VULCANO Workshop 2016

Frontier Objects in Astrophysics and Particle Physics

Future of LHC

Roger Forty (CERN)

Since this workshop has an astrophysics focus I have aimed for an overview — apologies if I tell you some things you already know (hopefully not all…)

1. Machine
2. Experiments
3. Physics

Vulcano workshop, 23 May 2016

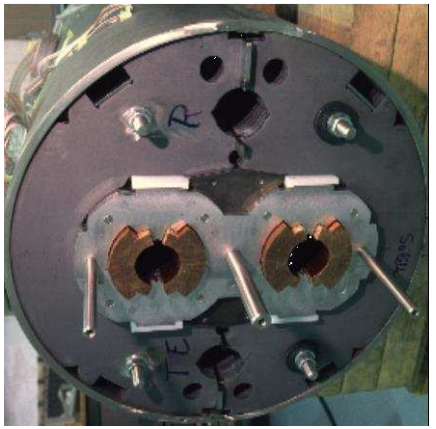
1. Machine

The Large Hadron Collider (LHC) at CERN is the highest energy collider in the world
27 km circumference – “the world’s largest scientific instrument”

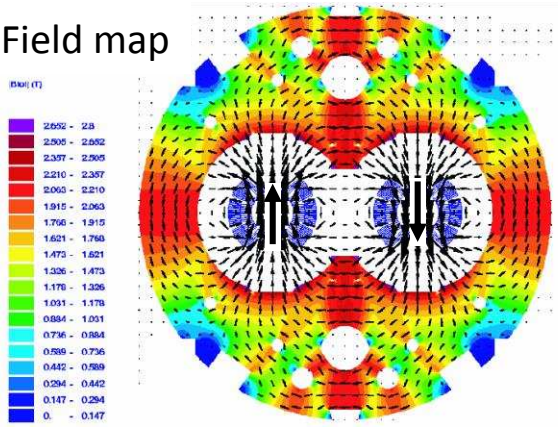
Machine parameters

- proton-proton collider, design energy $\sqrt{s}$ = 14 TeV
- Two-in-one magnet design to allow acceleration of same-charge particles in both directions around ring
- Superconducting magnets using niobium-titanium (NbTi) alloy cable, 8.3 T in the main dipoles
  operated at liquid helium temperature 1.9 K
- Design luminosity 10^{34} cm^{-2} s^{-1}
  2808 bunches, each with ~10^{11} protons
  Focusing at high-luminosity interaction points
  β^*= 40 cm → transverse beam size ~10 μm
- 25 ns bunch spacing → collisions at 40 MHz

Two-in-one LHC dipole

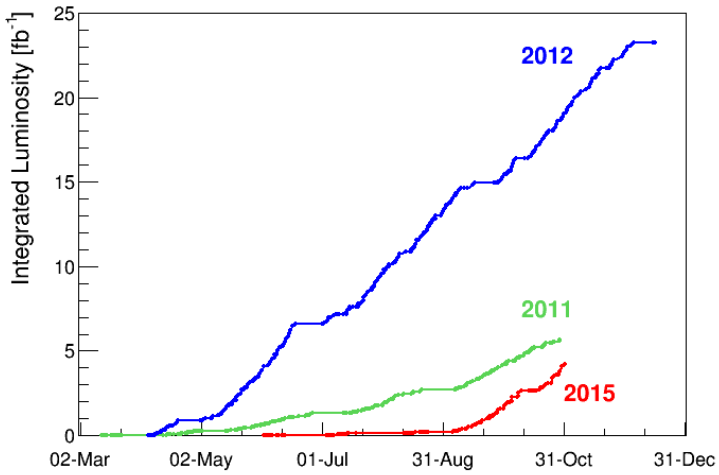


Field map

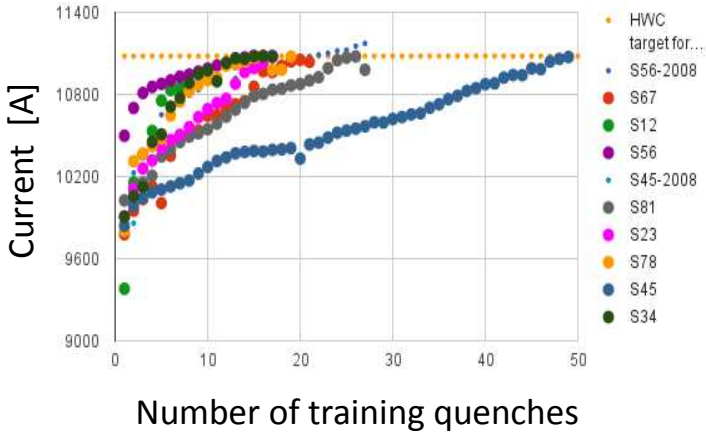


Brief history

- Conceived in early 1980s, re-uses tunnel of previous machine LEP (e^+e^-,1989-2000)
- Incident during commissioning in 2008: due to failure of a magnet interconnect
- Restarted at √s = 7 TeV in 2010
  then 8 TeV in 2012
  Integrated luminosity 5 + 24 fb^{-1} at the high-luminosity experiments (Run 1)
  Higgs discovery announced in 2012
- First long shutdown (LS1) 2013-14
  → Consolidation of all the interconnects
- Restarted in 2015 at 13 TeV
  Required quite a few training quenches:
  4 fb^{-1} integrated so far in Run 2



[Solfaroli, LHCC 23/9/15]



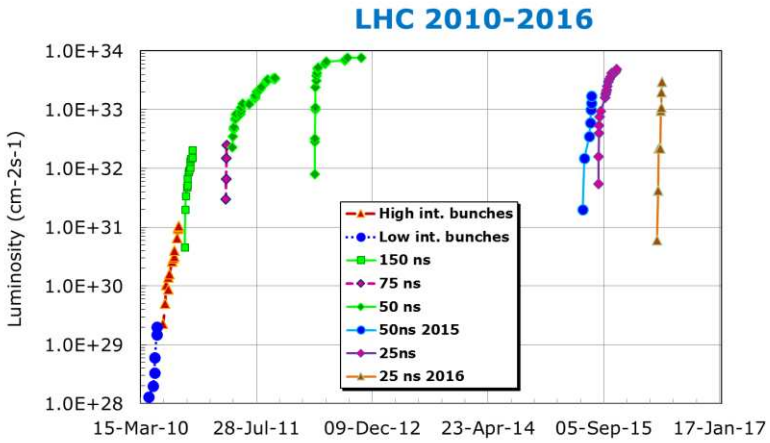
Short-term future

- 2016 is intended to be a "luminosity production year", aiming to reach the nominal luminosity of 10^{34} cm^{-2} s^{-1}
- Recently recovered from power failure during start-up (due to a weasel…)
- Last week ~900 bunches circulating Ramping up fast to higher luminosity:
- Pushing up energy to 14 TeV would require many further training quenches → stay at 13 TeV for this year (at least)

The Telegraph

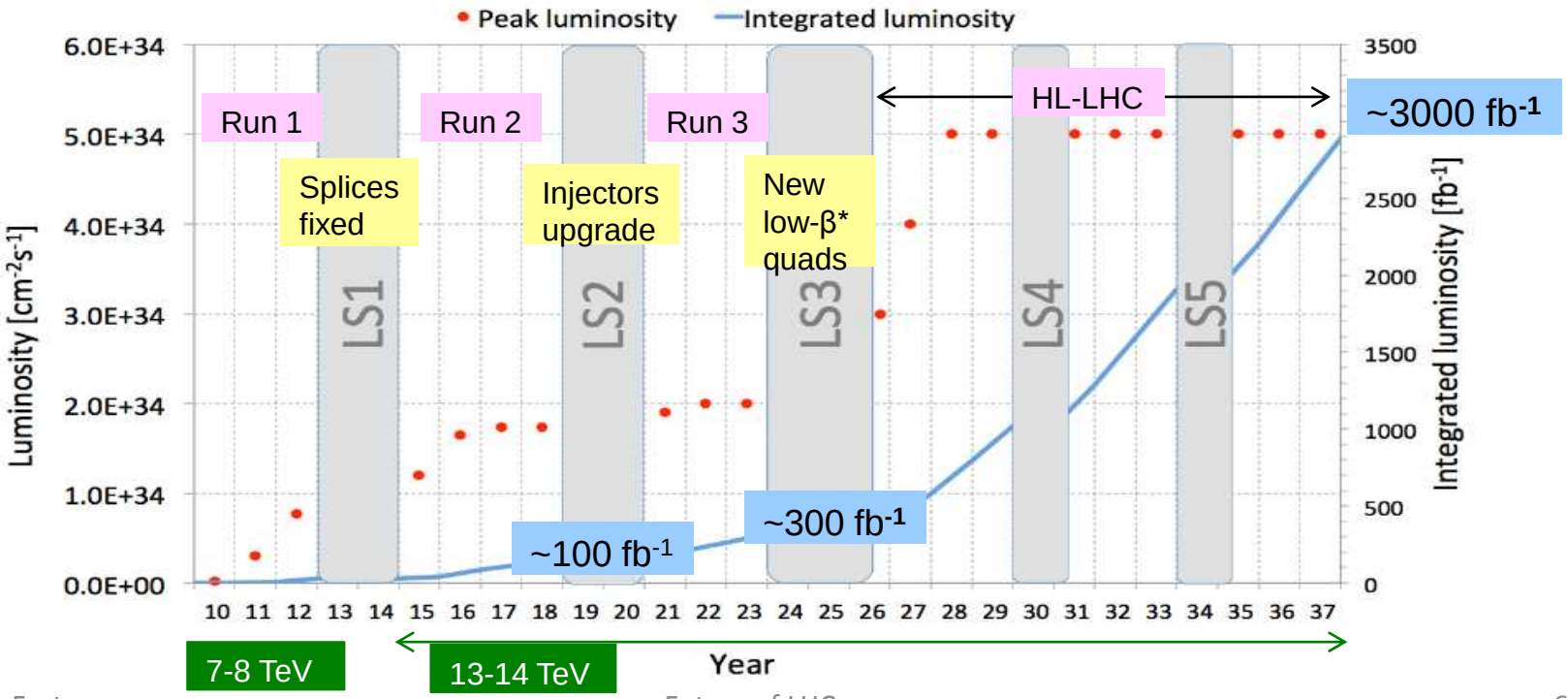
› News

Large Hadron Collider, world's largest machine, broken by 'rogue weasel who bit through power cable'



