Accelerating Science and Innovation

Physics Results at the LHC and Implications for Future HEP Programmes

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IPAC12, 25 May 2012

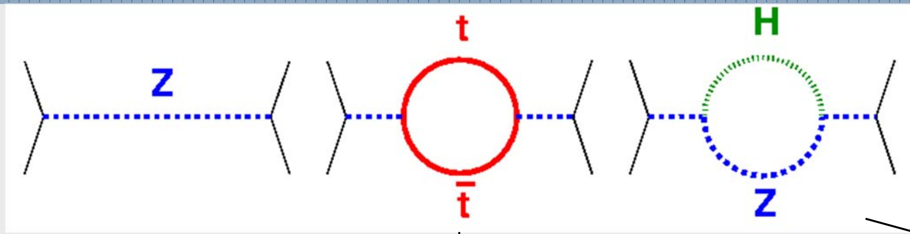
Past few decades

"Discovery" of Standard Model

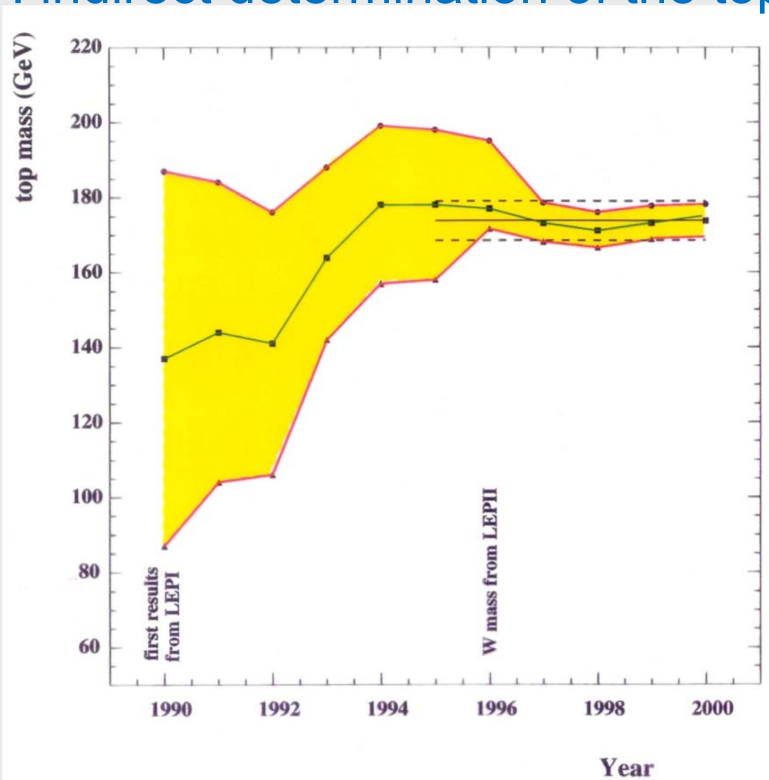
through synergy of

hadron - hadron	colliders	(e.g. Tevatron)
lepton - hadron	colliders	(HERA)
lepton - lepton	colliders	(e.g. LEP, SLC)

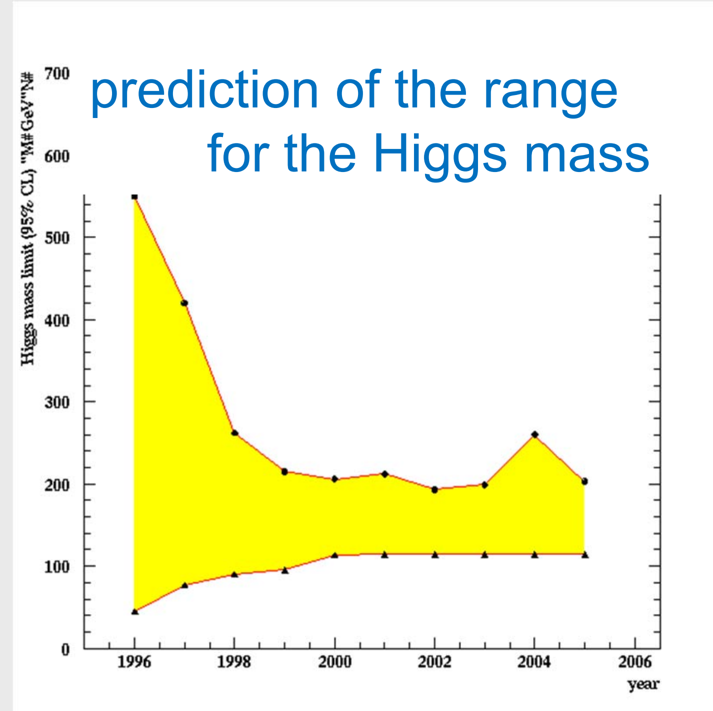
Test of the SM at the Level of Quantum Fluctuations



LEP: indirect determination of the top mass



prediction of the range
for the Higgs mass



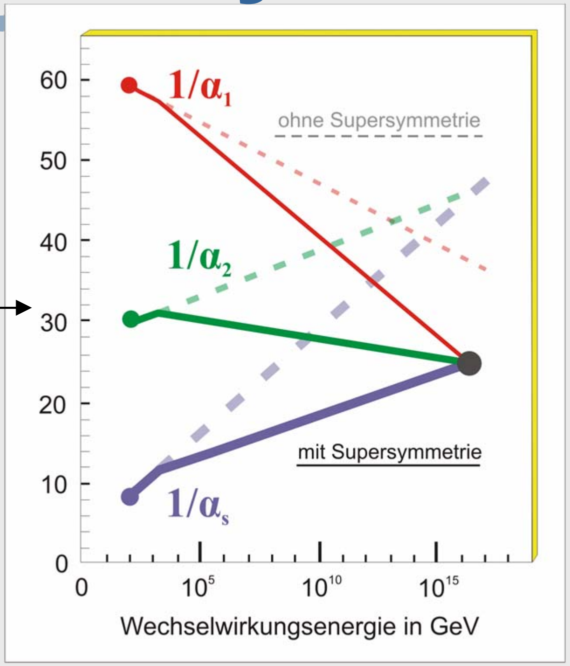
possible due to
- precision measurements
- known higher order electroweak corrections

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

Key Questions of Particle Physics

origin of mass/matter or
origin of electroweak symmetry breaking

unification of forces



fundamental symmetry of forces and matter

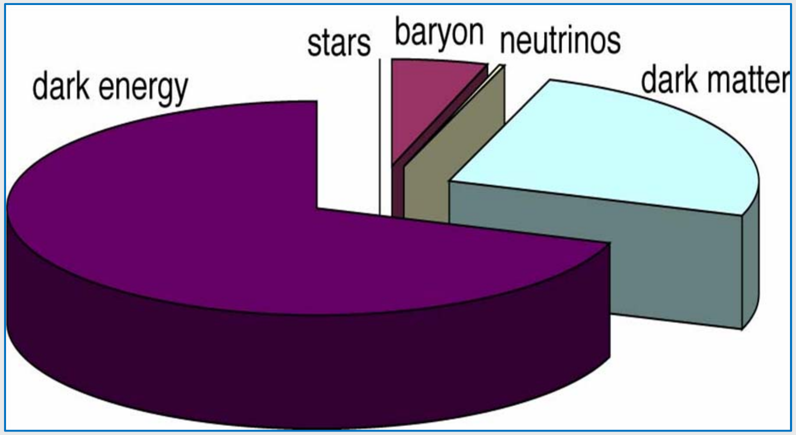
where is antimatter

unification of quantum physics and general relativity

number of space/time dimensions

what is dark matter

what is dark energy



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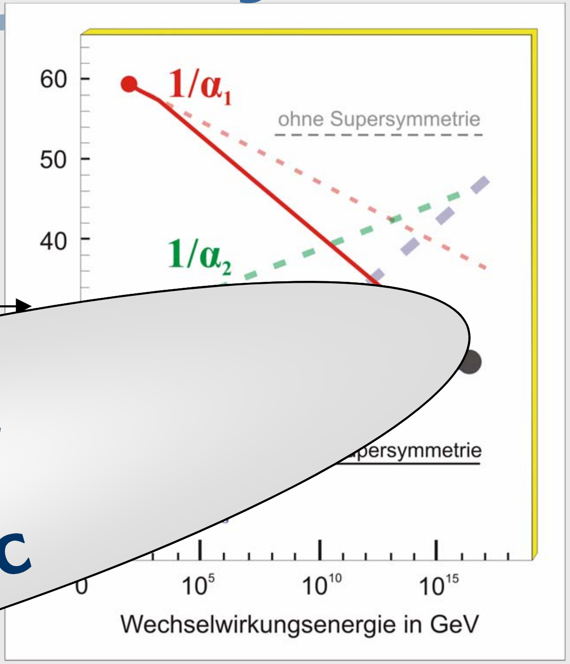


fundamental symmetry of forces an
matter

where is antima

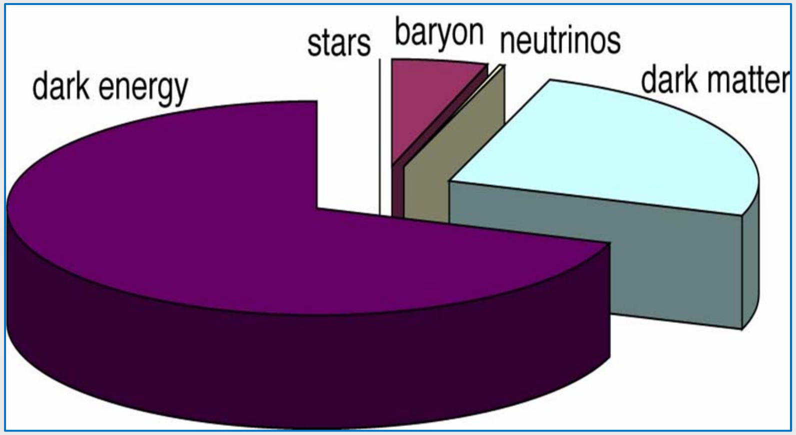
unificatio
genera

For most questions:
new particles should appear
at **TeV** scale or below
→ **territory of the LHC**

number of space/time dimensions

what is dark matter

what is dark energy



‘Today’

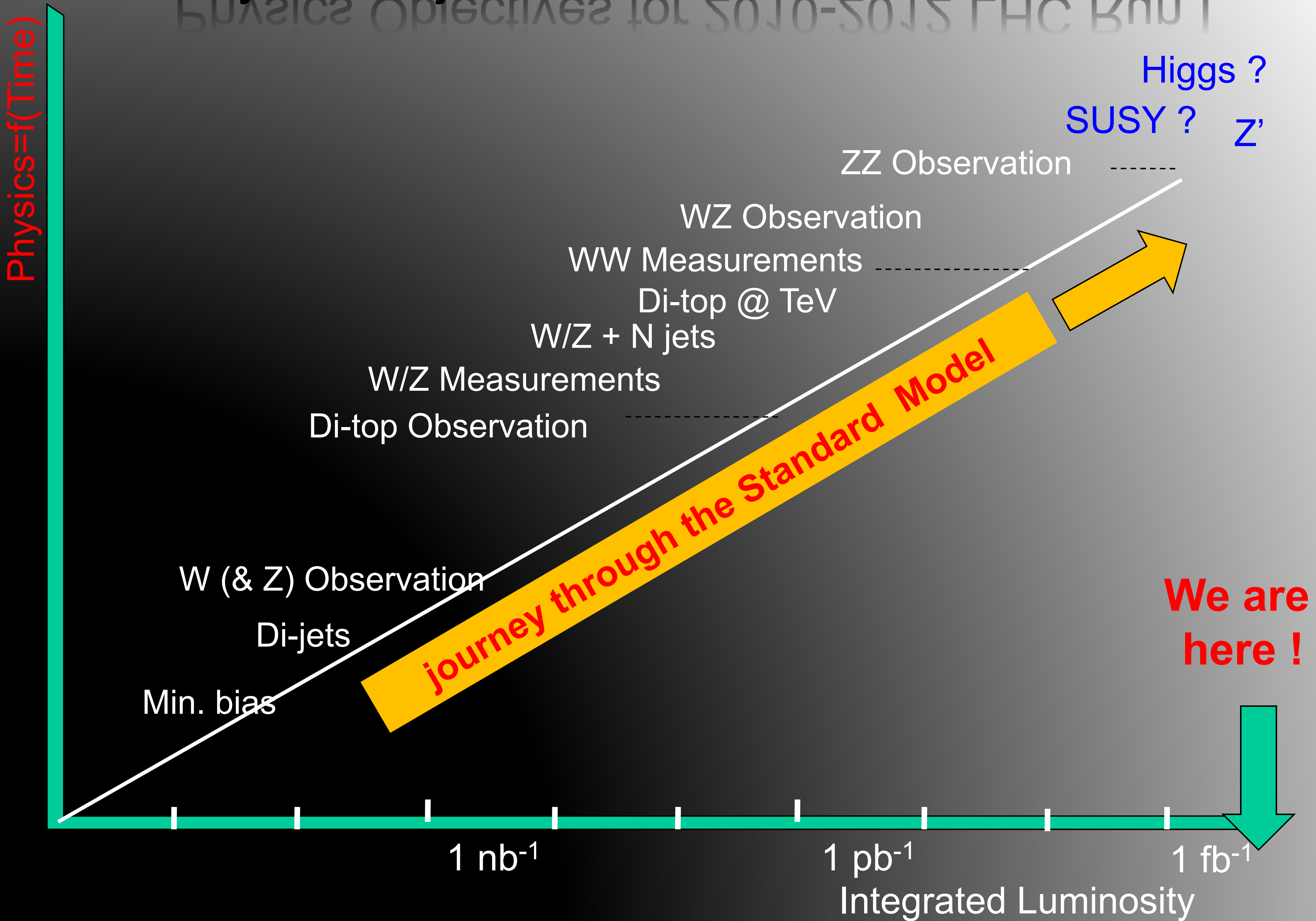
Exciting Times

At the energy frontier, the LHC brings us into unexplored territory:

Excellent progress

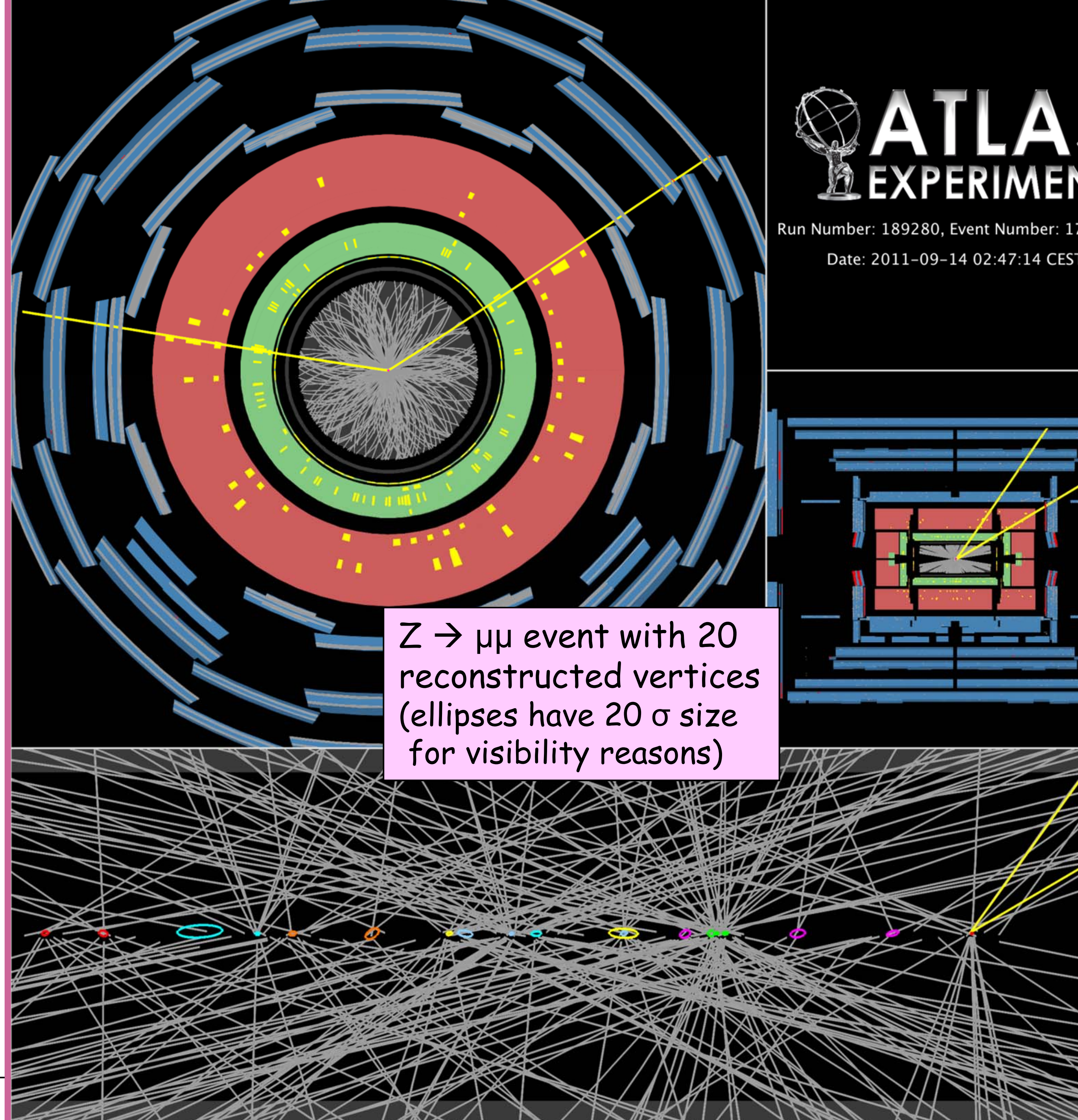
Accelerator – Experiments – Grid Comp.

