The Road to Measurements and Discoveries at the LHC

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Presented at "Hot Matter and Gauge Field Theories" Workshop
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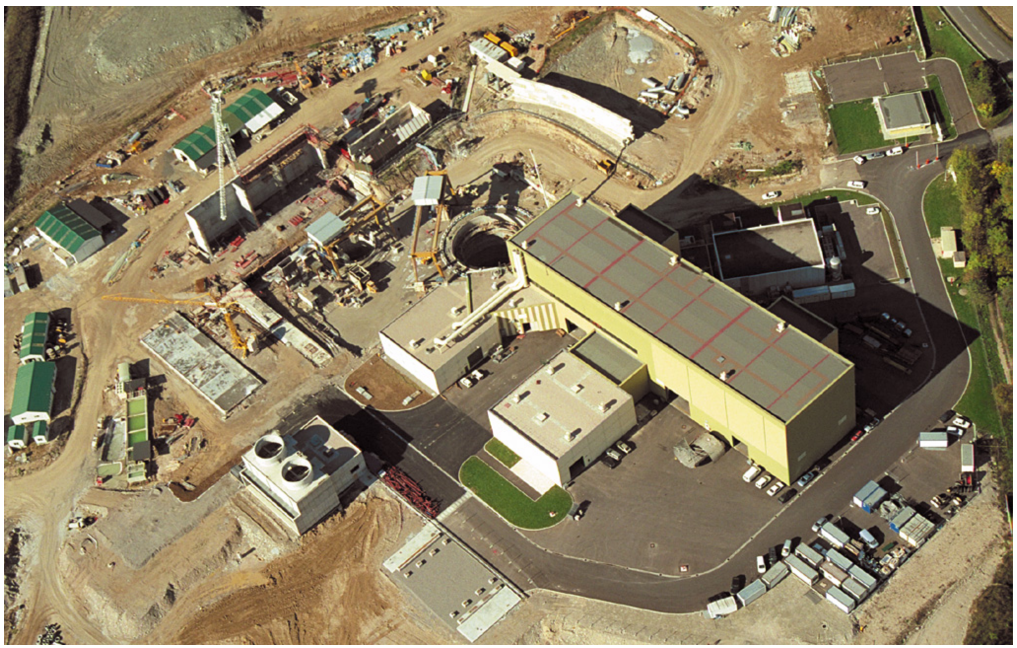
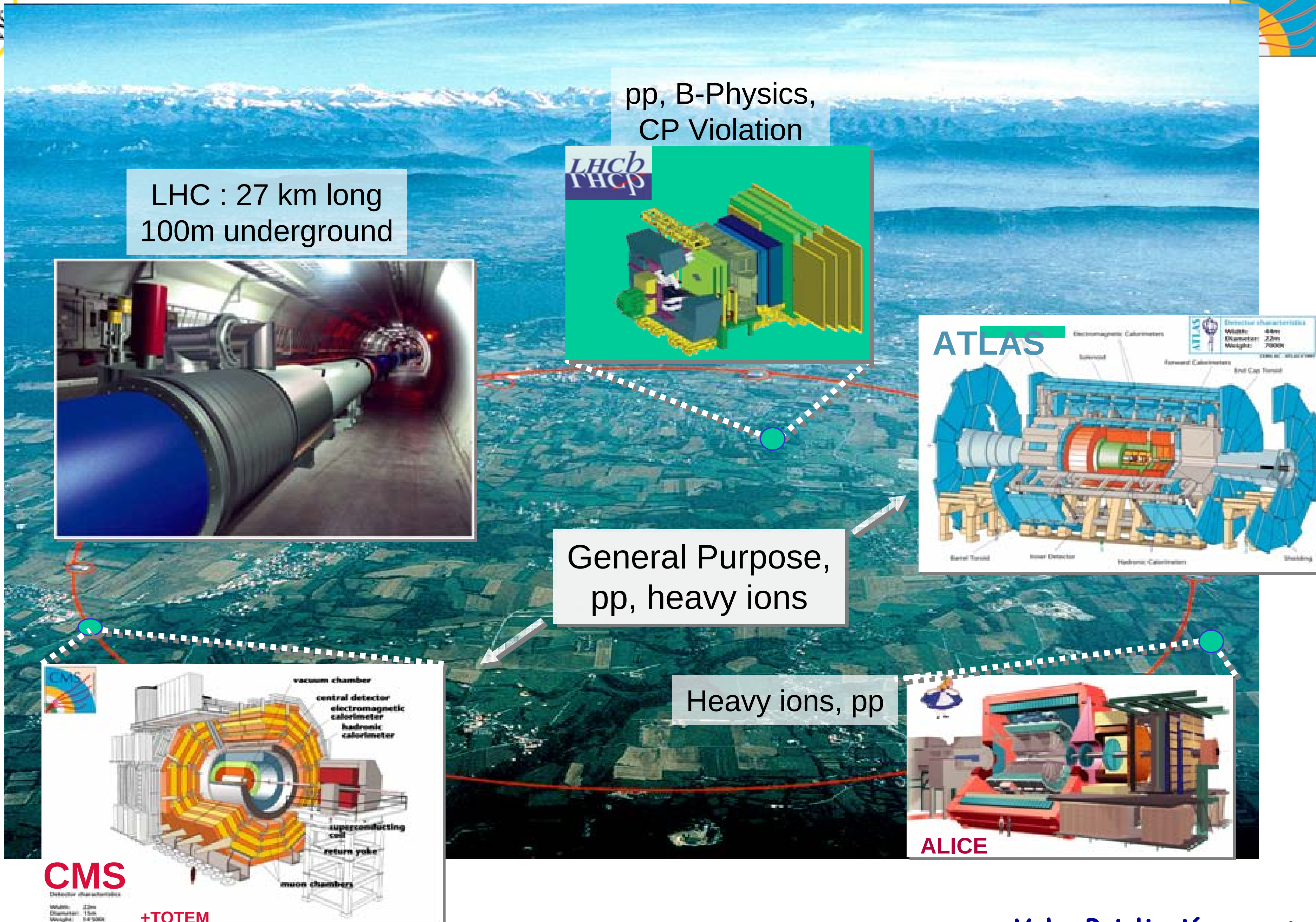


CMS Coil + inner vacuum tank

Contents

- The LHC and the experiments
- Short Overview the Physics Program at the LHC
  - Standard Model Physics
  - The Higgs particle
  - Supersymmetry
  - Large extra dimensions & Black holes
  - Heavy Ion Physics
- Summary


pp, B-Physics,
CP Violation
LHCb
LHC : 27 km long
100m underground
ATLAS
General Purpose,
pp, heavy ions
Heavy ions, pp
ALICE
CMS
vacuum chamber
central detector
electromagnetic calorimeter
hadronic calorimeter
superconducting coil
return yoke
muon chambers
+TOTEM

The LHC Machine and Experiments

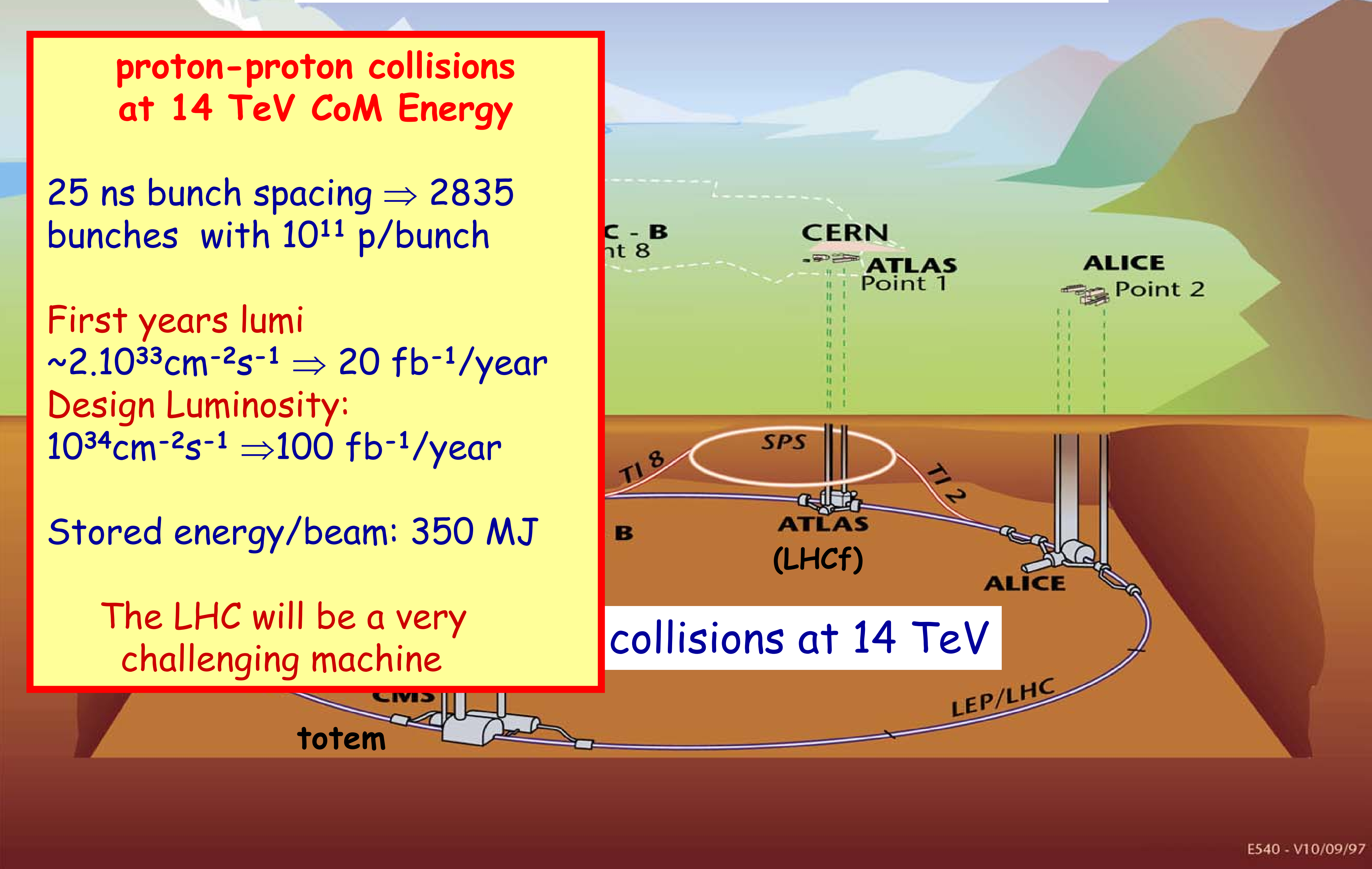
proton-proton collisions at 14 TeV CoM Energy

25 ns bunch spacing ⇒ 2835 bunches with 10^{11} p/bunch

First years lumi
~2.10^{33} $cm^{-2}s^{-1}$ ⇒ 20 fb^{-1}/year
Design Luminosity:
10^{34} $cm^{-2}s^{-1}$ ⇒100 fb^{-1}/year

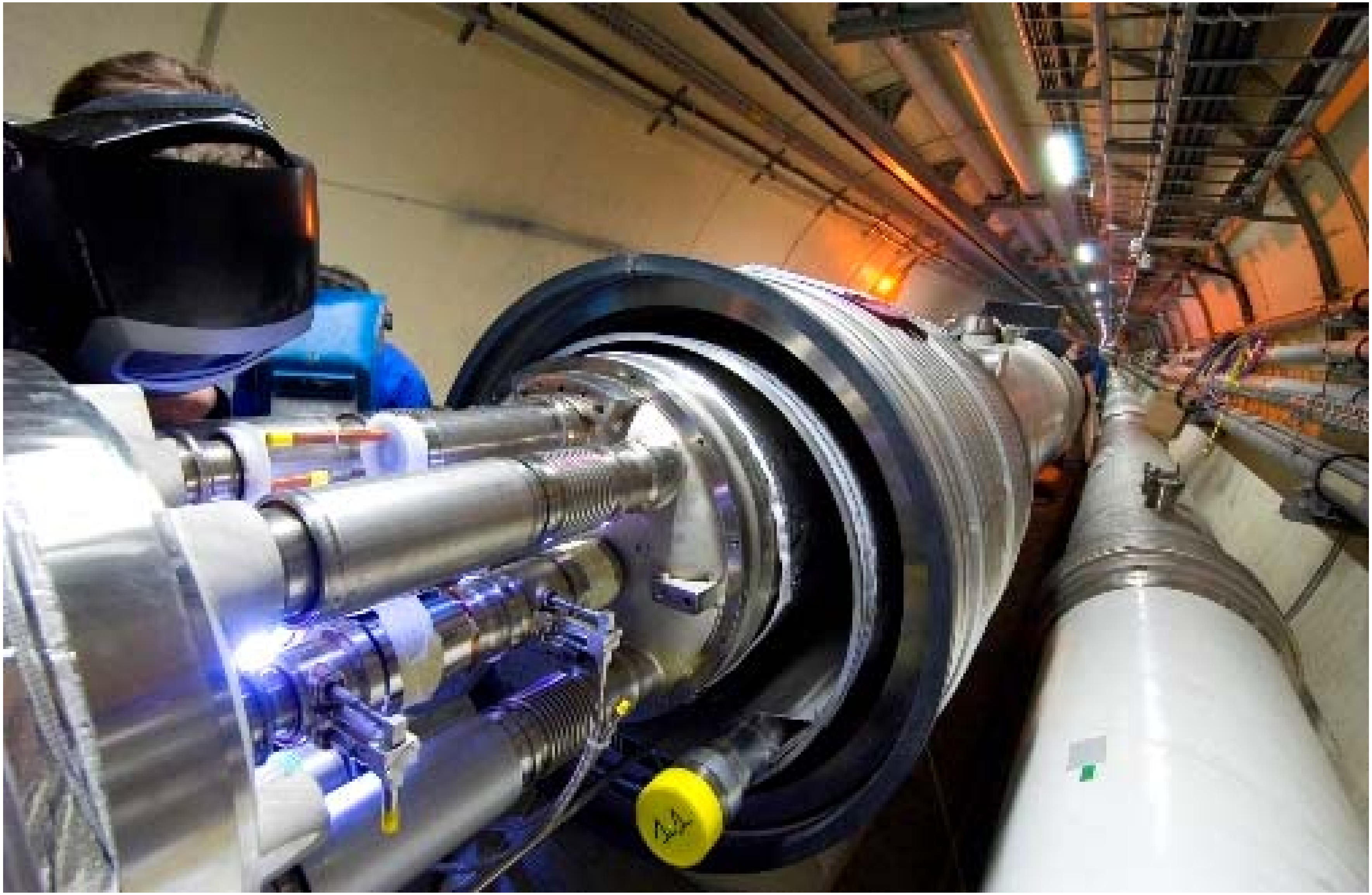
Stored energy/beam: 350 MJ

The LHC will be a very challenging machine



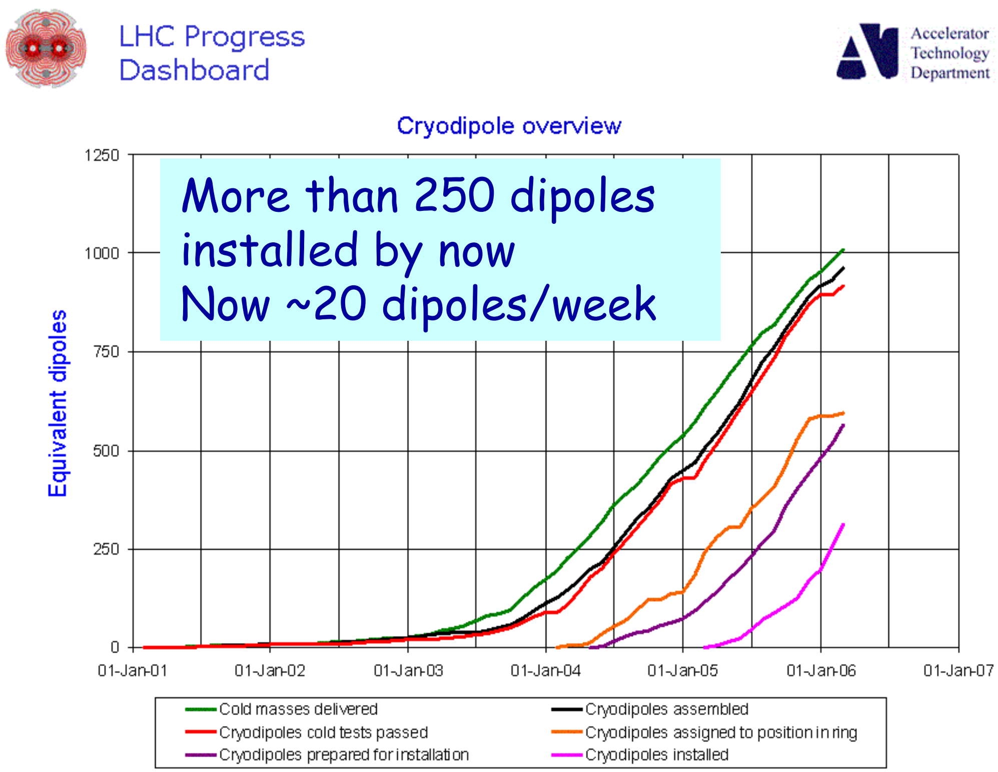
collisions at 14 TeV

The LHC is Coming!



The LHC Progress & Schedule

Crucial part: 1232 superconducting dipoles
Can follow progress on the LHC dashboard
http://lhc-new-homepage.web.cern.ch/lhc-new-homepage/



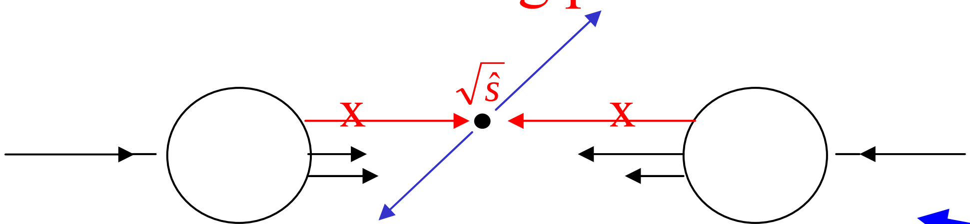
The LHC Schedule(*)

- LHC will be closed and set up for beam on 1 July 2007
- First beam in machine: August 2007
  LHC commissioning will take time!
- First collisions expected in October/November 2007
  Followed by a short pilot run
  O(10) pb^{-1} ?
- First physics run in 2008
  one to a few fb^{-1}?
- Physics run in 2009 +…
  10-20 fb^{-1}/year $\Rightarrow$100 fb^{-1}/year

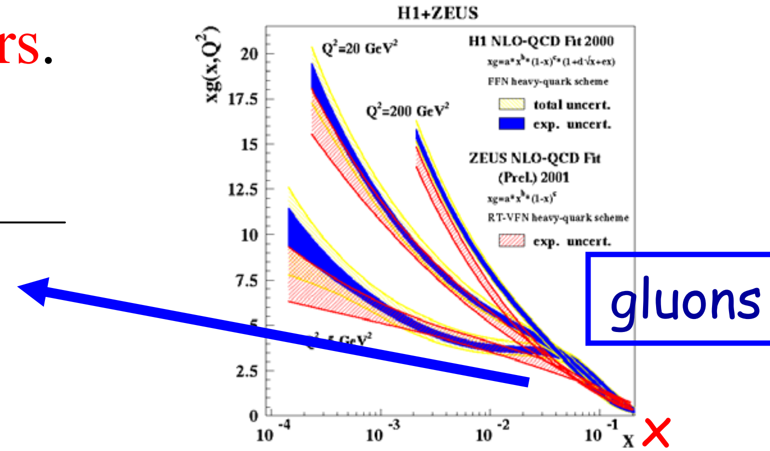
(*) eg. M. Lamont et al, April 2005.
Achtung! Lumi estimates are mine, not from the machine
Update expected in June-July 2006

Proton-proton collisions

Monochromatic proton beam can be seen as beam of quarks and gluons with a wide band of energy. Occasionally hard scattering (" head on") between constituents of incoming protons occurs.

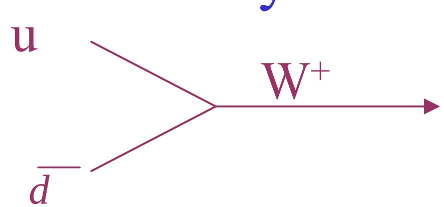


p ≡ momentum of incoming protons = 7 TeV



Interactions at small distance → large momentum transfer → massive particles and/or particles at large angle are produced.

These are interesting physics events but they are rare.



