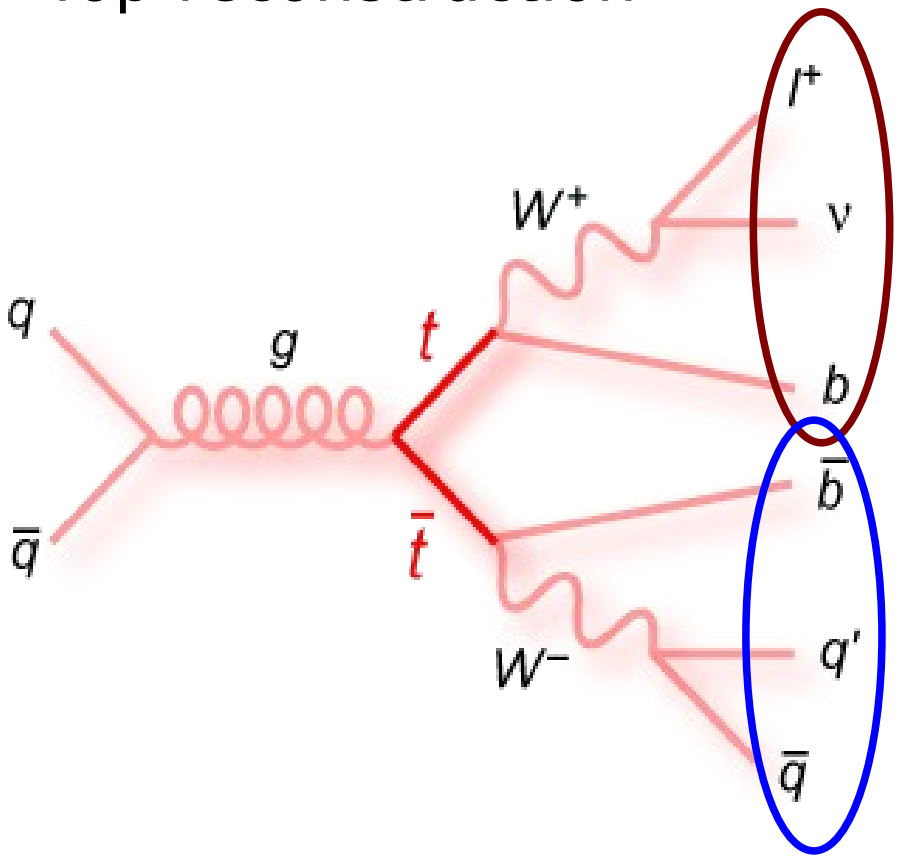
- Top reconstruction



Leptonic pseudo-top:
- construct leptonically decaying W from lepton and E_T^{miss}
- b-jet with smallest ΔR to lepton

Differential

- Top reconstruction

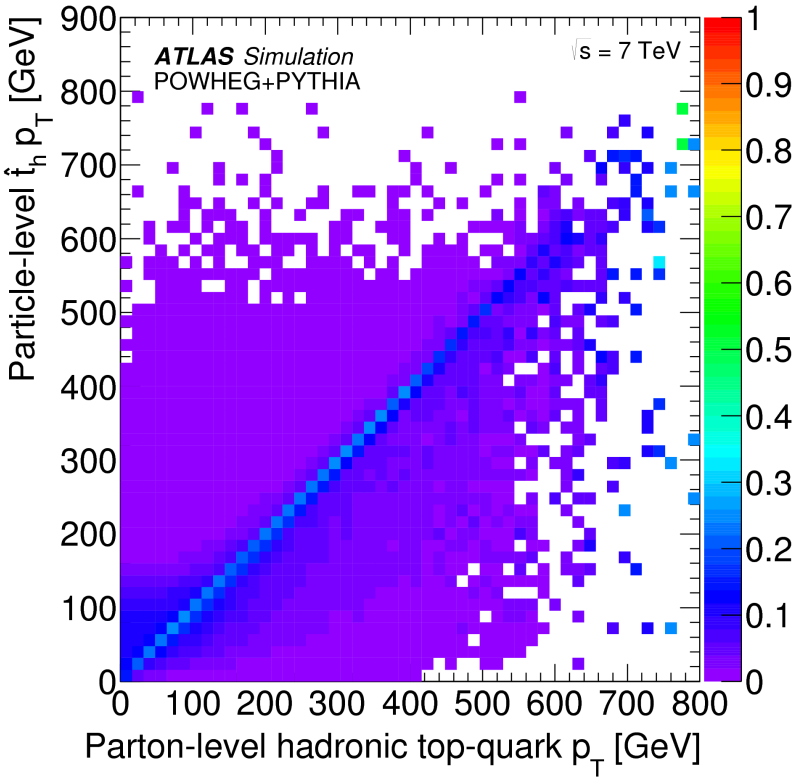


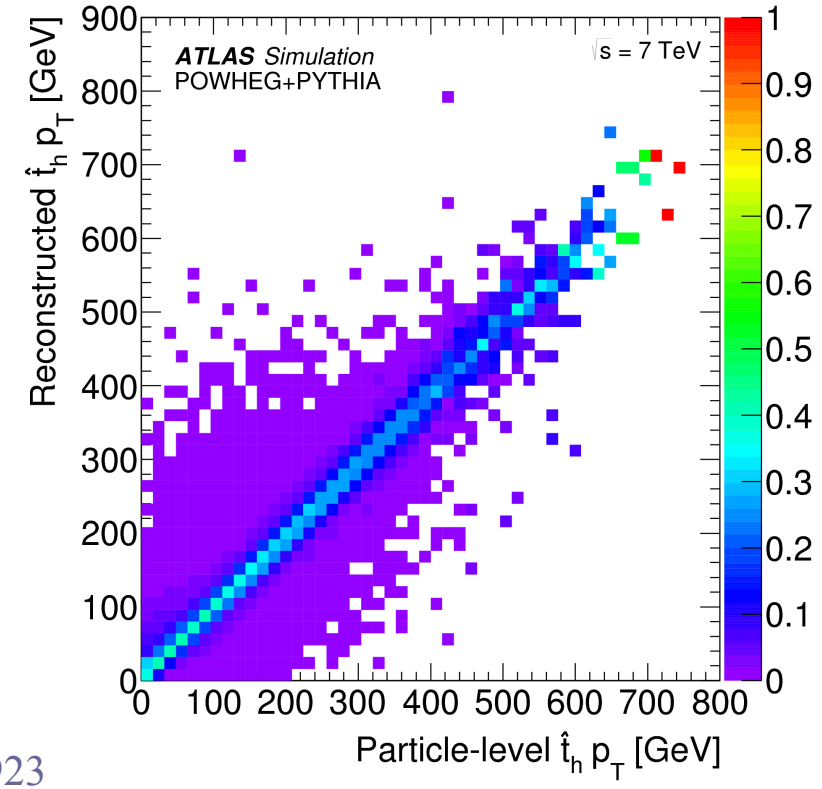
Leptonic pseudo-top:
- construct leptonically decaying W from lepton and E_T^{miss}
- b-jet with smallest ΔR to lepton

Hadronic pseudo-top:
- construct W from remaining two highest-p_T jets
- use remaining b-jet

Differential

- Reconstructed to particle level: minimize correction required!
- Unfolding via iterative Bayesian method



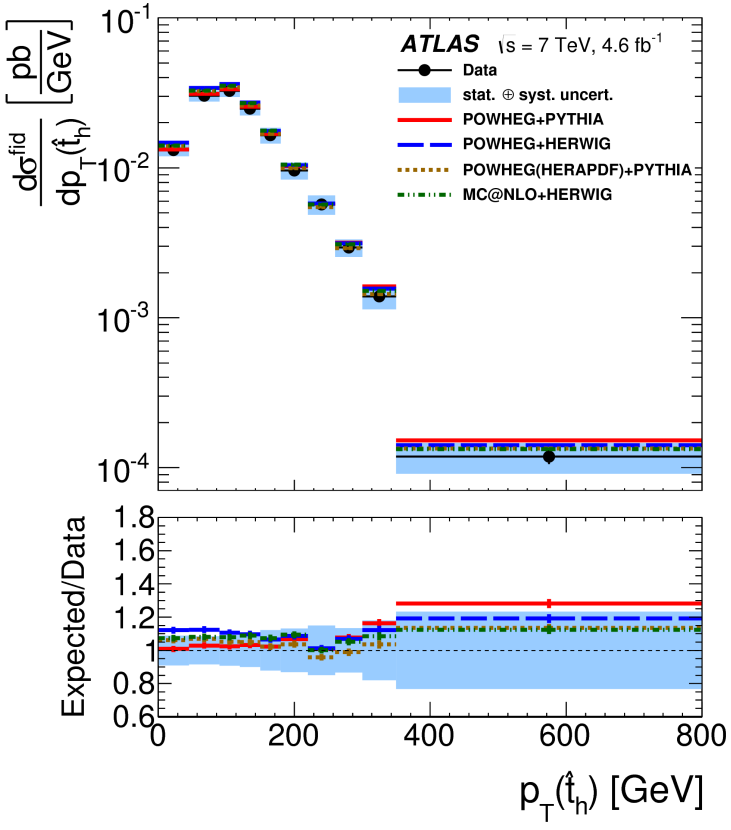


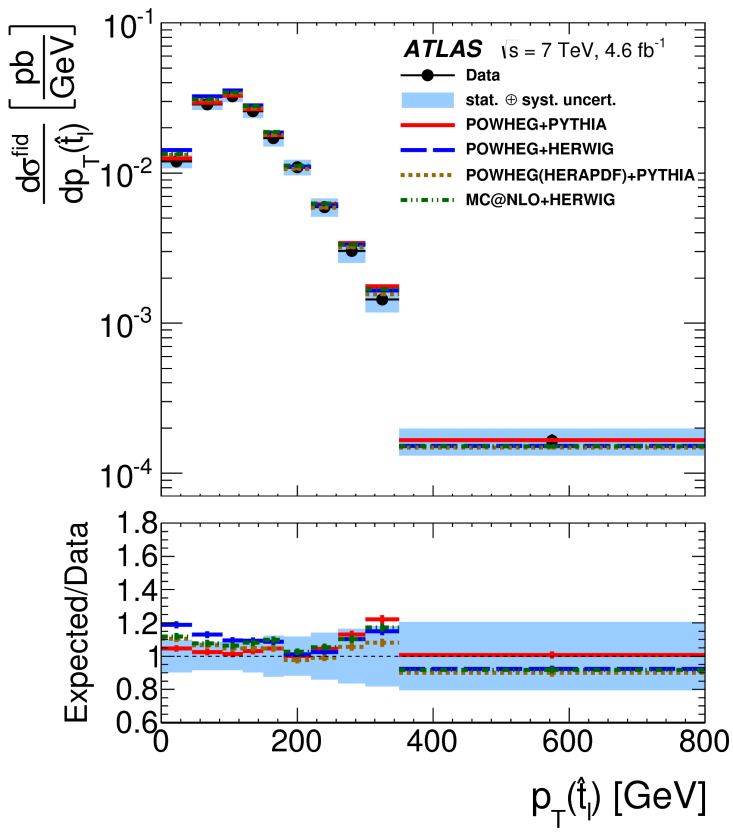
arxiv:1502.05923

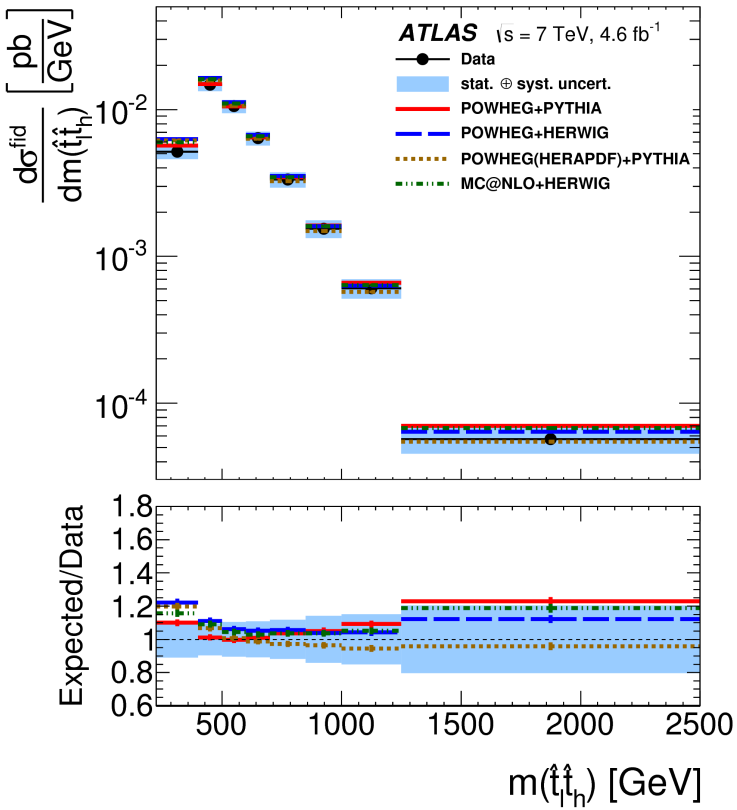
Differential

- Different distributions: show sensitivity to PDF, parton shower, etc.
  - Can be used for MC tuning and comparison to pQCD

