Top Physics: What has the LHC done for us?

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MANCHESTER 1824

European Research Council

Established by the European Commission

Top Physics: What have hadron colliders done for us?

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What have they ever given us in return?

Content

- Introduction
- Production
- Properties
- Future
- Summary

Introduction

The Top Quark

- Heaviest known elementary particle:
  m_t=~173GeV

- 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 → ~1

Brief History of the Top Quark

- 1976: Discovery of Upsilon at Fermilab → b-quark
  - Structure of quark families suggested existence of a 6th quark: the top
- From here on the race to find the top began
  - Lower limits by Petra (1984), Tristan (late 80s), UA1(1988), LEP(1990), UA2

Brief History of the Top Quark

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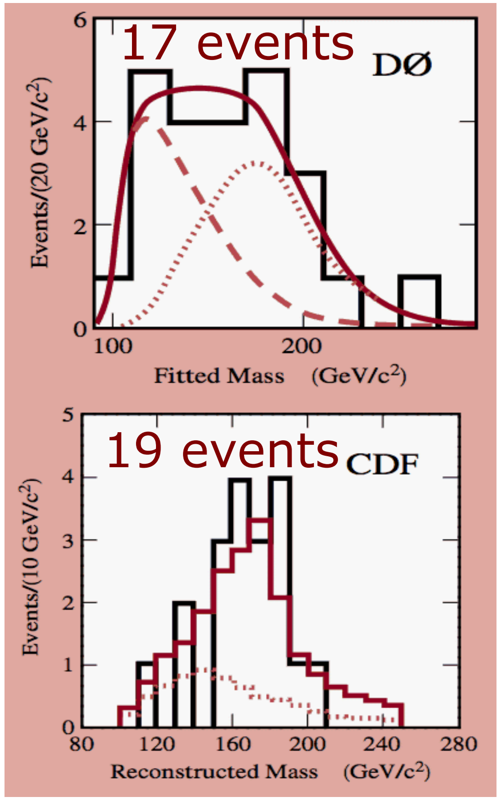
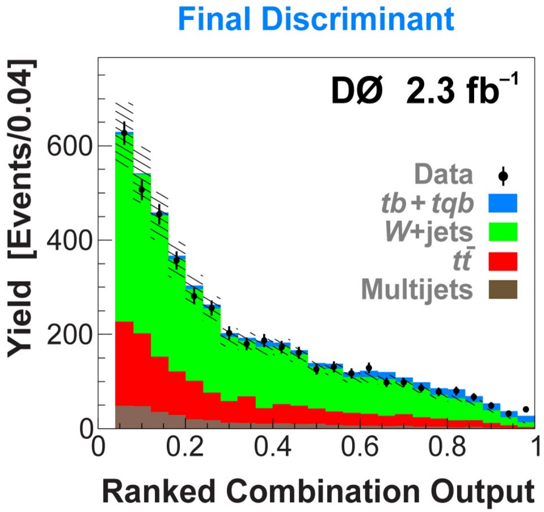
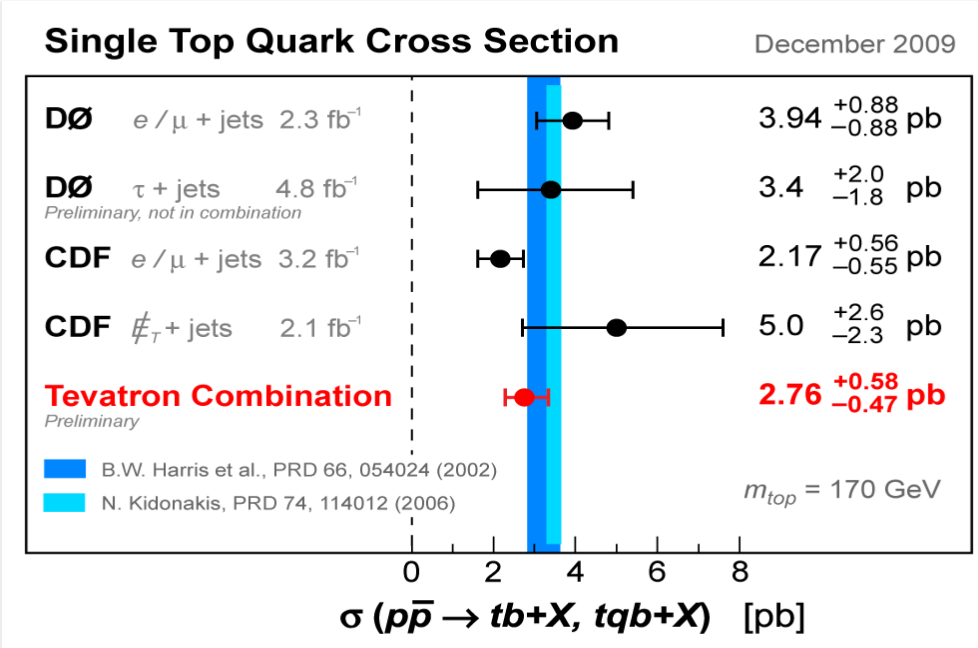
  - Lower limits by Petra (1984), Tristan (late 80s), UA1(1988), LEP(1990), UA2
- 1992: First lower limits on top from CDF (m_t>91GeV)
- 1994: First lower limits on top from DØ (m_t>131GeV)
- Early 1994: "Evidence" for top at CDF
- February 24th 1995: Simultaneous submission of Top Discovery papers to PRL, by CDF and DØ
  - 50pb^{-1} at D0, 67pb^{-1} at CDF



Discovery of lonely Tops

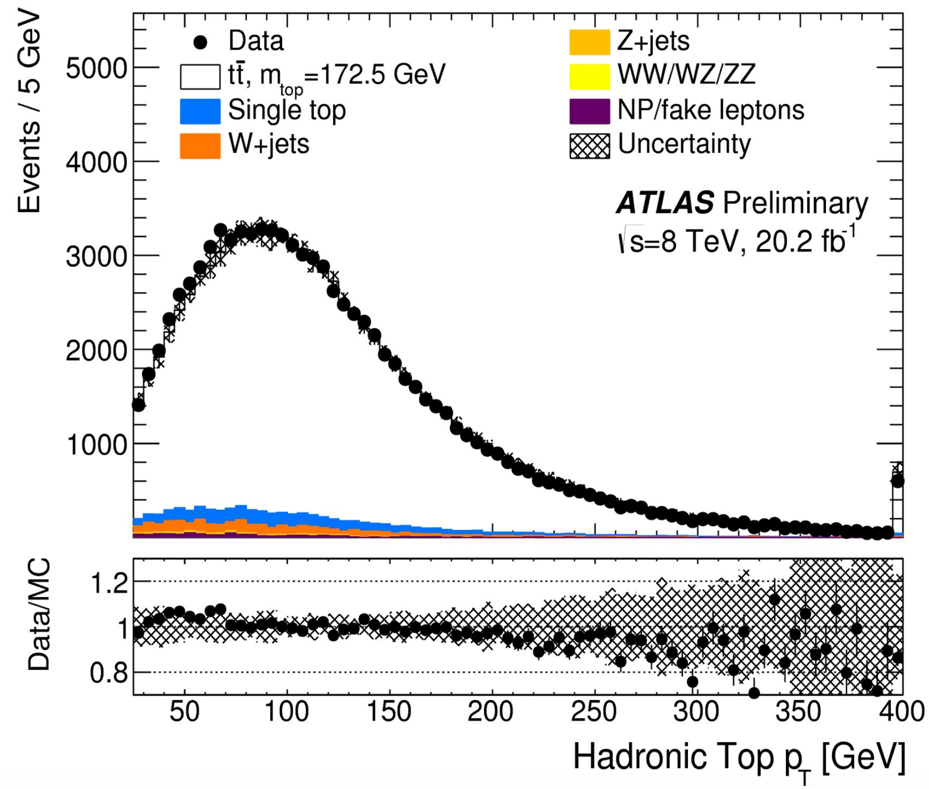
- 2009: Observation of top quarks in single top production
  - 5   by CDF & DØ!
- Single top: very challenging channel
  - Low signal: similar signature like W+jets!
  - Counting only: Uncertainty on background larger than expected signal → use of multivariate techniques





Where are we today?

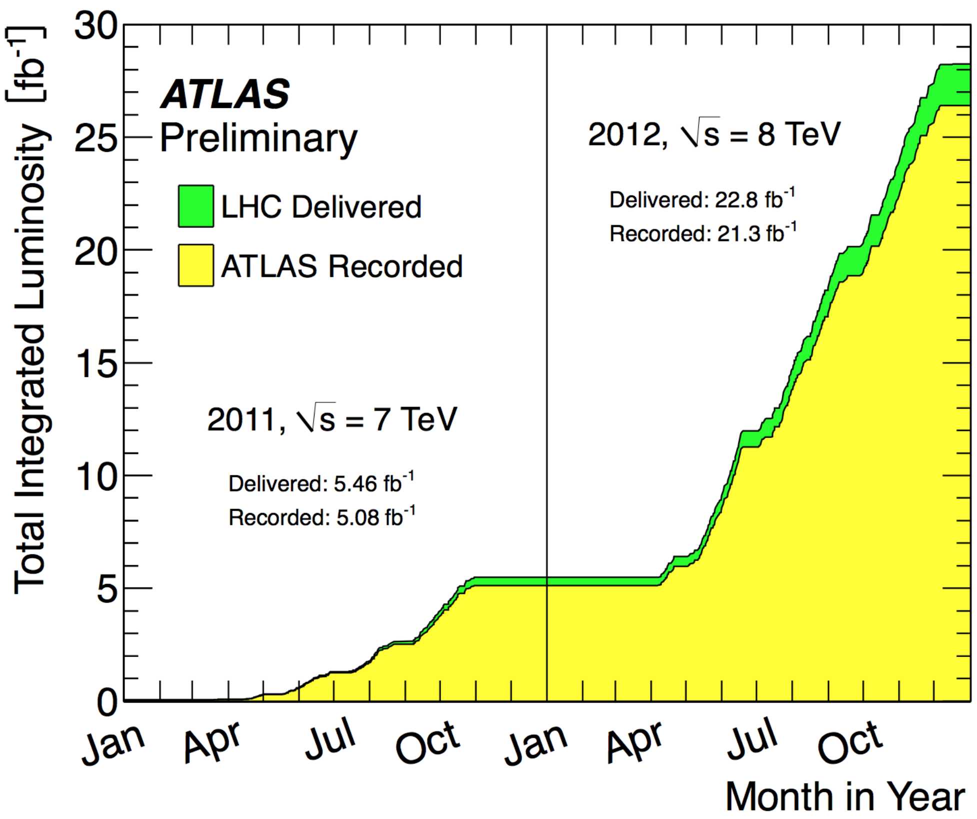
- Top Discovery with 17 (DØ) and 19 (CDF) events
- Today: LHC: top factory! Millions of events
  - Precision measurements of production cross section
  - Observation in single top in 2009
  - Precise study of top properties
  - Searches for new physics using top quarks

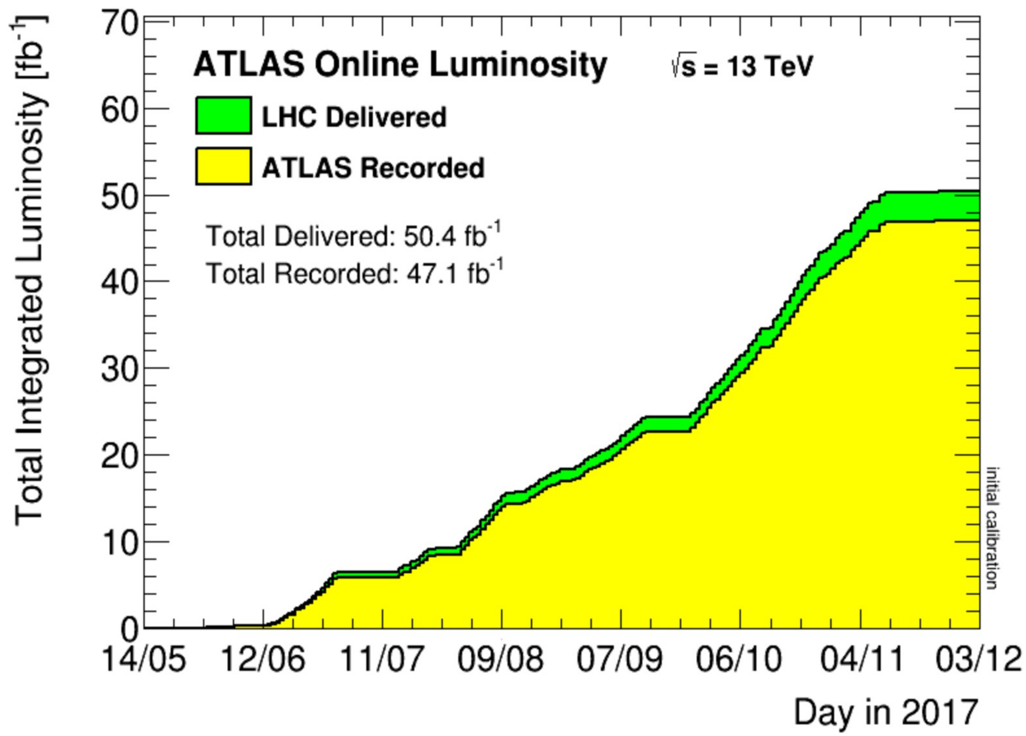


- From discovery to precision physics!
  → many results from Tevatron
  → many new tools
  → unprecedented possibilities at LHC!

