Top Quark Physics - I

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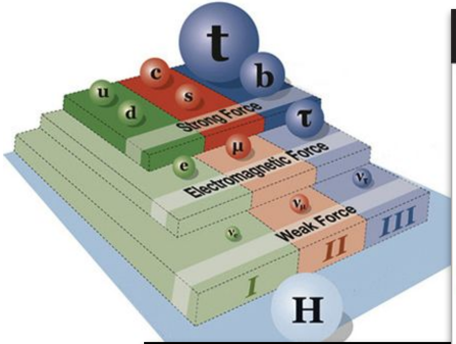
Outlook

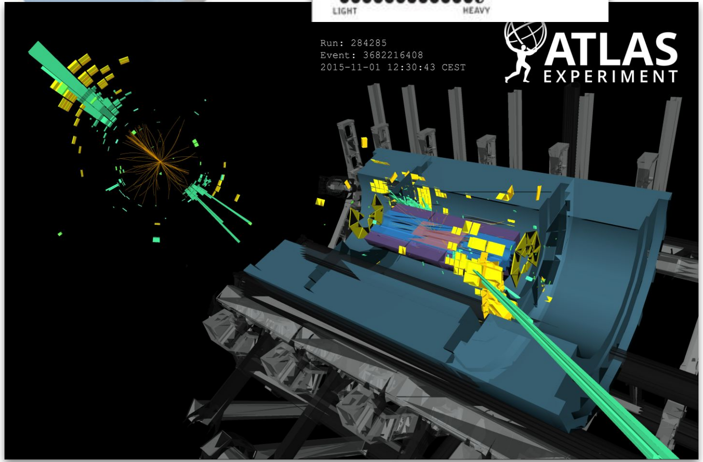
Disclamers:

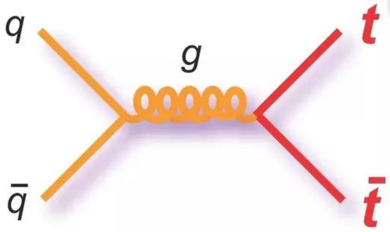
- ATLAS experiment perspective
- might repeat know concepts

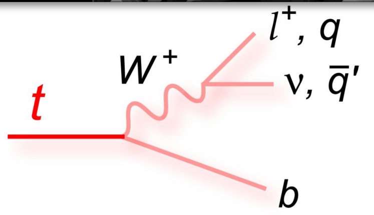
- **Lecture 1**:
  - A brief recap
  - The top quark
  - Tools for top quark physics
  - Top-pair production cross-section

- **Lecture 2**:
  - Single top
  - Top quark mass
  - Spin and angular properties
  - Top events as a tool for other measurements
  - Associated top production
  - New physics with top
  - Closing remarks









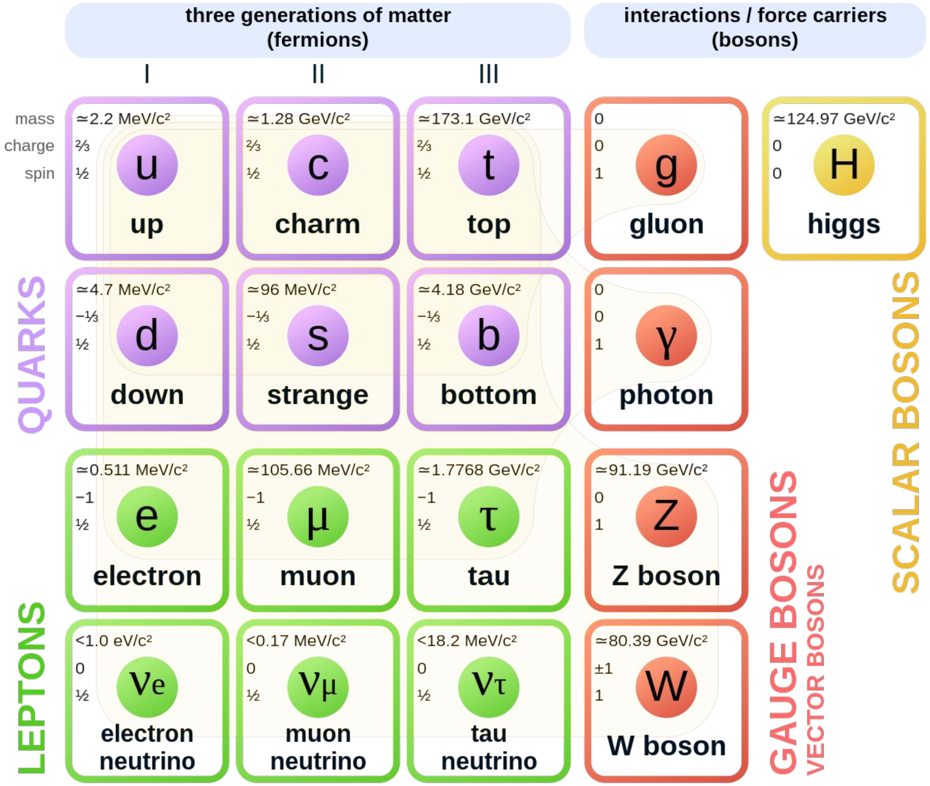
A brief recap

The Standard Model of elementary particles

- Best theory describing elementary physics
  - based on **quantum field theory**
  - 6 **quark** fields + 6 **lepton** fields
  - **electro-weak** interaction (+***EW bosons***)
  - **QCD** interaction (+***gluons***)
  - **Higgs** field

Standard Model Lagrangian

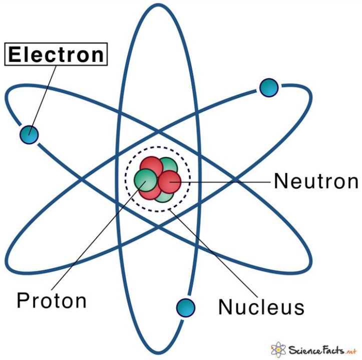
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\Psi} \not{D} \psi + h.c. + \bar{\Psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

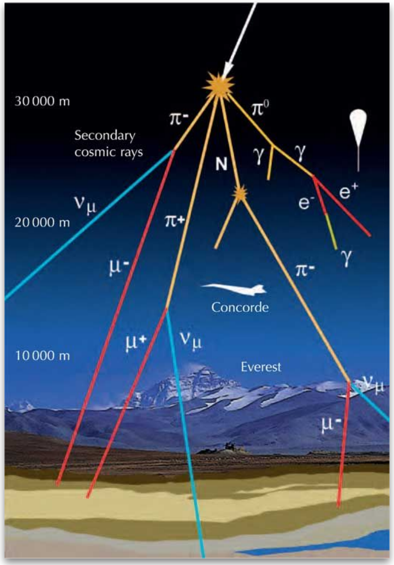


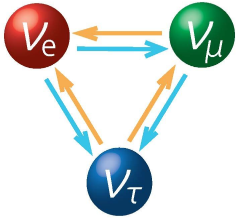
ATLAS EXPERIMENT

Leptons and Quarks

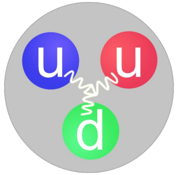
- **Leptons**:
  - interact via **QED** and **weak** interaction
  - heavier leptons decay to lighter leptons
    - conserving “flavour”
  - neutrinos:
    - zero electric charge (only weak interaction)
    - extremely small mass
    - almost invisible





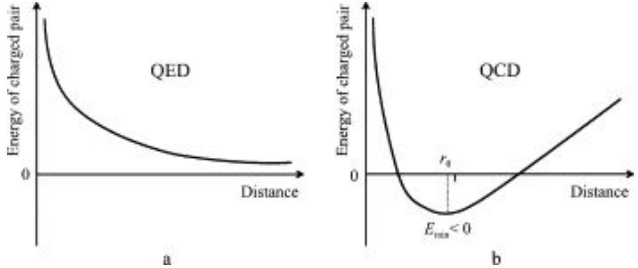


- **Quarks**:
  - interact via **EW** and **QCD**
  - heavier quarks decay to lighter quarks
    - **mixing** between quarks: **CKM matrix**
  - fractional **charge**: ⅔ or ⅓
  - quark “***confinement***” inside **hadrons**

