
CERN
Accelerating Science and Innovation
Der Large Hadron Collider –
Beginn einer neuen Ära
in der Grundlagenforschung
R.-D. Heuer, CERN
DPG Tagung, Karlsruhe, 30 März 2011

Past few decades

"Discovery" of Standard Model

through synergy of

hadron - hadron colliders (e.g. Tevatron)

lepton - hadron colliders (HERA)

lepton - lepton colliders (e.g. LEP, SLC)

What have we learned the last 50 years
or
Status of the **Standard Model**

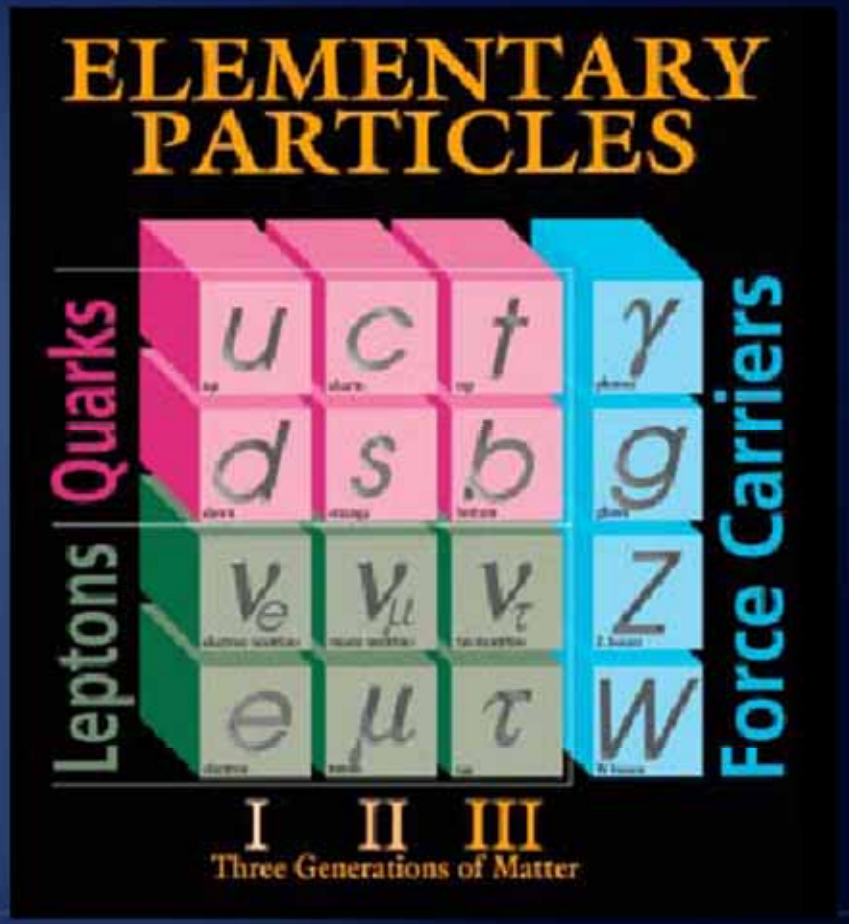
The physical world is composed of

Quarks and Leptons

(Fermions)

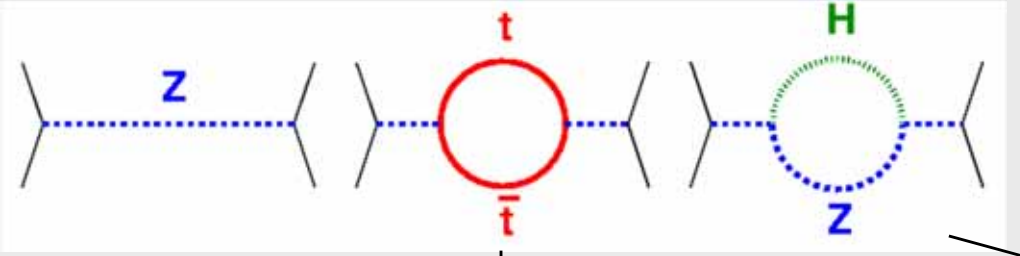
interacting via force carriers

(Gauge Bosons)

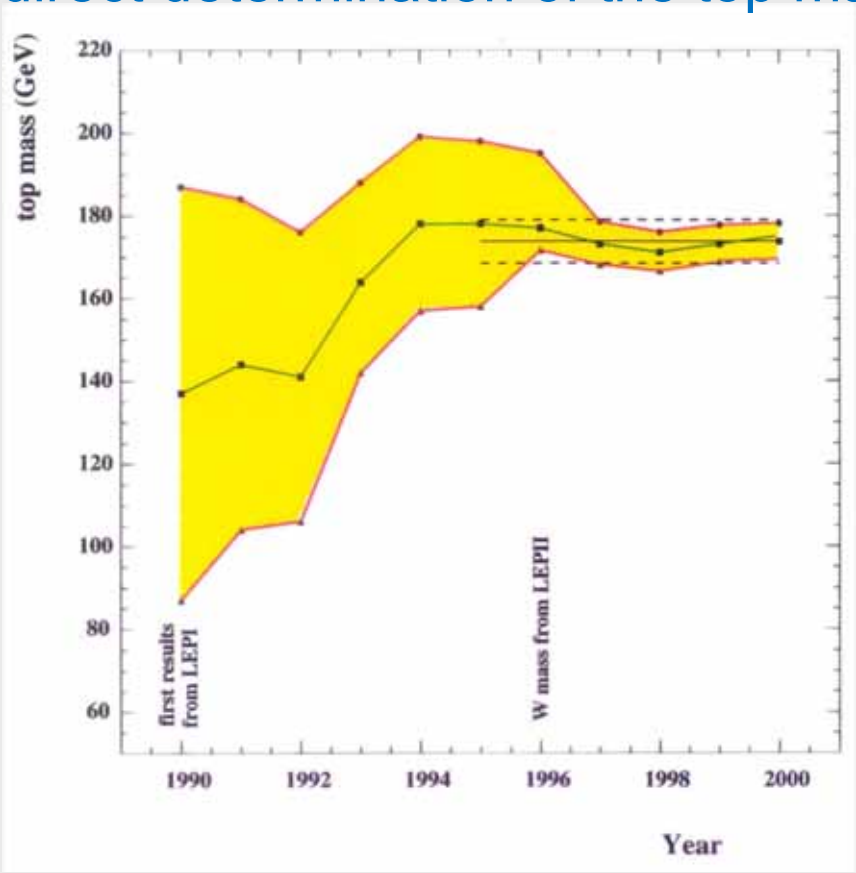


Last entries: **top-quark 1995**
tau-neutrino 2000

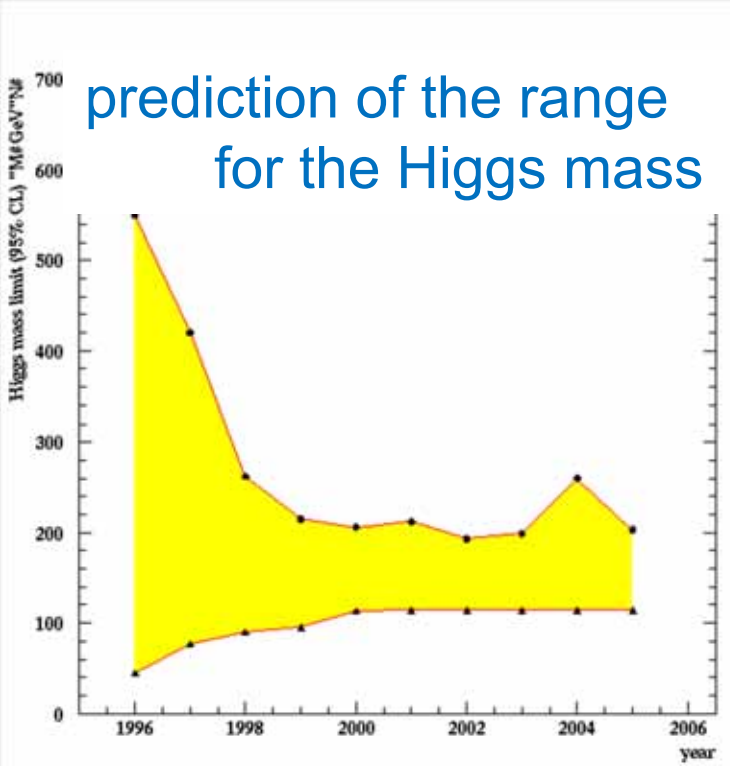
Test of the SM at the Level of Quantum Fluctuations



indirect determination of the top mass



prediction of the range for the Higgs mass



possible due to
- precision measurements
- known higher order electroweak corrections

$$\propto \left(\frac{M_t}{M_W}\right)^2, \ln\left(\frac{M_h}{M_W}\right)$$

Status recent Summer Conferences

Standard Model Analysis

	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ^0_{had} [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21586
R_c	0.1721 ± 0.0030	0.1722
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.374
Γ_W [GeV]	2.140 ± 0.060	2.091
m_t [GeV]	170.9 ± 1.8	171.3

Fit to 17 high-Q^2 observables plus $\Delta\alpha_{had}$:

χ^2/ndof = 18.2/13 (15.1%)

Largest χ^2 contribution:

A_l(SLD) vs. $A_{fb}b$(LEP)

Decided in favour of leptons by M_W

Without this point, the fit is *too* good!

Afb(b) has largest pull: 2.9σ!

however . . .

. . . many key questions open

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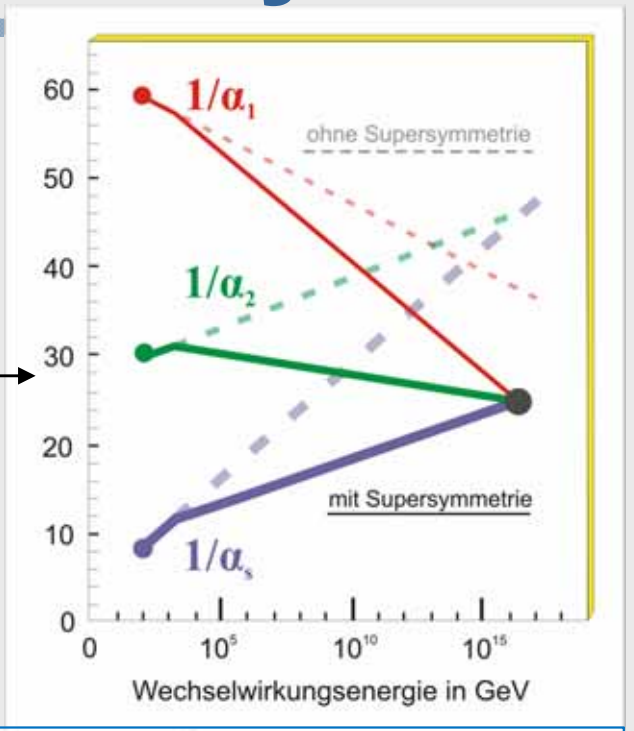
Key Questions of Particle Physics

origin of mass/matter or
origin of electroweak symmetry breaking

unification of forces



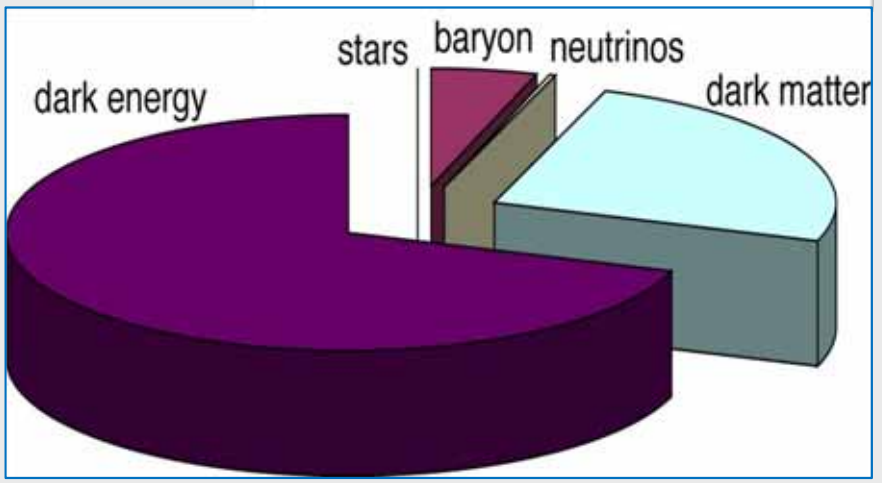
fundamental symmetry of forces and matter

unification of quantum physics and general relativity

number of space/time dimensions

what is dark matter

what is dark energy



Solutions?

Standard Model

For all proposed solutions:
new particles should appear
at **TeV** scale or below
→ **territory of the LHC**

Selected NP
since 1957
Except P. Higgs

Technicolor

New (strong) interactions produce EWSB

Extensions of the SM gauge group :
Little Higgs / GUTs / ...

Supersymmetry

New particles at ≈ TeV scale, light Higgs
Unification of forces
Higgs mass stabilized
No new interactions

Extra Dimensions

New dimensions introduced
$m_{Gravity} \approx m_{elw}$ ➲ Hierarchy problem solved
New particles at ≈ TeV scale

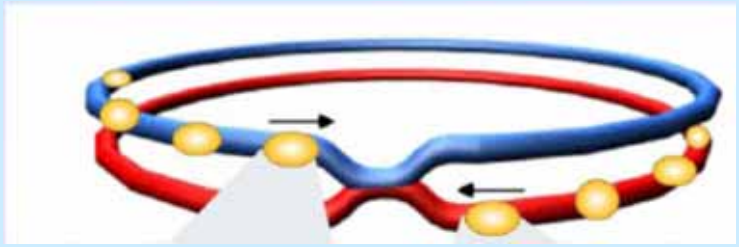
cessful for ever ??

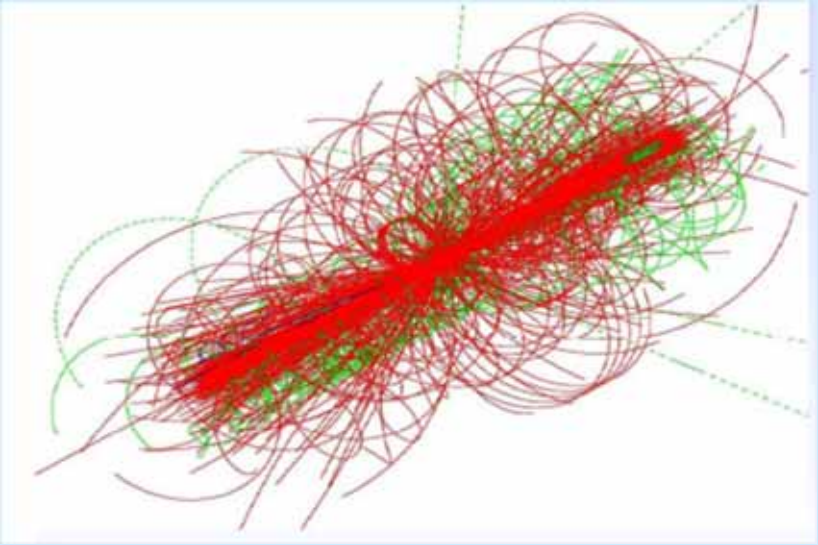
Enter a New Era in Fundamental Science

Start-up of the Large Hadron Collider (LHC), one of the largest and truly global scientific projects ever, is the most exciting turning point in particle physics.

Exploration of a new energy frontier
Proton-proton and Heavy Ion collisions
at E_{CM} up to 14 TeV

Proton-Proton Collisions at the LHC





- **2808 + 2808 proton bunches**
  separated by 7.5 m
  → collisions every 25 ns
  = 40 MHz crossing rate

- **10^{11} protons per bunch**

- **at $10^{34}/cm^2/s$**
  ≈ 35 pp interactions per crossing
  pile-up

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

- **in each collision**
  ≈ 1600 charged particles produced

enormous challenge for the detectors
and for data collection/storage/analysis

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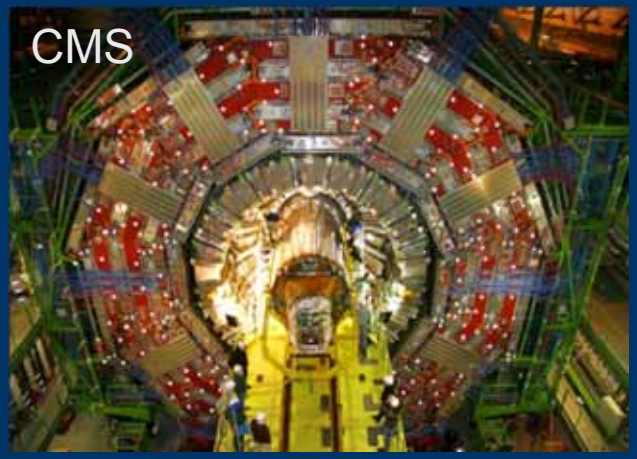
LHC Experiments → complementary

Specialised detector to study b-quarks → CPV

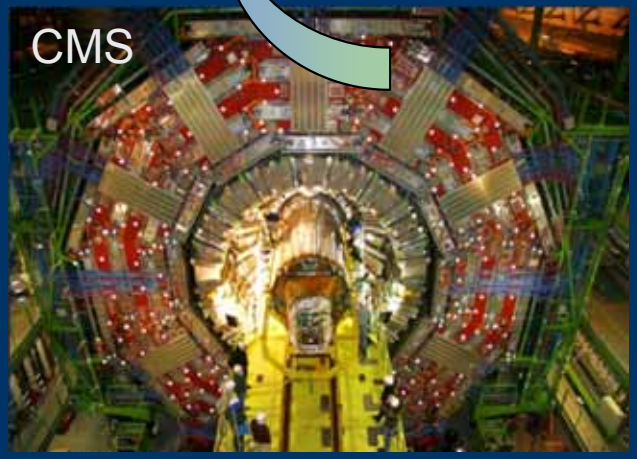


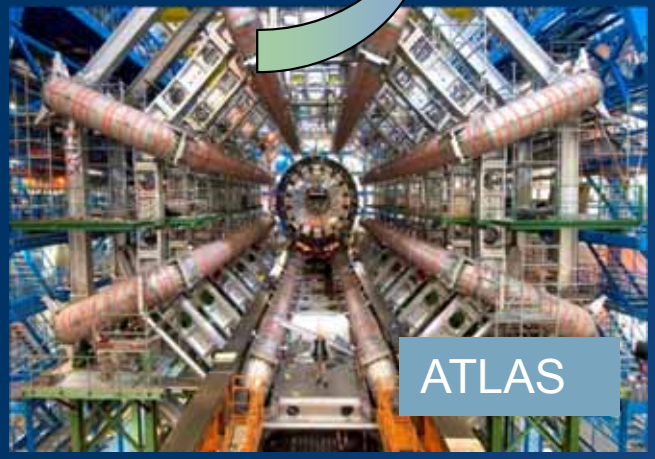
General purpose detectors

Specialised detector to study heavy ion collisions

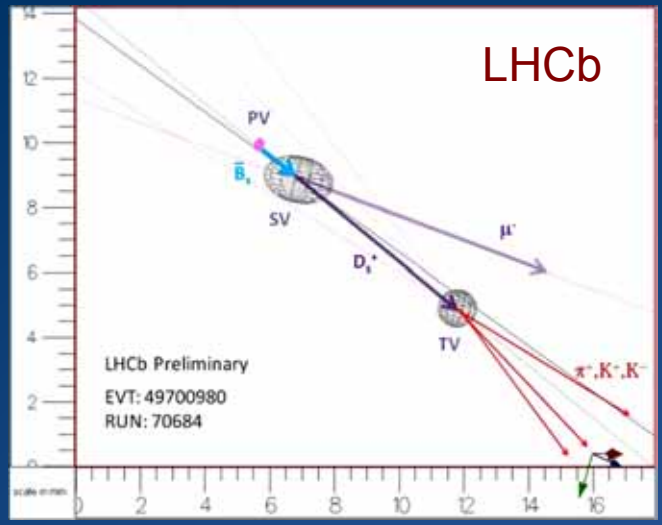
LHC Experiments → complementary

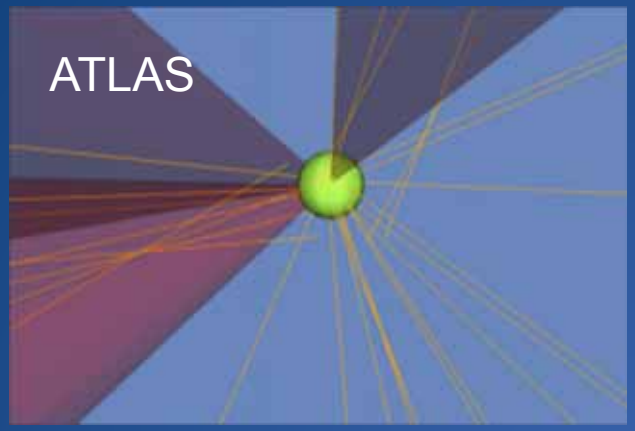
Overlap in physics reach





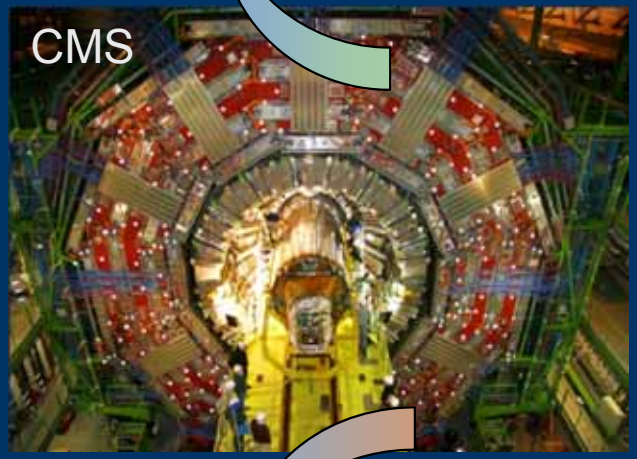
Key feature: reconstruct secondary vertex