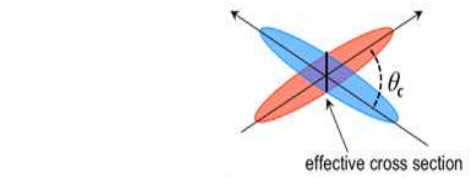
Longer-term future

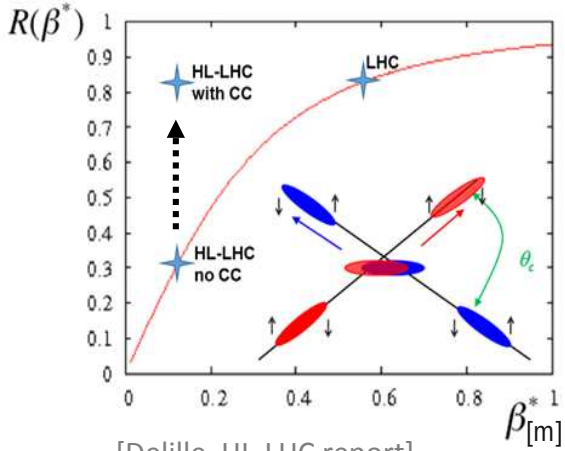
- *Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030.*
  [European Strategy for Particle Physics Update 2013]
- High-luminosity LHC (HL-LHC) is a project to increase the peak luminosity by a factor 5 and integrate 3000 fb^{-1} at the high-luminosity experiments



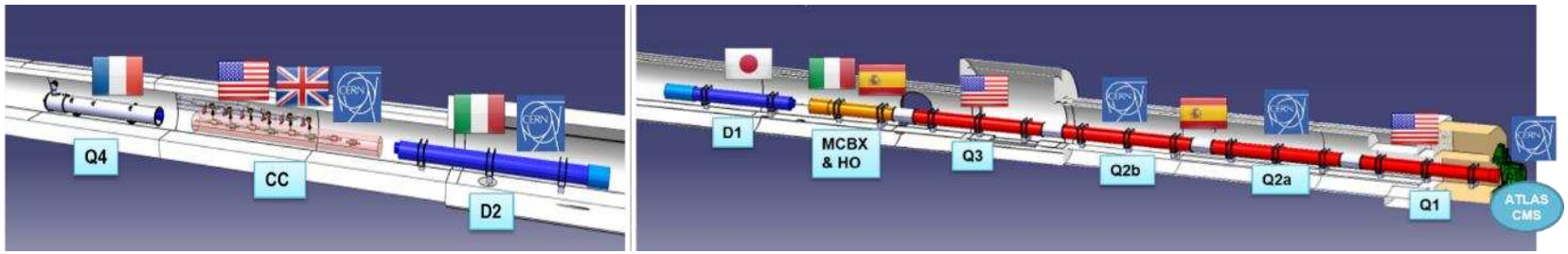
HL-LHC project

- Mostly focused on entirely renovating the insertion regions around the high-luminosity experiments (i.e. about 1.2 km of accelerator)
- Stronger focusing → replace low-beta triplet quadrupoles with higher field and larger aperture
- Low β* requires a larger crossing angle, would reduce the luminosity by a geometrical factor *R* → rotate bunches to collide head on (crab cavities)
- 1 BCHF-scale project





[Delille, HL-LHC report]



Quadrupole | Crab cavity module | Separating dipoles | Corrector | Low-beta quadrupoles | IP

2

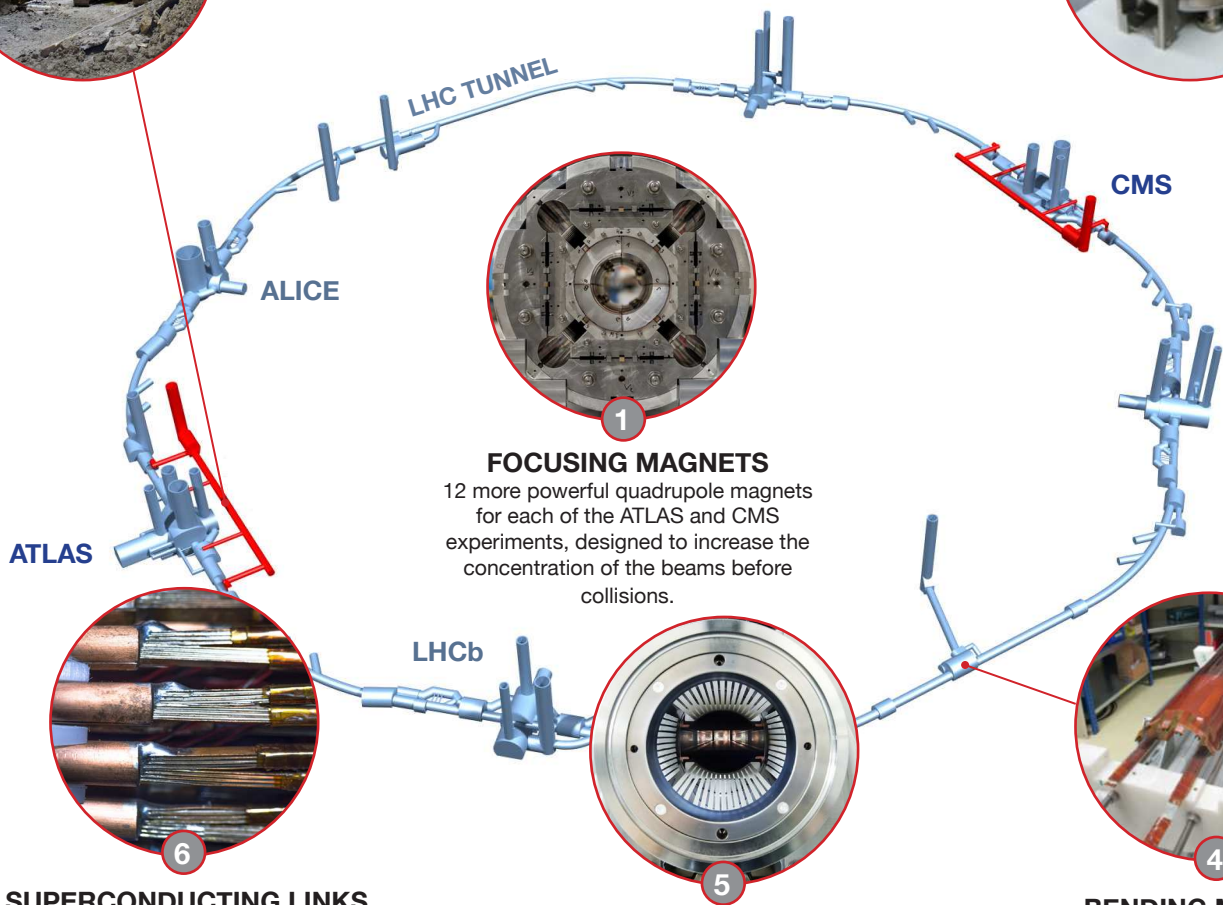
CIVIL ENGINEERING

2 new 300-metre service tunnels and 2 shafts near to ATLAS and CMS.

"CRAB" CAVITIES

16 superconducting „crab" cavities for each of the ATLAS and CMS experiments to tilt the beams before collisions.

3



1

FOCUSING MAGNETS

12 more powerful quadrupole magnets for each of the ATLAS and CMS experiments, designed to increase the concentration of the beams before collisions.

6

SUPERCONDUCTING LINKS

Electrical transmission lines based on a high-temperature superconductor to carry current to the magnets from the new service tunnels near ATLAS and CMS.

5

COLLIMATORS

15 to 20 new collimators and 60 replacement collimators to reinforce machine protection.

4

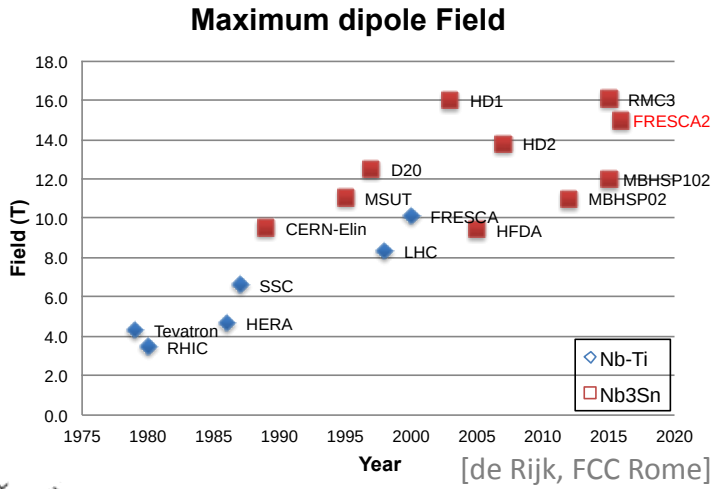
BENDING MAGNETS

4 pairs of shorter and more powerful dipole bending magnets to free up space for the new collimators.

