



*Accelerating Science and Innovation*

HERA

and the Future of Particle Physics

Past few decades

# “Discovery” of Standard Model

through synergy of

hadron - hadron colliders (e.g. Tevatron)

lepton - hadron colliders (HERA)

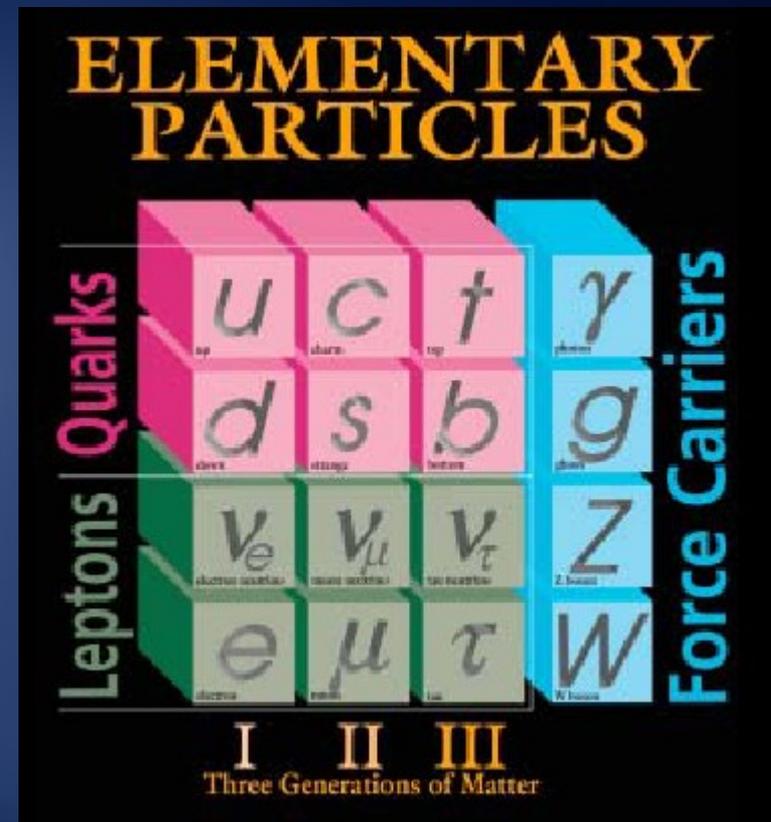
lepton - lepton colliders (e.g. LEP, SLC)

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

The physical world is  
composed of  
Quarks and Leptons  
(**Fermions**)

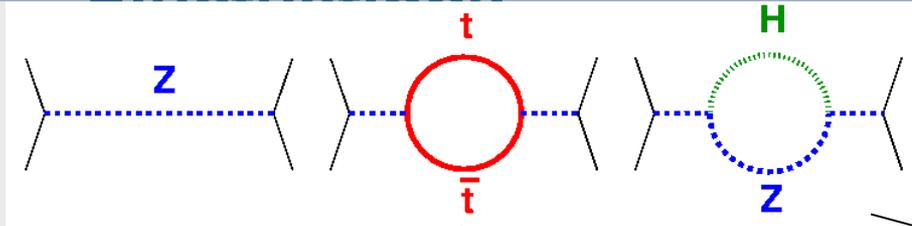
interacting via force carriers  
(**Gauge Bosons**)

Last entries: top-quark 1995  
tau-neutrino 2000

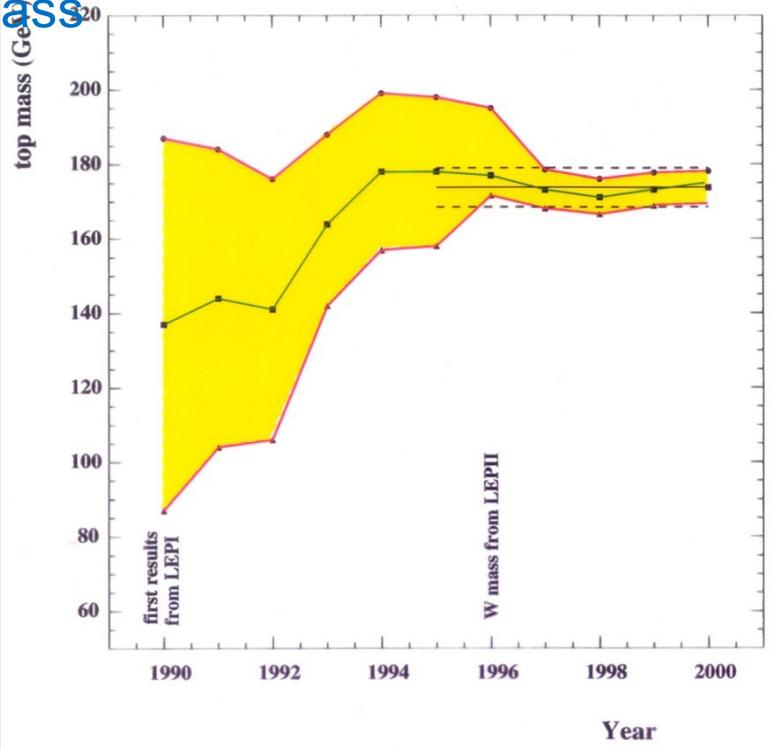


# Test of the SM at the Level of Quantum

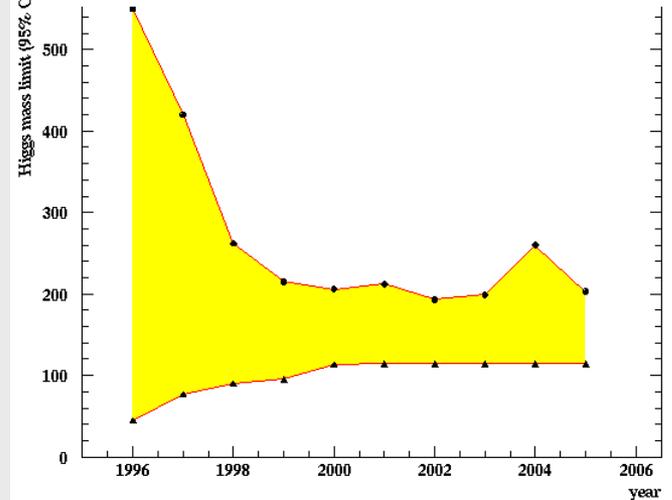
## Fluctuations



indirect determination of the top mass



prediction of the range for the Higgs mass

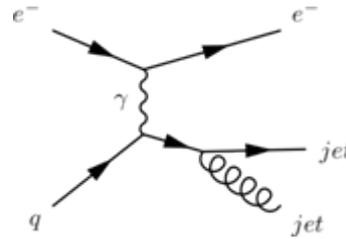


- possible due to
- precision measurements
- known higher order electroweak corrections

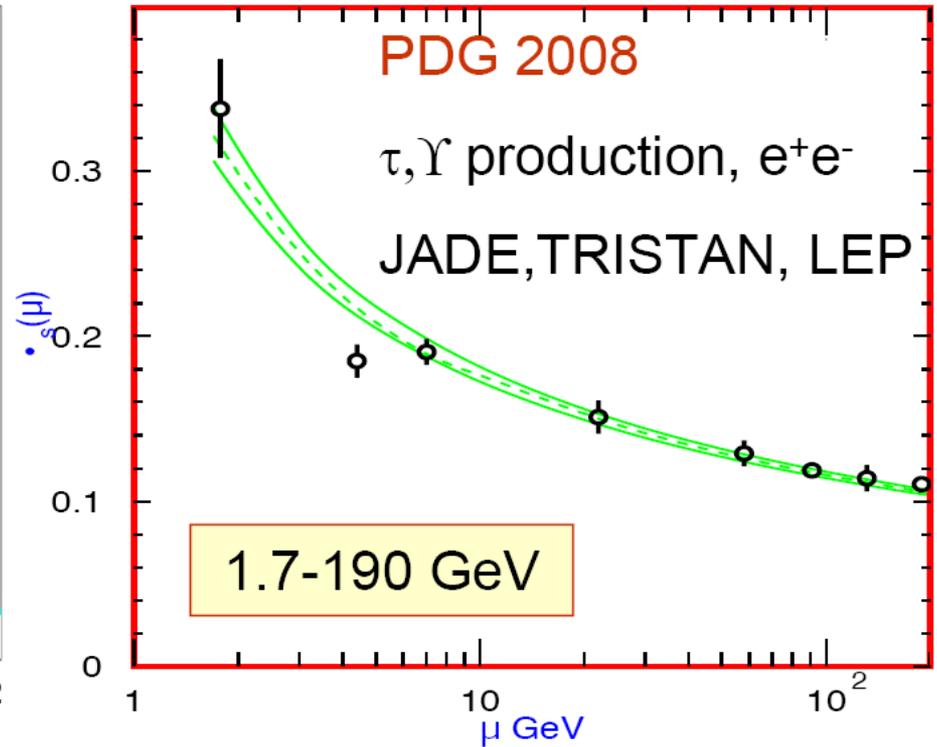
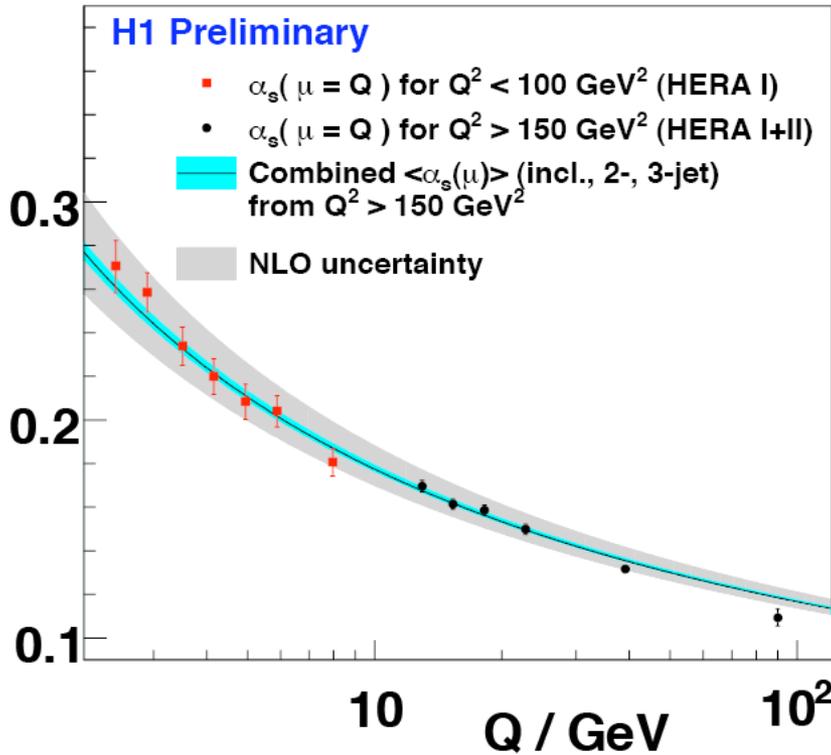


# HERA: Tests of QCD

## > Running of $\alpha_s$



$\alpha_s$  from Jet Cross Sections



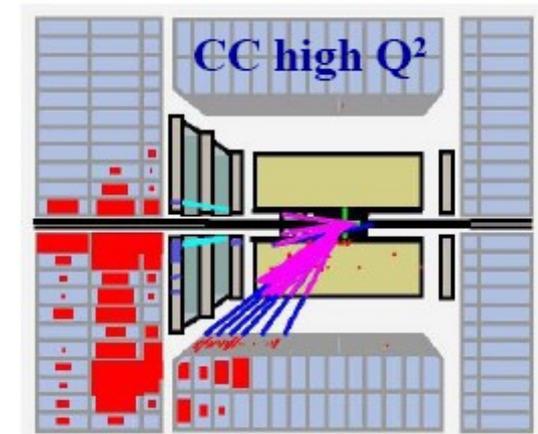
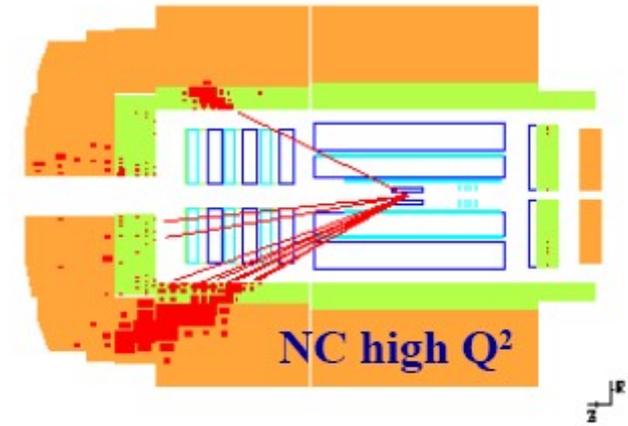
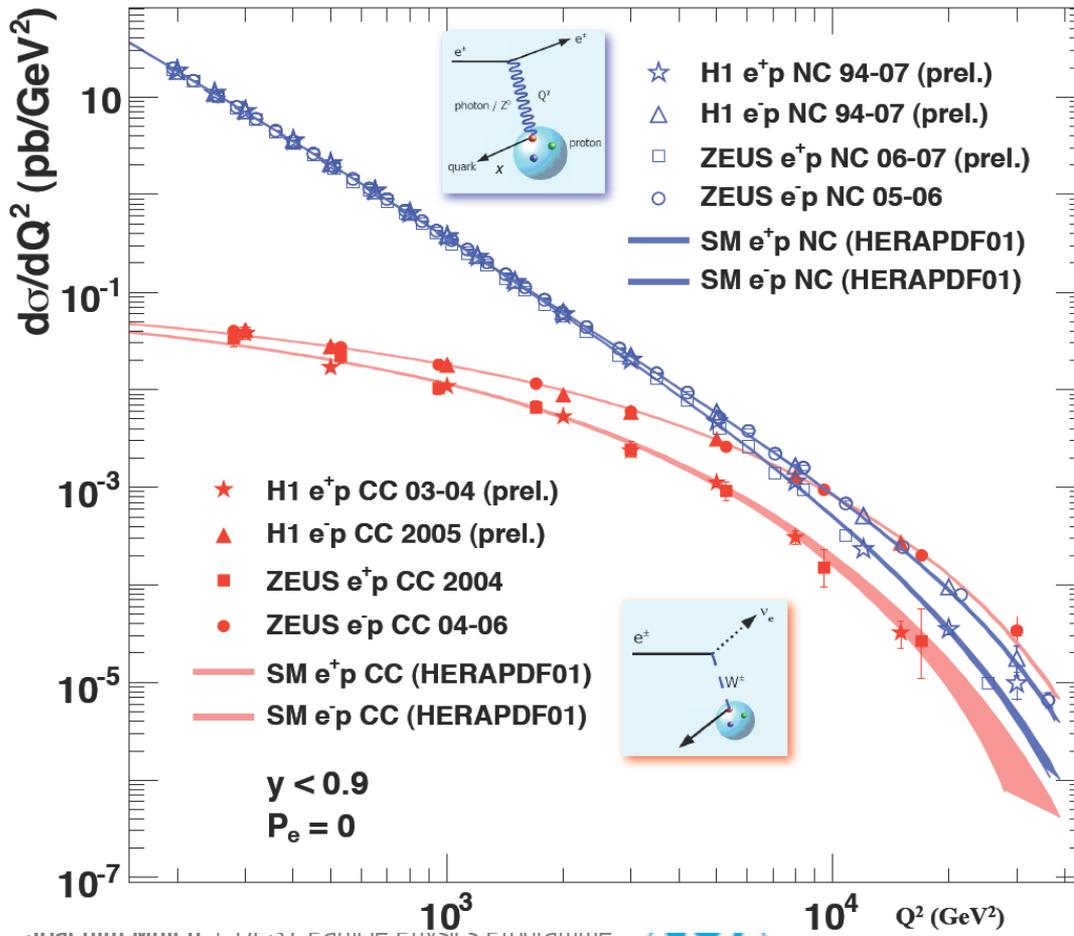
$$\alpha_s(M_Z) = 0.1168 \pm 0.0007 (\text{exp.}) \begin{matrix} +0.0046 \\ -0.0030 \end{matrix} (\text{th.}) \pm 0.0016 (\text{PDF})$$



