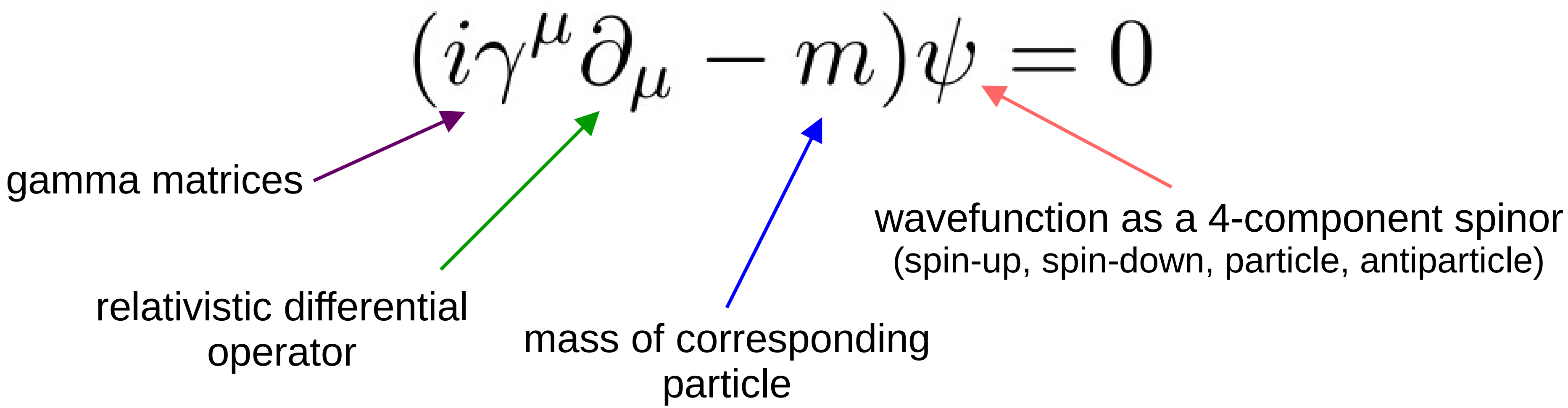
Searching beyond the Standard Model of Particle Physics with the LHCb experiment

Tim Gershon
University of Warwick

UCAS, 23 November 2023

A very brief introduction to the Standard Model (1)

- Relativistic quantum mechanics (Dirac, Weyl)



$$(i\gamma^\mu\partial_\mu - m)\psi = 0$$

gamma matrices

relativistic differential operator

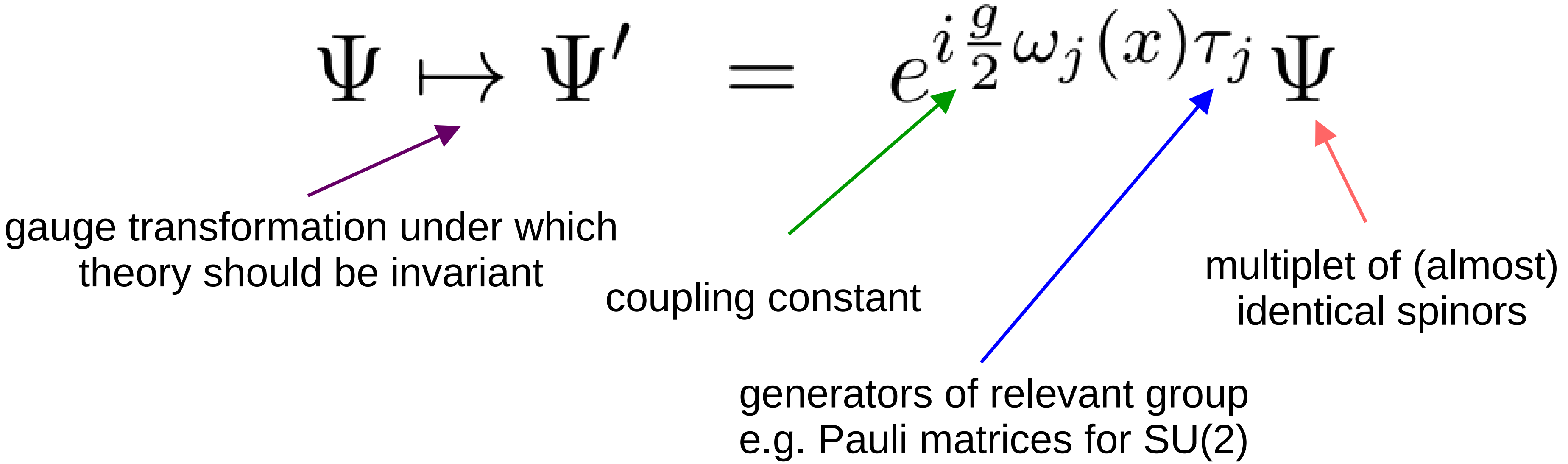
mass of corresponding particle

wavefunction as a 4-component spinor
(spin-up, spin-down, particle, antiparticle)

"It seems to be one of the fundamental features of nature that fundamental physical laws are described in terms of a mathematical theory of great beauty and power."

A very brief introduction to the Standard Model (2)

- Quantum field theory (Feynman, Schwinger, Tomonaga) with non-Abelian gauge fields (Yang, Mills)



$$\Psi \mapsto \Psi' \quad = \quad e^{i\frac{g}{2}\omega_j(x)\tau_j}\,\Psi$$

gauge transformation under which theory should be invariant

coupling constant

generators of relevant group
e.g. Pauli matrices for SU(2)

multiplet of (almost) identical spinors

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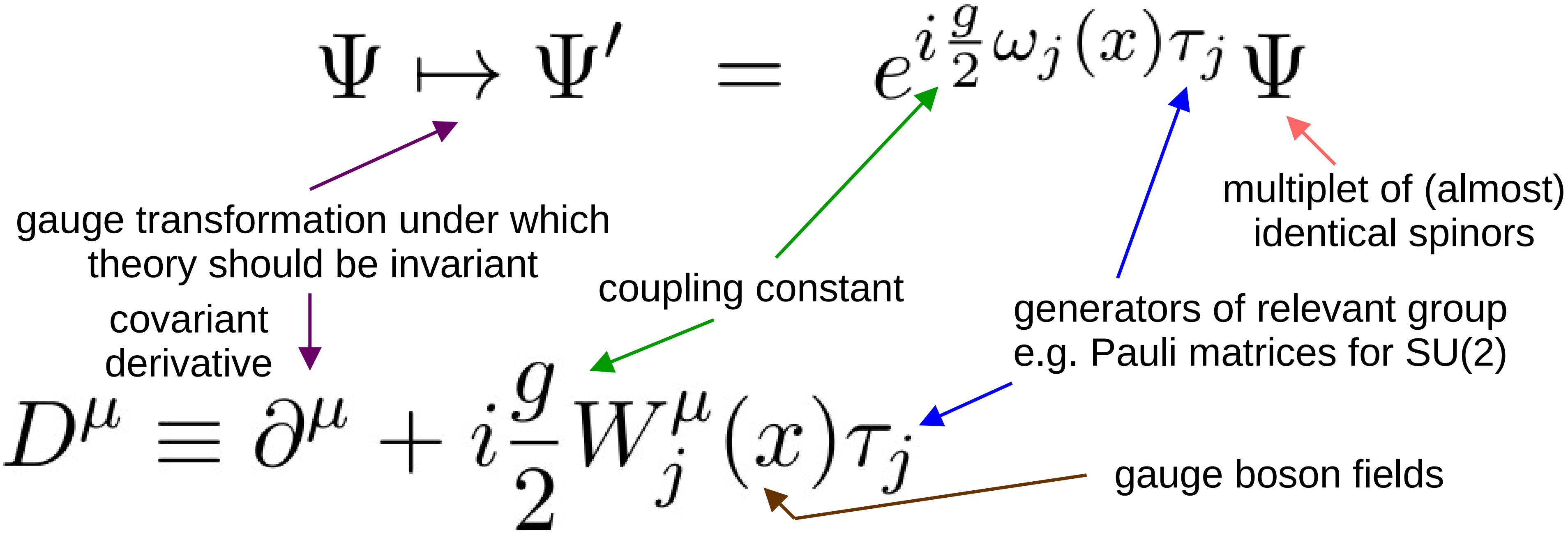

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covariant derivative

$$D^\mu \equiv \partial^\mu + i\frac{g}{2}W_j^\mu(x)\tau_j$$

gauge boson fields

A very brief introduction to the Standard Model (3)

- The Standard Model gauge group (Gell-Mann, Zweig, Weinberg, Glashow, Salam)

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

three copies (“colours”) of each fermion that interacts with the QCD gauge group

two copies (“weak isospin”) of each fermion that interacts with the SU(2) gauge group

weak hypercharge governs strength of (Abelian) U(1) interaction

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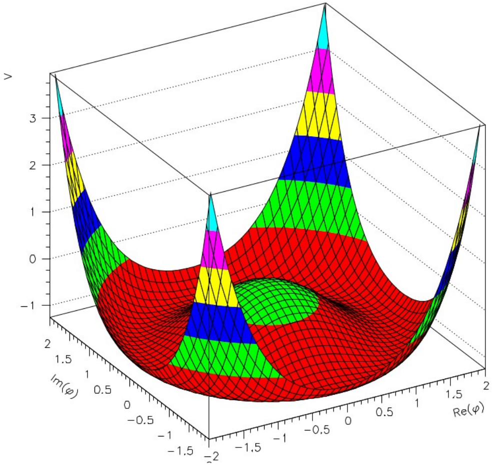
$SU(2)_L$ acts only on left-handed chiral component! (Parity violation: Lee, Yang, Wu)
Mass terms couple left- and right-handed components → only massless particles!

A very brief introduction to the Standard Model (4)

- Electroweak symmetry breaking (Weinberg, Glashow, Salam, Higgs, Brout, Englert, etc.)

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

Higgs field
(actually a complex scalar doublet)

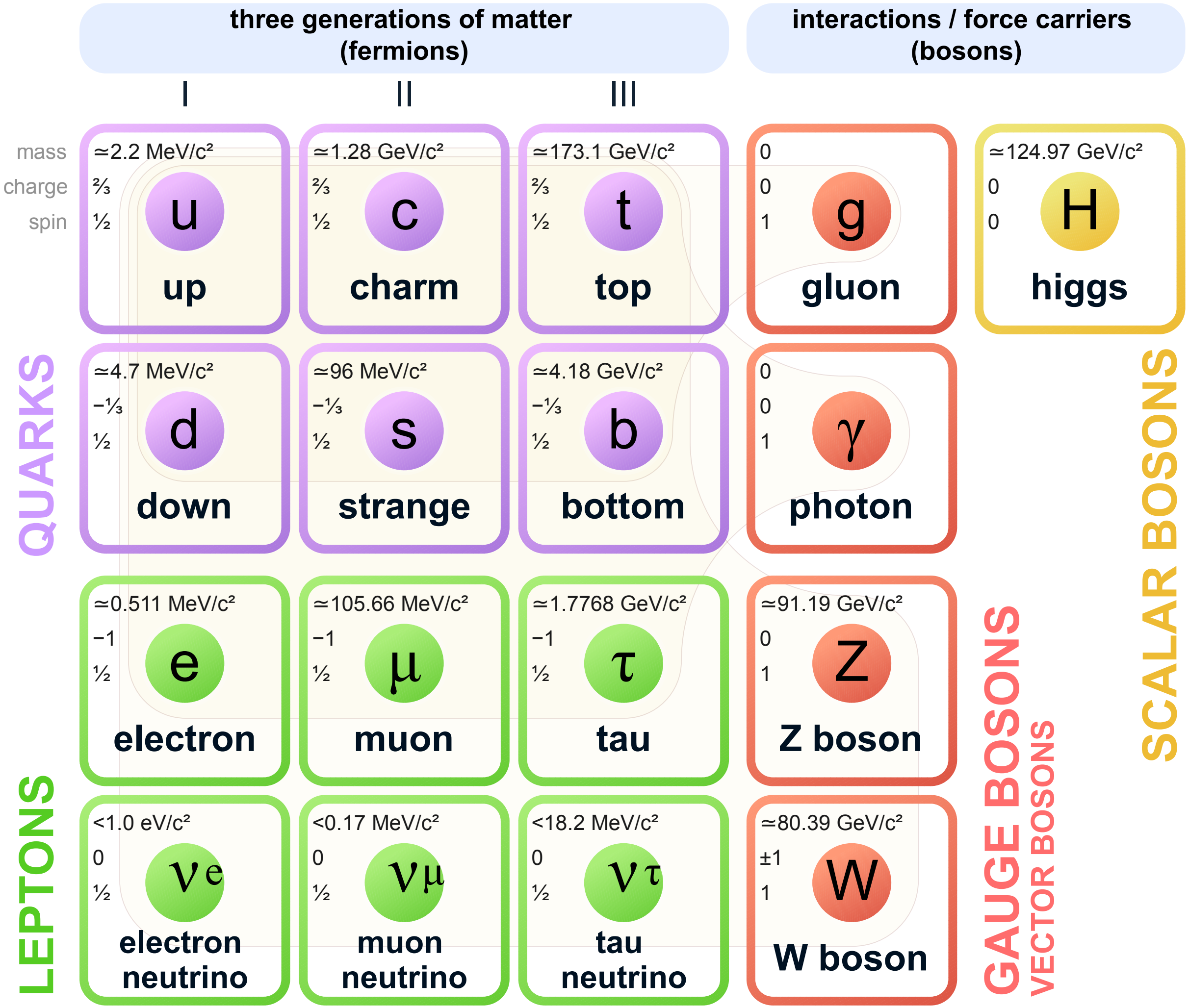


At low energies the $SU(2)_L \times U(1)_Y$ electroweak symmetry is broken

→ Explains gauge boson masses and differences in charged current and neutral current weak interaction strengths

→ Fermion masses arise through "Yukawa" interactions with Higgs field

Standard Model of Elementary Particles



	three generations of matter (fermions)			interactions / force carriers (bosons)	
mass charge spin	I	II	III		
QUARKS	≃2.2 MeV/c^2 ⅔ ½ u **up**	≃1.28 GeV/c^2 ⅔ ½ c **charm**	≃173.1 GeV/c^2 ⅔ ½ t **top**	0 0 1 g **gluon**	≃124.97 GeV/c^2 0 0 H **higgs**
	≃4.7 MeV/c^2 −⅓ ½ d **down**	≃96 MeV/c^2 −⅓ ½ s **strange**	≃4.18 GeV/c^2 −⅓ ½ b **bottom**	0 0 1 γ **photon**	
LEPTONS	≃0.511 MeV/c^2 −1 ½ e **electron**	≃105.66 MeV/c^2 −1 ½ μ **muon**	≃1.7768 GeV/c^2 −1 ½ τ **tau**	≃91.19 GeV/c^2 0 1 Z **Z boson**	
	<1.0 eV/c^2 0 ½ ν_e **electron neutrino**	<0.17 MeV/c^2 0 ½ ν_μ **muon neutrino**	<18.2 MeV/c^2 0 ½ ν_τ **tau neutrino**	≃80.39 GeV/c^2 ±1 1 W **W boson**	

