ELEMENTARY PARTICLE PHYSICS
Current Topics in Particle Physics
Laurea Magistrale in Fisica,
curriculum Fisica Nucleare e Subnucleare
Lecture 8

Simonetta Gentile*

* Università Sapienza,Roma,Italia.

November 17, 2017

Preliminaries

Simonetta Gentile
terzo piano Dipartimento di Fisica *Gugliemo Marconi*
Tel. 0649914405
e-mail: simonetta.gentile@roma1.infn.it
pagina web:http://www.roma1.infn.it/people/gentile/simo.html

Bibliography

♠ Bibliography

- K.A. Olive et al. (Particle Data Group), *The Review of Particle Physics*, Chin. Phys. C, 38, 090001 (2014)(PDG) update 2015, http://pdg.lbl.gov/
- F. Halzen and A. Martin, *Quarks and Leptons: An introductory course in Modern Particle Physics* , Wiley and Sons, USA(1984).

♠ Other basic bibliography:

- A.Das and T.Ferbel, *Introduction to Nuclear Particle Physics* World Scientific,Singapore, 2^{nd} Edition(2009)(DF).
- D. Griffiths, *Introduction to Elementary Particles* Wiley-VCH,Weinheim, 2^{nd} Edition(2008),(DG)
- B.Povh *et al.*, *Particles and Nuclei* Springer Verlag, DE, 2^{nd} Edition(2004).(BP)
- D.H. Perkins,*Introduction to High Energy Physics* Cambridge University Press, UK, 2^{nd} Edition(2000).
- Y.Kirsh & Y. Ne'eman, *The Particle Hunters*

♠ Particle Detectors bibliography:

- William R. Leo *Techniques for Nuclear and Particle Physics Experiments*,
  Springer Verlag (1994)(LEO)
- C. Grupen, B. Shawartz *Particle Detectors*,
  Cambridge University Press (2008)(CS)
- *The Particle Detector Brief Book*,(BB)
  http://physics.web.cern.ch/Physics/ParticleDetector/Briefbook/

Specific bibliography is given in each lecture

Lecture Contents - 1 part

1. Introduction. Lep Legacy
2. Proton Structure
3. Hard interactions of quarks and gluons: Introduction to LHC Physics
4. Collider phenomenolgy
5. The machine LHC
6. Inelastic cros section pp
7. W and Z Physics at LHC
8. Top Physics: Inclusive and Differential cross section $t\bar{t}$ W, $t\bar{t}$ Z
9. Top Physics: quark top mass, single top production
10. Dark matter

Specific Bibliography

♠ Bibliography of this Lecture

- T.Han, *Collider Phenomenology: Basic Knowledge and Techniques*, arXiv:hep-ph/0508097 (TAO)

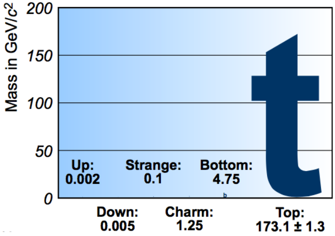
Contents

Introduction

Top quarks are special

- Top quark mass
  - The heaviest known particle: mass : $m_{top} = 173.21 \pm 0.51 \pm 0.71$ GeV
  - Pointlike particle with mass of gold atom, 35xheavier than bottom quark →why?
  - Being heavier than a W boson, it is the only quark that decays semi-weakly, i.e., into a real W boson and a b quark
- It is the only quark whose Yukawa coupling to the Higgs boson ≈ 1

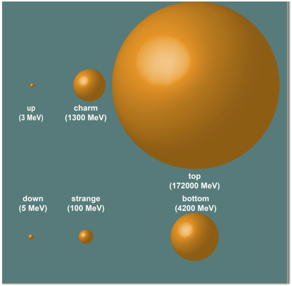
Understanding the origin of mass is a major open problem



- Top quark lifetime: $\tau \approx 5 \cdot 10^{-25}$ s
  - $\Gamma = 141^{+0.19}_{-0.15}$GeV
  - compare with hadronization scale $\Lambda_{QCD} \approx 250$ MeV
  - a very short lifetime and **decays before hadronization can occur**

Reasons to study

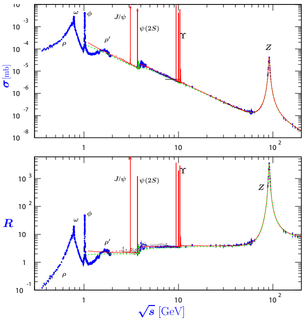
- Important consequence of top: top decay before hadronization
  - Top is the only *free* quark $\Longrightarrow$**no bound states**(e.g. toponium, top mesons/baryons)
  - The only place where to study property of bare quark
  - Spin/polarization passed on to decay productions without dilution/direct access to quark properties
  - Particularly if new particle couples to mass
- First place a new particle could be observed
- Top is background of many searches



- An accurate knowledge of **its properties**(mass, couplings, production cross section, decay branching ratios, etc.) can bring **key information on fundamental interactions** and beyond.

Contents

History of top discovery



$$R = \frac{\sigma(e^+ + e^- \to hadrons)}{\sigma(e^+ + e^- \to \mu\mu)}$$

- 1976: Discovery of Upsilon (Fermilab)
  - Contains a 5th quark - the b-quark
  - From family structure of SM
  - Expect a 6th quark - race to find it

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} \\ b \end{pmatrix}$$

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

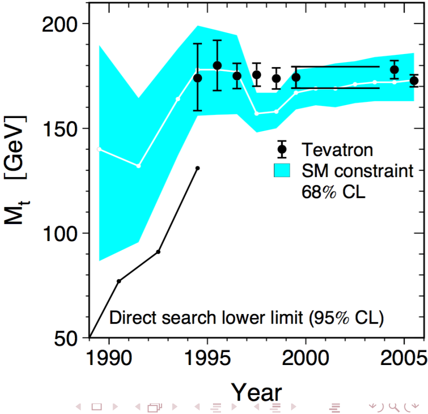
Electroweak precision data

- Analysis of radiative corrections within the framework of the SM using precision electroweak measurements (68%C.L.) shaded area.

$$\Delta\rho_t = \frac{3G_F}{8\pi^2\sqrt{2}} m_t^2$$

- Direct measurements of m_t at Tevatron(CDF D0) (error bars 68%C.L.)
- From precision Z osservable $m_t = 173^{+13}_{-10}$ GeV
- From Direct measurement $m_t = 174.34 \pm 0.64$ GeV

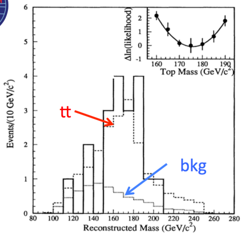
Direct and indirect determinations of the mass of the top quark, m_t, as a function of time.