$\sigma\,(pp \to W) \approx 150\text{ nb} \approx 10^{-6}\,\sigma_{tot}(pp)$

Need:

- High Energy
- Many collisions

High luminosity

E.g. 1 pb^{-1}/hour ⇒ 150 000 $pp \to W$ /h

(1 barn = 10^{-24} cm^2)

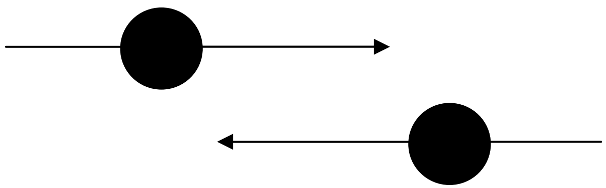
Proton-proton collisions

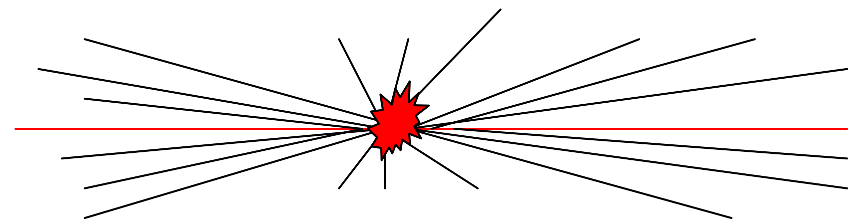
Most interactions due to collisions at large distance between incoming protons where protons interact as " a whole "

→ small momentum transfer ($\Delta p \approx \hbar / \Delta x$)

→particles in final state have large longitudinal momentum but small

→transverse momentum (scattering at large angle is small)





$< p_T > \approx 500$ MeV of charged particles in final state

Most energy escapes down the beam pipe.

Cross section ~ 100 mb
Huge!!

These are called minimum-bias events (" soft " events) ⇒background !!

On average 4-20 min bias events per bunch crossing at the LHC!!

LHC Physics Program

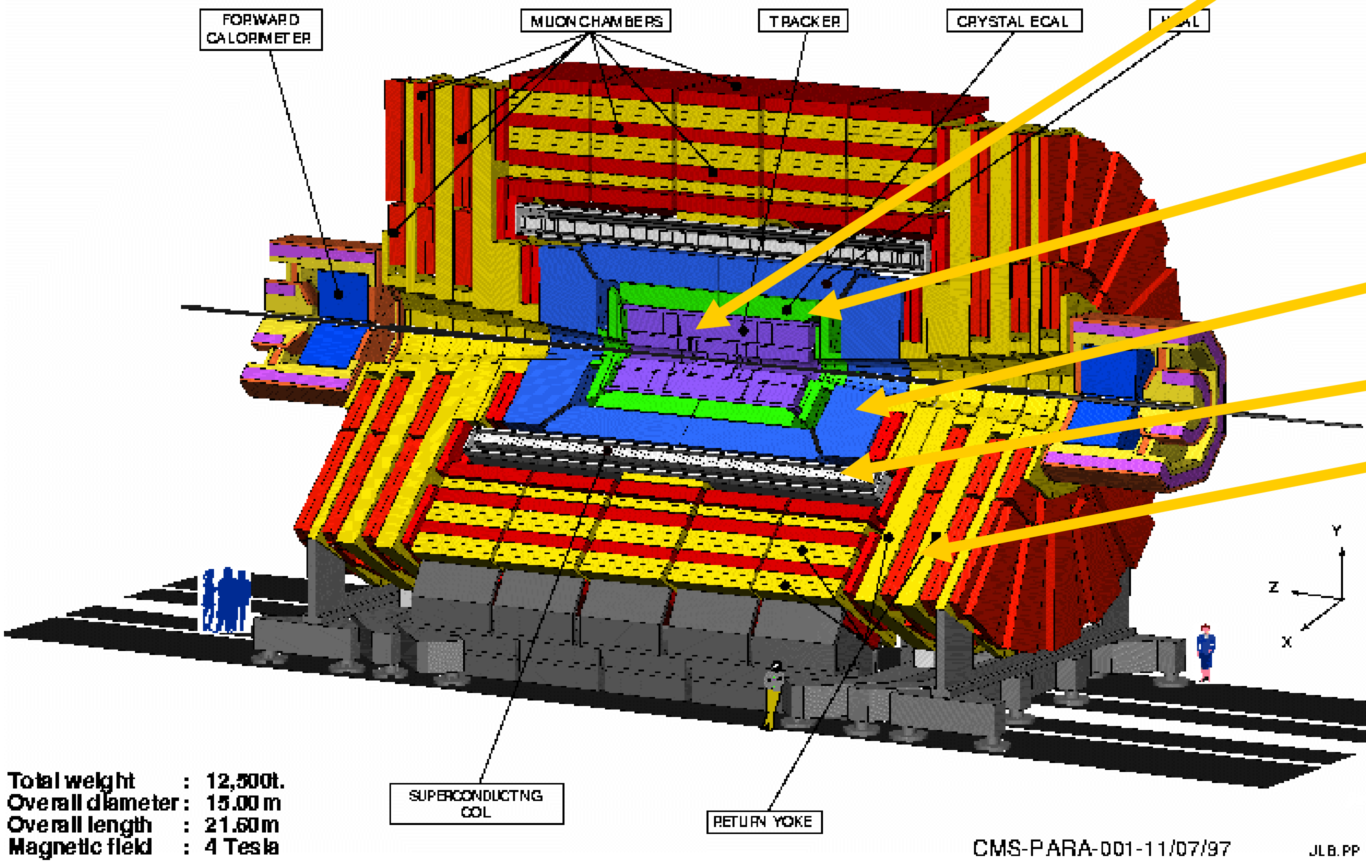
- Discover or exclude the Higgs in the mass region up to 1 TeV. Measure Higgs properties
- Discover Supersymmetric particles (if exist) up to 2-3 TeV
- Discover Extra space dimensions, if these are on the TeV scale, and black holes?
- Search other new phenomena (e.g. strong EWSB, new gauge bosons, Little Higgs model, Split Supersymmetry)
- Study CP violation in the B sector
- Precision measurements of m_{top}, m_W, anomalous couplings…
- Heavy ion collisions and search for quark gluon plasma
- QCD and diffractive (forward) physics in a new regime

Either at least one Higgs is found with mass below
1 TeV, or new phenomena (strong EWSB?) set on in the TeV region

The CMS experiment

~2300 people/~150 institutes

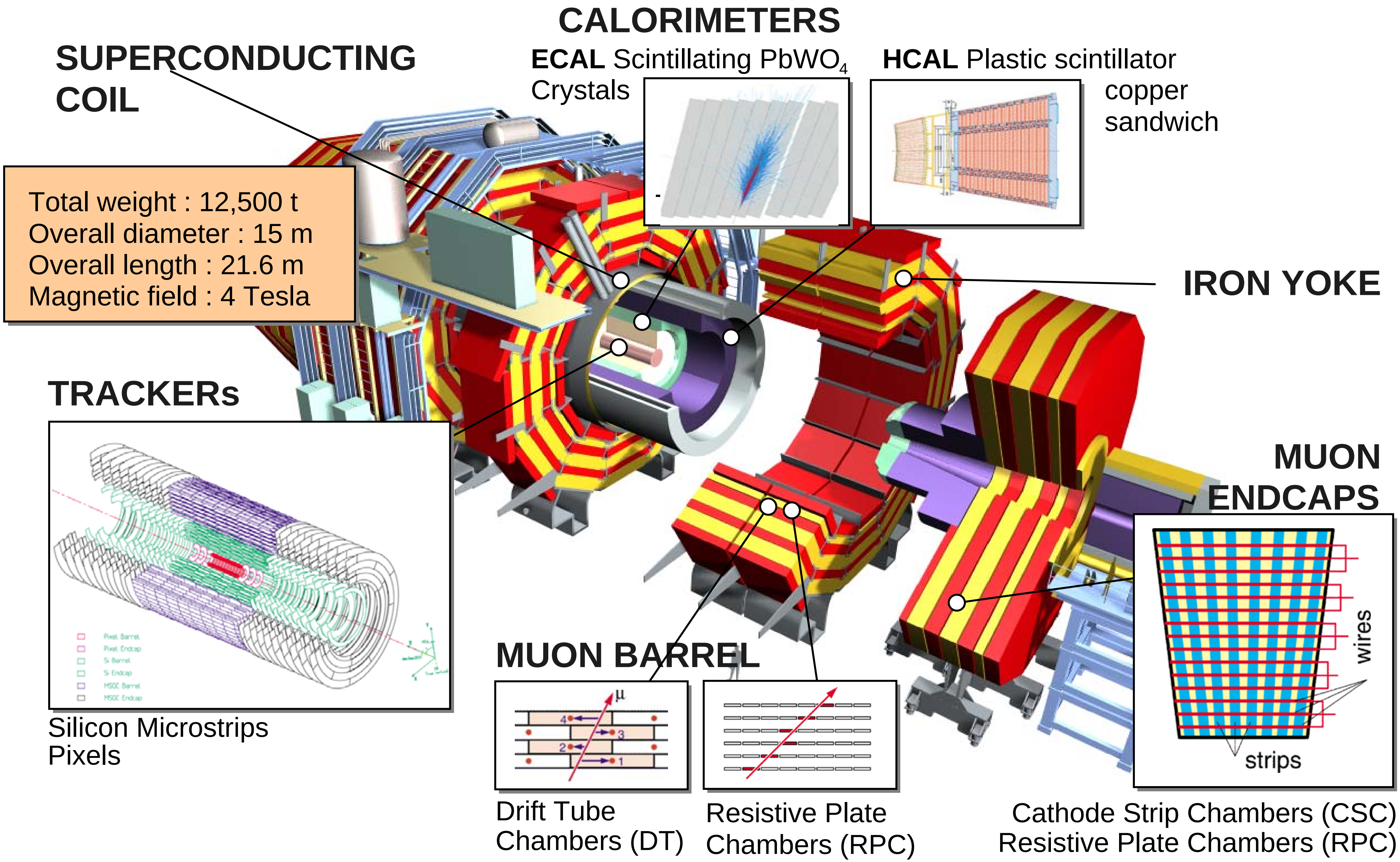
- Tracking
  - Silicon pixels
  - Silicon strips
- Calorimeters
  - PbW04 crystals for Electro-magn.
  - Scintillator/steel for hadronic part
- 4T solenoid
- Instrumented iron for muon detection



- In total about 98 000 000 channels
- Size of 1 event 1 000 000 Bytes
- Readout to disk 100 events/sec

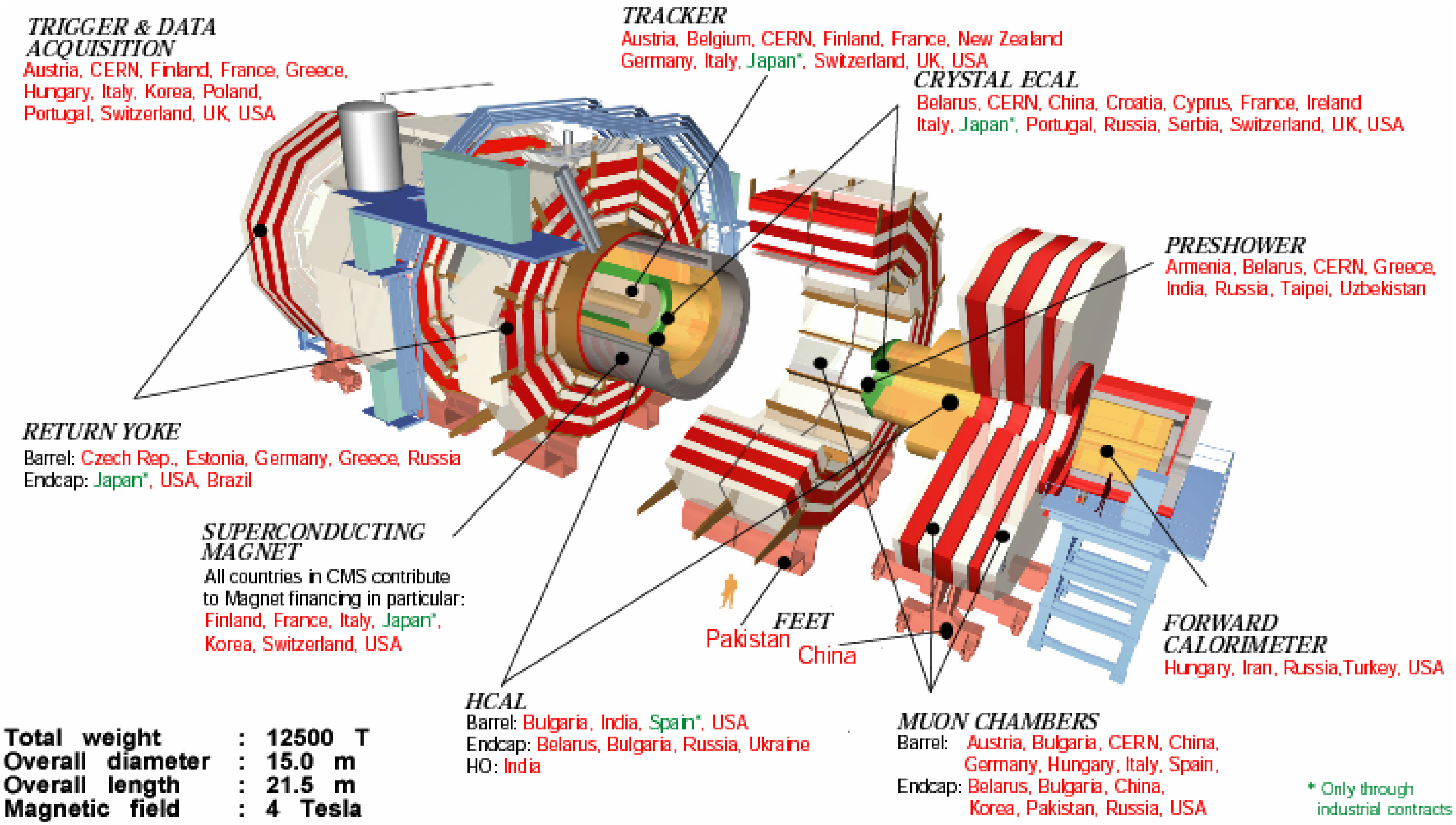
A Huge Enterprise !

The Compact Muon Solenoid



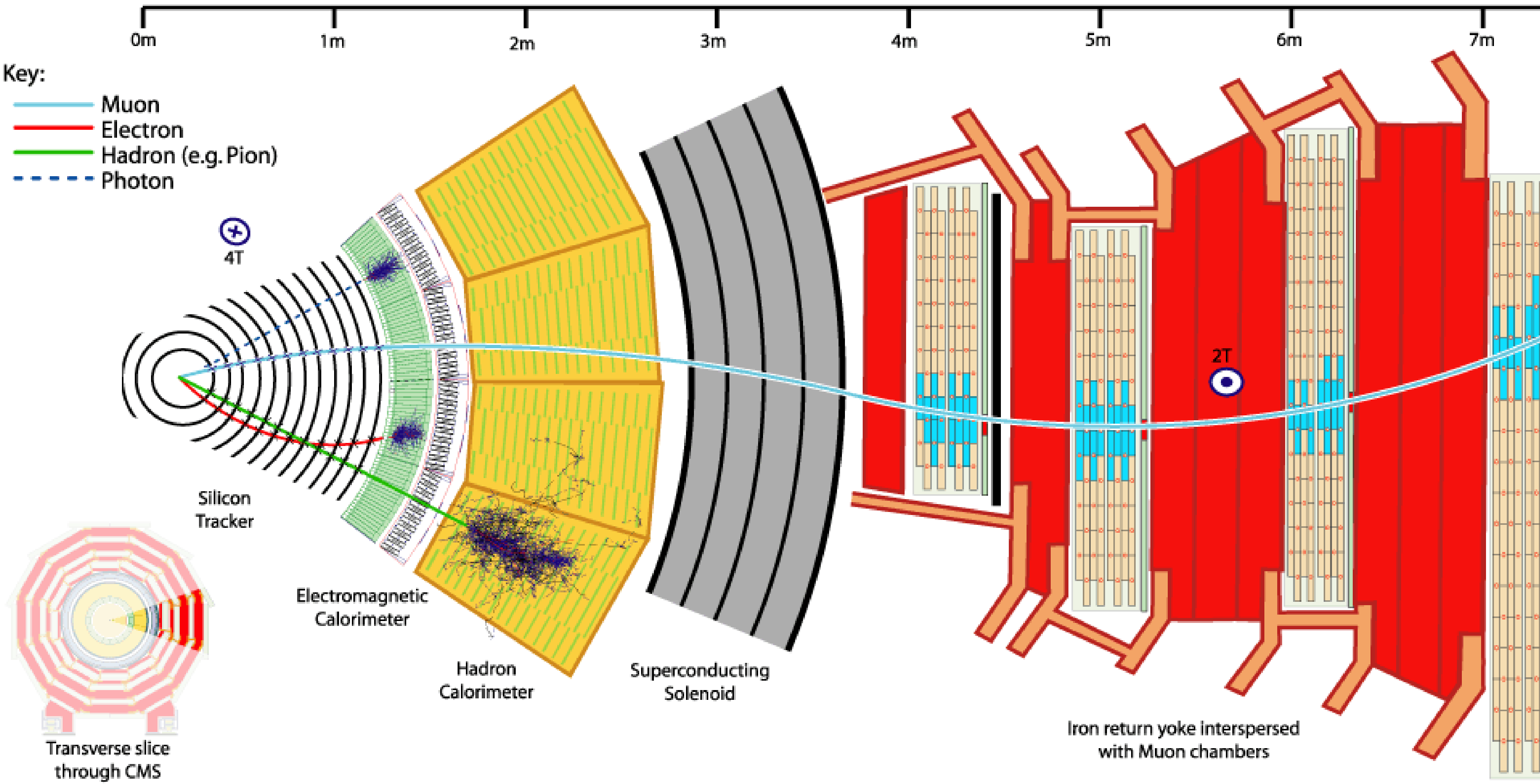
CMS Collaboration (Dec. 2005)

