



Accelerating Science and Innovation

Closing in on the Higgs-Boson ?

The Large Hadron Collider:
Highlights and Prospects

Past few decades

“Discovery” of Standard Model

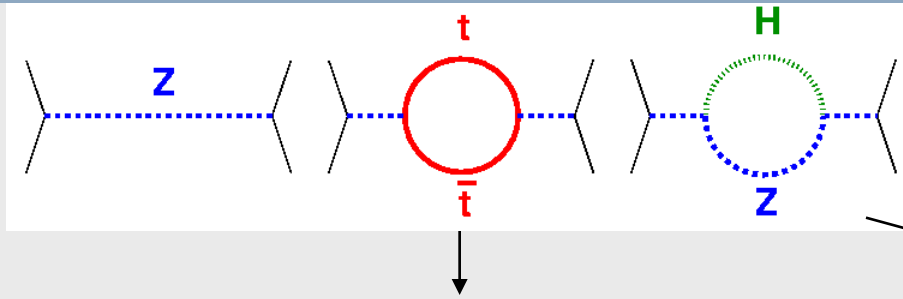
through synergy of

hadron - hadron colliders (e.g. Tevatron)

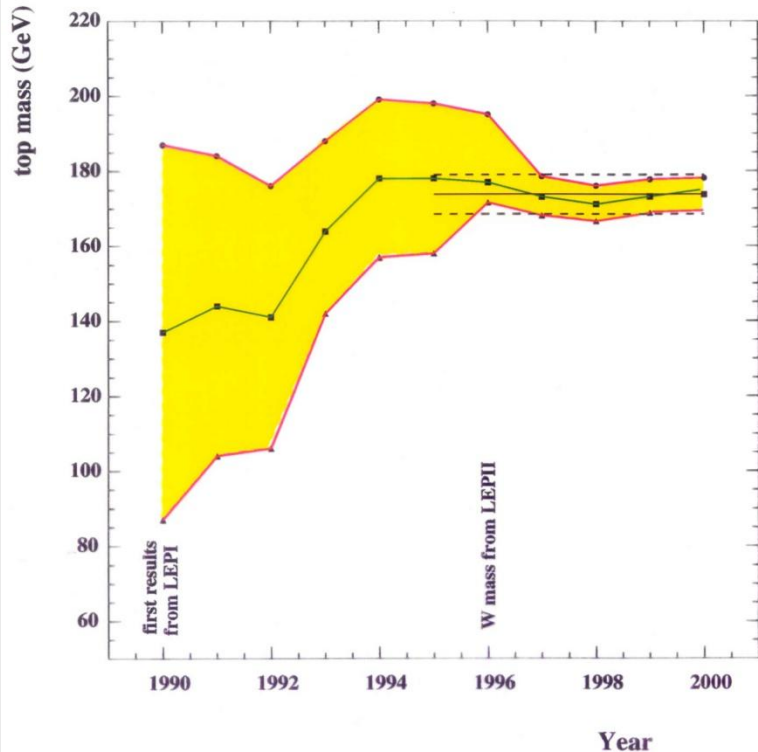
lepton - hadron colliders (HERA)

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

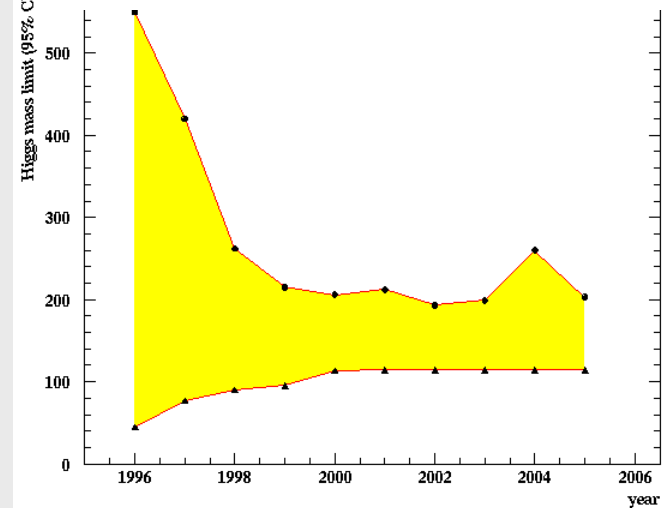
Test of the SM at the Level of Quantum Fluctuations



LEP: 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	$ O^{\text{meas}} - O^{\text{fit}} / \sigma^{\text{meas}}$
$\Delta\alpha_{\text{had}}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768	0.0001
m_Z [GeV]	91.1875 ± 0.0021	91.1875	0
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957	0.0005
σ_{had}^0 [nb]	41.540 ± 0.037	41.477	0.163
R_l	20.767 ± 0.025	20.744	0.023
$A_{\text{fb}}^{0,l}$	0.01714 ± 0.00095	0.01645	0.069
$A_l(P_{\bar{\nu}})$	0.1465 ± 0.0032	0.1481	0.016
R_b	0.21629 ± 0.00066	0.21586	0.0043
R_c	0.1721 ± 0.0030	0.1722	0.0001
$A_{\text{fb}}^{0,b}$	0.0992 ± 0.0016	0.1038	0.46
$A_{\text{fb}}^{0,c}$	0.0707 ± 0.0035	0.0742	0.103
A_b	0.923 ± 0.020	0.935	0.012
A_c	0.670 ± 0.027	0.668	0.002
$A_l(\text{SLD})$	0.1513 ± 0.0021	0.1481	0.152
$\sin^2\theta_{\text{eff}}^{\text{lept}}(Q_{\text{fb}})$	0.2324 ± 0.0012	0.2314	0.008
m_W [GeV]	80.398 ± 0.025	80.374	0.024
Γ_W [GeV]	2.140 ± 0.060	2.091	0.049
m_t [GeV]	170.9 ± 1.8	171.3	0.04

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

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

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

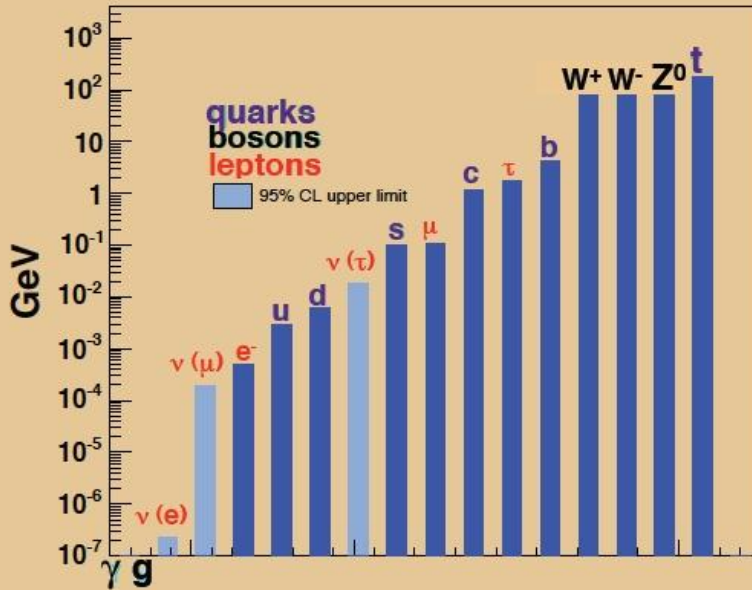
Decided in favour of leptons by fit
Without this point, the fit is too good!
 $A_{\text{fb}}(b)$ has largest pull: 2.9σ !

however ...

... corner stone missing within Standard Model

How to generate mass & break electroweak symmetry ?

Hierarchy of Standard Model particle masses



Higgs mechanism :
Non-zero field permeating the universe generates mass

- ▶ W and Z bosons gain mass through degrees of freedom of Higgs field
- ▶ Fermions gain mass interacting with the Higgs field
- ▶ New particle Higgs boson predicted

👁 Finding the Higgs boson

▶ Means Higgs field exists

□ Means we confirm our theory for the origin of mass



Key message

LHC and the Standard Model

Finding the Higgs: **Discovery**

Excluding the SM-Higgs: **Discovery**

Reminder:

LHC is poised to clarify the mechanism by which elementary particles acquire mass

Key Questions of Particle Physics

origin of mass/matter or
origin of electroweak symmetry breaking

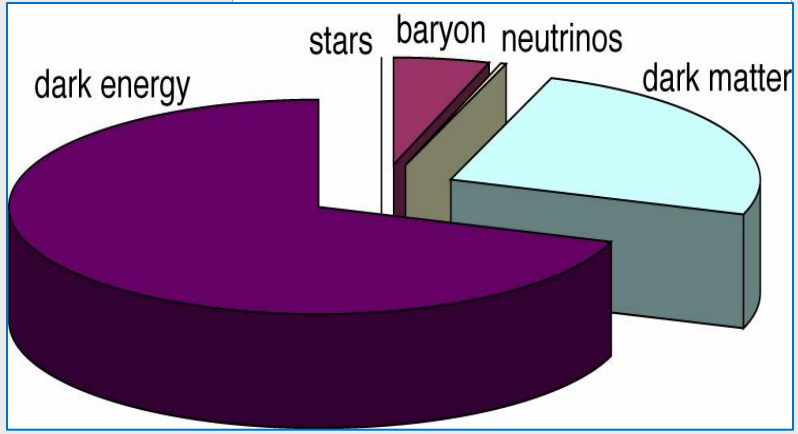
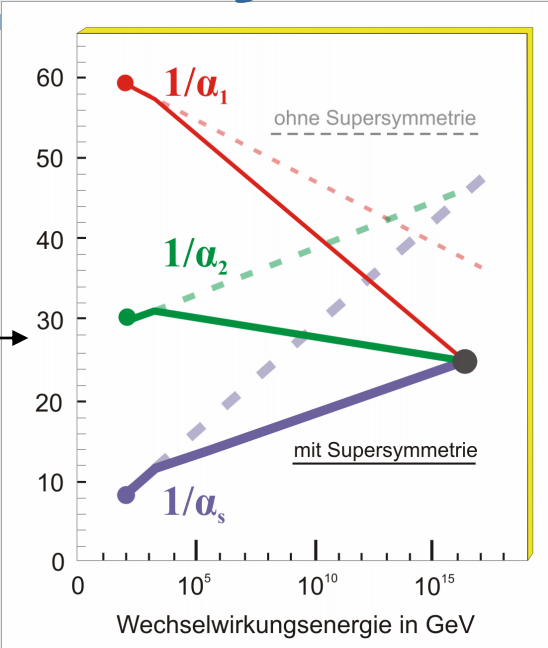
unification of forces

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



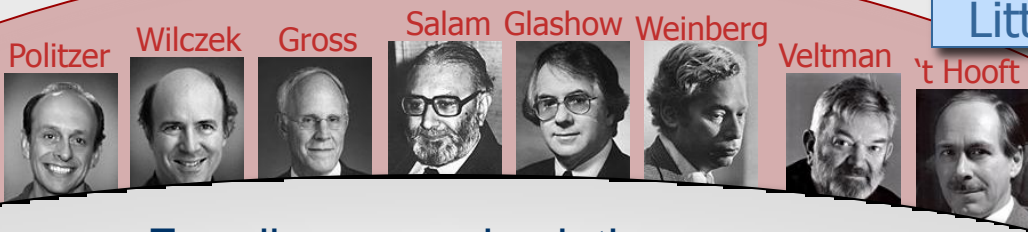
The LHC will address most of these questions

Solutions?



Standard Model

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



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



Selected NP
 since 1957
 Except P. Higgs

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

Extra Dimensions
 New dimensions introduced
 $m_{\text{Gravity}} \approx m_{\text{elw}} \Rightarrow$ Hierarchy problem solved
New particles at \approx TeV scale

Successful for ever ???



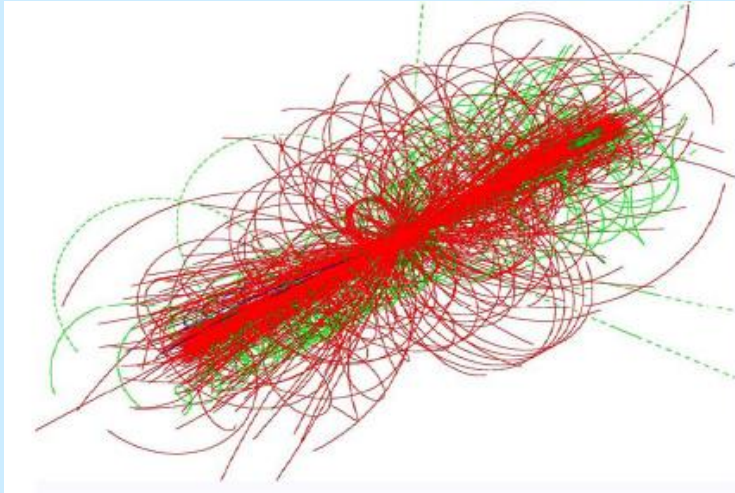
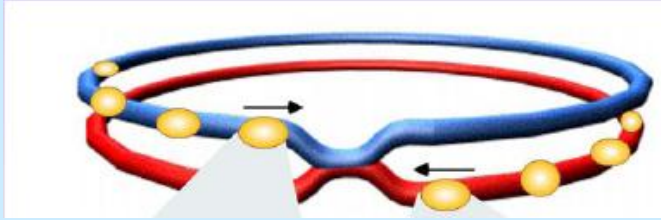
Enter a New Era in Fundamental Science

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



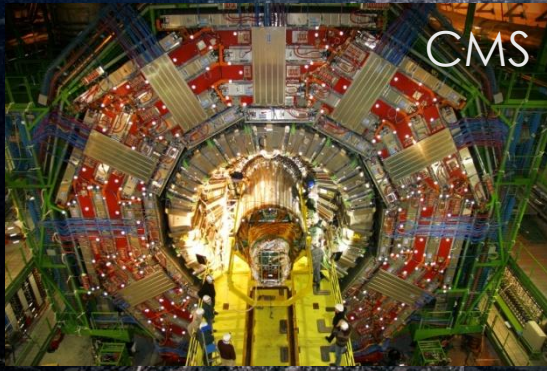
Proton-Proton Collisions at the LHC



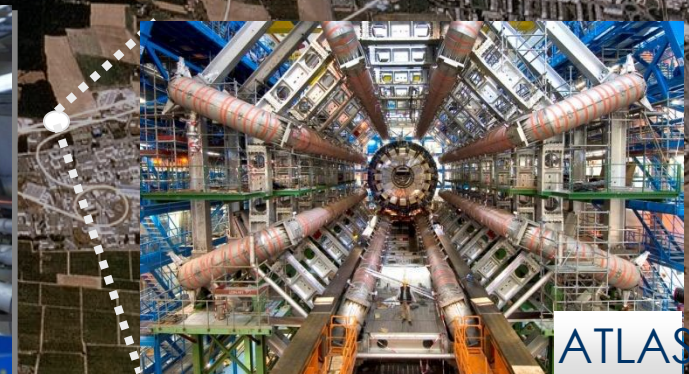
- 2808 + 2808 proton bunches separated by 7.5 m
 - collisions every 25 ns = 40 MHz crossing rate
 - 10^{11} protons per bunch
 - at $10^{34}/\text{cm}^2/\text{s}$
≈ 35 pp interactions per crossing pile-up
 - ≈ 10^9 pp interactions per second !!!
 - in each collision
≈ 1600 charged particles produced
- enormous challenge for the detectors and for data collection/storage/analysis**

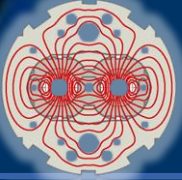
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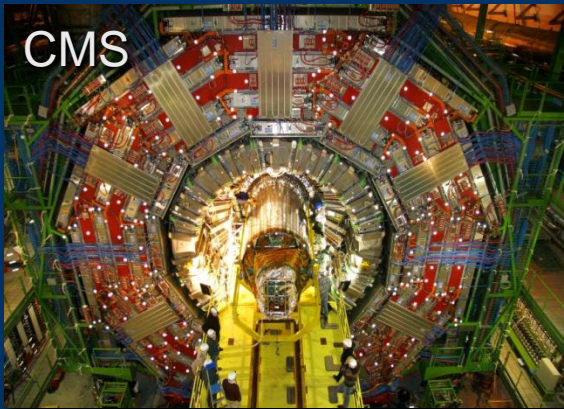




LHC Experiments → complementary



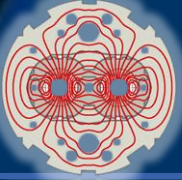
Specialised detector to study b-quarks → CPV



General purpose detectors



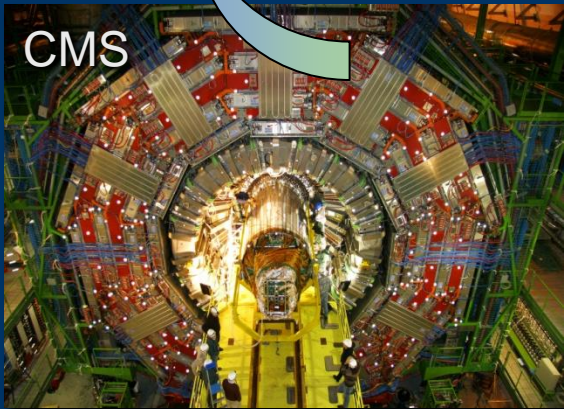
Specialised detector to study heavy ion collisions



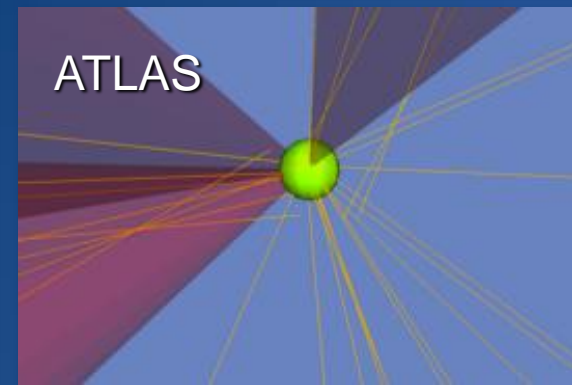
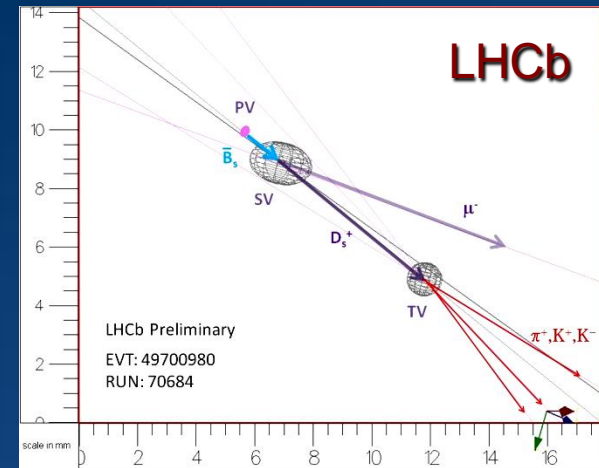
LHC Experiments → complementary

