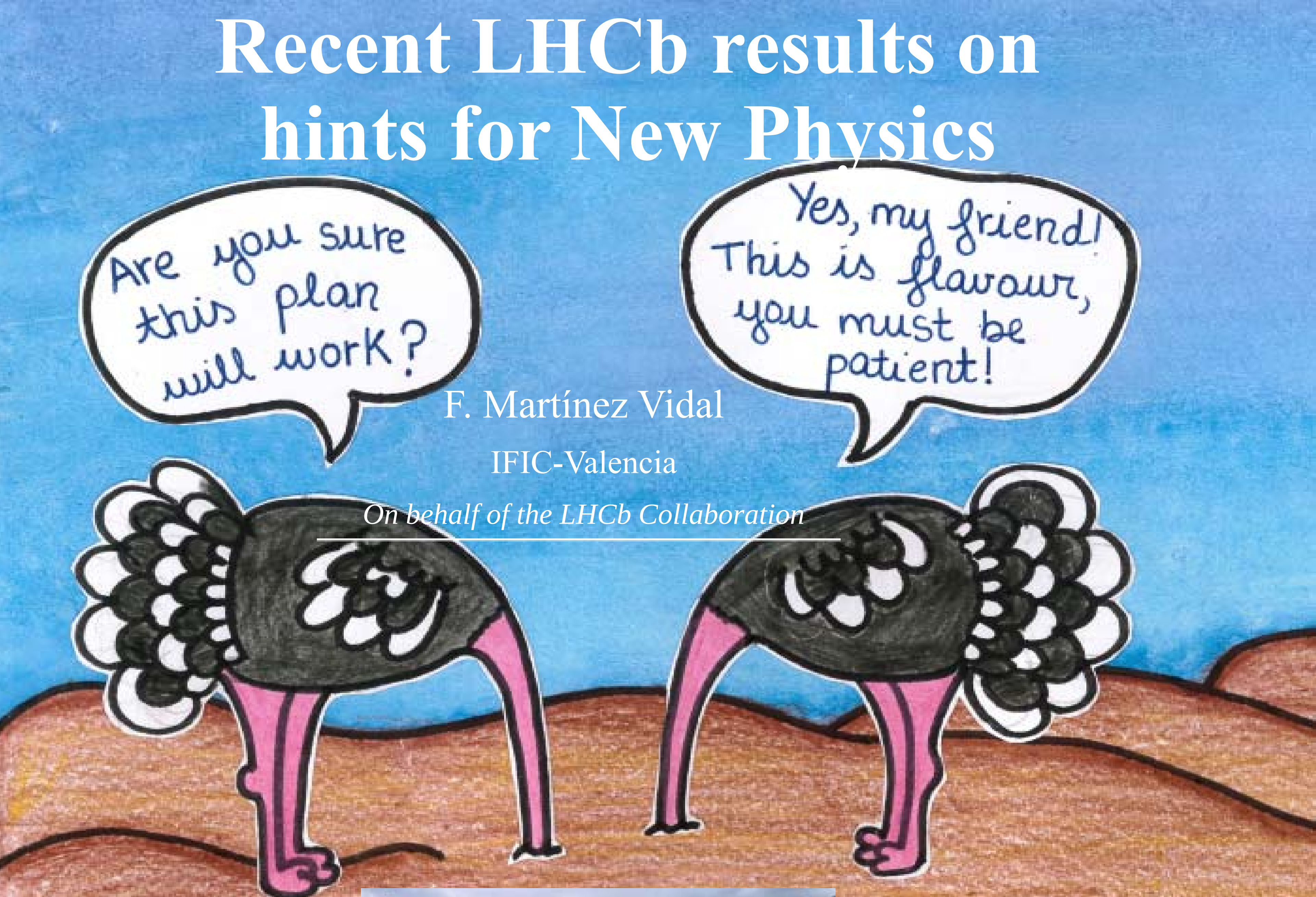
Recent LHCb results on hints for New Physics



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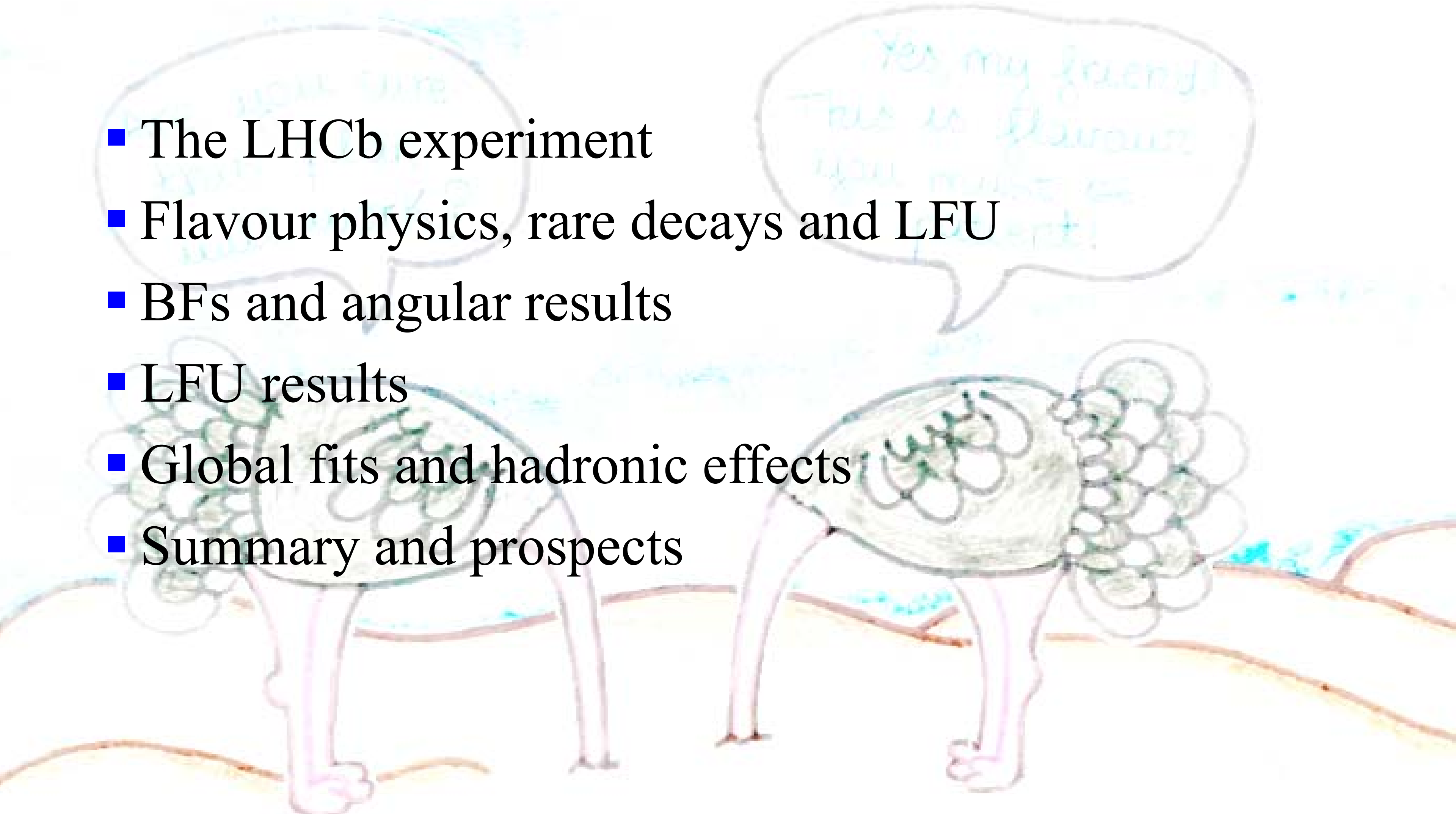
On behalf of the LHCb Collaboration

Adapted from N. Cabibbo at 1966 Berkeley Conference

INSTITUTO DE FISICA TEORICA IAM-CSIC
PASCOS 2017
19-23 JUNE, MADRID

LHCb IFIC INSTITUT DE FISICA CORPUSCULAR CSIC VNIVERSITAT DE VALÈNCIA

Outline

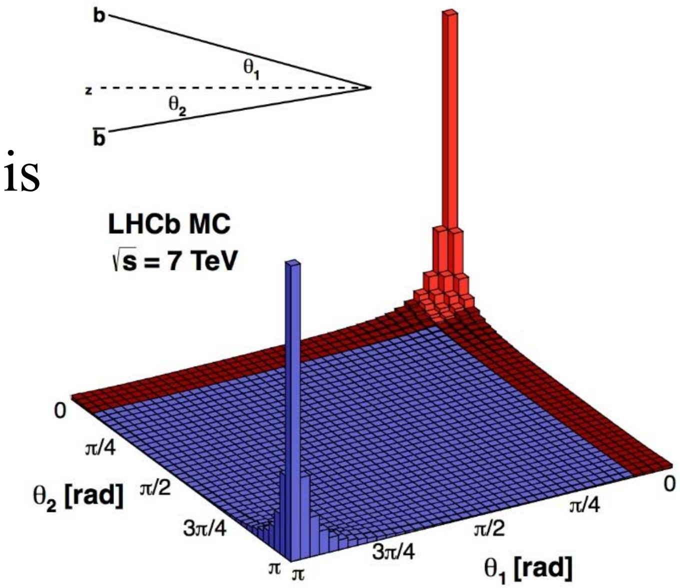


- The LHCb experiment
- Flavour physics, rare decays and LFU
- BFs and angular results
- LFU results
- Global fits and hadronic effects
- Summary and prospects

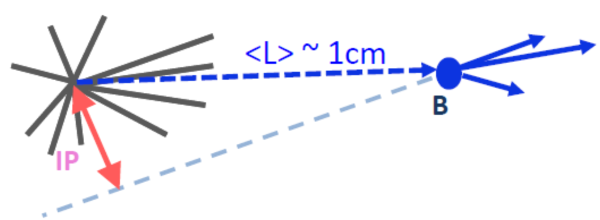
LHCb experiment

- $b\bar{b}$ cross section in high energy pp collisions is huge, mainly from gg fusion
  - ✓ ≈300 μb @ $\sqrt{s} = 7$ TeV
  - ✓ ≈600 μb @ $\sqrt{s} = 13$ TeV

PRL 118 (2017) 052002

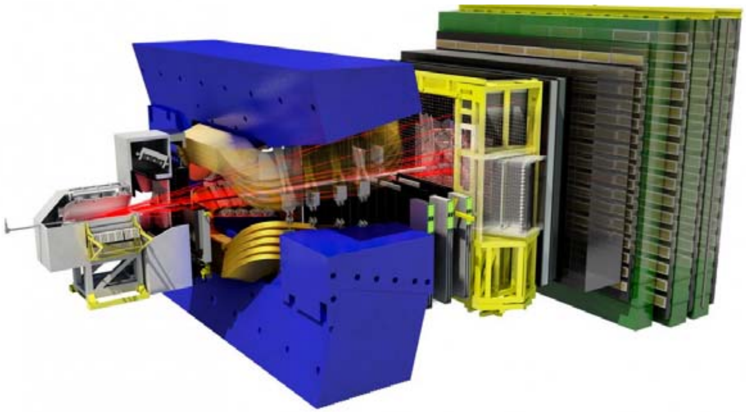


- b quarks hadronize in all b-hadron species: B, B_s, $B^*_{(s)}$, b baryons…
- Large average b-hadron momentum, ~80 GeV
  - ✓ large boost
  - ✓ ~1 cm B decay vertex displacement