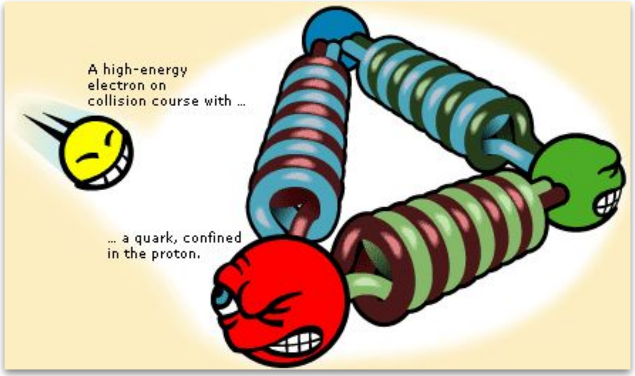


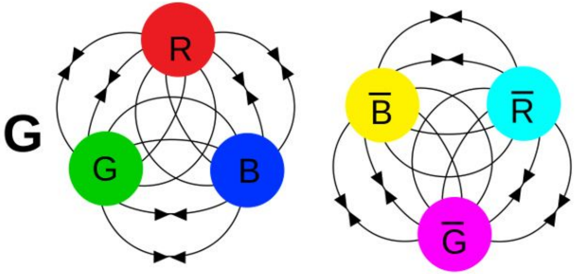
$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix} = \begin{bmatrix} d' \\ s' \\ b' \end{bmatrix}$$

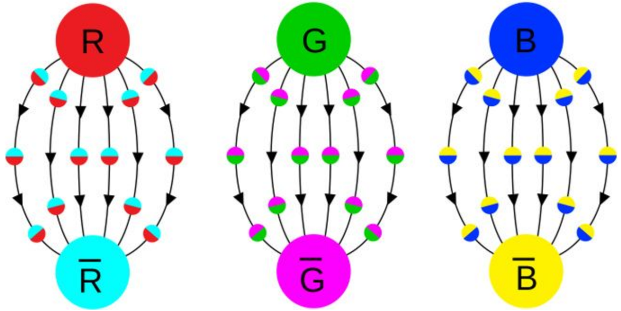
Quarks and QCD



- QCD interaction keeps quarks together inside nucleons:
  - 3 **colour** QCD charges: "**R**", "**G**", "**B**"
  - **strong attraction** between different colours, ***increasing*** with distance
  - as a consequence, quarks cannot live as stable states in nature, and are always in **colorless** **bound states** called **baryons** and **mesons**





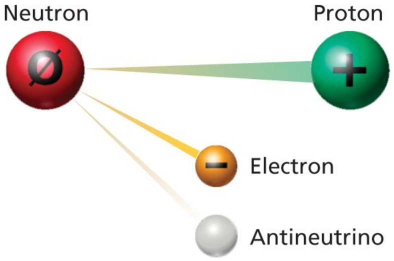


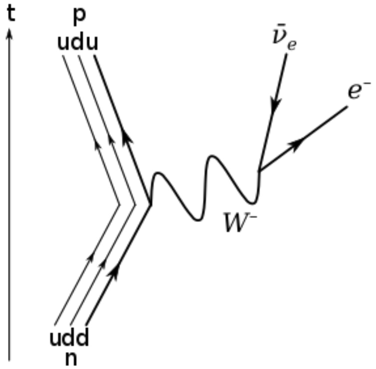
Gluon = spring

Electro-Weak interaction and Weak decay

- Most particle **decays** proceed through electron-weak interaction
  - able to **change flavour** of particles (*only* ***charged current***)

- For **light** particles ($m < m_W$) decay ***suppressed*** ⇒ **long lifetime**
  - *examples: neutron, muon…*



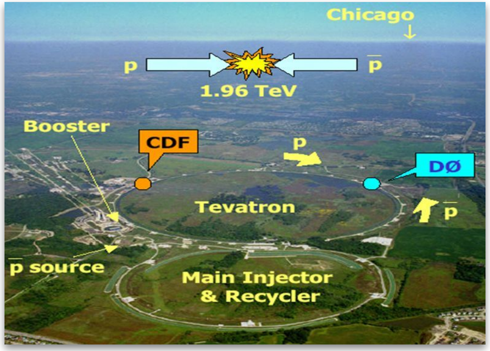


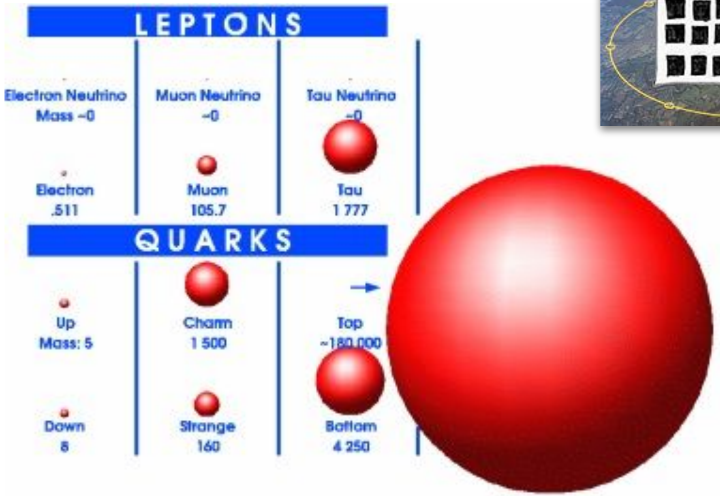
- For **heavy** particles ($m > m_W$) cascade decay to **on-shell *W*** boson and final state particles ⇒ can have **short lifetime**!

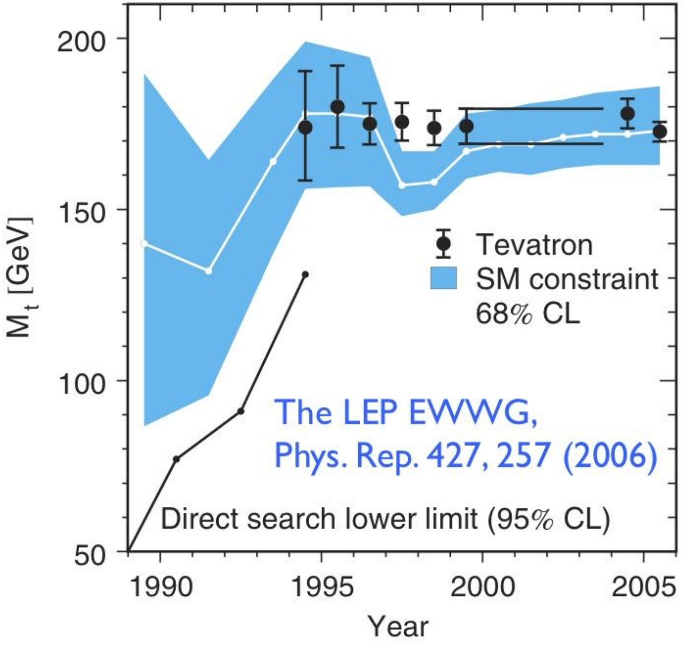
The top quark

Top quark history

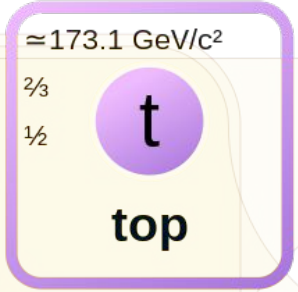
- **Discovered** in 1995 at the Tevatron $p\bar{p}$ collider @FermiLab
  - m_t ~ 173 GeV ≫ any other quark!
- **Predicted** since 1976, mass constrained by **EW precision data**
- Studied intensively at Tevatron and at LHC
  - **LHC → "top factory"**

