Introduction to Flavour Physics
(from an experimental point of view)

Angelo Carbone

University of Bologna
Italy

Outline

- The Flavour Physics in the Standard Model
  - Dictionary
  - The Yukawa Lagrangian
  - CKM matrix
  - CP violation
  - Flavour changing neutral current
  - The Unitary triangle
- How to practice Flavour Physics
- Discrepancy from Standard Model

Flavour

Flavour Physics

Flavour Parameters

Flavour Universal

Flavour Diagonal

Flavour Changing

Flavour Changing Charged Current

Flavour Changing Neutral Current

What flavour stands for?

- Flavour
  - several fields with the same quantum numbers
  - particles: mass eigenstate with the same charge
    - Same colours and same electromagnetic charge
    - In the Standard Model within $\mathrm{SU(3)_{QCD} \times U(1)_{EM}}$ representation we have

$(3)_{+\frac{2}{3}}$ u, c, t $\quad$ $(3)_{+\frac{2}{3}}$ d, s, b

$(1)_{-1}$ e, μ, τ $\quad$ $(1)_{0}$ ν_1, ν_2, ν_3

What flavour physics means?

- Flavour physics
  - Interaction that distinguish among the flavours
  - Gauge interactions (related to unbroken symmetries) mediated therefore by massless gauge bosons dot not distinguish among flavours

~~Strong interaction~~

~~Electromagnetic interaction~~

  - Within the Standard Model, flavour physics refers to the weak and Yukawa interactions

Weak interaction

OK

- $W^{\pm}$ and h mediated interaction are Flavour Physics

What are the flavour parameters?

- Flavour parameters
  - Parameters that carry a flavour index

9 masses of the charged fermions

↓

masses of lepton and quarks

4 mixing parameters (three angles and one phase)

↓

that describe the interactions of the charged weak-force carriers ($W^{\pm}$) with quark-antiquark pairs.

What Flavour Universal means?

- Flavour Universal
  - Interaction with couplings that are proportional to the unit matrix in flavour space

Strong interaction

Electromagnetic interaction

  - An alternative term for “flavour-universal” is “flavour blind”

What Flavour Diagonal means?

- Flavour Diagonal
  - interactions with couplings that are diagonal, but not necessarily universal, in the flavour space.

Weak interaction

↓

Yukawa interactions of the Higgs particle are flavour diagonal in the mass basis.

What Flavour Changing means?

- Flavour Changing
  - refers to processes where the initial and final flavour-numbers are different
  - Initial/final flavour-numbers = the number of particles of a certain flavour minus the number of anti-particles of the same flavour

Flavour Changing

Flavour Changing Charged Current

Flavour Changing Neutral Current

Flavour Changing Charged Current (FCCC)

- Flavour Changing Charged Current
  - are processes, both up-type and down-type flavour and/or both charged lepton and neutrino flavour involved

$$\mu \to e\,\bar{\nu}_e \nu_\mu$$

$$K^- \to \mu^- \,\bar{\nu}_\mu$$
$$(s\bar{u} \to \mu^- \,\bar{\nu}_\mu)$$

$$B^0 \to J/\psi K_s^0$$
$$(\bar{b}d \to c\bar{c}\,\bar{s}d)$$

  - within the Standard Model, these processes do not occur at tree level, and are often highly suppressed.

Flavour Changing Neutral Current (FCNC)

- Flavour Changing Neutral Current
  - are processes, either up-type or down-type flavours but not both, and/or either charged lepton or neutrino flavours but not both, are involved

$$\mu \to e\,\gamma$$

$$K_L^0 \to \mu^- \mu^+$$

$$(s\bar{d} \;\to \mu^- \mu^+)$$

$$B^0 \to \phi K_s^0$$

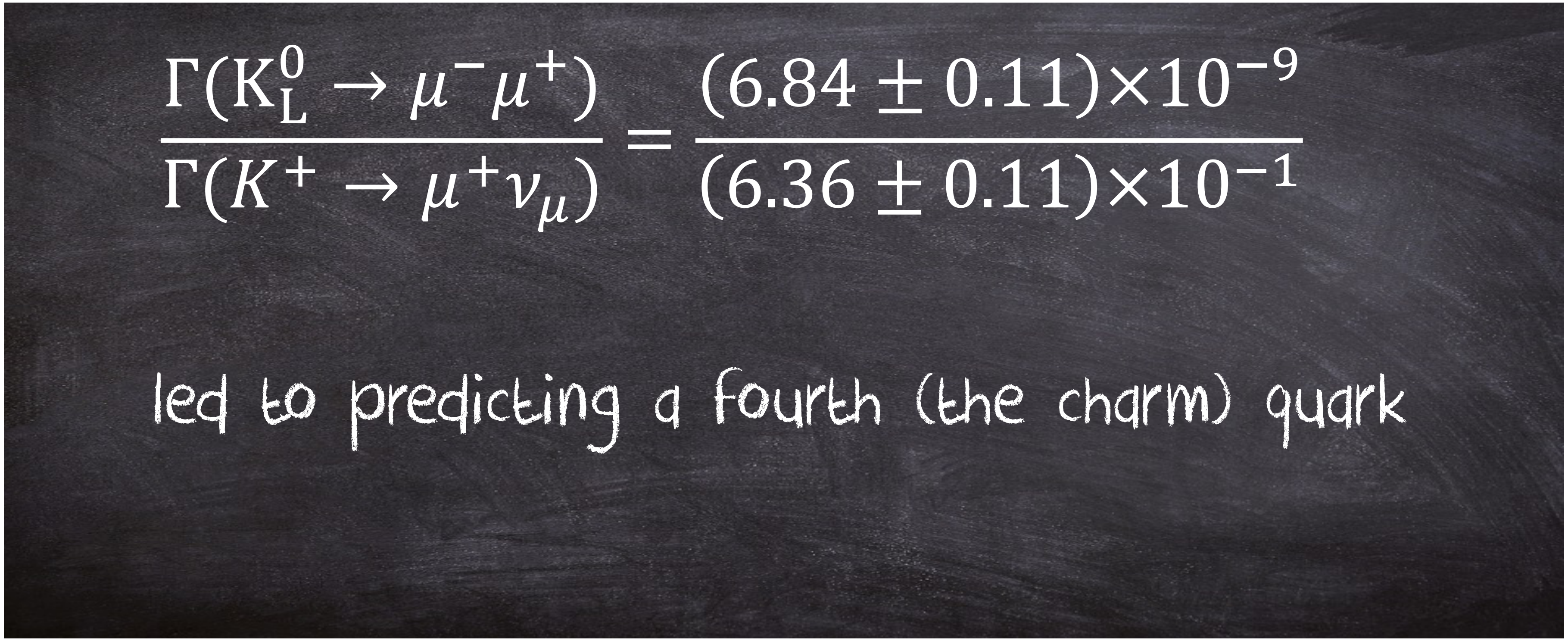
$$(\bar{b}d \;\to s\bar{s}\;\bar{s}d)$$

  - within the Standard Model, these processes do not occur at tree level, and are often highly suppressed.

Why is flavor physics interesting?

Tool for discovery

Intrinsic puzzling features



Why is flavor physics interesting?

Tool for discovery

Intrinsic puzzling features

The size of Δm_K led to a successful prediction of the charm mass

Why is flavor physics interesting?

Tool for discovery

Intrinsic puzzling features

The size of Δm_B led to a successful prediction of the top mass

Why is flavor physics interesting?

Tool for discovery

Intrinsic puzzling features

The size of Δm_B led to a successful prediction of the top mass

Why is flavor physics interesting?

Tool for discovery

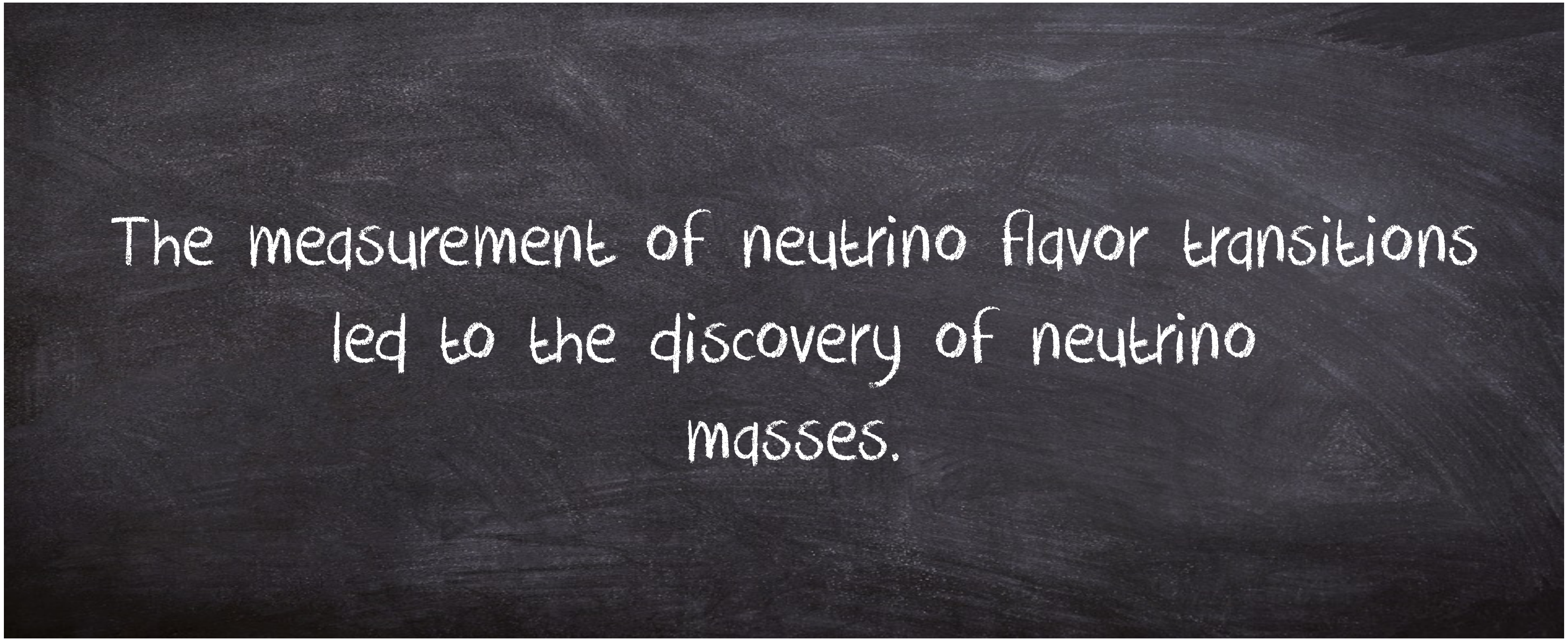
Intrinsic puzzling features

The measurement of ϵ_K led to predicting the third generation.

Why is flavor physics interesting?

Tool for discovery

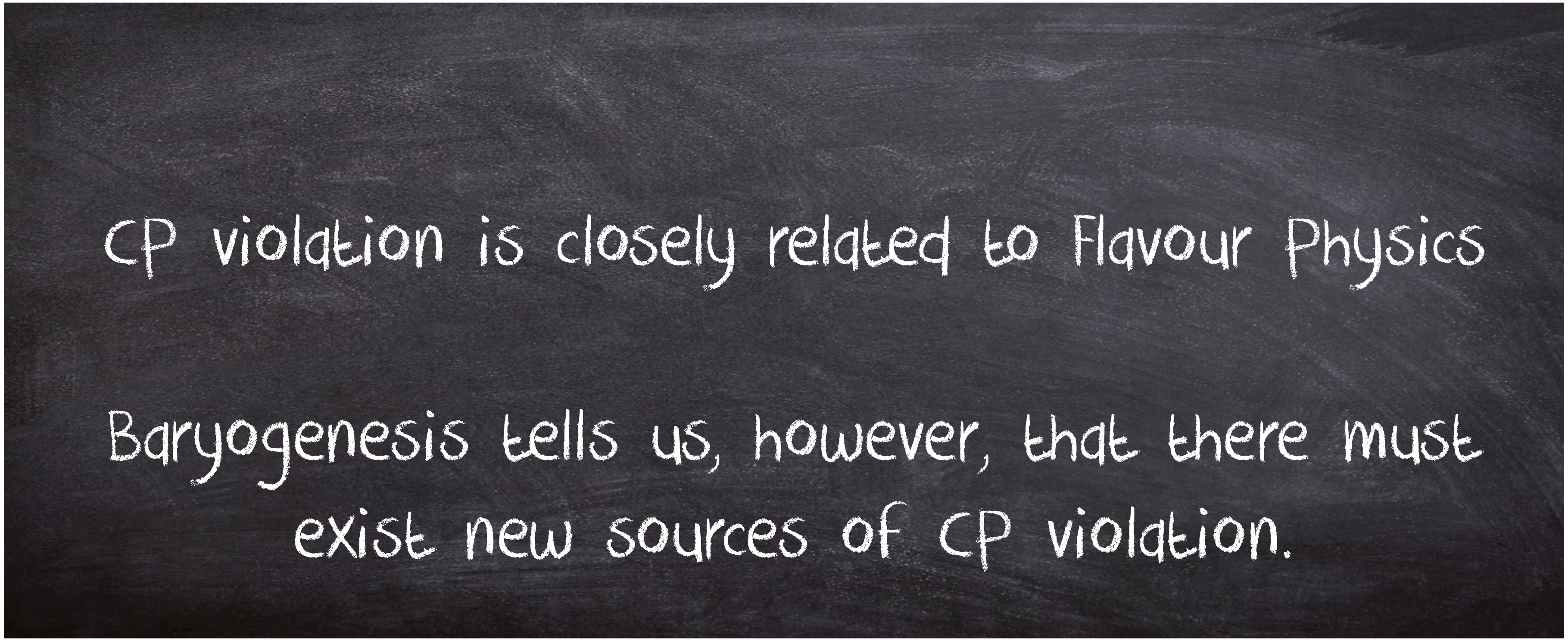
Intrinsic puzzling features



Why is flavor physics interesting?

Tool for discovery

Intrinsic puzzling features



Why is flavor physics interesting?

Tool for discovery

Intrinsic puzzling features

CP violation is closely related to Flavour Physics

Baryogenesis tells us, however, that there must exist new sources of CP violation.

Why is flavor physics interesting?

Tool for discovery

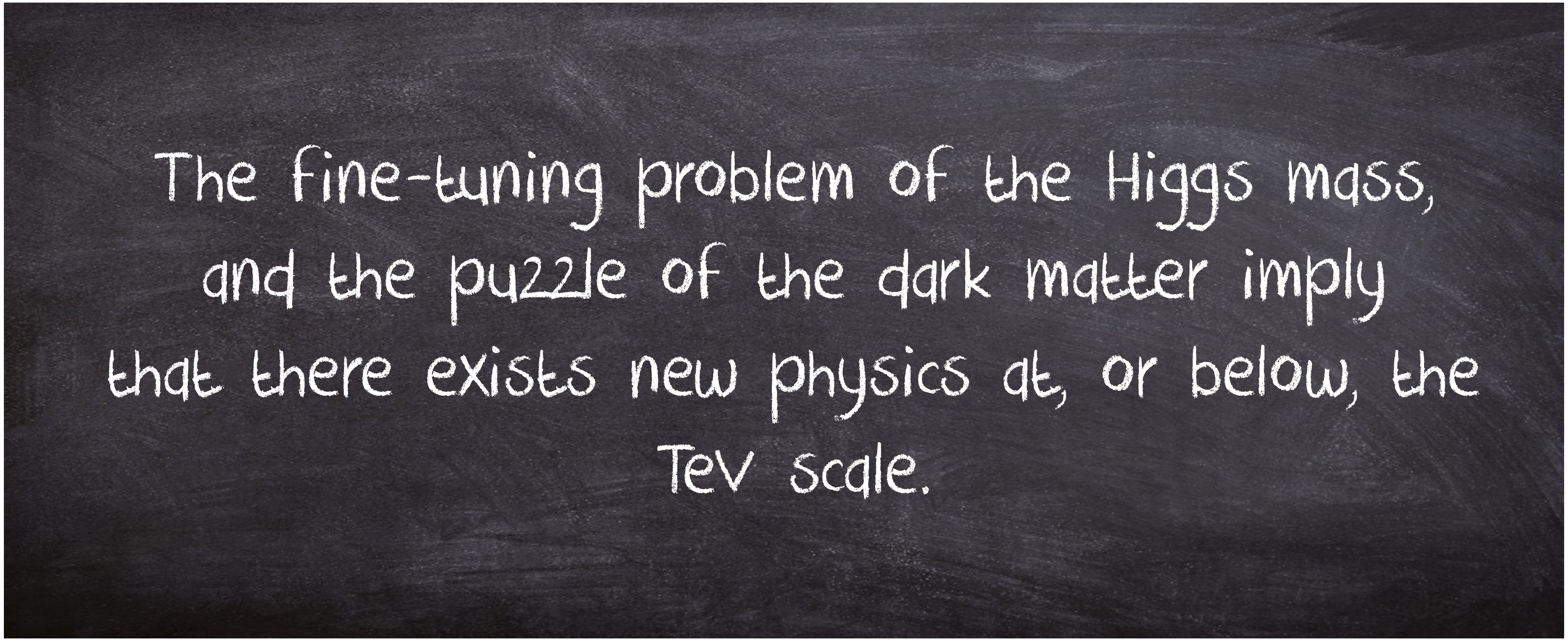
Intrinsic puzzling features

> The fine-tuning problem of the Higgs mass, and the puzzle of the dark matter imply that there exists new physics at, or below, the TeV scale.

Why is flavor physics interesting?

Tool for discovery

Intrinsic puzzling features



Why is flavor physics interesting?

Tool for discovery

Intrinsic puzzling features

Most of the charged fermion flavour parameters are small and hierarchical.

The standard model does not provide any explanation

This is the Standard Model flavor puzzle

The Yukawa Lagrangian

$$\mathcal{L} = \mathcal{L}_{kin} + \mathcal{L}_{\psi} + \mathcal{L}_{\phi} + \mathcal{L}_{Y}$$

Fermion fields: $Q_{L,i}(3,2)_{+1/6}$

$U_{R,i}(3,1)_{+2/3}$ $D_{R,i}(3,1)_{-1/3}$

$L_{R,i}(1,2)_{-1/2}$ $E_{R,i}(1,1)_{-1}$

Scalar field: $\phi, \tilde{\phi} = i\tau_2\phi^\dagger$

$$\mathcal{L}_Y^{SM} = Y_{ij}^{d}\overline{Q_{L,i}}\phi D_{R,j} + Y_{ij}^{u}\overline{Q_{L,i}}\tilde{\phi} U_{R,j} + Y_{ij}^{e}\overline{L_{R,i}}\phi E_{R,j} + h.c.$$

Y are general 3 x 3 matrices of dimensionless couplings

This part of the Lagrangian describes
the Yukawa interactions

The Yukawa Lagrangian

$$\mathcal{L}_Y^{SM} = Y_{ij}^d \overline{Q_{L,i}} \phi D_{R,j} + Y_{ij}^u \overline{Q_{L,i}} \tilde{\phi} U_{R,j} + Y_{ij}^e \overline{L_{R,i}} \phi E_{R,j} + h.c.$$

This part of the Lagrangian is made of the fermion fields and the scalar field, subject to the gauge symmetry and leading to the SSB

$$\phi(1,2)_{+1/2} \xrightarrow{\text{S.S.B.}} \phi(1,2)_{+1/2} = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$$

The Yukawa Lagrangian

$$\mathcal{L}_Y^{SM} = Y_{ij}^d \overline{Q_{L,i}} \phi D_{R,j} + Y_{ij}^u \overline{Q_{L,i}} \tilde{\phi} U_{R,j} + Y_{ij}^e \overline{L_{R,i}} \phi E_{R,j} + h.c.$$

After S.S.B. you want to write the Lagrangian for mass eigenstates

$$Y^e \rightarrow \hat{Y}^e = U_{e,L} Y^e U_{e,R}^\dagger$$

$\hat{Y}^e$ is diagonal and real

In this basis the Fermion fields are: $\begin{pmatrix} \nu_{e,L} \\ e_L \end{pmatrix} \begin{pmatrix} \nu_{\mu,L} \\ \mu_L \end{pmatrix} \begin{pmatrix} \nu_{\tau,L} \\ \tau_L \end{pmatrix} e_R \ \mu_R \ \tau_R$

The Yukawa Lagrangian

$$\mathcal{L}_Y^{SM} = Y_{ij}^d \overline{Q_{L,i}} \phi D_{R,j} + Y_{ij}^u \overline{Q_{L,i}} \tilde{\phi} U_{R,j} + Y_{ij}^e \overline{L_{R,i}} \phi E_{R,j} + h.c.$$

After S.S.B. you want to write the Lagrangian for mass eigenstates

$$Y^u \to \hat{Y}^u = V_{u,L} Y^u U_{u,R}^\dagger$$

$\hat{Y}^u$ is diagonal and real

In this basis the Fermion fields are: $\begin{pmatrix} u_L \\ d_{u,L} \end{pmatrix} \begin{pmatrix} c_L \\ d_{c,L} \end{pmatrix} \begin{pmatrix} t_L \\ d_{t,L} \end{pmatrix} u_R \; c_R \; t_R$

The Yukawa Lagrangian

$$\mathcal{L}_Y^{SM} = Y_{ij}^d \overline{Q_{L,i}} \phi D_{R,j} + Y_{ij}^u \overline{Q_{L,i}} \tilde{\phi} U_{R,j} + Y_{ij}^e \overline{L_{R,i}} \phi E_{R,j} + h.c.$$

After S.S.B. you want to write the Lagrangian for mass eigenstates

$$Y^d \to \hat{Y}^d = V_{d,L} Y^d U_{d,R}^\dagger$$

$\hat{Y}^d$ is diagonal and real

In this basis the Fermion fields are: $\begin{pmatrix} u_{d,L} \\ d_L \end{pmatrix} \begin{pmatrix} u_{s,L} \\ s_L \end{pmatrix} \begin{pmatrix} u_{b,L} \\ b_L \end{pmatrix} d_R \; s_R \; b_R$

The Yukawa Lagrangian

$$\mathcal{L}_Y^{SM} = Y_{ij}^d \overline{Q_{L,i}} \phi D_{R,j} + Y_{ij}^u \overline{Q_{L,i}} \tilde{\phi} U_{R,j} + Y_{ij}^e \overline{L_{R,i}} \phi E_{R,j} + h.c.$$

Now if we write the identity

$$Y^d = V_{d,L}^\dagger \underbrace{V_{d,L} Y^d V_{d,R}^\dagger}_{\hat{Y}^d} V_{d,R}$$

And you plugin in the Lagrangian

$$\mathcal{L}_Y^d = \frac{v}{\sqrt{2}} \bar{d}_L V_{d,L}^\dagger \underbrace{V_{d,L} Y^d V_{d,R}^\dagger}_{\hat{Y}^d} V_{d,R} d_R$$

