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Experimental issues

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NBI, PhD school on flavour physics

The Standard Model

The Standard Model is by now an old theory

- In particular in the area of flavour physics, a large number of anomalies have shown up in the past few years

Cracks are at a level where they can't be ignored

The Standard Model

Is this the rise of New Physics to prominence?

A new consistent theory arises from the ruins

Or will the Standard Model be restored to former glory?

Reappraisal of theoretical uncertainties makes anomalies go away

Why flavour physics?

- Any physics model (SM or NP) has to deal with the observed flavour structure we observe
  - In SM this is through the Yukawa couplings to the Higgs field and the weak force
  - Misalignment of these gives structure of CKM matrix
    - Wide range: $m_u = O(10^{-5})\ m_t$, $|V_{ub}|=O(10^{-3})\ |V_{tb}|$ Why???
- Any NP model with new flavoured particles or flavour breaking interactions must “hide” behind SM interactions
  - NP mass scale very large (>~100 TeV)
    - or
  - NP mimics Yukawa couplings (minimal flavour violation)
- Both choices can be argued to be un-natural
  - Further measurements required

Questions to ask

For a given prospective measurement, we need to ask the questions

- What are the theoretical uncertainties with measurement and can they be reduced?
- What level of statistical accuracy could be expected?
- How will experimental systematics be controlled?

From answers conclude if measurement is actually interesting

Will aim to show here that there are still plenty of interesting measurements

Overall structure

Historical perspective

How to make measurements

Experimental facilities

Measurement of quark couplings

CP violation

FCNC and other rare/forbidden decays

Future perspective

Prediction of charm quark

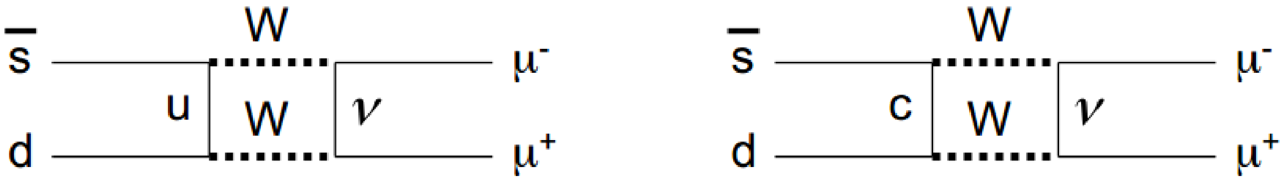
- Decay $K^+ \to \mu\nu$ observed with large BR

- Decay $K^0 \to \mu\mu$ observed but with tiny BR:

$$\frac{BR(K^0 \to \mu^+\mu^-)}{BR(K^+ \to \mu^+\nu_\mu)} = \frac{7\times10^{-9}}{0.64} \approx 10^{-8}$$

→ No neutral flavour changing currents

- Contribution from box diagram much too large to account for this:



- Led Glashow, Illiopolous, Maiani to postulate existence of the charm quark (GIM mechanism – 1970) before it was discovered (1974)
  - (nearly(*)) cancels the box diagram involving the u-quark

(*) not entirely: $m_u \neq m_c$

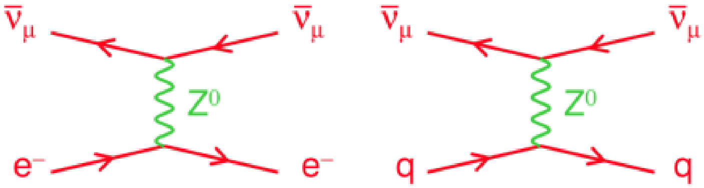
Discovery of neutral currents

- Also saw neutral current hadronic events

$$\boxed{\nu_\mu + N \rightarrow \nu_\mu + X} \qquad \boxed{\bar{\nu}_\mu + N \rightarrow \bar{\nu}_\mu + X}$$

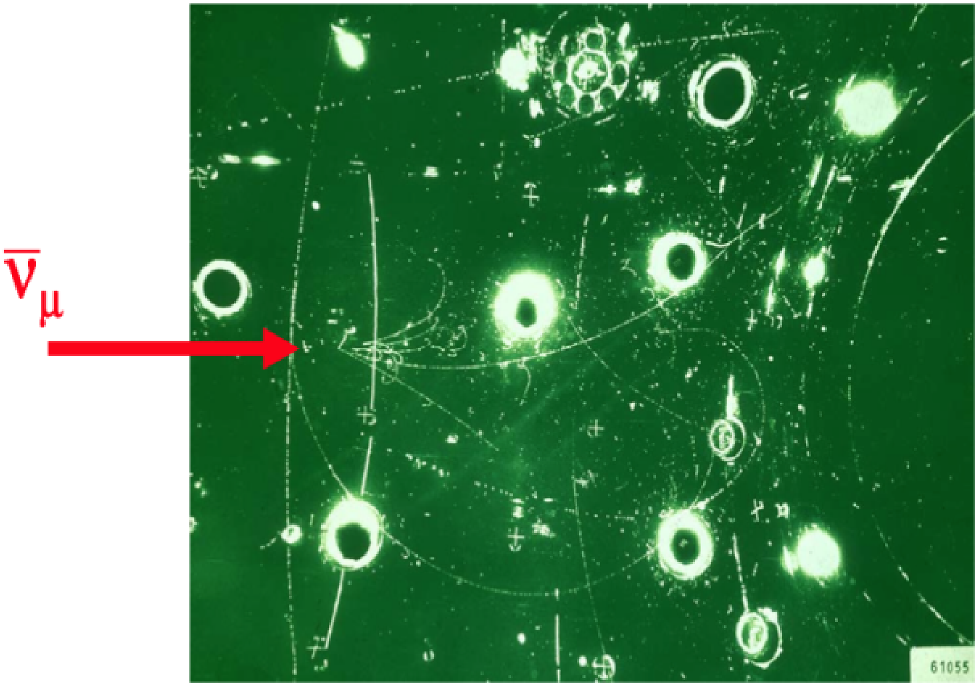
No μ^+ or μ^- in the final state

- Can only proceed via Z^0 exchange,



- No W diagrams possible

→ First "indirect" evidence for Z^0 boson



F.J. Hasert et al., Phys. Lett. **46B** (1973) 138

Kaon decays

The mass eigenstates for neutral kaons are

$K^0 = s\bar{d}$ $\bar{K}^0 = \bar{s}d$

We can express these in terms of CP eigenstates

$$K^0 = \frac{K_1 + K_2}{\sqrt{2}} \qquad \bar{K}^0 = \frac{K_1 - K_2}{\sqrt{2}}$$

If the weak force is conserving CP, then K_1 and K_2 will be the weak eigenstates as well

CP violation in kaon decays

We can write down time evolution of eigenstates

$$|K_1(t)\rangle = e^{-i(M_1-\frac{i}{2}\Gamma_1 t)}|K_1\rangle$$
$$|K_2(t)\rangle = e^{-i(M_2-\frac{i}{2}\Gamma_2 t)}|K_2\rangle$$

- Substitute in and rearrange to get:

$$|K^0(t)\rangle = f_+(t)|K^0\rangle + \frac{q}{p}f_-(t)|\bar{K}^0\rangle$$

where

$$f_\pm = \frac{1}{2}e^{-iM_1 t}e^{\frac{1}{2}\Gamma_1 t}[1 \pm e^{-i\Delta m t}e^{\frac{1}{2}\Delta\Gamma t}]$$

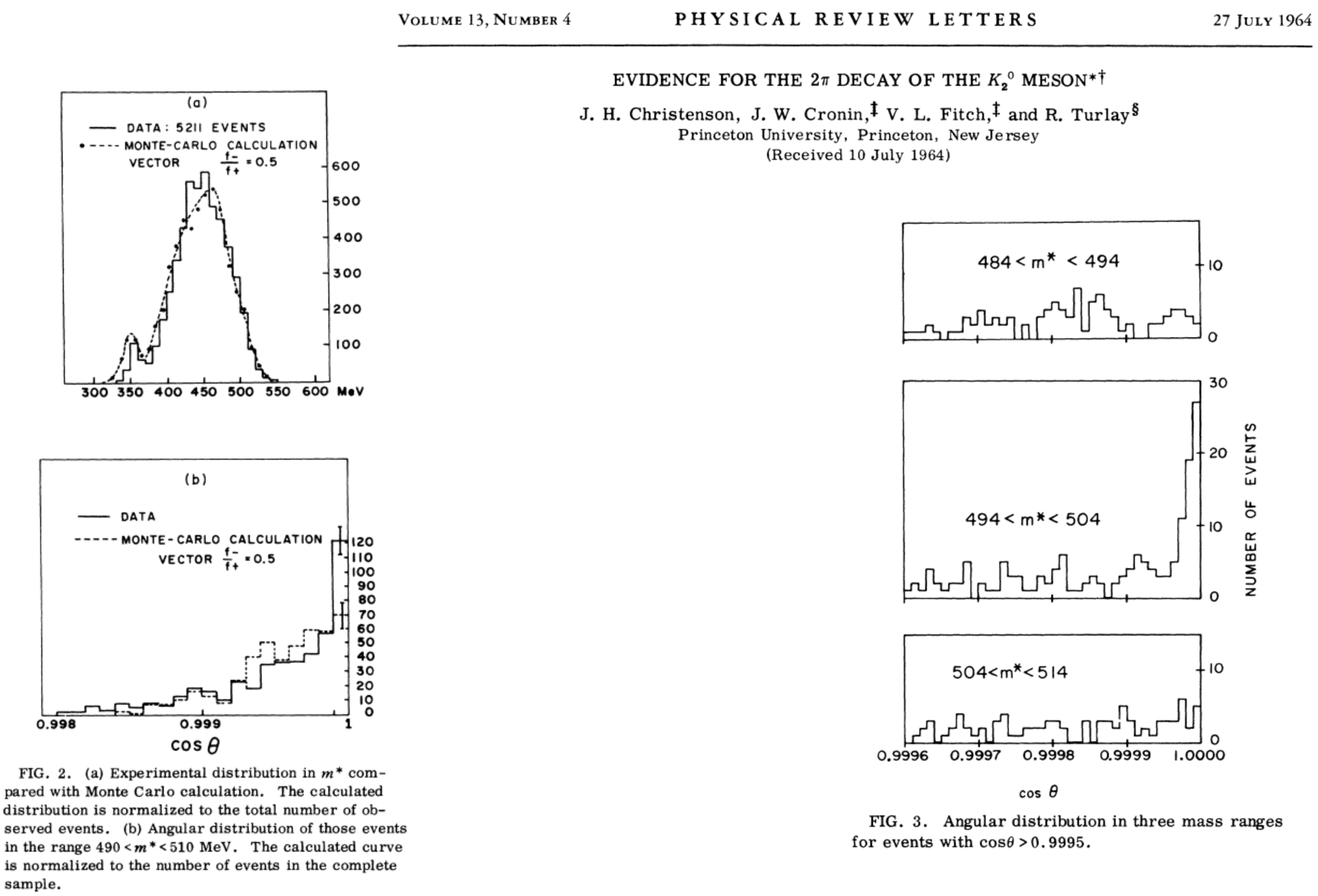
$$\frac{q}{p} = \pm\sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}}$$

Oscillating term

CP violation in kaon decays

- A CP-even and CP-odd state will decay differently
  - CP-even (~K_1) decays to 2 pions (parity of pion is -1)
  - CP-odd (~K_2) decays to 3 pions
- As $K \rightarrow 3\pi$ is almost kinematically forbidden, decay is supressed and lifetime long
  - Call K_1 for K^0_S and K_2 for K^0_L
- If we create K^0 or $\overline{K}^0$ (through strong interaction)
  - Start with equal amount of K^0_S and K^0_L
  - K^0_S decays and leaves pure K^0_L sample
  - If CP is conserved should only observe 3 pion decays

CP violation in kaon decays



Volume 13, Number 4 PHYSICAL REVIEW LETTERS 27 July 1964

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey

(Received 10 July 1964)

FIG. 2. (a) Experimental distribution in m^* compared with Monte Carlo calculation. The calculated distribution is normalized to the total number of observed events. (b) Angular distribution of those events in the range $490 < m^* < 510$ MeV. The calculated curve is normalized to the number of events in the complete sample.

FIG. 3. Angular distribution in three mass ranges for events with $\cos\theta > 0.9995$.

CP violation in kaon decays

As K^0_L decays to two pions observed

- K^0_L is not a CP eigenstate
- The weak force is not CP conserving
- What is seen here is "CP violation in mixing"

Nobel prize awarded in 1980

VOLUME 13, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JULY 1964

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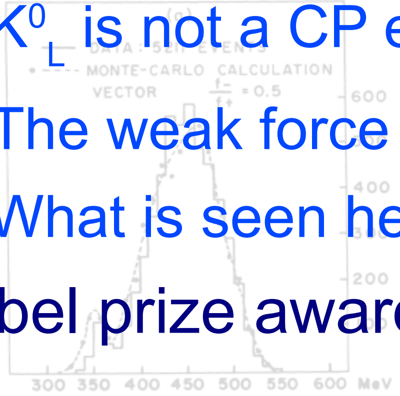

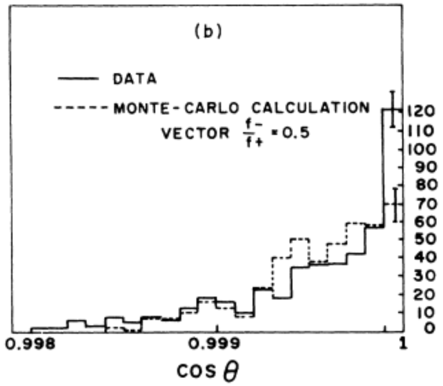

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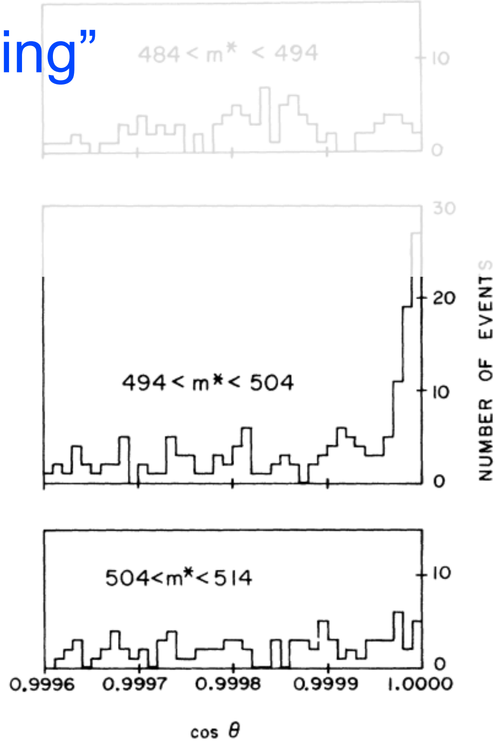


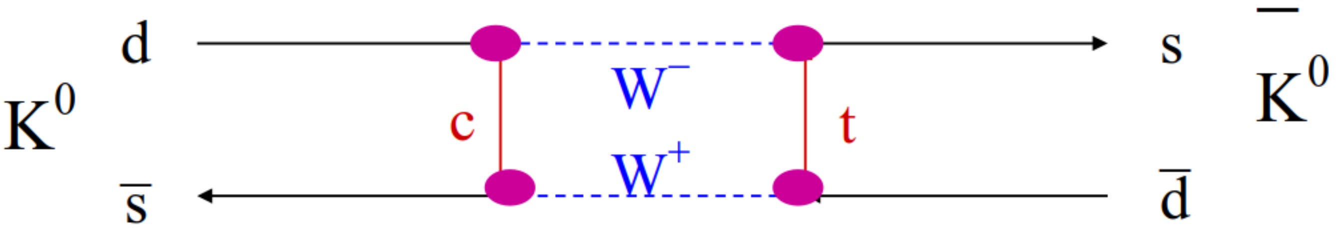
FIG. 3. Angular distribution in three mass ranges for events with $\cos\theta > 0.9995$.

C. Parkes

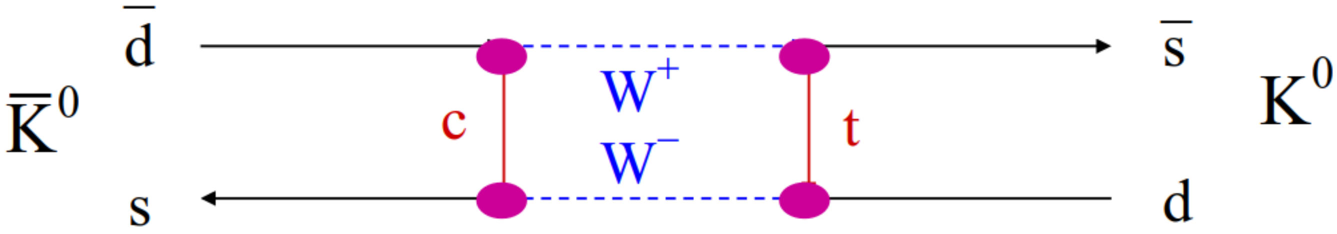
Consequence of CPV in kaon decays

CP violation in the Standard Model

One diagram only for simplicity



$$M_{fi} \propto V_{cd} V_{cs}^* V_{td} V_{ts}^*$$



$$M'_{fi} \propto V_{cd}^* V_{cs} V_{td}^* V_{ts} = M_{fi}^*$$

Hence difference in rates:

$$\Gamma(K^0 \to \overline{K^0}) - \Gamma(\overline{K^0} \to K^0) \propto M_{fi} - M_{fi}^* = 2\Im(M_{fi})$$

C. Parkes

Consequence of CPV in kaon decays

- Can only get difference if matrix element complex
- That two mixing rates are different implies T-violation
  - And thus CP violation if CPT invariance is assumed
- Kobayashi and Maskawa realised 3 generations of quarks required for creating complex phase
  - Prediction of b and t quarks
  - Nobel prize awarded in 2008

B oscillations

Take advantage of pair production of B^0-$\overline{B}^0$ to search for B oscillations

- $B^0 \to X\mu^+\nu$
- $\overline{B}^0 \to X\mu^-\nu$

Observation of two same sign muons is an indication of mixing

$$r=\frac{N(B^0B^0)+N(\bar{B}^0\bar{B}^0)}{N(B^0\bar{B}^0)}=0.22\pm0.09\pm0.04$$

$$x=\frac{\Delta M}{\Gamma}=32\pi\frac{Bf_B^2m_t^2m_b}{m_\mu^5}\frac{\tau_b}{\tau_\mu}|V_{td}|^2\eta_{QCD}$$

$$r=\frac{x^2}{x^2+2}$$

Volume 192, number 1,2 PHYSICS LETTERS B 25 June 1987

OBSERVATION OF B^0–$\bar{B}^0$ MIXING

ARGUS Collaboration

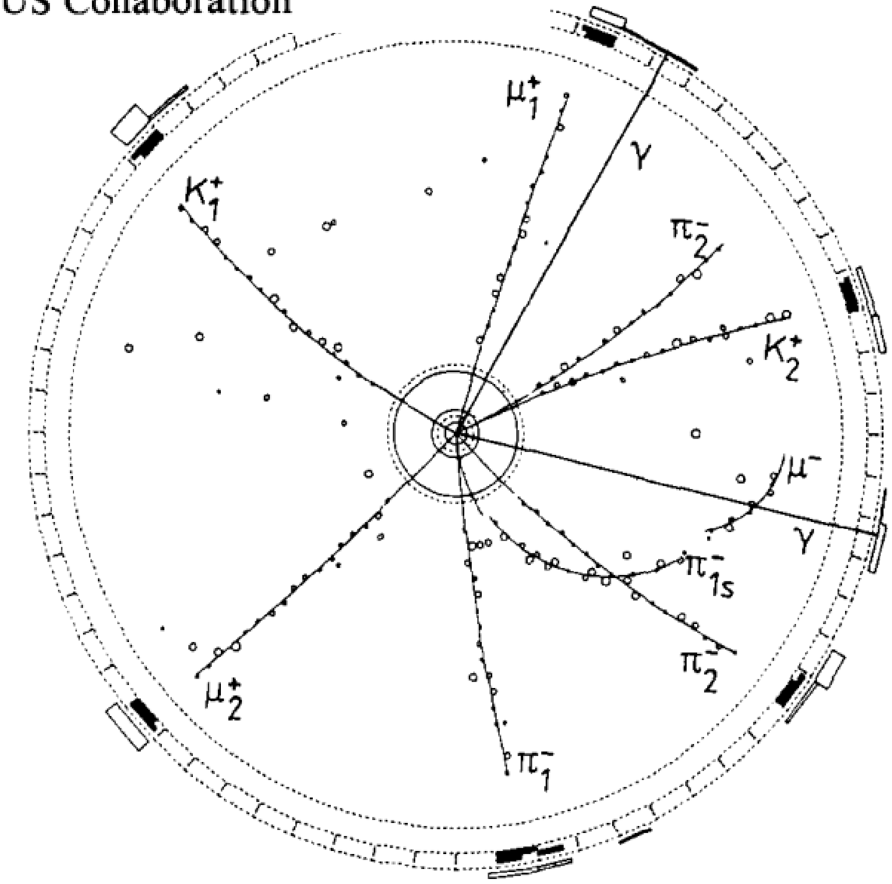


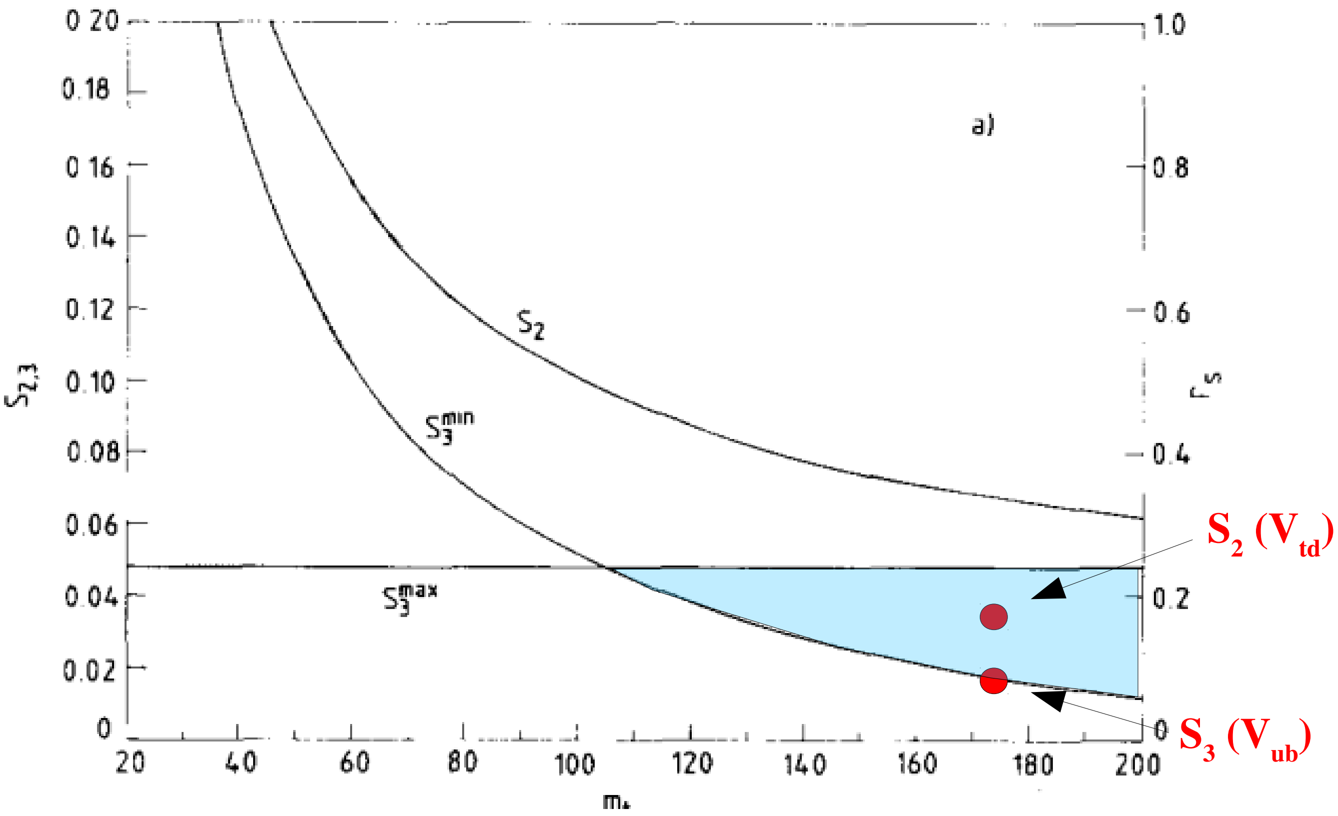
Fig. 2. Completely reconstructed event consisting of the decay $\Upsilon(4S)\to B^0B^0$.

