Results from the LHC

(with a particular focus on LHCb)

Roger Forty (CERN)

1. The LHC machine and experiments
2. LHCb results on flavour physics
3. Prospects

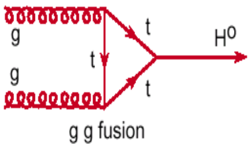
ISOLDE Workshop and Users meeting “50th Anniversary Edition”, 16 December 2014

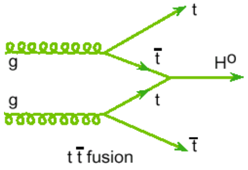
1. The LHC

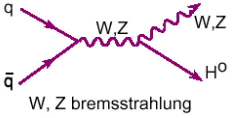
- Previous energy-frontier machine at CERN was **LEP**: e^+e^- collider designed to study Z and W production (90-200 GeV, 1990-2000)
- The LHC uses the same tunnel,
  27 km in circumference
  Collides protons to reach higher energy (reducing synchrotron losses)
- Key question it was designed to address is the origin of Electroweak Symmetry Breaking, explained in the Standard Model by the BEH (Brout-Englert-Higgs) mechanism

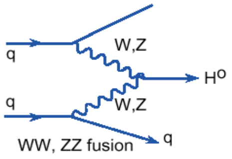
- Should have an associated Higgs boson, but its mass is a free parameter
  $114 < m_H <\sim 1000$ GeV (from LEP searches, and WW scattering unitarity)
- Since protons are composite (quarks, gluons) design energy of LHC = **14 TeV**

Digging out signal

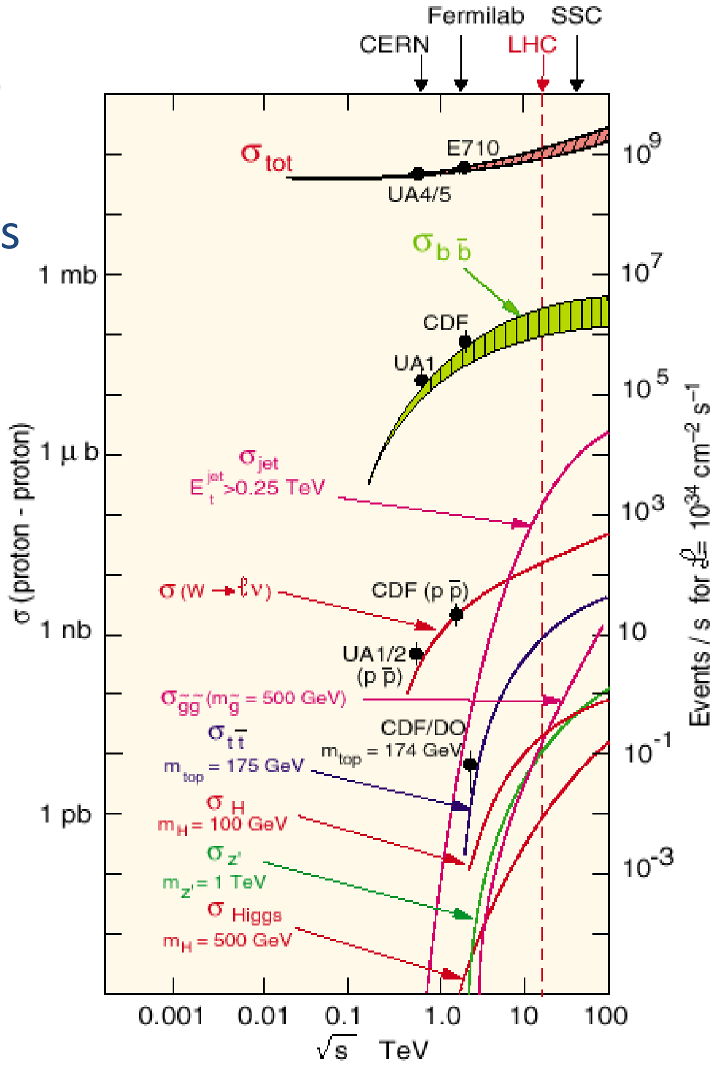






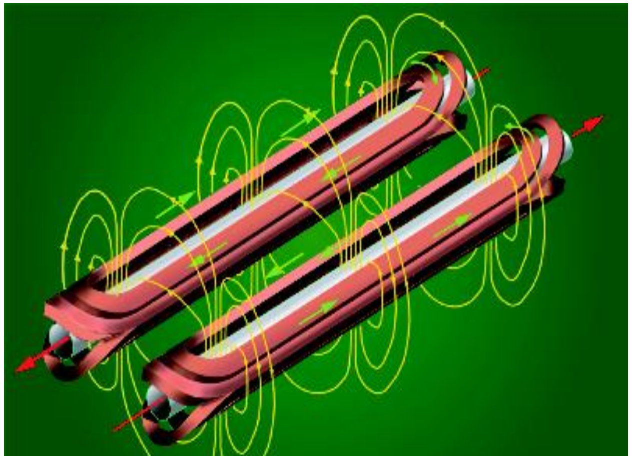


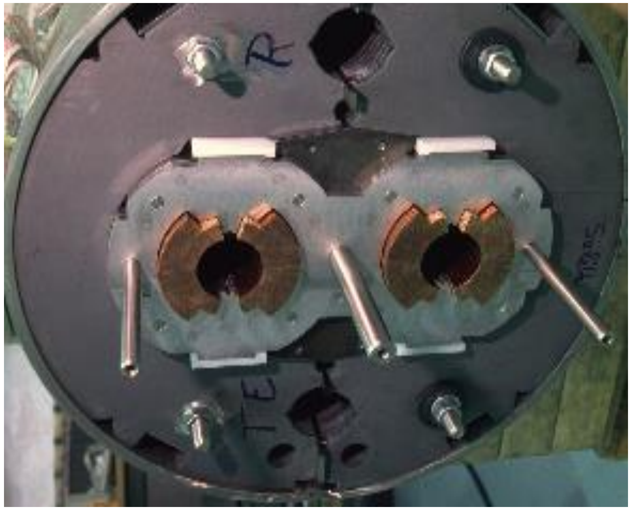
- Various production diagrams: gg → H dominates
  Cross-section is order of a few picobarns
- Total cross-section $\sigma(pp \rightarrow \text{anything}) \sim 0.1$ barn
  So few pb Higgs cross-section corresponds to one being *produced* every ~ 10^{10} interactions!
- Rate = $L\sigma$, need high luminosity
  Design luminosity $L = 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$
  Bunch crossing rate 40 MHz
- Experiments have been designed so that they can separate such rare signal processes from the background: **triggering** essential
  Typically select high transverse momentum, p_T



Cutting-edge technology

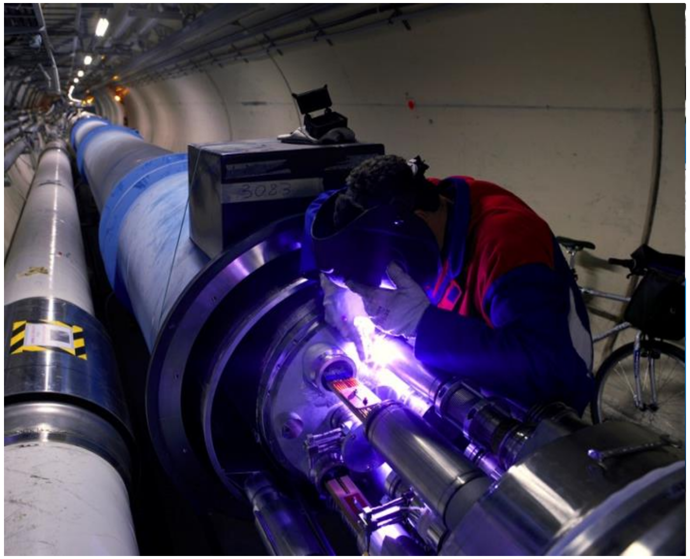
- The LHC has 1232 dipoles, 392 quadrupoles
  2 beam pipes/magnet, with opposite field
- 8.3 T field required to reach 14 TeV
  → dipole magnets are **superconducting**:
  Niobium-titanium cable (embedded in copper)
  carrying a current of 11,700 A
- Cooled to 1.9 K (colder than outer space)
  using liquid helium: ~ 700,000 litres required
  → the LHC is largest **cryogenic** system in world
- High vacuum in beam pipes ~ 10^{-10} mbar
- At the design luminosity of the LHC
  stored energy in each beam is
  2808 bunches × 10^{11} p × 7 TeV = 360 MJ
  ≈ energy of ~ 100 kg TNT → careful
  machine protection (collimation/beam dump)



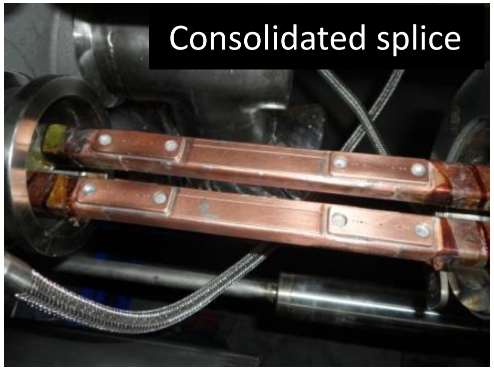


LHC timeline

- First preparatory meetings ~ 1984 — 30 years ago!
  Construction 1998–2007



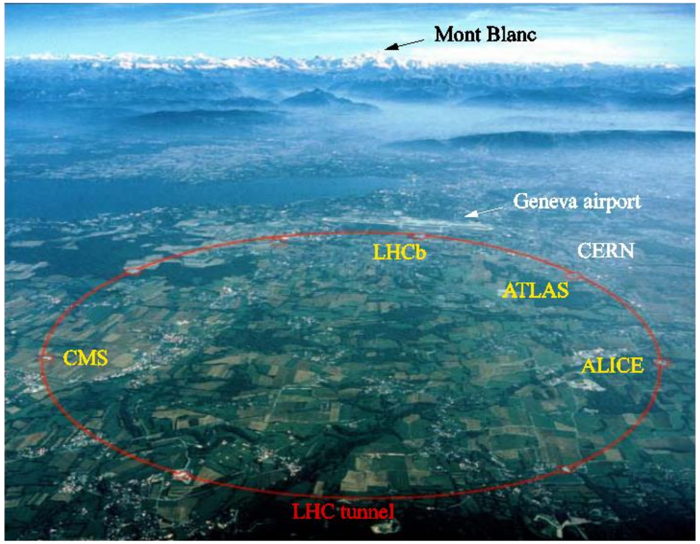
- Incident during commissioning in September 2008 caused by failure of a magnet interconnect
  Damage done by escaping helium delayed start-up by a year
- Ran at E_{cm} = 7 TeV in 2010-11
  and then 8 TeV in 2012
  } Run 1
- Repair campaign to improve interconnects and protection has taken place over the last two years
  10,170 splices, ~ 30% redone
  Now successfully completed

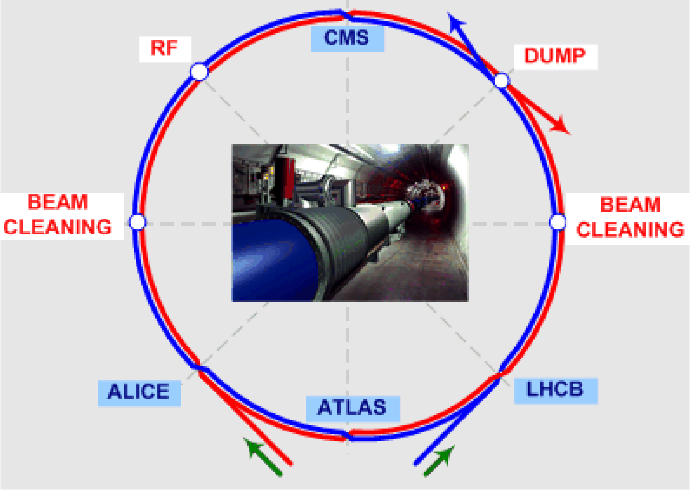


- Restart next year at E_{cm} = 13 TeV

LHC experiments

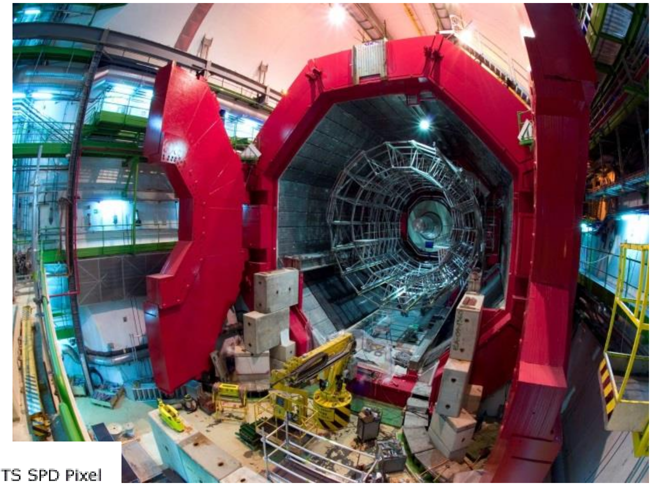
- Four interaction points with detectors installed
- Two “general-purpose” experiments
  ATLAS and **CMS**: high-p_T physics such as study of Higgs and search for new particles
- One for study of Heavy Ion collisions
  ALICE: investigating the properties of nuclear matter at high temperature/density
- One dedicated to flavour physics
  LHCb: studying charm and beauty quarks
- Additional smaller experiments sited at same interaction points
  TOTEM (CMS): total cross-section measurement
  LHCf (ATLAS): forward production of neutrals
  MoEDAL (LHCb): search for *magnetic monopoles* with plastic sheets to detect highly ionizing tracks

