# Top Physics at LHC

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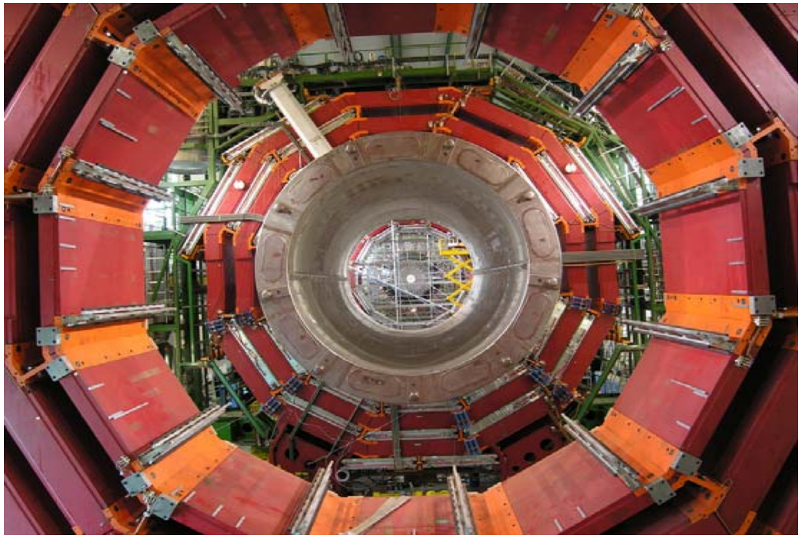
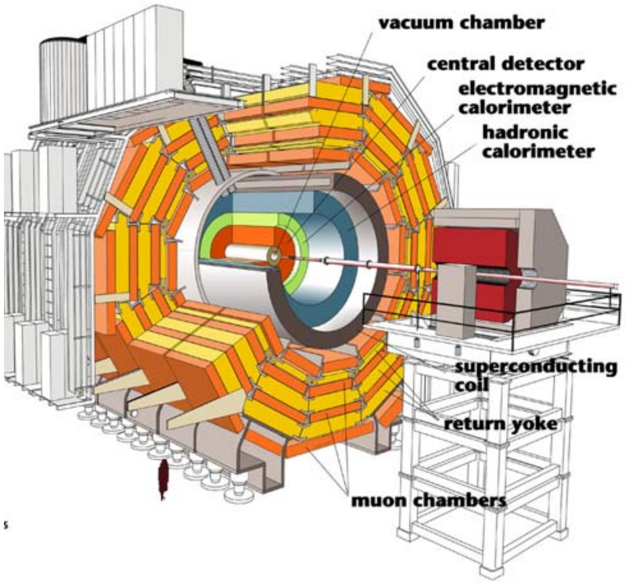
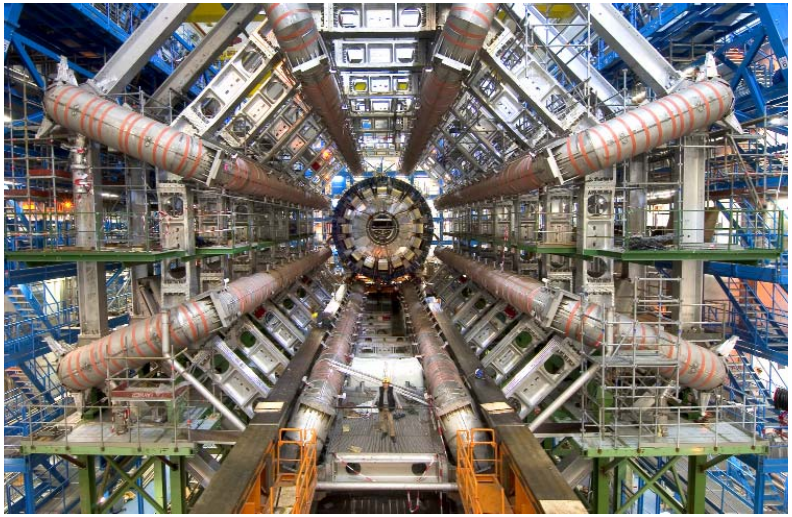
and CMS collaboration

LISHEP 2006





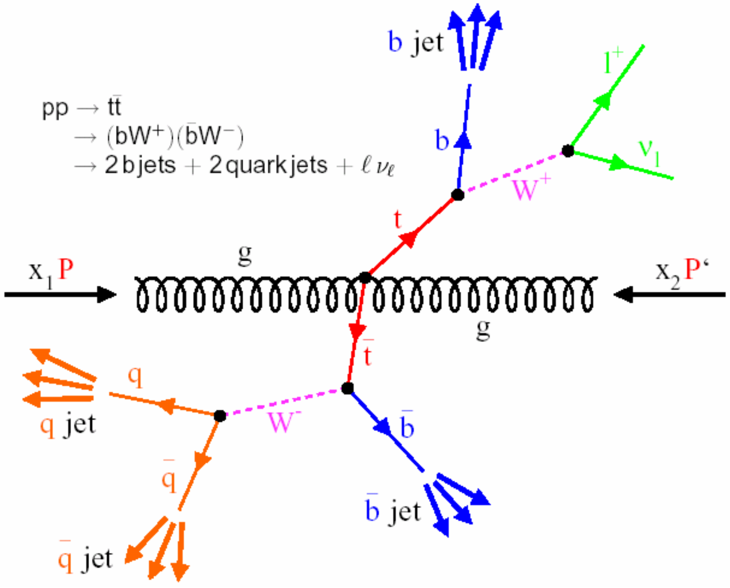



# Why is Top So Interesting?

**top physics is different!**

$$\tau_{top} \sim 10^{-24}\,\mathrm{s}\,,\ \ \Gamma^{-1} \approx (1.5\ \mathrm{GeV})^{-1} \ll \Lambda^{-1}_{QCD} \sim (200\ \mathrm{MeV})^{-1}$$

- Top quark lifetime is short: decays before hadronizing
  - No spectroscopy like other heavy flavor
  - Top momentum and spin transferred to decay products
- Probes physics at higher scales than other known fermions
  - Top (or heavy top) very hip in many EWSB models: Higgs, Top Color, Little Higgs, SUSY mirror models

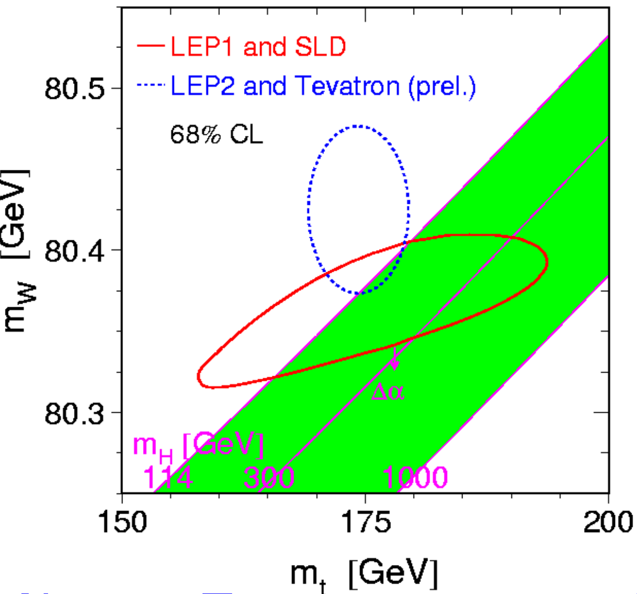


# Why is Top Mass Interesting?

**Fundamental Standard Model parameter.**

**Special Relation to Higgs mass, together with W boson mass.**


$$\delta M_W \propto ( M_{top}^2, \ \ln(M_H) )$$




**Top quark is heavy (~ 172 GeV)**
**Yukawa coupling ~ 1.**
**Near the EWSB scale.**
**If we can measure strength of this coupling (i.e.ttH), a test of the Higgs sector in the SM can be possible.**

**Detailed studies of top events by using $M_{top}$ can be performed. e.g. tt resonance, spin correlation, W helicity, new particle search**

Now at Tevatron : $m_t = 172.0 \pm 2.7$ GeV/c² **$m_H$ < 186 GeV/c² (95% C.L.)**

**What can be obtained with $\Delta m_t \sim 1$ GeV/c² ?**

→If $\delta m_W$ = 15 MeV/c² , $m_{top}$ = 175 GeV/c² for current $\Delta\alpha$, ($\delta m_H/m_H \approx 32\%$)

