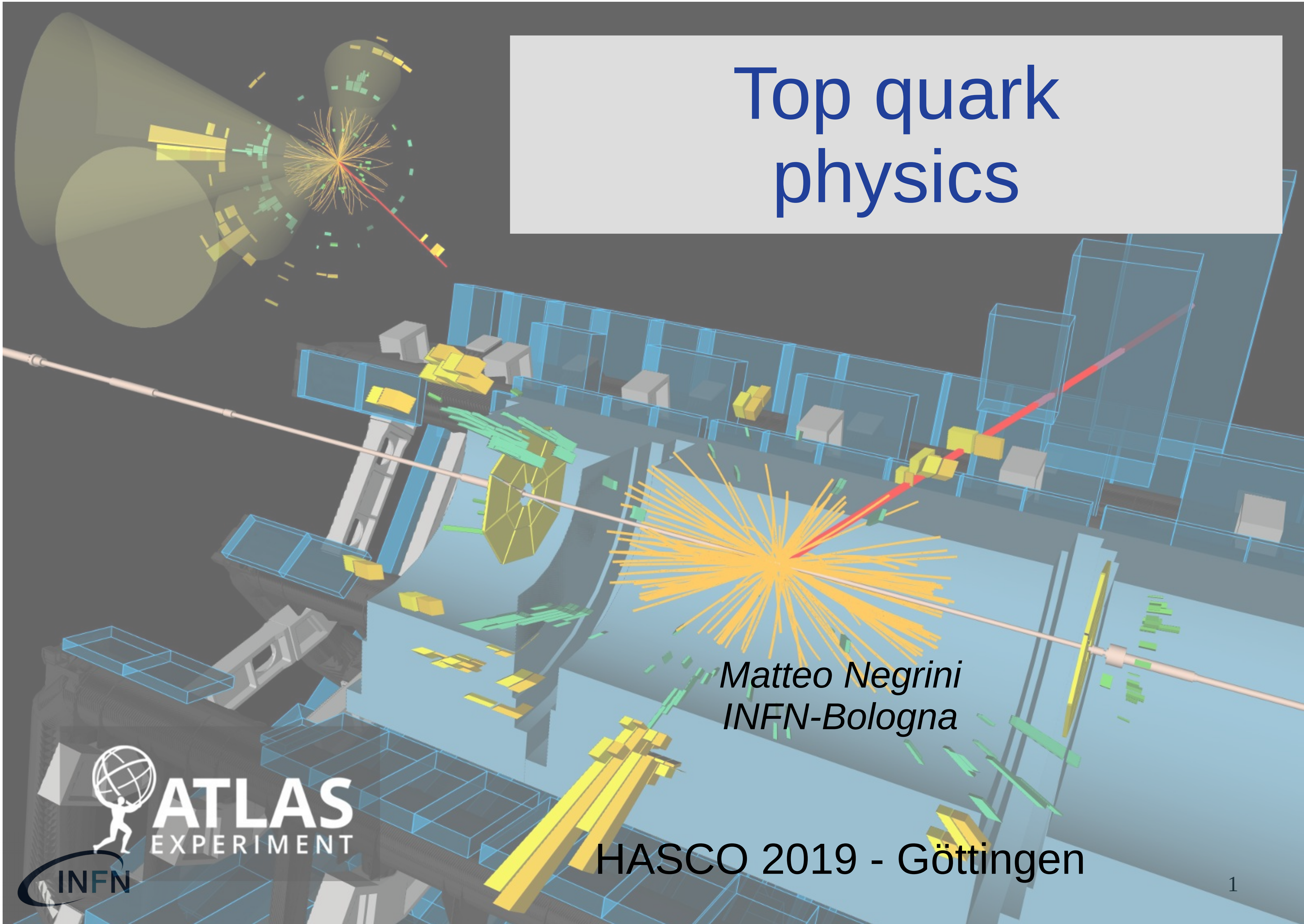
Top quark physics



Matteo Negrini
INFN-Bologna

HASCO 2019 - Göttingen

Before the top

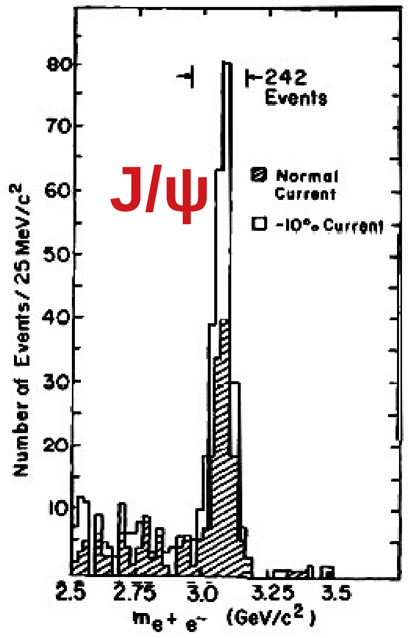
Kobayashi and Maskawa in 1973 (Nobel 2008) pointed out that CP violation can not occur if the flavor-changing weak interaction occurs between 2 quark generations but is possible with 3 generations (extension of Cabibbo theory)

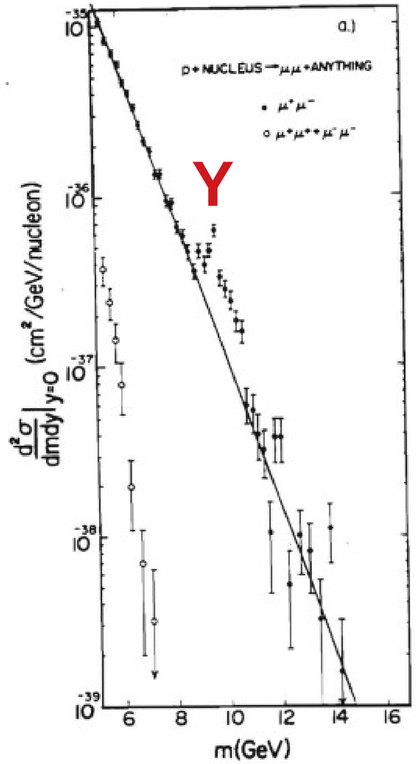
$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

Complete 3rd quark generation also needed for cancellation of triangular anomalies (divergences)

- The discovery of the charm quark in 1974 closed the 2nd quark generation → m_c~1.5 GeV
- The discovery of the bottom quark in 1977 proved that 2 generations are not enough → m_b~5.0 GeV

Everybody convinced that a positively charged of the bottom quark should exist!





Time machine! Back to the 80's

Make your bet!
What is the right m_{top} range?

☐	☐	☐	☐
< 5 GeV	5 - 50 GeV	50 - 100 GeV	> 100 GeV

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Time to wake up!

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Time to wake up!	Fair bet. Turn on your e^+e^- collider to get the prize...		

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Time machine! Back to the 80's

Make your bet!

What is the right m_{top} range?

☐	☐	☐	☒
< 5 GeV	5 - 50 GeV	50 - 100 GeV	> 100 GeV
Time to wake up!	Fair bet. Turn on your e^+e^- collider to get the prize...	Let's risk more and build a hadron collider!	**INSIDER TRADING!** (or "informed guess")

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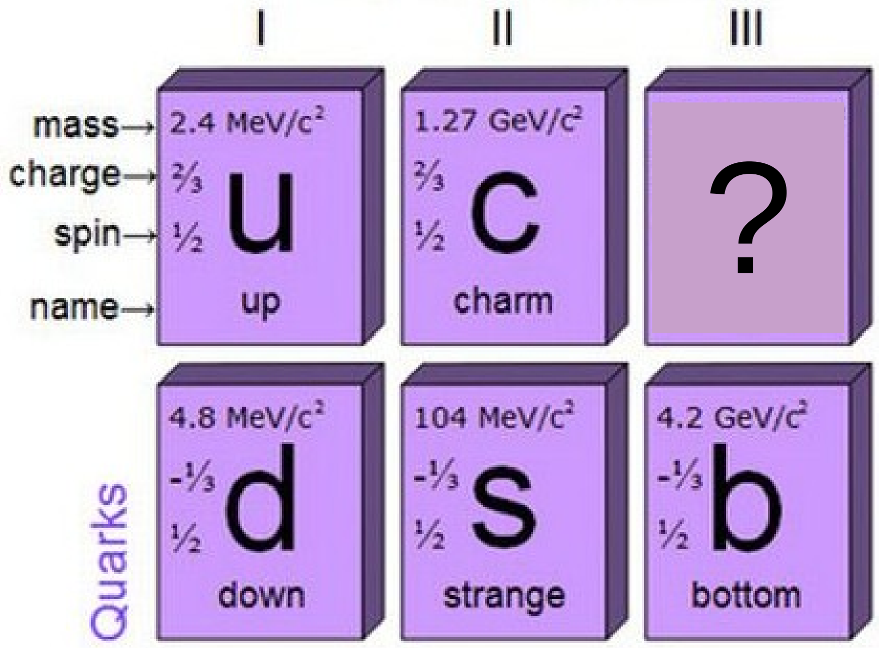
Chasing for a top quark

What to look for:

- $t\bar{t}$ resonances
- the decay: $W^+ \to t\,\bar{b}$ (+ charge conj.) possible if $m_t+m_b<m_W$
- the decay: $t \to W^+ b$ (+ c.c.) if $m_W+m_b<m_t$



Increasing limits at e^+e^- colliders:

- PETRA (DESY): $m_t>23$ GeV (1984)
- TRISTAN (KEK): $m_t>30$ GeV (late 80's)

Searches pass to hadron colliders.

- SppS (CERN): $m_t>70$ GeV (1989)
- Tevatron (FNAL): $m_t>130$ GeV (1993)

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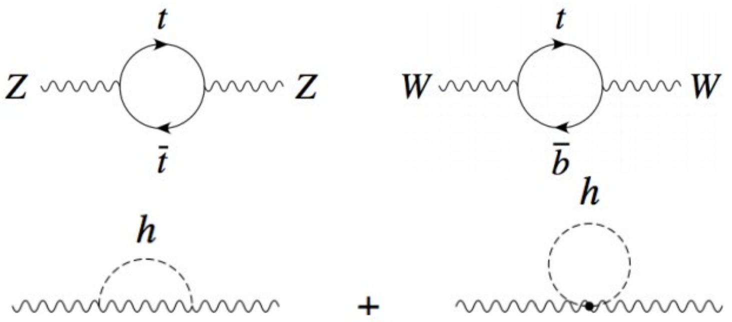
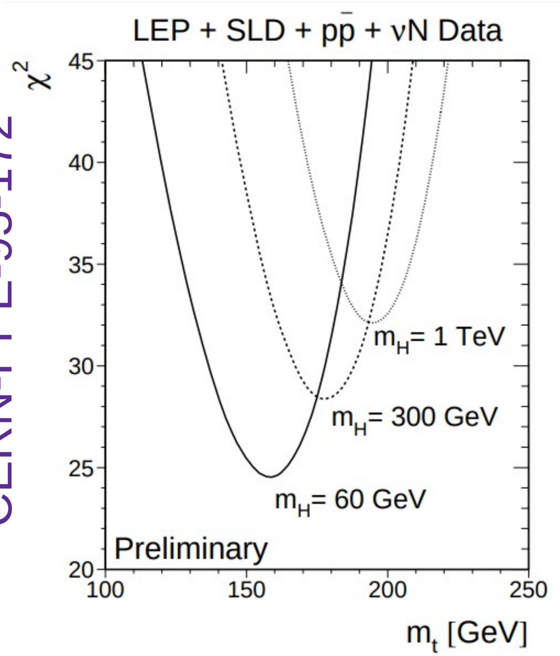
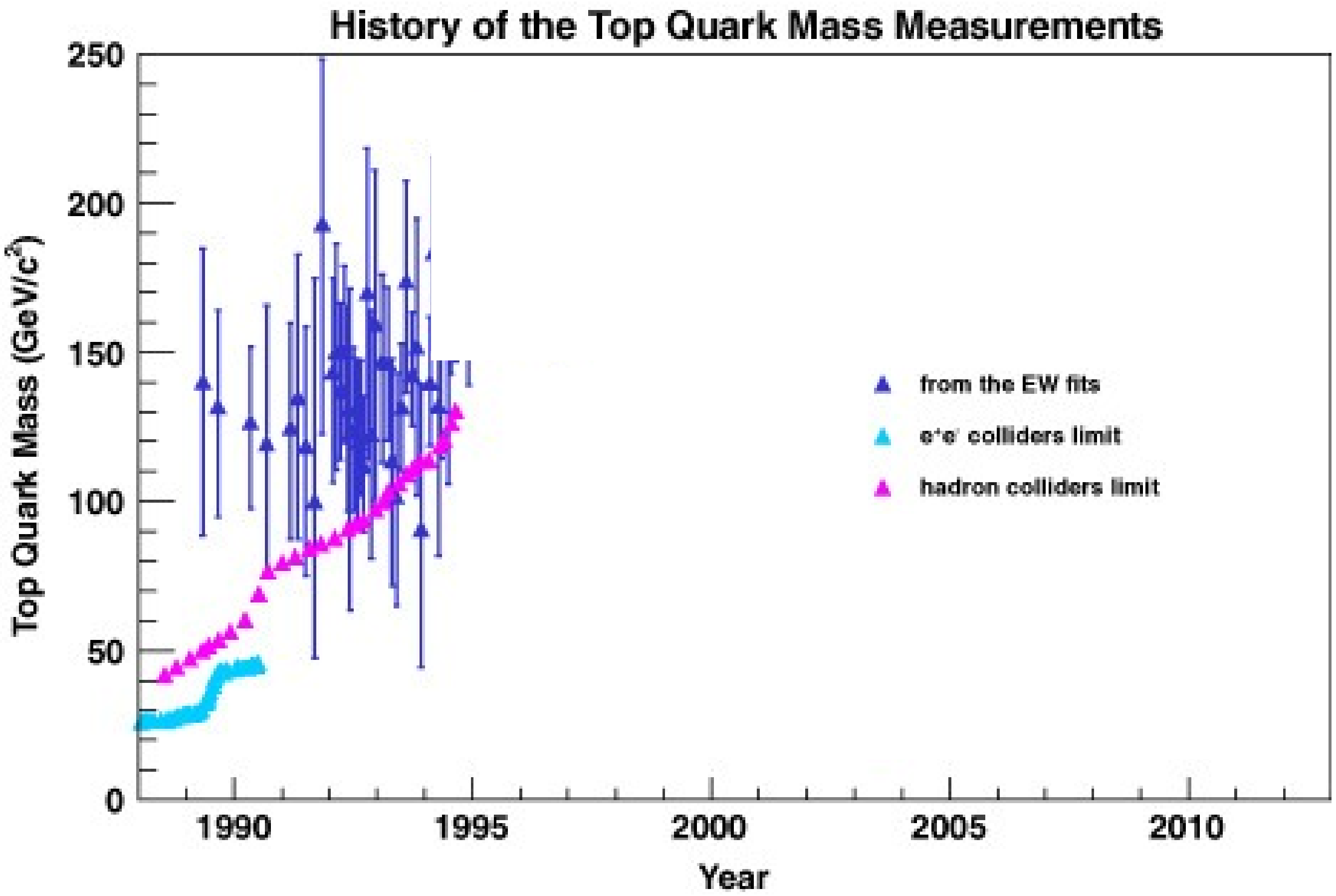
Indirect estimates of m_{top}

The collider energy may not be sufficient to produce the top quark if its mass is too large
However the top quark (and the Higgs boson) will play a role in SM observables entering in loop diagrams



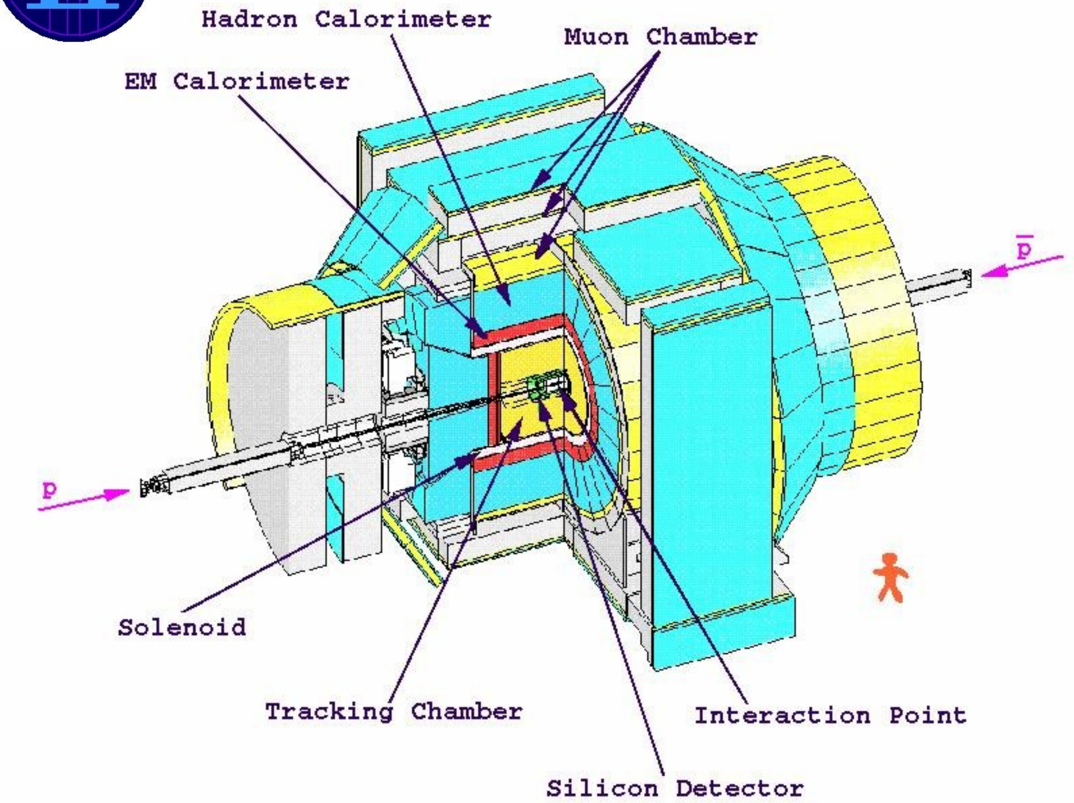
CERN-PPE-95-172



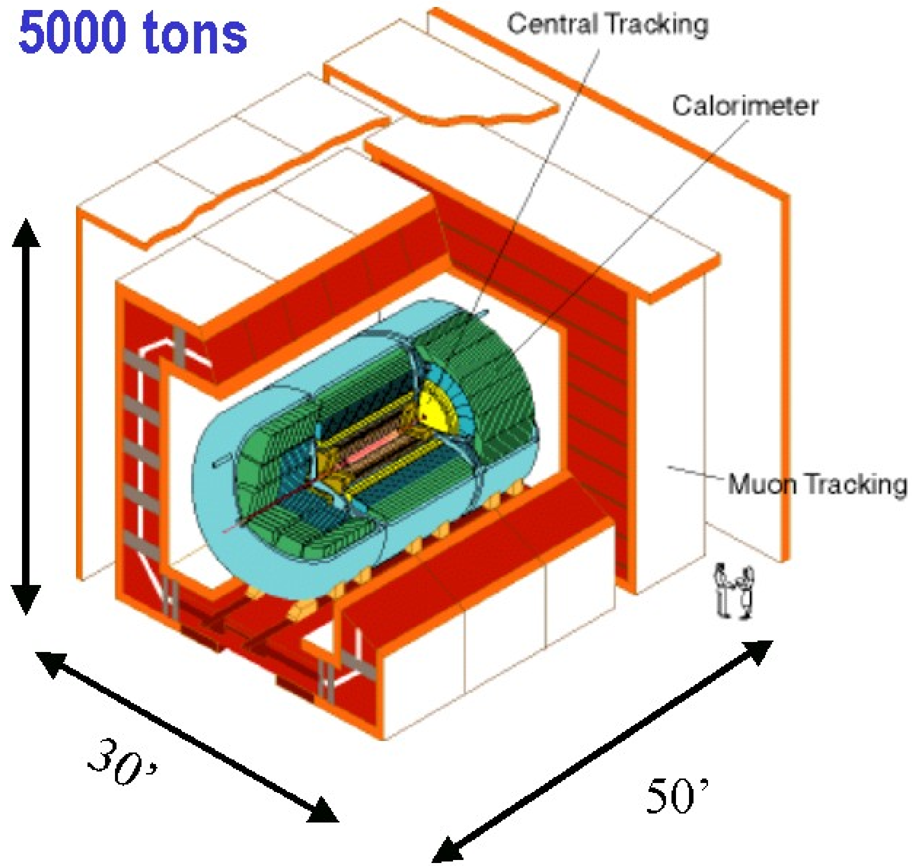


CDF and D0 experiments at the Tevatron

CDF and D0 experiments at the Tevatron



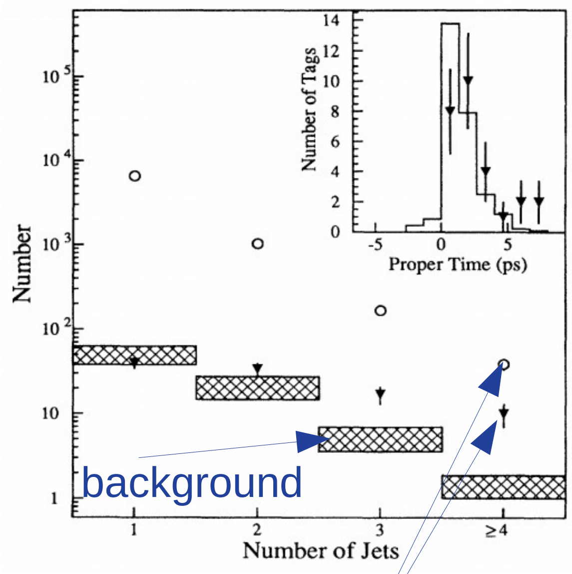
5000 tons

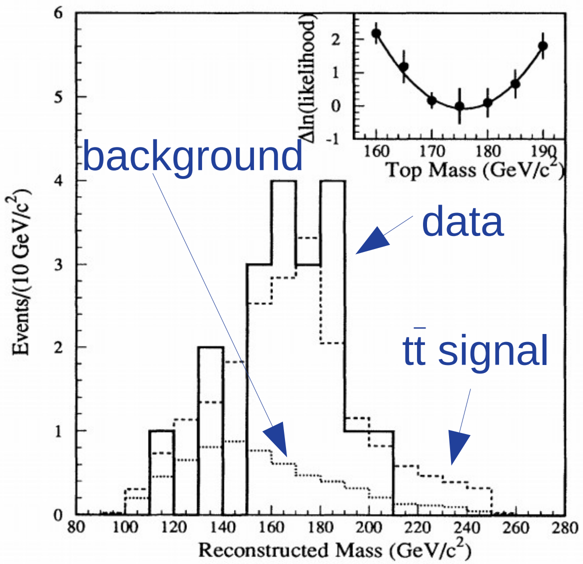


$m_t > m_W + m_b$ → $t\bar{t}$ events contain 2 b-jets and may have large jet multiplicity (depending on the decay channel)

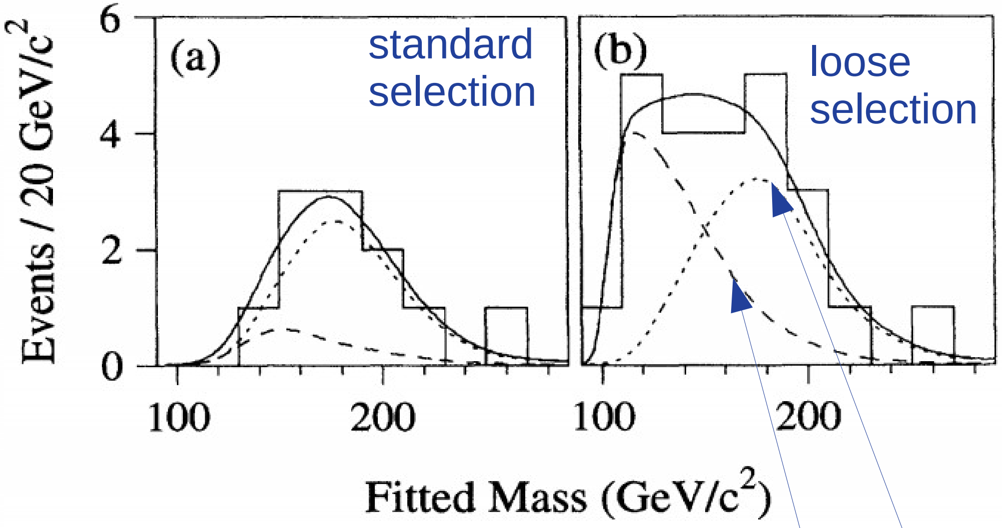
Discovery of the top quark - 1995

Evidence of top quark by CDF and D0 with ~70 pb^{-1} of Run1 data





Number of events before and after secondary vertex tagging
Excess for N_{jets}>2



background
tt̄ signal

m_{top} = 176 ± 8 ± 10 GeV

It's heavy!

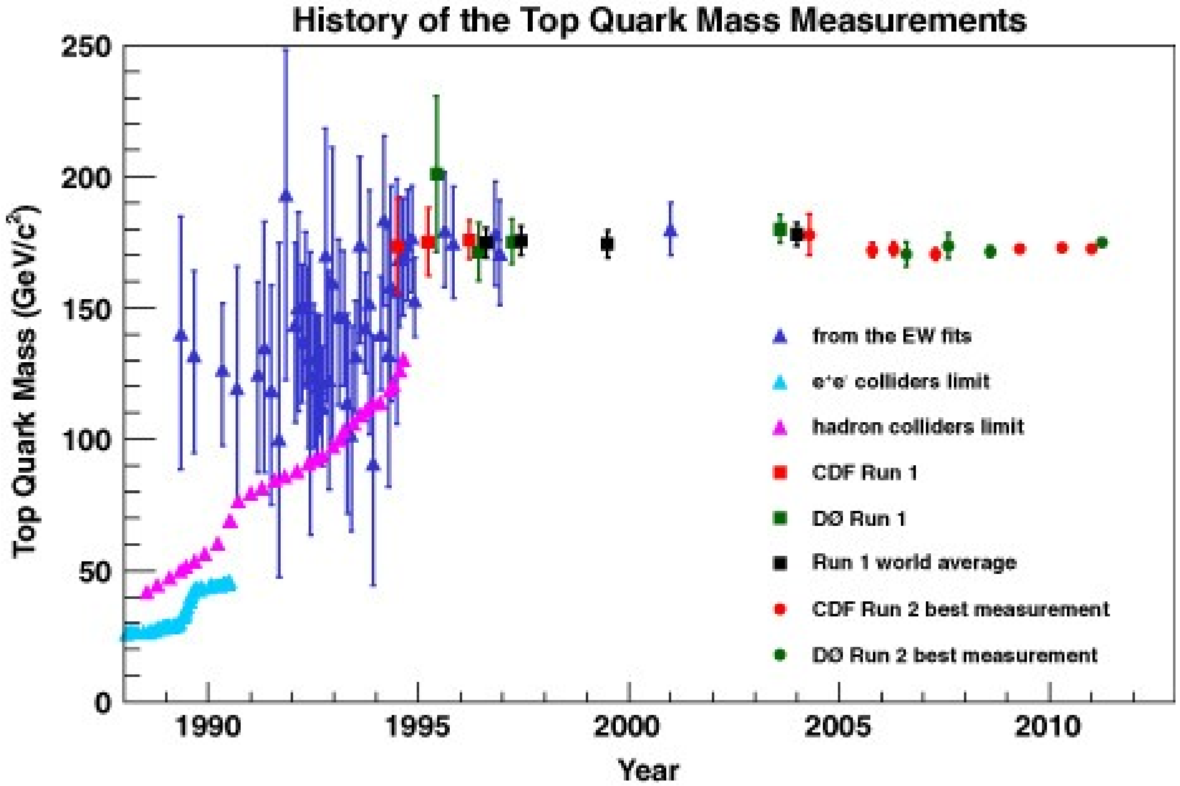
This implies that it decays very quickly to Wb!

LO calculation in the SM:

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

this means $\tau_{top} \sim 5 \cdot 10^{-25}$ s

Hadronization takes place on the timescale $\sim 1/\Lambda_{QCD}$ → $\tau_{had} \sim 10^{-23}$ s



The top quark decays before to hadronize
(no "toponium", no top hadrons)

It gives the unique opportunity to study a "bare" quark!