# HERA: Tests of Electroweak Interactions

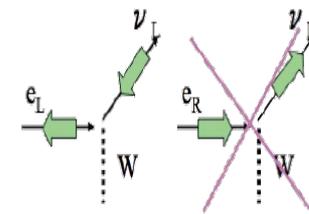
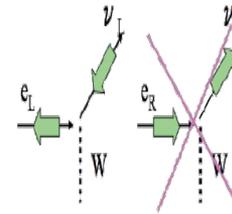
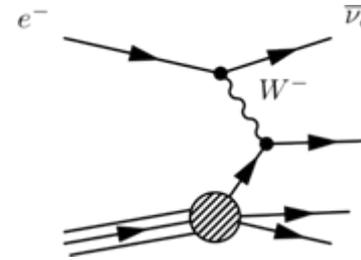
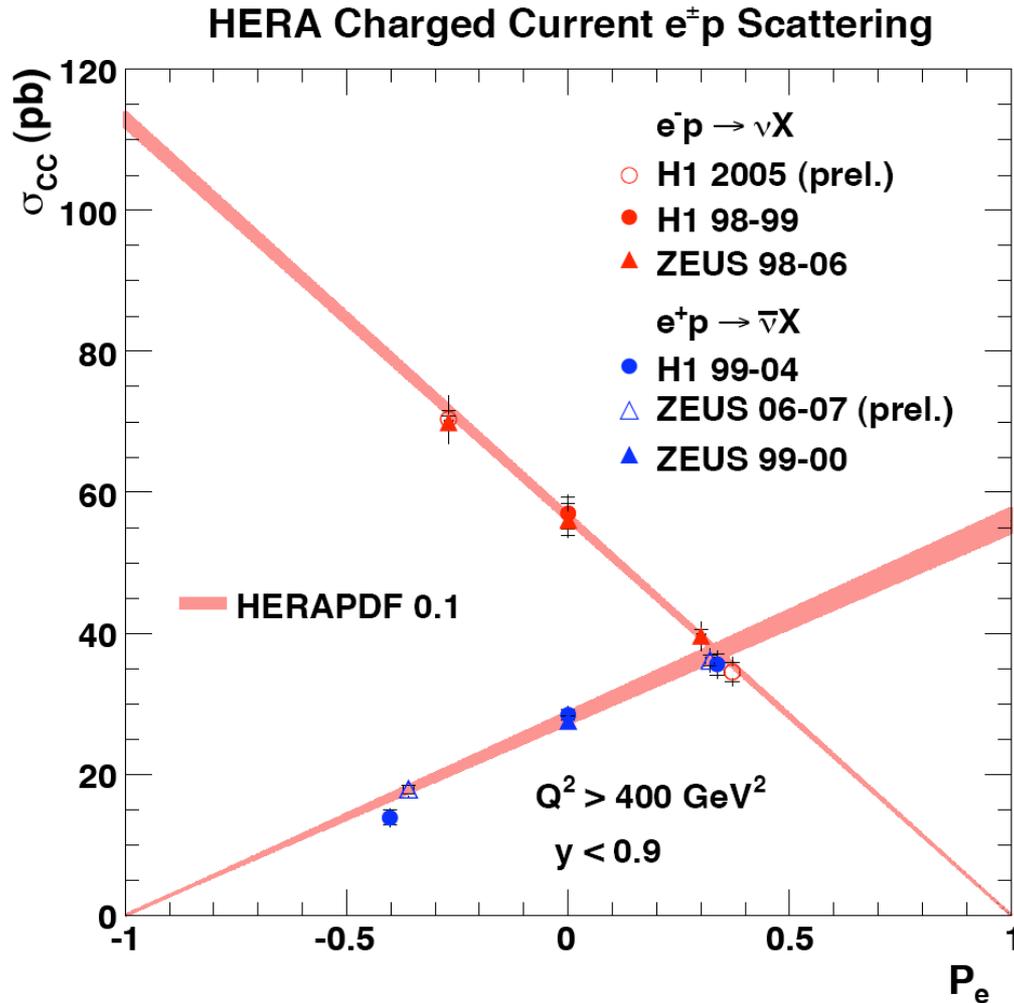
Textbook example: **electromagnetic and weak interactions become equally strong at high energies**

HERA I & II



# HERA: Tests of Electroweak Interactions

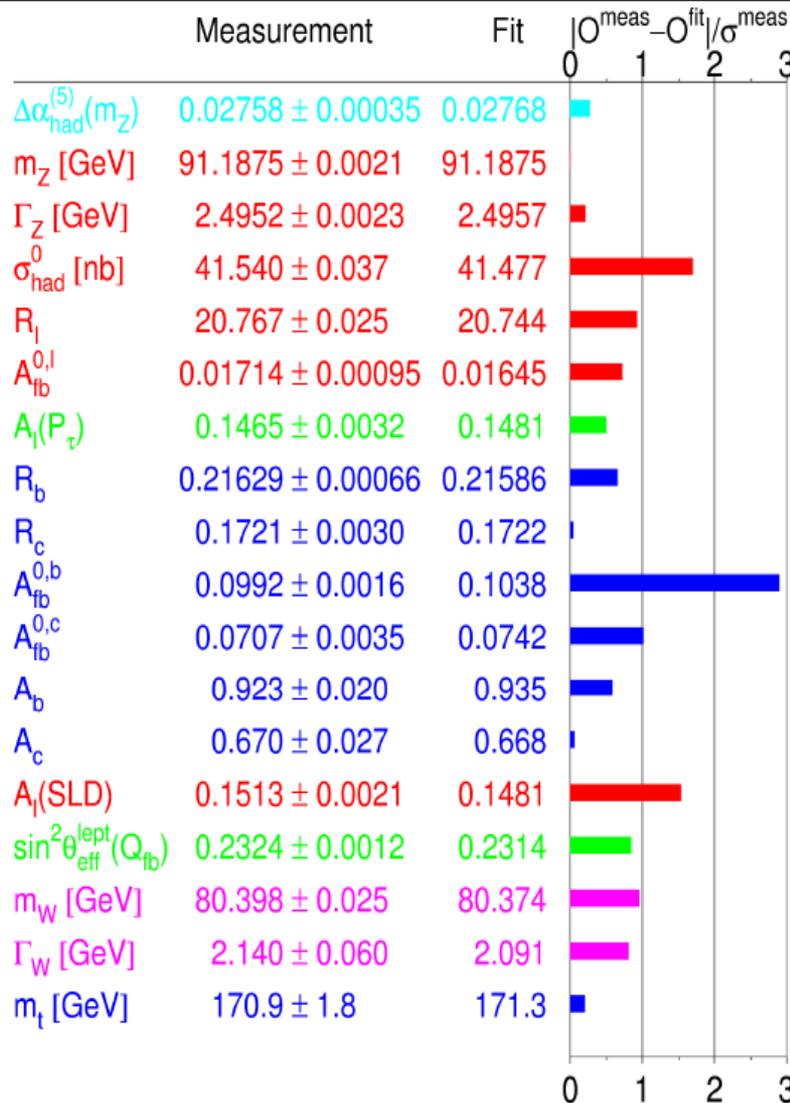
## > Polarised CC cross section



> No right-handed charged currents

# Status recent Summer Conferences

## Standard Model Analysis



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

$$\chi^2/ndof = 18.2/13 \text{ (15.1\%)}$$

Largest  $\chi^2$  contribution:  
 $A_l(\text{SLD})$  vs.  $A_{fb}^b(\text{LEP})$

Without this point, the fit is *too good!*  
 Decrease  $m_W$  of leptons by  $M_W$

$A_{fb}^b$  has largest pull:  $2.9\sigma$ !

however ...  
 ... many key questions open

# Key Questions of Particle Physics

origin of mass/matter or  
origin of electroweak symmetry breaking

unification of forces

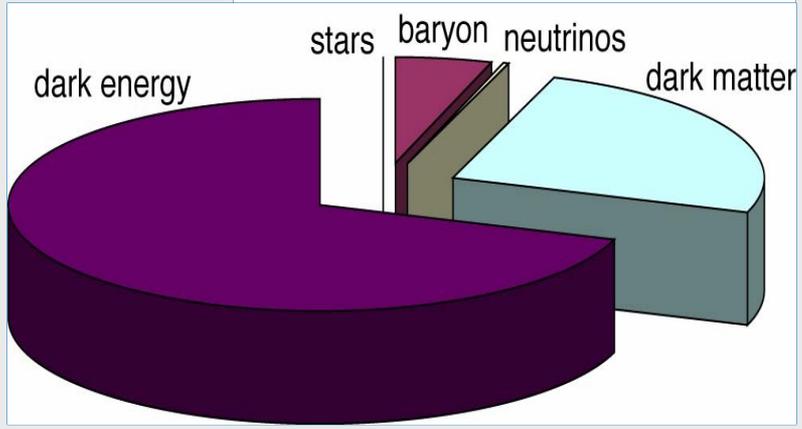
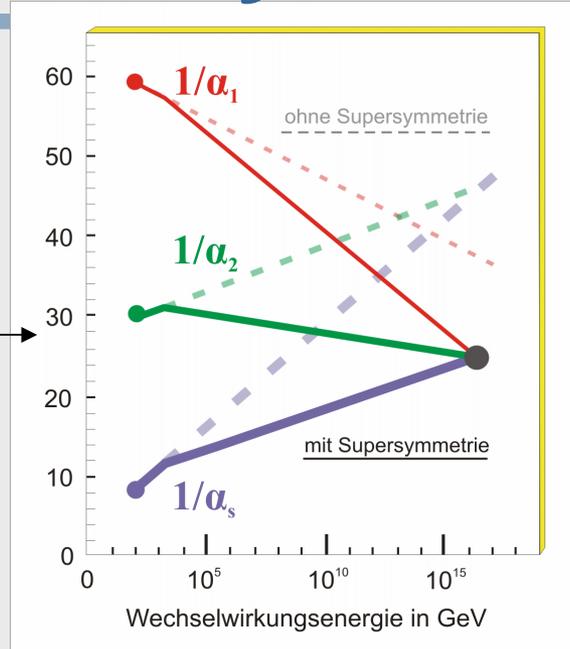
fundamental symmetry of forces and  
matter

unification of quantum physics and  
general relativity

number of space/time dimensions

what is dark matter

what is dark energy



# Solutions?



## Standard

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

**Technicolor**  
 New (strong) interactions produce EWSB  
 Extensions of the SM gauge group :  
**Little Higgs / GUTs / ...**

Selected NP  
 since 1957  
 Except P.  
 Higgs

Successful for ever ??

**Supersymmetry**  
 New particles at  $\approx$  TeV scale, light Higgs  
 Unification of forces  
 Higgs mass stabilized  
**No new interactions**

**Extra Dimensions**  
 New dimensions introduced  
 mGravity  $\approx$  melw □ Hierarchy  
 problem  
 solved  
**New particles at  $\approx$  TeV scale**



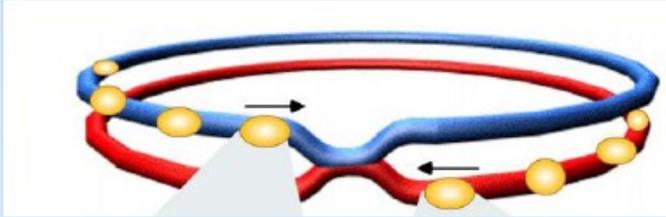
# Enter a New Era in Fundamental Science

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 ECM 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**

§ **1011 protons per bunch**

§ **at 1034/cm<sup>2</sup>/s**

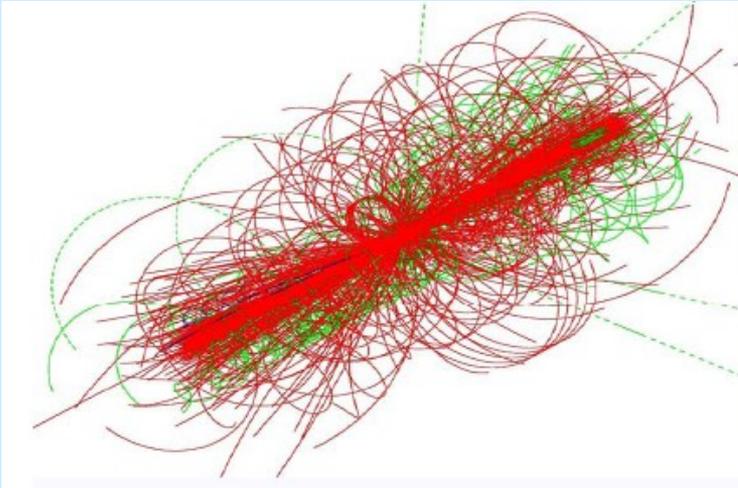
**≈ 35 pp interactions per crossing**  
**pile-up**

→ **≈ 109 pp interactions per second !!!**

§ **in each collision**

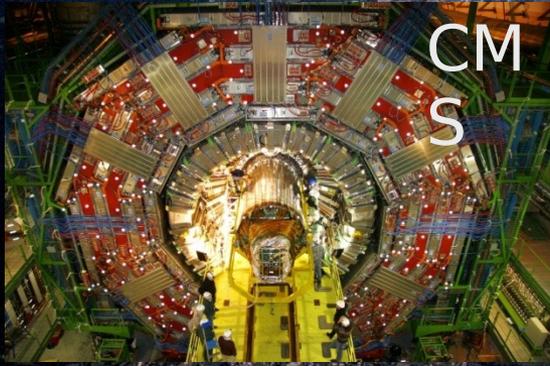
**≈ 1600 charged particles produced**

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

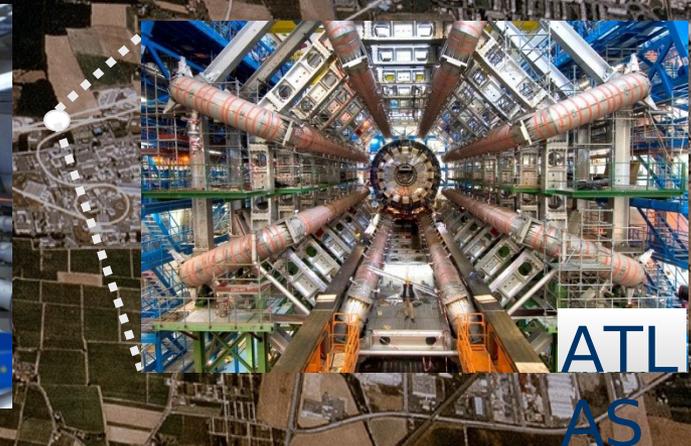


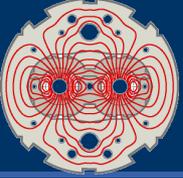
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at ECM up to 14 TeV

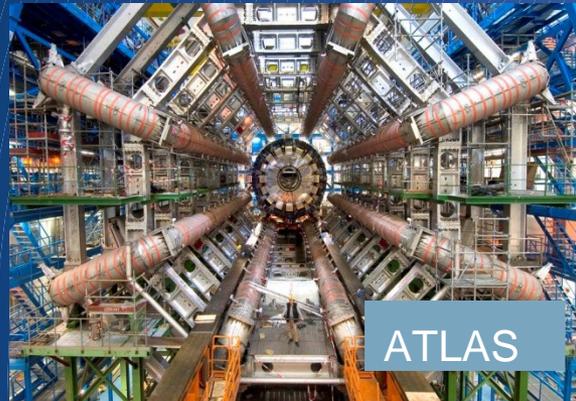
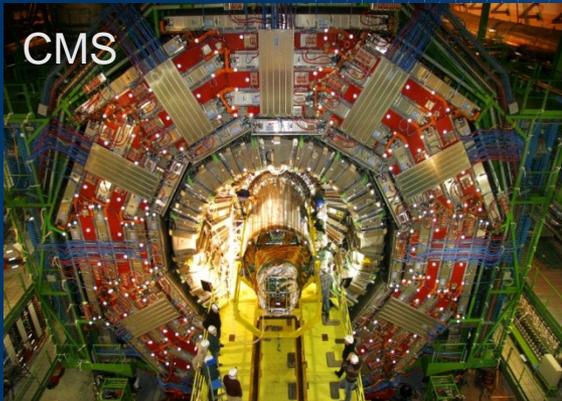




# LHC Experiments $\square$ complementary



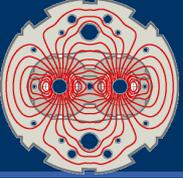
Specialised detector to study b-quarks  $\square$  CPV



General purpose detectors



Specialised detector to study heavy ion collisions



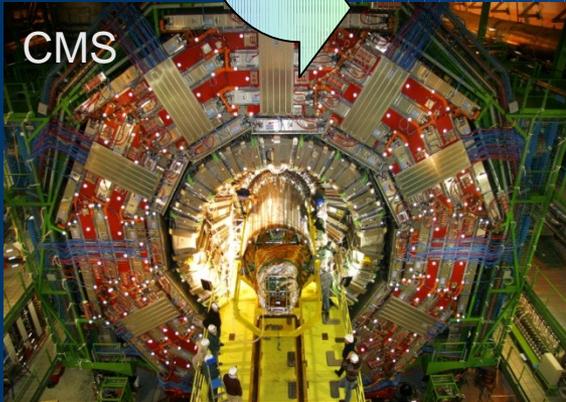
# LHC Experiments complementary



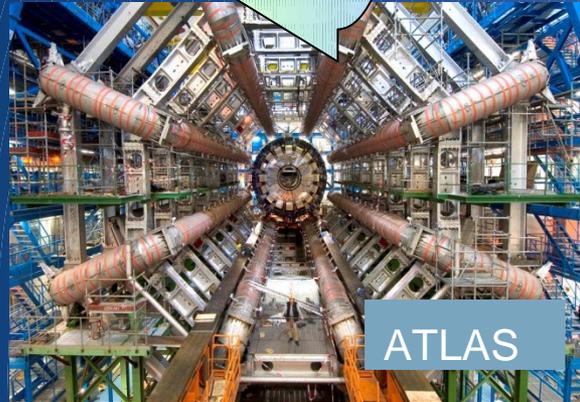
Overlap  
in  
physics  
reach



LHCb



CMS

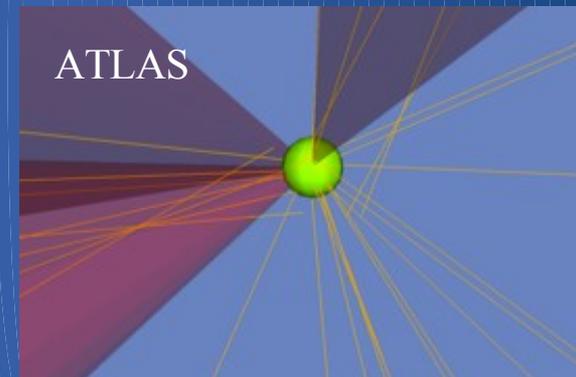
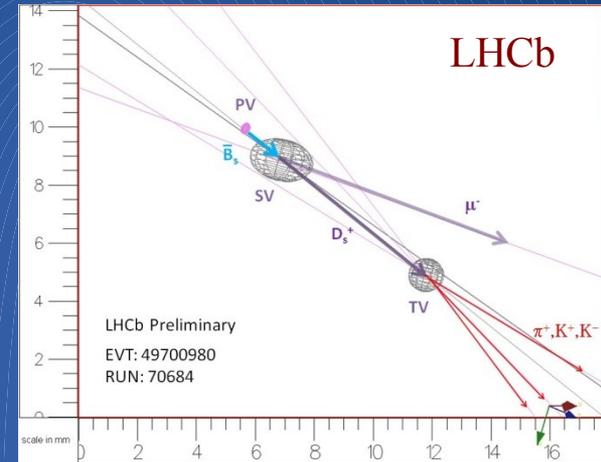


