Top Physics at Hadron Colliders

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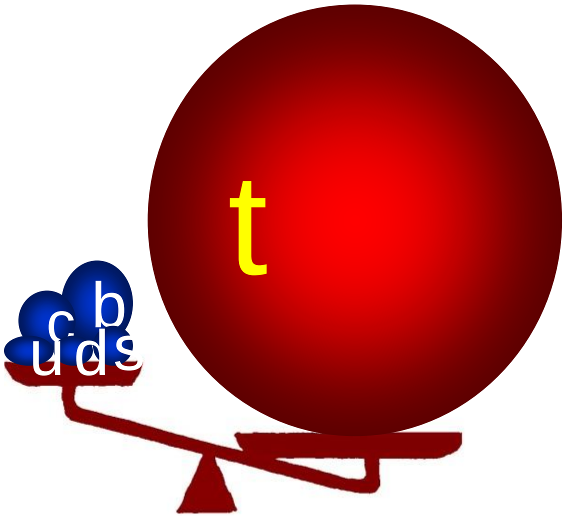
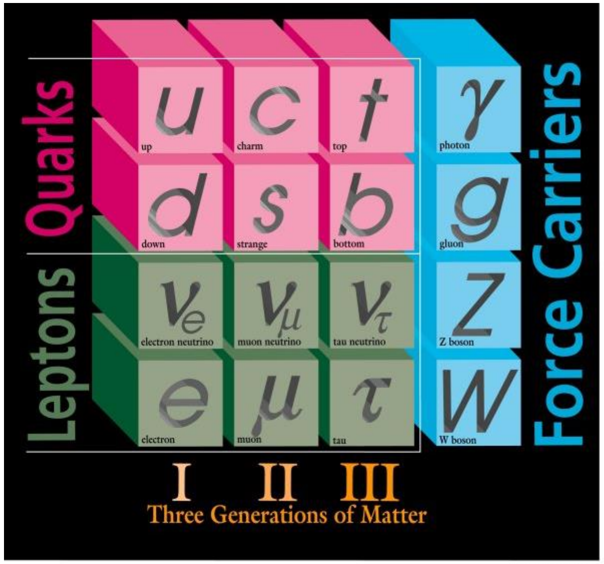
Gottingen HASCO School 2018

Outline

- Motivations for studying top
- A brief history
- Top production and decay
- Identification of final states
- Cross section measurements
- Mass determination
- Single top production
- Study of top properties

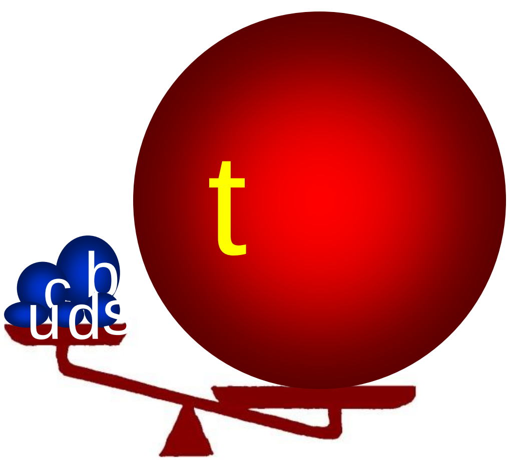


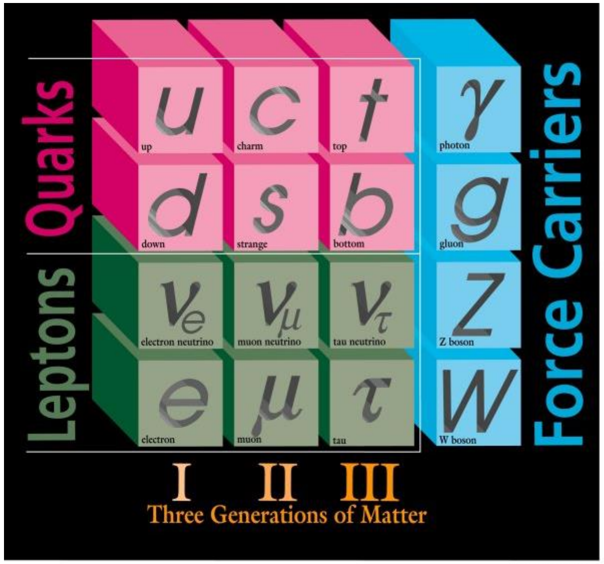


Fermilab 95-759

Motivations for Studying Top

- Only known fermion with a mass at the natural electroweak scale.
- Similar mass to tungsten atomic # 74, 35 times heavier than b quark.
  - ⇒ Why is Top so heavy?
  - ⇒ Is top involved in EWSB?
    - ⇒(Does $(2 \sqrt{2}\, G_F)^{-1/2} \approx M_{top}$ mean anything?)
  - ⇒ Special role in precision electroweak physics?
  - ⇒ Is top, or the third generation, special?
- New physics BSM may appear in production (e.g. topcolor) or in decay (e.g. Charged Higgs).





Pre-history of the Top quark

1964 Quarks (u,d,s) were postulated by Gell-Mann and Zweig, and discovered in 1968 (in electron – proton scattering using a 20 GeV electron beam from the Stanford Linear Accelerator)

1973: M. Kobayashi and T. Maskawa **predict the existence of a** third generation of quarks to accommodate the observed violation of CP invariance in K_0 decays.

1974: Discovery of the J/ψ and the fourth (GIM) "charm" quark at both BNL and SLAC, and the τ lepton (also at SLAC), with the τ providing major support for a third generation of fermions.

1975: Haim Harari names the quarks of the third generation "top" and "bottom" to match the "up" and "down" quarks of the first generation, reflecting their "spin up" and "spin down" membership in a new weak-isospin doublet that also restores the numerical quark/ lepton symmetry of the current version of the standard model.

1977: discovery of the fifth b quark at Fermilab (bound with the b antiquark in Y states of quarkonium), offering new evidence for the existence of a sixth **t quark** needed to complete this isospin doublet

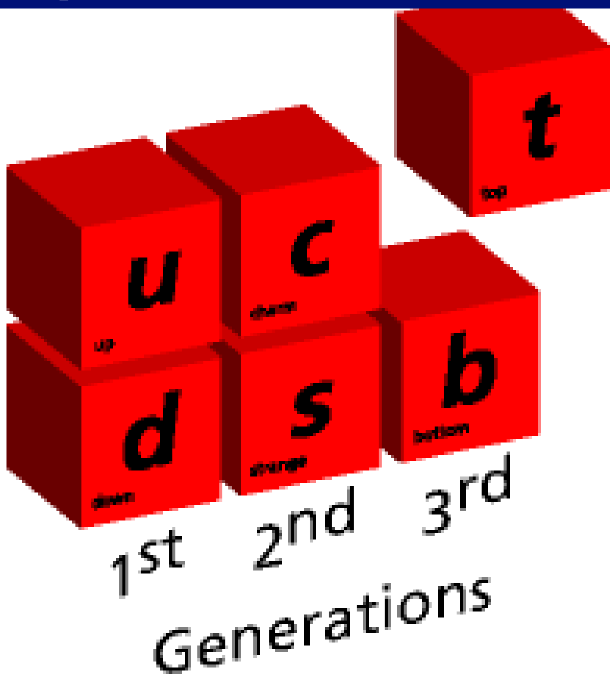
→ race to find the top quark starts

A Brief History of Top

- Top quark was expected in the Standard Model (SM) of electroweak interactions as a partner of b-quark in SU(2) doublet of weak isospin for the third family of quarks

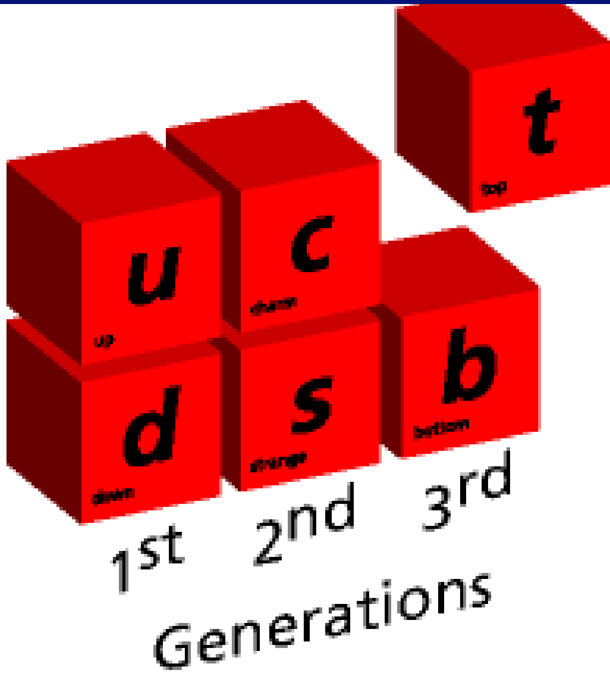
(weak isospin of b can be inferred from the forward-backward asymmetry in $e^+e^- \rightarrow b\bar{b}$)

- Anomaly free SM requires the sum of the family charges to be zero: given the b (and the tau lepton) there should be a 2/3 charge quark



- Everyone thought it likely that the top mass would be larger than m_b but few expected a factor of ≈35 for the ratio of the masses of these supposed isospin-partner quarks.
- And few, if any, expected that it would take so many years to finally confirm the existence of the top quark

A Brief History of Top II



- Initial searches for the top quark started quickly, and negative results came from e^+e^- colliders at SLAC, DESY and KEK.

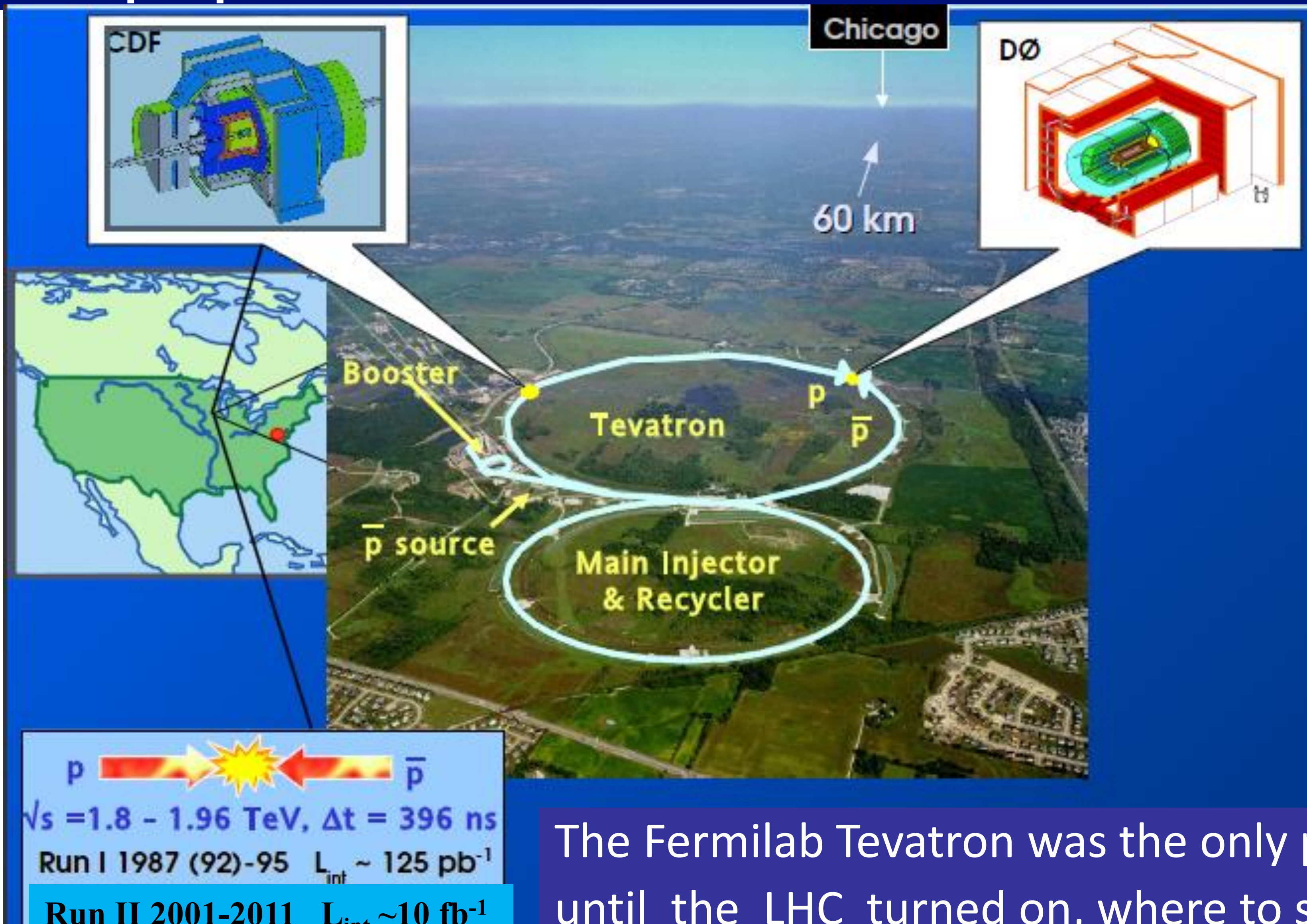
Petra (e+e-) at DESY, Hamburg, m_t > 23.3 GeV (1984)

Tristan (e+e-) in Japan: m_t > 30.2 GeV (late 1980s)

- Following the observations of the W and Z bosons at the SPS $p\bar{p}$ collider at CERN in the early 1980s, there were claims of a discovery of the top quark in 1984 at the UA1 experiment consistent with a mass of 40 GeV (not confirmed by UA2). By 1988, this had turned into a limit (> 44 GeV)
- LEP (e+e-) at CERN: m_t > 45.8 GeV (1990)
- This is when the Fermilab Tevatron entered the scene, and for more than two decades before the start of LHC operations at CERN in 2010, it was the only place in the world with enough energy to produce top quarks.

• 1977-1994: increasing lower top mass limits

Top quark observation: at the Tevatron



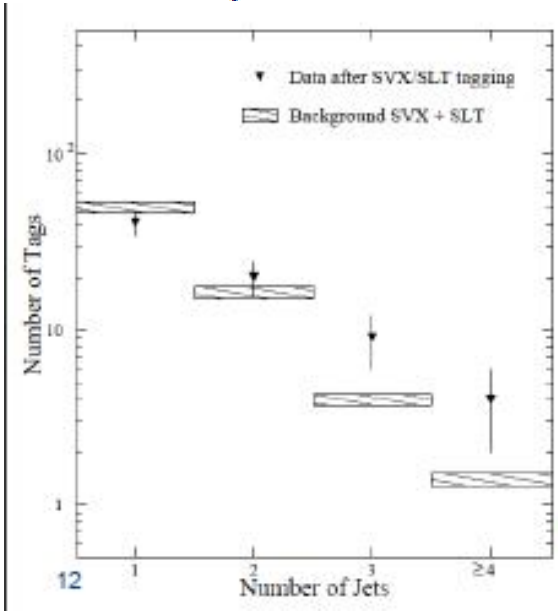
Run II 2001-2011 L_{int} ~10 fb^{-1}

The Fermilab Tevatron was the only place, until the LHC turned on, where to study the top quark.

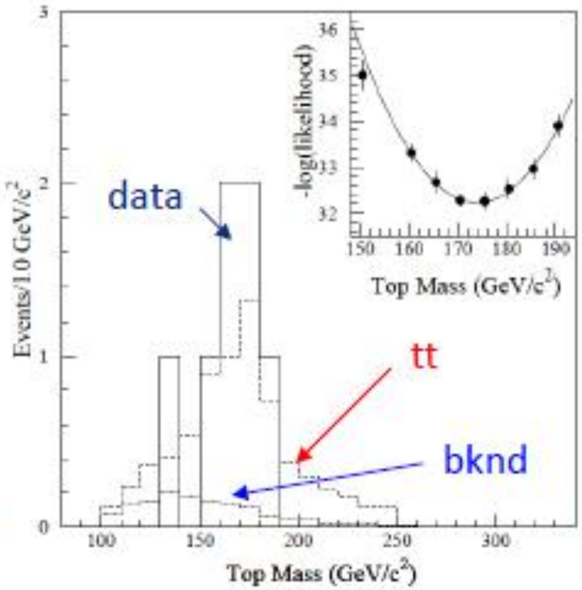
Top quark evidence (1994)

- First top evidence in 1994 in CDF data, 19 pb^{-1}, 12 events on a background of 6, (PRL 73,225(1994)) "Evidence for Top Quark Production.."
  - 2.8 σ excess, not enough to claim discovery

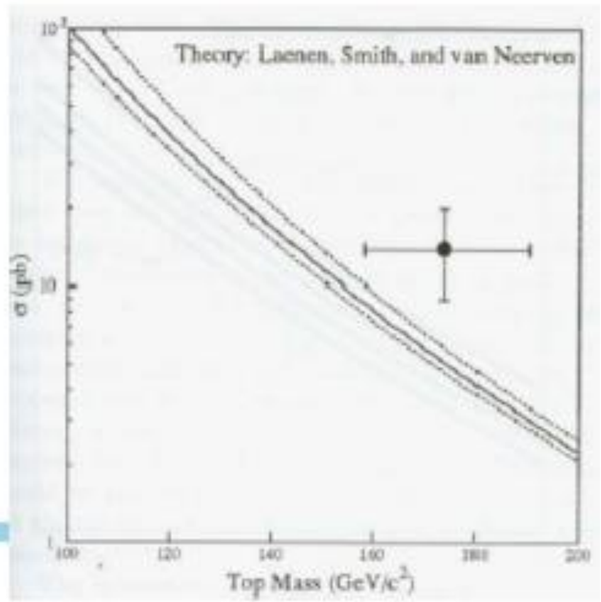
Excess over expectation appears for ≥3 jets



Mass fit from MC templates yields 174 ± 16 GeV



Cross section, σ=13.0 $^{+6.1}_{-4.8}$ pb, larger than the theoretical value of ~6 pb.



Top quark discovery (1995)

Physicists Discover Top Quark

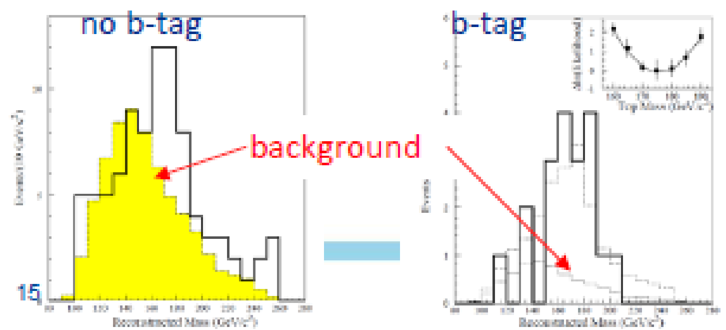
News Release - March 2, 1995

PHYSICISTS DISCOVER TOP QUARK

Evidence Confirmed in 1995 by CDF and D0 in first ~70 pb^{-1} of run 1 data (4.8 σ).

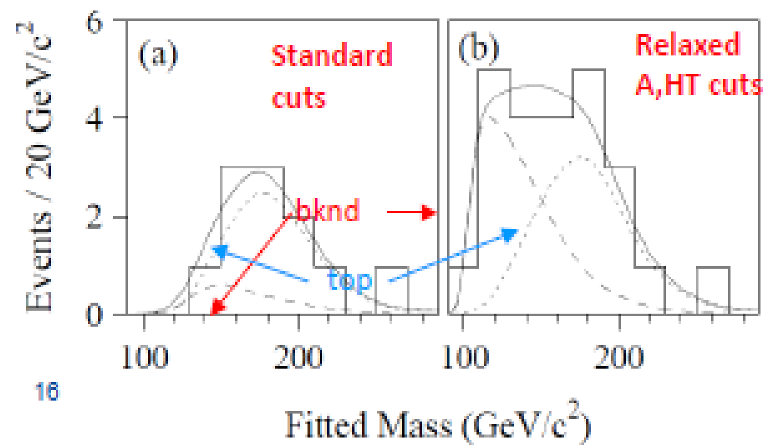
- **CDF top quark discovery**:
- found 6 dilepton events and 43 lepton+jets events (50 b-tags), with estimated background of 22.1±2.9 tags. (PRL74,2626(1995))
- **M_t = 176 ± 13 GeV σ_{tt} = $6.8^{+3.6}_{-2.4}$ pb**

Reconstructed mass distribution before and after b-tagging.



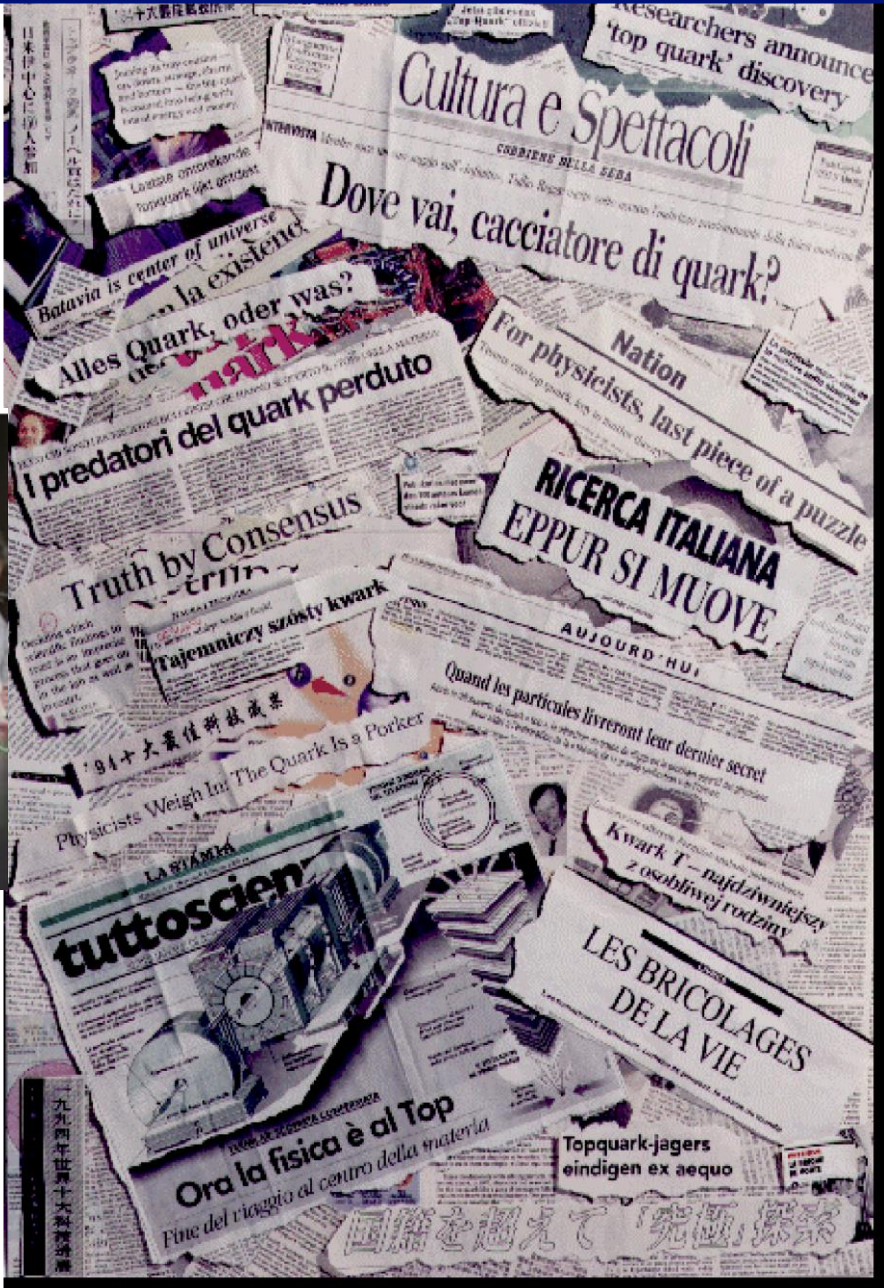
- **D0 top quark discovery**:
- found 3 dilepton events, 8 lepton+jets events (topological selection) and 6 lepton+jets events (μ tag). Estimated background to these 17 events was 3.8±0.6 events (PRL74,2632(1995))
- **M_t = 199±30 GeV σ_{tt} = 6.4±2.2 pb**

Reconstructed mass distribution



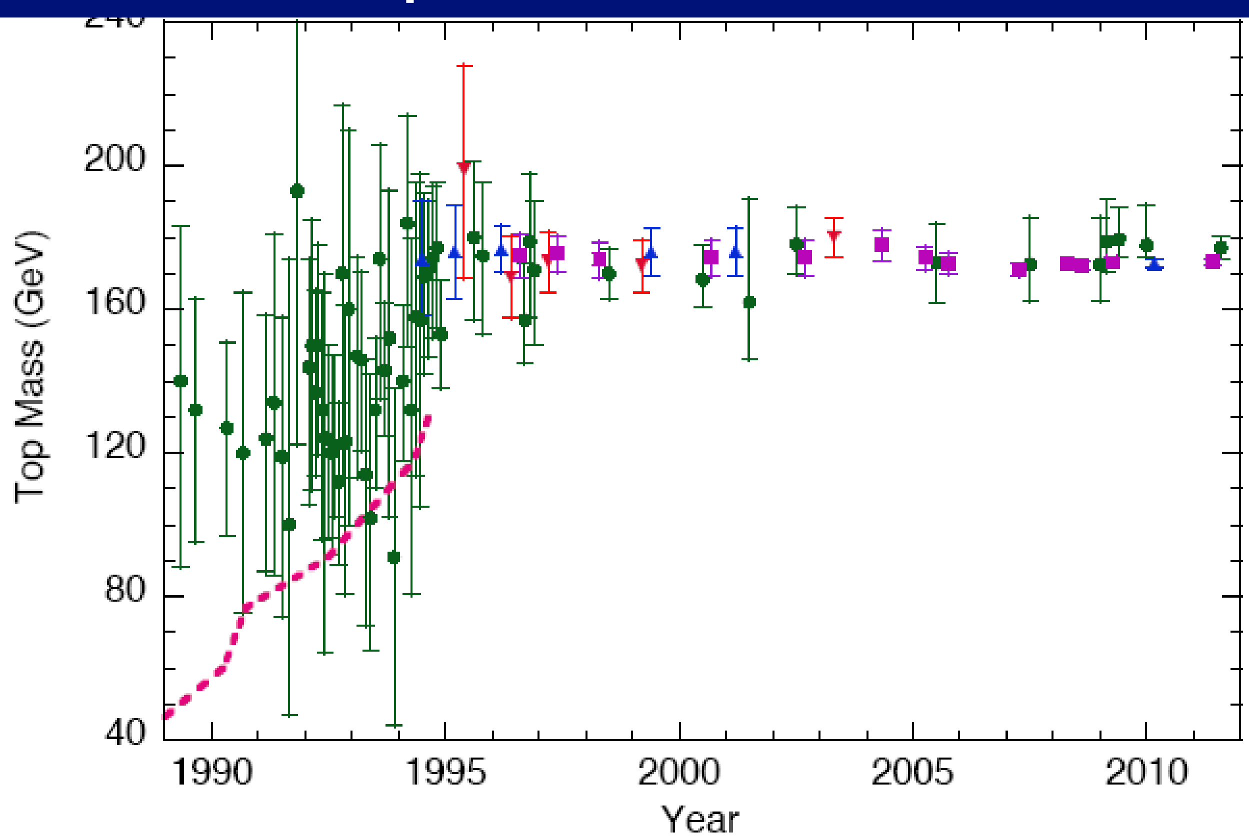
March 2nd 1995

Discovery is always exciting!!



Adding something to the core of human knowledge is profoundly satisfying.

Evolution of Top Mass Measurements (<2010)



Indirect estimates of mass of top quark from **fits to electroweak observables (green)**, and lower bounds at 95% CL on m_{top} from direct searches in ppbar collisions at CERN and at the **Tevatron (broken line),** assuming standard W->bt or t->bW decays. Results on m_{top} from **CDF (up-triangle)** and DØ **(down-triangle),** and **mean m_{top} (purple square).**

Top Quark is now "standard"!

A Brief History of Top (2011-2018)

- Tevatron Run 2 ends in 2011 after 26 years of successful operation: 10 fb^{-1} collected in Run II by each experiment
- LHC Run 1 starts in 2010 at 7 TeV : 5 fb^{-1} collected in 2011
- 2012: the energy is increased to 4 TeV per beam (8 TeV in collisions)
- 2015: RunII starts at 13 TeV
- LHC is a top factory

No. of produced $t\bar{t}$ events

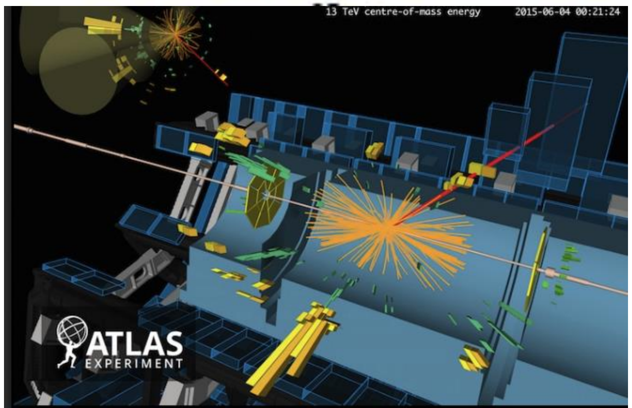
2011: ~800k (4.6/fb, 7 TeV)
2012: ~5.1 million (20.3/fb, 8 TeV)
2015: ~2.6 million (3.2/fb, 13 TeV)

Since 2016: > 30 million per year (36/fb, 13 TeV)

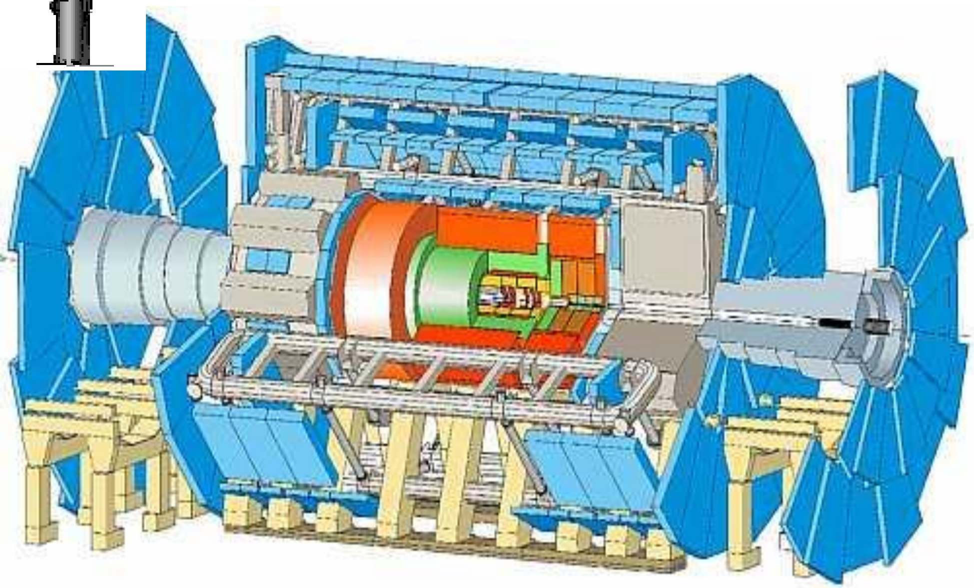
The Large Hadron Collider:

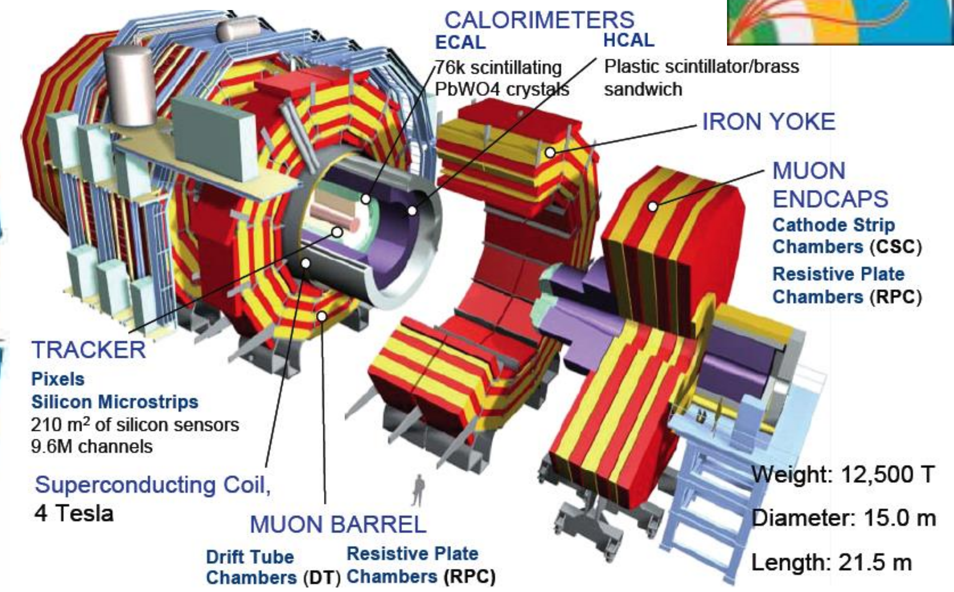
- proton−proton collider
- high energy: $\sqrt{s}$ = 7 TeV
- since 2012: $\sqrt{s}$ = 8 TeV
- 2014−2030??: $\sqrt{s}$ = 13 TeV

- Tevatron produced ten t-tbar pair per day
- LHC: one t-tbar pair per second
- Top quark is one of the major subject of study at LHC



ATLAS and CMS Detectors





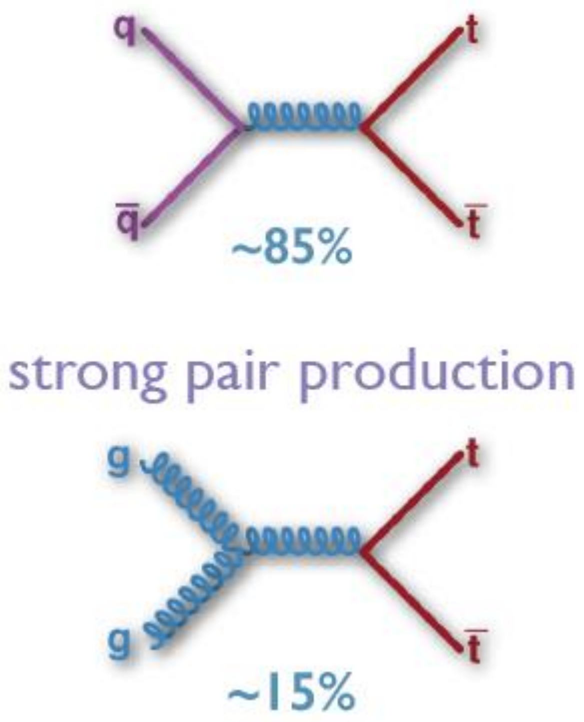
	Weight (tons)	Length (m)	Height (m)
ATLAS	7,000	42	22
CMS	12,500	21	15

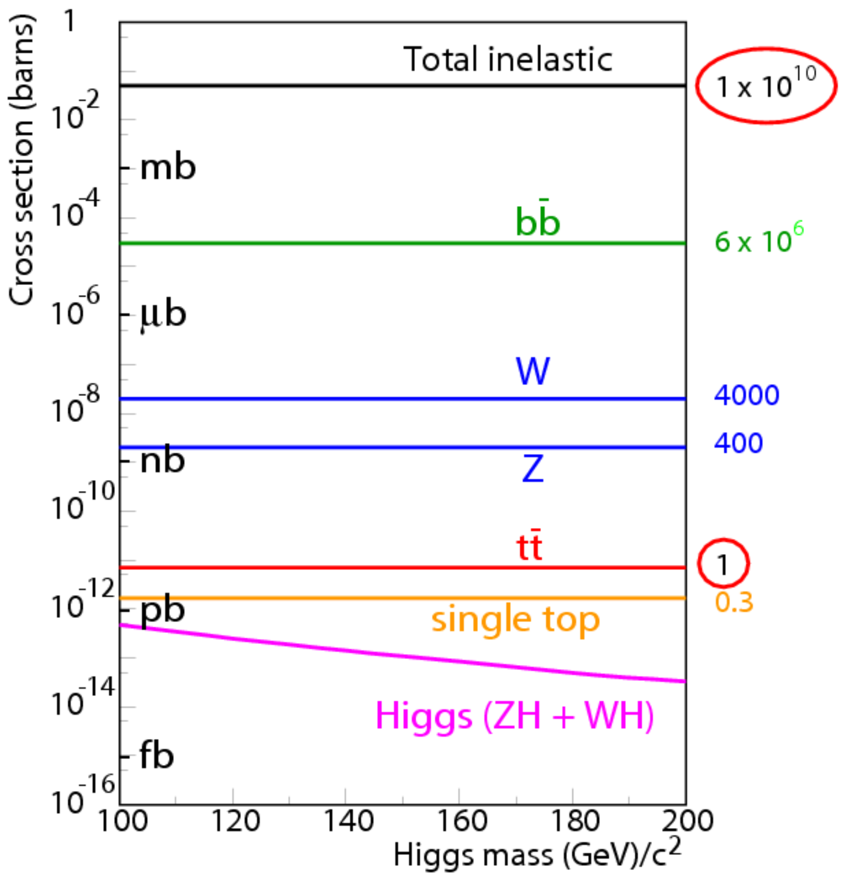
~3000 Scientists per experiment
+ many engineers and technicians

How is top quark produced?

Tevatron: preferentially top Pair Production

$\sigma_{SM} \sim 7.35\ pb$



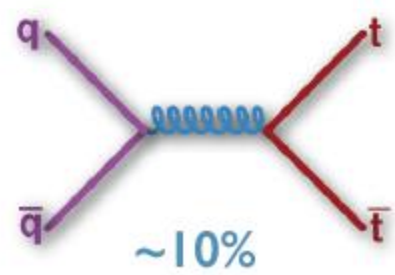


One top pair each 10^{10} inelastic collisions at $\sqrt{s}$ = 1.96 TeV

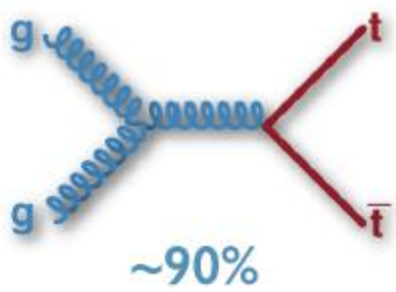
How is top quark produced?