Physics Objectives for 2010-2012 LHC Run I



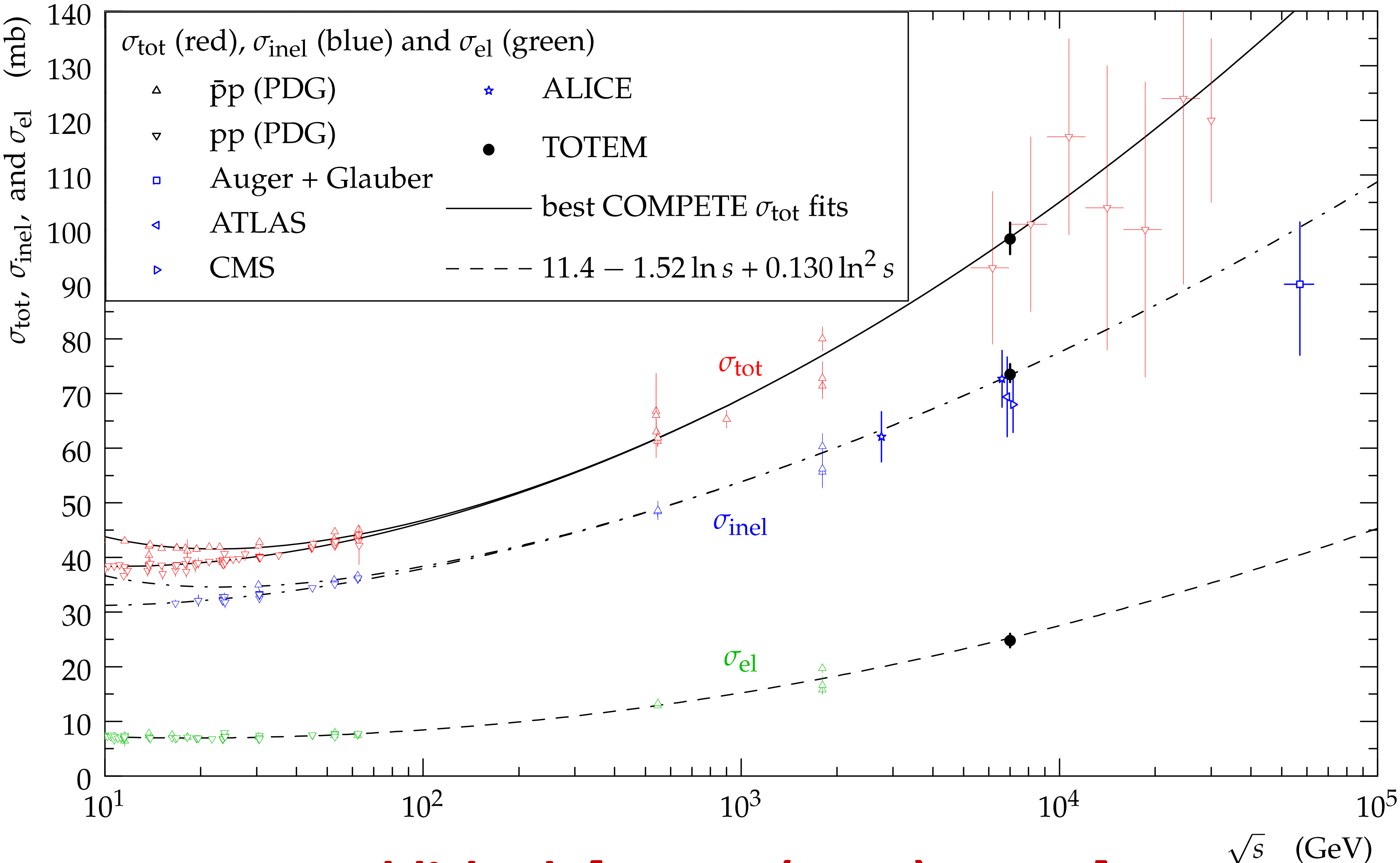
Pile-up

Experiments record data of **high quality** with **high efficiency** at luminosities not expected at such an early stage



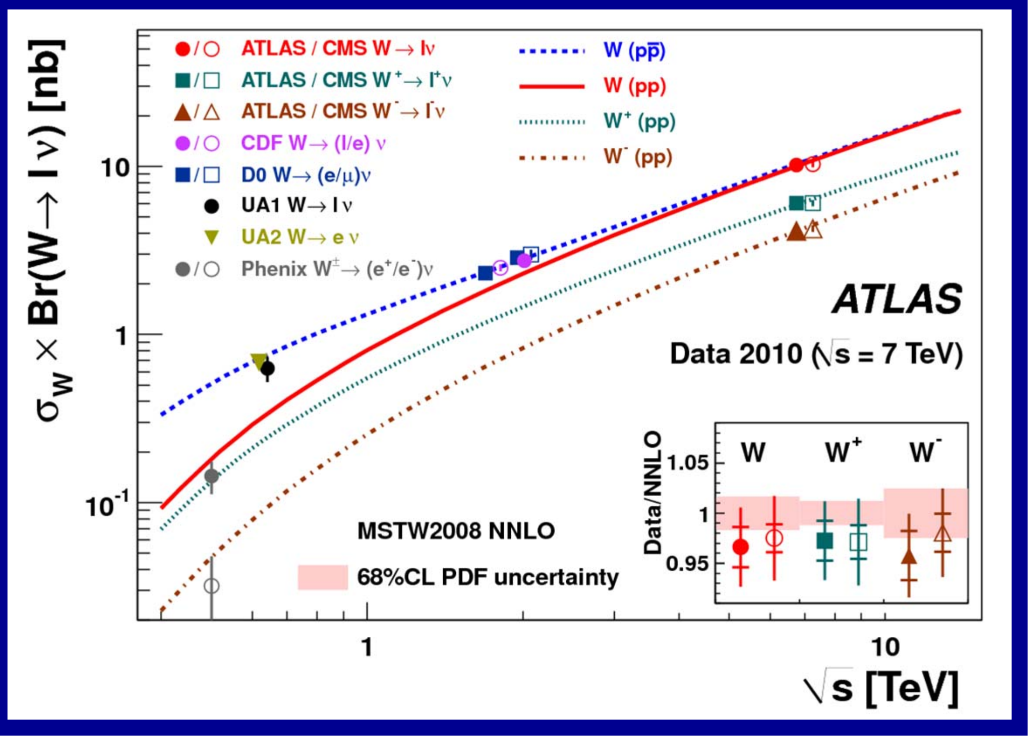
Z → μμ event with 20 reconstructed vertices (ellipses have 20 σ size for visibility reasons)

Total, Elastic, Inelastic Cross-Section

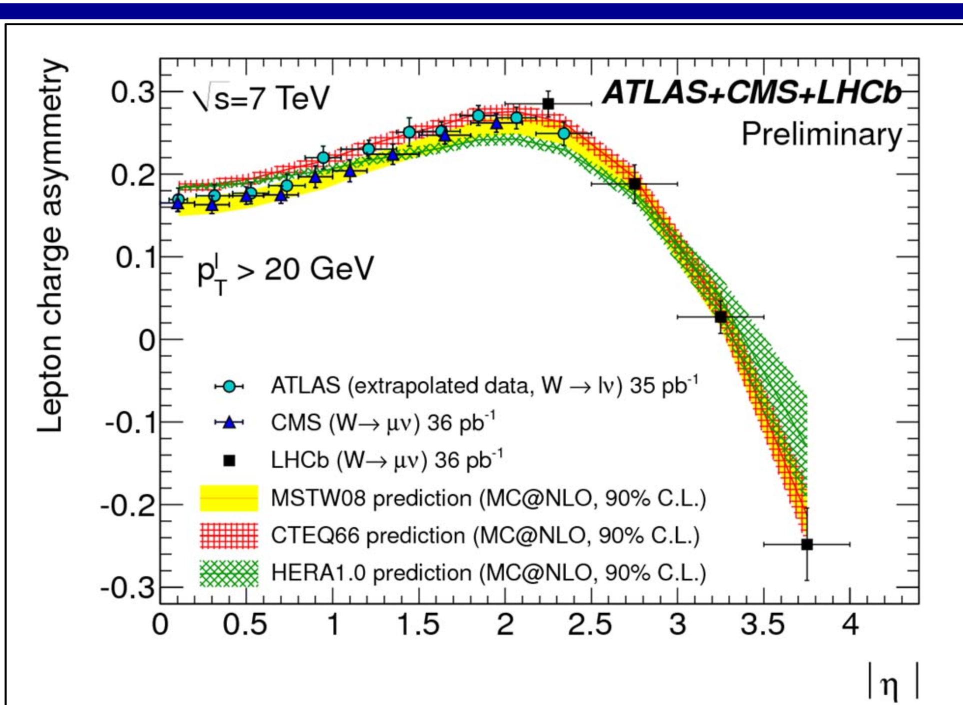


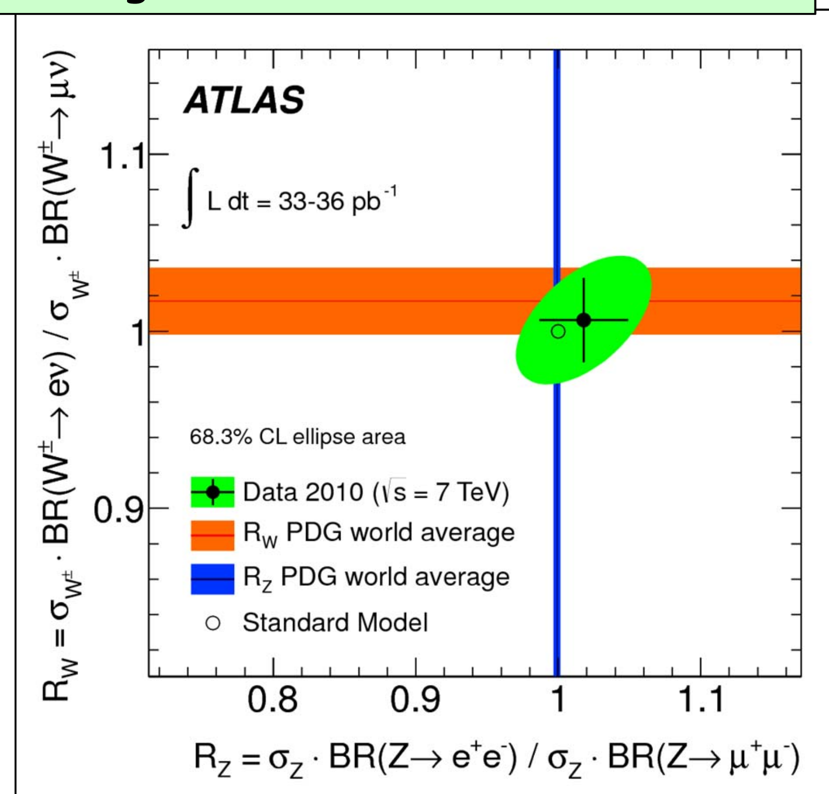
Published: [EPL 96 (2011) 21002]

W and Z physics



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

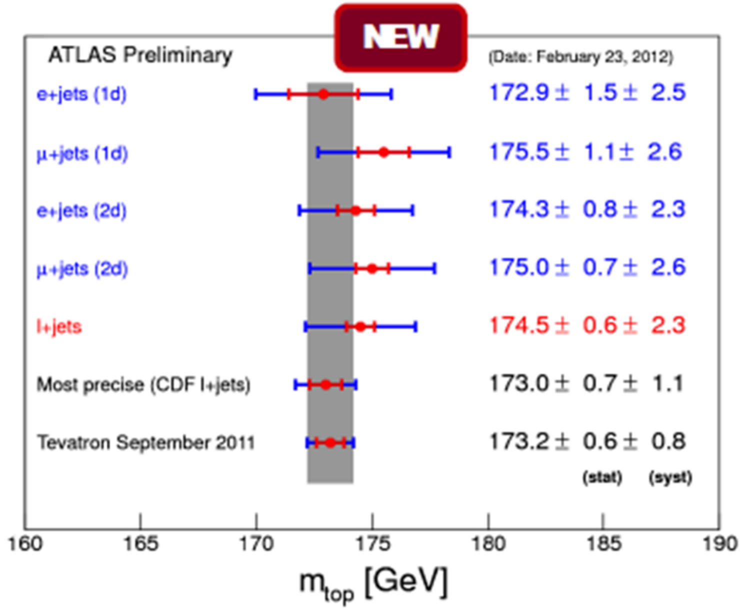


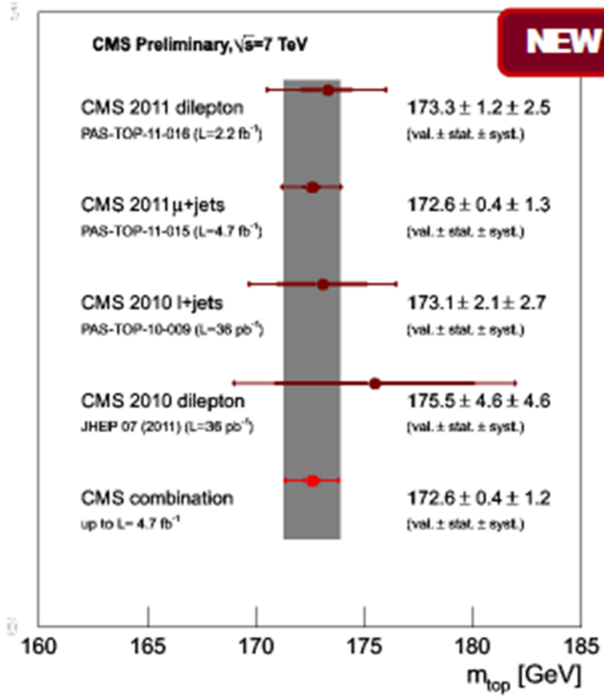


LHC is already in the game for m_{top}!

Top mass combination

CMS-PAS-TOP-11-018

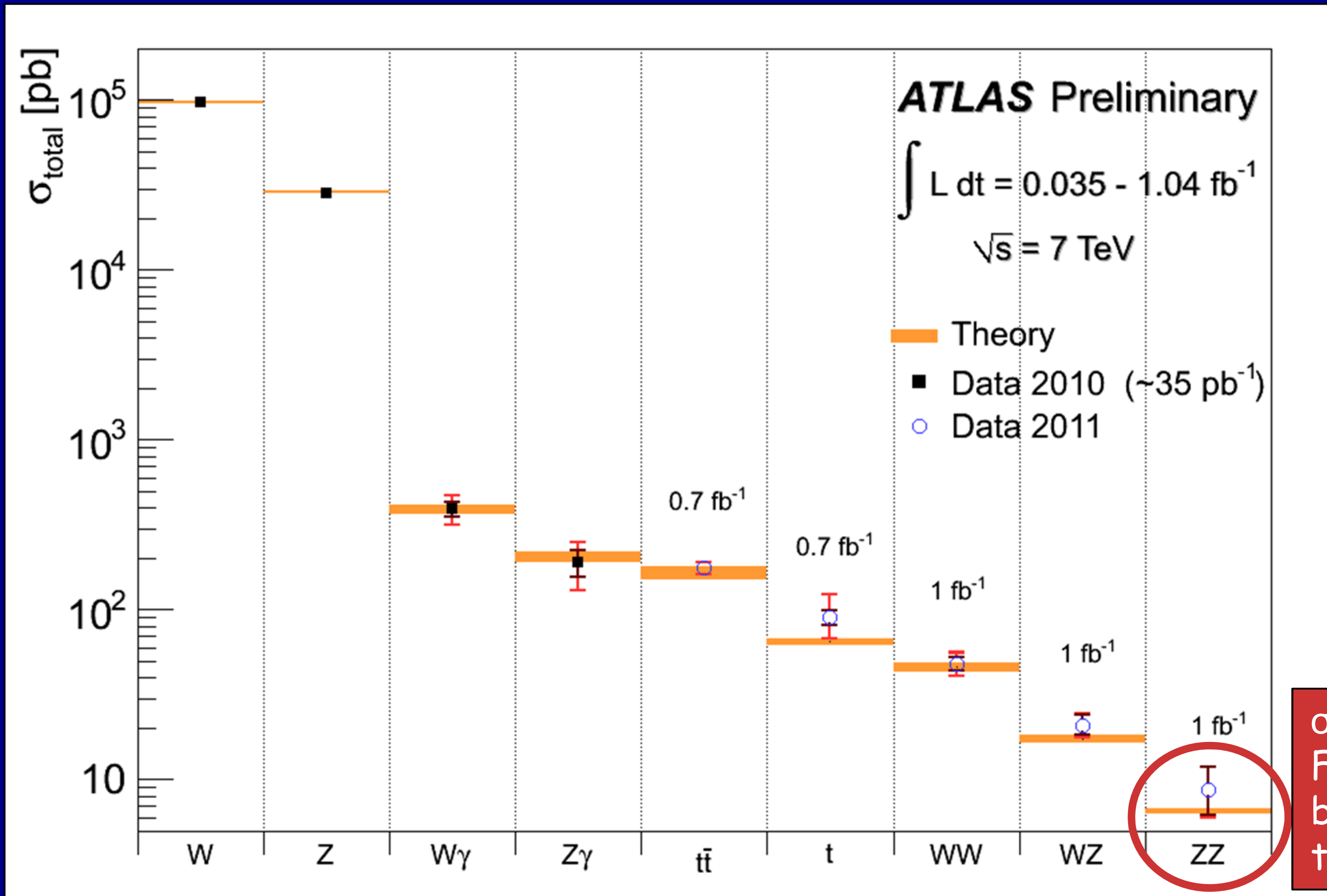




- **… and LHC combination is on the way**
- "Back of the envelope" calculation indicates that result will help decrease the current uncertainty from the Tevatron (partially uncorrelated systematics + higher statistics)

Headache error is color recombination – top quark is not a singlet and has « strings attached » ! (what does 'mass' mean?)
LHC vs tevatron …
Different process → different error? Or even different mass?