Data Samples

- LHC performed well





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

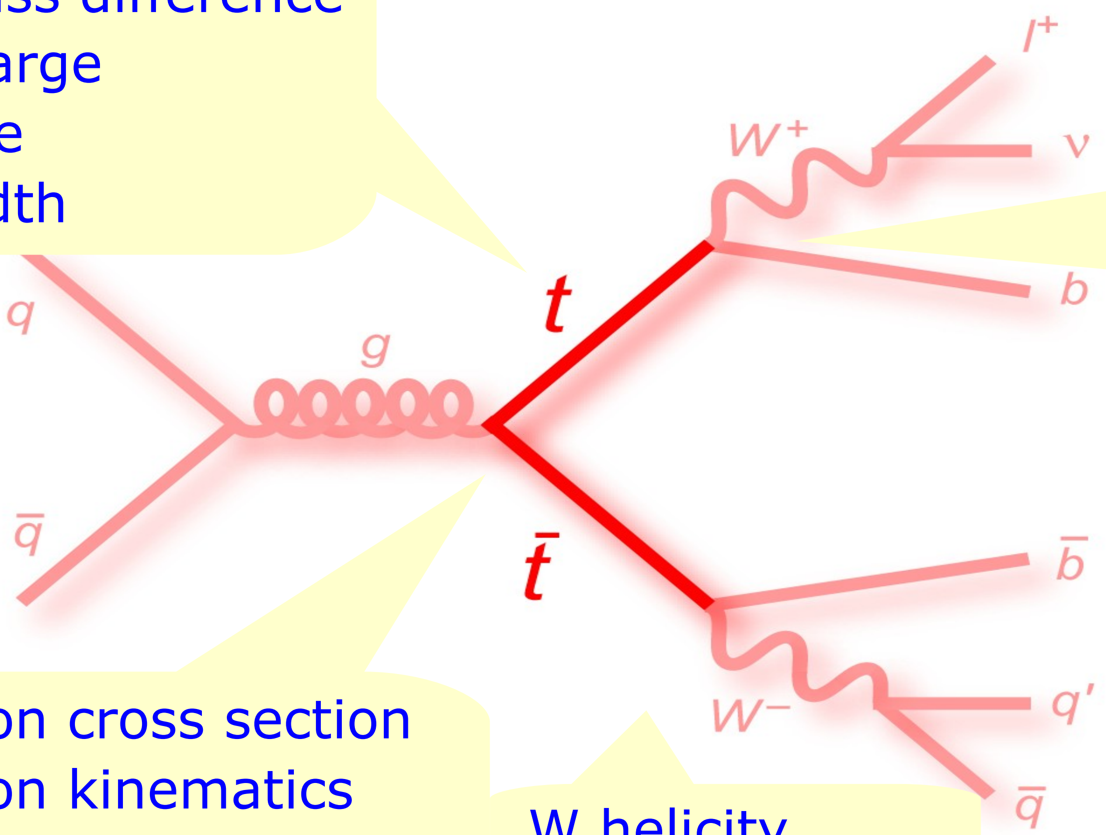
2017: ~50fb^{-1} of 13 TeV data

Why Top still interesting?

- With final Tevatron data set and the ever growing LHC data sample: top quark studies very interesting until today!
- What can we learn?
  - Is the top really the “SM top”, or something else?
    → need to measure its production cross section and properties and compare with SM calculations
  - Top quark: only quark decaying before it hadronises
    → can study a bare quark
    For example can study spin of a quark directly (as it transfers it to the decay products before it could hadronise); or study a quark's charge
  - Top production and decay: via strong and electroweak forces
    → we can learn more about these forces
    For example: W helicity in top decays
  - Top as window to new physics (since it is the heaviest known particle)
    → searches for many new physics models in the top sector
  - Large top samples at LHC: use top events to develop new tools
    → for example tools to access the colour flow between jet pairs

Top Studies: Overview

Top mass
Top mass difference
Top charge
Lifetime
Top width



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

Spin correlation
Charge asymmetry
Color Flow

Production cross section
Production kinematics
Production via resonance
New particles

W helicity

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

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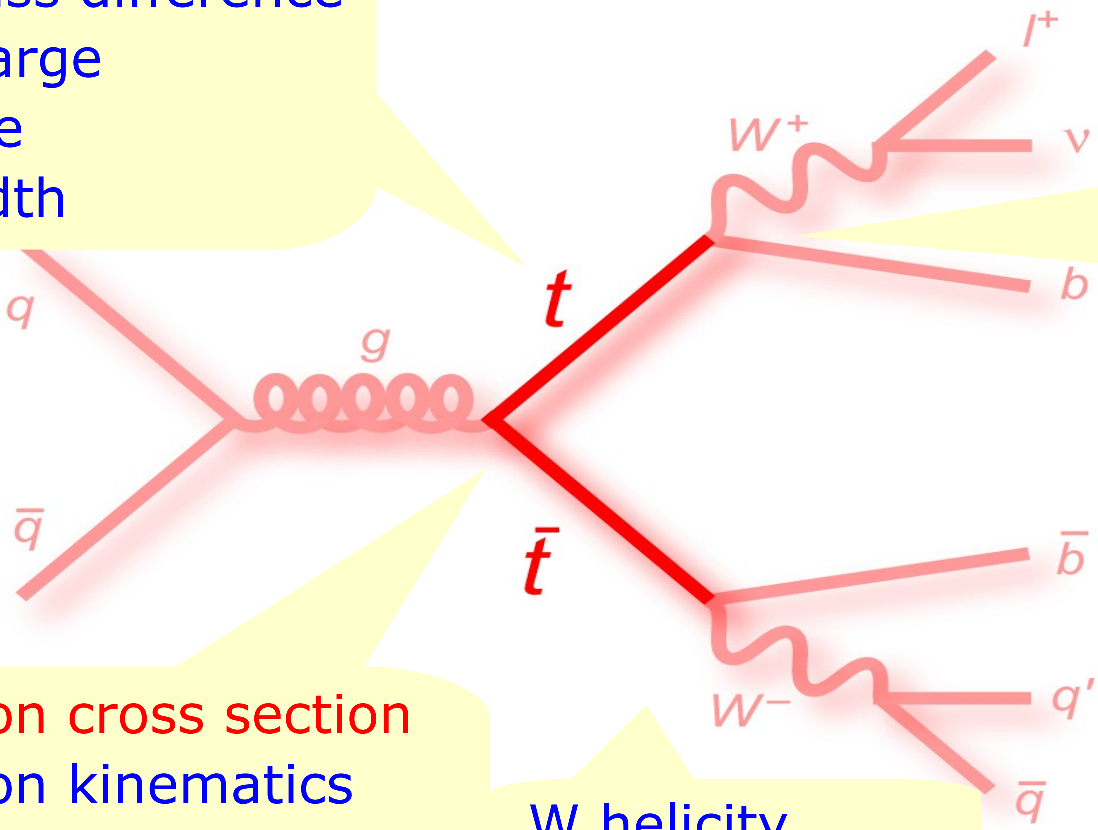

Spin correlation
Charge asymmetry
Color Flow

Production cross section
Production kinematics
Production via resonance
New particles

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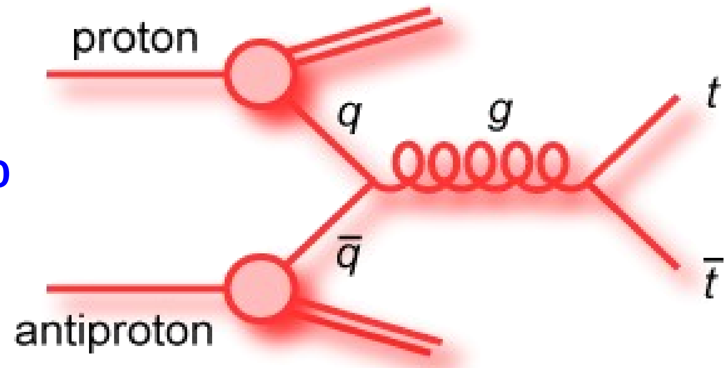
s-, t- and Wt-channel production, properties and searches in single top events

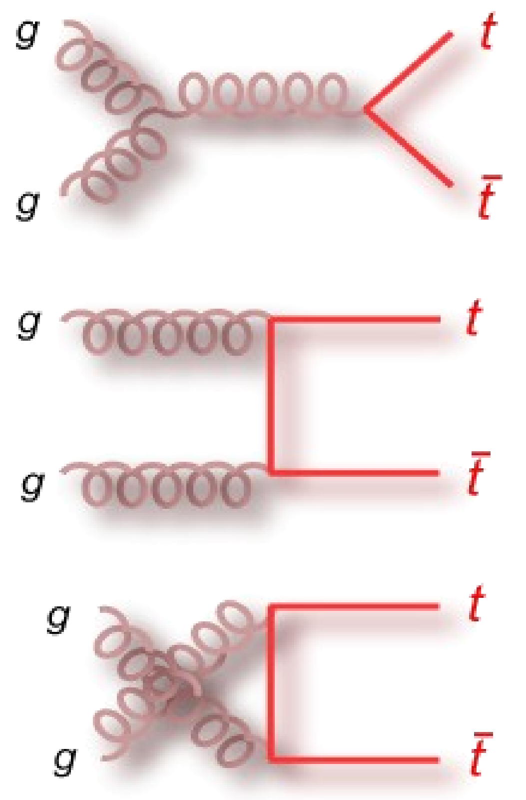
Production

Top Quark Pair Production

At the Tevatron:



85% + 15%



At LHC:

14 TeV: 10% + 90%

7 TeV: 30% + 70%

Cross Sections:

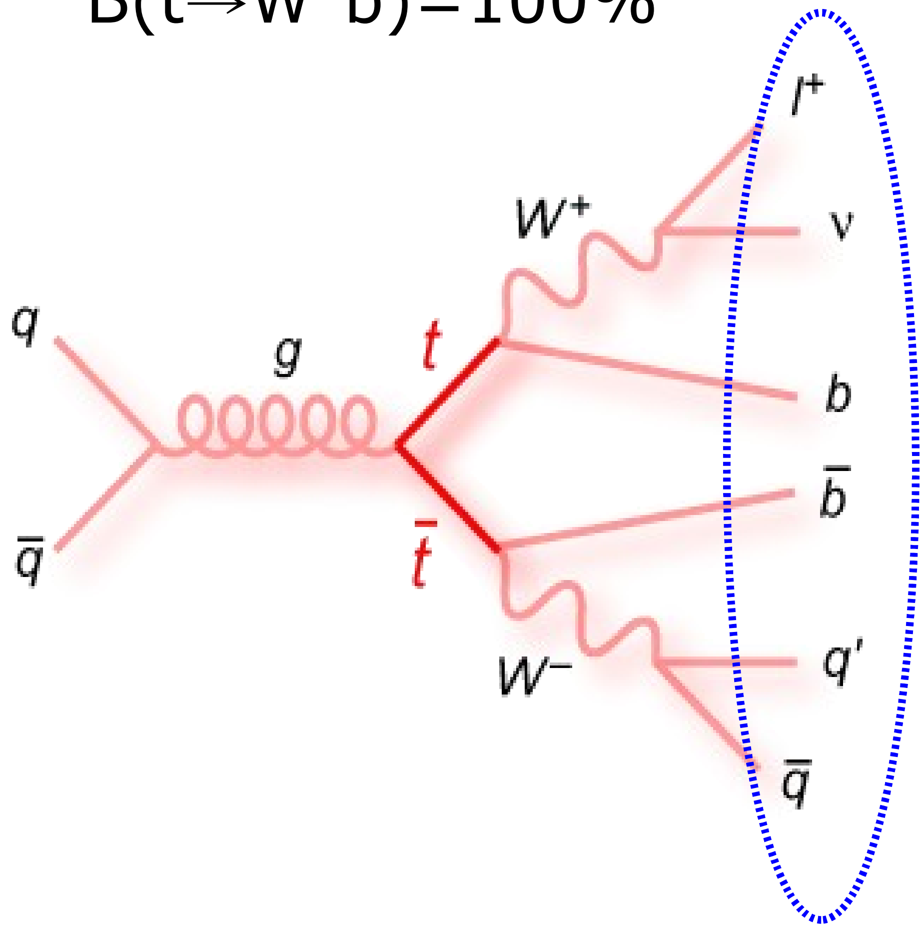
Collider	Cross section [pb]
Tevatron (1.96 TeV)	$7.35^{+0.23}_{-0.27}$
LHC (7 TeV)	$177.3^{+10.1}_{-10.8}$
LHC (8 TeV)	$252.9^{+13.3}_{-14.5}$
LHC (13 TeV)	$831.8^{+40.3}_{-45.6}$

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

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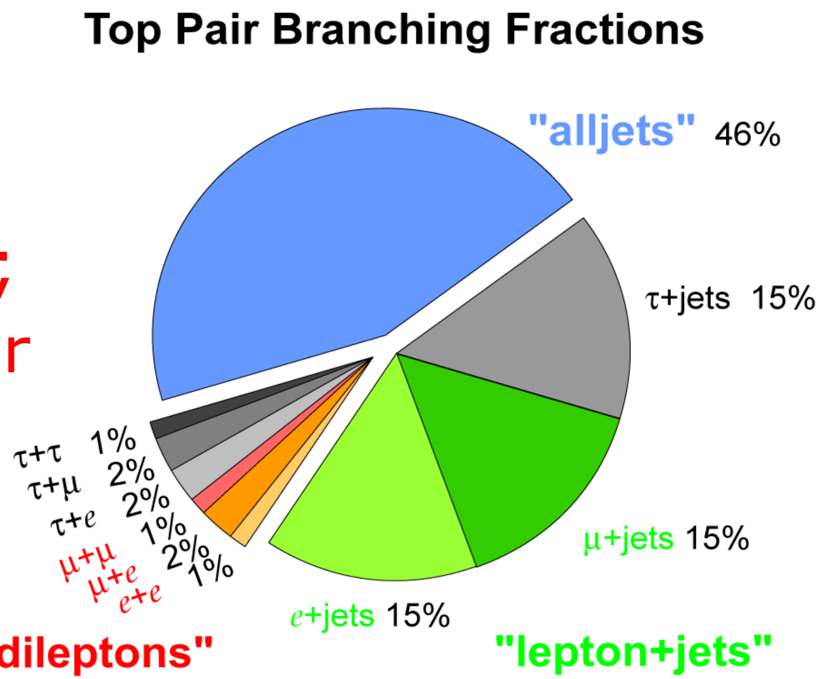
pure hadronic:
≥6 jets (2 b-jets)

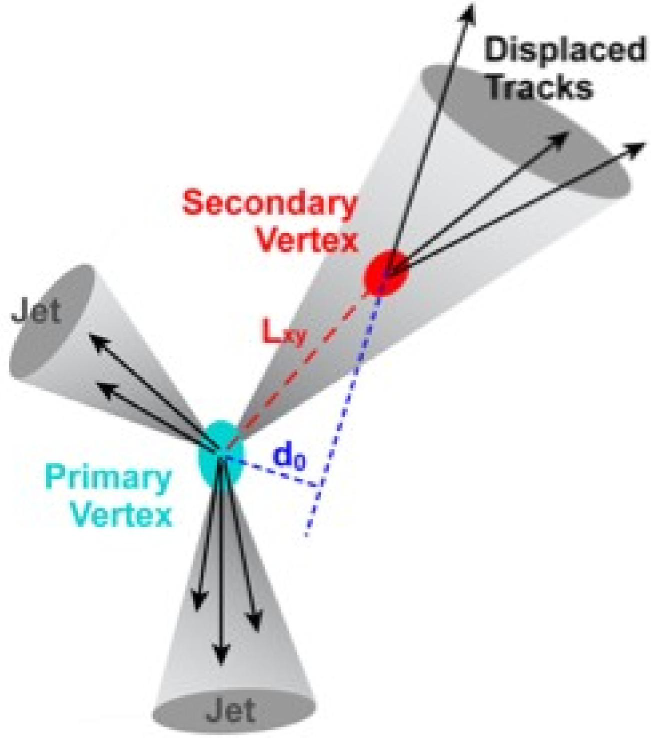
dilepton:
2 isolated leptons;
High missing E_T for neutrinos;
2 b-jets