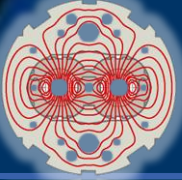


Overlap
in
physics
reach



Key feature: reconstruct
secondary vertex





LHC Experiments → complementary

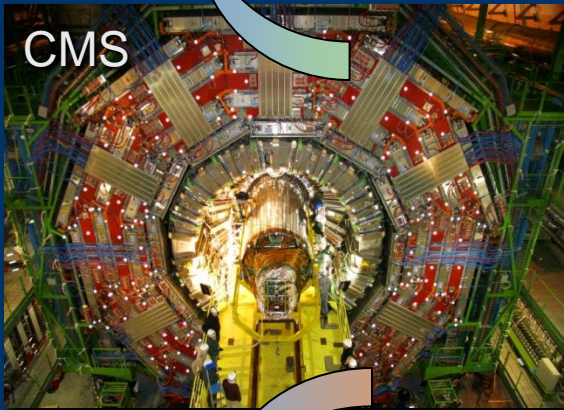


Overlap
in
physics
reach

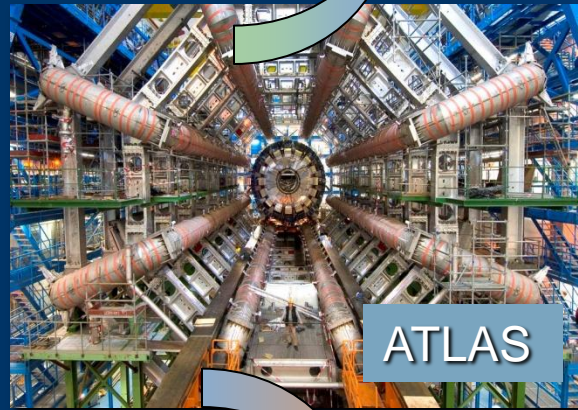


LHCb

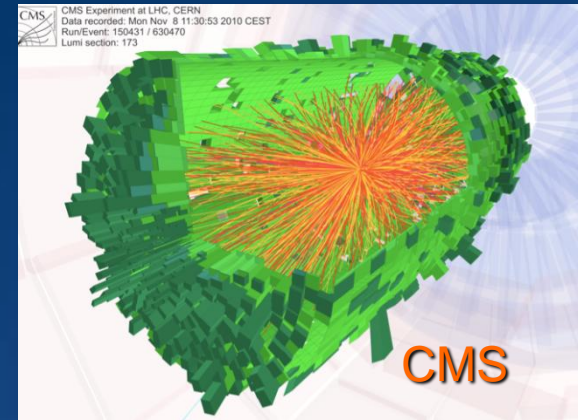
Key feature: reconstruct
> 20'000 charged tracks
in one event



CMS



ATLAS

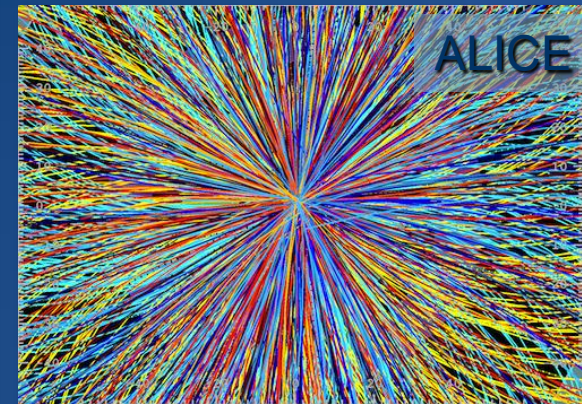


CMS

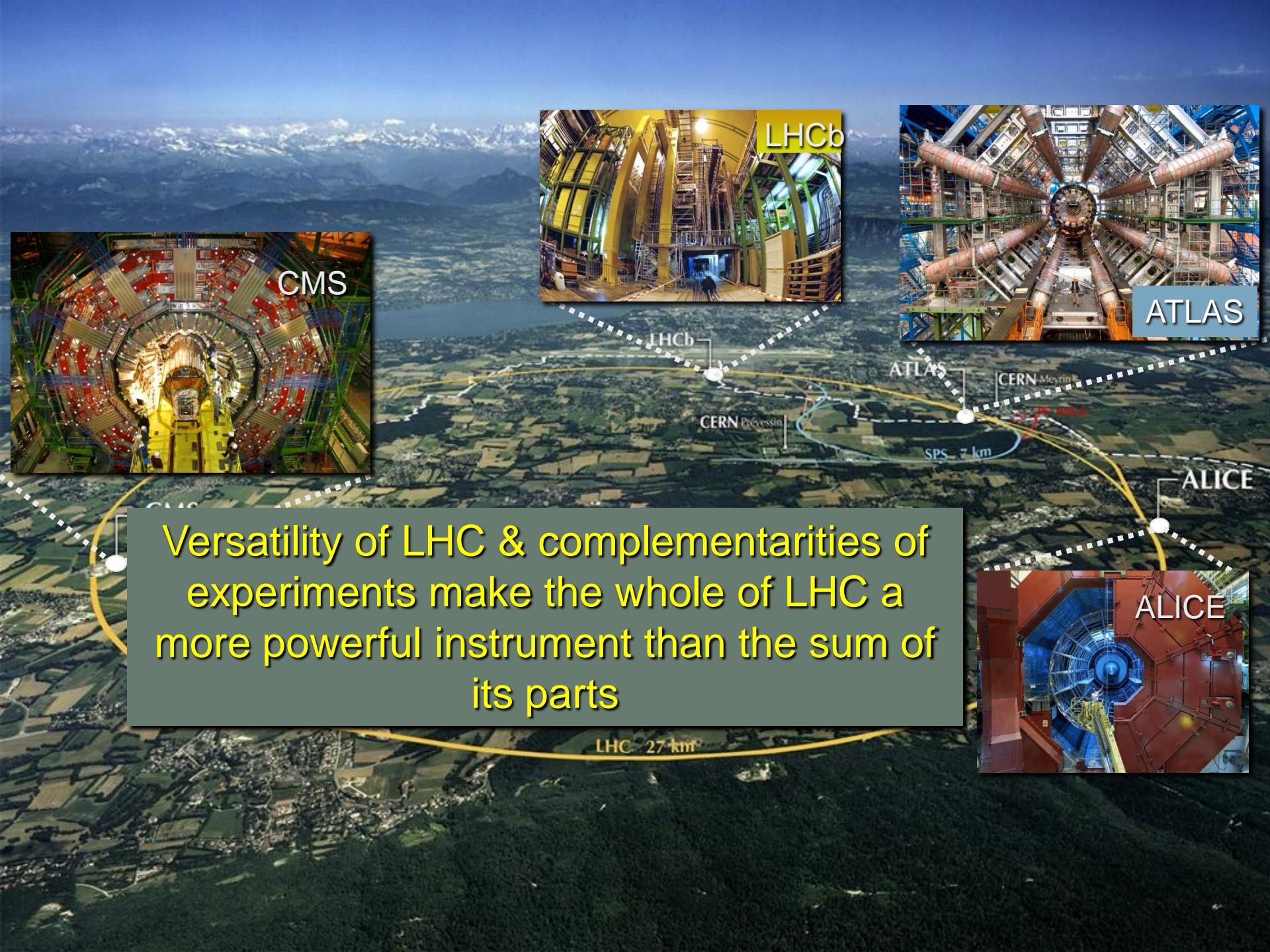
Overlap
in
physics
reach



ALICE



ALICE



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

LHCb

ATLAS

CERN-Meyrin

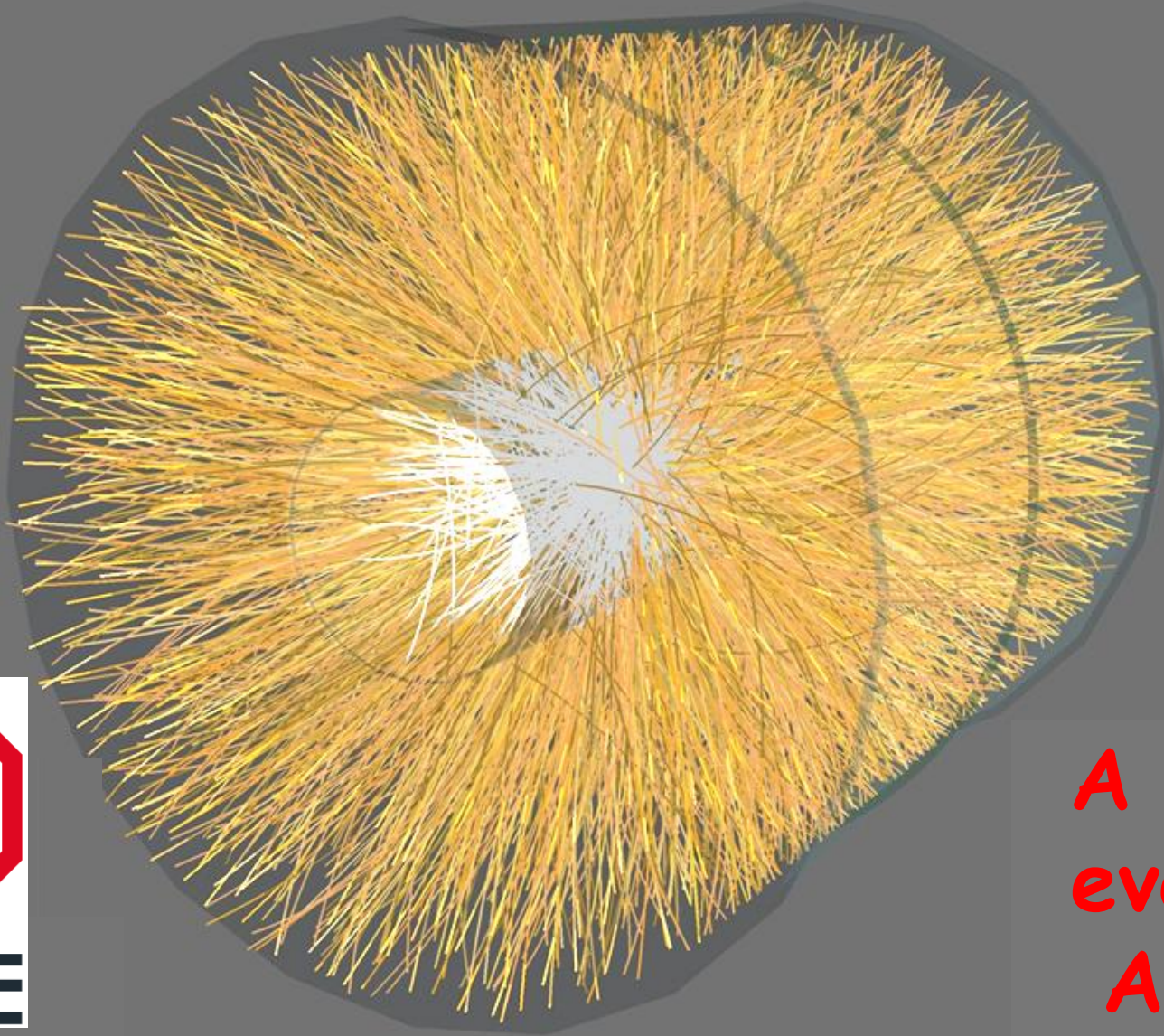
CERN-Preessin

SPS - 7 km

ALICE

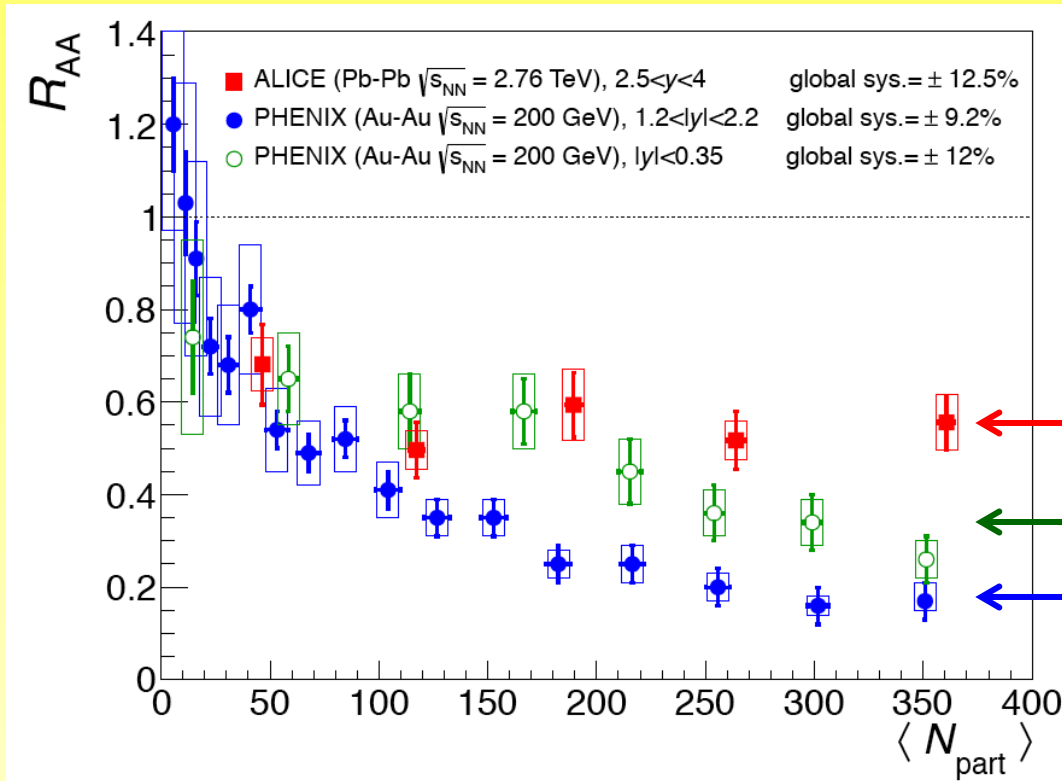
LHC - 27 km

Not just Higgs: a rich and diverse physics program at LHC



A Pb Pb
event in
ALICE

J/ψ in Pb-Pb: results and comparison with RHIC



ALICE Collaboration arXiv:1202.1383

ALICE, LHC, forward rapidity

PHENIX, RHIC, mid-rapidity

PHENIX, RHIC, forward rapidity

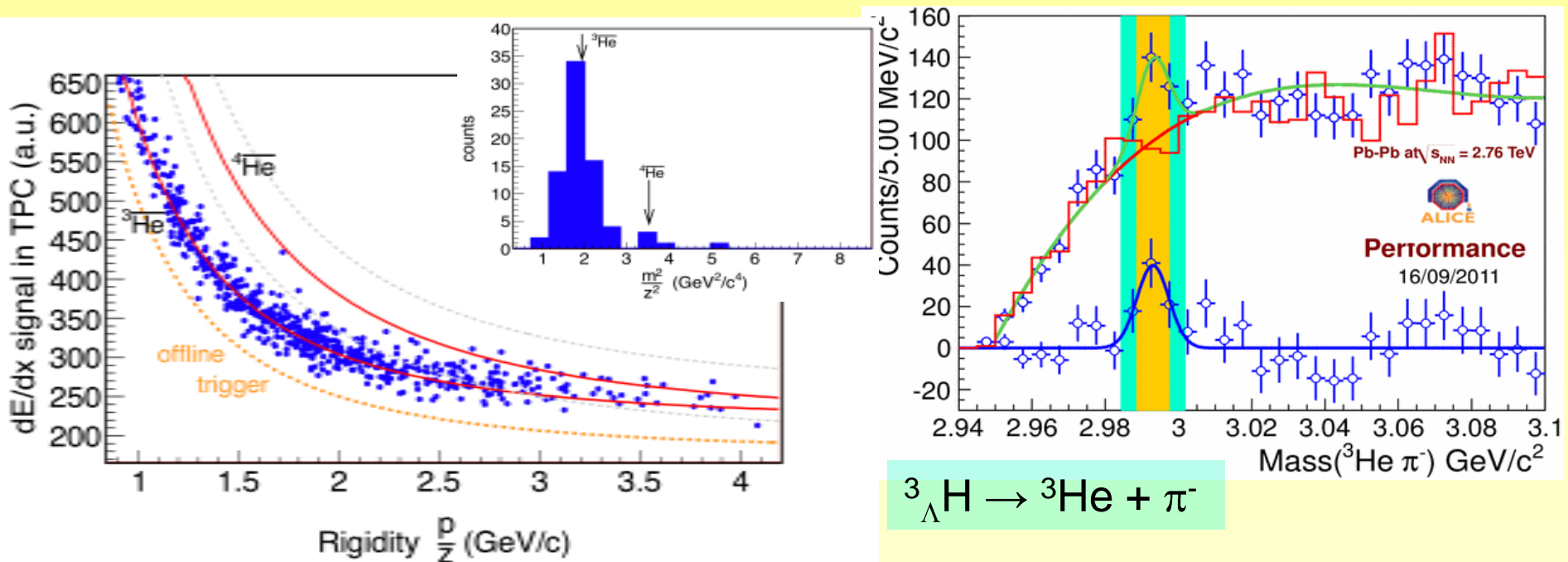


- Smaller J/ψ suppression at the LHC in spite of the factor 13 in \sqrt{s}
- Hint of (re)combination of charm quark from the Quark-Gluon Plasma phase in heavy-ion collisions ?



Nucleo-synthesis at LHC

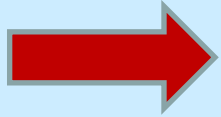
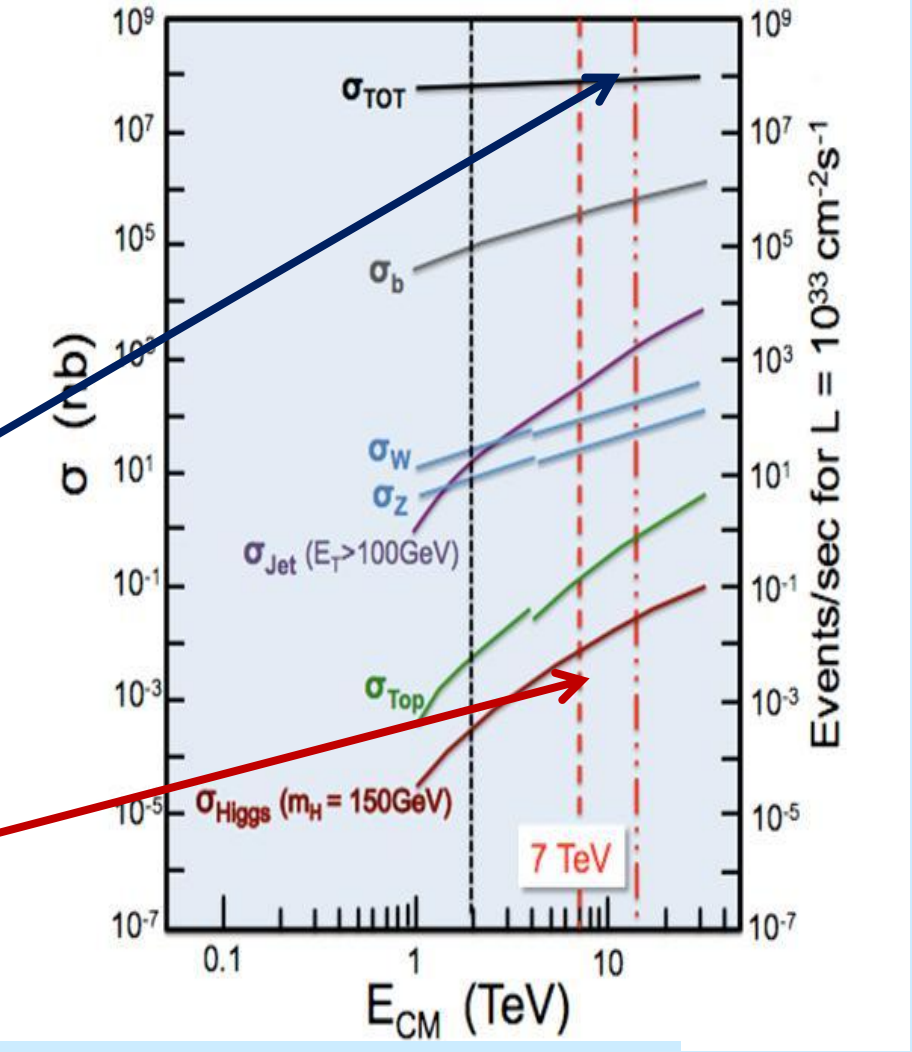
- Light Nuclei & anti-Nuclei
 - **Anti- ^4He** is the heaviest anti-nucleus ever observed
 - **Hypertriton**: one proton replaced by Λ particle



Cross Section („Production Rate“) of Various Processes

Proton-Proton Collisions

More than 10 orders of magnitude difference between total reaction rate and rate of new physics



select 1 out of much more than 10 billion ...