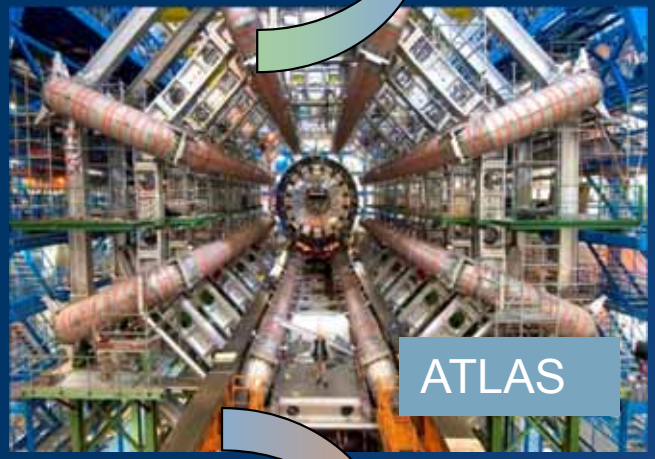




LHC Experiments → complementary

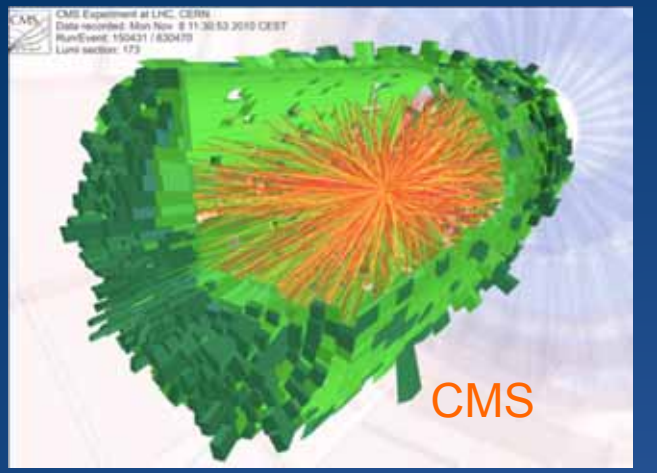
Overlap in physics reach

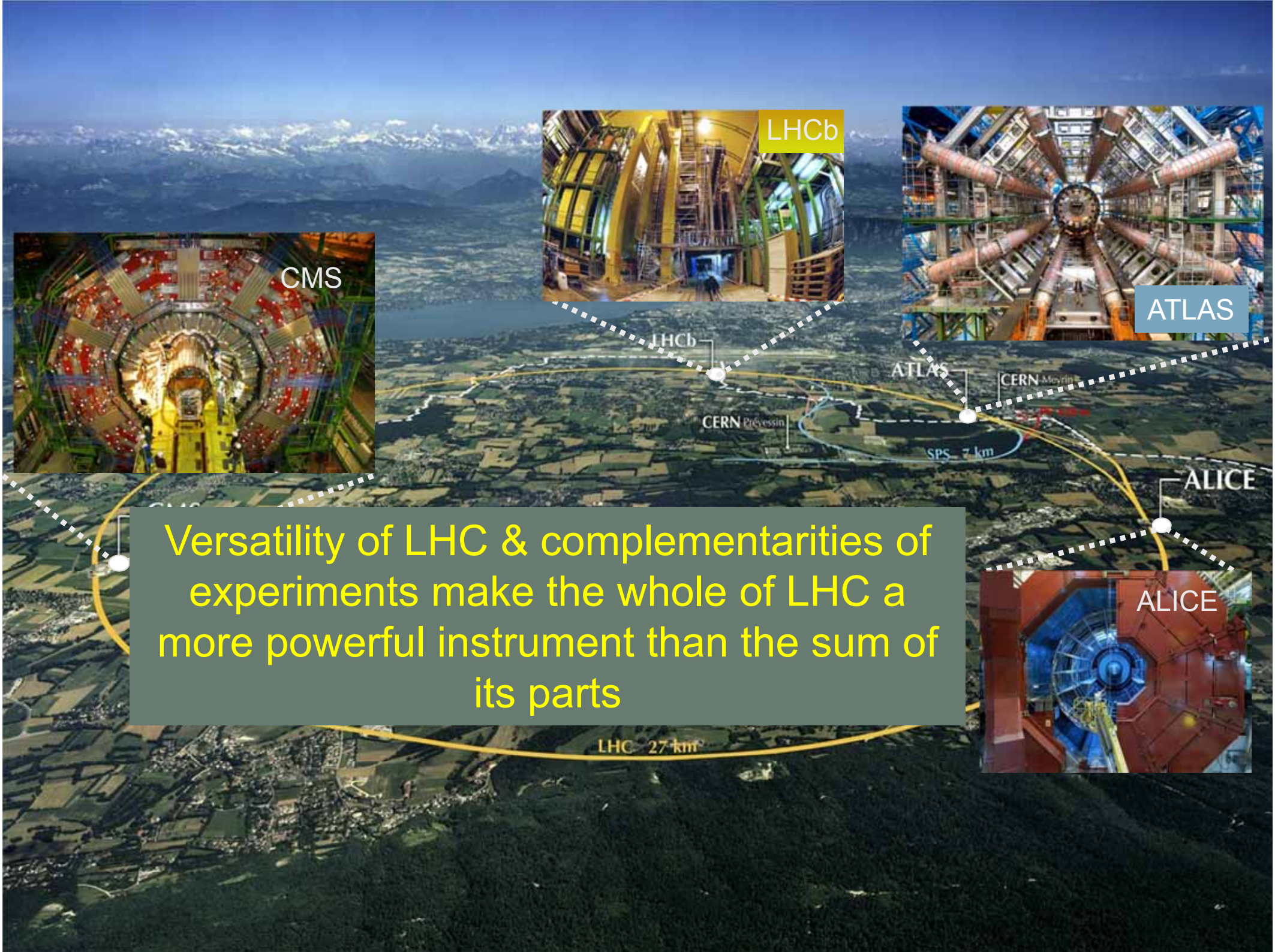




Overlap in physics reach

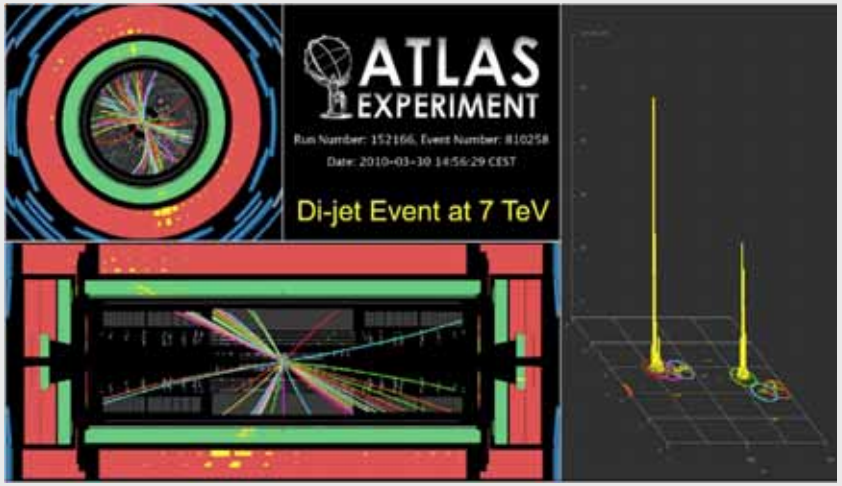
Key feature: reconstruct > 20'000 charged tracks in one event



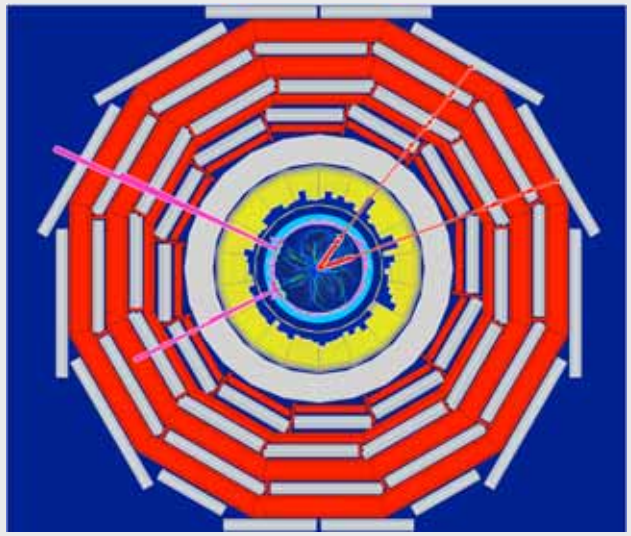


Versatility of LHC & complementarities of experiments make the whole of LHC a more powerful instrument than the sum of its parts

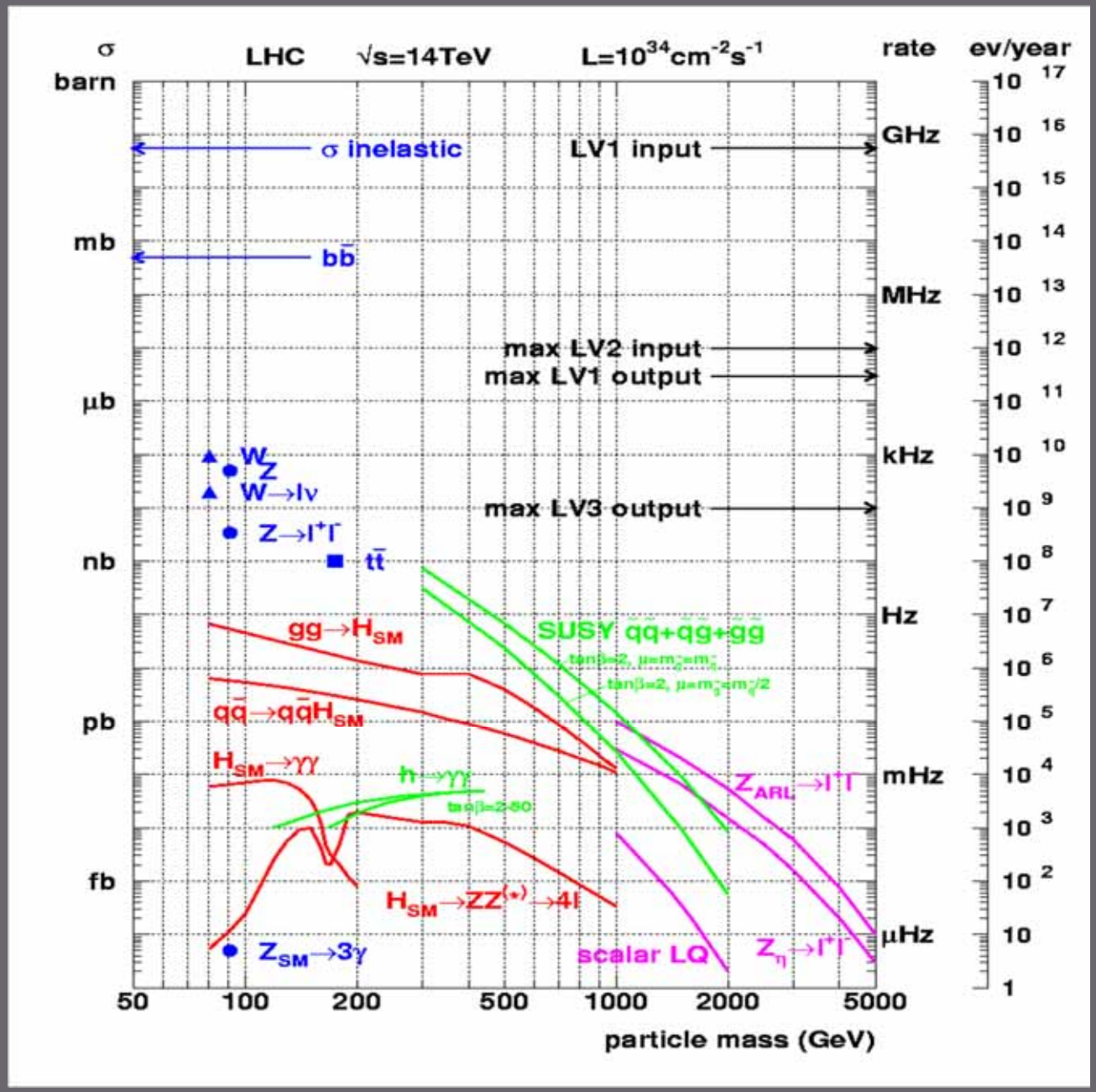
Basic processes at LHC



Basic processes at LHC



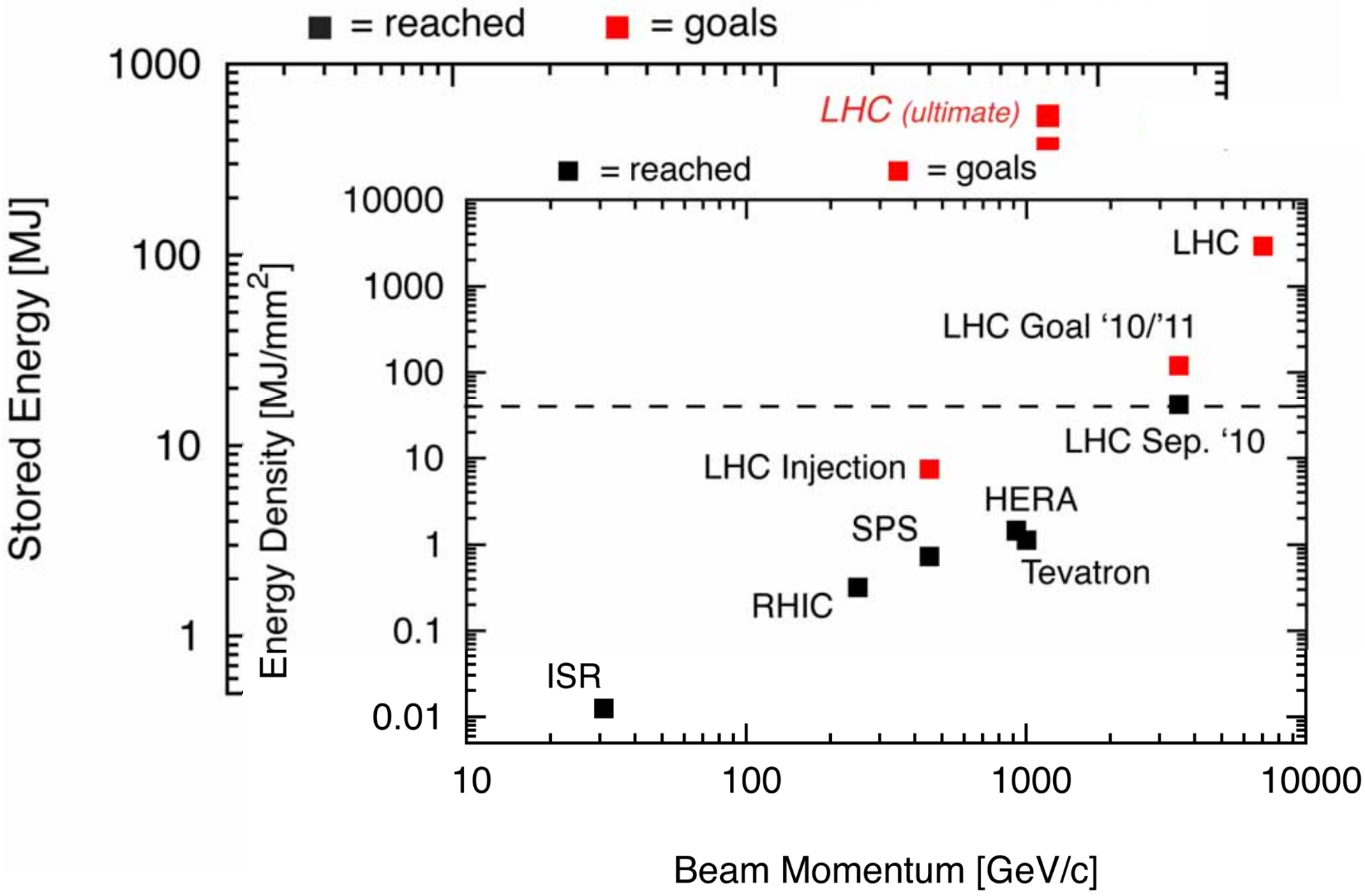
Cross sections at the LHC



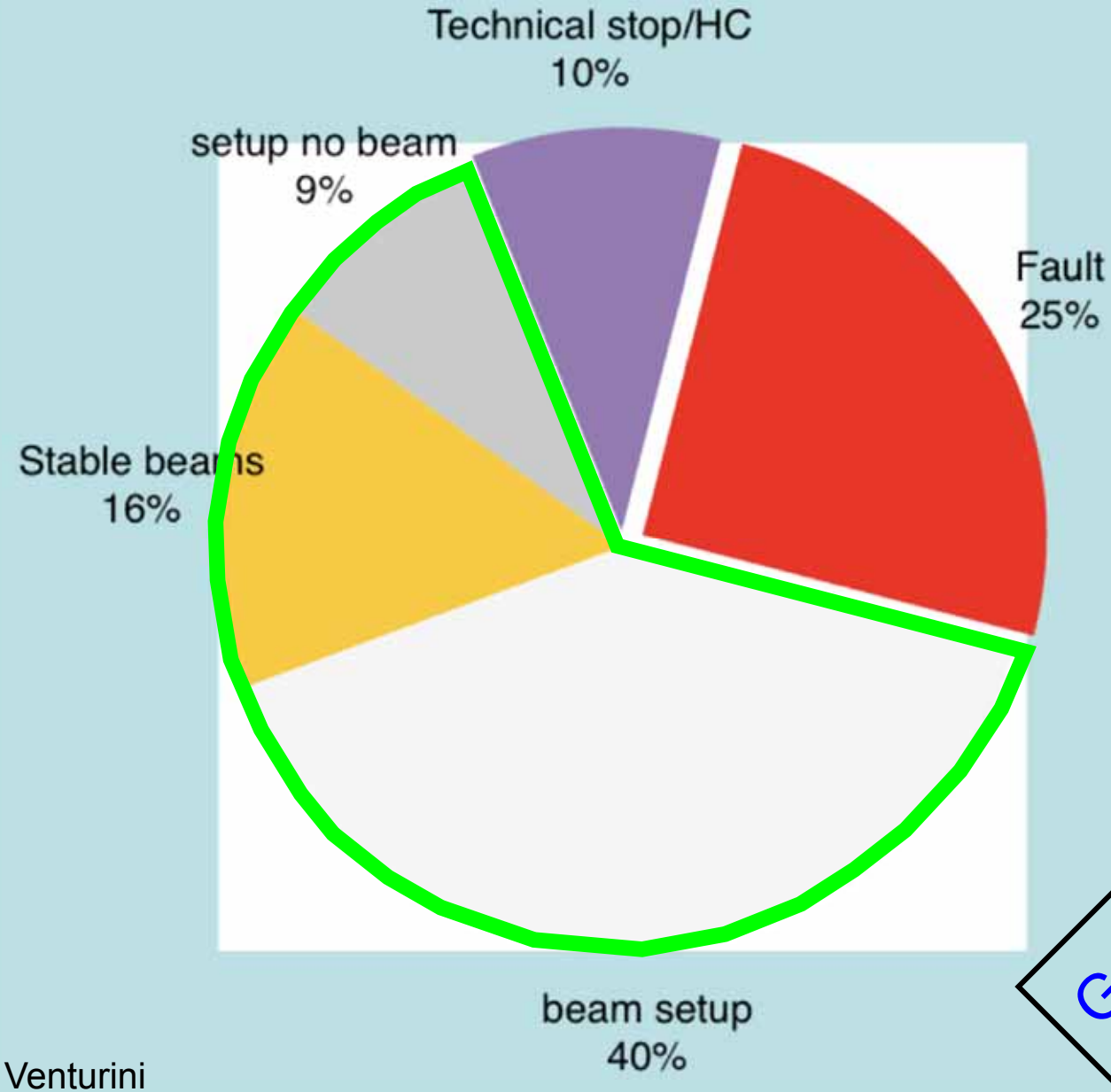
"Well known" processes. Don't need to keep all of them …

New Physics!!
We want to keep!!

Stored Energy in the LHC



Overall LHC efficiency in 2010



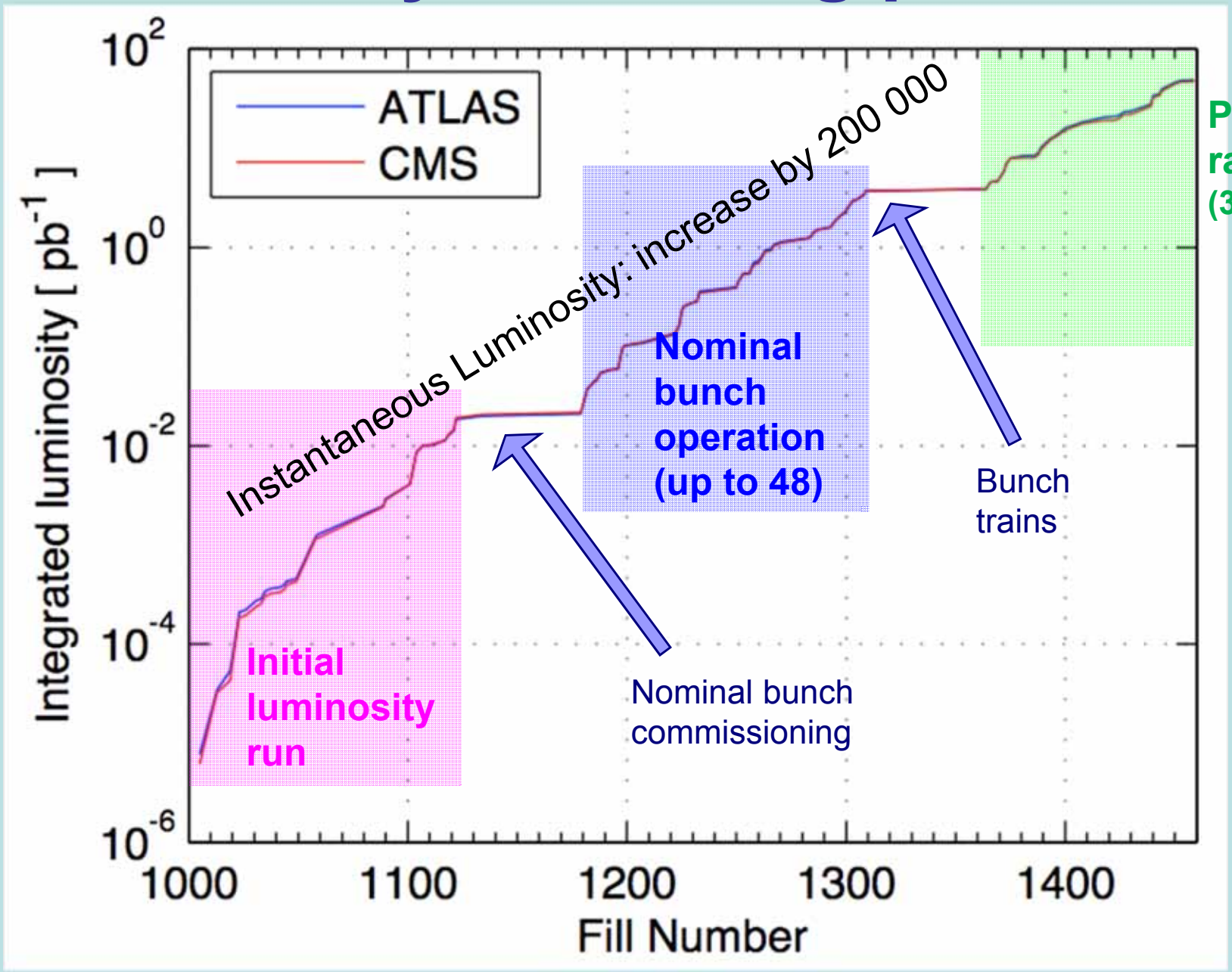
65% availability!

Great achievement for the first year of operation!

