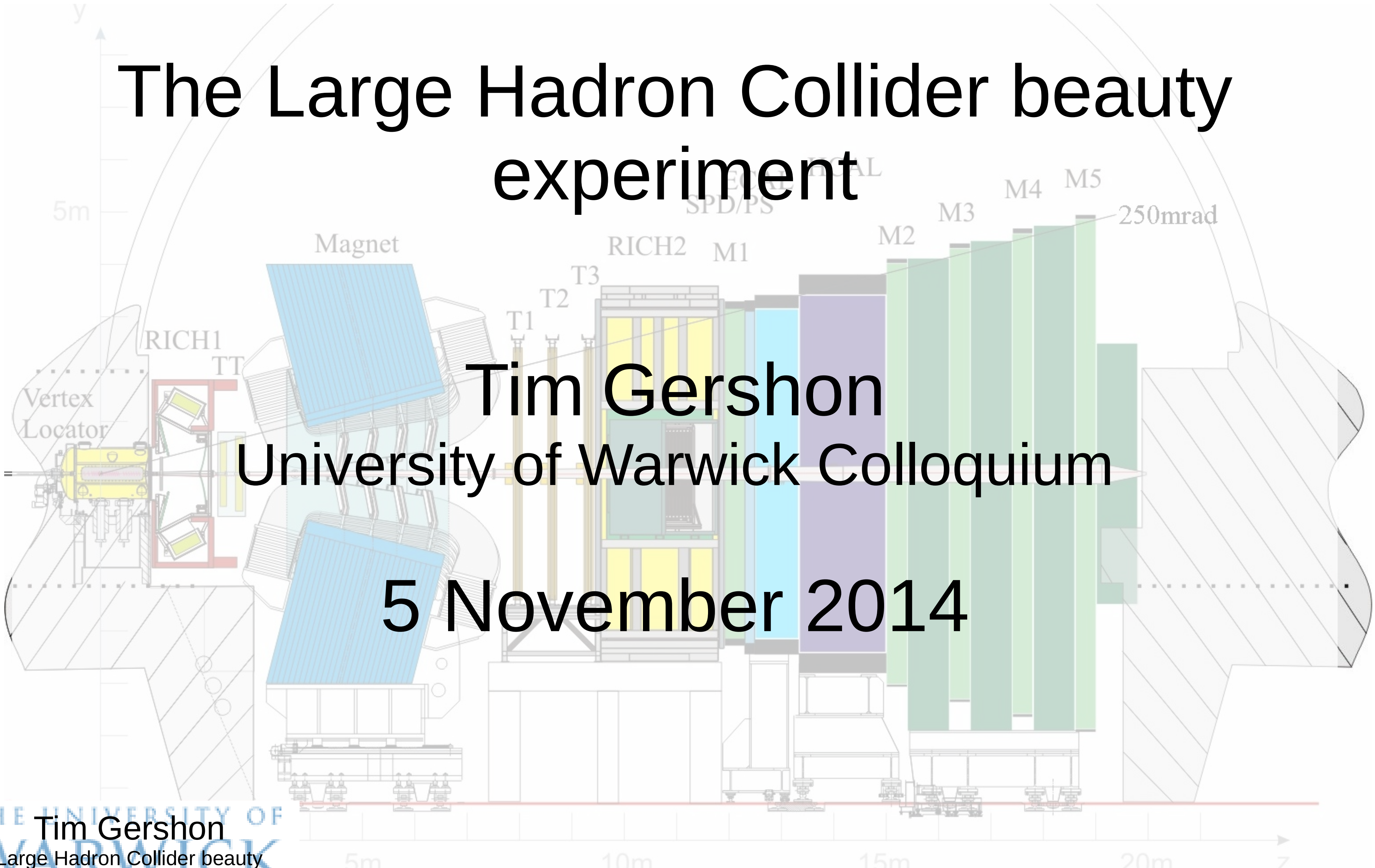
The Large Hadron Collider beauty experiment

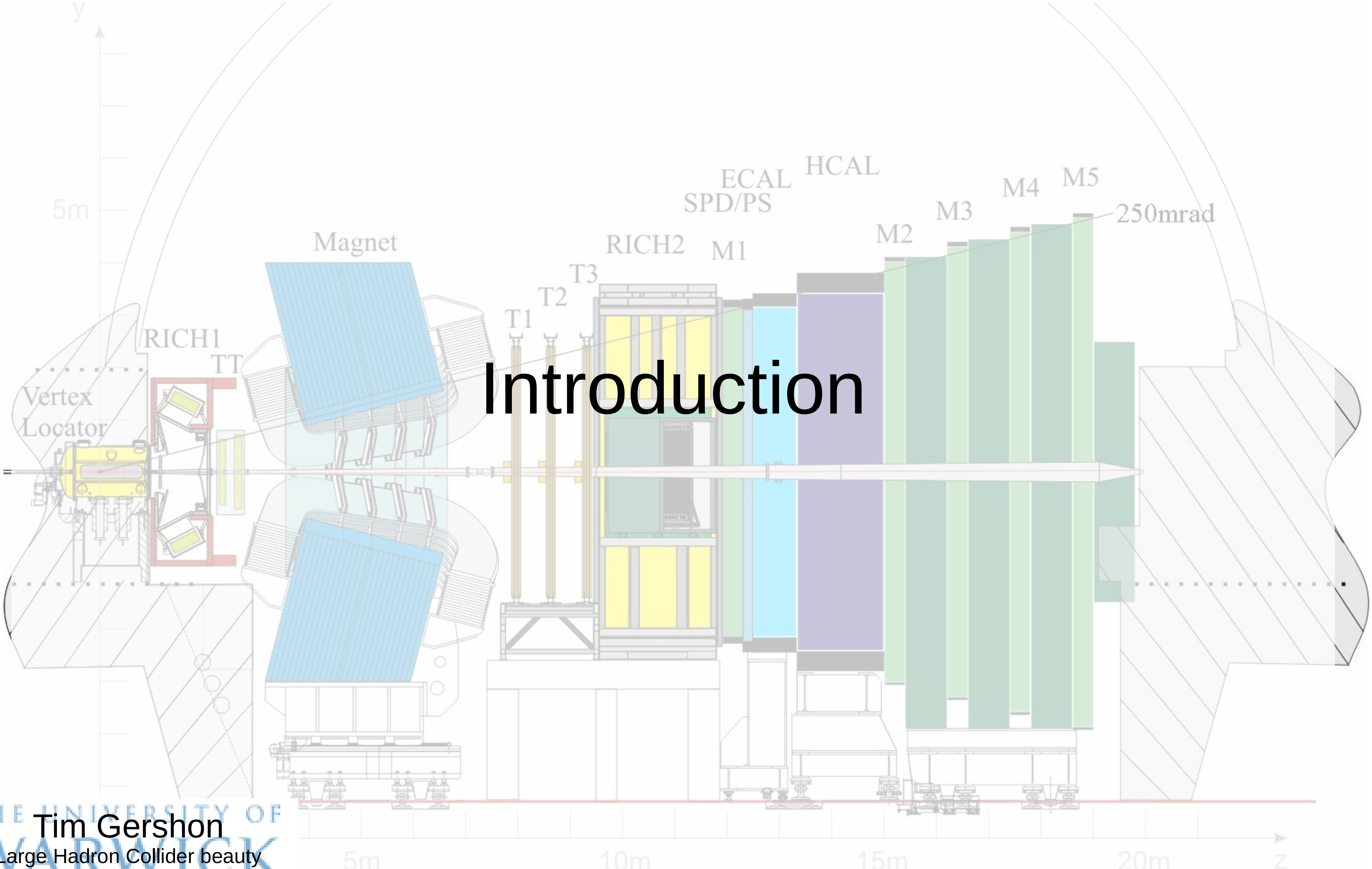
Tim Gershon

University of Warwick Colloquium

5 November 2014



Introduction



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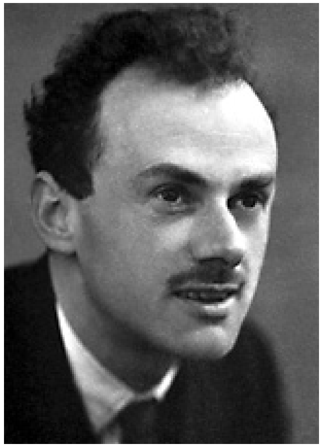
Large Hadron Collider beauty

Dirac's prescience



Concluding words of 1933 Nobel lecture

"If we accept the view of complete symmetry between positive and negative electric charge so far as concerns the fundamental laws of Nature, we must regard it rather as an accident that the Earth (and presumably the whole solar system), contains a preponderance of negative electrons and positive protons. It is quite possible that for some of the stars it is the other way about, these stars being built up mainly of positrons and negative protons. In fact, there may be half the stars of each kind. The two kinds of stars would both show exactly the same spectra, and there would be no way of distinguishing them by present astronomical methods."

From Dirac to LHCb

1956 T.D. Lee and C.N. Yang note that parity (P) could be violated in weak interactions

1957 C.S. Wu observes P violation (⇒ Nobel prize for Lee and Yang)

1957 L. Landau notes importance of CP symmetry

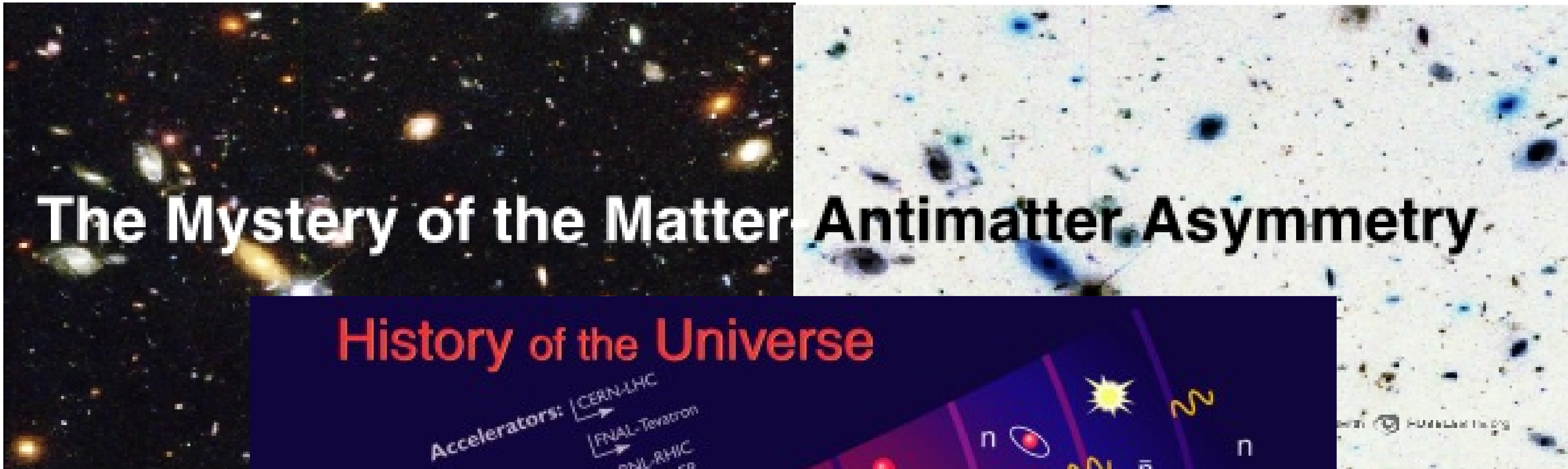
1964 Observation of CP violation (J. Cronin & V. Fitch; Nobel prize 1980)

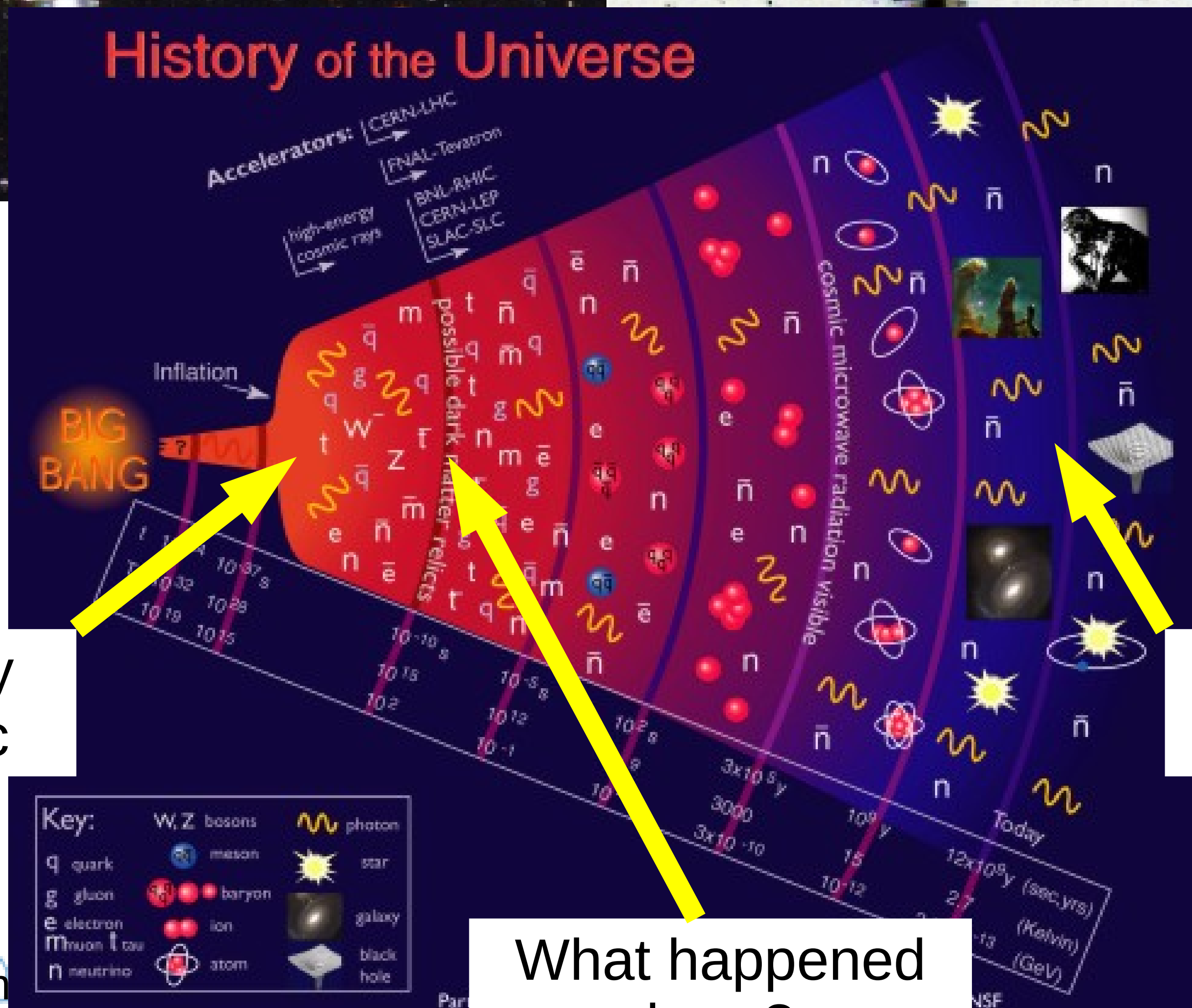
1967 A. Sakharov lists conditions for evolution of matter dominated Universe

1973 M. Kobayashi and T. Maskawa: theory of CP violation in 6 quark model (⇒ Nobel prize 2008)

1980s, 90s, 2000s Many experimental measurements of CP violation; all consistent with Kobayashi & Maskawa theory

The Mystery of the Matter-Antimatter Asymmetry





Completely symmetric

What happened here?

Completely asymmetric

Where is the antimatter?

CP violation and the matter-antimatter asymmetry

- Two important facts
  1) CP violation is one of 3 “Sakharov conditions” necessary for the evolution of a baryon asymmetry in the Universe
  2) The Standard Model (CKM) CP violation is not sufficient to explain the observed asymmetry
- Therefore, there must be more sources of CP violation in nature … but where?
  – extended quark sector, lepton sector (leptogenesis), supersymmetry, anomalous gauge couplings, extended Higgs sector, quark-gluon plasma, flavour-diagonal phases, …
- Testing the consistency of the CKM mechanism provides the best chance to find new sources of CP violation today

What causes the difference between matter and antimatter?