- LHCb concept: a single-arm forward spectrometer
  - ✓ ≈4% solid angle coverage
  - ✓ ≈30% b-hadron production acceptance

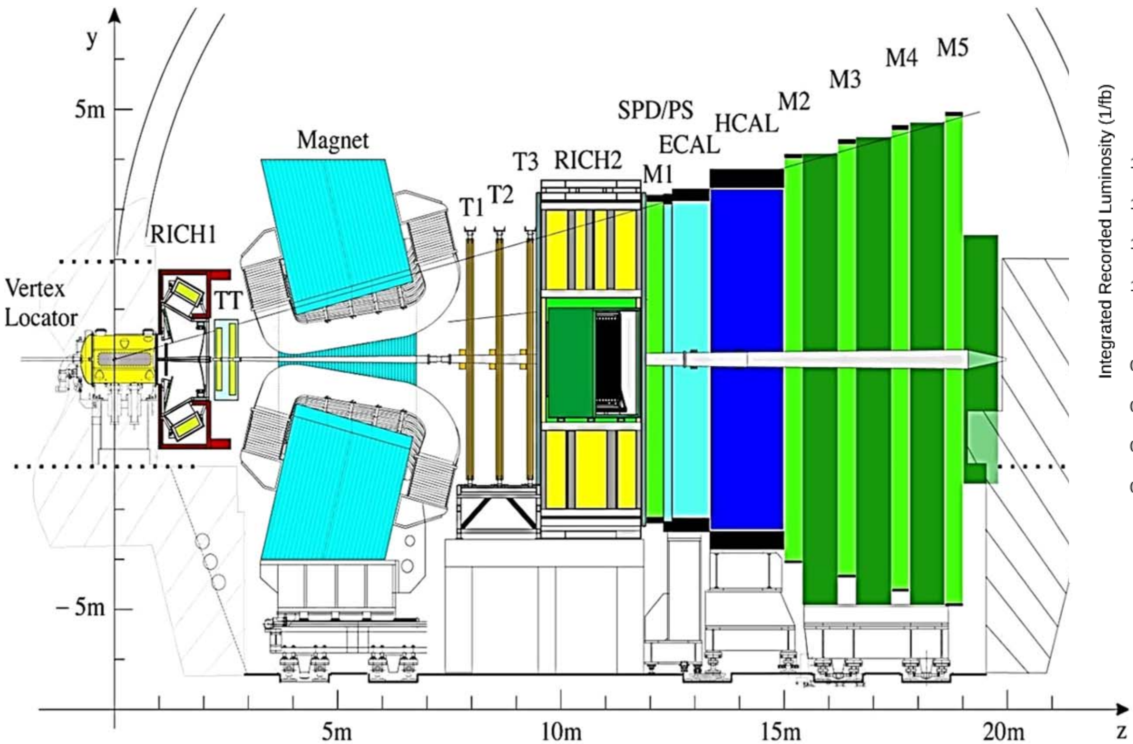
  ⇒ ~1.8×10^{11} $b\bar{b}$ pairs produced/fb^{-1}

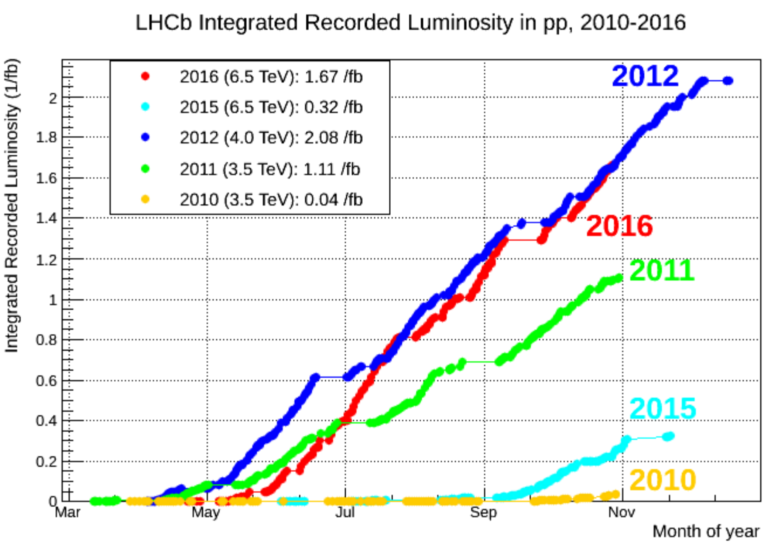


LHCb experiment

JINST 3 (2008) S08005
Int. J. Mod. Phys. A30 (2015) 1530022

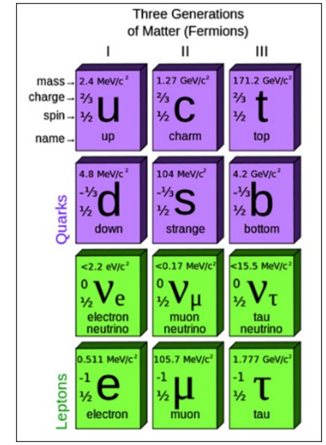
- Optimized for b- and c-hadron physics at large pseudorapidity ($2<\eta<5$)
  - ✓ Trigger: >95% (60-70%) efficient for muons (electrons)
  - ✓ Tracking: σ_p/p 0.4-1% (p from 5 to 200 GeV), $\sigma_{IP} = (15 + 29/p_T[\mathrm{GeV}/c])$ μm
  - ✓ Calorimeter: $\sigma_E/E \sim 10\%/\sqrt{E} \oplus 1\%$
  - ✓ PID: 97% μ,e ID for 1-3% $\pi \to \mu,e$ misID



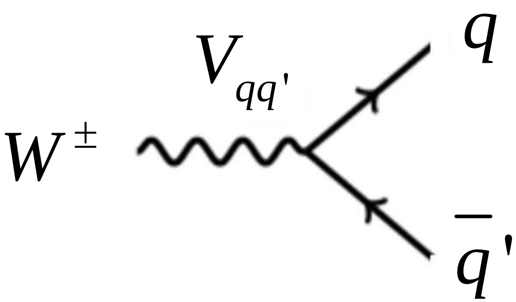


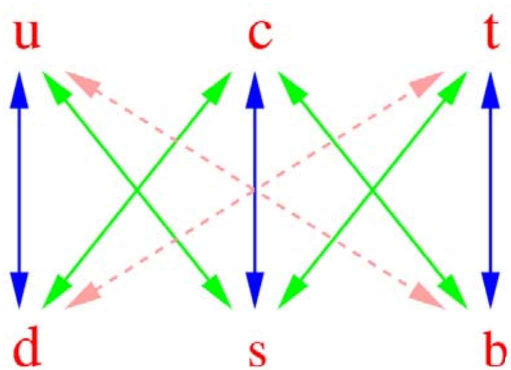
- Run I (2010-2012), 3 fb^{-1}
- Run II (2015→), 2 fb^{-1}

Flavour physics

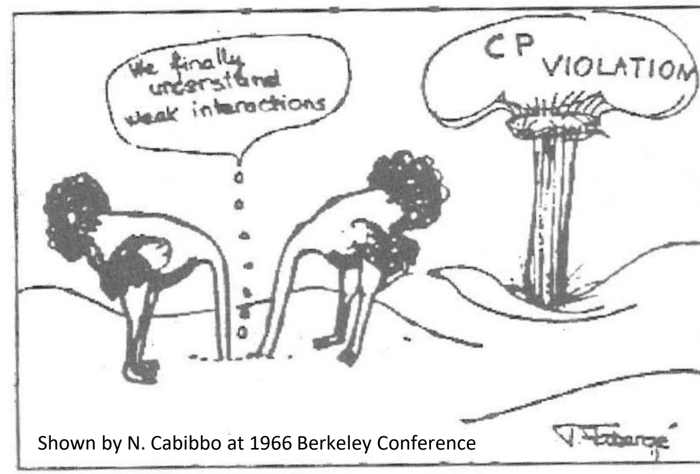


- Study of the different generations of fermions
- The generation of quarks interact via the CKM matrix



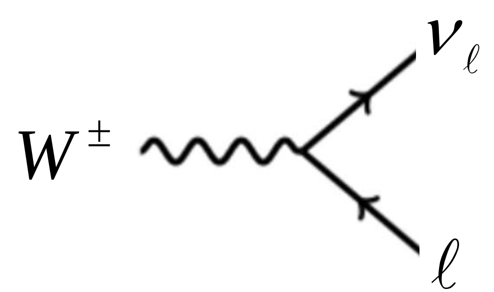


- Quark flavour processes have played a central role in the SM construction



Shown by N. Cabibbo at 1966 Berkeley Conference

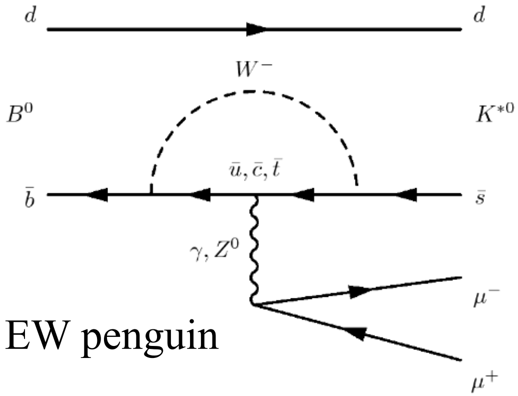
- Cornerstone ingredients of the SM are:
  - ✓ Absence of FCNC at tree level
  - ✓ LFU, i.e. the generations of charged leptons are identical copies of each other with regards their EW couplings



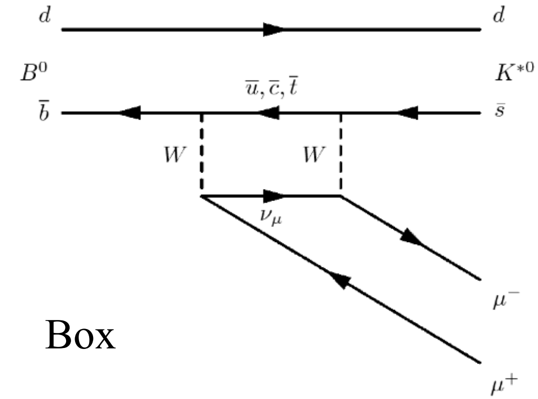
FCNC

- FCNC transitions only occur at loop order in the SM

E.g. $B^0 \rightarrow K^{*0}\mu\mu$



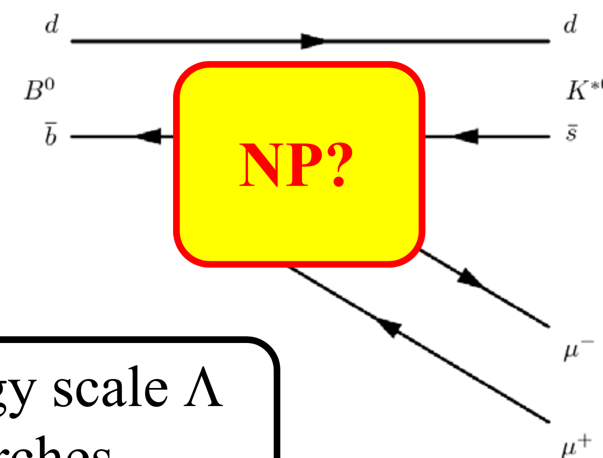
EW penguin



Box

Rare processes

- New particles/interactions can contribute to loop or tree level diagrams
  - ✓ enhancing/suppressing decay rates
  - ✓ introducing new CPV sources
  - ✓ modifying the angular distribution of the final-state particles



