Extracting the width of the top quark at the LHC

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Introduction

The Large Hadron Collider (LHC) is the world's largest and most powerful particle accelerator, the intent of which is to collide opposing particle beams, of either protons and lead nucleii at very high energies (TeV-range/nucleus). The Large Hadron Collider was built by the European Organisation for Nuclear Research (CERN) with the intention of testing various predictions of high-energy physics, including the existence of the hypothesized **Higgs boson** and of the large family of new particles predicted by supersymmetry. It lies in a tunnel 27 kilometres (17 mi) in circumference, as much as 175 metres (570 ft) beneath the Franco-Swiss border near Geneva, Switzerland. It is funded by and built in collaboration with over 10,000 scientists and engineers from over 100 countries as well as hundreds of universities and laboratories.

The unification of the forces of nature is considered as the **"holy grail"** for physicists, and the partial description of such is given by the **Standard Model (SM)**, which is defined as a **unified gauge theory of the strong, weak and electromagnetic interactions.**

The ATLAS experiment at the LHC

- ATLAS is one of two general-purpose detectors at the LHC
- Research focuses on the Higgs boson, extra dimensions and dark matter
- ATLAS record similar sets of measurements on particles created in the collisions (e.g. paths, energies, and identities).
- Main feature of ATLAS detector - enormous doughnut - shaped magnet system. This consists of eight 25-m long superconducting magnet coils, arranged to form a cylinder around the beam pipe through the centre of the detector. During operation, the magnetic field is contained within the central cylindrical space defined by the coils.