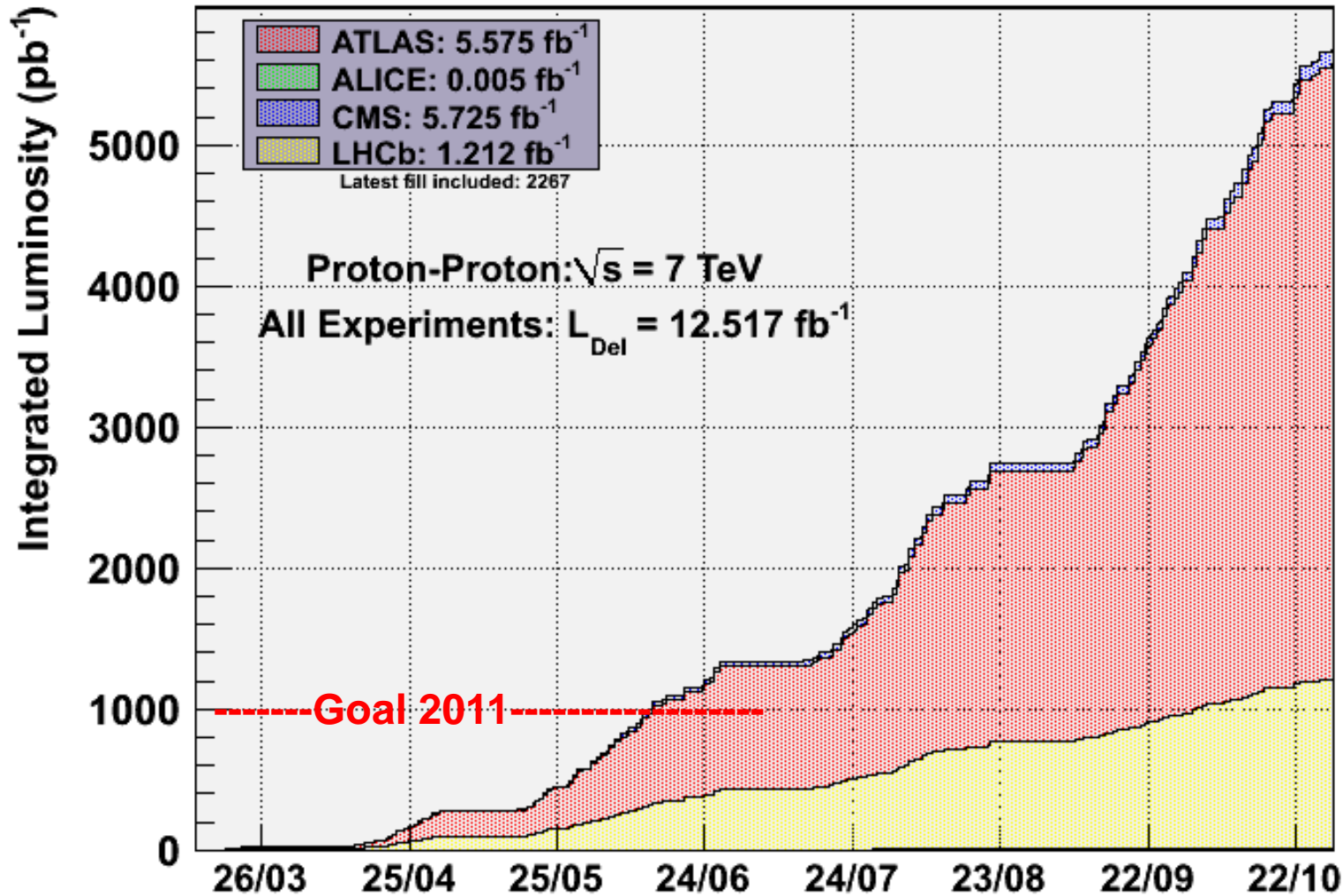


Accelerating Science and Innovation

LHC 2011

Excellent performance of the
whole accelerator complex
infrastructures
experiments
computing

2011 Luminosity Production

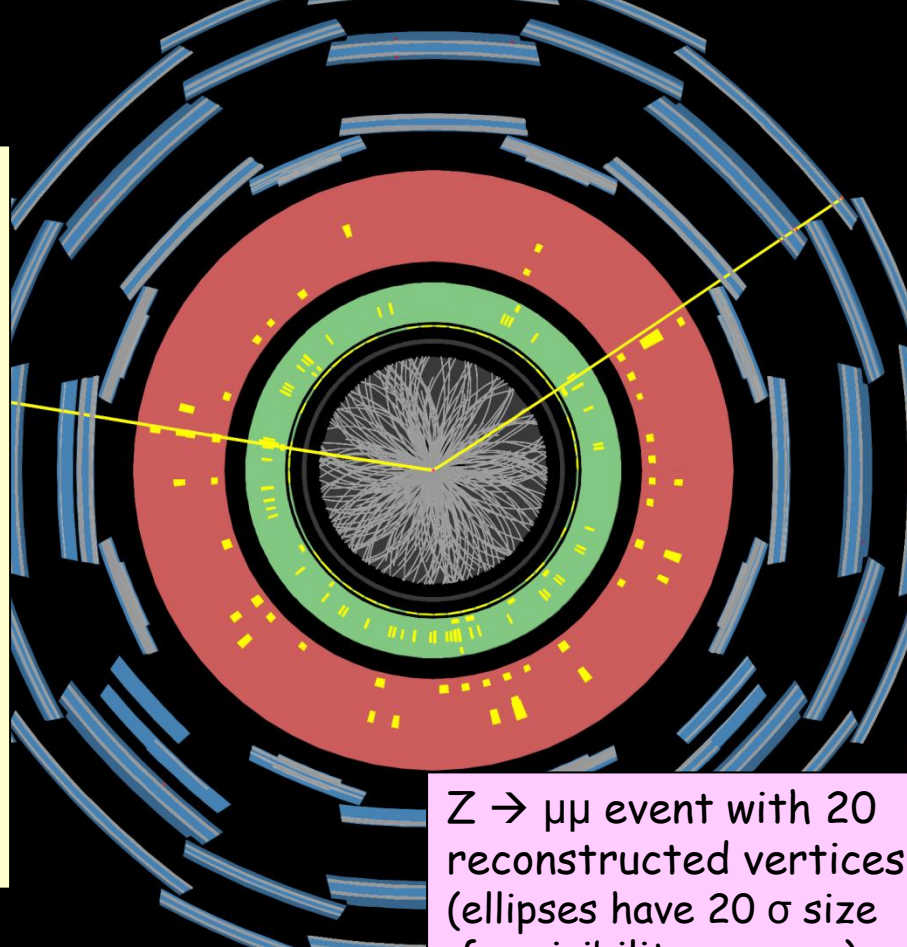


Pile-up

Experiment (trigger, detector, reconstruction, ..) is coping well with larger than expected at this stage and increasing pile-up.

Today: average over a fill is ~ 12 interactions/x-ing (was ~ 6 in Spring), with tails up to ~ 20

Pile-up could increase by up to ~ 2 in 2012



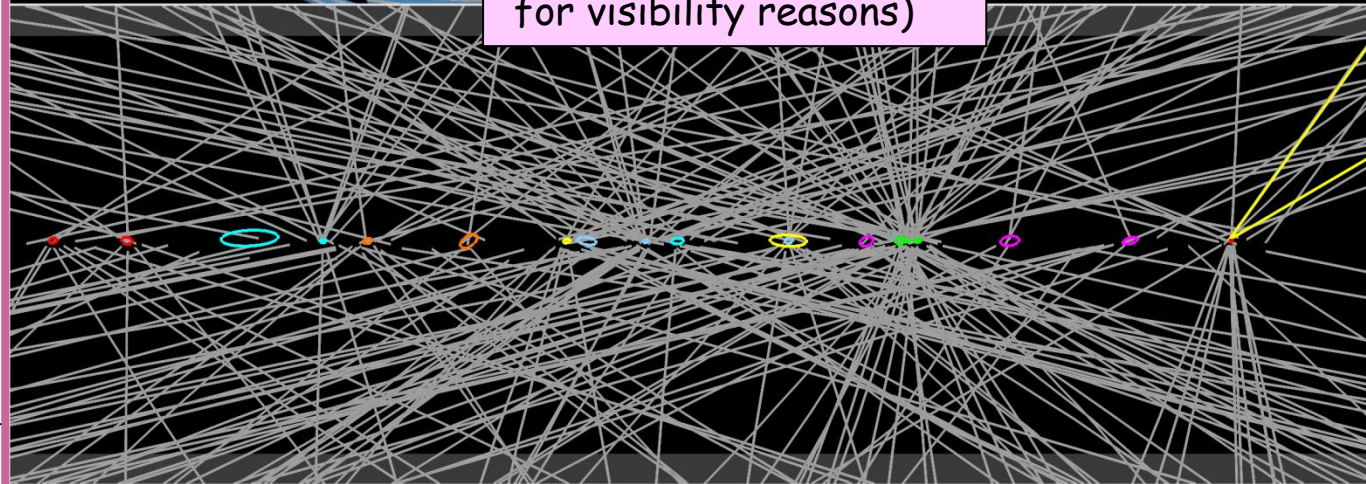
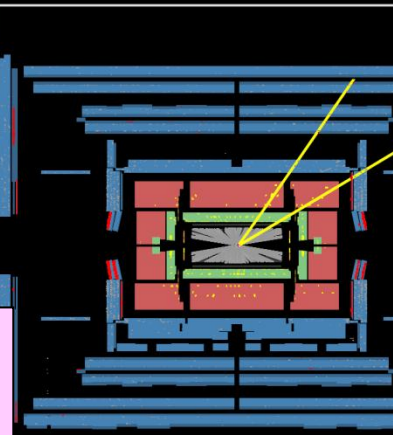
$Z \rightarrow \mu\mu$ event with 20 reconstructed vertices (ellipses have 20σ size for visibility reasons)



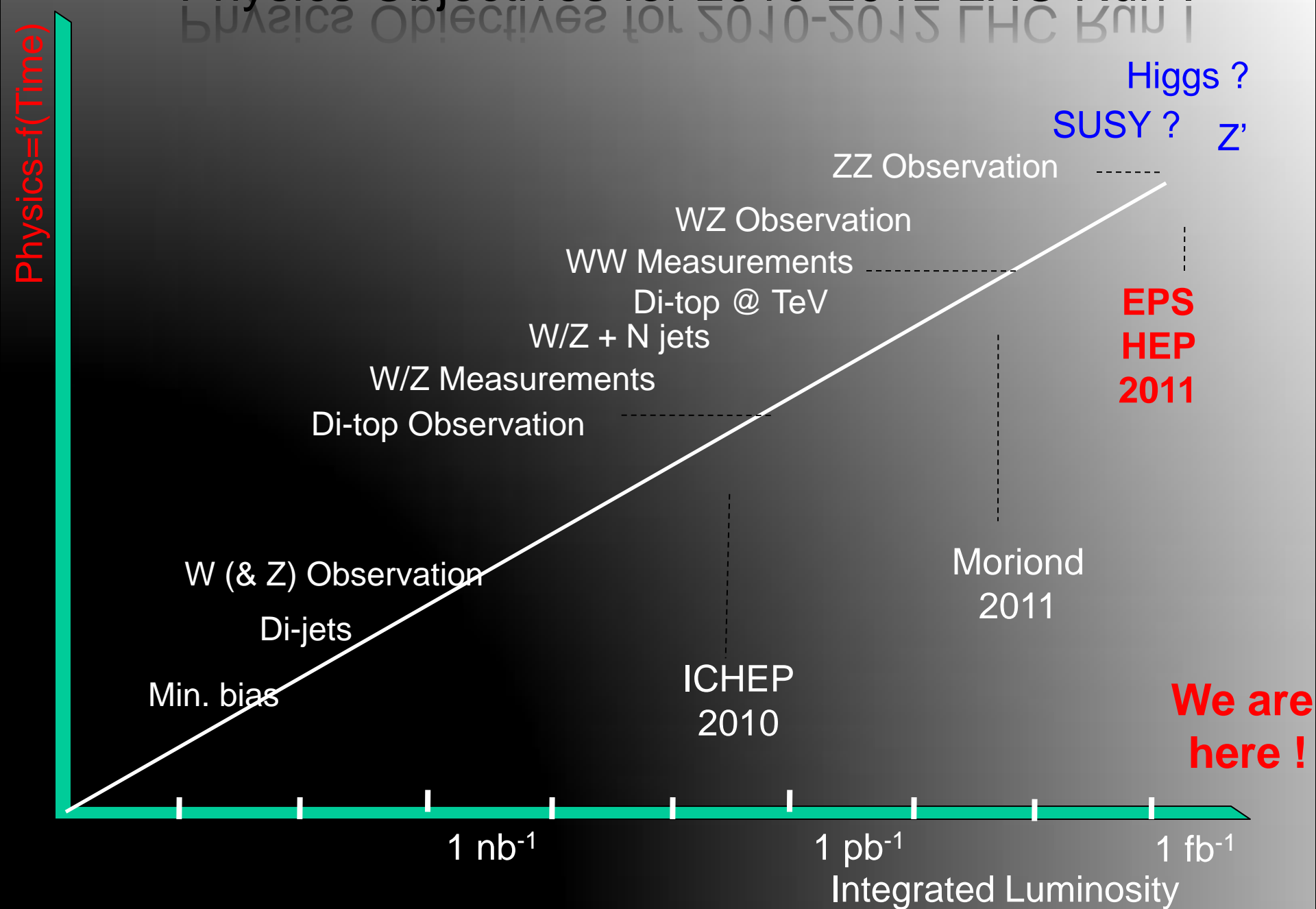
ATLAS EXPERIMENT

Run Number: 189280, Event Number: 17

Date: 2011-09-14 02:47:14 CEST

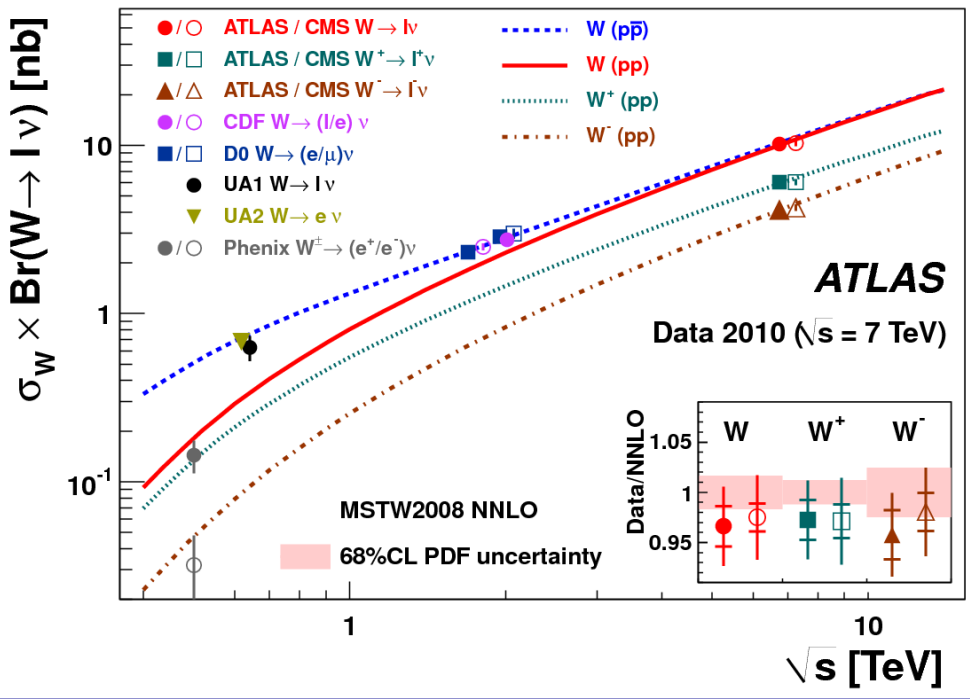


Physics Objectives for 2010-2012 LHC Run I

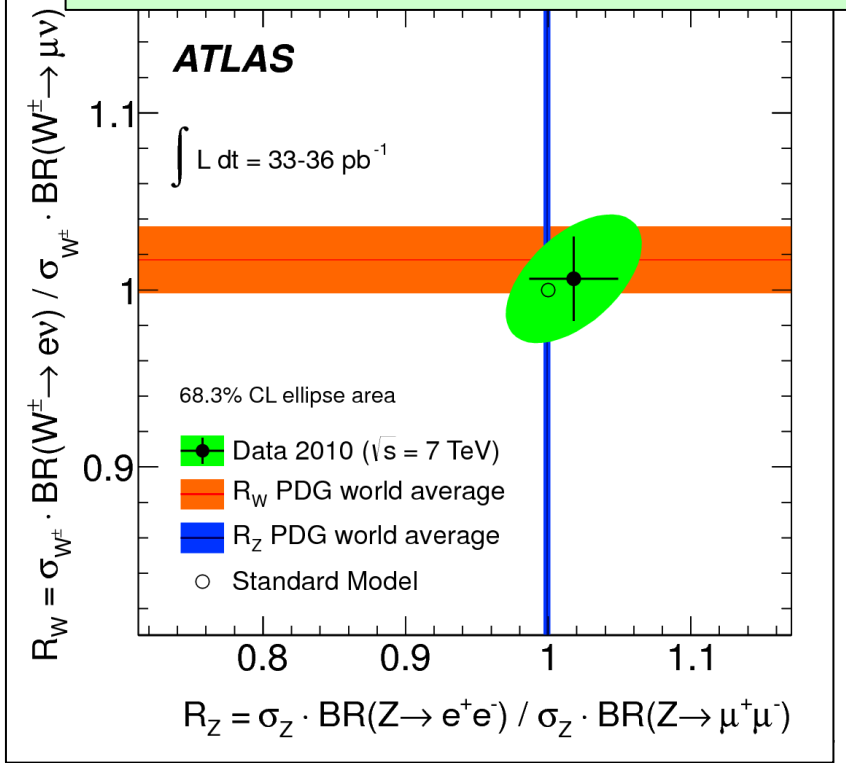
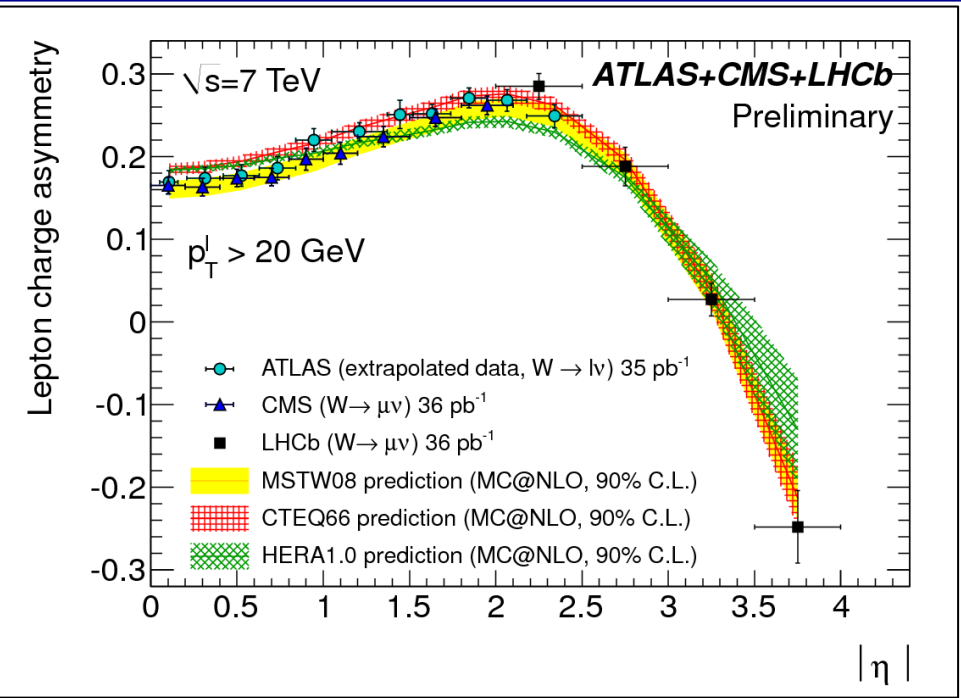