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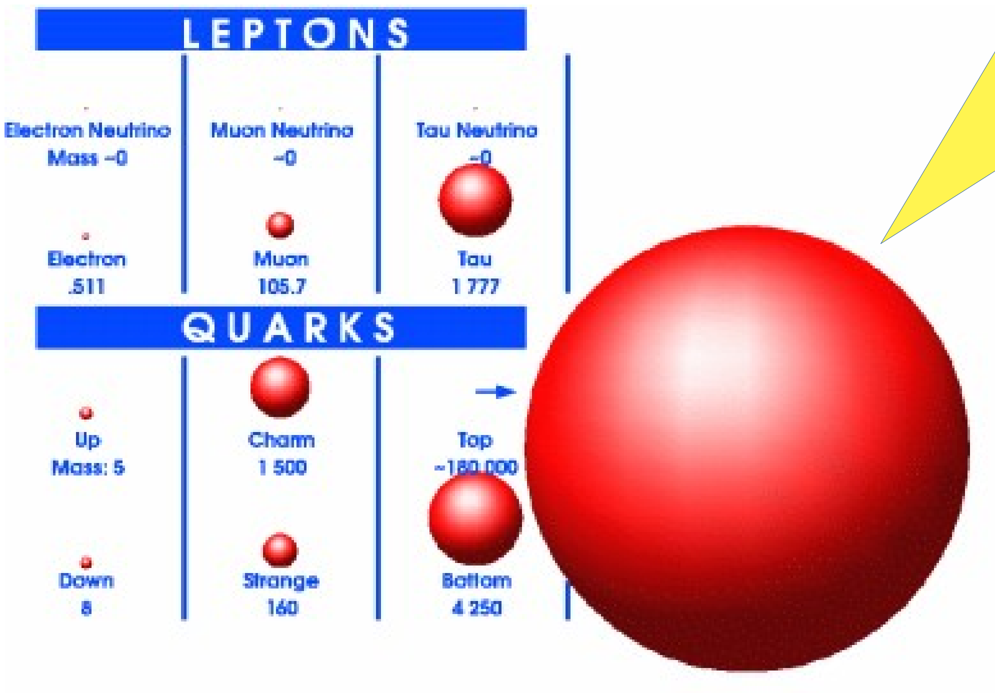
The top quark: ID card

Birth: 1995, Fermilab
Mass: 172.5 GeV
Charge: +2/3 |e|
Spin: 1/2
Witdh: 1.3 GeV



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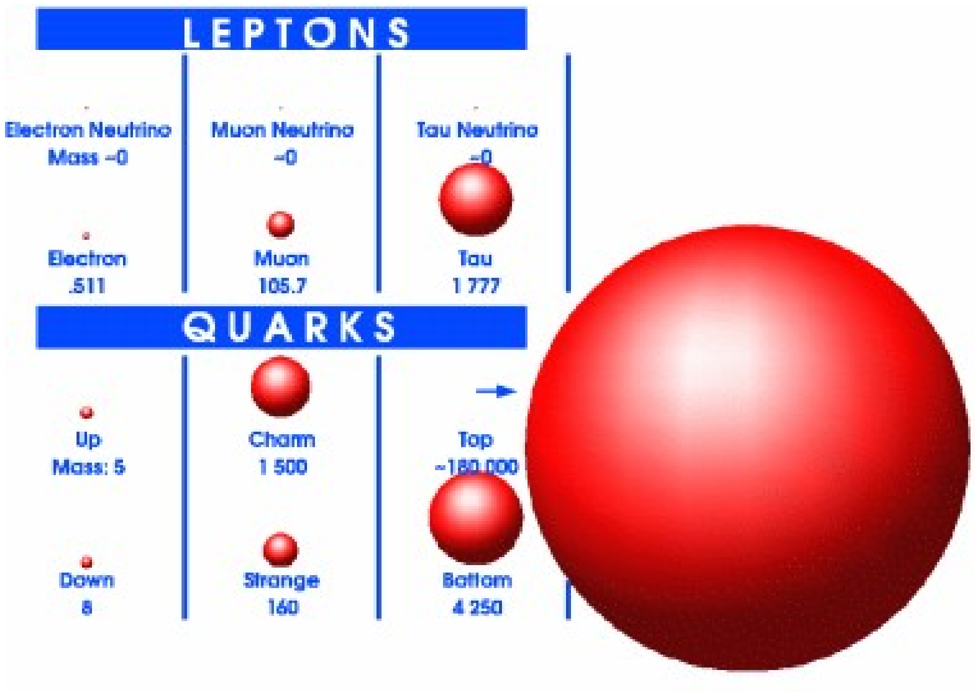
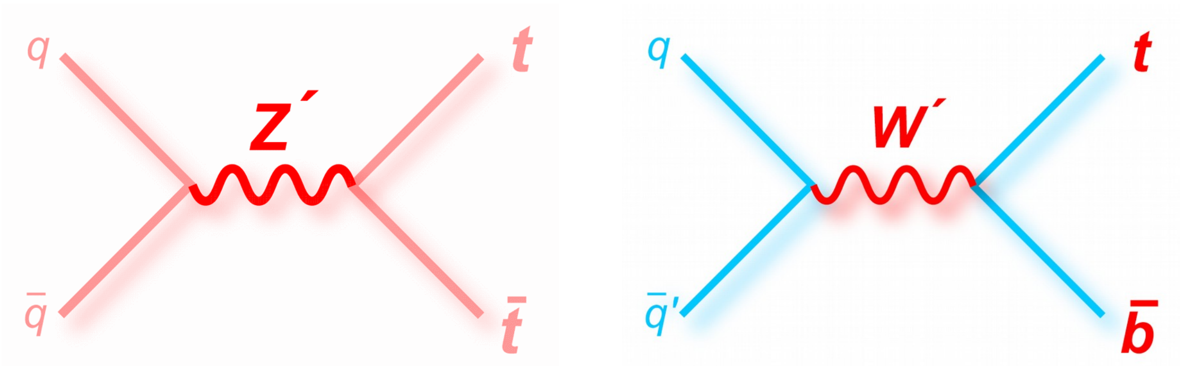
Why to study the top quark?

- The most massive quark (as heavy as tungsten nucleus)
- Strongly coupled to the higgs boson (special role in EW symmetry breaking?)
- It decays before to hadronize: only possibility to study a bare quark
- Some new physics scenarios strongly coupled to 3rd generation quarks





From Tevatron to LHC: a top factory

- Tevatron operations ended in 2011
  - Run1: L_{int}~125 pb^{-1}
  - Run2: L_{int}~10 fb^{-1}

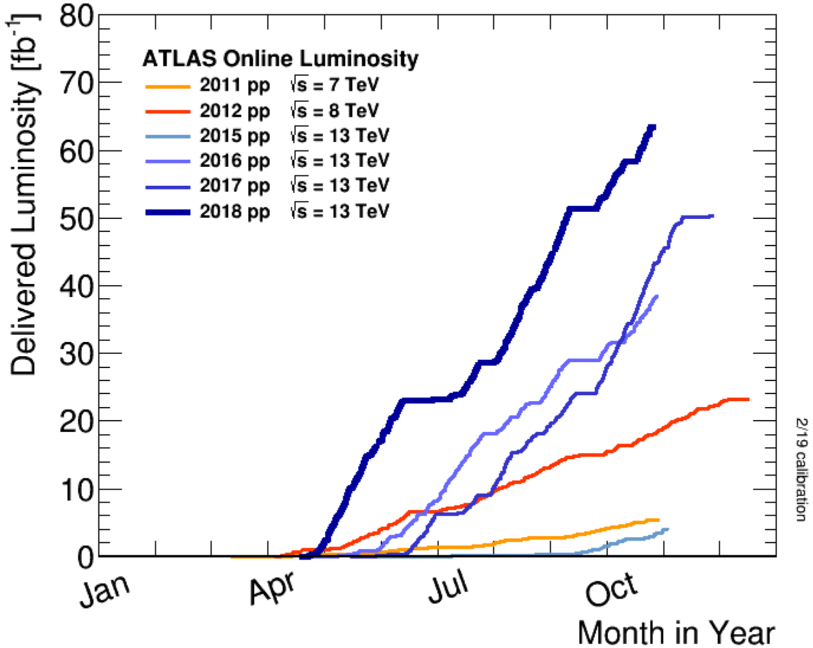
  $\sigma_{t\bar{t}}$=8 pb

  The only place where to study the top quark until the LHC turned on

- LHC: pp collisions starting in 2011
  - Run1: L_{int}~25 fb^{-1} at $\sqrt{s}$=7,8 TeV
  - Run2: L_{int}~140 fb^{-1} at $\sqrt{s}$=13 TeV

  $\sigma_{t\bar{t}}$=250 pb (8 TeV)

  $\sigma_{t\bar{t}}$=830 pb (13 TeV)

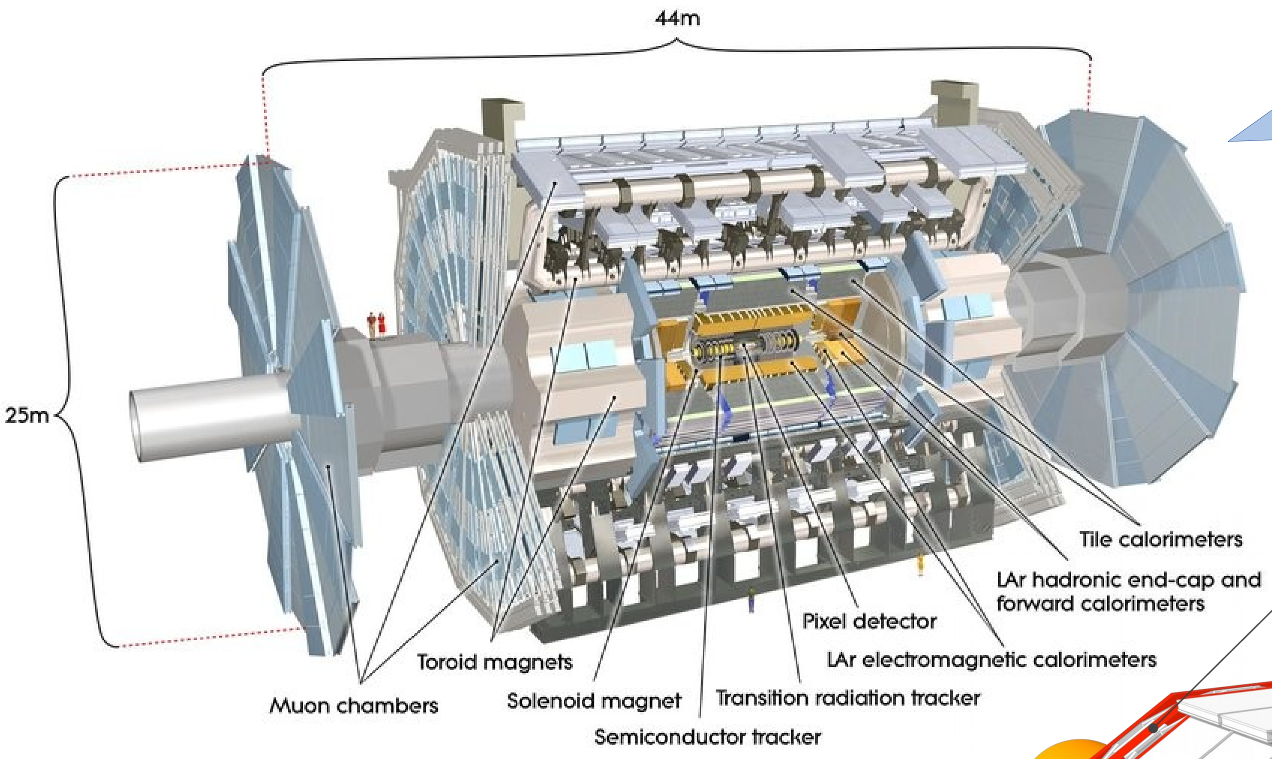


LHC is a top factory!

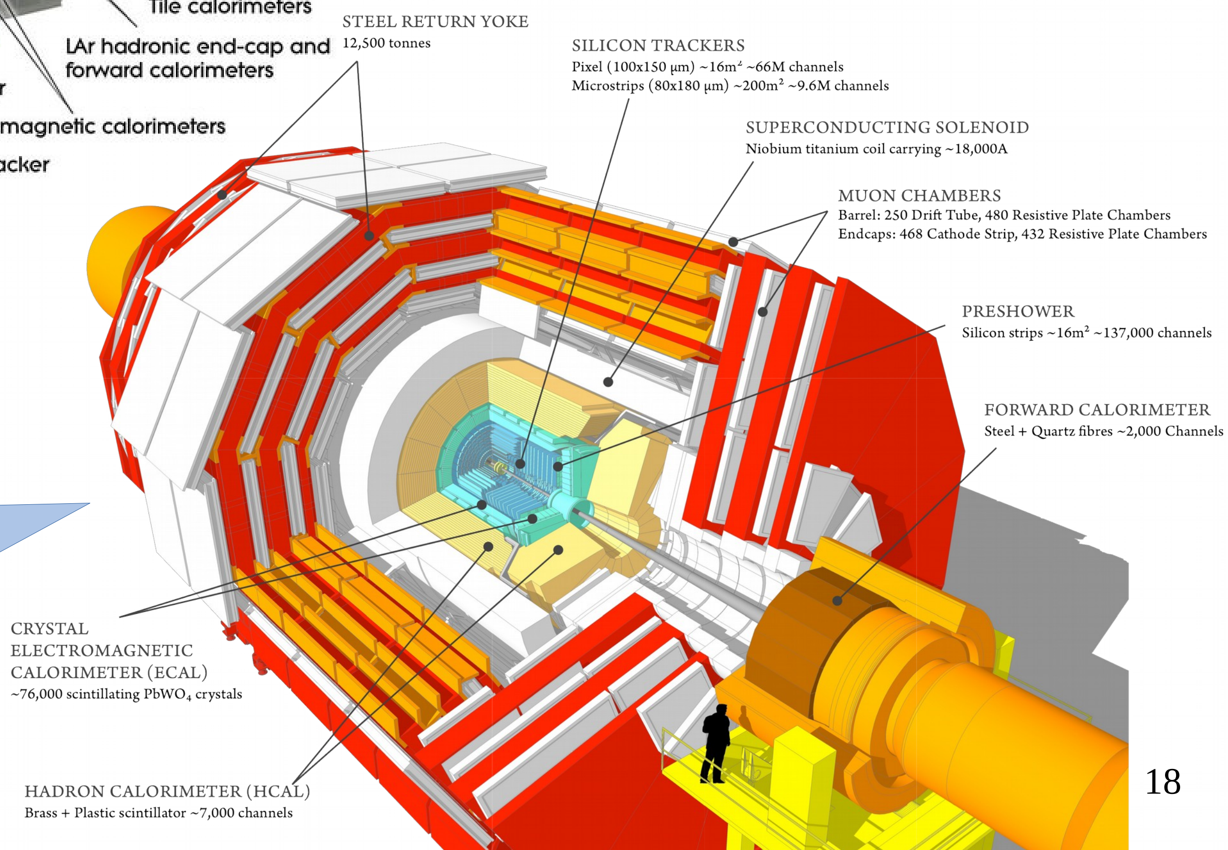
Huge tt production due to large L_{int} and $\sigma_{t\bar{t}}$

How to detect top quarks

The ATLAS and CMS detectors

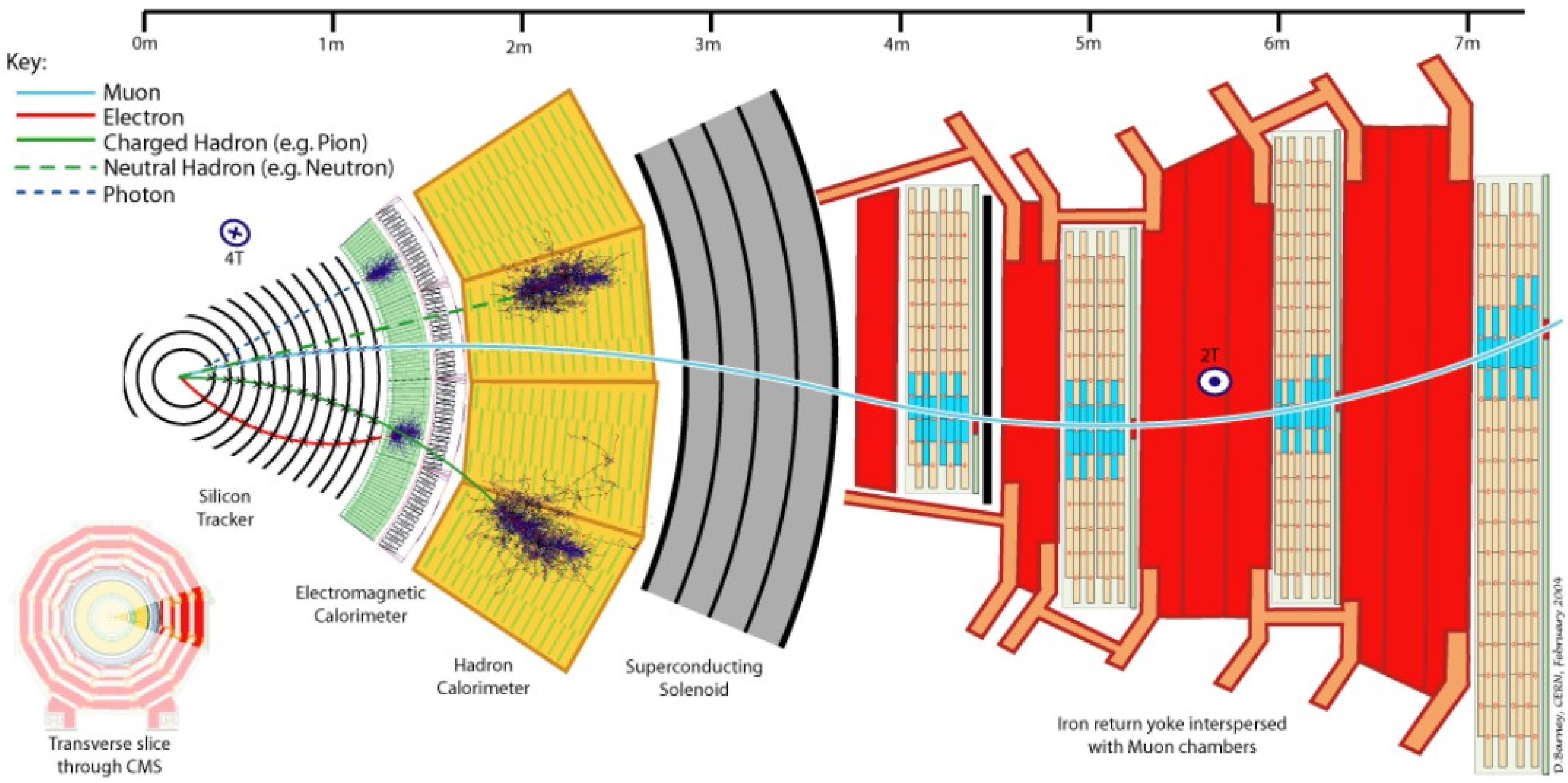


ATLAS
L = 44 m
h = 25 m
W = 7000 ton



CMS
L = 22 m
h = 15 m
W = 12500 ton

A slice of CMS



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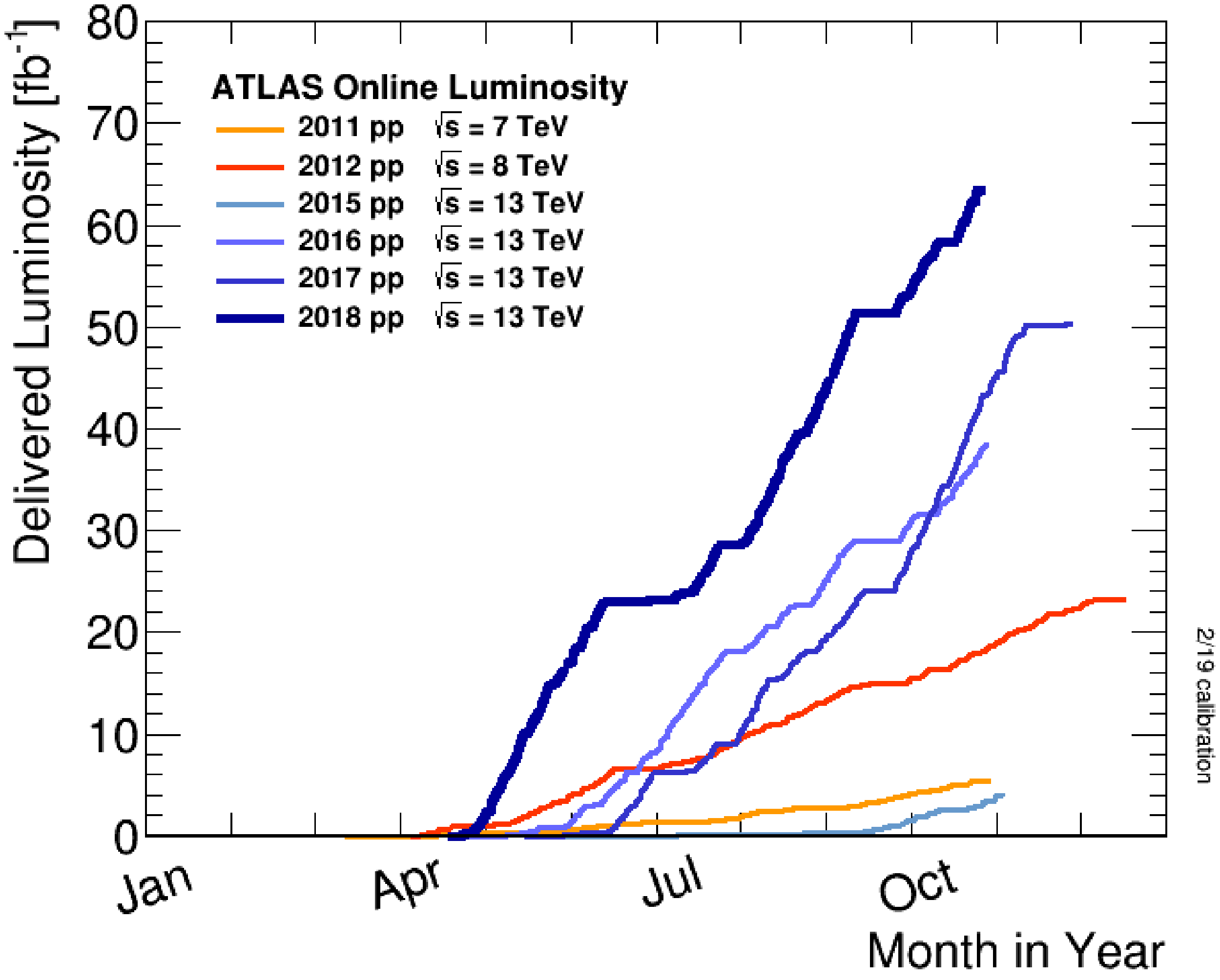
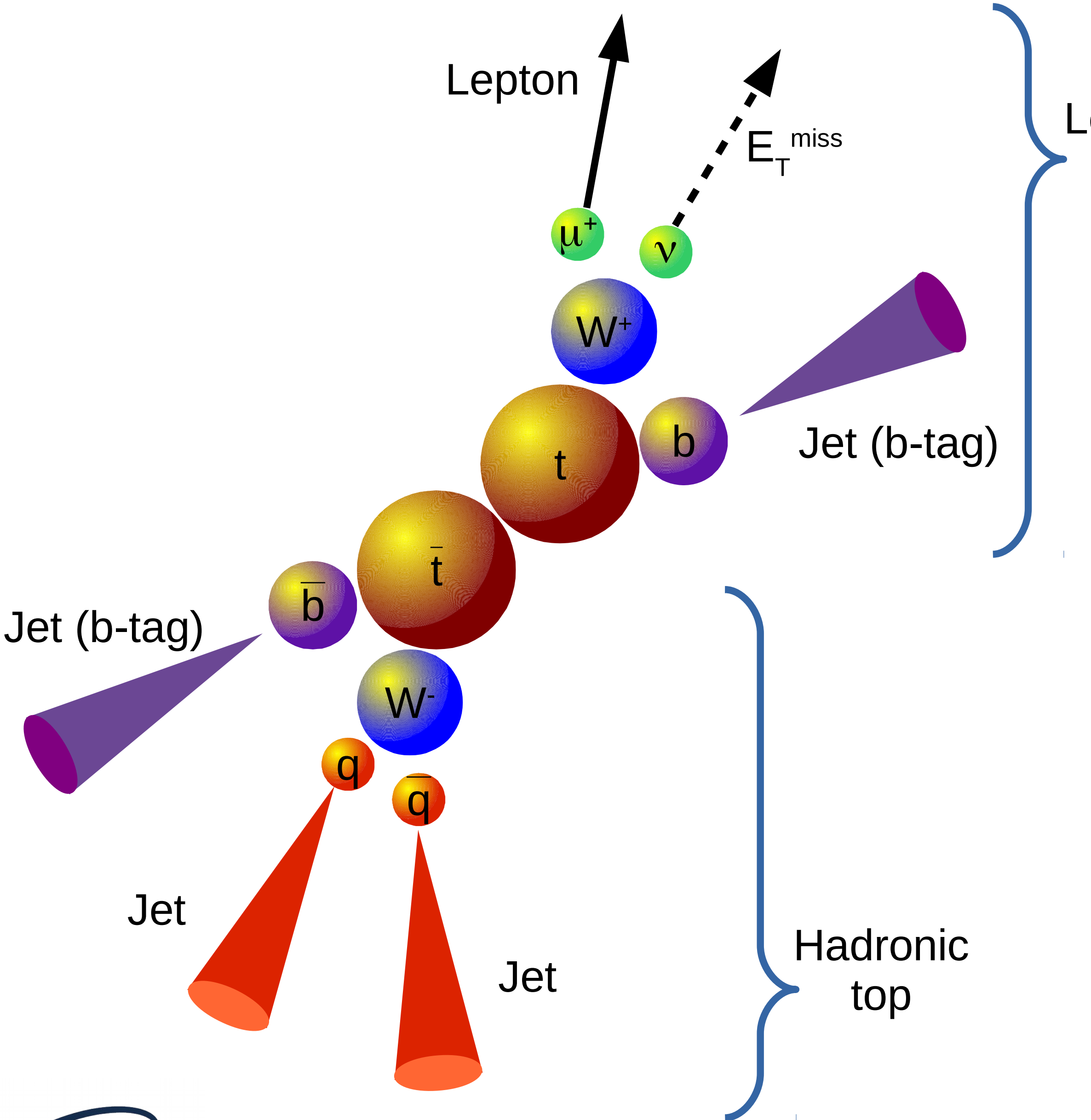
Integrated luminosity

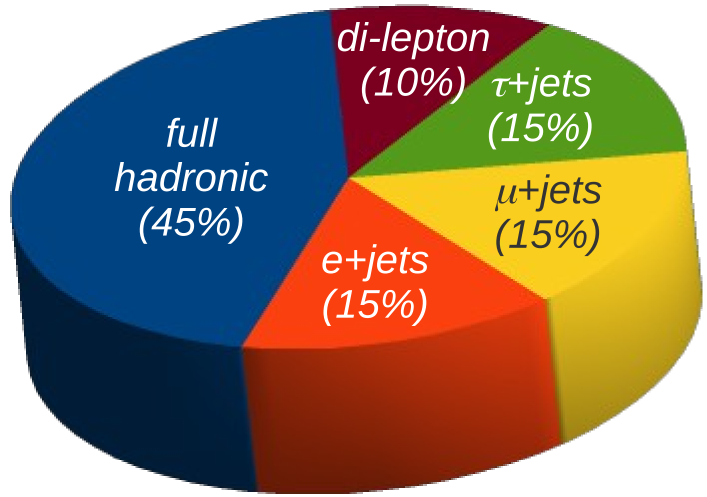
Excellent performance of the LHC!
Peak luminosity: $2x10^{34}$ $cm^{-2}s^{-1}$
Collected ~150 fb^{-1} of pp collision data at 13 TeV



Experimental signatures of $t\bar{t}$ events



Branching fractions for $t\bar{t}$ events



Different signatures based on:

- Number of leptons and jets
- E_T^{miss}
- b-tagged jets

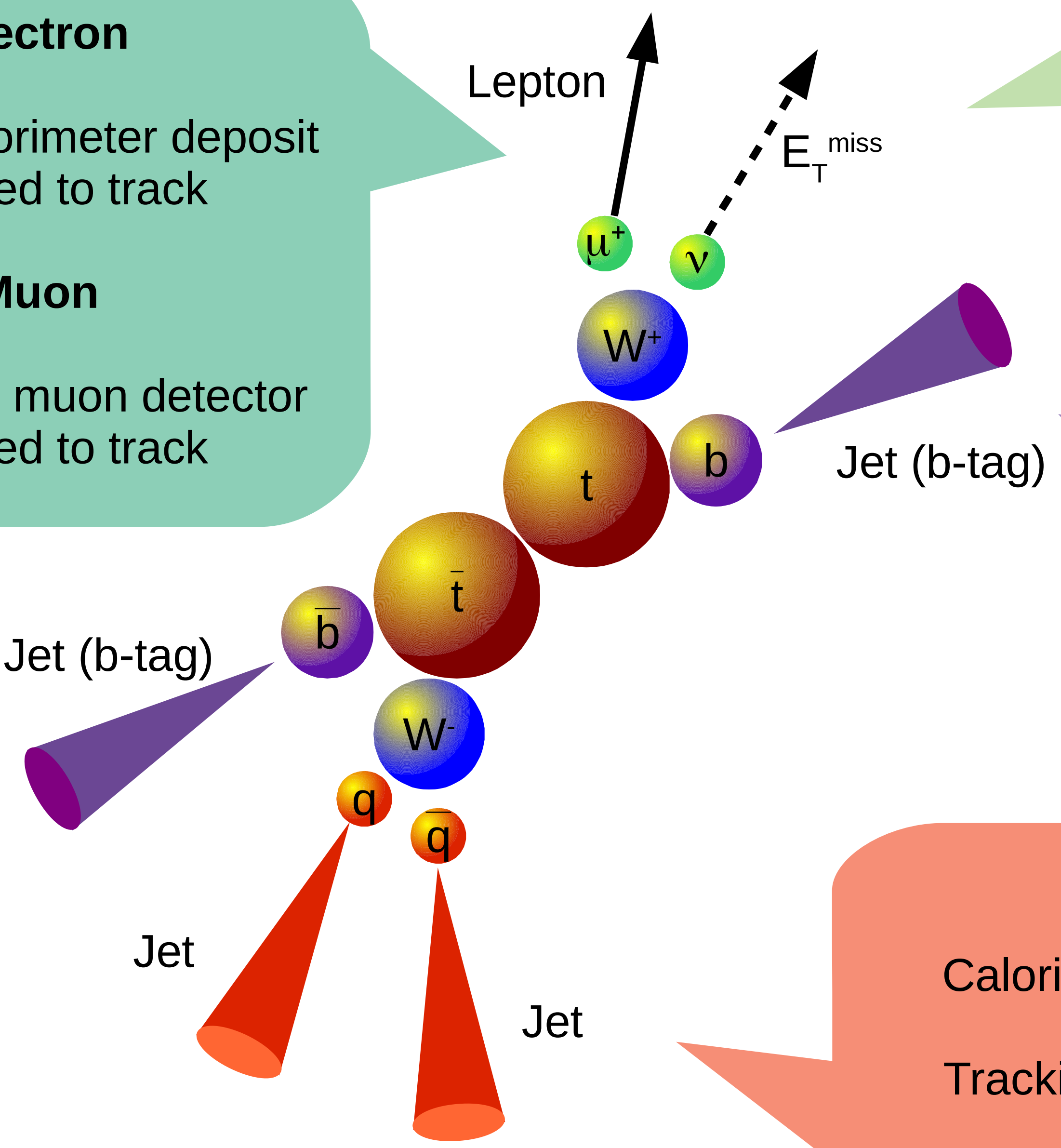
Experimental signatures of $t\bar{t}$ events

Electron

Isolated calorimeter deposit matched to track

Muon

Segment in muon detector matched to track



E_T^{miss}

Momentum unbalance (need complete coverage)

b-tagging

Tracking: secondary vertex
+
Tagging algorithms (multi-variate)

Jets

Calorimeters: clusters
+
Tracking: particle flow
+
Jet clustering algorithms

$t\bar{t}$ channels: the “clean”...

