Accelerating Science and Innovation

Closing in on the Higgs-Boson ?

The Large Hadron Collider: Highlights and Prospects

R.-D. Heuer, CERN

Prague, 4 May 2012

Past few decades

"Discovery" of Standard Model

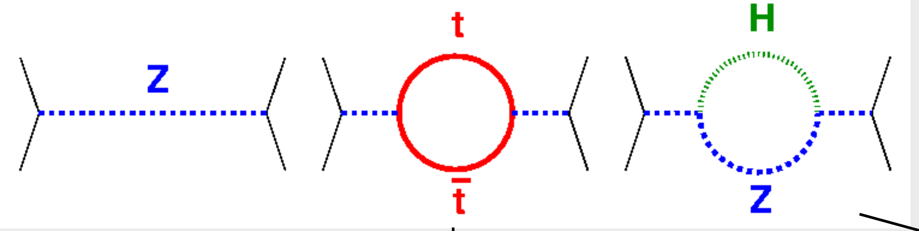
through synergy of

hadron - hadron colliders (e.g. Tevatron)

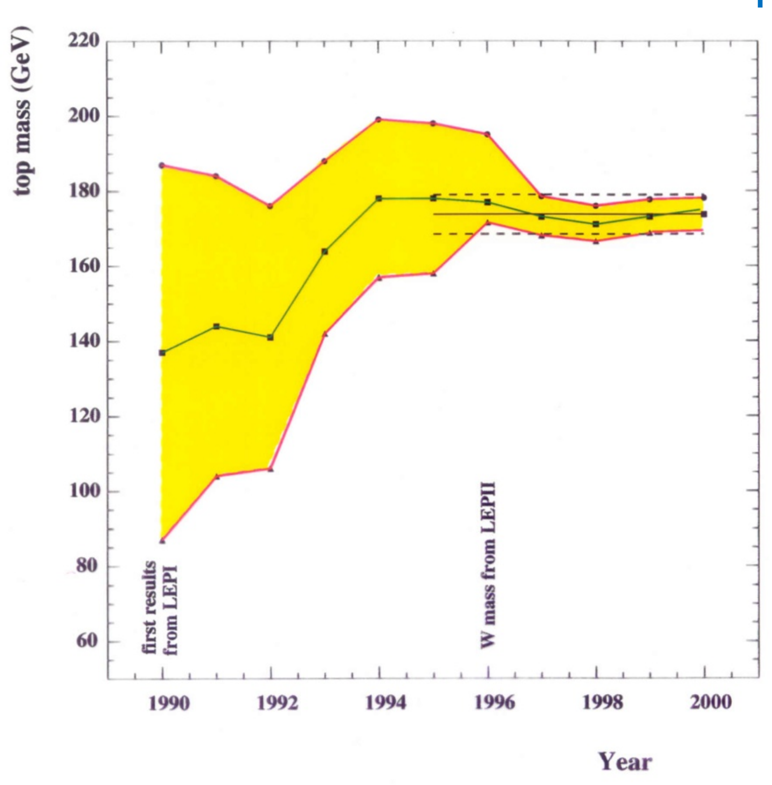
lepton - hadron colliders (HERA)

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

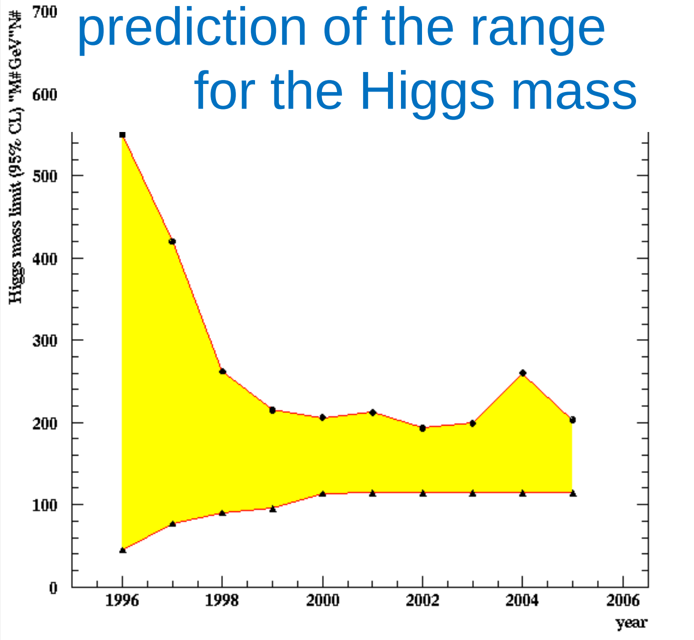
Test of the SM at the Level of Quantum Fluctuations



LEP: indirect determination of the top mass



prediction of the range for the Higgs mass

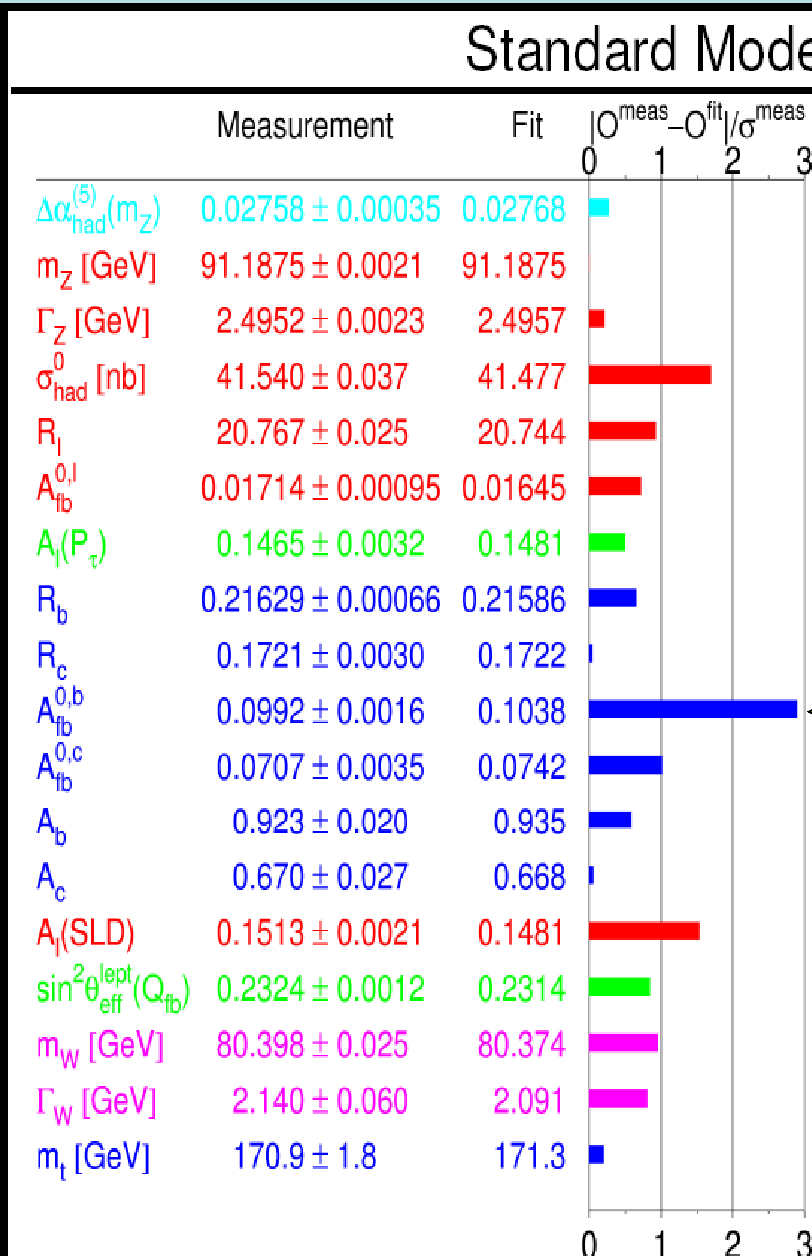


possible due to

- precision measurements
- known higher order electroweak corrections

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

Status recent Summer Conferences



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 MW

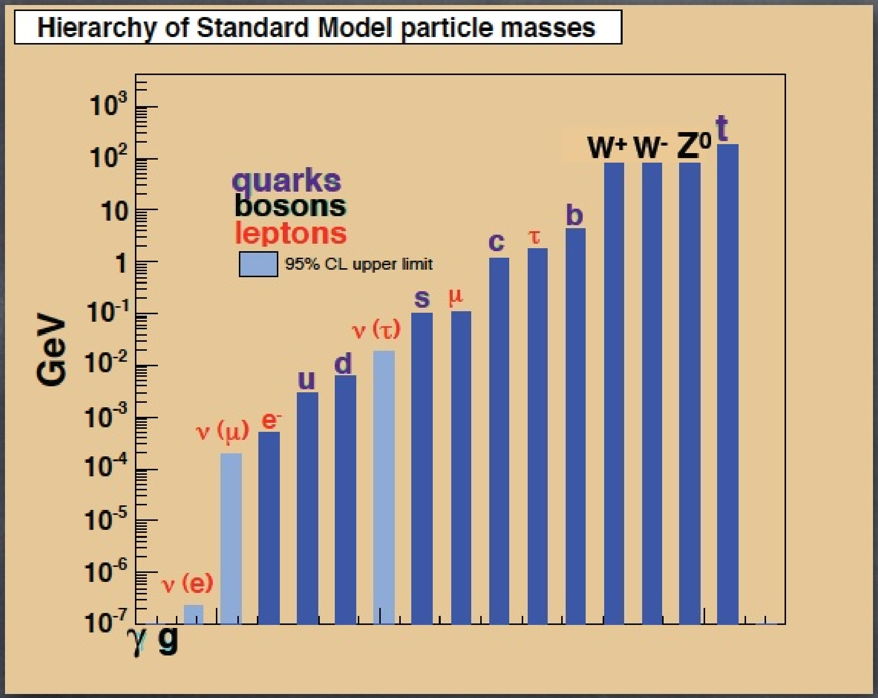
Without this point, the fit is *too* good!

Afb(b) has largest pull: 2.9σ!

however . . .

. . . corner stone missing within Standard Model

How to generate mass & break electroweak symmetry ?



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

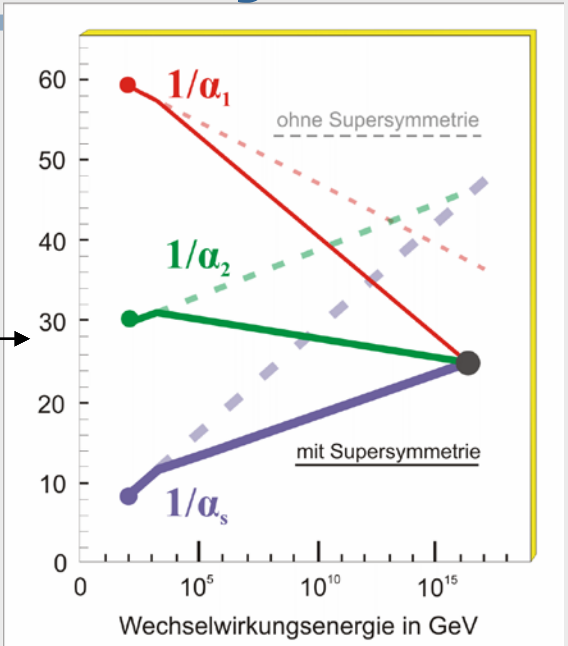
Reminder:

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



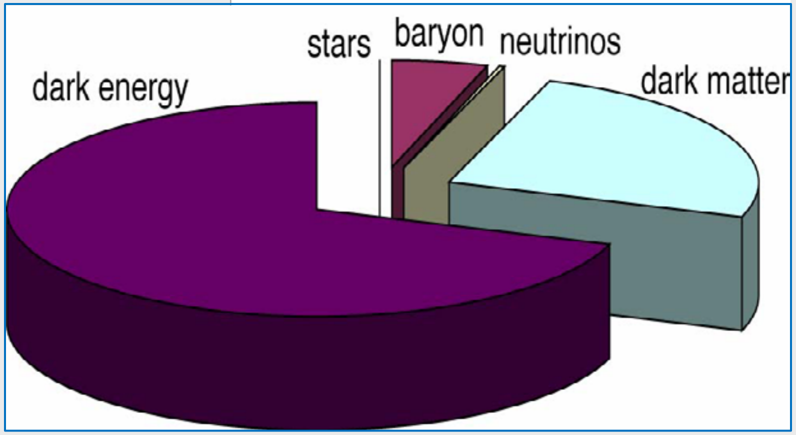
fundamental symmetry of forces and matter

unification of quantum physics and general relativity

number of space/time dimensions

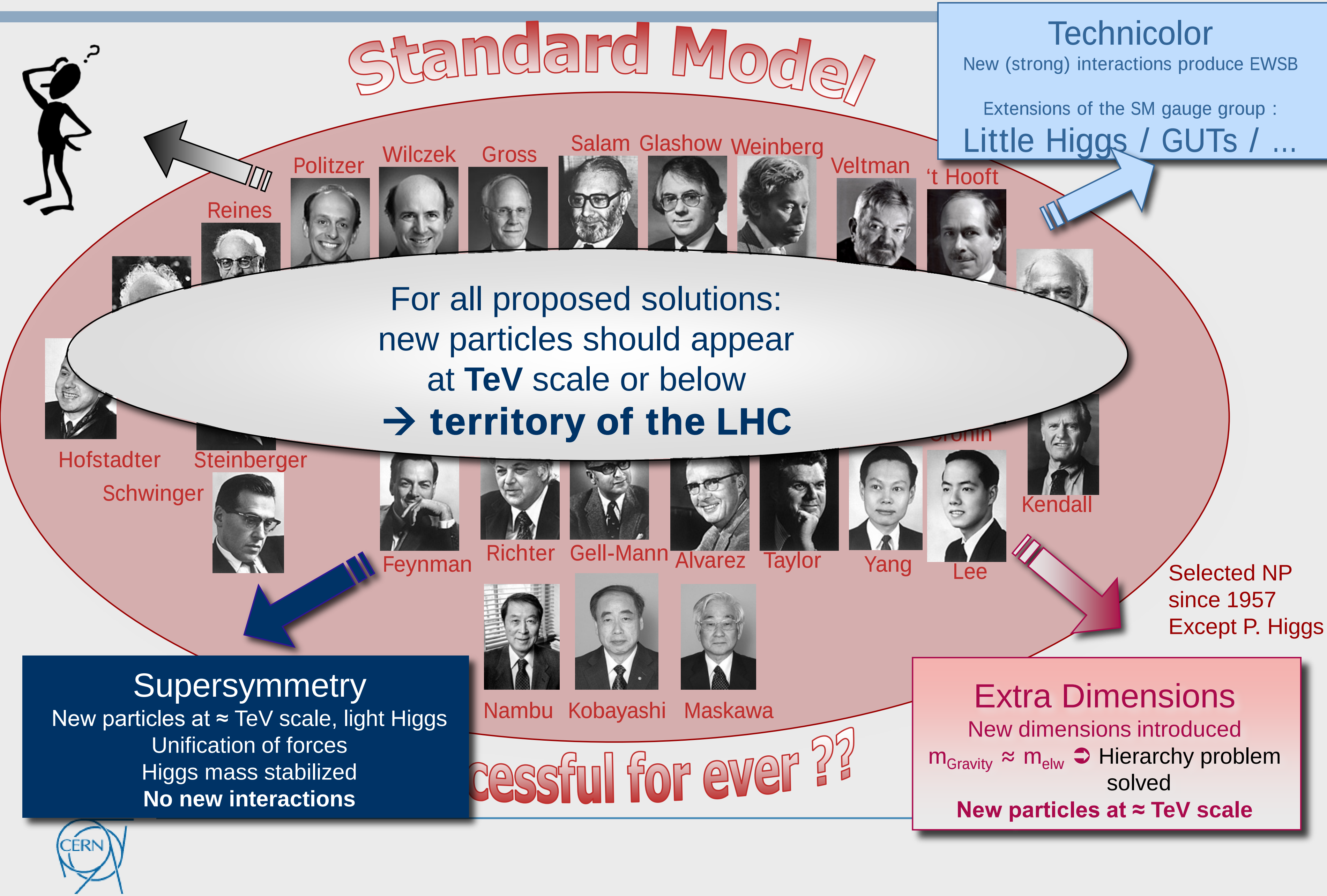
what is dark matter

what is dark energy



The LHC will address most of these questions . . . .

Solutions?