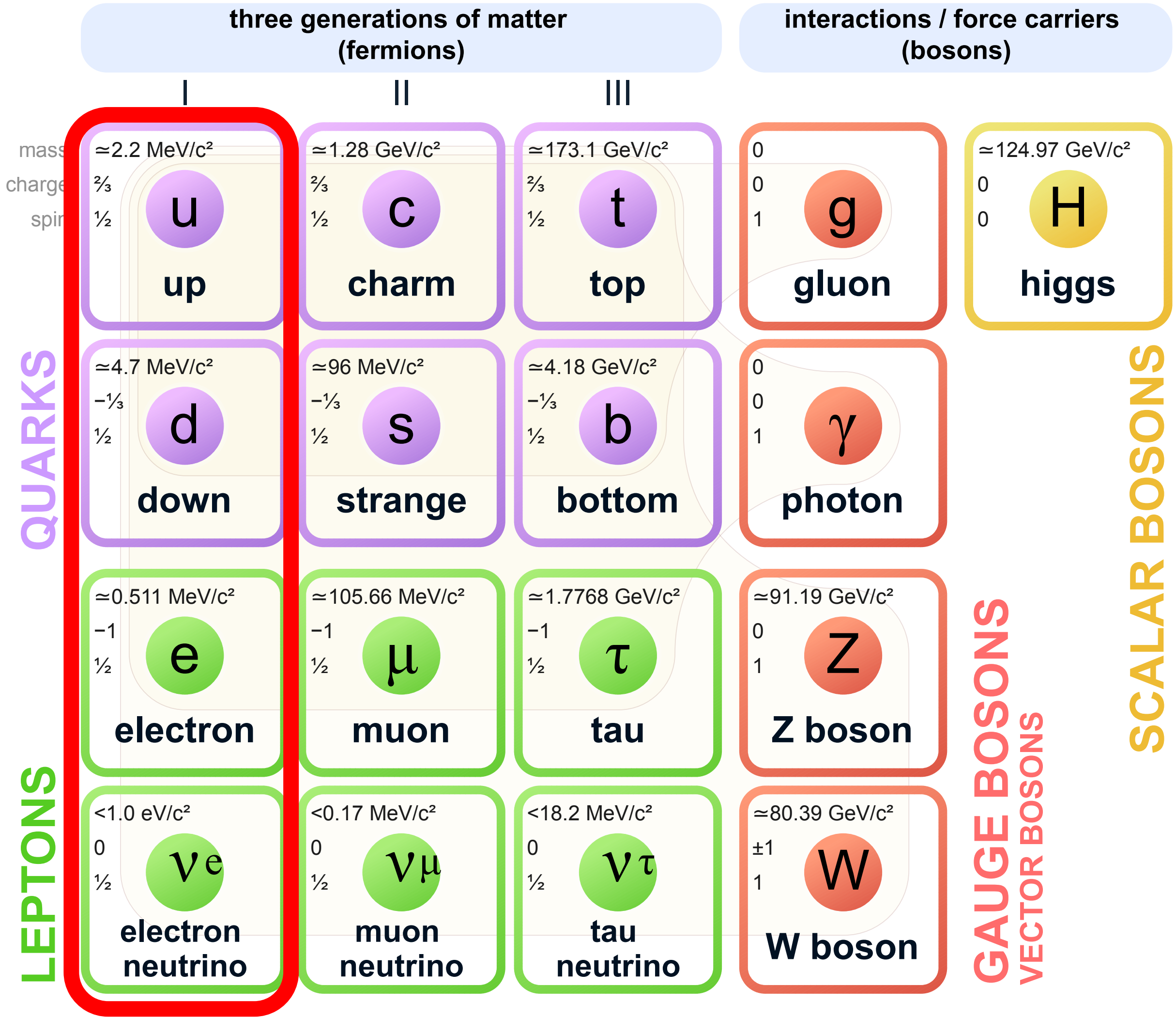
GAUGE BOSONS

VECTOR BOSONS

SCALAR BOSONS

Standard Model of Elementary Particles

First generation fermions make up all the visible matter in the Universe



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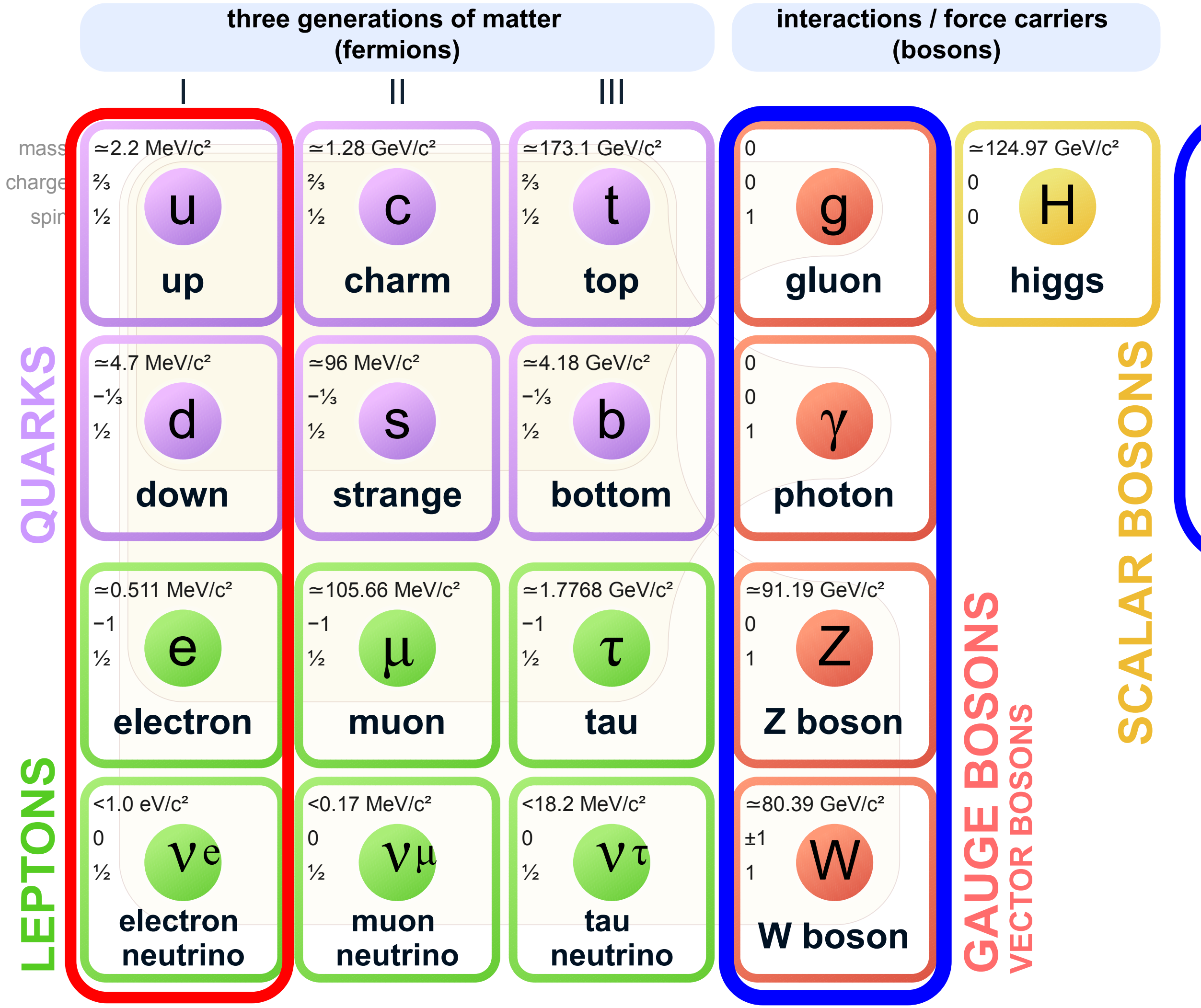

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GAUGE BOSONS

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SCALAR BOSONS

Force mediators
ɣ electromagnetic
g strong
W,Z weak

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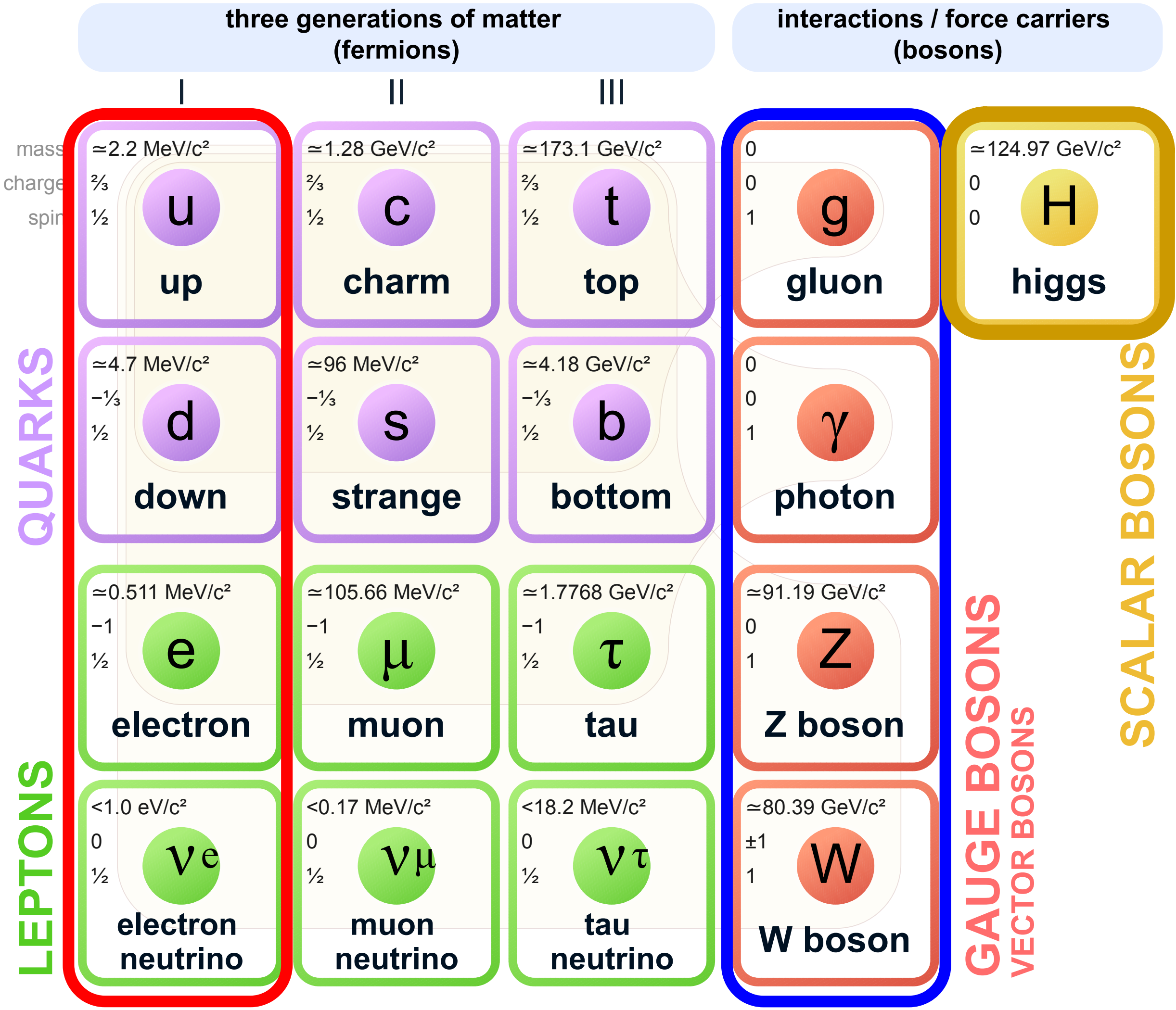

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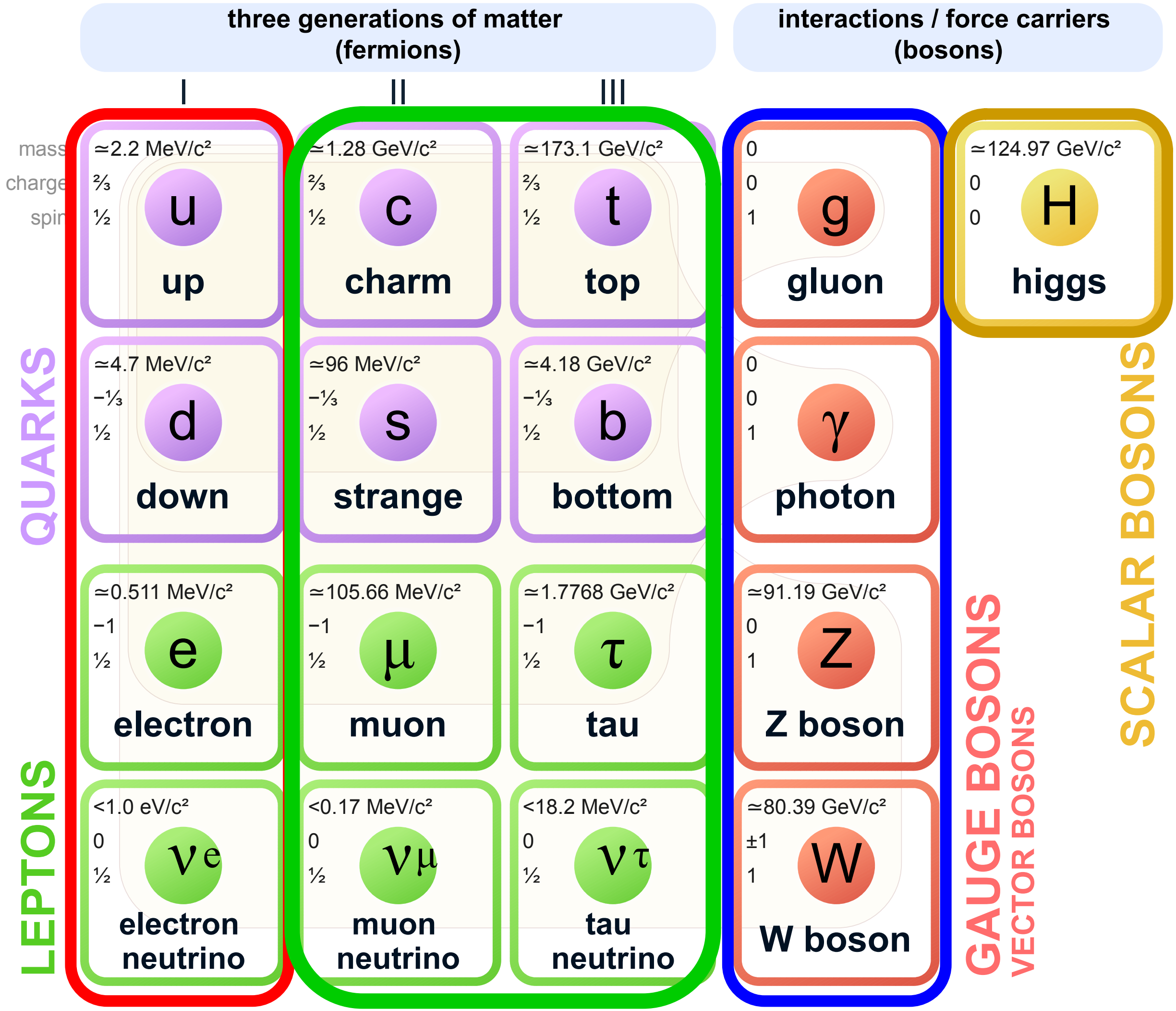
Origin of mass!