ATLAS

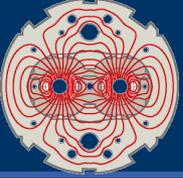


ALICE

Key feature: reconstruct  
secondary vertex



ATLAS



# LHC Experiments complementary

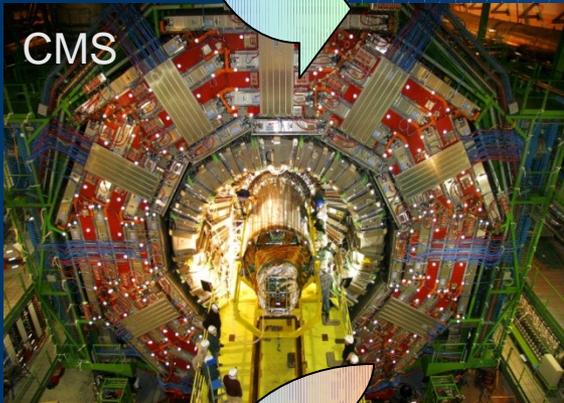


Overlap  
in  
physics  
reach

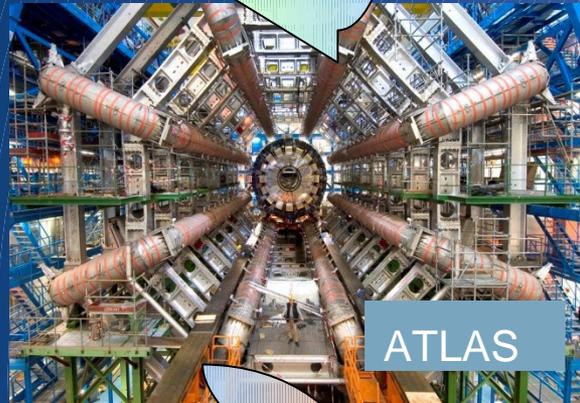


LHCb

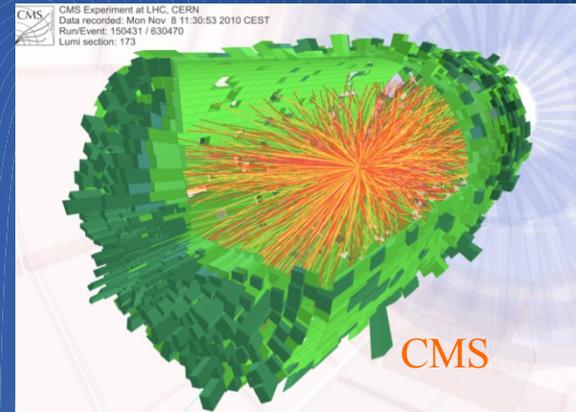
Key feature: reconstruct  
> 20'000 charged tracks in  
one event



CMS



ATLAS

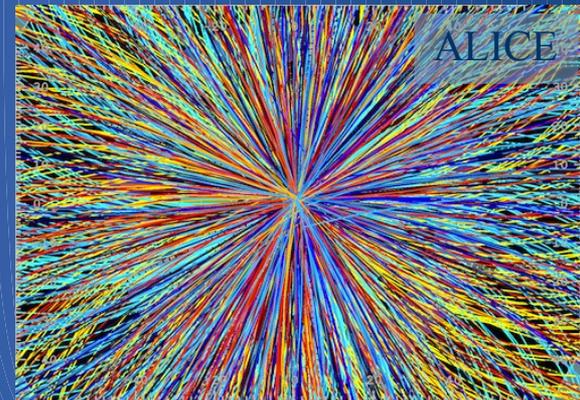


CMS

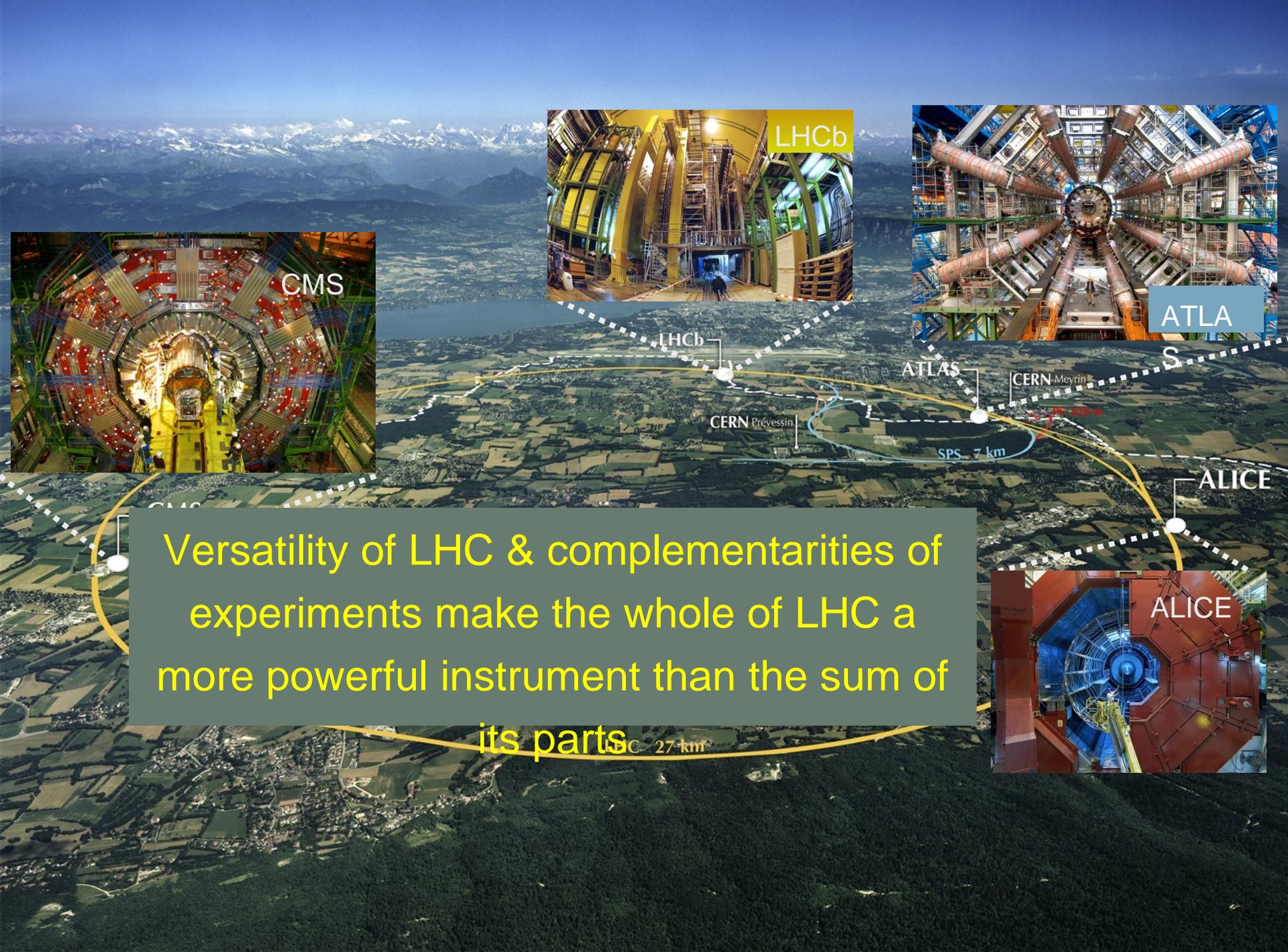
Overlap  
in  
physics  
reach



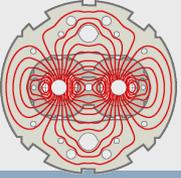
ALICE



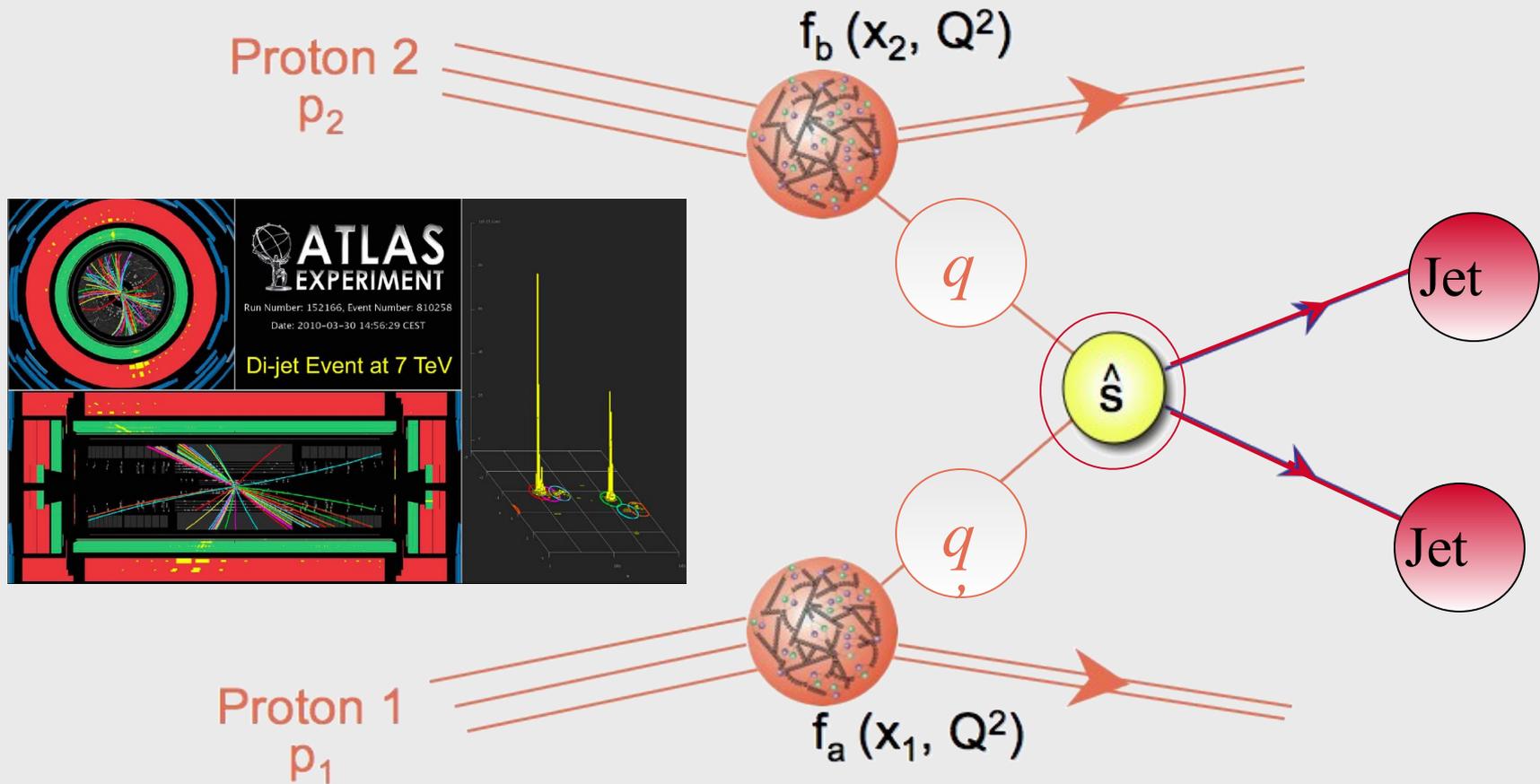
ALICE



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

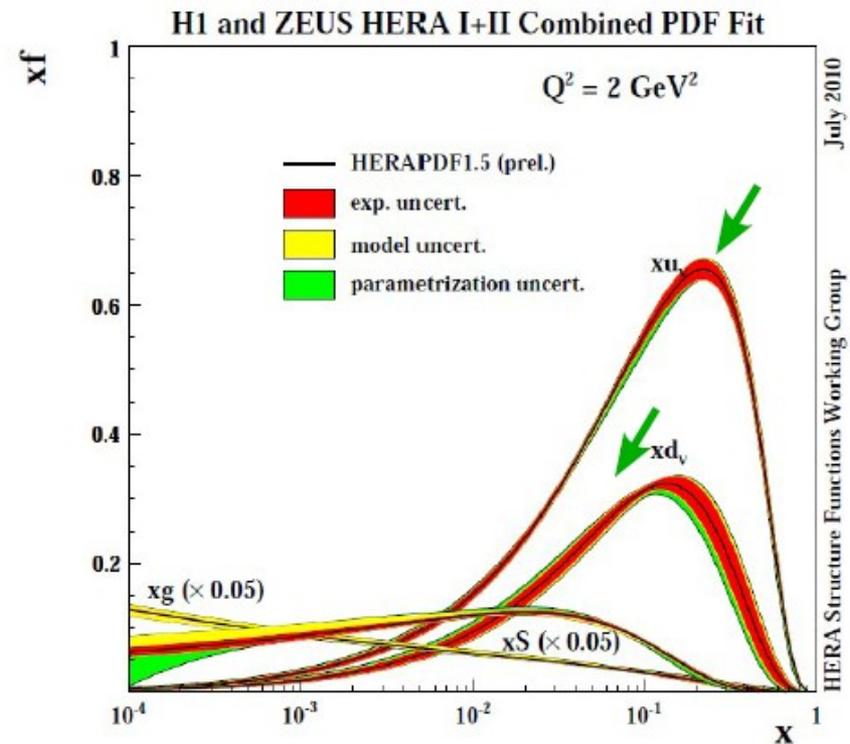
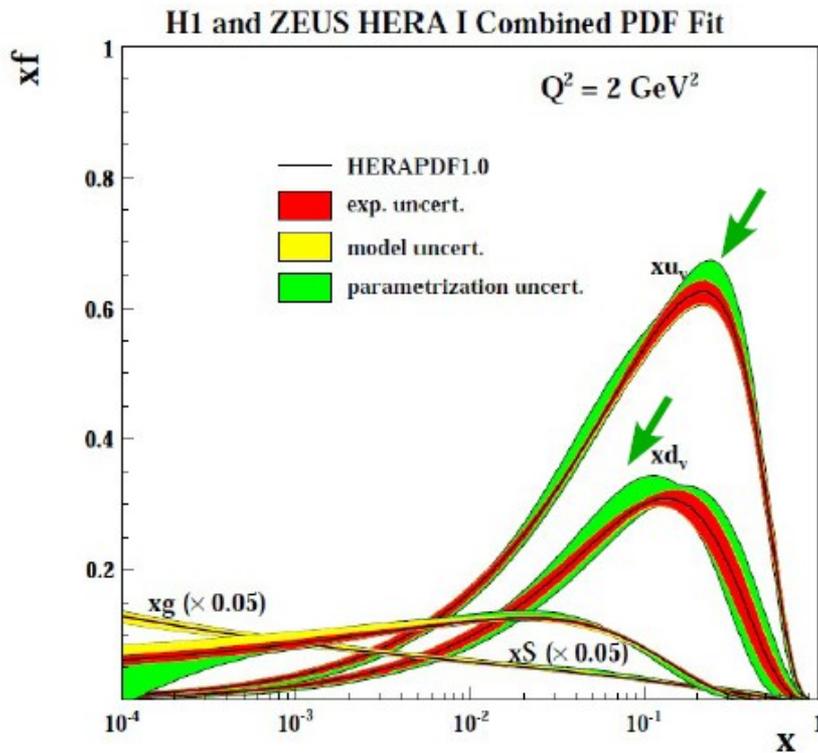