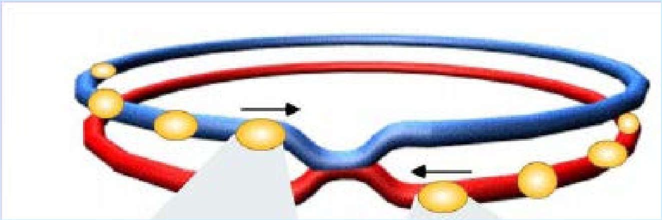
Standard Model
Technicolor
New (strong) interactions produce EWSB
Extensions of the SM gauge group :
Little Higgs / GUTs / ...
Politzer
Wilczek
Gross
Salam
Glashow
Weinberg
Veltman
't Hooft
Reines
For all proposed solutions:
new particles should appear
at **TeV** scale or below
→ **territory of the LHC**
Hofstadter
Steinberger
Schwinger
Kendall
Feynman
Richter
Gell-Mann
Alvarez
Taylor
Yang
Lee
Selected NP
since 1957
Except P. Higgs
Nambu
Kobayashi
Maskawa
Supersymmetry
New particles at ≈ TeV scale, light Higgs
Unification of forces
Higgs mass stabilized
No new interactions
cessful for ever ??
Extra Dimensions
New dimensions introduced
$m_{Gravity} \approx m_{elw}$ ➲ Hierarchy problem solved
New particles at ≈ TeV scale
CERN

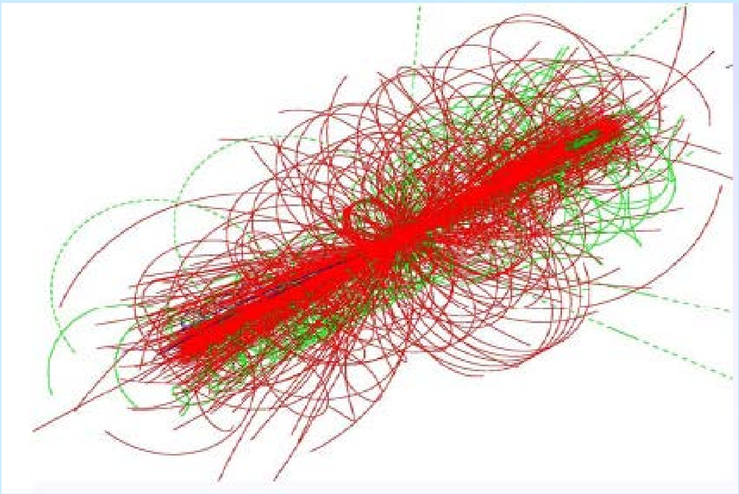
Enter a New Era in Fundamental Science

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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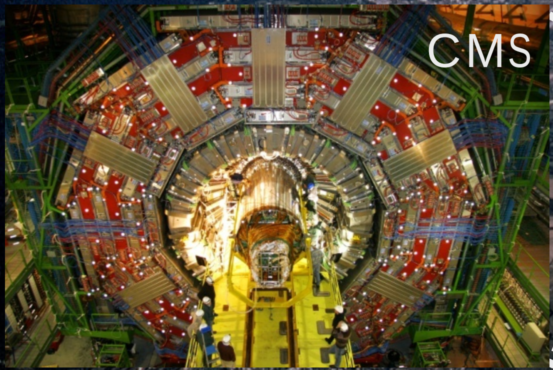

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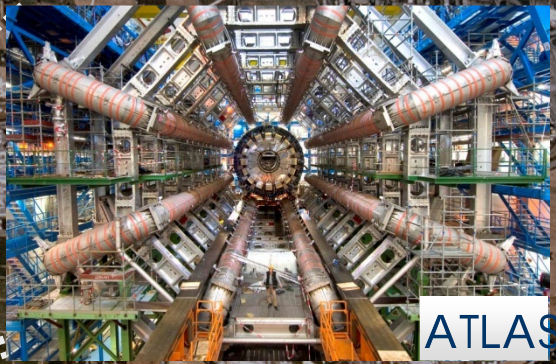
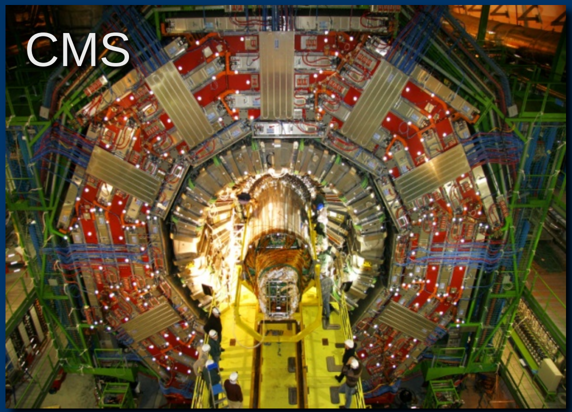
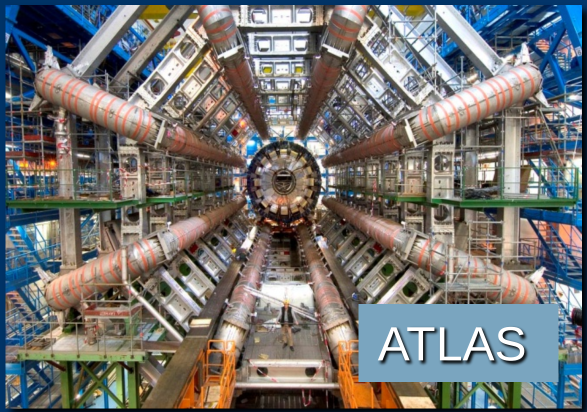


LHC Experiments → complementary

Specialised detector to study b-quarks → CPV



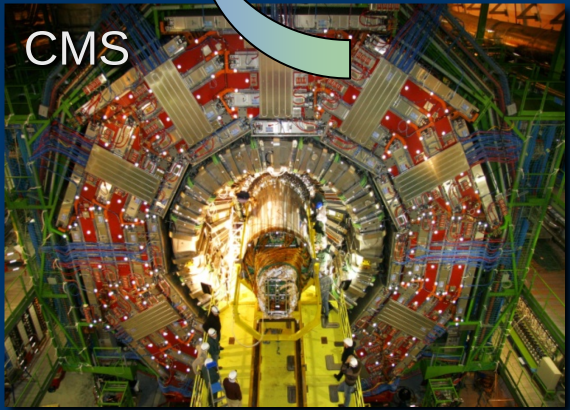


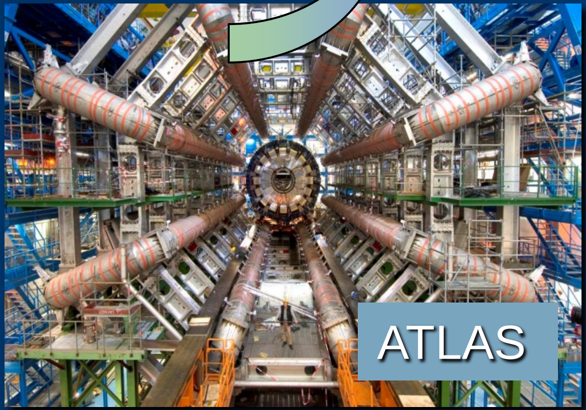
General purpose detectors

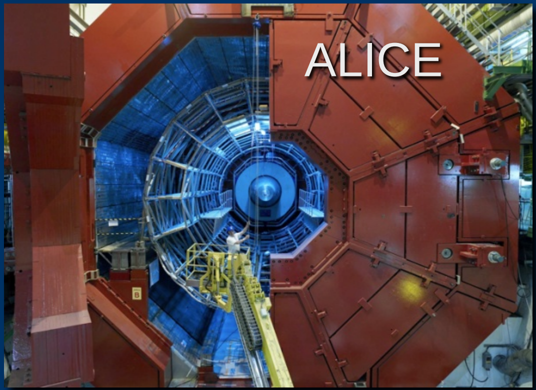
Specialised detector to study heavy ion collisions

LHC Experiments → complementary

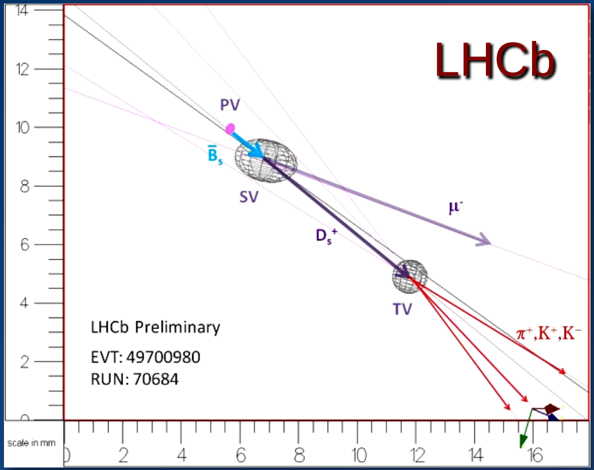
Overlap in physics reach

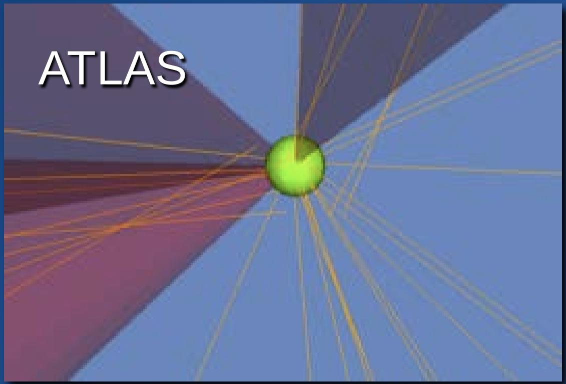






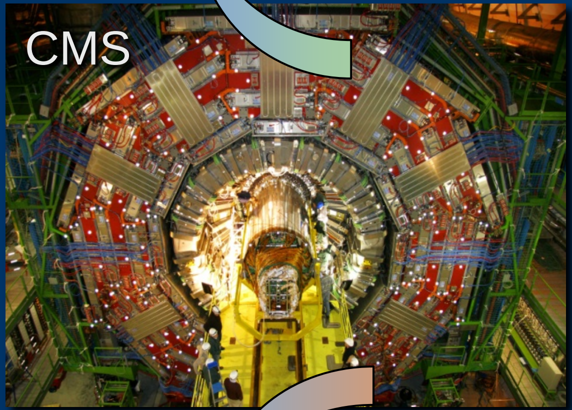
Key feature: reconstruct secondary vertex

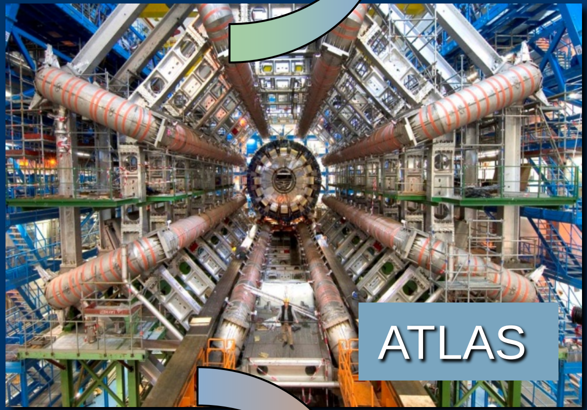




LHC Experiments → complementary

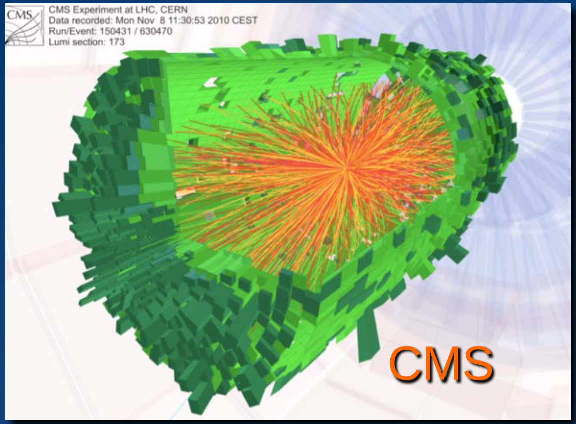
Overlap
in
physics
reach

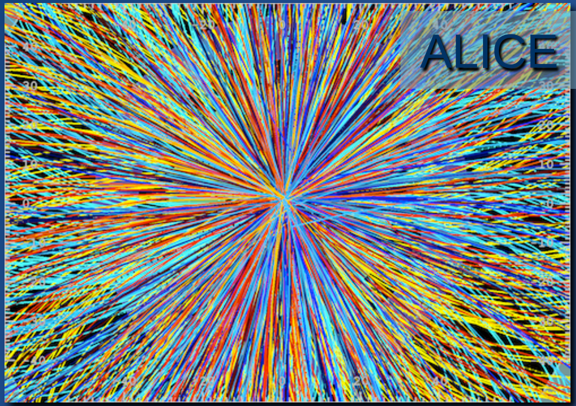




Overlap
in
physics
reach

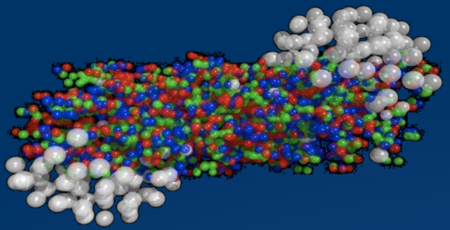
Key feature: reconstruct
> 20’000 charged tracks
in one event



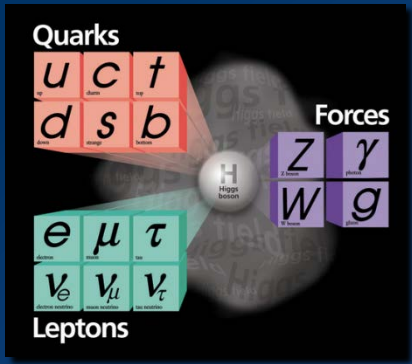


Versatility of LHC & complementarities of experiments make the whole of LHC a more powerful instrument than the sum of its parts

The study of LHC data will allow us to answer some of the big questions ...



Will we understand the primordial state of matter after the Big Bang before protons and neutrons formed?



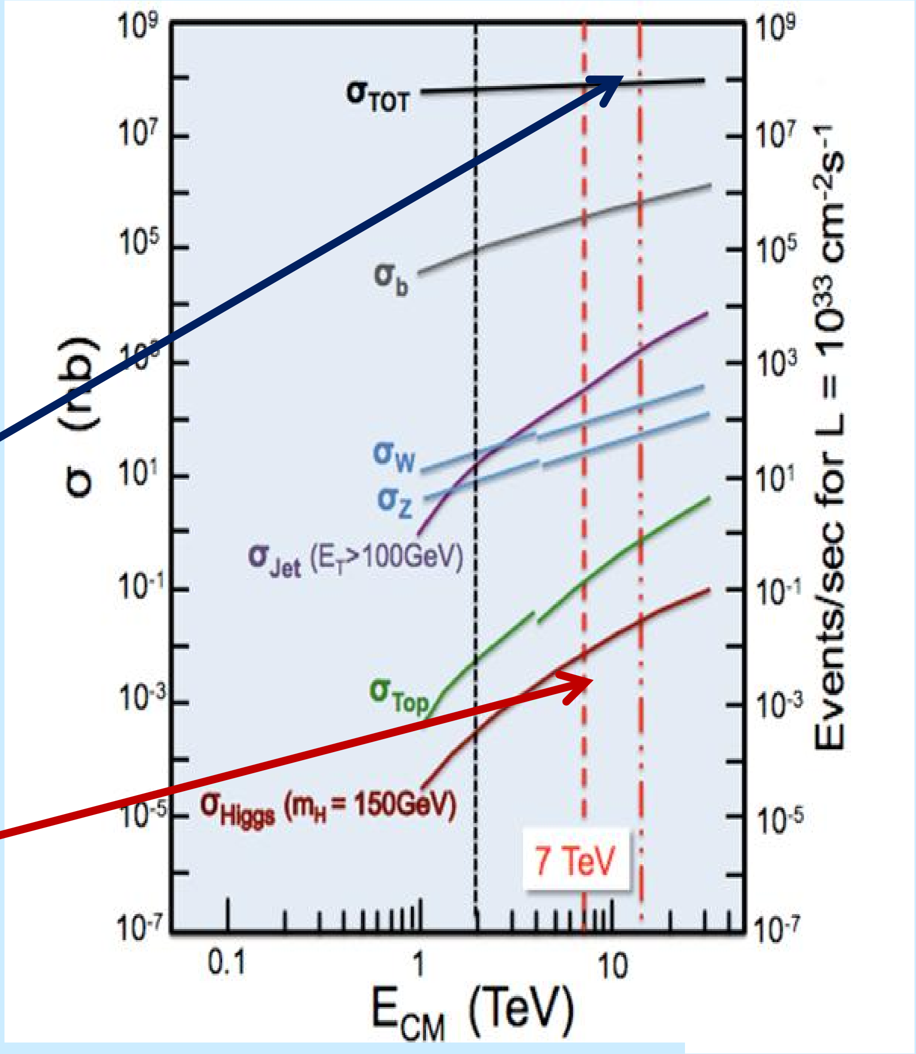
Will we find the Higgs particle that is responsible for giving mass to all particles?

Will we find the reason why antimatter and matter did not completely destroy each other?

Will we find the particle(s) that make up the mysterious ‘dark matter’ in our Universe?

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 . . .

