# Searches for New Heavy Quarks with the CMS Detector at the LHC


Silvia Costantini
Ghent University
CMS Collaboration, CERN


- ►LHC
- ►CMS
- ►Searches for $4^{th}$ Generation b′ Quarks
- ► Searches for Exotic partners of the top quark

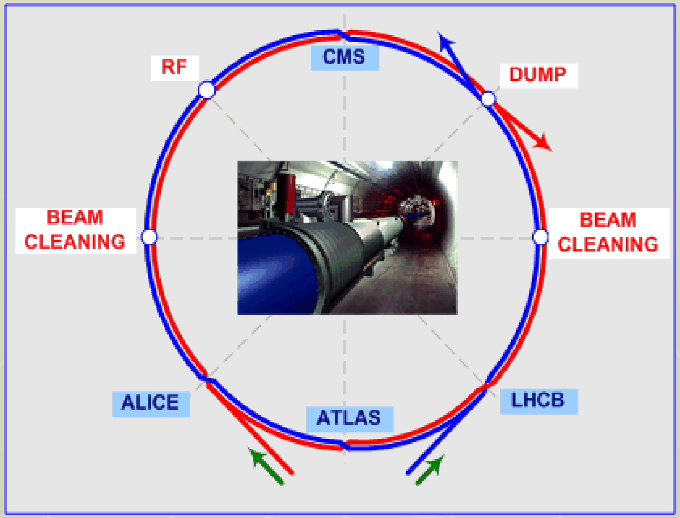
Emphasis on prospects for searches with early data at 10 TeV

More on

http://cms-physics.web.cern.ch/cmsphysics/CMS_Physics_Results.htm

# LHC

# Large Hadron Collider




- approved in 1994
- 26.66 km tunnel, ~100 m underground
- 1232 superconducting twin dipoles, 8.33 T at 1.9 K

- pp collisions, design $E_{beam}$=7 TeV
- Design Luminosity: 10 $^{34}$ cm-$^2$ s-$^1$ ,
  with 100 fb-$^1$ per year per experiment
  one crossing every 25 ns (40 MHz)

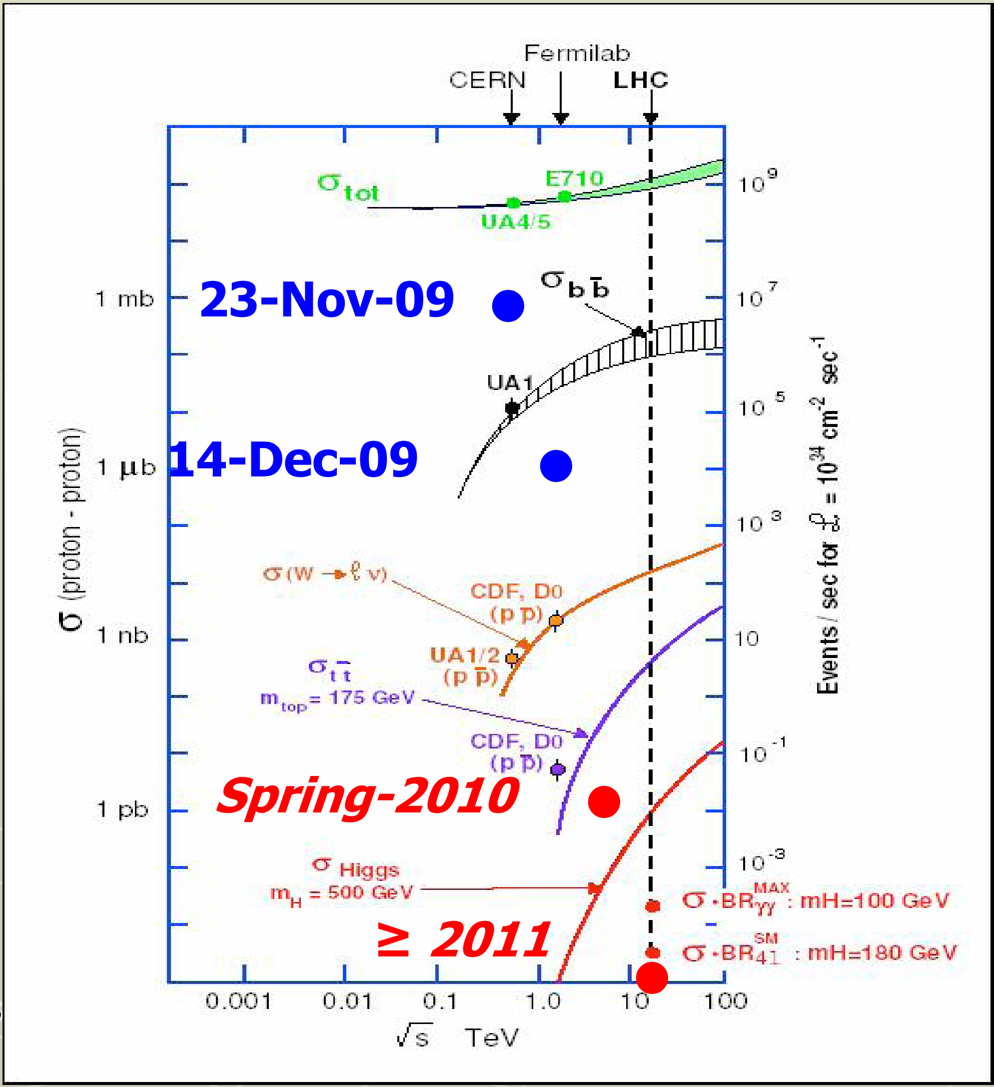
- two general purpose detectors: **ATLAS, CMS**
- two dedicated detectors: **ALICE, LHCb**
- two special purpose experiments:
  **TOTEM** (Total Cross Section, Elastic Scattering and Diffraction Dissociation at the LHC),
  **LHCf** (forward production of neutral particles in proton-proton collisions at extremely low angles)

Starting Date: November 2009
- First collisions in November/December 2009 (first beam in September 2008)
- Physics run in 2010: 3.5 + 3.5 TeV foreseen (to be confirmed)

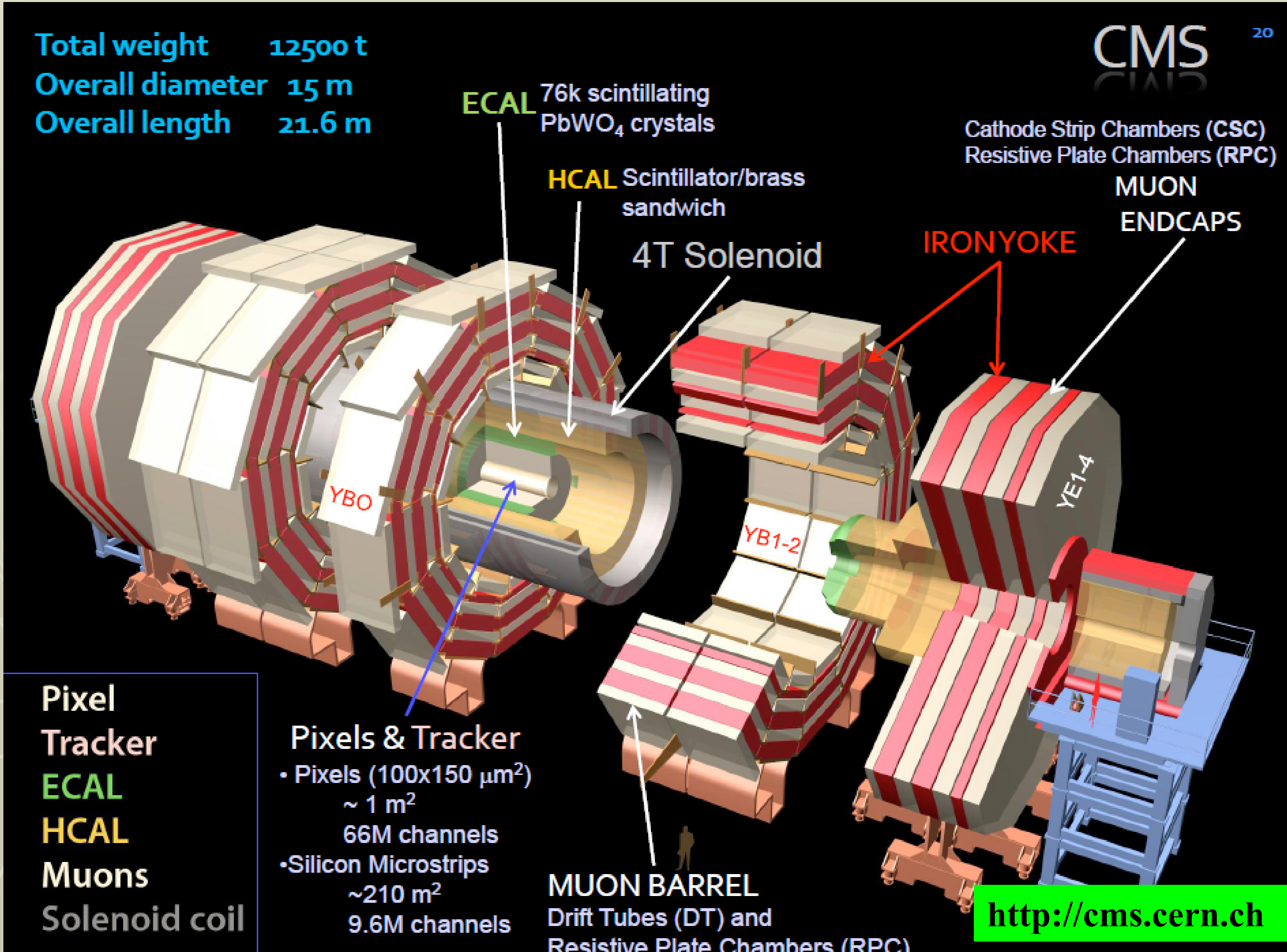
Schedule on: **http://lhc-commissioning.web.cern.ch/lhc-commissioning/**