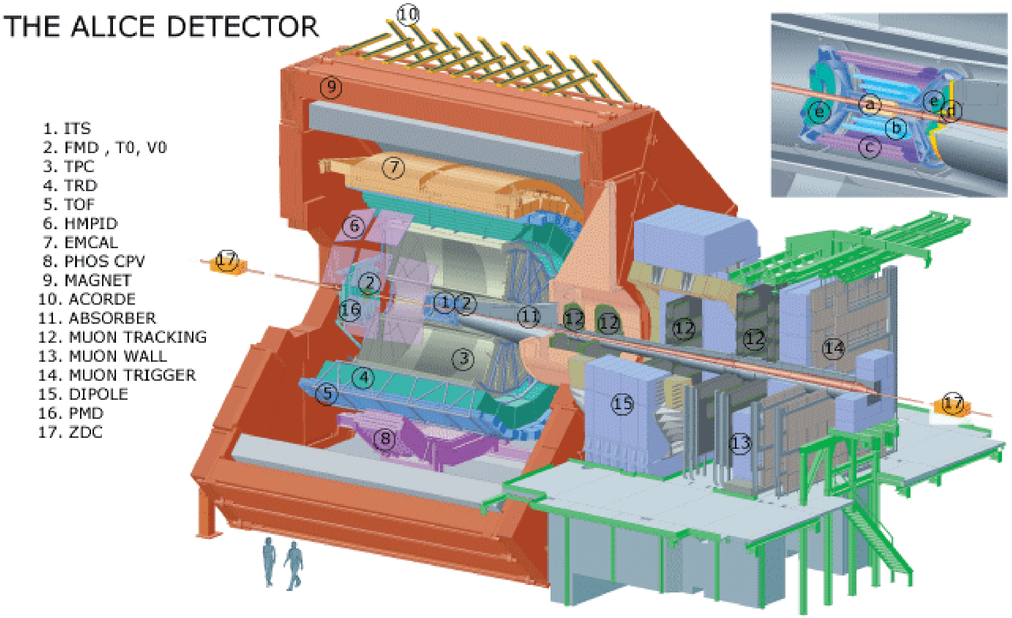


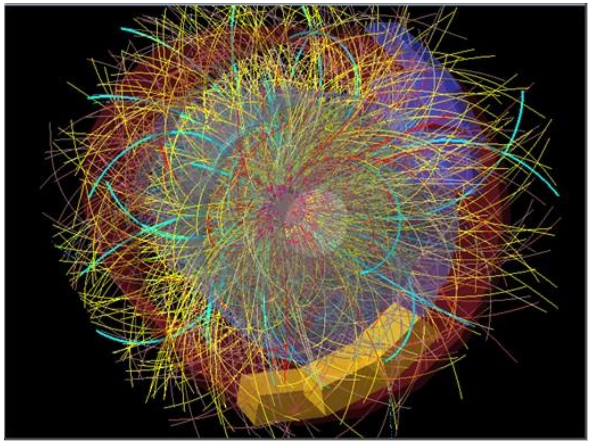


ALICE

- **A L**arge **I**on **C**ollider **E**xperiment
  Optimized for the study of Heavy Ion collisions such as Pb-Pb
  LHC runs with Pb^{82+} ions ~ 1 month/year
- ALICE reuses the magnet of one of the LEP experiments (L3)

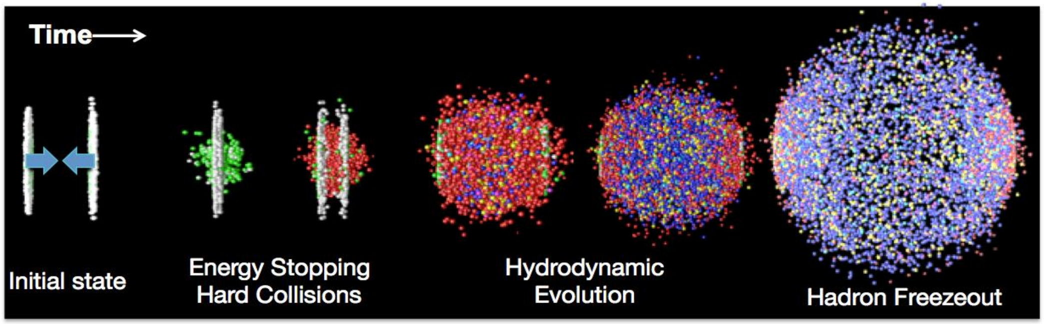






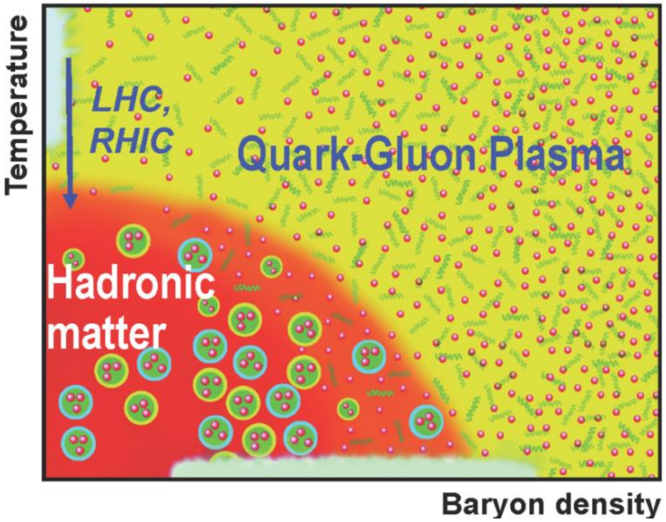
High multiplicity collisions!

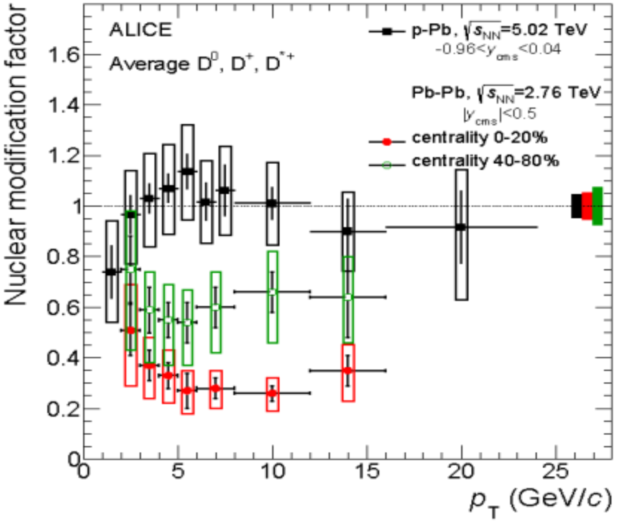
Heavy Ion physics



Simulation of collision between two Pb nuclei (Lorentz contracted)

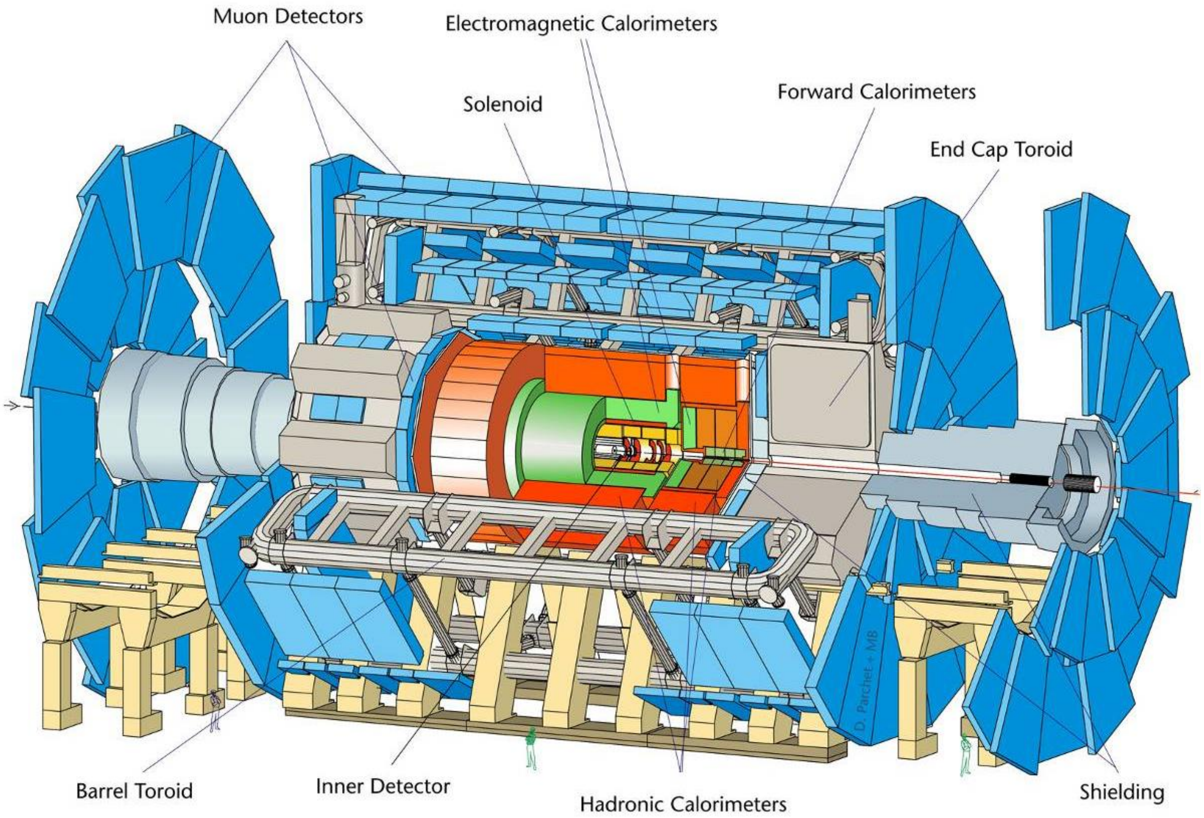
- In the high temperature environment of such collisions, lattice QCD predicts normal hadronic matter undergoes phase transition into a deconfined state
- Studying properties, such as suppression of heavy flavours (here charm)

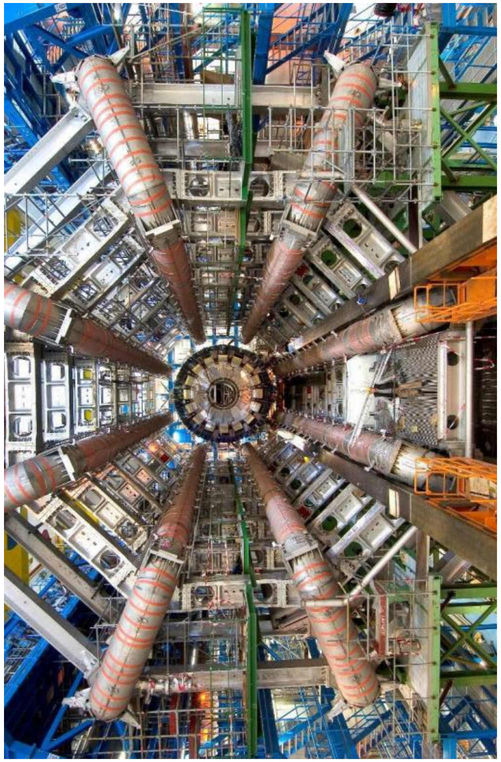




ATLAS

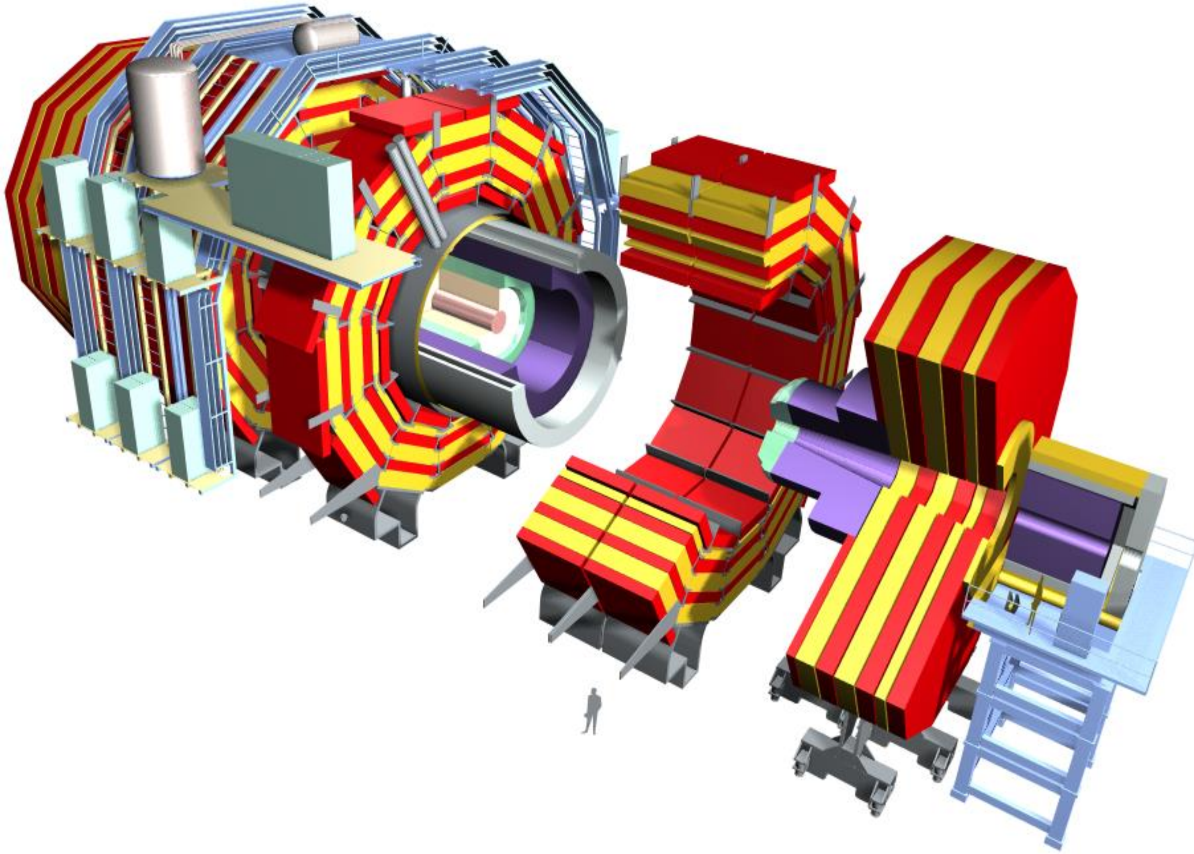
- Named with a slightly contrived acronym: **A T**oroidal **L**hc **A**pparatu**S**
  It is the largest HEP experiment ever – 45 m long, 7000 tons