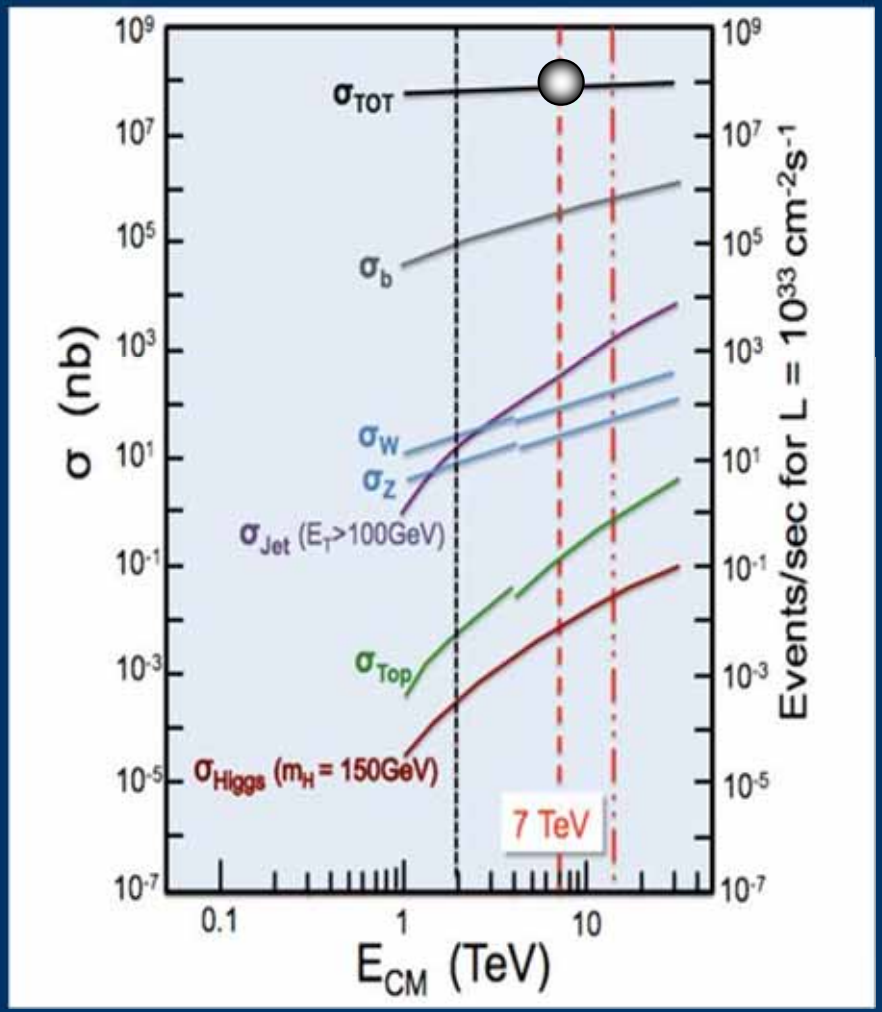
W. Venturini

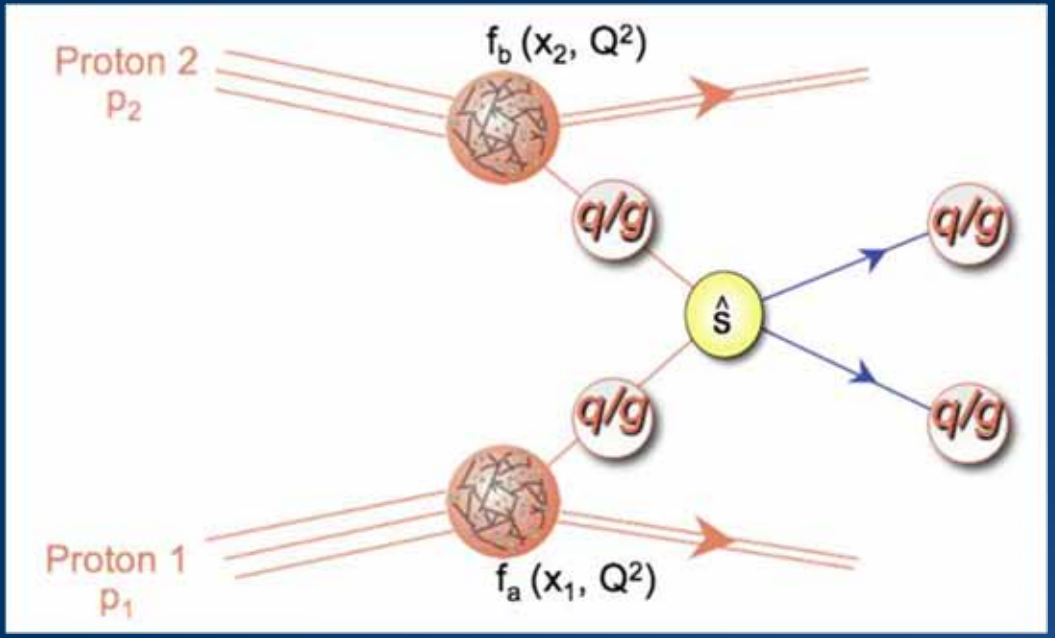
Luminosity: 3 running periods

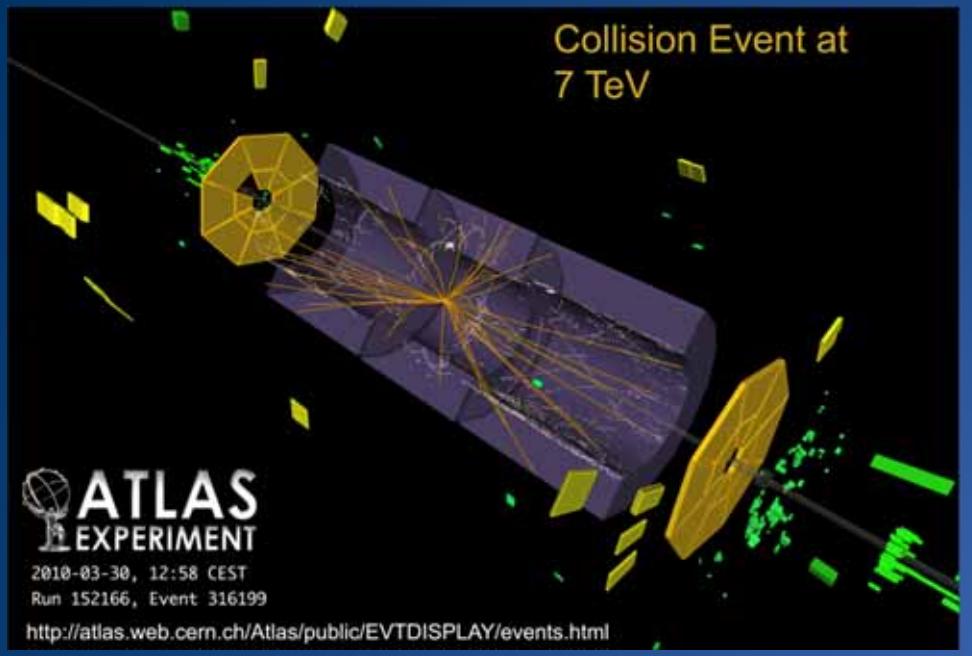
2010



"Min.Bias", low-p_T physics



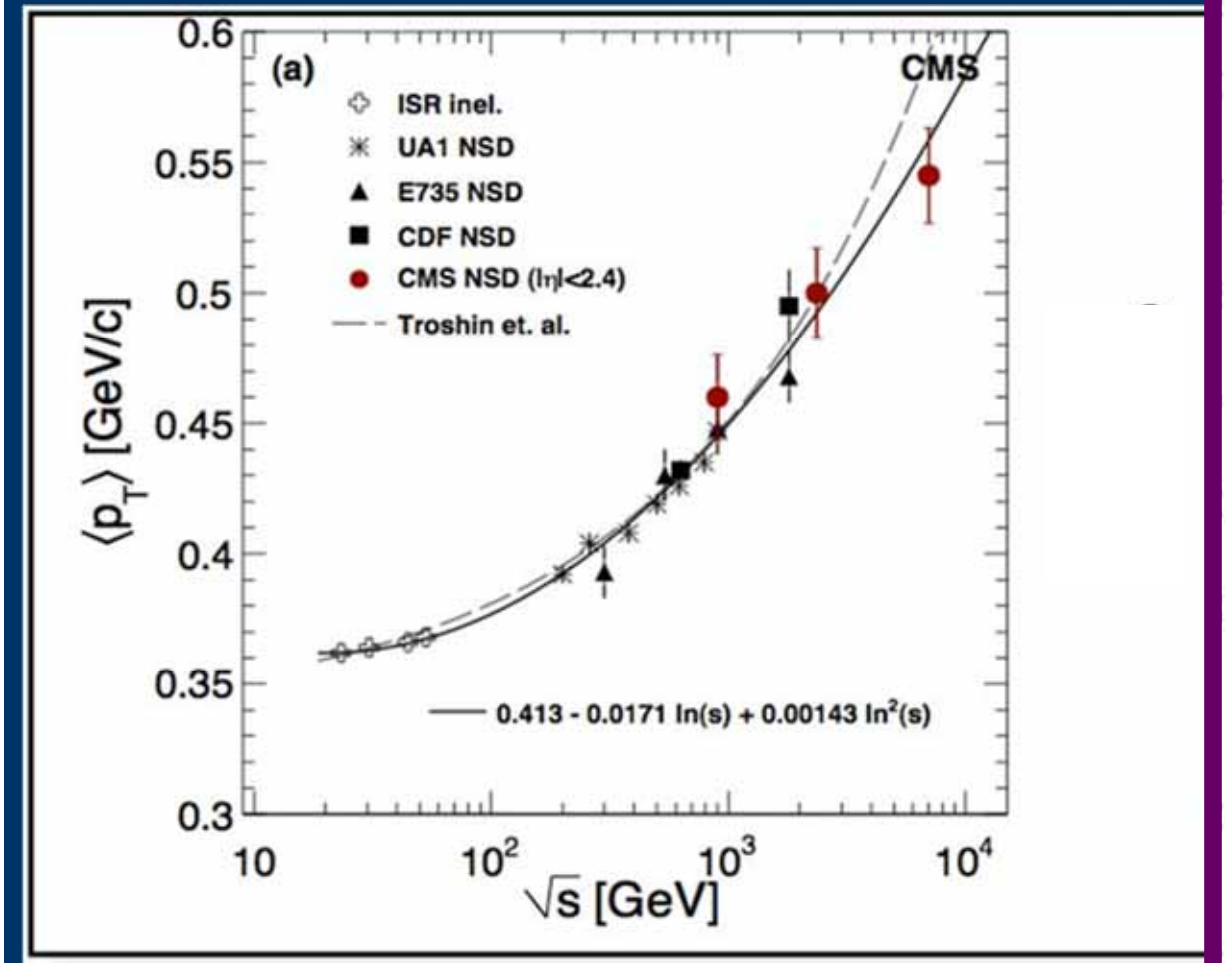


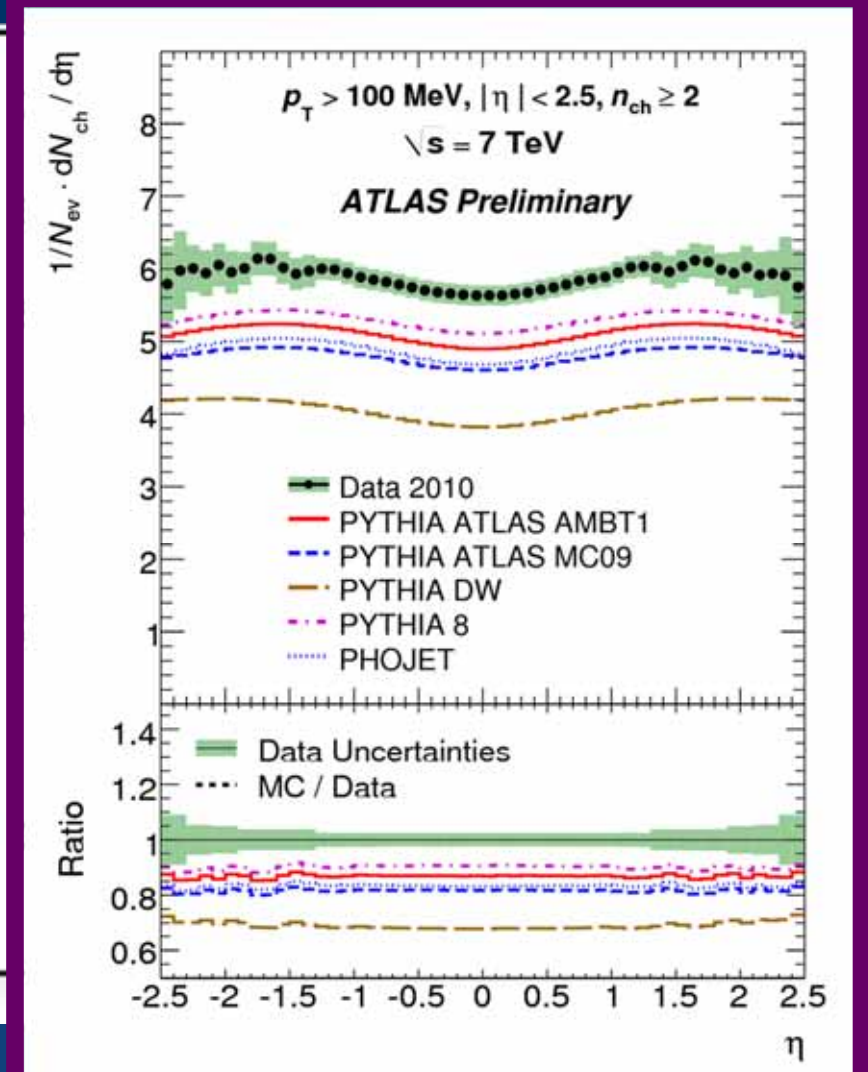


“Min.Bias”, low-p_T physics

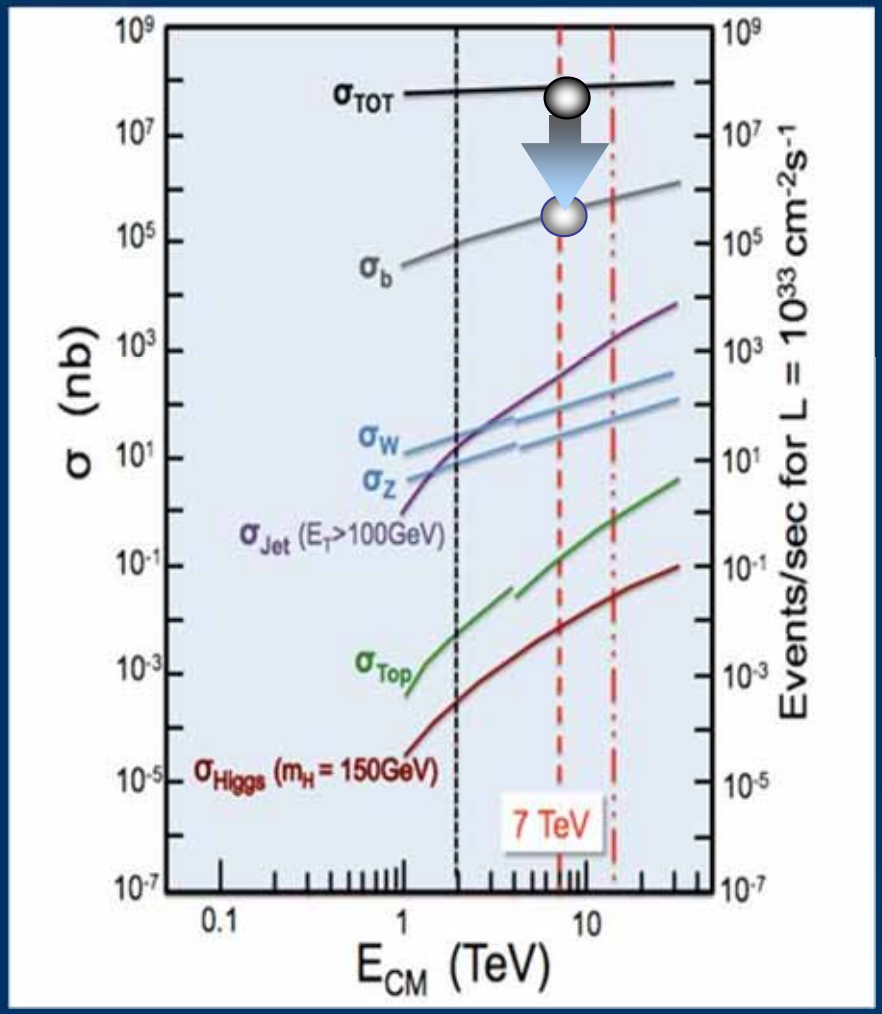
Soft collisions are not calculable reliably in pert. QCD, only phenomenological models available, but: parameters (multiplicity etc) poorly known (~50% or worse)

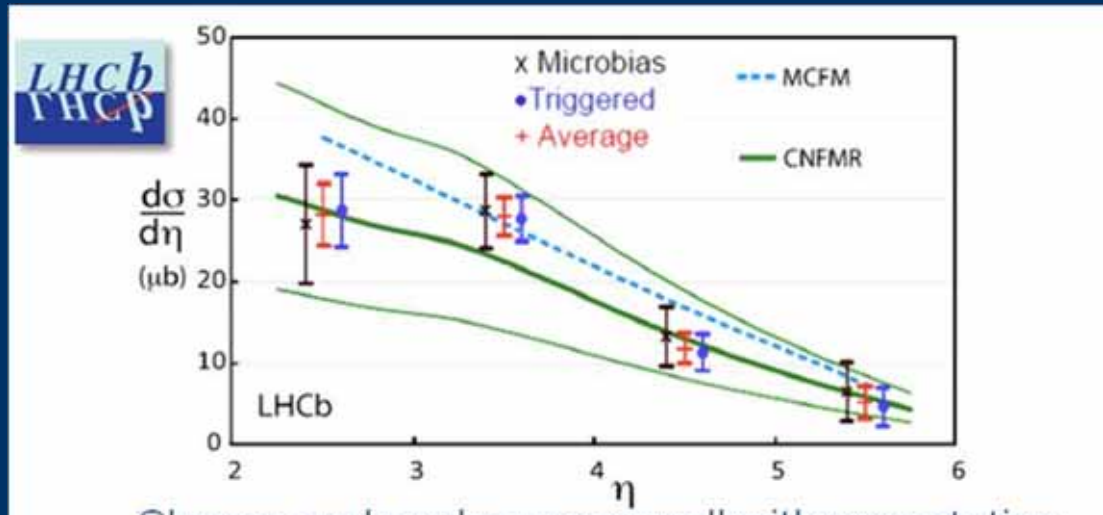
Important for tuning MC simulations and Pile-Up predictions



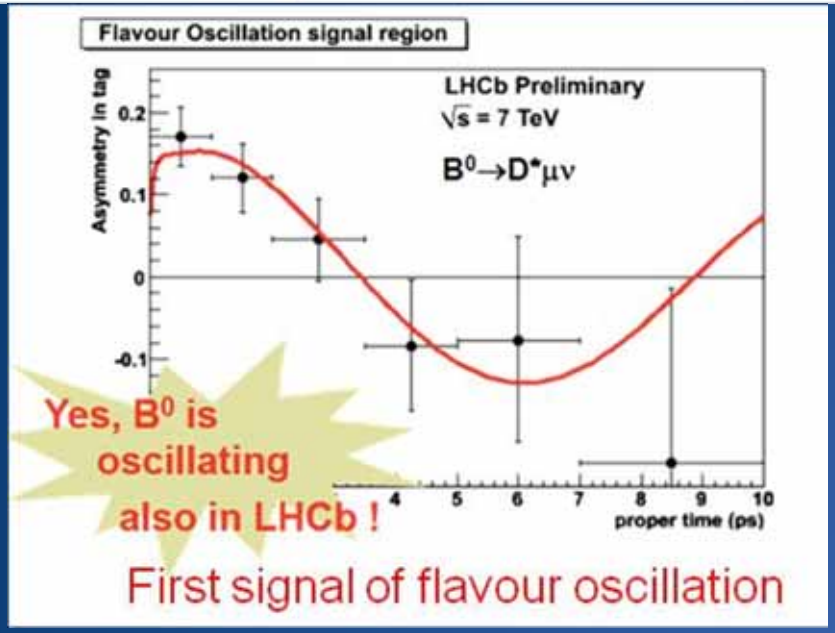


B-quark production at 7 TeV





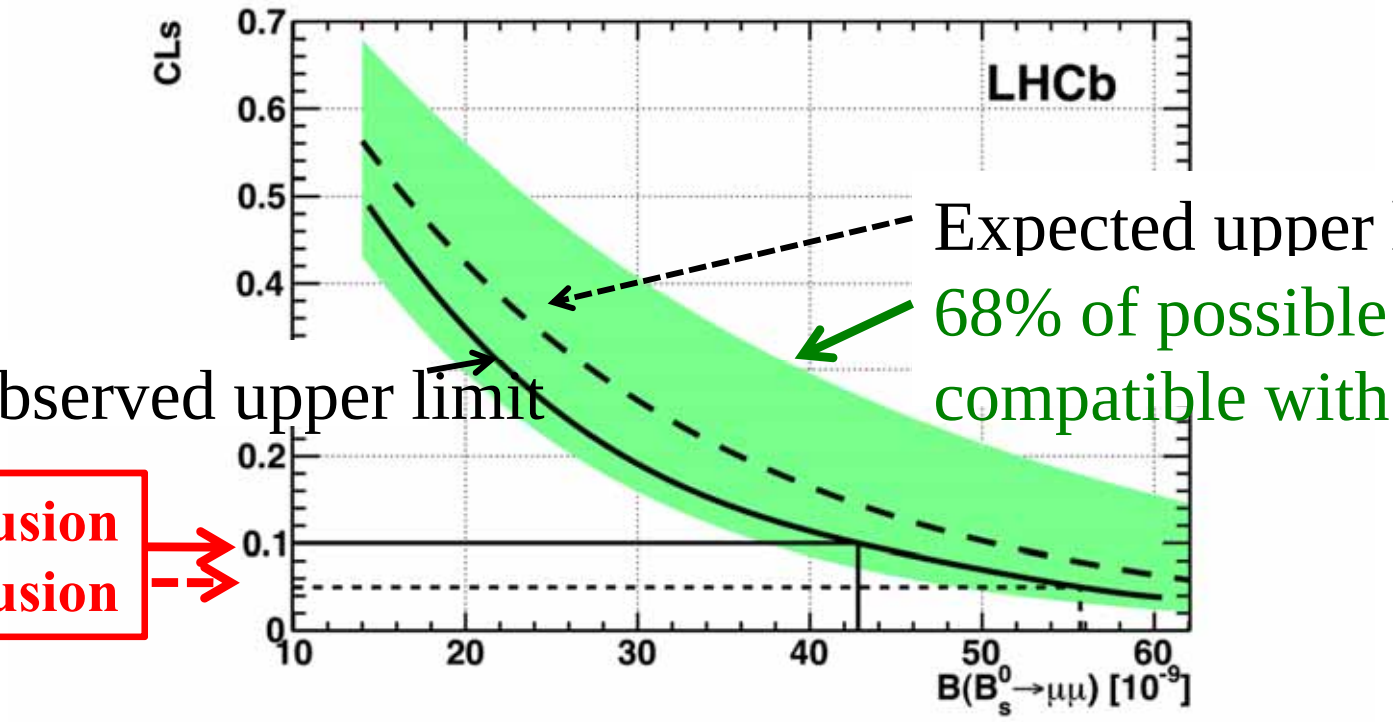
Shapes and scales agree well with expectation.
Validates QCD prediction at LHC energies.



First signal of flavour oscillation

Search for $B_s \rightarrow \mu\mu$

Paper submitted to Phys. Lett. B



Expected upper limit

68% of possible experiments compatible with expected limi

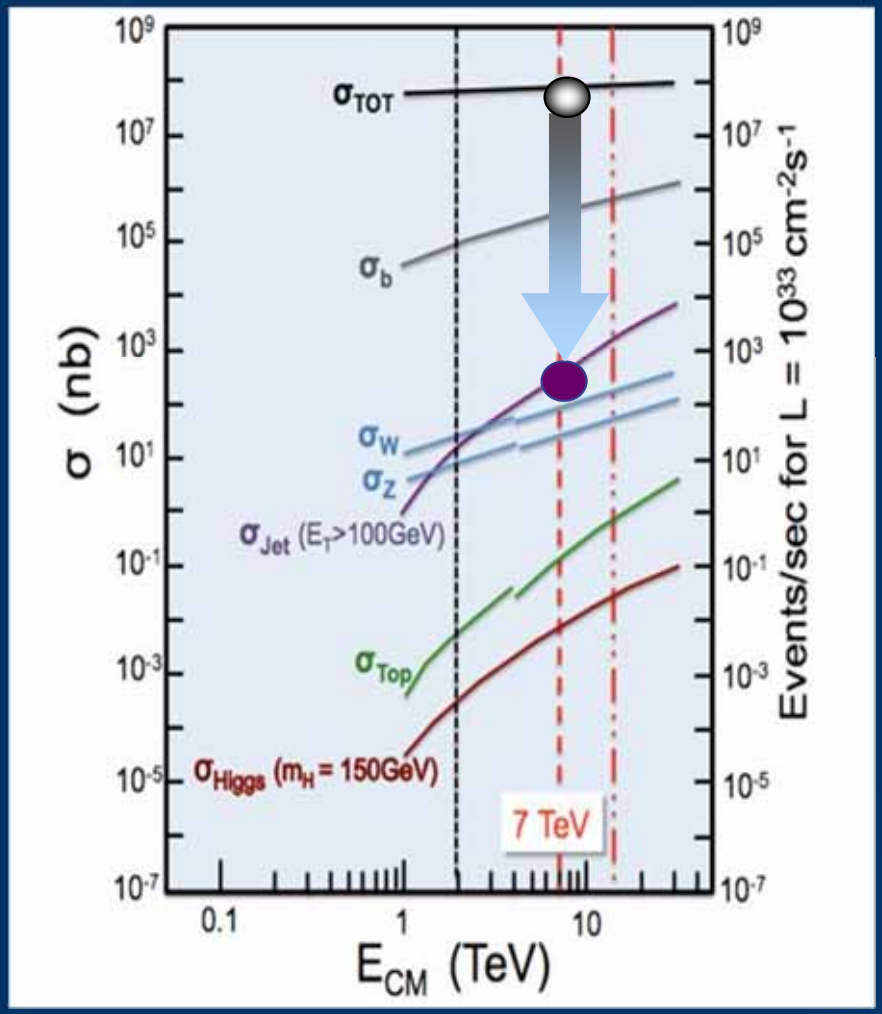
Observed upper limit

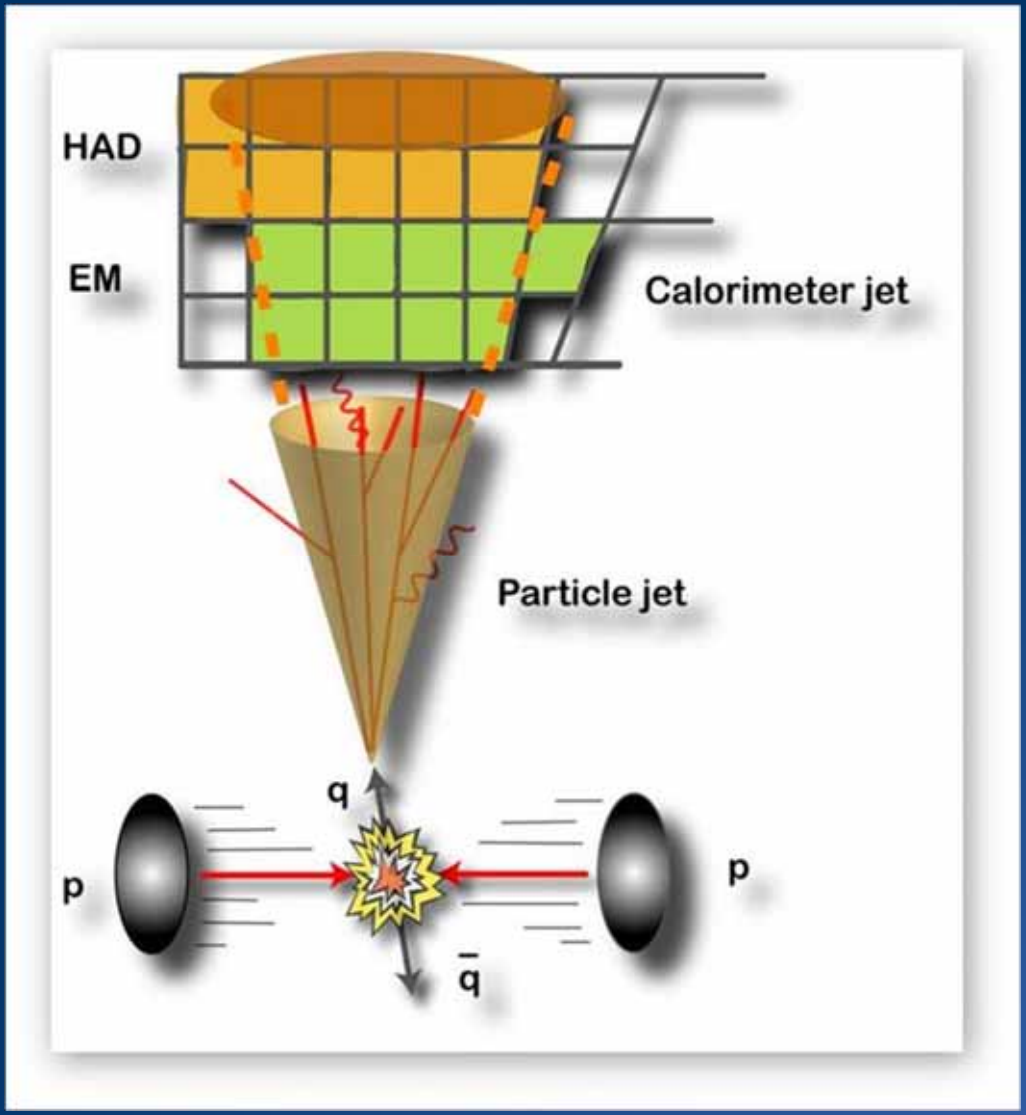
90% exclusion

95% exclusion

		@ 90% CL	@ 95% CL
LHCb	Today, **37 pb^{-1}**	**< 43 x10^{-9}**	**< 56 x10^{-9}**
D0	World best, **6.1 fb^{-1}** PLB 693 539 (2010)	**< 42 x10^{-9}**	**< 51 x10^{-9}**
CDF	Preliminary, **3.7 fb^{-1}** Note 9892	**< 36 x10^{-9}**	**< 43 x 10^{-9}**