The Yukawa Lagrangian

$$\mathcal{L}_Y^{SM} = Y_{ij}^d \overline{Q_{L,i}} \phi D_{R,j} + Y_{ij}^u \overline{Q_{L,i}} \tilde{\phi} U_{R,j} + Y_{ij}^e \overline{L_{R,i}} \phi E_{R,j} + h.c.$$

$$\left.\begin{aligned} \bar{d}_L^m &= \bar{d}_L V_{d,L}^\dagger \\ \mathrm{d}_R^m &= V_{d,R} d_R \end{aligned}\right\}$$

from interaction basis
to mass eigenstate basis

$$\mathcal{L}_Y^d = \frac{v}{\sqrt{2}} \bar{d}_L^m \hat{Y}^d \mathrm{d}_R^m \xrightarrow{\text{charm}} y_c c_L \frac{v}{\sqrt{2}} c_R$$

example: the charm mass $m_c = y_c \frac{v}{\sqrt{2}}$

The charge current Lagrangian

Mass basis

$$\mathcal{L}_{kin}^{cc} = \frac{g}{\sqrt{2}} \bar{u}_{L,i} V_{u,L}^{\dagger} \gamma_\mu W^{-\mu} d_{L,i} V_{d,L}$$

$$\frac{g}{\sqrt{2}} \bar{d}_{L,i} V_{d,L}^{\dagger} \gamma_\mu W^{+\mu} u_{L,i} V_{u,L}$$

$$V_{u,L}^{\dagger} V_{d,L} =$$

?

$$V_{d,L}^{\dagger} V_{u,L} =$$

The charge current Lagrangian

Mass basis

$$\mathcal{L}_{kin}^{cc} = \frac{g}{\sqrt{2}} \bar{u}_{L,i} V_{u,L}^{\dagger} \gamma_\mu W^{-\mu} d_{L,i} V_{d,L}$$

$$\frac{g}{\sqrt{2}} \bar{d}_{L,i} V_{d,L}^{\dagger} \gamma_\mu W^{+\mu} u_{L,i} V_{u,L}$$

$$\left.\begin{array}{l} V_{u,L}^{\dagger} V_{d,R} = \\ V_{d,L}^{\dagger} V_{u,R} = \end{array}\right\} V_{CKM}$$

The CKM matrix

$$V \approx \begin{pmatrix} 1 & 0.2 & 0.004e^{-i65^\circ} \\ -0.2 & 1 & 0.04 \\ 0.009e^{-i22^\circ} & -0.04 & 1 \end{pmatrix}$$

- 4 parameters, 3 real + 1 phase
- It's very close to the unitary matrix
- 0.2 transition between 1-2 generation
- 0.04 transition between 2-3 generation
- Highly suppressed from 1-3 generation
- 1,3 and 3,1 have phase

The CKM matrix

$$V \approx \begin{pmatrix} 1 & 0.2 & 0.004e^{-i65^\circ} \\ -0.2 & 1 & 0.04 \\ 0.009e^{-i22^\circ} & -0.04 & 1 \end{pmatrix}$$

$$V \approx \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

The CKM matrix

very suggestive pattern

$$\lambda \approx 0.2 \qquad A \approx 0.8$$

$$\rho^2 + \eta^2 \approx 0.15 \qquad \eta/\rho \approx 2.3$$

$$V \approx \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

Let's now have a look at the data

$$BR(D \to K\mu\nu) = 3.3\times10^{-2}$$

$$BR(D \to \pi\mu\nu) = 2.38\times10^{-3}$$

$$A_{CP}(K_L \to \pi l\nu) = 3.32\times10^{-3}$$

$$A_{CP}(D \to) < 10^{-2}$$

$$A_{CP}(B \to K\pi) = 0.082$$

$$BR(B \to X\mu\nu) = 10.86\times10^{-2}$$

$$BR(B \to Xe\nu) = 10.86\times10^{-2}$$

$$BR(B \to X\gamma) = 3.5\times10^{-4}$$

$$BR(B \to Dl\nu) = 2.19\times10^{-2}$$

$$BR(B \to \pi l\nu) = 1.49\times10^{-4}$$

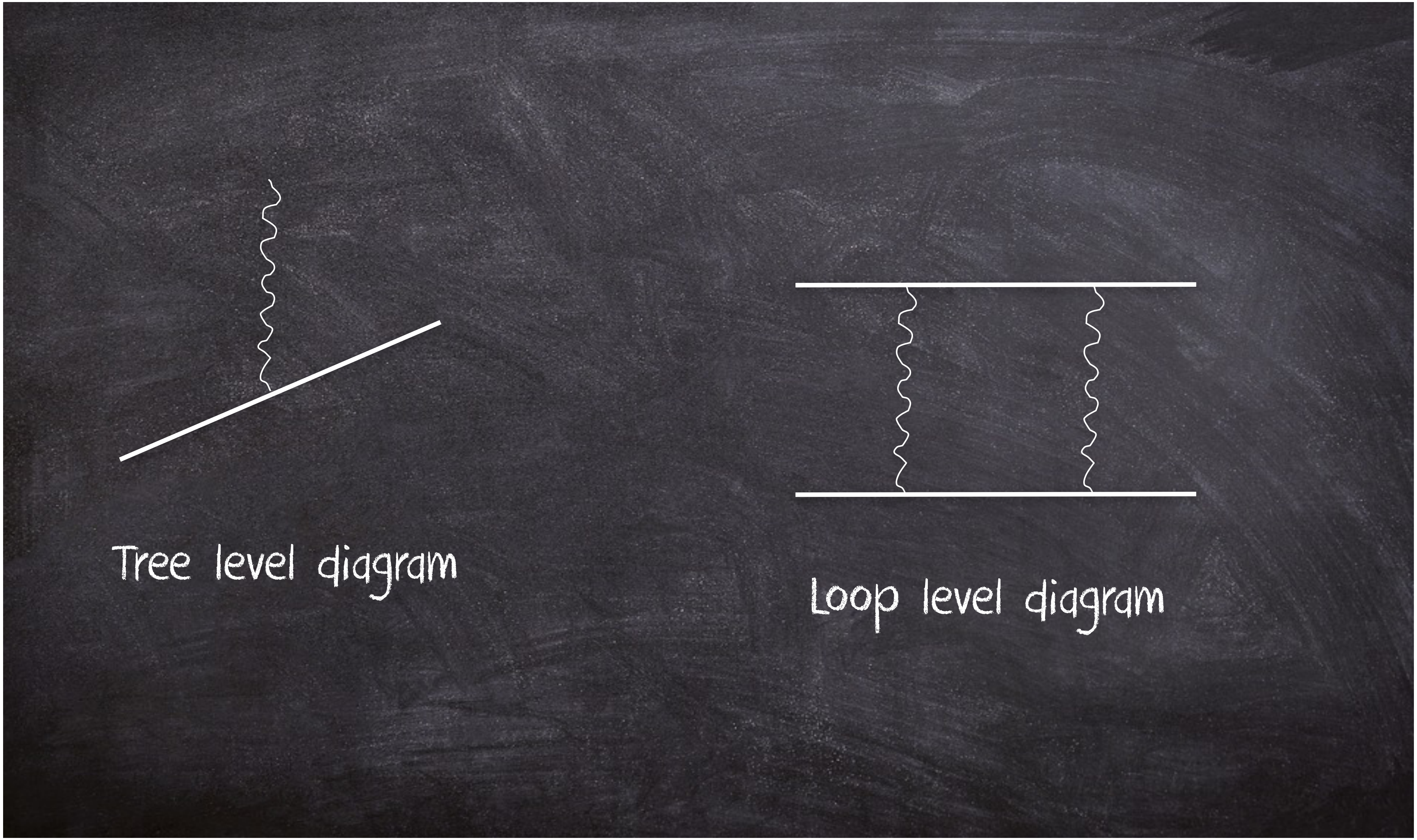
$$BR(B \to \mu^-\mu^+) = 3\times10^{-9}$$

$$BR(K_L \to \mu^-\mu^+) = 7\times10^{-9}$$

$$BR(D \to \mu^-\mu^+) < 6\times10^{-9}$$

$$BR(J/\psi \to \mu^-\mu^+) = 0.06$$

Tree level and loops



Why there is no FCNCs in the Standard Model?

No FCNC in SM at the three level

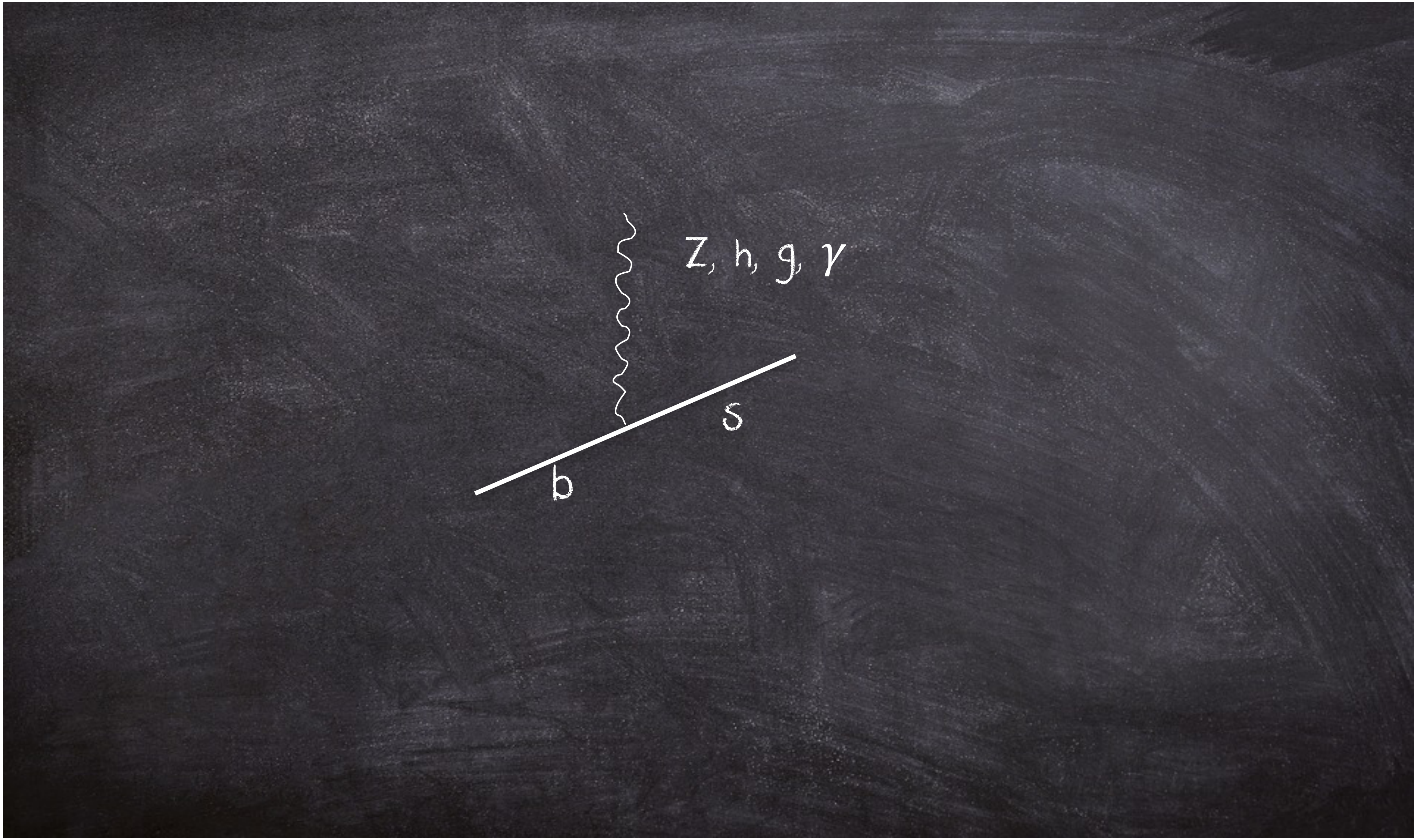
Who can contribute to have FCNC in SM at tree level?

Z, h, g, γ

All of them couple diagonally (to the same flavour) to fermions

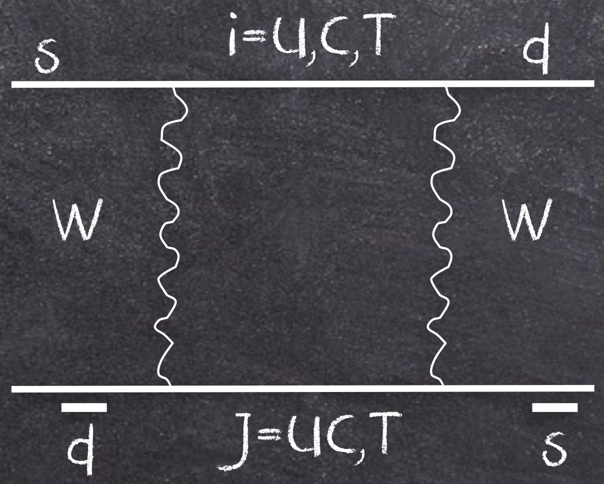
Why?

Is this diagram possible in the SM?



FCNCs @ one loop

$$K^0(d\bar{s}) \leftrightarrow \bar{K}^0(\bar{d}s)$$



GIM mechanism

GIM suppression

$$A \propto \sum (V_{is}V_{id}^*)(V_{js}V_{jd}^*) f\left(\frac{m_i}{m_w}, \frac{m_j}{m_w}\right)$$

Nine amplitudes

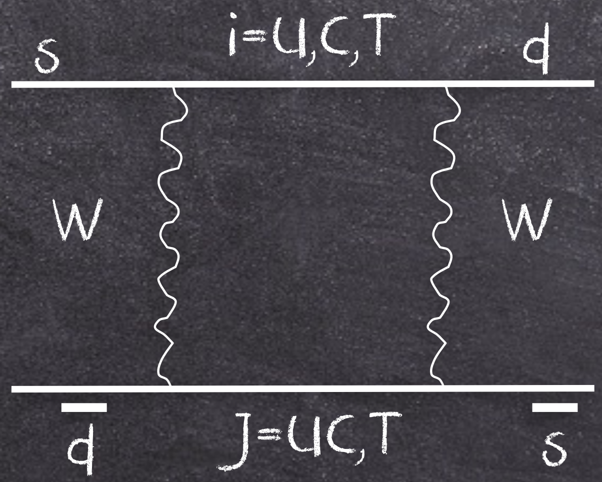
$$f(m_i, m_j) \propto m_c^2/m_w^2$$

FCNCs @ one loop

$$K^0(d\bar{s}) \leftrightarrow \bar{K}^0(\bar{d}s)$$

GIM mechanism

GIM suppression



$$A \propto \frac{1}{16\pi^2}(V_{cs}V_{cd}^*)^2\frac{m_c^2}{m_W^2}\times f_{QCD} \approx 10^{-7}$$

CP violation

In nature we see CP violation only in weak interaction

In order to have CP violation the Lagrangian need to have a phase, i.e. it is not real

$$\mathcal{L}_{kin}^{cc} = \frac{g}{\sqrt{2}}\bar{u}_{L,i}V_{u,L}^{\dagger}\gamma_{\mu}W^{-\mu}d_{L,i}V_{d,L} + \frac{g}{\sqrt{2}}\bar{d}_{L,i}V_{d,L}^{\dagger}\gamma_{\mu}W^{+\mu}u_{L,i}V_{u,L}$$

$$\Big\downarrow \quad \text{CP transformation}$$

$$\mathcal{L}_{kin}^{cc} = \frac{g}{\sqrt{2}}\bar{d}_{L,i}V_{u,L}\gamma_{\mu}W^{+\mu}u_{L,i}V_{d,L}^{\dagger} + \frac{g}{\sqrt{2}}\bar{u}_{L,i}V_{d,L}\gamma_{\mu}W^{-\mu}d_{L,i}V_{u,L}^{\dagger}$$

Only left-handed particles take part in charged-current interactions.

Parity is violated by these interactions.

CP violation

In the SM CP is small: $A_{CP} \times BR \ll 1$

To have a phase in the Lagrangian it is necessary the third generation

Any CP violation observables must involve all the CKM matrix elements and hence small elements

CP violation: The Jarlskog invariant

Independently by any parameterization any CP violation observable must be proportional to this invariant

$$J = c_{12}c_{23}c_{13}^2 s_{12}s_{23}s_{13}\delta_{CKM} \approx \lambda^6 A^2 \eta$$

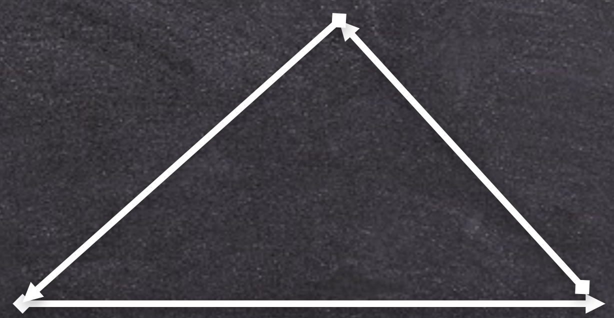
Phase must be non zero

All the mixing angle should be no zero or $\pi/2$

δ_{CKM} is large, CP violation is small due to mixing

The Unitarity triangle

$$\sum V_{is} V_{id}^{*} = 0$$ Unitarity relation of CKM matrix



A unitarity triangle

How many unitarity triangle in SM? 6

The area is equal to J/2

The unitarity triangle

$$\sum V_{id}V_{ib}^{*} = 0$$

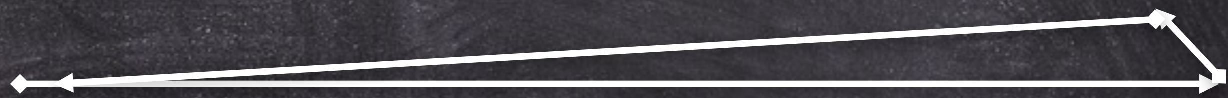
$$V_{ud}V_{ub}^{*} \propto 1 \cdot \lambda^3$$

$$V_{cd}V_{cb}^{*} \propto \lambda^2 \cdot \lambda$$

$$V_{td}V_{tb}^{*} \propto 1 \cdot \lambda^3$$

The unitarity triangle

$$\sum V_{is}V_{id}^{*} = 0$$



All the CP violation measurement are related to J

Let's now have a look at the data

$BR(D \to K\mu\nu) = 3.3\times10^{-2}$

$BR(D \to \pi\mu\nu) = 2.4\times10^{-3}$

$A_{CP}(K_L \to \pi l\nu) = 3.32\times10^{-3}$

$A_{CP}(D \to) < 10^{-2}$

$A_{CP}(B \to K\pi) = 0.082$

$BR(B \to X\mu\nu) = 10.86\times10^{-2}$

$BR(B \to Xe\nu) = 10.86\times10^{-2}$

$BR(B \to X\gamma) = 3.50\times10^{-4}$

$BR(B \to Dl\nu) = 2.19\times10^{-2}$

$BR(B \to \pi l\nu) = 1.49\times10^{-4}$

$BR(B \to \mu^-\mu^+) = 3\times10^{-9}$

$BR(K_L \to \mu^-\mu^+) = 7\times10^{-9}$

$BR(D \to \mu^-\mu^+) < 6\times10^{-9}$

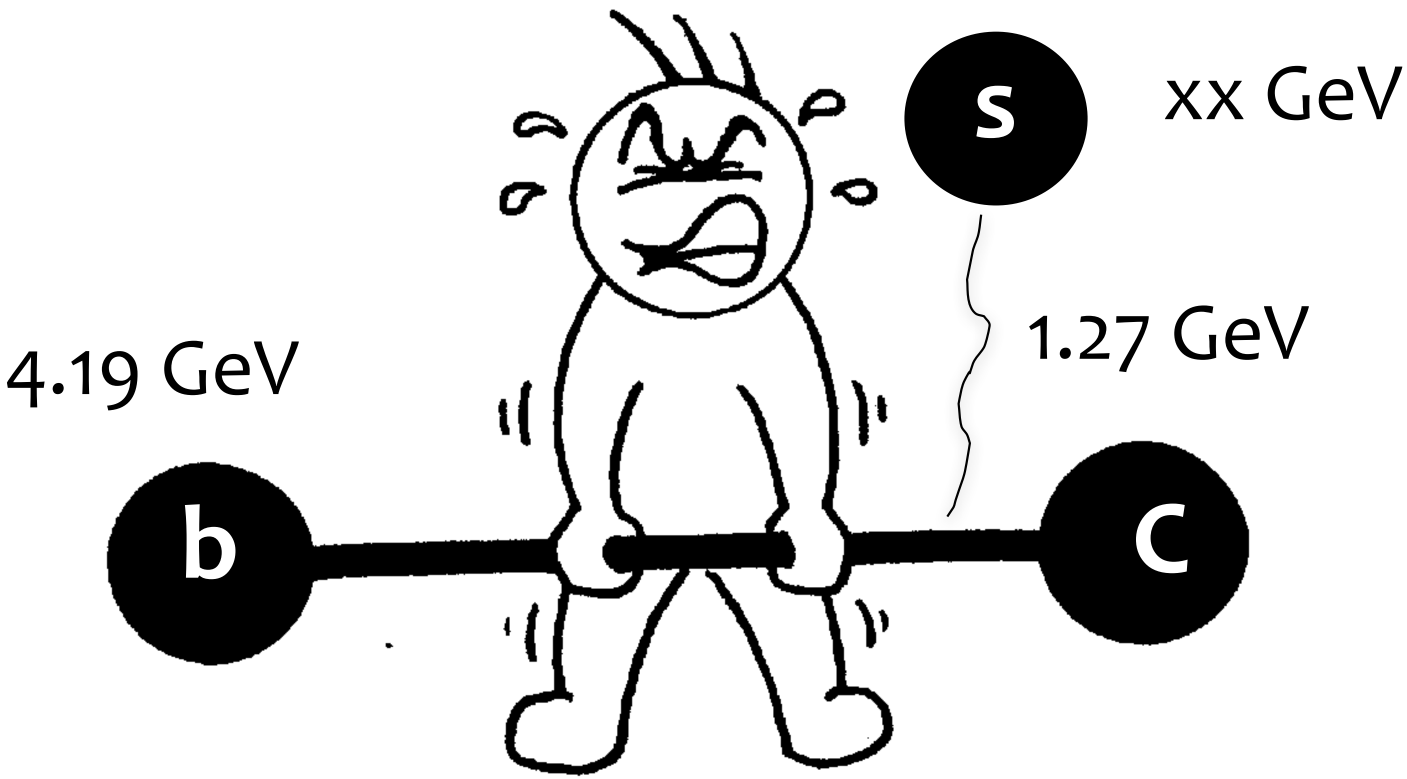
$BR(J/\psi \to \mu^-\mu^+) = 0.06$

$BR(K \to \mu^-\nu_\mu) = 0.64$

What we have learned so far?