## Fits to new combined HERA data: HERAPDF1.5

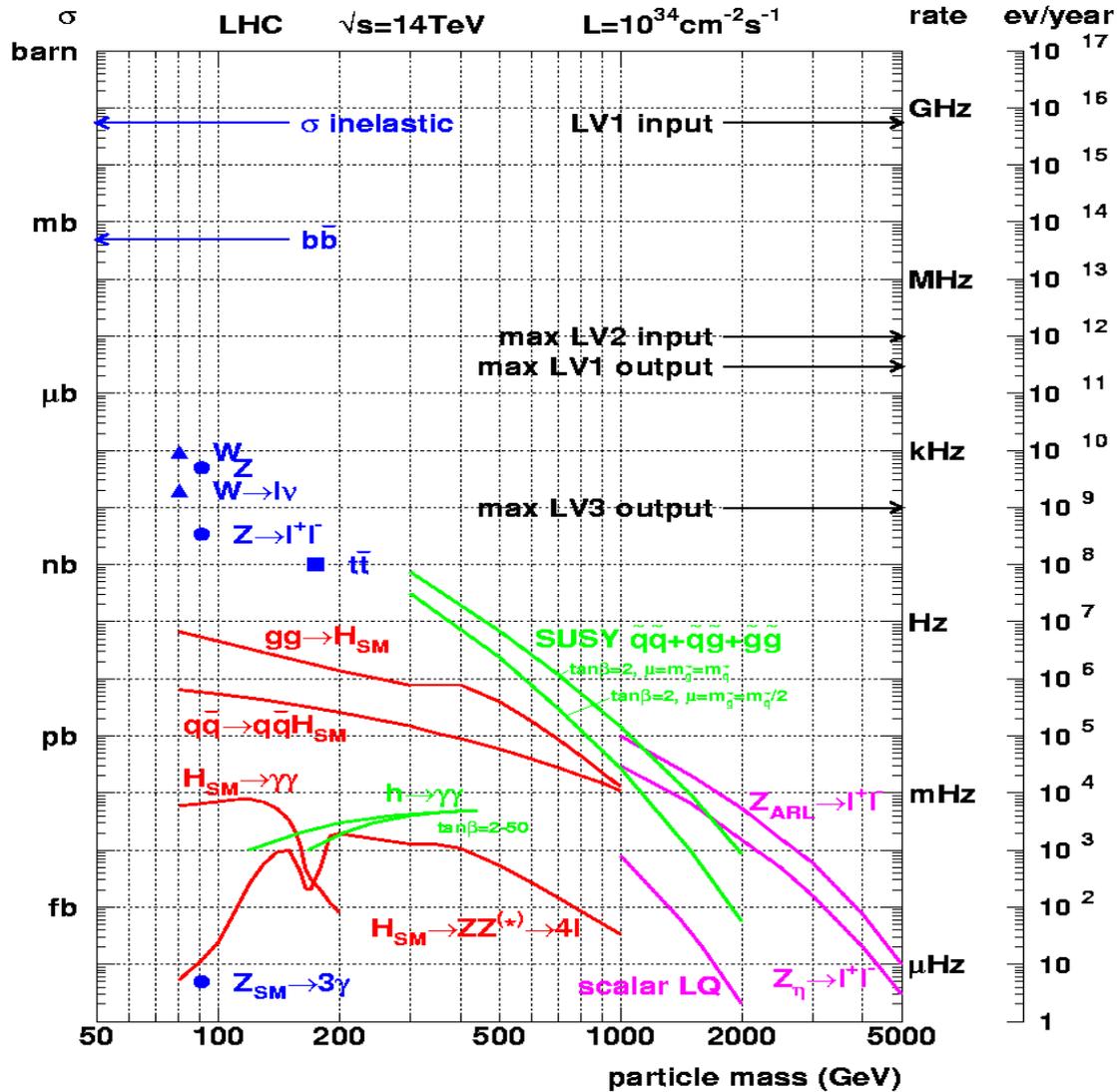


HERAPDF1.0

HERAPDF1.5

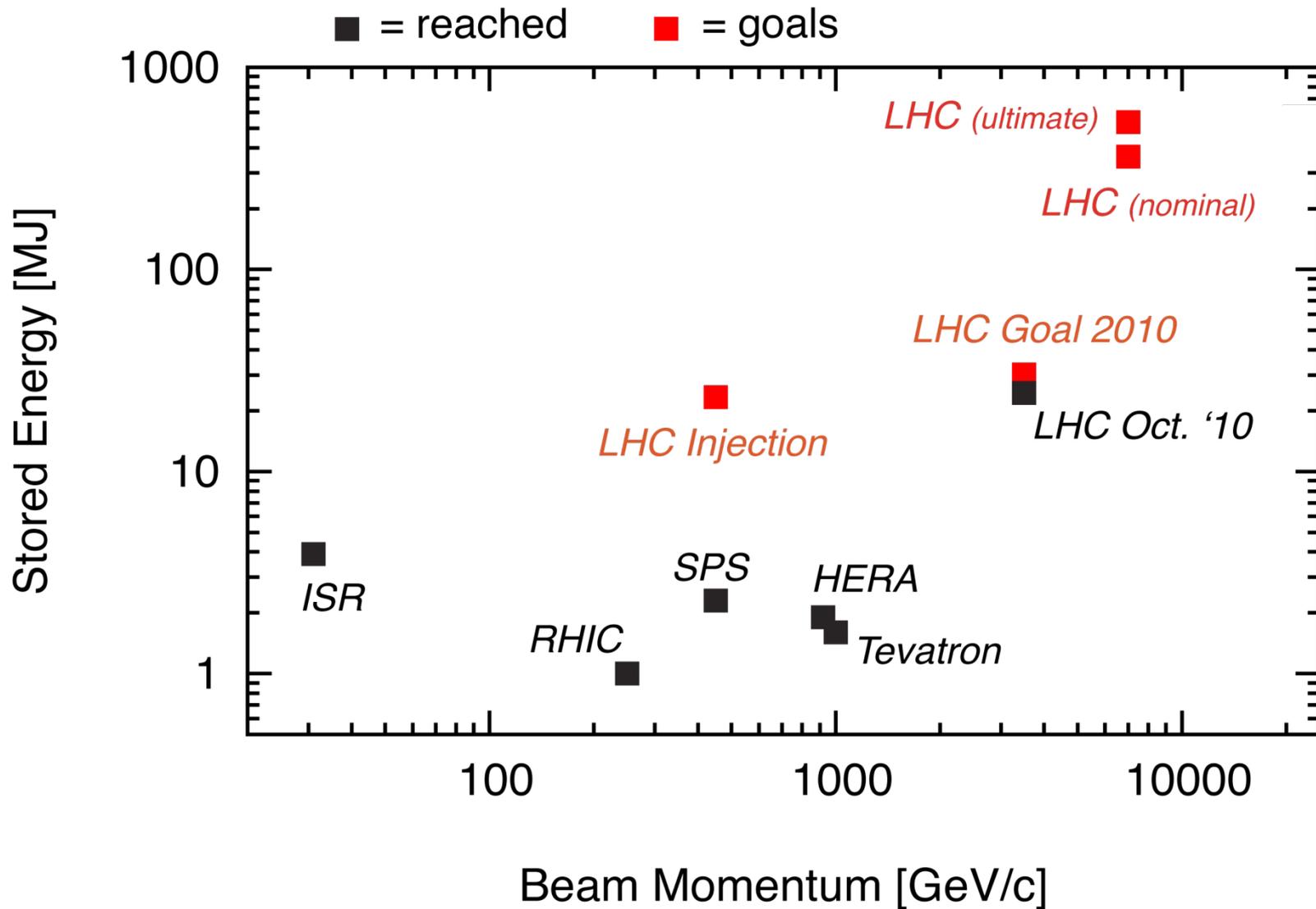


# Cross sections at the LHC



New Physics!!

# Stored Energy in the LHC



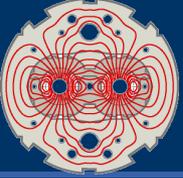
# Overall LHC efficiency in 2010

65%  
availability

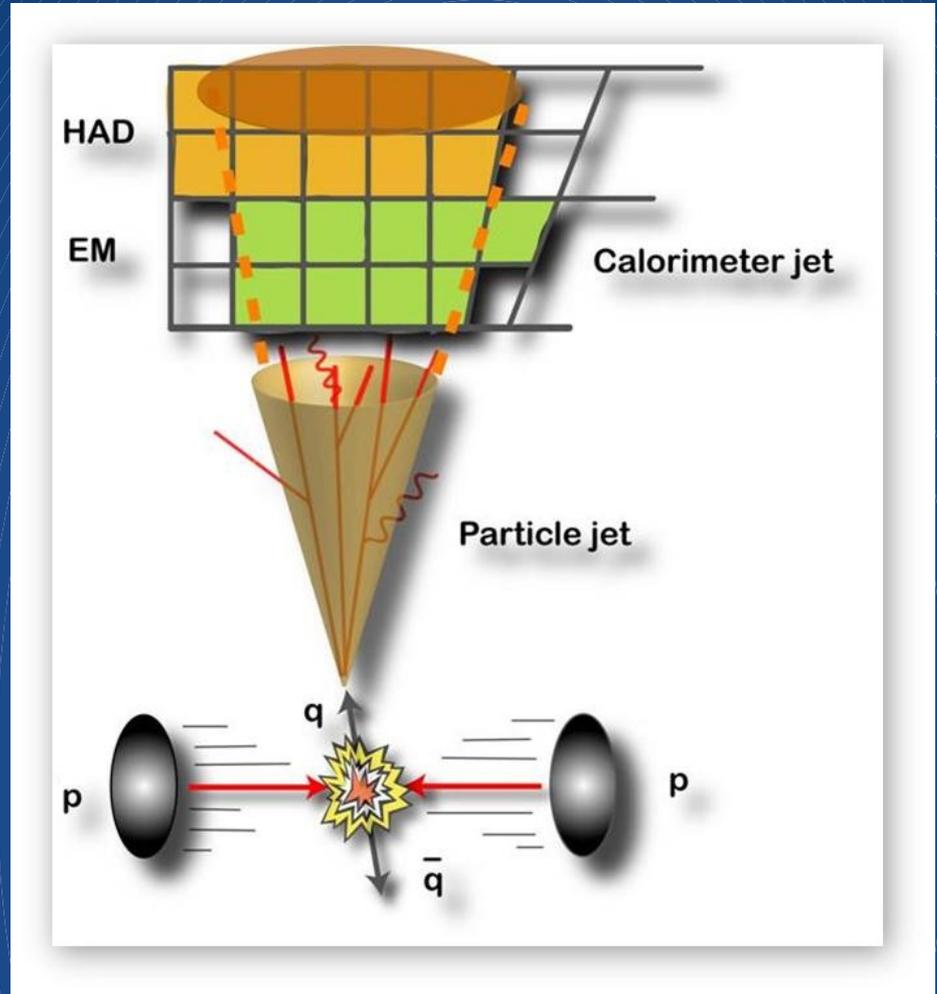
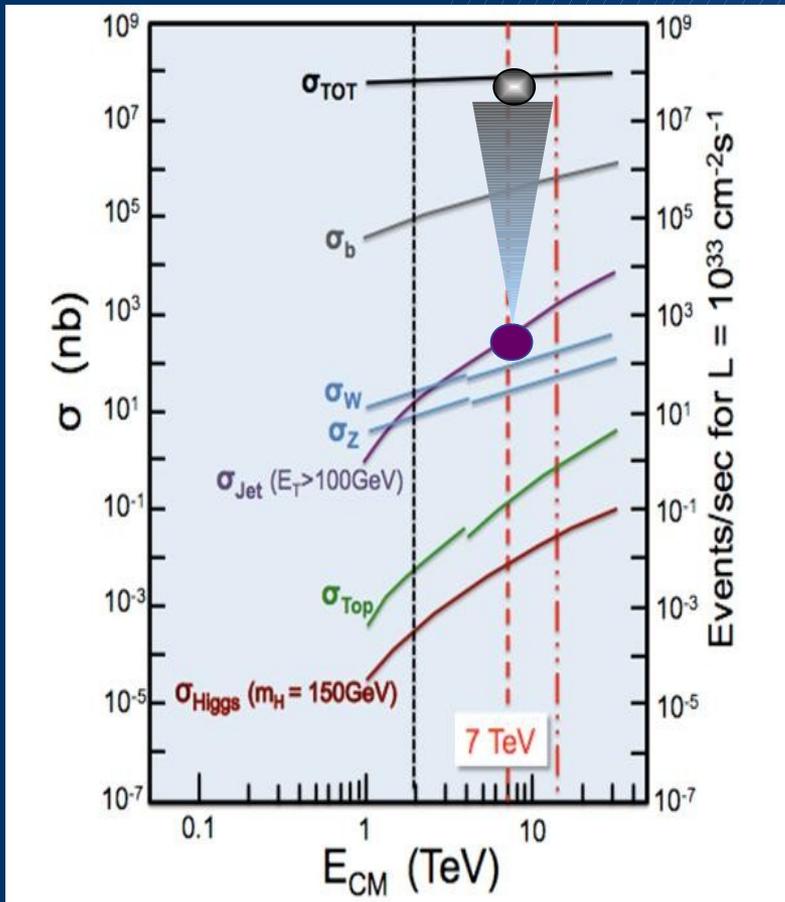
!  
~50/pb  
delivered



Great achievement for the  
first year of operation!

