Heavy flavour physics II

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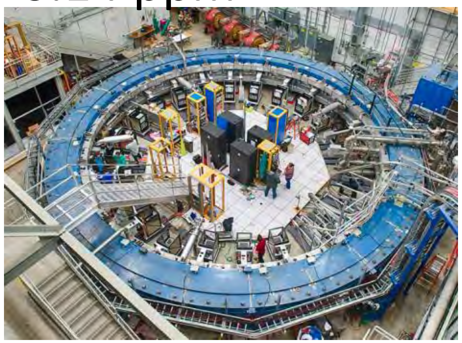
Outline of the lectures

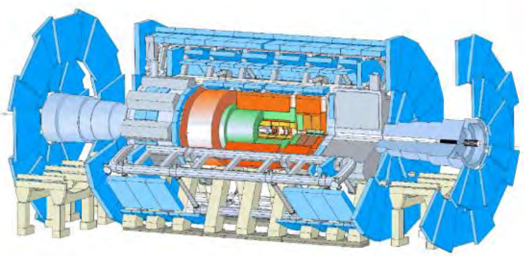
- Introduction to the CKM formalism and objectives
- Historical perspective
- LHCb: a flavour-physics detector at the LHC
- Selected *B*-physics results
- Future prospects

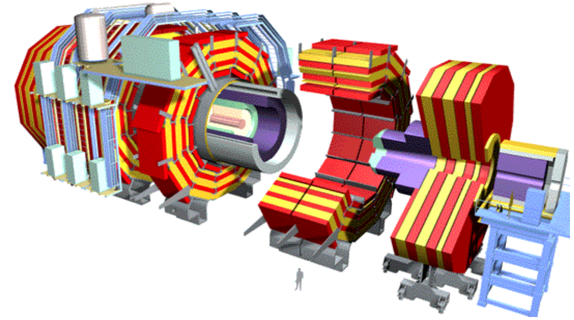
The main players today

$(g\text{-}2)_\mu$ at FNAL: measure muon magnetic moment with a precision of 0.14 ppm

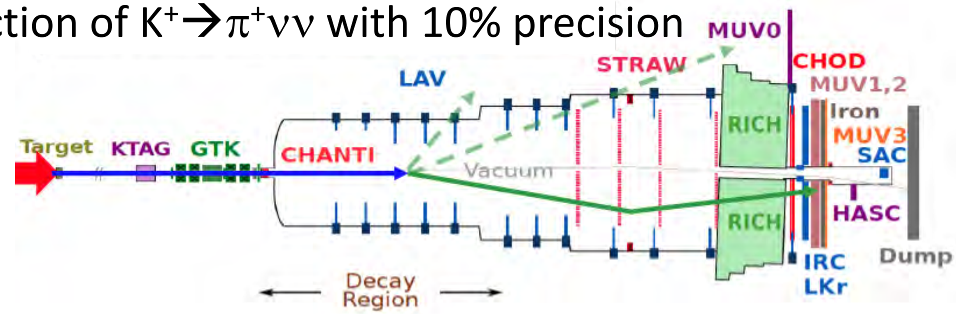


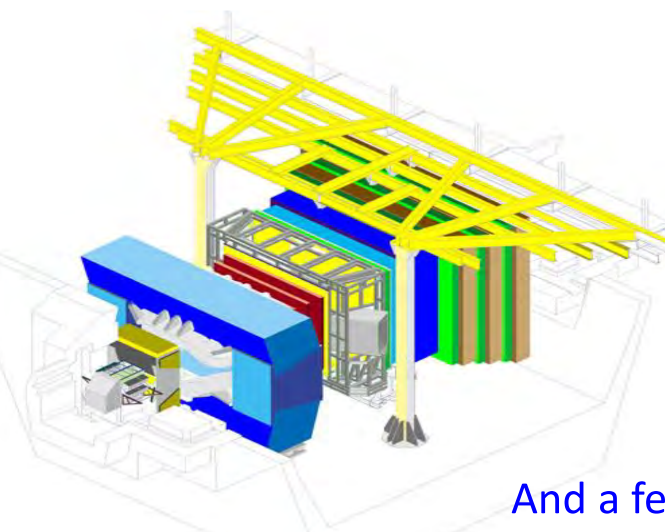
ATLAS and CMS at CERN: can measure a few flavour observables, mainly with muons in the final state



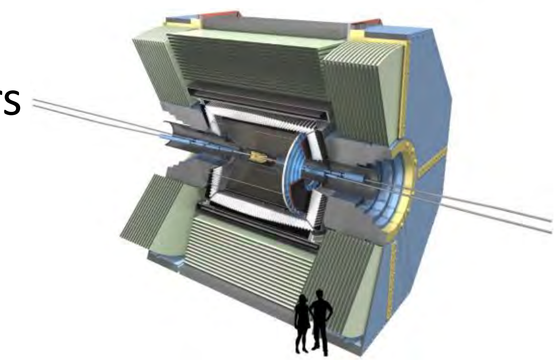


NA62 at CERN: measure the SM branching fraction of $K^+ \rightarrow \pi^+ \nu\nu$ with 10% precision





LHCb at CERN and Belle II at KEK: dedicated detectors for flavour physics with wide range of measurements



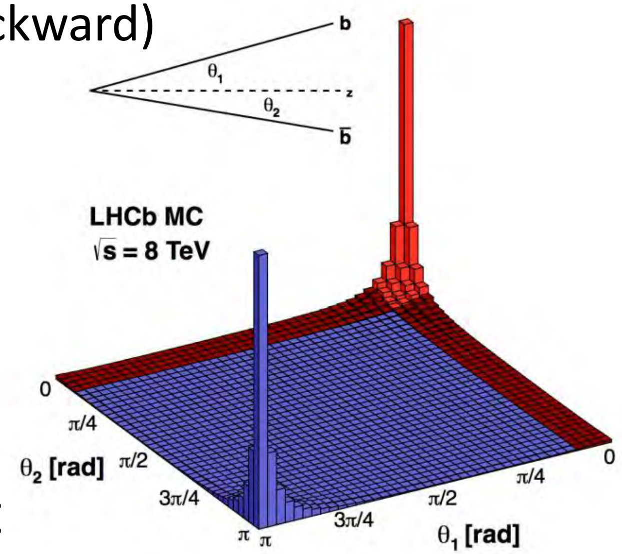
And a few others not to forget: BES-III, MEG-II, Mu2e, …

The birth of the LHCb experiment

- When the constructions of the BaBar and Belle detectors were being scrutinised for approval, three distinct proposals for a dedicated b-physics experiment at the LHC were put forward, so-called COBEX, GAJET, and LHB
  - GAJET and LHB were both based on fixed targets, the former working with a gas target placed inside the LHC beam pipe and the latter exploiting an extracted LHC beam
  - COBEX was instead proposed to work in proton-proton collider mode
- The three groups of proponents were asked to join together and submit to the LHC Experiments Committee (LHCC) a proposal for a single collider-mode experiment, namely LHCb
- LHCb was then designed to exploit the potential for heavy-flavour physics at the LHC by instrumenting the forward region of proton-proton collisions, in order to take advantage of the large $b\bar{b}$ cross section in the forward (or backward) LHC beam direction
- The LHCb experiment was approved in 1998, and started taking data with the start-up of LHC in 2009

LHCb detector layout

- LHCb is studying beauty and charm
  - At LHC, the production is peaked forward/backward
  - The detector is a single arm spectrometer
    - Both b hadrons go together forward (or backward)
    - LHCb acceptance $2 < \eta < 5$
  - The b meson / baryon is boosted
    - It flies several millimetres before decaying
    - This is the main experimental signature



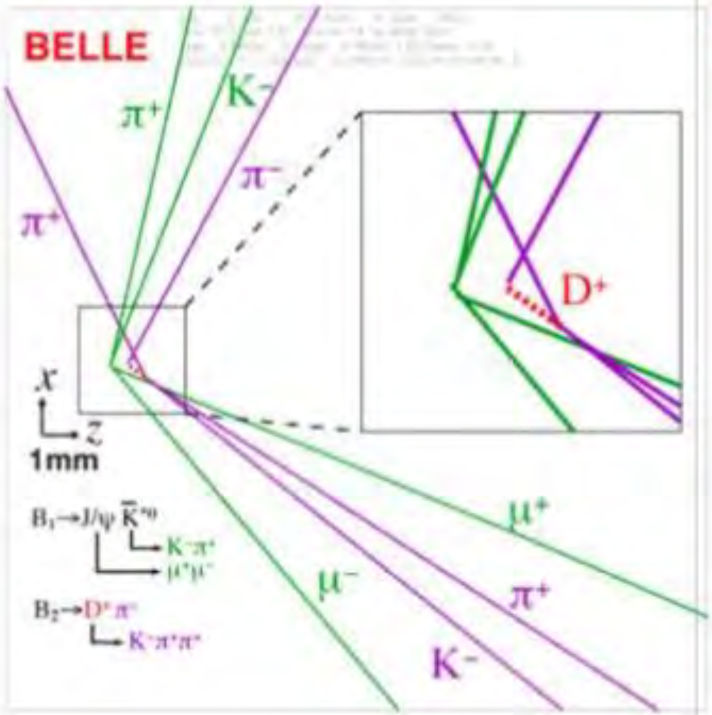
- General detector layout
  - The vertex detector is a key component
  - Dipole magnet, and tracking stations after, to measure accurately the momentum
  - Particle identification by 2 RICH detectors, electromagnetic and hadronic calorimeters, and a muon system

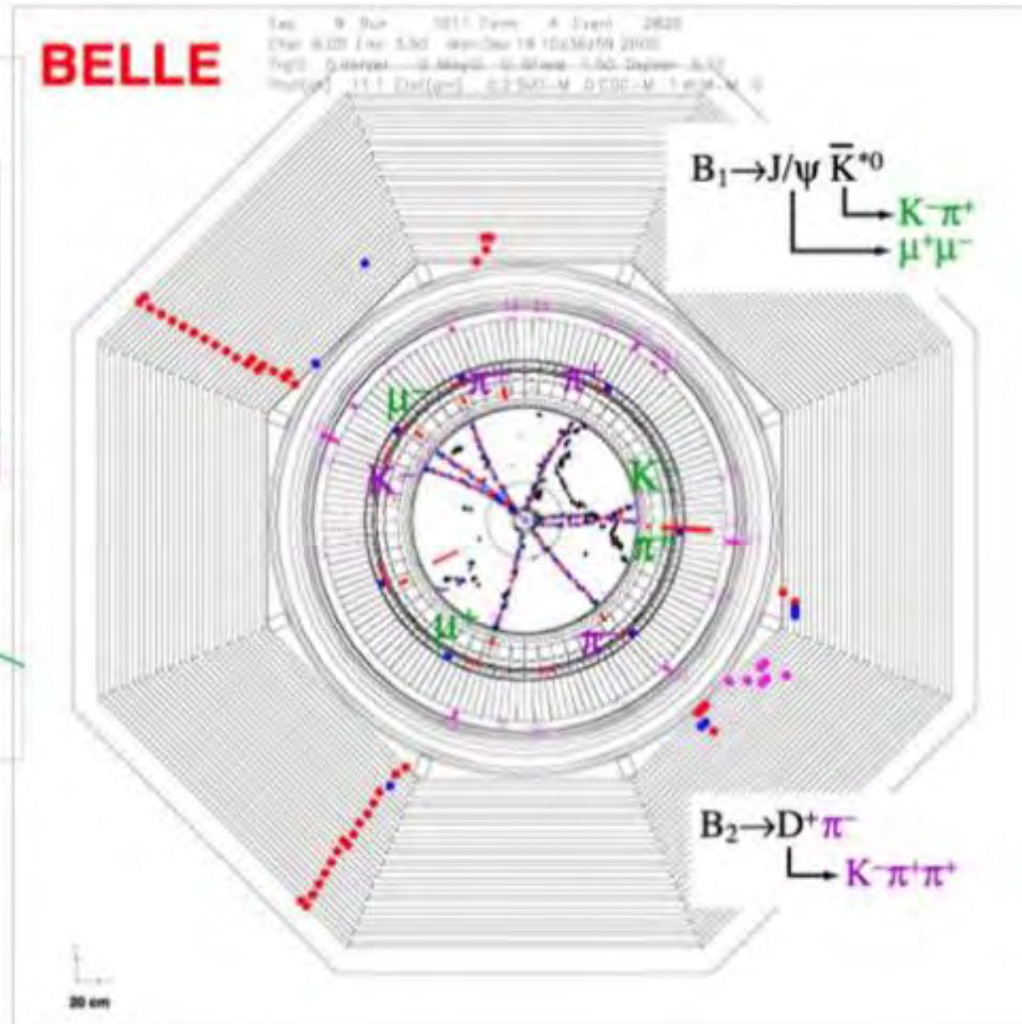
e^+e^- *B*-factory vs *pp* LHCb

Experiment	Luminosity [$cm^{-2}\ s^{-1}$]	$b\bar{b}$ cross-section [μb]	$b\bar{b}$ pairs produced per year	Pros	Cons
BaBar/Belle	2×10^{34}	0.001	2×10^{8}	Cleaner environment, simpler trigger	Smaller production rate, mostly B^0/B^+ physics
LHCb	4×10^{32}	500	2×10^{12}	Larger production rate, all b-hadron species	Harsher environment, difficult trigger
Belle-2	8×10^{35}	0.001	8×10^{9}	Less clean but still clean environment, less simple but still simple trigger	Less small but still small production rate, mostly B^0/B^+ physics
LHCb Upgrade-I	2×10^{33}	500	1×10^{13}	Even larger production rate, all b-hadron species	Even harsher environment, even more difficult trigger

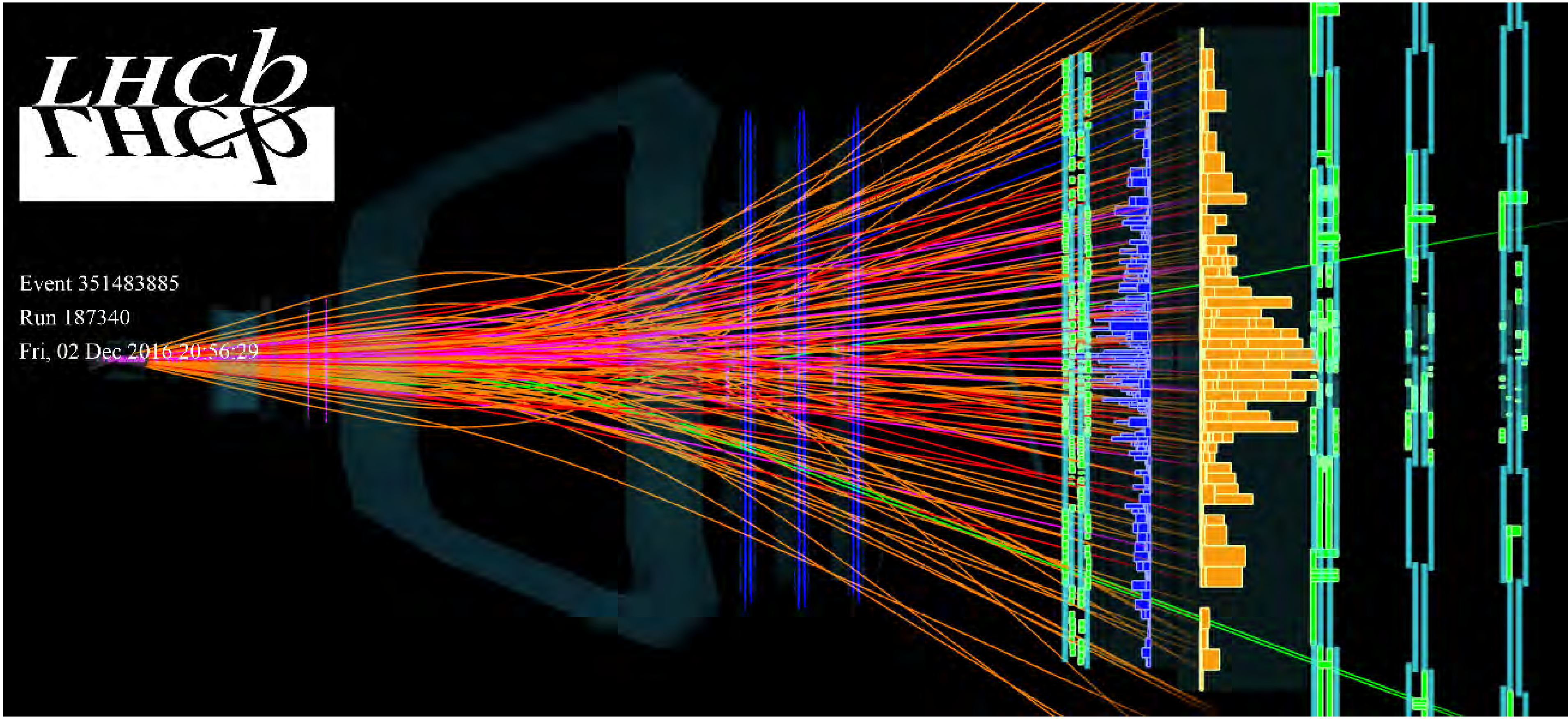
- Admittedly, very rough comparison, but gives the idea of a good example of complementary facilities!