Standard Model of Elementary Particles

First generation fermions make up all the visible matter in the Universe

Why do we need these?



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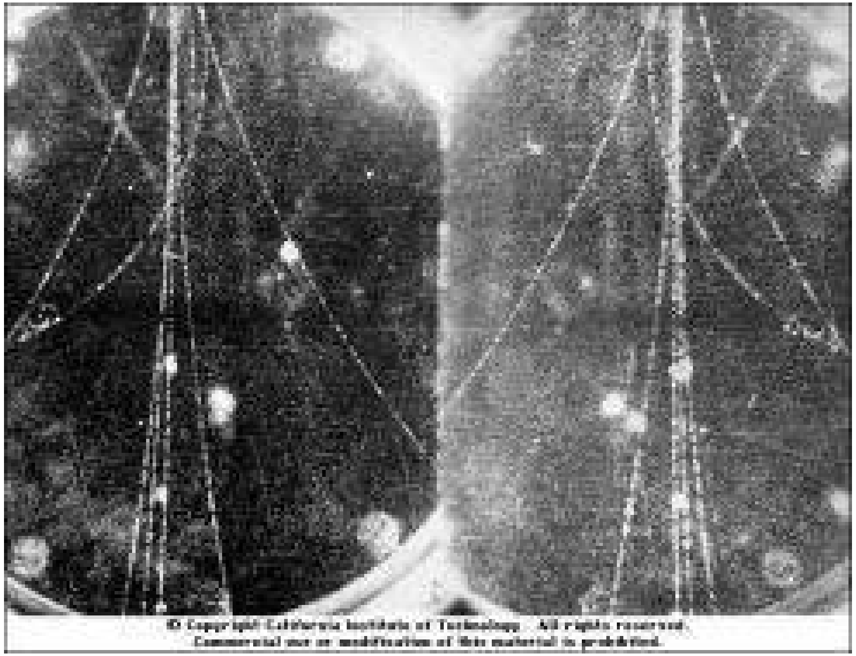
Origin of mass!

Muons were discovered in 1936 from studies of cosmic radiation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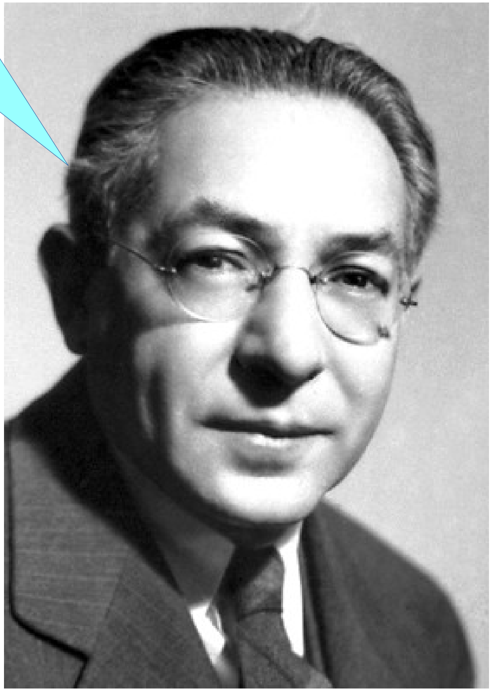
Radius of curvature of charged particle in magnetic field ∝ charge/mass

Who ordered that?



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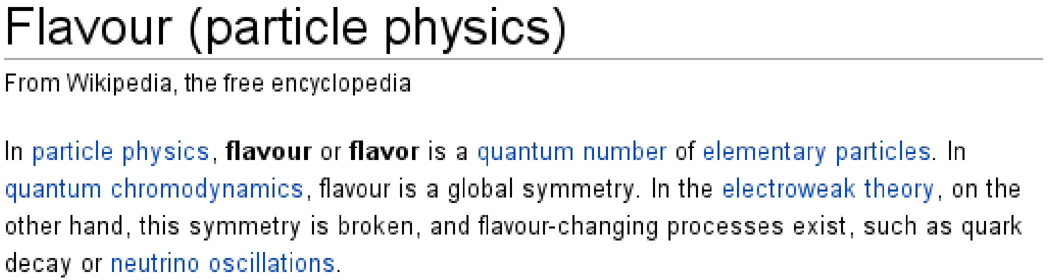
Flavour physics



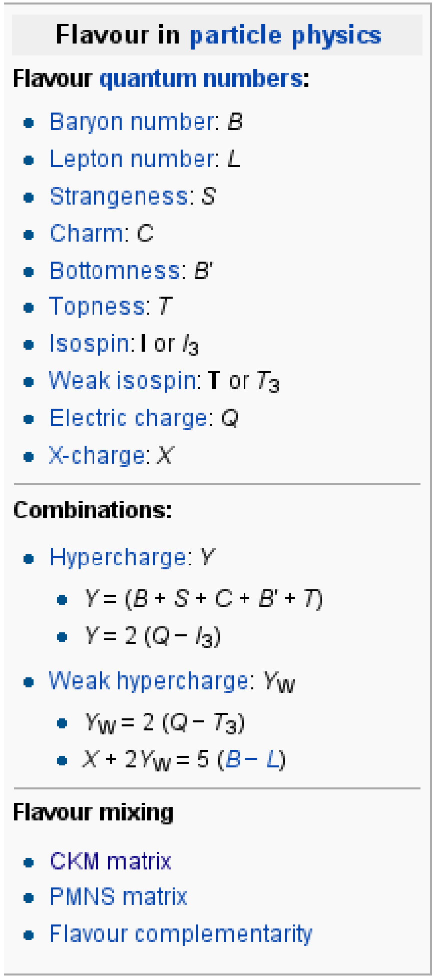
Flavour (particle physics)

From Wikipedia, the free encyclopedia

In particle physics, **flavour** or **flavor** is a quantum number of elementary particles. In quantum chromodynamics, flavour is a global symmetry. In the electroweak theory, on the other hand, this symmetry is broken, and flavour-changing processes exist, such as quark decay or neutrino oscillations.

> “The term flavor was first used in particle physics in the context of the quark model of hadrons. It was coined in 1971 by Murray Gell-Mann and his student at the time, Harald Fritzsch, at a Baskin-Robbins ice-cream store in Pasadena. Just as ice cream has both color and flavor so do quarks.”

RMP 81 (2009) 1887



Flavour in particle physics

Flavour quantum numbers:

- Baryon number: B
- Lepton number: L
- Strangeness: S
- Charm: C
- Bottomness: B'
- Topness: T
- Isospin: **I** or I_3
- Weak isospin: **T** or T_3
- Electric charge: Q
- X-charge: X

Combinations:

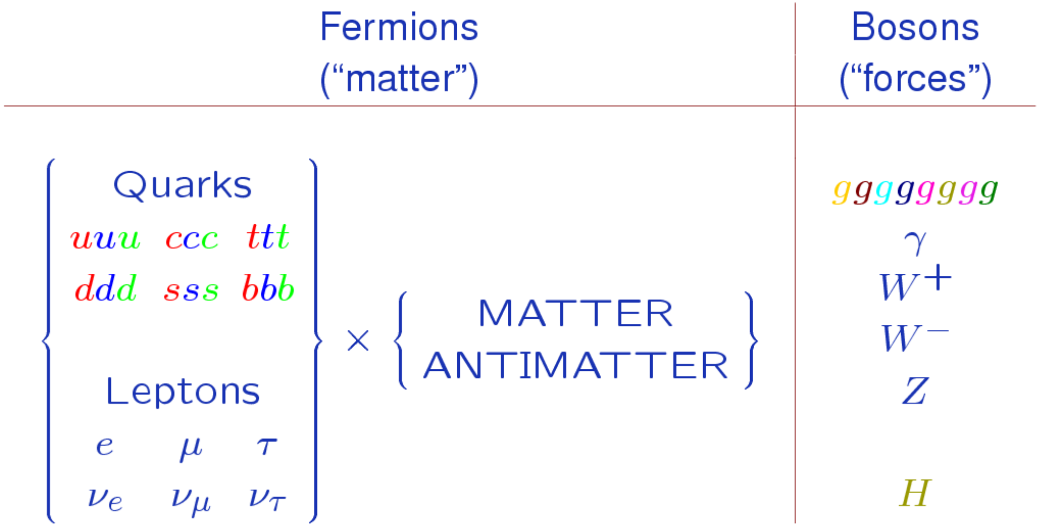
- Hypercharge: Y
  - $Y = (B + S + C + B' + T)$
  - $Y = 2\,(Q - I_3)$
- Weak hypercharge: Y_W
  - $Y_W = 2\,(Q - T_3)$
  - $X + 2Y_W = 5\,(B - L)$

Flavour mixing

- CKM matrix
- PMNS matrix
- Flavour complementarity

Mysteries of flavour physics

- Why so many fermions?
- What explains
  - the mixing patterns?
  - the matter-antimatter asymmetries (CP violation)?
- Are there connections between quarks and leptons?



Fermions ("matter")

Quarks

uuu ccc ttt

ddd sss bbb

Leptons

e μ τ

ν_e ν_μ ν_τ

× MATTER ANTIMATTER

Bosons ("forces")

$gggggggg$

γ

W^+

W^-

Z

H

Quark (and lepton) mixing

- Quarks acquire mass after electroweak symmetry breaking
  - Separate 3x3 mass matrices for “up-type” and “down-type” quarks (weak isospin +½ or –½)
- Eigenstates of these matrices different for weak interactions and Yukawa interactions
  - Require diagonalisation matrix to convert between bases
- Diagonalisation different for “up-type” and “down-type” quarks
  - Relative misalignment: CKM matrix (Cabibbo, Kobayashi, Maskawa)

CP violation

- Concluding words of Dirac’s 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.”

- In fact there are no “anti-stars” because there is **not** complete symmetry between matter and antimatter → CP violation

The CKM matrix

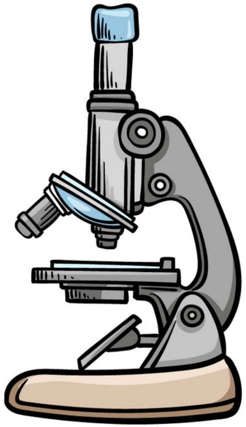
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- A 3x3 unitary matrix
  - Encodes relative misalignment of mass and flavour bases that arises in the Standard Model following electroweak symmetry breaking (Higgs mechanism)
- Described by 4 real parameters – allows CP violation (KM: Prog.Theor.Phys. 49 (1973) 652)
- Highly predictive
  - Describes phenomena at energies from nuclear β decay to top quark decays

Particularly interesting to study the b quark …
which means studies of b hadrons (important role of QCD)

The flavour ~~micro~~zeptoscope

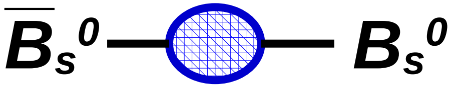
- Flavour physics provides a wide range of Standard Model tests
  - Genuine potential for discovery of physics beyond
- SM structure is distinctive, and need not be replicated BSM
  - Absence of tree-level flavour-changing neutral currents
  - V-A structure of the charged current
  - Universality of couplings to different leptons
- Quark mixing (CKM matrix) described by only 4 parameters
  - Highly overconstrained → allows powerful consistency tests
- Sensitivity limited by precision
  - For theoretically clean channels, this means data sample size

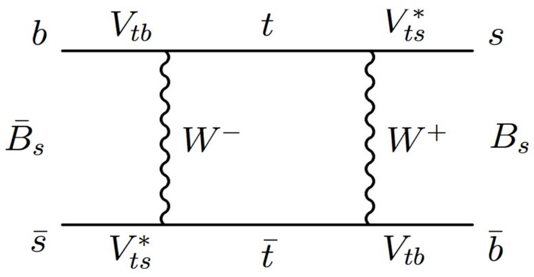


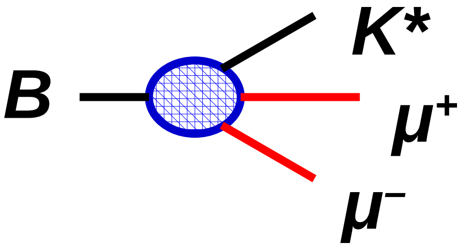
iHeartCraftyThings.com

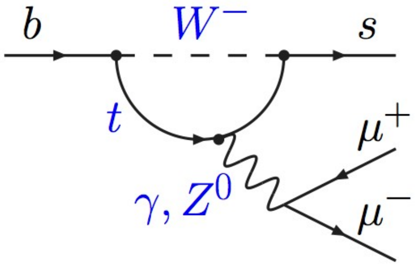
Seeing and inferring

- Weak decays of b hadrons involve virtual mediators
- We only “see” the final state particles
  - but can “infer” information about the mediators
  - advantage: not limited by energy of collisions
  - loop processes particularly interesting due to SM structure
- Formally, use effective field theory