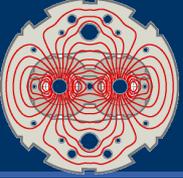


# Jet production at 7 TeV



Important tests of pQCD and detector performance

Germany and CERN / January 2011

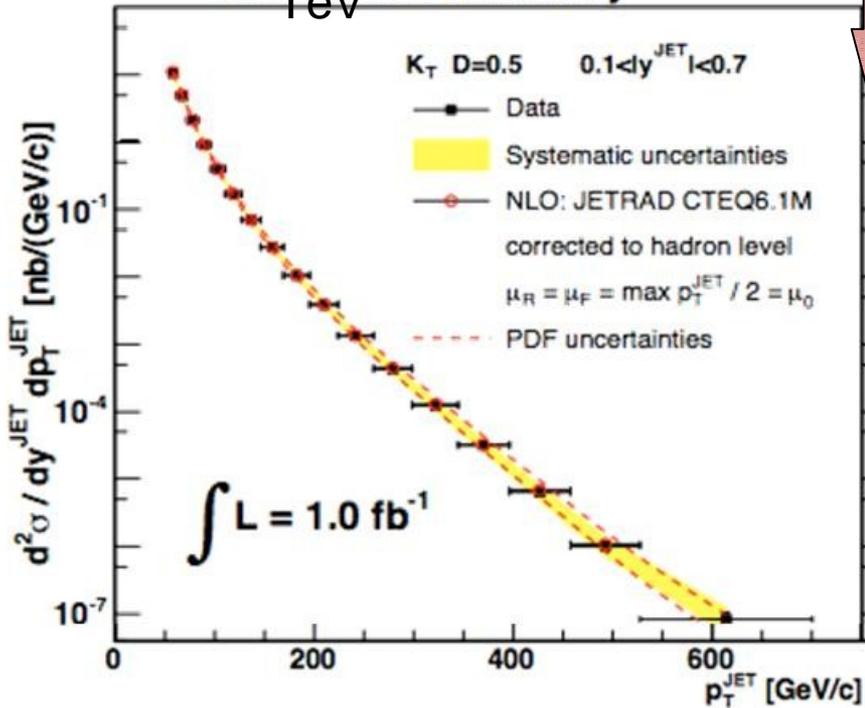


# Jet production at 7 TeV

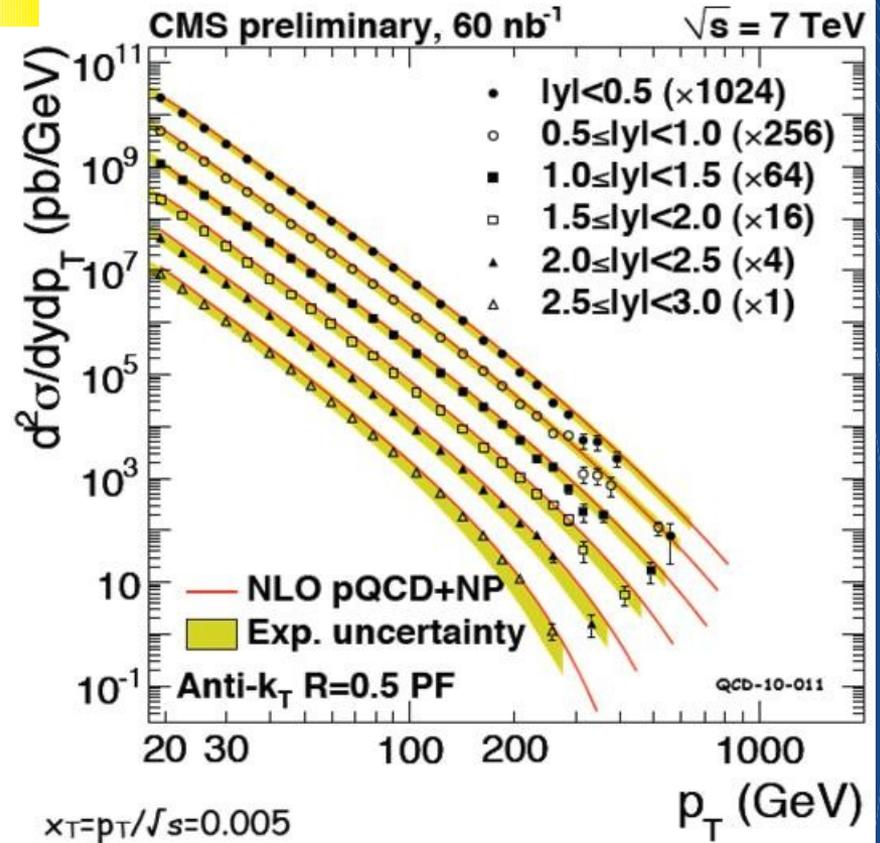
Tevatron  
ECM= 2  
TeV

CDF Run II Preliminary

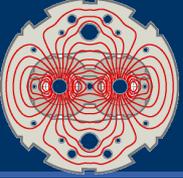
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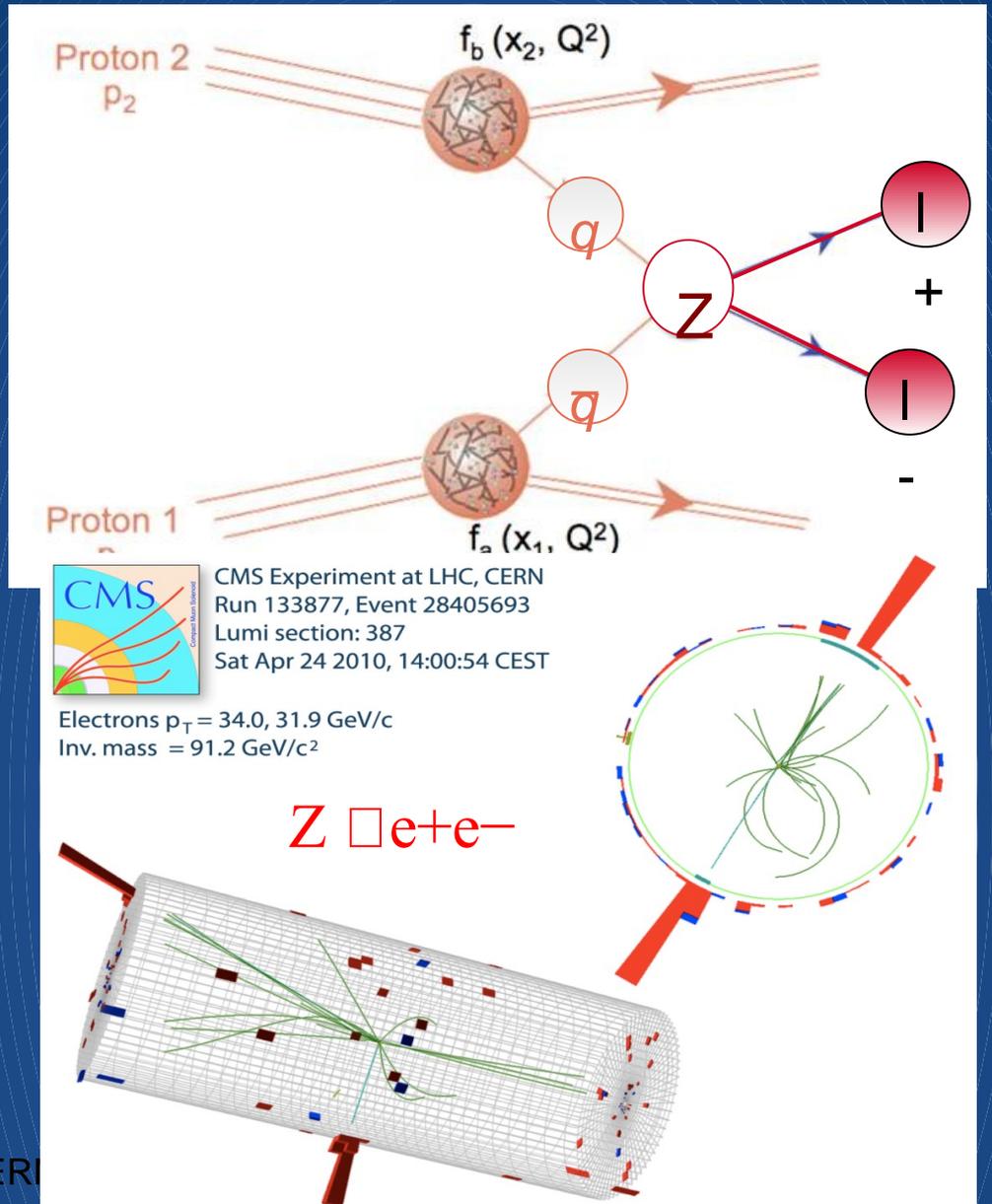
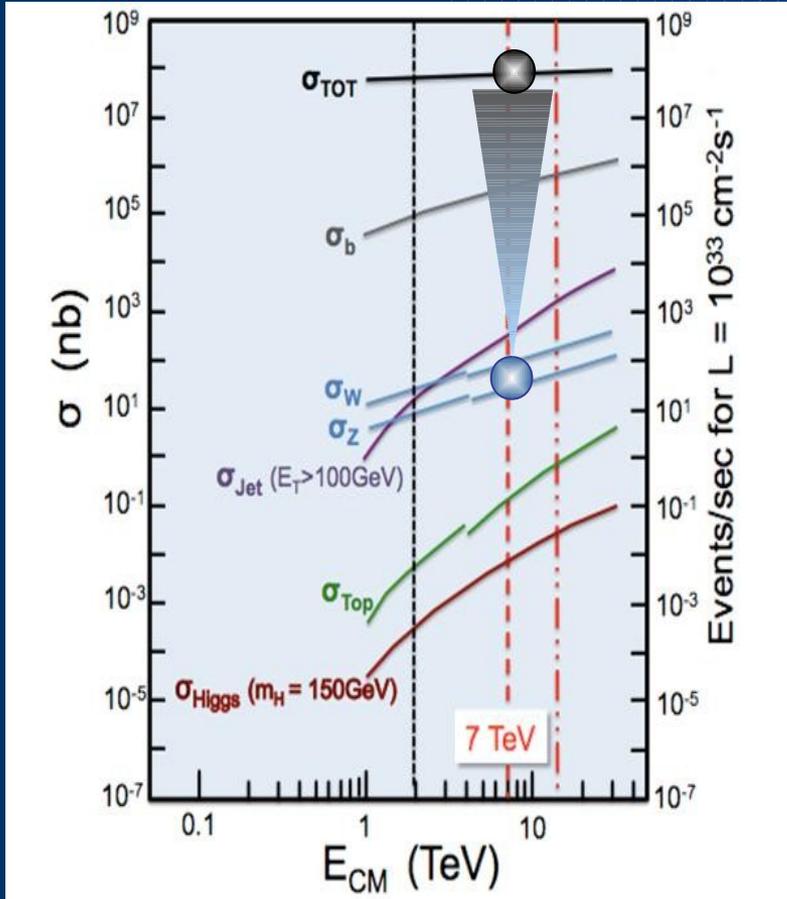
LHC  
E<sub>CM</sub> = 7 TeV

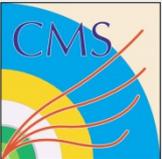


Important test of pQCD over many orders of magnitude



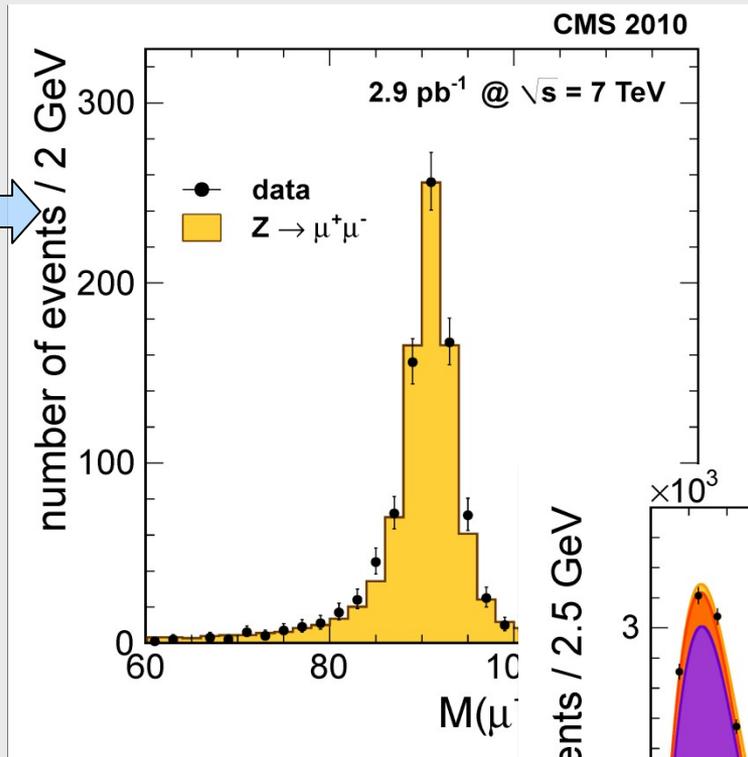
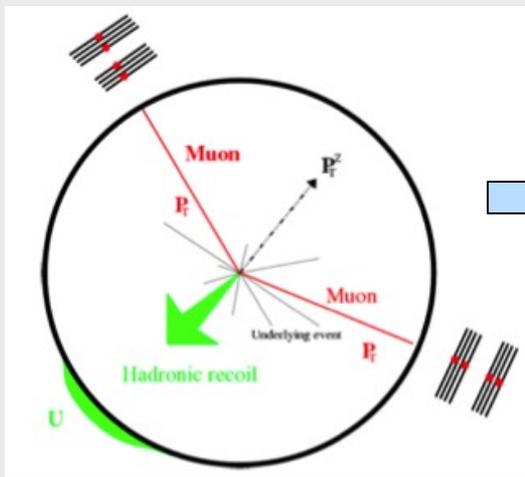
# W and Z production at 7 TeV



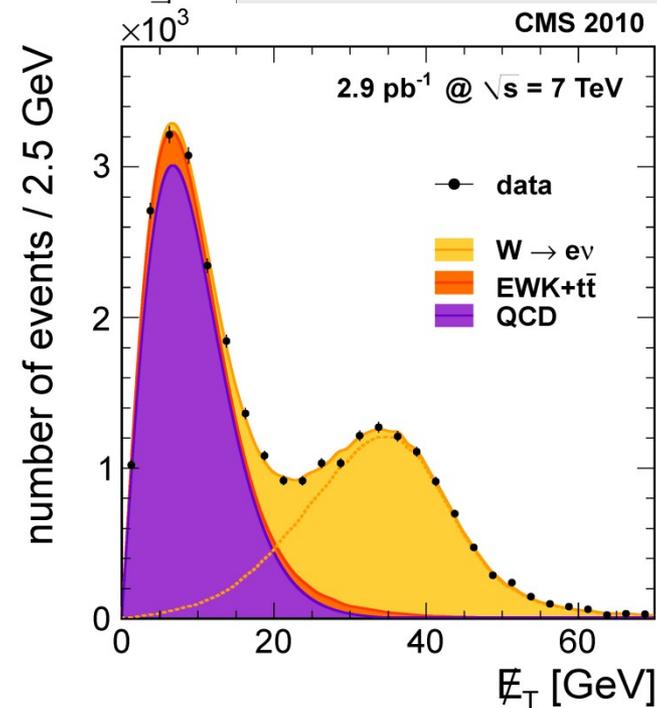
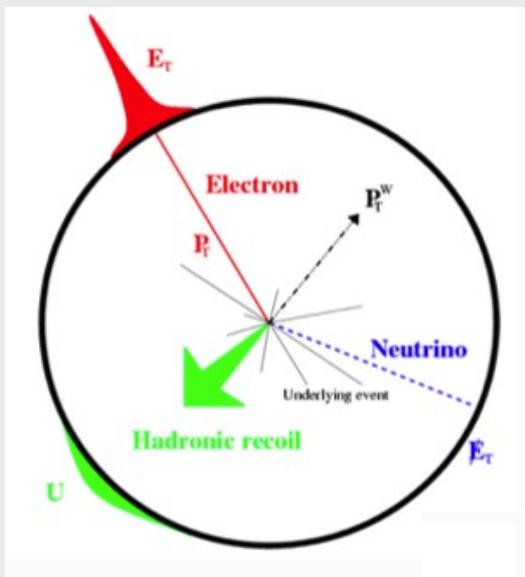


# W and Z production at 7 TeV

Z



W



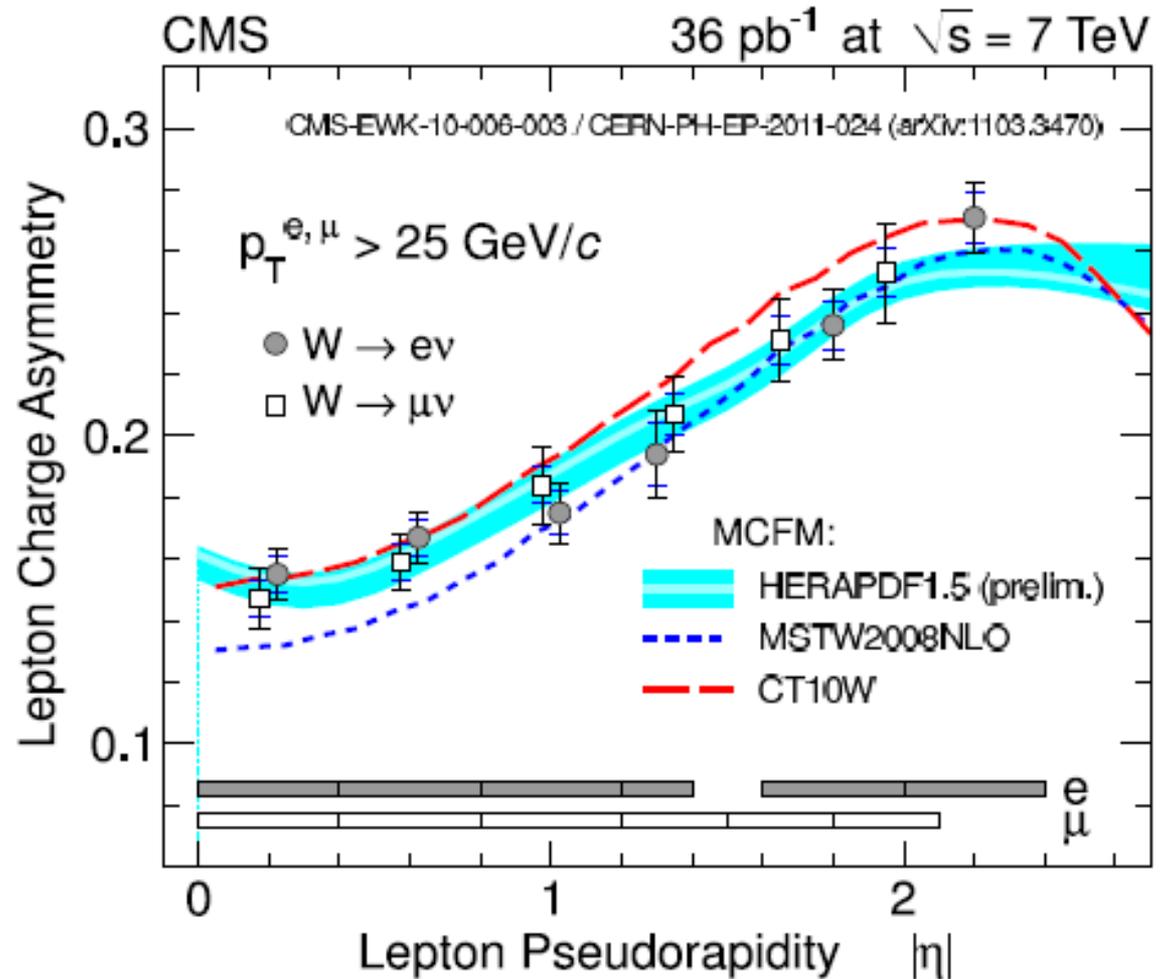
## > Combination of experiments

§ e.g. proton structure

## > HERA PDF important to describe LHC results

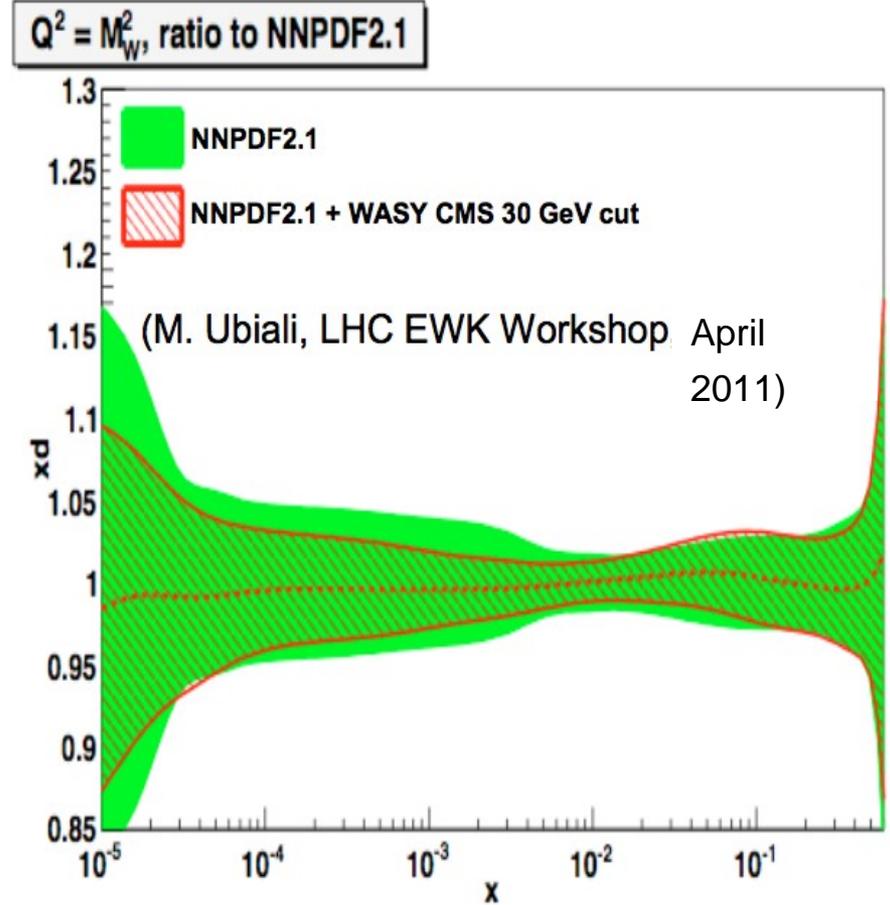
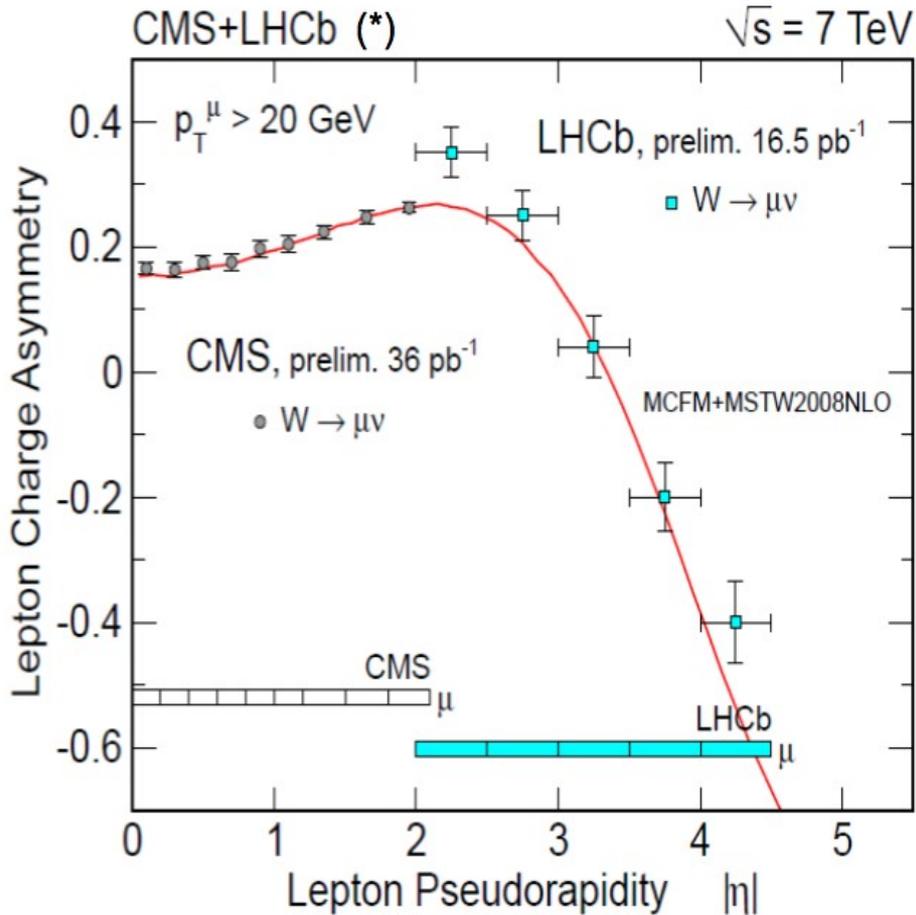
§ e.g. W asymmetry

