Standard Model Physics with CMS

Seminar IPM Tehran
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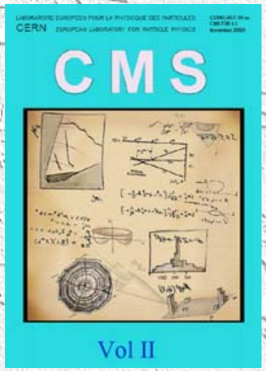
DESY

Outline

- The CMS experiment and status of the detector
- Prospects for SM physics at the LHC
  - QCD & jet physics
  - b-physics
  - top physics
  - electroweak physics
  - (diffractive and forward physics)

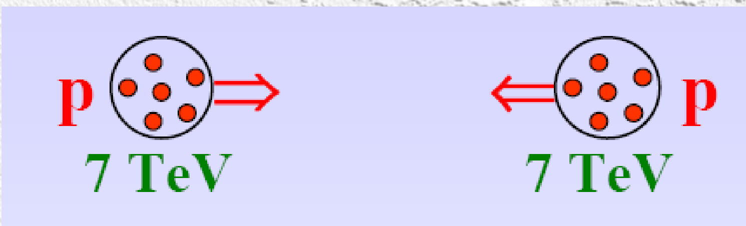
- This talk is mainly based on recent CMS Physics TDR
  - some interesting results from ATLAS included



http://cms.cern.ch/iCMS/

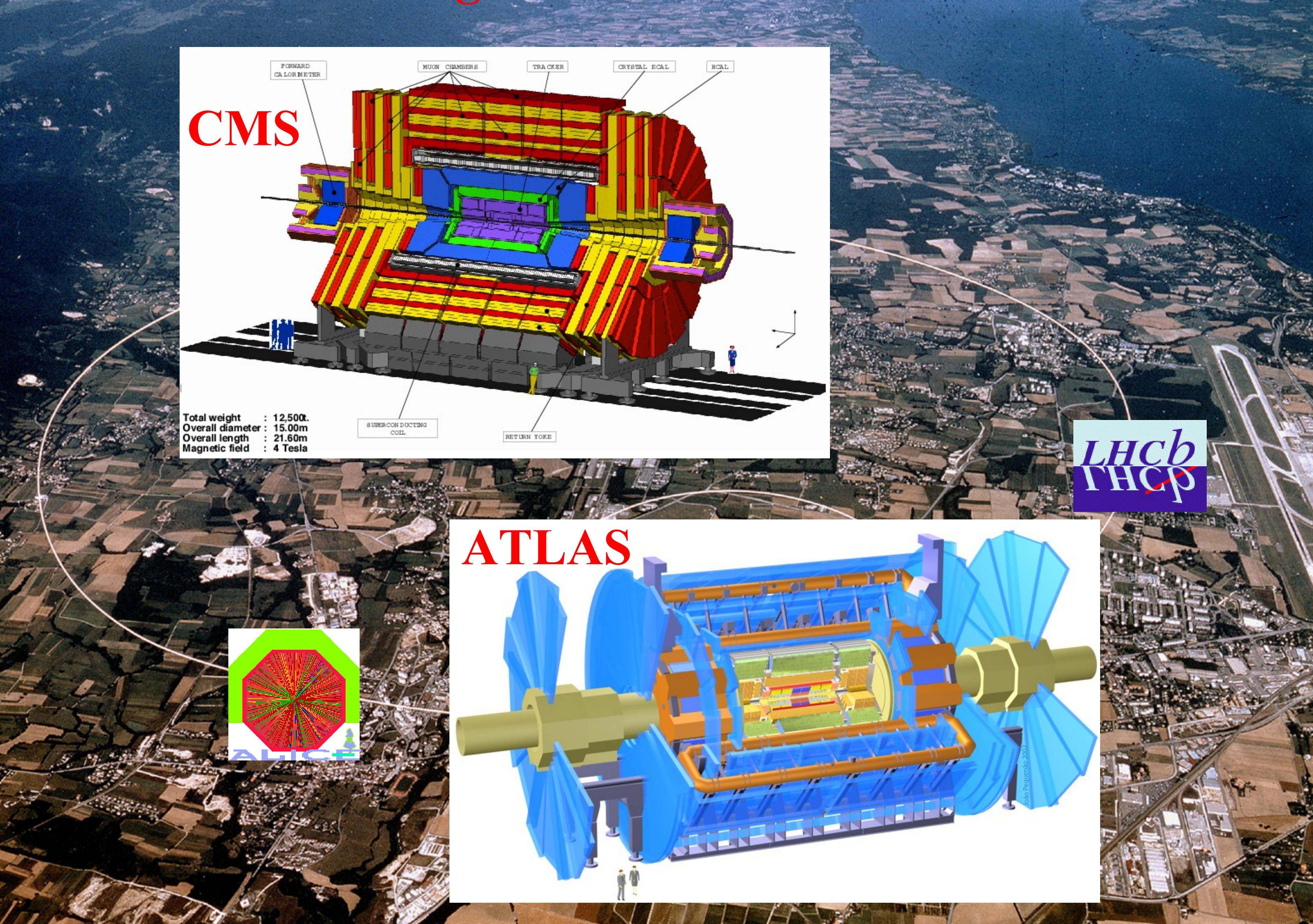
The Large Hadron Collider (LHC) at CERN

- Proton-proton collider in the former LEP tunnel at CERN (Geneva)

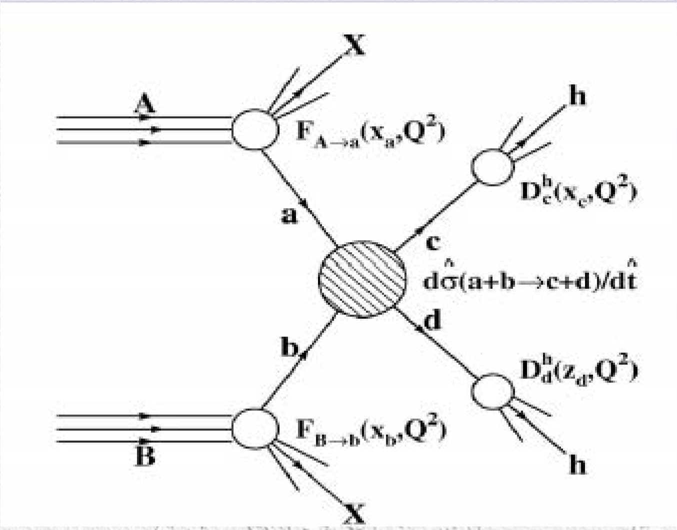


- Highest ever energy per collision
  14 TeV in the pp-system
- Conditions as $10^{-13} – 10^{-14}$ s after the Big Bang
- 4 experiments:
  ATLAS
  CMS
  LHC-B specialised on b-physics
  ALICE specialised for heavy ion collisons
- Constructed in a worldwide collaboration
- Start planned for 2008

The Large Hadron Collider LHC

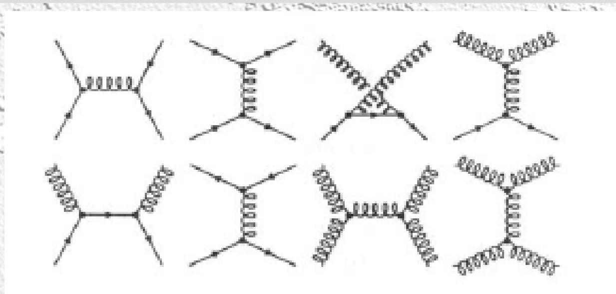


Physics at Proton Colliders



- **Protons are composite, complex objects**
  - partonic substructure
  - quarks and gluons

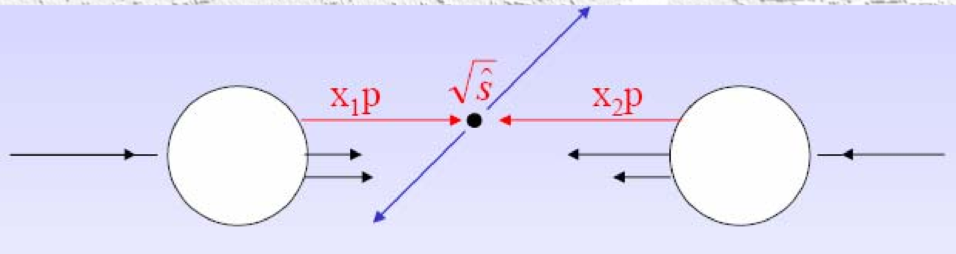
- **Interesting hard scattering processes**
  quark-(anti)quark
  quark-gluon
  gluon-gluon



However, hard scattering (high momentum transfer) processes are only a small fraction of the total cross section
- total inelastic cross section ≈ 70 mb (huge!)
- dominated by events with small momentum transfer

Proton-Proton Collisions

- Proton beam can be seen as beam of quarks and gluons with a wide band of energies
- The proton constituents (partons) carry only a fraction $0 \leq x \leq 1$ of the proton momentum



- The effective centre-of-mass energy $\sqrt{\hat{s}}$ is smaller than $\sqrt{s}$ of the incoming protons

$$p_1 = x_1 p_A$$

$$p_2 = x_2 p_B$$

$$p_A = p_B = 7 \text{ TeV}$$

$$\sqrt{\hat{s}} = \sqrt{x_1 x_2 s} = x\sqrt{s}$$

$$(\text{if } x_1 = x_2 = x)$$

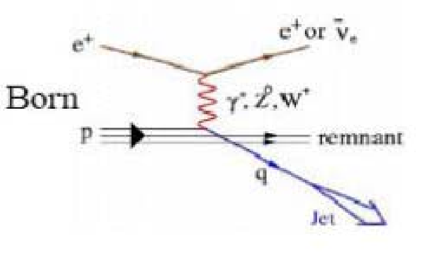
Note:

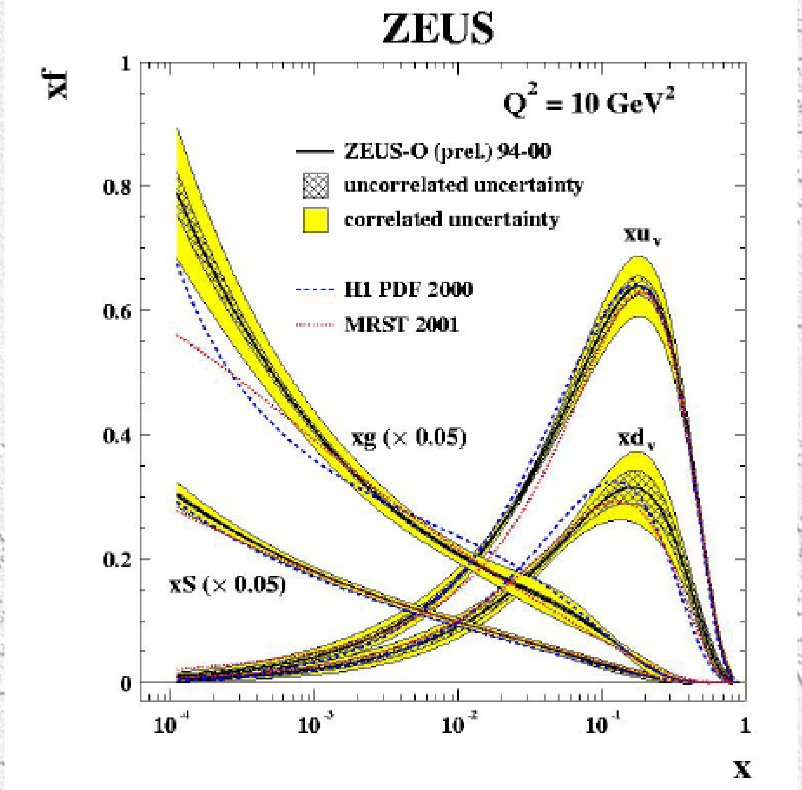
- the component of the parton momentum parallel to the beam can vary from 0 to the proton momentum ($0 \leq x \leq 1$)
- the variation of the transverse component is much smaller (of order the proton mass)

To produce a particle of mass		
mass	LHC	Tevatron
100 GeV	$x \approx 0.007$	$x \approx 0.05$
5 TeV	$x \approx 0.36$	---

Parton Density Functions

How do the distributions of the x-values look like?
Measured at HERA in ep-scattering, e.g.:





- **u- and d-quarks at large x-values**
- **gluons dominate at small x**
- **large uncertainties for gluons**

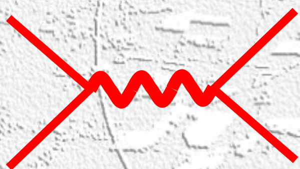
Parton Density Functions at the LHC

LHC is a proton-proton collider

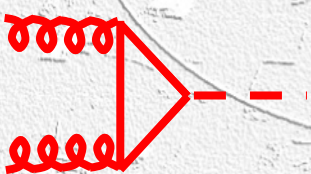
But fundamental processes are the scattering of

- **Quark – Antiquark**
- **Quark – Gluon**
- **Gluon – Gluon**

<u>Examples:</u>

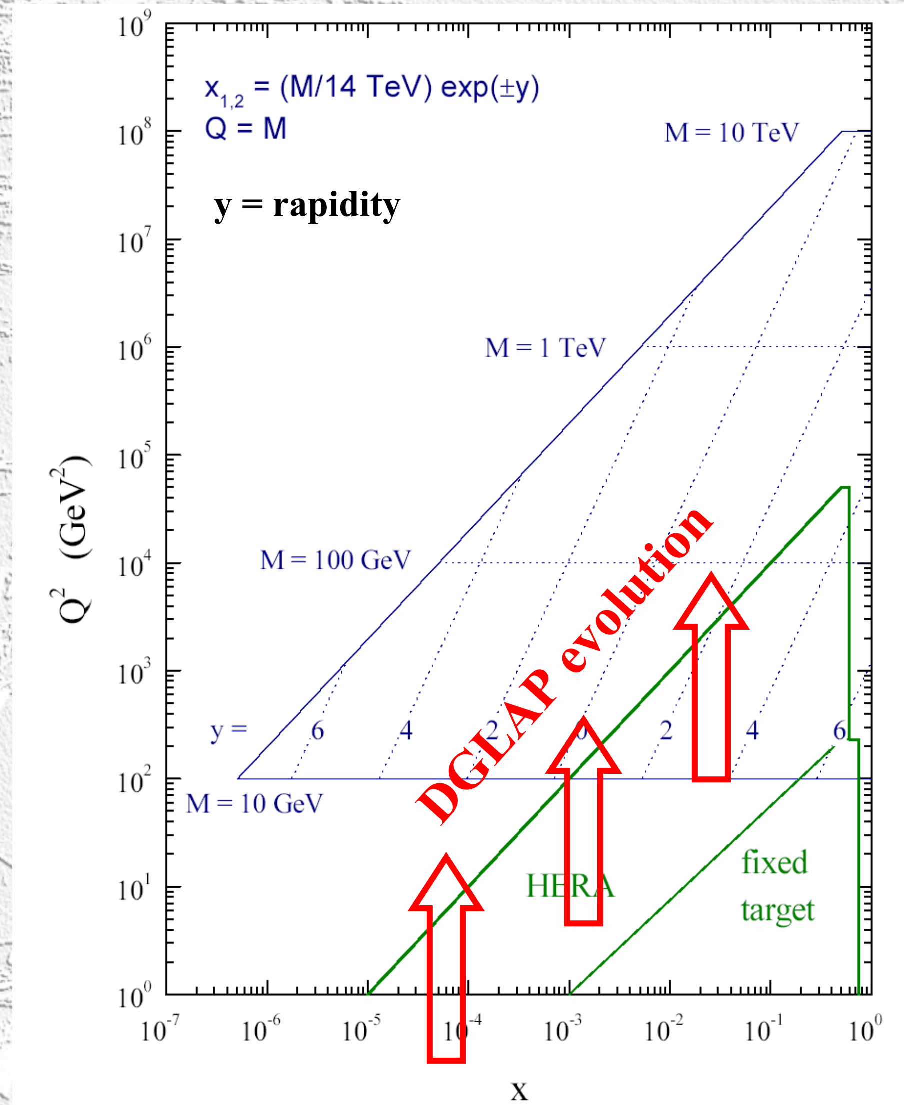


$q\bar{q} \rightarrow W \rightarrow l\nu$

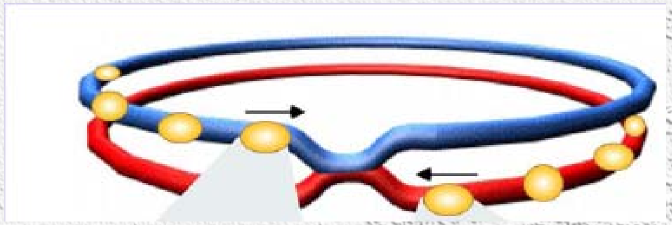


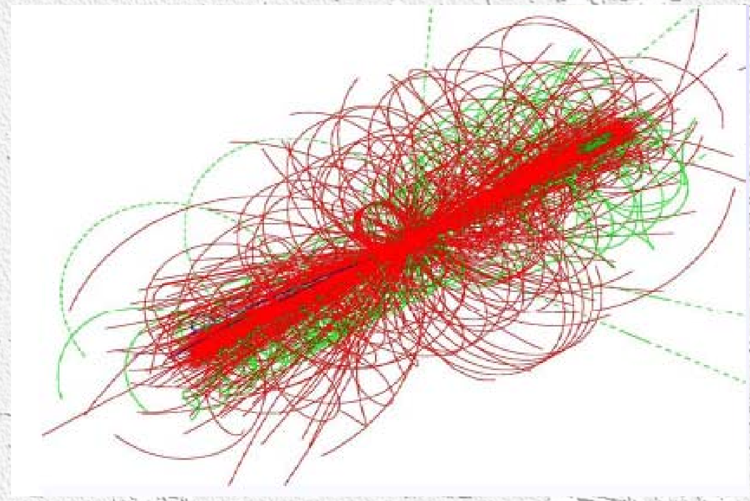
$gg \rightarrow H$

$\Rightarrow$ **need precise PDF(x,Q^2)**
+ QCD corrections (scale)



Proton-Proton Collisions at the LHC





- 2835 + 2835 proton bunches
  separated by 7.5 m

→ collisions every 25 ns
  = 40 MHz crossing rate

- 10^{11} protons per bunch

- at $10^{34}/cm^2/s$
  ≈ 25 pp interactions per crossing
  pile-up

→ ≈ 10^9 pp interactions per second !!!

- in each collision
  ≈ 1600 charged particles produced

enormous challenge for the detectors

Cross Section of Various SM Processes

⇒ Low luminosity phase

$10^{33}/cm^2/s = 1/nb/s$

approximately

- 10^8 pp interactions
- 10^6 bb events
- 200 W-bosons
- 50 Z-bosons
- 1 tt-pair

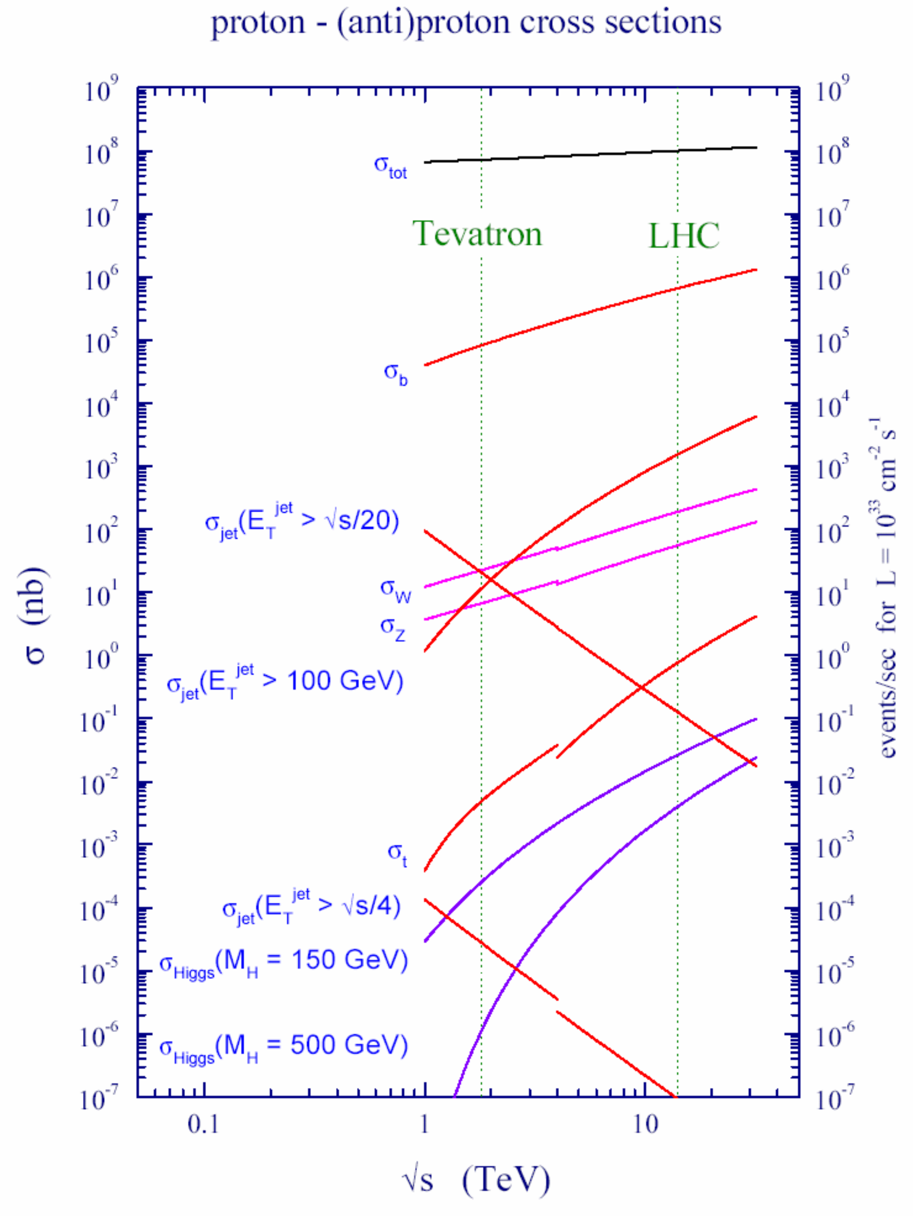
will be produced per second and

- 1 light Higgs

per minute!