Probes NP models at energy scale Λ higher than direct searches

LFU

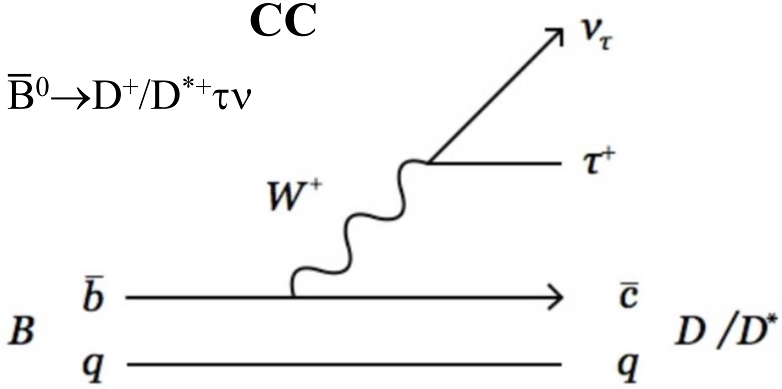
- Violation of LFU has been searched for in various systems (Z, W, π, …)
  - ✓ No evidence so far, only 2.8σ tension in W→τν wrt to W→eν & W→μν

PRD93 (2016) 093008

- Consider also B decays. Two types:

CC

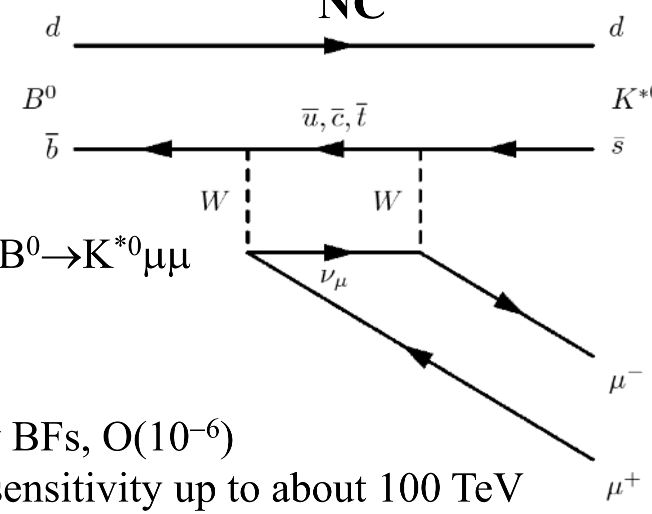
E.g. $\bar{B}^0 \to D^+/D^{*+}\tau\nu$



Large BFs, O(%)
NP sensitivity to about 1 TeV

NC

E.g. $B^0 \to K^{*0}\mu\mu$



Low BFs, O(10^{-6})
NP sensitivity up to about 100 TeV

- Take R_X ratios, e.g. $R_{D^{(*)}}, R_{K^{*0}}$, of BFs between (semi)leptonic decays that can be factorised into weak and strong parts, e.g.

$$d\Gamma(B \to D\ell\nu)/dq^2 \propto G_F^2 \, |V_{cb}|^2 \, f(q^2)^2$$

- Remark: many NP models with LFU breaking imply LF violation

How

- B hadron decay processes over a wide energy range

Prog. Part. Nucl. Phys. 92 (2017) 50

0.2GeV......	4GeV......	80GeV......	~ 100 TeV ?
Λ_{QCD}	Λ_b	Λ_{EW}	Λ_{NP}
(non-perturbative regime)	(b mass)	(W mass)	(NP scale)

- Described by effective field theory and operator product expansion:

[OPE: a series of effective vertices multiplied by effective coupling constants C_j and C'_j]

LH currents — RH currents (suppressed in SM)

$$A(B\to f)=\langle f|H_{\text{eff}}|B\rangle=\frac{G_F}{\sqrt{2}}\sum_j V_j^{\text{CKM}}\left(C_j\langle f|O_j|B\rangle+C'_j\langle f|O'_j|B\rangle\right)$$

Wilson coefficients @ the b quark scale μ_b
(perturbative,
short-distance physics,
sensitive to $E>\Lambda_{EW}$)

i=1, 2	Tree
i=3-6, 8	Gluon penguin
i=7	Photon penguin
i=9, 10	Electroweak penguin
i=S	Higgs (scalar) penguin
i=P	Pseudoscalar penguin

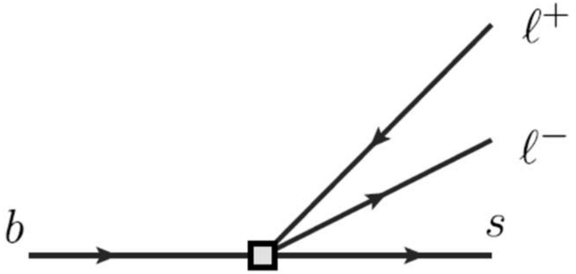
Hadronic matrix elements @ μ_b scale
(include non-perturbative QCD,
long-distance physics;
HQE, LQCD, LCSR, fQCD)

How

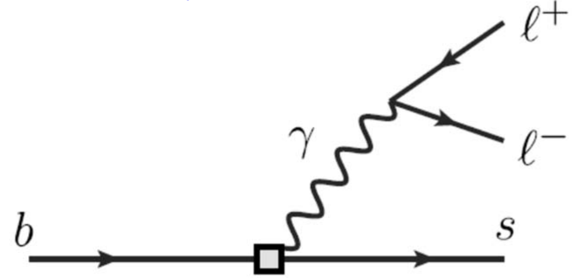
- NP expected to affect the Wilson coefficients:

$$C_j = C_j^{\mathrm{SM}} + C_j^{\mathrm{NP}}$$
$$C'_j = C'^{\mathrm{SM}}_j + C'^{\mathrm{NP}}_j$$

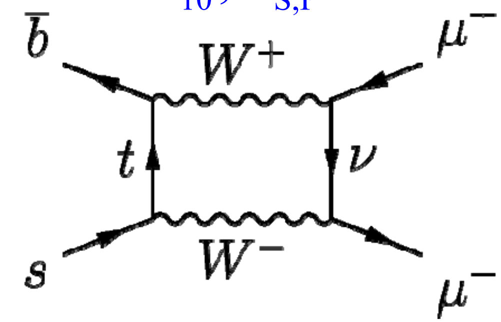
C_9, C_{10}



C_7



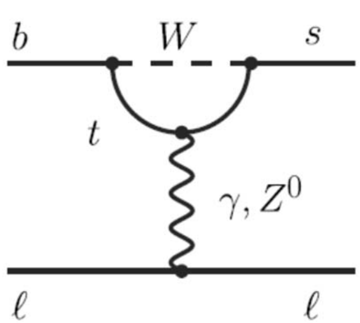
$C_{10}, C_{S,P}$

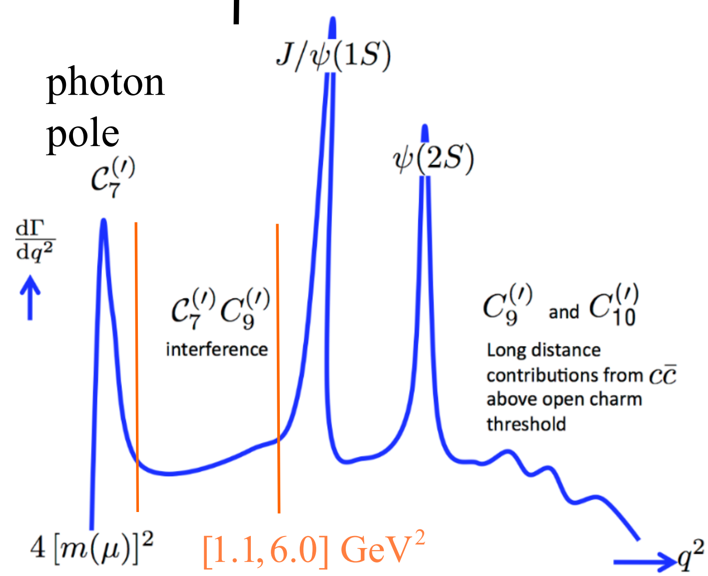


- Different q^2 regions probe different processes

E.g.
$d\Gamma/dq^2$ $B \to K^* ll$

$C_7 \approx -0.33$
$C_9 \approx 4.27$
$C_{10} \approx -4.17$





Today

Semileptonic B decays ($b \to sll$ transitions)

d[BFs]/dq² of $B^{0/+} \to K^{(*)0/+}\mu\mu$, $B^0_s \to \phi\mu\mu$,, $\Lambda_b \to \Lambda\mu\mu$ Hadronic uncertainties in theory predictions

Angular analyses of $B \to K^{(*)}\mu\mu$, $B^0_s \to \phi\mu\mu$, $\Lambda_b \to \Lambda\mu\mu$ Observables less form factor dependent

…

Also electrons

Leptonic B decays

BF of $B \to \mu\mu$

$B \to \mu\mu$ effective lifetime

BF's of $B \to \tau\tau$, $B \to \mu\mu\mu\mu$, $B \to ee$

…

LFV, e.g. $B \to Ke\mu$, $B \to e\mu$

LFU tests

~cancellation of hadronic uncertainties in theory predictions

$B \to K^{(*)} ll$

…

$B \to D^{(*)} l\nu$

Radiative decays

$B^0 \to K^{*0}\gamma$

$B^0_s \to \phi\gamma$

$B \to K\pi\pi\gamma$ …

Strange decays

$K^0_s \to \mu\mu$

$\Sigma^+ \to p\mu\mu$

Baryon rare decays

$\Lambda_b \to pK\mu\mu$

$\Lambda_b \to p\pi\mu\mu$

Charm decays

$D \to \pi\pi\mu\mu$

$D \to K\pi\mu\mu$

$D \to e\mu$

$D \to \mu\mu$ …

τ decays

$\tau \to \mu\mu\mu$

$\tau \to p\mu\mu$ …

Enormous physics program constantly expanding. Will cover small part

B→μμ

- Additional helicity & CKM suppression, theoretically clean
- Searched for over 30 years
- $B^0_s \to \mu\mu$ observed (6.2σ) from LHCb & CMS Run I combination, 3.0σ evidence for $B^0 \to \mu\mu$, consistent with SM
- Recent new result from LHCb adding 1.4 fb^{-1} from Run II & improved analysis

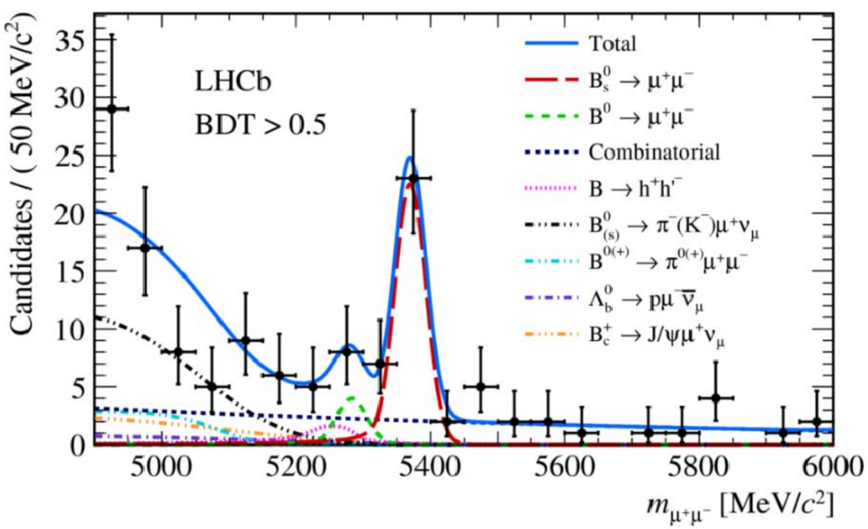
$$BF(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$$
$$BF(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