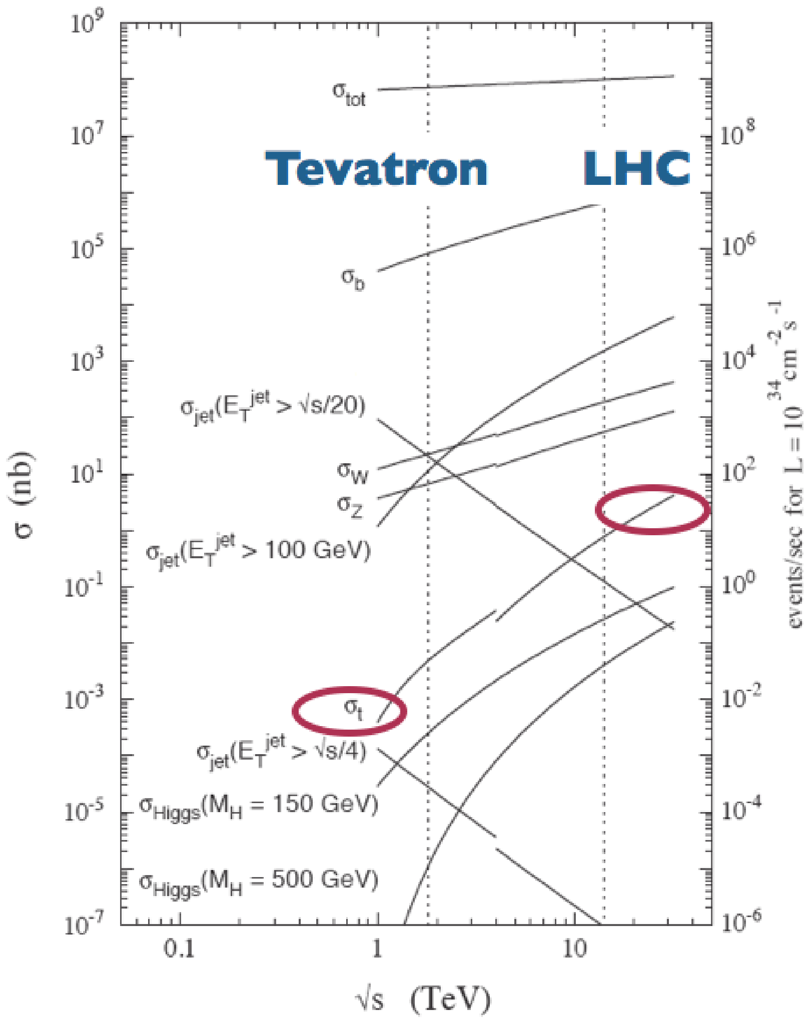
LHC (13 TeV) preferentially
top Pair Production

$\sigma_{SM} \sim 830\,\text{pb}$



strong pair production





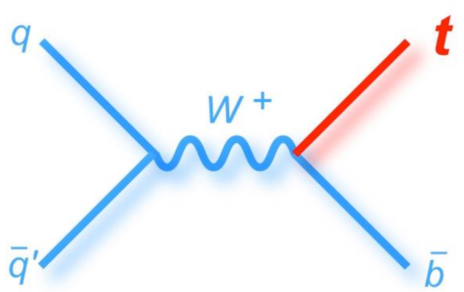
One top pair each 10^8 inelastic collisions at √s = 13 TeV

LHC is a top factory!!

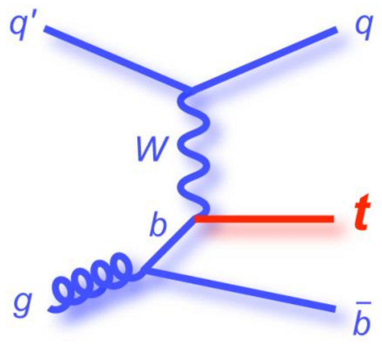
How is top quark produced?

- Top quark can be produced also singly, via electroweak interactions, with a smaller cross section, at both Tevatron and LHC
- Single top observed for the first time at the Tevatron in 2009 (see later…)

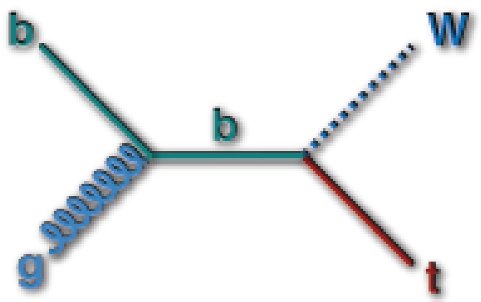
s-channel



t-channel



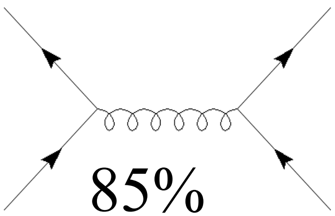
Wt-production



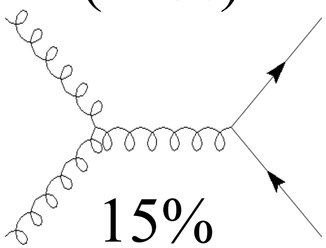
Production and Decay Basics

At the Tevatron and LHC top quarks are mainly pair produced via strong interaction:

SM predicts: BR($t \to Wb$) ≈ 100%

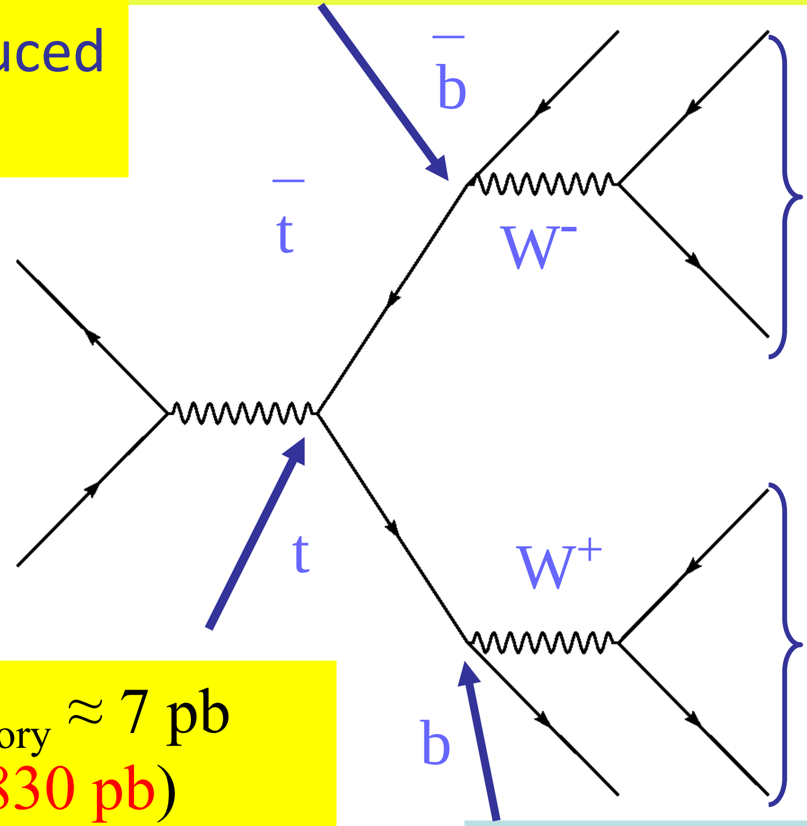


85% (10%)



15% (90%)

NB: qq, gg fractions reversed at LHC



$\sigma_{theory} \approx 7$ pb
($\approx$ 830 pb)
QCD predicts cross section well

Event topology determined by the decay modes of the 2 W's (W^+W^-) in final state

b-jet: identify via secondary vertex or soft lepton tag

Top Decay : add. Motivation for Studying Top

- **In the SM, assuming V-A coupling:**

$$\Gamma(t \to d_j W^+) \sim |V_{tj}|^2 \frac{G_F m_t^3}{8\pi\sqrt{2}}$$

assuming $|V_{tb}| = 1$ for the $t \to bW$ decay vertex, one gets (LO):

$$\Gamma(t \to bW) \approx 175 \text{ MeV } (M_T/M_W)^2 \quad (M_T, M_W >> M_b)$$

$$\Rightarrow \Gamma(t \to bW) \approx 1.5 \text{ GeV } (> \Lambda_{QCD}) \Rightarrow \tau(\text{top}) \approx 5 \times 10^{-25} \text{ s}$$

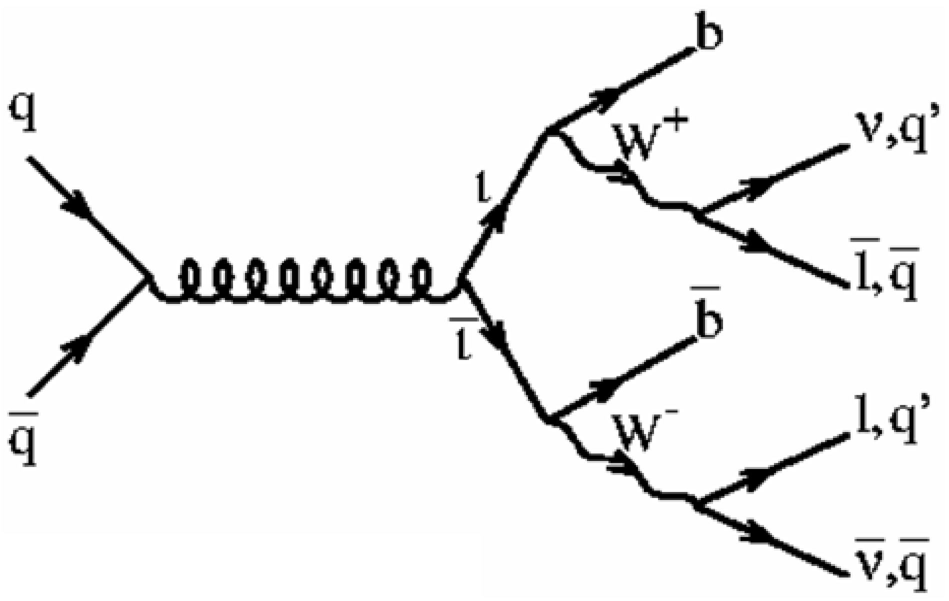
- Non-perturbative QCD hadronization takes place in a time of order: $\Lambda^{-1}_{QCD} \sim (100 \text{ MeV})^{-1} \sim 10^{-23}$ s
  - **top decays before hadronizing, as free quark (no top hadrons, no toponium spectroscopy)**
  - **the top quark provides the first opportunity to study the decay characteristics of a “bare” quark.**
- $t \to Ws$, $t \to Wd$ allowed but suppressed by factors of $\sim 10^{-3}$ and $\sim 5 \times 10^{-5}$ respectively

How to identify the top quark

SM: $t\bar{t}$ pair production, Br($t \rightarrow bW$)=100% , Br($W \rightarrow l\nu$)=1/9=11%

dilepton	*(4/81)*	2 leptons + 2 jets + missing E_T
lepton+jets	*(24/81)*	1 lepton + 4 jets + missing E_T
fully hadronic	*(36/81)*	6 jets

(here: l=e,μ)



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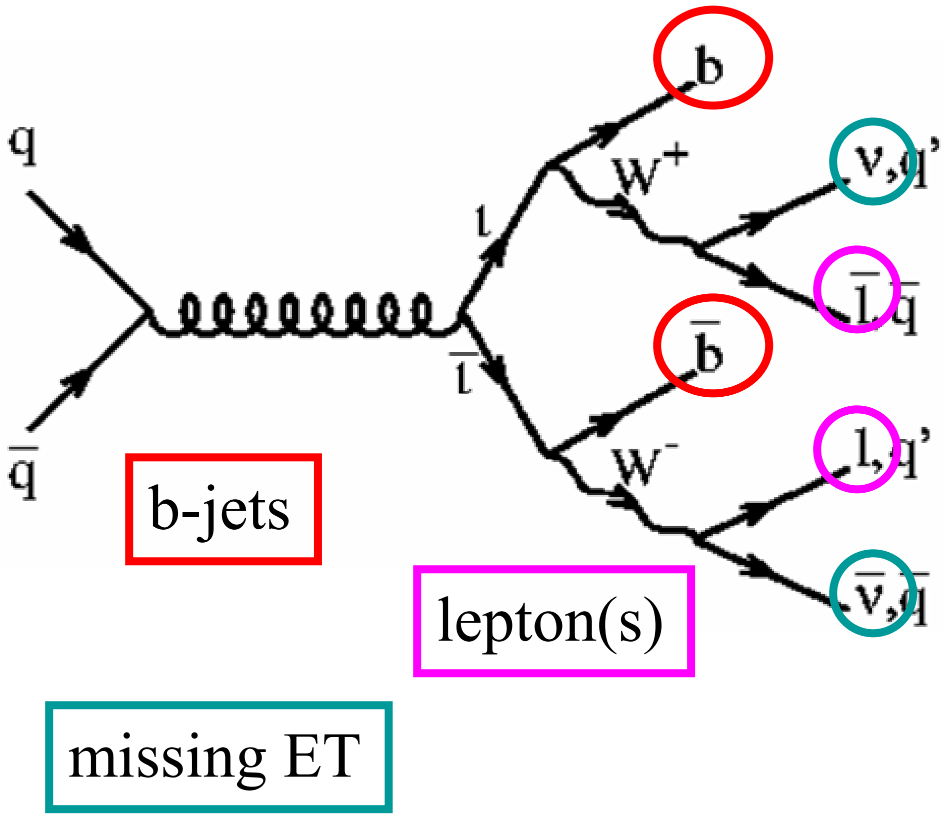

Dilepton (ee, μμ, eμ)
$\Rightarrow$ BR = 5%

- Relatively clean:
  - Very small amount of SM bkgds
  - Down side: small event samples
- Select:
  - 2 leptons: ee, eμ, μμ
  - Large missing E_T
  - 2 jets (with or w/o b-tag)
- Expect: S/B > 1
- Dominant backgrounds: Drell-Yan, W+jets (“fakes”)

How to identify the top quark

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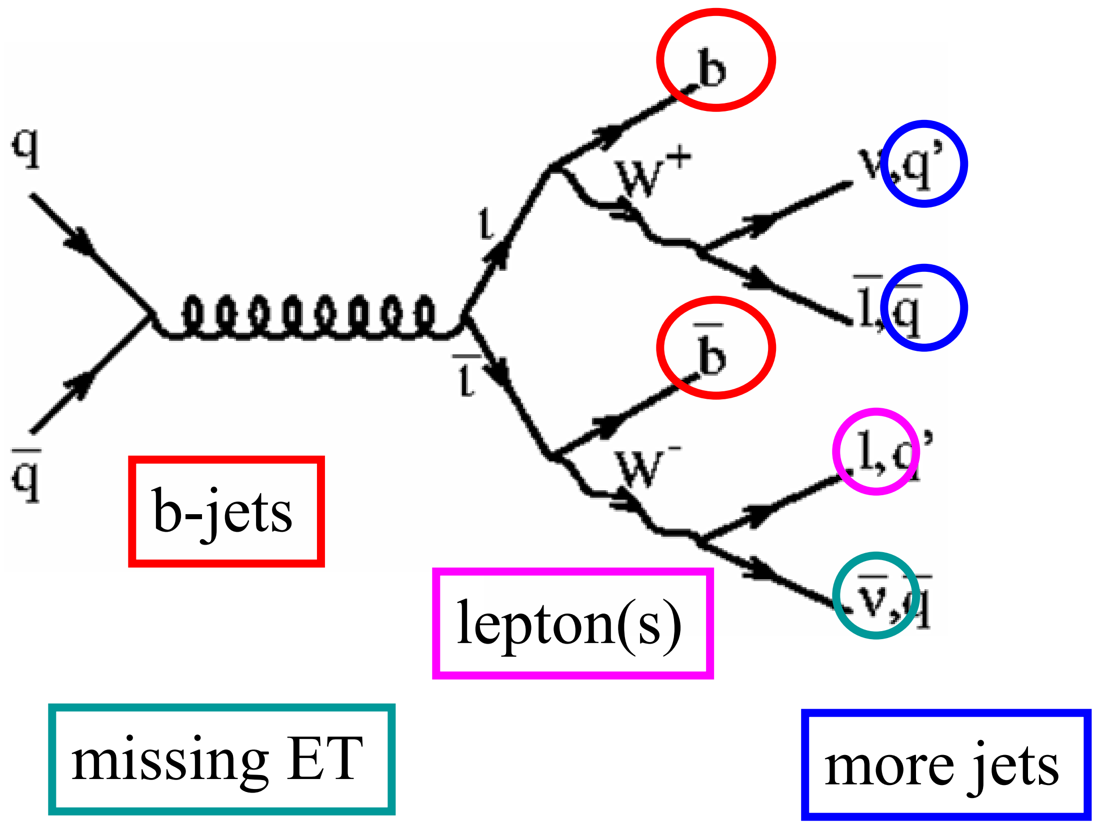
dilepton *(4/81)* 2 leptons + 2 jets + missing E_T

lepton+jets *(24/81)* 1 lepton + 4 jets + missing E_T

fully hadronic *(36/81)* 6 jets



Lepton (e or μ) + jets

$\Rightarrow$ BR = 30%

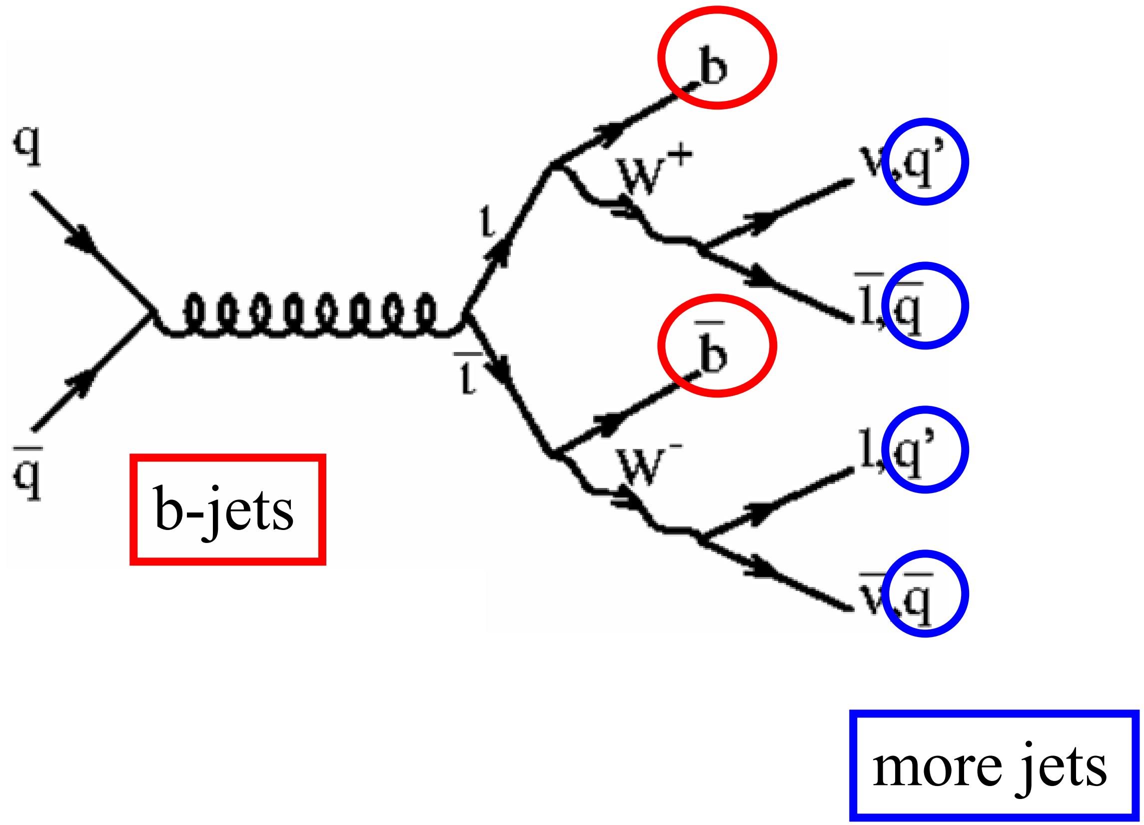
- Select:
  - 1 electron or muon
  - Large missing E_T
  - 1 or 2 b-tagged jets
- Fully reconstructable, small backgrounds
- Main backgrounds:
  - W/Z +jets
  - WZ +heavy flavor
  - QCD multijet (data-driven)
  - Diboson (from MC)

How to identify the top quark

SM: $t\bar{t}$ pair production, Br($t\rightarrow bW$)=100% , Br($W\rightarrow l\nu$)=1/9=11%

dilepton	*(4/81)*	2 leptons + 2 jets + missing E_T
lepton+jets	*(24/81)*	1 lepton + 4 jets + missing E_T
fully hadronic	*(36/81)*	6 jets

All-hadronic
⇒ BR = 44%

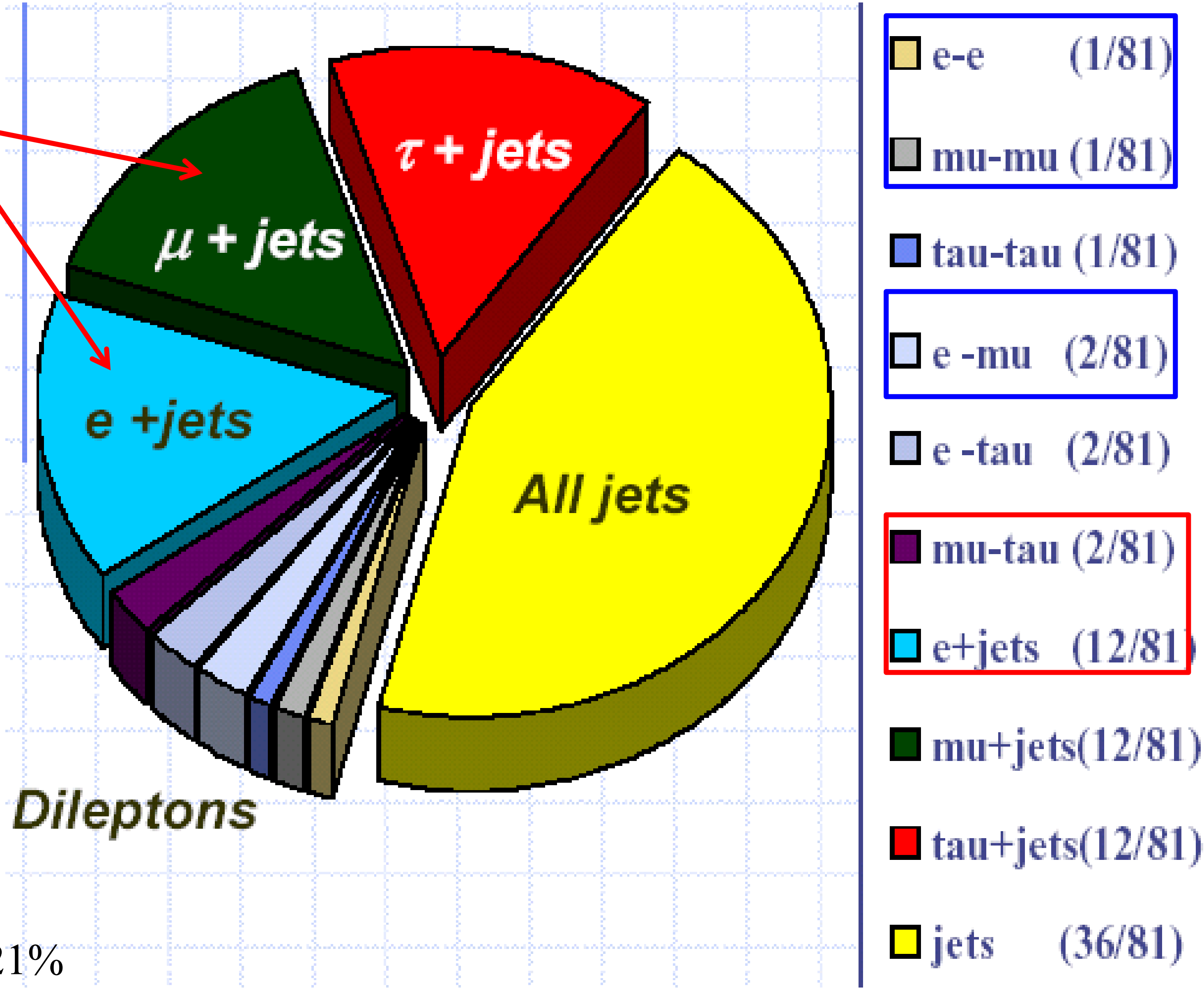


Signature:
- 6 or more jets
- kinematical selection
- ≥ 1 vertex tag.

Large backgrounds from QCD multijet production

Top Event Categories

L+Jets

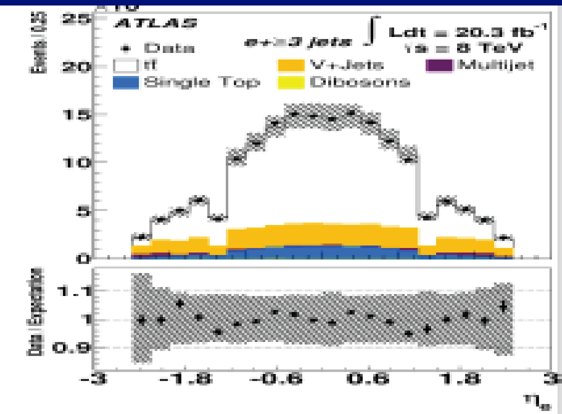


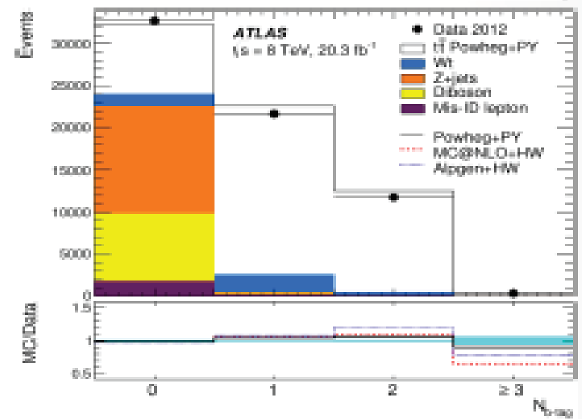
τ_{had} +X

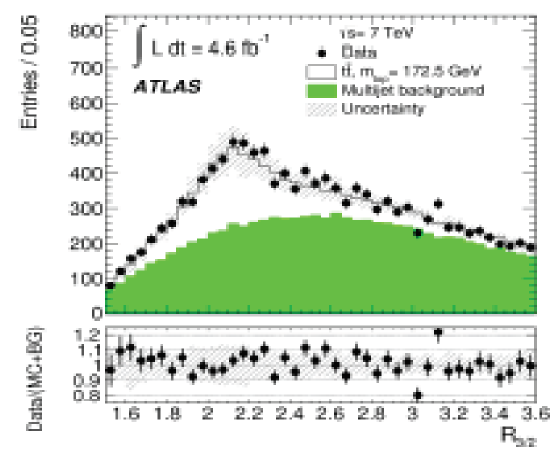
$\Rightarrow$ BR = 21%

Pros and cons by final state channel:

- Lepton + jets ("golden" channel)
  - fairly good branching ratio
  - Reasonable S/B
  - One ν so can fully reconstruct t-tbar system
- Dilepton:
  - Lowest branching ratio but...
  - Highest S/B
  - 2ν→reconstruction of t-tbar system ambiguous
- All hadronic
  - Highest branching ratio, but...
  - lowest S/B ratio
  - Dominant QCD background hard to determine
  - combinatorics of t-tbar reconstruction complex







Method to identify a top signal

- Start from "counting events" passing cuts in all decay channels

  $\Rightarrow$ Optimization of signal region with respect to SM background processes (control region)

- Background dominates the production of ttbar pairs
- How to separate signal from background:

  $\Rightarrow$Top events have very distinctive signatures

  ✓Decay products (leptons, neut., jets) have large p_T's

  ✓Event topology: central and spherical

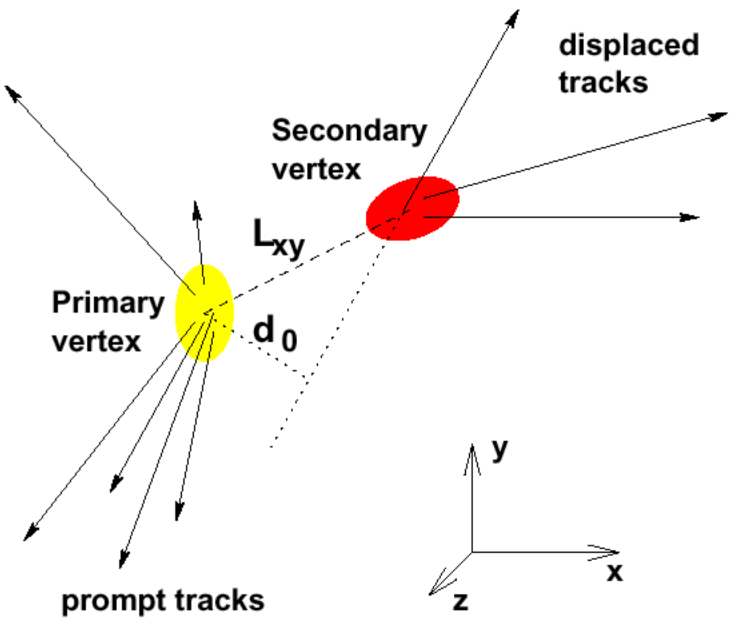
  ✓Heavy flavor content: always 2 b jets in the final state!

B-Tagging Tools: Vertexing and Soft Muons

B hadrons in top signal events:

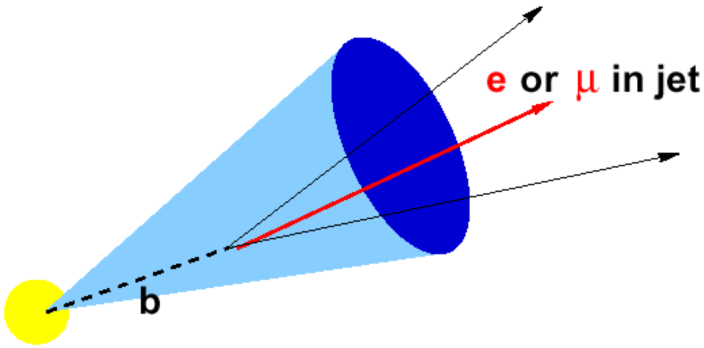
are long-lived and massive

Vertex of displaced tracks



may decay semileptonically

Identify low-pt muon from decay



- $b \to \ell \nu c$ (BR $\sim$ 20%)
- $b \to c \to \ell \nu s$ (BR $\sim$ 20%)

~60% ←Top Event Tag Efficiency→ ~15%

~0.5% ←False Tag Rate (QCD jets) → ~2%

Why measure the ttbar Cross Section?

- Basic "engineering number", absolute measurement ($\rightarrow$ very difficult!), prior step to any top property study.
- Requires detailed understanding of backgrounds and selection efficiencies.
- Test of SM QCD predictions
  - Departures from QCD prediction could indicate nonstandard production mechanisms, i.e. production through decays of SUSY states.
- It is Important to measure cross section in all decay channels

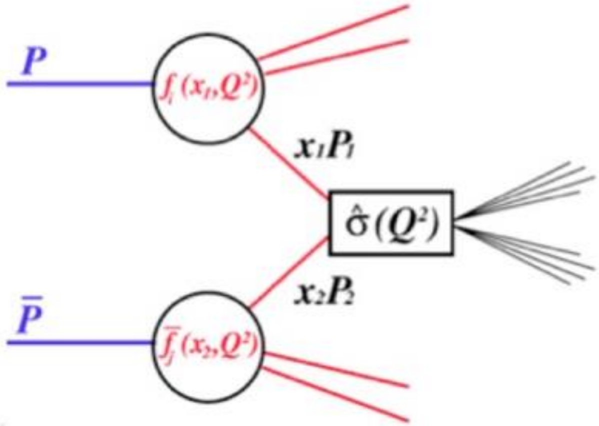
$$\sigma(t\bar{t}) = \frac{N_{obs} - N_{back}}{\varepsilon \times A \times \int L dt}$$

- ε: selection efficiency for events in acceptance (affected by errors in trigger and reconstruction)
- A: Acceptance (depends on PDF, and other modeling uncertainties)
- $\int$Ldt: integrated luminosity

What is a cross section?

Integrated cross section: $\sigma = \int [d\sigma/d\Omega]\, d\Omega$

Calculation:



$$\sigma = \sum_{i,j=q,\bar{q},g} \int dx_1\, dx_2\, f_i(x_1, Q^2) \cdot \bar{f}_j(x_2, Q^2) \cdot \hat{\sigma}(Q^2)$$

Sum over incoming partons i, j

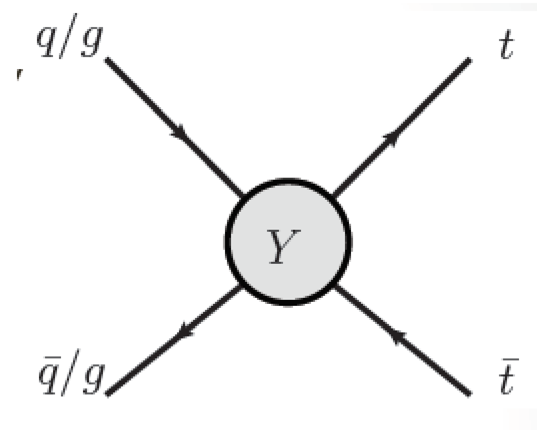
Momentum fraction for incoming parton

PDF for incoming parton i

“partonic” cross section

Partonic cross section

- Need to calculate everything that goes into Y
- Use perturbative expansion of Y in orders of strong coupling constant (α_s)
- $\alpha_s \sim 0.1$ so series should converge



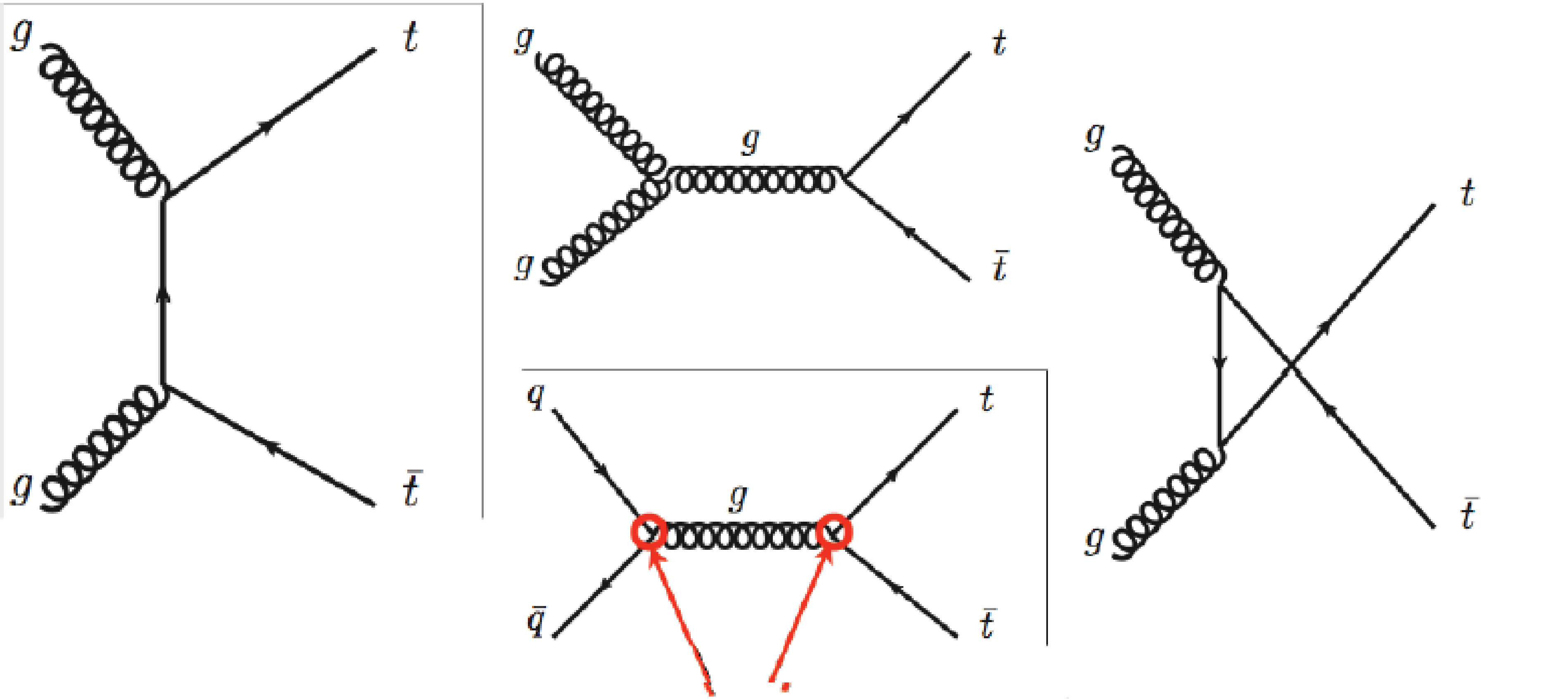
$$\sigma\left(q\bar{q}/gg \rightarrow t\bar{t} + X\right) = H^{(0)} + \alpha_s H^{(1)} + \alpha_s^2 H^{(2)} + \ldots$$

Leading order (LO) term, proportional to α_s^2

Next-to-leading order (NLO) term, proportional to α_s^3

Next-to-next-to-leading order term, proportional to α_s^4

Leading order

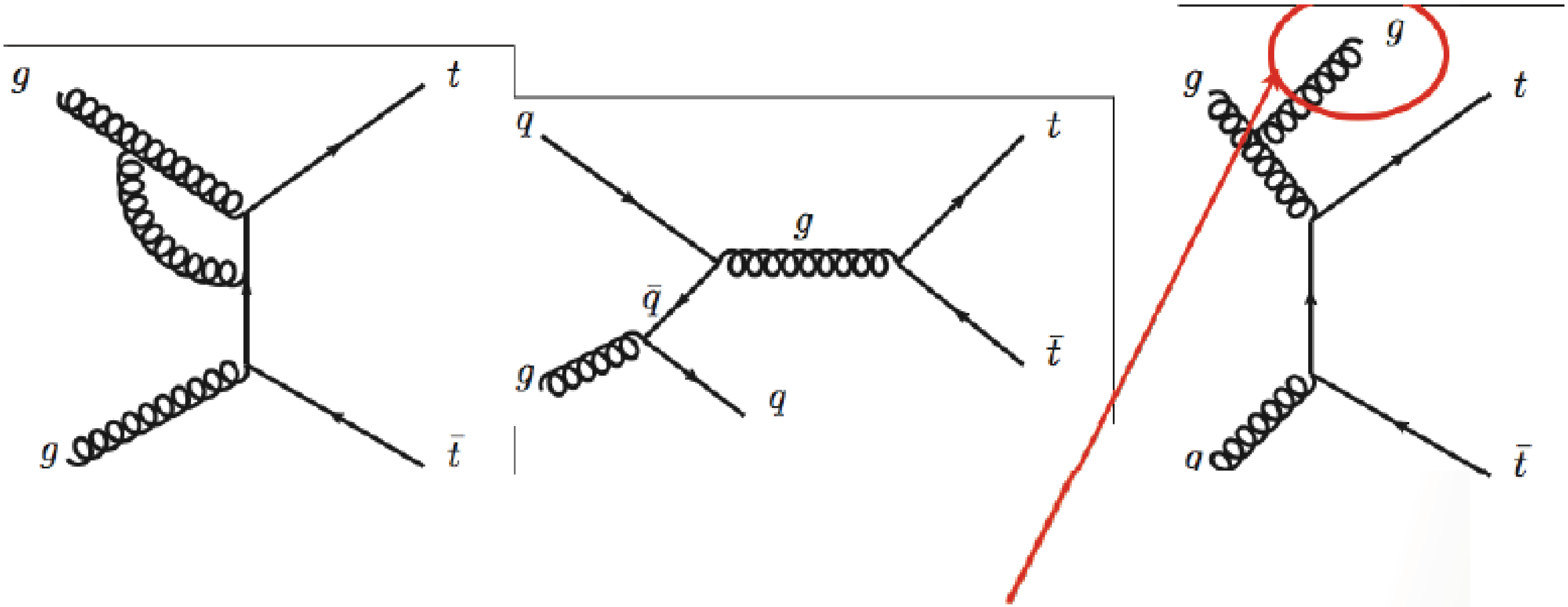


Each vertex contributes: $\sqrt{\alpha_s}$

α_s = strong force (QCD) coupling constant

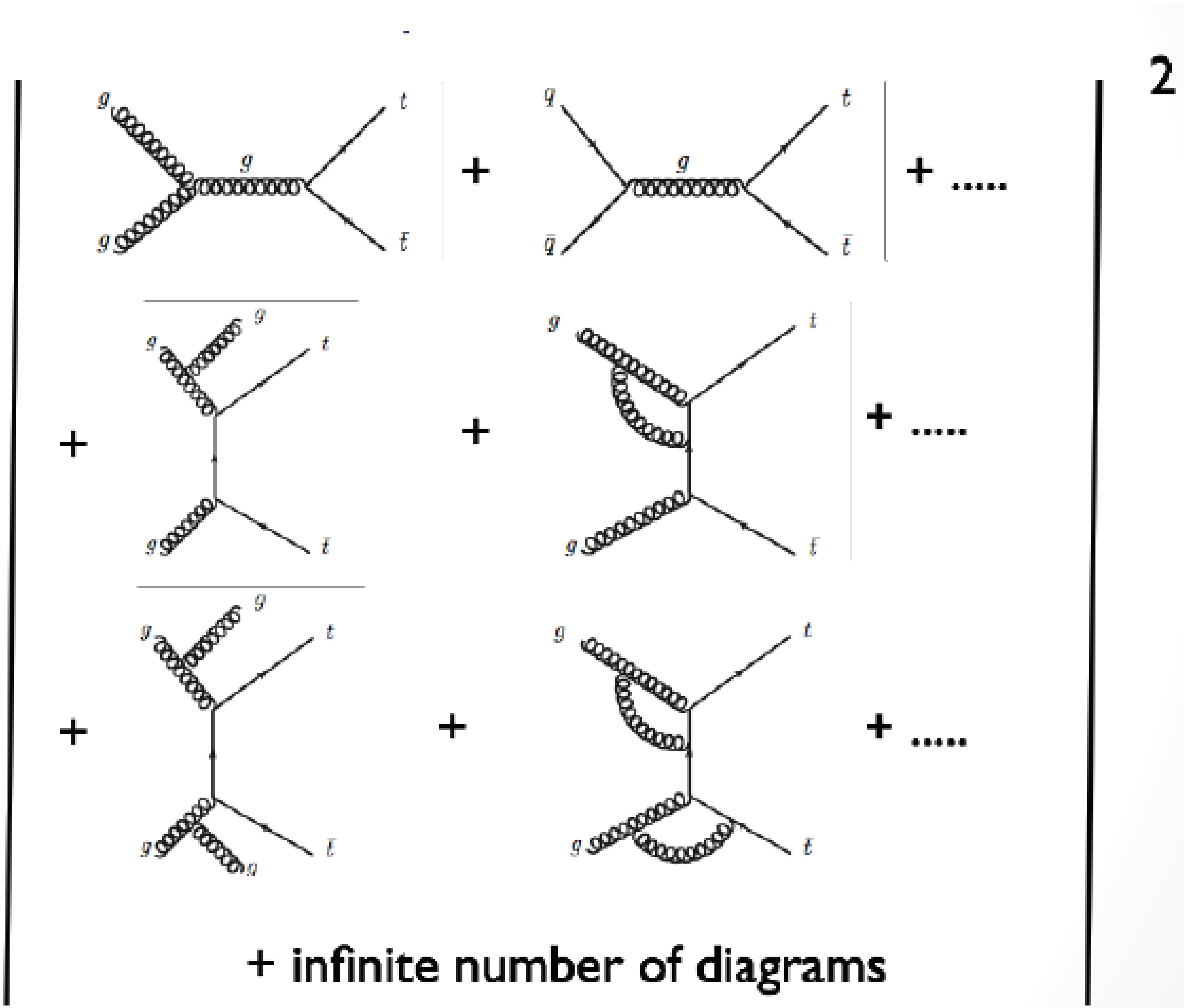
Leading order (LO): contains all terms proportional to $\alpha_s^{\ 2}$