2701 scientists & engineers	176 institutions	37 countries

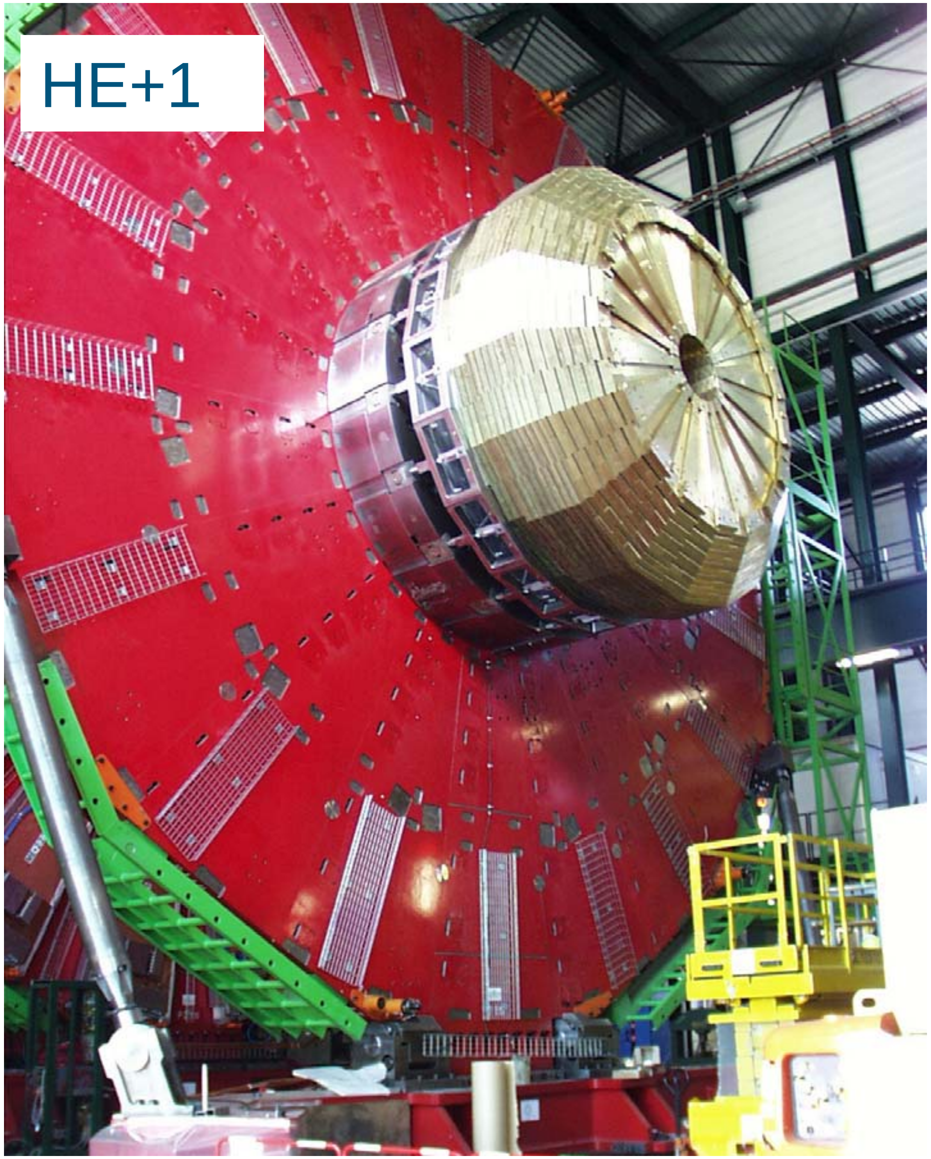


See http://cmsdoc.cern.ch/peopleCMS.shtml

Particles in the detector



CMS HCAL: The two HEs have been completed

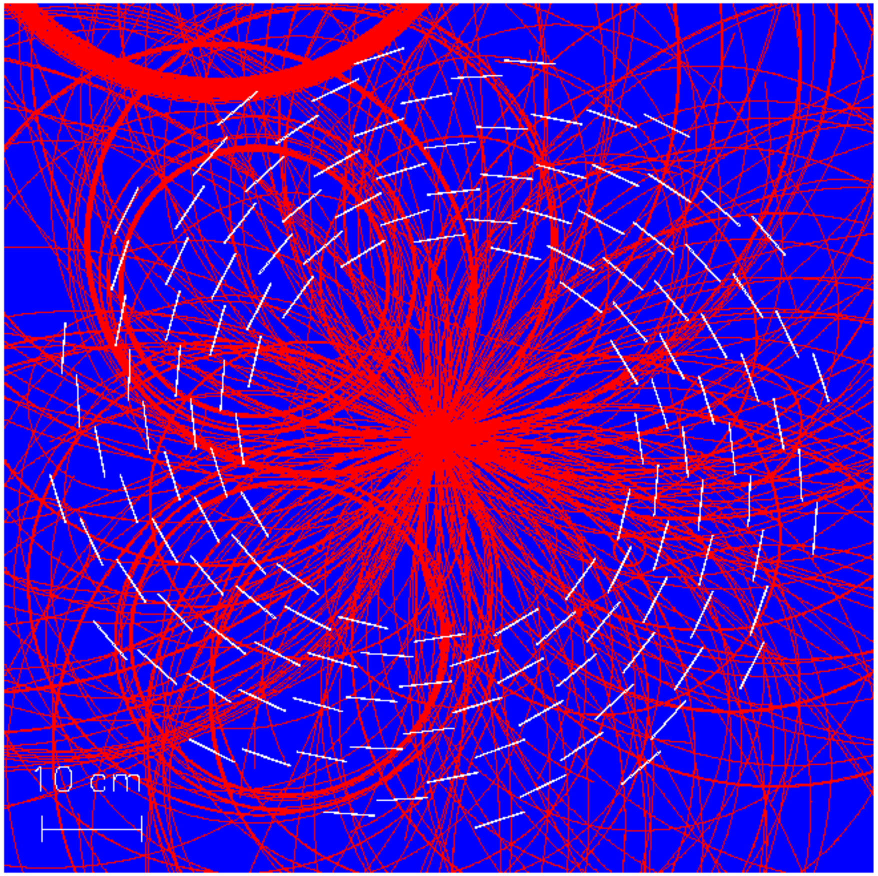



MB stations installed in YB+2,

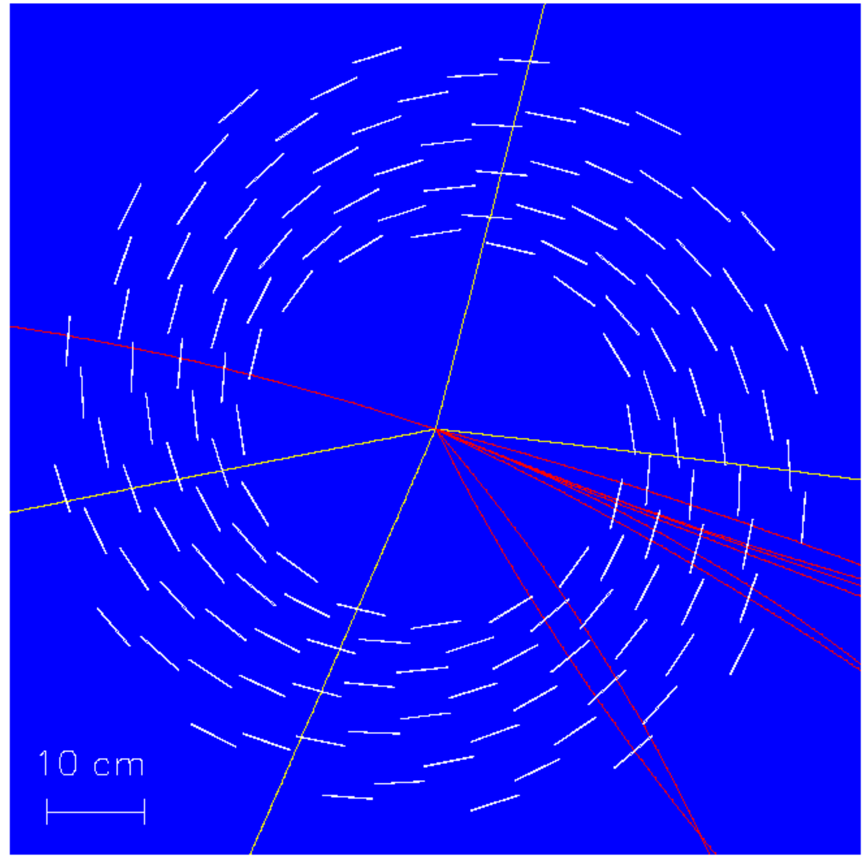
How to find the interesting signals

This event contains pp →H+X, with H→ZZ→μμμμ

↳ X ~ 100 charged particles



All tracks shown



Only tracks with transverse momentum > 2 GeV shown

Finding New Physics at the LHC

Per year, the LHC will provide ~10^{16} *pp* collisions (few/ 25 nanoseconds)

An observation of ~ 10 events could be a discovery of new physics.

→ One has to find these 10 events among 10^{16} non-interesting ones!!

Searching for a needle in a hay stack?

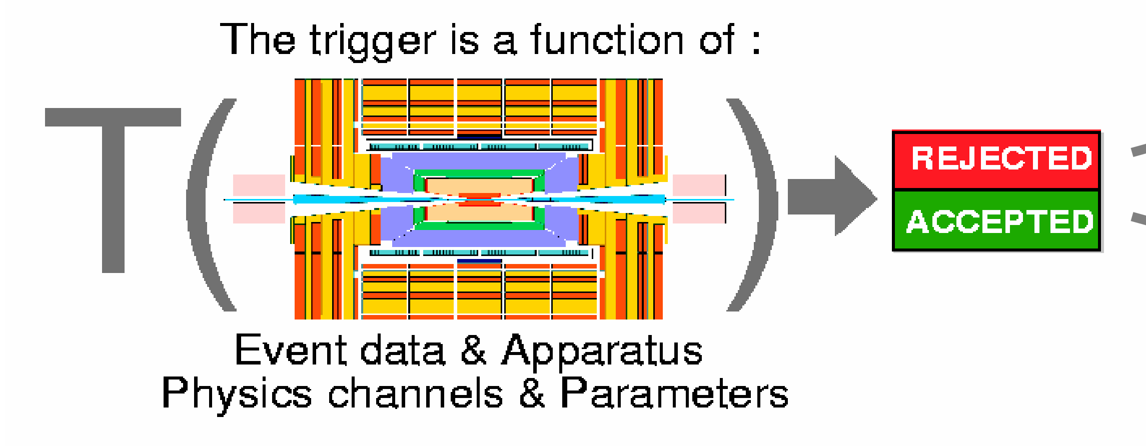
- typical needle: 5 mm^3
- typical haystack: 50 m^3

→ needle : haystack = 1 : 10^{10}

→ Looking for new physics at the LHC is like looking for a needle in 100000 haystacks …

Event filtering: the trigger system

Collision rate is 40 MHz Event size ~1 Mbyte
2007 technology (and budget) allows only to write 100 Hz of events to tape → need a factor ~10^7 online filtering!!

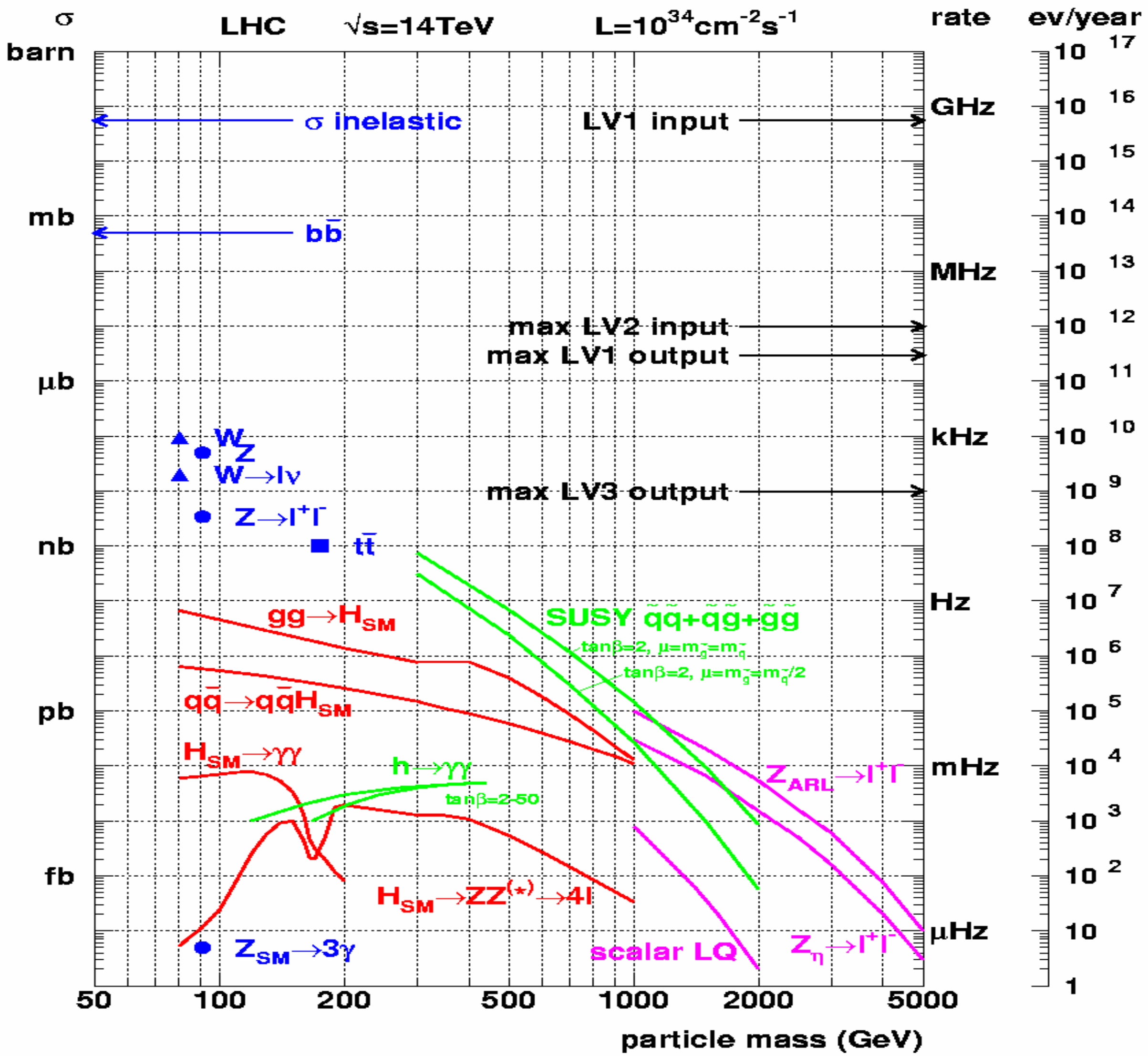


lost forever!!

written to disk for offline analysis

The event trigger is one of the biggest challenges at the LHC
⇒ Based on hard scattering signatures: jets, leptons, photons, missing Et,…

Cross sections at the LHC



“Well known” processes, don’t need to keep all of them …

New Physics!!
This we want to keep!!

Expected Event Rates

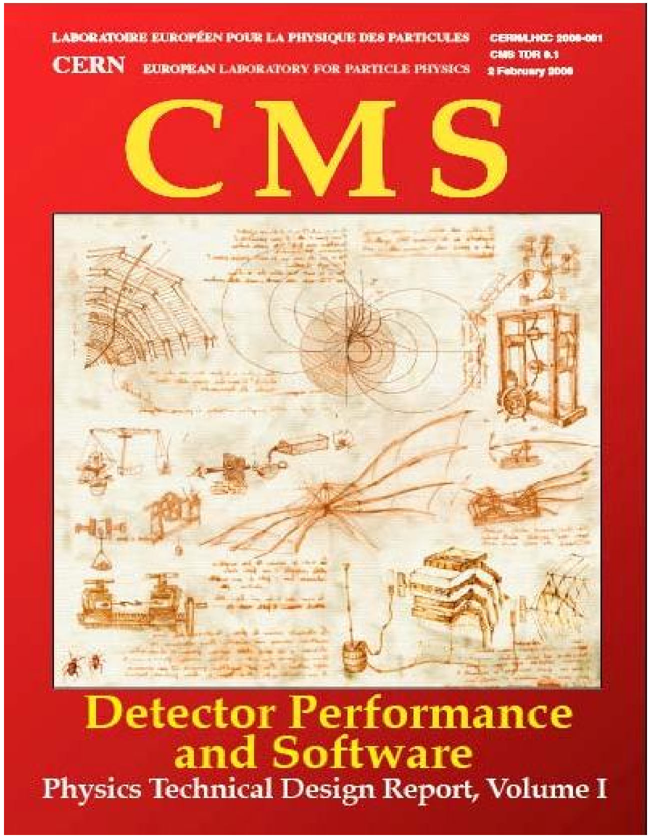
Process	Events/s	Events/year	Other machines
$W \to e\nu$	15	10^8	10^4 LEP / 10^7 Tev
$Z \to ee$	1.5	10^7	10^7 LEP
$t\bar{t}$	0.8	10^7	10^4 Tevatron
$b\bar{b}$	10^5	10^{12}	10^8 Belle/BaBar
$\tilde{g}\tilde{g}$ (m=1 TeV)	0.001	10^4	—
H (m=0.8 TeV)	0.001	10^4	—
QCD jets $p_T > 200$ GeV	10^2	10^9	10^7

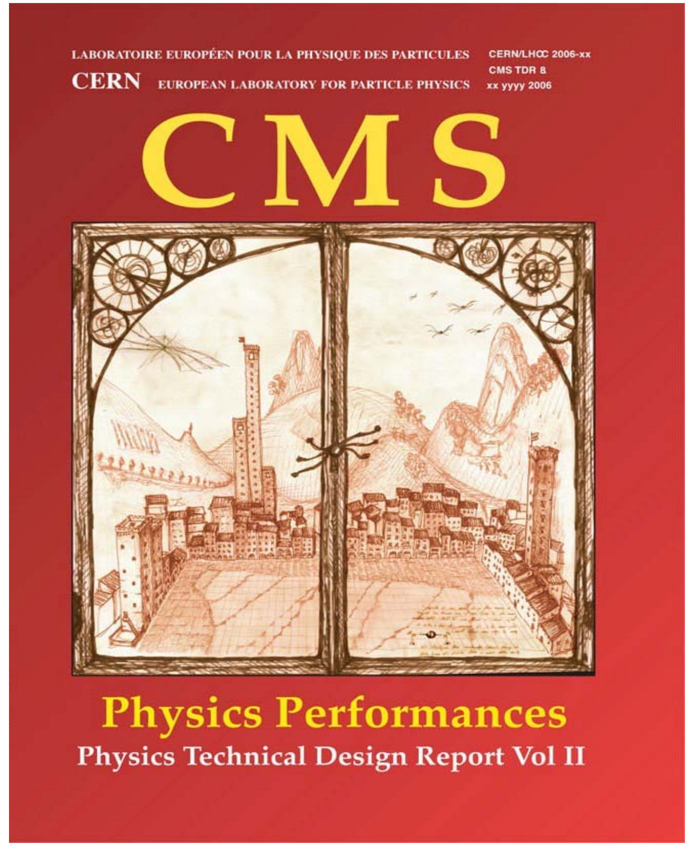
Huge event rates: ($10^{33} cm^{-2} s^{-1}$)

The LHC will be a W-factory, a Z-factory, a top factory, a Higgs factory etc..

Precision physics will be limited by systematics

New Analysis Developments from CMS



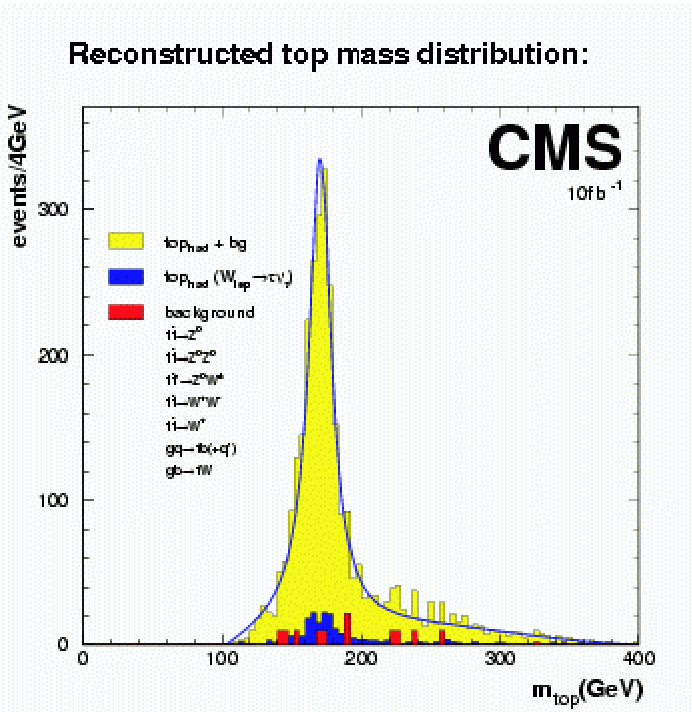


http://cmsdoc.cern.ch/cms/cpt/tdr/

CERN/LHCC 2006-001	**CERN/LHCC 2006-021**
Published	**Coming June 2006**

1. Standard Model

Precision measurements of Standard Model processes and parameters

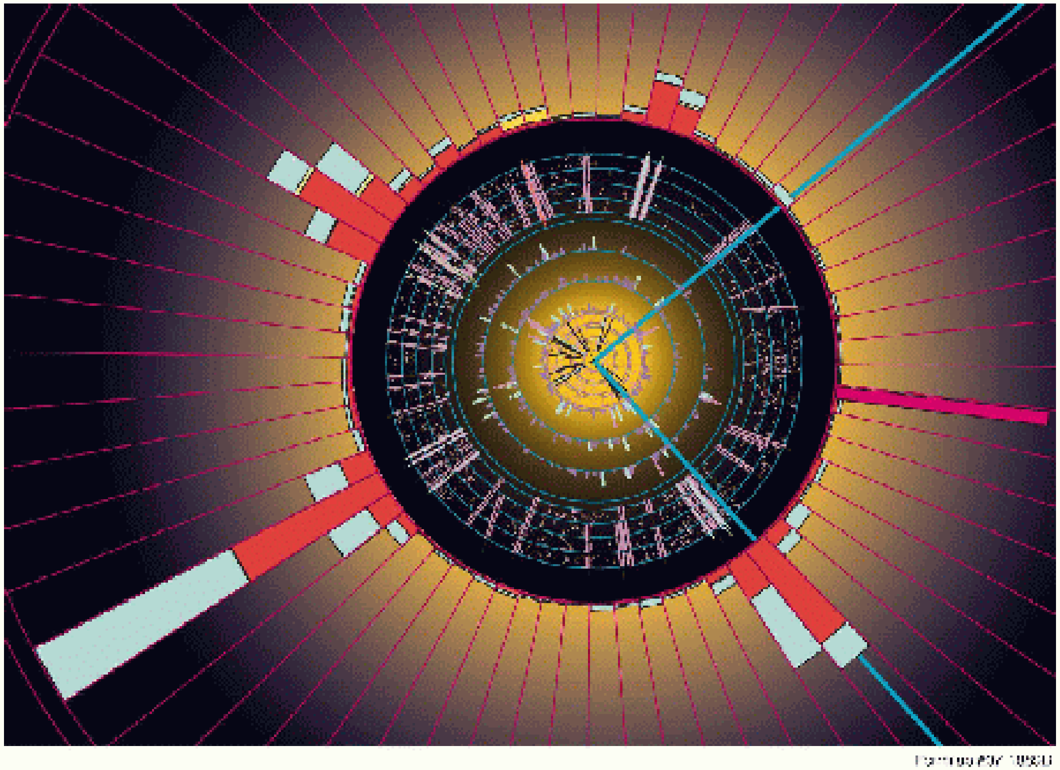


- Physics of the top quark
- Electroweak physics
- Quantum Chromo Dynamics
- Physics of the b-quark
- Forward physics

Tevatron at Fermilab (Chicago)

Recent Steps

The Last Quark



1994
Top mass
174 +/- 5 GeV

i.e. this quark is as heavy as a gold nucleus

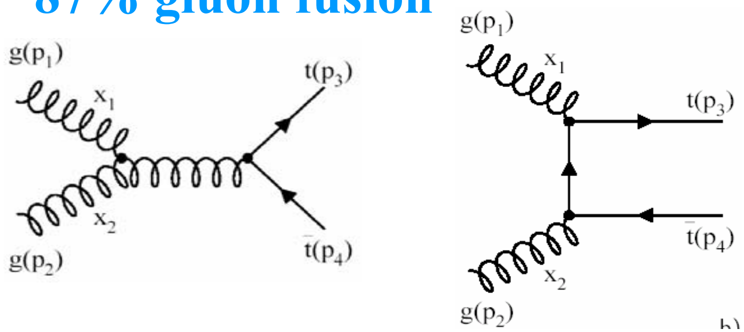
Top Quark discovered at Fermilab

All 3 families in the SM are now complete

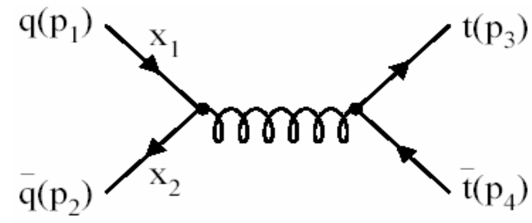
Top Physics

- $t\bar{t}$ production

87% gluon fusion



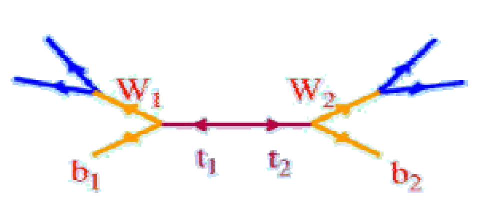
13% quark annihilation



Inverse ratio of production mechanism as compared to Tevatron

- Approximately one $t\bar{t}$-pair per second at $10^{33}/cm^2/s$

LHC is a top factory!