Dilepton

- The cleanest channel (largest S/B) because of 2 leptons in the final state

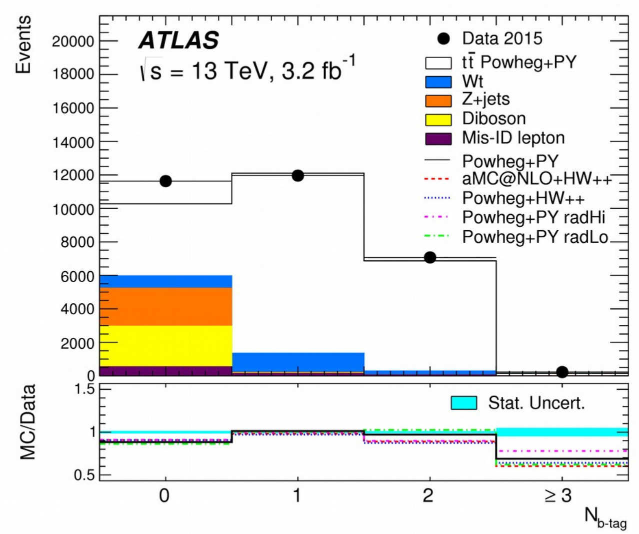
BUT

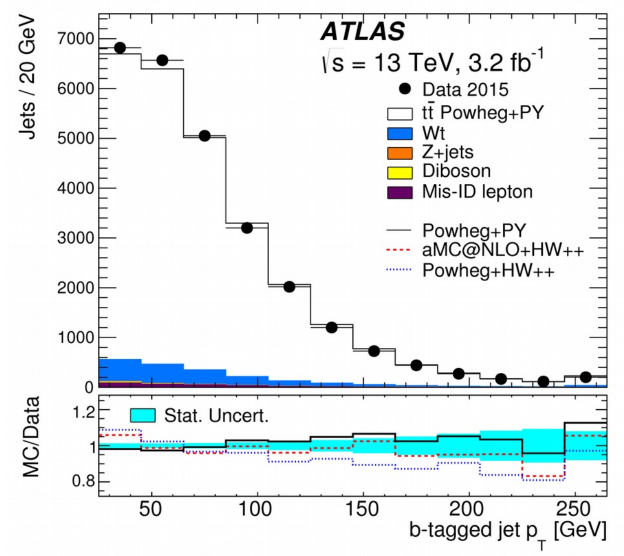
- smallest branching fraction
- need kinematical assumptions to fully reconstruct the event because of 2 neutrinos

Main backgrounds

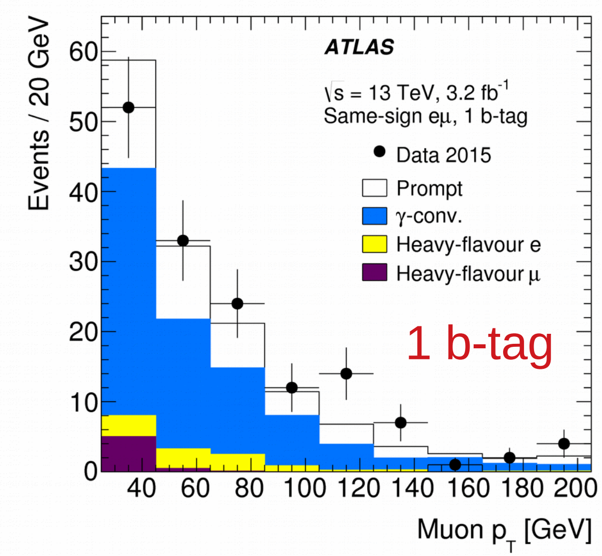
- Z/γ + jets
- diboson
- single top

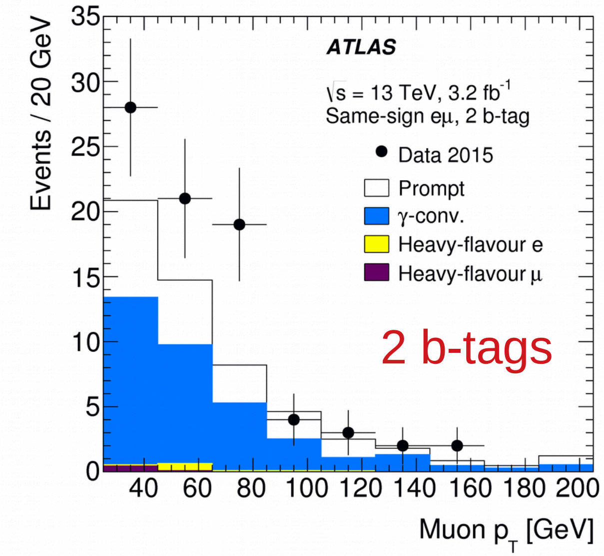
Example plots for the eμ channel





Background is well under control (same sign eμ events)





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...the “fair”...

Lepton+jets

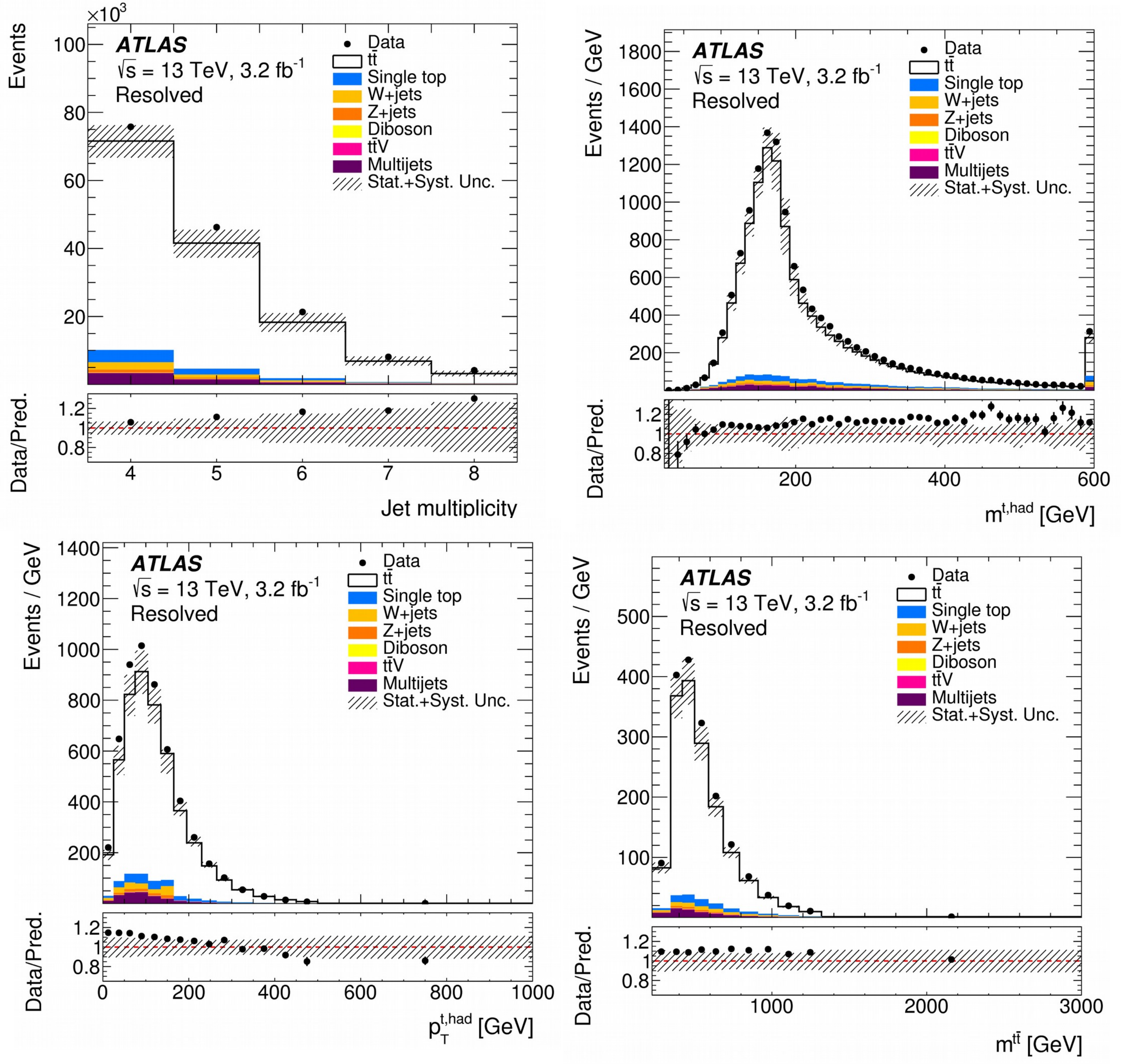
- Clean channel because of the presence of the lepton
- “fair” branching ratio

BUT

- kinematical fit to reconstruct the leptonic top because of the neutrino

Main backgrounds

- W+jets
- multijet QCD
- single top



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...and the "dirty"

All-hadronic

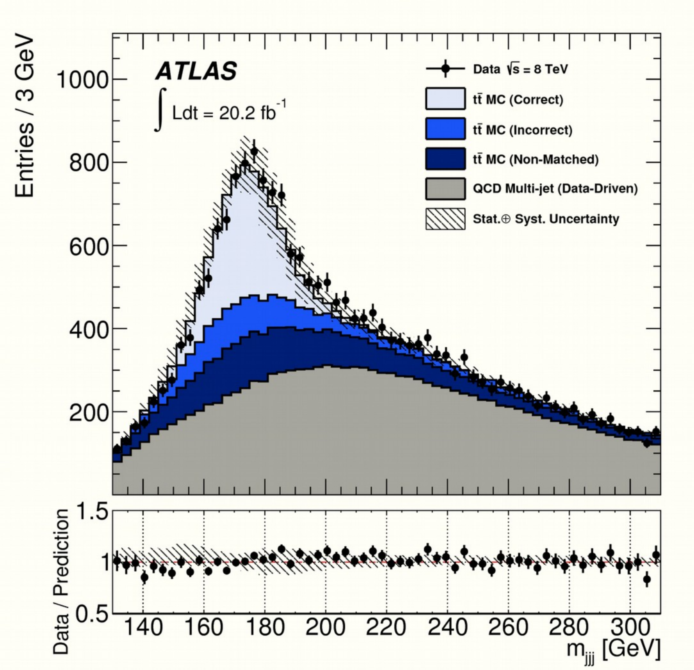
- The largest branching ratio

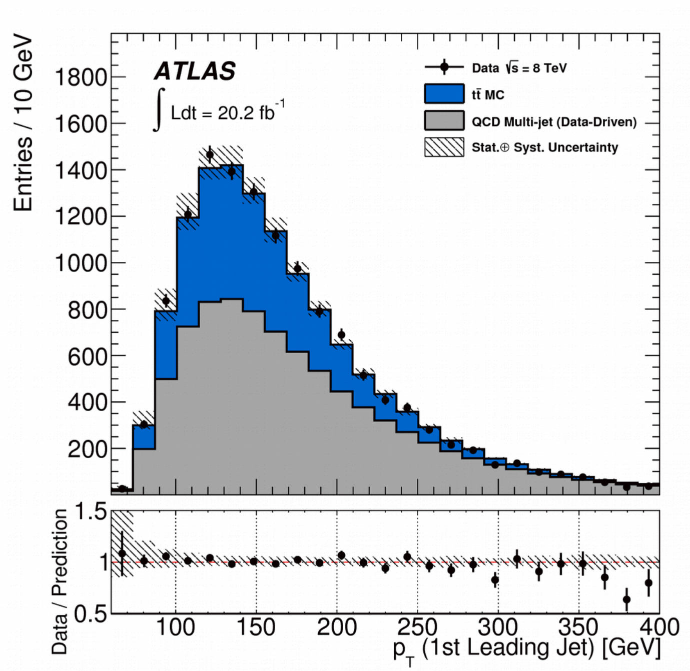
BUT

- large hadronic background
- Combinatorial effect in $t\bar{t}$ event reconstruction

Main background

- multi-jet QCD

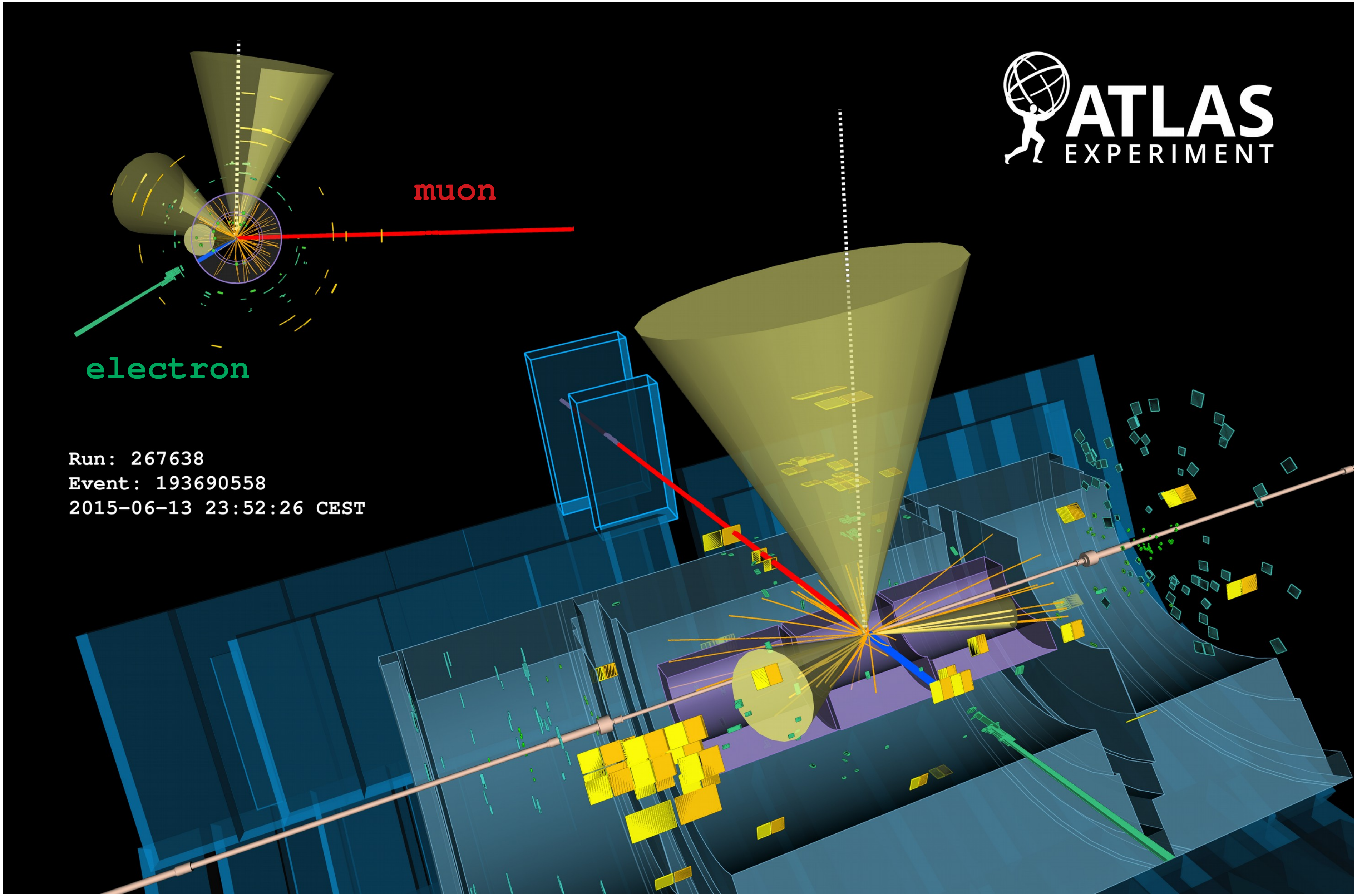




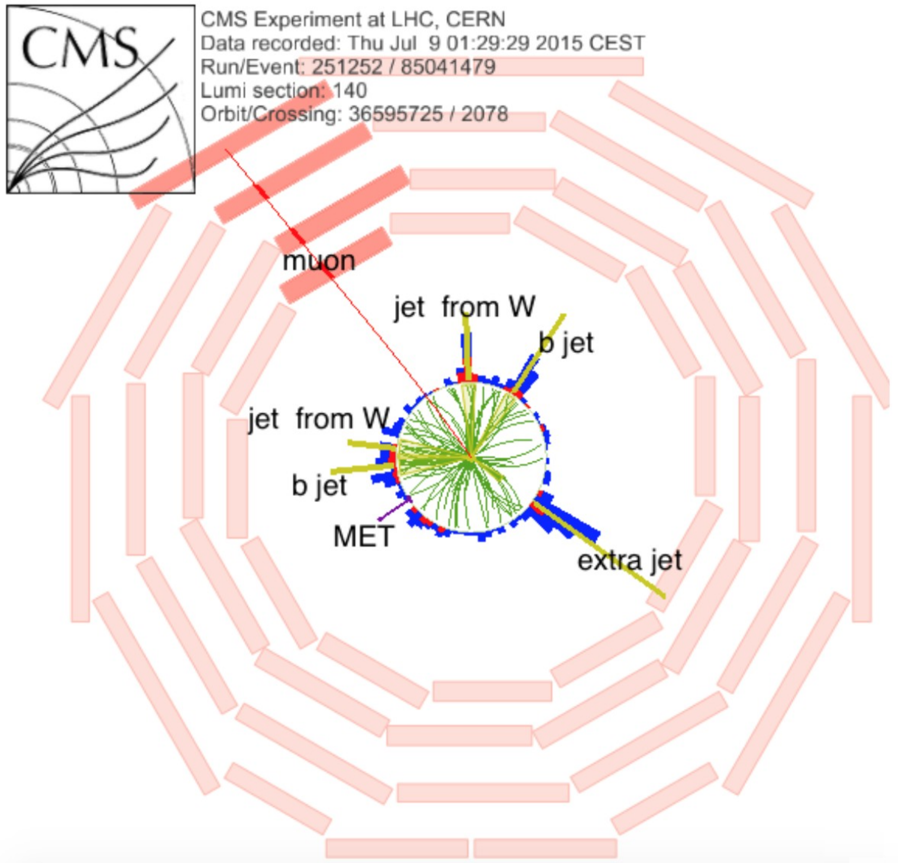
Large QCD multi-jet background

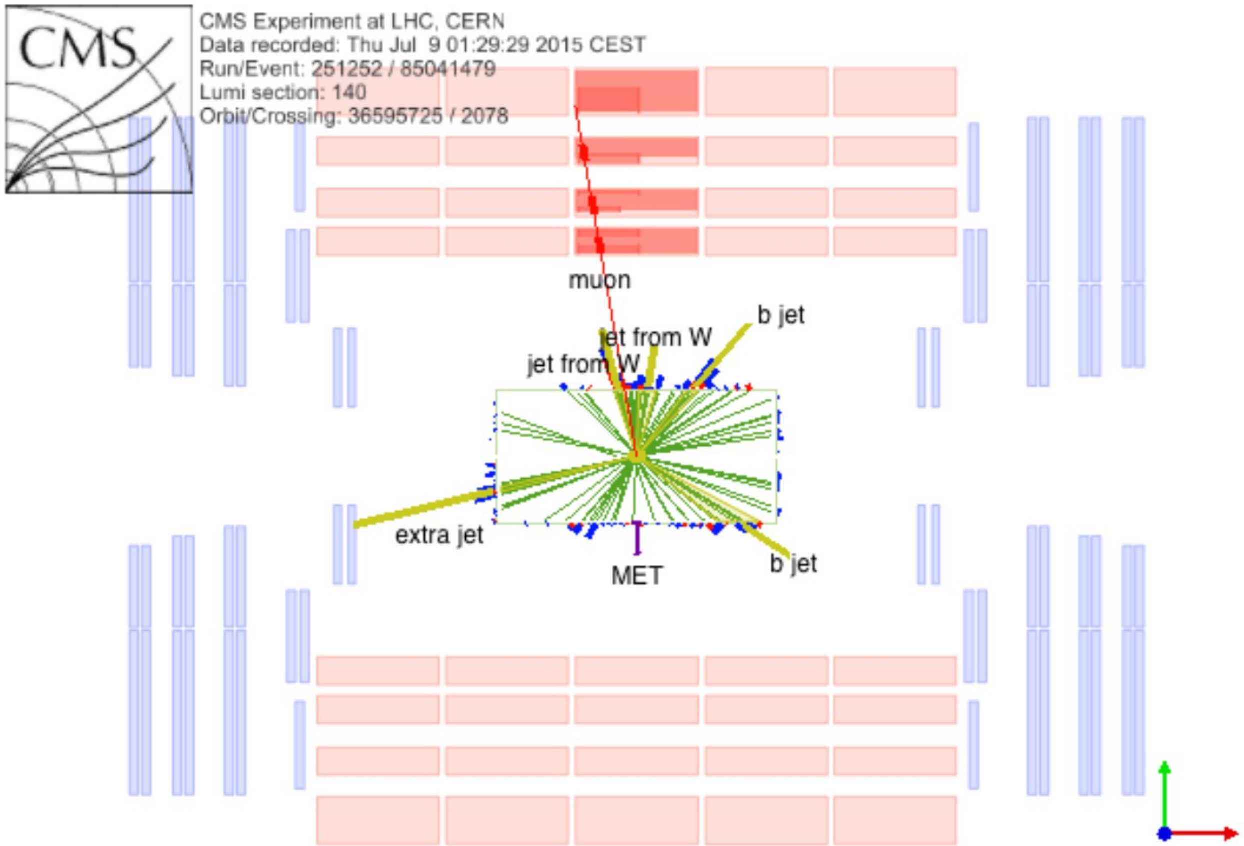
Obtained from data using control regions close to the signal region (invert some of the selection requirements)

Dilepton $t\bar{t}$ event display



l+jets $t\bar{t}$ event display





Recap

- Can you explain why the top quark gives us the unique opportunity to study a “bare” quark? What is the difference with respect to other quarks?

- Can you tell the advantages and disadvantages of the three $t\bar{t}$ reconstruction channels (dilepton, lepton+jets, all-hadronic)?

- What are the detector components used in top quark physics?

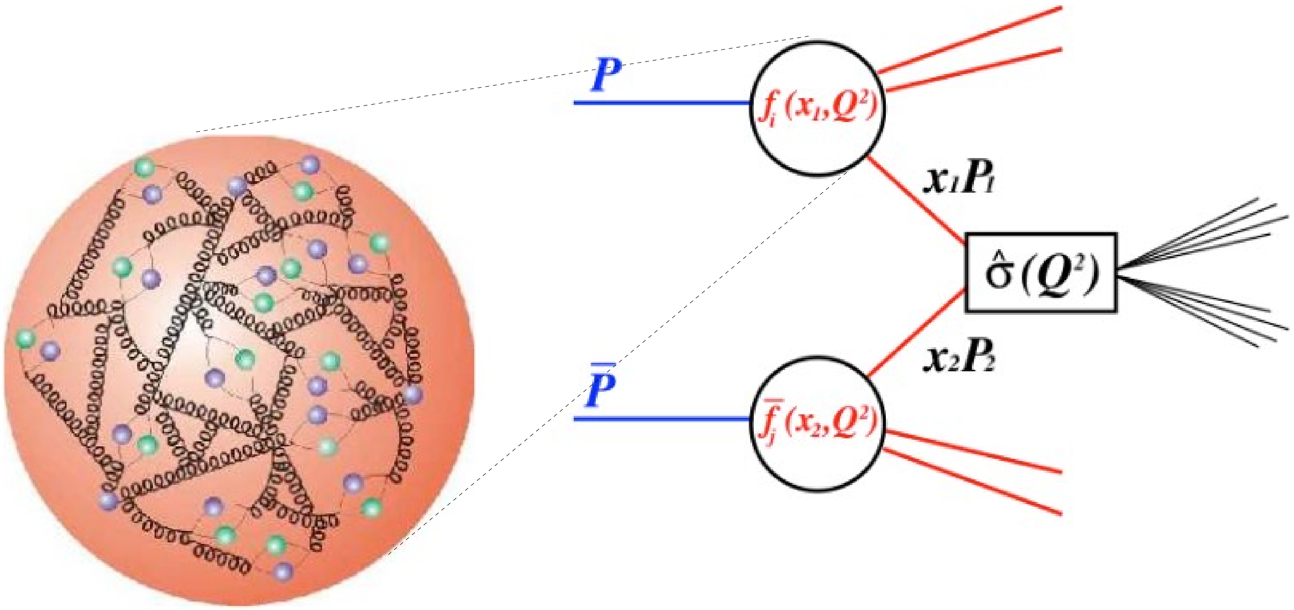
?