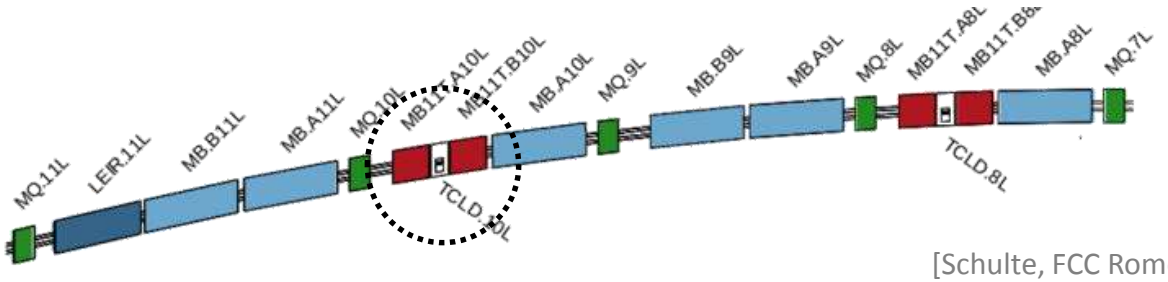
CERN November 2015

High-field magnets

- R&D on high-field magnets in progress using niobium-tin (Nb_3Sn) alloy as superconductor:
- December 2015: Nb_3Sn two-in-one dipole (1.8 m long) reached 11.3 T without quench
- Will allow space for extra collimation in dispersion suppressor region:

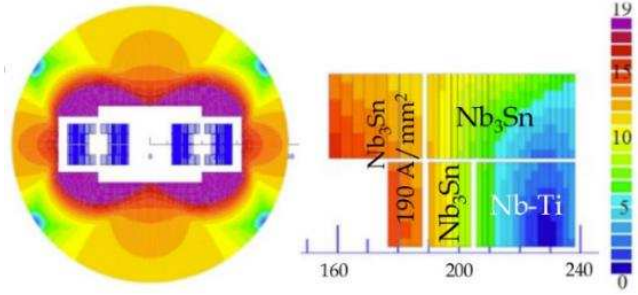


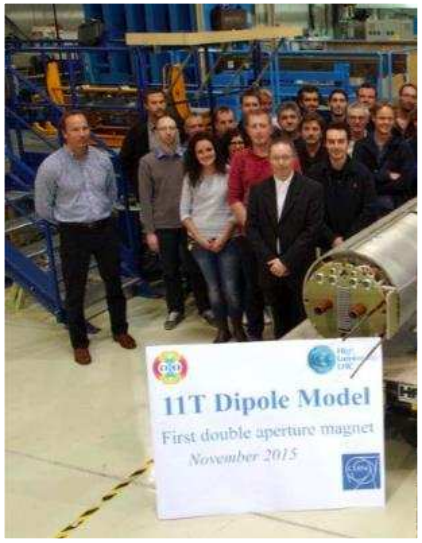
[de Rijk, FCC Rome]



[Schulte, FCC Rome]

16 T magnets studied for FCC:

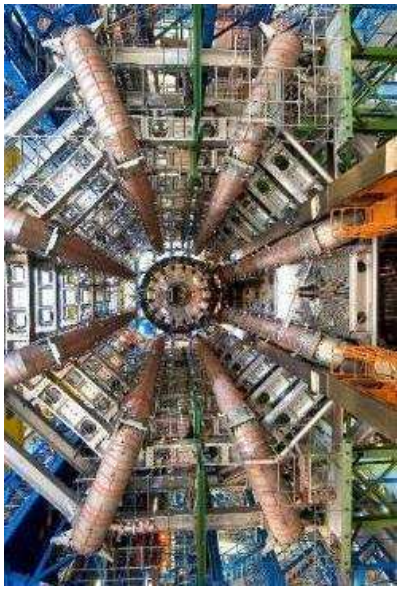




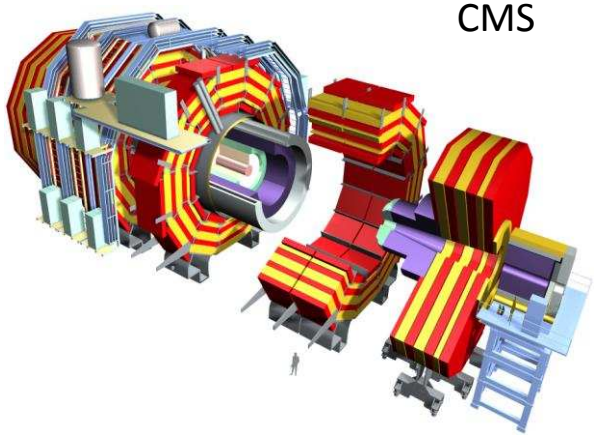
2. Experiments

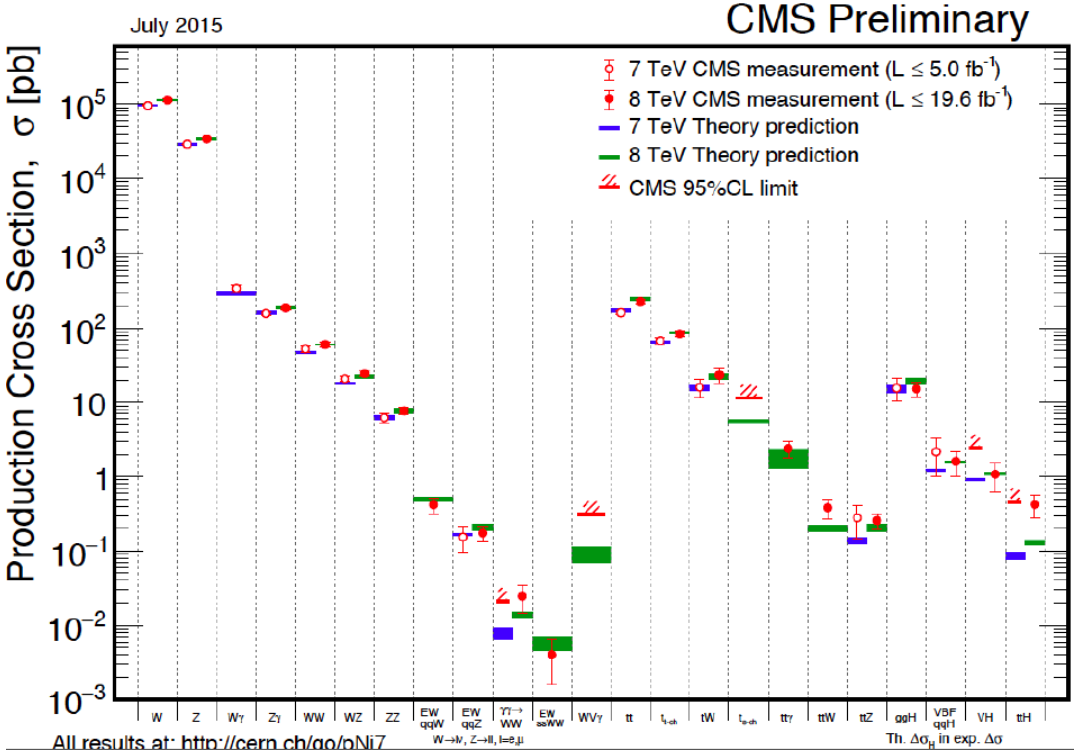
- General-purpose high-p_T experiments **ATLAS** & **CMS**
- Precision study of the Standard Model (including new field of Higgs properties) and search for physics beyond the Standard Model

ATLAS



CMS

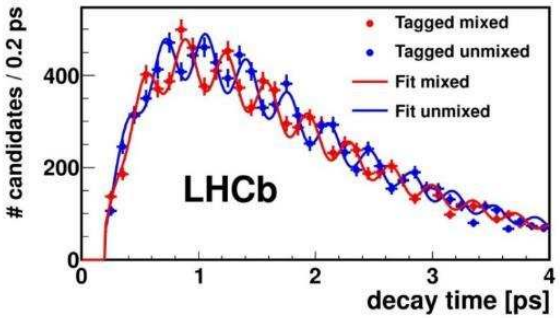




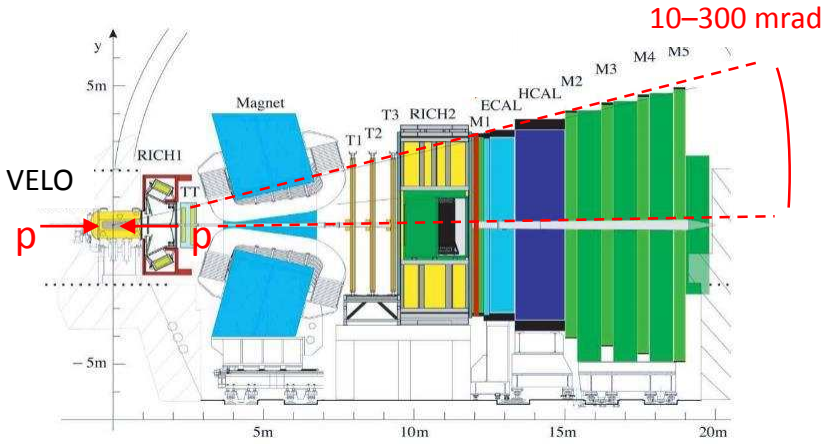
→ talk of Monica Pepe Altarelli

Flavour physics

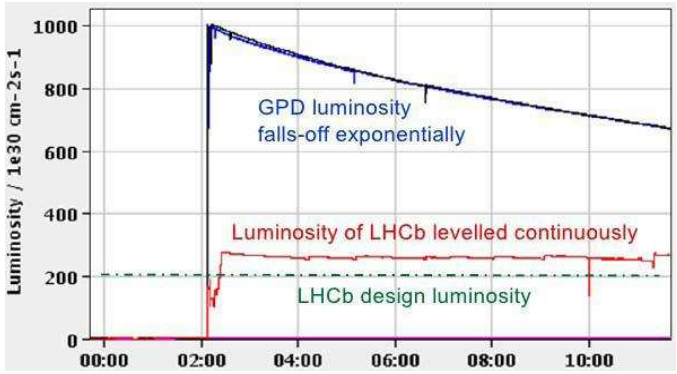
- Enormous rate of b & c hadrons at LHC
  Dominantly produced in forward region
- Dedicated flavour experiment **LHCb**
  Exquisite proper-time resolution (40 fs)