CERN

Accelerating Science and Innovation

LHC 2011

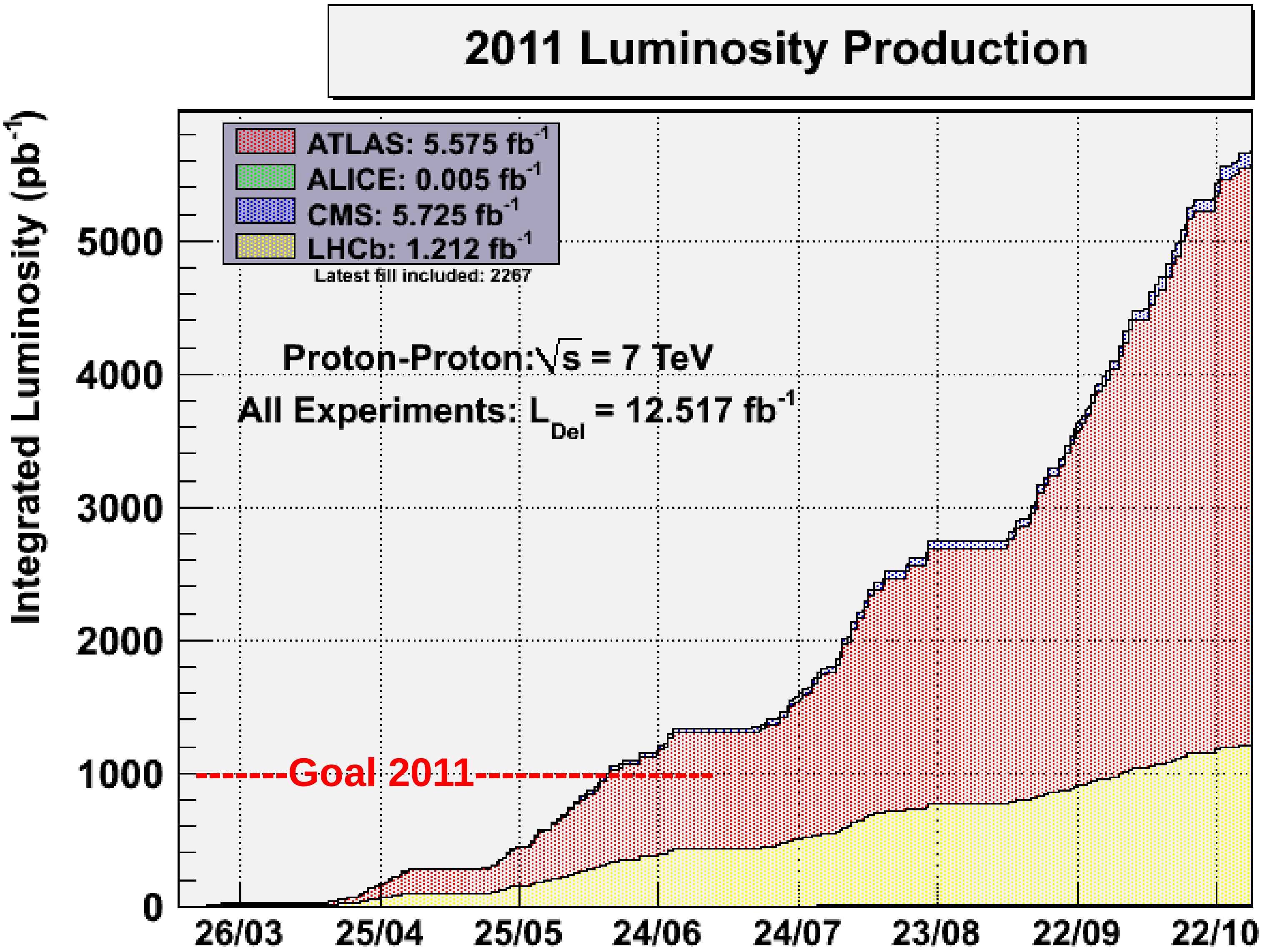
Excellent performance of the

whole accelerator complex

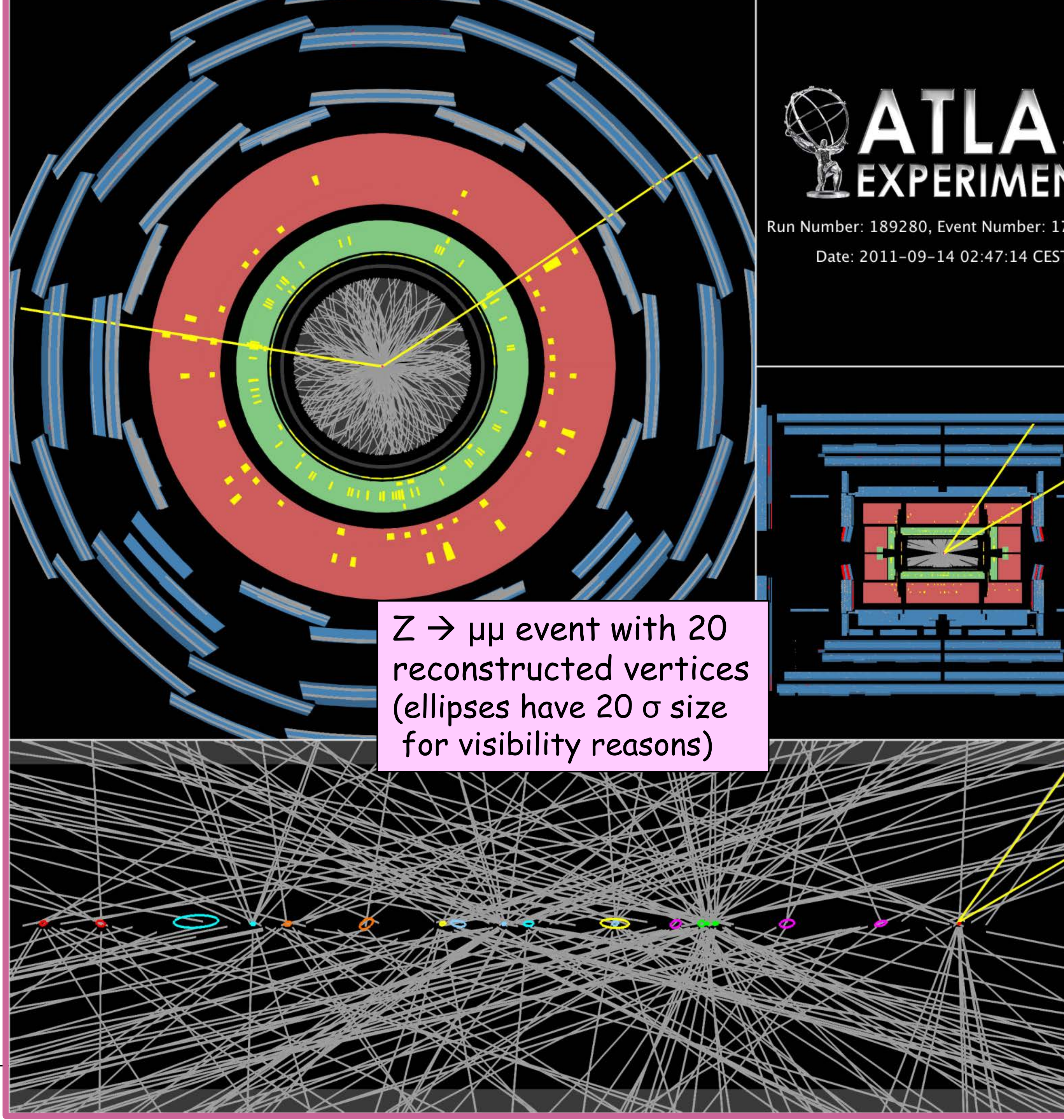
infrastructures

experiments

computing

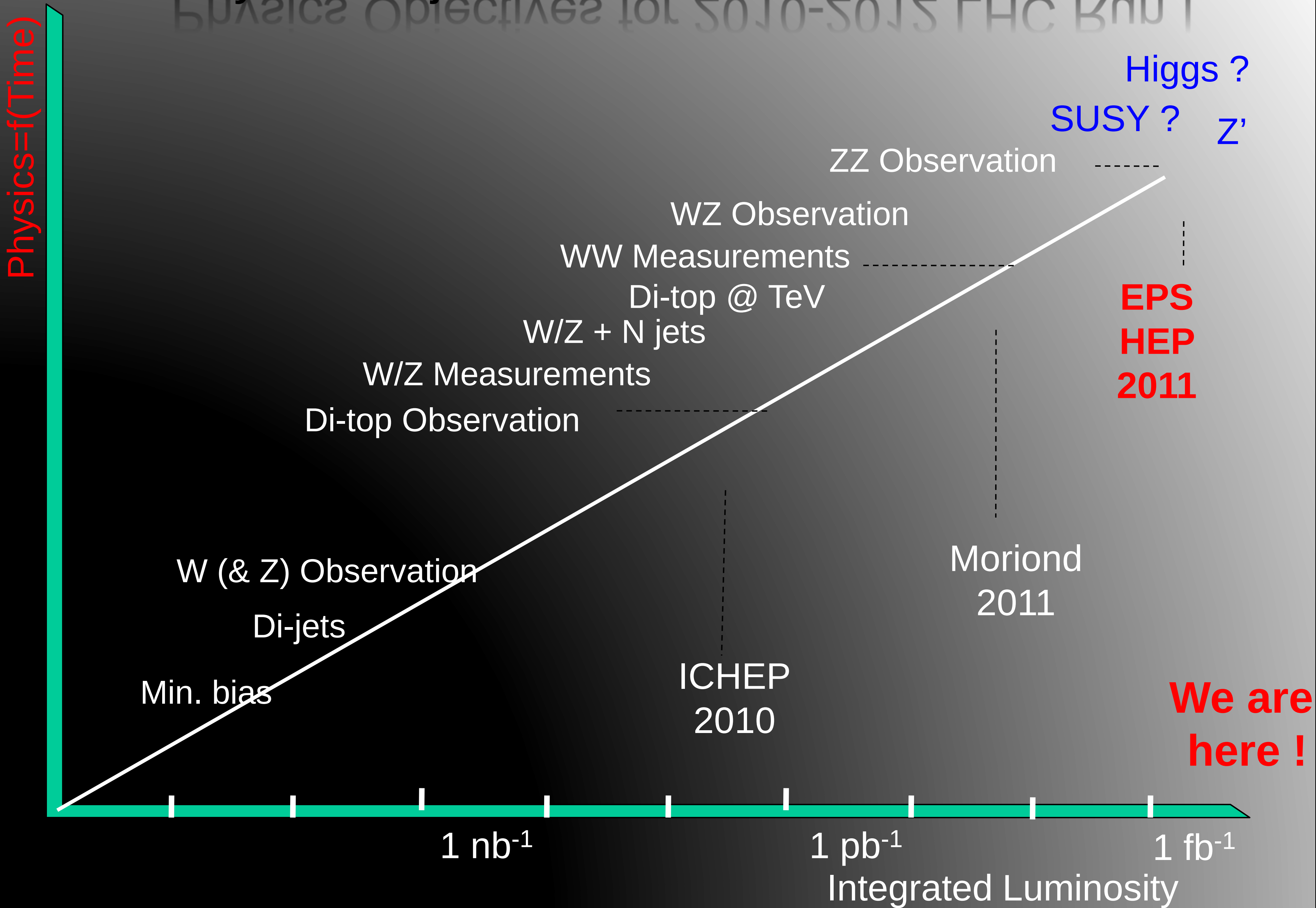

2011 Luminosity Production
Integrated Luminosity (pb^{-1})
ATLAS: 5.575 fb^{-1}
ALICE: 0.005 fb^{-1}
CMS: 5.725 fb^{-1}
LHCb: 1.212 fb^{-1}
Latest fill included: 2267
Proton-Proton: $\sqrt{s}$ = 7 TeV
All Experiments: L_{Del} = 12.517 fb^{-1}
Goal 2011
0
1000
2000
3000
4000
5000
26/03
25/04
25/05
24/06
24/07
23/08
22/09
22/10

Pile-up

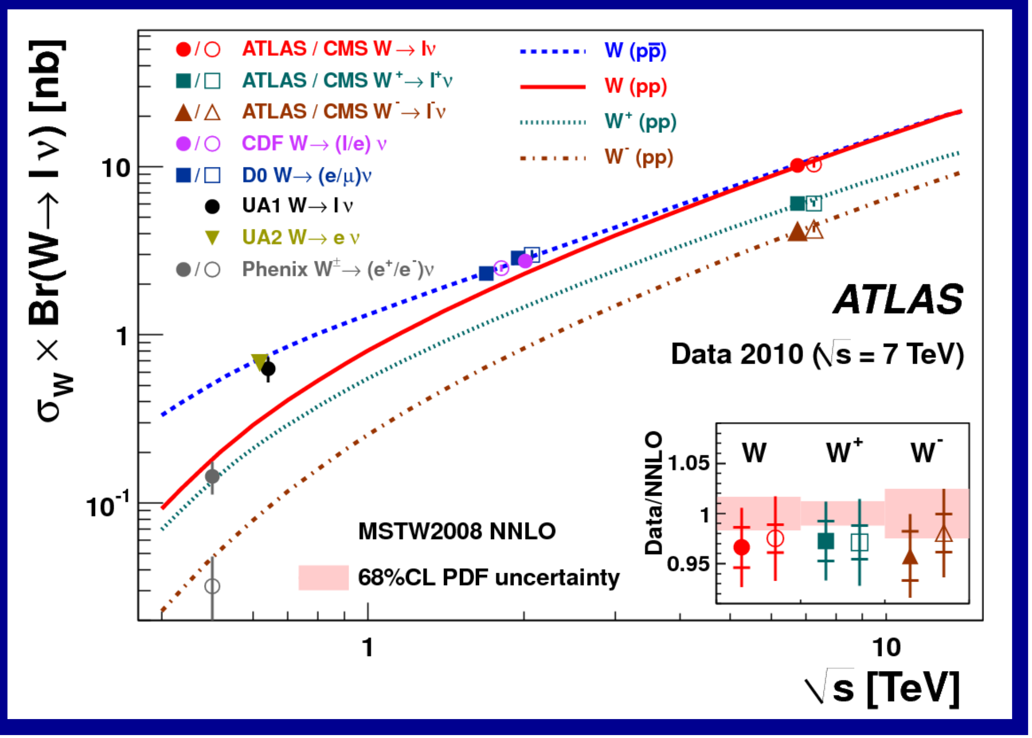


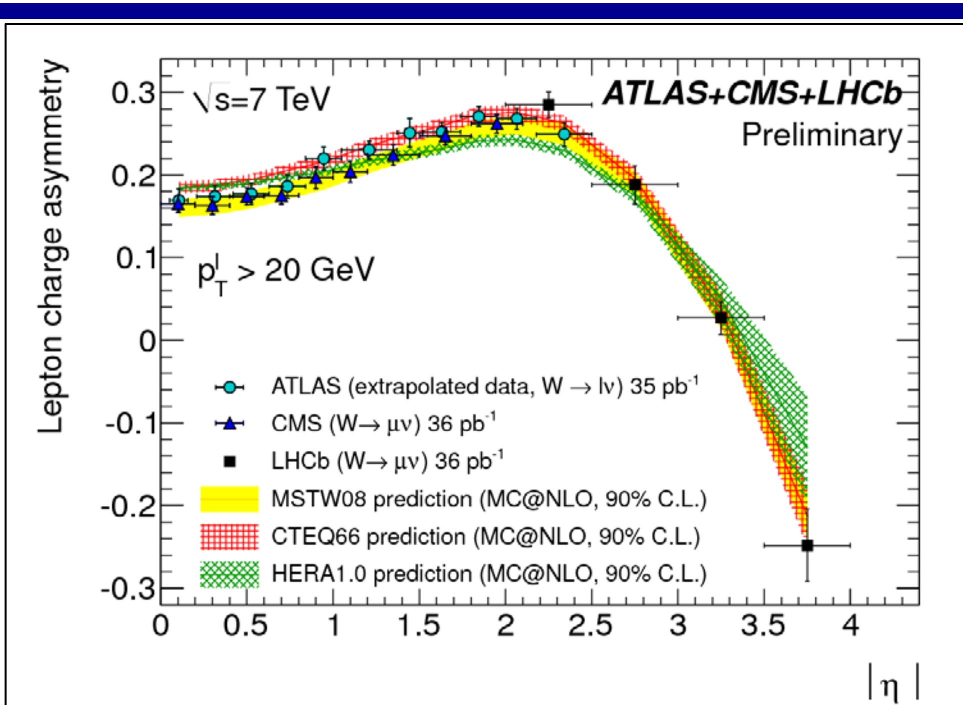
Z → μμ event with 20 reconstructed vertices (ellipses have 20 σ size for visibility reasons)

Physics Objectives for 2010-2012 LHC Run I

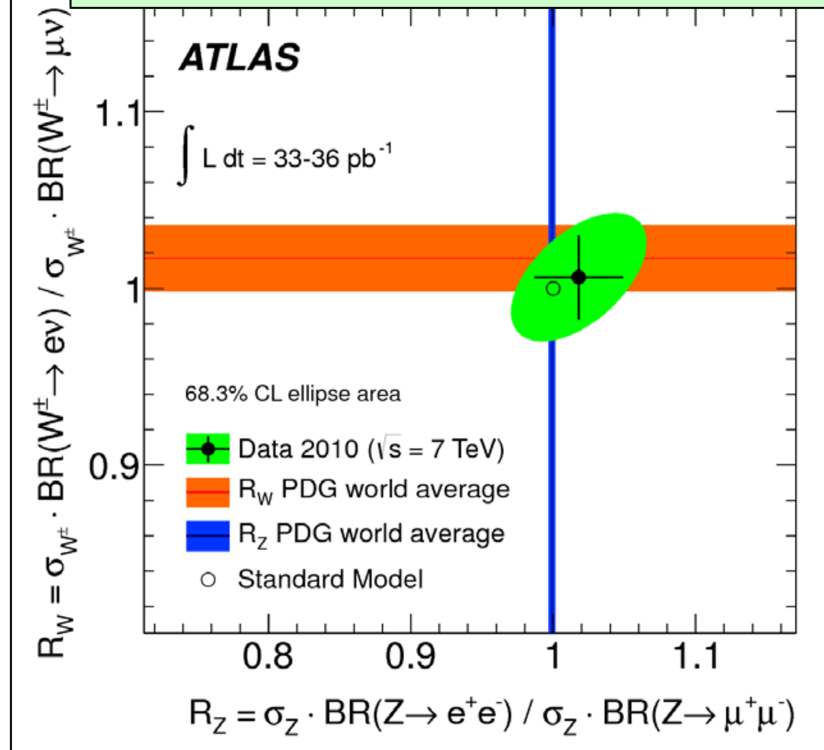


W and Z physics





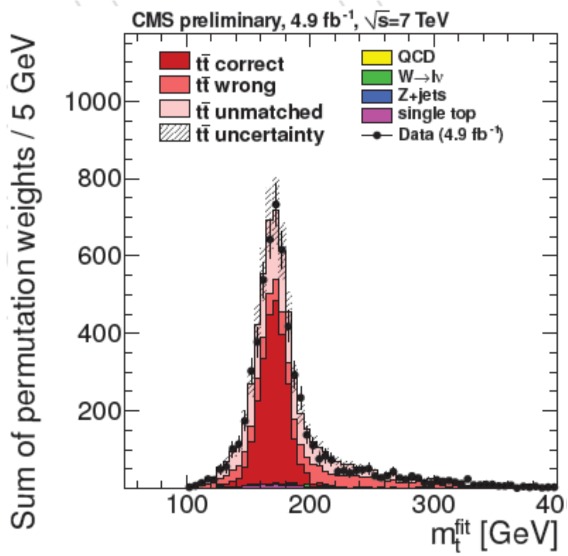
Probing lepton universality with accuracy comparable to PDG world average (from LEP and TeVatron) for W