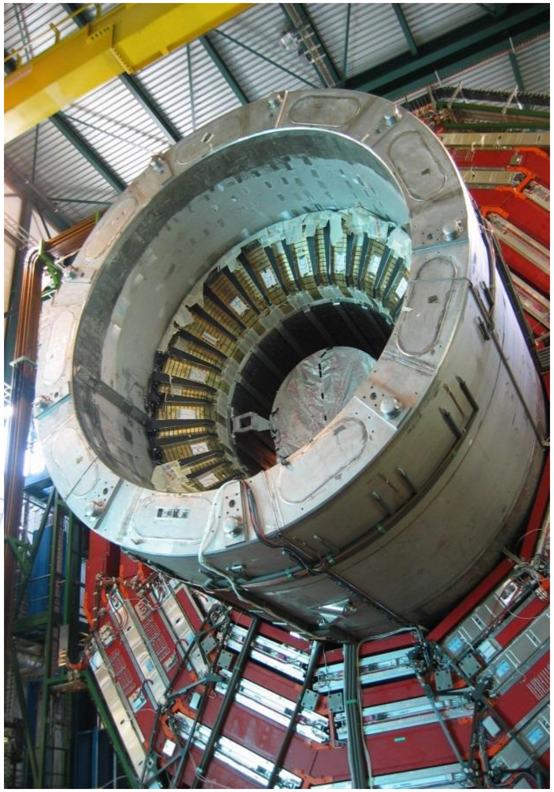




CMS

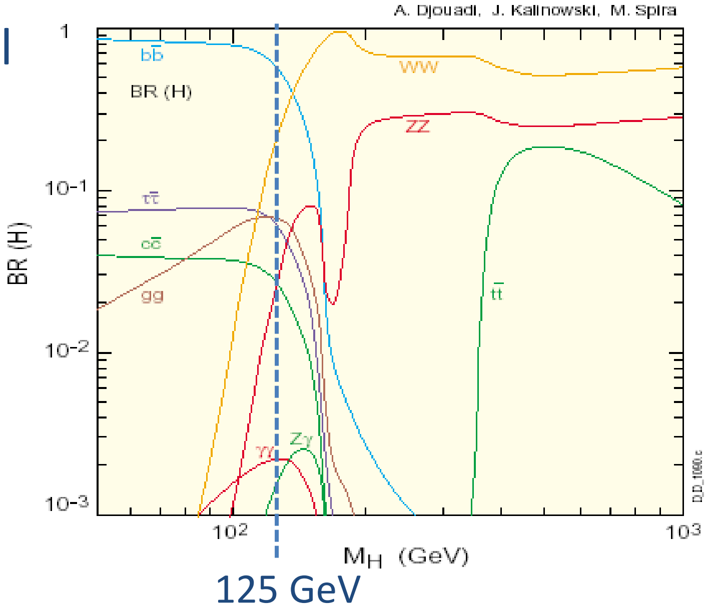
- **C**ompact **M**uon **S**pectrometer
  Compact compared to ATLAS, but ~2× heavier: 21 m long, 12500 tons

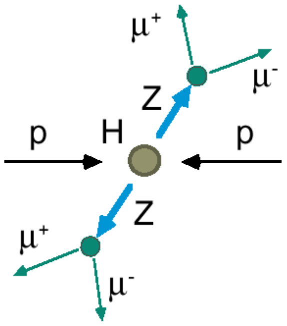


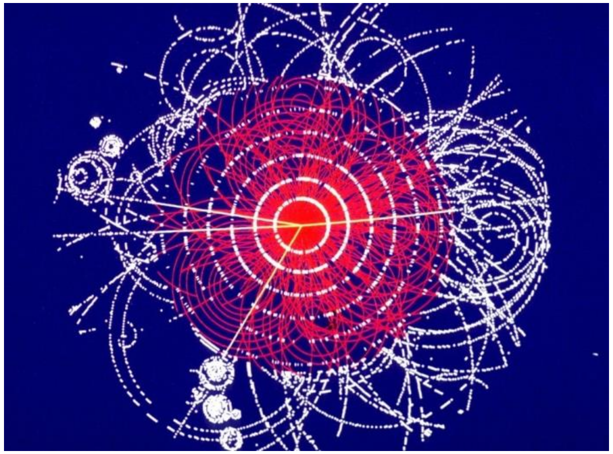


Higgs search

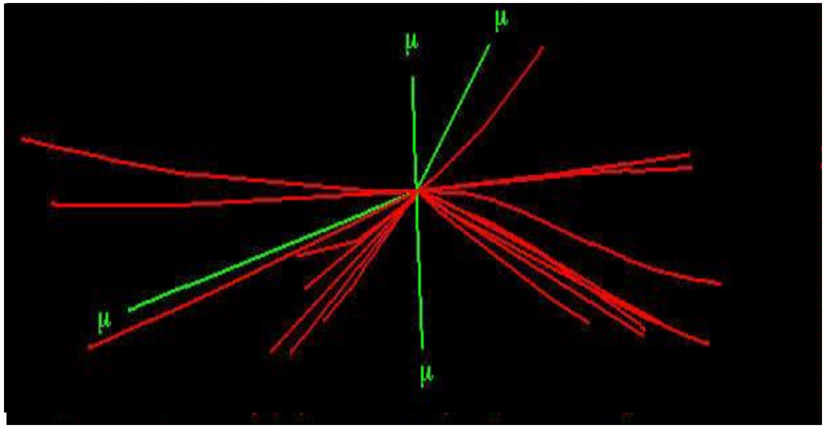
- At high mass, H → ZZ → 4μ is easiest channel
- At low mass, dominant channel H → bb has a huge QCD jet background
  Instead H → γγ is preferred search channel despite low branching ratio ~ 10^{-3}
- "Pile-up" of minimum-bias interactions: up to 20 superimposed pp interactions as luminosity increased



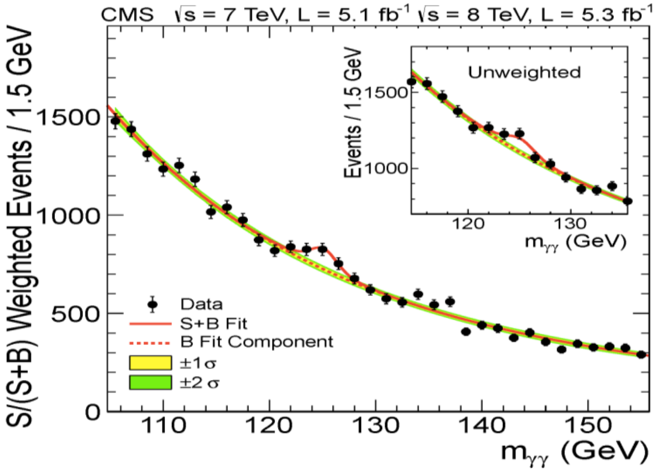


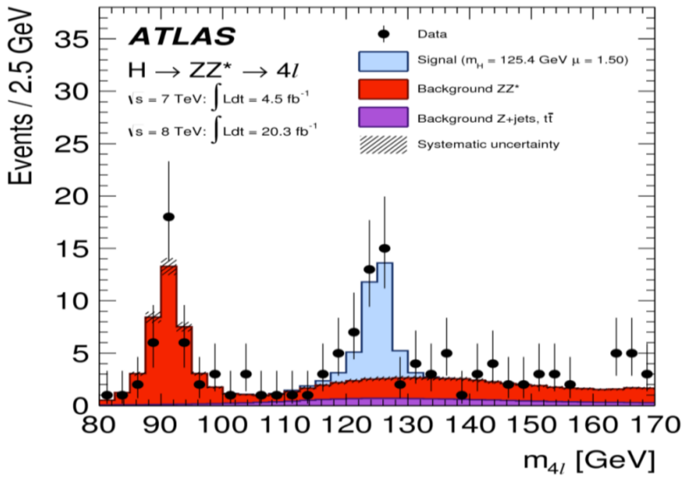


Keeping only tracks with $p_T > 25$ GeV



Higgs discovery





- Discovery announced in July 2012
  Nobel prize for Englert + Higgs the following year
  Initially 5σ significance, but now overwhelming

- **Latest results**: $\mu = \sigma(\text{observed})/\sigma(\text{SM})$
  μ (CMS) = 1.00 ± 0.09 (stat) $\pm^{0.07}_{0.08}$ (th) ± 0.07(syst)
  μ (ATLAS) = 1.30 ± 0.12 (stat) ± 0.10 (th) ± 0.09(syst)

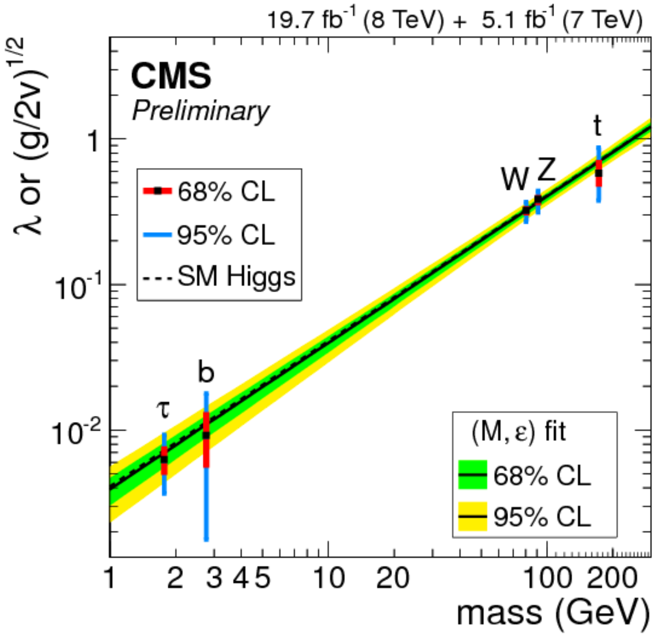
- m_H (CMS) = 125.03 $\pm^{0.27}_{0.26}$ (stat) $\pm^{0.15}_{0.13}$ (syst) GeV
  m_H (ATLAS) = 125.36 ± 0.37 (stat) ± 0.18 (syst) GeV

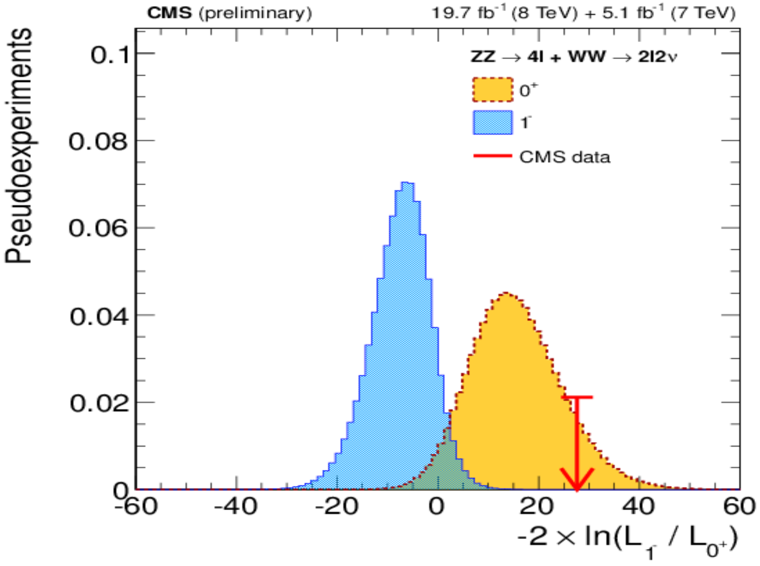
2013

Englert Higgs

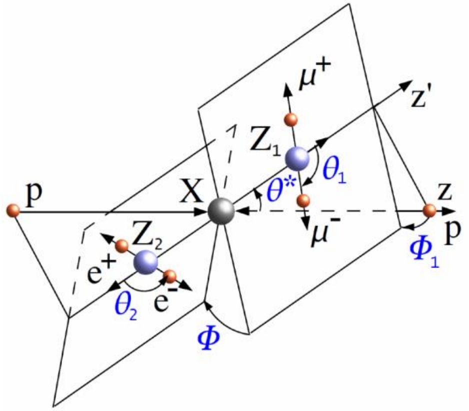
Higgs properties

- Now Higgs has been discovered, focus has moved to measuring its properties
- Check couplings dependence on mass
- Couples to fermions as well as bosons
- Quantum numbers $J^P = 0^+$ as expected for Standard Model Higgs