Jet production at 7 TeV





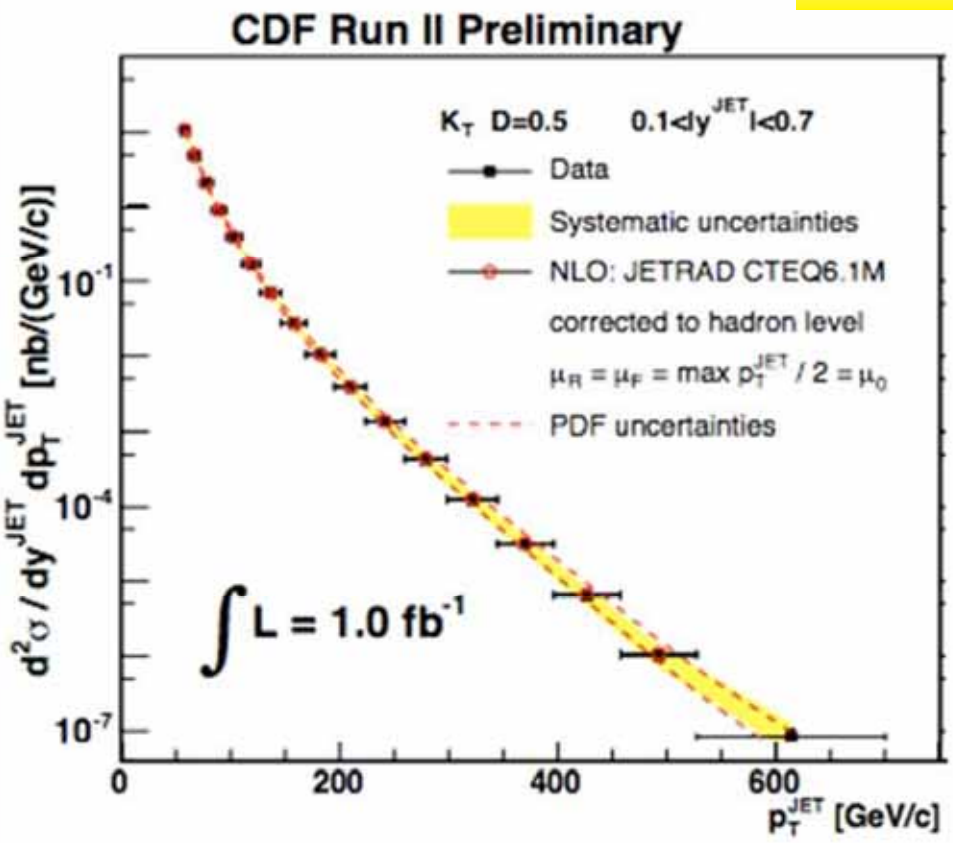
Important tests of pQCD and detector performance

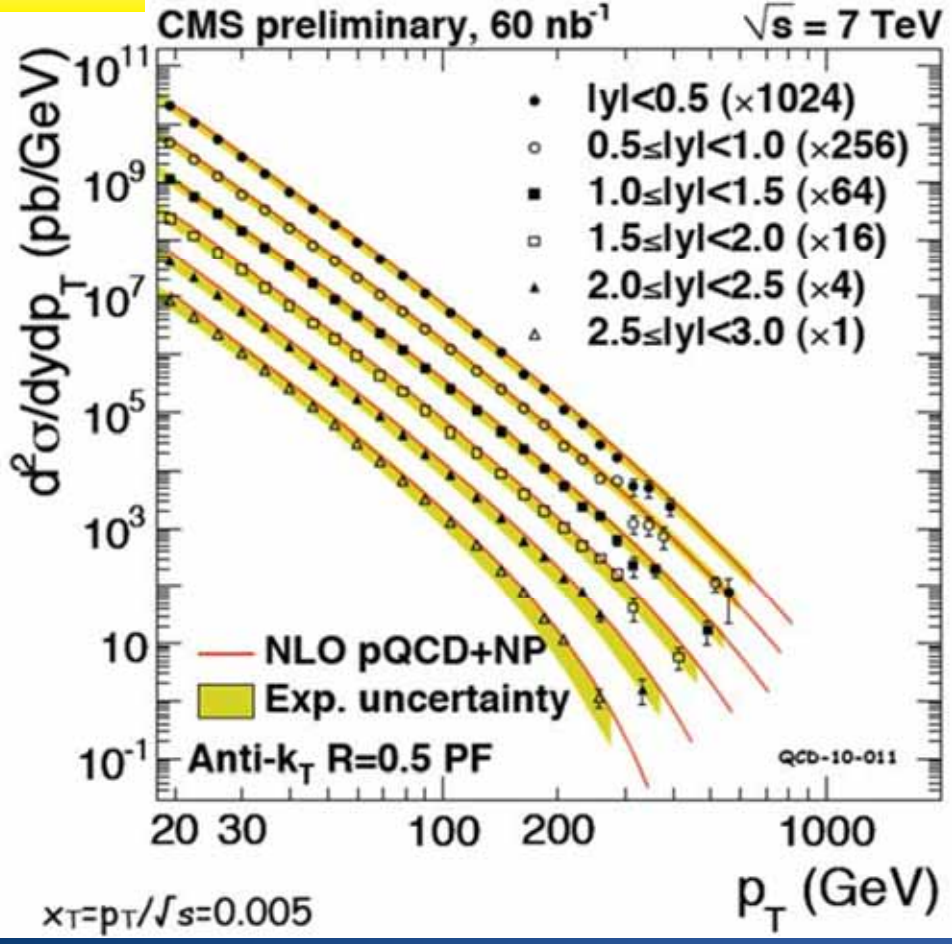
Jet production at 7 TeV

Tevatron
E_{CM}= 2 TeV

Factor >10^4
in integr. L

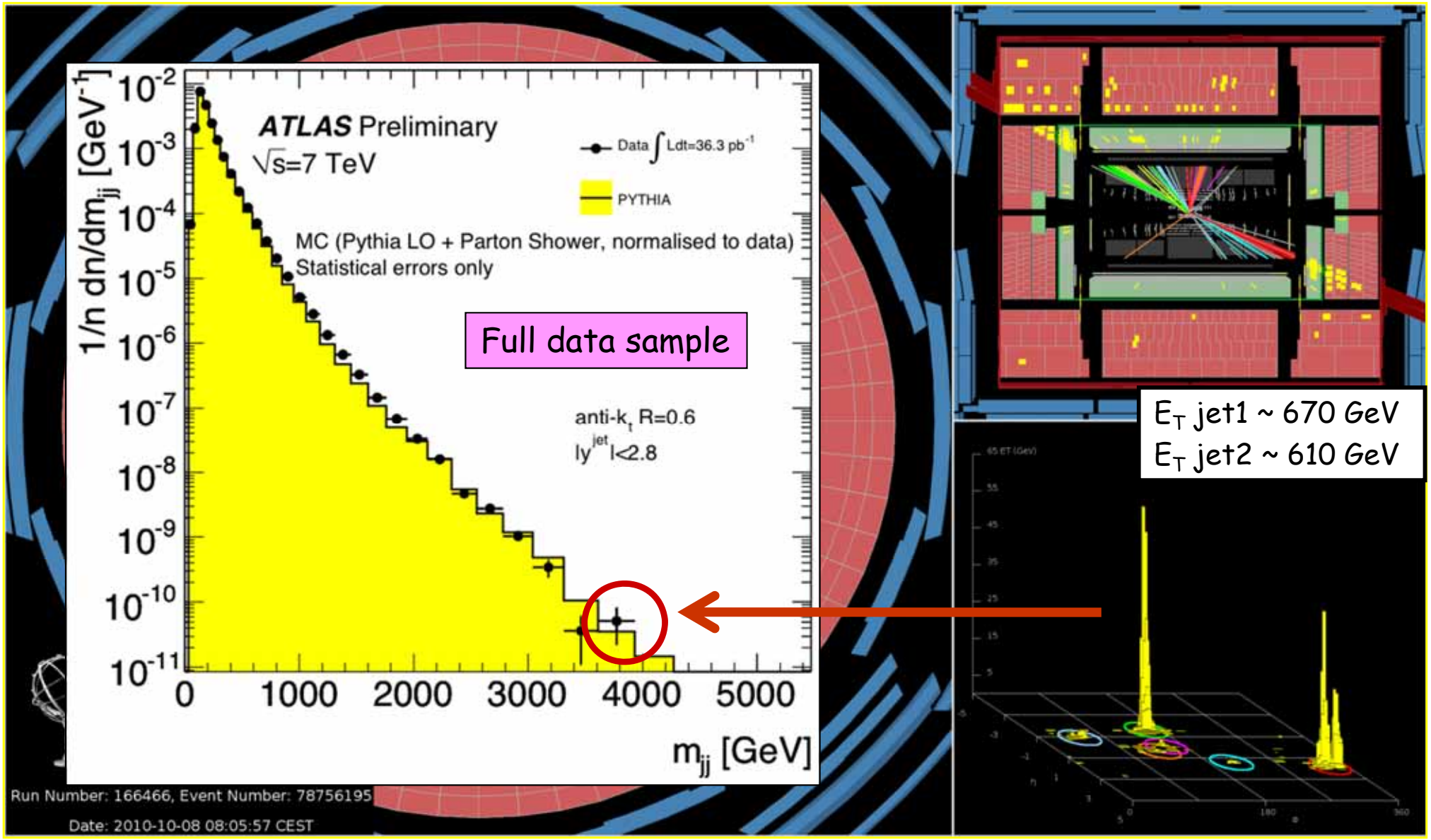
LHC
E_{CM}= 7 TeV



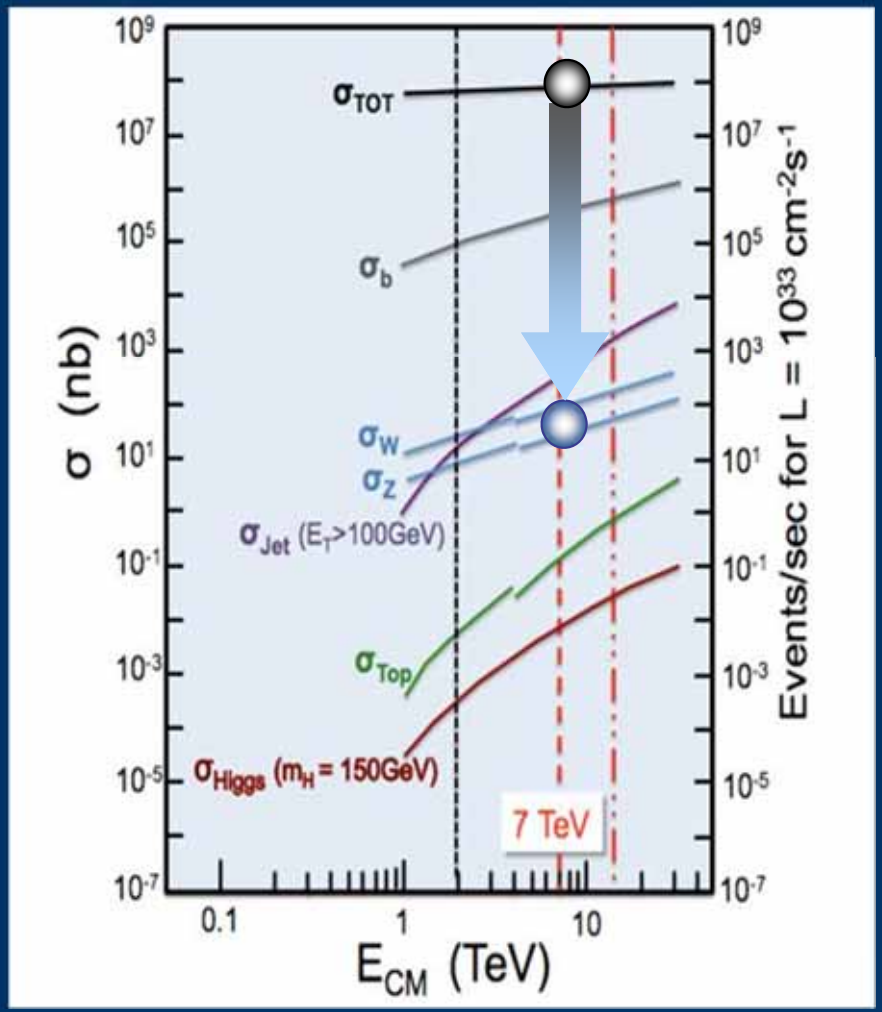


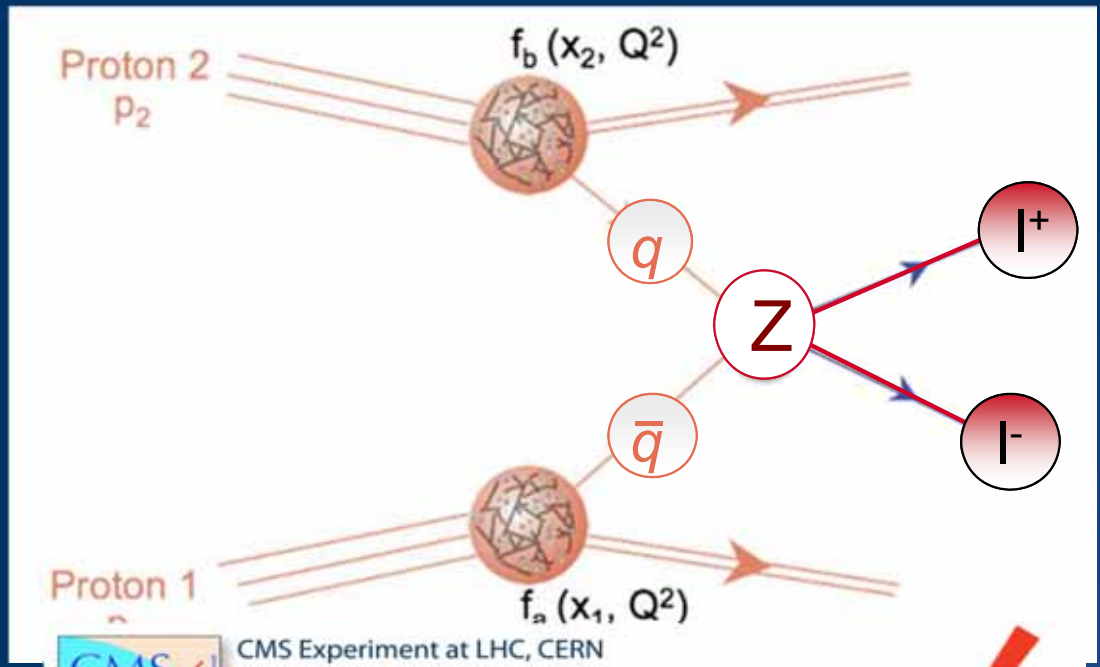
Important test of pQCD over many orders of magnitude

Highest mass dijet event recorded by ATLAS: M_{jj} =3.7 TeV



W and Z production at 7 TeV

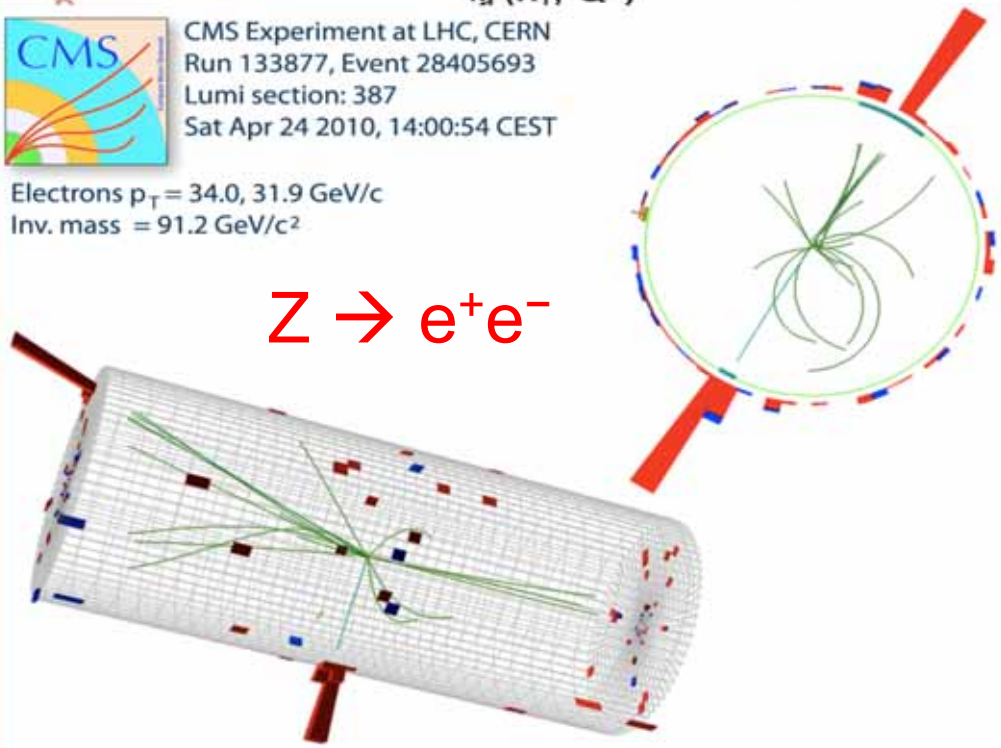




CMS Experiment at LHC, CERN
Run 133877, Event 28405693
Lumi section: 387
Sat Apr 24 2010, 14:00:54 CEST

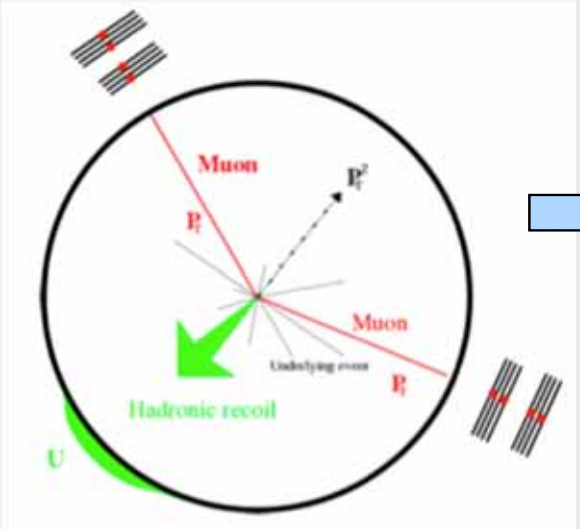
Electrons p_T = 34.0, 31.9 GeV/c
Inv. mass = 91.2 GeV/c²