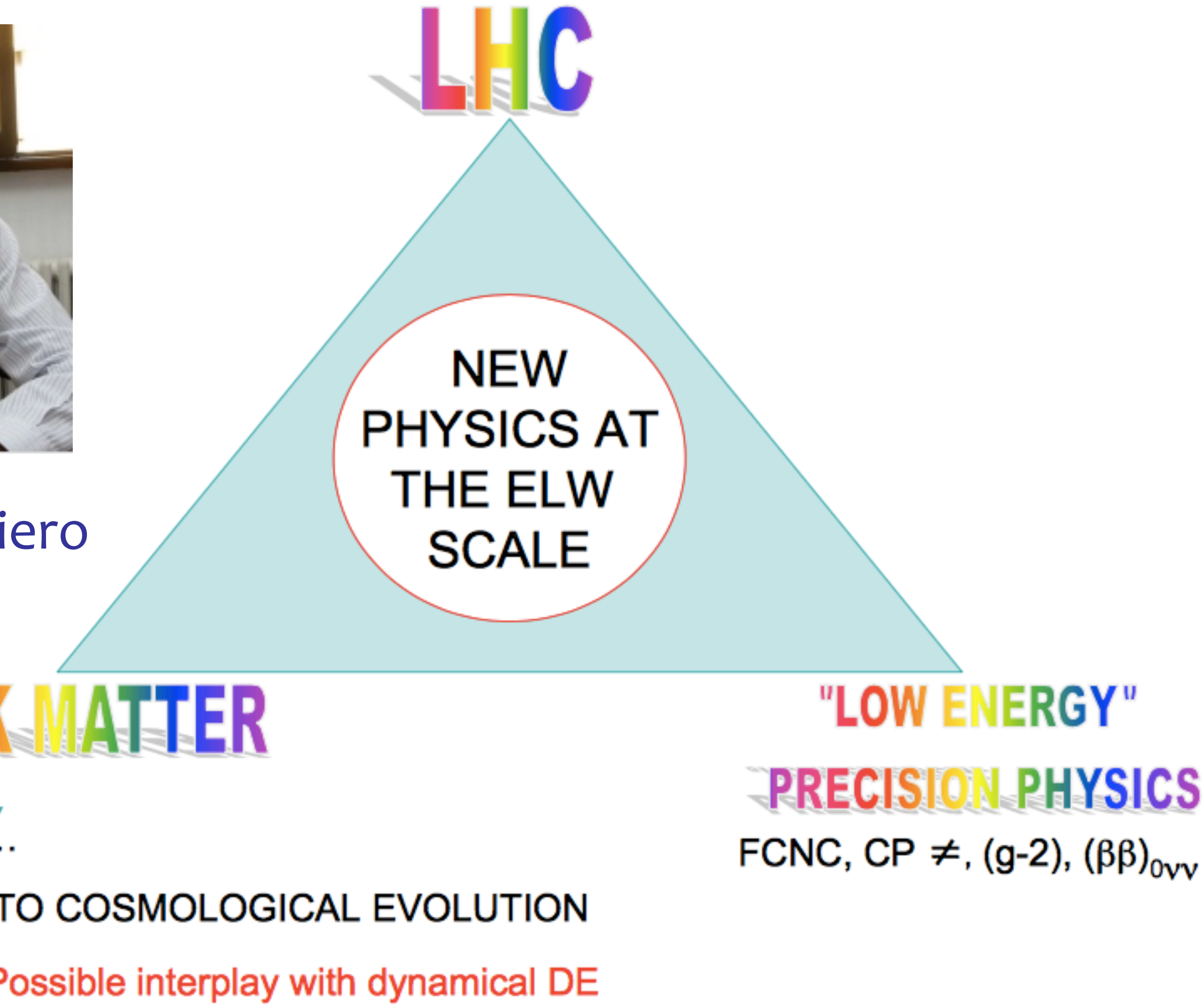
1) SM is constructed from data
2) FCCC are at the tree level in SM
3) FCNC are suppressed in the SM
4) CP violation times BR is small in SM
5) Charged currents with leptons are universal
6) Charged currents with quarks are NOT universal (V_{CKM})
7) Transition from 3 -> 2 >> 3 -> 1
8) Transition from 2 -> 2 >> 2 -> 1

Flavour Physics: how to practice?



Why do we practice Flavour Physics ?

Prof. Antonio Masiero

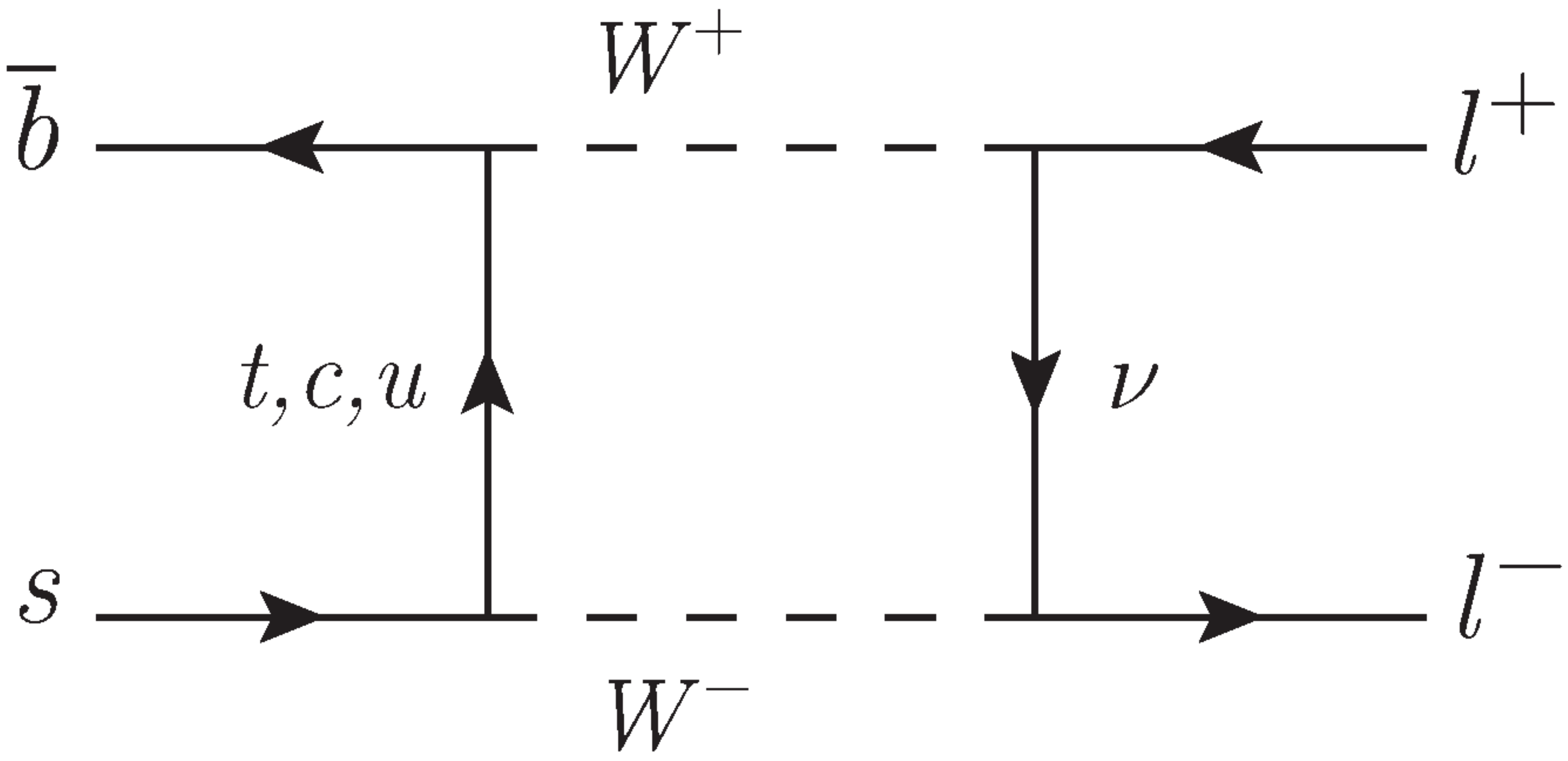


The indirect search of New Physics

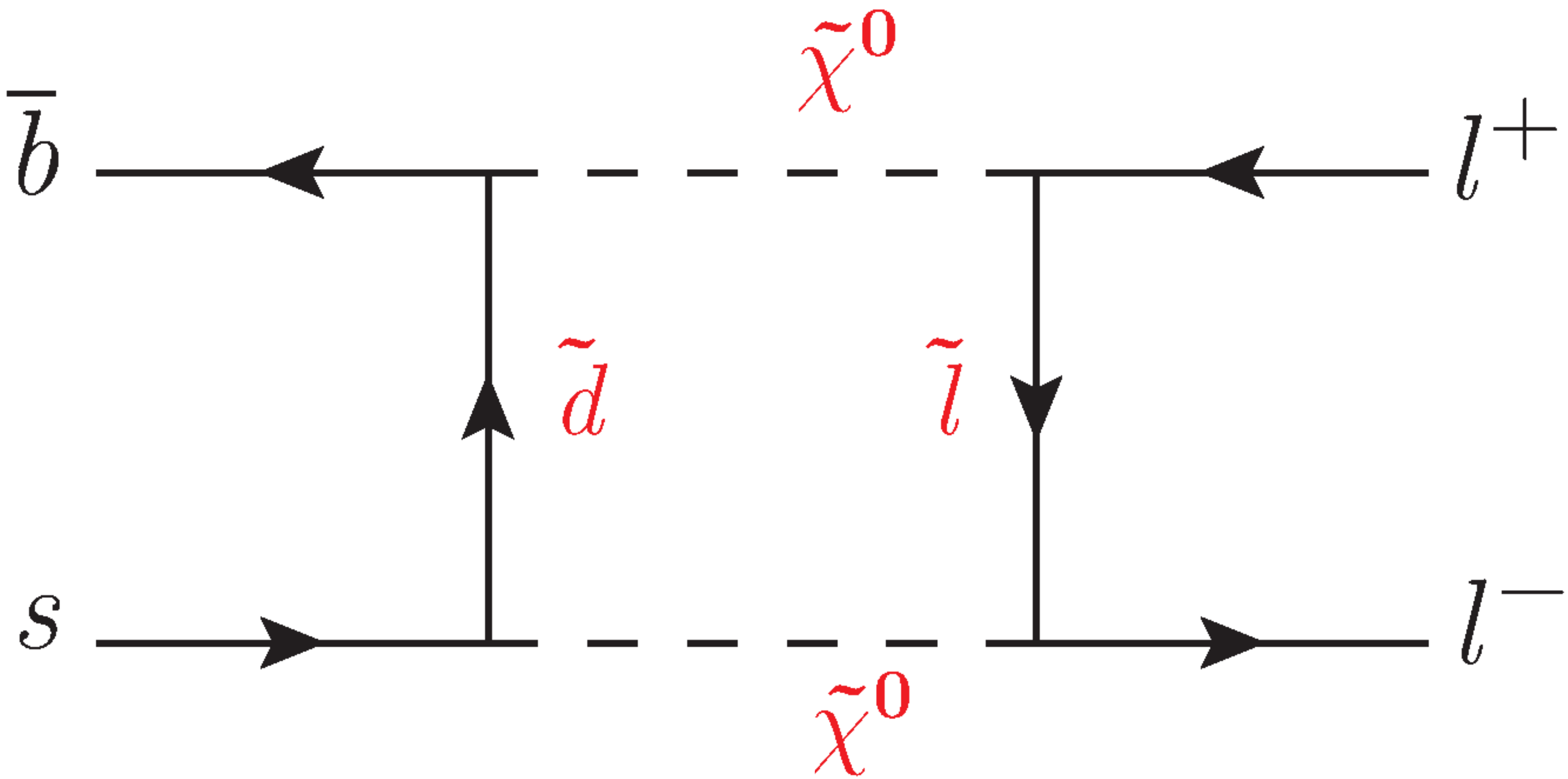
Observed deviations from values expected according to the Standard Model will indirectly hint to the existence of New Physics

Why?

