The first results of the Large Hadron Collider

Igor Ivanov

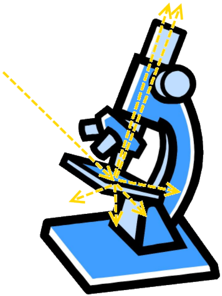
CFTP, Instituto Superior Técnico, Lisbon

AYSS-2016, JINR, Dubna, March 15, 2016

What we study

Why do we collide particles???

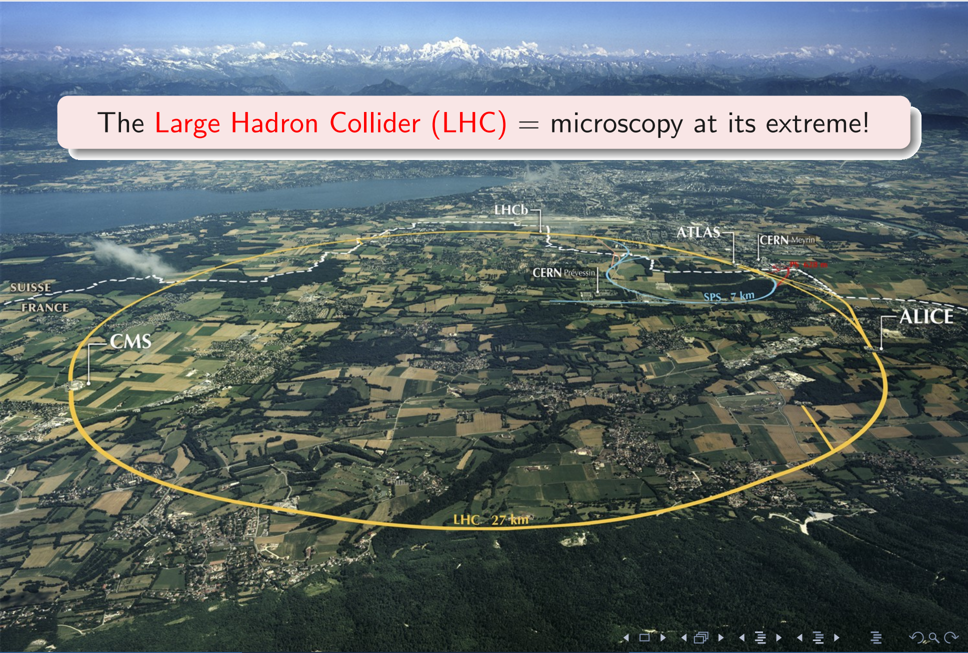
We want to see our world in smallest details!



Microscopes are colliders:

- optical microscope: object $+ \gamma \to$ object $+ \gamma$
- electron microscope: object $+ e \to$ object $+ e$

The Large Hadron Collider (LHC) = microscopy at its extreme!



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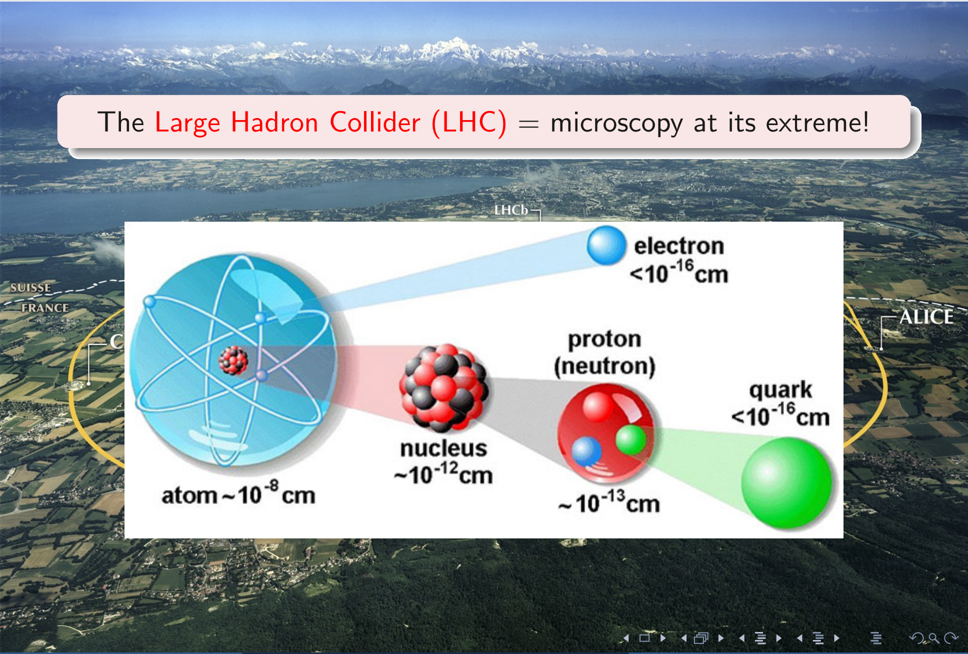
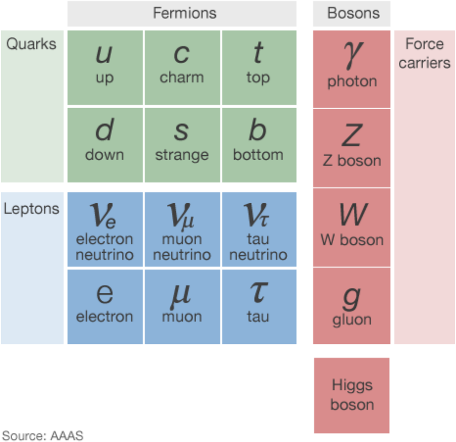


The Standard model

The Standard Model (SM): the most fundamental experimentally proven level of understanding of our world we have so far.