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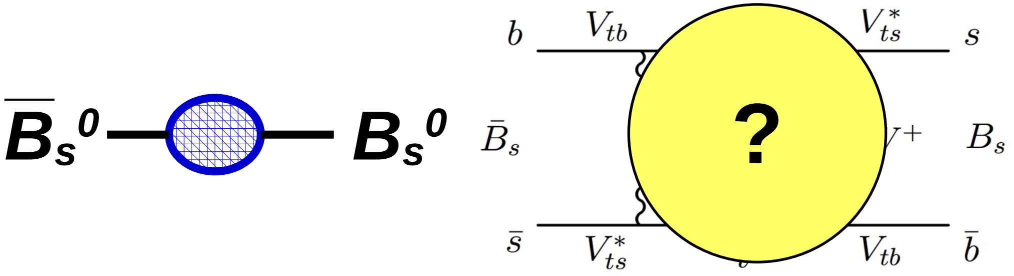
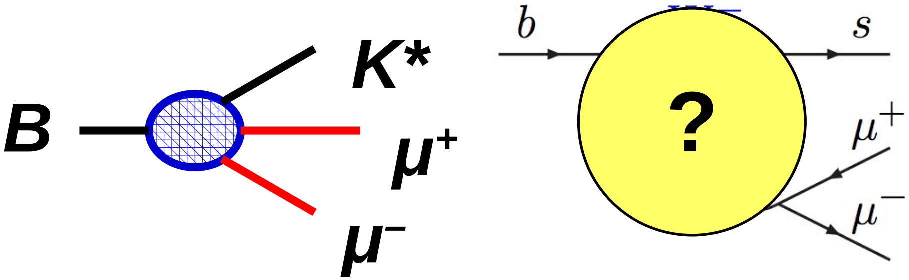
? could be at O(10 TeV)

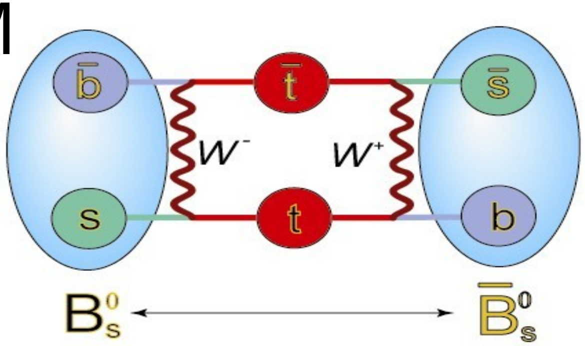




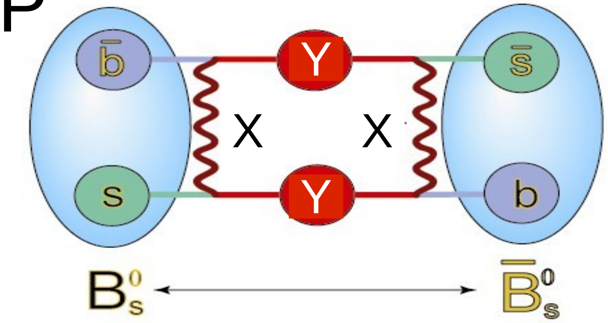
Loop diagrams for discovery

- Contributions from virtual particles in loops allow to probe far beyond the energy frontier
- History shows this approach to be a powerful discovery tool
- Interplay with high-p_T experiments:
  - NP discovered: probe the couplings
  - NP not discovered: explore high energy parameter space

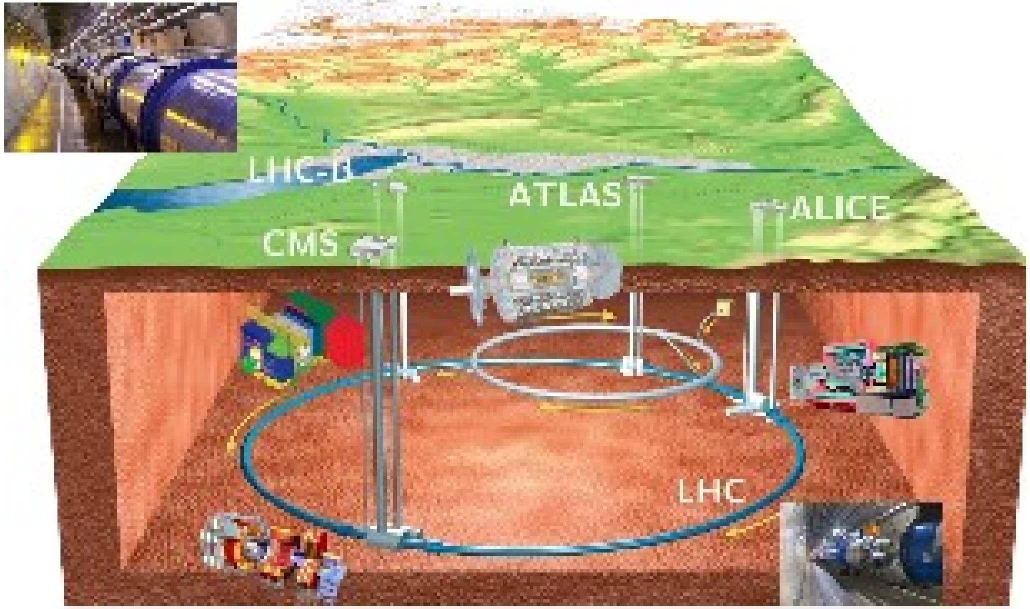
SM

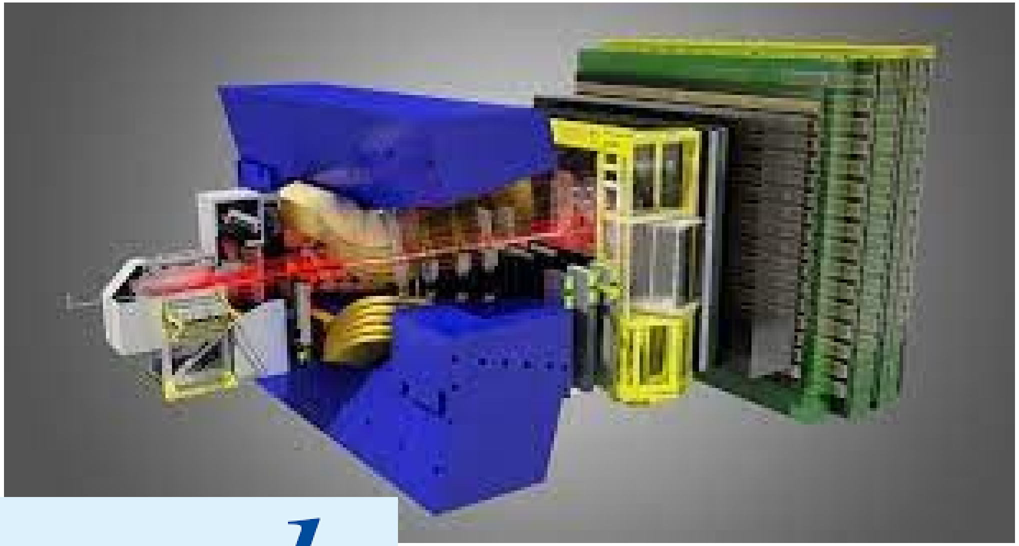


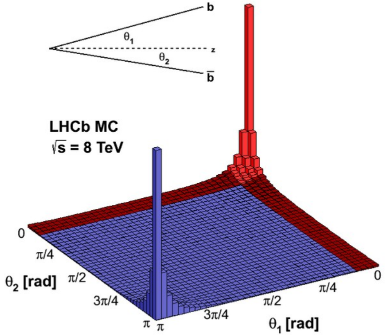
NP



LHCb experiment at CERN







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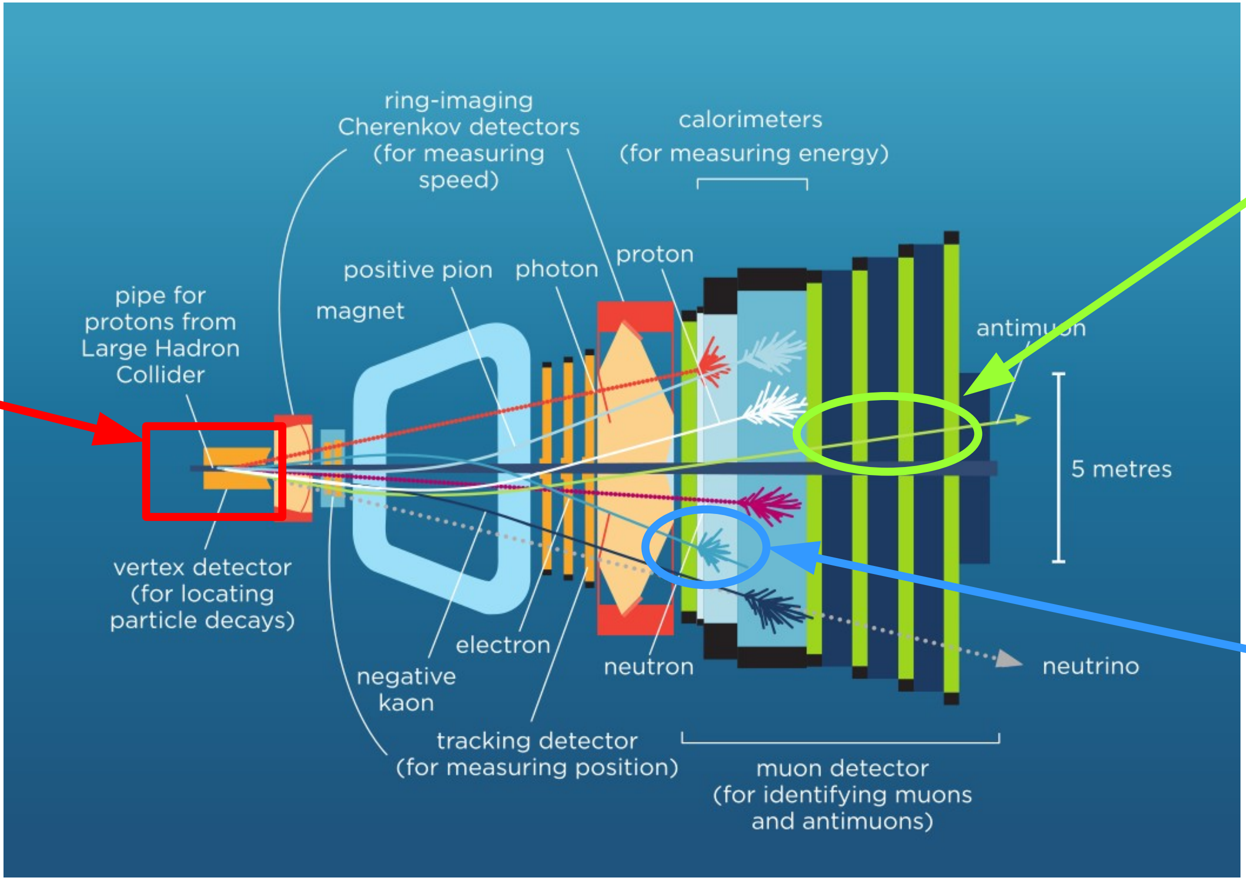


Proton proton collisions occur inside vertex detector

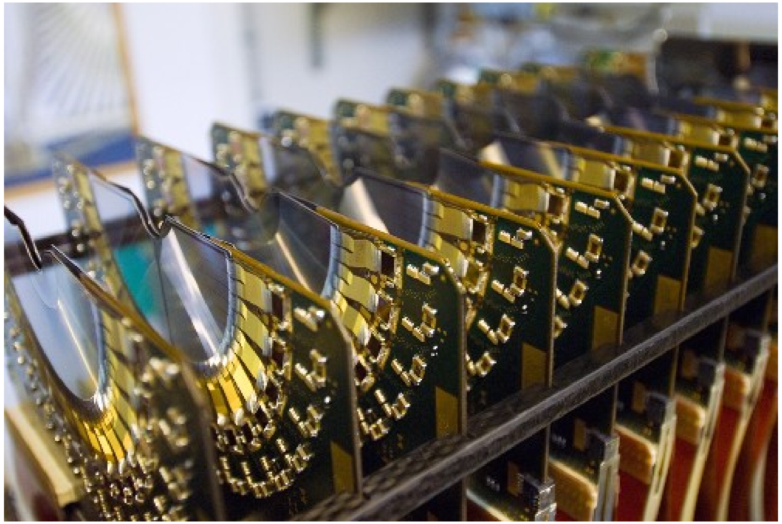
B particles produced in forward direction

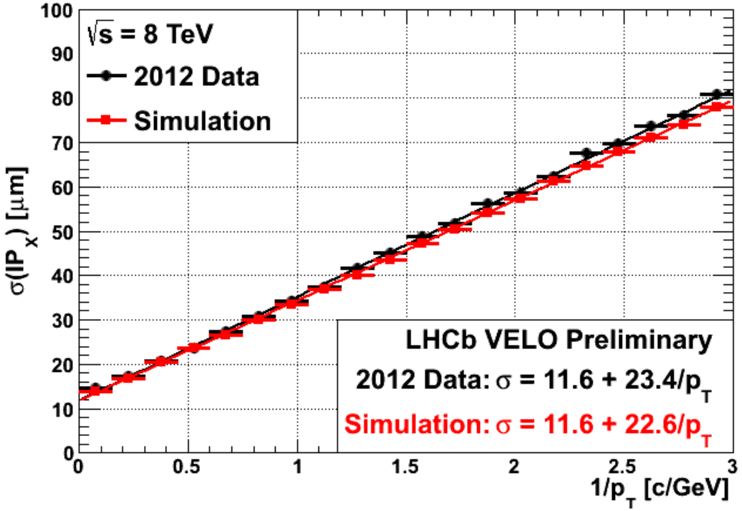
These decay rapidly to particles that traverse the detector

Muons penetrate detector & reach muon counters

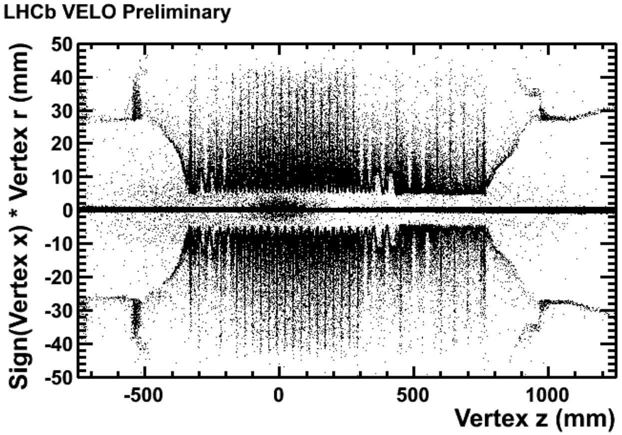
Electrons deposit all their energy in calorimeter