B_s-$\overline{B}_s$ oscillation



Luminosity is levelled for LHCb
by adjusting separation of beams
Levelling will be important at HL-LHC

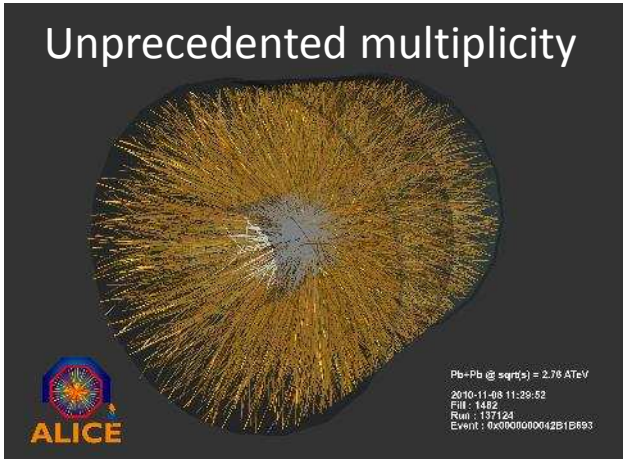


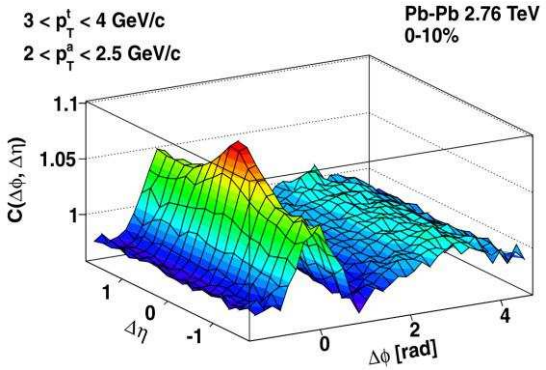
- **MoEDAL**: monopole search experiment (at LHCb IP) surrounds VELO region with plastic sheets to reveal tracks of highly-ionizing particles (after etching)
  First limits recently set [arXiv:1604.06645]

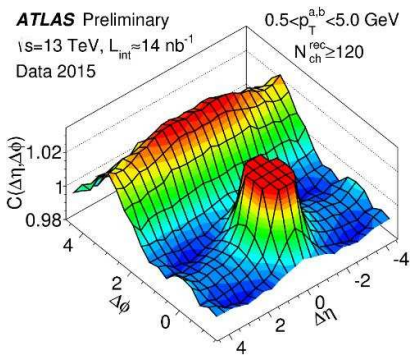
→ talk of Giuseppe Battistoni

Heavy Ion physics

- The LHC also accelerates heavy ions (Pb^{82+})
  Typically run with Pb-Pb or Pb-p collisions for one month at the end of each year
- Dedicated experiment **ALICE**
  (but by now all experiments participate)
  Studying properties of matter at high temperature/density: total energy > 1 PeV
- Example of near-side "ridges" in two-particle correlations seen first in Pb-Pb, then Pb-p now also in high-multiplicity pp (surprise)



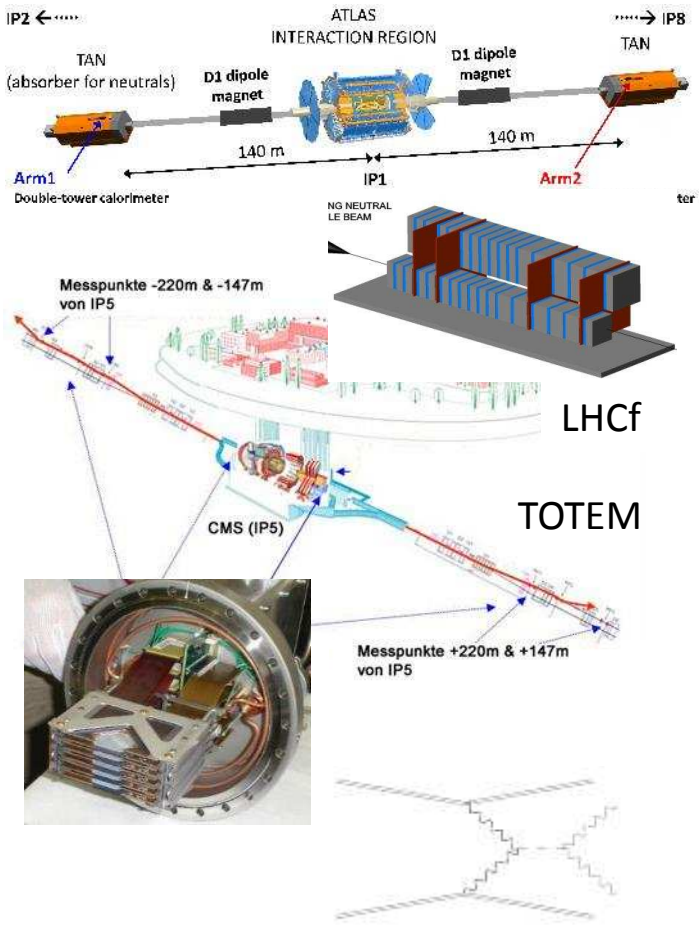


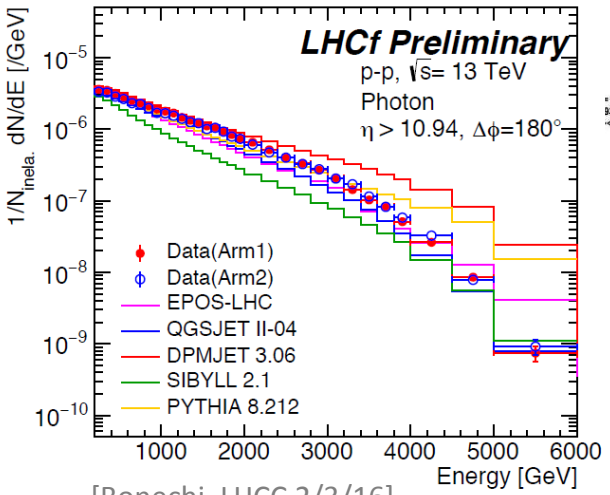


→ talk of Anatoly Petrukhin

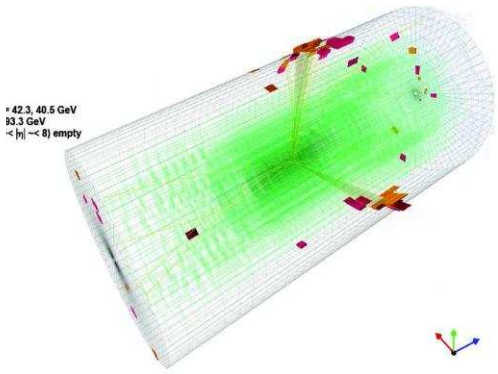
Forward physics

- **LHCf** (at ATLAS IP): zero-degree calorimeter to study neutral prod^{n}, relevant for cosmic rays
- **TOTEM** (at CMS IP): silicon tracking detectors in Roman Pots to study elastic/diffractive scattering of protons
- Can also study Central Exclusive Production (with CMS): may be interesting for states in γγ





[Bonechi, LHCC 2/3/16]



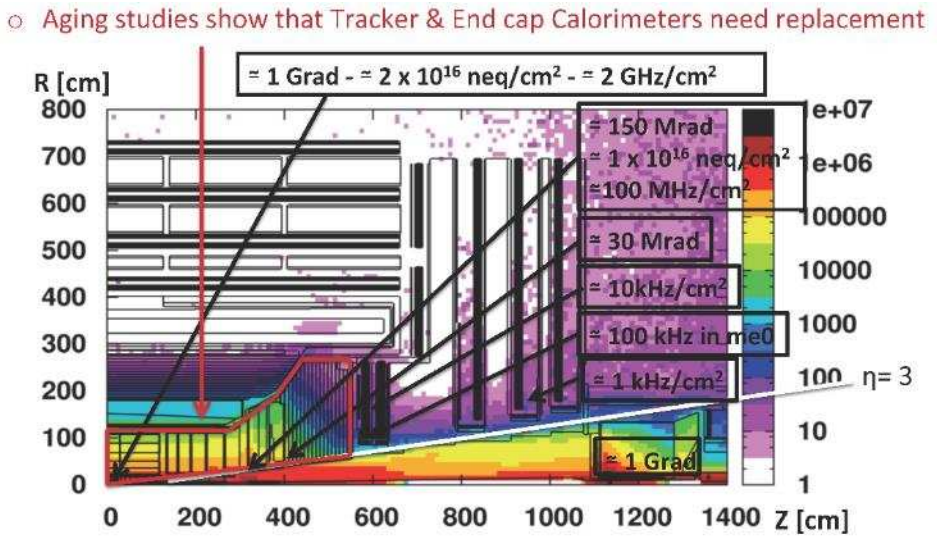
Clean dijet CEP event in CMS
from 90m β* run with TOTEM: p+ JJ +p
[Albrow, DIS 2015]

Target of joint CT-PPS project
(similar project AFP in ATLAS)

Detector upgrades

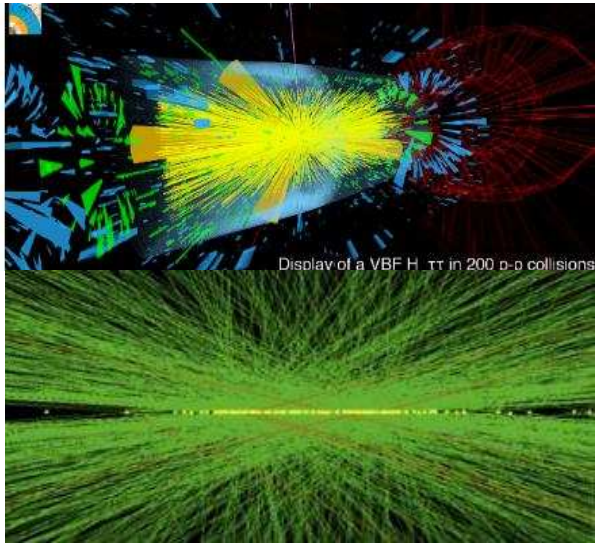
- Increase in energy brings less for LHCb and ALICE than high-p_T experiments so they have major upgrades planned already for 2019 (LS2): "Phase 1"
- Major upgrades for ATLAS & CMS are to prepare for HL-LHC in LS3: "Phase 2"
  Agreed funding scale ~250 MCHF for each experiment
  (LHCb and ALICE will also continue during HL-LHC phase)
- **Major challenges:** radiation dose, and occupancy/pile-up