arxiv:1502.05923

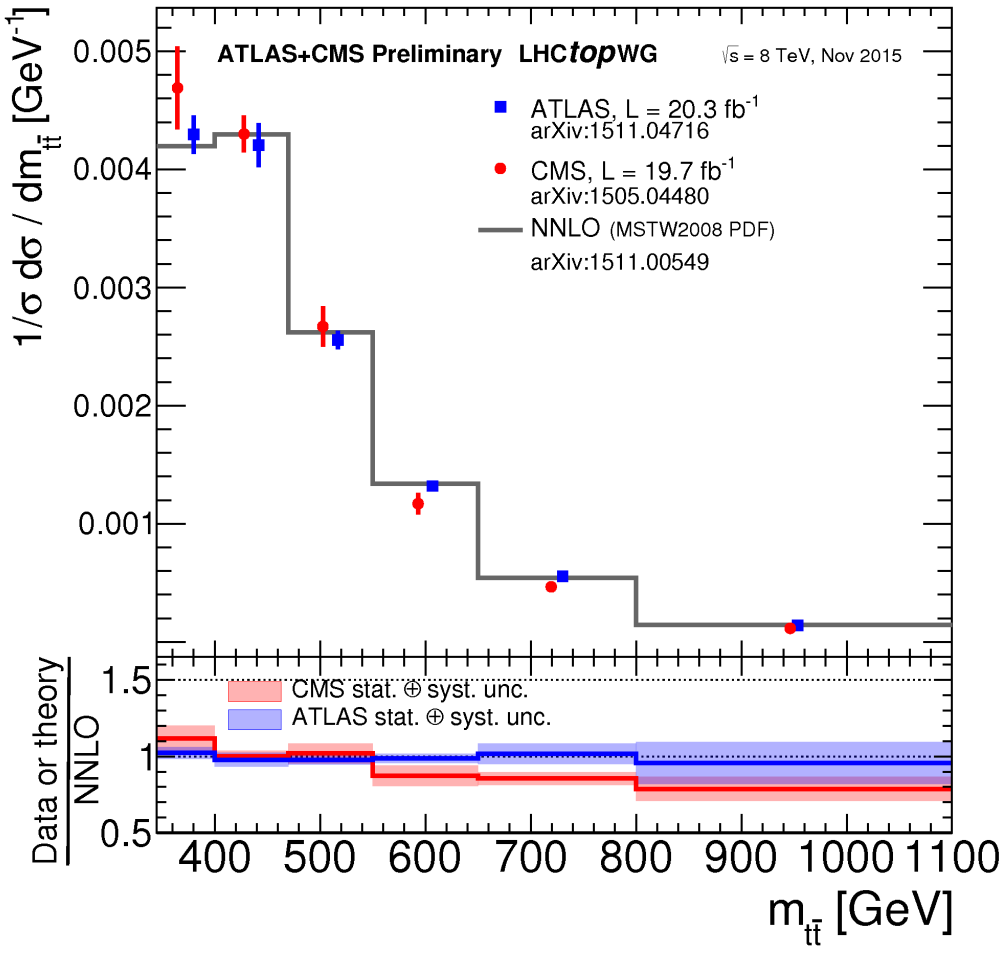


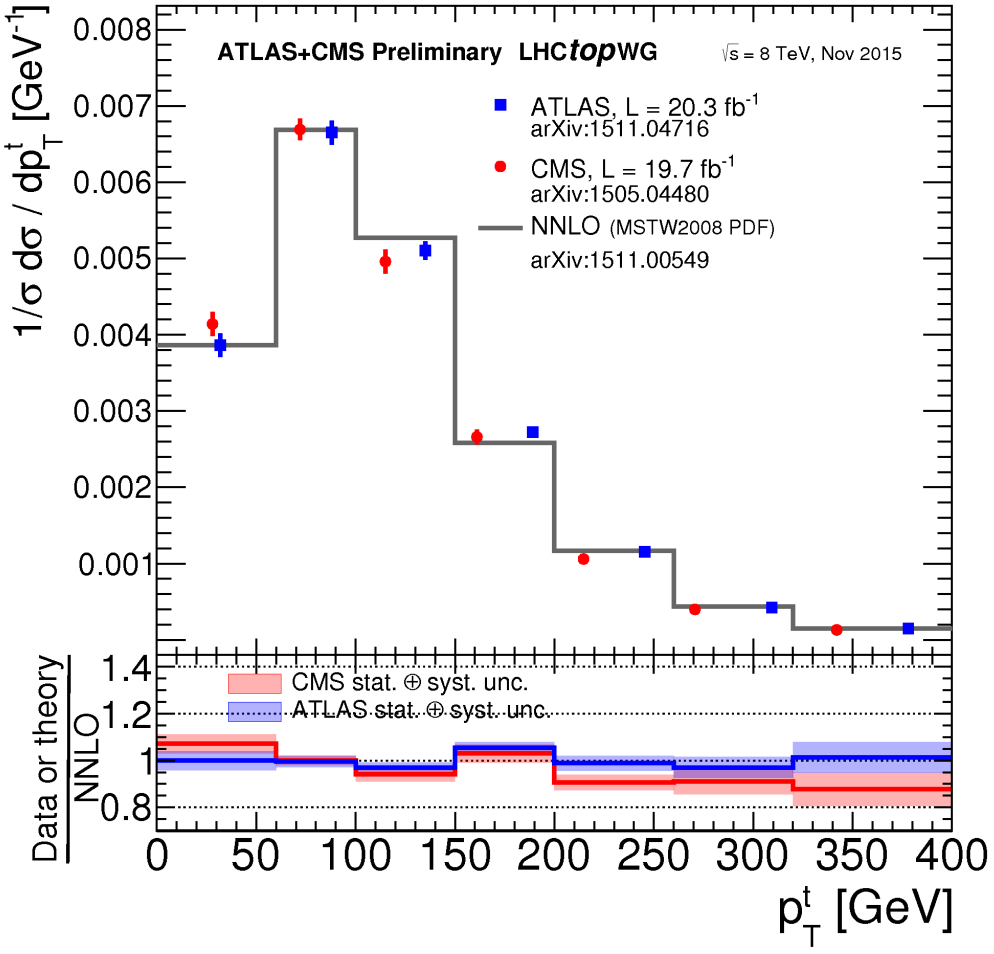




Differential

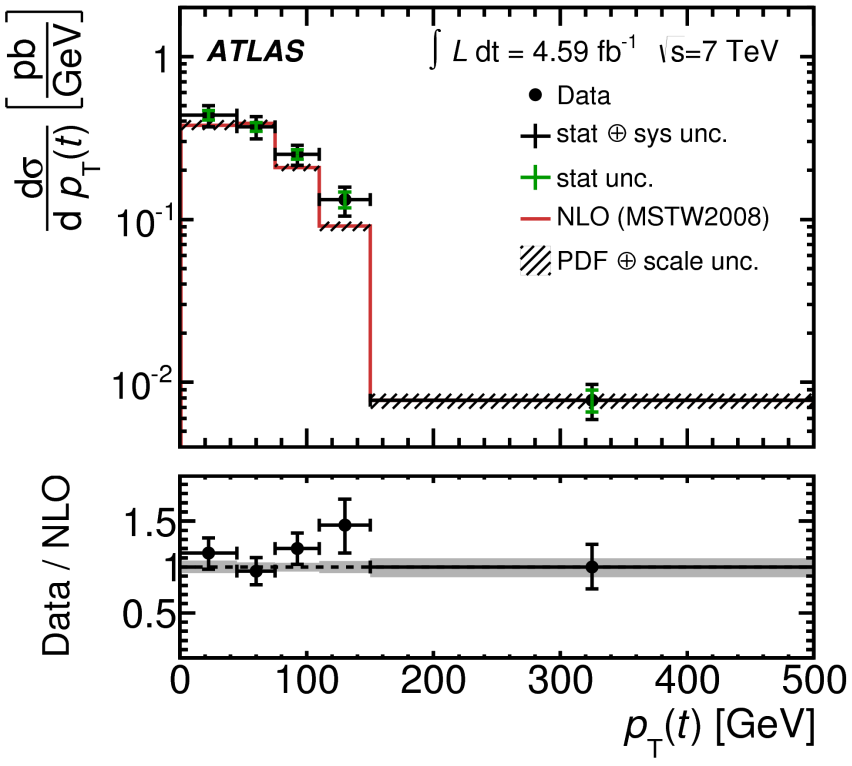
- Many distributions now available in NNLO!

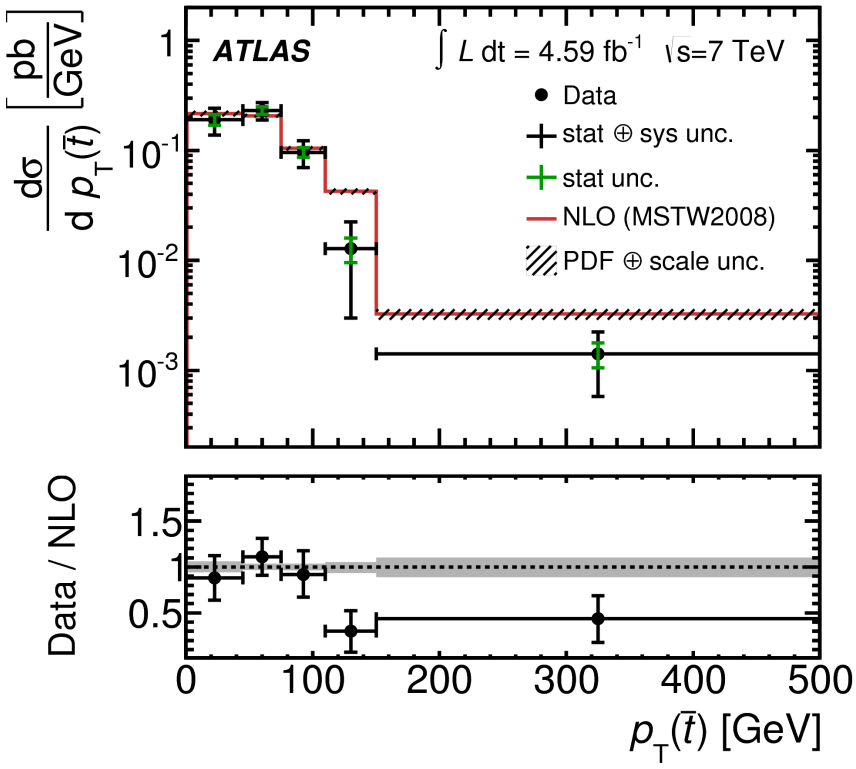




Differential Distributions in single top

- Now also possible to perform differential measurements in single top!





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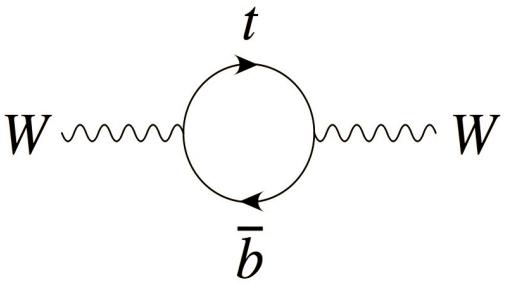
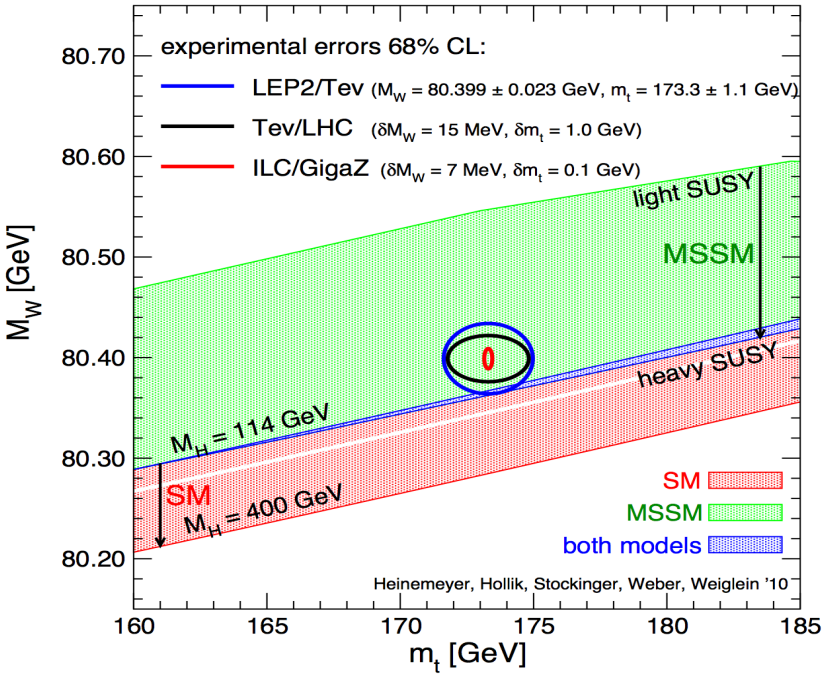
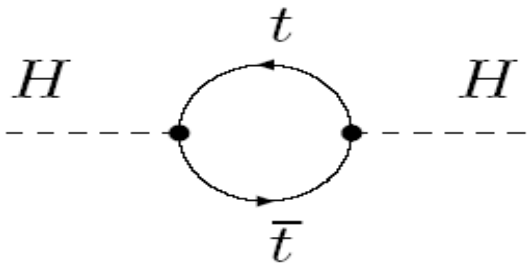
Hot Topic 2: Top Quark Mass

- Free parameter of the SM
- Together with W mass: puts constraint on Higgs mass → self-consistency check



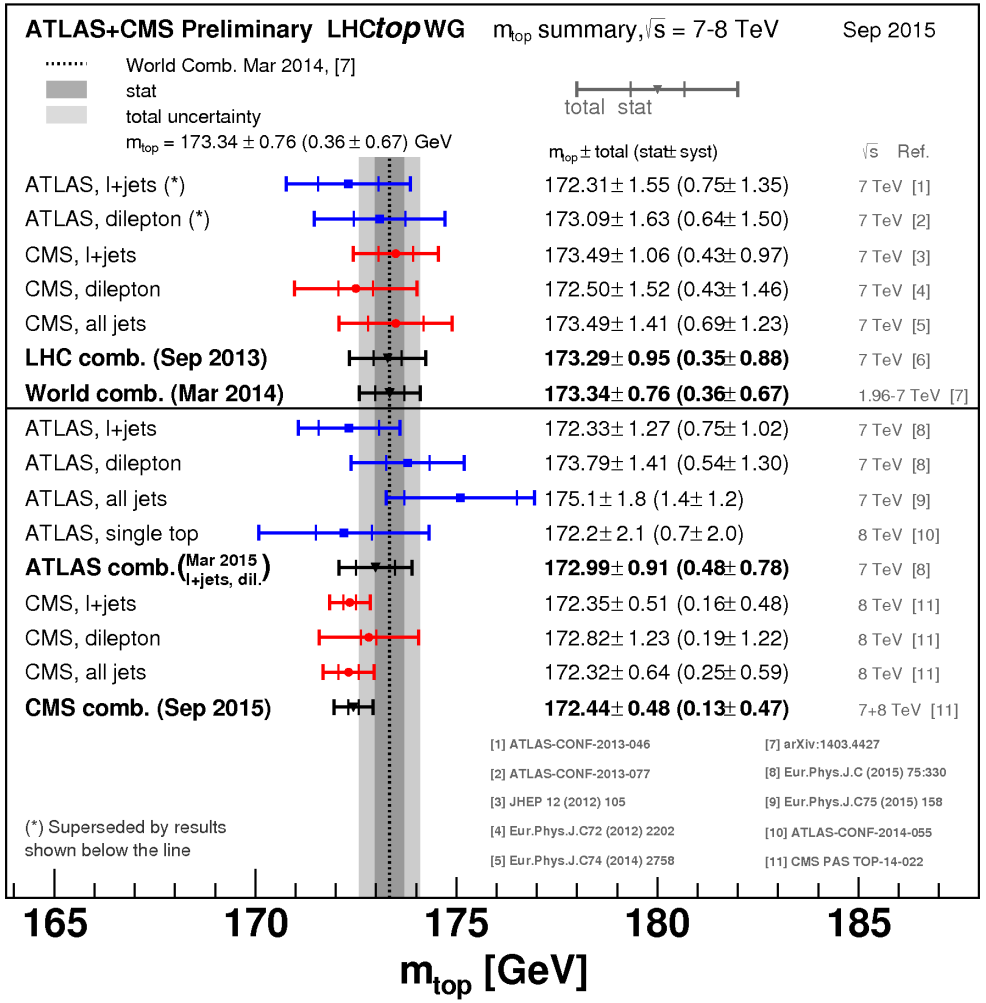




- Measurement done with several methods: Template method, ideogram, matrix element, etc.
  - Methods also used for other analyses, e. g. W helicity & spin correlations

Top Mass

- Precision results of top quark mass
  - With many different methods
- Results: limited by systematic uncertainties!