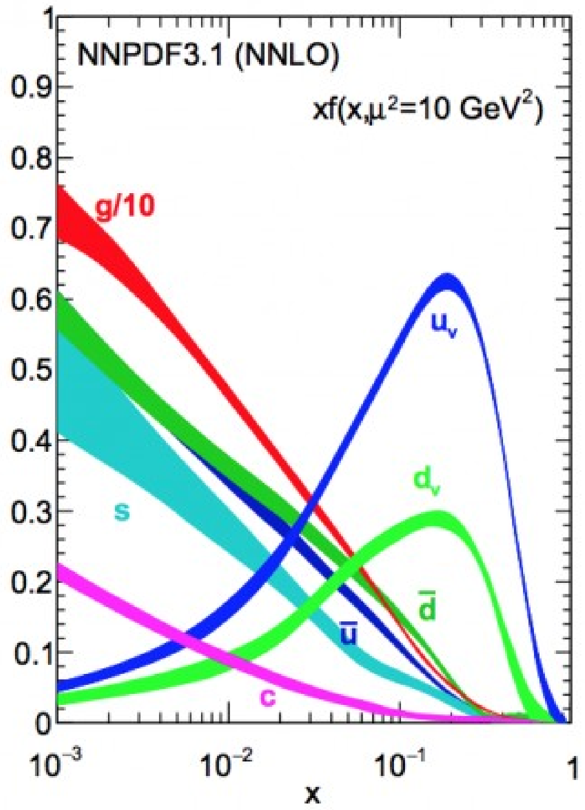
Production cross sections

$t\bar{t}$ cross section
differential cross sections
single top cross section

Cross section calculation

LHC is pp collider. Top quarks are produced by the interaction of partons composing the protons.





$$\underbrace{\sigma^{t\bar{t}}(\sqrt{s}, m_t)}_{\text{Cross section}} = \underbrace{\sum_{i,j=q,\bar{q},g} \int dx_i\, dx_j}_{\text{Sum over all parton type and momenta}}\ \underbrace{f_i(x_i,\mu^2)\cdot \bar{f}_j(x_j,\mu^2)}_{\text{PDF}} \cdot \underbrace{\hat{\sigma}^{ij\to t\bar{t}}\left(\rho, m_t^2, \alpha_s(\mu^2), \mu^2\right)}_{\text{Partonic cross section}}$$

Cross section

Sum over all parton type and momenta

PDF

Partonic cross section

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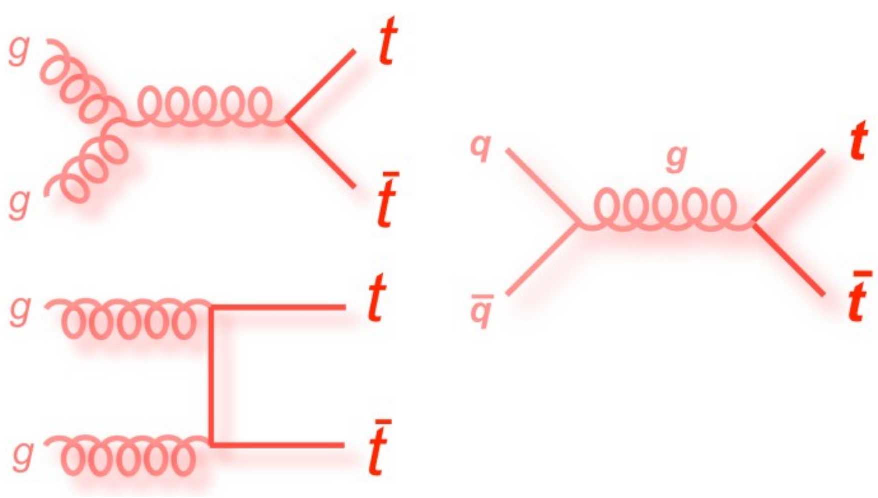
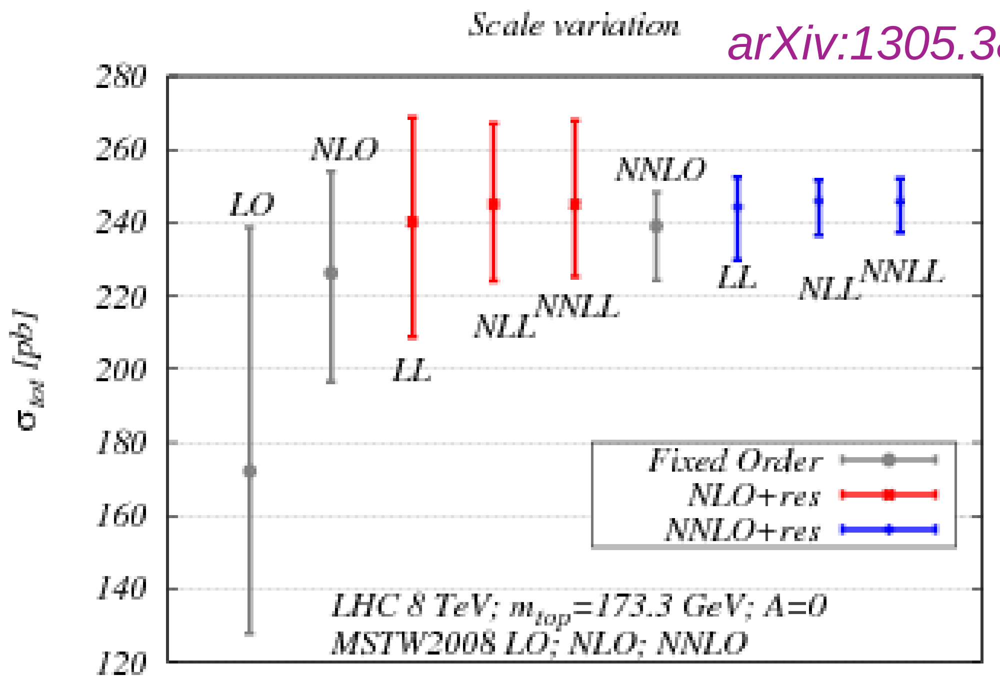
Production: $t\bar{t}$ pair

- $q\bar{q}$ annihilation dominates at the Tevatron
- Gluon fusion dominates at the LHC



arXiv:1305.3892



	Tevatron	LHC 14 TeV
$q\bar{q}$	85%	10%
gg	15%	90%

- Calculations available at the NNLO+NNLL
  - Such calculations are tough!
    Milestone in top quark physics.
- Comparing the theory and the calculation represent a stringent test of the SM
- Sensitive to the gluon PDF

$t\bar{t}$ production cross section measurement

$t\bar{t}$ production cross section is one of the "basic" quantities in top physics

$$\sigma_{t\bar{t}} = \frac{N_{obs} - N_{bkg}}{\epsilon L}$$

ϵ : efficiency, including acceptance and BR
L : integrated luminosity

Basically count events (N_{obs}), but…

- need precision estimates of the background contributions (N_{bkg})
  - from MC generators
  - measured from data
- need to precisely determine the efficiency (ϵ)
  - detector modeling and calibration
  - signal efficiency and acceptance
- reaching ~2% on L is a tough job

Analysis techniques to obtain the smallest possible N_{bkg} and ϵ

↓

choice of final state
analysis strategy / technique

Systematic uncertainties

Experimental uncertainties arise from an imperfect knowledge of:

- **Detector modeling and calibration:** analysis repeated after 1σ variations of each source of systematic uncertainty
  - include: Jet and MET calibration, lepton reconstruction, b-tagging
- **Background modeling:** analysis repeated after variation of the backgrounds by 1σ from their nominal values
- **Signal modeling:** each source of uncertainty is estimated using a different MC sample for the correction (efficiency, acceptance, mis-reconstruction). The uncertainty is obtained as the difference between the true and the corrected distributions of the baseline sample
  - include: ME generator, PS+hadronization, ISR/FSR, PDF

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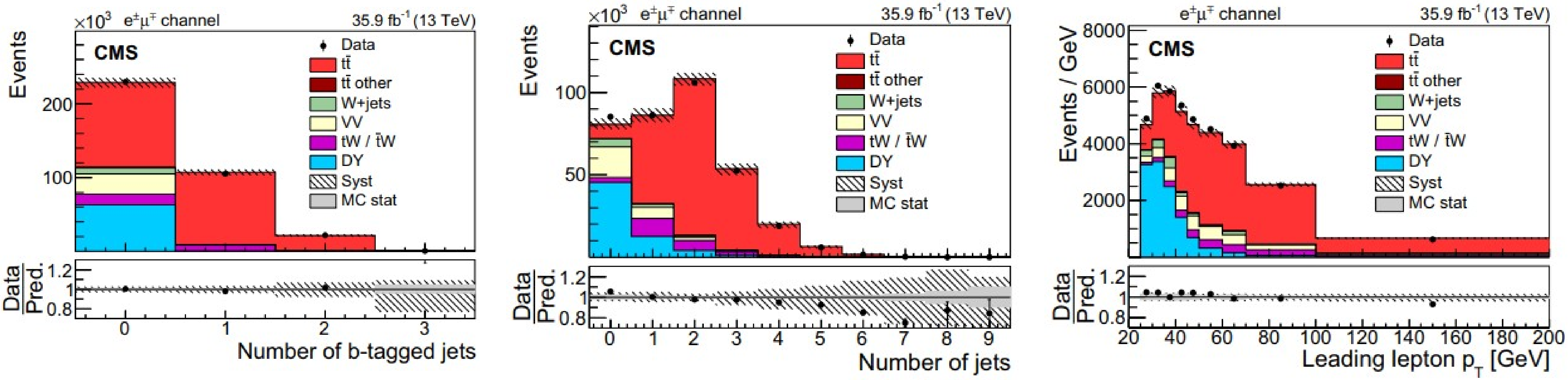
Measurement of $\sigma_{t\bar{t}}$: dilepton channel

Cleanest channel: eμ

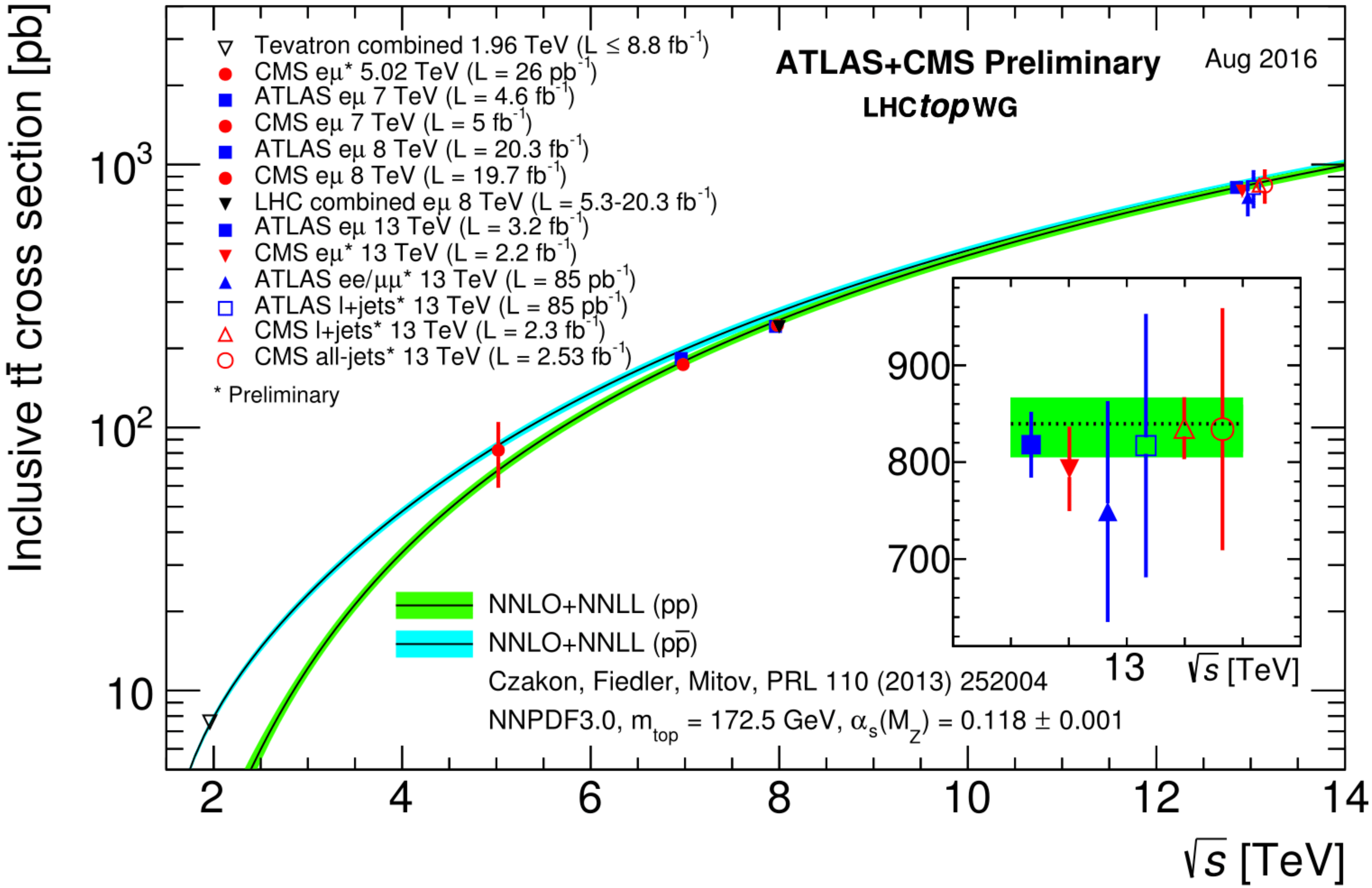


$\sigma_{t\bar{t}}$(13 TeV) = 803 ± 2 (stat) ± 25 (syst) ± 20 (lumi) pb

Total systematic uncertainty ~3% (from a long list, <1% each)
Among the main contributions:

- Modeling of $t\bar{t}$ (generator, IFSR, hadronization)
- Lepton isolation / identification
- Jet energy calibration

Measurement of $\sigma_{t\bar{t}}$: summary



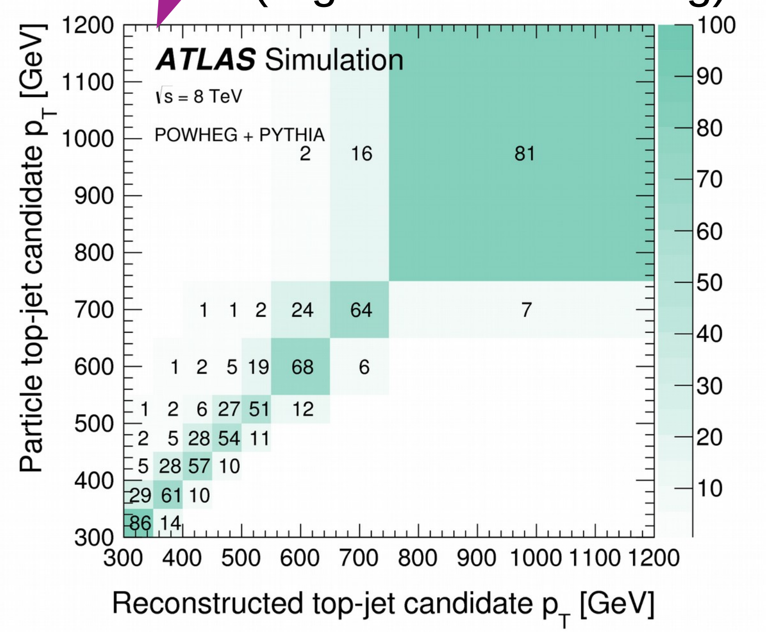
$t\bar{t}$ differential cross sections

- Measure production cross sections in "bins" of given variables of interest
- Complicating a bit the procedure but…
  - need to take into account migrations between different bins → **unfolding**
- … gain sensitivity to effects that can be present only in some regions of the $t\bar{t}$ phase space
  - check SM in "tails" of the distributions
  - look for deviations with respect to the SM
- Fiducial measurements can be done to minimize the extrapolation (uncertainty on ϵ) → useful to tune MC generators

$$\frac{d\sigma_{t\bar{t}}}{dX}(X^i) = \frac{\sum_j M^{-1}_{ij}(N^j_{obs} - N^j_{bkg})}{\Delta^i_X \epsilon^i L}$$

bin width

inverse of the migration matrix (regularized unfolding)



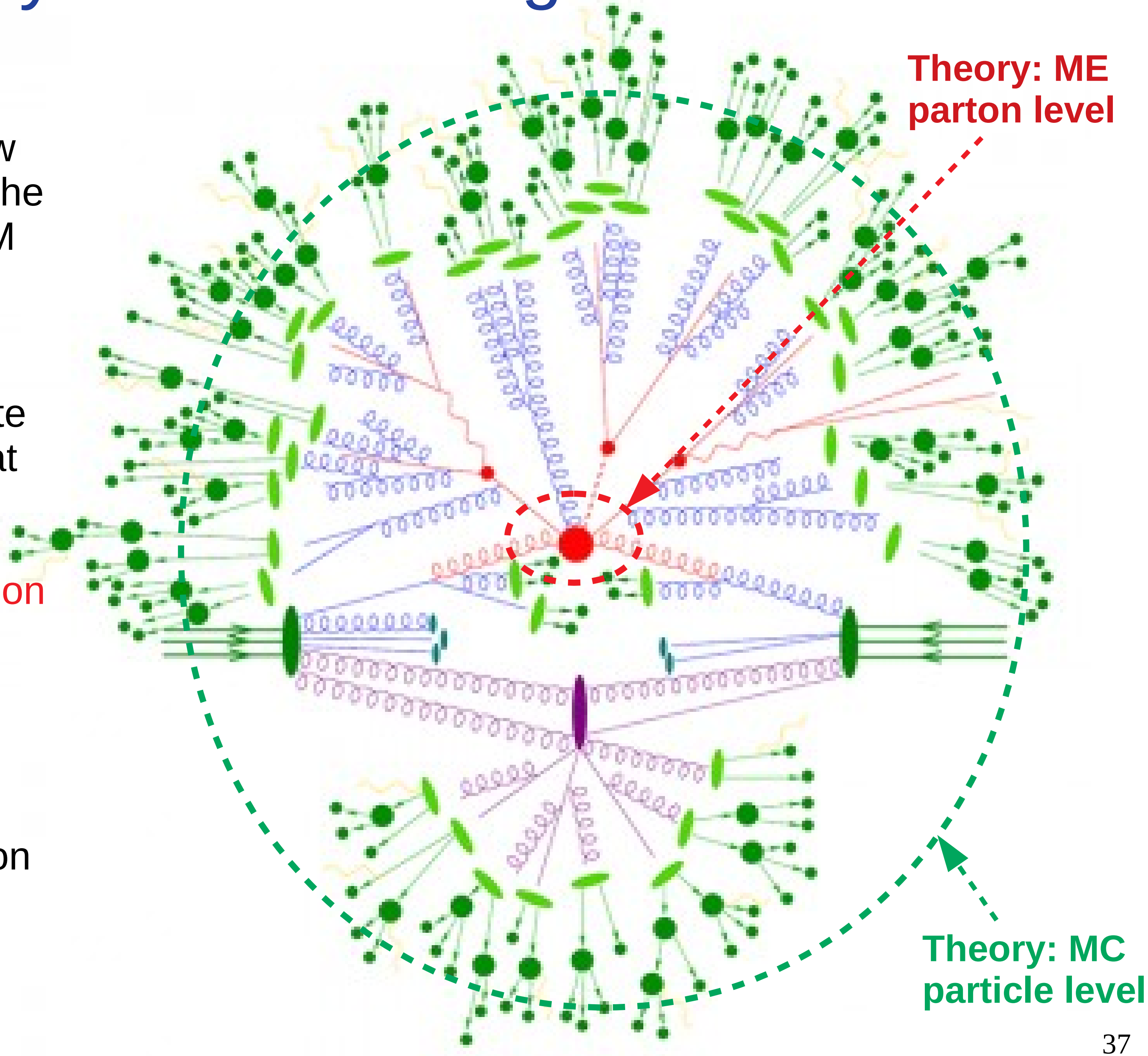
Theory: Monte Carlo generators

SM measurements and possible observation of new phenomena are based on the comparison of data with SM expectation

Expected observables are obtained by means of Monte Carlo event generators, that take into account:

- Proton PDF
- Matrix Element calculation
- Parton shower
- Hadronization
- Hadron decay

To be interfaced with a complete detector simulation (Geant4)
→ Detector level

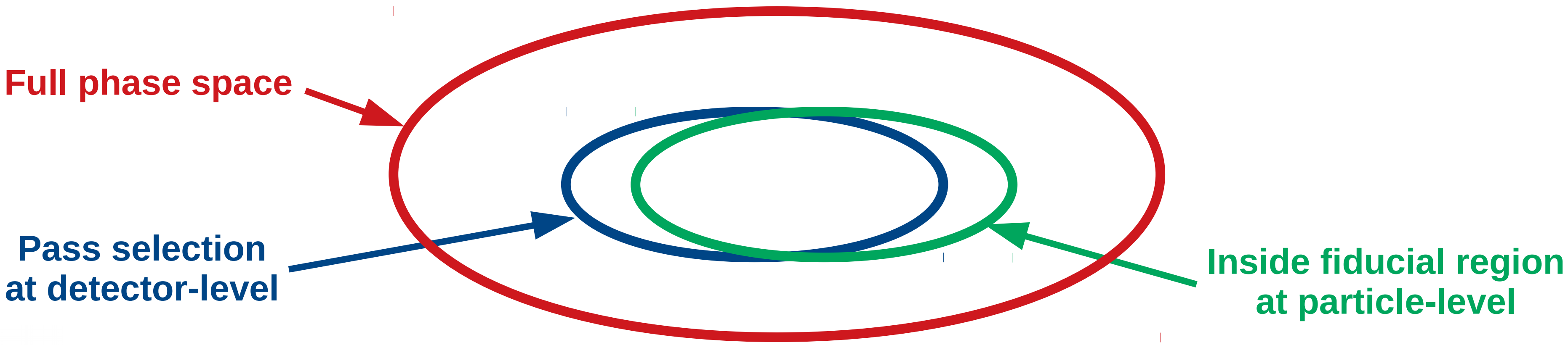


Differential cross sections: correction

Measure $t\bar{t}$ production differential cross section as a function of a kinematic quantity X

- **Particle-level correction:**
  - Reconstruct objects using “stable” particles ($\tau > 0.3\times10^{-10}$ s) produced by the MC
  - Correct to X obtained using particle-level reconstructed quantities
  - Extrapolate to a fiducial region defined to closely follow the event selection
  - Minimize the extrapolation and the theoretical uncertainty
- **Parton-level correction:**
  - Correct to X obtained from parton kinematics
  - In the full phase-space of events
  - Allow comparison with theoretical fixed-order calculations

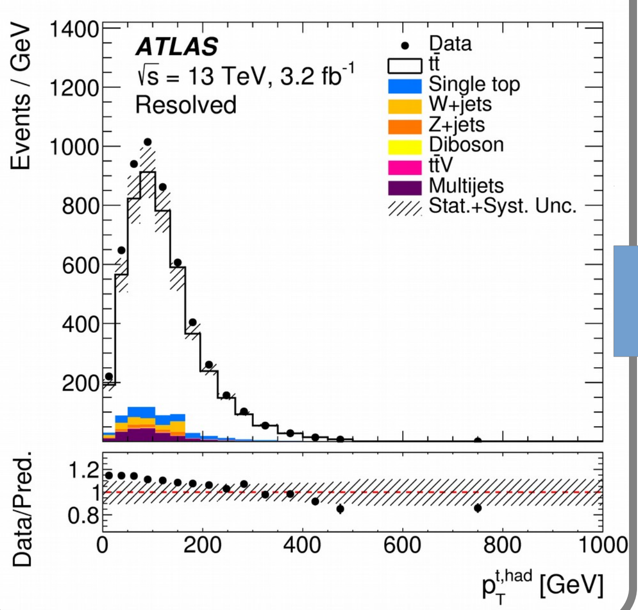
Schematic representation of $t\bar{t}$ event sets



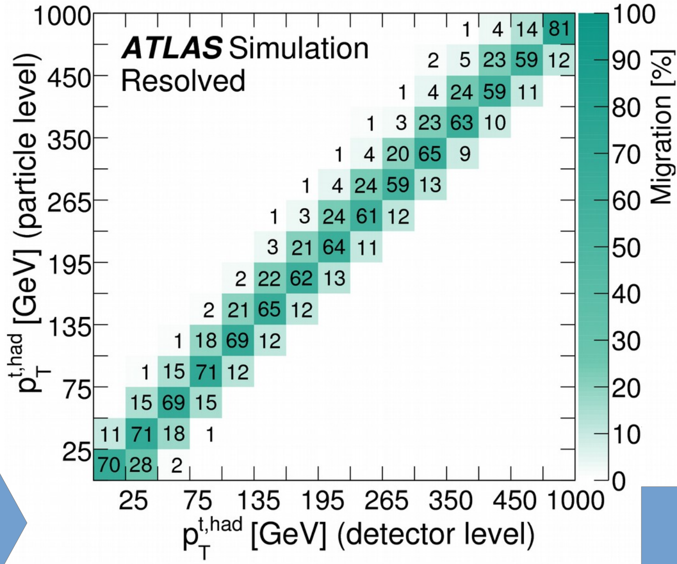
$t\bar{t}$ differential cross sections

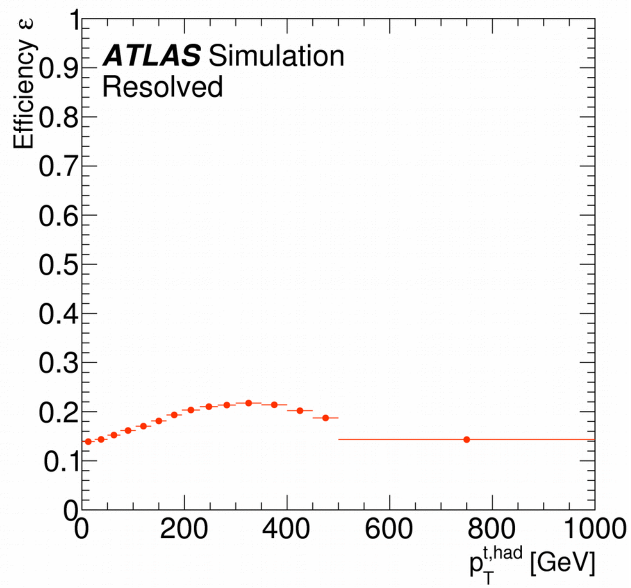
Example: p_T of the hadronic top in l+jets events

Reconstruction

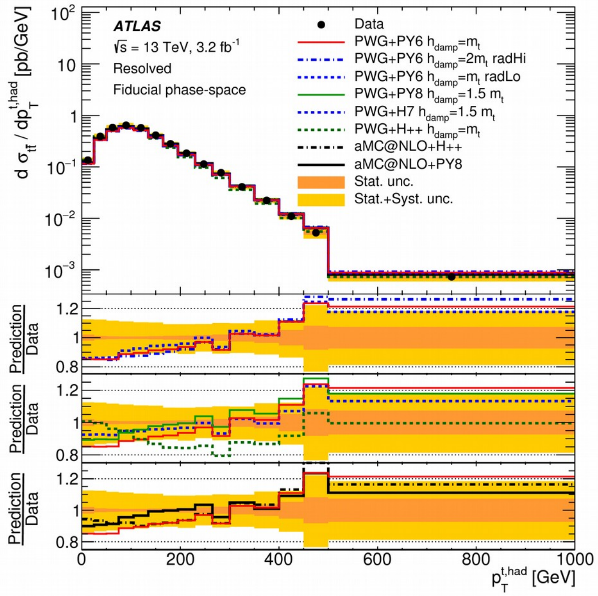


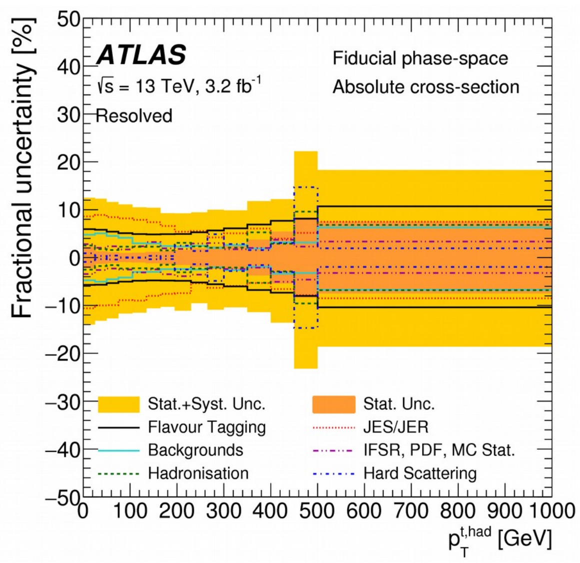
Correction



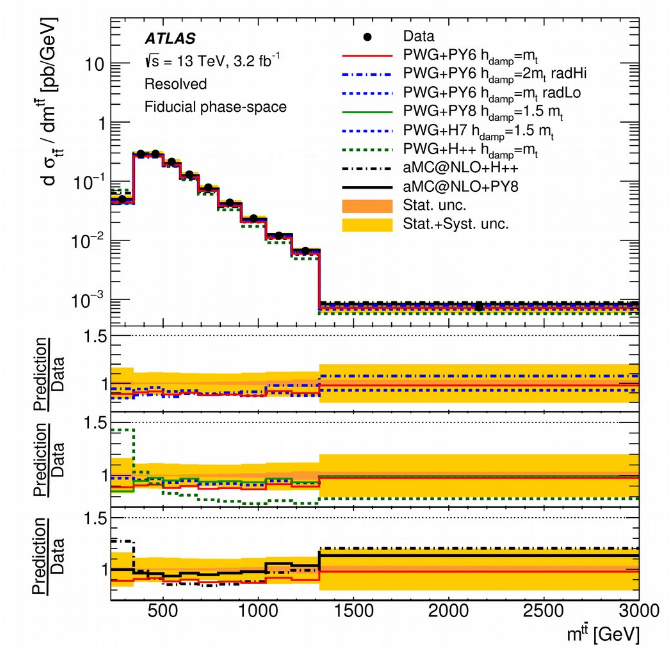


Measurement

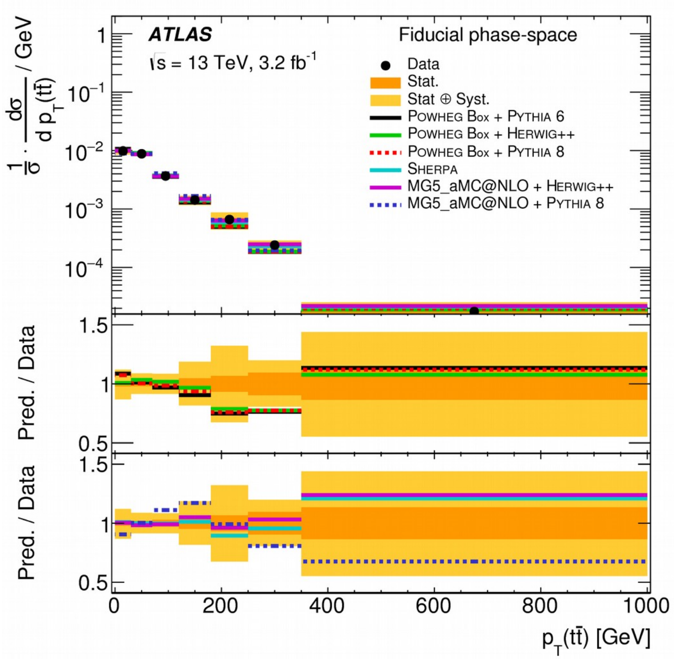




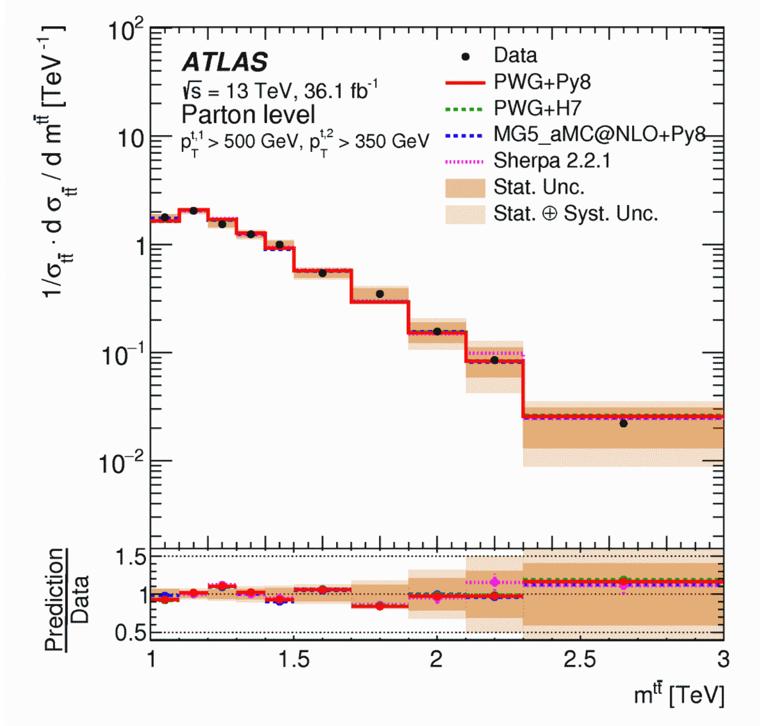
Comparison with theory



l+jets - particle level



dilepton - particle level



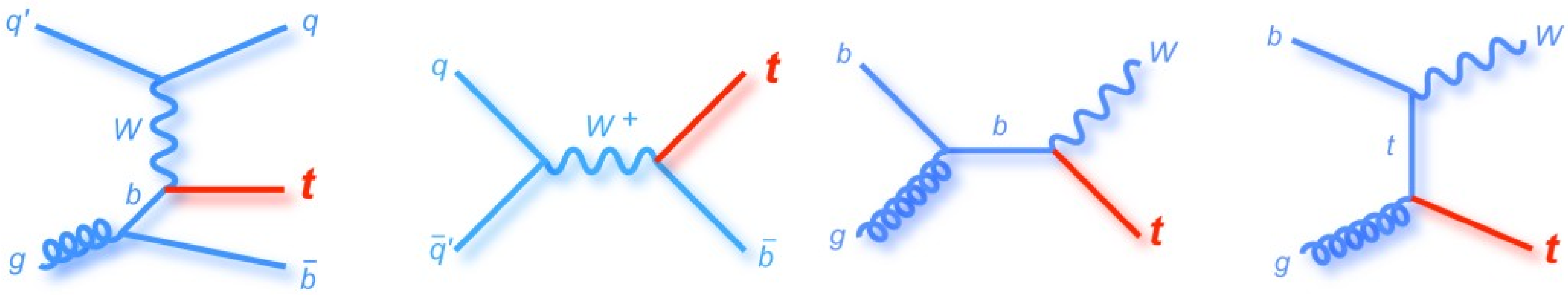
all-hadron - parton level

Measurements of several kinematic variables can be compared with theory (MC predictions or fixed order calculations, only for parton-level corrections)

