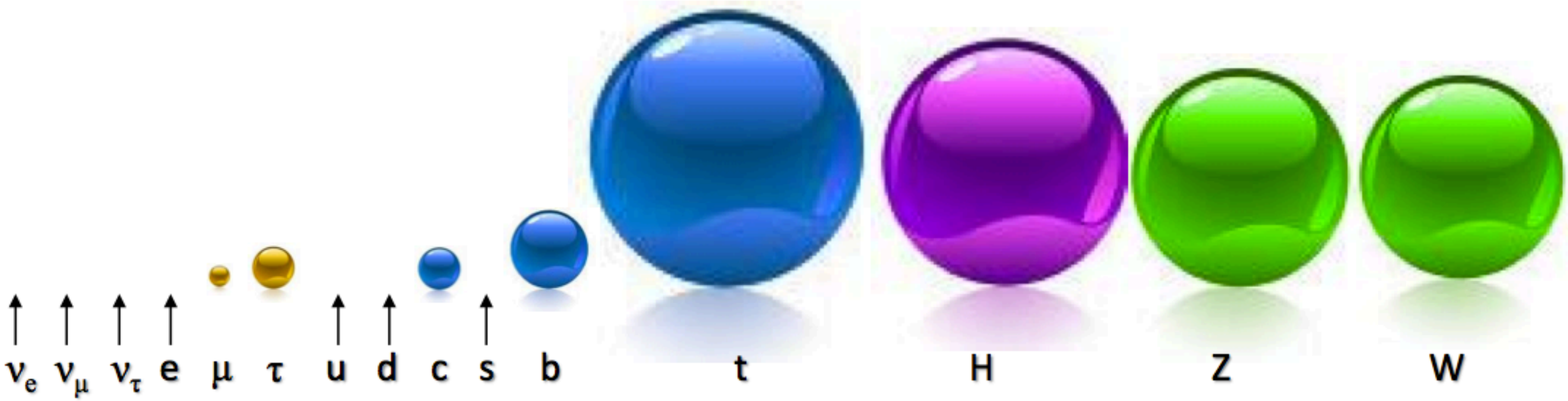
TOP QUARK PHYSICS AT THE LHC

María José Costa - IFIC (CSIC-UV)

MOTIVATION

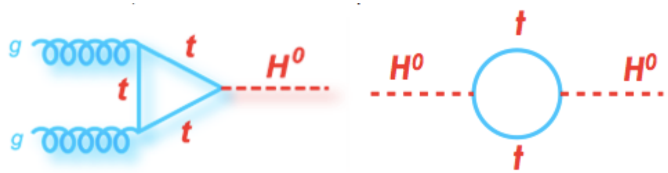


Interesting per se: A fundamental fermion weighting more than a tungsten atom!

MOTIVATION

1 **Heaviest fundamental particle in the Standard Model**

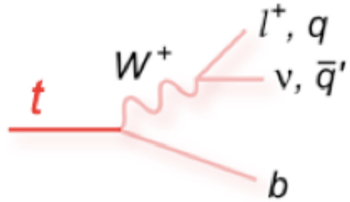
Larger mass → Larger coupling to SM Higgs + m_{top} is a fundamental parameter in SM



Allows for Self-Consistency Checks of SM Post Higgs Discovery

2 **Short Lifetime(~10^{-25} s)**

Decays before hadronization – Unique among the quarks!



Access to Polarization and Spin Correlations

3 **Processes including top are backgrounds for new physics**

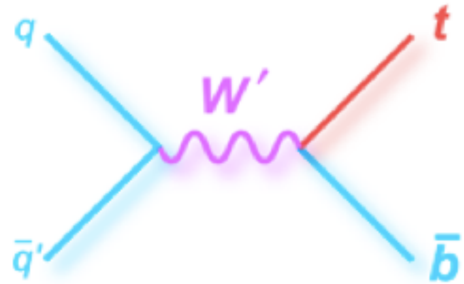
e.g. $H \to b\bar{b}$

$H \to WW$

+ Exotics and SUSY

Good Understanding → Improvements in Searches

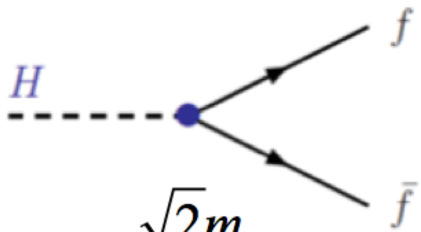
4 **Hints of new BSM/physics?**



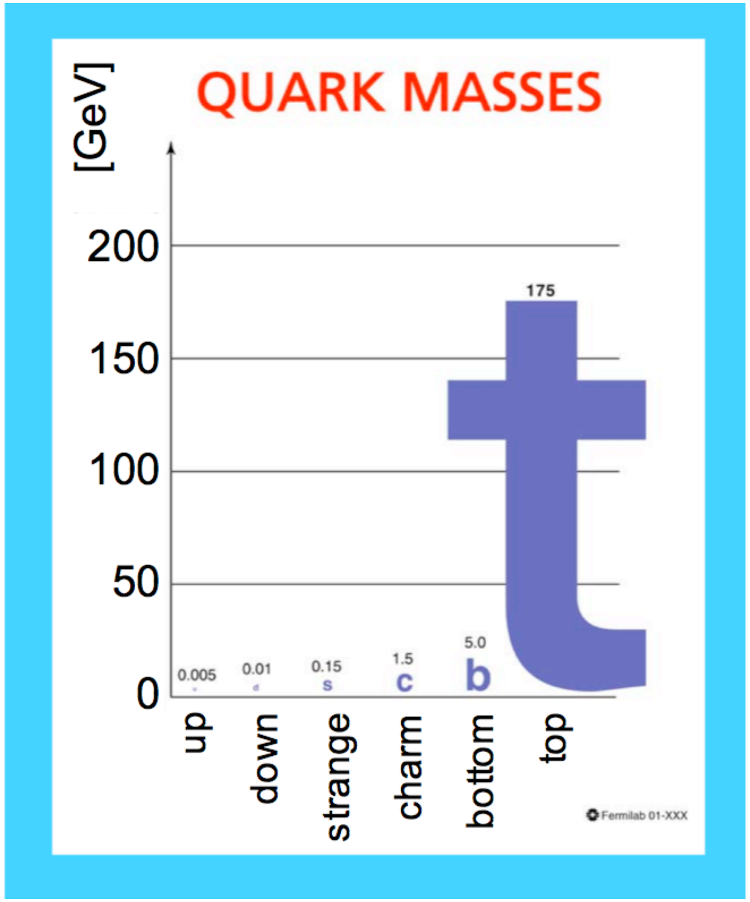
Exotic Particles Could Decay Preferentially to Top Quarks

LARGE TOP QUARK YUKAWA COUPLING

- Particle masses are generated by the Higgs mechanism (spontaneous symmetry breaking mechanism)
- The coupling of elementary particles to the Higgs boson is proportional to the particle mass.
- The top mass is of the order of the Fermi scale $v = (\sqrt{2}\,G_F)^{-1/2} = 246$ GeV → The top quark Yukawa coupling is large (~1)!



$$y_t = \frac{\sqrt{2}m_t}{v} \cong 1$$

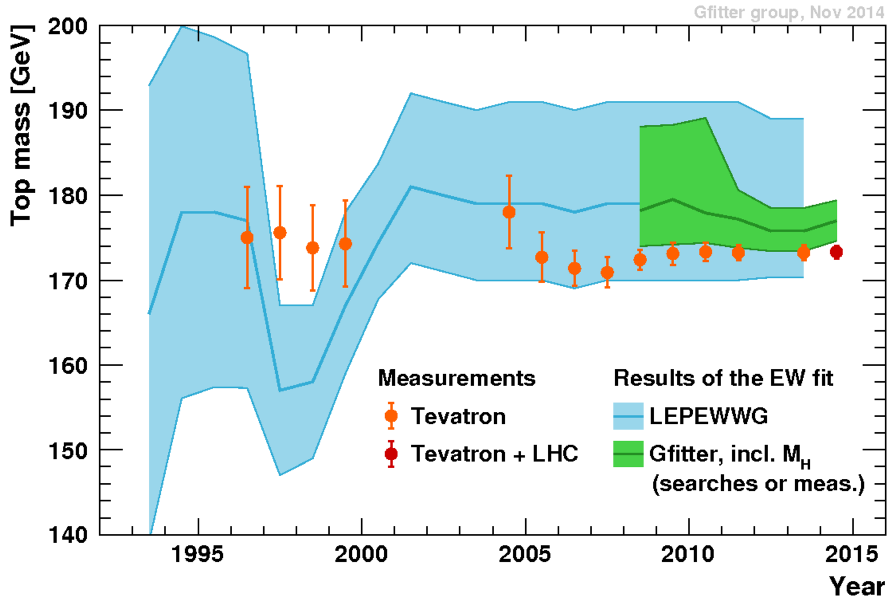


The top quark might have a natural relation to EWSB.

Maybe its detailed properties (interactions) are more sensitive to new physics.

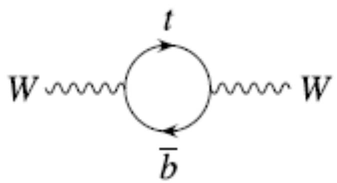
LARGE CONTRIBUTION TO EW RADIATIVE CORRECTIONS

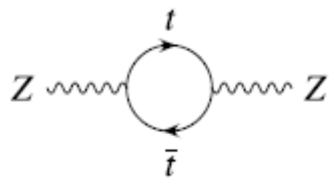
- Electroweak theory has shown that new heavy states can affect precision measurements (non decoupling property, Veltman 1977).
- The top quark gives large contributions to pure EW radiative corrections ≈ $G_F\, m_t^2$
- The precision measurements of the W and Z mass, together with other EW observables can be used to test the SM consistency and infer information about its fundamental parameters,

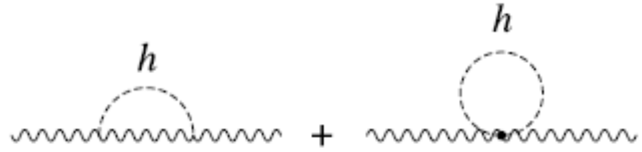


The top quark mass was predicted from radiative corrections before its discovery in 1995!

$$m_W^2 = \frac{\frac{\pi\alpha}{\sqrt{2}G_F}}{\sin^2\theta_W(1-\Delta r)}$$



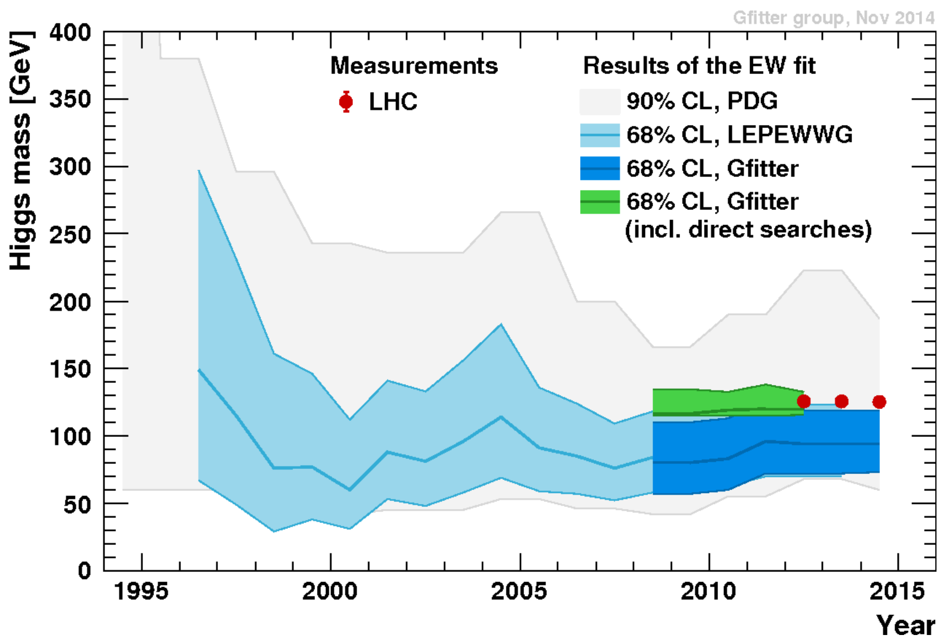


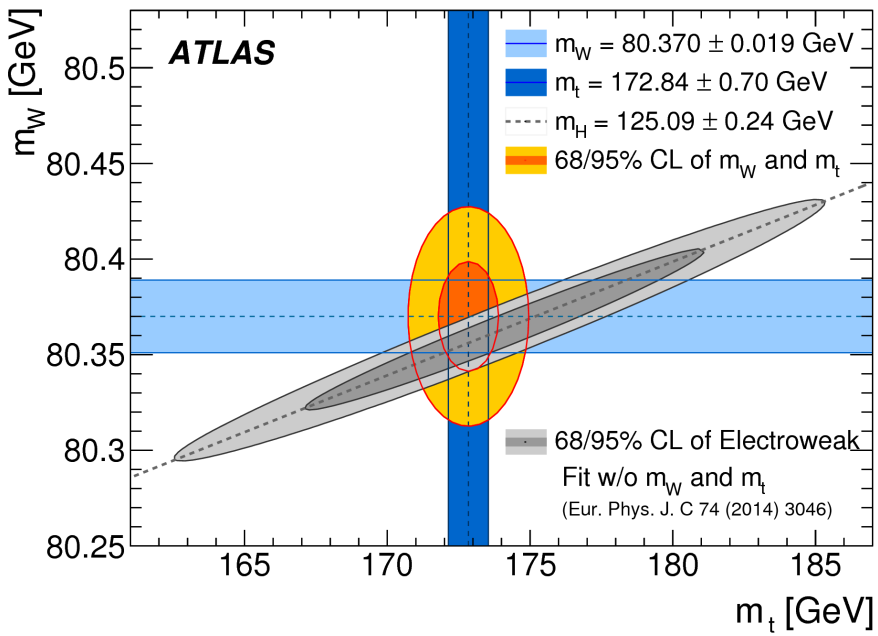


$$(\Delta r)_{\rm top} \simeq -\frac{3G_F}{8\sqrt{2}\pi^2\tan^2\theta_W} m_t^2$$

$$(\Delta r)_{\rm Higgs} \simeq \frac{3G_F m_W^2}{8\sqrt{2}\pi^2}\left(\ln\frac{m_H^2}{m_Z^2} - \frac{5}{6}\right)$$

LARGE CONTRIBUTION TO EW RADIATIVE CORRECTIONS

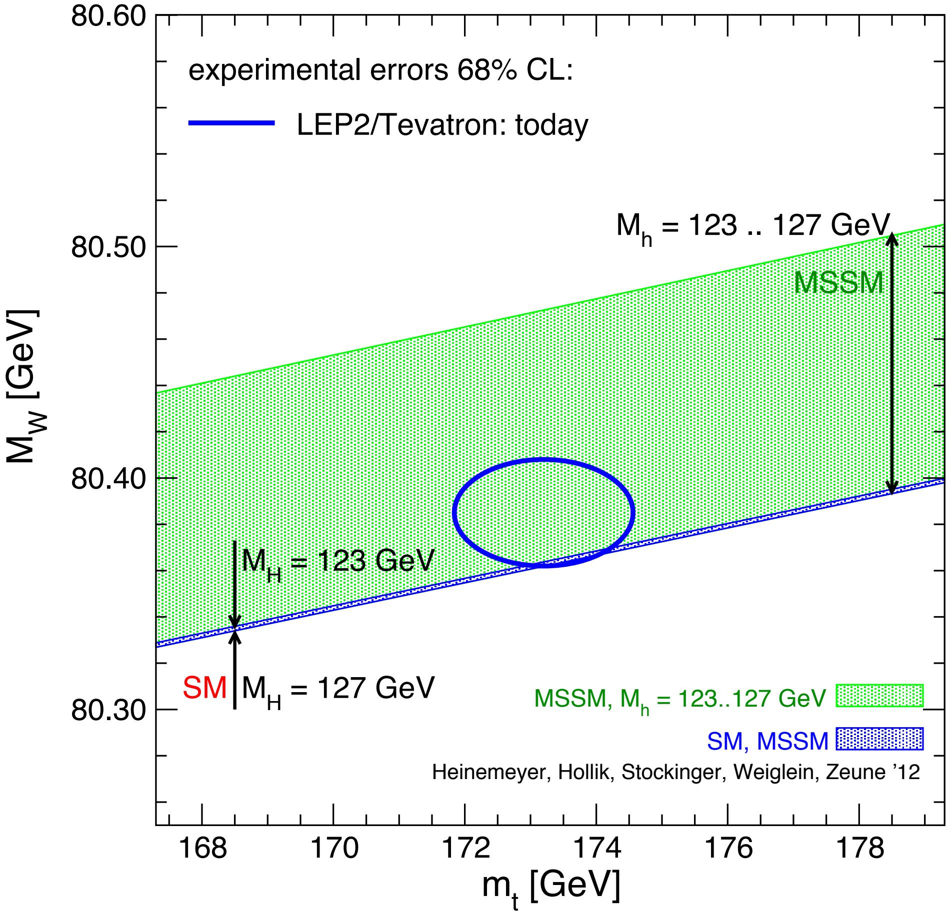




The predicted Higgs mass before its discovery (94^{+25}_{-22} GeV) consistent with the current measurement.

We can test the self consistency of the Standard Model using the top mass and other inputs.

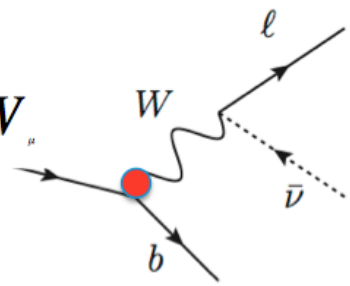
LARGE CONTRIBUTION TO EW RADIATIVE CORRECTIONS



We can test the self consistency of the Standard Model using the top mass and other inputs (and also beyond SM models).

SHORT LIFETIME

$$-\frac{ig}{2\sqrt{2}}\bar{t}\gamma^{\mu}(1-\gamma^{5})V_{tb}bW_{\mu}$$



- Top decay width from NLO QCD calculation:

$$\Gamma(t \to Wb) = \frac{G_F m_t^3}{8\pi\sqrt{2}} |V_{tb}| \left(1 + \vartheta(\frac{m_W^4}{m_t^4})\right) \approx 1.5\ GeV.$$

$$\tau_t \approx 4.3 \times 10^{-25}\ \mathrm{s}$$
$$c\tau \approx 0.12\ \mathrm{fm}.$$

- Compared to typical hadronization scale: $\Lambda_{QCD} \approx 250$ MeV → Top decays before hadronization, no bound states formed (e.g. toponium, top mesons/baryons)
- Spin/polarization passed on to decay products without dilution.