Typical Belle event

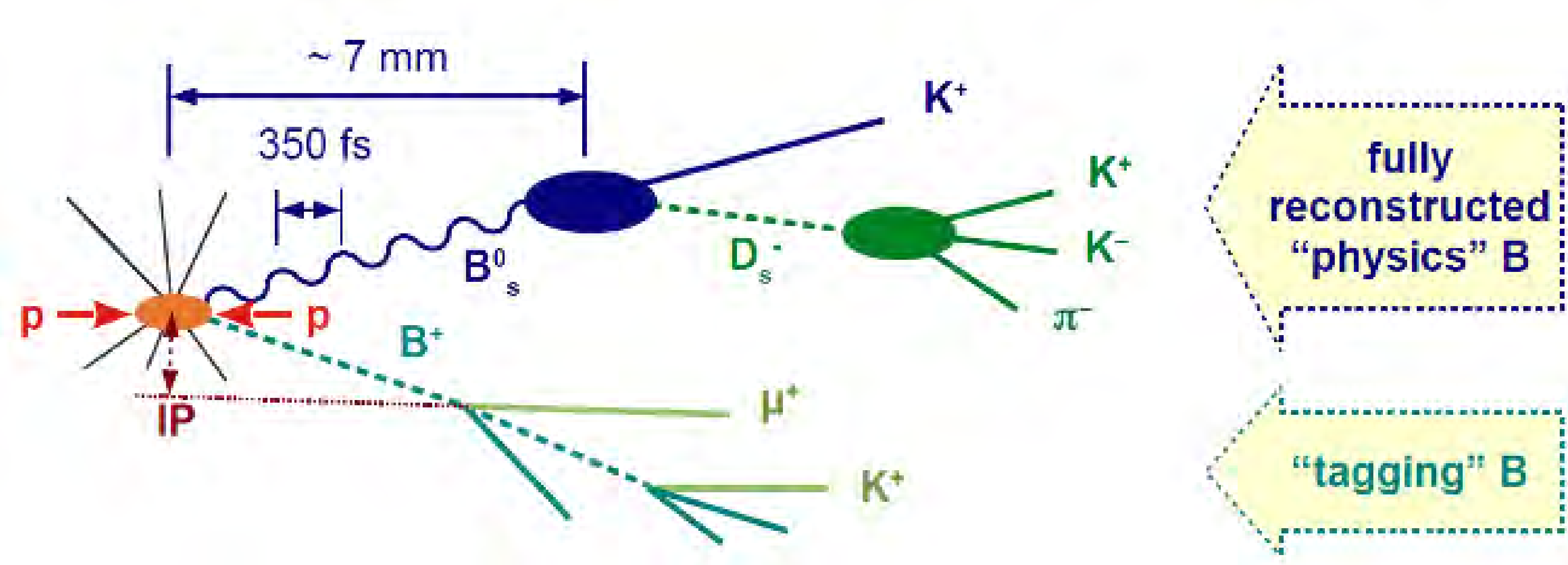




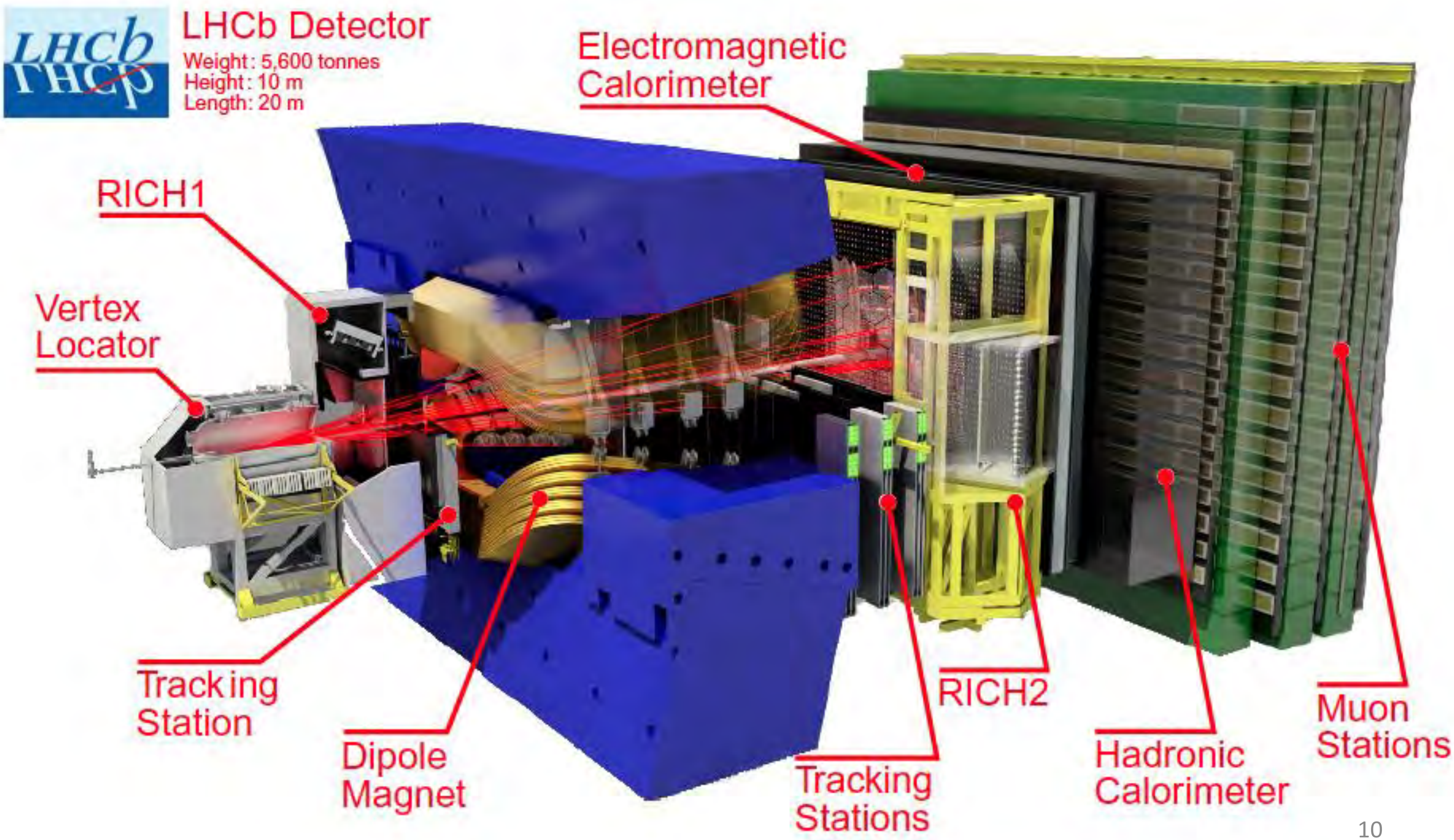
Typical LHCb event



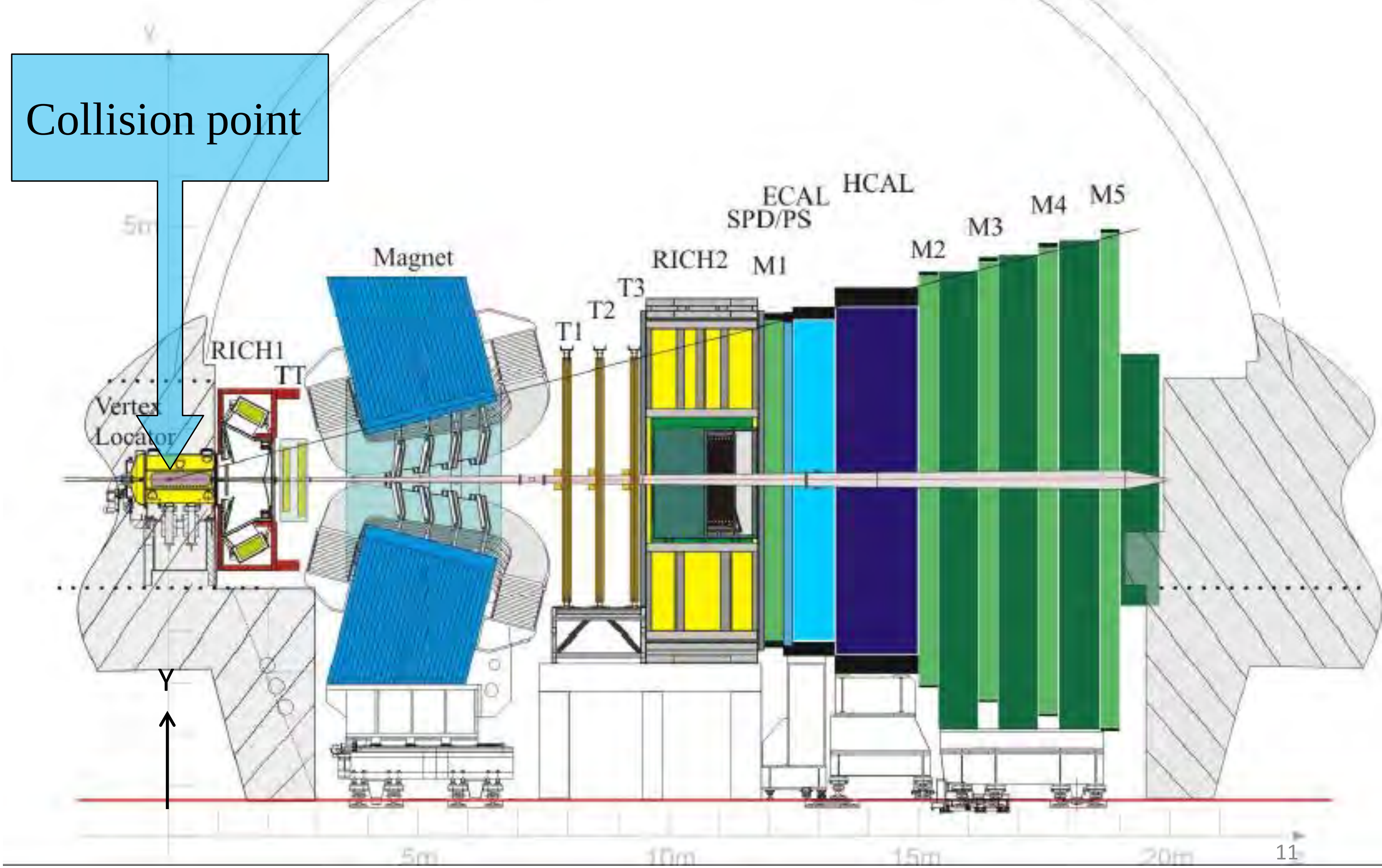
But we are only interested in a few tracks: typical signal at LHCb



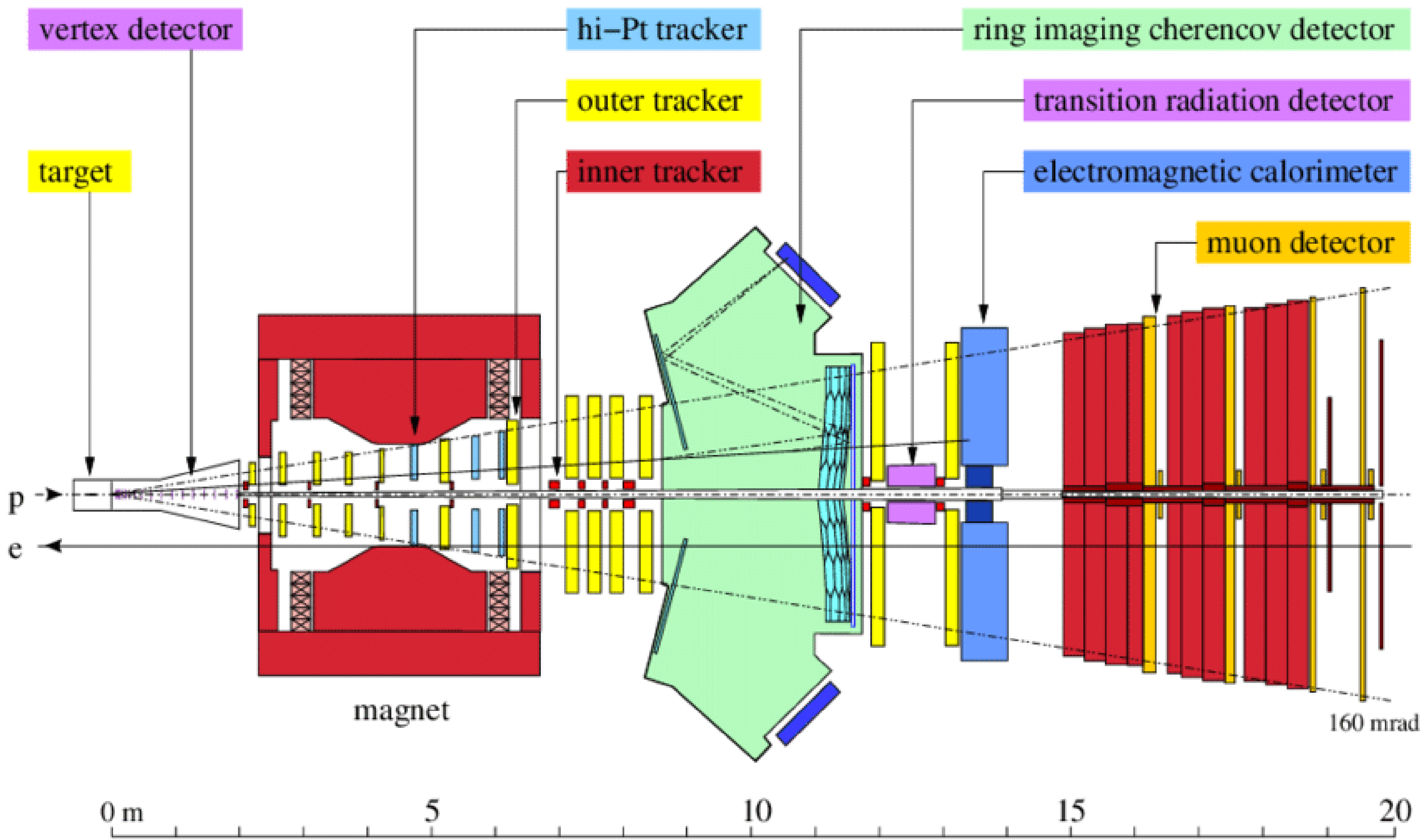
LHCb 3D sketch

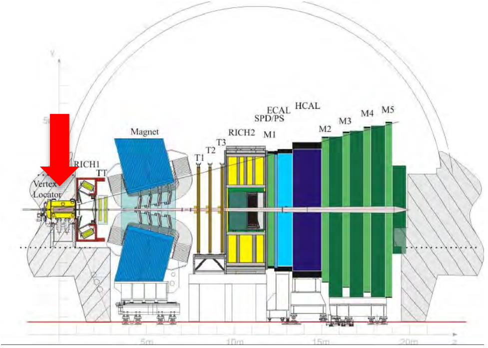


Maybe easier to visualise it in 2D

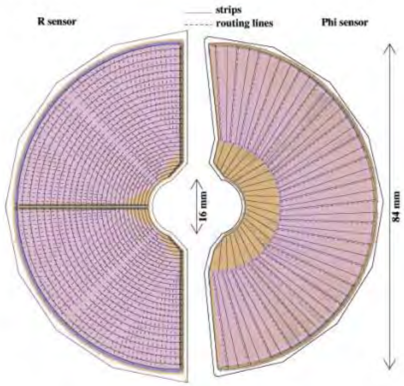


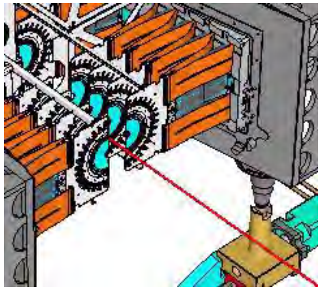
A very similar concept: HERA-B

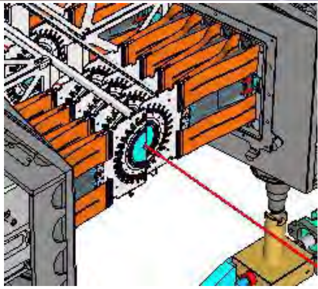




Vertex detector (VELO)



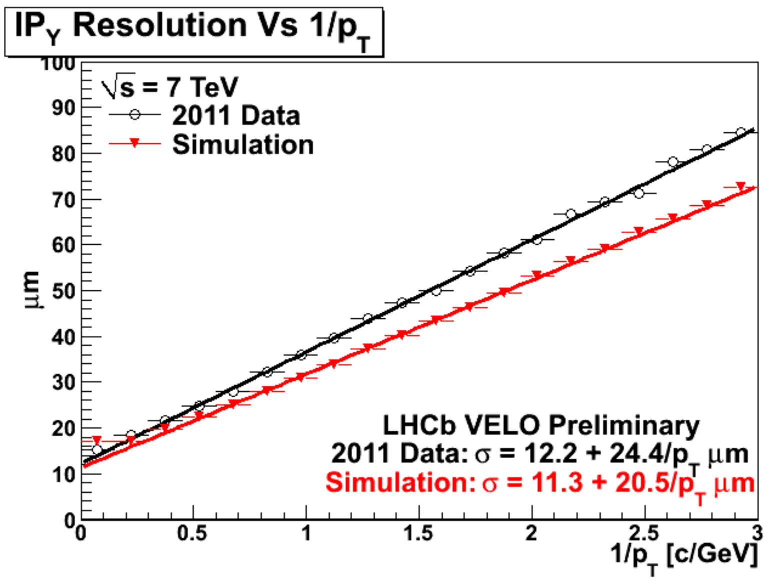


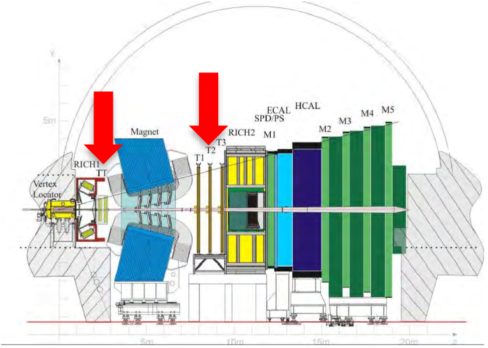


- 84 silicon micro strip sensors
  - 44 mm radius
  - R or ϕ geometry
- Open and closes for each fill to avoid damages from unstable beams
  - Centred around the current beam position
    - It does not move during a fill
  - Mechanically reproducible to ~5 µm
- The silicon sensors come as close as 8 mm to the LHC beam

VELO performance

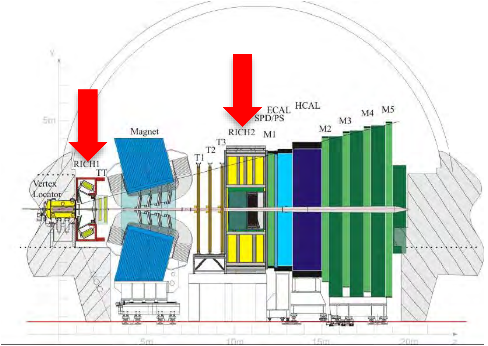
- The VELO allows for very precise measurement of the track trajectories close to the interaction point, which is crucial to separate decays of beauty and charm hadrons from the background
- Impact parameter (distance of a track to a pp collision vertex) resolution is essential
  - Very good resolution
    - ~20 μm at p_T >2 GeV
  - Primary vertex resolution excellent
    - ~16 μm in x,y, ~76 μm in z (20 tracks)



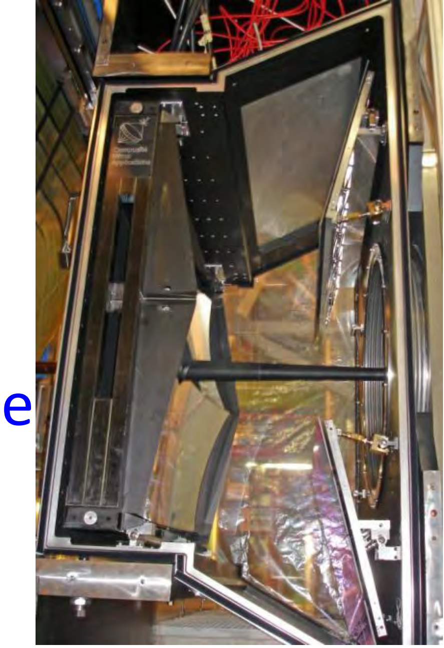


Tracking system

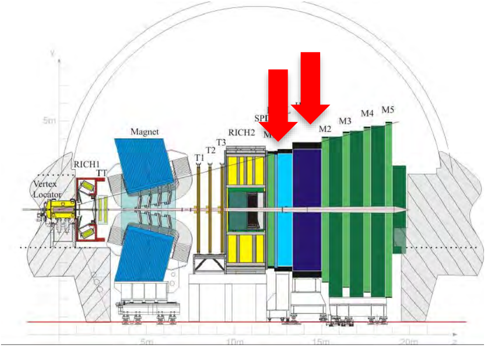
- One station (TT) before the dipole magnet
  - Si strips, 4 layers
- Three stations after the magnet
  - Si strips in centre (IT), straw tubes outside (OT)
  - 4 layers per station x-u-v-x, (5 degree stereo angle)
- Tracking efficiency over 96%
  - For tracks traversing the whole detector, over 5 GeV/*c* momentum
- The tracking system provides a measurement of momentum of charged particles with a relative uncertainty that varies from 0.5% at low momentum to 1% at 200 GeV/c