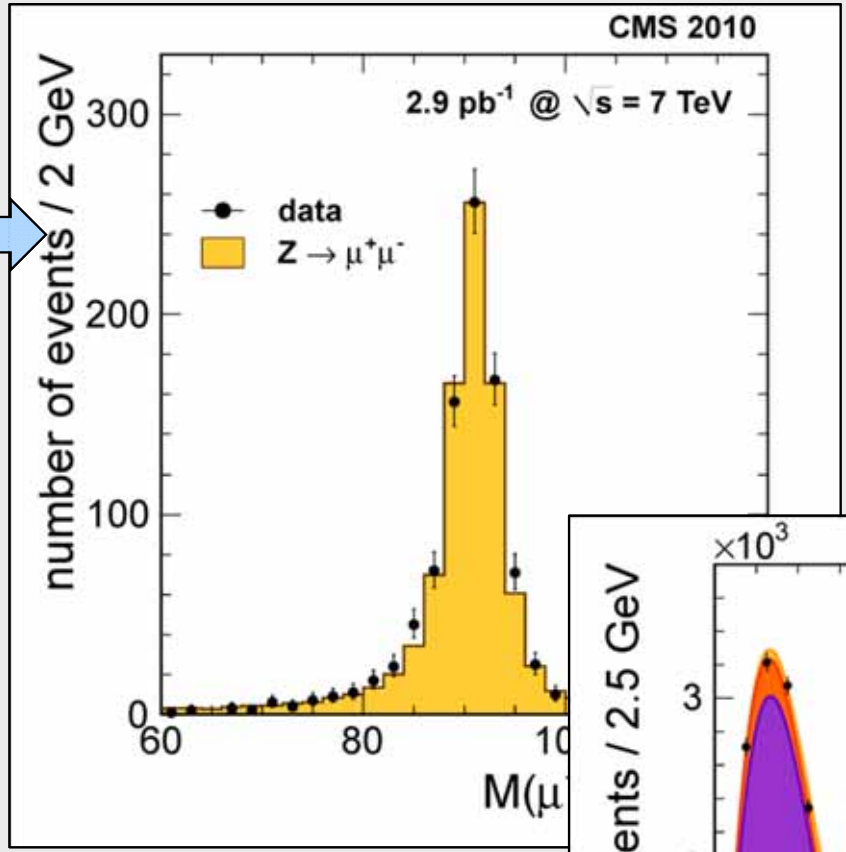
$Z \rightarrow e^+e^-$



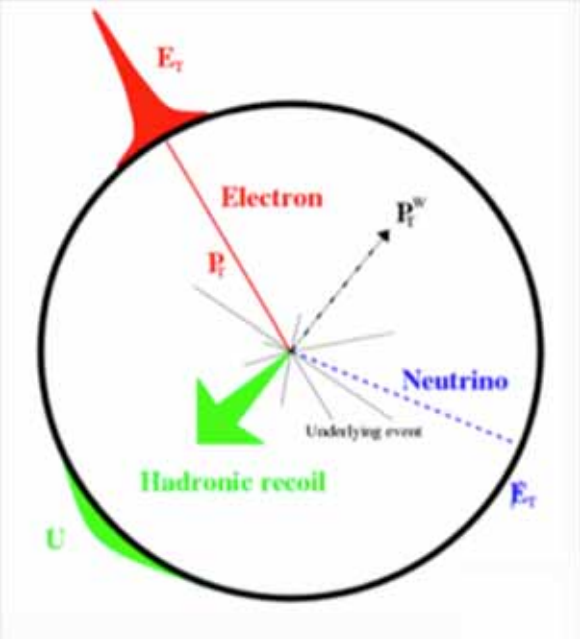
W and Z production at 7 TeV

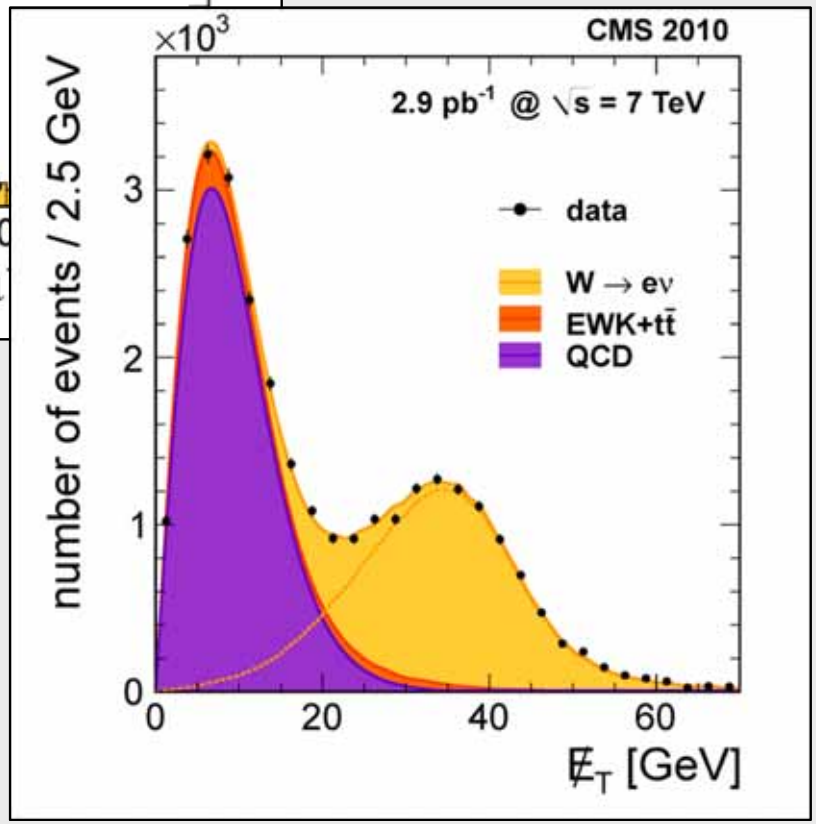
Z





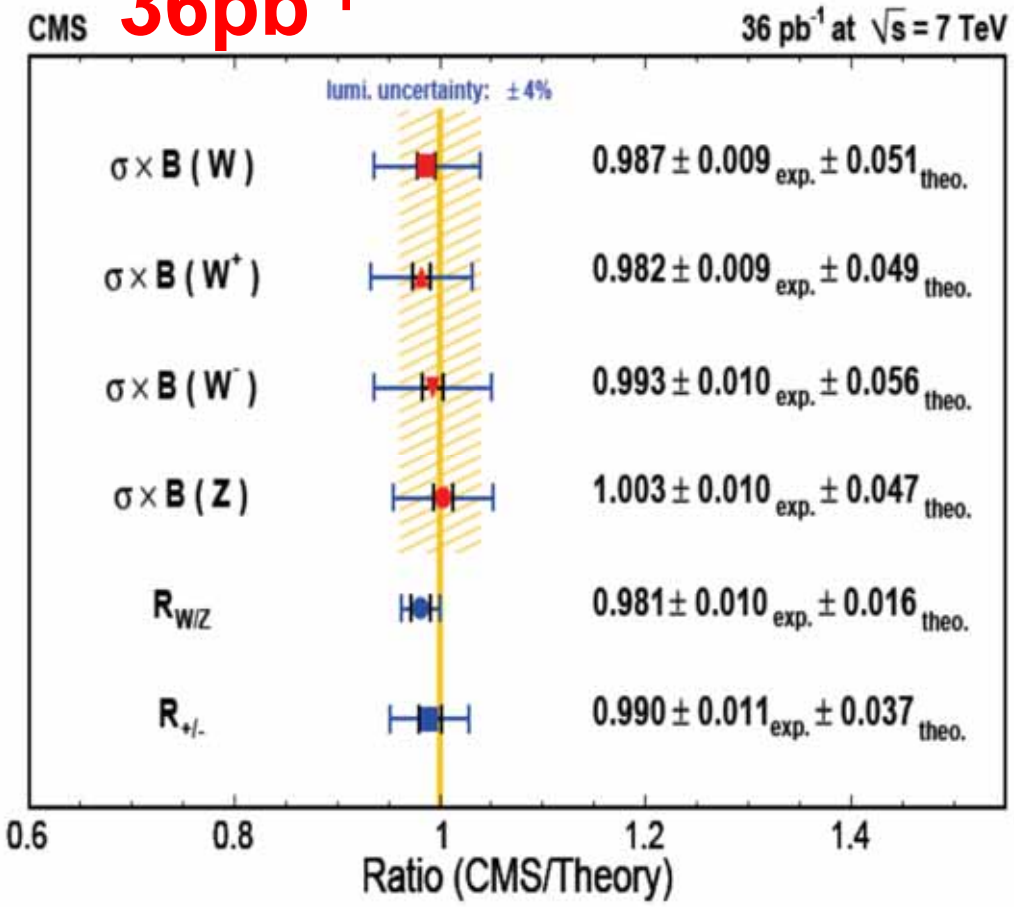
W

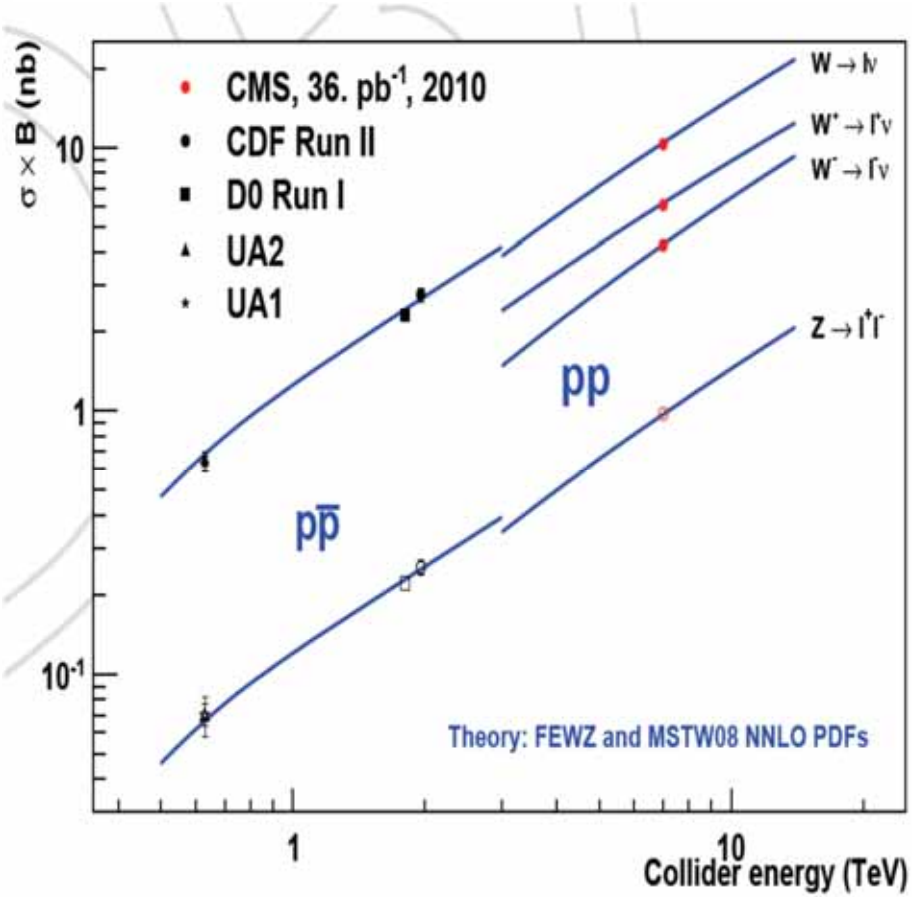




W and Z production cross sections

36pb^{-1}





Notice: all major components of the measurements (efficiency, background, systematic errors etc) are carefully evaluated using data driven methods.

1) CMS PAS EWK-10-005

2) arXiv:1012.2466 ; *J. High Energy Phys. 01 (2011) 080*

Electroweak

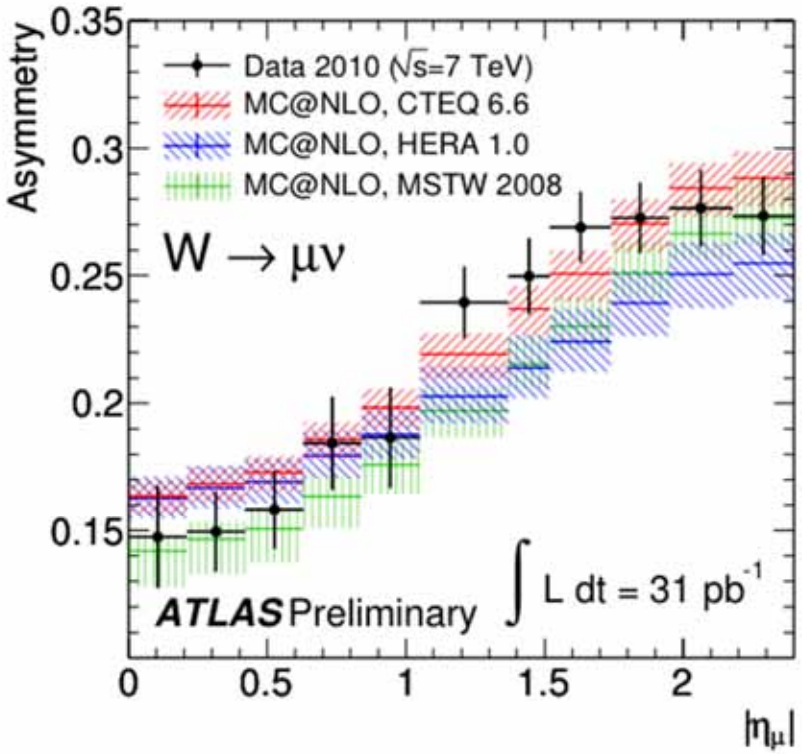
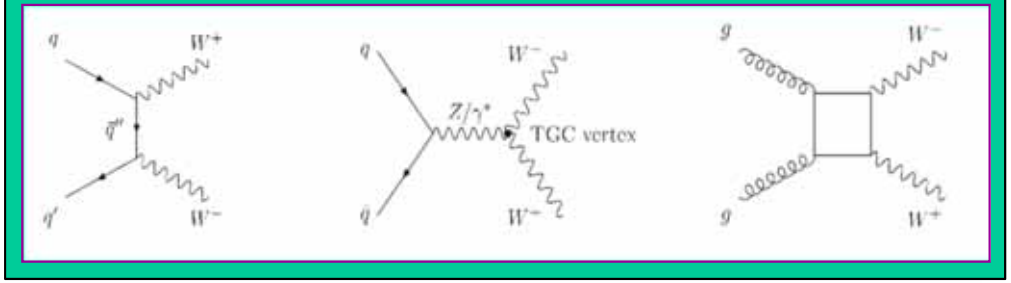
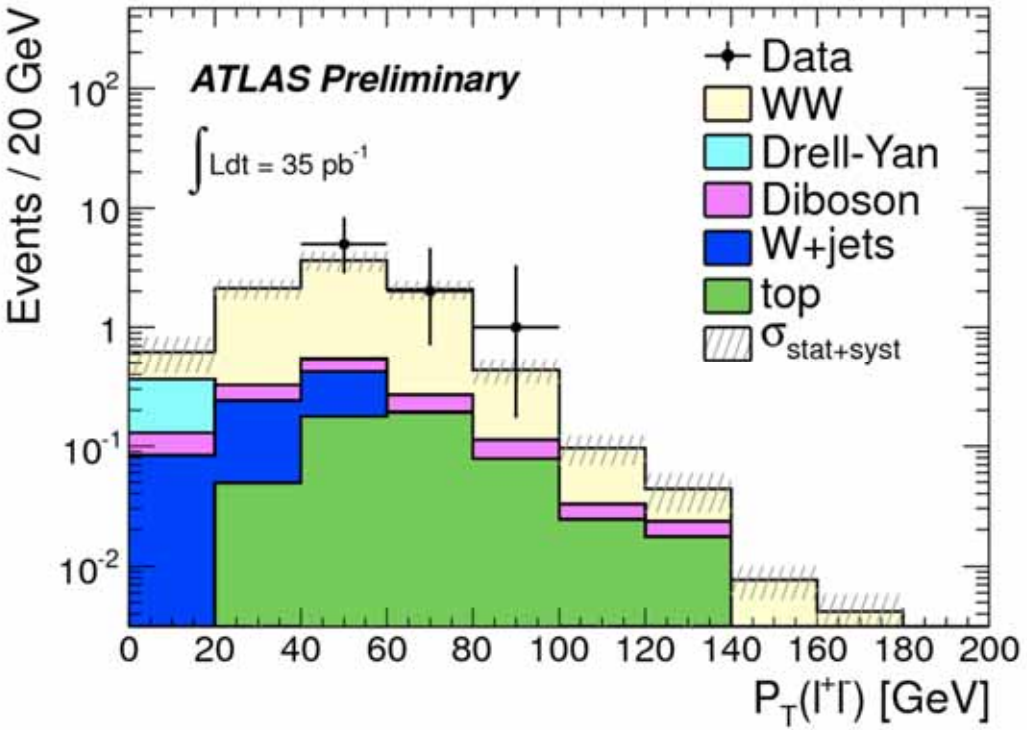


Figure 4: The muon charge asymmetry from W-boson decays in bins of absolute pseudorapidity. The data points (shown with error bars including the statistical and systematic uncertainties) are compared to different PDF predictions. The PDF uncertainty bands are described in the text and include experimental uncertainties as well as model and parametrization uncertainties.

WW cross-section



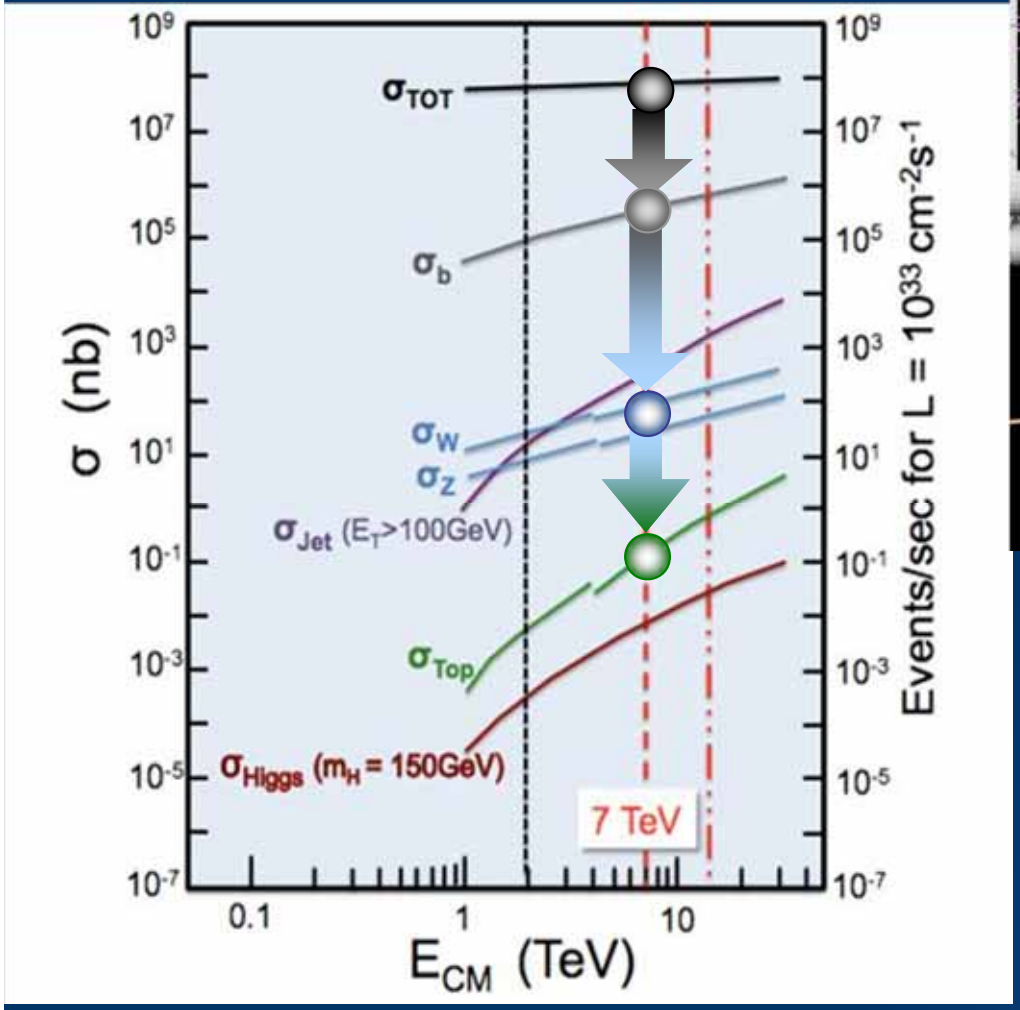


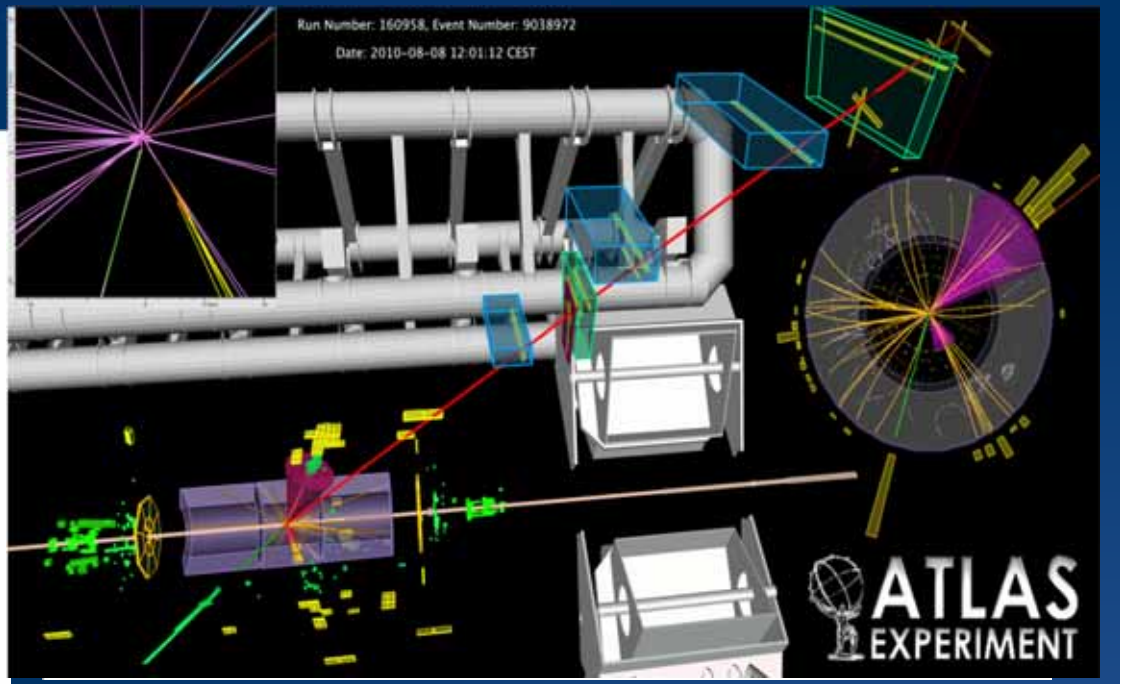
8 candidates selected in the 2010 data
(estimated background: 1.7 ± 0.6)

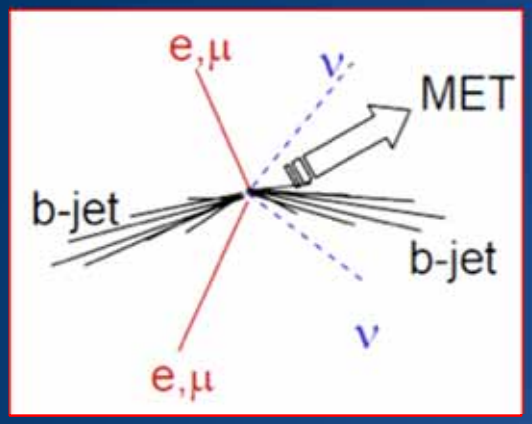
$$\sigma_{WW} = 40^{+20}_{-16}(\text{stat}) \pm 7(\text{syst})\ \text{pb}$$