W and Z physics



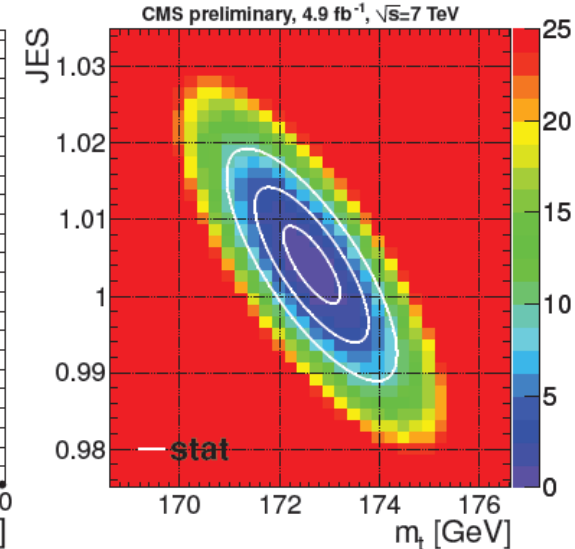
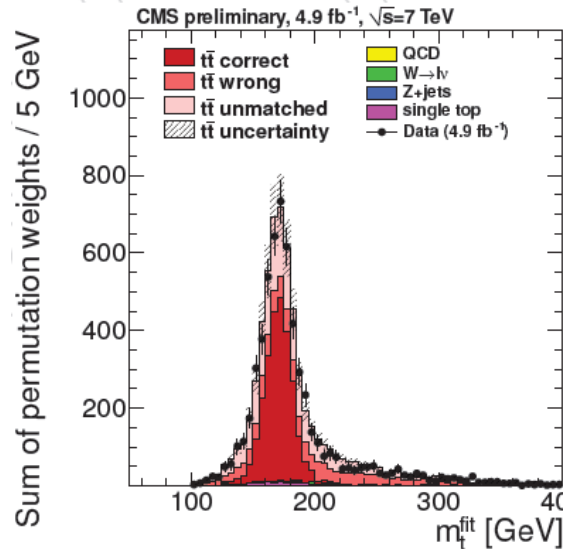
Probing lepton universality with accuracy comparable to PDG world average (from LEP and Tevatron) for W



Top mass

TOP-11-015

- New for Moriond 2012
 - Likelihood method simultaneously fitting the top mass and Jet Energy Scale
 - Lepton+jets: all 2011 data

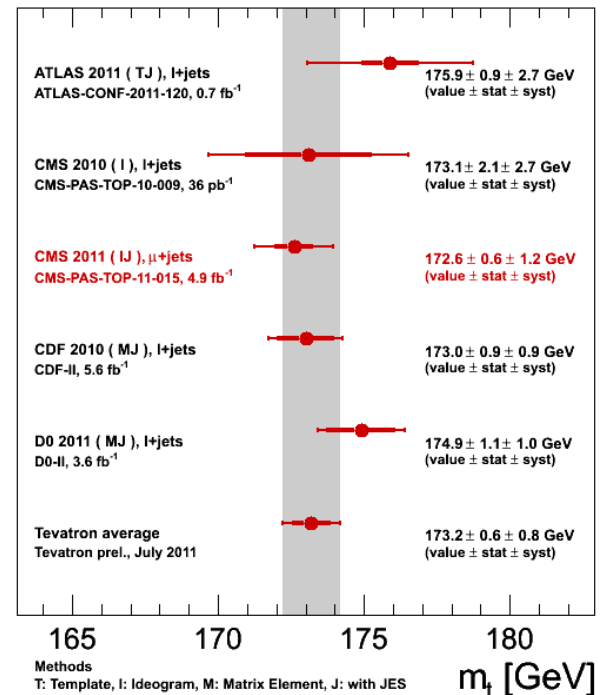


- Best LHC result on top mass

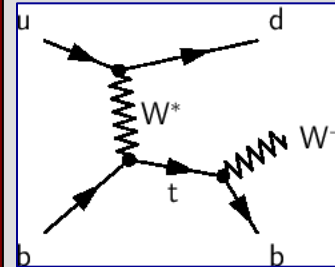
$$m_t = 172.64 \pm 0.57 \text{ (stat+JES)} \pm 1.18 \text{ (syst)} \text{ GeV}$$

$$\text{JES} = 1.004 \pm 0.005 \text{ (stat)} \pm 0.012 \text{ (syst)}$$

- Competitive with individual measurements at the Tevatron
- Working towards a combination of the CMS results and the Tevatron+LHC combination

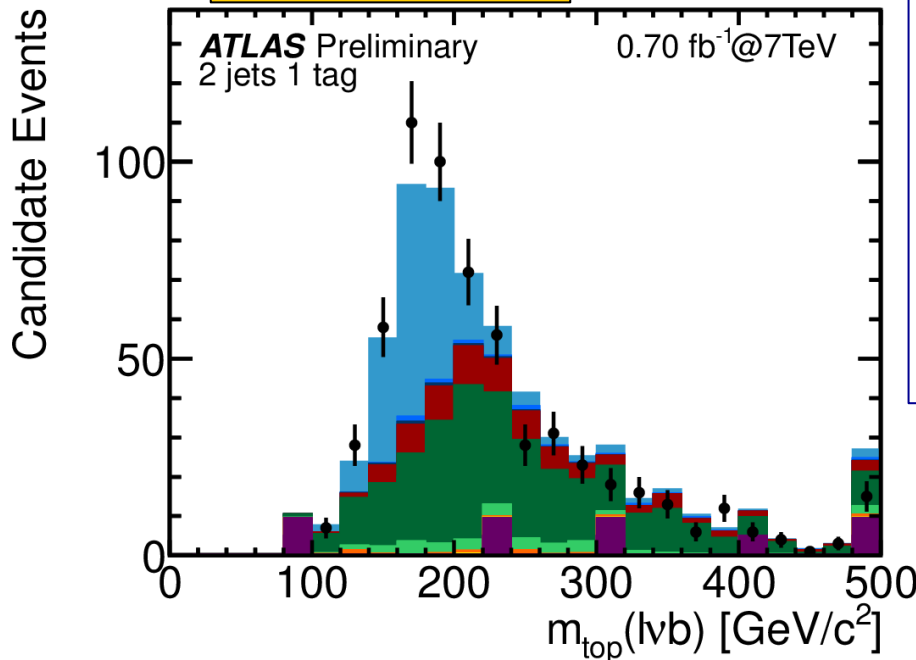


Single top production



t-channel single-top production

$t \rightarrow bW \rightarrow bl\nu$



- ATLAS data
- single-top t-channel
- single-top Wt
- single-top s-channel
- top pairs
- W+heavy flavour
- W+light jets
- Diboson
- Z+jets
- Multijets

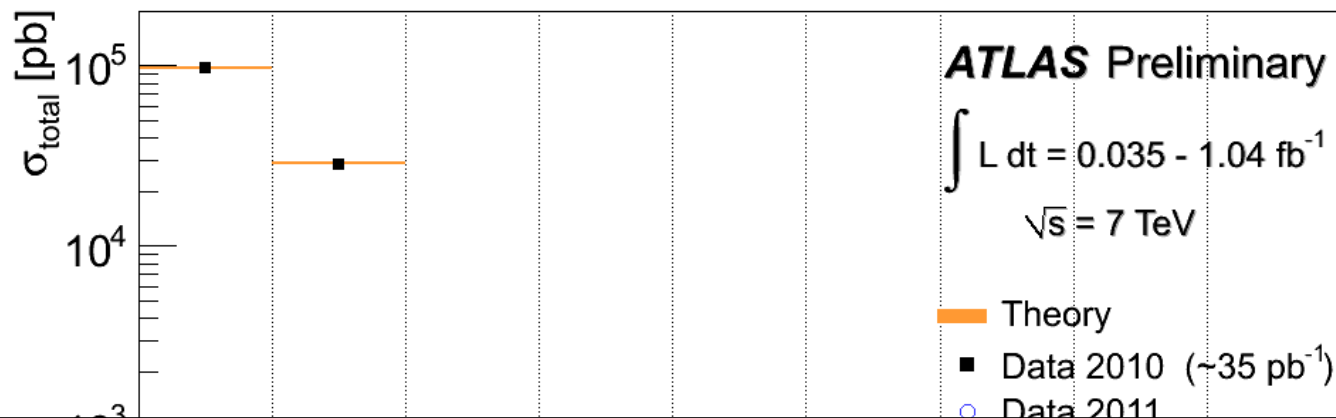
Measured cross-section:

$$\sigma_t = 90_{-9}^{+9}(\text{stat})_{-20}^{+31}(\text{syst})$$

Expected from SM: $\sim 65 \pm 3$ pb

Single-top signal significance: $> 7\sigma$

Summary of main electroweak and top cross-section measurements



Inner error: statistical
Outer error: total

In our present dataset ($\sim 5 \text{ fb}^{-1}$) we have (after selection cuts):

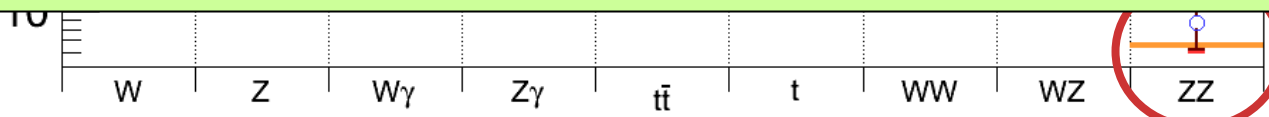
$\sim 30 \text{ M } W \rightarrow \mu\nu, e\nu$ events

$\sim 3 \text{ M } Z \rightarrow \mu\mu, ee$ events

~ 60000 top-pair events

\rightarrow factor ~ 2 (W, Z) to 10 (top) more than total CDF and D0 datasets

\rightarrow will allow more and more precise studies of a larger number of (exclusive) processes



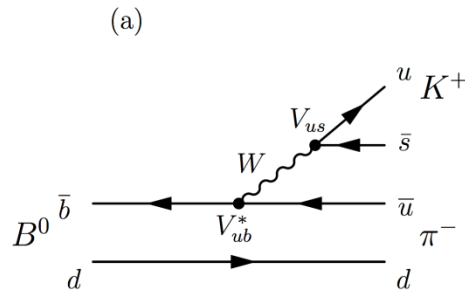
bin \rightarrow comparable
to $H \rightarrow ZZ^{(*)} \rightarrow 4l$

Good agreement with SM expectations (within present uncertainties)

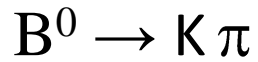
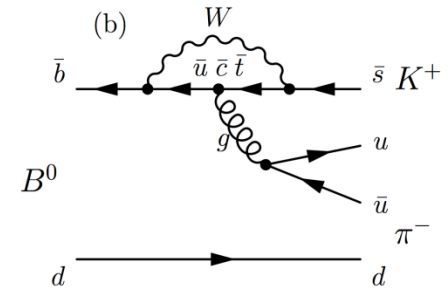
Experimental precision starts to challenge theory for e.g. tt (background to most H searches)

Measuring cross sections down to few pb ($\sim 10 \text{ pb}$ including top quark branching ratio)

The Interference Experiment Works!

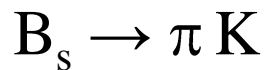
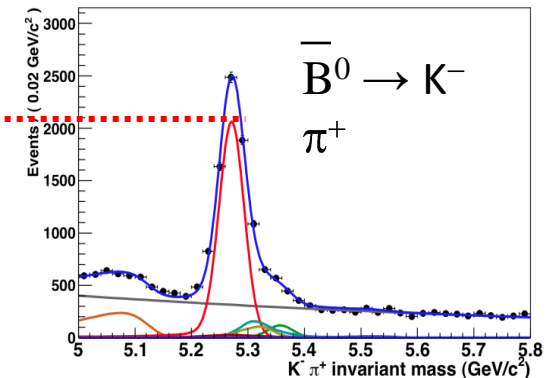
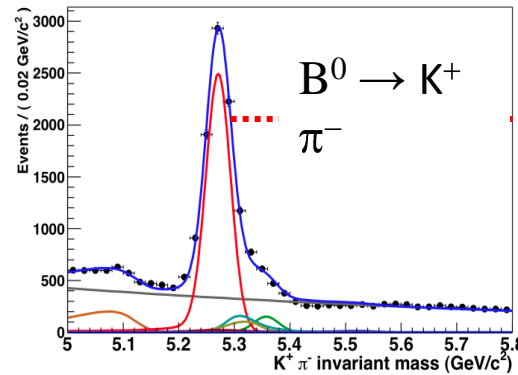


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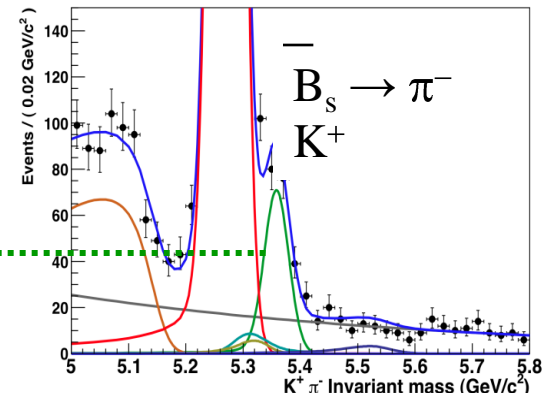
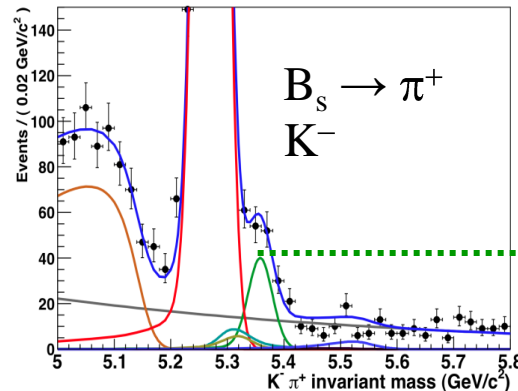
$$A_{CP} = -0.088 \pm 0.011 \pm 0.008$$

Most precise and first 5σ
Observation of CP violation
in a hadronic machine



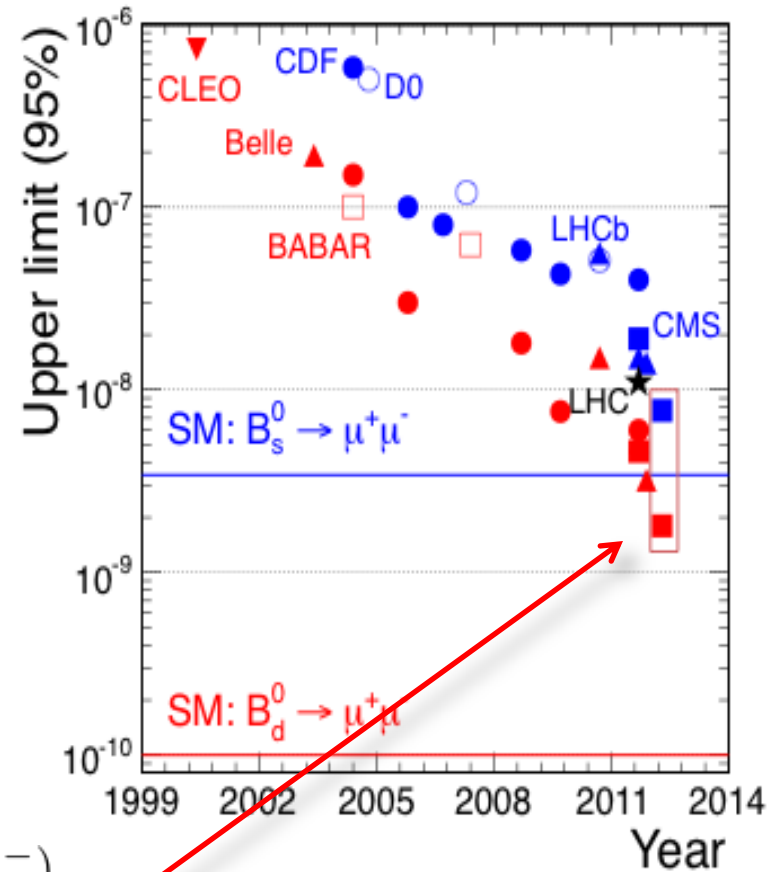
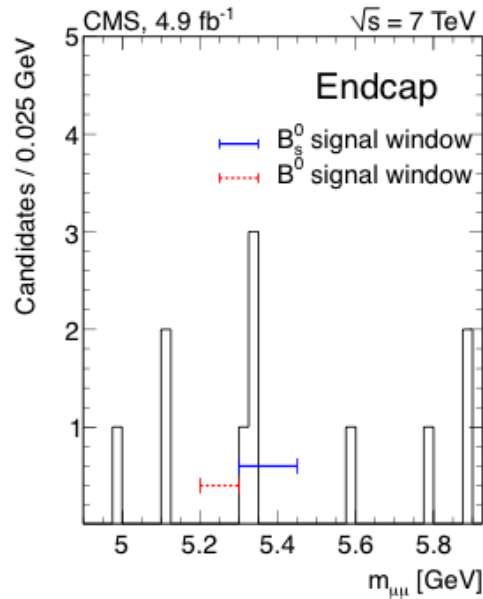
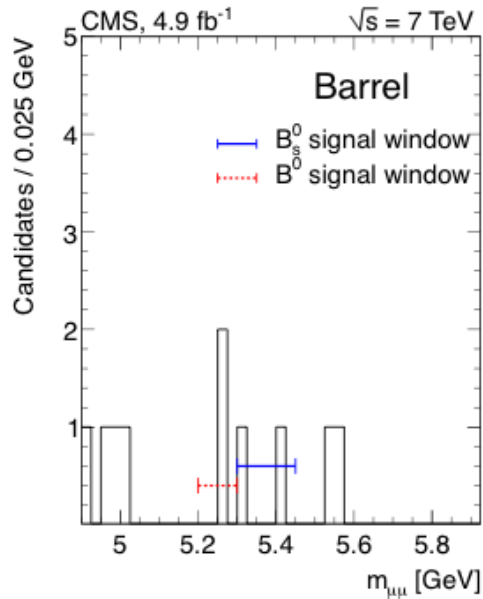
$$A_{CP} = 0.27 \pm 0.008 \pm 0.02$$

First 3σ evidence for
CP asymmetry in B_s decays





$$B_{d/s} \rightarrow \mu\mu$$



- Upper limit on $\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)$ and $\mathcal{B}(B^0 \rightarrow \mu^+\mu^-)$

upper limit (95%CL)	observed	(median) expected
$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)$	7.7×10^{-9}	8.4×10^{-9}
$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-)$	1.8×10^{-9}	1.6×10^{-9}

The “beauty” of charm

- LHCb can profit of the huge charm production cross section at the LHC (~6 mb):

LHC is a charm-factory !