Radiation dose in CMS after 3000 fb^{-1}



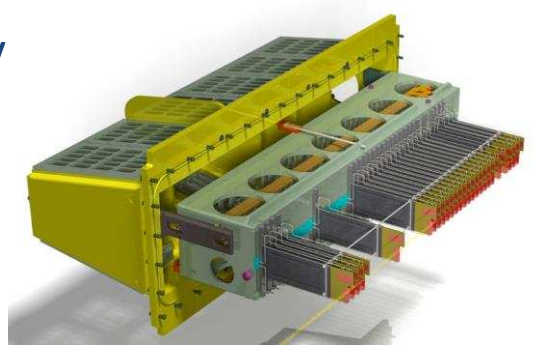
[Contardo, LHCC 2/6/15]

Simulation of 200 pile-up vertices

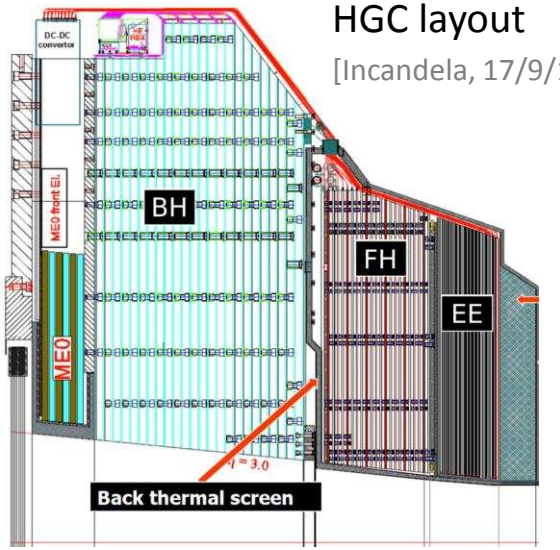


Increased granularity

- Increase in occupancy is fought using higher granularity
- All experiments will replace their silicon trackers
  Example from LHCb: VELO with 55 x 55 µm pixels instead of current strips
- CMS: High-Granularity Calorimeter in forward region
  Tungsen + 6 million silicon pads each ~ 1 cm^2

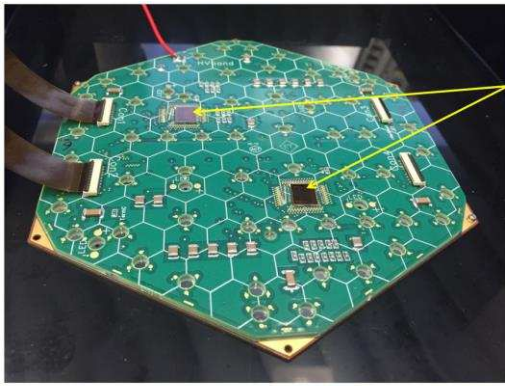


VELO half

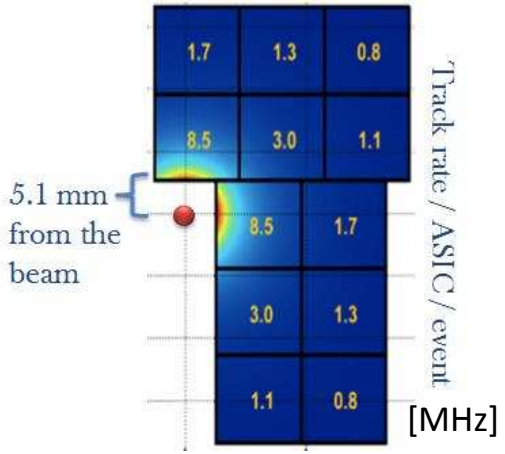


HGC layout
[Incandela, 17/9/15]

Prototype of HGC silicon sensor



6-inch module with W/Cu plate and 128 channels readout.

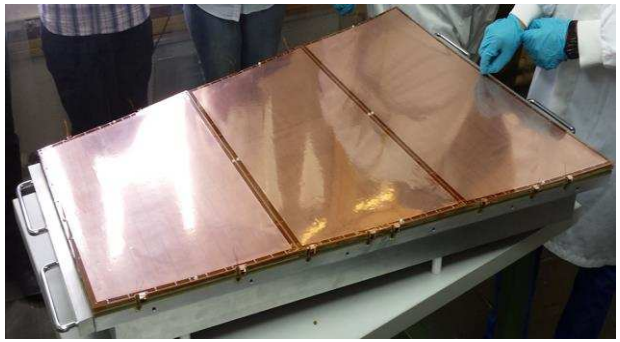


VELO pixel chips
[LHCb-TDR-013]

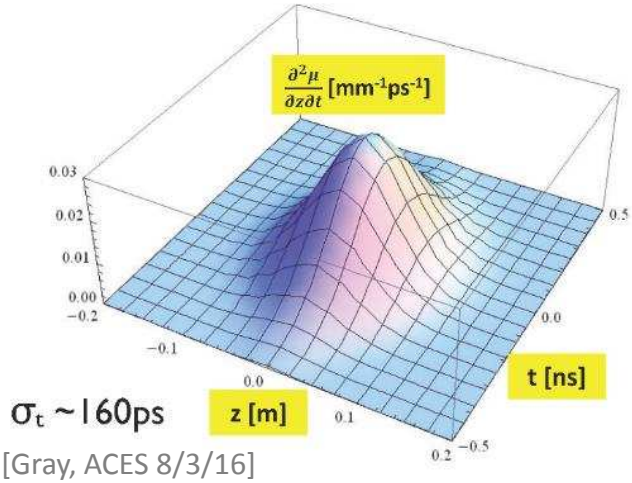
Increased speed

- ALICE TPC wire chamber readout currently limits data taking rate: replace with GEM endplates → 50 kHz readout (20x higher)
- LHCb signal yield currently limited for hadronic modes by first-level trigger
  For upgrade will *remove* hardware trigger and read out full detector at 40 MHz
  → Enormous data rate: ~5 TB/s
  12000 optical links to CPU farm on surface
- Fast timing detectors studied by all experiments to fight pile-up:
  Beam-spot spreads over ~300 ps
  If could be divided into O(25 ps) slices
  → reduce occupancy to current level

[ALICE-TDR-016]



Beam-spot (t vs. z)

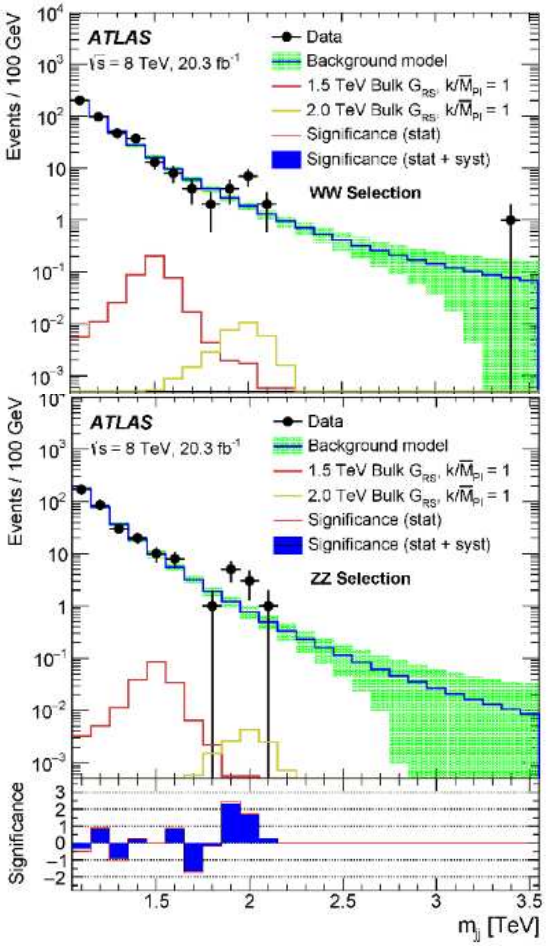


[Gray, ACES 8/3/16]

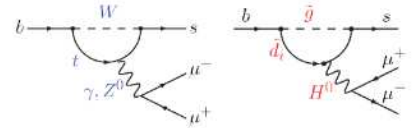
3. Physics

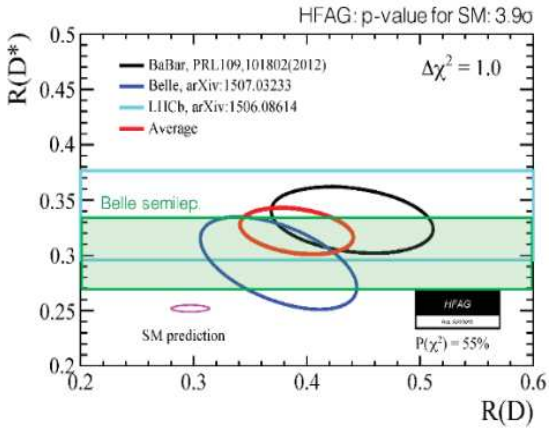
- Major focus at the LHC is on search for physics beyond the Standard Model
- Some hints of anomalies in Run 1 data:
  e.g. in flavour physics, e.g. LFV in $B^0 \to D^{(*)}\tau\nu$, angular analysis (P_5') of $B \to K^*\mu\mu$ decays;
  & in search for resonances in vector-boson pairs