# Large Hadron Collider

- **First collisions** on Nov.23 at **900 GeV**
  - ~0.1 Hz collisions
  - L ~ few $10^{24}$ $cm^{-2}s^{-1}$
- Mid-December: collisions at **900 GeV and 2236 GeV**
  - ~10 Hz collisions
  - L ~ few $10^{26}$ $cm^{-2}s^{-1}$
- **Expectations for 2010 (to be confirmed)**:
  - integrated luminosity up to 500 $pb^{-1}$
  - 1 month commissioning and pilot physics
  - 1-2 month @ 7 TeV
  - 1 month Technical Stop
  - 4-5 months @ >7 TeV
- Ultimate values:
  - 14 TeV, L ~ $10^{34}$ $cm^{-2}s^{-1}$, ~$10^9$ Hz collisions



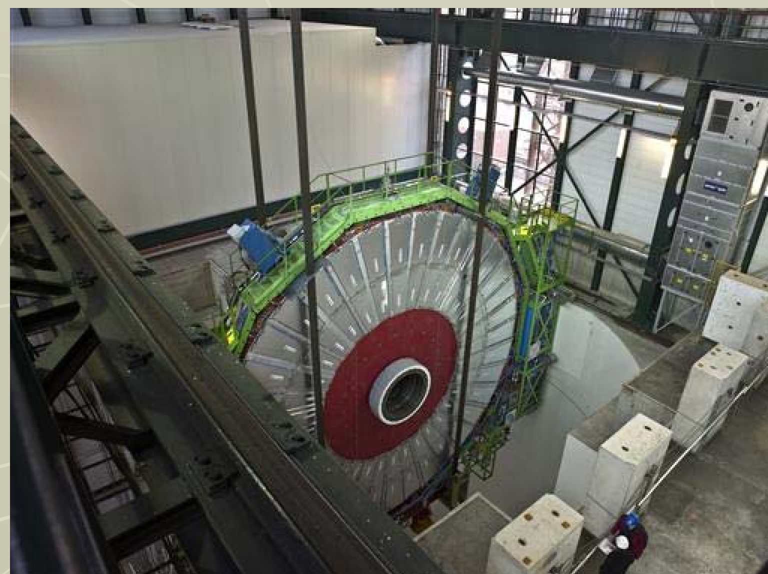
# CMS

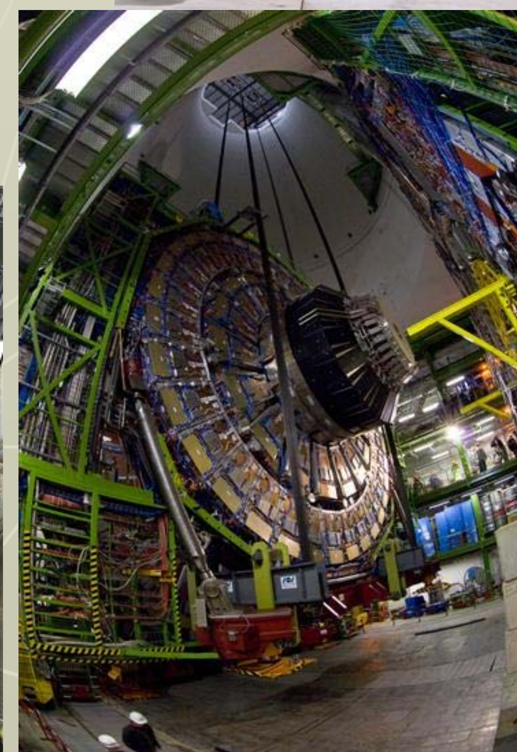

Total weight 12500 t
Overall diameter 15 m
Overall length 21.6 m
CMS
20
ECAL 76k scintillating $PbWO_4$ crystals
HCAL Scintillator/brass sandwich
4T Solenoid
Cathode Strip Chambers (CSC)
Resistive Plate Chambers (RPC)
MUON ENDCAPS
IRONYOKE
YB0
YB1-2
YE1-4
Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil
Pixels & Tracker
• Pixels (100x150 $\mu m^2$)
~ 1 $m^2$
66M channels
•Silicon Microstrips
~210 $m^2$
9.6M channels
MUON BARREL
Drift Tubes (DT) and
Resistive Plate Chambers (RPC)
http://cms.cern.ch