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

Features of Top Events

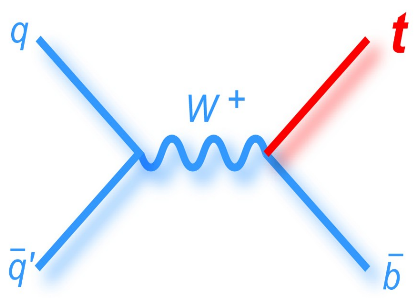
- To measure top events: enrich data sample with signal events
  - Separation from background and estimation of the background
- Features in $t\bar{t}$ events helping to select them:
  - Presence of 2 b-jets! Usage of b-tagging
    - B-hadrons have lifetime of about 1.5ps
      → travel (on average) few mm before decay
      - Secondary vertex and displaced tracks can be used to identify B-hadrons in a jet
        → "b-tagging"

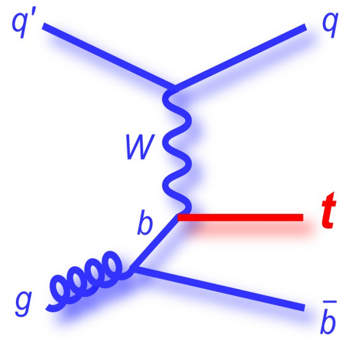


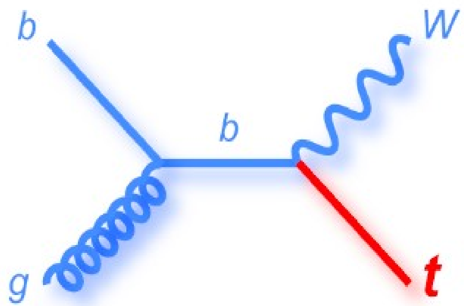
  - Tops are quite heavy: many topological variables can be used to distinguish top from background
    - For example: reconstruct top mass from combinations of jets

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





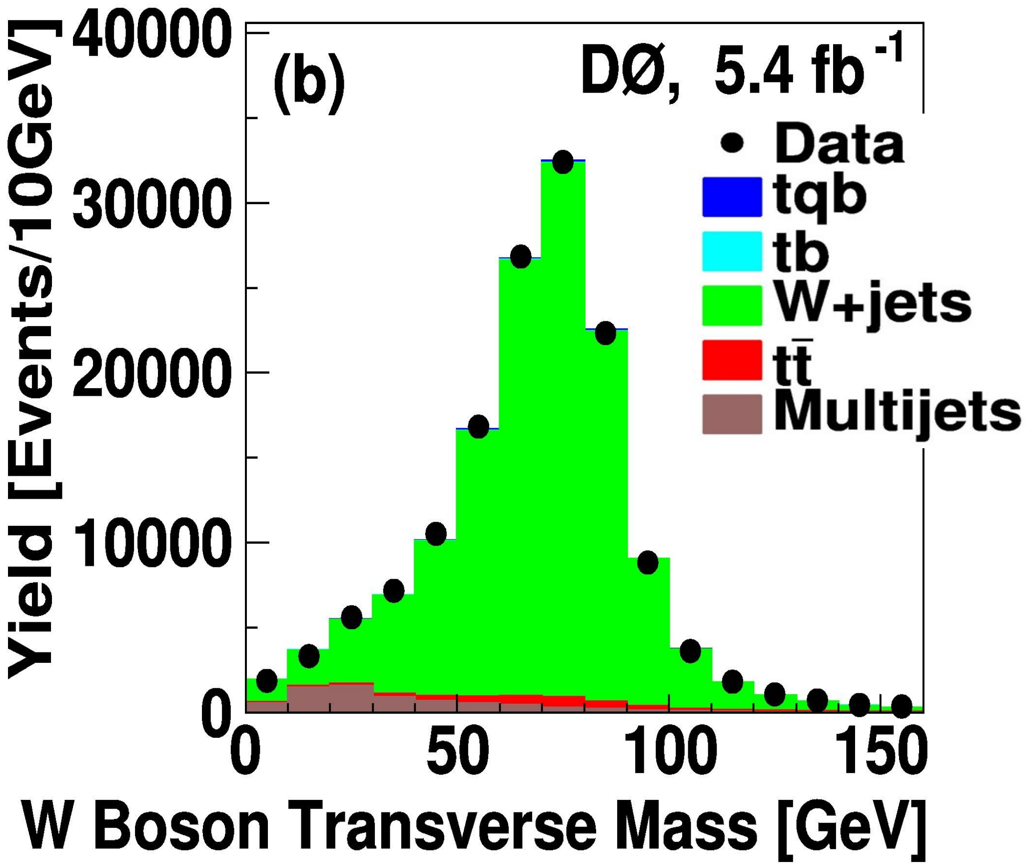


Collider	s-channel: σ_{tb}	t-channel: σ_{tbq}	Wt-channel: σ_{tW}
Tevatron: $p\bar{p}$ (1.96TeV)	1.04 pb	2.26 pb	0.28 pb
LHC: pp (7TeV)	4.3 pb	63.9 pb	15.7 pb
LHC: pp (8TeV)	5.2 pb	84.7 pb	22.4 pb
LHC: pp (13TeV)	10.3 pb	216.99 pb	71.7 pb

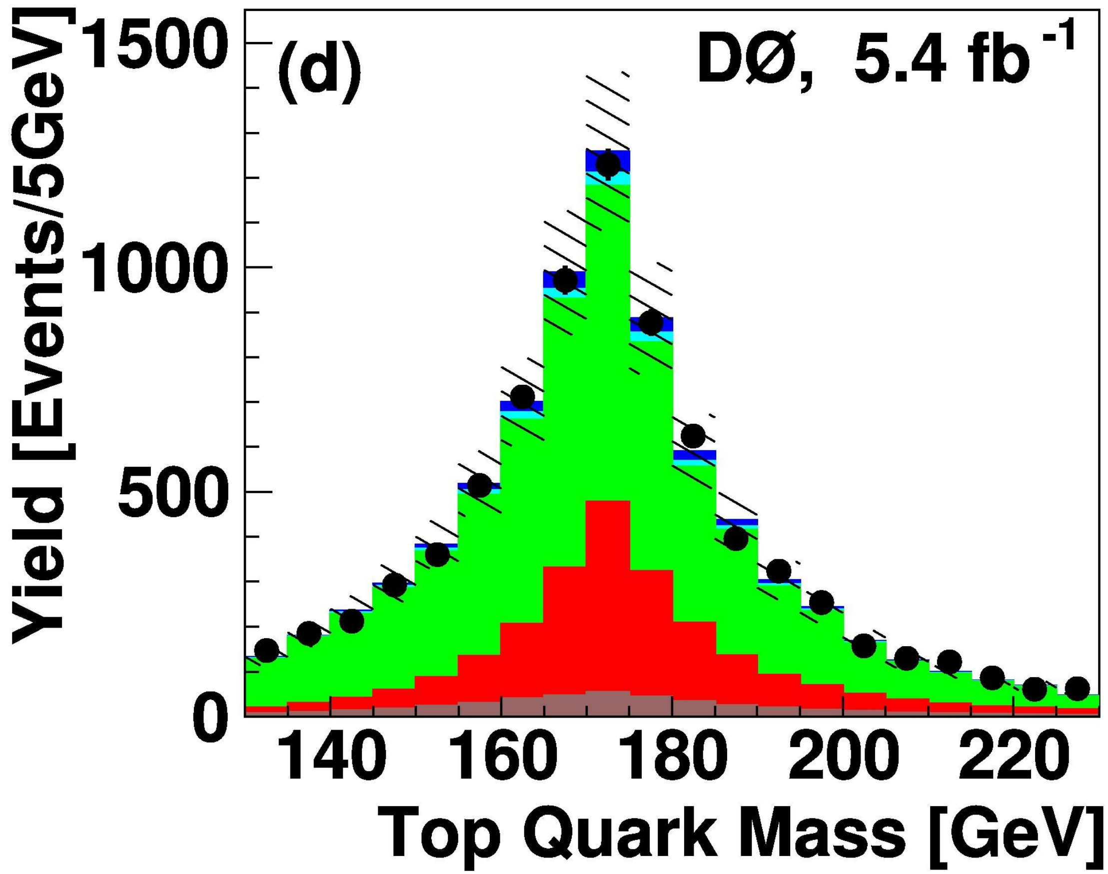
Single Top

- Example observable:

before b-tagging



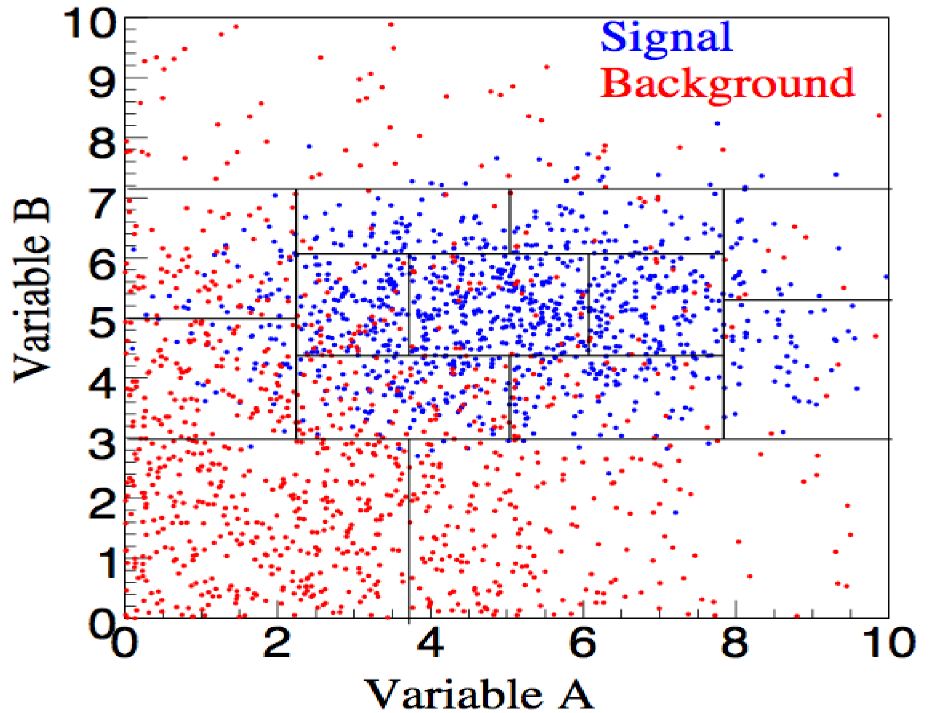
after b-tagging



- Background dominates; uncertainties larger than signal!

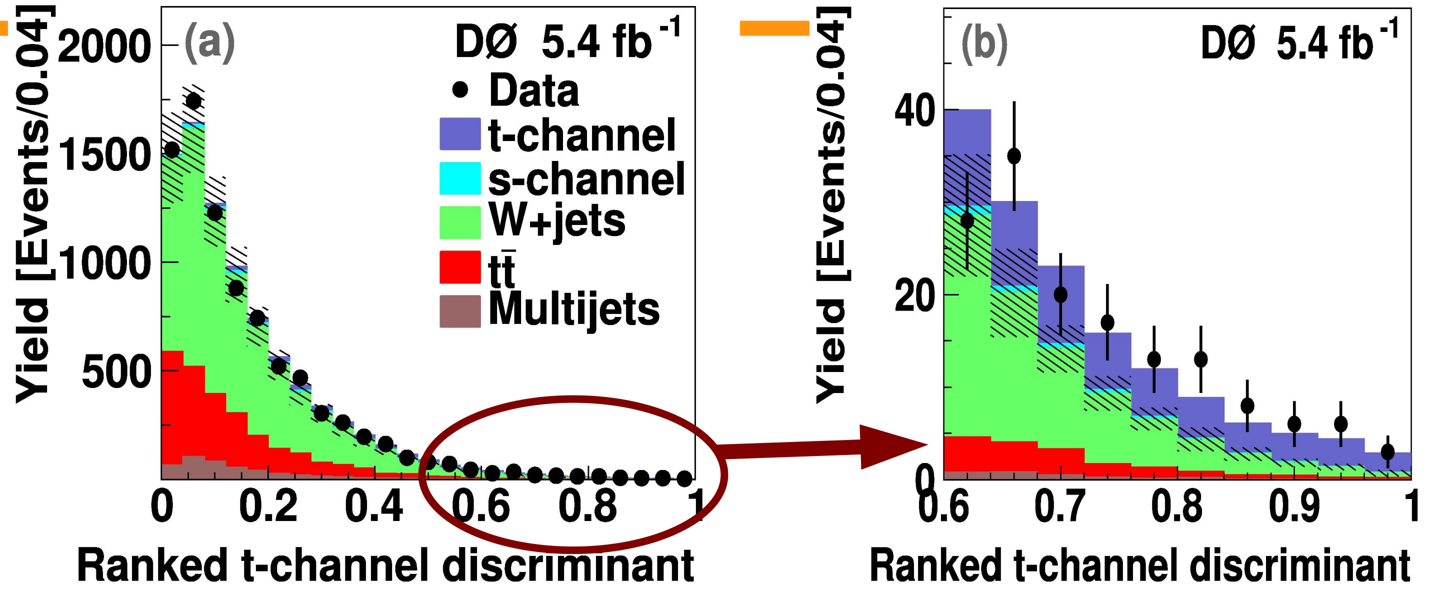
Multivariate Analysis Techniques

- Observation of single top required the usage of multivariate analyses techniques
  - Single top the first observation where these were used extensively, and thus established in particle physics
- Idea: combine many different variables, with small discrimination power, into one powerful discriminant
  - Various techniques exist, for example neural networks, boosted decision trees, random forests..
- Example: decision tree
  - Idea: divide multi-dimensional event-space into cells
  - For each cell, estimate the purity
  - Chose cuts to separate high and low purity regions