- In the SM, fermion masses arise from the Yukawa couplings of the quarks and charged leptons to the Higgs field (taking m_ν=0)
- The CKM matrix arises from the relative misalignment of the Yukawa matrices for the up- and down-type quarks

$$V_{CKM} = U_u U_d^+$$

U matrices from diagonalisation of mass matrices

- It is a 3x3 complex unitary matrix
  - described by 9 (real) parameters
  - 5 can be absorbed as phase differences between the quark fields
  - 3 can be expressed as (Euler) mixing angles
  - the fourth makes the CKM matrix complex (i.e. gives it a phase)
    - weak interaction couplings differ for quarks and antiquarks
    - CP violation

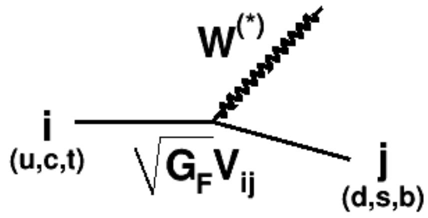
Breaking of the electroweak (gauge) symmetry leads to violation of the CP (discrete) symmetry

The Cabibbo-Kobayashi-Maskawa Quark Mixing Matrix

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- A 3x3 unitary matrix
- Described by 4 real parameters – allows CP violation
- Highly predictive

Quark flavour mixing
a.k.a. CKM phenomenology

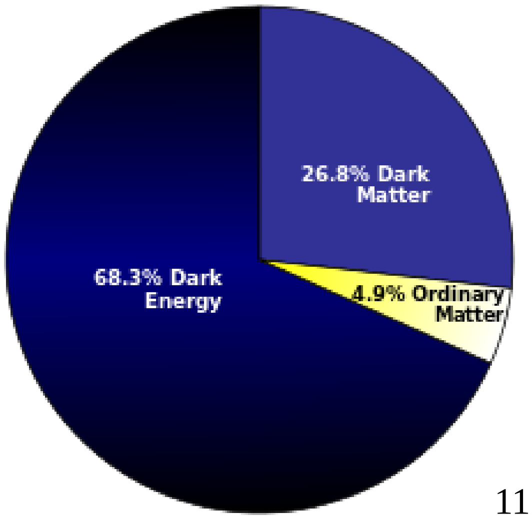


$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

- CKM theory is highly predictive
  - huge range of phenomena over a massive energy scale predicted by only 4 independent parameters (+ QCD)
- CKM matrix is hierarchical
  - theorised connections to quark mass hierarchies, or (dis-)similar patterns in the lepton sector
    - origin of CKM matrix from diagonalisation of Yukuwa (mass) matrices after electroweak symmetry breaking
  - distinctive flavour sector of Standard Model not necessarily replicated in extended theories → strong constraints on models
- CKM mechanism introduces CP violation
  - only source of CP violation in the Standard Model ($m_\nu = \theta_{QCD} = 0$)

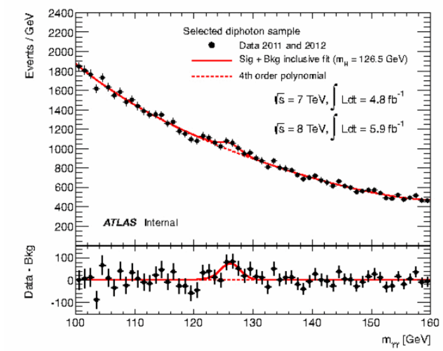
Beyond the Standard Model

- CKM phenomenology a part of the Standard Model of particle physics
  - Extensively tested over ~30 years
  - Astonishingly, unreasonably successful
- But clearly only an approximate theory
  - Higgs sector is “unnatural” (“hierarchy problem”)
  - Neutrino mass is not explained
  - Too many free parameters (origin of flavour)
  - No unification of gauge interactions
  - No explanation for dark matter, dark energy
  - There must be more CP violation



Two routes to heaven

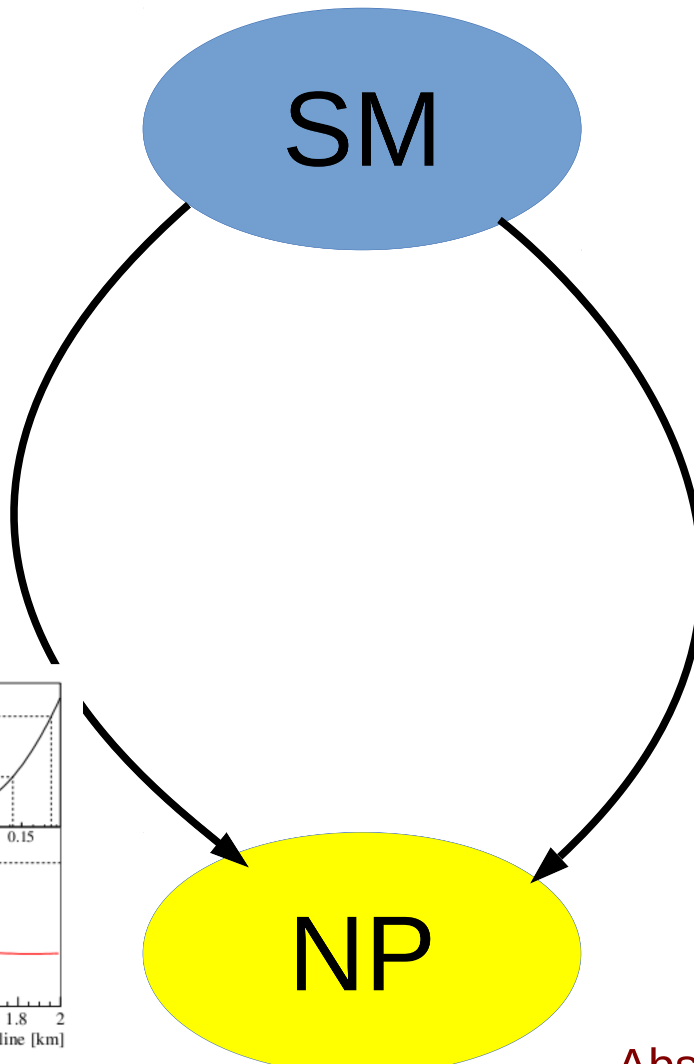
for LHCb



CP violation

(extra sources must exist)

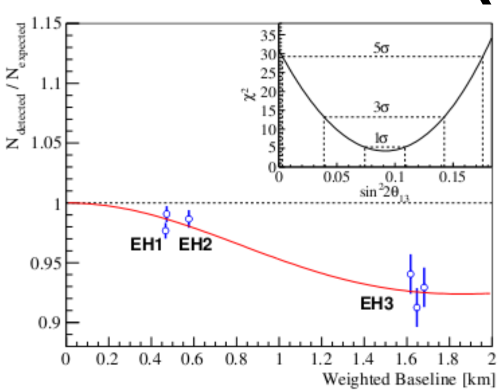
But
- No guarantee of the scale
- No guarantee of effects in the quark sector
- Realistic prospects for CPV measurement in νs due to large θ_{13}

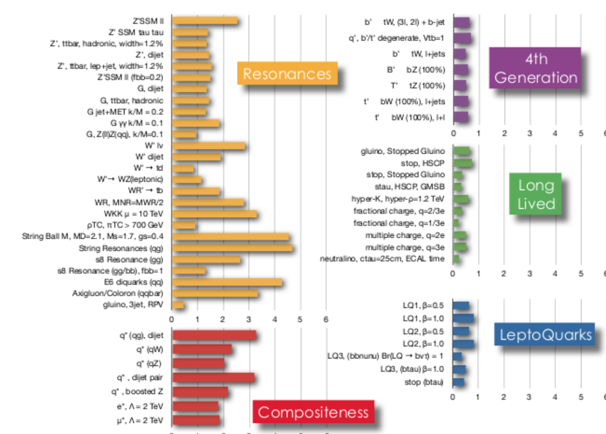


Rare decays

(strong theoretical arguments)

But
- How high is the NP scale?
- Why have FCNC effects not been seen?





Absence of NP signals at ATLAS/CMS → argument for searches via rare decays stronger

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The Large Hadron Collider and the LHCb experiment

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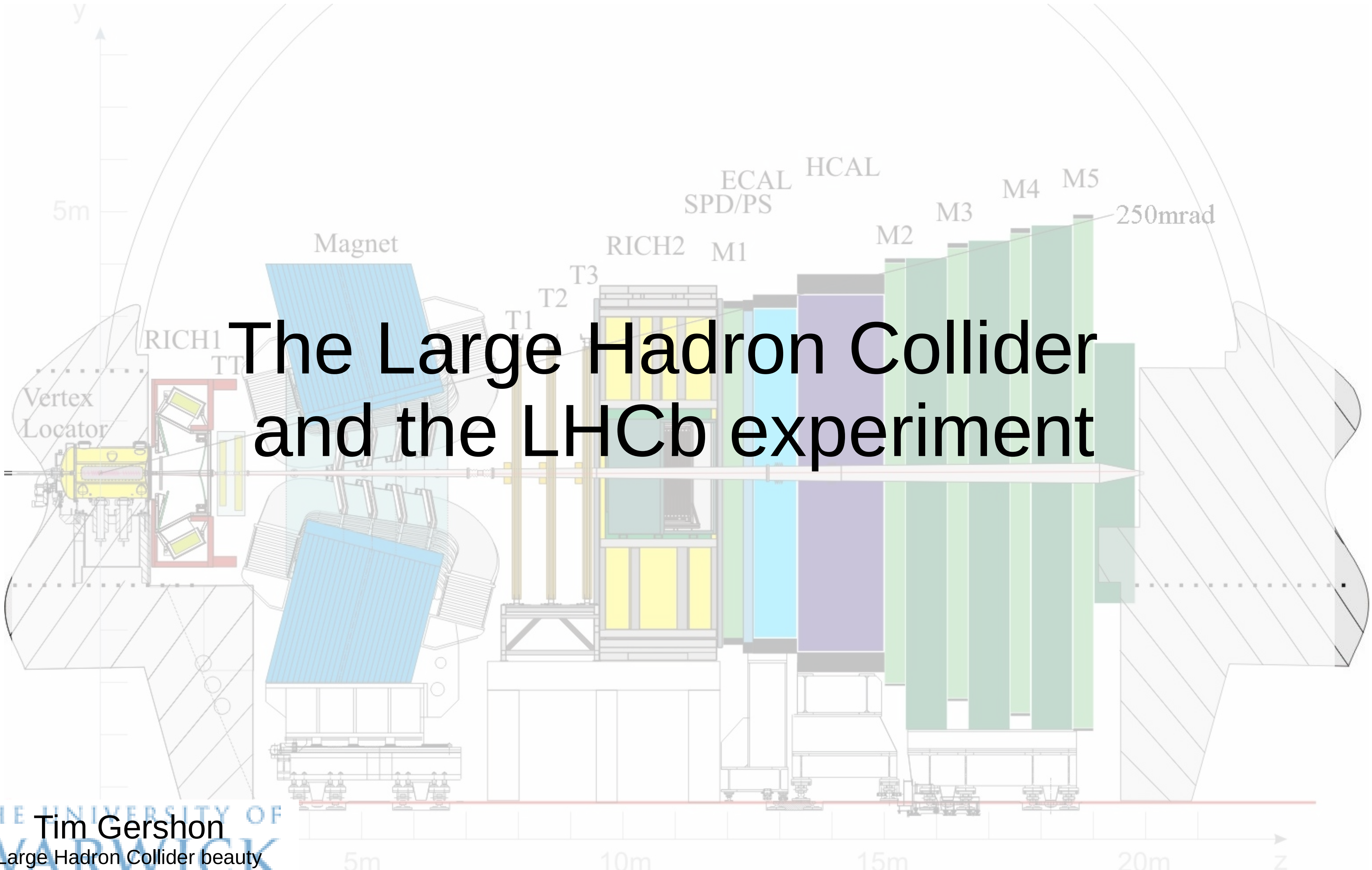
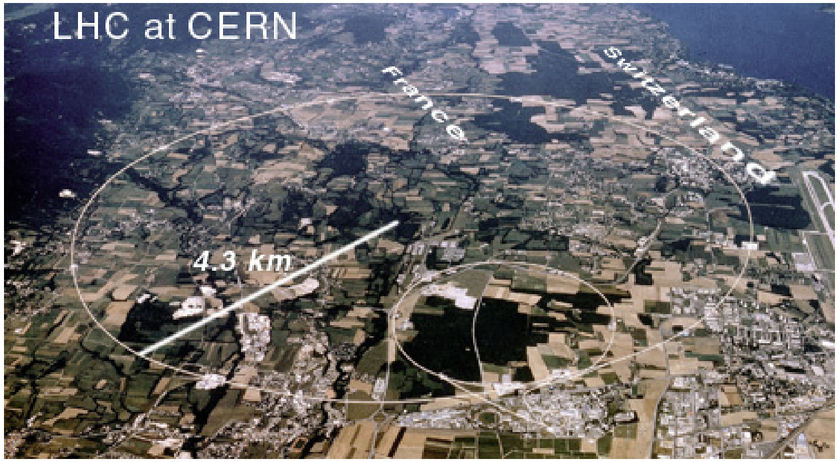
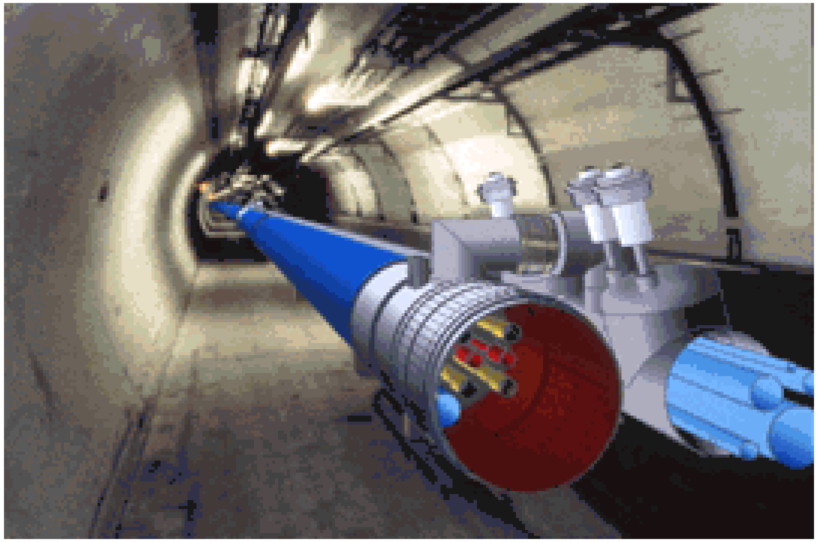
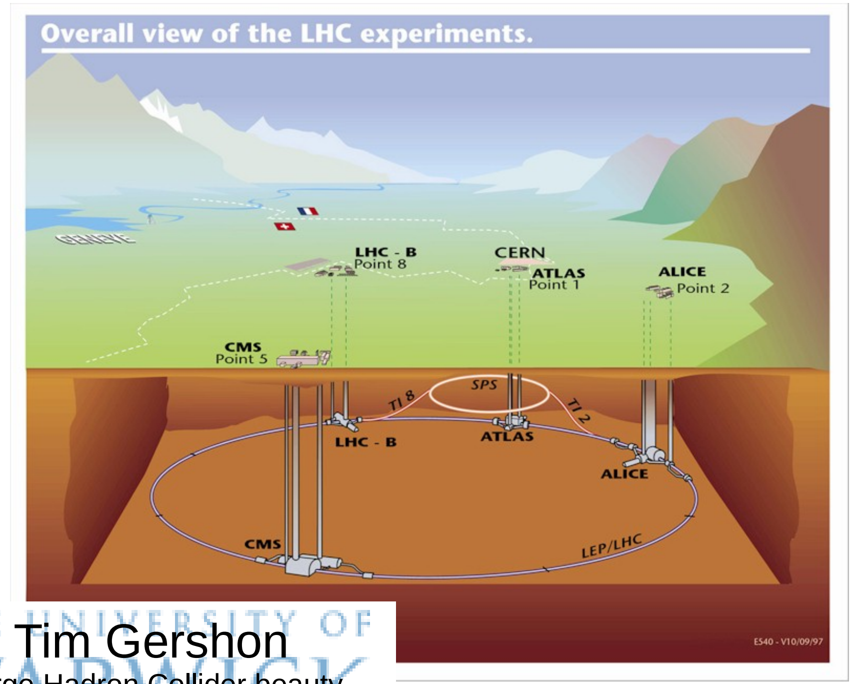
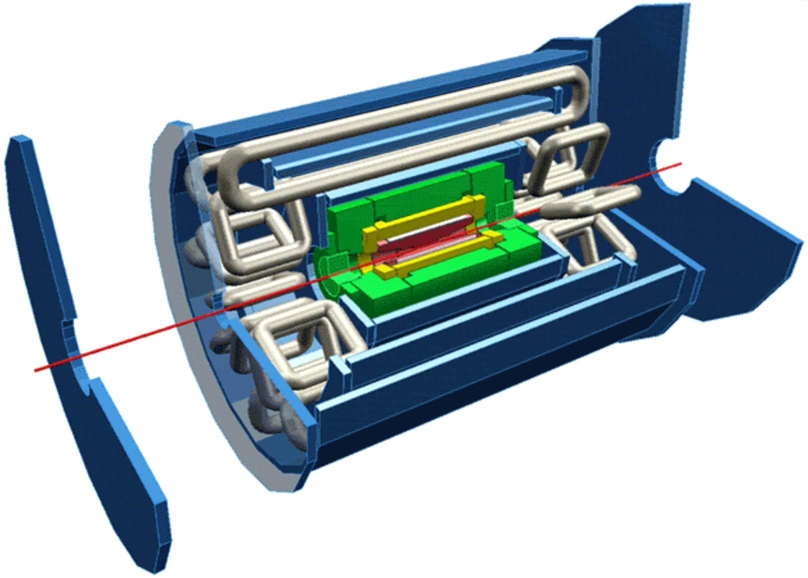


The Large Hadron Collider







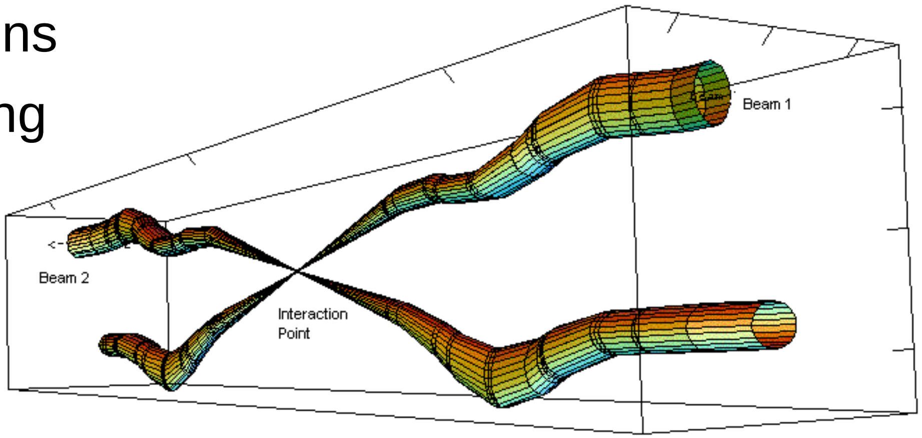


The Large Hadron Collider

- Aims of the LHC include:
  - to discover the Higgs boson (✓)
  - to find hints of a more fundamental theory, that may
    - provide better understanding of the Higgs mechanism
    - allow unification of the forces (strong, EM & weak)
    - explain the origin of dark matter
  - to improve understanding of matter-antimatter asymmetry