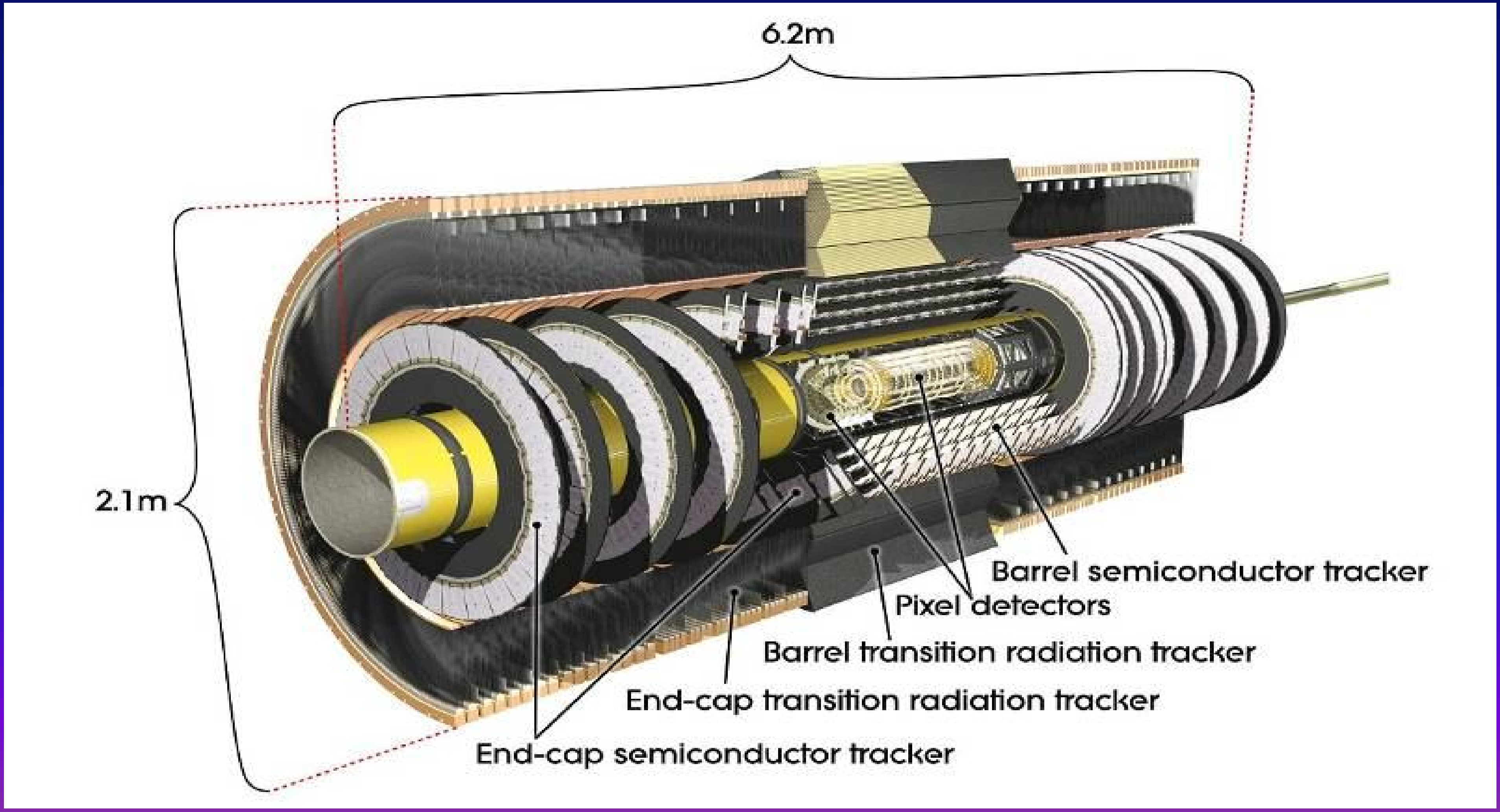
Main Detector Characteristics

LHC design luminosity: 10^{34} cm^{-2} s^{-1}

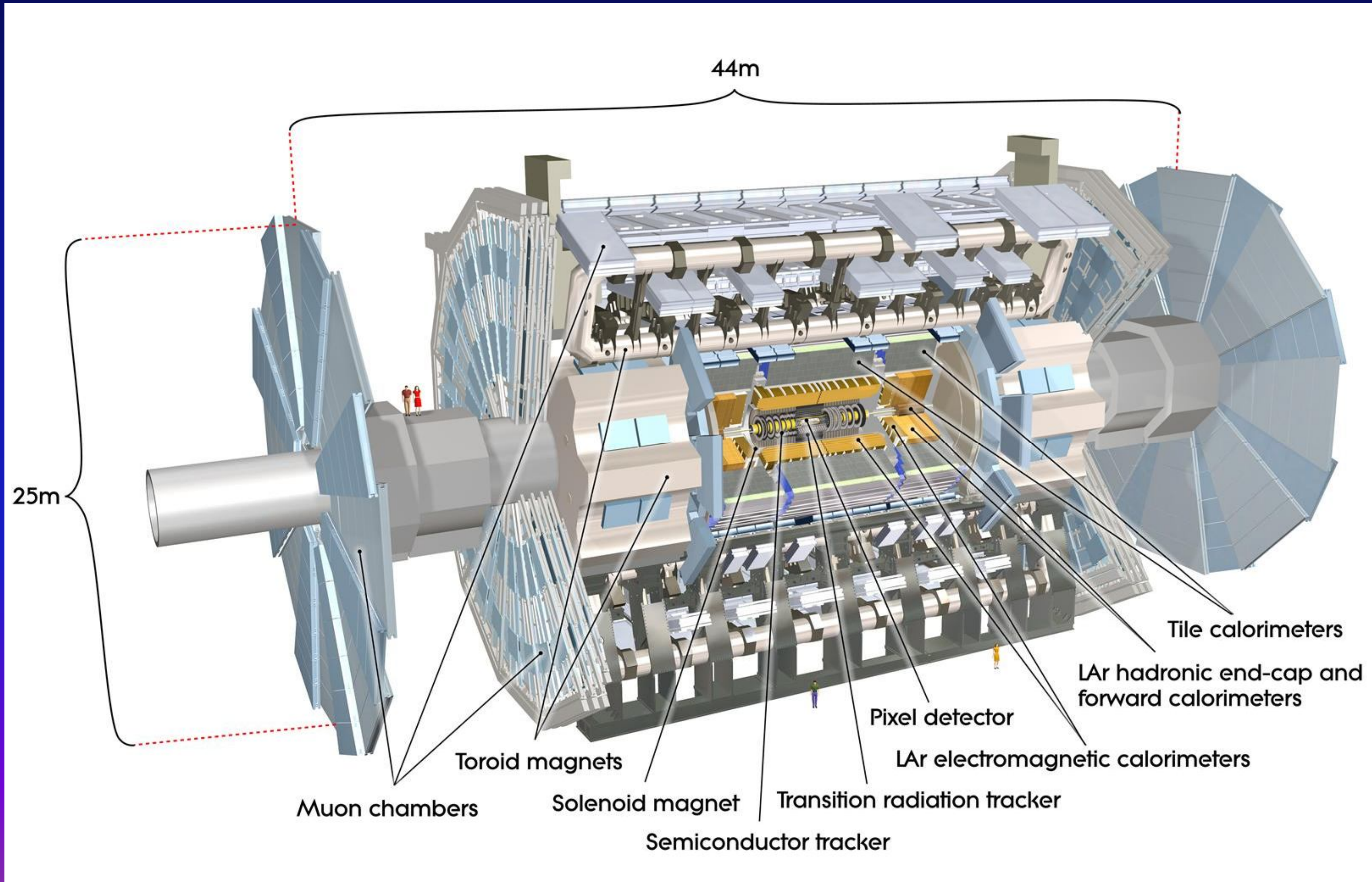
Emerging particles: 10^3 per 25 ns for $|\eta| < 2.5$, $|\eta| = - \ln(\tan(\theta/2))$