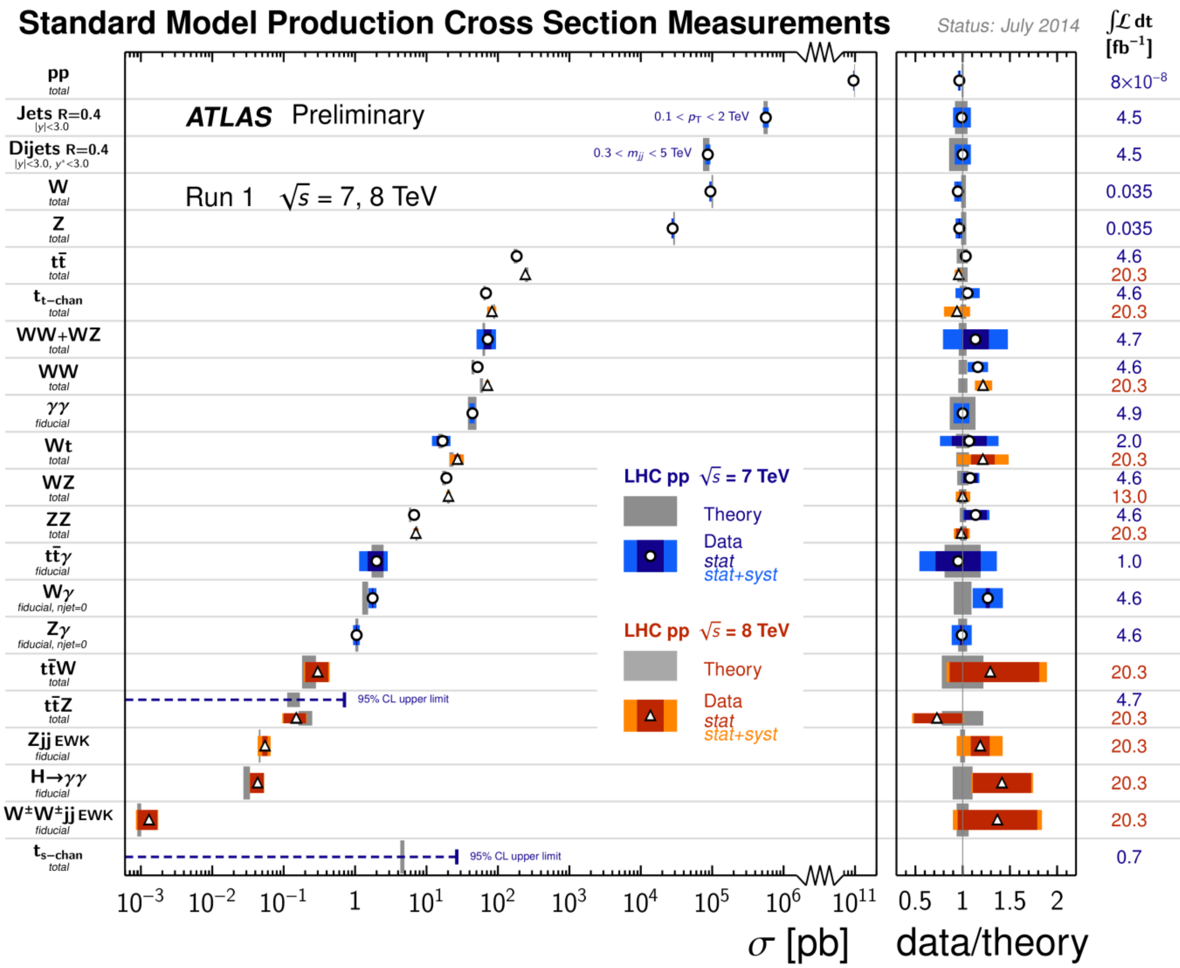


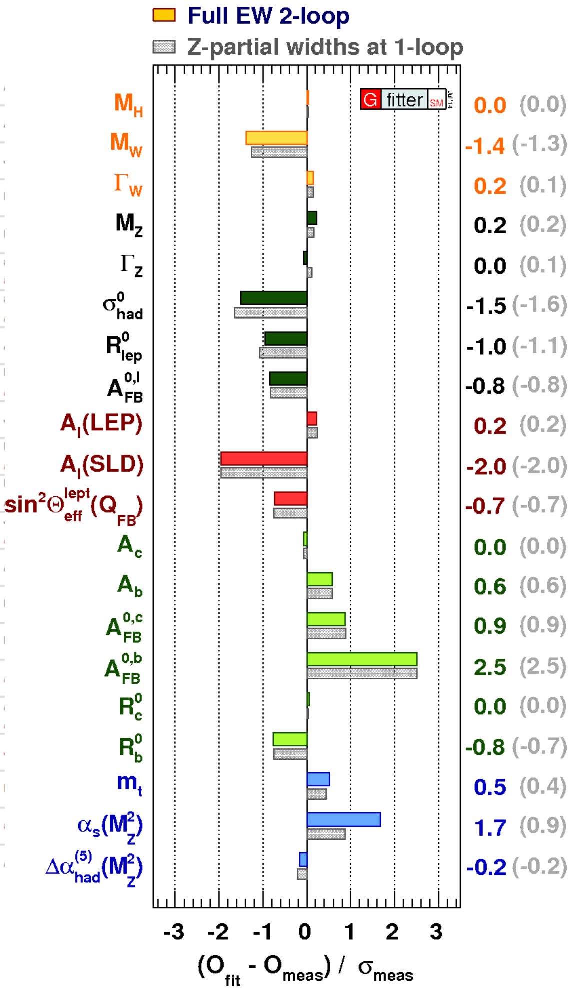
From angular analysis of H → 4 leptons



Standard Model tests

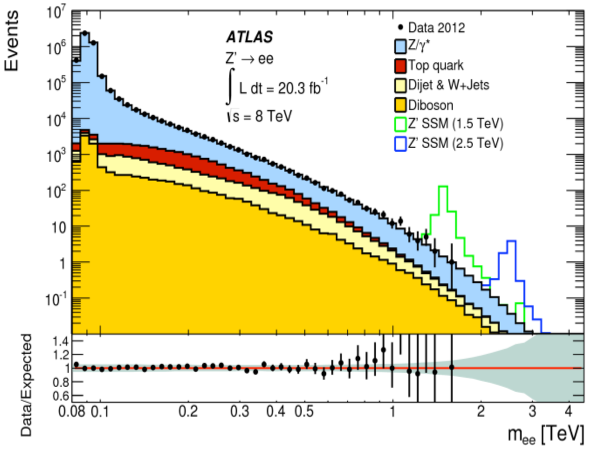
- Many measurements performed, in agreement with SM expectation



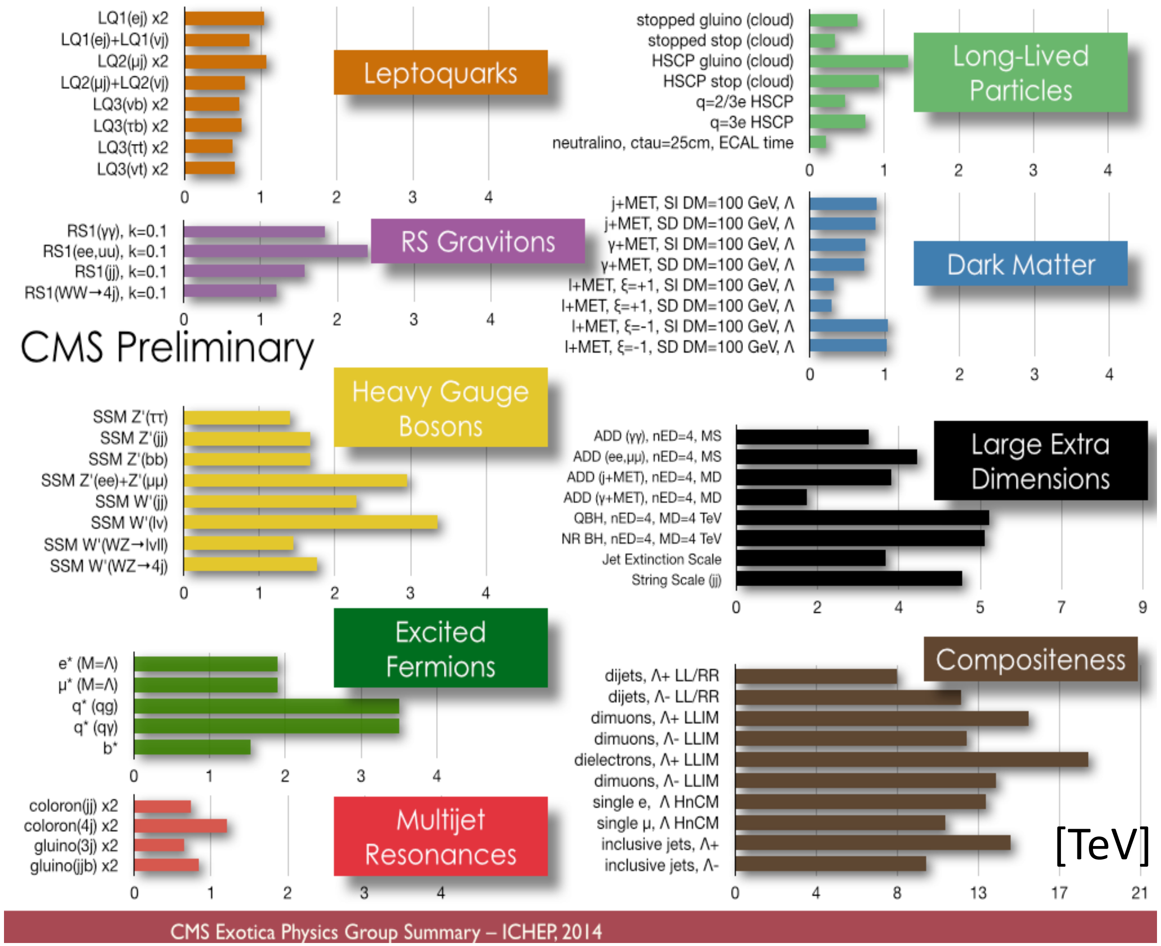


Searches for New Physics

- Also *many* searches for physics beyond the SM e.g. heavy $Z \rightarrow e^+e^-$



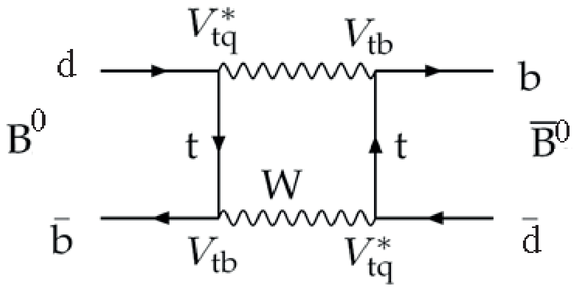
- So far no clear sign



CMS Exotica Physics Group Summary – ICHEP, 2014

2. The LHCb experiment

- LHCb is the dedicated **flavour physics** experiment at the LHC
- ATLAS and CMS search for the *direct* production of new states
LHCb is designed to search for the *indirect* effect of such states on **charm** and **beauty** decays via virtual production in *loop* diagrams:



- Such an indirect approach can be very powerful:
e.g. B^0–$\overline{B}^0$ mixing discovered at ARGUS (1987) → $m(t) > 50$ GeV/c^2 long before the top quark was discovered
(Note that top quark decays before hadronising, so does not have rich structure seen with b and c hadrons)
- **CP violation** and **rare decays** (such as $B_s \to \mu^+\mu^-$) involve similar loops: accurately predicted in the Standard Model, sensitive to new physics

CP violation

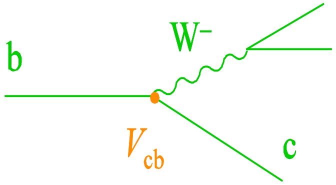
- Weak interaction thought to conserve Charge-Parity (CP) symmetry until experiment of Christenson *et* al (in 1964 — another 50th anniversary!)