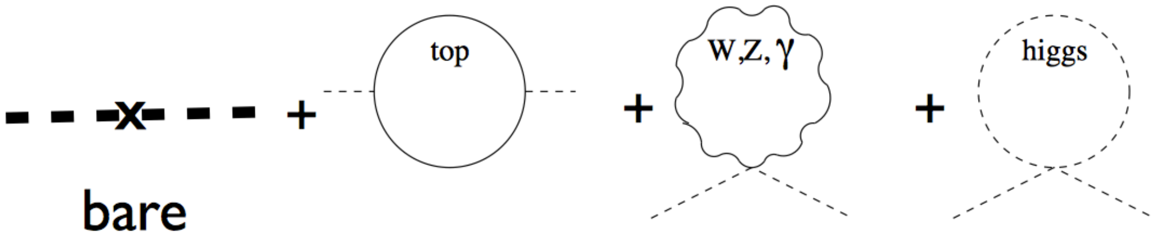
$1/m_t <$	$1/\Gamma_t <$	$1/\Lambda <$	m_t/Λ^2
Production time<	Lifetime <	Hadronization time <	Spin decorrelation time

Opportunity to study a "free" quark, measure precisely top quark properties from its decay products.

NEW PHYSICS/BSM MODELS

- Hierarchy problem of the SM Higgs sector:

  Instability of small Higgs mass to large corrections in a theory with a large mass scale in addition to the weak scale (i.e. in the context in which the SM is a low E remnant of a more fundamental theory with a large mass scale Λ)



$$-\frac{3}{8\pi^2}\lambda_t^2\Lambda^2 \qquad \frac{9}{64\pi^2}g^2\Lambda^2 \qquad \frac{1}{16\pi^2}\lambda^2\Lambda^2$$

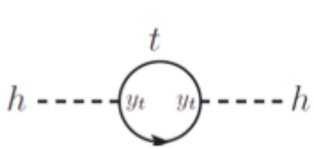
$$m_h^2(\text{physical}) = m_h^2(\text{bare}) + \sum_i a_i\Lambda^2$$

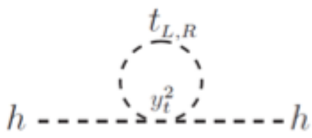
In GUT, $\Lambda = M_{GUT} \sim 10^{16}$ GeV → huge corrections!

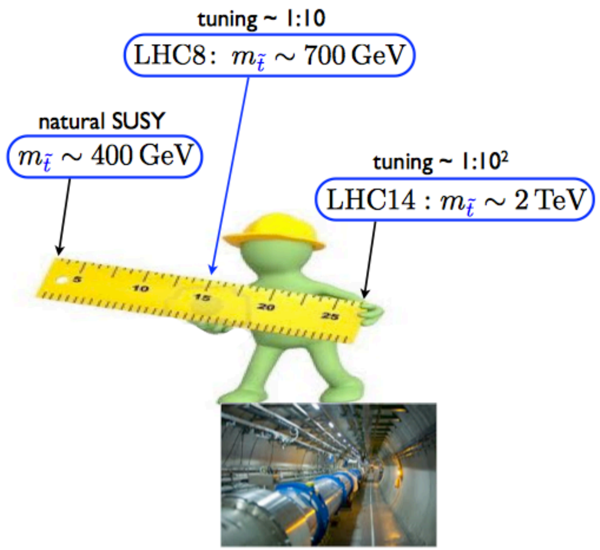
NEW PHYSICS/BSM MODELS

Remedies:

- Extending the top sector adding top partners states that contribute to the Higgs mass in opposite way
- Potentially within the LHC reach







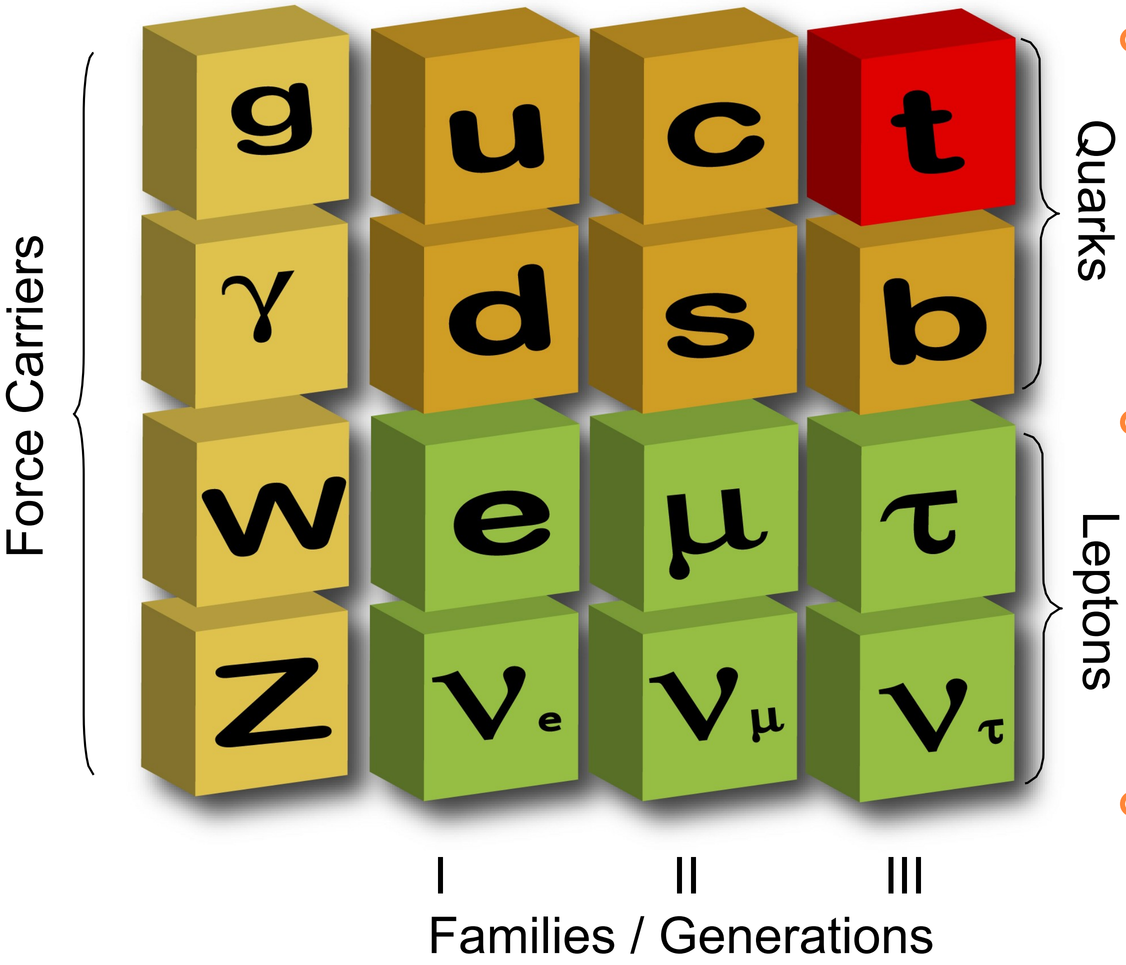
- 2 leading frameworks:
  - Supersymmetry (top partners scalars = stops)
  - Composite Higgs models (top partners fermions = "T")

High motivation to perform direct searches for new physics in the top sector.

Will however focus on precision measurements that can also reveal the presence of new physics.

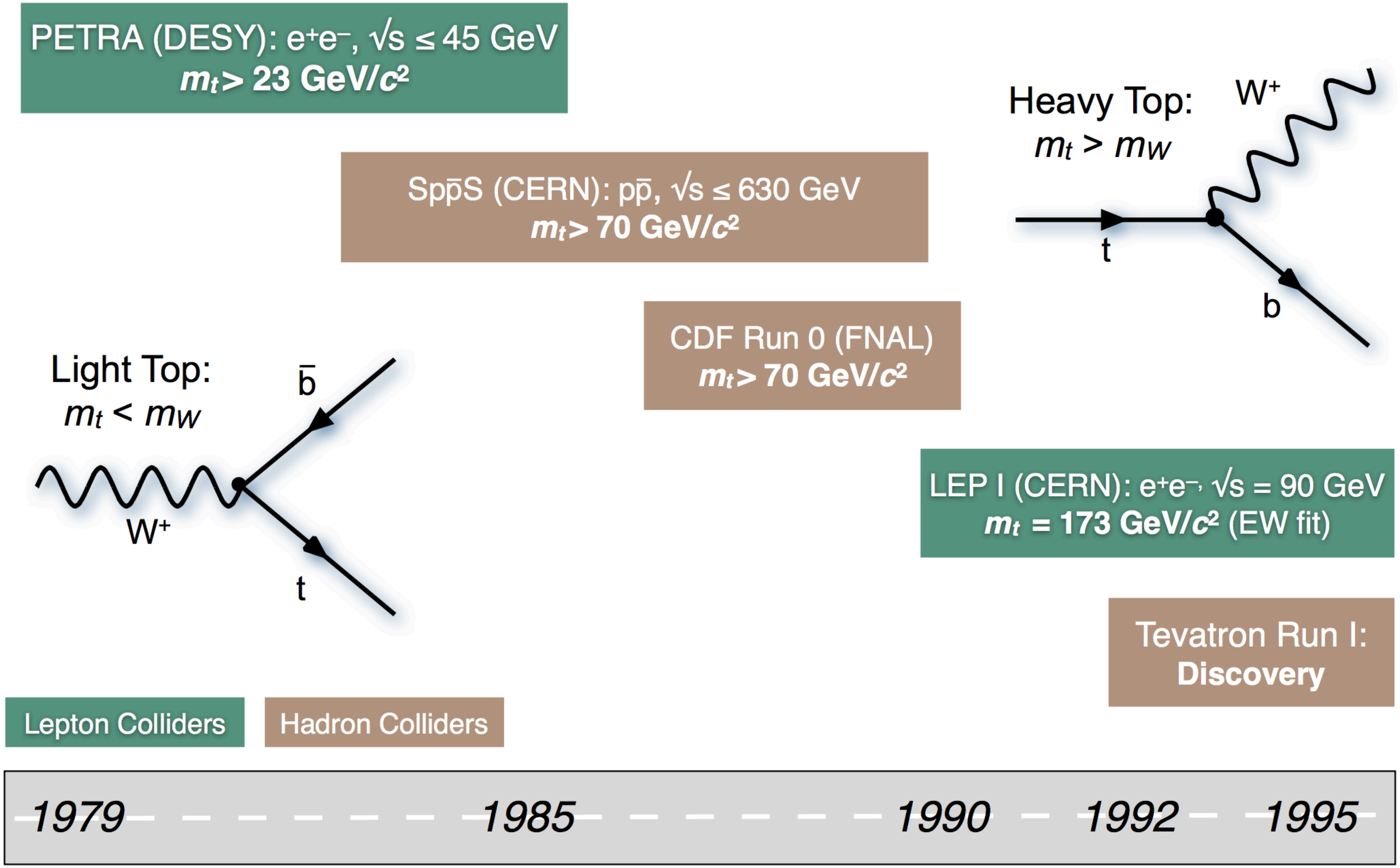
THE ROAD TO TOP QUARK DISCOVERY

- The top quark is the last piece of the third generation.
- How did we get hints of its existence?



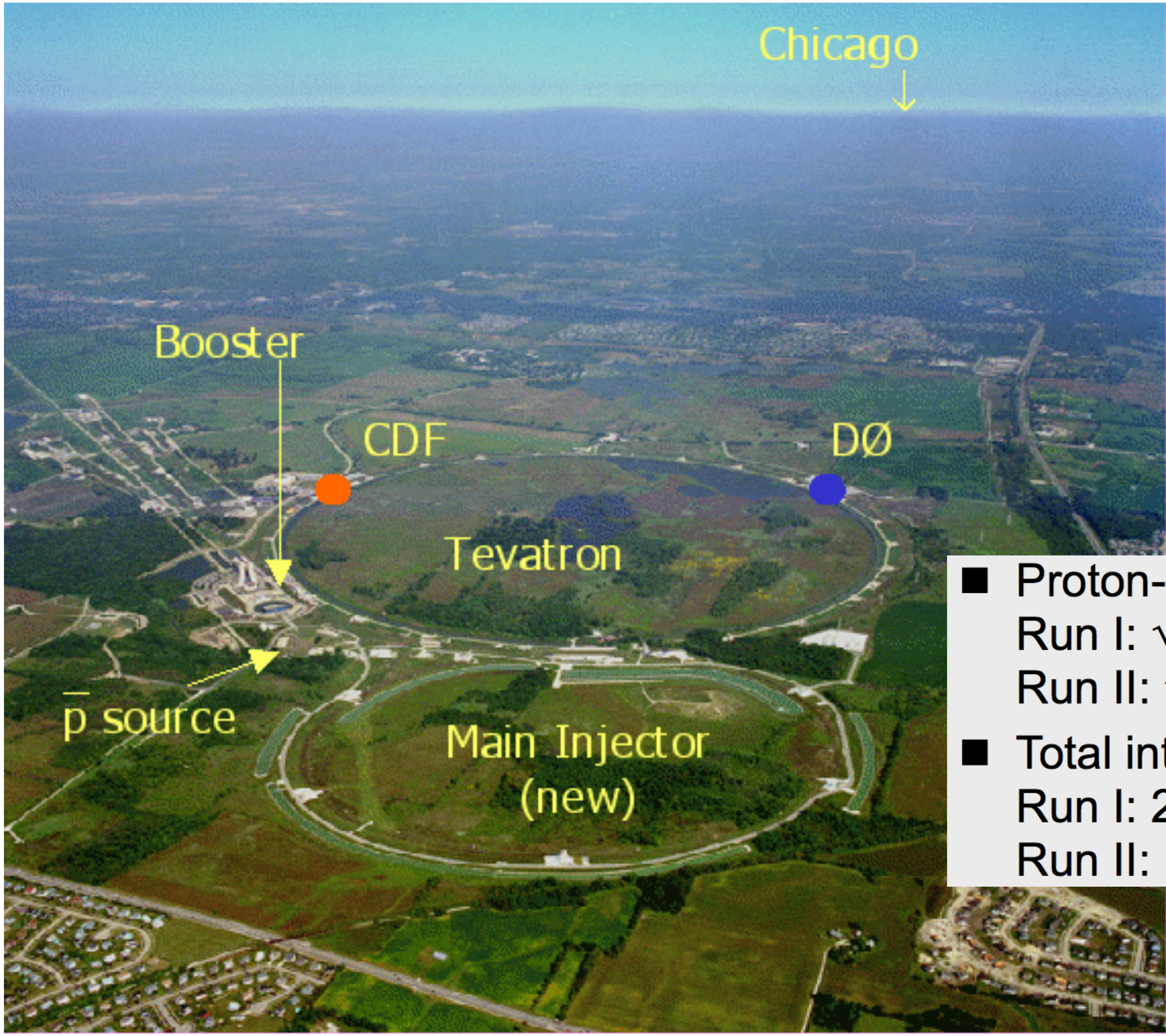
- 1973: M.Kobayashi and T. Maskawa predicted the existence of a third generation of quarks to explain observed CP violations in kaon decay.
- 1977: bottom quark (5th quark) was discovered by the E288 exp. at Fermilab, and its quantum numbers Q= -1/3, I_3= -1/2 determined at DESY.
- The b-quark was a member of an isospin doublet and needed a 'top' partner.

THE ROAD TO TOP QUARK DISCOVERY



- Direct searches for top quark were done at both e^+e^- and ppbar colliders at DESY, CERN and FNAL.

TOWARDS THE TOP QUARK DISCOVERY



- Proton-antiproton collider:
  Run I: $\sqrt{s}$ = 1.8 TeV
  Run II: $\sqrt{s}$ = 1.96 TeV
- Total integrated luminosity:
  Run I: 200 pb^{-1}
  Run II: 12 fb^{-1}

THE TOP QUARK DISCOVERY

- March 2, 1995: Joint CDF/D0 seminar announcing the top quark discovery.
- Run-1 data used: 67 pb^{-1} (CDF), 50 pb^{-1} (D0)

THE TOP QUARK DISCOVERY

VOLUME 74, NUMBER 14 PHYSICAL REVIEW LETTERS 3 APRIL 1995

Observation of Top Quark Production in $\overline{p}p$ Collisions with the Collider Detector at Fermilab

F. Abe,[14] H. Akimoto,[32] A. Akopian,[27] M. G. Albrow,[7] S. R. Amendolia,[24] D. Amidei,[17] J. Antos,[29] C. Anway-Wiese,[4]

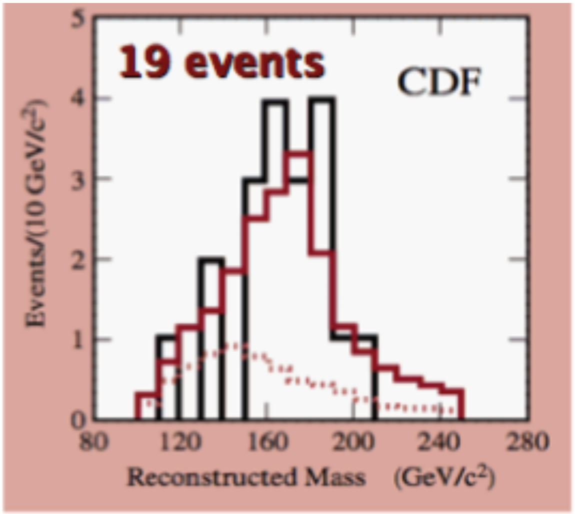
We establish the existence of the top quark using a 67 pb^{-1} data sample of $\overline{p}p$ collisions at $\sqrt{s} = 1.8$ TeV collected with the Collider Detector at Fermilab (CDF). Employing techniques similar to those we previously published, we observe a signal consistent with $t\bar{t}$ decay to $WWb\bar{b}$, but inconsistent with the background prediction by 4.8σ. Additional evidence for the top quark is provided by a peak in the reconstructed mass distribution. We measure the top quark mass to be 176 ± 8(stat) ± 10(syst) GeV/c^2, and the $t\bar{t}$ production cross section to be $6.8^{+3.6}_{-2.4}$ pb.

VOLUME 74, NUMBER 14 PHYSICAL REVIEW LETTERS 3 APRIL 1995

Observation of the Top Quark

S. Abachi,[12] B. Abbott,[33] M. Abolins,[23] B. S. Acharya,[40] I. Adam,[10] D. L. Adams,[34] M. Adams,[15] S. Ahn,[12] H. Aihara,[20]

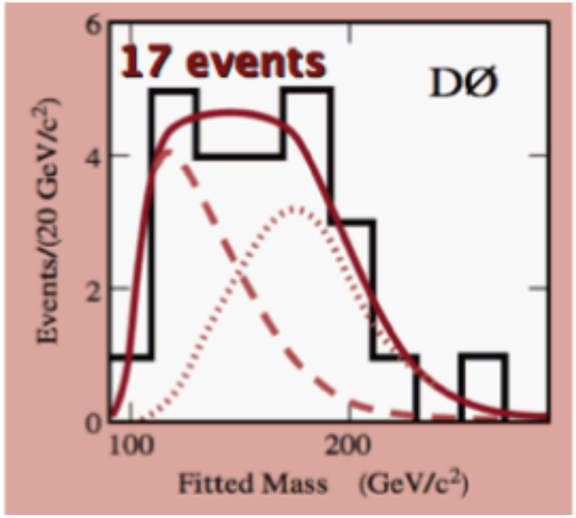
The D0 Collaboration reports on a search for the standard model top quark in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV at the Fermilab Tevatron with an integrated luminosity of approximately 50 pb^{-1}. We have searched for $t\bar{t}$ production in the dilepton and single-lepton decay channels with and without tagging of b-quark jets. We observed 17 events with an expected background of 3.8 ± 0.6 events. The probability for an upward fluctuation of the background to produce the observed signal is 2×10^{-6} (equivalent to 4.6 standard deviations). The kinematic properties of the excess events are consistent with top quark decay. We conclude that we have observed the top quark and measured its mass to be 199^{+19}_{-21} (stat) ±22 (syst) GeV/c^2 and its production cross section to be 6.4 ± 2.2 pb.