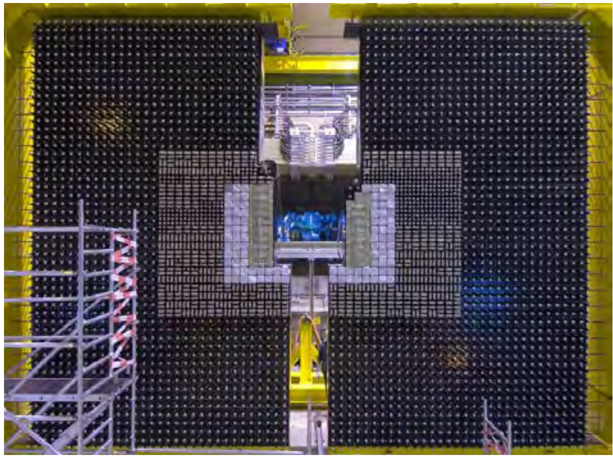
Cherenkov detectors



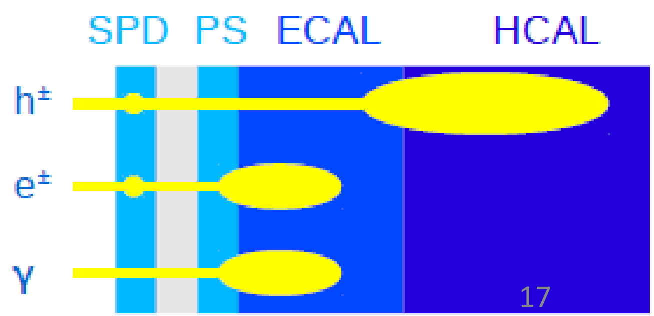
- A distinctive feature of LHCb, when compared to the ATLAS and CMS detectors, lies in its particle identification capabilities for charged hadrons
- Achieved by means of two ring-imaging Cherenkov detectors placed on either side of the tracking stations
  - Once particle momenta are measured, the two RICH detectors enable the identification of protons, kaons and pions to be obtained
- Excellent hadron identification between 2 and ~100 GeV/c
  - 2 RICH detectors with different radiators optimized for complementary momentum regions
  - Readout by Hybrid Photo Detectors
    - High efficiency and low noise
- Typical particle ID performance: ~95% efficiency for 5% contamination

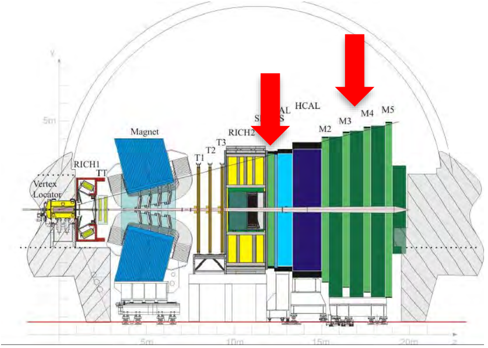


Calorimeters

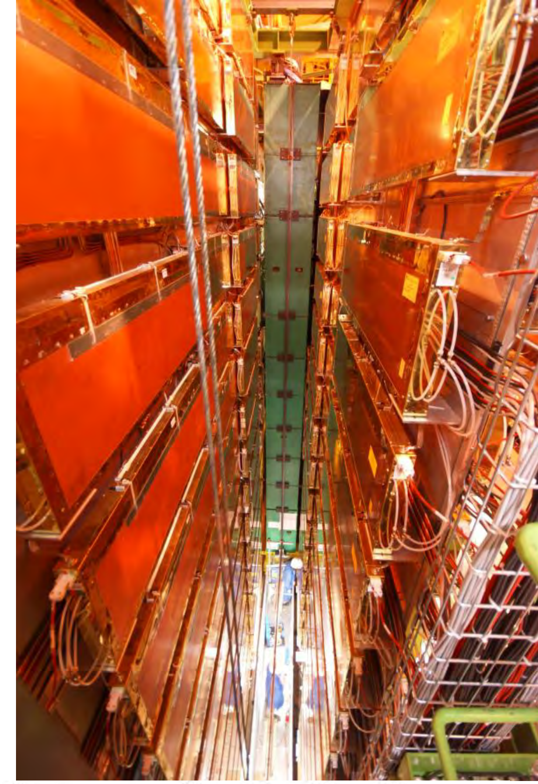


- An electromagnetic calorimeter (ECAL), complemented with scintillating-pad (SPD) and preshower (PS) detectors, provides energy and position of photons and electrons, and allow for their identification in conjunction with information from the tracking system
  - Shashlik blocks: lead-scintillator stack with ~6000 channels readout by PMT
  - Energy resolution ~10% / √E + 1%
- The ECAL is followed by a hadronic calorimeter (HCAL) that also gives some information to identify hadrons
  - Scintillating tiles in iron with ~1500 channels and same ECAL readout
  - Energy resolution ~70% / √E + 9%
- PreShower and SPD
  - Scintillator tiles readout by MAPMT
  - Identify electron/photon, used in L0 trigger

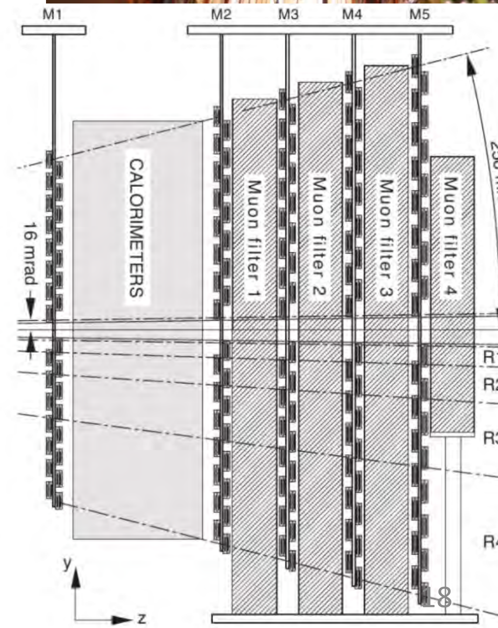




Muon system



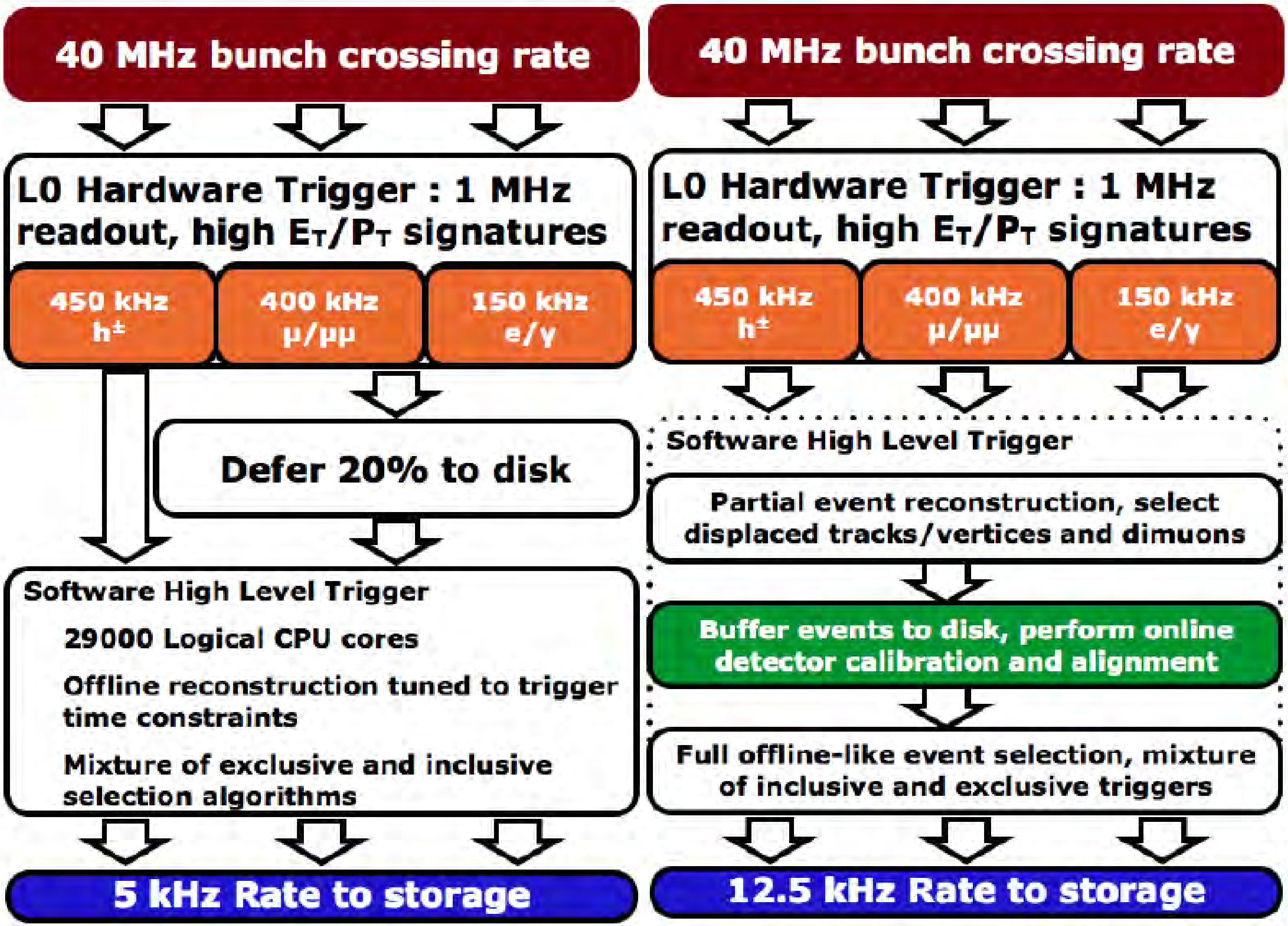
- Finally, muons are identified by a system composed of alternating layers of iron absorbers and multiwire proportional chambers
- 5 stations: the first placed before the calorimeters and 4 after
- Typical muon identification performance
    - ~97% efficiency for 3% mis-ID



LHCb trigger

- The online event selection is performed by a trigger which consists of a hardware stage, solely based on information from the calorimeter and muon systems, followed by a software stage, which applies full event reconstruction
- L0 hardware trigger, custom electronics
  - High p_T local cluster in HCAL or ECAL
  - High p_T muon (1.4 GeV) or di-muon
  - Accept rate limited to 1 MHz, latency < 4 μs
- HLT software trigger, running on thousands of computing nodes
  - HLT1 mainly a topological trigger
    - At least one track with p_T >1.6 GeV and impact parameter >100 μm
    - Accept event rate around 50 kHz
  - HLT2 selects by physics channel, inclusive or exclusive
    - Full track reconstruction but no particle-identification
  - Total accept rate around 5 kHz (Run 1) and 12.5 kHz (Run 2)

LHCb trigger schematics

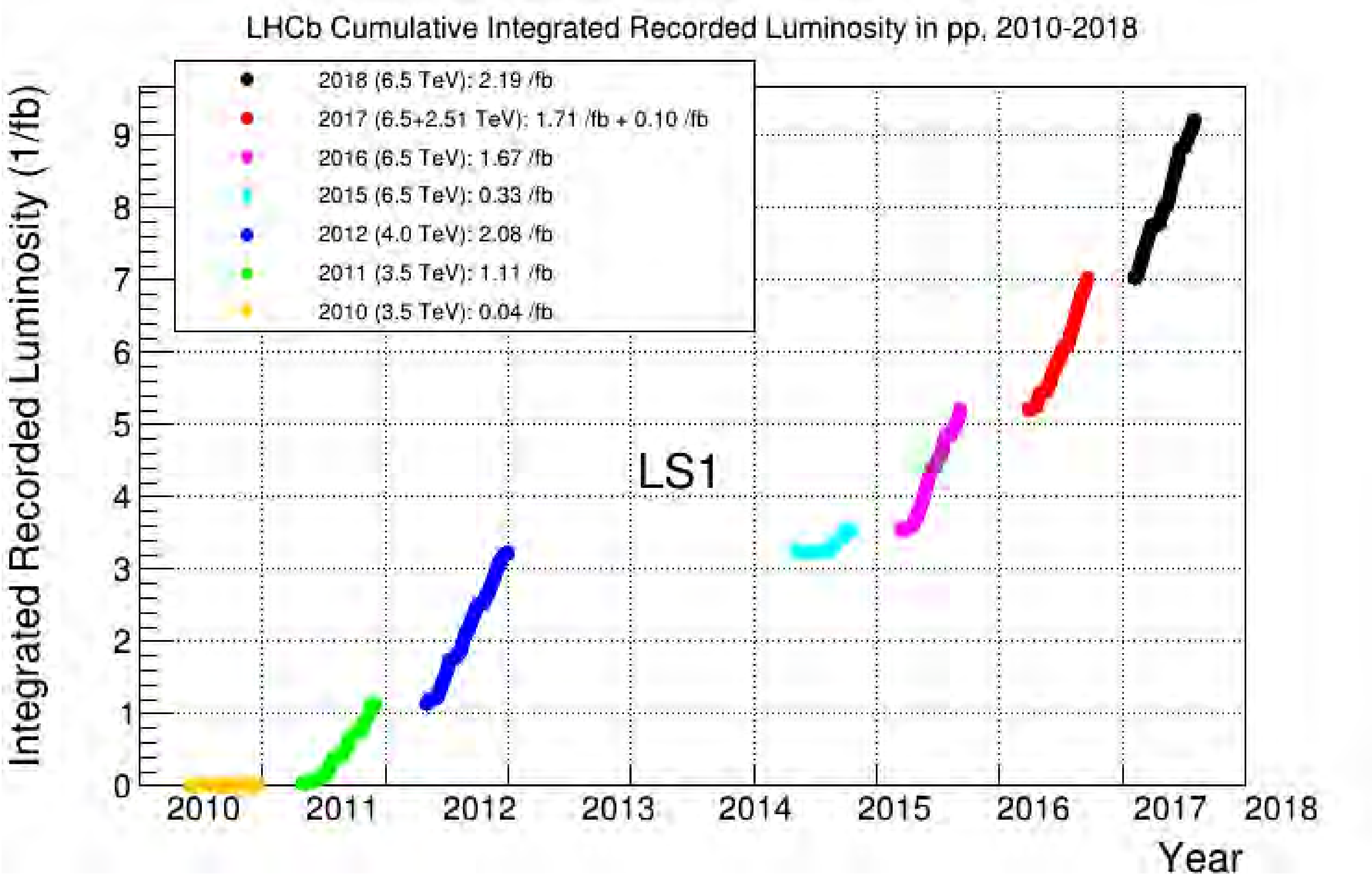


Run 1 Run 2

LHC luminosity at the LHCb interaction point

- LHCb runs at reduced instantaneous luminosity with respect to the LHC design to limit event pileup
  - In Run 1 and Run 2 at $4x10^{32}$ cm^{-2} s^{-1}
- The luminosity was kept constant thanks to the technique of "luminosity levelling", achieved by a dynamical adjustment of the transverse offset between the LHC beams during the fill
  - The beam separation adjusted a few times per hour to maintain the luminosity constant

LHCb data harvest



- Note that beauty production cross section is almost doubled passing from 7 to 13 TeV *pp* collisions

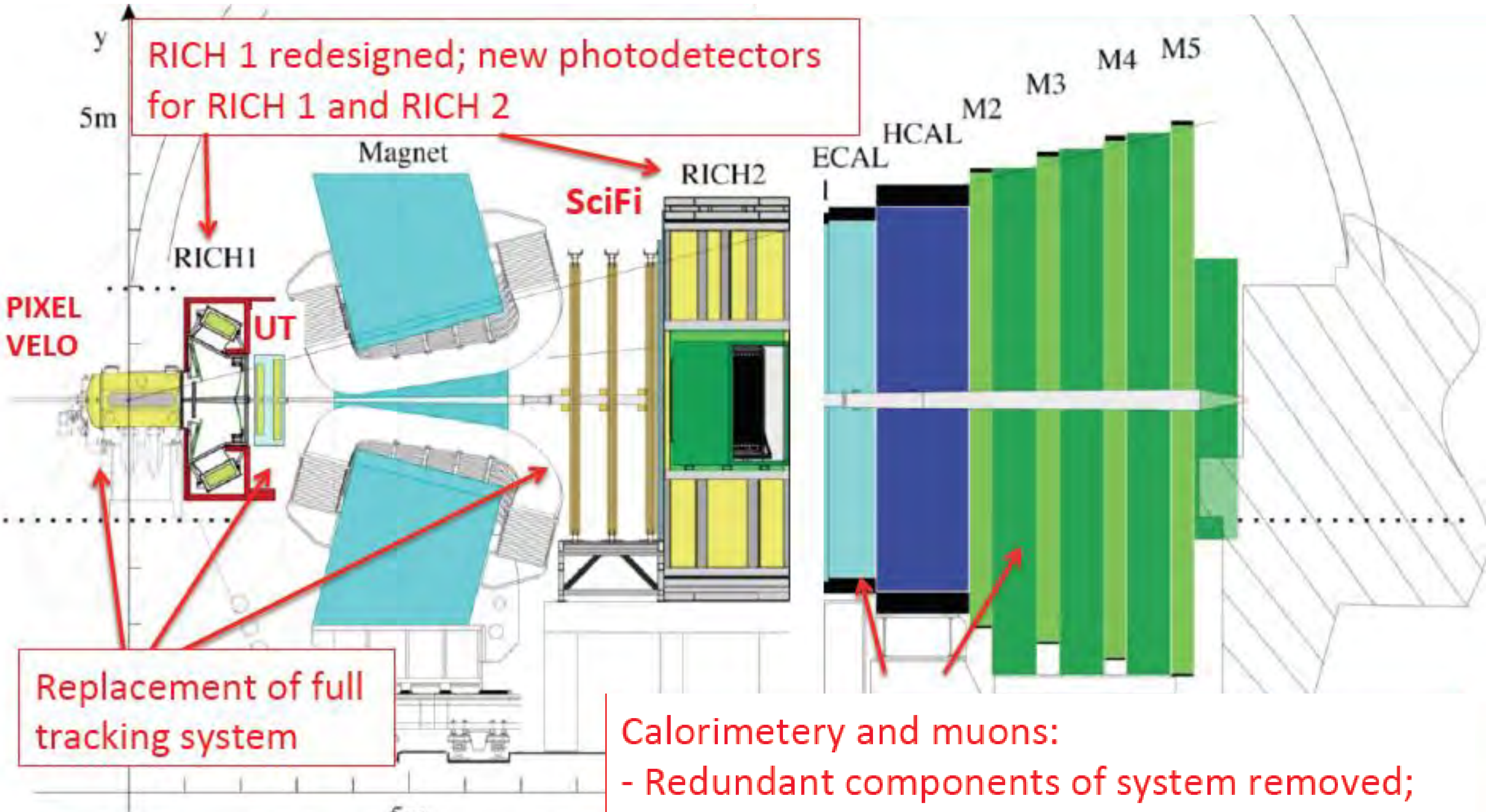
LHCb now upgrading

- Main limitation that prevents exploiting higher luminosity available from the LHC with the present detector is the Level-0 (hardware) trigger
  - Level-0 output rate < 1 MHz (readout rate) requires raising trigger thresholds
- This is particularly problematic for hadronic final states