  $K_L \to 3\pi$ (CP = -1) BR = 34%
  $K_L \to \pi^+\pi^-$ (CP = $+1$) BR = 2×10^{-3} → CP violation

- Unambiguously differentiates matter from antimatter:
  e.g. BR $(K_L \to \pi^- e^+ \nu) = 19.46\% > \mathrm{BR}(K_L \to \pi^+ e^- \bar{\nu}) = 19.33\%$
  Related to **baryogenesis***:* CP violation is required, to go from a symmetric initial state (the Big Bang) to an asymmetric final state (our world)

- In Standard Model, CP violation arises from quark mixing
  Weak eigenstates are a rotated combination of flavour states

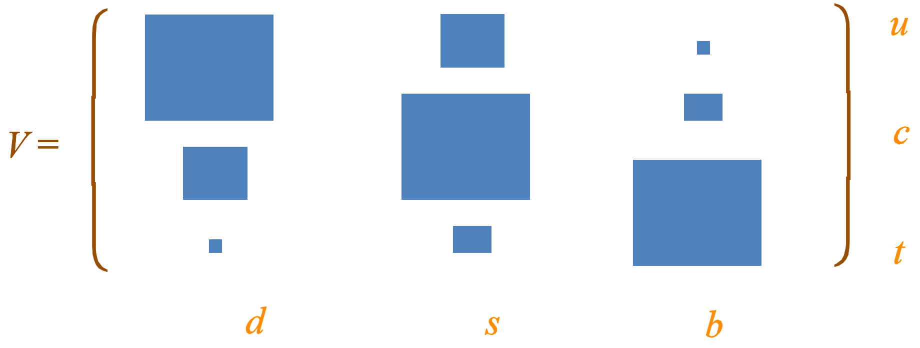
$$\text{Weak charged current} \sim (u, c, t)\,(1-\gamma_5)\,\gamma_\mu \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



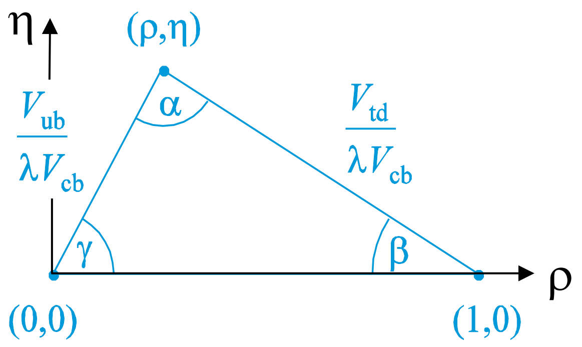
V = unitary **CKM** (Cabibbo-Kobayashi-Maskawa) matrix
Elements give the weak couplings between quarks: also studied at ISOLDE

CKM matrix

- For 3 generations of quark families CKM matrix has 4 independent parameters: 3 angles and one non-trivial phase (giving rise to CP violation)
- CKM matrix observed to have a hierarchy of elements
  Parameterized expanding in powers of the Cabibbo angle $\lambda = \sin \theta_C \approx 0.22$



- Parameters (λ, A, ρ, η) [Wolfenstein]
  $A \approx 0.8$, measured → leaves ρ and η to be determined ($\eta \neq 0 \leftrightarrow$ CP violation)
- Unitarity of the CKM matrix gives relationships between rows and columns: $\Sigma\, V_{ij}\, V_{ik}^{*} = 0 \;\; (j \neq k)$
  → triangle relationships in the complex plane



Rescaling by $V_{cd}\, V_{cb}^{*}$

Unitarity Triangle

- Many of the measurements made in flavour physics can be presented as constraints on this triangle

  e.g. measurements of lifetime → V_{cb}

  fraction of charmless b decays → V_{ub}

- In addition, CP violation in B decays measures relative *phases* of the matrix elements → measure the *angles* (α, β, γ)

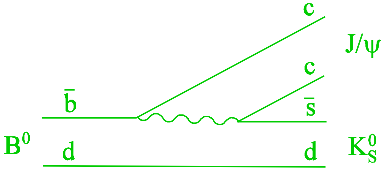
eg:

$$\begin{tikzcd} B^0 \arrow[rr] \arrow[dr] & & J/\psi\, K^0_S \\ & \bar{B}^0 \arrow[ur] & \end{tikzcd}$$

(CP eigenstate)

Decay via oscillation has different phase

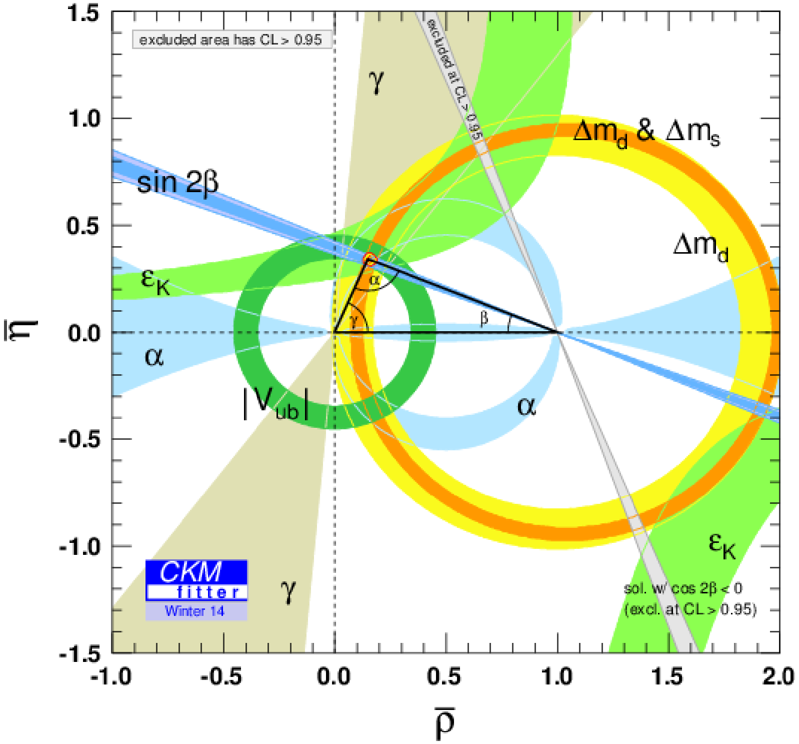
arg(V_{td}) → angle β



- Measured by B Factory experiments: Triumphant agreement!

Nobel prize for Kobayashi and Maskawa

2014

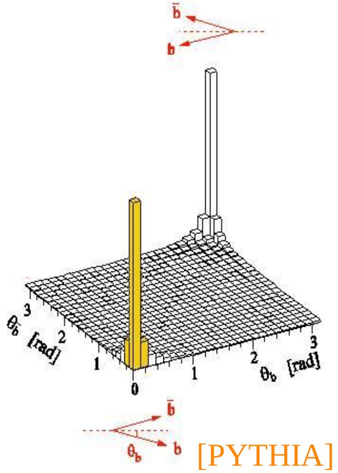


2008

Kobayashi Maskawa

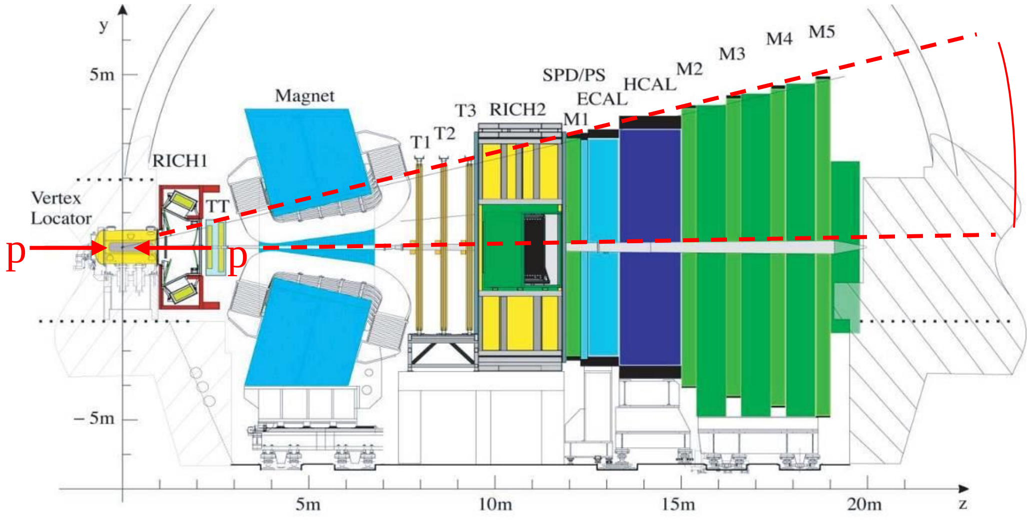
LHC as a flavour factory

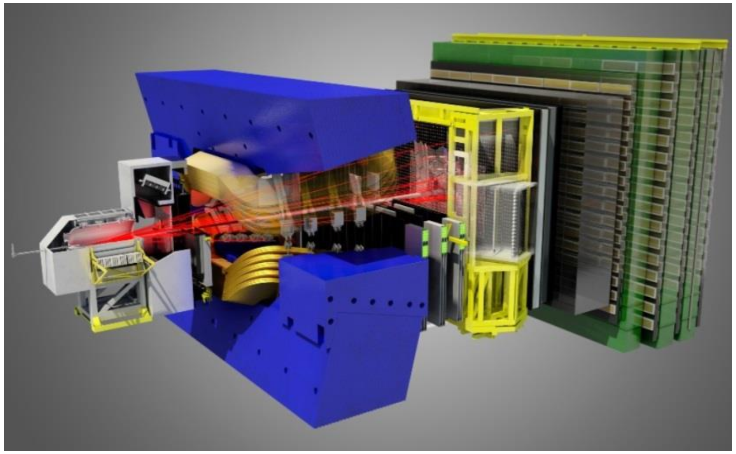
- Forward-peaked production of heavy quarks at the LHC
  → LHCb designed as forward spectrometer (collider mode)
- $b\bar{b}$ cross-section = 284 ± 53 μb at the LHC (at 7 TeV)
  → ~ 100,000 $b\bar{b}$ pairs produced/second ($10^4\times$ B Factories)
  Charm production factor 20 higher!
- *All* hadron species produced: B^+, B^0, B_s, B_c, Λ_b, other baryons…



[PYTHIA]

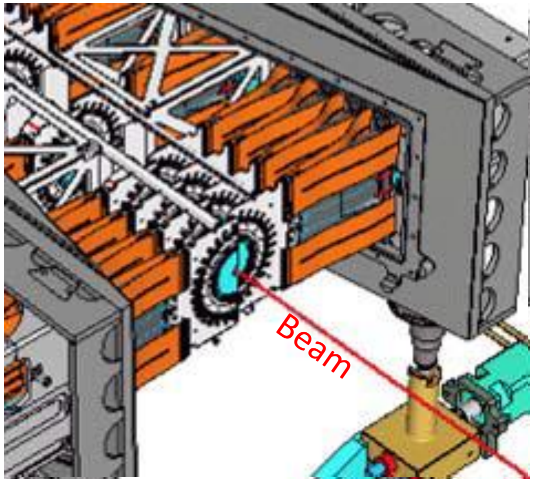
10 – 300 mrad (2 < η < 5)

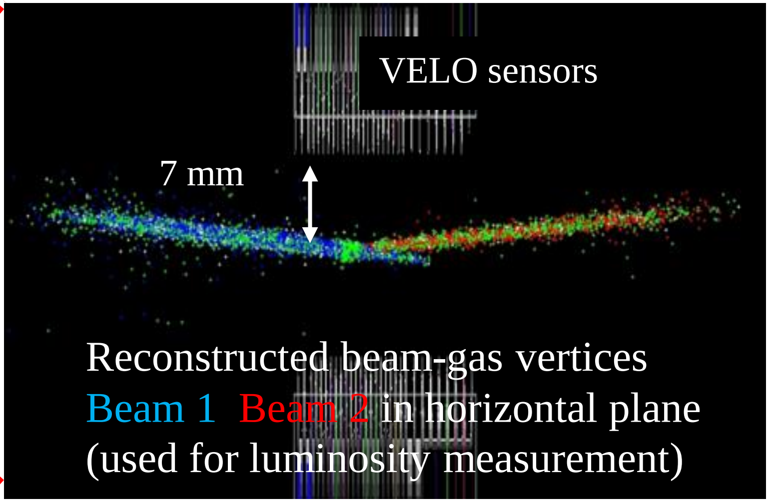




Vertex Locator

- Particles containing b and c quarks have lifetime of ~ ps, so fly a few mm in lab
- Important to have excellent vertex detection to identify such decays
- 21 modules silicon sensor disks, *R*-ϕ strips
  Approach to within 7 mm of beam
  Retracted for safety during beam injection



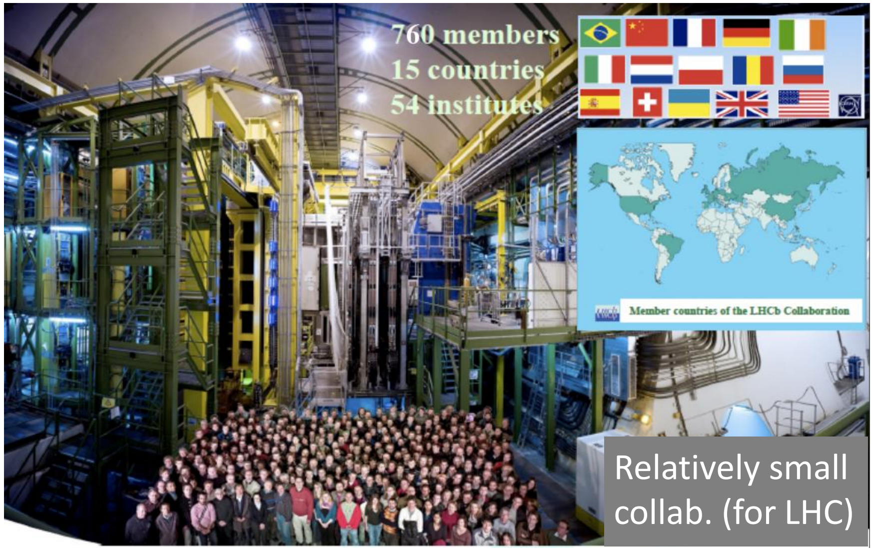


Reconstructed beam-gas vertices
Beam 1 Beam 2 in horizontal plane
(used for luminosity measurement)