CDF: 67 pb^{-1} , 4.8 σ

M_{top} = 176 ± 13 GeV

$\sigma_{t\bar{t}}$= $6.8^{+3.6}{}_{-2.4}$ pb



D0: 50 pb^{-1} , 4.6 σ

M_{top} = 199 ± 30 GeV

$\sigma_{t\bar{t}}$ = 6.4 ± 2.2 pb

FROM DISCOVERY TO MEASUREMENTS

Particle Data Group

End of Tevatron Run I
PRD 54, 1 (1996)

→

One year before end of Tevatron Run II
J.Phys. G37, 075021 (2010)

t-Quark Mass in $p\bar{p}$ Collisions

The *t* quark has now been observed. Its mass is sufficiently high that decay is expected to occur before hadronization.

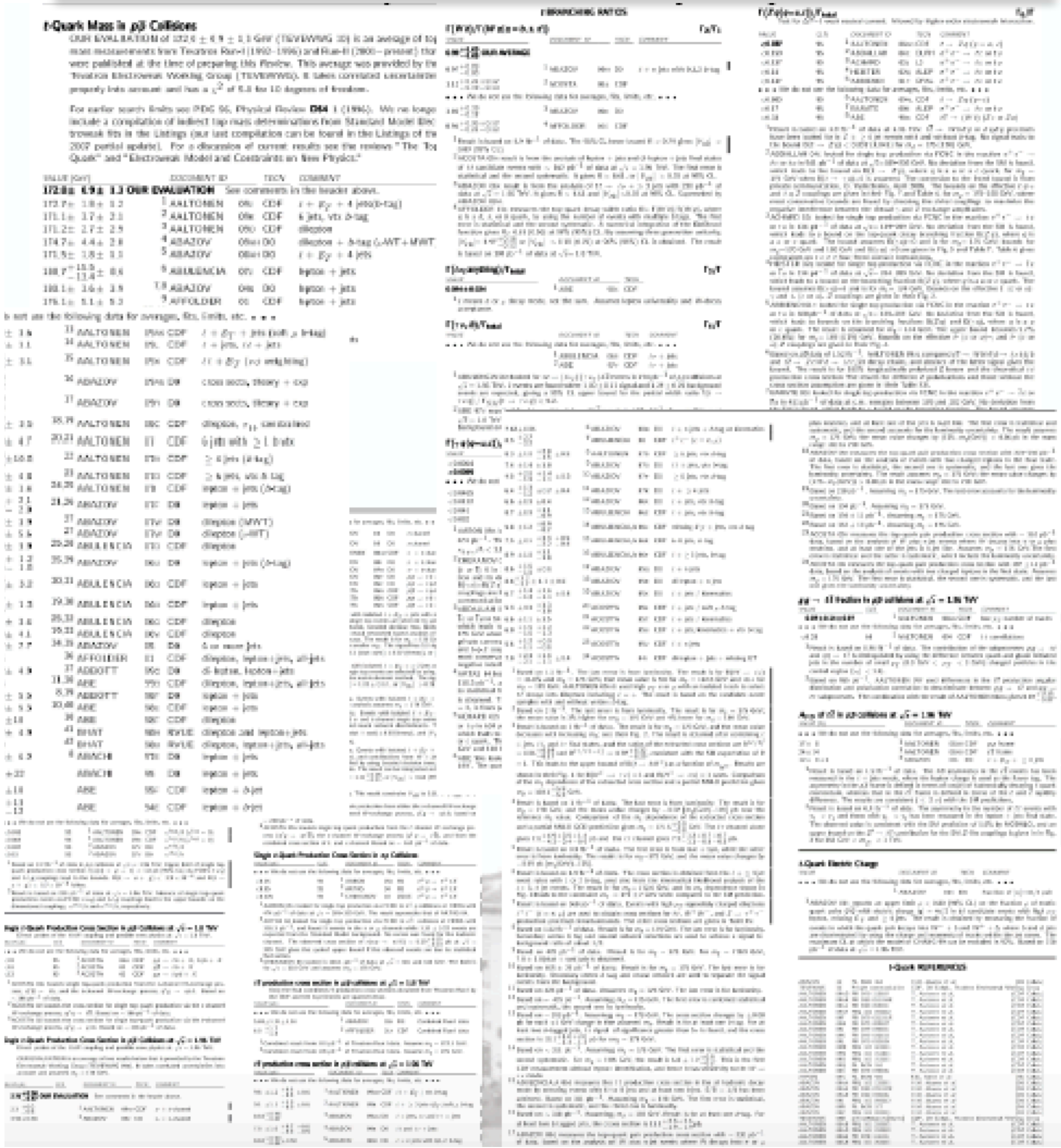
Preliminary results for the top mass based on the full (Run Ia+Ib) data set have been presented by CDF and DØ at conferences in early 1996:

$m_t = 175.6 \pm 5.7 \pm 7.1$ GeV	CDF	lepton + jets
$m_t = 159^{+24}_{-22} \pm 17$ GeV	CDF	dilepton
$m_t = 187 \pm 8 \pm 12$ GeV	CDF	hadronic
$m_t = 170 \pm 15 \pm 10$ GeV	DØ	lepton + jets
$m_t = 158 \pm 24 \pm 10$ GeV	DØ	$e\mu$

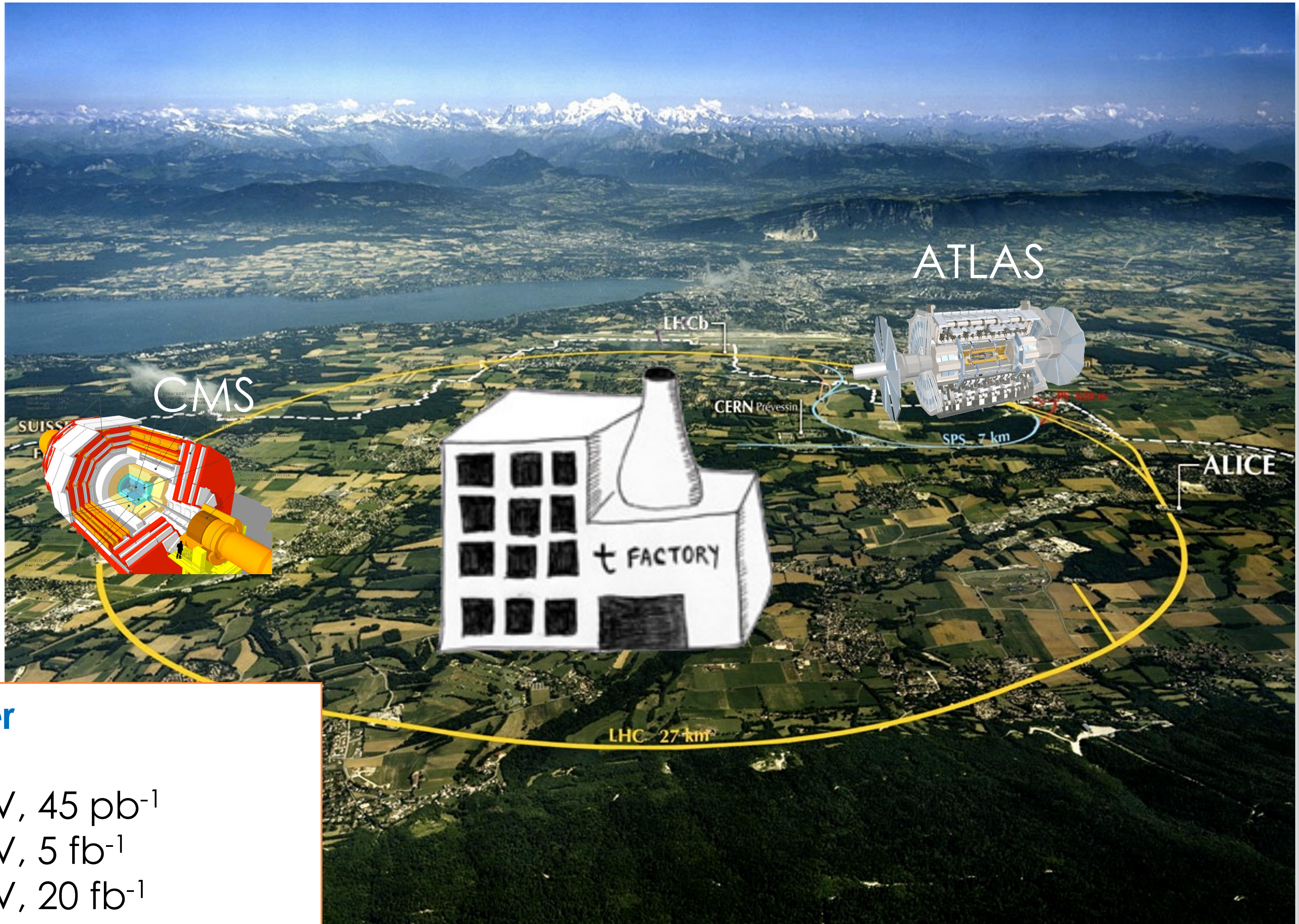
Because of the high current interest, we mention these preliminary results here but do not average them or include them in the Listings or Tables. See the note on the top quark for references.

Search limits, which are now primarily of historical interest, are based on the assumption that no nonstandard decay modes such as $t \to bH^+$ are available, except as noted in the comments.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
180±12 OUR AVERAGE					
$199^{+19}_{-21} \pm 22$		[1] ABACHI	95	D0	ℓ + jet
$176 \pm 8 \pm 10$		[2] ABE	95F	CDF	ℓ + *b*-jet
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[3] ABACHI	95B	D0	$\ell\ell$ + jets, ℓ + jets
>128	95	[4] ABACHI	95F	D0	$\ell\ell$ + jets, ℓ + jets
		[5] ABE	95O	CDF	
		[6] ABE	95V	CDF	
		[7] ABE,F	95	CDF	$W + \geq 4$ jets
>131	95	[8] ABACHI	94	D0	$\ell\ell$ + jets, ℓ + jets
$174 \pm 10^{+13}_{-12}$		[9] ABE	94E	CDF	ℓ + *b*-jet
>118	95	[9] ABE	94E	CDF	$\ell\ell$
		[10] ABE	94H	CDF	$t \to bH^+, H^+ \to \tau^+\nu_\tau$
		[11] ABE	94I	CDF	$t \to bH^+, H^+ \to \tau^+\nu_\tau$
> 91	95	[12] ABE	92	CDF	$\ell\ell$, ℓ + *b*-jet
		[13] ALITTI	92F	UA2	$t \to bH^+, H^+ \to \tau^+\nu_\tau$
> 60	95	[14] ALBAJAR	91B	UA1	$t \to bH^+, H^+ \to \tau^+\nu_\tau$
		[15] BAER	91B	RVUE	$t \to \tilde{t}_1 \tilde{\chi}^0_1$
> 72	95	[16] ABE	90B	CDF	$e + \mu$
> 77	95	[17] ABE	90C	CDF	e + jets + missing E_T
> 69	95	[18] AKESSON	90	UA2	e + jets + missing E_T
> 60	95	ALBAJAR	90B	UA1	e or μ + jets, $\mu\mu$ + jet
		[19] BARGER	90E	RVUE	$t \to bH^+$
> 41	95	[20] ALBAJAR	88	UA1	e or μ + jets



TOP PRODUCTION AT THE LHC



LHC pp collider

Run I:

2010: $\sqrt{s}$ = 7 TeV, 45 pb^{-1}

2011: $\sqrt{s}$ = 7 TeV, 5 fb^{-1}

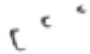
2012: $\sqrt{s}$ = 8 TeV, 20 fb^{-1}

Run II:

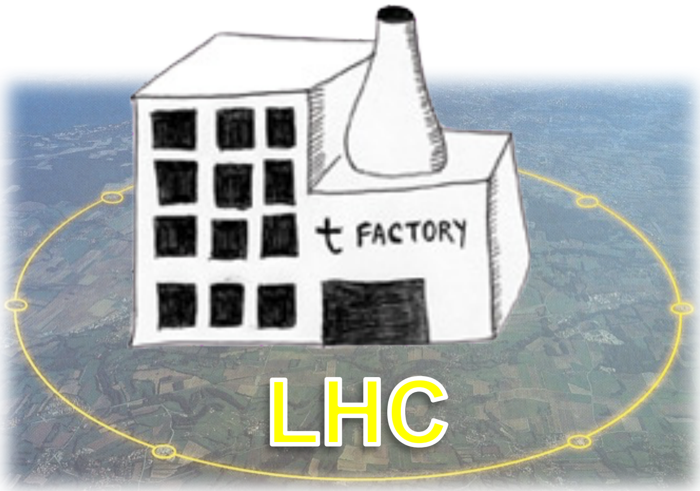
2015-2016: $\sqrt{s}$ = 13 TeV, 36 pb^{-1}

Expected by 2018: 100 fb^{-1}

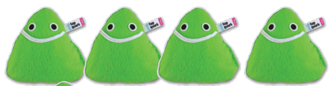
(per experiment)

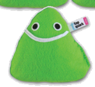
TOP PRODUCTION AT THE LHC 

- Impressive performance at the LHC and in the ATLAS and CMS experiments
- LHC is the first top factory ever!

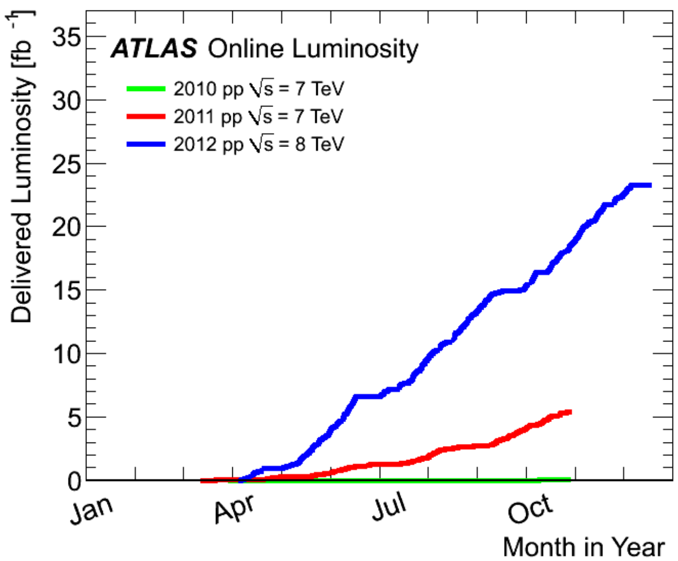


At the peak of instantaneous luminosity during 2012 the top production was :

~ 2 top pairs/s 

~ 1 single top/s 

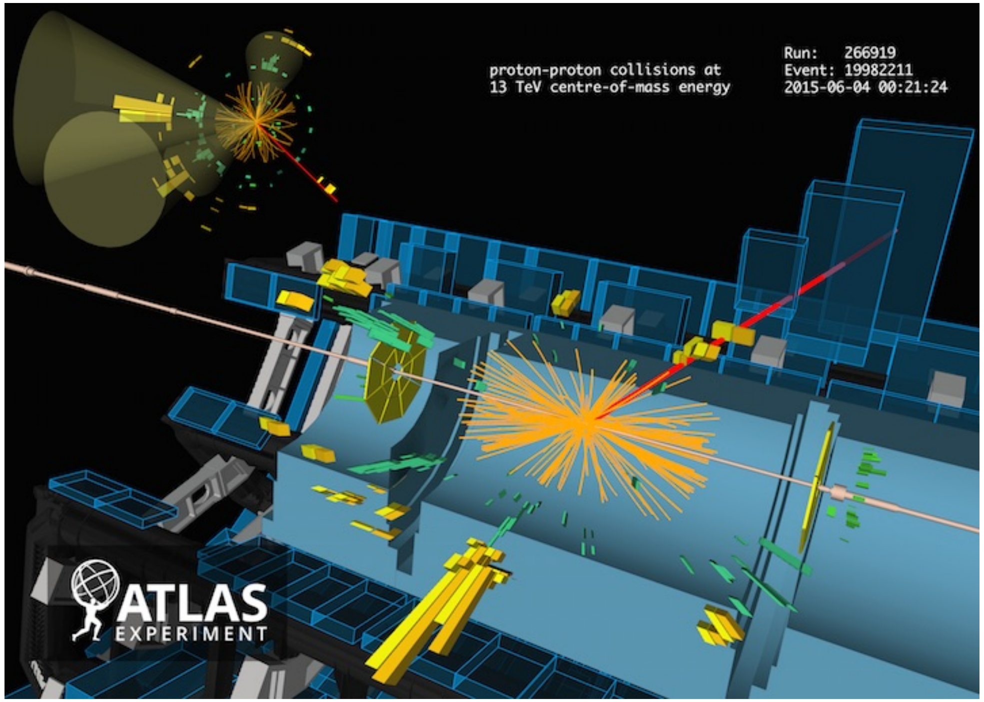
Around **15M** quark tops were produced during 2011 and 2012!