→ If $\delta m_W$ = 15 MeV/c² et $\Delta\alpha = 0.00012$, ($\delta m_H/m_H \approx 25\%$)

# Top properties

We still know *little* about the top quark, limited by Tevatron statistics

| | |
|---|---|
| **Mass** | **precision <2%** |
| **Electric charge ⅔** | **-4/3 excluded @ 94% C.L.** (preliminary) |
| **Spin ½** | **not really tested – spin correlations** |
| **Isospin ½** | **not really tested** |
| **BR to b quark ~ 100%** | **at 20% level in 3 generations case** |
| **V – A decay** | **at 20% level** |
| **FCNC** | **probed at the 10% level** |
| **Top width** | **??** |
| **Yukawa coupling** | **??** |

This leaves plenty of room for **new physics** in top production and decay

Tevatron run II starts to incisely probe the top quark sector

The LHC will open a new opportunity for **precision measurements**

# LHC: A new Factory for Top quarks

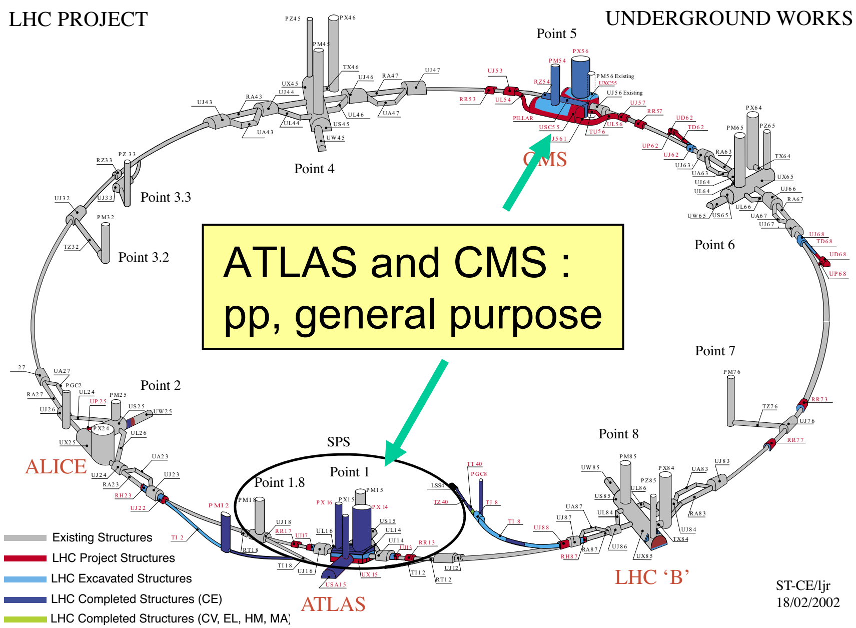
- The Top quark is studied with an increasing level of precision at Tevatron
- However most of the measurements are still statistically limited
- Data taking will continue up to 2009 at Tevatron allowing experiments to perform precision measurements on the Top.
- In the meantime the Large Hadron Collider will enter into operation.
- **The LHC will open a new opportunity for precision measurements of Top quark properties.**

# The Large Hadron Collider

- pp collision cm : 14 TeV (x7 Tevatron)
- 25 ns bunch spacing
- 1.1 $10^{11}$ proton/bunch
- Design luminosity $10^{34}$ $cm^{-2}s^{-1}$

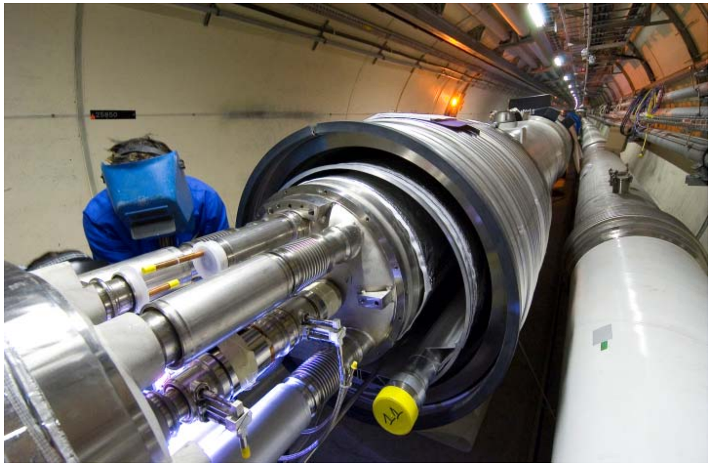
  **100 $fb^{-1}$ /year; ≈ 20 int./x-ing**
- Initial/low lumi L≤$10^{33}$ $cm^{-2}$ $s^{-1}$

  **10 $fb^{-1}$ /year ; ≈ ≤2 int./x-ing**
- 4 interaction regions




ATLAS and CMS :
pp, general purpose

27 km ring
1232 dipoles B=8.3 T



# Possible LHC startup scenario

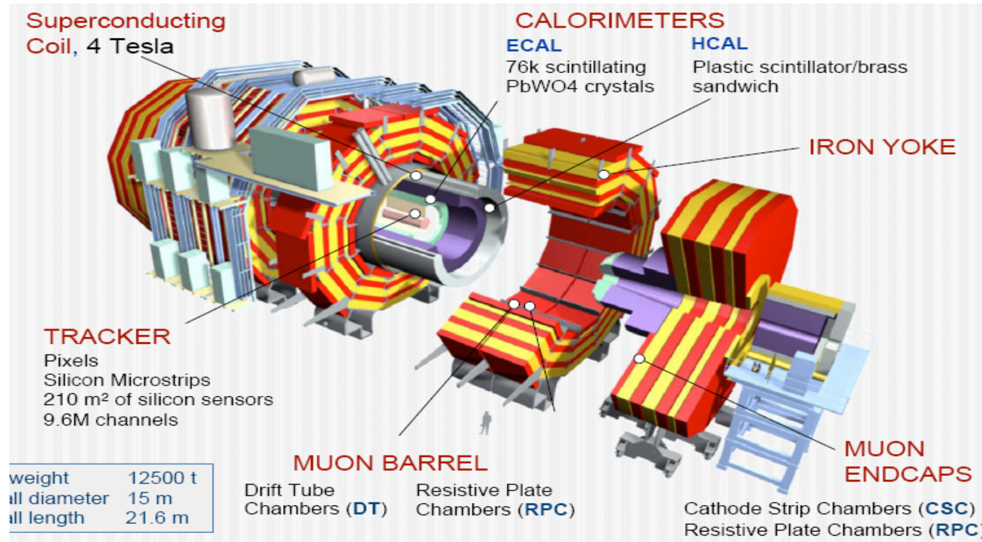
Machine startup in 4 phases gradually to nominal Luminosity

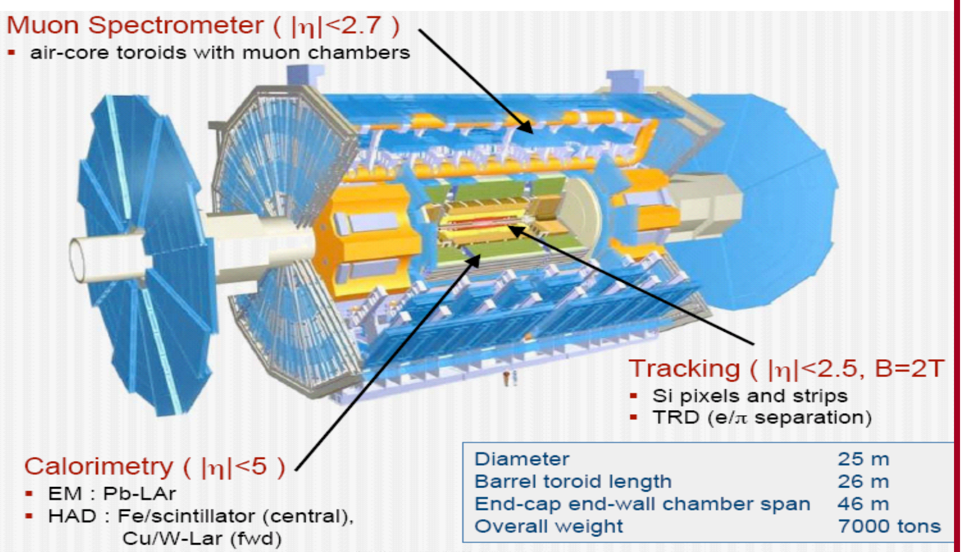
| | | |
|---|---|---|
| Summer 2007 | **first collisions** | |
| 2007 | (43+43 to 156+156 bunches) | **1/100 nominal L** |
| 2008 | (936+936 bunches; 75ns) | **1/10 nominal L** |
| 2009-2010 | (2808+2808 bunches; 25ns) | **up to nominal L** |