Summary of main electroweak and top cross-section measurements



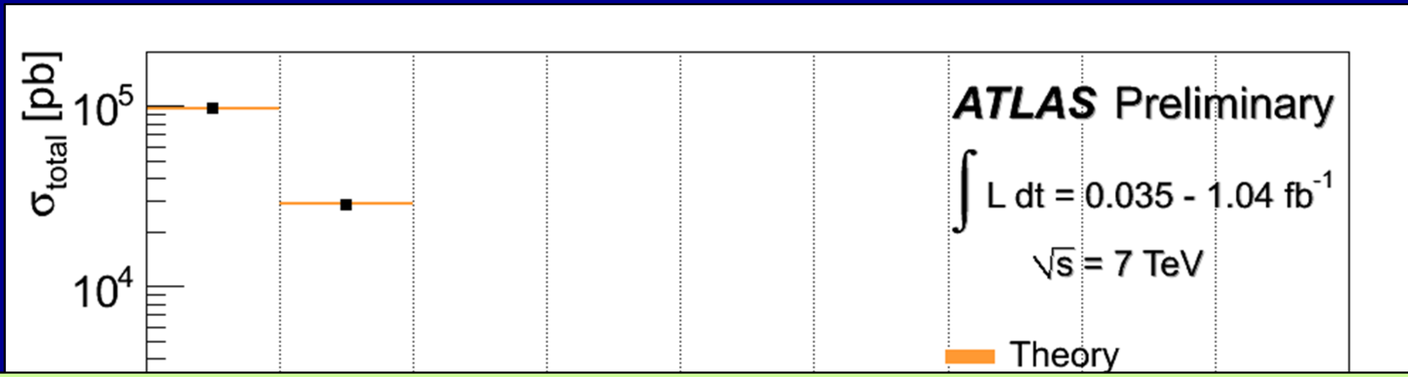
Inner error: statistical
Outer error: total

σxBR(ZZ→ 4l) ~ 40 fb
Few fb in narrow mass 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)

Summary of main electroweak and top cross-section measurements



Inner error: statistical
Outer error: total

In our 2010/2011 dataset (~ 5 fb^{-1}) we have (after selection cuts):

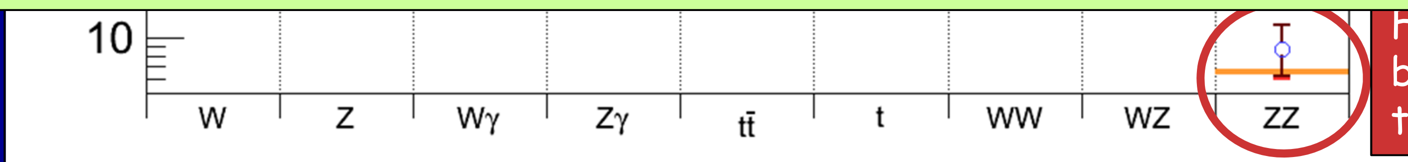
~ 30 M W→ μν, eν events

~ 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) processes



Few fb in narrow mass bin → comparable to H→ZZ$^{(*)}$→ 4l

Good agreement with SM expectations (within present uncertainties)

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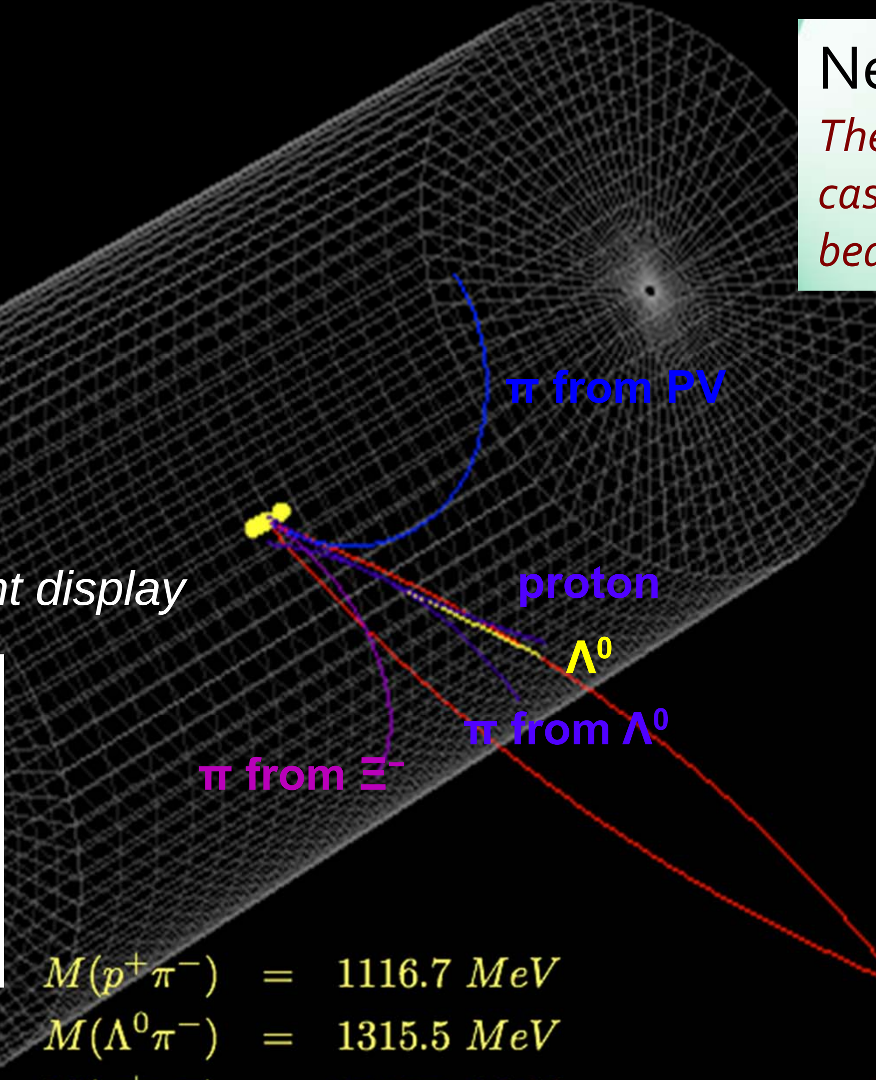
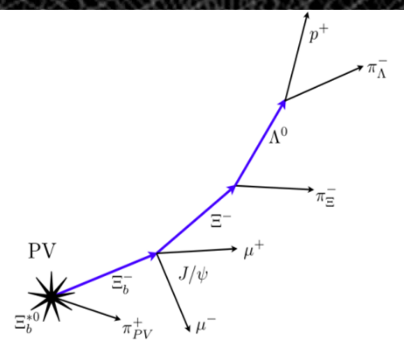
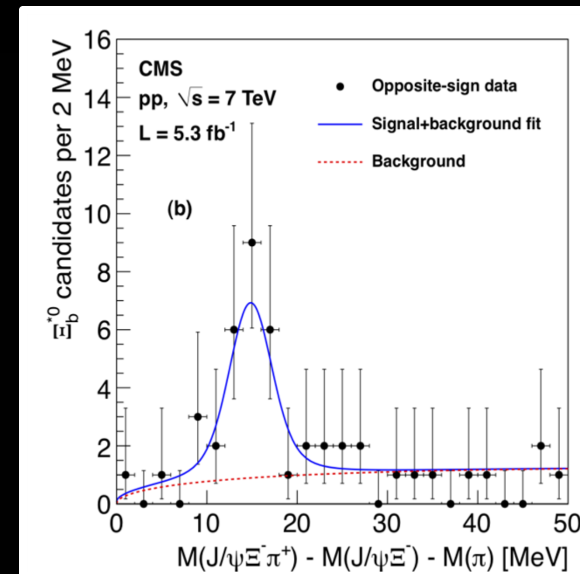
New ParticleDiscovery

The $\Xi_b{}^{*0}$ involves elegant cascade that CMS tracker handles beautifully.

Candidate event display



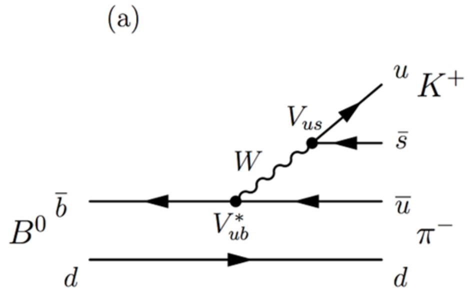




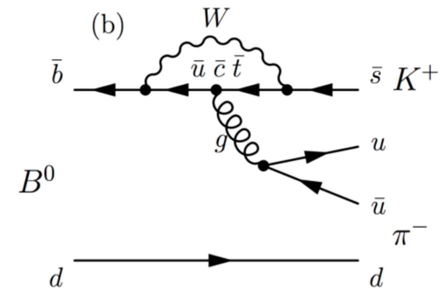
$$
\begin{aligned}
M(p^+\pi^-) &= 1116.7\ MeV \\
M(\Lambda^0\pi^-) &= 1315.5\ MeV \\
M(\mu^+\mu^-) &= 3117.1\ MeV \\
M(J/\psi\Xi^-) &= 5787.8\ MeV \\
Q(J/\psi\Xi^-\pi^+) &= 15.7\ MeV
\end{aligned}
$$

$$\Xi_b{}^{*0}\rightarrow\Xi_b{}^{-}\pi^+\rightarrow\Xi^- J/\psi\,\pi^+\rightarrow\Lambda\pi^-\mu^+\mu^-\pi^+\rightarrow p^+\pi^-\pi^-\mu^+\mu^-\pi^+$$

The Interference Experiment Works!



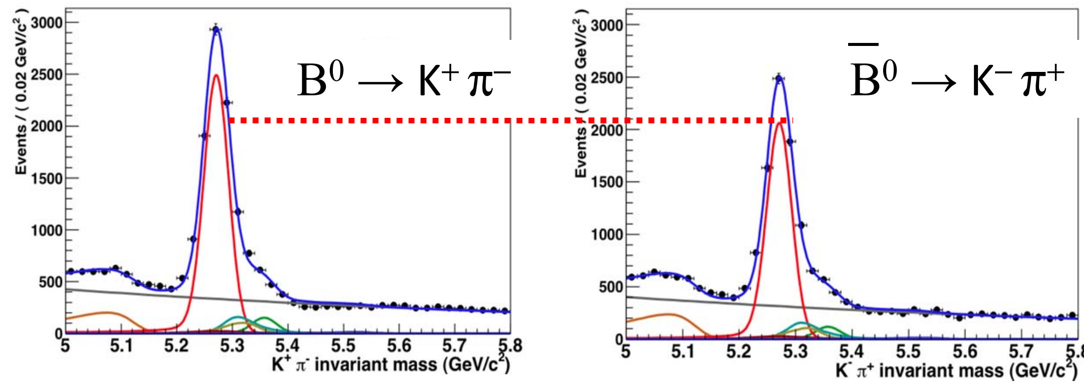
+



$B^0 \to K\pi$

A_{CP} = -0.088 ± 0.011 ± 0.008

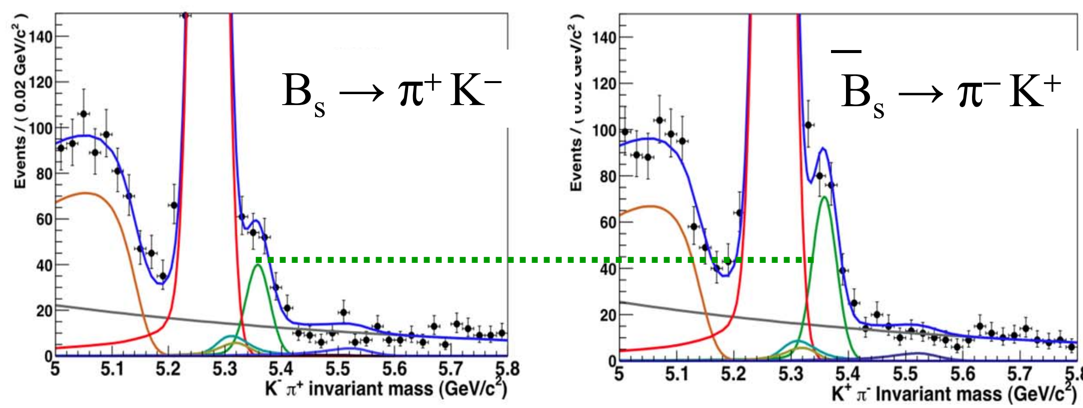
Most precise and first **5σ** Observation of CP violation in a hadronic machine



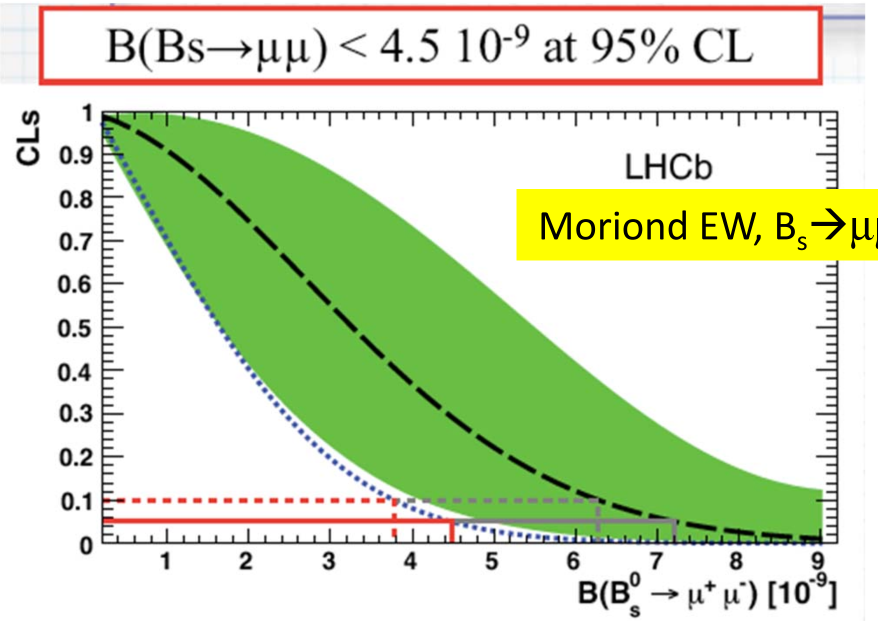
$B_s \to \pi K$

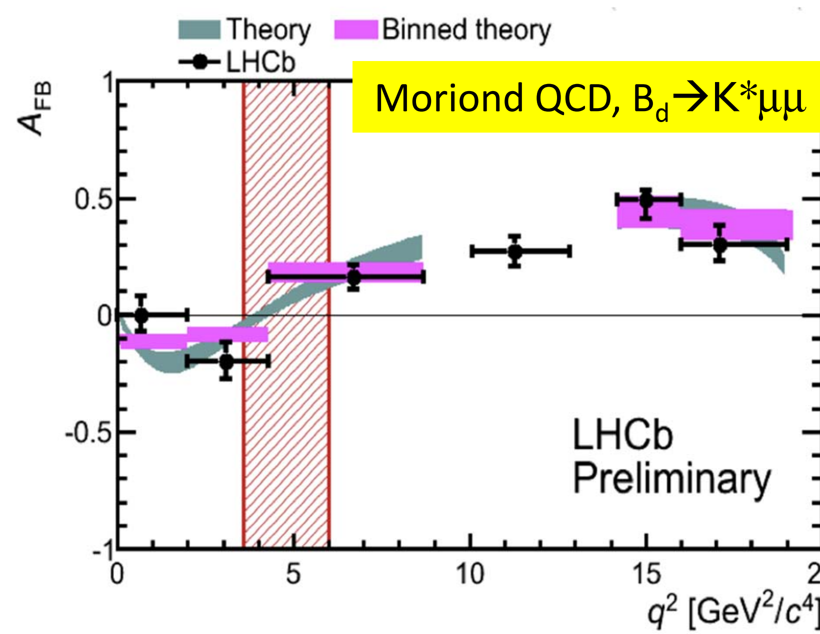
A_{CP} = 0.27 ± 0.008 ± 0.02

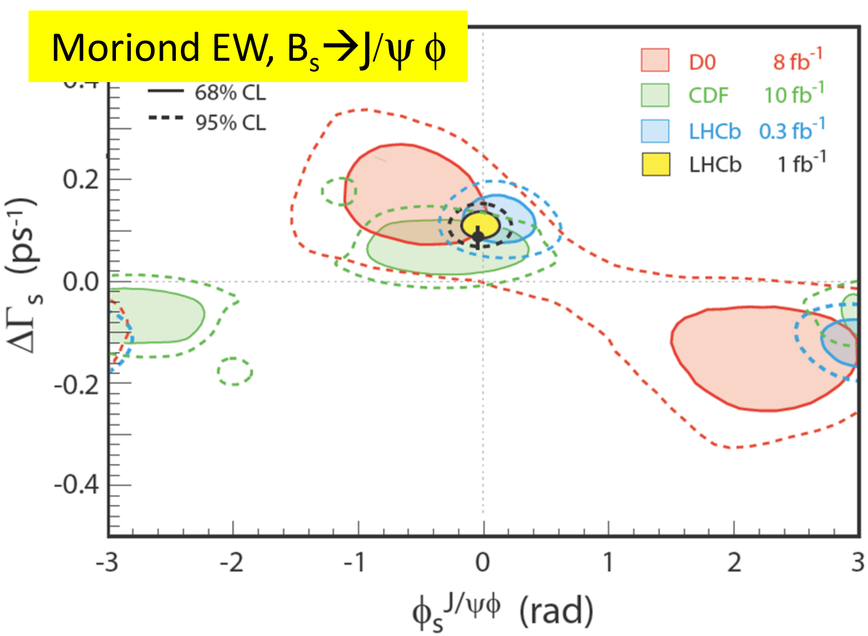
First **3σ** evidence for CP asymmetry in Bs decays