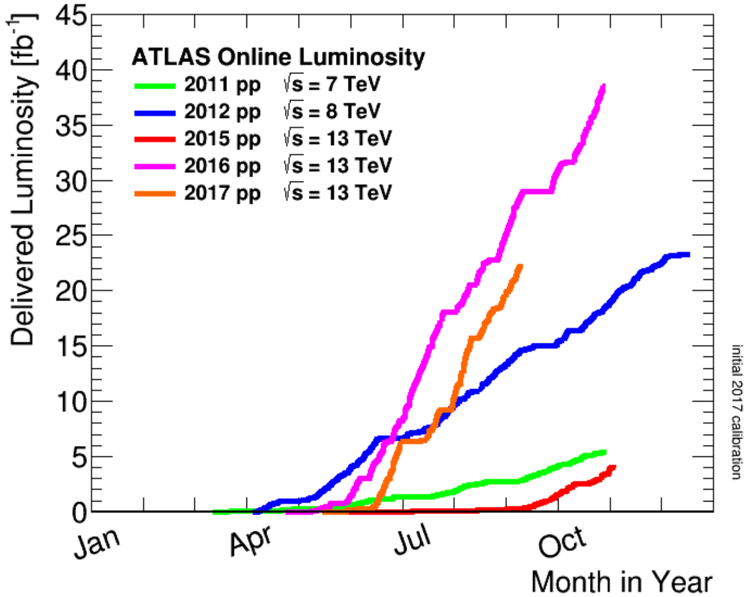


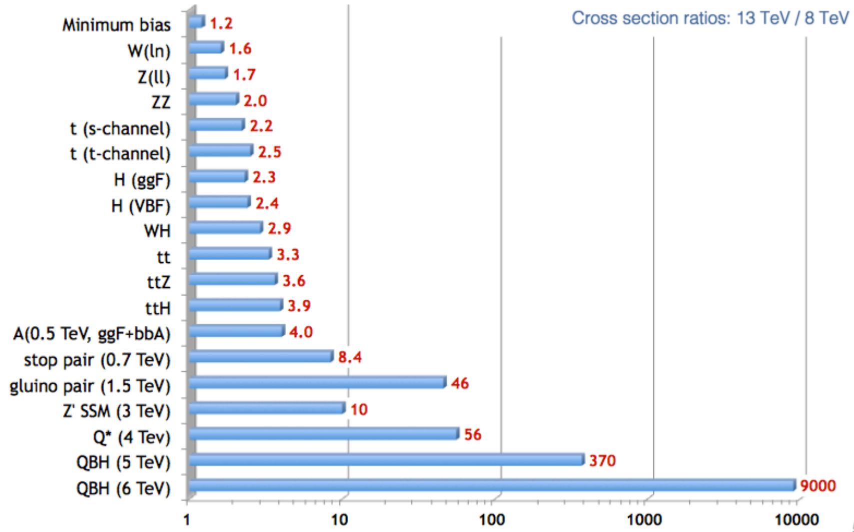
- Run 1 legacy papers from both ATLAS and CMS Collaborations mostly available.

TOP PRODUCTION AT THE LHC

- Run II: LHC re-started operation at √s= 13 TeV in 2015; expect 100 fb^{-1} by 2018.



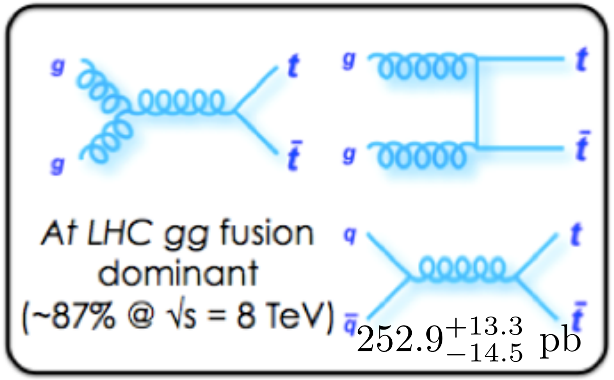




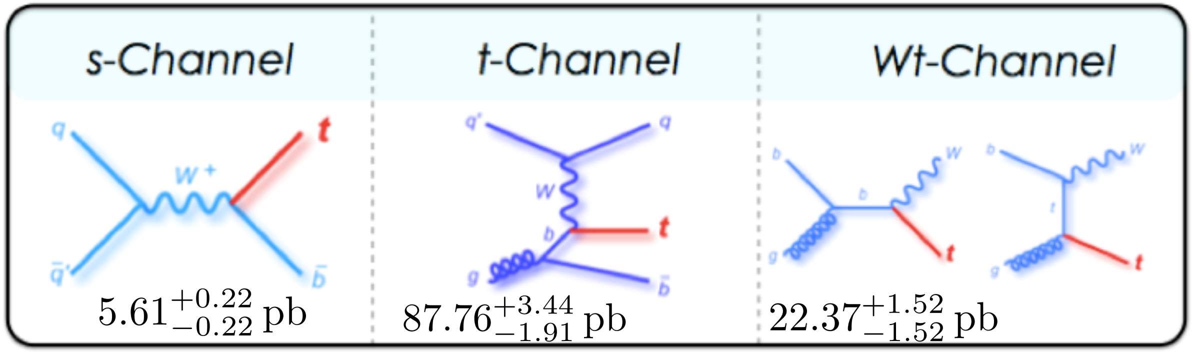
- Top quark production increases when going from 8 to 13 TeV by a factor 2.5-3.3 (depending on the production mode).
- While precision measurements soon/already limited by systematic uncertainties, many possibilities for other studies open up.

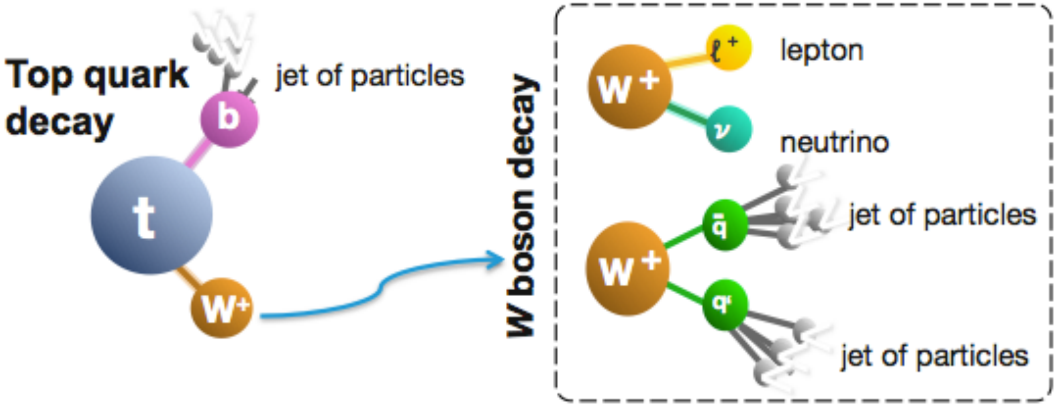
TOP PRODUCTION AT THE LHC

top pair production



single top : production via EW interaction



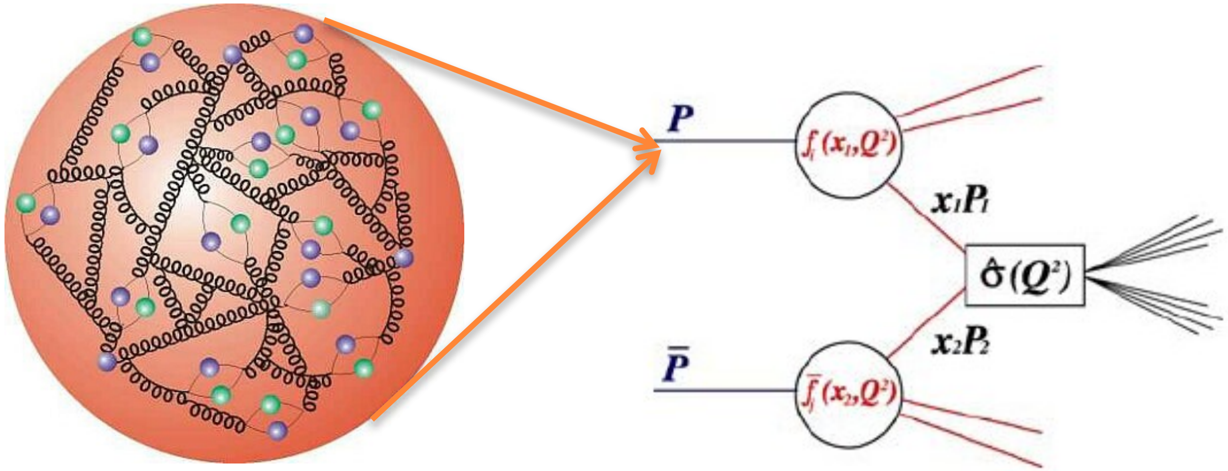


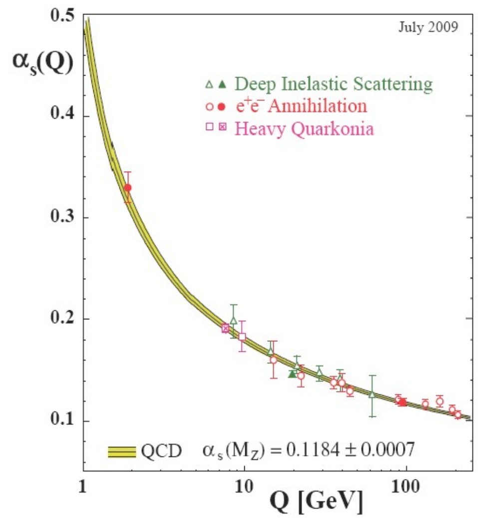
Top quarks can be produced in pairs via QCD or singly via EW interactions.

Top quark decays almost exclusively to Wb.

TOP QUARK PAIR PRODUCTION

- Top quark pairs can be produced via hard scattering of gluons and quarks within the collider hadrons (protons at the LHC).
- The description of the hard collision is separated into short and long distance processes.





$$\sigma_{pp\to t\bar{t}}(s,m_t)=\sum_{i,j=partons}\int dx_1\,dx_2\,f_i^{pdf}(x_1,\mu_f^2)\,f_j^{pdf}(x_2,\mu_f^2)\,\hat{\sigma}_{ij\to t\bar{t}}(\hat{s},m_t,\mu_f,\mu_r,\alpha_s(\mu_r))$$

$\oplus$ showering/ & hadronization

Non-perturbative | *Perturbative in α_s*

factorization ➔ $PDFs(x,\mu_f^2)\otimes\hat{\sigma}(\hat{s},m_t,\mu_f,\mu_r,\alpha_s(\mu_r))$

$p_T^{parton} < \mu_F$ | $p_T^{parton} > \mu_F$

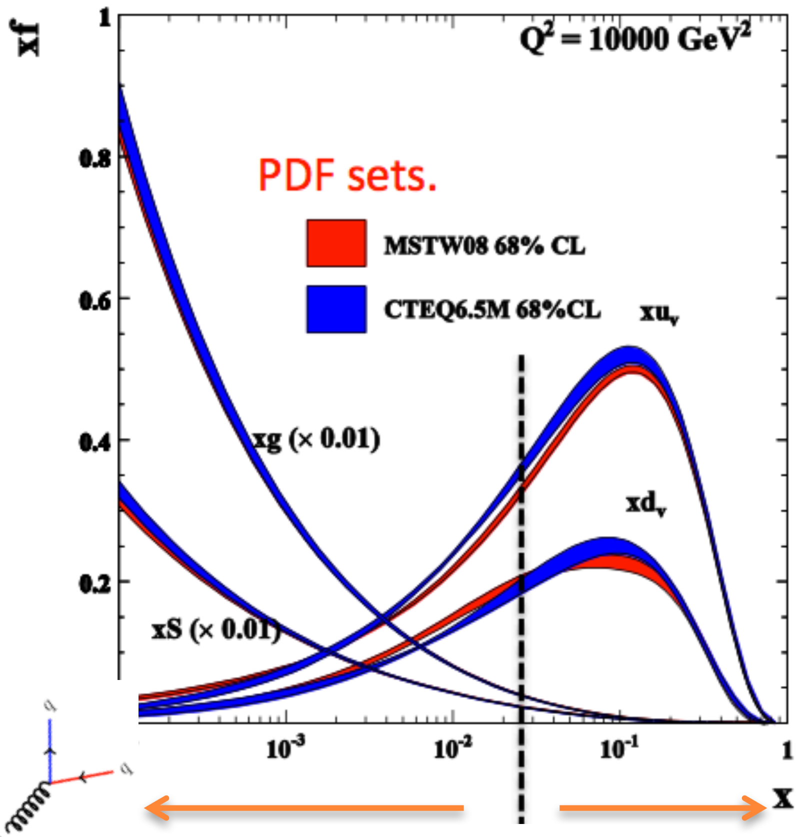
$$\mu_f \sim Q \sim \sqrt{\hat{s}} \sim \sqrt{x_1 x_2 s}$$

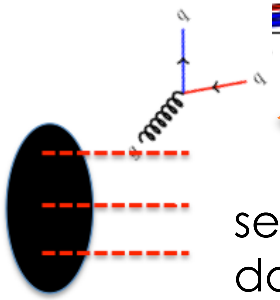
TOP QUARK PAIR PRODUCTION

- The Parton Density Function (PDFs) $f_i(x,Q^2)$ can be interpreted as the probability density to observe a parton of flavour i and a fraction x of the original hadron longitudinal momentum when probed at a scale Q^2 (Extracted from global fits to data).

$\hat{s}=x_i x_j s \geq 4m_t^2$.

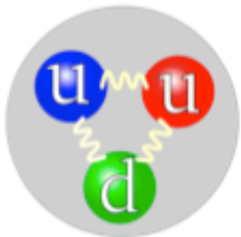
assuming $x_i=x_j$ the typical $x = 2m_t/\sqrt{s}$





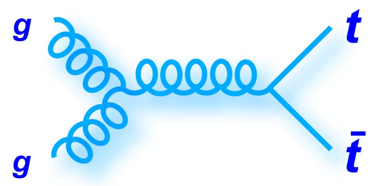
sea quarks dominate

Valence quarks dominate



Accelerator energy	$x = 2m_t/\sqrt{s}$
Tevatron $\sqrt{s}$=1.96 TeV	***0.18***
LHC $\sqrt{s}$= 7 TeV	***0.05***
LHC $\sqrt{s}$=8 TeV	***0.043***
LHC $\sqrt{s}$=13 TeV	***0.026***

Gluon fusion processes dominate at LHC (~90%)



TOP QUARK PRODUCTION AT THE LHC

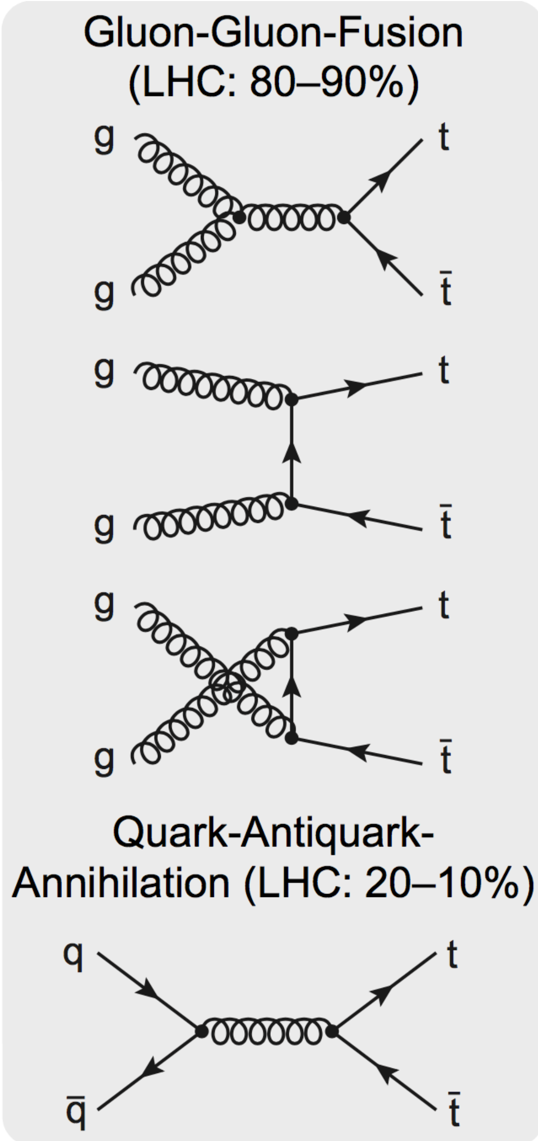
Theoretical calculations:

- Leading-order QCD by far not sufficient, large corrections.
- Types of corrections: higher orders in α_s, resummation of large logarithms.
- State of art (Czakon, Fiedler, Mitov, 2013): NNLO+NNLL (next-to-next-to- leading order and next-to-next-to-leading logarithms).

Czakon *et al.*, PRL 110 252004 (2013)

σ_{7TeV} (pb)	$172^{+4.4}_{-5.8}{}^{+4.7}_{-48}$
σ_{8TeV} (pb)	$245^{+6.2}_{-8.4}{}^{+6.2}_{-6.4}$
σ_{13TeV} (pb)	$831^{+19}_{-29}{}^{+35}_{-35}$

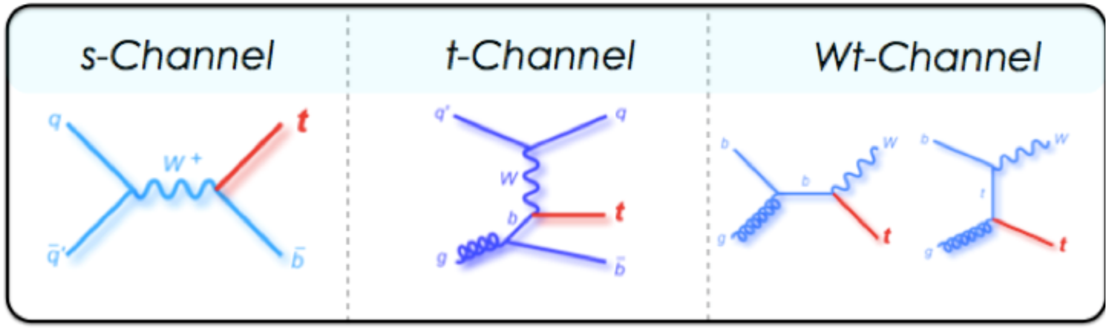
@ NNLO + NNLL m_{top} = 172.5 GeV



SINGLE TOP PRODUCTION

- Single top quarks can be produced via EW interaction and Wtb vertex (almost exclusively $|V_{tb}| >> |V_{td}|, |V_{ts}|$)
- Lower energy threshold for single top production.
- Weaker interaction strength.
- Single production of top quarks is larger than that of anti-top in the t- and s-channels (due to different PDFs).