Many uncertainties here: a more precise schedule soon (in spring 2006)

expect 1 - 10 fb-1 /expt on tape by end 2008

# CMS and Atlas Detectors




Detectors will not be complete in 2007

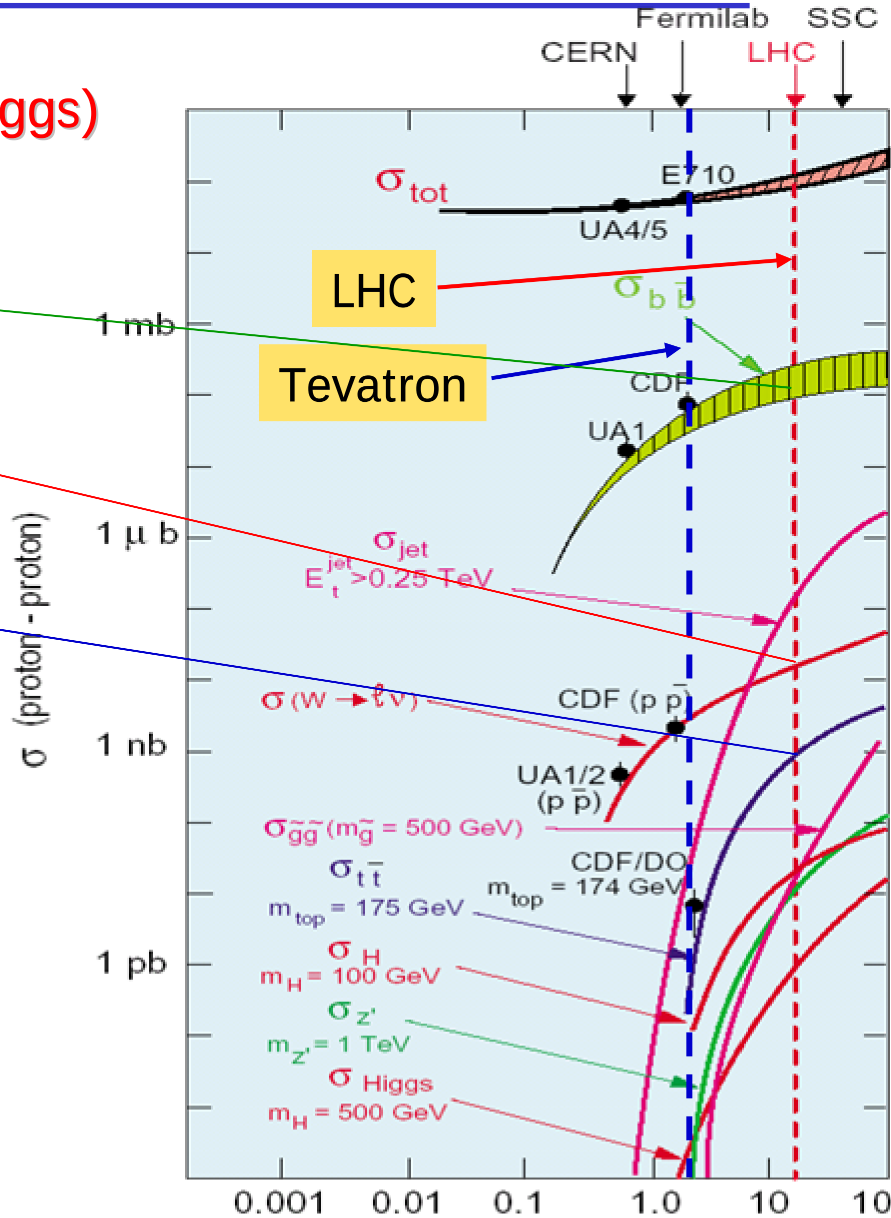
- ATLAS because of staging TRT coverage over $|\eta|<2$ instead of 2.4
- CMS pixel and end-cap ECAL installed during first shutdown
- BOTH reduced trigger bandwidth due to deferrals on HLT processors (~50% of full capability)

Small impact on performances at low L (except for B physics)

# Typical cross-sections and rates

Triggering and selection phase typically require reduction factors of $10^{11}$ ! (i.e. Higgs)

| process | σ(pb) | Events/s | Events/y |
|---|---|---|---|
| bb | $5\times10^{8}$ | $10^{6}$ | $10^{12}$ |
| $Z\to ee$ | $1.5\times10^{3}$ | ~3 | $10^{7}$ |
| $W\to e\nu$ | $1.5\times10^{4}$ | ~30 | $10^{8}$ |
| $WW\to e\nu X$ | 6 | $10^{-2}$ | $6\times10^{3}$ |
| tt | 830 | ~2 | $10^{7}$ |
| H(700 GeV) | 1 | $2\times10^{-3}$ | $10^{4}$ |




LHC σ(tt) ~830 pb

X100

Tevatron σ(tt) ~ 6,7 pb

LHC Low L $10^{33}\ cm^{-2}s^{-1}$

Tevatron $10^{32}$

X10

Prod Rate X1000

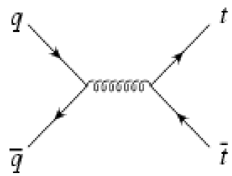
# Top production and decay at LHC

## Strong Interaction → $t\bar{t}$

**LHC**

**σ ~850 pb**

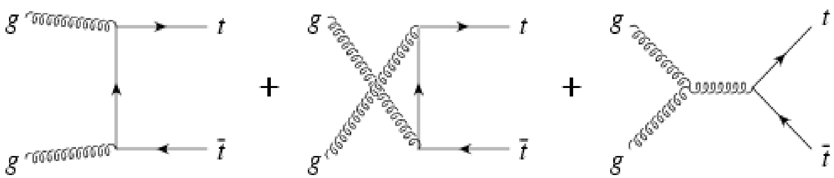
**10% $q\bar{q}$, 90% gg**




**Tevatron**

**σ ~7 pb**

**85% $q\bar{q}$, 15% gg**



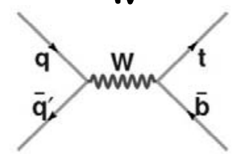

## Weak Interaction → single top*

**LHC**

**σ ~300 pb**

**75%Wg, 20%Wt**

**W***

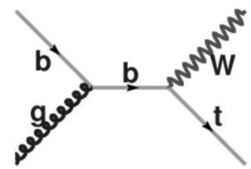



**Tevatron**

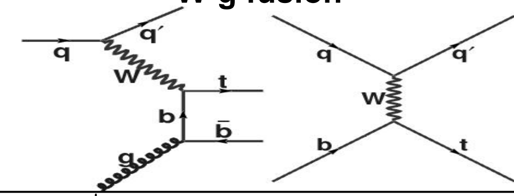
**σ ~3 pb**

**65%Wg, 30%Wt**

**W t**




**W-g fusion**




*not observed yet !