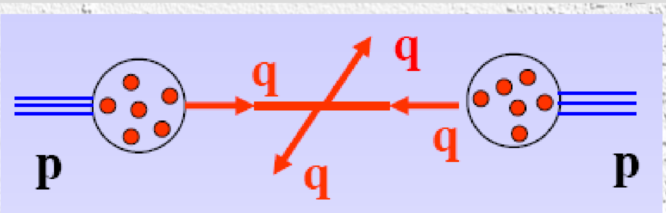
The LHC is a b, W, Z, top, Higgs, … factory!

The problem is to detect the events!



Experimental Signatures

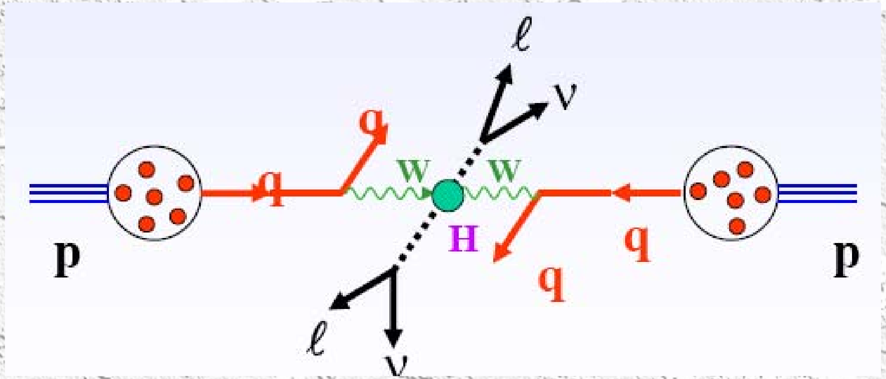
1. Hadronic final states, e.g. quark-quark



no high p_T leptons or photons in the final state

holds for the bulk of the total cross section

2. Lepton/photons with high p_T, example Higgs production and decay



Important signatures for interesting events:
- leptons and photons
- missing transverse energy

Detector Design Aspects

- good measurement of leptons (high p_T)
  muons: large and precise muon chambers
  electrons: precise electromagnetic calorimeter and tracking
- good measurement of photons
- good measurement of missing transverse energy (E_T^{miss})
  requires in particular good hadronic energy measurements
  down to small angles, i.e. large pseudo-rapidities ($\eta \approx 5$, i.e. $\theta \approx 1°$)
- in addition identification of b-quarks and τ-leptons
  precise vertex detectors (Si-pixel detectors)

Very important: radiation hardness
e.g. flux of neutrons in forward calorimeters
10^{17} n/cm^2 in 10 years of LHC operation

Online Trigger

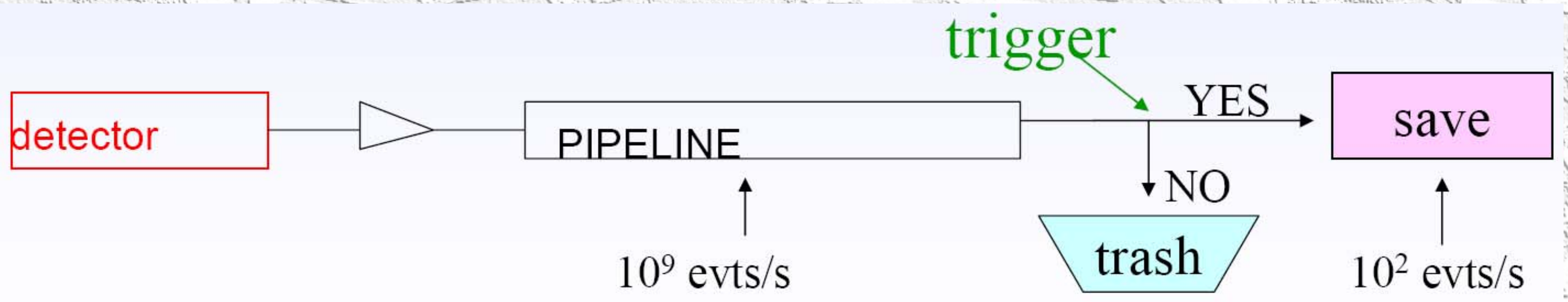
Trigger of interesting events at the LHC is much more complicated than at e^+e^- machines

- **interaction rate: $\approx 10^9$ events/s**
- **max. record rate: ≈ 100 events/s** **event size $\approx$ 1 MByte $\Rightarrow$ 1000 TByte/year of data**

$\Rightarrow$ trigger rejection $\approx 10^7$

- **collision rate is 25 ns (corresponds to 5 m cable delay)**
- **trigger decision takes $\approx$ a few µs**

$\Rightarrow$ store massive amount of data in front-end pipelines while special trigger processors perform calculations



The ATLAS experiment

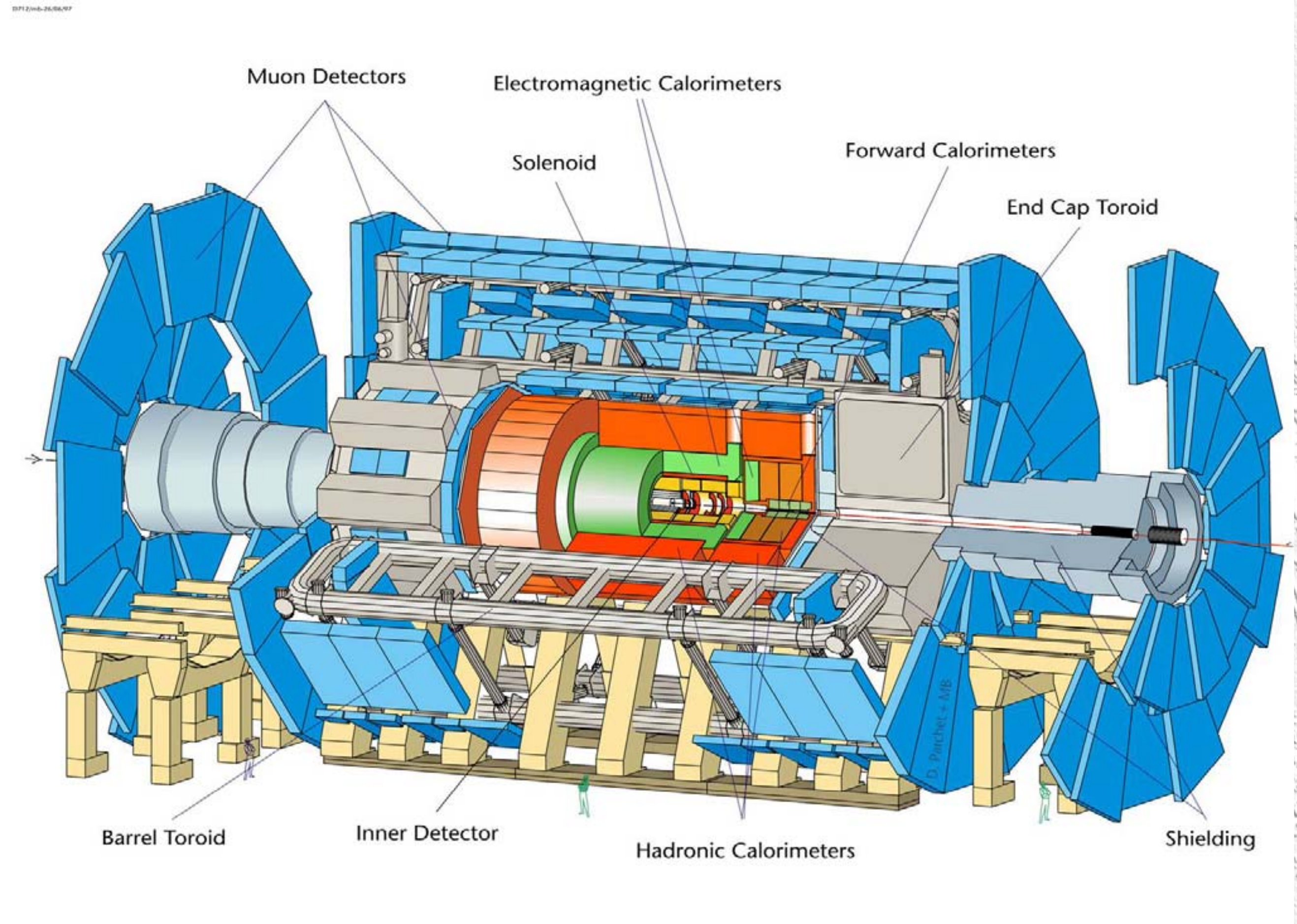
A Toroidal LHC ApparatuS

ATLAS in a nutshell:

- Large air toroid with μ chambers
- HCAL: steel & scintillator tiles
- ECAL: LAr
- Inner solenoid (2 T)
- Tracker: Si-strips & straw tubes (TRD)
- Si-pixel detector

10^8 channels

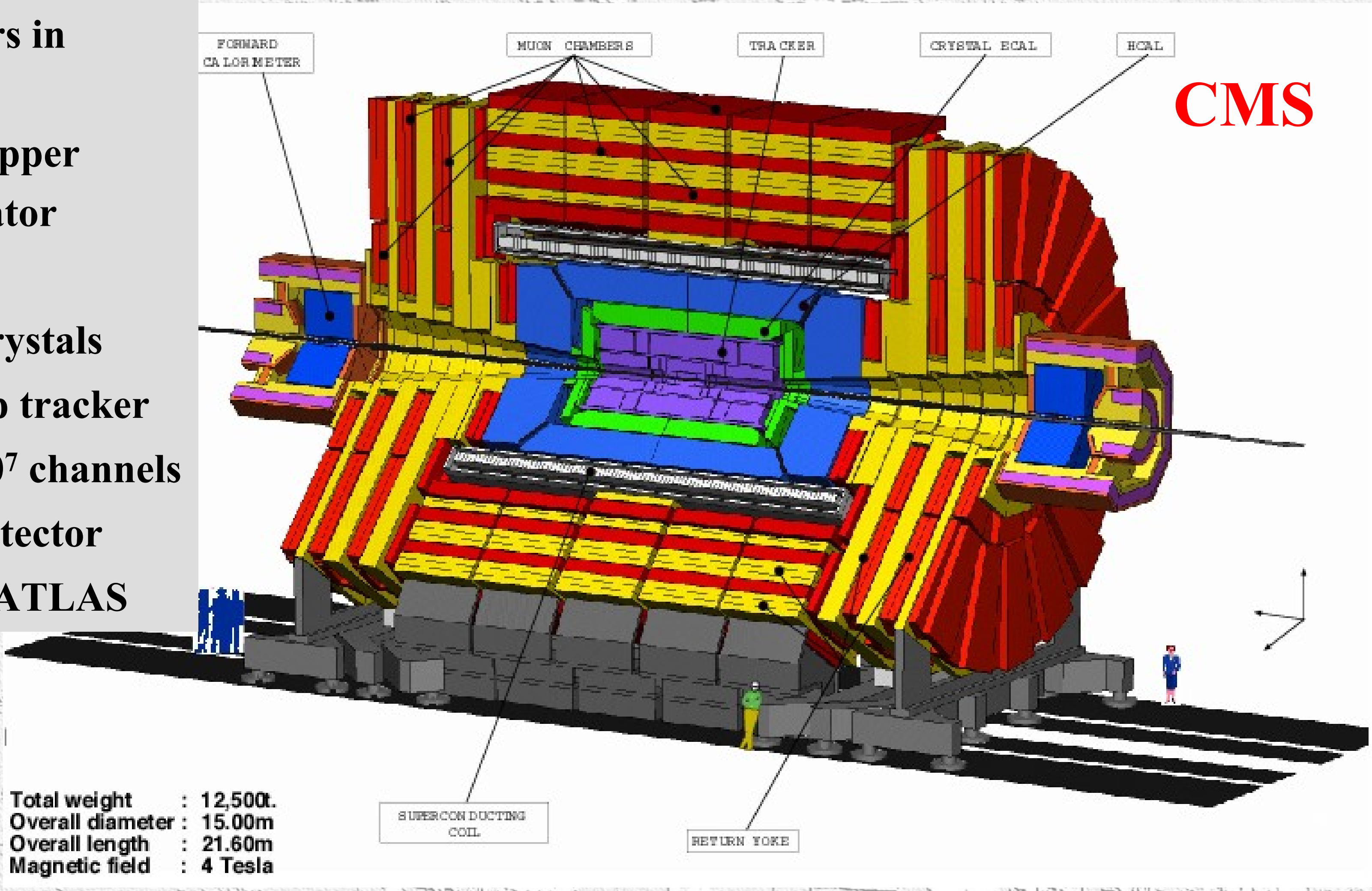
15 μm resolution



The CMS experiment

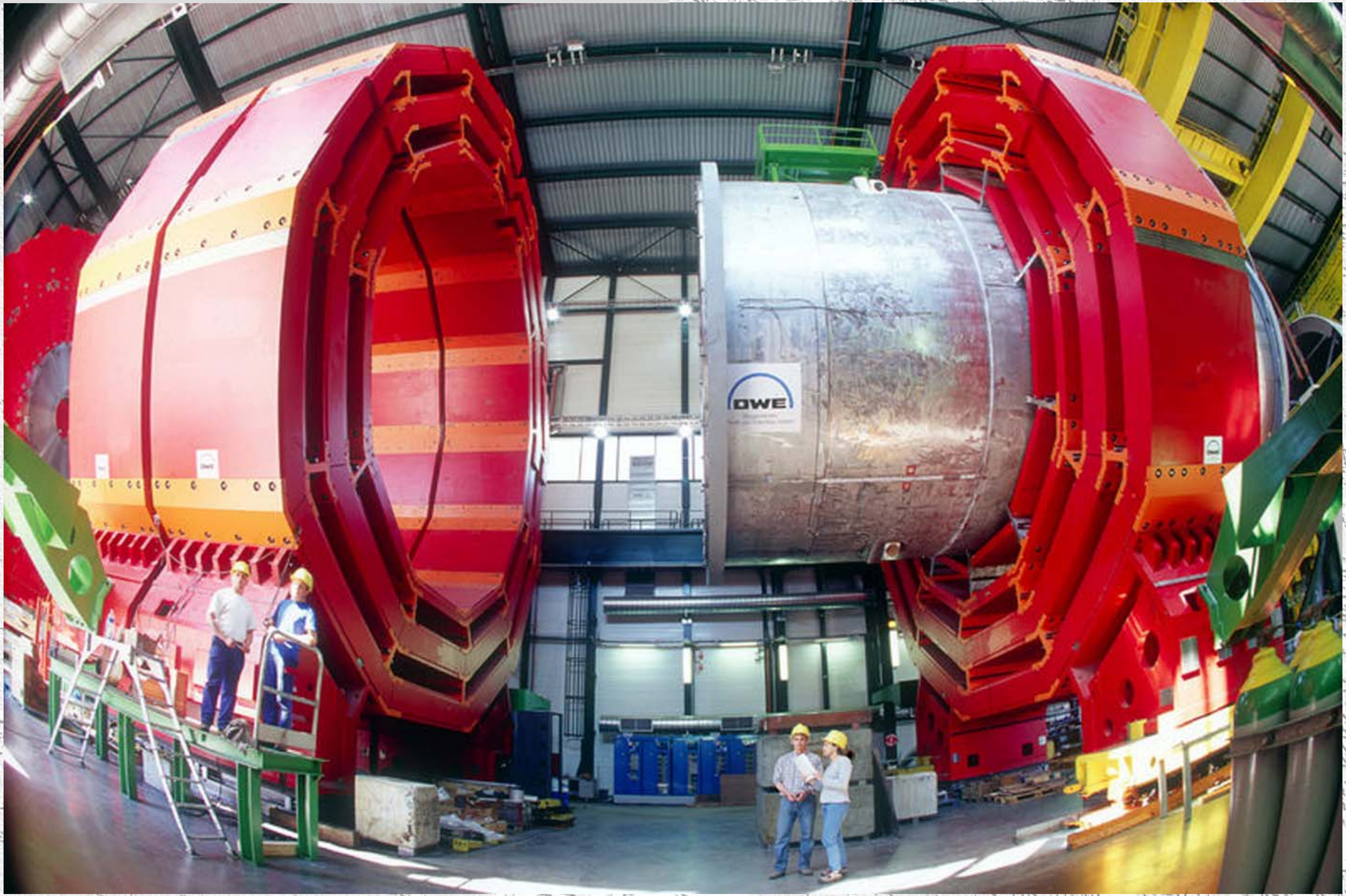
Compact Muon Solenoid

CMS in a nutshell:
- 4 T solenoid
- μ chambers in iron yoke
- HCAL: copper & scintillator
- ECAL: $PbWO_4$ crystals
- All Si-strip tracker $220\ m^2$, 10^7 channels
- Si-pixel detector similar to ATLAS



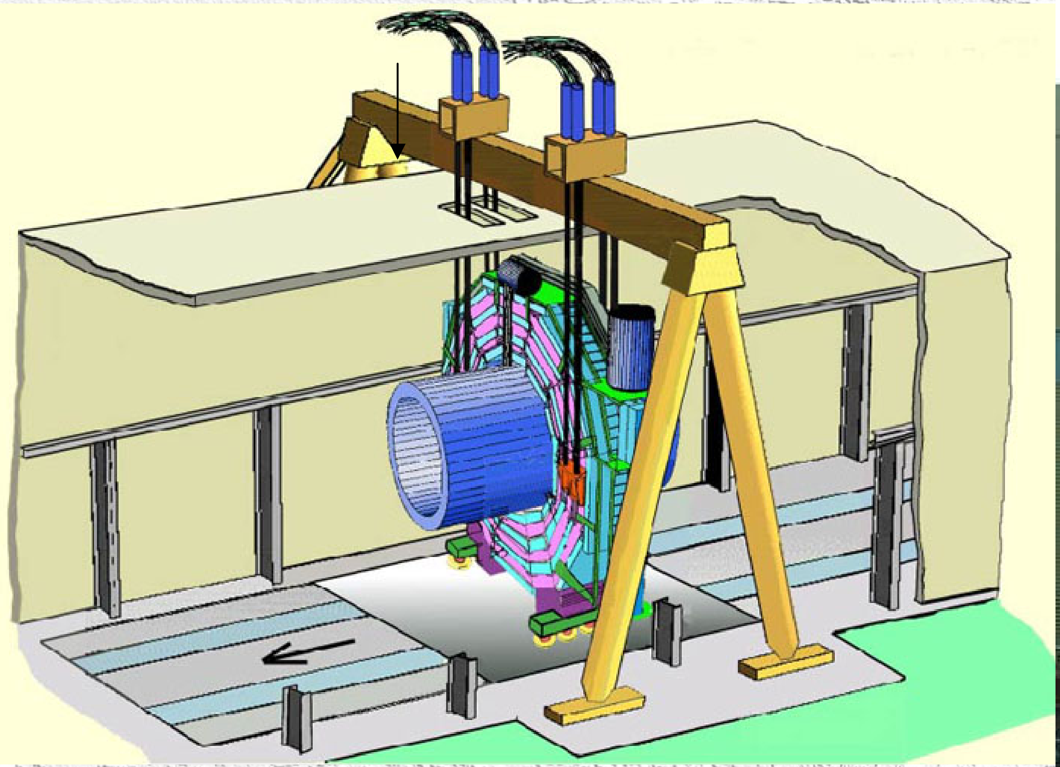
Layout of CMS

- 11 slices: 5 barrel and 2*3 endcaps



Lowering of CMS

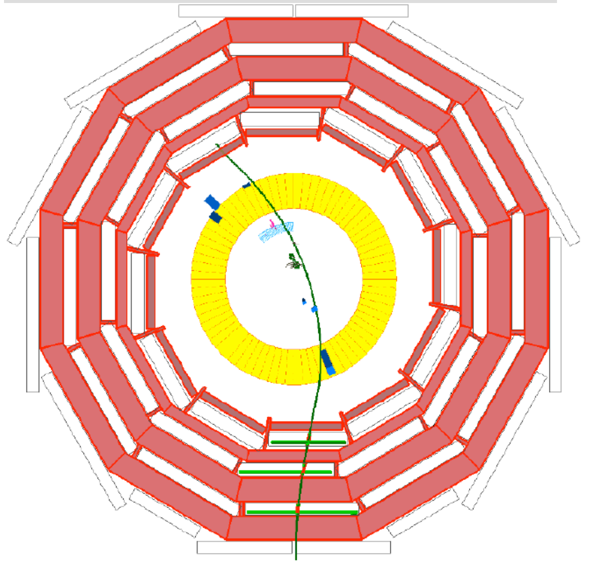
- Crane installed
- Lowering started end 2006



Status of the CMS detector

- solenoid sucessfully operated at 4 Tesla (11/06), field map
- lowering of central magnet slice (YB0) on February 28th, 2007