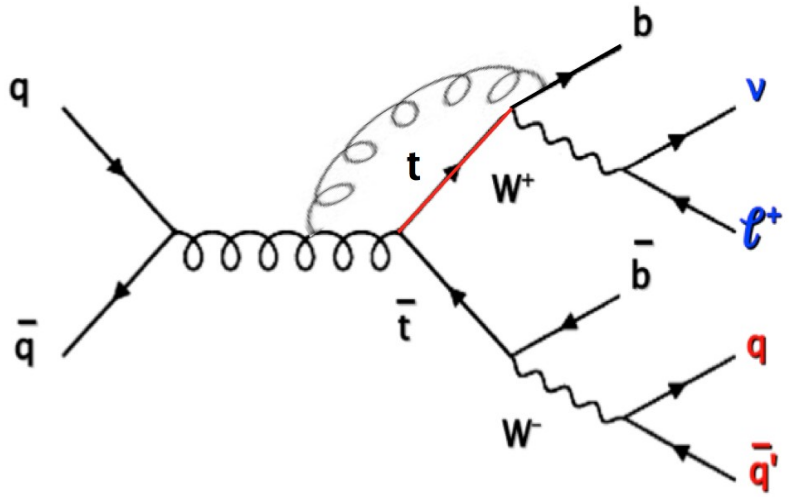


Top Mass

	$t\bar{t} \to$ lepton+jets			$t\bar{t} \to$ dilepton	Combination	
	$m_{\text{top}}^{\ell+\text{jets}}$ [GeV]	JSF	bJSF	$m_{\text{top}}^{\text{dil}}$ [GeV]	$m_{\text{top}}^{\text{comb}}$ [GeV]	ρ
Results	172.33	1.019	1.003	173.79	172.99	
Statistics	0.75	0.003	0.008	0.54	0.48	0
Stat. comp. (m_{top})	0.23	n/a	n/a	0.54		
Stat. comp. (JSF)	0.25	0.003	n/a	n/a		
Stat. comp. (bJSF)	0.67	0.000	0.008	n/a		
Method	0.11 ± 0.10	0.001	0.001	0.09 ± 0.07	0.07	0
Signal MC	0.22 ± 0.21	0.004	0.002	0.26 ± 0.16	0.24	+1.00
Hadronisation	0.18 ± 0.12	0.007	0.013	0.53 ± 0.09	0.34	+1.00
ISR/FSR	0.32 ± 0.06	0.017	0.007	0.47 ± 0.05	0.04	−1.00
Underlying event	0.15 ± 0.07	0.001	0.003	0.05 ± 0.05	0.06	−1.00
Colour reconnection	0.11 ± 0.07	0.001	0.002	0.14 ± 0.05	0.01	−1.00
PDF	0.25 ± 0.00	0.001	0.002	0.11 ± 0.00	0.17	+0.57
W/Z+jets norm	0.02 ± 0.00	0.000	0.000	0.01 ± 0.00	0.02	+1.00
W/Z+jets shape	0.29 ± 0.00	0.000	0.004	0.00 ± 0.00	0.16	0
NP/fake-lepton norm.	0.10 ± 0.00	0.000	0.001	0.04 ± 0.00	0.07	+1.00
NP/fake-lepton shape	0.05 ± 0.00	0.000	0.001	0.01 ± 0.00	0.03	+0.23
Jet energy scale	0.58 ± 0.11	0.018	0.009	0.75 ± 0.08	0.41	−0.23
b-Jet energy scale	0.06 ± 0.03	0.000	0.010	0.68 ± 0.02	0.34	+1.00
Jet resolution	0.22 ± 0.11	0.007	0.001	0.19 ± 0.04	0.03	−1.00
Jet efficiency	0.12 ± 0.00	0.000	0.002	0.07 ± 0.00	0.10	+1.00
Jet vertex fraction	0.01 ± 0.00	0.000	0.000	0.00 ± 0.00	0.00	−1.00
b-tagging	0.50 ± 0.00	0.001	0.007	0.07 ± 0.00	0.25	−0.77
$E_{\text{T}}^{\text{miss}}$	0.15 ± 0.04	0.000	0.001	0.04 ± 0.03	0.08	−0.15
Leptons	0.04 ± 0.00	0.001	0.001	0.13 ± 0.00	0.05	−0.34
Pile-up	0.02 ± 0.01	0.000	0.000	0.01 ± 0.00	0.01	0
Total	1.27 ± 0.33	0.027	0.024	1.41 ± 0.24	0.91	−0.07

Top Quark Mass and Issues

- Constantly discussed: what is it that we measure?
  - All direct mass measurements rely on MC for calibration
  - No clean definition of the top mass
    - e. g. contributions like this missing:

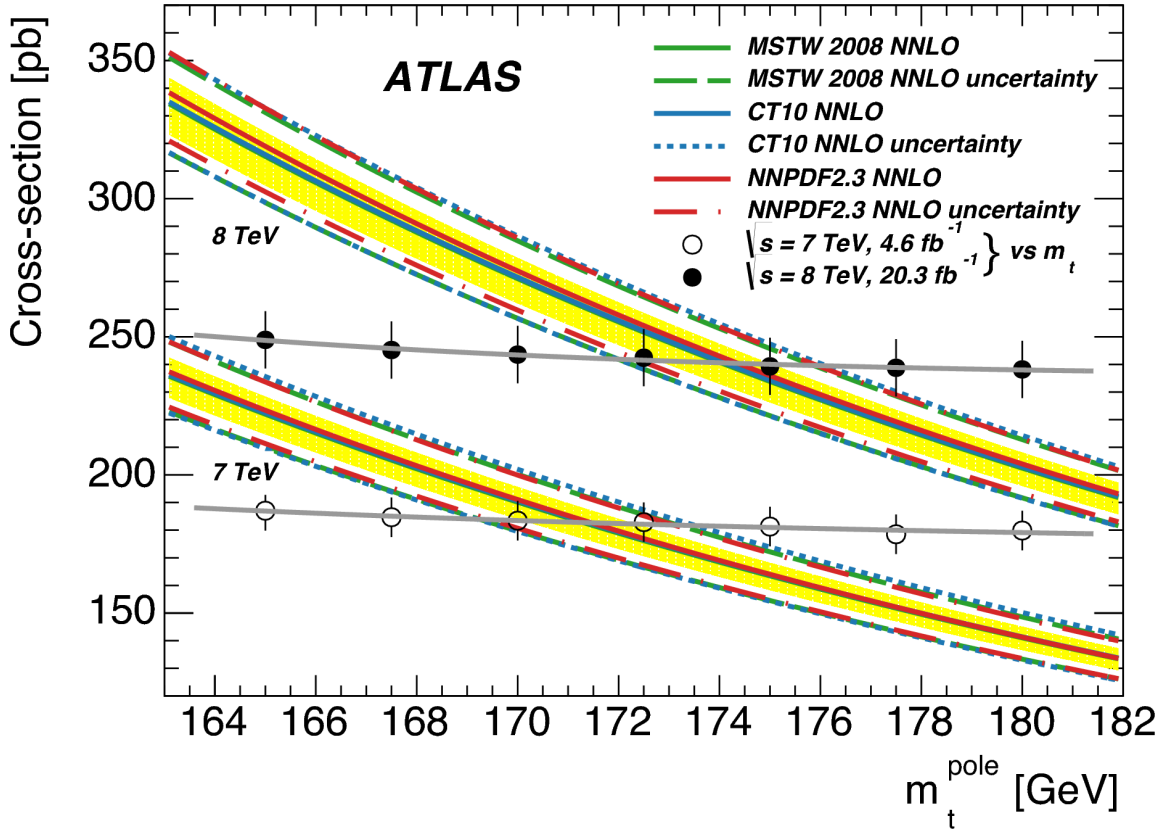


- Task mainly for theorists
- Experimentally: explore alternative methods

Top Quark Mass: Be aware

- Alternative method: Extract m_t from cross section measurement
  - Assuming pole or $\overline{\text{MS}}$ mass

- Unambiguous extraction of top quark mass!
  - Contra: uncertainty quite large compared to direct methods



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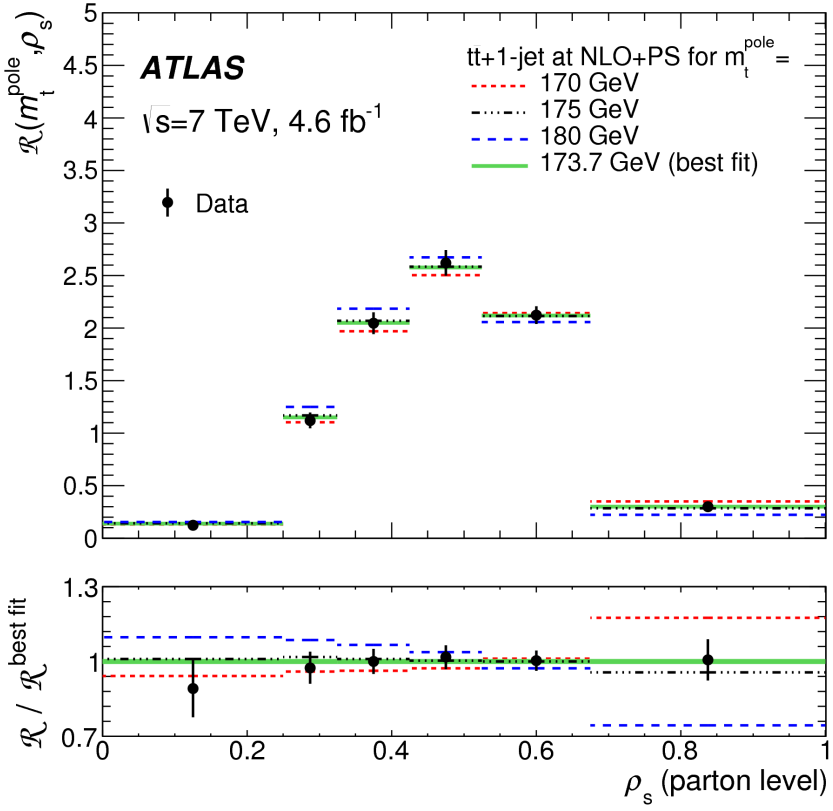
Mass from $t\bar{t}$+jets

- Extract mass from distribution in $t\bar{t}$+jets events
  - Gluon radiation depends on mass of quark
  - Compare unfolded distribution to calculation → allows to uniquely define mass scheme

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

$$\rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}j}}},$$



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

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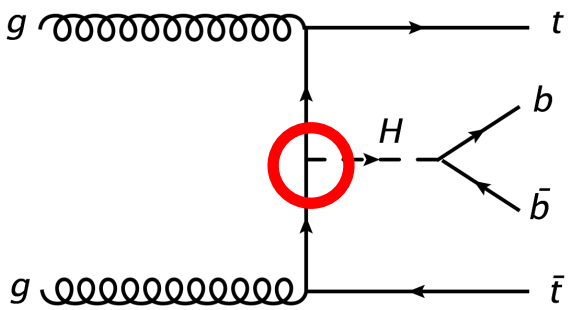
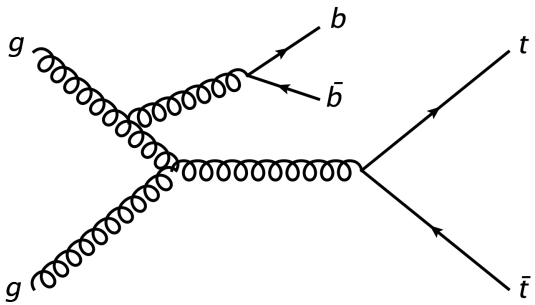
Hot Topic 3: Top-Higgs Yukawa Coupling ($t\bar{t}H$)

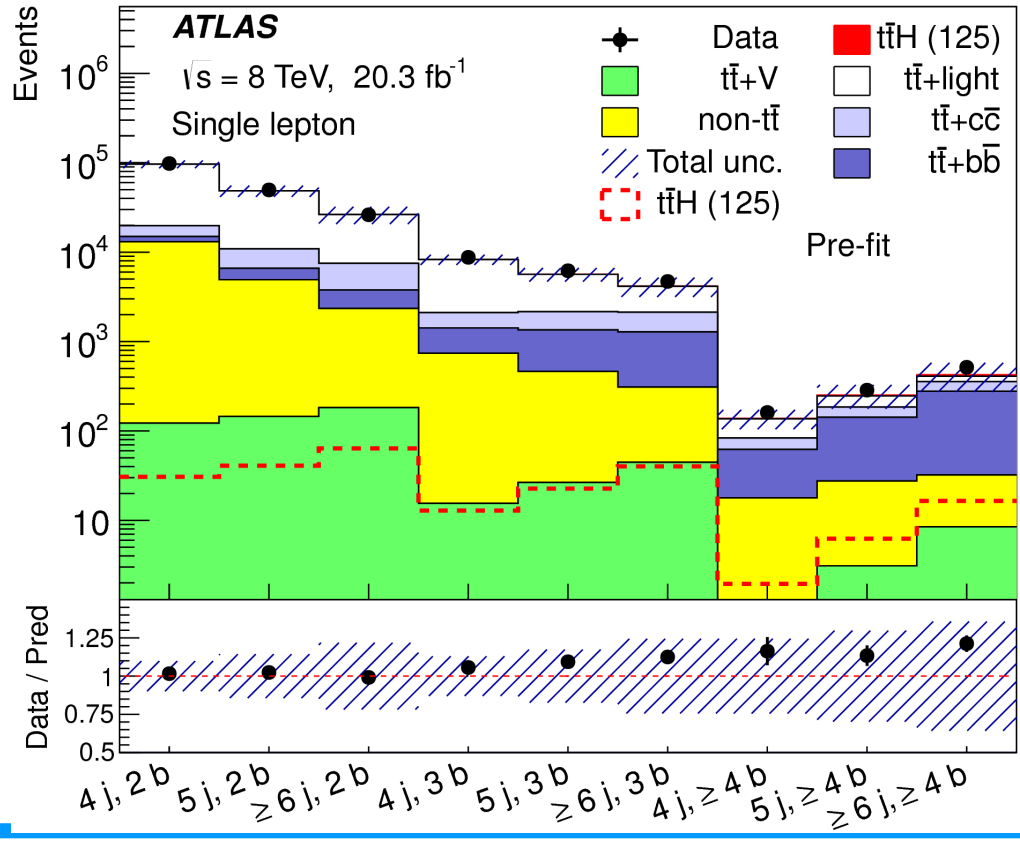
- Motivation: Measure top-Higgs Yukawa coupling
  - Only channel for direct measurement
- Very challenging analyses
  - Large backgrounds, small signal