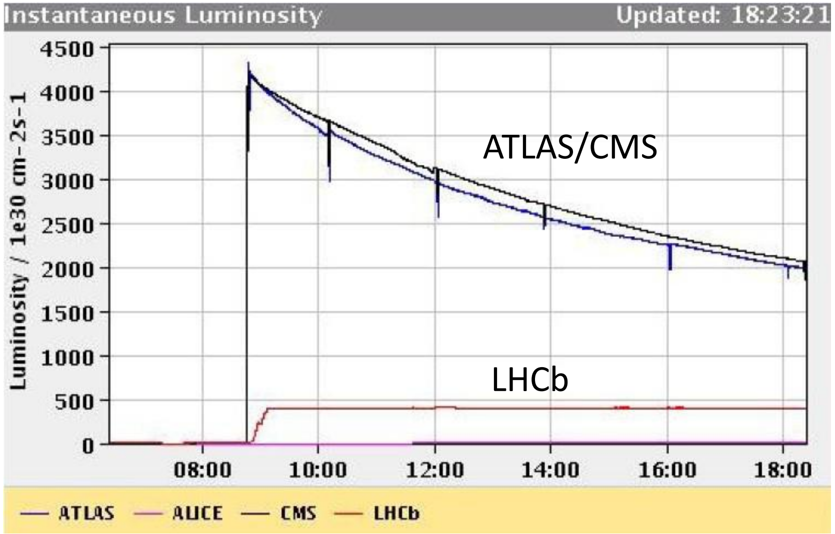
LHCb data taking

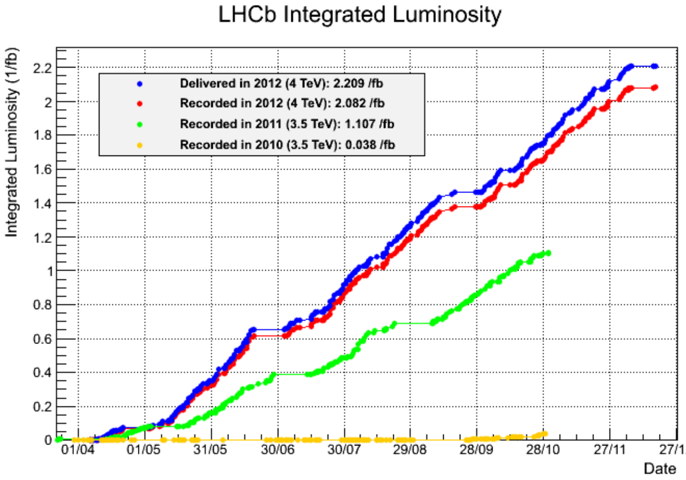
- Since study vertex structure need to avoid too much pileup (and track density is already high in the forward region)
  → limit luminosity by adjusting overlap of bunches in LHC

ATLAS/CMS luminosity falls exponentially
LHCb luminosity continually levelled



Relatively small collab. (for LHC)

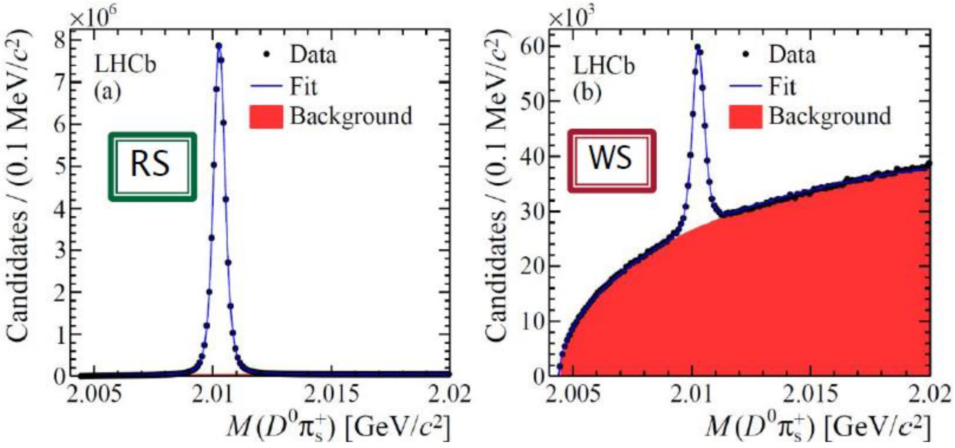


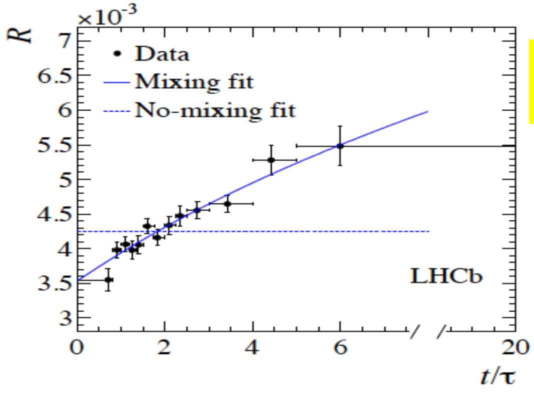


1 fb^{-1} in 2011 and 2 fb^{-1} in 2012

Neutral meson oscillations

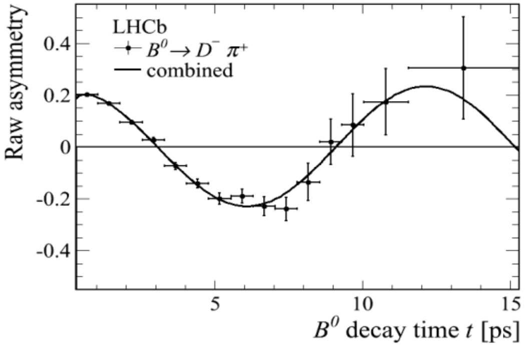
- Particle-antiparticle oscillations possible for all neutral mesons: K^0, D^0, B^0, B_s
- Studied by comparing “right-sign” and “wrong sign” decays vs. time
  e.g.
$$R(t) = \frac{N(D^0 \to K^+\pi^-)}{N(D^0 \to K^-\pi^+)}$$
- Beautifully clean signals, most precise measurement of oscillation frequencies





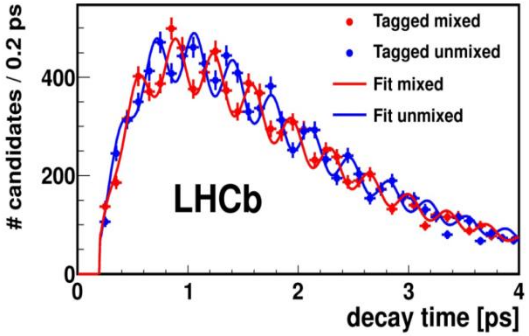
D^0

$(c\bar{u})$



B^0

$(b\bar{d})$

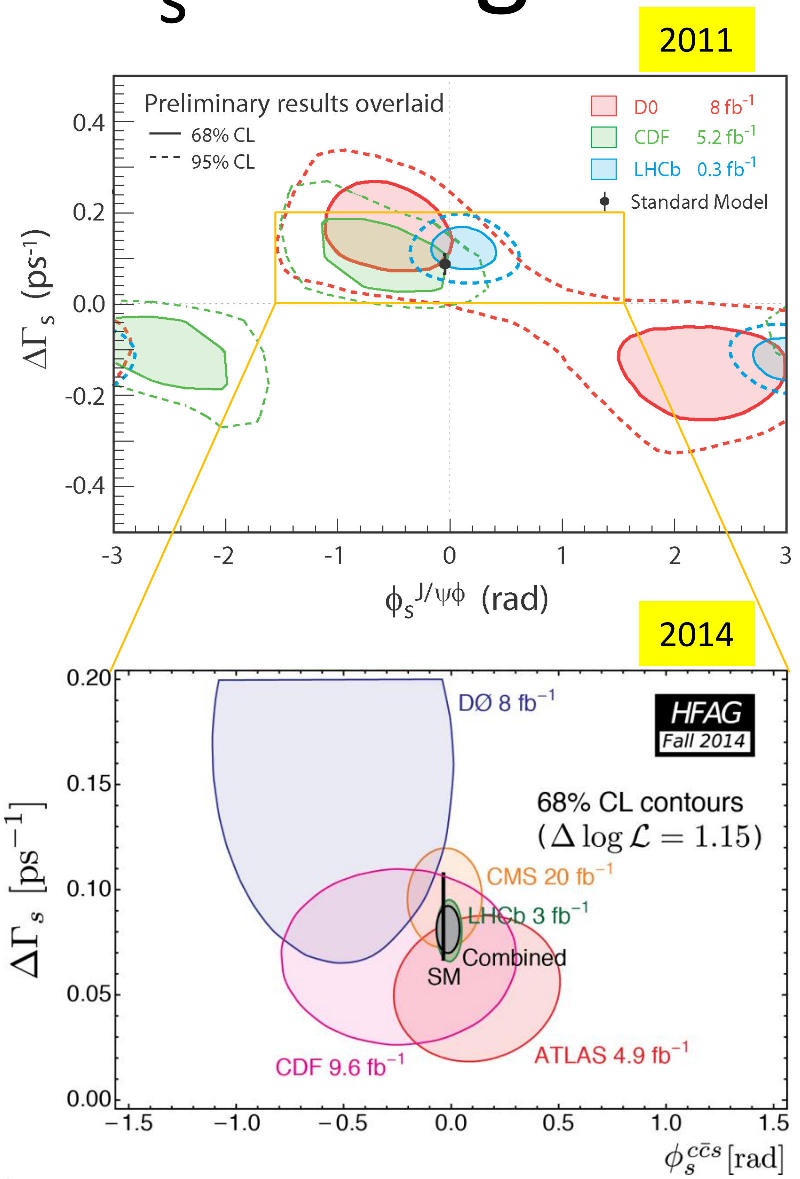


B_s

$(b\bar{s})$

CP violation in B_s mixing

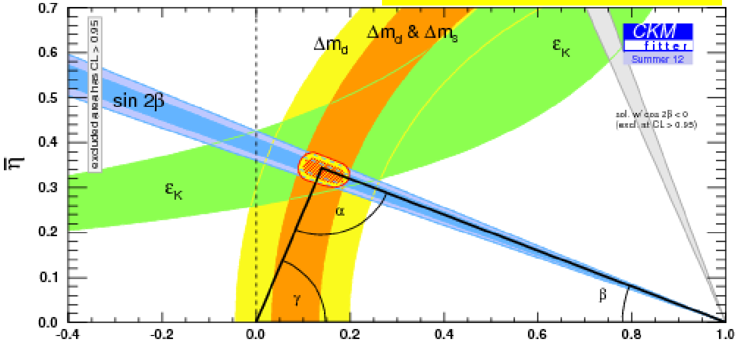
- Oscillation frequency is proportional to *mass difference* of eigenstates
  e.g. $\Delta m(B_s) = 17.8\ \hbar/\text{ps} \approx 0.01$ eV
- They can also have a *lifetime difference*, $\Delta\Gamma$, predicted to be of order 10% for the B_s
- CP violation in B_s mixing measured using $B_s \rightarrow J/\psi\ \phi$ decays
  Analog of sin2β for B^0, known as ϕ_s
  predicted to be tiny in SM
- Early measurements from Tevatron hinted at non-SM values
  Not confirmed by LHCb results
  Very precise, but still room for new physics contribution

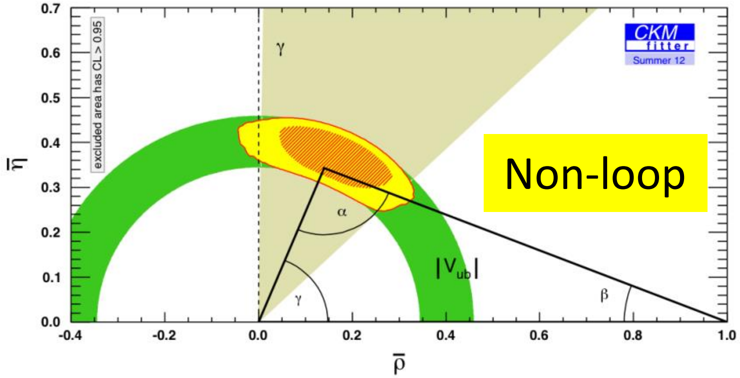


CP angle γ

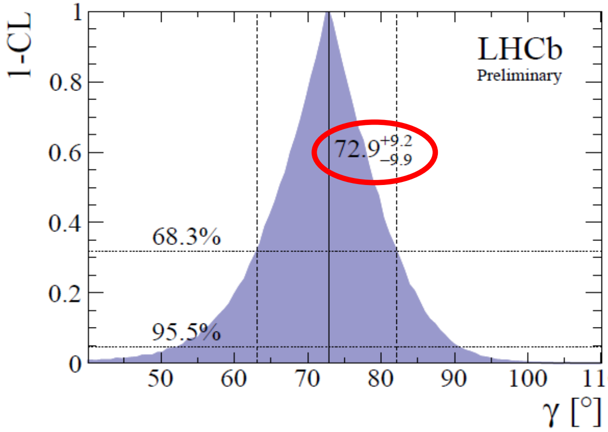
- Although all flavour physics results currently consistent with the CKM picture, important to compare separately processes that occur via loop diagrams or not
  New physics should only affect loops
- Angle γ determined from combination of observables in many B → DK decays
  World's most precise measurement