Cosmic from magnet test

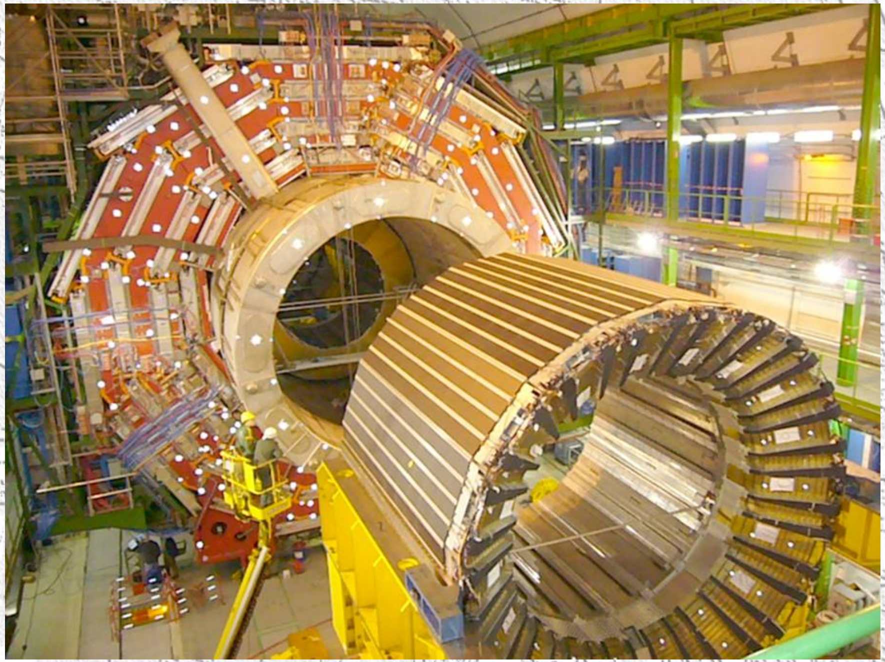


- most μ chambers installed

- 5/13 heavy pieces still to be lowered but all of known type
- 2nd endcap cabled, tested & commissioned on surface

Status of the CMS detector

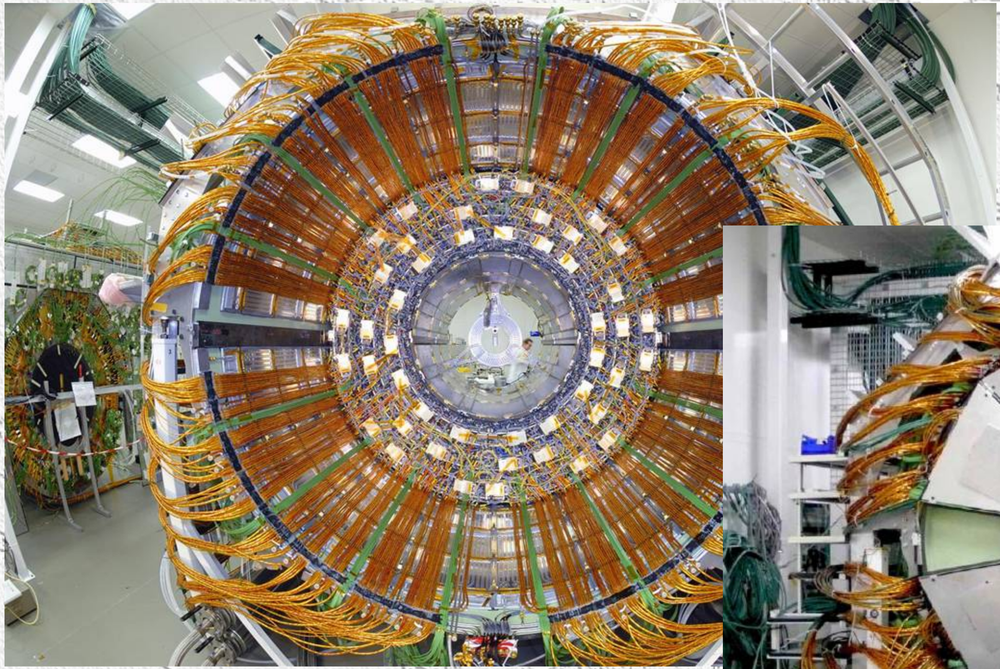
- more recent photographs from CMS

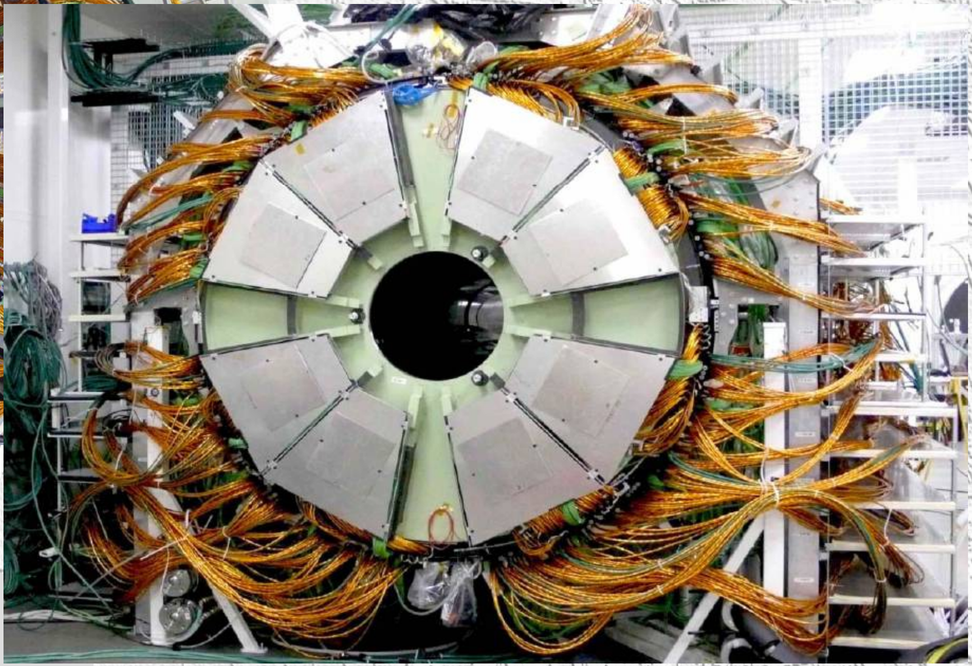


The CMS Tracker

- Silicon tracker ready
  - under test at surface
  - to be installed in August 2007

CMS tracker:
- ≈ 220 m^2 of Si sensors
- 10.6 million Si strips
- 65.9 million Si pixel





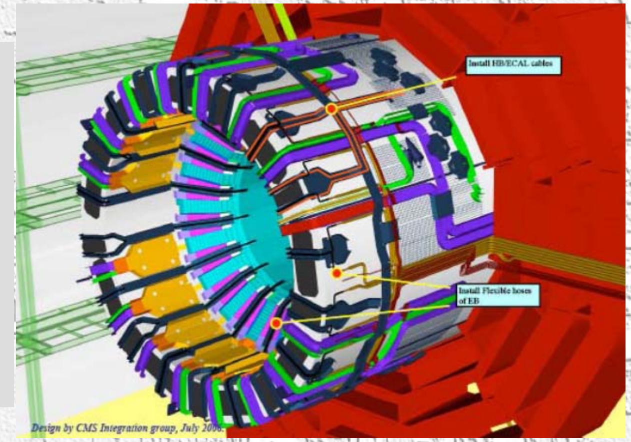
- Pixel detector:
  - 2/3 of modules produced
  - ready for installation end 2007

Status of the CMS detector

- ECAL:
  - barrel crystal production and module assembly completed
  - installation May/June
  - endcap crystal prodcution started
  - full endcaps ready for 2008 physics run

- Trigger and DAQ:
  - is progressing well
  - 400/2000 HLT PC (being) installed
  - global run May/June

- Summary status CMS:
  - on track for taking data in fall
  - on critical path: installation of services on YB0
  - complete detector (+ Pixel + ECAL endcaps) ready for 2008 run



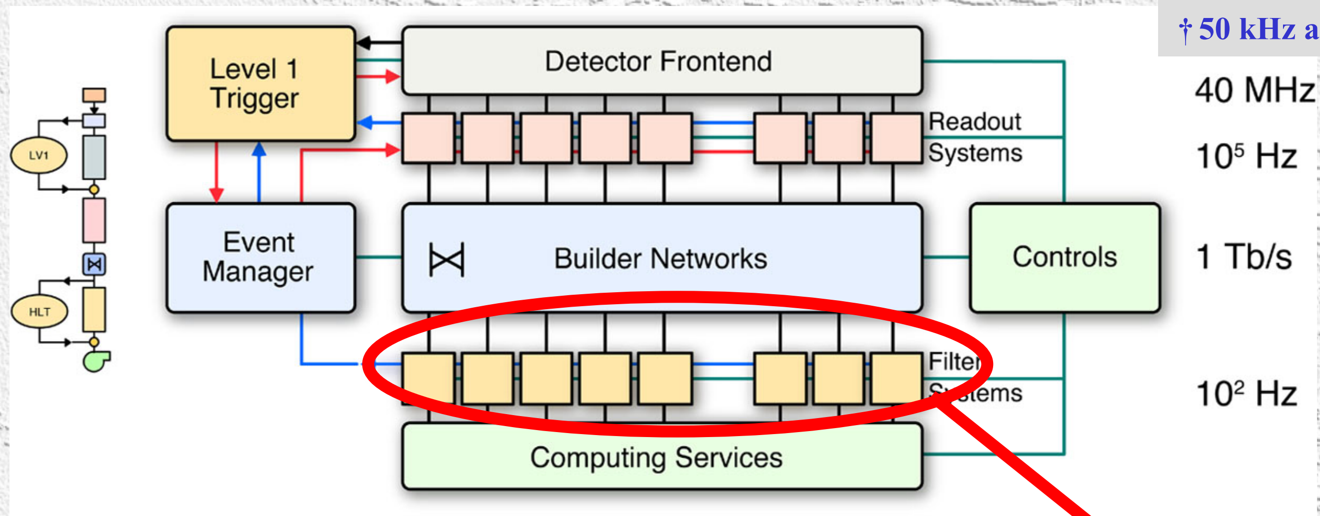
Trigger & DAQ system

Similar design for ATLAS & CMS

Example CMS:

Collision rate	40 MHz
Level-1 max. trigger rate	100 kHz†
Average event size	≈ 1 Mbyte

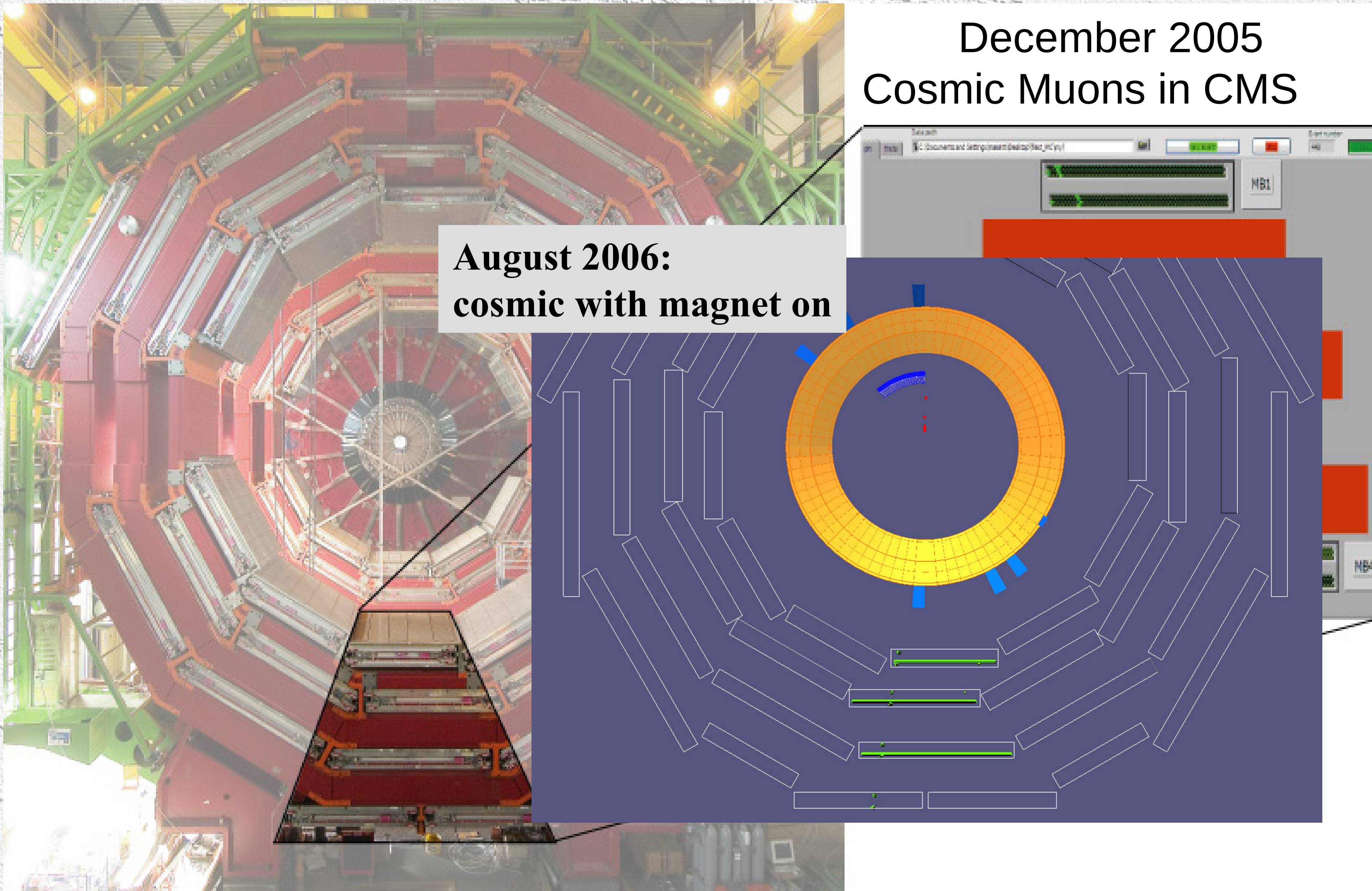
† 50 kHz at startup (DAQ staging)



Filter farm:
- approx. 2000 CPUs
- easily scaleable
- staged (lower lumi & saves money)
- uses offline software

The longest journey starts with the first step…

- Cosmic data taking with assembled detector components…



Comparison of ATLAS and CMS

	ATLAS	CMS
length	≈ 46 m	≈ 22 m
diameter	≈ 25 m	≈ 15 m
weight	≈ 7000 t	≈ 12000 t

Possible LHC Schedule

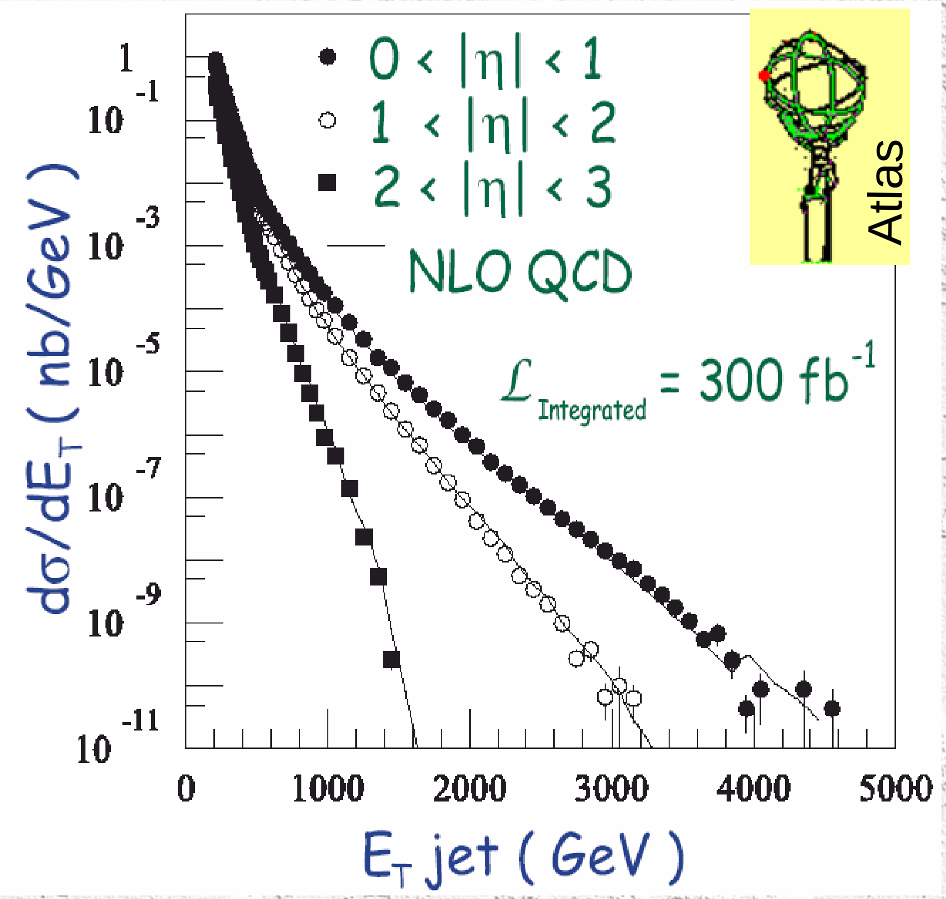
- 2007 Completion of machine and detectors
- 2008 first physics year
  - at 7 TeV proton energy
  - try to reach $\geq 10^{32}/cm^2/s$
  - integrated luminosity $O(1\ fb^{-1})$
- 2008 - 2010 three years at $1 - 2 \cdot 10^{33}/cm^2/s$
  - $\geq 30\ fb^{-1}$ in total
  - important for precision physics and discoveries
- $\geq$ 2011 high luminosity running at $10^{34}/cm^2/s$
  - $100\ fb^{-1}$ per year
- 2015 Upgrade to Super LHC $10^{35}/cm^2/s$
  - under discussion
  - requires major machine and detector upgrades

Standard Model Physics

Jet Physics

Jet physics at the LHC

- E_T spectrum, rate varies over 11 orders of magnitude
- Test QCD at the multi-TeV scale

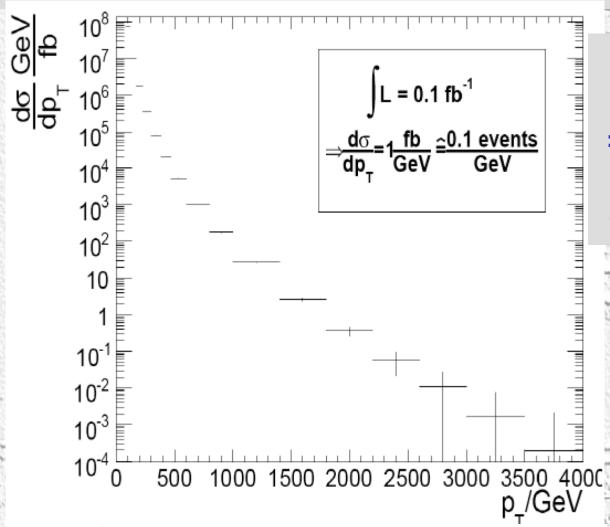


Inclusive jet rates for 300 fb^{-1}:

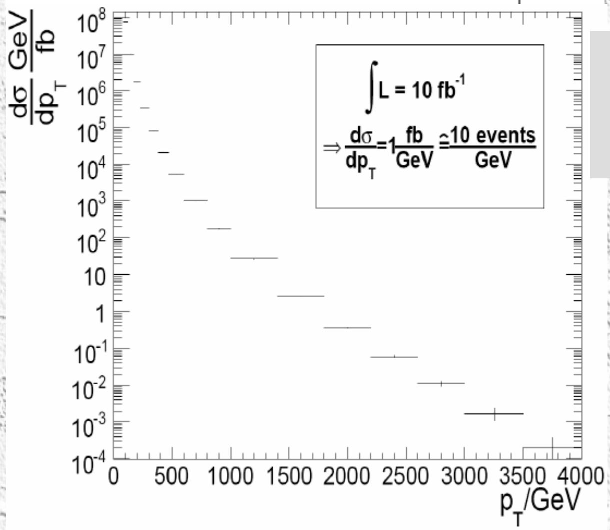
E_T of jet	Events
> 1 TeV	$4 \cdot 10^6$
> 2 TeV	$3 \cdot 10^4$
> 3 TeV	400

LHC Jet Physics

- Jet rates will be one of the first LHC result: statistical precision

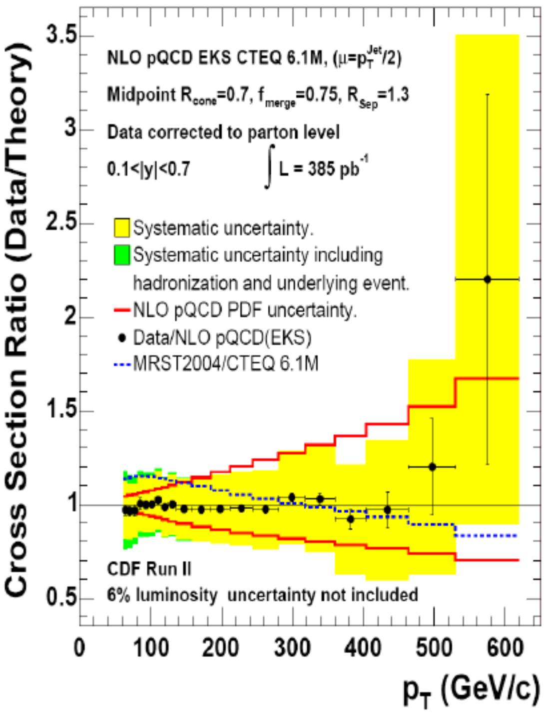


100 pb-1
= few weeks
at 14 TeV



10 fb-1
= 1 year

- compare to CDF result run II



- detector systematic effects expected to be similar to Tevatron

QCD

Measurement of α_s at LHC limited by

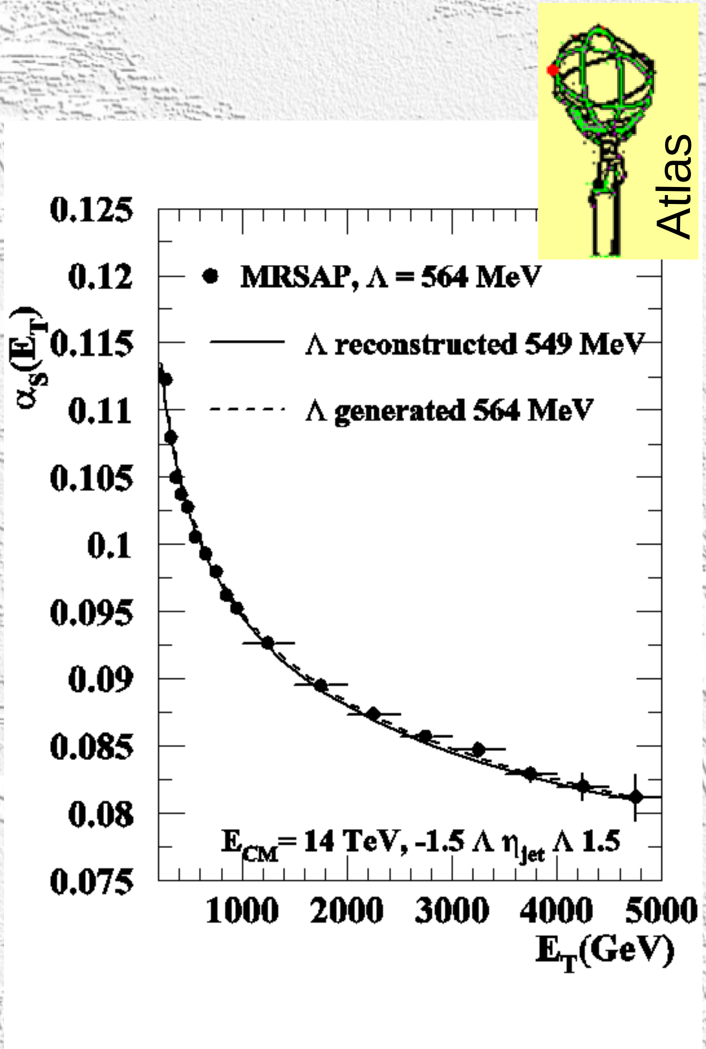
- **PDF (3%)**
- **Renormalisation & factorisation scale (7%)**
- **Parametrisaton (A,B)**

$$\frac{d\sigma}{dE_T} \sim \alpha_S^2(\mu_R)A(E_T) + \alpha_S^3(\mu_R)B(E_T)$$

- **10% accuracy $\alpha_s(m_Z)$ from incl. jets**
- **Improvement from 3-jet to 2-jet rate?**