SM (NLO):
46 ± 3 pb

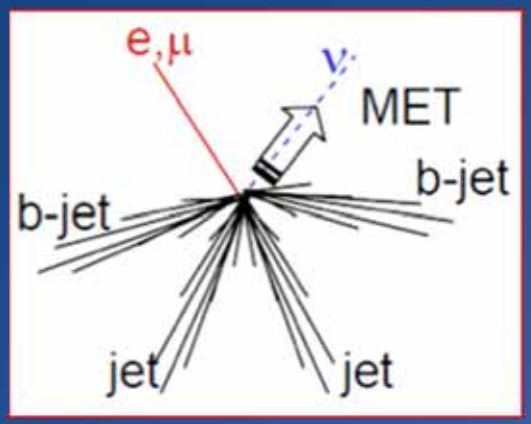
Top quark production at 7 TeV





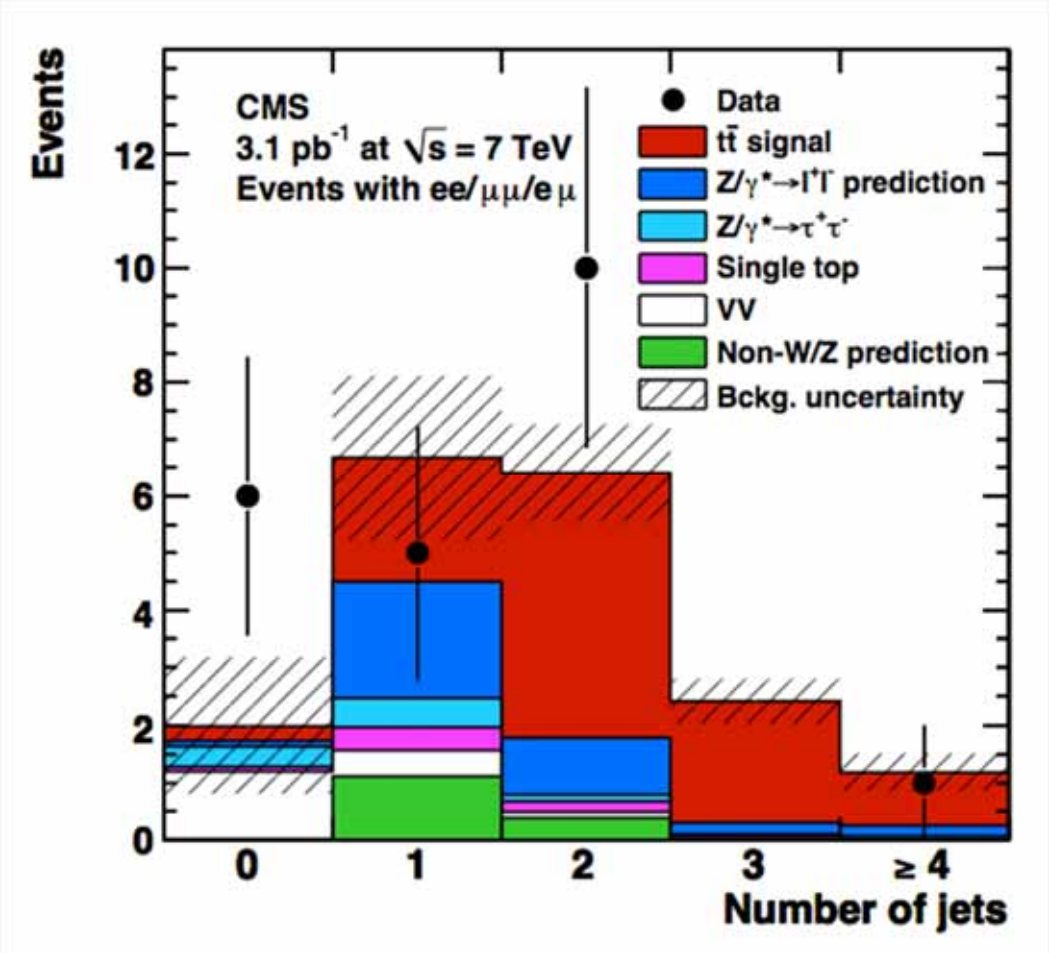


di-leptons



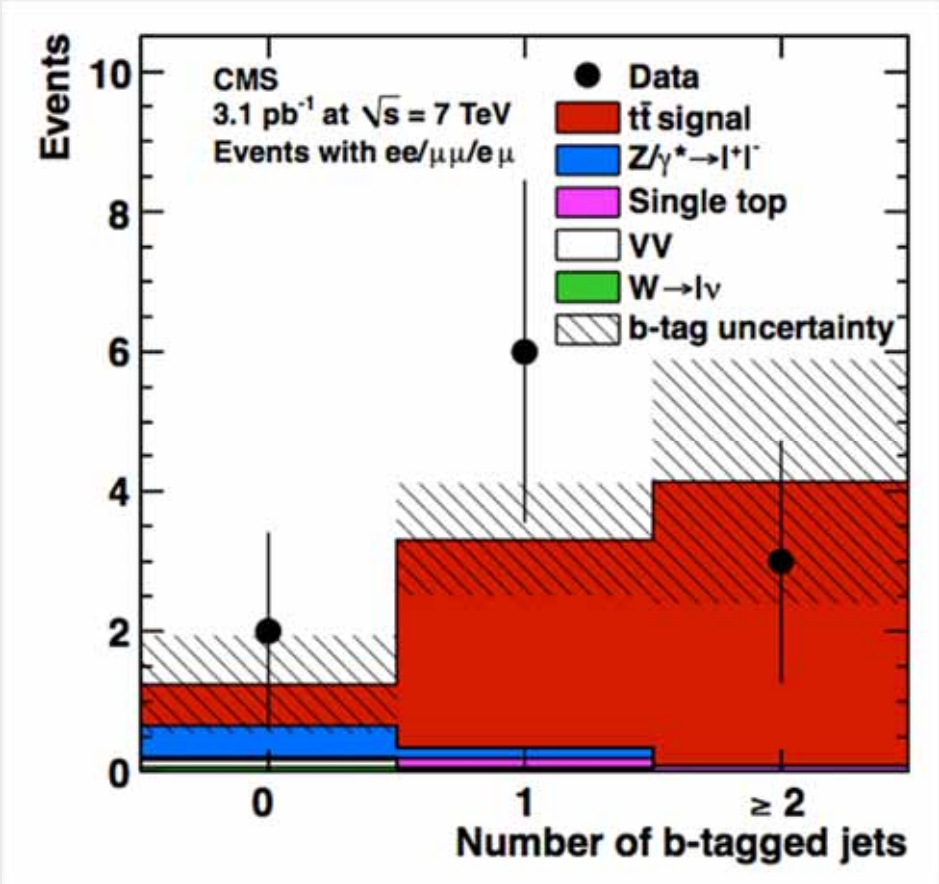
Lepton + jet

Top production at 7 TeV



First Publication on Top cross section at LHC

in the di-lepton channel

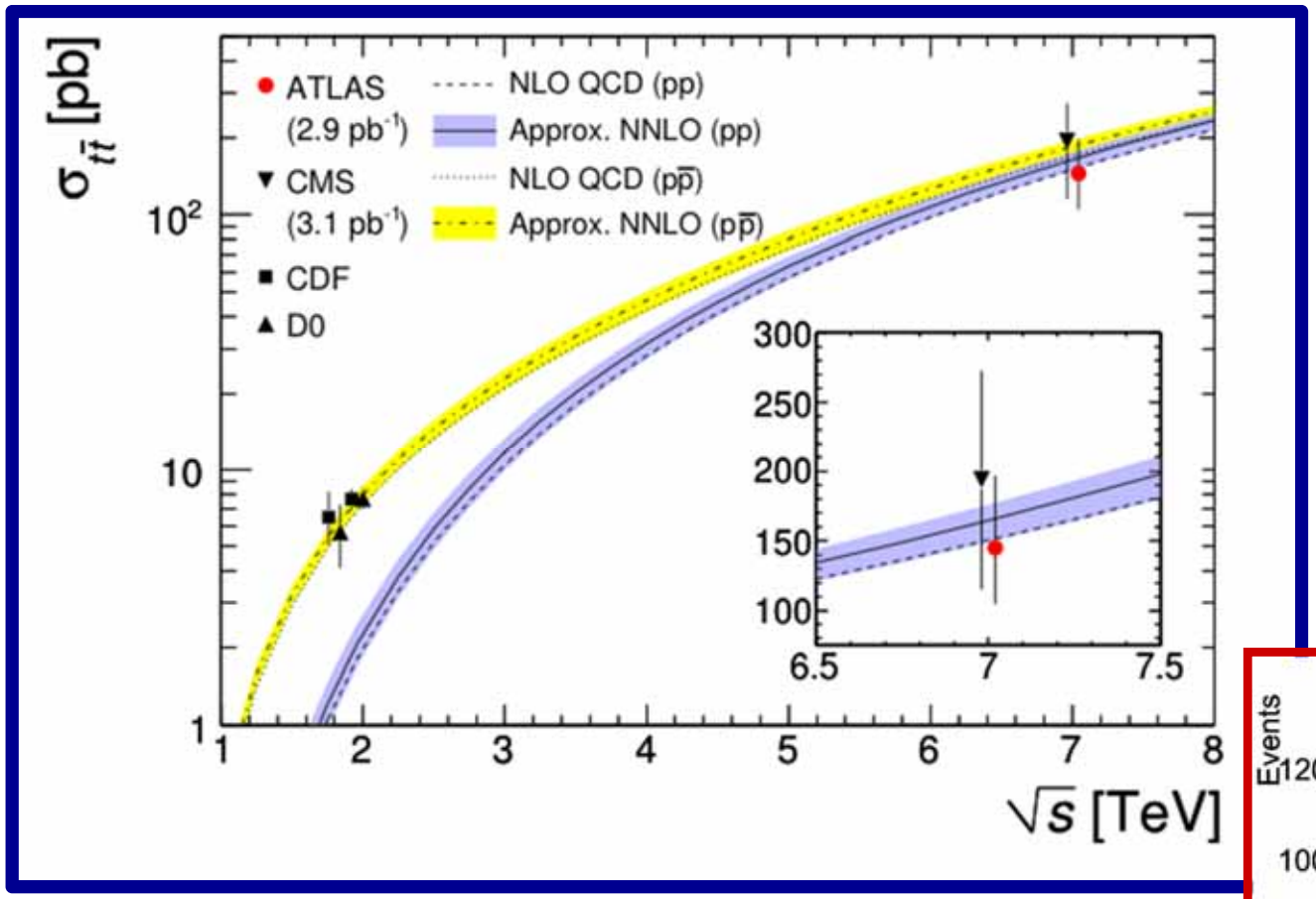


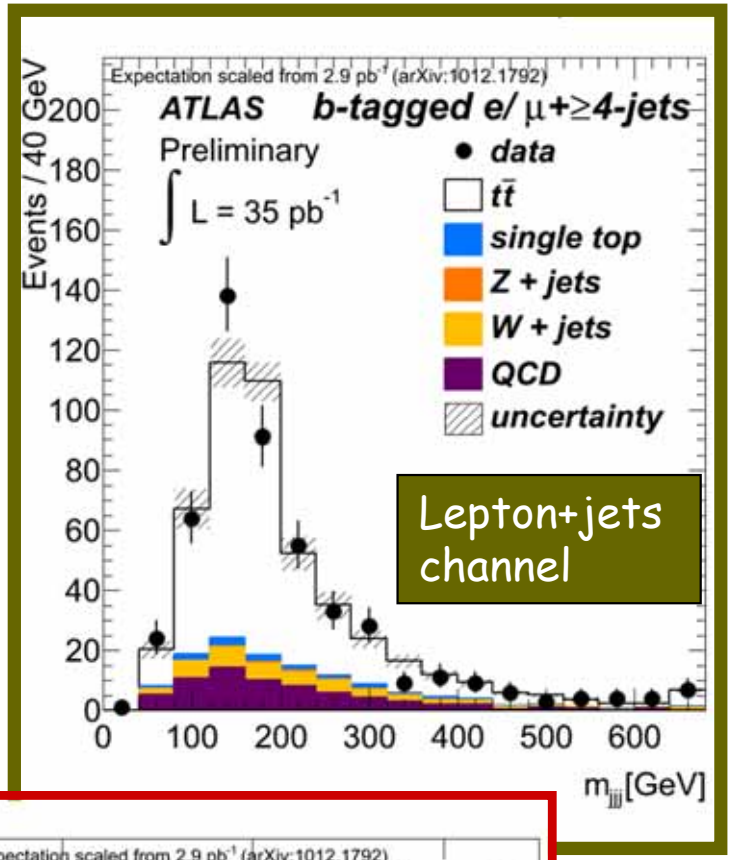
Observed: N_{data} =11

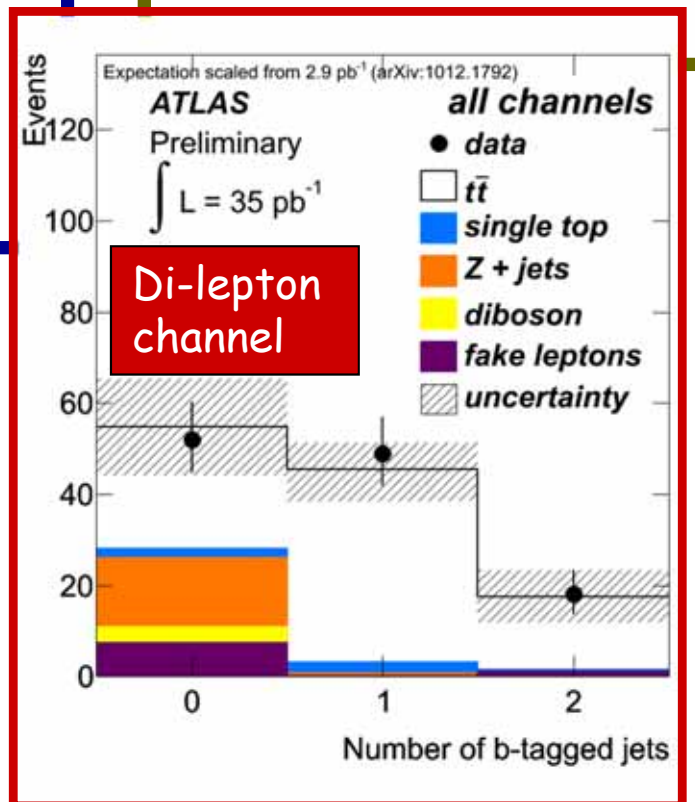
Predicted background: N_{BG} = 2.1

Predicted signal: N_{ttbar} = 7.7

First top measurements at $\sqrt{s}$ = 7 TeV

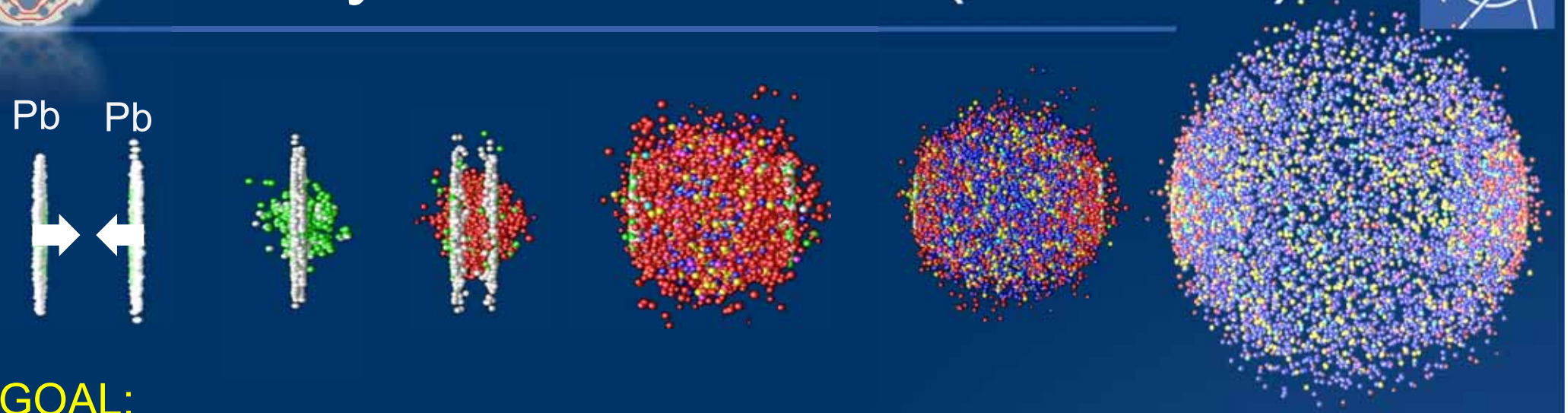






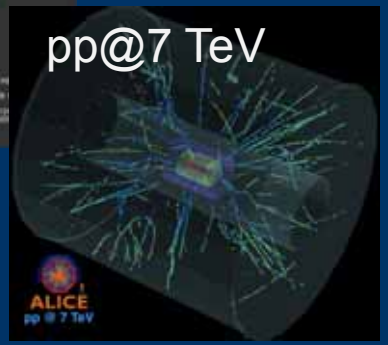
In the full data sample recorded so far, ATLAS has ~ 700 top-antitop events
→ only ~ 8 times less than CDF or D0

Heavy Ion Collisions (Pb – Pb)



GOAL:

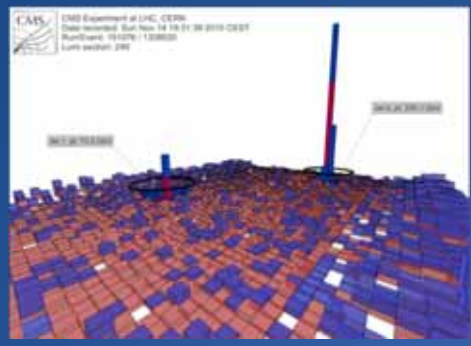
- Study the 'primordial' state of matter in the early Universe (~10^{-6} sec after BB)
- At increasing temperature & energy density → new state of matter: QGP
- Study strong interaction sector (QCD) of the Standard Model



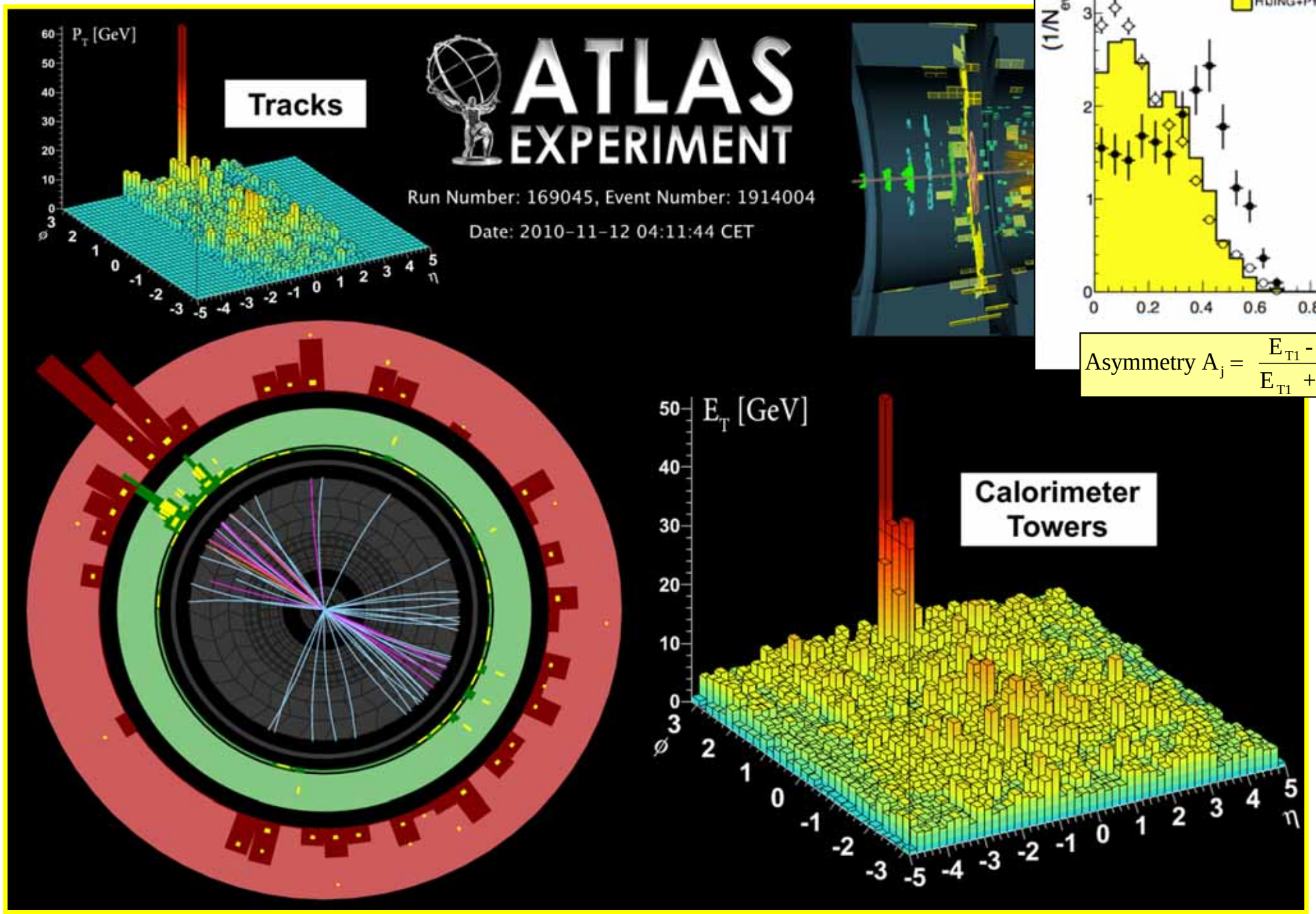
Already interesting results presented:

- QGP behaves like a liquid
- Jet quenching
- …

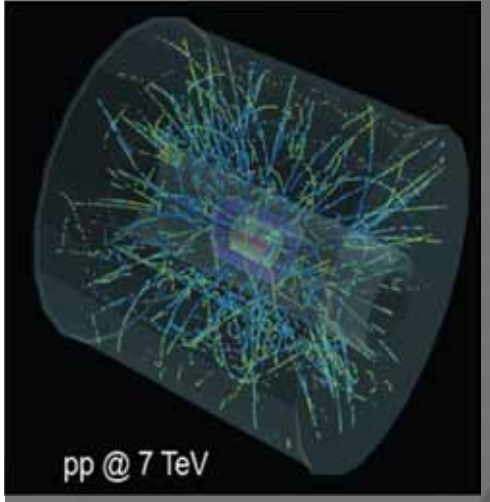
→ There is plenty of exciting physics ahead!



Observation of dijet asymmetry in Pb-Pb collisions



Asymmetry $A_j = \dfrac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$



ALICE Highlights

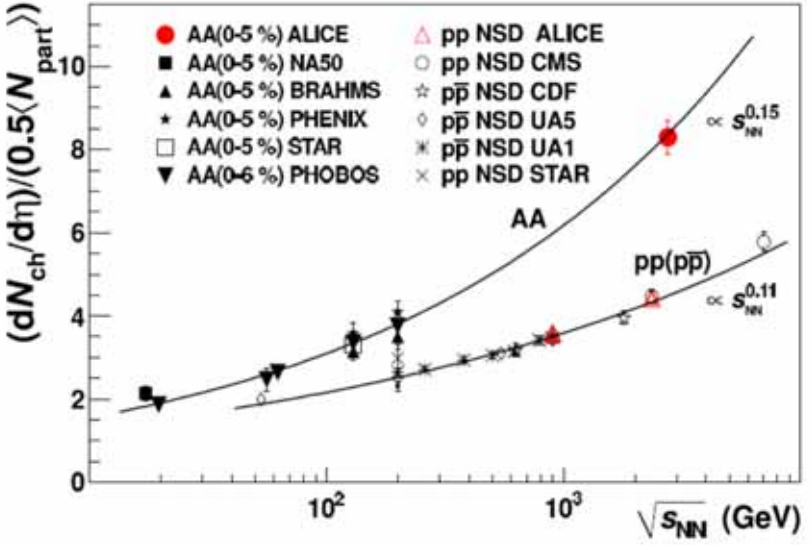
Pb+Pb @ sqrt(s) = 2.76 ATeV

2010-11-08 11:30:46
Fill : 1482
Run : 137124
Event : 0x00000000D3BBE69

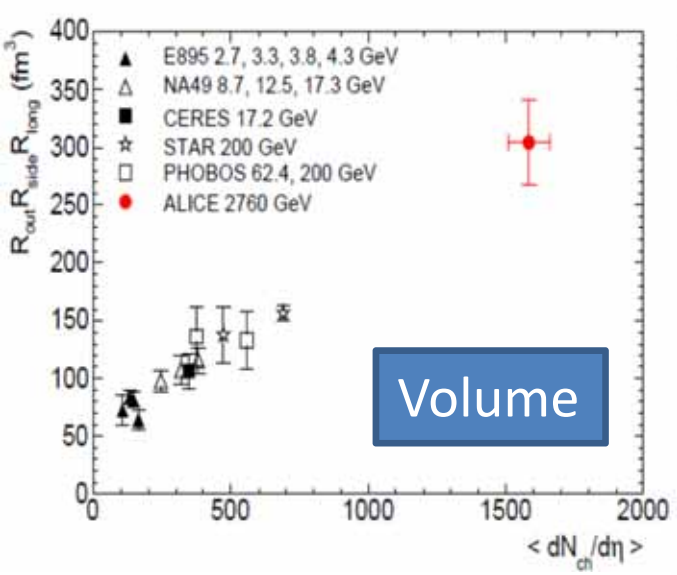
ALICE

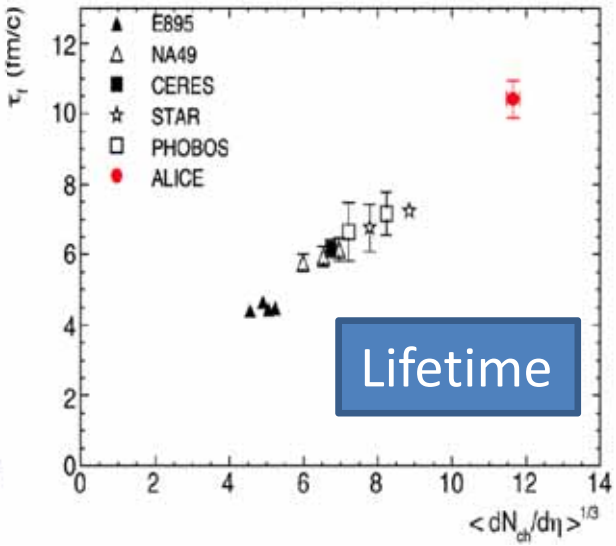
Characteristics of Central Pb+Pb Collisions at 2.76 TeV/N

- **Energy density from $dN_{ch}/d\eta$**
  - $dN_{ch}/d\eta = 1599 \pm 4$ (stat.) ± 80 (syst.)
  - constrains / rules out models
  - 100 times cold nuclear matter density
  - ~3 times the density reached at RHIC ($\varepsilon \approx 15$ GeV/fm^3)



- **Volume and lifetime from HBT interferometry**



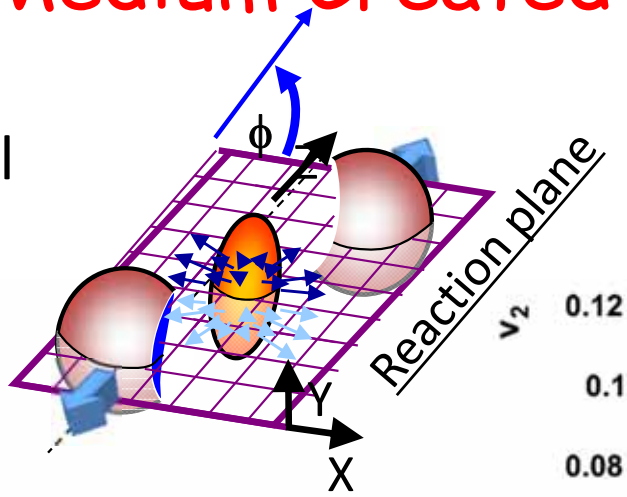


- Freeze-out volume ~ 300 fm^3
- ~ 2 times the volume measured at RHIC (AuAu@200 GeV)
- Lifetime until freeze-out ~ 10 fm/c

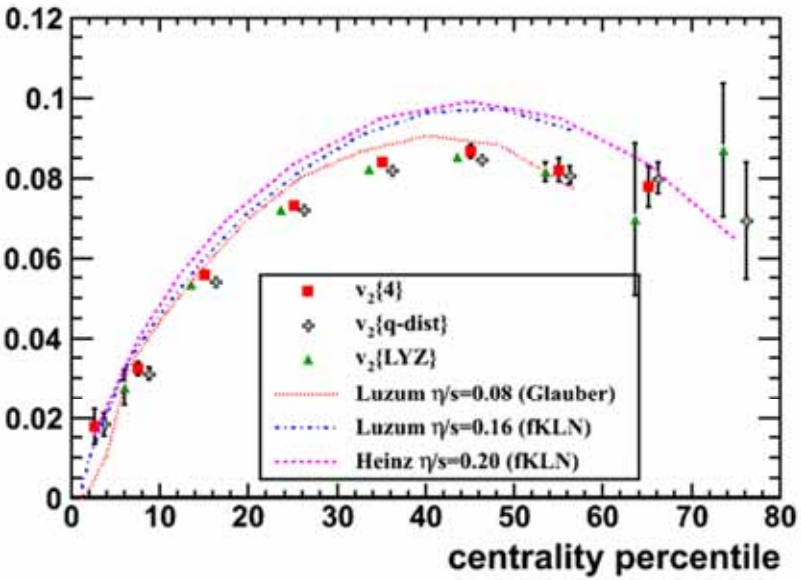
Properties of the Medium Created in Pb+Pb Collisions

The LHC QGP, much hotter than the RHIC QGP, has still the properties of a ~perfect fluid (elliptic flow measurement)

$\eta/s \approx 1/4\pi$ (conjectured quantum bound)

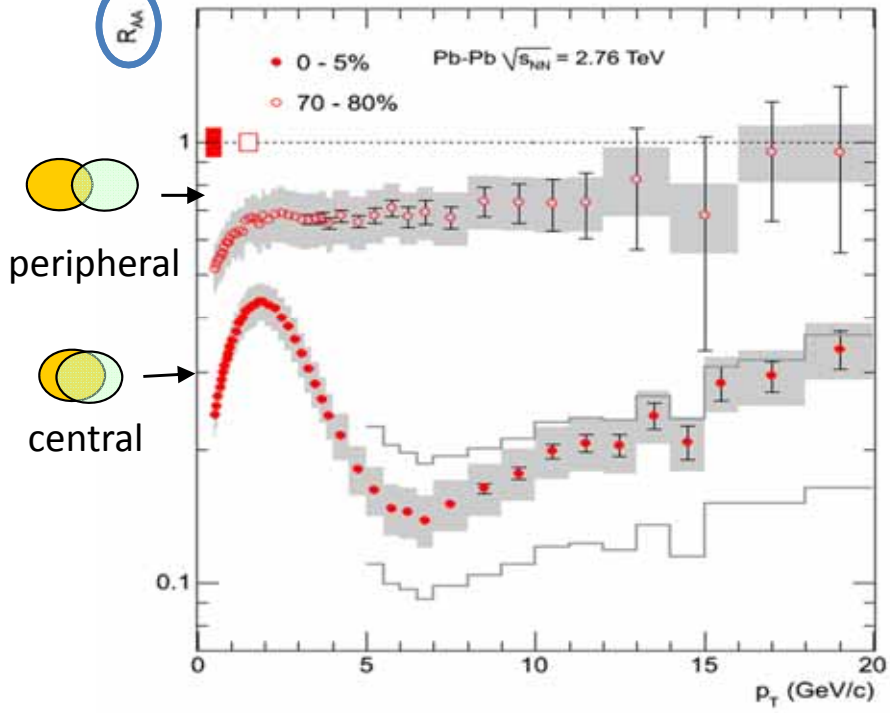


Most extreme state of matter ever created in the lab …

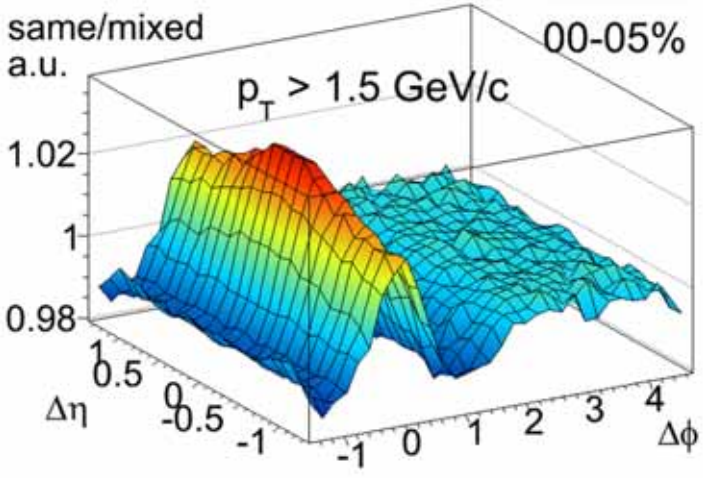


- Strong energy loss of particles in hot and dense medium
- Quantified by nuclear suppression factor R_{AA}
- Maximum suppression R_{AA} ~ 1.5 – 2 x stronger than at RHIC

$$R_{AA}(p_T) = \frac{(1/N_{evt}^{AA})\, d^2N_{ch}^{AA}/d\eta dp_T}{\langle N_{coll}\rangle\,(1/N_{evt}^{pp})\, d^2N_{ch}^{pp}/d\eta dp_T}$$



- now addressing features of the medium via correlations



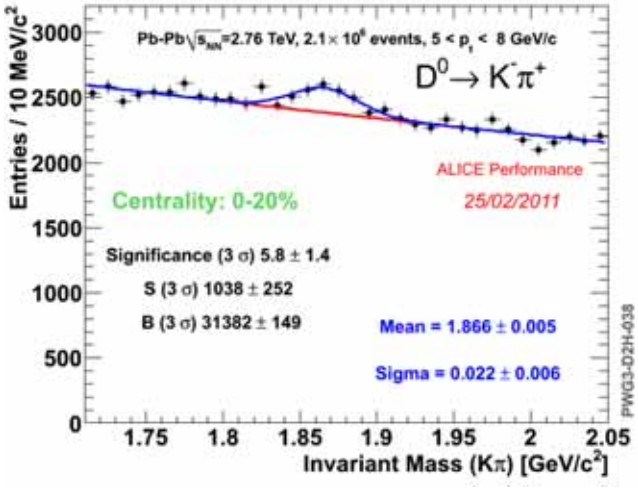
Heavy quarks in Pb-Pb

- Charm via D mesons, beauty via leptons (e, m):

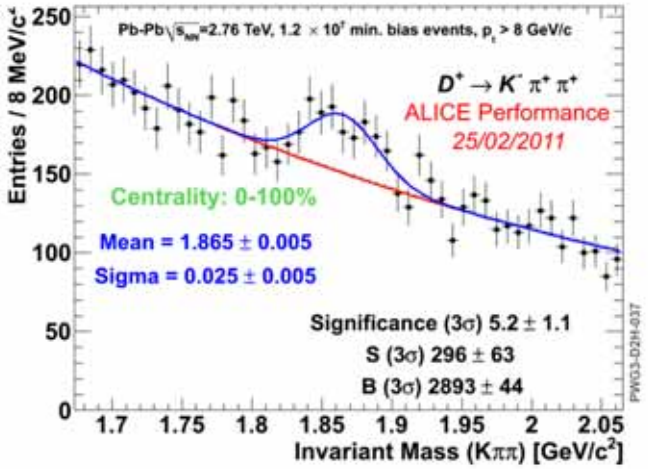
→ colour charge and mass dependence of energy loss

$D^0 \rightarrow K\pi$, $D^+ \rightarrow K\pi\pi$ via secondary vertex reconstruction

central Pb-Pb!