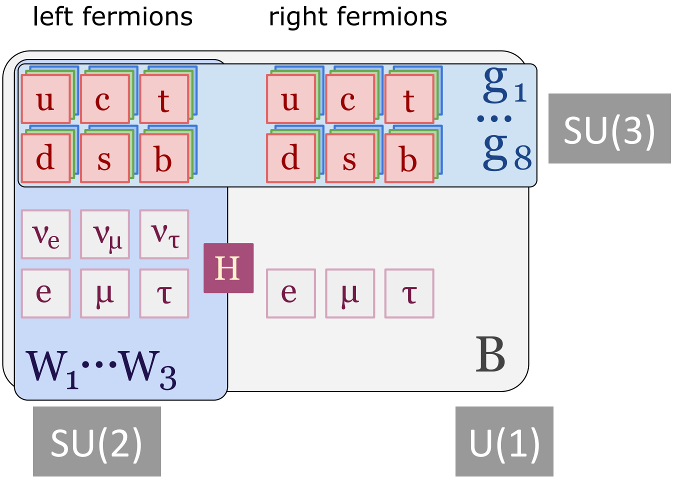
- SM = 3 fermion generations + gauge interactions + Higgs mechanism.
- Gauge group of SM: $SU(3)_c \times SU(2)_L \times U(1)_Y$ (strong and electroweak interactions).
- The electroweak symmetry of SM is not manifest but broken: Brout-Englert-Higgs mechanism.

Usual picture of the SM particle content:



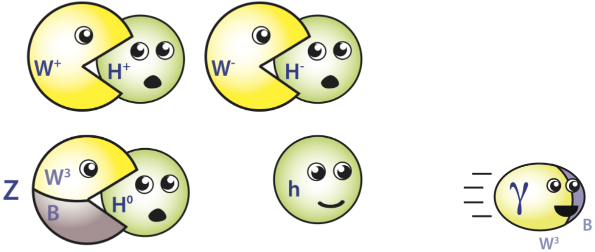
Source: AAAS

Does not really represent which forces act on which particles...


left fermions
right fermions
u c t
d s b
u c t
d s b
g1
g8
SU(3)
νe νμ ντ
e μ τ
H
e μ τ
W1···W3
B
SU(2)
U(1)

Electroweak symmetry breaking

Brout-Englert-Higgs mechanism of electroweak symmetry breaking:



Bosons partially mix:

$$W_1,\, W_2,\, W_3,\, B,\, (H^+,\, H^0) \to W^{\pm},\, Z,\, \gamma,\, h\,.$$

The problems of the Standard Model

The SM is a minimalistic, fully predictive theory, extremely efficient in describing collider data.

But within the SM, there is:

- something it definitely cannot accommodate (dark matter, efficient baryogenesis);
- something it could accommodate at the price of becoming extremely unnatural;
- something it can describe but not explain.

There must exist physics Beyond the Standard Model!
We just don't know what it is and at which energy scale it lives.

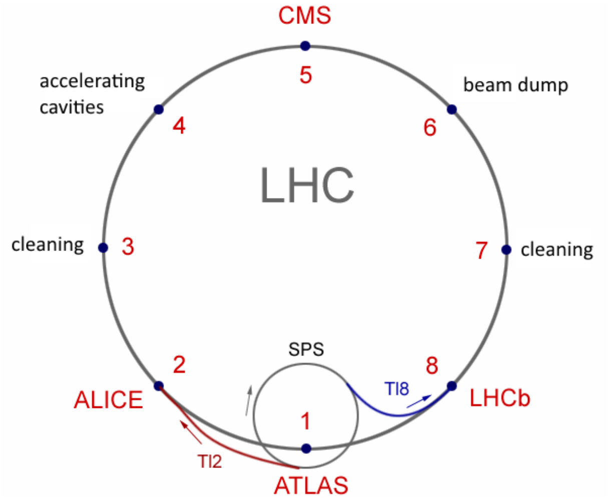
Scientific program of the LHC

The main goal of the LHC is to find New Physics.

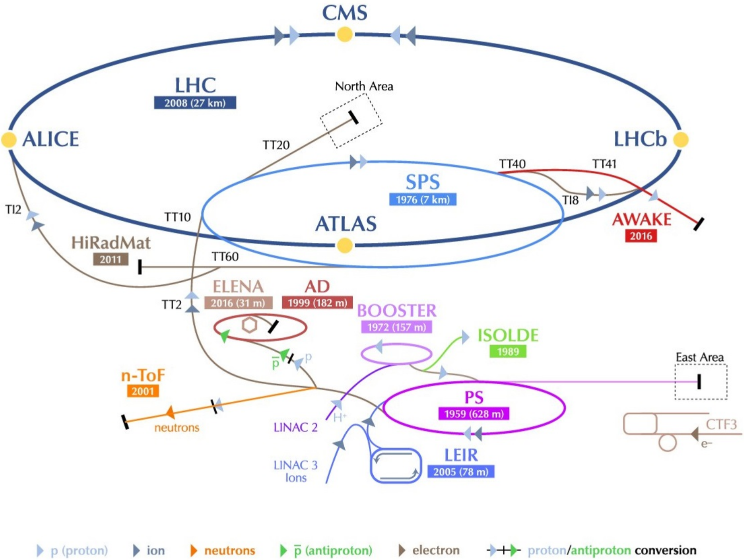
- tests of the SM at the new energy frontier,
- Higgs boson physics: number of Higgses, their mass, CP-parity, couplings, self-coupling, etc.
- search for various beyond-SM signatures: supersymmetry (SUSY), new gauge interactions, exotic gravity models, dark sectors, etc.
- B-physics as another window into New Physics: study rare B-decays with highest precision,
- $+$ other issues which I don't touch.