- Good agreement with SM predictions so far, in all regions of the phase space
- Main uncertainties: JES, b-tag, $t\bar{t}$ modeling
- Measurements can be used to test/tune MC generators

Production: single top

Electroweak process! Allows to probe structure of the W-t-b vertex
Three channels contributing: t-channel, s-channel, tW

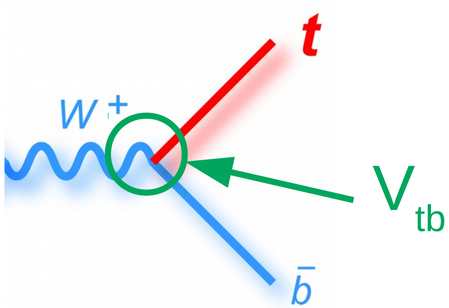


What do we learn from single top?

- Cross section proportional to $|V_{tb}|^2$
  - Test of the SM
- New Physics can affect single top production cross section
  - 4th generation
  - W'
  - Flavor Changing Neutral Currents

LHC 14 TeV	σ (pb)
t-channel	243
tW	84
s-channel	12

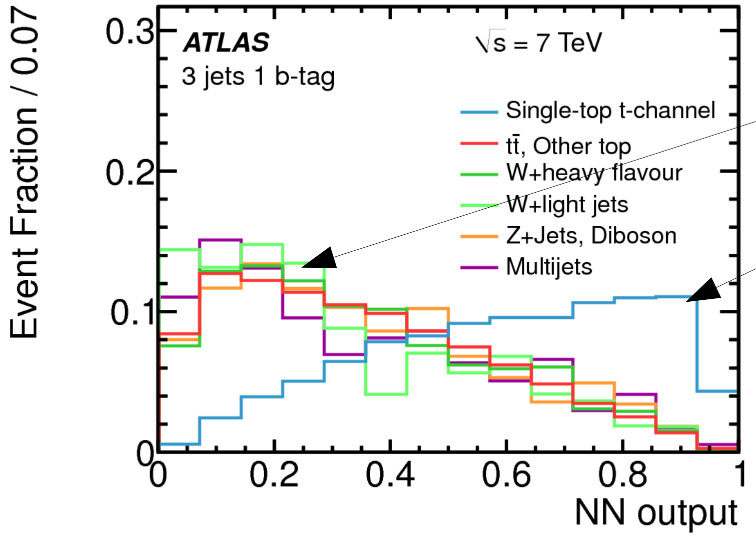
- Harder to measure than $t\bar{t}$
  - Need to fight with large background



Single top cross section measurements

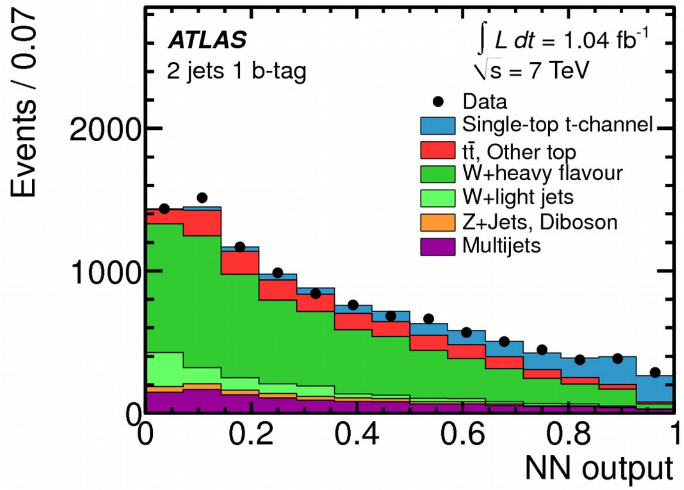
Small differences in kinematic distributions with respect to backgrounds
Need to apply multi-variate analysis techniques → Signal/background separation obtained exploiting small differences in several observables

Use distribution of discriminant to extract signal yield

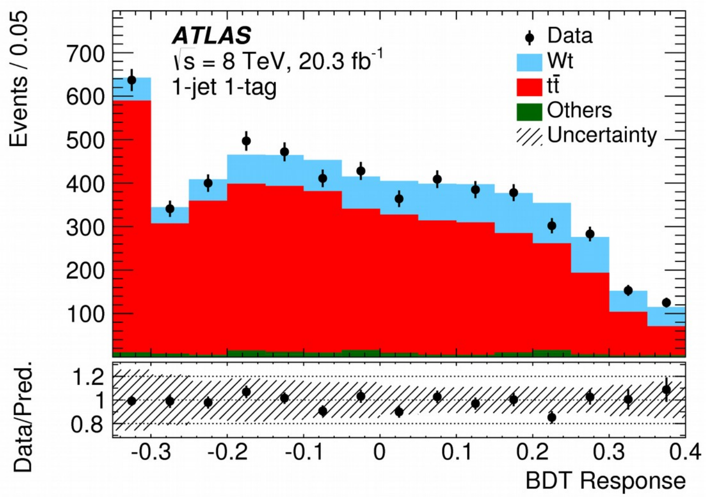


Backgrounds

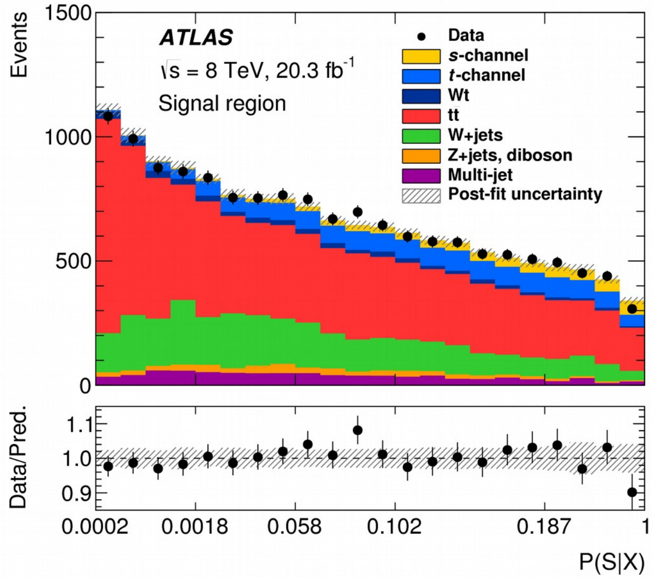
Signal



t-channel

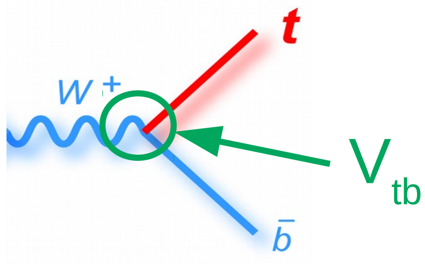


Wt-channel

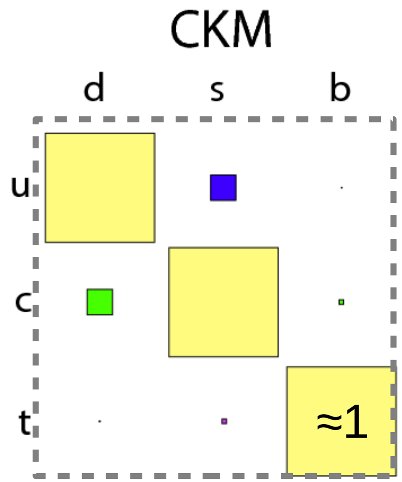


s-channel

Determination of V_{tb}



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



Visualization of the size of the CKM matrix elements

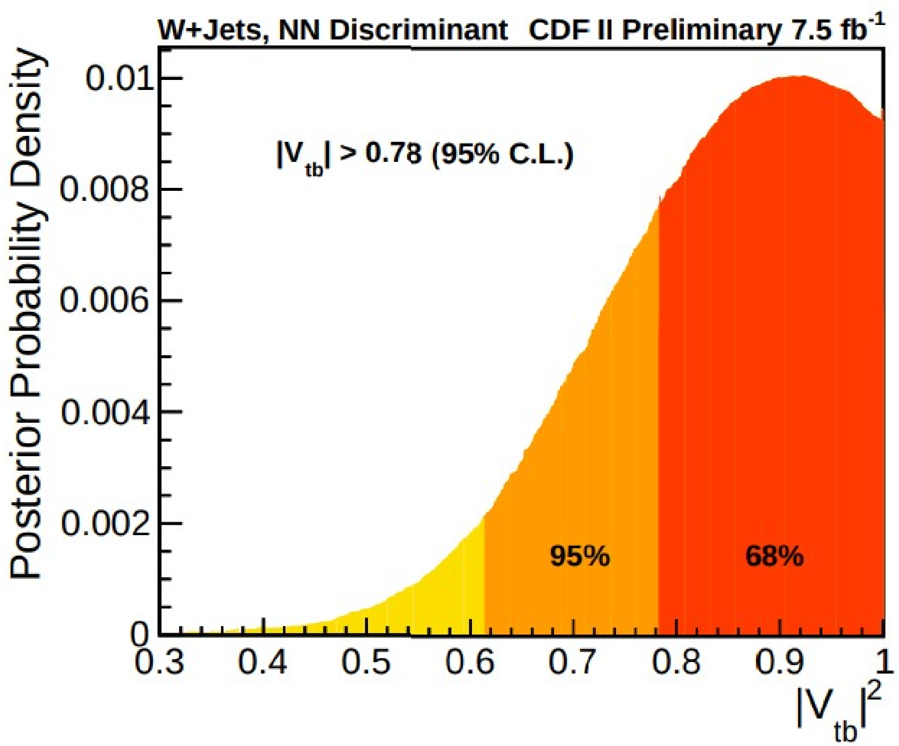
The single top cross section has a W-t-b vertex → proportional to $|V_{tb}|^2$

SM: $|V_{tb}| \approx 1$ → Physics beyond the SM can alter this value

$|V_{tb}|$ can be infered from single top cross section, if:

- $|V_{tb}| >> |V_{td}|, |V_{ts}|$
- Assume same V-A coupling (as in the SM)
- No need to assume number of quark generations

$$|V_{tb}|^2 = |V_{tb,SM}|^2 \frac{\sigma_{single-t,meas}}{\sigma_{single-t,SM}}$$



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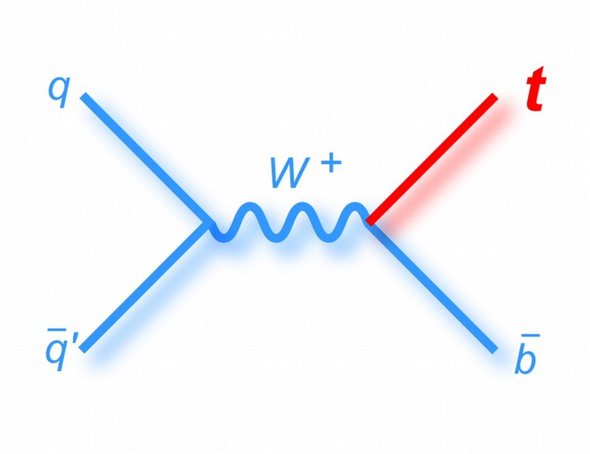
Measurement of the s-channel

Hardest channel to measure (measured at Tevatron and LHC-8 TeV)



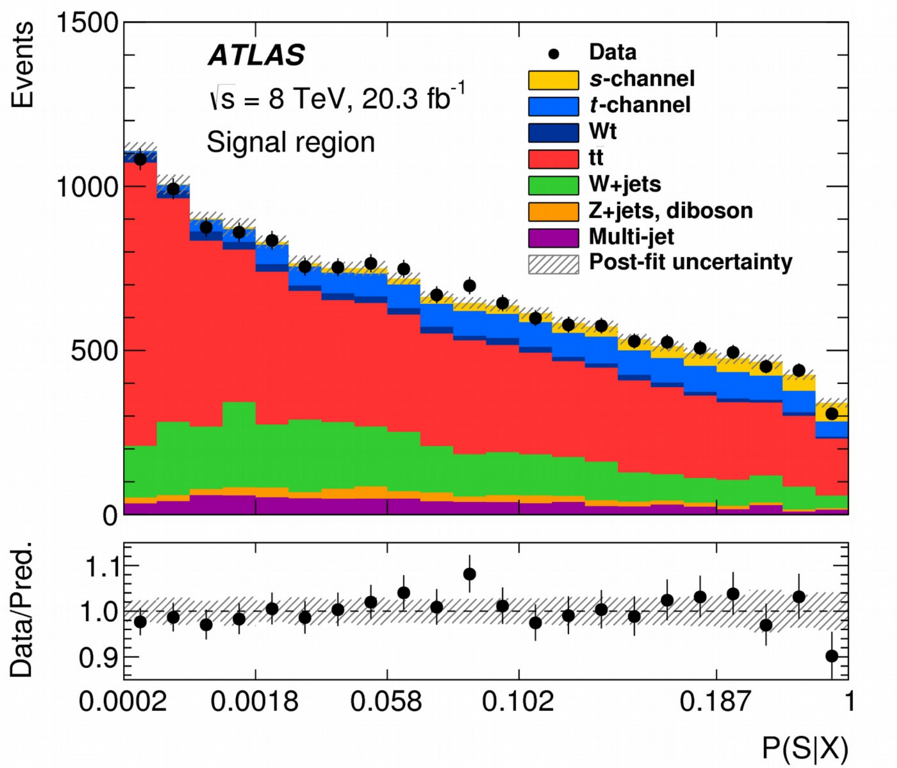
ATLAS analysis strategy:

- Selection: 1 lepton, 2 b-jets, large E_T^{miss}
- include t-chan and Wt in the backgrounds
- Matrix Element method to extract signal: use theoretical calculation to extract per-event signal probability
- Fit to ME discriminant (P(S|X)) to extract signal

Measured s-channel cross section at 8 TeV:

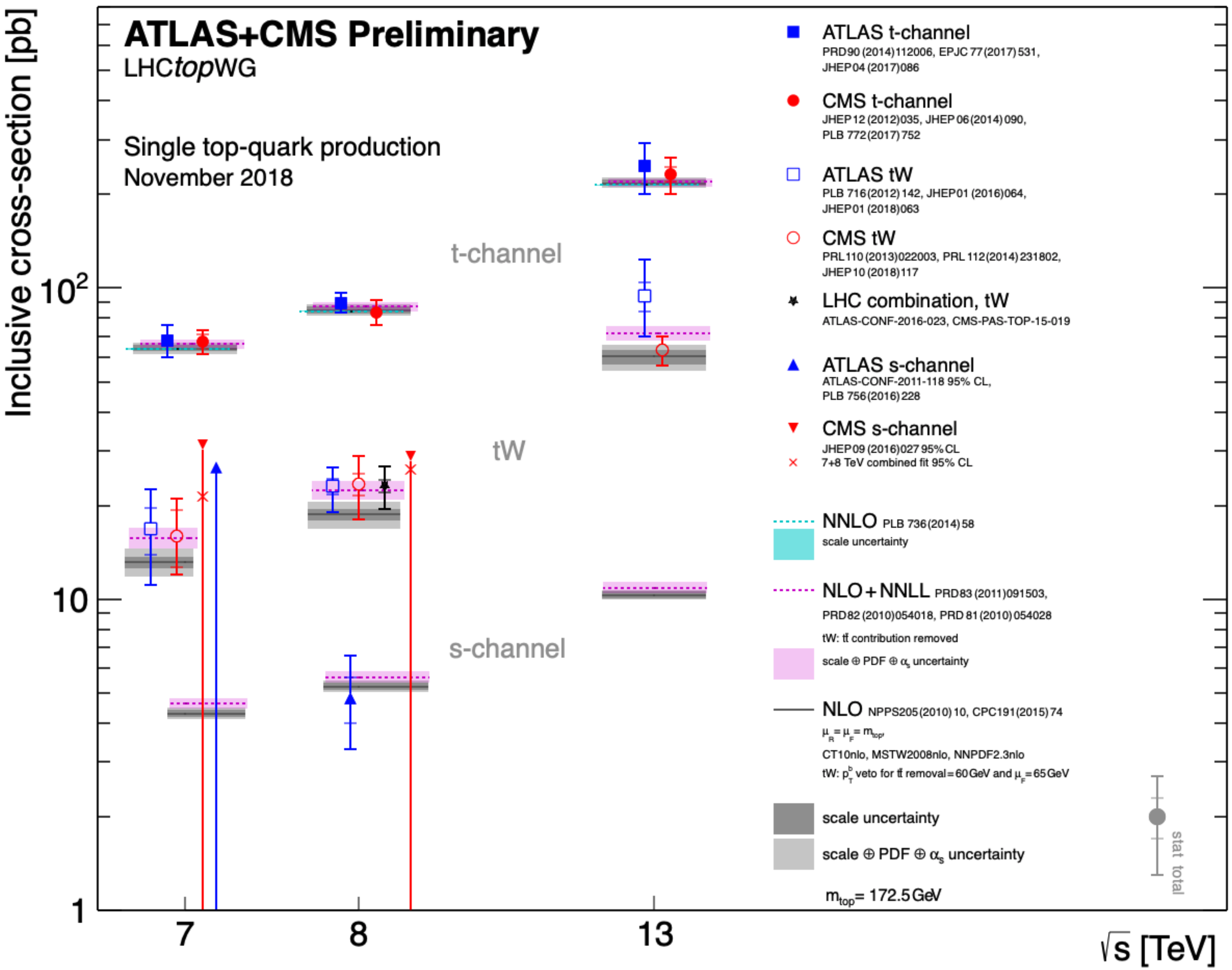
$$\sigma_{t,s-chan}(LHC\ \ 8\,TeV) = 4.8\ ^{+1.8}_{-1.6}\ pb$$

In agreement with SM expectations



Phys. Lett. B756 (2016) 228

Single top measurements at LHC



Recap

- What are the main $t\bar{t}$ production channels at the Tevatron and at the LHC?
- What are the reasons to measure differential cross sections corrected at parton and at particle level?
- Is it possible to determine $|V_{tb}|$ from $t\bar{t}$ or single top production?

?

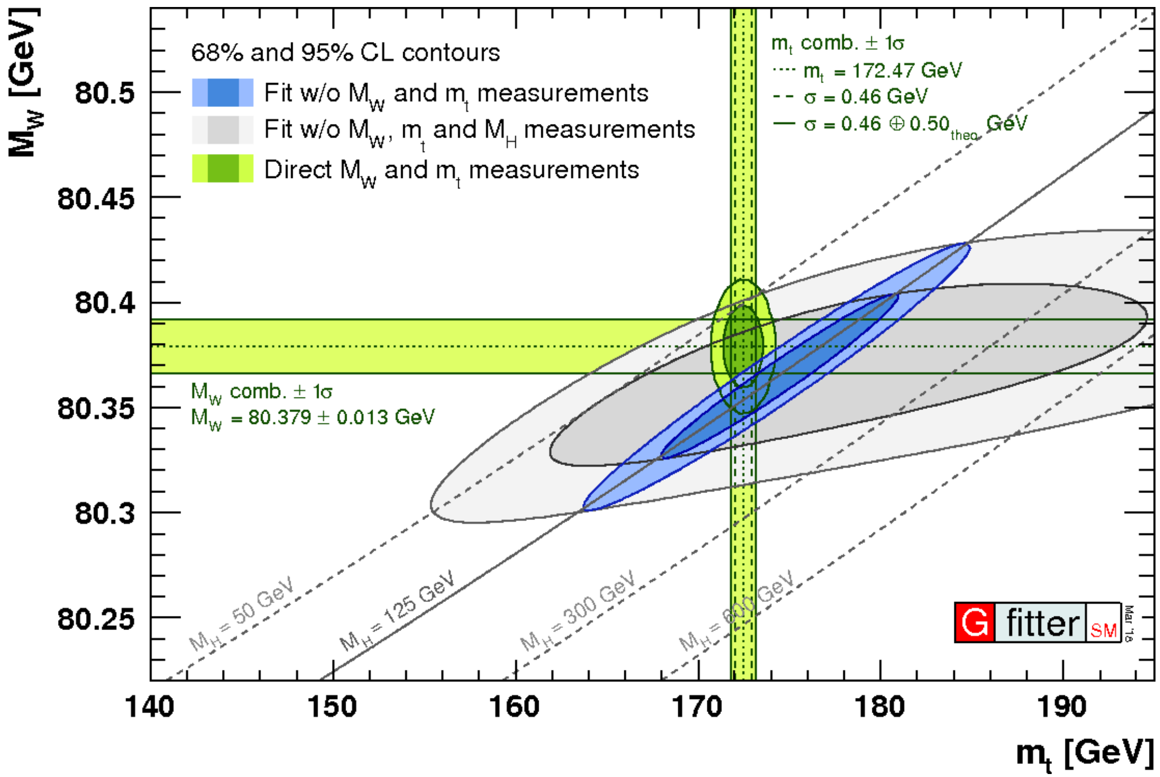
The top quark mass

The top quark mass

m_{top} is a fundamental parameter of the SM

In the SM it is linked to m_W and m_H through EW observables.

New physics may imply inconsistencies in the fit

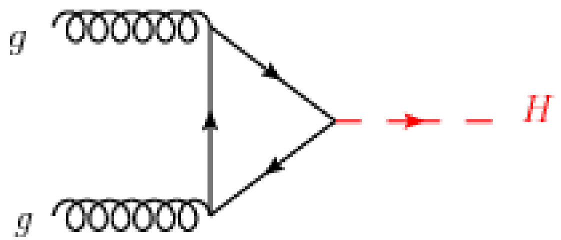


Plot show consistency between direct M_W and m_t measurements and their indirect determinations through EW fits, obtained excluding and including M_H measurements.