The heavy top quark

The oscillation was much faster than anticipated

- Led to a change in the expectation of the top quark mass
- “Preferred” scenario was $m_t > 100$ GeV

Ellis, Hagelin and Roudas, PLB 192, 201 (1987)

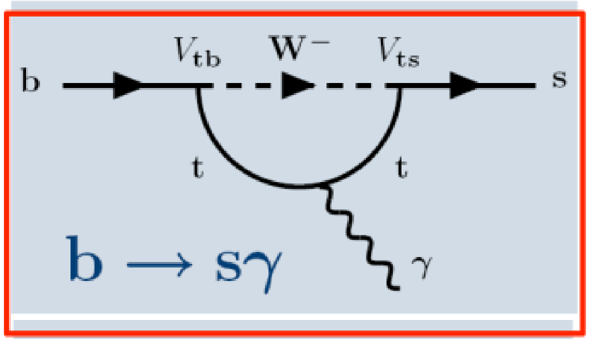


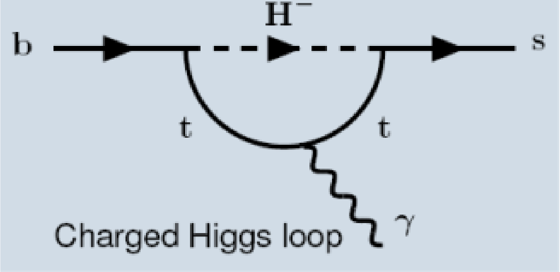
The long road to new physics

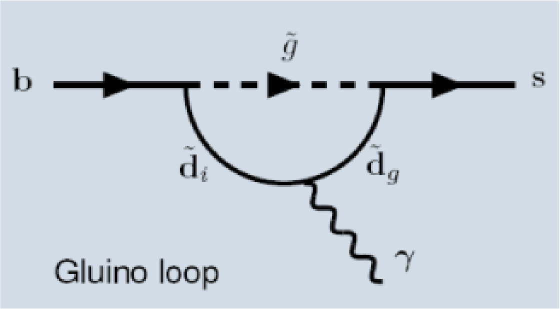
The “normal” level of b→sgamma

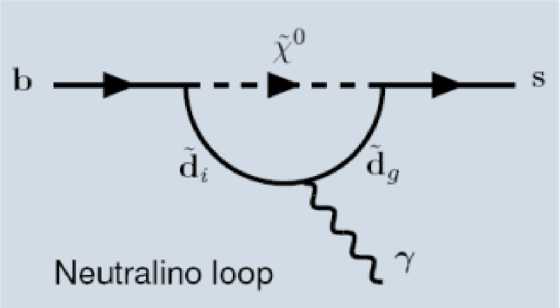
- Flavour Changing Neutral Current (FCNC) process
- Occurs through a dominating W-t loop (so-called penguin diagram)
- Possible NP diagrams:
  - Could be same order as SM → possibility of observing interference effects between two routes to same final state

    (similar amplitudes → large interference effects)
  - SUSY: interference could be constructive → expect a larger BR
  - UED models: destructive interference → expect a smaller BR









The long road to new physics

- CLEO experiment observed this process in the exclusive decay mode $B_d^0 \to K^{*0}\gamma$ in 1993
  - two years before the discovery of the top quark!
  - BR was expected to be $(2\text{-}4)\times10^{-4}$
  - Observation of something other than 4×10^{-4} → evidence for non-SM contributions: SUSY, 4th generation of quarks, charged Higgs …
  - Measured 7 $B_d^0 \to K^{*0}(\to K^+\pi^-)\gamma$, over a background of 1.1±0.2 events

    $\to$ BR = $(4.5\pm1.7)\times10^{-4}$

    [also saw 2 $B^- \to K^{*-}(\to K_S\pi^-)\gamma$ decays and 3 $B^- \to K^{*-}(\to K^-\pi^0)\gamma$ decays]

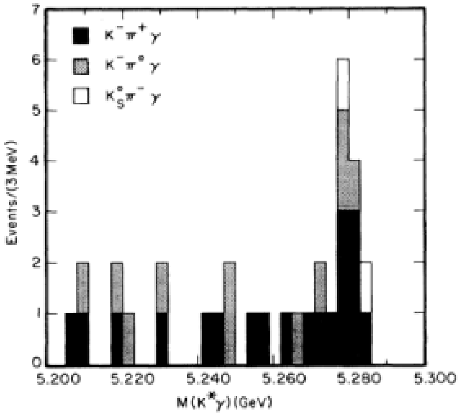


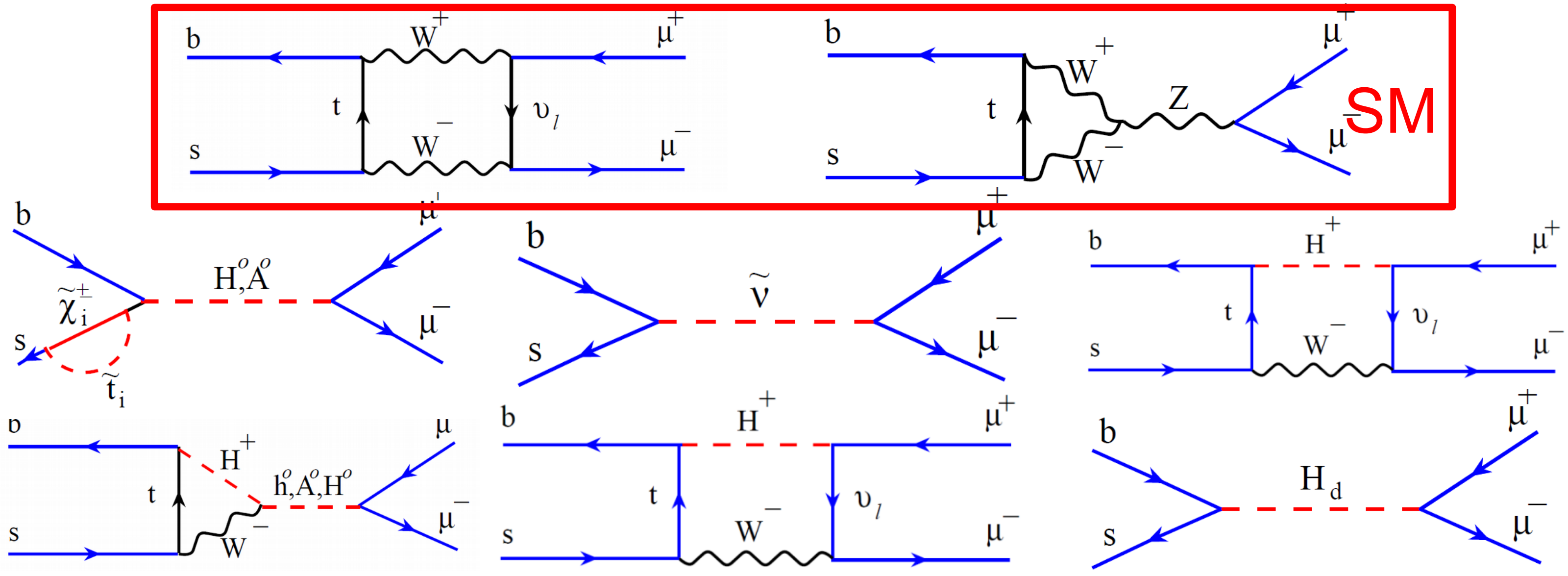
FIG. 2. The $K^*\gamma$ mass distributions for $B^0 \to K^{*0}\gamma$; $B^- \to K^{*-}\gamma$, $K^{*-} \to K_S^0\pi^-$; and $B^- \to K^{*-}\gamma$, $K^{*-} \to K^-\pi^0$ candidates.

[Phys.Rev.Lett. 71 (1993) 674 - Cited by 605 records
Phys.Rev.Lett. 74 (1995) 2885 - Cited by 836 records
Phys.Rev.Lett. 87 (2001) 251807 - Cited by 565 records]

The long road to new physics

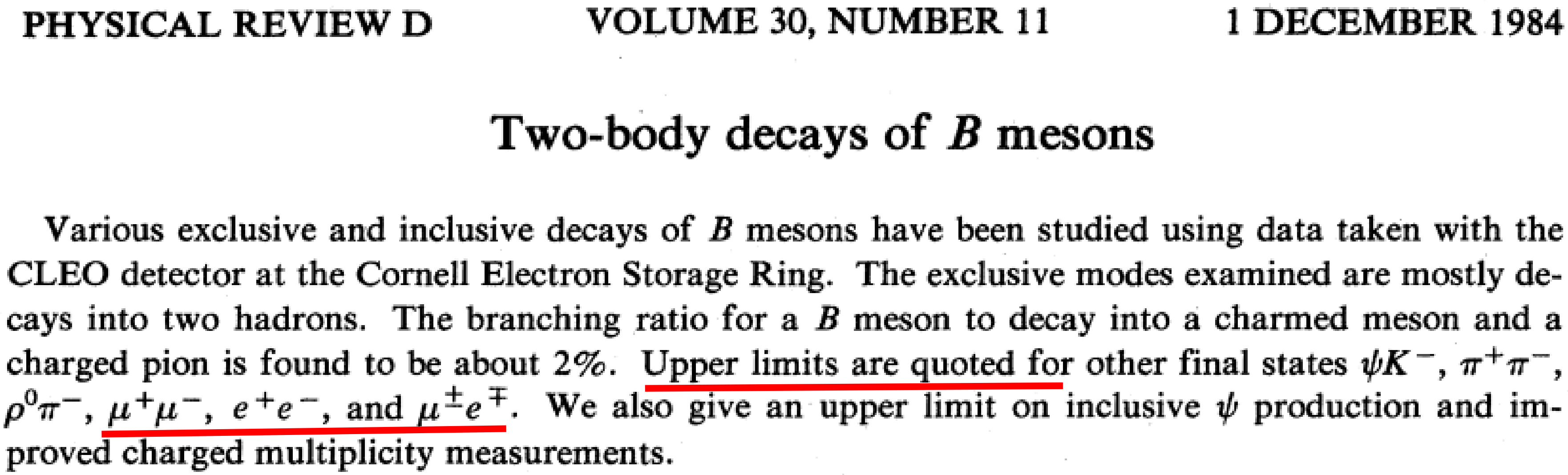
The two very rare decays $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ have attracted much interest

- Easy to predict SM branching fraction with great precision
  - $BF(B^0_s \to \mu^+\mu^-)_{SM} = (3.56 \pm 0.18) \times 10^{-9}$ (time averaged)
  - $BF(B^0 \to \mu^+\mu^-)_{SM} = (0.10 \pm 0.01) \times 10^{-9}$
- Sensitive to the scalar sector of flavour couplings



The long road to new physics

For B mesons the rare decay search started in 1984 at CLEO



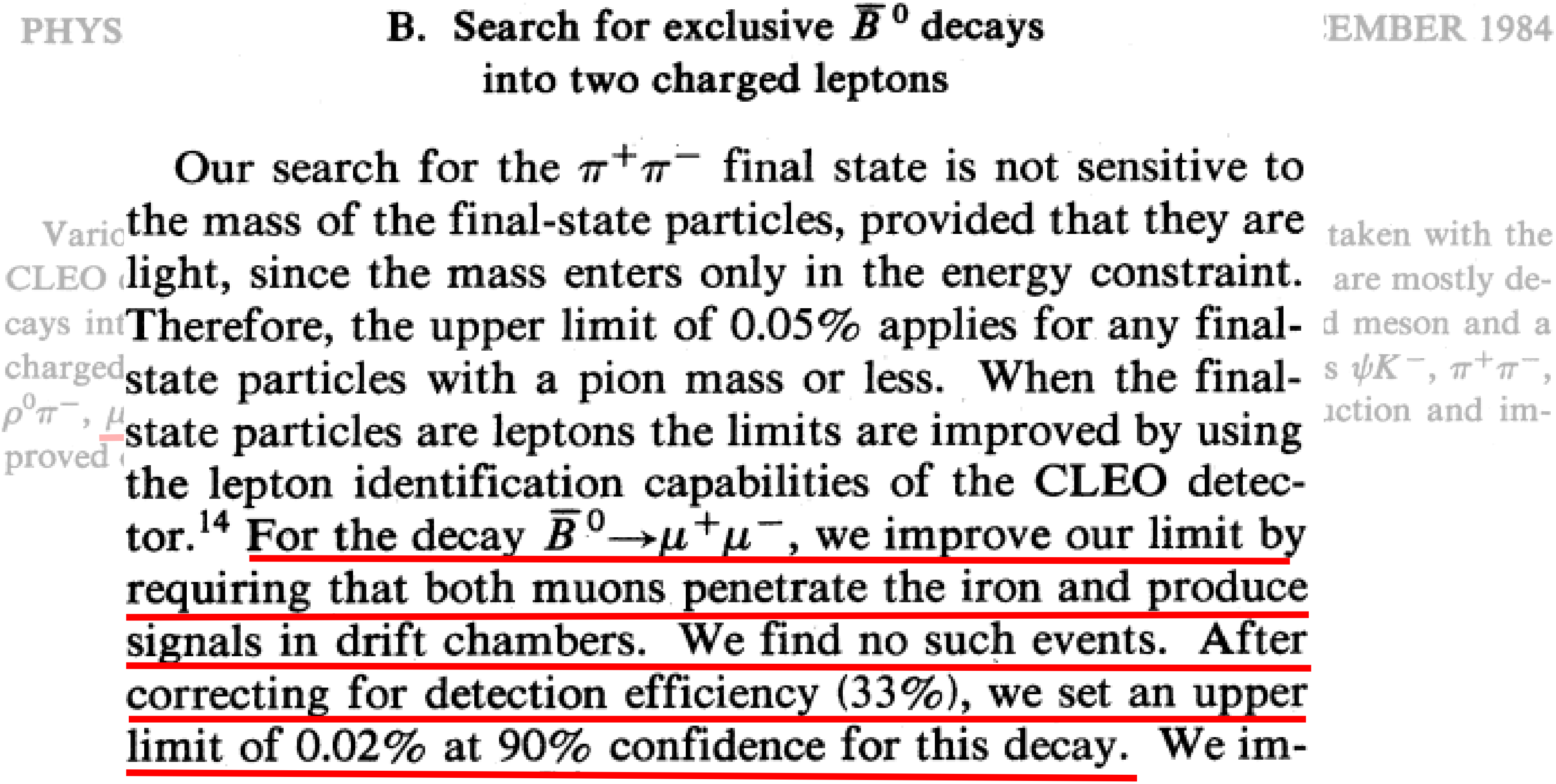
PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1984

Two-body decays of *B* mesons

Various exclusive and inclusive decays of *B* mesons have been studied using data taken with the CLEO detector at the Cornell Electron Storage Ring. The exclusive modes examined are mostly decays into two hadrons. The branching ratio for a *B* meson to decay into a charmed meson and a charged pion is found to be about 2%. Upper limits are quoted for other final states ψK^-, $\pi^+\pi^-$, $\rho^0\pi^-$, $\mu^+\mu^-$, e^+e^-, and $\mu^\pm e^\mp$. We also give an upper limit on inclusive ψ production and improved charged multiplicity measurements.

The long road to new physics

For B mesons the rare decay search started in 1984 at CLEO

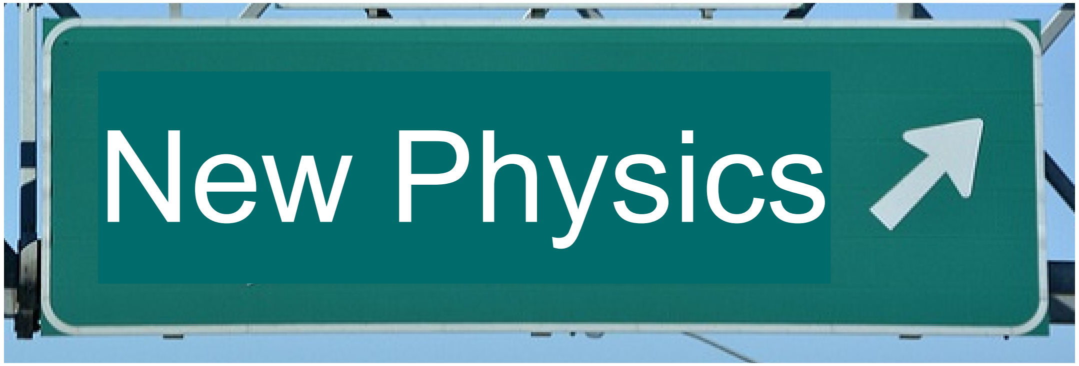


B. Search for exclusive $\overline{B}^0$ decays into two charged leptons

Our search for the $\pi^+\pi^-$ final state is not sensitive to the mass of the final-state particles, provided that they are light, since the mass enters only in the energy constraint. Therefore, the upper limit of 0.05% applies for any final-state particles with a pion mass or less. When the final-state particles are leptons the limits are improved by using the lepton identification capabilities of the CLEO detector.[14] For the decay $\overline{B}^0 \rightarrow \mu^+\mu^-$, we improve our limit by requiring that both muons penetrate the iron and produce signals in drift chambers. We find no such events. After correcting for detection efficiency (33%), we set an upper limit of 0.02% at 90% confidence for this decay. We im-

Found the exit?

Previous results pointed to high mass scale of new physics



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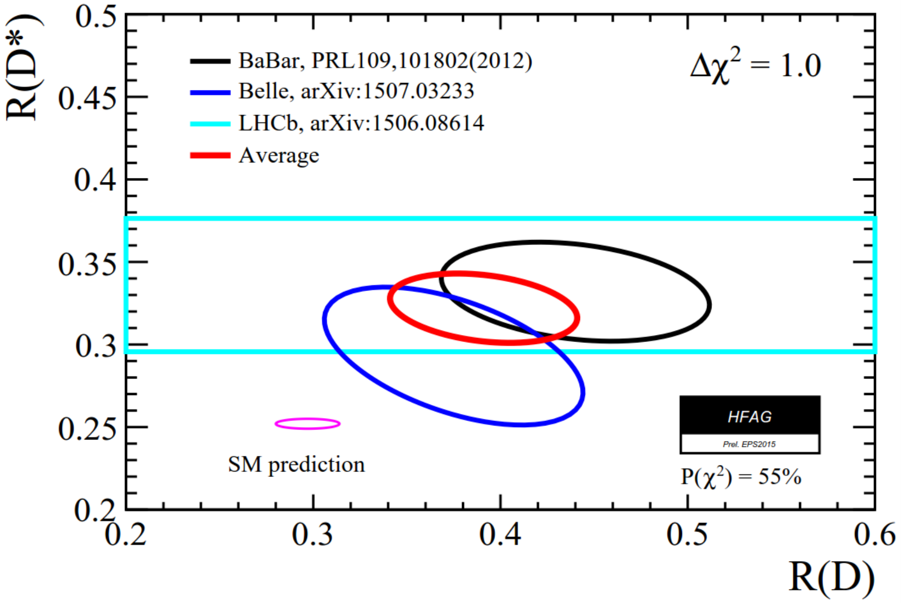
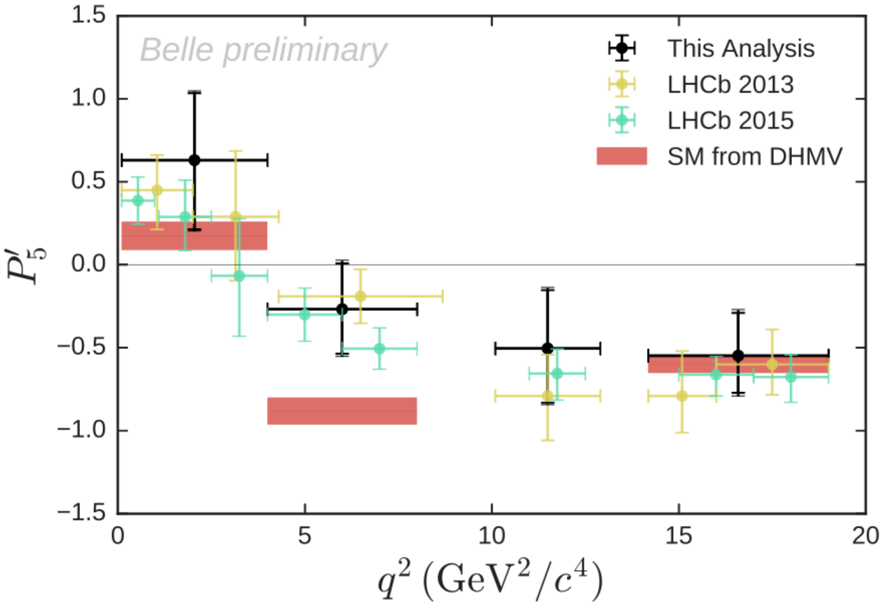
But have indirect measurements reached it now?





How to make measurements

For a given prospective measurement, we need to ask the questions

- **What are the theoretical uncertainties with measurement and can they be reduced?**
- What level of statistical accuracy could be expected?
- How will experimental systematics be controlled?