LHC collisions

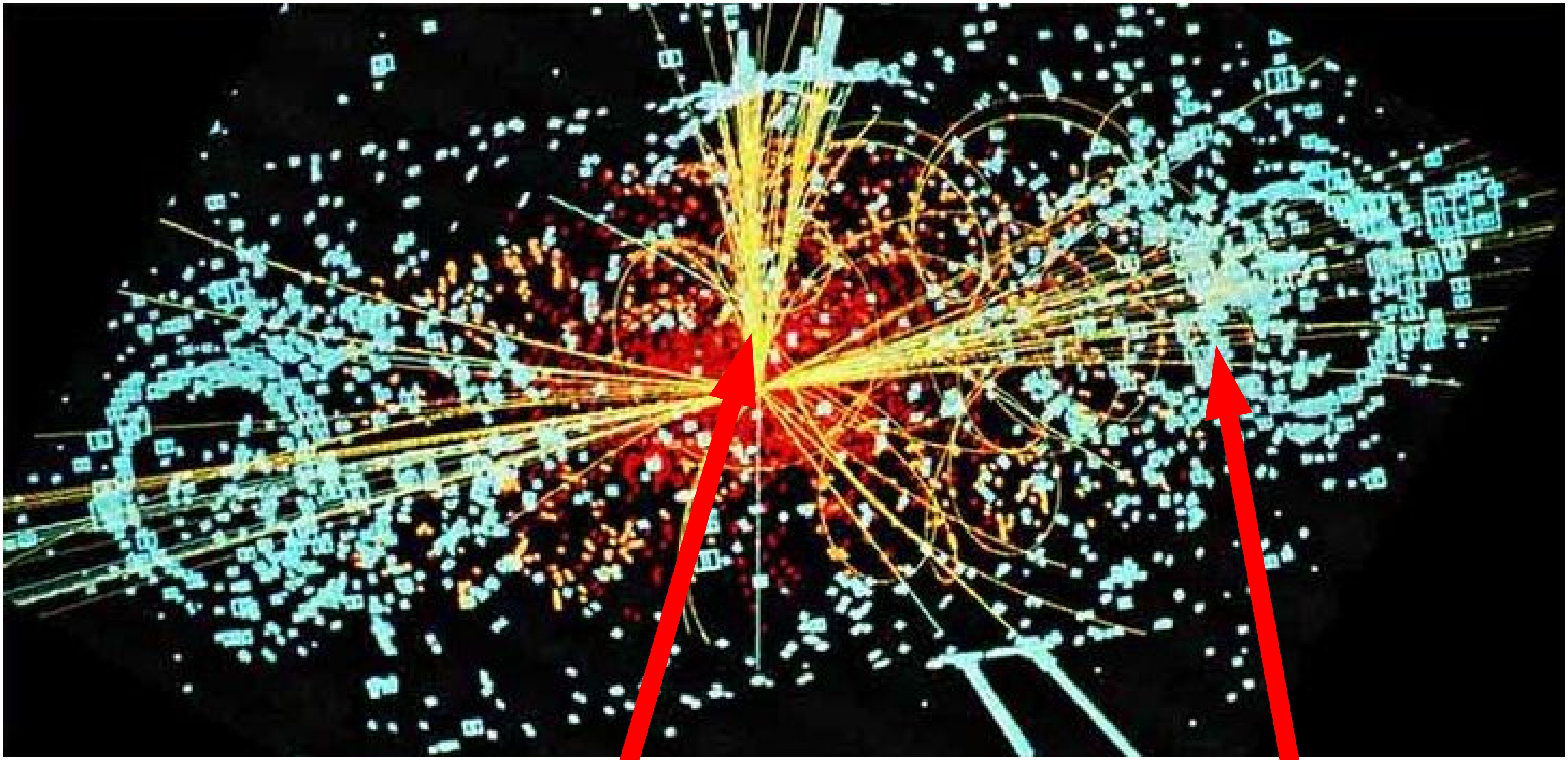
- Two counter-rotating beams of protons accelerated to high energy
  - 3.5 TeV, 4.0 TeV, 6.5 TeV in 2011, 2012, 2015+
  - n.b. proton mass = 0.938 GeV, so γ = 3731, 4264, 6930
- Beams are bunched, with ~10^{11} protons/bunch
- Bunches are squeezed at collision point to ~50 μm
- Collisions every 50 (25) ns in 2011/12 (2015+)
- Protons contain uud valence quarks, but are mainly composed of strong interaction "glue" (gluons + sea $q\bar{q}$)
  - Most pp collisions are gg collisions
  - Can have >1 interaction / crossing



Relative beam sizes around IP1 (Atlas) in collision

LHC collisions

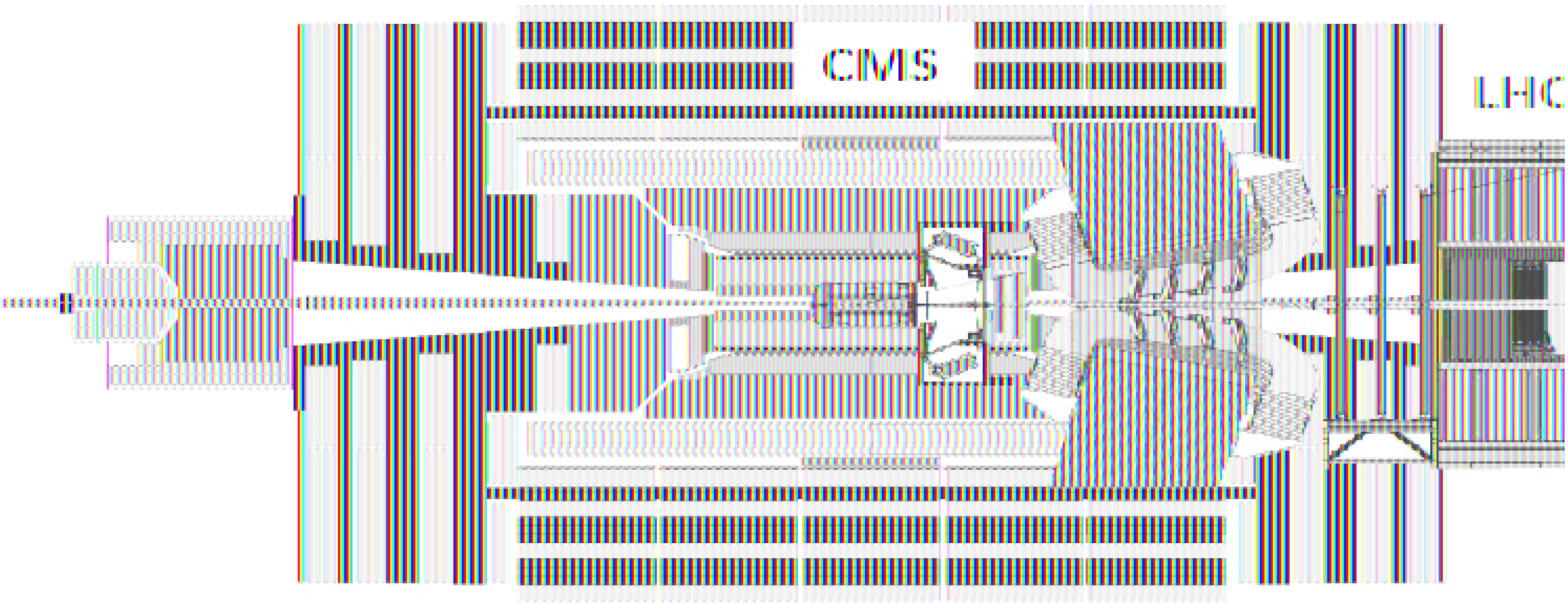
(illustrated with an unusually clean CMS simulated Higgs event)



heavy (≳100 GeV) particles mainly produced centrally

light (≲10 GeV) particles mainly produced forward

Different objectives, different detectors

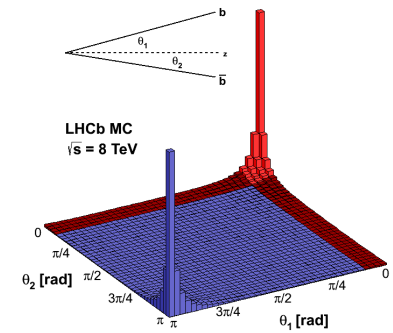


CMS (& ATLAS)
- Symmetrical, ~4π coverage
- Optimised for detection of high energy objects (central region)

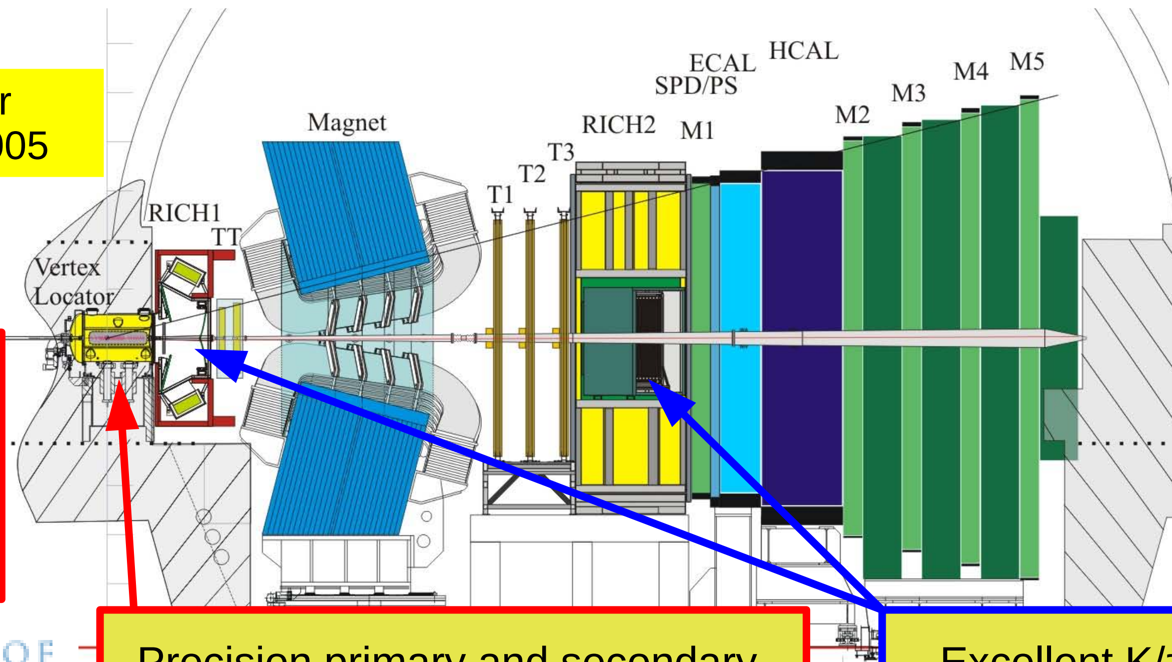
LHCb
- Highly asymmetrical
- Optimised for precise studies of forward-going particles (e.g. $b\bar{b}$)

The LHCb detector

- In high energy collisions, $b\bar{b}$ pairs produced predominantly in forward or backward directions
- LHCb is a forward spectrometer
  - a new concept for HEP experiments



The LHCb Detector
JINST 3 (2008) S08005

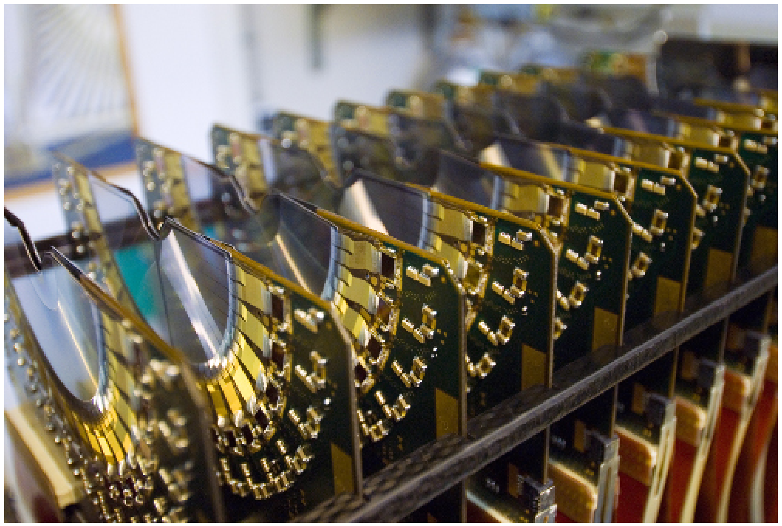


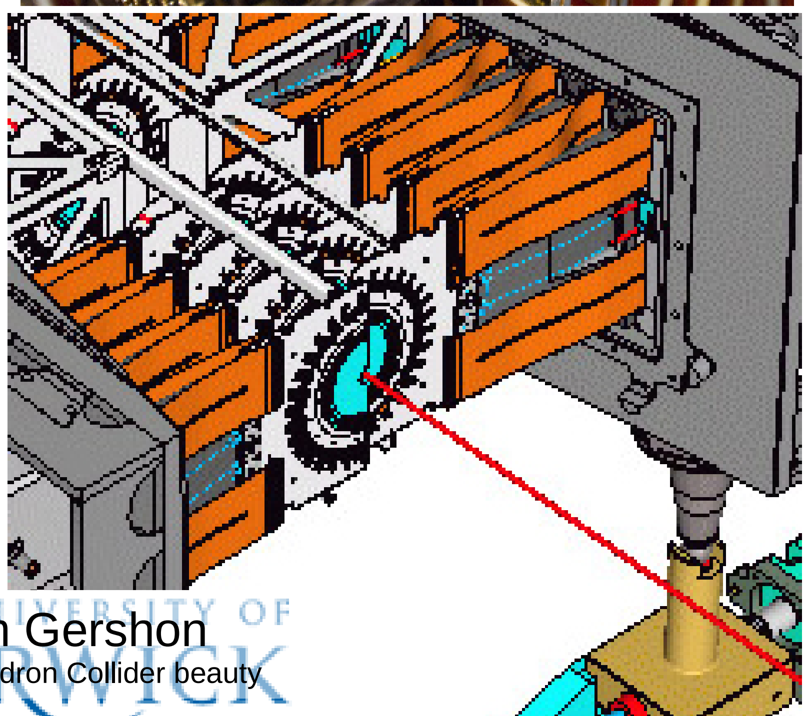
Precision primary and secondary vertex measurements

Excellent K/π separation capability

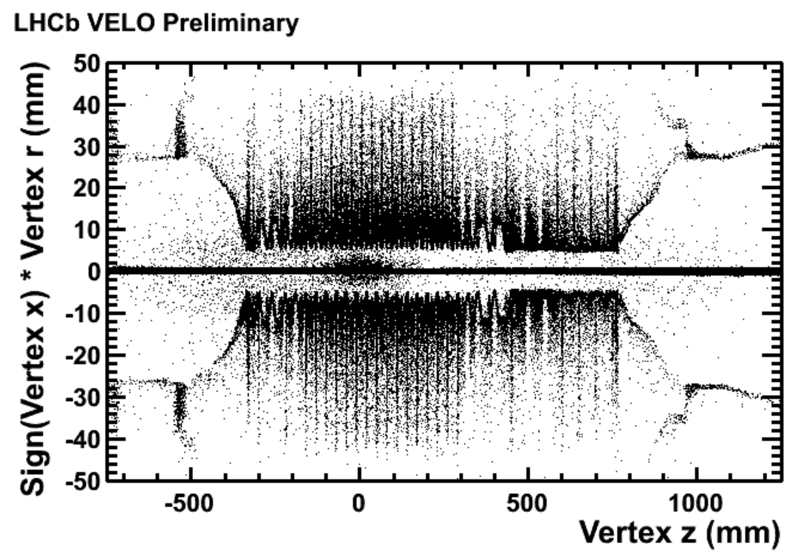
https://cds.cern.ch/record/1752882?ln=en

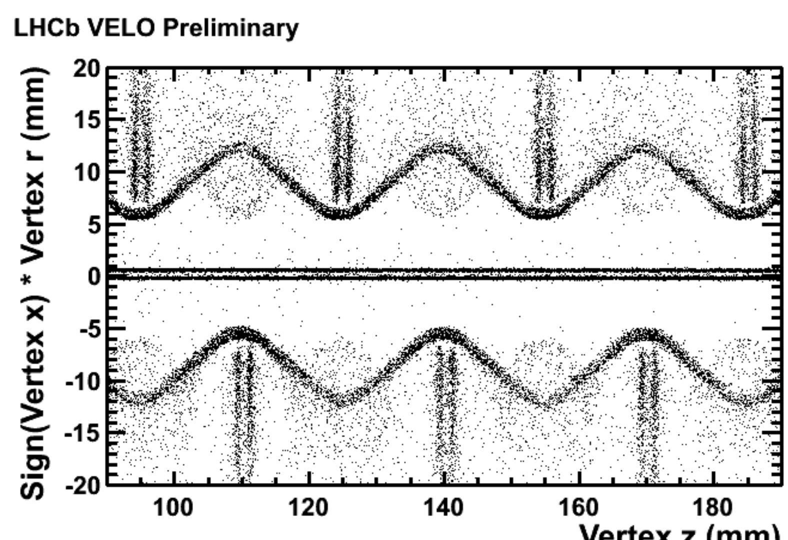
The Vertex Locator (VELO)





Material imaged used beam gas collisions





The LHCb trigger

JINST 8 (2013) P04022

Challenge is

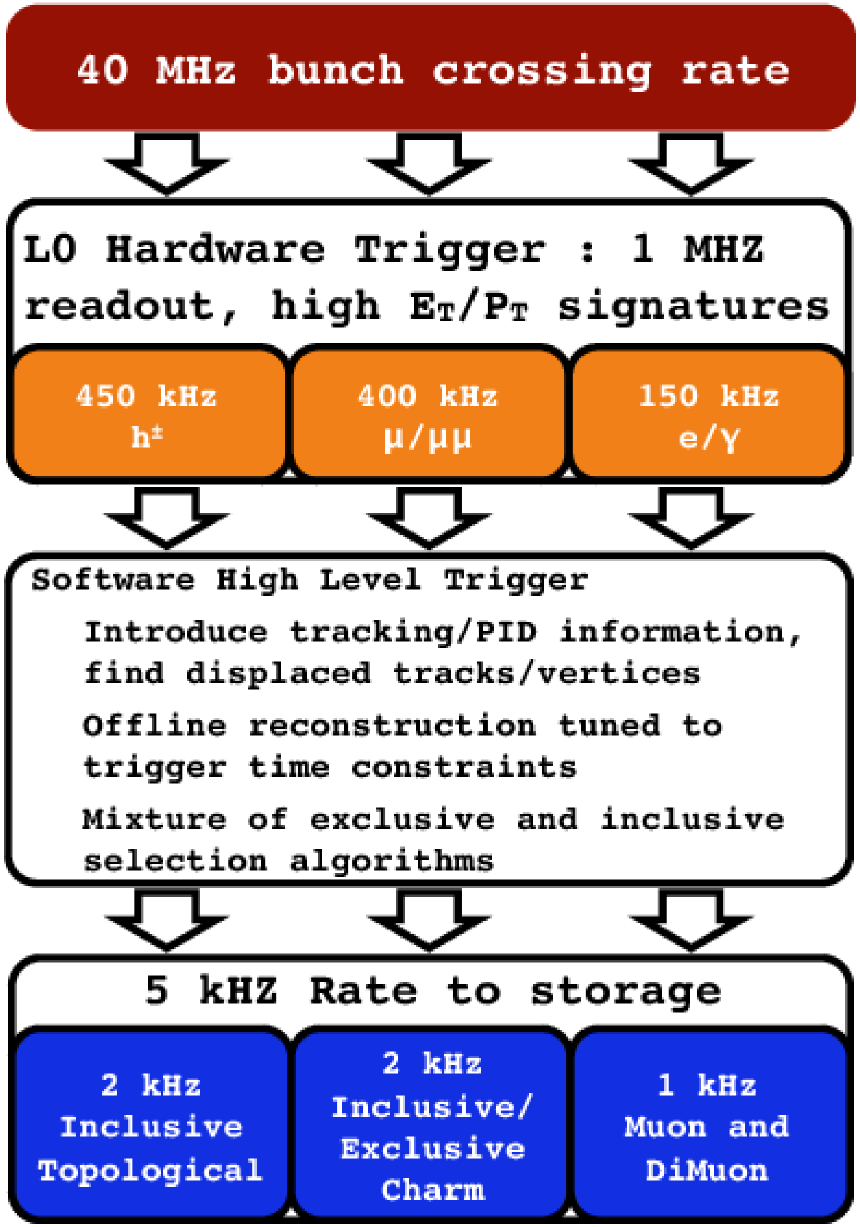
- to efficiently select most interesting B decays
- while maintaining manageable data rates

Main backgrounds

- “minimum bias” inelastic pp scattering
- other charm and beauty decays

Handles

- high p_T signals (muons)
- displaced vertices due to B lifetime & boost



Some highlights of results

(from ~225 papers, so far)