  $\rightarrow$ separate in many channels; multivariate techniques



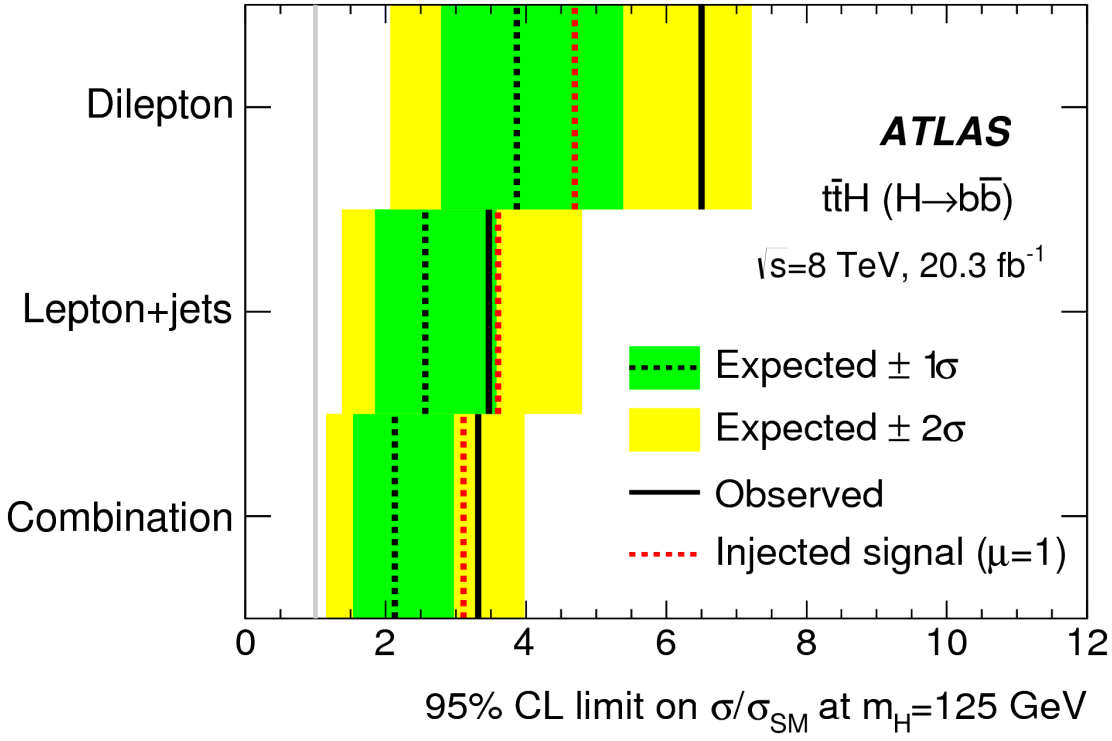


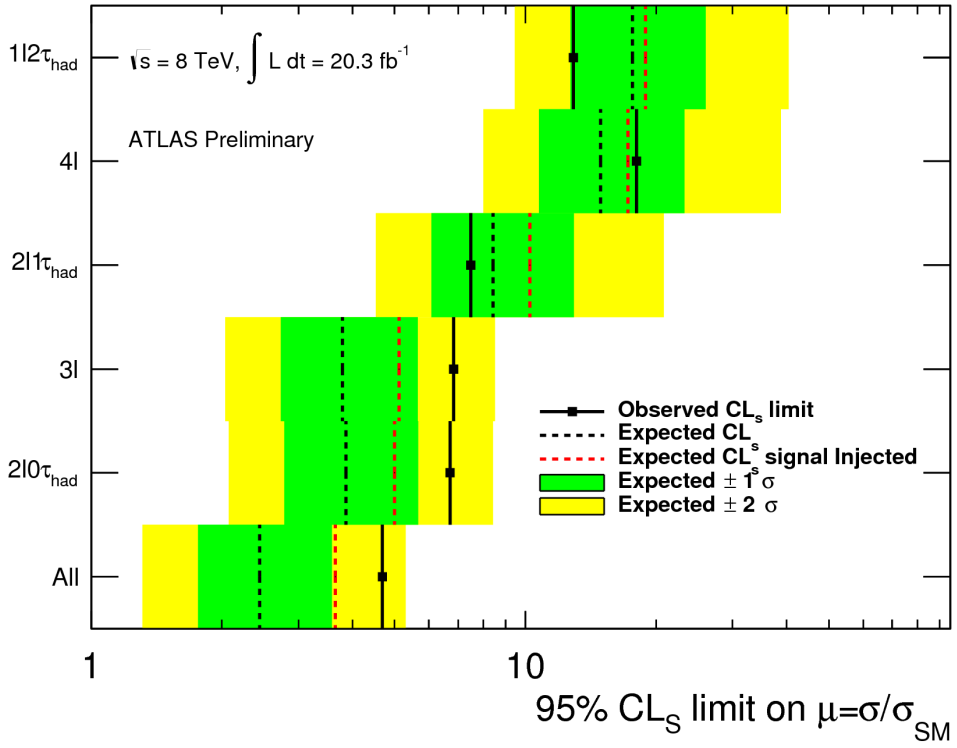
arXiv:1503.05066



$t\bar{t}H$

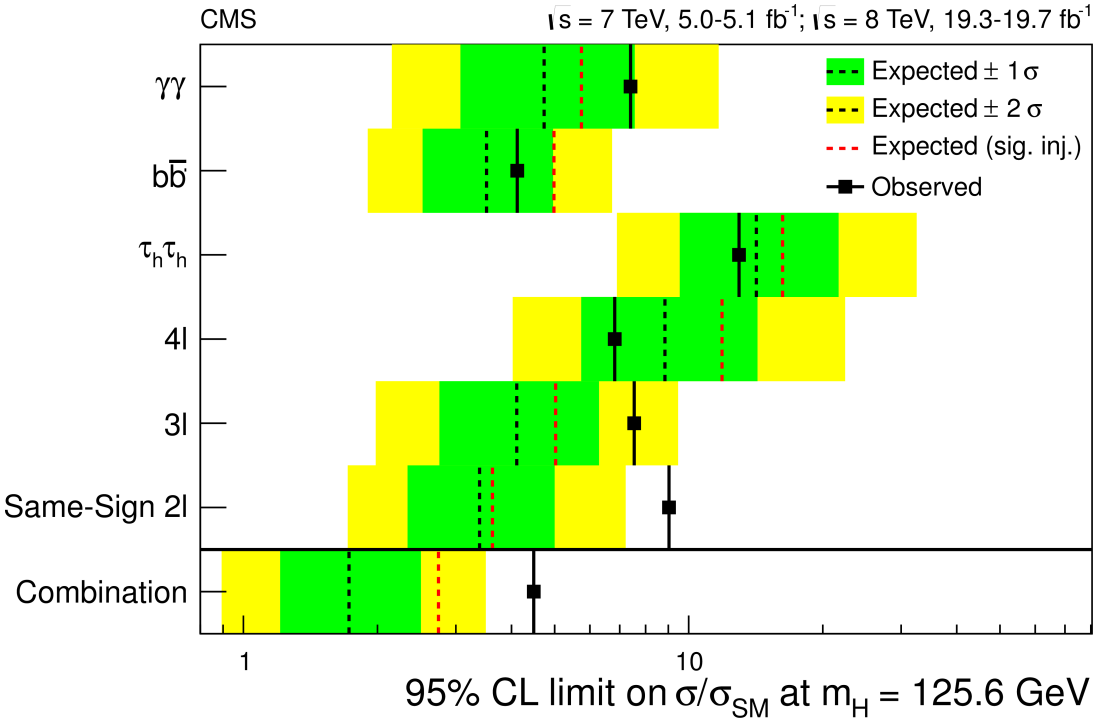
- Limits several times SM
  - Observation in new LHC run → after ~2 years

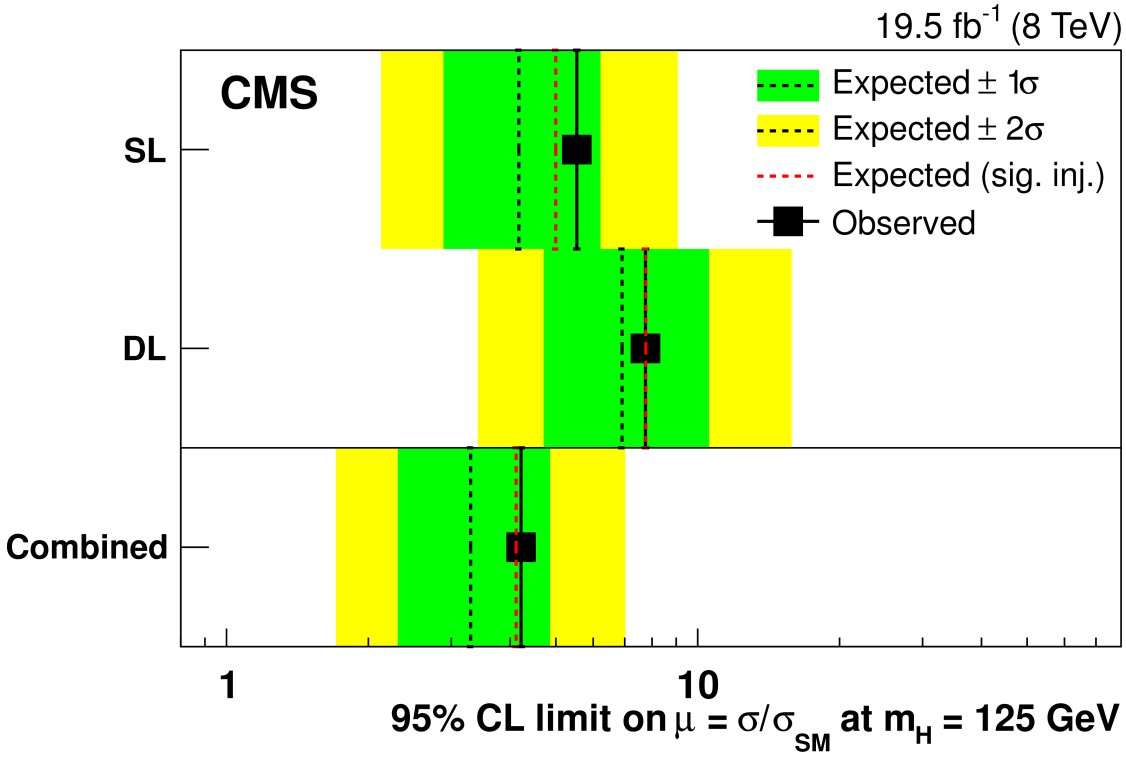




ATLAS-CONF-2015-006

- And the limits for CMS

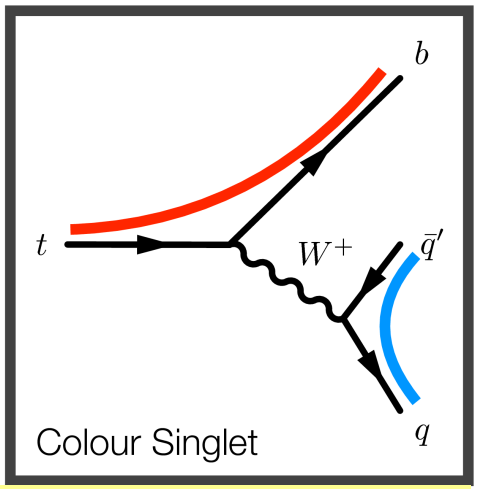


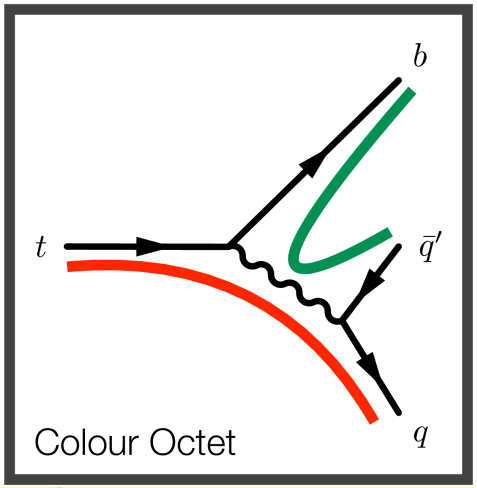


Hot Topic 4.1: Colour Flow

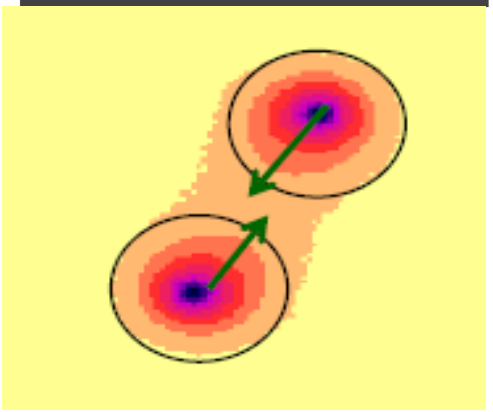
- Top events as laboratory to test new tools
- Jets carry color, and are thus color connected to each other
  - Pairing of connection depends on nature of decaying particles

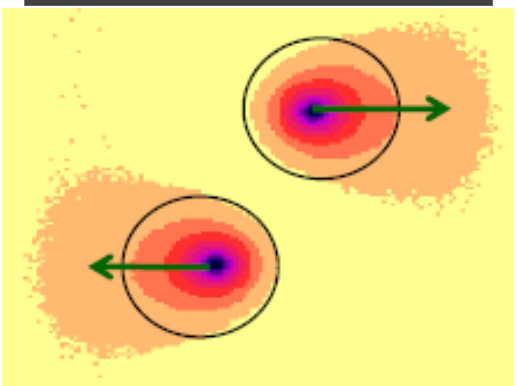
Gallichio, Schwartz,
PRL 105, 022001 (2010)