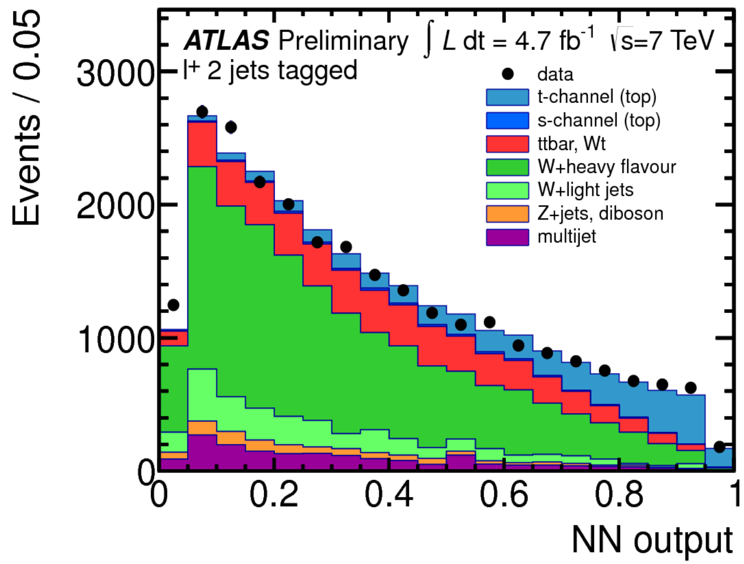
Single Top

- Example: t-channel trained discriminant



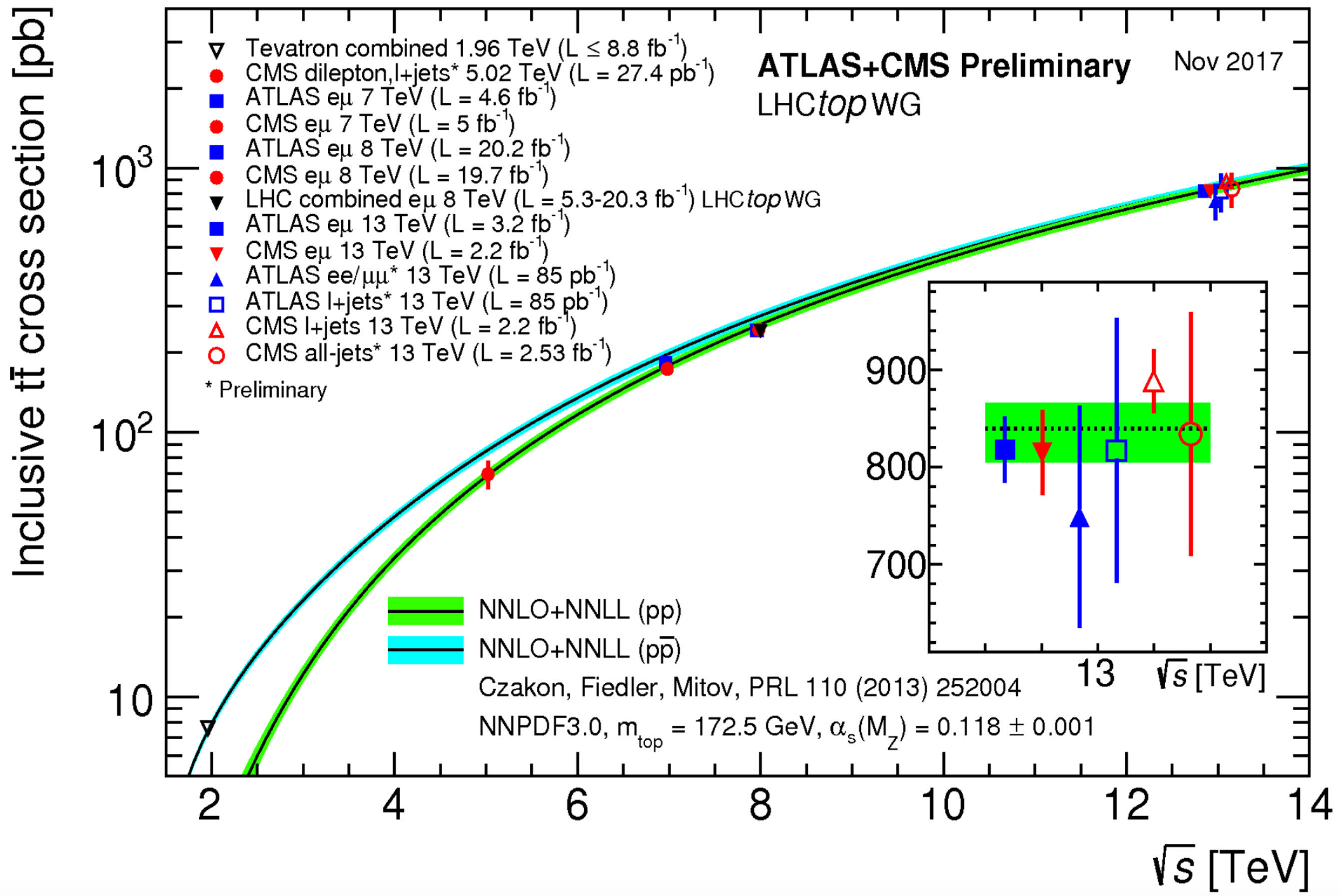
  - Signal can be clearly seen!

- At LHC: t-channel much easier
  - Large cross section
  - s-channel challenging
    → so far only observed at Tevatron



Status

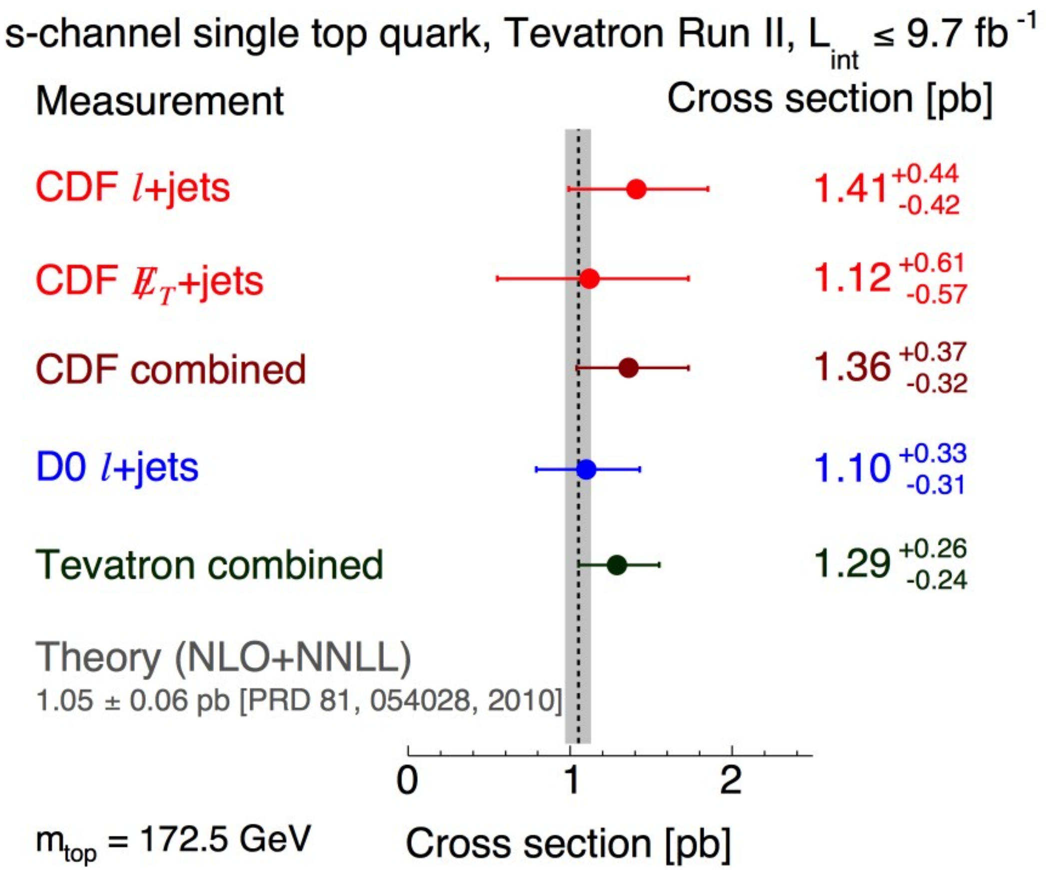
- Precision measurement of production cross section
  - At Tevatron and LHC
  - In single top and $t\bar{t}$ production

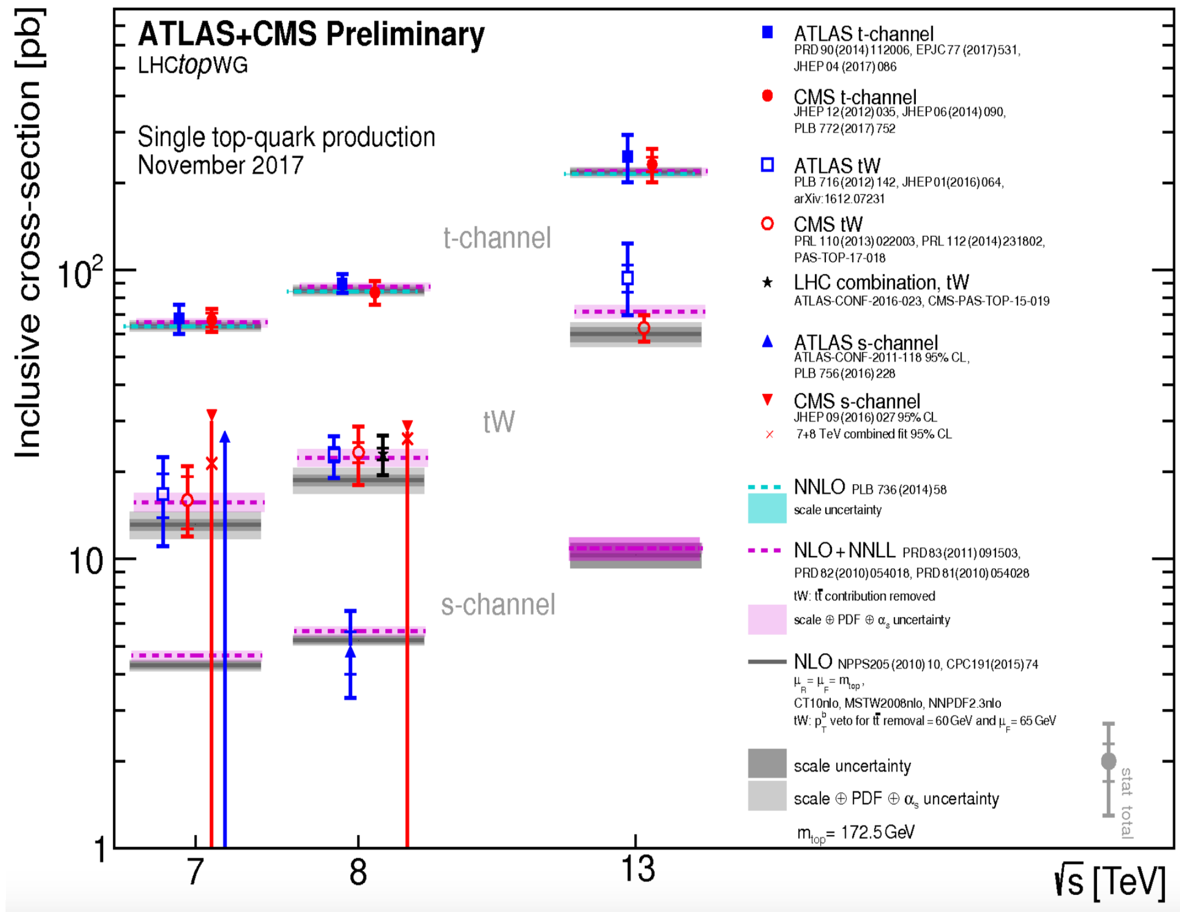


Experimental precision close to theory uncertainty!

Status

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



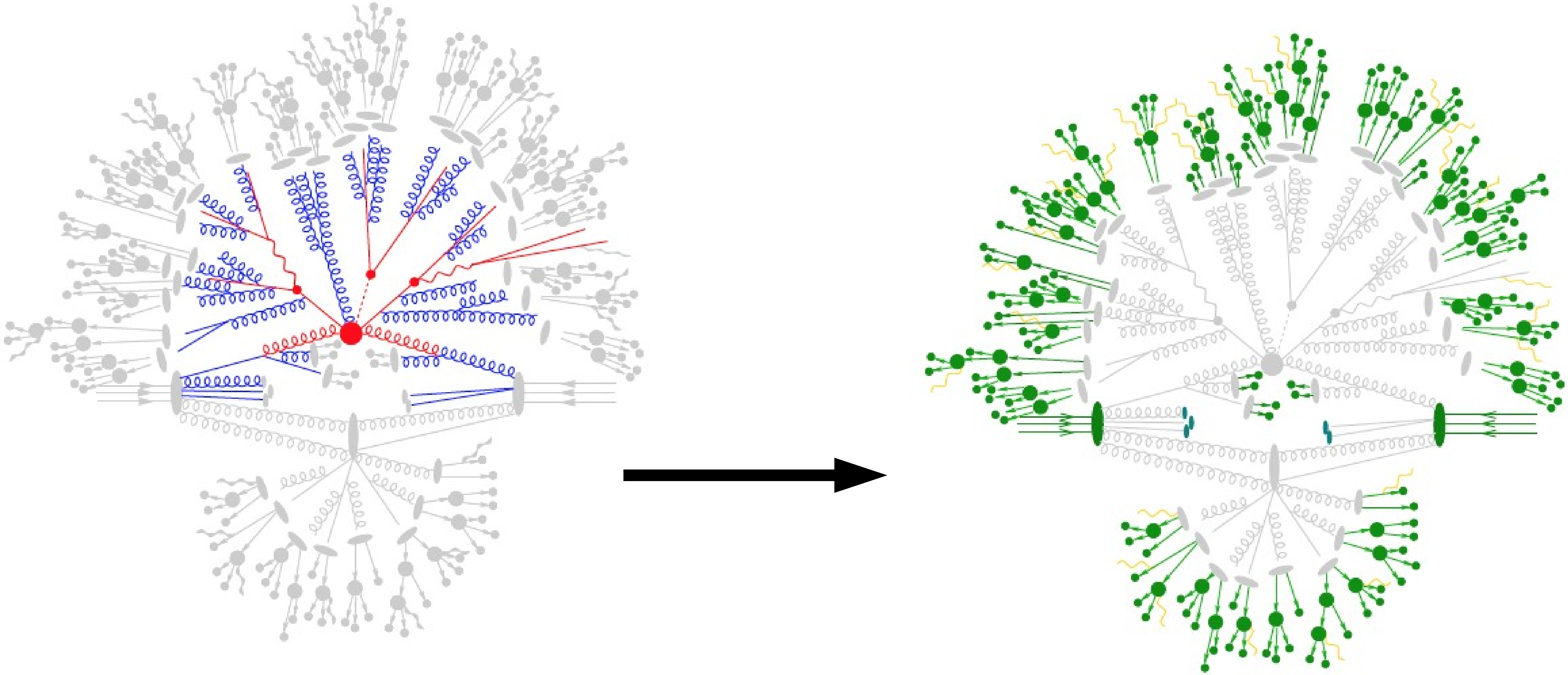


From Inclusive to Differential Cross Sections

- 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?