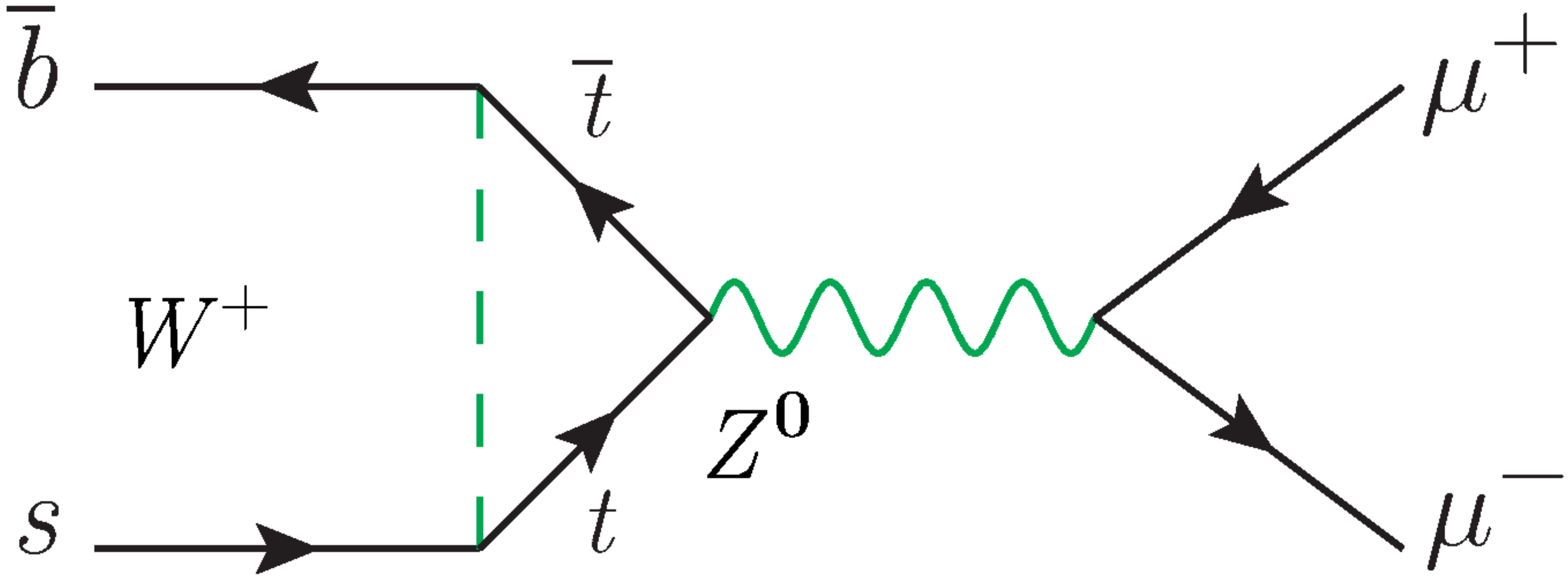
Standard Model



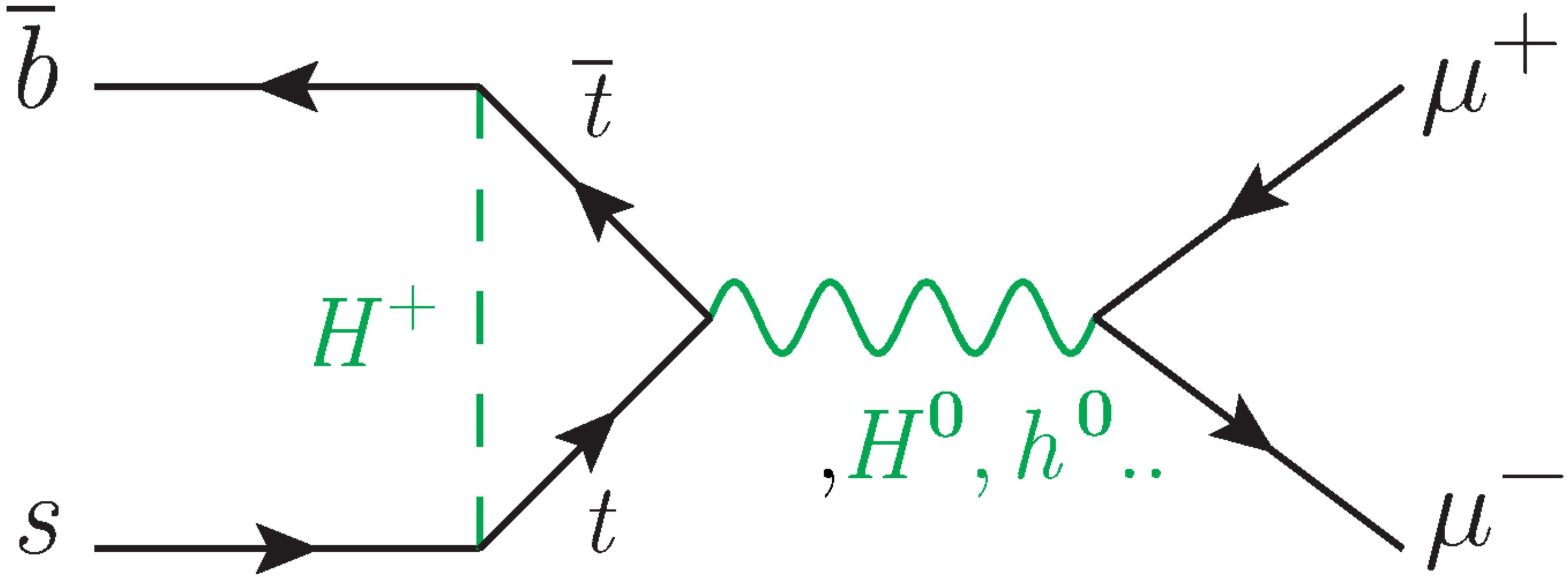
Beyond Standard Model



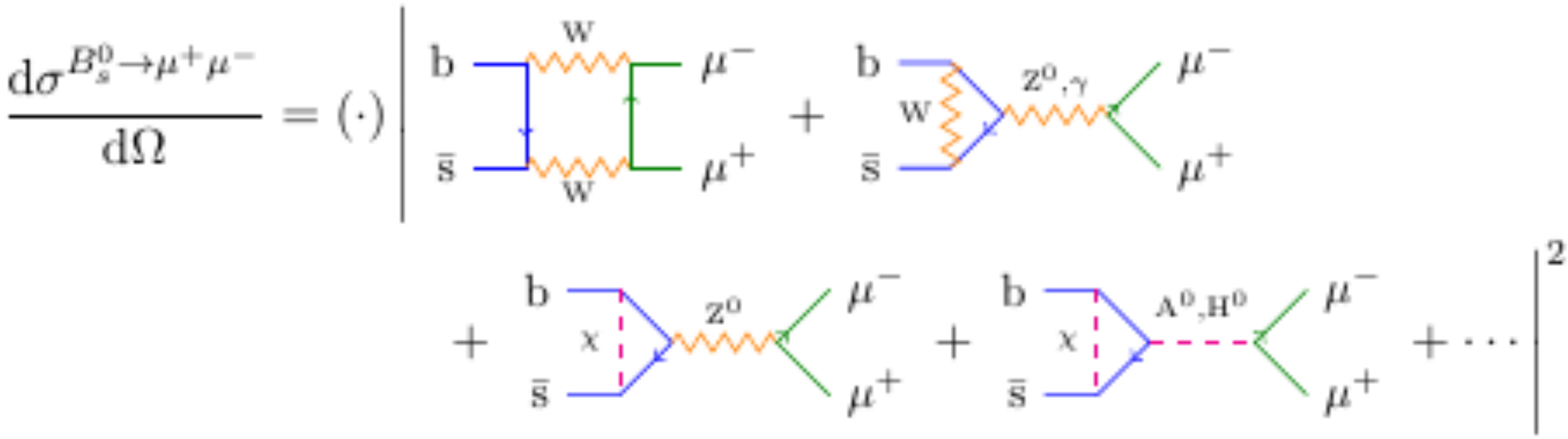
Standard Model



Beyond Standard Model

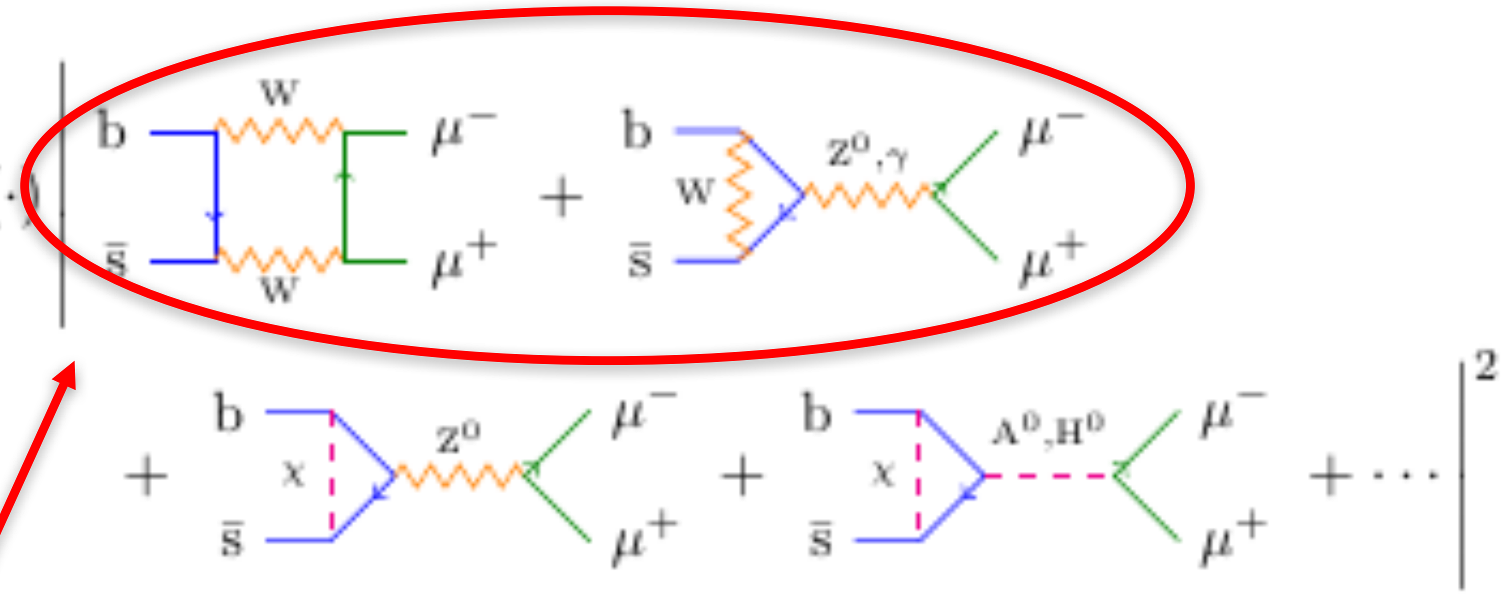


If this the nature…



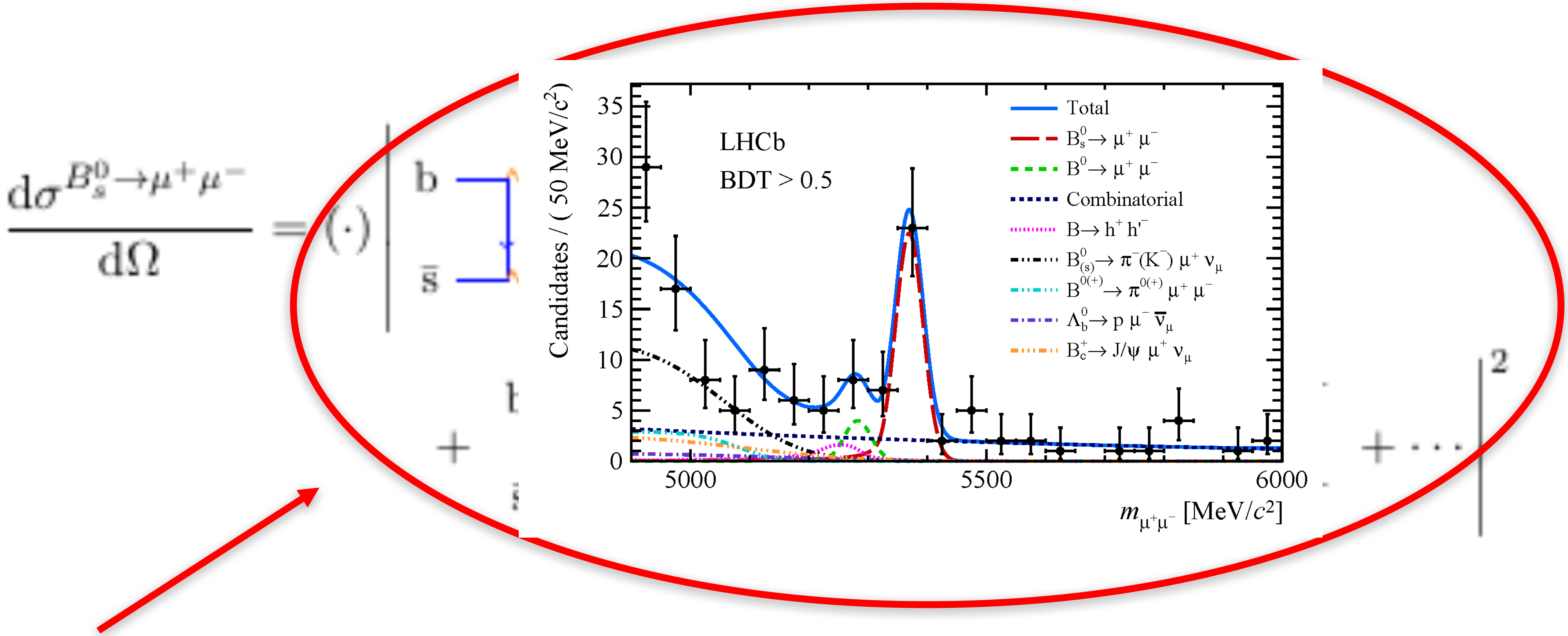
… and

$$\frac{d\sigma^{B_s^0\to\mu^+\mu^-}}{d\Omega} = (\cdot)$$



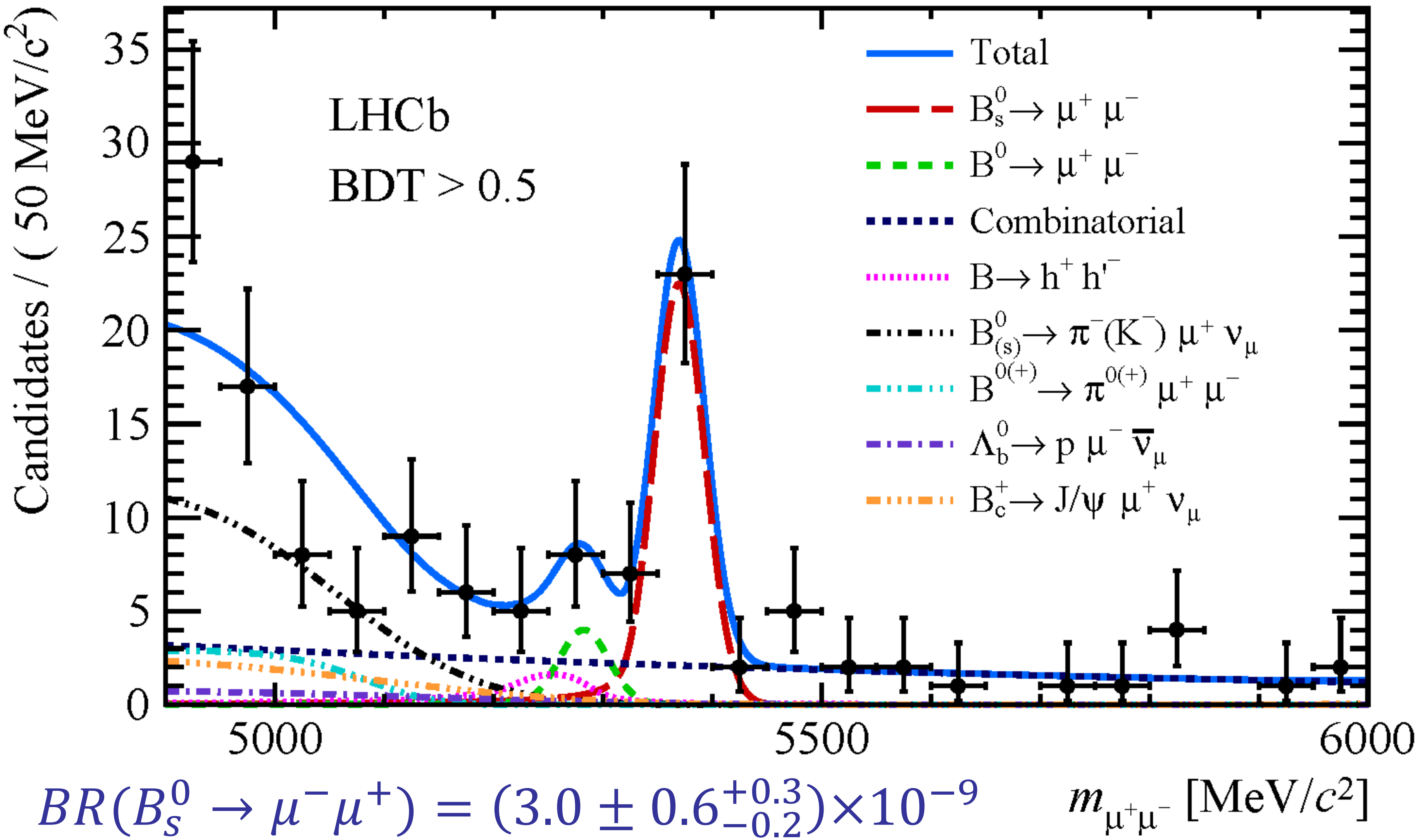
SM predicts this

…



… and you measure a value significantly different from SM (which is not the case so far)

$B \to \mu^-\mu^+$ @ LHCb

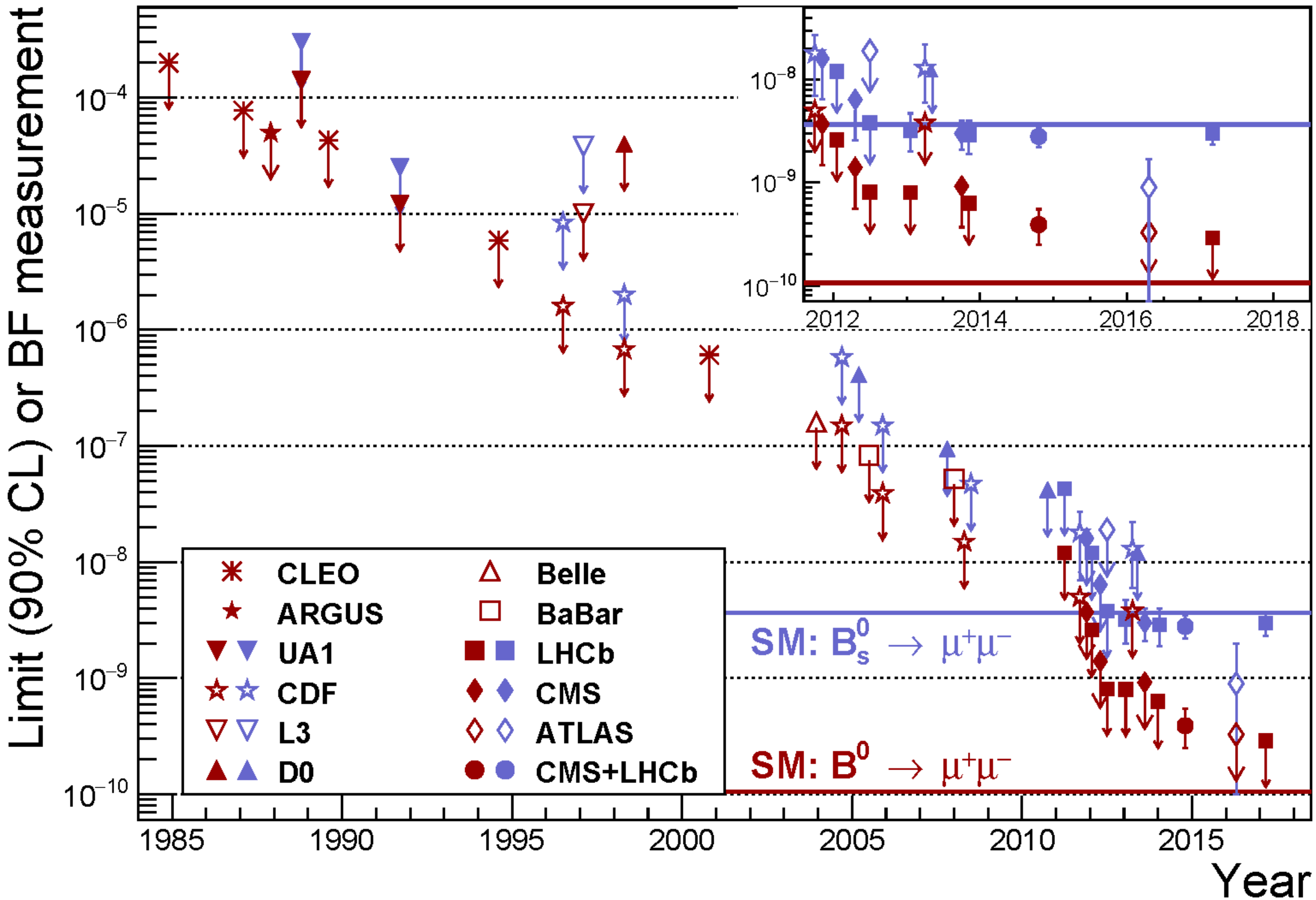


$$BR(B_s^0 \to \mu^-\mu^+) = (3.0 \pm 0.6^{+0.3}_{-0.2})\times 10^{-9}$$

$$BR(B^0 \to \mu^-\mu^+) < 3.14 \times 10^{-10}$$

You win the Nobel prize…

… but SM works perfectly!



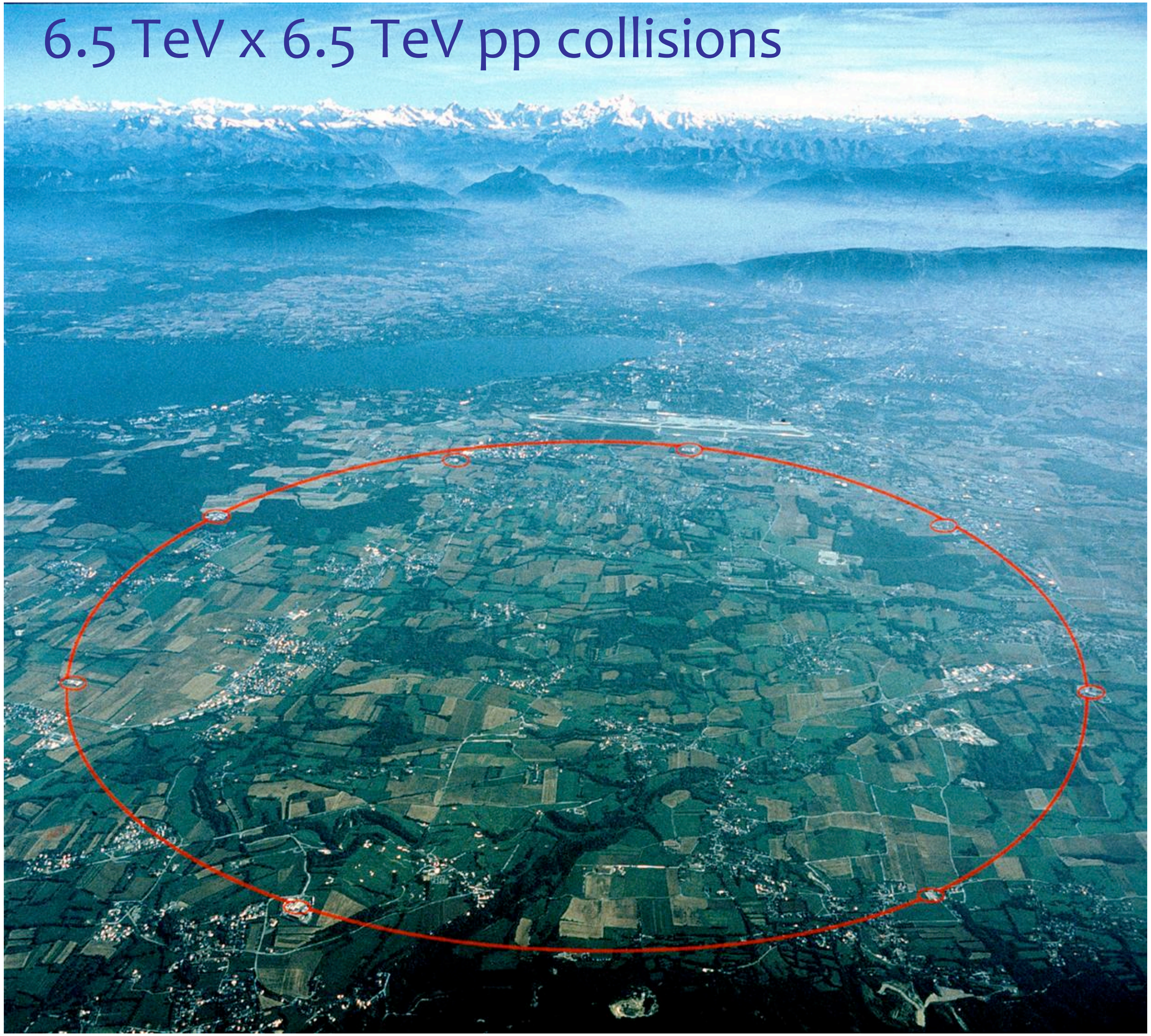
Where practice Flavour Physics?

Present:

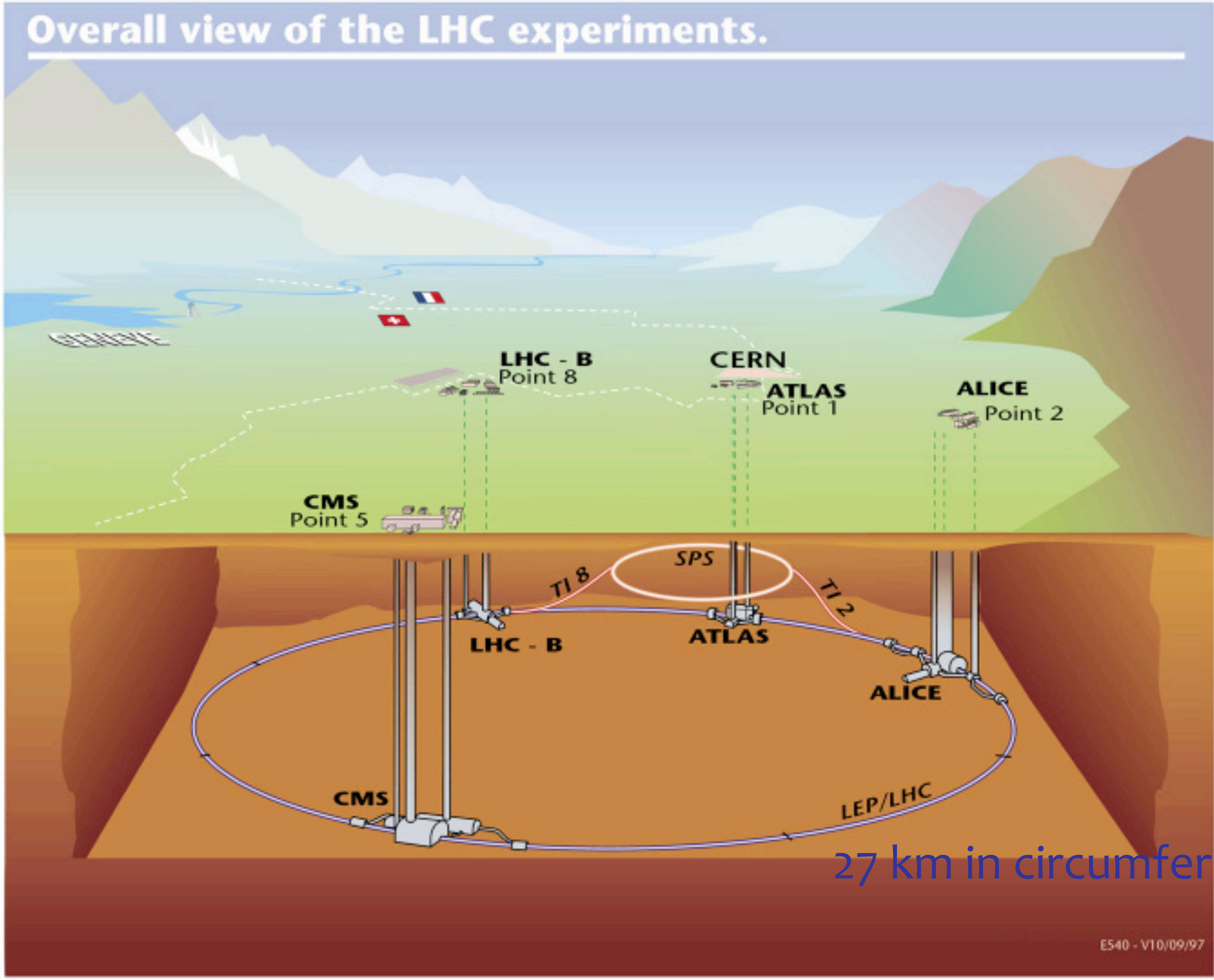
- LHC
  - LHCb high precision measurements
  - but complemented in certain important channels by ATLAS and CMS
- NA62, kaon physics
  - Search for the very rare decays
  - $K^{+} \to \pi^{+}\bar{\nu}\nu$ and $K_{L}^{0} \to \pi^{0}\bar{\nu}\nu$
  - SM expectation $(9.11 \pm 0.71)\times 10^{-11}$ and $(3.00 \pm 0.30)\times 10^{-11}$