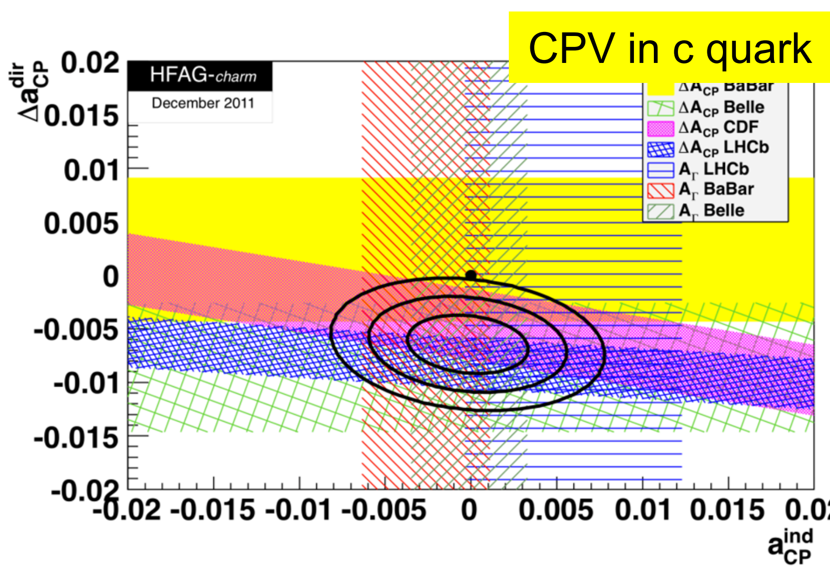


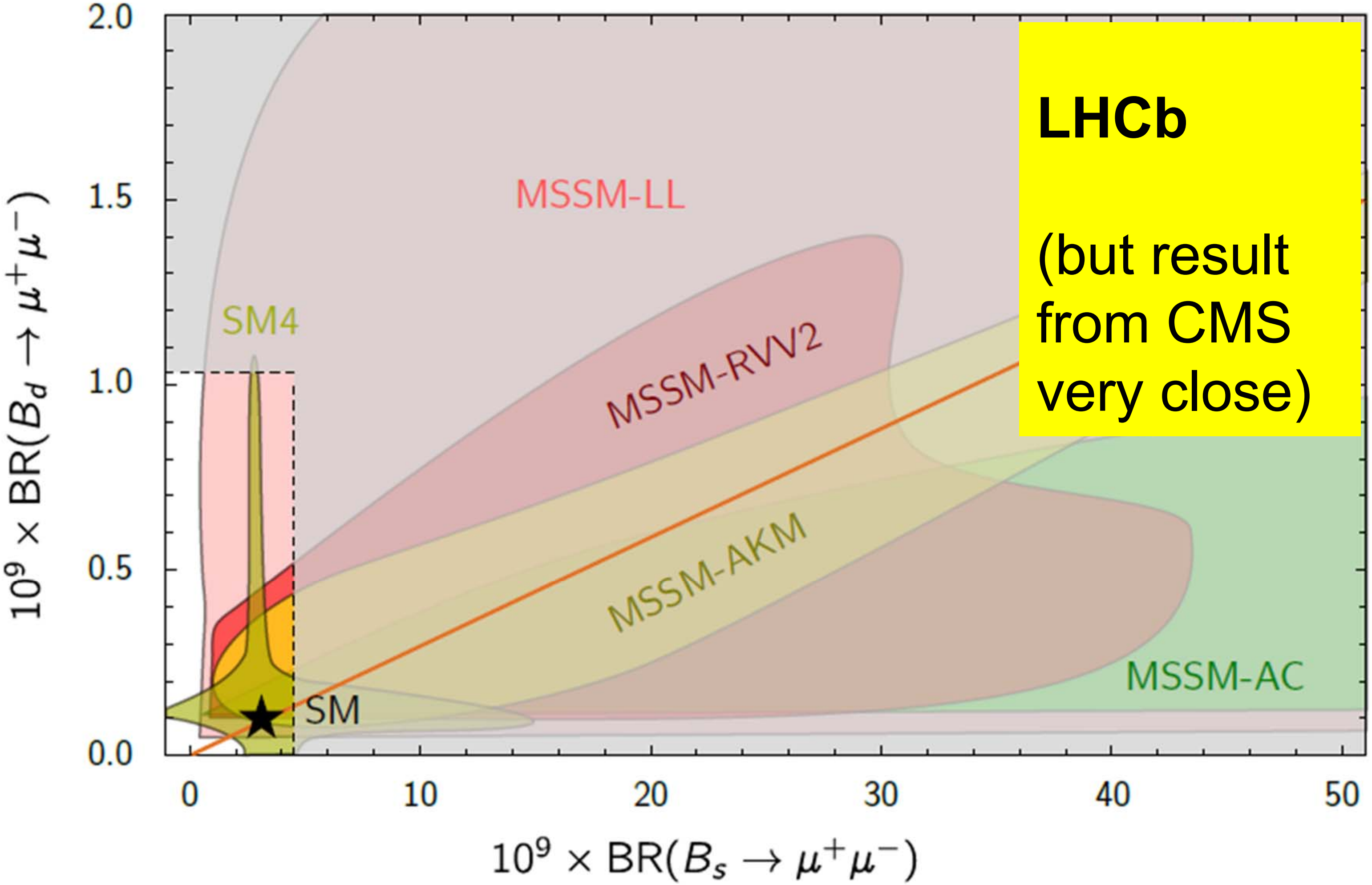
Highlights of LHCb results from 2012 Winter Conferences











New experimental bounds already exclude large part of model parameter space

The “beauty” of charm

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

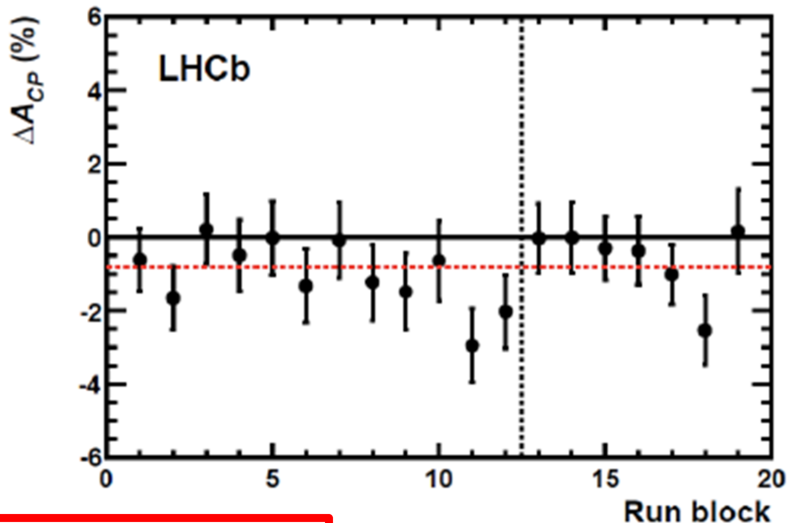
- First Evidence of CP viol. in charm decays in the measurement of D→hh asymmetry

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

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

$$\boxed{\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (-0.82 \pm 0.21 \pm 0.11)\%}$$

- 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

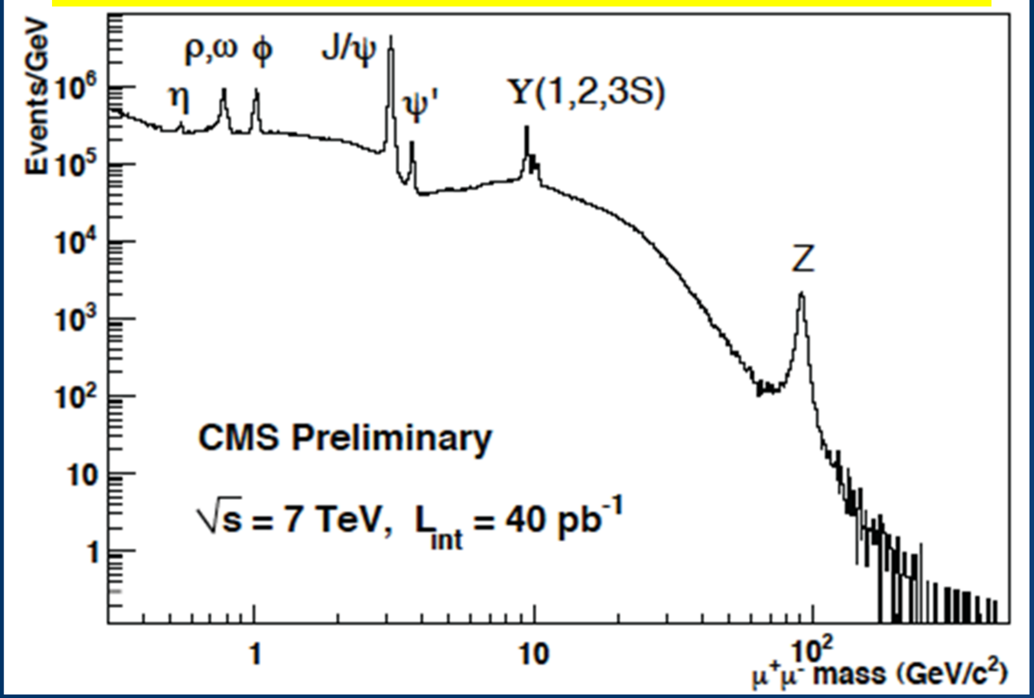


CDF confirms this result: (- 0.62 ± 0.21 ± 0.10) %

Excellent performance……

….in 2010 and 2011
over 5/fb delivered

re-discovery of the Standard Model



- Experiments have about completed their journey through the Standard Model …

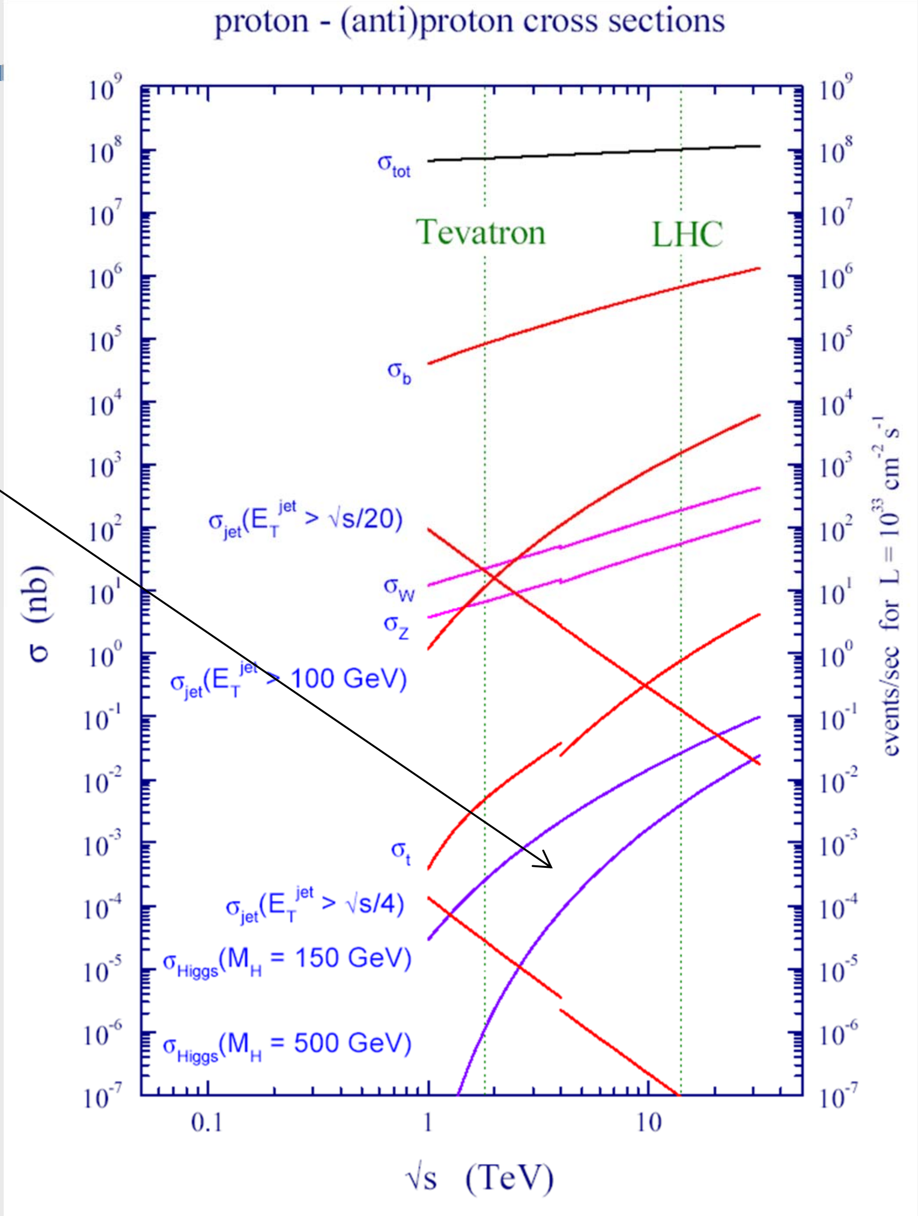
  and have started to take us into uncharted territories …

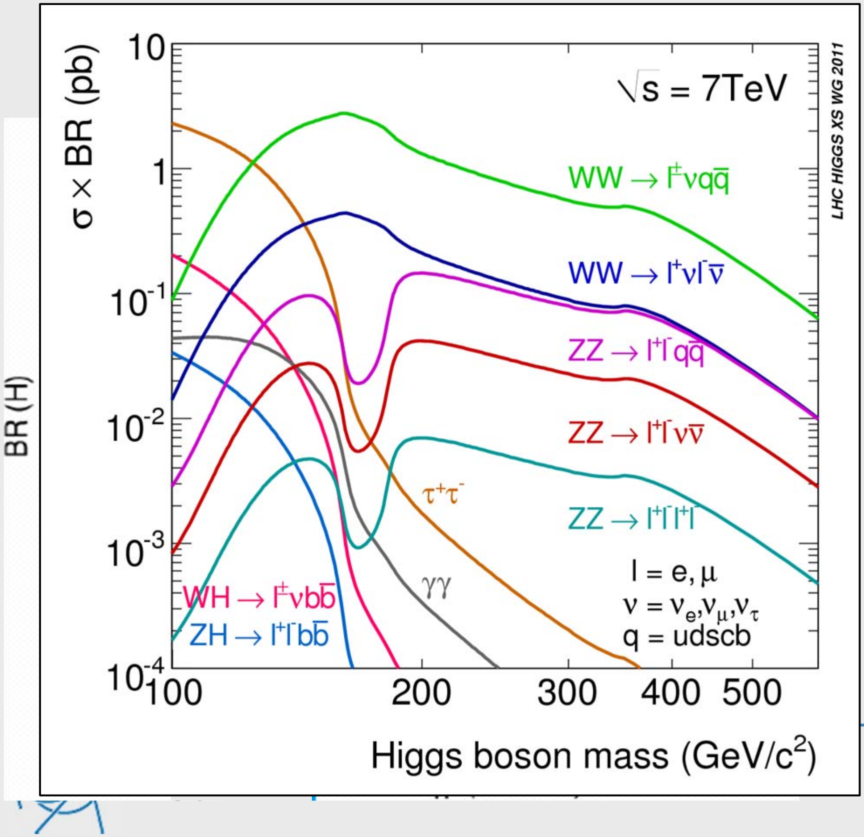
So: what about the Higgs ?