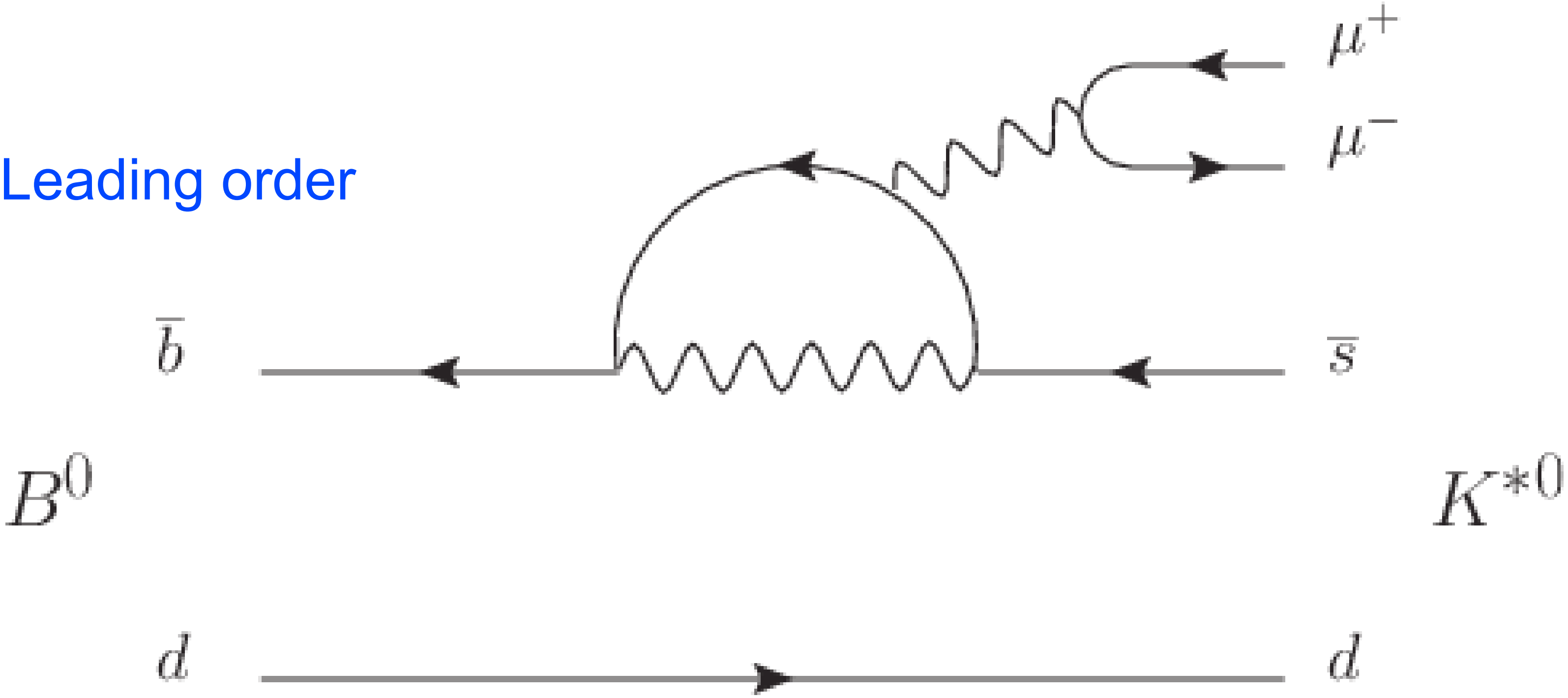
The impact of QCD on any measurements

Strong force in the way

Most calculations of expected decay rates are done using Feynman diagrams

- Works just like a Taylor expansion

Leading order

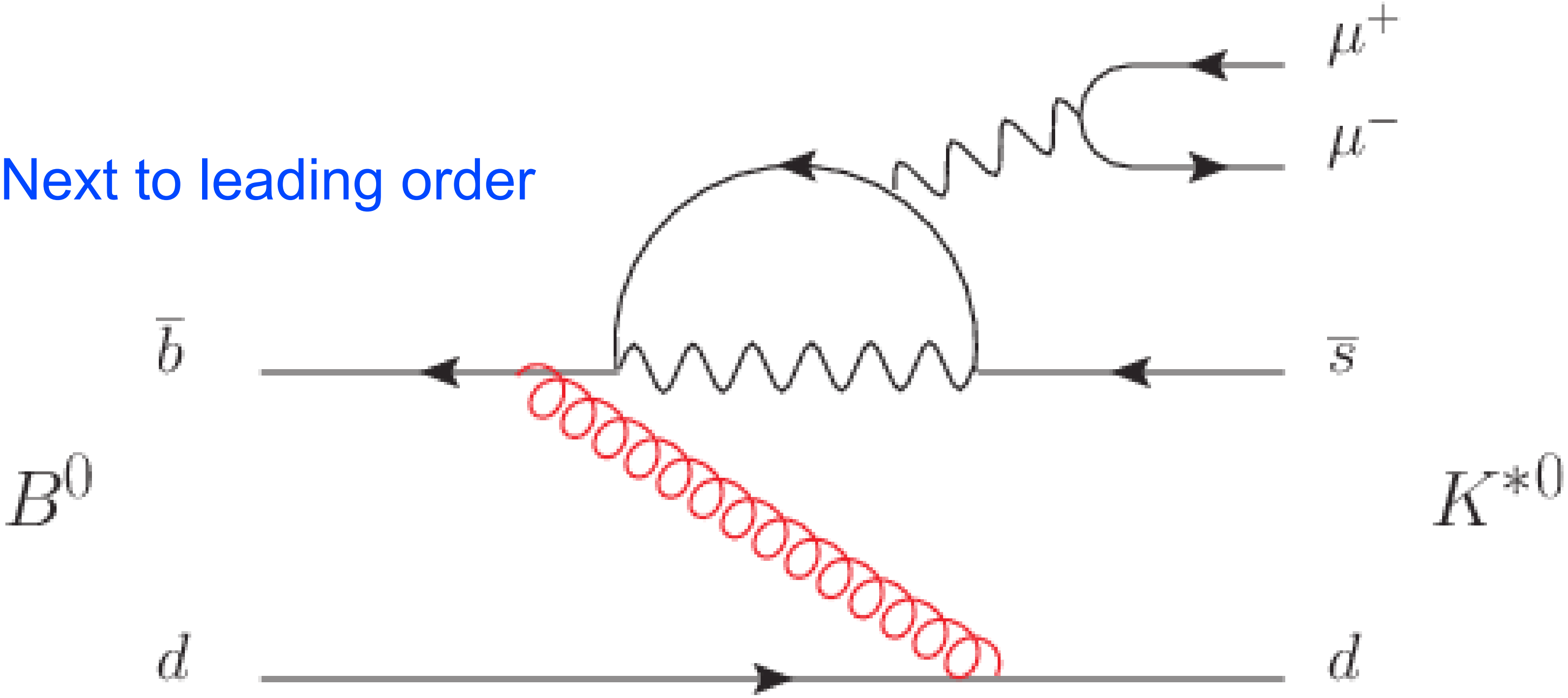


Strong force in the way

Most calculations of expected decay rates are done using Feynman diagrams

- Works just like a Taylor expansion

Next to leading order

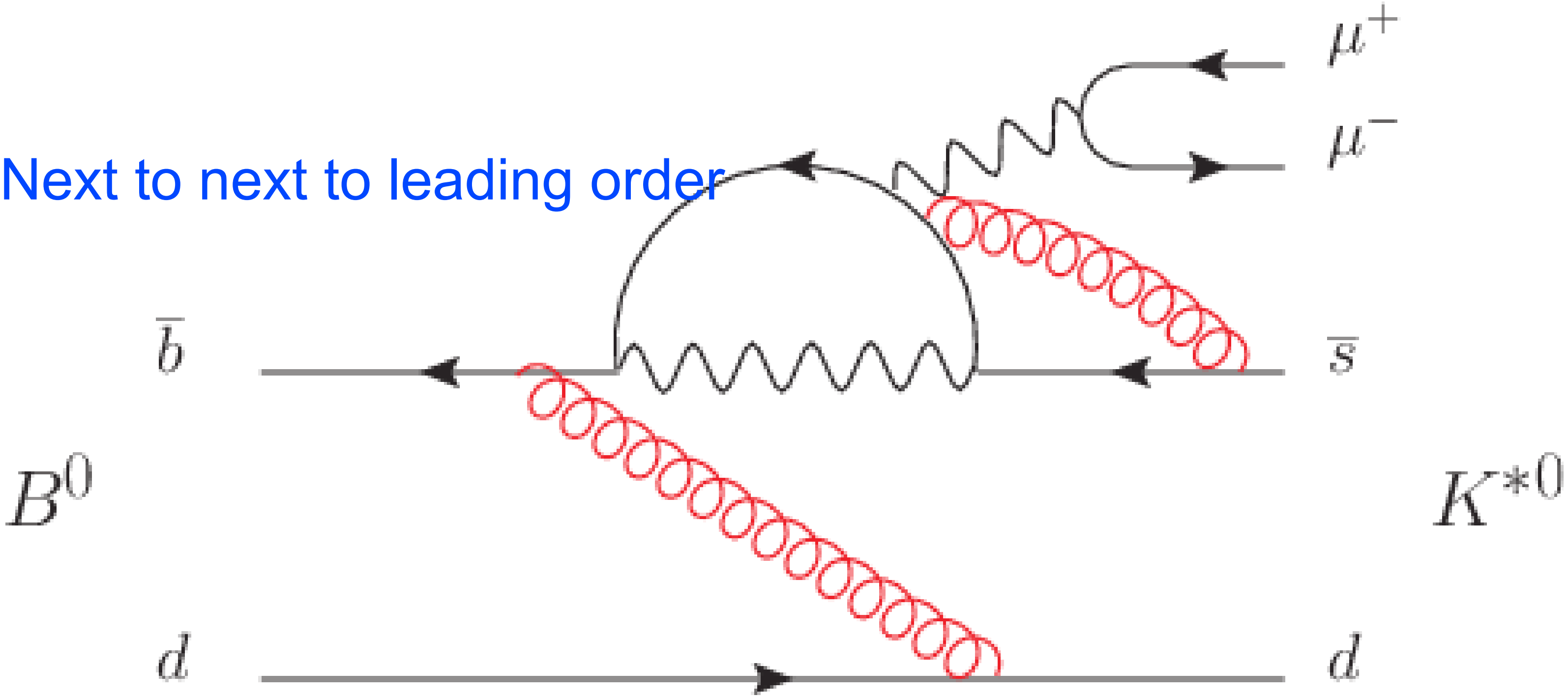


Strong force in the way

Most calculations of expected decay rates are done using Feynman diagrams

- Works just like a Taylor expansion

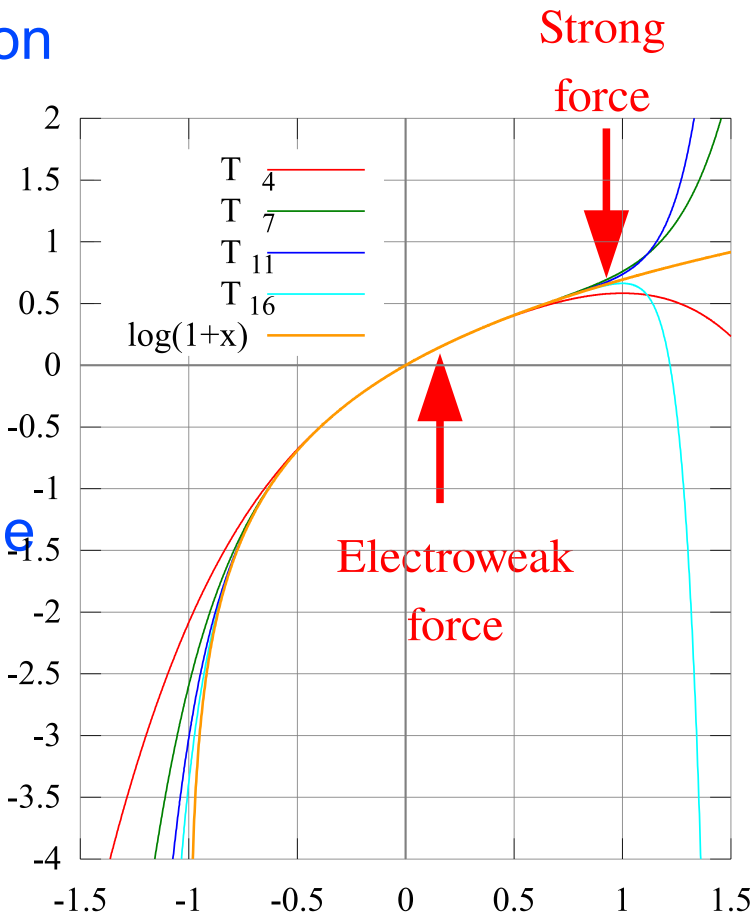
- Next to next to leading order



Strong force in the way

Most calculations of expected decay rates are done using Feynman diagrams

- Works just like a Taylor expansion
- But can in just the same way turn problematic
- Strong coupling constant too large so series may not converge

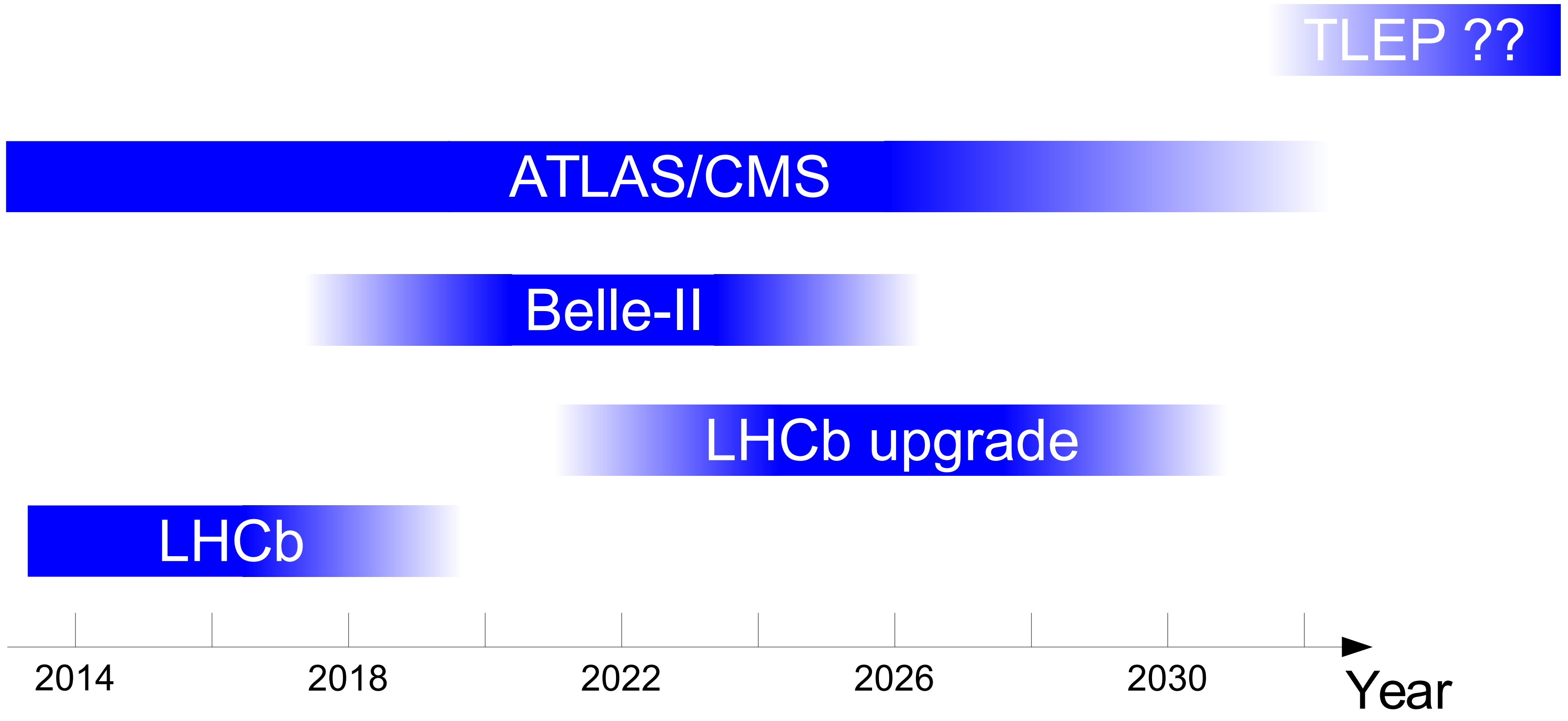


Strong force in the way

There are different ways out of the problem of non-convergence

- Run a discrete numerical simulation
  - Make use of Lattice QCD results where available
  - Semileptonic decays
- Ratios where QCD influence is cancelling
  - Angular analysis of penguin decays
- Subtraction where QCD influence cancels
  - CP violation
  - Lepton non-universality
- Forbidden processes
  - Lepton flavour violation

The proposed facilities available



Production of heavy flavour

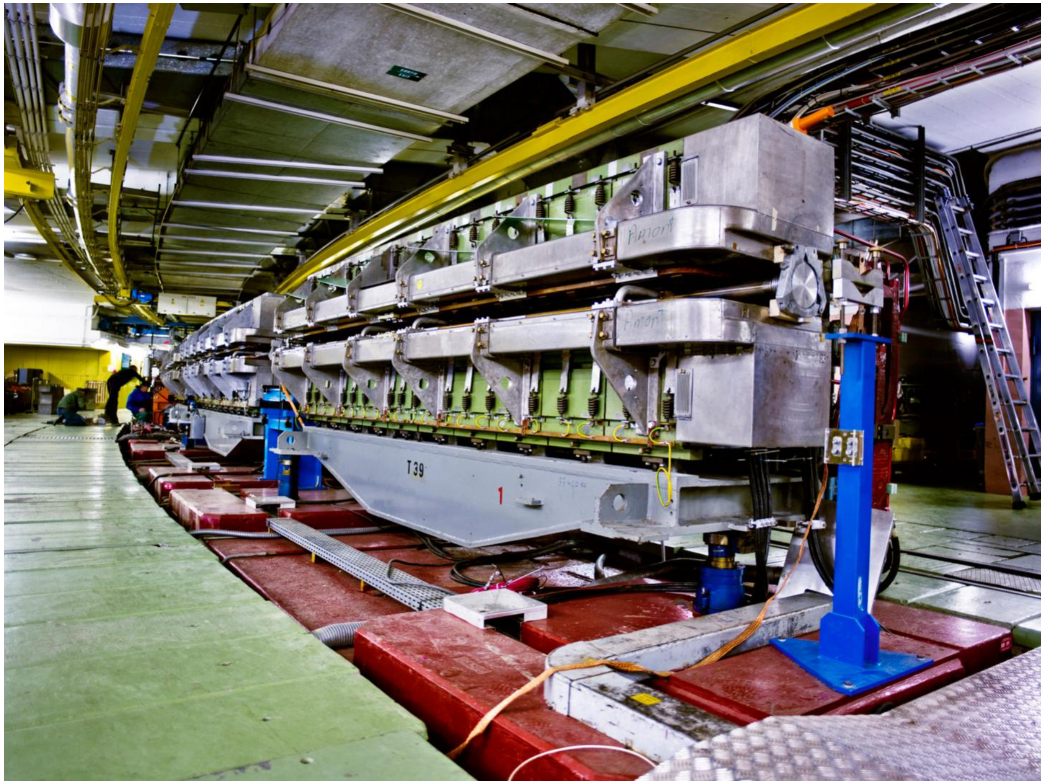
Think of properties of quarks that we are interested in

- Lifetime
  - Kaons and are very long lived
  - Both b- and c-hadrons have lifetime in ps region
  - Top quark has insignificant lifetime
- Mass of hadrons
  - Scales from 0.5 GeV for kaons to 175 GeV for top
- Decays
  - Are interested in measuering decays with branching fractions in 10^{-10} region

Large differences in properties leads to different facilities

Facilities

- Fixed target
  - Will extract proton beam from storage ring
    - CERN – Proton Synchroton (PS), 27 GeV
      - Can provide kaons and pions for testbeams

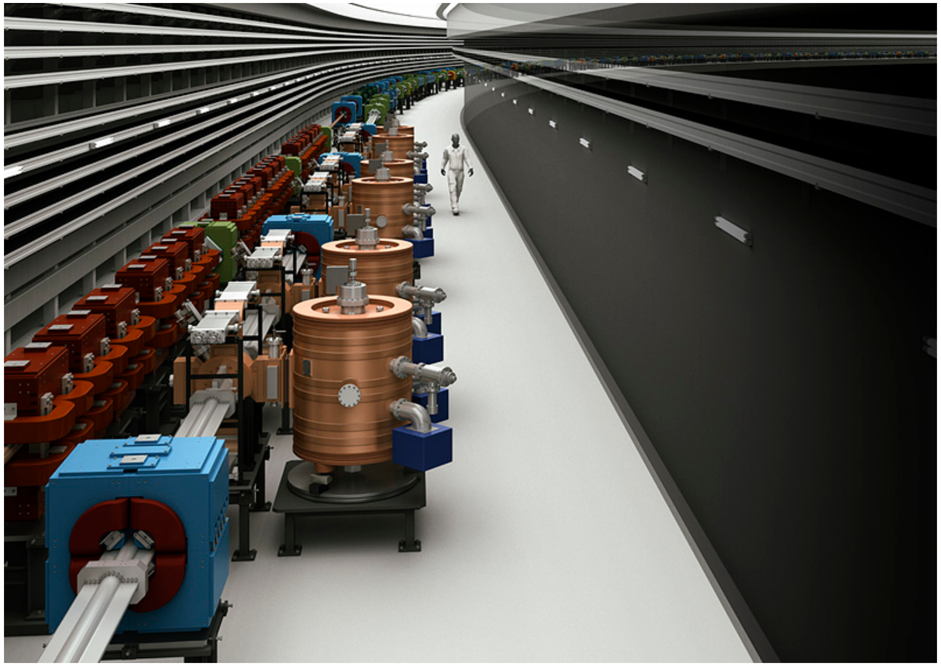


Facilities

- Fixed target production
  - Will extract proton beam from storage ring
    - CERN – Proton Synchroton (PS), 27 GeV
      - Can provide kaons and pions for testbeams
    - Fermilab – Booster, 8GeV
      - Proposals for future kaon expriments
    - CERN – SPS, 450 GeV
      - Can produce pions, kaons, c-hadrons, (b-hadrons)
      - Home to several active experiments

Facilities

- e^+e^- collisions for pair production on resonance
  - DAΦNE – collisions at the φ resonance (~1 GeV)
  - Beijing Electron–Positron Collider II (BEPC II)
    - Collisons in the charmonium region (3-4.5 GeV)
  - CESR – symmetric collisions at Υ(4S) (terminated)
  - PEP-II – asymmetric collisions at Υ(4S) (terminated)
  - Super-KEKB – asymmetric collisions at Υ(4S)



Facilities

Hadron colliders for production in fragmentation process

- Fermilab – TeVatron, 2 TeV (terminated)
- CERN – LHC, 13 TeV

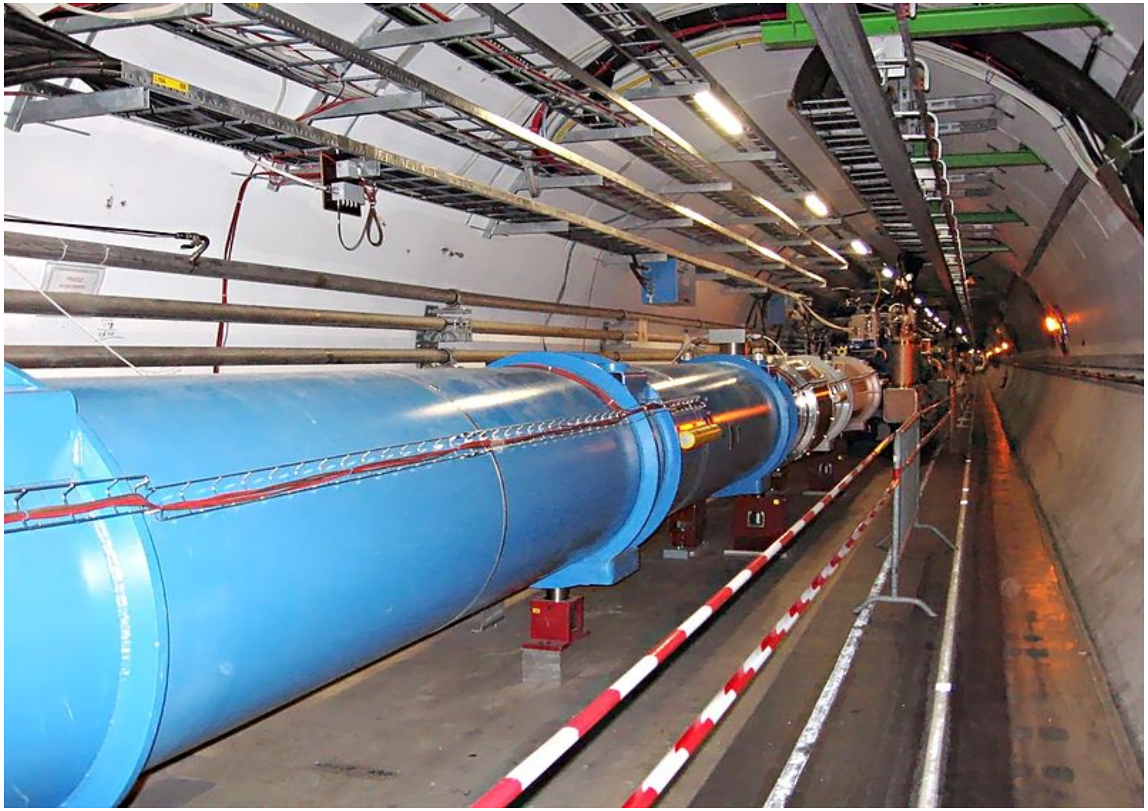
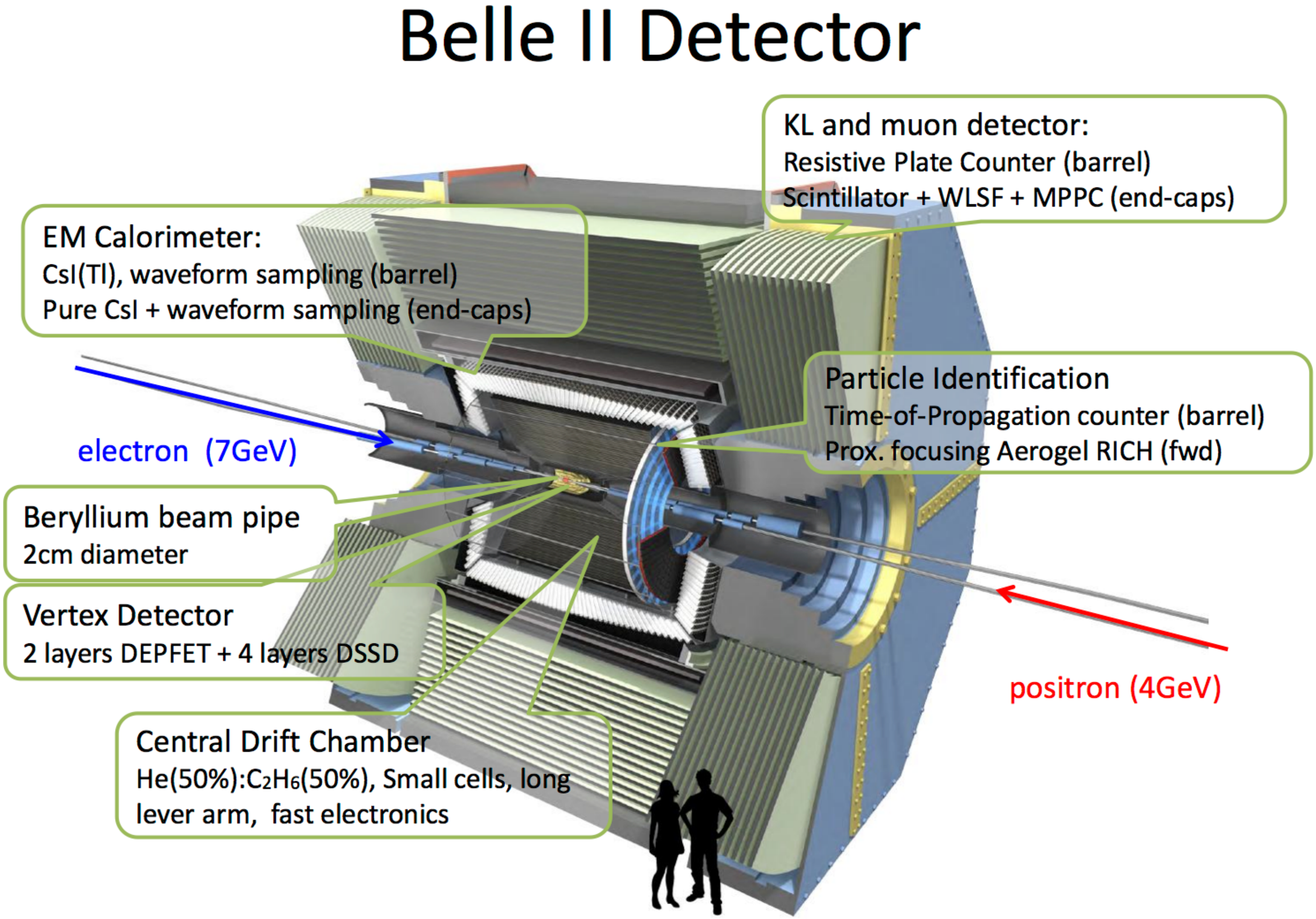
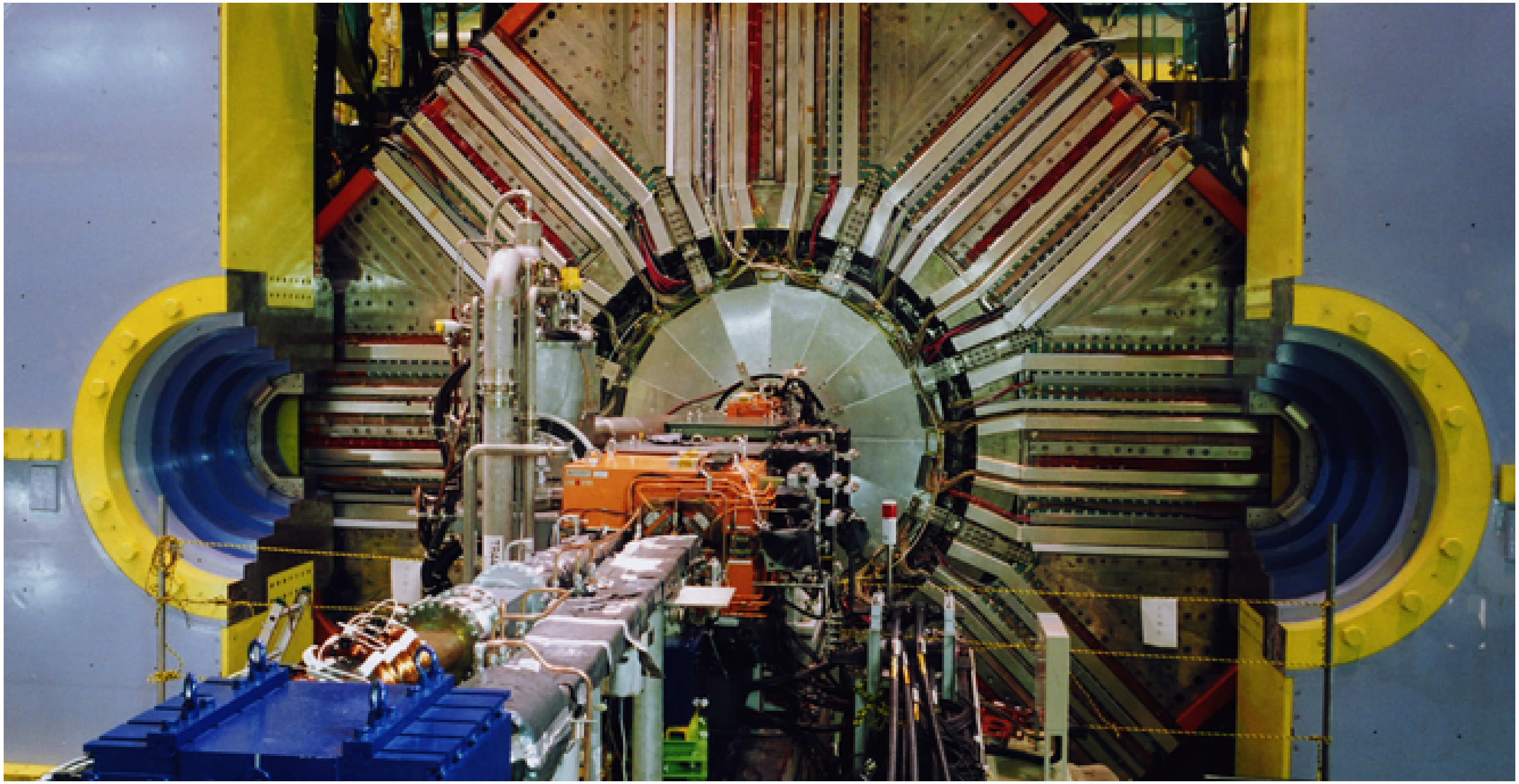