Belle-II and LHCb-upgrade

The LHC

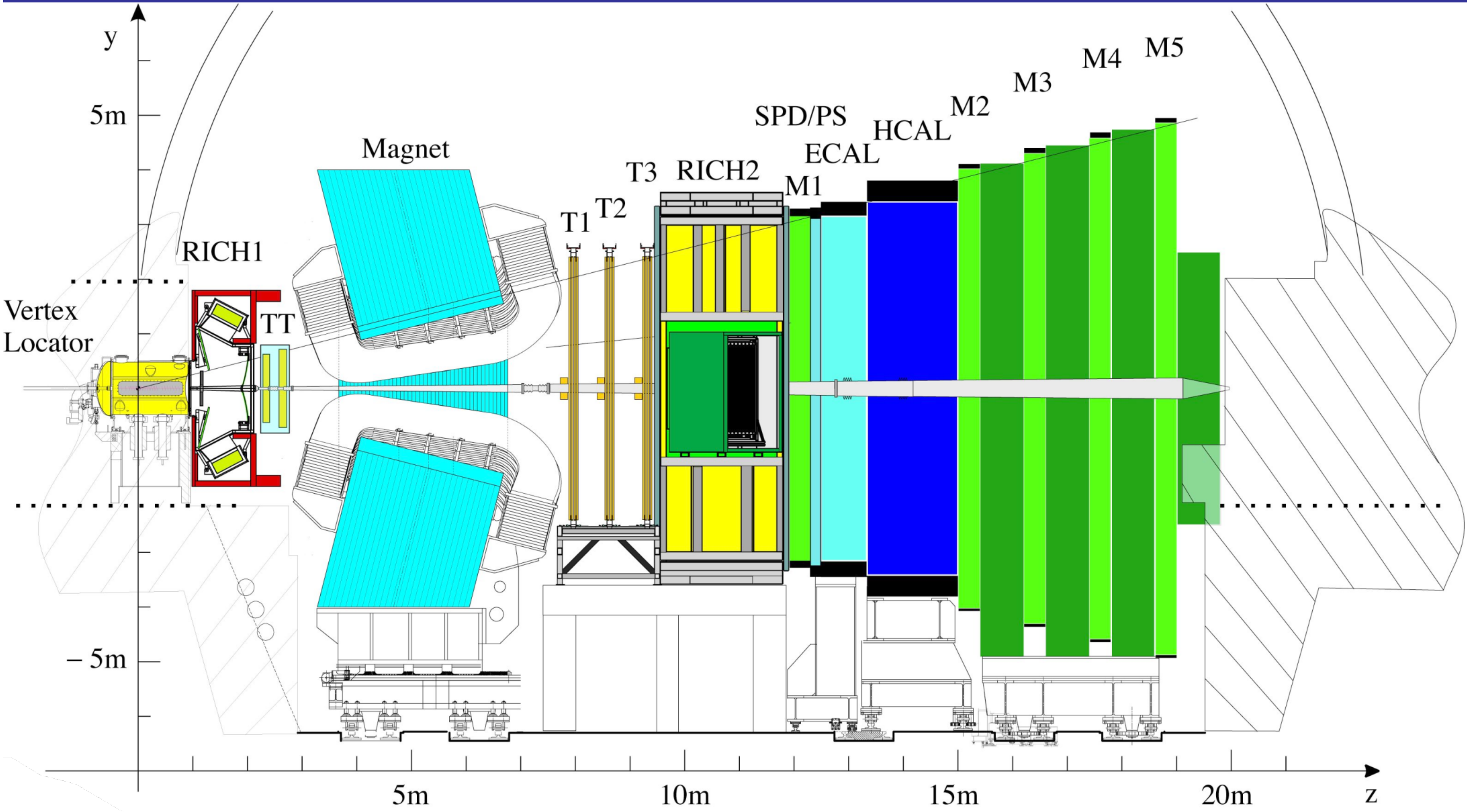


The LHC



27 km in circumference

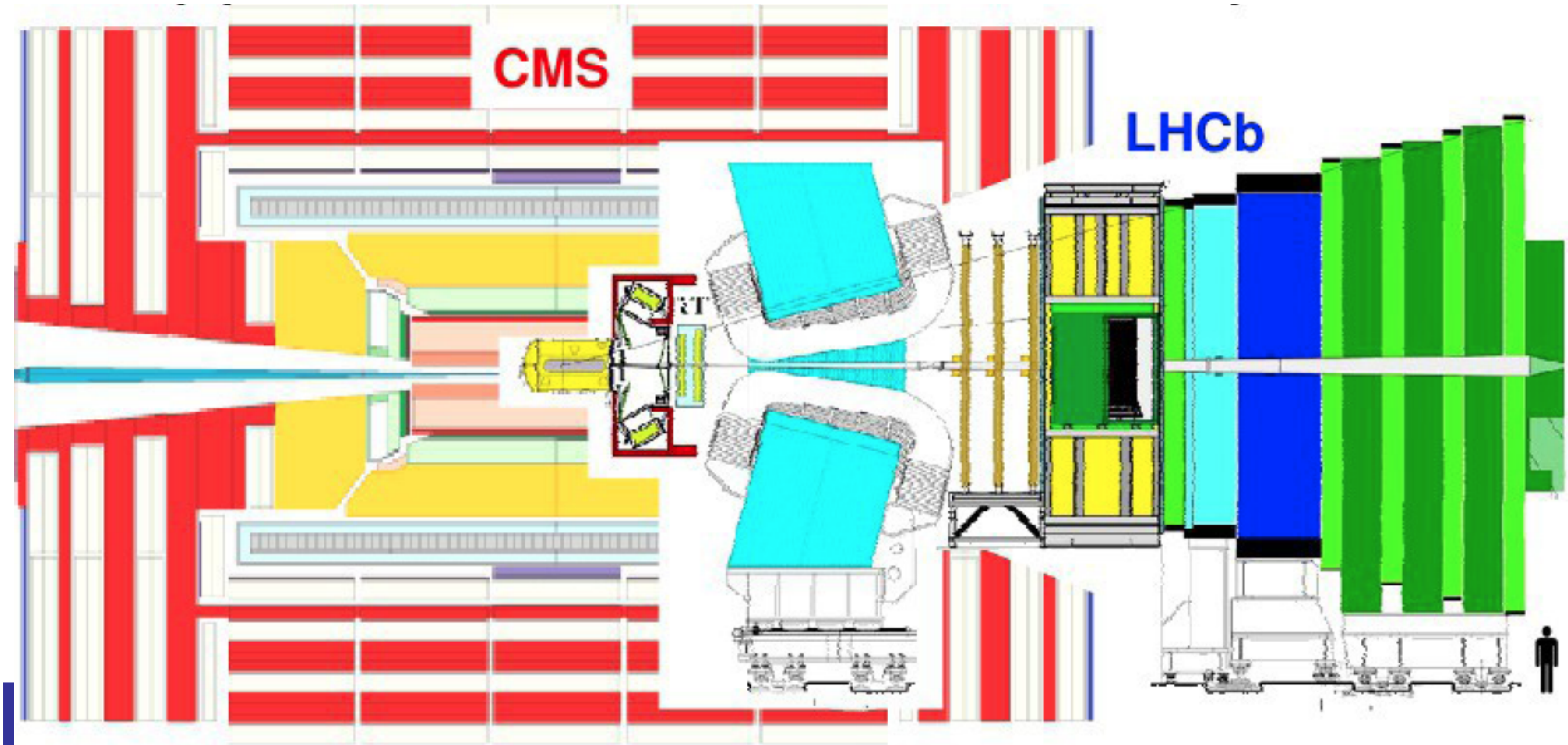
The LHCb Detector



64

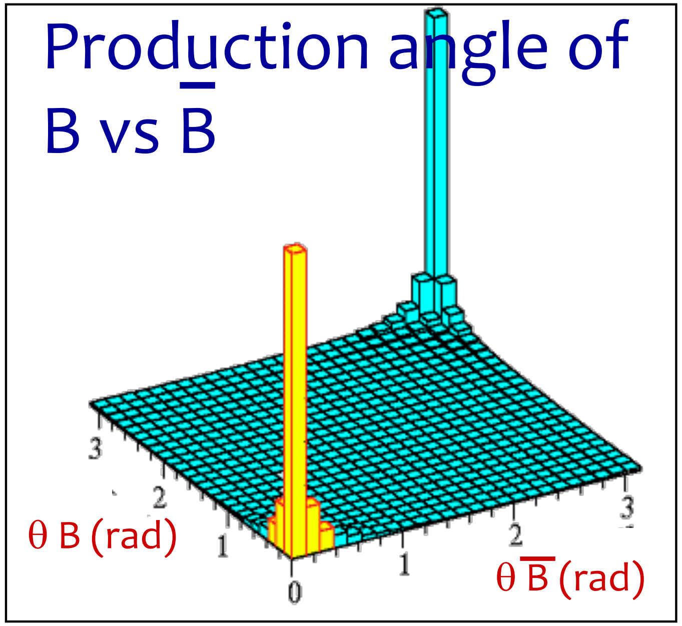
Detector Geometry

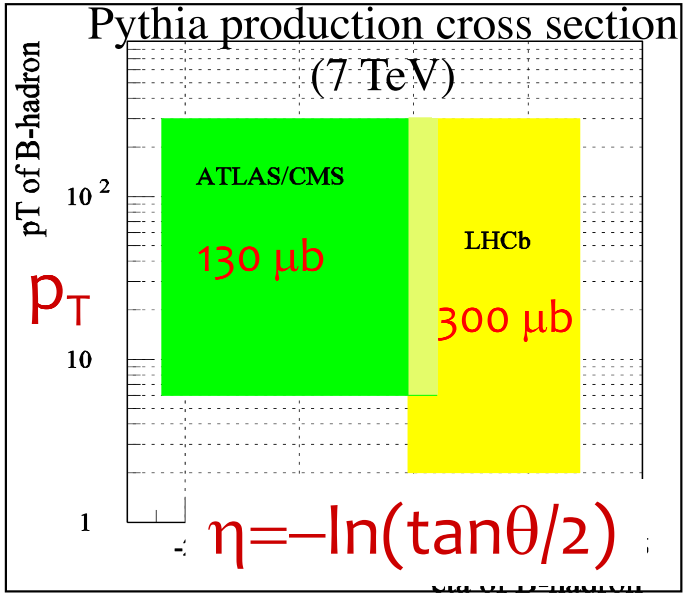
- Complementary to ATLAS & CMS
- Much less expensive



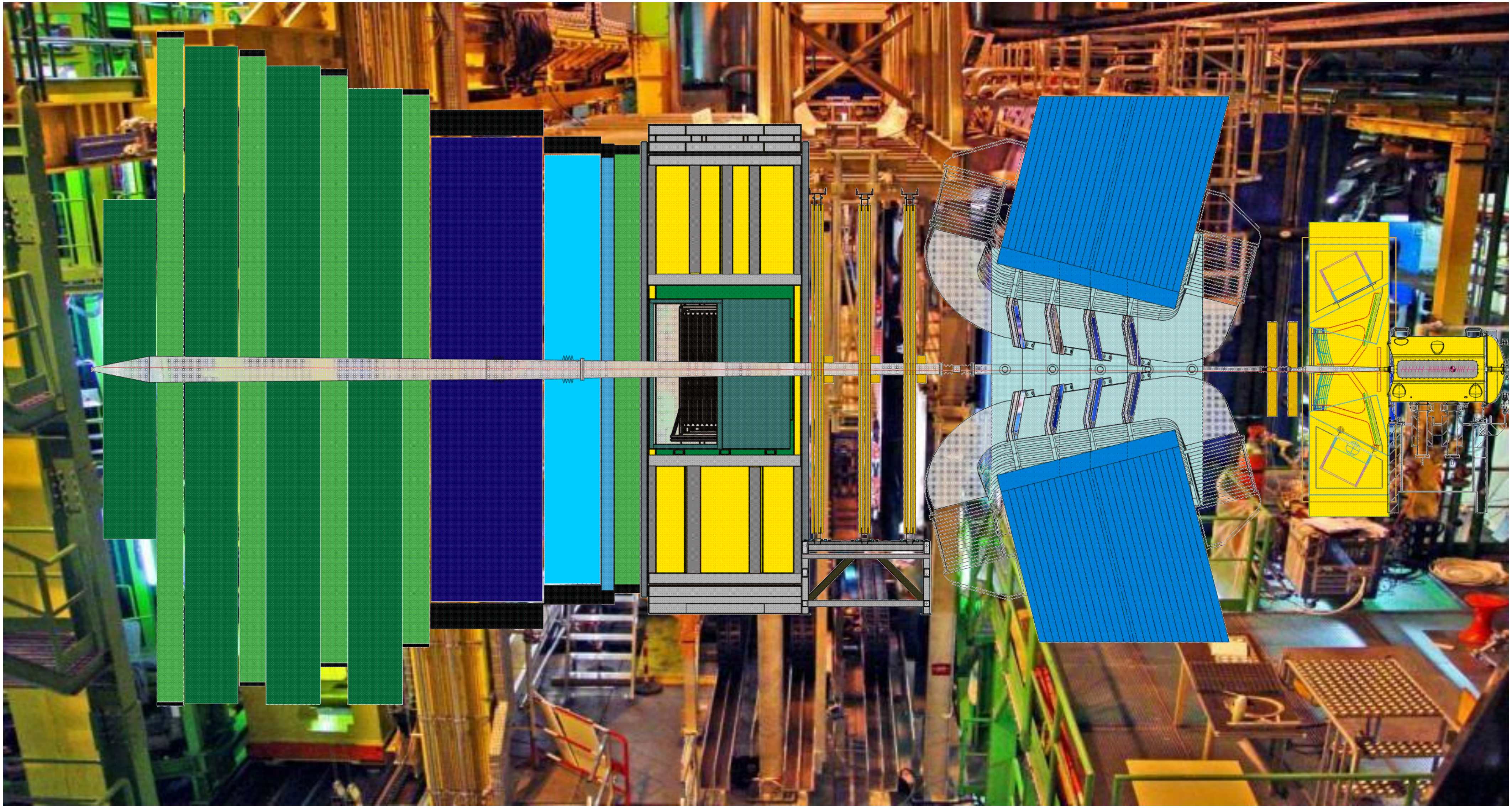
The Forward Direction at the LHC

- The primary pp collision produces a pair of $b\bar{b}$ quarks. They then form hadrons. In the forward region at LHC the $b\bar{b}$ production σ is large
- The hadrons containing the b and $\bar{b}$ quarks are both likely to be in the acceptance.
- Essential for knowing if a neutral B meson started out as a B^0 or $\bar{B}^0$, determined by "flavor tagging"
- At $\mathcal{L} = 2\times10^{32}\,\mathrm{cm}^{-2}s^{-1}$, we get $\sim10^{12}$ B hadrons in 10^7 sec

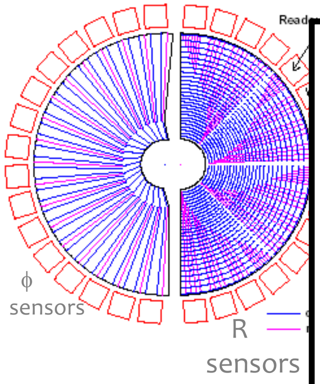




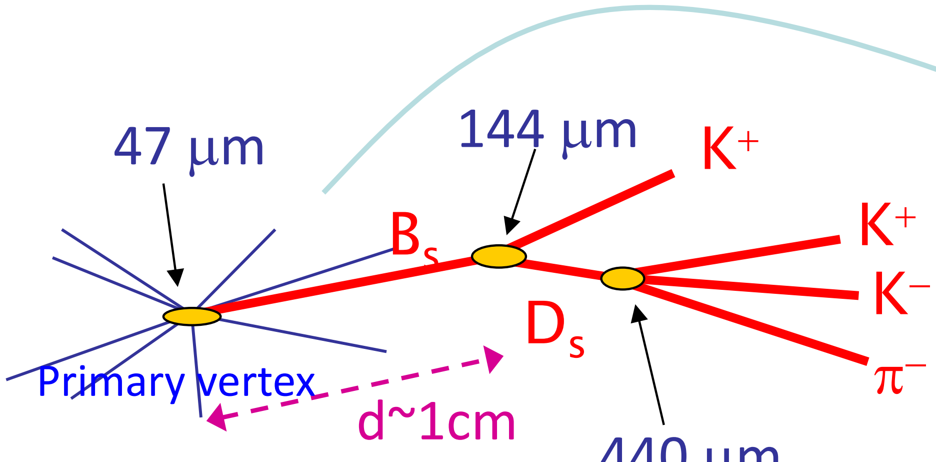
LHCb detector

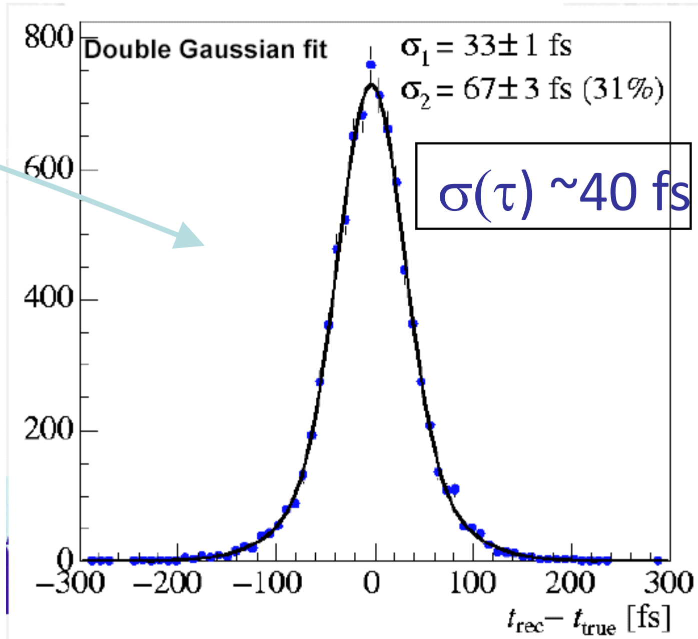


B-Vertex Measurement



Example: $B_s \rightarrow D_s K$





Decay time resolution = 40 fs

Vertex Locator (Velo)

Silicon strip detector with

~ 5 μm hit resolution

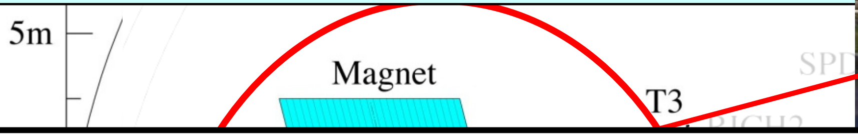
→ 30 μm IP resolution

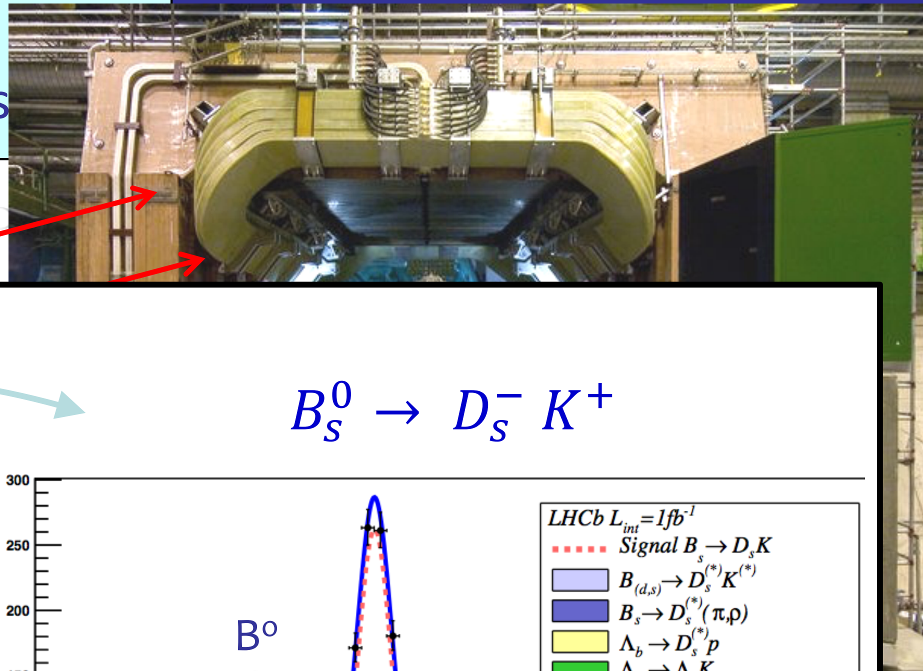
Vertexing:

- trigger on impact parameter
- measurement of decay distance & decay time=d/v=md/p