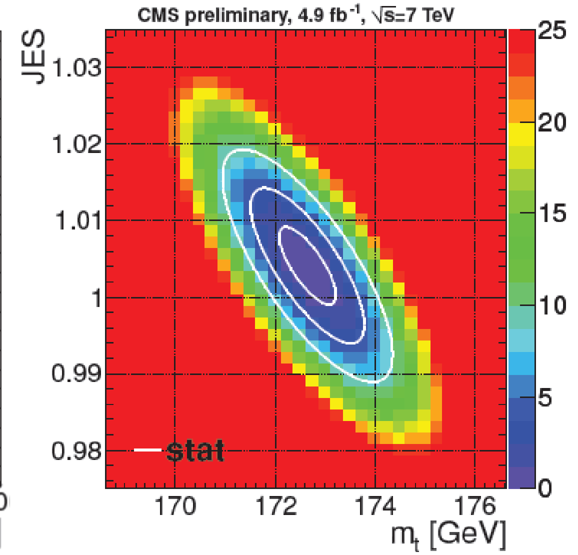


Top mass

TOP-11-015

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

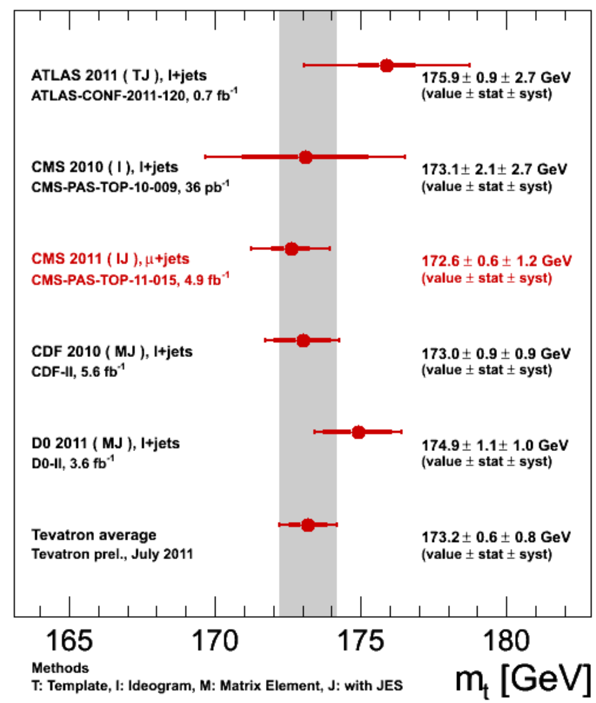




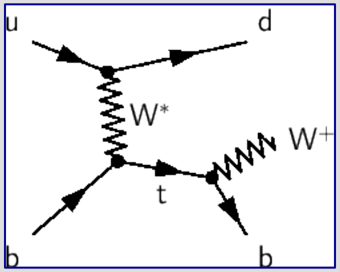
- Best LHC result on top mass

$$m_t = 172.64 \pm 0.57\ (\text{stat+JES}) \pm 1.18\ (\text{syst})\ \text{GeV}$$
$$\text{JES} = 1.004 \pm 0.005\ (\text{stat}) \pm 0.012\ (\text{syst})$$

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

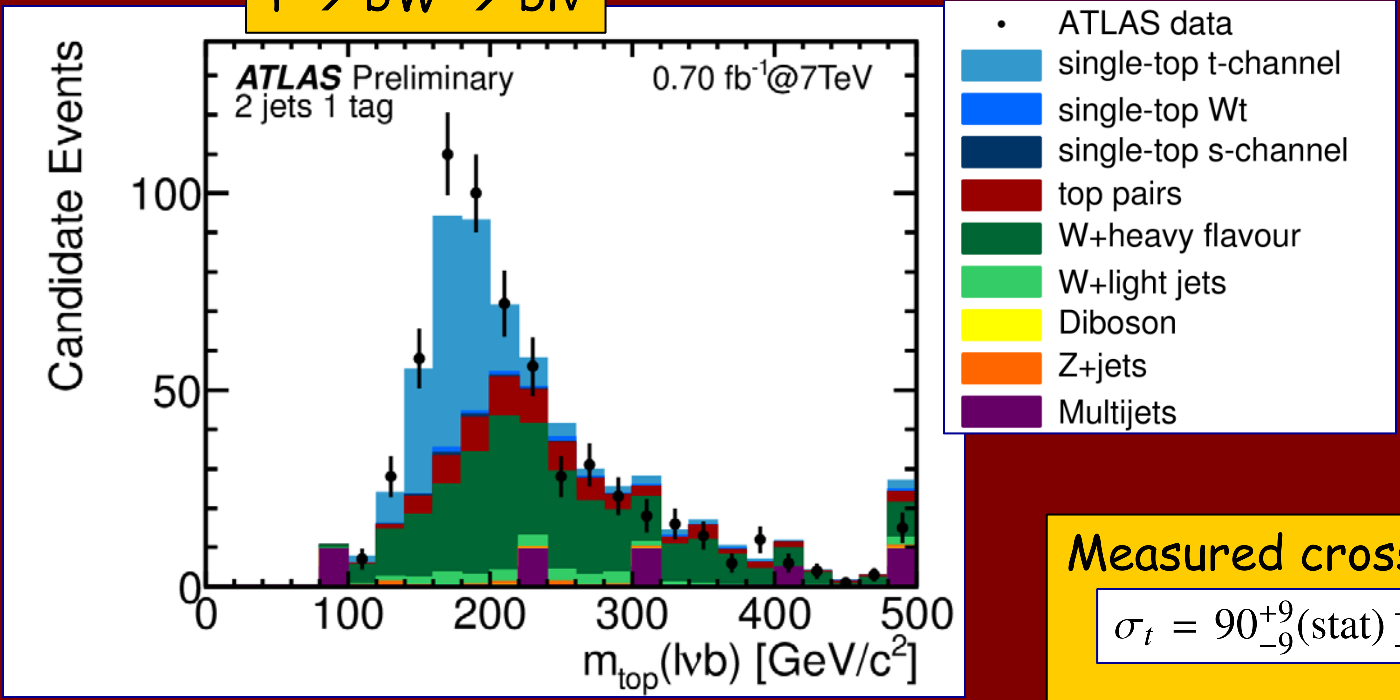


Single top production



t-channel single-top production

$t \rightarrow bW \rightarrow bl\nu$



Measured cross-section:

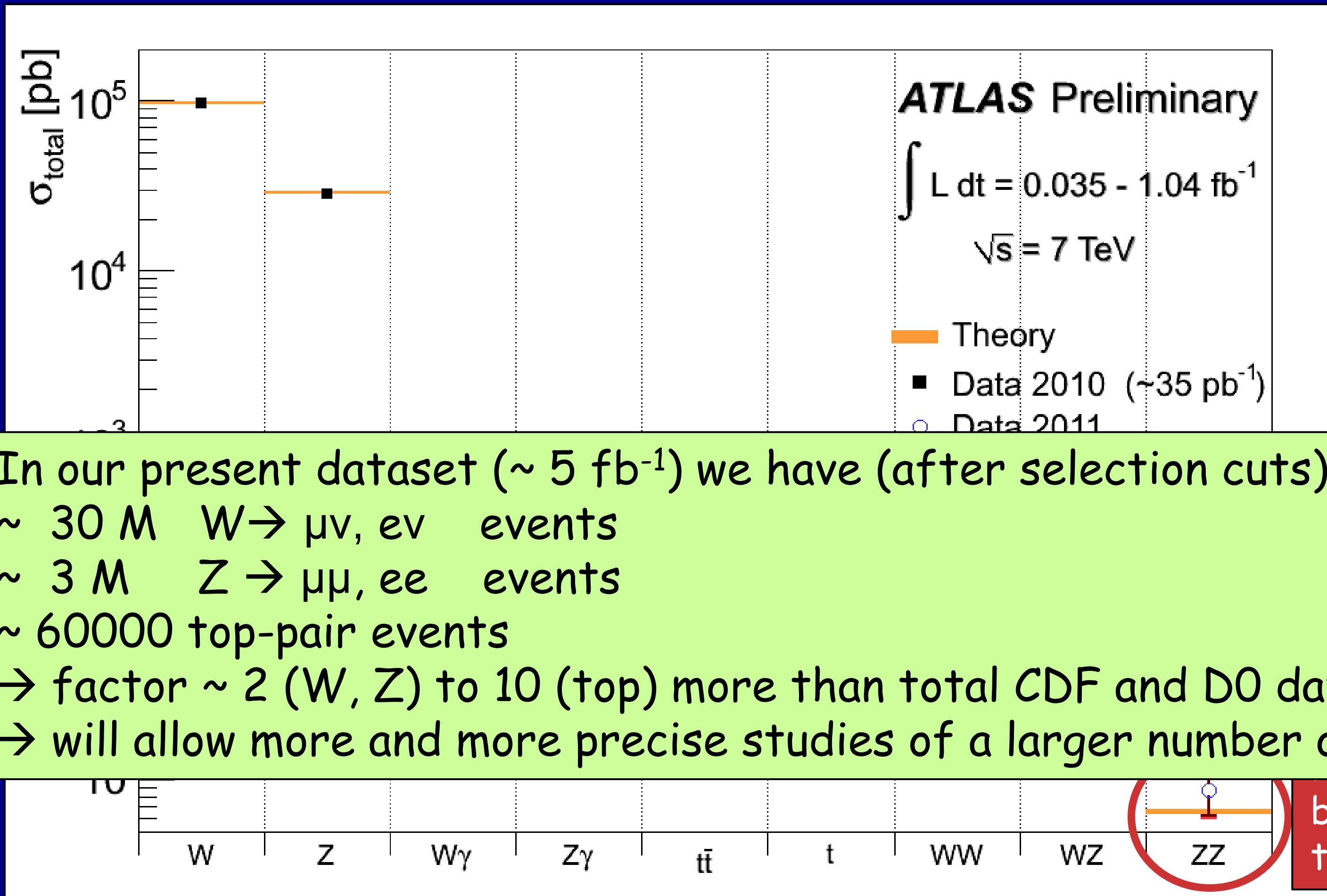
$$\sigma_t = 90^{+9}_{-9}(\text{stat})\,^{+31}_{-20}(\text{syst})$$

Expected from SM: ~ 65 ± 3 pb

Single-top signal significance: > 7σ

Summary of main electroweak and top cross-section measurements

Inner error: statistical
Outer error: total



In our present dataset (~ 5 fb^{-1}) we have (after selection cuts):

~ 30 M W → μν, eν events

~ 3 M Z → μμ, ee events

~ 60000 top-pair events

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

→ will allow more and more precise studies of a larger number of (exclusive) proces

bin → comparable to H→ZZ$^{(*)}$→ 4l

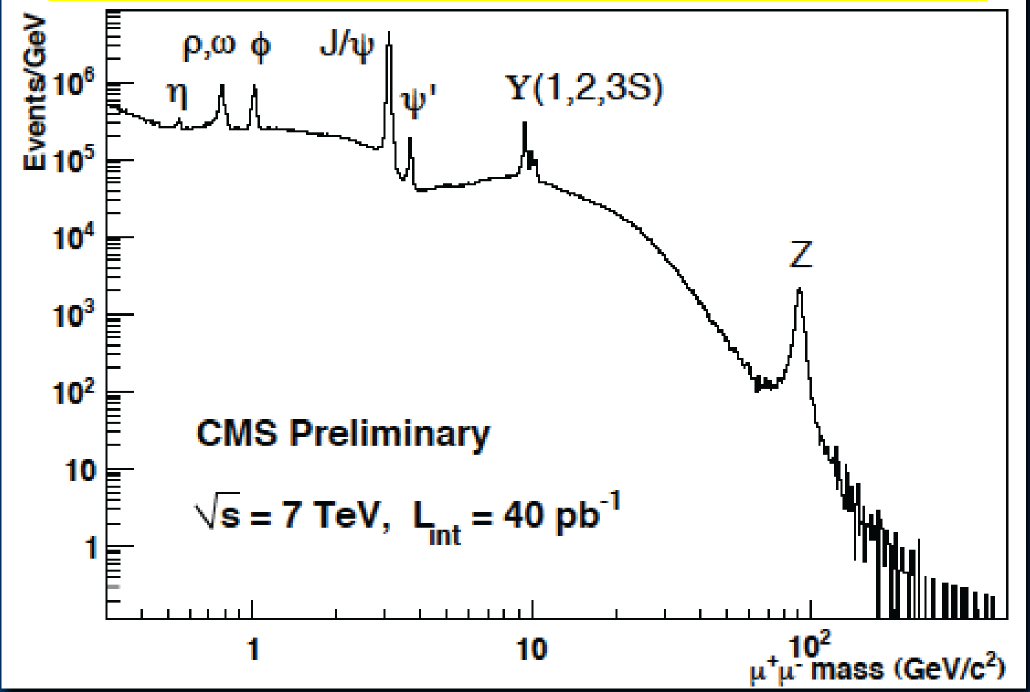
Good agreement with SM expectations (within present uncertainties)

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

Excellent performance……

….in 2010 and 2011 over 5/fb delivered

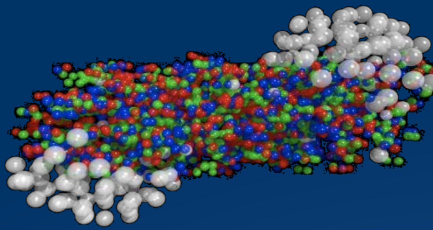
re-discovery of the Standard Model



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

The study of LHC data will allow us to answer some of the big questions ...

Will we understand the primordial state of matter after the Big Bang before protons and neutrons formed?



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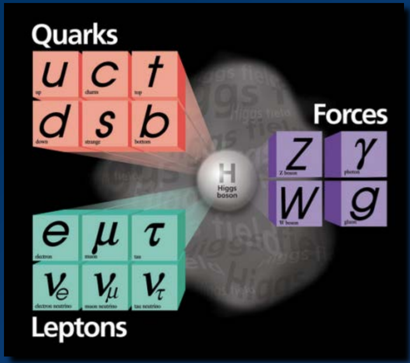

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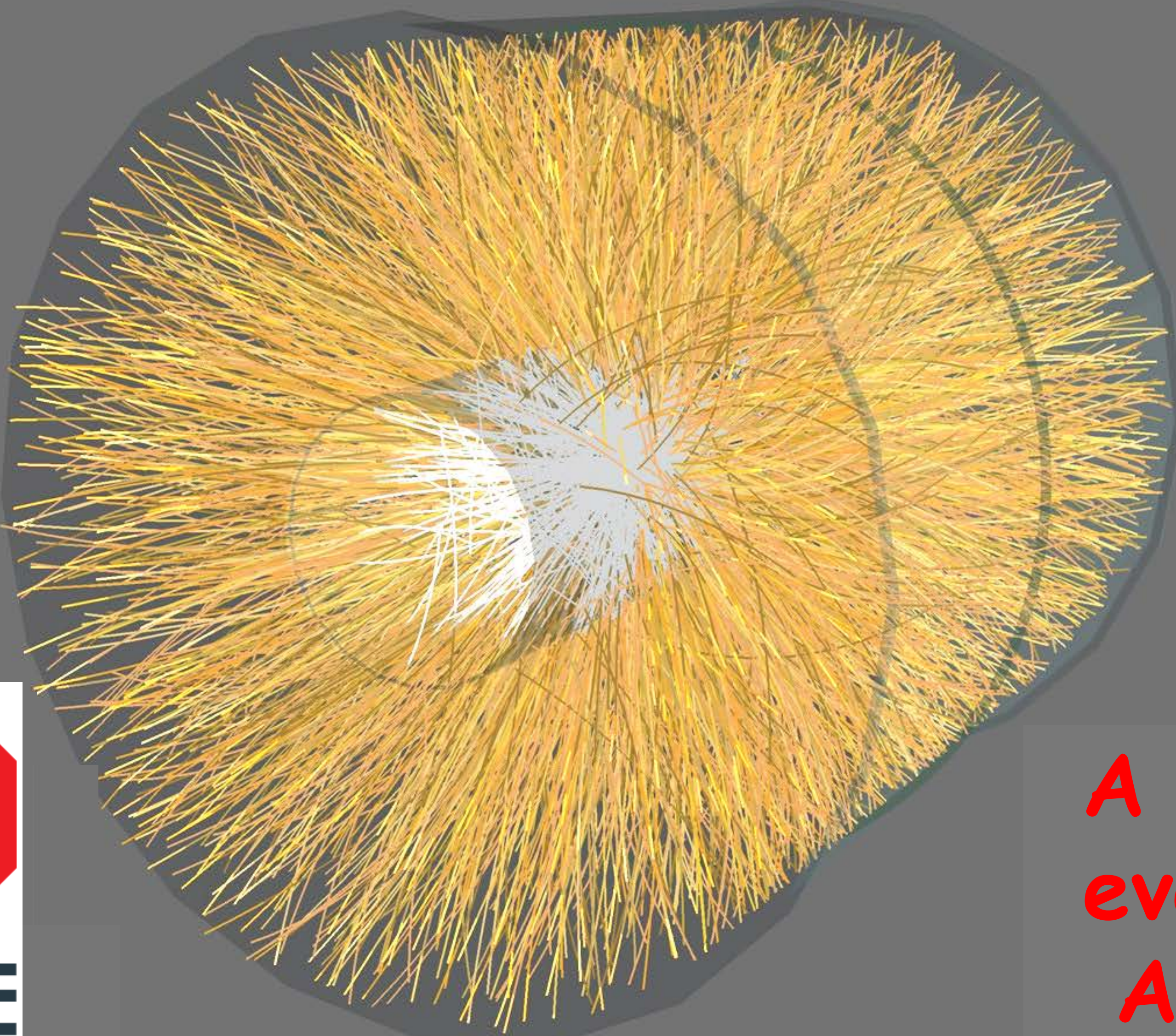
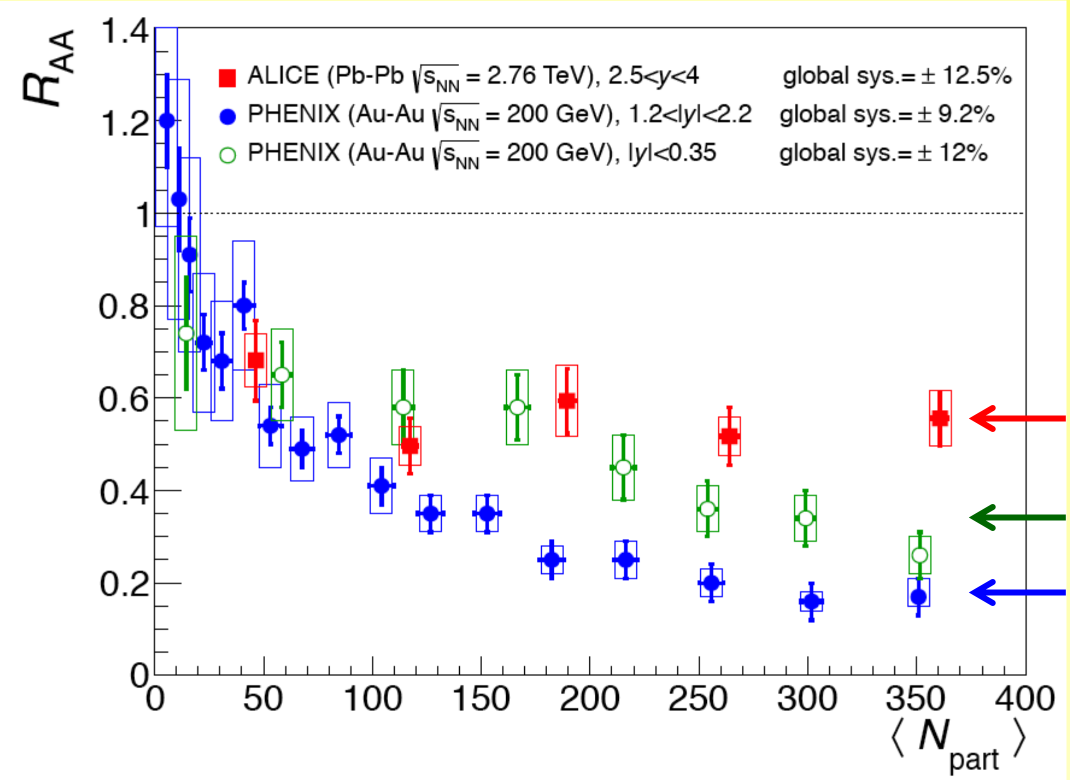
Not just Higgs: a rich and diverse physics program at LHC