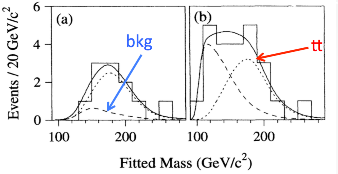
Top discovery

- 1995 discovery at Tevatron $\sqrt{s} = 1.8$ TeV. CDF and D0 experiments

4.8 sigma



4.6 sigma

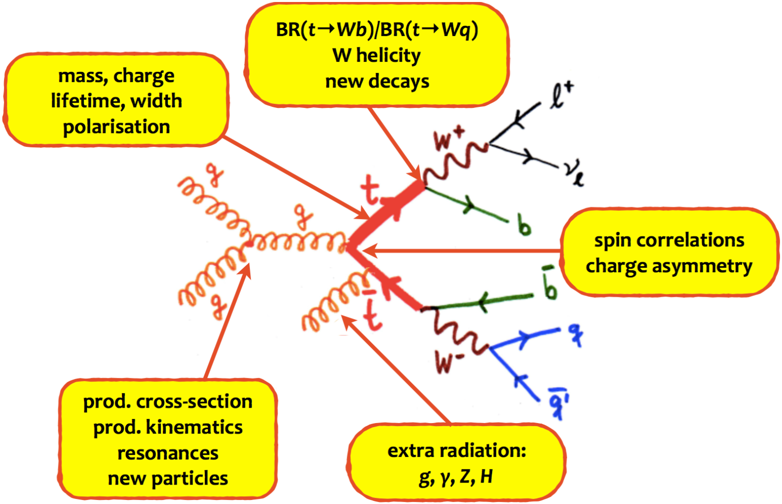


$$m_{top} = 199^{+19}_{-21}(stat) \pm 22(sys) \quad GeV/c^2$$
$$\sigma_{tt} = 6.4 \pm 2.2 \text{ pb}$$

[1]
$$m_{top} = 176 \pm 8(stat) \pm 10(sys) \quad GeV/c^2$$
$$\sigma_{tt} = 6.8^{+3.6}_{-2.4} \text{ pb}$$

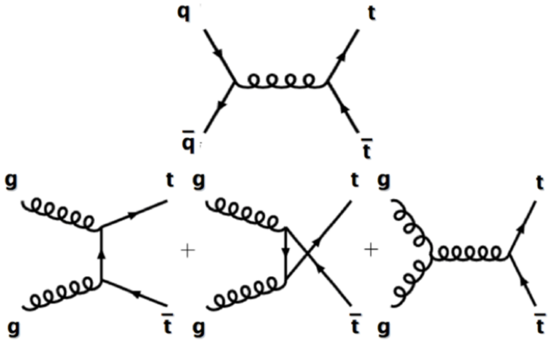
[1] CDF: Phys. Rev. Lett. 74,2626 (1995), D0:Phys. Rev. Lett. 74,2632 (1995)

Top overview



Contents

Top production



	TeVatron	LHC 7 TeV	LHC 8 TeV	LHC 14 TeV
gg	15.4%	84.8%	86.2%	90.2%
$qg + \bar{q}g$	-1.7%	-1.6%	-1.1%	0.5%
qq	86.3%	16.8%	14.9%	9.3%

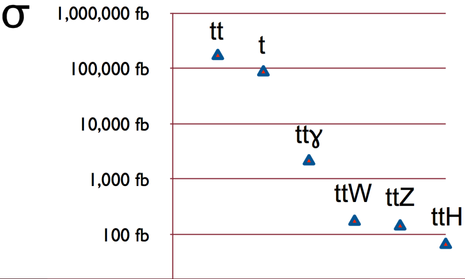
@LO with MSTW2008NNLO Tevatron $gg \sim 15\%$ and $qq \sim 85\%$
LHC(14 TeV) $gg \sim 90\% qq \sim 10\%$)

$t\bar{t}$ cross section

NNLO theoretical predictions:[2]

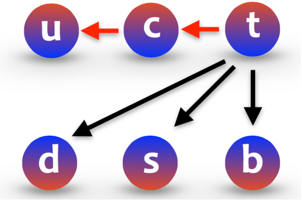
Collider	beam	$\sqrt{s}$ TeV	σ_{tot} pb	rate at $10^{34}cm^{-2}s^{-1}$
Tevatron	$p\bar{p}$	1.96	7.009	
LHC	pp	7	167.0	$\sim$ 2 Hz
LHC	pp	8	239.0	$\sim$ 2 Hz
LHC	pp	14	933.0	$\sim$ 9 Hz

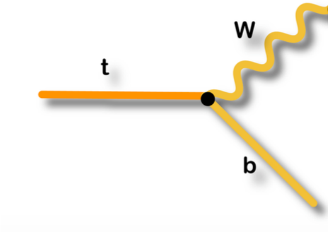
$\Longrightarrow$ Top Factory!