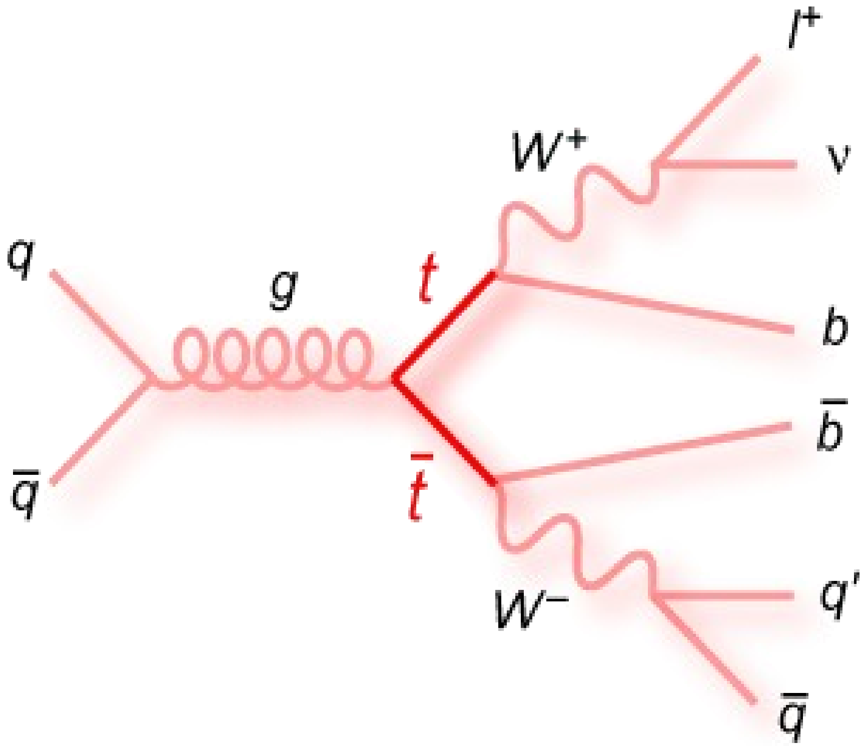


MC generator dependencies

Stable particles

Differential

- 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

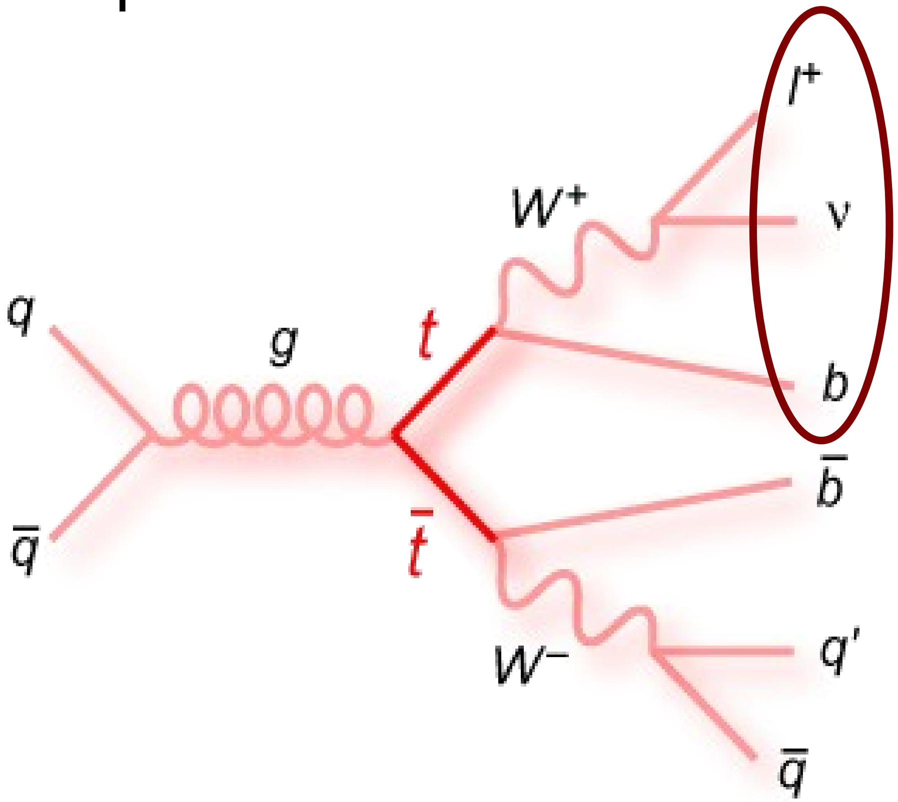
Missing p_T for neutrino ($\not{E}_T$): >30GeV

≥4 jets with p_T>25GeV; $|\eta|$<2.5

≥2 jets b-tagged

Differential

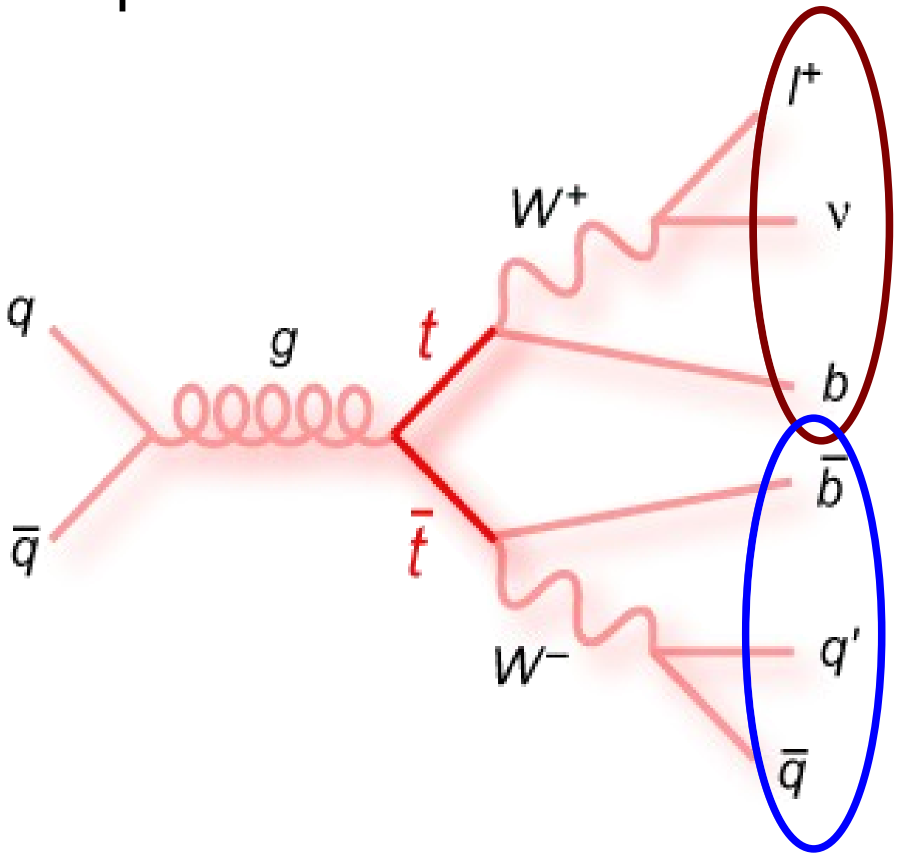
- Top reconstruction



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:

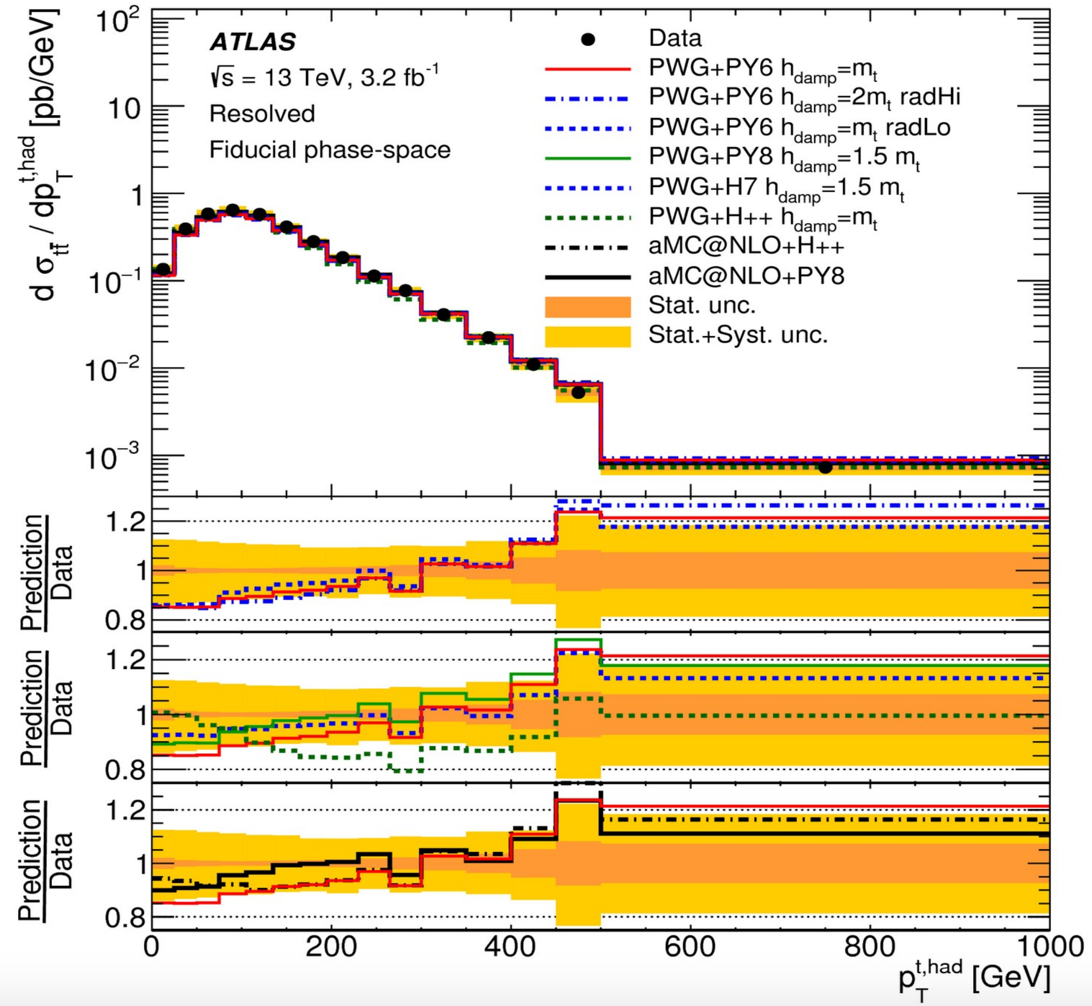
- construct leptonically decaying W from lepton and E_T^{miss}
- b-jet with smallest ΔR to lepton

Hadronic pseudo-top:

- construct W from remaining two highest-p_T jets
- use remaining b-jet

Differential

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



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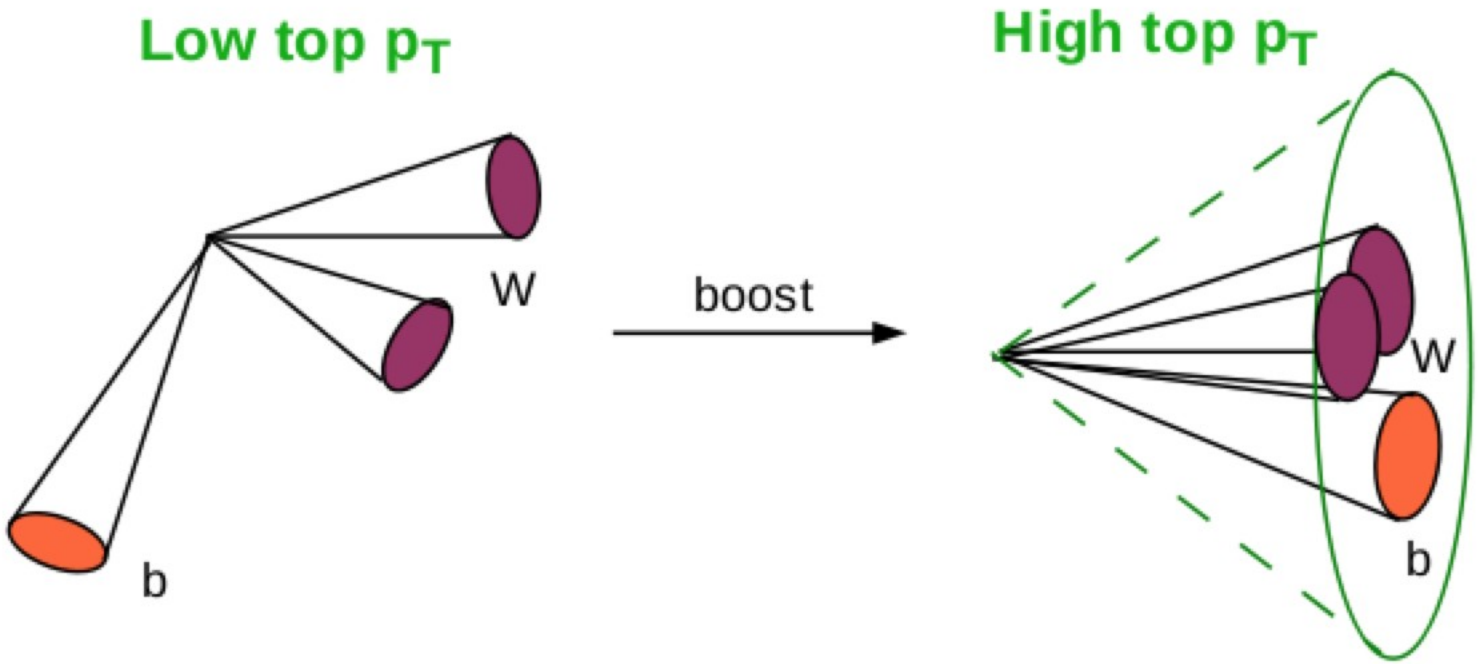
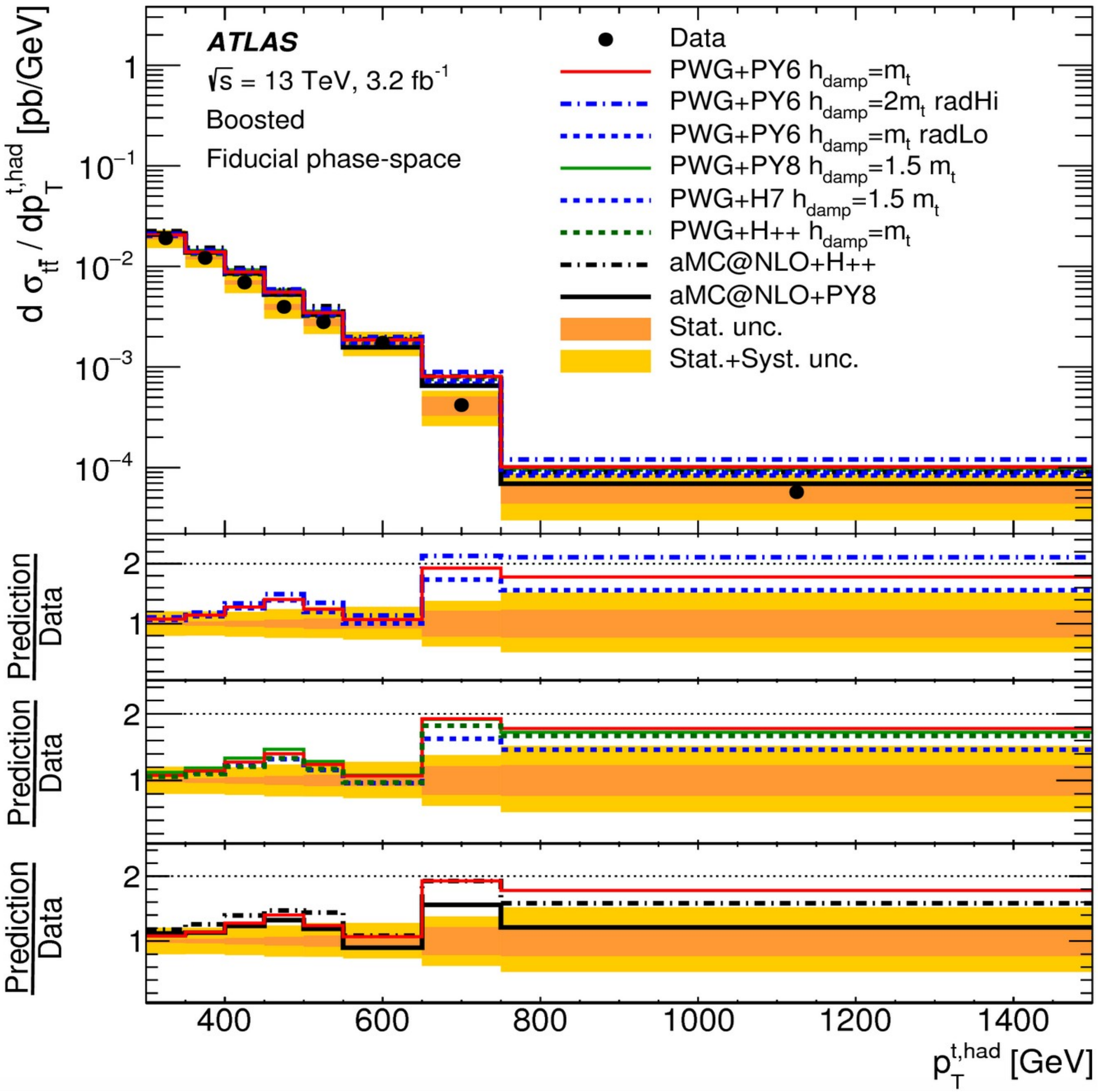
Boosting algorithms