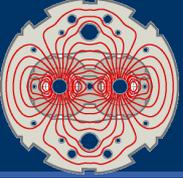
$$\mathcal{A}(\eta_\ell) = \frac{d\sigma_{W^+}/d\eta_{\ell^+} - d\sigma_{W^-}/d\eta_{\ell^-}}{d\sigma_{W^+}/d\eta_{\ell^+} + d\sigma_{W^-}/d\eta_{\ell^-}}$$



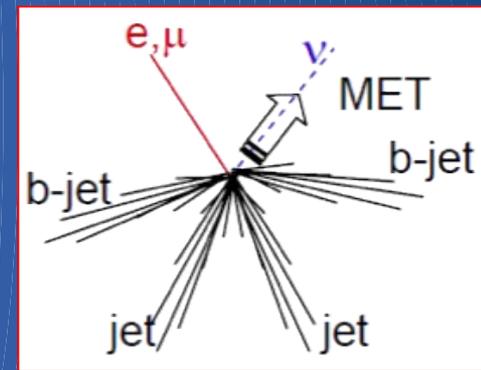
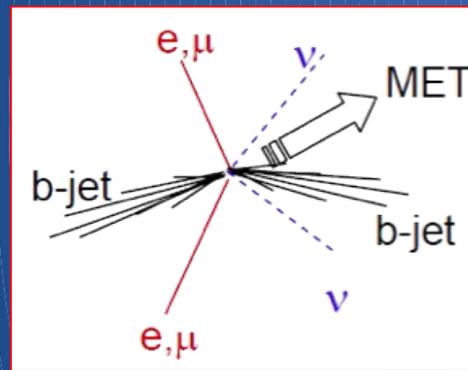
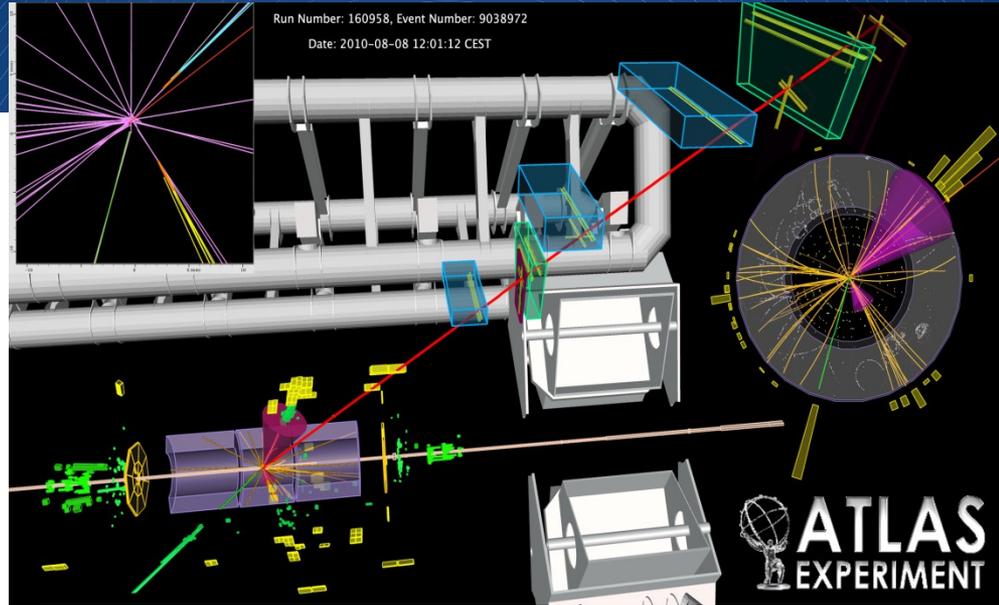
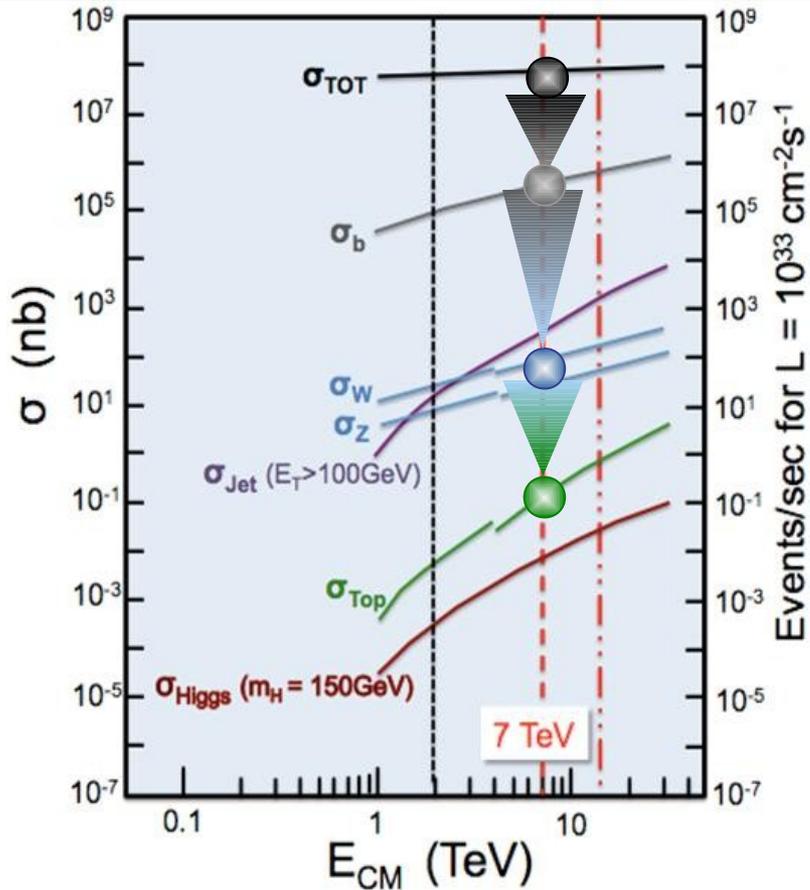


We are able to produce precision EWK measurements good enough to constrain significantly the PDF global fits





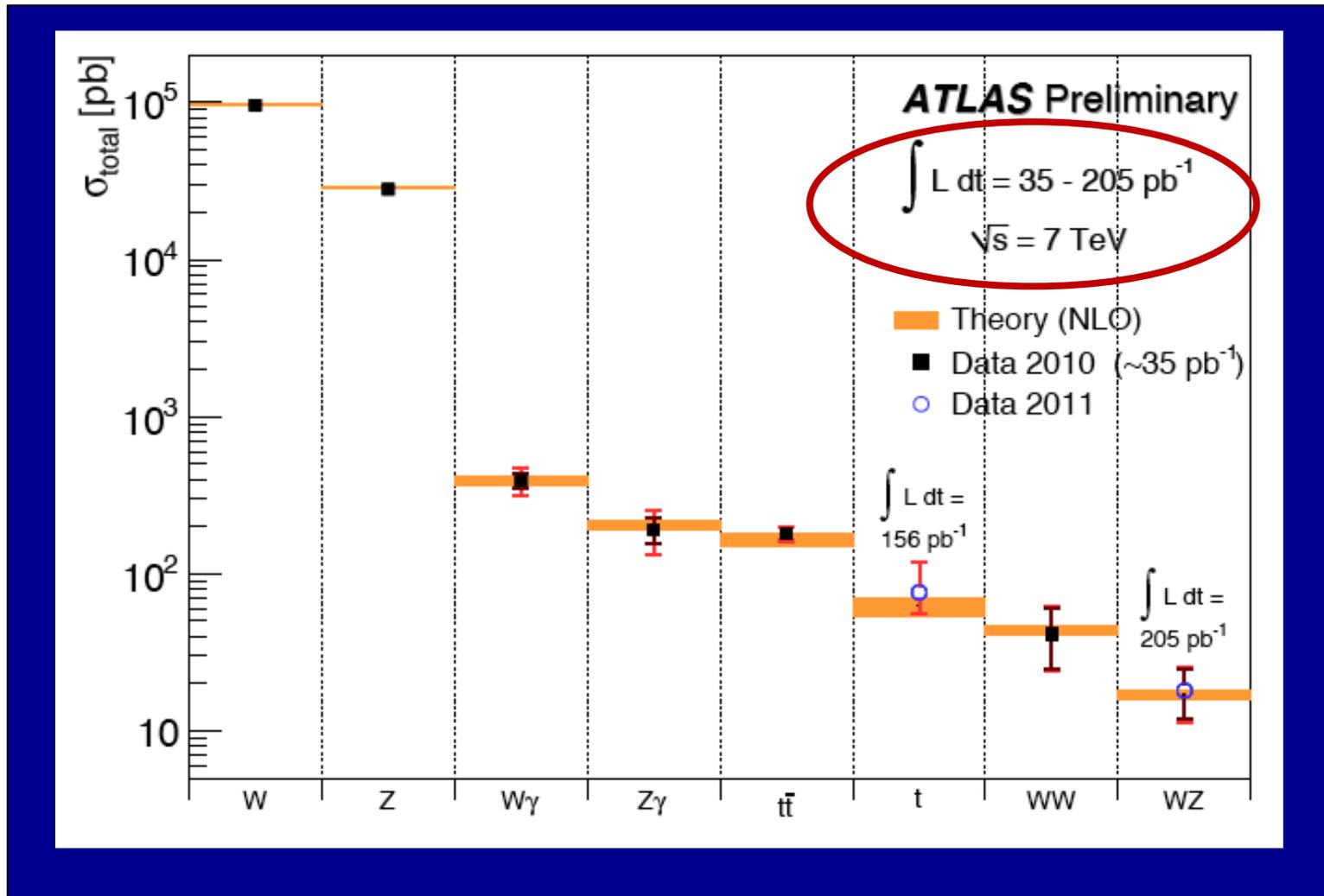
# Top quark production at 7 TeV



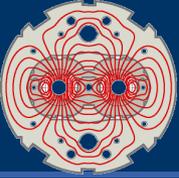
di-leptons

Lepton + jet

# Summary of main electroweak and top cross-section measurements



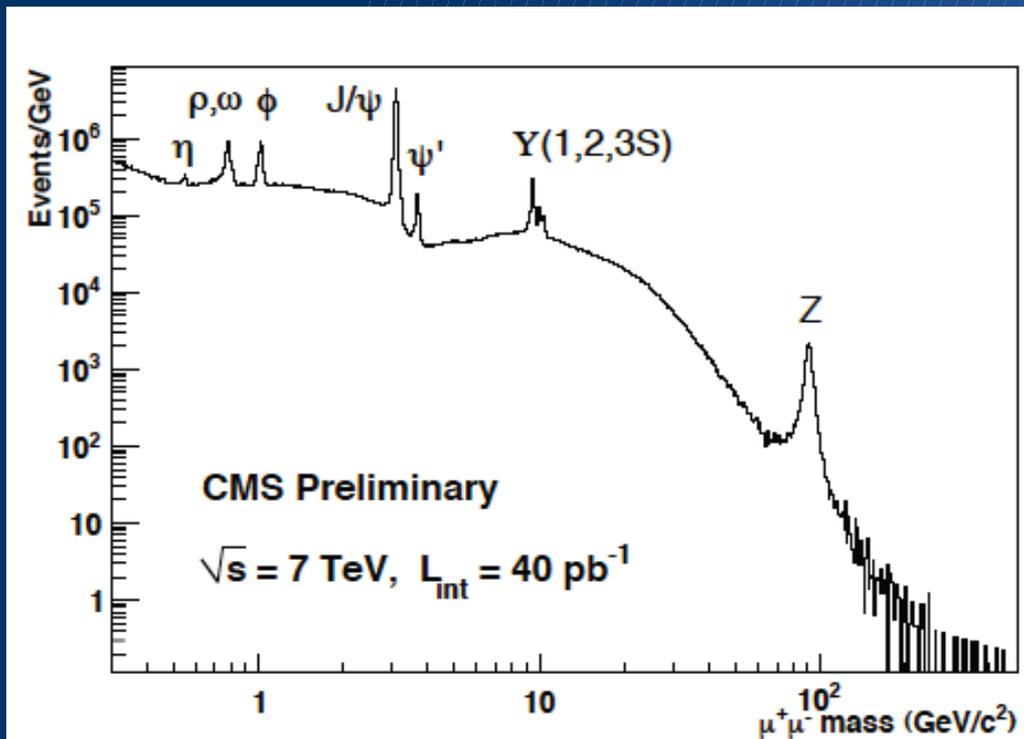
- Measuring cross-sections down to  $\sim 10 \text{ pb}$
- Uncertainties dominated by systematics in all cases except  $Z\gamma$ , WW, WZ
- Good agreement with SM expectations (within present uncertainties)
- Experimental precision starts to challenge theory for W, Z, top-pairs



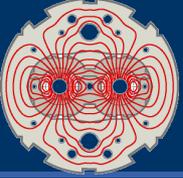
# Excellent performances 2010

Excellent start-up in 2011:

already some **1.3/fb** (!) delivered



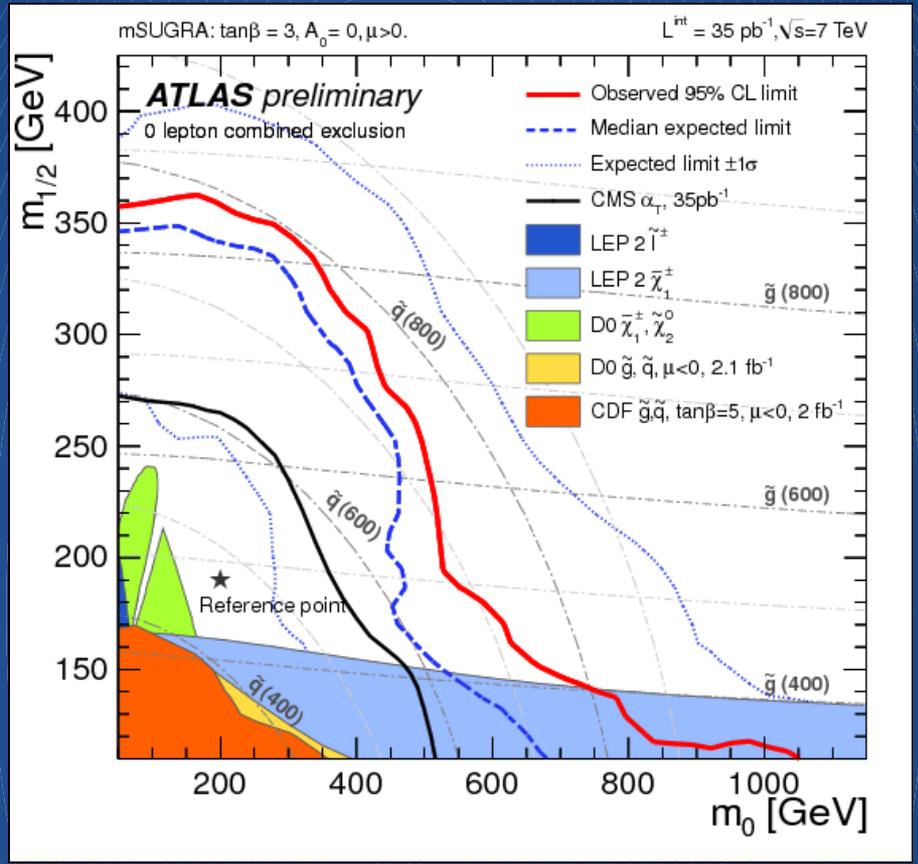
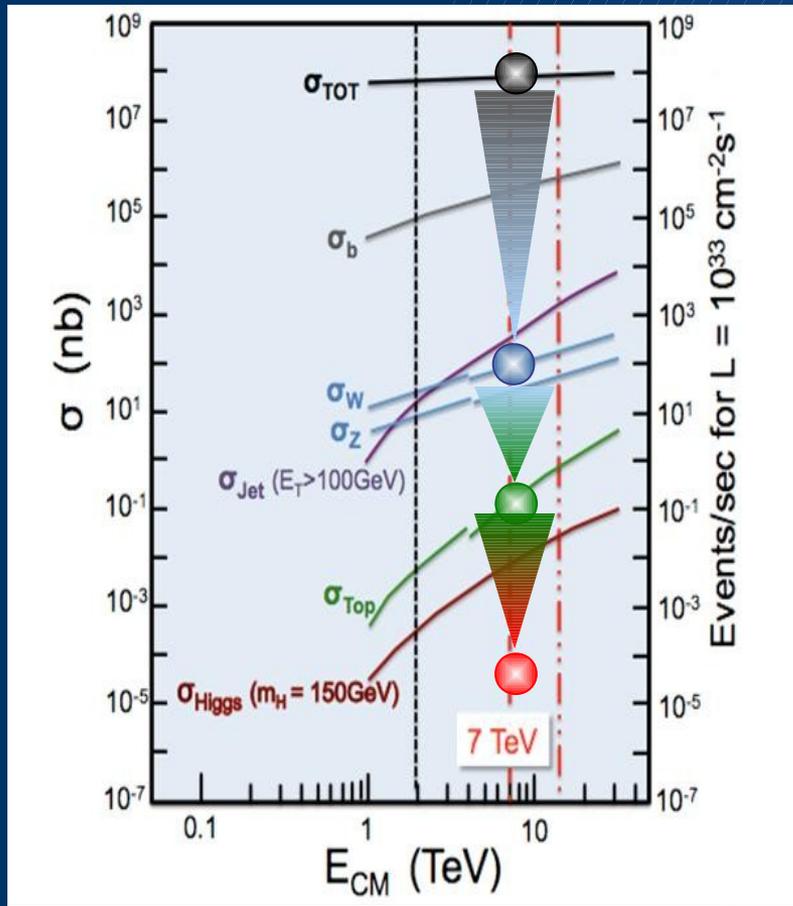
- q Experiments demonstrated readiness in the exploitation of the 7 TeV p-p and 2.76 TeV Pb-Pb data;
- q analyses proceeded very rapidly;
- q Experiments have about completed their journey through the Standard Model ... and have started to take us into uncharted territories



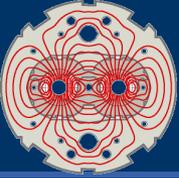
# Physics beyond the Standard Model ?