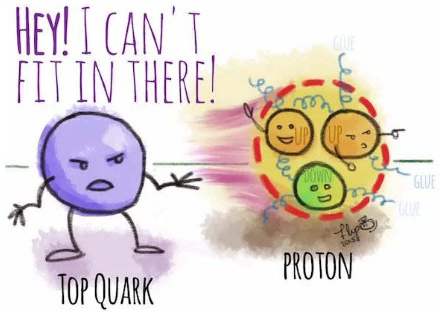




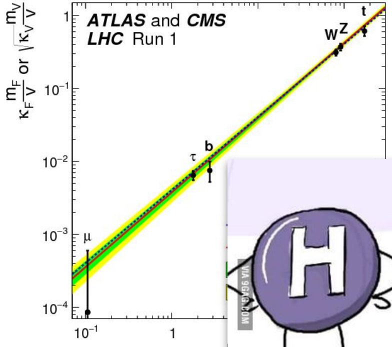


Top quark properties





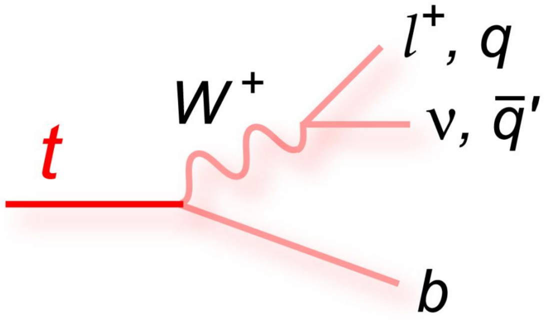
- **Quantum numbers**:
  - same as *u* and *c* quark:
    - spin ½
    - charge +⅔
- **Very large mass** ⇒ many nice features:
  - **decay time** (~5×10^{-25} s) < hadronization time (~2×10^{-24} s)
    ⇒ **no top bound states**
    ⇒ the **only quark** that can be "seen" **outside hadrons**
  - largest **coupling with Higgs** among all SM particles
    - Yukawa coupling y_t ~ 1



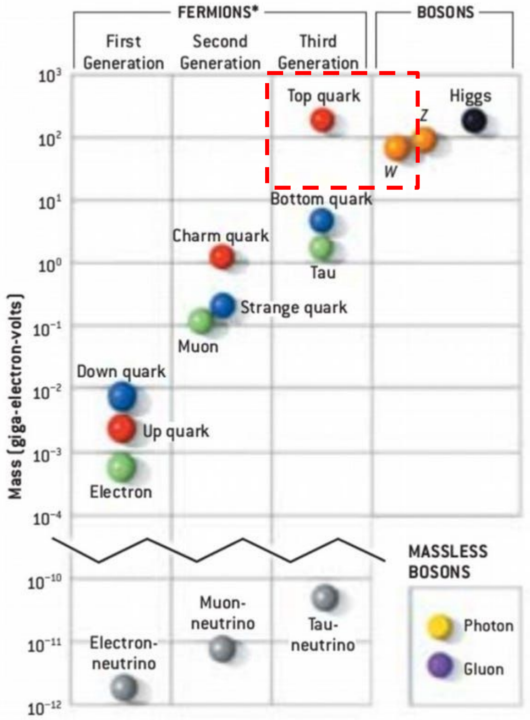
- **CKM mixing**:
  - only relevant CKM matrix element is V_{tb} ~ 1
  - mixing with other quarks very small

$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} \approx \begin{bmatrix} 0.974 & 0.225 & 0.003 \\ 0.225 & 0.973 & 0.041 \\ 0.009 & 0.040 & 0.999 \end{bmatrix}$$

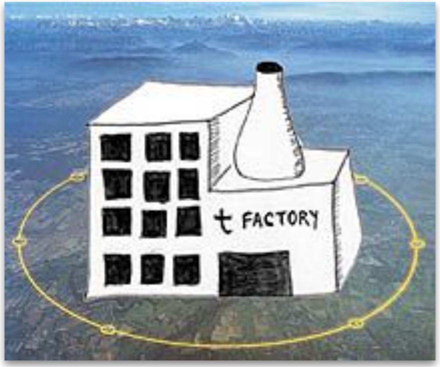
Top quark decay



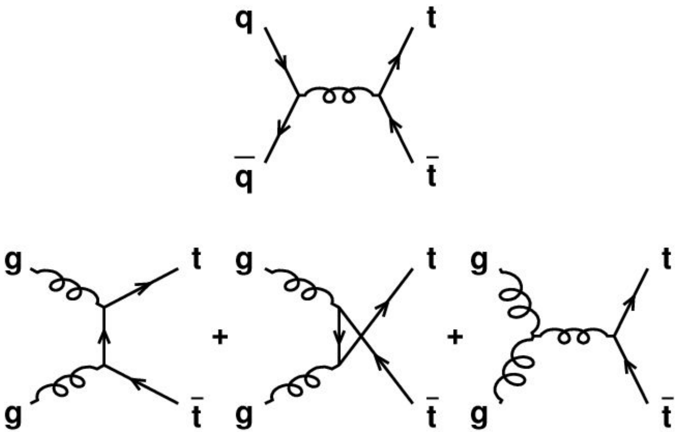
- <u>**"Weak" decay**</u>:
    - $m_t > m_W + m_b$
      ⇒ not suppressed!
      ⇒ $\tau \sim 5\times10^{-25}$ s
- Almost **exclusive** decay:
    - $t \rightarrow W^+ b$
      (other CKM elements too small)
- ***W boson*** can decay to:
    - **leptons**
    - **quarks**
- ***b-quark*** hadronizes and forms a high energy **hadronic jet**
- <u>**Fast decay**</u>:
    - no bound states
    - **spin information** not disturbed by hadronization proces
      ⇒ passed to decay products



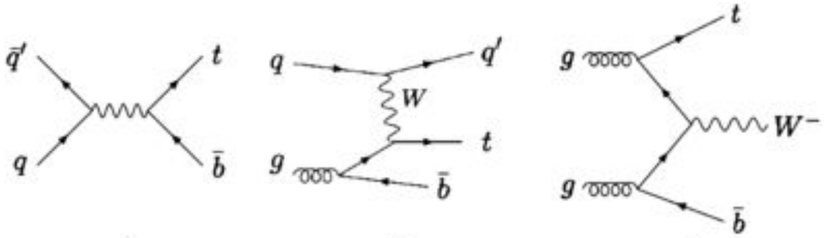
Top quark production



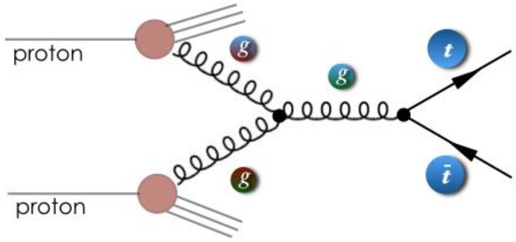
- **At hadron colliders** (Tevatron $p\bar{p}$, LHC pp):
  - **QCD** production $\rightarrow$ ***$t\bar{t}$* pairs**