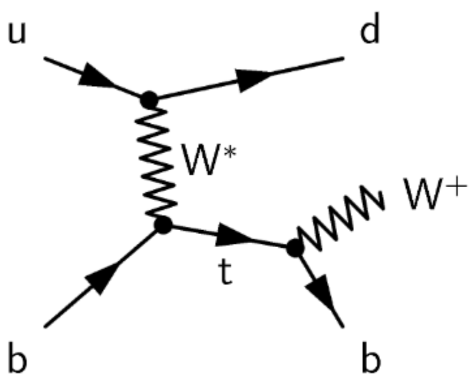
single top : production via EW interaction

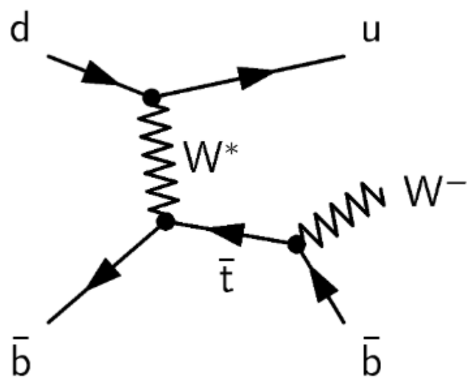


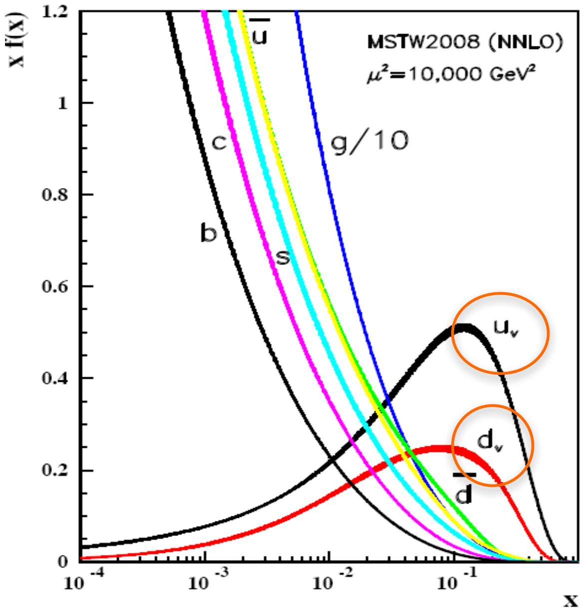
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \quad \text{with} \quad V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$\begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.00065 & 0.00351^{+0.00015}_{-0.00014} \\ 0.22520 \pm 0.00065 & 0.97344 \pm 0.00016 & 0.0412^{+0.0011}_{-0.0005} \\ 0.00867^{+0.00029}_{-0.00031} & 0.0404^{+0.0011}_{-0.0005} & 0.999146^{+0.000021}_{-0.000046} \end{pmatrix}$$

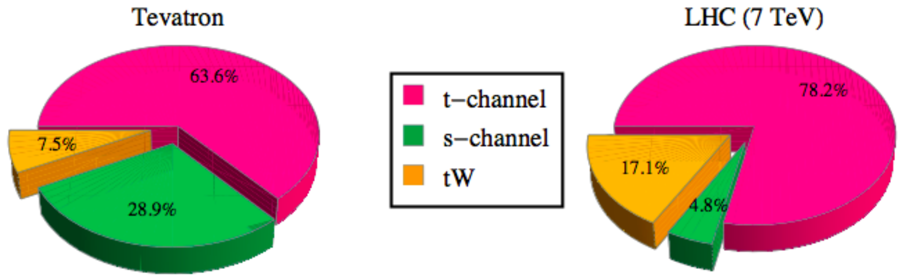
$$\sigma = A_d|V_{td}|^2 + A_s|V_{ts}|^2 + A_b|V_{tb}|^2$$







SINGLE TOP QUARK PRODUCTION



Theoretical calculations:

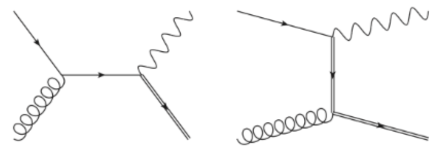
- t-channel: NNLO (the NLO corrections to the LO are accidentally small).
- s-channel: approximate NNLO
- Wt: approximate NNLO.
  - NLO corrections double resonant processes share the same final state with top quark pair production.

In MC generators, the overlap can be removed:"digramal removal" or "diagram subtraction" schemes.
A more comprehensive way: Consider the full process pp→ WbWb+X at NLO.

Overlap between Wt and ttbar

LO partonic process

$b+g \to W+t$



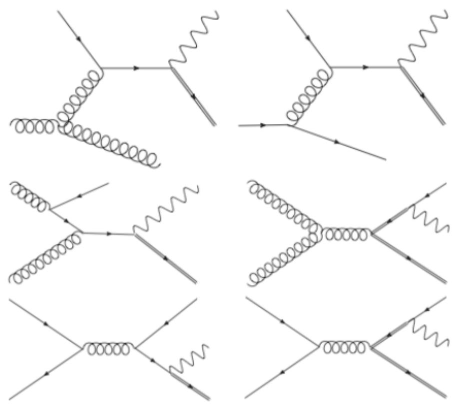
NLO real contributions

$b+g \to W+t+g$

$b+q(\bar{q}) \to W+t+q(\bar{q})$

$g+g \to W+t+\bar{b}$

$q+\bar{q} \to W+t+\bar{b}$



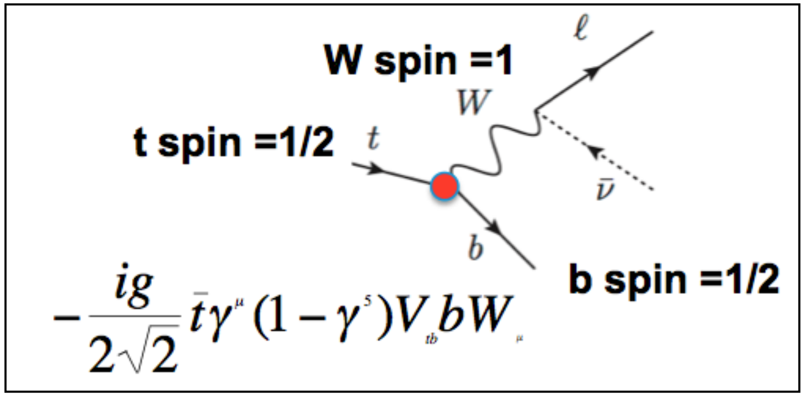
LHCTopWG

	8TeV	13 TeV	order
t-chan.	84^{+3}_{-3} pb	217^{+9}_{-8} pb ($213.7^{1.6}_{0.8}$pb)	NLO (NNLO)
tW-chan.	22^{+4}_{-4} pb	71^{+4}_{-4} pb	aNNLO
s-chan.	$5.2^{+0.22}_{-0.20}$ pb	10^{+4}_{-4} pb	NLO

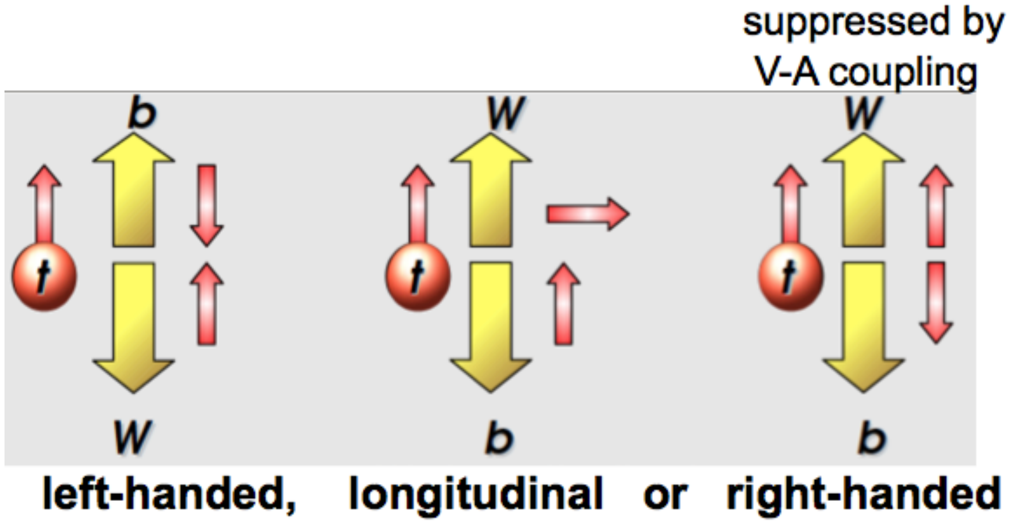
3

TOP QUARK DECAYS

- The top quark is above the Wb threshold → decays weakly almost exclusively to Wb (V-A).
- Since $|V_{tb}| >> |V_{td}|, |V_{ts}|$ → t→W(d,s) are strongly suppressed.
- 3 possible helicity states for the W boson. SM prediction (LO, m_b=0): no right handed W bosons.



$$\Gamma(t \to W^+d) : \Gamma(t \to W^+s) : \Gamma(t \to W^+b) = |V_{td}|^2 : |V_{ts}|^2 : |V_{tb}|^2$$



SM (LO m_b=0)

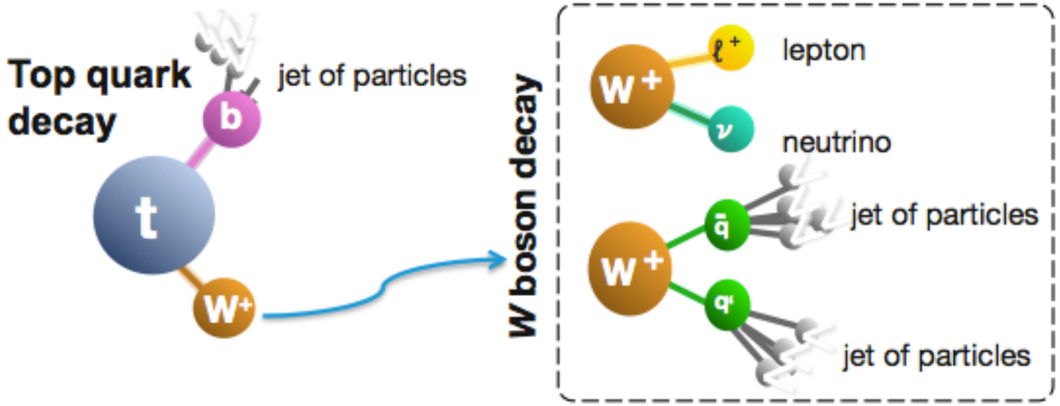
$$F_{LH} = \frac{2m_W^2}{m_t^2 + 2m_W^2} \approx 0.3$$

$$F_{long} = \frac{m_t^2}{m_t^2 + 2m_W^2} \approx 0.7$$

$$F_{RH} \approx 0$$

TOP QUARK DECAYS

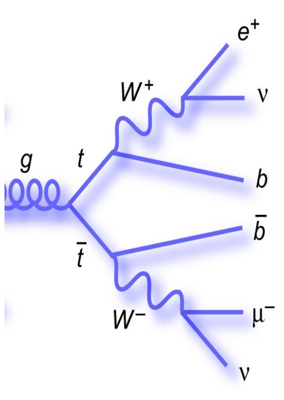
- Channels are classified depending on the W decay mode.



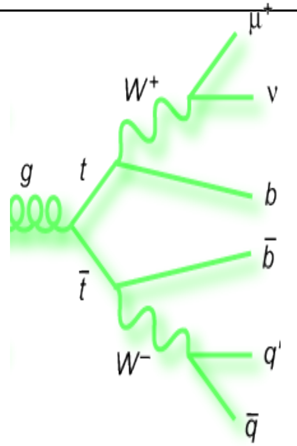
Assuming lepton universality:

$$\frac{\text{hadronically}}{\text{leptonically}} = \frac{\{cs, ud\} \times colour}{\{e, \mu, \tau\}} = 6/3$$

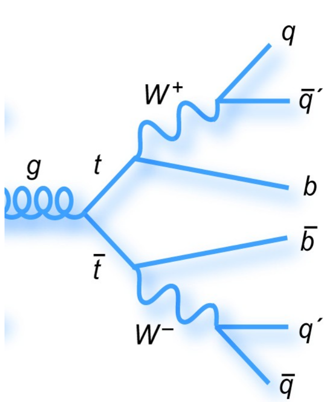
Ex: Channels considered in top quark pair events



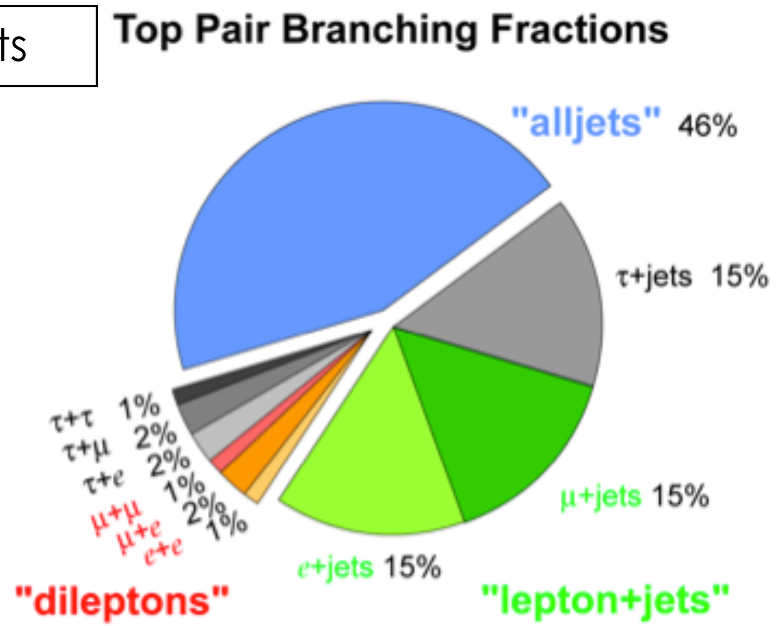
Dilepton (e,μ)
5%



lepton (e,μ)+jets
30%



All hadronic
46%



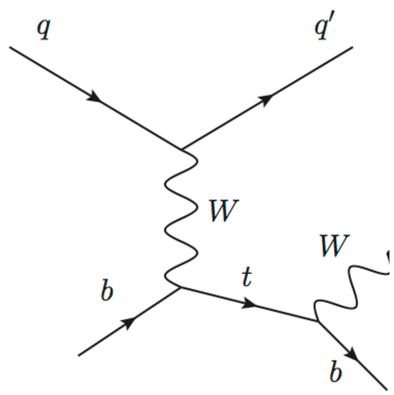
A DATA ANALYSIS EXAMPLE

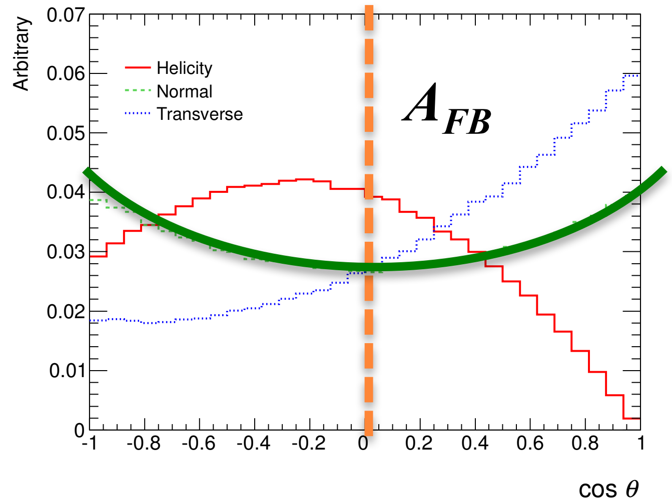
Typical steps:

- (1) Event selection to enhance signal
- (2) Background estimation (MC or data driven)
- (3) Fit/correct data using MC simulation to account for acceptance, detector and resolution effects.
- (4) Estimate statistical and systematic uncertainties (due to physics modelling and experimental sources)

Ex: Forward backward asymmetry measurement from an angular distribution in single top t-channel

$$A_{FB}^{X} = \frac{N(\cos\theta_l^X > 0) - N(\cos\theta_l^X < 0)}{N(\cos\theta_l^X > 0) + N(\cos\theta_l^X < 0)}$$





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- This is done with the LHCTOPWG

A DATA ANALYSIS EXAMPLE

PRESELECTION:
- Single lepton triggers
- **1 $e^{\pm}$ or $\mu^{\pm}$**
- **2 jets**, $p_T > 30$ GeV, $|\eta| < 4.5$
  1 b-jet
- Cuts on E_T^{miss} and $m_T(W)$

SELECTION:
- $|\eta_{light\text{-}jet}| > 2.0$
- $H_T > 210$ GeV
- $m_{top} \in (150,190)$ GeV
- $|\Delta\eta$ (b-jet, light-jet)$| > 1.0$

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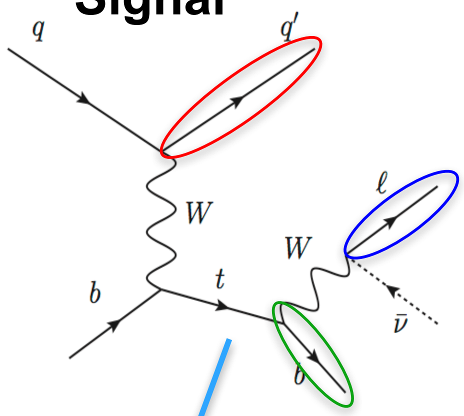
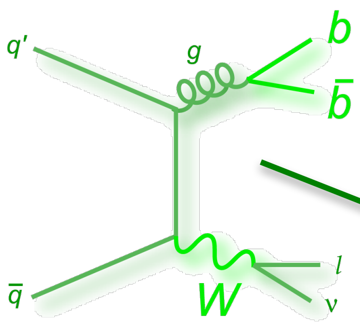
- (2) Background estimation (MC or data driven)

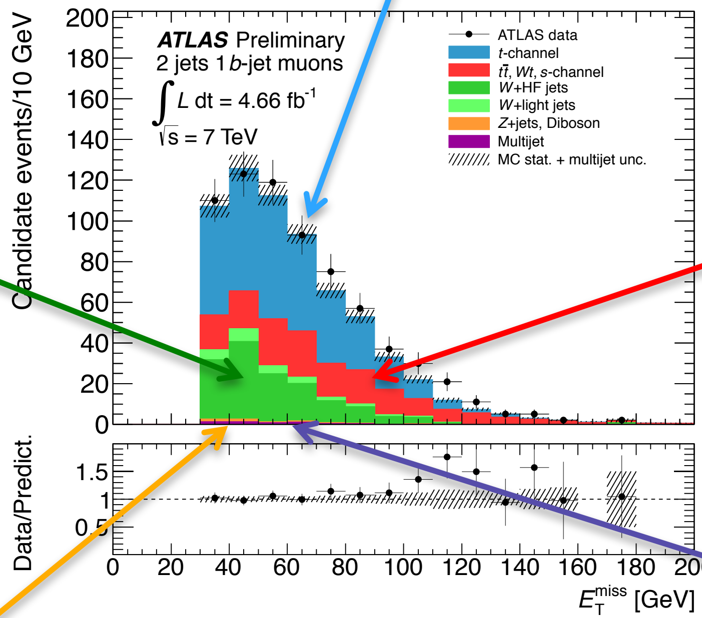
Signal

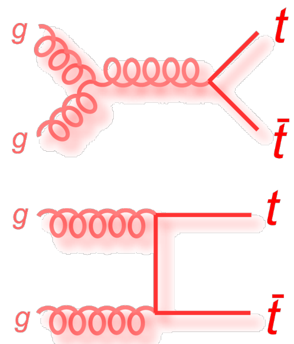


Background processes

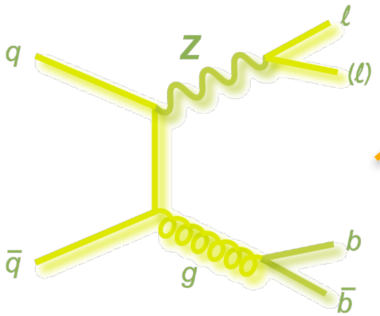


W+jets (W+bb)
One of the dominant ones.
Same final state as the signal.