**CMS Detector: assembled on surface and then lowered between end 2006 and beginning 2008**

# CMS


**Jan. 2008: lowering the last element (YE-1) of the CMS detector**





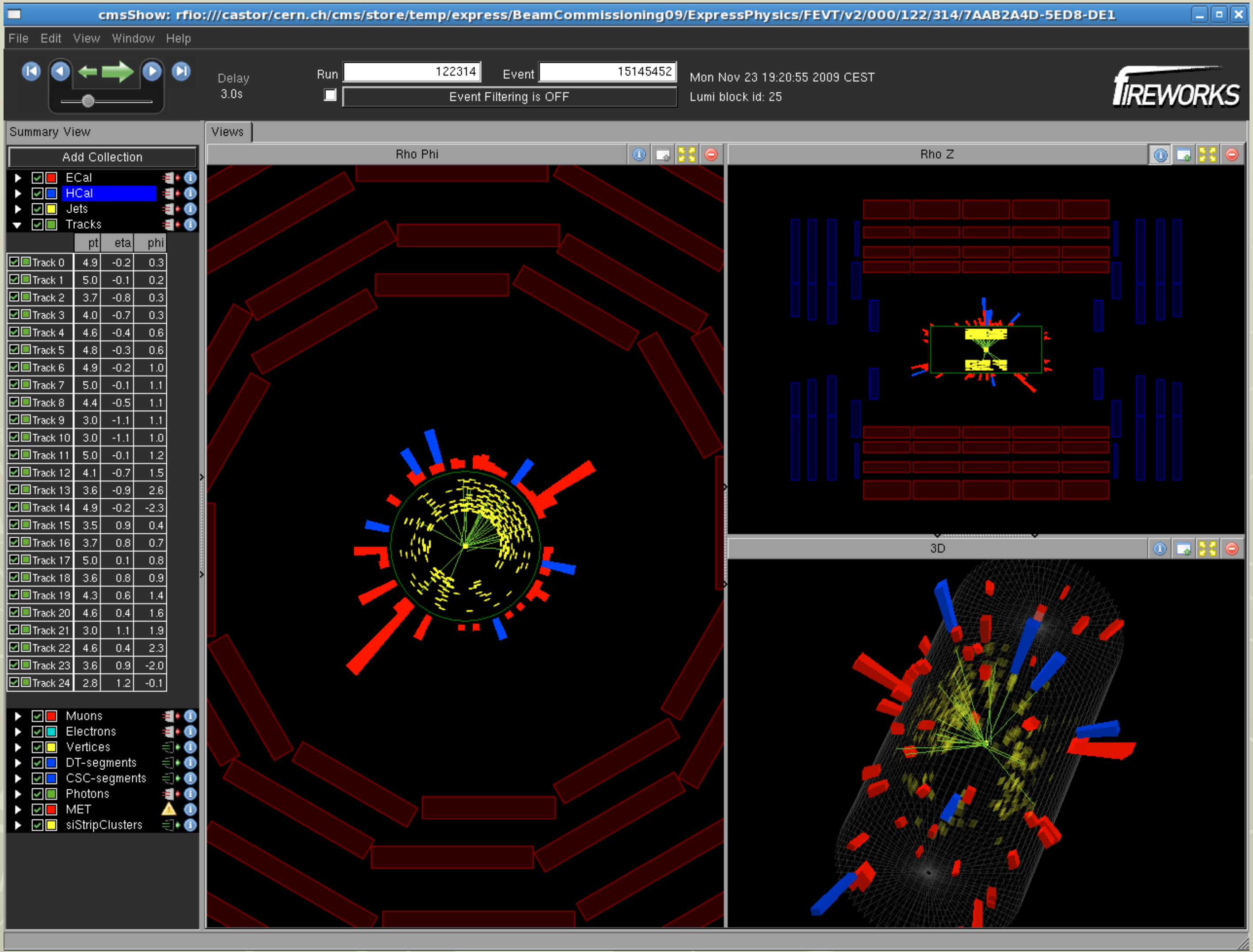
# First Collisions

- Collision data taken at:
  - 900 GeV (500 k events)
  - 2.36 TeV (50 k events)

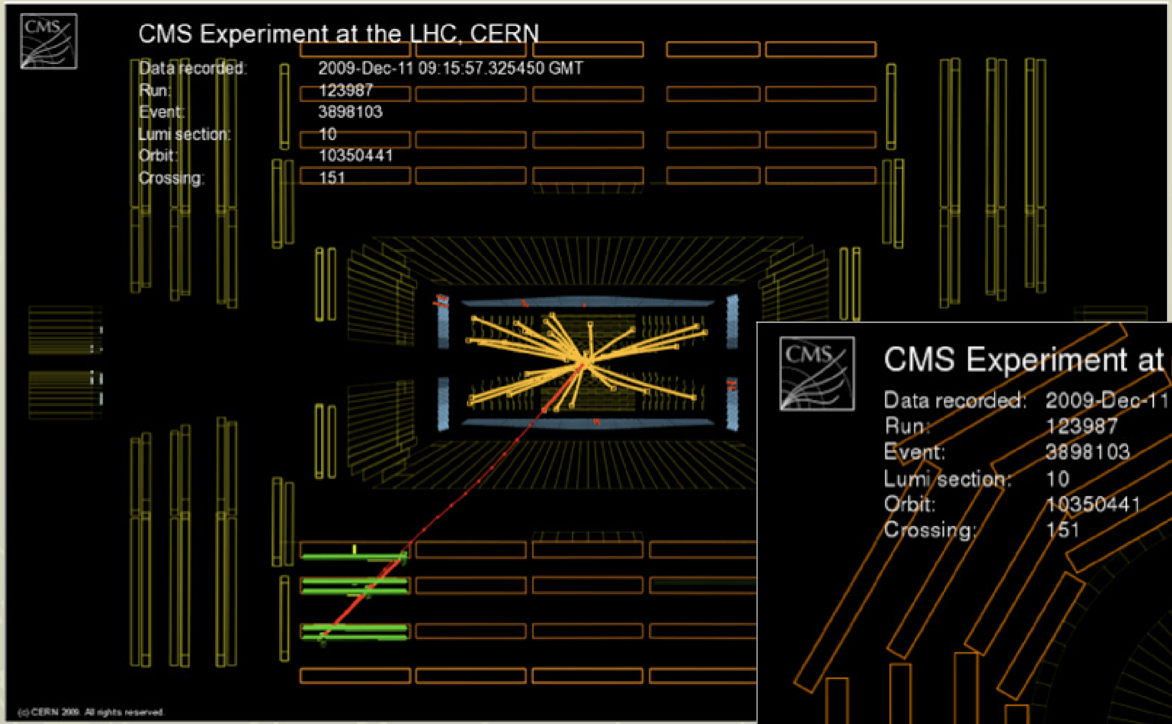
- CMS has taken good quality data:
  - > 99% of detector channels operational
  - high data-taking efficiency
  - data analyzed very quickly
  - first results to appear soon