Next to leading order



Extra gluon –> results in extra jet of hadrons in detector
Next to Leading order (NLO): contains all terms proportional to α_s^2 and α_s^3

Calculate all allowed processes

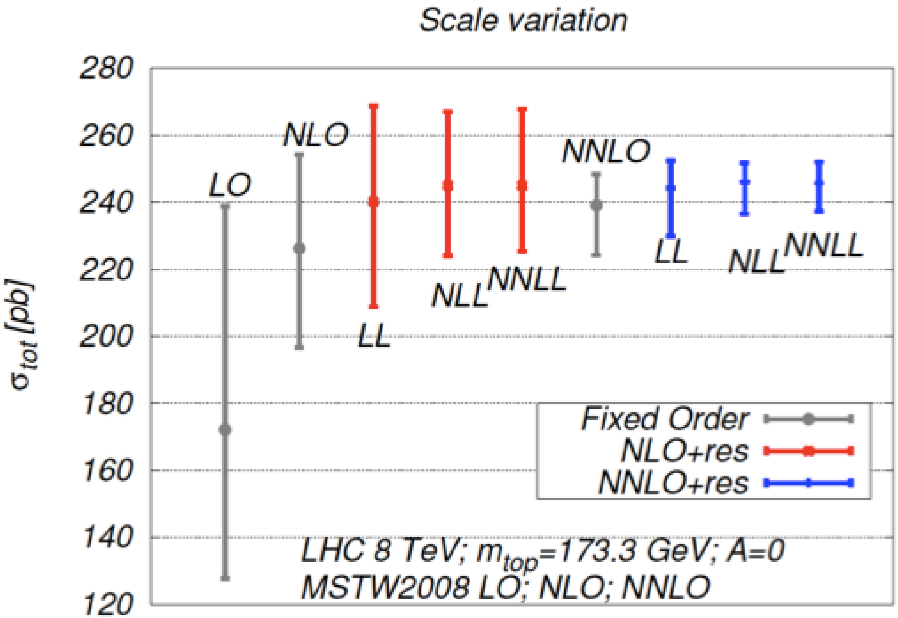


State of the art: NNLO

- Latest calculation for the inclusive ttbar cross section: NNLO

For differential cross section: NLO

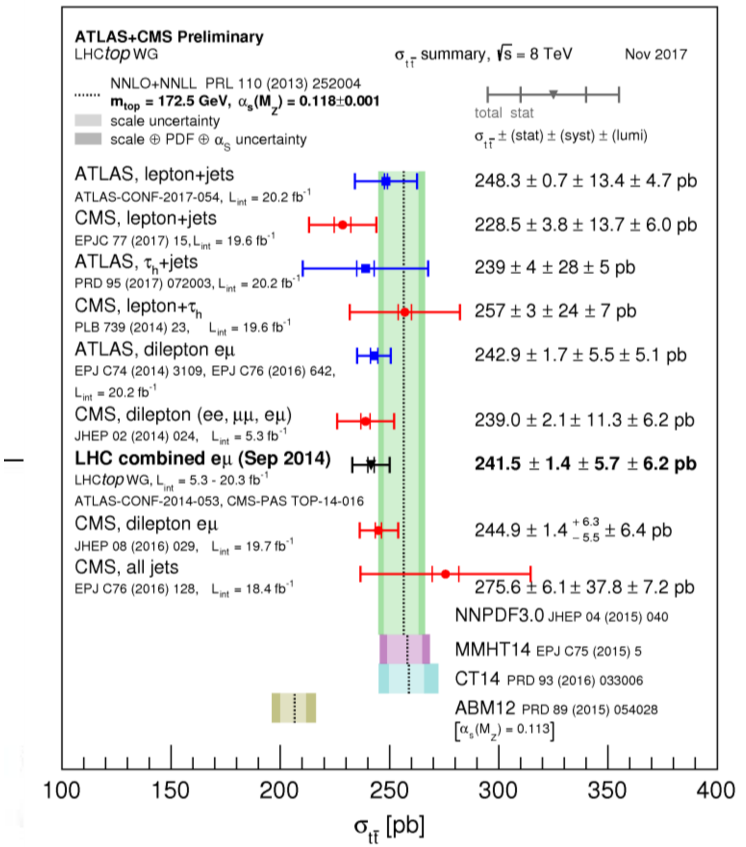
Collider	$\sigma_{\rm tot}$ [pb]	scales [pb]	pdf [pb]
Tevatron	7.164	$+0.110(1.5\%)$ $-0.200(2.8\%)$	$+0.169(2.4\%)$ $-0.122(1.7\%)$
LHC 7 TeV	172.0	$+4.4(2.6\%)$ $-5.8(3.4\%)$	$+4.7(2.7\%)$ $-4.8(2.8\%)$
LHC 8 TeV	245.8	$+6.2(2.5\%)$ $-8.4(3.4\%)$	$+6.2(2.5\%)$ $-6.4(2.6\%)$
LHC 14 TeV	953.6	$+22.7(2.4\%)$ $-33.9(3.6\%)$	$+16.2(1.7\%)$ $-17.8(1.9\%)$



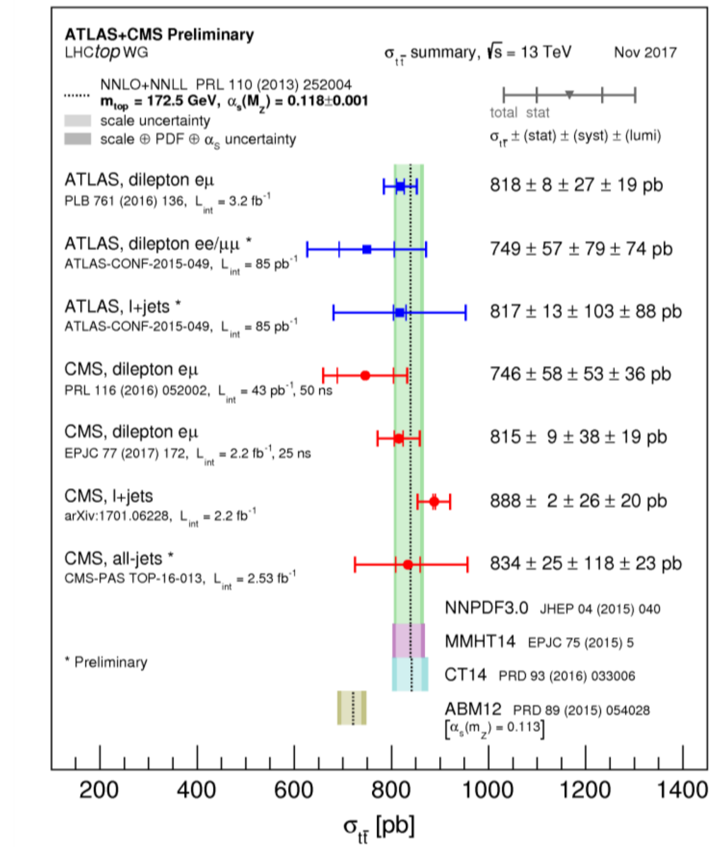
[Bärnreuther, Czakon, Mitov 2012]
[Czakon, Mitov 2012]
[Czakon, Mitov 2012]
[Czakon, Fiedler, Mitov 2013]

Summary of cross section measurements at LHC

ATLAS & CMS 8TeV

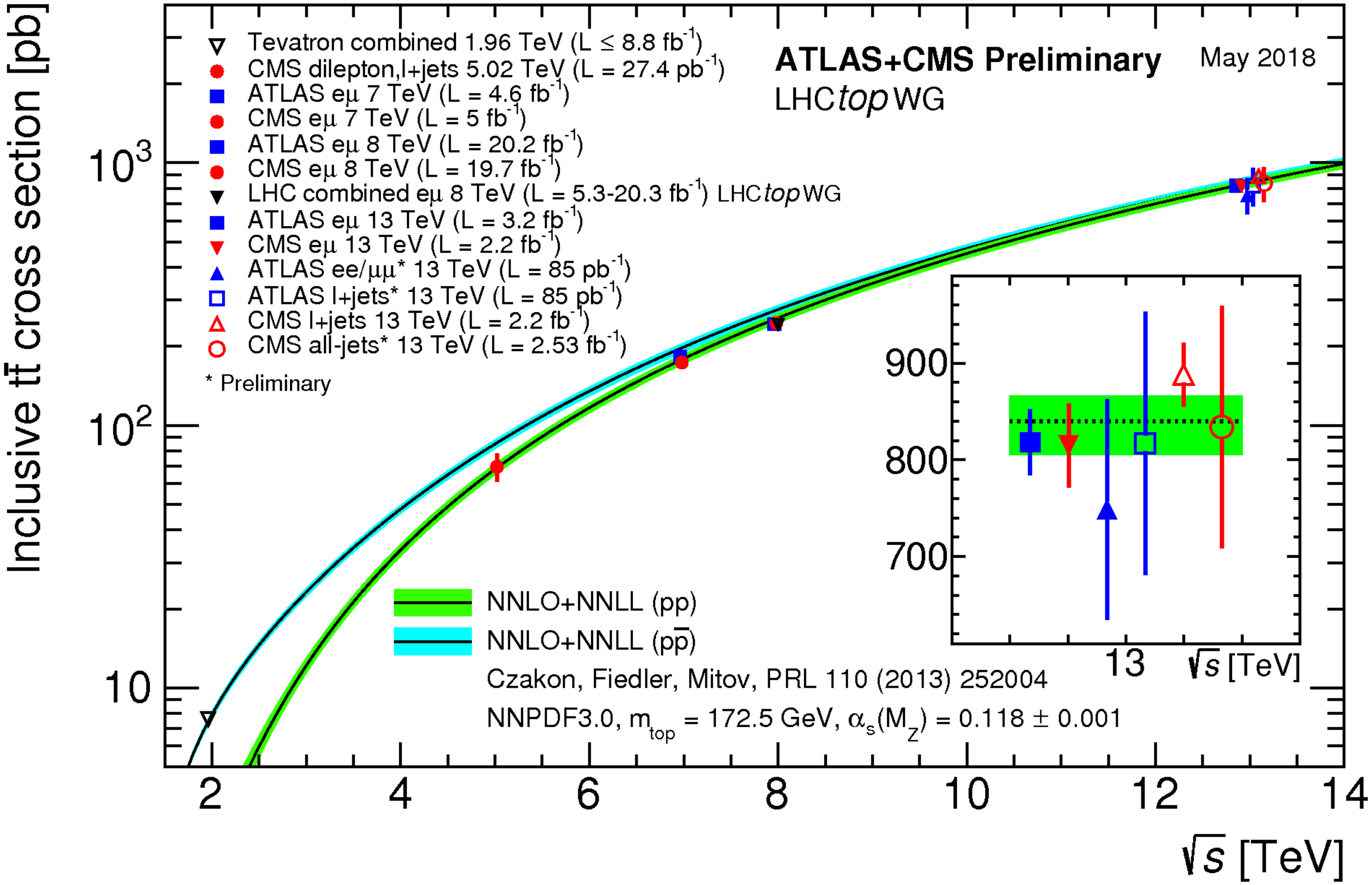


ATLAS & CMS 13TeV



- Many measurements that use different techniques
- Good agreement
  - ⇒ between all measurements
  - ⇒ between data and theory
- Measurement precision now comparable to theory

ttbar inclusive cross section: summary



- Tevatron and LHC results consistent with NNLO+NNLL over a large range of CM energies
- Comparable uncertainties (~ 6 % in lepton+jets, ~4 % in dilepton) with theoretical uncertainties at NNLO+NNLL precision (~5.5%)

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/TOP/

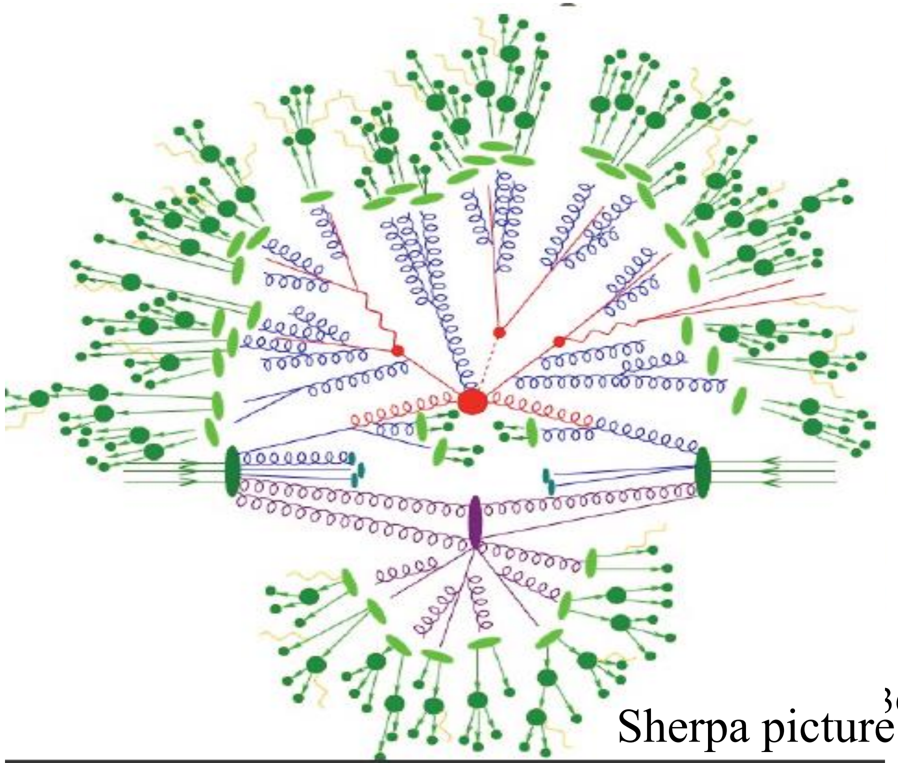
Differential Top Cross Sections

- Given the available ttbar statistics, differential measurements are the baseline now
- It's even more complicated but ....

  ⇒ provides more detailed information

  ⇒ sensitive to new physics on the tails…
- fiducial measur. to avoid large model-dependent corrections to full phase-space

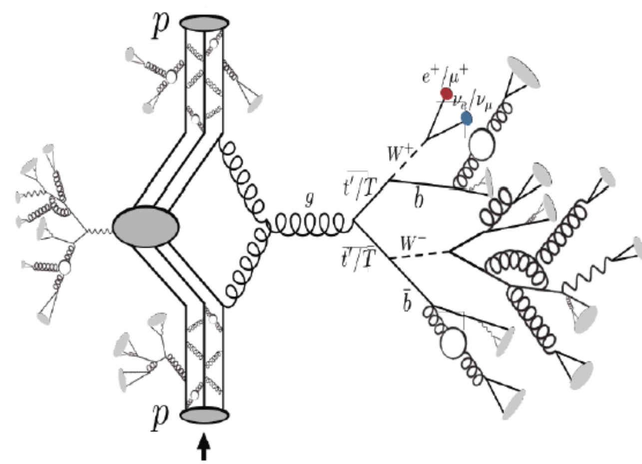
  ⇒ fiducial differential measurements unfolded to particle/parton level
- test of QCD calculations
- can constrain gluon PDF
- double-differential will soon provide even higher sensitivity

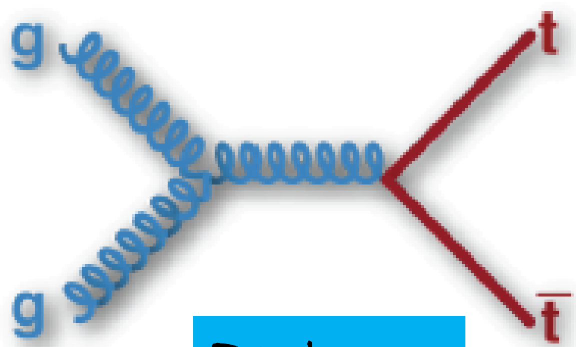


Sherpa picture

Unfolding: parton vs particle

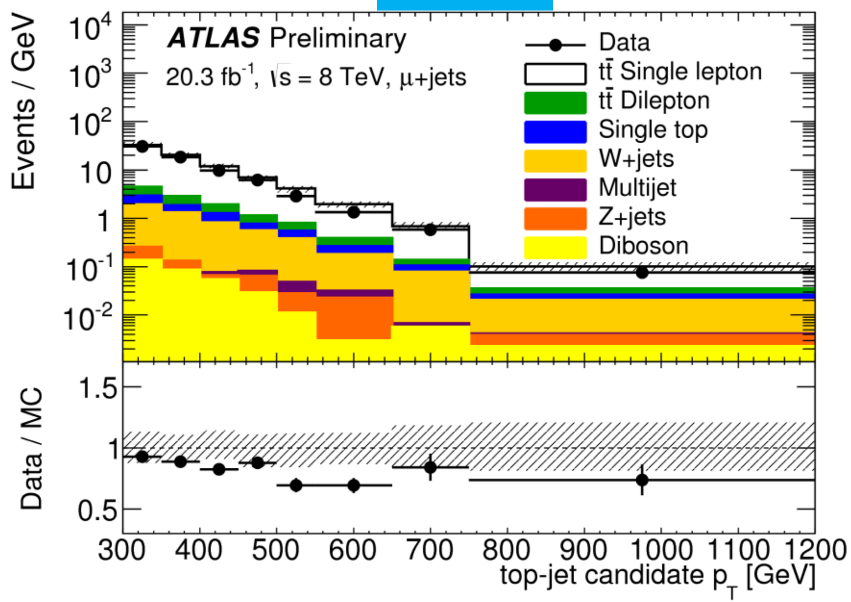
Particle





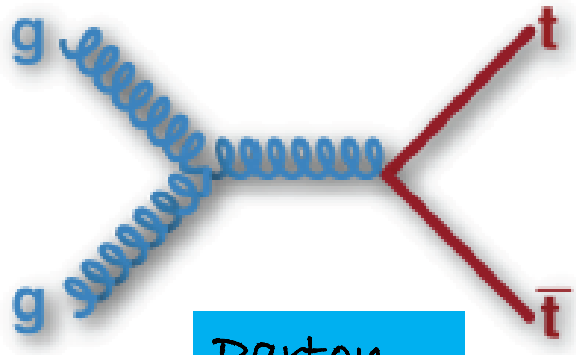
Parton

Reco



Unfolding: parton vs particle

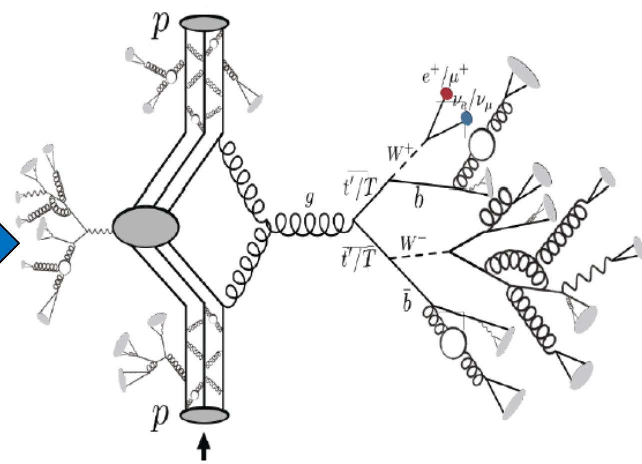
Matrix Element calculation (usually perturbative)



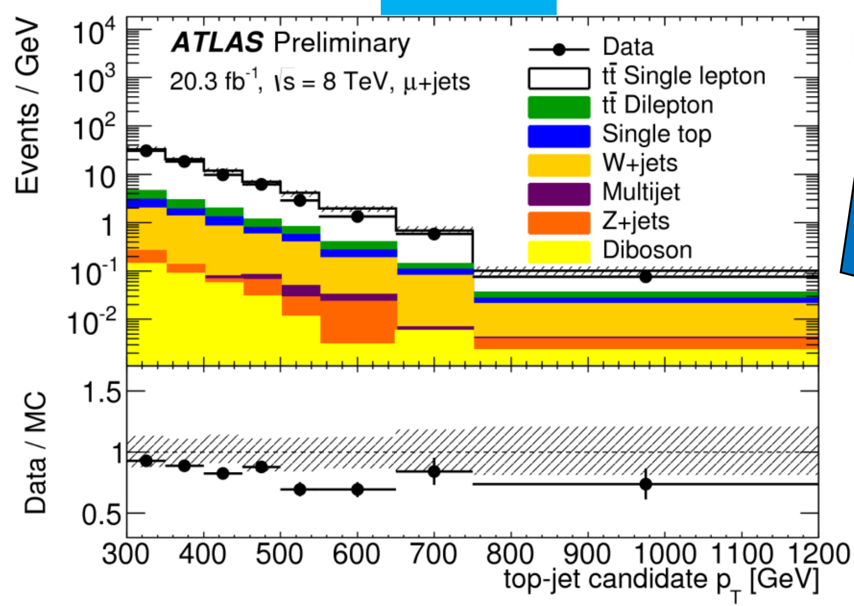
Parton

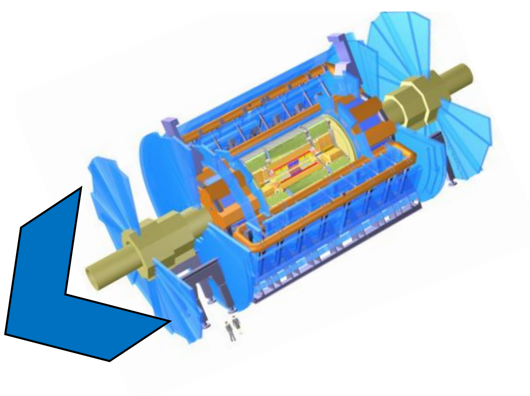
Fragmentation, parton shower, hadronization, PDFs… (often non-perturbative)