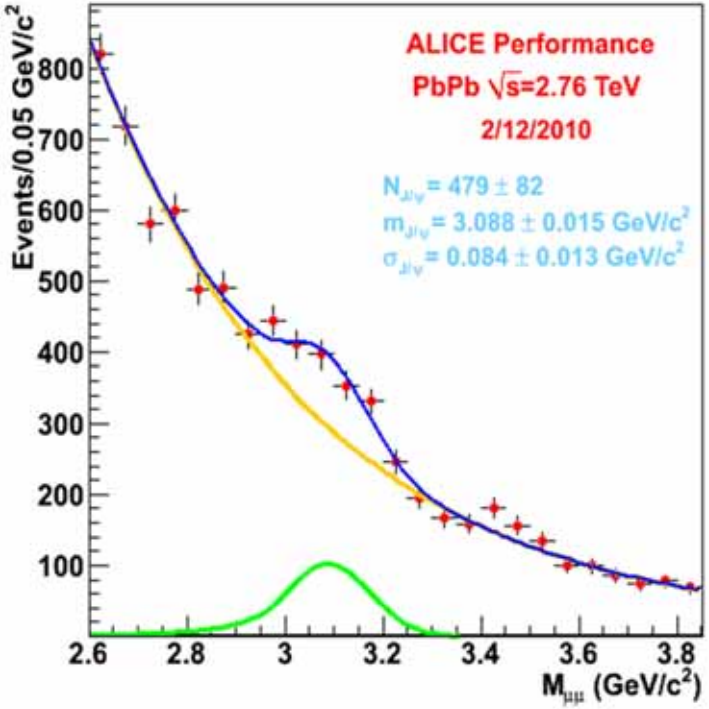


minimum bias Pb-Pb



- Quarkonia: suppression or regeneration?

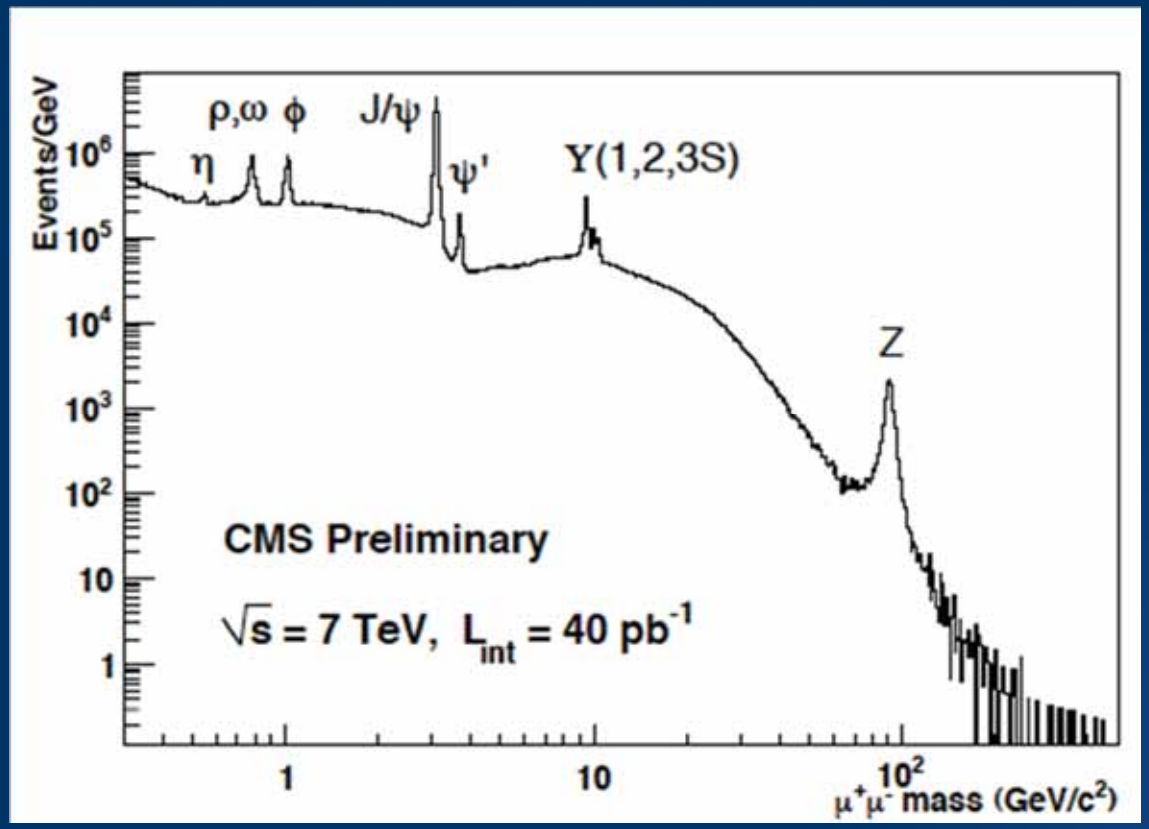
$J/\psi \rightarrow \mu\mu$ at forward rapidity, starting from p_t~0



Expect ~2000 J/ψ from full 2010 statistics

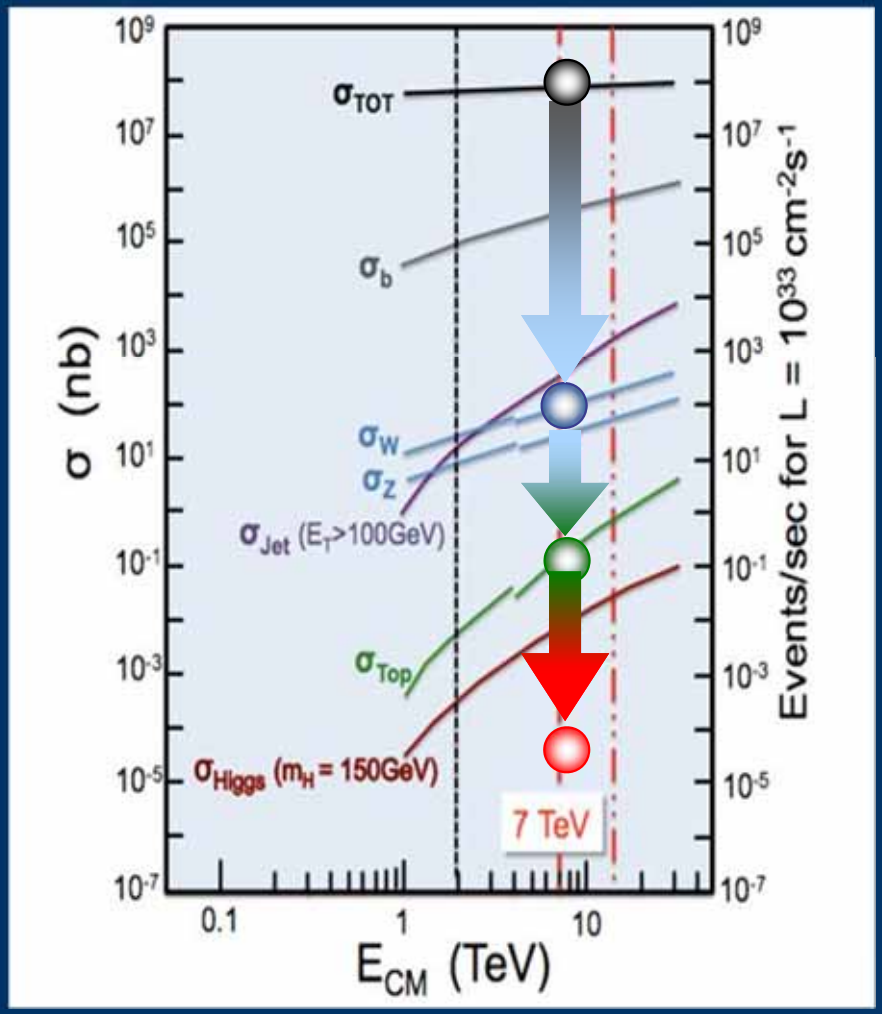
Excellent performances 2010

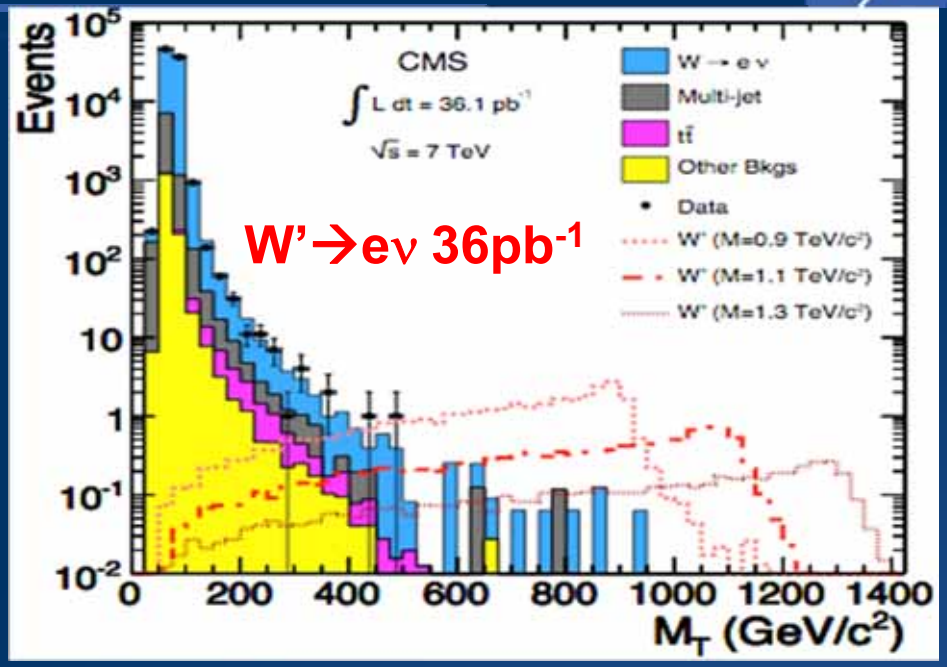
Excellent start-up in 2011:
already some 27/pb delivered

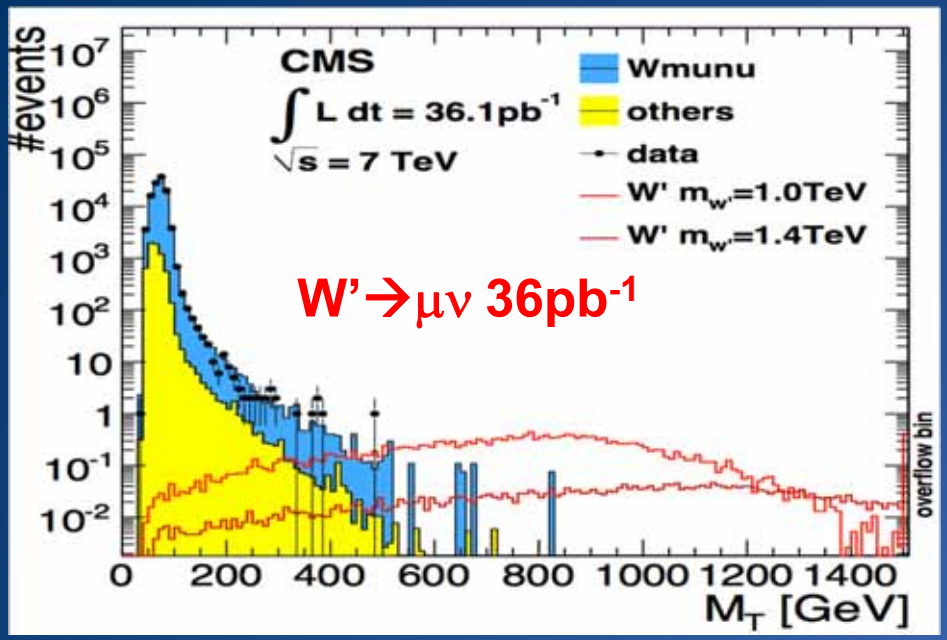


- Experiments demonstrated readiness in the exploitation of the 7 TeV p-p and 2.76 TeV Pb-Pb data;
- analyses proceeded very rapidly;
- Experiments have about completed their journey through the Standard Model … and have started to take us into uncharted territories …

Physics beyond the Standard Model ?

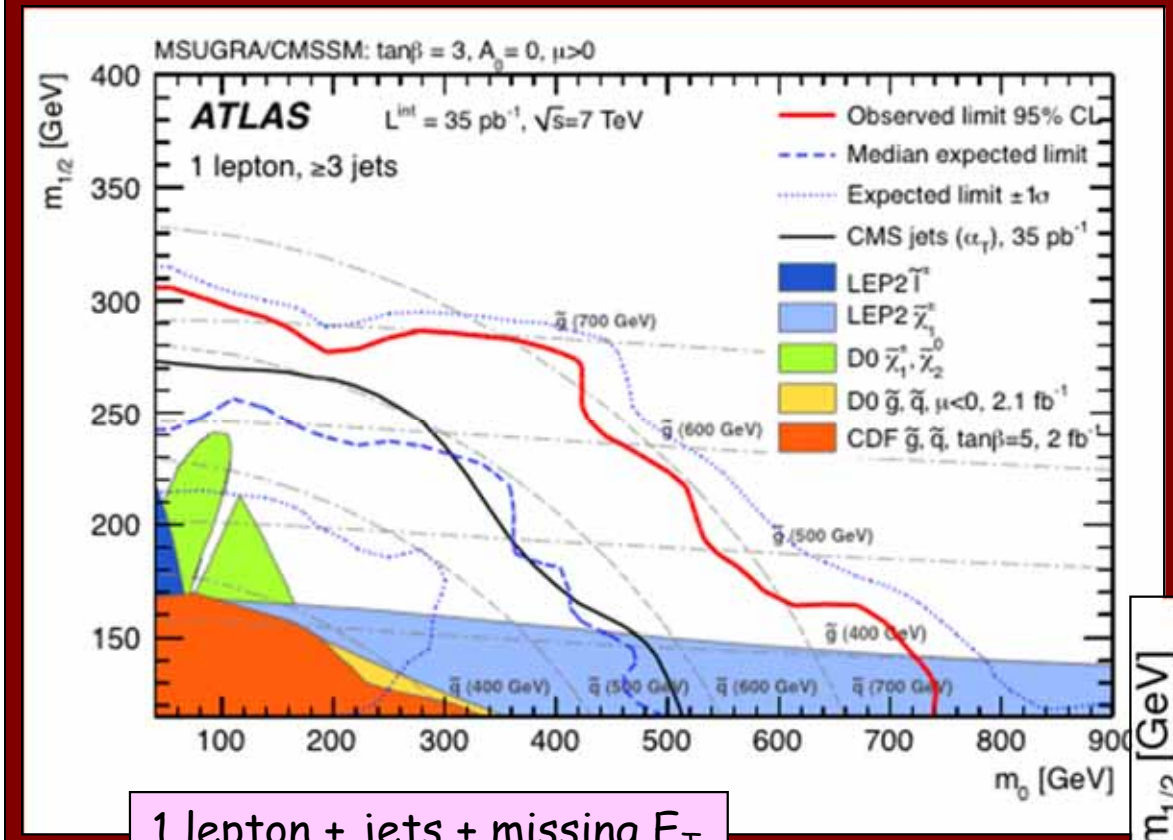






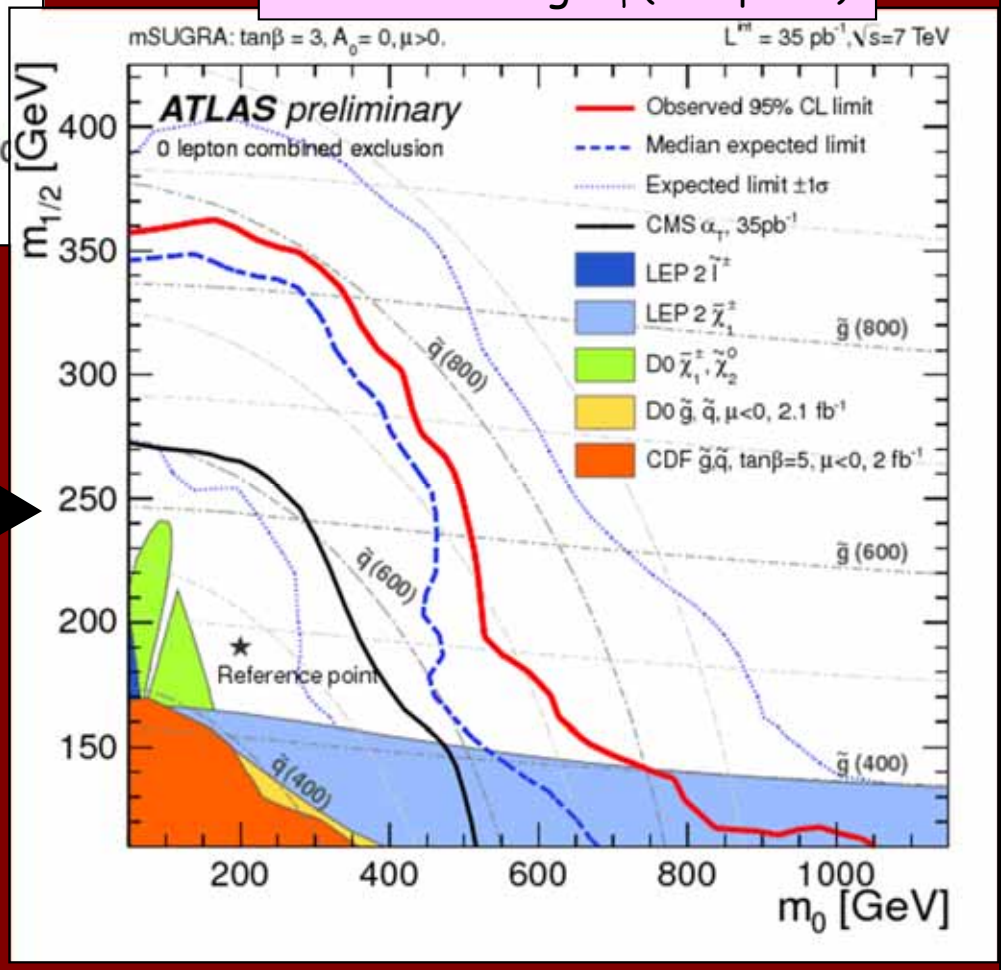
Assuming standard-model-like couplings and decay branching fractions W' with mass<1.58 TeV (95%CL) excluded

Searches for Supersymmetry



1 lepton + jets + missing E_T

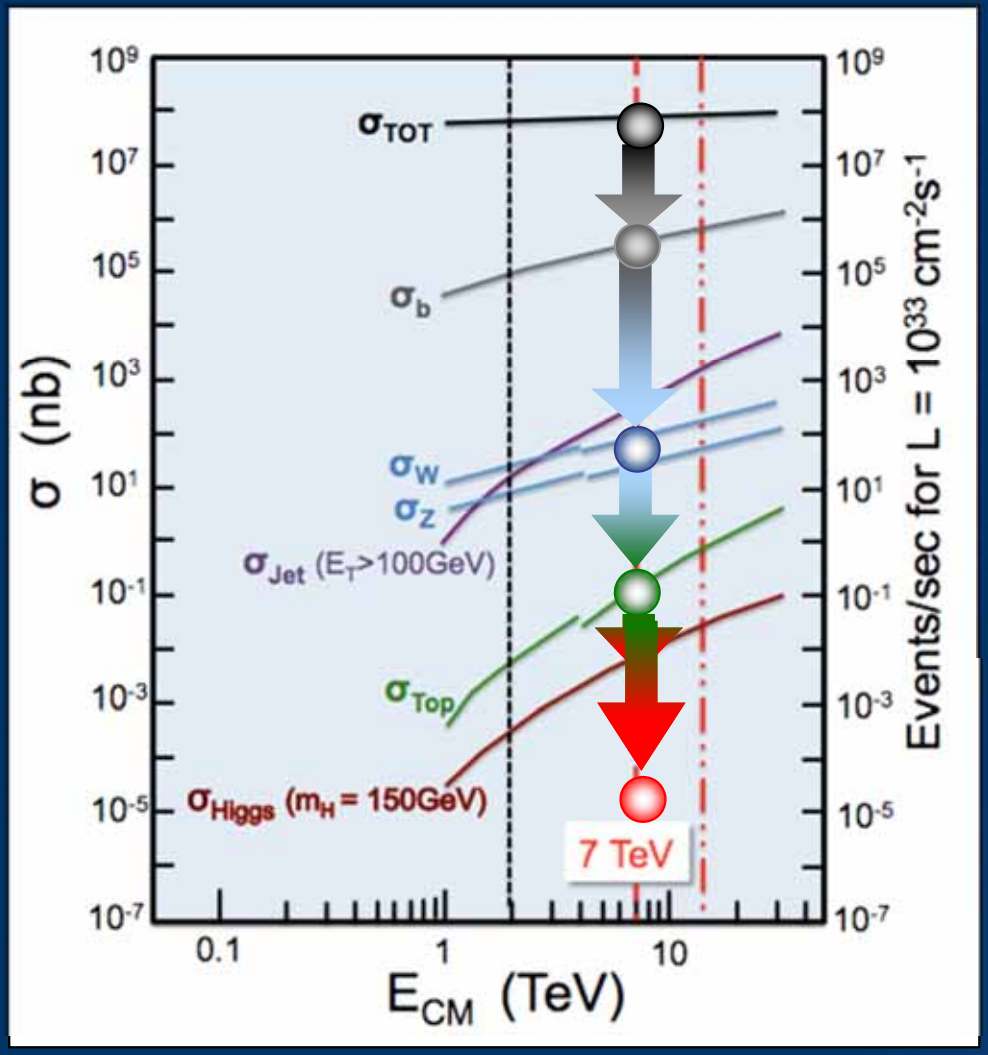
Jets + missing E_T (no leptons)