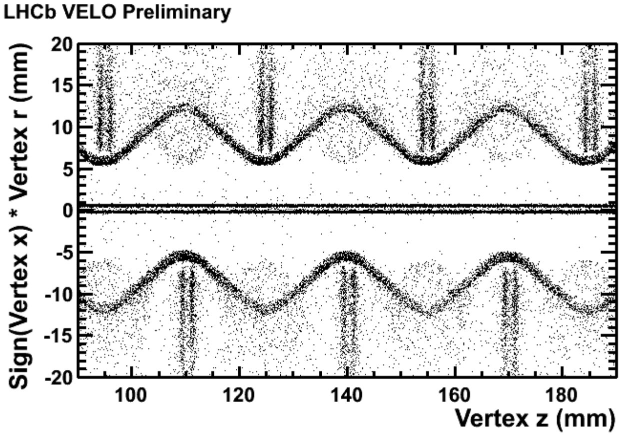
VELO



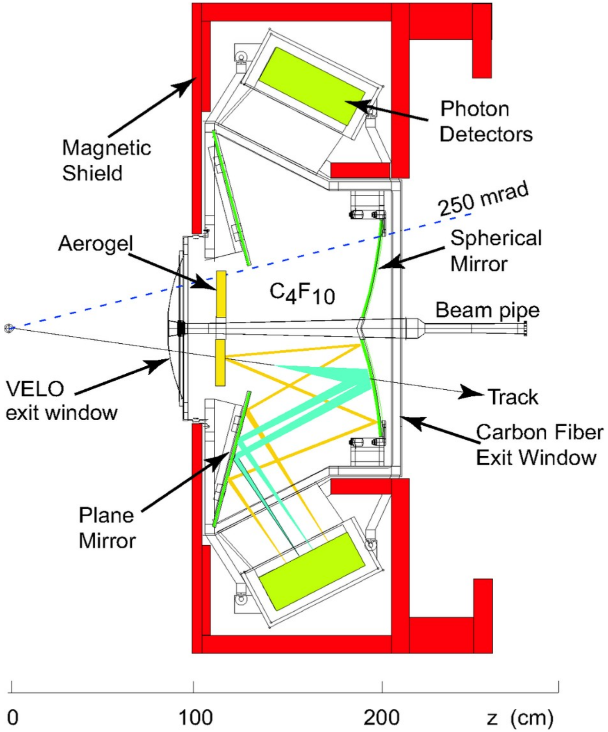


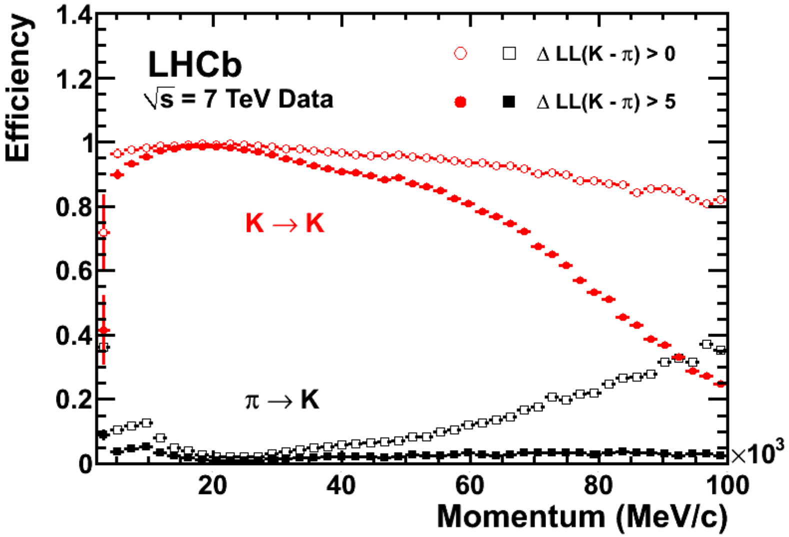
Material imaged used beam gas collisions



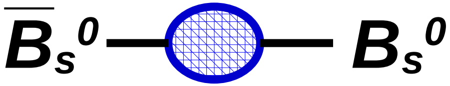


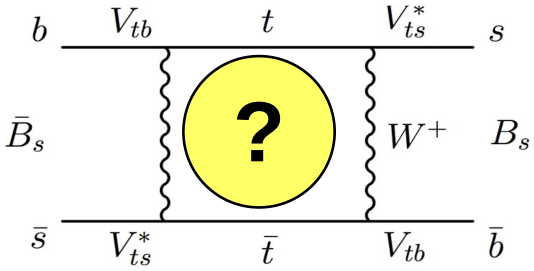
RICH


Magnetic Shield
Photon Detectors
250 mrad
Aerogel
Spherical Mirror
C4F10
Beam pipe
VELO exit window
Track
Carbon Fiber Exit Window
Plane Mirror
0
100
200
z (cm)


Efficiency
1.4
1.2
1
0.8
0.6
0.4
0.2
0
LHCb
√s = 7 TeV Data
○ □ Δ LL(K - π) > 0
● ■ Δ LL(K - π) > 5
K → K
π → K
×10³
20
40
60
80
100
Momentum (MeV/c)

Quantum oscillations





To measure rate of this process in which a $\bar{B}_s^0$ meson “oscillates” into B_s^0 (or vice versa) need to

- Measure flavour ($B_{(s)}^0$ or $\bar{B}_{(s)}^0$) at production
  - “flavour tagging” from properties of other particles produced at same time
- Measure flavour at decay
  - use flavour-specific decay like $B_s^0 \rightarrow D_s^- \pi^+$
- Measure time between production and decay
  - $\Delta z = \beta\gamma c \Delta t$

βγ are Lorentz boost factors

B_s^0 mixing rate

Nature Phys. 18 (2022) 1

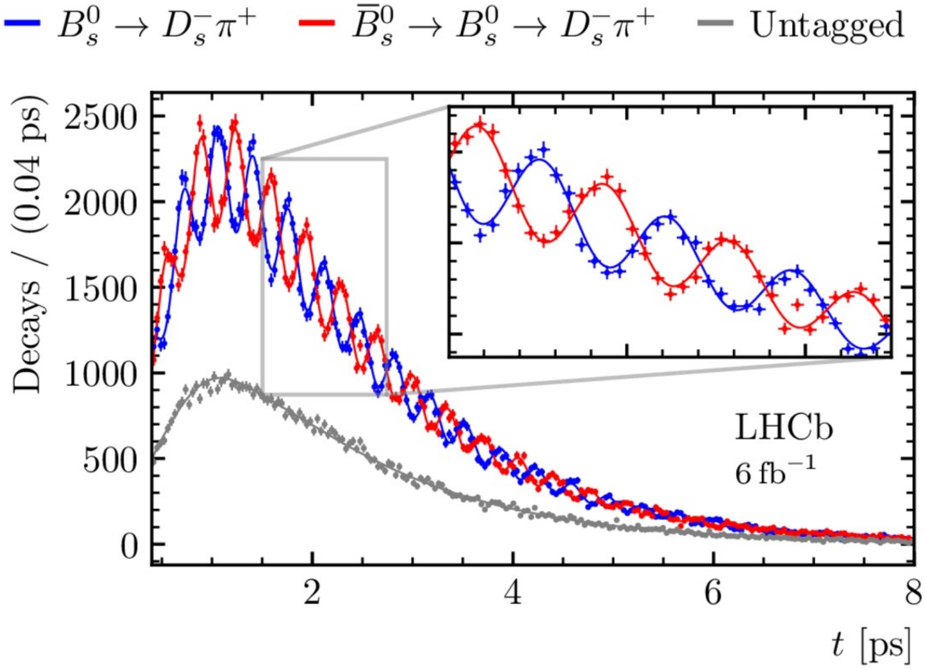
Clear difference between cases where flavour is same or different between production and decay

B_s^0 oscillates much faster than it decays!

- experimental challenge to resolve oscillations overcome

Period of oscillation related to mass difference (Δm_s)

Measurement consistent with Standard Model prediction



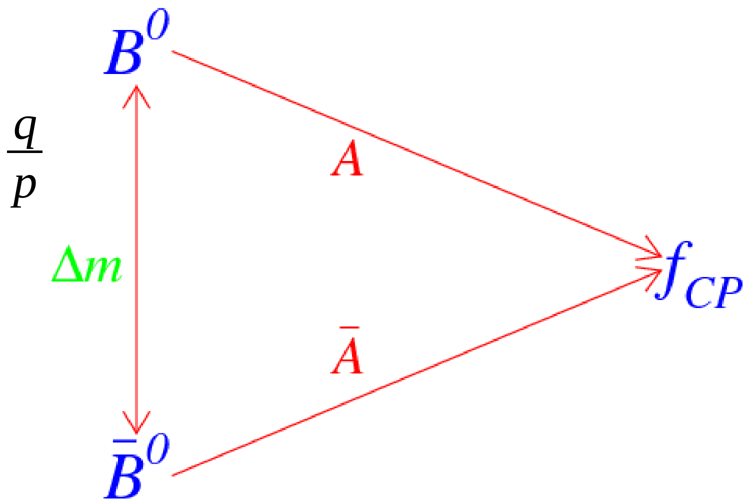
$\Delta m_s = 17.7683 \pm 0.0051 \pm 0.0032\ \mathrm{ps}^{-1}$

Quantum oscillations, with CP violation

- For a B meson known to be 1) B^0 or 2) $\overline{B}^0$ at time t=0, then at later time t:

$$\Gamma\left(B^0_{phys}\rightarrow f_{CP}(t)\right)\propto e^{-\Gamma t}\left(1-\left(S\sin(\Delta m t)-C\cos(\Delta m t)\right)\right)$$

$$\Gamma\left(\overline{B}^0_{phys}\rightarrow f_{CP}(t)\right)\propto e^{-\Gamma t}\left(1+\left(S\sin(\Delta m t)-C\cos(\Delta m t)\right)\right)$$



$$S=\frac{2\Im(\lambda_{CP})}{1+|\lambda^2_{CP}|}\qquad C=\frac{1-|\lambda^2_{CP}|}{1+|\lambda^2_{CP}|}\qquad \lambda_{CP}=\frac{q}{p}\frac{\bar{A}}{A}$$

For B^0 → $J/\psi\ K_S$, $S=\sin(2\beta)$, $C=0$

NPB 193 (1981) 85

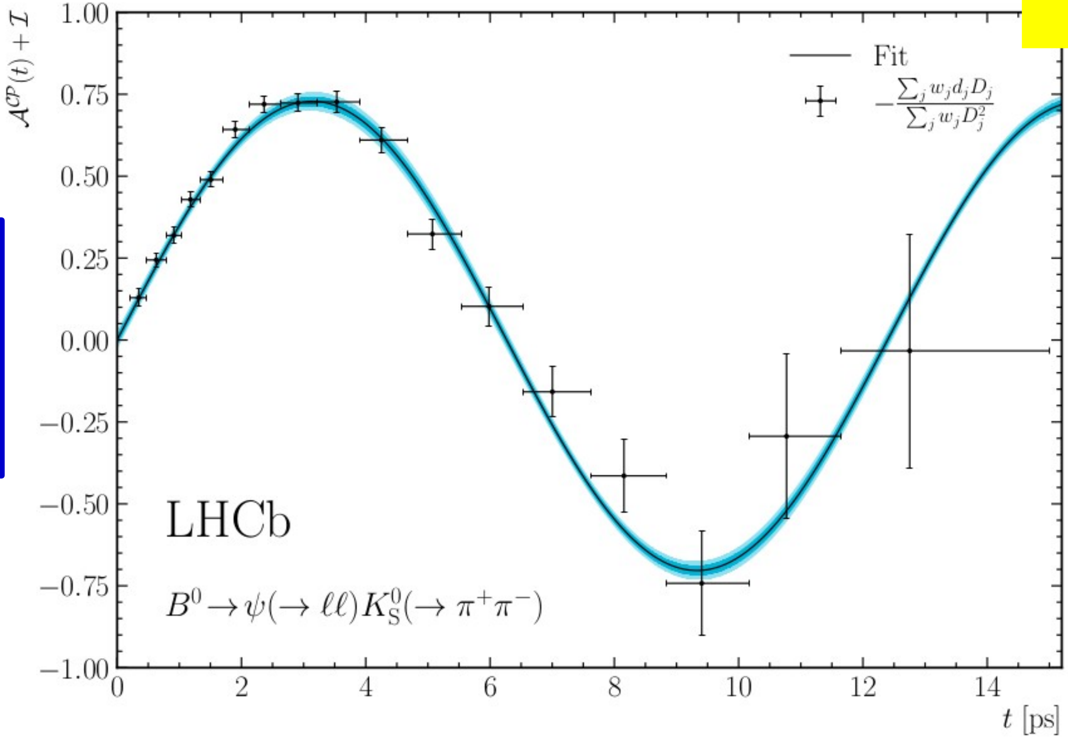
$$\beta = \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$

sin(2β) from $B^0 \to J/\psi K_S$

LHCb-PAPER-2023-013
arXiv:2309.09728

τ(B^0) = 1.52 ps

Range of plot covers ten B^0 lifetimes!



sin(2β) = 0.717 ± 0.013 (stat) ± 0.008 (syst)

$$\gamma = \arg\left[-\frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}}\right]$$

γ from B → DK

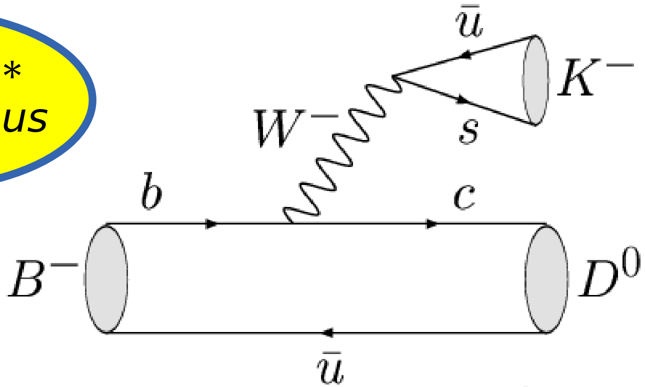
- γ plays a unique role in flavour physics

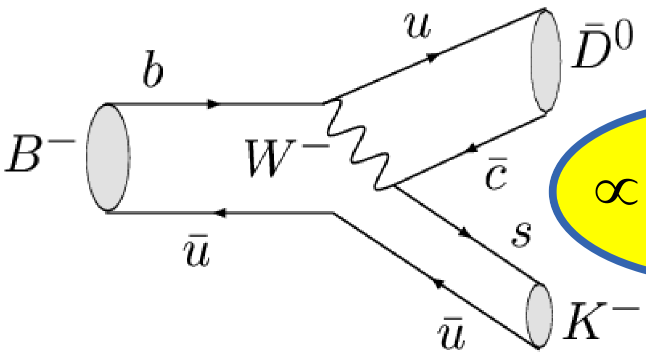
the only CP violating parameter that can be measured through tree decays