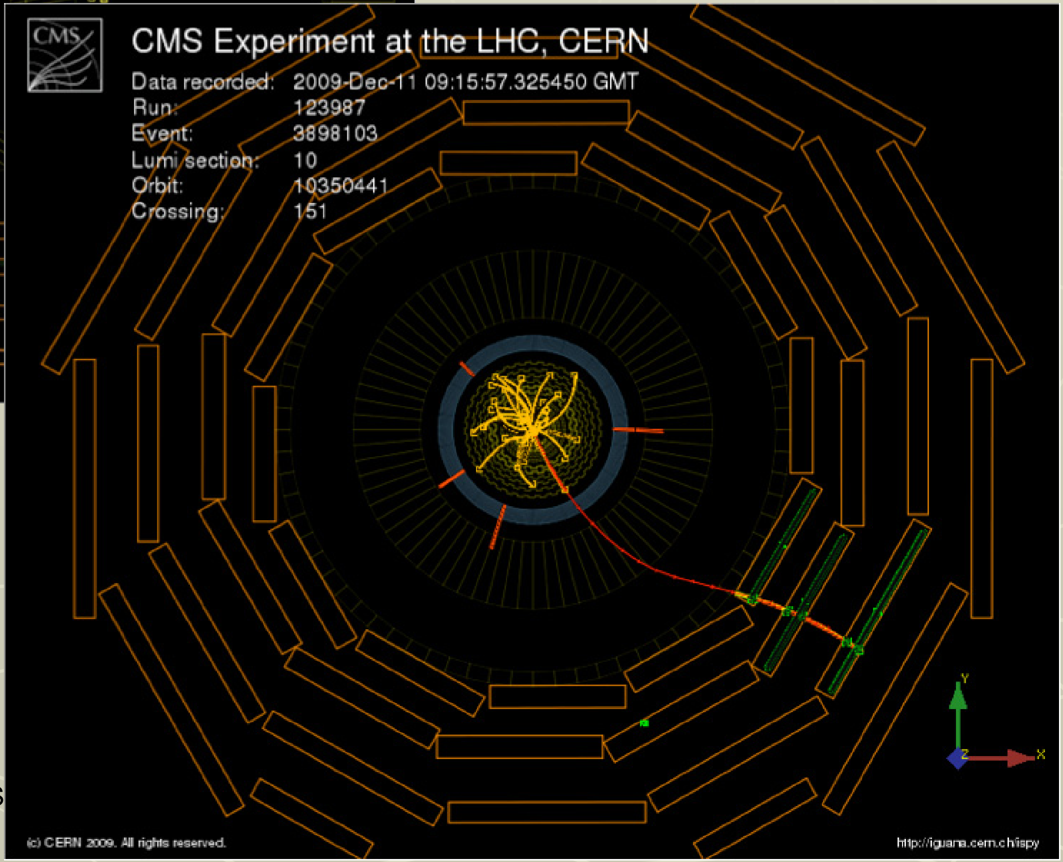
# First collision event – 23/11/09

**http://cms.web.cern.ch/cms/Media/Images/EventDisplays/index.html**



# Barrel muon candidate



# Detector Performance

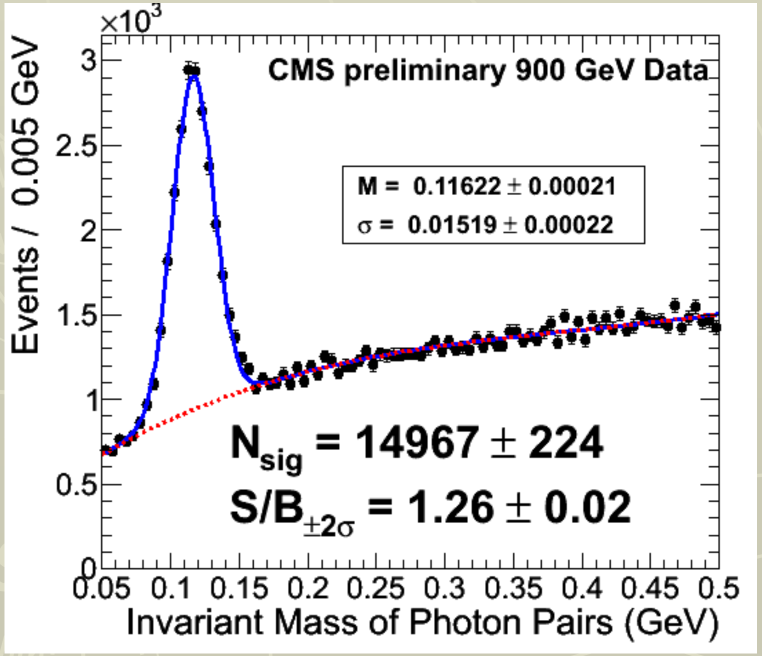
- Detector performance is according to design
- First data distribution agree well with simulation
- Results on:
  - **http://cms-physics.web.cern.ch/cmsphysics/CMS_Physics_Results.htm**
  - **CMS presentation at Aspen 2010:** **http://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=73860**

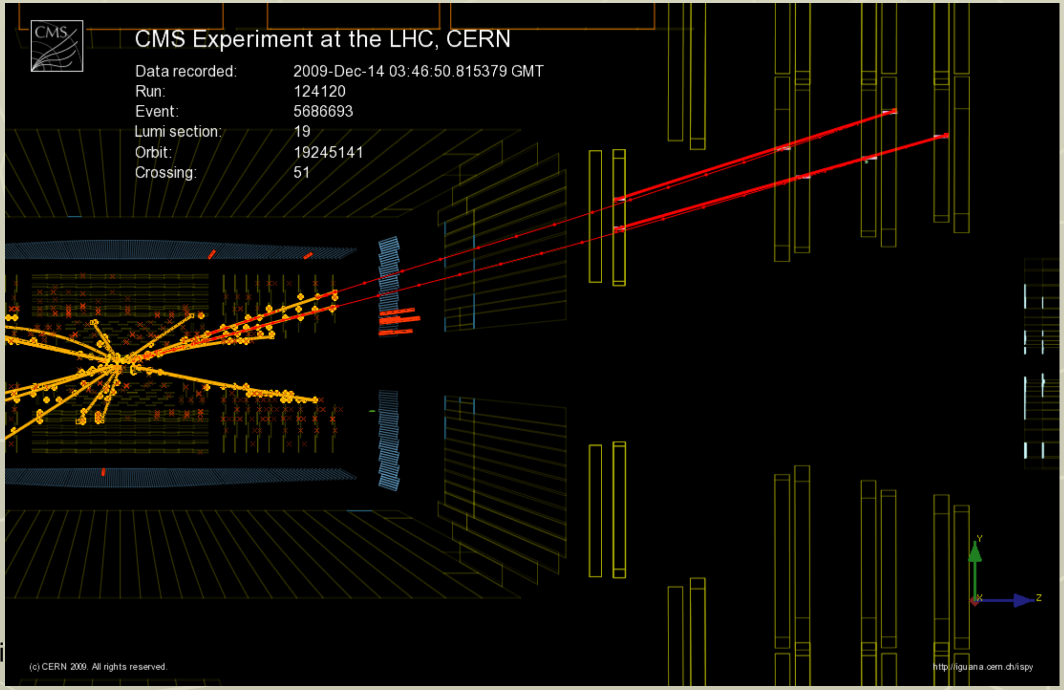
# Detector Performance

- Calorimetry ($\pi^0$, $\eta$), tracking ($K_S$,$\Lambda$, $\varphi$), muons, …
- Missing $E_T$, jets, particle ID (dE/dx), …

**Dimuon event at 2.36 TeV**

- $p_T(\mu_1)$ = 3.6 GeV/c, $p_T(\mu_2)$ = 2.6 GeV/c
- $M(\mu_1, \mu_2)$ = 3.03 GeV/c



# Key points for Searches

- Physics objects (electrons, muons, jets, missing $E_T$ …) are well understood

- Priority to processes with clean final states

  including leptons
- E.g. very low SM background for final states with same sign dileptons and trileptons (examples in this talk)
- Exploit excellent performances of CMS detector, in particular ECAL and Muon system for final states with electrons and muons

# Searches for New Heavy Quarks at CMS

# $4^{th}$ Generation Quarks: Motivations

- In the Standard Model: at least three generations of quarks to describe CP violation
- LEP measurements of Z width: $N_\nu = 2.92 \pm 0.05$
- However $4^{th}$ family with heavy neutrino ($M_\nu > M_Z/2$) is not excluded

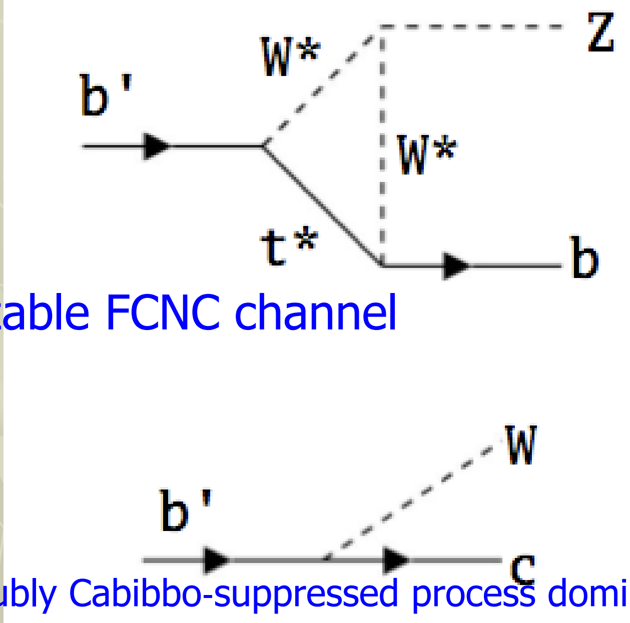
- Additional quark generation may account for the asymmetry between matter and anti-matter [arXiv:0803.1234] (SM source of CP violation is too small)
- EW precision measurements favour $|M_{t'} - M_{b'}| < M_W$ [PhysRevD.77.037302]
- Experimental limits from the Tevatron (assuming BR = 100%):
- $M(b' \rightarrow tW) > 325$ GeV [CDF/PHYS/EXO/PUBLIC/9759]
- $M(t' \rightarrow qW) > 311$ GeV [CDF/PHYS/EXO/PUBLIC/9234]
- $M(b' \rightarrow bZ) > 268$ GeV [arXiv:0706.3264]