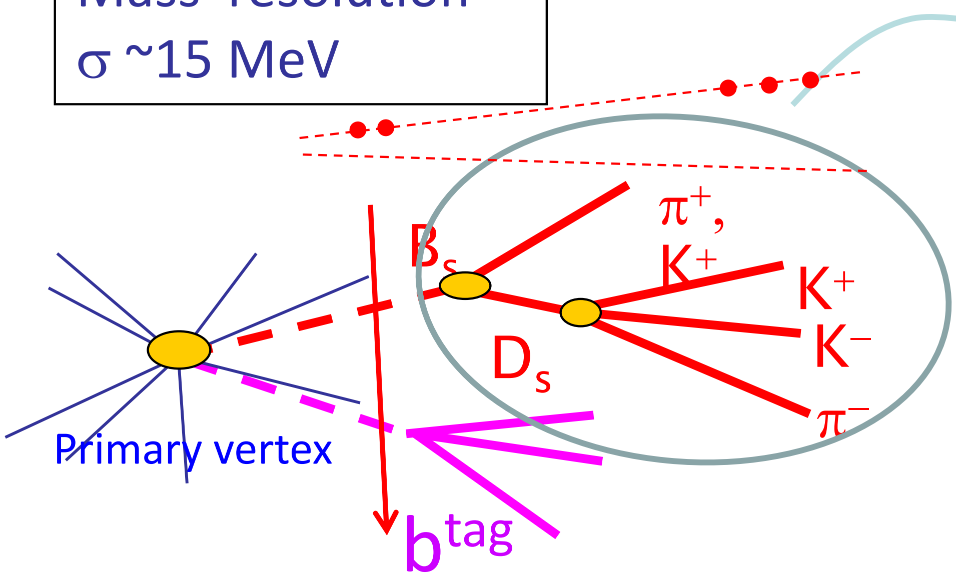
Momentum and Mass measurement

Momentum meas. + direction (VELO):
Mass resolution for background suppres

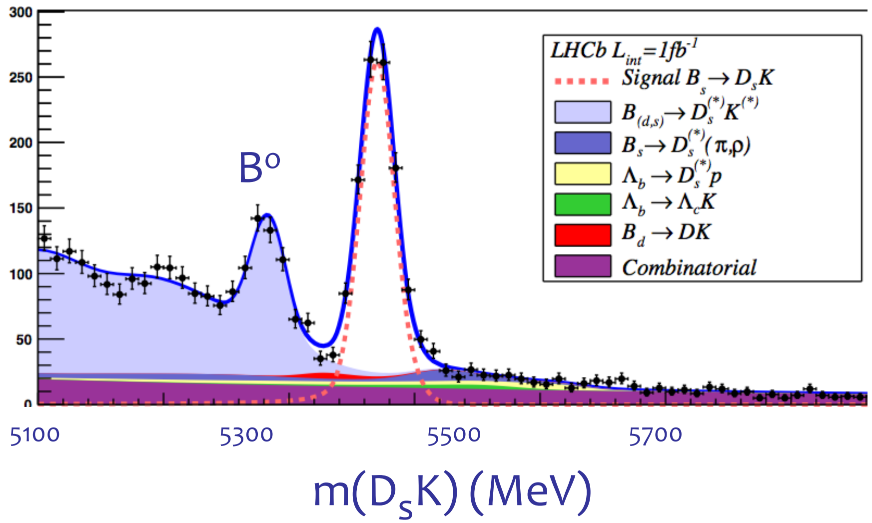




Mass resolution
σ ~15 MeV

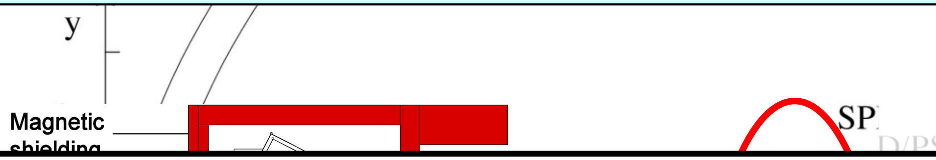


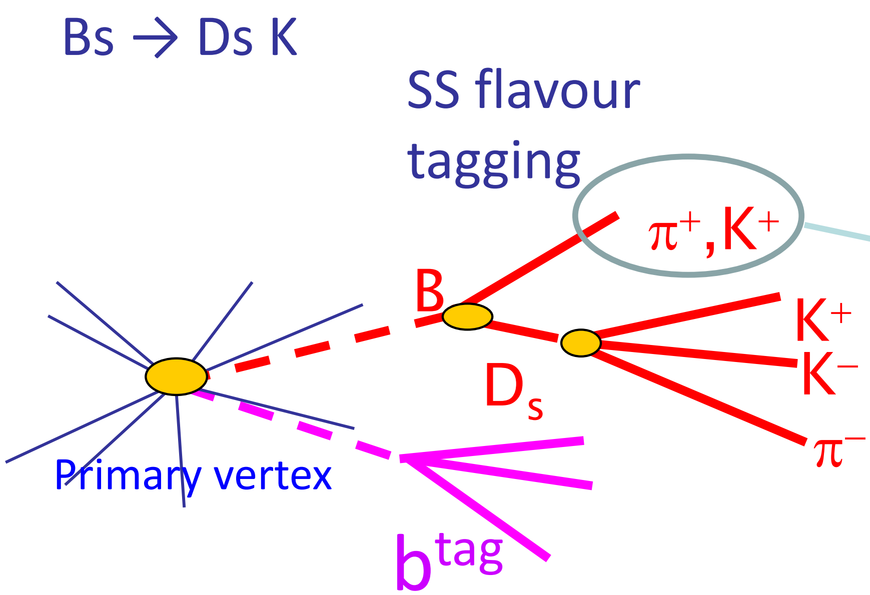
$B_s^0 \to D_s^- K^+$

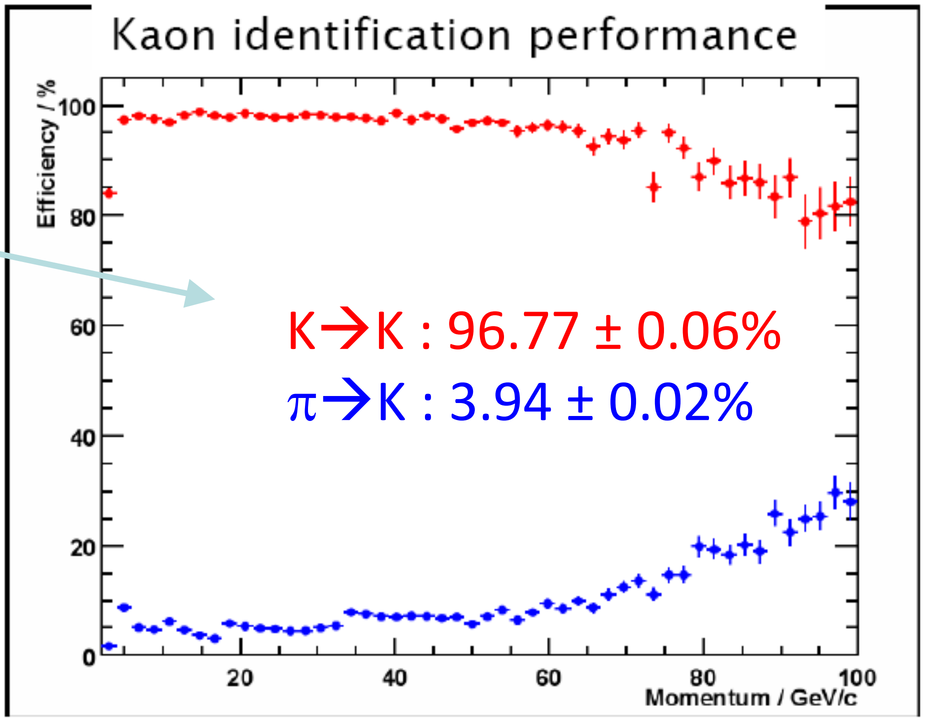


Hadron Identification

RICH: K/π identification using Cherenkov light emission angle





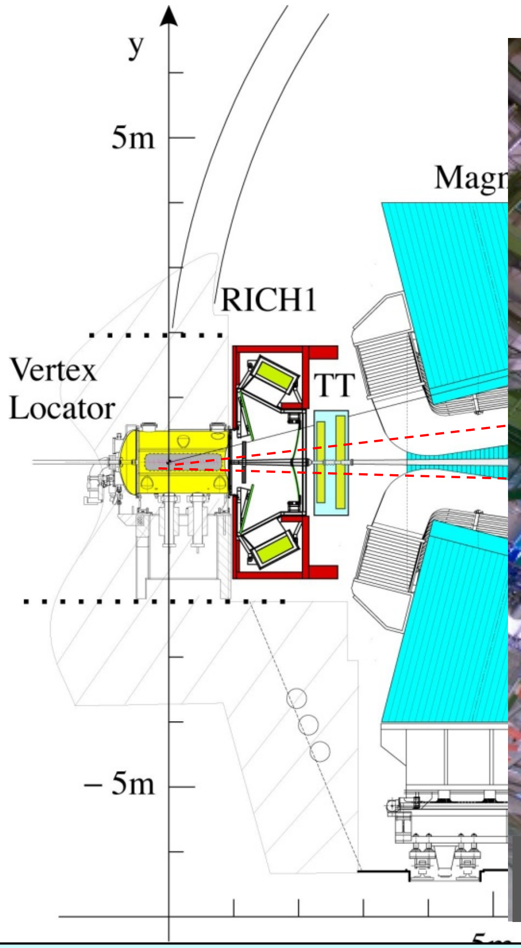


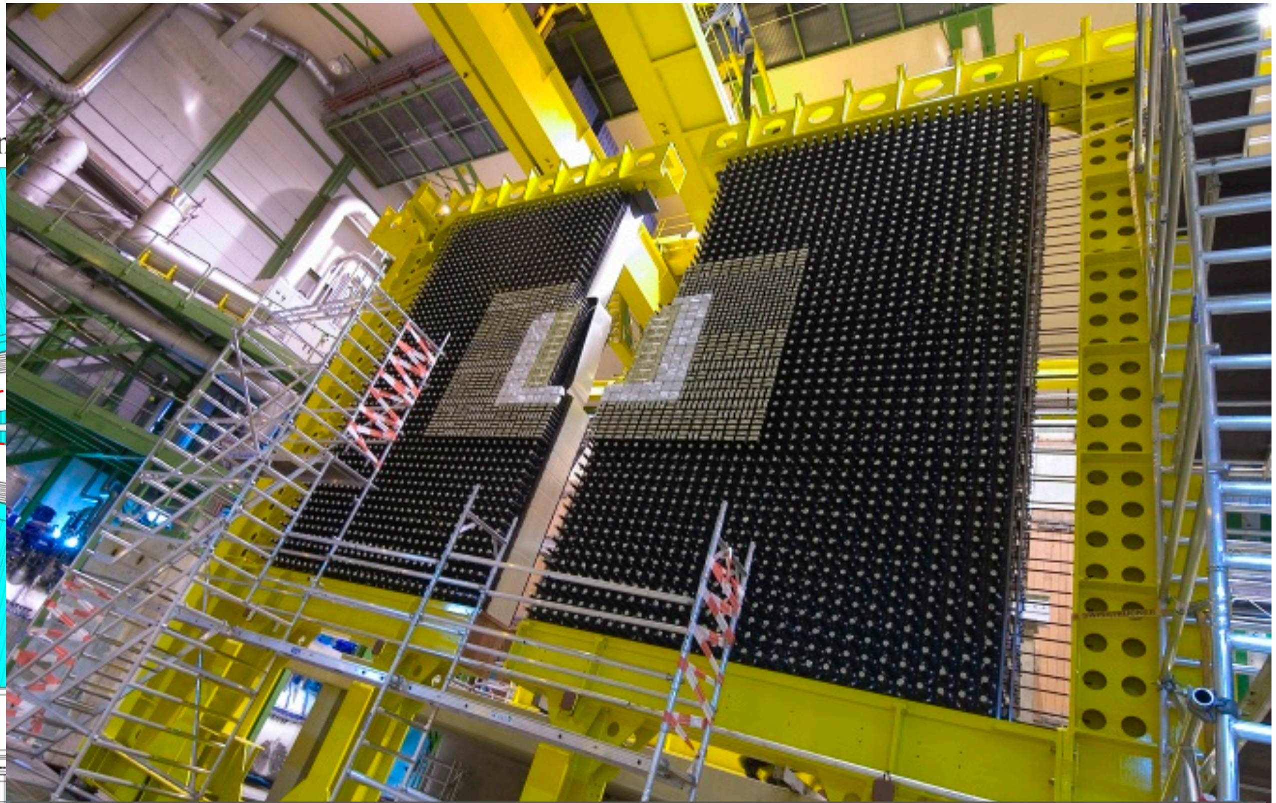
RICH1: 5 cm aerogel n=1.03

$4\ m^3\ C_4F_{10}$ n=1.0014

RICH2: 100 m3 CF_4 n=1.0005

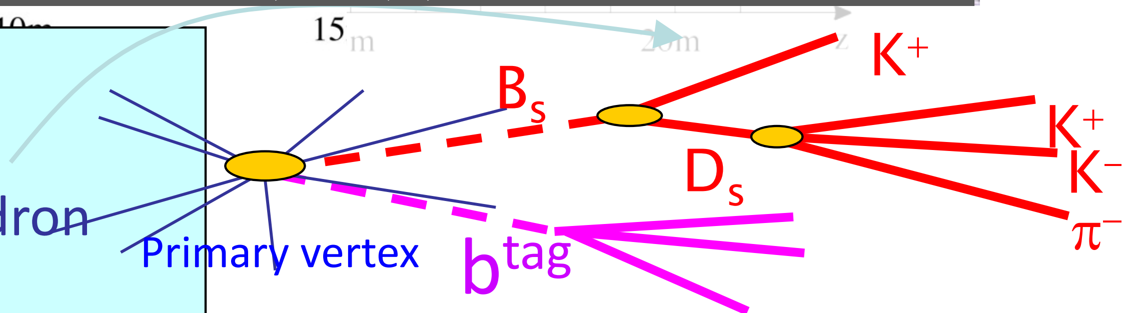
Calorimetry and L0 trigger



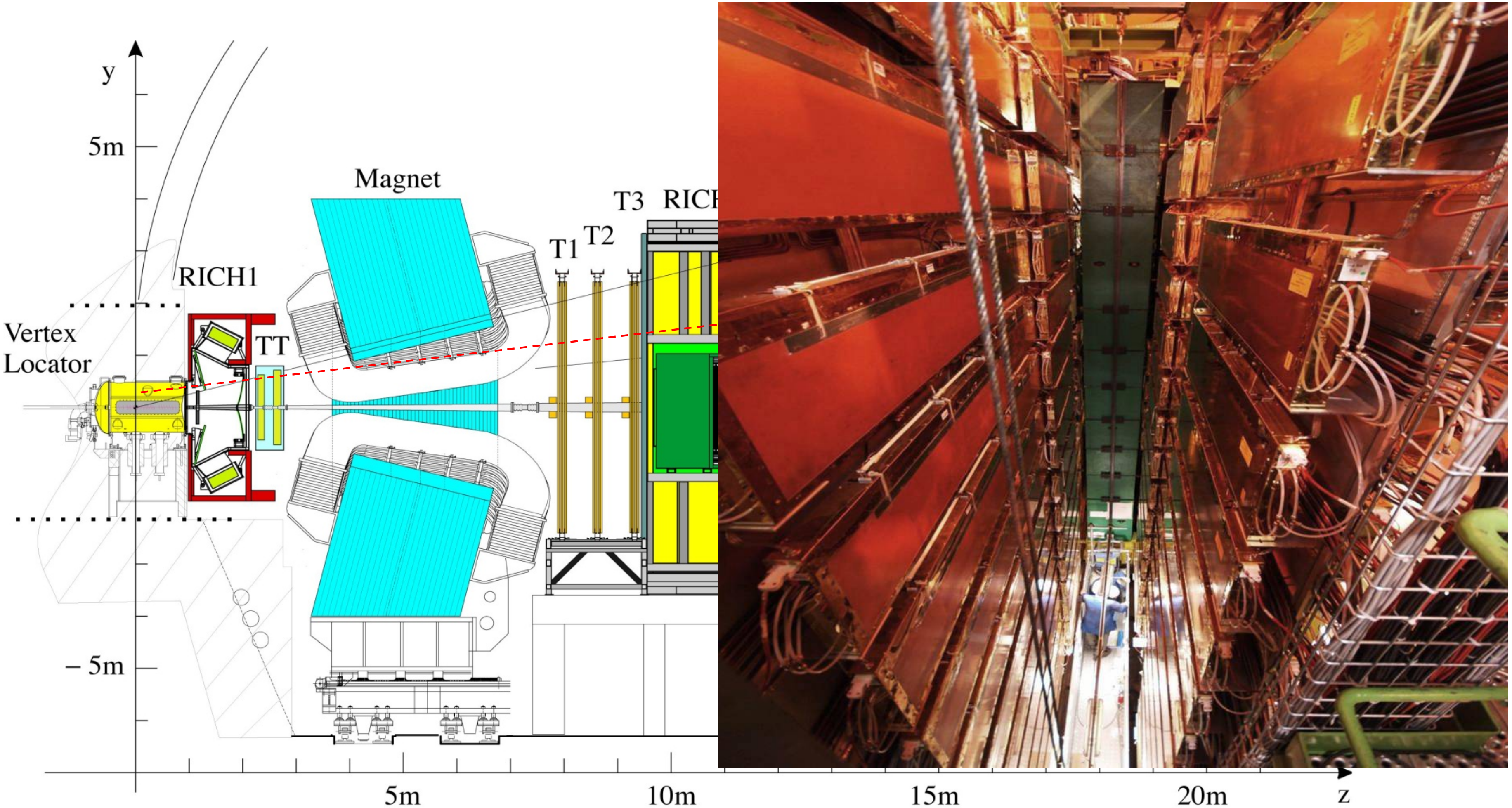


ECAL (inner modules): $\sigma(E)/E \sim 8.2\% /\sqrt{E} + 0.9\%$

Calorimeter system :
- Identify electrons, hadrons, π^0 ,γ
- Level 0 trigger: high E_T electron and hadron

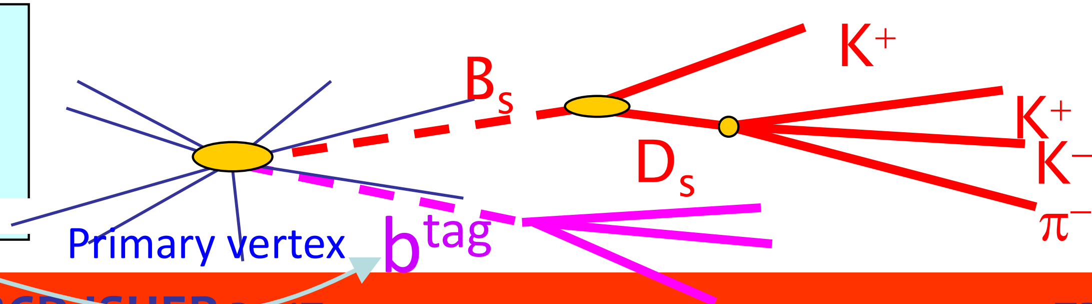


Muon identification and L0 trigger

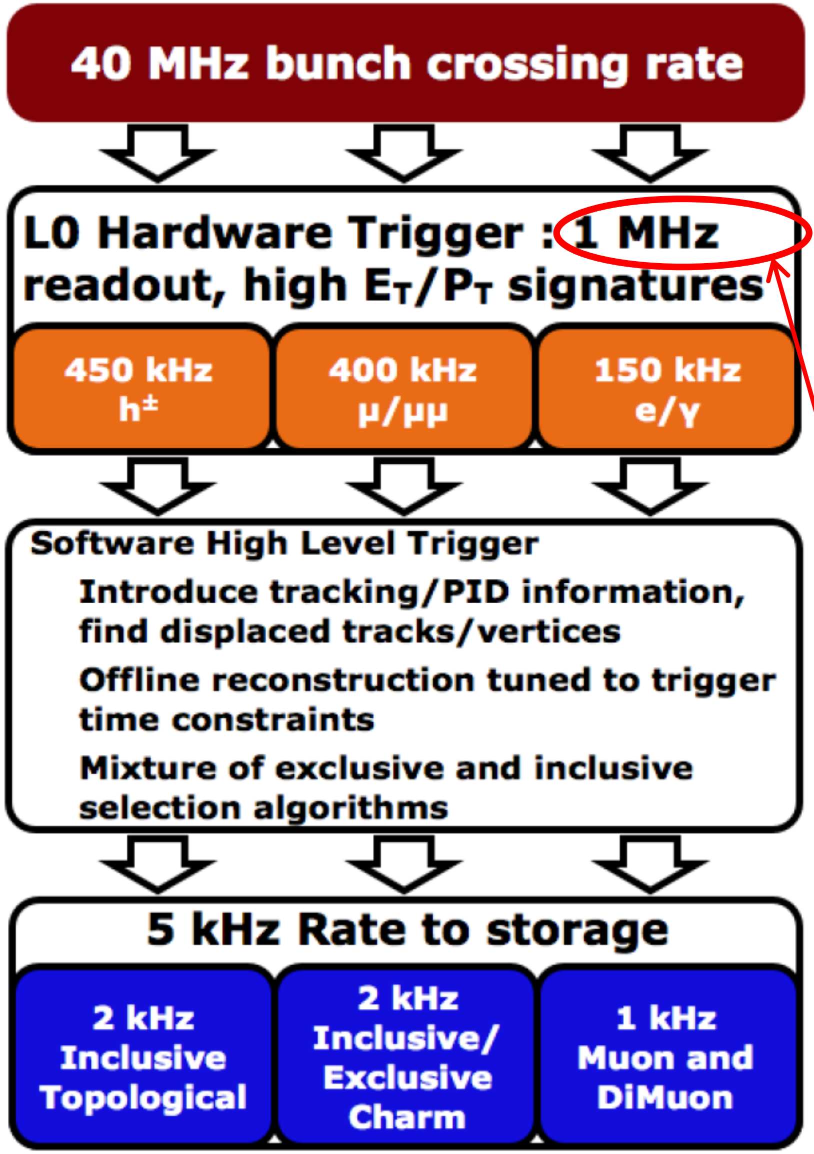


Muon system:

- Level 0 trigger: High P_t muons
- OS flavour tagging



Triggering

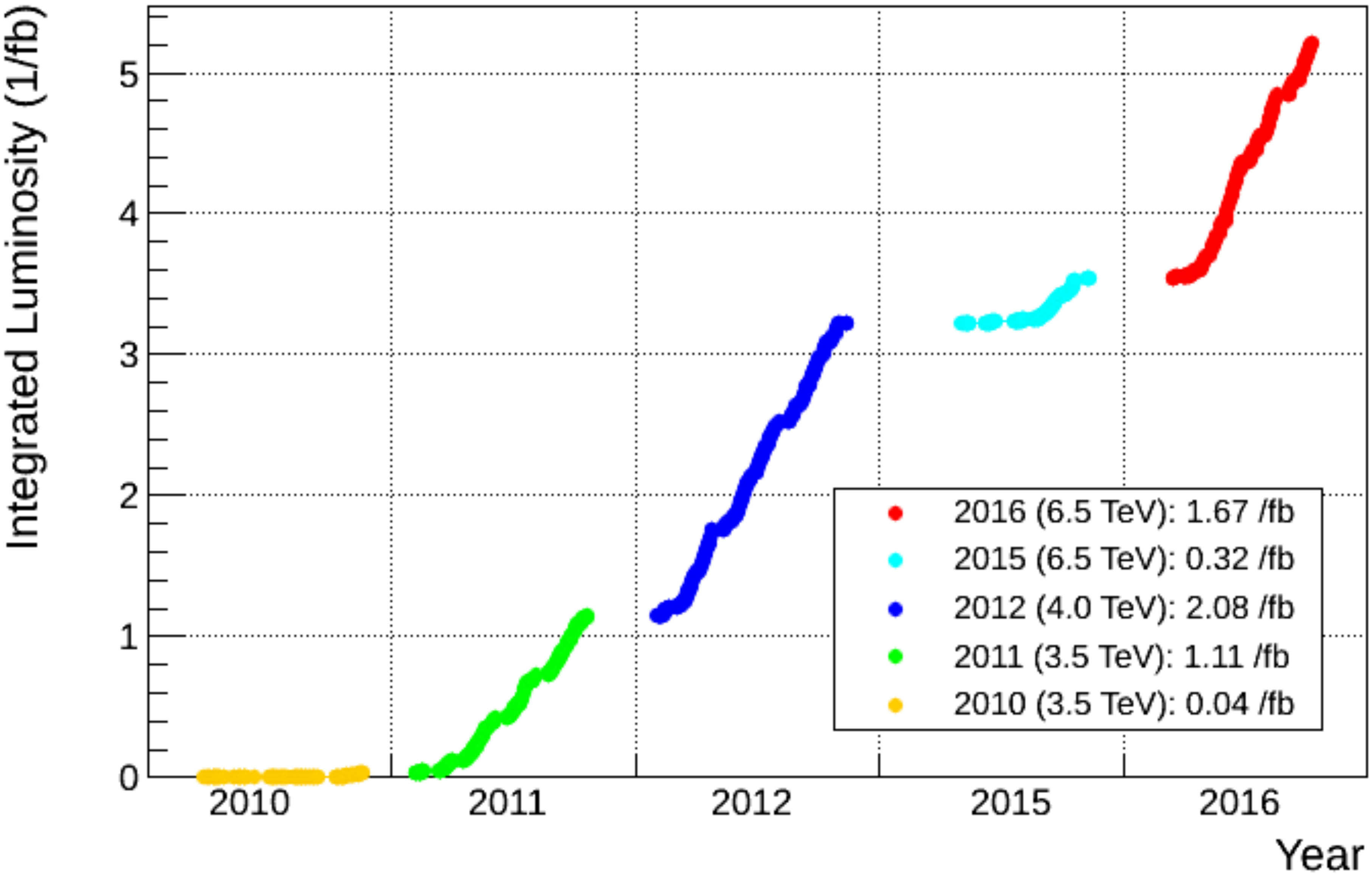


- Trigger is crucial as $\sigma_{b\bar{b}}$ is less than 1% of total inelastic cross section and B decays of interest typically have B ranching ratios of $<10^{-5}$
- Hardware level (L0), search for high-p_T μ, e, γ and hadron candidates
- Software level (High Level Trigger, HLT)
- Farm with O(29000) multi-core processors)