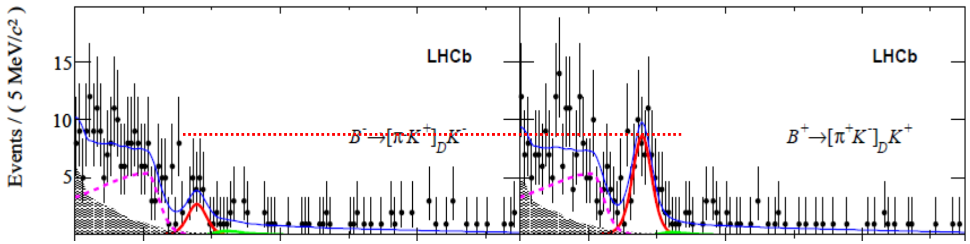
Loop processes





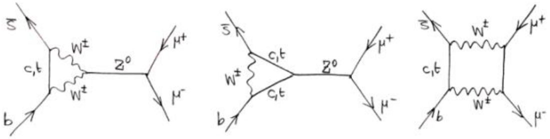
Non-loop



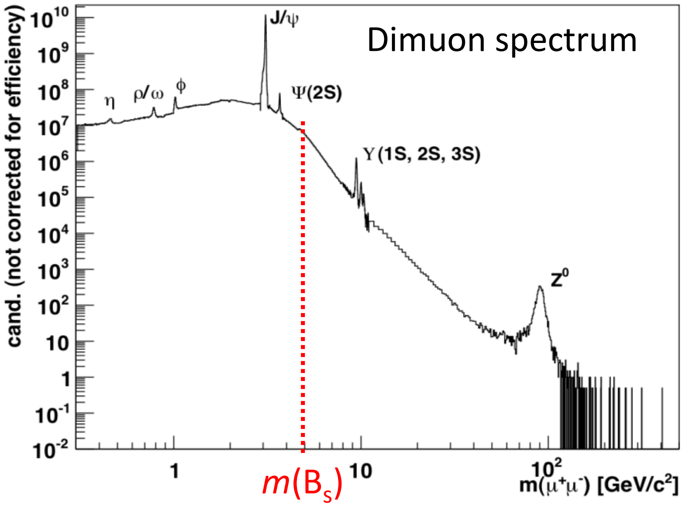


DK invariant mass

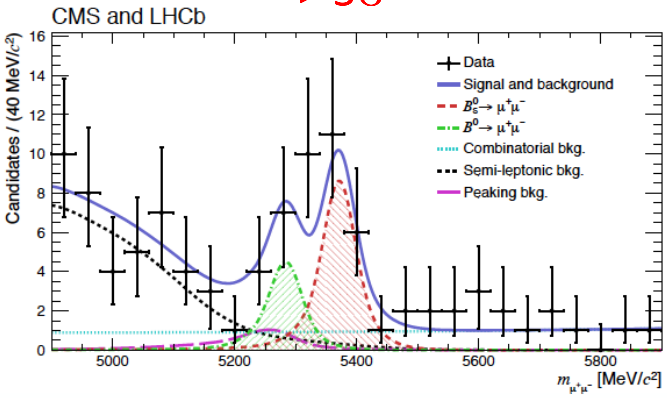
Rare decays



- $B_s \to \mu^+ \mu^-$ is most famous example Highly suppressed in SM, but precise prediction: BR = $(3.7 \pm 0.2) \times 10^{-9}$
- Only a handful of events expected → sophisticated selections used
- Signals seen by both LHCb and CMS → first combined paper from LHC



> 5σ

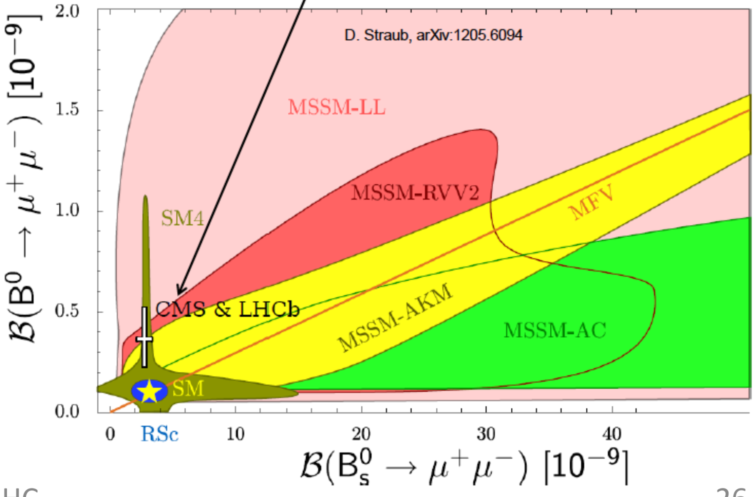


CMS-PAS-BPH-13-007
LHCb-CONF-2013-012

combining CMS & LHCb →

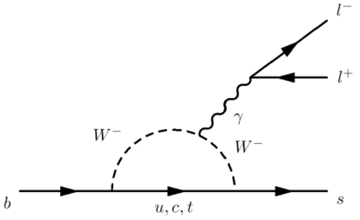
$BR(B^0 \to \mu^+\mu^-) = (3.6^{+1.6}_{-1.4}) \times 10^{-10}$

$BR(B_S^0 \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$



- Agrees with SM, many models ruled out $B^0 \to \mu^+ \mu^-$ to be studied next

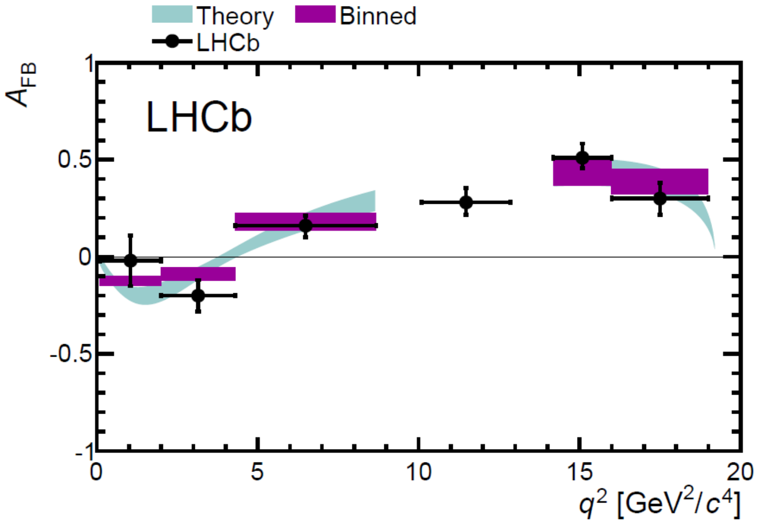
Penguin decays

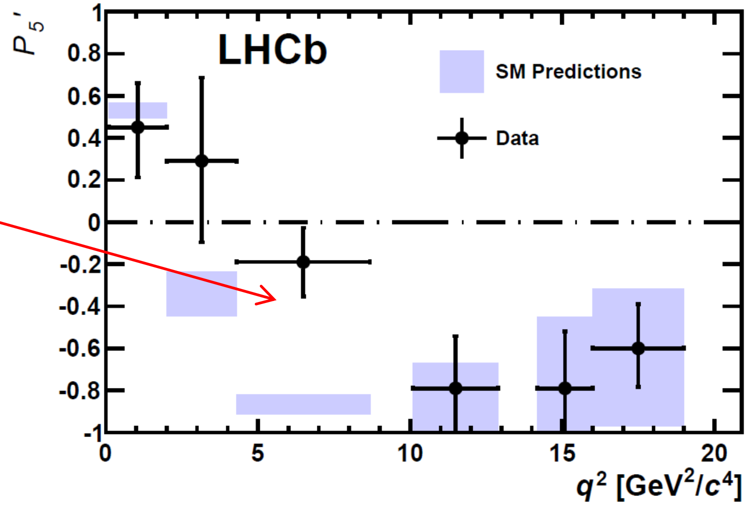


- b → s γ transition occurs via another loop known as a “penguin” diagram
  Final states such as $B^0 \to K^{*0} \mu^+ \mu^-$
- Angular analysis allows powerful test
  Initial study of forward-backward asymmetry in good agreement with SM
  Full angular distribution:

$$\frac{1}{\Gamma}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos2\theta_\ell$$
$$- F_\mathrm{L}\cos^2\theta_K\cos2\theta_\ell + \frac{1}{2}(1-F_\mathrm{L})A_\mathrm{T}^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos2\phi +$$
$$\sqrt{F_L(1-F_\mathrm{L})}P'_4\sin2\theta_K\sin2\theta_\ell\cos\phi + \sqrt{F_L(1-F_\mathrm{L})}P'_5\sin2\theta_K\sin\theta_\ell\cos\phi +$$
$$(1-F_\mathrm{L})A_{Re}^\mathrm{T}\sin^2\theta_K\cos\theta_\ell + \sqrt{F_\mathrm{L}(1-F_\mathrm{L})}P'_6\sin2\theta_K\sin\theta_\ell\sin\phi +$$
$$\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}P'_8\sin2\theta_K\sin2\theta_\ell\sin\phi + (S/A)_9\sin^2\theta_K\sin^2\theta_\ell\sin2\phi\Big]$$

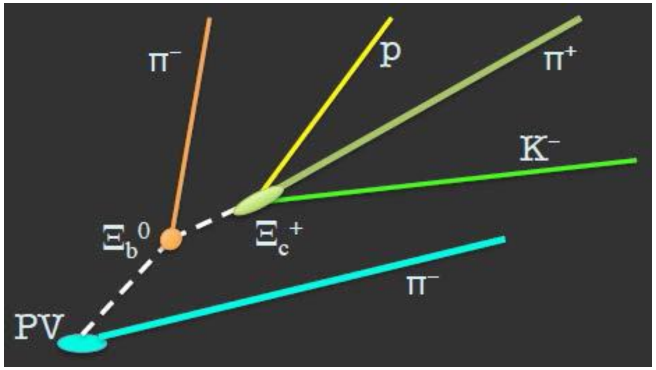
- Large (3.7σ) local deviation seen in P5’
- However, treatment of uncertainties of higher order corrections can dilute the significance, update eagerly awaited

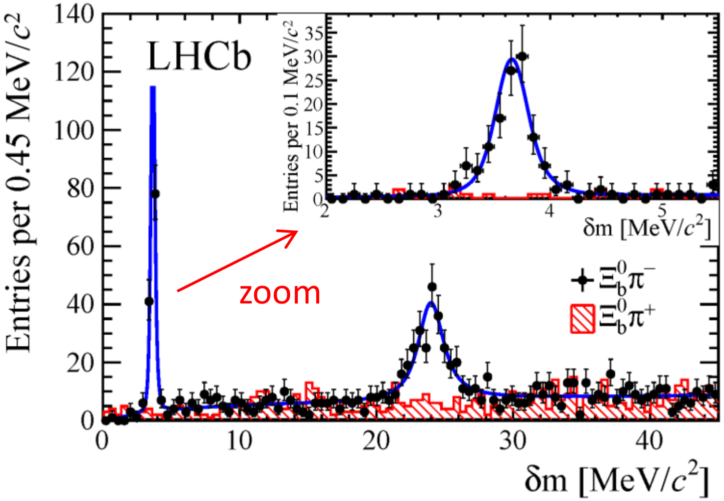




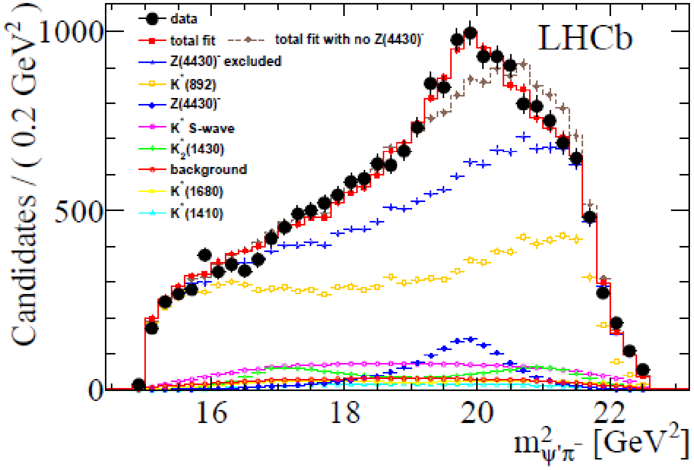
Spectroscopy

- LHCb also has a strong program of hadronic spectroscopy studies
- Recent first observation of two new strange-beauty baryons: $\Xi_b'^-$ and Ξ_b^{*-}