~2 TeV
2.7 $fb^{-1}$

# 4th generation quarks

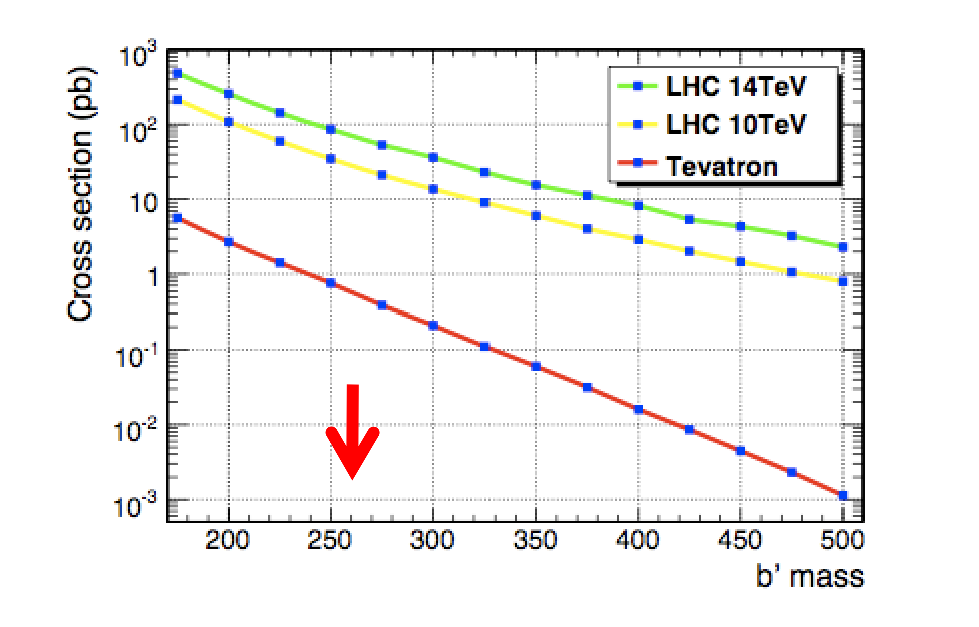
- Bottom-like (b′) in this talk
- Light b′:
  - b′ -> cW
  - b′ -> bZ

Heavy b′ :
- b′ ->tW




Sizable FCNC channel

Doubly Cabibbo-suppressed process dominates




tW mass threshold

# Light b'

EXO-08-013

$$b'\overline{b'} \to bZ\,cW$$
$$cW \to q\ell\nu$$
$$bZ \to q\ell^+\ell^-$$

- Signal: b′b′ -> cWbZ
  - – Assume BR(b′->bZ)=5%,10%,20%

    BR(b′->cW)= ~90%
  - – Tri-leptonic final state

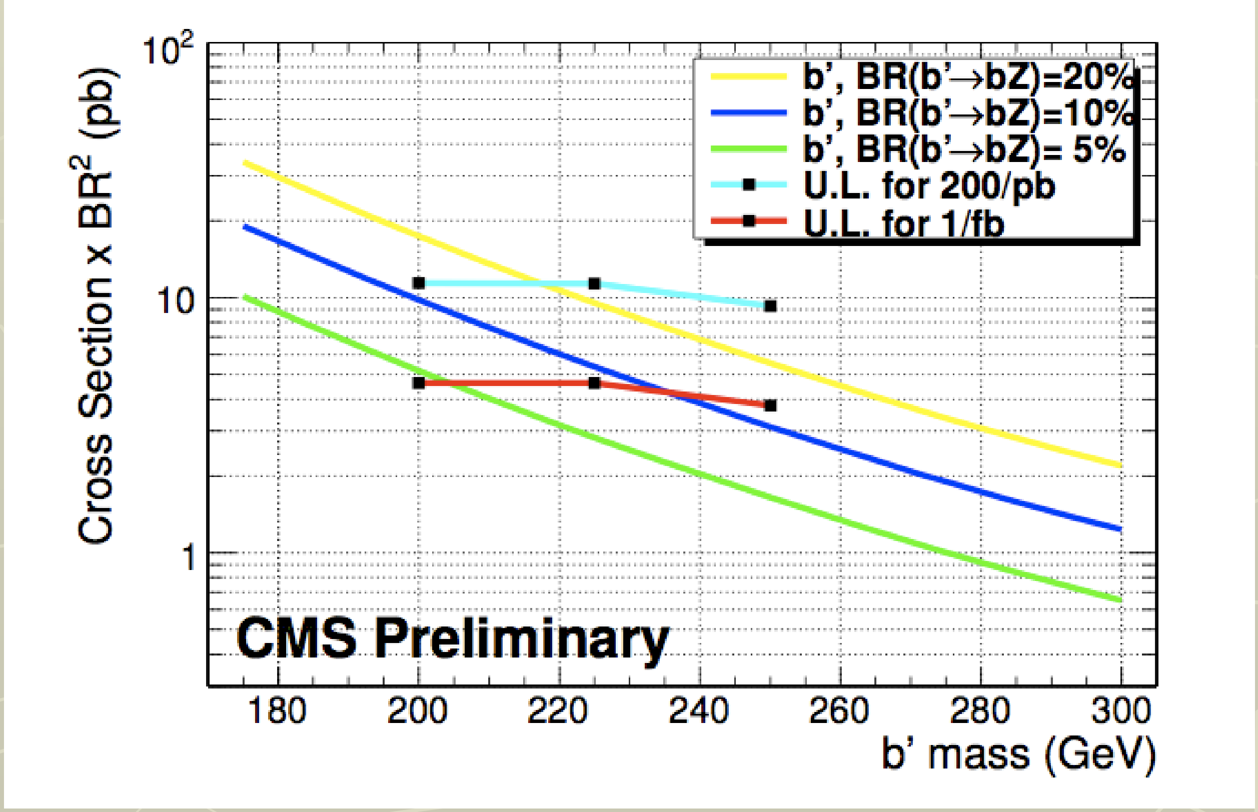
  Signature: 3 leptons (WZ) and 2 jets
- Background:
  - – Z+jets, WZ+jets, tt
  - – Background rejection by requiring
    - one Z and one W
    - two isolated jets from the lepton candidates

# Light b': Results

| M(b') | 200 GeV | 225 GeV | 250 GeV |
|---|---|---|---|
| Cross section | 113 pb | 65 pb | 11 pb |
| Exp. Yields @1fb$^{-1}$ | 29.9 | 16.7 | 11.4 |
| Exp. Bkg. @1fb$^{-1}$ | | 13.8 | |
| Significance | 3.8 σ | 1.9 σ | 1.1 σ |

**Evidence for the existence of light b' with 1 fb$^{-1}$**

**(with 200 pb$^{-1}$ if BR is higher)**



# Heavy b'

$$b'\overline{b'} \rightarrow tW\,tW$$
$$\hookrightarrow qqqq\ell^{\pm}\nu\ell^{\pm}\nu$$
$$\hookrightarrow qq\ell^{\pm}\nu\ell^{\mp}\nu\ell^{\pm}\nu$$

- b ‘ -> tW ( mass > 255 GeV)
- Decay chain with 4 W bosons
  b’b’ -> tW tW -> bbW+W-W+W-
- Possible final states:
  4 leptons + 2 jets, **3 leptons + 4 jets, 2 leptons + 6 jets**, 1 lepton + 8 jets, 0 lepton + 10 jets
- **Signal selection: Trilepton and same sign dilepton** final states with **multijets:**
  low SM background
- At least one energetic lepton with $p_T$ > 35 GeV
- At least one hard jet with $p_T$ > 85 GeV
- Background: tt+jets, tt+W/Z+jets, W/Z+jets
- Additional background suppression by requiring: Z invariant mass veto, lepton-jet separation (rejects leptons inside jets)