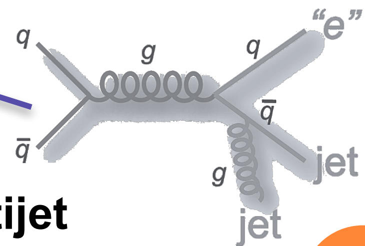




top-antitop pairs
One of the main backgrounds.



Z+jets (Z+bb)
Final state in which one lepton is missed.

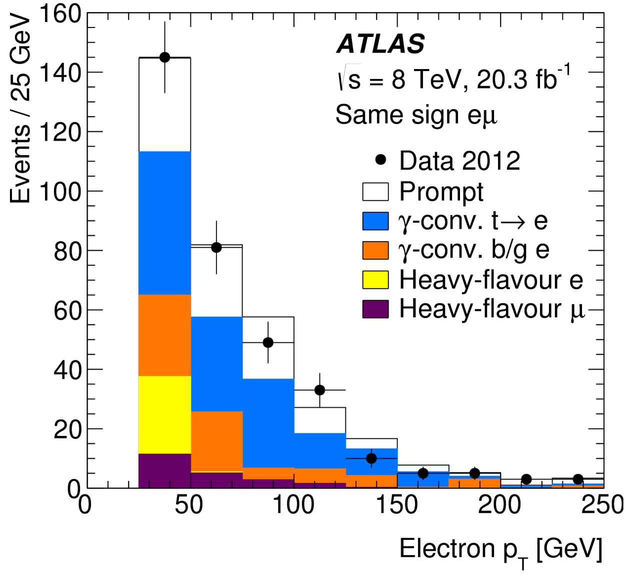


Multijet
Events with jets in which one of them is incorrectly identified as a lepton.

EX: FAKE BACKGROUND

- Selection of top quark events often based on the identification of one or more charged isolated leptons ($W \rightarrow l\nu$)
- Fake leptons (non-prompt leptons or non-leptonic particles as jets) can come from:

> - Electrons: **photon conversions**, tracks overlapping with photons, jets, **semileptonic b/c quark decays**
> - Muons: **b/c quark semileptonic decays**, punch-through hadrons, pion and kaon decays in flight



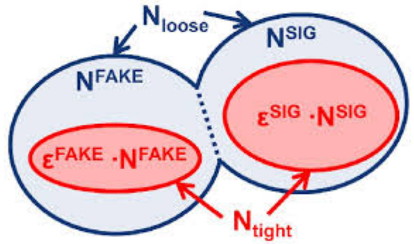
- Lepton isolation and kinematical cuts used to reduce this background

- Data driven methods developed to estimate this background (analysis dependent). Most common methods:
  - Matrix method
  - Fit methods (jet-lepton, anti-lepton)

ATLAS has released a note (ATLAS-CONF-2014-058) providing detailed information about the methods commonly used and their applicability in top quark pair leptonic channels

EX: FAKE BACKGROUND (DATA DRIVEN)

Example: Matrix method (widely used)



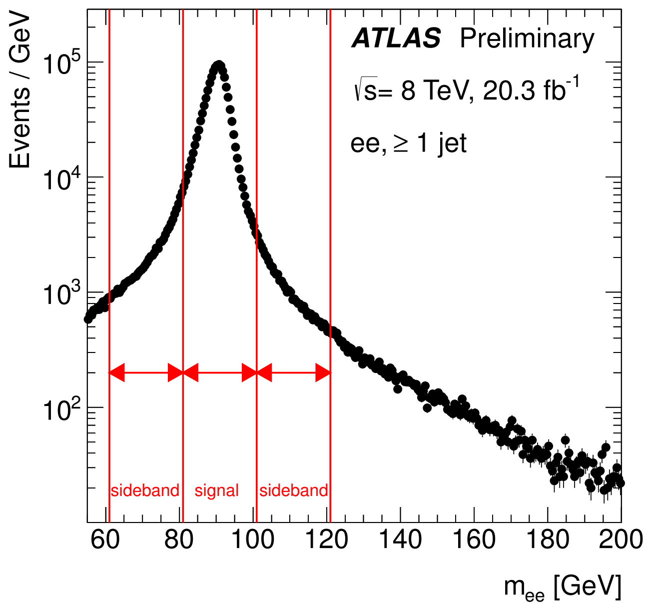
Basic form for lepton+jets (extension to 4x4 matrix in dilepton)

$$N^{loose} = N^{loose}_{real} + N^{loose}_{fake}$$
$$N^{tight} = \varepsilon_{real} \cdot N^{loose}_{real} + \varepsilon_{fake} \cdot N^{loose}_{fake}$$
$$\Rightarrow \quad N^{tight}_{fake} = \frac{\varepsilon_{fake}}{\varepsilon_{real} - \varepsilon_{fake}} \cdot \left(\varepsilon_{real} \cdot N^{loose} - N^{tight}\right)$$

- Efficiencies measured from data:

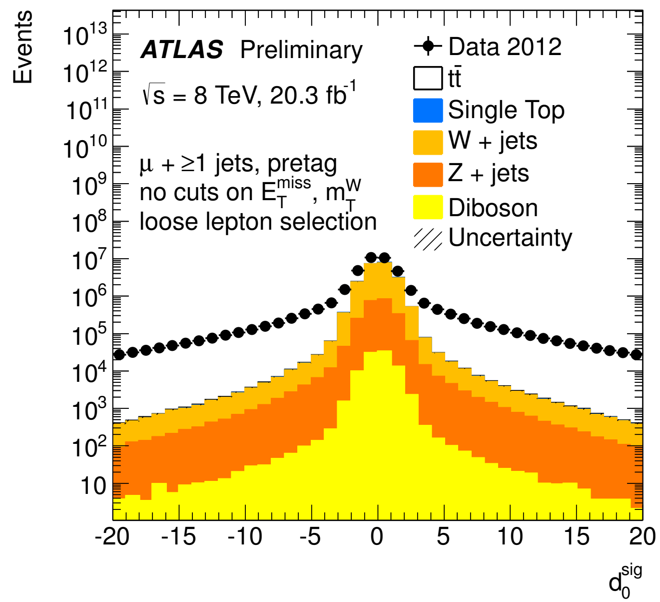
Real efficiency (ε_{real}):

- Tag & Probe using Z→ ll + top/Z MC corrections for electrons



Fake efficiency (ε_{fake}):

- From control regions dominated by fake leptons (low E_T^{miss}, low m_T^W, high d_0 significance)



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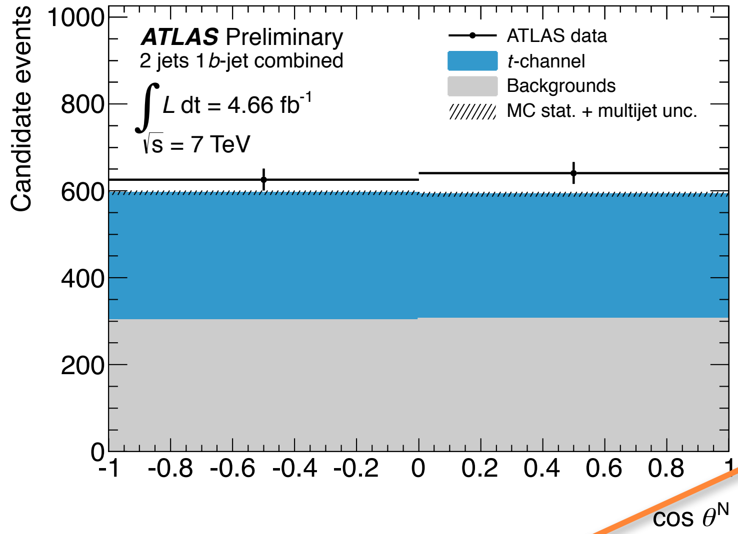
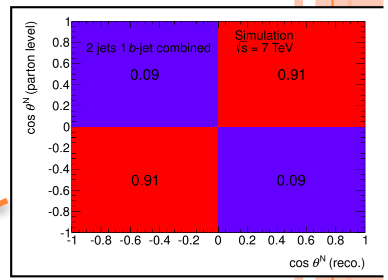
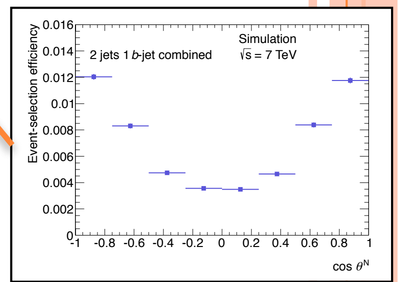




$$N_j^{unfold} = \frac{\sum_i M_{ij}^{-1} \cdot [N_i^{data} - N_i^{bkg}]}{\varepsilon_j}$$

$$A_{FB}^{N} = \frac{N_+^{unfold} - N_-^{unfold}}{N_+^{unfold} + N_-^{unfold}}$$



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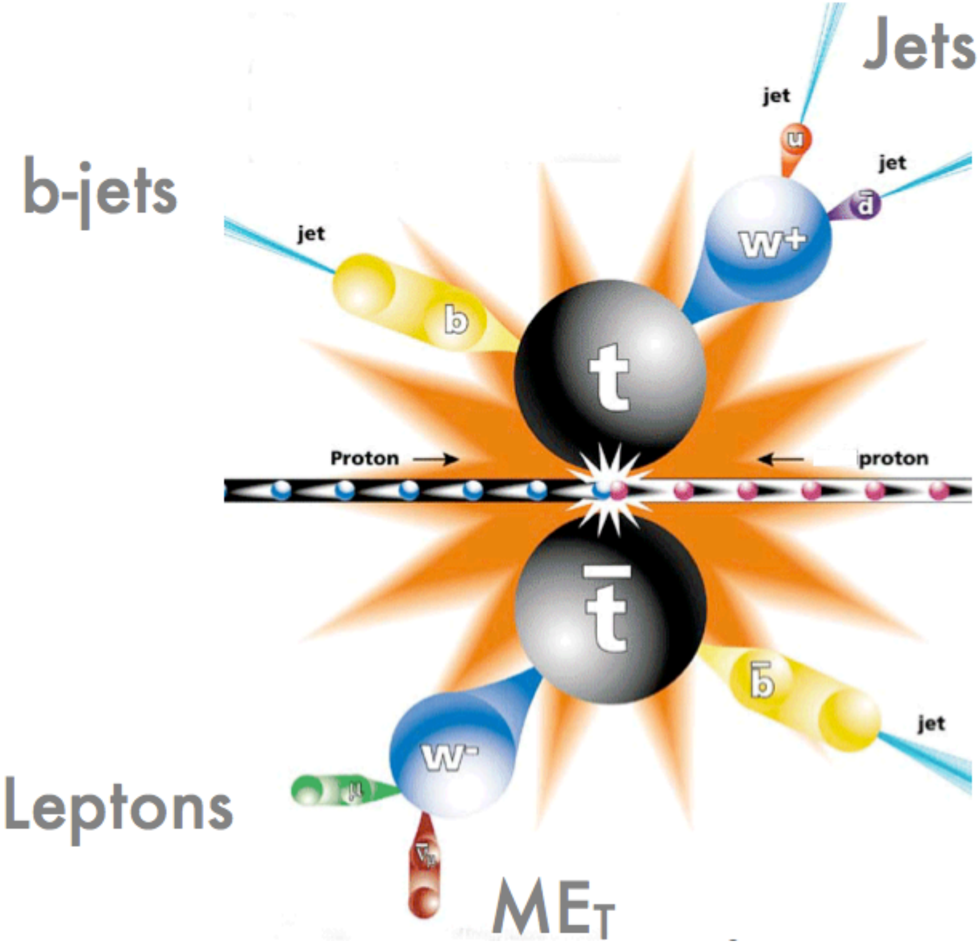
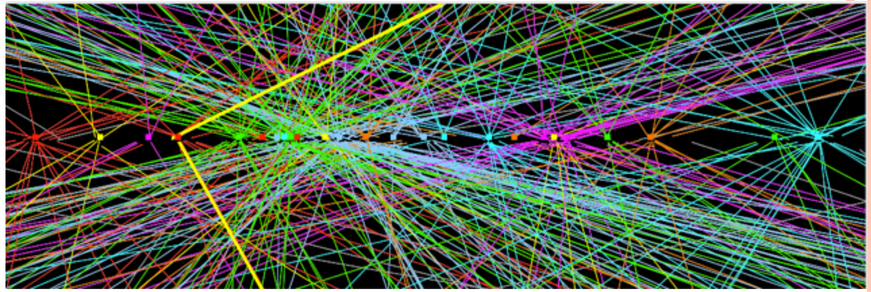
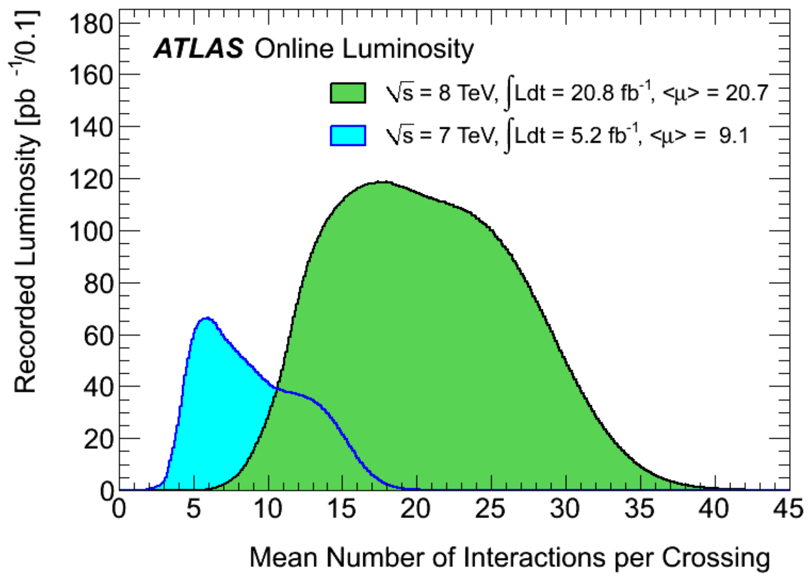
ANALYSIS CHALLENGES – EXPERIMENTAL UNCERTAINTIES



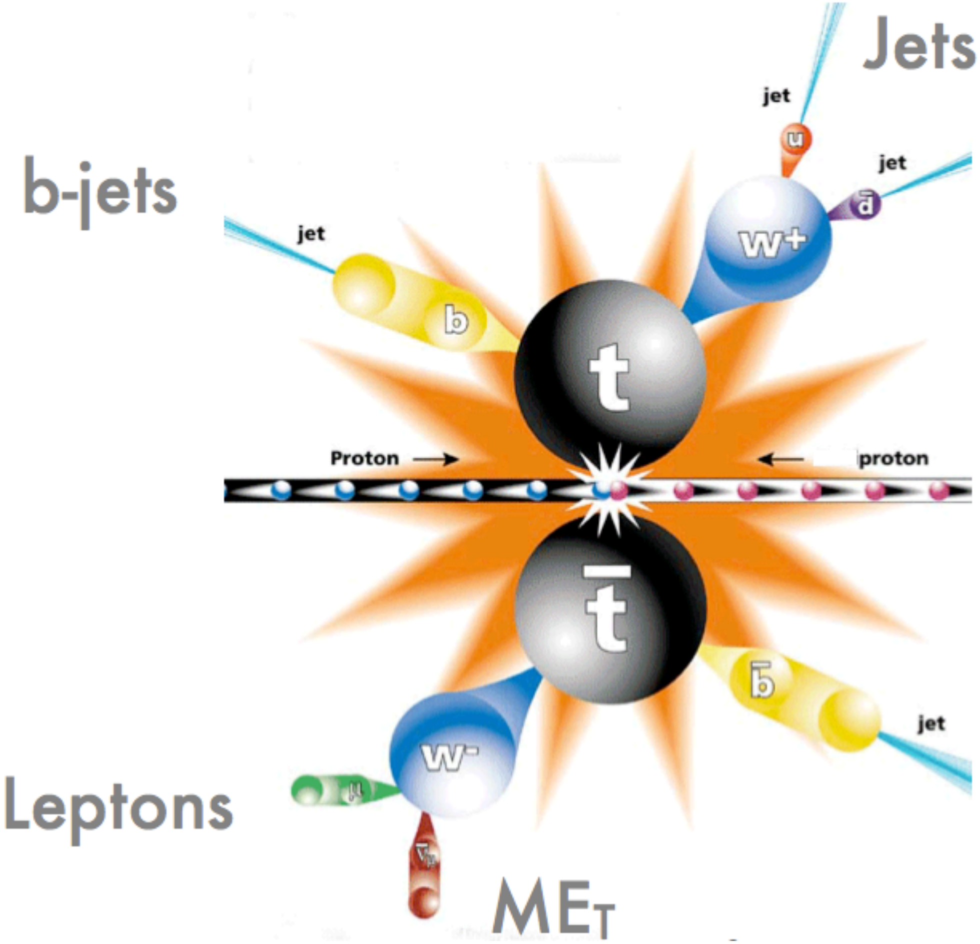




Top quark measurements will rely on a good performance of jets, b-tagging, leptons and Missing Transverse Energy.

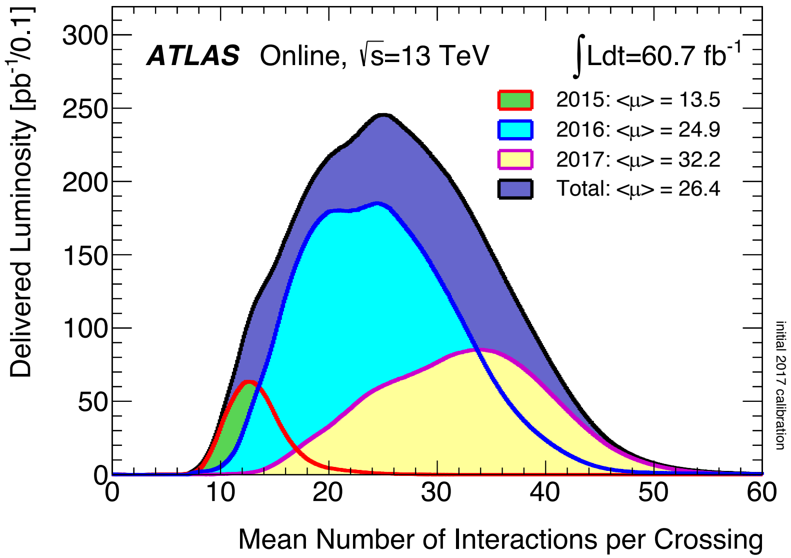
Main experimental uncertainties in most top quark analyses are coming from jets (Jet Energy Scale) and b-tagging uncertainties.

ANALYSIS CHALLENGES – EXPERIMENTAL UNCERTAINTIES



Run-2 conditions even more challenging!