How the LHC works

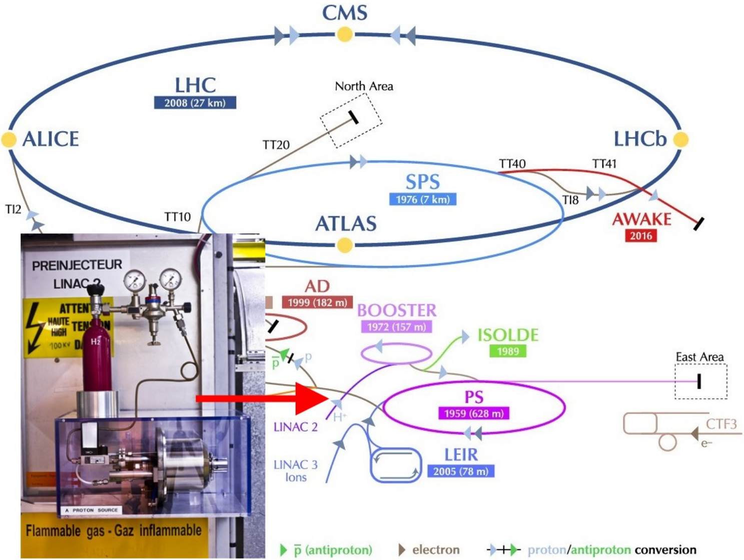
LHC layout


CMS
5
accelerating
cavities
beam dump
4
6
LHC
cleaning
3
7
cleaning
SPS
2
8
ALICE
TI8
LHCb
1
TI2
ATLAS

Accelerator complex at CERN



Accelerator complex at CERN



LHC basic facts

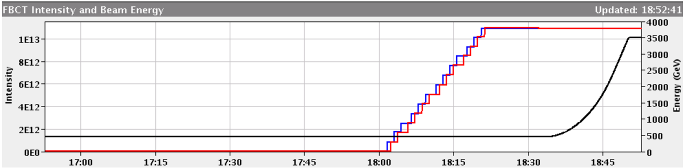
- cyclic collider: circ. 27 km, nominal proton energy 7 TeV; nominal beam intensity: 2808 bunches with 10^{11} p/bunch separated by 25 ns, which gives 300 MJ of beam energy;
- almost 10,000 magnets including 1232 main dipoles holding 11 kA, producing 8.3 T, and storing 10 MJ of energy each;
- Cryo: multi-stage cooling including He-II at 1.9K, heat transport capacity: few kW with the gradient of 0,1 K/km.
- elaborate protection systems (collimators, beam dump, controls), numerous unexpected difficulties (UFO's, electron clouds, ULO, etc.).

Four main detectors: ATLAS and CMS (multi-purpose), LHCb (mostly *B*-physics), ALICE (mostly ion collisions), and several smaller detectors.

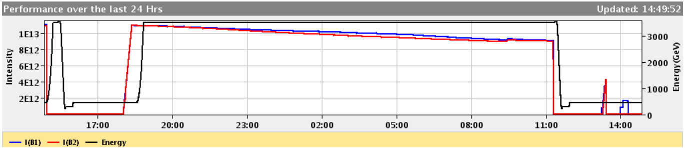
Working cycle

The LHC can be monitored online in real time via LHC Vistars.

- injection + ramp up



- cleaning + focusing → stable beams → data taking

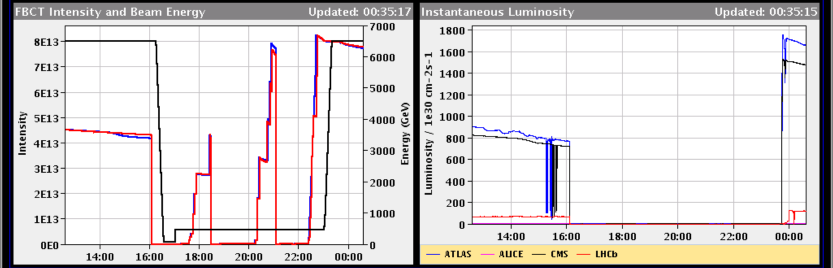


- beam dump.

LHC Page1 | Fill: 4341 | E: 6500 GeV | t(SB): 00:38:22 | 10-09-15 00:35:17

PROTON PHYSICS: STABLE BEAMS

Energy:	6500 GeV	I(B1):	7.73e+13	I(B2):	7.76e+13



Comments (10-Sep-2015 00:03:28)

** STABLE BEAMS **

Tomorrow meeting at 09:00

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	true	true
Global Beam Permit	true	true
Setup Beam	false	false
Beam Presence	true	true
Moveable Devices Allowed In	true	true
Stable Beams	true	true

AFS: 25ns_745b_733_633_648_72bpi13inj | PM Status B1 ENABLED | PM Status B2 ENABLED

LHC schedule and luminosity production

Lumi goal: $10^{34} cm^{-2} s^{-1} \to 100$ fb^{-1}/"accelerator year" ($= 10^7$ sec).

Run 1 (2010–2012): $E_{tot} = 7 \to 8$ TeV.

- ATLAS, CMS: 25 fb^{-1}.

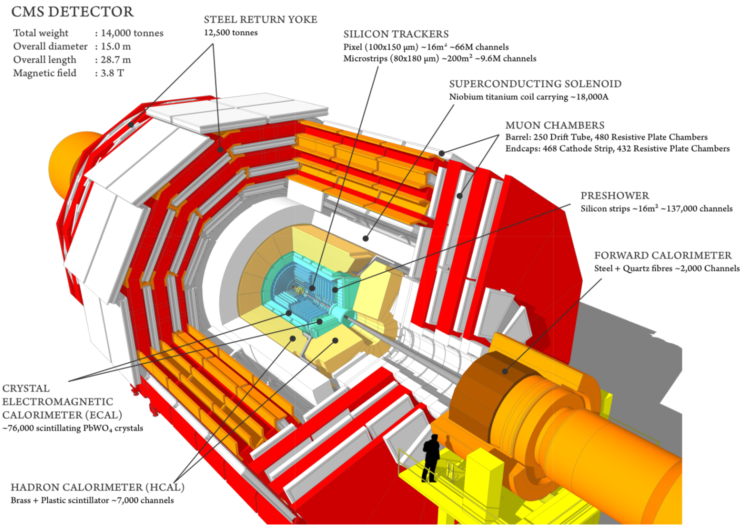
Run 2 (2015–2018): $E_{tot} = 13$ TeV.

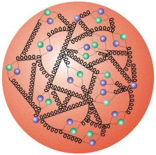
- 2015: commissioning year, 3–4 fb^{-1}
- 2016–2018: data production, 100 fb^{-1}

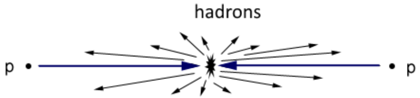
Run 3 (2021–2023): $E_{tot} = 14$ TeV, 300 fb^{-1}.