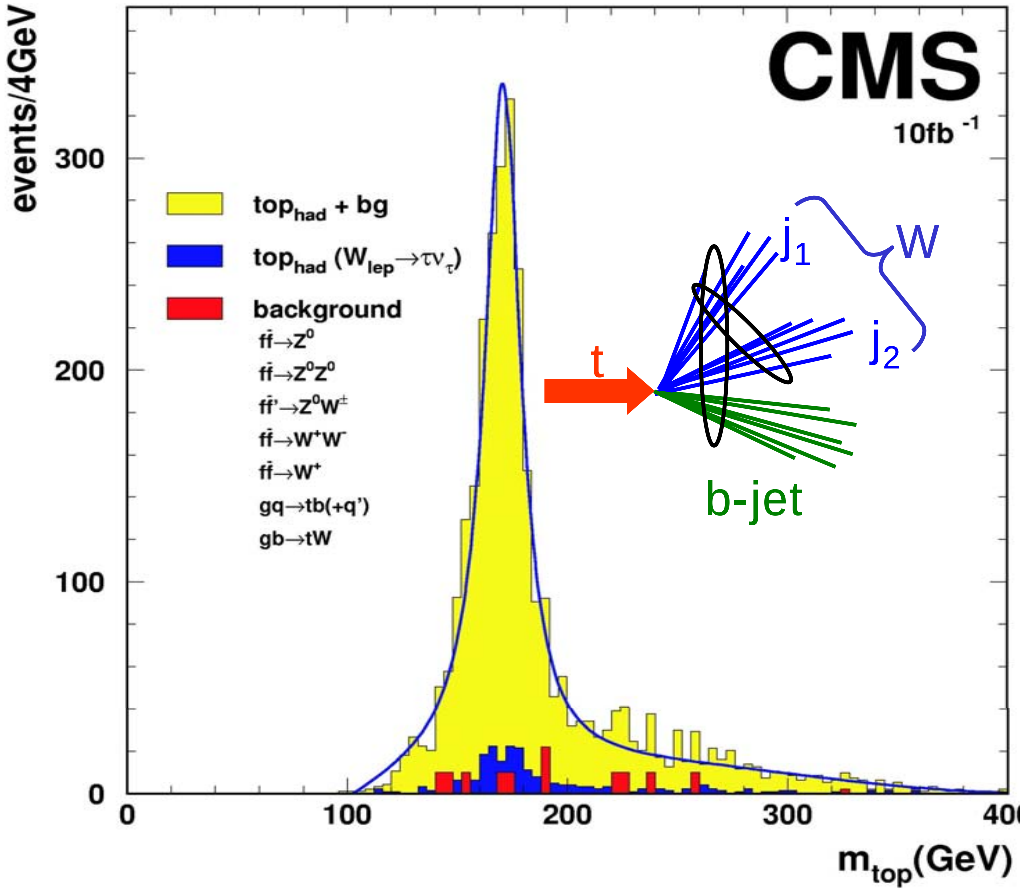


- Top decay: $\approx$ 100% t → bW
- Study top mass, couplings etc.
- Other rare SM decays:
  - CKM suppressed t → sW, dW: 10^{-3} – 10^{-4} level
  - t→bWZ: $O(10^{-6})$

  difficult, but since $m_t \approx m_b + m_W + m_Z$ sensitive to m_t

Top Quark Mass Measurements

- „easiest“ channel tt → bb qq lν (semi-leptonic)



- 3.5 million semileptonic events corresponding to 10 fb^{-1}
- CMS analysis with hard cuts: 0.14% of the events kept (!!!)

⇒ Error on $m_t \approx \pm 1$ GeV

statistical error	250 MeV
largest sys. errors:	
p_T spectrum	400 MeV
b-jet energy scale	?

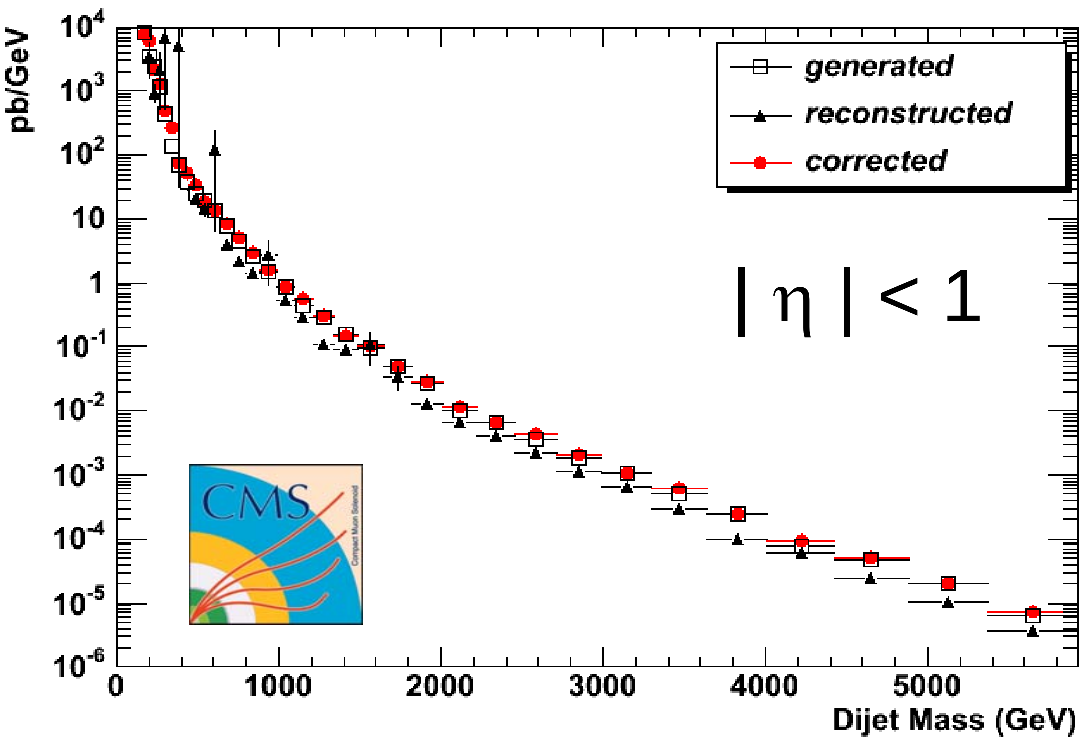
Measurements at 1 fb^{-1}
- initial mass determination
- total & diff. cross sections

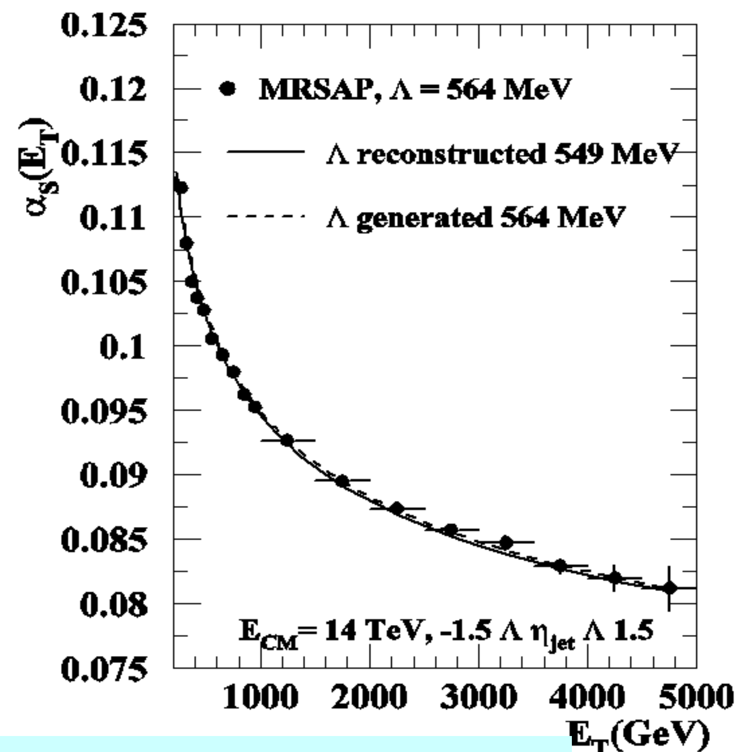
QCD and Jet physics

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

Running of the strong Coupling constant α_s

Example: di-jet mass rate in central detector

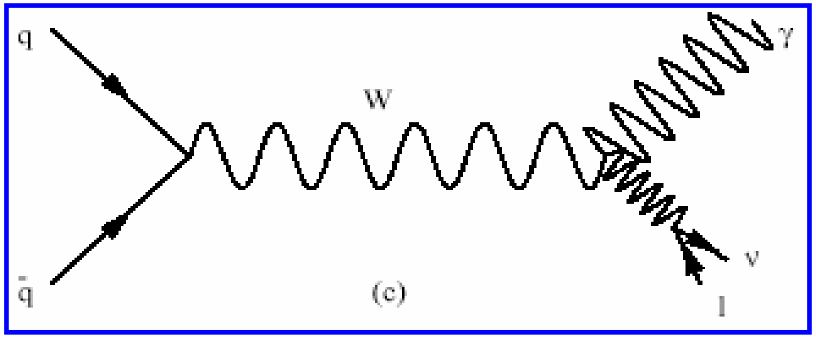




2004 Nobel Prize in Physics

Triple Gauge Boson Couplings

Test CP conserving anomalous couplings at the WWγ vertex Δκ and λ



Method:

- Wγ final states
- W → eν and μν
- p_T spectrum of photon

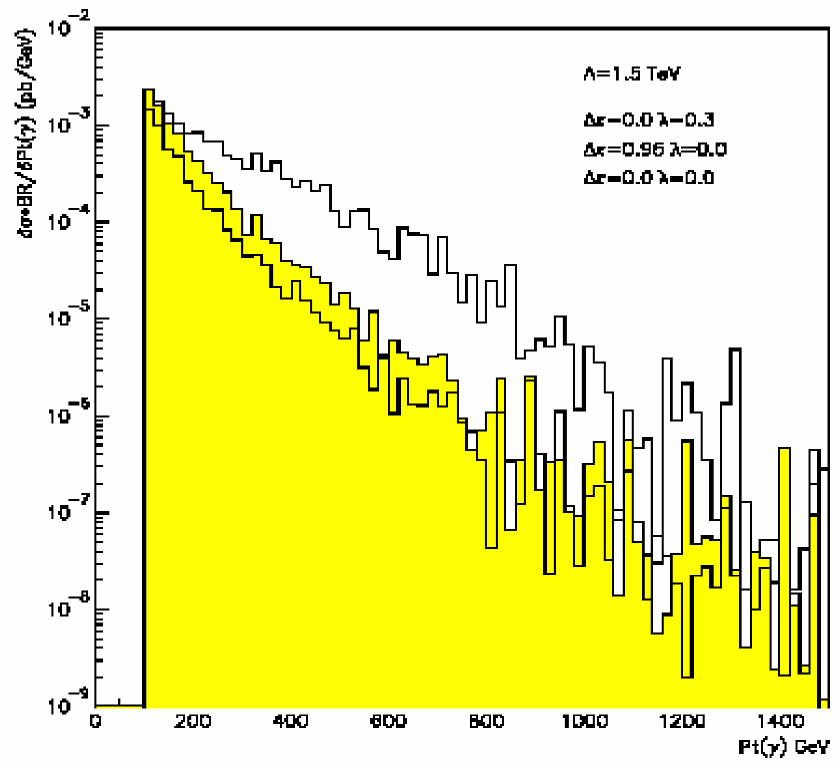
•Further WWZ vertex

•WZ → 3 lepton final state

⇒ Zagreb Croatia

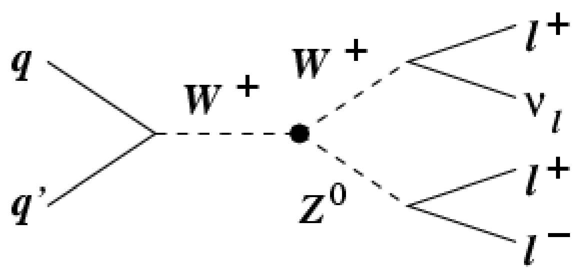
Sensitivity:

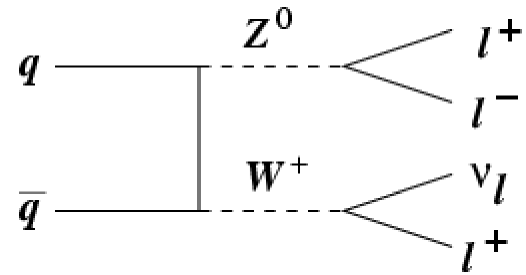
p_T spectrum SM couplings vs current limits at 1.5 TeV



The process pp->WZ -> 3l + neutrino

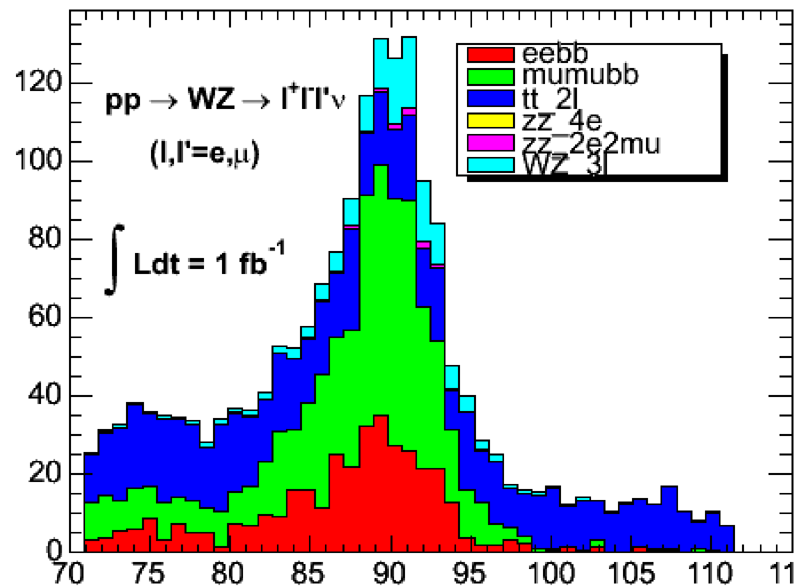
(First full simulation performed at IRB, to be published in CMS PTDR)