Photo: J. Herzog, CC-BY-SA 3.0

BELLE-II detector



BELLE-II detector



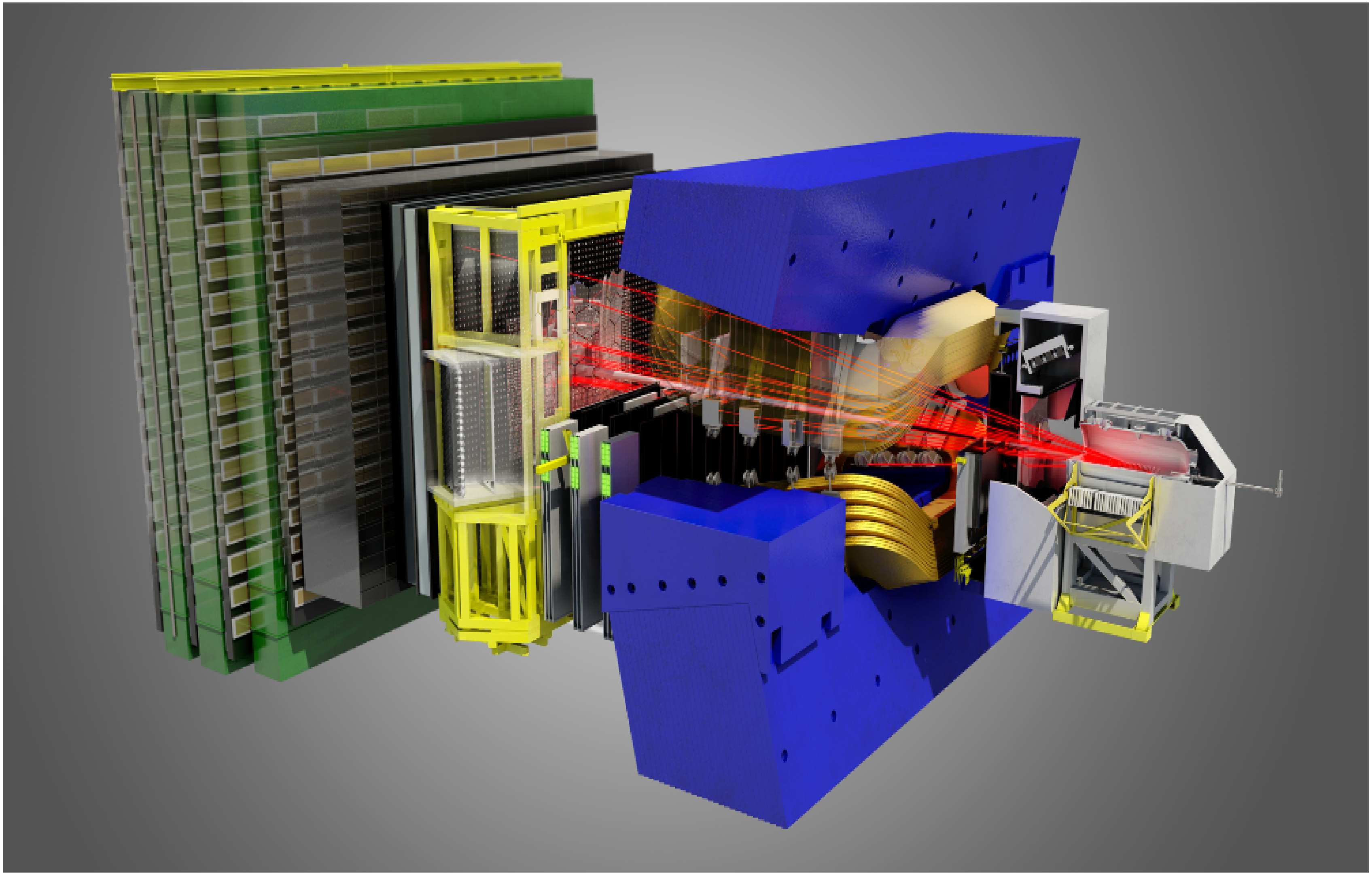
Hadron collider detector design

- Vertex detector
  - Both b- and c-hadrons have lifetime in ps region.
  - With momentum in 100 GeV region this gives decay distance around 10 mm.
- Mass of bottom and top
  - Mass of decaying quark sets transverse momentum scale
    - p_T/p sets geometry of detector
    - Forward detector for c- and b-hadrons
    - 4π for t decay

Hadron collider detector design

- Trigger
  - Charm hadrons produced in every 50 collisions
    - Precision *CP* violation in Charm → kHz signal
  - Beauty hadrons produced in every 500 collisions
    - B decays with 10^{-10} branching fraction → 10 nHz signal
    - Need high efficiency for low mass decay
  - Top quark
    - Much rare in production
    - Trigger based on very high p_T leptons and jets
- LHCb experiment is designed for charm and beauty
- ATLAS and CMS has top physics among primary design goals

The LHCb experiment



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The LHCb experiment

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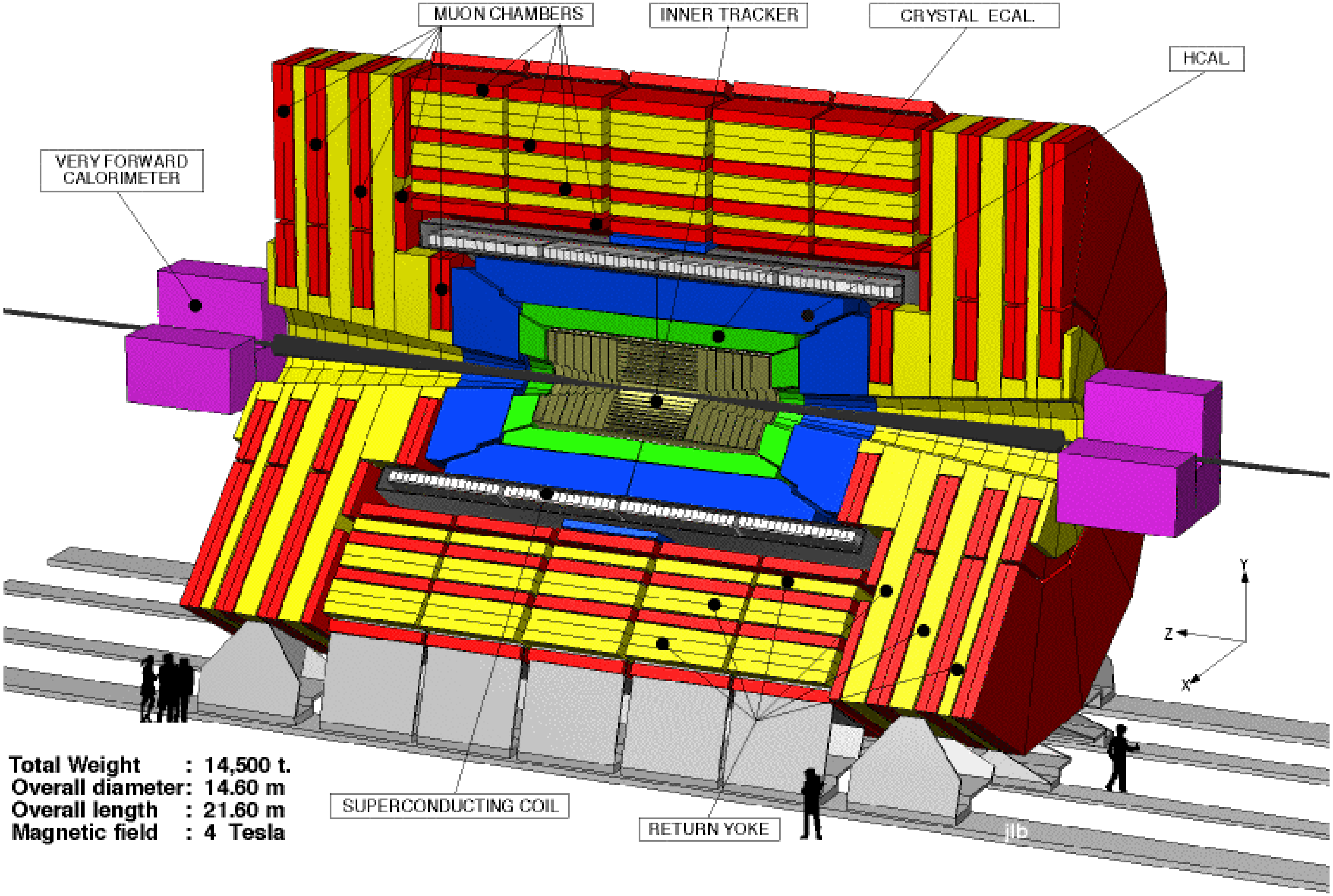
CMS experiment



Total Weight	: 14,500 t.
Overall diameter	: 14.60 m
Overall length	: 21.60 m
Magnetic field	: 4 Tesla

Relative strengths

	LHCb	ATLAS/ CMS	BELLE-II
B-hadron mass resolution	✓✓✓	✓	✓✓✓
B vertex resolution	✓✓✓	✓✓	✓
Heavy flavour trigger rate	✓✓✓	✓	✓✓✓
Muon ID	✓✓✓	✓✓✓	✓✓
Electron ID	✓	✓✓	✓✓✓
Hadron ID	✓✓✓	X	✓✓
Coverage (top)	✓	✓✓✓	X
Coverage (bottom)	✓✓✓	✓	✓✓✓
Backgrounds	✓	✓	✓✓
Statistics	✓✓✓	✓✓	✓
Production of Λ_b, B^0_s, B_c^+	✓✓✓	✓✓✓	X

Measurement of quark couplings

CKM matrix

Unitary triangle

Why semileptonic measurements, inclusive vs. exclusive

Lepton universality

CKM matrix

The CKM matrix determines the coupling of the W boson to the quarks

- Provides the majority of the free parameters in the Standard Model
- Just as essential a part of the Higgs coupling as the mass of the quarks

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \sim \begin{pmatrix} 0.97 & 0.23 & 0.004 \\ 0.23 & 1.00 & 0.04 \\ 0.008 & 0.04 & 1.00 \end{pmatrix}$$

CKM matrix

The CKM matrix is unitary which gives six constraints of the type

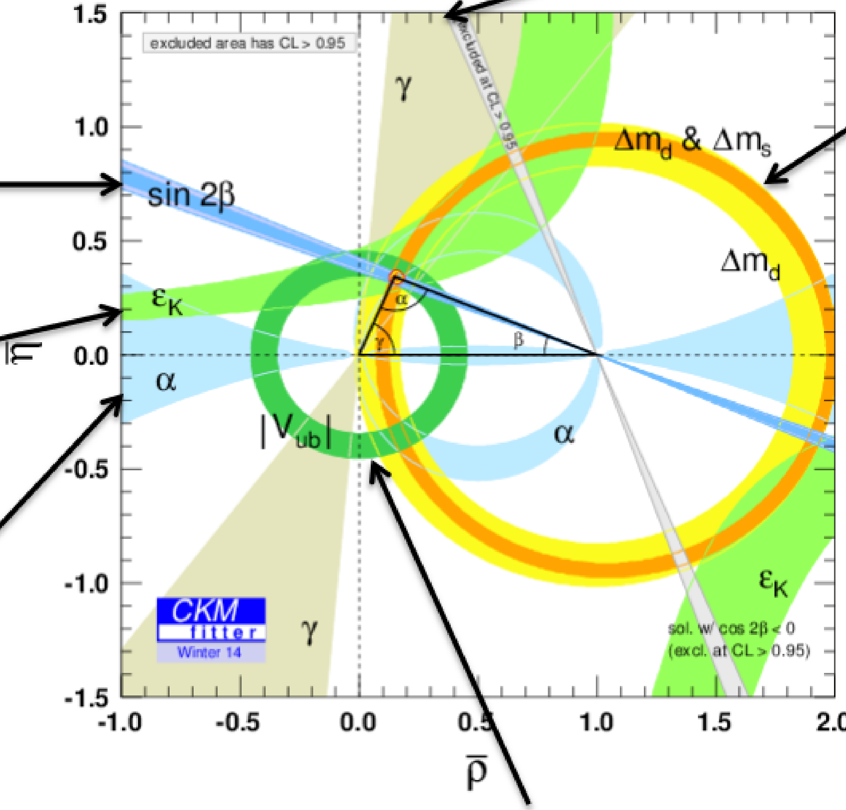
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

Draw a sketch of the 6 triangles

What about their areas?

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \sim \begin{pmatrix} 0.97 & 0.23 & 0.004 \\ 0.23 & 1.00 & 0.04 \\ 0.008 & 0.04 & 1.00 \end{pmatrix}$$

CKM matrix



CPV in B decays

rate of $B^0_{(s)}$ mixing

CPV in B^0 mesons

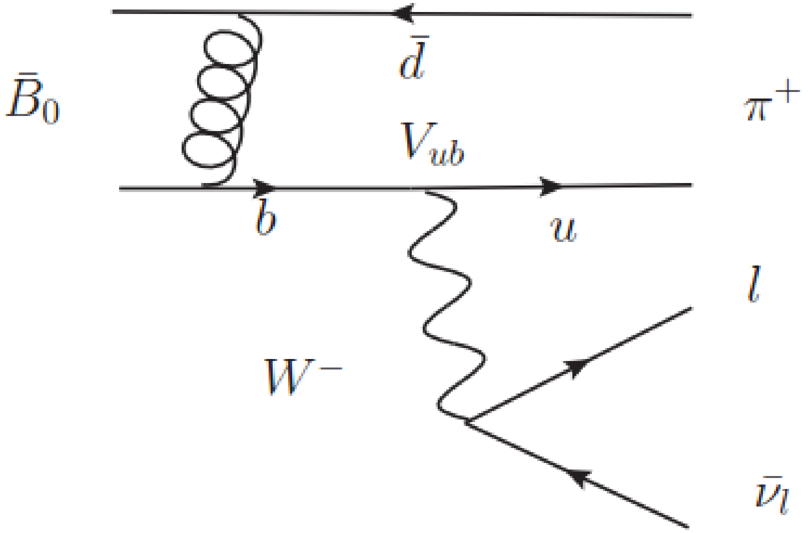
CPV in kaons

CPV in B decays

rate of suppressed B decays

Measuring V_{ub}

Use so-called 'semi-leptonic' decays to make $|V_{ub}|$ measurements



Having a ground state hadron, such as a pion, is useful to control theoretical uncertainties.

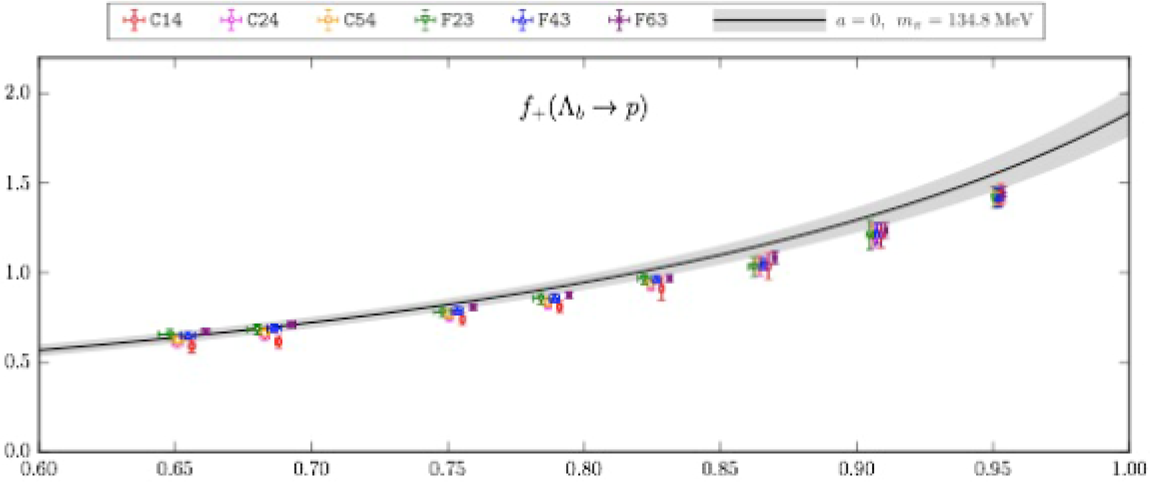
$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 |V_{ub}|^2 p_\pi^3}{24\pi^3} |f^+(q^2)|^2 \leftarrow$$

QCD part encompassed by form-factor.

Measuring V_{ub}

- Always measure product of $|V_{ub}|$ and form factors.
- Rely techniques such as Lattice QCD to calculate latter.
- Lattice QCD works by discretising space-time, with lattice spacing, a.
- Uncertainties best with momentum << cutoff (1/a)

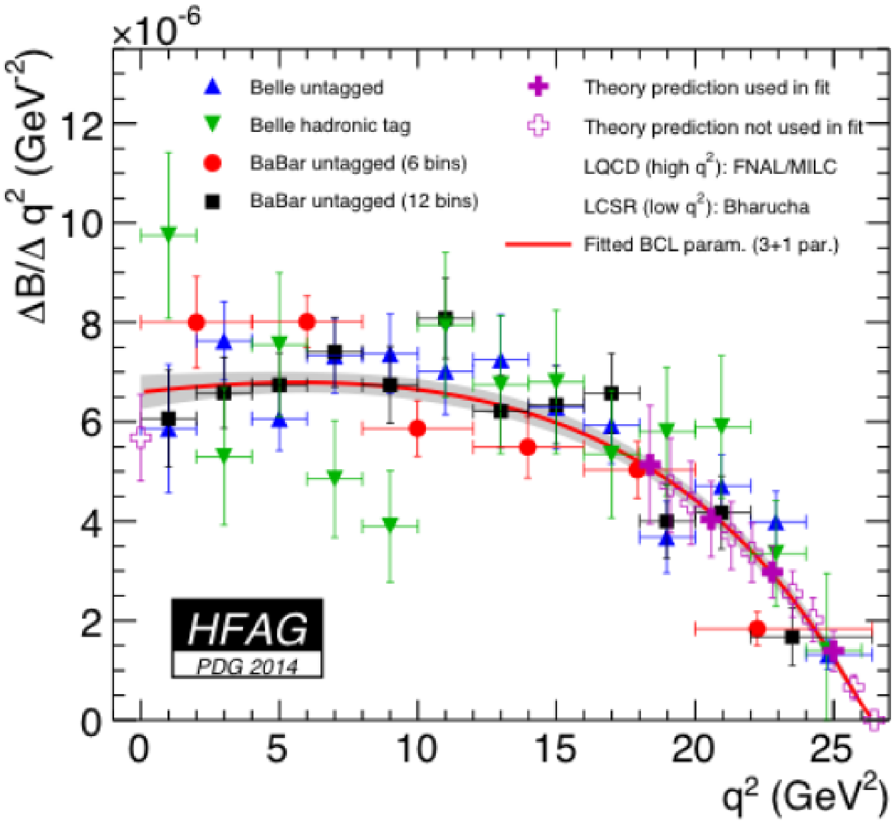
Example of form factor from [1].



[1] W. Detmold, C. Lehner, S. Meinel, arXiv:1503.01421

Measuring V_{ub} (exclusive)

Historically measurement performed exclusively with $B^0 \to \pi^- l^+ \nu$

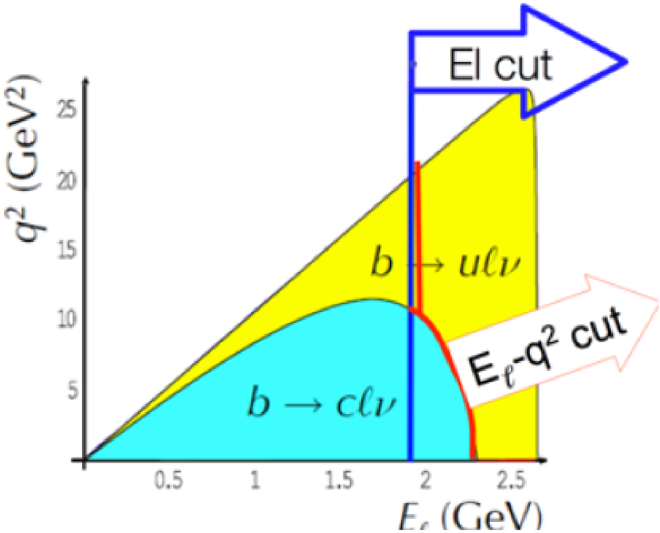


- Simultaneous fit to experimental and lattice data yields:

$$|V_{ub}| = (3.28 \pm 0.29) \times 10^{-3}$$

Measuring V_{ub} (inclusive)

- Forget about form factors, just measure all $b \to u\ell\nu$
- Experimentally very difficult, need fiducial cut to remove large V_{cb} background.
- Efficiency of this fiducial cut introduces model dependence, and drives systematic uncertainty.