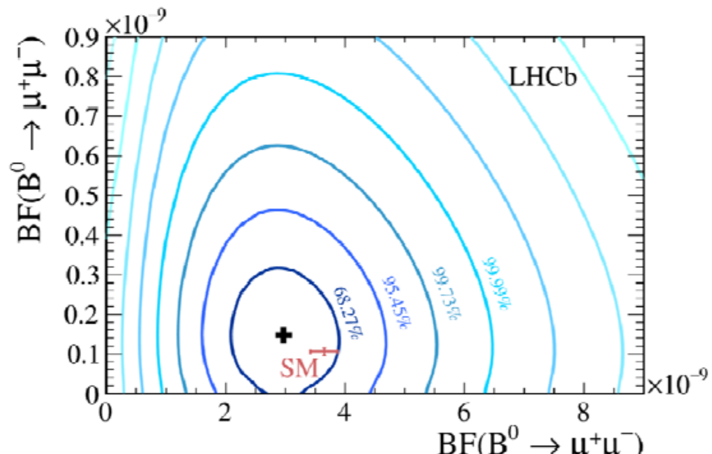
PRL112 (2014) 101801

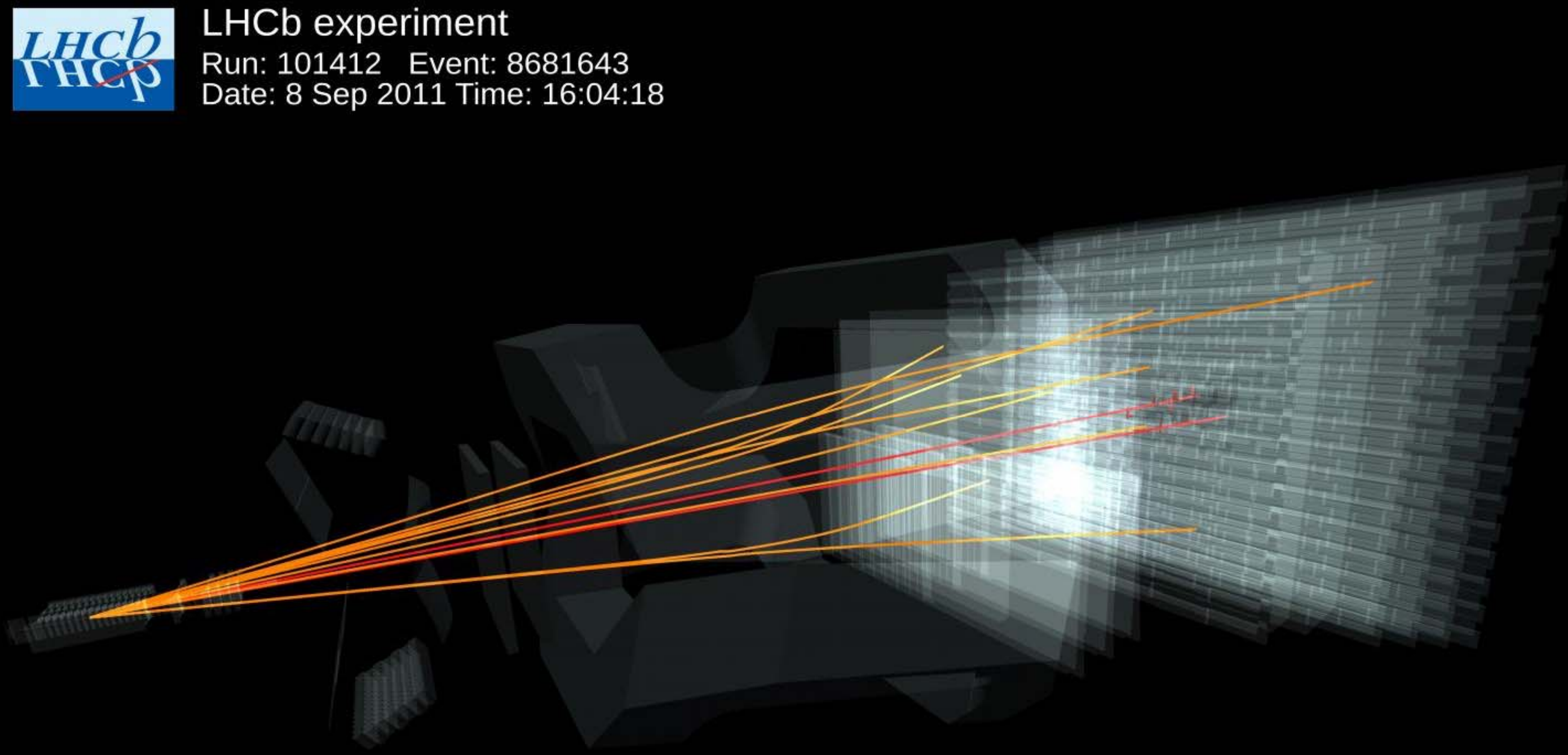
Nature 522 (2015) 68

PRL 118 (2017) 191801

$$BF(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9} \quad 7.8\sigma$$
$$BF(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10} \text{ @95\%CL}$$






LHCb experiment
Run: 101412 Event: 8681643
Date: 8 Sep 2011 Time: 16:04:18

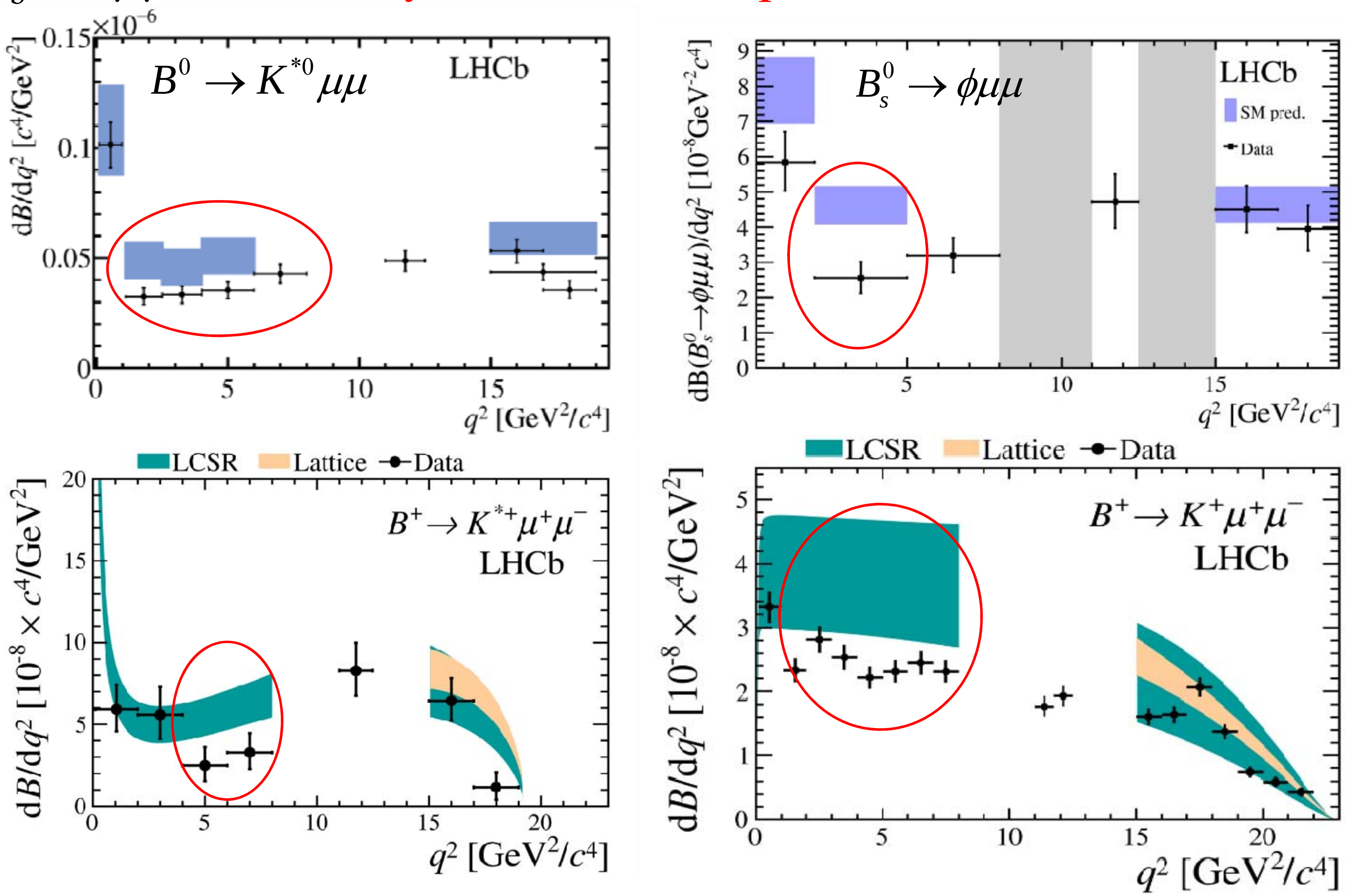
b→sll differential BFs

- Measured differential BFs in q^2 for $B^0 \to K^{(*)0}\mu\mu$, $B^+ \to K^{(*)+}\mu\mu$, $B^0_s \to \phi\mu\mu$, $\Lambda_b \to \Lambda\mu\mu$ consistently lower than SM predictions at 2-3σ

JHEP 11 (2016) 047

JHEP 09 (2015) 179

JHEP 06 (2014) 133



SM LCSR:
PRD 71 (2005) 014029
JHEP 09 (2010) 089
JHEP 08 (2016) 098

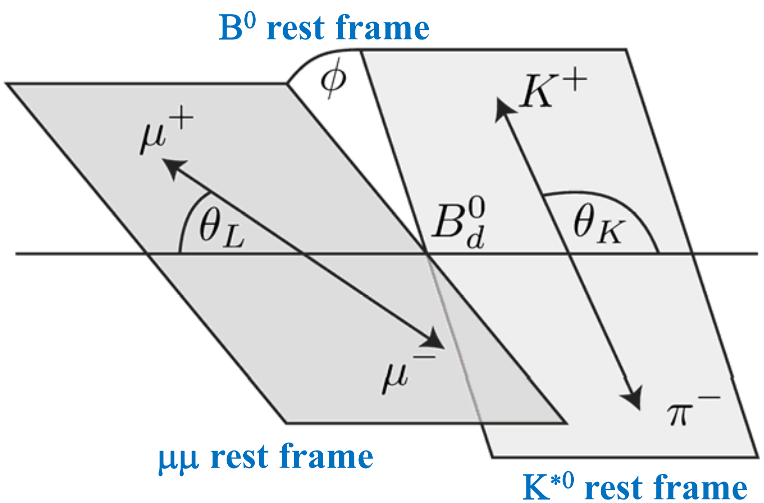
SM Lattice:
PRD 88 (2013) 054509
PRD 89 (2014) 094501
PRL 111 (2013) 162002
PRL 112 (2014) 212003
PRD 87 (2013) 074502