Search for the Higgs-Boson at the LHC

Production rate
of the Higgs-Bosons
depends on its mass

as well as its decay possibilities





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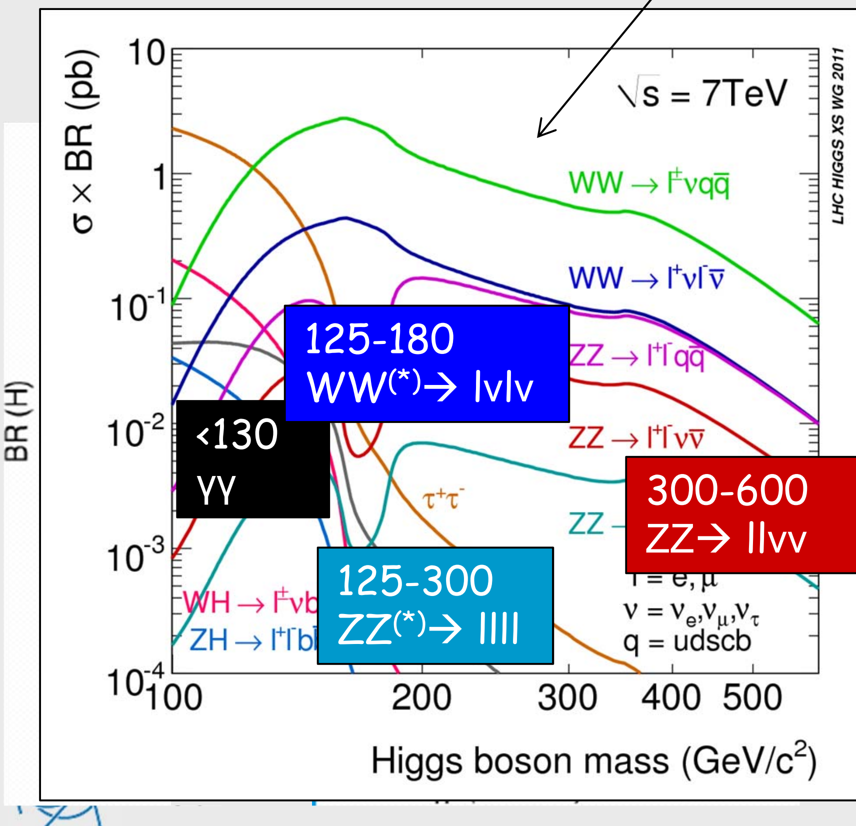
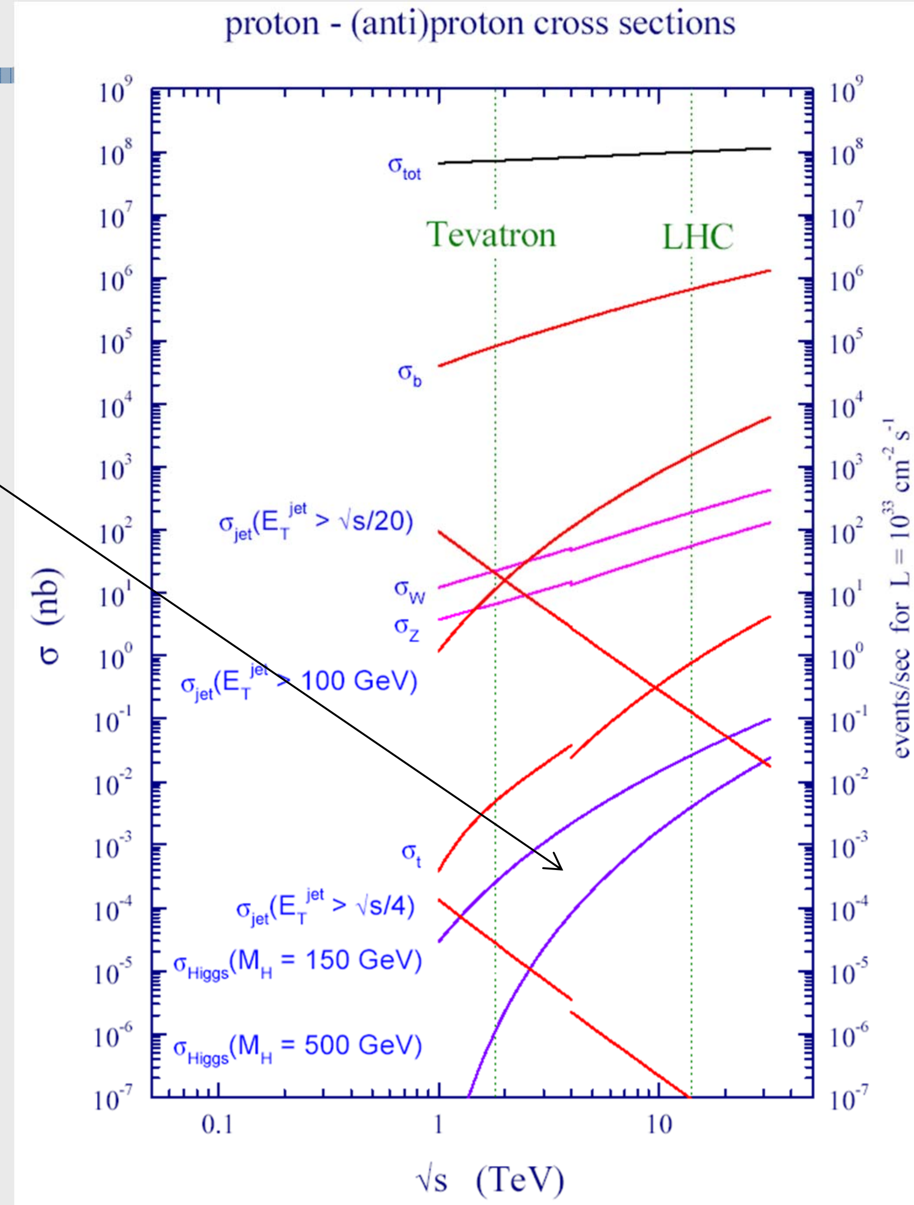
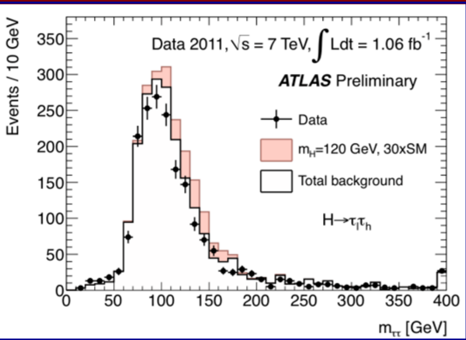
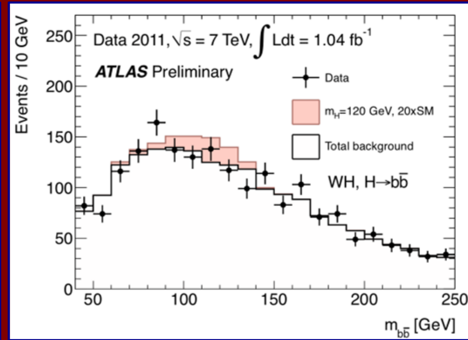
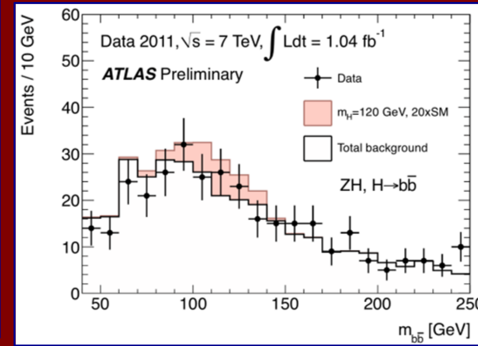
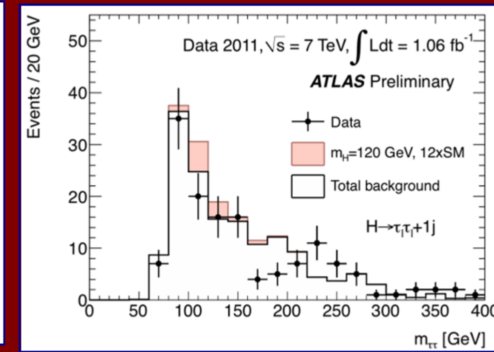
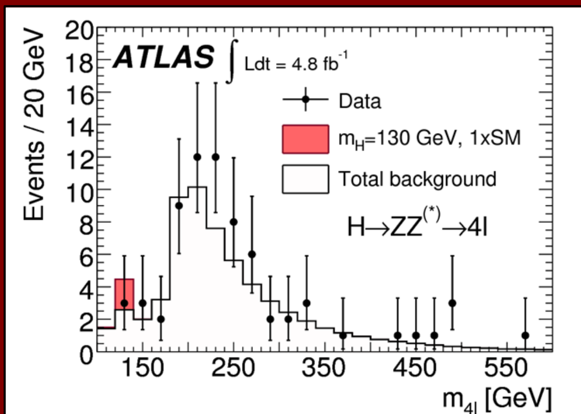
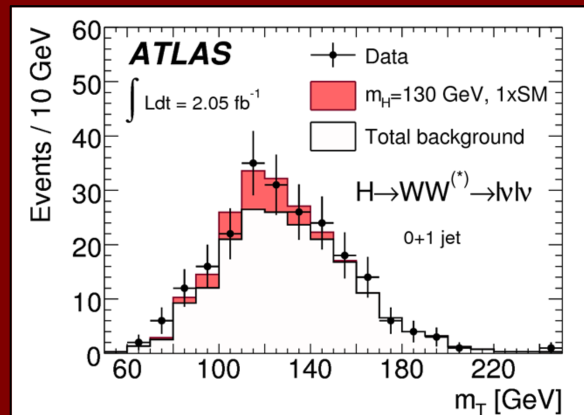
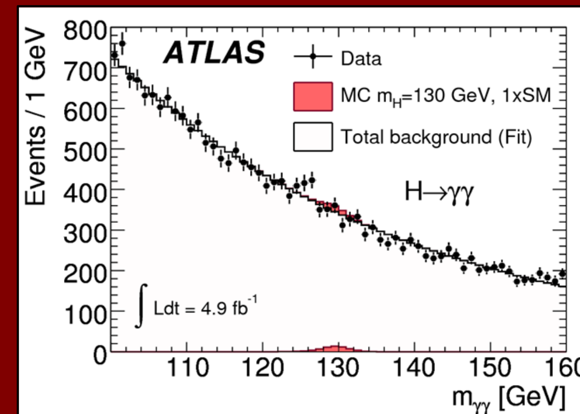
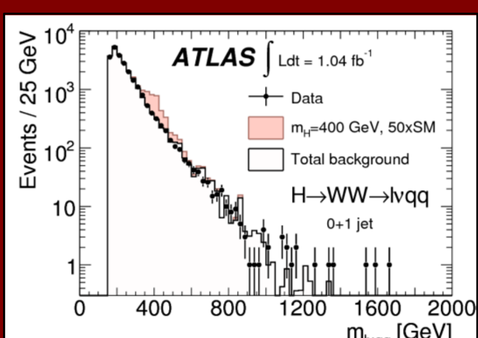
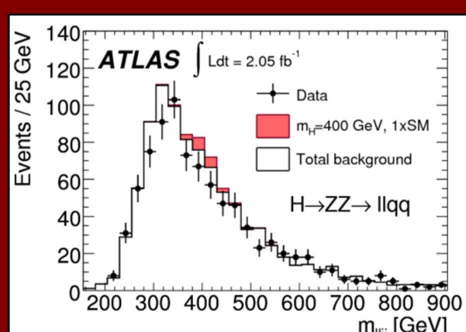
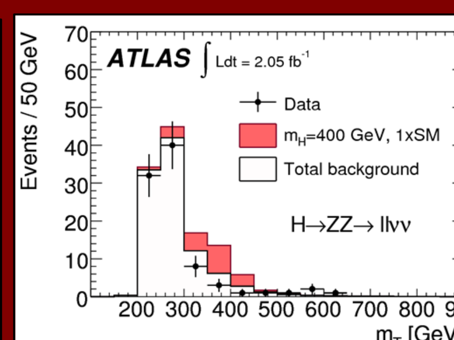
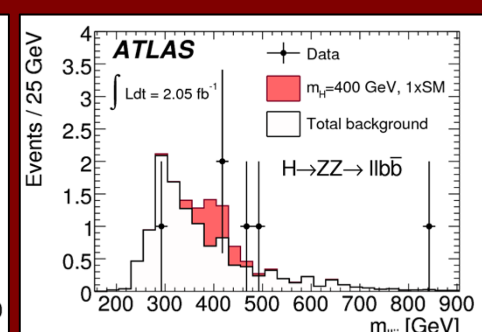


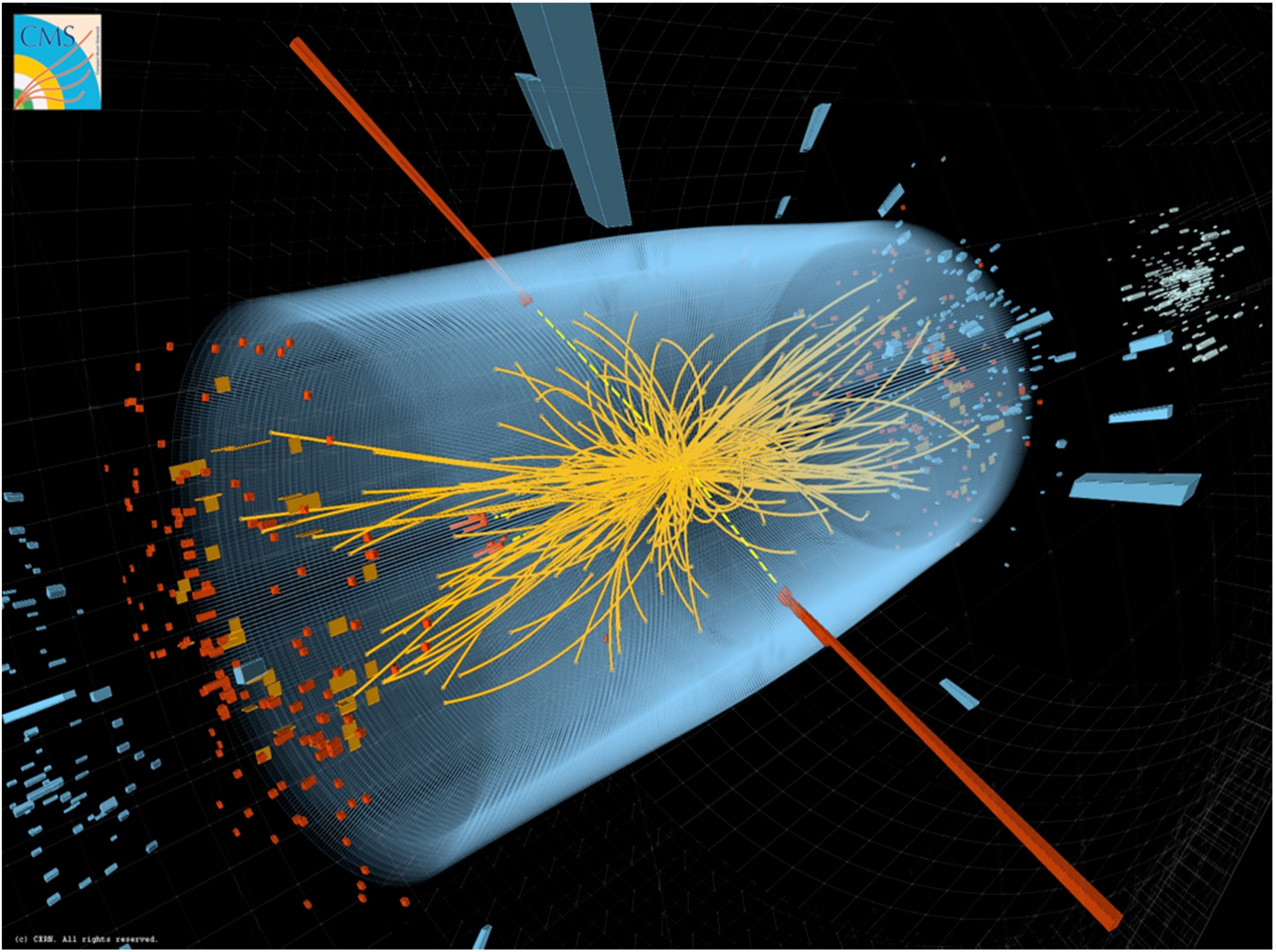


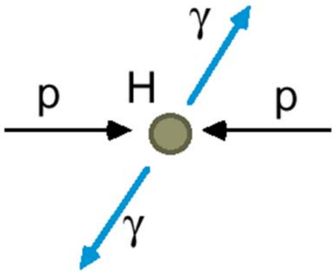

Data 2011, √s = 7 TeV, ∫Ldt = 1.06 fb⁻¹
ATLAS Preliminary
Data
m_H=120 GeV, 30xSM
Total background
H→τ_lτ_h
Events / 10 GeV
m_ττ [GeV]