- 2016: Record instantaneous luminosity $1.4 \cdot 10^{34}$ $cm^{-2}s^{-1}$, average (max) pile-up 25 (45-50) interactions/bunch crossing.
- 2017: Instantaneous luminosity already $1.7 \cdot 10^{34} cm^{-2}s^{-1}$.



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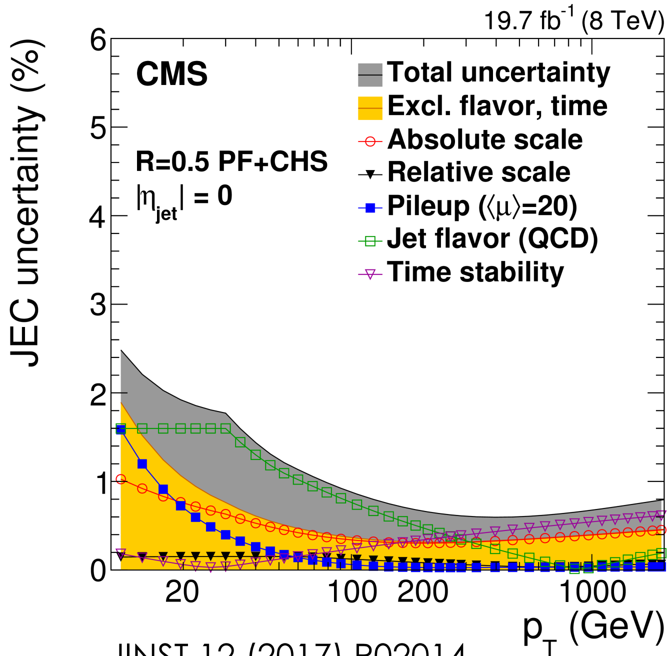
Main experimental uncertainties in most top quark analyses are coming from jets (Jet Energy Scale) and b-tagging uncertainties.

EXPERIMENTAL UNCERTAINTIES

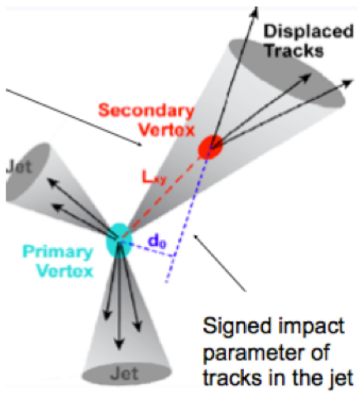
Jets

- The anti-k_t algorithm with R=0.4 (0.5 for Run-1) is used in ATLAS (CMS) (several other R also used).
- The jet calibration restores the jet energy scale to that of jets from stable particles.

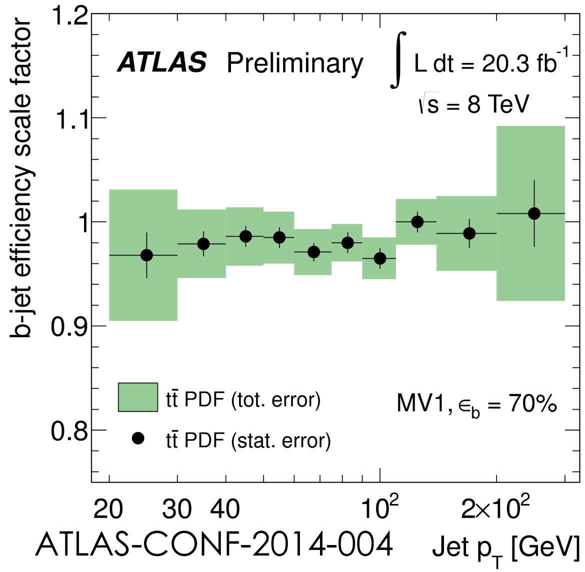


JINST 12 (2017) P02014

b-tagging



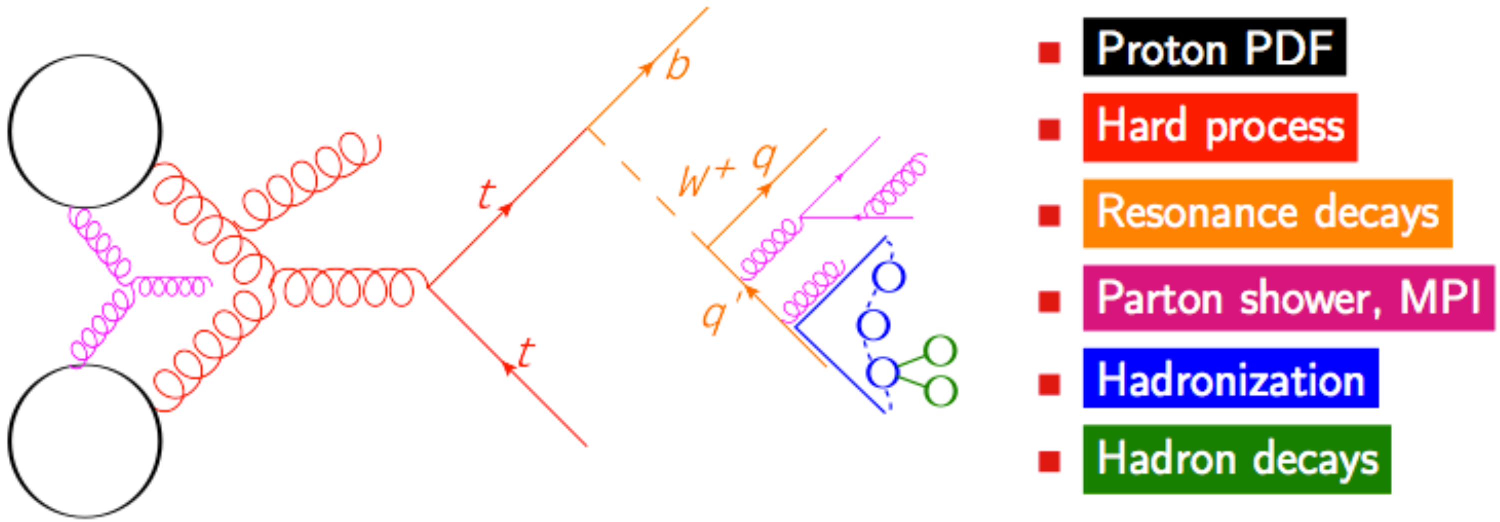
- b-jets are identified by exploiting the track impact parameters and secondary vertices information
- Top quark pair events can be used for calibration



ATLAS-CONF-2014-004

ANALYSIS CHALLENGES – PHYSICS MODELLING UNCERTAINTIES

- The Monte Carlo generators used at LHC include multi-leg or NLO predictions for signal and main background processes.
- Signal modelling uncertainties are typically important/dominant (e.g. radiation, parton shower & hadronisation models, PDF, CR)

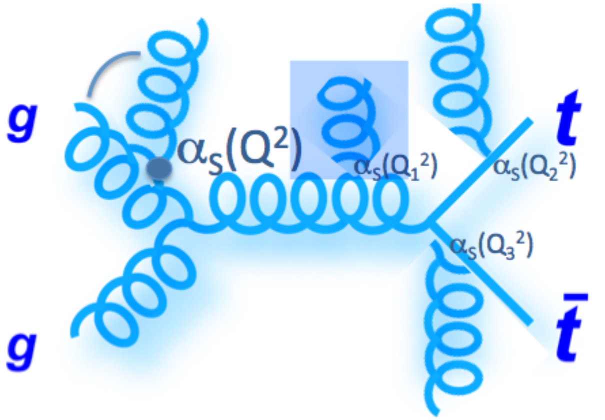


Two important strategies:

- Perform measurements in top events that allow constraining these modelling uncertainties from data.
- Reduce generator dependency on measurements by providing results at particle level in a fiducial region experimentally accessible.

PHYSICS MODELLING

Measurements sensitive to QCD radiation in top pair production



Measurements $|\eta|<2.5$, $p_t>20$ GeV

Single jet based observables

N_{jet}, jet p_t, η, jet shapes

Integrated observables

jet veto, H_T, S_T

Indirect observables (recoil)

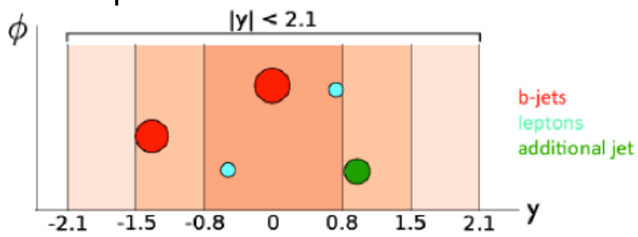
Lepton p_t, E_{tmiss}, p_t^W

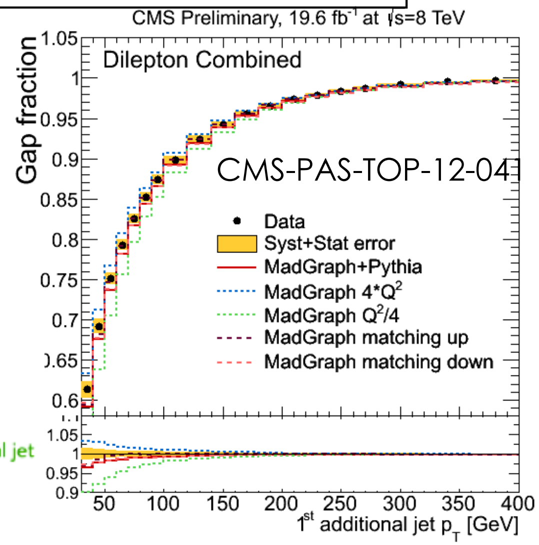
Derived quantities

top p_t, ttbar p_t

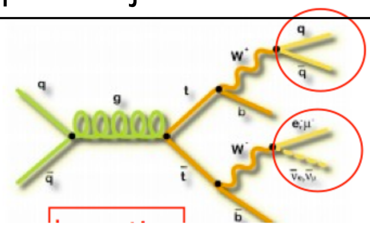
Ex: Gap fraction analysis (dilepton channel)

Study the fraction of top pair events that do not contain an additional jet using dilepton events.

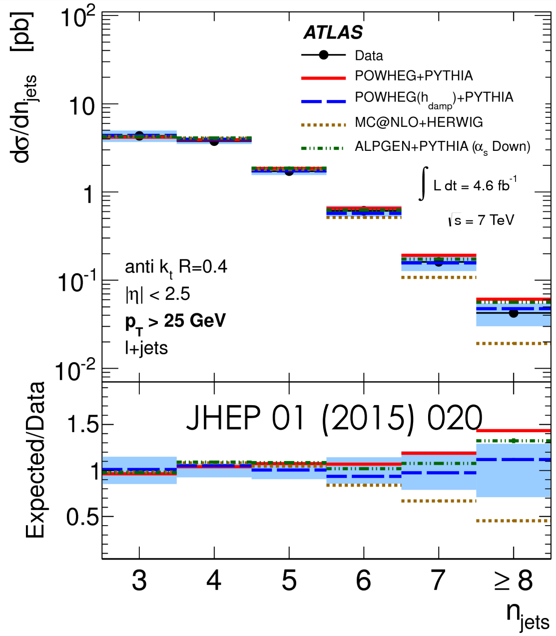




Ex: Jet multiplicity (lepton+jets channel)

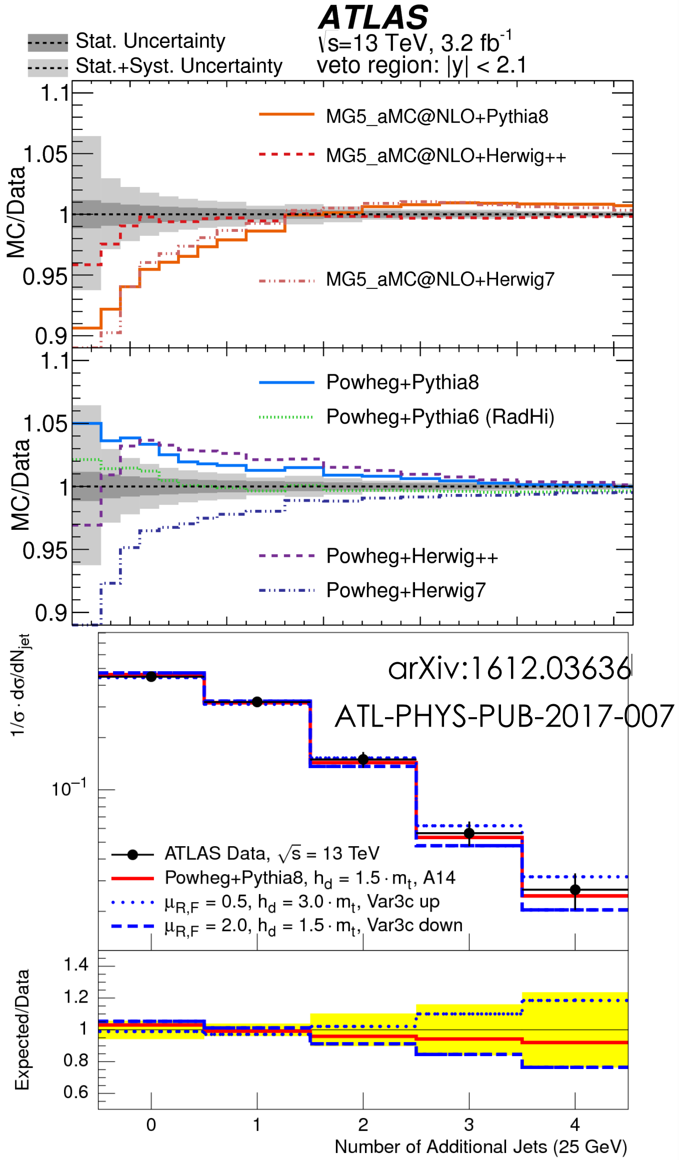


4 jets "belong" to the top pair process, the 5th leading p_T jet corresponds to the first additional emission.



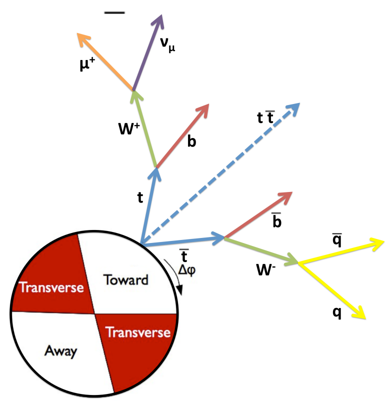
PHYSICS MODELLING

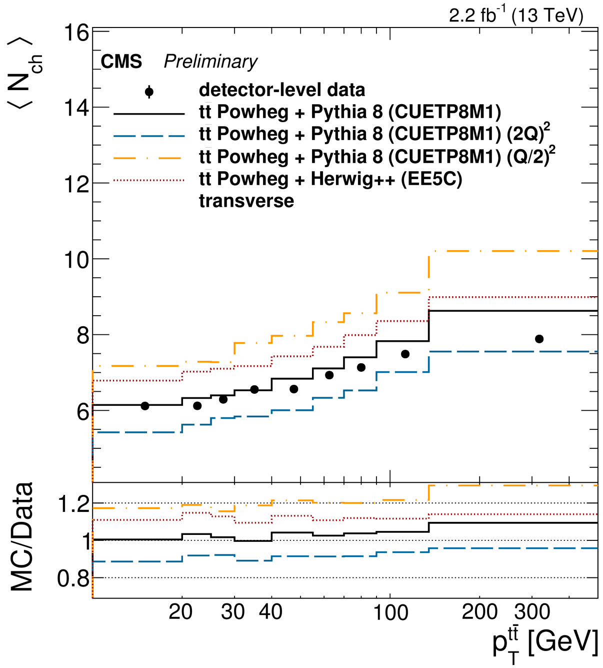
ATLAS: Ex: Measurement of jet activity produced in top-quark events with an electron, a muon and two b-tagged jets



- We learnt from Run-I that it was important to make such measurements as soon as possible
- Many of those already available with first Run-II data to define default MC setups and systematic variations.

CMS: Ex: Measurement of the Underlying Event in top quark pair events

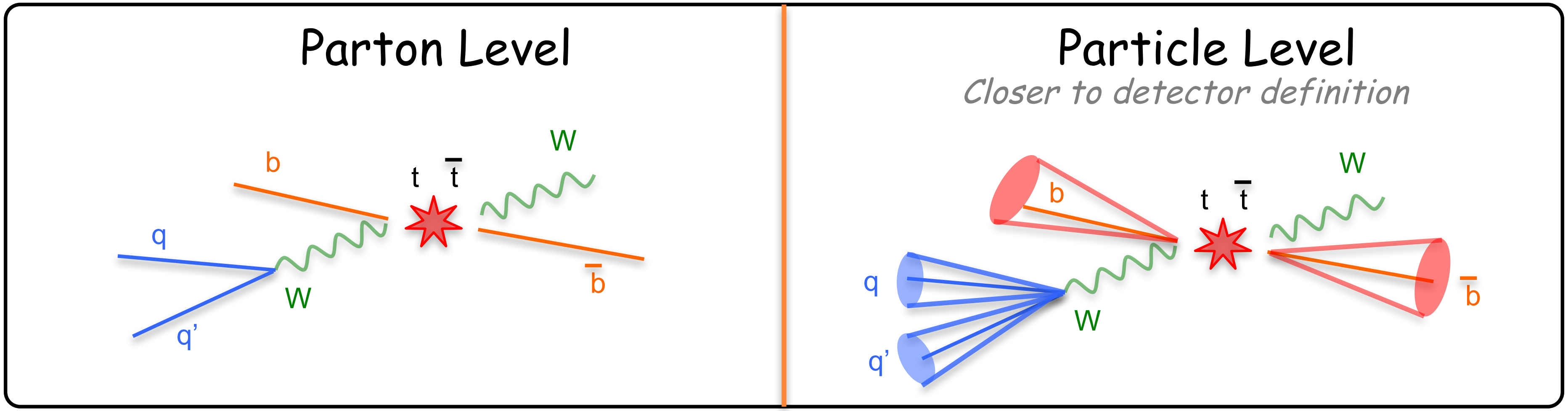




These measurements are crucial to achieve the required precision in the most interesting measurements!

PARTICLE LEVEL DEFINITIONS

- Parton level (full phase space):
  - Top defined after QCD radiation and before it decays.
  - Mimics definitions of bare quark widely used in fixed order theory calculations.
- Particle level (fiducial phase space):
  - Based on stable particles after hadronisation (see exact definition used https://twiki.cern.ch/twiki/bin/view/LHCPhysics/ParticleLevelTopDefinitions).
  - Fiducial phase space defined according to detector level cuts.
  - Reduced effect from extrapolation.



Both measurements are important to provide, but particle level measurements are less model dependent and therefore more precise.