High-granularity measurements – Silicon pixel sensors (size = 50×400 μm^2)

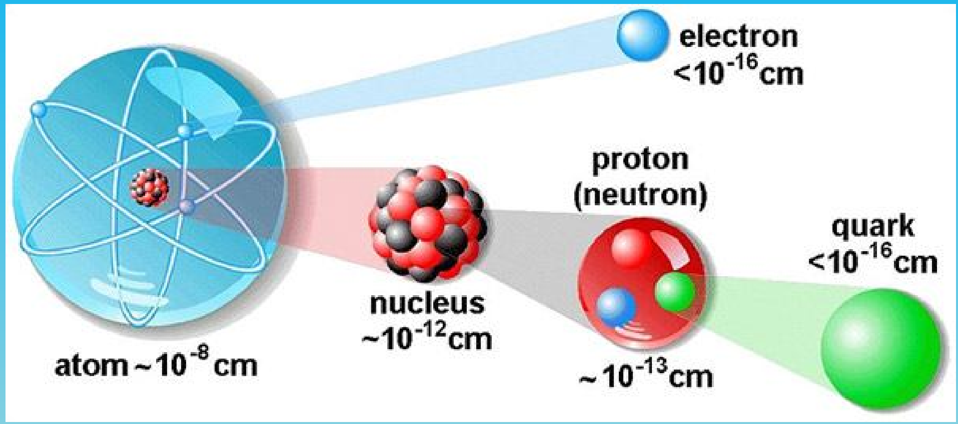
Intrinsic accuracy: (barrel: 10 μm (R - ϕ) ; 115 μm (z), and disks: 10 μm (R - ϕ) ; 115 μm (z)). Pixel detector ~ 80.4 million readout channels. SCT (Pixel and Silicon microstrip sensors): 8 strip layers, barrel region – small angle (40 mrad) stereo strips – measuring (R - ϕ). Detector module – Intrinsic accuracies (module in barrel) – 17 μm (R - ϕ) ; 580 μm (R).