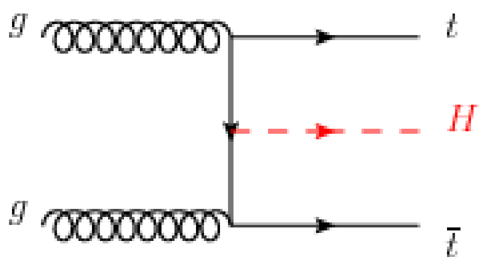
Top-Higgs coupling

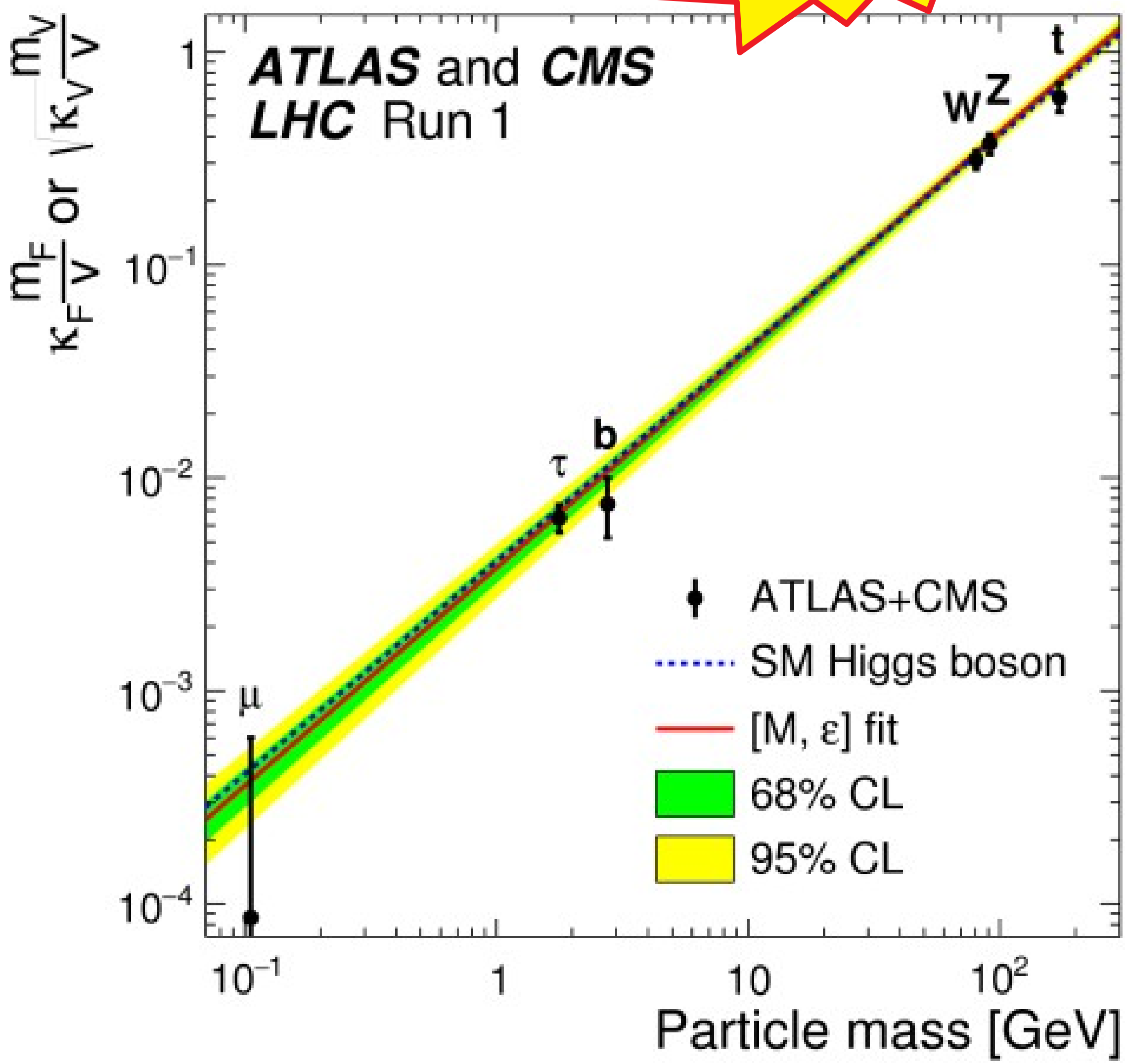
Spoiler!
see Paolo's talk

2012: Higgs boson discovered (top in the loop of main production process)



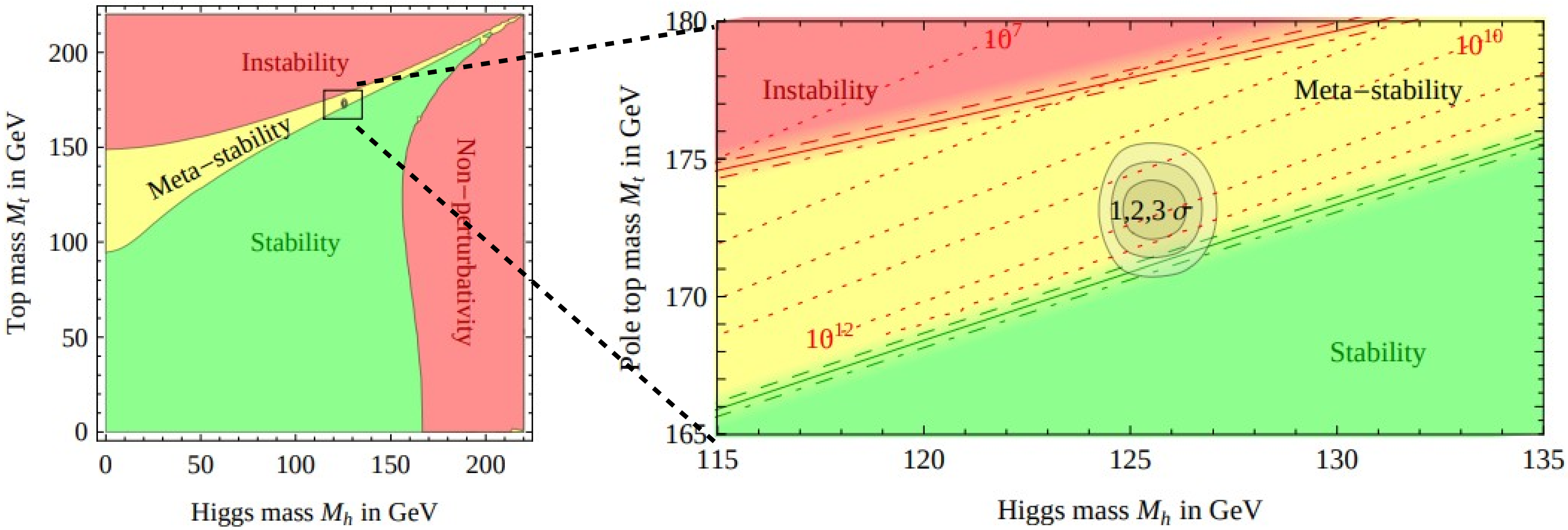
2018: ttH measured



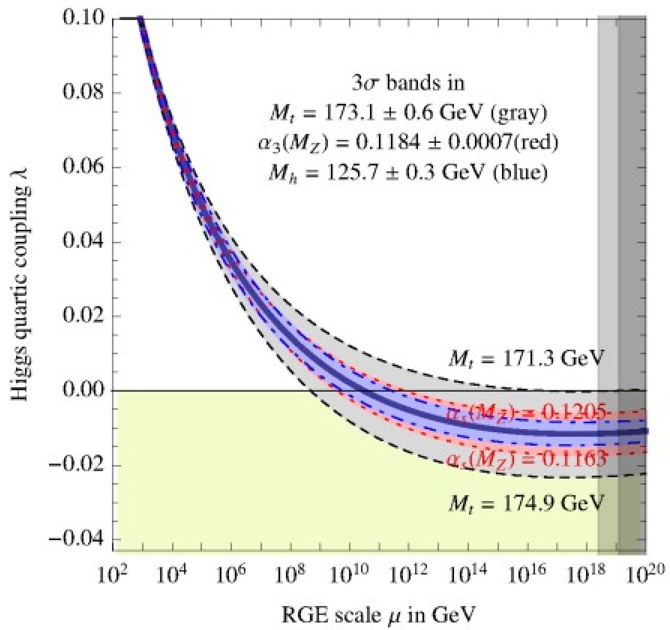


Strongest interaction ~1 with the Higgs boson

m_H, m_{top} and the stability of the universe



arXiv:1205.6497



The higgs potential can have other minima (metastability) if the coupling λ becomes negative.
Strongly dependent on the top mass.

The vacuum is metastable

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How to measure m_{top}

Measure quantities that depend on m_{top}

In top decay: measure kinematic distributions of decay products (including invariant mass of the reconstructed top quarks)

- Affected by radiation
- Need to be compared with MC predictions ($\rightarrow$ “MC” mass)

In top production: production cross sections depend on m_{top}

- Can be inclusive or differential (exploit particularly sensitive kinematic regions)
- Can be compared with fixed order QCD calculations ($\rightarrow$ pole mass)

Ingredients to reach ultimate precision:

- perform m_{top} measurements with different techniques
- use better calibrations
- look for quantities with small dependence on MC modeling

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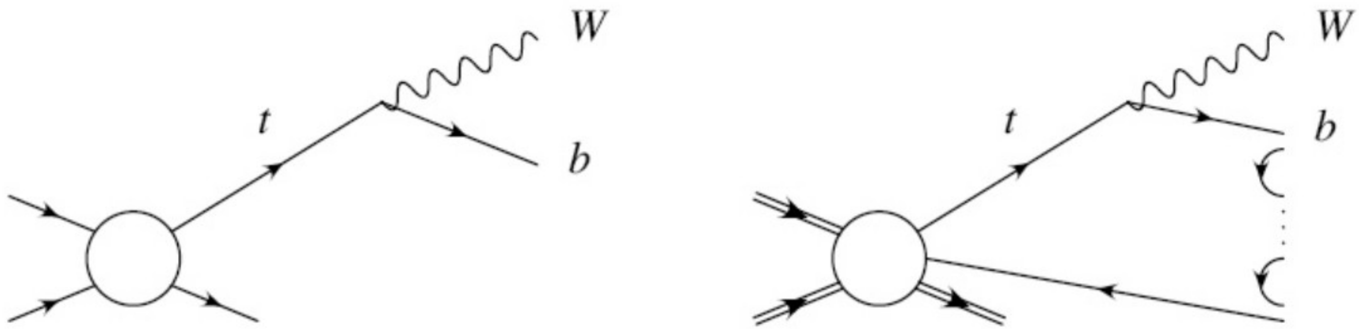
m_{top} what do we measure?

With experimental uncertainties <1 GeV we need to start worrying about the conceptual definition of m_{top}.

The pole mass is the mass of the freely propagating top quark. However free top quarks do not exist. The mass definition is affected by long distance effects (radiation, color connection, hadronization)



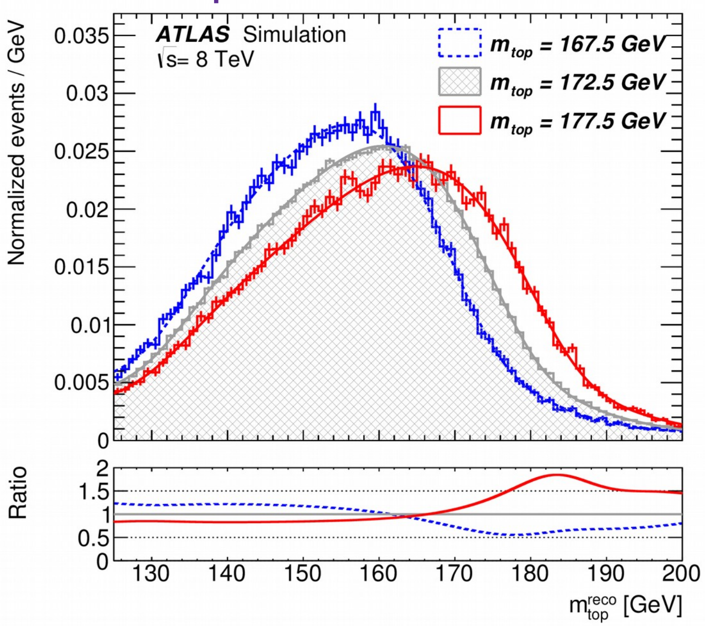
The MC mass is what is measured at collider through kinematic distributions of top decay products → close to pole mass
Ambiguity of the order of ΛQCD (few 100 MeV)

m_{top} measurements: Template method

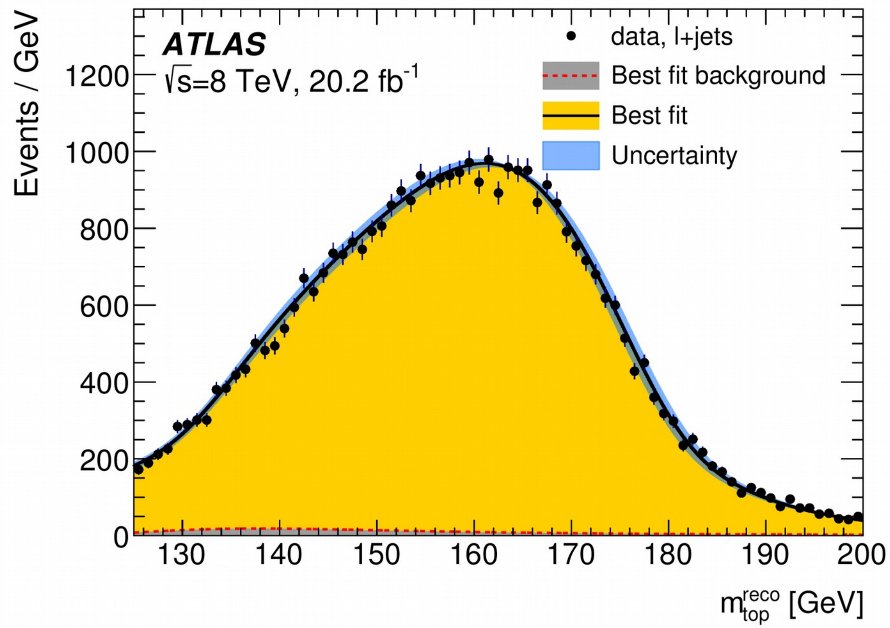
Overview of the technique:

- choose variables sensitive to m_{top}
- produce MC samples for different values of m_{top} and produce templates (distributions of the variable of interest)
- find the m_{top} value providing the best agreement with data
- additional quantities impacting the distributions of interest can be fitted simultaneously to m_{top}

Templates



Measured distribution with best fit

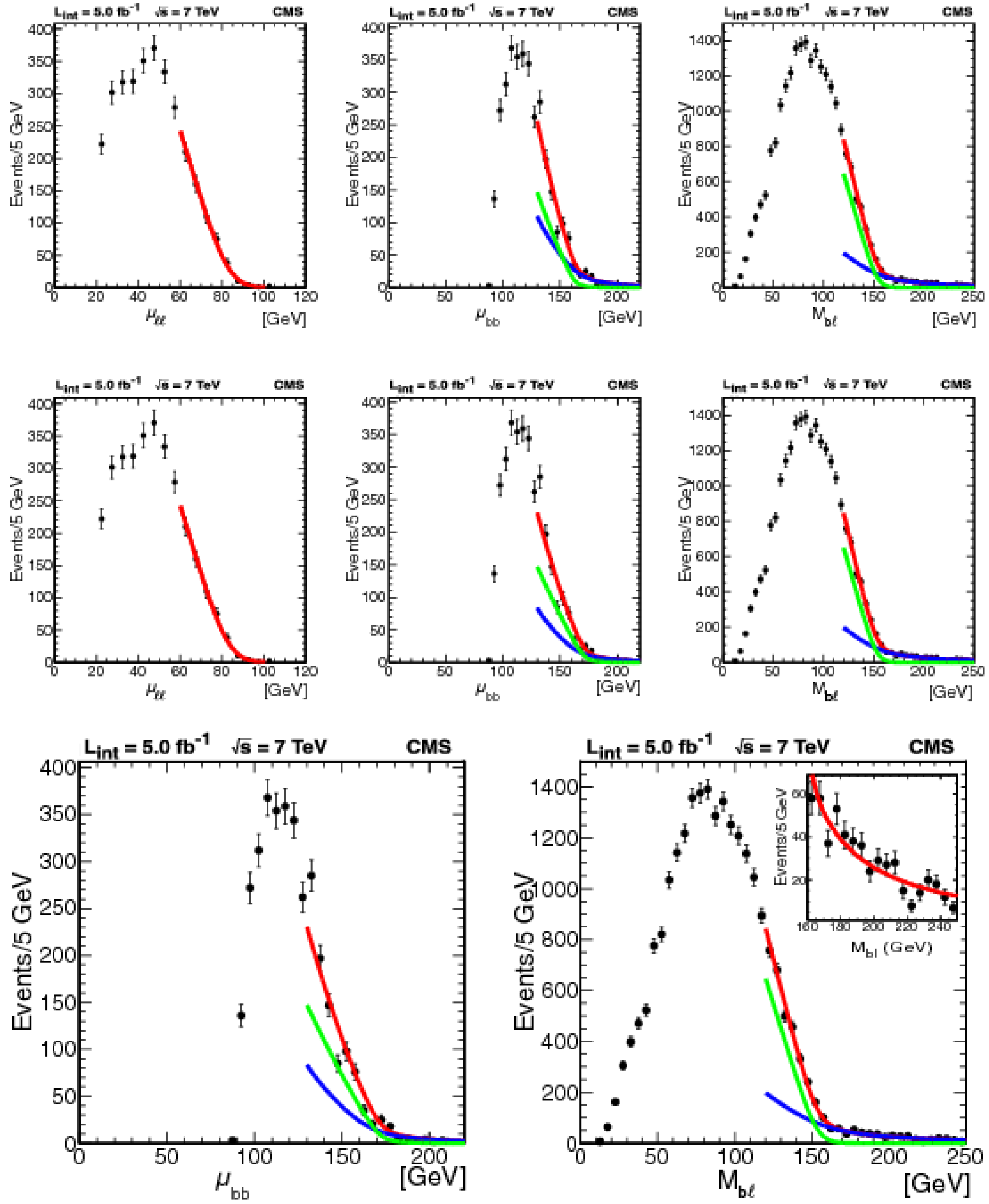


Eur. Phys. J. C79 (2019) 290

m_{top} measurements: Kinematic endpoints

Overview of the technique (CMS):

- use dilepton events
- in 3 body decays ($t \rightarrow b\, e^{+}\, \nu_e$) the kinematic endpoints are related to the mass of the decaying particle
- complications: at hadron colliders the $t\bar{t}$ production kinematic is not fully constrained
- choose kinematic variables particularly sensitive to m_{top}



$$m_{top} = 173.9 \pm 0.9\,(stat)\,^{+1.7}_{-2.1}\,(syst)\,GeV$$

Uncertainy dominated by the JES

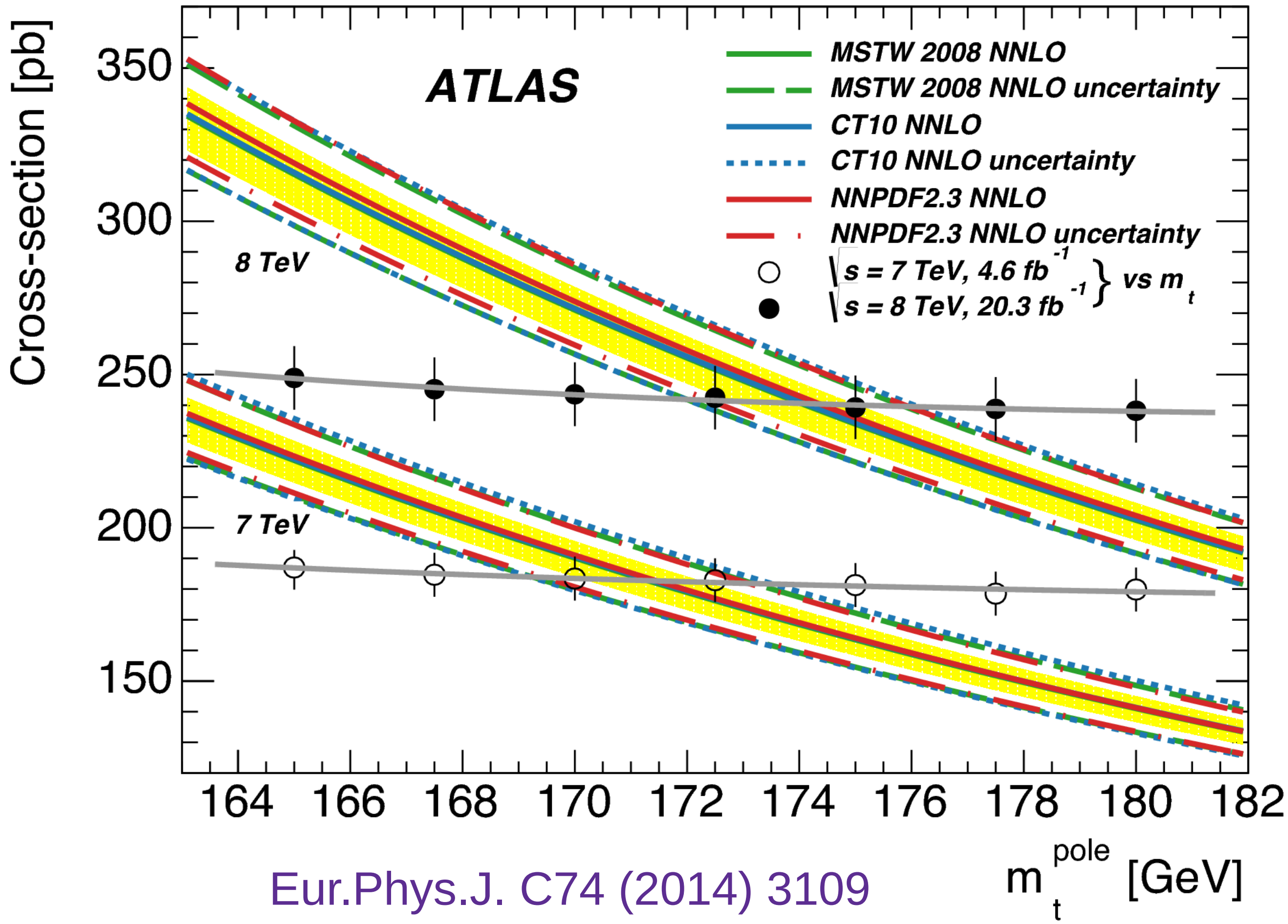
Total - Background - Signal

EPJC 73 (2013) 2494

m_{top} measurements: from $\sigma_{t\bar{t}}$

Overview of the technique:

- the total production cross section $\sigma_{t\bar{t}}$ is calculable as a function of m_{top}
- measuring $\sigma_{t\bar{t}}$ allows the indirect determination of m_{top} (pole mass)
- theoretical uncertainties (mainly scales) limit the precision



Eur.Phys.J. C74 (2014) 3109

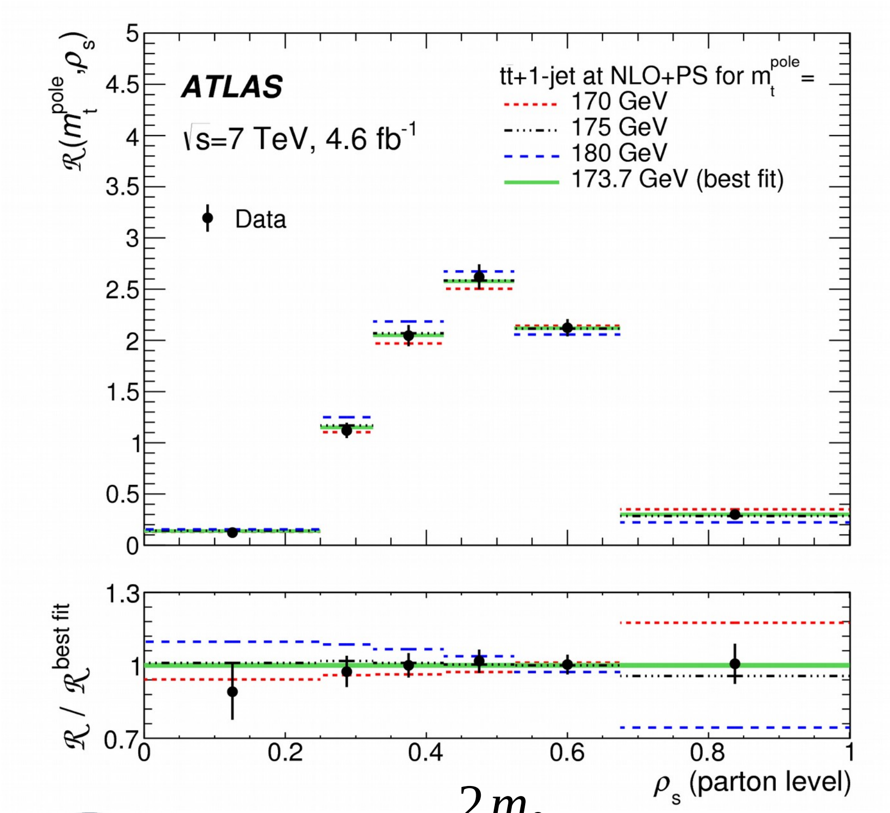
m_{top} measurements: from $d\sigma_{t\bar{t}}/dX$

Overview of the technique:

- specific regions of the phase space can be particularly sensitive to m_{top}
- exploit differential cross sections to reduce pole m_{top} uncertainties

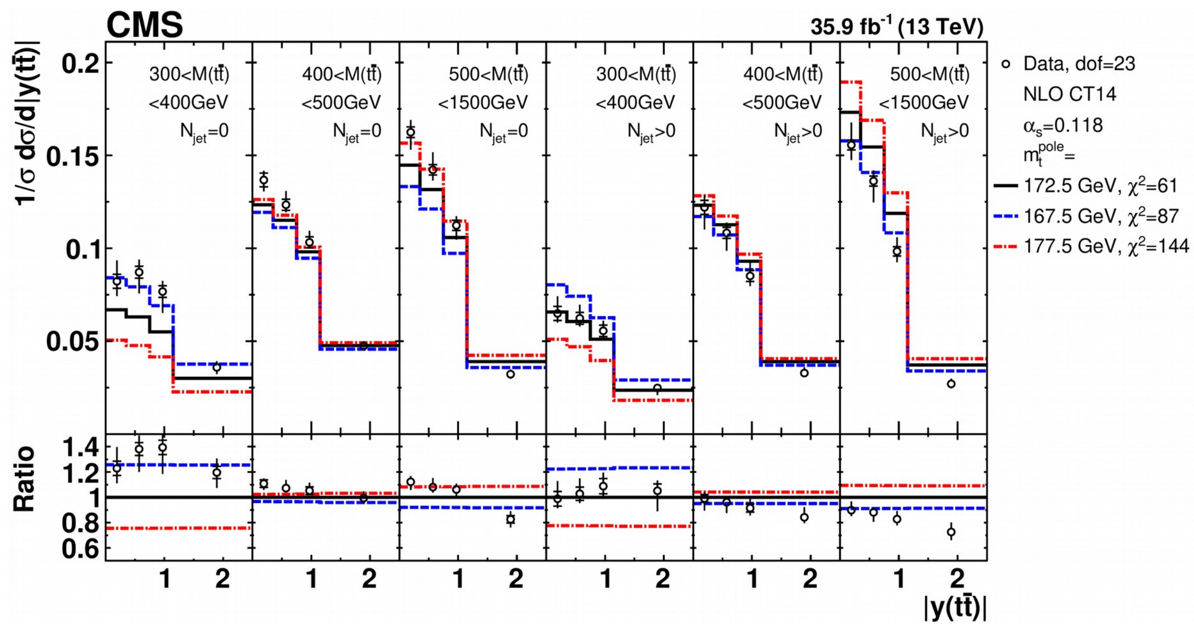
ATLAS $\sigma_{t\bar{t}+1jet}$ (JHEP 10 (2015) 121)

Exploit $t\bar{t}$+1jet cross section calculations

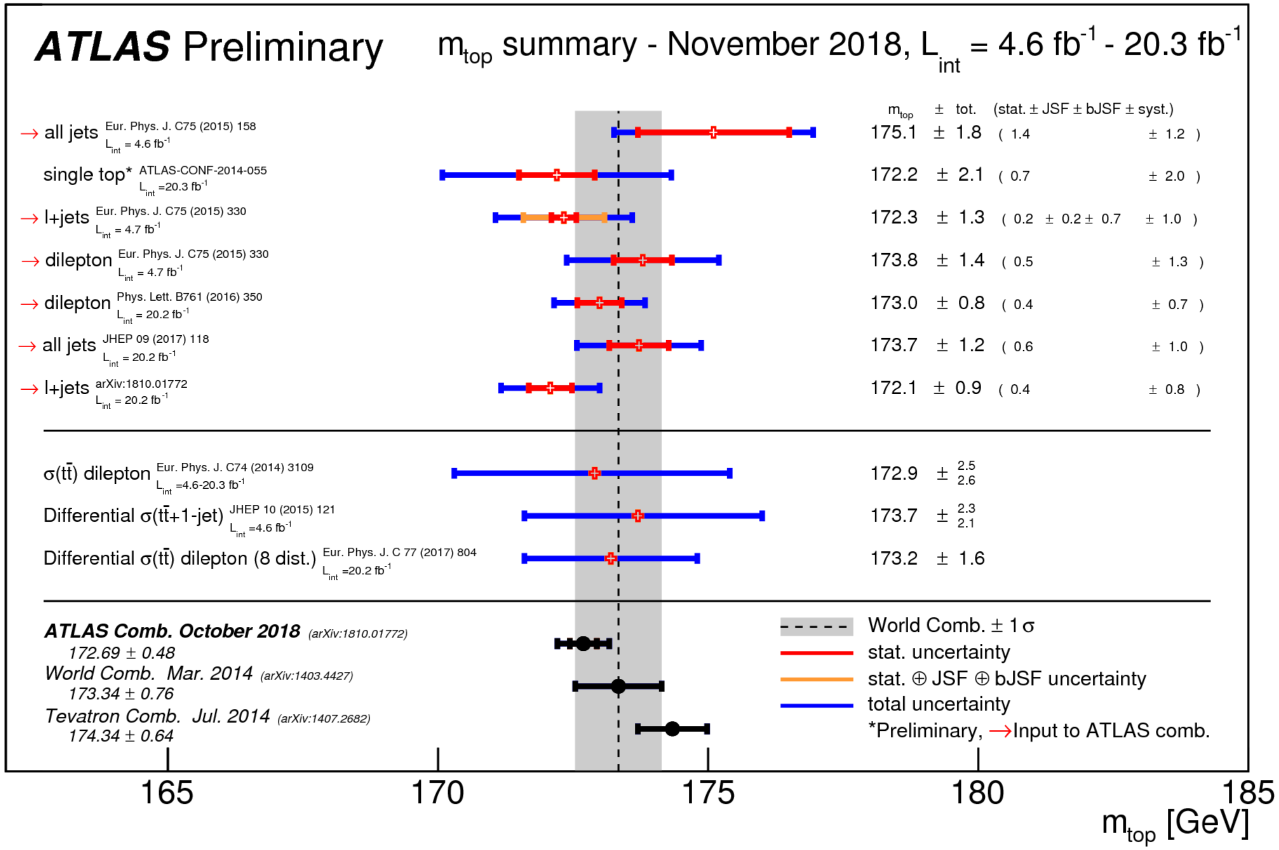


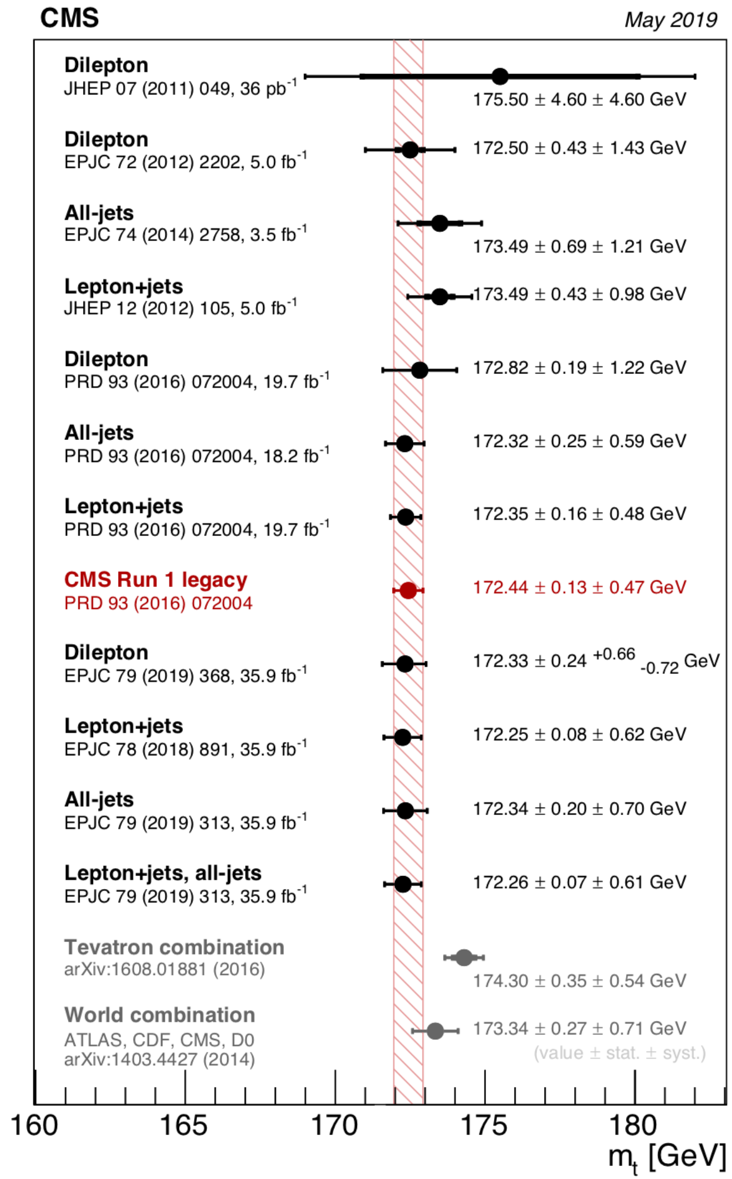
$$\rho_s = \frac{2 m_0}{\sqrt{s_{t\bar{t}+1\,jet}}}$$

CMS multi-differential (arXiv:1904.05237)



Top mass measurements





Reaching sub-GeV uncertainty in single measurements!