- *s-channel contribution dominant*
- *Sensitive to TGC*

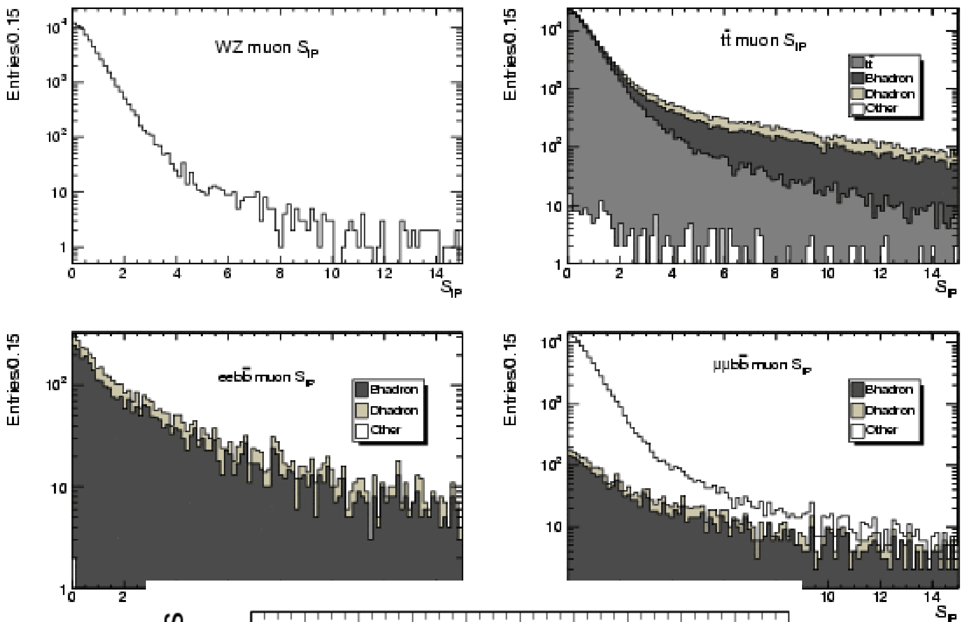
All events with

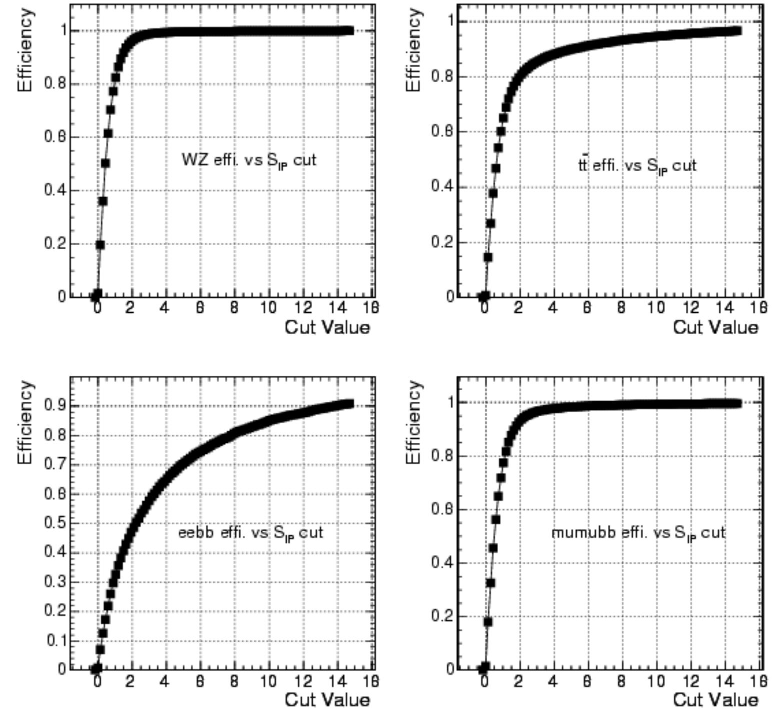


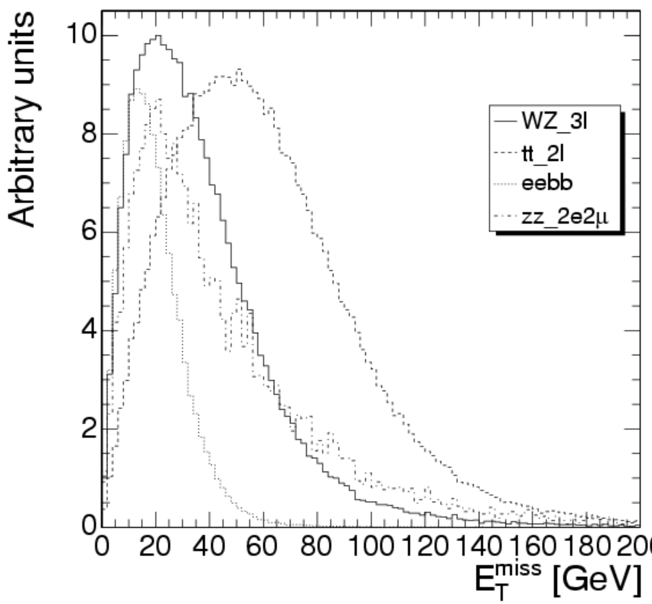
Excellent channel to

- Measure SM TGC
- Look for anomalous GC
- Can be seen early at the LHC

The process pp->WZ -> 3l + neutrino







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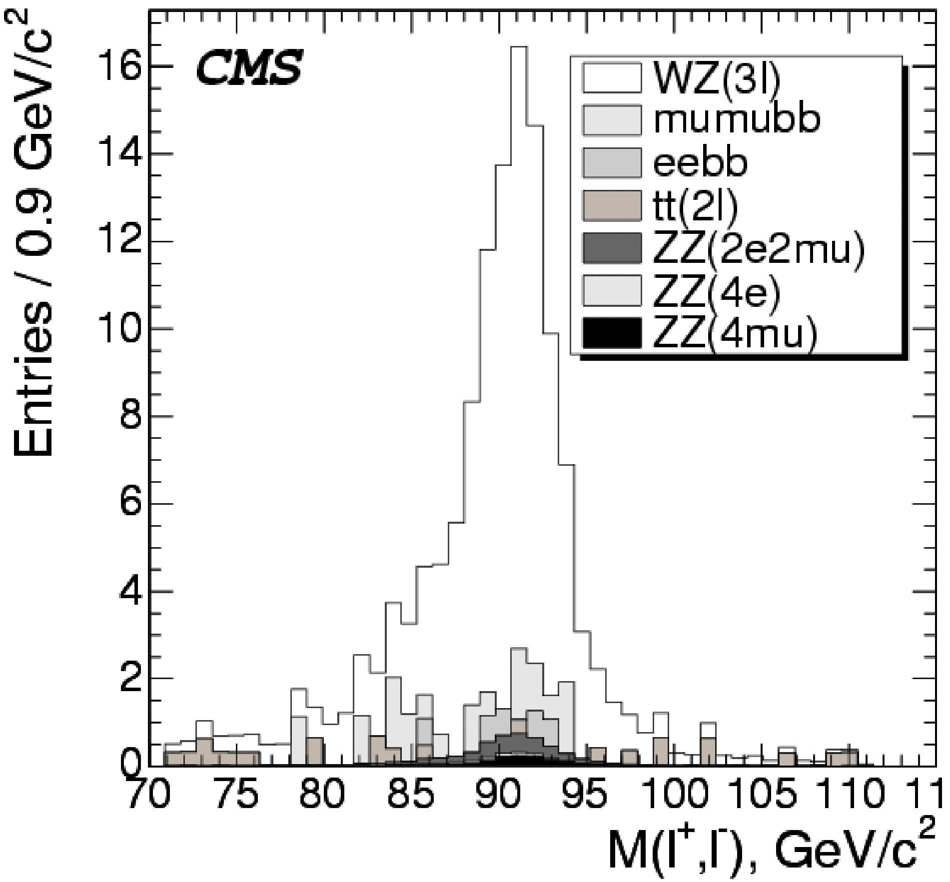
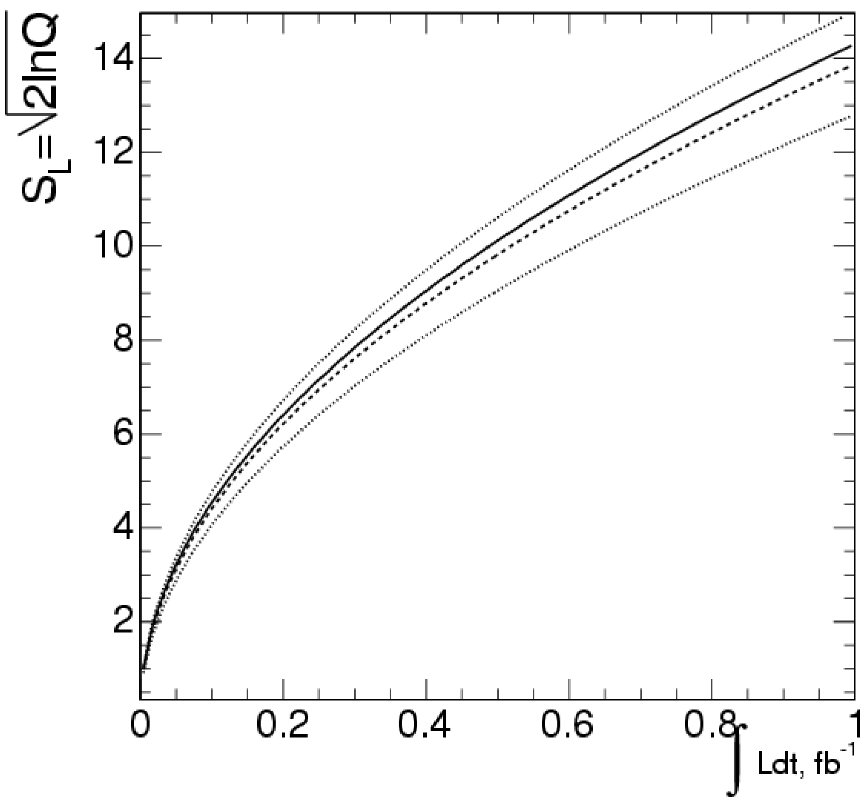




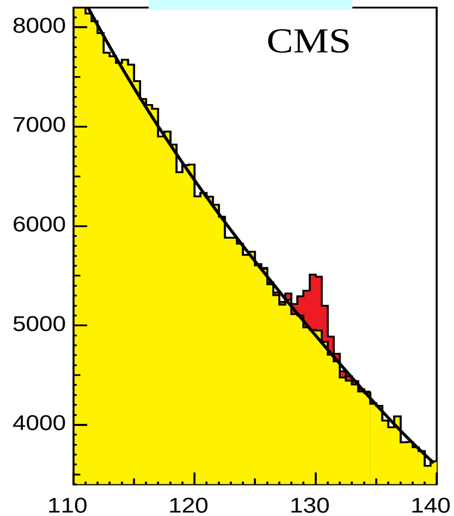
2. Higgs Physics

⇒ What is the origin of Electro-weak Symmetry Breaking?

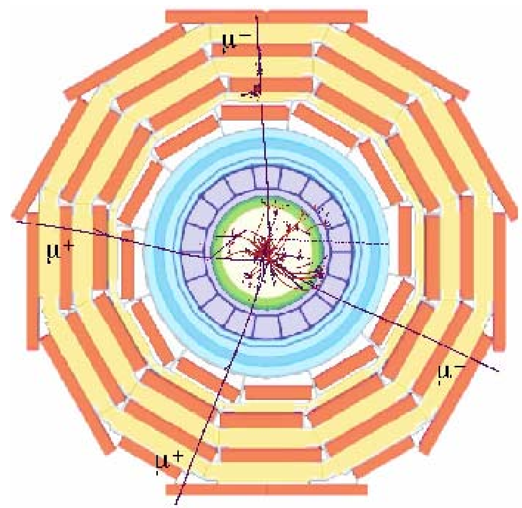
⇒ If Higgs field at least one new scalar particle should exist: The Higgs

One of the main missions of CMS: discover the Higgs for $m_H < 1$ TeV

$H \to \gamma\gamma$



$H \to ZZ \to \mu\mu\mu\mu$

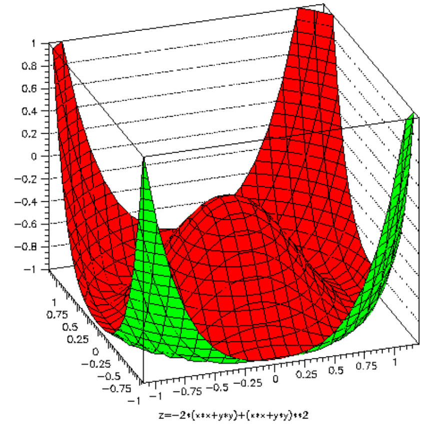


The Higgs Mechanism

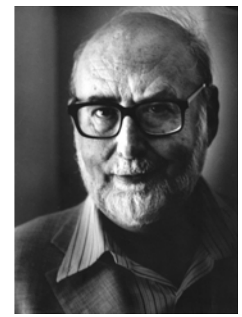
1964 Higgs, Englert and Brout propose to add a complex scalar field to the Lagrangian

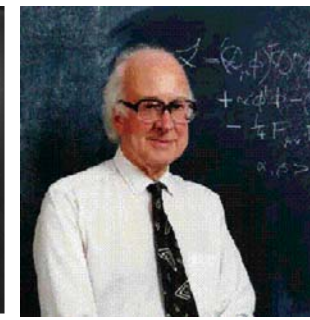
$$\phi = \phi_1 + i\phi_2$$

$$\mathcal{L} = (\partial^\mu \phi^\dagger)(\partial_\mu \phi) - \mu^2 \mid \phi \mid^2 - \lambda \mid \phi \mid^4$$



Expect at least one new scalar particle:
The (Brout-Englert-) Higgs particle





- SM Higgs (LEP)
  - M_H>114.1 GeV @95% CL
- MSSM neutral Higgs bosons (LEP)
  - M_h, M_A>92.9, 93.3 GeV @95% CL
  - $M_{H\pm}$ >89.6 GeV @95% CL for BR($M_{H\pm} \rightarrow \tau\nu$) =1
  - $M_{H\pm}$ >78.6 GeV @95% CL for any BR
- Electroweak fits to all high Q^2 measurements give:
  - $M_H=98^{+52}_{-36}$ GeV (old top mass)
  - M_H<186 GeV @ 95% CL (new top mass)
- Tevatron searches → negative so far

Probably the most wanted particle in HEP
Discover … or prove that it does not exist

SM Higgs mass constraints from the data and theory

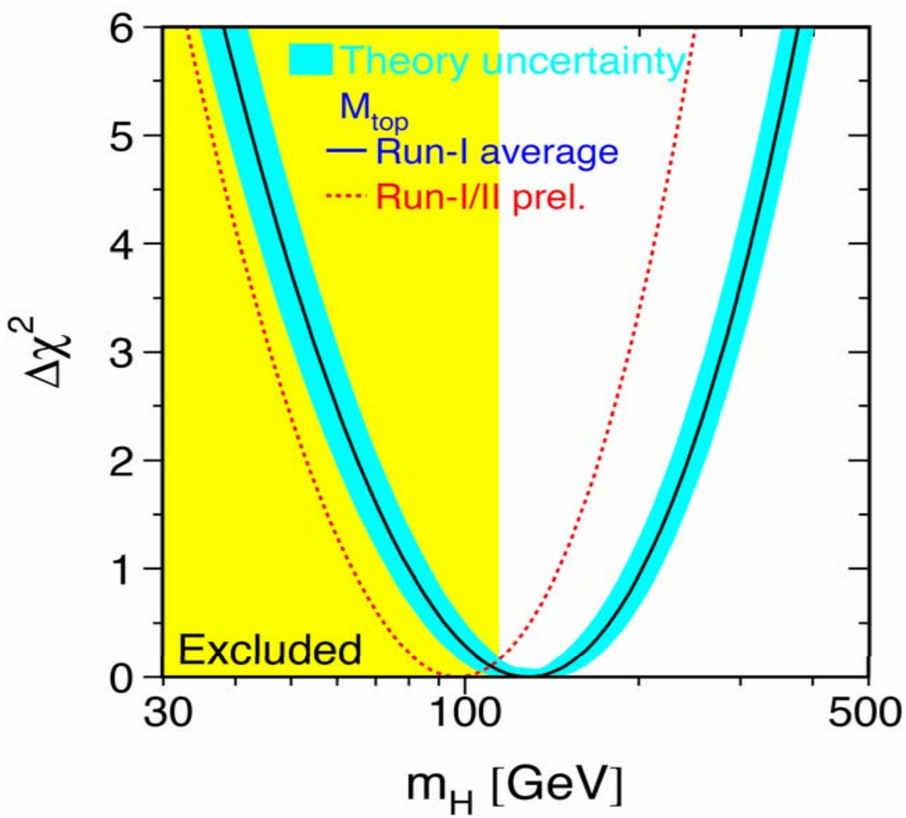
Experiment

Indirect constraints from precision EW data :

M_H < 260 GeV at 95 %CL (2004)

M_H < 186 GeV with Run-I/II prelim. (2005)

Direct limit from LEP2: M_H > 114.4 GeV

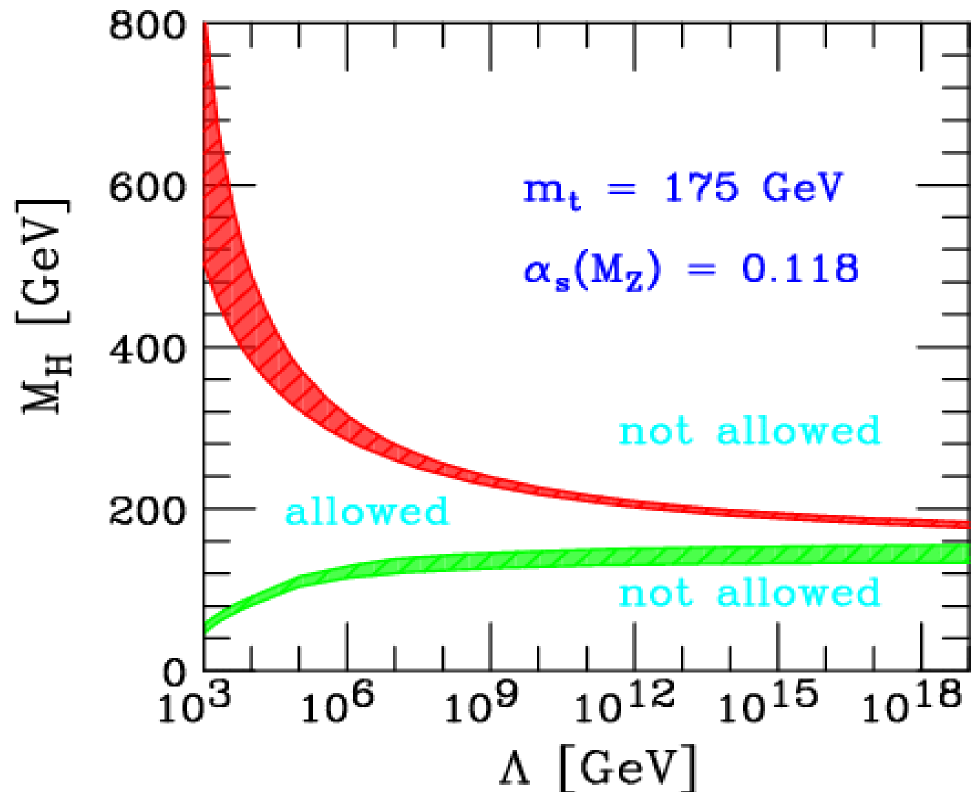


SM theory

The triviality (upper) bound and vacuum stability (lower) bound as function of the cut-off scale Λ

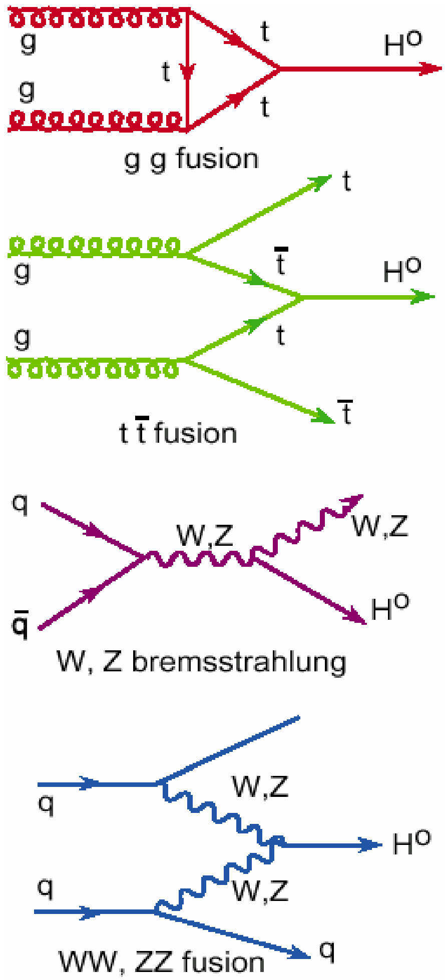
"triviality" :

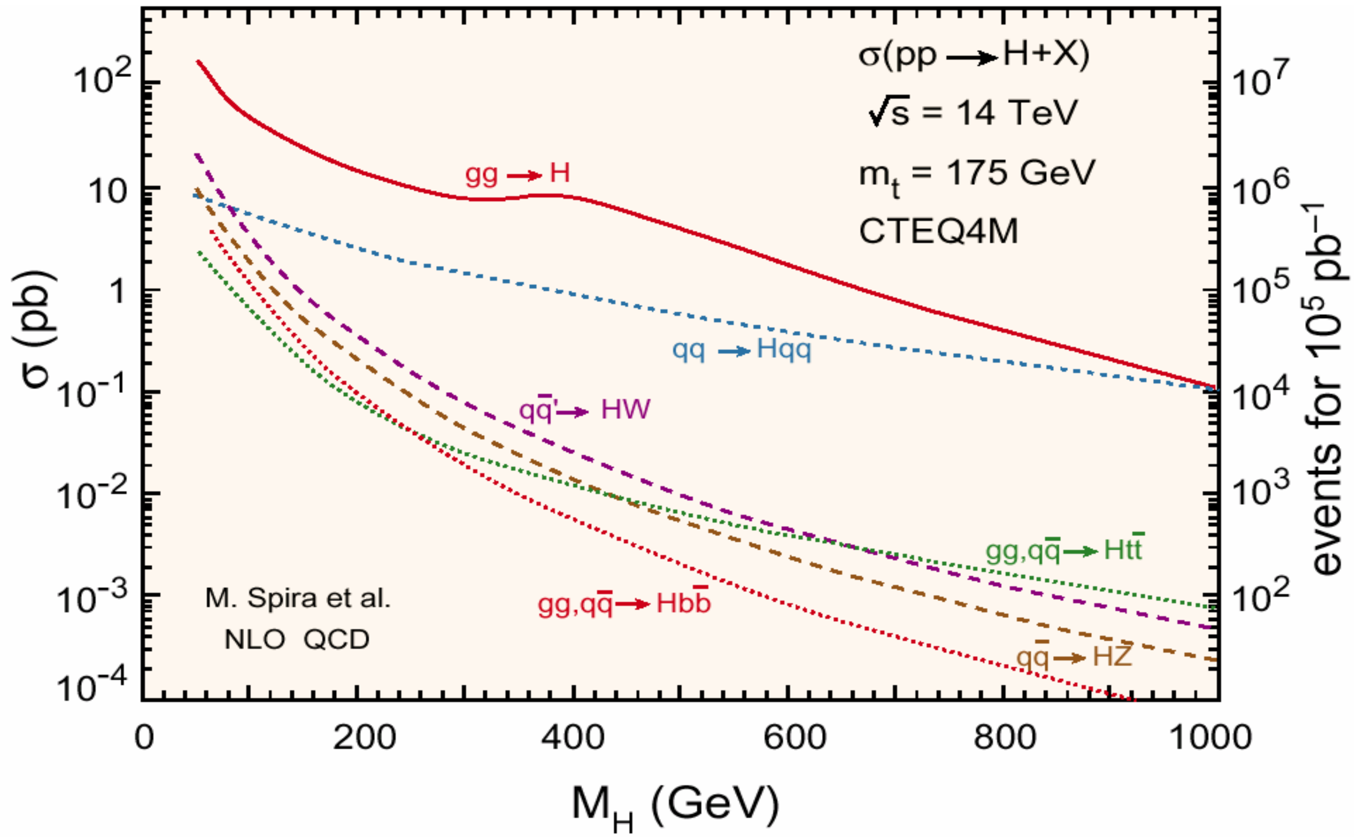
Higgs self-coupling remains finite



SM Higgs at the LHC

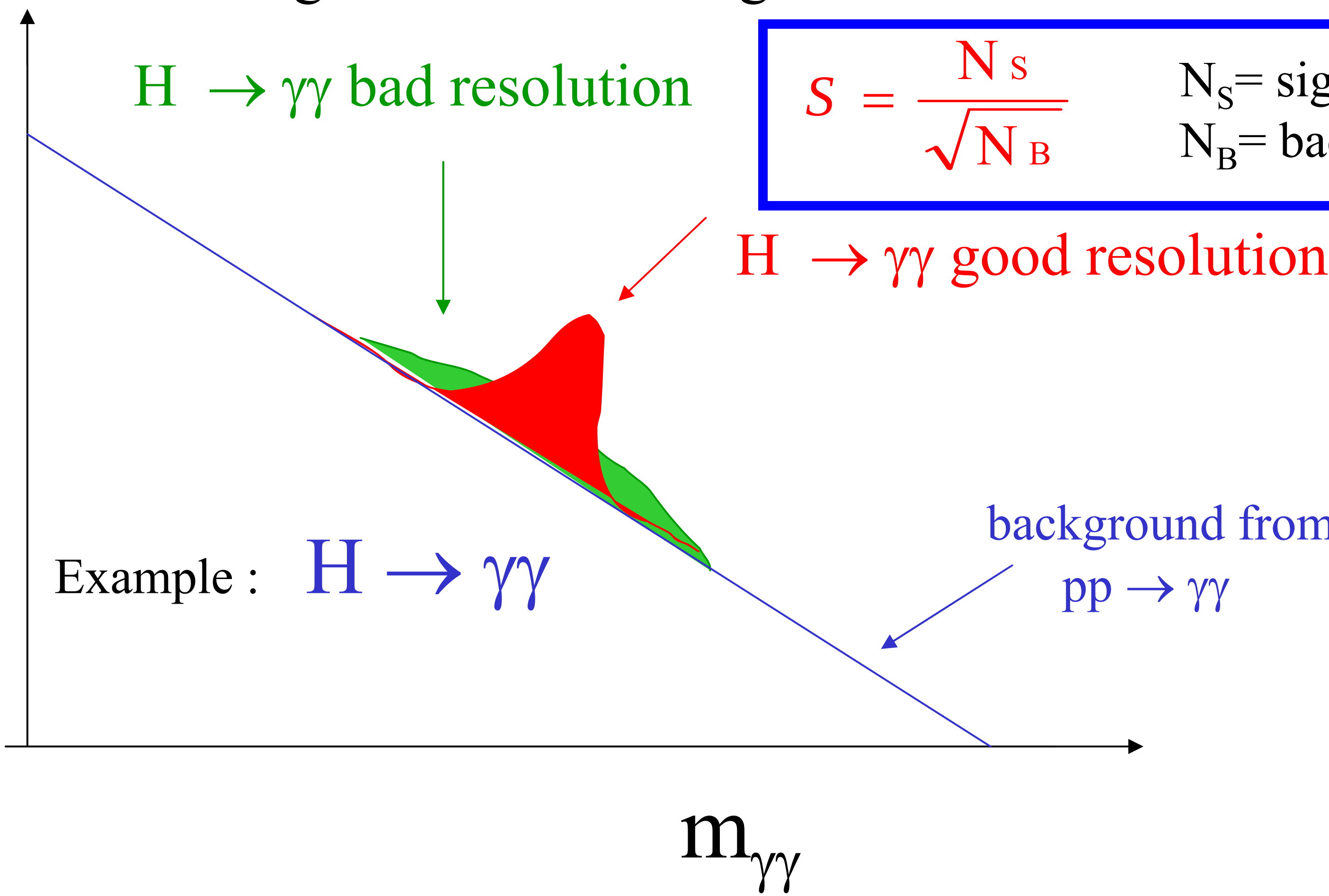
Production mechanisms & cross section





SM Higgs Search Strategy

- Excellent energy resolution of EM calorimeters for e/γ and of the tracking devices for μ in order to extract a signal over the backgrounds.