✓ SM predictions limited by hadronic uncertainties on form factors

$B \to K^{*0}\mu\mu$ angular analysis

- Study of the full angular distribution of the final state particles (θ_l, θ_K, ϕ)
- Measure all CP-averaged angular, described by eight observables S_i, F_L, A_{FB}, function of Wilson coefficients

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K + \frac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l - F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi + \frac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi + S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

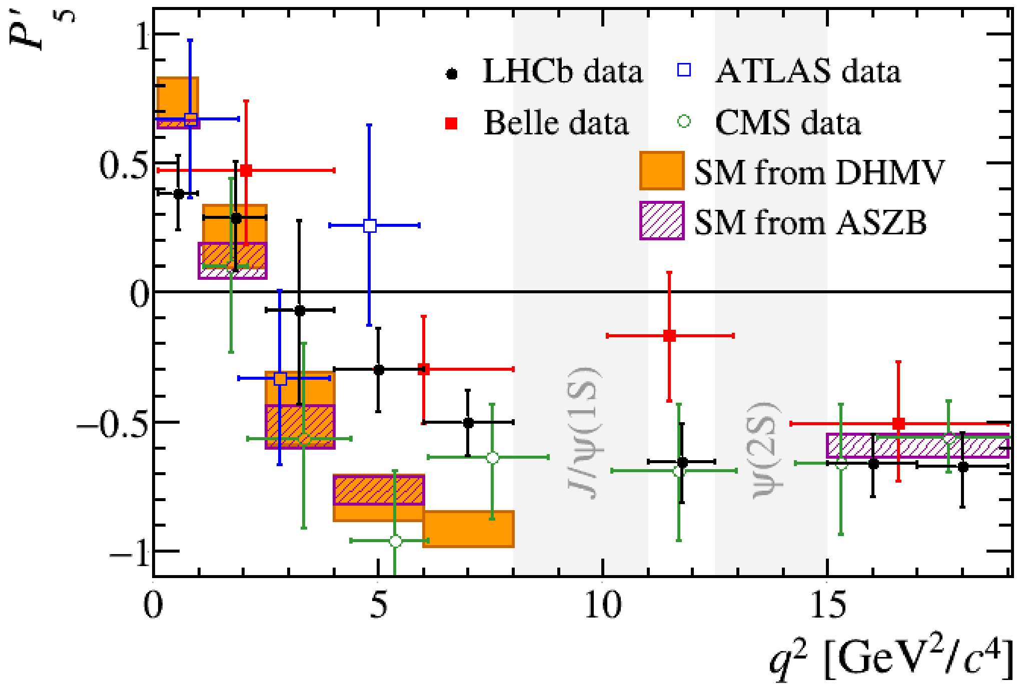


- Define observables in which hadronic form factor uncertainties cancel at leading order, like

$$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

JHEP 05 (2013) 137

$B \to K^{*0}\mu\mu$ angular analysis



JHEP 02 (2016) 104
ATLAS-CONF-2017-023
CMS-PAS-BPH-15-008
PRL 118 (2017) 111801

DHMV: JHEP 12 (2014) 125 & JHEP 10 (2016) 075
ASZB: EPJC (2015) 75 & JHEP 08 (2016) 098

- P'_5 LHCb local deviation from SM
  - ✓ 2.8σ in $4 < q^2 < 6$ GeV^2/c^4
  - ✓ 3.0σ in $6 < q^2 < 8$ GeV^2/c^4
- $B \to J/\psi K^{*0}$ angular distribution in excellent agreement with existing measurements
- $B^0_s \to \phi\mu\mu$ angular analysis consistent with SM predictions JHEP 09 (2015) 179

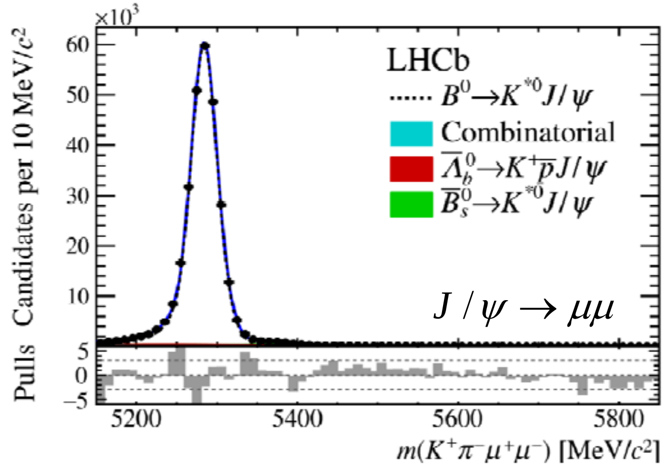
LFU with NC: $R_{K^{(*)}}$

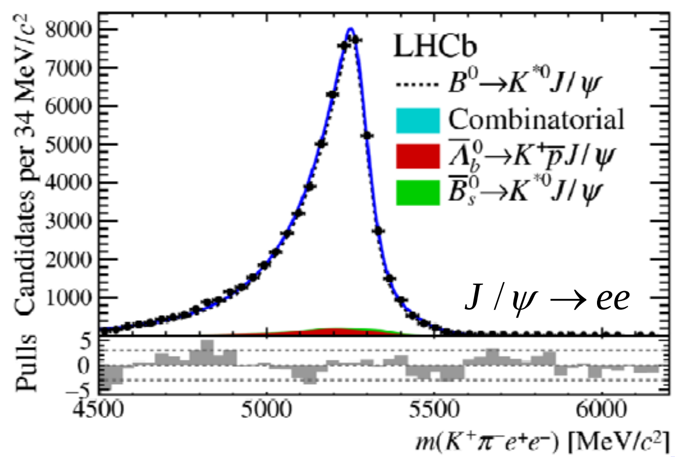
- Take ratio of lighter leptons, $R_{K^{(*)}} = \frac{BF(B \to K^{(*)}\mu^+\mu^-)}{BF(B \to K^{(*)}e^+e^-)}$
  - ✓ $m_\mu, m_e \ll m_b$

$$R_{K^{(*)}} = 1 \pm O(m_\mu^2 / m_b^2)$$

  - ✓ Precise theory prediction due to cancellation of hadronic form factor uncertainties
- Experimentally, use $B \to K^{(*)} J/\psi(e^+e^-)$ and $B \to K^{(*)} J/\psi(\mu^+\mu^-)$
  - ✓ to perform a double ratio
  - ✓ to correct simulation and extract signal mass shapes
  - ✓ to cross check
- If NP doesn't couple to 1st generation, from b→sμμ d[BFs]/dq² lower than SM one naively would expect $R_{K^{(*)}} < 1$