**BR (t→Wb) ~ 100 % in SM and no top hadronisation**

W→eν, μν, **qq**

W→eν, μν

## $t\bar{t}$ final states (LHC,10 $fb^{-1}$)

- Full hadronic **(3.7 M)** : 6 jets
- Semileptonic **(2.5 M)** : l + ν + 4jets
- Dileptonic **(0.4 M)** : 2l + 2ν + 2jets

## Single top final states (LHC, 10 $fb^{-1}$)

- W-g **(0.5 M)** : l + ν + 2jets
- Wt **(0.2 M)** : l + ν + 3jets
- W* **(0.02 M)** : l + ν + 2jets

At nominal Luminosity, ~ One top pair produced per second **LHC is a Top factory**

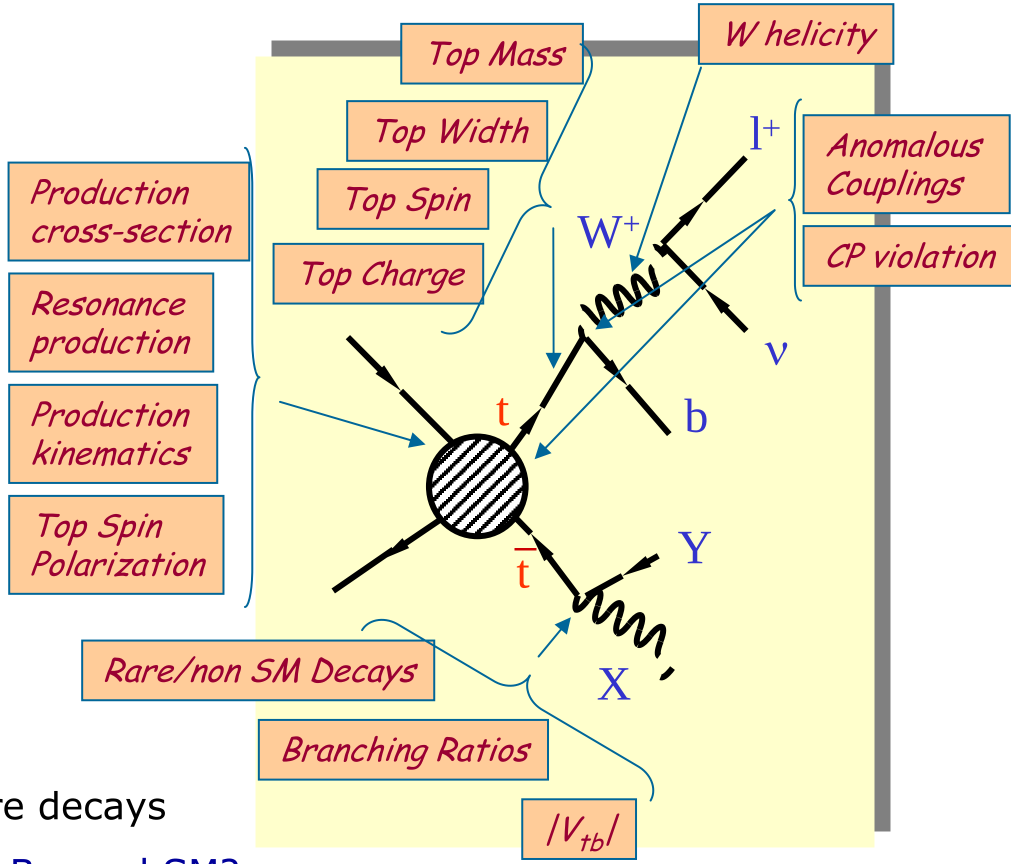
# Top physics

- **Detector Commissioning with early data**
  - Use Top as calibration tool for jet scale, b-tagging
  - Crucial parameters for Top physics: jet energy scale,tagging, trigger,luminosity
- **Precision Measurements**

- **Precise Top Mass determination**
  - Provide Higgs mass constraint
  - W mass & Top mass are important

  measurements to scrutinize SM
- **Cross sections**
  - Main background for searches

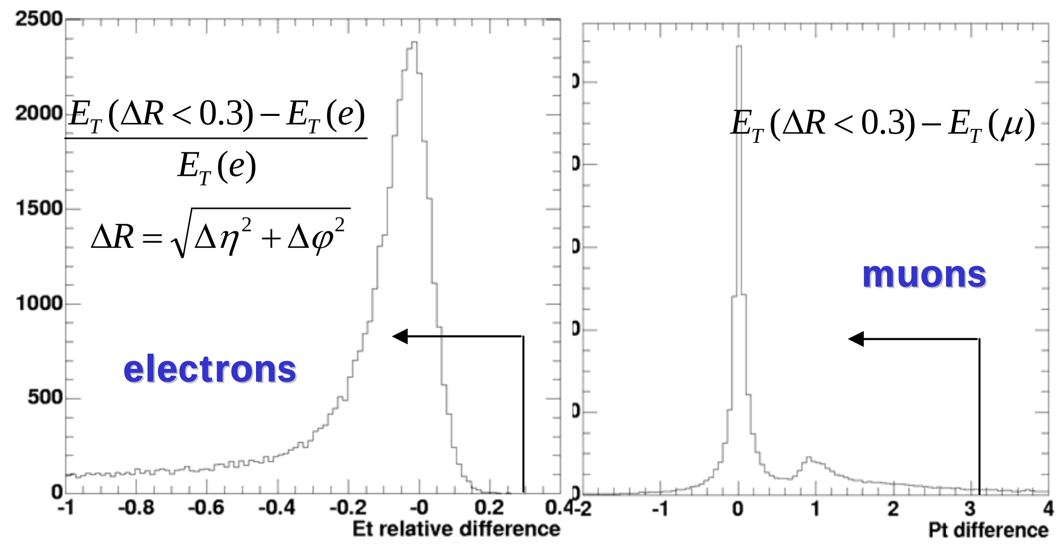
  Beyond the Standard Model at the LHC
  - $V_{tb}$
- **Top properties**
  - Top electric charge
  - Top spin polarization, W polarisation
  - Top quark decays & coupling ,fcnc, rare decays
  - Possible deviations due to New physics Beyond SM?

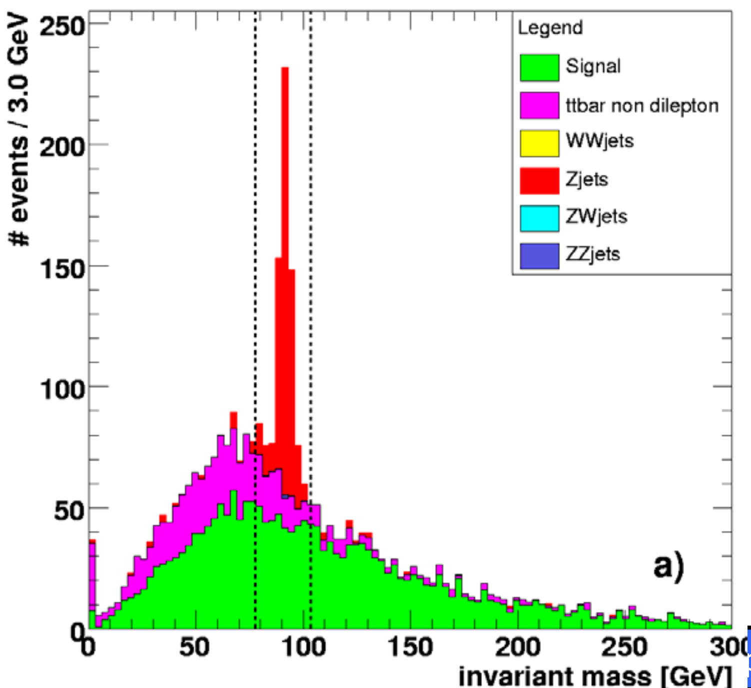


# Di-lepton event selection

Selection is cut based:

- Single or di-lepton trigger
- Two isolated oppositely charged leptons with $E_T$>20 GeV and $|\eta|$<2.5
- Missing $E_T$>40 GeV
- At least two jets with $E_T$>20 GeV and $|\eta|$<2.5
- Two tightly b-tagged jets




Main background represented by Z+jets when no b-tagging is present.