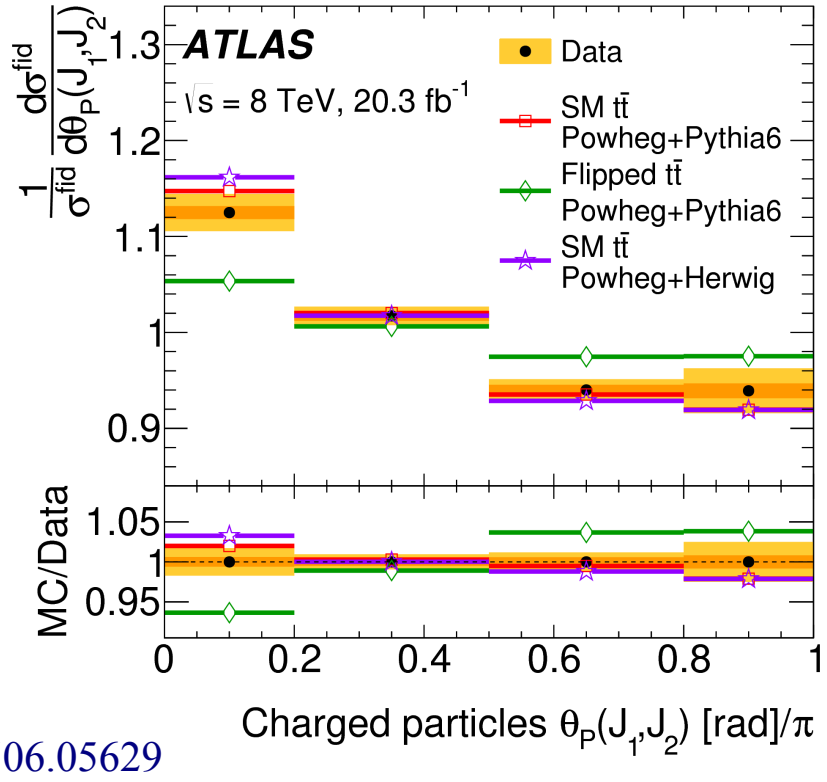
Jet pull: vectorial sum of components within each jet
→ jet pull angle: angle wrt. connection line of pair of jets





Colour Flow

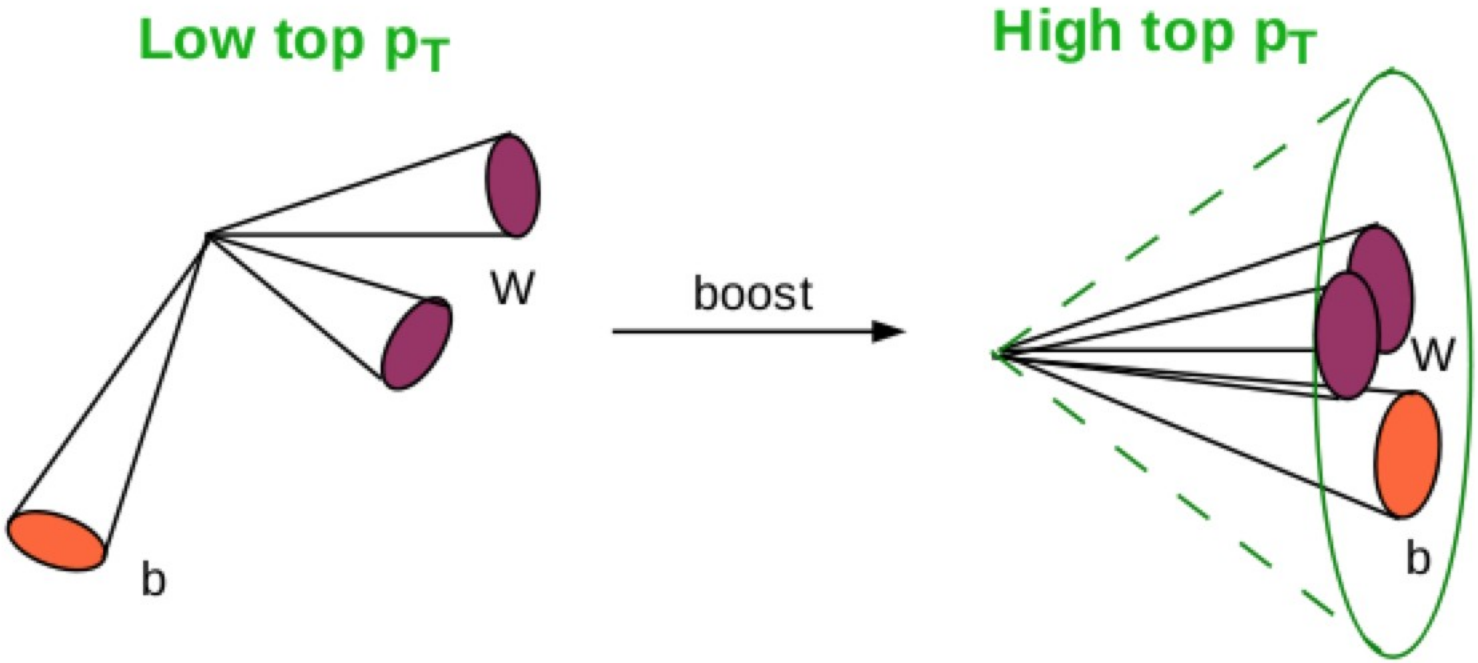
- Top events as laboratory to test new tools
- Jets carry color, and are thus color connected to each other
  - Pairing of connection depends on nature of decaying particles
- Analysis performed in l+jets events with >1 b-tagged jets
  - Take non-tagged jets for jet pull angle calculation
  - Correct to particle level
    - Done for all particles or charged particles
  - Colour octet model disfavoured by >3σ S.D.
- Jet pull: potential variable for NP searches



arXiv:1506.05629

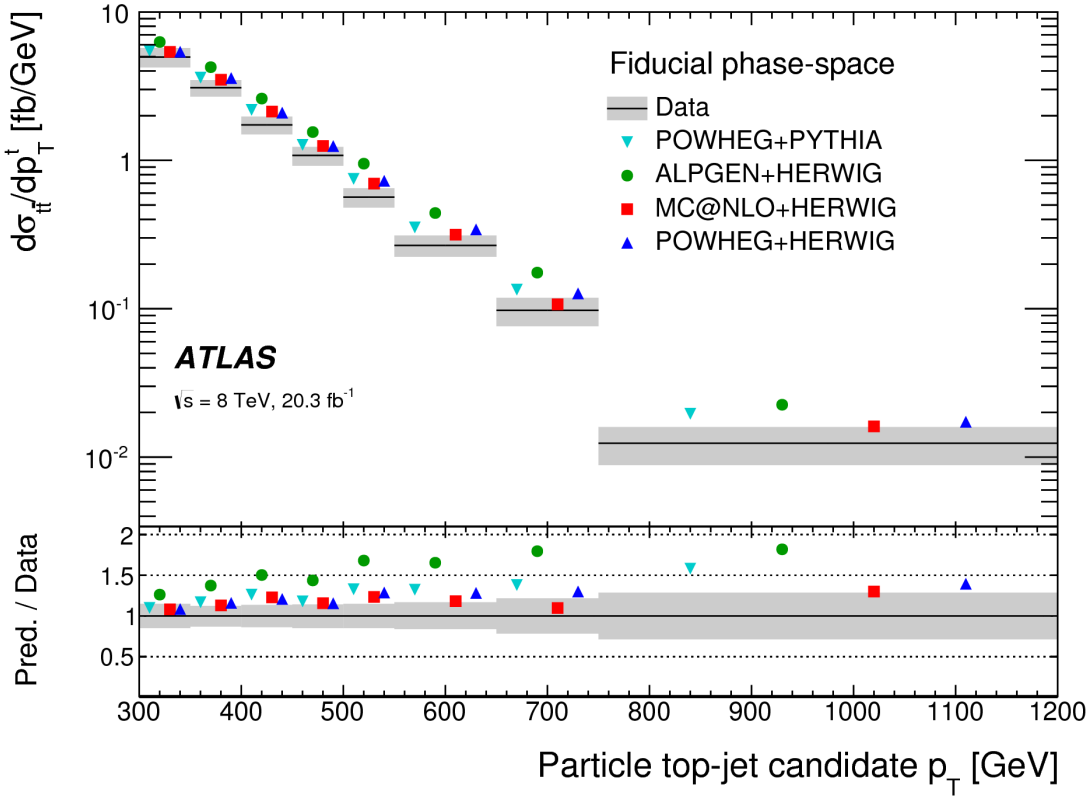
Hot Topic 4.2: Boosting algorithms

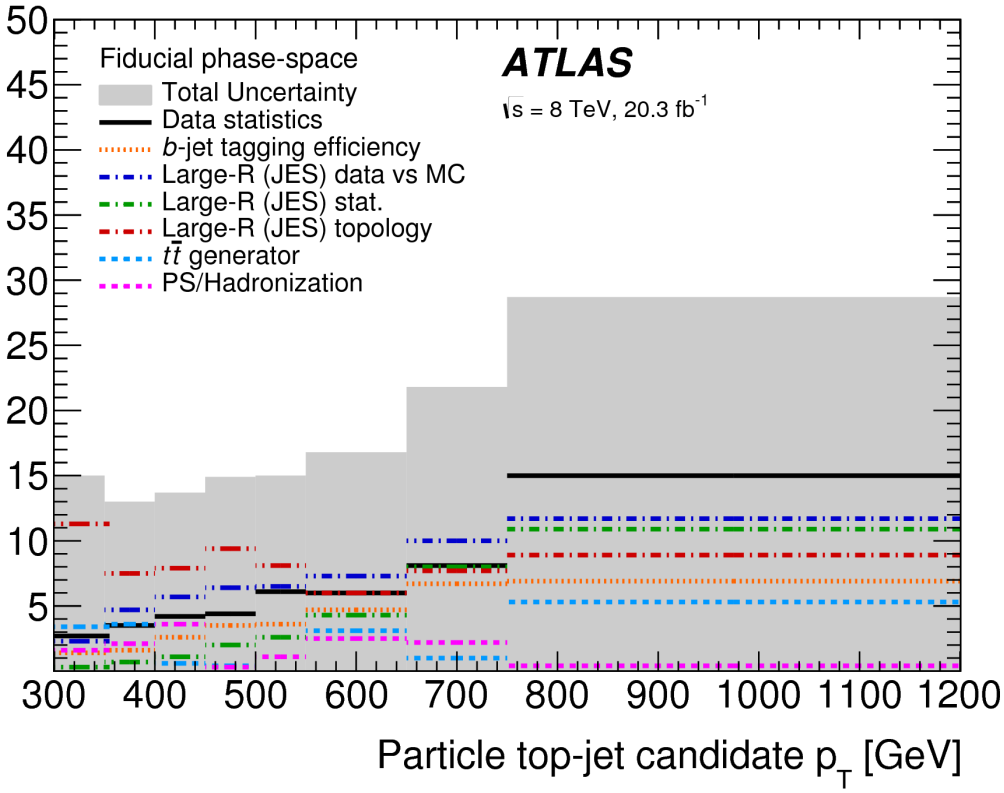
- Boosting algorithms important
  - Higher collision energy → more events can be boosted
  - Production of heavy particles → decay products can be boosted



Boosting

- Still large uncertainties
  → need to reduce e. g. energy scale uncertainty for large R jets

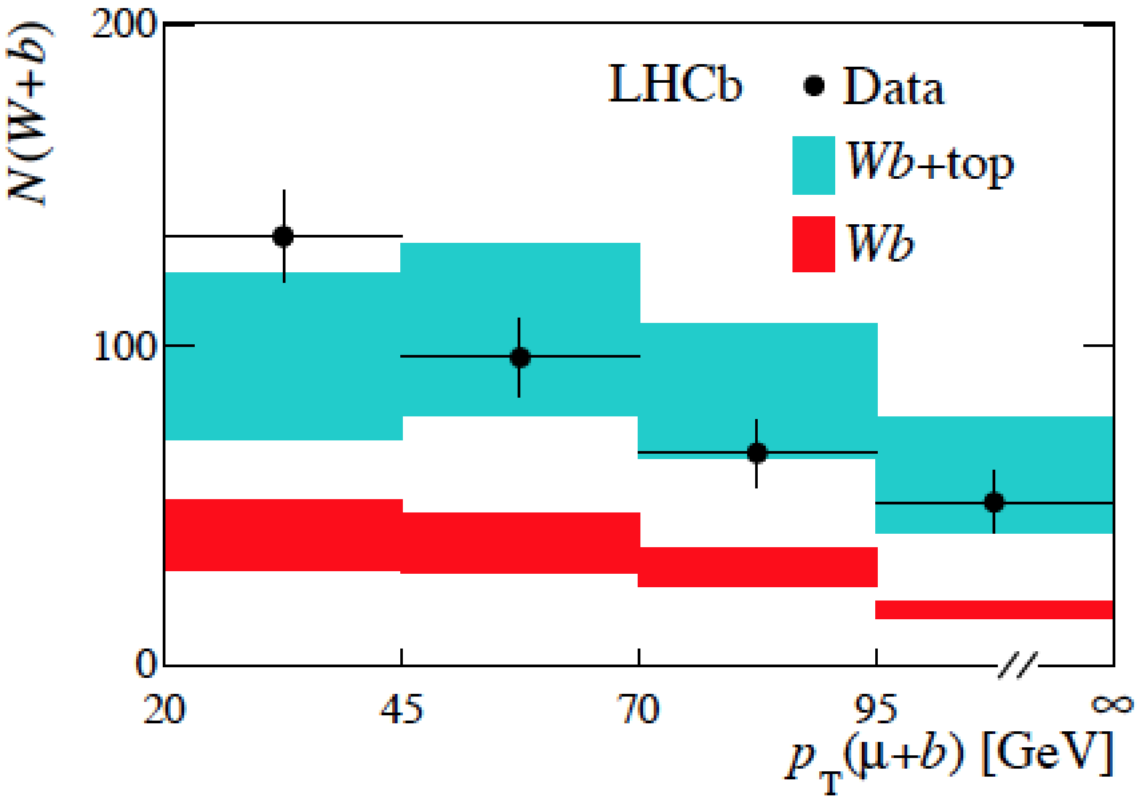


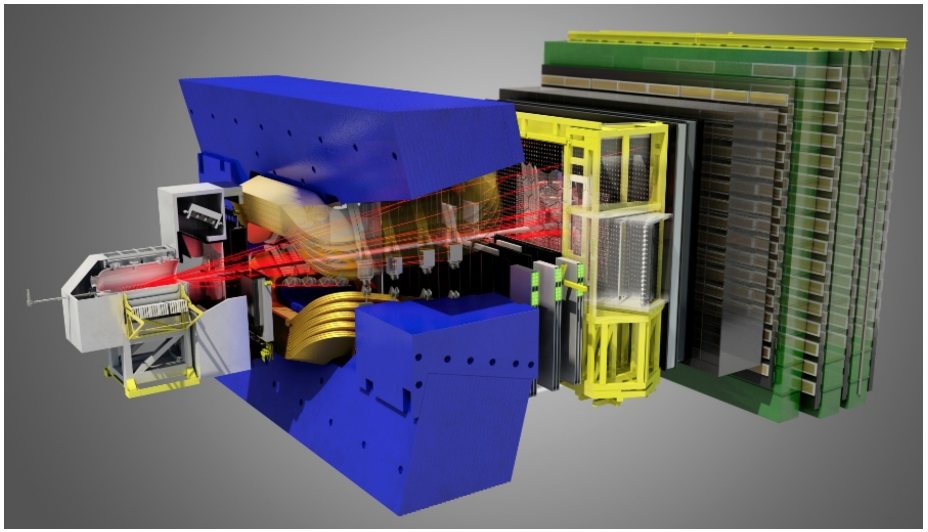


arXiv:1510.03818

Another Run I Top result!