Particle



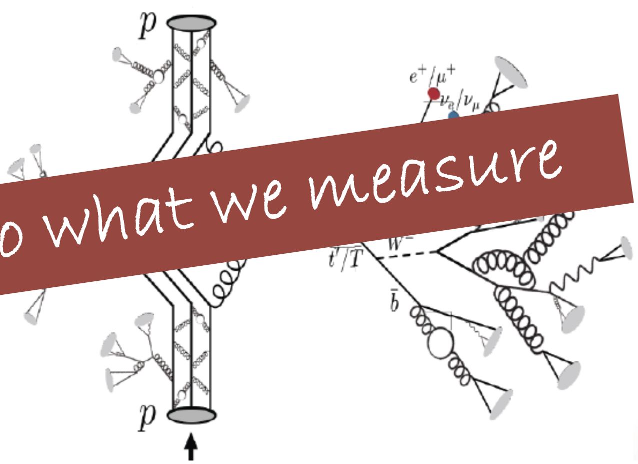
Reco



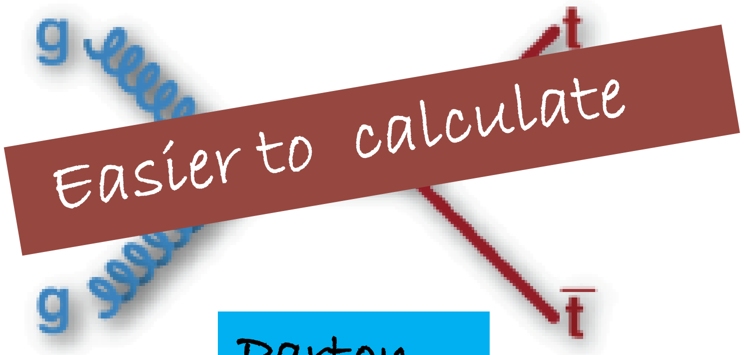


Unfolding: parton vs particle

Particle



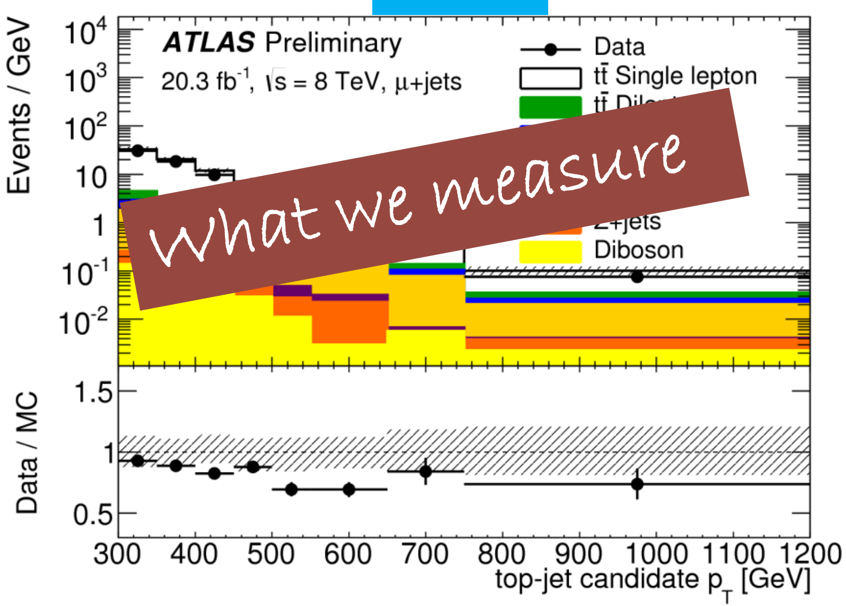
Closer to what we measure



Easier to calculate

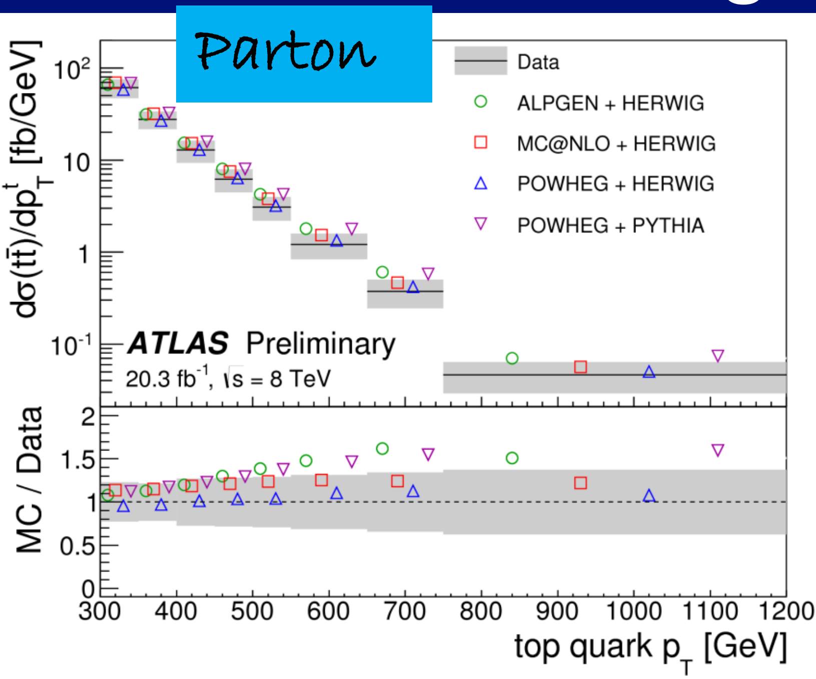
Parton

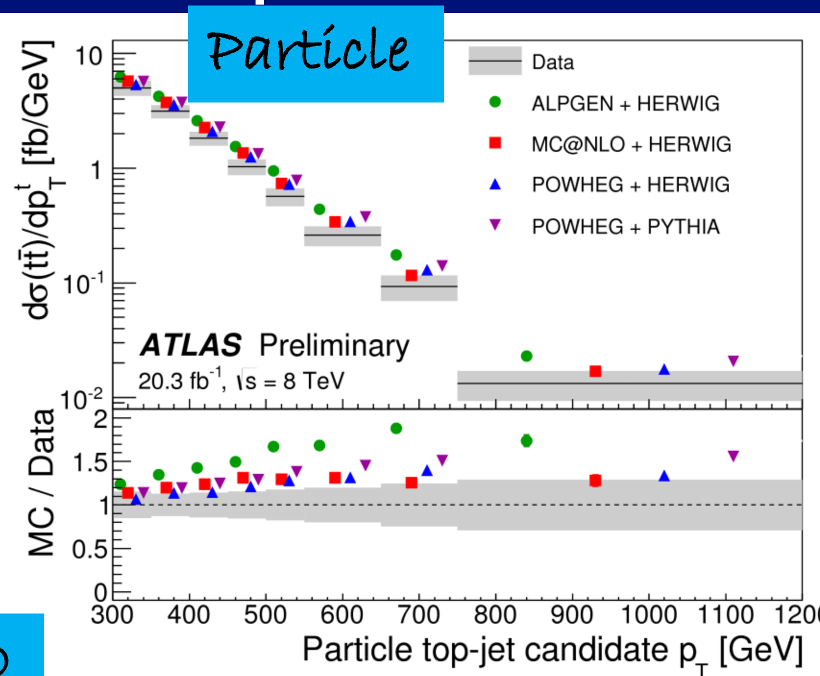
Reco

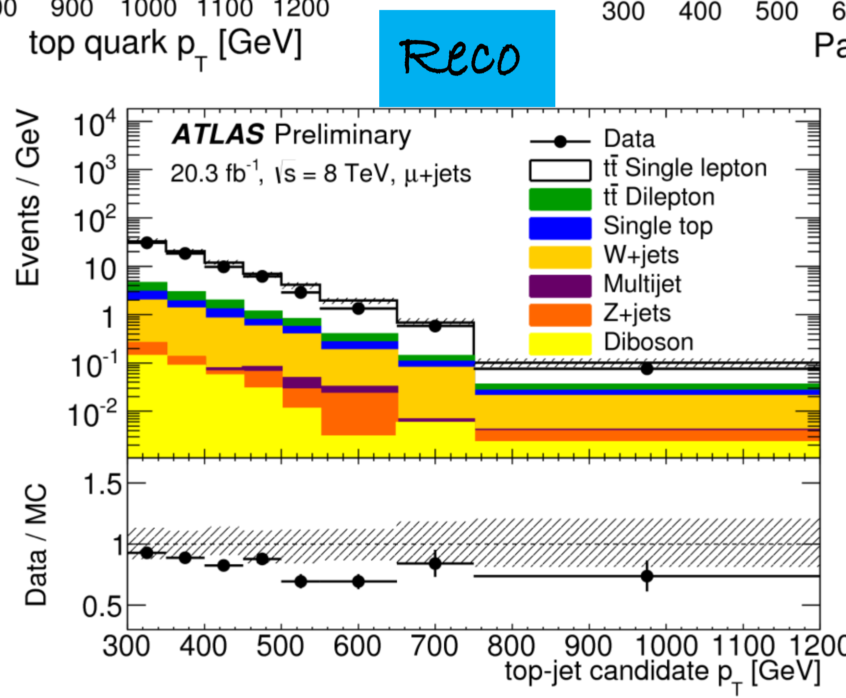


What we measure

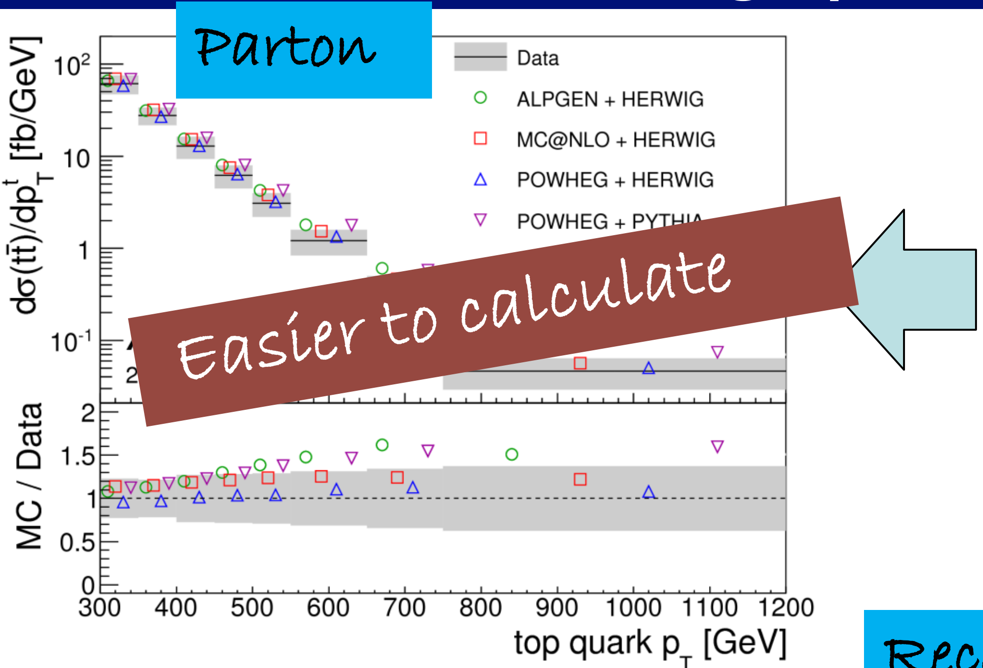
Unfolding: parton vs particle

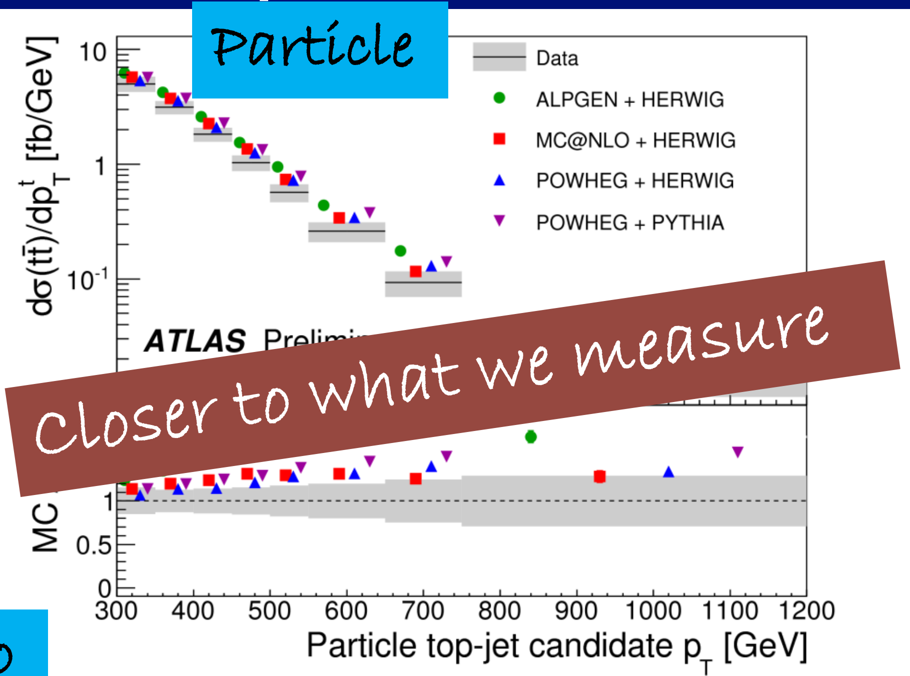


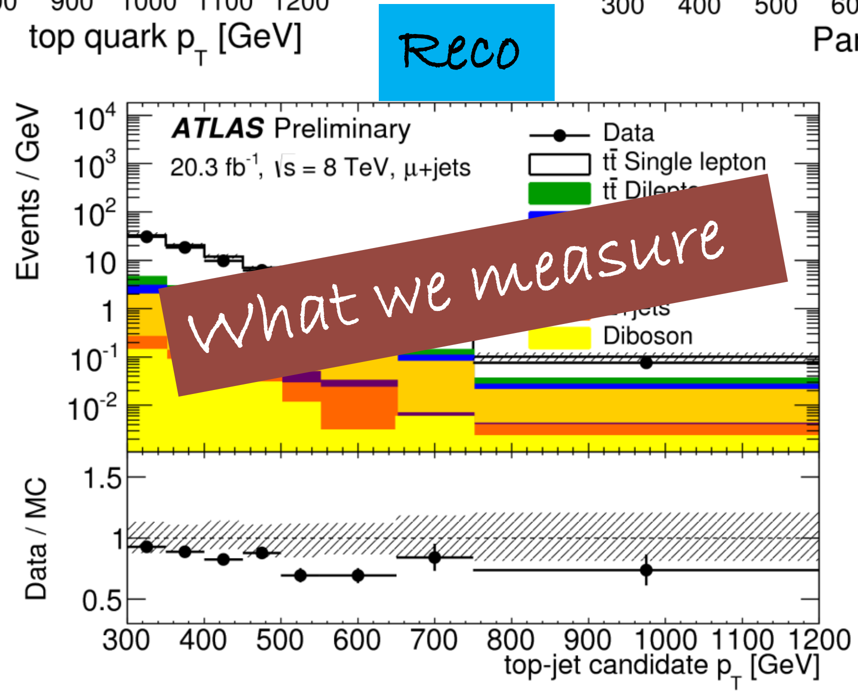




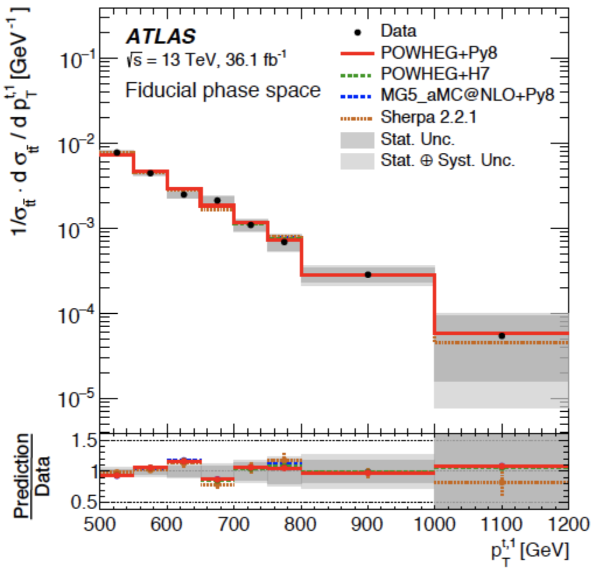
Unfolding: parton vs particle





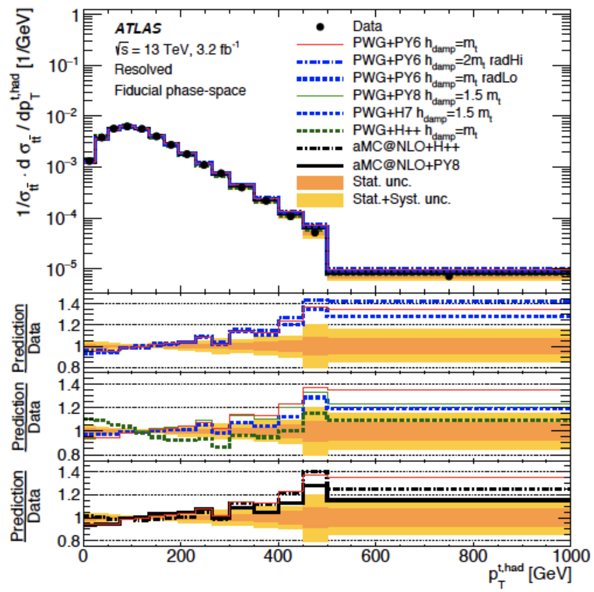


Differential cross section at 13 TeV



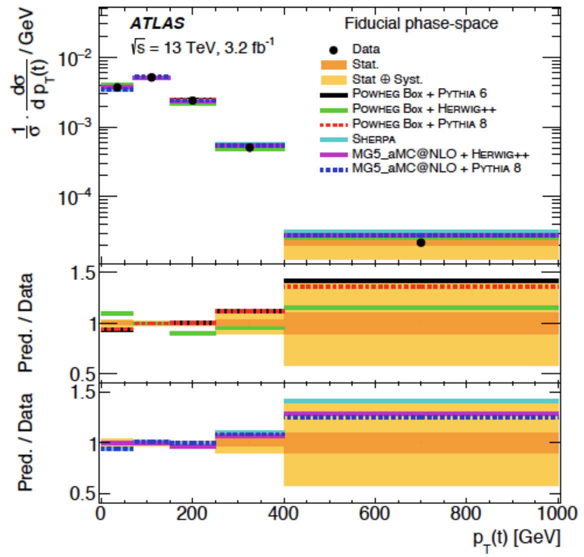
all-jets

arXiv:1801.02052



lepton+jets

JHEP 11 (2017) 191

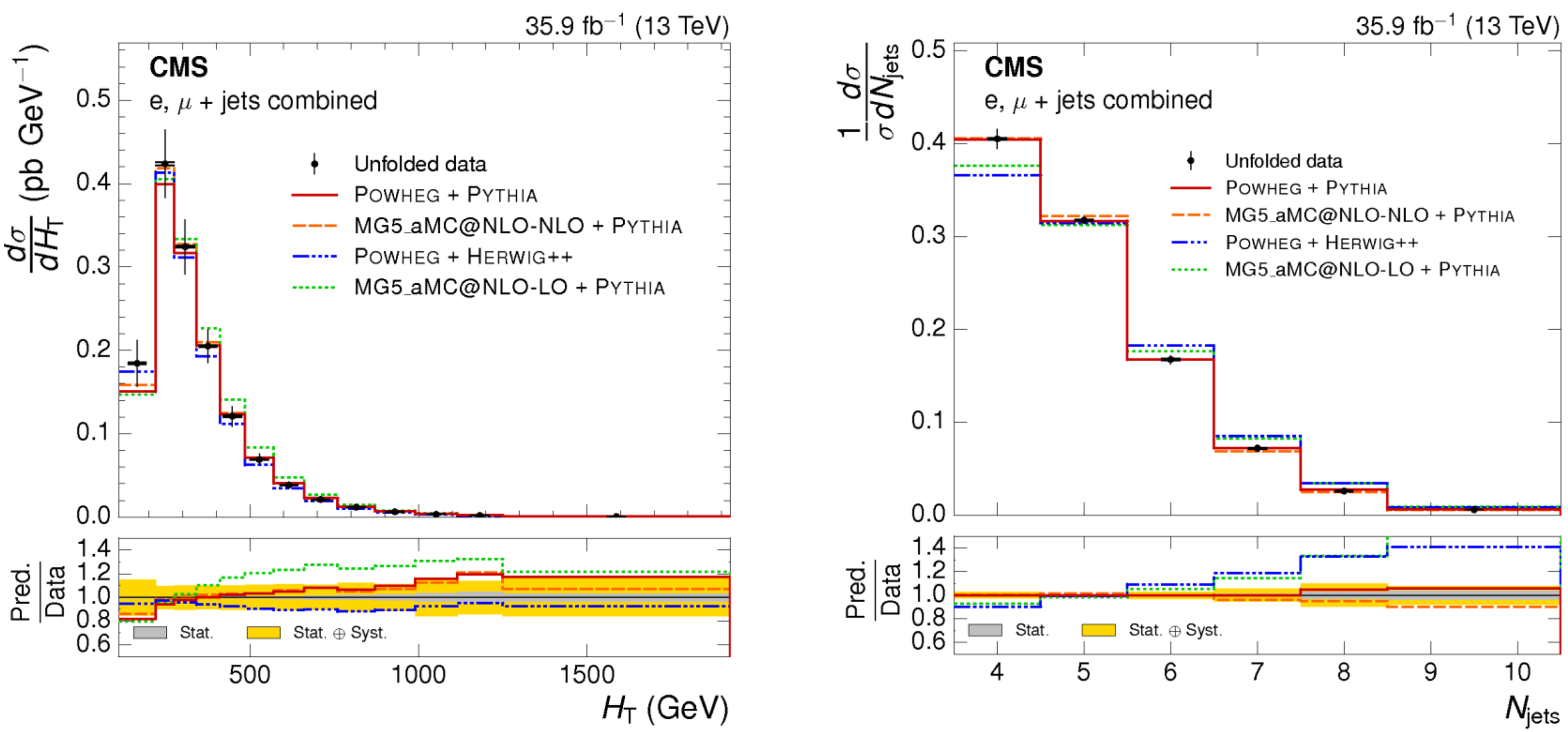


dilepton

Eur. Phys. J. C77 (2017) 292

- Main uncertainties: JES, b-tagging, signal modeling
- Most SM predictions (NLO QCD + parton shower) are consistent with data
- These measurements allow to tune MC generators for the future

Differential cross section at 13 TeV



JHEP 06 (2018) 002

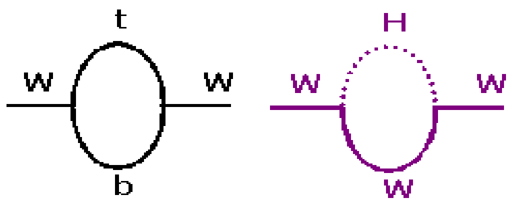
- Wide range of differential cross sections
- Precision measurements of the SM
- Improving the modelling uncertainties in ttbar production can help to see new physics!

Measurements of top mass

Why is Top Mass so special?

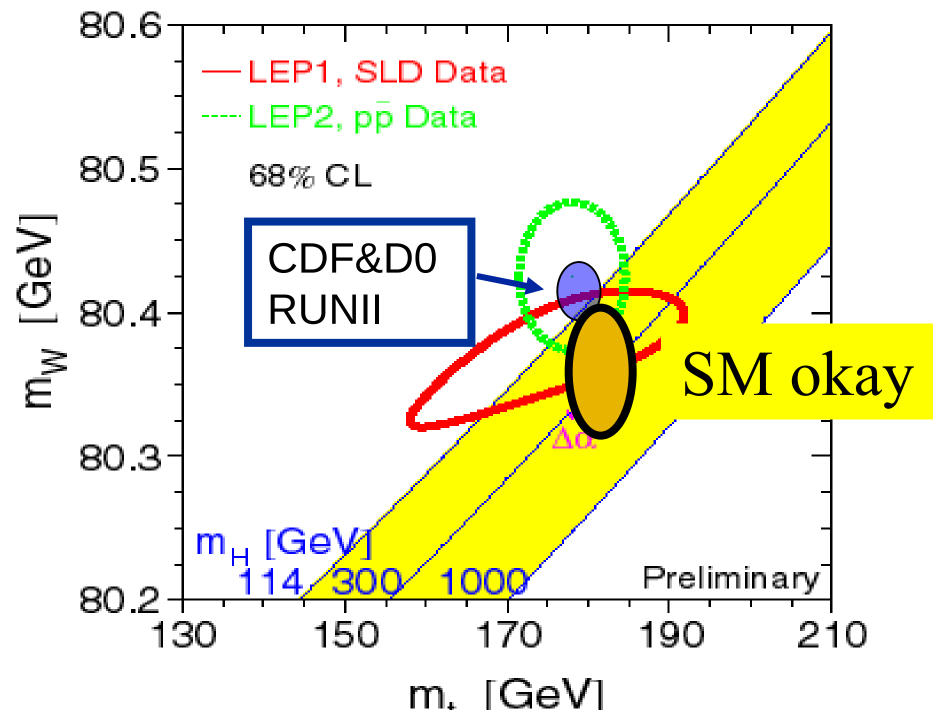
Top mass is a fundamental SM parameter

- Related through radiative corrections to other EW observables.



$\Delta M_W \propto M_T^2$ $\Delta M_W \propto \ln M_H$

- If there are new particles the relation might change



- Very important for precision tests of SM.
- Together with M_w and other electroweak precision measurements, it constrains M_{higgs}
- Is this large mass telling us something about electroweak symmetry breaking? (Top Yukawa coupling close to 1)

$$m_{top} = y_t v/\sqrt{2} \approx 173 \text{ GeV} \Rightarrow y_t \approx 1$$

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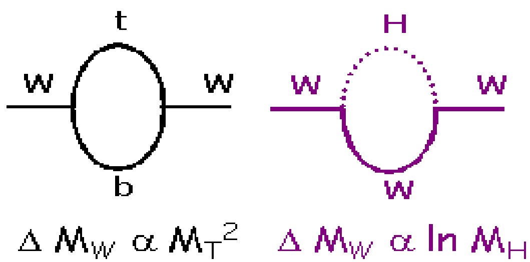
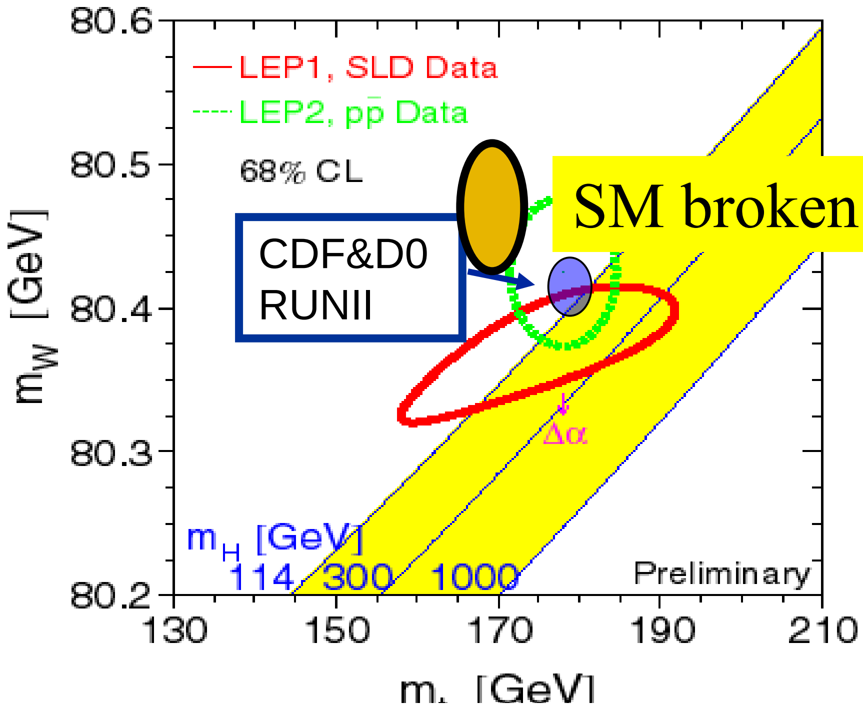


- If there are new particles the relation might change



- Very important for precision tests of SM.
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- Is this large mass telling us something about electroweak symmetry breaking? (Top Yukawa coupling close to 1)

$$m_{top} = y_t v/\sqrt{2} \approx 173 \text{ GeV} \Rightarrow y_t \approx 1$$

Top mass: what do we measure?

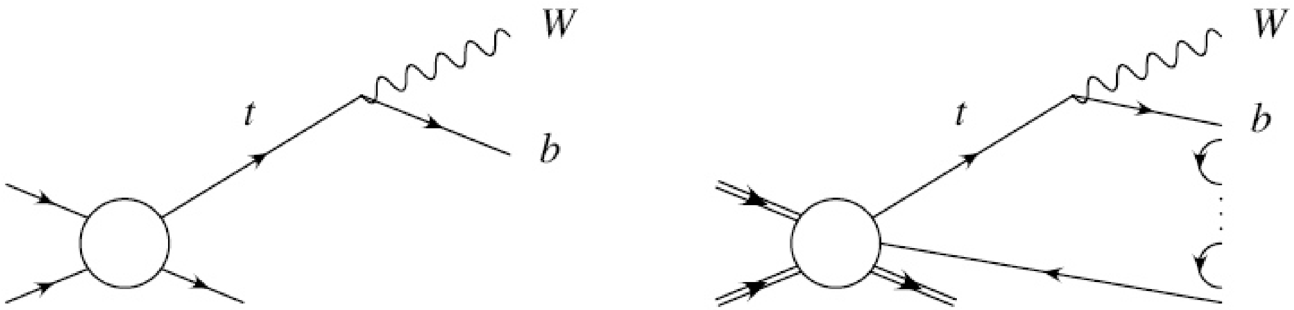
- > 20 years ago, CDF & D0 first assembled all the pieces needed to discover the top
  → The strategy to study the top quark remains the same today

- Top quark mass "standard" measurements:
  - make kinematic reconstruction of final state objects (leptons, jets, and missing transverse energy)
  - measurement based on comparison of kinematic observables with MC generated at different top masses (most sensitive variable: invariant mass distribution)
  - determination of the best-fit value of the MC top-quark mass parameter
- On going theoretical work:
  - to translate the measured top-quark mass into a mass in a well defined renormalization scheme
- Experimental way to address the question of the top-quark mass definition:
  - Use alternative methods to determine the top-quark mass
    - With less inputs from MC
    - With different sensitivity to systematics
    - Using theory computation with well defined mass (i.e. from cross section, single top events, ttbar+jets etc.)
- Best measurements: $\delta M_{top} \sim \pm 0.50$ GeV/c^2 (< 0.4%)

Top mass: what do we measure?

- Conceptual uncertainty of < 1 GeV/c^2 when relating the MC mass to a field theory mass….

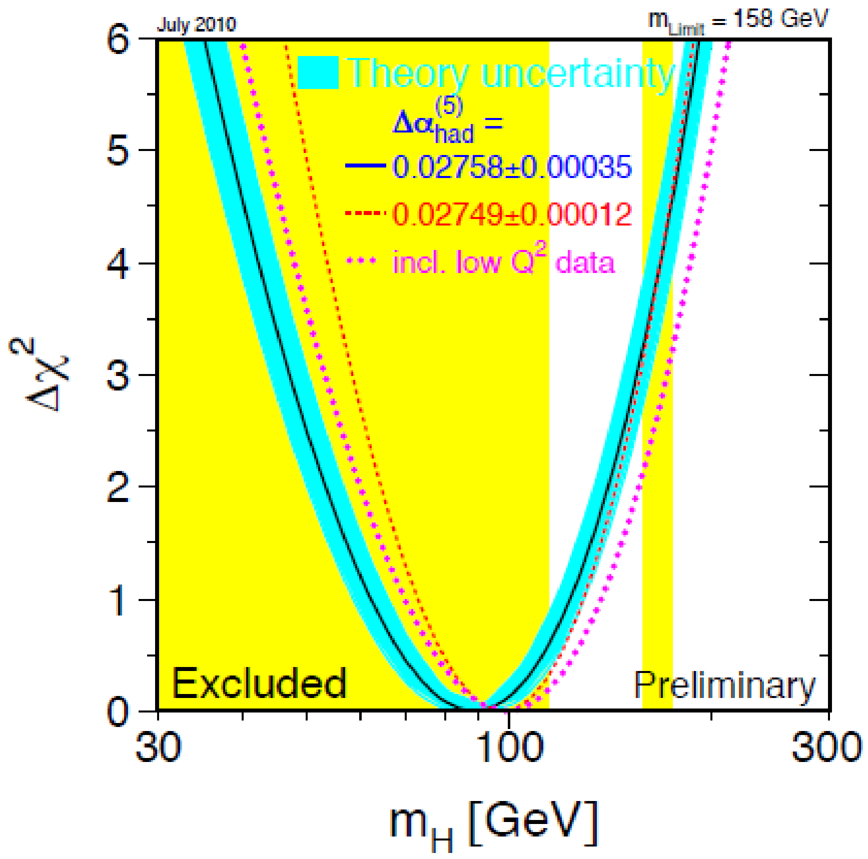
$$\left| m_t^{\text{gen}} - m_t^{\text{pole}} \right| \lesssim 1 \text{ GeV}$$



- The pole mass corresponds to our physical intuition of a stable particle (pole = top quark as a free parton, though a quark doesn't really propagate - hadronisation!) however, it can never be determined with accuracy better than O(Λ_{QCD}) (≈ 0.2 GeV)
- The pole mass is closer to what we measure at colliders through invariant mass of the top decay products.
  - The ambiguities are in the modeling of extra radiation, the color connect effects and hadronization.
  - Uncertainties estimated by various theoretical groups between 0.1 and 0.25 GeV
- Importance of measuring the mass using alternative techniques:

  $\rightarrow$ theoretically a good approach is to extract the mass from measurements of the cross section

W and top quark mass tells us Higgs mass



$\Delta\chi^2$ fit to electroweak precision observables as a function of the Higgs boson mass in the Standard Model. The line is the result of the fit using all available data

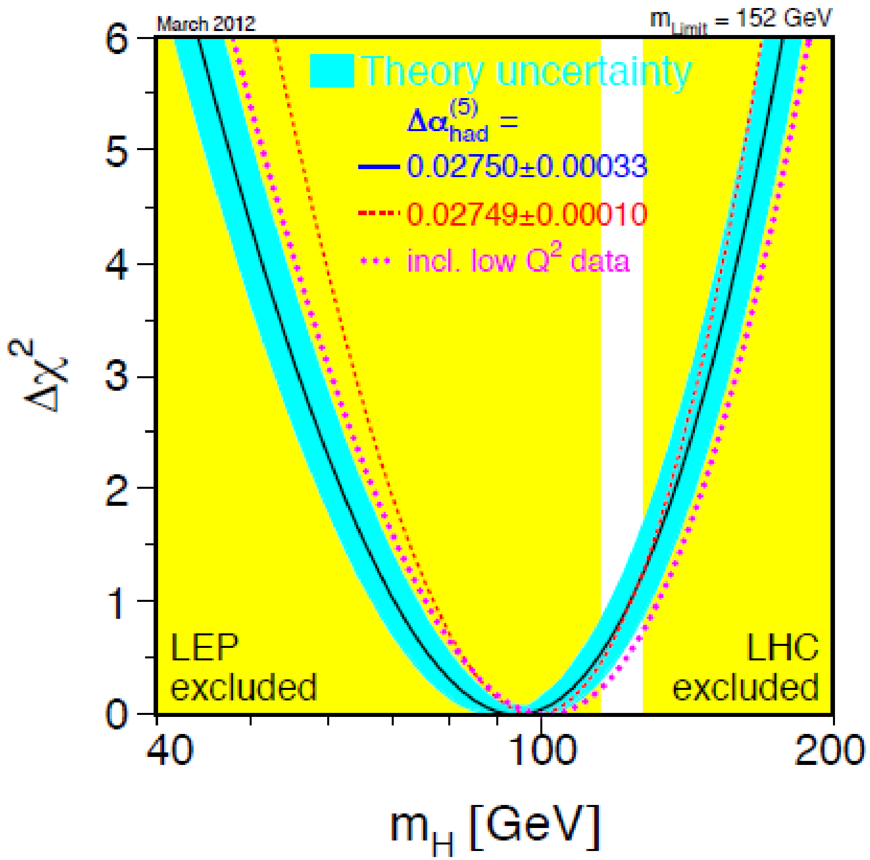
Preferred value for m_H: corresponds to the minimum of the curve

Example of variables used in EWK fit

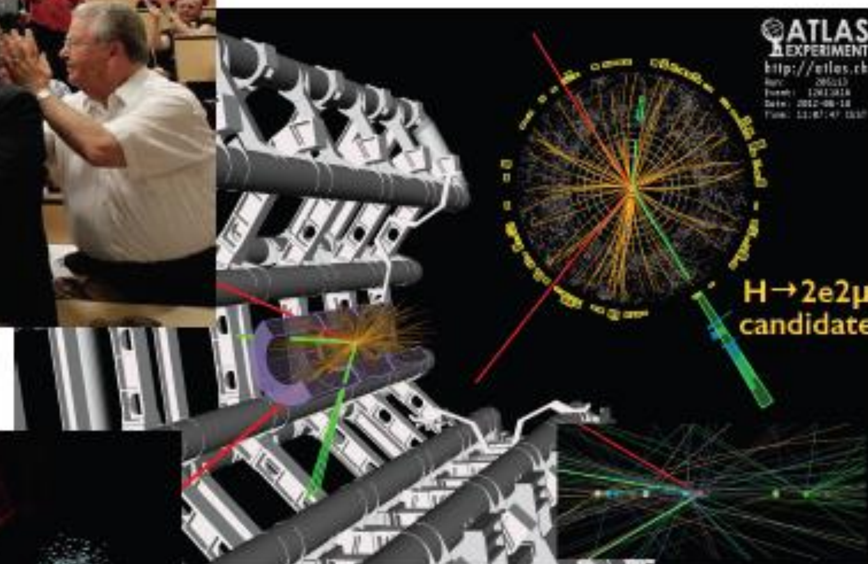
arXiv:0909.0961

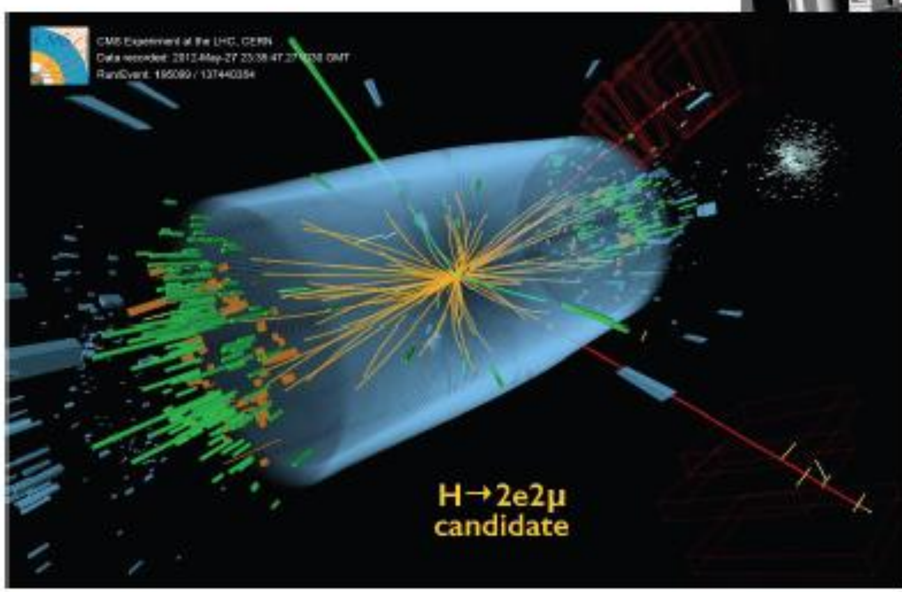
Parameter	Input value	Free in fit	Results from global EW fits: *Standard fit*	*Complete fit*
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1874 ± 0.0021	91.1876 ± 0.0021
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4960 ± 0.0015	2.4956 ± 0.0015
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	–	41.478 ± 0.014	41.478 ± 0.014
R^0_ℓ	20.767 ± 0.025	–	20.742 ± 0.018	20.741 ± 0.018
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	–	0.01638 ± 0.0002	0.01624 ± 0.0002
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	0.1478 ± 0.0010	$0.1472^{+0.0009}_{-0.0008}$
A_c	0.670 ± 0.027	–	$0.6682^{+0.00045}_{-0.00044}$	$0.6679^{+0.00042}_{-0.00036}$
A_b	0.923 ± 0.020	–	0.93469 ± 0.00010	$0.93463^{+0.00007}_{-0.00008}$
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	–	$0.0741^{+0.0006}_{-0.0005}$	0.0737 ± 0.0005
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	–	0.1036 ± 0.0007	$0.1032^{+0.0007}_{-0.0006}$
R^0_c	0.1721 ± 0.0030	–	0.17225 ± 0.00006	0.17225 ± 0.00006
R^0_b	0.21629 ± 0.00066	–	0.21578 ± 0.00005	0.21577 ± 0.00005
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	–	0.23142 ± 0.00013	$0.23151^{+0.00010}_{-0.00012}$
M_W [GeV]	80.399 ± 0.023	–	$80.384^{+0.014}_{-0.015}$	$80.371^{+0.008}_{-0.011}$
Γ_W [GeV]	2.098 ± 0.048	–	$2.092^{+0.001}_{-0.002}$	2.092 ± 0.001
$\overline{m}_c$ [GeV]	1.25 ± 0.09	yes	1.25 ± 0.09	1.25 ± 0.09
$\overline{m}_b$ [GeV]	4.20 ± 0.07	yes	4.20 ± 0.07	4.20 ± 0.07
m_t [GeV]	173.1 ± 1.3	yes	173.2 ± 1.2	173.6 ± 1.2
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ $^{(\dagger\triangle)}$	2767 ± 22	yes	2772 ± 22	2764^{+22}_{-21}
$\alpha_s(M_Z^2)$	–	yes	$0.1192^{+0.0028}_{-0.0027}$	0.1193 ± 0.0028
$\delta_{\rm th} M_W$ [MeV]	$[-4, 4]_{\rm theo}$	yes	4	4
$\delta_{\rm th}\sin^2\theta^\ell_{\rm eff}$ $^{(\dagger)}$	$[-4.7, 4.7]_{\rm theo}$	yes	4.7	0.8
$\delta_{\rm th}\rho^f_Z$ $^{(\dagger)}$	$[-2, 2]_{\rm theo}$	yes	2	2
$\delta_{\rm th}\kappa^f_Z$ $^{(\dagger)}$	$[-2, 2]_{\rm theo}$	yes	2	2

W and top quark mass tells us Higgs mass



Higgs is Discovered! 2012

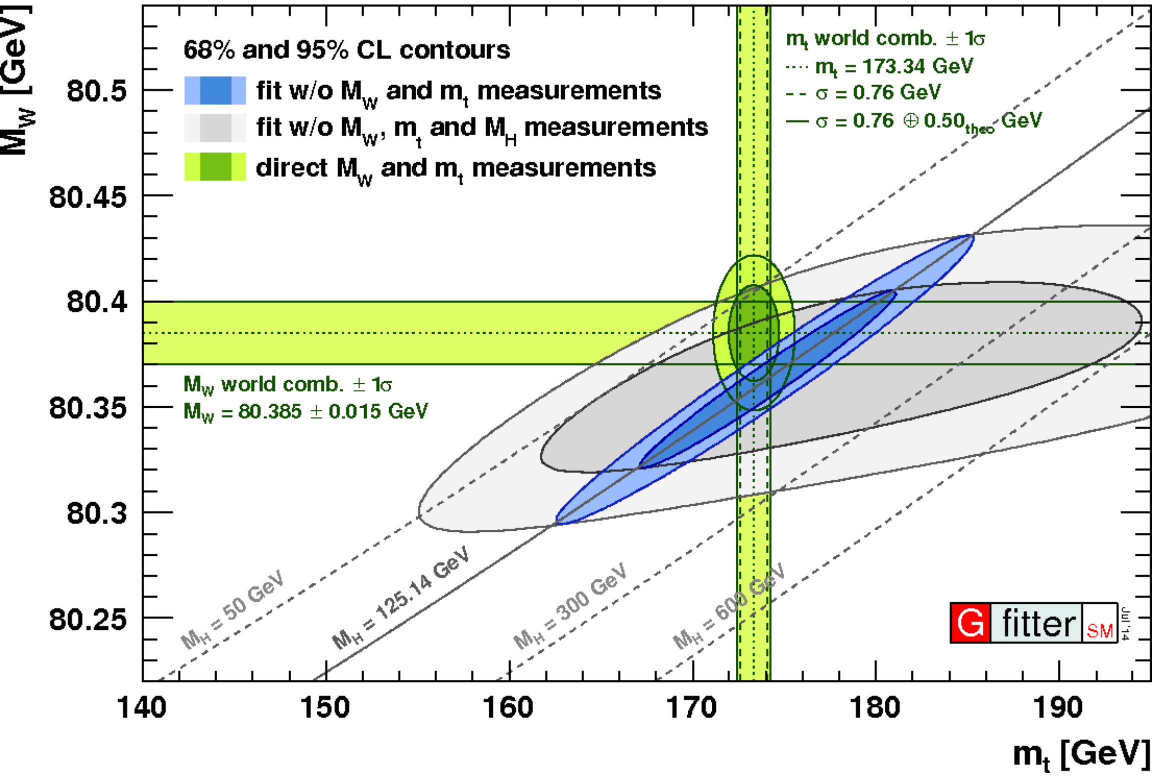




theory: 1964
design: 1984
construction: 1998
collisions: 2010

Consistency of the Standard Model

arXiv:1306.0571 (2013)

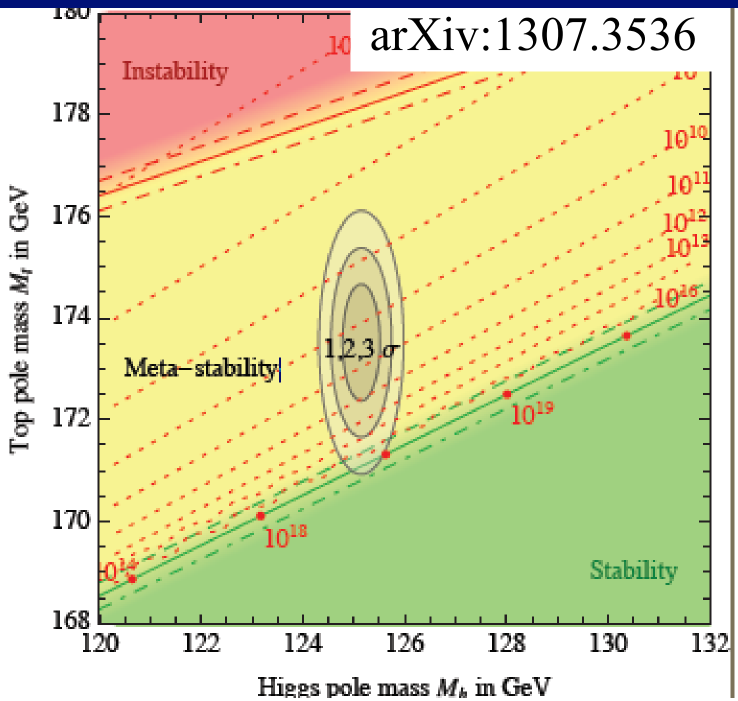


- 68% and 95% CL contours in the m_{top}-M_W plane for the fit including M_H (blue) and excluding M_H (grey).
- In both cases the direct measurements of M_W and m_{top} were excluded from the fit.

- The knowledge of M_H improves the precision of the indirect determination of M_W and m_{top} significantly.

- Very good agreement between the indirect determinations of M_W and m_{top} and the direct measurements is observed, showing impressively the consistency of the SM and leaving little room for signs of new physics.

The Fate of the universe…..



… depends on 1GeV in m_{top}

SM phase diagram in terms of Higgs and top pole masses.

Stability of the EW vacuum is an important property of the SM

- Measurements of the top mass and Higgs mass for the first time allow us to infer properties of the vacuum we live in!

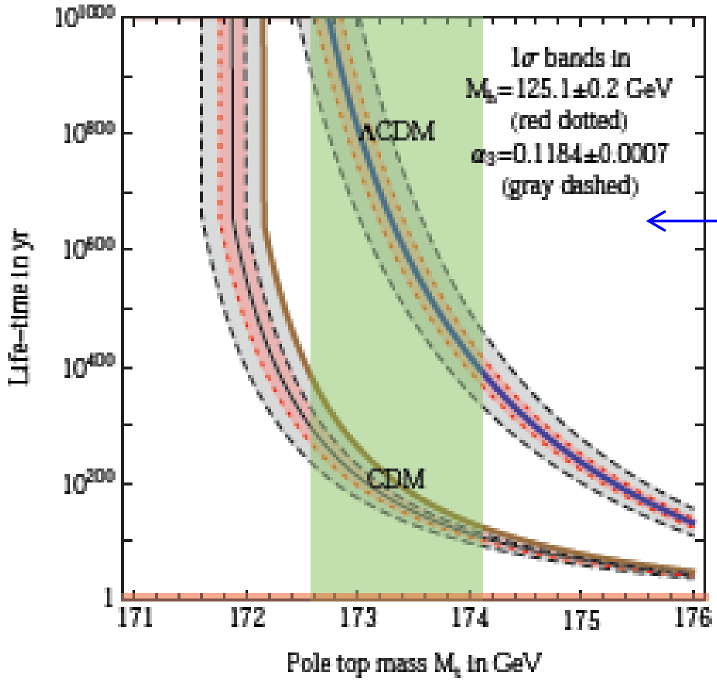
The measured values of M_{higgs} and M_{top} appear to be rather special → they place the SM vacuum in a near-critical condition, at the border between stability and metastability.

A fine-tuned situation: vacuum on the verge of being either stable or unstable. ~1-2 GeV in either mass could tip the scales. (But new physics could possibly change this scenario.)

- What top mass are we measuring??

The Fate of our universe

arXiv:1307.3536



The life-time of the electroweak vacuum, with two different assumptions for future cosmology: universes dominated by the cosmological constant (ΛCDM) or by dark matter (CDM).

The measured values of M_{higgs} and M_{top} indicate that the SM Higgs vacuum is not the true vacuum of the theory and that our universe is potentially unstable.
The lifetime of the present EW vacuum depends on the future cosmological history: If the future universe is matter dominated (flat universe) or if instead the universe keeps being accelerated by the cosmological constant
→ As shown, the SM vacuum is likely to survive for times that are enormously longer than any significant astrophysical age

- What top mass are we measuring??

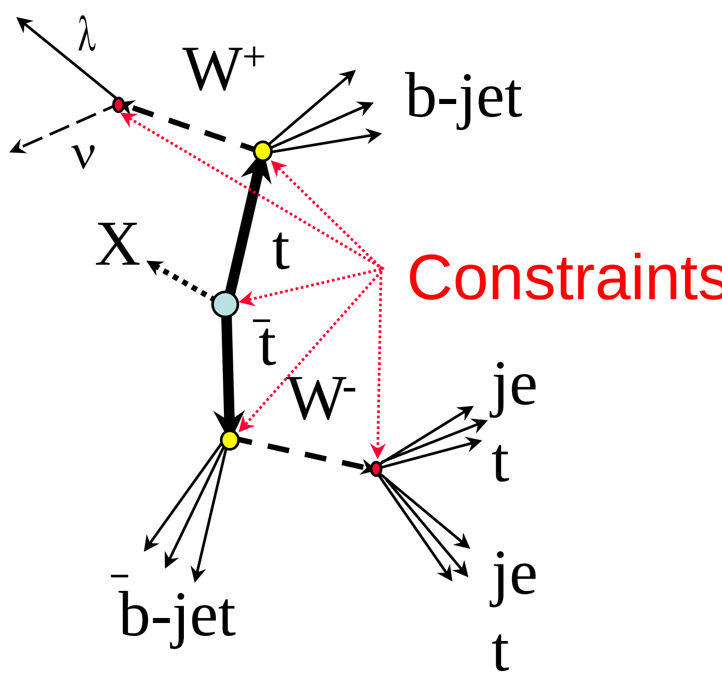
Top Mass: Experimental Challenges

Why so challenging? It is a difficult measurement

Many combinations of leptons and jets:

⇒Events are complicated!

⇒ Experimental observations are not as *pretty* as Feynman diagrams!



- Large backgrounds
- Missing neutrino(s)
- Confusion in ID assignment (add. Jets from ISR/FSR, b-tag: not 100% correct)
- Measurements are not perfect!