Top decays

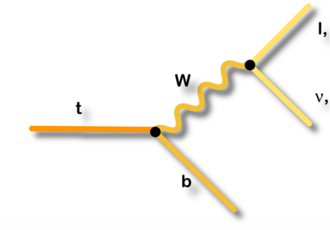
- Top decays before can hadronize
- Top decay via the electroweak interactions
- Governed by CKM matrix, $Br(t \rightarrow Wb) \sim 1$
- Final state characterized by the decays of the W boson: $W \rightarrow \ell\nu, \tau_{\text{had}}\nu$ or $W \rightarrow q\bar{q} \longrightarrow$ different sensitivity and challenges in each channel

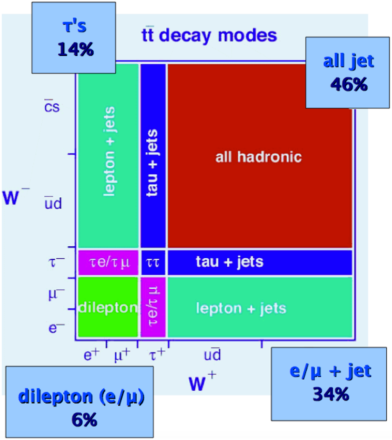




Top decays

Final state characterized by the decays of the W boson:
$\mathrm{Br}(W \to \ell\nu = 10.86\%), \mathrm{Br}(W \to \tau\nu = 11.38\%),$
$\mathrm{Br}(W \to \text{hadrons} = 67.41\%)$:

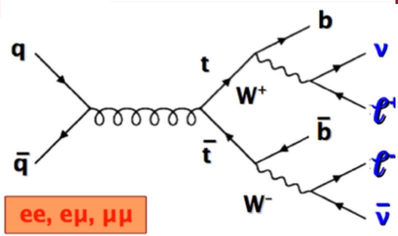




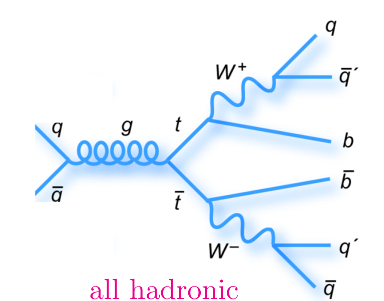
Top pair events classification according W decays:

- dileptons
- lepton + jets
- all hadronic

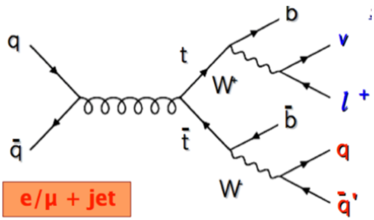
Top decays



dileptons



all hadronic

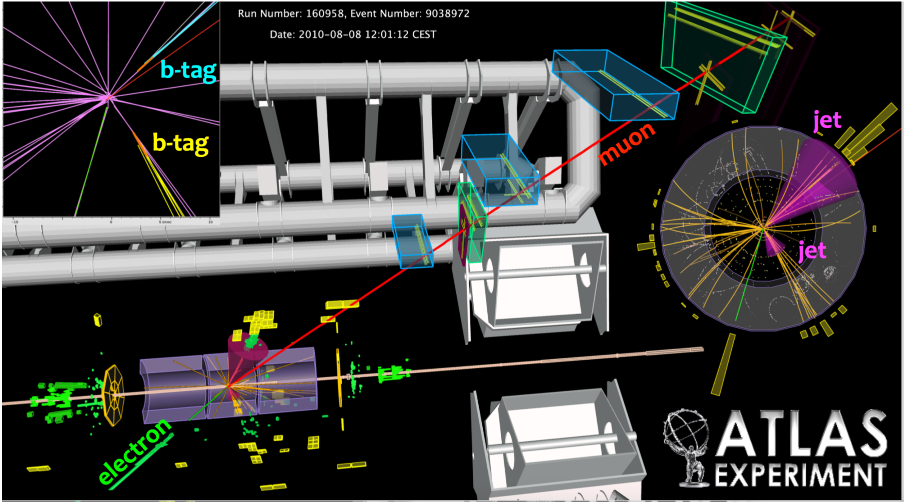


lepton+jets

- **dileptons**:Br $\sim 6\%$.
  Background:
  Few (mainly Z + jets)
- **lepton+jets**: Br $\sim 35\%$
  Background:
  Few (mainly W + jets)
- **all hadronic**: Br $\sim 46\%$
  Background:
  Huge (mainly QCD)

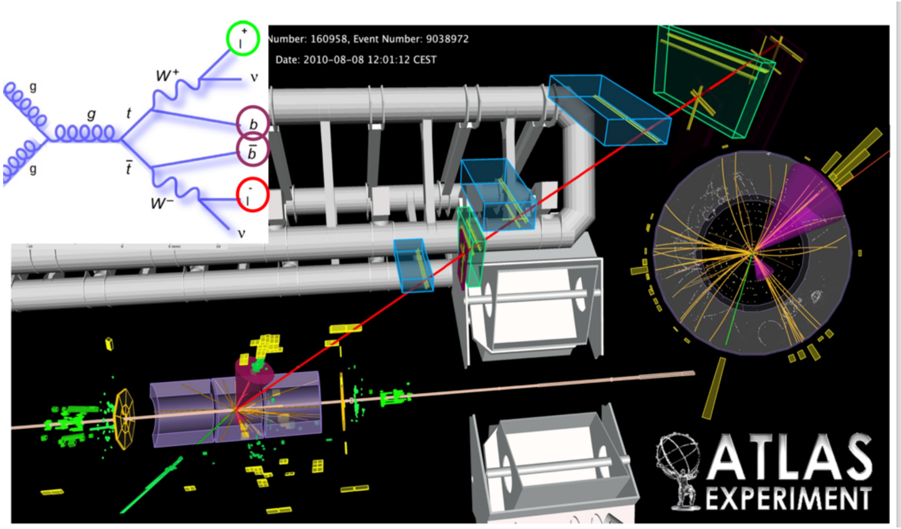
Top decays-dileptons

$$t\bar{t} \to W^+ b W^- \bar{b} \to e^+ \nu_e b \mu^- \bar{\nu}_\mu \bar{b}$$



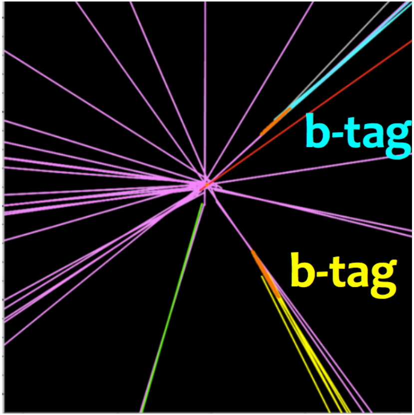
Top decay-dileptons

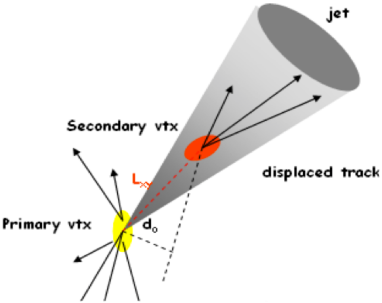
$$t\bar{t} \to W^+ b W^- \bar{b} \to e^+ \nu_e b \mu^- \bar{\nu}_\mu \bar{b}$$