arXiv:1705.05802

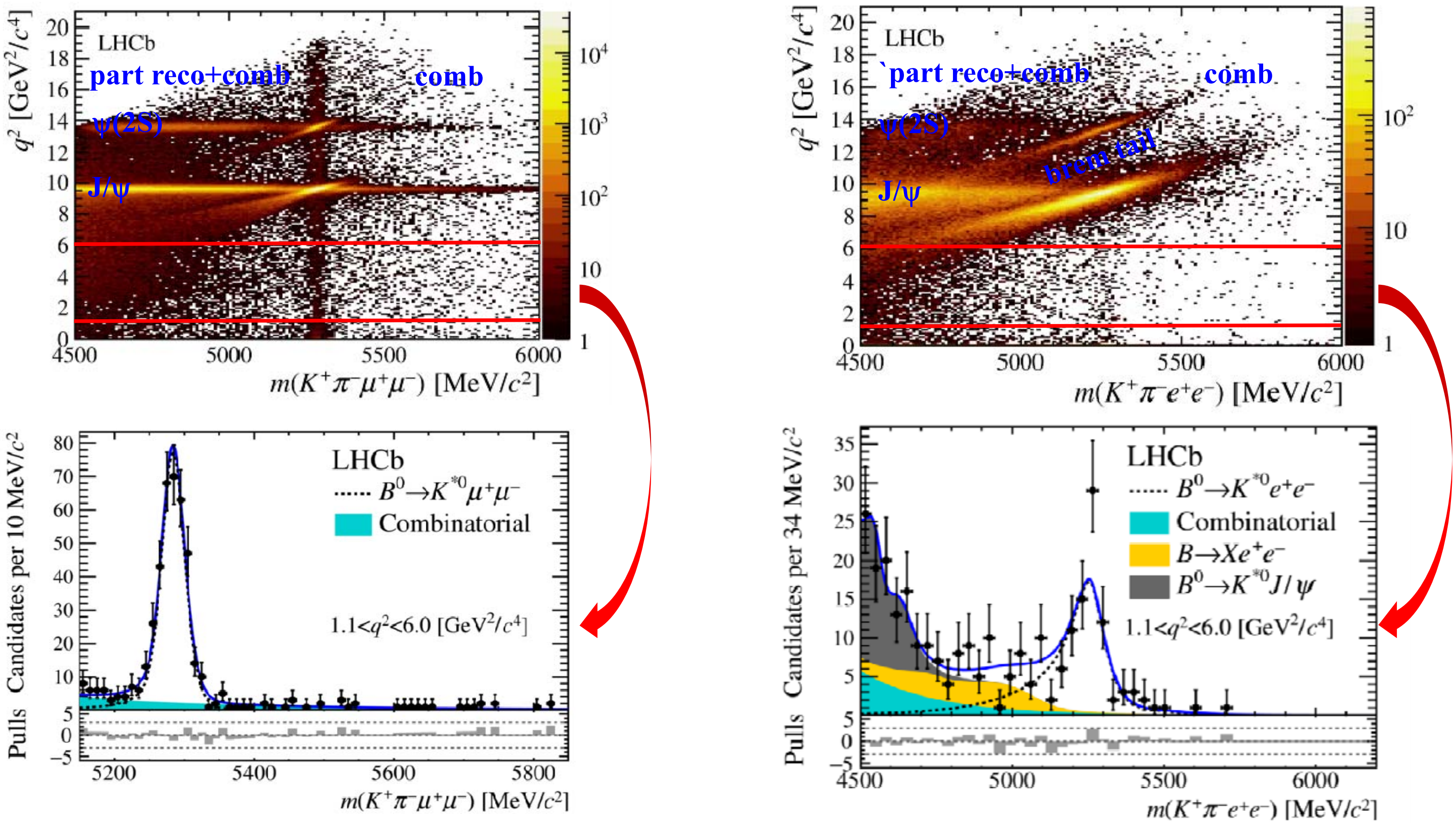




LFU with NC: $R_{K^{(*)}}$

- Determine signal yields from B mass fits in q^2 bins

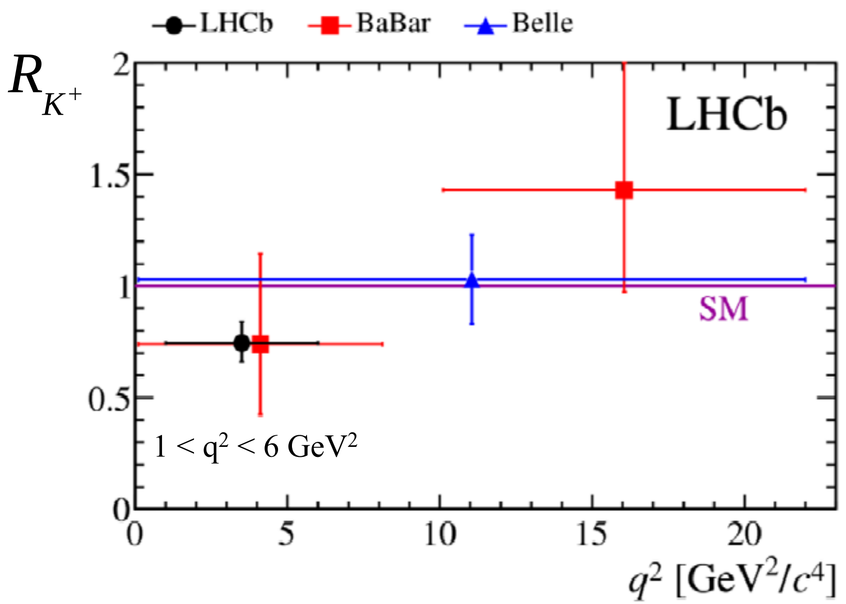
arXiv:1705.05802

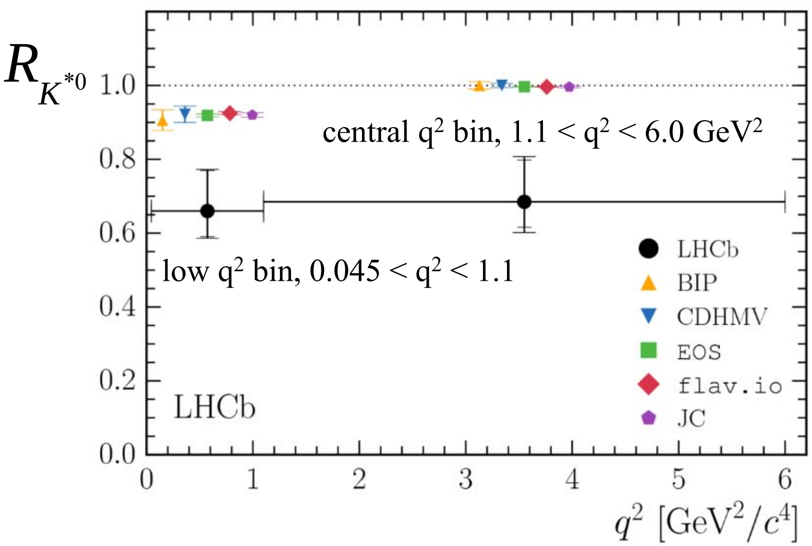


LFU with NC: $R_{K^{(*)}}$ results

- Correct yields for J/ψ vs non-resonant efficiency differences (only due to kinematics) to obtain $R_{K^{(*)}}$

PRL 113 (2014) 15161 | PRD 86 (2012) 032012 | PRL 103 (2009) 171801 | arXiv:1705.05802

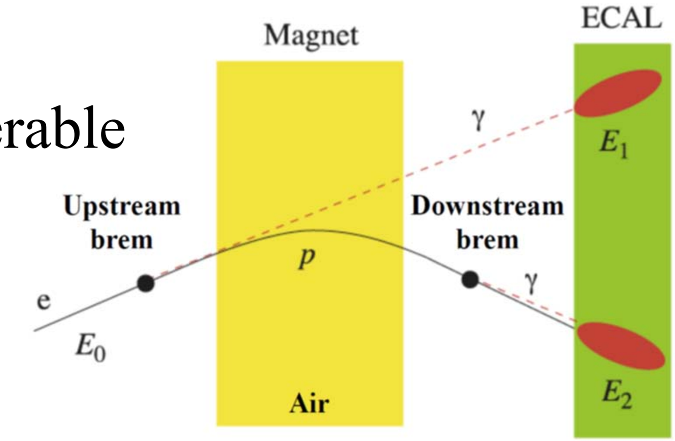




- LHCb results for R_{K^+}, $R_{K^{*0}}$ (low q^2), $R_{K^{*0}}$ (central q^2) are 2.6, 2.4 and 2.2σ from SM prediction, all in the same direction

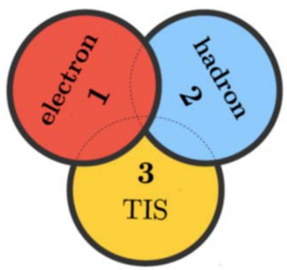
LFU with NC: $R_{K^{(*)}}$ remarks

- Electrons are more difficult than muons due to bremsstrahlung; only partially recoverable



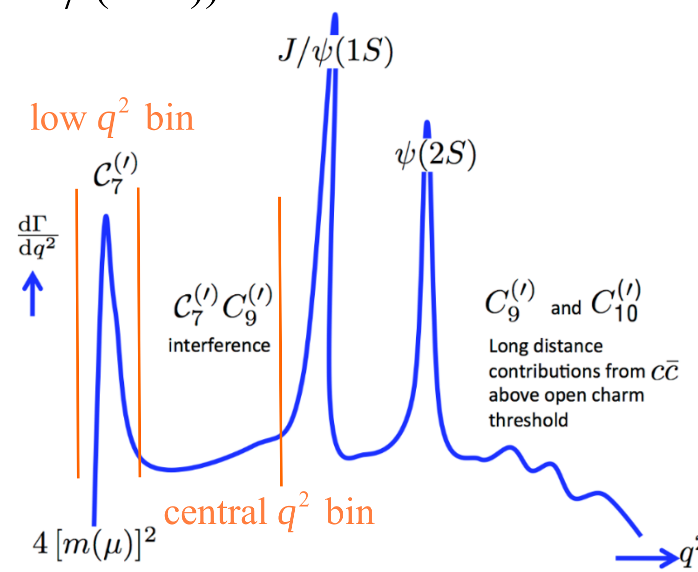
- Worse q^2 resolution, more difficult to separate brem tail from 'partially reconstructed' bkg
- Many cross-checks, e.g.

trigger categories



$$r_{J/\psi} = \frac{BF(B^0 \to K^{*0} J/\psi(\mu^+\mu^-))}{BF(B^0 \to K^{*0} J/\psi(e^+e^-))} = 1.043 \pm 0.006 \pm 0.045$$

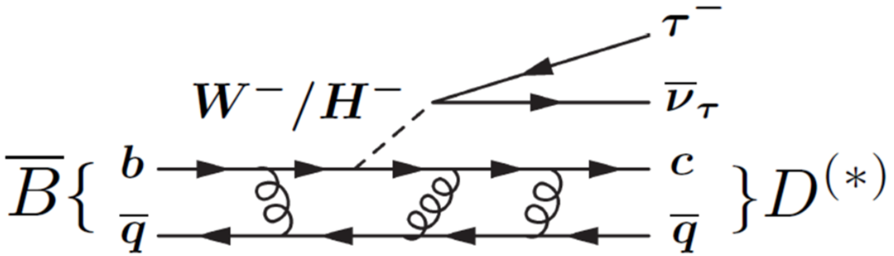
- If NP is heavy, hard to accommodate shift in first q^2 bin
  - ✓ At low q^2, the decay amplitude is dominated by the photon pole – must be LFU
  - ✓ There are models which get around this with light mediators arXiv:1704.06188



LFU with CC: $R_{D^{(*)}}$

- Take ratio of heavier leptons,

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



  - ✓ $m_\tau \approx m_b/3$

$$R_D = 0.229 \pm 0.003 \qquad R_{D^*} = 0.252 \pm 0.003$$

PRD 92 (2015) 054510
PRD 85 (2012) 094025
PRD 94 (2016) 094008

  - ✓ Precise theory prediction due to cancellation of hadronic uncertainties

- Highly sensitive to NP models favouring 3rd generation leptons, e.g. charged Higgs or leptoquarks up ~1 TeV
- BaBar first measured an excess of $\overline{B}^0 \to D^{(*)+}\tau^-\overline{\nu}$, ~3σ away SM
- LHCb has measured R_{D^*} using
  - ✓ Muonic $\tau^+ \to \mu^+\nu\nu$ decays
  - ✓ Hadronic $\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\nu$ (3-prong) decays NEW!

PRD 88 (2013) 072012
Nature 546 (2017) 227

LFU with CC: R_{D^*} muonic mode

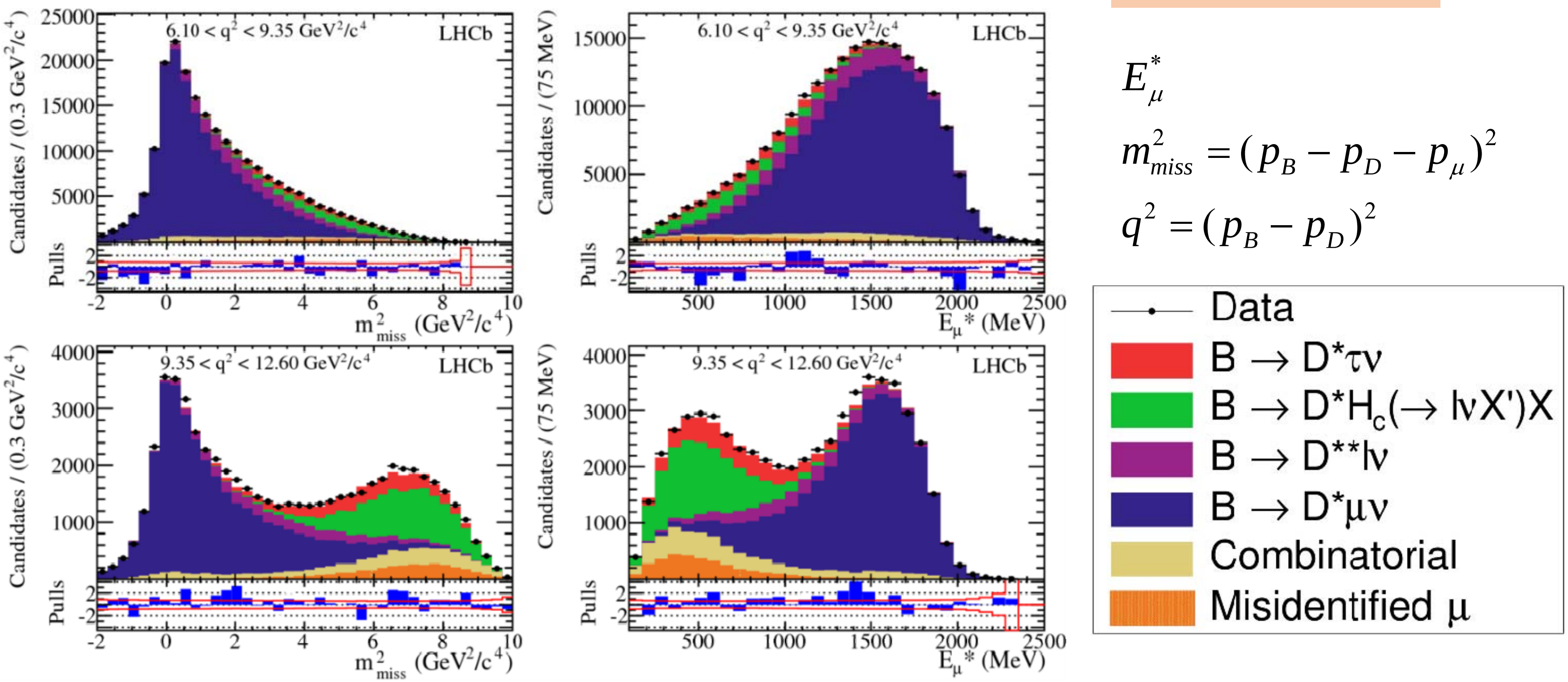
- $D^*\mu$ final state with 3 ν's ⇒ no sharp peak in any variable
- Exploit large boost, kinematic & topological properties, and huge B prod.
- Signal yields from 3D fit to kinematic variables able to discriminate τ/μ modes