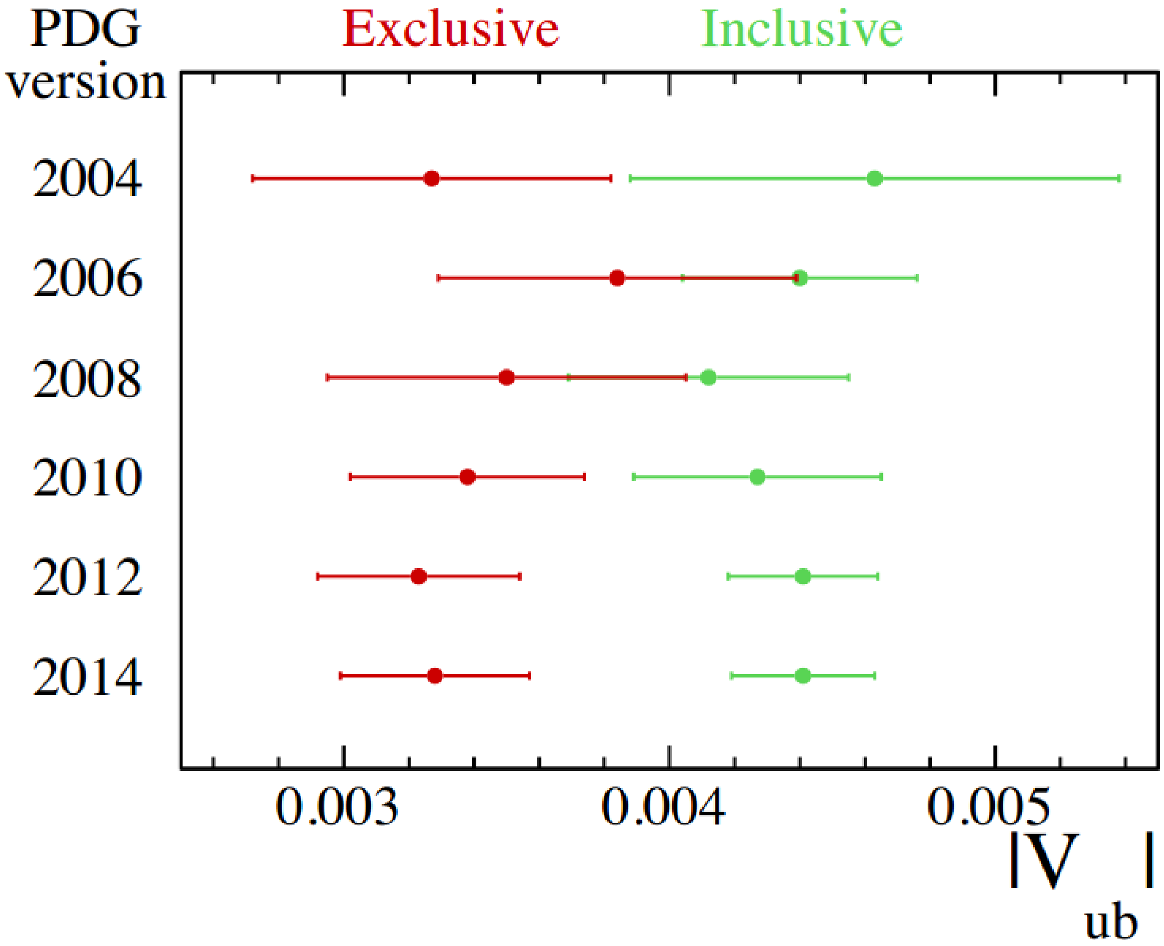
Measurement found to be:

$$|V_{ub}| = (4.41 \pm 0.15 \, {}^{+\,0.15}_{-\,0.17}) \times 10^{-3}$$

Doesn't agree with exclusive determination at all.

Measuring V_{ub}

The exclusive and inclusive Vub measurements have long history of disagreement

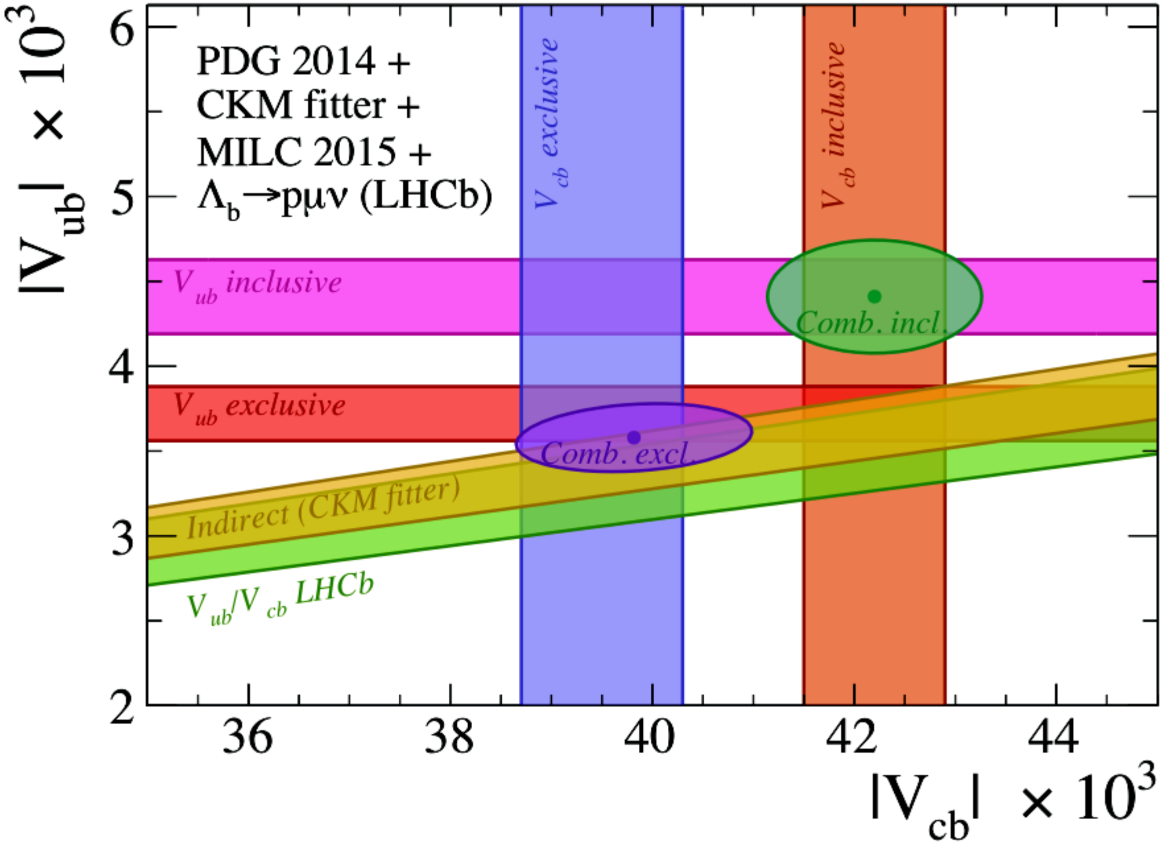


V_{ub} analysis in LHCb

See separate slides ...

CKM matrix elements (incl. vs excl.)

Combining the new LHCb measurement with existing measurements of $|V_{cb}|$ and $|V_{ub}|$ enhance discrepancy between inclusive and exclusive measurements



Lepton non-universality

Lepton universality is one of the corner stones of the Standard Model

- But it is an “accidental” symmetry. Could easily be broken in New Physics models.

Only theoretical uncertainty in ratios of semileptonic decays is from different masses of quarks

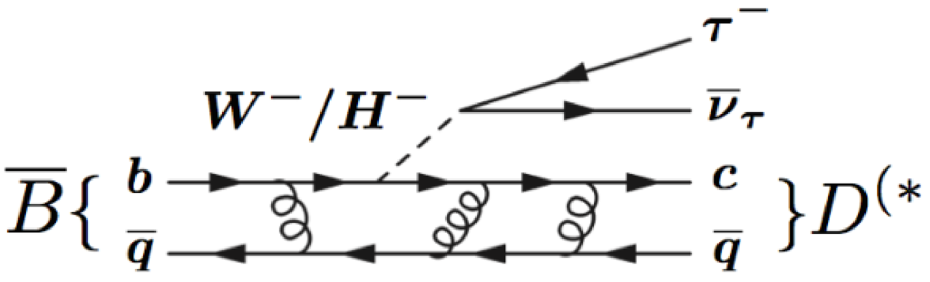
- Z decays tested lepton universality at the per-mille level
- Heavy flavour decays test e-μ universality in B→Klν at the 5% level

For μ-τ universality to constraints are poorer

- In charm, a single constraint by BF($D_s^+ \to \tau^+\nu$)/BF($D_s^+ \to \mu^+\nu$) at 10% level

Lepton universality

Lepton universality can be checked in semileptonic B decays



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

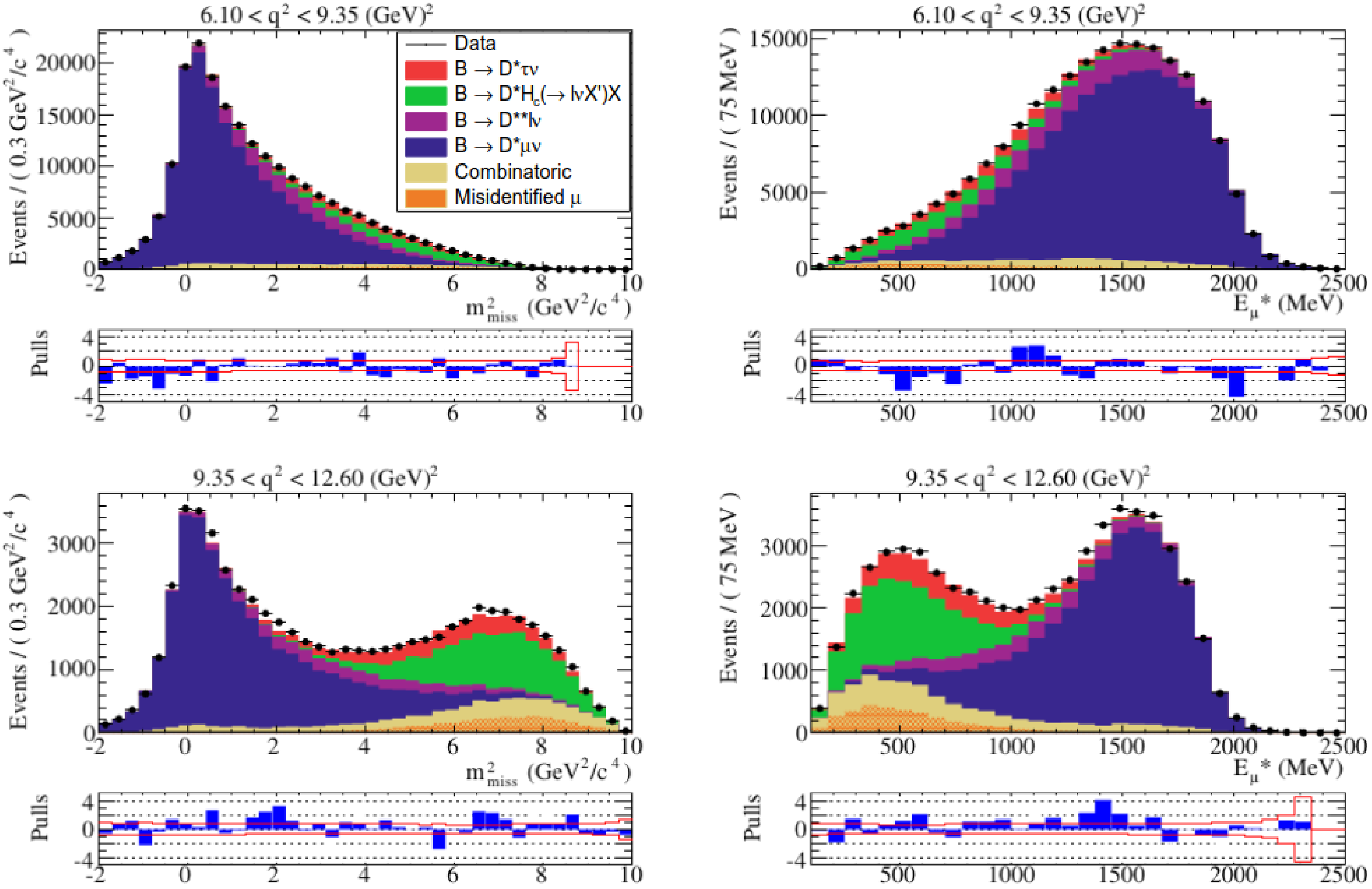
To look for τ decays is a particular challenge

- Using $\tau^-\to\mu^-\bar{\nu}_\mu\nu_\tau$ we get 3 neutrinos in final state
- Using $\tau^-\to\pi^-\pi^+\pi^-\nu_\tau$ we emulate decays like $D_s^-\to K^-\pi^+\pi^-$
  - Compare PDG entries for τ- and Ds-

Lepton universality

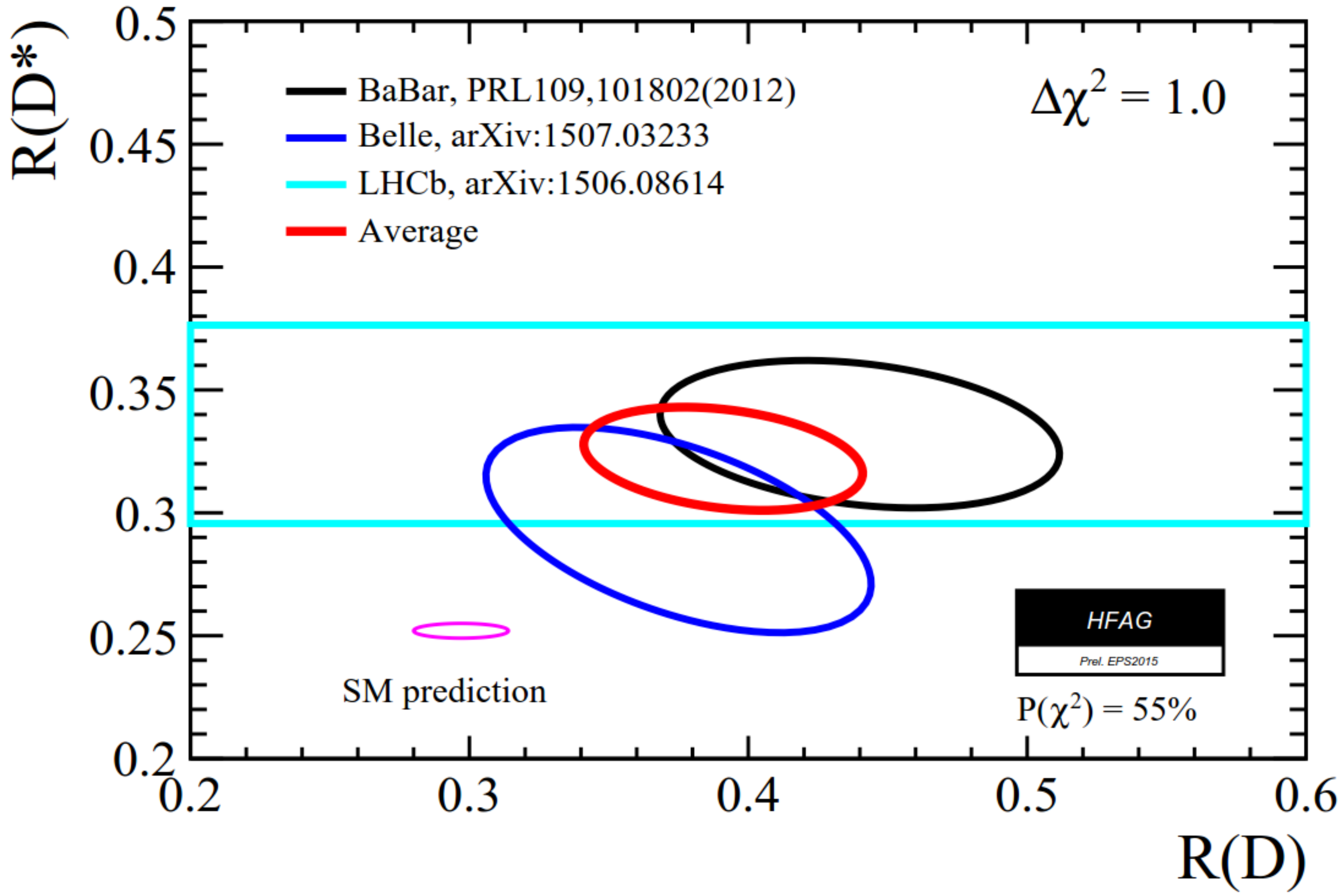
LHCb $B^+ \rightarrow D^{*+} \tau \nu$ result

Phys. Rev. Lett. 115 (2015) 112001



$B^+ \to D^{(*)+} \tau \nu$ global fit

The measurements are internally consistent and have a 4σ tension with SM prediction



Direct CP violation

- Direct CPV is a difference in decay rate $B \to f$ and $\bar{B} \to \bar{f}$
- Consider the decay amplitude, A^P and its CP conjugate $\bar{A}^P$:

$$A^P = |A^P| e^{\delta_S^P} e^{\delta_W^P}$$

Weak phase

Strong phase

- With only one decay route, A^P, $A^P = \bar{A}^P$.

Direct CP violation

- With two decay routes P and T:

$$A = A^P + A^T = |A^P|\delta_S^P\delta_W^P + |A^T|\delta_S^T\delta_W^T$$

- Then taking the difference in rates:

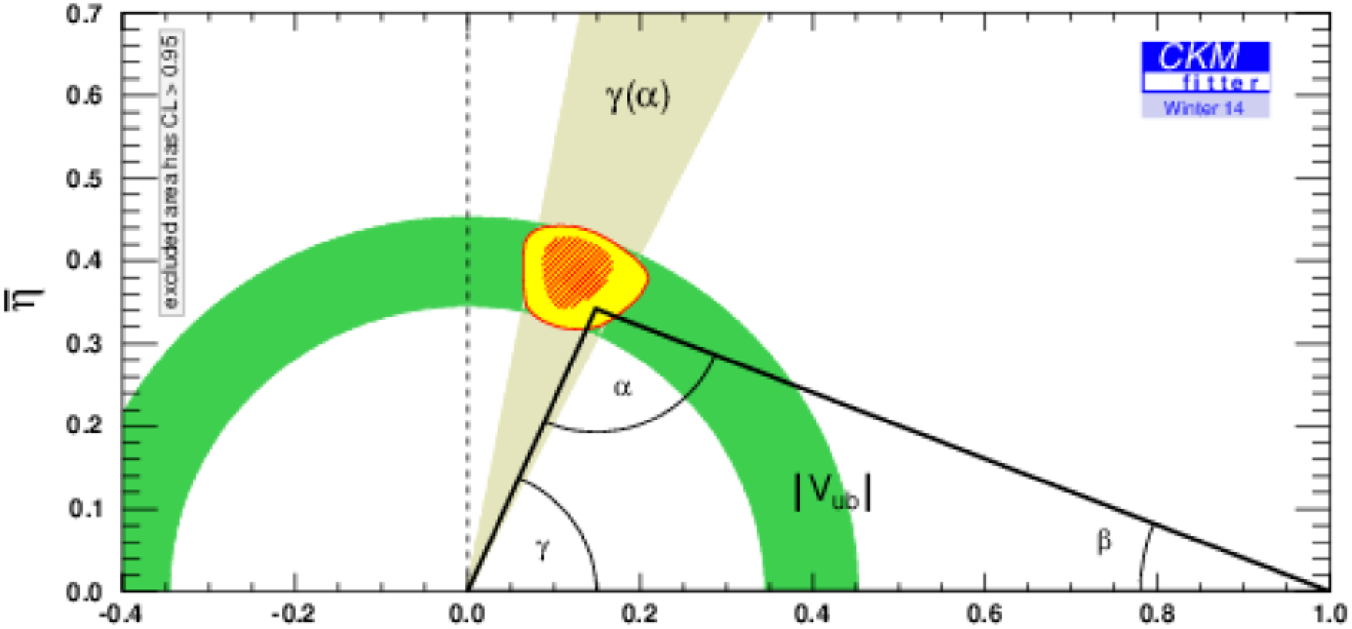
$$|A|^2 - |\bar{A}|^2 = -4|A^P||A^T|\sin(\delta_{\mathrm{S}}^{\mathrm{P}} - \delta_{\mathrm{S}}^{\mathrm{T}})\sin(\delta_{\mathrm{W}}^{\mathrm{P}} - \delta_{\mathrm{W}}^{\mathrm{T}})$$

- So if the strong and weak phase of the two decay routes are different, get direct CPV.
  - Size of CPV depends on relative strengths and phase differences between the two routes.

CP angle γ

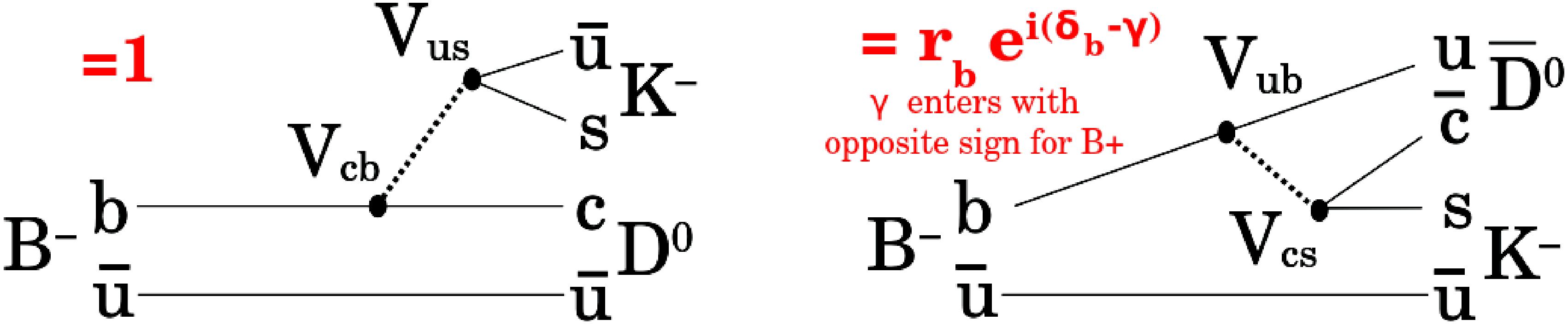
The biggest current challenge is to measure the angle γ

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



CP angle γ

Main measurement is from direct CP violation where there is interference between V_{ub} and V_{cb} diagrams



=1

$= r_b \, e^{i(\delta_b - \gamma)}$

γ enters with opposite sign for B+

Need final state of charm decay that is shared between D^0 and $\bar{D}^0$ like $K^-\pi^+$