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]

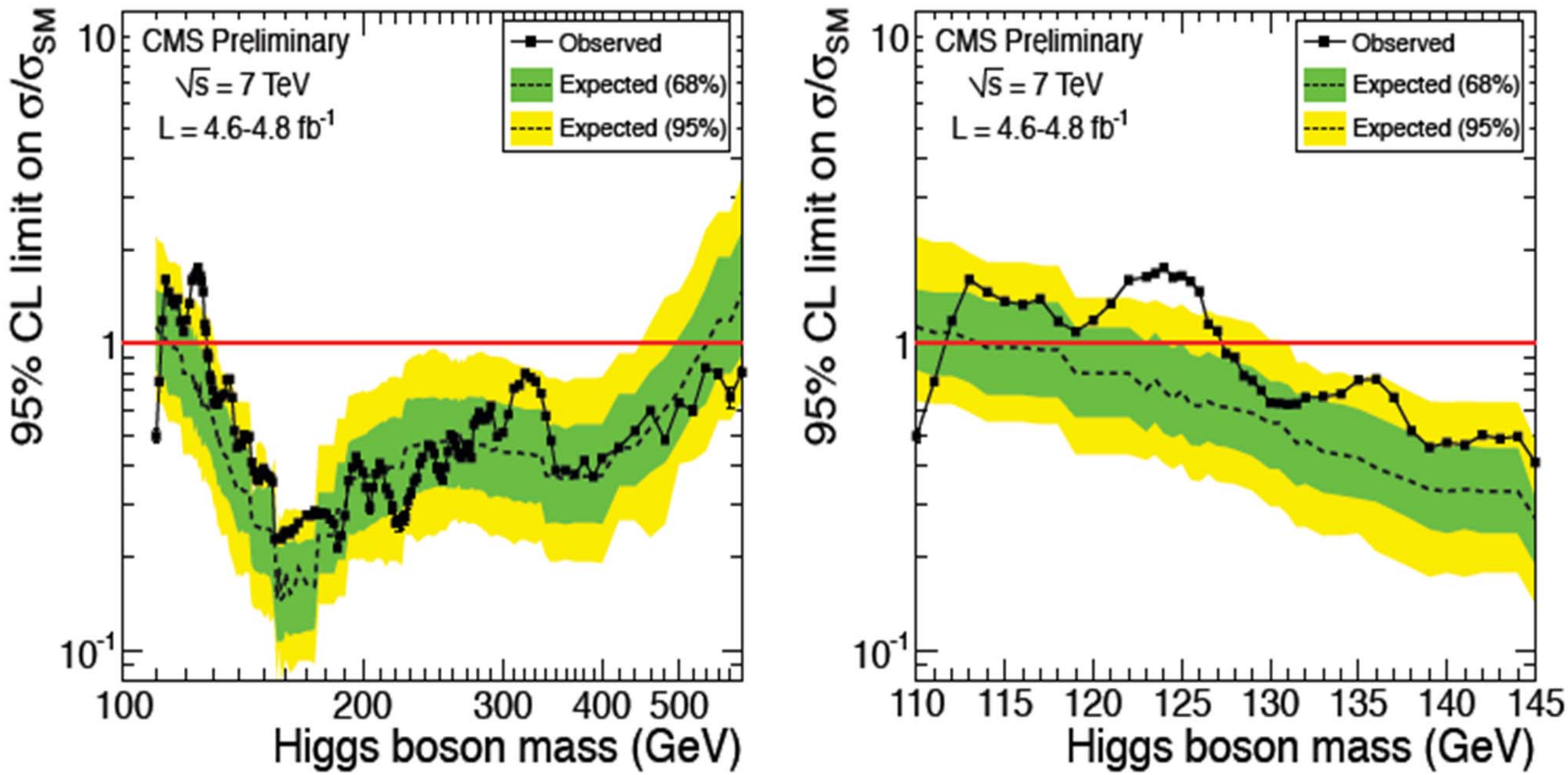
A Collision with two Photons





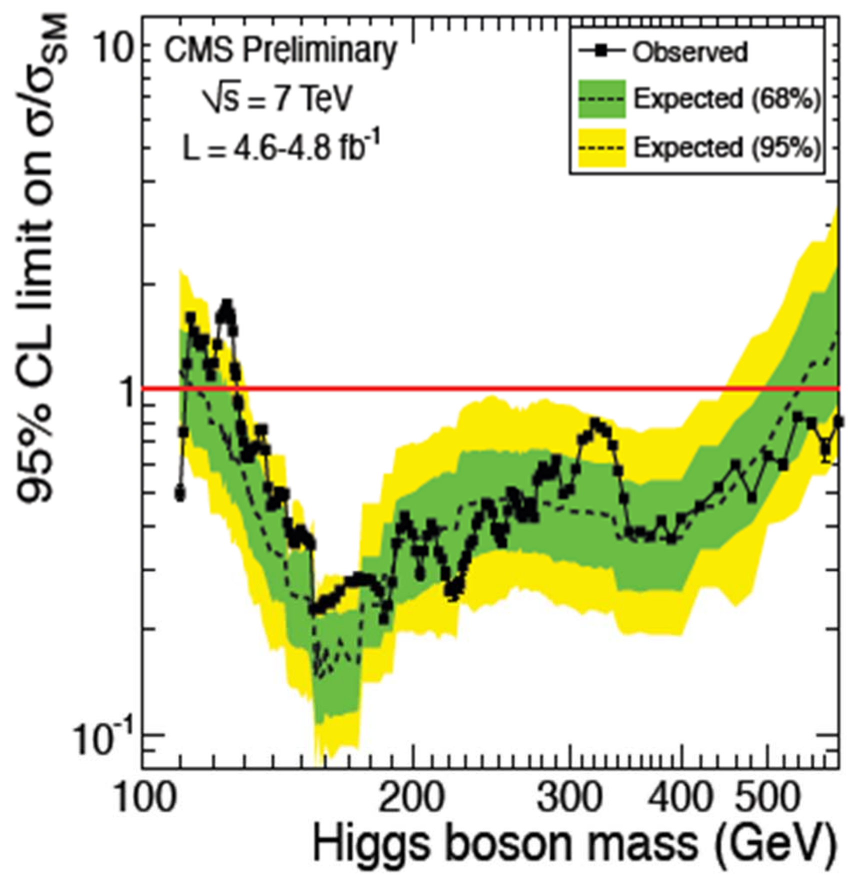
A Higgs or
a ‘background’
process without
a Higgs?

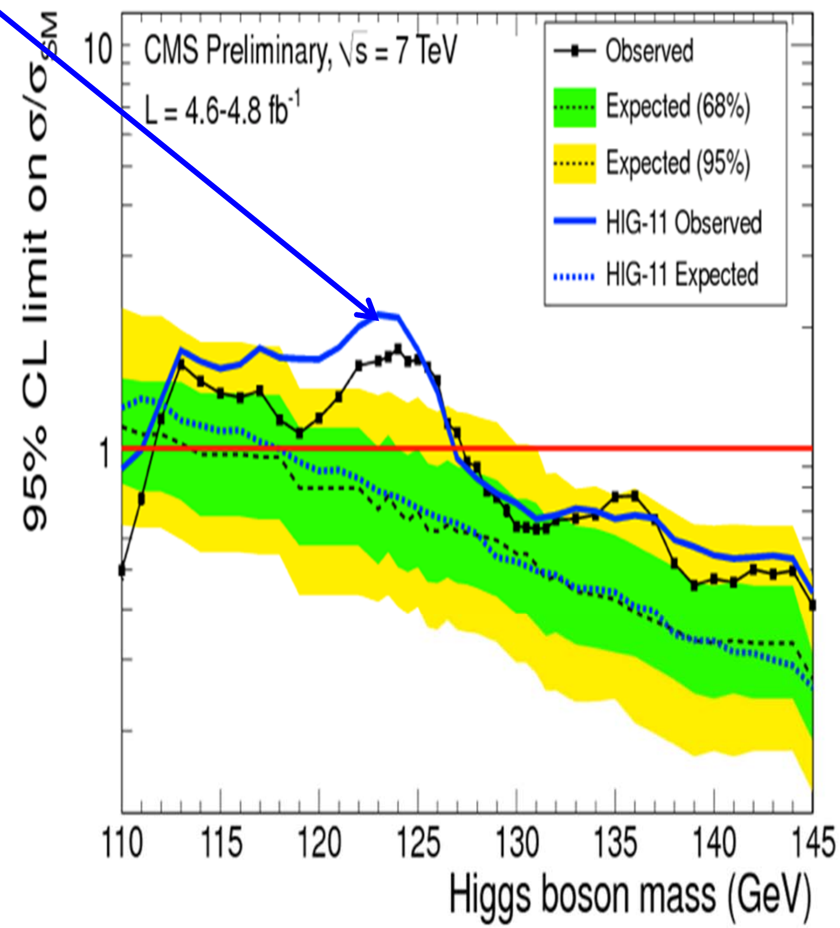
New Combination



New Combination

Published



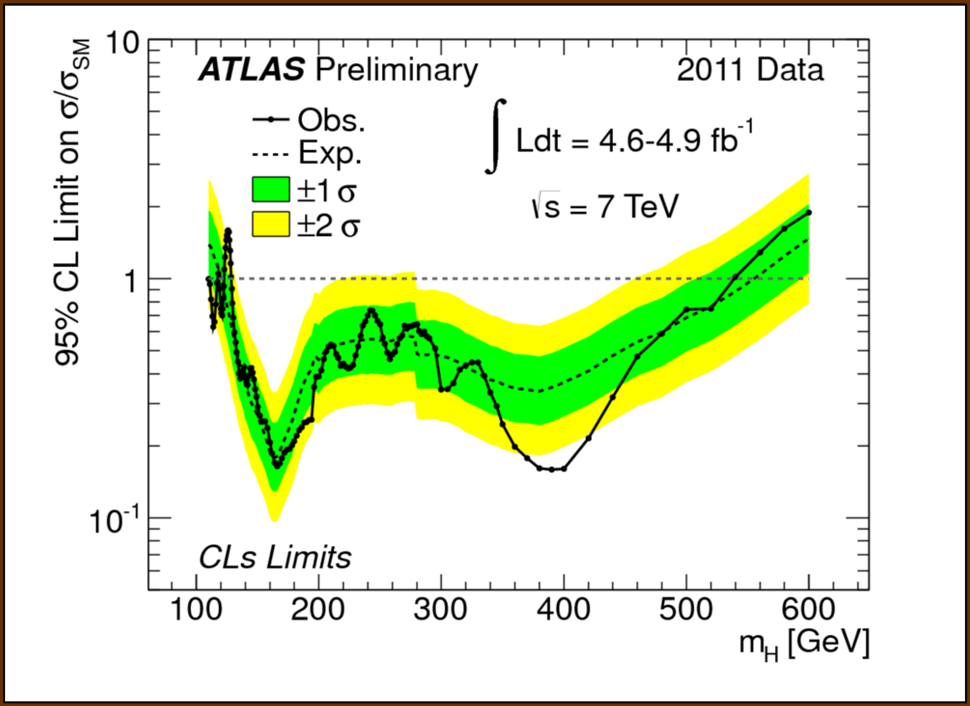


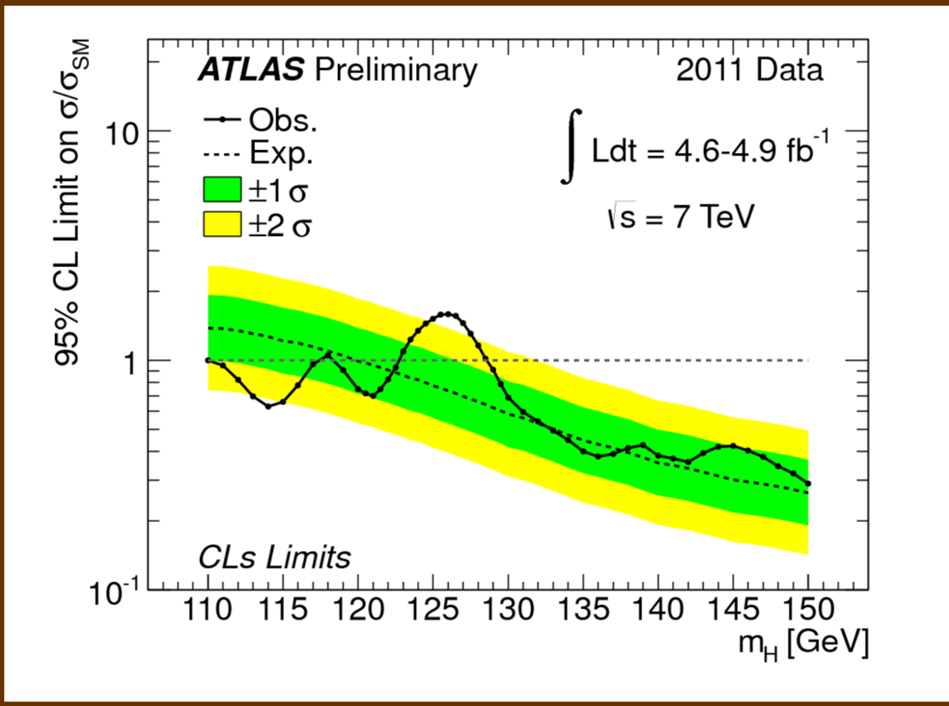
It took ~30 years to experimentally restrict the SM Higgs mass to be above 114 GeV
CMS and ATLAS independently eliminated another ~475 GeV of the range in 2011

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

T

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



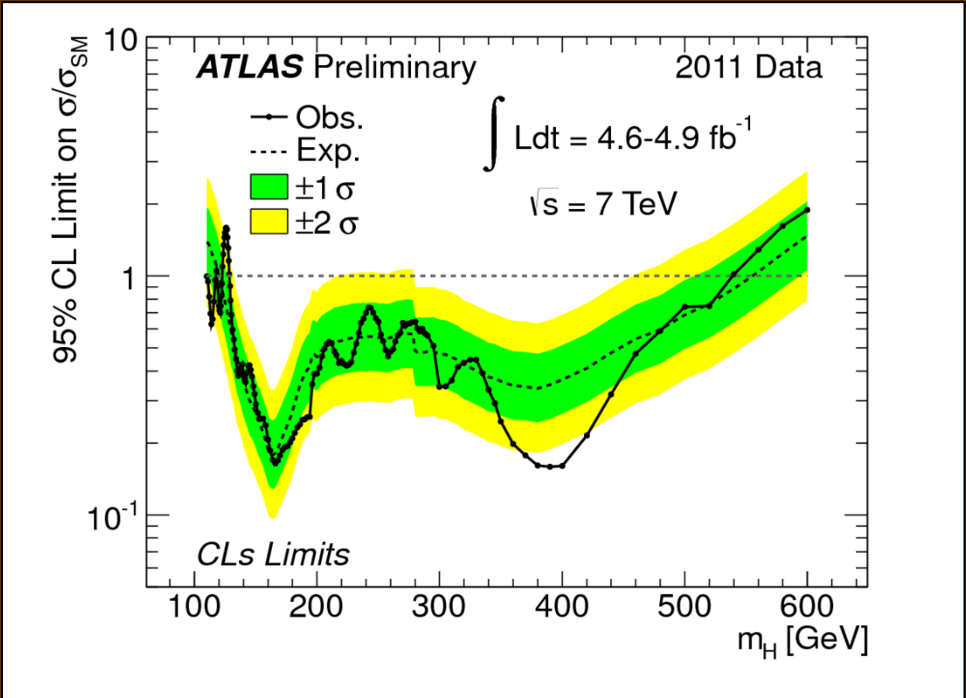


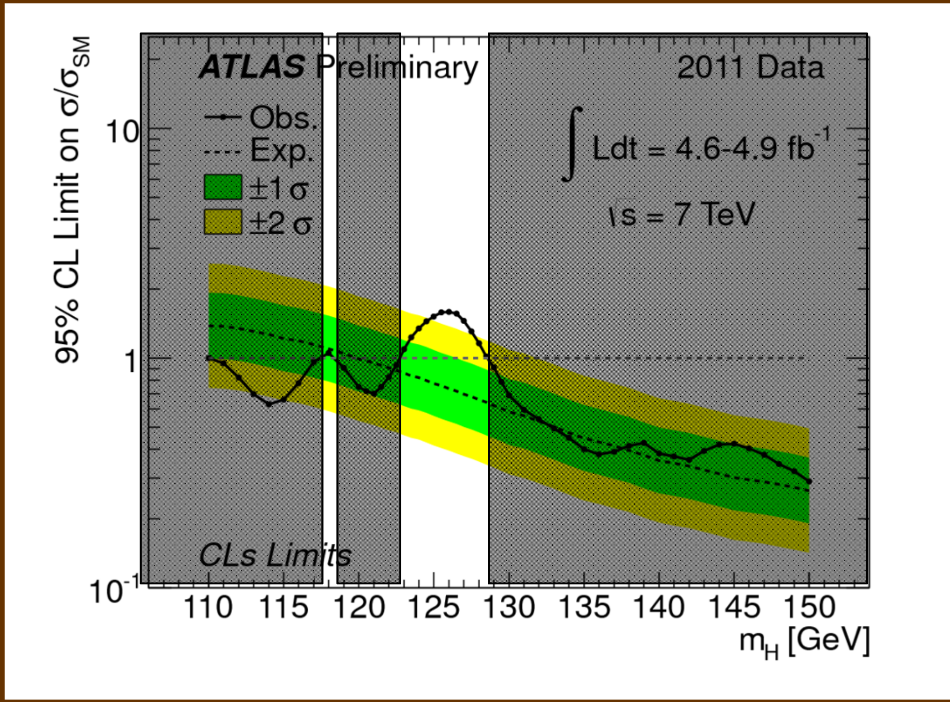
Excluded at 95% CL	$110 < m_H < 122.5$ GeV (except 117.5-118.5) $129 < m_H < 539$ GeV	Expected if no signal 120-555 GeV
Excluded at 99% CL	$130 < m_H < 486$ GeV	