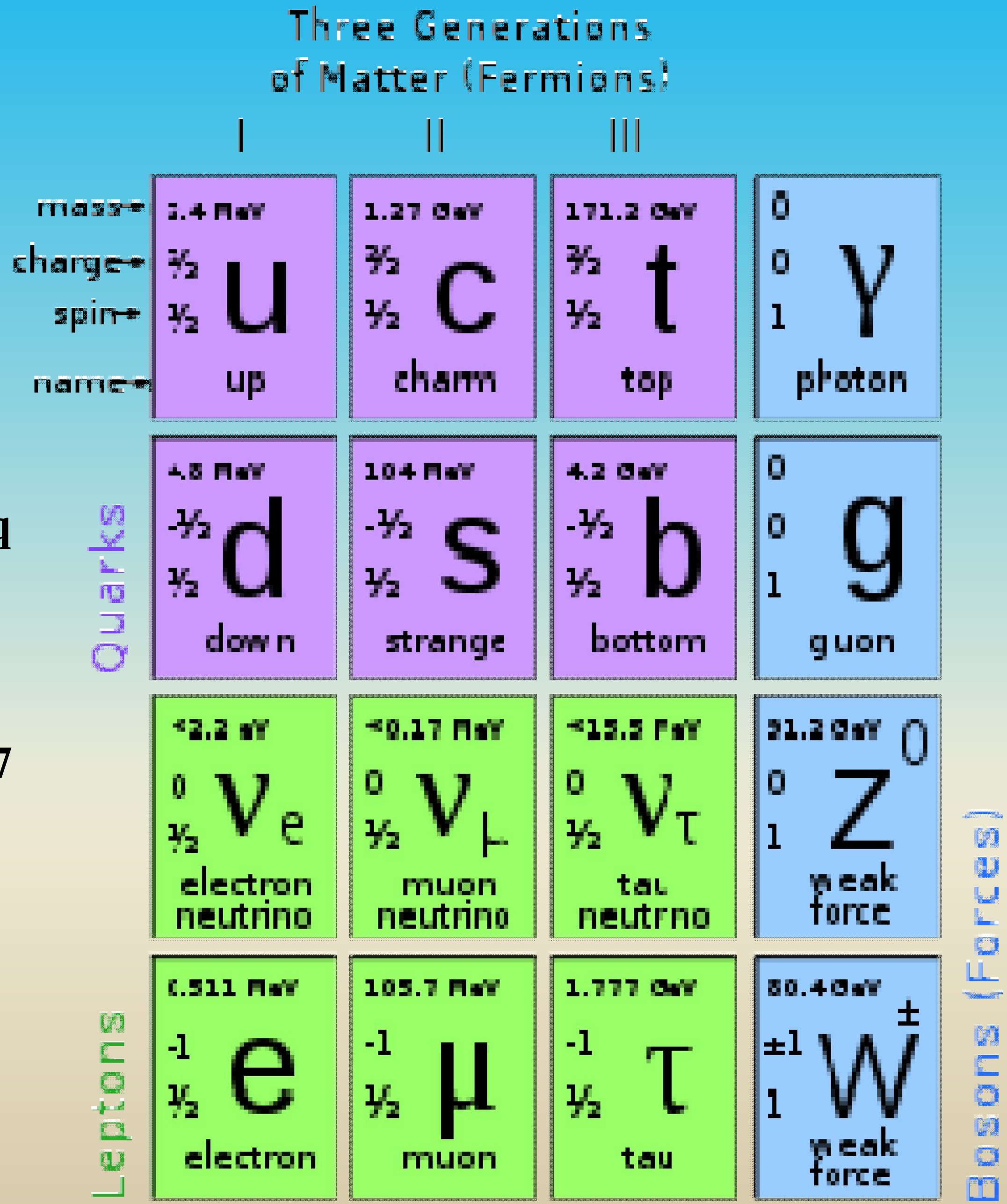


TRT (Transition radiaition tracker) (R - ϕ): Intrinsic accuracy – 130 μm (up to $|\eta|$ = 2.0), 351 000 channels. Charged particle tracks (transverse momentum P_t > 0.5 GeV, $|\eta|$ < 2.5) measured on inner detector and soleniod field.



Properties of the top quark and methods of its production





Properties of t quark different from other quarks (m_t >> $W^\pm$, m_b, m_s,..etc.)