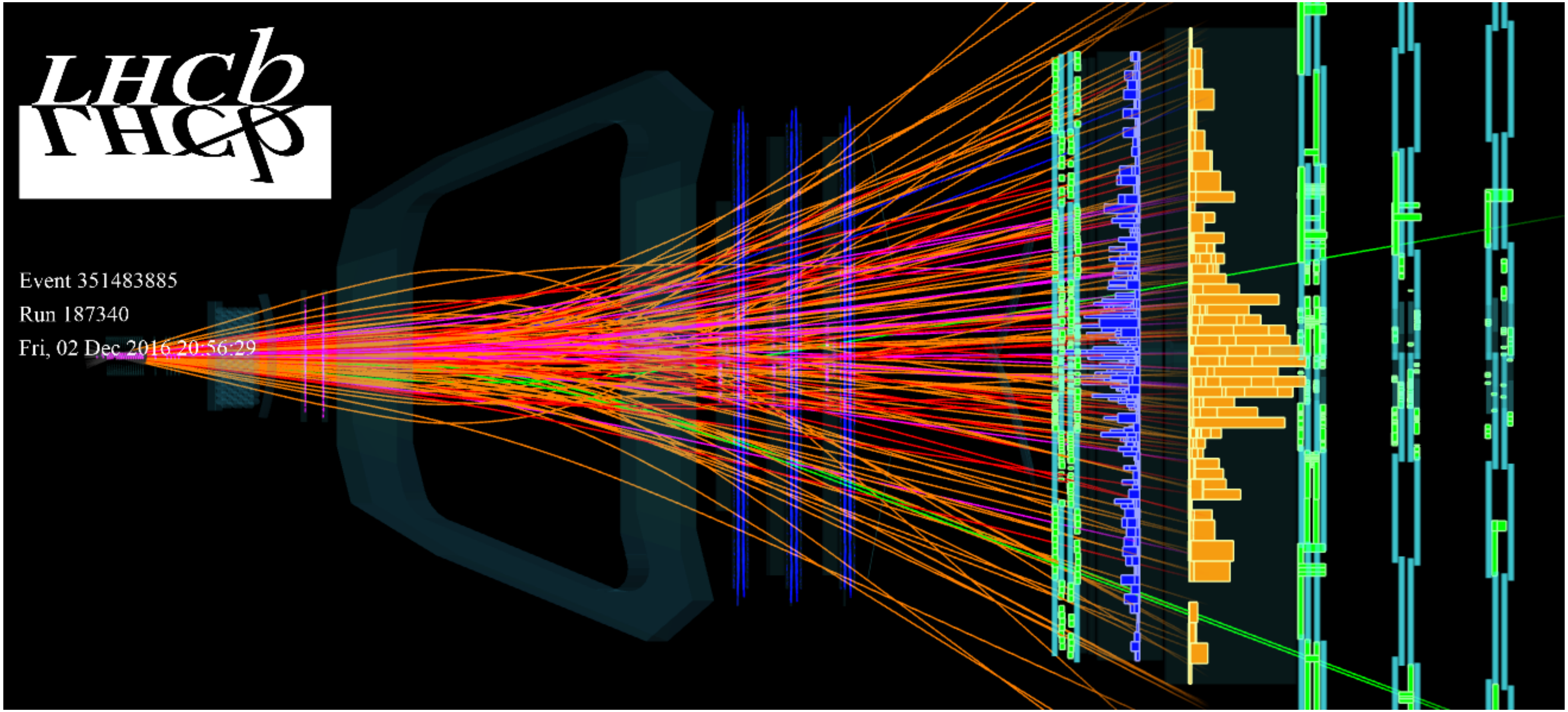
This is the bottleneck

- Very flexible algorithms, writes ~5 kHz to storage

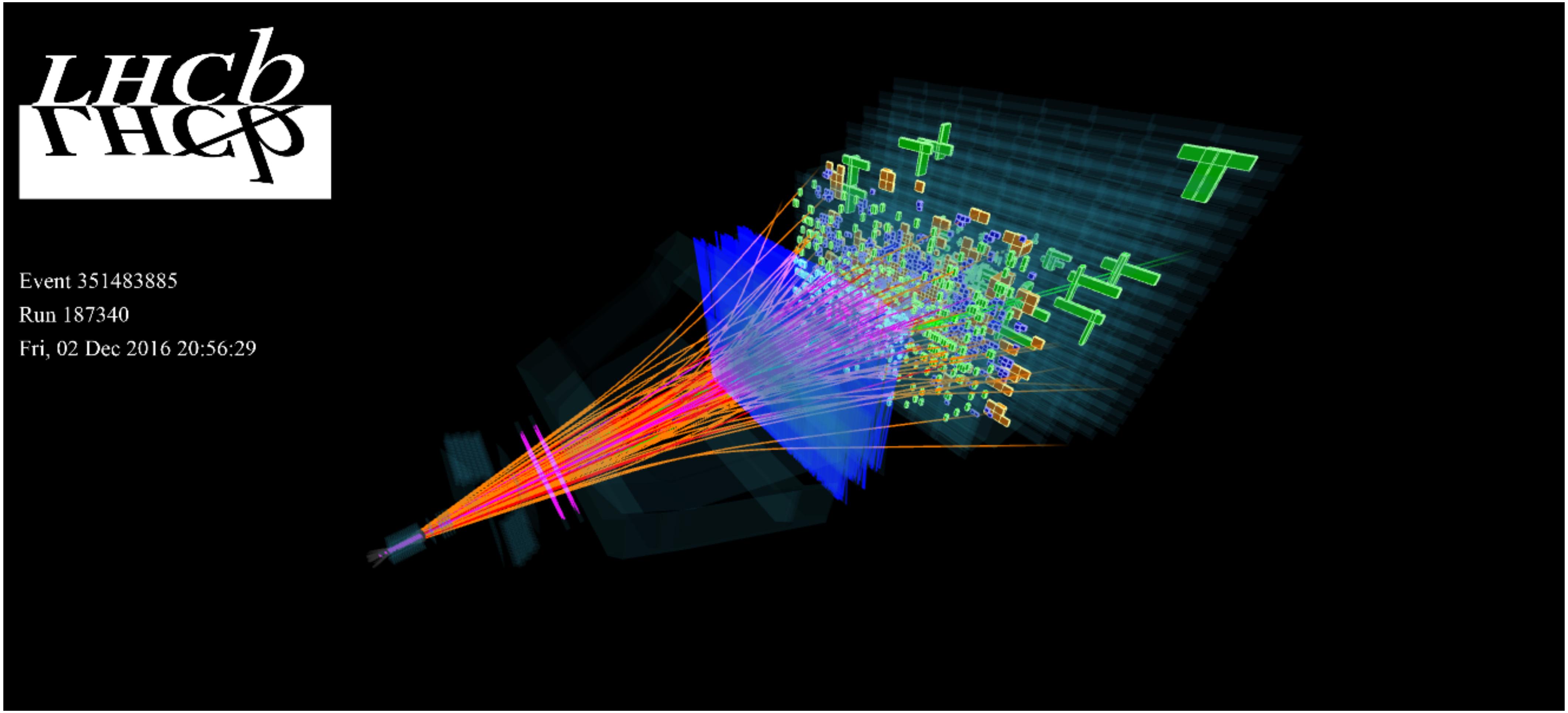
LHCb data taking history



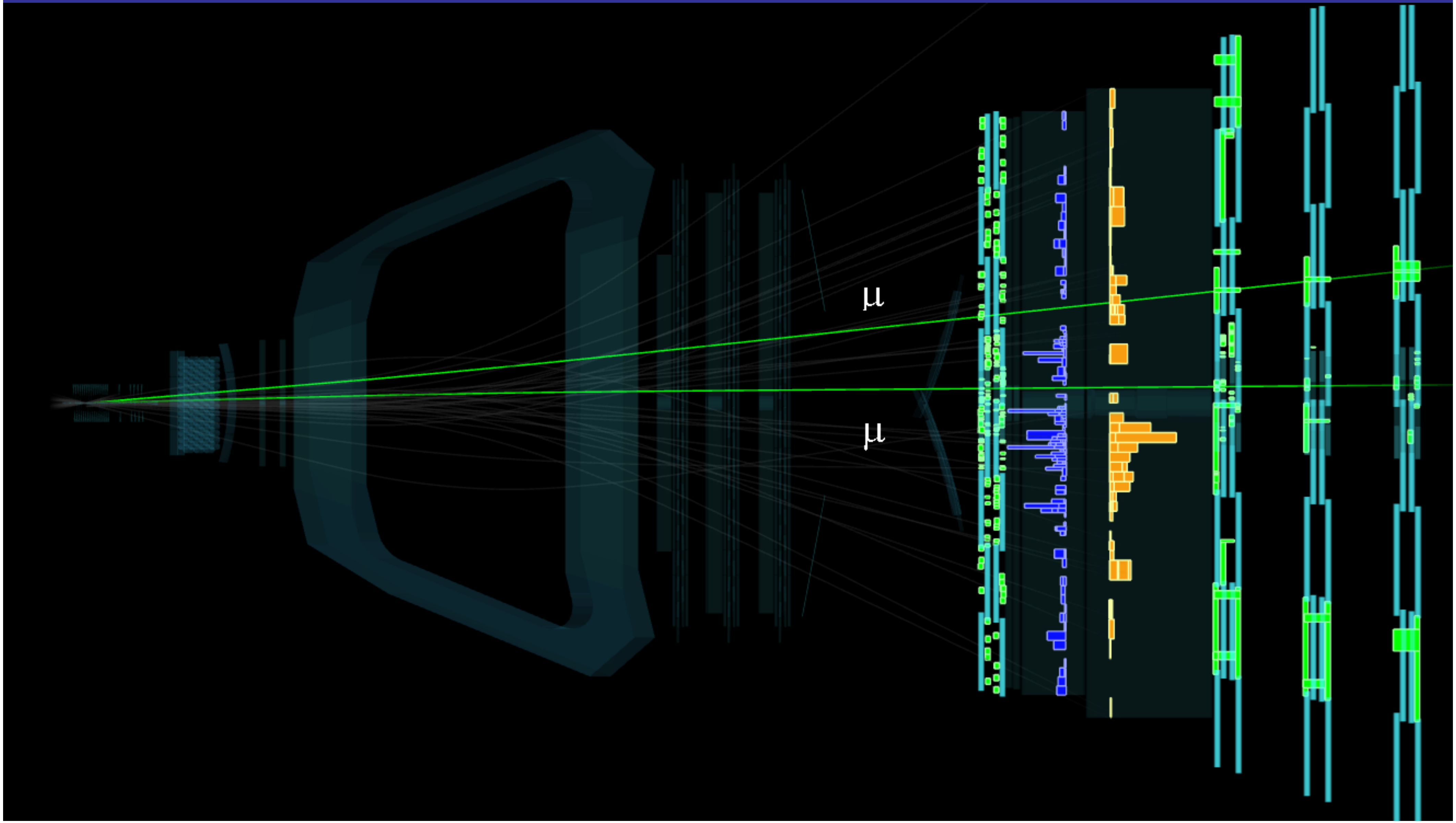
LHCb event display



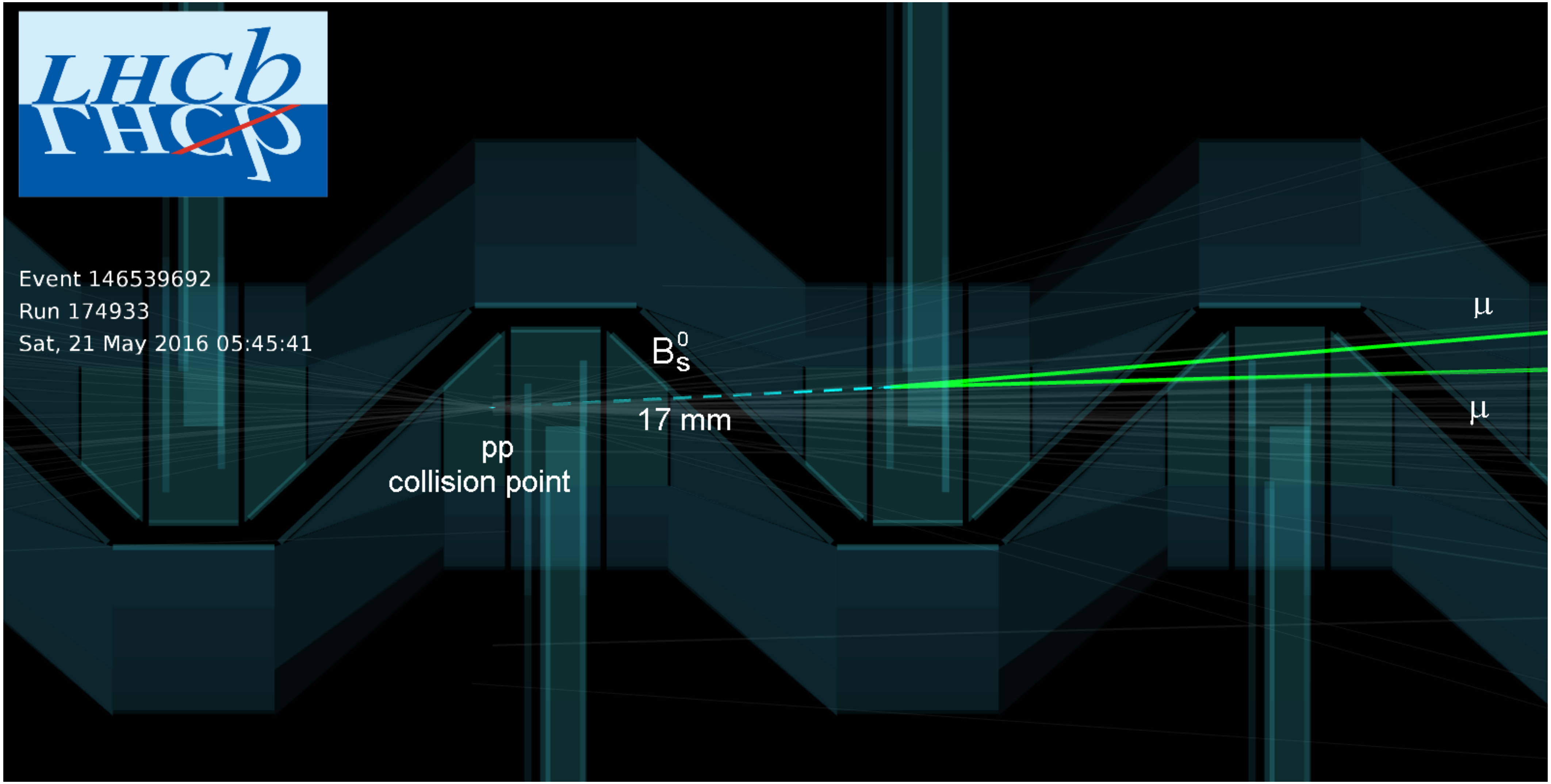
LHCb event display



$B \to \mu^- \mu^+$



$B \to \mu^- \mu^+$


Event 146539692
Run 174933
Sat, 21 May 2016 05:45:41
B_s^0
17 mm
pp
collision point
μ
μ

Search for new particles: latest new from Moriond (ATLAS and CMS)

Summary slides of T. Gershon

One year ago ...

(from Andreas Hoecker's summary slides)

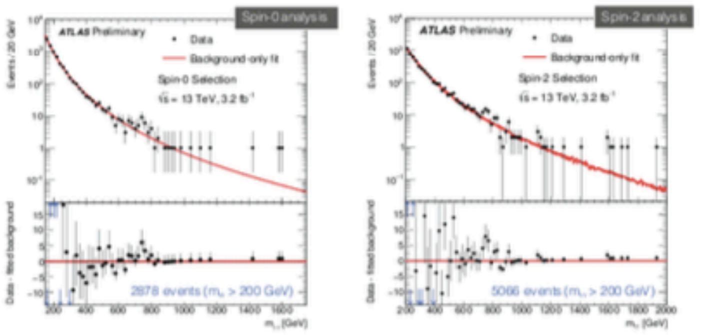
Marco Delmastro

Diphoton resonance searches: ATLAS

Updated preliminary results presented this week

ATLAS showed dedicated searches for a spin-0 and a spin-2 diphoton resonance.

- Main difference is acceptance: spin-0: $E_T(\gamma_1) > 0.4 \cdot m_{\gamma\gamma}$, $E_T(\gamma_2) > 0.3 \cdot m_{\gamma\gamma}$, spin-2: $E_T(\gamma_{1/2}) > 55$ GeV
- Photons are tightly identified and isolated. Typical purity ~94%
- Background modelling empirical in spin-0, and (mainly) theoretical in spin-2 case (for high-mass search)



Pasquale Musella

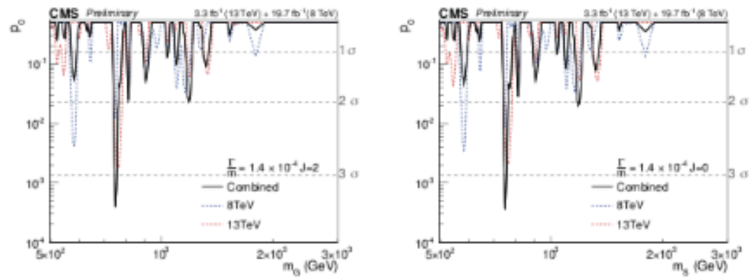
Diphoton resonance searches: CMS

Updated preliminary results presented this week

CMS has also looked into event properties of excess region and found them consistent with sidebands

CMS combines 13 TeV with spin-0 and 2 searches from 8 TeV data. Results found to be compatible.

Resulting p-value scans (lowest width models, giving largest excess at 750 GeV, shown here):



Lowest p-value at ~750 GeV (760 for 13 TeV data only), narrow width

Local / global Z = 3.4σ / 1.6σ (2.9σ / < 1 for 13 TeV data only)

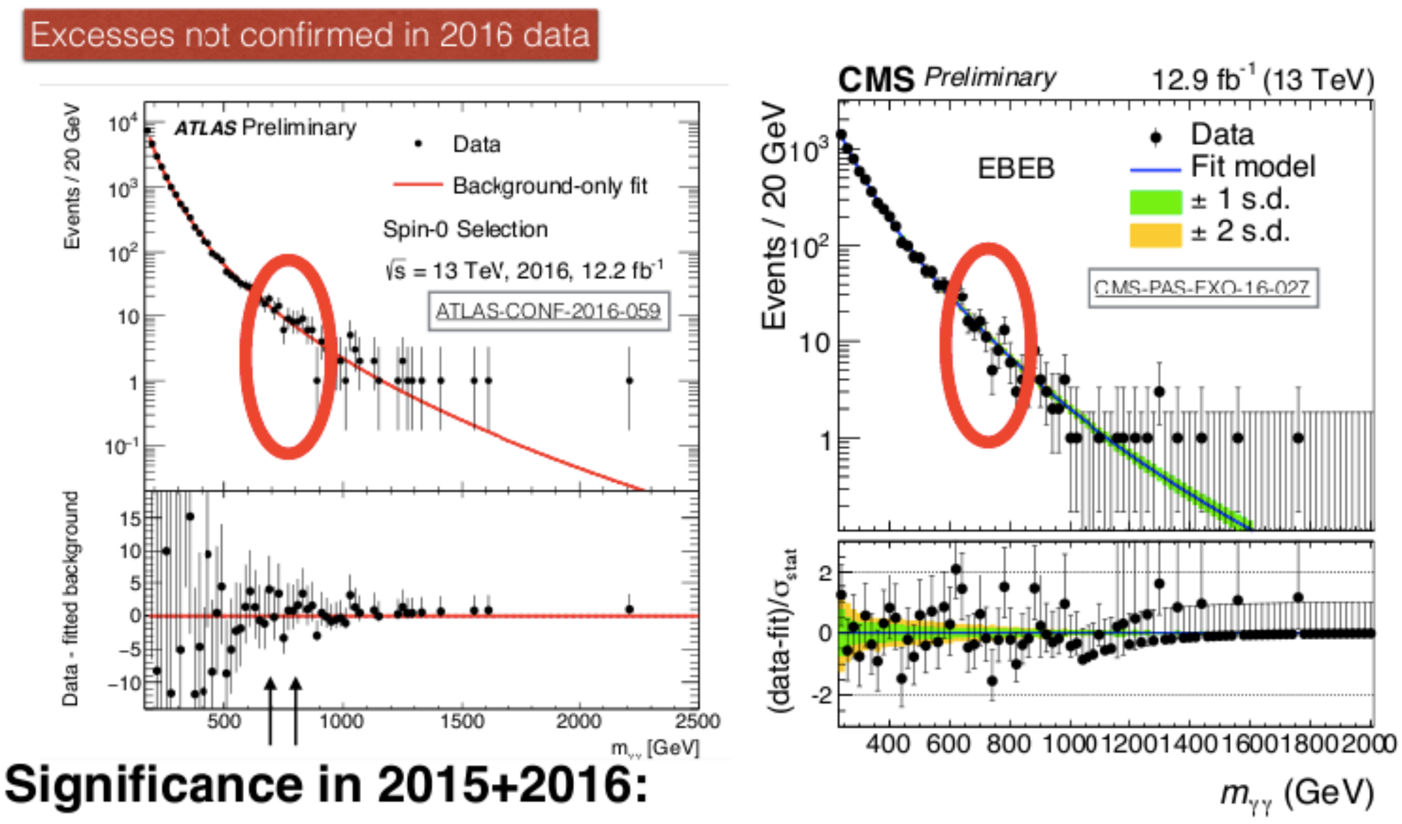
Alessandro Strumia:

Today it could be everything, including nothing.

4

Then at ICHEP 2016 ...

(from Shih-Chieh Hsu's plenary talk)



Significance in 2015+2016:

m=710 GeV (Γ/M=10%)
2.3σ(local)/<1σ (global)

m=760 GeV (Γ/M=1.4x10^{-4})
<1σ(local)

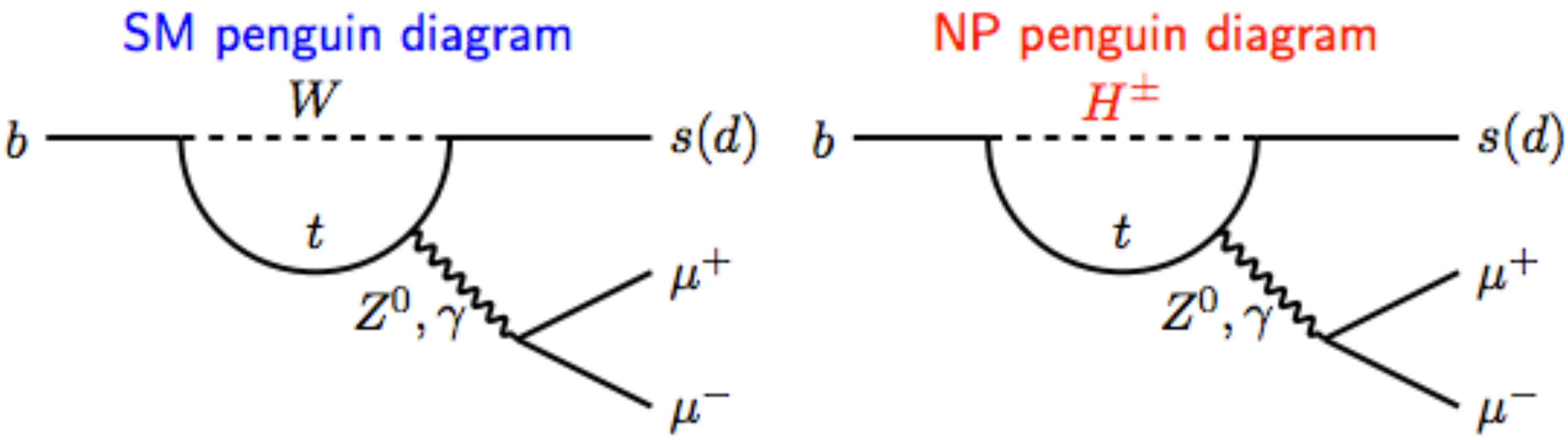
5

You can imagine the rest of the talk…

https://indico.in2p3.fr/event/13763/session/17/contribution/117/material/slides/1.pdf

Test of standard model with FCNC

FCNC: b $\rightarrow s(d)\mu^-\mu^+$



New heavy particles in SM extensions can appear in competing diagrams can affect branching ratios and angular distributions