NEW: full 2011 dataset

T

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





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Tevatron also sees enhancement in this mass region in the decay mode H→bb

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

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

2012 run:
8 TeV, expect ~15/fb

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

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

What about Physics

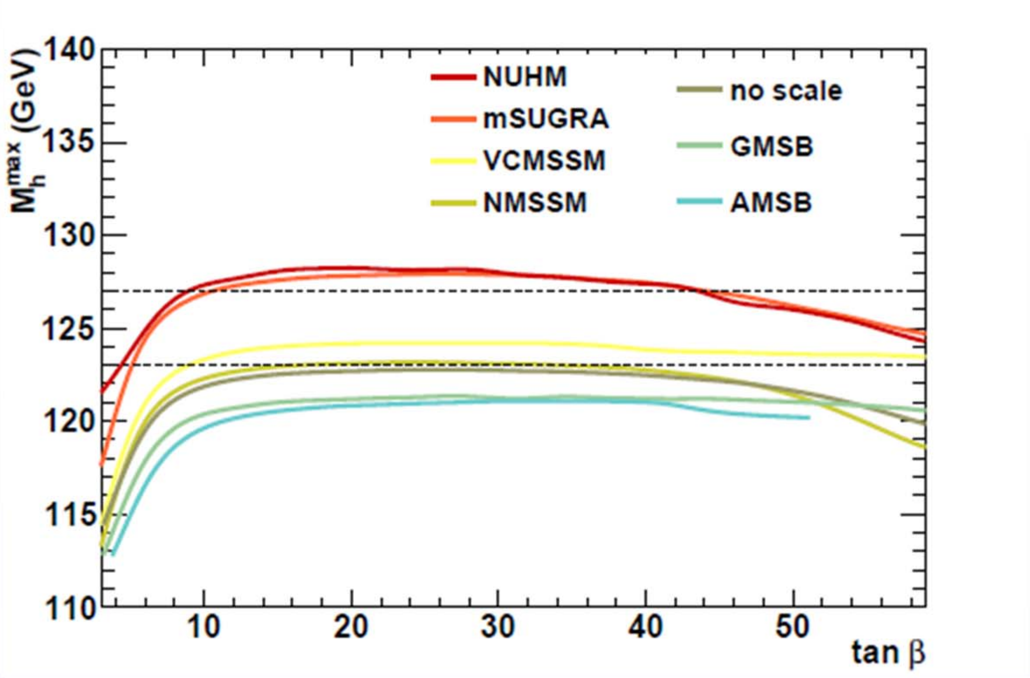
beyond the Standard Model ?

Supersymmetry

Is SUSY in trouble ?

So far no excess in missing energy events,…,
go beyond CMSSM, consider pMSSM

SUSY requires a low mass Higgs Boson with severe constraints on the max. mass value



Mahmoudi

A. Arbey, M. Battaglia, A. Djouadi, F.M., J. Quevillon, Phys.Lett. B708 (2012) 162

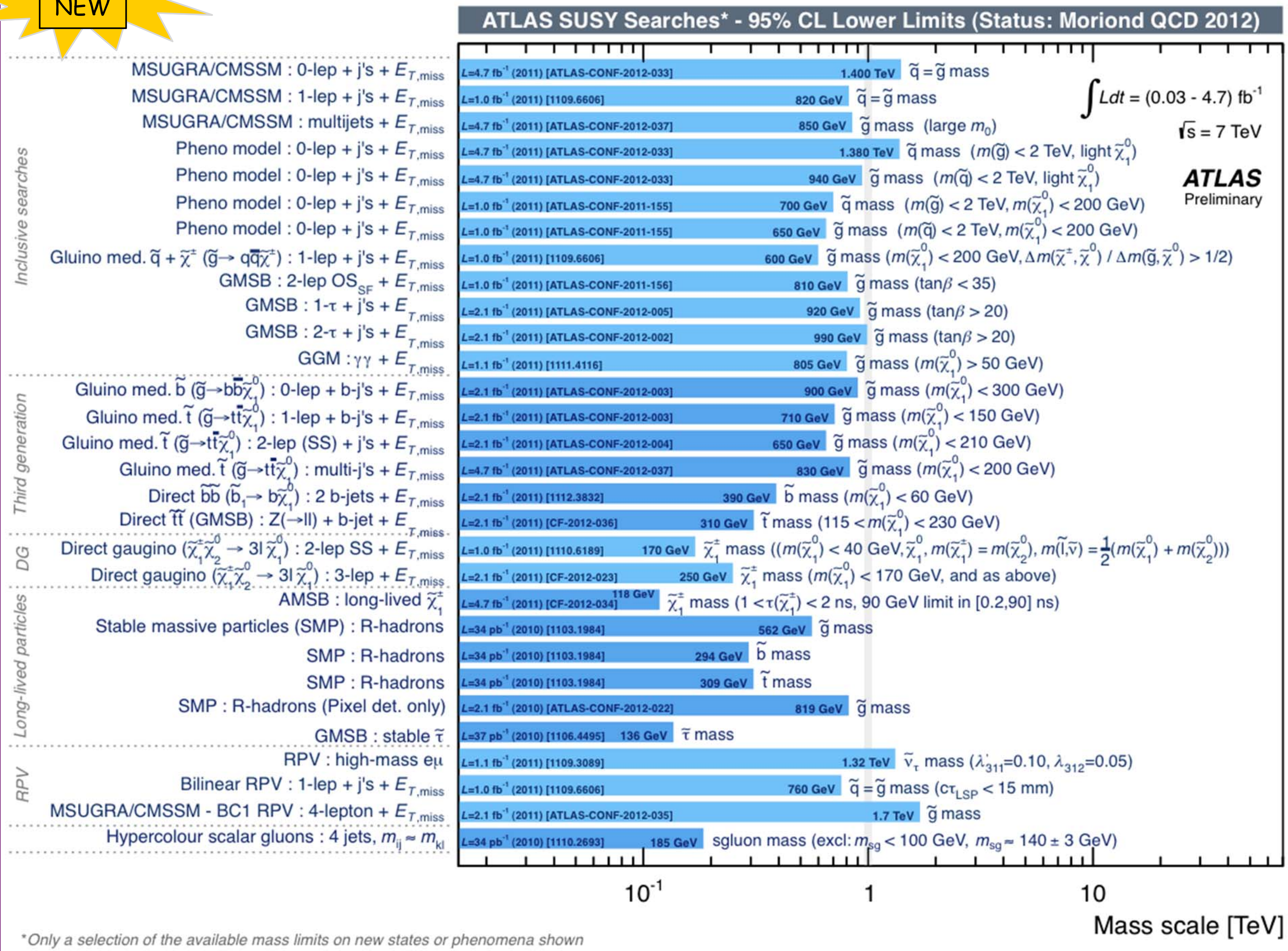
model	AMSB	GMSB	mSUGRA	no-scale	cNMSSM	VCMSSM	NUHM
M_h^{max}	121.0	121.5	128.0	123.0	123.5	124.5	128.5

End of AMSB and GMSB in their minimal versions!

Higgs mass of 125 GeV severe constraint on all models!

Main ATLAS results on SUSY searches

NEW



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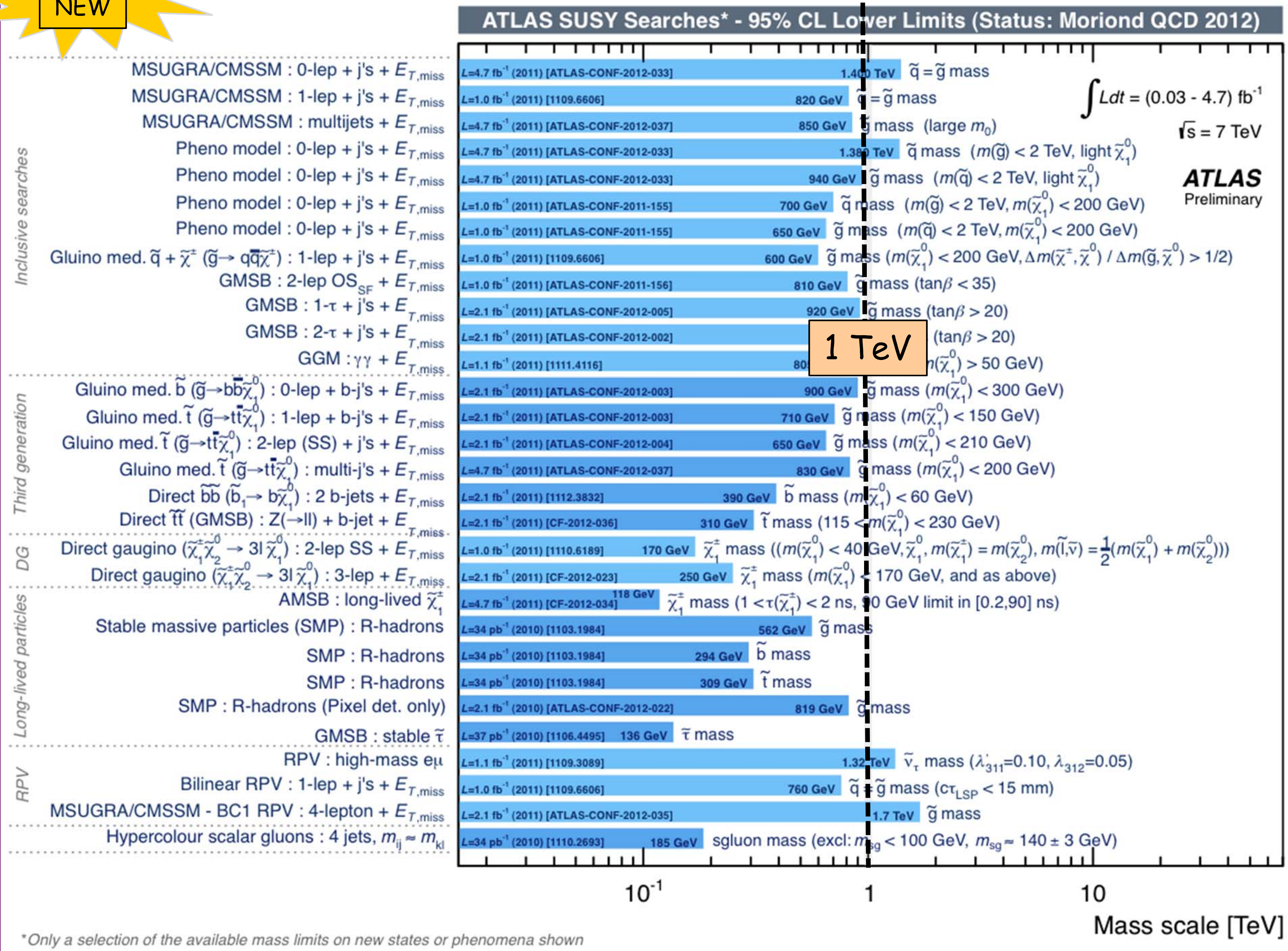

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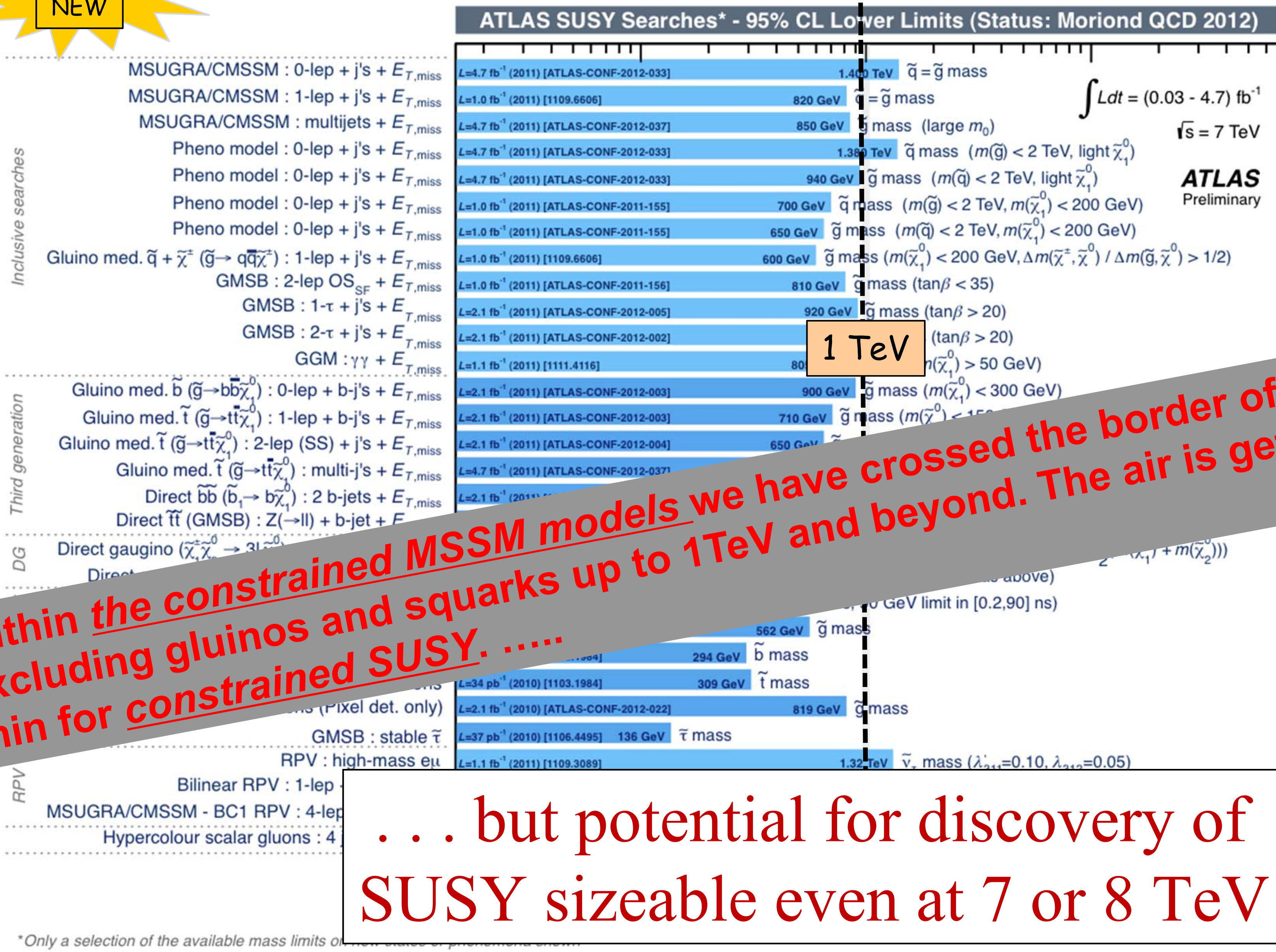
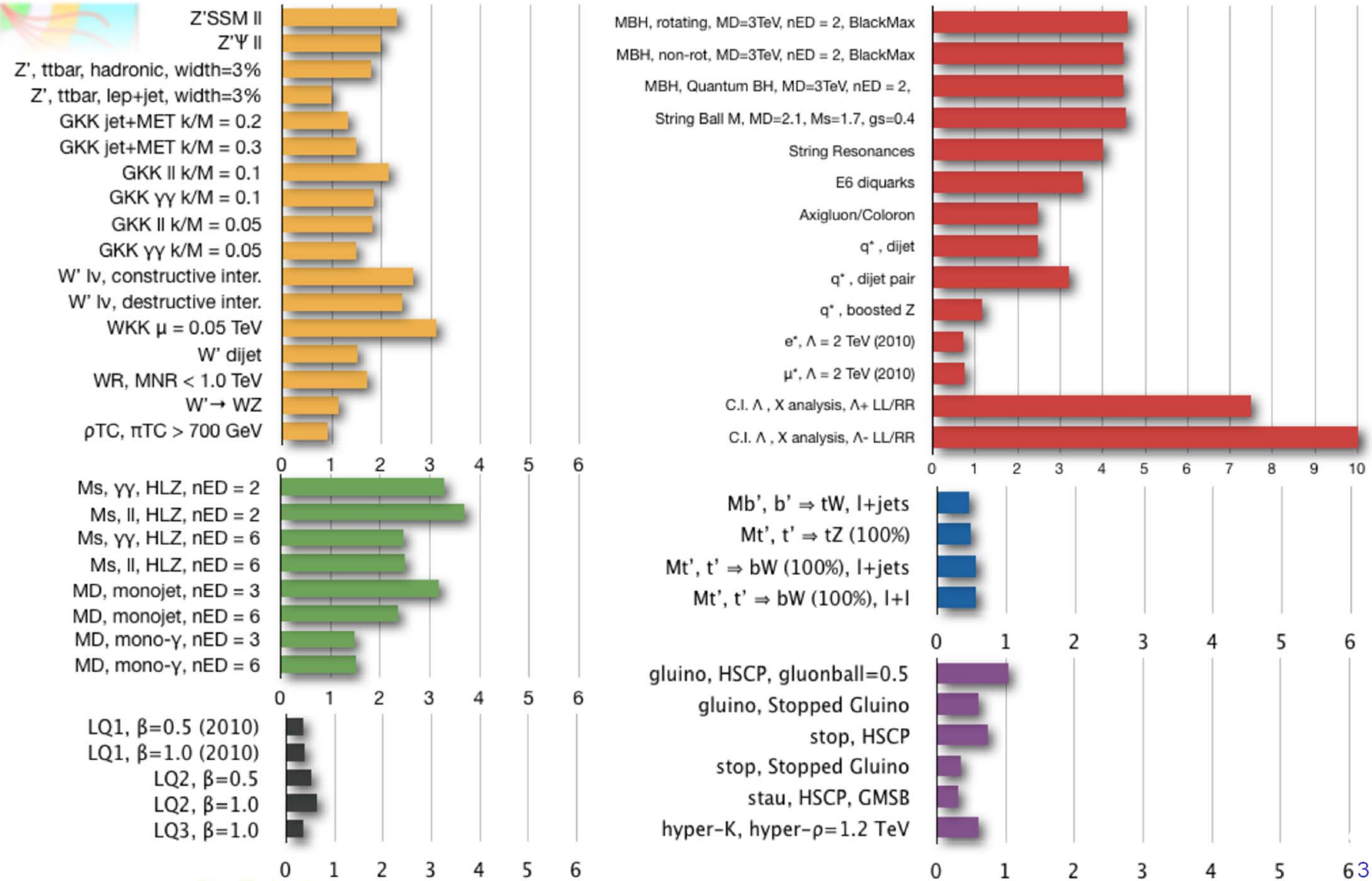