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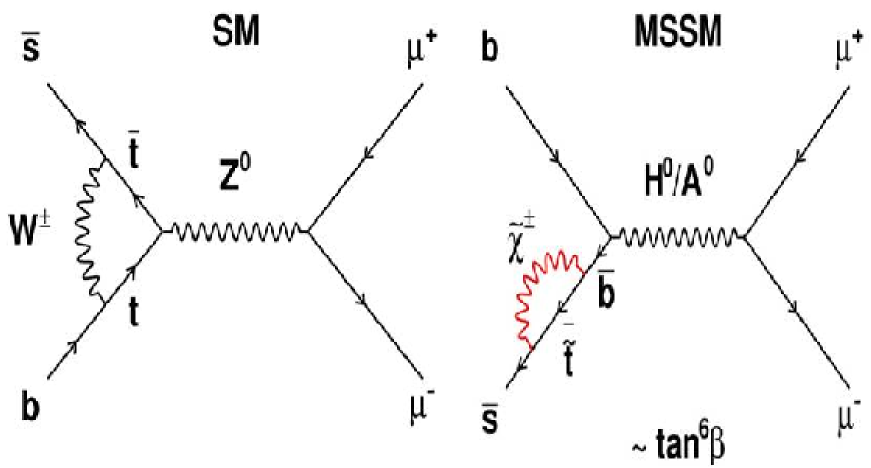
$B_s \to \mu^+\mu^-$

Killer app. for new physics discovery

Very rare in Standard Model due to

- absence of tree-level FCNC
- helicity suppression
- CKM suppression

… all features which are not necessarily reproduced in extended models



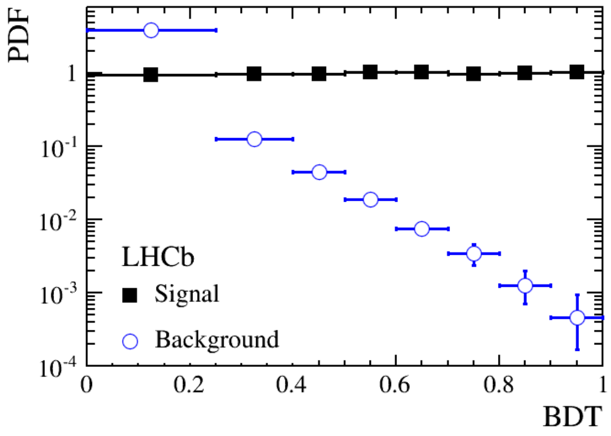
$\mathcal{B}(B_s \to \mu^+\mu^-)^{SM} = (3.65 \pm 0.23) \times 10^{-9}$

PRL 112 (2014) 101801

$\mathcal{B}(B_s \to \mu^+\mu^-)^{MSSM} \sim \tan^6\beta/M^4_{A0}$

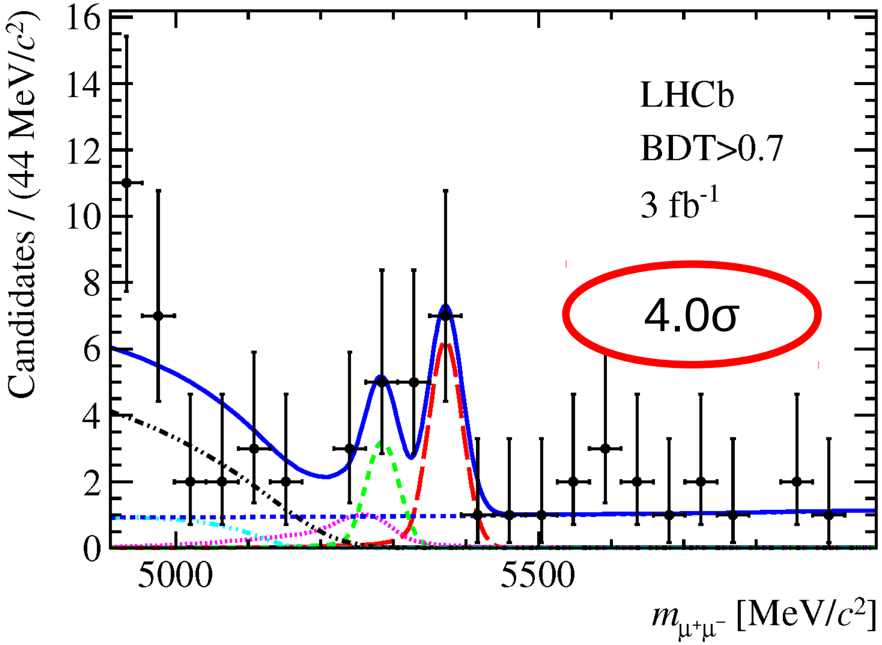
$B_{(s)}^0 \to \mu^+\mu^-$ – analysis ingredients

- Produce a very large sample of B mesons
- Trigger efficiently on dimuon signatures
- Reject background
  - excellent vertex resolution (identify displaced vertex)
  - excellent mass resolution (identify B peak)
    - also essential to resolve B^0 from B_s^0 decays
  - powerful muon identification (reject background from B decays with misidentified pions)
  - typical to combine various discriminating variables into a multivariate classifier
    - e.g. Boosted Decision Trees algorithm

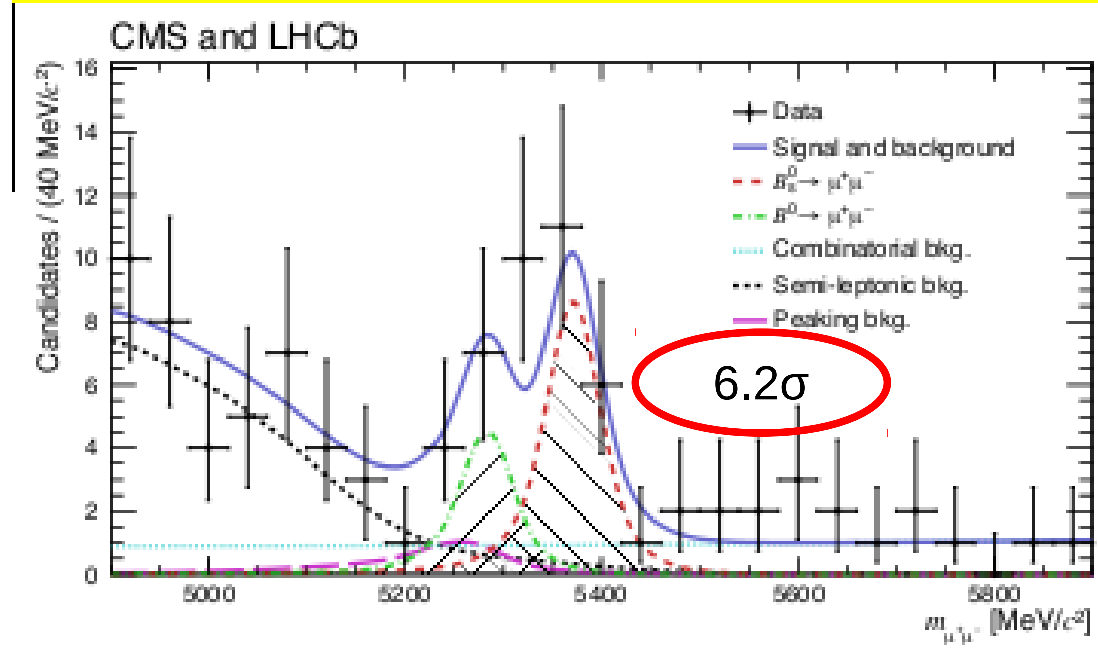


$B_{(s)}^0 \to \mu^+\mu^-$

LHCb
PRL 111 (2013) 101805

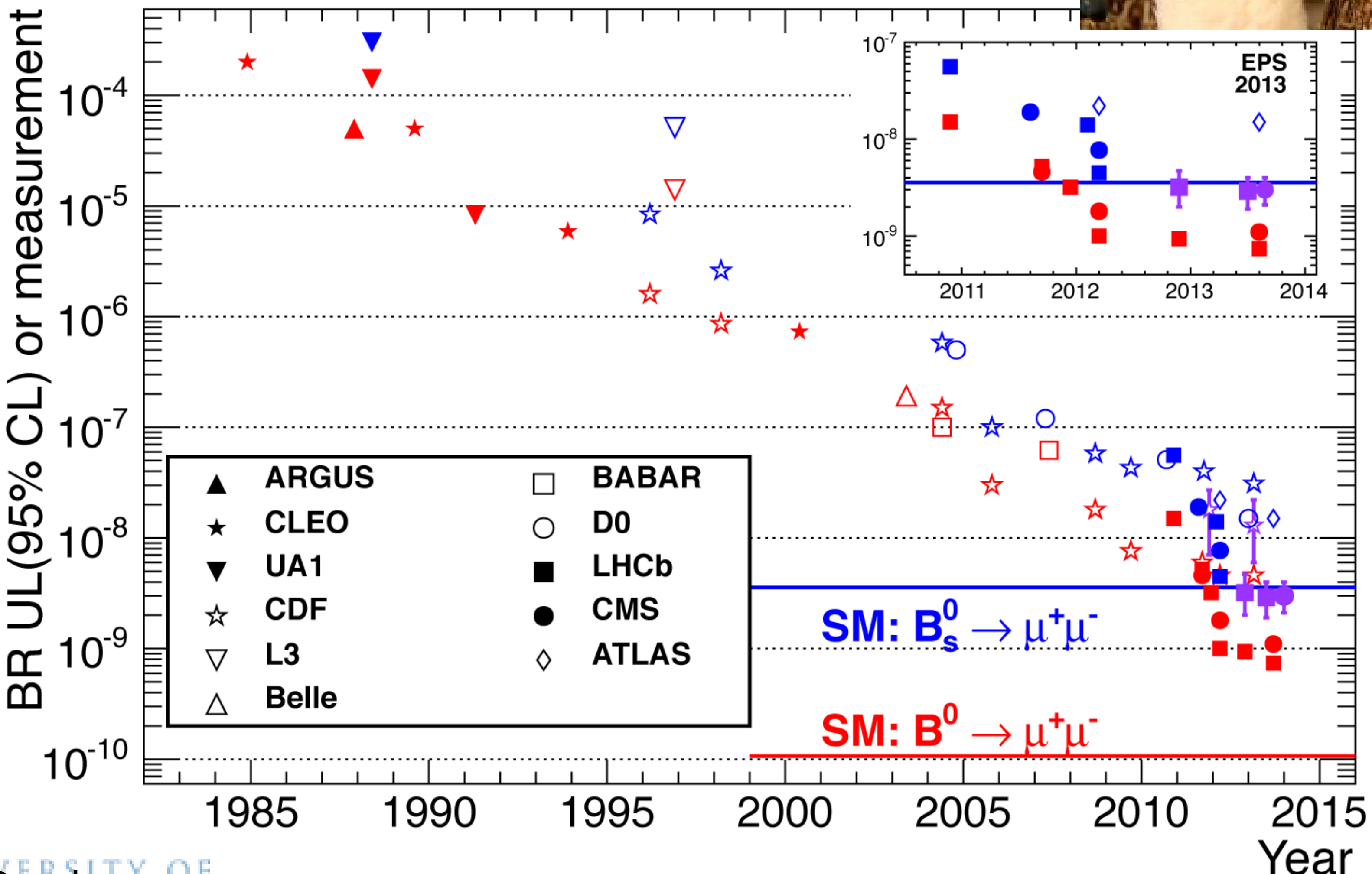


NEW! Combination with CMS data
To be submitted to Nature



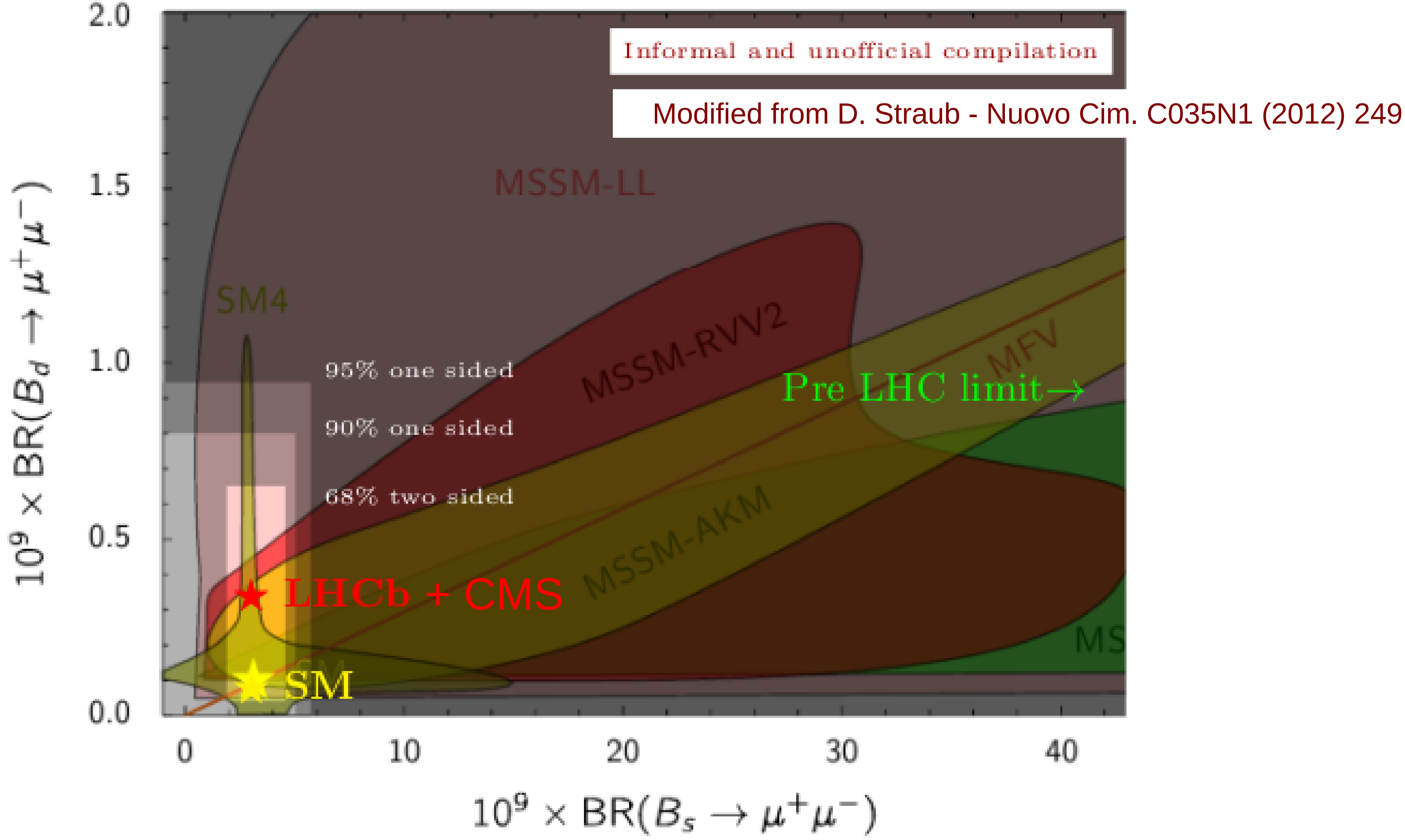
Updated results confirm earlier evidence from LHCb (PRL 110 (2013) 021801)

$B_{(s)}^0 \to \mu^+\mu^-$



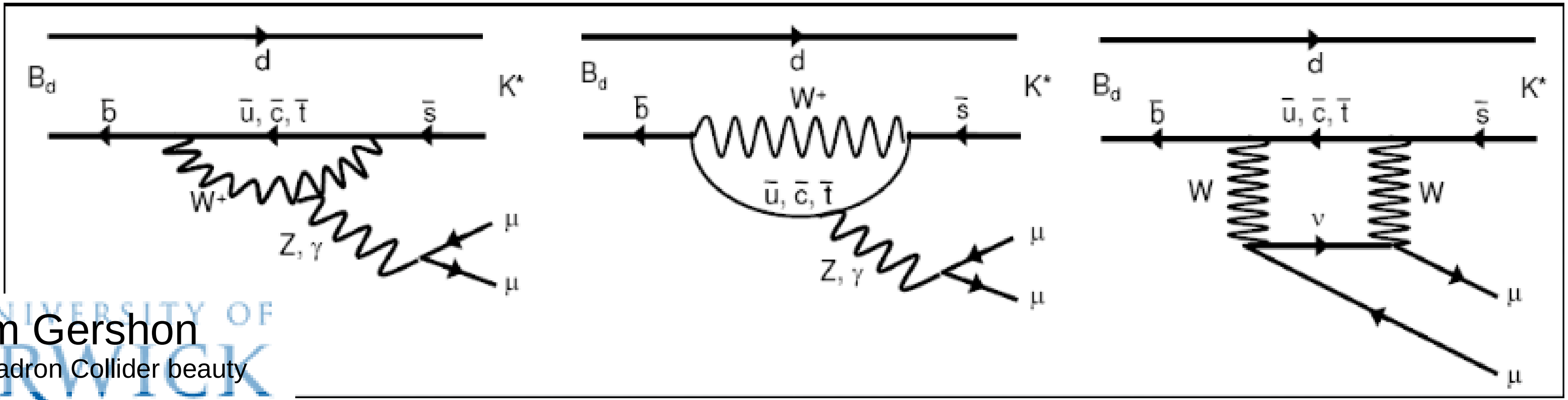
Searches over 30 years

Impact of $B_s \to \mu^+\mu^-$

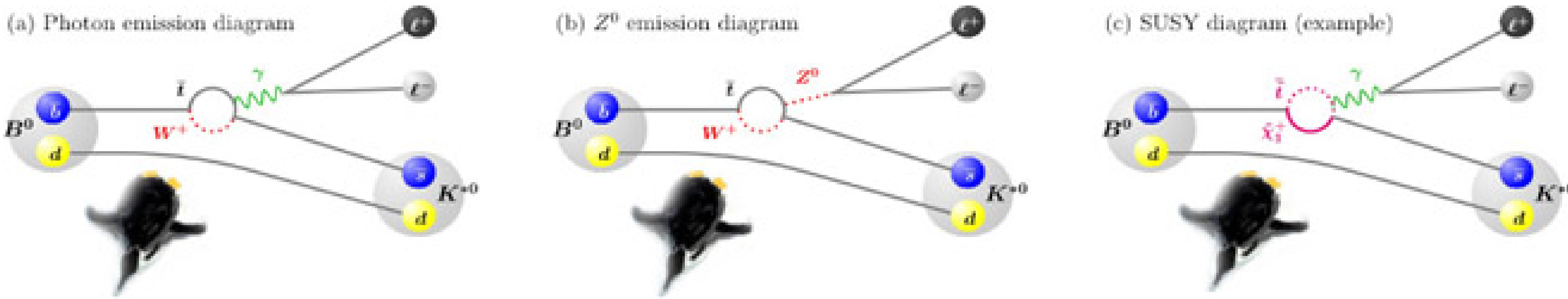


$B \to K^{*}\mu^{+}\mu^{-}$

- $B_d \to K^{*0}\mu^{+}\mu^{-}$ provides complementary approach to search for new physics in $b \to sl^{+}l^{-}$ FCNC processes
  - rates, angular distributions and asymmetries sensitive to NP
  - superb laboratory for NP tests
  - experimentally clean signature
  - many kinematic variables …
  - … with clean theoretical predictions