- Link observables to parton-level energies
- Large syst uncert. from jet energy scale
- Need accurate detector simulation

Backgrounds

- Hadron colliders:
  - →Very high backgrounds!
- Backgrounds can bias the top mass measurement

Typical Backgrounds:

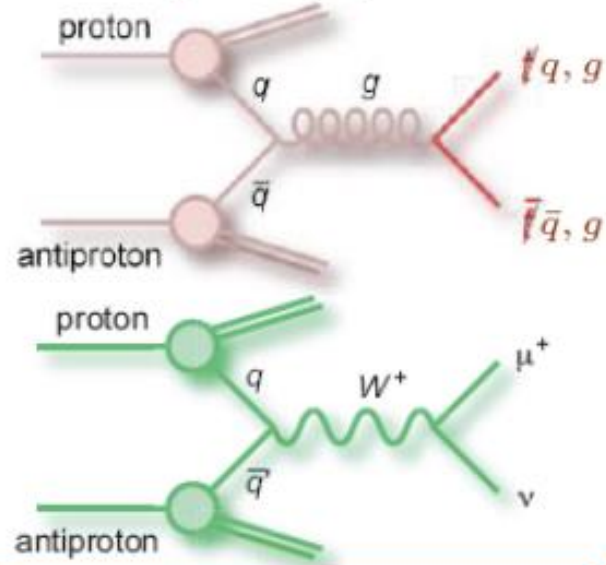
W+jets

Z+jets

QCD multijet prod'n

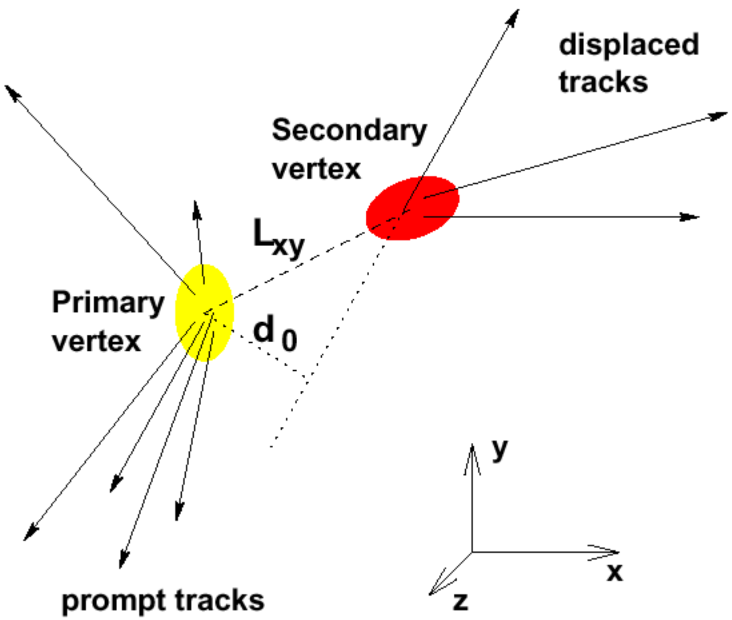
Diboson prod'n

Single top prod'n



Backgrounds & b-tagging algorithms

- Hadron colliders:
  - $\rightarrow$Very high backgrounds!
- Backgrounds can bias the top mass measurement
- Control backgrounds using b-tagging information

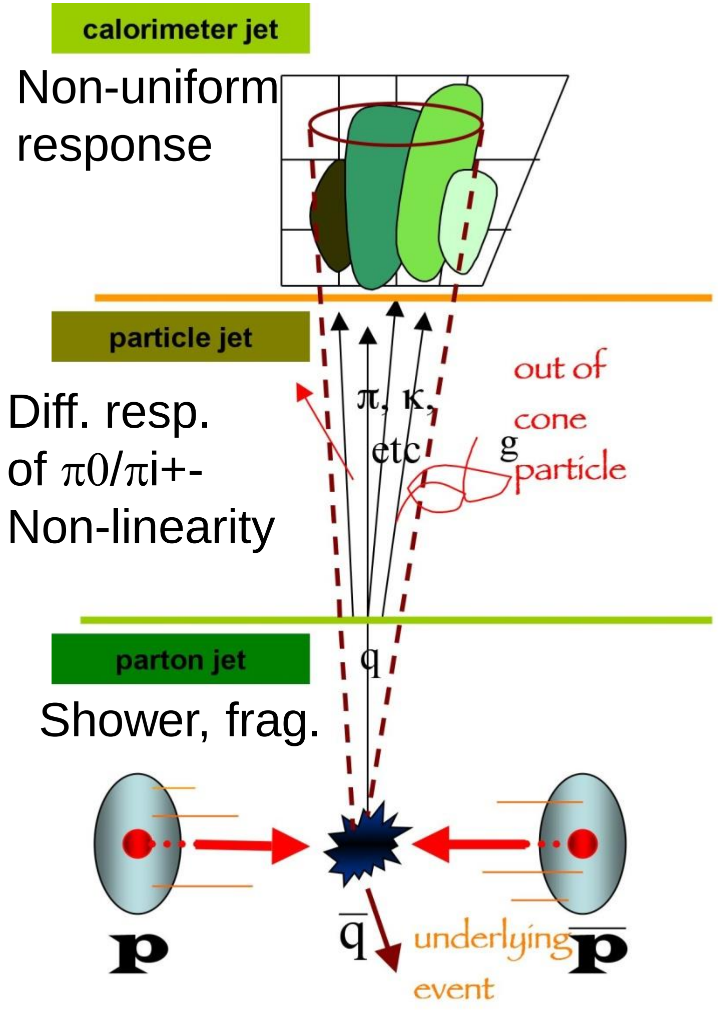


- At the same time:
  - $\rightarrow$help combinatorics!
- In lepton+jets:
  - 2 b-tags $\rightarrow$ 2 combinations
  - 1 b-tag $\rightarrow$ 6 combinations
  - 0 b-tags $\rightarrow$ 12 combinations

Channel	B-tags	S:B	Perm.
Dilepton	≥ 0	1:4	2
	≥ 1	4:1	2
Lepton+jets	≥ 0	< 1:1	12
	≥ 1	2.5:1	6
	≥ 2	10:1	2
All-hadronic	≥ 1	1:4	30
	≥ 2	4:1	6

Jet Energy Correction

Determine true "parton" (or particle) energy from measured jet energy



The correction factor depends on jet E_T and η and is meant to reproduce the average jet E_T correctly, (not to reduce the jet fluctuations around this mean)

Corrections for generic jets:

⇒ Use Z→ ee for EM energy calibration

⇒Absolute corrections (γ-jet balancing)

⇒ Relative corrections (central-forward calorimeters, dijet balancing)

Out-of-Cone: correction to parton outside the reconstruction cone

Underlying event: energy which enters the reconstruction cone

"top-specific correction" to light quark jets and b-jets separately

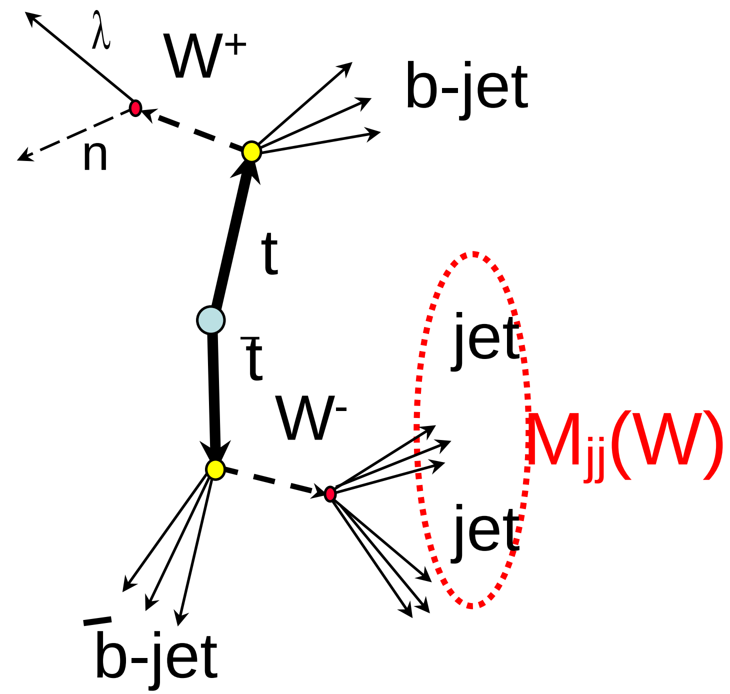
"In situ" jet energy calibration in top events

"Creative" solution to improve jet energy scale precision:

Simultaneous fit to M_{jj} and M_{top} using top mass and jet energy scale (JES) templates for 'lepton plus jets' and 'all hadronic' final states:

M_t (true M_{top}, JES), M_{jj} (true M_{top}, JES)

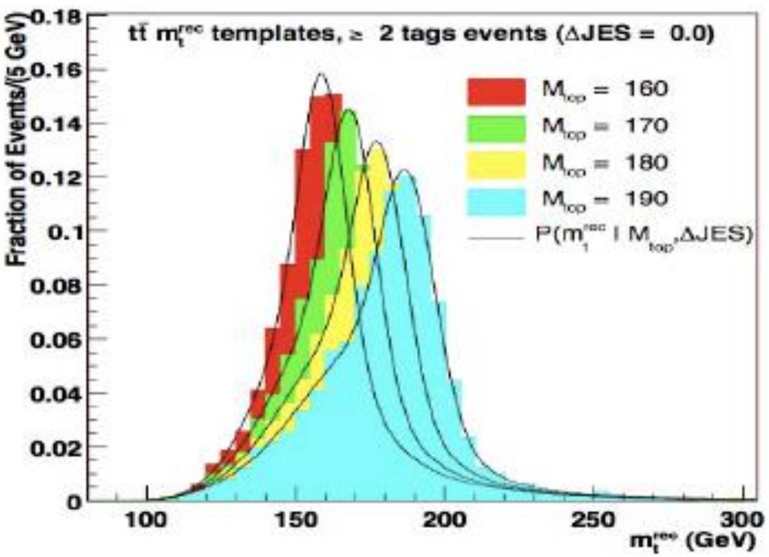
- Identify jets coming from W
  - All non-btagged jets pairs are taken into account equally.
  - 1/3/6 m_{jj} per event with 2/1/0 b-tag
- Reconstruct their invariant mass m_{jj}
- M_{jj} strongly dependent on JES
  - Make M_{jj} templates by varying JES
  - Fit data with Wjj to measure JES!
- M_W uncertainty is negligible (< 50 MeV)
- M_{jj} mostly independent of M_{top}
- This scale is applied to b-jets and light-quark jet



JES from W→jj is mostly statistical → luminosity scale !

Top Mass Measurement: standard methods

- The first "standard" methods (still used) are:
  1) Template method
  2) Matrix Element method
- 1) Template method (simplest technique):
  - ⇒ Choose a variable sensitive to the top mass (xi)
  - ⇒ Exploit dependence on m_{top} of kinematic observable xi
  - ⇒ Create "templates" = distributions of xi using MC
    - For signal: xi=xi(m_{top})
    - For background
  - ⇒ Maximise consistency with the … n, given m_{top}
  - ⇒ Advantages:
    - Few assumptions
    - fairly straight-forward
  - ⇒ Drawback:
    - Sub-optimal sensitivity



Invariant mass of 3 jets, 2 from W, 1 from b

Top Mass Measurement: standard methods

- The first standard methods (still used) are:
  1) Template method
  2) Matrix Element method
- 2) Matrix element method:

  $\Rightarrow$ Directly calculate the event probability as:

$$P_{\mathrm{evt}}(m_{\mathrm{top}}) \propto f P_{\mathrm{sig}}(m_{\mathrm{top}}) + (1-f) P_{\mathrm{bgr}}$$

$$P_{\mathrm{sig}}(m_{\mathrm{top}}) \propto \int ... \mathrm{d}\sigma_{t\bar{t}}(m_{\mathrm{top}}) \qquad \mathrm{d}\sigma_{t\bar{t}} \propto |\mathcal{M}_{t\bar{t}}|^2 (m_{\mathrm{top}})$$

  $\Rightarrow$ Advantages:

- Use full 4-vectors with maximal kinematic and topological information
- higher weight is assigned to events that are more likely to be from ttbar

  $\Rightarrow$ Drawbacks:

- High computational demand
- Theory assumptions: incorrect modeling due to missing theory corrections

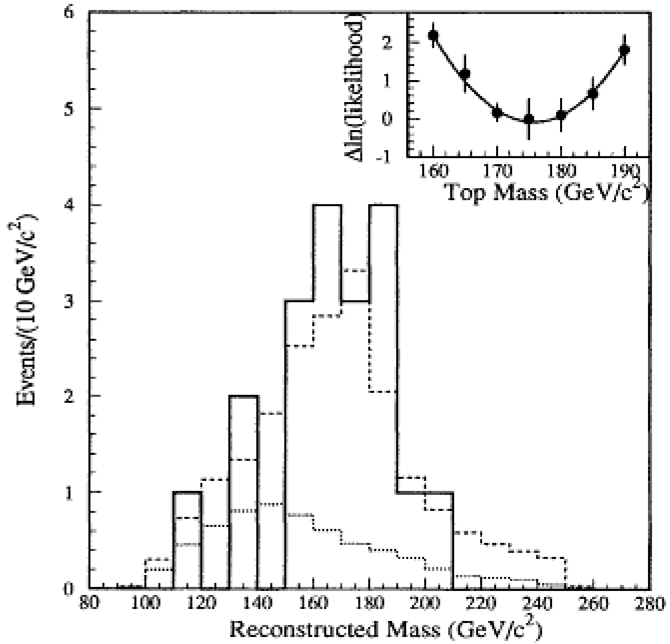
First measurement of top quark mass

- First measurement of top quark mass in 1995 performed in the lepton plus jets channel, using a sample of 19 events with an expected background of ~ 7 at CDF and 17 events with ~ 4 backg at D0 .

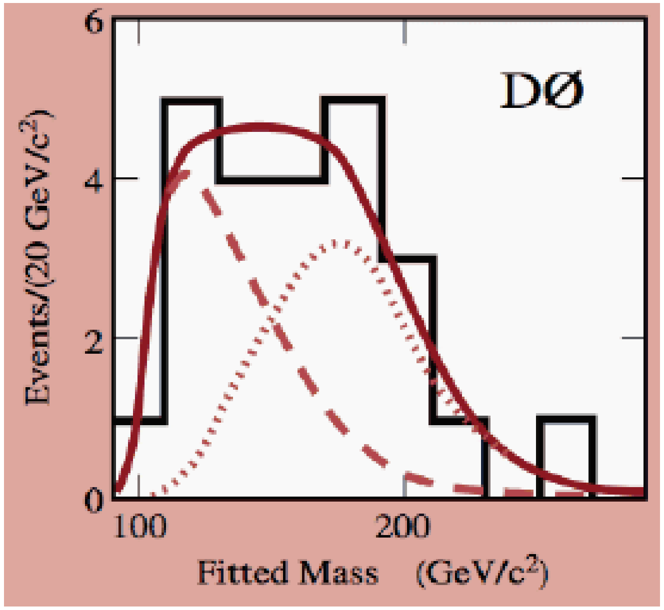
Reconstruct M_{top} with 2 constraints: $M(W^+)=M(W^-)$, $M(t)=M(tbar)$

- $\mathbf{M_{top} = 176 \pm 13\ GeV/c^2}$

$\mathbf{M_{top} = 199 \pm 30\ GeV/c^2}$



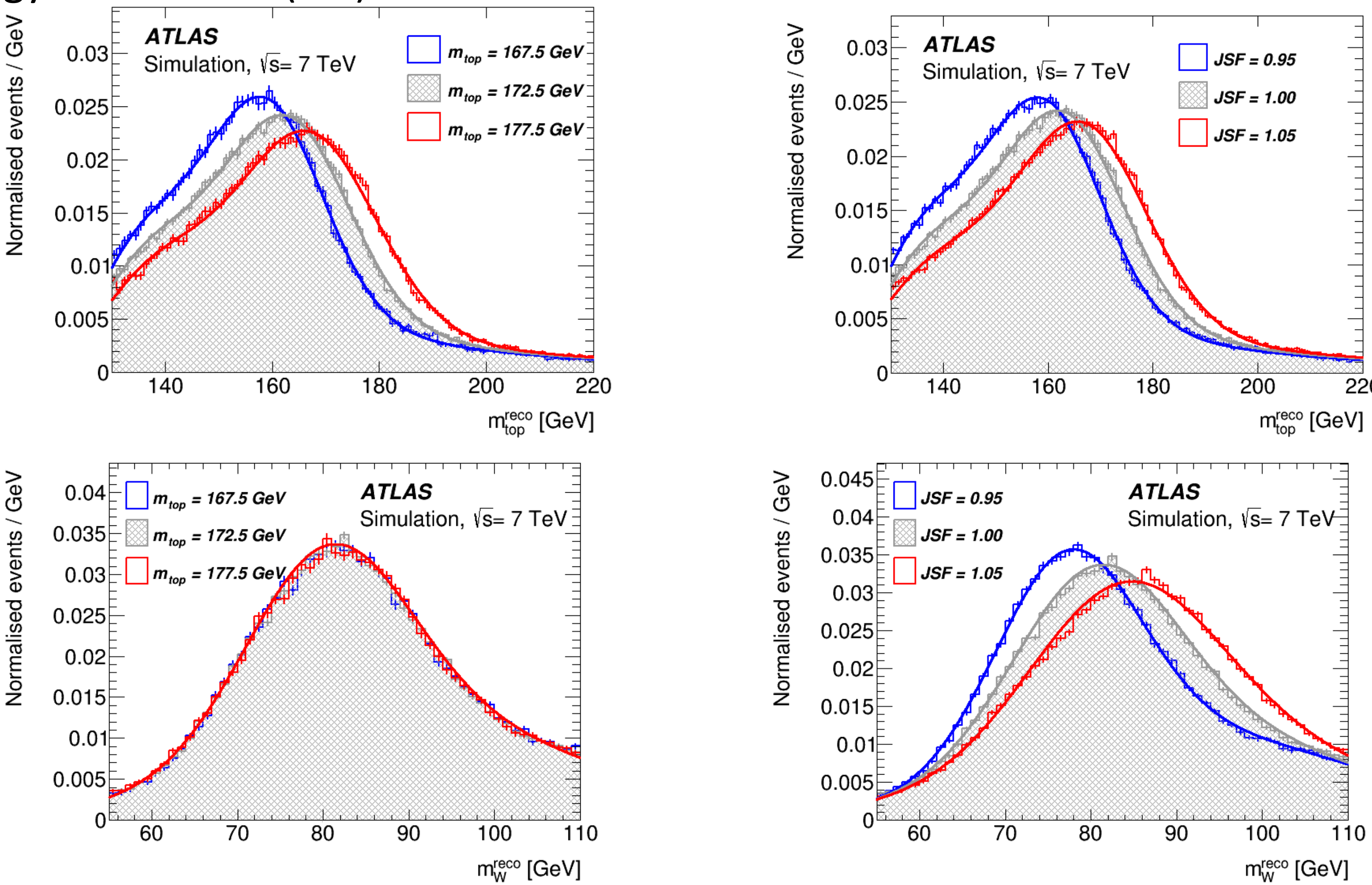
PRL 74 2626 (1995)



PRL 74 2632 (1995)

ATLAS top mass

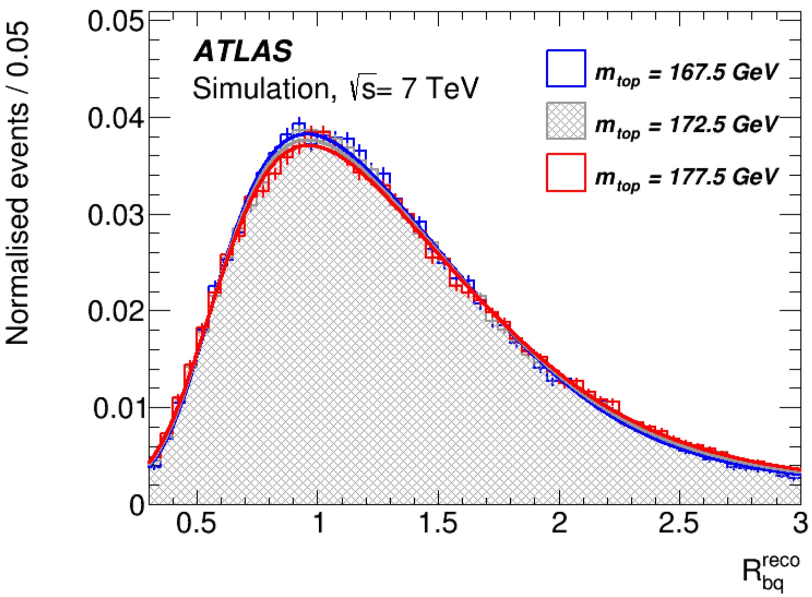
- Similar template measurement in ATLAS
- W mass used to constrain the JES in situ
- Simulated plots obtained for 3 values of top quark mass and 3 values of the jet energy scale factor (JSF)

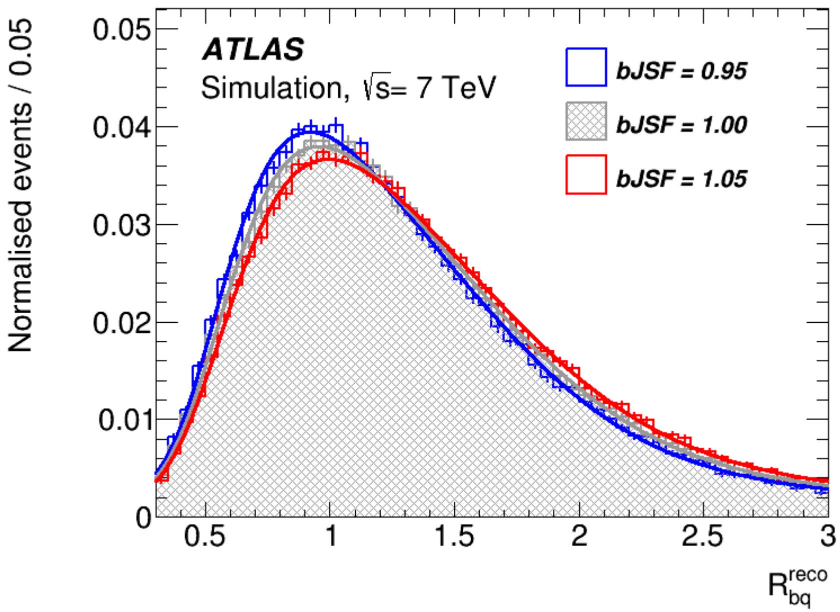


ATLAS top mass

- Fitting the invariant mass of the 3 jets system is very sensitive to the jet energy scale
- W mass used to constrain the JES in situ
- New Idea: Can use a variable sensitive to the relative energy scale of b-jets compared to q/g jets
- $R_{bq} = (p_T^{b1} + p_T^{b2})/(p_T^{q1}+p_T^{q2})$

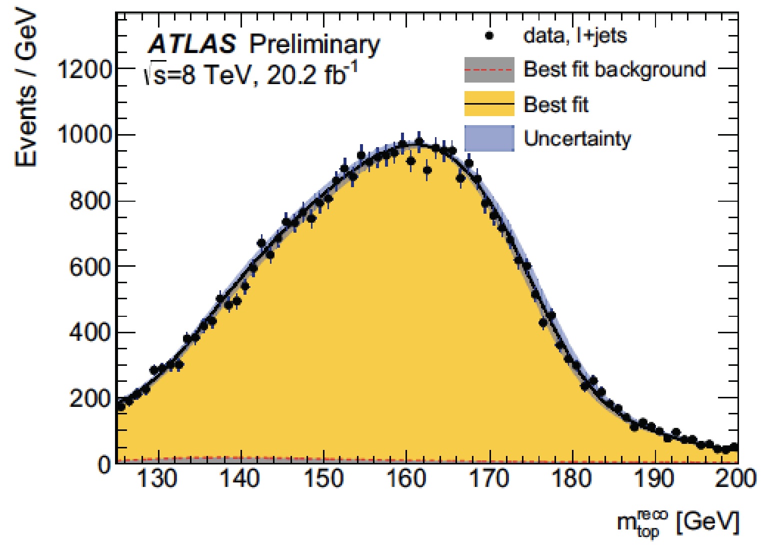
Eur. Phys. J. C (2015) 75:330



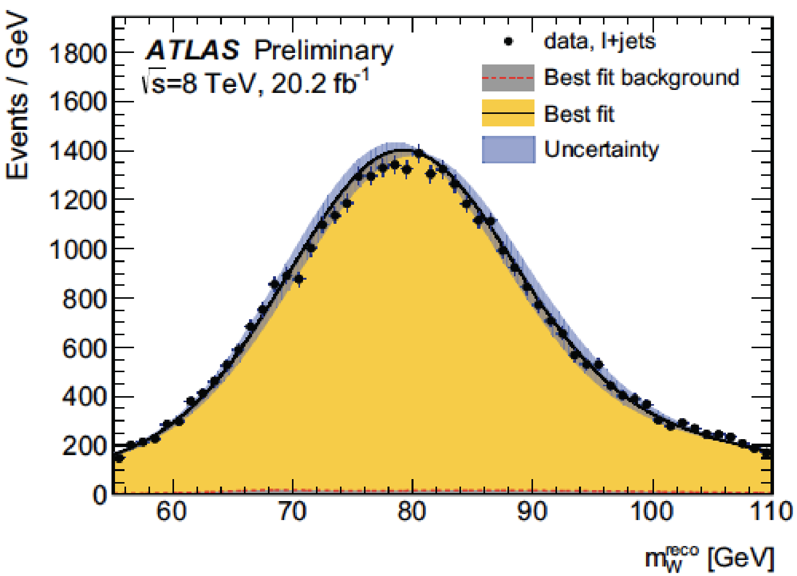


ATLAS 3D template fit in lepton+jets

ATLAS-CONF-2017-071



(a) Reconstructed top quark mass



(b) Reconstructed *W* boson mass

- Reconstruct the top pairs using kinematic likelihood fit to select combination of assignments that best fits ttbar hypothesis
- Use 3-dimensional template fit to determine m_{top} with the jet energy scale factor (JSF) and the relative b-to-light-jet energy scale factor (bJSF)

m_{top} = 172.08 ± 0.39 (stat) ± 0.82 (syst)GeV

Biggest systematic uncertainties: JES, and bJES

Precision: 0.5%

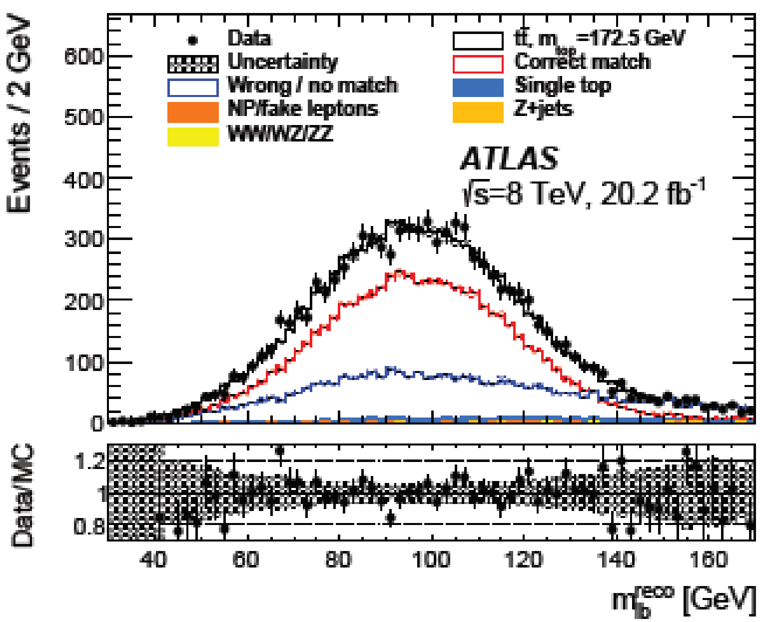
ATLAS dilepton top quark mass @8TeV

- Dilepton analysis with 2 oppositely charged leptons + 2 b-tagged jets
- For ee and $\mu\mu$ require E_T^{miss} > 60 GeV, Z-veto and $m_{\ell\ell}$ > 15 GeV
- For eμ require scalar sum of p_T of leptons and jets > 130 GeV
- Optimisation of the final uncertainty with $p_T(l,b)$ > 120 GeV
- The analysis uses a template fit to $m_{reco}(l,b)$ with m_{top} as free parameter
- Largest systematics from jet energy scale, relative b-to-light-jet energy scale (bJES).
- The m_{top} value that best describes the data is:

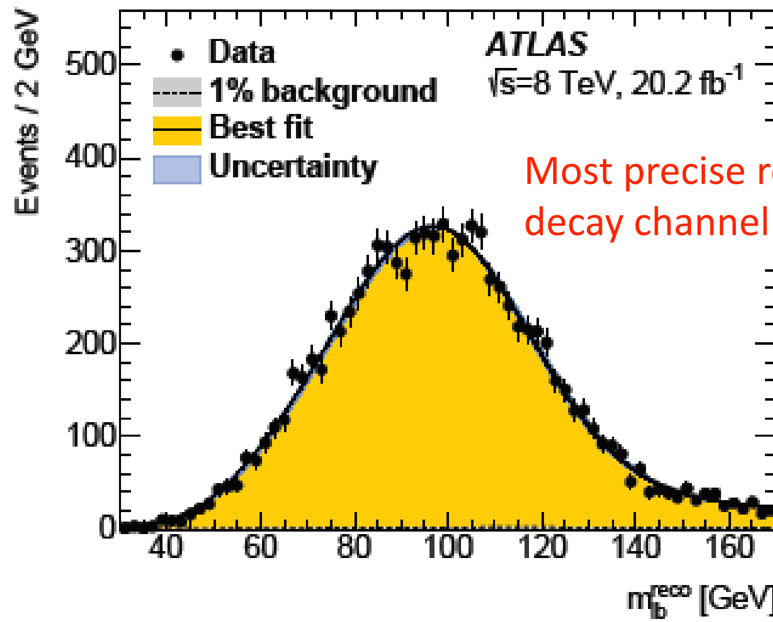
$$m_{top} = 172.99 \pm 0.41(stat) \pm 0.74(syst)\ \text{GeV}$$

Precision: 0.46%

PLB 761 (2016) 350 - 371



(b) $m_{\ell b}^{reco}$ in data and simulation



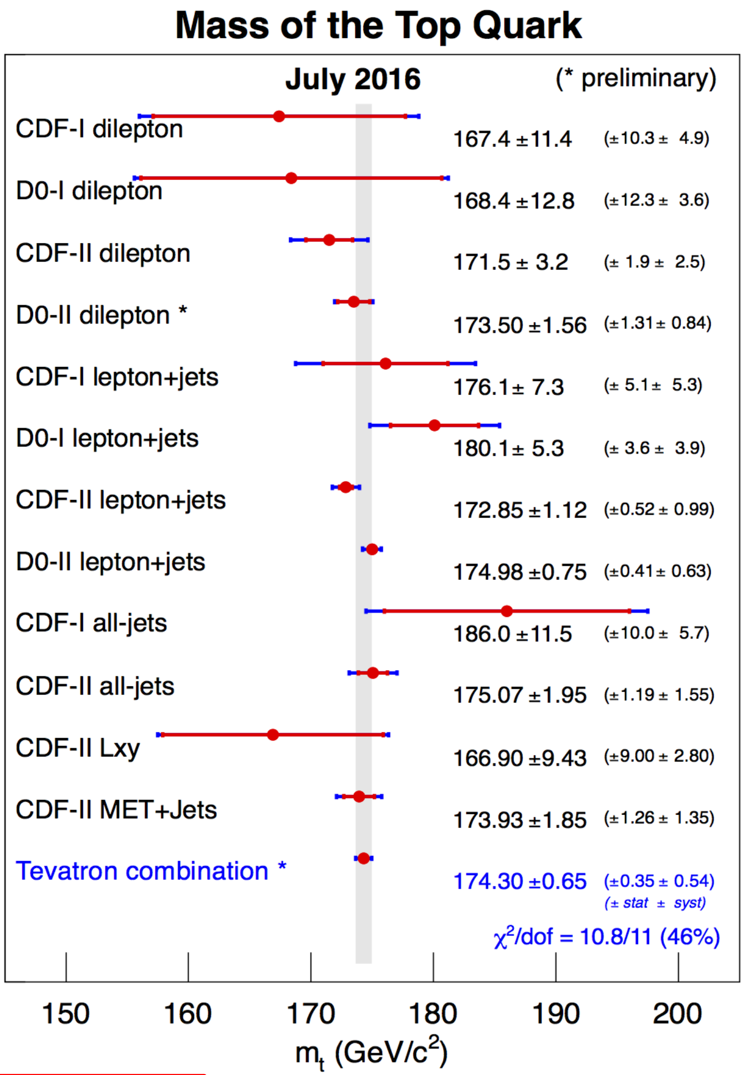
(c) Fit to $m_{\ell b}^{reco}$ in data

Most precise result in this decay channel to date

Tevatron top mass combination

- 5 Run I and 7 Run II results
- Combination performed using BLUE
- Limited by systematic uncertainties
  - ⇒ Dominant: signal modeling and jet energy scale uncertainties
- Total uncertainty ± 0.65 GeV/c^2 (< 0.4%)

(better than world comb. March 2014: ± 0.76 GeV/c^2)



$$M_{top} = 174.30 \pm 0.35\,(\text{stat}) \pm 0.54\,(\text{syst})\ \text{GeV/c}^2$$

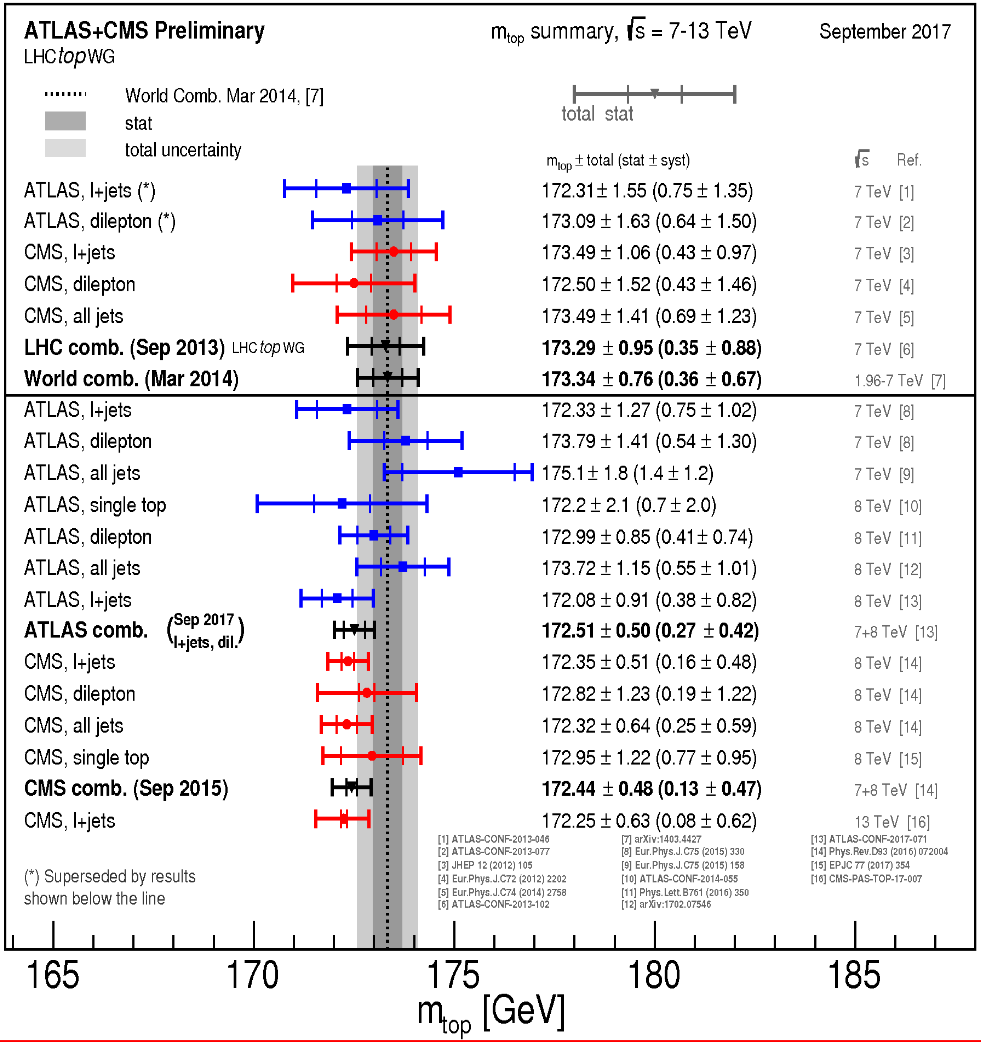
arXiv:1407.2682
arXiv:1608.01881

ATLAS and CMS top mass measurements

- Best precision is reached when combining all methods/channels across all experiments

- LHC and Tevatron results with nearly comparable precision of 3-4 permille (~0.5 GeV)

- LHC top mass systematically limited: MC modelling,(b)JES



⇒Since LHC is a top quark factory, it's all about controlling systematics
⇒ new approaches with complementary systematics can constrain combined systematics

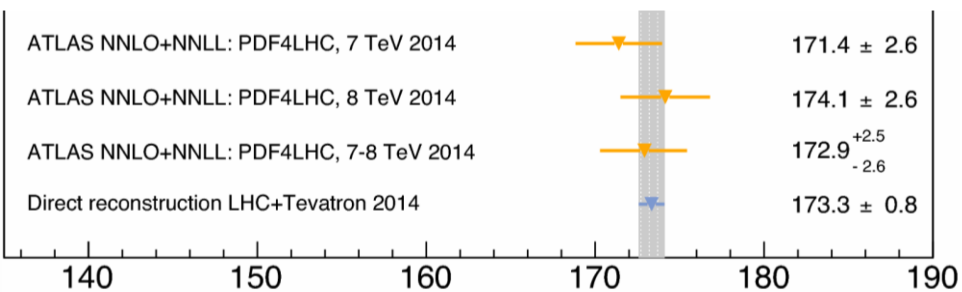
ATLAS top pole mass in dilepton channel

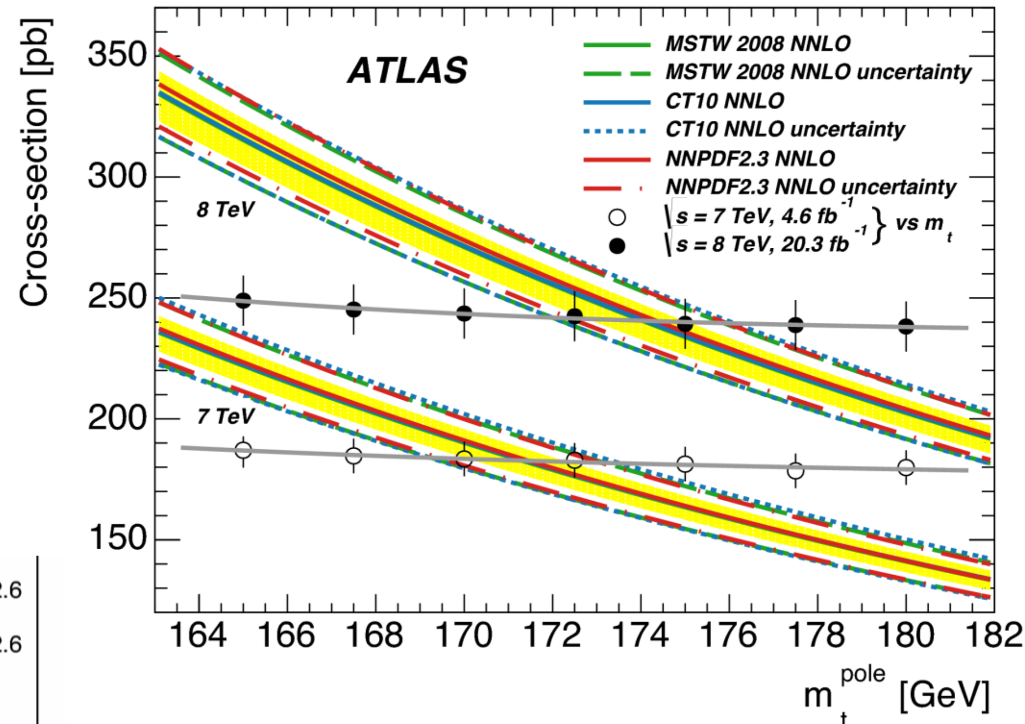
- Advantage of the ``indirect'' method: extract the top «pole» mass in a well-defined renormalization scheme (NNLO calculations)
- Mass from precision cross section in eμ dilepton channel

⇒ Designed to be not very sensitive to the top mass

- Plot the observed (measured) cross section as a function of top mass (dots with error bars)
- Plot the expected cross section as a function of top mass in the pole mass scheme (curves)
- Intercept of the two gives the pole mass
- Drawback: less precise than direct measurements
- Limited by theoretical uncertainties: scale and PDF