→ cut the Z peak for leptons of same flavour

With tight b-tagging, efficiency about 5% (15% without b-tagging) with excellent background reduction

→ S/B~5 (B mainly from leptonic τ decays)

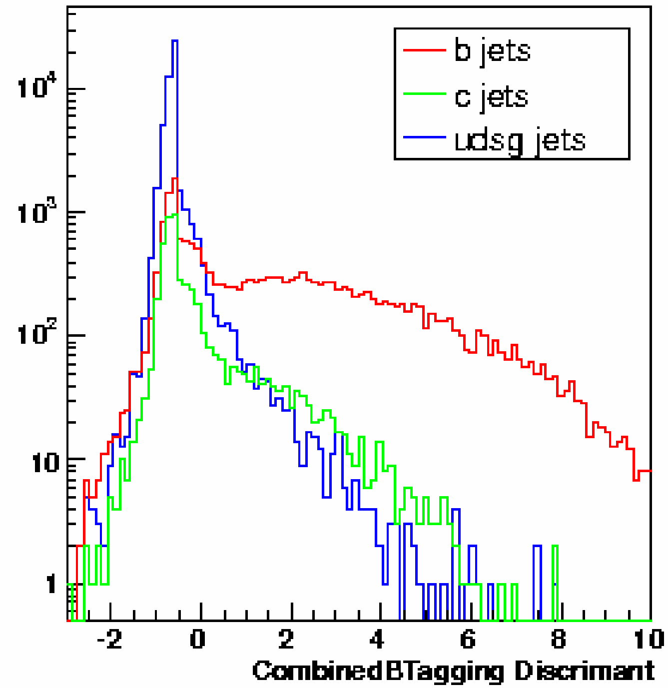
# Semileptonic event selection

## Selection is cut based:

- ☞ Single lepton trigger
- ☞ One isolated lepton with $E_T$>20 GeV and $|\eta|$<2.5
- ☞ Exactly four jets with $E_T$>30 GeV and $|\eta|$<2.4
- ☞ Exactly two tightly b-tagged jets (P>60%)
- ☞ Exactly two anti b-tagged jets (P<30%)

## Main background represented by W+jets

(to a minor extent Z+jets and di-bosons)

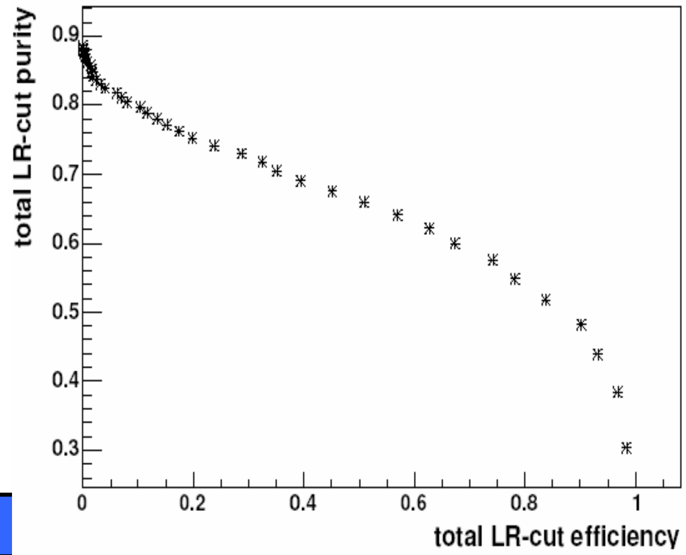



→ Efficiency about 4% with excellent background reduction (S/B~4)

## Further improvement can be obtained by a mass cut after the full event reconstruction

Jet pairing via a likelihood ratio technique based on:

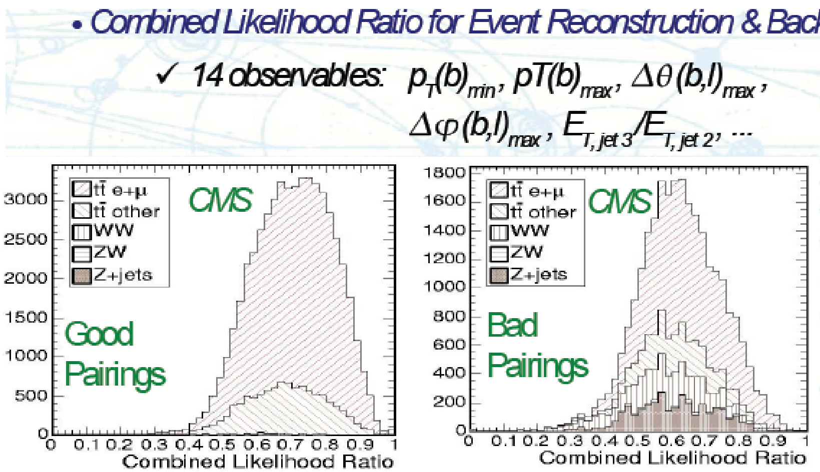
- **$\chi^2$ of the constrained fit imposing the W masses**
- **transverse momentum of the resulting tops**
- **difference between the fitted and the reconstructed W boson masses**
- **$\Delta$R between the lepton and the hadronic b**
- **the b tagging probabilities**

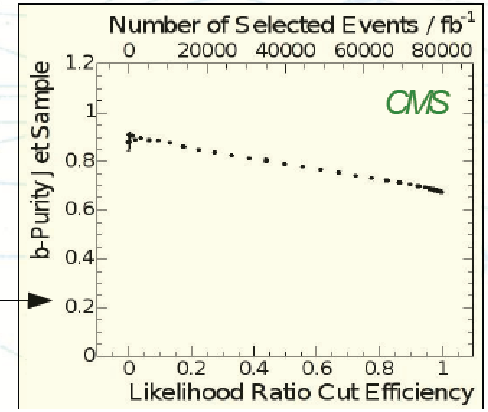


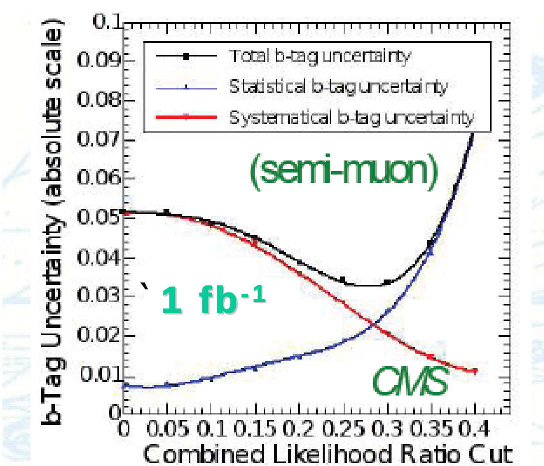
# b-tag effciency measurement

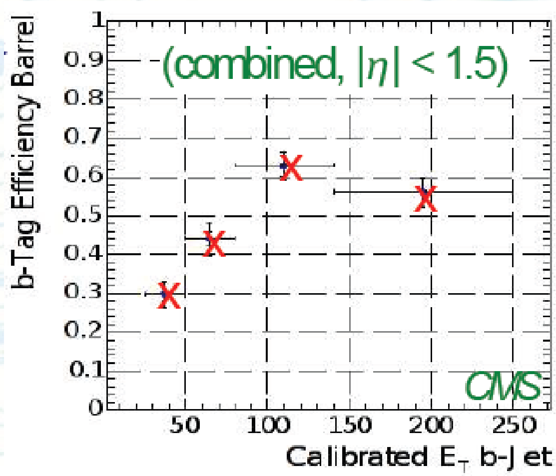
- Calibrate b-tag algorithms on data using large tt statistics at LHC

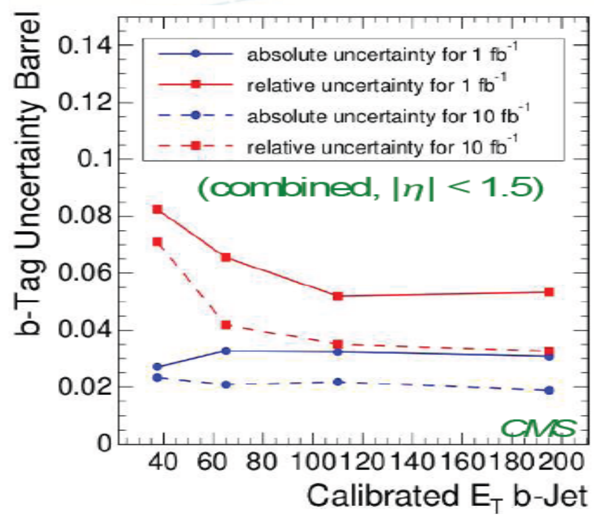
- Enrich b-content of a jet sample
- Estimate b-purity from MC
- Apply any b-tagging algorithm on sample and estimate efficiency
- Semileptonic decaying tt-pairs (μ o e) combinatorial background
- Fully leptonic cleaner but lower statistics