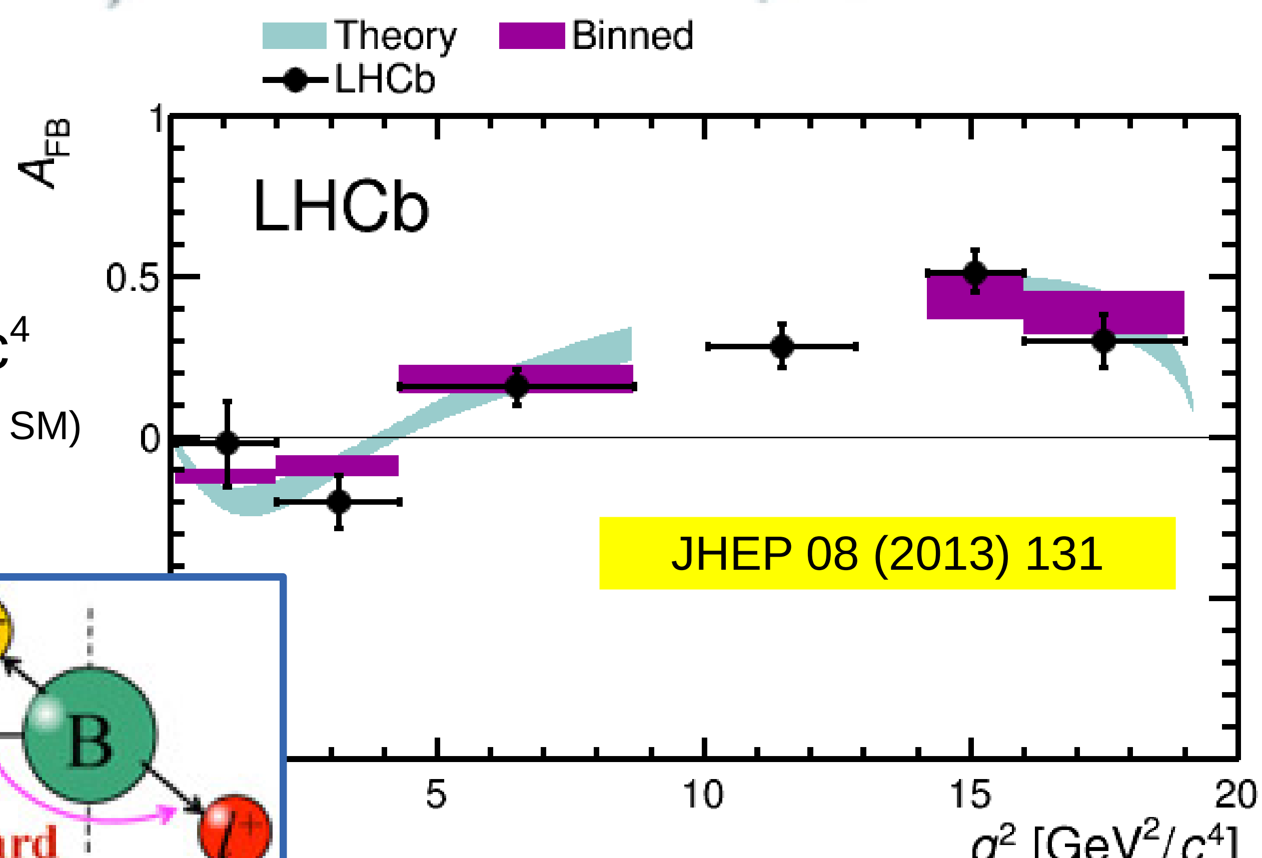
Forward-backward asymmetry in $B \to K^* \mu^+ \mu^-$

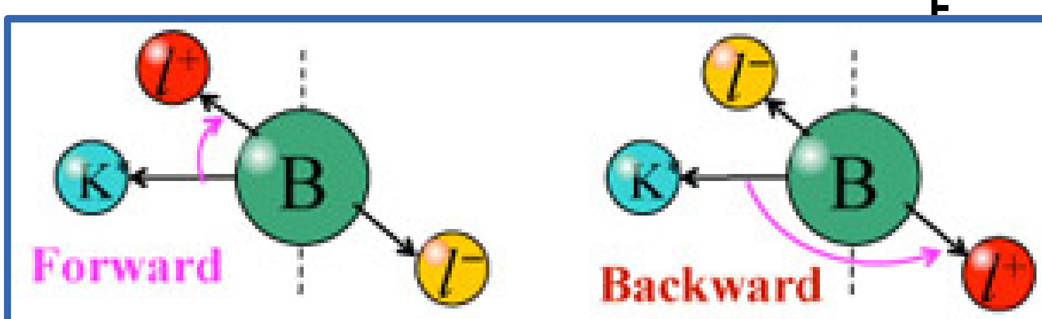


Zero crossing-point

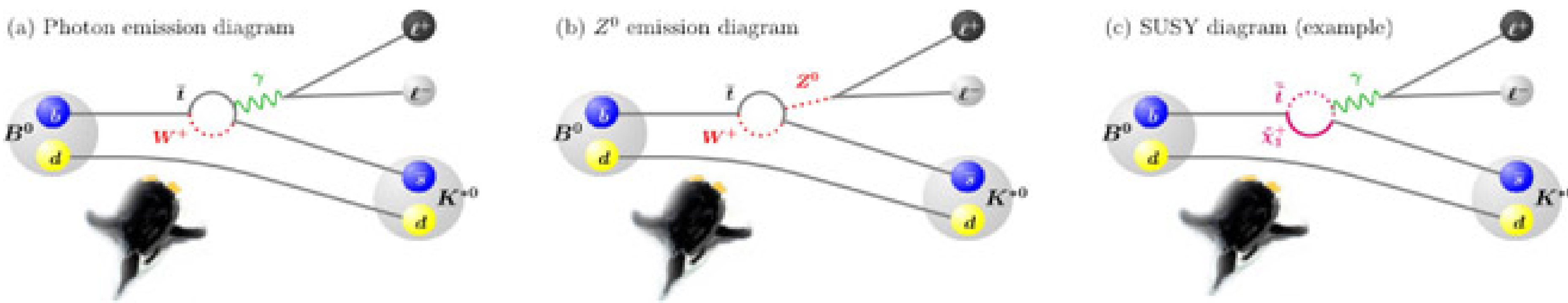
$q^2_0 = (4.9 \pm 0.9)\ \mathrm{GeV}^2/c^4$

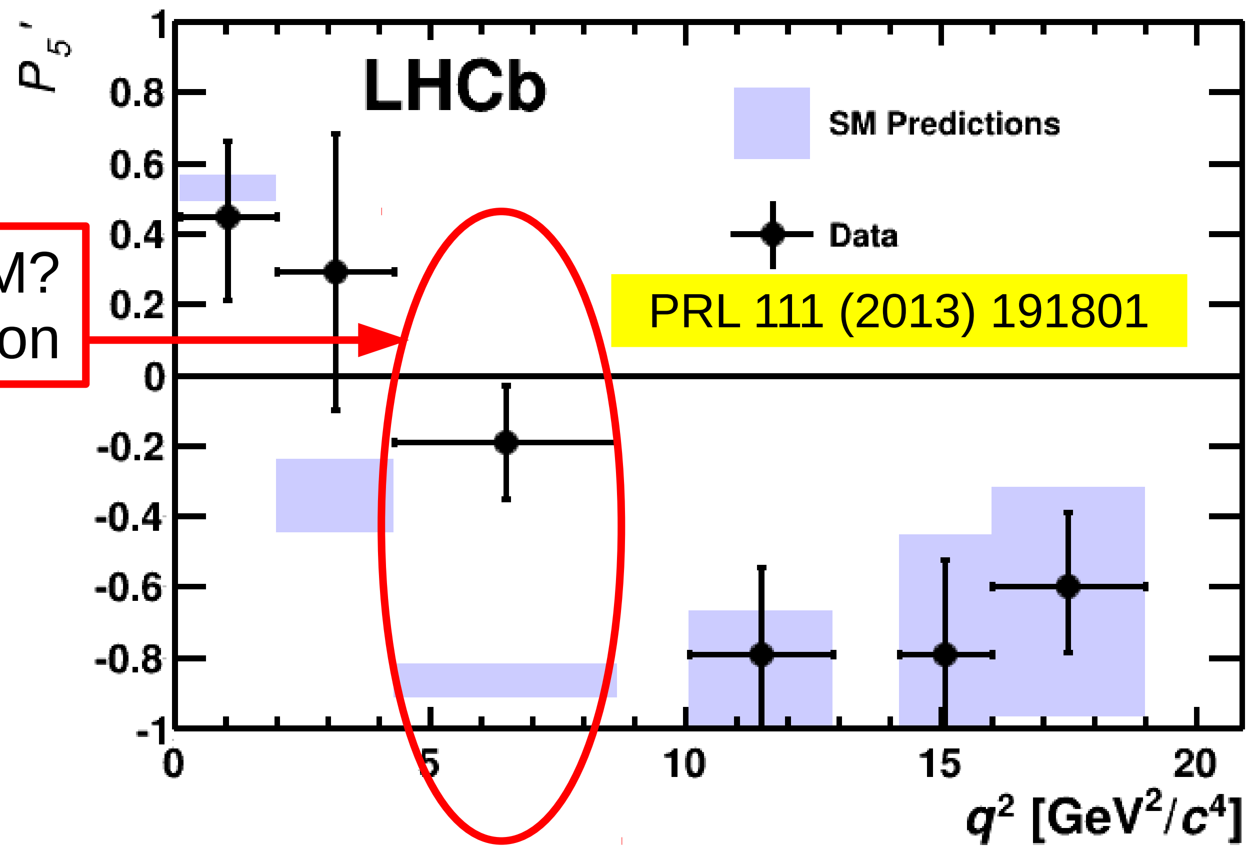
(consistent with SM)





Another angular observable in $B \to K^*\mu^+\mu^-$



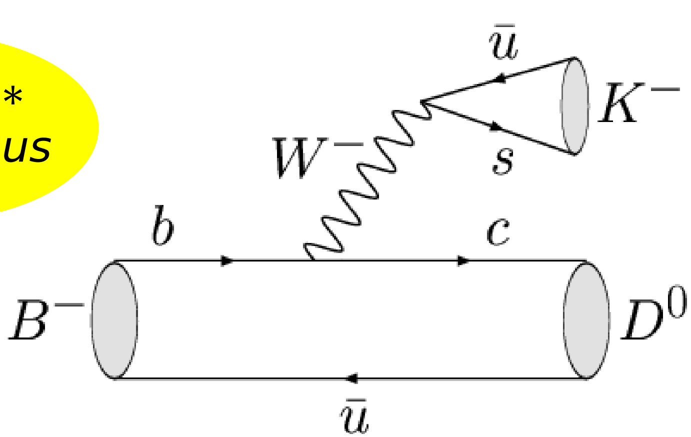


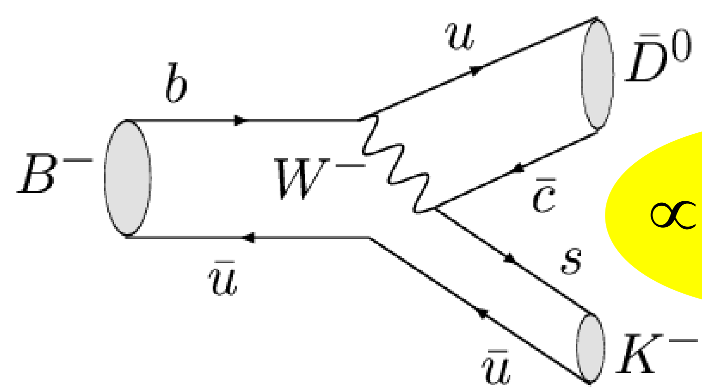
Possible discrepancy with SM?
Updated results expected soon

CP violation

- Measure relative phase between amplitudes by exploiting quantum-mechanical interference
  - Compare results for B and $\overline{B}$ to see if the phase is CP-conserving (strong) or CP-violating (weak)
- Identify processes with contributions from two different sets of CKM matrix elements, e.g.

$\propto V_{cb} V_{us}^*$



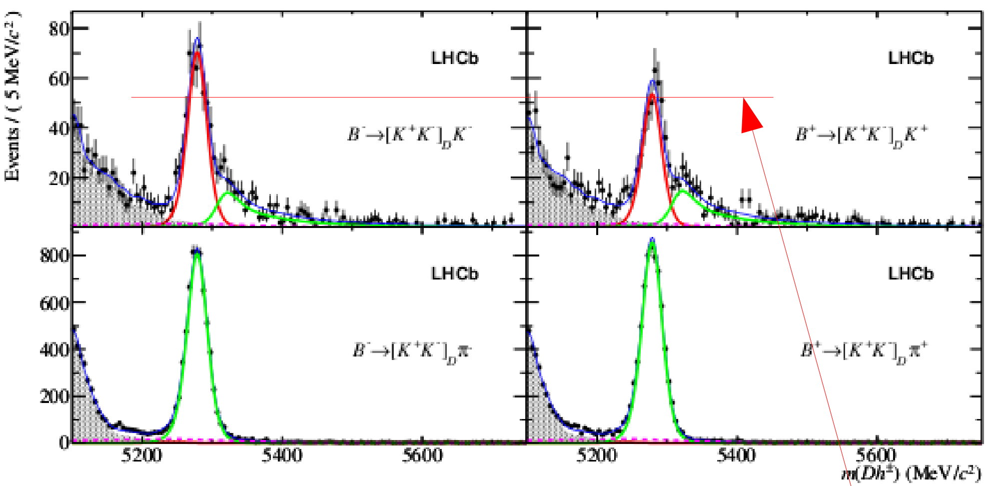


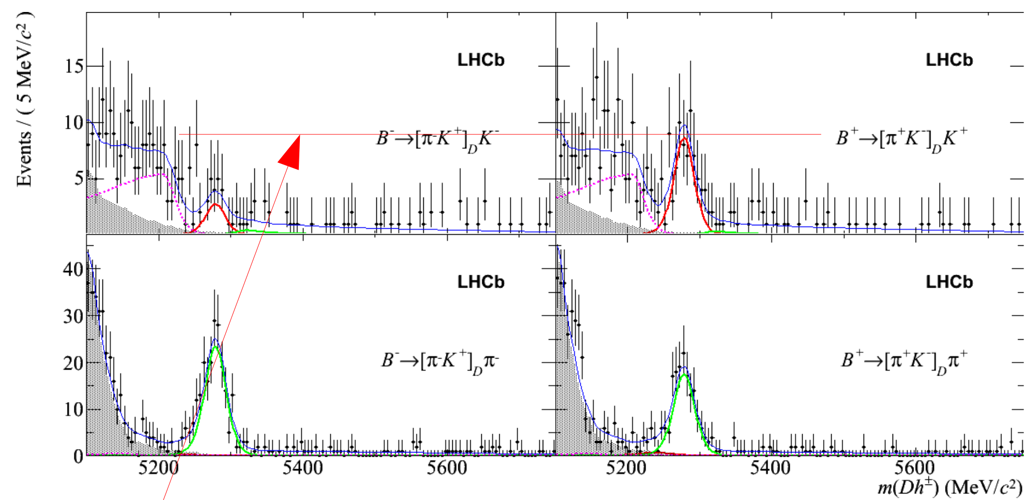
$\propto V_{ub} V_{cs}^*$

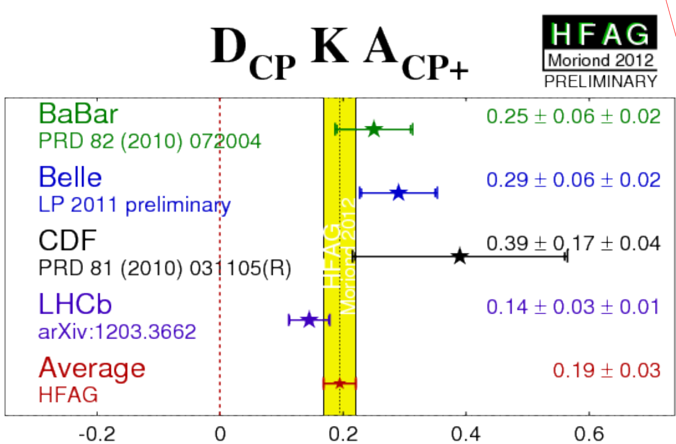
Interference & CP violation when D^0 and $\overline{D}^0$ decay to common final state (e.g. K^+K^-)

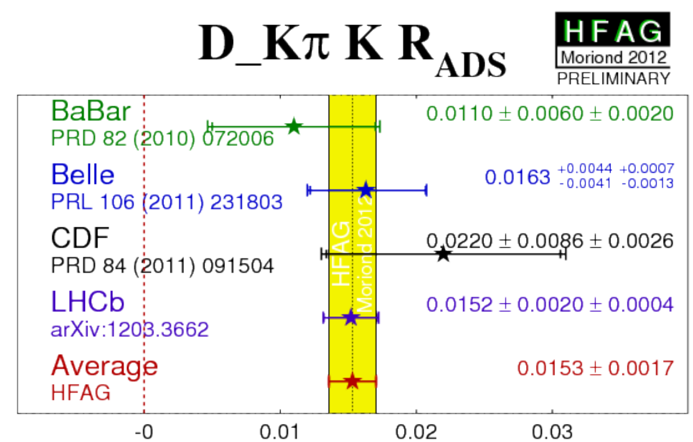
CP violation in B → DK decays

PLB 712 (2012) 203









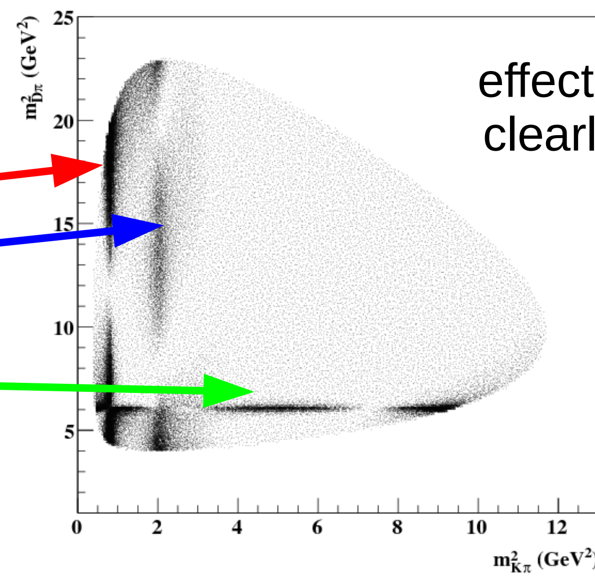
Observation of CP violation in B → DK decays

Extension to B→DπK decays

TG PRD 79 (2009) 051301(R)
TG & M. Williams PRD 80 (2009) 092002

- Powerful extension of the method exploits additional sources of interference that occur in multibody decays
  - $B^0 \to D(\pi^- K^+)$ decays can have CP violation
  - $B^0 \to (D\pi^-)K^+$ decays have no CP violation
    - Provides ideal reference amplitude from which to determine relative phases via interference between different resonances on the Dalitz plot