$m_{top} = 172.9^{+2.5}_{-2.6}$ GeV





Eur.Phys.J. C74 (2014) 3109

D0 pole mass from inclusive and differential σ

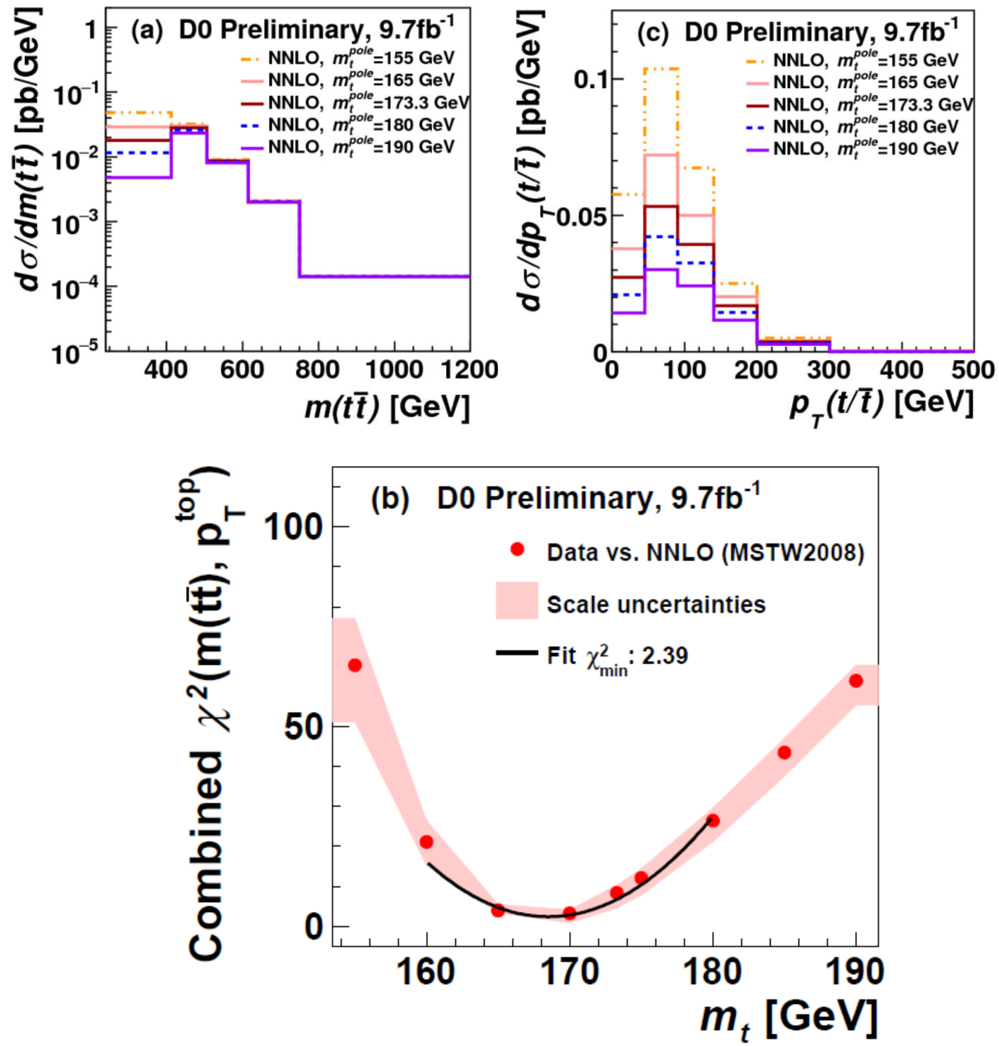
- From <u>inclusive</u> cross-section measur. in lepton+jets and dilepton channels, similar to ATLAS method:

$m_{top}=172.8 \pm 1.1 \text{ (theo.) } ^{+3.3}_{-3.1} \text{ (exp.) GeV}$

- Using the <u>differential</u> tt̄ cross section:
  - ✓ additional information coming from the shape of the distributions
  - ✓ possible since NNLO differential predictions are now available (JHEP 1605, 034 (2016))
- $p_T^{\ top}$ and m_{tt} distributions sensitive to pole mass
- compared to NNLO QCD calc. , four different PDF sets
- χ^2 fit to both distributions
  - p_T vs. m_{tt}

$m_{\ top}=169.1 \pm 2.5 \text{ (total) GeV}$

- smaller uncertainty than from D0 inclusive cross section (1.5%)



FERMILAB-CONF-16-383-PPD

D0 Note 6473-CONF

D0 pole mass from inclusive and differential σ

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m_{top}=172.8 ±1.1 (theo.) $^{+3.3}_{-3.1}$ (exp.) GeV

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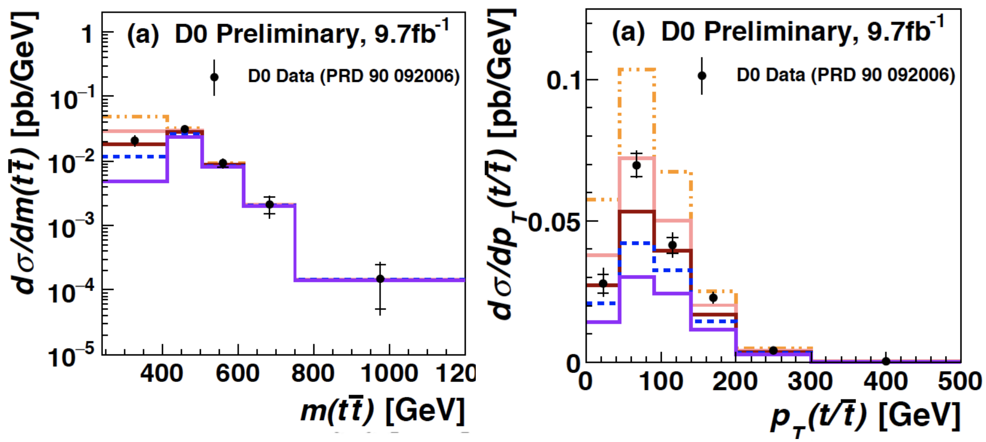
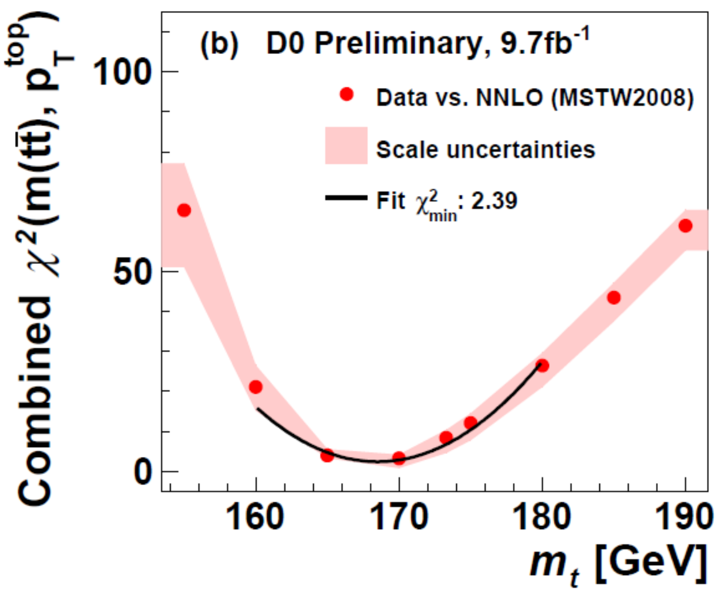




FERMILAB-CONF-16-383-PPD

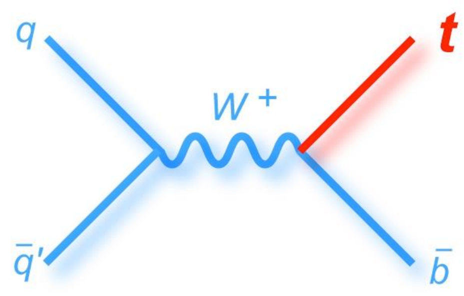
D0 Note 6473-CONF

Single top production

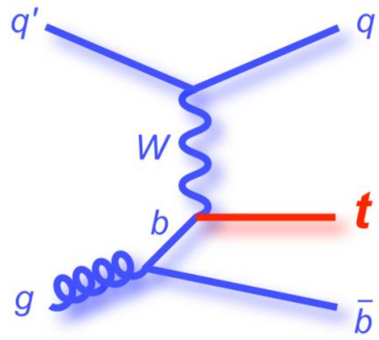
How else is top quark produced?

- Electroweak single top production:

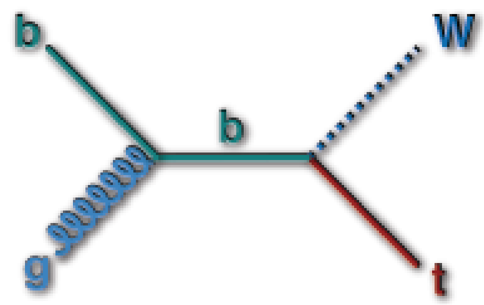
s-channel



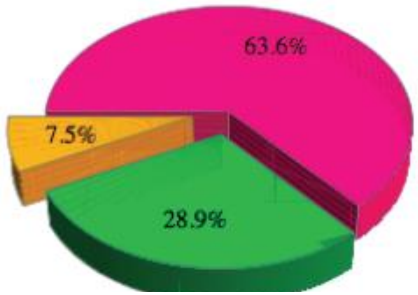
t-channel



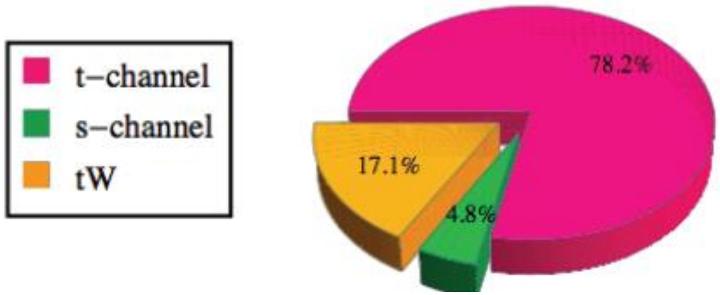
Wt-production



Tevatron: σ_{tot} = 3 pb



LHC: σ_{tot} = 114 pb @ 8 TeV

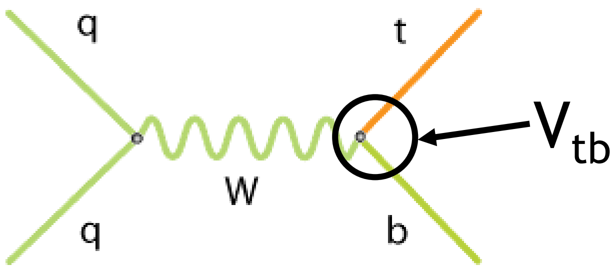


Cross section(pb)	$t\bar{t}$	s-channel	t-channel	**Wt**
Tevatron(1.96 TeV)	7.08	1.05	2.08	0.12
	×33	×5.3	×42	x160
LHC(8 TeV)	234	5.55	87.2	20
LHC(13 TeV)	830	10.5	217	72

(N. Kidonakis, arXiv:1210.7813)

Why measure Single Top Production ?

- $\sigma_{\text{single top}} \propto |V_{tb}|^2$
- Give access to the W-t-b vertex
  - $\Rightarrow$ probe V-A structure
  - $\Rightarrow$ access to top quark spin
- Allows direct measurement of Cabibbo-Kobayashi-Maskawa (CKM) matrix element $|V_{tb}|$:



Direct measurements

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Ratio from Bs oscillations

Not precisely measured
Inferred using unitarity

Why measure Single Top Production ?

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  - $\Rightarrow$ probe V-A structure
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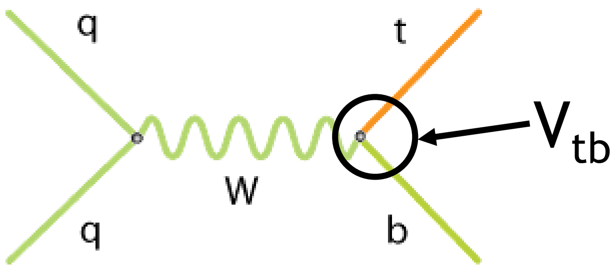


- Allows direct measurement of Cabibbo-Kobayashi-Maskawa (CKM) matrix element $|V_{tb}|$:
  - Is this Matrix 3x3 ?
  - Is there a 4th generation ?
  - Does unitarity hold ?

$$|V_{ub}|^2 + |V_{cb}|^2 + |V_{tb}|^2 \stackrel{?}{=} 1$$

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} & V_{uX}? \\ V_{cd} & V_{cs} & V_{cb} & V_{cX}? \\ V_{td} & V_{ts} & V_{tb} & V_{tX}? \\ V_{Yd}? & V_{Ys}? & V_{Yt}? & V_{YX}? \end{pmatrix}$$

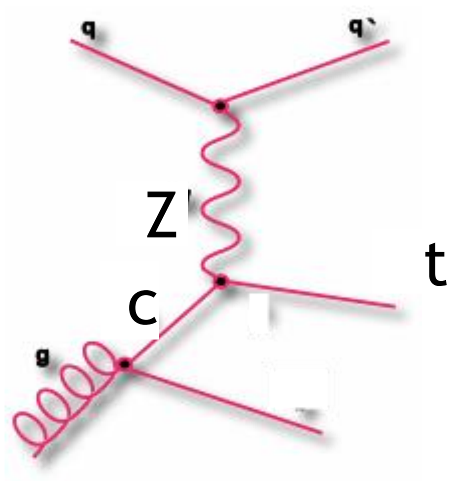
- Precision electroweak measurements rule out "simple" fourth generation extensions, but see for example:

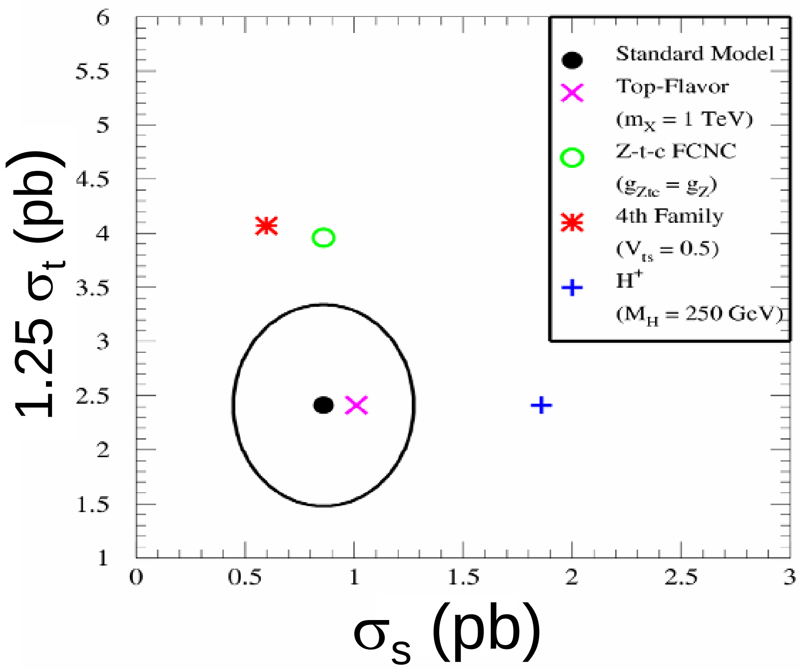
  J. Alwall et. al., "Is $|V_{tb}|\sim 1$?" Eur. Phys. J. C49 791-801 (2007).

Sensitivity to New Physics

- New physics may affect the rate of t and s channel differently

t-channel

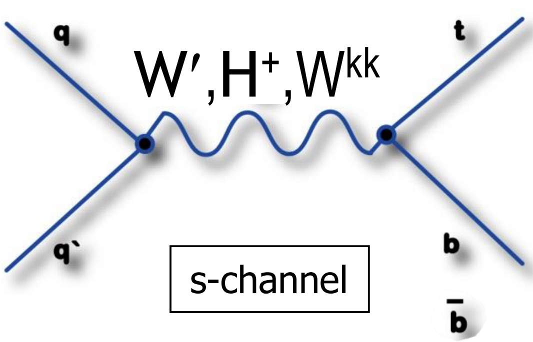




T. Tait, CP Yuan PRD63, 014018 (2001)

- Flavor changing neutral currents (t-Z-c, t-γ-c, t-g-c)

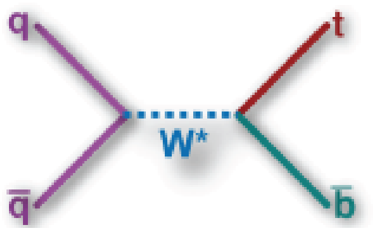
- heavy W' boson
- charged Higgs H^+
- Kaluza Klein excited W^{kk}



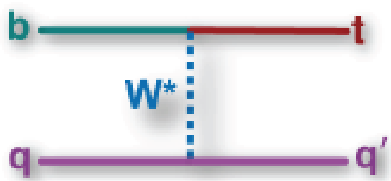
s-channel

The Challenge (1)

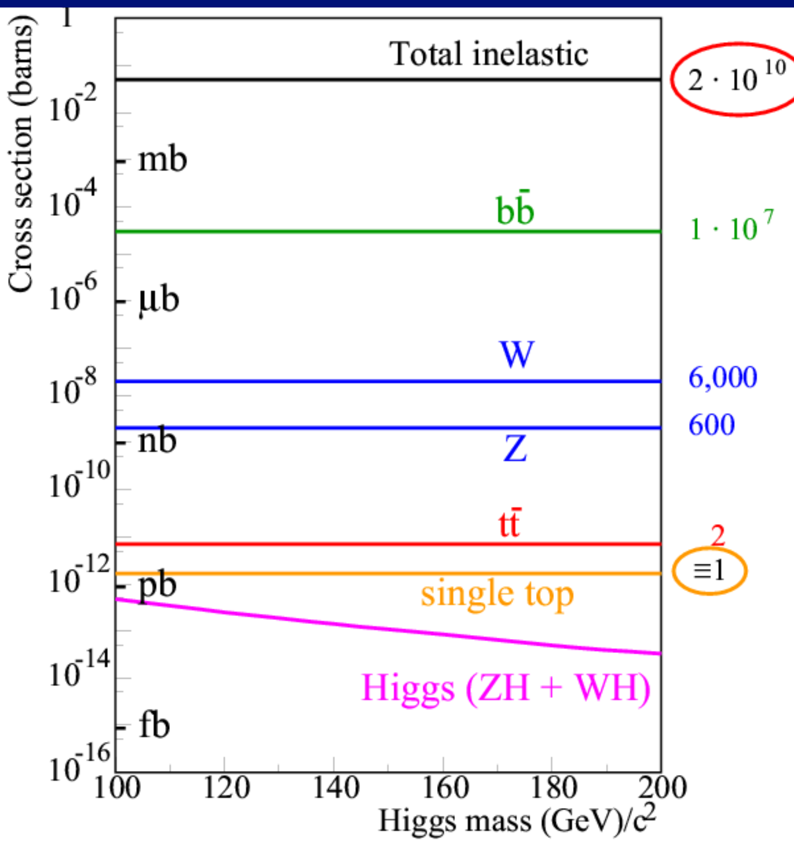
- Single Top observation came 14 years after top discovery….
  - ⇒ Single Top production was a rare process at the Tevatron: S/B ~ 1:10^9 before any selection
  - not an easy measurement



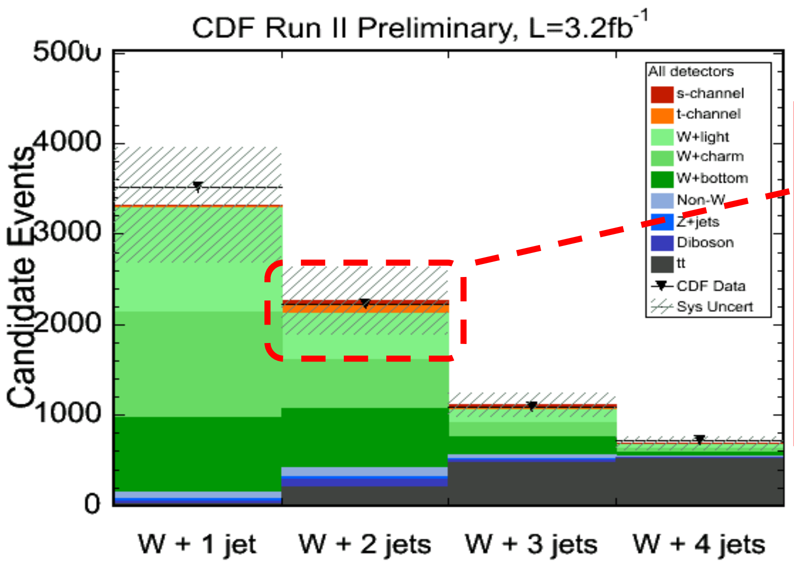
s-channel
1.05 ± 0.06 pb



t-channel
2.12 ± 0.16 pb



The Challenge (2)



Single top top quark production with decay into Lepton + 2 Jets final state hidden behind large backgrounds with large uncertainties (i.e. W+HF uncertainty ~ 30%)

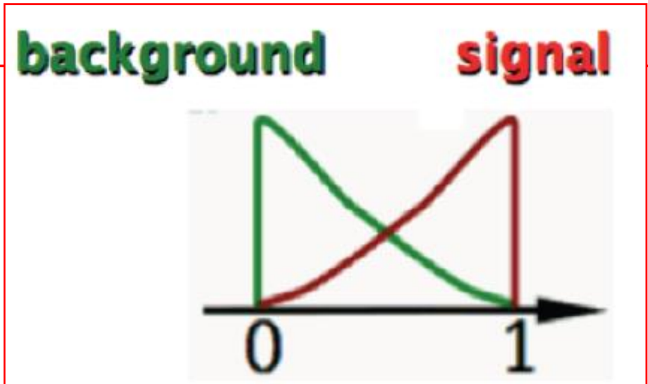
⇒ Makes counting experiment impossible!

- Third step: no single variable provides sufficient signal-background separation:

⇒take advantage of small signal-background separation in many variables

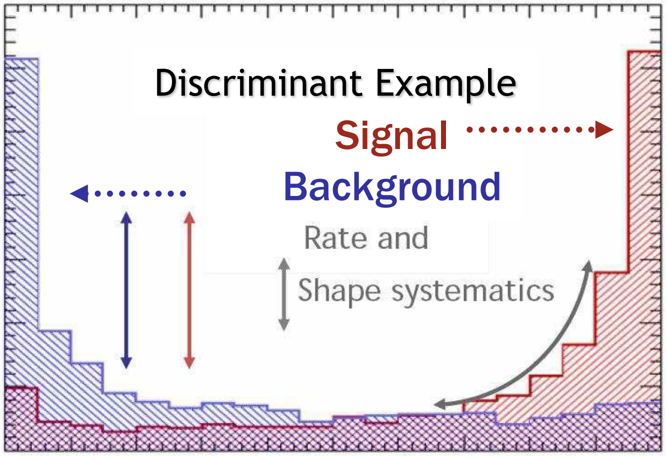
⇒Perform multivariate analysis (MV)

⇒ Multiple variables combined into a single more powerful discriminant to separate S from B



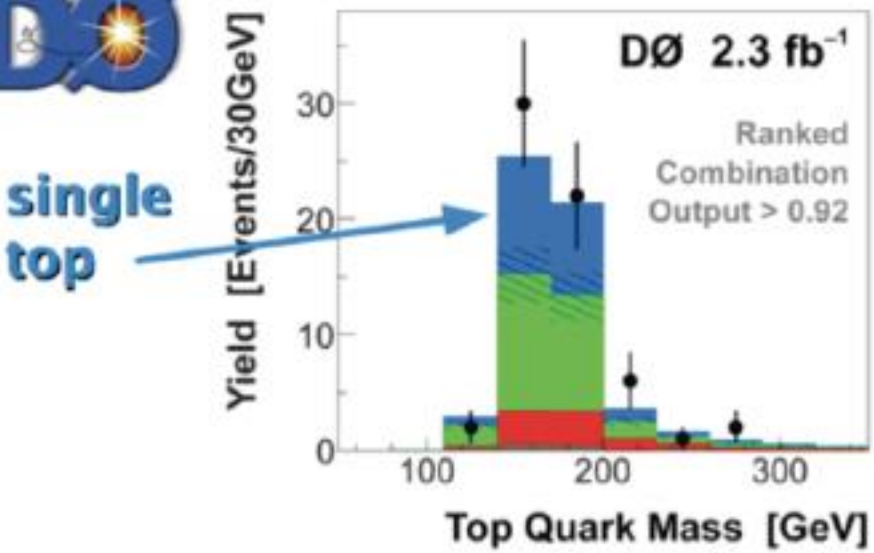
Analysis strategy

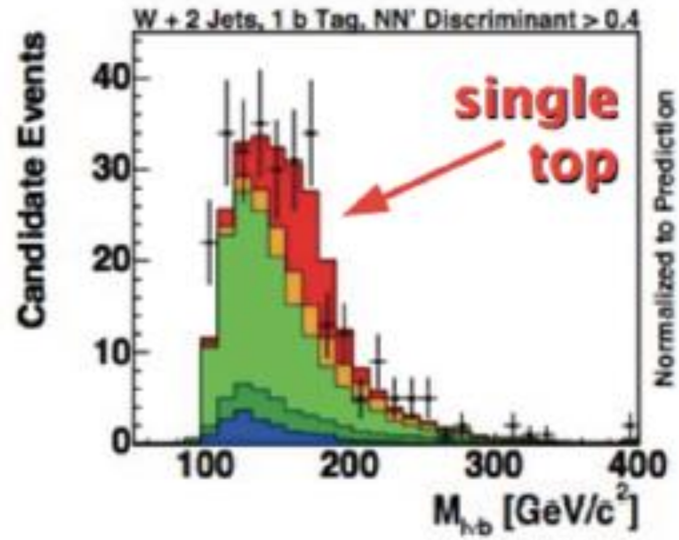
- Maximize signal acceptance
- Calculate discriminant functions that separate signal from background
  - Likelihood functions
  - Matrix element
  - Neural network (NN)
  - Bayesian Neural Network (BNN)
  - Boosted decision tree



- Check discriminant performance using data control samples
- Perform the statistical analysis

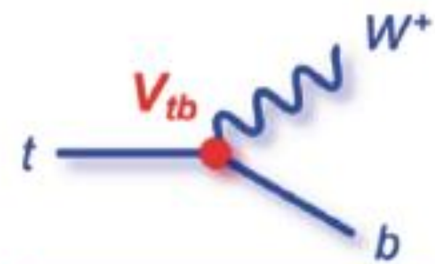
2009: Single top discovered at Tevatron





Single Top Cross Section	Signal Significance	
	Expected	Observed
DØ 2.3 fb^{-1} arXiv:0903.0850 m_{top} = 170 GeV		
3.94 ± 0.88 pb	4.5 σ	5.0 σ
CDF 3.2 fb^{-1} arXiv:0903.0885 m_{top} = 175 GeV		
2.3 $^{+0.6}_{-0.5}$ pb	>5.9 σ	5.0 σ

⇒ **observation with 5.0σ!**



DØ: $|V_{tb}| = 1.07 \pm 0.12$

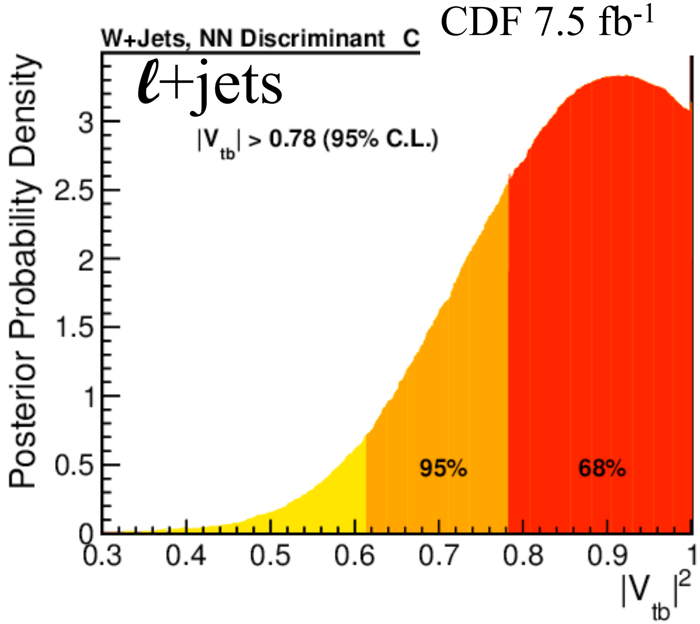
CDF: $|V_{tb}| = 0.91 \pm 0.13$

CKM matrix element $|V_{tb}|$

- $\sigma(s+t+Wt) \propto |V_{tb}|^2 \rightarrow$ calculate posterior probability density function in terms of $|V_{tb}|^2$

- To transform $\sigma(s+t)$ measurement into $|V_{tb}|$, assume:
  - $\Rightarrow$SM top quark decay: $|V_{td}|^2+|V_{ts}|^2 \ll |V_{tb}|^2$
  - $\Rightarrow$V-A and CP conserving Wtb vertex
  - $\Rightarrow$No assumption on number of families or CKM unitarity

$$|V_{tb,meas}|^2 = \frac{\sigma_{meas}}{\sigma_{SM}} \cdot |V_{tb,SM}|^2$$

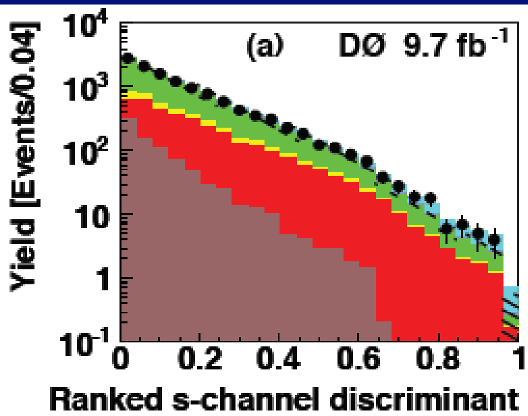


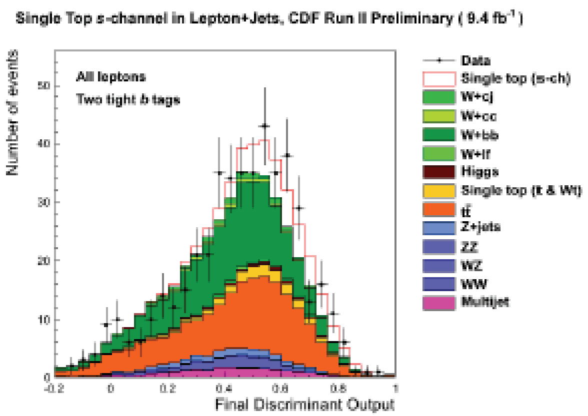
$|V_{tb}| = 0.95 \pm 0.09$ (stat+syst) $\pm$ 0.05 (theo)
$|V_{tb}| > 0.78$ (95 % C.L.)

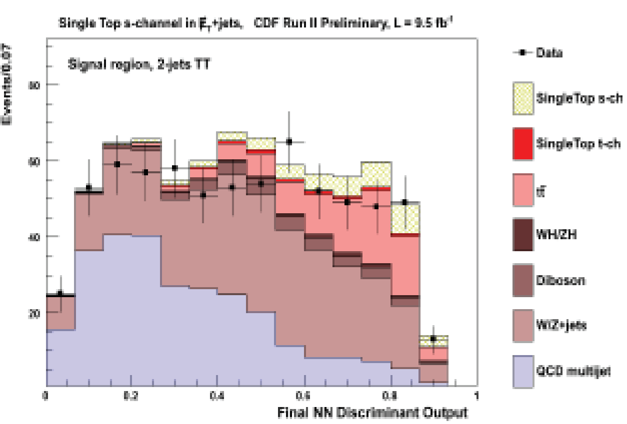
11% precision

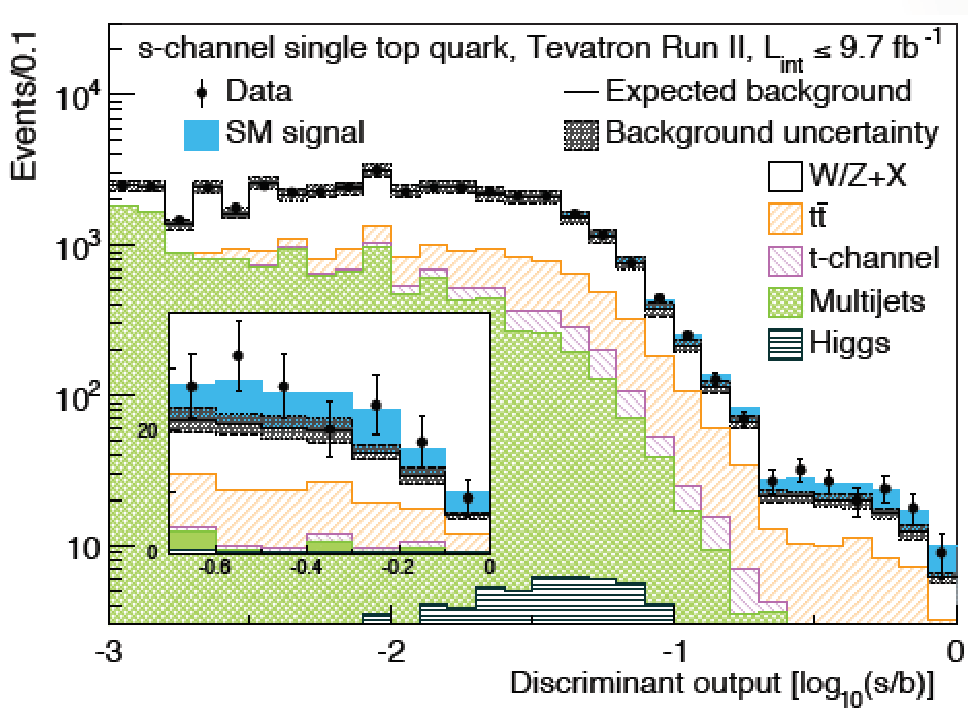
PRL 113, 261804 (2014)

Tevatron s-channel results







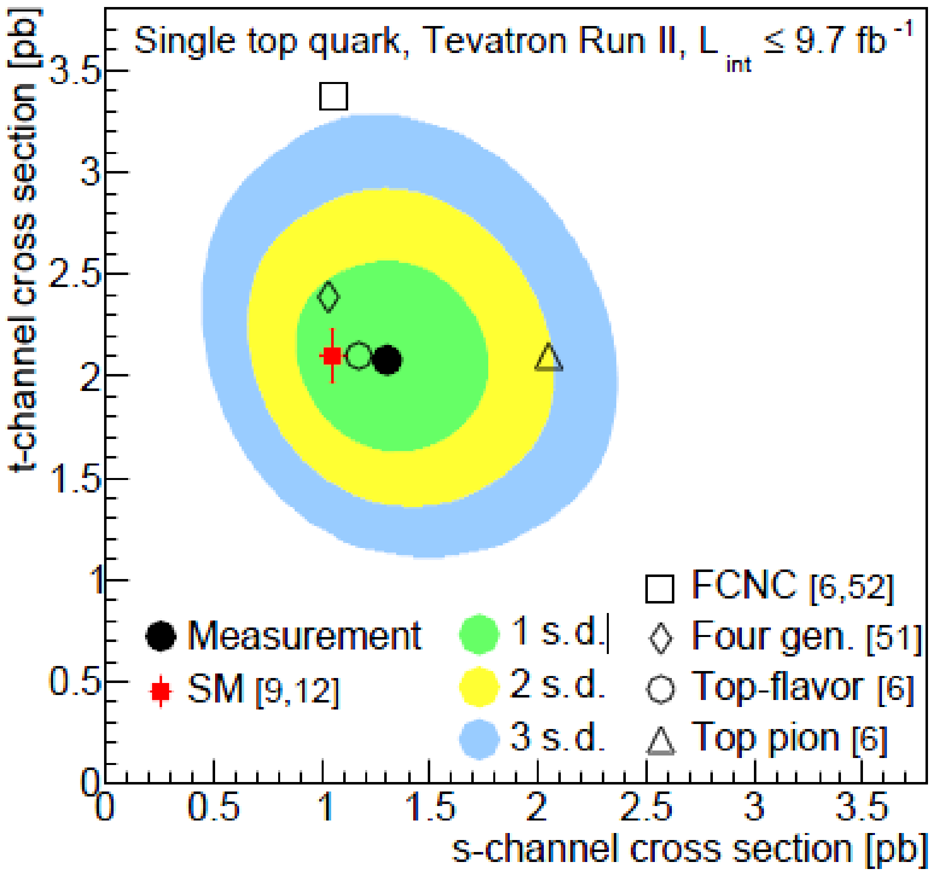


$\sigma_{s\text{-channel}} = 1.29^{+0.26}_{-0.24}$ pb

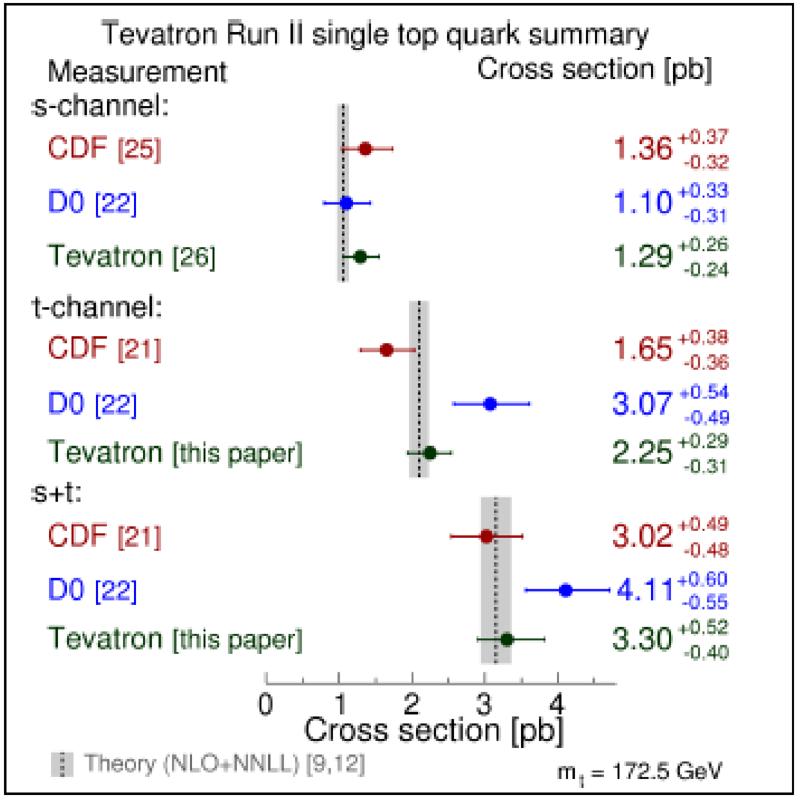
Obs (exp) significance: 6.3 (5.1) σ

Phys. Rev. Lett. 112, 231803

Single top at the Tevatron: summary



Phys. Rev. Lett. 115, 152003 (2015)

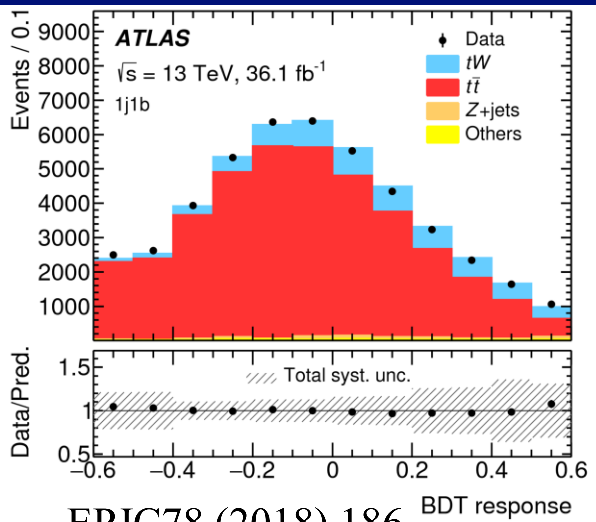


Single top at the LHC: full program of studies

ATLAS 13 TeV - Wt channel

BDT used to separate signal and background

- Main background: ttbar
- The differential cross-section for the production of a *W* boson in association with a top quark is measured for several particle-level observables.
- Results are found to be in good agreement with predictions from several MC event generators.