- Top observation at LHCb!
  → Run II: statistics!



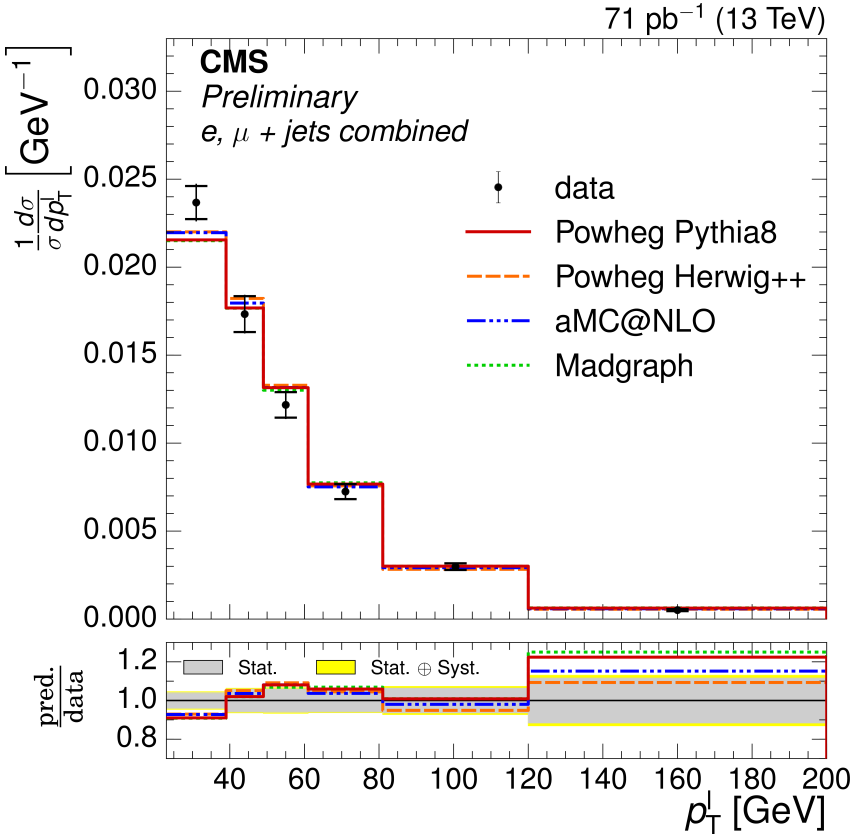


arXiv:1506.00903

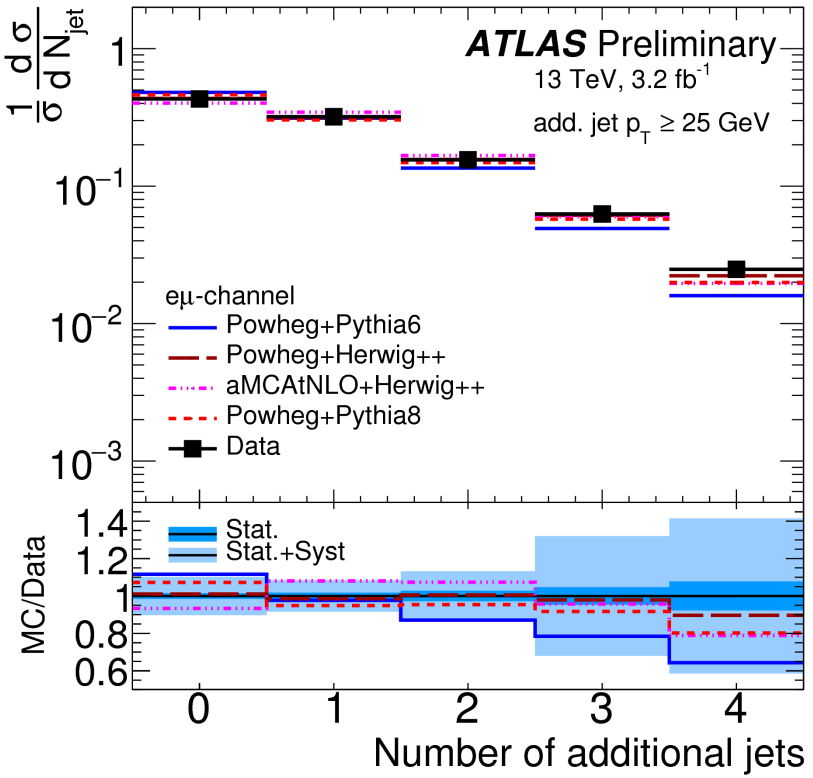
Run II

Differential Cross Section in $t\bar{t}$

- Already now inclusive and differential cross sections public!



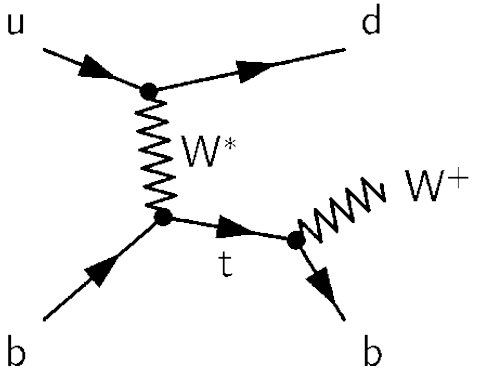
CMS-PAS-TOP-15-013

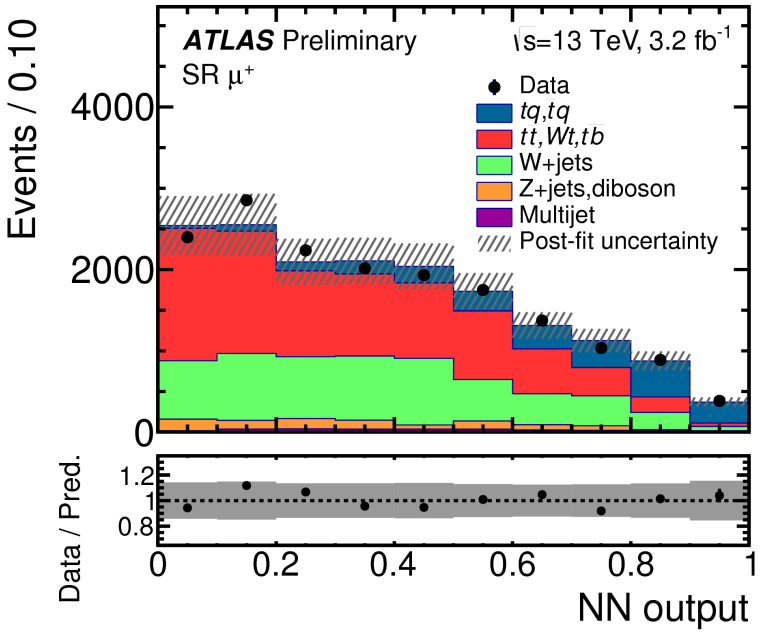


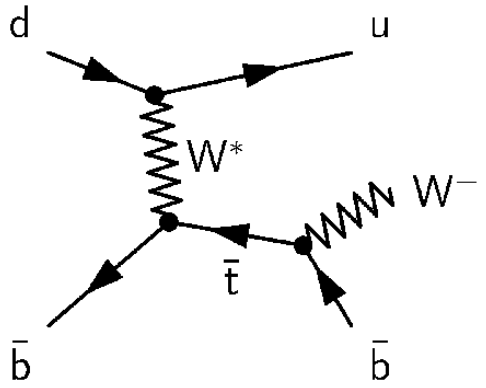
ATLAS-CONF-2015-065

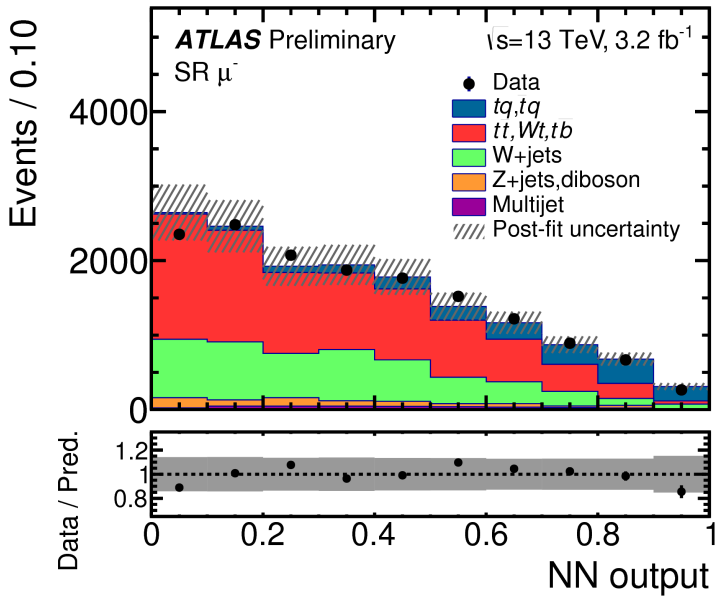
Single Top

- Measure t-channel top and antitop production separately
  - Yields information on b-quark PDF





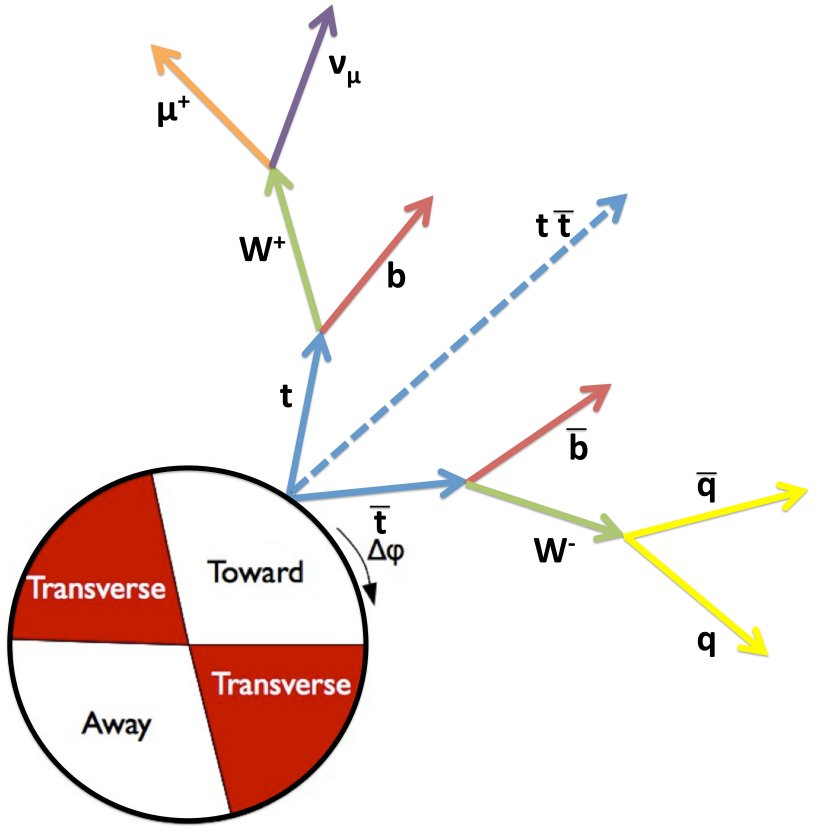




ATLAS-CONF-2015-079

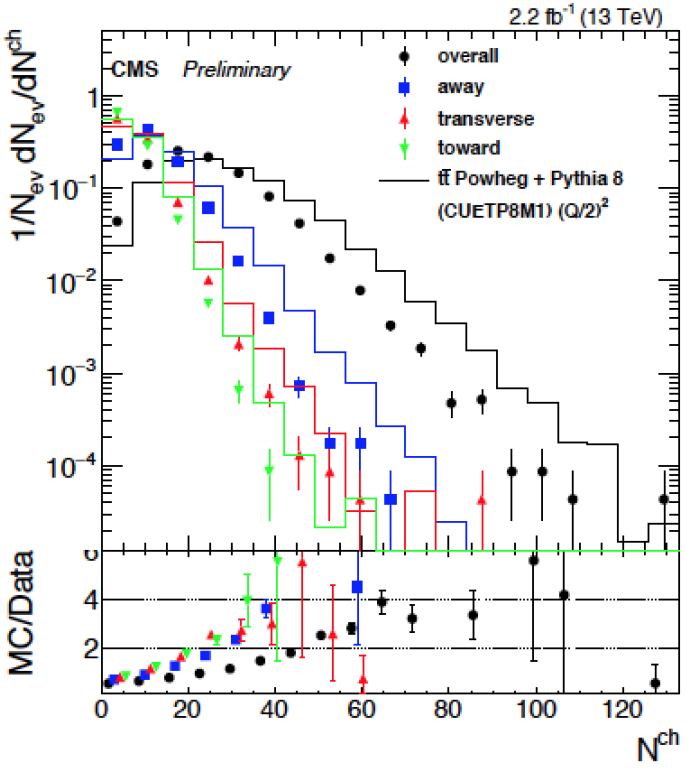
Underlying event analysis

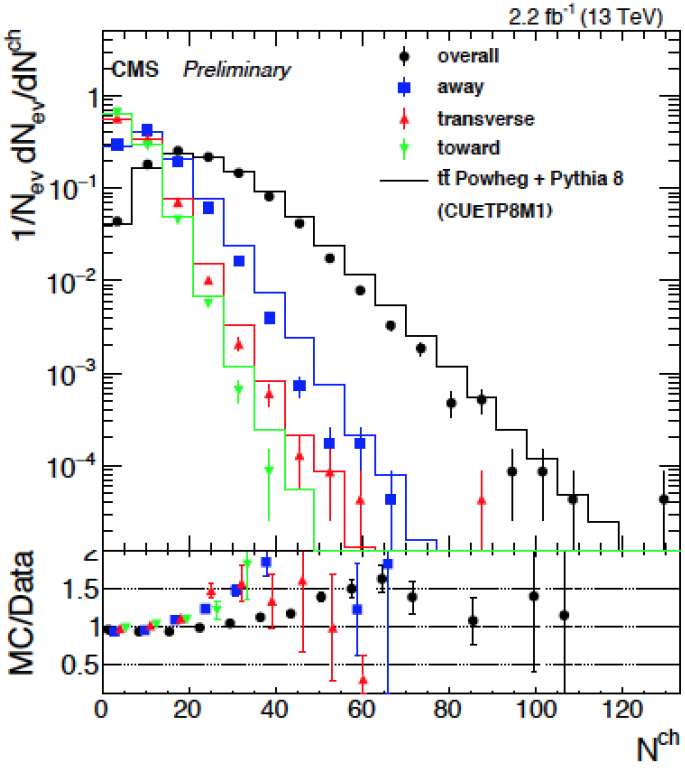
- Modeling in $t\bar{t}$ events: using charged particle properties to explore underlying event activities
  - Underlaying event: mean-beam remnants and multi-parton interactions
- Define different regions wrt. axis of $t\bar{t}$ system