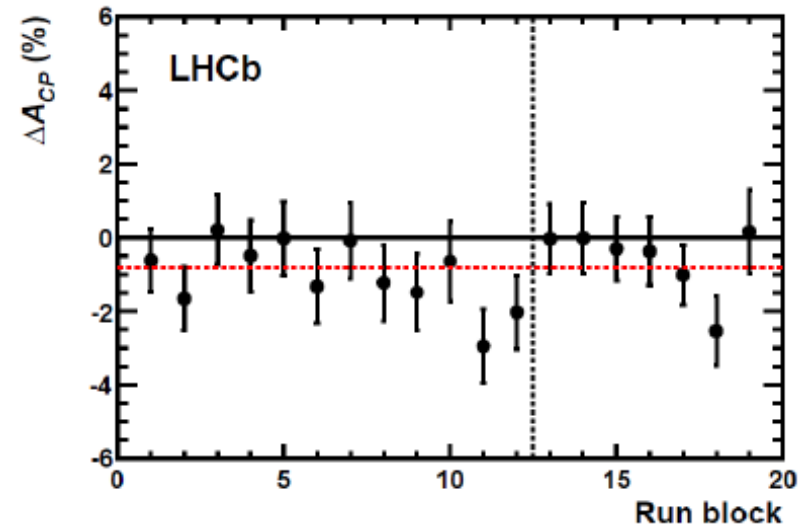
- Evidence of CP violation in charm decays

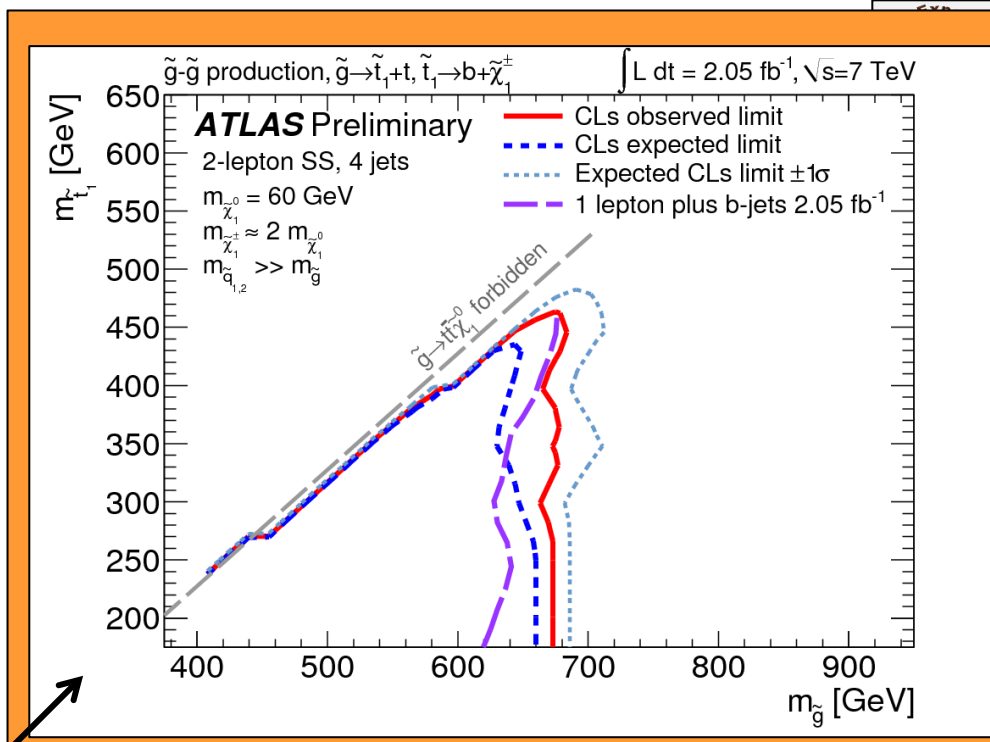
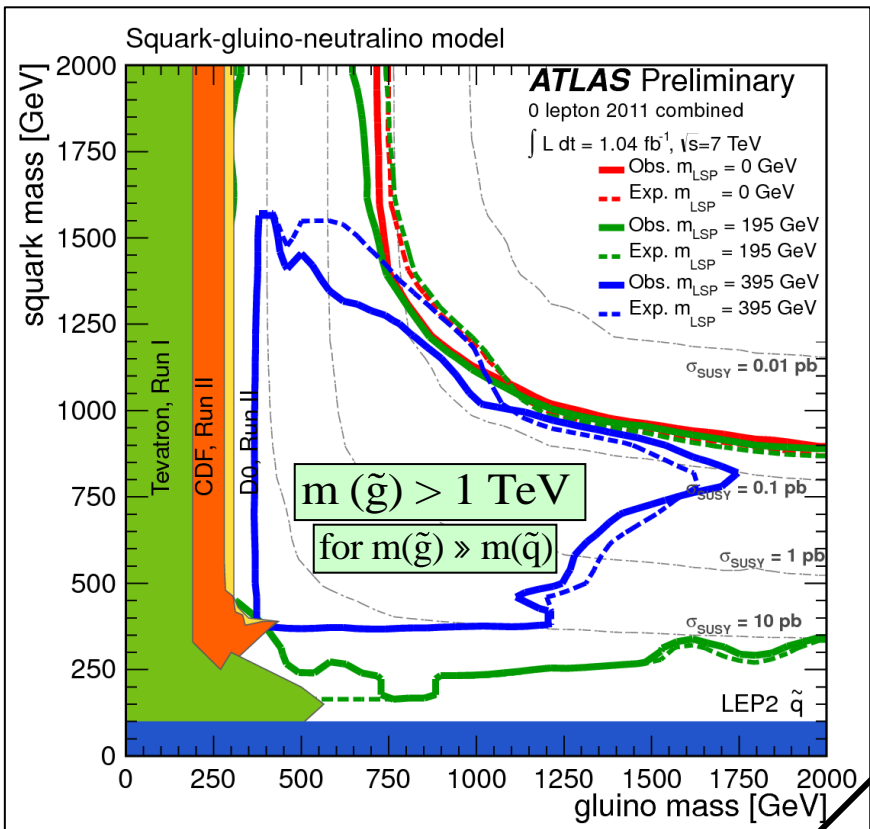
$$A_{CP}(f) = \frac{\Gamma(D^0 \rightarrow f) - \Gamma(\bar{D}^0 \rightarrow f)}{\Gamma(D^0 \rightarrow f) + \Gamma(\bar{D}^0 \rightarrow f)}$$

$f = KK$ or $\pi\pi$

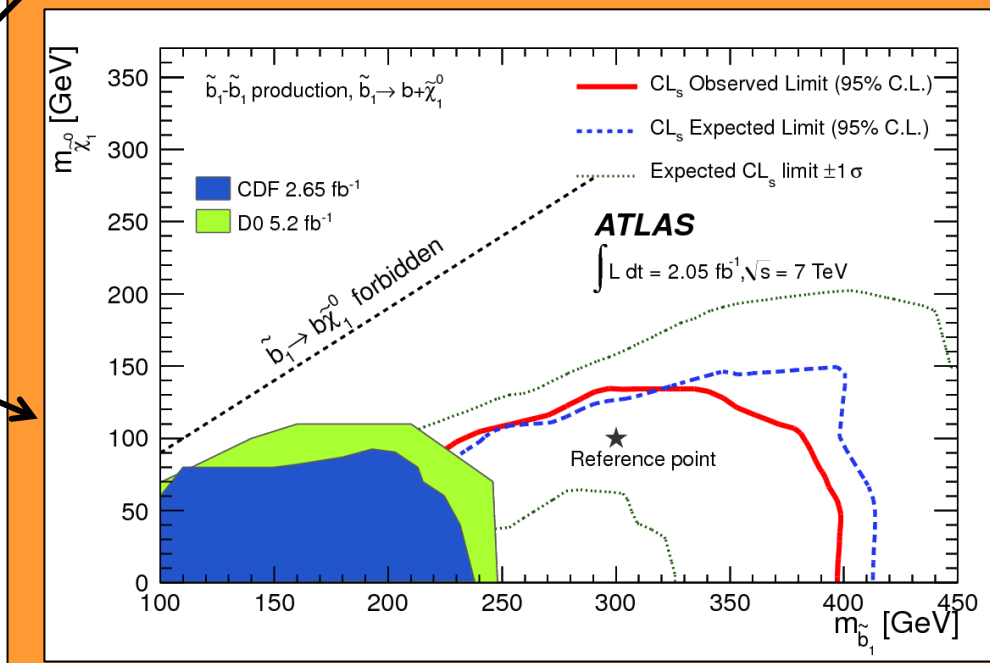
$$\Delta A_{CP} = [-0.82 \pm 0.21(\text{stat.}) \pm 0.11(\text{sys.})] \%$$

- Theoretical community is evaluating the compatibility of this result (to be cross checked with independent measurements) with New Physics beyond the Standard Model
- Extra contribution to CP coming from “conventional” hadronic physics unlikely, but still possible



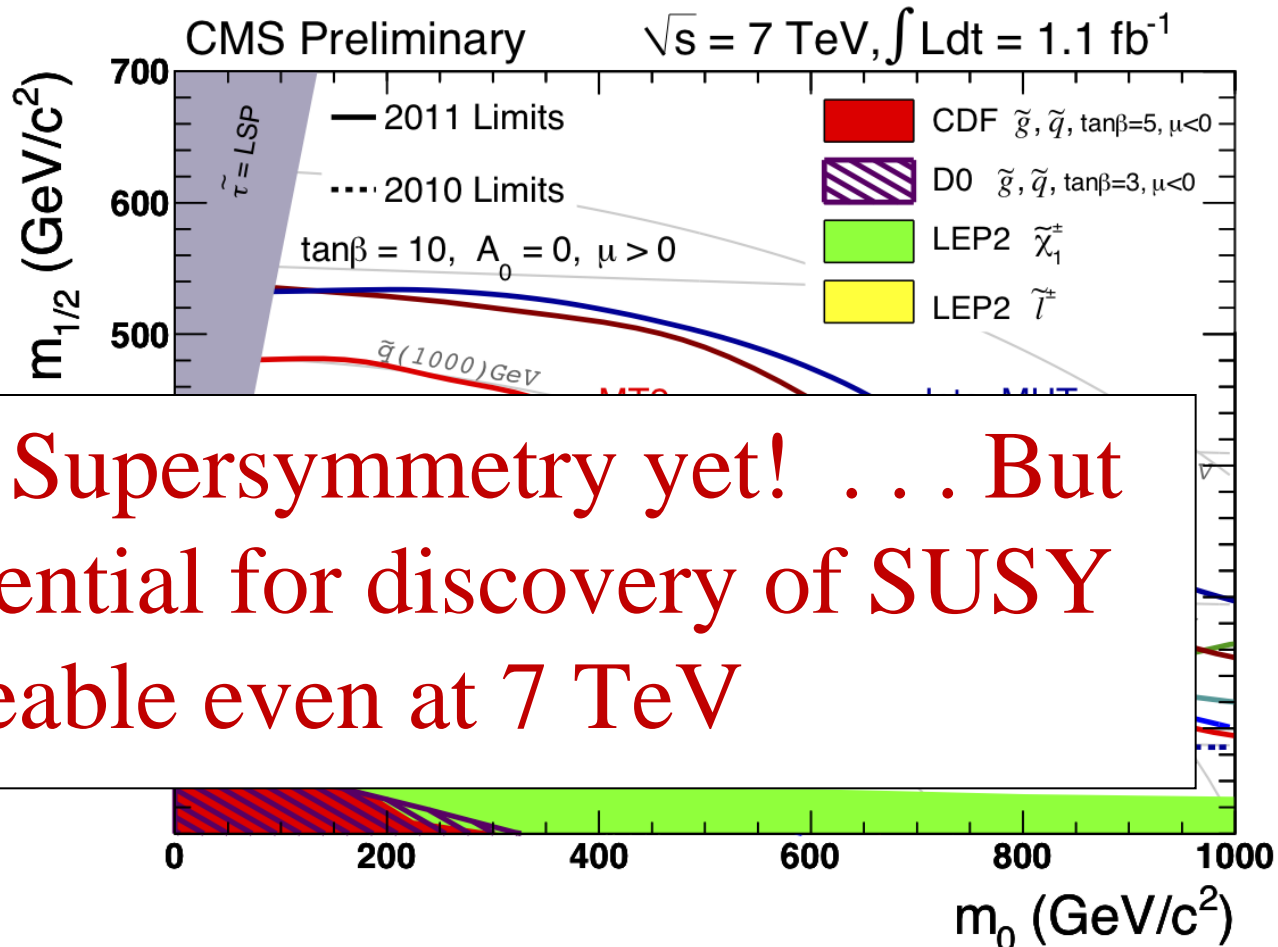


Stop and sbottom searches highly motivated today, as 3rd generation squarks are those that are expected to stabilize the Higgs mass





SUSY: new limits on CMSSM

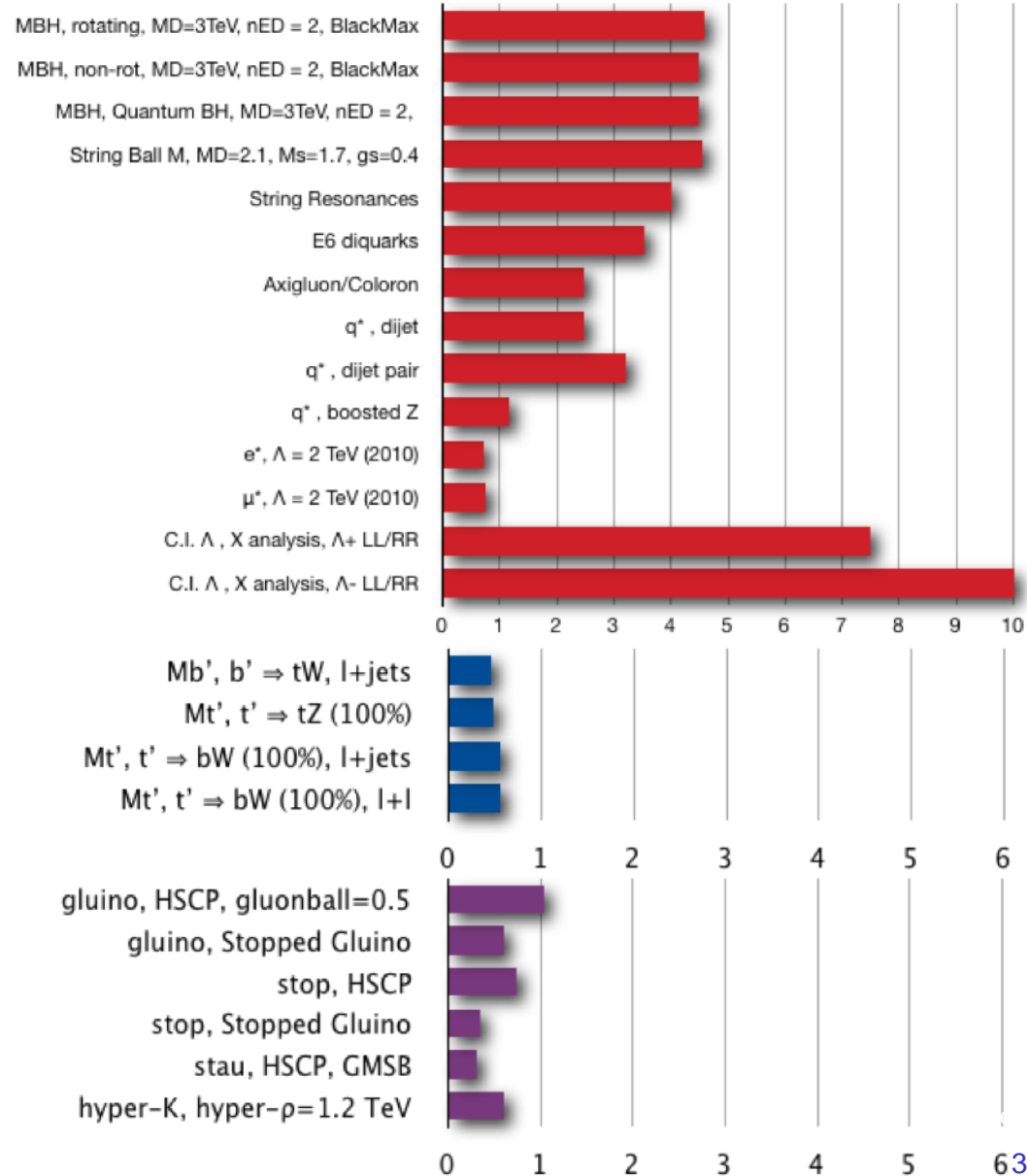
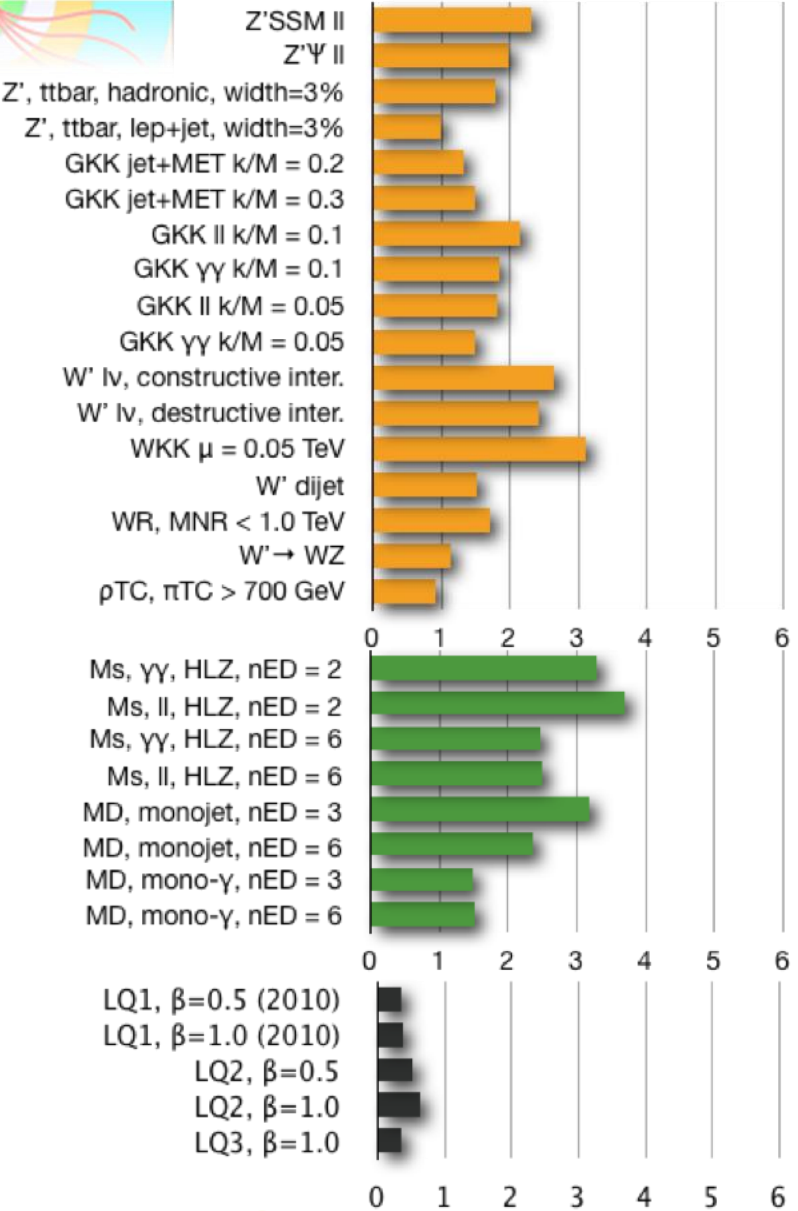


No Supersymmetry yet! . . . But potential for discovery of SUSY sizeable even at 7 TeV

Within the constrained MSSM models we have crossed the border of excluding gluinos and squarks up to 1TeV and beyond. The air is getting thin for constrained SUSY. More conclusive results for the winter conferences 2012.