- LHCb upgrade-I will be running at $2\text{x}10^{33}$ $cm^{-2}s^{-1}$ with full software trigger, recording an event rate of 20 kHz

Sub-detectors to be upgraded

All subdetectors are read out at 40 MHz

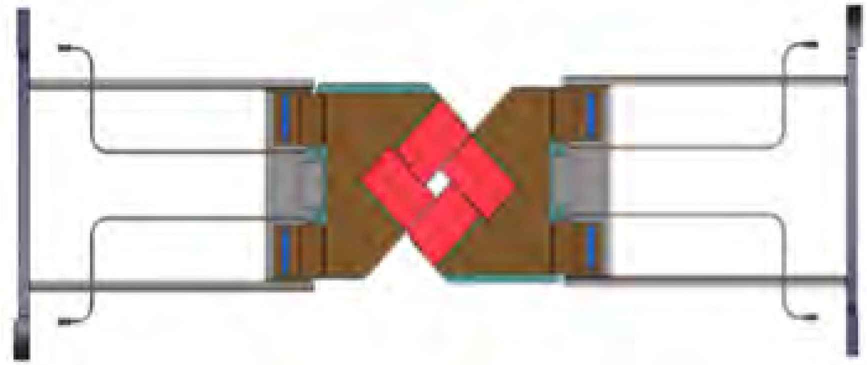


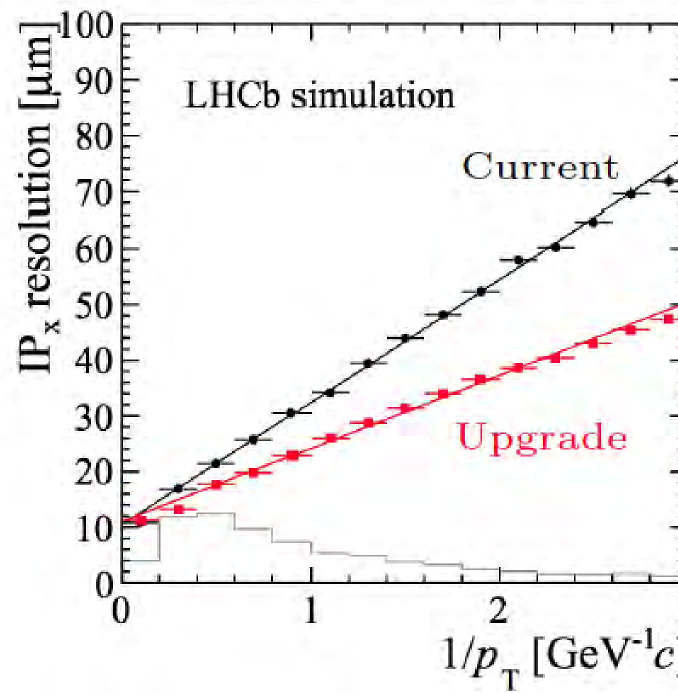
Calorimetery and muons:
- Redundant components of system removed; new electronics added; more shielding included

VELO upgrade

- Pixel based vertex detector
  - 50x50 μm^2 pixels

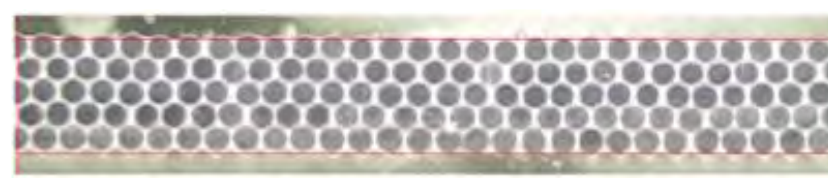
The layout is critical: 5 mm distance to the beam when closed!





Large area tracker upgrade

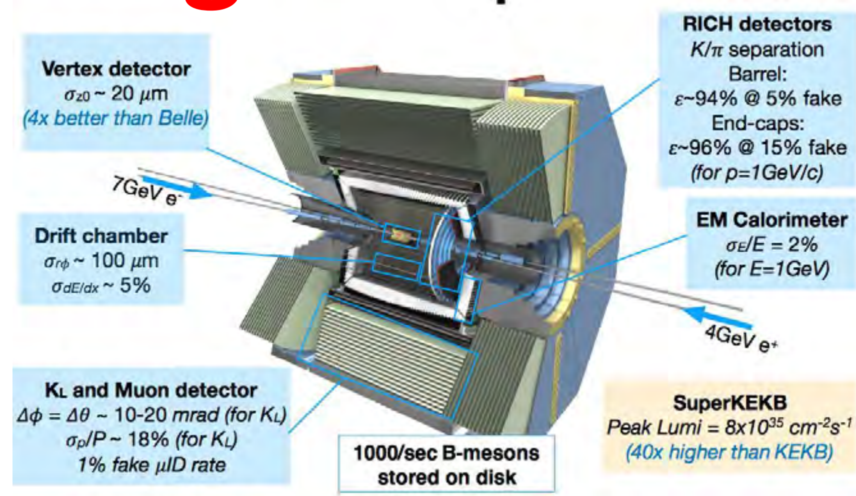
- Large scale tracking system based on mats of 2.5 m long scintillating fibres of 250 μm diameter, readout by SiPMs
- About 10000 km of scintillating fibres

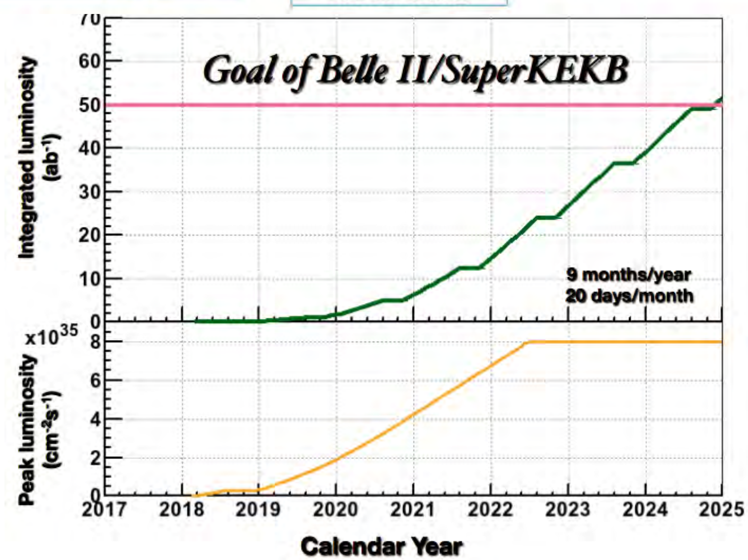


Cross-section of a fibre mat

Belle-2 taking off

- Exciting prospects from the SuperKEKB machine and new Belle-II detector
- An integrated luminosity of 5 ab^{-1} will be collected by 2021, and 50 ab^{-1} by 2025
- By around 2021, enough luminosity will be available to perform competitive measurements
- There are important areas, especially with neutrals and missing energy modes, where Belle-II will provide crucial complementary measurements to LHC experiments in the flavour sector

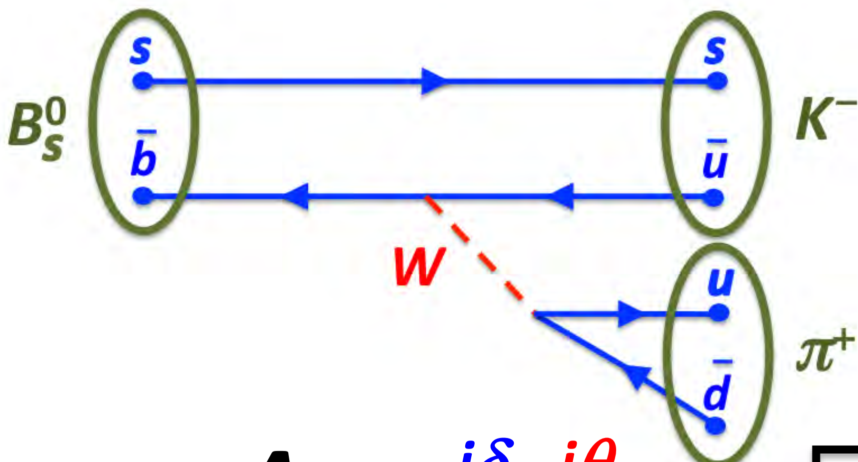


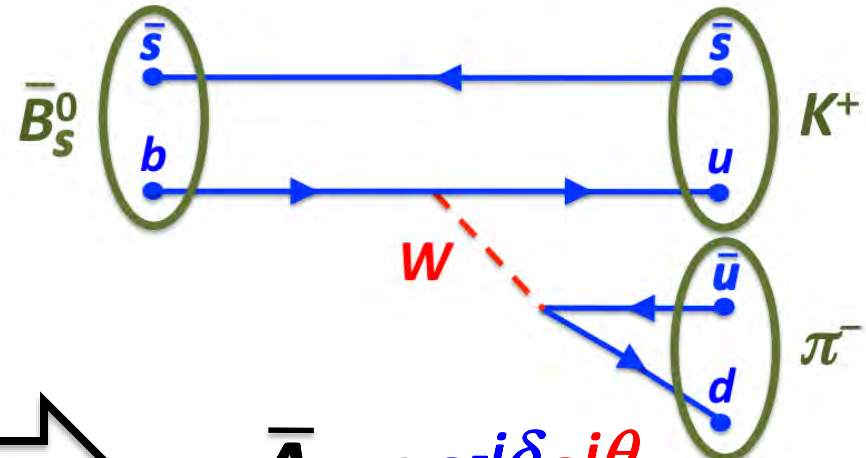


Selected *B*-physics results

CKM metrology

CP violation primer

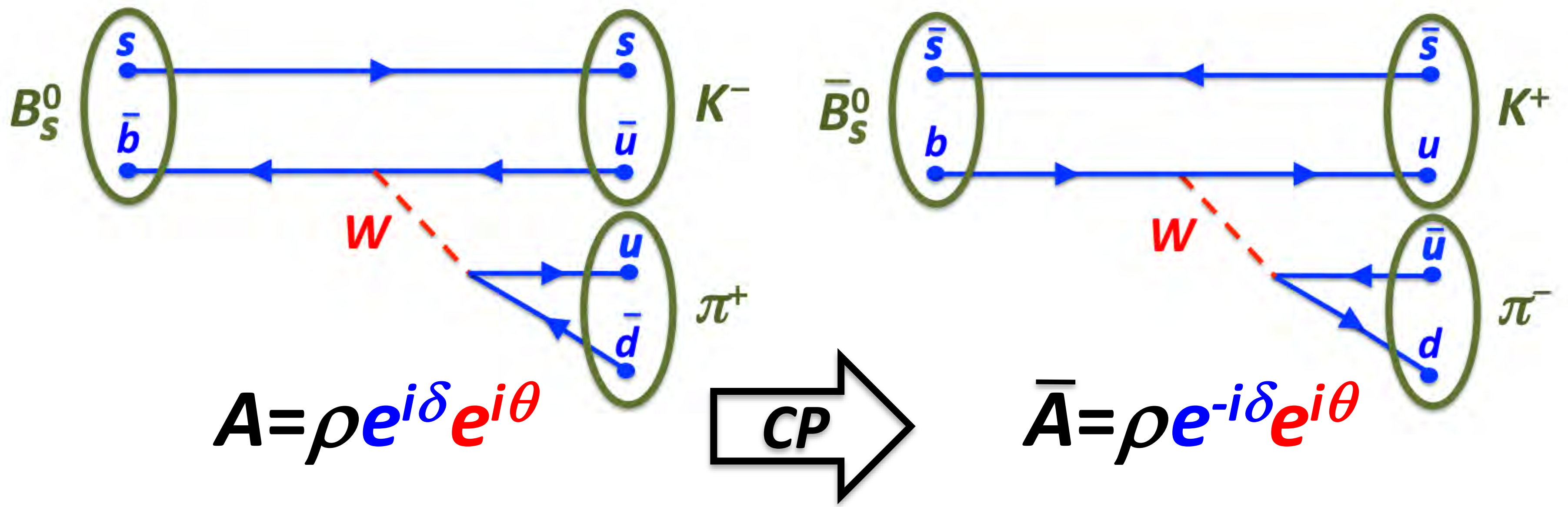




$$A=\rho e^{i\delta}e^{i\theta} \xrightarrow{CP} \bar{A}=\rho e^{-i\delta}e^{i\theta}$$

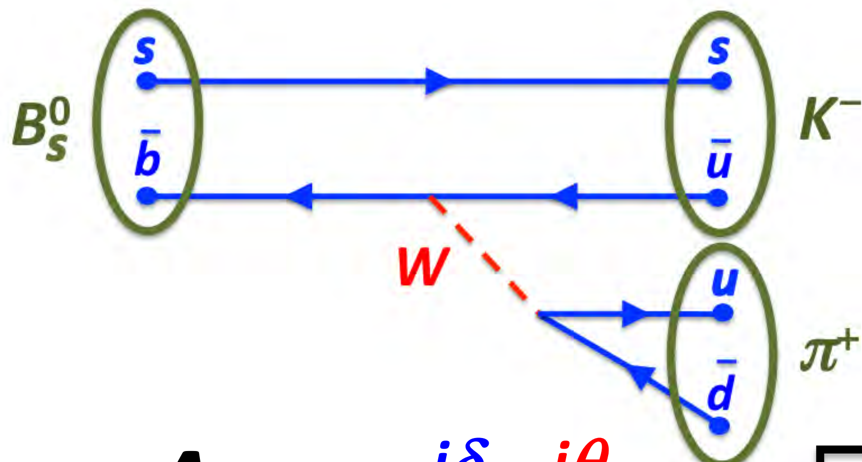
- A *CP* transformation has the effect of changing the sign of the phase due to weak interactions, leaving that due to strong interactions unchanged

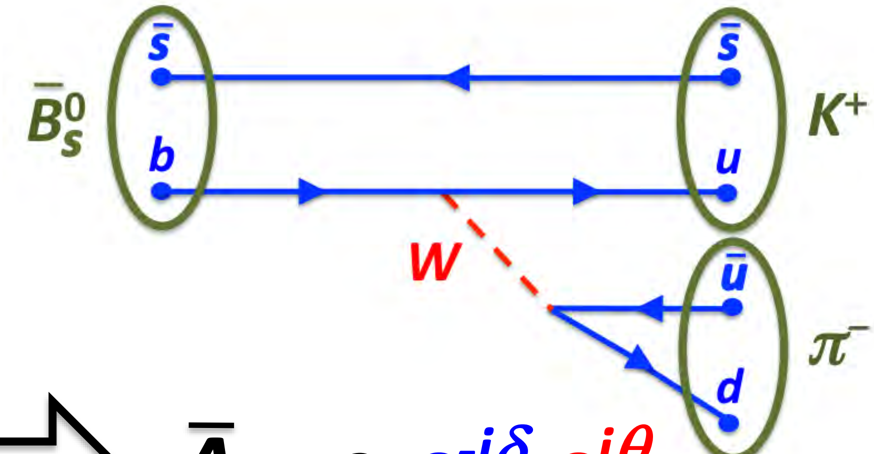
CP violation primer



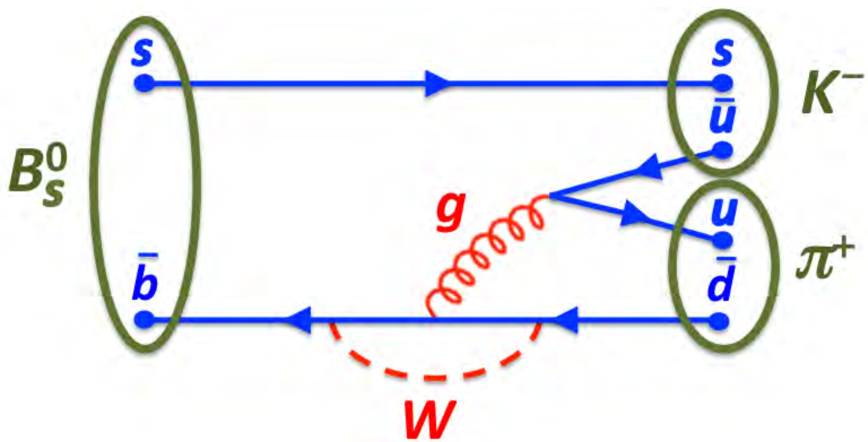
- But since $|\bar{A}|^2 - |A|^2 = 0$, this unfortunately means that the number of decays to $K^+\pi^-$ in this example is identical to that of those to $K^-\pi^+$
  →no asymmetry is observable...