$$S = \frac{N_S}{\sqrt{N_B}}$$

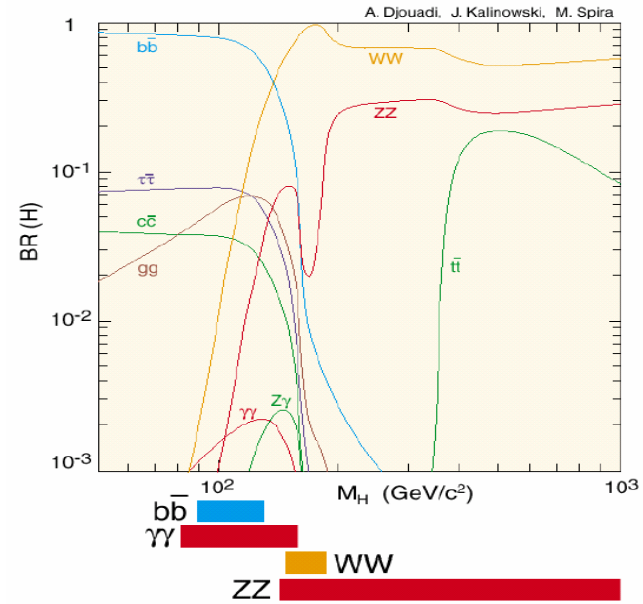
N_S= signal events
N_B= background events

SM Higgs search channels

Low mass $M_H \lesssim 200$ GeV

M. pieri

Production DECAY	Inclusive	VBF	WH/ZH	ttH
$H \to \gamma\gamma$	YES	YES	YES	YES
$H \to bb$			YES	YES
$H \to \tau\tau$		YES		
$H \to WW^*$	YES	YES	YES	
$H \to ZZ^*$, $Z \to \ell^+\ell^-$, ℓ=e,μ	YES			
$H \to Z\gamma$, $Z \to \ell^+\ell^-$, ℓ=e,μ	very low σ			



Intermediate mass
(200 GeV $\lesssim M_H \lesssim$ 700 GeV)

inclusive $H \to WW$
inclusive $H \to ZZ$

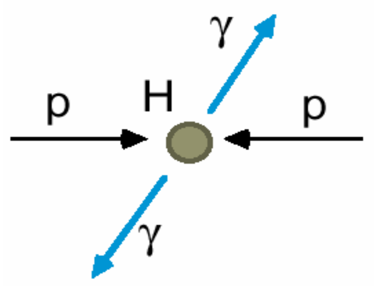
High mass ($M_H \gtrsim$ 700 GeV)

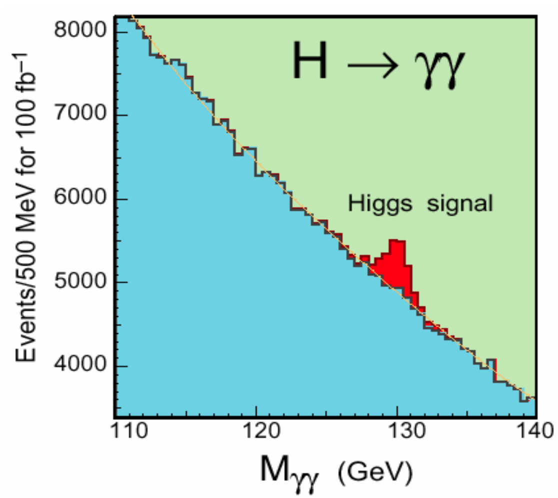
VBF $qqH \to ZZ \to \ell\ell\nu\nu$
VBF $qqH \to WW \to \ell\nu jj$

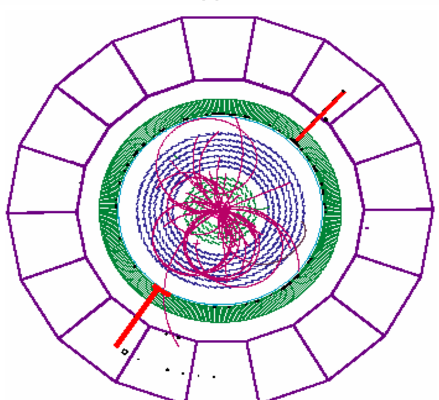
$H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ are the only channels with a very good mass resolution ~1%

Examples

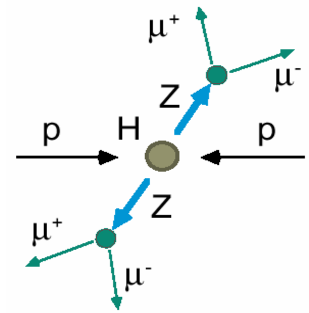
Low M_H < 140 GeV/c²

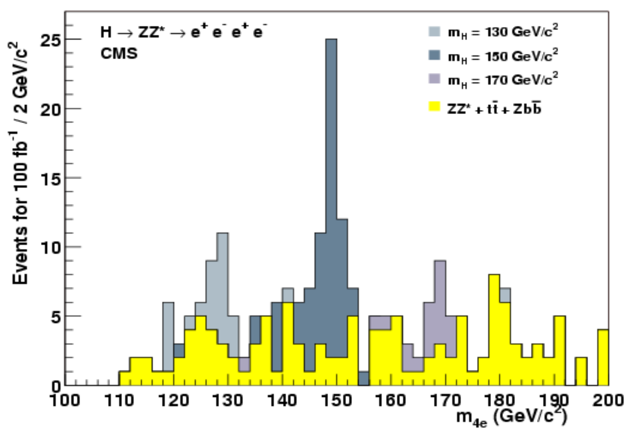




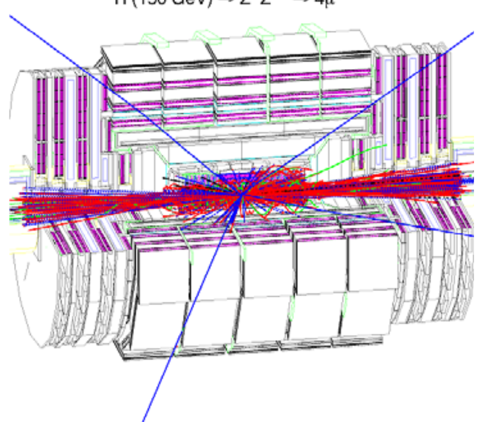


Medium 130<M_H<500 GeV/c²

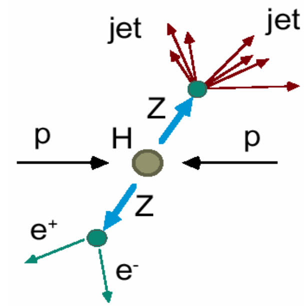


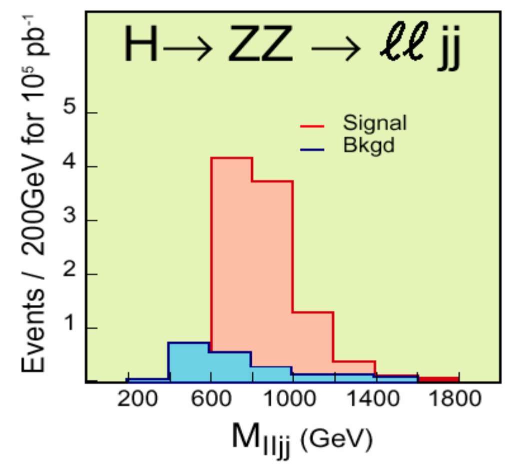


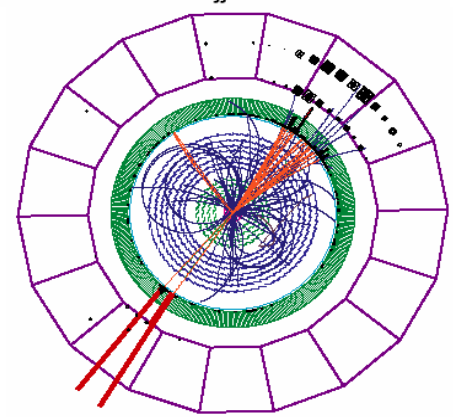
H (150 GeV) → Z^0Z^{0*} → 4μ



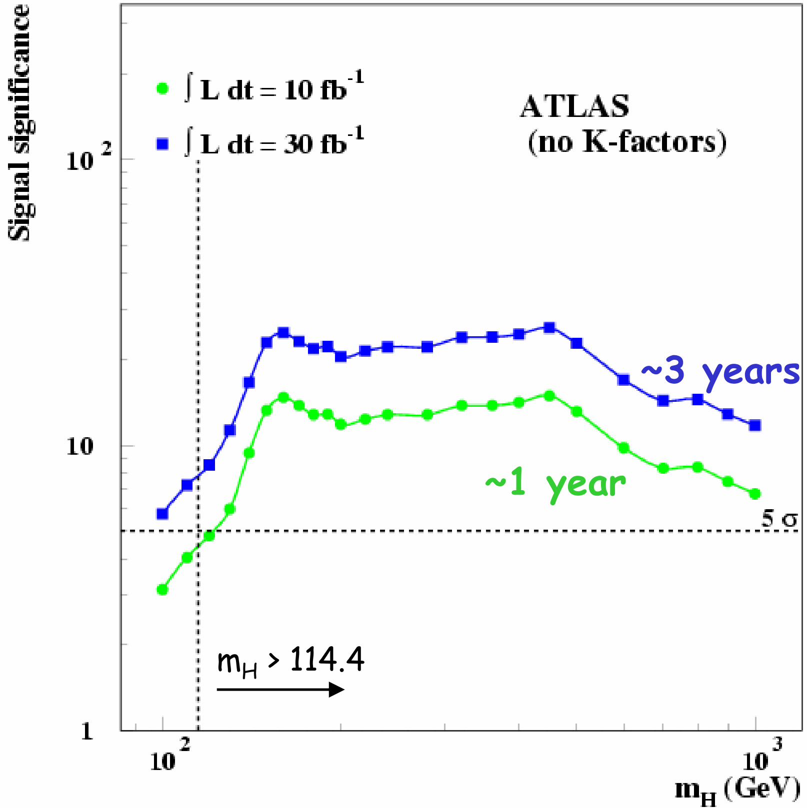
High M_H > ~500 GeV/c²







Higgs Reach



5σ ≡ dis

- Higgs can be discovered over full allowed mass range in 1 year of good LHC operation
  → final word about SM Higgs mechanism by 2009 or so
- However: it will take time to understand and calibrate ATLAS and CMS …
- In most difficult region m_H < 130 GeV ≥3 different channels observable → robustness

What can the LHC do?

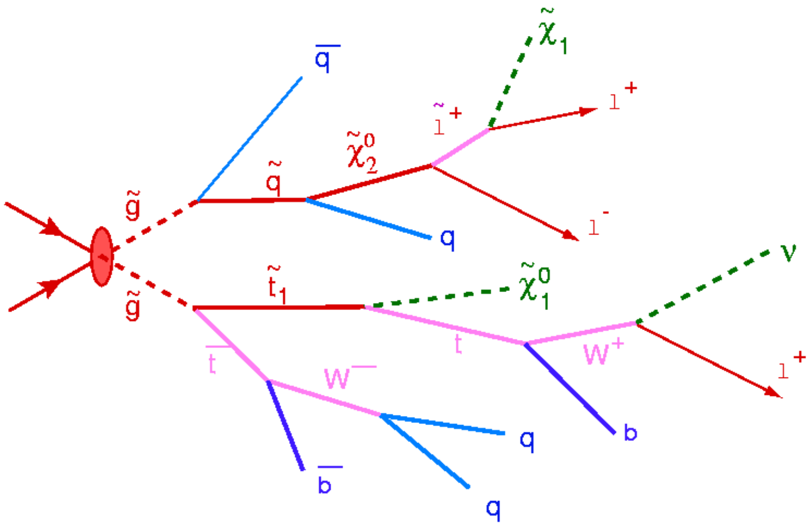
- LHC will discover the SM Higgs in the full region up to 1 TeV or exclude its existence. If no Higgs, other new phenomena in the WW should be observed around 1 TeV
- The LHC will measure with full luminosity (100 fb^{-1})
  - The Higgs mass with 0.1-1% precision
  - The Higgs width, for m_H> 200 GeV, with ~5-8% precision
  - Cross sections x branching ratios with 5-20% precision
  - Ratios of couplings with 10-30% precision
  - Absolute couplings only with additional assumptions
  - Spin information in the ZZ channel for m_H>200 GeV
  - CP information from exclusive central production: $pp \to pHp$

..⇒will get a pretty good picture of the Higgs @ LHC
More detailed information at an ILC

3. Beyond the SM

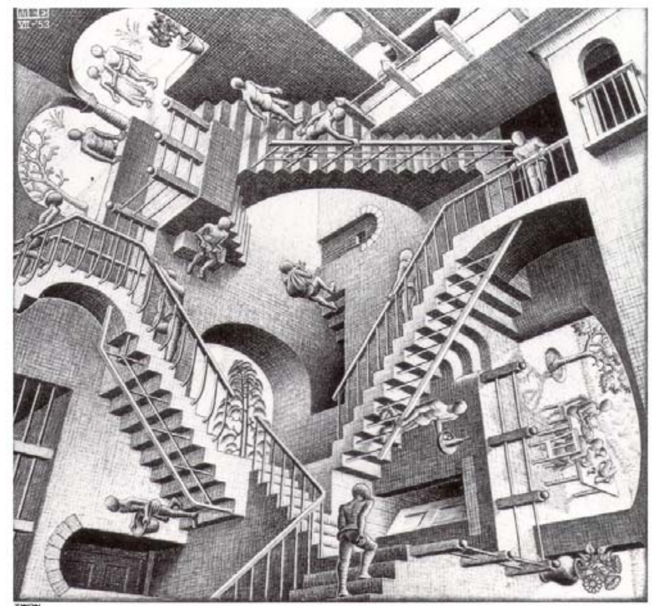
New physics expected around the TeV scale ⇒
Stabelize Higgs mass, Hierarchy problem, Unification of gauge couplings, CDM,...

Supersymmetry



3 isolated leptons
+ 2 b-jets
+ 4 jets
+ E_t^{miss}

Extra dimensions

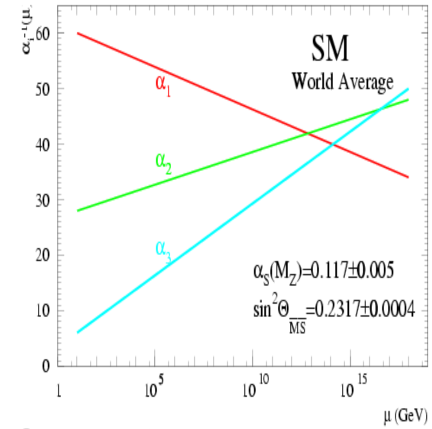


+...

Is the Standard Model the Ultimate Theory?

The Standard Model agrees with all data so far (to 10^{-3}) but

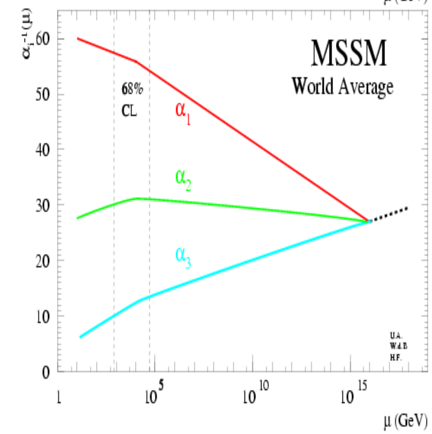
- it tells us how but not why (contains 19 parameters!)
  3 flavour families? Mass spectra? Hierarchy?
- it can get unstable if extrapolated to very high energies
  Needs fine tuning of parameters to level of 10^{-30} !
- it has no connection with gravity
- no unification of the forces at high energy



Most popular extensions these days (2002)

If a Higgs field exists:

- Supersymmetry
- Extra space dimensions



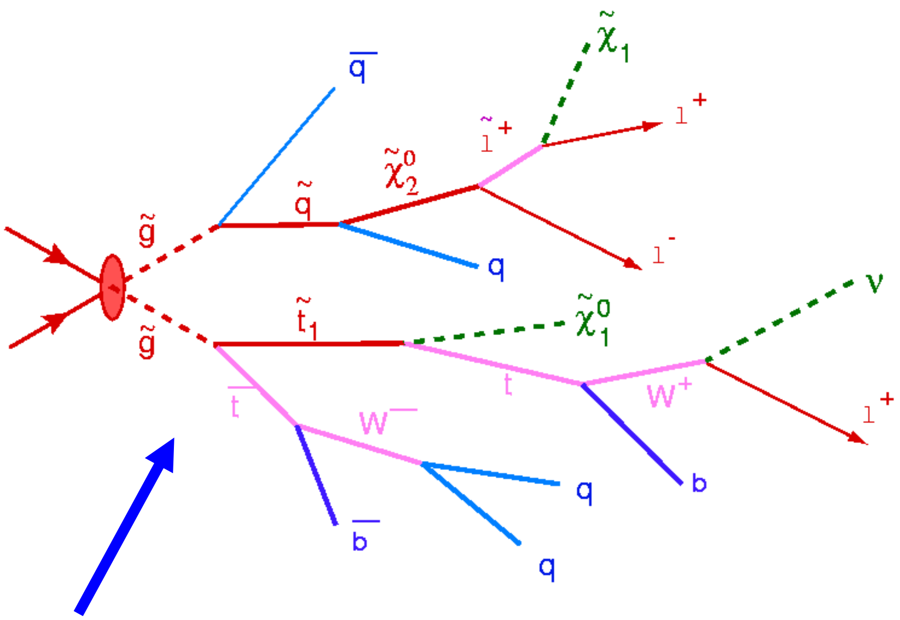
If there is no Higgs below ~ 700 GeV

- Strong electroweak symmetry breaking around 1 TeV
  (technicolor, strong WW scattering)

Other ideas: more gauge bosons/quark & lepton substructure

Supersymmetry

⇒Lots of new particles (squarks, sleptons,…) predicted with masses in the range from 10's of GeV's up to several TeV range