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



Boosting

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



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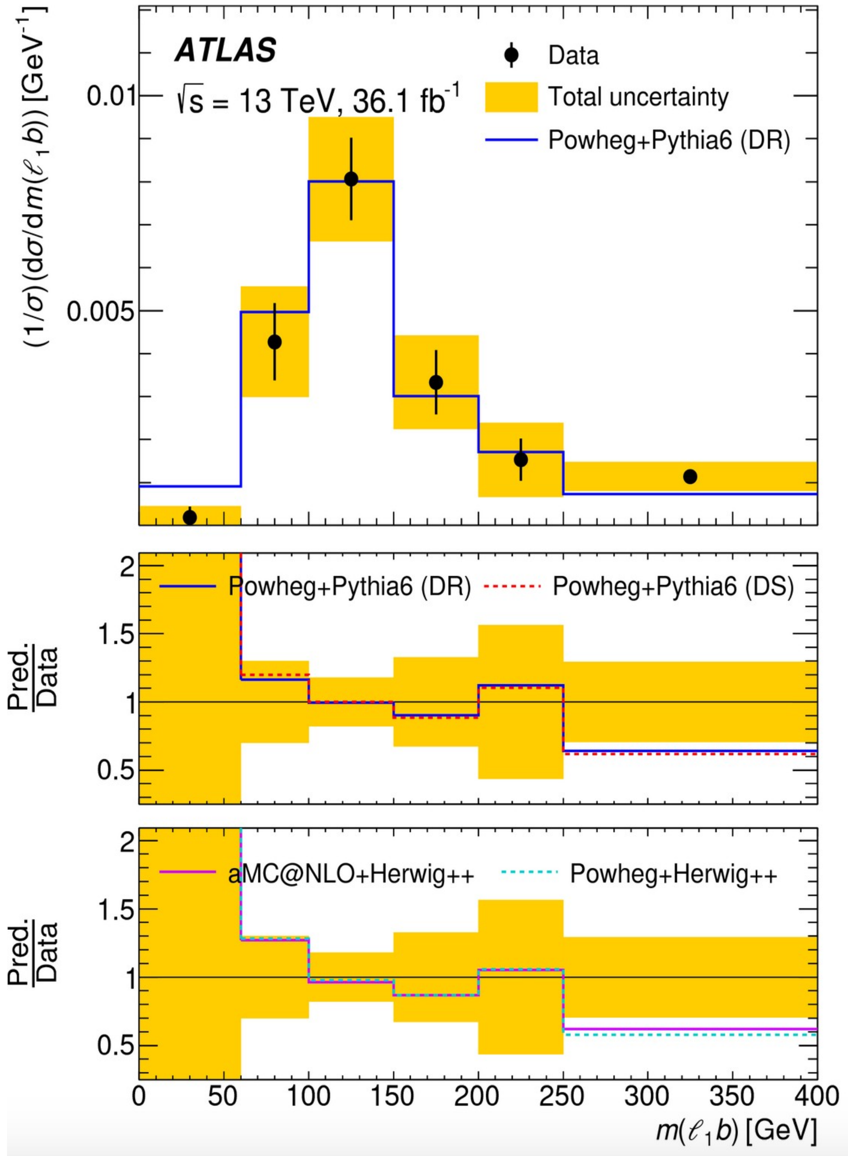
Differential Distributions in single top

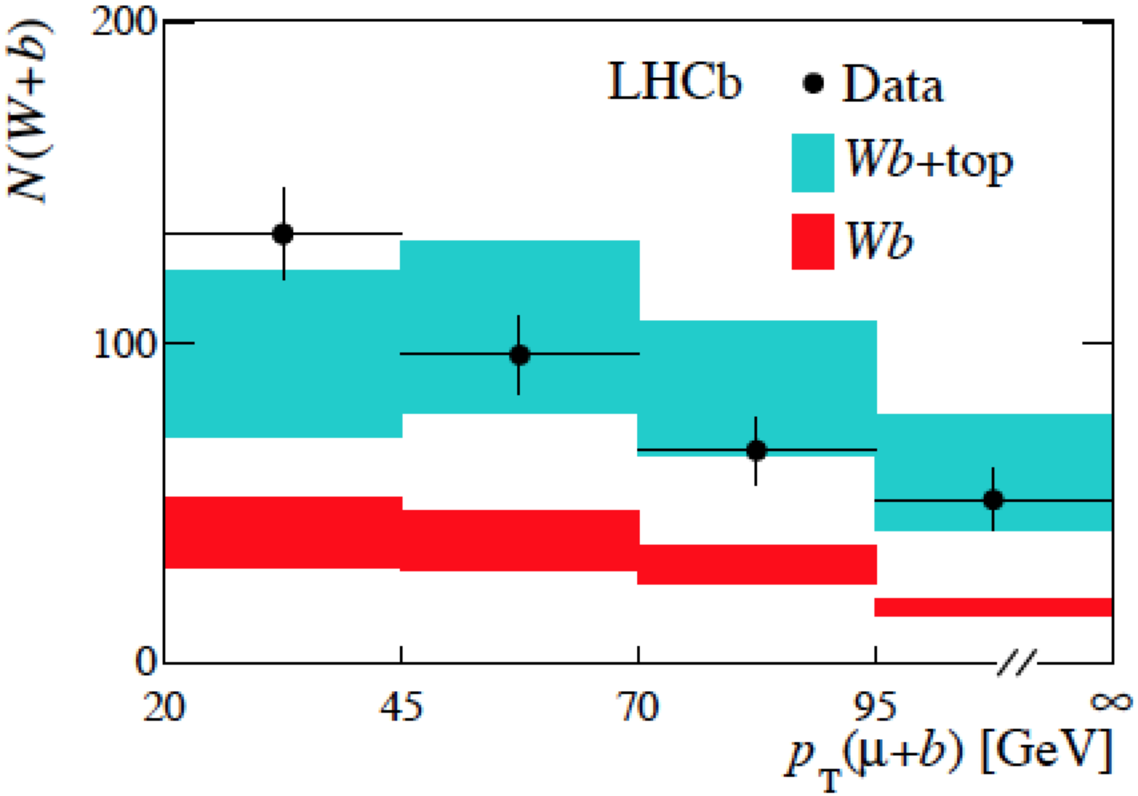
- Now also possible to perform differential measurements in single top!

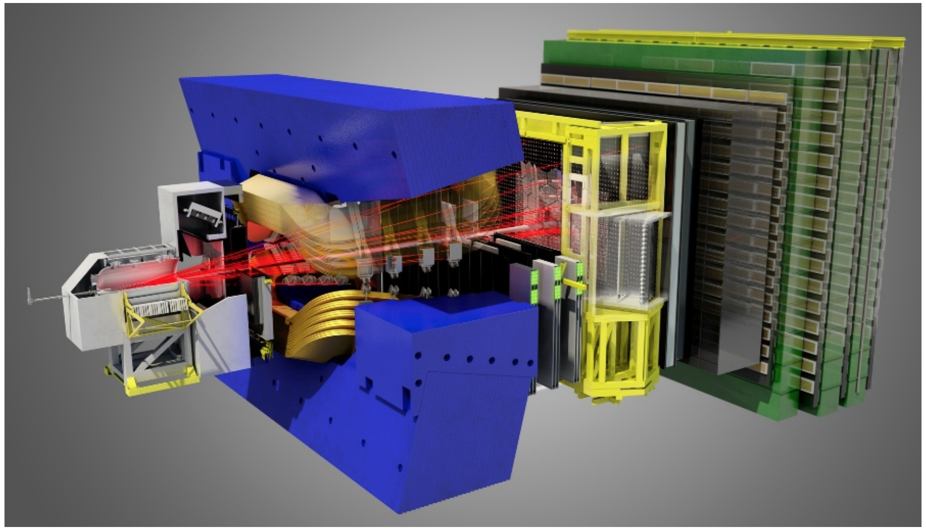


arXiv:1712.01602

Another Run I Top result!

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





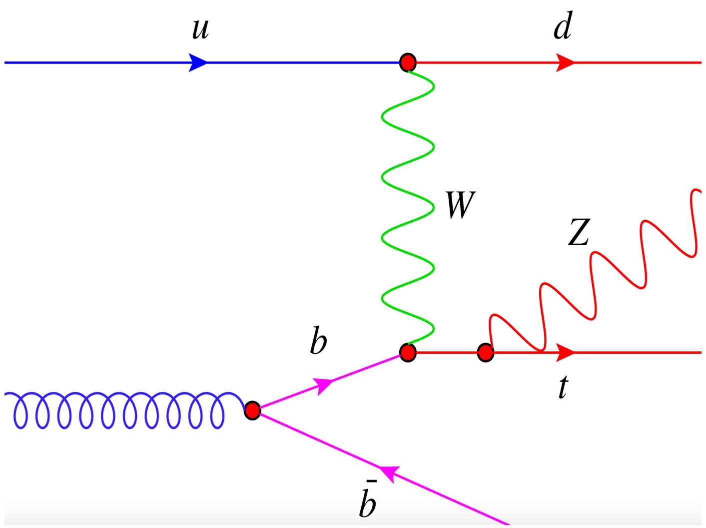
arXiv:1506.00903

Properties

Overview

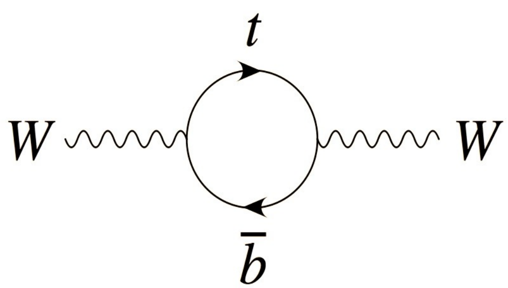
- Many important properties measured
  → comparison to calculation: test for BSM!