- A benchmark Standard Model reference point

doubly important after New Physics is observed

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





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

require a final state common to both D^0 and $\bar{D}^0$

$$\gamma = \arg\left[-\frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}}\right]$$

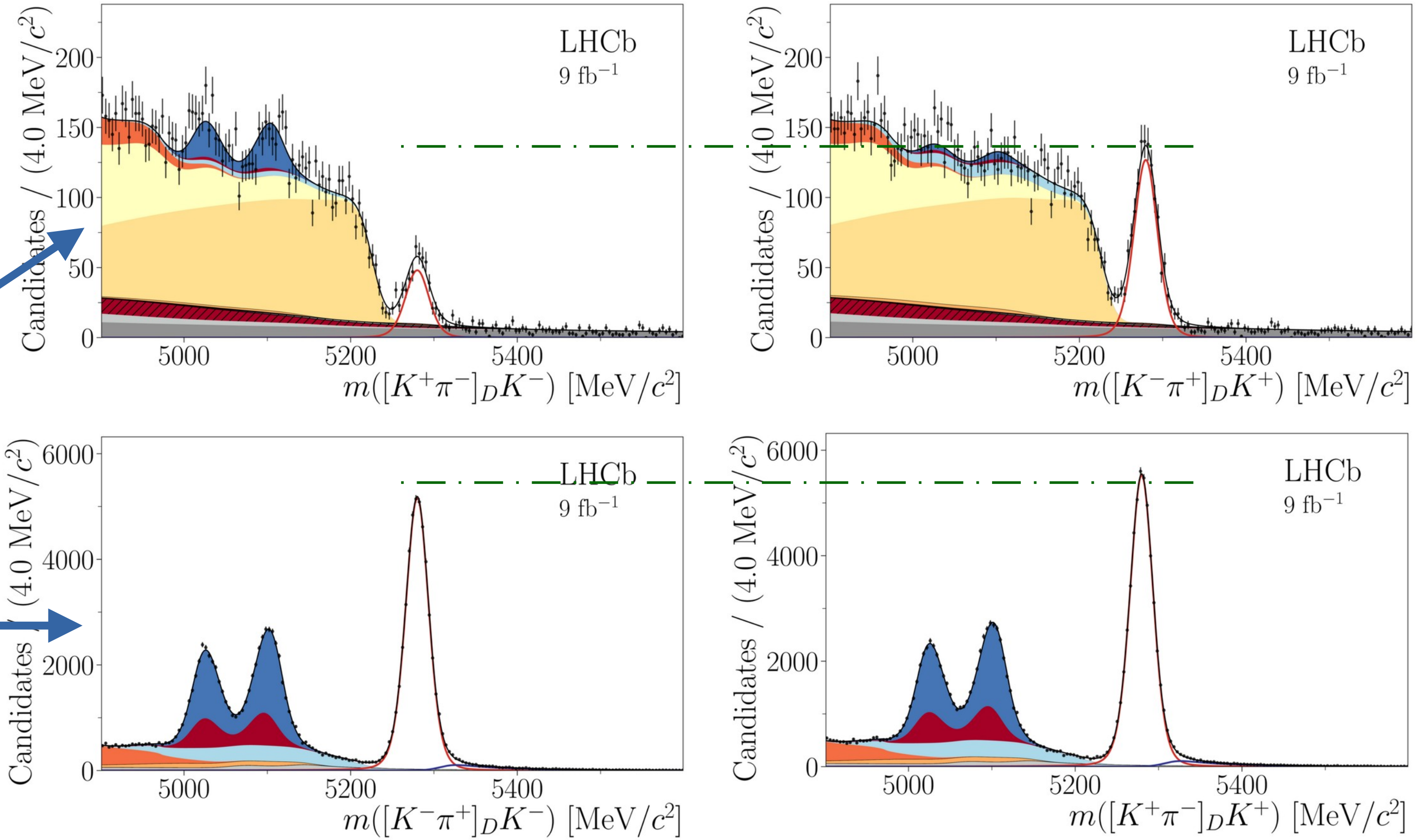
γ from $B^{+/-} \rightarrow DK^{+/-}$

JHEP 04 (2021) 081

Neutral D meson different admixture of D^0 and $\overline{D}^0$ depending on final state

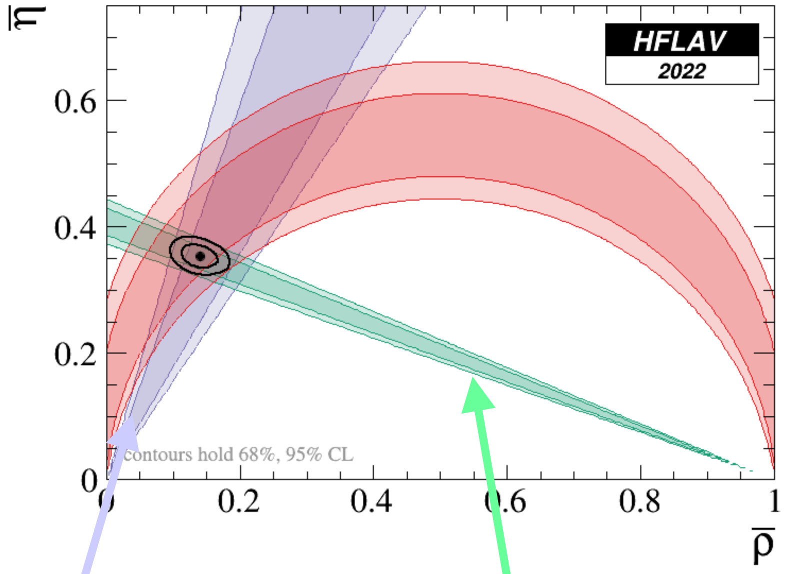
Suppressed mode: enhanced CP violation as two amplitudes of comparable magnitude

Favoured mode: little CP violation (but important to control systematics)

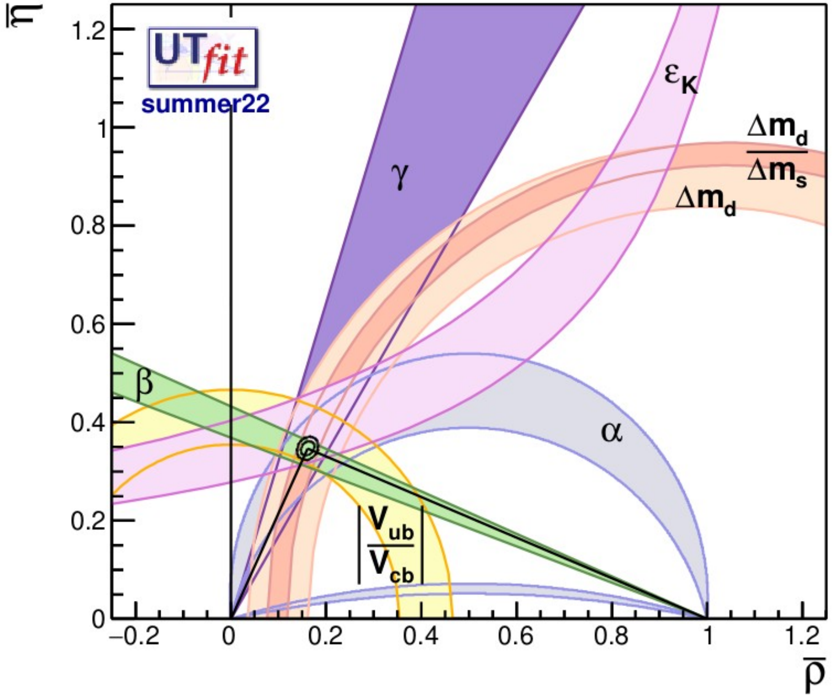


The CKM description of CP violation

arXiv:2206.07501



arXiv:2212.03894



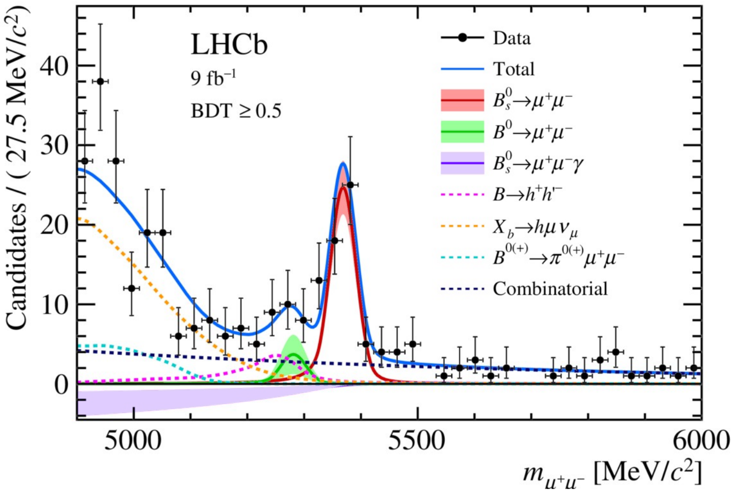
Decay-time dependent asymmetry in $B^0 \rightarrow J/\psi K^0$

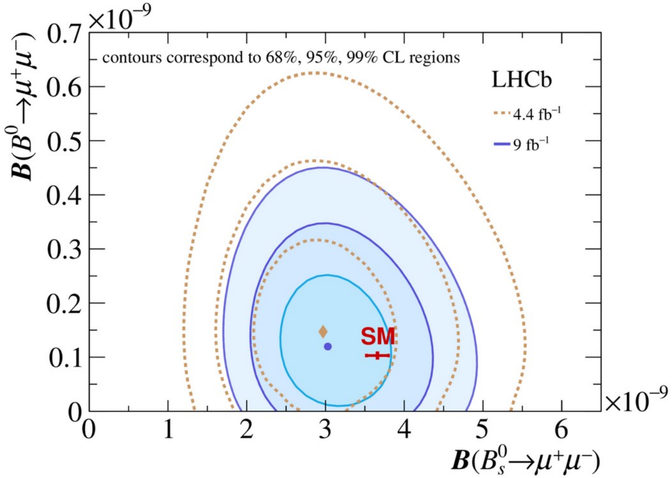
Partial rate asymmetries in $B^{+/-} \rightarrow DK^{+/-}$

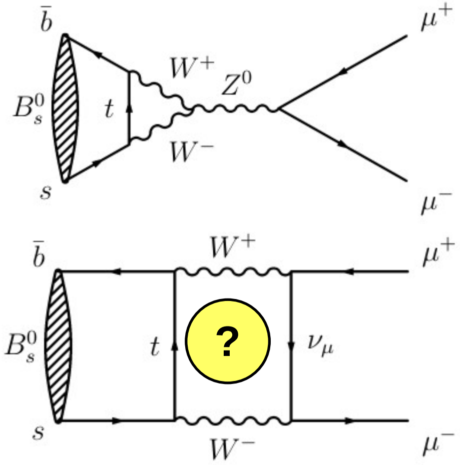
All constraints from different measurements overlap!

Testing the SM with highly suppressed $B_{(s)}^0 \to \mu^+\mu^-$

PRL 128 (2022) 041801







$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) \;=\; \left(3.09\,^{+0.46}_{-0.43}\,^{+0.15}_{-0.11}\right) \times 10^{-9}$$

c.f. SM: $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$

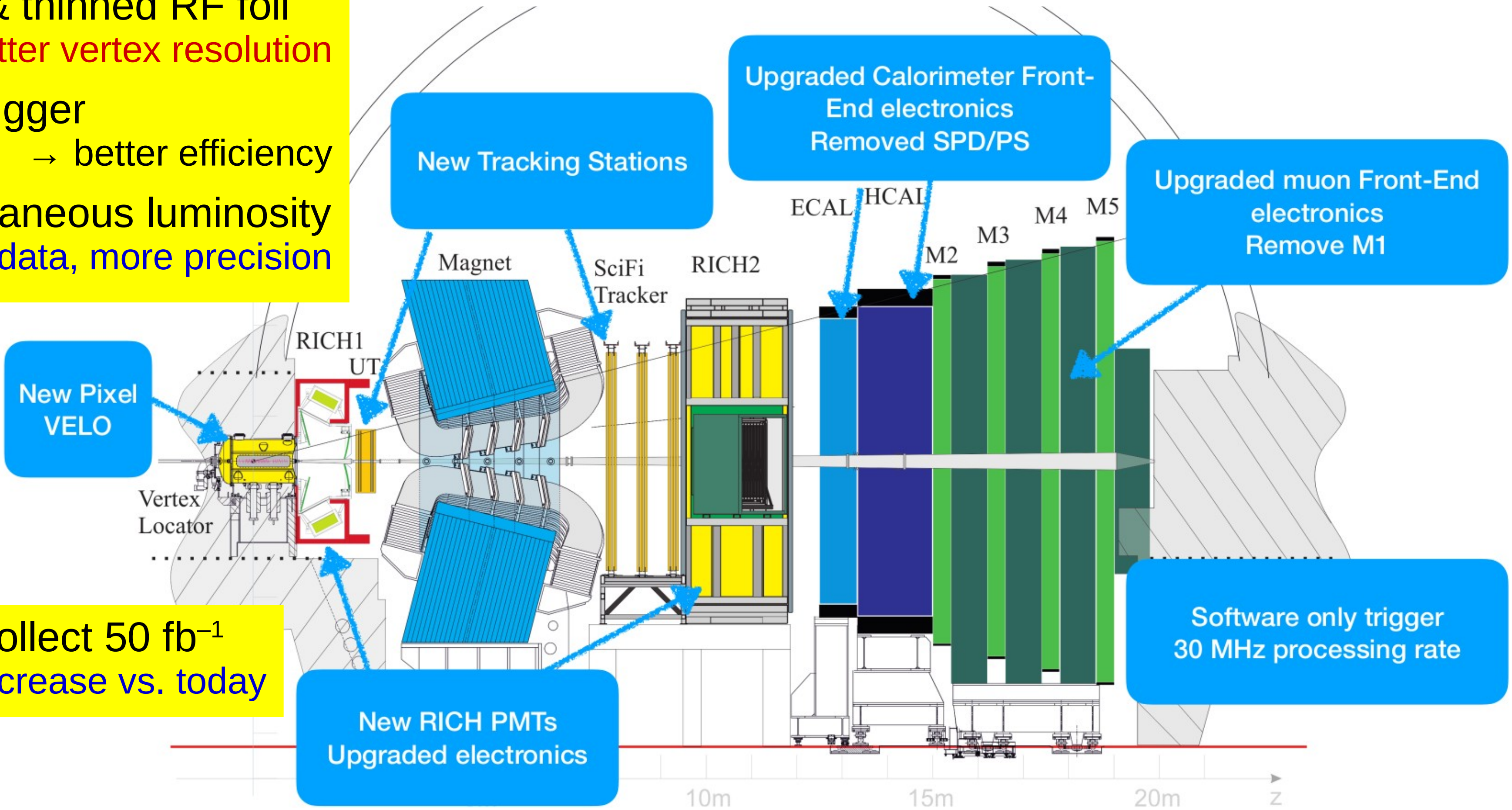
See also CMS PL B842 (2023) 137955
and ATLAS JHEP 04 (2019) 098