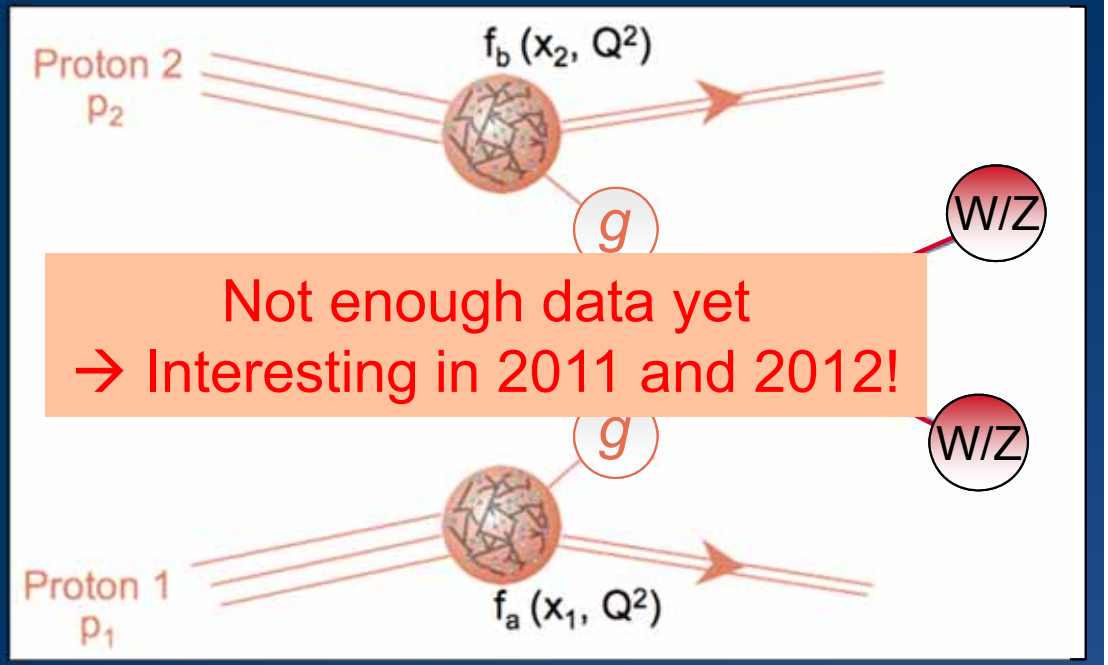


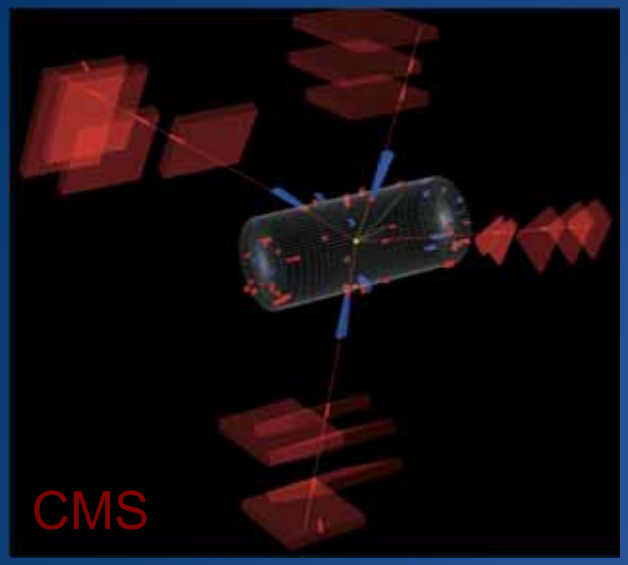
$m(\tilde{g}) > 775$ GeV for $m(\tilde{g}) = m(\tilde{q})$

Most stringent limits to date

Higgs-Boson at 7 TeV





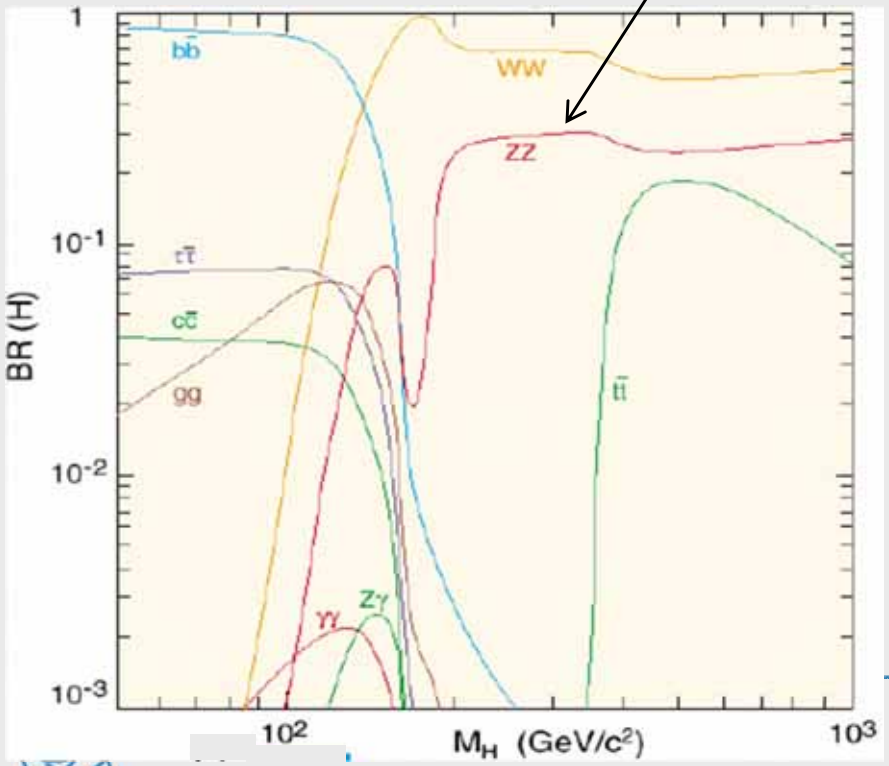


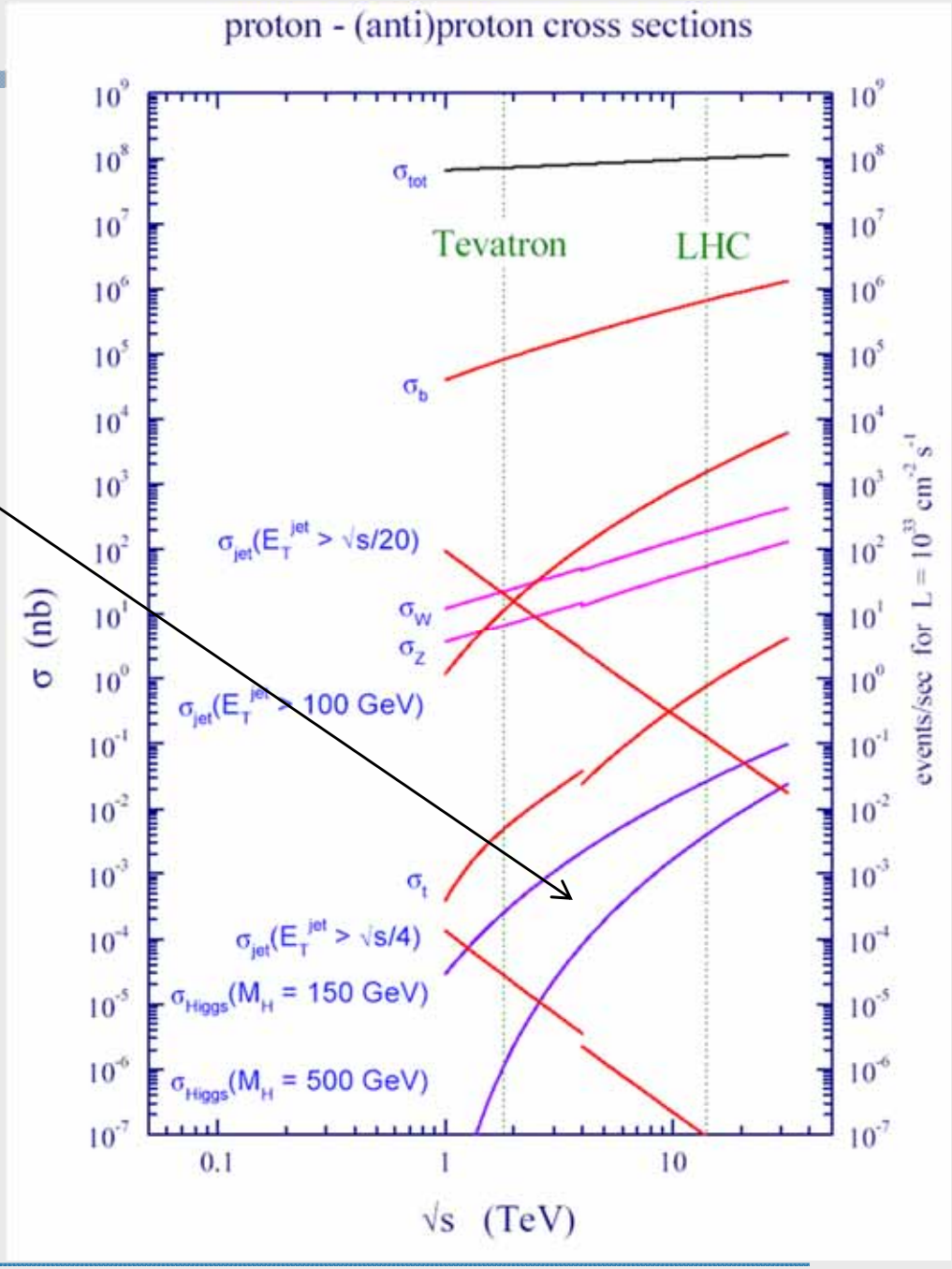
$m_{4\mu}$=201 GeV

Search for the Higgs-Boson at the LHC

Production rate
of the Higgs-Bosons
depends on its mass

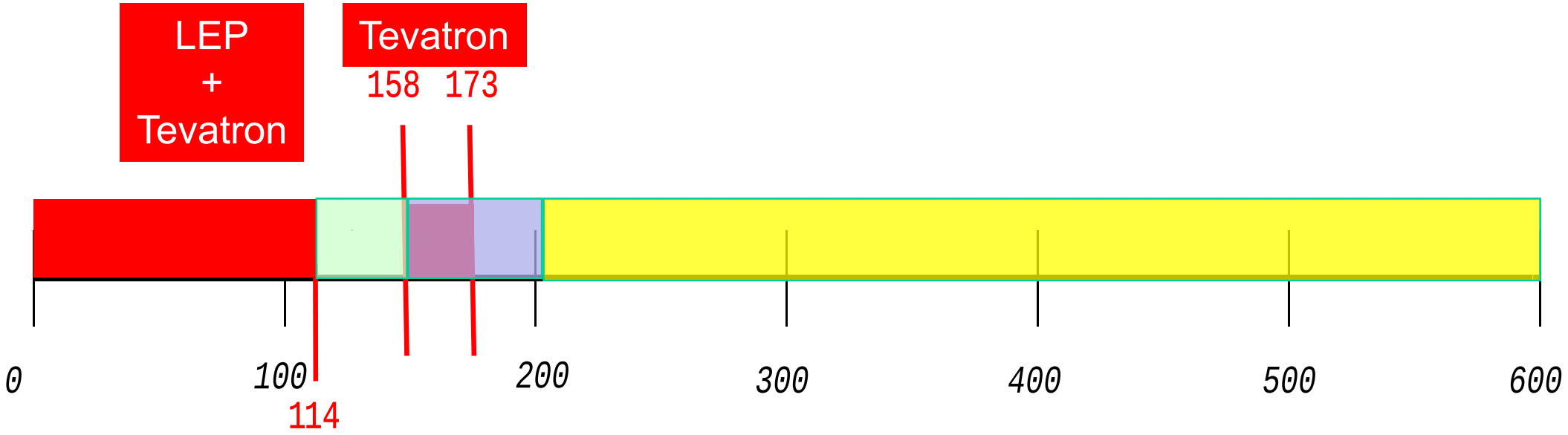
as well as its decay possibilities
("Signature (or picture)"
as seen in the detector)





The Higgs Search Landscape: LHC Joins The Fray !

95% CL Excluded Mass range

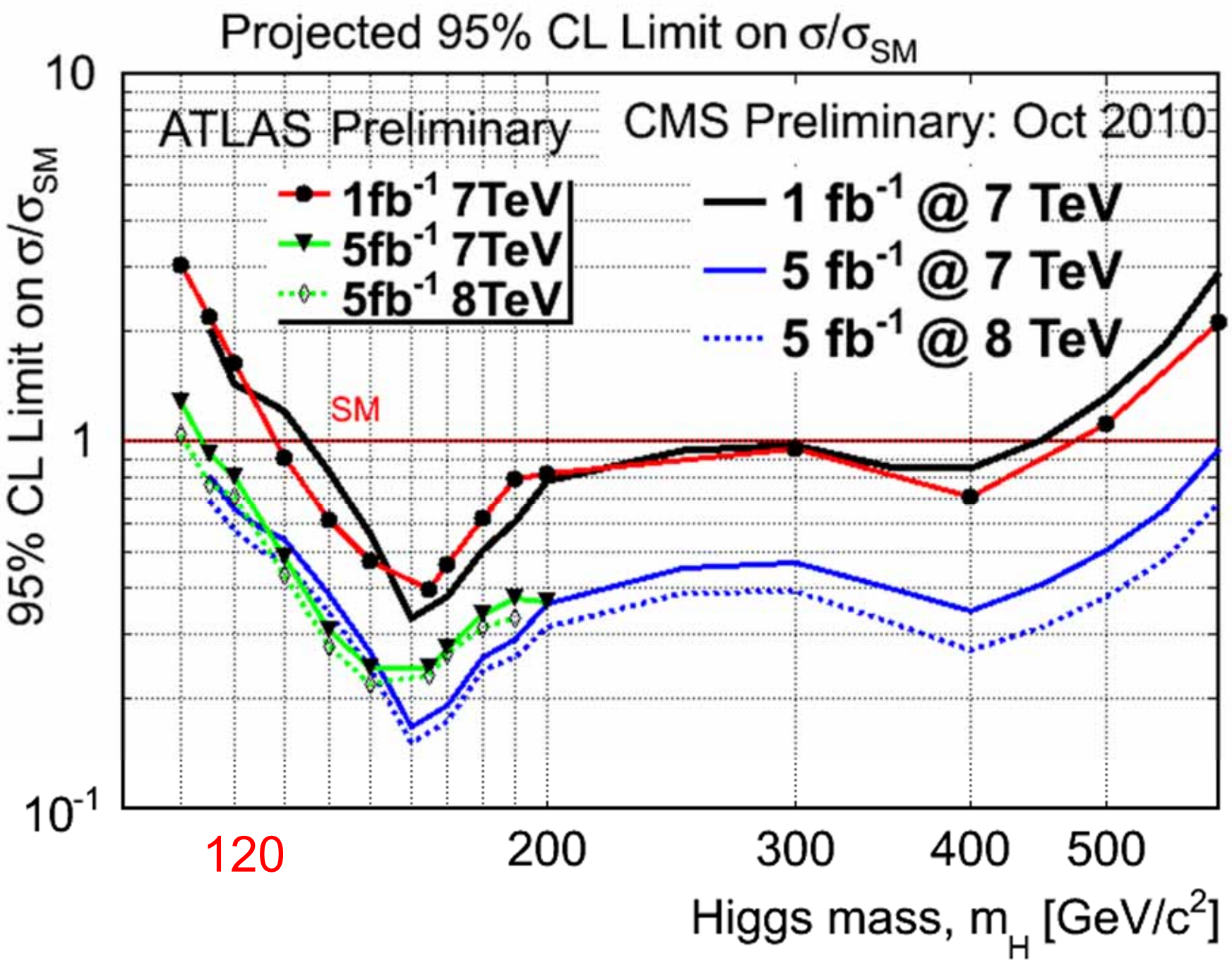


Low Mass
($M_H \approx$ 120 GeV)
H→©©
H → WW
qqH→ | |
V+ H→bb
qqH→bb
V+ H→WW

Mid Mass
($M_H \approx$ 160 GeV)
H→WW
H→ZZ

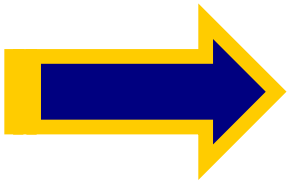
High Mass
($M_H \approx$ 400 GeV)
H→ZZ
H→WW

CMS & ATLAS Projections Compared



Summary of Prospects

SM Higgs Search Prospects (Mass in GeV)			
ATLAS + CMS ≈ 2 x CMS	95% CL exclusion	3 σ sensitivity	5 σ sensitivity
1 fb^{-1}	120 - 530	135 - 475	152 - 175
2 fb^{-1}	114 - 585	120 - 545	140 - 200
5 fb^{-1}	114 - 600	114 - 600	128 - 482
10 fb^{-1}	114 - 600	114 - 600	117 - 535



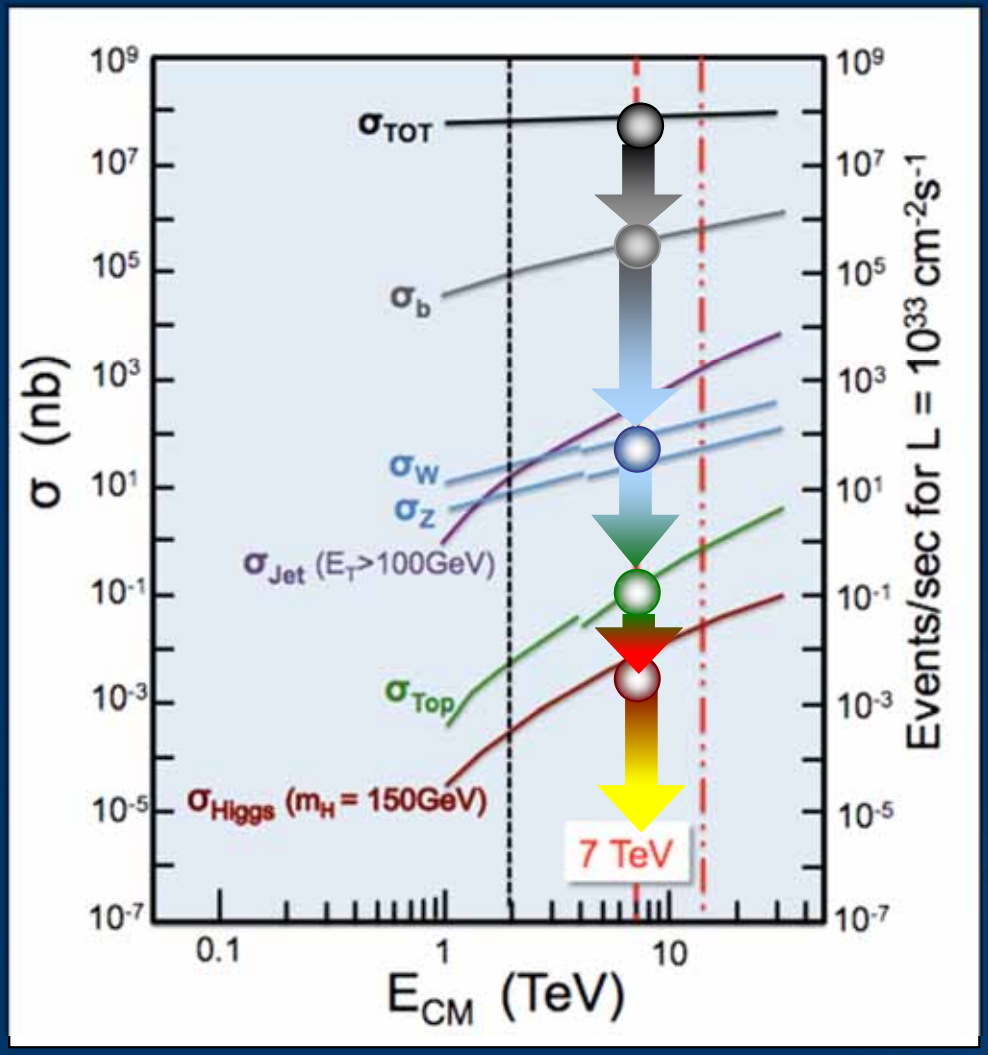
Higgs Boson, if it exists between masses of (114 - 600 GeV) will either be discovered or ruled out in ≈ next two years

→ **Decided to run in 2011 and 2012**

Operate LHC in 2011 and 2012:

- 2011: E_{cm} = 7 TeV, expect L_{int} = 1 fb^{-1} (baseline), hope for more
- 2012: L_{int} possible increase by factor of ~ 2 (?)
- 2013/2014: shut down (≥ 15 months) to prepare LHC for 14 TeV operation

The 2011 and 2012 run …

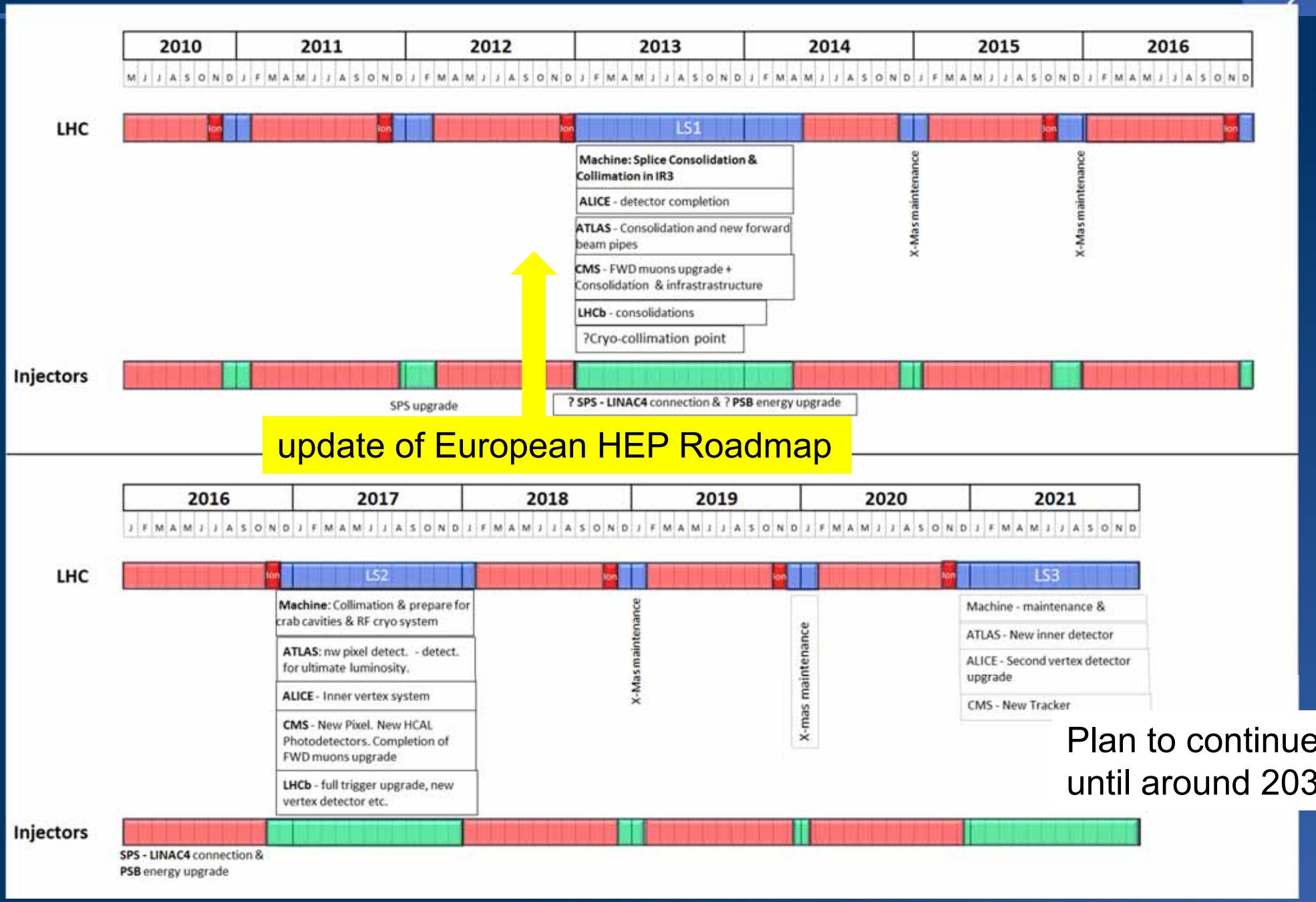


Search for physics beyond SM

- Discovering new particles
- Making precise measurements of properties of known particles/forces: e.g. LHCb: $B_s \rightarrow \mu^+\mu^-$

→ will enter new territory !

New ***Rough Draft*** 10 year plan




beyond LHC ?

Next decades

Road beyond Standard Model

through synergy of

hadron - hadron colliders (LHC, HL/HE-LHC?)

lepton - hadron colliders (LHeC ??)

lepton - lepton colliders (LC (ILC or CLIC) ?)

LHC results will guide the way at the energy frontier

Past decades saw precision studies of 5 % of our Universe → Discovery of the Standard Model

The LHC is delivering data

We are just at the beginning of exploring 95 % of the Universe

Past decades saw precision studies of 5 % of our Universe → Discovery of the Standard Model

The LHC is delivering data

We are just at the beginning of exploring 95 % of the Universe

exciting prospects