  - **EW** production $\rightarrow$ **single top**

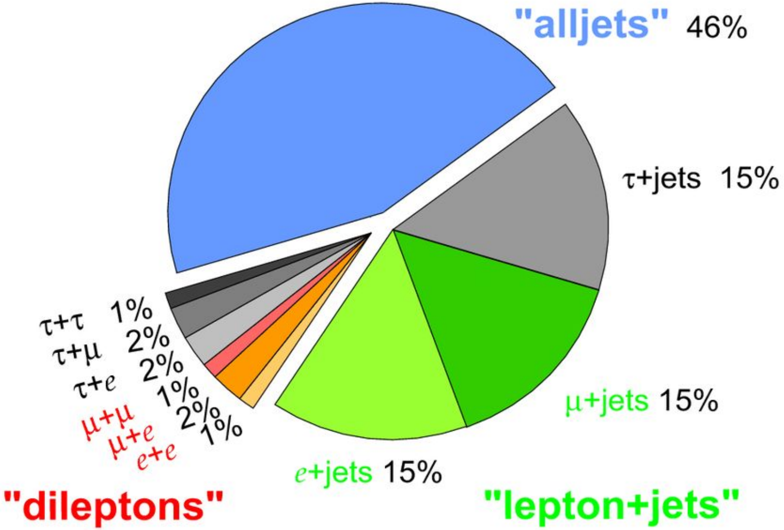


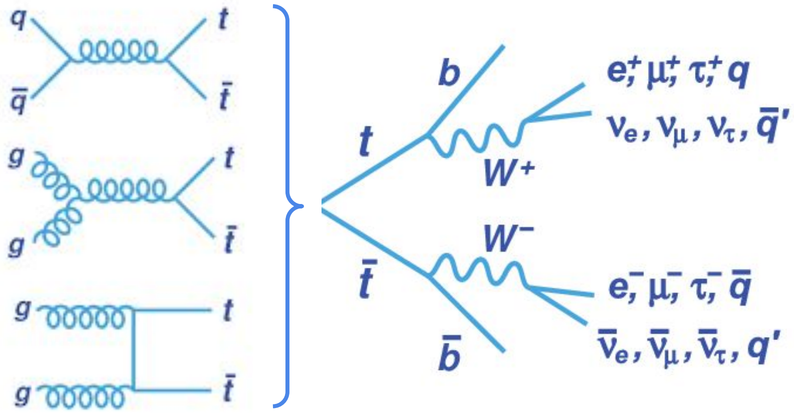
Top-quark pair production



- **Largest cross-section** @hadron colliders

- Final state determined by ***W*** **decays**:
  - **all-hadronic**: 6 jets
  - **single-lepton / lepton+jets**: 1$\ell^{\pm}$ (+1ν) + 4 jets
  - **dilepton**: 2$\ell^{\pm}$ (+2ν) + 2 jets

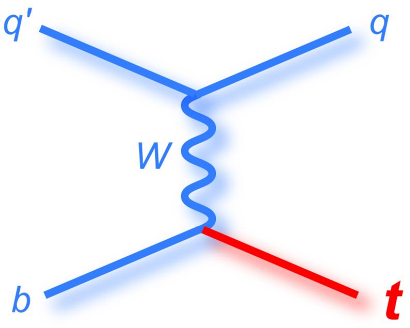




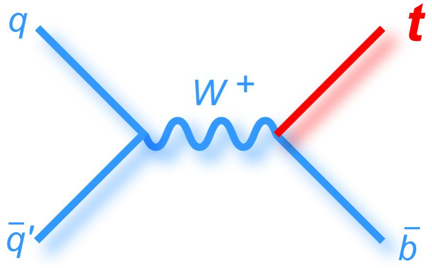
Single-top quark production

- 3 production modes:

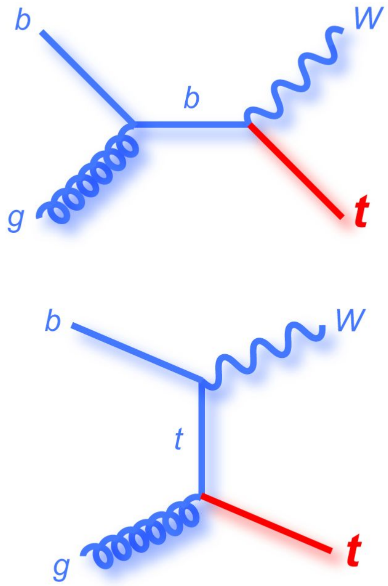
***t*-channel**



***s*-channel**



***Wt*-channel**



  - **direct** measurement of V_{tb}
  - study of ***tW* vertex**

Why is the top so special?

- Relatively **recent** particle
- The **only** quark ***not*** hadronizing:
  ⇒ allows to study **quark properties** more directly
  ⇒ allows to study **spin** properties
- Strong relationship with **Higgs** (*boson and field*) ↔ **large mass**
  - important **high-order corrections** to most SM processes
    ⇒ important player of **EW precision tests** of the SM
  - many models of **physics beyond the SM** (BSM) predict top playing a special role
- Top events are a **background** for other physics processes (*Higgs, BSM…*)
- Detection of tops involves most of the **detector** components and data analysis techniques:
  - ***jets***, ***b-tagging***, ***electrons***, ***muons***, ***missing energy*** (from neutrinos)

What we can do with top quark?

Measure production cross-section:

- *$t\bar{t}$* and single top
- total and differential
- comparison with theory predictions
- extraction of PDFs, αs
- extraction of Vtb

Study of tWb vertex

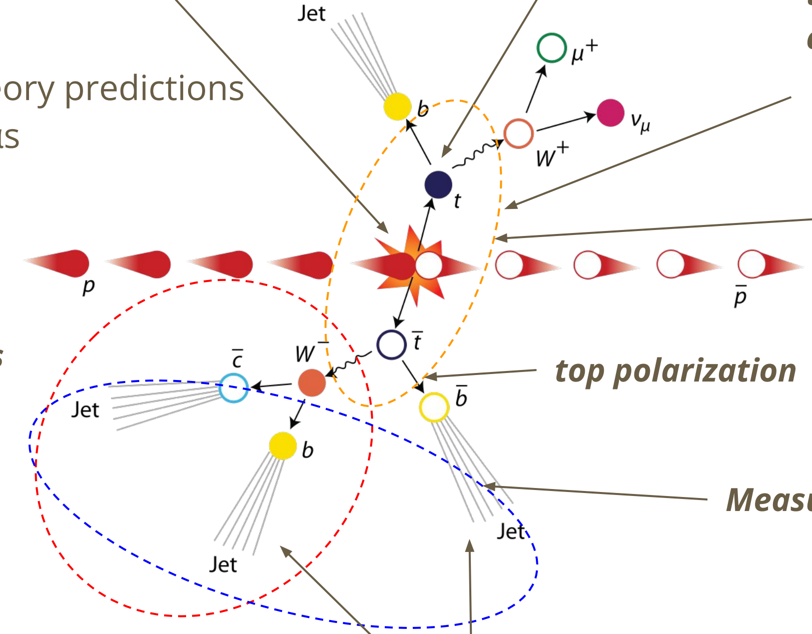
$t\bar{t}$ forward-backward asymmetry / charge asymmetry

$t\bar{t}$ spin correlation

Study of W decay to hadrons

top polarization

Measure b-tagging performance

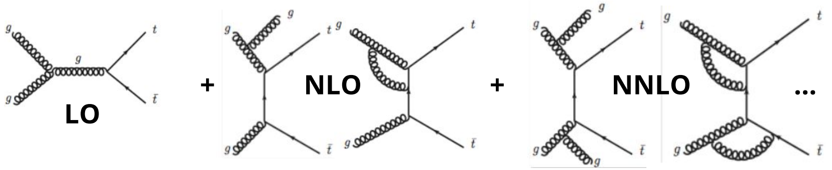


Top mass measurement

Study modelling of (b)quark fragmentation to jets

Tools for top-quark physics

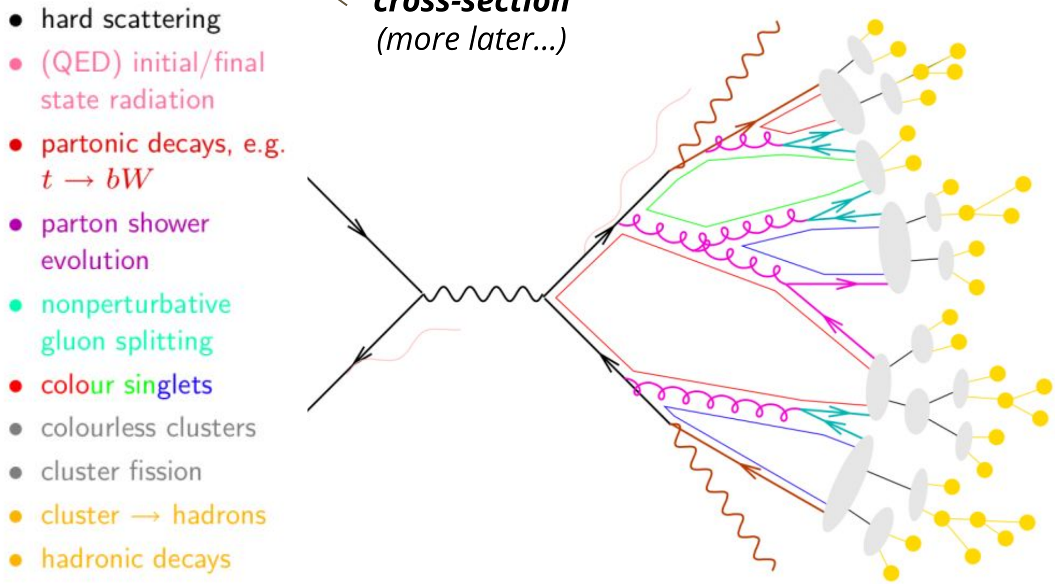
Theory predictions



- Theory predictions for HEP quantities based on **perturbation theory**

$$\sigma(pp \to t\bar{t} + X) = \sum_{i,j} \int dx_i dx_j \times \underbrace{F_i(x_i,\mu_i)F_i(x_j,\mu_j)}_{\textit{PDFs}}\underbrace{\hat{\sigma}_{ij}(x_i,x_j,m_{top}^2,\mu_f^2)}_{\textit{partonic cross-section}}$$

"cross-section"
(more later...)