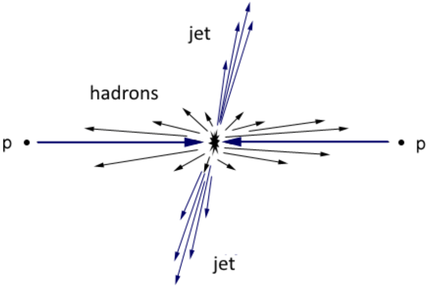
Beyond 2025 (up to 2035): HL-LHC, 300 fb^{-1}/year.

How we detect collisions

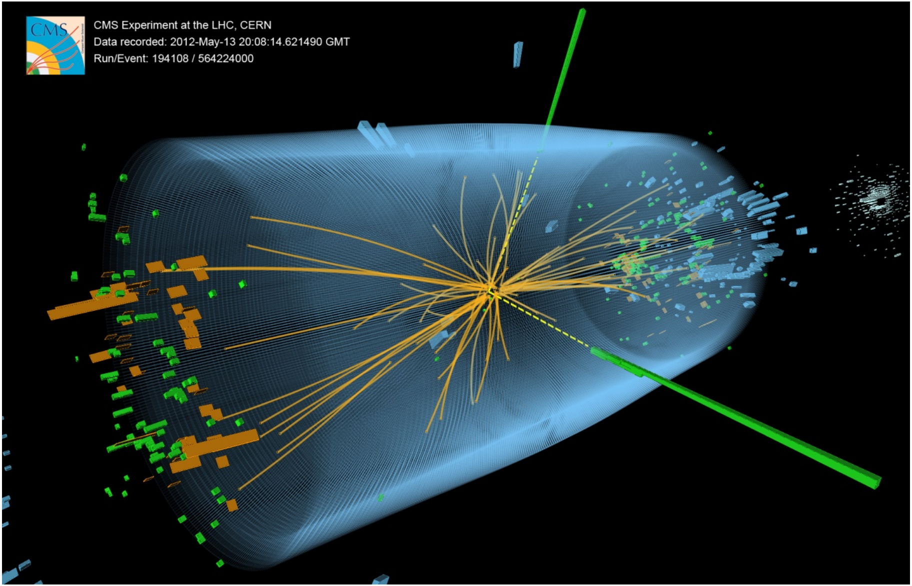

CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating PbWO4 crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

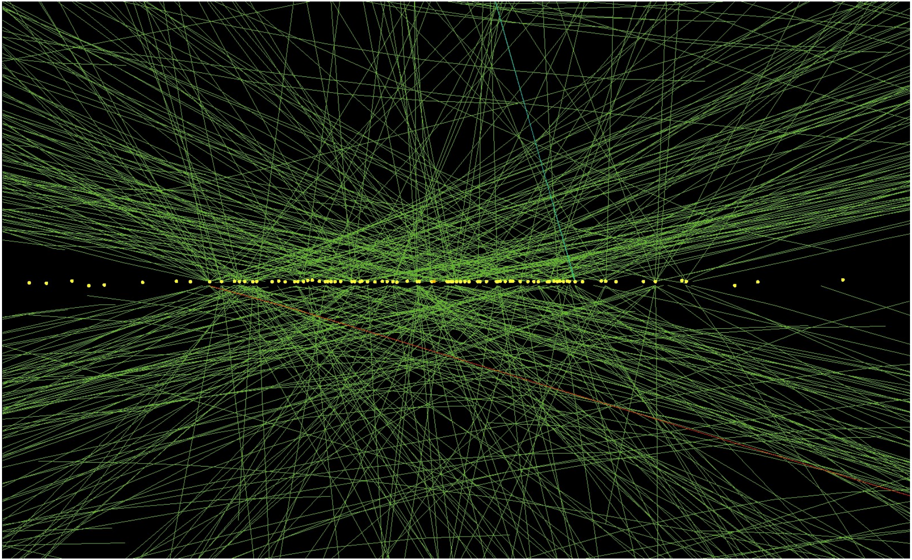


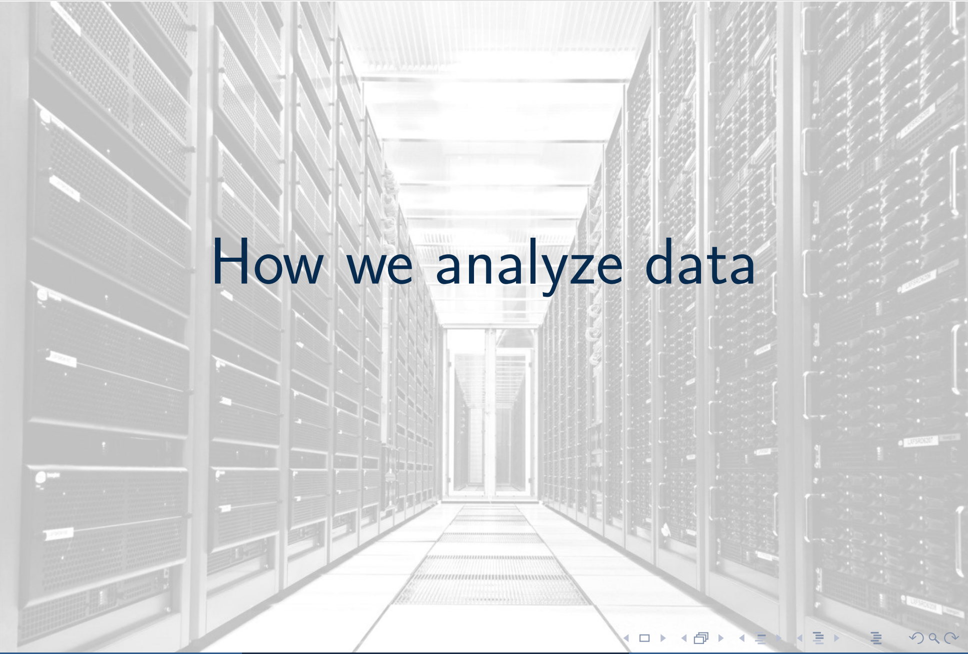




Key objects: jets, isolated leptons/photons, missing transverse momentum.