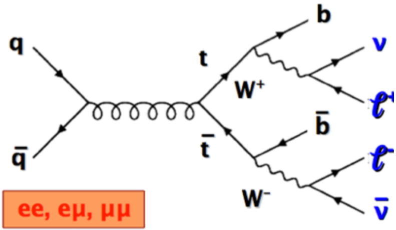


b-tag

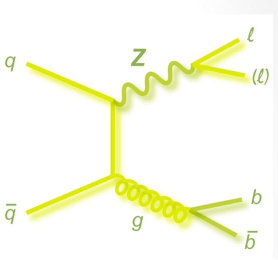
- B-hadron lifetime $\tau \sim 1$ ps
- B hadron trave $L_{xy} \sim 3$mm before decay







dileptons



Z +jets

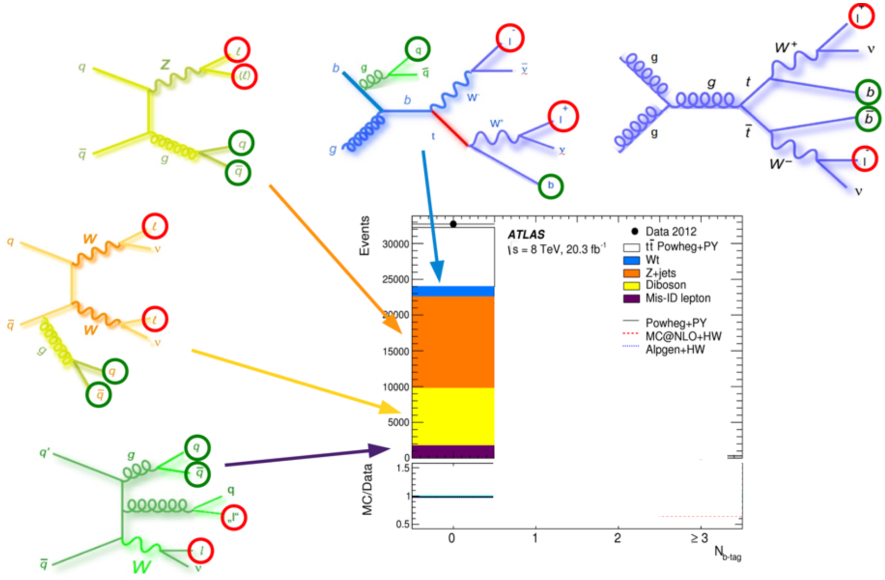
Selection criteria for Signal

- 2 leptons
- Missing transverse energy
- $\geq$ 2 jets
  - from b-hadrons

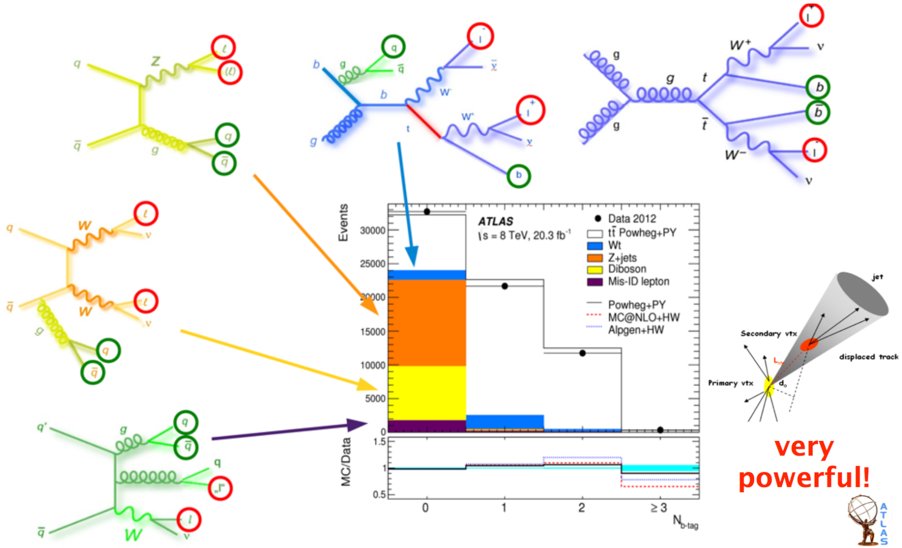
Background

- Z + jets
- Single top
- Dibosons
- QCD multi-jets *fakes*

di-lepton signatures

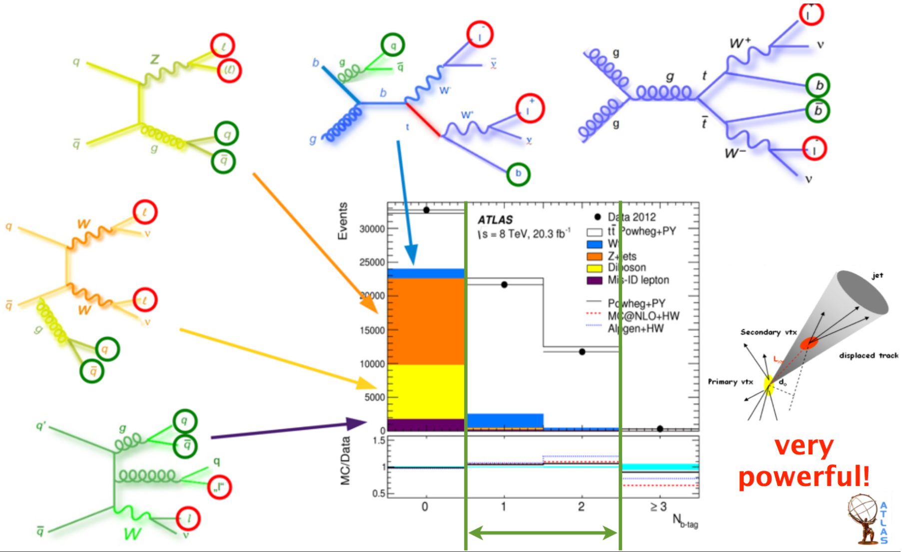


di-lepton signatures

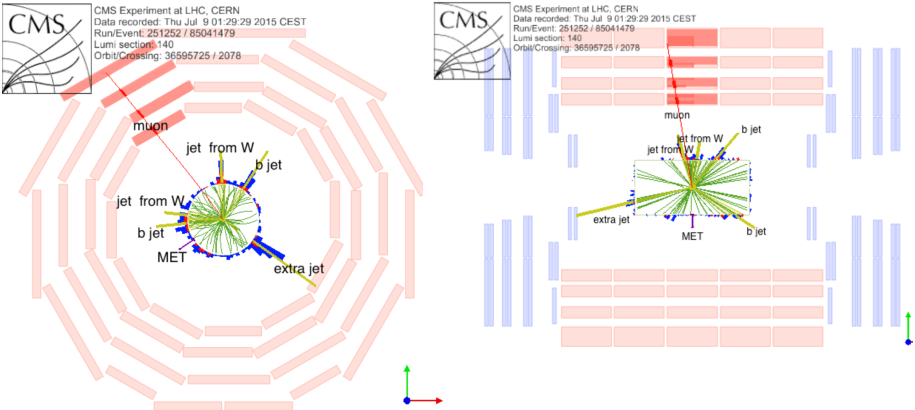


very powerful!

di-lepton signatures



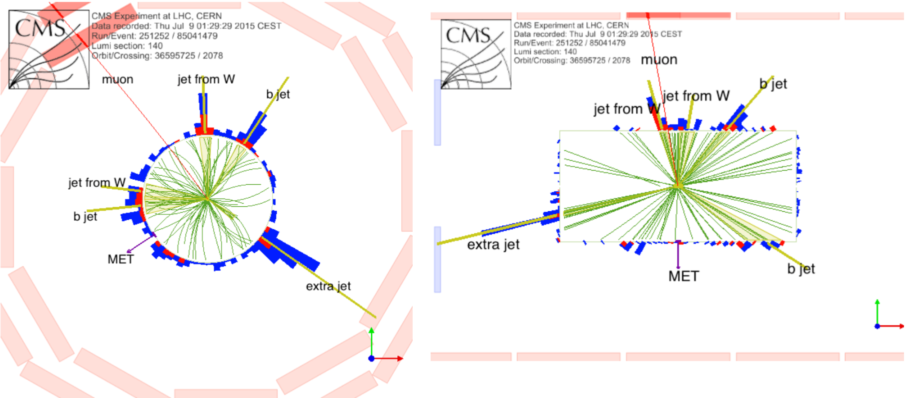
Top decay- lepton plus jets



Event display of a top-quark pair candidate.This event has **one isolated muon**,**transverse missing energy** of 34 GeV, and **five hadronic jets**.**Two**of the jets pass the tight threshold on the b-tagging discriminant and are interpreted as originating from the **b quarks** from top quark decay.**Two**of the others form an invariant mass of 72 GeV and are interpreted as coming from a hadronically-decaying **W boson**.

(CMS DP -2015/019 https://cds.cern.ch/record/2037376?ln=it)

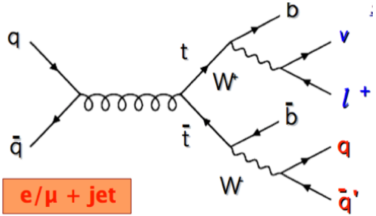
Top decay- lepton plus jets



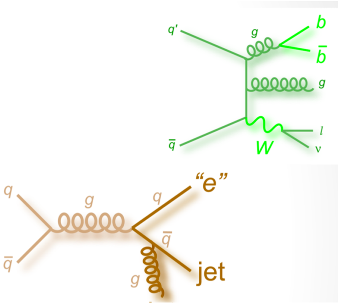