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

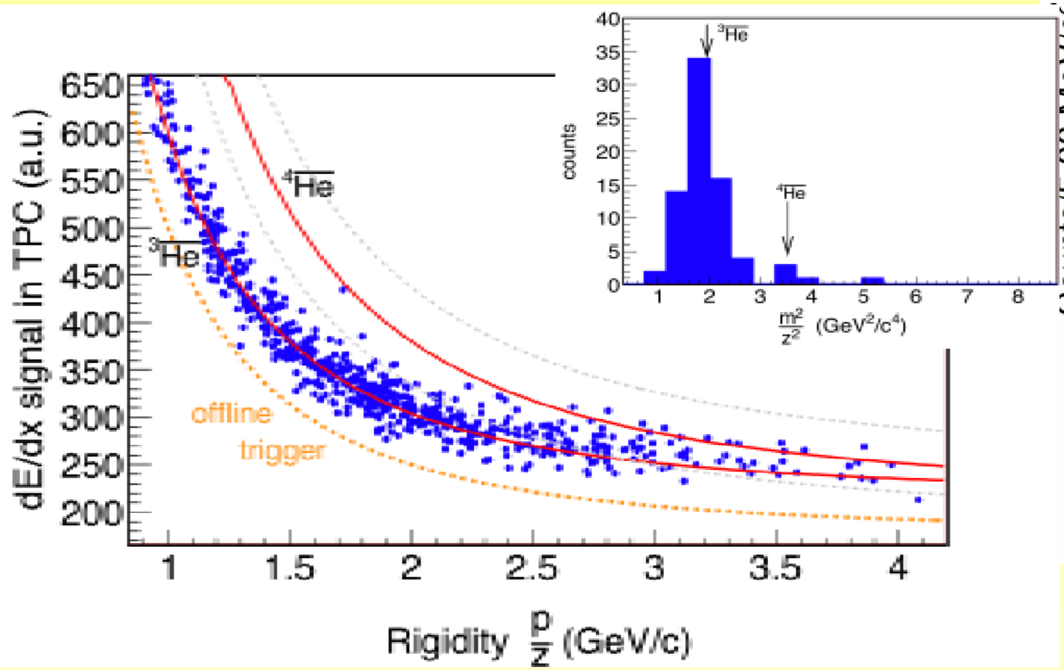
PHENIX, RHIC, mid-rapidity

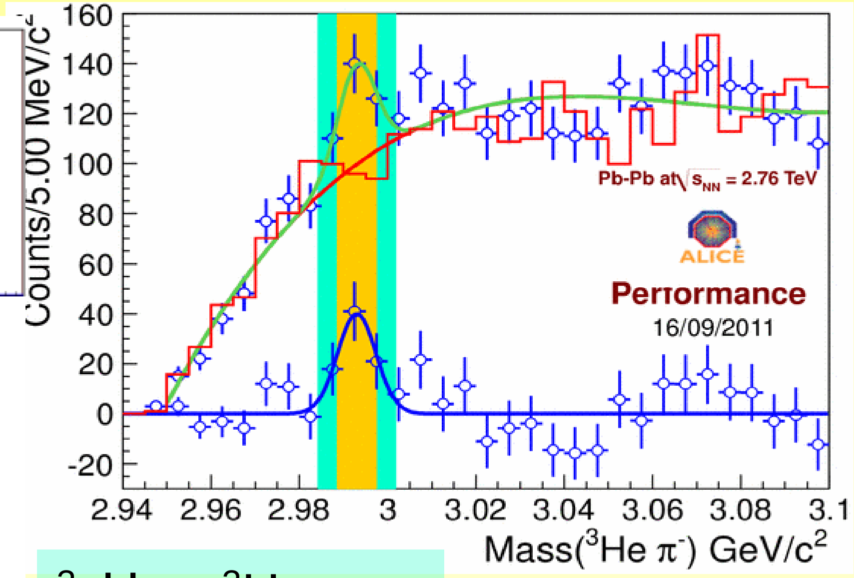
PHENIX, RHIC, forward rapidity

- Smaller J/ψ suppression at the LHC in spite of the factor 13 in √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-^{4}He** is the heaviest anti-nucleus ever observed
  - **Hypertriton:** one proton replaced by Λ particle





$^3_\Lambda H \rightarrow {}^3He + \pi^-$

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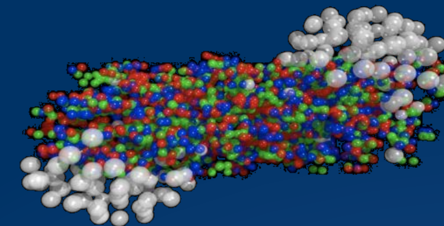

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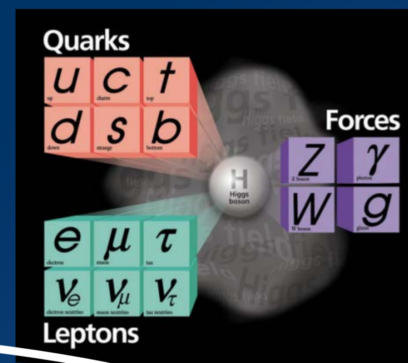

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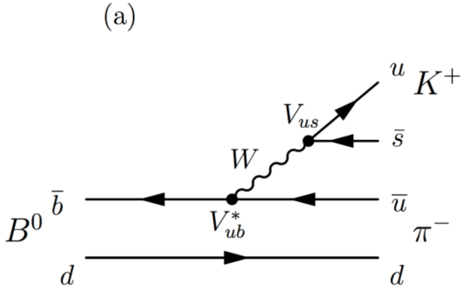
The Interference Experiment Works!



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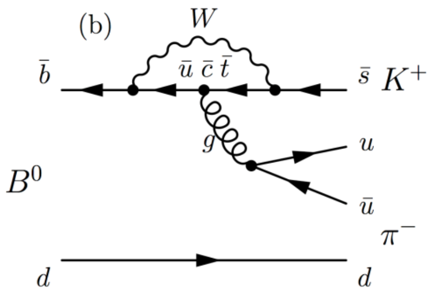
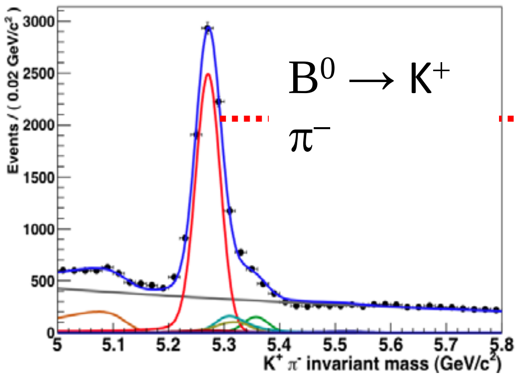
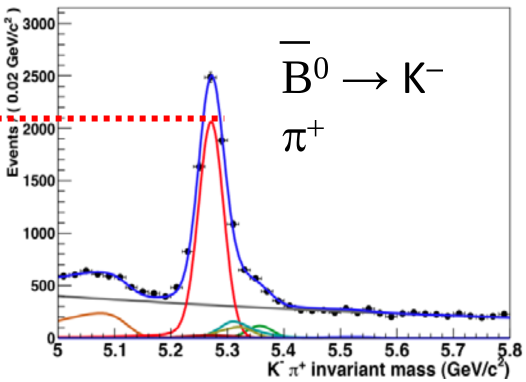


$B^0 \to K\pi$

A_{CP} = -0.088 ± 0.011 ± 0.008

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

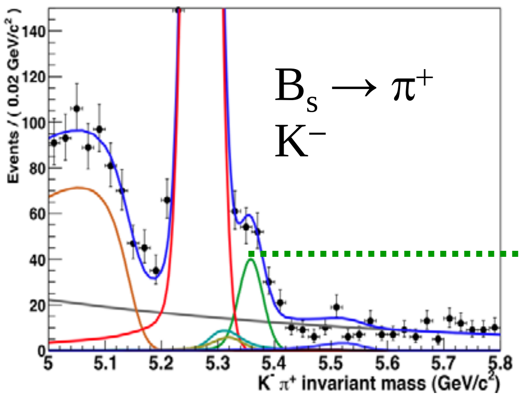


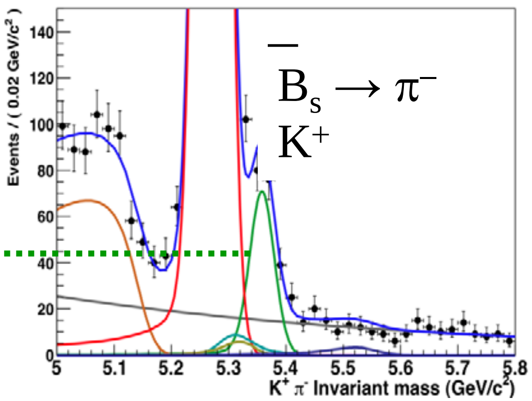


$B_s \to \pi K$

A_{CP} = 0.27 ± 0.008 ± 0.02

First **3σ** evidence for CP asymmetry in Bs decays



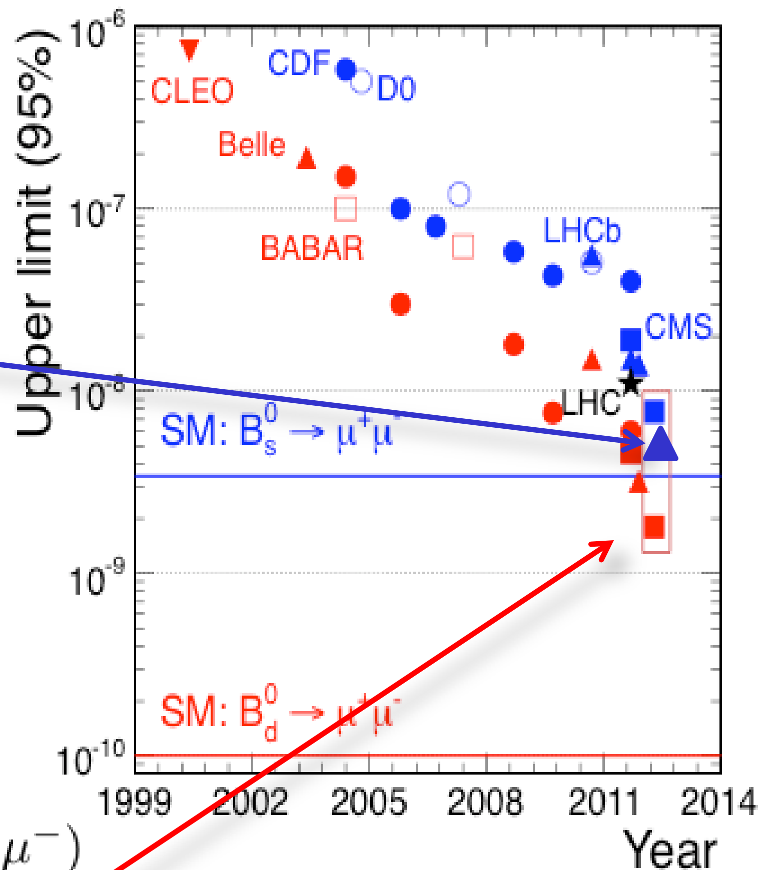


$B_{d/s} \to \mu\mu$

LHCb

LHCb only factor 1.4 above SM expectation
→ Space for "expected" new physics constraint

CMS



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

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

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

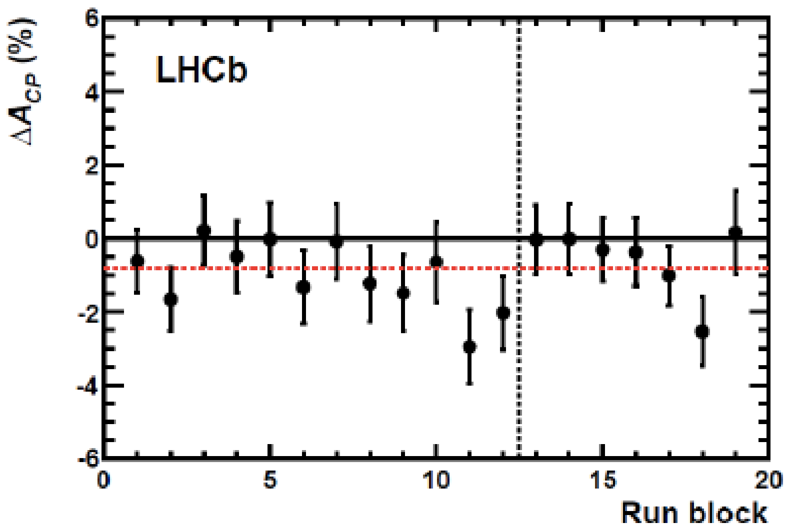
f = KK or $\pi\pi$

- Evidence of CP violation in charm decays

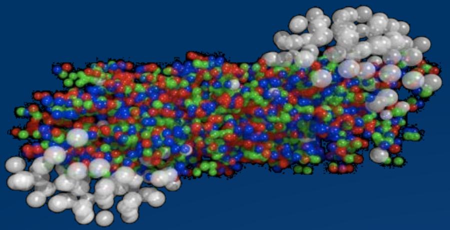
$$\boxed{\Delta A_{CP} = [-0.82 \pm 0.21(\mathrm{stat.}) \pm 0.11(\mathrm{sys.})]\,\%}$$

- Theoretical community is evaluating the compatibility of this result (to be cross checked with independent measurements) with New Physics beyond the Standard Model

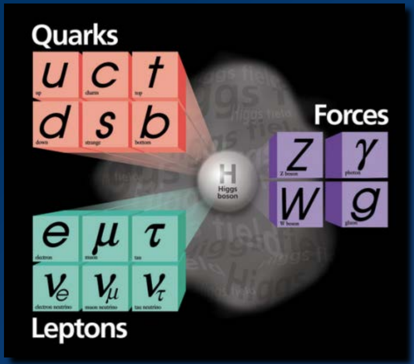
- Extra contribution to CP coming from “conventional” hadronic physics unlikely, but still possible



The study of LHC data will allow us to answer some of the big questions ...