PRL 115 (2015) 111803

$$E_\mu^*$$

$$m_{miss}^2 = (p_B - p_D - p_\mu)^2$$

$$q^2 = (p_B - p_D)^2$$



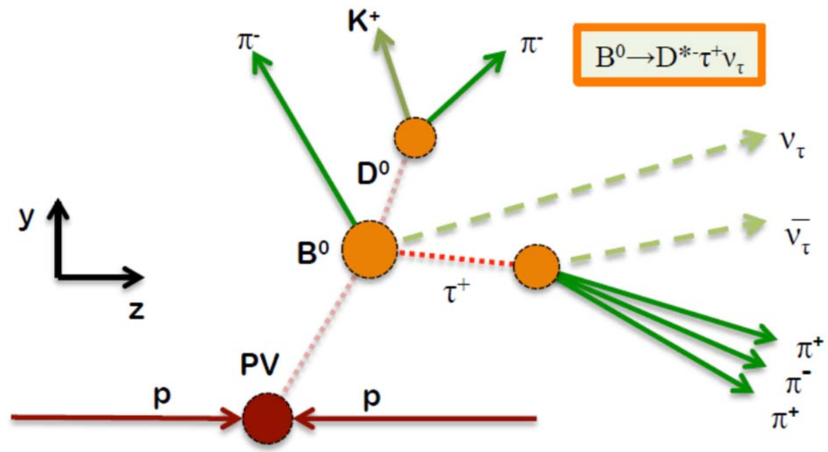
LFU with CC: R_{D^*} hadronic mode

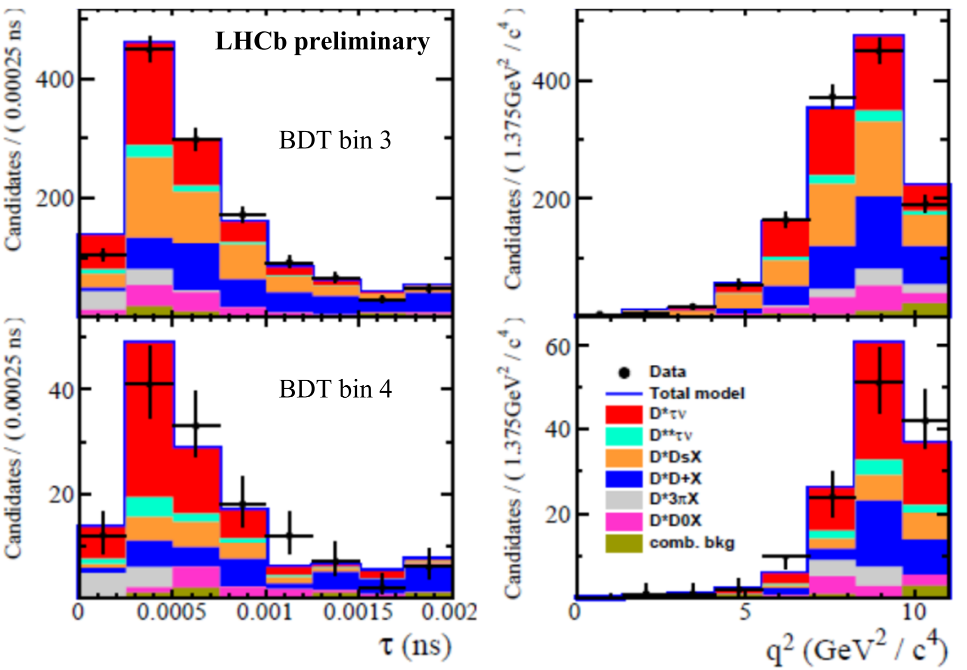
LHCb-PAPER-2017-017, in preparation

- $D^*3\pi$ final state with 2 ν's
- $D^*3\pi X$ is one of the most common B decay final states, large background
- Suppress through τ vertex displacement wrt B vertex (large boost)
- Data driven modelling of backgrounds due to $B \to D^*(D_s/D/D^0)X$ decays
- BF for $B^0 \to D^*3\pi$ normalization mode measured by BaBar

PRD94 (2016) 091101

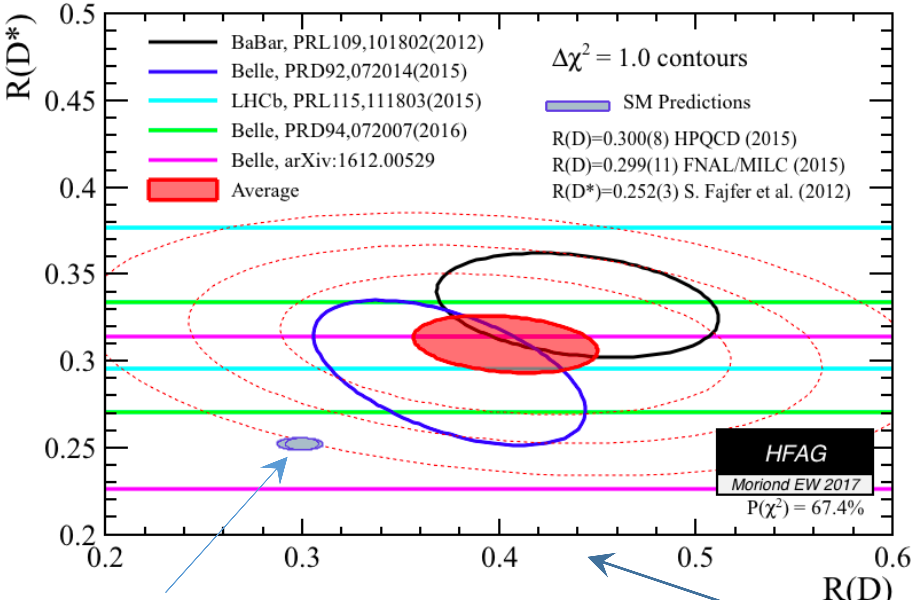
- Signal yields from 3D fit to q^2, 3π decay time and BDT





LFU with CC: $R_{D^{(*)}}$ results

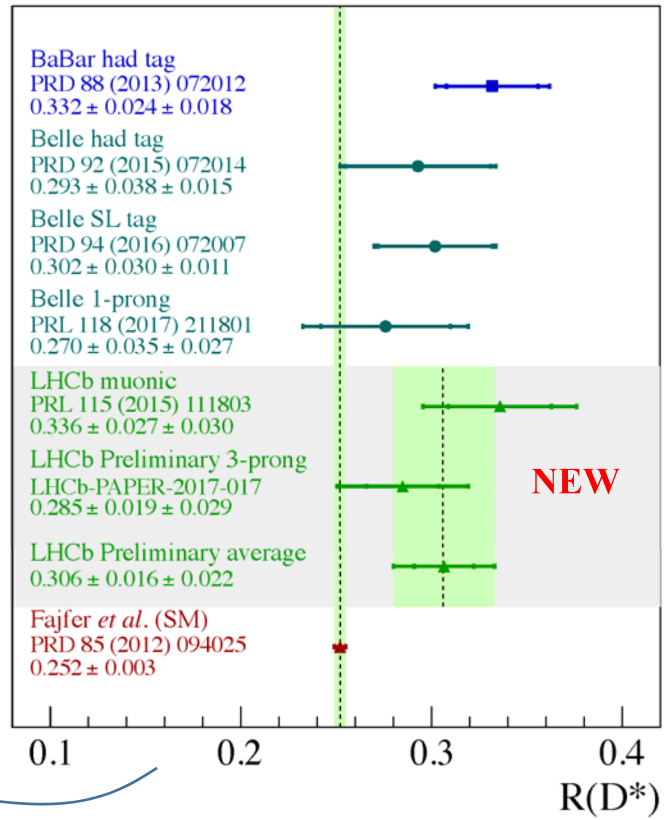
- Consistent with BaBar & Belle experiments



QCD uncertainties very small !

Not yet included

- New LHCb hadronic mode

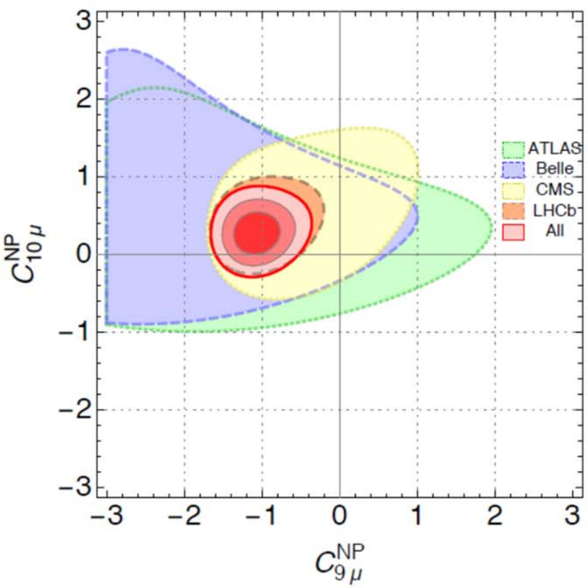


- R_{D^*} is 3.3σ from SM
- R_{D^*}-R_D is ~4σ

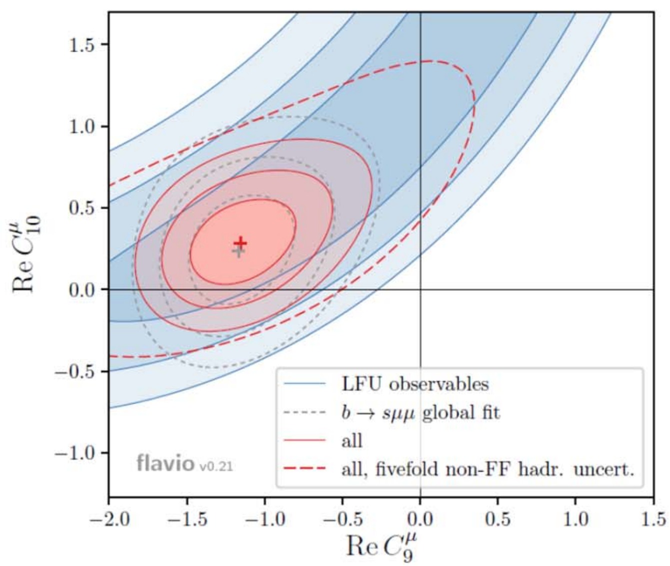
- Pulls down average towards SM, tension increases slightly