CMS
CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000





How we analyze data

Event rates

process	σ	rate	interesting?
total pp	$4r_p^2 \approx 100$ mb	$10^9/\text{sec}$	no
inclusive hadronic	nb–μb range	$\sim 1000/\text{sec}$	not really
electroweak	pb range	few/sec	yep
rare EW (e.g. $t\bar{t}H$)	fb range	1/day	oh yeah!!!

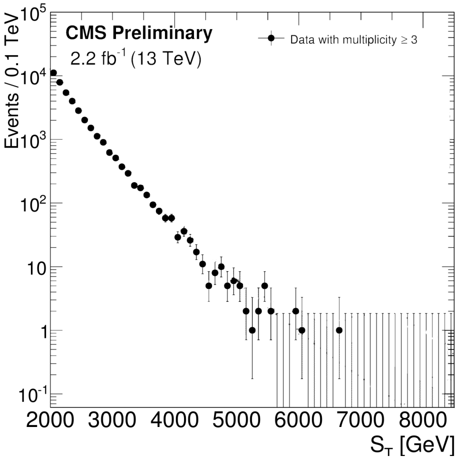
Selection needed:

- $\sim 10^{-9}$ for something minimally interesting,
- $\sim 10^{-12}$ for detecting something new.

Data taking and analysis

- Collision rate: (1 bunch crossing per 25 ns) $\times$ ($\sim$ 50 independent *pp* collisions per bunch crossing) $\times$ ($\sim$ 10–100 particles per *pp* collision).
- Data taking: 1 MB/25ns = 40 TB/s, impossible to store + not needed $\to$ triggers (only interesting events stored). Total data volume: $\sim$ 100 PBytes.
- A typical analysis process takes months to years. It includes comparison with full simulation and thousands of pseudoexperiments.

Searches and interpretation



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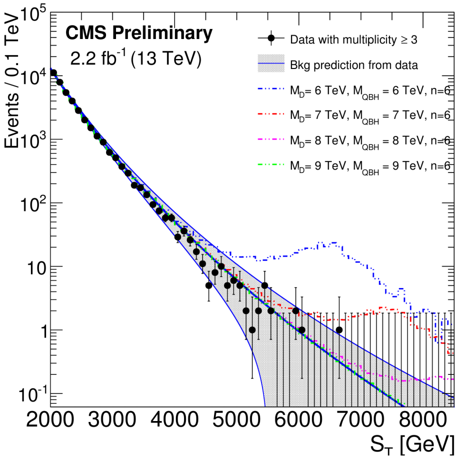

The Higgs boson

Higgs mechanism vs. Higgs boson

A key task of the LHC was to find the Higgs boson(s).

- The Higgs mechanism was suggested in 1964 by Brout-Englert, by Higgs, and by Guralnik-Hagen-Kibble. It was the mechanism that was the key development, and the boson was initially just a minor consequence mentioned in 1966.
- The searches began in late 1970's, and every new collider was checking if it can spot the Higgs boson.
- But again: the main interest lies in the Higgs mechanism as it might be the first door to New Physics. Higgs boson is just an "echo of the mechanism", a convenient tool to study it.

Popular misconception: "Higgs boson gives mass to everything in the Universe".

In fact, it is the Higgs field gives mass to fundamental particles → only ≈ 1% of the mass of the usual matter, and it most probably does not explain the masses of neutrinos and DM.

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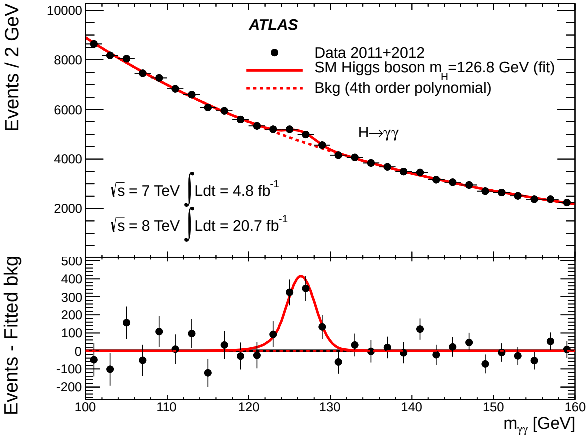
Nobel Prize 2013

- 2012: Higgs boson discovered at the LHC
- 2013: Nobel prize awarded to F. Englert and P. Higgs for their theoretical discovery of the Higgs mechanism in 1964!
- Unfortunately, the Higgs boson looks a way too standard...

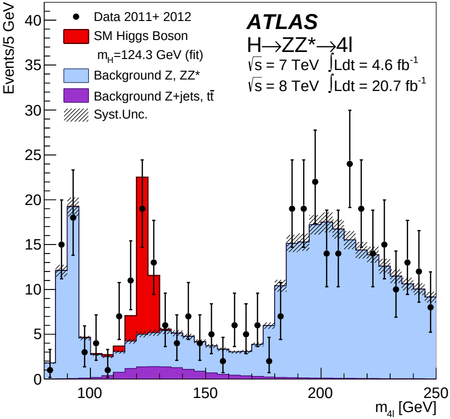
$H \to \gamma\gamma$

The easiest decay channel: $H \to \gamma\gamma$ with $Br = 0.23\%$ (at $m_H = 125$ GeV).



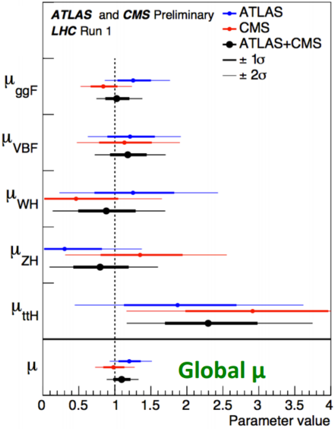
$H \to ZZ^* \to 4\ell$

The cleanest decay channel: $H \to ZZ^* \to 4\ell$ with $Br = 0.012\%$.