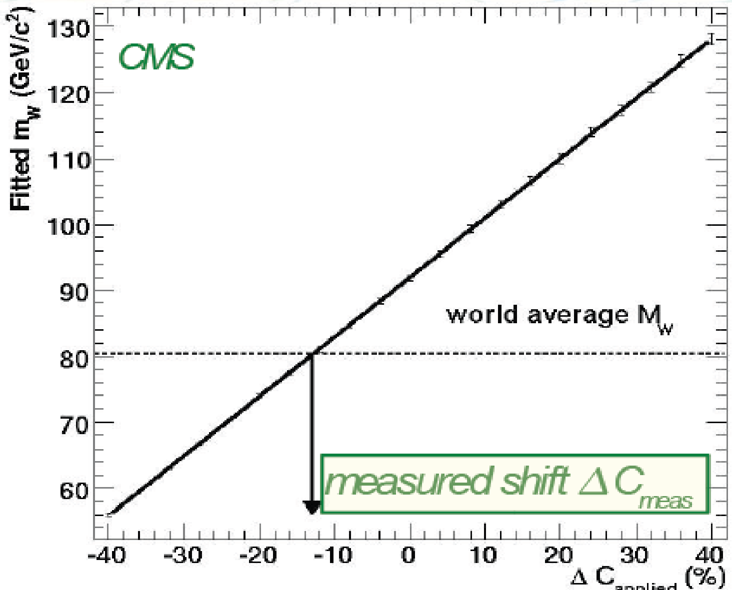



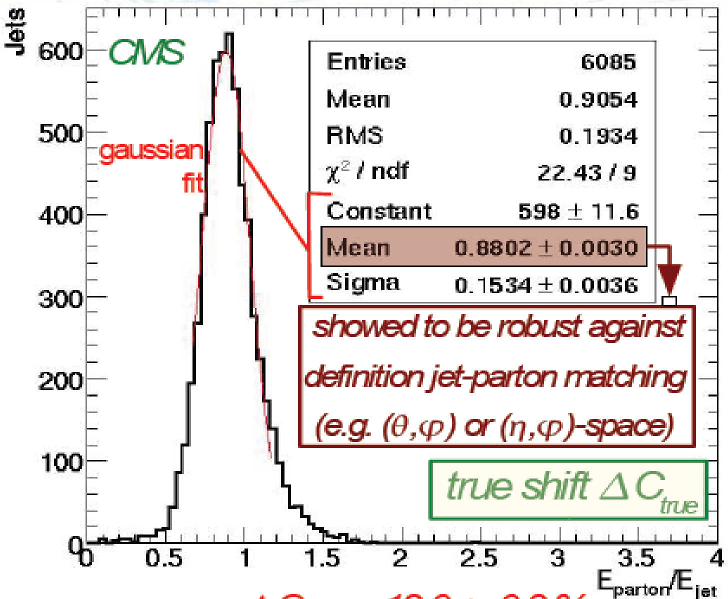



# Light quark jet energy scale calibration

- *Determine absolute light quark jet energy scale from data itself using W-mass from the abundantly produced tt pairs at LHC*

1. *rescale each light jet energy with a relative scaling factor $\Delta C$ keeping the $E/|\vec{p}|$-ratio constant*
2. *Remake/refit the obtained W mass spectrum → $m_W(\Delta C)$*
3. *Solve simple equation $m_W(\Delta C_{meas} \mid data) = m_W^{PDG}$ → best estimate for $\Delta C$*
4. *Compare this shift with the true one from MC $\Delta C_{true}$*



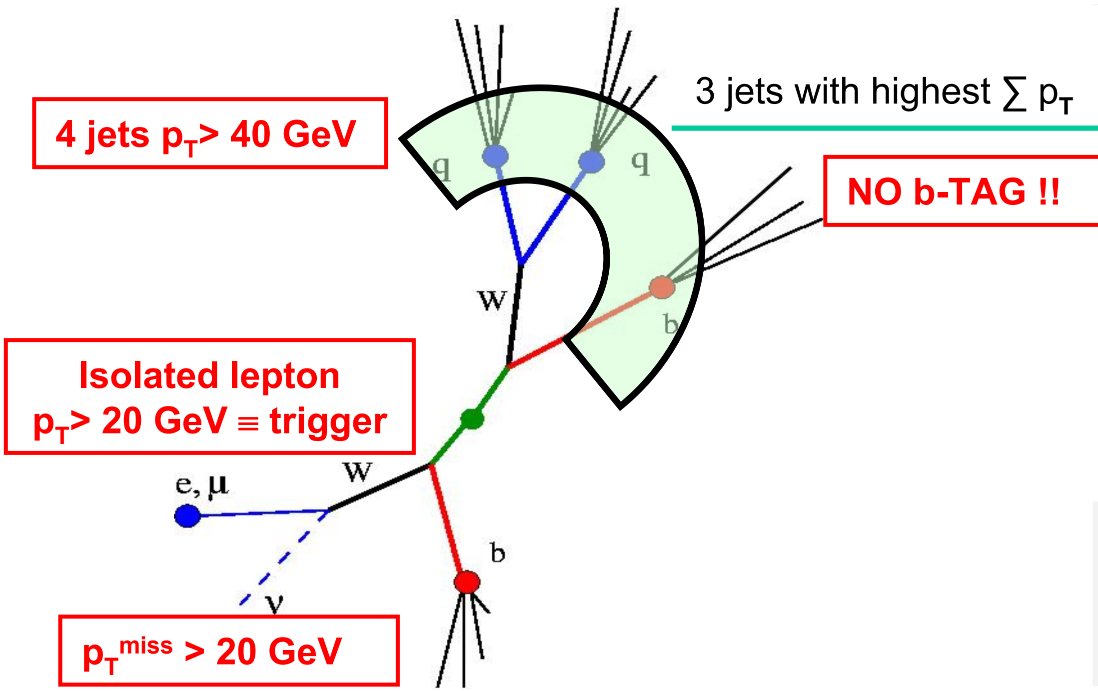

$\Delta C_{meas} = -12.7 \pm 0.3\,\%$ ← bias ~0.7 % → $\Delta C_{true} = -12.0 \pm 0.3\,\%$

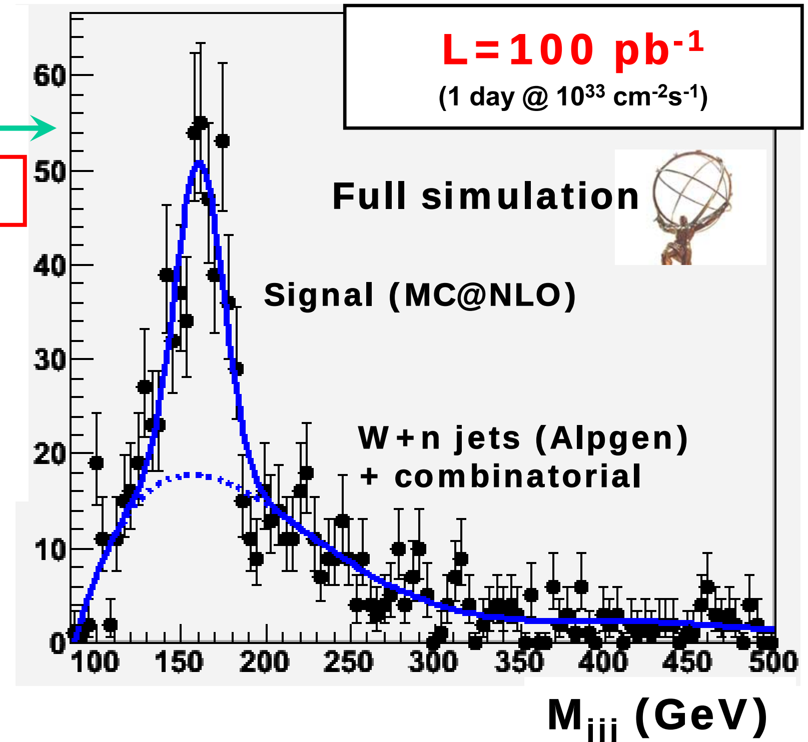
*for 1 $fb^{-1}$, statistical uncertainty < 1%, systematics (pile-up) ~3%*