EPJC78 (2018) 186

CMS 13 TeV t-channel

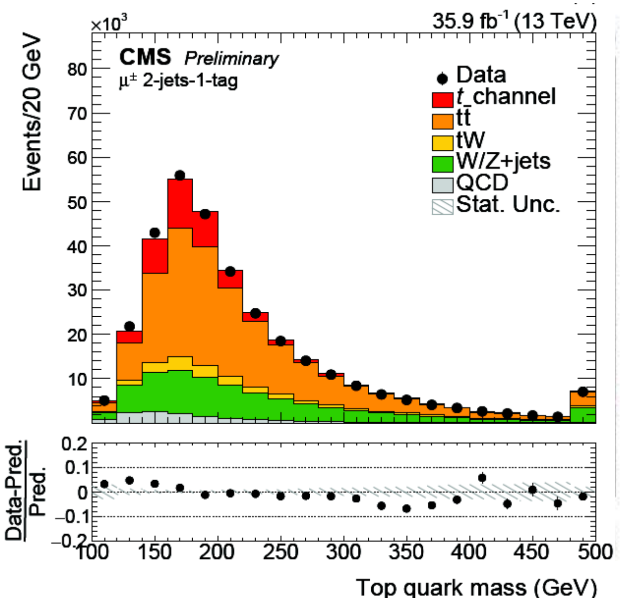
Measurement focused on σ(t)/σ(tbar)

- Measurement of cross section limited by systematics
- Train BDTs for signal extraction
- CKM Matrix element V_{tb} assuming:

$$\mathcal{B}(\mathrm{t} \rightarrow \mathrm{Wb}) \approx 1 \Rightarrow f_{\mathrm{LV}}^2 \mathrm{V}_{\mathrm{tb}}^2 = \sigma_{\mathrm{meas.}}/\sigma_{\mathrm{theo.}}$$

$$|f_{\mathrm{LV}} \mathrm{V}_{\mathrm{tb}}| = 1.00 \pm 0.05 \ (\mathrm{exp}) \pm 0.02 \ (\mathrm{theo.})$$

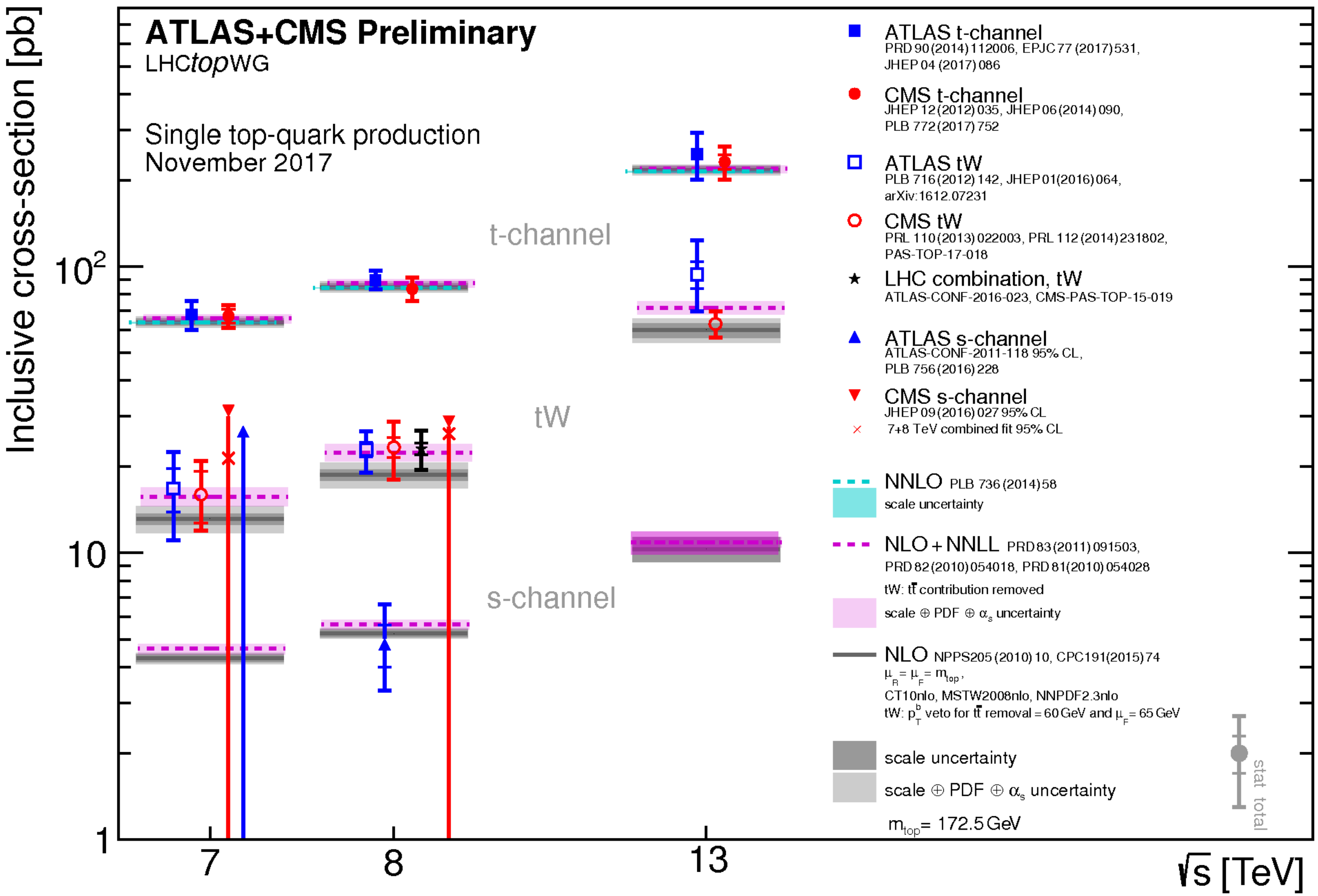
$$\left[f_{\mathrm{LV}}^{\mathrm{SM}} = 1 \right]$$



TOP-17-011

Single top at the LHC

LHC: observed t-channel and W-t, getting closer to s-channel!

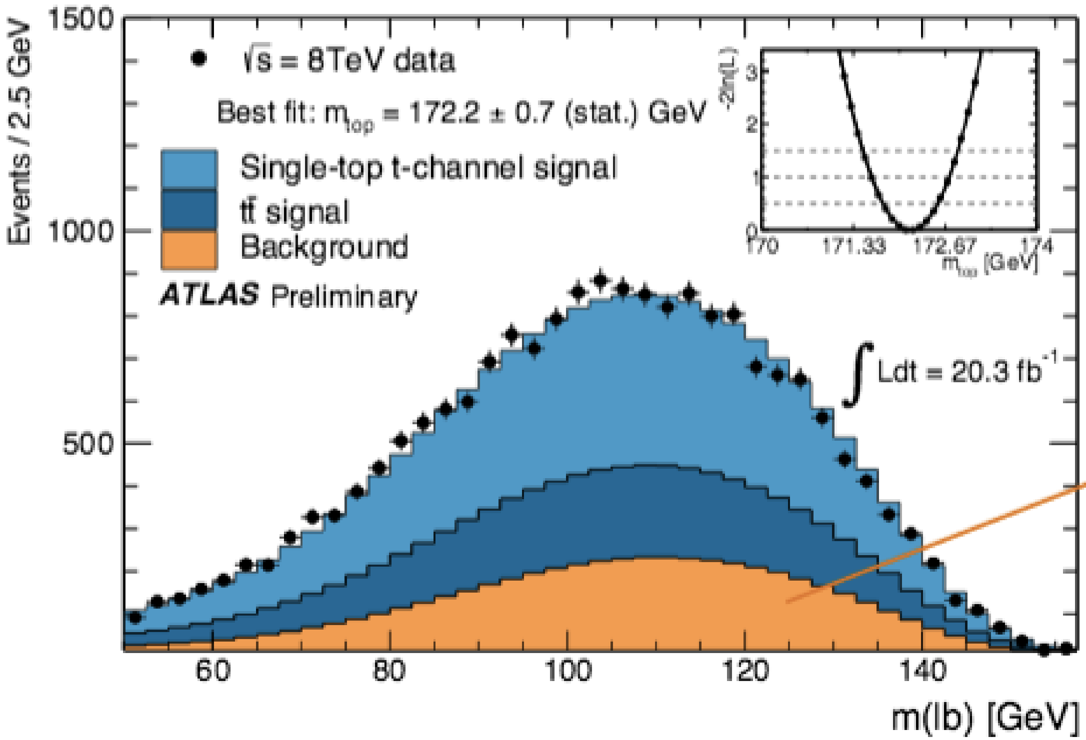


m_t in single top events (ATLAS)

ATLAS-CONF-2014-055

$m_t = 172.2 \pm 0.7\ (\text{stat}) \pm 2.0\ (\text{syst})$ GeV

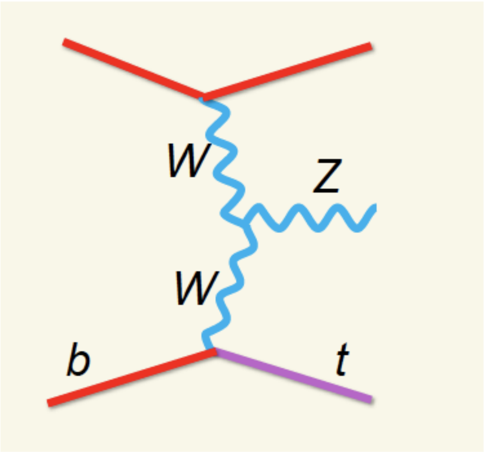
- Results are complementary to ttbar measurements.
  - Different regime for single top production.

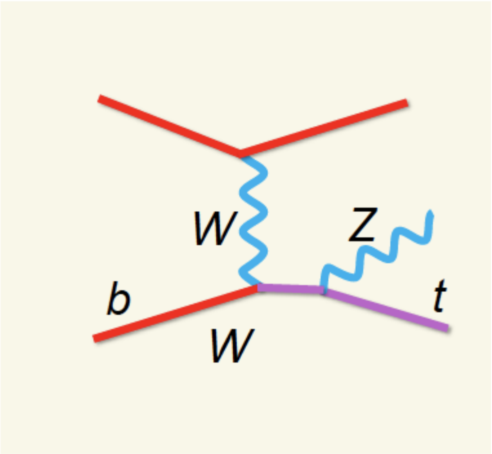


Dominant systematics:

- **JES + bJES:** 1.5 GeV.
- t-channel parton showering & hadronization: 0.7 GeV.
- **W+jets shape & normalization:** 0.5 GeV.
  - Shape component due to PDFs and flavor of jets produced in association with the W.

tZq production: a rare SM channel





- Sensitive to WWZ and tZ coupling

→ Not seen before

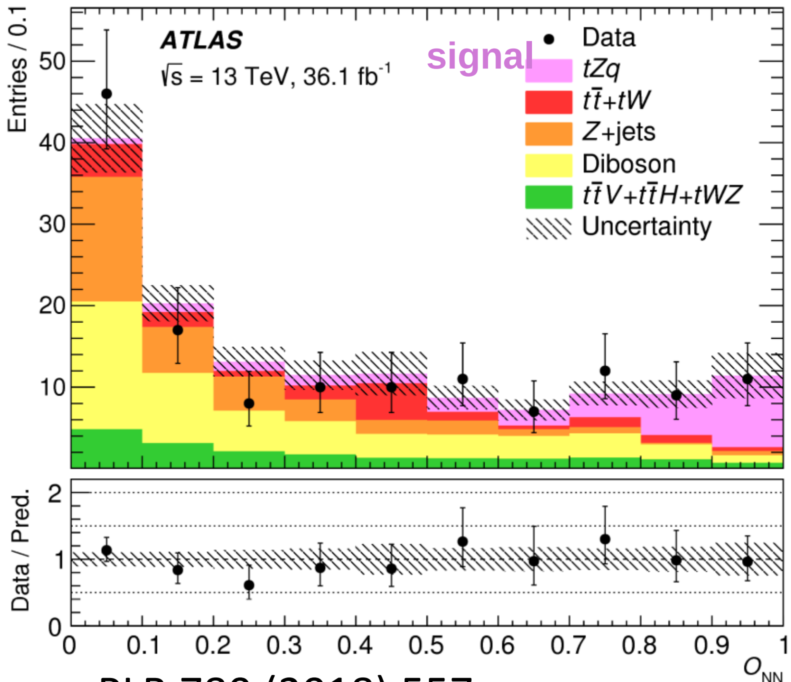
→ Background to tH channel

Signal region:

Three charged leptons in final state

1 b-tagged jet

1 untagged jet



PLB 780 (2018) 557

- Neural network to separate signal and backgr

Signal obtained in likelihood fit

σ = 600 ± 170 (stat) ±140 (syst) fb

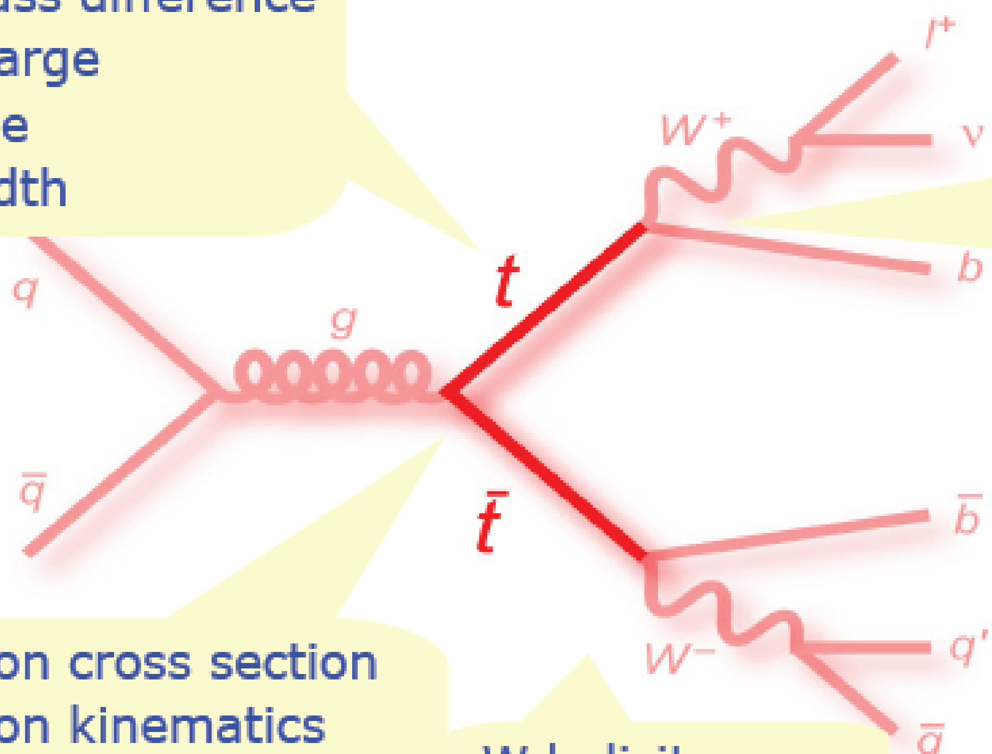
(theory NLO 800 fb ± 7%)

- Main systematics:
  - Radiation signal MC
  - Jet energy scale
  - b-tagging
- Significance 4.2 (5.4 expected) → EVIDENCE

→ The hunt for rare single-top processes started!

Other top properties

- 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

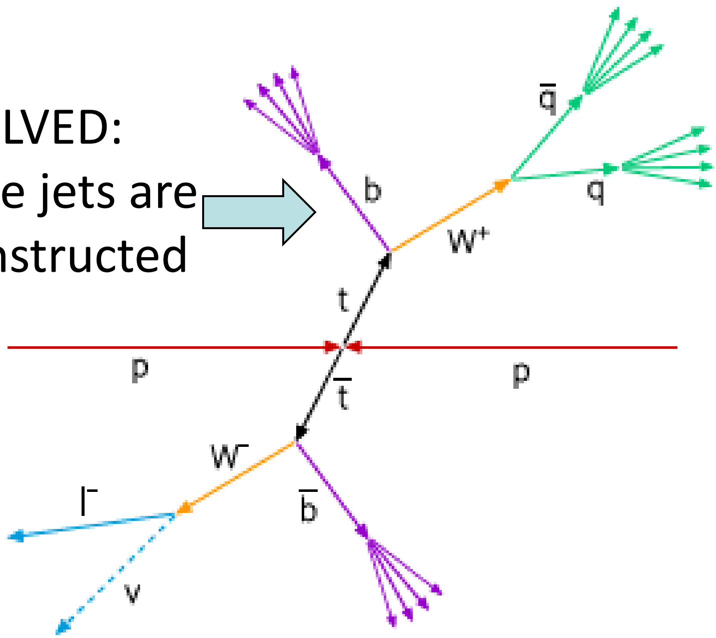
- W helicity

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

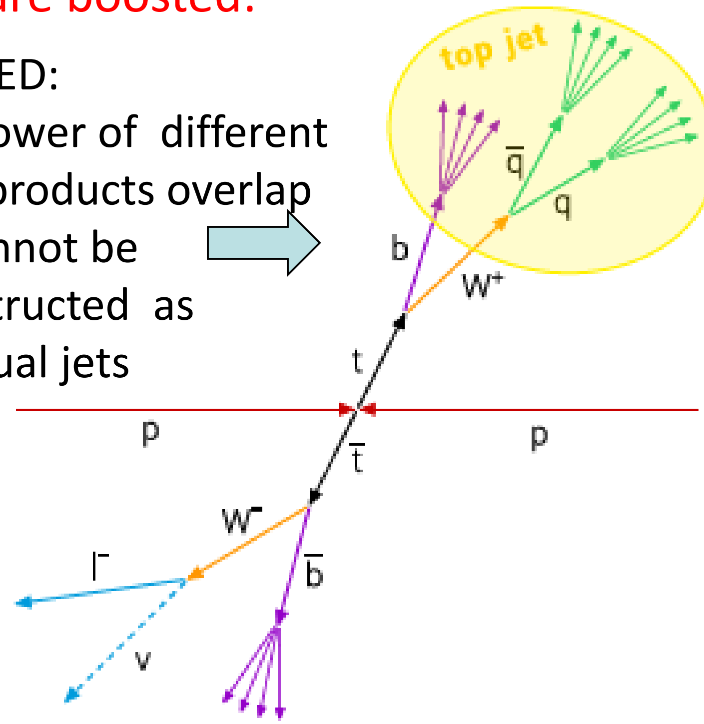
Event selection: resolved vs boosted

At higher energies, more top-quark candidates are boosted:

RESOLVED:
All the jets are reconstructed



BOOSTED:
The shower of different decay products overlap and cannot be reconstructed as individual jets



Resolved topology:
==1 lepton
>=4 small-R jets
>=2 b-tags

Pseudo-top object definitions:

$\hat{t}^{\,\mathrm{lep}} = \ell + E_{\mathrm{T}}^{\mathrm{miss}}$ + b-jet closest to ℓ

$\hat{t}^{\,\mathrm{had}}$ = other b-jet + 2 jets with min. $|m_{jj} - m_W|$

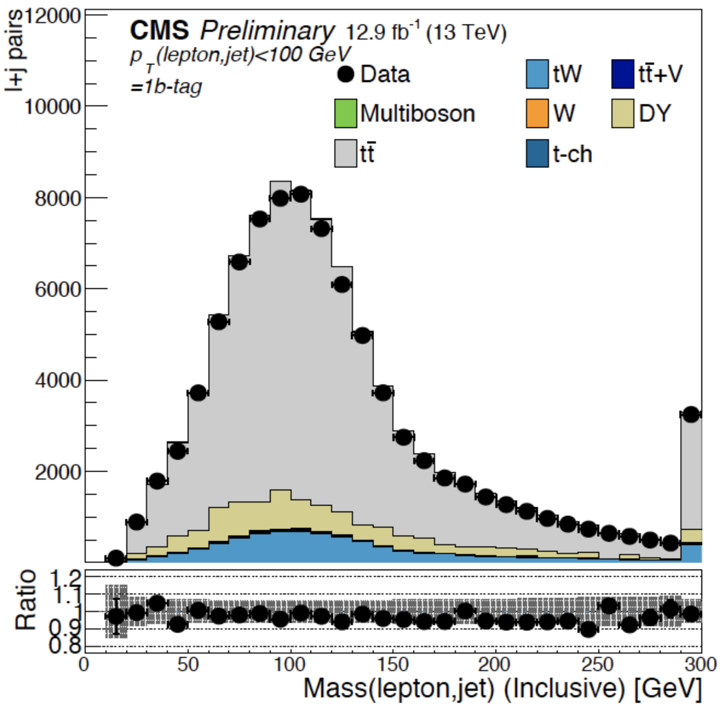
Boosted topology:
==1 lepton
>=1 large-R jet and >=1 small-R jet
>=1 top-tag (large-R)
>=1 b-tag (small-R) within the top-jet
or close to the lepton
+ some additional topological cuts

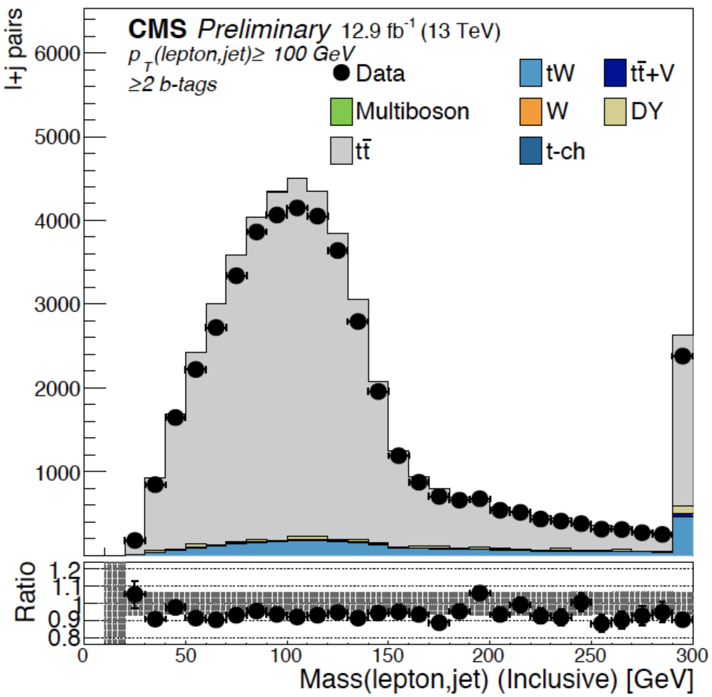
Highest-p_{T} top-jet serves as $\hat{t}^{\,\mathrm{had}}$

Top quark width

CMS first direct measurement at 13TeV

- Dilepton channel used: very small background contamination but small BR
- 2 categories: =1 or >= 2 b-tagged jets, boosted or non-boosted





- Compare the SM expectation for different width scenarios to data.

Measured bounds at 95% C.L.: **$0.6 < \Gamma_t < 2.5$ GeV**

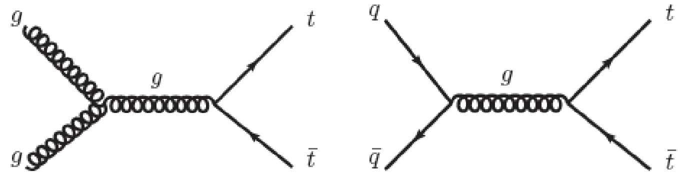
- The most precise direct bound of the top quark width to date
- Systematically limited by MC modeling

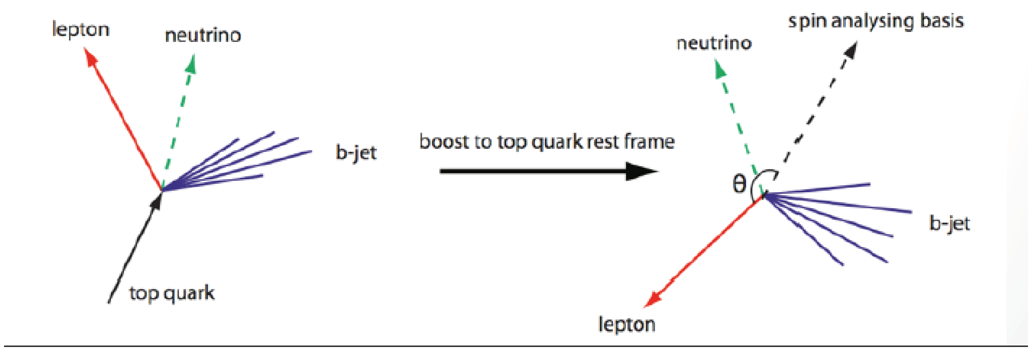
Top spin correlation

- Top quark decays before it hadronizes → spin information is transferred to the decay products
- Hadron colliders: top quarks produced un-polarized, but:
  - New physics (NP) could induce polarization
  - Spins of top and anti-top are slightly correlated due to QCD production mechanism
- Correlations depend on production mechanism:

⇒ i.e. difference for gluon fusion vs quark annihilation

- Highest spin analysing power: leptons from top decay
- Use dileptonic events
- Unfolded differential measurements at parton level and particle level
- Full ttbar event reconstruction

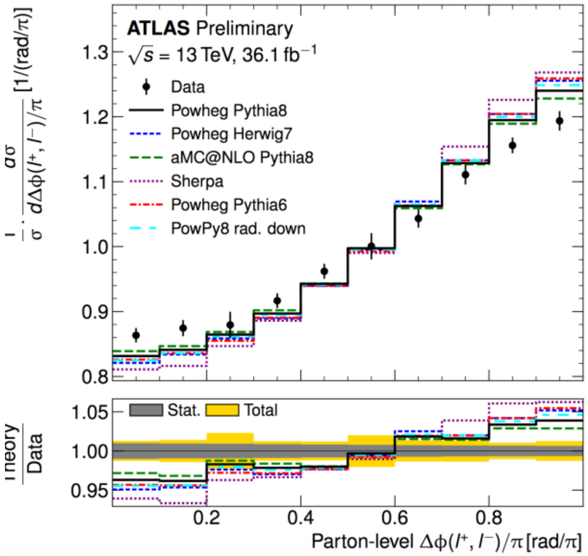


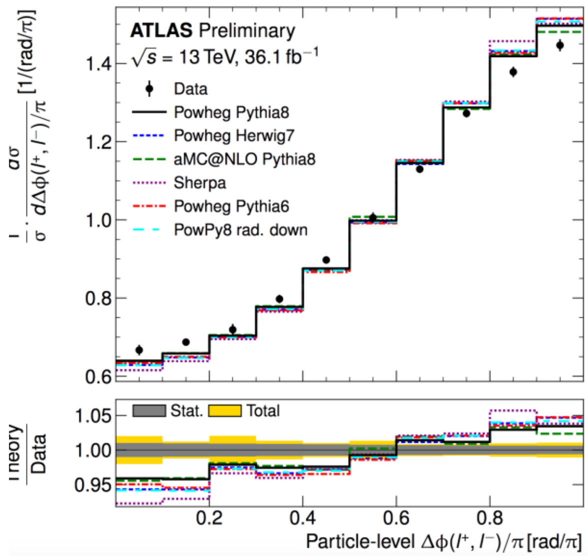


Top spin correlation

Unfolded distributions compared to different MC predictions:

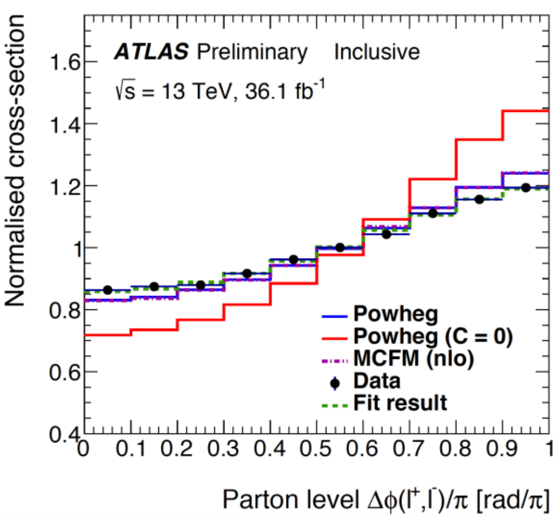
ATLAS-CONF-2018-027





Data shows shallower slope than prediction

Fitting spin and no-spin hypotheses to parton-level distributions:

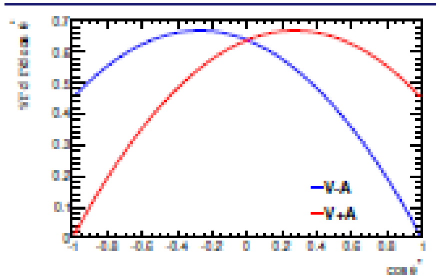


Region	f_{SM}	Significance (incl. theory uncertainties)
$m_{t\bar{t}} < 450$ GeV	$1.11 \pm 0.04 \pm 0.13$	0.85 (0.84)
$450 < m_{t\bar{t}} < 550$ GeV	$1.17 \pm 0.09 \pm 0.14$	1.00 (0.91)
$550 < m_{t\bar{t}} < 800$ GeV	$1.60 \pm 0.24 \pm 0.35$	1.43 (1.37)
$m_{t\bar{t}} > 800$ GeV	$2.2 \pm 1.8 \pm 2.3$	0.41 (0.40)
inclusive	$1.250 \pm 0.026 \pm 0.063$	3.70 (3.20)

Spin correlations higher than SM prediction by 3.7 σ (3.2 σ including theory uncertainty)

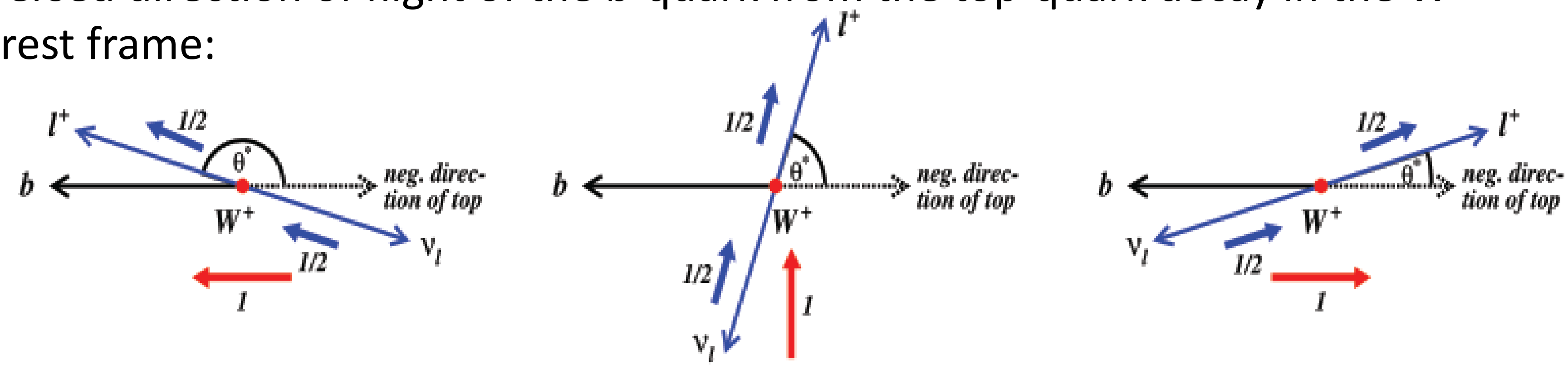
Measurement of the **W** polarisation in top-quark decays

- W bosons from top-quark decays $t \rightarrow Wb$ are polarised due to the V-A structure of the Wtb vertex



$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*} = \frac{3}{8}\left(1-\cos\theta^*\right)^2 F_L + \frac{3}{4}\sin^2\theta^* F_0 + \frac{3}{8}\left(1+\cos\theta^*\right)^2 F_R$$

- The angle θ^* between the “spin analyser” (charged lepton or down-type quark) and the reversed direction of flight of the b-quark from the top-quark decay in the W-boson rest frame:

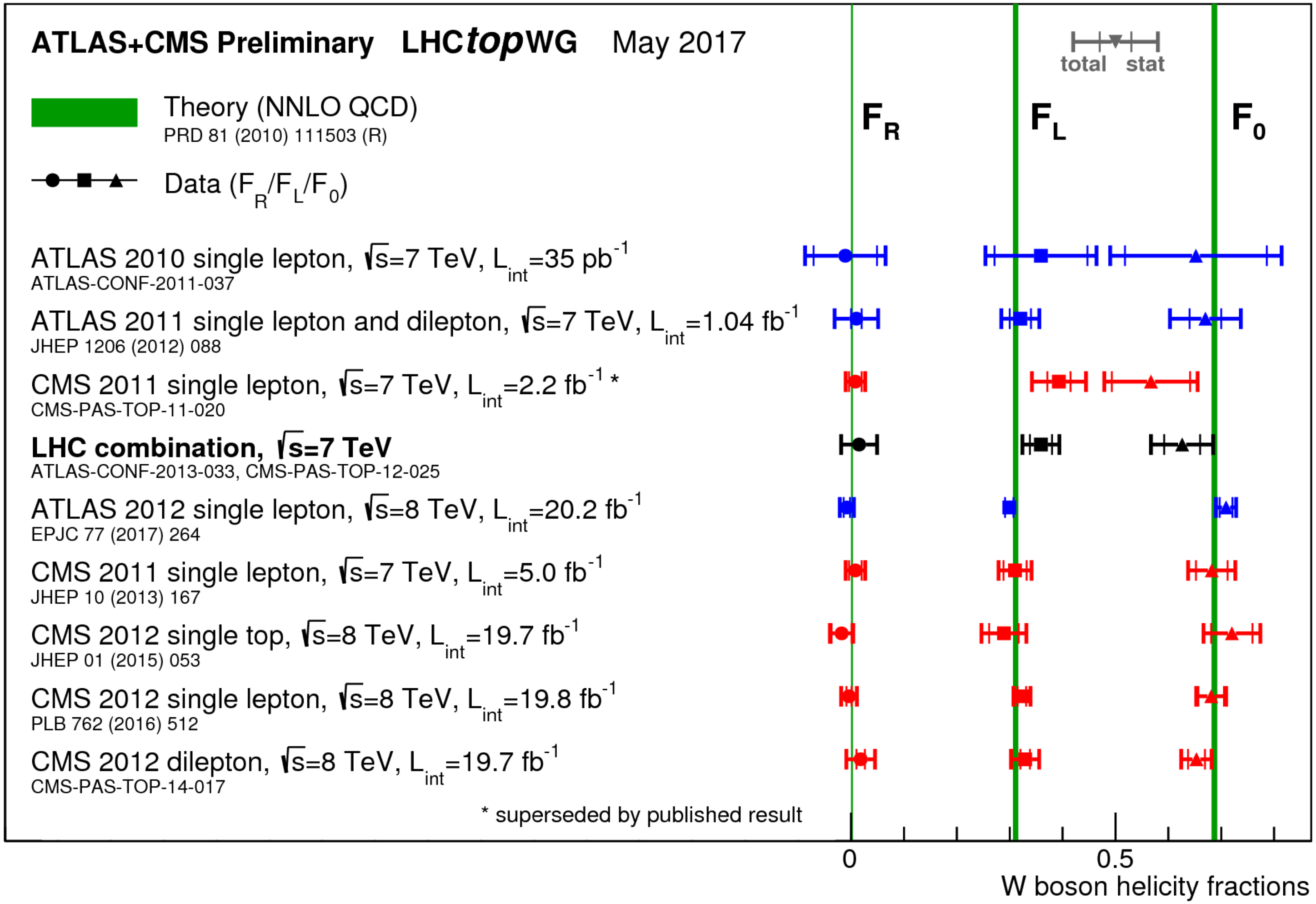


$$\frac{dN(h_W=-1)}{d\cos\theta^*} \propto \frac{3}{8}(1-\cos\theta^*)^2 \qquad \frac{dN(h_W=0)}{d\cos\theta^*} \propto \frac{3}{4}(1-\cos^2\theta^*) \qquad \frac{dN(h_W=+1)}{d\cos\theta^*} \propto \frac{3}{8}(1+\cos\theta^*)^2$$

SM prediction (NNLO) **F_L = 0.311 ± 0.005** **F_0 = 0.687 ± 0.005** **F_R = 0.0017 ± 0.0001**

W-boson helicity fractions

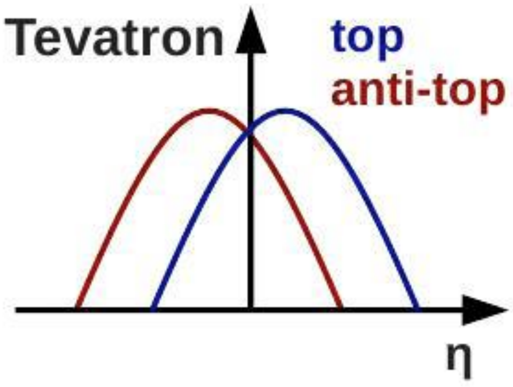
Measurement of the W polarisation in top-quark decays



Summary of the W boson helicity fraction measurements from ATLAS and CMS compared to the theory predictions. The uncertainty on the theory predictions is shown by the width of the green band.

ttbar charge asymmetry

- NLO QCD predicts small (~8%) asymmetry from qqbar → ttbar, while gg remains symmetric (→ asymmetry DIFFERENT at Tevatron and LHC). Recent NNLO calculation predicts inclusive $A_{Tevatron}$~9.5% (arXiv:1411.3007)
- New physics can modify this asymmetry (Z´,axigluons,..)
- Experimentally, asymmetries based on fully reconstructed top using the rapidity difference (Δy) of t→lvb and antitop t→jjb or using decay leptons



$$\Delta y^{\mathrm{TEV}} = y_t - y_{\bar{t}}$$

- In terms of top-antitop rapidity difference: →

$$A_{\mathrm{FB}}^{t\bar{t}} = \frac{N(\Delta y_{t\bar{t}} > 0) - N(\Delta y_{t\bar{t}} < 0)}{N(\Delta y_{t\bar{t}} > 0) + N(\Delta y_{t\bar{t}} < 0)}$$

- In terms of rapidity of charged lepton from top decay : →

$$A_{\mathrm{FB}}^{\ell} = \frac{N(q_\ell \eta_\ell > 0) - N(q_\ell \eta_\ell < 0)}{N(q_\ell \eta_\ell > 0) + N(q_\ell \eta_\ell < 0)}$$