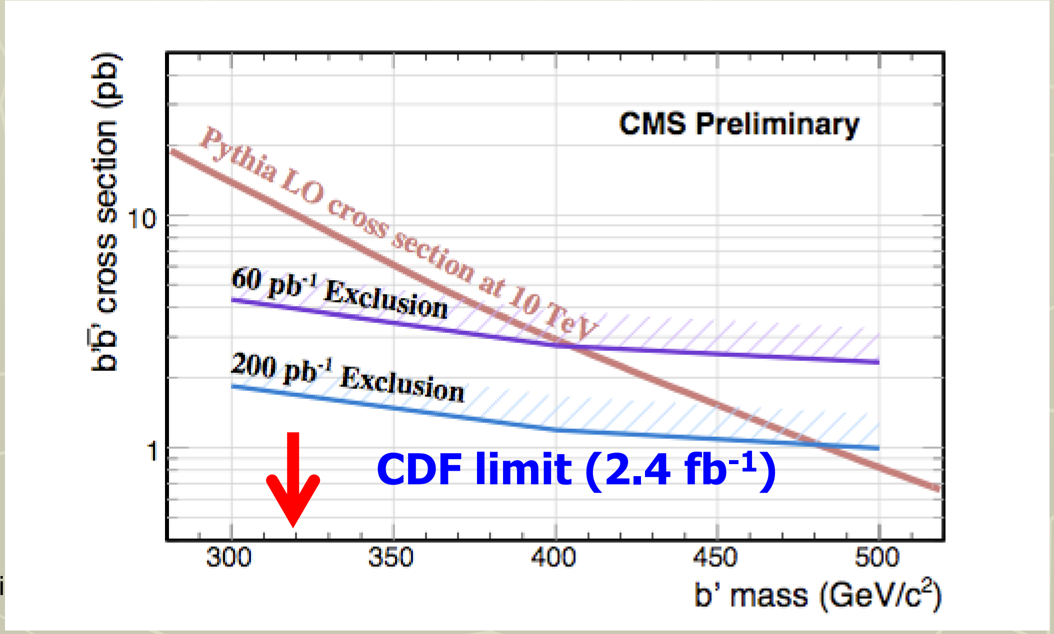
# Heavy b': Results

| M(b′) | 300 GeV | 400 GeV | 500 GeV |
|---|---|---|---|
| Cross section | 13.6 pb | 2.8 pb | 0.78 pb |
| Exp. Yields @200pb-1 | 34.1 | 10.6 | 3.5 |
| Exp. Bkg. @200pb-1 | | $1.1_{-0.7}^{+1.2}$ | |
| Significance | 9.0 σ | 3.7 σ | 1.4 σ |

**3 σ evidence up to 400 GeV**

**Exclude b′ masses less than 485 (405) GeV with 200 (60) pb$^{-1}$**

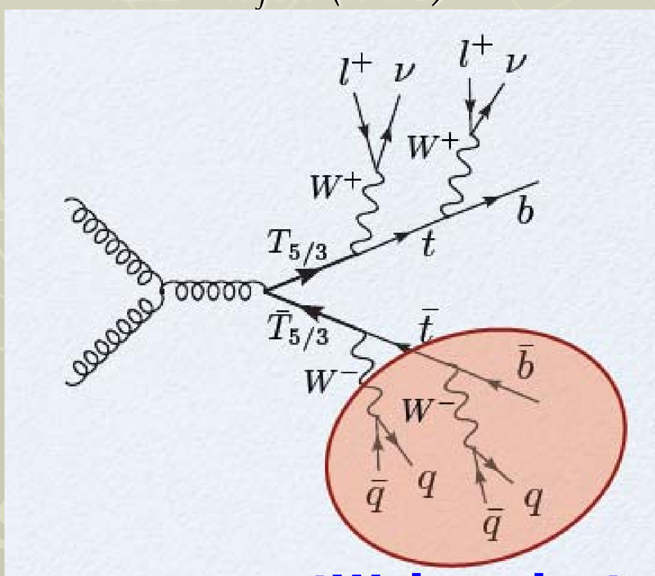
**Sensitivity exceeds that at the Tevatron with only few tens pb$^{-1}$**



# Exotic partners of top quark

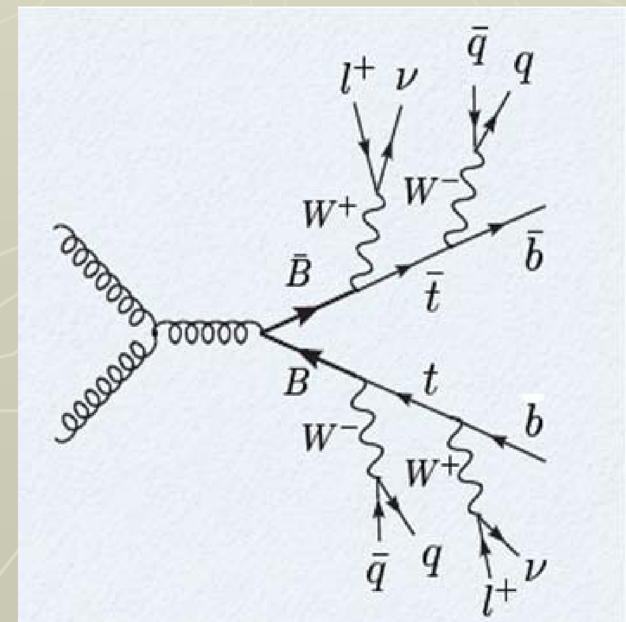
- Natural, non-supersymmetric solutions of the hierarchy problem generally require **fermionic partners of the top quark**, with masses not much heavier than **~500 GeV**

- Pair production of top partners at LHC [Contino and Servant: arXiv:0801.1679 (2008)]: $T_{5/3}$ with $Q_e = 5/3$ and B with $Q_e = -1/3$
- Both $T_{5/3}$ and B decay into t(bW)W
- **Same sign dileptons plus multijet final states**
  *$l^{\pm}l^{\pm}$ + n jets ($n \geq 5$)*



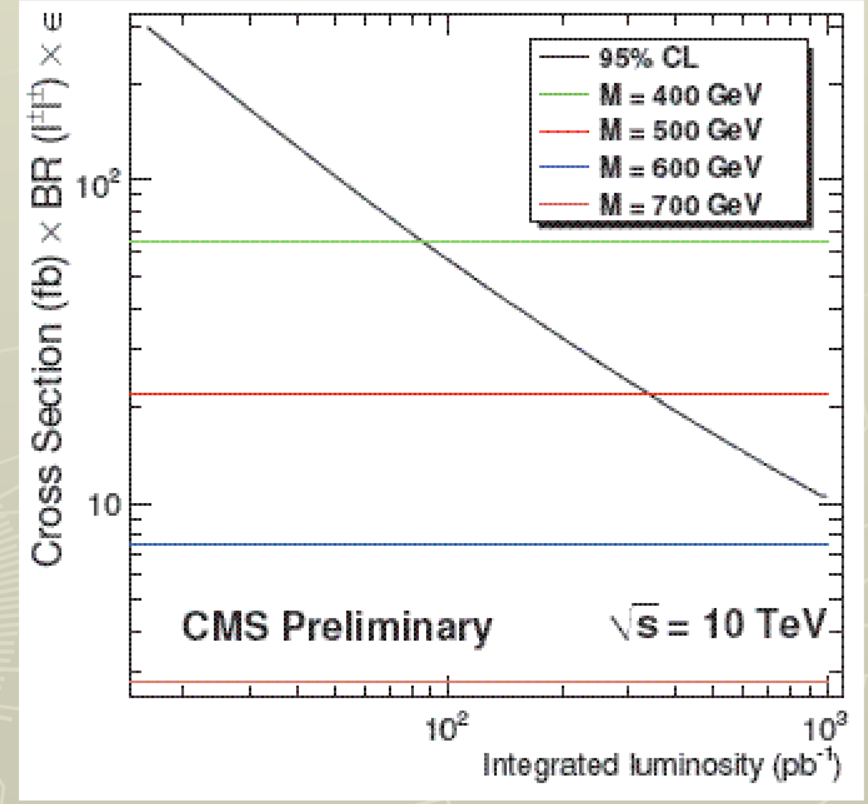

tW invariant mass peak ($T_{5/3}$)

Top pair production the major background, reduced by requiring two isolated same sign leptons and five or more jets