Toy example containing
$K^*(892)^0$
$K_2^*(1430)^0$
$D_2^*(2460)^-$



effects of spin clearly visible

Extension to B→DπK decays

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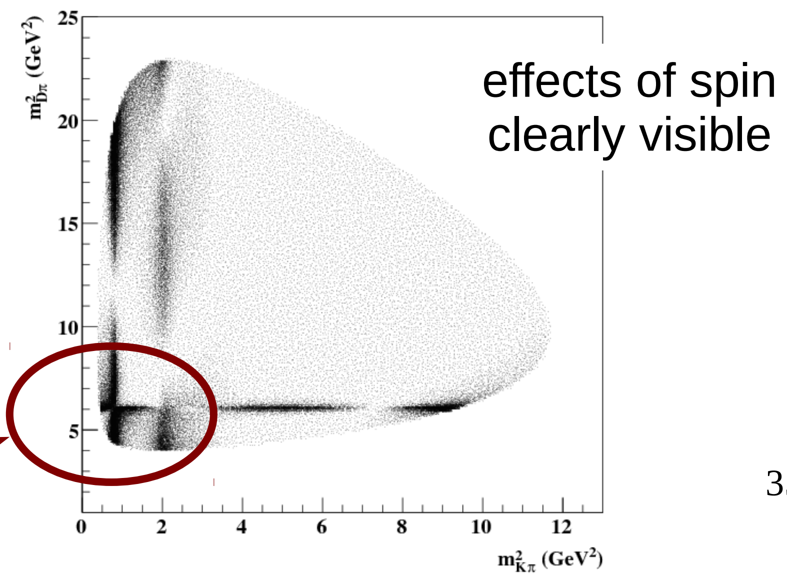
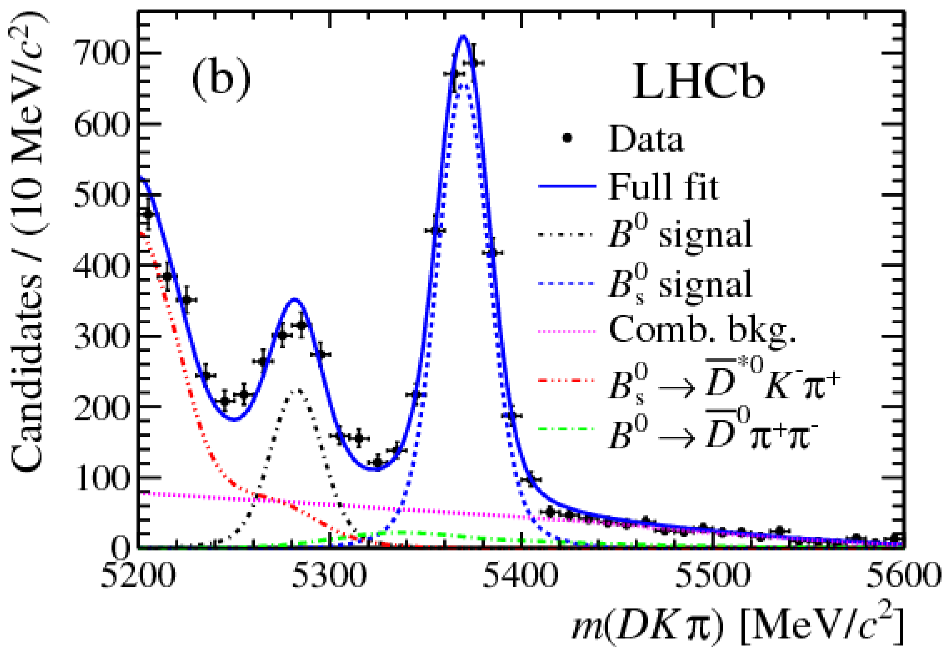


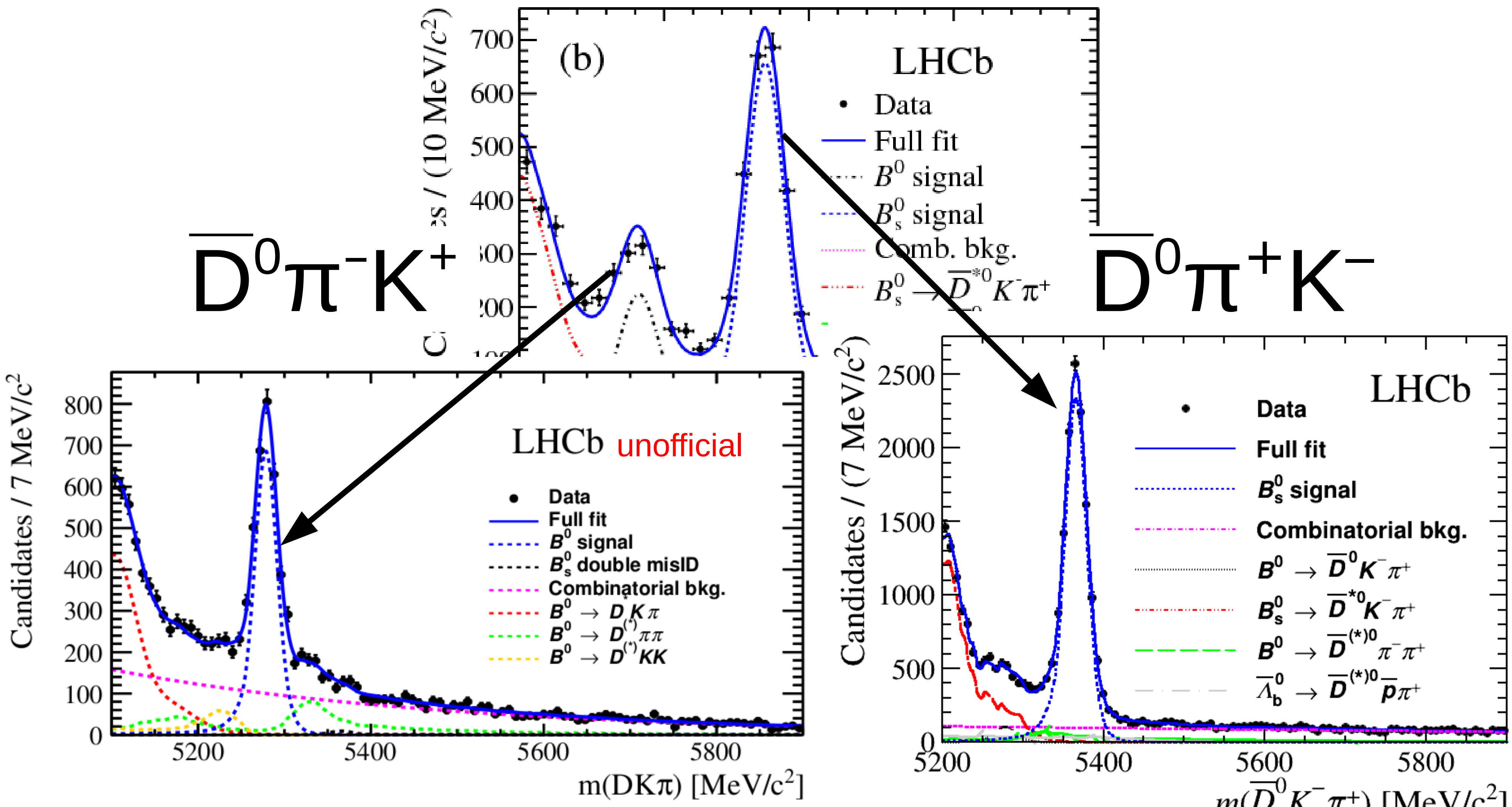
Observation of $B^0_{(s)} \to \overline{D}^0 \pi^{\mp} K^{\pm}$

PRD 87 (2013) 112009



Observation of $B^0_{(s)} \to \overline{D}^0 \pi^\mp K^\pm$

PRD 87 (2013) 112009



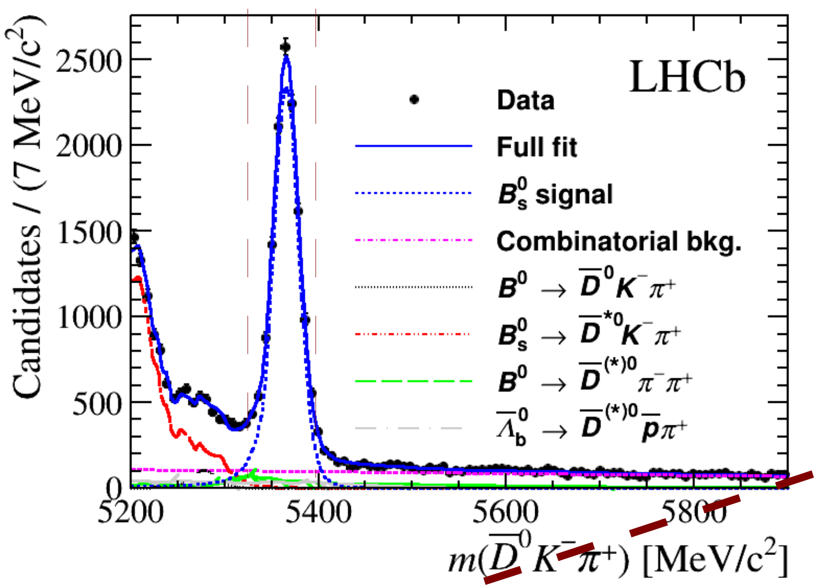
Large Hadron Collider beauty

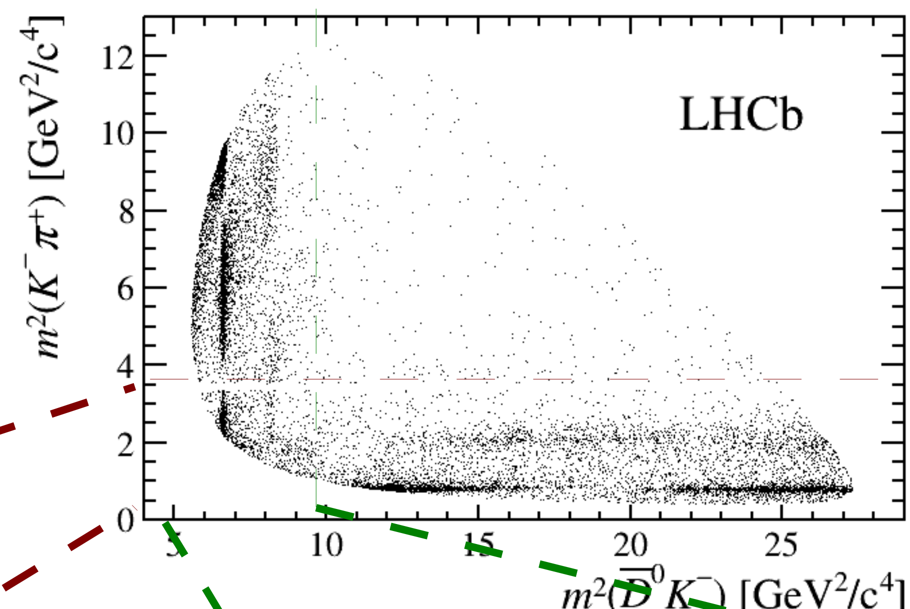
Bottom plots based on larger data sample, with improved selection

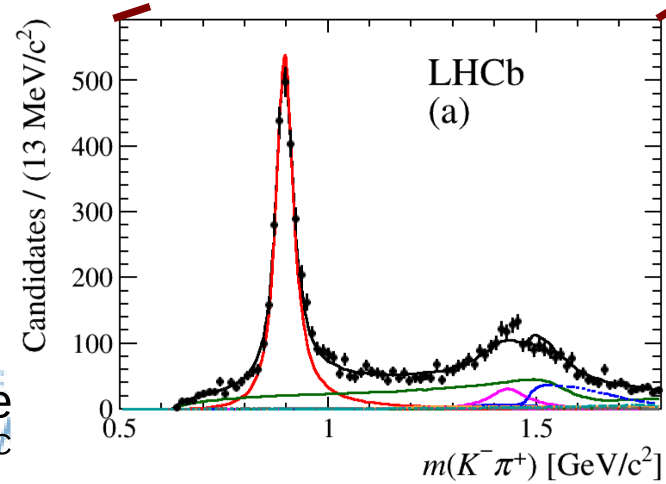
Dalitz plot analysis of $B^0_s \rightarrow \overline{D}^0\pi^+K^-$

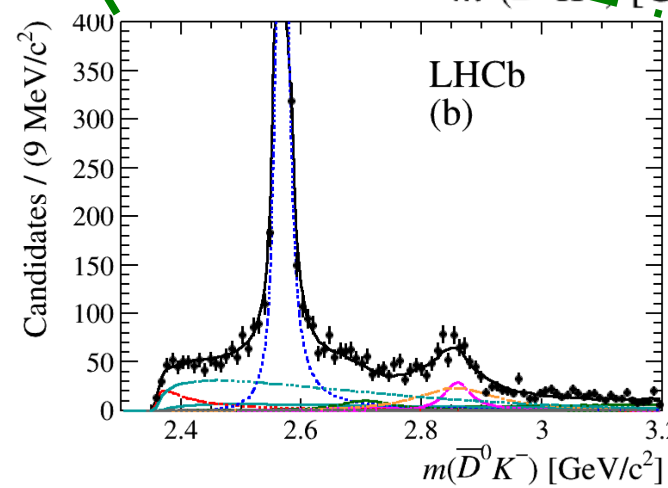
Analysis performed with Laura++
https://laura.hepforge.org/

PRL 113 (2014) 162001
PRD 90 (2014) 072003





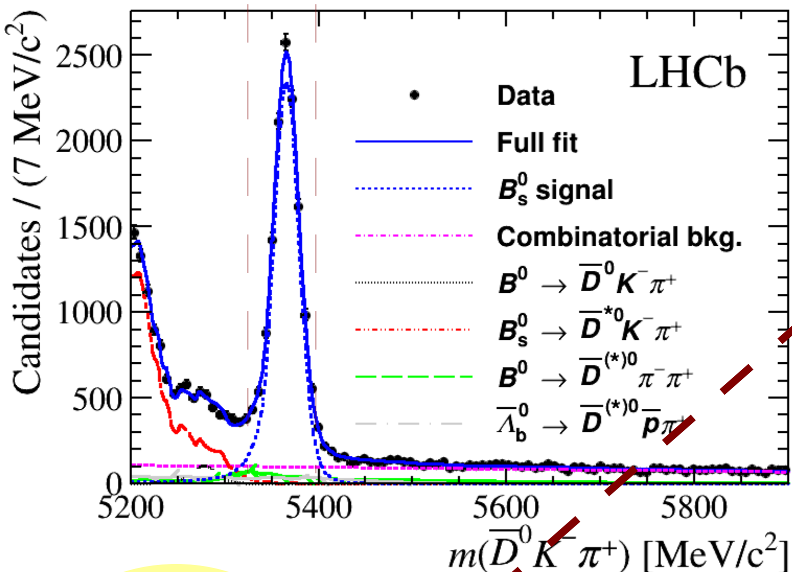


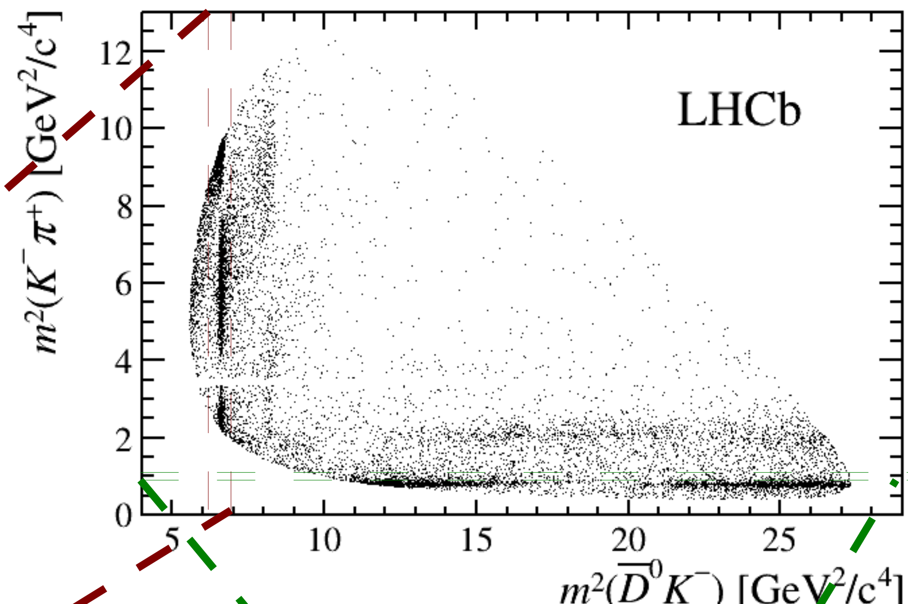


Dalitz plot analysis of $B^0_s \to \overline{D}^0 \pi^+ K^-$

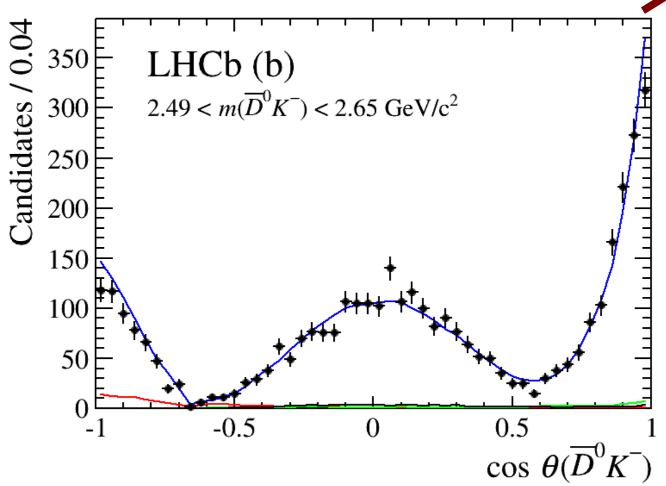
Analysis performed with Laura++
https://laura.hepforge.org/

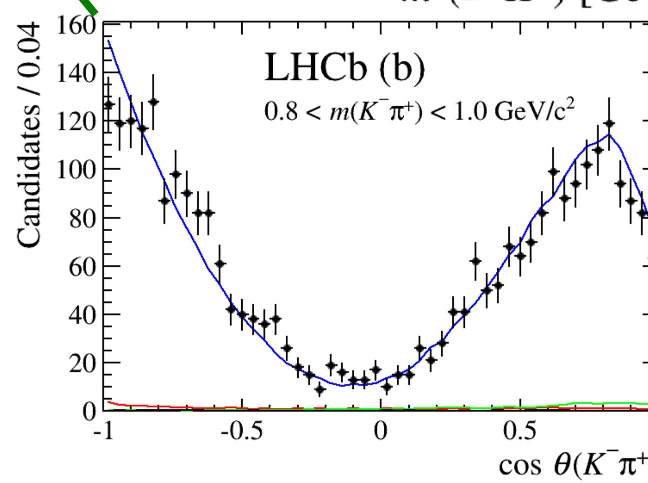
PRL 113 (2014) 162001
PRD 90 (2014) 072003