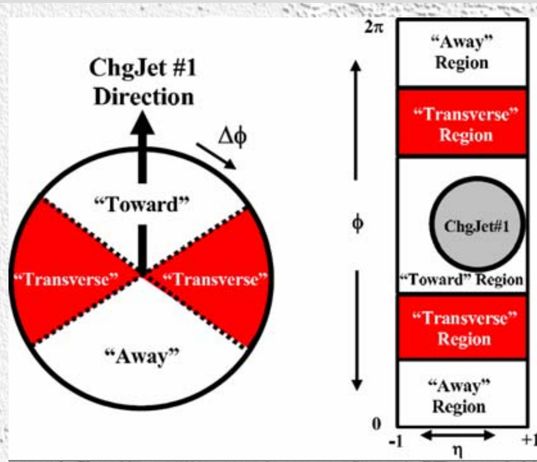
Verification of running of α_s and test of QCD at the smallest distance scale

- **$\alpha_s = 0.118$ at m_Z**
- **$\alpha_s \approx 0.082$ at 4 TeV (QCD expectation)**

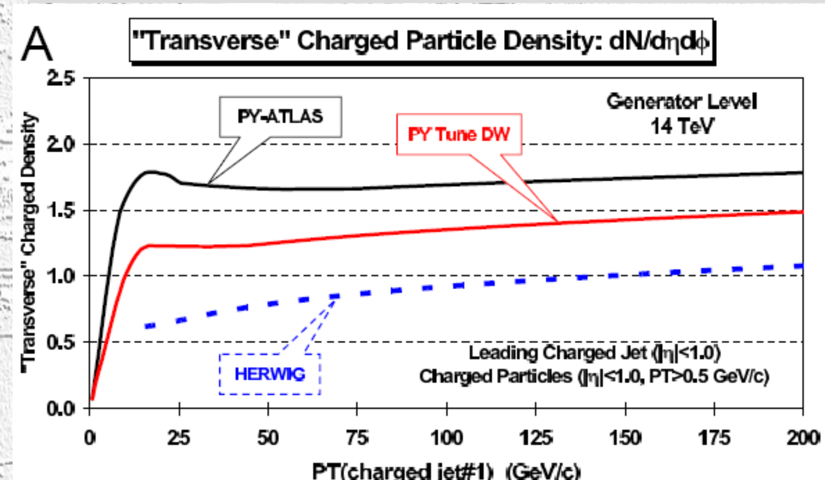


Underlying Event

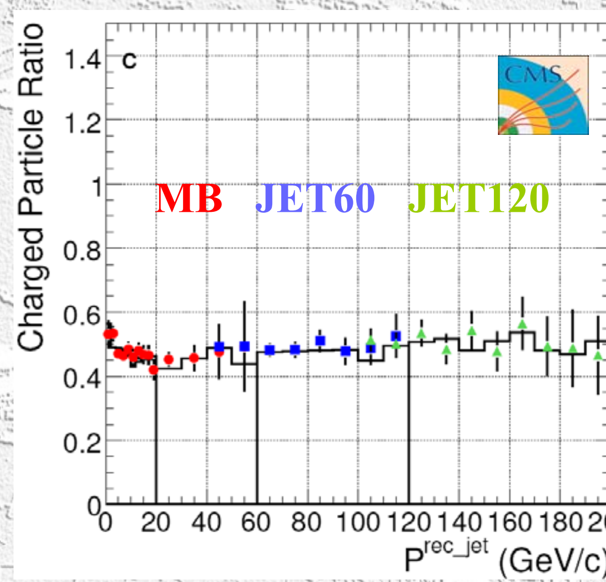
- Everything accompanying the event but the hard scattering process



- Divergent MC predictions, e.g. average particle density vs. jet p_T



- Measurement possible from data:
  - feasibility of the measurement proven
  - agreement between triggers
  - spin-off for soft-track reconstruction $p_T > 0.5$ GeV

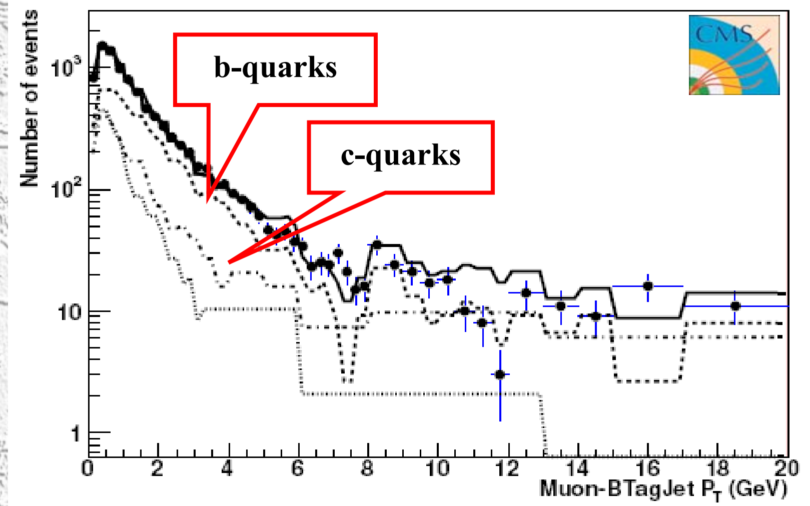


B-Physics

Inclusive b-production

- Selection
  - $b \rightarrow \mu$ $p_T^{\mu} > 19$ GeV non-isolated
  - 1 b-tagged jet, $E_T > 50$ GeV
- For 10 fb^{-1} sensitivity up to $E_T^b \approx 1.5$ TeV
- Cross section error ± 18%

- p_T^{μ} wrt b-tagged jet
  e.g. 230 GeV < E_T^b < 300 GeV



Systematic error

Source	uncertainty, %
jet energy scale	12
event selection	6
B tagging	5
luminosity	5
trigger	3
muon Br	2.6
misalignment	2
muon efficiency	1
$t\bar{t}$ background	0.7
fragmentation	9
total	18

Selection for 10 fb^{-1}

$\hat{p}_T$, GeV/c	$N^{QCD}_{generated}$	$b\bar{b}$ purity, %	$c\bar{c}$ fraction, %	uds fraction, %	$N^{b\bar{b}}_{expected}$
50 – 80	198993	66	32	2	1.4 M
80 – 120	294986	66	32	2	6.1 M
120 – 170	291982	72	26	2	5.1 M
170 – 230	355978	71	26	3	2.4 M
230 – 300	389978	73	24	3	0.9 M
300 – 380	283983	70	25	5	0.3 M
380 – 470	191989	68	27	5	88 k
470 – 600	190987	64	29	7	34 k
600 – 800	94996	60	31	9	10 k
800 – 1000	89999	60	30	10	2.0 k
1000 – 1400	89998	55	31	14	0.5 k

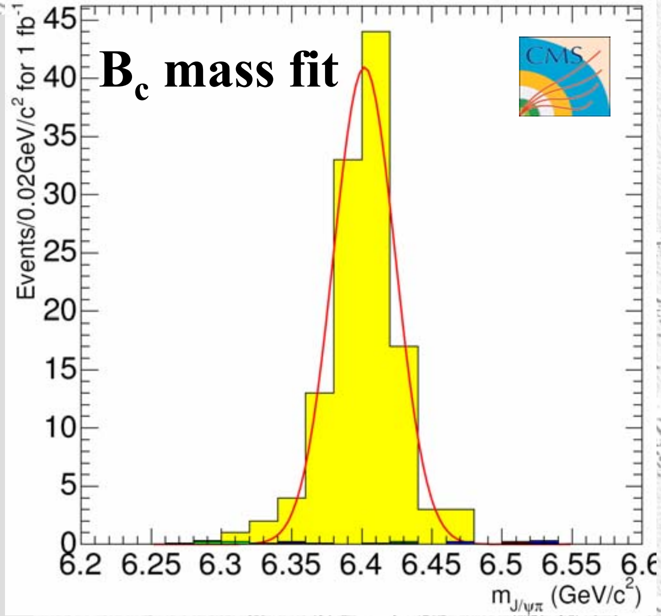
B_c Hadrons

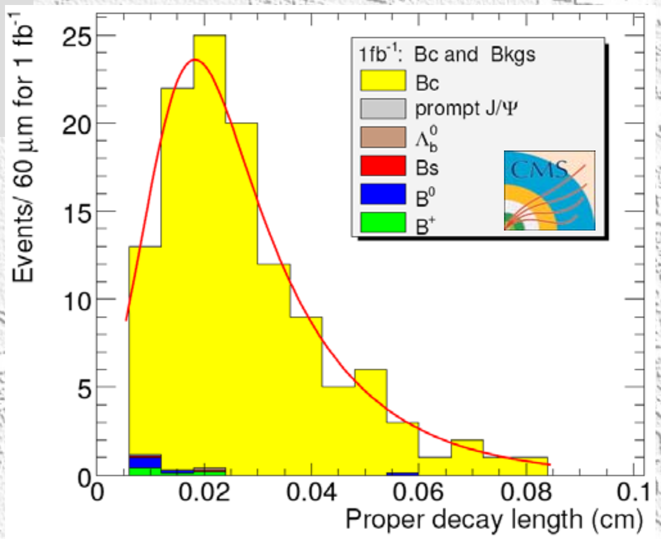
B_c hadrons

- Measurement of mass and lifetime in 1 fb^{-1} integrated luminosity
- $\approx$ 120 events $B_c \rightarrow J/\Psi\pi$ with $J/\Psi \rightarrow \mu\mu$

$\Delta m = 22.0 \pm 14.9$ MeV
$\Delta\tau = 0.044 \pm 0.010$ ps

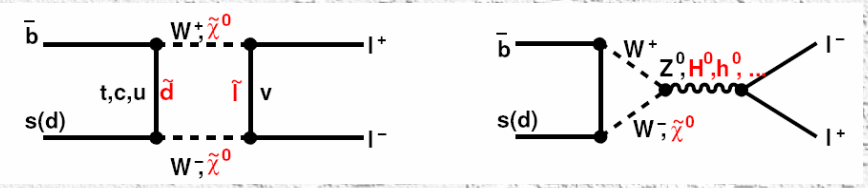
- Need for J/Ψ trigger algorithm





$B_s^0 \to \mu\mu$

- Rare SM process sensitive to New Physics



- CMS study in AN 2006/097
  - 1.6% signal effciency
    → ≈ 6 events in 10 fb^{-1} (SM)
  - $2.7 \cdot 10^{-7}$ bkgd reduction
    → ≈ 48 bkgd events in 10 fb^{-1}
- Expected upper limit

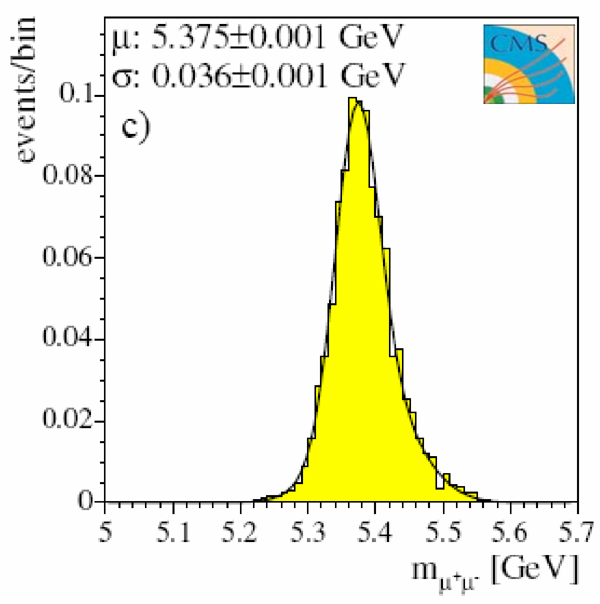
  $BR(B_s^0 \to \mu\mu) < 1.2 \cdot 10^{-8}$

  ≈ 4 times SM expectation

- better bkgd determination from data (sidebands) will improve sensitivity

- SM branching ratio and exp. upper limits

Mode	$B_s^0 \to \mu^+\mu^-$
SM Expect.	$(3.42 \pm 0.54) \times 10^{-9}$
CLEO [2]	-
BELLE [3]	-
CDF [4]	5.8×10^{-7}
D0 [5]	4.1×10^{-7}
BABAR [6]	-
CDF [7]	1.5×10^{-7}



Electroweak Physics (W and Z Bosons)

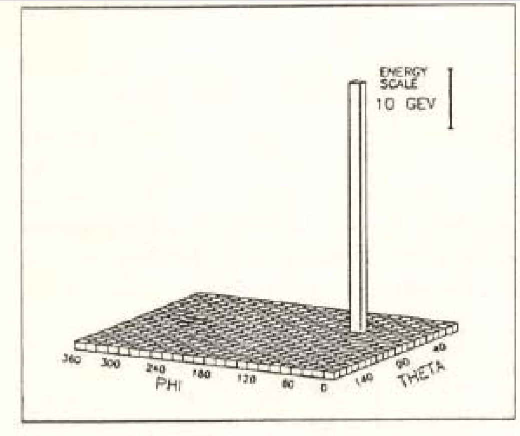
W and Z bosons were discovered in proton-antiproton collisions
1983: UA1 & UA2 at the SppS collider at CERN

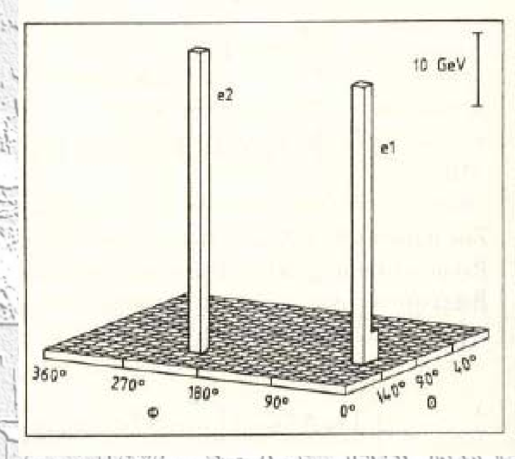
How do W/Z events look like at proton colliders?

Use leptonic decays (electrons & muons)

- **W →lν** — high p_T lepton + missing E_T
- **Z → ll** — 2 oppositely charged, high p_T leptons

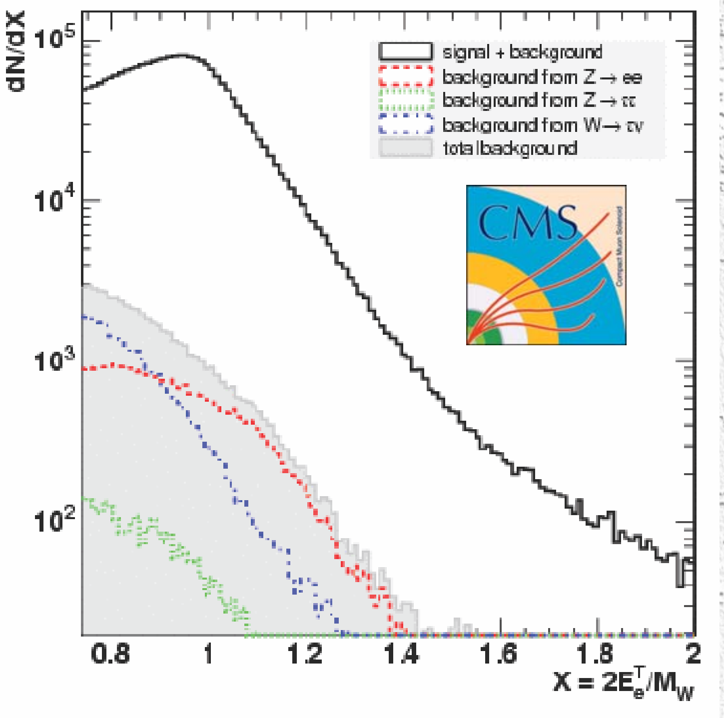
Examples of early W/Z events

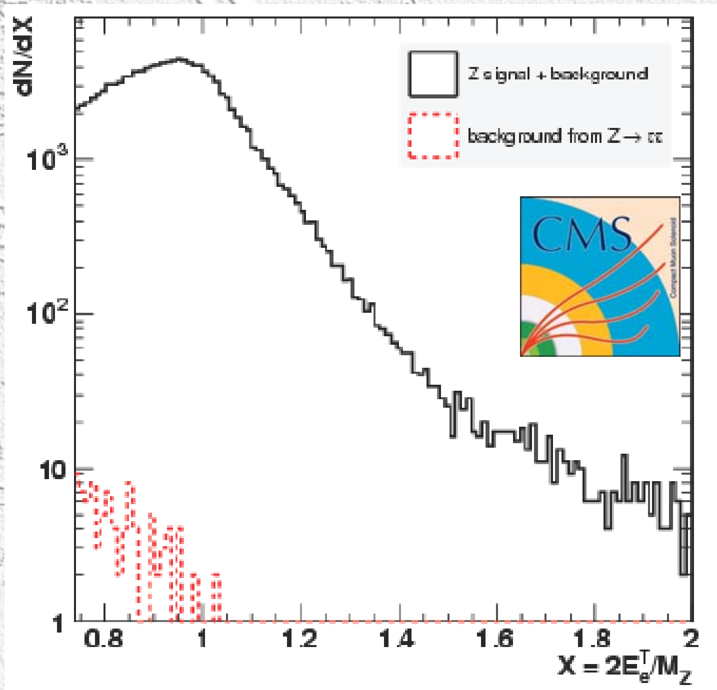




W/Z Physics at the LHC

- **Very clean selection of W and Z boson possible e.g. CMS study of W→ eν and Z → ee**



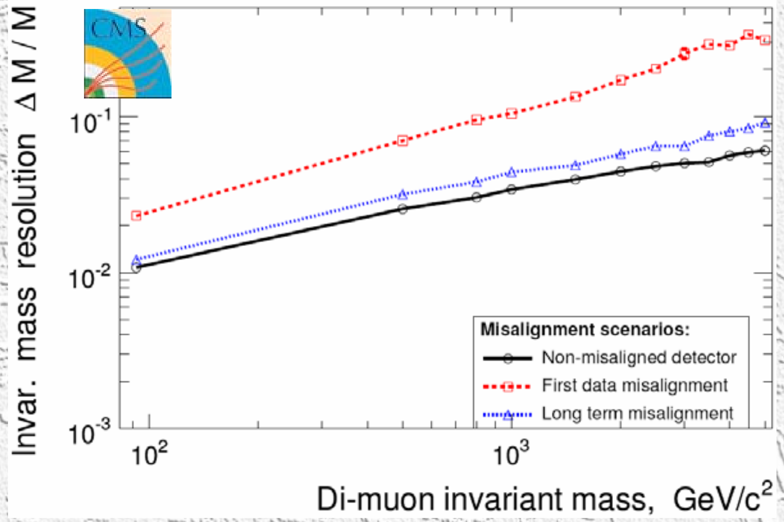


- **Recall rates (initial phase 10^{33}/cm^2/s):**
  ≈ 200 W/s → ≈ 20 W→eν /s
  ≈ 50 Z/s → ≈ 1.5 Z → ee /s
  plus the same rates for muon decays!