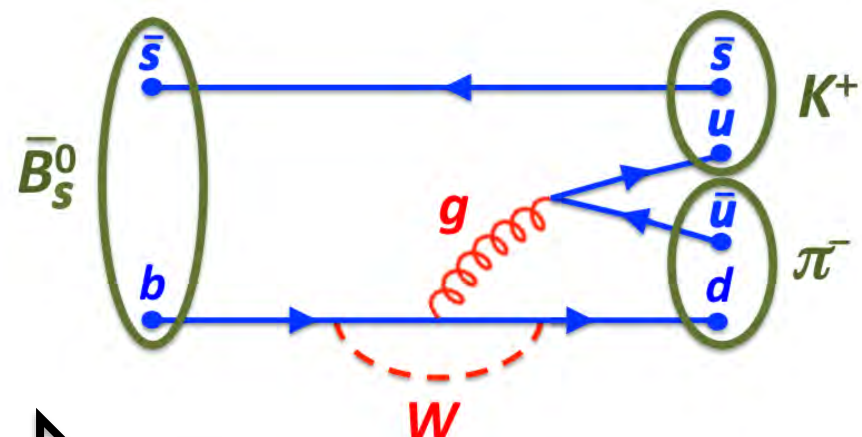
CP violation primer





$A_1 = \rho_1 e^{i\delta_1} e^{i\theta_1}$ CP $\Rightarrow$ $\bar{A}_1 = \rho_1 e^{-i\delta_1} e^{i\theta_1}$





$A_2 = \rho_2 e^{i\delta_2} e^{i\theta_2}$ CP $\Rightarrow$ $\bar{A}_2 = \rho_2 e^{-i\delta_2} e^{i\theta_2}$

CP violation primer

- Now the situation looks different

$$|\bar{A}_1+\bar{A}_2|^2 - |A_1+A_2|^2 = 4\rho_1\rho_2 \sin(\delta_1 - \delta_2) \sin(\theta_1 - \theta_2)$$

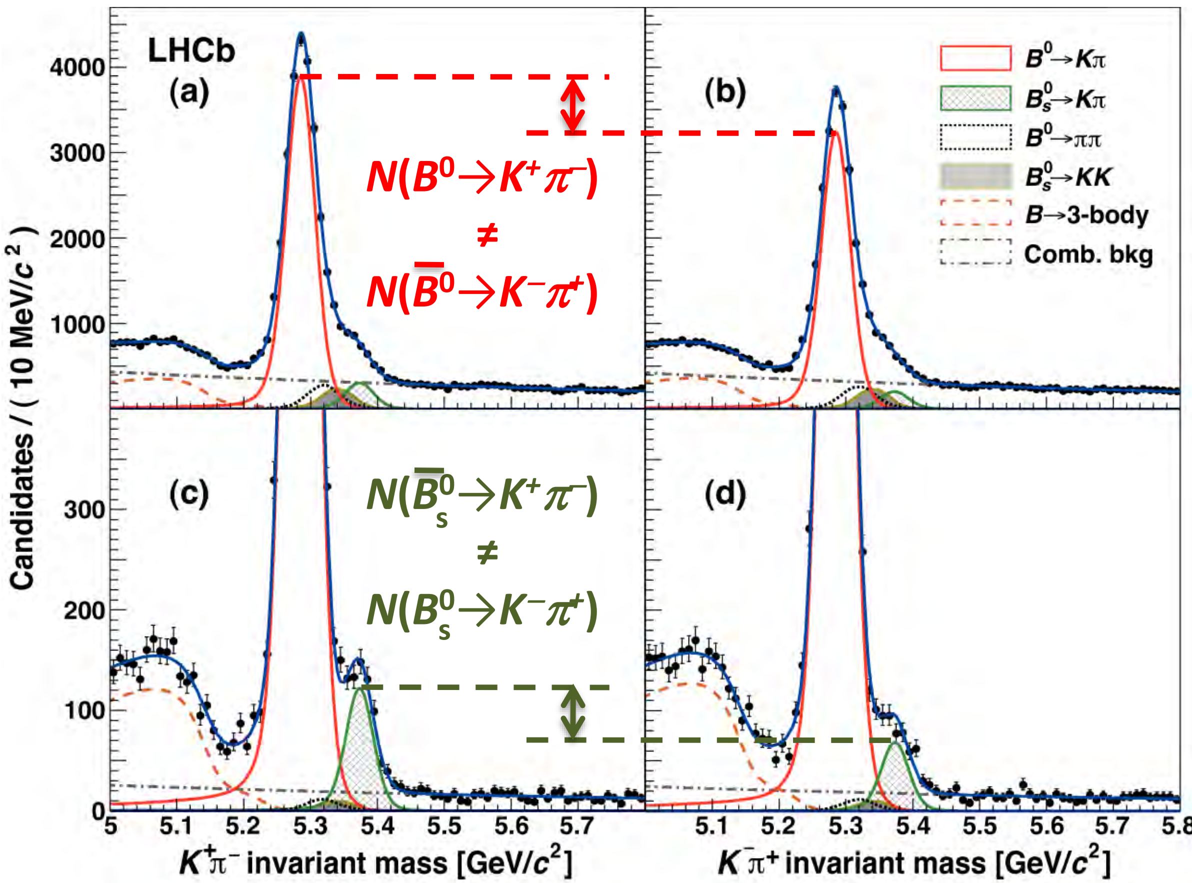
that differs from zero if weak phase differ $\delta_1 \neq \delta_2$ and strong phases differ $\theta_1 \neq \theta_2$

→the asymmetry becomes observable!

- This is a typical effect of quantum interference, where one has two paths with amplitudes of different phases and it is impossible to understand which of the two paths the system has been following to reach the final state
- In particular this is called "direct" *CP* violation

Example: time-integrated CP asymmetry in $B \to K\pi$ decays

Plot from Phys. Rev. Lett. 110 (2013) 221601



- Very simple idea: count the number of decays $B \to f$, and compare with the CP conjugate $\overline{B} \to \overline{f}$ by measuring the time-integrated CP asymmetry

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

- If $A_{CP} \neq 0 \to$ CP violation!

- If we start with a symmetric number of B and $\overline{B}$ mesons, we end up with more positive kaons than negative kaons, and viceversa for pions

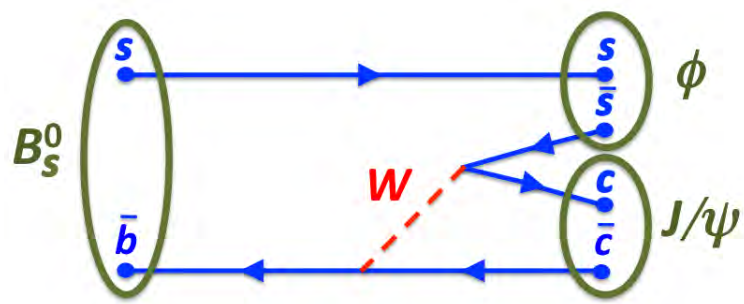
Time-dependent CP violation: interference between oscillations and decay

- A more subtle way to get quantum interference and observe CP violation shows up when both B and $\bar{B}$ mesons can decay to the same final state
- For example

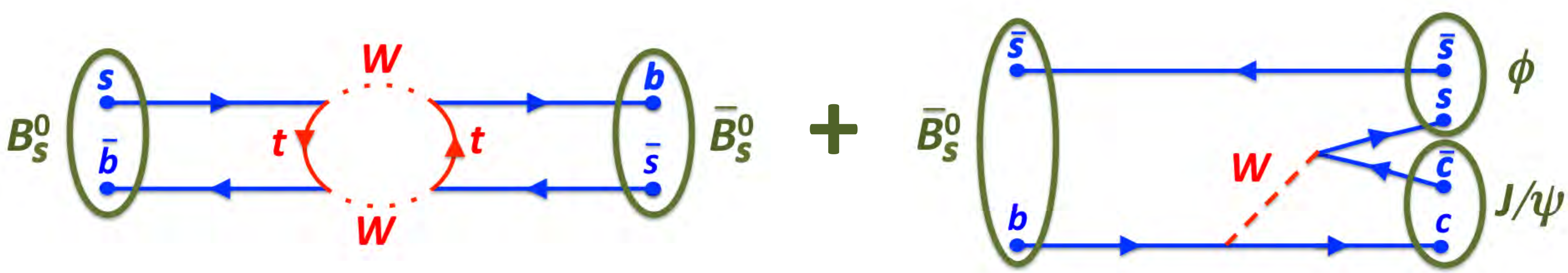
$$B_s^0 \rightarrow J/\psi\phi \qquad \bar{B}_s^0 \rightarrow J/\psi\phi$$

Time-dependent CP violation: interference between oscillations and decay

- Starting from a given B or $\bar{B}$ meson, there are two different quantum paths to get the same final state → interference!



OR



Time-dependent CP violation: formalism

- It gets more complicated but also more interesting

Decay rates at time *t* for states that were *B* or $\bar{B}$ at time zero

$$\Gamma_{B^0_{(s)}\to f}(t) = |A_f|^2 \quad (1+|\lambda_f|^2)\frac{e^{-\Gamma t}}{2}\left(\cosh\frac{1}{2}\Delta\Gamma t + D_f \sinh\frac{1}{2}\Delta\Gamma t + C_f\cos\Delta m t - S_f\sin\Delta m t\right)$$

$$\Gamma_{\bar{B}^0_{(s)}\to f}(t) = |A_f|^2\left|\frac{p}{q}\right|^2(1+|\lambda_f|^2)\frac{e^{-\Gamma t}}{2}\left(\cosh\frac{1}{2}\Delta\Gamma t + D_f \sinh\frac{1}{2}\Delta\Gamma t - C_f\cos\Delta m t + S_f\sin\Delta m t\right)$$

CP-violating coefficients

$$D_f = \frac{2\Re\lambda_f}{1+|\lambda_f|^2} \qquad C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2} \qquad S_f = \frac{2\Im\lambda_f}{1+|\lambda_f|^2}$$

with $\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$

Instantaneous decay rates

$$A_f = A\left(B\to f\right) = \langle f|\mathcal{H}_{eff}\,|B\rangle$$

$$\bar{A}_f = A\left(\bar{B}\to f\right) = \langle f|\mathcal{H}_{eff}\,|\bar{B}\rangle$$

Heavy and light mass eigenstates

$$|B_H\rangle = \frac{p\,|B\rangle + q\,|\bar{B}\rangle}{\sqrt{|p|^2+|q|^2}} \qquad |B_L\rangle = \frac{p\,|B\rangle - q\,|\bar{B}\rangle}{\sqrt{|p|^2+|q|^2}}$$

Average decay width and decay width difference

$$\Gamma = (\Gamma_H+\Gamma_L)/2 \qquad \Delta\Gamma = \Gamma_L - \Gamma_H$$

Mass difference (oscillation frequency)

$$\Delta m = m_H - m_L$$

Time-dependent CP violation: formalism

- Constructing an asymmetry from these rates one gets

$$A_{CP}(t) = \frac{\Gamma_{\bar{B}^0_{(s)}\to f}(t) - \Gamma_{B^0_{(s)}\to f}(t)}{\Gamma_{\bar{B}^0_{(s)}\to f}(t) + \Gamma_{B^0_{(s)}\to f}(t)} = \frac{-C_f\cos(\Delta m_{d,s}t) + S_f\sin(\Delta m_{d,s}t)}{\cosh\left(\frac{\Delta\Gamma_{d,s}}{2}t\right) + D_f\sinh\left(\frac{\Delta\Gamma_{d,s}}{2}t\right)}$$

- In particular, for a B^0 meson, the decay width difference $\Delta\Gamma$ is very small in the SM, and so the time-dependent CP asymmetry reduces to the more familiar expression

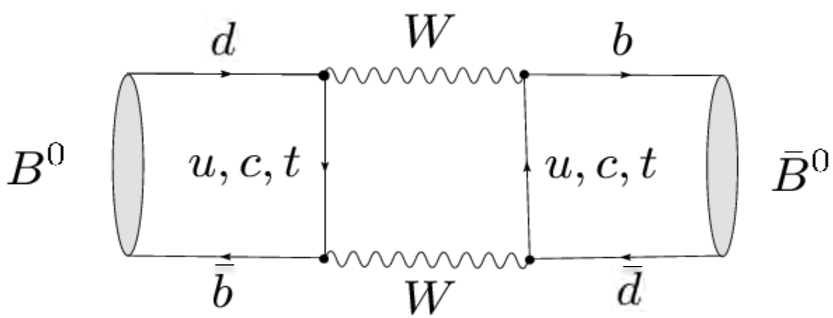
$$A_{CP}(t) = -C_f\cos(\Delta m_d\, t) + S_f\sin(\Delta m_d\, t)$$

- Here *C* and *S* parameterize CP violation in the decay amplitude and, respectively, in the interference between mixing and decay processes

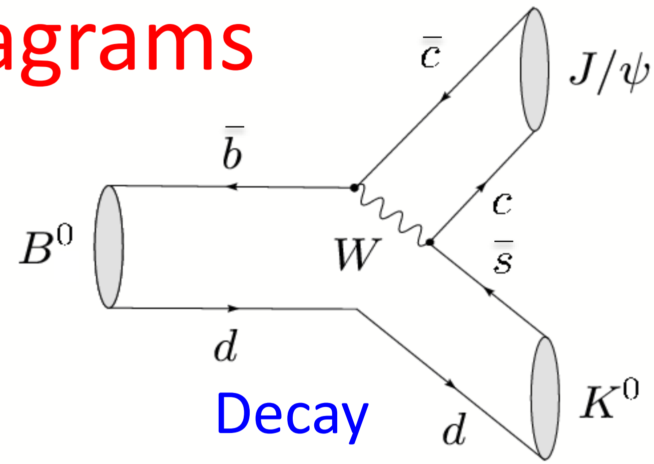
Concrete example: measurement of sin(2β)

- CP violation due to interference between B^0-$\bar{B}^0$ mixing and $B^0 \rightarrow J/\psi K_S$ decay

Interfering diagrams



Mixing

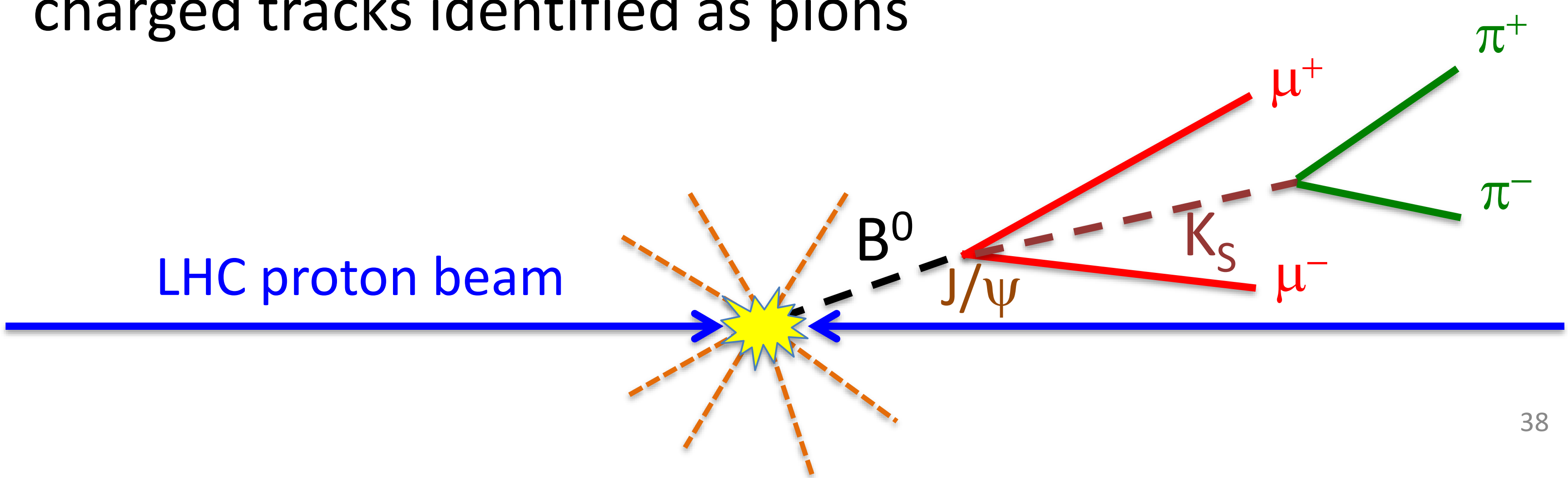


Decay

$$\mathcal{A}_{J/\psi K^0_S}(t) \equiv \frac{\Gamma(\overline{B}^0(t) \to J/\psi K^0_S) - \Gamma(B^0(t) \to J/\psi K^0_S)}{\Gamma(\overline{B}^0(t) \to J/\psi K^0_S) + \Gamma(B^0(t) \to J/\psi K^0_S)}$$
$$= S_{J/\psi K^0_S} \sin(\Delta m_d t) - C_{J/\psi K^0_S} \cos(\Delta m_d t).$$

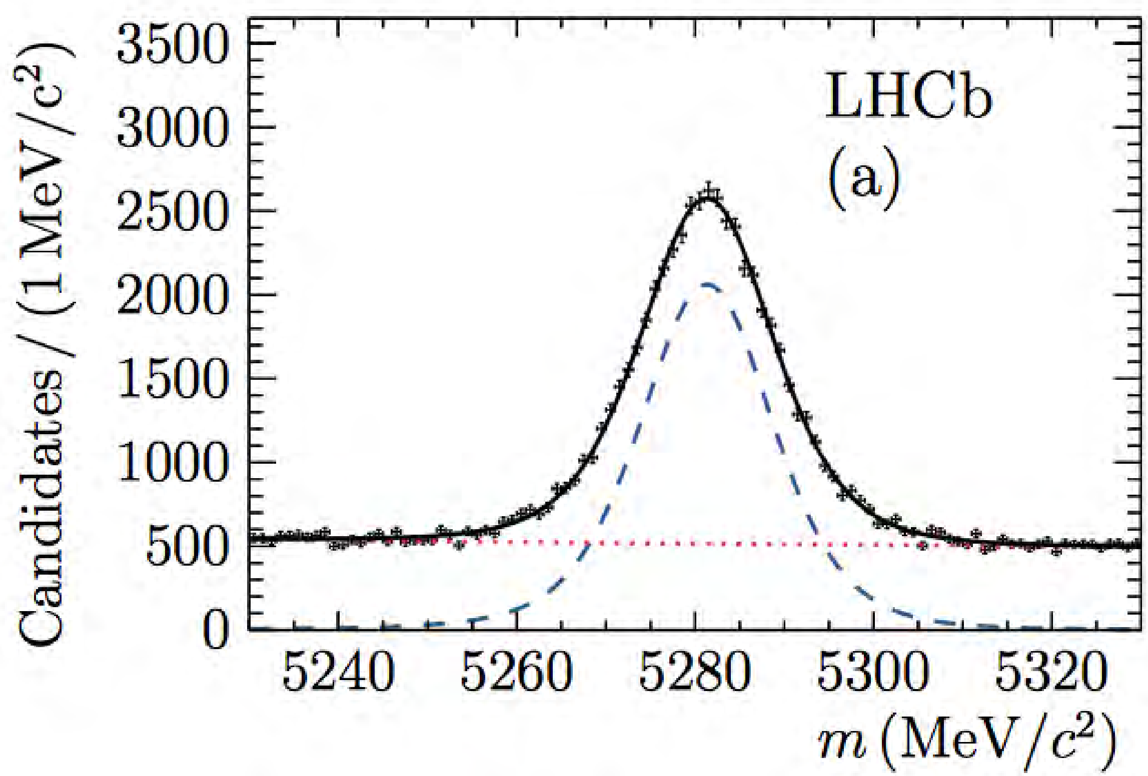
Basic steps of the sin(2β) analysis

- One starts with all tracks reconstructed in the vertex detector and tracking system, with associated particle identification information, and precise determination of trajectory and momentum
- J/ψ candidates are reconstructed via the $J/\psi \to \mu^+\mu^-$ decay by combining all oppositely charged tracks identified as muons in the event two-by-two, and calculating for each pair the invariant mass
- Similarly, K_S candidates are reconstructed via the $K_S \to \pi^+\pi^-$ decay by calculating the invariant mass of all oppositely charged tracks identified as pions



Basic steps of the sin(2β) analysis

- The subsequent step is the reconstruction of *B*-meson candidates, and this is done by combining all J/ψ and K_S candidates in each event and computing an invariant mass
- Typical Gaussian-like signal over flat background