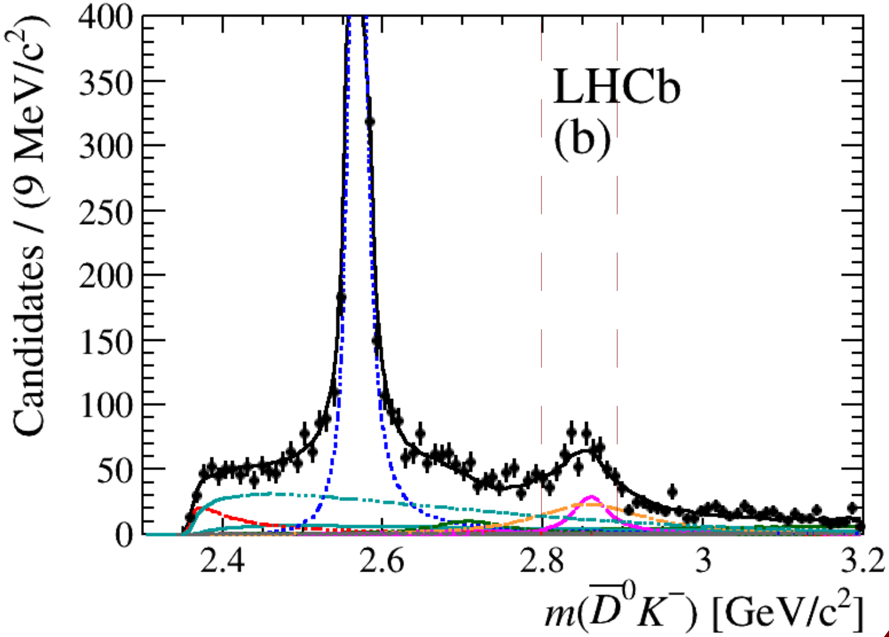


First measurement of the spin = 2 of the $D_{s2}^*(2573)$ state

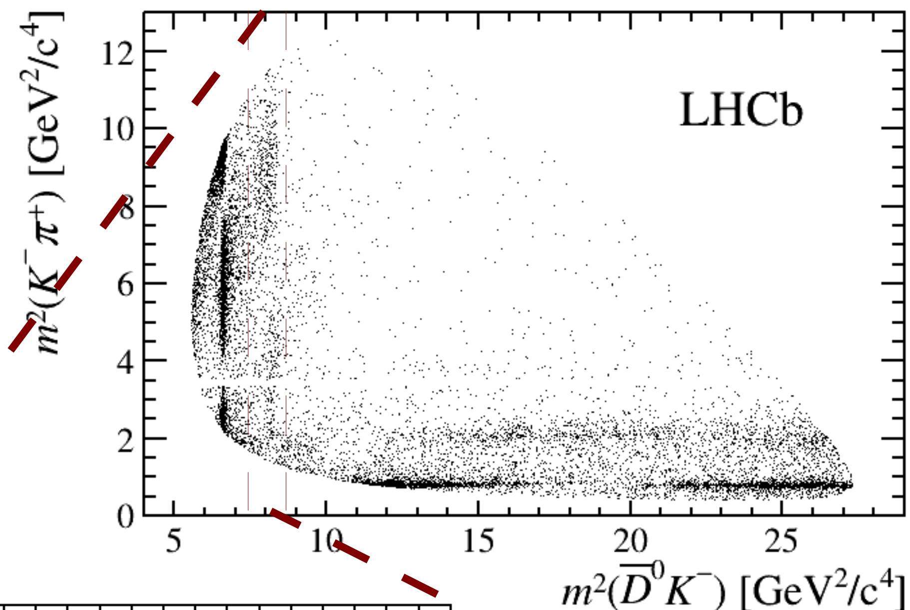




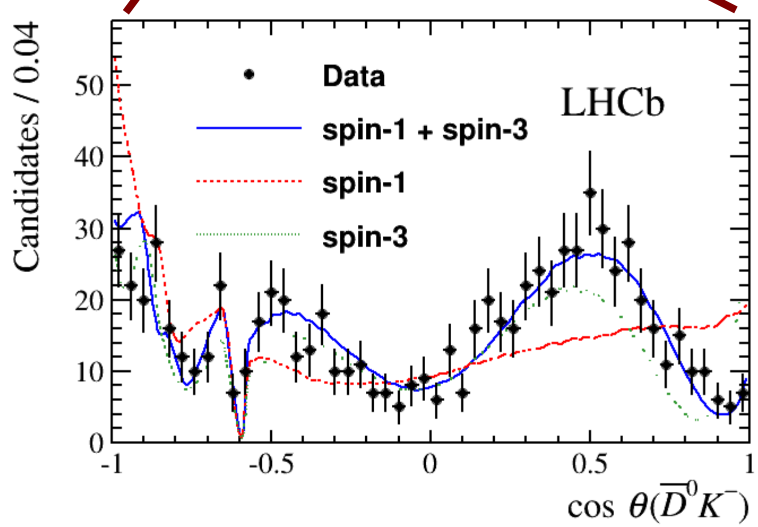
Observations of new particles!



PRL 113 (2014) 162001
PRD 90 (2014) 072003

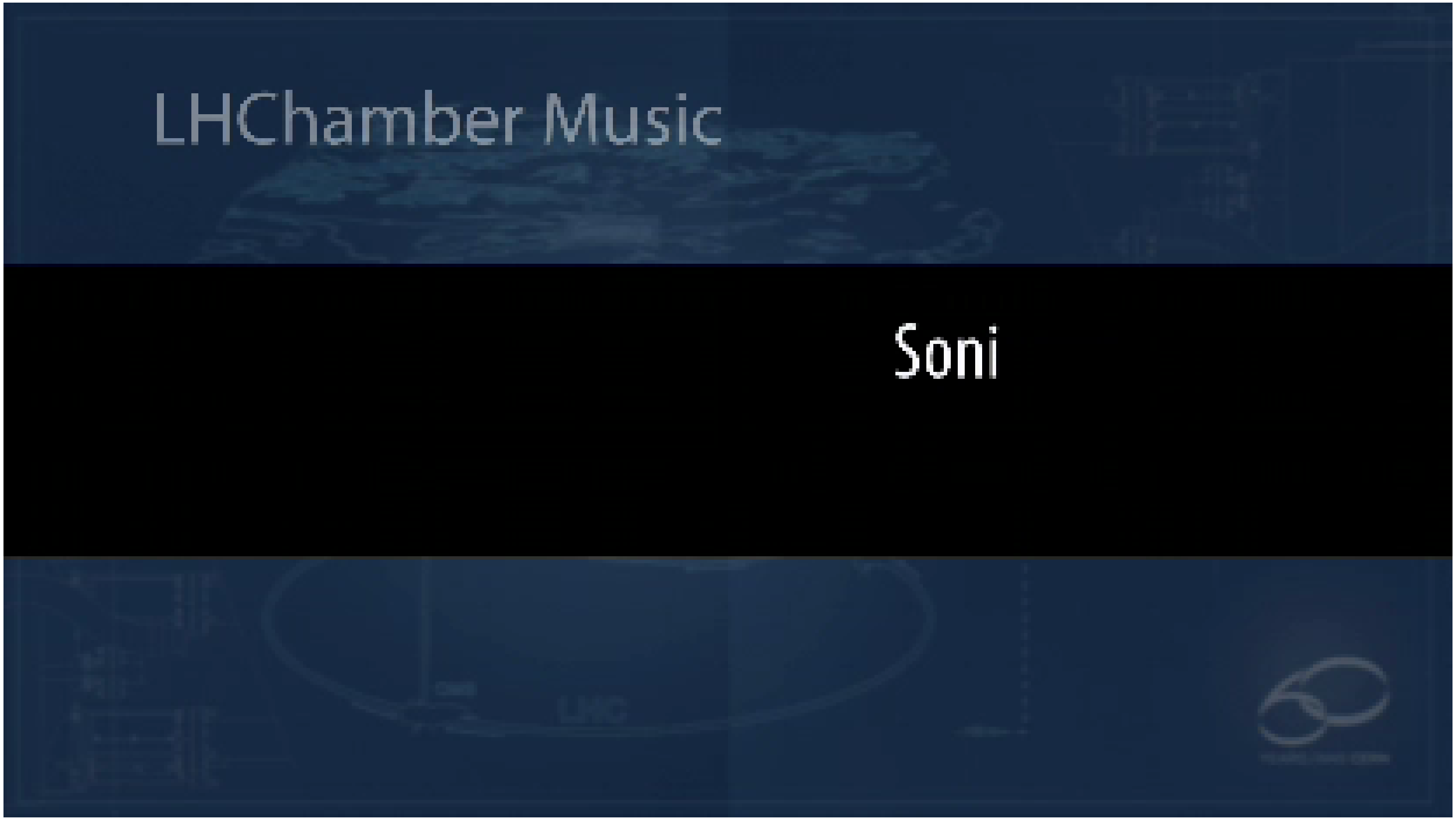


Observation of interfering spin-1 and spin-3 resonances around m(DK) ~ 2.86 GeV



First observation of any spin-3 resonance containing a heavy quark

Yes, but what does it *sound* like?

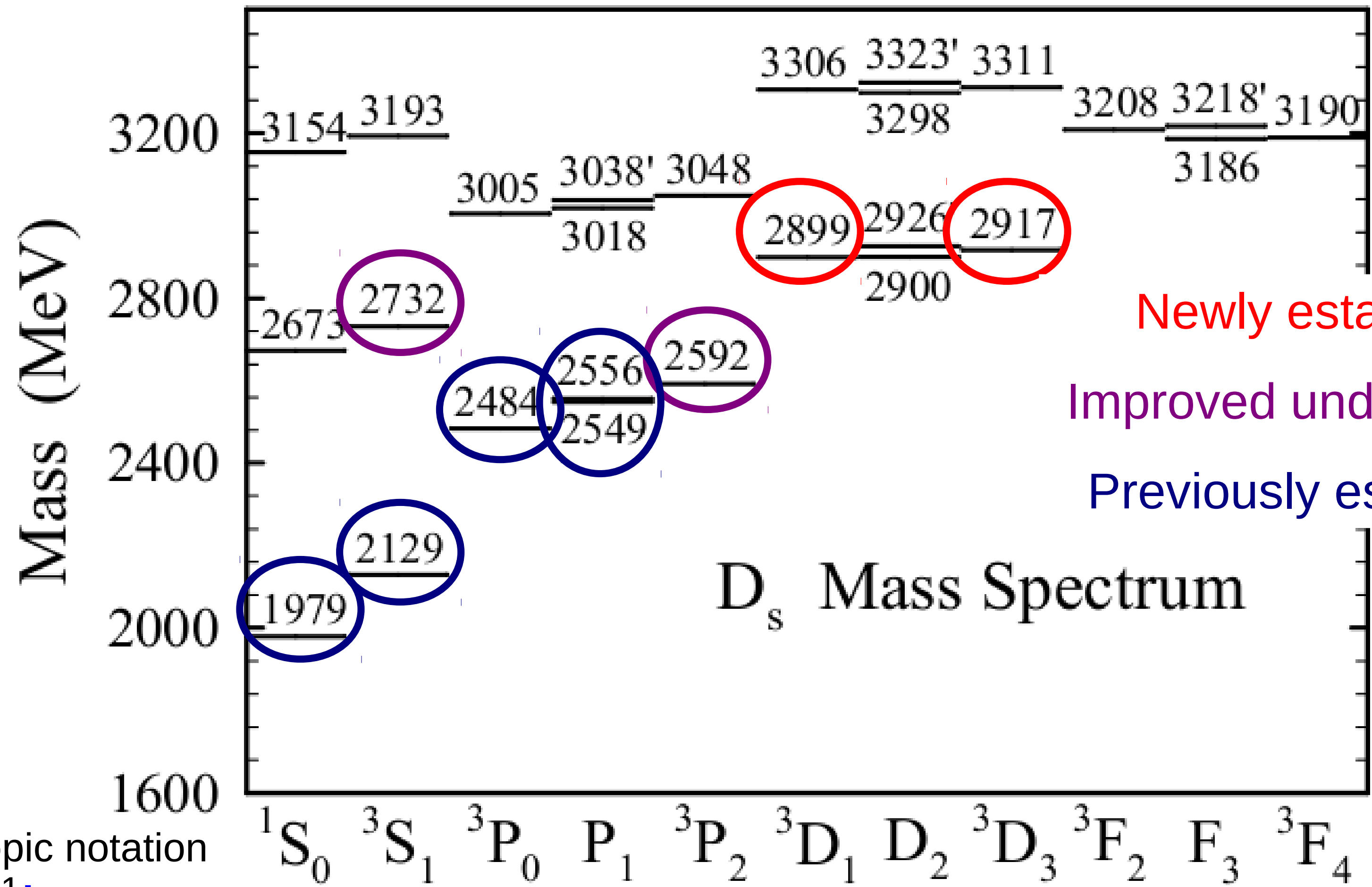


at 08:00 minutes

https://www.youtube.com/watch?feature=player_embedded&v=gPmQcviT-R4

D_s meson spectroscopy

Figure from PRD 89 (2014) 074023
Most masses offset from measurements



Newly established

Improved understanding

Previously established

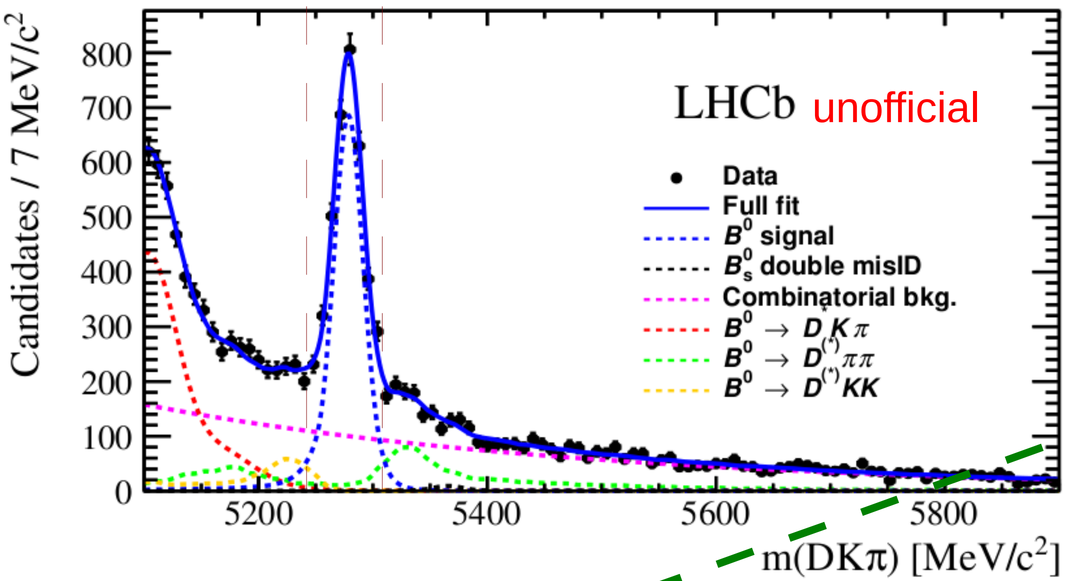
Spectroscopic notation
$^{2S+1}L_J$

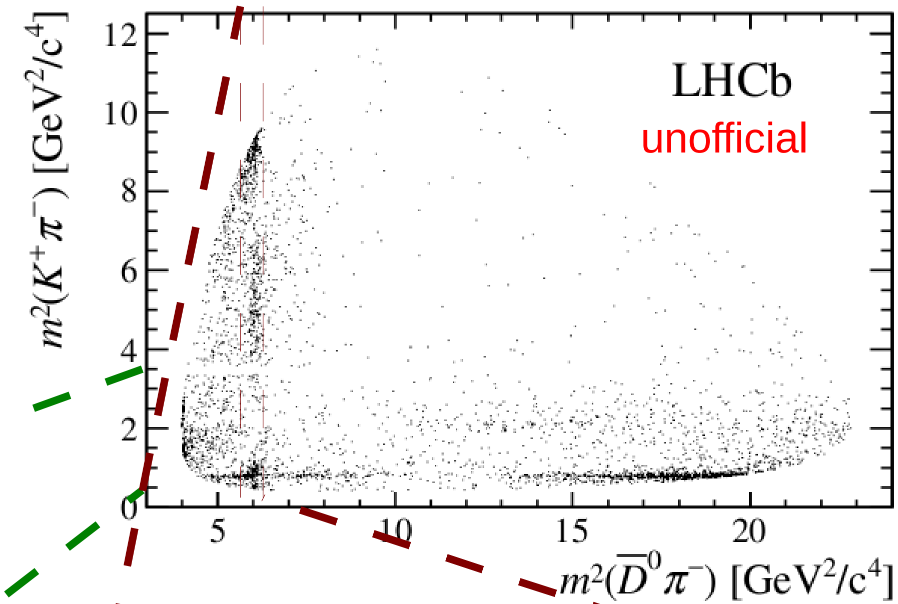
S = sum of quark spins
L = orbital angular momentum (S,P,D,F)
J = total spin

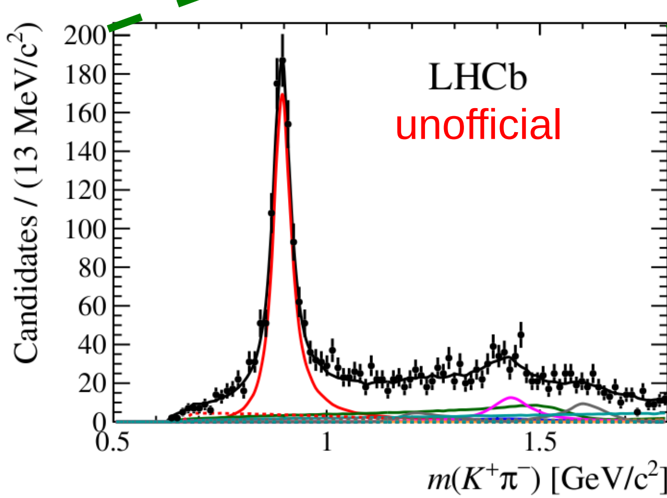
Dalitz plot analysis of $B^0 \to \overline{D}^0 \pi^- K^+$