# Top mass: early studies (<1 fb$^{-1}$)

t and $\bar{t}$ are produced central and back-to-back in the transverse plane

Easy to trigger and select




Observation of clean top sample should be very fast

Initial measurement of cross-section and mass

Feedback on detector performance (JES, b-tagging, …) and on MC description

# Top mass: precision studies (1-10 $fb^{-1}$)

**Measurement method (semileptonic)**

Kinematic fit event by event using t and $\bar{t}$ sides

$M_{jj} = M_{l\nu} = M_W$ and $M_{jjb} = M_{l\nu b} = M_t^{fit}$ ➔

| Source (ATLAS hep-ex/0403021) | Error 10 $fb^{-1}$ |
|---|---|
| b-jet scale (±1%) | 0.7 |
| Final State Radiation | 0.5 |
| Light jet scale (±1%) | 0.2 |
| b-quark fragmentation | 0.1 |
| Initial State Radiation | 0.1 |
| Combinatorial bkg | 0.1 |
| TOTAL: Stat ⊕ Syst | 0.9 |

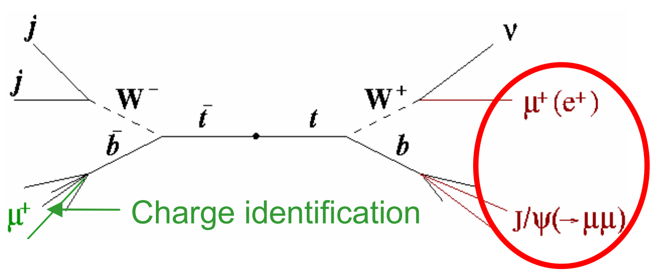
**Dileptonic (10 $fb^{-1}$)**

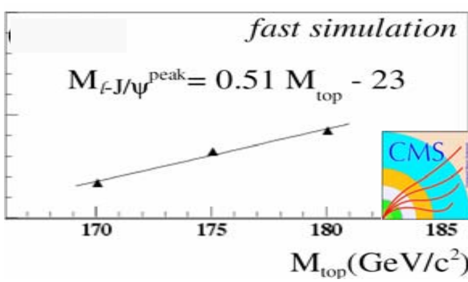
- Need to reconstruct full tt event to assess the 2 ν momenta
  ➔ 6 equations ($\Sigma p_T=0$, $M_{l\nu}= M_W$, $M_{l\nu b}= M_t$)
- Assume $m_t$ and compute solution probability event by event using MC kinematic distributions
- Choose $m_t$ with highest mean probability on all events
- Systematic uncertainty: ~2 GeV (PDF + b-frag.)

**A ~1 GeV accuracy on $m_{top}$ seems achievable with 10 $fb^{-1}$ with ATLAS/CMS**

**Final states with J/ψ (100 $fb^{-1}$)**

- Correlation between $M_{lJ/\psi}$ and $m_t$
- Low statistics: ~1000 evts/100 $fb^{-1}$
- No systematics on b-jet scale !
- Systematic uncertainty: ~1 GeV (b-frag.)



# W polarization in top decay

- Top decay faster than hadronization timescales ->Spin information transmitted to Wb → jjb / lνb Test SM couplings with clean probe, Top decay : major source of longitudinal W's -> Polarization depends only on $M_t$ and $M_W$ (LO)

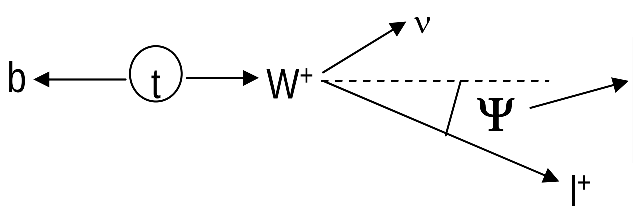
| | **Longitudinal $W^+$ ($F_0$)** | **Left-handed $W^+$ ($F_L$)** | **Right-handed $W^+$ ($F_R$)** |
|---|---|---|---|
| Standard Model ($M_{top}$=175 GeV) | **0.703** $\left(=\frac{M_t^2}{M_t^2+2M_W^2}\right)$ | **0.297** $\left(=\frac{2M_W^2}{M_t^2+2M_W^2}\right)$ | **0.000** |
| NLO | 0.695 | 0.304 | 0.001 |

**Sensitive to EWSB** ($F_0$)

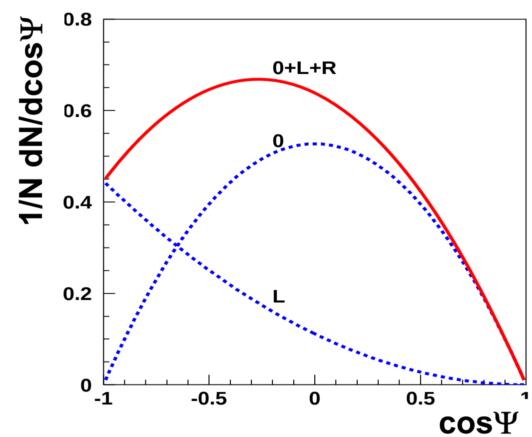
**Test of V-A structure** ($F_R$)

- All 3 components in angular distribution of lepton in W rest frame :

$$\frac{1}{N}\frac{dN}{d\cos\Psi}=\frac{3}{2}\left[F_0\cdot\left(\frac{\sin\Psi}{\sqrt{2}}\right)^2+F_L\cdot\left(\frac{1-\cos\Psi}{2}\right)^2+F_R\cdot\left(\frac{1+\cos\Psi}{2}\right)^2\right]$$




Angle between:
- lepton in W rest frame and
- W in top rest frame



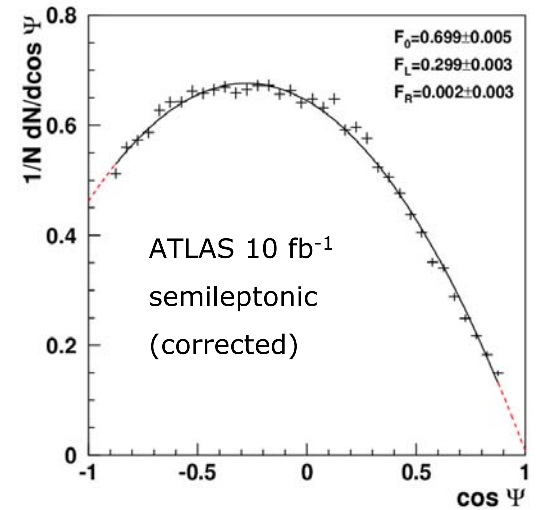
# W helicity results

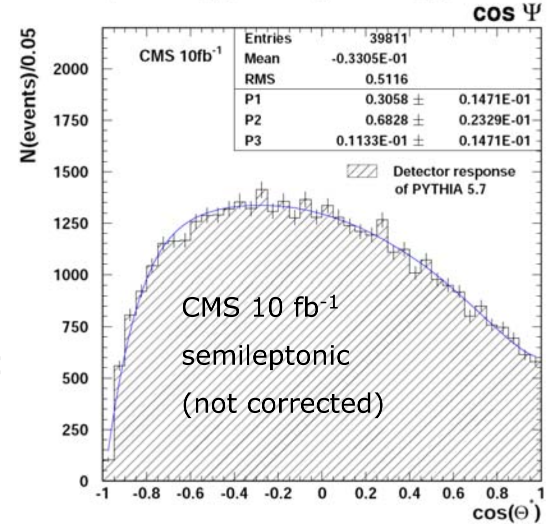
hep-ex/0508061

- Results for 10 $fb^{-1}$, fast simulation :

| | | $F_0$ | $F_R$ |
|---|---|---|---|
| SM values | | 0.703 | 0.000 |
| ± Stat | CMS semileptonic | ± 0.023 | ± 0.015 |
| | ATLAS semi + dilep | ± 0.004 | ± 0.003 |
| ± Syst | CMS semileptonic | ± 0.022 | ± 0.053 |
| | ATLAS semi + dilep | ± 0.016 | ± 0.012 |

Precision driven by semileptonic




Precision between 1% and 7% dominated by systematics

# Top Physics at the LHC: goals at $10fb^{-1}$

- Does the Top quark behaves as expected in the SM?