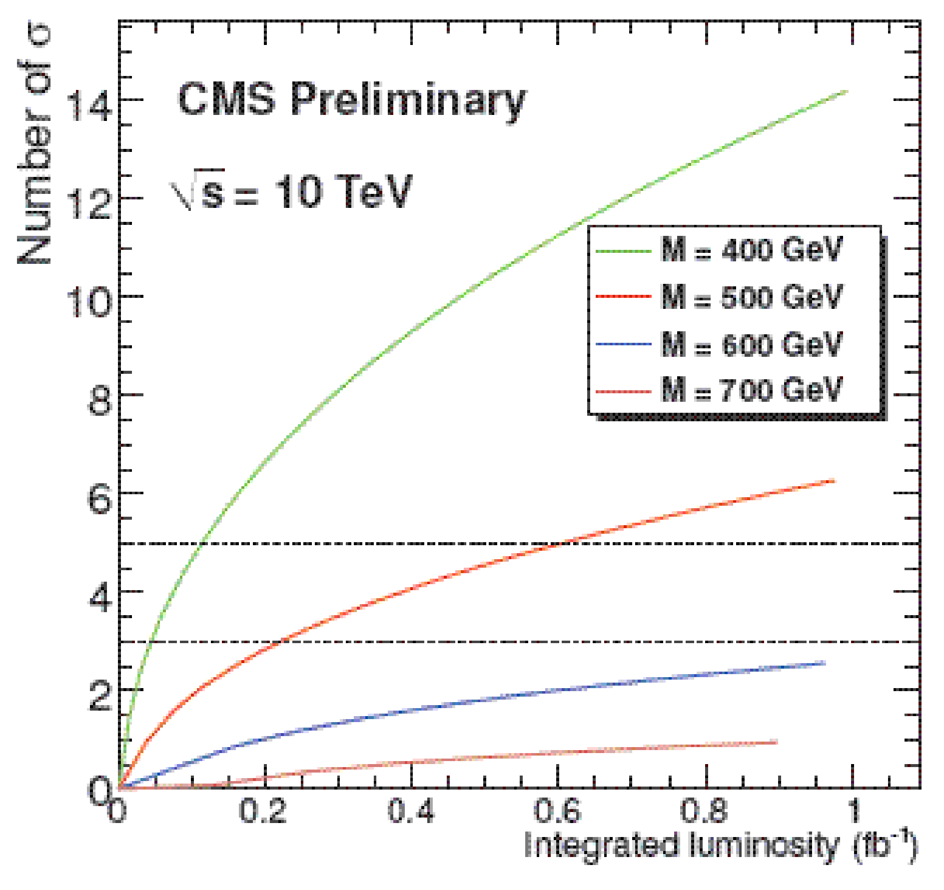
# Exotic top partners: Results

- T5/3 and B expectations combined
- Exclude masses up to 400 GeV with 80 pb-1, **500 GeV** with 340 $pb^{-1}$



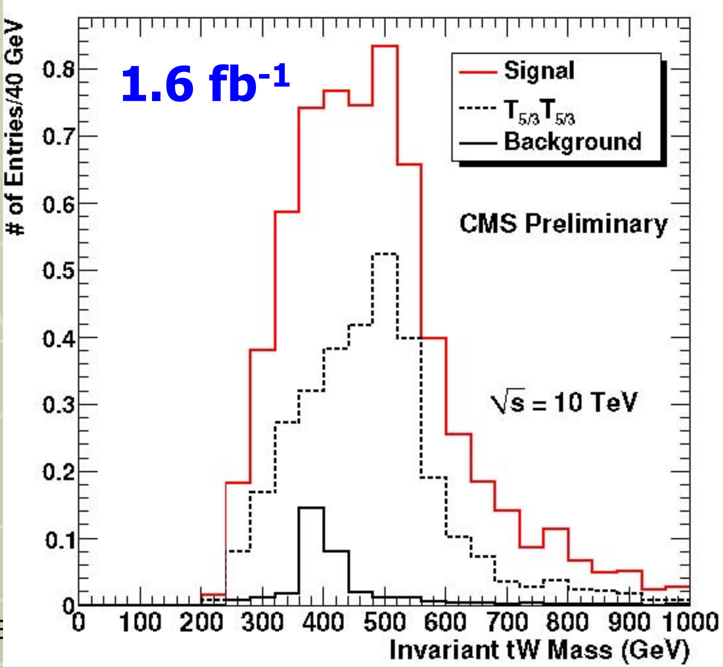

**Stringent limits can be set at the LHC with early data**

# Exotic top partners: Results




Discovery Potential

- **For M = 400 GeV**
  - **3σ at ~50$pb^{-1}$**
  - **5σ at ~115$pb^{-1}$**
- For M = 500 GeV
  - 3σ at ~220$pb^{-1}$
  - 5σ at ~600$pb^{-1}$



# Summary

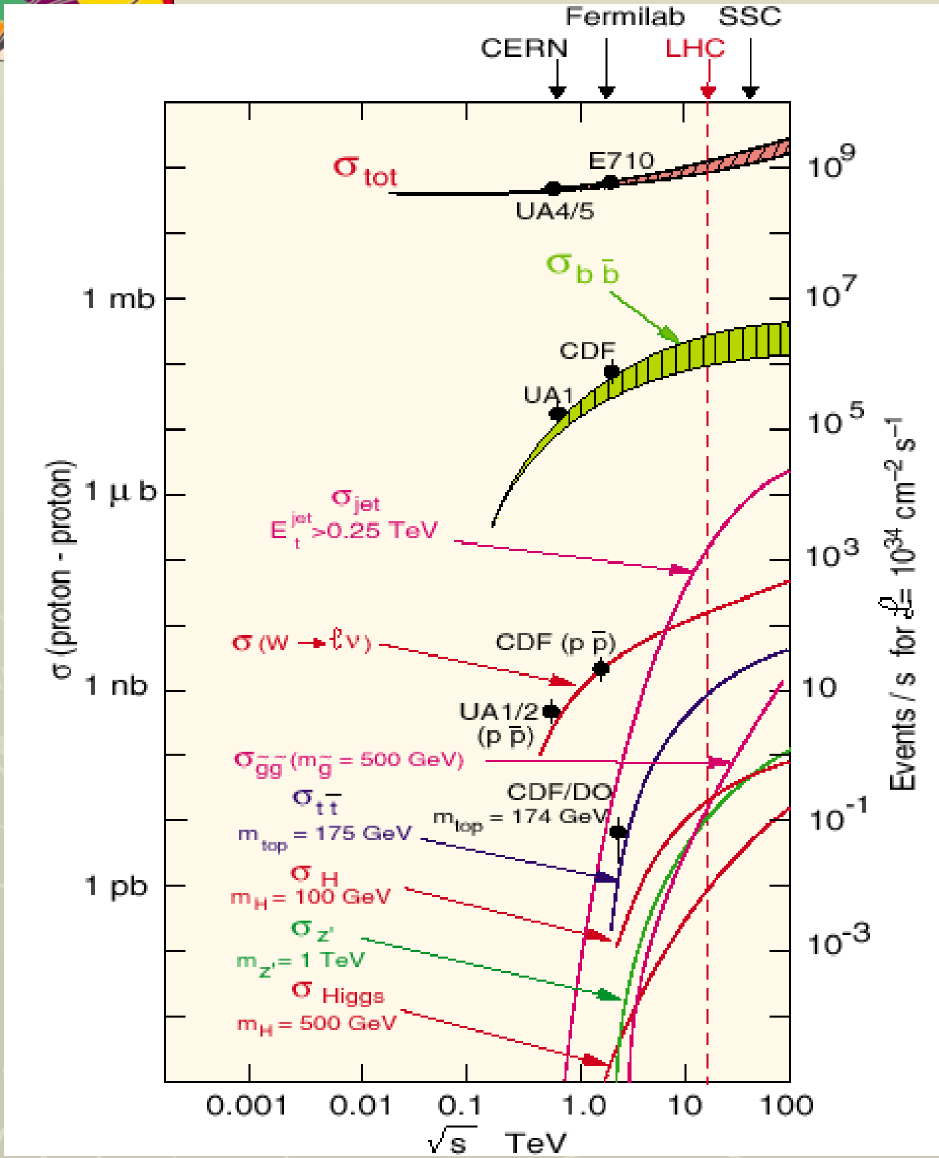
- Long physics run at LHC in 2010
- CMS excellent detector for BSM analyses
- Evidence for new physics could be obtained in CMS during the first period of the LHC
- Early data (50-500 pb $^{-1}$ ) will allow to reach sensitivity beyond LEP and Tevatron
- Good understanding of the detector performances and possible systematic effects will be achieved in situ at LHC, using data driven methods whenever possible
- Showed only a thin fraction of CMS BSM searches
- Much more can be found on:

  **http://cms-physics.web.cern.ch/cms-physics/CMS_Physics_Results.htm**

# Thank you

# Additional slides

## pp cross section



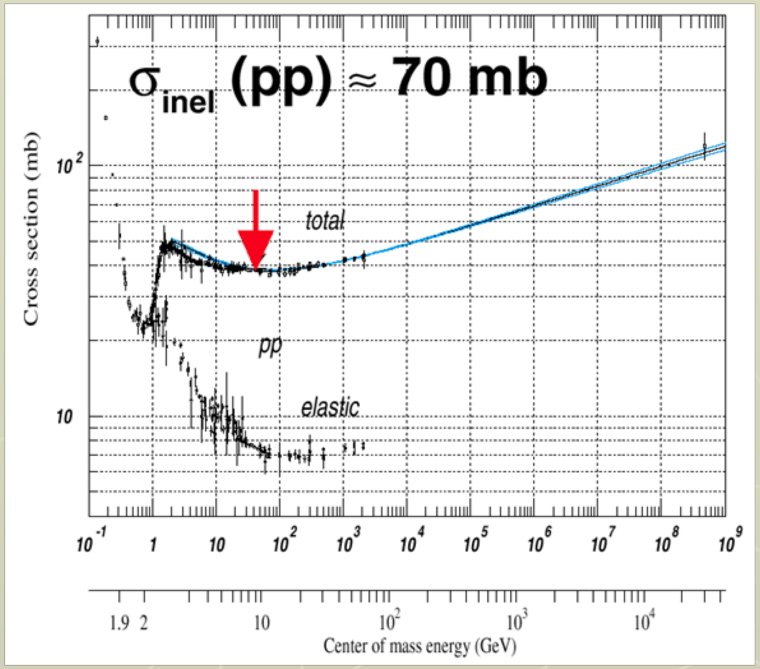

## Statistics at low lumi (L=10 $^{33}$ cm-$^{2}$ s-$^{1}$)

| Process | Ev./s | Ev./yr | Other machines |
|---|---|---|---|
| W→ eν | 15 | $10^8$ | $10^4$ LEP/ $10^7$ Tev. |
| Z→ ee | 1.5 | $10^7$ | $10^7$ LEP |
| tt | 0.8 | $10^7$ | $10^4$ Tev. |
| bb | $10^5$ | $10^{12}$ | $10^8$ Belle/ BaBar |
| gg | 0.001 | $10^4$ | - |
| H M=0.8TeV | 0.001 | $10^4$ | - |
| QCD jets $P_T$>200 GeV | $10^2$ | $10^9$ | $10^7$ Tev |

**LHC is going to be a B-, top-, W/Z, Higgs- and SUSY-factory!**

# Event Rate

- N = no. events / second
- L = luminosity = $10^{34}$ cm$^{-2}$ s$^{-1}$
- Total cross-section = 70 mb
- E = no. events / bunch crossing
- $\Delta t$ = bunch spacing = 25 ns

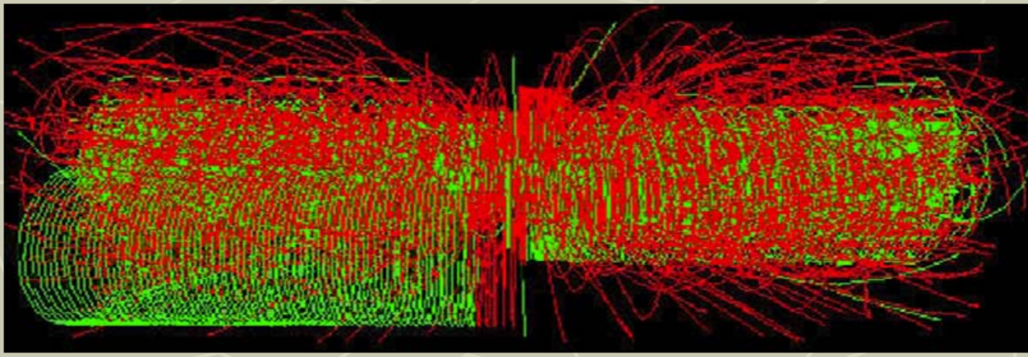



► $N = L \times \sigma = 7\ 10^{8}$ Hz

► $E = N / \Delta t$
~ 20 events / bunch crossing

**LHC will produce ~20 overlapping p-p interactions every 25 ns**

**Clean final states needed!**



# Large Hadron Collider

- Planned start up: 2009.
- Particles used: Protons and heavy ions (Lead, full stripped 82+)
- Circumference: 26,659 m.
- Injector: SPS
- Injected beam energy: 450 GeV (protons)
- Nominal beam energy in physics: 7 TeV (protons)
- Magnetic field at 7 TeV: 8.33 Tesla
- Operating temperature: 1.9 K
- Number of magnets: ~9300
- Number of main dipoles: 1232
- Number of quadrupoles: ~858
- Number of correcting magnets: ~6208
- Number of RF cavities: 8 per beam; Field strength at top energy ≈ 5.5 MV/m
- RF frequency: 400.8 MHz
- Revolution frequency: 11.2455 kHz.
- Power consumption: ~120 MW
- Gradient of the tunnel: 1.4%
- Difference between highest and lowest points: 122 m.

# CMS-ECAL Resolution and Calibration

Barrel: 60200 $PbWO_4$ crystals, endcap 15000 crystals

added in quadrature

- **Energy resolution:** **$\sigma/E \sim 2.7\% / \sqrt{E\,(GeV)} + 0.5\% + 150\ MeV/E$**

Stochastic term: depends on photoelectron statistics: LY ~ 4-5 pe/MeV
Constant term: shower containment, crystal non-uniformity, crystal intercalibration
Noise term: electronic noise, pile-up

- **Angular resolution:** **$\sigma_\theta = 50\ mrad / \sqrt{E}$**
- Transverse granularity $\Delta\eta \times \Delta\phi = 0.0175 \times 0.0175$
  Corresponds to crystal front face ($22 \times 22\ mm^2$) and matches Mol. Radius = 21.9 mm

**Design en. resolution of 0.5% required for H → γγ measurement → detector calibration**

**Find calibration constants $c_i$** **$E\,(GeV) = \Sigma\, c_i\, ADC_i$**

- **Lab. measurements → ~4%** **(crystal light yield, APD gain)**
- **Cosmics → 3-4%**
- **Test beam precalibration → 2-4%** **(only a few supermodules)**
- **Minimum bias events → 2%** **(fast calibration using φ symmetry)**
- **Z→ e+e-, W → eν → 0.5%** **(design value, with tracker and 2 months)**

# CMS: crystal calorimeter

## Why $PbWO_4$ crystals?

Scintillating crystals are the most precise calorimeters for energy measurements

•Excellent energy resolution over a wide range

•High detection efficiency for low energy e and γ

•Structural compactness

- simple building blocks for mech. assembly
- hermetic coverage
- fine transverse granularity

•Tower structure eases event reconstruction

- straightforward cluster algorithms for energy and position
- electron/photon identification

PWO Drawback: low Light Yield: ~10 pe/MeV (with PMT and tyvek wrapping at T=18 oC)

Solution: APD's internal gain (~50)

| Physics Requirements | CMS-ECAL Solution |
|---|---|
| Very good resol. for high energy e/g | Crystal calorimeter |
| High LHC lumin.: $10^{34}$ cm $^{-2}$ s $^{-1}$ | PWO is radiation hard |
| LHC bunch separation: 25 ns | PWO is fast: 80% light collected within 25 ns |
| Compact det. with high granularity | PWO has $X_0 = 0.89$ cm Mol. Radius = 2.2 cm |
| Magnetic field inside CMS: 4T | Compact solid state photodet. (APD's) in the barrel (Endcaps:VPT's) |