- Amplitude of $\bar{D}^0 \rightarrow K^-\pi^+$ suppressed by r_{DCS}

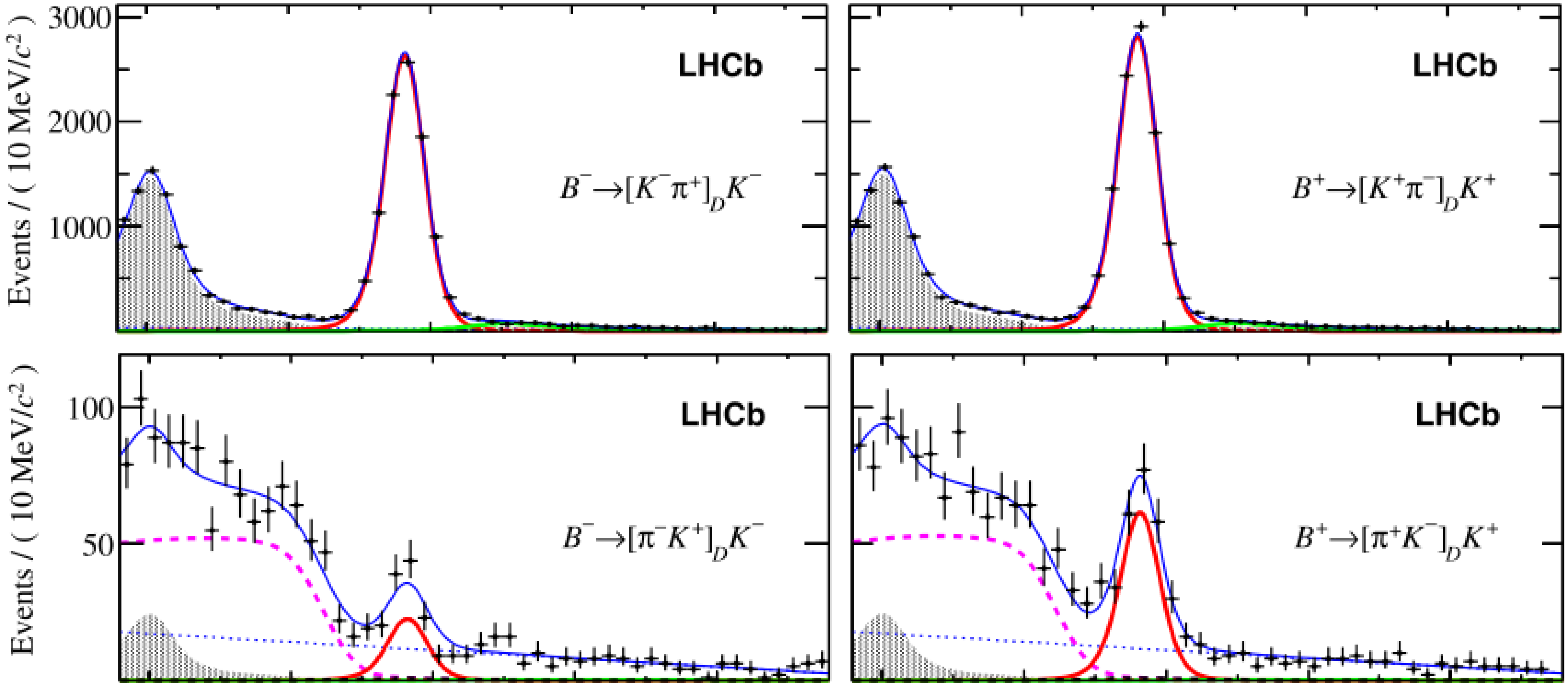
Try to write down amplitude of all four decays

- $B^- \rightarrow K^- (K^\pm \pi^\mp)$ and charge conjugate

CP angle γ

Measurement in LHCb

Physics Letters B 760 (2016) 117



CP violation in mixing

Very much suppressed in B decays as $\Delta\Gamma_d$ is tiny

$$a_{\rm sl}^d \equiv \frac{\Gamma(\bar{B}^0 \to f) - \Gamma(B^0 \to \bar{f})}{\Gamma(\bar{B}^0 \to f) + \Gamma(B^0 \to \bar{f})} \approx \frac{\Delta\Gamma_d}{\Delta m_d} \tan\phi_d^{12}$$

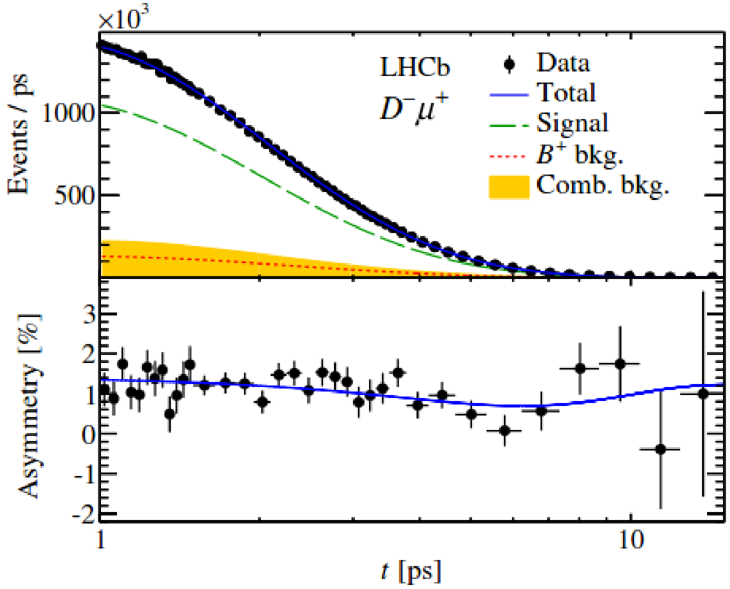
Requires flavour tagging

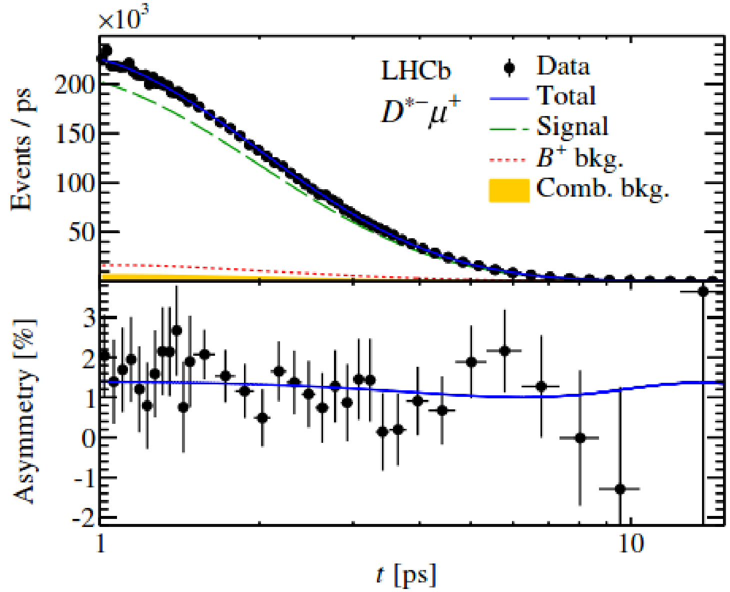
- Can instead look at untagged rate to f and $\bar{f}$

$$N(t) \propto e^{-\Gamma_d t}\left[1 + \zeta A_D + \zeta\frac{a_{\rm sl}^d}{2} - \zeta\left(A_P + \frac{a_{\rm sl}^d}{2}\right)\cos\Delta m_d t\right]$$

+1 for f, -1 for $\bar{f}$

Will look at this in detail in problem this afternoon





CP violation in interference

Looking at $B^0_{(s)}/\overline{B}^0_{(s)}$ decaying into a CP eigenstate

- Measuring this in $B^0 \rightarrow J/\psi K^0_s$ decays was the reason for building the BaBar and BELLE experiments

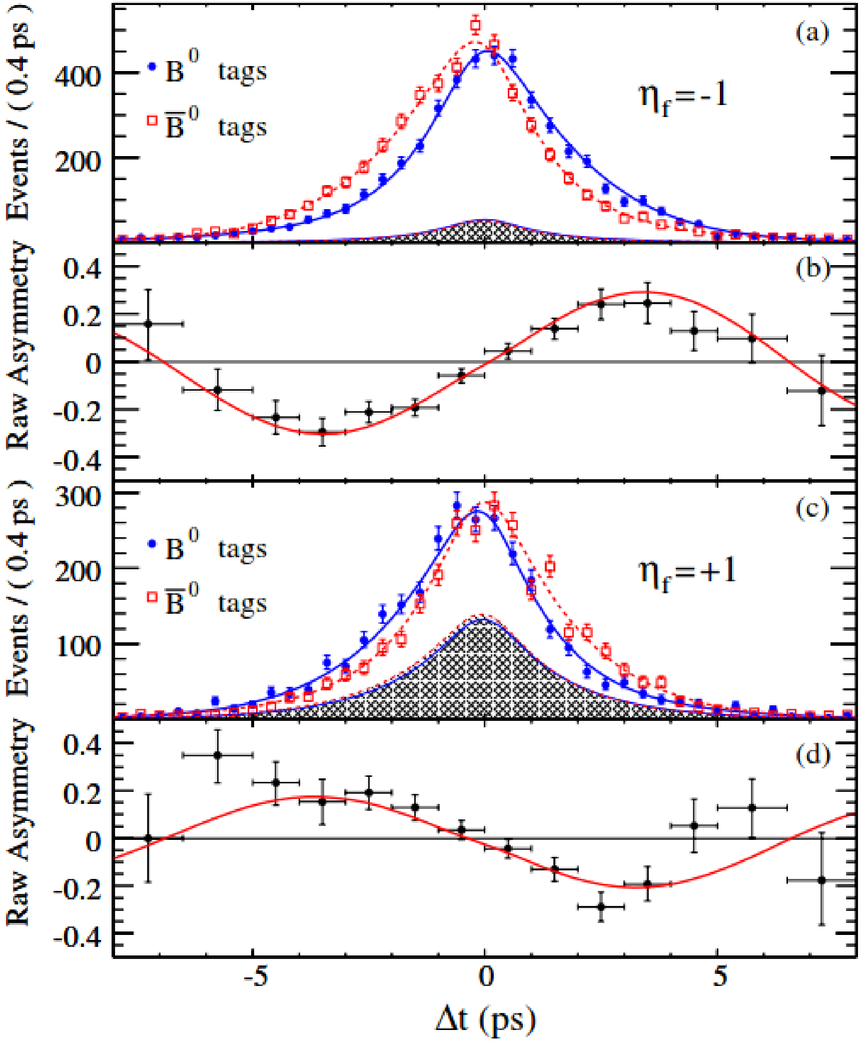
$$g_\pm(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\{(1 \mp \Delta w) \pm (1 - 2w) \times [S_f \sin(\Delta m_d \Delta t) - C_f \cos(\Delta m_d \Delta t)]\}$$

where

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

How can we have negative times?

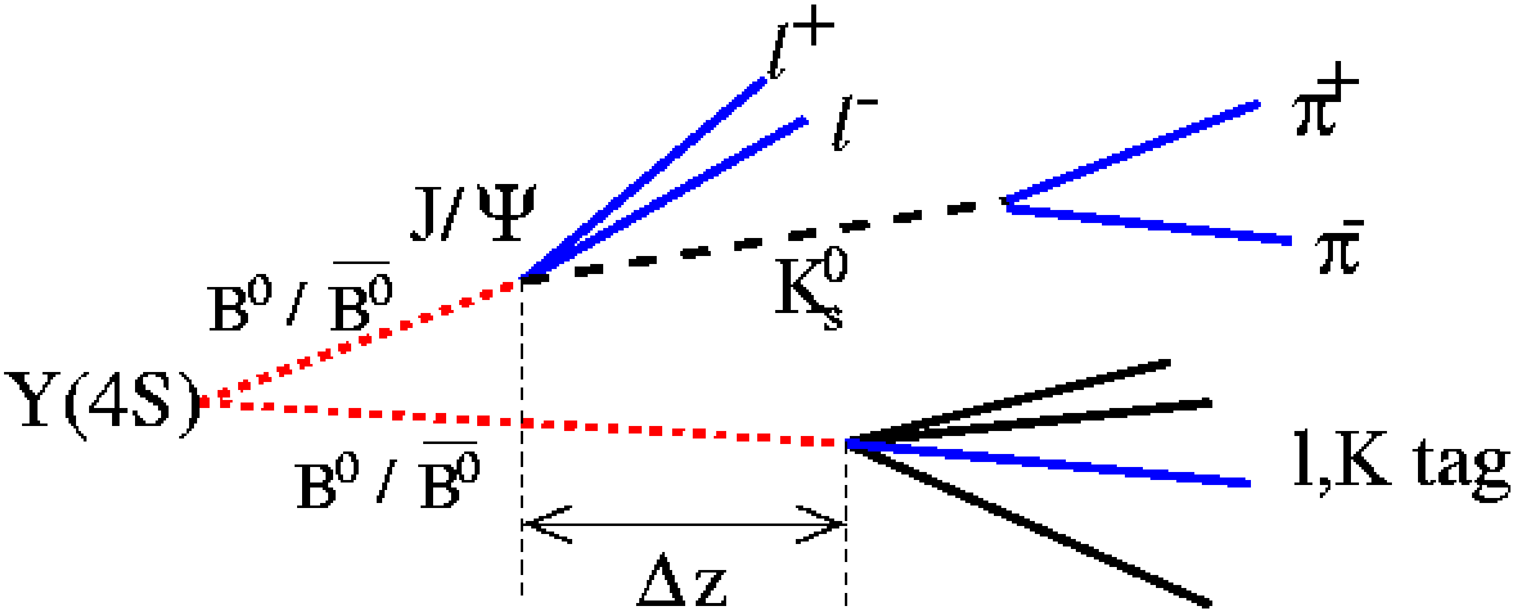
PHYSICAL REVIEW D **79**, 072009 (2009)



CP violation in interference

With production from Y(4S) resonance and asymmetric collision is required

- The B^0 and $\overline{B}^0$ are produced in a coherent state

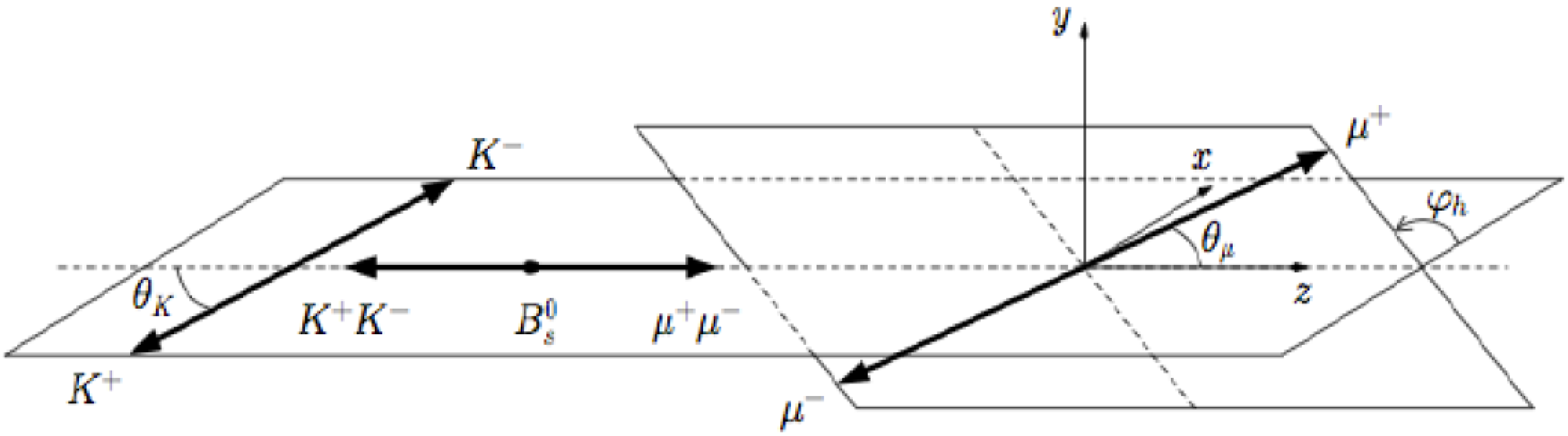


CP violation in interference

- At a hadron collider we can look for the same thing in B0s decays
  - The Standard Model prediction is for a very small CP violation
  - Anything larger would be a sign of New Physics
- Look at $B^0_s \rightarrow J/\psi\ \varphi$ decay
  - Complication in that the φ is a vector
    - We have a mixture of CP-even and CP-odd final states
    - We have to disentangle this through an angular analysis

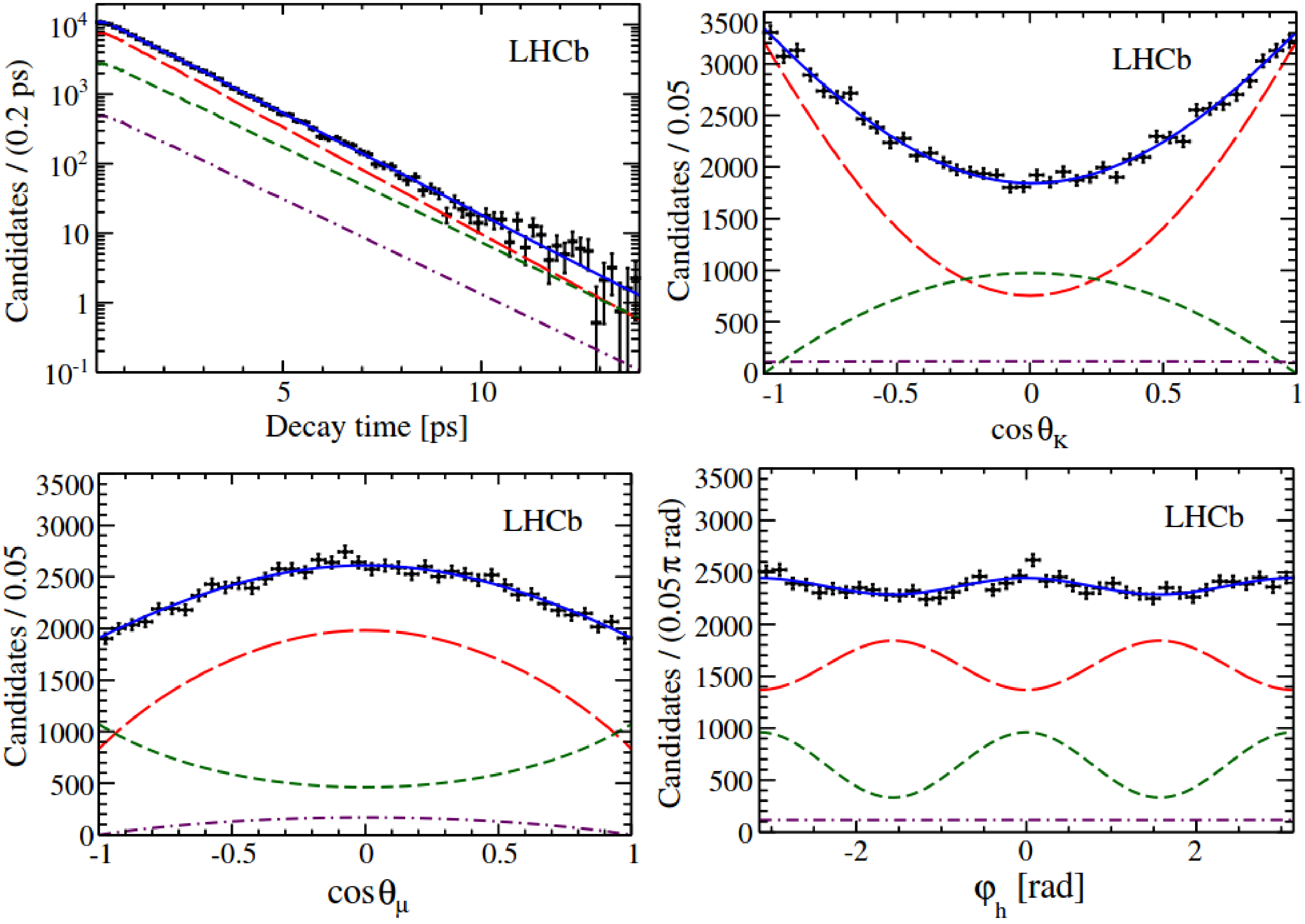
CP violation in interference

Have to consider the decay as a function of 3 angles and the K^+K^- mass



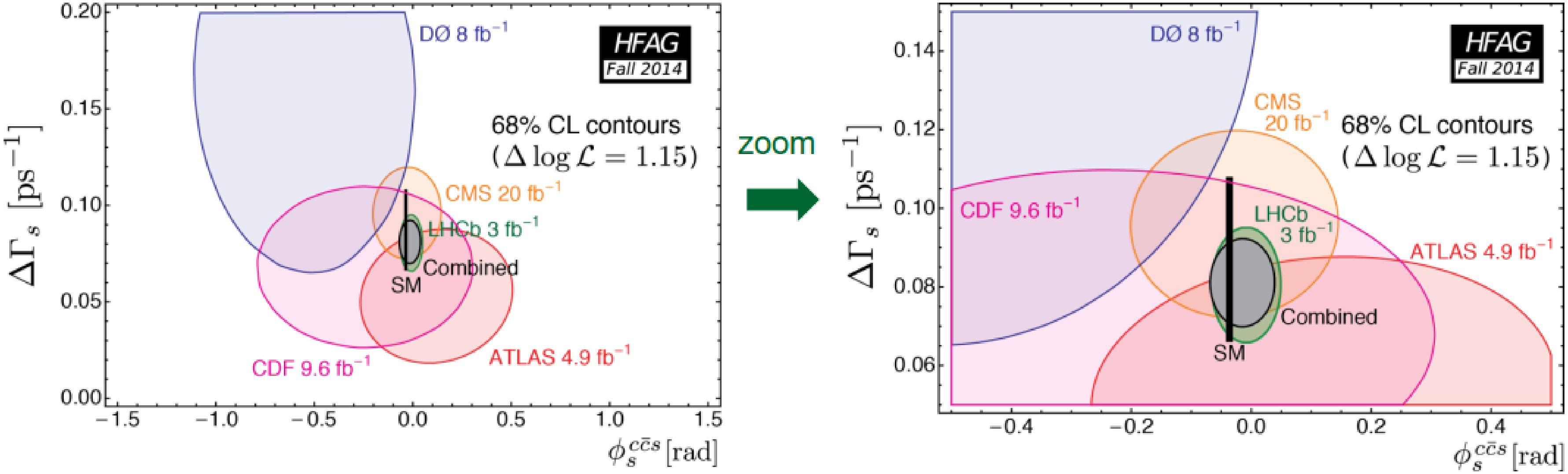
CP violation in interference

PRL **114**, 041801 (2015)



No heavy flavour *CP* violation anomalies?

But there is still plenty of scope for NP to show up in B^0_s oscillations



The theoretical uncertainty is still very small compared to experimental uncertainty

The Operator Product Expansion

- Make an *effective theory* which gives us *model independent things to measure*
  - Rewrite (part of) SM Lagrangian as:

$$L = \sum_i C_i O_i$$

  - "Wilson Coefficients" C_i
    - Describe the short distance part, can compute perturbatively in a given theory
    - Integrate out the heavy degrees of freedom that can't resolve at some energy scale μ → Wilson coefficient just a (complex) number
    - All degrees of freedom with mass>μ are taken into account by the Wilson Coefficients, while those with mass<μ go into the operators ...
  - "Operators" O_i
    - Describe the long distance, non-perturbative part involving particles below the scale μ
    - Form a complete basis – can put in all operators from NP/SM
    - Account for effects of strong interactions and are *difficult to calculate reliably*

Wilson Coefficients

- Can be computed perturbatively in SM and in NP models
- If we were able to calculate the full perturbative series then the dependence of our Hamiltonian on μ would fall out... this is never the case in practice and the residual scale dependence introduces some theoretical error
- For β decays $\mu \sim m_W$
- For K decays $\mu \sim 1$ GeV (below the c-quark mass)
  - info. about diagrams with a c-quark or some NP particle that is heavier than 1 GeV is in the Wilson Coefficient
- For B decays $\mu \sim m_b$ (above the c-quark mass)
  - info. about diagrams with a top quark or some NP particle that is heavier than b-quark is in the Wilson Coefficient

OPE in the Weak Sector

- When applied to the weak sector of SM (where we might expect NP to appear to sort out lots of the stuff we don't understand) we find:

$$\mathrm{L}_{\mathrm{eff}} = \mathrm{L}_{\mathrm{QCD}\times\mathrm{QED}} + \frac{4G_F}{\sqrt{2}} \mathrm{V}_{\mathrm{CKM}} \sum_i C_i Q_i$$

  - The scale μ (which for the SM is m_W) has been absorbed into the Wilson coefficients
  - CKM-matrix elements are factorised out

- Effective Wilson Coefficients
  - While e.g. $b \to s\gamma$ process is dominated by O_7 operator, get higher order contributions from other operators – hide this by absorbing these contributions st $C_7 \to C_7^{\mathrm{eff}}$

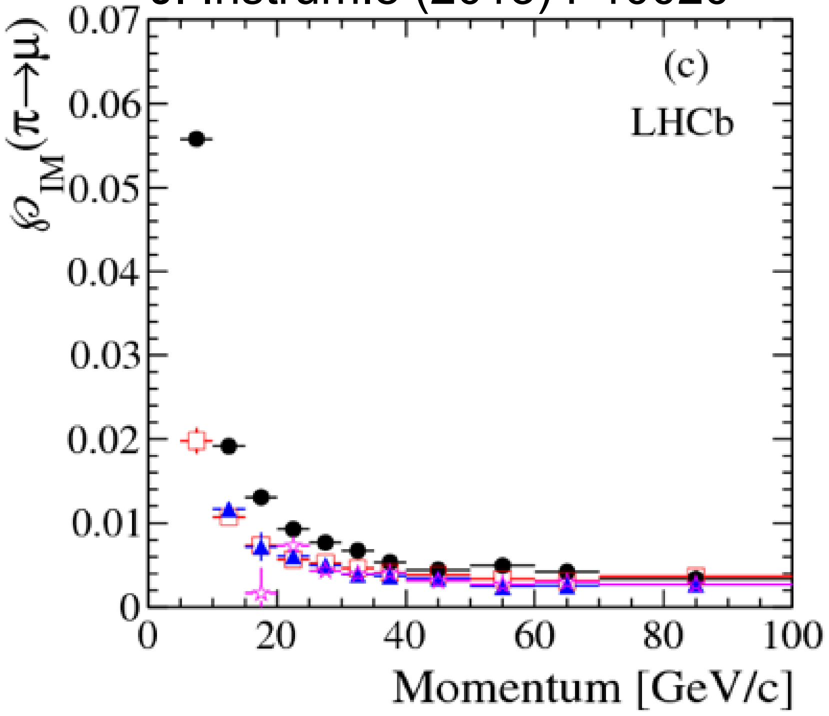
How do we get information from rare decays?