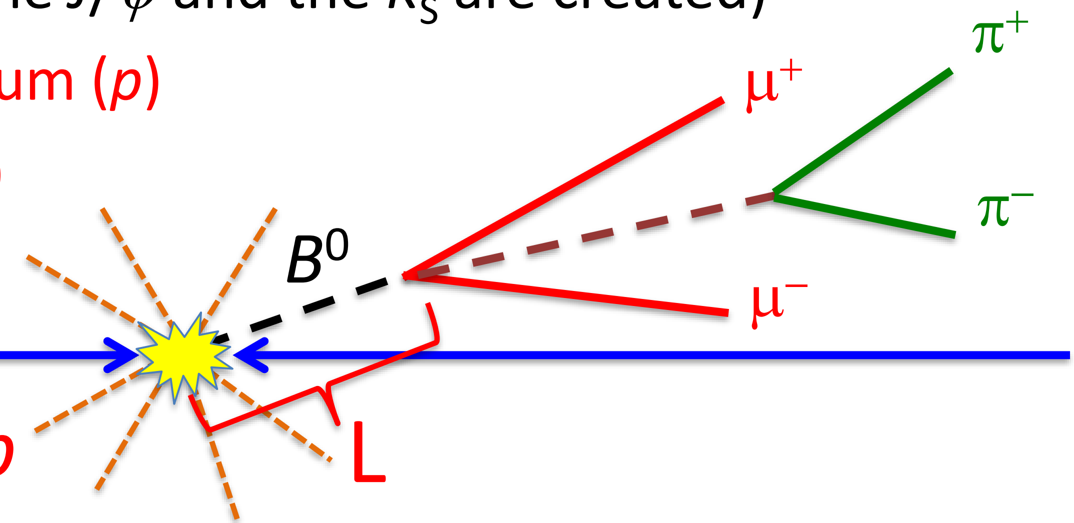


Plot from Phys. Rev. Lett. 115 (2015) 031601

Basic steps of the sin(2β) analysis

- In order to calculate the decay time t of the B meson in its rest frame, one needs to know
  - the distance (L) between the proton-proton collision point (where the B meson is created) and the point where the B meson decays (i.e. the point where the J/ψ and the K_S are created)
  - the B-meson momentum (p)
  - the B-meson mass (m)

LHC proton beam



$$t = L / (\beta\gamma c) = L\, m / p$$

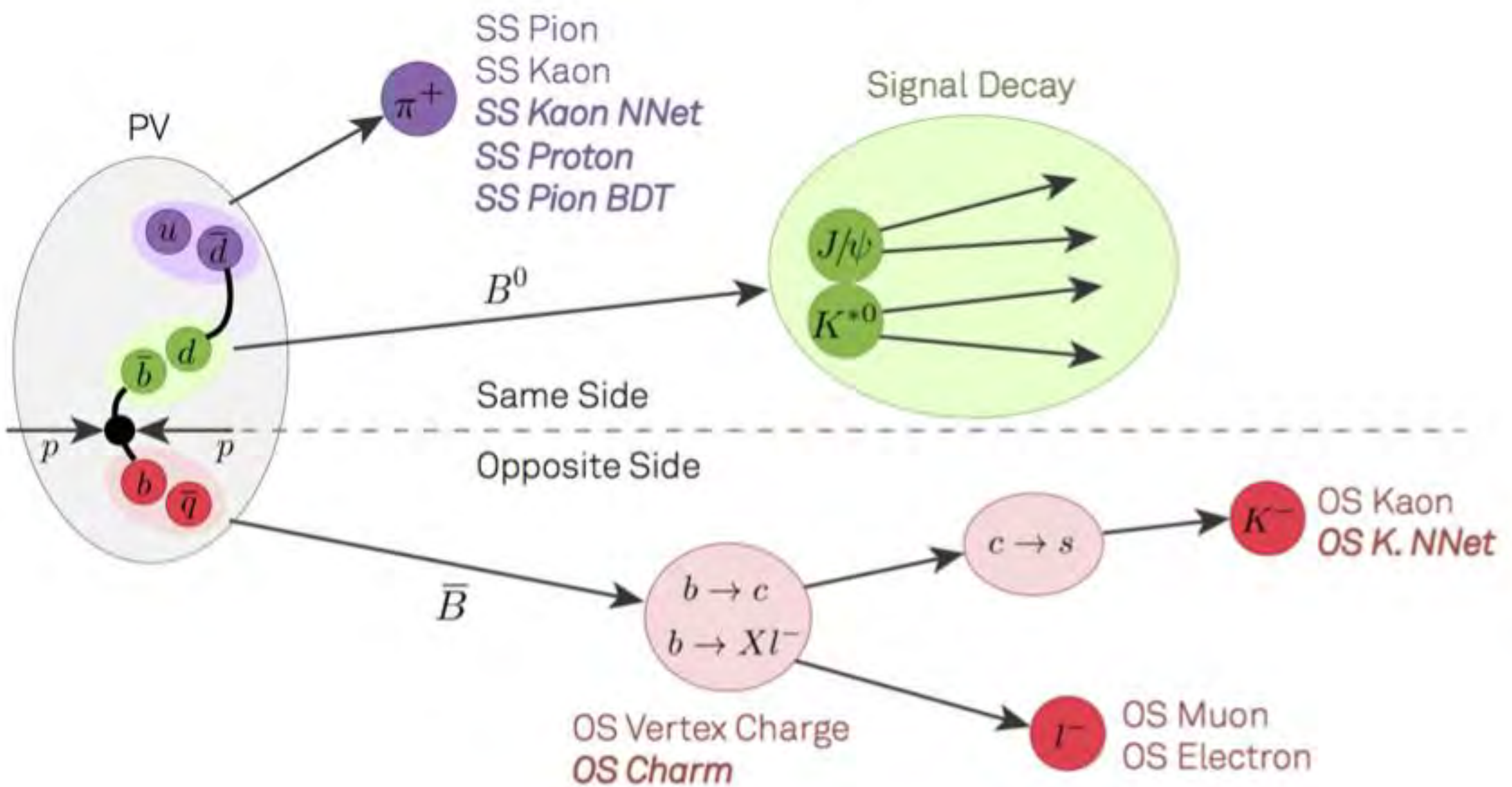
$t \approx 1.5$ ps
$m \approx 5$ GeV/c^2
$p \approx 100$ Gev/c

$L \approx 1$ cm

Typical B-meson decay length at LHCb

Basic steps of the sin(2β) analysis

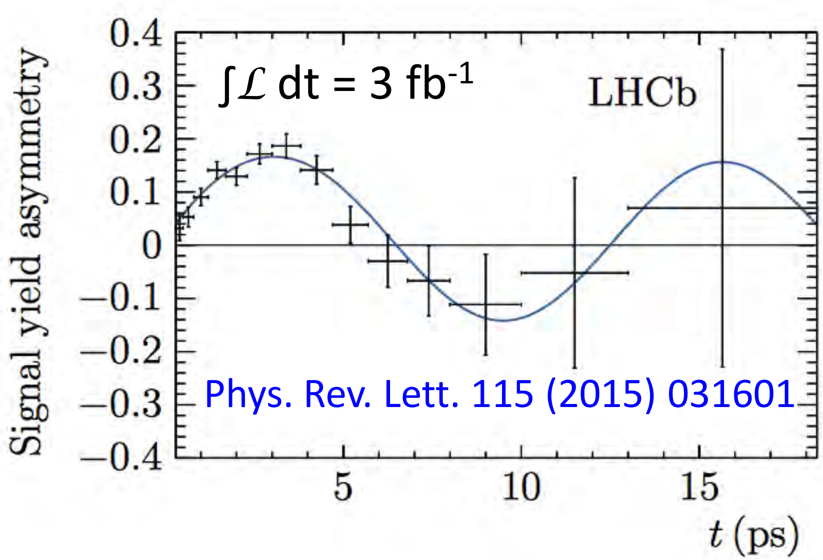
- As a final step one needs to understand whether the *B* meson that was produced was a B^0 or a $\bar{B}^0$
- This is the so-called flavour tagging



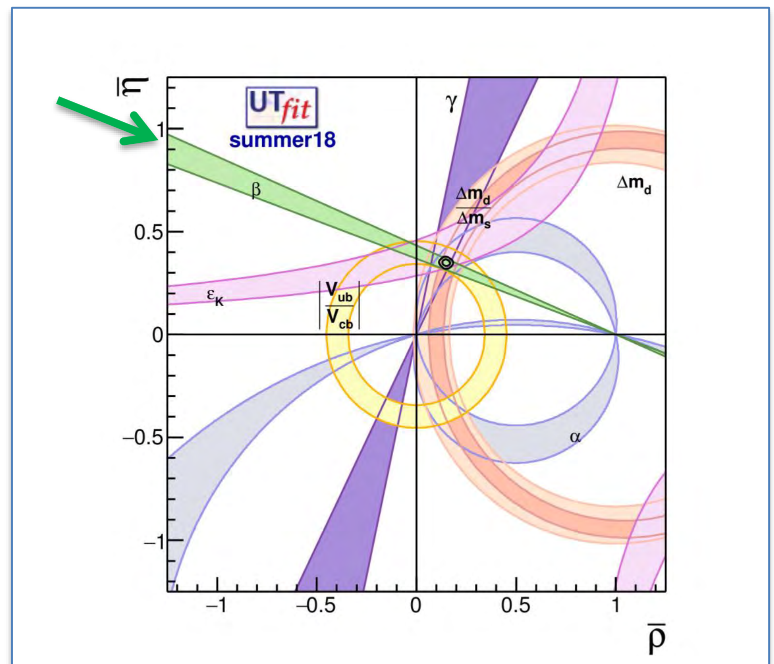
Putting everything together

- Decays reconstructed and *B*-meson candidates identified
- Decay time of *B*-meson candidates determined
- Flavour of the *B*-meson at time zero determined
- We can build the asymmetry and fit the expected shape

$$\mathcal{A}_{J/\psi K^0_S}(t) \equiv \frac{\mathcal{N}(\overline{B}^0(t) \to J/\psi K^0_S) - \mathcal{N}(B^0(t) \to J/\psi K^0_S)}{\mathcal{N}(\overline{B}^0(t) \to J/\psi K^0_S) + \mathcal{N}(B^0(t) \to J/\psi K^0_S)} = S_{J/\psi K^0_S} \sin(\Delta m_d t) - C_{J/\psi K^0_S} \cos(\Delta m_d t)$$



Interpretation

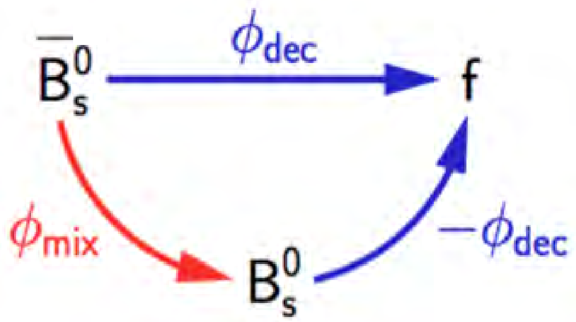


LHCb result with Run-1 data only

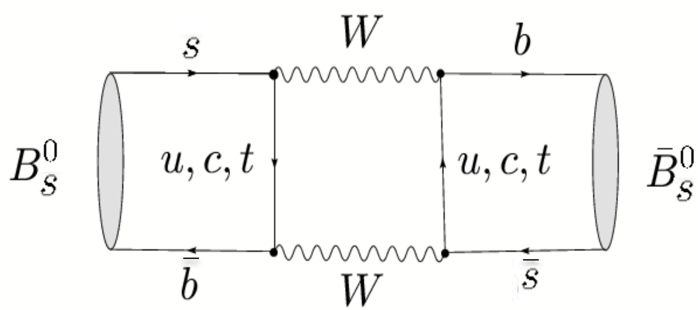
$C = -0.038 \pm 0.032 \pm 0.005$

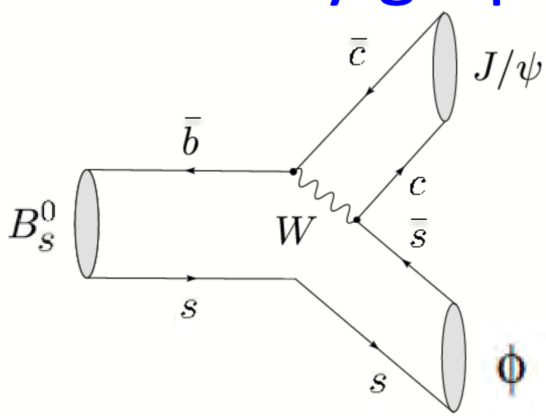
$S = 0.731 \pm 0.035 \pm 0.020$ ⟶ It can be shown that $S_{\psi K_S} = \sin 2\beta$

Measurement of ϕ_s



- Golden mode $B_s \rightarrow J/\psi\phi$ is the B_s analogue to $B^0 \rightarrow J/\psi K_S$
- Interference between B_s mixing and decay graphs

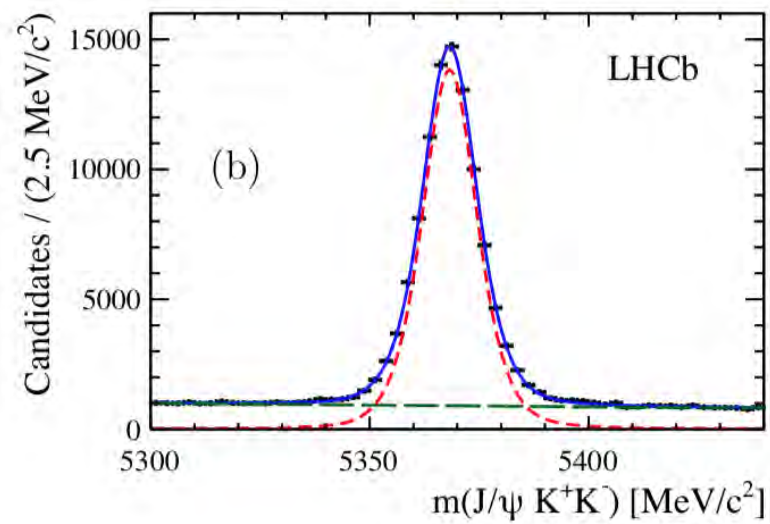




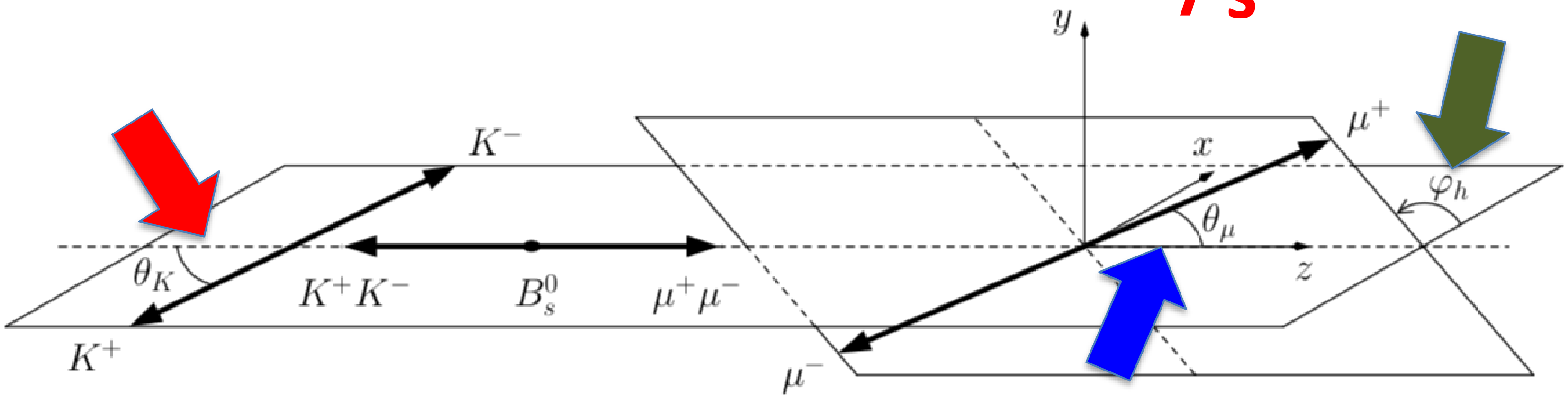
- One measures the phase-difference ϕ_s between the two diagrams, precisely predicted in the SM to be $\phi_s = -2\lambda^2\eta = -37.4 \pm 0.7$ mrad → very small, can receive sizeable contributions from new physics

Measurement of ϕ_s

- Conceptually similar to measuring sin(2β), but now we have a pseudoscalar to vector-vector decay
- The final state is not a CP eigenstate, but a mixture of CP=+1 and CP=-1 eigenstates
  - Angular analysis of decay products is needed to disentangle the two eigenstates
- Furthermore, for a B_s meson the decay width difference $\Delta\Gamma_s$ is not negligible, and needs to be measured
- The full formalism is significantly more complicated, but besides that the analysis steps are similar
  - Reconstruct $B_s \rightarrow J/\psi(\mu\mu)\phi$(KK)
  - Measure B_s-meson decay time
  - Measure angular variables (helicity angles) of decay products
  - Determine flavour of the B_s-meson at time zero determined