LHCb Upgrade I

VELO pixels & thinned RF foil
→ better vertex resolution

All software trigger
→ better efficiency

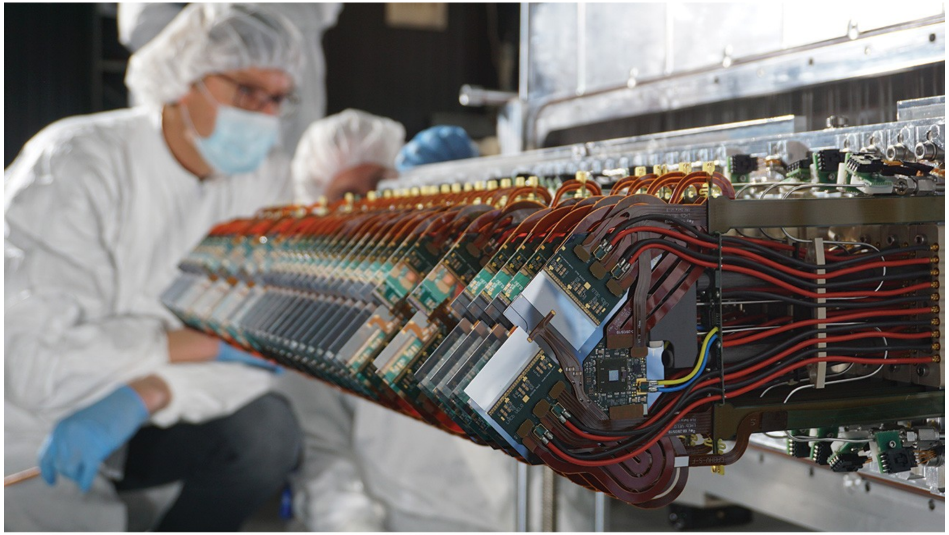
Higher instantaneous luminosity
→ more data, more precision

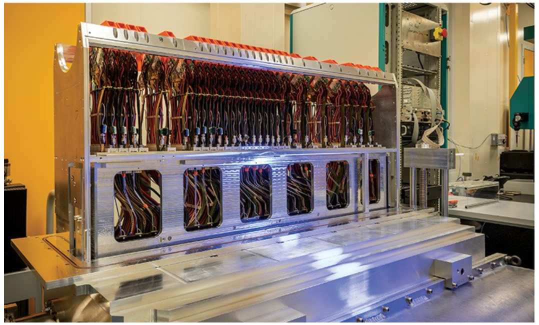


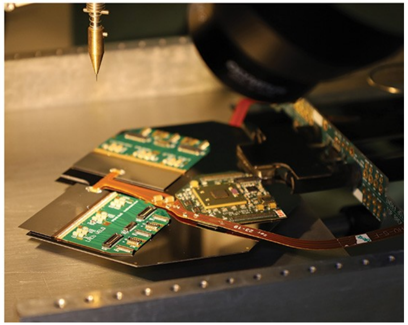
Designed to collect 50 fb^{-1}
→ ×10 data increase vs. today

Pixel VELO

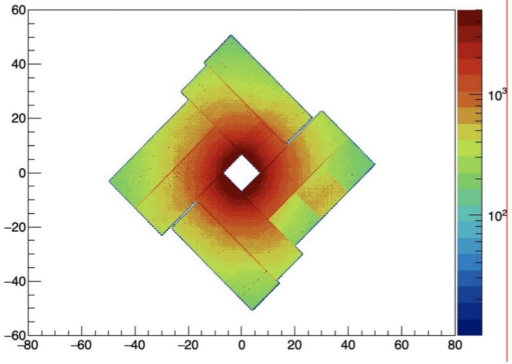
Identification of displaced vertices crucial to identify B decays at hadron colliders

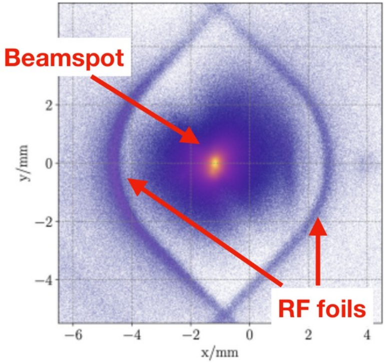


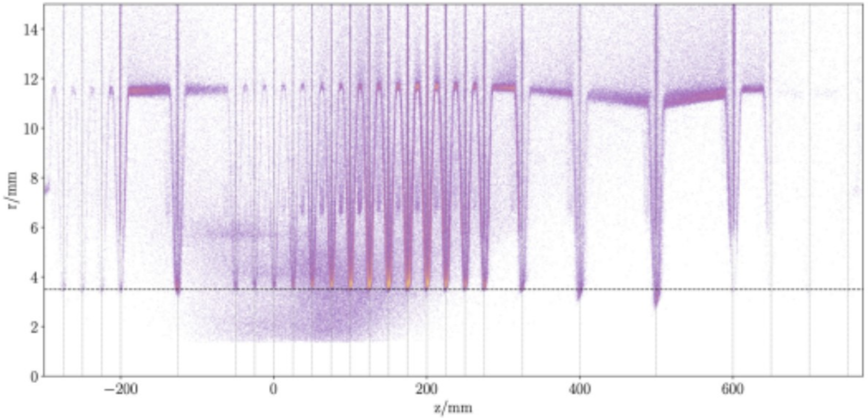




Commissioning ongoing!







Data processing at 30 MHz

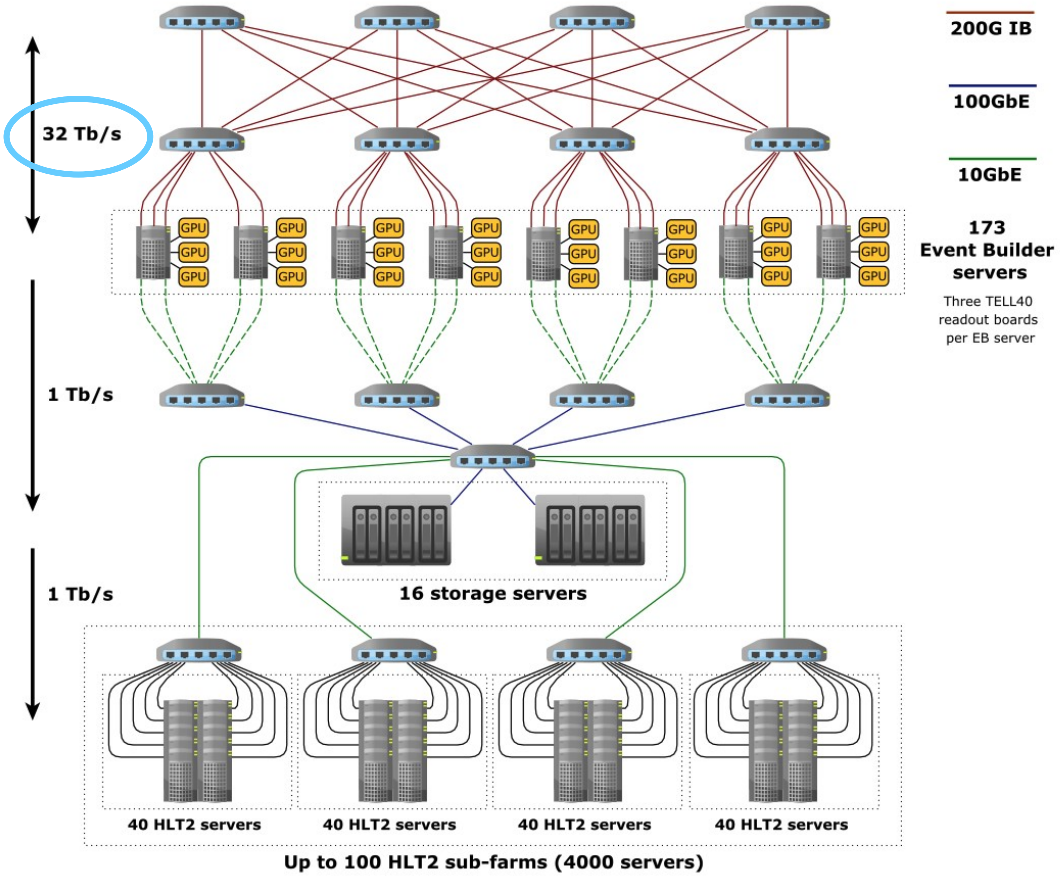
Traditional HEP trigger model:
 – select interesting events with loose criteria for later offline analysis

At high luminosity, every pp bunch-crossing contains a potentially interesting event

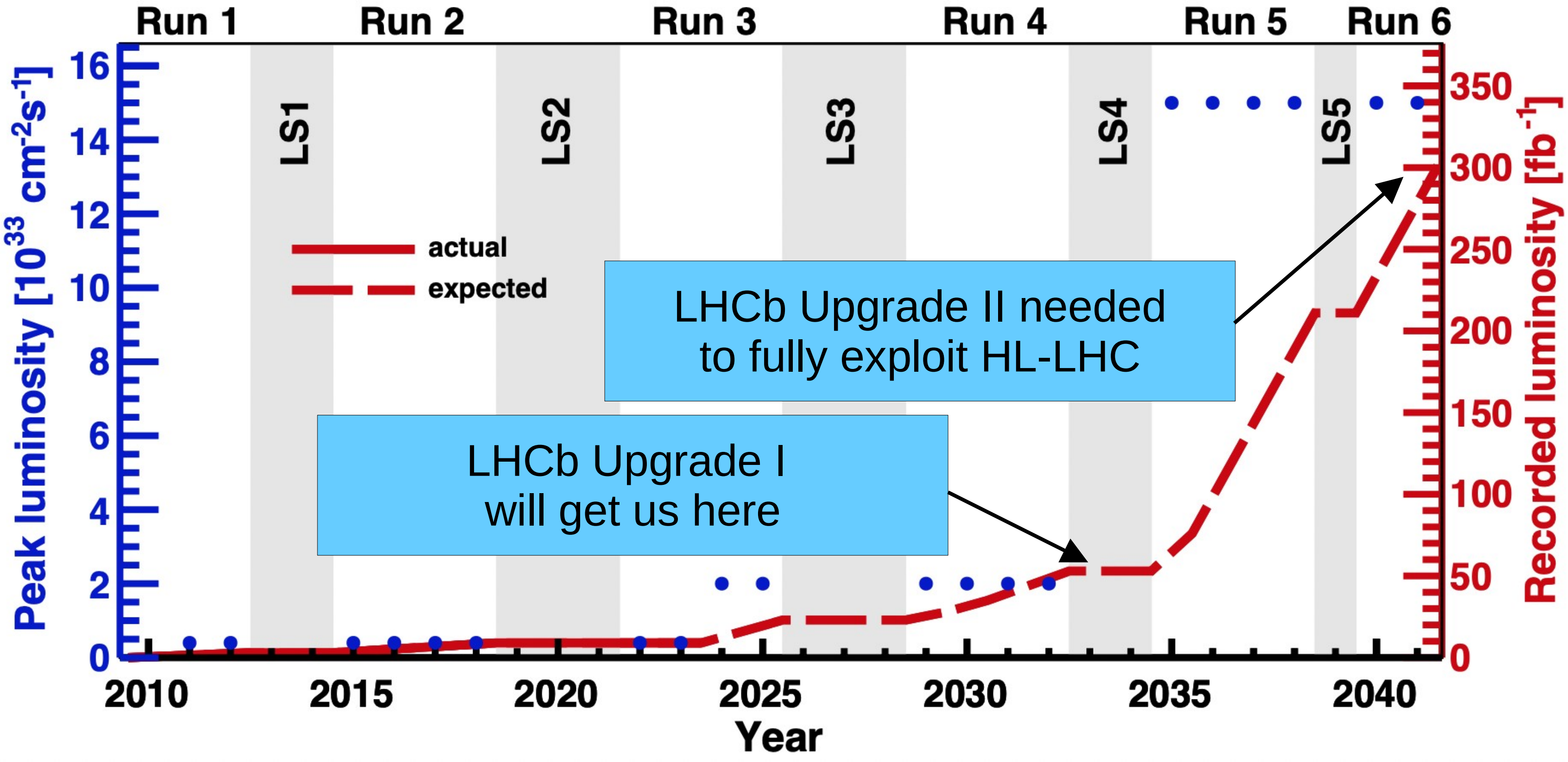
Need a new paradigm
 – full software trigger
 – first level trigger (HLT1) implemented in GPUs
 – offline quality reconstruction: calibration and alignment performed before HLT2
 – select relevant information in each event to store for offline analysis

n.b:
data rate from LHCb detector (32 Tb/s)
global internet traffic 2022 (997 Tb/s)

Comput.Softw.Big Sci. 6 (2022) 1



Why stop there?