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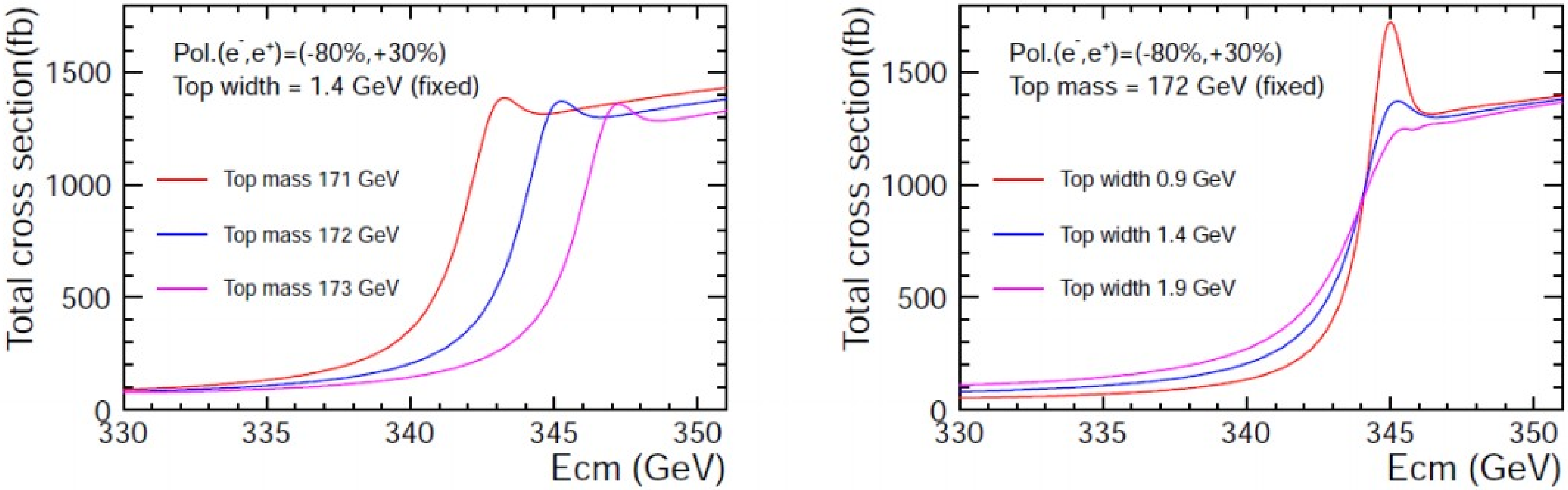
Top decay width

The top decay width can be computed as:

$$\Gamma_t = \frac{G_F m_t^3}{8\sqrt{2}\pi}\left(1-\frac{m_W^2}{m_t^2}\right)^2\left(1+2\frac{m_W^2}{m_t^2}\right) \approx 1.5\,GeV$$

It is too small to be measured directly at hadron colliders.
Indirect measurements provide tests of the SM and allow to check the top lifetime.

Ideal tool: top width could be measured from energy scan at the $t\bar{t}$ production threshold at a future e^+e^- collider
Uncertainties: σ_m~50 MeV, σ_Γ~20 MeV



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Indirect width measurement (CMS)

Phys. Lett. B 736 (2014) 33

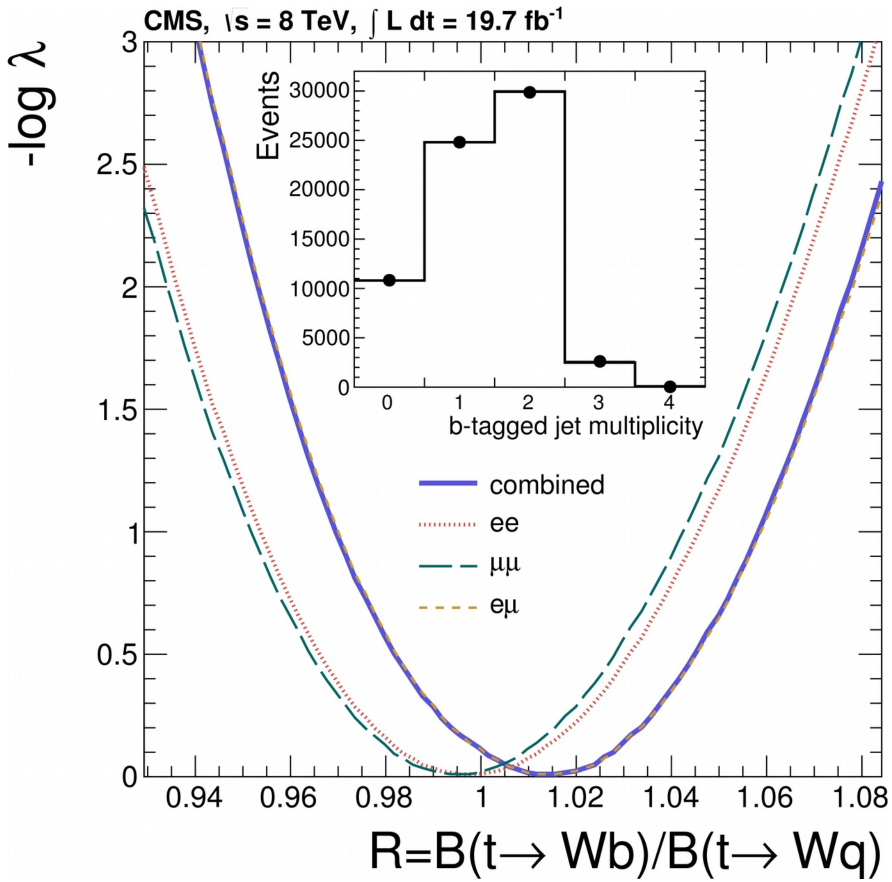
Starting from a measurement of:
R=B(t→Wb)/B(t→Wq)

Assuming $\Sigma_q B(t \to Wq)=1 \to R=B(t \to Wb)$

It is possible to extract the top width by comparing the measured values with the theoretical expectations

$$\Gamma_t = \frac{\sigma_{t-chan}}{B(t \to Wb)} \cdot \frac{\Gamma(t \to Wb)}{\sigma_{t-chan}^{theo}}$$

where Γ(t→Wb)=1.33 GeV is the theoretical partial width



$$\Gamma_t = 1.36 \pm 0.02(stat)\,^{+0.14}_{-0.11}(syst)\,GeV$$

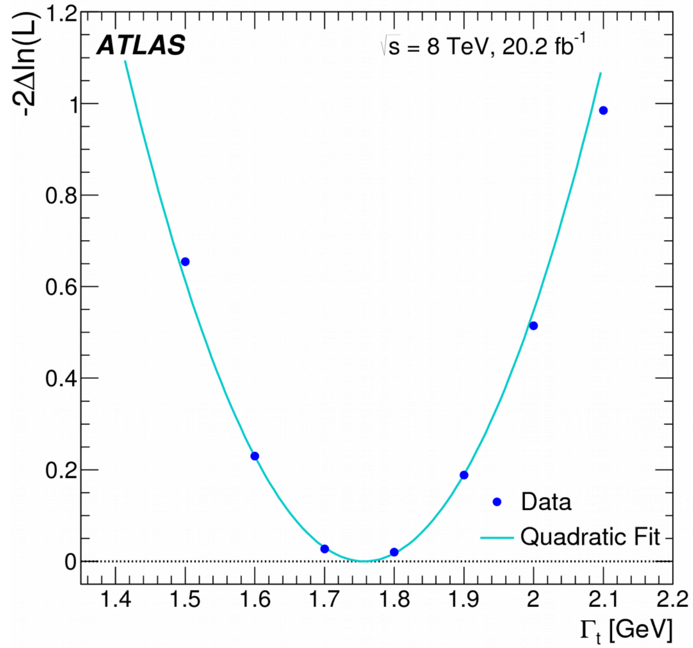
Width from template fit (ATLAS)

Some kinematical distributions are particularly sensitive to the top width

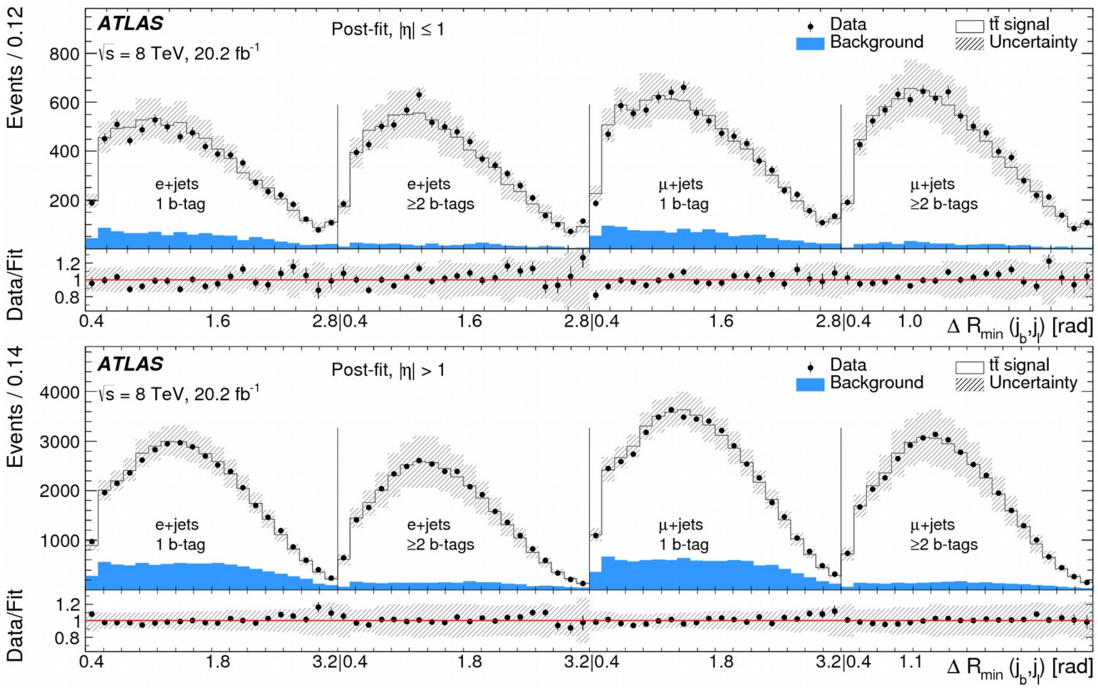
- m_{lb} = inv. mass of the lepton and the b-jet in leptonic top
- $\Delta R_{min}(j_b,j_l)$ = min. angular separation between b-jet and light jet in hadronic top

Less precise than indirect measurements but avoid model-dependent assumptions

Eur. Phys. J. C 78 (2018) 129



$$\Gamma_t = 1.76 \pm 0.33\,(stat)\,^{+0.79}_{-0.68}\,(syst)\,GeV$$



Data/predictions for $\Delta R_{min}(j_b,j_l)$ based on the templates corresponding to the best fit (similar plots for m_{lb})

Recap

- Are there ambiguities in the measurement of the top quark mass?
- Can you summarize a way to measure the top “pole” mass?
- What is the ideal tool to measure the top quark mass and width?

?

Other top quark properties

Top spin correlation
W polarization
$t\bar{t}$ production asymmetries

Top spin correlation

Top quarks decay very rapidly, before spin decorrelation effects occur.
Information on the spin can be obtained from the decay products.

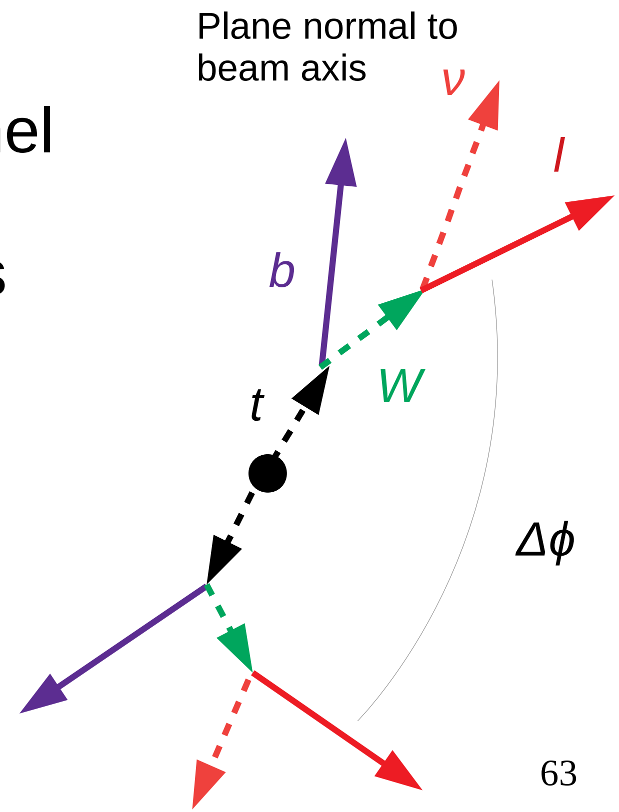
Top quarks are not expected to be polarized in the SM.
However, the spins of t and $\bar{t}$ are predicted to be correlated.

- Spin correlation depends on the production mechanism
- New physics can affect spin correlation

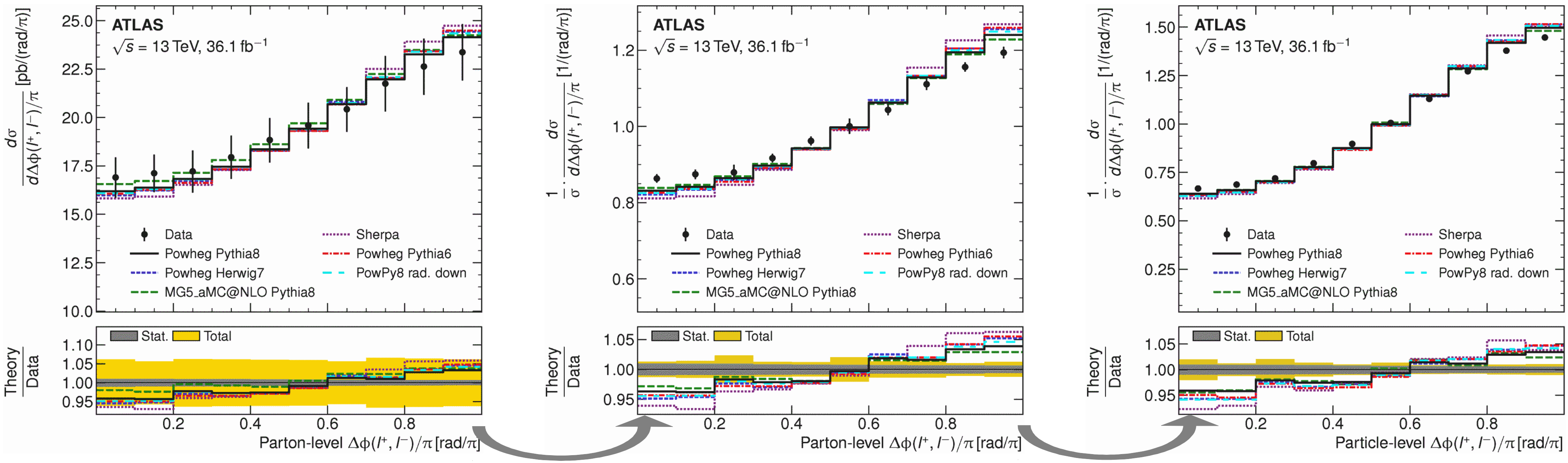
Most powerful analyzers: leptons → dilepton channel

Δϕ: azimuthal opening angle between the 2 leptons

- particle level → fiducial phase space
- parton level → full phase space



Top spin correlation



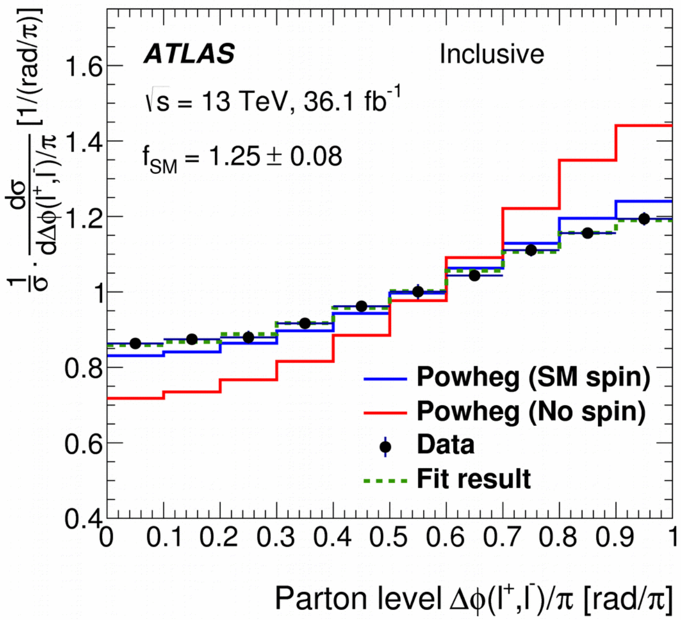
Normalized

Particle-level

Effect of spin correlation observed → OK!

Measured Δϕ show a trend with respect to NLO+PS predictions, clearly visible in normalized measurements
→ Spins seem to be slightly “more” correlated than SM

Investigation of possible explanations on theory and experiment sides.



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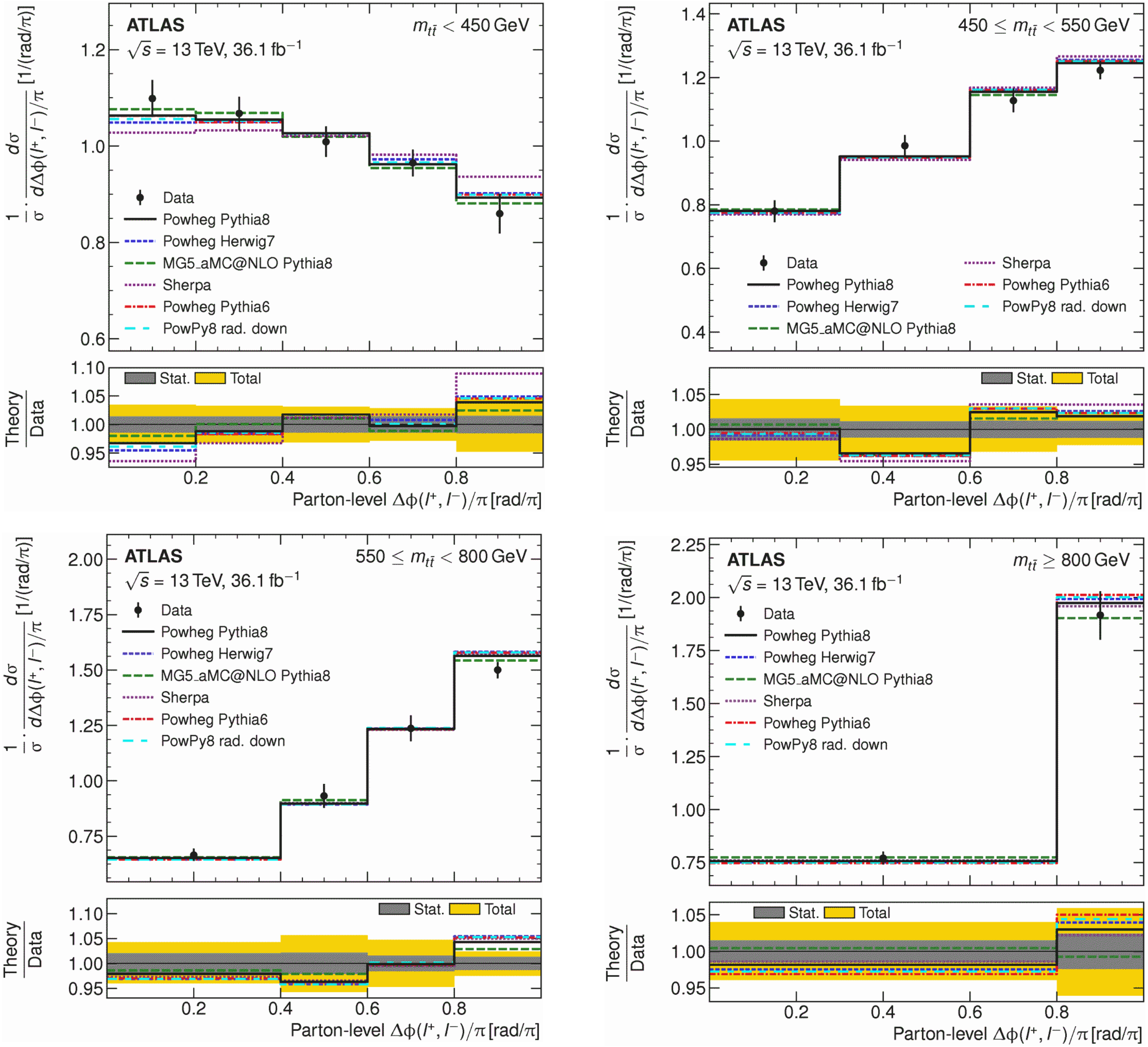
arXiv:1903.07570

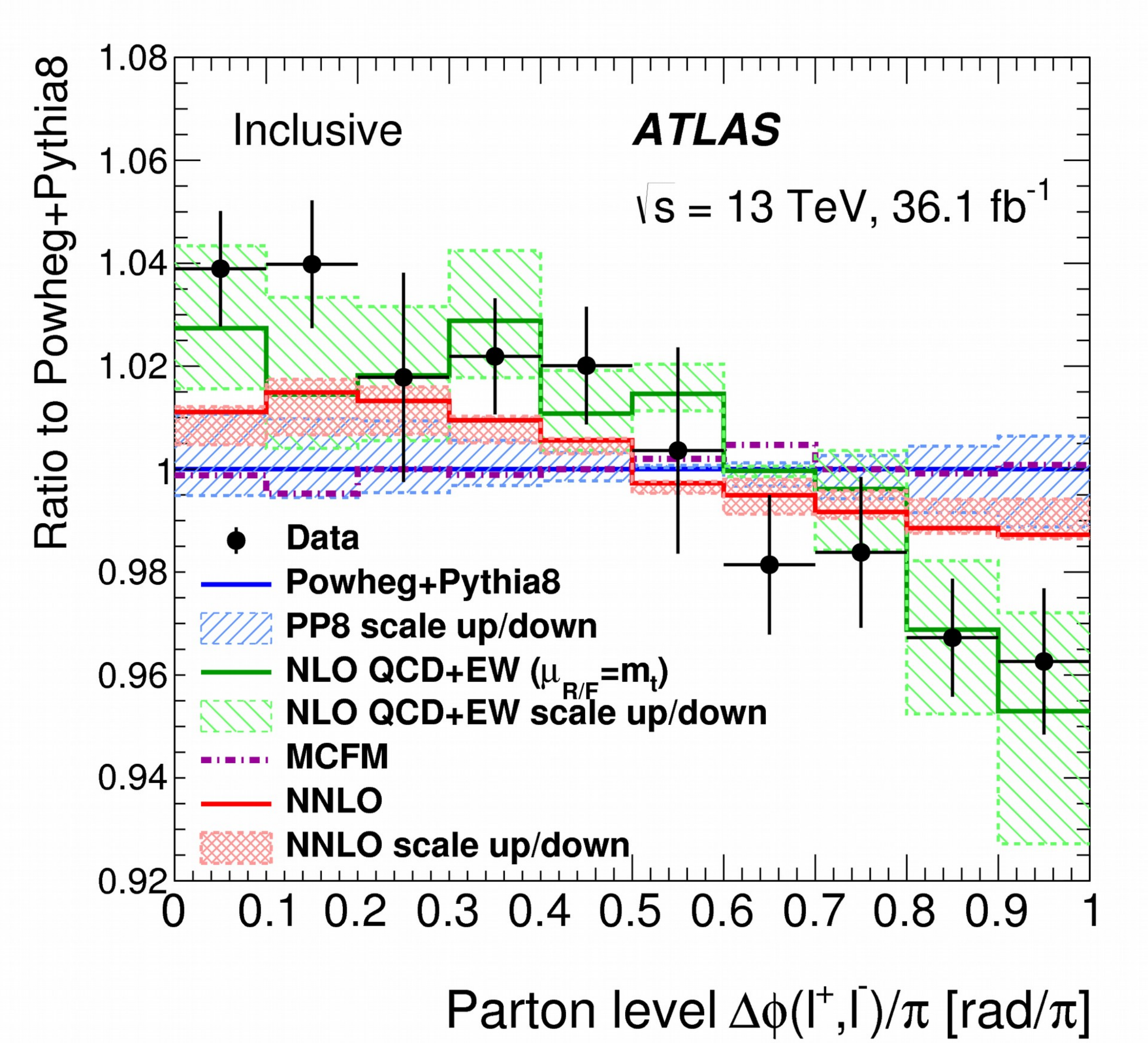
Top spin correlation

$\Delta\phi$ dependent on p_T of the t and $\bar{t}$ → check dependence on $m_{t\bar{t}}$



Top spin correlation

Reasonable description obtained with NLO QCD+EW

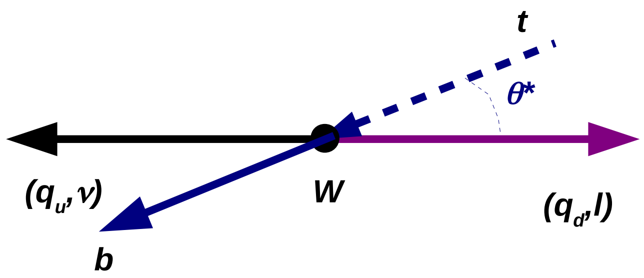


W polarization in top decays

- W bosons from t decay polarized because of V-A structure of decay vertex
- Three W boson helicity fractions F_i ($i = 0, L, R$) for longitudinal, left- and right-handed

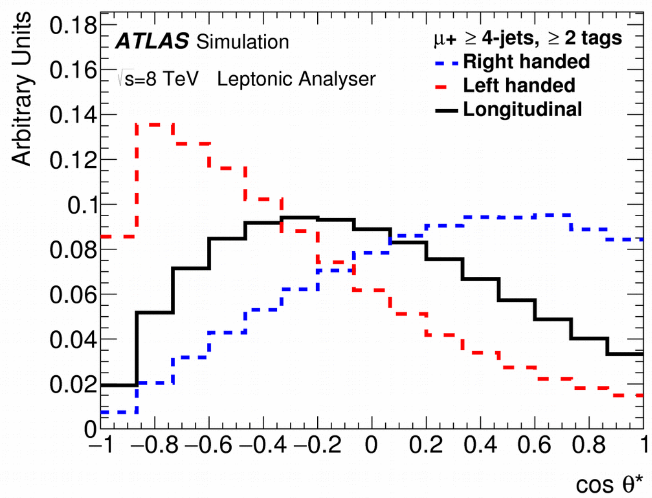
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*} = \frac{3}{4}(1-\cos^2\theta^*)F_0 + \frac{3}{8}(1-\cos\theta^*)^2 F_L + \frac{3}{8}(1+\cos\theta^*)^2 F_R$$