Decay 1st order weak interaction: $t \rightarrow W^+ + q$, where q = (d, s, b),

but $t \rightarrow W^+ + b$ overwhelmingly Important

(Γ_t = Decay width $\propto g_w{}^2 \approx 1$ GeV, HIGHLY UNSTABLE!) and for m_t = 180 GeV/c^2 then $\Gamma \approx 1.7$ GeV such that $\tau \approx 4 \times 10^{-25}$ sec, (relativistic hadron state < 10^{-15} m cannot form in $t_f < 10^{-22}$ s)

However!

for q = (u, d , s , c, b): $\tau \approx 10^{-12}$ s; can form observable hadron states measurable in a laboratory, this not possible for top quarks since they decay too rapidly: $t \rightarrow W^+ + q \rightarrow q_1 + q'_2 + q$ where $q_1 q'_2$= (ud', us', cd', cs') or $W^+ \rightarrow l^+ + \nu_l$; l = (e, μ, τ)

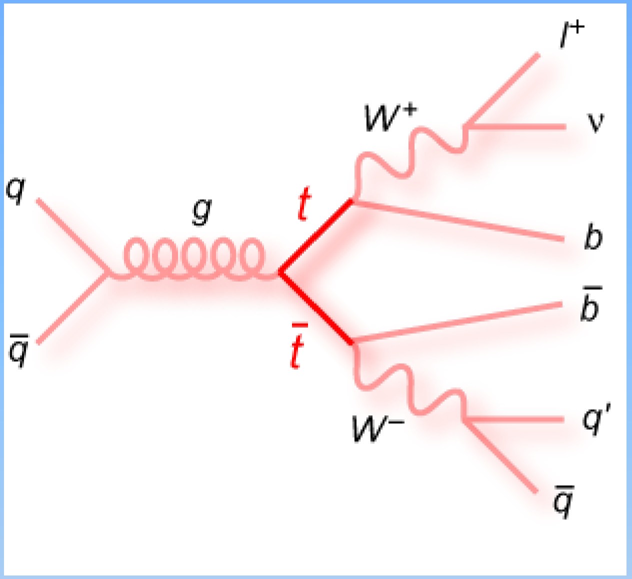
Top quarks are the most massive of natures building blocks yet discovered, and were first produced in 1995 at CDF II Fermilab by colliding opposing proton-antiproton beams:

$p + p' \rightarrow t + t' + X^0$; where X^0 = arbitrary hadronic state, $\sqrt{s} = 1.8 – 1.96$ TeV

Quark-anti quark annihilation process i.t.o. Feynman:

$q + q' \rightarrow t + t' \rightarrow b + W^+ + b' + W^-$

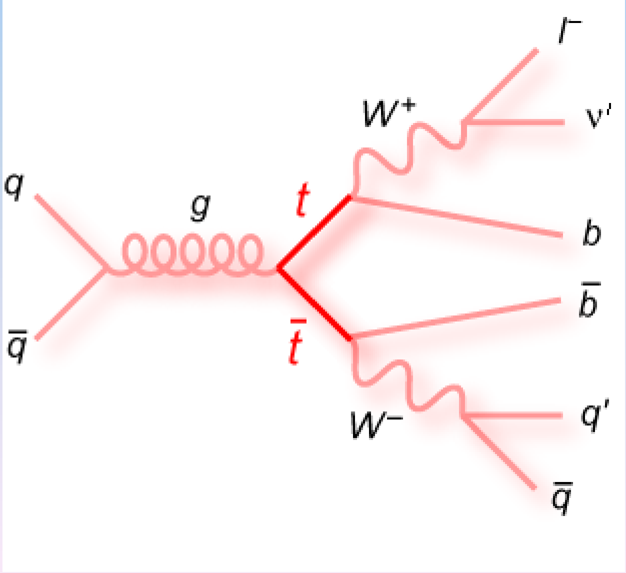
$\rightarrow b + l^+ + \nu + b' + q + q'$ $\Rightarrow$