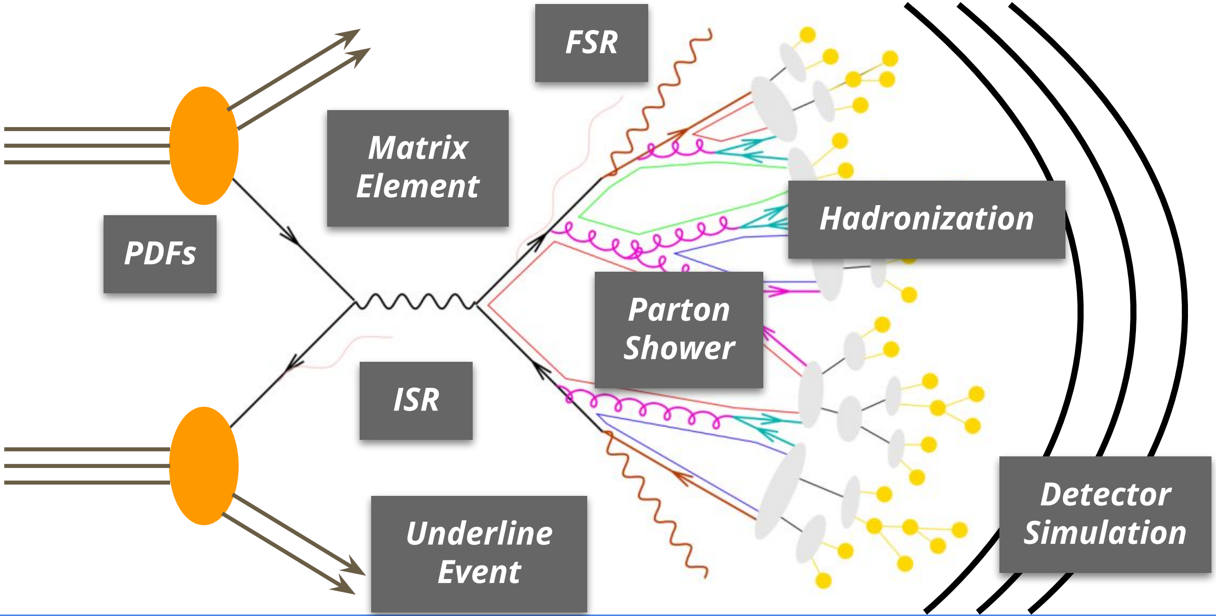


- Predictions involve:
  - parton distribution functions (**PDFs**)
  - **hard scattering**
    - "fixed order" in QCD and/or EW (*leading order* (LO), *next-to-leading order* (NLO) ...)
  - final-state **evolution** (*particle decays, emission of QCD/EW radiation...*)

Monte Carlo simulation

Pythia MadGraph H7 Sherpa DELPHES fast simulation

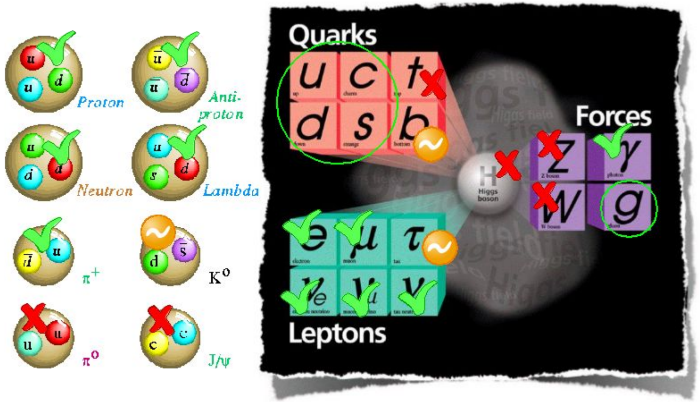
- Useful tool to bring theory predictions as close as possible to experimental data:
    - **simulated events** are produced
    - following the same steps as described before

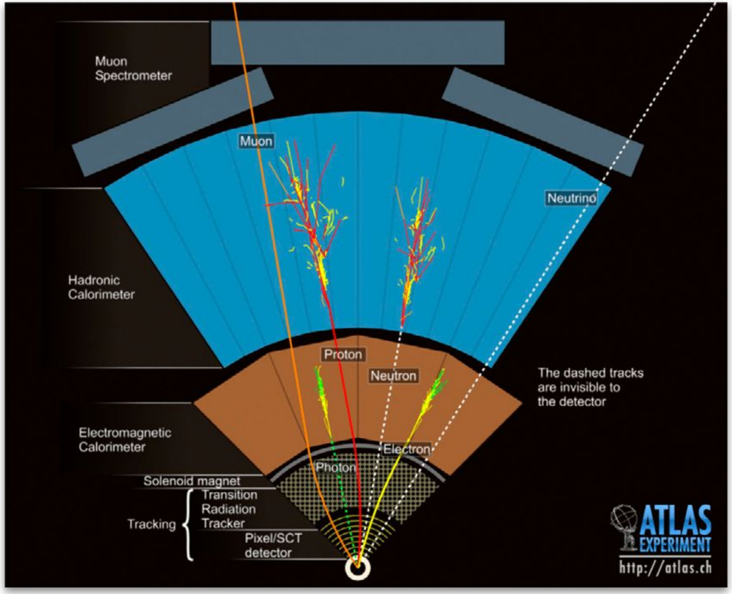


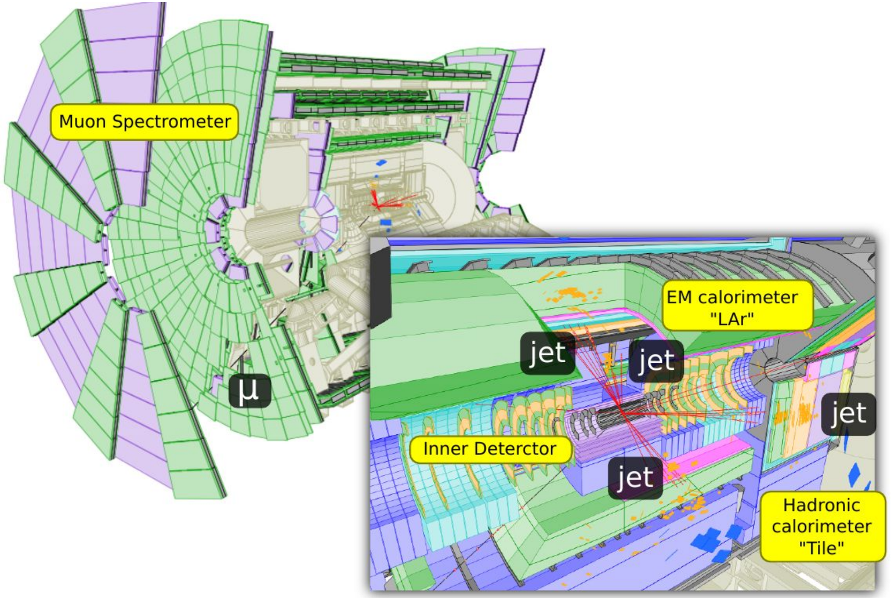
- final state **evolution** (“***parton shower***”) and hadronization handled in **approximate** / empirical ways
- **detector response** simulation also added (*full simulation or fast simulation*)