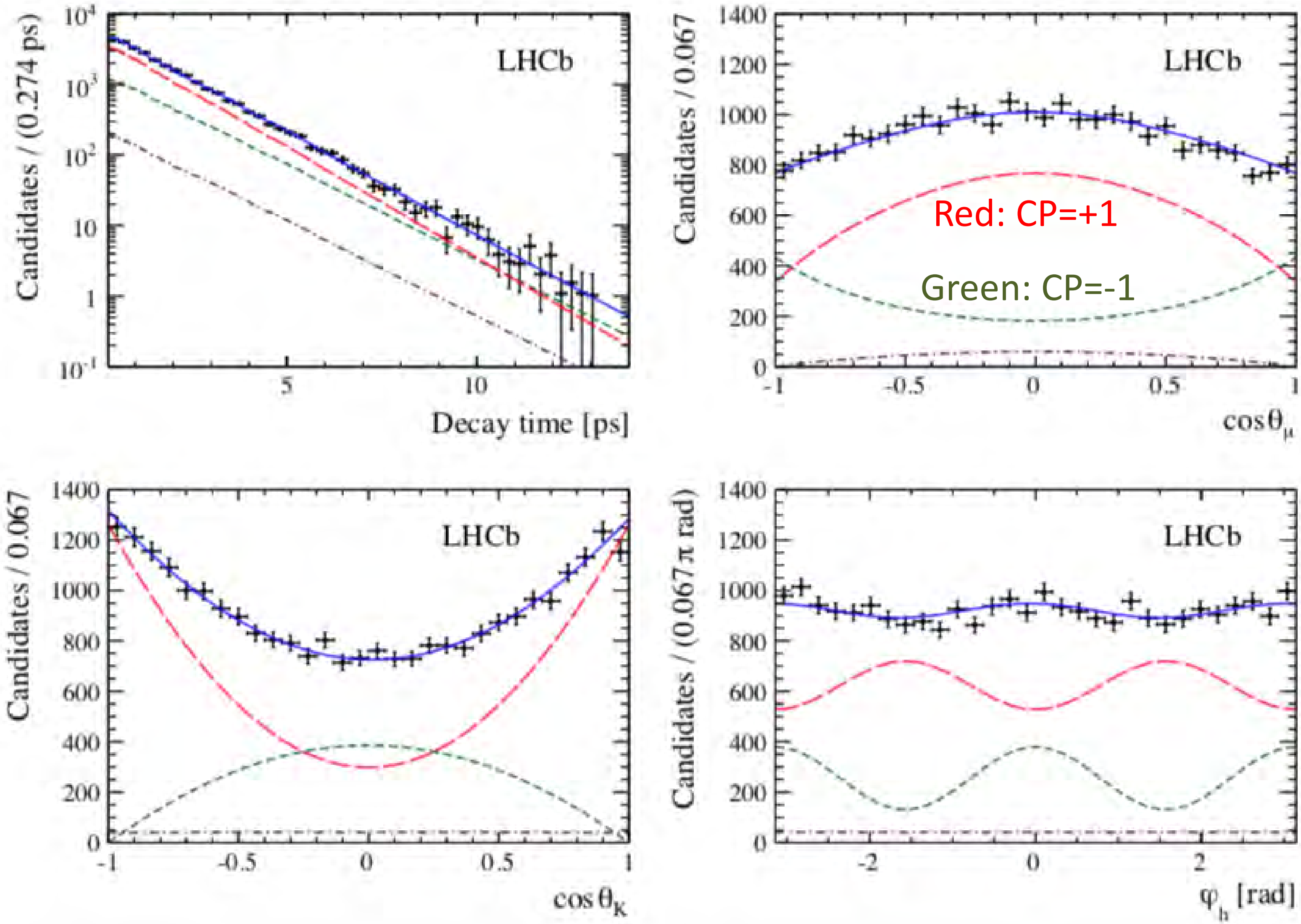


Measurement of ϕ_s



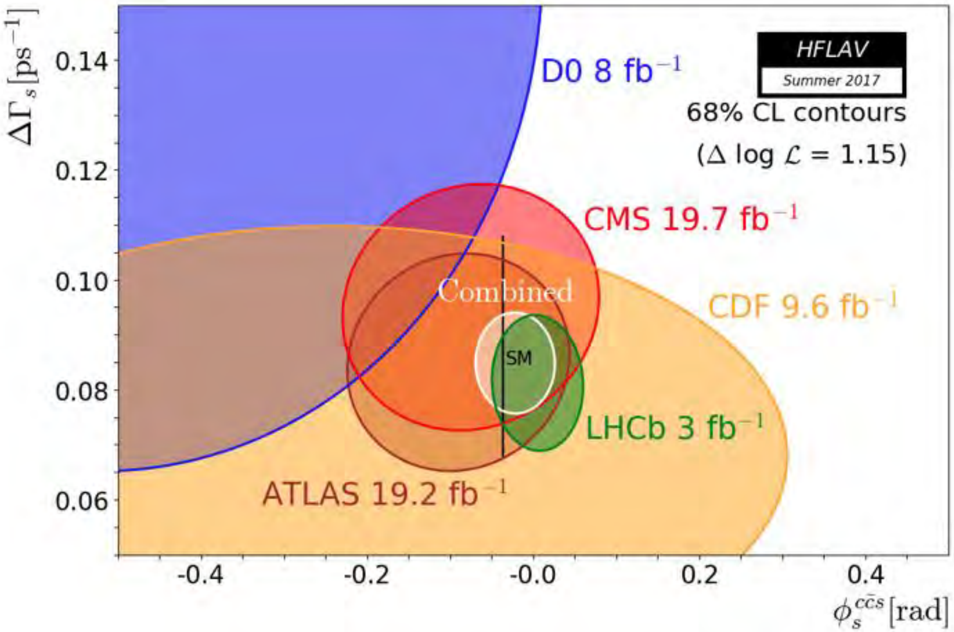
- θ_K is the angle between the K^+ momentum and the direction opposite to the B_s momentum in the K^+K^- centre-of-mass system
- θ_μ is the angle between the μ^+ momentum and the direction opposite to the B_s momentum in the $\mu^+\mu^-$ centre-of-mass system
- φ_h is the azimuthal angle between the K^+K^- and $\mu^+\mu^-$ decay planes

Measurement of ϕ_s



Plots from Phys. Rev. Lett. 114 (2015) 041801

Measurement of ϕ_s



- ϕ_s precision mostly driven by LHCb, with significant contributions from ATLAS and CMS (only Run-1 data)
- Latest HFLAV world average
  - $\phi_s = -21 \pm 31$ mrad
- Well compatible with the SM at the present level of precision

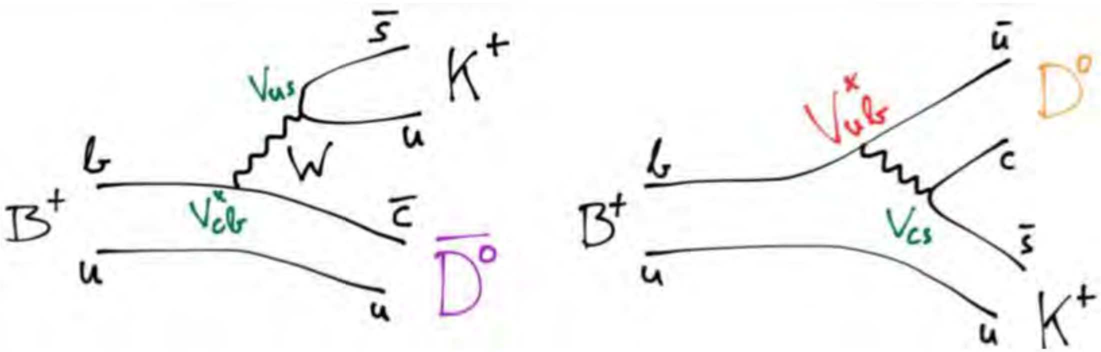
Exp.	Mode	Dataset	$\phi_s^{c\bar{c}s}$	$\Delta\Gamma_s$ (ps^{-1})	Ref.
CDF	$J/\psi\phi$	9.6 fb^{-1}	$[-0.60, +0.12]$, 68% CL	$+0.068 \pm 0.026 \pm 0.009$	[2]
D0	$J/\psi\phi$	8.0 fb^{-1}	$-0.55^{+0.38}_{-0.36}$	$+0.163^{+0.065}_{-0.064}$	[3]
ATLAS	$J/\psi\phi$	4.9 fb^{-1}	$+0.12 \pm 0.25 \pm 0.05$	$+0.053 \pm 0.021 \pm 0.010$	[4]
ATLAS	$J/\psi\phi$	14.3 fb^{-1}	$-0.110 \pm 0.082 \pm 0.042$	$+0.101 \pm 0.013 \pm 0.007$	[5]
ATLAS	above 2 combined		$-0.090 \pm 0.078 \pm 0.041$	$+0.085 \pm 0.011 \pm 0.007$	[5]
CMS	$J/\psi\phi$	19.7 fb^{-1}	$-0.075 \pm 0.097 \pm 0.031$	$+0.095 \pm 0.013 \pm 0.007$	[6]
LHCb	$J/\psi K^+K^-$	3.0 fb^{-1}	$-0.058 \pm 0.049 \pm 0.006$	$+0.0805 \pm 0.0091 \pm 0.0032$	[7]
LHCb	$J/\psi\pi^+\pi^-$	3.0 fb^{-1}	$+0.070 \pm 0.068 \pm 0.008$	—	[8]
LHCb	$J/\psi K^+K^{-\,a}$	3.0 fb^{-1}	$+0.119 \pm 0.107 \pm 0.034$	$+0.066 \pm 0.018 \pm 0.010$	[9]
LHCb	above 3 combined		$+0.001 \pm 0.037$(tot)	$+0.0813 \pm 0.0073 \pm 0.0036$	[9]
LHCb	$\psi(2S)\phi$	3.0 fb^{-1}	$+0.23^{+0.29}_{-0.28} \pm 0.02$	$+0.066^{+0.41}_{-0.44} \pm 0.007$	[10]
LHCb	$D_s^+D_s^-$	3.0 fb^{-1}	$+0.02 \pm 0.17 \pm 0.02$	—	[11]
All combined			-0.021 ± 0.031	$+0.085 \pm 0.006$	

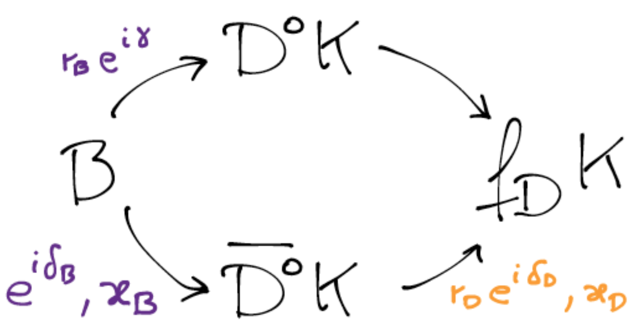
[a] $m(K^+K^-) > 1.05$ GeV$/c^2$.

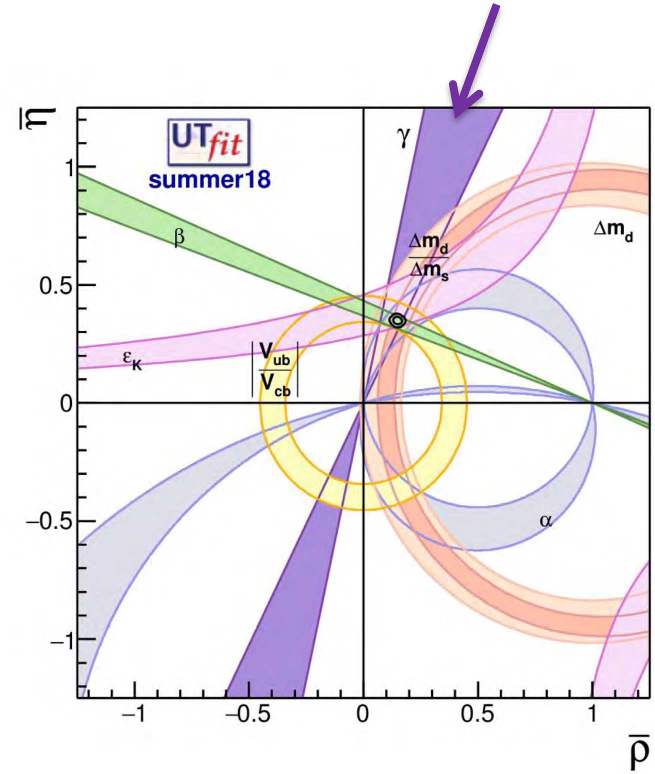
Browse HFLAV page for the list of references https://hflav.web.cern.ch

Measurement of γ

- γ is the least known angle of the unitarity triangle
- It is measured via the interference between *b*→*c* and *b*→*u* tree-level quark transitions



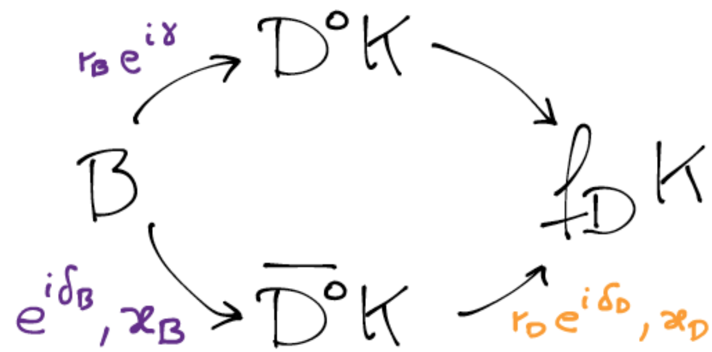




- Simple and clean theoretical interpretation, but statistically very challenging

Measurement of γ

- To achieve the interference and measure CP violation one needs a final state that does not distinguish between D^0 and $\bar{D}^0$



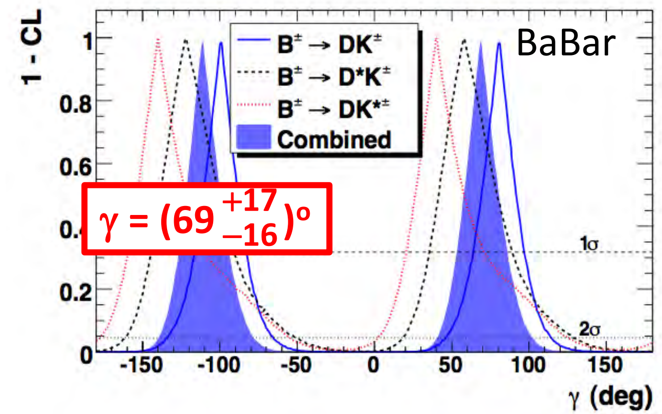
- Gronau, London, Wyler (GLW) approach
  – Use decays to CP eigenstates like $D^0 \rightarrow K^+K^-$ or $D^0 \rightarrow \pi^+\pi^-$
- Atwood, Dunietz, Soni (ADS) approach
  – Use decays to flavour-specific final states accessible to both D^0 and $\bar{D}^0$, e.g. $D^0 \rightarrow K^+\pi^-$ and $D^0 \rightarrow K^-\pi^+$
- Giri, Grossman, Soffer, Zupan (GGSZ) approach
  – Use three-body decay like $D^0 \rightarrow K_S\pi^+\pi^-$ → requires Dalitz analysis

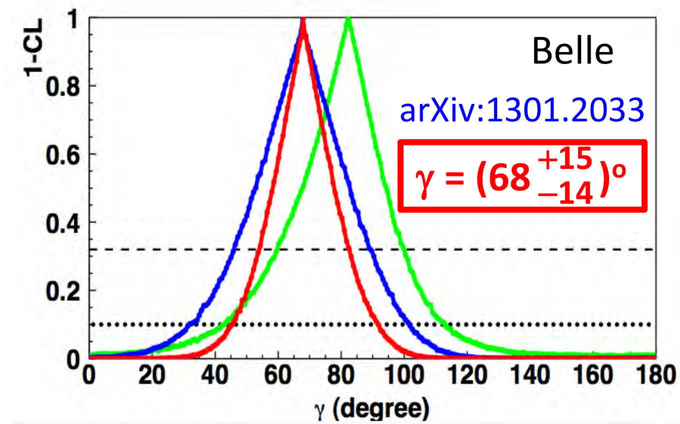
Measurement of γ

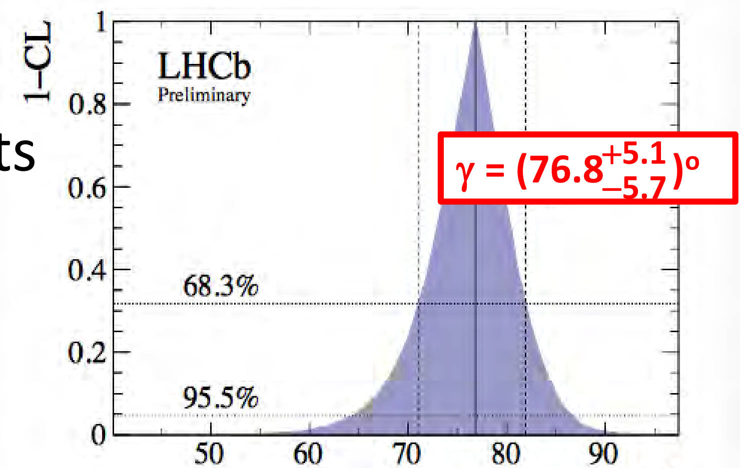
B decay	D decay	Method
$B^+ \to Dh^+$	$D \to h^+h^-$	GLW/ADS
$B^+ \to Dh^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS
$B^+ \to Dh^+$	$D \to h^+h^-\pi^0$	GLW/ADS
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ
$B^+ \to DK^+$	$D \to K^0_S K^+\pi^-$	GLS
$B^+ \to Dh^+\pi^-\pi^+$	$D \to h^+h^-$	GLW/ADS
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	GGSZ
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	TD

- A plethora of independent measurements exploiting different methods and decays
- LHCb significantly more precise than previous results from the *B*-factories and undergoing continuous improvements

Phys. Rev. **D87** (2013) 052015



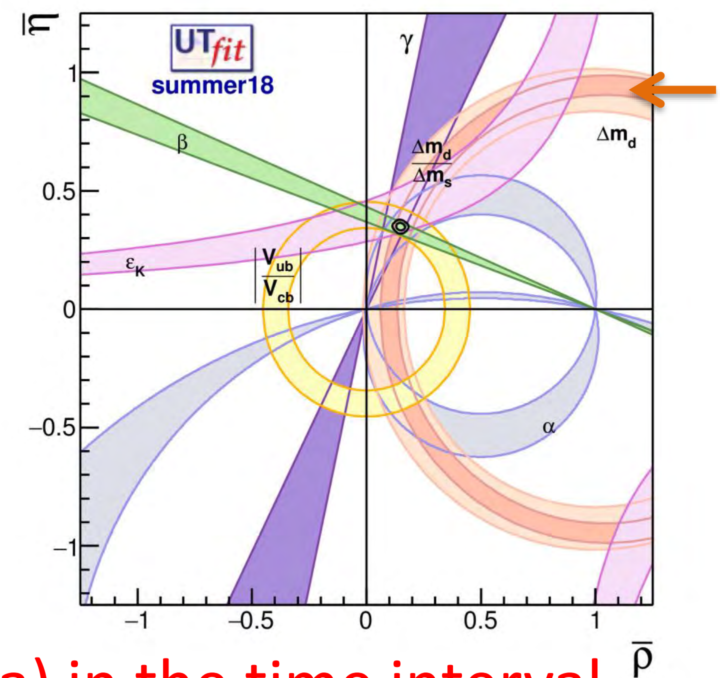




LHCb-CONF-2017-004

Measurement of Δm_d and Δm_s

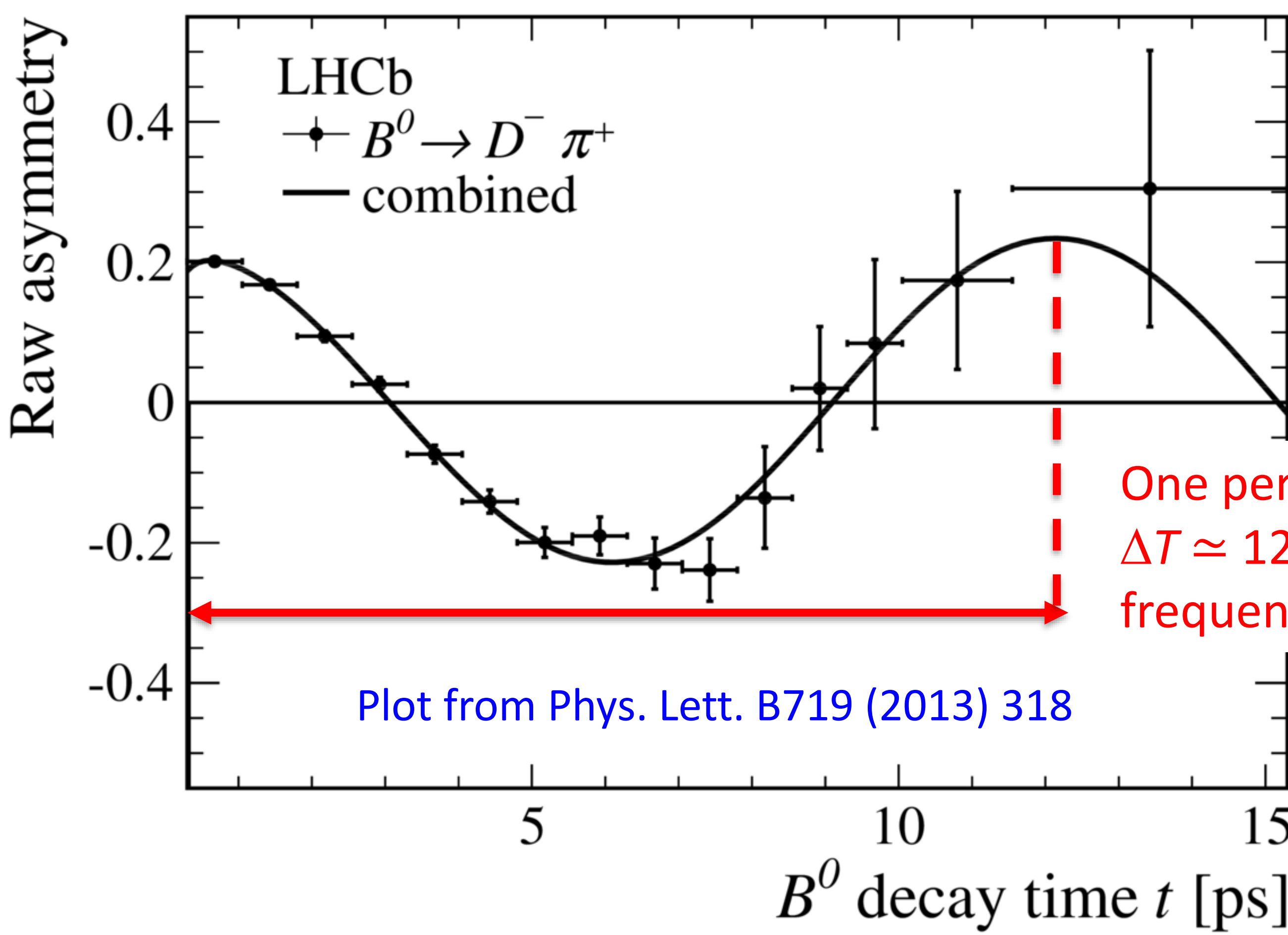
- B^0 and B_s oscillation frequencies measure the right-hand side of the unitarity triangle
- Here one uses decays like $B^0 \rightarrow D^- \pi^+$ and $B_s \rightarrow D_s^- \pi^+$
- The idea is simple
  - Define whether the meson was a B or $\bar{B}$ at the time of decay
    - This is simply understood by the final state, e.g. $B^0 \rightarrow D^- \pi^+$ vs $\bar{B}^0 \rightarrow D^+ \pi^-$
  - Determine whether the meson at production was a B or a $\bar{B}$: tagging
  - In this way it is possible to determine whether the initial B oscillated to a $\bar{B}$ or not (or viceversa) in the time interval between production and decay, and so define a mixing asymmetry like