Top pair production

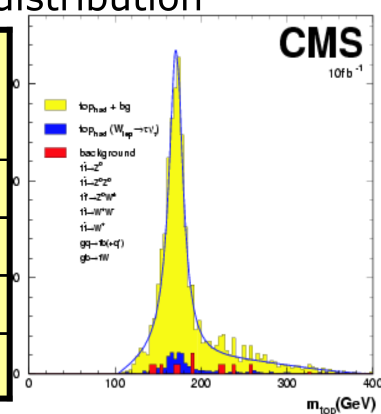
Top mass, cross section , W&Top polarisations ≈ same event selection

- stat error negligible on measurements, syst Limitations from jet scale FSR, PDF, lumi

Top properties measurements

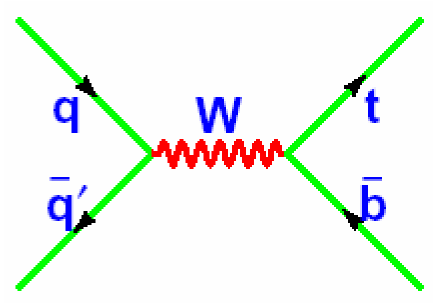
- Test the top decay with W Polarisations F0 $F^L$ $F^R$ (1-2%)
- Test the Top production with ttbar spin correlations
- ttbar invariant mass distribution

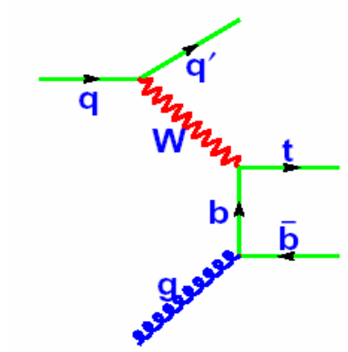
| channel | Selected @$10fb^{-1}$ |
|---|---|
| lνb jjb | 70K |
| lνb jjb (high pt) | 3,6K |
| lνb lνb | 20K |
| jjb jjb (high pt) | 3,4K |




| Precision | Tevatron @$2fb^{-1}$ | LHC goals $10fb^{-1}$ |
|---|---|---|
| Top Mass | <2% | <1% |
| Cross section | 10% | <10%? |
| Top properties | | |
| BR Wb | 20% | |
| W pol | 40% | 2% |
| Spin corr | | 4% |
| Charge | Exclude -4/3 | Confirm 2/3 |
| fcnc | | Improvex100 |
| Single Top | 5σ discovery? | Measure separately cross sections |
| Understand Top as BKG | | |

# Single top at the LHC




In principle s-channel more difficult than t-channel:

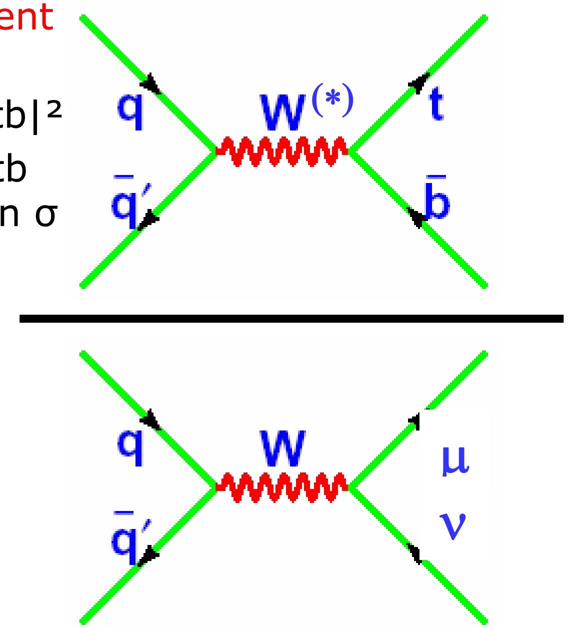
- Smaller cross section (1/25)
- There is not the characteristic feature of the extra forward jet
- t-channel itself is a very similar background

- Use leptonic decay of the W
- Measure cross sections separately
- Even if statistical precision range from ~2% (t channel) to ~8% (s channel), studies will be mainly on BKG understanding to assess systematics which are dominant.
- First results are expected with 30fb$^{-1}$. cross sections and $V_{tb}$.

| channel | Selected @10fb-1 |
|---|---|
| t channel | 2,5K |
| WT channel | 1,5K |
| s channel | 0,5K |

- direct measurement
- Cross-sections proportional to $|Vtb|^2$
- Uncertainty on Vtb ~ ½ uncertainty on σ

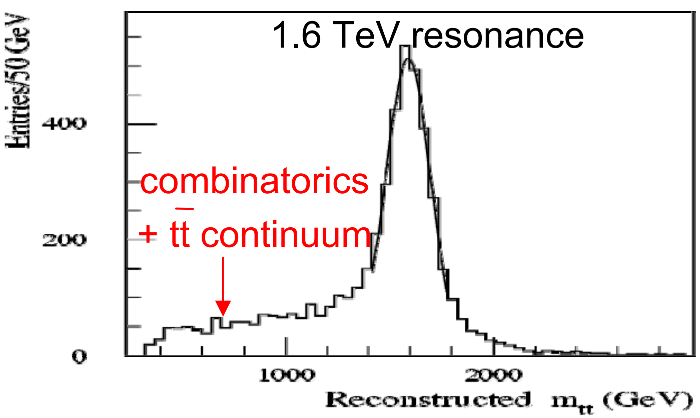
**R(|V$_{tb}$|) =**

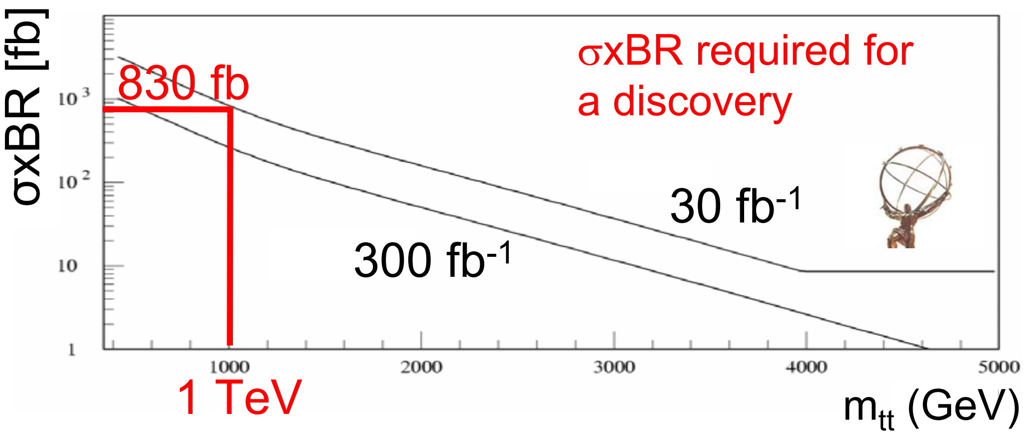


# Direct searches for new particles

**In top production**

- Example of resonances decaying to $t\bar{t}$, as predicted by various models
- Generic analysis for a resonance X with $\sigma_X$, $\Gamma_X$ and BR($X \rightarrow t\bar{t}$)




**In top decay**

- Example of $t \rightarrow H^+ b$ with subsequent $H^+ \rightarrow \tau\nu$ ($2<\tan\beta<40$)
- Search for excess of $\tau$-events or deficit of dilepton events

➔ $H^+$ discovery for $M_{H+}$<160 GeV with 30 fb$^{-1}$

**J.Phys.G28 (2002) 2443**

# Summary

- **LHC will be a top factory: almost $10^7$ events produced with 10 $fb^{-1}$**
  - Measurements with negligible statistical uncertainties
  - First steps towards precision measurements driven by systematics
  - Challenge to get top mass **~1 GeV** ➔ SM $M_H$ constrained to **<30%**
  - Test top production and decay e.g. by measuring W polarization **~1-2%** and top spin correlation **~4%** ➔ anomalous tWb/gtt couplings, t→$H^+$b, FCNC,
- LHC is on the road
  - First collisions in Summer 2007, initial measurements in 2 years from now, first precision measurements in 3 years from now with 1-10$fb^{-1}$
- **A huge work needed prior to initial measurements**
  - to understand the detectors & control systematics(BKG, PDF..)
  - Early top signals will also be critical to commissioning the detectors
- LHC has a great potential for Top physics
- Some of the earliest LHC physics results, and earliest sensitivity to new physics, could come from top physics
- **Improvement of Top understanding & window BSM**