Signatures in particle detectors

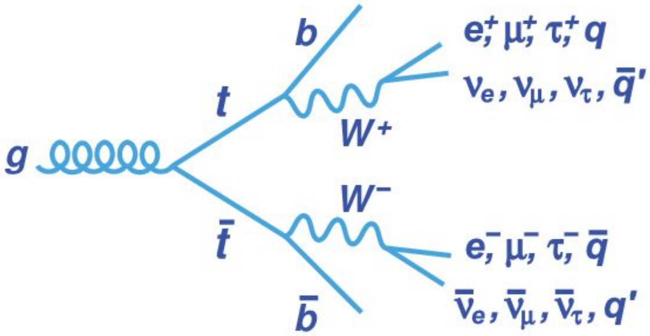
- How do we see top quarks in our detector?
- “Visible” particles are just:
  - **electrons**, **photons**
  - hadronic **jets** (protons, neutrons, pions, kaons…)
  - **muons**



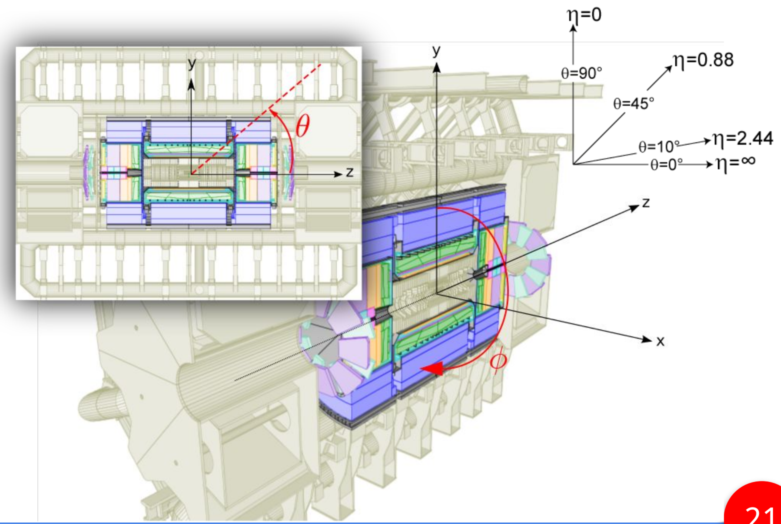




Top pair event selection



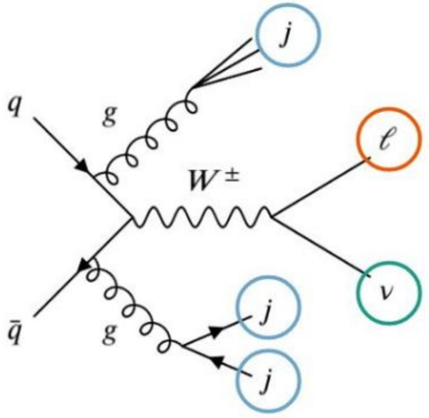
- Single-lepton typical event selection:
  - **1 electron or muon**
    - p_T > 20 / 25 / 30 GeV
    - $|\eta| < 2.5$
    - identification cuts and isolation requirements
  - **≥ 4 jets**
    - p_T > 25 GeV
    - $|\eta| < 2.5$
    - up to 2 "***b*-tagged**"
      - using powerful multi-varied algorithms
  - Presence of **missing transverse energy**, E_T^{miss}
    - e.g. E_T^{miss} > 30 GeV or $m_T(W_{\nu,\ell})$ > 60 GeV ...

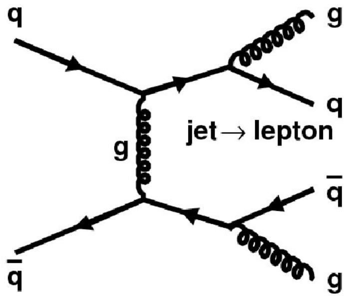


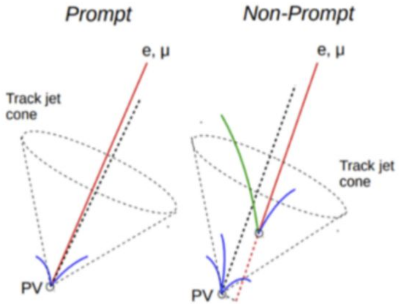
Backgrounds

- **Non-top events** can ***mimic*** final state topology (*and kinematics*)
  → "**background**" events (*as opposed to "signal events"*)

- Main backgrounds (for $t\bar{t}$ ℓ+jets and dilepton):
  - ***W*+jets**
  - ***Z*+jets**
  - *WW*, *WZ*, *ZZ* (+jets) → "**diboson**"
  - **single top**
  - events with **fake** / **non-prompt** / **mis-identified** electrons or muons



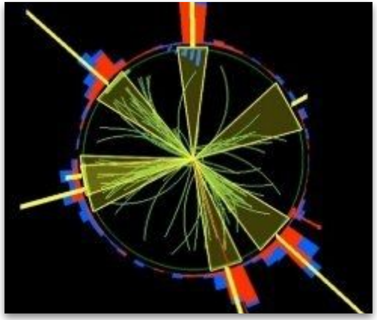


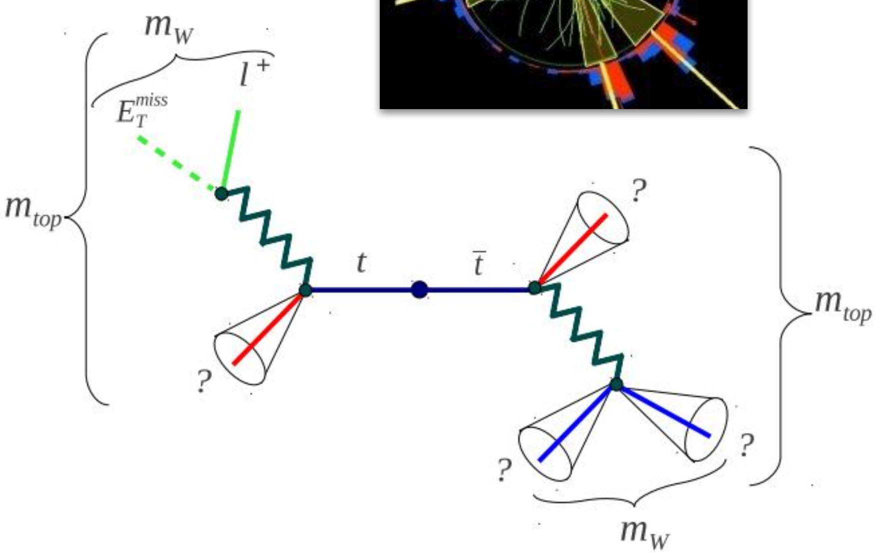


- **Backgrounds need to be**:
  - **estimated** (via Monte Carlo simulation or data-driven methods)
  - **rejected** as much as possible with event selection
  - **subtracted** from data to extract signal from data

Top pair event reconstruction

- Reconstruction of **top four momenta** from **final-state particles** not always trivial…





- **Example (ℓ+jets): χ^2 minimization**:
  - consider **all possible** jet and lepton ***assignments*** to tops (and *W*s) in an event
  - find the assignment that **minimizes χ^2** defined as:

$$\chi^2 = \sum \frac{(m_{ijk} - m_t)^2}{\sigma_t^2} + \frac{(m_{ij} - m_W)^2}{\sigma_W^2} + \frac{(m_{n\ell\nu} - m_t)^2}{\sigma_t^2}$$

    - **$p_z(\nu)$ obtained by imposing $m(E_T^{miss}+\ell) = m_W$**

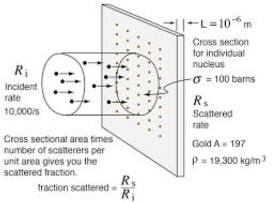
Top-pair production cross section

ATLAS
EXPERIMENT

(useful link: http://www.thomasgmccarthy.com/an-introduction-to-collider-physics-iii)