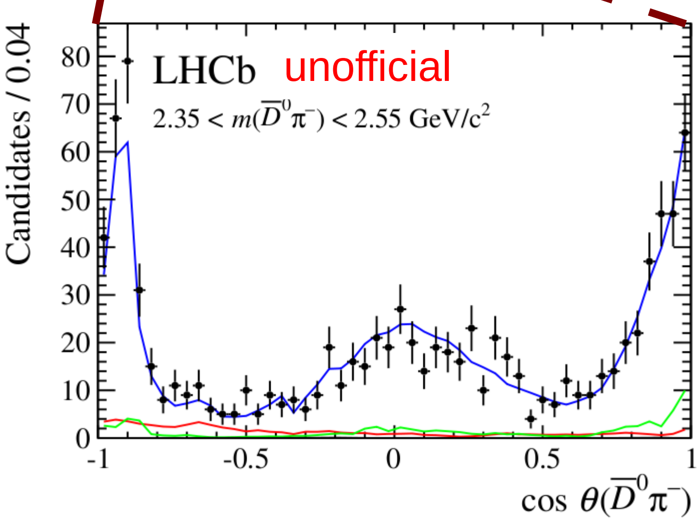
Analysis performed with Laura++
https://laura.hepforge.org/

Work in progress

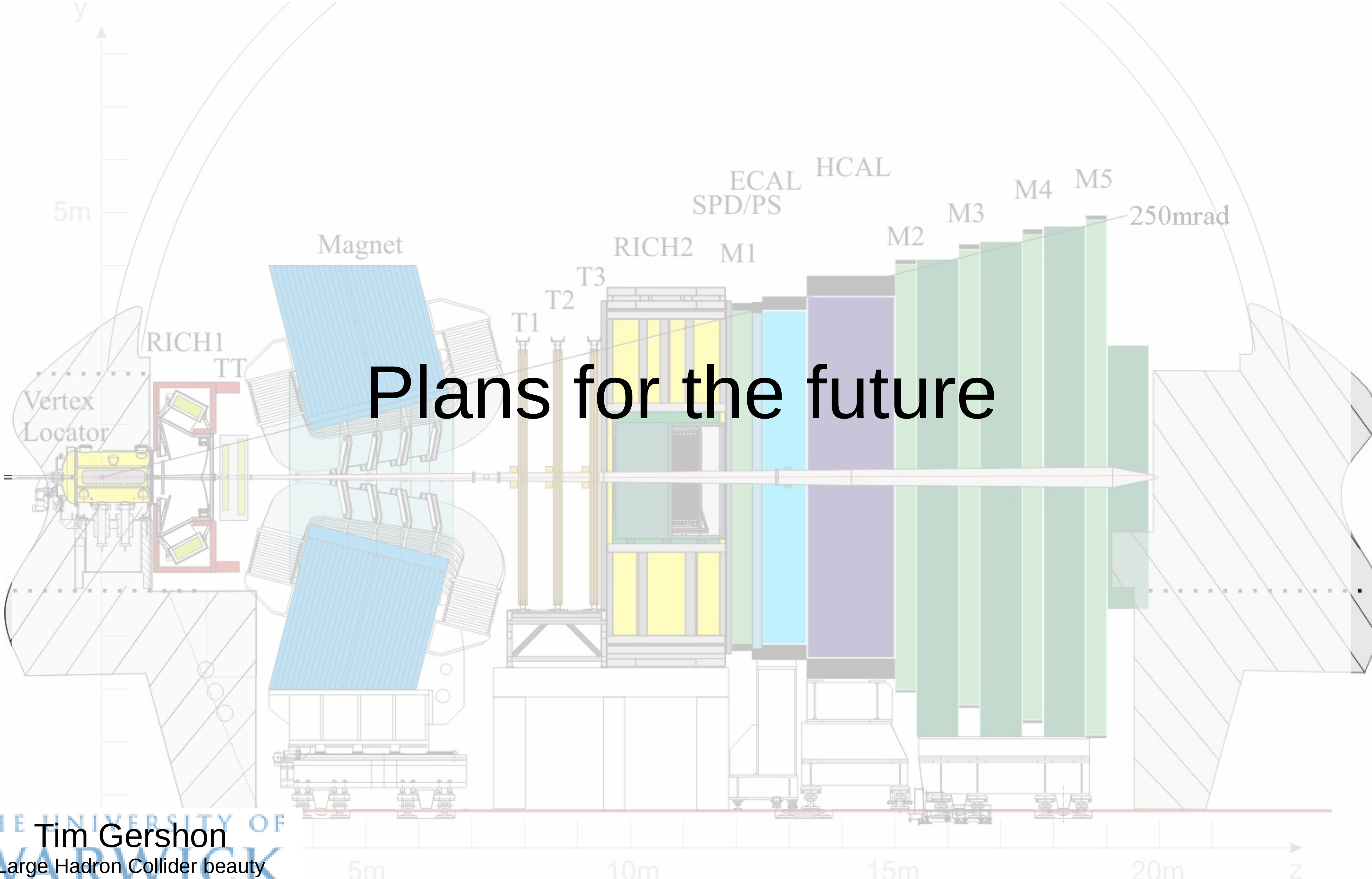








Plans for the future



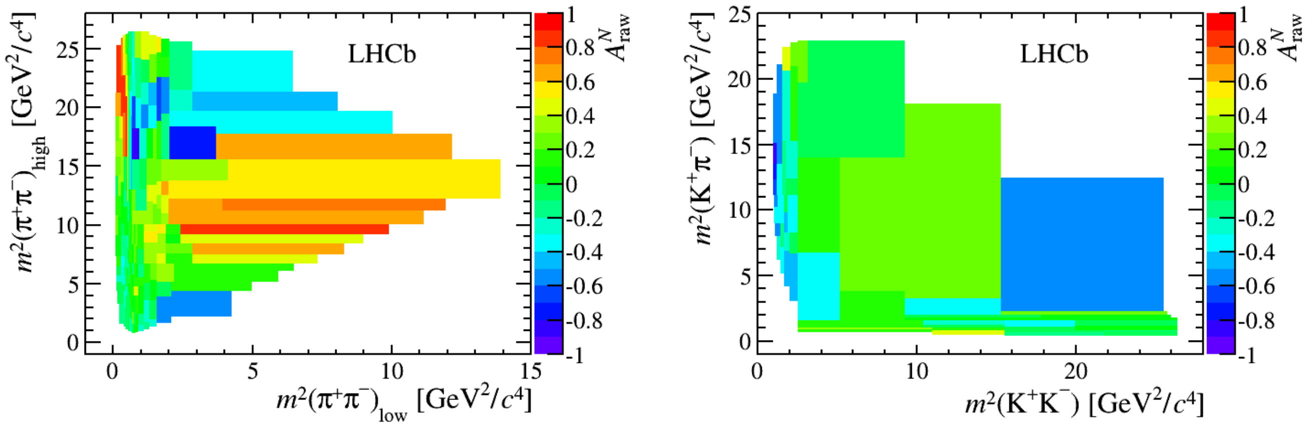
Tim Gershon
Large Hadron Collider beauty

Short- & mid-term plans

- Complete analysis of Run I data
  - Measurement of CP violation in $B^0 \to D\pi^- K^+$
  - Apply similar methods to other B decays

arXiv:1408.5373, submitted to PRD

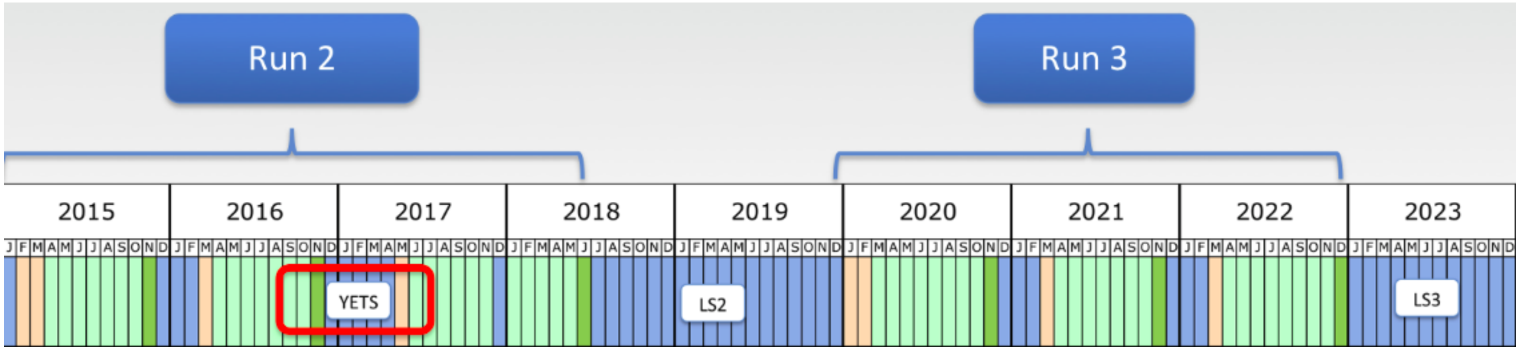
    - Can we understand CP violation effects in, e.g. $B^+ \to \pi^+\pi^+\pi^-$ decays?



- More than quadruple available statistics in Run II (2015-18)
  - Update key measurements with much improved precision
  - Extend programme to spectroscopy and CP violation in $B \to D^*_{(s)}hh$ decays

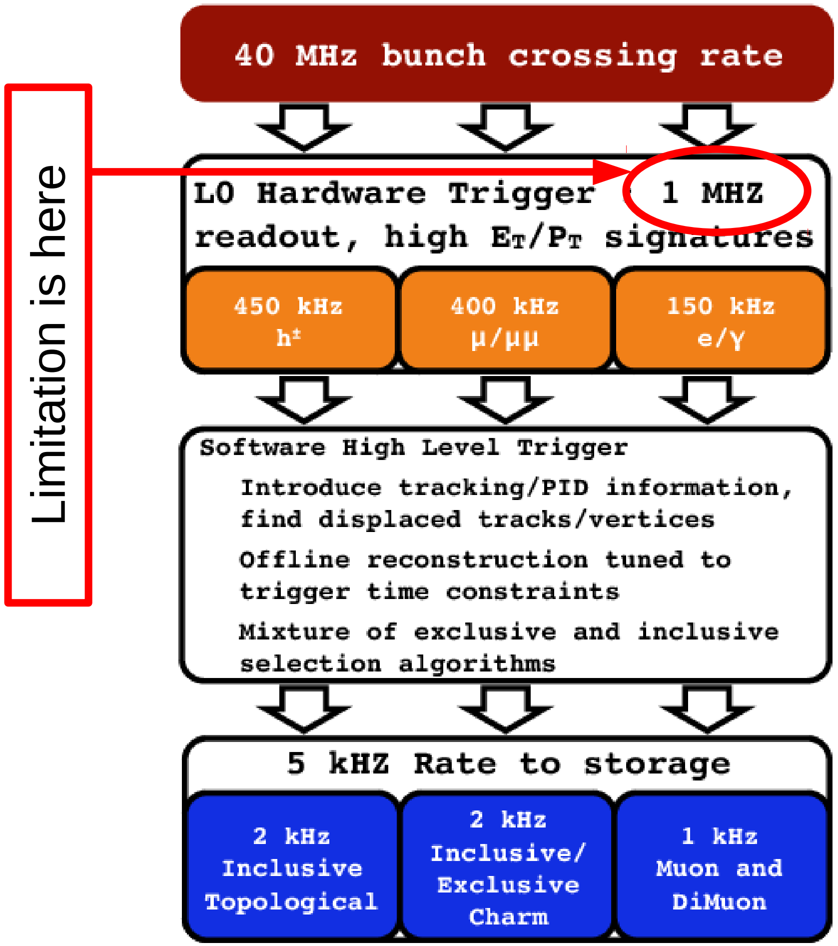
Longer-term plan

- Beyond LHC Run II, the data-doubling time for LHCb becomes too long
  - Due to 1 MHz readout limitation and associated hardware (L0) trigger
- However, there is an excellent physics case to push for improved precision and an ever-broader range of observables
- Will upgrade the LHCb detector in the LHC LS2 (2018-20)
  - Upgrade subdetector electronics to 40 MHz readout
  - Make all trigger decisions in software
  - Operation at much higher luminosity with improved efficiency
    - order of magnitude improvement in precision (compared to today)

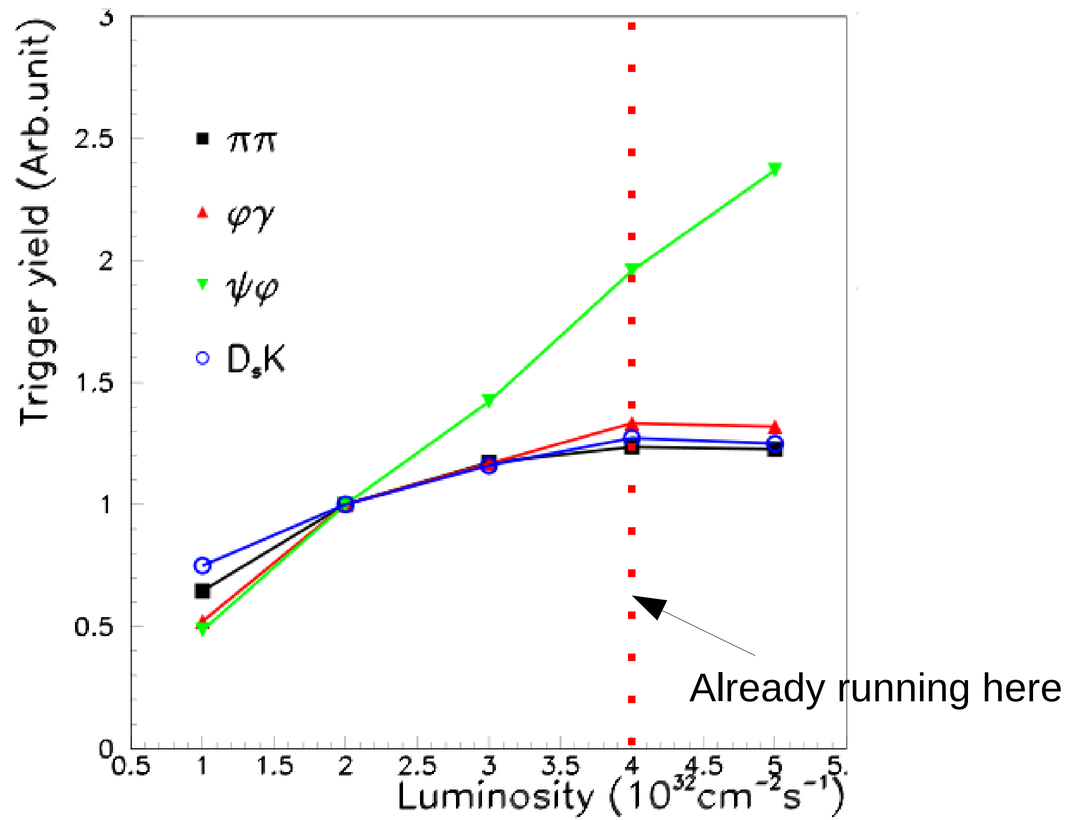


LHCb upgrade operation from 2020 for 10+ years

LHC upgrade and the all important trigger

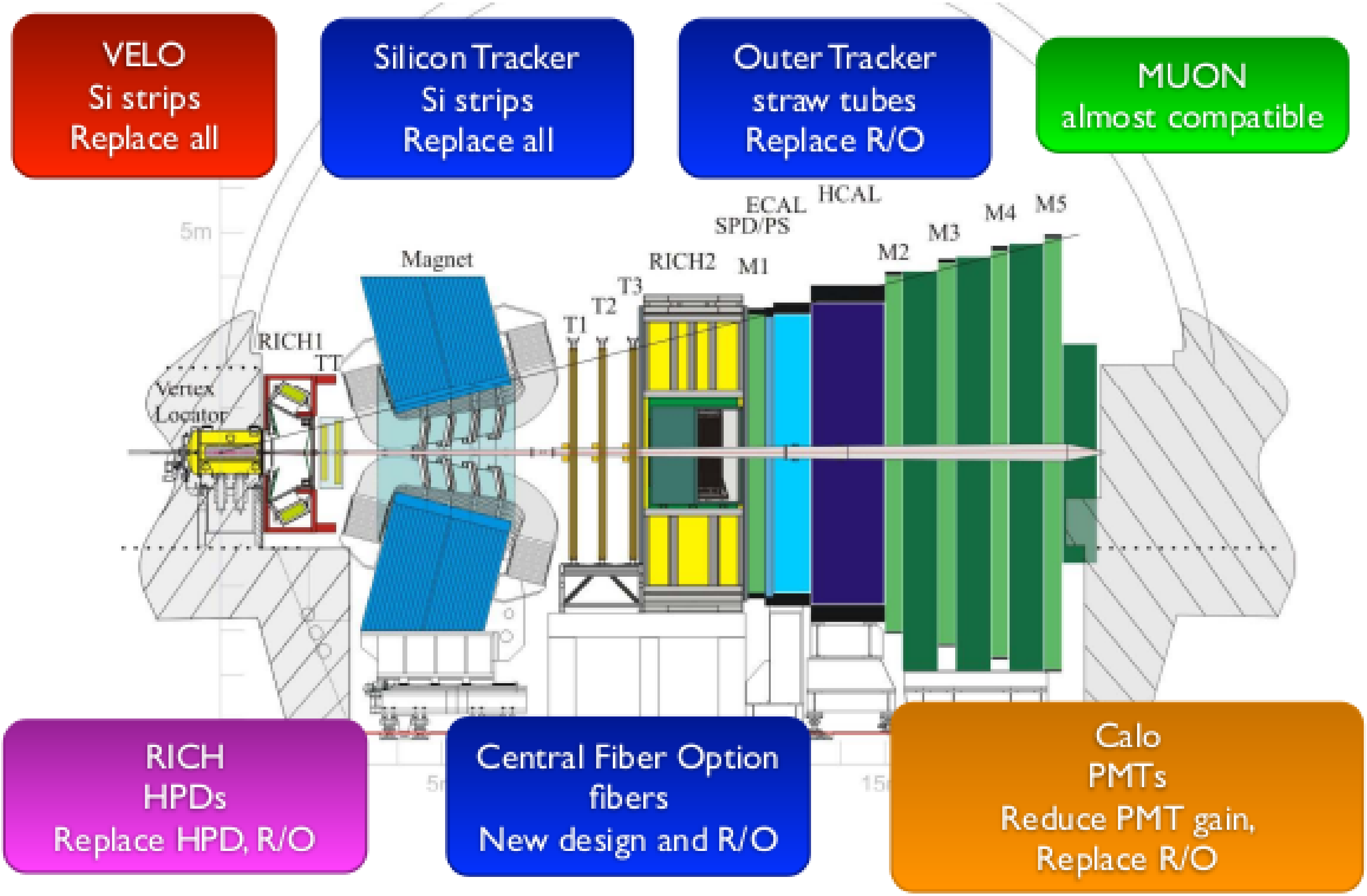


higher luminosity
→ need to cut harder at L0 to keep rate at 1 MHz
→ lower efficiency



- readout detector at 40 MHz
- implement trigger fully in software → efficiency gains
- run at L_{inst} up to 2 10^{33}/cm^2/s

LHCb detector upgrade



Summary

- Hugely successful operation of the Large Hadron Collider and the LHCb experiment
- Dramatic improvement in precision in key observables
  - pushing at the boundaries of the Standard Model, searching for cracks …
  - observing new hadrons, changing understanding of QCD
  - obtaining new insights into matter-antimatter asymmetry
- Exciting prospects for both near- and long-term future