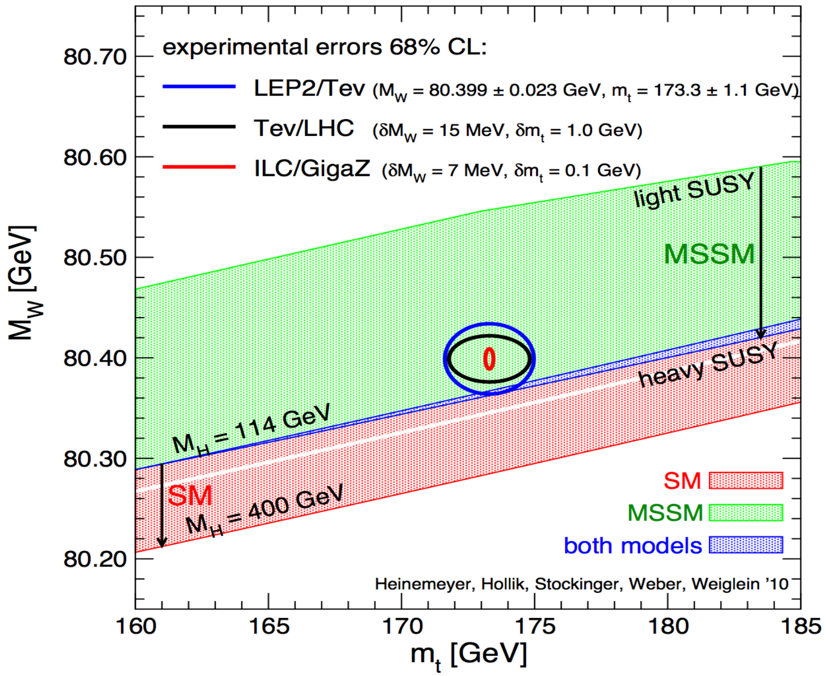
- From top mass to W helicity, spin correlations, charge, couplings...
  → the top has been tested extensively
  → nonetheless: still room to test more!
  - More precision
  - More properties
  - More “resolution”
  - New processes becoming measurable
    - e.g. tZ

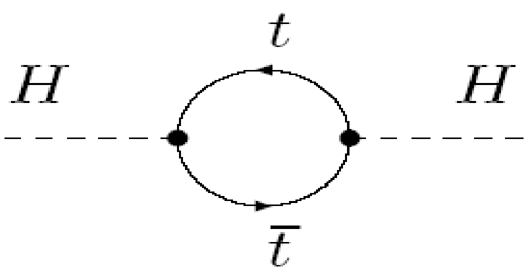


Top Quark Mass

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



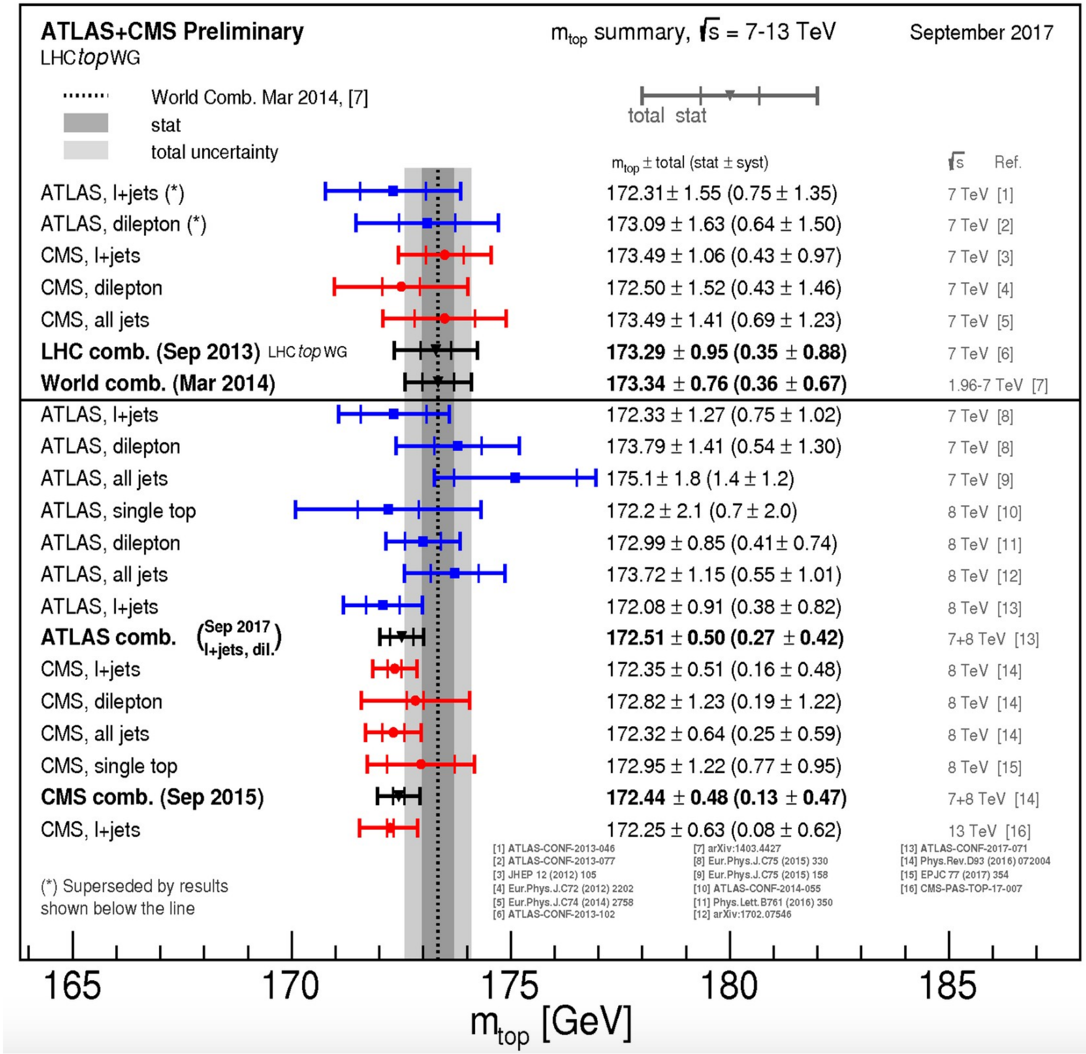




- Measurement done with several methods: Template method, ideogram, matrix element, etc.
    - Methods also used for other analyses, e. g. W helicity & spin correlations

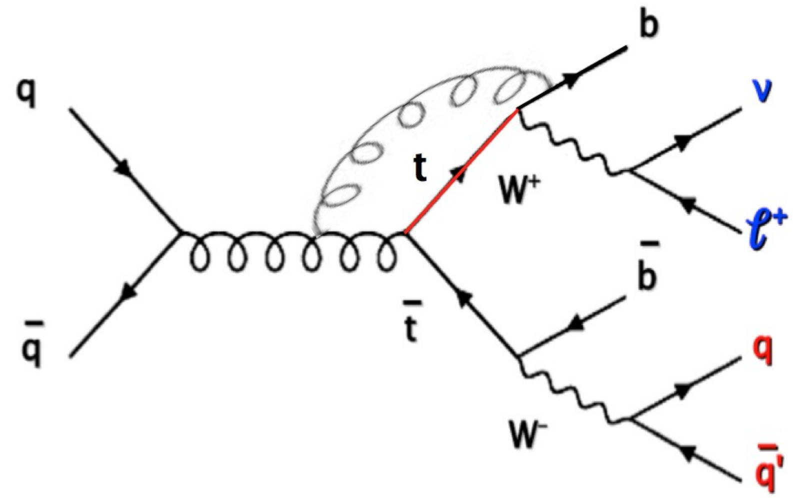
Top Mass

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



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:

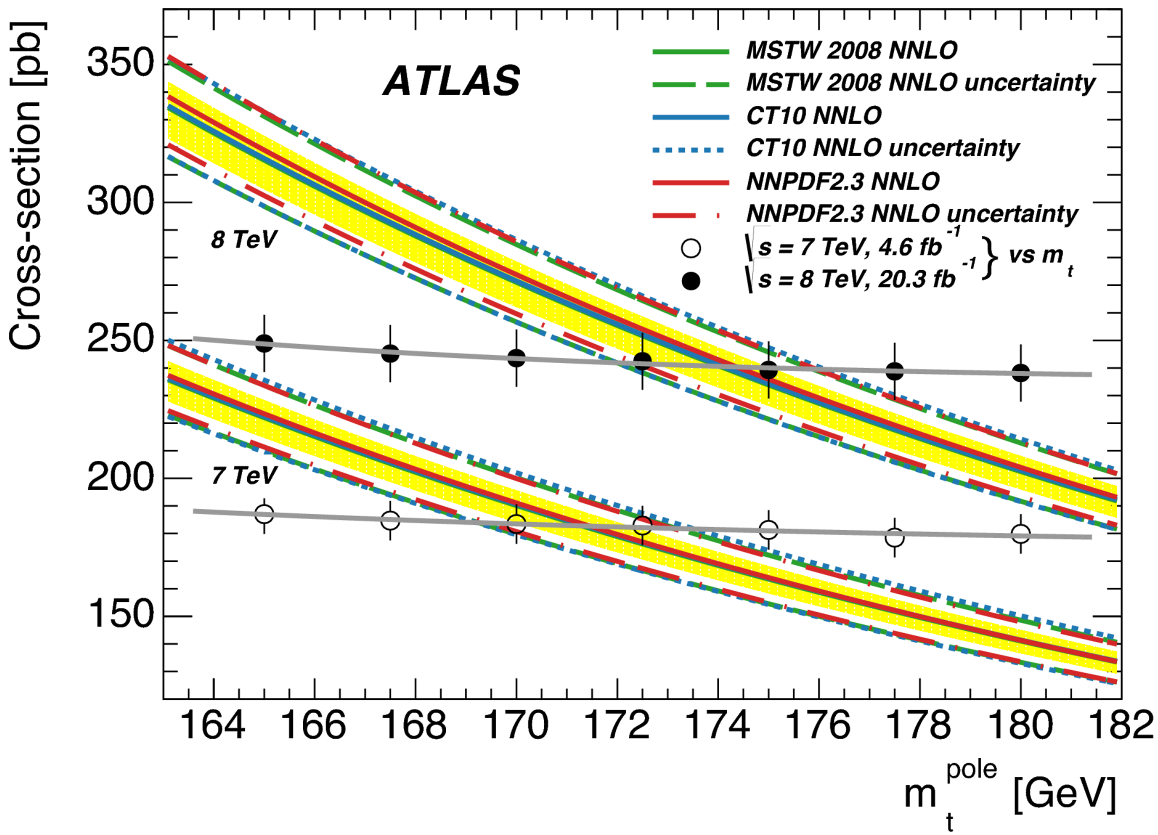


- Task mainly for theorists
- Experimentally: explore alternative methods

Top Quark Mass: Be aware

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

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



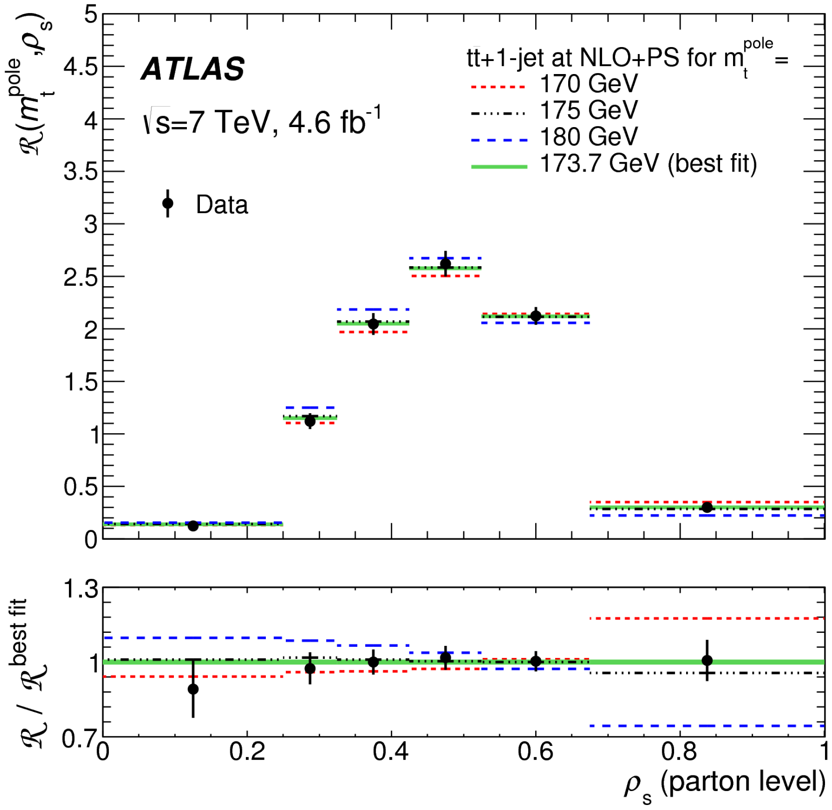
Eur.Phys.J. C74 (2014) 3109

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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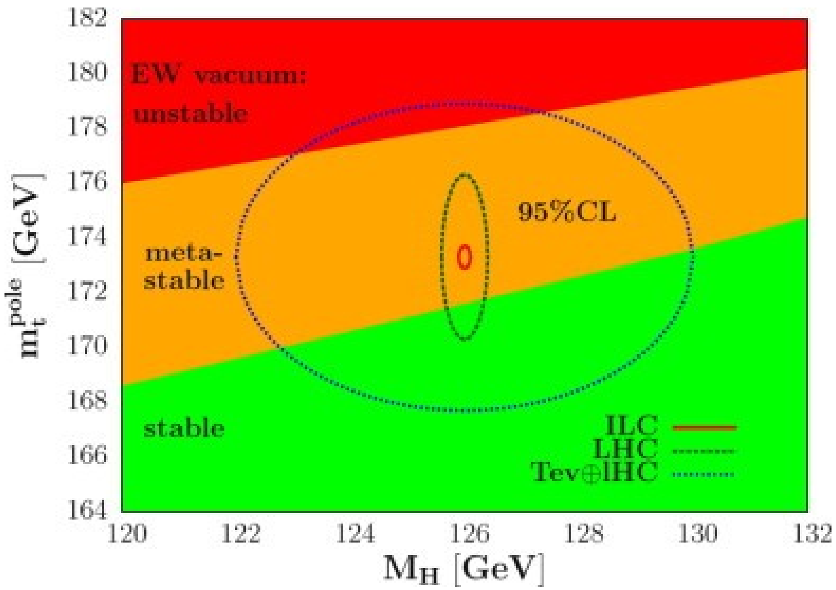
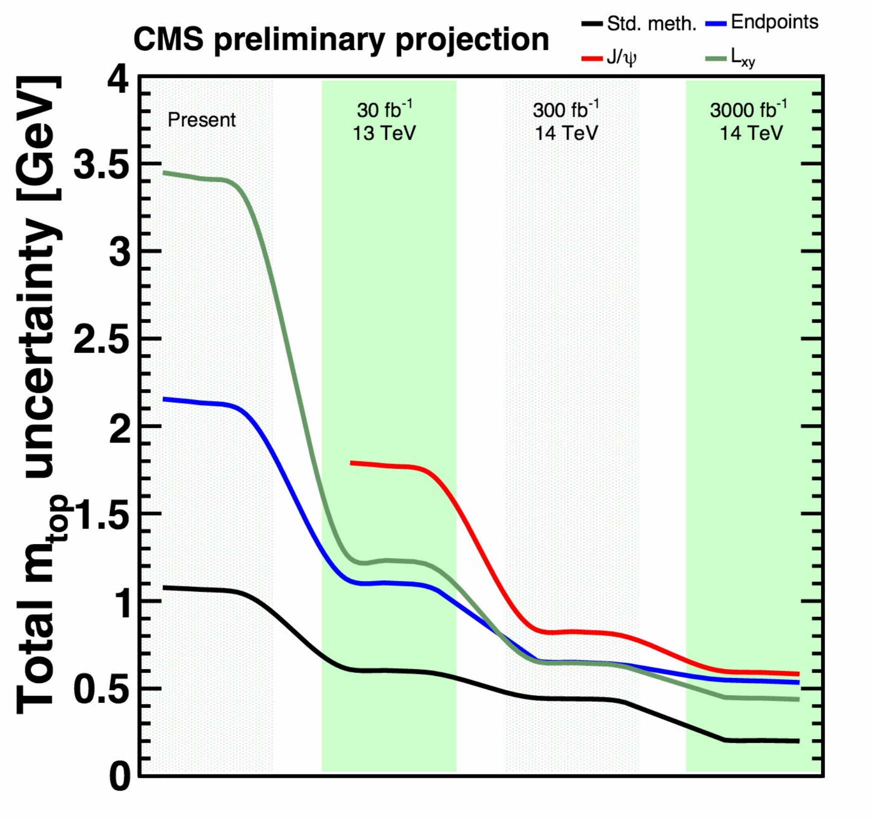
Mass

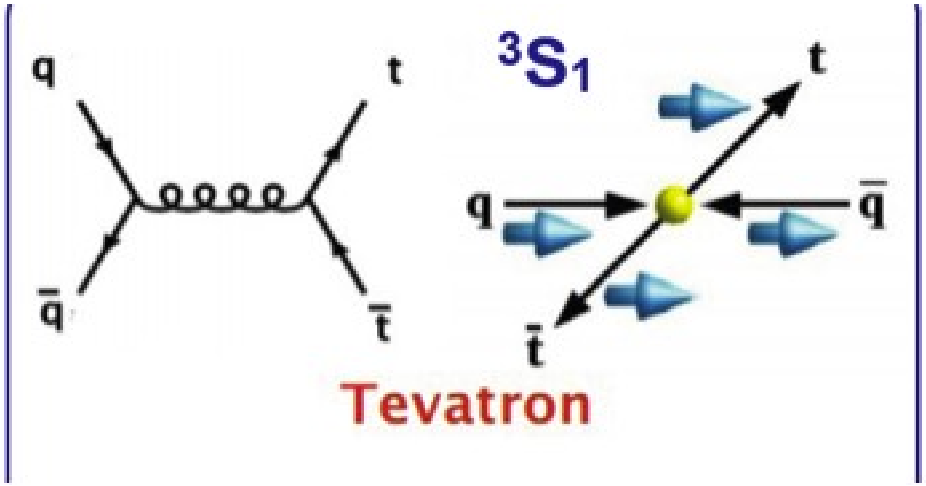
- Aim at improved precision!
  - Fate of the universe!
    → top-Higgs coupling important
    → $t\bar{t}H$!