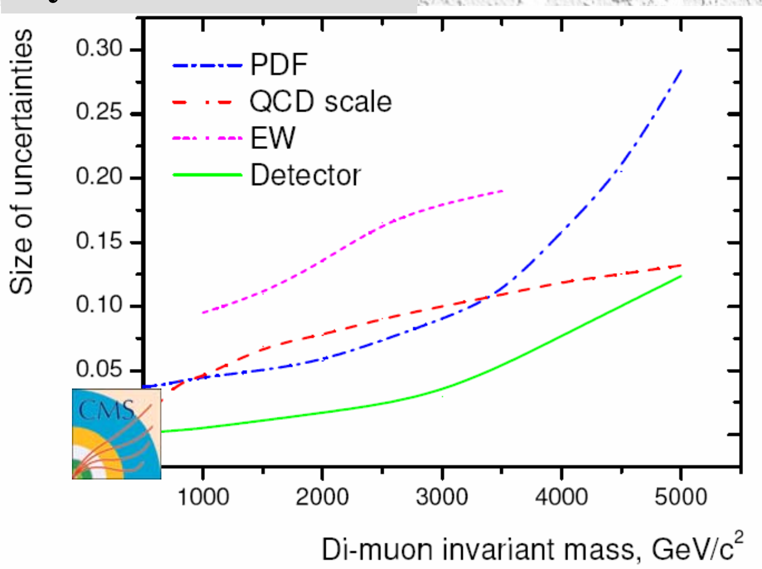
- **W and Z events will provide an excellent tool for detector calibration**

Drell-Yan Muon-Pairs

Goal:
- **measurement of μμ cross section from Z to multi-TeV rgion**
- **asymmetry**
- **constrain PDFs**



Systematic errors:



$M_{\mu^+\mu^-}$, TeV/c^2	Detector smearing	Statistical 1 fb^{-1}	Statistical 10 fb^{-1}	Statistical 100 fb^{-1}	Theor. Syst.
≥ 0.2	$8 \cdot 10^{-4}$	0.025	0.008	0.0026	0.058
≥ 0.5	0.0014	0.11	0.035	0.011	0.037
≥ 1.0	0.0049	0.37	0.11	0.037	0.063
≥ 2.0	0.017		0.56	0.18	0.097
≥ 3.0	0.029			0.64	0.134

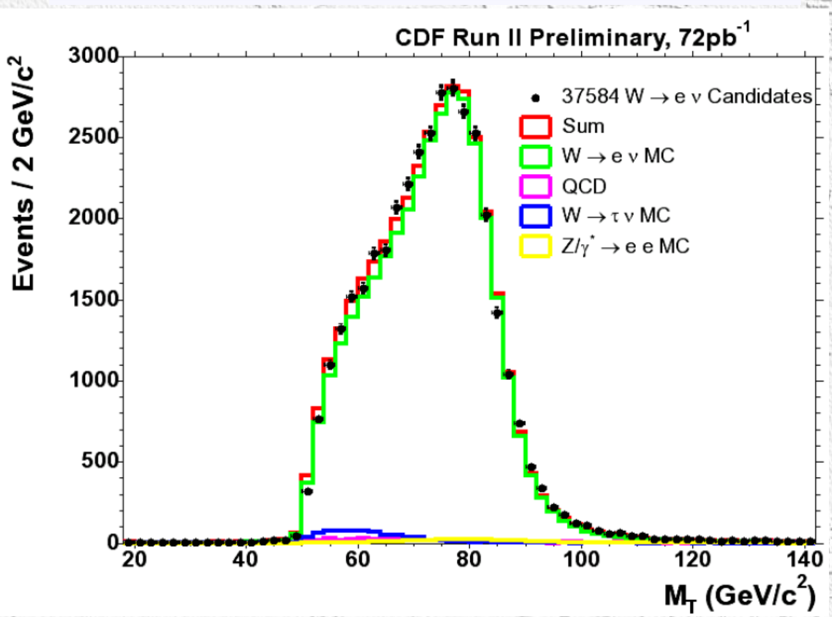
Detector systematics small wrt. to statistics

Mass of the W

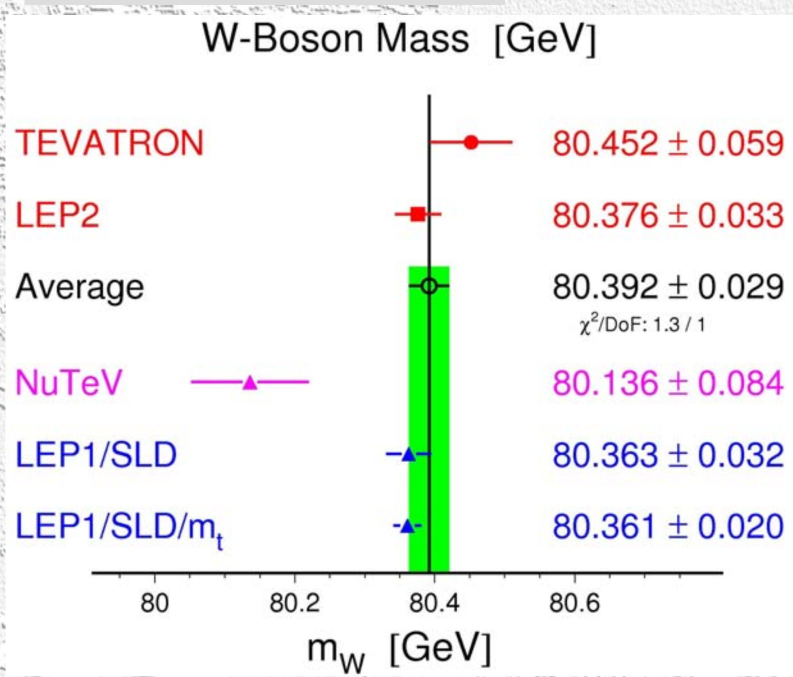
- precision measurement at proton colliders possible
- results competitive to LEP experiments

- define transverse mass from missing E_T

$$M_W^T = \sqrt{2 \cdot P_T^l \cdot P_T^\nu \cdot \left(1 - \cos\Delta\phi^{l,\nu}\right)}$$



Latest results on m_W



- $4 \cdot 10^{-4}$ rel. precision on m_W
- Tevatron results will improve with increasing Run II statistics

- main challenge: electron/muon energy scale
- use $Z \rightarrow ee, \mu\mu$ events and precise m_Z from LEP

W Mass at the LHC

- **Any improvement at the LHC requires control of systematic error to 10^{-4} level**
  - **take advantage from large statistics $Z \to e^+e^-, \mu^+\mu^-$**
  - **most experimental and theoretical uncertainties cancel in W/Z ratio**
    e.g. Scaled Observable Method

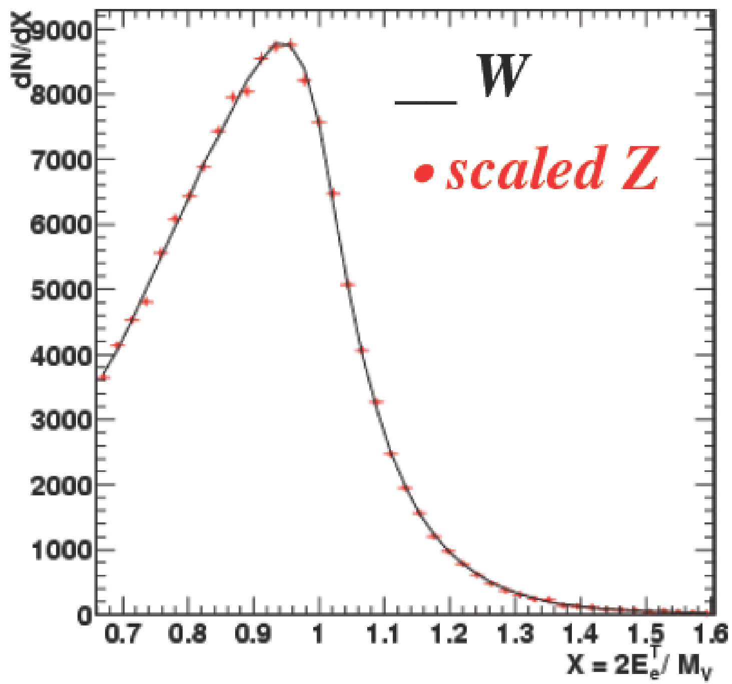
$O_V = E^T, M^T$ distributions are scaled according to

$$\frac{d\sigma^W}{dO_W}(O_W = XM_W) = \frac{M_Z}{M_W} R(X) \frac{d\sigma^Z}{dO_Z}(O_Z = XM_Z)$$

T.Giele, S.Keller, PR D57 (1998)

$$R(X) = \frac{d\sigma^W / dX_W}{d\sigma^Z / dX_Z}$$

- **NNLO calculations (p_T spectra) probably needed to achieve the required precision**



W Mass at the LHC

CMS: detailed study of statistical and systematic errors

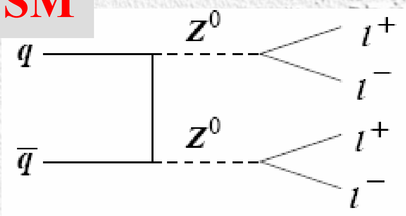
- **1 fb-1: early measurement**
- **10 fb-1: asymptotic reach, best calibrated & understood detector, improved theory etc.**

Source of uncertainty	uncertainty (with 1 fb^{-1})	ΔM_W [MeV/c^2] (with 1 fb^{-1})	uncertainty (with 10 fb^{-1})	ΔM_W [MeV/c^2] (with 10 fb^{-1})
scaled lepton-p_T method applied to W→ $e\nu$				
statistics		40		15
background	10%	10	2%	2
electron energy scale	0.25%	10	0.05%	2
scale linearity	0.00006/ GeV	30	<0.00002/ GeV	<10
energy resolution	8%	5	3%	2
MET scale	2%	15	<1.5%	<10
MET resolution	5%	9	<2.5%	< 5
recoil system	2%	15	<1.5%	<10
total instrumental		**40**		**<20**
PDF uncertainties		20		<10
Γ_W		15		<15
p_T^W		30		30 (or NNLO)
transformation method applied to W→ $\mu\nu$				
statistics		40		15
background	10%	4	2%	negligible
momentum scale	0.1%	14	<0.1%	<10
$1/p^T$ resolution	10%	30	<3%	<10
acceptance definition	η-resol.	19	$< \sigma_\eta$	<10
calorimeter E_T^{miss}, scale	2%	38	≤1%	<20
calorimeter E_T^{miss}, resolution	5%	30	<3%	<18
detector alignment		12	–	negligible
total instrumental		**64**		**<30**
PDF uncertainties		≈20		<10
Γ_W		10		< 10

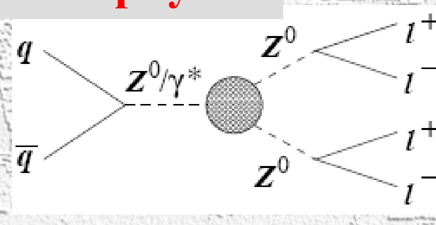
Di-Boson Production at the LHC

- very interesting: WW,WZ,ZZ final states not yet observed at the Tevatron
- test triple gauge boson couplings (TGC)
  - γWW and ZWW precisely fixed in SM
  - γZZ and ZZZ do not exist in SM!

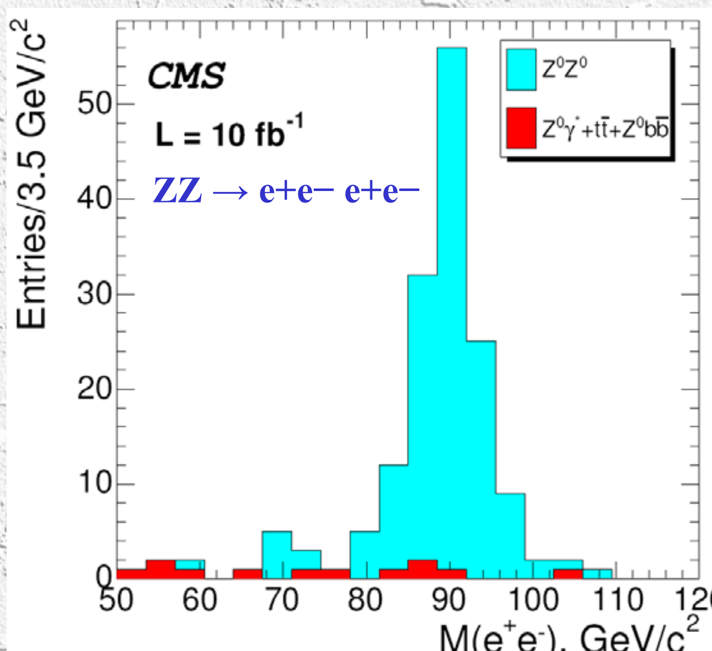
SM

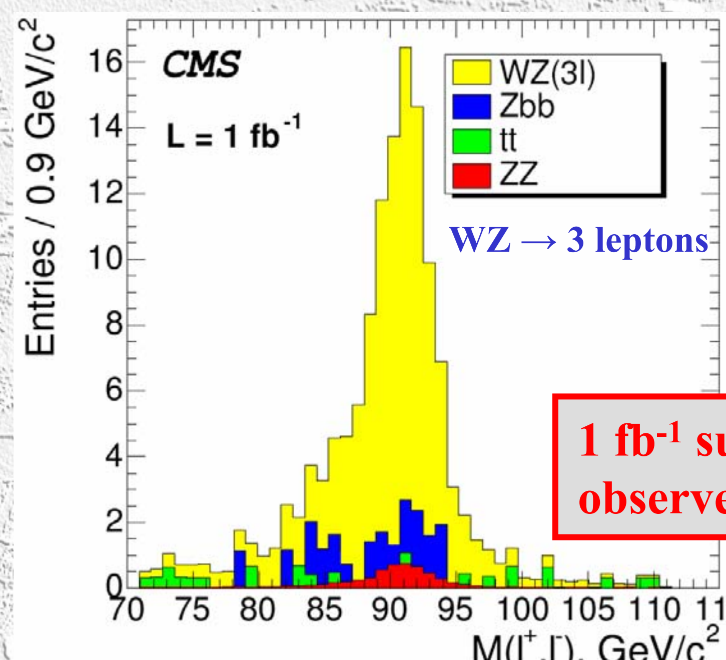


New physics



- deviations from SM are amplified with E
- also Wγ and Zγ final states can be used



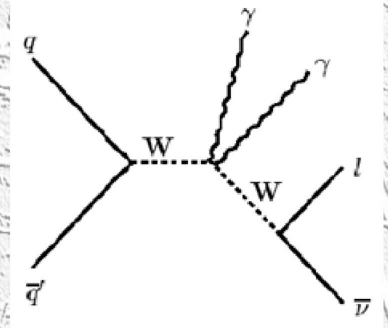


1 fb^{-1} sufficient to observe both processes

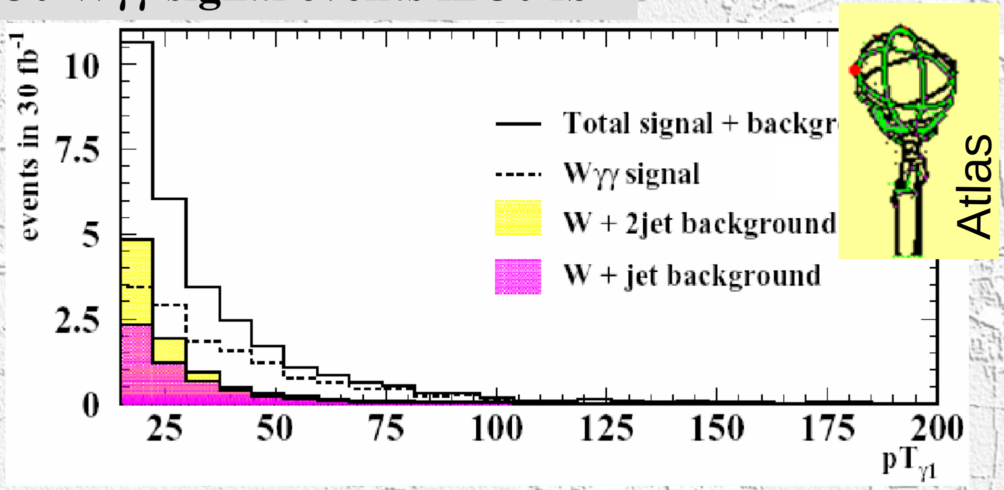
Triple-Boson Production

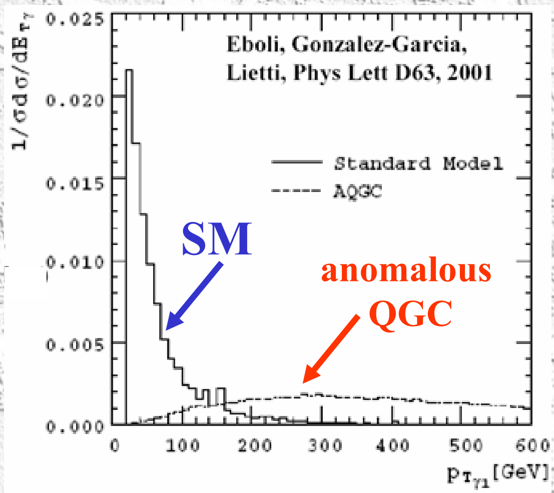
Sensitive to quartic gauge boson couplings (QGC)

Events for 100 fb^{-1} (m_H = 200 GeV)	Produced (no cuts, no BR)	Selected (leptons, p_T > 20 GeV, $\|\eta\| < 3$)
$pp \to WWW$ (3 ν´s)	31925	180
$pp \to WWZ$ (2 ν´s)	20915	32
$pp \to ZZW$	6378	2.7
$pp \to ZZZ$	4883	0.6
$pp \to W\gamma\gamma$	best channel for analysis	

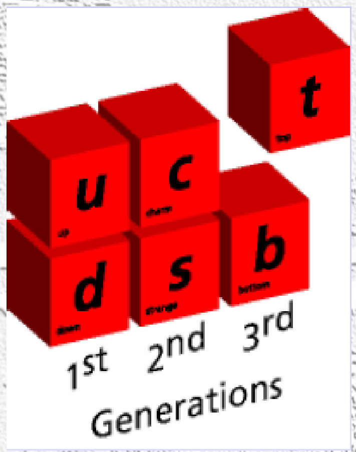


30 Wγγ signal events in 30 fb^{-1}



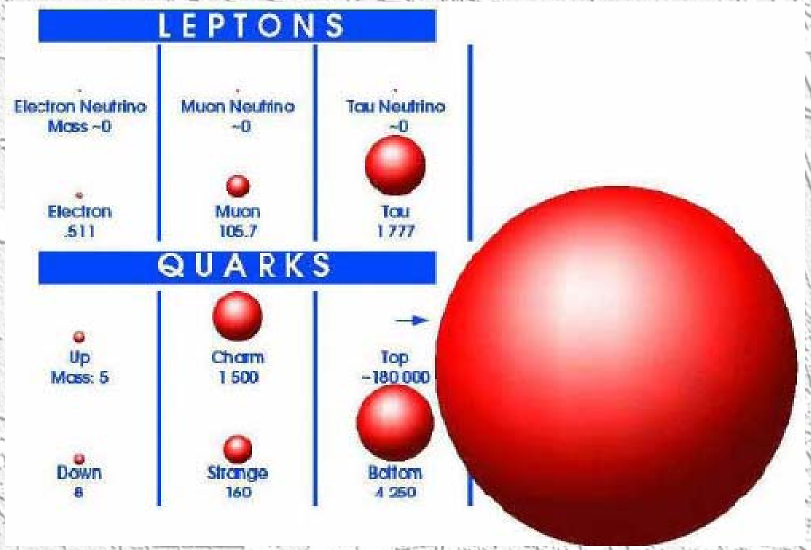


Top Physics



Why is the top quark so interesting special?

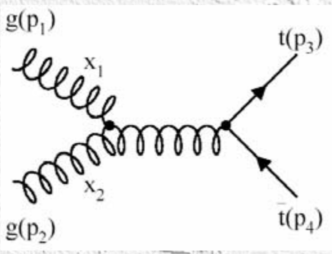
- by far the heaviest fermion
- could provide window to New Physics
  (mass generation)
- discovered 1995 at the Tevatron
  O(100) events observed in Run I
- still we know very little about it (mass)
  would like to measure all other properties
- top has a very short lifetime
  the <u>only</u> quark that decays before forming hadrons
  → can determine spin, polarisation from ist decay products

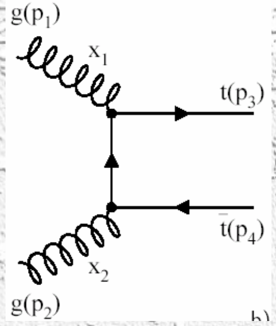


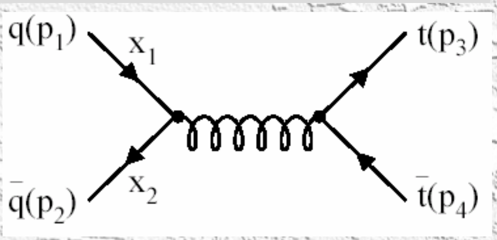
Top Quark Production

Top quarks are mainly produced in pairs (top-antitop) two main mechanisms:

gluon fusion | **quark annihilation**







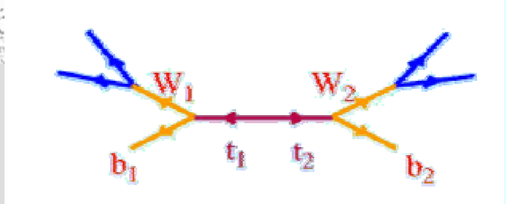
Tevatron: mainly quark annihilation O(90%)
LHC: mainly gluon fusion O(90%)

Cross sections:
≈ 7 pb (Tevatron)
≈ 800 pb (LHC)

→ approx. 1 $t\bar{t}$-pair per second at $10^{33}/cm^2/s$
LHC is a top factory!