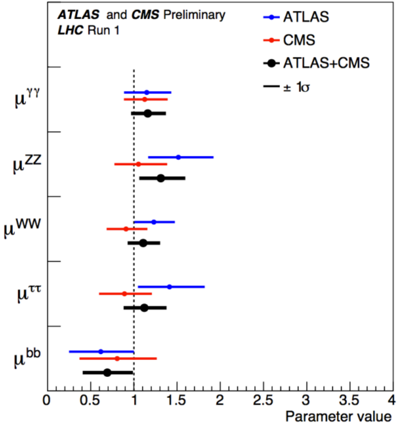


$\mu = \text{measured}/\text{SM prediction}$:

SM BRs assumed



SM production σ assumed



Two deviations from SM

- $H \to \mu\tau$ decay. In SM, there is no lepton flavour violating Higgs decays, but they can appear due to New Physics.

  CMS result [1502.07400]: $Br(H \to \mu\tau) = (0.84^{+0.39}_{-0.37})\%$.

  ATLAS result [1508.03372]: $Br(H \to \mu\tau) = (0.77 \pm 0.62)\%$.

  Combined excess: 2.6σ away from SM.

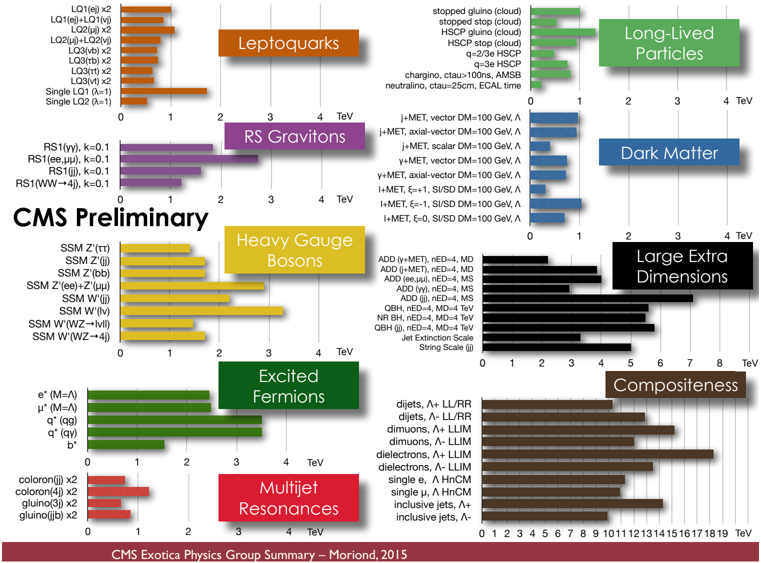
- $t\bar{t}H$ coupling seems to be too strong:

  CMS [1408.1682]: $\mu = 2.9^{+1.0}_{-0.9}$, ATLAS [1503.05066]: $\mu = 1.5 \pm 1.1$.

  Combined excess: 2.3σ away from SM.

- Too early for strong suspicions, but definitely to watch in Run 2.

New Physics searches


CMS Preliminary
Leptoquarks
LQ1(ej) x2
LQ1(ej)+LQ1(νj)
LQ2(μj) x2
LQ2(μj)+LQ2(νj)
LQ3(νb) x2
LQ3(τb) x2
LQ3(τt) x2
LQ3(νt) x2
Single LQ1 (λ=1)
Single LQ2 (λ=1)
RS Gravitons
RS1(γγ), k=0.1
RS1(ee,μμ), k=0.1
RS1(jj), k=0.1
RS1(WW→4j), k=0.1
Heavy Gauge Bosons
SSM Z'(ττ)
SSM Z'(jj)
SSM Z'(bb)
SSM Z'(ee)+Z'(μμ)
SSM W'(jj)
SSM W'(lν)
SSM W'(WZ→lνll)
SSM W'(WZ→4j)
Excited Fermions
e* (M=Λ)
μ* (M=Λ)
q* (qg)
q* (qγ)
b*
Multijet Resonances
coloron(jj) x2
coloron(4j) x2
gluino(3j) x2
gluino(jjb) x2
Long-Lived Particles
stopped gluino (cloud)
stopped stop (cloud)
HSCP gluino (cloud)
HSCP stop (cloud)
q=2/3e HSCP
q=3e HSCP
chargino, ctau>100ns, AMSB
neutralino, ctau=25cm, ECAL time
Dark Matter
j+MET, vector DM=100 GeV, Λ
j+MET, axial-vector DM=100 GeV, Λ
j+MET, scalar DM=100 GeV, Λ
γ+MET, vector DM=100 GeV, Λ
γ+MET, axial-vector DM=100 GeV, Λ
l+MET, ξ=+1, SI/SD DM=100 GeV, Λ
l+MET, ξ=-1, SI/SD DM=100 GeV, Λ
l+MET, ξ=0, SI/SD DM=100 GeV, Λ
Large Extra Dimensions
ADD (γ+MET), nED=4, MD
ADD (j+MET), nED=4, MD
ADD (ee,μμ), nED=4, MS
ADD (γγ), nED=4, MS
ADD (jj), nED=4, MS
QBH, nED=4, MD=4 TeV
NR BH, nED=4, MD=4 TeV
QBH (jj), nED=4, MD=4 TeV
Jet Extinction Scale
String Scale (jj)
Compositeness
dijets, Λ+ LL/RR
dijets, Λ- LL/RR
dimuons, Λ+ LLIM
dimuons, Λ- LLIM
dielectrons, Λ+ LLIM
dielectrons, Λ- LLIM
single e, Λ HnCM
single μ, Λ HnCM
inclusive jets, Λ+
inclusive jets, Λ-
TeV
CMS Exotica Physics Group Summary – Moriond, 2015

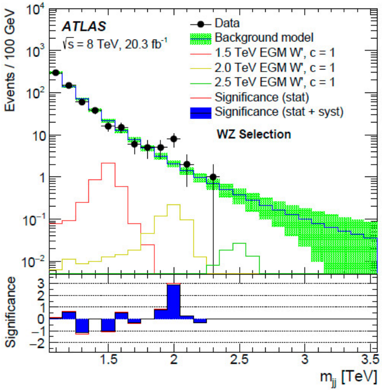
2 TeV excesses

Both ATLAS and CMS see something interesting in diboson spectra around 2 TeV.

ATLAS [1506.00962]: excess in $WZ \to$ hadrons, global significance 2.5σ (local SS: 3.4σ).