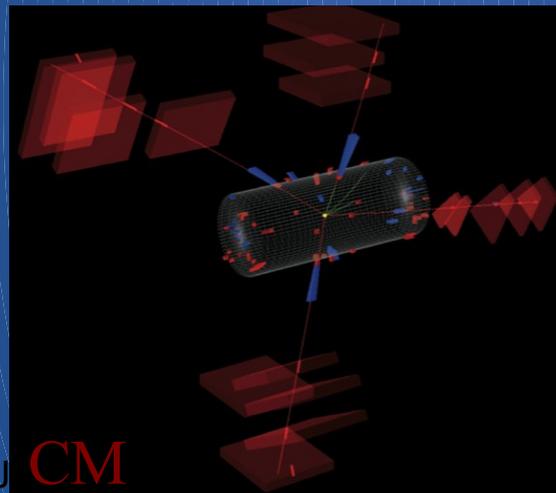
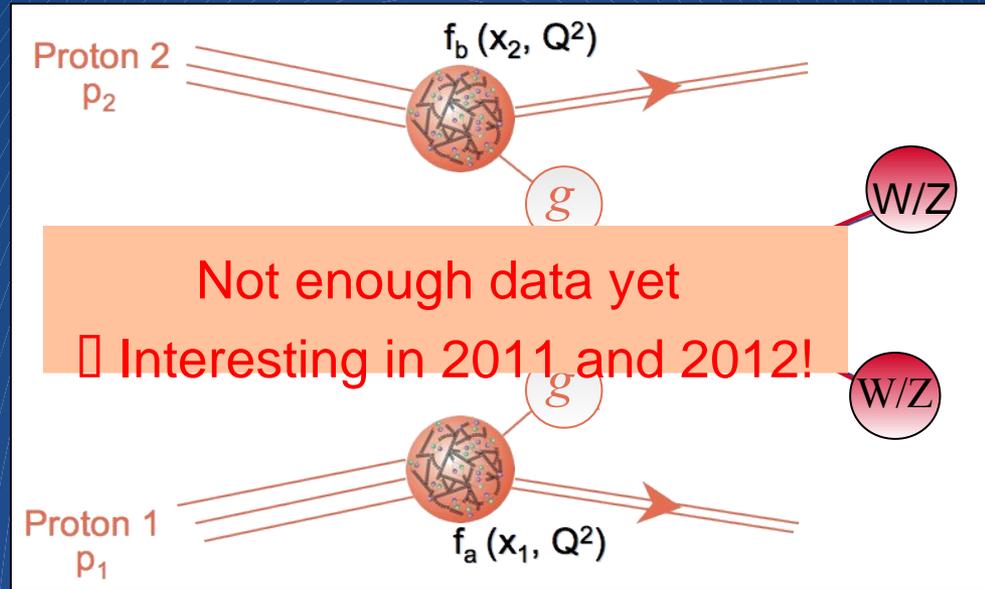
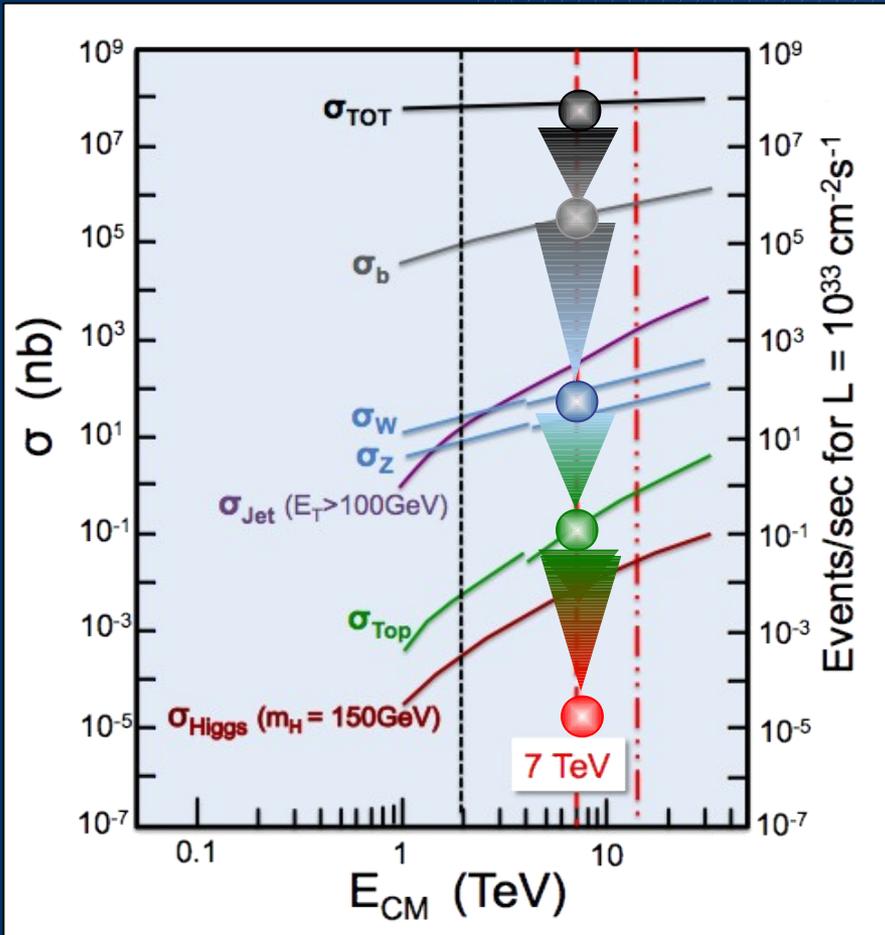
## Searches for Supersymmetry



Most stringent limits to date



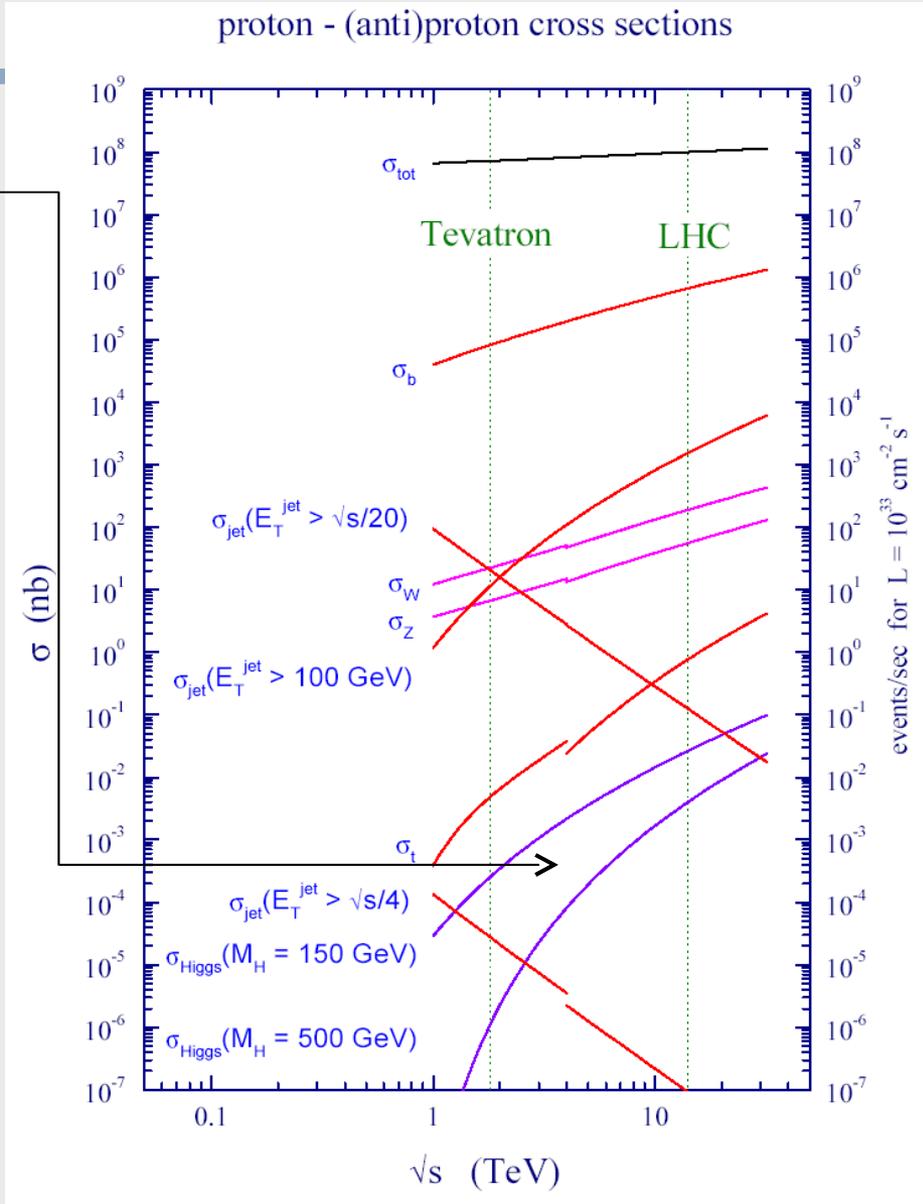
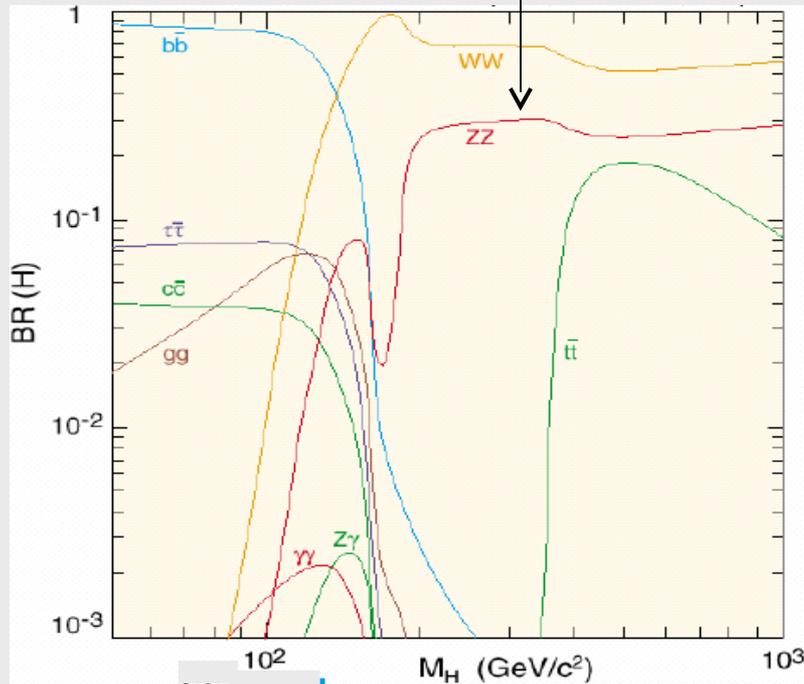
# Higgs-Boson at 7 TeV



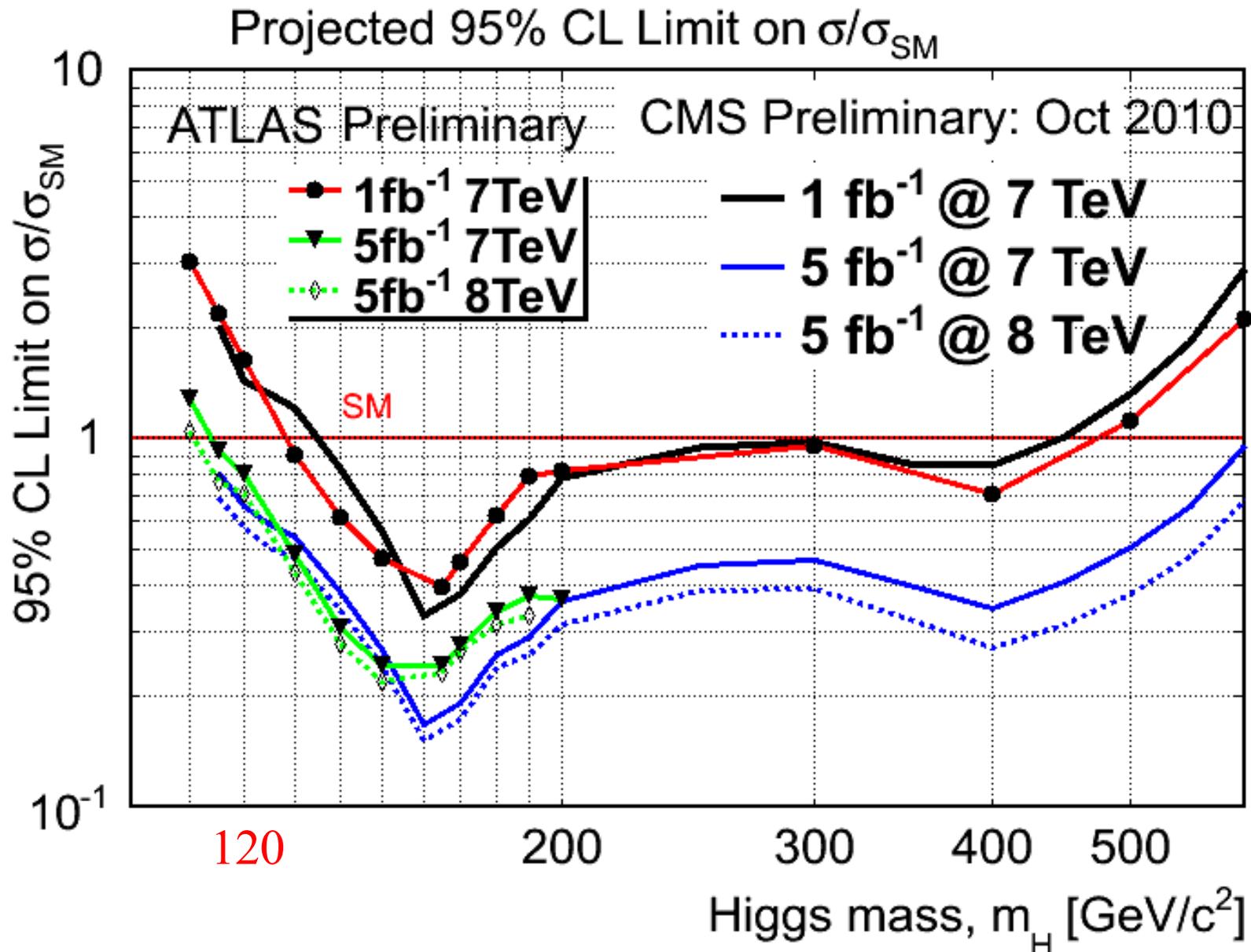
# Search for the Higgs-Boson at the LHC

Production rate  
of the Higgs-Bosons  
depends on its mass

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



# CMS & ATLAS Projections Compared



# Summary of Prospects

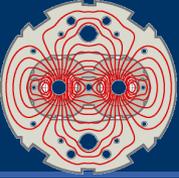
## SM Higgs Search Prospects (Mass in GeV)

ATLAS + CMS $\approx 2 \times$ CMS	95% CL exclusion	3 $\sigma$ sensitivity	5 $\sigma$ sensitivity
1 fb <sup>-1</sup>	120 - 530	135 - 475	152 - 175
2 fb <sup>-1</sup>	114 - 585	120 - 545	140 - 200
5 fb <sup>-1</sup>	114 - 600	114 - 600	128 - 482
10 fb <sup>-1</sup>	114 - 600	114 - 600	117 - 535