Also single top production → Mojtaba

Top Quark Decay

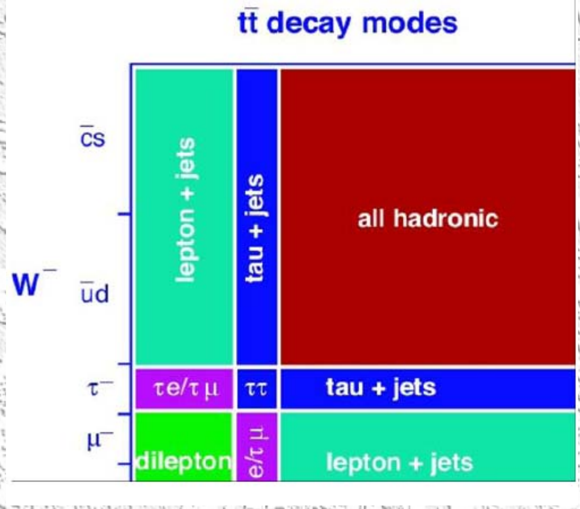


- Top decay: ≈ 100% $t \to bW$
- Other rare SM decays:
  - CKM suppressed $t \to sW$, dW: $10^{-3} - 10^{-4}$ level
  - $t \to bWZ$: $O(10^{-6})$

    difficult, but since $m_t \approx m_b + m_W + m_Z$ sensitive to m_t
- & non-SM decays, e.g. $t \to bH^+$

In SM topologies and branching ratios are fixed:

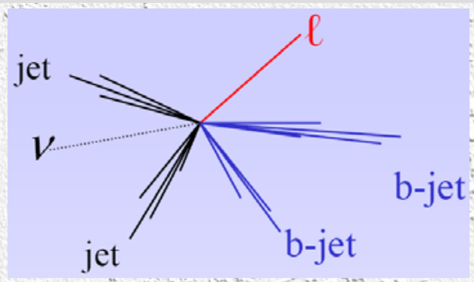
- expect two b-quark jets
- plus W+W- decay products:
  - 2 charged leptons + 2 neutrinos
  - 1 charged lepton + 1 neutrino + 2 jets
  - 4 jets (no b-quark!)



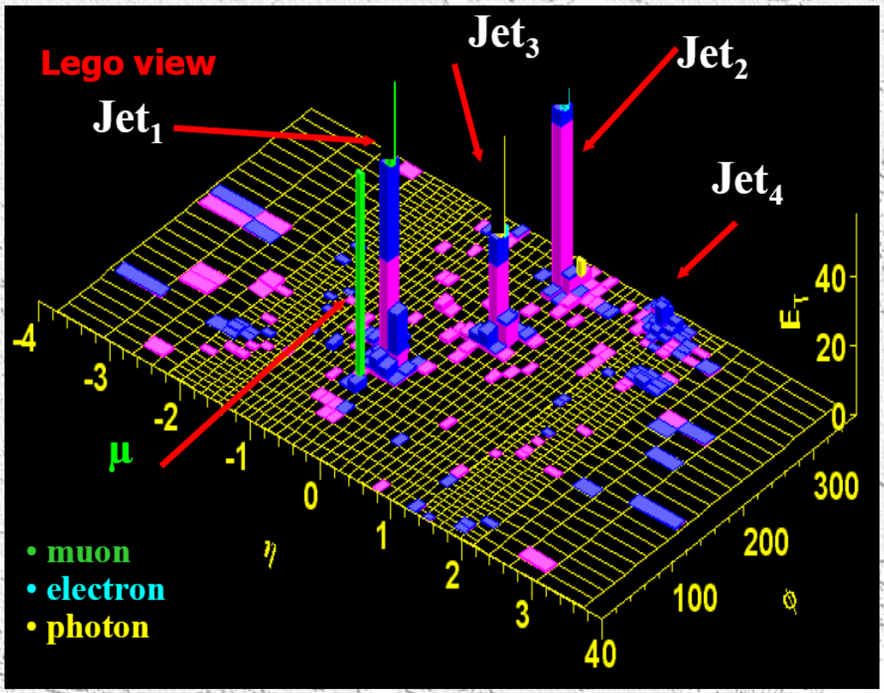
$t\bar{t} \to l\nu l\nu bb$	5%	$(e+\mu)$
$t\bar{t} \to l\nu qqbb$	30%	$(e+\mu)$
$t\bar{t} \to qqqqbb$	46%	

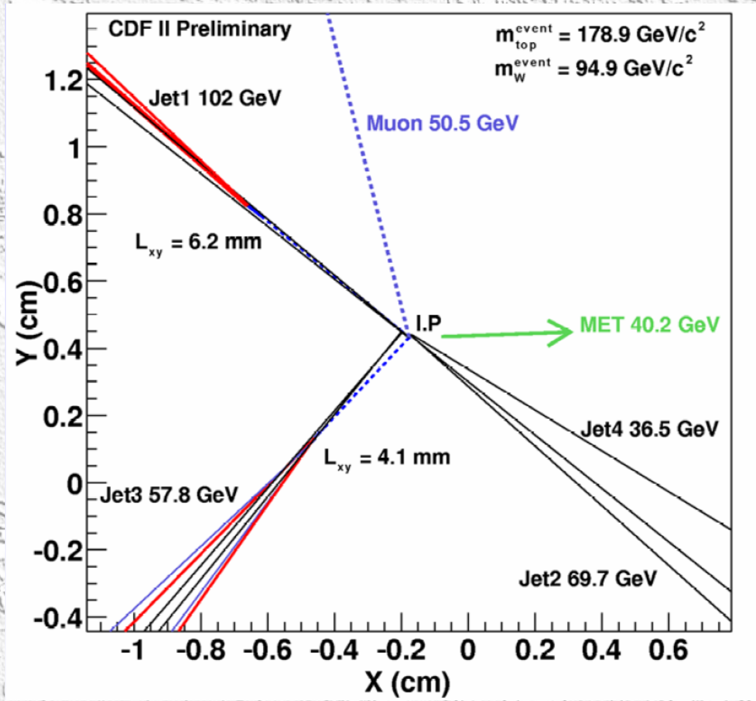
A Top-Pair Event at CDF

- single-lepton channel

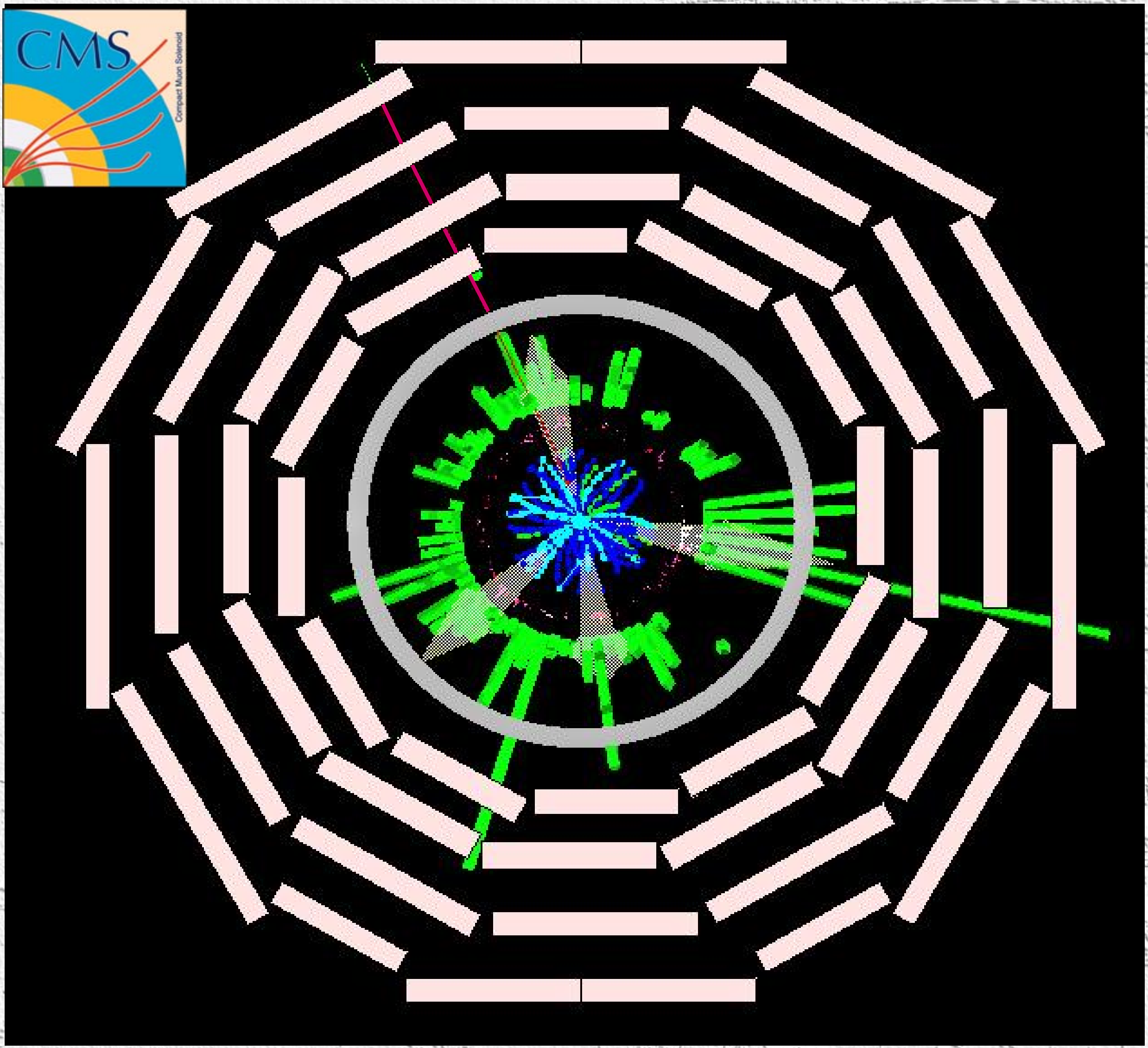


- 1 muon
- 1 neutrino (missing E_T)
- 2 light quark jets
- 2 b-quark jets
  tagged by displaced vertices





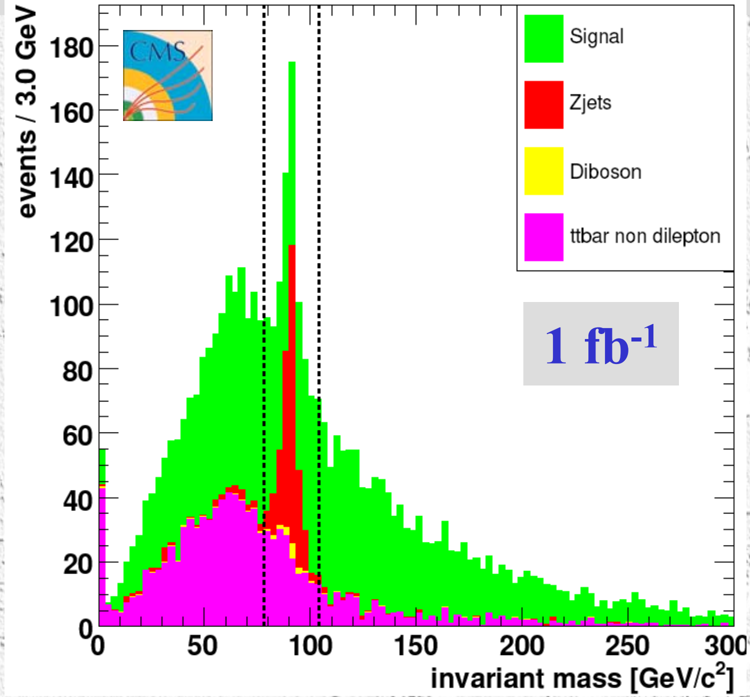
Top Event at CMS



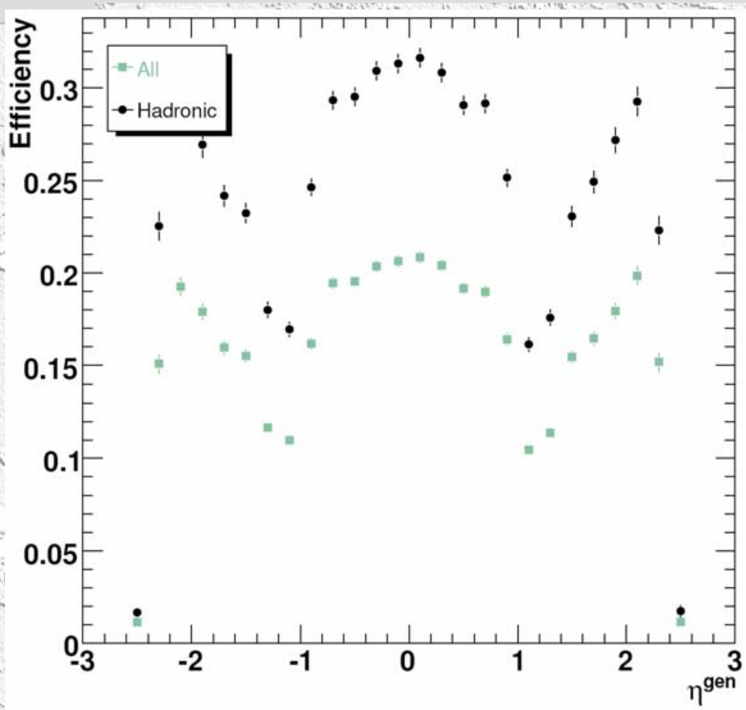
Example of simulated tt → bb qq μν events from CMS

Di-Lepton Channel

- Cleanest channel but lowest BR (11%)
  - signal can be seen < 1 fb^{-1}
  - S/B = 12 achieved (e and μ)
- Kinematic reconstruction
  → mass measurement
- Cross section error ≈ 10%
- Selection e and μ:



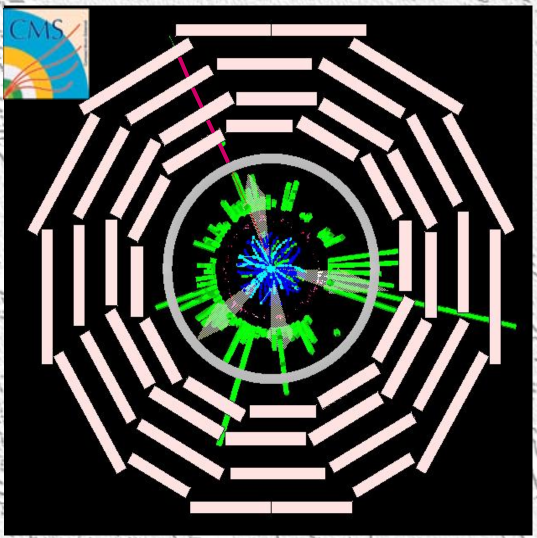
- Study of decays into tau leptons
  tau efficiency

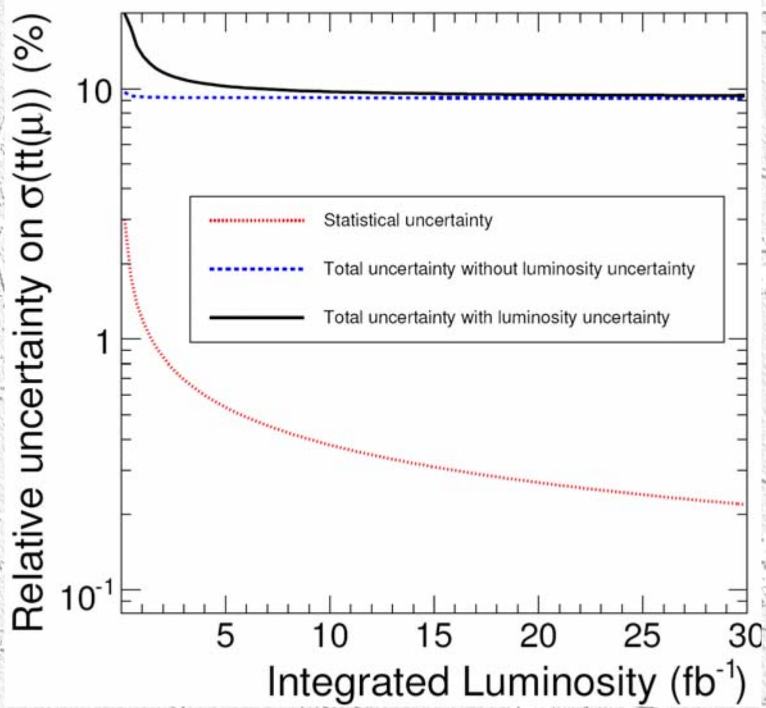


Single-Lepton Channel

- golden channel
- clean signature and large branching ratio < 4% non-ttbar bkgd

μ channel
tt→bbqqμν





	$\Delta\hat{\sigma}_{t\bar{t}(\mu)}/\hat{\sigma}_{t\bar{t}(\mu)}$		
	1 fb^{-1}	5 fb^{-1}	10 fb^{-1}
Simulation samples (ϵ_{sim})		0.6%	
Simulation samples (F_{sim})		0.2%	
Pile-Up (30% On-Off)		3.2%	
Underlying Event		0.8%	
Jet Energy Scale (light quarks) (2%)		1.6%	
Jet Energy Scale (heavy quarks) (2%)		1.6%	
Radiation (Λ_{QCD}, Q_0^2)		2.6%	
Fragmentation (Lund b, σ_q)		1.0%	
b-tagging (5%)		7.0%	
Parton Density Functions		3.4%	
Background level		0.9%	
Integrated luminosity	10%	5%	3%
Statistical Uncertainty	1.2%	0.6%	0.4%
Total Systematic Uncertainty	13.6%	10.5%	9.7%
Total Uncertainty	13.7%	10.5%	9.7%

- Cross section error ≈ 10%

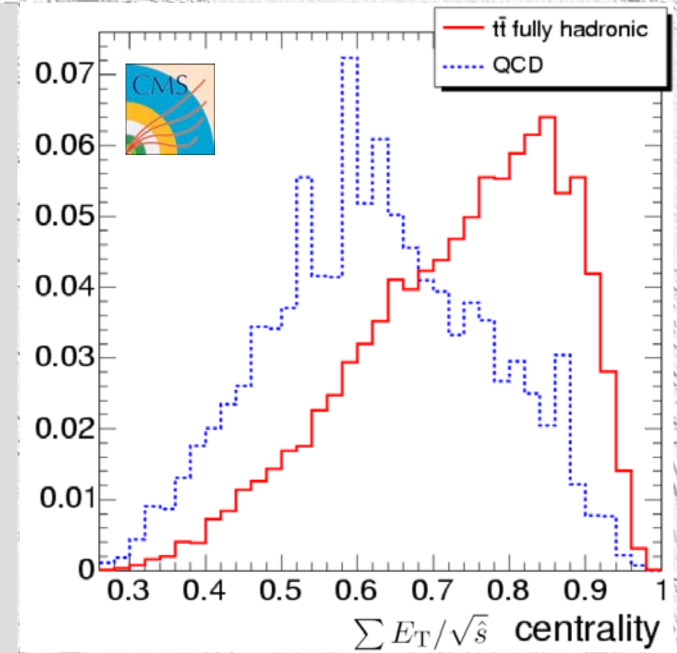
Fully Hadronic Channel

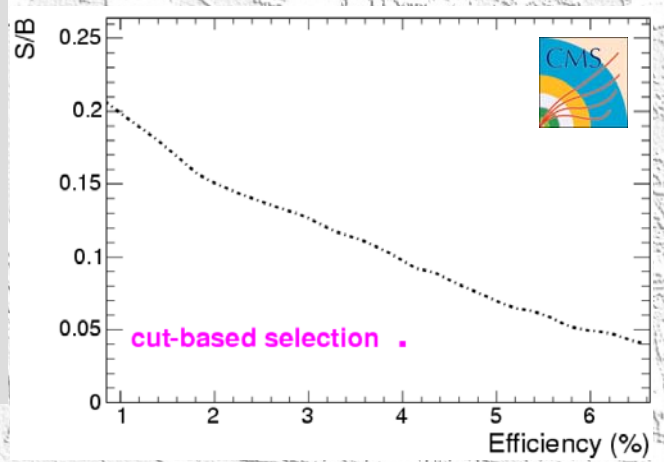
- $t\bar{t} \rightarrow b\bar{b}$ qqqq
- well defined final state with ≥ 6 jets
- enormous QCD background

- Need special trigger scheme, e.g. CMS
  - optimised E_T thresholds
  - pixel b/tag
  - 17% signal efficiency
  - S/B ≈ 1/300

- selection based on kinematic variables e.g. centrality
  - simple cut-based
  - and NN selection

- Cross section measurement to ≈ 20%

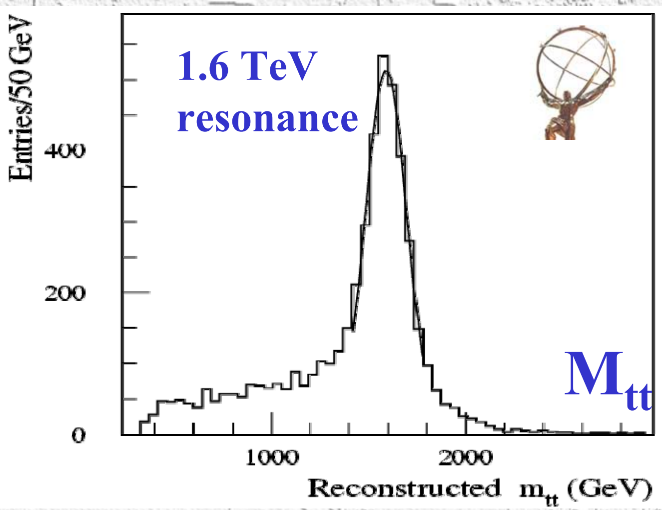


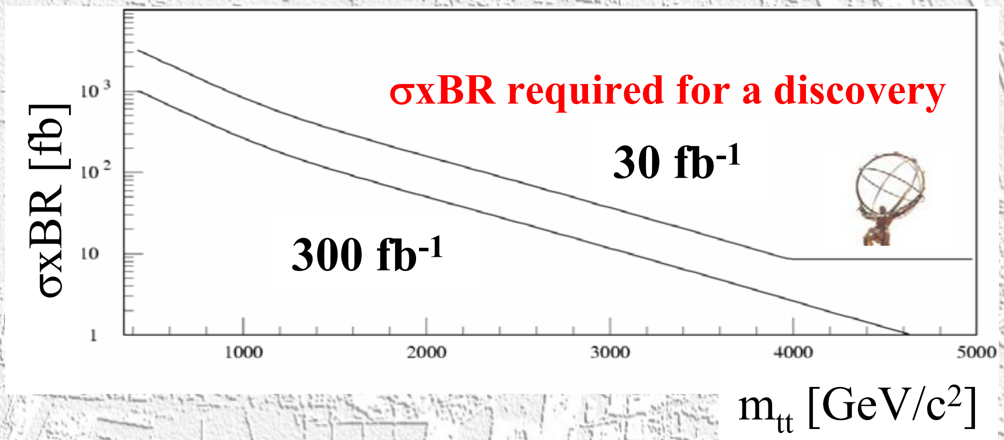


Top-Pair Cross Section

- Total cross section:
  - At 14 TeV interesting in itself
  - Sensitive to top mass $\sigma_{tt} \propto 1/m_t^2$