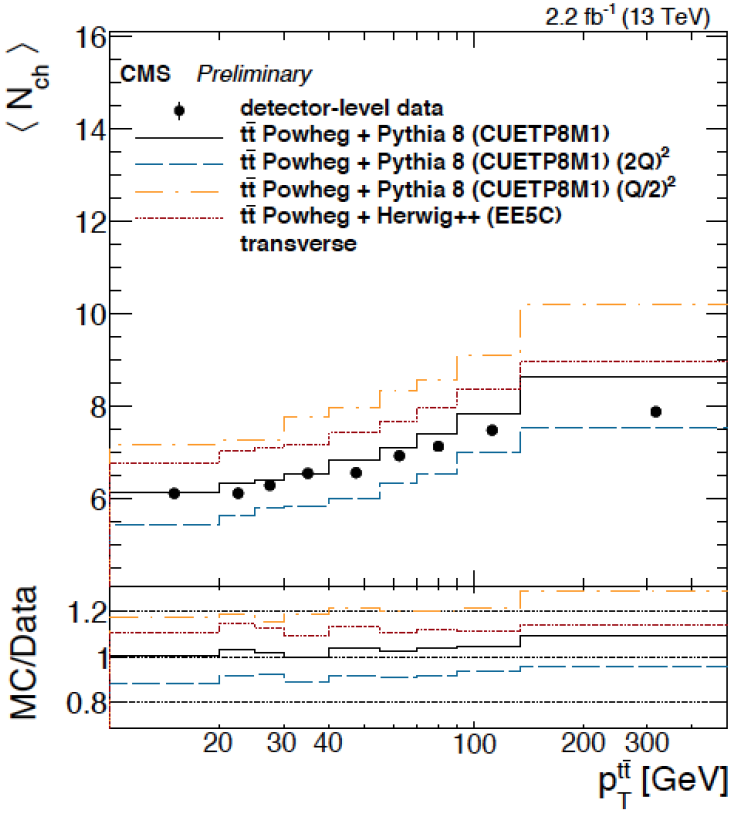


Underlying event analysis

- Can explore different observables conencted to the charged particle activity
  → gives discrimination of different MC tunes



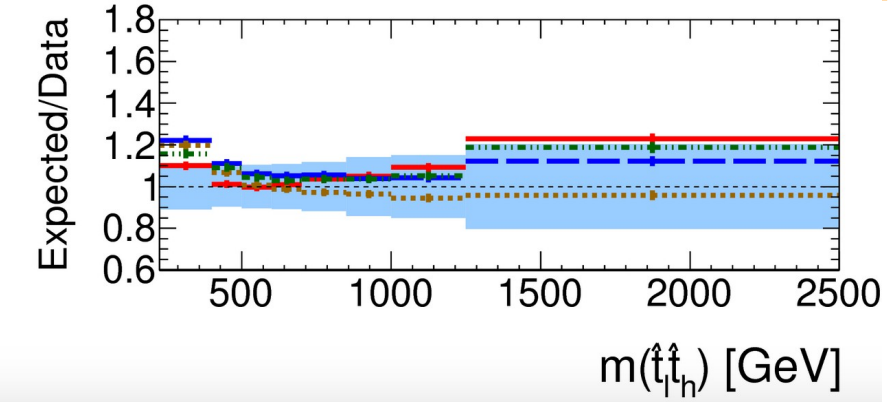




CMS-PAS-TOP-15-017

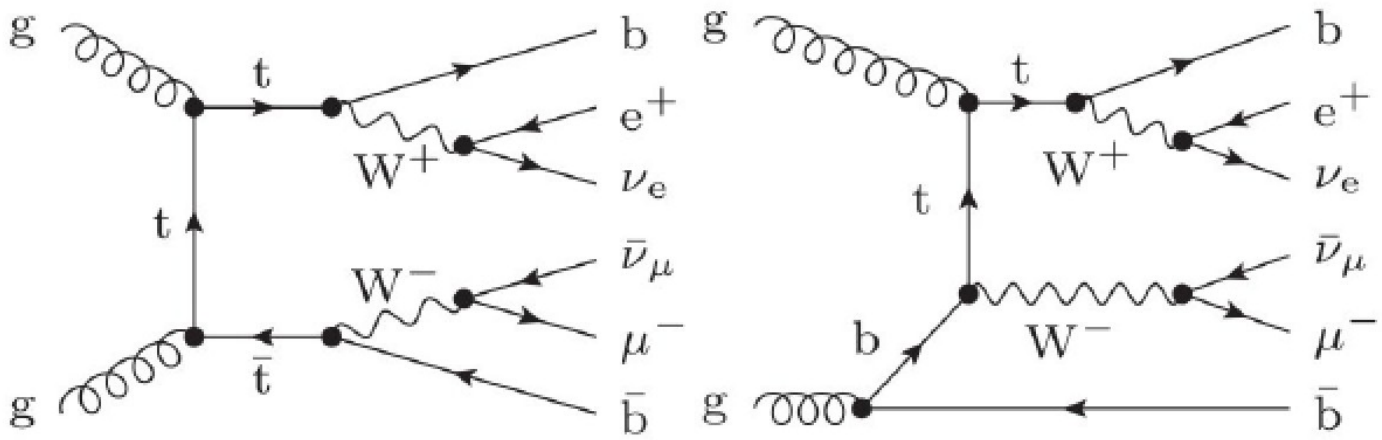
Main Focus

- Understand modeling
  - Important for many analyses



Modeling

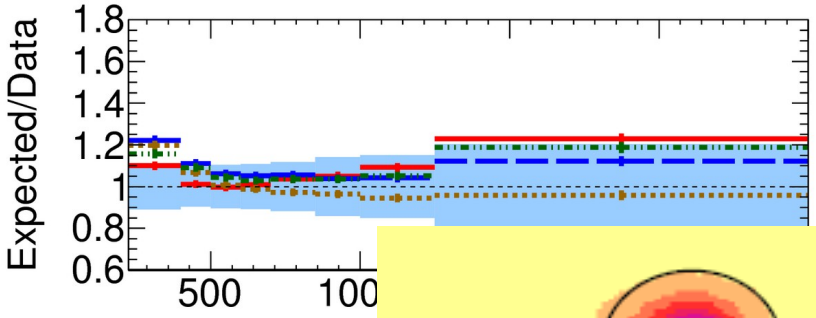
- In particular MC modeling!
  → on experimental side: differential distributions become even more important!
- Need theorist input though!
  - For example MC:
    - Interference single top Wt channel and $t\bar{t}$
      → instead of separate MCs get WbWb MC?

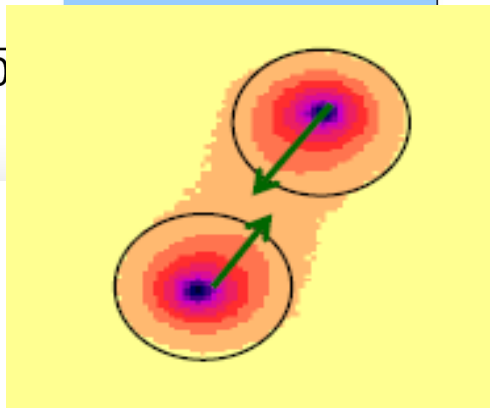


  - Higher-order calculations in various distributions

Main Focus

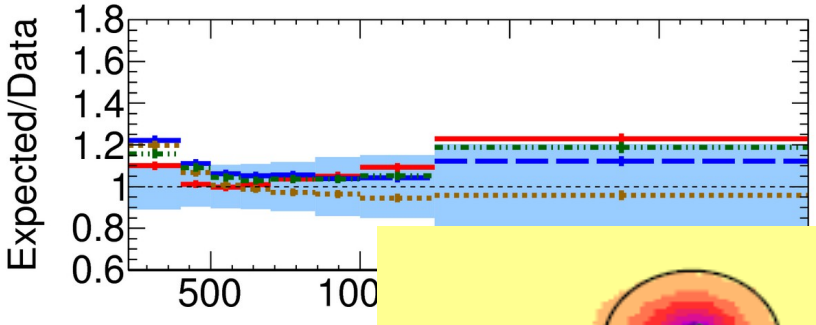
- Understand modeling
  - Important for many analyses
- Top as a calibration tool
  - Development of new tools
  - Calibration of b-taggers and boosted taggers

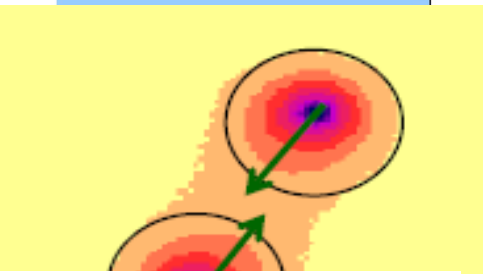


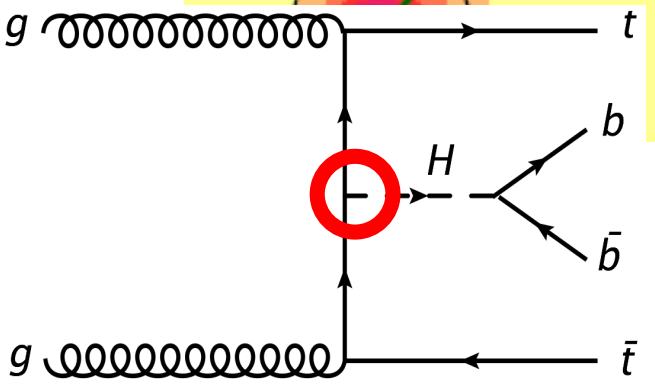


Main Focus

- Understand modeling
  - Important for many analyses
- Top as a calibration tool
  - Development of new tools
  - Calibration of b-taggers and boosted taggers
- Precision determination of rare processes
  - Best way to indirectly search for new physics!

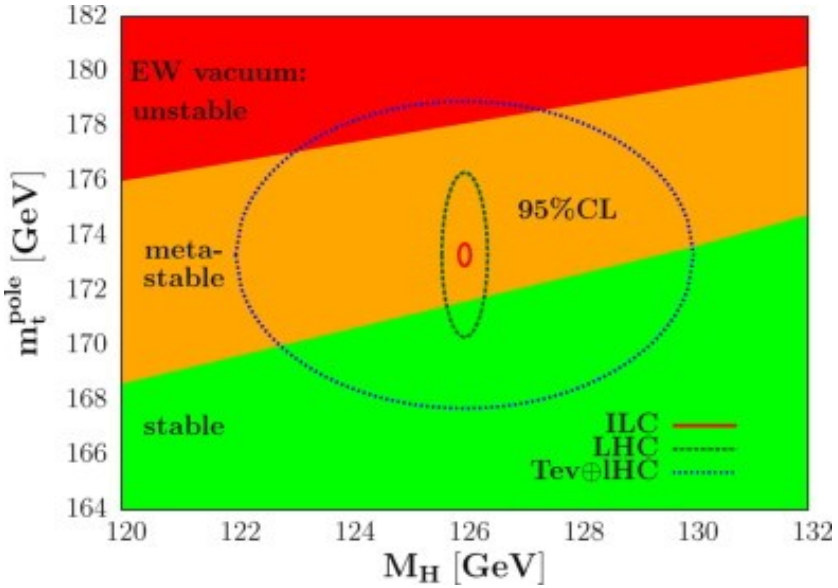


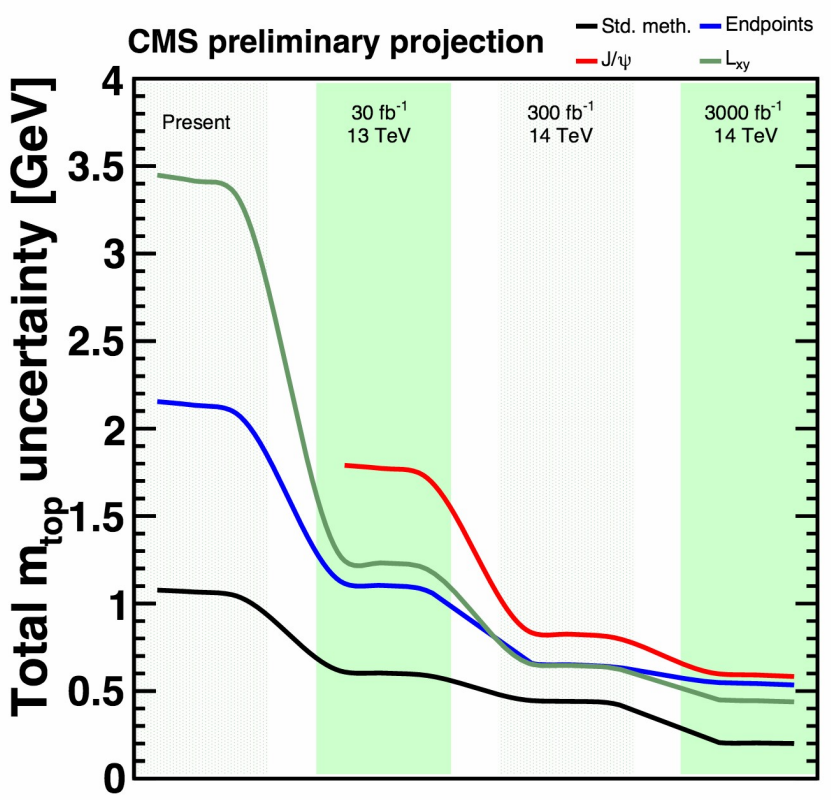




Mass

- Aim at improved precision!
  - Fate of the universe!