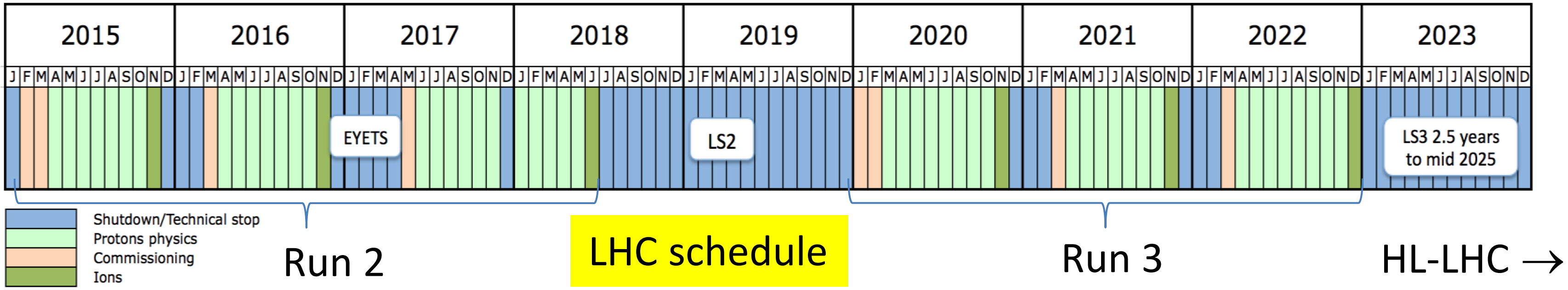


- $Z(4430)^-$ is an exotic four-quark state
  minimal quark content is $c\bar{c}d\bar{u}$
  First seen at B Factories, but quantum
  numbers $J^P = 1^+$ confirmed by LHCb



And much more …

3. Prospects

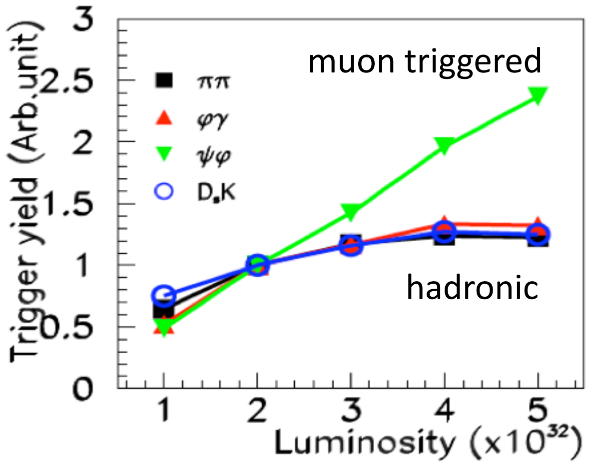


LHC schedule

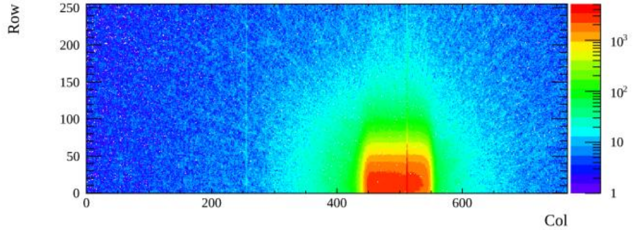
- LHC physics run will restart in May 2015 with E_{cm} = 13 TeV (later → 14 TeV) Start off with 50 ns bunch spacing, then move to 25 ns
- Estimate integrated luminosity of ~ 10–15 fb^{-1} for ATLAS/CMS in 2015
  Luminosity ramp up to ~ $2 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$ in 2016-18 giving ~ 100 fb^{-1}
  LHCb expects ~ 8 fb^{-1} over this period
  Levelled luminosity → data-doubling time becomes long, so upgrade planned
  Important to do so promptly: aiming for next long-shutdown LS2 (2018/19)
- ALICE also planning significant upgrade at this time to increase DAQ rate
- Major upgrades of ATLAS and CMS come later (LS3) to be ready for HL-LHC when integrated luminosity will be increased by an order of magnitude

LHCb Upgrade

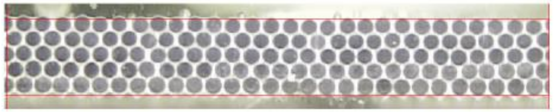
- Main limitation that prevents exploiting higher luminosity is the current hardware trigger
  To keep output rate < 1 MHz requires raising thresholds → hadronic yields reach plateau
- Proposed upgrade is to *remove* hardware trigger read out detector at 40 MHz bunch crossing rate
  Trigger *fully in software* in a large CPU farm
- Will allow increased luminosity: 2×10^{33} cm^{-2} s^{-1} (available from LHC by adjusting beam overlap)
- Requires replacing all front-end electronics during the long shutdown LS2 in 2018/19
  Running for 10 years will then give ~ 50 fb^{-1}
- Upgrade approved, final detector R&D underway e.g. for pixel VELO and scintillating-fibre tracker



VELO pixel chip test

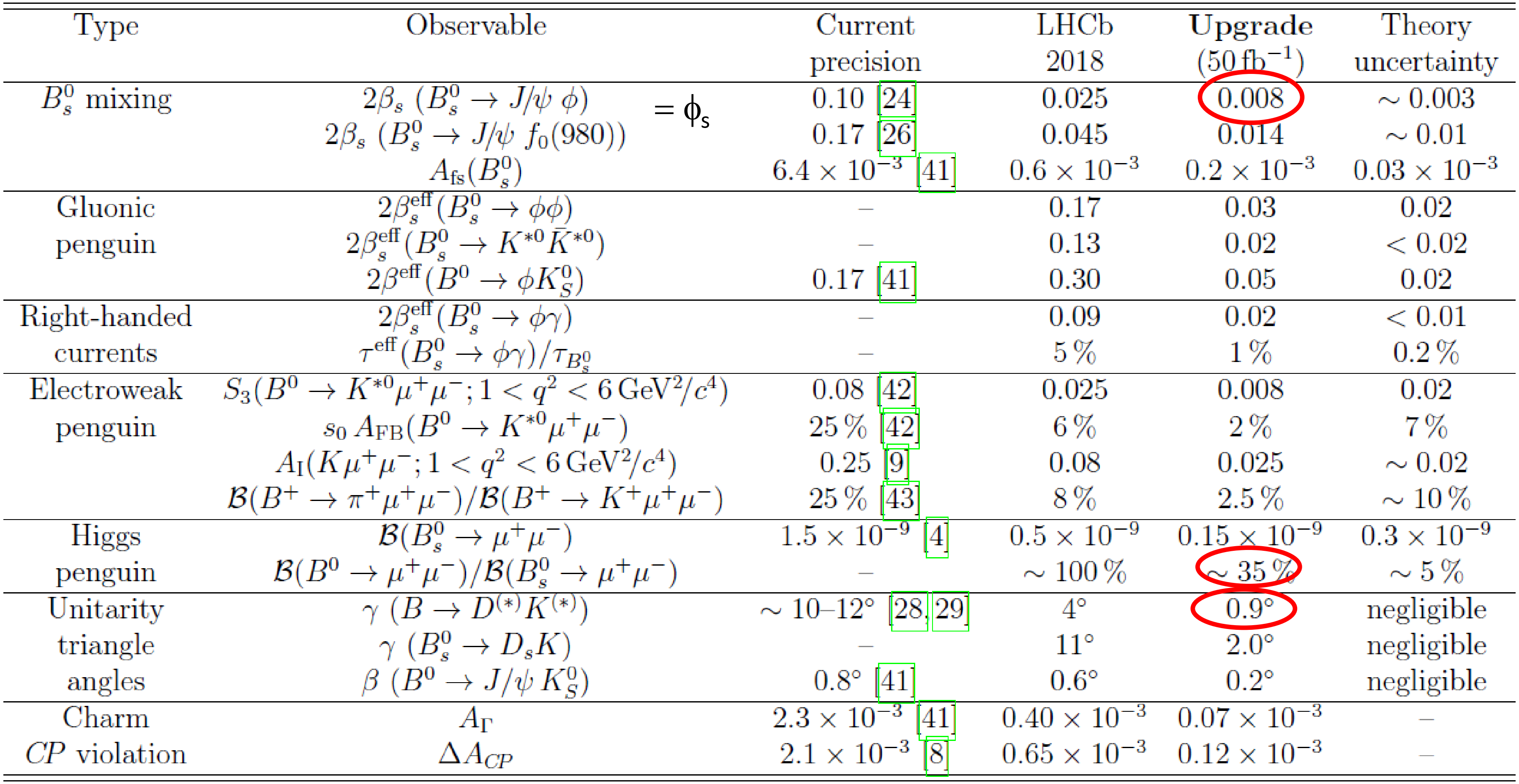


Scintillating-fibre mat



Upgrade sensitivity

Eur. Phys. J C (2013) 73:2373



Type	Observable	Current precision	LHCb 2018	Upgrade ($50\,\mathrm{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s$ ($B_s^0 \to J/\psi\ \phi$) $= \phi_s$	0.10 [24]	0.025	0.008	~ 0.003
	$2\beta_s$ ($B_s^0 \to J/\psi\ f_0(980)$)	0.17 [26]	0.045	0.014	~ 0.01
	$A_{\mathrm{fs}}(B_s^0)$	6.4×10^{-3} [41]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\mathrm{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K_S^0)$	0.17 [41]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\mathrm{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.08 [42]	0.025	0.008	0.02
	$s_0\, A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [42]	6 %	2 %	7 %
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.25 [9]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [43]	8 %	2.5 %	~ 10 %
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [4]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	γ ($B \to D^{(*)}K^{(*)}$)	$\sim$ 10–12° [28, 29]	4°	0.9°	negligible
	γ ($B_s^0 \to D_s K$)	–	11°	2.0°	negligible
	β ($B^0 \to J/\psi\ K_S^0$)	0.8° [41]	0.6°	0.2°	negligible
Charm CP violation	A_Γ	2.3×10^{-3} [41]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [8]	0.65×10^{-3}	0.12×10^{-3}	–

Conclusions

- The **LHC** is flagship of CERN: the highest energy accelerator in the world
- Ran successfully in 2010-12, although at ~ half design energy
  Major breakthrough for particle physics: discovery of the **Higgs boson**
  So far consistent with being the final missing piece of the Standard Model
- However, we know SM is not whole story, but no clear sign of **new physics**
  LHC about to restart with double the energy — the last big step forward in discovery potential for many years: exciting times!
- Important to maintain a diverse physics program in search for new physics (at the LHC, as well as at CERN in general: as exemplified by ISOLDE)
  LHCb is making big steps in flavour physics, for small additional cost
  - 235 publications already! (largest rate/author at CERN?)
- LHCb (and the LHC) have a long-term future, with **upgrades** planned to take particle physics through the next decade and beyond

Additional results

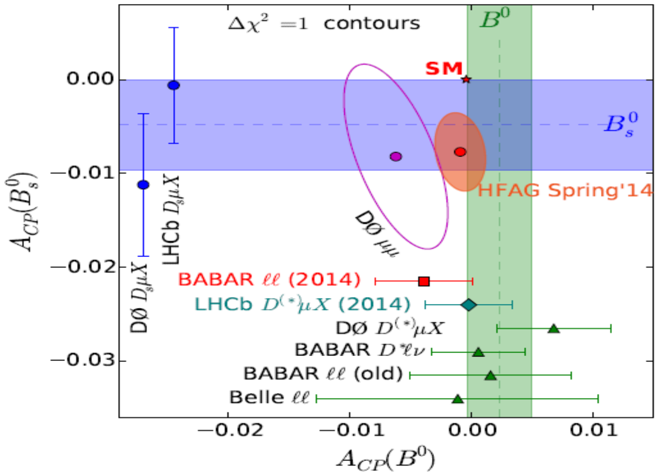
- **Flavour-specific CP asymmetry in B decays**
  most easily measured using semileptonic decays, accesses CP violation in mixing
  Extremely small in SM

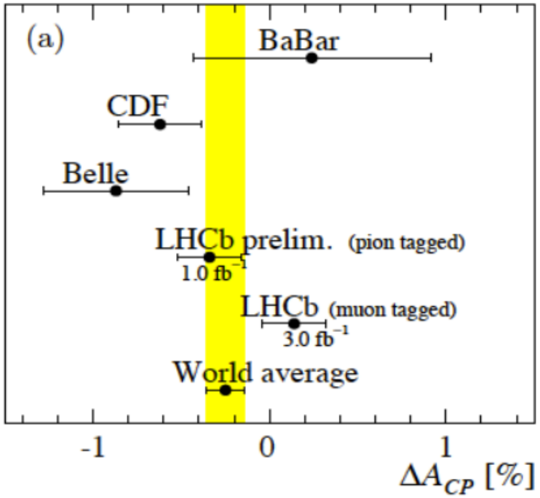
- D0 measurement made with dileptons, measures a superposition of B_s and B^0
  Result ~ 3 σ from SM
  Not confirmed by individual measurements

- **CP violation in charm:** flurry of excitement when indication seen for CP violation in $D^* \to D\pi$ decays via $\Delta A_{CP} = A_{CP}(KK) - A_{CP}(\pi\pi)$

- However, not confirmed with further data or using muon tagged decays

- Both will be the focus of future studies





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