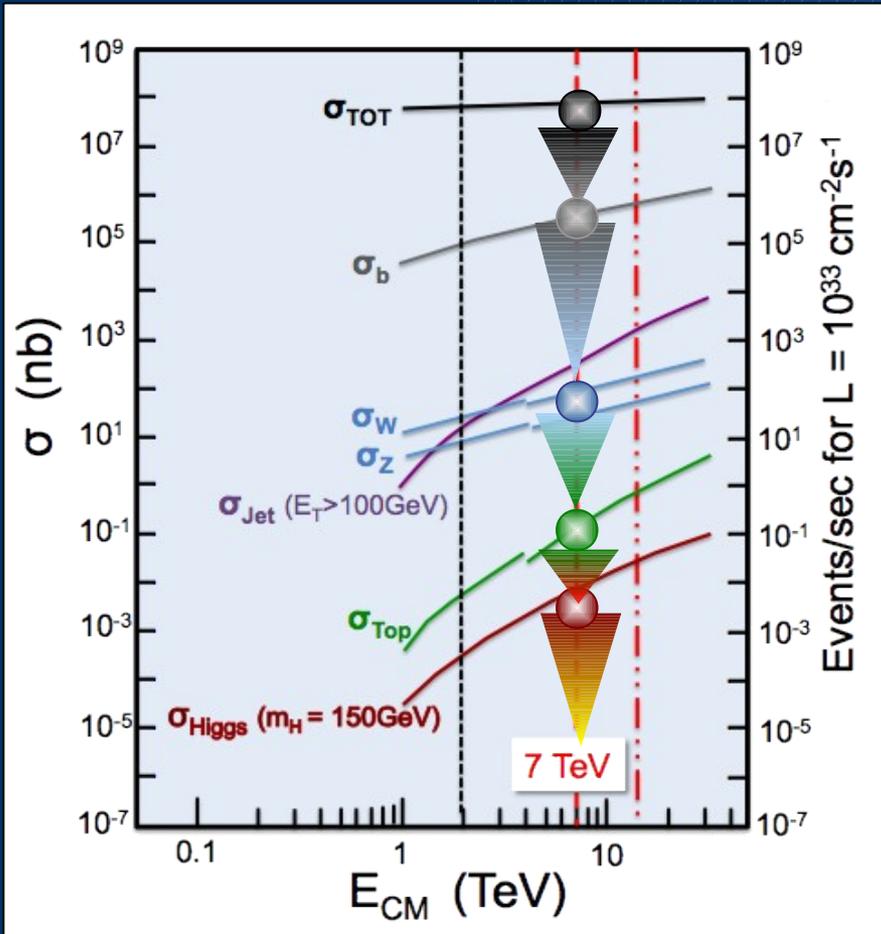


Higgs Boson, if it exists between masses of (114 - 600 GeV) will either be discovered or ruled out in  $\approx$  next two years

□ Decided to run in 2011 and 2012



# The 2011 and 2012 run ...



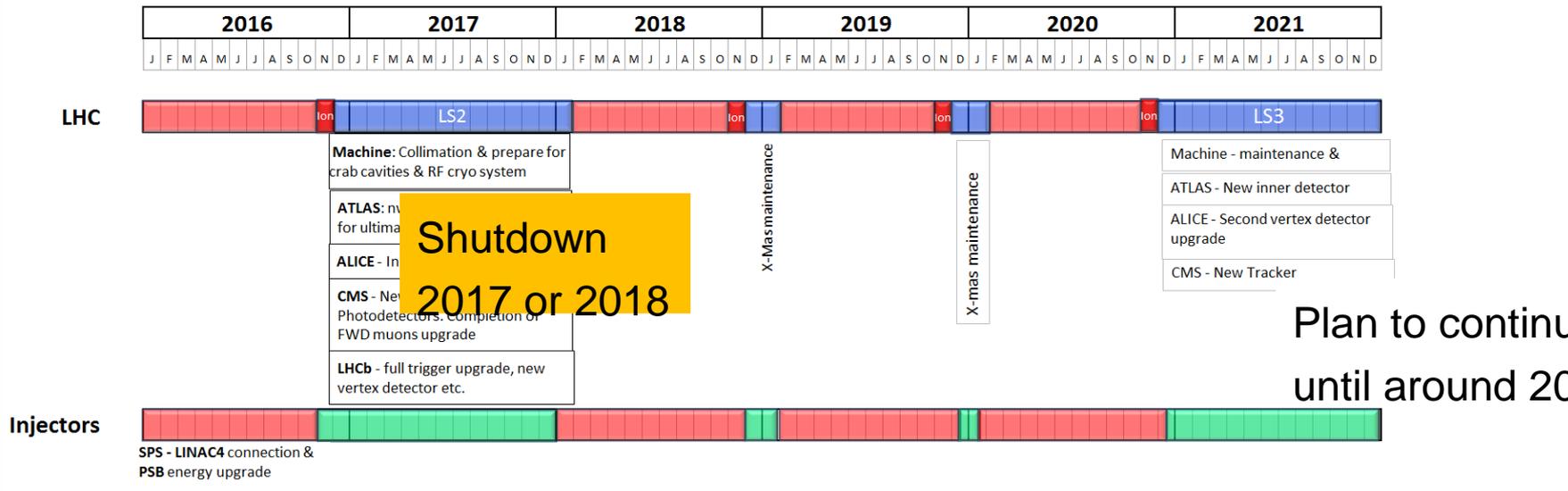
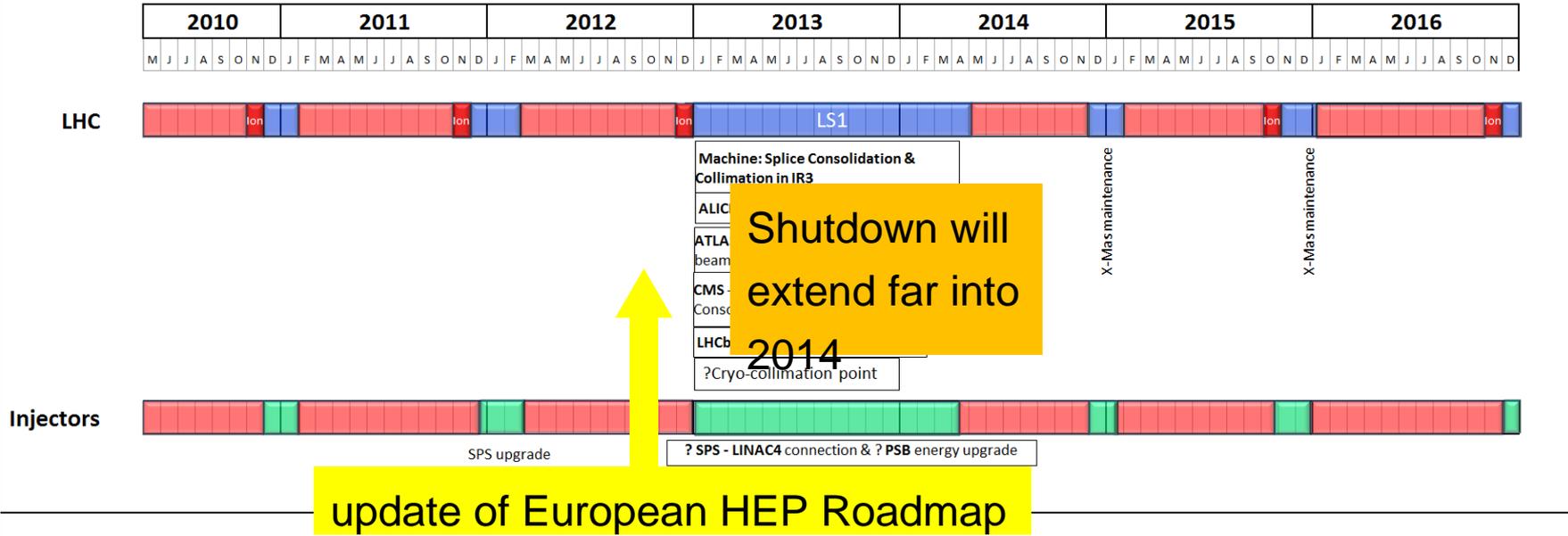
## Search for physics beyond SM

- q Discovering new particles
- q 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



An aerial photograph of a rural landscape, likely in Europe, showing a patchwork of agricultural fields in various shades of brown and green. A large, thin white circle is drawn over the center of the image, encompassing a significant portion of the landscape. The text "beyond LHC?" is written in a bold, yellow, sans-serif font across the middle of the circle. In the background, a large body of water is visible on the right side, and a road or railway line runs along the bottom right edge. The overall scene is a mix of natural and human-made elements.

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) ?)

# Linear e+e-Colliders

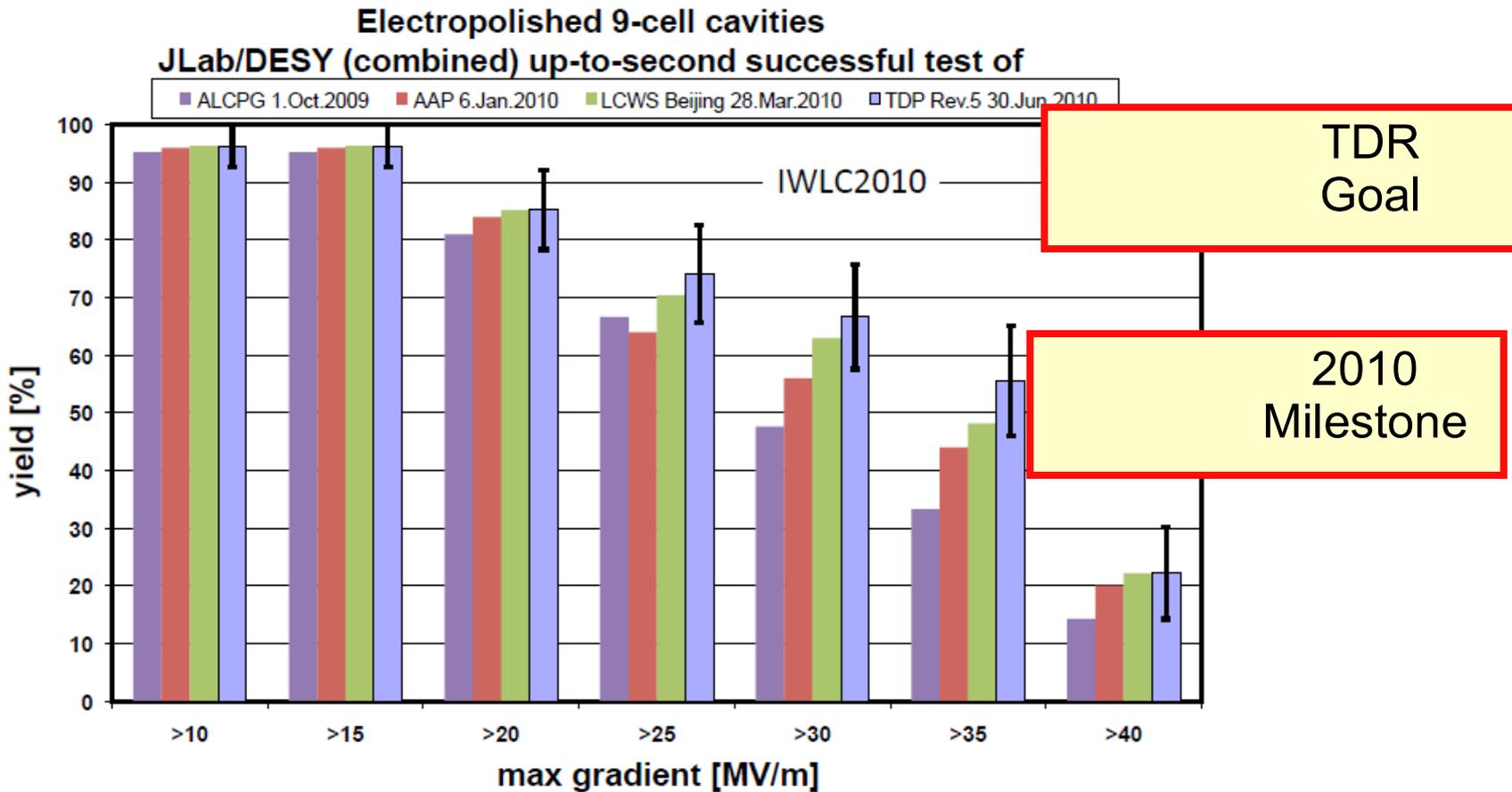
- n The machine which will complement and extend the LHC best, and is closest to be realized, is a Linear e+e- Collider with a collision energy of at least 500 GeV.

## PROJECTS:

- TeV Colliders (CMS energy up to 1 TeV) □ Technology ~ready  
ILC with superconducting cavities
- Multi-TeV Collider (CMS energies in multi-TeV range) □ R&D  
CLIC □ Two Beam Acceleration

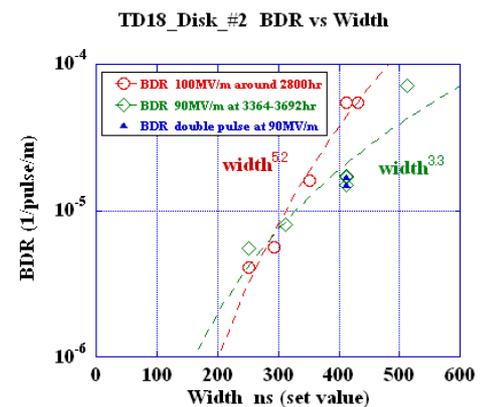
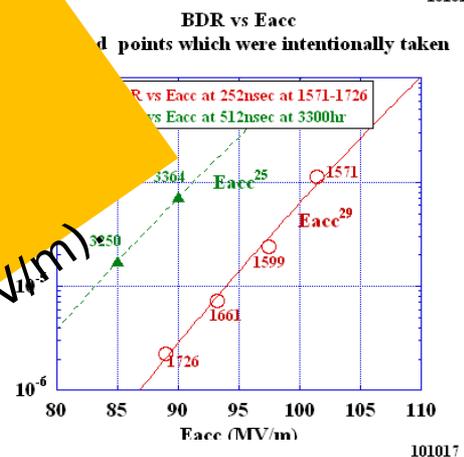
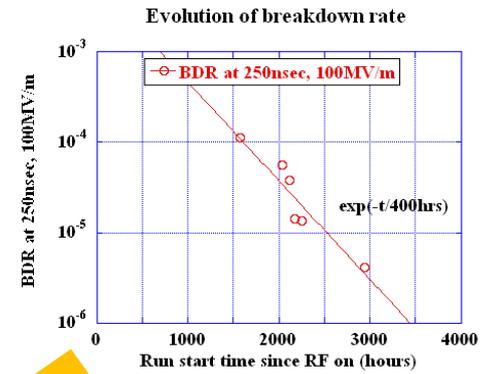
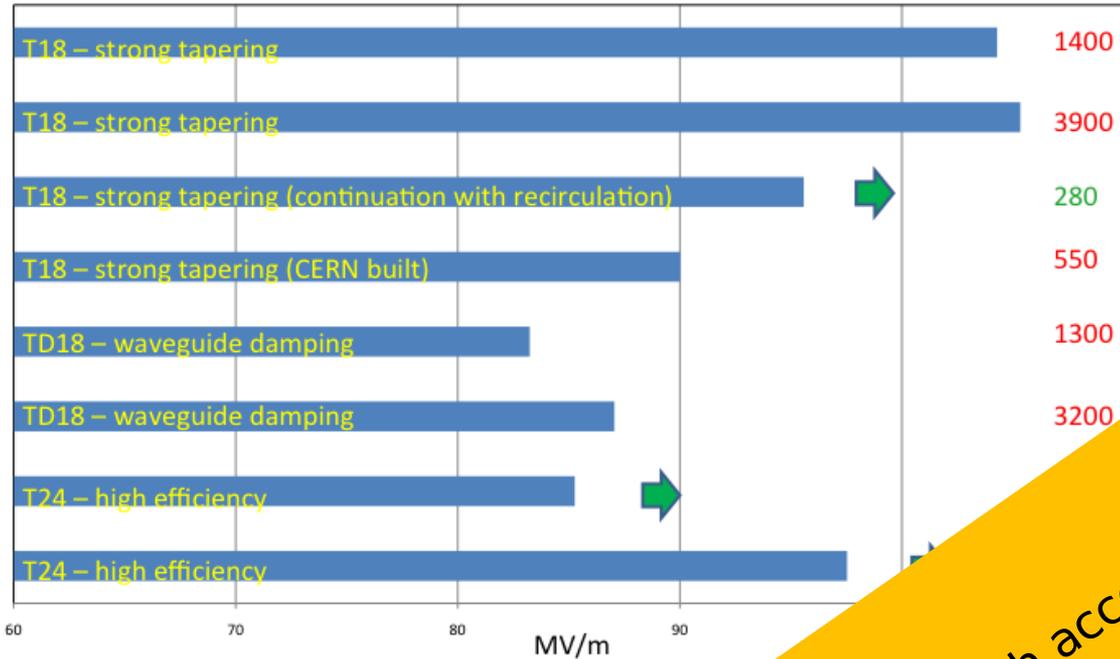


# Cavity Gradient Milestone Achieved





# Gradient at CLIC $4 \cdot 10^{-7}$ BDR and 180 ns pulse length



**Today:**  
 CTF3 running with accelerating structures reaching design value (100 MV/m)



- T18 and TD18 built and tested at SLAC and KEK
- real prototypes with improved design are T24 and TD24
- measurements in plot on the right for TD18 at KEK

Next decades

# Road beyond Standard Model

through synergy of

hadron - hadron colliders (HL/LHC)

lepton - lepton colliders (LHeC ??)

hadron - 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

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exciting prospects