Event display of a top-quark pair candidate.This event has **one isolated muon**,**transverse missing energy** of 34 GeV, and **five hadronic jets**.**Two**of the jets pass the tight threshold on the b-tagging discriminant and are interpreted as originating from the **b quarks** from top quark decay.**Two**of the others form an invariant mass of 72 GeV and are interpreted as coming from a hadronically-decaying **W boson**.

(CMS DP -2015/019 https://cds.cern.ch/record/2037376?ln=it)

lepton plus jets channel



lepton + jet



W +jets

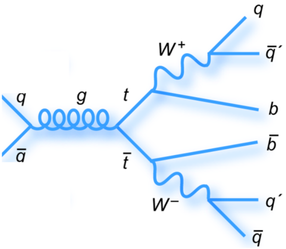
Selection criteria for lepton+jets

- 1 leptons
- Missing transverse energy
- $\geq$ 4 jets
  - 2 from b-hadrons

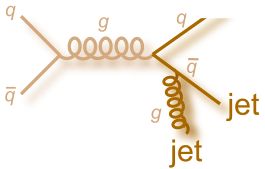
Background

- W + jets
- Single top
- Dibosons
- Z +jets
- QCD multi-jets *fakes*

All hadronic decays



all jets



QCD jets

Selection criteria

Signal

- 0 leptons
- NO Missing transverse energy
- $\geq$ 6 jets
  - 2 from b-hadrons

Background

- QCD multi-jets

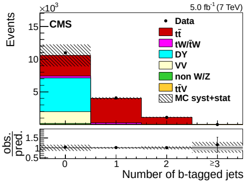
Relative Merits

Relative Merits:

- **Dileptons:** Br $\sim 6\%$
  - lowest branching ratio
  - Highest Signal/Background
  - 2 neutrinos $\Longrightarrow$ harder reconstruct $t\bar{t}$ system
- **lepton+jets:** Br $\sim 35\%$
  - Reasonable branching ratio
  - Reasonable Signal/Background
  - Only 1 neutrino $\Longrightarrow$ so can fully reconstruct $t\bar{t}$ system
- **all hadronic:** Br $\sim 46\%$
  - Highest branching ratio
  - Lowest Signal/Background
  - Hard determine background from QCD
  - Reconstructing $t\bar{t}$ system system: combinatorial complexity