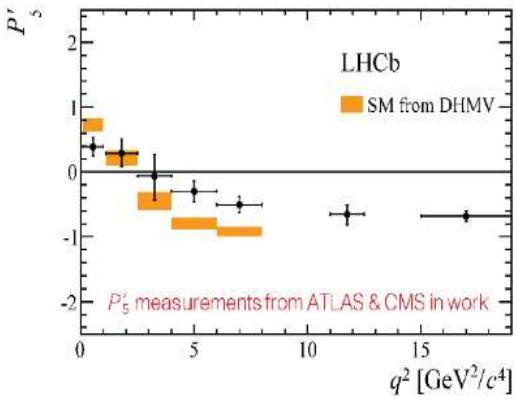
[Hoecker, Moriond EW 2016]



$$R_{D^{(*)}} = \frac{\mathrm{BR}(B^0 \to D^{(*)}\tau\nu)}{\mathrm{BR}(B^0 \to D^{(*)}\ell\nu)}$$



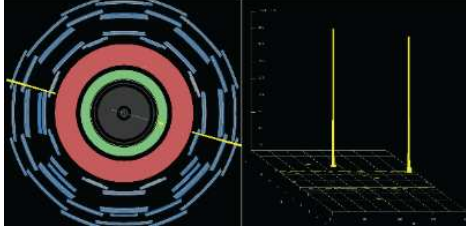




→ To be followed up with new data

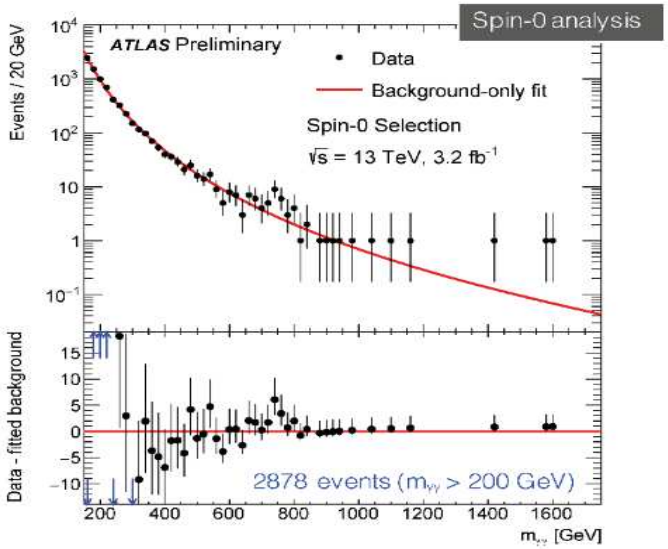
(not confirmed by CMS)

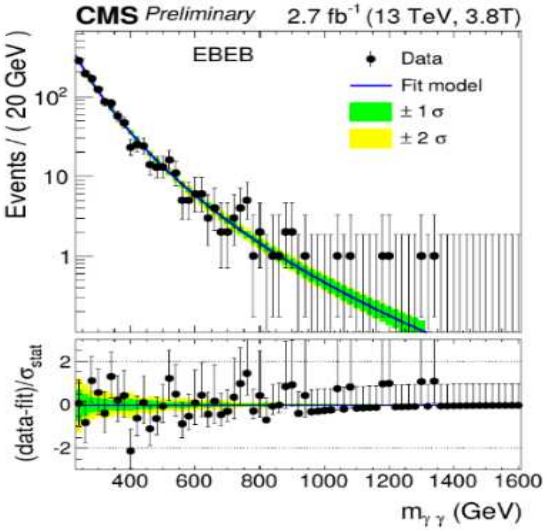
Diphoton excess



[Hoecker, Moriond EW 2016]

- **Latest excitement:** excess seen in diphoton mass spectrum in 13 TeV data by both ATLAS & CMS at around 750 GeV
- ATLAS significance = 3.9 σ local/2.0 σ global
  Consistent with spin 0 or 2 resonance
  Width ~ 45 GeV (6%) preferred
- Would clearly be new physics if confirmed:
  Over 200 papers on its interpretation so far…
- No official combined significance yet
  Using ATLAS to define the test mass and CMS to measure the significance gives 3.4σ
- If it is confirmed, this will be *huge*
  but it may still be a statistical fluctuation
  This year's data is eagerly awaited…



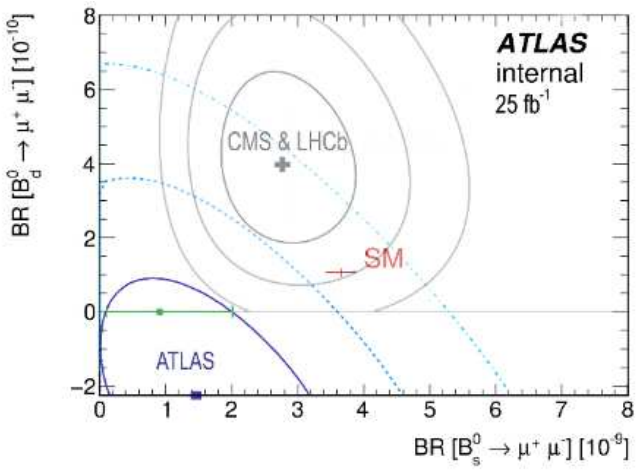


→ talk of Pierluigi Campana

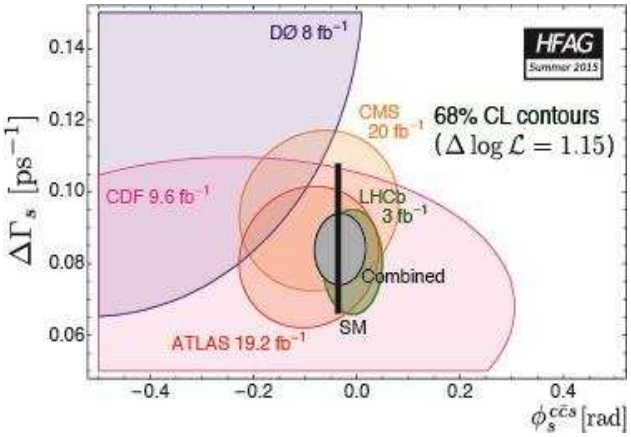
Flavour prospects

- LHCb integrated 3 fb^{-1} of data in Run 1 with levelled luminosity of 4 x 10^{32} $cm^{-2}s^{-1}$
- Precision measurements made of rare decays and CP violation of many b & c hadrons
- Upgrade luminosity increased to few x 10^{33}
  → aim to integrate 50 fb^{-1}
- Examples of precision expected:
  - BR($B_{(s)} \rightarrow \mu^+\mu^-$) at the 10^{-10} level
  - ϕ_s (ϕ of B_s oscillation) ±0.008
  - Unitarity angle gamma to ±1°
- Discussions underway for the HL-LHC phase

$B_{(s)} \rightarrow \mu^+\mu^-$ [arXiv:1604.04263]

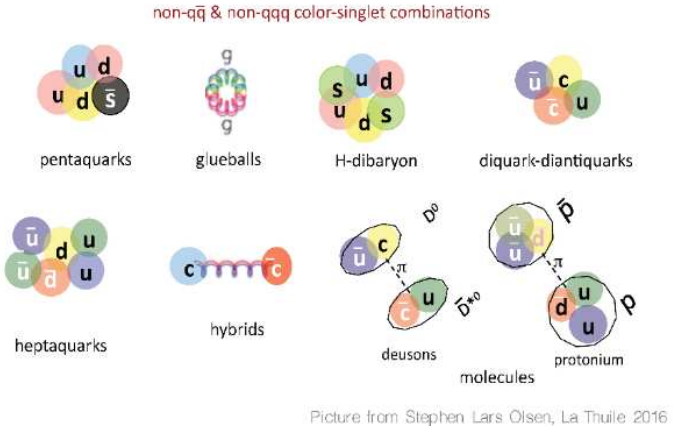


B_s phase vs. width difference

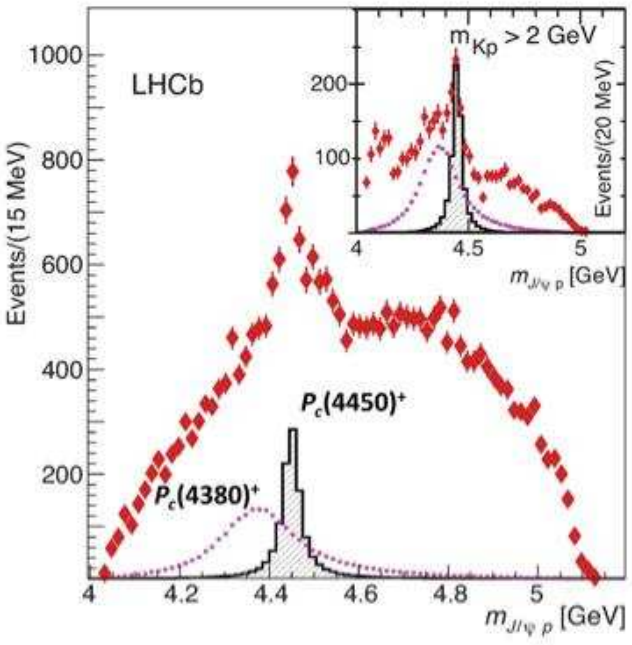


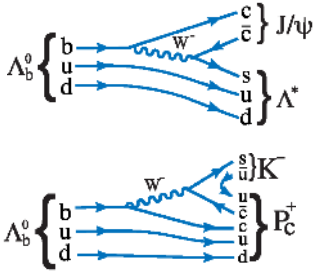
Exotic hadron spectroscopy

- Zoo of possible exotic hadron states:
- LHCb has established a pentaquark state $P_c(4450)^+ \rightarrow J/\psi\, p$ using full angular analysis
- But do not confirm recent tetraquark claim
  Such states will be studied with new data