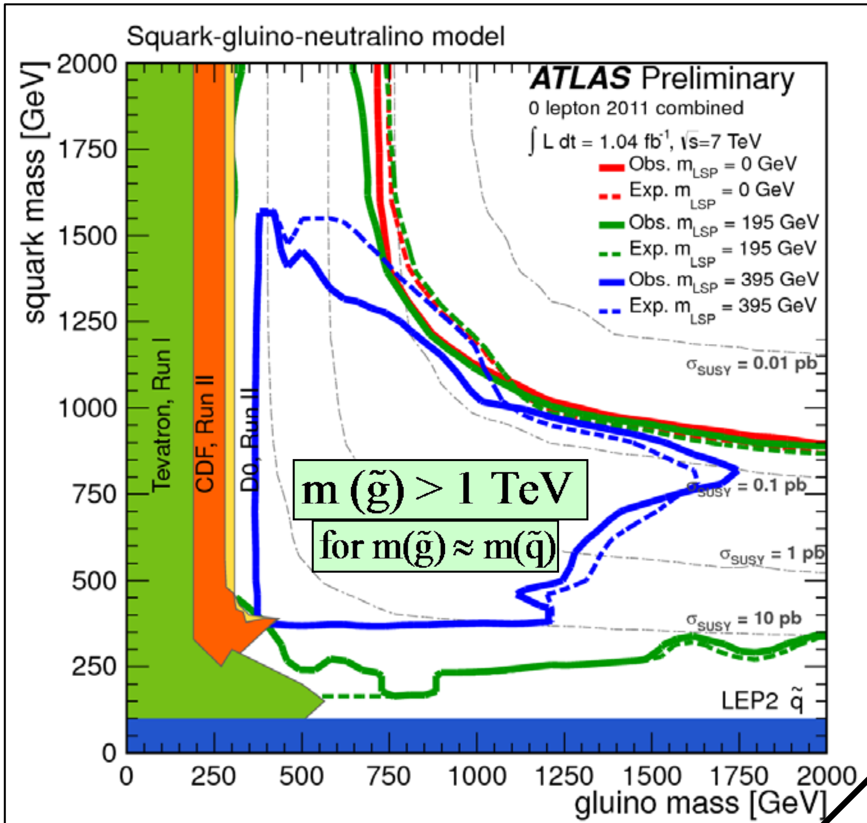
Will we understand the primordial state of matter after the Big Bang before protons and neutrons formed?

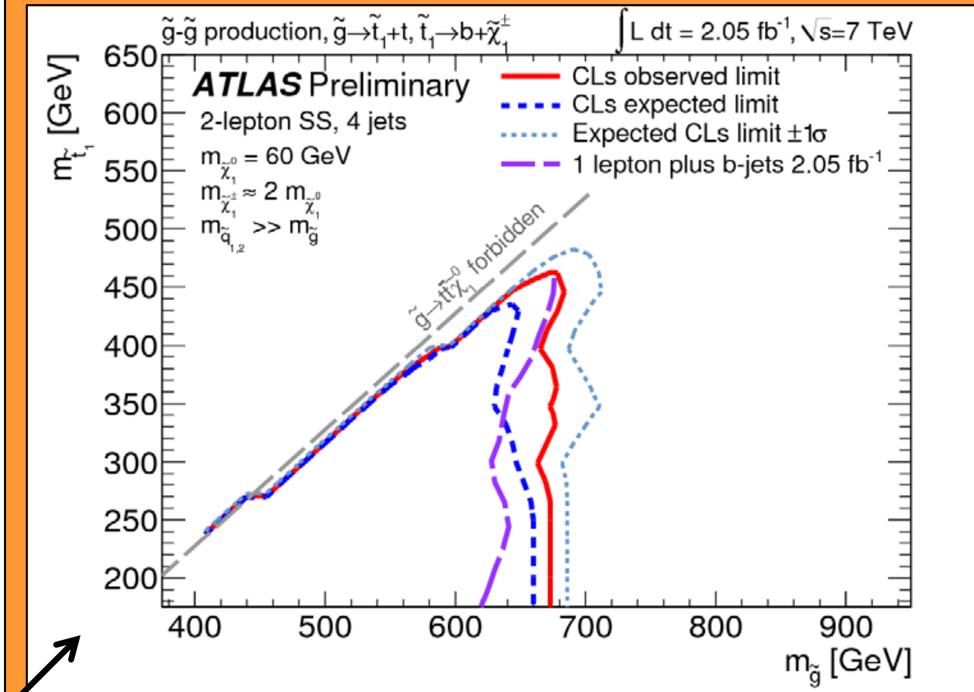


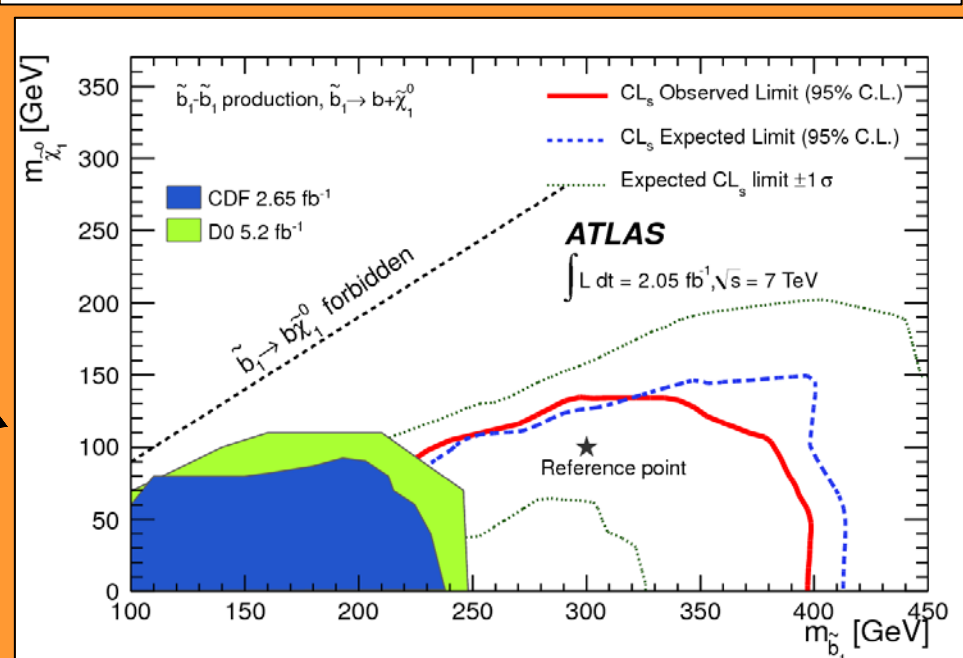
Will we find the Higgs particle that is responsible for giving mass to all particles?

Will we find the reason why antimatter and matter did not completely destroy each other?

Will we find the particle(s) that make up the mysterious 'dark matter' in our Universe?

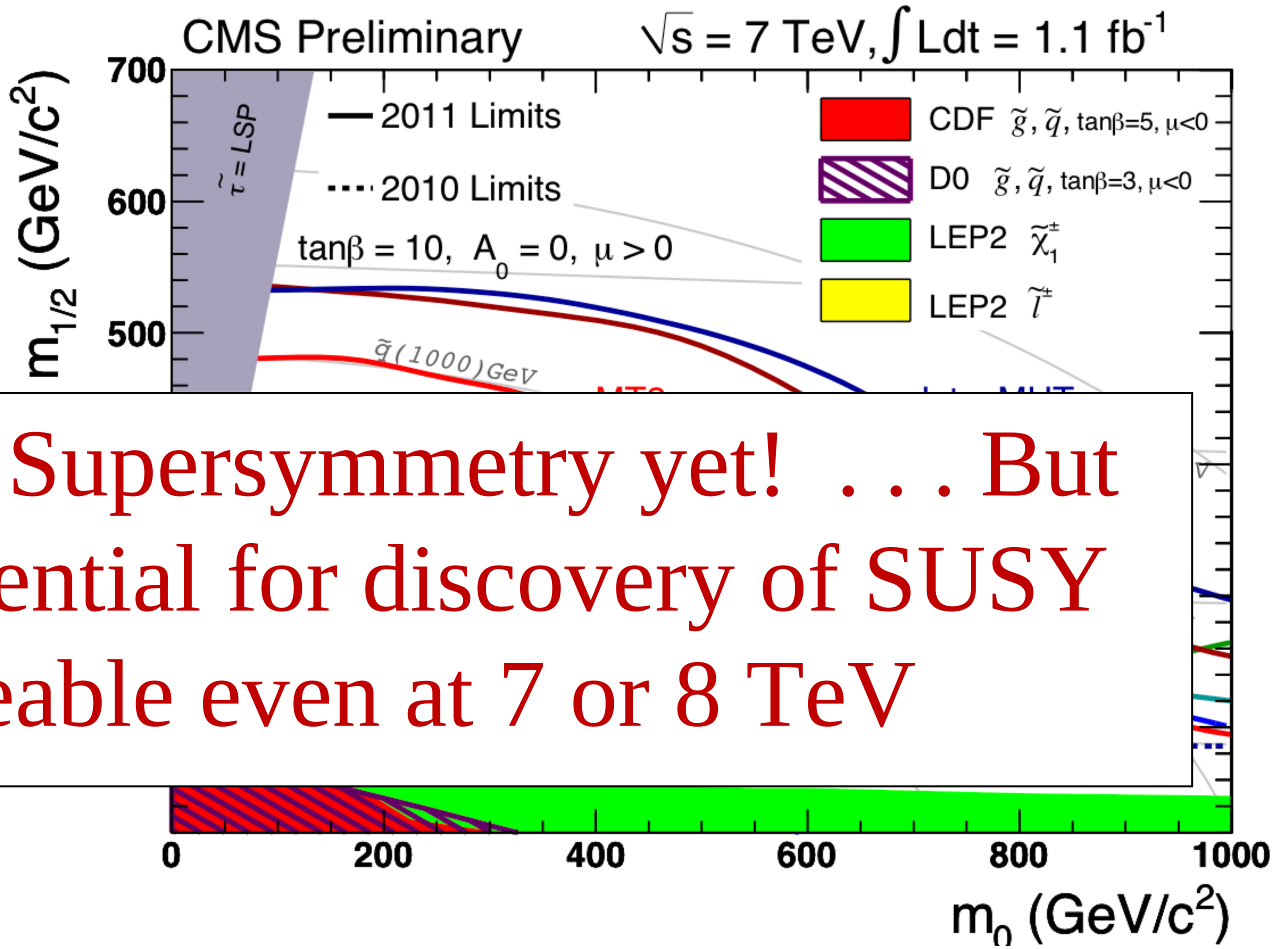






Stop and sbottom searches highly motivated today, as 3rd generation squarks are those that are expected to stabilize the Higgs mass

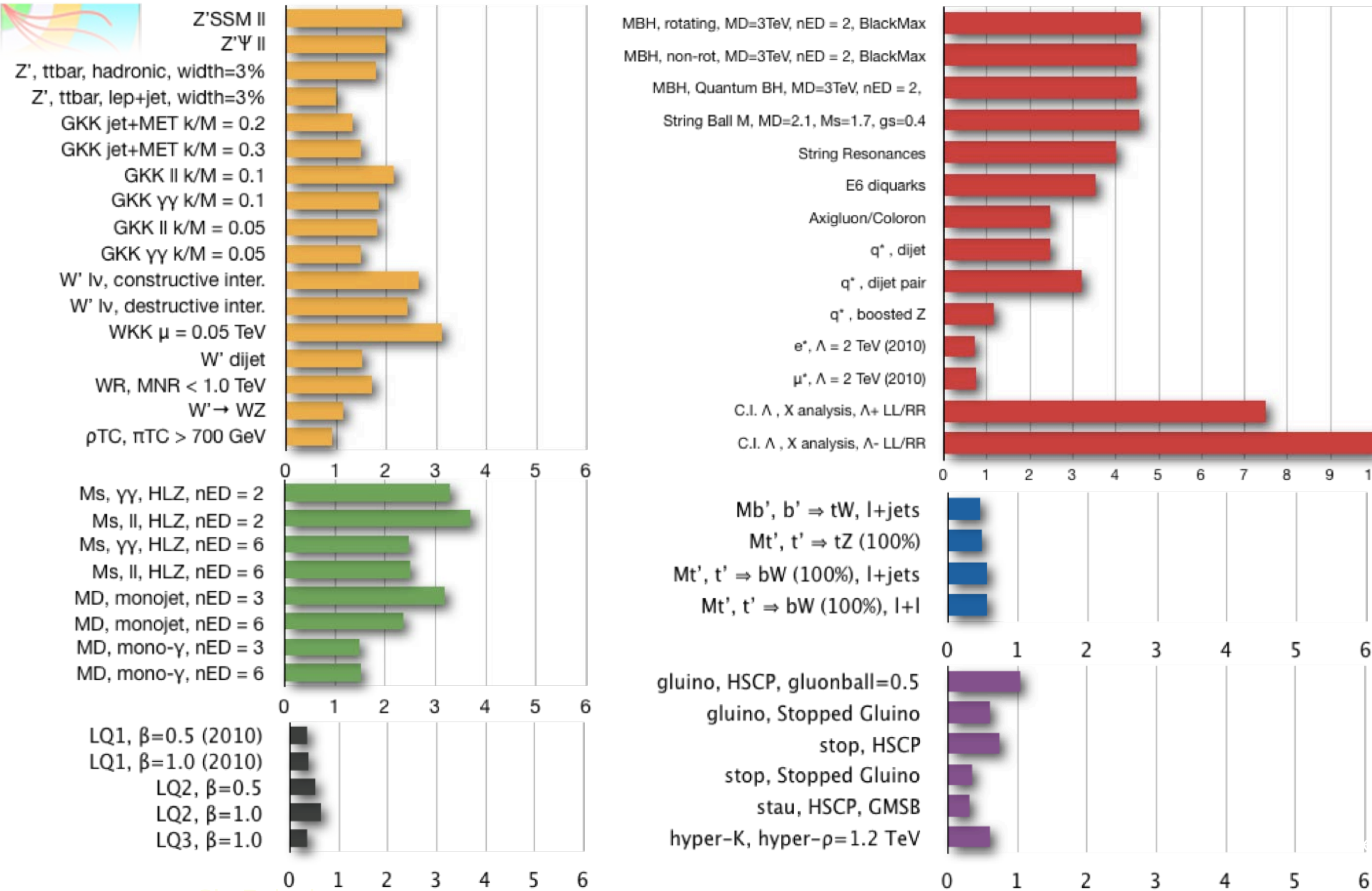
SUSY: new limits on CMSSM



No Supersymmetry yet! . . . But potential for discovery of SUSY sizeable even at 7 or 8 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*.

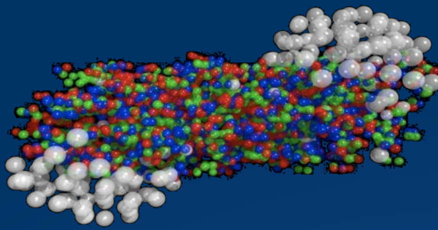
CMS Exotica: Summary for Moriond 2012



Murayama, ICFA Seminar, 2011 CERN

LHC and Theory…

The study of LHC data will allow us to answer some of the big questions ...



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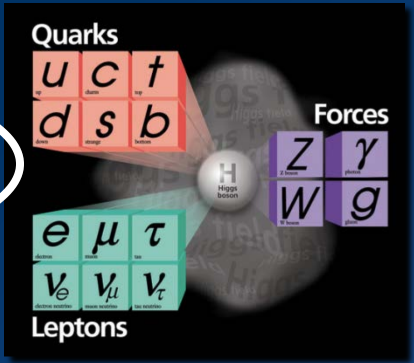