and

$q + q' \rightarrow t + t' \rightarrow b + W^+ + b' + W^-$

$\rightarrow b + l^- + \nu' + b' + q + q'$ $\Rightarrow$



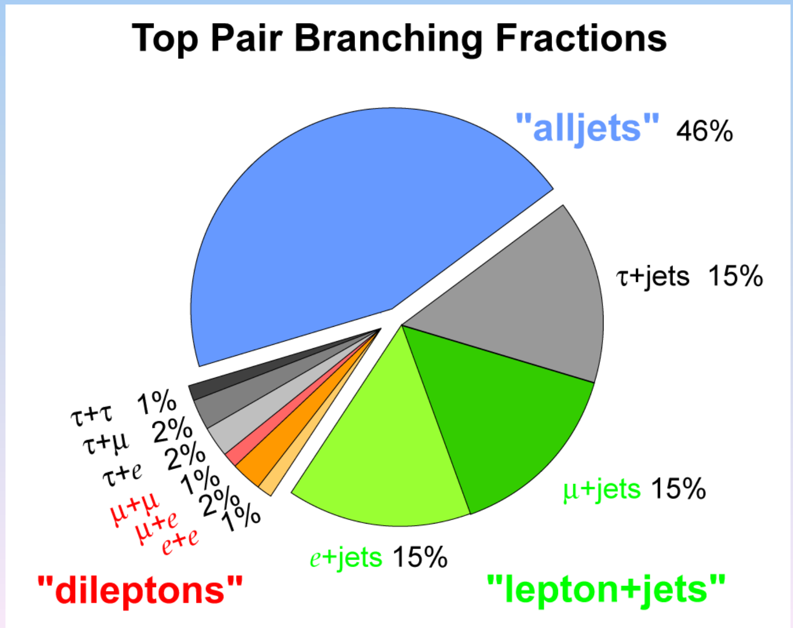
New physics associated with electroweak symmetry breaking

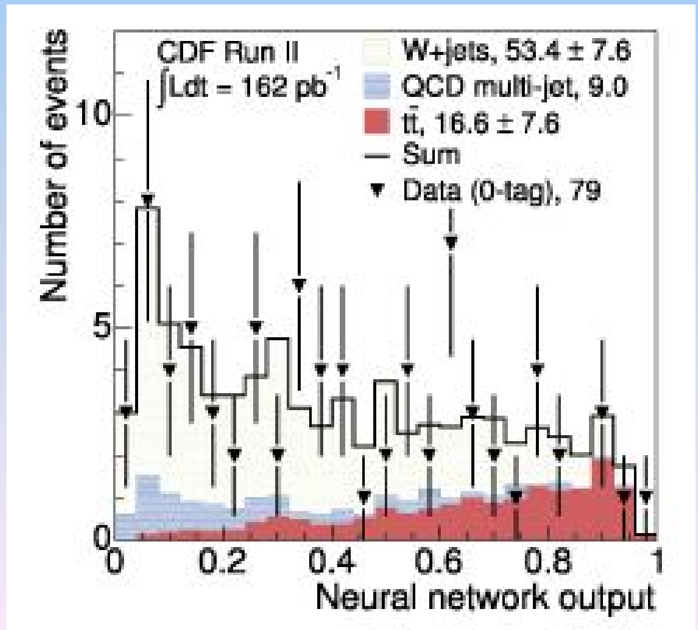
→ coupling between particles of proportionate mass

→ important to measure top quark couplings accurately

In SM, top quark decays 99.8% of time to W boson and b quark → measurement of top quark branching fraction R = B(t → Wb)/B(t → Wq) where q = (b, d, s) quark is very important

R < 1 implies non-SM top decay, non-SM background to top-pair production, or a 4th generation of quarks (⇒ H^0?!!) To maintain high detection and trigger efficiencies and background levels only the tt' final states in which at least one W has decayed leptonically, the latter being called "lepton-plus-jets" (L + J) events, and "dilepton" events (2 lepton decays, R-events determined separately here).