CMS 1601.06431: excess in $WH \to \ell\bar{\nu}b\bar{b}$ at $M_{WH} = 1.8$ TeV

CMS [1407.3683]: sees 2.8σ in $eejj$ at 2.1 TeV.



Unfortunately, preliminary Run 2 data do not confirm this peak :'-(

Diphoton peak at 750 GeV

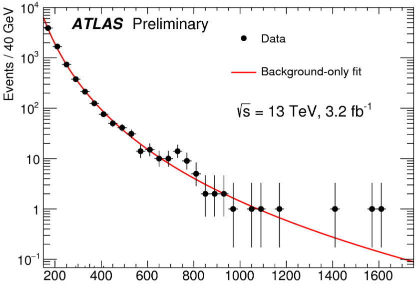
Diphoton excess at $m_{\gamma\gamma} \approx 750$ GeV seen by both ATLAS and CMS in early Run 2:

Statistical significance:

- ATLAS: 3.6σ (local), 1.9σ (global)
- CMS: 2.6σ (local), 1.2σ (global)
- combined: ??? ($\approx 3\sigma$)

Unprecedented flurry of theoretical papers:

- 10 theory papers in arXiv on the next day,
- > 200 papers in three months.



An update expected on March 17 at Moriond!

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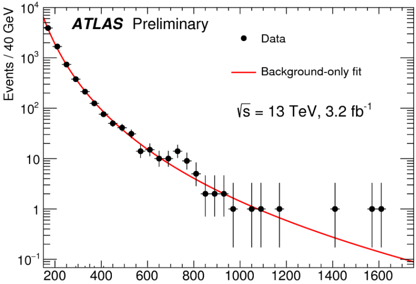
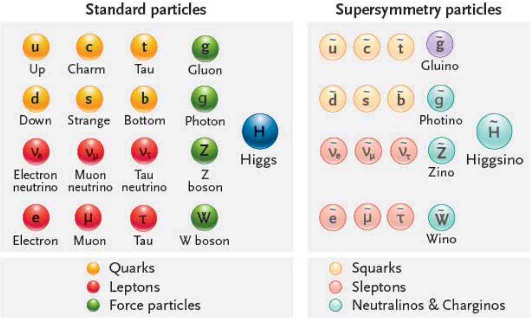


An update expected on March 17 at Moriond!

Searching for Supersymmetry

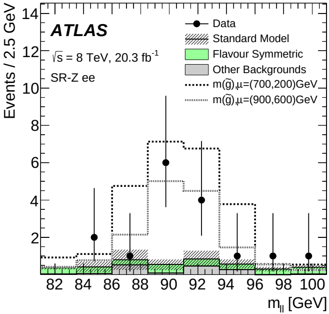
Supersymmetry (SUSY): broad theoretical framework based on a bosons $\leftrightarrow$ fermion symmetry.

Doubling of particle content: quarks $q \to$ squarks $\tilde{q}$; gluons $g \to$ gluinos $\tilde{g}$, etc.



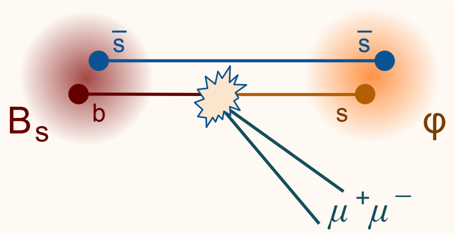
- supersymmetry is spontaneously broken $\to$ sparticle spectrum is different from SM and it cannot be predicted $\to$ immense number of possible phenomenological realizations.
- generic prediction: lightest SUSY particle is stable and escapes detection $\to$ missing p_T.

Strongest deviation: $e^+e^- + \geq 2j +$ large p_T^{miss} by ATLAS [1503.03290]



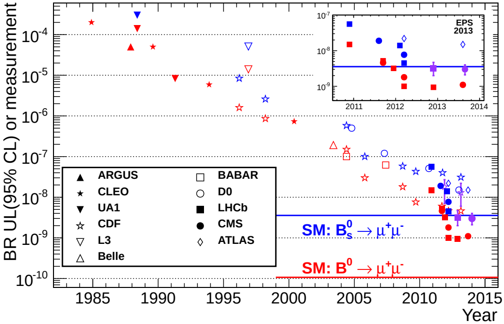
- excess in resonant ee: 16 events vs. 4.2 ± 1.6 bkgd expected $\to 3.0\sigma$.
- excess in resonant $e^+e^- + \mu^+\mu^-$: 29 events vs. 10.6 ± 3.2 $\to 3.0\sigma$ deviation.
- moderately confirmed by early Run 2 data.

B-physics assorti



Extremely rare $B \to \mu^+\mu^-$ and $B_s \to \mu^+\mu^-$ decays: a key goal of the LHC B-physics program. SM predictions:

$$\mathrm{Br}(B_s \to \mu^+\mu^-) = (3.66 \pm 0.23) \cdot 10^{-9}\,, \;\; \mathrm{Br}(B \to \mu^+\mu^-) = (1.06 \pm 0.09) \cdot 10^{-10}\,.$$

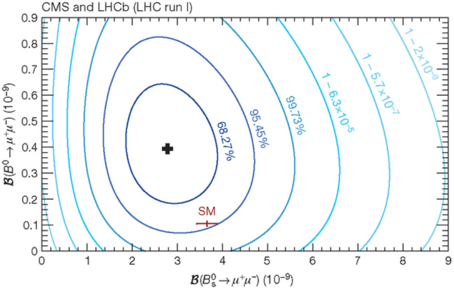


Dramatic year 2011: controversy between Tevatron and LHC → LHC wins.

$B_s \to \mu^+\mu^-$: discovery

First hints by LHCb in 2012, evidence by LHCb+CMS in 2013, discovery by LHCb+CMS in 2014.

Current result [1411.4413] = Nature 522, 68 (04 June 2015):



$B_s \to \mu^+\mu^-$ is OK, $B \to \mu^+\mu^-$ is too large, 2.2σ away from SM.