$$A_{mix}(t) = \frac{N_{B\to B}(t) - N_{B\to\bar{B}}(t)}{N_{B\to B}(t) + N_{B\to\bar{B}}(t)} \propto \cos(\Delta m\, t)$$

Measurement of Δm_d and Δm_s

- And you get something like this



One period of B^0 oscillations $\Delta T \simeq 12$ ps → B^0 oscillation frequency $\Delta m_d \simeq 0.5$ ps^{-1}

Measurement of Δm_d and Δm_s

- Experimental precision has reached a remarkable per mille level
  - $\Delta m_d = 0.5065 \pm 0.0019\ \text{ps}^{-1}$
  - $\Delta m_s = 17.757 \pm 0.021\ \text{ps}^{-1}$
- But the interpretation requires inputs from Lattice QCD

$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_W^2\ \eta_c S(x_t)\ A^2\lambda^6\ [(1-\bar{\rho})^2+\bar{\eta}^2]\ m_{B_d} f_{B_d}^2 \hat{B}_{B_d}$$

~7%

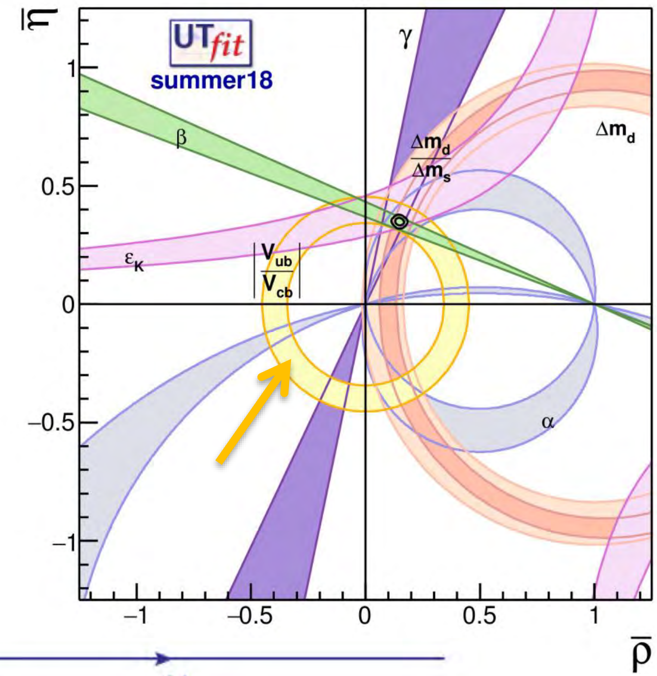
$$\frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d} f_{B_d}^2 \hat{B}_{B_d}}{m_{B_s} f_{B_s}^2 \hat{B}_{B_s}} \left(\frac{\lambda}{1-\frac{\lambda^2}{2}}\right)^2 [(1-\bar{\rho})^2+\bar{\eta}^2]$$

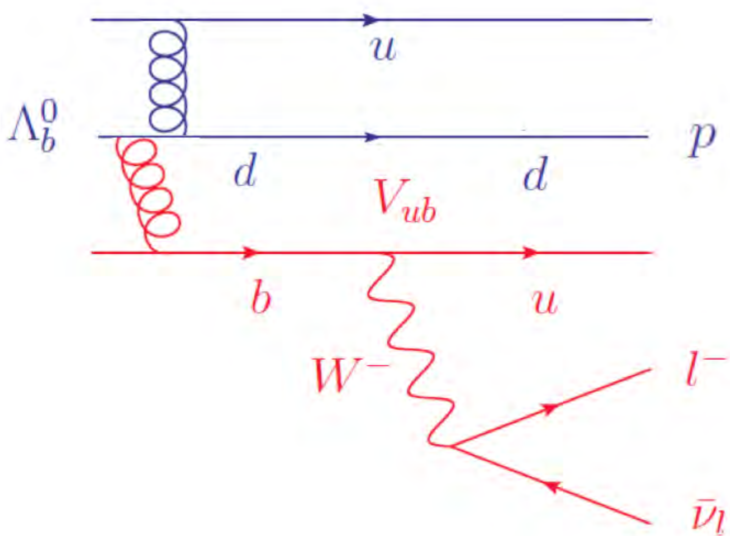
~4%

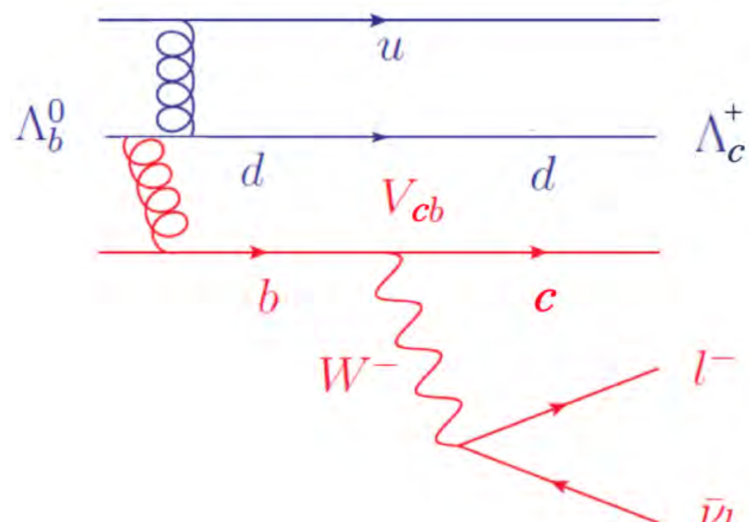
- Hence the quest for precision with these constraints on the unitarity triangle is now on Lattice QCD
  - Need to reduce the theoretical uncertainties by x10

Measurement of $|V_{ub} / V_{cb}|$

- This ratio gives the left-hand side of the unitarity triangle
- Measured at *B* factories with semileptonic *B* decays and more recently by LHCb using semileptonic Λ_b decays
  - $\mathfrak{B}(\Lambda_b \rightarrow p\mu\nu) / \mathfrak{B}(\Lambda_b \rightarrow \Lambda_c\mu\nu)$





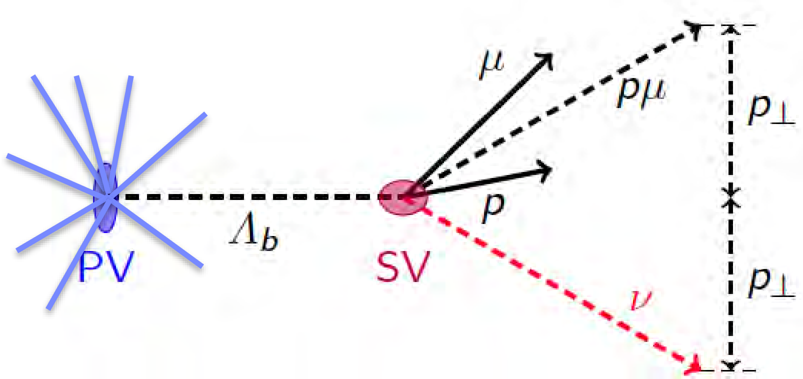


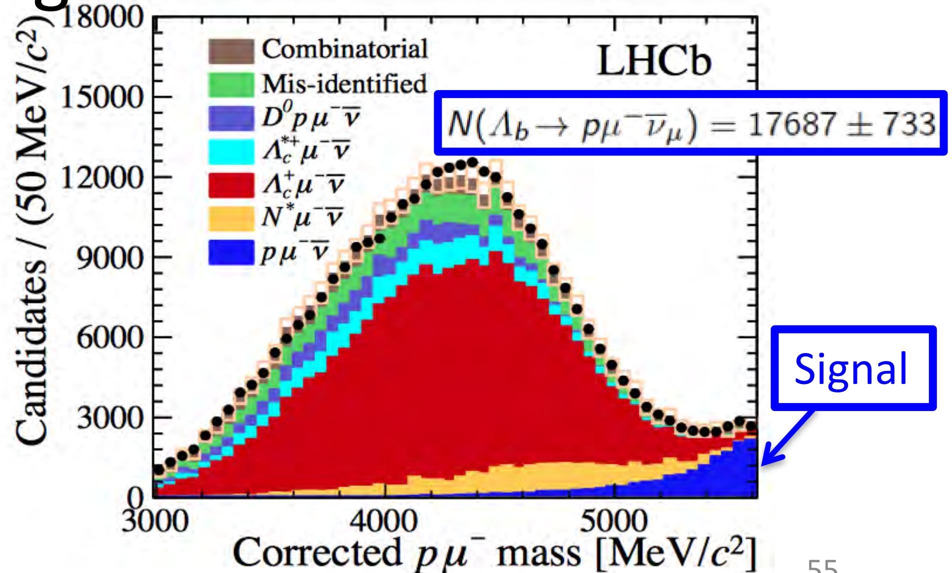
- Why a ratio instead of individual branching fractions?

Measurement of $|V_{ub} / V_{cb}|$

- …because absolute measurements of branching fractions at a hadron collider are very challenging
  - Much more convenient (and precise) to measure ratios of processes with similar experimental efficiencies
- Furthermore, this is an example of a decay that cannot be fully reconstructed due to a missing neutrino
- The trick is to define a "corrected mass" that partially compensates for the missing momentum

$$M_{corr} = \sqrt{p_\perp^2 + M_{p\mu}^2} + p_\perp$$





Plot from Nature Physics 10 (2015) 1038

Measurement of $|V_{ub} / V_{cb}|$

- By taking the ratio of signal yields determined from corrected-mass fits and applying appropriate efficiency factors, the experimental ratio R_{exp} is measured

$$R_{exp} = \frac{\mathcal{B}(\Lambda_b^0 \to p\mu^- \overline{\nu}_\mu)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \mu^- \overline{\nu}_\mu)}$$

- But be reminded that we do not deal with free quarks → interpretation in terms of CKM matrix elements needs input from Lattice QCD

$$R_{exp} = R_{theory}(|\mathrm{V_{ub}}|^2/|\mathrm{V_{cb}}|^2)$$

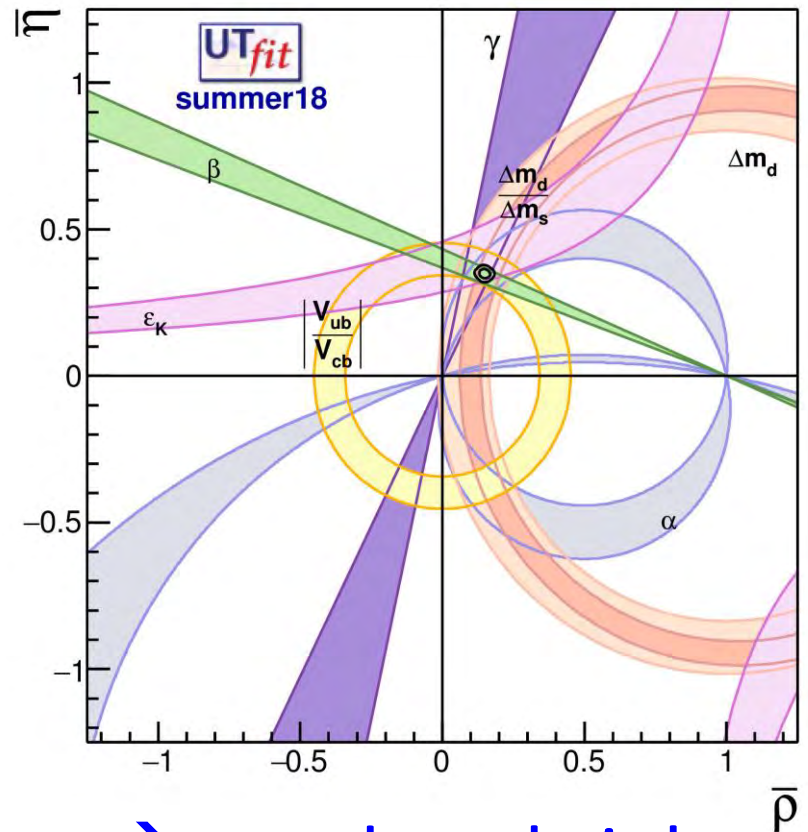
$$R_{theory} = 1.470 \pm 0.115(stat) \pm 0.104(syst)$$ Phys. Rev. D 92, 034503 (2015)

- Finally

$$\boxed{\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004 \pm 0.004}$$

Recap on CKM metrology

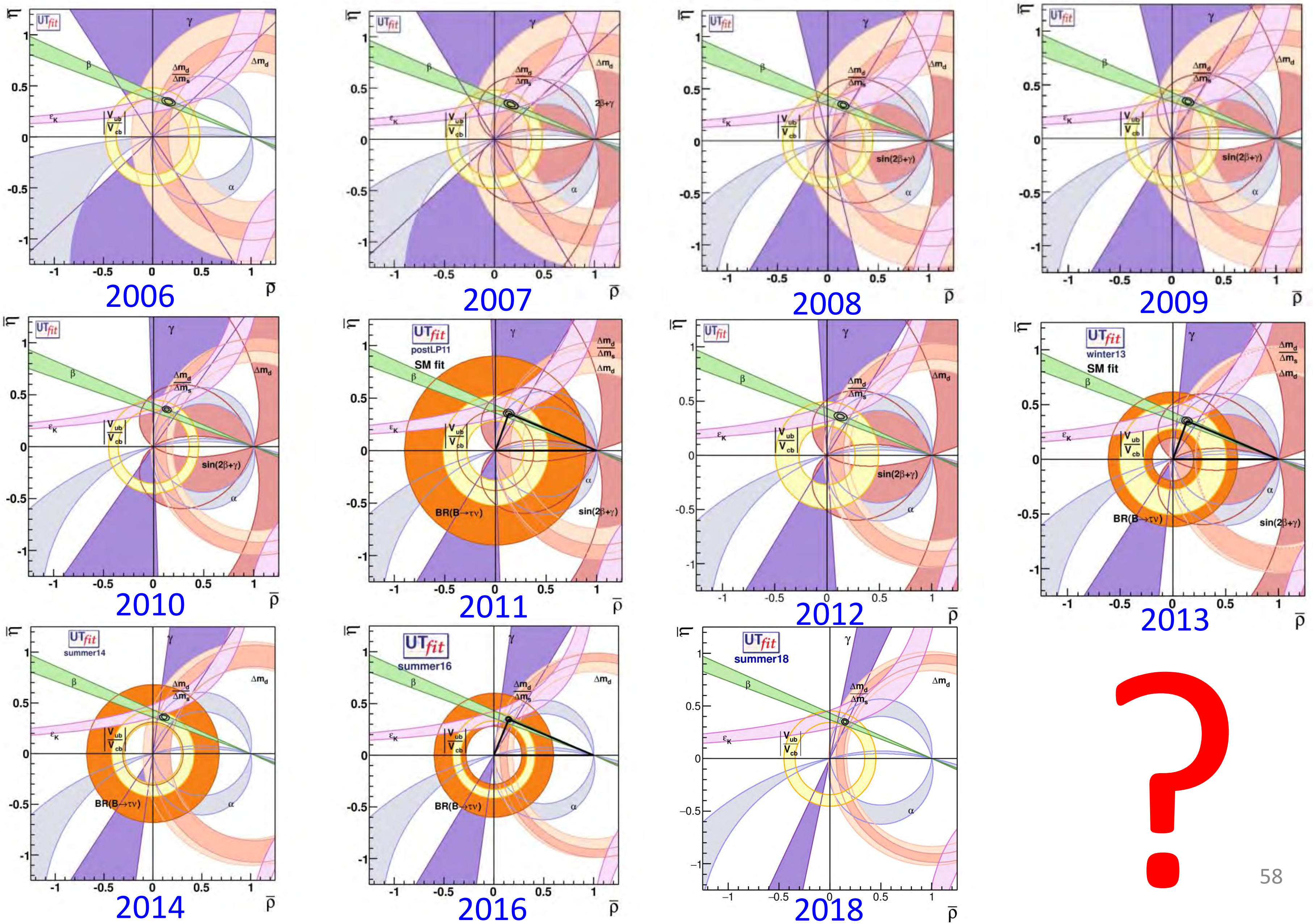
- Several quantities are measured to overconstrain the unitarity triangle and look for discrepancies
  - Some of them skipped for brevity today



- No discrepancies in the determination of the apex of the unitarity triangle at the present level of precision → need to shrink uncertainties further!

Theoretical and experimental improvements needed

A long journey



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Selected *B*-physics results

Rare decays and

B-physics anomalies