1 TeV

Within <u>the constrained MSSM models</u> we have crossed the border of excluding gluinos and squarks up to 1TeV and beyond. The air is getting thin for <u>constrained SUSY</u>. …..

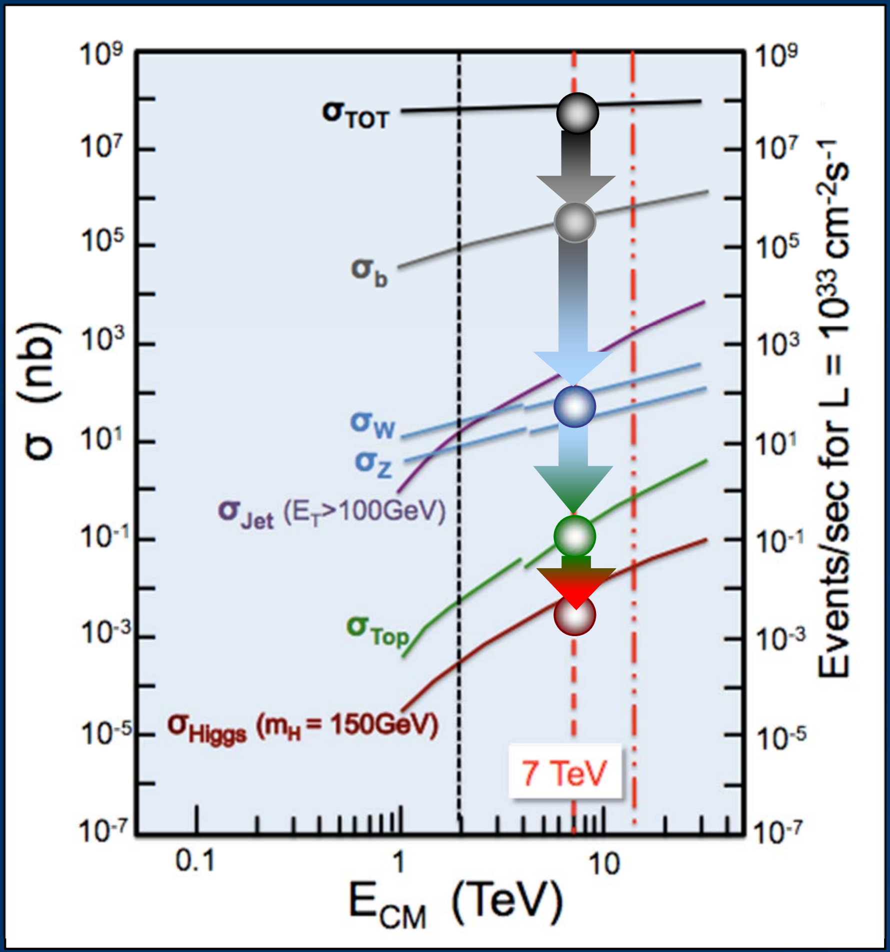
. . . but potential for discovery of SUSY sizeable even at 7 or 8 TeV

CMS Exotica: Summary for Moriond 2012

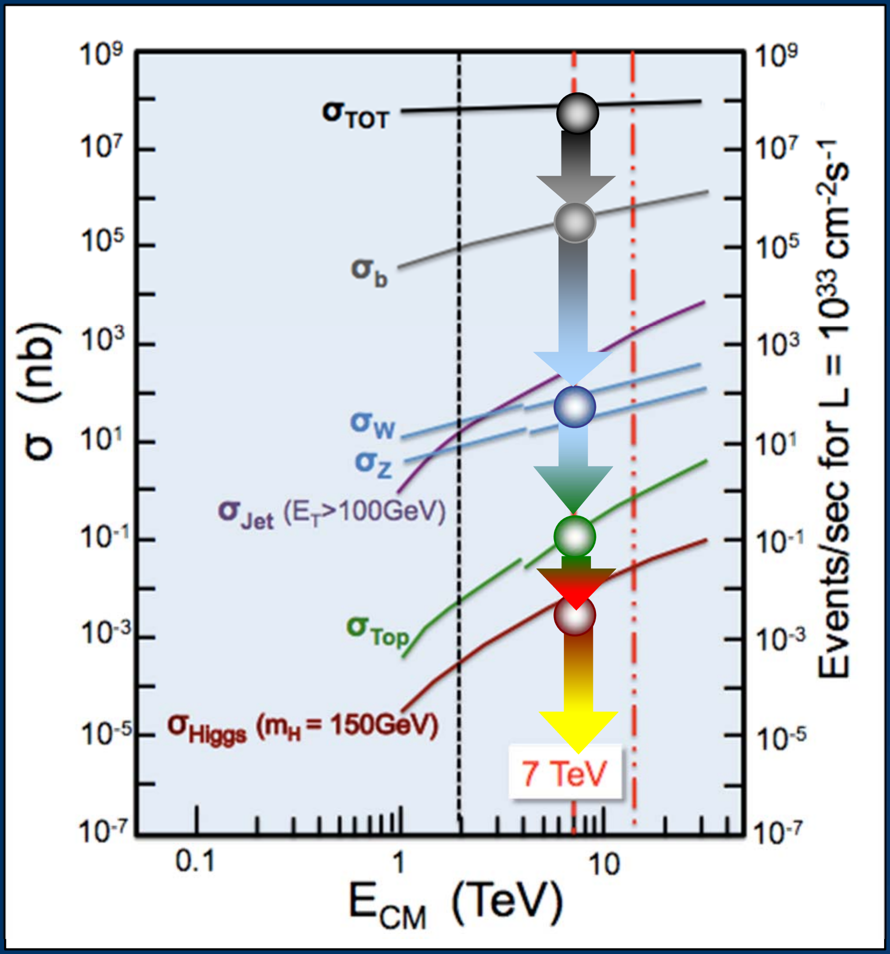


LHC and Theory…

The 2011 and 2012 run …



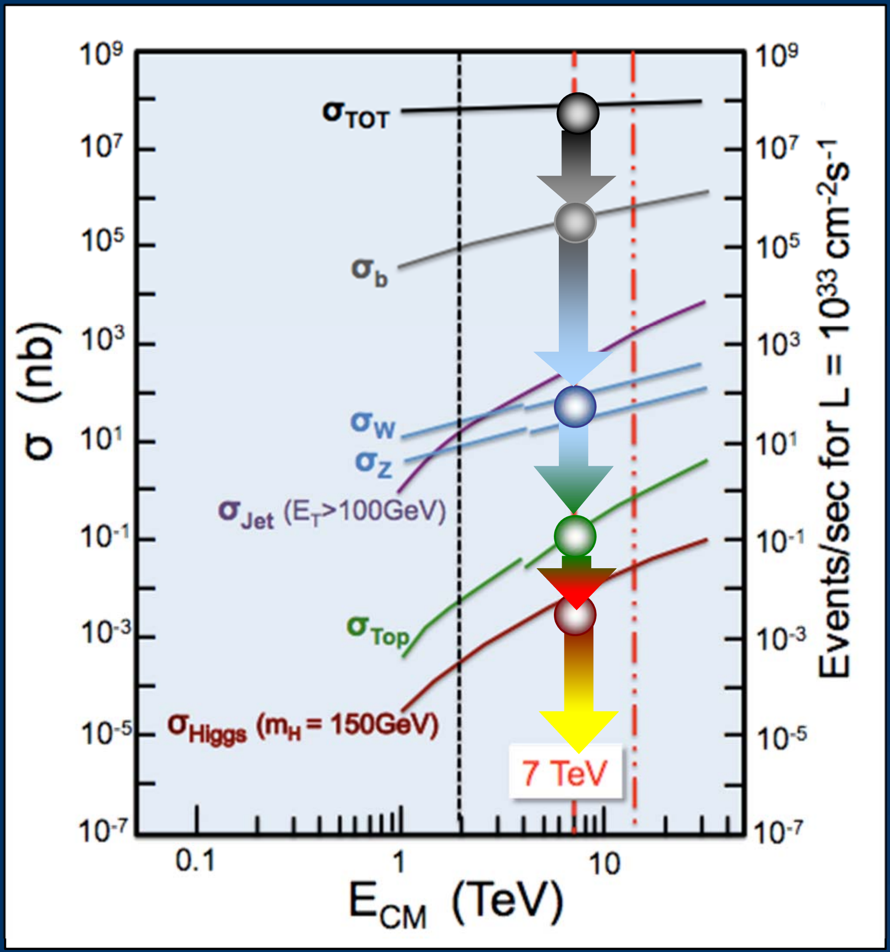
The 2011 and 2012 run …



Search for physics beyond SM

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

The 2011 and 2012 run …



Search for physics beyond SM

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

….in 2012 already about 3/fb delivered

→ 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

The predictable future: LHC Time-line

2009 — Start of LHC

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~2021/**22** — Phase-I… …ng magnets and CRAB ca… …with levelling

Run 4: C… → 3000 fb^{-1}

2030

Study of the properties of the Higgs Boson
or
Other ew symmetry breaking mechanism
and
Physics beyond the Standard Model

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 - hadron colliders (LHC, HE-LHC?)

lepton - hadron colliders (LHeC ??)

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

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

High Energy Hadron – Hadron Collider

HE - LHC

Study of New Physics Phenomena

main challenge: High-Field Magnets

Lepton – Hadron Collider

LHeC

QCD, Leptoquarks?

Lepton – Lepton Colliders

Linear Colliders: ILC / CLIC

Both projects are global endeavours

Wide range of Physics Topics, e.g.

- Higgs (self) couplings
- Z, W, Top studies
- new physics phenomena

Key message

High Priority Items for Linear Collider Projects

ILC and CLIC projects → LC project

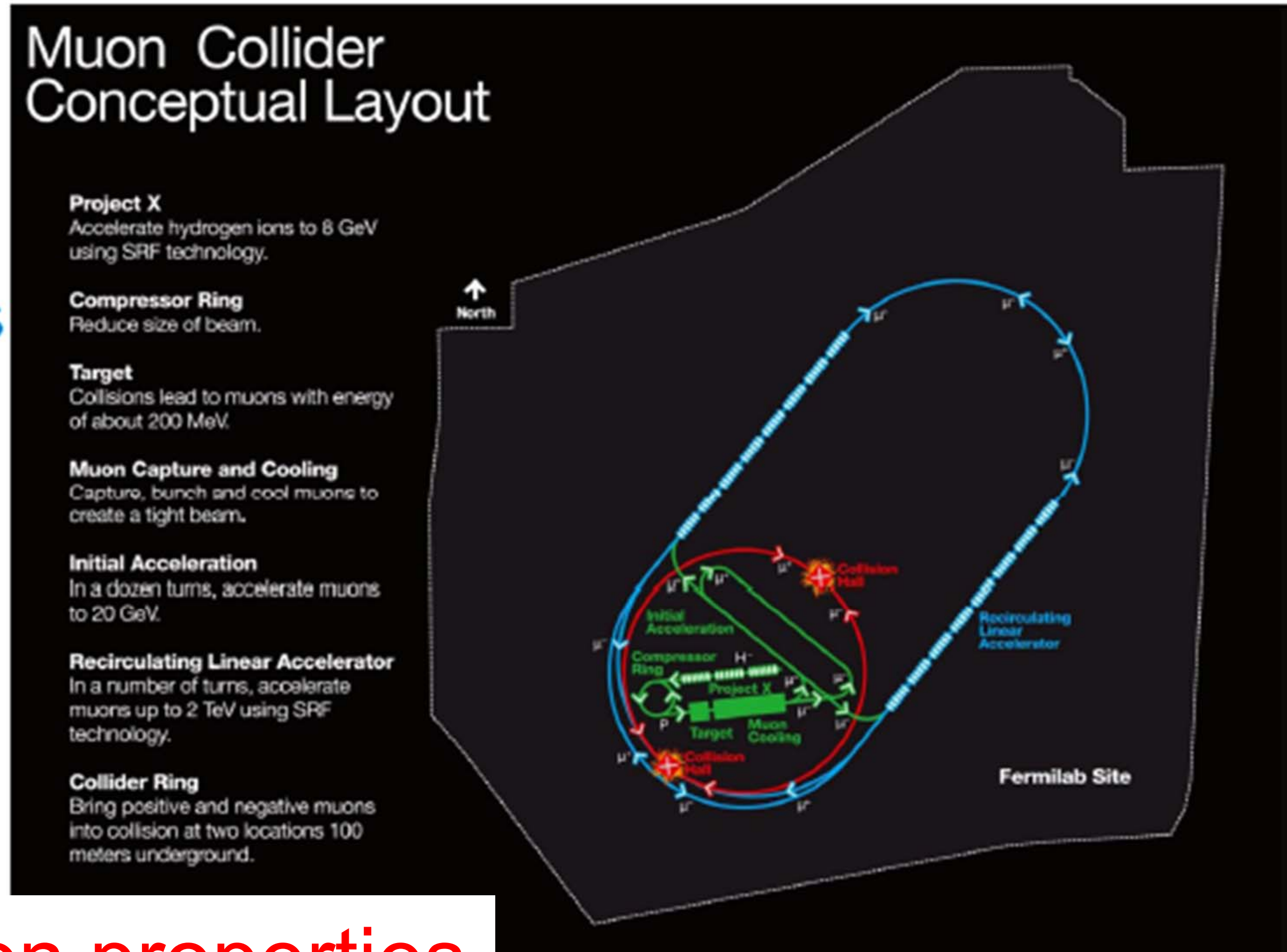
Construction Cost

Power Consumption

Value Engineering

Muon Collider

- Compact facility accelerating muons with recirculating linacs



Major Challenges

1. Muon generation
2. Cooling of muons
3. Cost-efficient acceleration
4. Collider ring and backgrounds from decays

- Higgs Boson properties

Key message

All projects need continuing accelerator and detector R&D;

All projects need continuing attention concerning a convincing physics case;
close collaboration exp-theo mandatory

so that the right decision can be made when the time comes to identify the next energy frontier accelerator (collider).
Today, we need to keep our choices open.

Choices ?

- Rich variety of projects under study
  at the energy frontier
  and the intensity frontier
- Global – Regional – National Projects

→ Need to present and discuss all these projects in an international context before making choices

→ Need to present physics case(s) always taking into account latest results at existing facilities

→ Need to present (additional) benefits to society from the very beginning of the project

Choices ?

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Key message

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, Cracow

  - 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

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exciting prospects