CMS Exotica: Summary for Moriond 2012



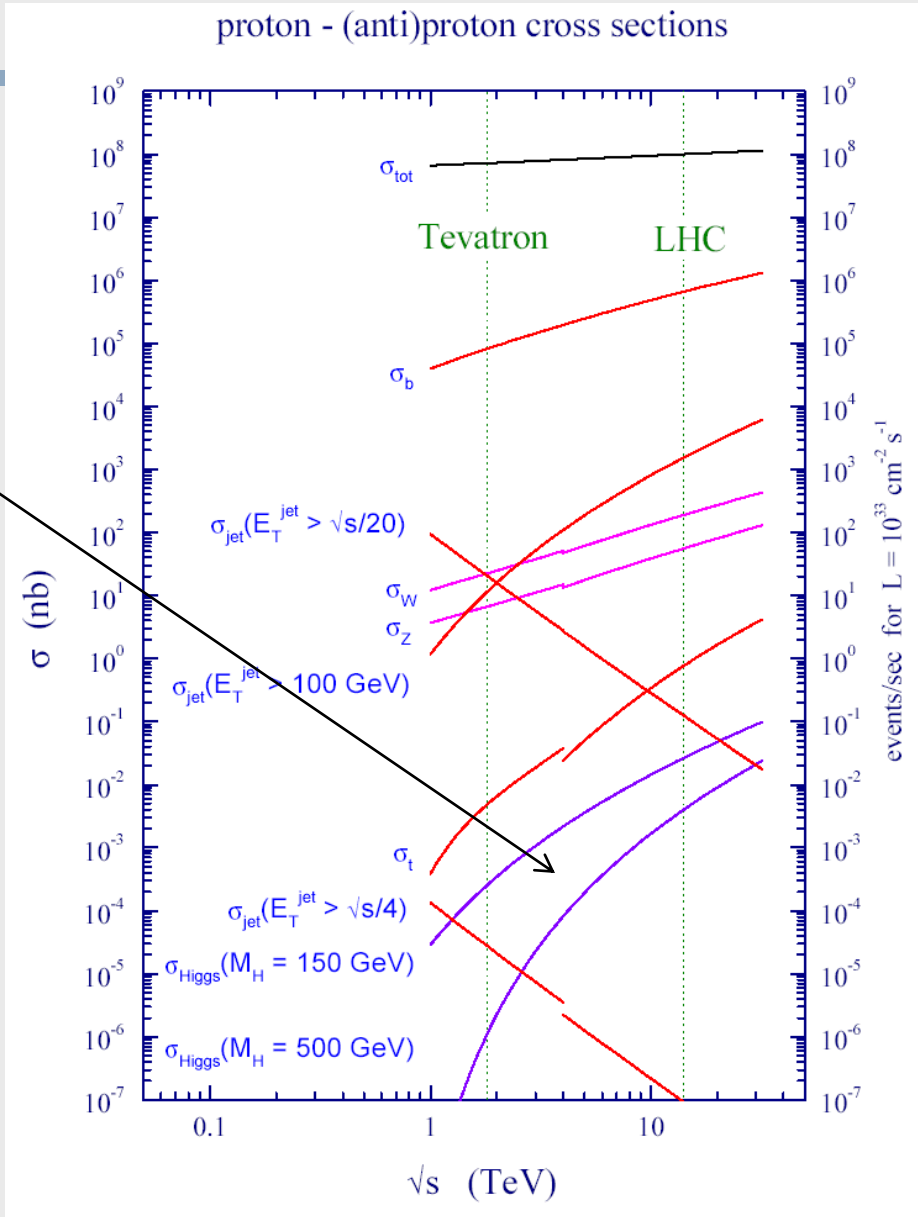
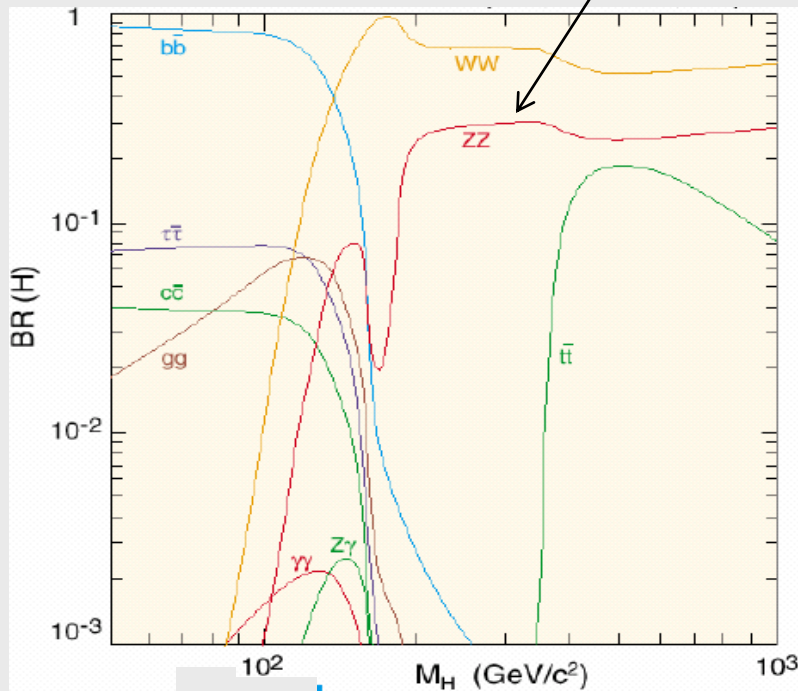
LHC and Theory...



Search for the Higgs-Boson at the LHC

Production rate
of the Higgs-Bosons
depends on its mass

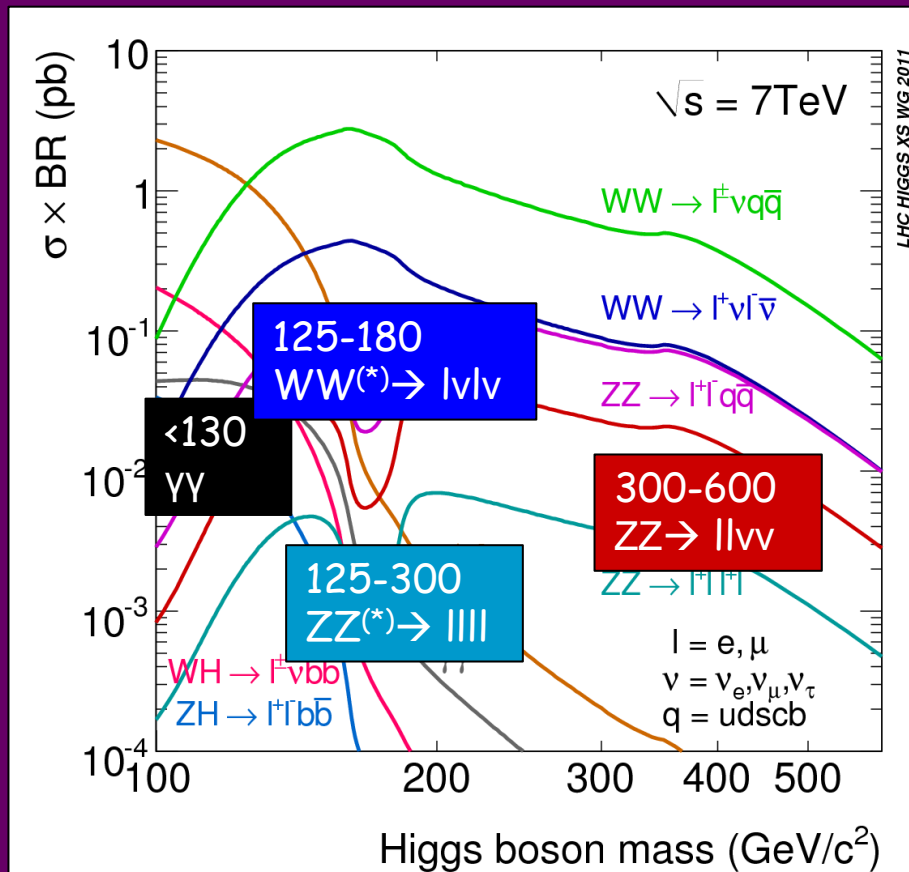
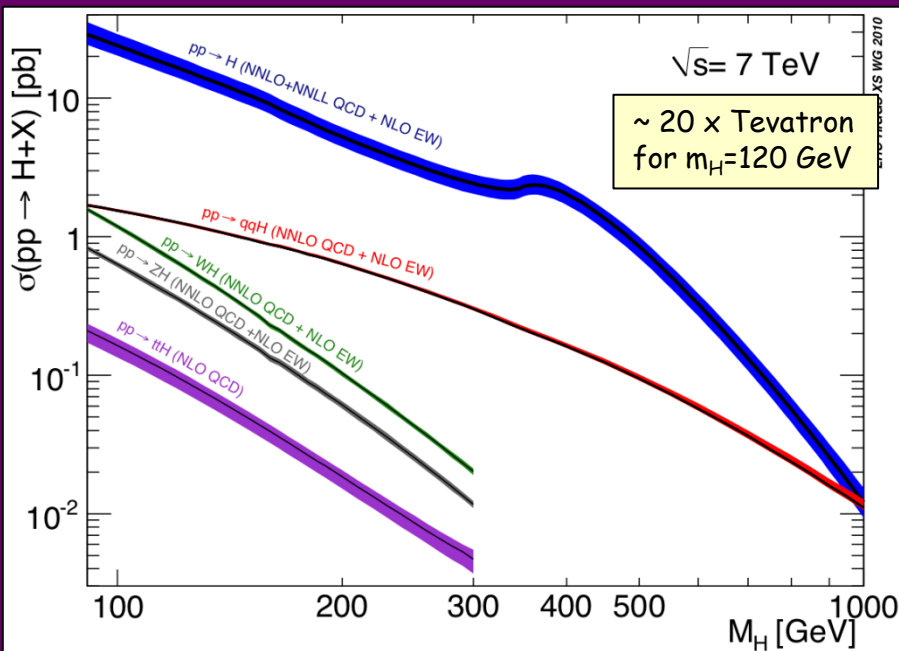
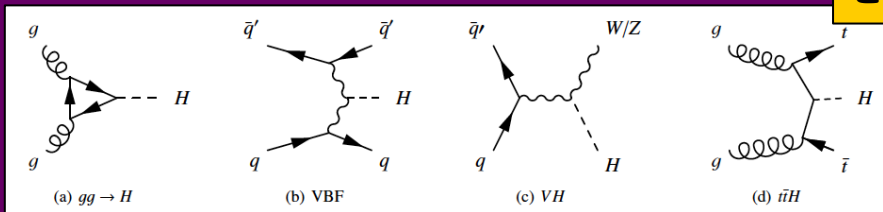
as well as its decay possibilities

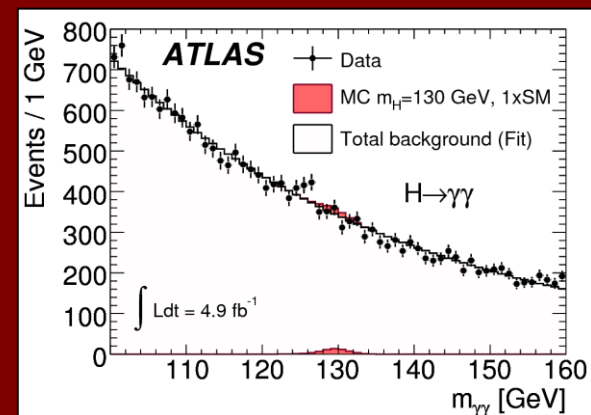
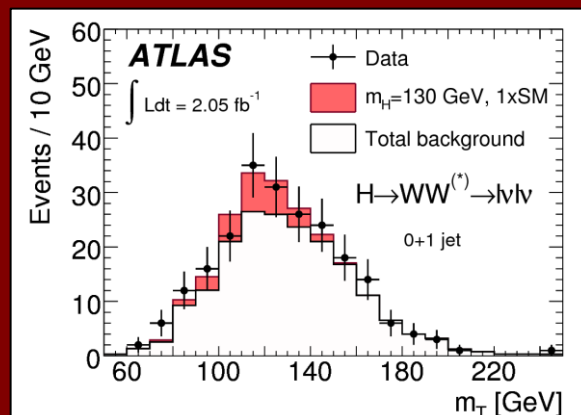
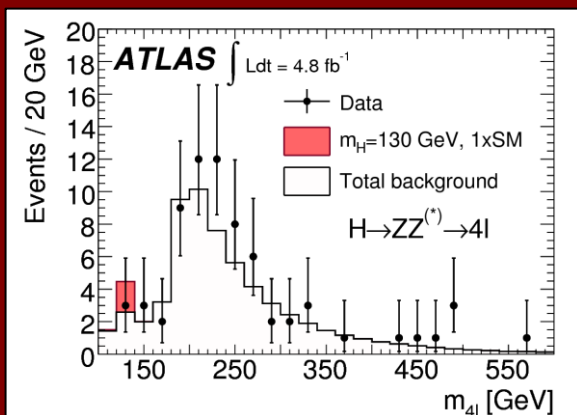
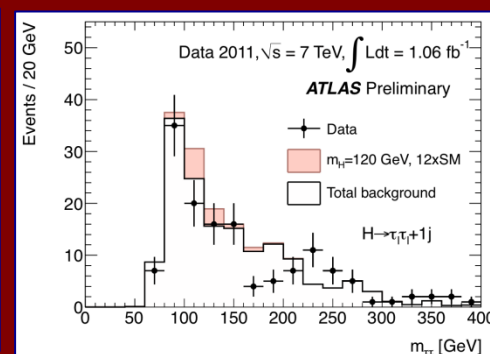
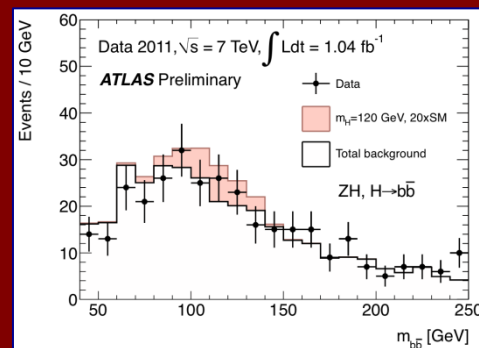
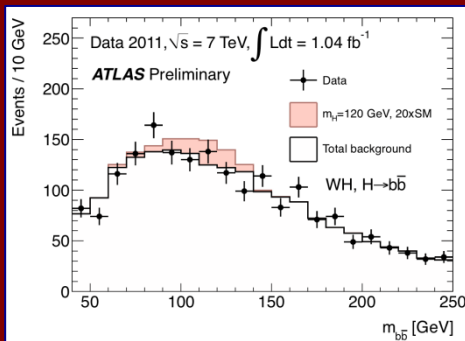
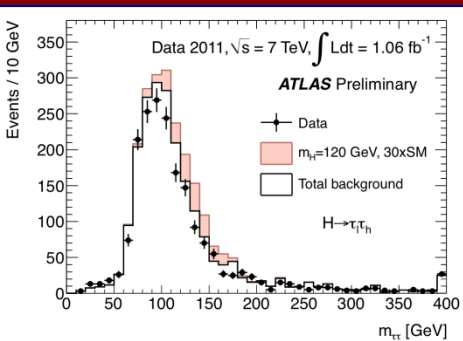


SM Higgs production cross-section and decay modes

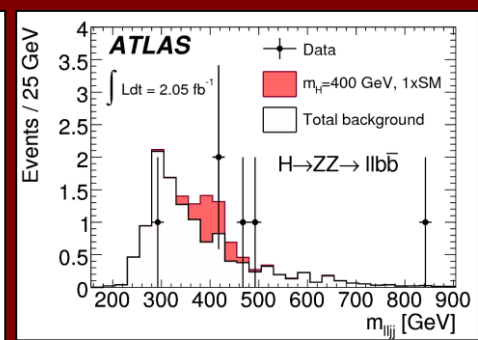
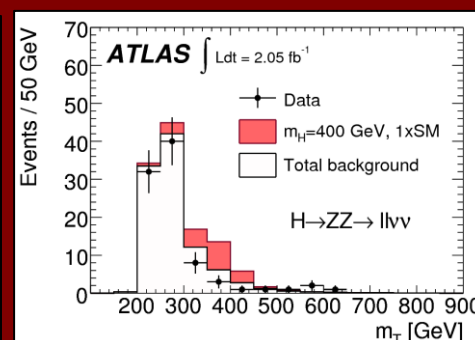
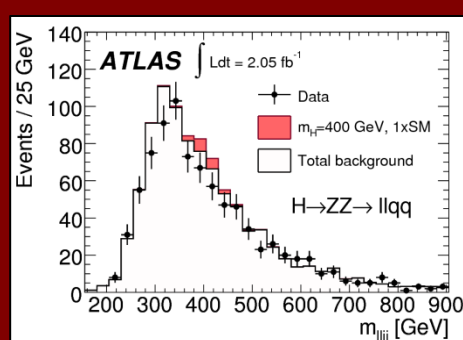
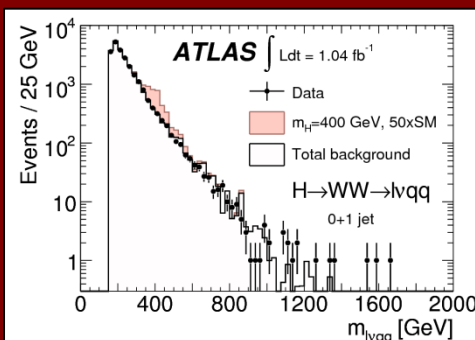