Cross-section in Collider Physics

- *"Cross-section what?"*

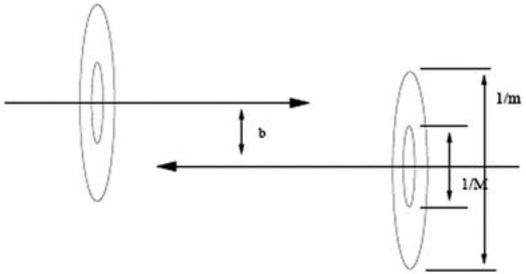


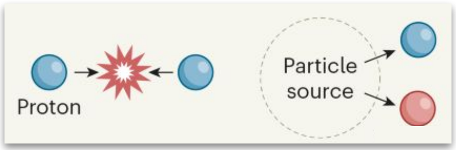
Wikipedia
The Free Encyclopedia

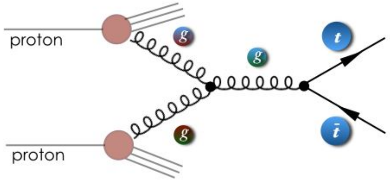
In physics, the cross section is a **measure of the probability** that a specific process will take place when some kind of ***radiant excitation*** (e.g. a particle beam, sound wave, light, or an X-ray) intersects a ***localized phenomenon*** (e.g. a particle or density fluctuation). [...] Cross section is typically **denoted σ (sigma)** and is expressed in units of **area**, more specifically in barns. In a way, it can be thought of as the size of the object that the excitation must hit in order for the process to occur [...]

- Essentially, in the case of **particle colliders**:
  - **probability of interaction** / reaction between two colliding particles
  - multiplied by the effective beam intensity ("**luminosity**") → **rate** of interactions / reactions
  - integrated over time (i.e. multiplying by "**integrated luminosity**") → **number** of "events"

$$N = \sigma \cdot \int L$$







- Besides ***inclusive*** cross-section we define **partial cross-sections** for specific process:
  - probability of production of **specific final state** from certain colliding particles

Measuring a cross-section

- Cross-section measurement **golden formula**:

*number of **produced** events*

*number of data events passing the **event selection***

OBSERVED / COUNTED

*number of **background** events passing the **event selection***

ESTIMATED

$$\sigma = \frac{N}{\int L} = \frac{N(data) - N(background)}{\epsilon \cdot \int L}$$

integrated luminosity

selection efficiency

Statistical and systematic uncertainties

- **Statistical uncertainty** = uncertainty on event counting
  - Poisson statistics ⇒ at high N, error = √N

$$\sigma = \frac{N}{\int L} = \frac{N(data) - N(background)}{\epsilon \cdot \int L}$$

(usually) from MC simulation

- **Systematic uncertainties** = other uncertainties, related to experimental instrumentation, tools, techniques, assumptions, theoretical predictions...

Systematic uncertainties

- Typically most important systematic uncertainties:

lepton energy/momentum scale & resolution

background prediction

jet energy scale & resolution

lepton selection efficiency

b-tagging efficiency

$$\sigma = \frac{N}{\int L} = \frac{N(data) - N(background)}{\epsilon \cdot \int L}$$

parton-shower and hadronization model choice

luminosity uncertainty

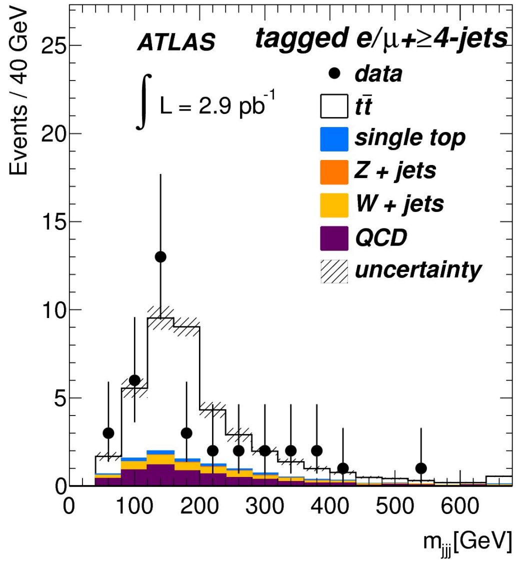
Total $t\bar{t}$ cross section measurements in ATLAS

2010, √s = 7 TeV, ∫L = 3 pb^{-1}

Eur. Phys. J. C 71 (2011) 1577

- "Cut & Count"

$$\sigma_{t\bar{t}} = 145 \pm 31 \,^{+42}_{-27} \text{ pb}$$

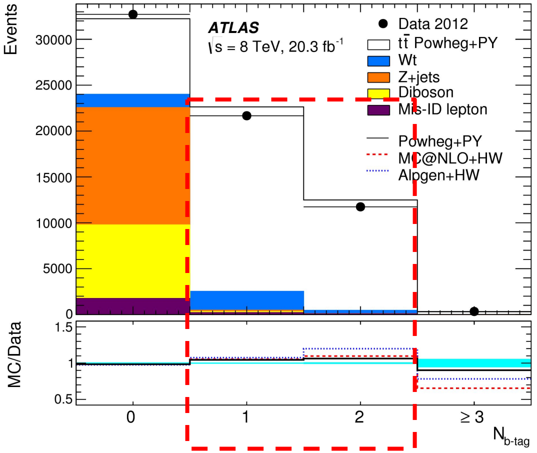


2014, √s = 8 TeV, ∫L = 20 fb^{-1}

Eur. Phys. J. C 74 (2014) 3109

- dilepton eμ only
- extract σ and b-tagging efficiency at the same time

$$\sigma_{t\bar{t}} = 242.4 \pm 1.7 \pm 10.2 \text{ pb}$$

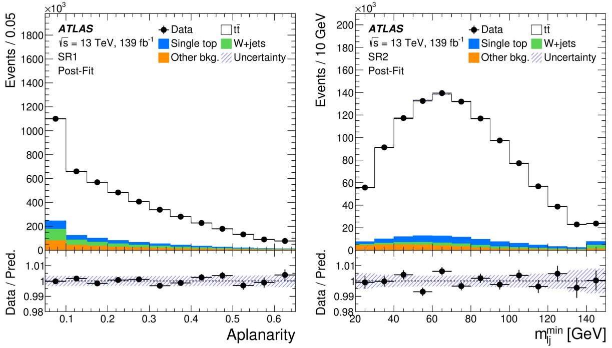


2020, √s = 13 TeV, ∫L = 139 fb^{-1}

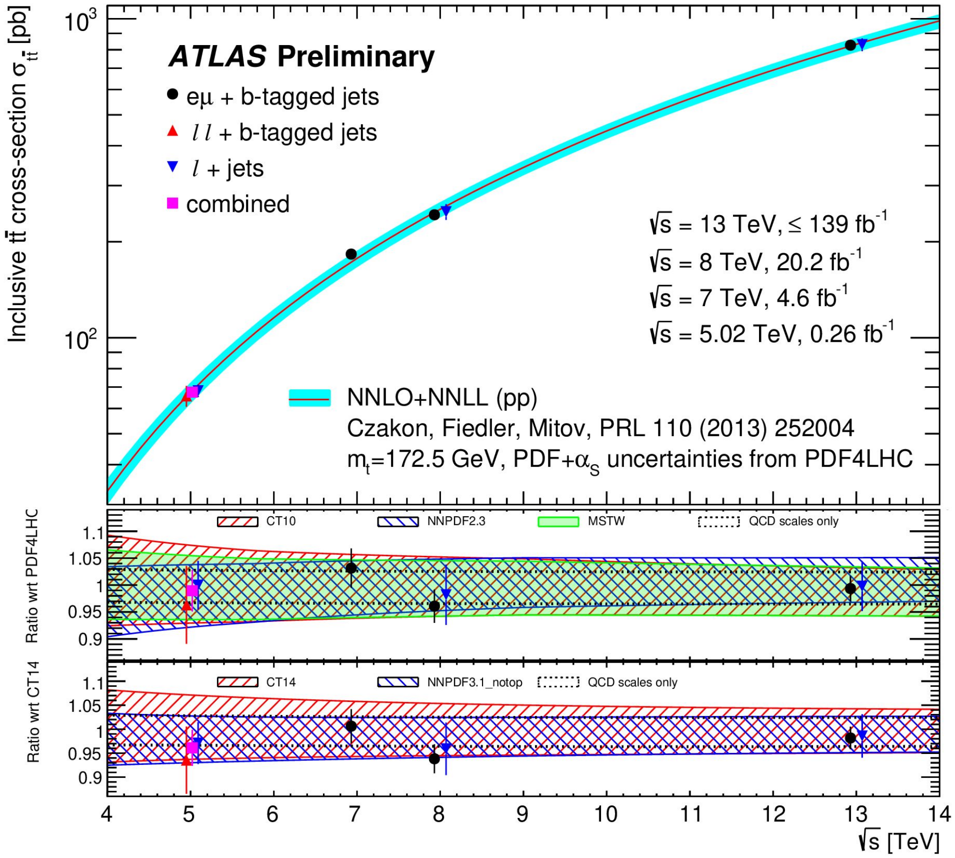
Phys. Lett. B 810 (2020) 135797

- ℓ + jets
- "profile likelihood fit" ⇒ *in situ* constraint of all systematic uncertainties