Data Flow at ATLAS

RAW:

- Original data at **Tier-0**
- Complete replica distributed among all **Tier-1**

ESD:

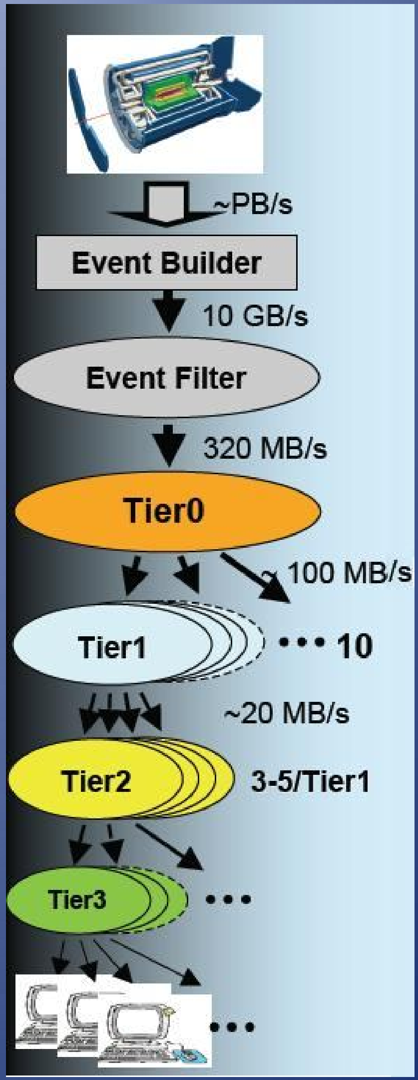
- ESDs produced by primary reconstruction reside at **Tier-0** and are exported to 2 **Tier-1s**
- Subsequent versions of ESDs, produced at **Tier-1s** (each one processing its own RAW), are stored locally and replicated to another **Tier-1**, to have globally 2 copies on disk

AOD:

- Completely replicated at each **Tier-1**
- Partially replicated to **Tier-2s** (depending on each **Tier-2** size) so as to have at least a complete set in the **Tier-2s** associated to each **Tier-1**
- Every **Tier-2** specifies which datasets are most interesting for their reference community; the rest are distributed according to capacity

TAG:

- TAG files or databases are replicated to all **Tier-1s** (Root/Oracle)
- Partial replicas of the TAG will be distributed to **Tier-2** as Root files
- Each **Tier-2** will have at least all Root files of the TAGs that correspond to the AODs stored there



Analysis procedure at the LHC and ATLAS: Data acquisition and physics analysis

- **Monte Carlo** - Event generator output
- **Digits/RAW** - Simulation/detector output
- **Event Summary Data (ESD)** - Output of reconstruction
- **Analysis Object Data (AOD)** - Summary of reconstruction - primary analysis data
- **Tag** - Thumbnail of each event used for identifying interesting events at the analysis stage
- **dESD, dAOD** - Data derived from ESD or AOD
- Physics analysis can be done directly with Athena to produce n-tuples readable by ROOT, or directly with ROOT using Athena-ROOT-Access - then the AOD, ESD etc is the n-tuple
- Analysis can be done in either framework

on every event, steered by the tag selection

mechanism – only certain events selected

How should physics analyses proceed?

- The environment is set up using configuration manager (CMT)
- Datasets are chosen for analysis using a metadata browser (AMI)
- Files are downloaded locally using a data management tool (DQ2)
- Inspect the files using Athena-ROOT-Access (ARA) or are looked at visually with ATLANTIS
- The analysis code is built in Athena or ARA using the local data to check that it is doing what is expected
- The jobs can then be sent to the to the Grid to process large datasetsand downloaded and the data displayed using scientific programs, e.g. ROOT.

Top quark width determination using the LHC

- If a charged Higgs lighter than the top-quark exists, then the latter's decay of such a charged Higgs would compete with the normal and the very much favoured SM decay of the top quark into the W-boson, $t \rightarrow W^+ + b \rightarrow b + (l, q)$ or (ν, q)

- The partial with of the top-quark decay into the W- boson would be unchanged and can be extracted from the measurement of the single top-quark production at the LHC

- The branching fraction of the top-quark into the W-boson can be extracted from the measurements of ratios in the top/anti-top sector (branching ratio)

- From the measurements of the partial width into the W-boson and the branching fraction in the W-boson, the total width of the top-quark can be extracted at the LHC

- The total width of the top-quark can be calculated in the SM to a high precision, only radiative corrections would modify the SM value, or the existence of new physics.