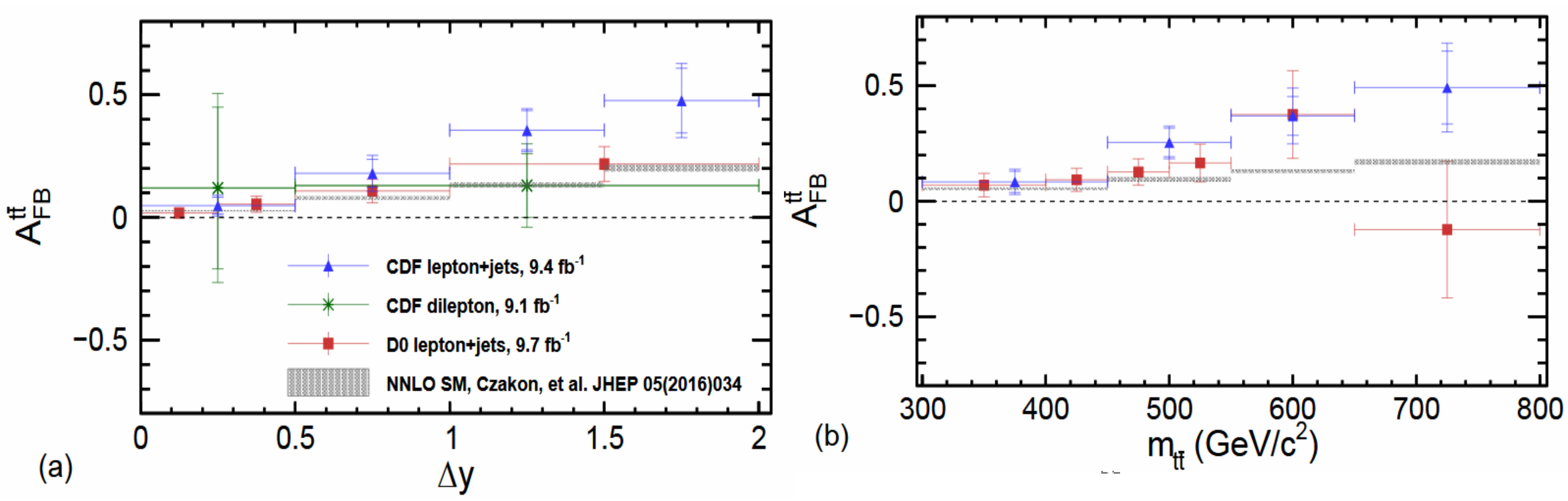
- For dilepton channel in terms of Δη between l^+ and l^- →

$$A_{\mathrm{FB}}^{\ell\ell} = \frac{N(\Delta\eta > 0) - N(\Delta\eta < 0)}{N(\Delta\eta > 0) + N(\Delta\eta < 0)}$$

Forward backward asymmetry (A_{FB})

Lepton + jets and dilepton channels:

- Check rapidity and mass kinematic dependence of asymmetry

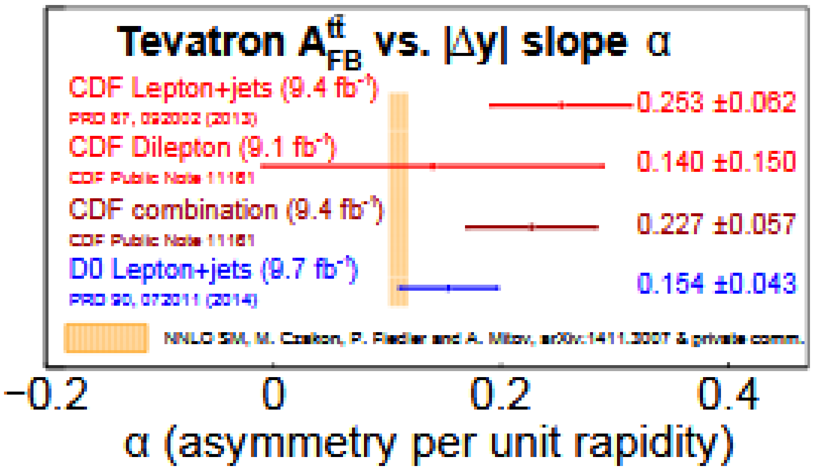


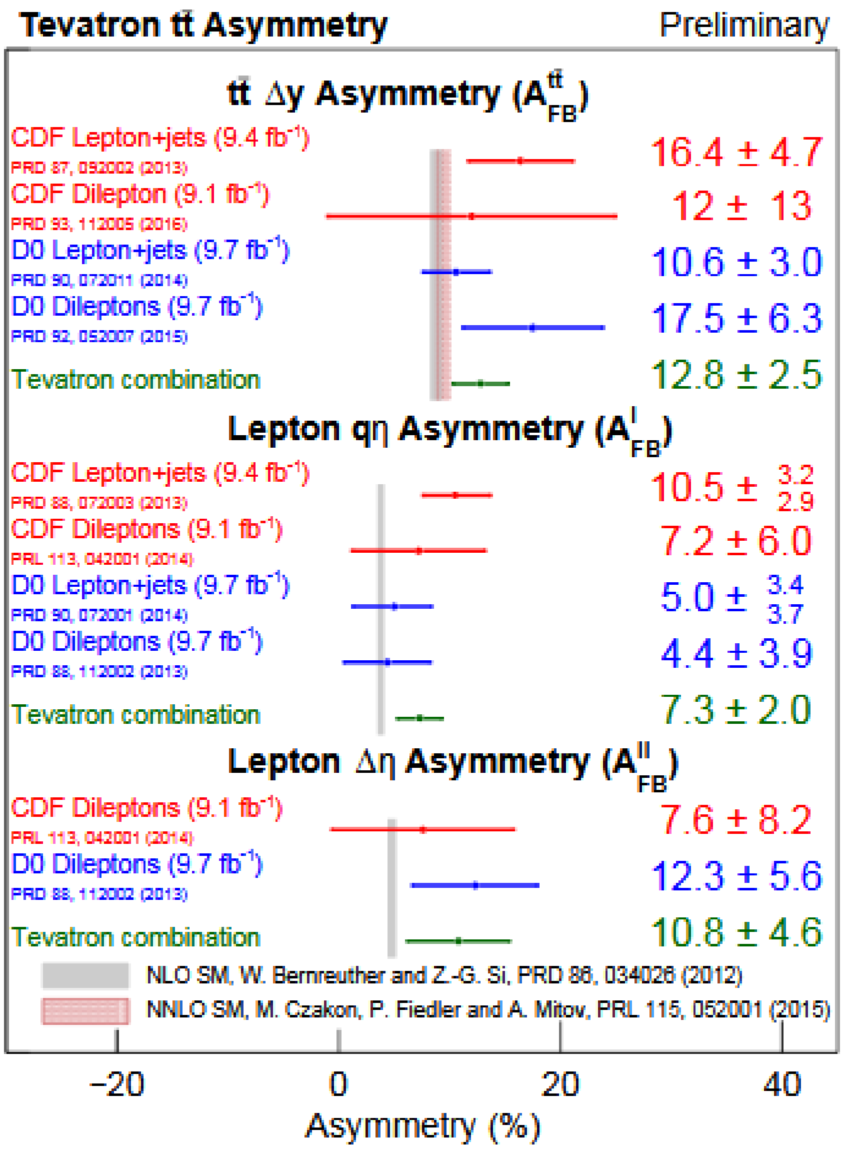
- Kinematic dependencies in CDF data slightly larger than predicted by SM at both NLO and NNLO (~ 2 s.d. effect)
- Overall NNLO predicted asymmetry; 9.5 ± 0.7 %

M. Czakon, P. Fiedler and A. Mitov arXiv:1411.3007

Summary of top asymmetries at Tevatron

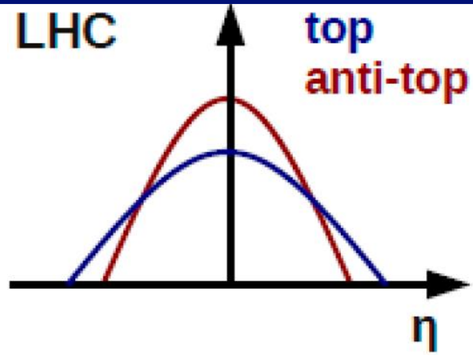
- $t\bar{t}$-based and lepton-based results using full RunII dataset
- The measurements are in agreement with the existing predictions of the SM





ATLAS charge asymmetry in dilepton

Asymmetries expected from valence quark – sea antiquark fusion → antitop more central than top



Leptonic asymmetries:

$$A_C^{\ell\ell} = \frac{N(\Delta|\eta| > 0) - N(\Delta|\eta| < 0)}{N(\Delta|\eta| > 0) + N(\Delta|\eta| < 0)}, \quad \Delta|\eta| = |\eta_{\ell^+}| - |\eta_{\ell^-}|$$

$t\bar{t}$ asymmetries:

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

- 3 different measurements of both observables:

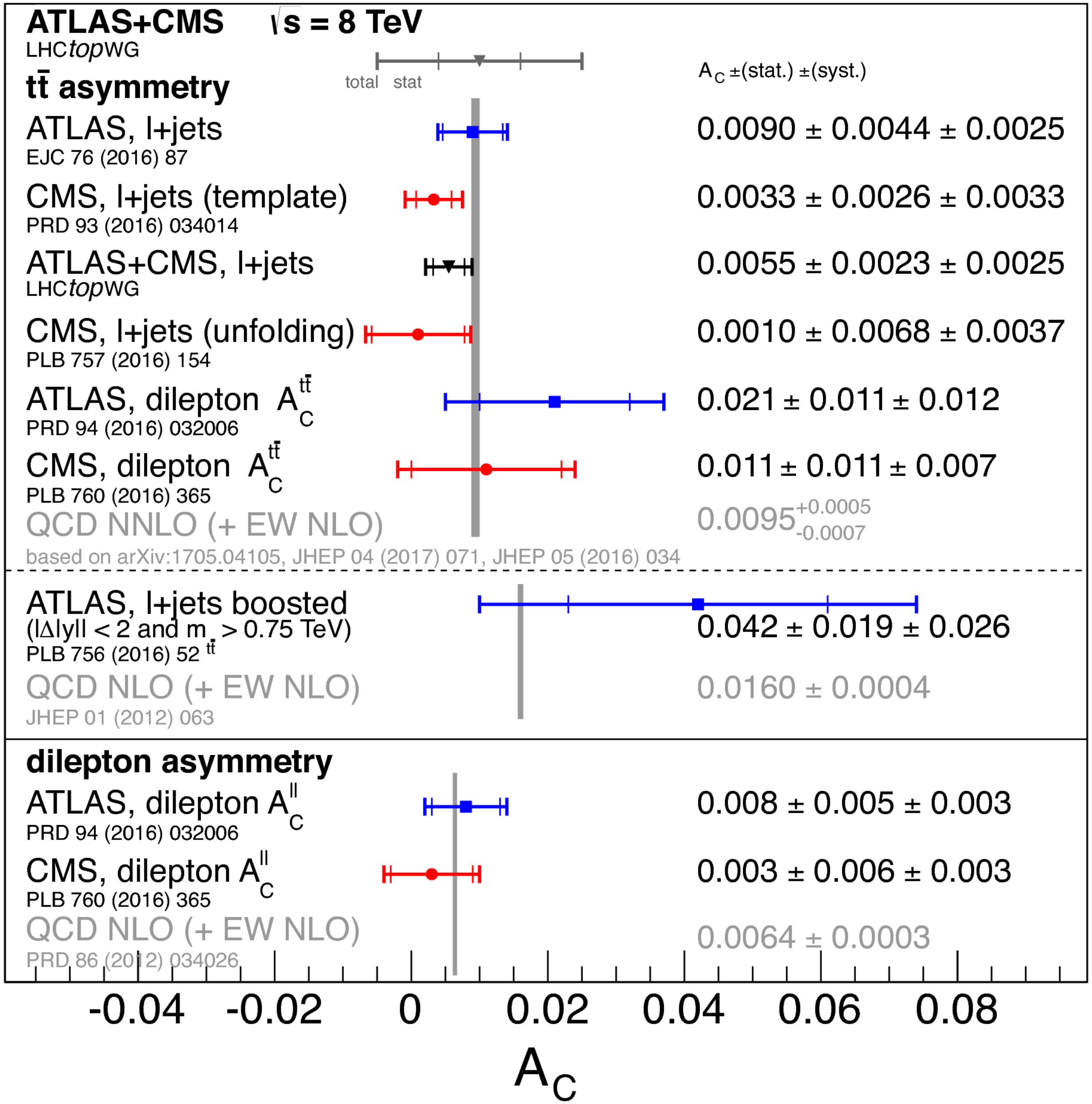
⇒inclusive measurements on parton level in the full phase space

⇒inclusive measurements on particle level in the fiducial region

⇒ differential measurements:

inv. Mass, p_T $(m_{t\bar{t}})$, $p_{T,t\bar{t}}$, and longitudinal boost $(\beta_{z,t\bar{t}})$ of *ttbar* system in the fiducial regions and the full phase space

ATLAS and CMS charge asymmetry



Summary

- Despite being discovered more than 20 years ago, there are still many intriguing things to learn about the top quark

- LHC is a top factory

$\Rightarrow$ Can make precision measurements on:
  - Production, decay and properties
  - Mass as a fundamental parameter of the SM

$\Rightarrow$ Investigate kinematics of events
  - Constrain 'empirical' models in MC generators and in PDFs
  - Look at agreement with NLO and NNLO predictions

- Top may show us the way to narrowing down BSM physics

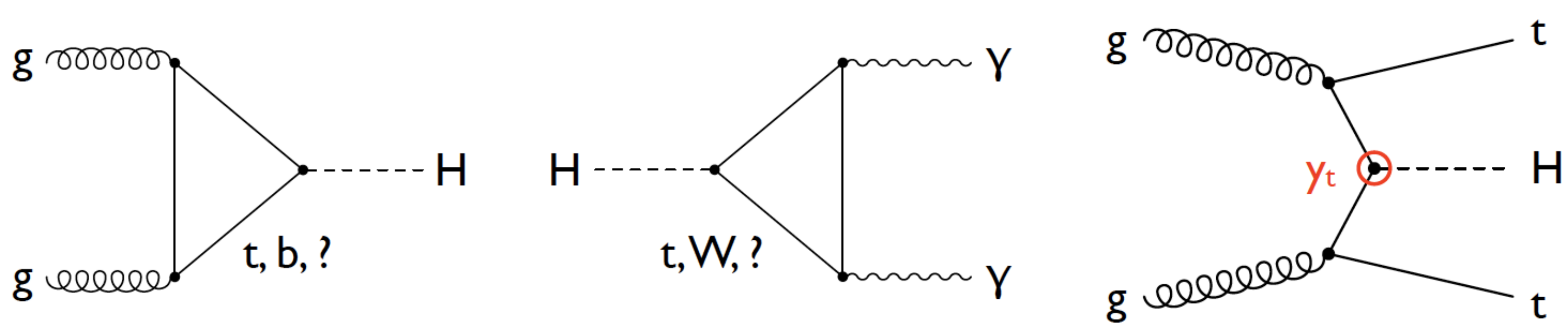
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

Backup

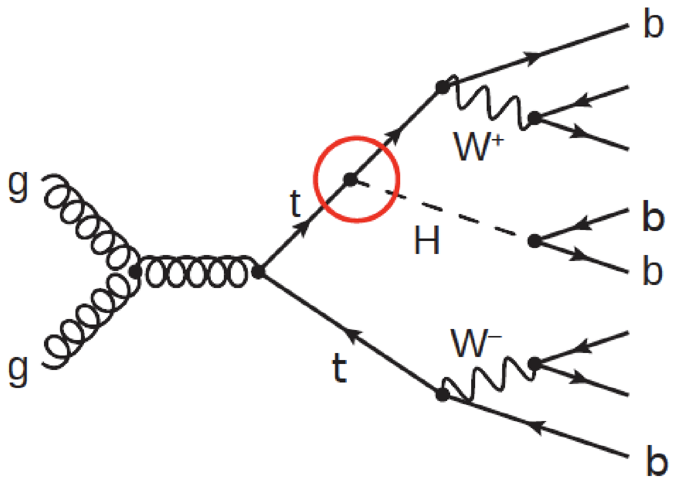
Observation of ttH

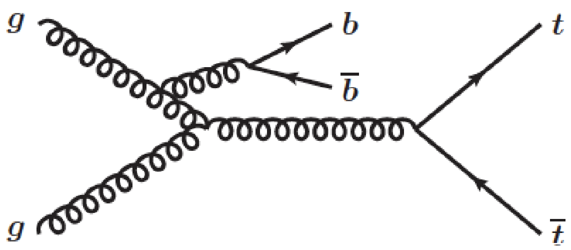
- Best direct probe of the top-Higgs Yukawa coupling, vital step towards verifying the SM nature of the Higgs boson
  - ☐ Top quark is the most strongly-coupled SM fermion (y_t ~1)
  - ☐ Direct measurement of y_t in ttH production:
    - gluon-gluon fusion: assumes no BSM coupling
    - Allows probing new physics in gg → H and H → γγ effective vertices
- Top quark x Higgs decay channels
- ☐ Challenges: ttH ~ 0.5 pb, ttbar = 830 pb @13 TeV
  - Crucial to understand tt+X (X = b-bbar, W, Z)
  - Large combinatorics of leptons and jets from top quark decays
- ☐ Exploiting all ttbar decay channels and Higgs decays to:
  - bottom quarks → large BR, large background contributions
  - W, Z bosons, taus → smaller production rate, lower backgrounds
  - photons → clean final state, very small rate



ttH (b-bbar) production

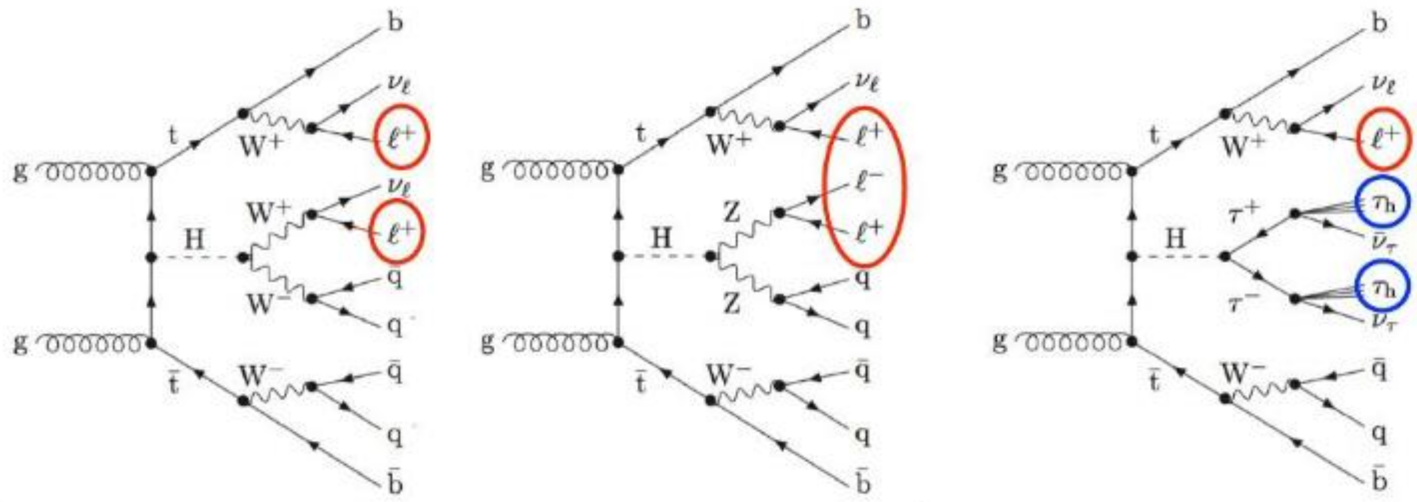
- Large B (H → bb), access to coupling 3rd generation quarks
- Challenging final state:
  - Huge combinatorics in event reconstruction
  - Poor H → b-bbar mass resolution
  - Large tt + bb background of O(10)pb with associated large theory uncertainties: from simulation
- Search channels:
  - Leptonic ttbar : higher purity
  - Fully-hadronic ttbar : higher rate





ttH multilepton

- Multilepton final states: Higgs decay to W^+W^- , ZZ, and $\tau\tau$
- Events categorised based on number of leptons and τ_h candidates
- 1 lepton + 2 τ_h , 2 same-sign leptons + 0, 1 τ_h , 3 leptons + 0, 1 τ_h , 4 leptons
- Additional requirements on jets, b-tagged jets
- Major backgrounds:
  - Irreducible: ttbar + V and diboson, predicted from simulation and control regions
  - Reducible: non-prompt leptons in ttbar + jets events, estimated from data
  - Large ttbar + fake τ_h for 1 lepton + 2 τ_h
- BDT and MEM discriminants to separate signal from backgrounds

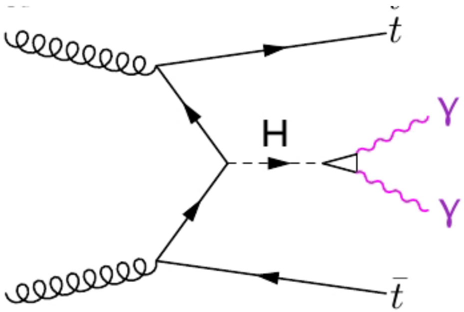


$t\bar{t}H \to ZZ^* \to 4$ leptons

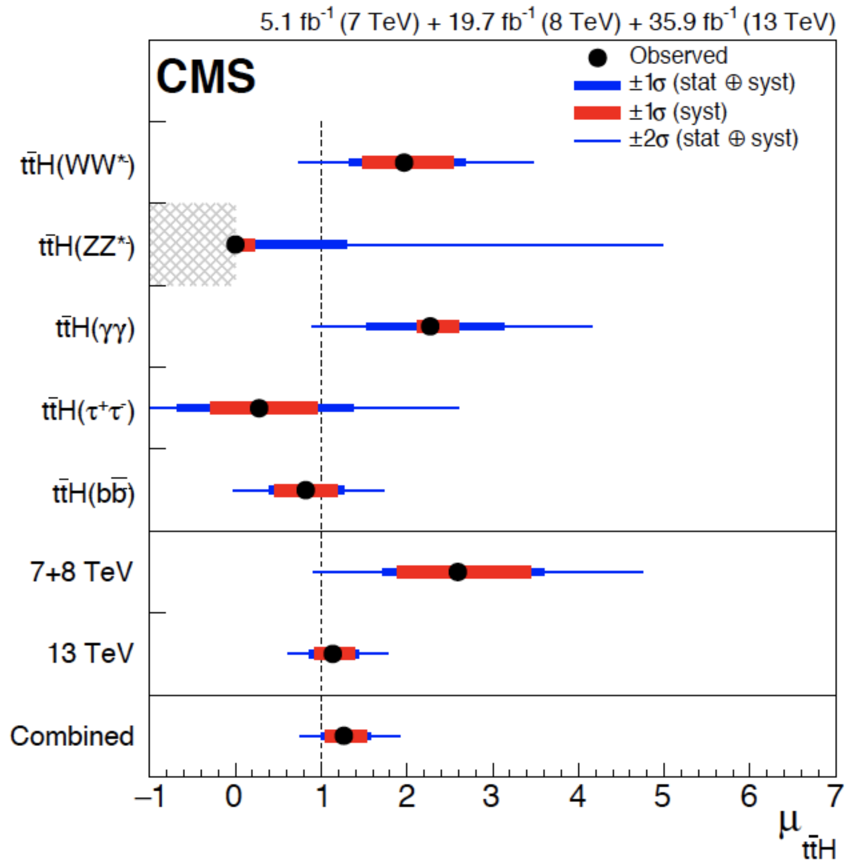
- Analysis with full 2017 dataset
- Very clean final state, but tiny branching fraction
- Dedicated ttH channel part of the global $H \to ZZ$ analysis
- ttbar hadronic and leptonic channels
  - >=4 jets, >=1 b-tagged jet and additional 0/1 leptons
- Combined fit (relying on $m_{4leptons}$ and a kinematic discriminant) with analysis of 2016 data

ttH ($\gamma\gamma$)

- Clear signature coming from the photons
- Higgs boson can be reconstructed as a narrow peak
- Dedicated ttH channel part of the global $H \to \gamma\gamma$ analysis
- ttbar hadronic and leptonic channels
- Signal extracted from fit to $m_{\gamma\gamma}$



First observation of ttH (CMS)



$$\mu_{t\bar{t}H} = 1.26^{+0.31}_{-0.26} = 1.26^{+0.16}_{-0.16}(\text{stat})^{+0.17}_{-0.15}(\text{expt})^{+0.14}_{-0.13}(\text{Th. bkg})^{+0.15}_{-0.07}(\text{Th. sig})$$

Observed significance is 5.2σ $(4.2\sigma$ exp.)

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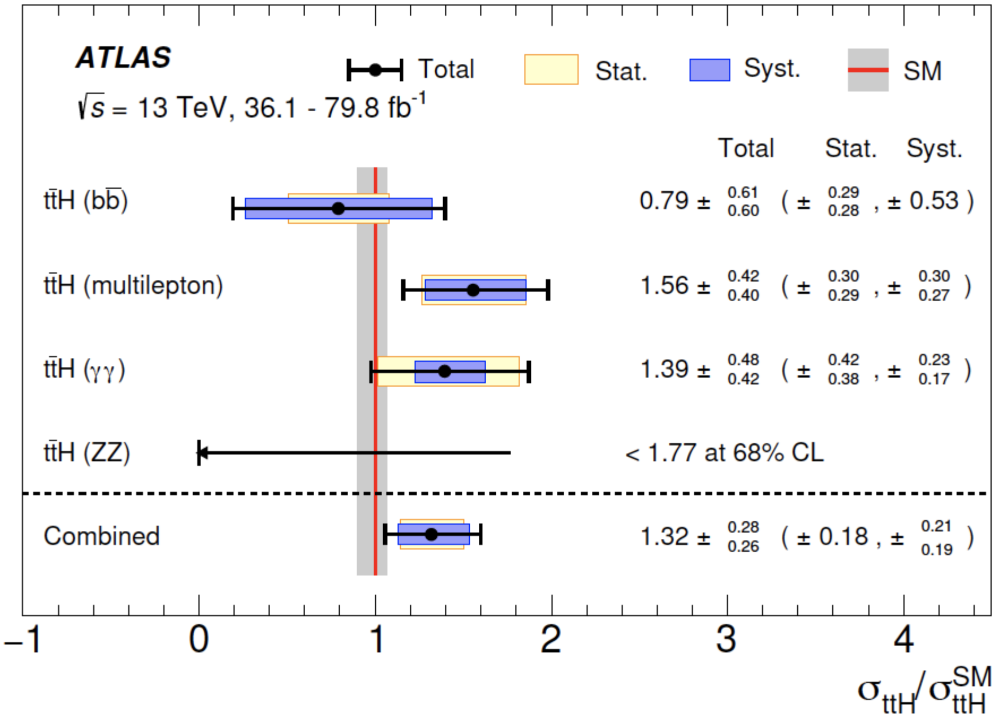
First observation of ttH (ATLAS)



Significance

Obs. (Exp.)

1.4σ (1.6σ)

4.1σ (2.8σ)

4.1σ (3.7σ)

0σ (1.2σ)

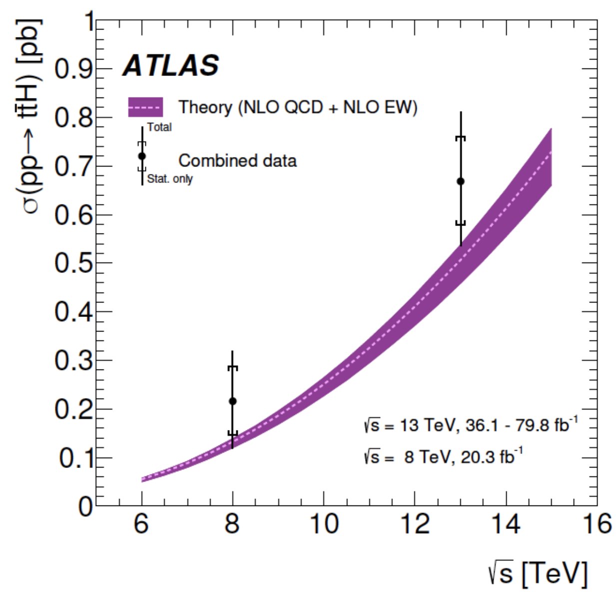
5.8σ (4.9σ) — 13 TeV only

6.3σ (5.1σ) — 7, 8, and 13 TeV

Observation of ttH production!

Cross section for pp→ttH is extracted assuming SM branching ratios.

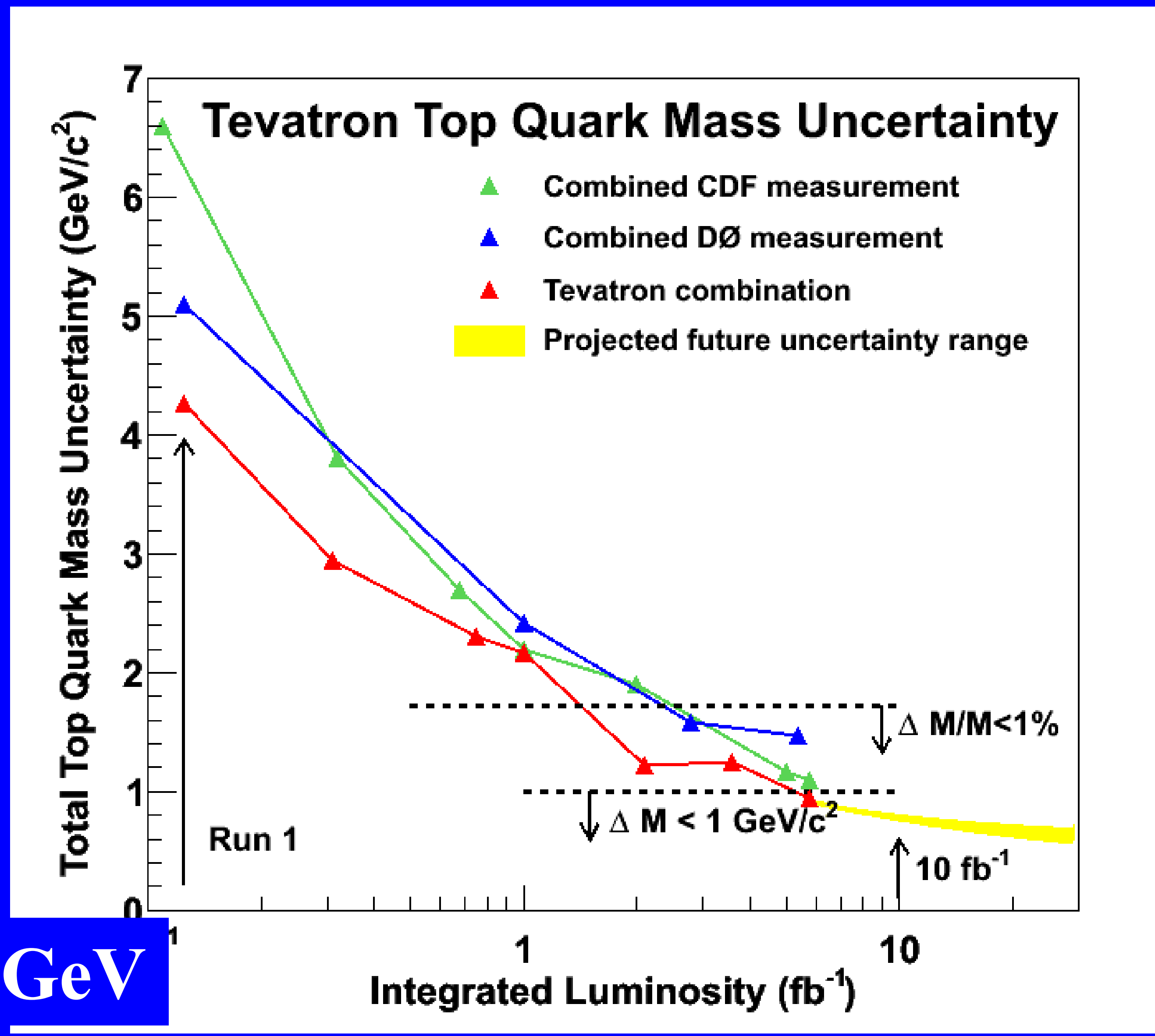
Analysis	$t\bar{t}H$ cross section [fb]
$H \to \gamma\gamma$	$710\ ^{+210}_{-190}\ \text{(stat.)}\ ^{+120}_{-90}\ \text{(syst.)}$
$H \to$ multilepton	$790 \pm 150\ \text{(stat.)}\ ^{+150}_{-140}\ \text{(syst.)}$
$H \to b\bar{b}$	$400\ ^{+150}_{-140}\ \text{(stat.)} \pm 270\ \text{(syst.)}$
$H \to ZZ^* \to 4\ell$	<900 (68% CL)



Tevatron top mass combination

- 5 Run I and 7 Run II r
- Combination perfor
- Limited by systemat
  - ⇒ Dominant: signal r uncertainties
- Total uncertainty ±

(better than world comb. Ma

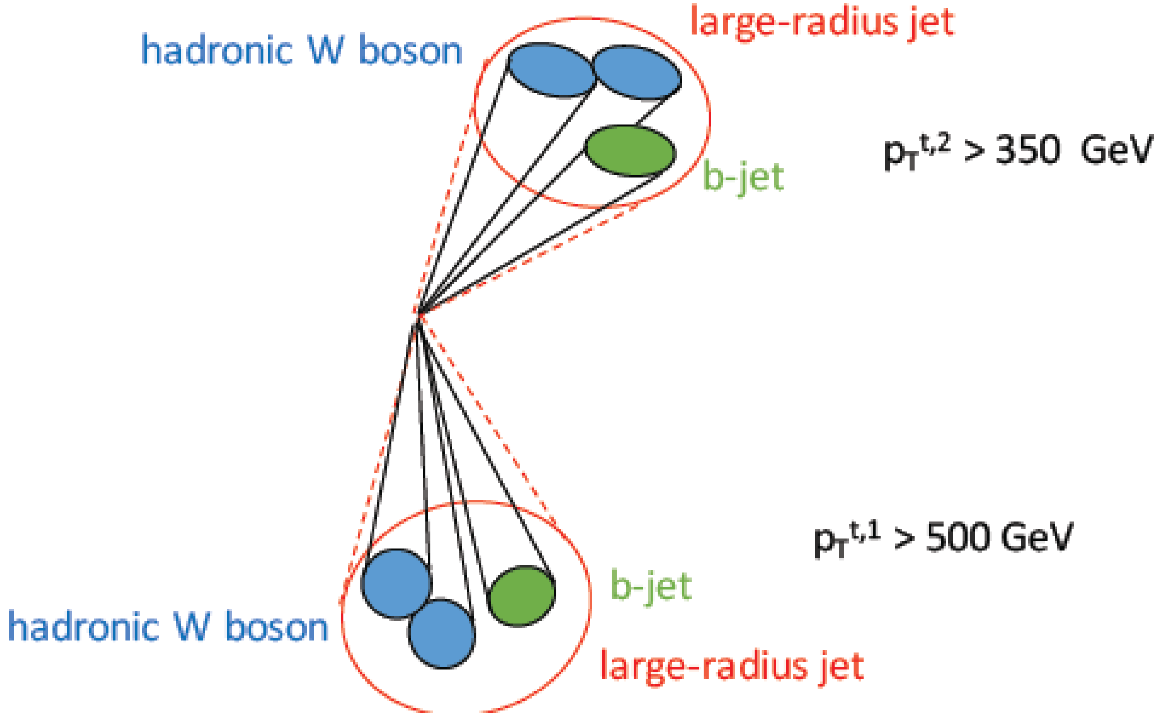


goal was <1 GeV

arXiv:2008.01331

Boosted differential cross section in all had

- All hadronic channel with boosted top quark
- Use 14.7 fb^{-1} of 2015 and 2016 data at $\sqrt{s}$ = 13 TeV



all-hadronic
boosted

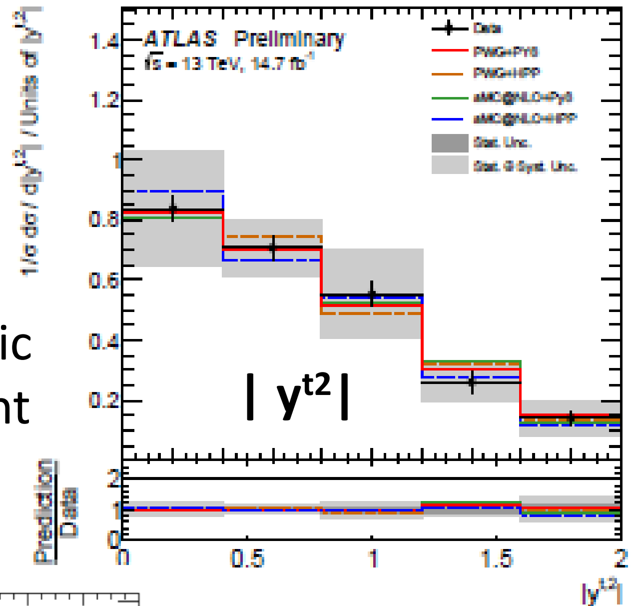
- highest BR → large statistics
- high QCD multijet background
- top-tagged jets can be used directly as top-quark proxies
- boosted topologies allow to reach higher in top p_T
- more precise $t\bar{t}$ reconstruction thanks to the lack of neutrinos

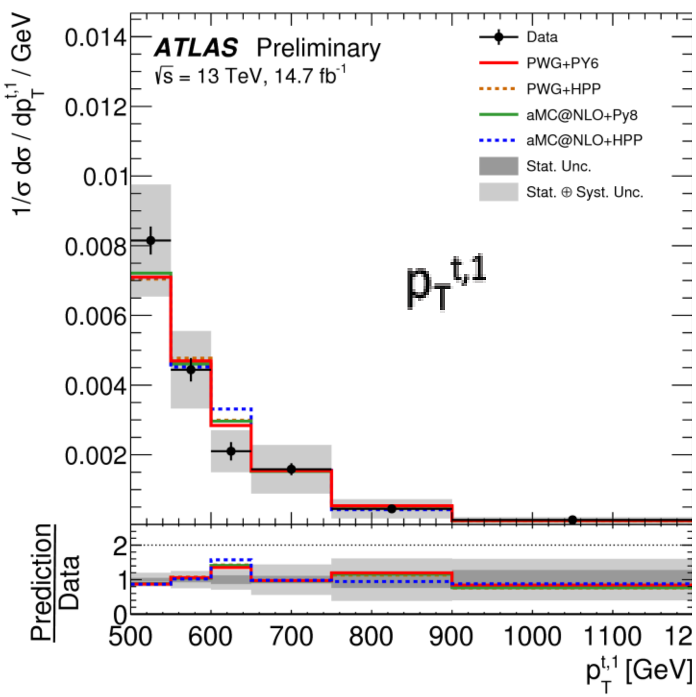
Event selection:
0 leptons, ≥2 top-tagged large-R jets, each containing a b-jet

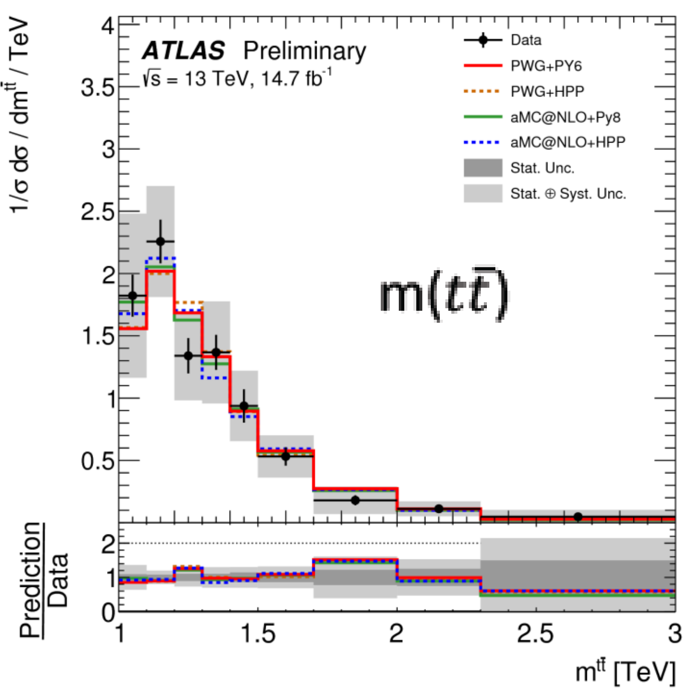
ATLAS-CONF-2016-100

Boosted differential cross section in all had

- Use 12 observable of top quarks and ttbar system
- Most important uncertainties:
  - ⇒ large-R jet calibration and reconstruction
  - ⇒ ttbar MC modelling
  - ⇒ b-tagging
- All generators provide good agreement in wide kinematic range, but each one shows local disagreements in different parts of the phase-space ⇒ must further improve the generators and the tuning.







No deviations seen in top rapidity