$$\sigma_{t\bar{t}} = 830 \pm 0.4 \pm 39 \text{ pb}$$



Total $t\bar{t}$ cross section measurements in ATLAS



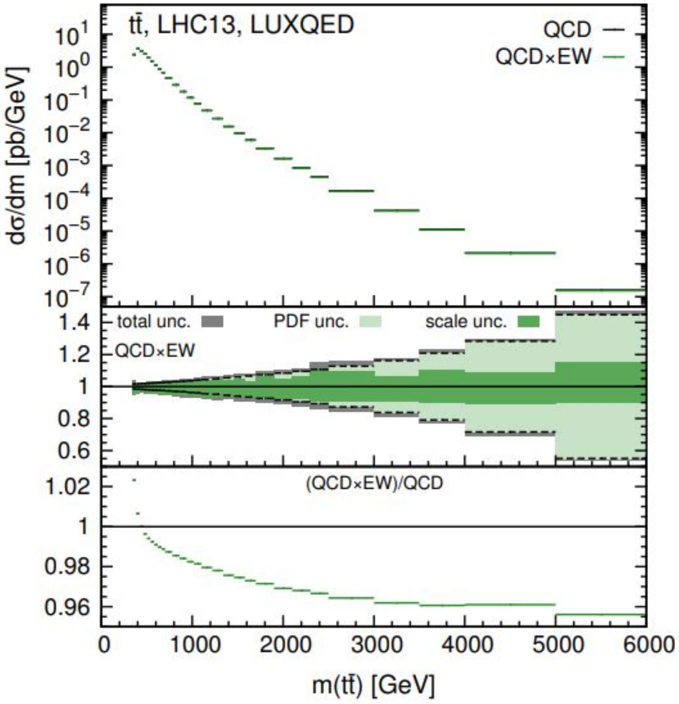
Differential cross section

- Cross-section can be measured "***differentially***",
  i.e. as a function of **kinematic properties** of final state

$$\sigma(pp \to t\bar{t}) \Rightarrow \frac{d\sigma(pp \to t\bar{t})}{dm_{t\bar{t}}}, \quad \frac{d\sigma(pp \to t\bar{t})}{dp_T^t}, \quad \frac{d\sigma(pp \to t\bar{t})}{dY_{t\bar{t}}}$$

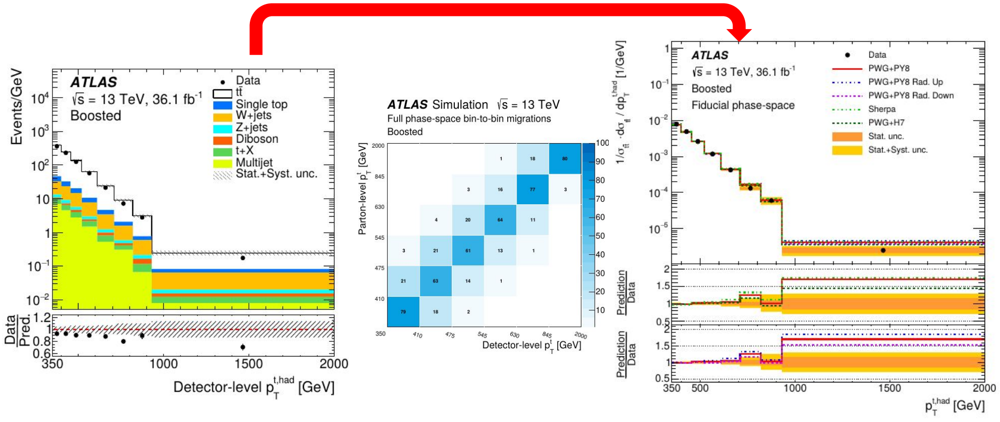
...

arXiv:1705.04105 - Mitov et al.



The unfolding technique

- **Unfolding** is:
  - *removal of detector resolution effects from observed distribution, to extract (our best-guess of) underlying true distribution*
  - i.e. extraction of a **differential cross-section**
- Can be done to extract:
  - **total-phase-space** or **fiducial-phase-space** cross-sections
  - cross-sections vs. variable defined at **particle-level** or at **parton-level**
- The unfolding problem can be essentially reduced to a **response-matrix**-inversion problem



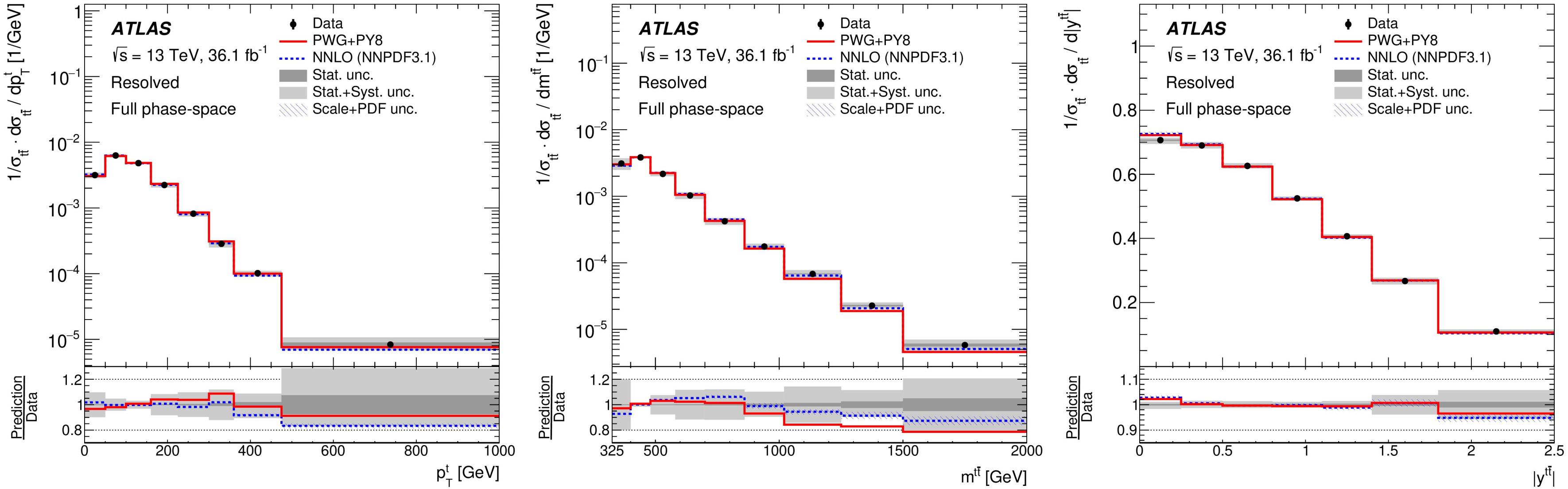
Comparison of results with predictions

2019, $\sqrt{s}$ = 13 TeV, ∫L = 36 fb^{-1}

Eur. Phys. J. C 79 (2019) 1028

- ℓ + jets differential

Just one example out of many analyses…
… and just 3 observables out of a many many ones!



- Useful to test & tune theoretical predictions, Monte Carlo simulation, PDFs..
  - or to look for new physics effects!

Questions?