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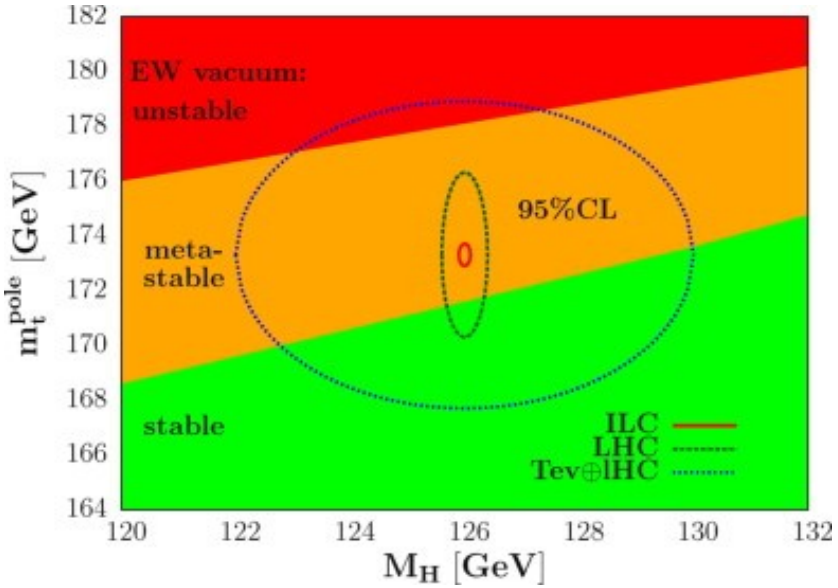
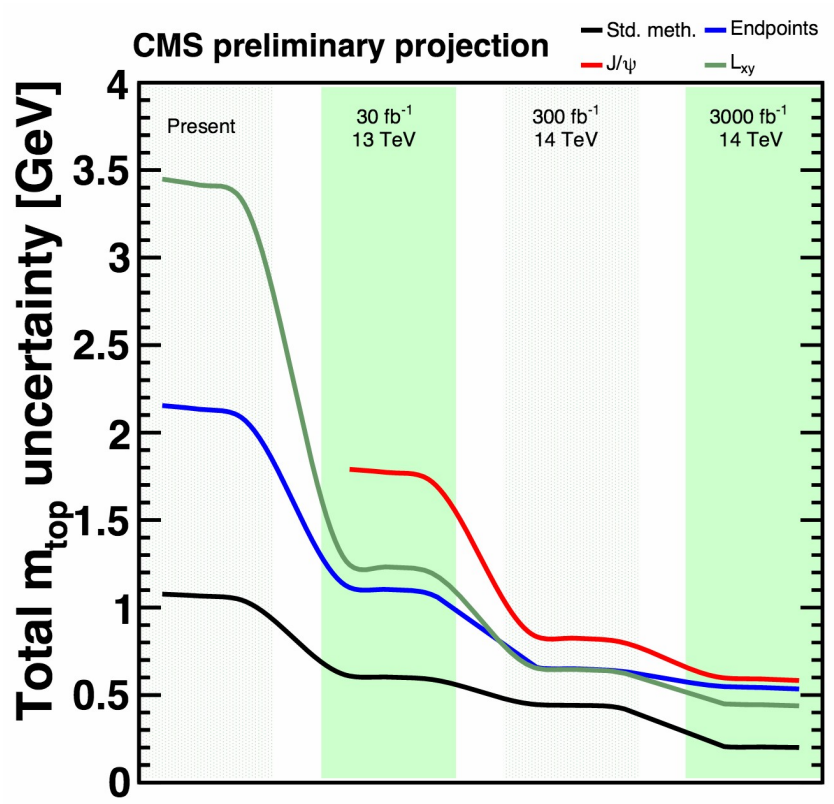
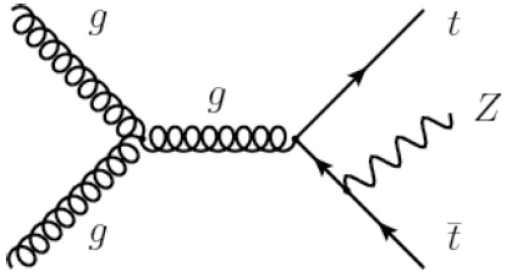


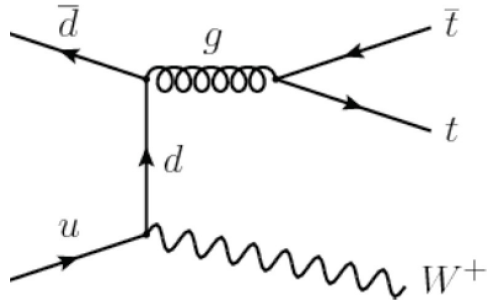


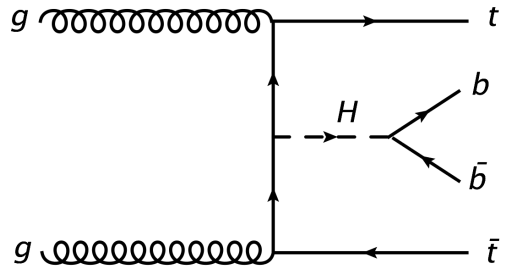
- Resolve ambiguity!
- Need to
  - Improve systematic uncertainties → modeling and jet energy scale
  - Explore new methods; e. g. the top mass from $t\bar{t}$+jets

$t\bar{t}$+Boson

- Many rare processes can be measured
- Measurements of $t\bar{t}Z$, $t\bar{t}\gamma$, $t\bar{t}H$:
  direct measurement of top couplings to bosons
  - First time sensitive at LHC Run I
    $\rightarrow$ more exploration in Run II!
- $t\bar{t}Z$: direct measurement of coupling to Z boson
- $t\bar{t}W$: source of same-sign dilepton events
  - Signature of many NP models
- $t\bar{t}\gamma$:can constrain models of new physics
  - e. g. composite top quarks or
    with excited top quark production
- $t\bar{t}H$: measurement of top-Higgs Yukawa coupling

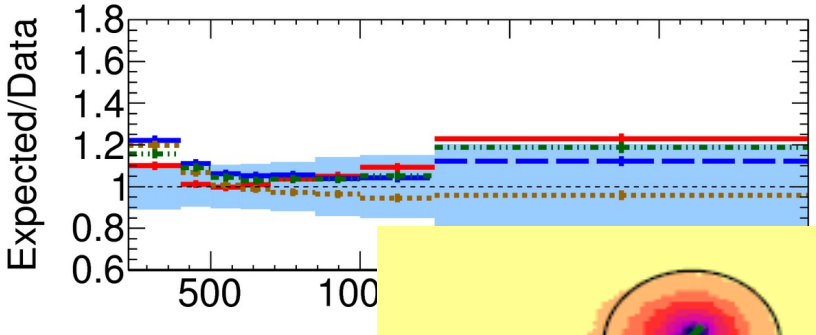


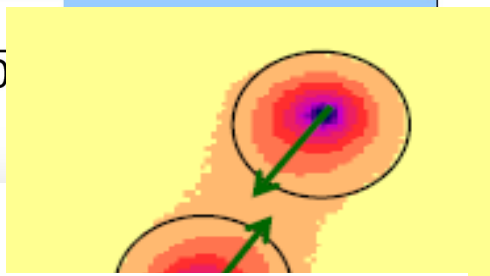


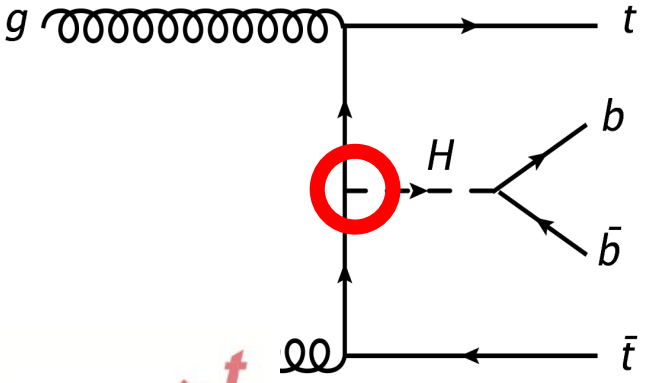


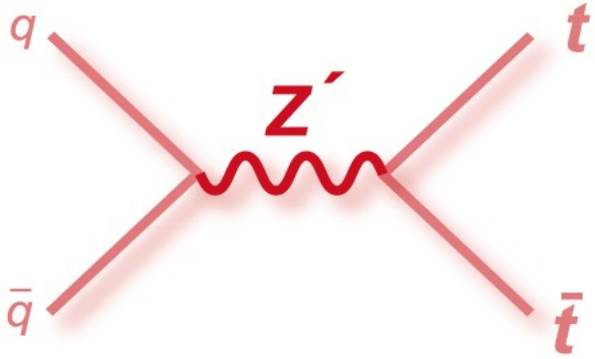
Main Focus

- Understand modeling
  - Important for many analyses
- Top as a calibration tool
  - Development of new tools
  - Calibration of b-taggers and boosted taggers
- Precision determination of rare processes
  - Best way to indirectly search for new physics!
- Searches for new physics
  - Dark matter
  - Stop and other SuSy particles
  - Extended Higgs sector





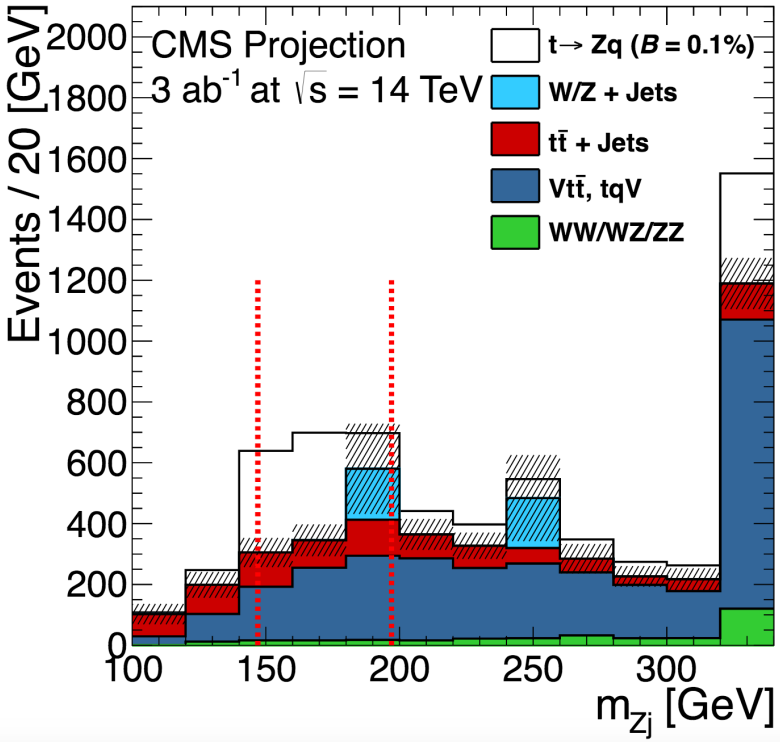




Searches

- Higher centre-of-mass energy → searches for heavier particles
  - For example: $t\bar{t}$ resonances

    → important to understand high-tail modeling of SM background processes!
- More top quarks → rare processes
  - Like FCNC!



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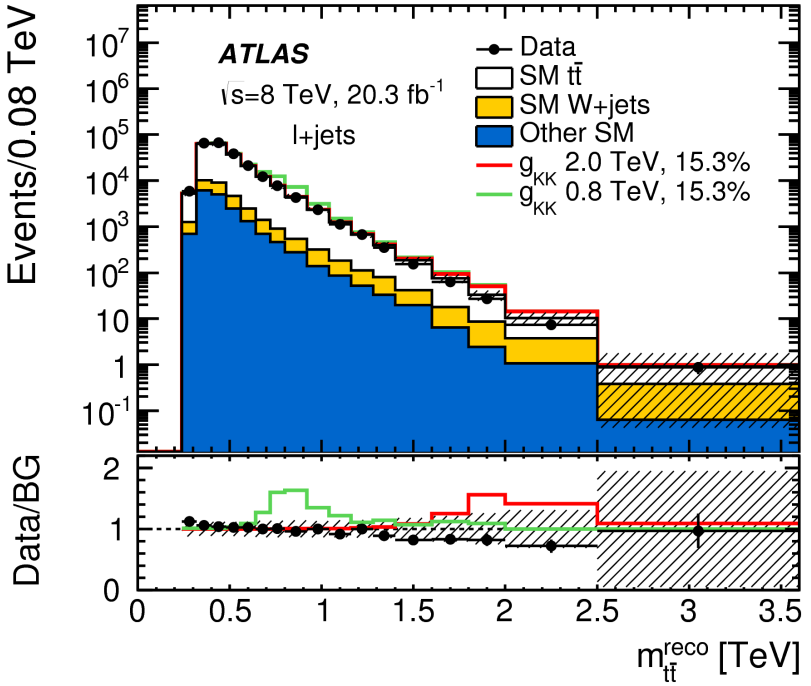

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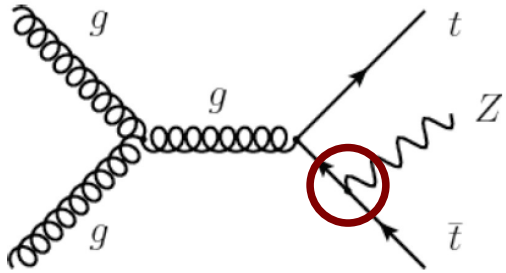
Beyond Run II

More Tops

- After Run II at LHC → more top events
  - → explore rare processes
    - Anomalous couplings?
  - → more in-situ fit of systematic uncertainties
    - "profiling"



- Lepton colliders (see Eric's talk and talk by K. Ellis)
  - → top mass threshold scans
  - Precise measurements of couplings
    - For example top-Higgs Yukawa coupling!

Summary

- Many interesting top physics analyses already ongoing!

- Goals:
  - Reduce systematic uncertainties
    - In particular: modeling
  - Precision measurements of rare processes and couplings
    - Major milestone for Run II: top-Higgs Yukawa coupling
  - Searches for new physics

- Even 20 years after its discovery: tops are hot topic!