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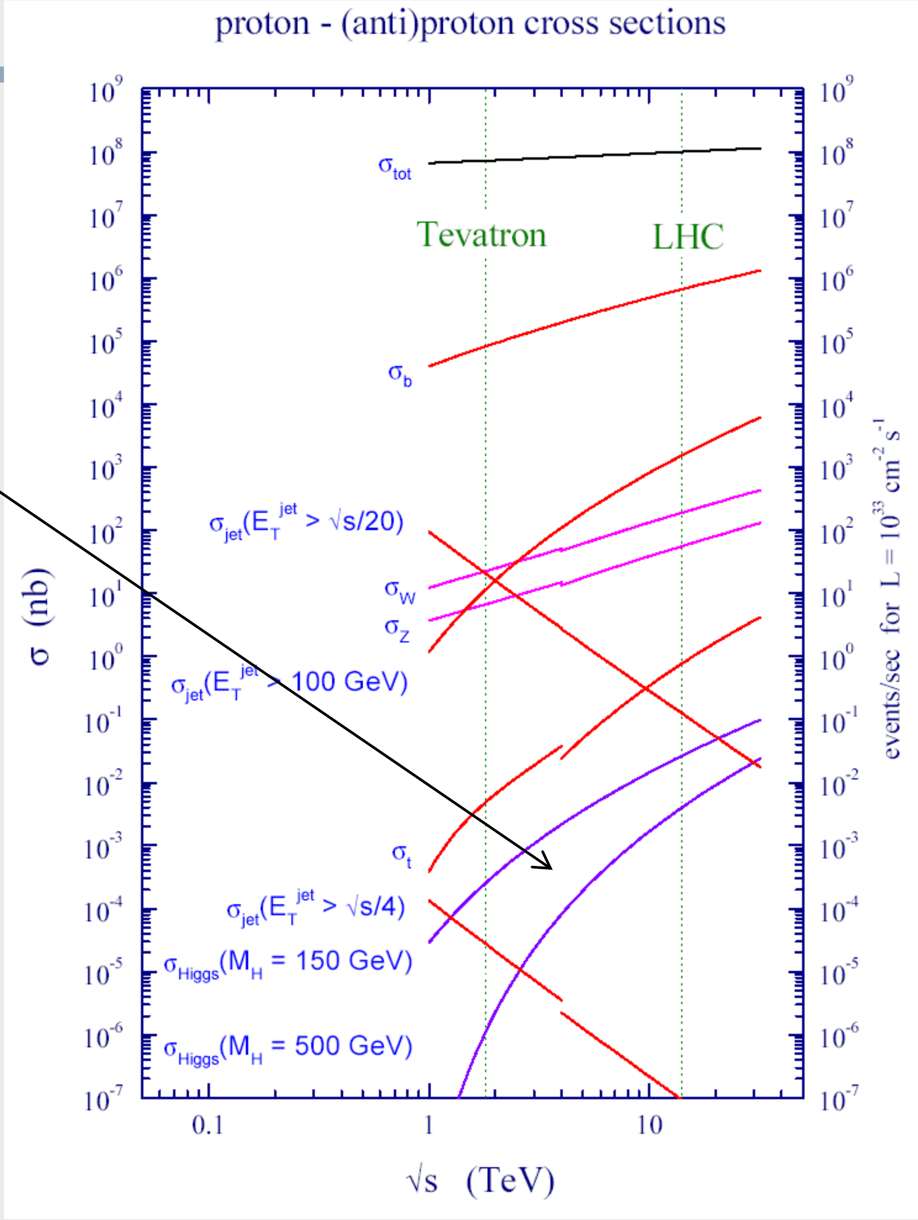
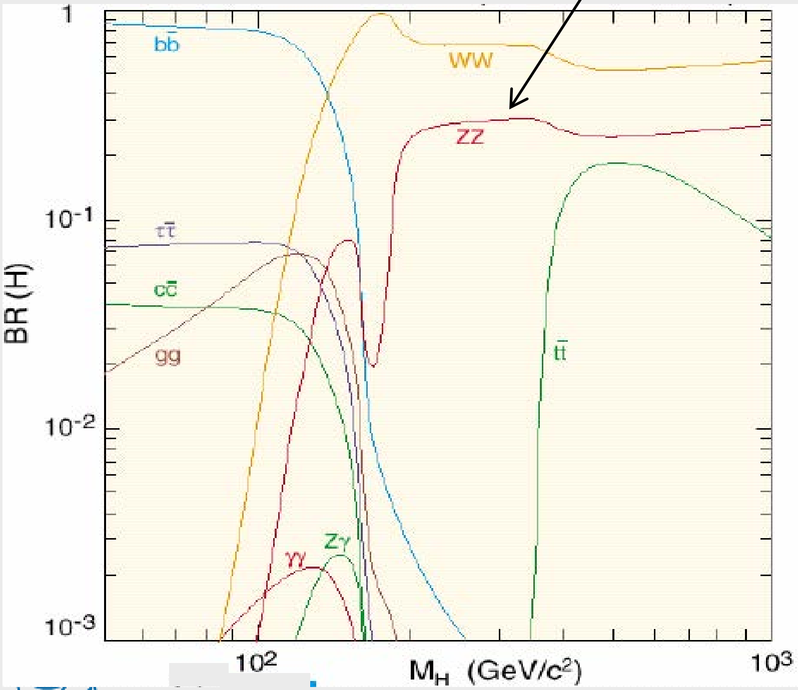
Search for the Higgs-Boson at the LHC

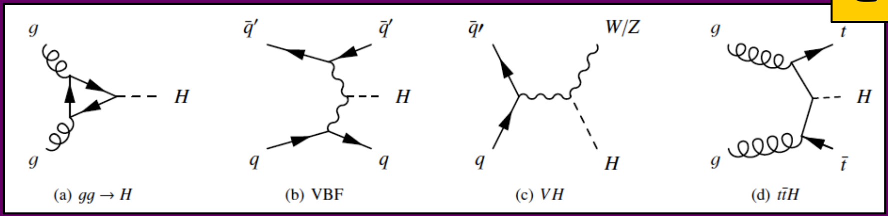
Production rate
of the Higgs-Bosons
depends on its mass

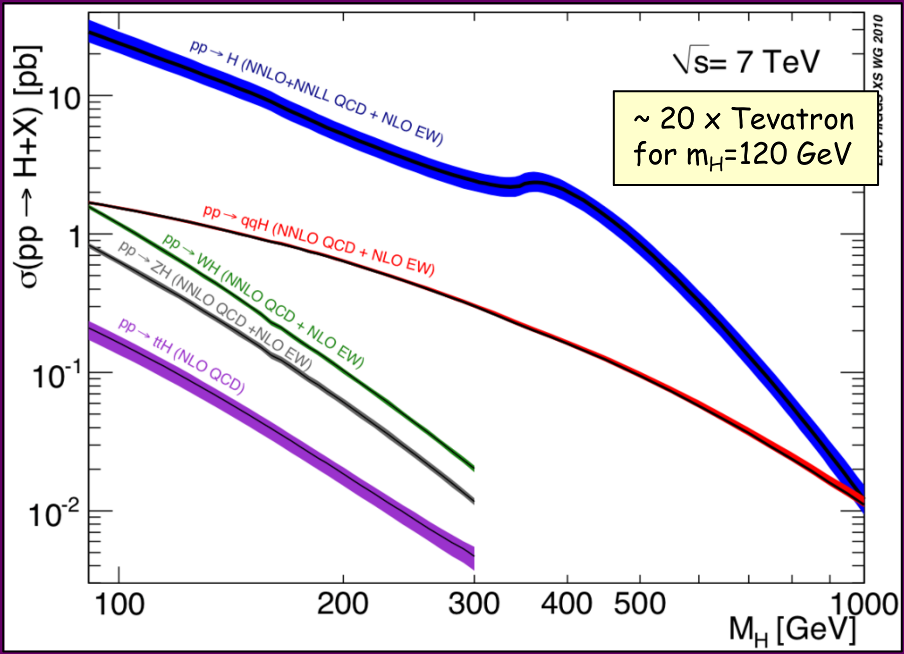
as well as its decay possibilities



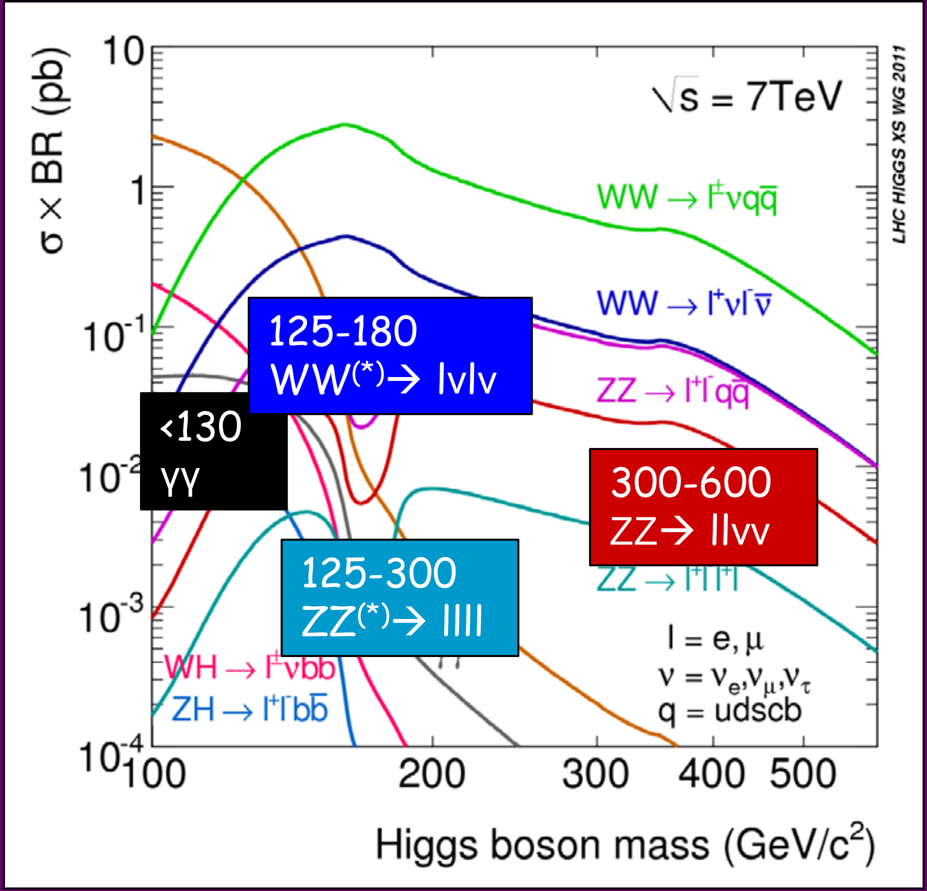


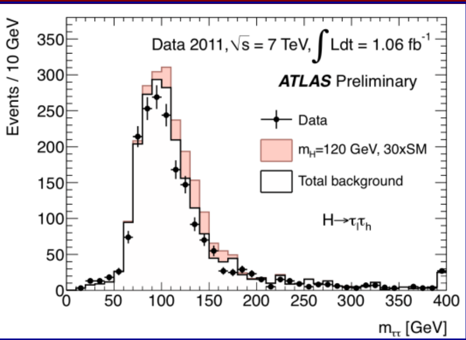
SM Higgs production cross-section and decay modes

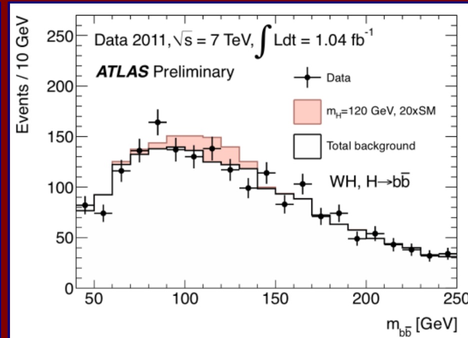


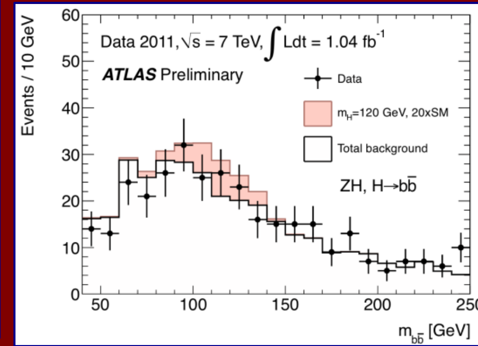


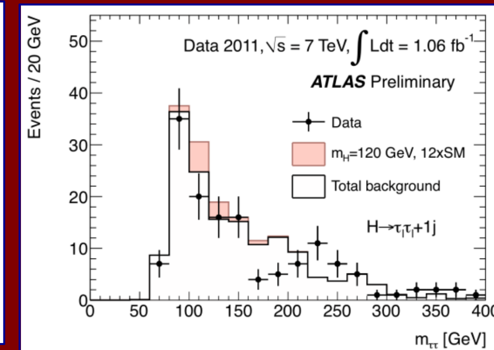
Experimentally most sensitive channels vs m_H

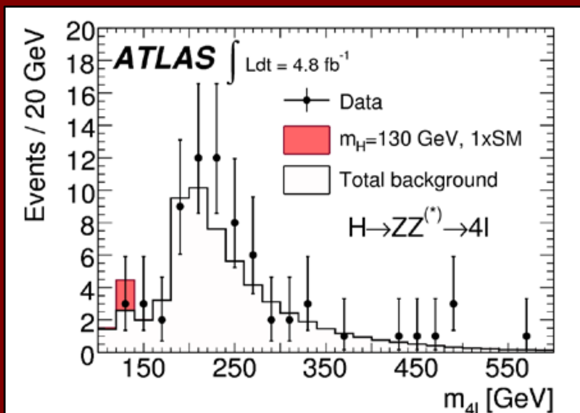


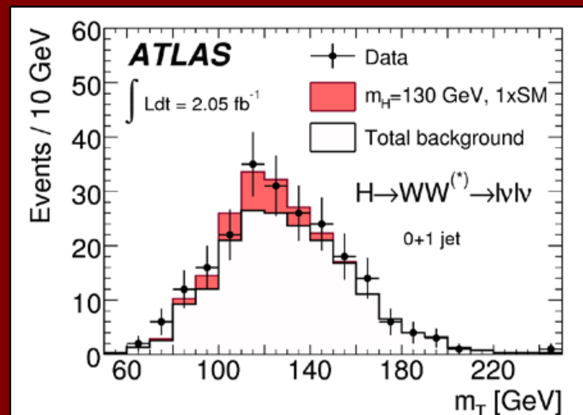

Data 2011, √s = 7 TeV, ∫Ldt = 1.06 fb⁻¹
ATLAS Preliminary
Data
m_H=120 GeV, 30xSM
Total background
H→τ_lτ_h
Events / 10 GeV
m_ττ [GeV]

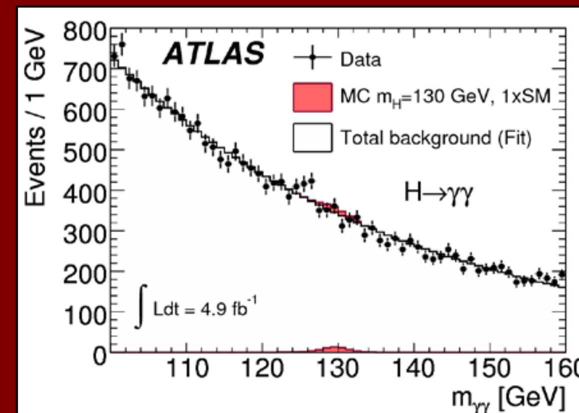

Data 2011, √s = 7 TeV, ∫Ldt = 1.04 fb⁻¹
ATLAS Preliminary
Data
m_H=120 GeV, 20xSM
Total background
WH, H→bb̄
Events / 10 GeV
m_bb̄ [GeV]


Data 2011, √s = 7 TeV, ∫Ldt = 1.04 fb⁻¹
ATLAS Preliminary
Data
m_H=120 GeV, 20xSM
Total background
ZH, H→bb̄
Events / 10 GeV
m_bb̄ [GeV]

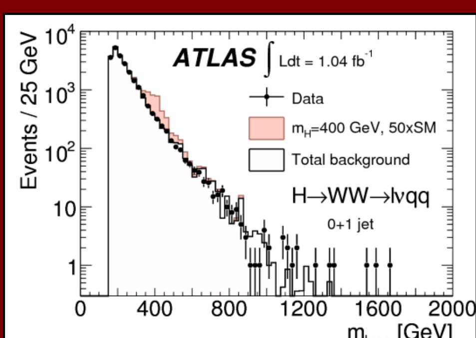

Data 2011, √s = 7 TeV, ∫Ldt = 1.06 fb⁻¹
ATLAS Preliminary
Data
m_H=120 GeV, 12xSM
Total background
H→τ_lτ_l+1j
Events / 20 GeV
m_ττ [GeV]

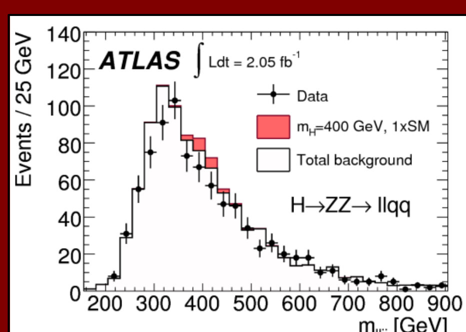

ATLAS ∫Ldt = 4.8 fb⁻¹
Data
m_H=130 GeV, 1xSM
Total background
H→ZZ^(*)→4l
Events / 20 GeV
m_4l [GeV]

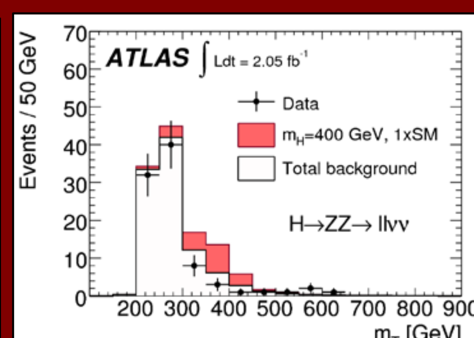

ATLAS
∫Ldt = 2.05 fb⁻¹
Data
m_H=130 GeV, 1xSM
Total background
H→WW^(*)→lνlν
0+1 jet
Events / 10 GeV
m_T [GeV]

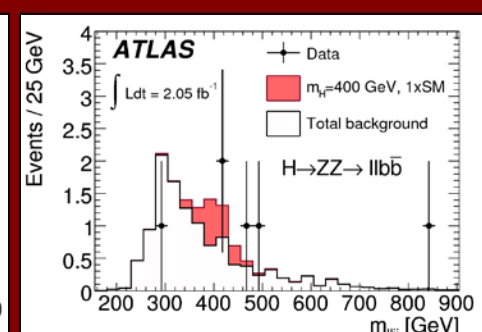

ATLAS
Data
MC m_H=130 GeV, 1xSM
Total background (Fit)
H→γγ
∫Ldt = 4.9 fb⁻¹
Events / 1 GeV
m_γγ [GeV]