- The measurement of the top-quark total width at the level of 10% or better would suffice to infer the existence of the new physics beyond the SM. the direct measurement of the top quark total width is not possible at the LHC and would require the next generation of colliders, namely the Linear Collider (Eka-CERN LAN II??)

SM prediction and calculations for the top quark width

$$\Gamma^{(1)} = \frac{G_F{}^2 m_t{}^5}{192\pi^3}\left(9 + 6\frac{\alpha_s}{\pi}\right)\int_0^{(1-\epsilon)^2} \frac{dy}{(1 - y/\bar{y})^2 + \gamma^2}\left[F_0(y,\epsilon) - \frac{2\alpha_s}{3\pi}F_1(y,\epsilon)\right]$$

where: G_F = Fermi coupling constant, α_s = strength parameter, $\varepsilon = m_b/m_t$, $\tilde{y} = (M_W/m_t)^2\gamma = \Gamma_W/M_W$, $\Gamma_W = (G_F M_W{}^3/6\sqrt{2}\pi)(9 + 6\,\alpha_s/\pi)$, and $F_0(y,\varepsilon)$ and $F_1(y,\varepsilon)$ are functions which indicate the top mass inertia.

The above equation includes the QCD and electroweak correction , in addition the b quark mass is finite. The t quark is very heavy, thus b and s quark mass can be neglected while assuming:

$$90\ \mathrm{GeV}/c^2 < M_t < 200\ \mathrm{GeV}/c^2$$

SM prediction at the Born level

QCD radiative correction (~ 10%)

Γ_t: Threshold region $t\bar{t}$ production

SUSY extended Higgs channel

Dominant decay mode:
$t \rightarrow W^+b$

e^+e^- annihilation (CERN LEP II and beyond??)

p^+p^- collisions ($\sqrt{s}$ = 1.8 – 1.96 TeV; Tevatron)

p^+ collisions (Indirect: LHC at 7 TeV ??)

With a mass above the Wb threshold, the decay width of the top quark is expected to be dominated by the two-body channel t→Wb. Neglecting terms of order m^2_b/m^2_t, α^2_s and those of order $(\alpha_s/\pi)m^2_W/m^2_t$ in the decay amplitude, the width predicted in the Standard Model is:

$$\Gamma_t = \frac{G_F m_t^3}{8\pi\sqrt{2}} \left(1 - \frac{M_W^2}{m_t^2}\right)^2 \left(1 + 2\frac{M_W^2}{m_t^2}\right) \times \left[1 - \frac{2\alpha_s}{3\pi}\left(\frac{2\pi^2}{3} - \frac{5}{2}\right)\right] .$$

The G_F Fermi coupling appearing in this equation contains the largest part of the one-loop electroweak radiative corrections, providing an expression accurate to better than 2%. The width increases with mass, changing, for example, from 1.02 GeV/c^2 for m_t = 160 GeV/c^2 to 1.56 GeV/c^2 for m_t = 180 GeV/c^2 (using α_s(MZ) = 0.118). With its correspondingly short lifetime of ≈ 10^{-25} s, the top quark is expected to decay before top-flavoured hadrons or tt-quarkonium bound states can form.

The order α^2_s QCD corrections to Γ_t are also available, thereby improving the overall theoretical accuracy to better than 1%.

Conclusion on top quark physics at the LHC

- Physics of top quark - one of the main physics topics at the LHC
- Analysis can be done with the first 10 fb^{-1}
- Due to the large production cross section, the statistical uncertainty will be, in most of the cases, negligible
- The study of the top quark sector highlights several theoretical areas, where further improvements are expected such as the higher order QCD calculations and the b-fragmentation
- Finally, most of the analyses carried out so far make use of fast simulation of the ATLAS detectors. At present, many of those studies are repeated with full simulation and a serious focus on the systematic uncertainties. First attempts are also started to reduce the systematic uncertainties and make measurements of selection efficiencies, resolutions and on the level of background contamination from data type analyses in control samples rather than from the Monte Carlo simulations
- These are crucial steps in the preparation for the upcoming LHC era ahead of us in the near future