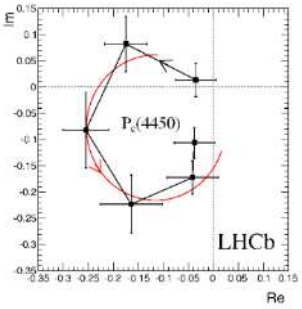


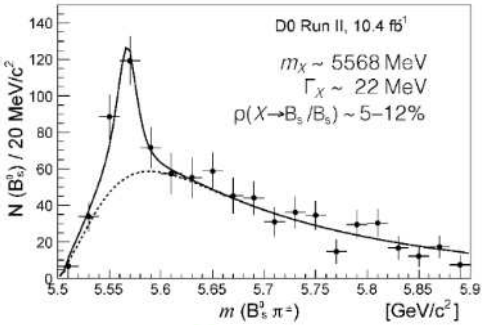
[PRL 115, 072001]

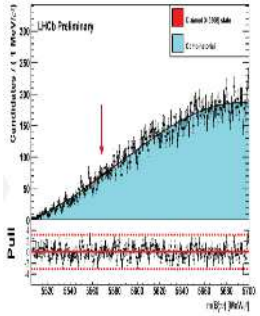




Argand diagram







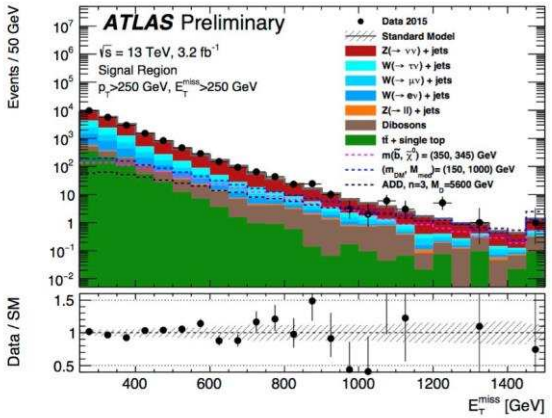
[arXiv:1602.07588]

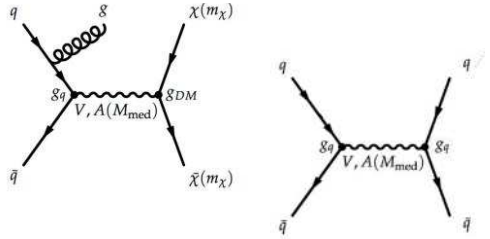
[Gandini, Moriond QCD 2016]

→ talk of Mario Antonelli

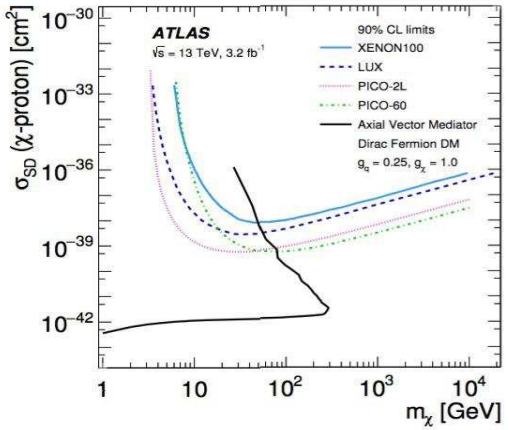
Dark Matter searches

- Assuming dark matter is made of particles that couple to quarks via a mediator
  → may be produced at LHC
- Would leave no trace in detector, so to tag its production need a particle from initial state radiation → **monojet** search (missing E_T)
- Can also expect that mediator would couple to quarks in final state → **dijet** resonance search

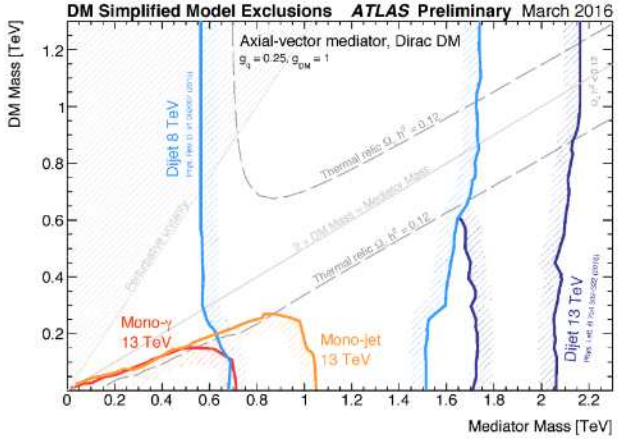


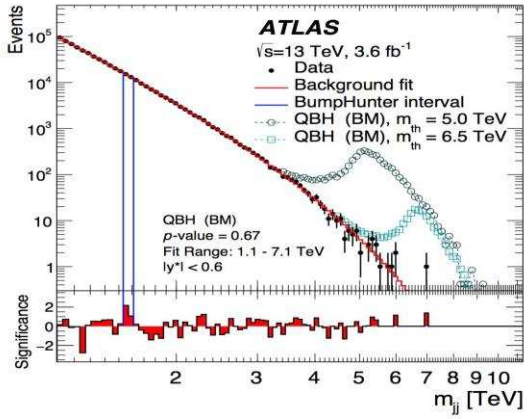


[Boveia, CERN seminar 26/4/16]



Dark matter vs. mediator mass

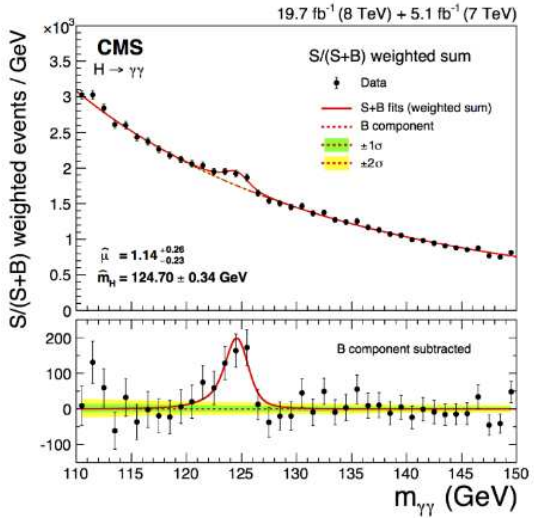




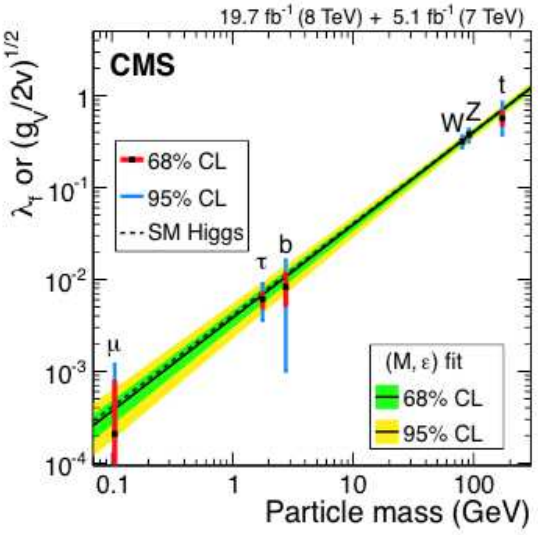
→ talk of Roberto Di Nardo

Higgs physics

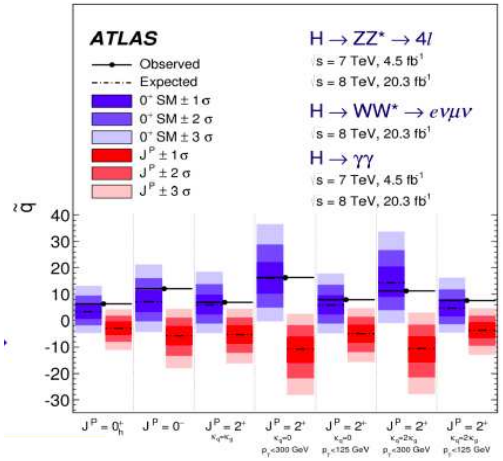
- Higgs Boson discovered in γγ and ZZ modes
- ATLAS & CMS results now combined [PRL 114, 191803]
  Mass = 125.09 ± 0.21 (stat) ± 0.11 (syst) GeV
- Alternative spin-parities disfavoured > 99.9%
- Behaves like Standard Model Higgs, so far

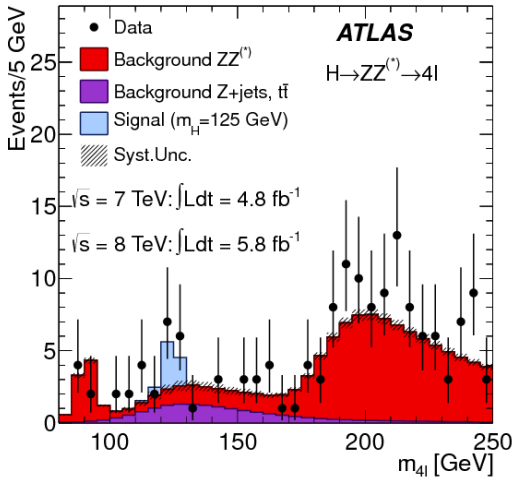


Higgs coupling vs. mass



Spin-parity tests
[arXiv:1506.05669]