SM Higgs

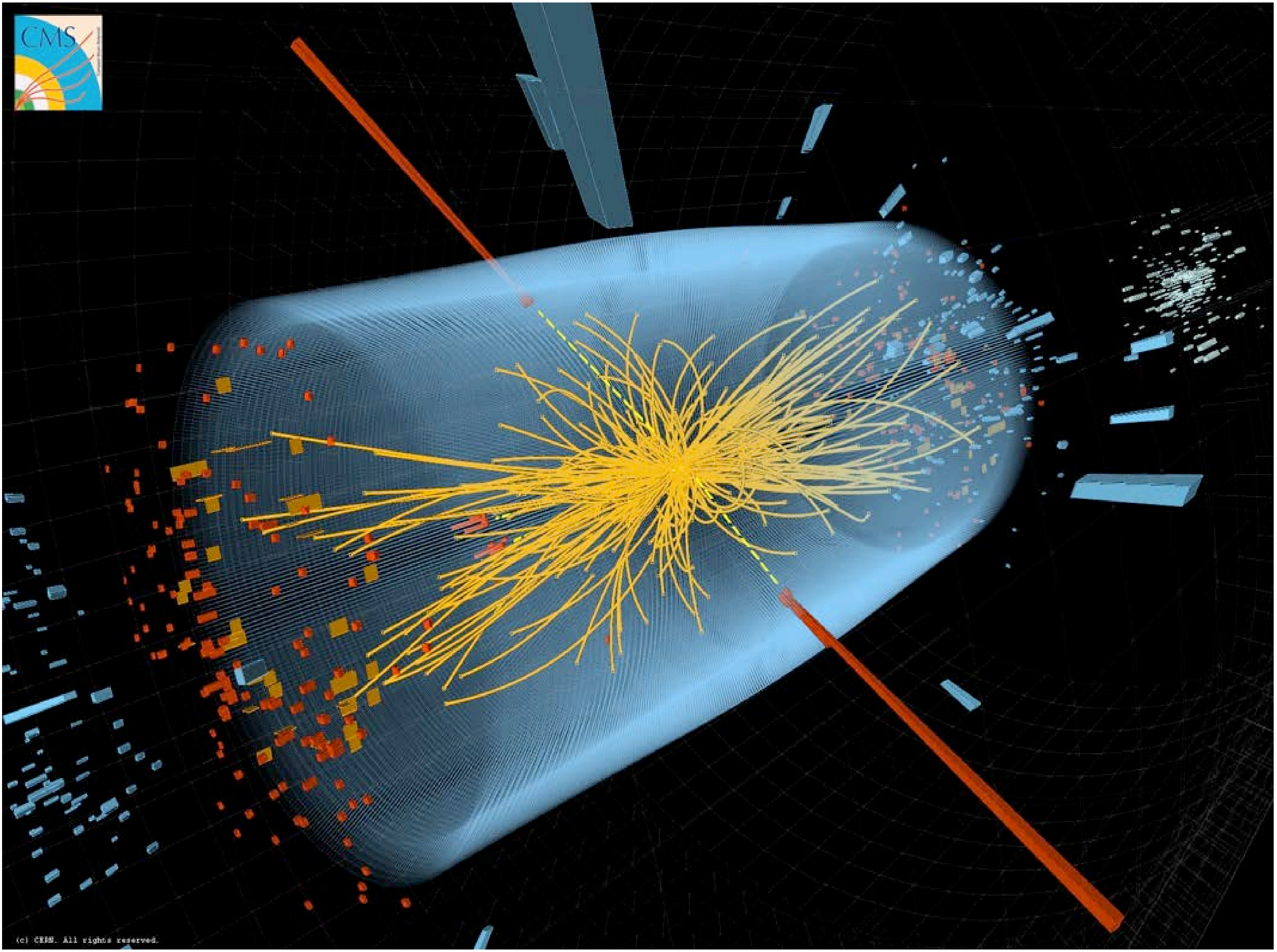

ATLAS ∫Ldt = 1.04 fb⁻¹
Data
m_H=400 GeV, 50xSM
Total background
H→WW→lνqq
0+1 jet
Events / 25 GeV
m_lνqq [GeV]

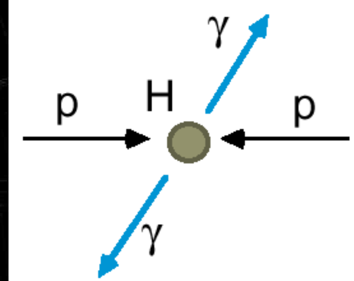

ATLAS ∫Ldt = 2.05 fb⁻¹
Data
m_H=400 GeV, 1xSM
Total background
H→ZZ→ llqq
Events / 25 GeV
m_lljj [GeV]


ATLAS ∫Ldt = 2.05 fb⁻¹
Data
m_H=400 GeV, 1xSM
Total background
H→ZZ→ llνν
Events / 50 GeV
m_T [GeV]


ATLAS
∫Ldt = 2.05 fb⁻¹
Data
m_H=400 GeV, 1xSM
Total background
H→ZZ→ llbb̄
Events / 25 GeV
m_lljj [GeV]

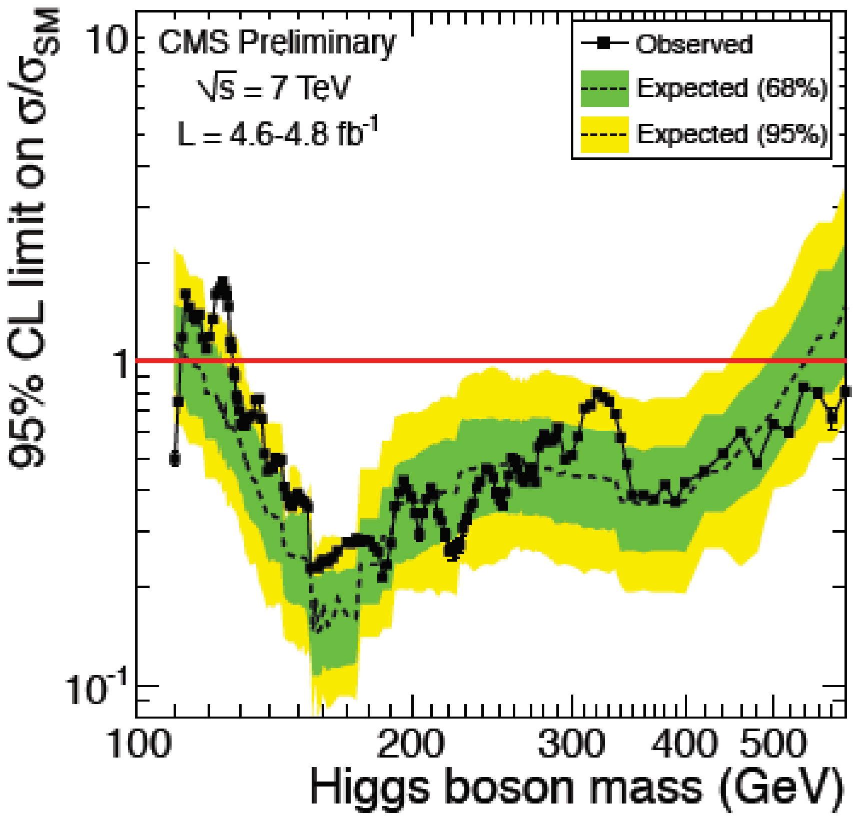
A Collision with two Photons

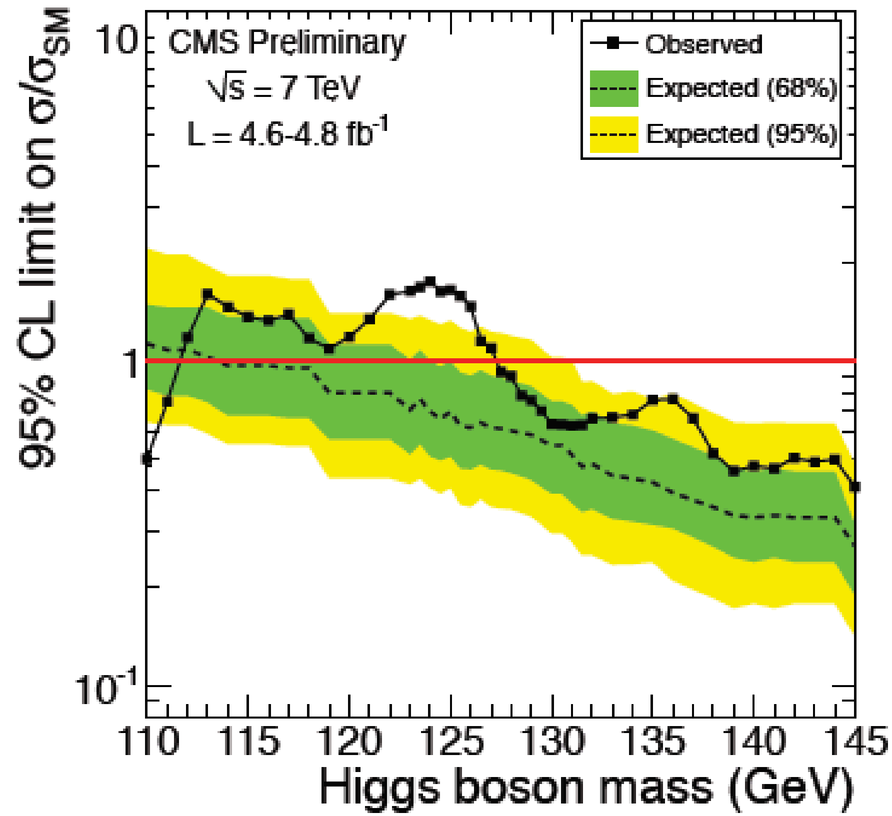




A Higgs or
a ‘background’
process without
a Higgs?

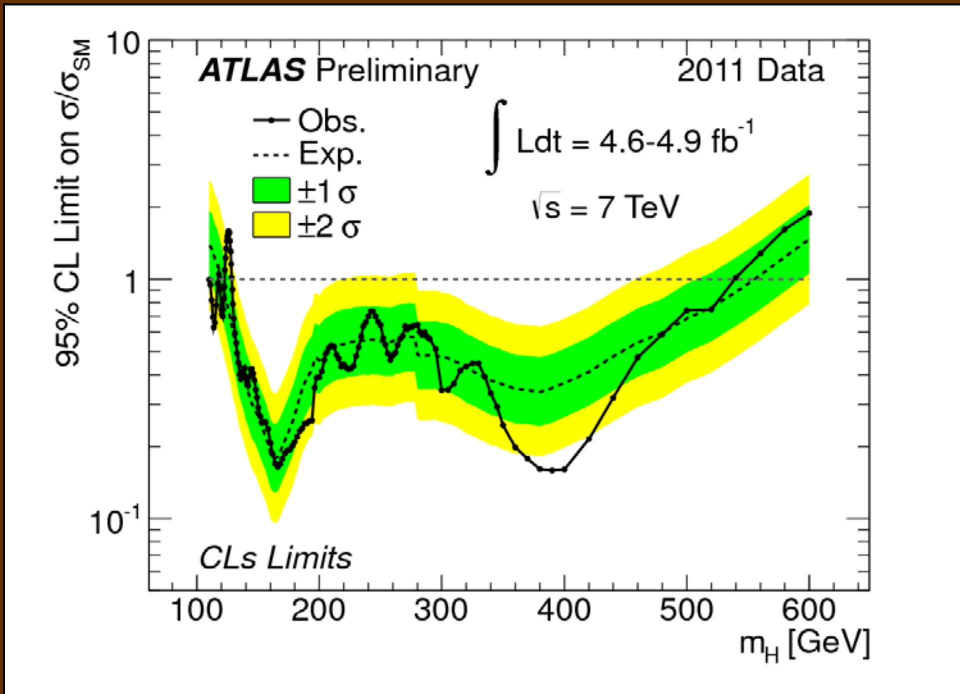
CMS Combination

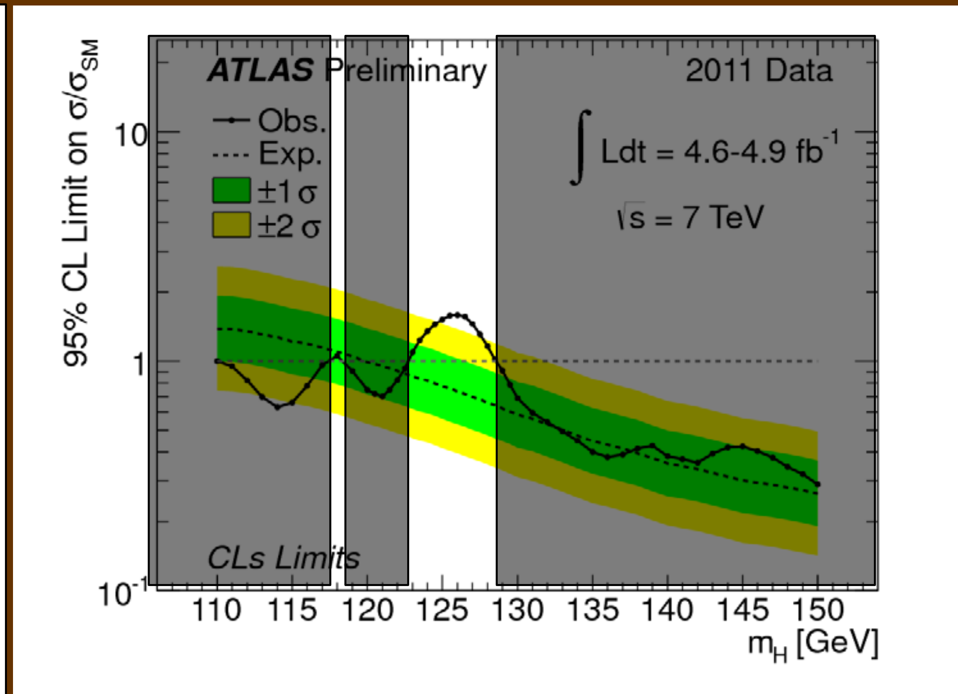




Expected exclusion 114.5 - 543 GeV
Observed exclusion 127.5 - 600 GeV

ATLAS: Combining all (12 !) channels together, full 2011 dataset





Excluded at 95% CL	$110 < m_H < 122.5$ GeV (except 117.5-118.5) $129 < m_H < 539$ GeV	Expected if no signal 120-555 GeV

Excluded at 99% CL	$130 < m_H < 486$ GeV

NEW: full 2011 dataset

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 **122.5 to 127.5** GeV

“interesting fluctuations” around masses
of **124 to 126** GeV

Data Taking in 2012

Energy: 8 TeV

Expected Amount of Data:

Factor 3 more than in 2011

Higgs-Boson at 7 and 8 TeV

Status ~ today

SM Hi … % cl
up to …
excep … 7.5 GeV

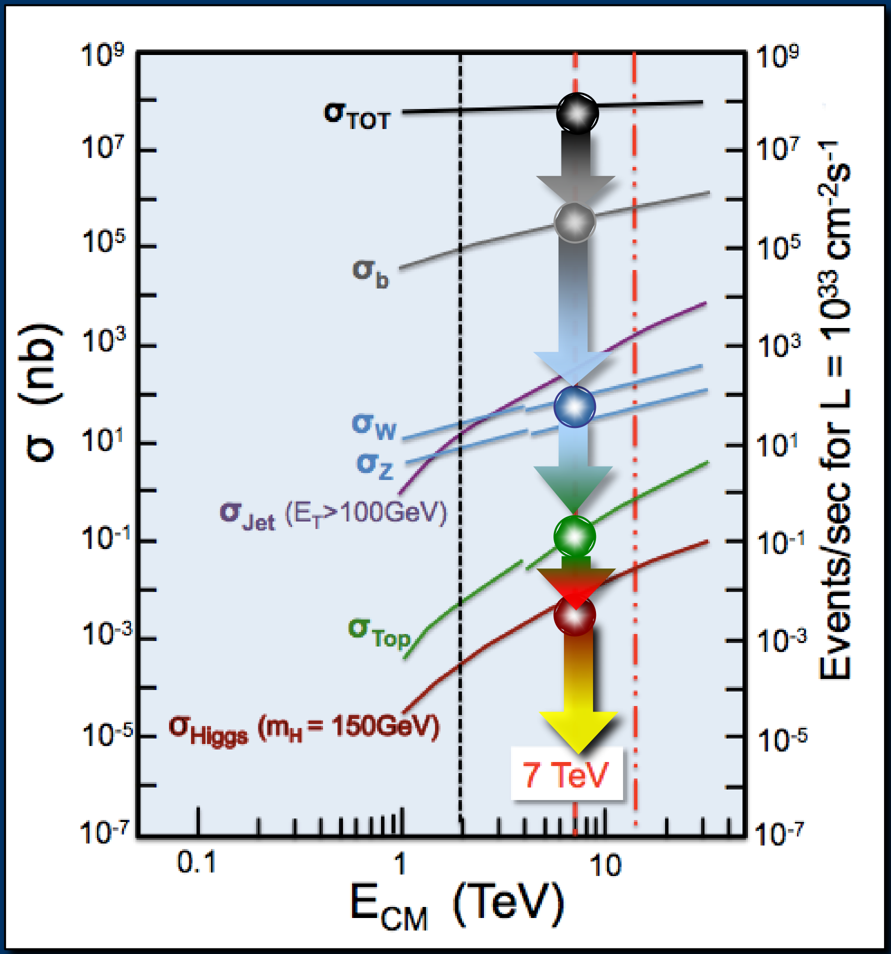
"intere … asses
of **124 to 126** GeV

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

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

2009 — Start of LHC

Run 1: 7 and 8 TeV centre of mass energy, luminosity ramping up to few 10^{33} cm^{-2} s^{-1}, few fb^{-1} delivered

2013/14 — LHC shut-down to prepare machine for design energy and nominal luminosity

Run 2: Ramp up luminosity to nominal (10^{34} cm^{-2} s^{-1}), ~50 to 100 fb^{-1}

2017/**18** — Injector and LHC Phase-I upgrades to go to ultimate luminosity

Run 3: Ramp up luminosity to 2.2 x nominal, reaching ~100 fb^{-1} / year accumulate few hundred fb^{-1}

~2021/**22** — Phase-II: High-luminosity LHC. New focussing magnets and CRAB cavities for very high luminosity with levelling

Run 4: Collect data until > 3000 fb^{-1}

2030

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)


beyond LHC ?

Next decades

Road beyond Standard Model

through synergy of

hadron - hadr … (LHC, HE-LHC?)

… **adron colliders** (LHeC ??)

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

LHC results will guide the way at the energy frontier

CERN today….into the future

- CLIC conceptual design report by 2012
- Participation in all LC activiti
- LHeC conceptu sign report ready
- 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

      1^{st} open meeting September 2012, Cracow

  - Finalization: May/June 2013

- Started with the ICFA Seminar 3-6 October 2011 at CERN

  Use as 1^{st} 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

The LHC is delivering data

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

exciting prospects