- We use the Operator Product Expansion:
  - New particles at masses above scale μ only contribute to the Wilson Coefficients
  - If we measure those Wilson Coefficients we can see if there's other (virtual) non-SM contribution in the loop processes [or if the SM particles couple in some non-SM way]
  - In NP models the Wilson Coefficient can be computed perturbatively, hence you can check experiment against prediction of a given theory
  - Complication: the non-perturbative bit involving the operator e.g. $\langle F|Q_i|K\rangle$ has to be computed and this can have a large theory uncertainty
  - Therefore focus on processes where, for one reason or another, the theory uncertainty on this part is small or cancels... hence observables often involve ratios

Rare decays

- Look at decays which in the SM model can't happen at tree level
  - Flavour changing neutral current decays the largest group
  - NP can enter in at either tree or loop level
  - Decays with dimuons are good candidates for rare searches
    - Rely on excellent muon identification

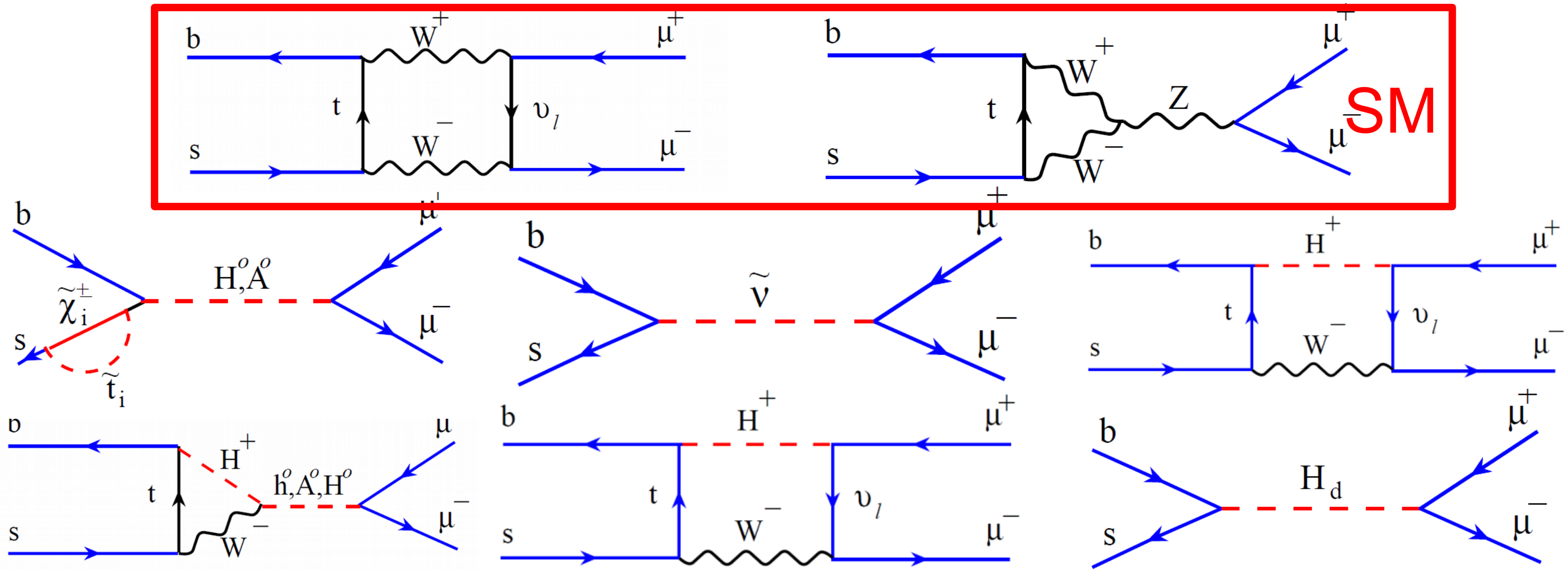
J. Instrum.8 (2013) P10020



$B \rightarrow \mu^+\mu^-$

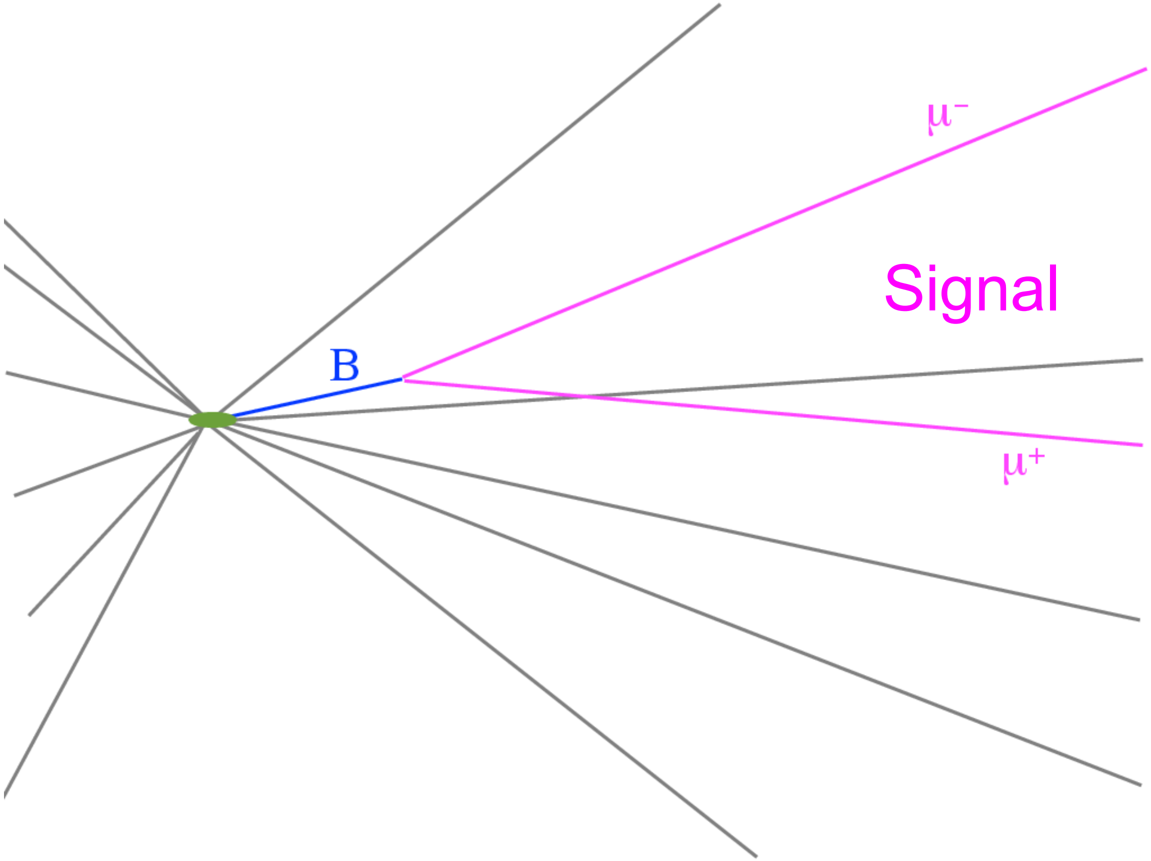
The two very rare decays $B^0_s \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$ have attracted much interest

- Easy to predict SM branching fraction with great precision
  - $BF(B^0_s \rightarrow \mu^+\mu^-)_{SM} = (3.56 \pm 0.18) \times 10^{-9}$ (time averaged)
  - $BF(B^0 \rightarrow \mu^+\mu^-)_{SM} = (0.10 \pm 0.01) \times 10^{-9}$
- Sensitive to the scalar sector of flavour couplings


SM

$B \rightarrow \mu^+\mu^-$

- Topology of decay simple
  - Challenge is to keep trigger and selection efficiency high, while rejecting combinatorial background



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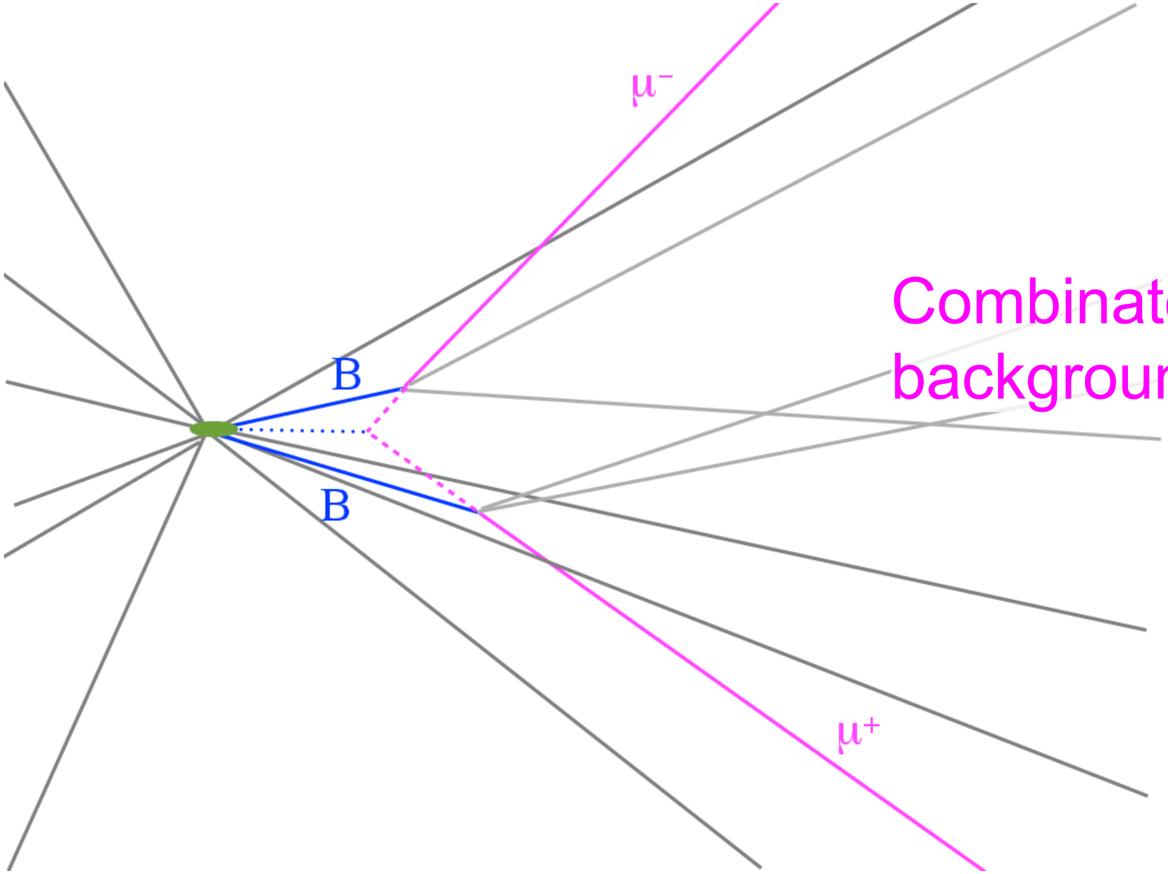


Combinatorial background

$B \rightarrow \mu^+\mu^-$

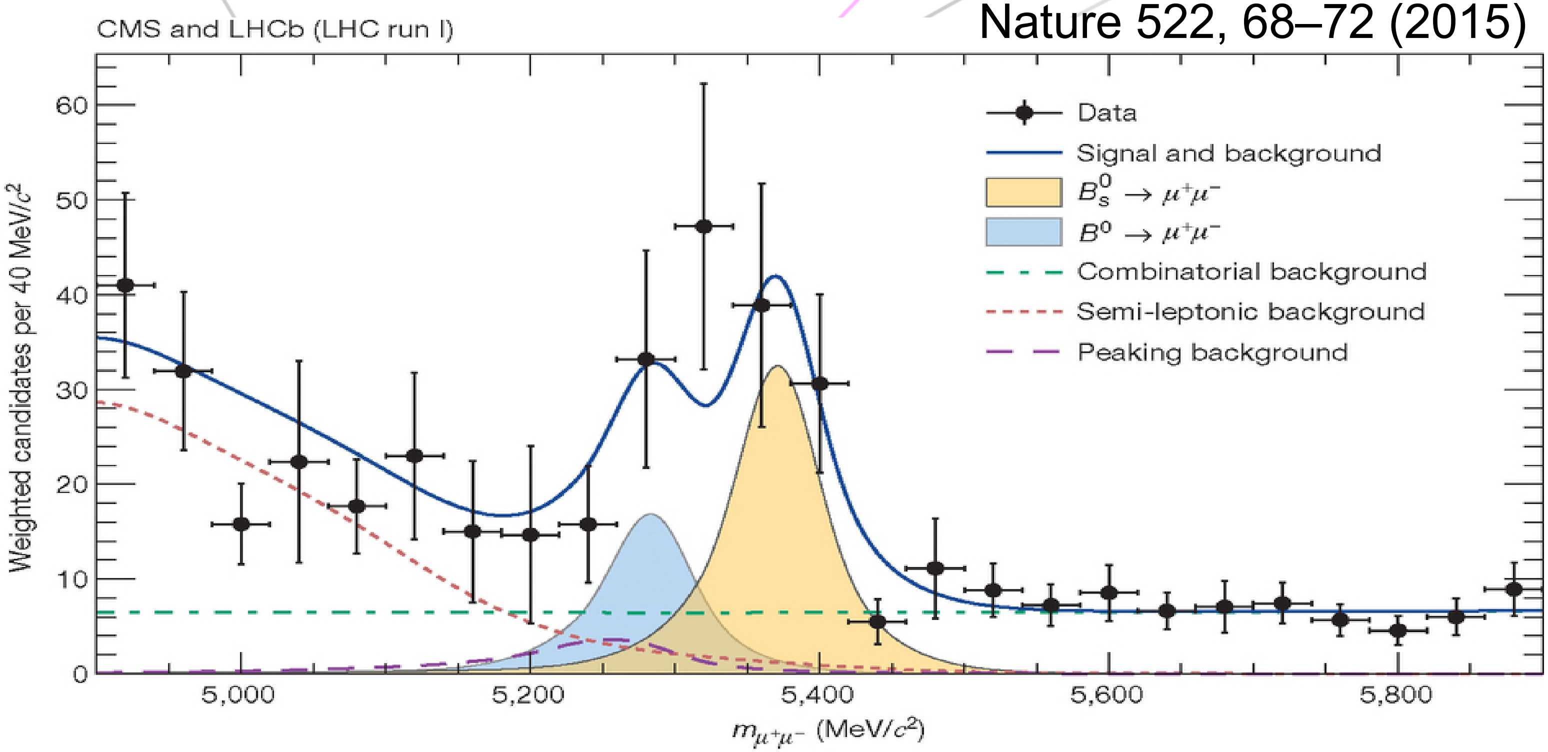
LHCb+CMS combined for observation of $B^0_s \rightarrow \mu^+\mu^-$

$BF = \left(2.8^{+0.7}_{-0.6}\right) \times 10^{-9}$ 6.2σ significant

Evidence for $B^0 \rightarrow \mu^+\mu^-$

$BF = \left(3.9^{+1.6}_{-1.4}\right) \times 10^{-10}$ 3.2σ significant

Nature 522, 68–72 (2015)



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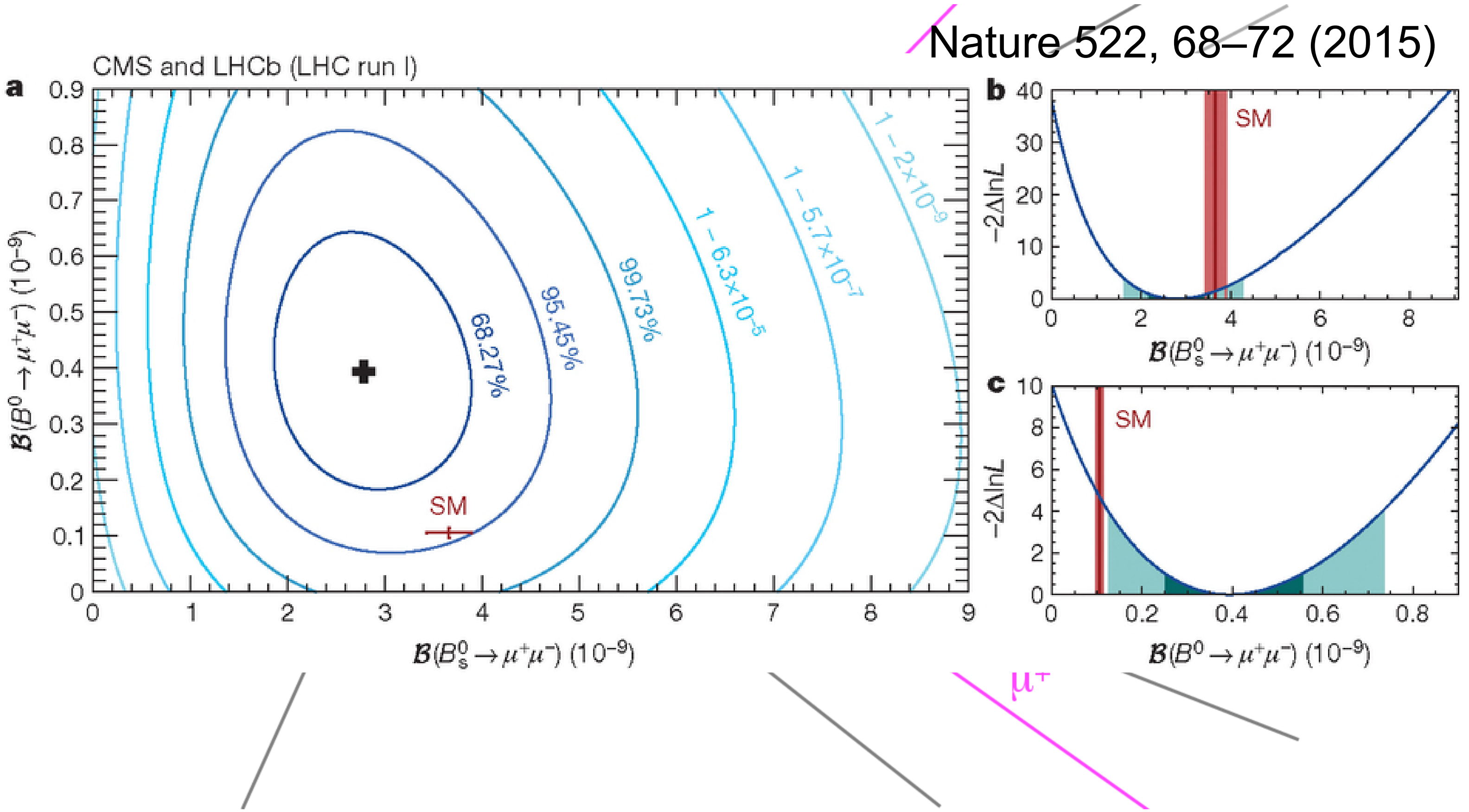

Nature 522, 68–72 (2015)

Papers make it sound so easy ...

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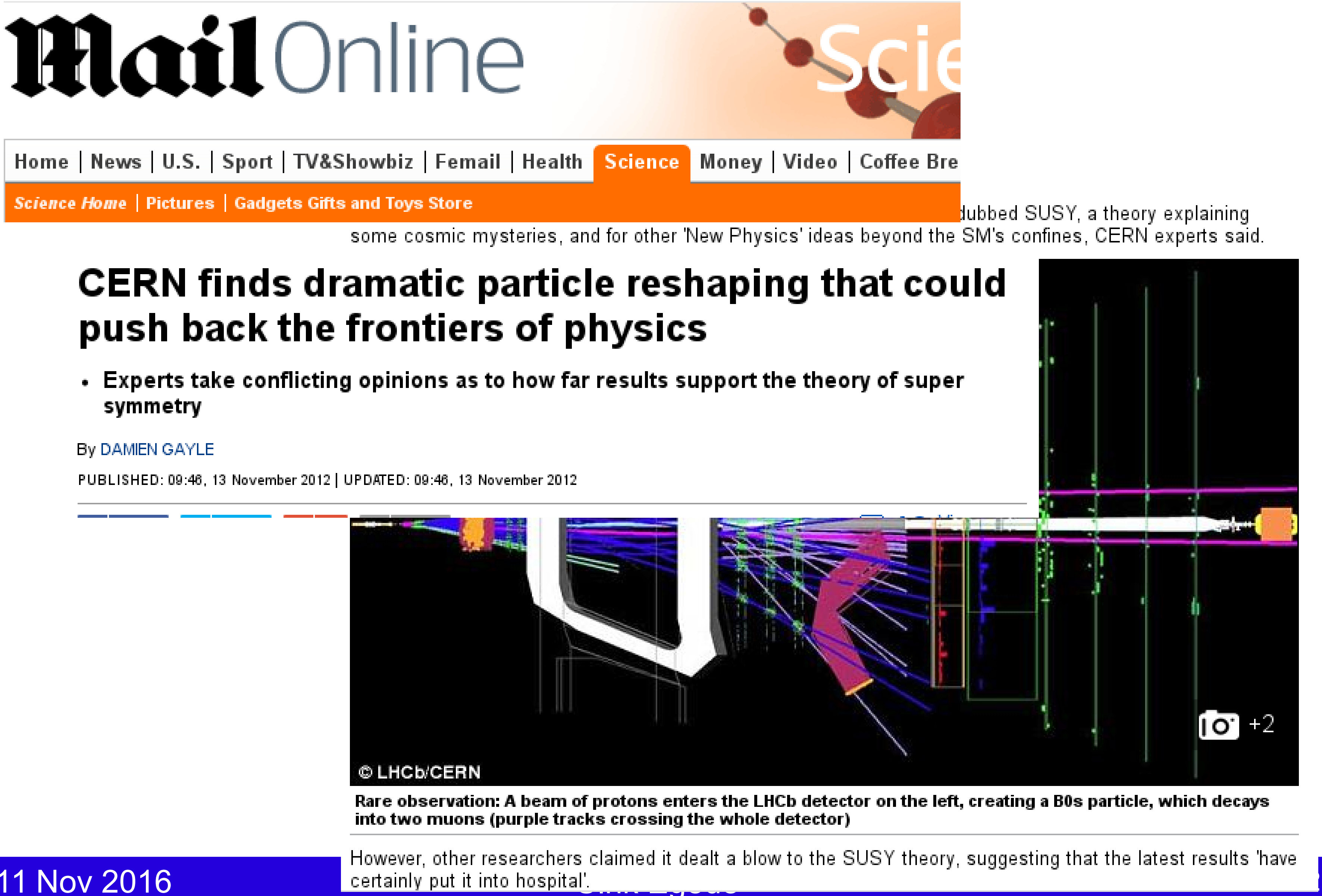

dubbed SUSY, a theory explaining some cosmic mysteries, and for other 'New Physics' ideas beyond the SM's confines, CERN experts said.

CERN finds dramatic particle reshaping that could push back the frontiers of physics

- **Experts take conflicting opinions as to how far results support the theory of super symmetry**

By DAMIEN GAYLE

PUBLISHED: 09:46, 13 November 2012 | UPDATED: 09:46, 13 November 2012

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+2

Rare observation: A beam of protons enters the LHCb detector on the left, creating a B0s particle, which decays into two muons (purple tracks crossing the whole detector)

However, other researchers claimed it dealt a blow to the SUSY theory, suggesting that the latest results 'have certainly put it into hospital'.

Papers make it sound so easy ...