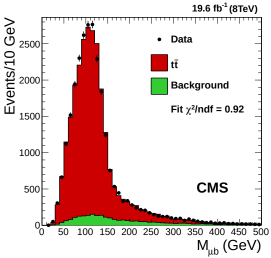
Distributions

dileptons:



Number of b-tagged jets after the $e\mu$ selection at $\sqrt{s}=7$ TeV.
https://arxiv.org/abs/1603.02303

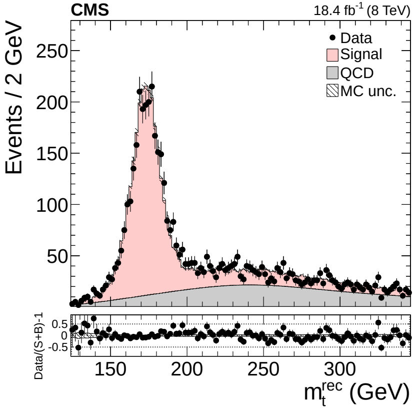
lepton+jets



Distributions of the lepton-jet mass in the muon+jets
https://arxiv.org/abs/1602.09024

Distributions

all hadronic



Distribution of the reconstructed top quark mass after the kinematic fit.The normalizations of the $t\bar{t}$ signal and the QCD multijet background are taken from the template fit to the data.

https://arxiv.org/abs/1509.06076

Contents

$$t\bar{t} \to e\mu\nu\bar{\nu}b\bar{b}$$

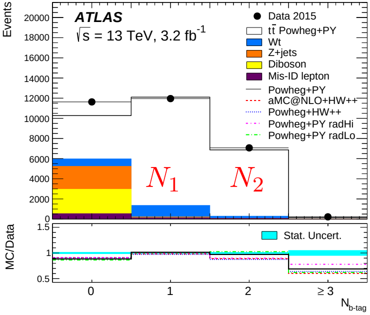


Figure : Distribution of the number of b-tagged jets in preselected opposite-sign $e\mu$ events

ATLAS https://arxiv.org/abs/1606.02699

$\sigma_{t\bar{t}}$ is determined by counting the numbers of opposite-sign $e\mu$ events with exactly one (N_1) and exactly two (N_2) b-tagged jets, ignoring any jets that are not b-tagged which may be present:

$$N_1 = \mathcal{L}\sigma\epsilon_{e\mu}2\epsilon_b(1 - C_b\epsilon_b) + N_{b1}^{\text{bkg}}$$

$$N_2 = \mathcal{L}\sigma\epsilon_{e\mu}\epsilon_b^2 C_b\epsilon_b + N_{b2}^{\text{bkg}}$$

$\mathcal{L}$ = integrated luminosity

$\epsilon_{e\mu}$ = efficiency for ℓ to be in the detector and reconstructed

ϵ_b = efficiency for b-jets from top to be in the detector and reconstructed

C_b = term to account the correlations between the two b-jets.

Measuring the $t\bar{t}$ inclusive cross section

$$N_1 = \mathcal{L}\sigma\epsilon_{e\mu}2\epsilon_b(1 - C_b\epsilon_b) + N_{b1}$$
$$N_2 = \mathcal{L}\sigma\epsilon_{e\mu}\epsilon_b^2 C_b\epsilon_b + N_{b2}$$

♠ Measure $N_1$and N_2 $\Longrightarrow$ extract ϵ_b and σ;solved by minimising a likelihood function.

- Analysis designed to be as sensitive as possible to large detector uncertainties
- Takes as much information as possible from the detector

Event counts	N_1
Data	11958
Single top	1140 ± 100
Diboson	34 ± 11
$Z(\to \tau\tau \to e\mu)$+jets	37 ± 18
Misidentified leptons	164 ± 65
Total background	1370 ± 120

Observed numbers of opposite-sign $e\mu$ events with one and two b-tagged jets (N_1 and N_2), together with the estimates of non-$t\bar{t}$ backgrounds and associated systematic uncertainties. Uncertainties quoted as 0 are < 0.5.

Measuring the $t\bar{t}$ inclusive cross section: Systematics

Uncertainty (inclusive $\sigma_{t\bar{t}}$)	$\Delta\epsilon_{e\mu}/\epsilon_{e\mu}$ [%]	$\Delta C_b/C_b$ [%]	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ [%]
Data statistics			0.9
$t\bar{t}$ NLO modelling	0.7	−0.1	0.8
$t\bar{t}$ hadronisation	−2.4	0.4	2.8
Initial- and final-state radiation	−0.3	0.1	0.4
$t\bar{t}$ heavy-flavour production	-	0.4	0.4
Parton distribution functions	0.5	-	0.5
Single-top modelling	-	-	0.3
Single-top/$t\bar{t}$ interference	-	-	0.6
Single-top Wt cross-section	-	-	0.5
Diboson modelling	-	-	0.1
Diboson cross-sections	-	-	0.0
Z+jets extrapolation	-	-	0.2
Electron energy scale/resolution	0.2	0.0	0.2
Electron identification	0.3	0.0	0.3
Electron isolation	0.4	-	0.4
Muon momentum scale/resolution	−0.0	0.0	0.0
Muon identification	0.4	0.0	0.4
Muon isolation	0.2	-	0.3
Lepton trigger	0.1	0.0	0.2
Jet energy scale	0.3	0.1	0.3
Jet energy resolution	−0.1	0.0	0.2
b-tagging	-	0.1	0.3
Misidentified leptons	-	-	0.6
Analysis systematics	2.7	0.6	3.3
Integrated luminosity	-	-	2.3
LHC beam energy	-	-	1.5
Total uncertainty	2.7	0.6	4.4

⇐

results:

$$\sigma_{t\bar{t}} = 818 \pm 8(stat) \pm 27(syst) \pm 19(lumi) \pm 12(beam)\text{pb}$$

⇐

⇐

$t\bar{t}$ cross section

NNLO theoretical predictions:[3]