A DATA ANALYSIS EXAMPLE

Typical steps:

- (1) Event selection to enhance signal
- (2) Background estimation (MC or data driven)
- (3) Fit/correct data using MC simulation to account for acceptance, detector and resolution effects.
- (4) Estimate statistical and systematic uncertainties (due to physics modelling and experimental sources)

Example: Top quark mass combination

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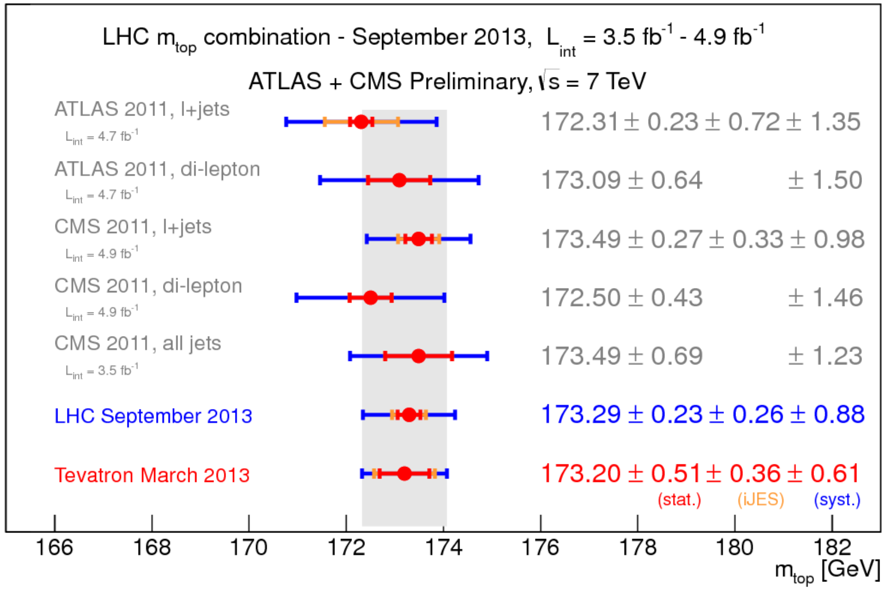

The measurements provided at ATLAS and CMS can then be combined

- This is done within the LHC TOPWG

ATLAS/CMS COMBINATIONS

- Assumptions:
  - Individual measurements are unbiased (checked in each experiment)
  - Uncertainties are gaussian distributed
  - All sources of uncertainties are independent.
- Tools: Best Linear Unbiased Estimate (BLUE)
  - Results obtained from a linear weighted sum of the input measurements
  - Weights are determined to minimise the total uncertainty
- Inputs:
  - Results of each experiment with a detailed breakdown of uncertainties

Main combination challenges:

- Find the proper mapping between the corresponding systematics in different experiments.
- Understanding the correlations in each category.

ATLAS/CMS COMBINATIONS

Example: Jet Energy Scale uncertainty categorisation and correlations

Example: Top quark mass combination stability checks

Table 4: Range of correlation coefficients to be used when combining measurements between the ATLAS and CMS experiment, for each of the uncertainty categories and respective components.

Description	Component names, CMS	Component name, ATLAS	Correlation range
1a. Statistical	RelativeStatEC2; RelativeStatHF; AbsoluteStat	Statistical components for *in situ* calibration, Z-jet width	Uncorrelated
1b. Detector	AbsoluteScale; RelativeJEREC1; RelativeJEREC2; RelativeJERHF	Electron/photon energy scale, γ-jet jet energy resolution	Uncorrelated
2. Modeling uncertainties for γ-jet and Z-jet	AbsoluteMPFBias	γ-jet and Z-jet: radiation suppression, out-of-cone and MC generator difference; γ-jet photon purity; Z-jet extrapolation;	0-50%
3. Modeling uncertainties for relative correction	RelativeFSR	η–intercalibration modeling	50-100%
4. Uncertainties related to jet partonic flavor	Flavor; AbsoluteFlavorMapping	Flavor composition and response	0-100%
5. b–jet uncertainties	Flavor	b–jet response	50-100%
6. Pileup correction	PileUpDataMC; PileUpPtBB; PileUpBias; PileUpOOT; PileUpJetRate; PileUpPtEC; PileUpPtHF	Pileup calibration; effects of pileup on *in situ* methods	Uncorrelated
7. High-p_T uncertainties	HighPtExtra; SinglePion	High-p_T	Uncorrelated
8. Close-by jet uncertainties		Close-by	Uncorrelated
9. Other uncertainties not matching between the two experiments	Time	Multijet balance components, Closure of the calibration	Uncorrelated

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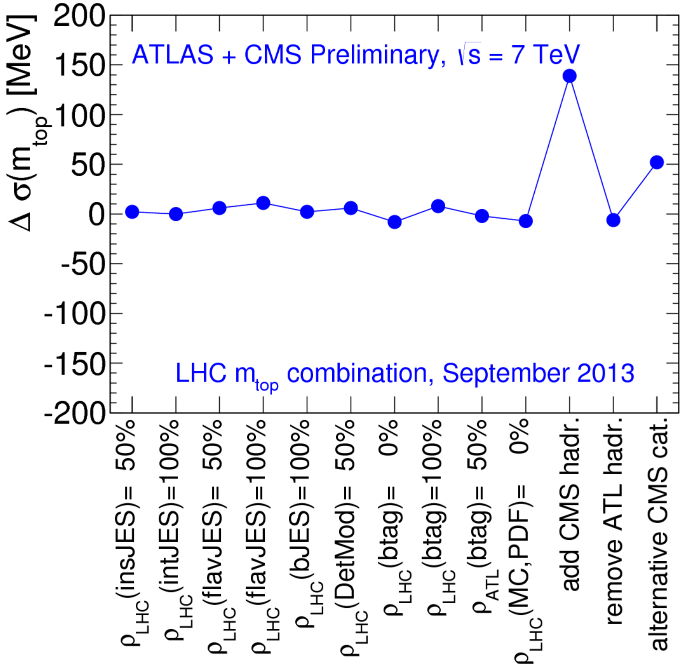

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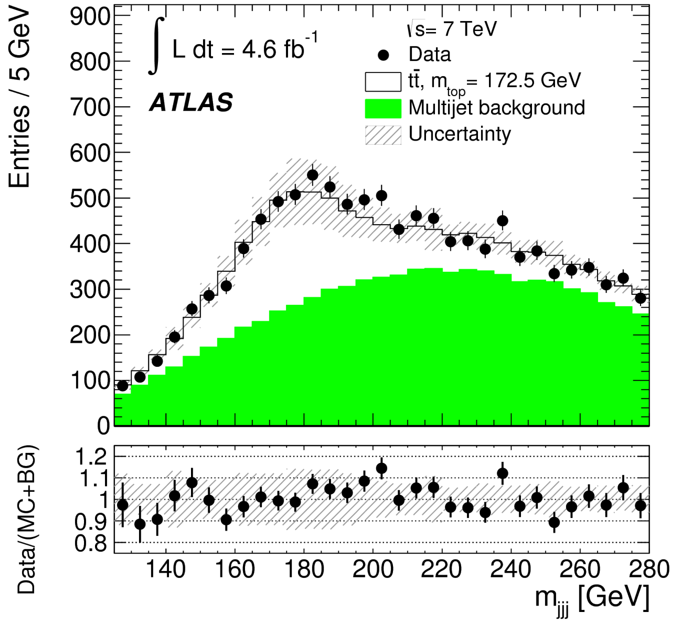
- A lot of progress made in understanding the treatment of the main experimental systematic uncertainties (jet energy scale and b-tagging efficiency) and towards a harmonisation of the main modelling uncertainties (top quark pair and single top) with input from theorists and data.
- Important to perform stability checks (e.g. changing correlation assumptions or different treatment of modelling uncertainties).

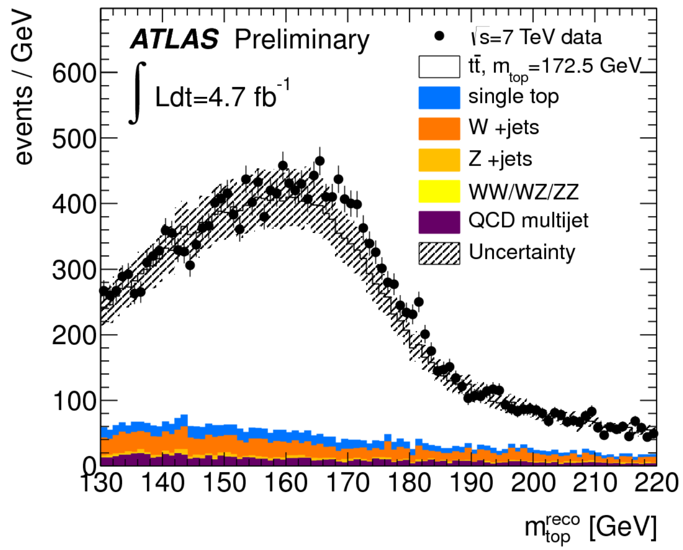
CONCLUSIONS

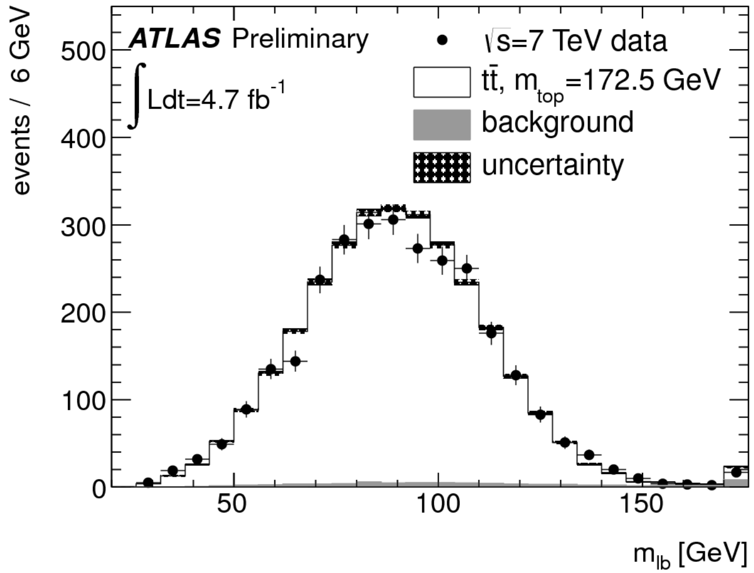
- Studying the top quark at the LHC is extremely interesting!
  - Perhaps a window for new phenomena.
- The LHC is a top factory → a new era for top physics after the Tevatron.
  - Top quarks are mainly produced in pairs via the strong interaction (gg fusion dominant).
  - Singly via the EW interaction (Wtb vertex).
  - t→ Wb (almost exclusively).
- We've learned the main steps and challenges typically phased when doing a top measurement at the LHC:
  - Important to control the dominant experimental (usually JES, b-tagging) and modelling uncertainties (signal related).
- To get the ultimate precision is a challenge for both experimental and theoretical communities.

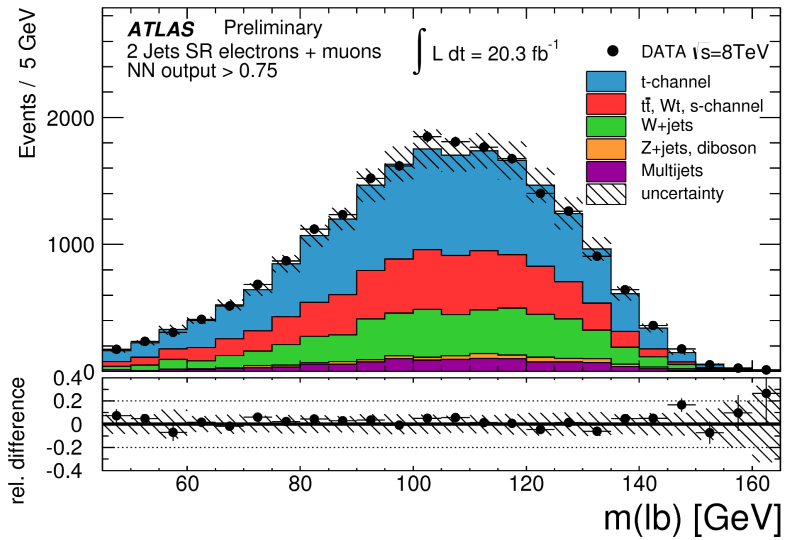
Backup

A DATA ANALYSIS EXAMPLE







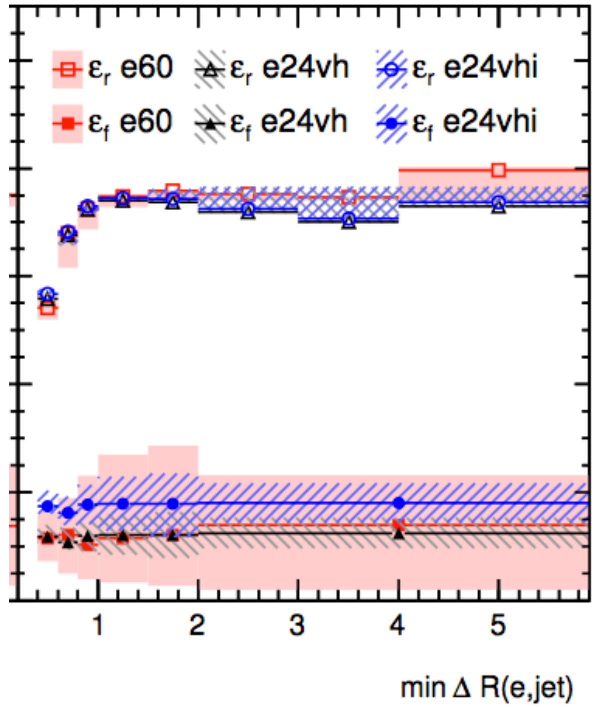


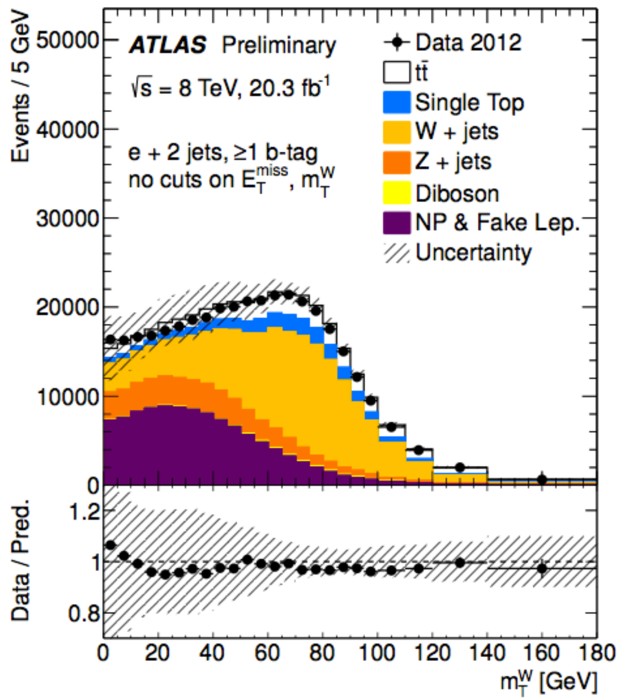
FAKE BACKGROUND

- Efficiencies are parametrised considering the observed dependencies, small correlations and agreement in CRs

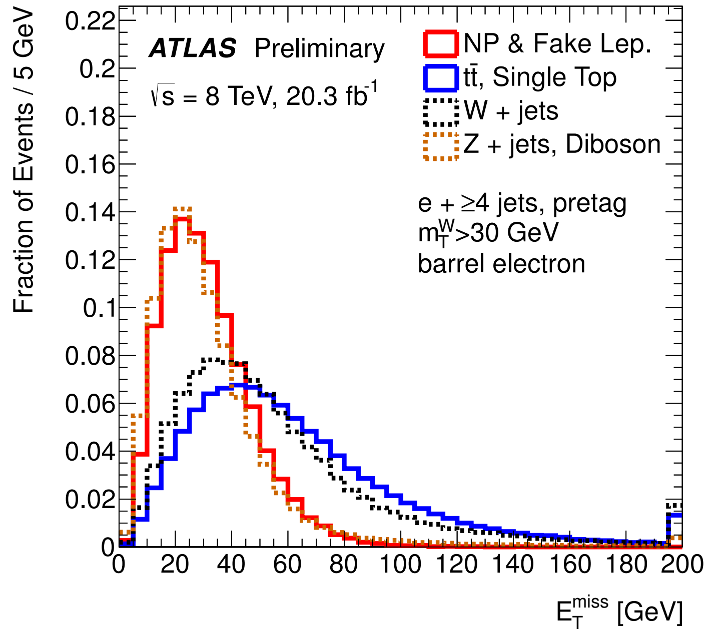
	$\lvert\eta^{\ell}\rvert$	p_T^{ℓ}	$p_T^{\text{lead.jet}}$	$\Delta R(\ell,\text{jet})$	$\Delta\phi(\ell,E_T^{\text{miss}})$	n_{jet}	$n_{b-\text{jet}}$
$\varepsilon_r(e)$	✓	✓		✓		✓	
$\varepsilon_r(\mu)$	✓	✓		✓		✓	
$\varepsilon_f(e)$	✓		✓		✓		✓
$\varepsilon_f(\mu)$	✓	✓		✓			✓

- Systematic uncertainties (obtained from different CRs and parameterisations, varying amount of real leptons to subtract from the fake CR) are typically:
  - lepton+jets: 10-50% (depending on jet and tag multiplicity, larger for electrons, smaller for muons)
  - dileption eμ: 70-100% in signal region, 30-50% in the validation regions



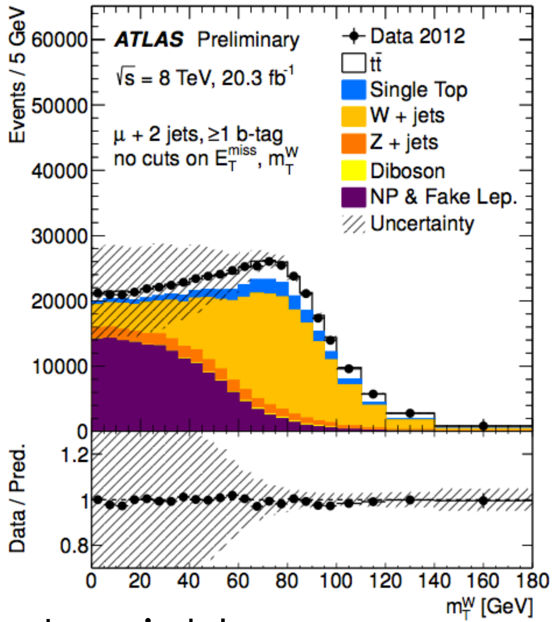


FAKE BACKGROUND



Fit method

- Define a fit model to predict the fake leptons background shape
  - Jet-electron: from a multijet MC sample asking one jet to be electron-like
  - Anti-muon: from data, selecting a sample enriched in non-prompt muons by inverting some of the muon identification cuts
- Choose a discriminating variable (E_T^{miss} for e+jets, m_T^W for μ+jets)
- Loosen/remove cuts on E_T^{miss} , m_T^W
- Perform maximum likelihood fit to predict its normalisation



- Systematic uncertainties (obtained from fitting different variables, variations on the fit constraints, W+jets and Z+jets modelling) lead to 50% uncertainty