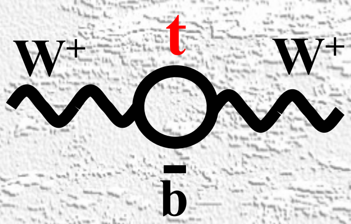
- Differential cross sections:
  - $d\sigma/dp_T$ checks pdf
  - $d\sigma/d\eta$ checks pdf
  - $d\sigma/dm_{tt}$ sensitive to production of heavy object decaying to top-pairs $X \rightarrow tt$





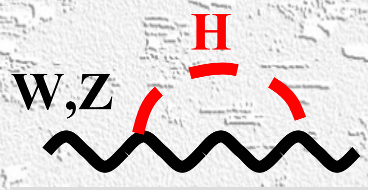
Importance of Top Mass

- m_t enters quadratically in electroweak loop corrections

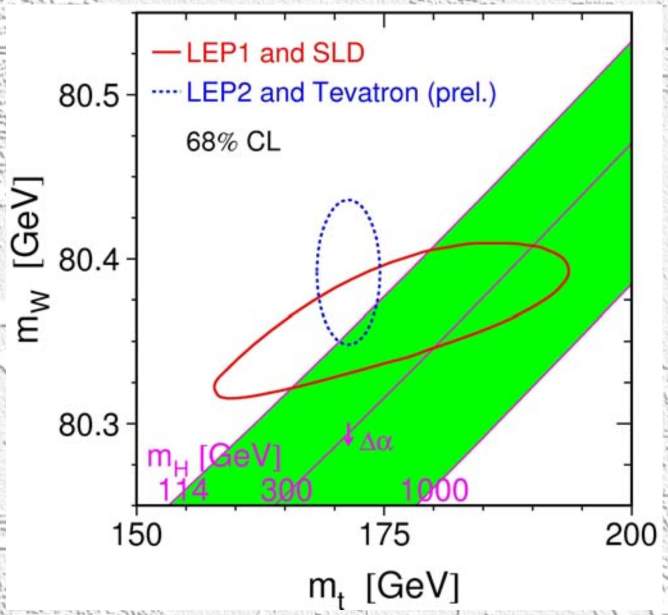


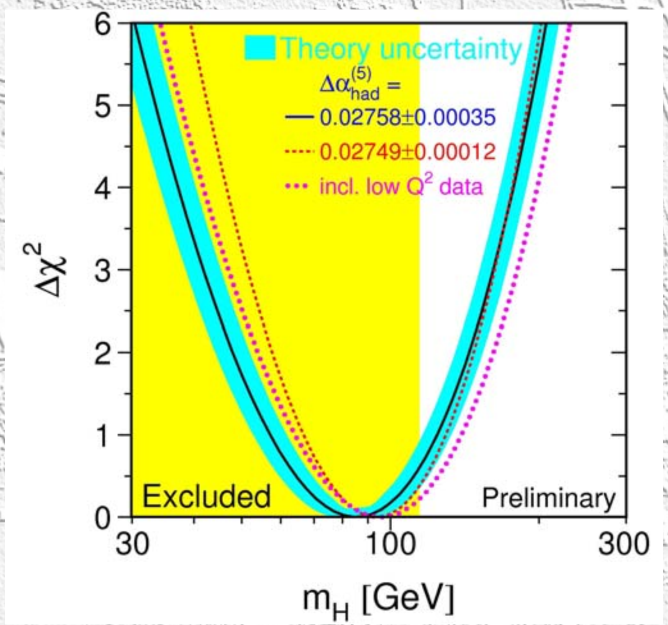
$\propto (m_t^2 - m_b^2)$

- m_H only logarithmically



$\propto \log m_H/m_W$





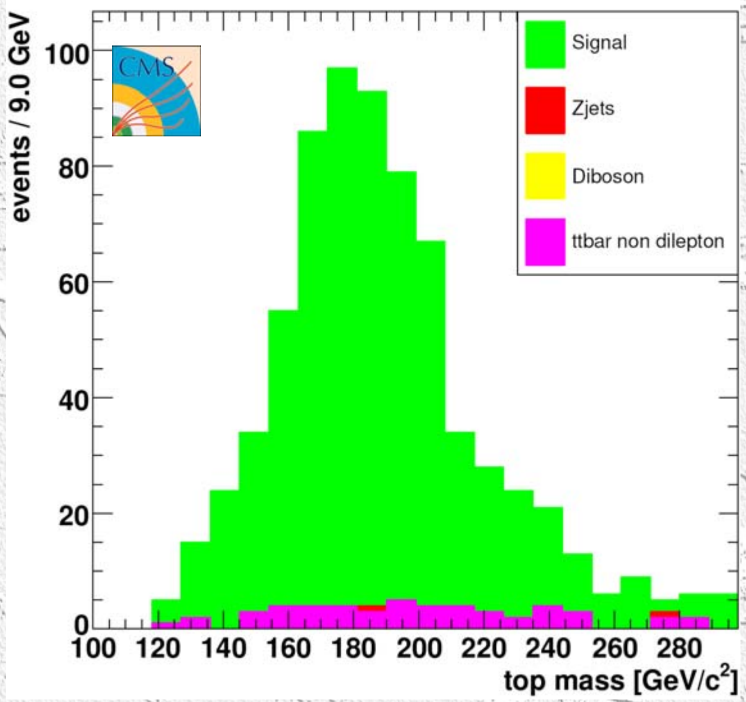
All observables include the combined effect!

→ m_t plays a key role in precision test of the SM
- to predict the Higgs mass
- and once the Higgs is discovered to check the consistency of the model

Measurement of the Top Mass

- di-lepton channel
  - kinematically underconstraint
  - use m_W, assume m_t and try to solve kinematics
  - weight solutions with SM neutrino spectrum

  → distribution of most likely solutions



main systematics: b-jet E scale

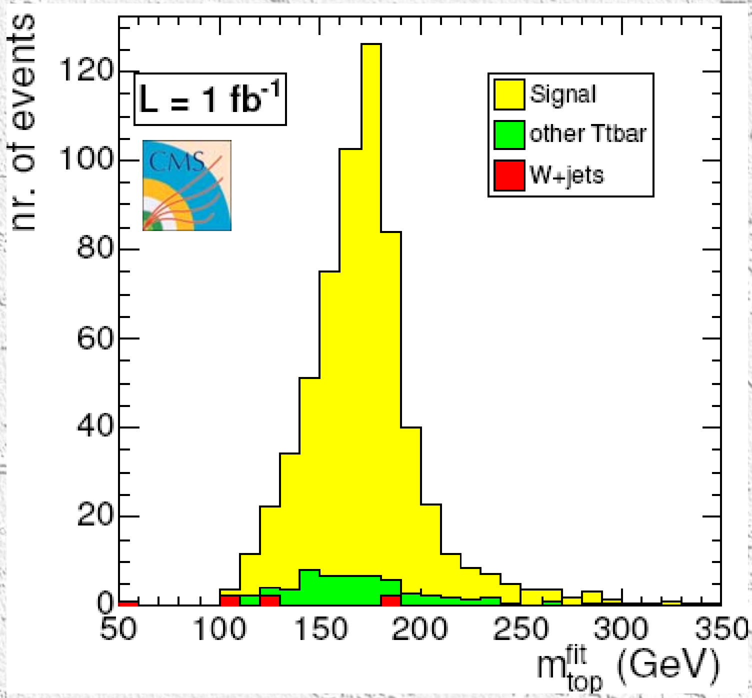
1 fb^{-1}: Δm_t = 1.5 GeV + 4.5 GeV
10 fb^{-1}: Δm_t = 0.5 GeV + 1.1 GeV

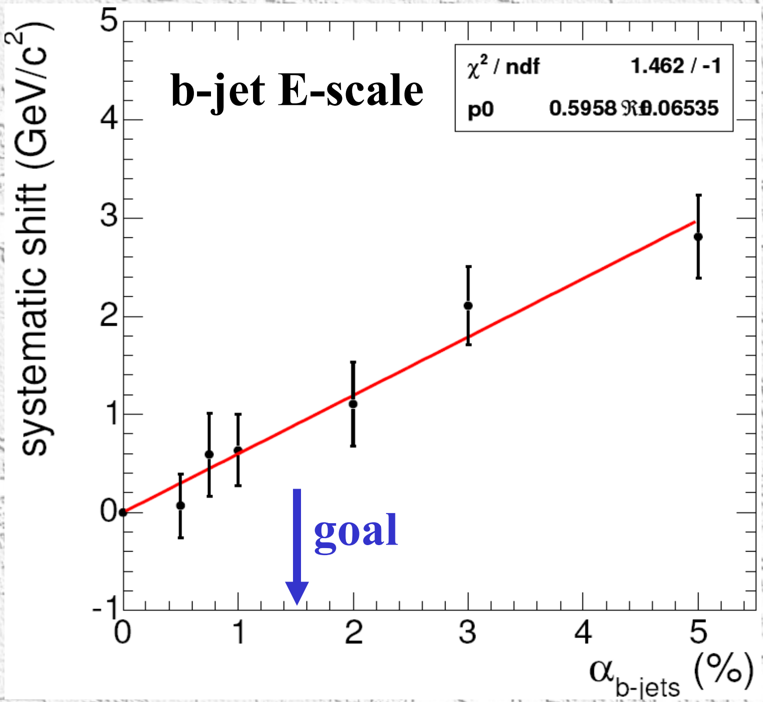
Measurement of the Top Mass

- single-lepton channel
  - sophisticated ideogramm method developed
  - self-calibrating using m_W constraint
  - reduced bias and sys error

- study of systematic errors:

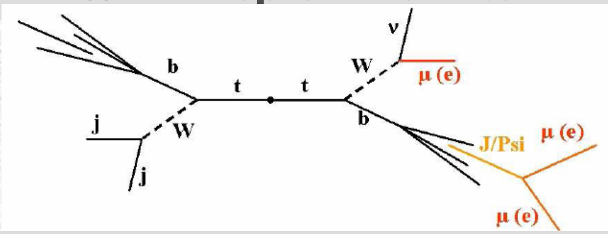
	Standard Selection Gaussian Fit Δm_t (GeV/c^2)	Gaussian Ideogram Δm_t (GeV/c^2)	Full Scan Ideogram Δm_t (GeV/c^2)
Pile-Up (5%)	0.32	0.23	0.21
Underlying Event	0.50	0.35	0.25
Jet Energy Scale (1.5%)	2.90	1.05	0.96
Radiation (Λ_{QCD}, Q_0^2)	0.80	0.27	0.22
Fragmentation (Lund b, σ_q)	0.40	0.40	0.30
b-tagging (2%)	0.80	0.20	0.18
Background	0.30	0.25	0.25
Parton Density Functions	0.12	0.10	0.08
Total Systematical uncertainty	3.21	1.27	1.13
Statistical Uncertainty (10 fb^{-1})	0.32	0.36	0.21
Total Uncertainty	3.23	1.32	1.15



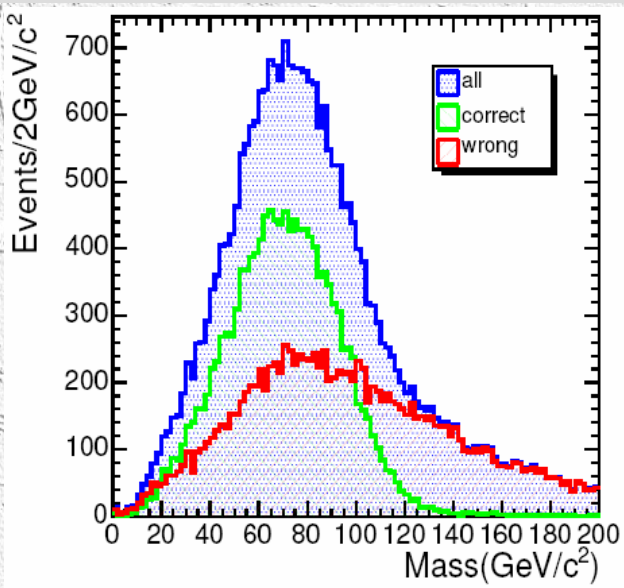


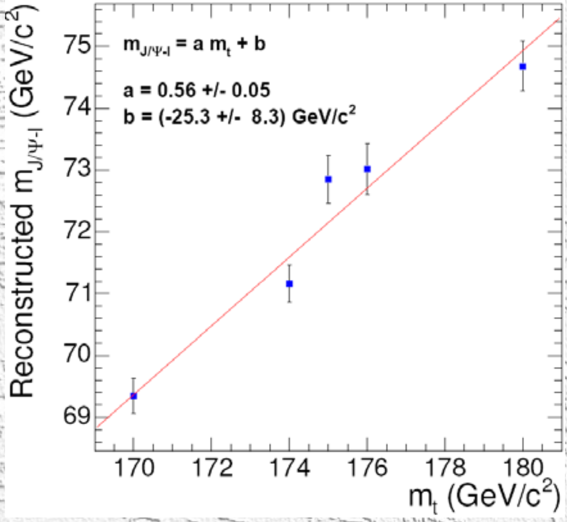
Measurement of the Top Mass

- **exclusive t → J/Ψ + X decays**
  - **partial reconstruction of J/ Ψ + lepton from W**



- **low statistics, but different systematics**
  - **only leptons, no jets**
  - **theory is important**





Source	δm_t (GeV/c²)
Λ_{QCD}	0.31
Q^2	0.56
Scale definition	0.71
b-quark fragmentation	0.51
Light jet fragmentation	0.46
Minimum bias/Underlying event	0.64
Proton PDF	0.28
Total theoretical	1.37
Electron E scale	0.21
Muon p scale	0.38
Electron E resolution	0.19
Muon p resolution	0.12
Jet E scale	0.05
Jet E resolution	0.05
Background knowledge	0.21
Total experimental	0.54
Total systematic	1.47

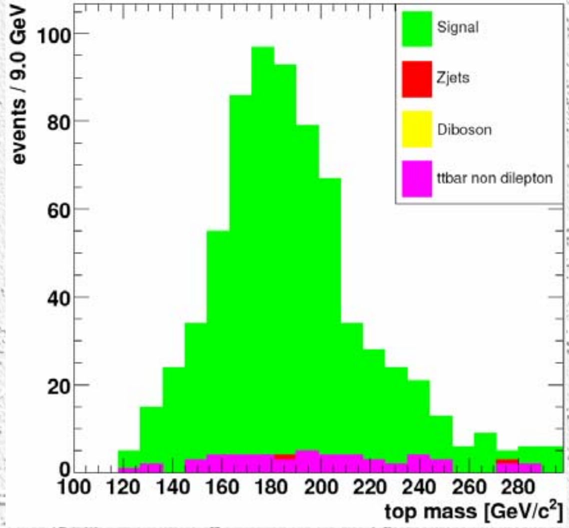
- **± 0.8 GeV (stat) ± 1.5 GeV with 20 fb^{-1} achievable**

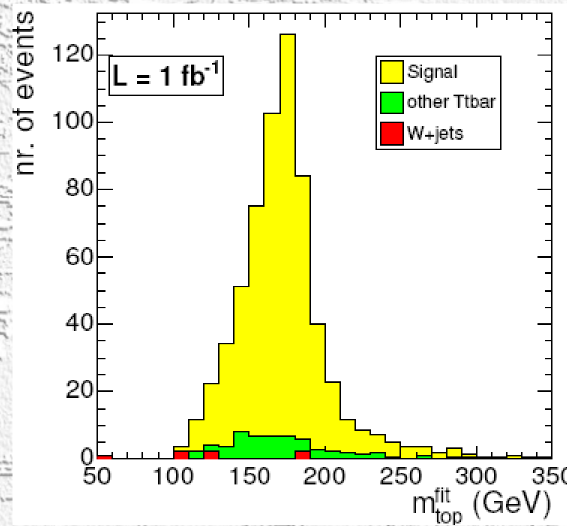
Top Mass with CMS

Recent detailed studies by CMS:

di-leptonic

± 1.2 GeV



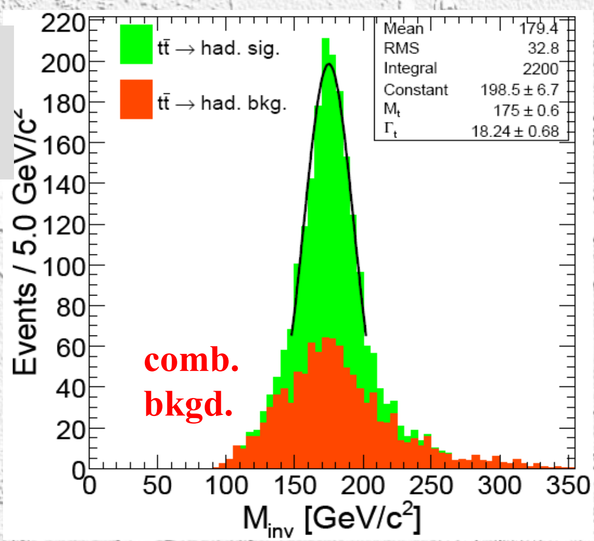


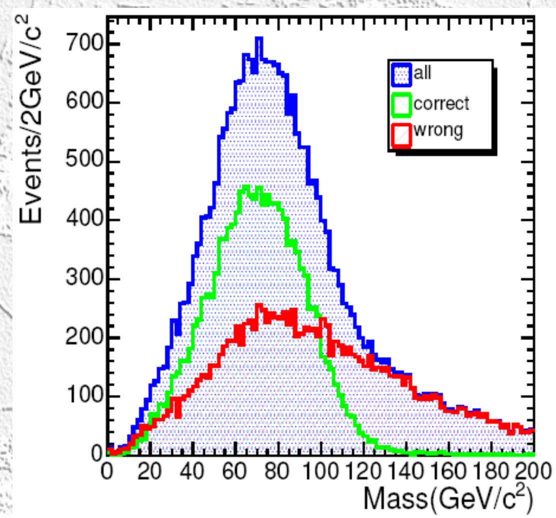
semi-leptonic

± 1.2 GeV

fully hadronic

± 2 GeV





t→ J/Ψ + l + X

± 1.5 Ge

→ total top mass error ≤ 1 GeV possible with O(10 fb⁻¹) of well understood data

Spin Correlation in Top-Pair Production

**Top: Very short lifetime,
no top bound states**

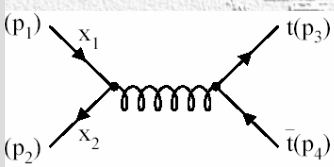
⇒ Spin info not diluted

Definition spin correlation:

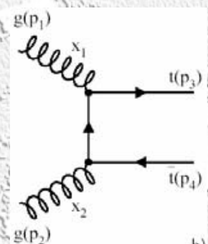
$$\mathcal{A} = \frac{N_{\|} - N_X}{N_{\|} + N_X} = \frac{N(t_L\bar{t}_L + t_R\bar{t}_R) - N(t_L\bar{t}_R + t_R\bar{t}_L)}{N(t_L\bar{t}_L + t_R\bar{t}_R) + N(t_L\bar{t}_R + t_R\bar{t}_L)}$$

Distinguishes

- **quark annih.**
  A = -0.469



- **and gluon fusion**
  A = +0.431

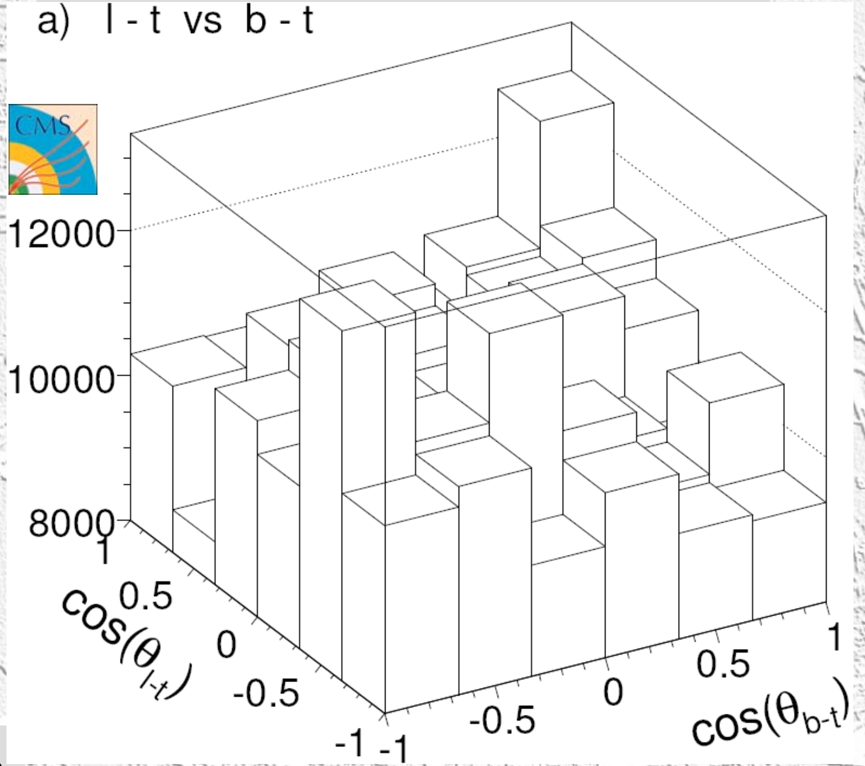


Measure in double diff. distribution

$$\frac{1}{N}\frac{d^2N}{d\cos\theta_l \, d\cos\theta_q} = \frac{1}{4}(1 - \mathcal{A}\kappa_l\kappa_q \cos\theta_l \cos\theta_q)$$

Results:

- **semi-leptonic channel**
- **two angular correlations, e.g.**



$$\mathcal{A}_{b-t\,l-t} = 0.375 \pm 0.027\,(\text{stat.})^{+0.055}_{-0.084}\,(\text{syst.})$$
$$\mathcal{A}_{q-t\,l-t} = 0.346 \pm 0.021\,(\text{stat.})^{+0.026}_{-0.055}\,(\text{syst.})$$

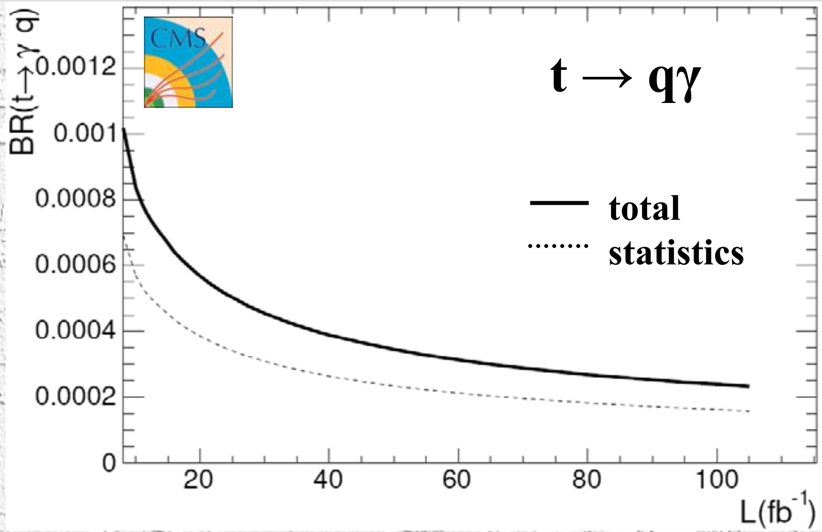
FCNC in Top Decays

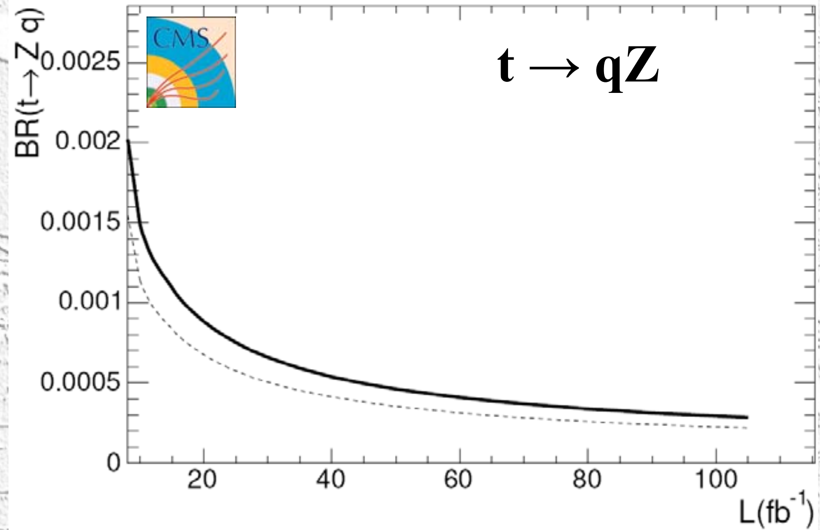
Top decay in SM: ≈ 100% t → bW
FCNC decays: t → qZ, qγ (or qg)

Decay	SM	two-Higgs	SUSY with $R\!\!\!/$	Exotic Quarks	Exper. Limits(95% CL)
$t \to gq$	5×10^{-11}	$\sim 10^{-5}$	$\sim 10^{-3}$	$\sim 5 \times 10^{-4}$	< 0.29 (CDF+TH)
$t \to \gamma q$	5×10^{-13}	$\sim 10^{-7}$	$\sim 10^{-5}$	$\sim 10^{-5}$	< 0.0059 (HERA)
$t \to Zq$	$\sim 10^{-13}$	$\sim 10^{-6}$	$\sim 10^{-4}$	$\sim 10^{-2}$	< 0.14 (LEP-2)

- **use top pairs**
- **select a SM decaying top and jet + Z (or γ)**
- **SM top pairs are main background**

Result: FCNC signals detectable at 5 σ





Summary & Conclusions

- Experiments at the LHC will soon explore the highest energy frontier
  - for discoveries of new particles and phenomena
  - for precision meaurements

- CMS is well on track for start-up in 2008
- Preparation of physics analyses in full swing

- Many opportunities for SM physics at the LHC
  Precisions measurements already in low luminosity phase
  - QCD & jet physics
  - W/Z production, e.g. W mass
  - Di-boson production
  - Top physics, e.g. top mass
  - Discoveries: Higgs, SUSY & the unexpected

Very exciting times are ahead of us!

Backup

Challenges for the LHC

- Superconducting dipole magnets to keep 7 TeV protons on circular path (r ≈ 3 km)

  |B| = 8.33 Tesla

- 1232 dipole magnets are needed
  (+ quadrupole, sextupoles etc.)
  each dipole is 15 m long

- 1.9 K operating temperature
  supraliquid He
  largest cyrogenic facility in the world

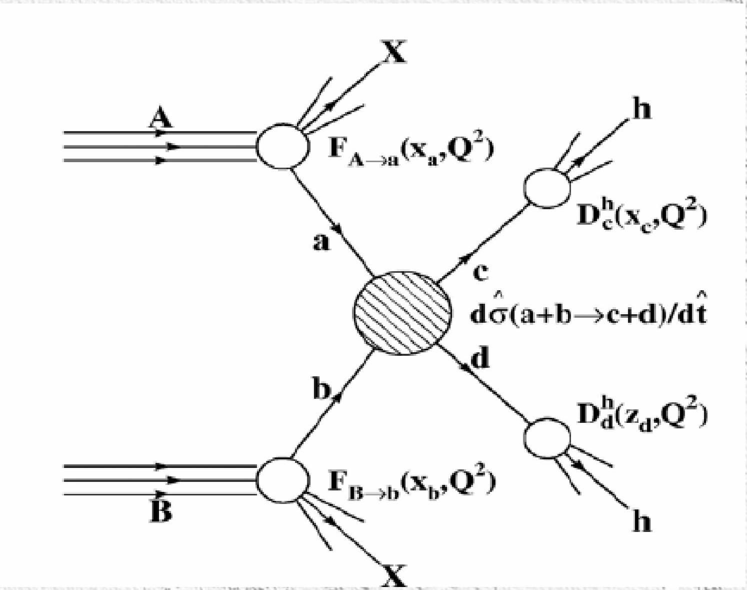
- Quench protection
  stored energy in one dipole: 8 MJ

  corresponds to a
  40 t truck at 50 km/h!

- LHC dipole design
  incoporates reversed field for oppositely rotating proton beam

BTW:
the stored energy in the LHC proton beams is 350 MJ
enough to melt 500 kg of copper!

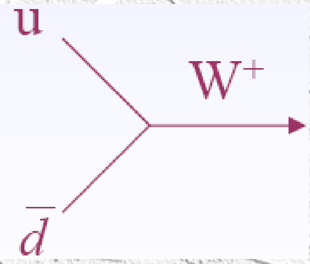
Cross Section Calculation



$$\sigma = \sum_{a,b} \int dx_a\, dx_b\, f_a(x_a, Q^2)\, f_b(x_b, Q^2)\, \hat{\sigma}_{ab}(x_a, x_b)$$

- **sum over initial states a,b**
- **$f_i(x_i,Q^2)$ = parton density functions**

- **Example: W production in leading order**



$\sigma(pp\rightarrow W) \approx 150$ nb $\approx 2\cdot10^{-6}\,\sigma_{tot}$

Luminosity

Rate of produced events for a given process

$$N = \sigma L$$

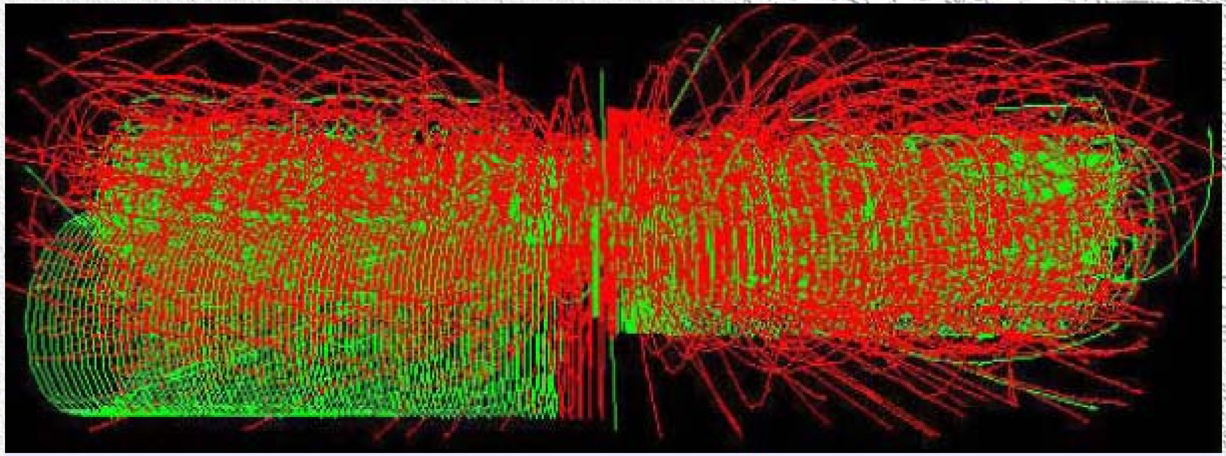
σ cross section [barn $= 10^{-24}$ cm^2]
L luminosity [1/cm^2/s]

- luminosity depends on machine parameters:
  number of protons stored, beam focus at the interaction point, …
- luminosity should be high to achieve acceptable rates for rare processes

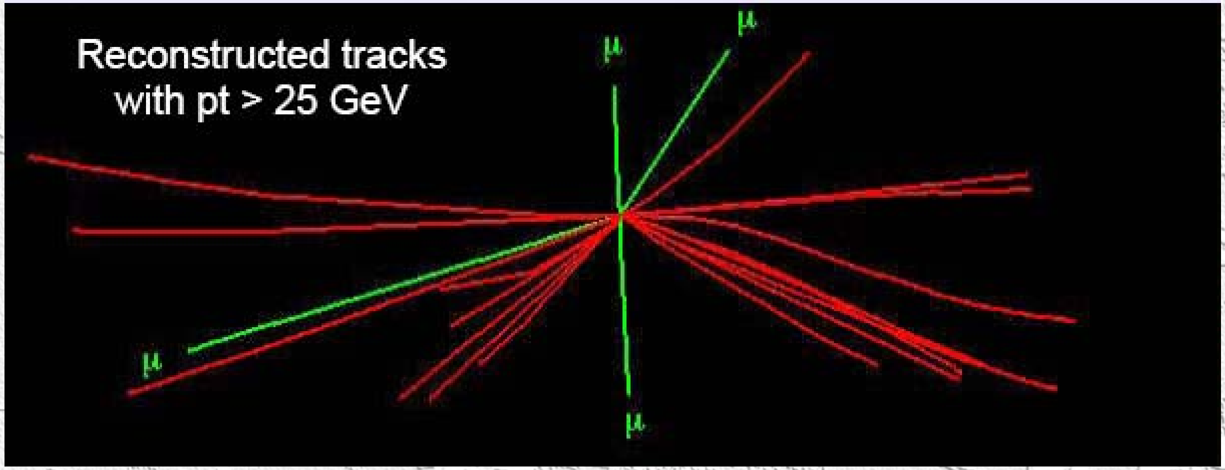
Comparison of colliders:
- 10^{31}/cm^2/s LEP
- $2 \cdot 10^{32}$/cm^2/s Tevatron Run II design
- 10^{33}/cm^2/s LHC initial phase (≈ 3 years)
- 10^{34}/cm^2/s LHC design luminosity (> 2010)

1 experimental year is about 10^7 s
- 10 fb^{-1} per year in the initial LHC phase
- 100 fb^{-1} per year later

Suppression of Background



with 25 pile-up events



removing tracks with $p_T < 25$ GeV

- requires high granularity (many channels)
- good position, momentum and energy resolution

Status of ATLAS

Major structures assembled underground

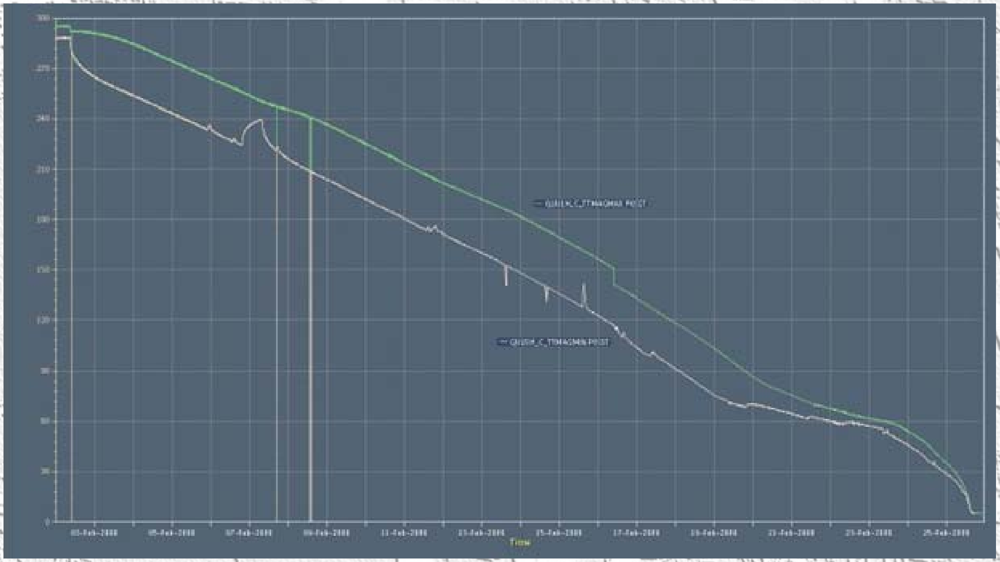
August 2005: 8/8 toroid coils installed

Status of CMS

Major structures assembled on surface
Detector slices to be lowered in cavern

September 2005: coil inserted in yoke

Coil cooled down to 4.5°K February 2006



Large fraction of muon chambers installed

Comparison of ATLAS and CMS

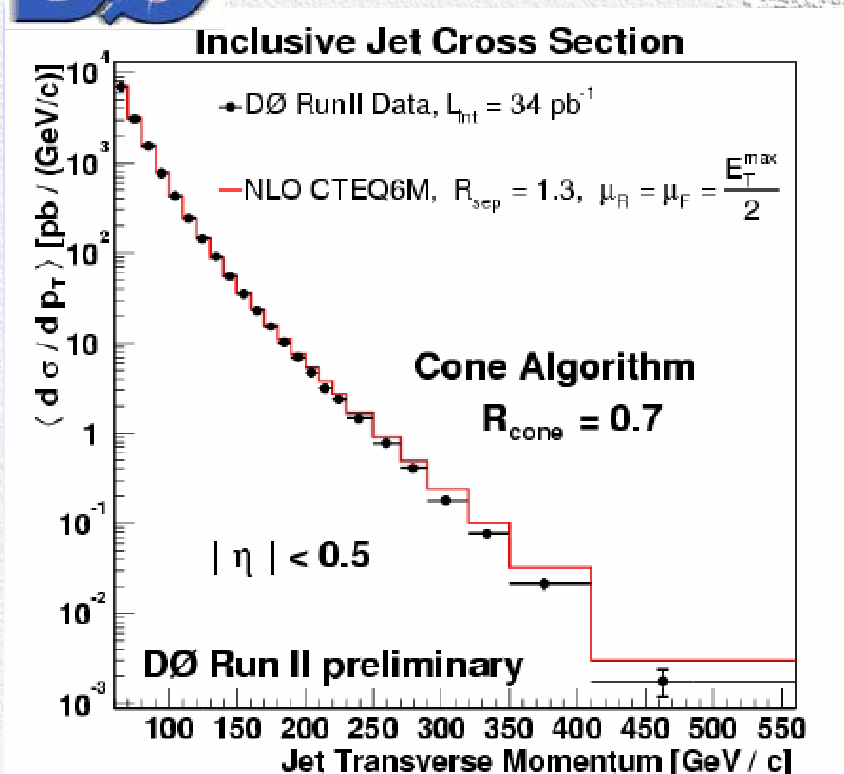
Physics performance:
comparison in terms of mass resolutions

Table 8
Mass resolution for various states in the different experiments (at a luminosity of 2×10^{33} cm^{-2} s^{-1} in the case of ATLAS and CMS)

	ATLAS (GeV c^{-2})	CMS (GeV c^{-2})	LHCb (GeV c^{-2})	ALICE (GeV c^{-2})
$B \to \pi\pi$	0.070	0.031	0.017	—
$B \to J/\psi K^0_S$	0.019	0.016	0.010	—
$Y \to \mu\mu$	0.152	0.050	—	0.107
$H(130\,\text{GeV}\,c^{-2}) \to \gamma\gamma$	1.55	0.90	—	—
$H(150\,\text{GeV}\,c^{-2}) \to ZZ^* \to 4\mu$	1.60	1.35	—	—
$A(500\,\text{GeV}\,c^{-2}) \to \tau\tau$	50.0	75.0	—	—
$W \to$ jet jet	8.0	10.0	—	—
$Z'(3\,\text{TeV}\,c^{-2}) \to \mu\mu$	240	170	—	—
$Z'(1\,\text{TeV}\,c^{-2}) \to ee$	7.0	5.0	—	—

From T. Virdee, Phys. Rep. 403-404 (2004) 401

QCD and Jet Physics

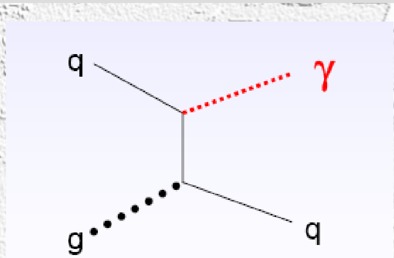


- Measured jet cross section versus E_T:
  - comparison to theory
  - good agreement over many orders of magnitude
- theoretical errors
  - QCD higher order (difficult)
  - pdf

  measurement can be used to check pdf
- experimental errors
  - jet energy scale

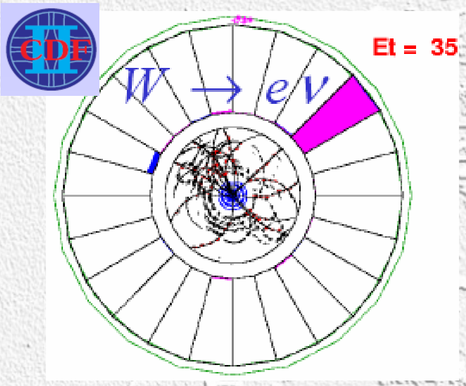
A jet is not a very well defined object:
- need algorithm to define it
- relation to parton energy → correction
- pile-up

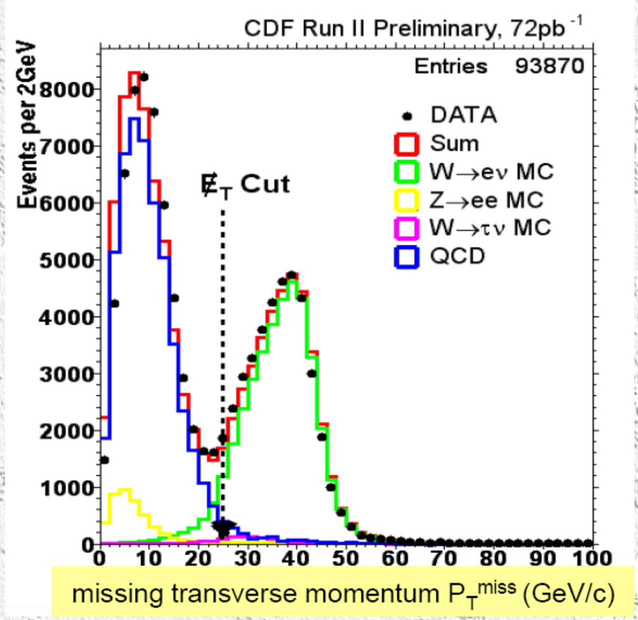
Calibration processes: γ+jet



W and Z Bosons

Example from the Tevatron:





Electrons

- Isolated el.magn. cluster in the calorimeter
- P_T > 25 GeV/c
- Shower shape consistent with expectation for electrons
- Matched with tracks

Z → ee

- 70 GeV/c² < m_{ee} < 110 GeV/c²

W → eν

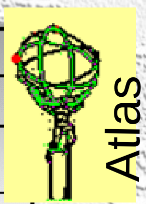
- Missing transverse momentum > 25 GeV/c

Separation of W →lν events from background

W Mass at the LHC

ATLAS study:

Source	CDF Run Ib	ATLAS or CMS	$W \rightarrow l\nu$, one lepton species
	30K evts, 84 pb^{-1}	60M evts, 10fb^{-1}	
Statistics	**65 MeV**	**< 2 MeV**	
Lepton scale	**75 MeV**	**15 MeV**	most serious challenge
Energy resolution	25 MeV	5 MeV	known to 1.5% from Z peak
Recoil model	33 MeV	5 MeV	scales with Z statistics
W width	10 MeV	7 MeV	$\Delta\Gamma_W \approx 30$ MeV (Run II)
PDF	**15 MeV**	**10 MeV**	
Radiative decays	**20 MeV**	**<10 MeV**	(improved Theory calc)
$P_T(W)$	45 MeV	5 MeV	$P_T(Z)$ from data, $P_T(W)/P_T(Z)$ from theory
Background	5 MeV	5 MeV	
TOTAL	**113 MeV**	**≤ 25MeV**	Per expt, per lepton species



- **Combine both channels & both experiments**

  $\Rightarrow \; \Delta m_W \leq$ 15 MeV (LHC)

Compare to

2006: m_W = 80 392 ± 29 MeV **LEP & Tevatron Run I/II**

2007: $m_W \approx$ 80 ... ± 20 MeV ($2.5 \cdot 10^{-4}$) **expected after Tevatron Run II**