Global fits

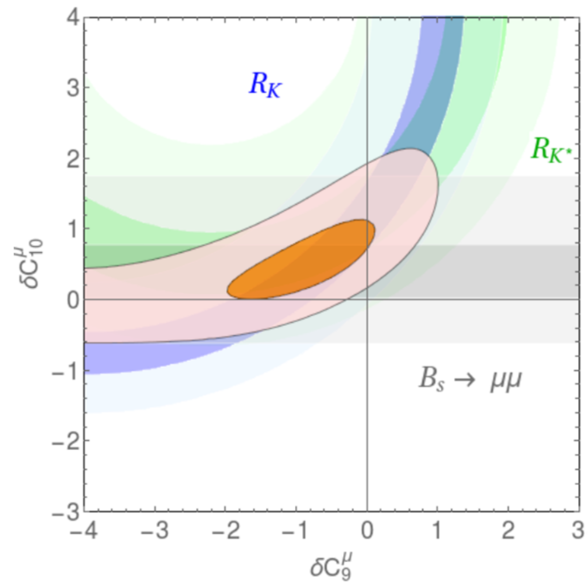
- Global fits using b→s*ll*, B→μμ, LFU data, ~100 observables



arXiv:1704.05340



arXiv:1704.05435

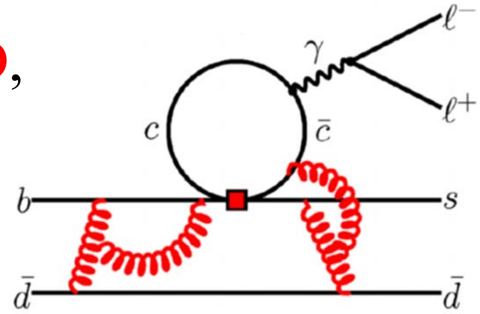


arXiv:1704.05446

- NP contributions to Wilson coefficients preferred over SM at 4-5σ level
- Preference on C_9 at ~4σ level
- Z', leptoquarks and composite Higgs models could explain

Understanding effects from charm

- Or there is a problem with the understanding of QCD, e.g. estimating the contributions from charm loops?
- Measure resonance effects in C_9 in inclusive analysis of $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+ X_{c\bar{c}}(\mu^+\mu^-)$



- Fit μμ mass spectrum to $d\Gamma/dm_{\mu\mu}$, function of form factors and C_i
  - ✓ Model resonances as RBW × relative scale and phase (9 vector poles)
  - ✓ $C_9^{\text{eff}} = C_9 + \sum_j \eta_j e^{i\delta_j} A_j(q^2)$

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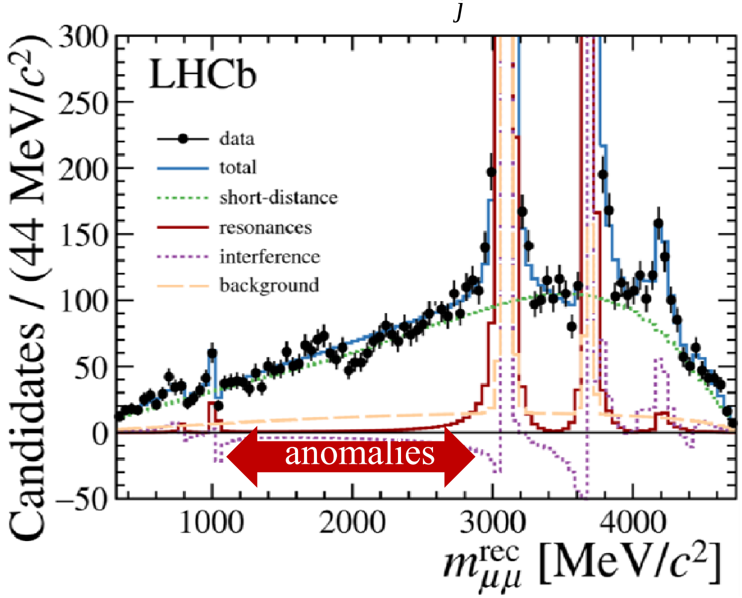
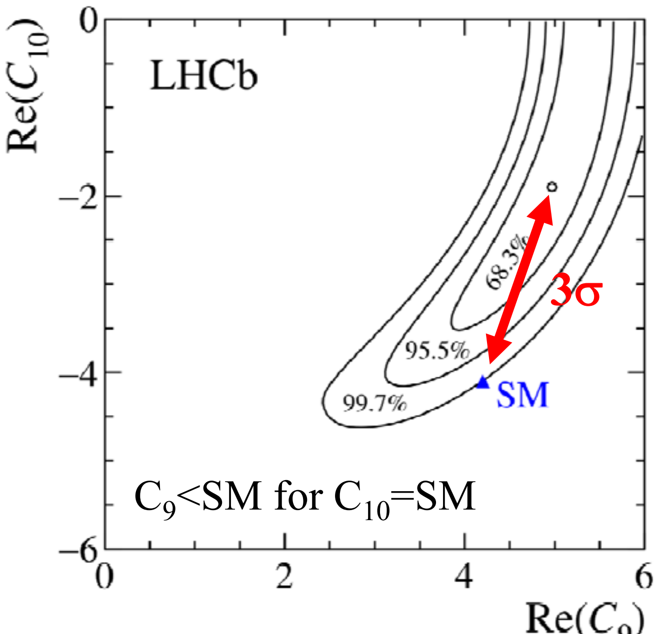


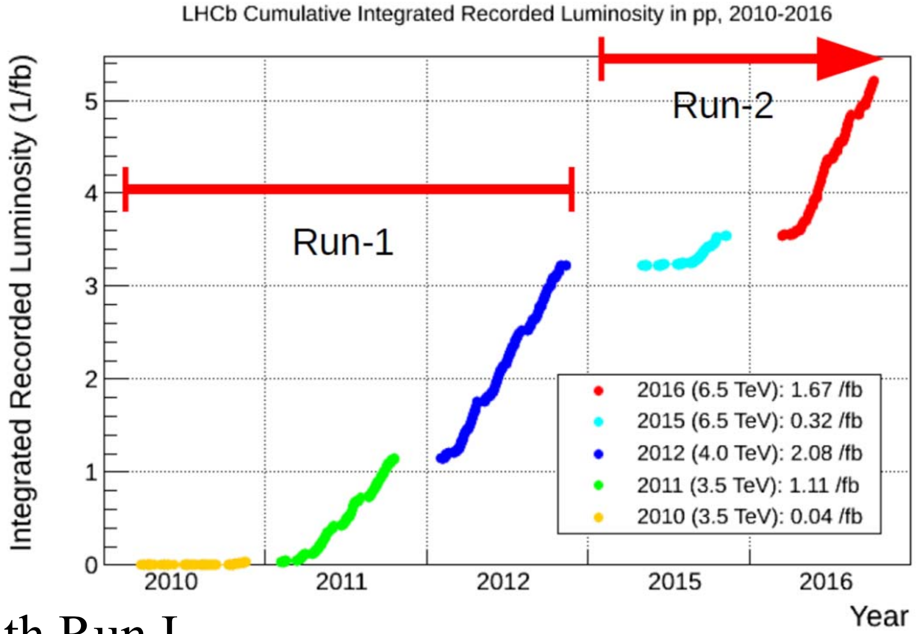


Minimal effect of vector resonances below the pole masses

Summary

- Many FCNC and LFU observables measured, few anomalies
- $B^0/B^0_s \to \mu\mu$ BF probed down to $10^{-9}/10^{-10}$ level, consistent with SM, challenging NP scenarios
- Individual 2-3σ tensions in $b \to s\mu\mu$ differential BFs and P'_5 angular observable, tree- and loop-level LFU tests with semileptonic B decays
- The pattern is coherent with NP models coupling more strongly to 2nd or 3rd generations
- Global fits accommodate consistently all these anomalies with a preference for NP in C_9 at ~4σ level

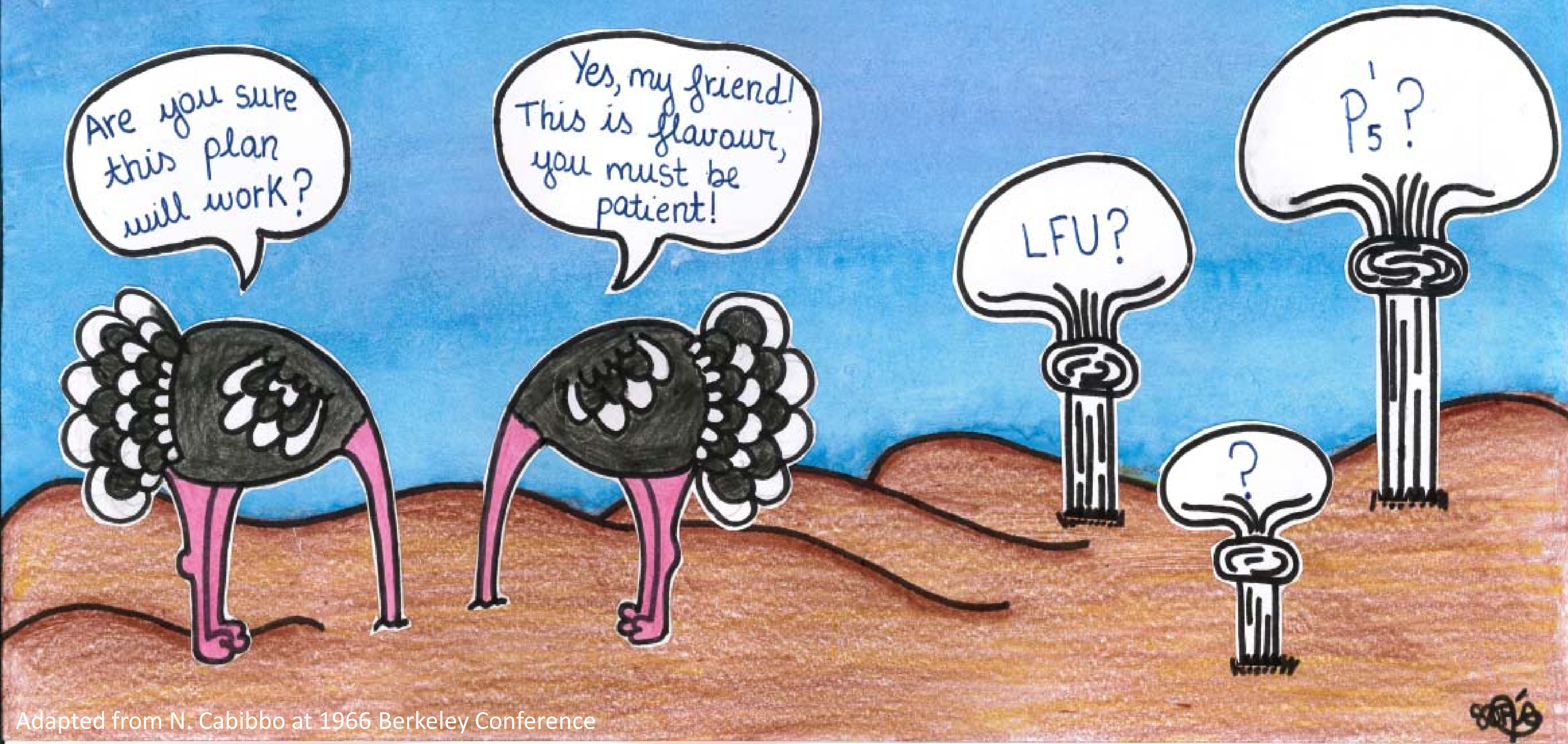
Prospects



- Run II will last until end 2018
  - ✓ ~factor ×5 on yields
- More R_X's and angular measurements
- Precise angular measurements with electrons
  - ✓ Expect similar yields to muons with Run I
  - ✓ Exploration of potential link between angular and LFU anomalies, e.g. $Q_5 = P'_5(ee) - P'_5(\mu\mu)$
- LFV, eg. B→eμ, τμ, Keμ

- The LHCb upgrade will start taking data in 2021
  - ✓ ~factor ×40 wrt Run I, ignoring trigger improvements

Exciting times



Adapted from N. Cabibbo at 1966 Berkeley Conference