Experimentally most sensitive channels vs m_H

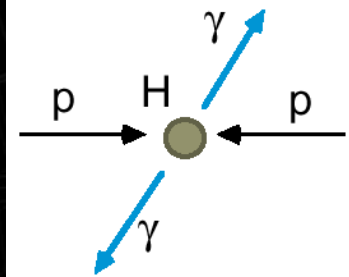
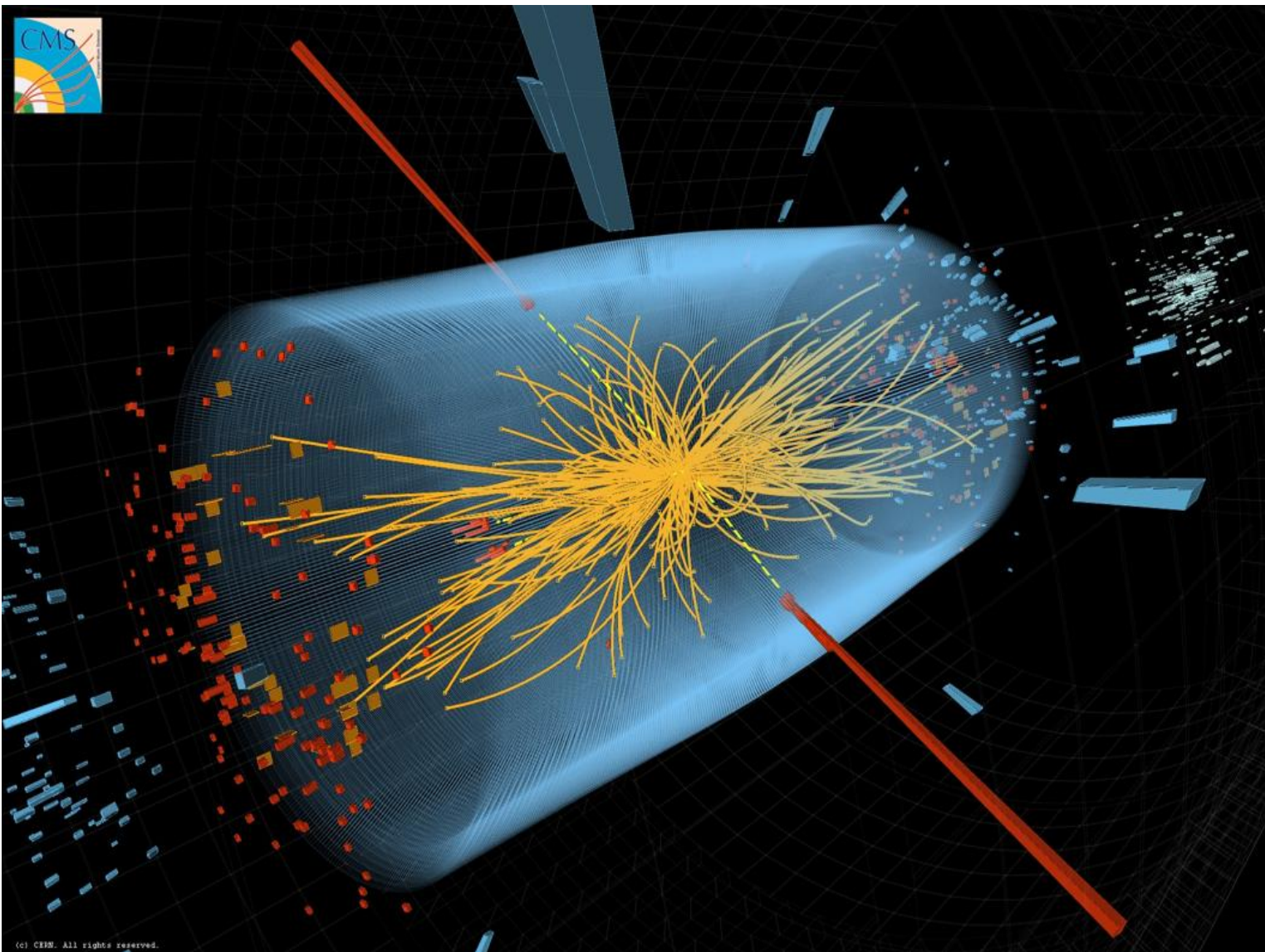




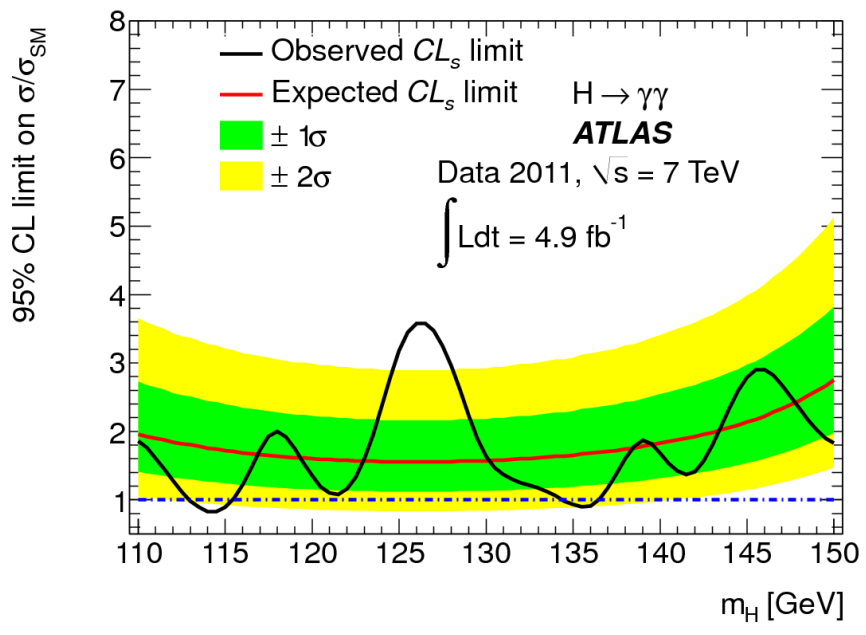
SM Higgs



A Collision with two Photons



A Higgs or
a 'background'
process without
a Higgs?

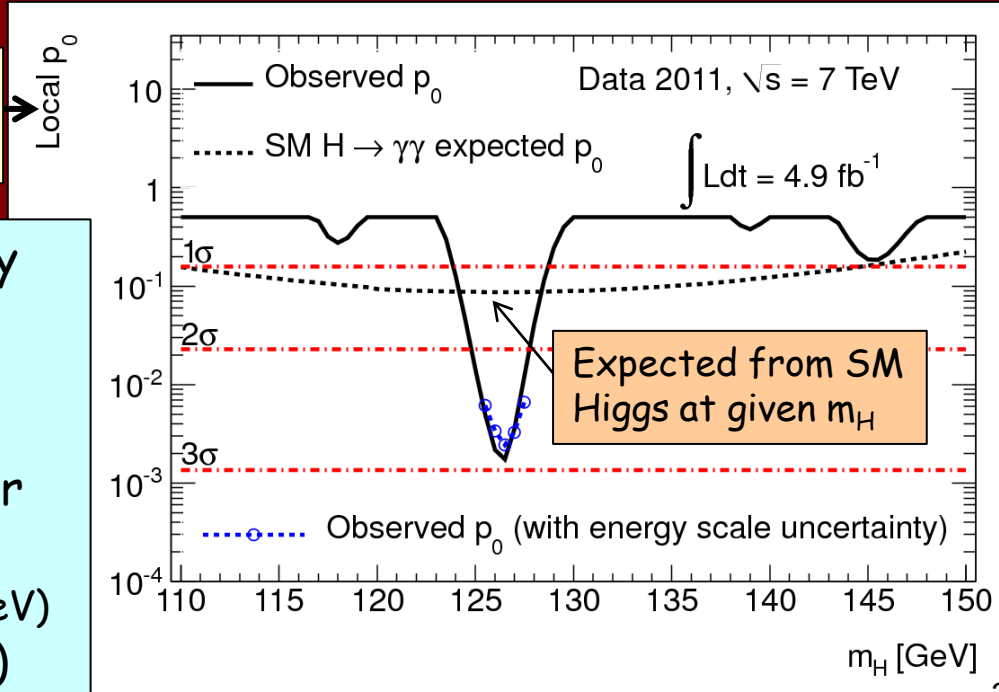


Excluded (95% CL):
 $113 \leq m_H \leq 115 \text{ GeV}, 134.5 \leq m_H \leq 136 \text{ GeV}$

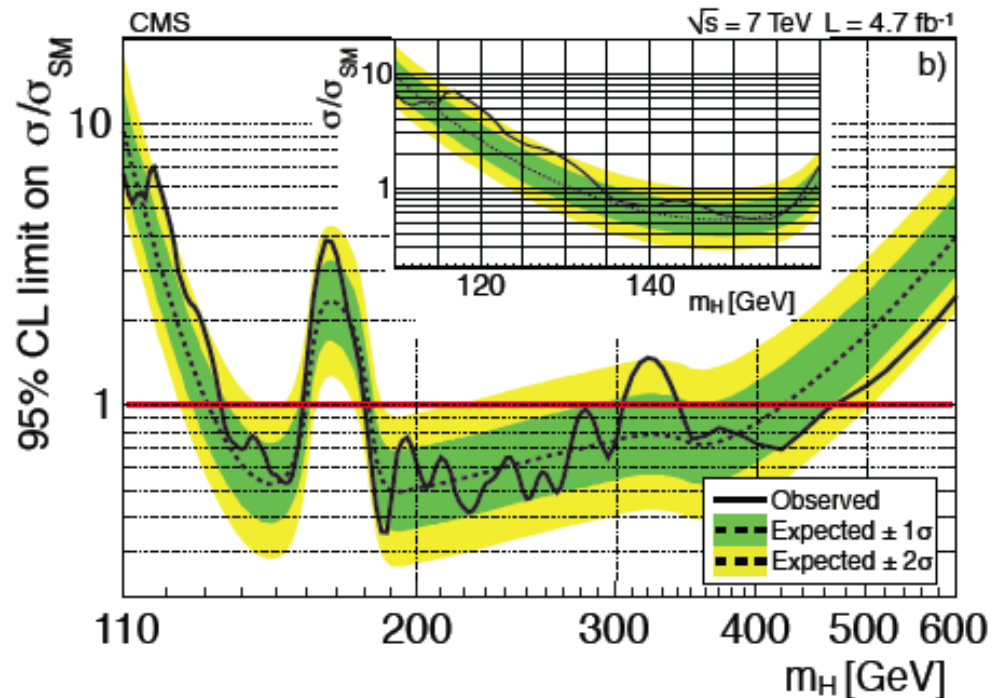
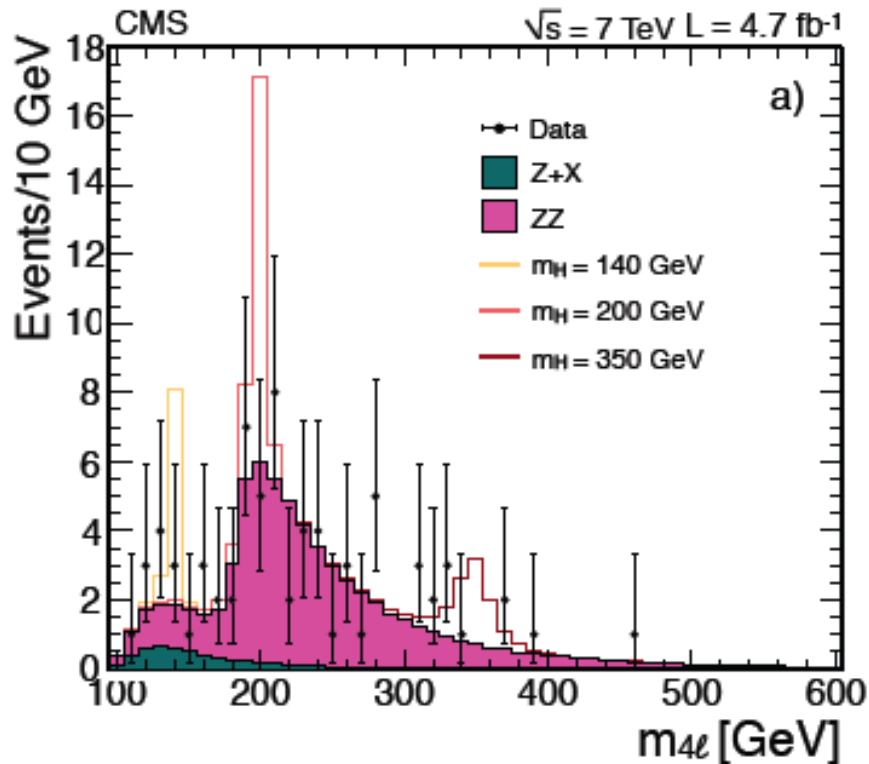
Consistency of the data with the background-only expectation

Maximum deviation from background-only expectation observed for $m_H \sim 126 \text{ GeV}$:

- local p_0 -value: 0.27% or 2.8σ
- expected from SM Higgs: $\sim 1.4\sigma$ local
- global p_0 -value: includes probability for such an excess to appear anywhere in the investigated mass range (110-150 GeV) ("Look-Elsewhere-Effect"): $\sim 7\%$ (1.5σ)



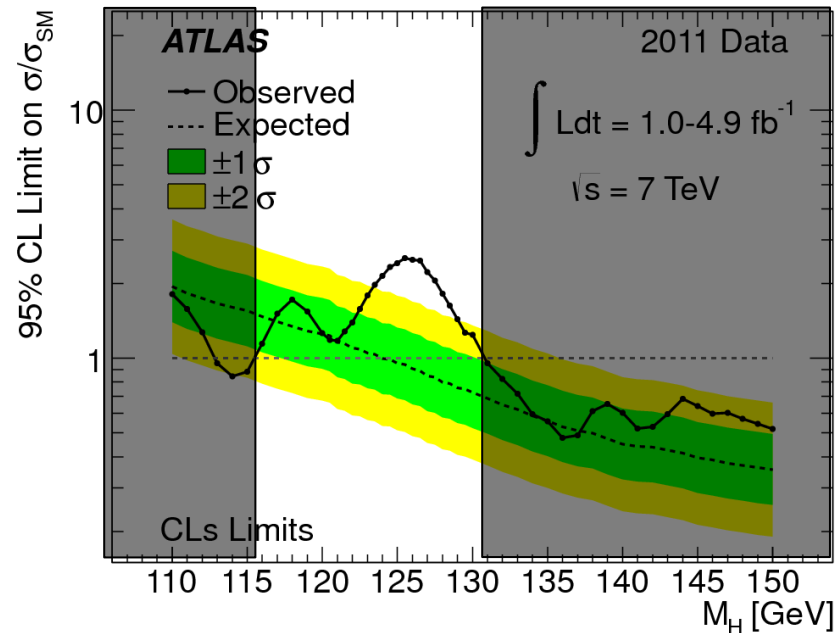
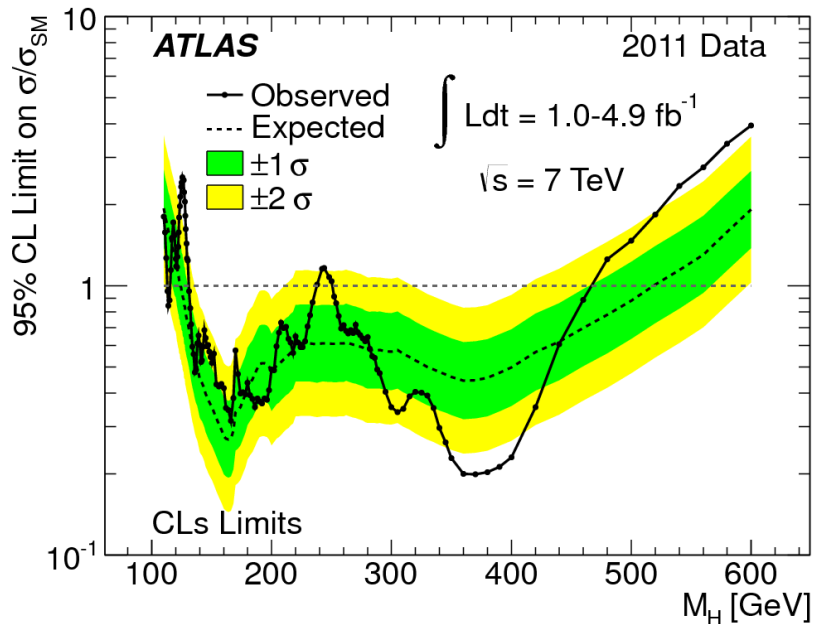
$H \rightarrow ZZ \rightarrow 4 \text{ leptons channel}$



Baseline	$4e$	4μ	$2e2\mu$
ZZ	12.27 ± 1.16	19.11 ± 1.75	30.25 ± 2.78
Z+X	1.67 ± 0.55	1.13 ± 0.55	2.71 ± 0.96
All background	13.94 ± 1.28	20.24 ± 1.83	32.96 ± 2.94
$m_H = 120 \text{ GeV}/c^2$	0.25	0.62	0.68
$m_H = 140 \text{ GeV}/c^2$	1.32	2.48	3.37
$m_H = 350 \text{ GeV}/c^2$	1.95	2.61	4.64
Observed	12	23	37

Combined constraints

$H \rightarrow \gamma\gamma, H \rightarrow WW^{(*)} \rightarrow l\nu l\nu,$
 $H \rightarrow ZZ^{(*)} \rightarrow 4l, H \rightarrow ZZ \rightarrow ll\nu\nu$
 $H \rightarrow ZZ \rightarrow llqq, H \rightarrow WW \rightarrow l\nu qq$



Excluded at 95% CL

$112.9 < m_H < 115.5 \text{ GeV}$
 $131 < m_H < 466 \text{ GeV}$, except 238-251 GeV