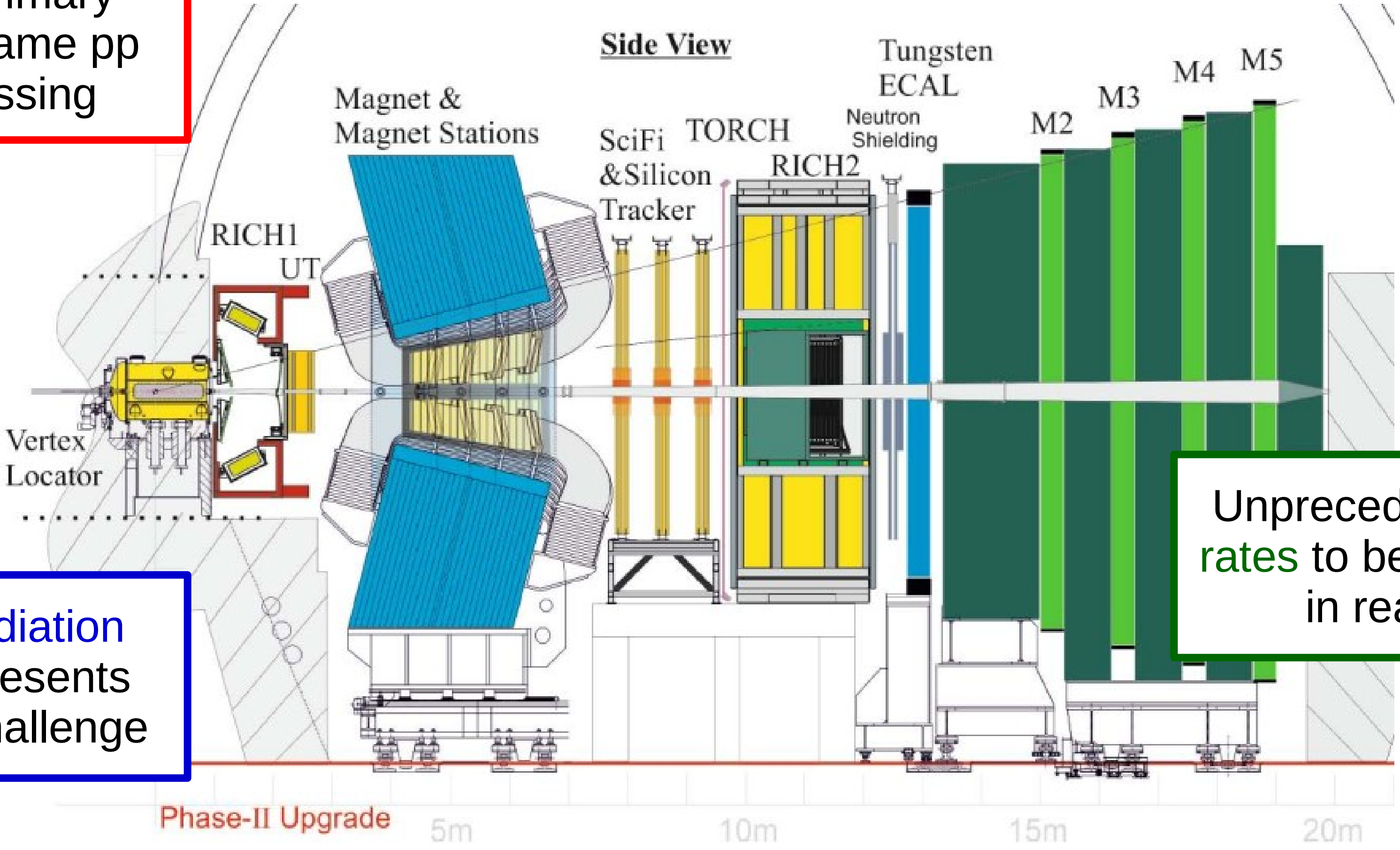
LHCb Upgrade II needed
to fully exploit HL-LHC

LHCb Upgrade I
will get us here

LHCB-TDR-023

LHCb Upgrade II

Crucial to use precision timing information to separate primary vertices in same pp bunch crossing



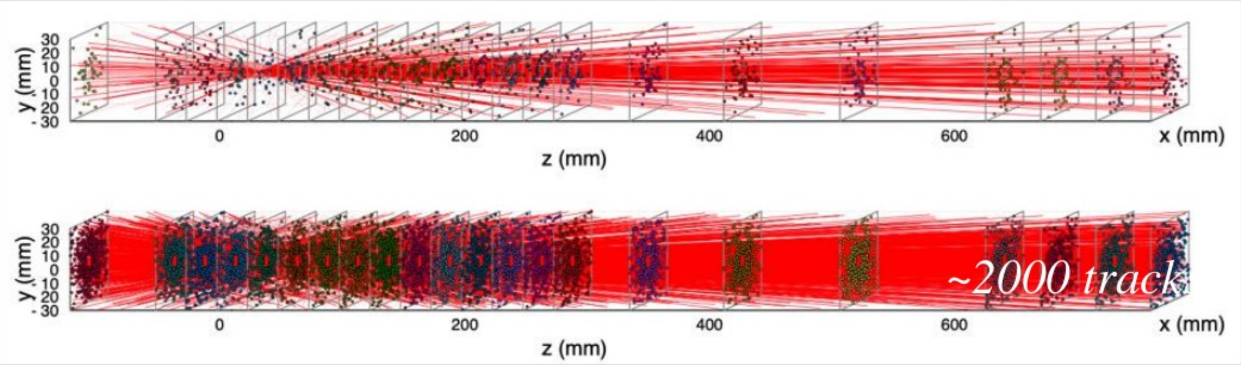
Need for radiation hardness presents significant challenge

Unprecedented data rates to be processed in real time

The need for timing

Run 3: pile-up ~5

Upgrade II: pile-up ~40

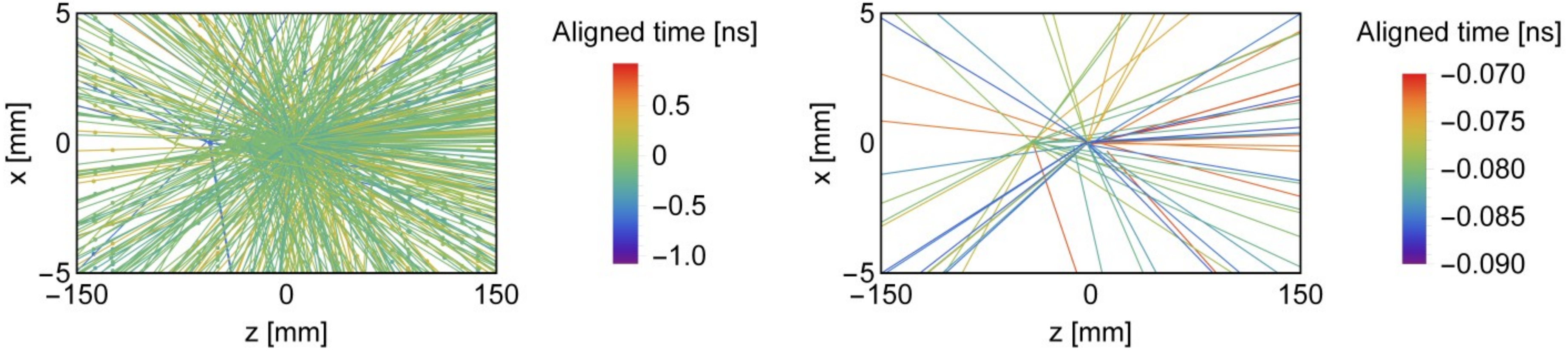


In VELO

~6 cm

- High LHC luminosity achieved by increasing number of pp interactions per bunch crossing
- Large detector occupancies → many possible fake combinations
- But LHC bunches are long (~50 mm); collisions in each bunch crossing occur over ~0.2 ns
- Detection with ~20 ps resolution per track gives new handle to associate hits correctly

The need for timing



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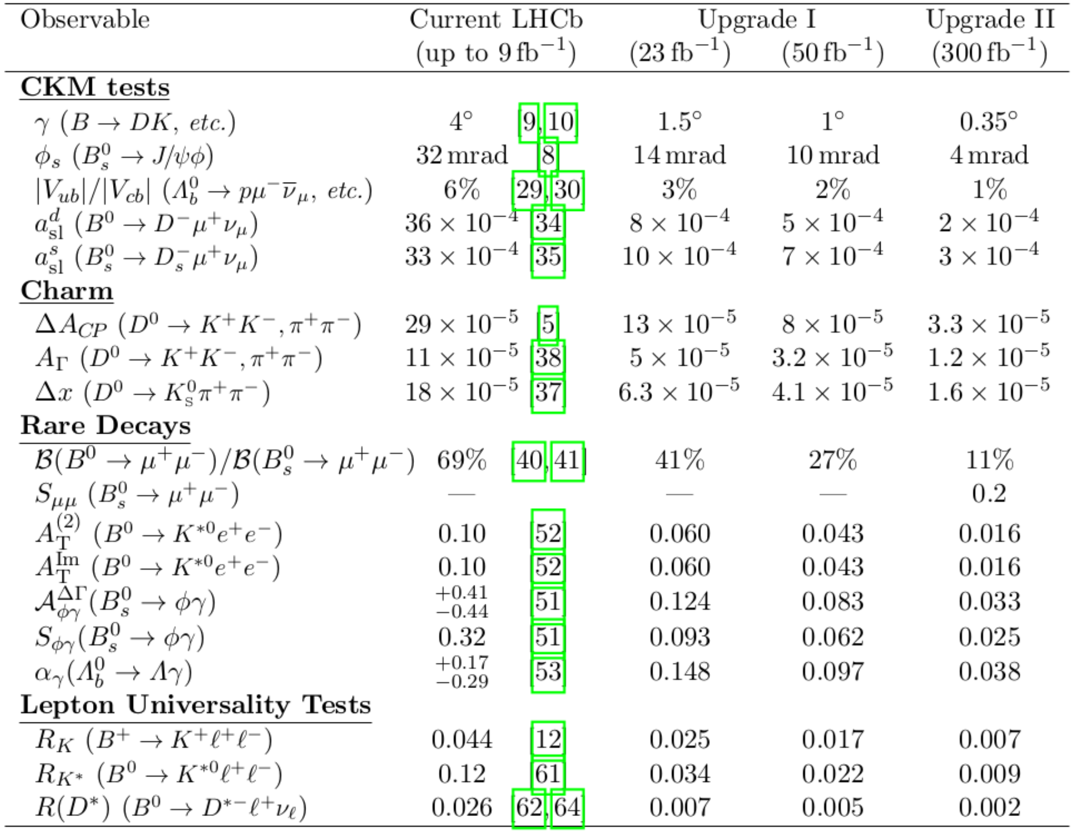
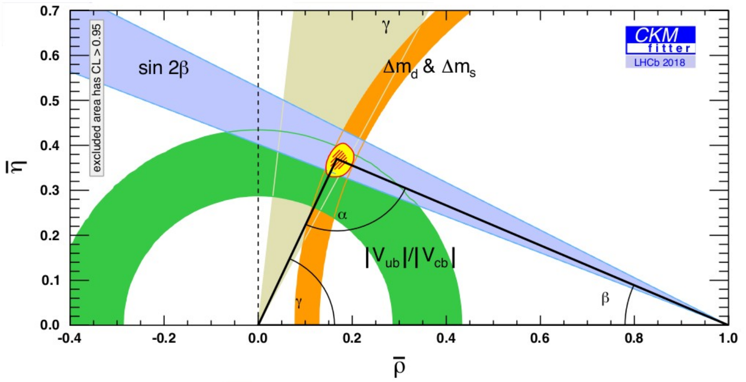
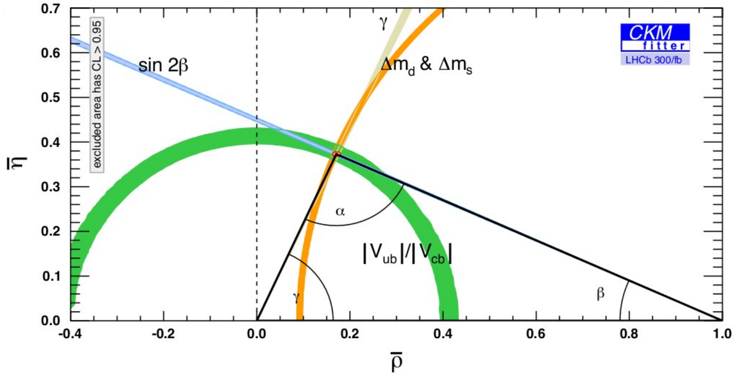
LHCb Upgrade II physics impact

LHCB-TDR-023



Observable	Current LHCb (up to 9 fb^{-1})		Upgrade I (23 fb^{-1})	Upgrade I (50 fb^{-1})	Upgrade II (300 fb^{-1})
CKM tests					
γ ($B \to DK$, *etc.*)	4°	[9, 10]	1.5°	1°	0.35°
ϕ_s ($B_s^0 \to J/\psi\phi$)	32 mrad	[8]	14 mrad	10 mrad	4 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6%	[29, 30]	3%	2%	1%
$a_{\rm sl}^d$ ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4}	[34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
$a_{\rm sl}^s$ ($B_s^0 \to D_s^-\mu^+\nu_\mu$)	33×10^{-4}	[35]	10×10^{-4}	7×10^{-4}	3×10^{-4}
Charm					
ΔA_{CP} ($D^0 \to K^+K^-, \pi^+\pi^-$)	29×10^{-5}	[5]	13×10^{-5}	8×10^{-5}	3.3×10^{-5}
A_Γ ($D^0 \to K^+K^-, \pi^+\pi^-$)	11×10^{-5}	[38]	5×10^{-5}	3.2×10^{-5}	1.2×10^{-5}
Δx ($D^0 \to K_{\rm S}^0\pi^+\pi^-$)	18×10^{-5}	[37]	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}
Rare Decays					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	69%	[40, 41]	41%	27%	11%
$S_{\mu\mu}$ ($B_s^0 \to \mu^+\mu^-$)	—		—	—	0.2
$A_{\rm T}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$A_{\rm T}^{\rm Im}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$\mathcal{A}_{\phi\gamma}^{\Delta\Gamma}(B_s^0 \to \phi\gamma)$	$^{+0.41}_{-0.44}$	[51]	0.124	0.083	0.033
$S_{\phi\gamma}(B_s^0 \to \phi\gamma)$	0.32	[51]	0.093	0.062	0.025
$\alpha_\gamma(\Lambda_b^0 \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$	[53]	0.148	0.097	0.038
Lepton Universality Tests					
R_K ($B^+ \to K^+\ell^+\ell^-$)	0.044	[12]	0.025	0.017	0.007
R_{K^*} ($B^0 \to K^{*0}\ell^+\ell^-$)	0.12	[61]	0.034	0.022	0.009
$R(D^*)$ ($B^0 \to D^{*-}\ell^+\nu_\ell$)	0.026	[62, 64]	0.007	0.005	0.002





Summary

- Flavour physics provides a powerful zeptoscope to probe the smallest scales
  - complementary to Higgs physics and high energy probes
- LHCb experiment has achieved incredible successes, exploiting huge $b\bar{b}$ production rate in LHC collisions
  - some tensions with SM predictions to be understood
- Exciting prospects for 2020s with LHCb Upgrade I
- Developing technology for LHCb Upgrade II to operate throughout 2030s
  - unique potential to test the Standard Model with many discovery opportunities
  - I hope some of you will come and join us in this adventure