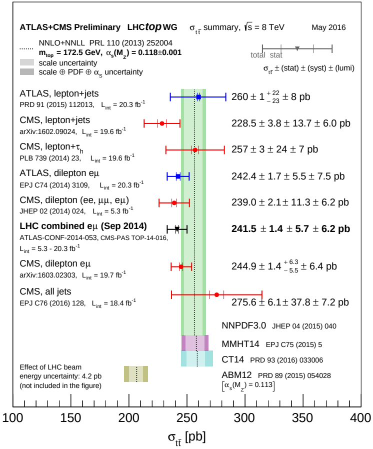
Collider	σ_{tot} [pb]	scales [pb]	pdf [pb]
Tevatron	7.009	+0.259(3.7%) −0.374(5.3%)	+0.169(2.4%) −0.121(1.7%)
LHC 7 TeV	167.0	+6.7(4.0%) −10.7(6.4%)	+4.6(2.8%) −4.7(2.8%)
LHC 8 TeV	239.1	+9.2(3.9%) −14.8(6.2%)	+6.1(2.5%) −6.2(2.6%)
LHC 14 TeV	933.0	+31.8(3.4%) −51.0(5.5%)	+16.1(1.7%) −17.6(1.9%)

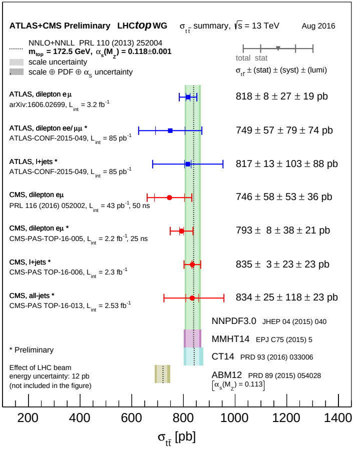
It has been calculate($\alpha_s^2 \sim 0.1$ the series should be converge) :

- Leading order term (LO $\propto \alpha_s^2$)
- Next-to-Leading order term (NLO $\propto \alpha_s^3$)
- Next-to-next-to-leading order term (NNLO $\propto \alpha_s^4$)

[3] M. Czakon, P. Fiedler, A. Mitov, Phys. Rev. Lett. 110 (2013) 252004,https://arxiv.org/pdf/1303.6254v1.pdf

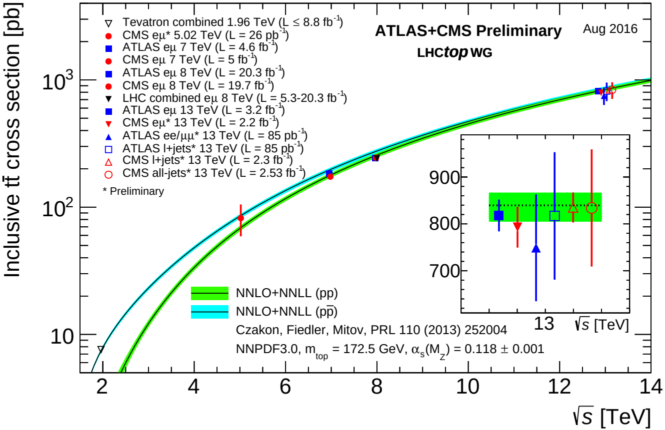
$t\bar{t}$ experimental cross section





Precision of measurement comparable to theory precision LHC and Tevatron results consistent and in agreement with NNLO

$t\bar{t}$ experimental inclusivecross section



LHC and Tevatron results consistent and in agreement with NNLOover a large range of centre-of-mass energies[4]

[4] ATLAS, 3.2fb-1, 13TeV, Dilept., arXiv:1606.02699, CMS, 2.3fb-1,13TeV, l+jets CMS-PAS-TOP-16-006, CMS, 2.53fb-1,13TeV, all jets CMS-PAS-TOP-16-013, CMS, 26pb-1,5TeV, dilept. CMS-PAS-TOP-16-015

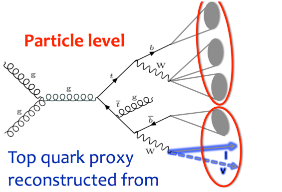
Contents

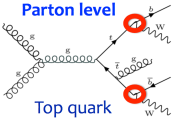
$t\bar{t}$ differential cross section

- Motivation
  - detailed test of pQCD, constrain PDF and MC parameters
  - background for Higgs, rare processes and many BSM searches
- General analysis strategy
  - tight event selection → pure $t\bar{t}$ sample
  - $t\bar{t}$ system / top quark kinematic reconstruction
  - background subtraction
  - corrections: acceptance, resolution → unfolding

$$\frac{1}{\sigma}\frac{d\sigma_i}{dX} = \frac{1}{\sigma}\frac{\text{unfold}(s_i^X - b_i^X)}{\Delta_i^X \cdot \int \mathcal{L}dt}$$

  - compare to theory predictions at particle or parton level
  - unfold to particle level normalized: cancellations of many systematic uncertainties

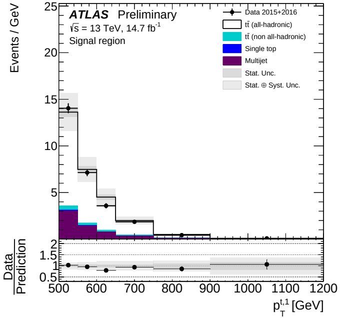




$t\bar{t}$

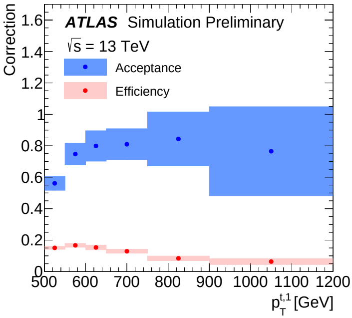
1. Starting with a relevant detector distribution of a reconstructed variable: e.g.the p_T distributions of the leading jet.
2. Subtraction of the estimated backgrounds.
3. Application of **acceptance correction** f_{acc} that accounts for events that are generated outside the fiducial phase-space but pass the detector-level selection.

ATLAS 16-09-2016: http://cds.cern.ch/record/2217231



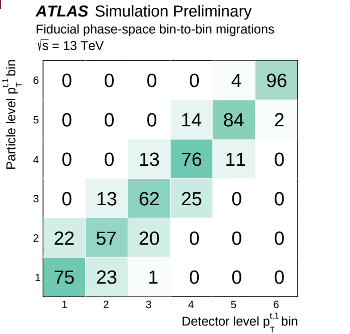
5. Account for **detector resolution and efficiency corrections** ϵ_{eff} correct for events that are in the fiducial phase-space but are not reconstructed at the detector level
6. The drop in efficiency at higher top-quark candidate p_{T} arises primarily from the b-tagging requirements.