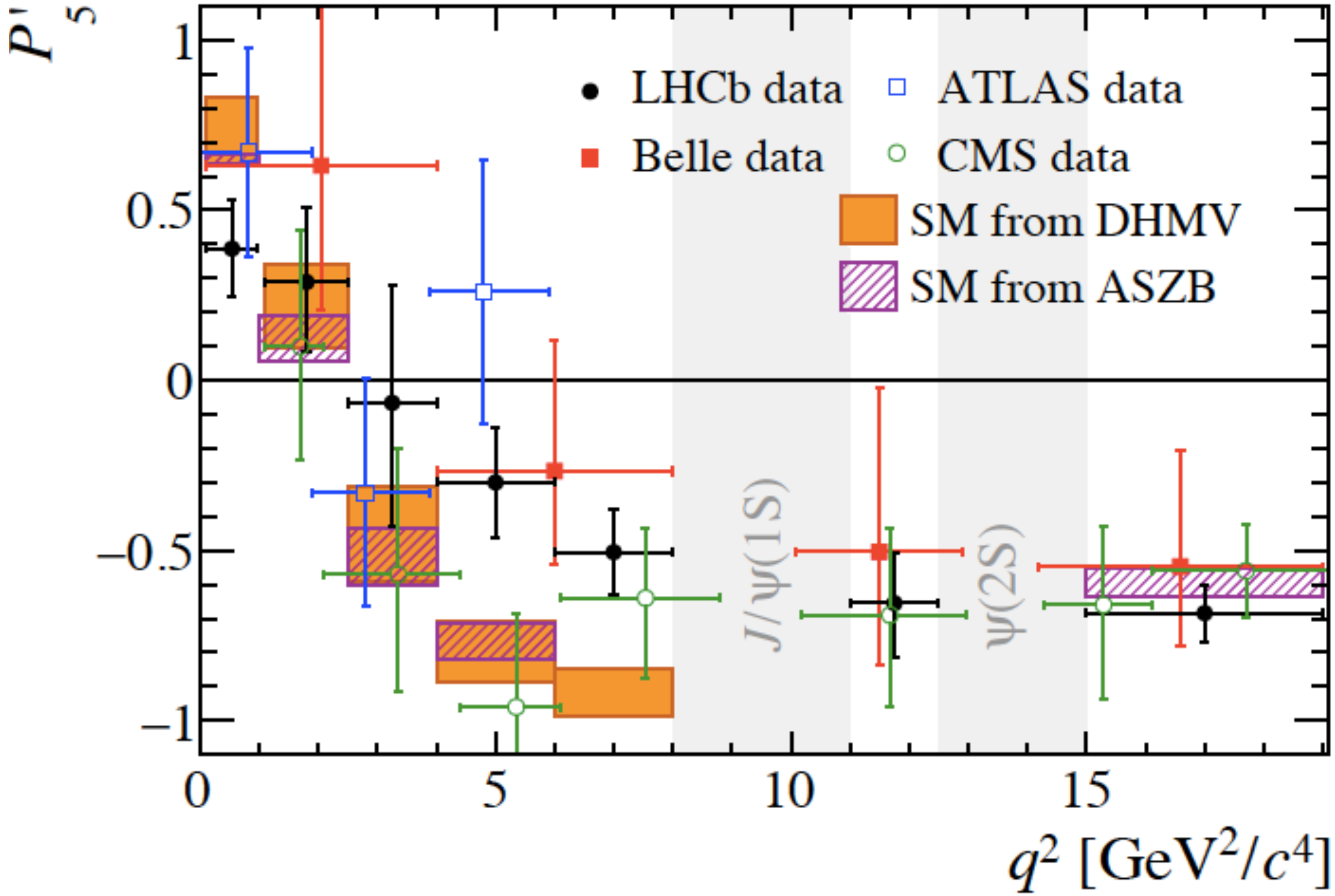
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{\text{tb}} V_{\text{tq}}^* \sum_i \underbrace{\mathcal{C}_i \mathcal{O}_i}_{\text{Left handed}} + \underbrace{\mathcal{C}_i' \mathcal{O}_i'}_{\text{Right handed, } \frac{m_s}{m_b} \text{ suppressed}} + \sum \frac{c}{\Lambda_{\text{NP}}^2} \mathcal{O}_{\text{NP}}$$

$i = 1, 2$	Tree
$i = 3-6, 8$	Gluon penguin
$i = 7$	Photon penguin
$i = 9, 10$	EW penguin
$i = S, P$	(Pseudo)scalar penguin

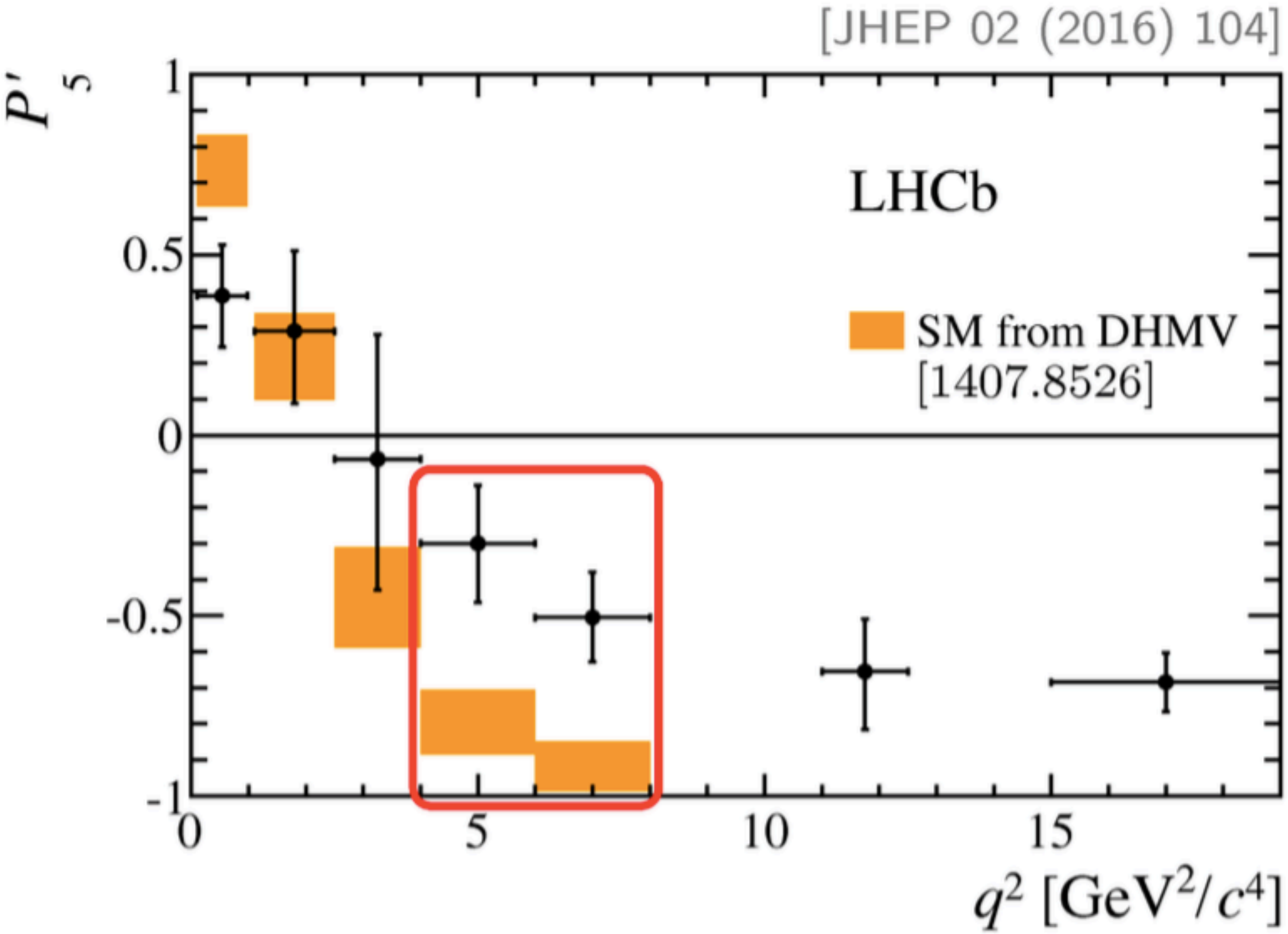
Model independent description in effective field theory

$B^0 \to K^{*0}\mu^-\mu^+$

P_5^i is an observable related to angular distribution of the decay
q^2 is di-muon effective mass squared



Latest LHCb result: deviation to 3.4σ

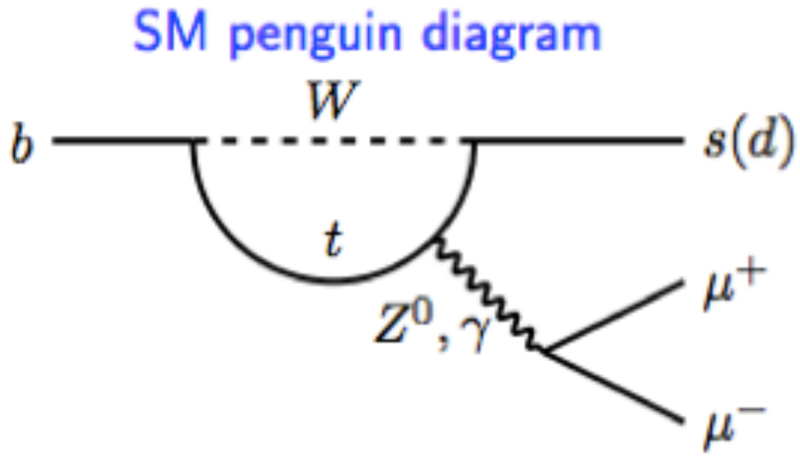


- In q^2 bins $[4.0, 6.0]$ and $[6.0, 8.0]$ GeV^2/c^4 local deviations of $2.8\,\sigma$ and $3.0\,\sigma$
- Global $B^0 \to K^{*0}\mu^+\mu^-$ analysis finds deviation corresponding to $3.4\,\sigma$

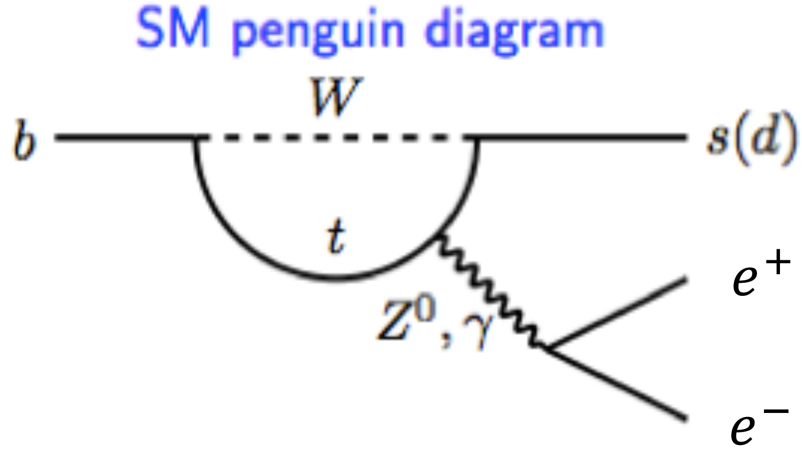
Lepton universality in B decays

$B^+ \to K^+ \mu^- \mu^+$

$B^0 \to K^+ e^- e^+$



=?



$$R_K = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{\mathrm{d}\Gamma[B^+ \to K^+\mu^+\mu^-]}{\mathrm{d}q^2}\mathrm{d}q^2}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{\mathrm{d}\Gamma[B^+ \to K^+e^+e^-]}{\mathrm{d}q^2}\mathrm{d}q^2}$$

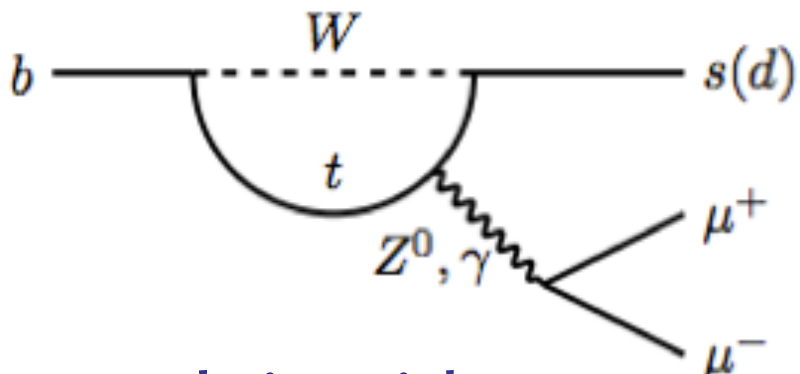
LHCb measured in this range

$$1 < q^2 < 6\,\mathrm{GeV}^2/c^4$$

Lepton universality in B decays

$B^+ \to K^+ \mu^- \mu^+$

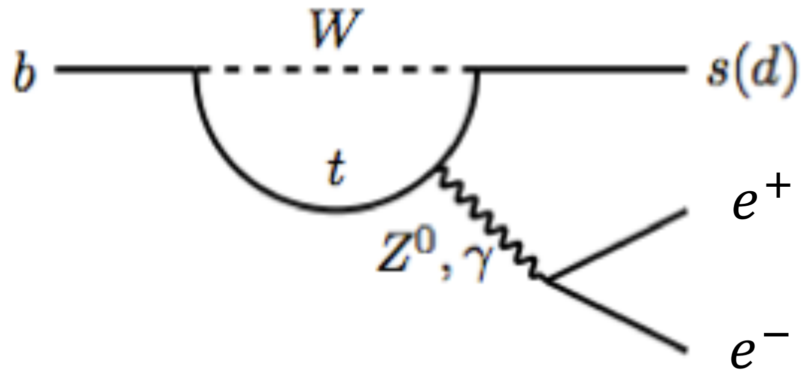
SM penguin diagram



$= ?$

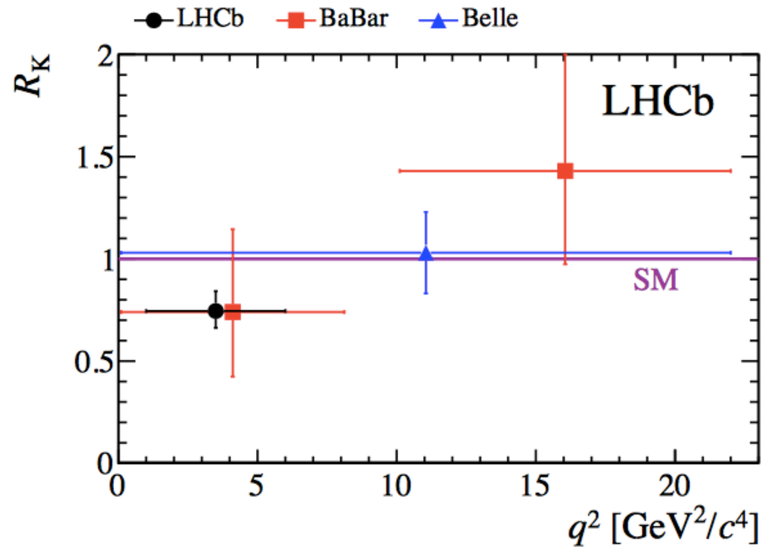
$B^0 \to K^+ e^- e^+$

SM penguin diagram



This result is with RUN-1 LHCb data

$$R_K = 0.745^{+0.090}_{-0.074}\,(\text{stat}) \pm 0.036\,(\text{syst})$$

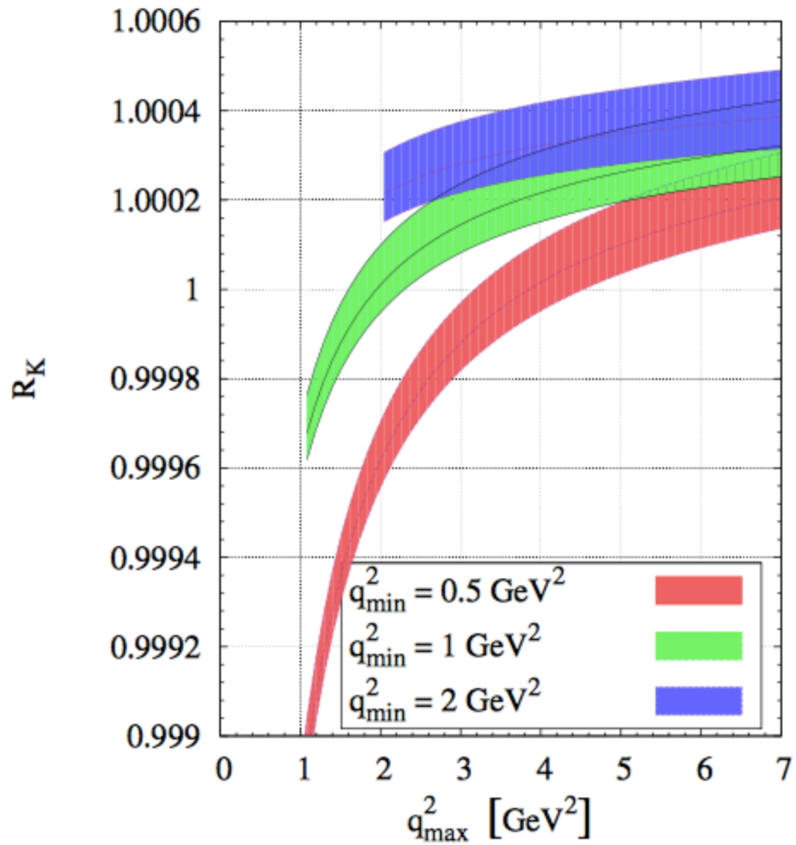


What about SM prediction?

Let's ask to the expert

The answer is $R_K = 1$

Christoph Bobeth, Gudrun Hiller and Giorgi Piranishvili

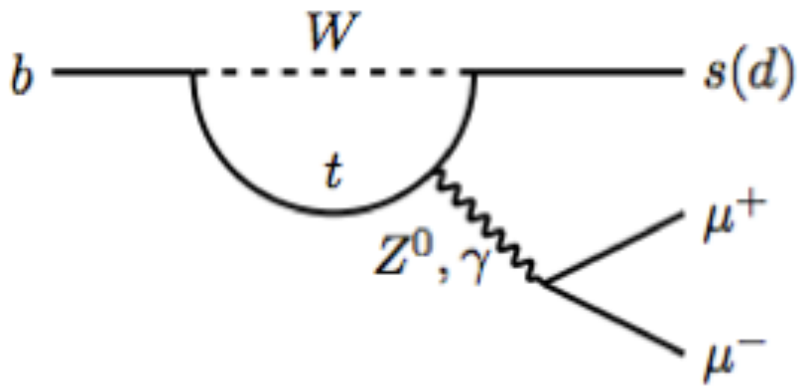


https://arxiv.org/pdf/0709.4174.pdf

Lepton universality in B decays with $B^0 \to K^{*0} l^- l^+$

$B^0 \to K^{*0}\mu^-\mu^+$

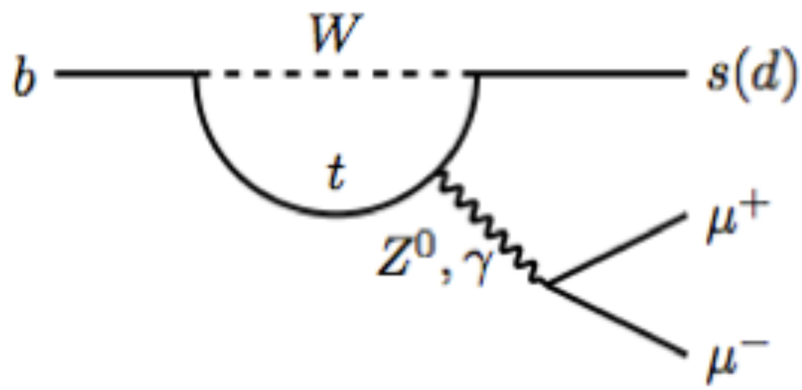
SM penguin diagram



$= ?$

$B^0 \to K^{*0}e^-e^+$

SM penguin diagram

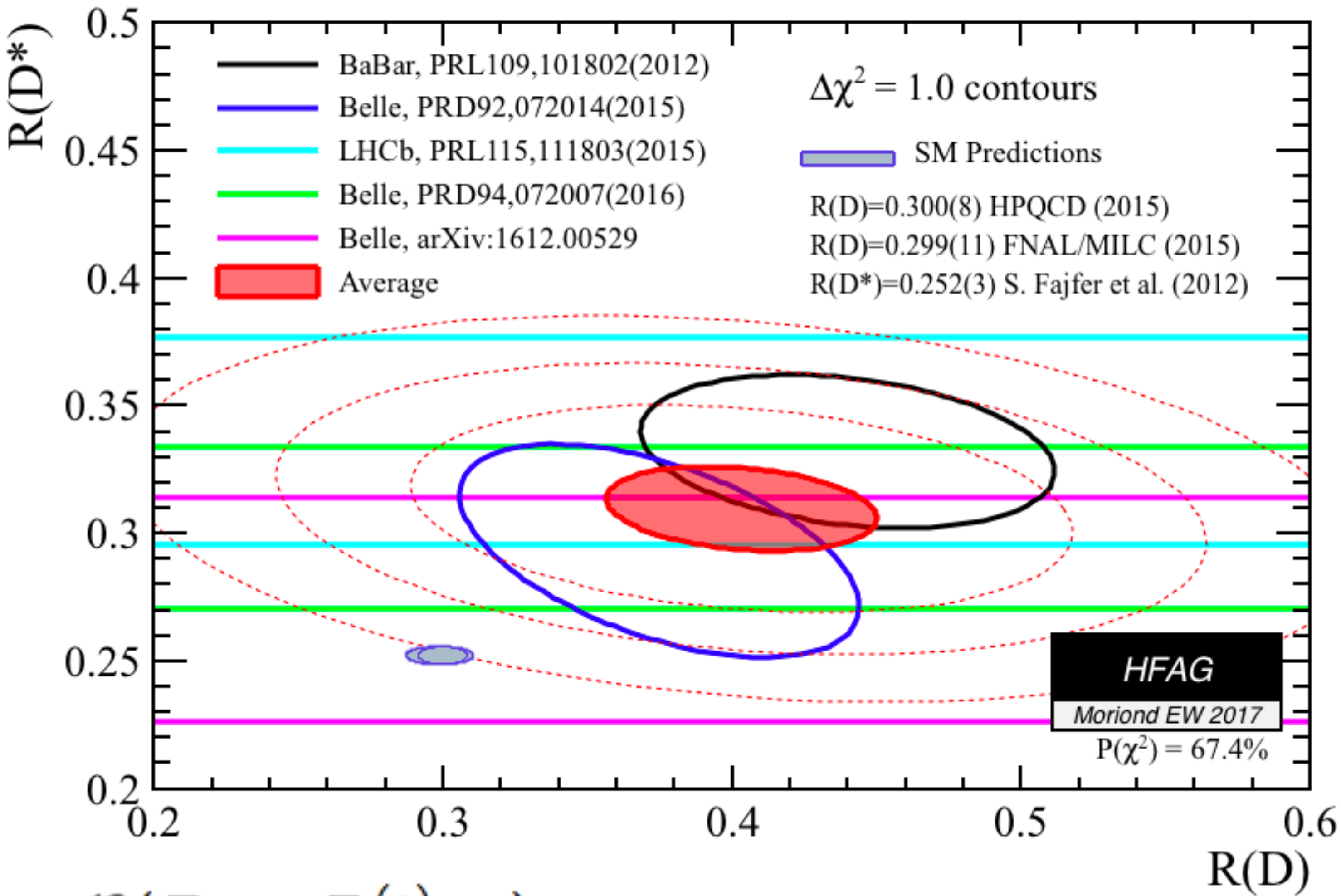


Are you ready to know the new number?

$R_K^* =$ Central value: distance from the rock divided by the number of cigarettes smoked by Stephan in 2.5 hours

Errors : distance swam, by Jean, Gudrun and Joachim divided by the time (in minutes)

Lepton universality in B decays with $B^0 \to D^{*+}\tau^-\nu_\tau$



$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\mu\nu)}$$