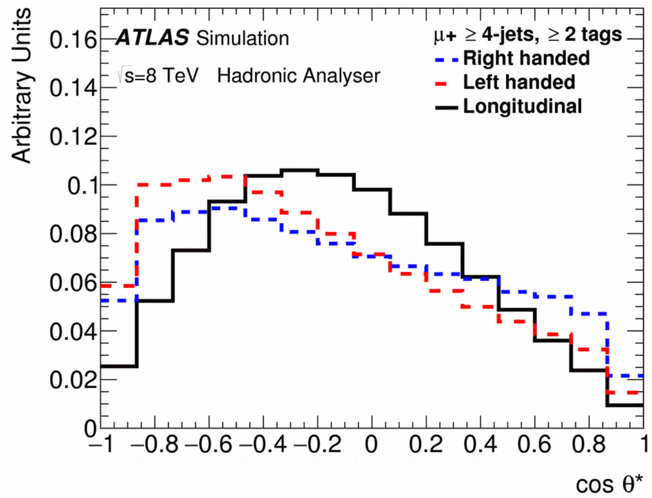
NNLO predictions:
- F_0: 0.687±0.005
- F_L: 0.311±0.005
- F_R: 0.0017±0.0001



θ* : Angle between the reversed direction of flight of the b-quark and the lepton or d-type quark in the W rest frame

Fit of the cosθ* distributions using templates





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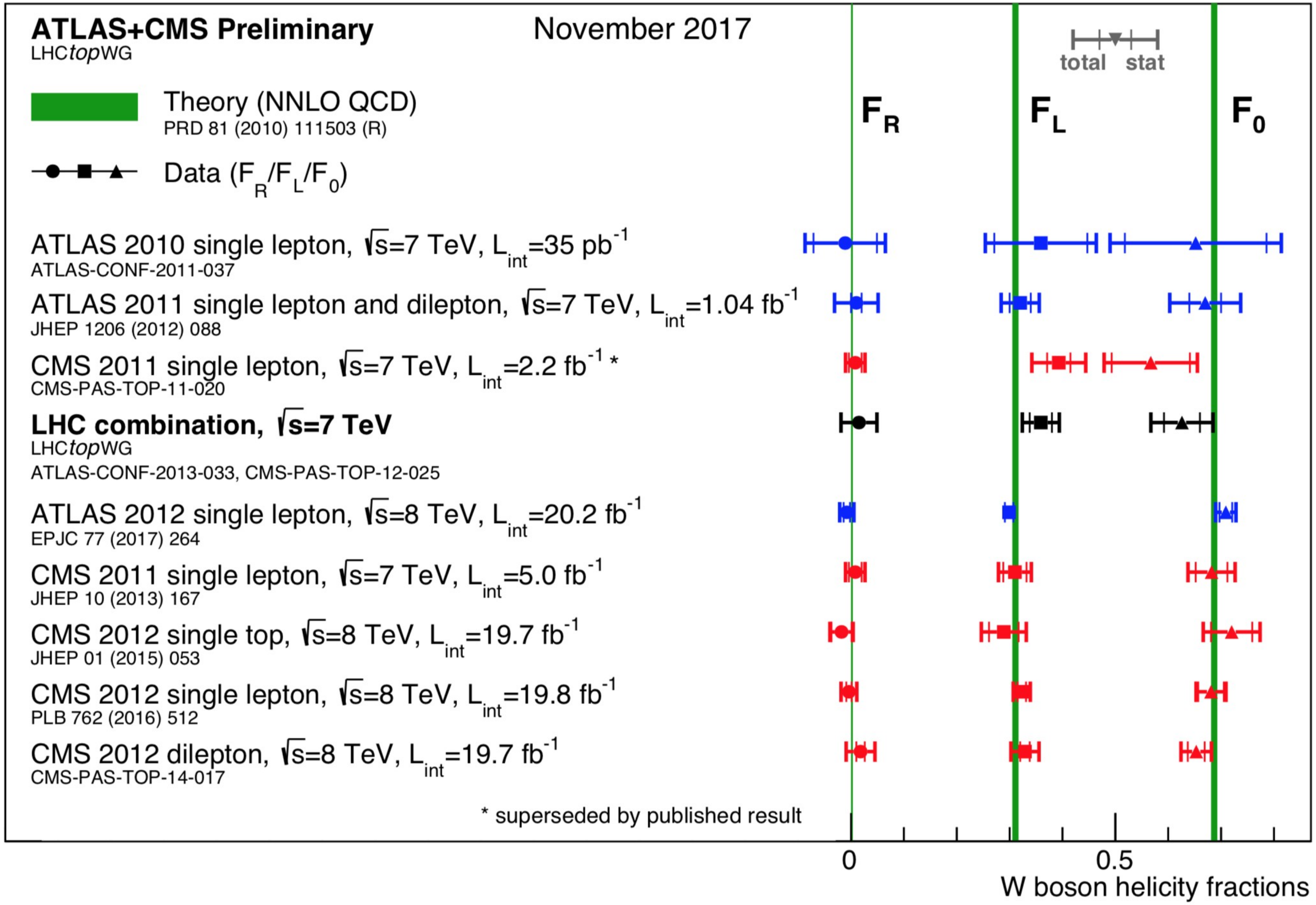
W polarization in top decays

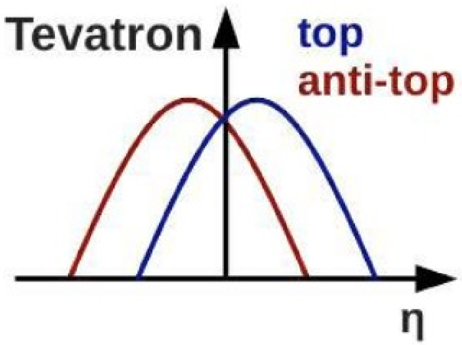


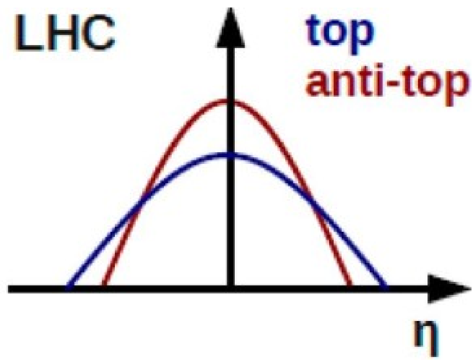
Summary of ATLAS and CMS measurements of W helicity fractions
Theory predictions: green line (uncertainty is the line width)

Asymmetries at hadron colliders

NLO calculations predict a small asymmetry for $t\bar{t}$ produced in $q\bar{q}$ annihilation, from interference between tree and box diagrams (no asymmetry at LO). No asymmetry in gg fusion.

- **Tevatron is $p\bar{p}$ collider**
  - possible to define "forward" and "backward" directions
  - $t\bar{t}$ production dominated by $q\bar{q}$ annihilation
- **LHC is a pp collider**
  - impossible to define "forward" and "backward" directions
  - $t\bar{t}$ production dominated by gg fusion





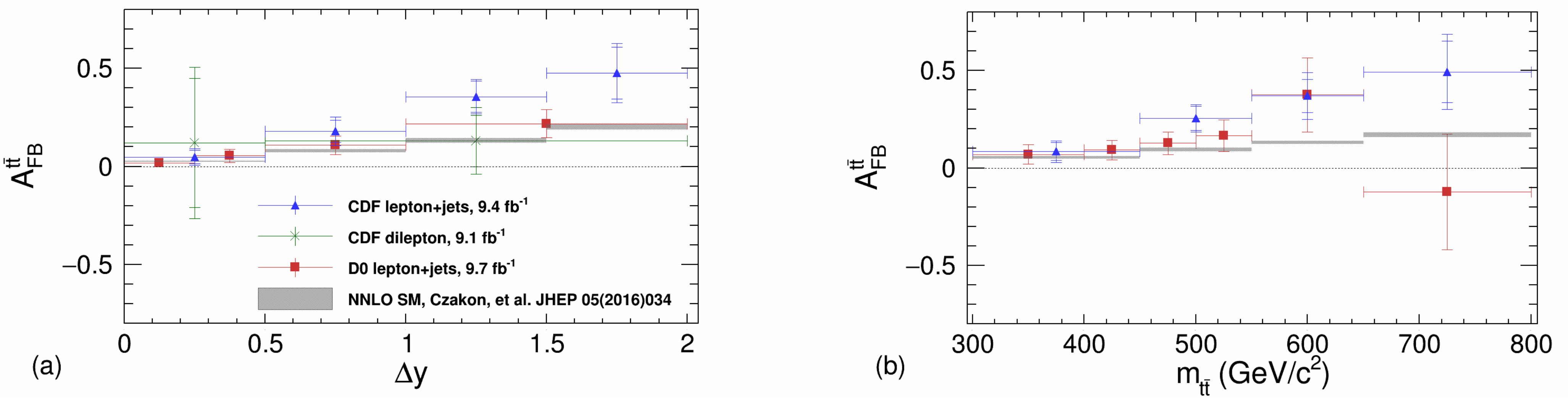
At the LHC, asymmetry in the suppressed $q\bar{q} \rightarrow t\bar{t}$ (valence quark interaction with sea anti-quark). Anti-top produced more "centrally"

Forward-Backward asymmetry - Tevatron

Measure asymmetry in Forward-Backward $t\bar{t}$ production

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

Compare with SM expectation (small but not null asymmetry).
Calculations also predict A_{FB} as a function of $y_{t\bar{t}}$ and $m_{t\bar{t}}$



A_{FB} in good agreement with NNLO calculation

Charge asymmetry - LHC

Small asymmetry expected from $q\bar{q}$ annihilation

$t\bar{t}$ asymmetry:

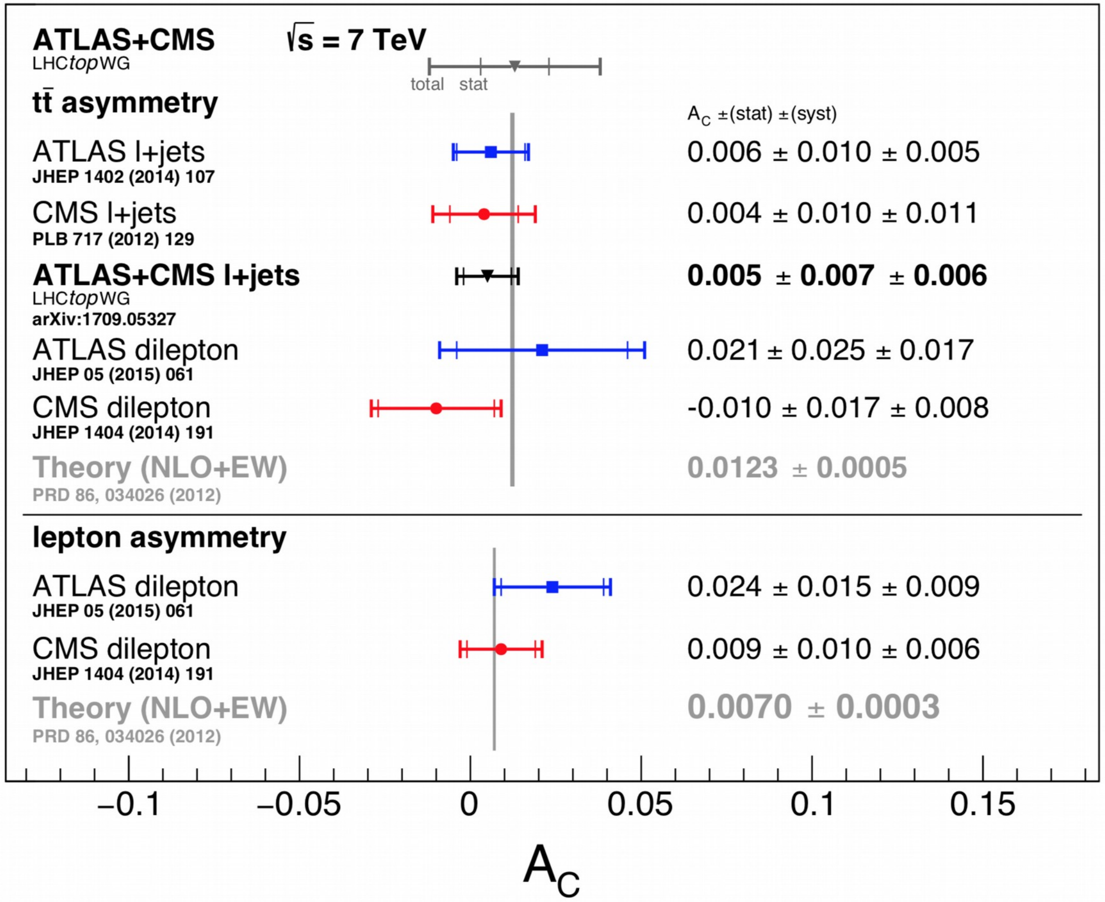
$$A_C^{t\bar{t}} = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)}$$

$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$

Leptonic asymmetry:

$$A_C^{ll} = \frac{N(\Delta|\eta|>0) - N(\Delta|\eta|<0)}{N(\Delta|\eta|>0) + N(\Delta|\eta|<0)}$$

$$\Delta|\eta| = |\eta_{l^+}| - |\eta_{l^-}|$$

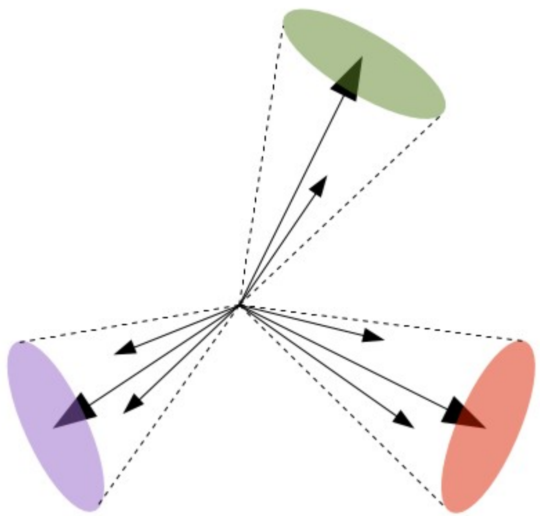


Looking for new physics effects

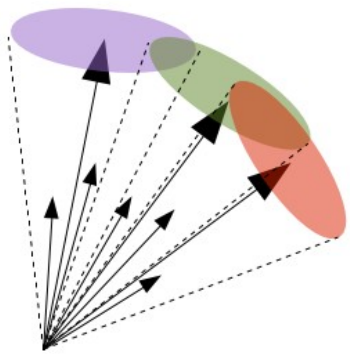
Boosted tops and tt resonances
Flavor Changing Neutral Currents

Boosted tops

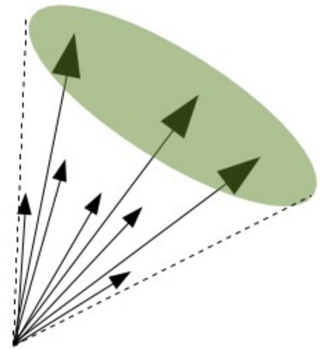
At very high p_T the top decay product (hadronic decay) tend to be more collimated and cannot be reconstructed as separate jets



Hadronic decay of low-p_T top



Hadronic decay of high-p_T top
Jets can partially overlap



Hadronic decay of high-p_T top
Reconstruction as large-R jet

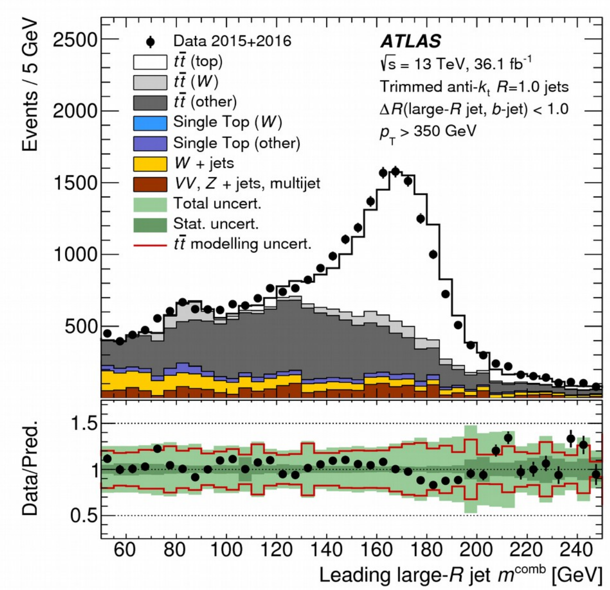
The identification of top quarks is based on jet sub-structure analysis

- Jet mass
- Splitting scales (distance among proto-jets during jet construction)
- … and many others

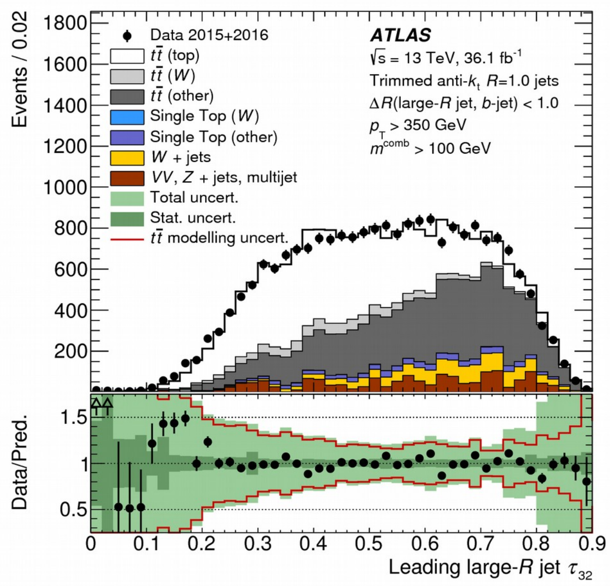
Large-R jet substructure

Active research on large-R jet reconstruction, calibration, tagging

- Need tool to remove pile-up contribution (soft radiation)
- Identify jets with “multi-prong” hard structure

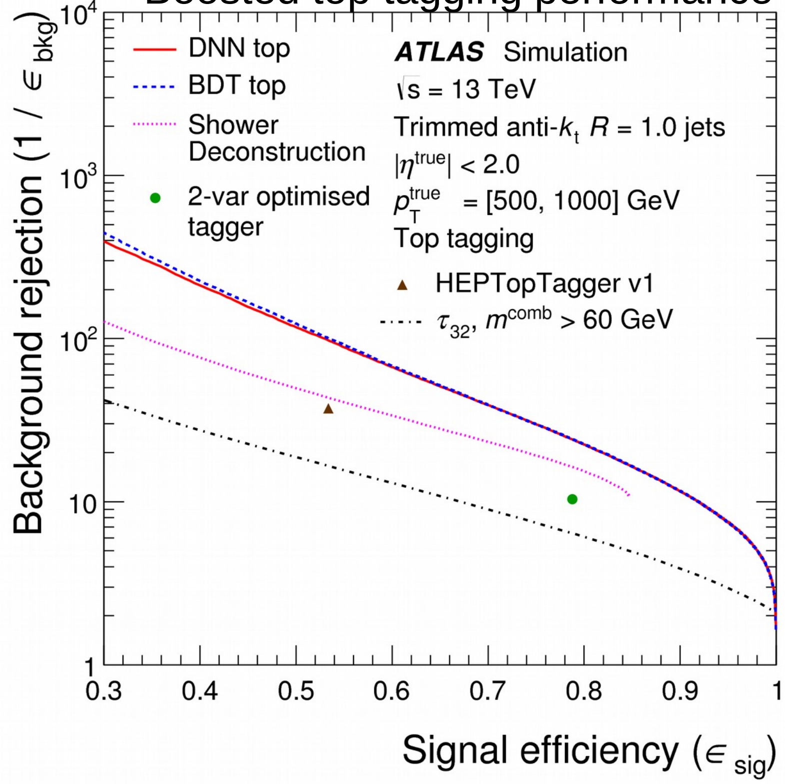


Jet mass



N-subjettiness ratio

Boosted top tagging performance



Substructure information also used in Machine Learning taggers to increase efficiency

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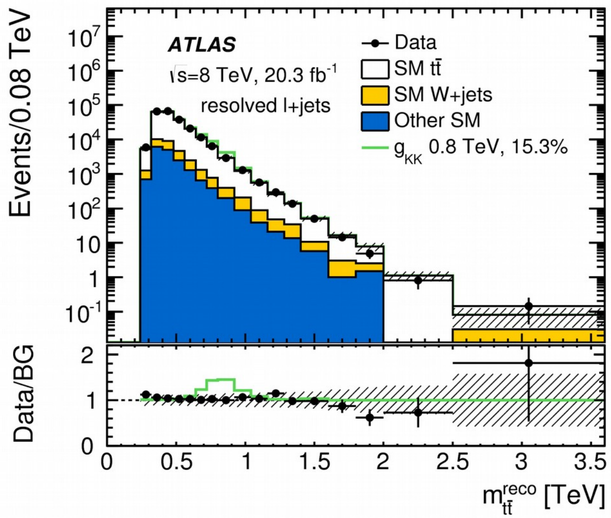
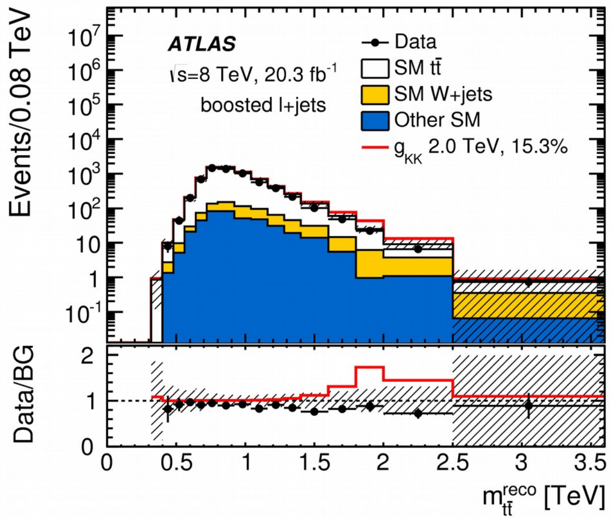
$t\bar{t}$ resonance search

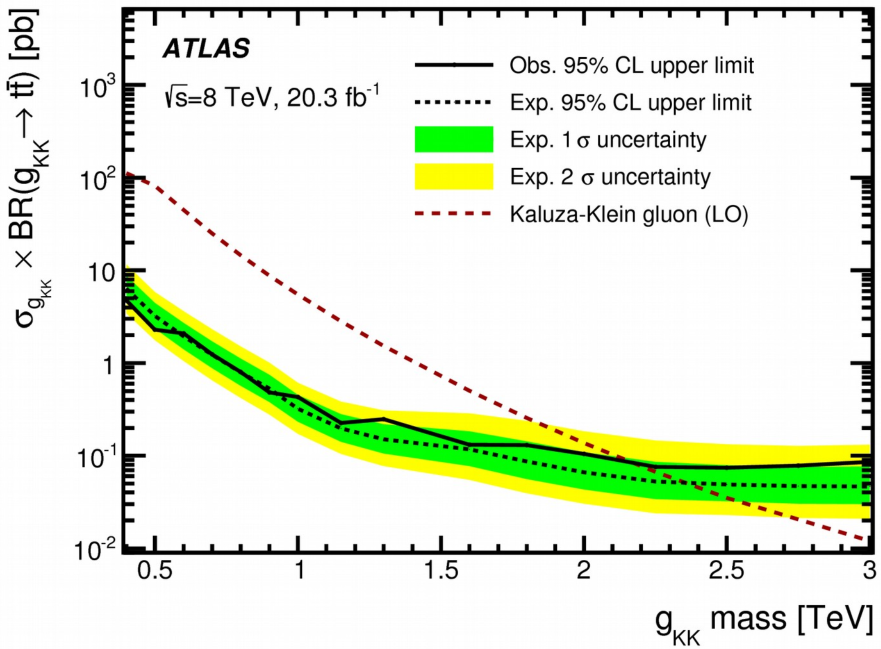
The use of boosted top reconstruction techniques allows to push the mass limits in $t\bar{t}$ resonance searches

$m_{t\bar{t}}$ resolved selection



$m_{t\bar{t}}$ boosted selection





Extract limits on the mass of hypotethical resonance based on production cross section predictions (here Kaluza-Klein gluon).

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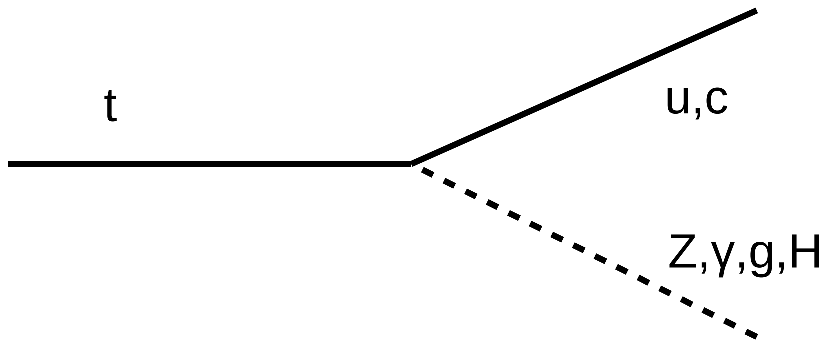
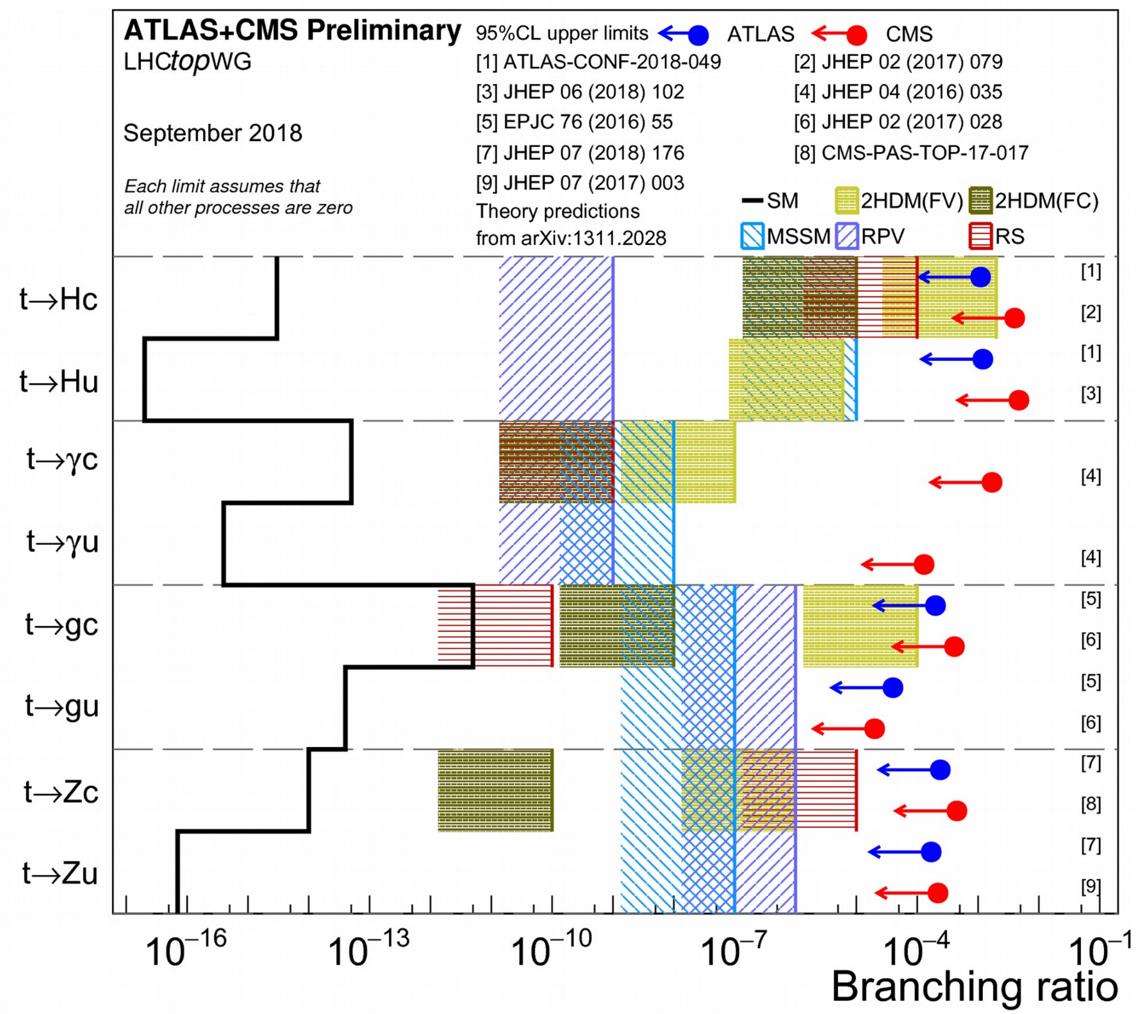
Flavor Changing Neutral Currents



- In the SM: forbidden at tree level, expected BR at 10^{-10}-10^{-15} level
- BSM models can enhance BR to ~10^{-7}-10^{-3}
- Current experimental reach ~10^{-3}-10^{-4}



Summary

- The top quark is **special**!
  - It gives the unique opportunity to study a bare quark
  - It has the strongest coupling to the Higgs boson
  - Its mass gives us indications on the (meta-)stability of our universe
- The top quark is **complicate**!
  - Need to use the full detector to reconstruct top quark events
  - … but there are leptons and b-jets to make our life easier
- The top quark is **precise**!
  - LHC is a top factory, we have huge samples
  - Theoretical calculation at NNLO available
- The top quark **poses questions**!
  - Why its mass is so large?
  - Does it have a special role in new physics?

The top quark is very interesting!

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QUESTIONS