Semileptonic B decays

Several strong deviations in semileptonic B decays:

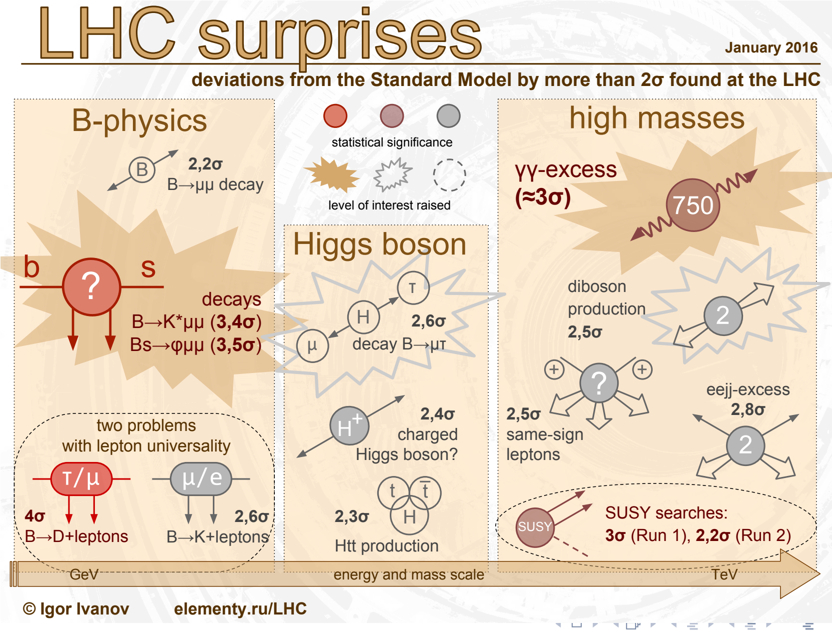
- LHCb [1512.04442]: $B \to K^* \mu^+ \mu^-$, discrepancy at 3.4σ.
- LHCb [1506.08777]: $B_s \to \phi \mu^+ \mu^-$, discrepancy at 3.5σ.
- LHCb [1406.6482]: violation of lepton universality in $B \to K \ell\ell$, 2.6σ away from SM,
- LHCb+BaBar+Belle [1506.08896]: violation of lepton universality in $\bar{B} \to D^{(*)} \tau \nu$, $\sim 4\sigma$ deviation from SM.

So far, these seem to be the strongest deviations from SM found at the LHC.

However, the interpretation is far from clear. Global analyses of these discrepancies (e.g. in the space of C_i for $b \to s\ell\ell$ decay) show 2–4σ deviation depending on the analysis [1510.04239, 1603.00865].

After Run 1 + preliminary Run 2

process	deviation	collaboration
$\gamma\gamma$ peak at 750 GeV	$\sim 3\sigma$	ATLAS+CMS
2 TeV dibosons	low	ATLAS+CMS
$eejj$	2.8σ	CMS
same sign ℓ's $+b$'s	2.5σ	ATLAS
leptons+jets+E_T^{miss}	2.5σ	CMS
	2.2σ	ATLAS
$H \to \tau\mu$	2.4σ	CMS
$Ht\bar{t}$	2.3σ	CMS
$B \to K^*\mu\mu$	3.4σ	LHCb
$B_s \to \phi\mu\mu$	3.5σ	LHCb
$B \to \mu^+\mu^-$	2.2σ	LHCb+CMS
$B^+ \to K^+\ell\ell$	2.6σ	LHCb
$B \to D^{(*)}\tau\bar{\nu}$	2.1σ	LHCb
	$\sim 4\sigma$	LHCb+BaBar+Belle


LHC surprises
January 2016
deviations from the Standard Model by more than 2σ found at the LHC
B-physics
B
2,2σ
B→μμ decay
b
?
s
decays
B→K*μμ (3,4σ)
Bs→φμμ (3,5σ)
two problems
with lepton universality
τ/μ
4σ
B→D+leptons
μ/e
2,6σ
B→K+leptons
statistical significance
level of interest raised
Higgs boson
τ
H
μ
2,6σ
decay B→μτ
H+
2,4σ
charged
Higgs boson?
t
t̄
H
2,3σ
Htt production
high masses
γγ-excess
(≈3σ)
750
diboson
production
2,5σ
2
?
2,5σ
same-sign
leptons
eejj-excess
2,8σ
2
SUSY
SUSY searches:
3σ (Run 1), 2,2σ (Run 2)
GeV
energy and mass scale
TeV
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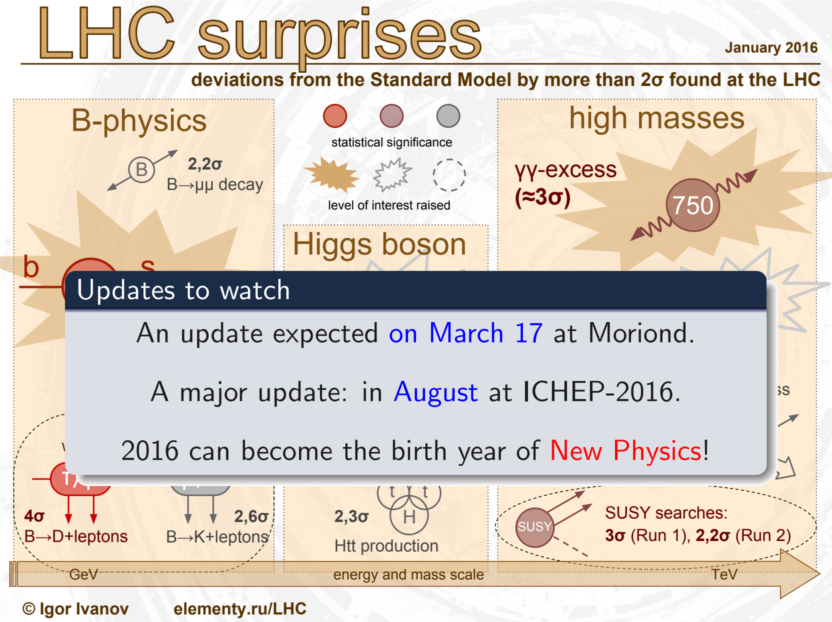

Updates to watch

An update expected on March 17 at Moriond.

A major update: in August at ICHEP-2016.

2016 can become the birth year of New Physics!