ATLAS 16-09-2016: http://cds.cern.ch/record/2217231



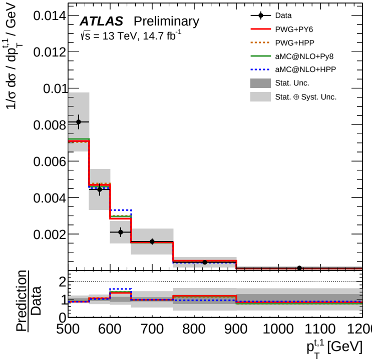
- **Unfolding** step uses a migration matrix (M) derived from the simulated $t\bar{t}$ events in the fiducial phase-space that have been matched to detector-level jets, where the rows represent MC events produced within a given bin normalized to 100, and the columns represent the binning of the same detector-level variable.

ATLAS 16-09-2016: http://cds.cern.ch/record/2217231



The probability for particle-level events to remain in the same bin is therefore represented by the elements on the diagonal, and the **off-diagonal elements describe the fraction of particle-level events that migrate into other bins.**

$$\frac{d\sigma^{\text{fid}}}{dX^i} \equiv \frac{1}{\int \mathcal{L}dt \cdot \Delta X^i} \cdot \frac{1}{\epsilon_{\text{eff}}} \cdot \sum_j \mathcal{M}_{ij}^{-1} \cdot f_{\text{acc}}^j \cdot \left(N_{\text{reco}}^j - N_{\text{bg}}^j\right)$$



- **Normalized fiducial phase-space differential cross-sections as a function of transverse momentum of the leading top-quark jet.**

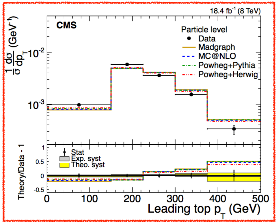
Unfolding Parton vs Particle

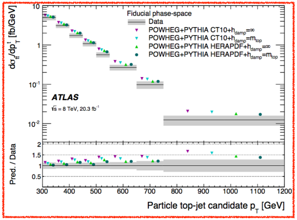
Few unfolding can be elaborated:

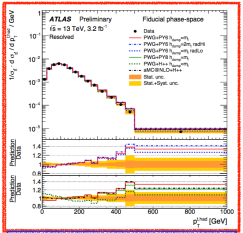
- Particle level
  - Closer to our reconstructed quantities
  - Constraining the MC parameters (*tuning*)
- Parton level
  - Easier to calculate
  - Necessary for comparison to fixed predictions
  - PDF fitting

$t\bar{t}$ differential top quark p_T

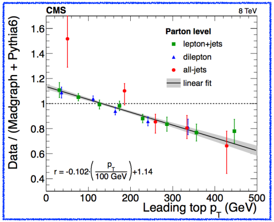
S

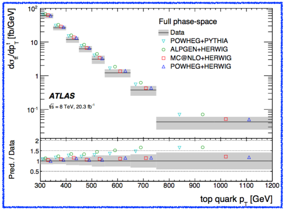


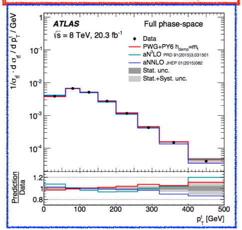




Particle-level







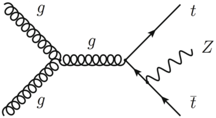
Parton-level

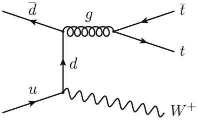
Top p_T modelled too hard (improves with NNLO pQCD). New Full NNLO calculation available. M. Czakon, D. Heymes and A. Mitov arXiv:1511.00549, PRL 116 (2016) 082003

Contents

ttZ and ttW

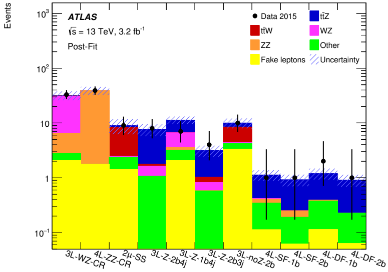
- Couplings of top quark to Z are largely unexplored
  - Production sensitive to new physics
  - ttZ and ttW backgrounds to new physics searches and $t\bar{t}H$



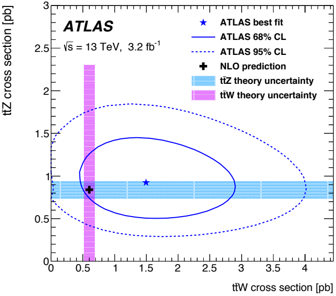


- Four signal regions: 2ℓ OS, 2ℓ SS, 3ℓ, 4ℓ
  OS = Opposite sign ,SS = Same sign

ttZ and ttW



Expected yields after the fit compared to data for the fit to extract $\sigma_{t\bar{t}Z}$ and $\sigma_{t\bar{t}W}$ in the signal regions and in the control regions used to constrain the WZ and ZZ backgrounds SF= same flavour DF= different flavour



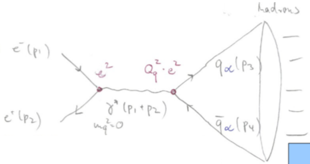
Simultaneous fit to the $t\bar{t}Z$ and $t\bar{t}W$ cross sections

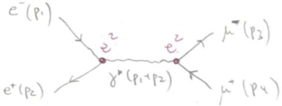
$$\sigma_{t\bar{t}Z} = 0.9 \pm 0.3\text{pb}$$
$$\sigma_{t\bar{t}W} = 1.5 \pm 0.8\text{pb}$$

ATLAS: https://arxiv.org/pdf/1609.01599v1.pdf

Contents

Ratio R





$$R = \frac{\sigma(e^+ + e^- \to hadrons)}{\sigma(e^+ + e^- \to \mu^+ + \mu^-)} = \frac{3\sum(quark\ charge)^2}{1^2}$$