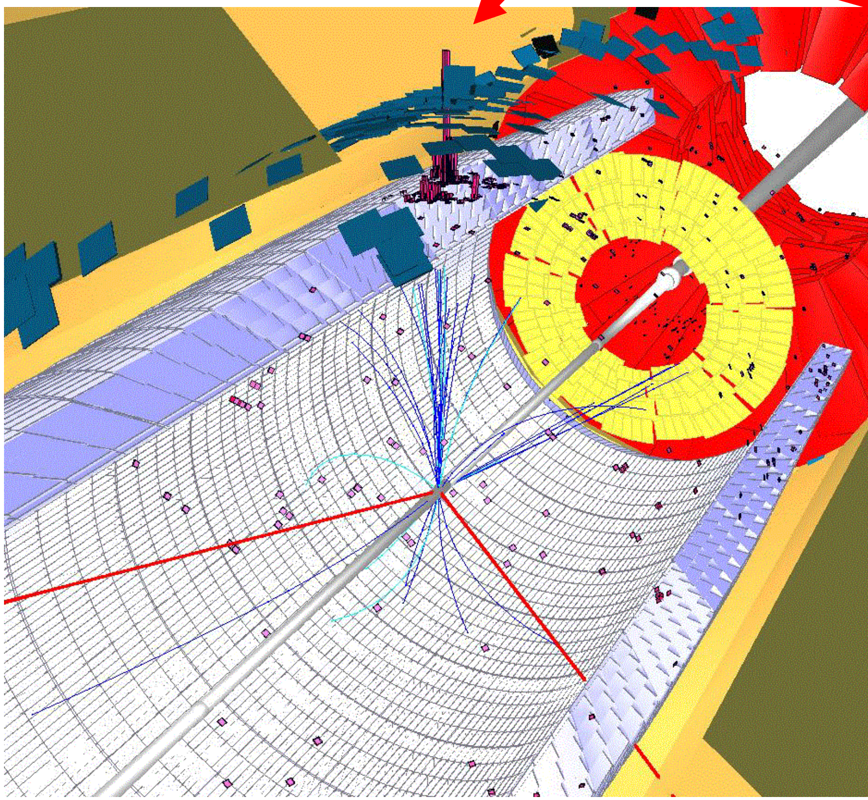


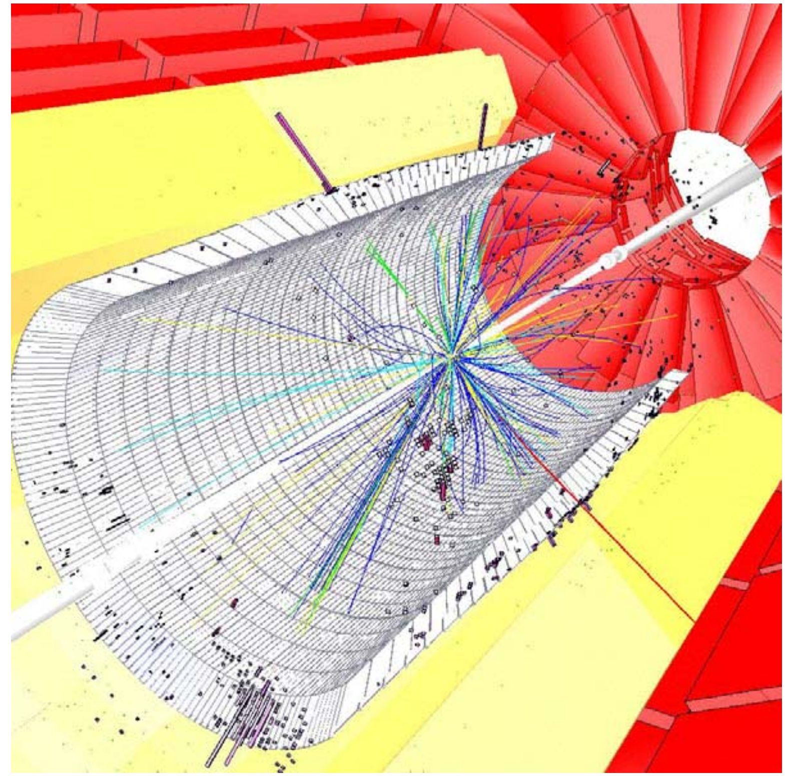
3 isolated leptons
+ 2 b-jets
+ 4 jets
+ E_t^{miss}

FERMIONS		SUSY PARTNER (SCALARS)	
LEPTONS			
e		Selectron	$\tilde{e}$
μ		Smuon	$\tilde{\mu}$
τ		Stau	$\tilde{\tau}$
ν_e, ν_μ, ν_τ		Sneutrinos	$\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau$
QUARKS			
u, c, t		Squarks	$\tilde{u}, \tilde{c}, \tilde{t}$
d, s, b			$\tilde{d}, \tilde{s}, \tilde{b}$
GAUGE PARTICLES (BOSONS)		SUSY PARTNER (FERMIONS)	
$W^\pm, H^\pm$		Charginos	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$
$\gamma, Z^0, h^0, H^0, A^0$		Neutralinos	$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$
g_i		Gluinos	$\tilde{g}_i$
Graviton G		Gravitino	$\tilde{G}$

Lightest SUSY particle stable: dark matter candidate ?

SUSY events (LM4 point: leptons, missing E_T)

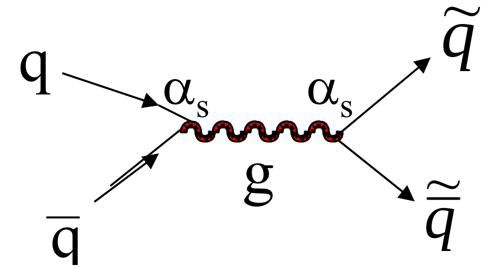




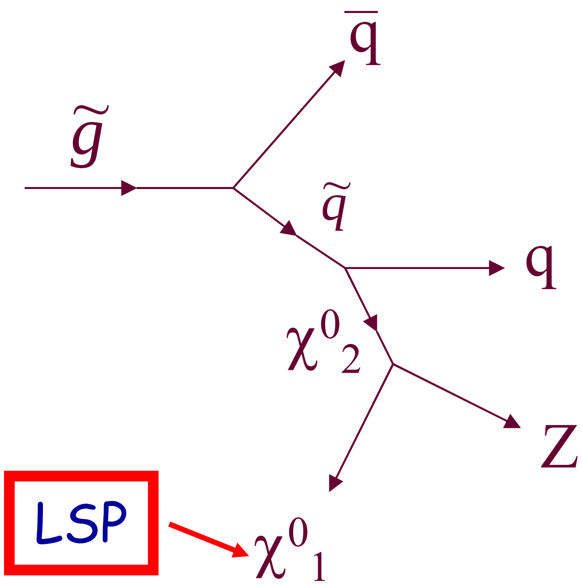
Samples of "standard sets" of events now automatically produced for each new release

Supersymmetric particles

Squarks and gluinos are produced via strong processes:
!Large cross sections!

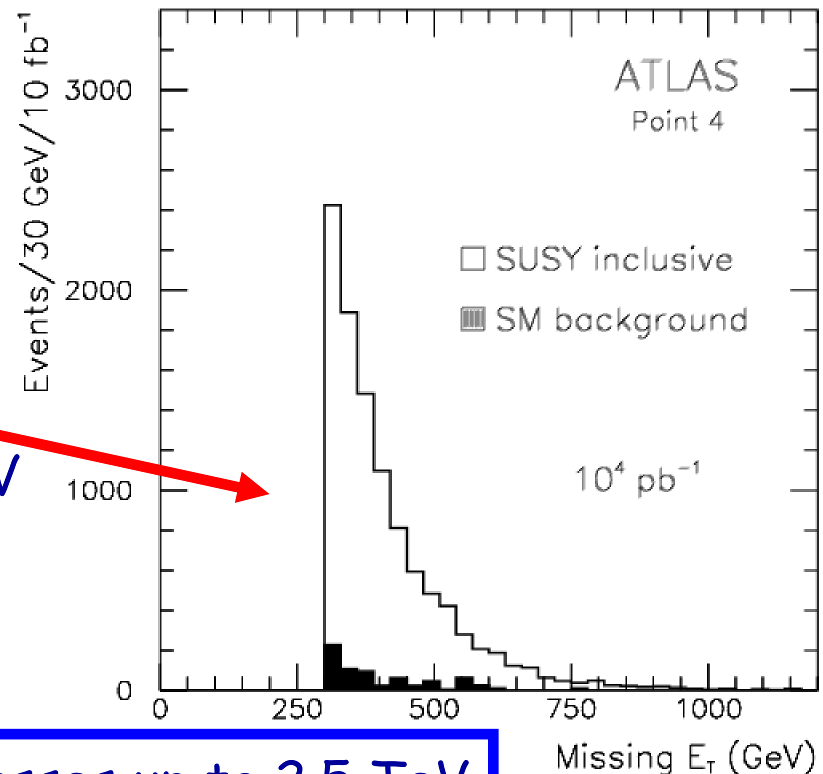


Complicated decay chains: many jets and missing energy from the lightest stable SUSY particle (LPS)



LSP

E.G. 900 GeV squarks
E_t^{miss} > 300 GeV
+ 4 jets

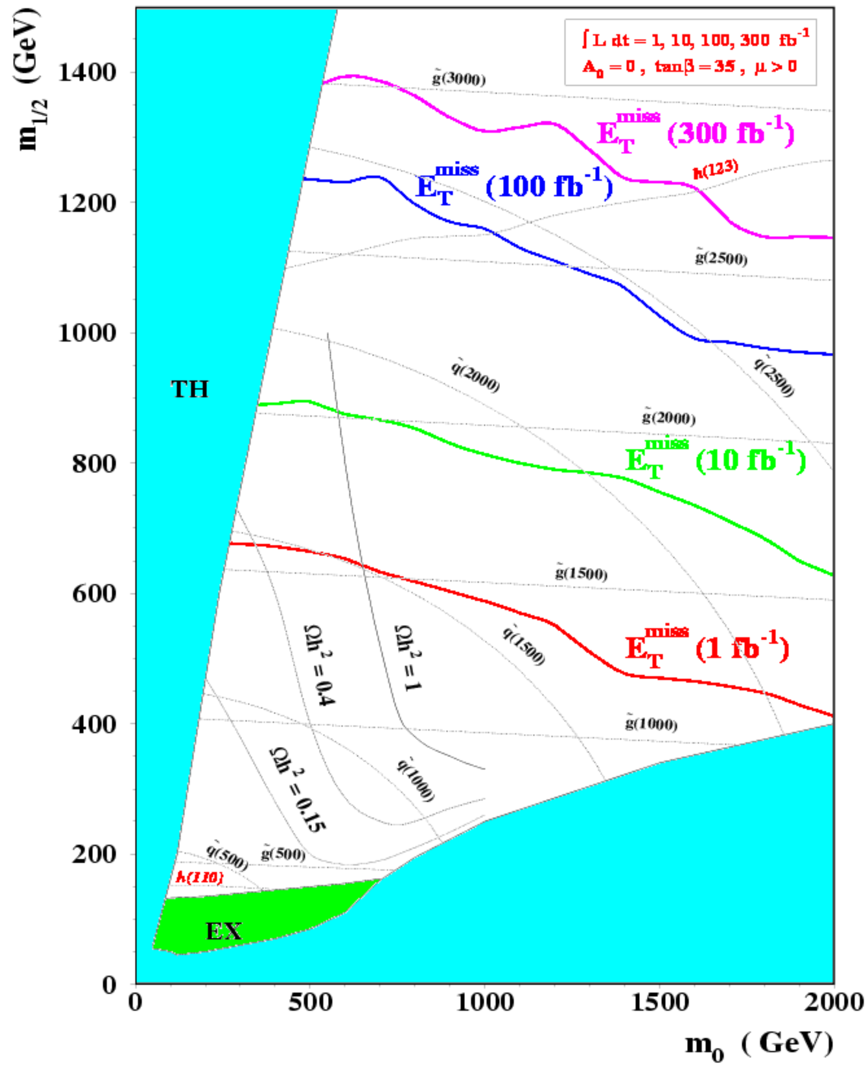


Discover/exclude squarks and gluinos for masses up to 2.5 TeV

SUSY @ LHC

LHC = a SUSY factory

M_{sp}(GeV)	σ (pb)	Evts/yr
500	100	10^6-10^7
1000	1	10^4-10^5
2000	0.01	10^2-10^3



Universal gaugino mass at GUT scale

Universal scalar mass at GUT scale →

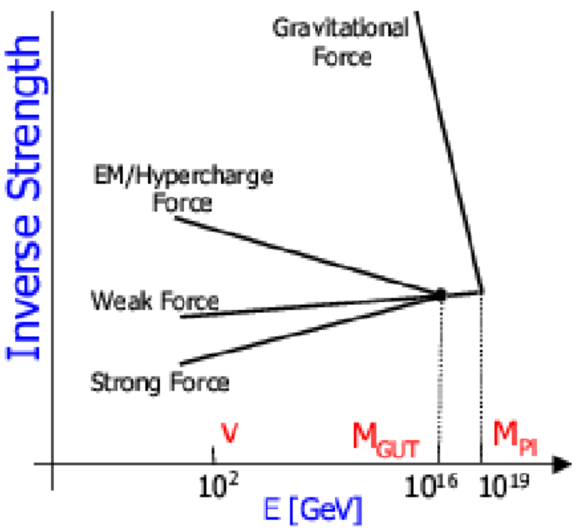
Large Extra Dimensions

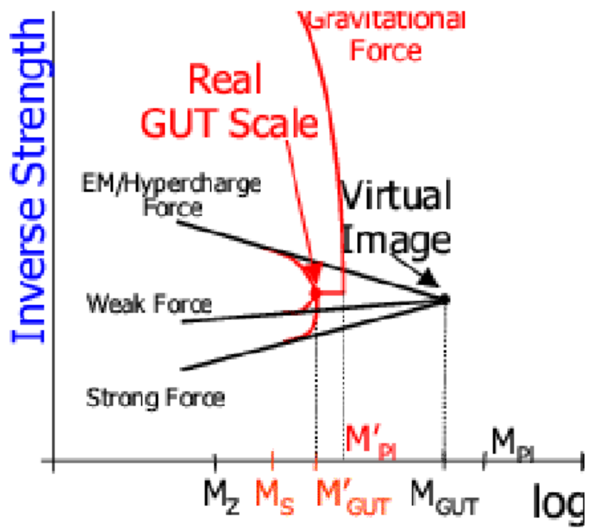
Assume that gravity can propagate in extra dimensions of size R

Newton's law changes from $F \sim 1/R^2 \rightarrow 1/R^{n+2}$

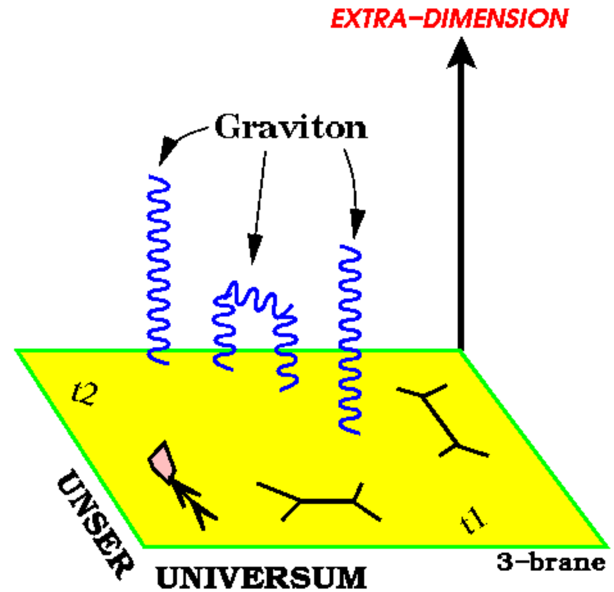
Gravity gets stronger

Effective Planck Scale: $M_S^{n+2} \sim M_{pl}^2/(R)^n$

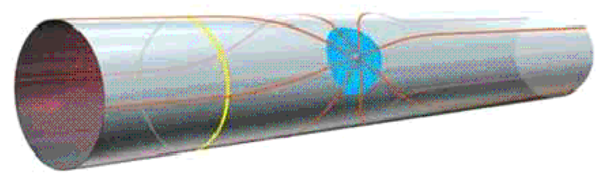




$\Rightarrow$ M_S could be of O(1) TeV



Curled up…

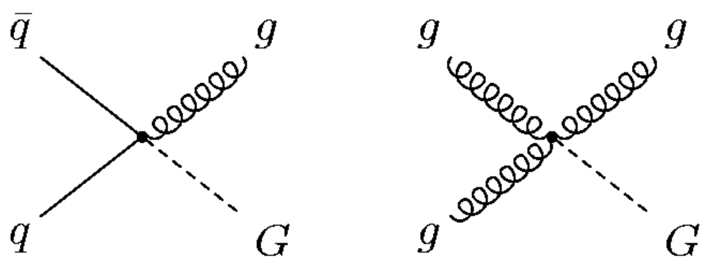


Many different models…

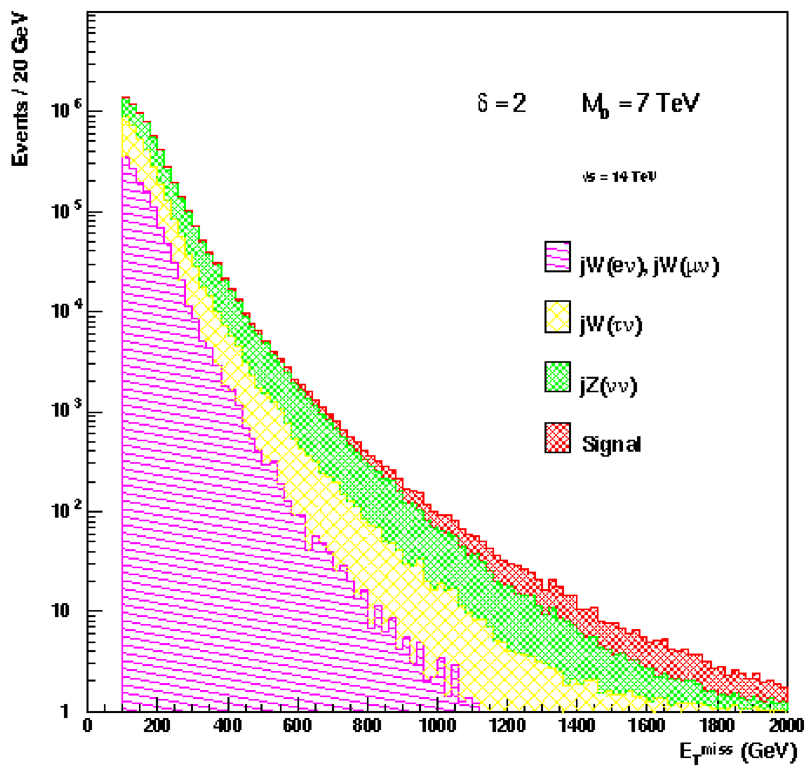
Extra Dimension signals at the LHC

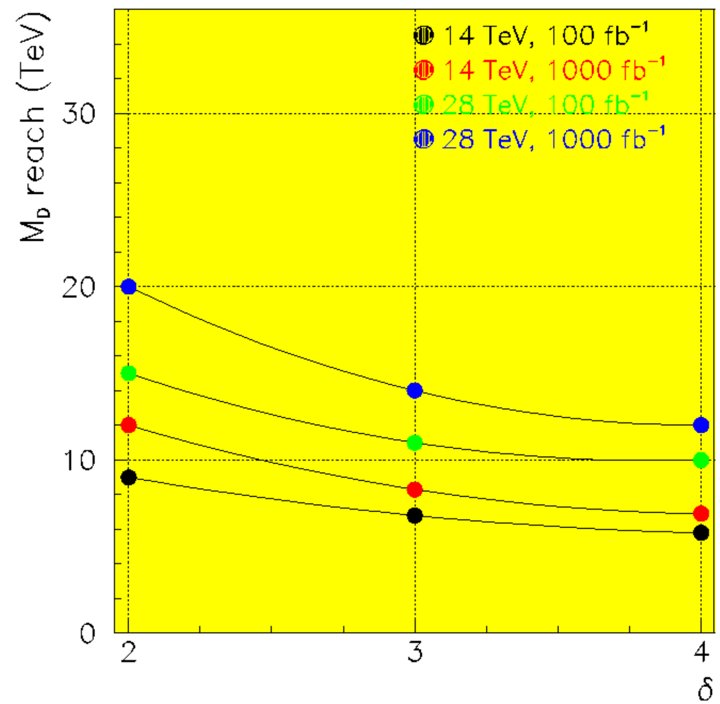
Planck scale ~ TeV range

Graviton production!
Graviton escapes detection



Signal: single jet + large missing ET



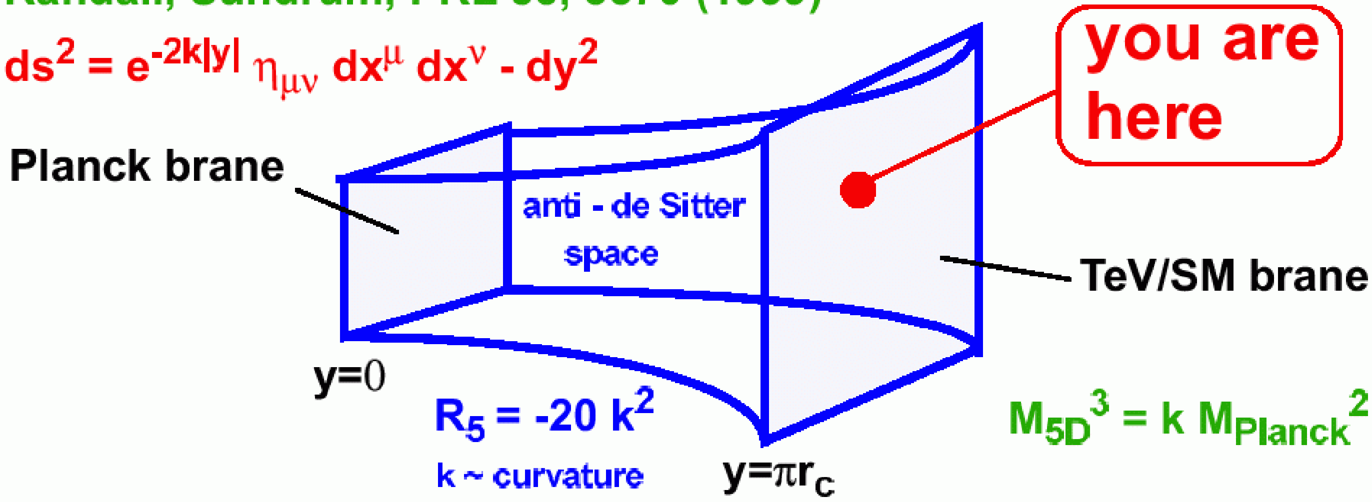


Other ED models lead to other signals
(e.g. heavy resonances)