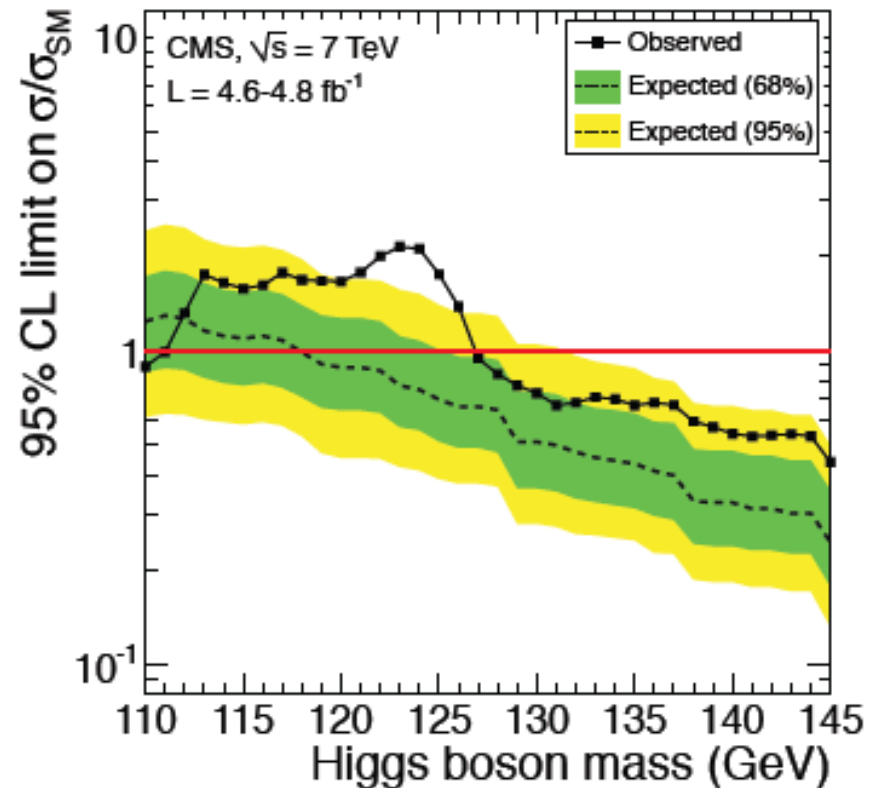
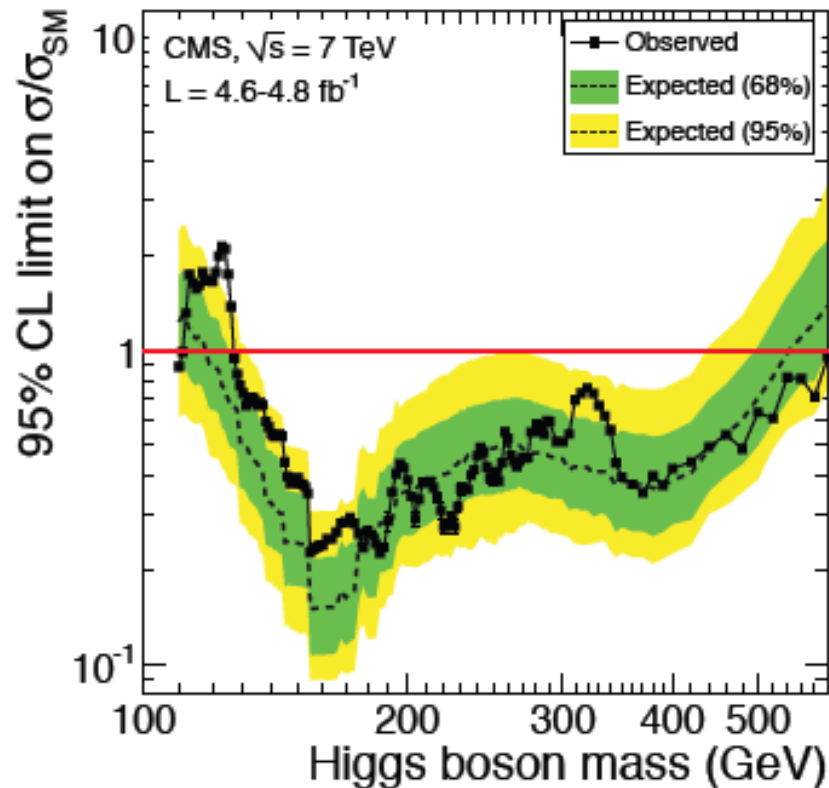
Expected if no signal

124-519 GeV

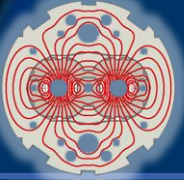
Excluded at 99% CL

$133 < m_H < 230 \text{ GeV}, 260 < m_H < 437 \text{ GeV}$

Combination: Exclusion Limits on $\mu = \sigma/\sigma_{SM}$



95% CL expected limits: 118—543 GeV
95% CL observed limits: 127—600 GeV



Higgs-Boson at 7 TeV



Status ~ today

SM Higgs boson excluded with 95% cl
up to a mass of 600 GeV
except for the window 115 to 127 GeV

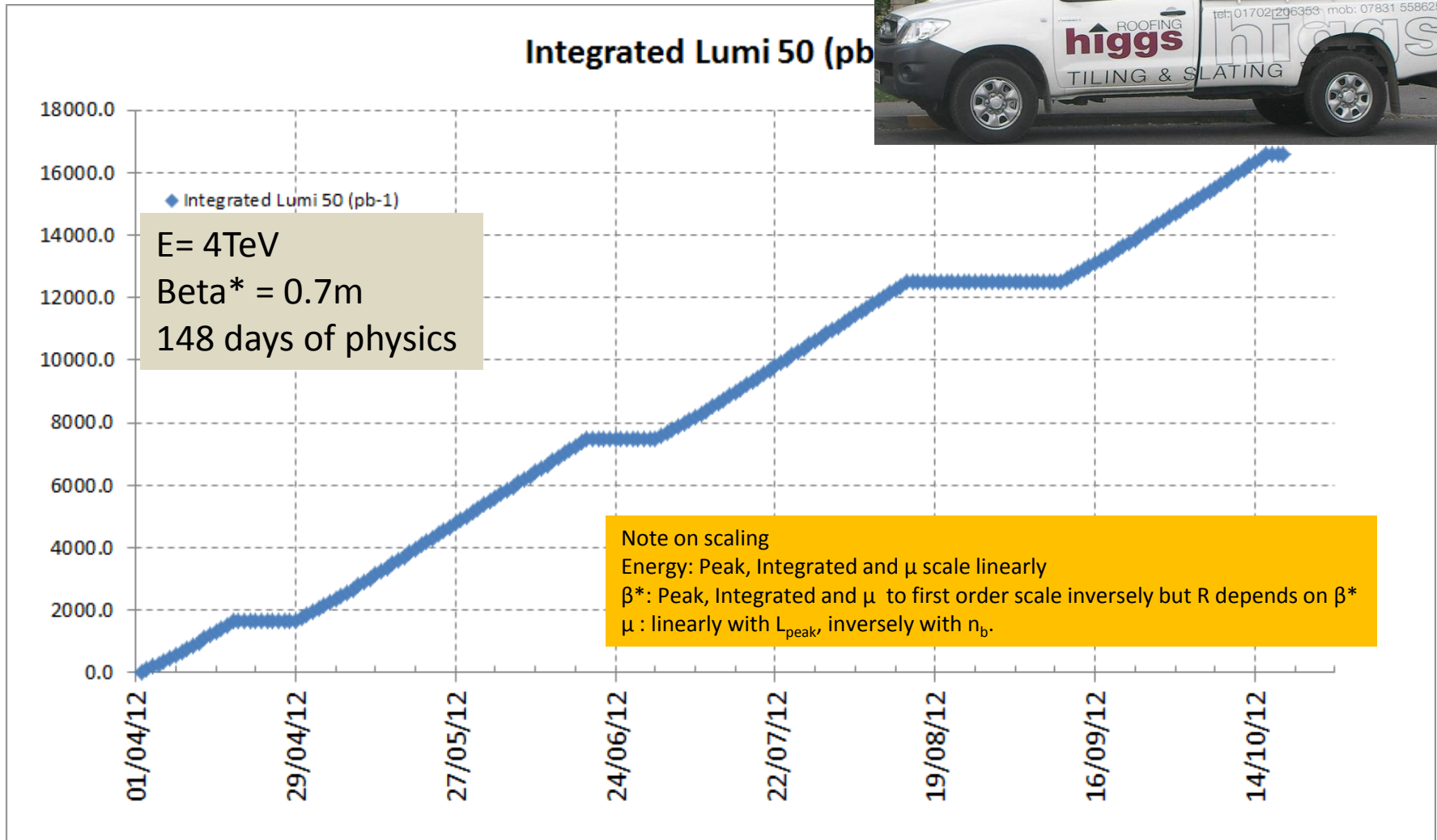
“interesting fluctuations” around masses
of 124 to 126 GeV

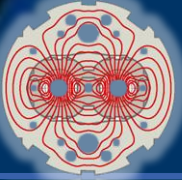
Running in 2012

Energy: 8 TeV

Expected Luminosity: ?

2012 Integrated with 50ns





Higgs-Boson at 7 TeV



Status ~ today

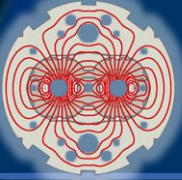
SM Higgs
up to
except
“interest
of 124 to 126 GeV

Excellent performance of
Collider, Experiments, Computing

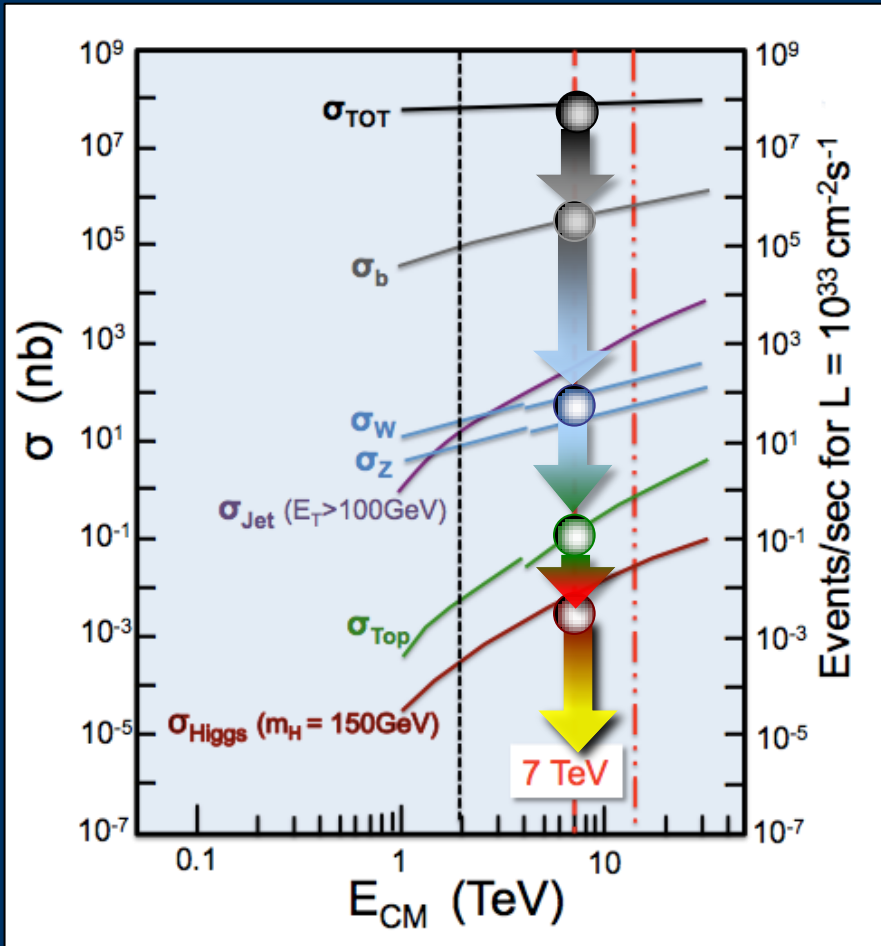


SM-Higgs Boson up to a mass of some
600 GeV will either be discovered or ruled
out until end 2012

% cl
GeV
masses



The 2011 and 2012 run ...



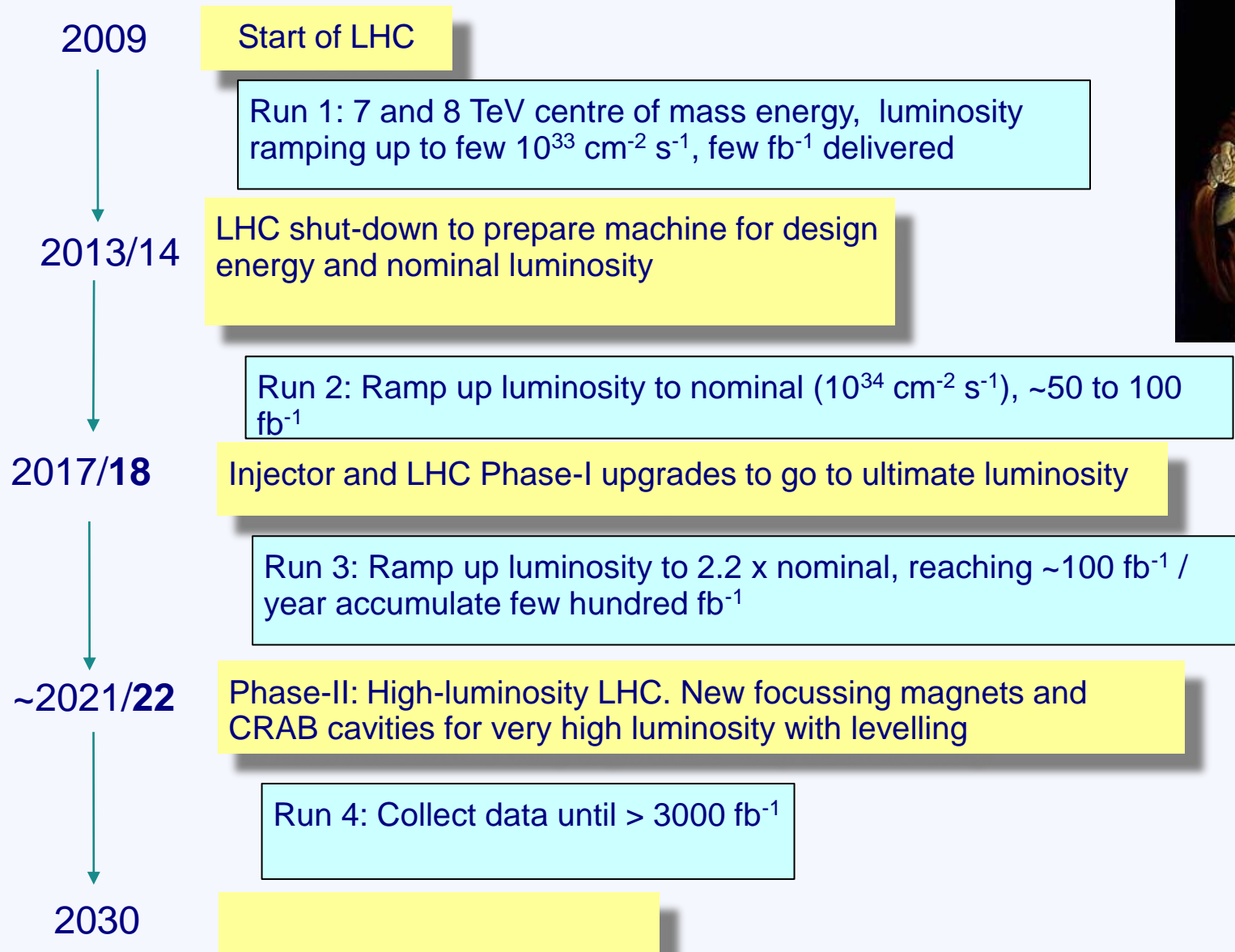
Search for physics beyond SM

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

→ will enter new territory !

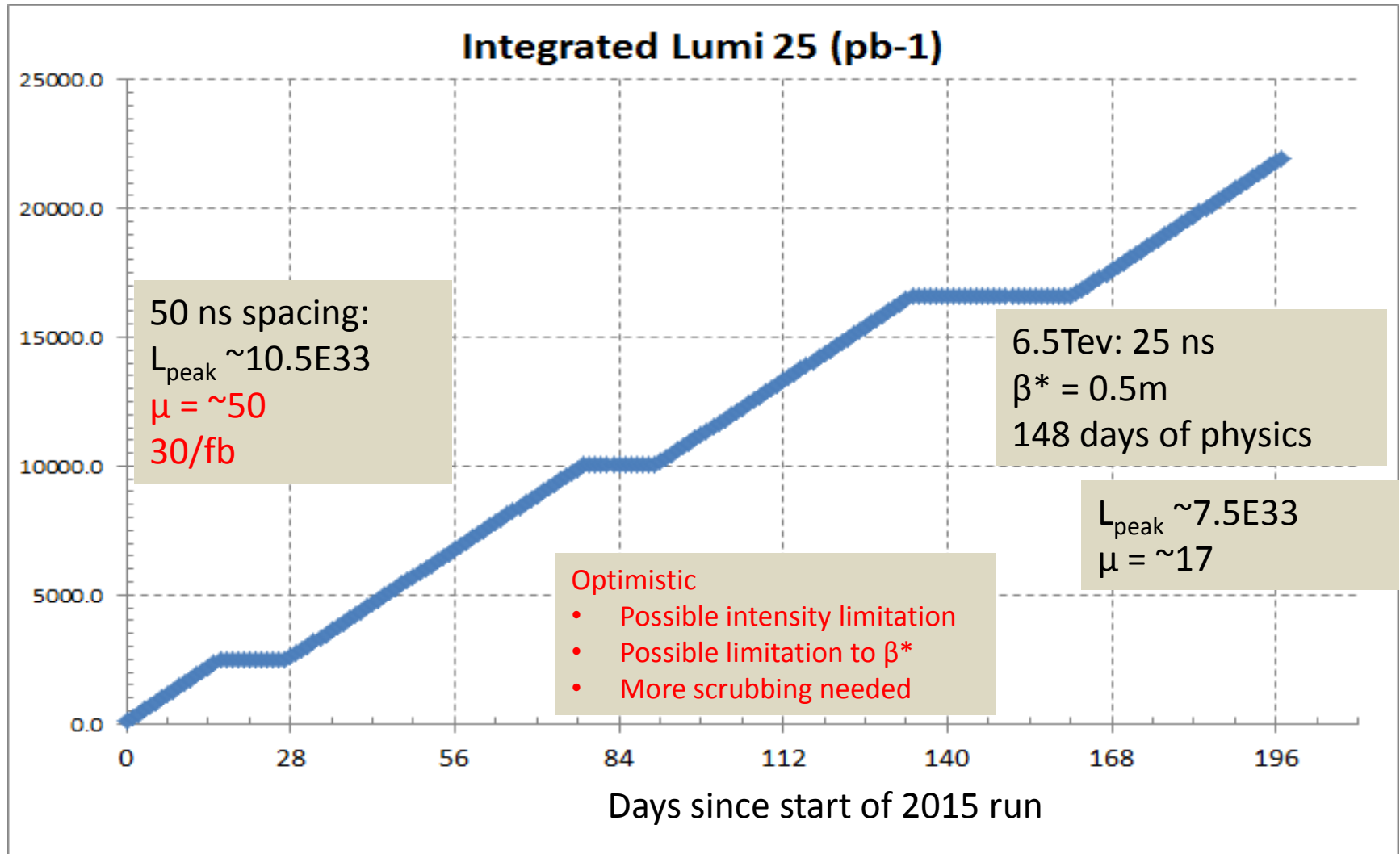


The predictable future: LHC Time-line



Estimating 2015 Luminosities

6.5TeV per beam with 25ns



Key message

There is a program at the energy frontier with the LHC for at least 20 years:

7 and 8 TeV

14 TeV design luminosity

14 TeV high luminosity (HL-LHC)

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, suggesting a focus on land use or environmental impact in the context of high-energy physics research like the LHC.

beyond LHC ?

Next decades

Road beyond Standard Model

through synergy of

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

LHC results will guide the way at the energy frontier

lepton - hadron colliders (LHeC ??)

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



CERN today....into the future

- CLIC conceptual design report by 2012
- Participation in all LC activities
- LHeC conceptual design report early 2012
- R&D high-field magnets (towards HE-LHC)
- Generic R&D (high-power SPL, Plasma Acc)
- Participation in Neutrino-Projects studied

Position CERN as Laboratory at the energy frontier



from Choices ? to Choice !

- Update of the European Strategy for Particle Physics in 2012/13
 - Several Meetings with international participation
 - bottom-up process: community input requested
 - 1st open meeting September 2012
 - Finalization: May/June 2013
- Started with the ICFA Seminar 3-6 October 2011 at CERN
 - Use as 1st step to harmonize globally Particle Physics Strategy

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

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

exciting prospects