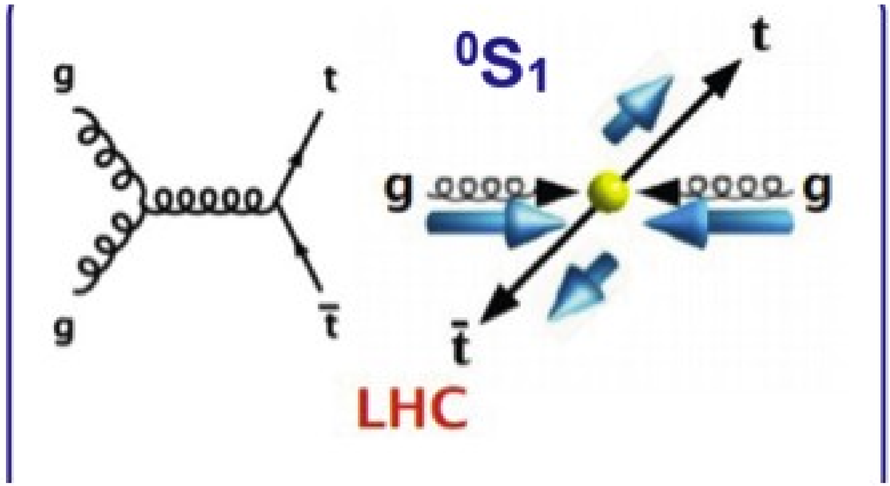




Spin Structure

- Top decays before hadronisation
  → allows spin structure of a quark to be measured directly
- Problem: production of $t\bar{t}$ at hadron colliders is unpolarised
  → all spin states randomly possible
- Feature that allows notheless to access spin information: spin between top and antitop are correlated!
- Dominant at Tevatron: Dominant at LHC:



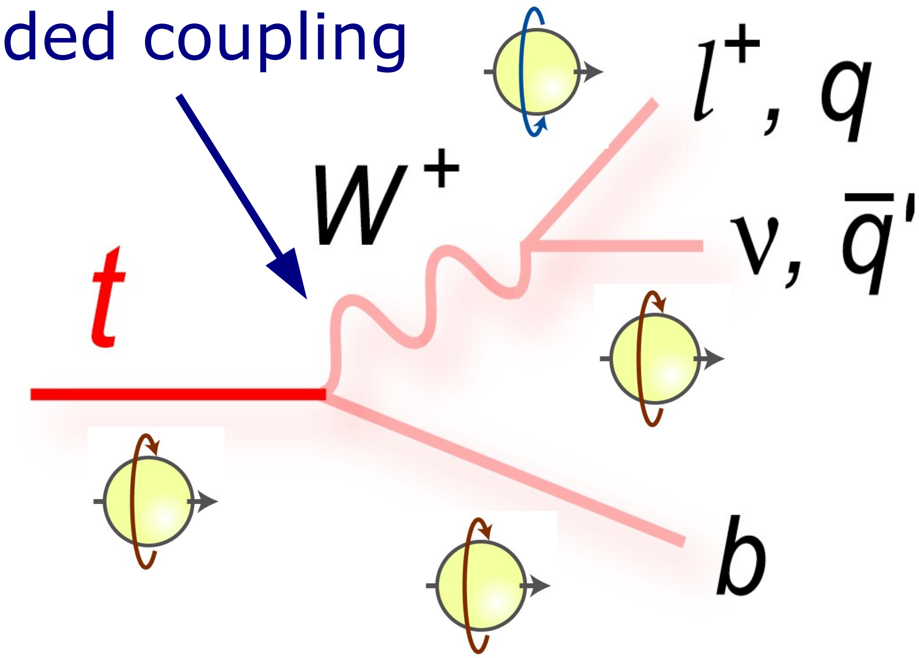


Notation: $^{2s+1}L_J$; s: spin; J total angular momentum; L: orbital angular momentum (S for ℓ=0)

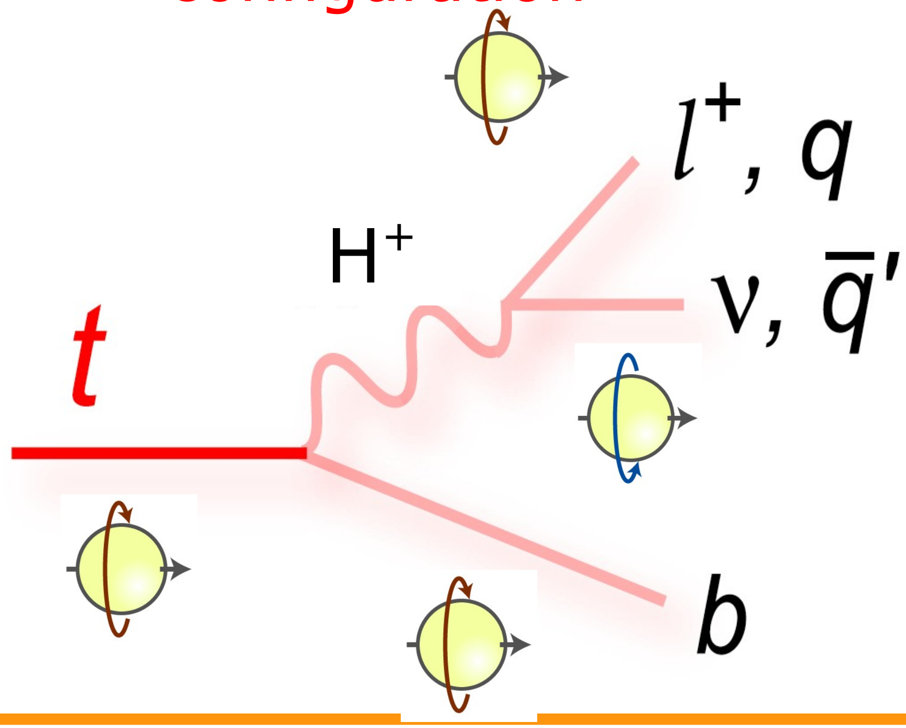
Measurement of Spin Correlations

- Spin correlations allows not only to access if there is new physics in production, but also decay!
- Short lifetime of top quarks (~$0.5*10^{-25}$s)
  → Top quarks decay before fragmentation
  - Spin information of top is preserved

Left-handed coupling

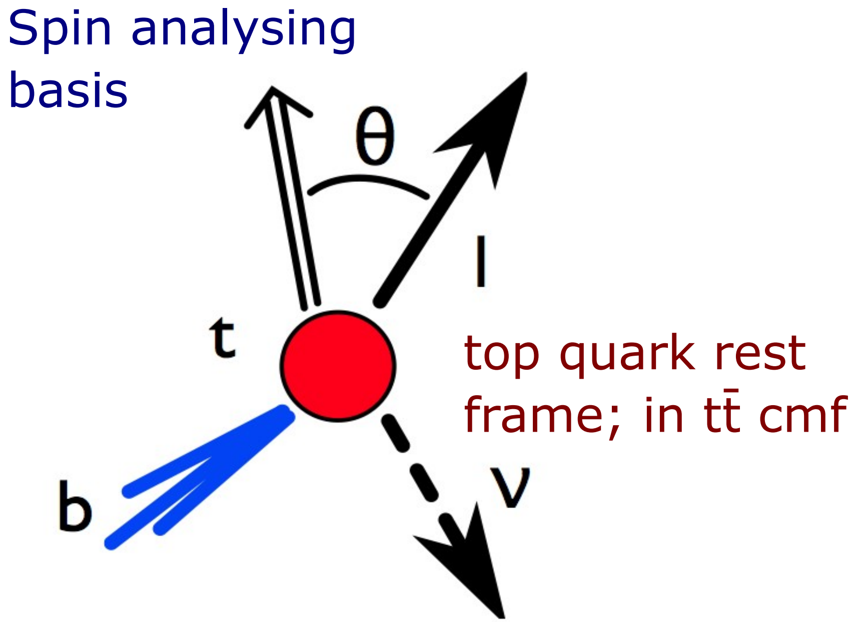


New Physics in decay could change configuration



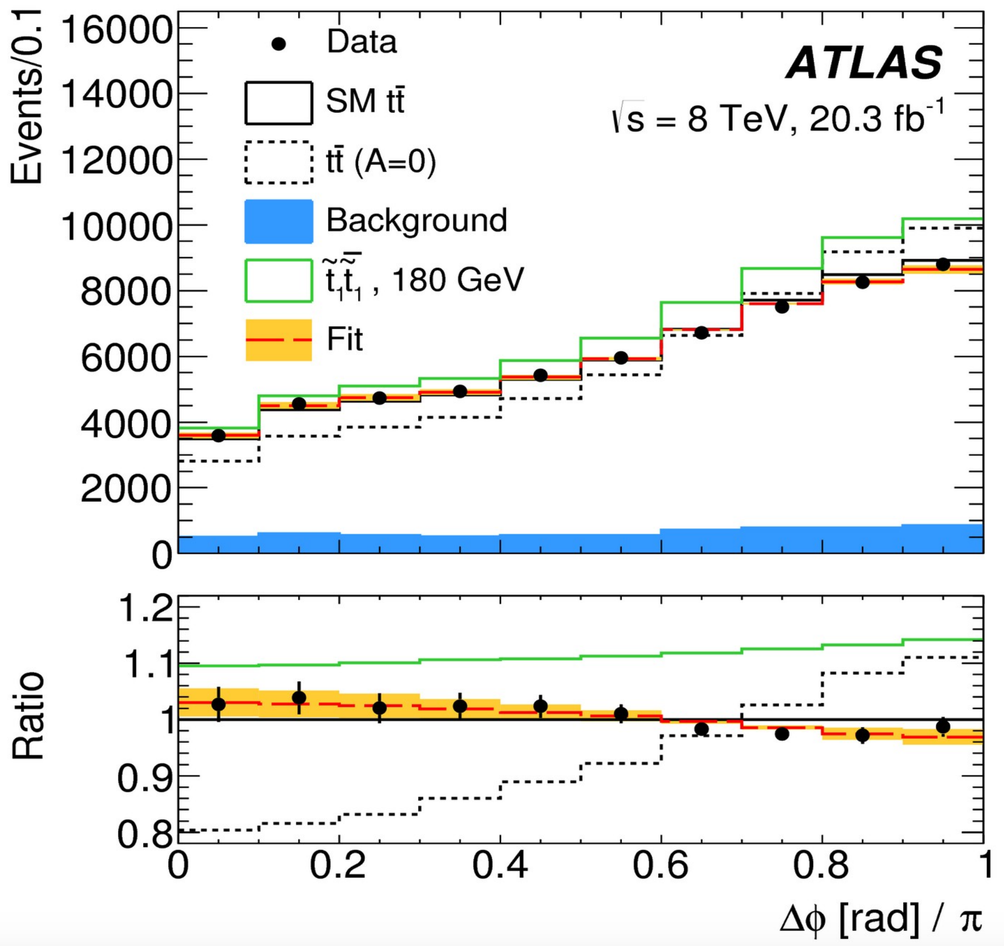
Measurement of Spin Correlations

- Measurement by looking at angular distributions between the down-type fermions from the W^+ and W^- decays from $t\bar{t}$ decays
  - Any deviation from SM expectation would hint at new physics in production or decay!
- Different sensitive variables at Tevatron and LHC



Spin Correlations

- All measurements in good agreement with SM
- But need more data to become more sensitive
  - Can be used for new physics searches: for example stop



Future

The Top Future

- Despite the large progress: much to do
  → many BSM models: top plays a special role

- Production: precision differential distributions allow precision tests of QCD/EW interaction

- Properties:
  - test of BSM admixtures/influence
  - Top mass: free parameter → influence o many BSM predictions

- Direct searches: many BSM models to look for in the top sector
  - Example: $t\bar{t}t\bar{t}$ getting interesting → test for extended Higgs sectors

Summary

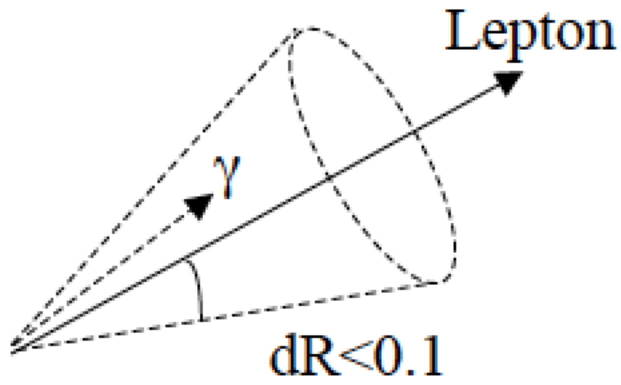
- What have hadron colliders done for us?
  → they brought us
  - Top discovery
  - Precise understanding of the top quarks
  - A window to new physics

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

Backup

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