Curved Space: RS Extra Dimensions

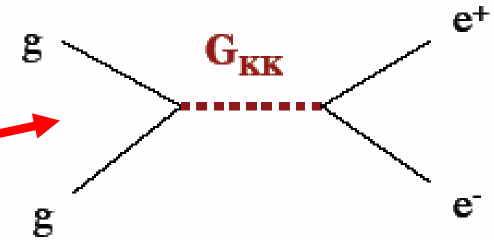
Randall, Sundrum, PRL 83, 3370 (1999)

$$ds^2 = e^{-2k|y|}\,\eta_{\mu\nu}\, dx^\mu\, dx^\nu - dy^2$$

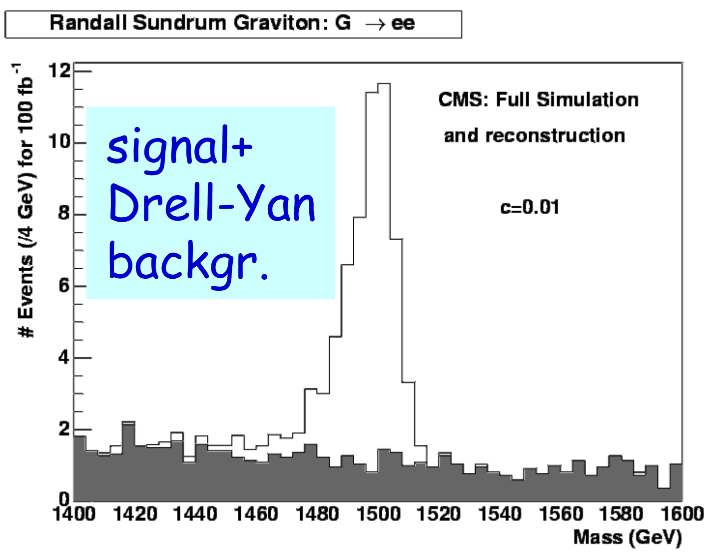


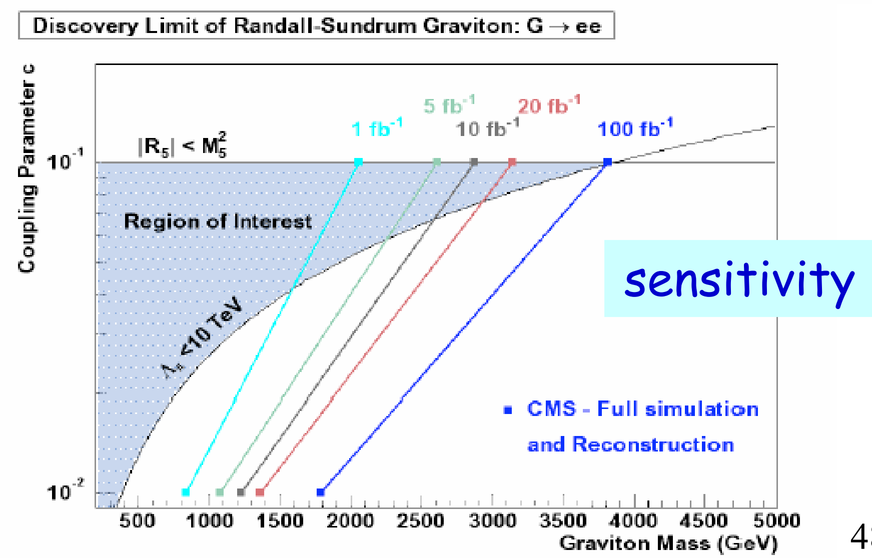
$$M_{5D}^3 = k\, M_{Planck}^2$$

phenomenology



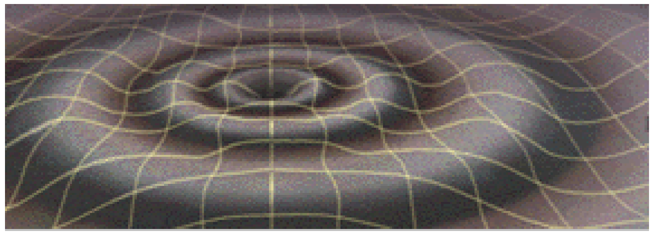
Study the channel pp→Graviton→ e+e-

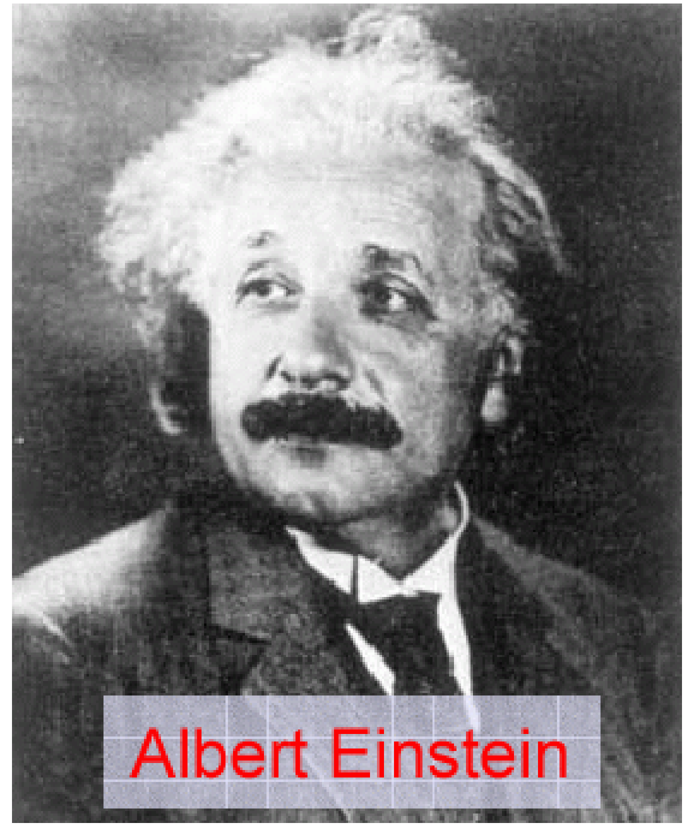




A bit of fun: Black Holes in General Relativity

Black Holes are a direct prediction of Einstein's general theory on relativity (though never quite accepted by Einstein)





Schwarzschild Radius:
within which nothing escapes gravitational force
If the radius of an object is less than R_s a black hole is formed

$$R_S \equiv 2MG/c^2$$

with $G = 1/(M_{Planck})^2$

Smallest scale: Planck Length (10^{-35} m)
Need to squeeze 10^{19} GeV in such small area!!

No chance to produce a black hole in the lab if gravity remains weak

What if Planck Scale in TeV Range?

- Schwarzschild radius

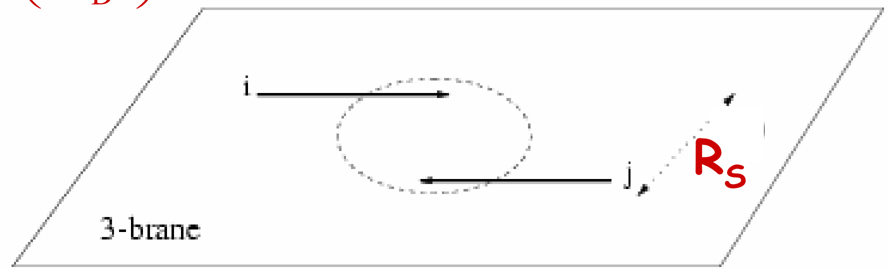
4-dim., $M_{gravity} = M_{Planck}$ $$R_S \sim \frac{2}{M_{Pl}^2}\frac{M_{BH}}{c^2}$$

4 + n-dim., $M_{gravity} = M_D \sim$ TeV $$R_S \sim \frac{1}{M_D}\left(\frac{M_{BH}}{M_D}\right)^{\frac{1}{n+1}}$$

$R_s \rightarrow \ll 10^{-35}$ m

$R_s \rightarrow \sim 10^{-19}$ m

Since M_D is low, tiny black holes of $M_{BH} \sim$ TeV can be produced if partons ij with $\sqrt{s_{ij}} = M_{BH}$ pass at a distance smaller than R_S



- Large partonic cross-section : $\sigma(ij \rightarrow BH) \sim \pi R_S^2$
- $\sigma(pp \rightarrow BH)$ is in the range of 1 nb – 1 fb

e.g. For M_D ~1 TeV and n=3, produce 1 event/second at the LHC

- Black holes decay immediately by Hawking radiation (democratic evaporation) :

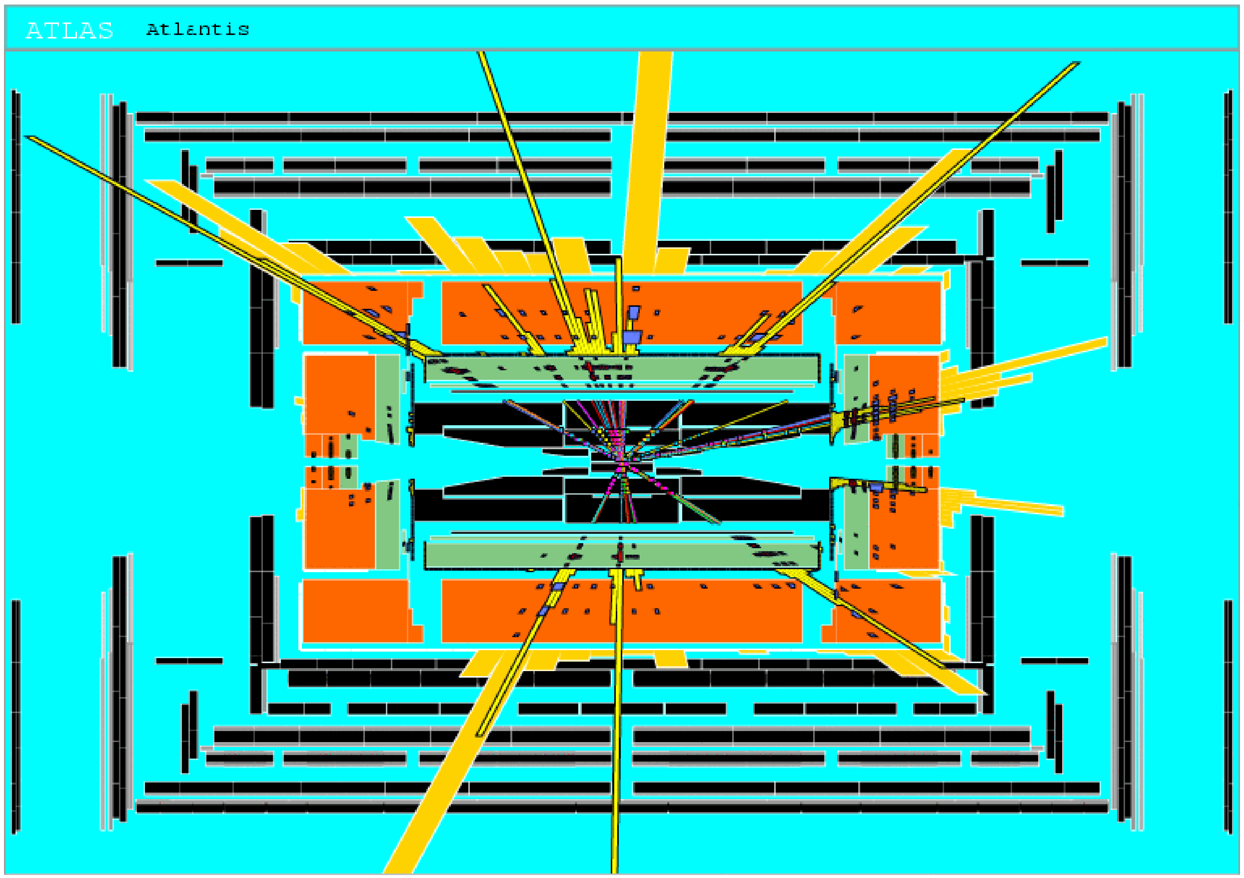
-- large multiplicity
-- small missing E
-- jets/leptons ~ 5

} expected signature (quite spectacular …)

Black Holes production

If the Planck scale in ~TeV region: can expect Black Hole production

Simulation of a black hole event with $M_{BH} \sim 8$ TeV in ATLAS $M_D \sim 1$ TeV, n=6

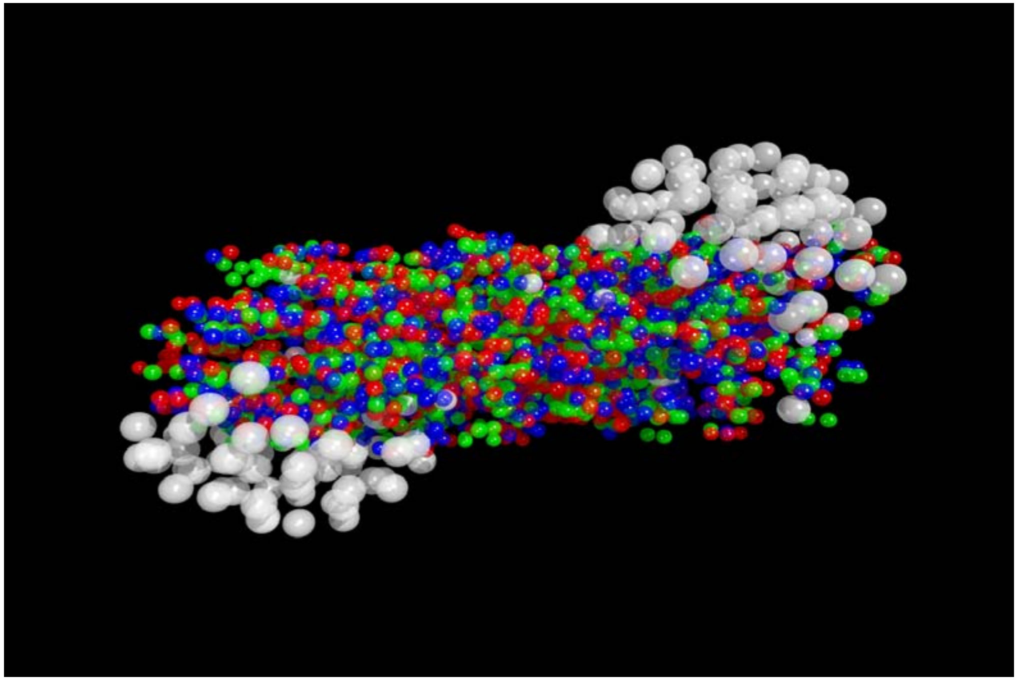


~ Spherical events
Many high energy jets leptons, photons etc.

Ecological comment: BH's will decay within 10^{-27} secs or so

Detectors, electronics (and rest of the world) are safe!!

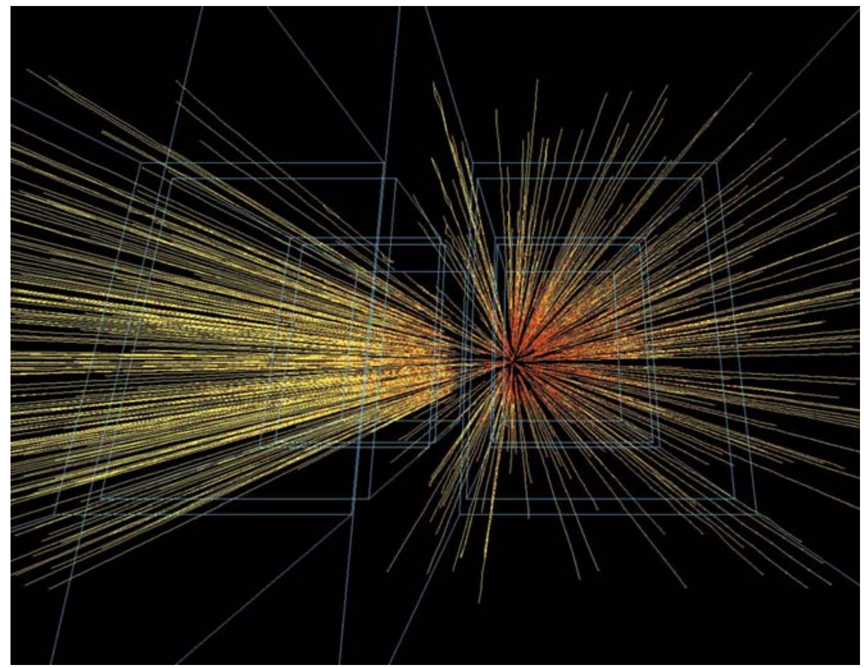
Heavy Ions in LHC



Search for a new state of matter: quark gluon plasma

At LHC: ALICE & CMS (& ATLAS?)

10000-50000 particles



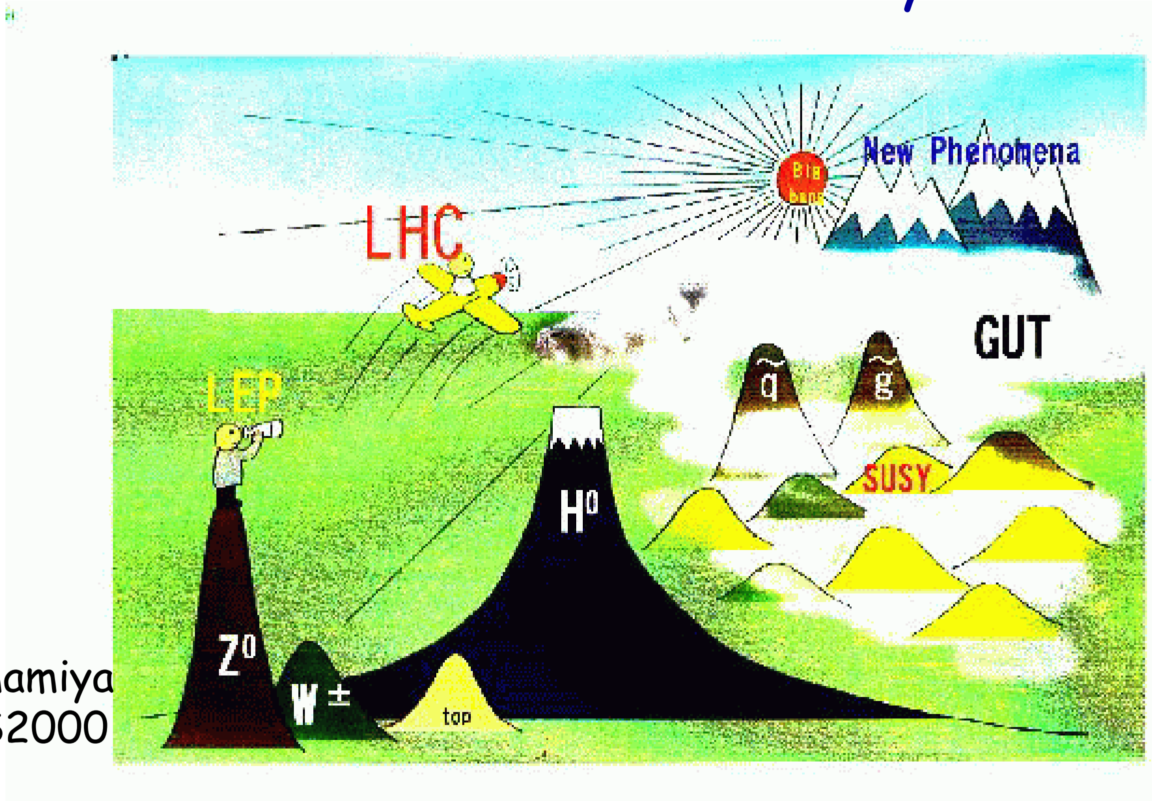
Some evidence from CERN fixed target and RHIC experiments (J/ψ suppression, strangeness production, low mass e^+e^- pairs…)

Summary

Exciting times ahead!

The LHC is expected to bring us over the mountains in the land of new phenomena.

With its data we expect to understand better **why** Nature is the way it is



S.Komamiya LCWS2000

We look forward to the startup in **2007**