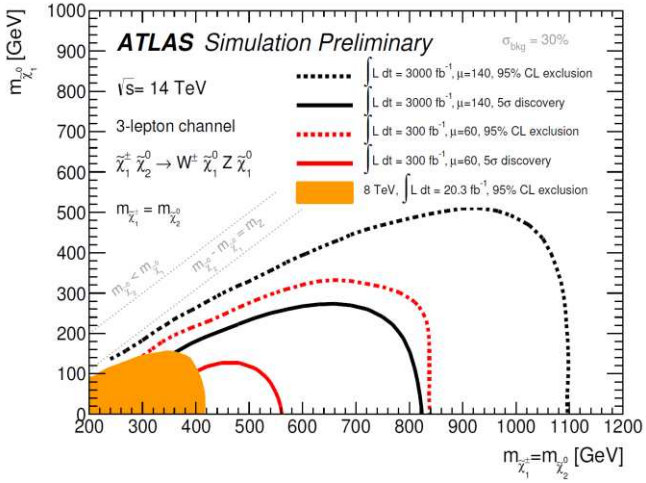


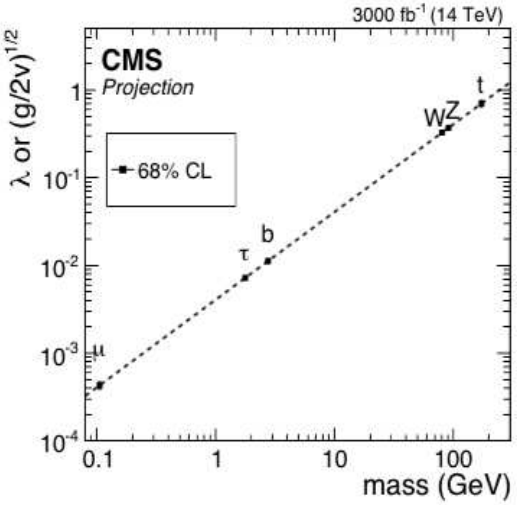


HL-LHC prospects

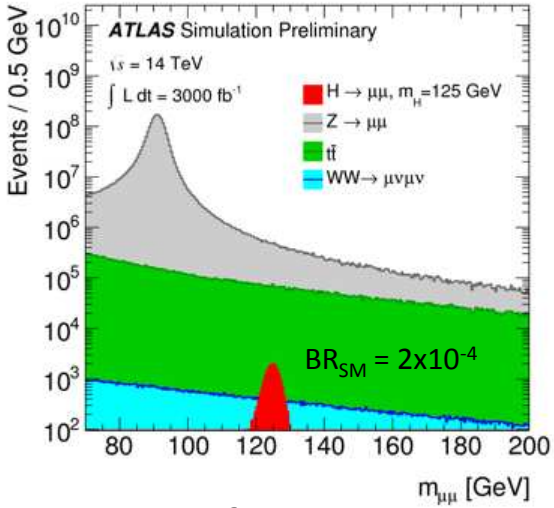
- If new physics discovered in Runs 2/3
  → first detailed exploration with well understood machine and experiments
- Otherwise extend direct discovery potential by 20-30% in mass reach
- In either case: >100 million Higgs produced measure Higgs couplings to a few percent
  including 2nd generation via $H \longrightarrow \mu^+\mu^-$

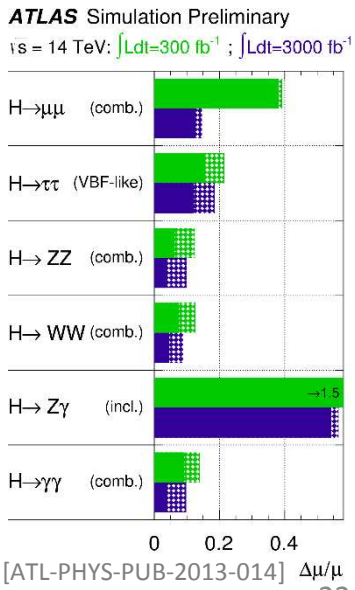
SUSY search [ATL-PHYS-PUB-2013-011]





[arXiv:1307.7135]

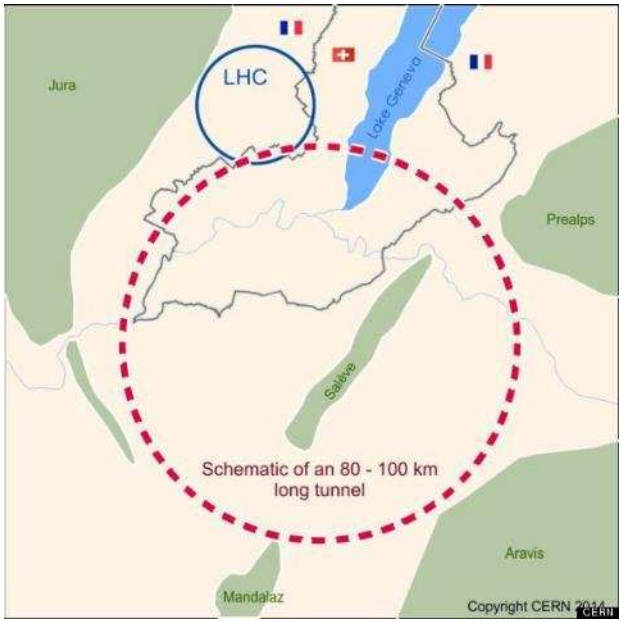


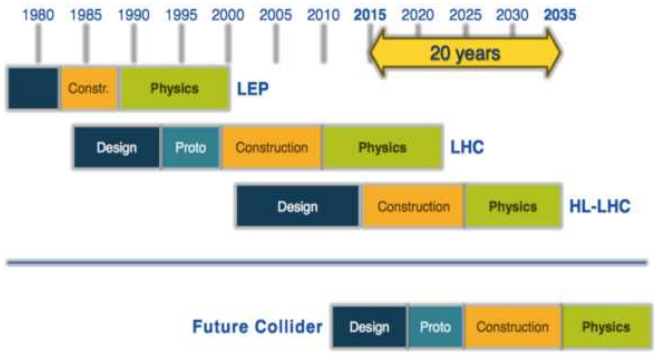


[ATL-PHYS-PUB-2013-014]

Far future

- Results from Run 2 will hopefully clarify best choice for the next energy-frontier machine in time for the next update of the European Strategy in 2019-20
- One option is the Future Circular Collider (**FCC**): 100 TeV-scale pp collider (with e^+e^- machine as a possible first step) LHC likely to be reused as injector
- Key R&D for FCC is to develop 16 T magnets to reach 100 TeV in 80-100 km tunnel
- Using such magnets in the *existing* tunnel would give $\sqrt{s}$ ~ 30 TeV Investigation of this possible High-Energy LHC (**HE-LHC**) is now part of the FCC study



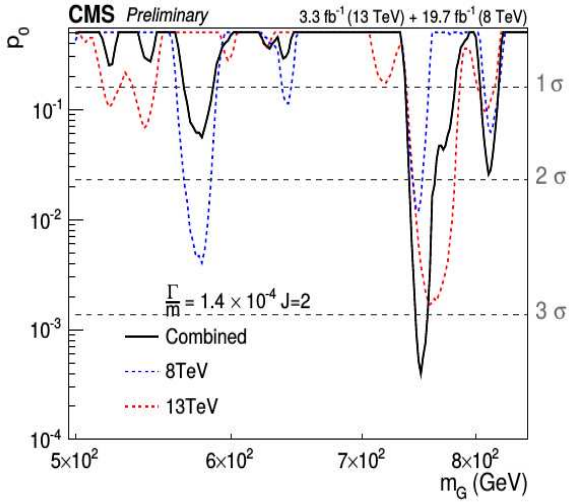


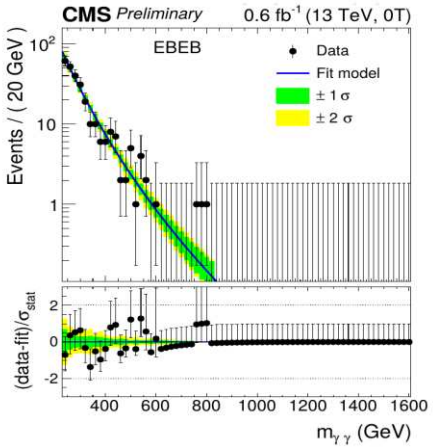
Conclusions

- The LHC at CERN is the flag-ship facility of world-wide particle physics
  Has been operating successfully over the last 5 years
  - Higgs discovery, and a vast array of other results
    >1500 scientific publications (and counting)
- This is a very exciting time for particle physics
  - Recent increase in energy is the last such major step for some time
    Strong hopes for discoveries over the coming years
- Upgrade program is in preparation for both machine and experiments
  - To integrate over 100 times the current dataset
    Exploit the LHC to its full potential over the next 20 years
- Results from the LHC will play a key role in defining the future direction
  - Long lead time → choice of its successor will need to be made soon

Extra slide

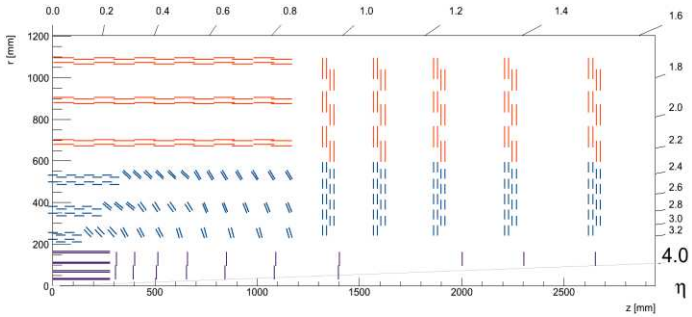
- CMS had a problem in 2015 with oil inside cryogenic system of solenoid (now cleaned)
  → ~25% of data was taken with field off
- Have now analyzed that data too for the γγ search and found an extra candidate
  Run 1 data also consistent with excess



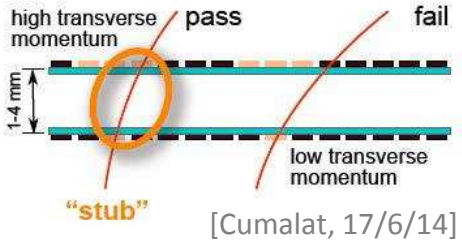


[Musella, Moriond EW 2016]

Upgraded CMS silicon tracker layout



Includes some trigger functionality



[Cumalat, 17/6/14]

Tilted pixel modules:

[Onnela, Forum 2014]

- **Offline computing** will also be an challenge for HL-LHC:
  Total LHC data rate projected to increase x10 to 500 PB/year