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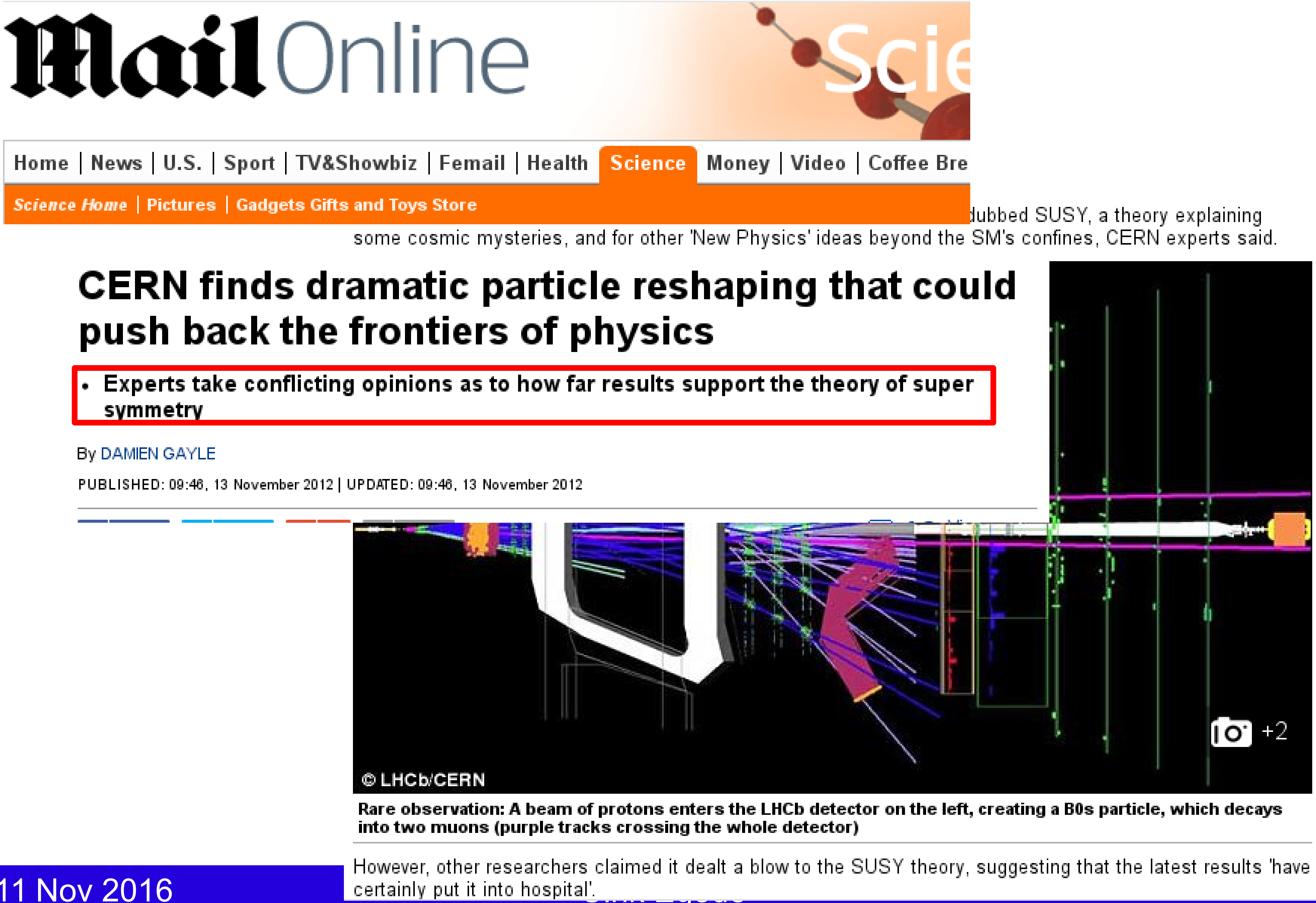

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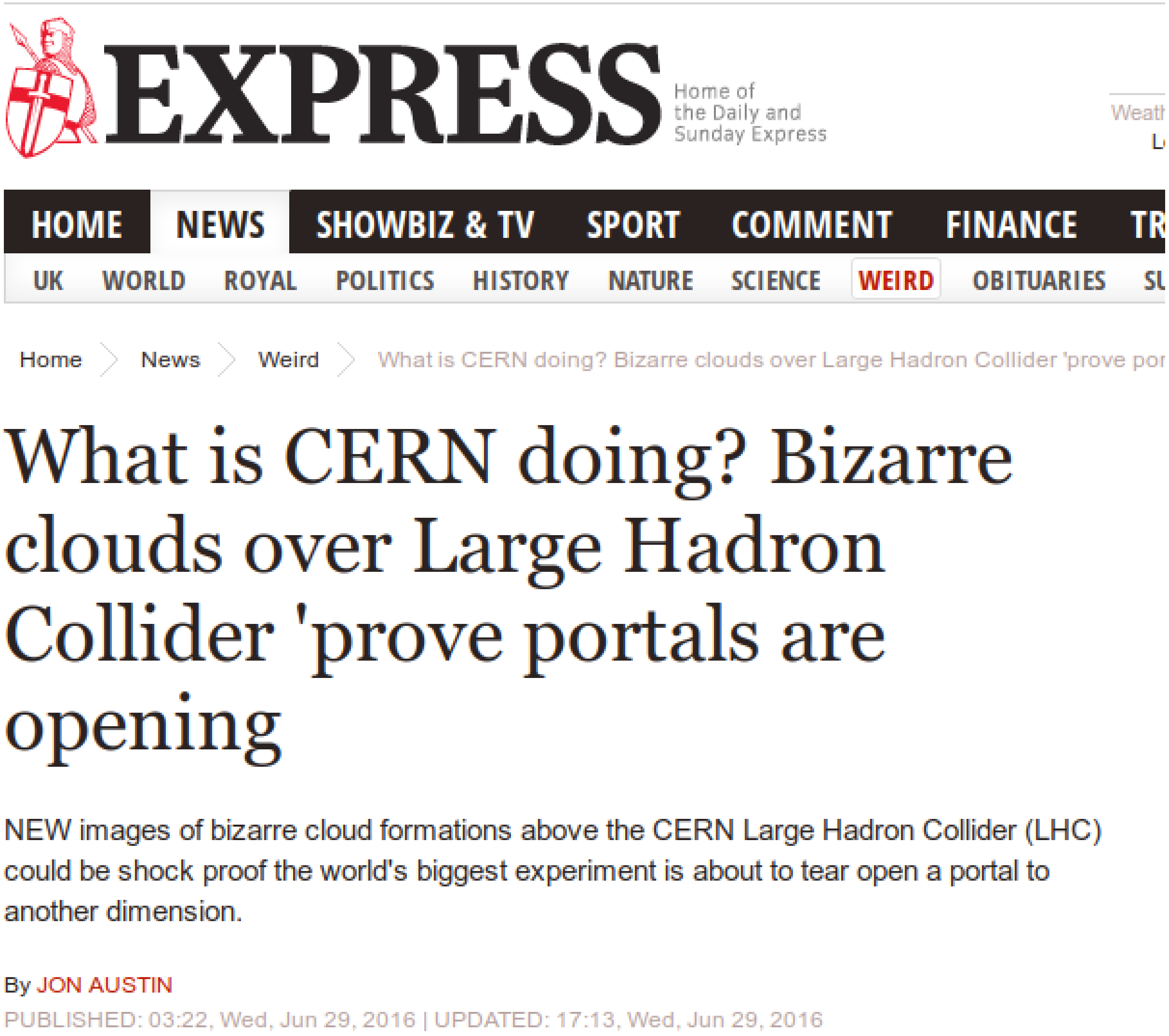
... but are not always quite getting it



What is CERN doing? Bizarre clouds over Large Hadron Collider 'prove portals are opening

NEW images of bizarre cloud formations above the CERN Large Hadron Collider (LHC) could be shock proof the world's biggest experiment is about to tear open a portal to another dimension.

By JON AUSTIN

PUBLISHED: 03:22, Wed, Jun 29, 2016 | UPDATED: 17:13, Wed, Jun 29, 2016

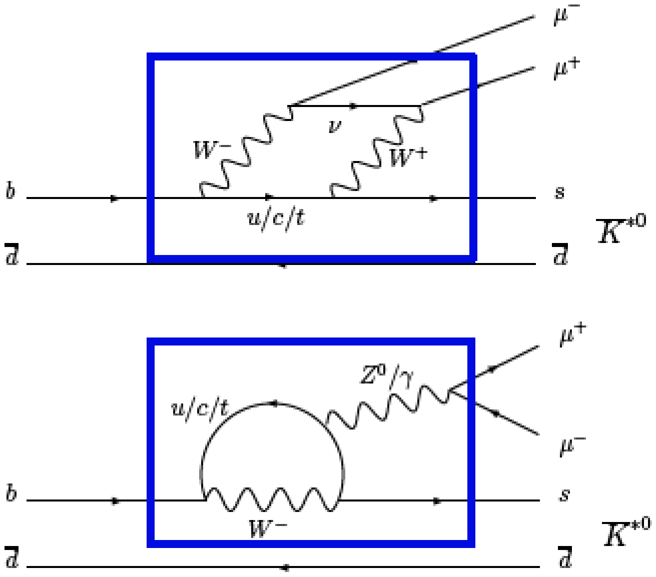
The penguin laboratory

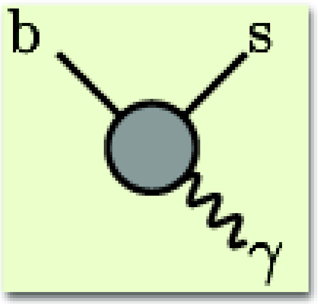
The decay $B^0\to K^{*0}\mu^+\mu^-$, $K^{*0}\to K^-\pi^+$ is in the SM only possible at loop level

On the other hand NP can show up at either tree or loop level

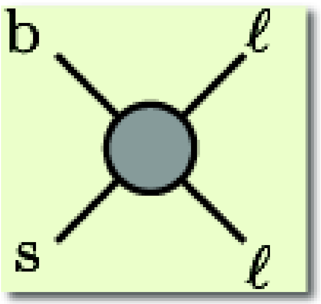
Angular analysis of 4-body $K^-\pi^+\mu^+\mu^-$ final state brings large number of observables

Interference between these





$O_{7\gamma}$



$O_{9,10}$

... and their right-handed counterparts

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

- The Wilson coefficients describe the effective couplings from a higher energy scale
- The matrix element of the decay is controlled by the K^{*0} polarisation amplitudes
  - These are functions of the Wilson coefficients as well as the form factors arising from hadronic effects
    - The form factors can be calculated using light cone sum rules (mainly at low q^2) or lattice QCD (mainly large q^2)

$$A_{\perp}^{L,R} = N\sqrt{2}\lambda^{1/2}\left[\left\{(\mathcal{C}_9^{(\mathrm{eff})} + \mathcal{C}_9^{\prime(\mathrm{eff})}) \mp (\mathcal{C}_{10}^{(\mathrm{eff})} + \mathcal{C}_{10}^{\prime(\mathrm{eff})})\right\}\frac{V(q^2)}{m_B + m_{K^*}} + \right.$$
$$\left. + \frac{2m_b}{q^2}(\mathcal{C}_7^{(\mathrm{eff})} + \mathcal{C}_7^{\prime(\mathrm{eff})})T_1(q^2)\right],$$

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

The angular distribution can be fully described through the coefficients of an expansion in spherical harmonics

$$\frac{\mathrm{d}^4\Gamma[\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-]}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\sum_j I_j(q^2) f_j(\vec{\Omega})$$

$$\frac{\mathrm{d}^4\bar{\Gamma}[B^0 \to K^{*0}\mu^+\mu^-]}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\sum_j \bar{I}_j(q^2) f_j(\vec{\Omega})$$

Which can then form CP averaged quantities and CP asymmetries

$$S_j = \left(I_j + \bar{I}_j\right) \bigg/ \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} + \frac{\mathrm{d}\bar{\Gamma}}{\mathrm{d}q^2}\right)$$

$$A_j = \left(I_j - \bar{I}_j\right) \bigg/ \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} + \frac{\mathrm{d}\bar{\Gamma}}{\mathrm{d}q^2}\right)$$

$B^0 \rightarrow K^{*0}\mu^+\mu^-$ angular analysis

Each of the angular coefficients can be expressed as a sum of bilinears of the K^{*0} polarisation amplitudes

$$I_5 = \Re\mathfrak{e}\left(\mathcal{A}_0^L \mathcal{A}_\perp^{L*} - \mathcal{A}_0^R \mathcal{A}_\perp^{R*}\right)$$

And ratios can be formed where the theoretical uncertainty can be reduced

$$P'_5 = S_5\sqrt{F_L(1-F_L)} \quad , \quad 2F_L \equiv S_{1c}$$

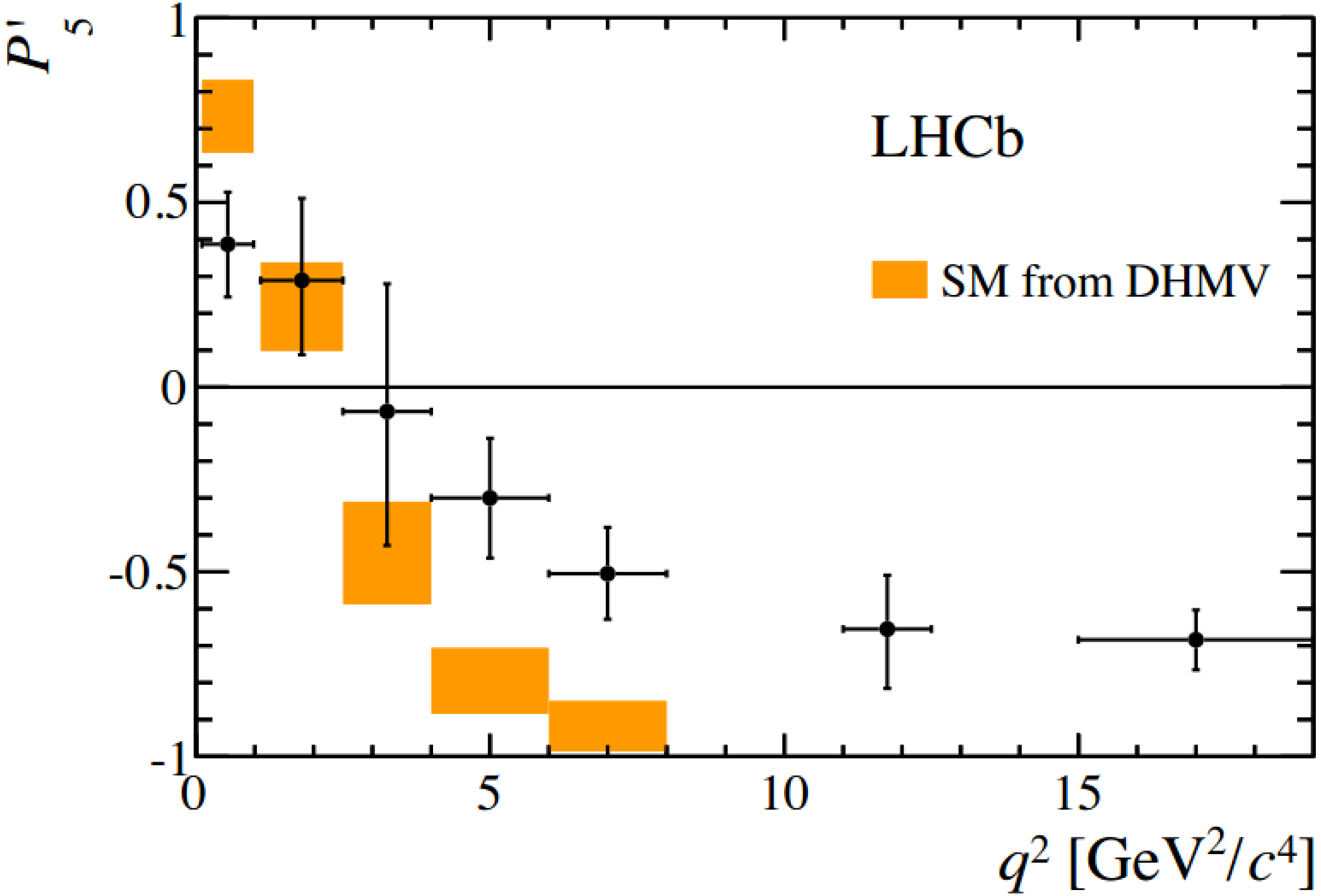
Several observables also have reduced uncertainty of zero points

$$A_{\mathrm{FB}} = \frac{3}{4} S_{6s}$$

LHCb : ArXiv: 1512.04442

$B^0 \rightarrow K^{*0}\mu^+\mu^-$ angular analysis

Results based on 3 fb^{-1} from LHCb

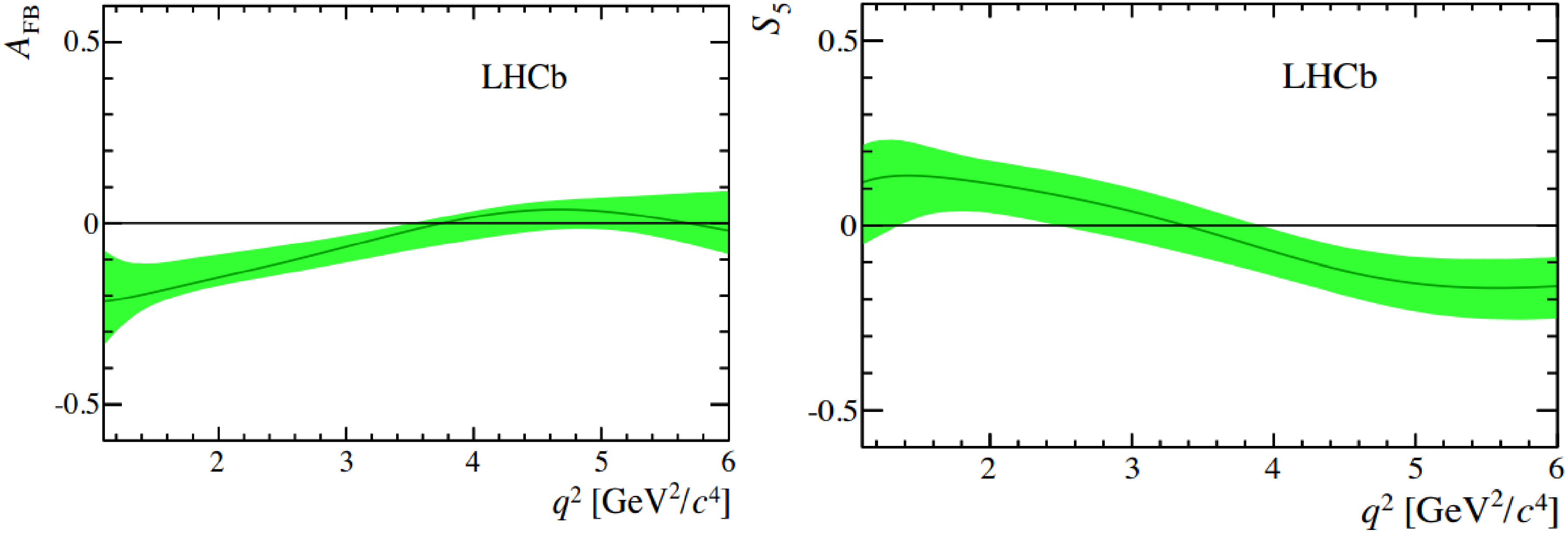


LHCb : ArXiv: 1512.04442

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

Unbinned fit result in region $1<q^2< 6$ GeV^2

See UE, Petridis, Patel (JHEP 06 (2015) 084) for method



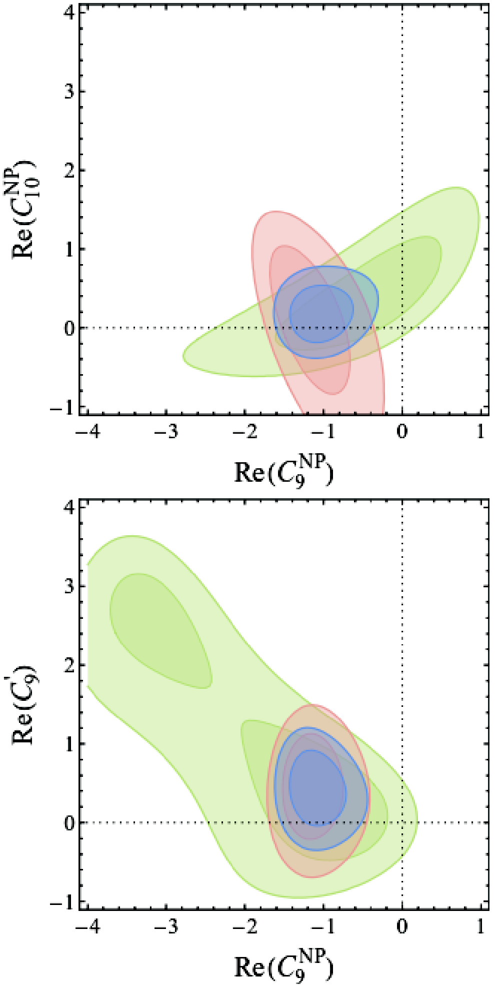
$$q_0^2(S_5) \in [2.49, 3.95]\,\mathrm{GeV}^2/c^4 \quad @\ 68\%\ \mathrm{CL}$$

$$q_0^2(A_{\mathrm{FB}}) \in [3.40, 4.87]\,\mathrm{GeV}^2/c^4 \quad @\ 68\%\ \mathrm{CL}$$

Performing global fits

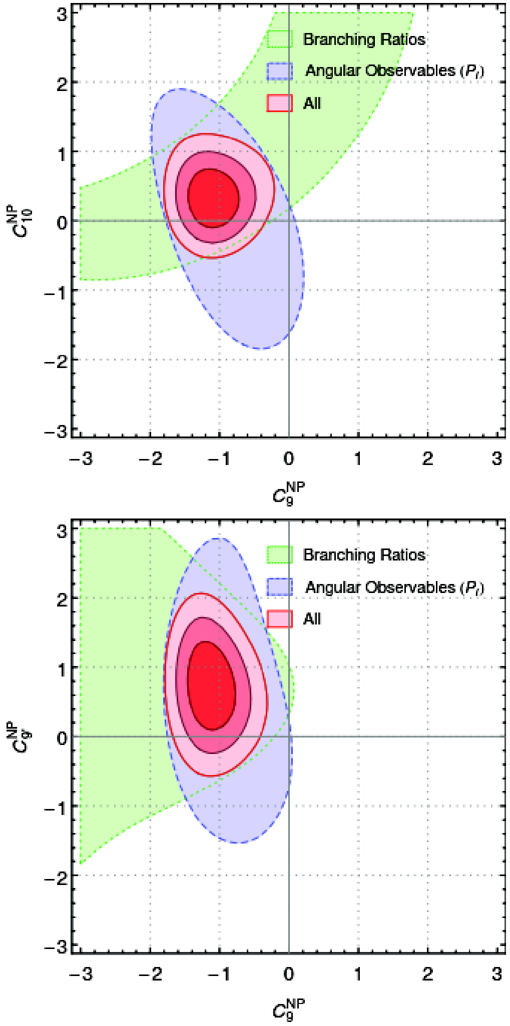
From C. Bobeth, LHCb implications workshop

[Altmannshofer/Straub 1411.3161 & 1503.06199]



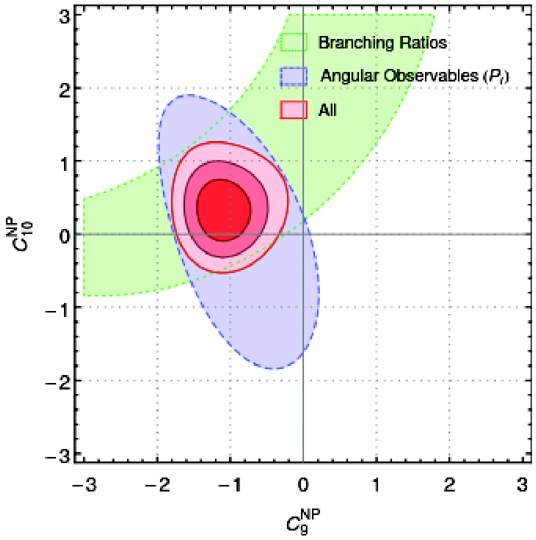
angular obs's (S_i) branching ratios

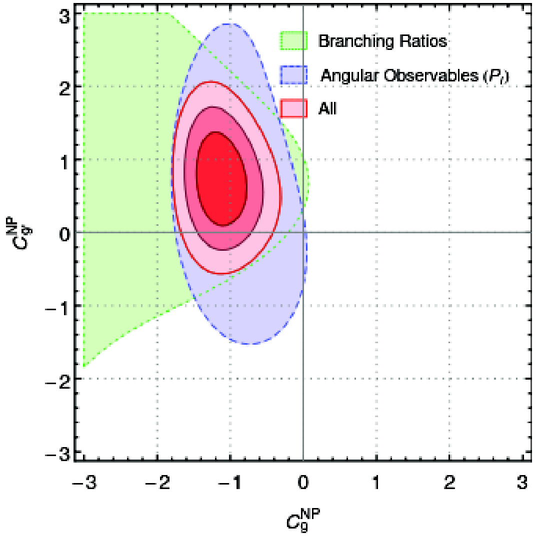
[Descotes-Genon/Hofer/Matias/Virto 1510.04239]



Performing global fits

[Descotes-Genon/Hofer/Matias/Virto 1510.04239]





The SM is disfavoured at ~4σ in all the different fits

Several options for NP fit that are hard to distinguish

- $C_9^{NP} = -1, C_{10}^{NP} = 0$
  - Leads towards Z' type models
- $C_9^{NP} = -C_{10}^{NP} = -1$
  - Leptoquark models
- $C_9^{NP} = -C_9^{'NP} = -1$
  - Leads to L-R symmetric models

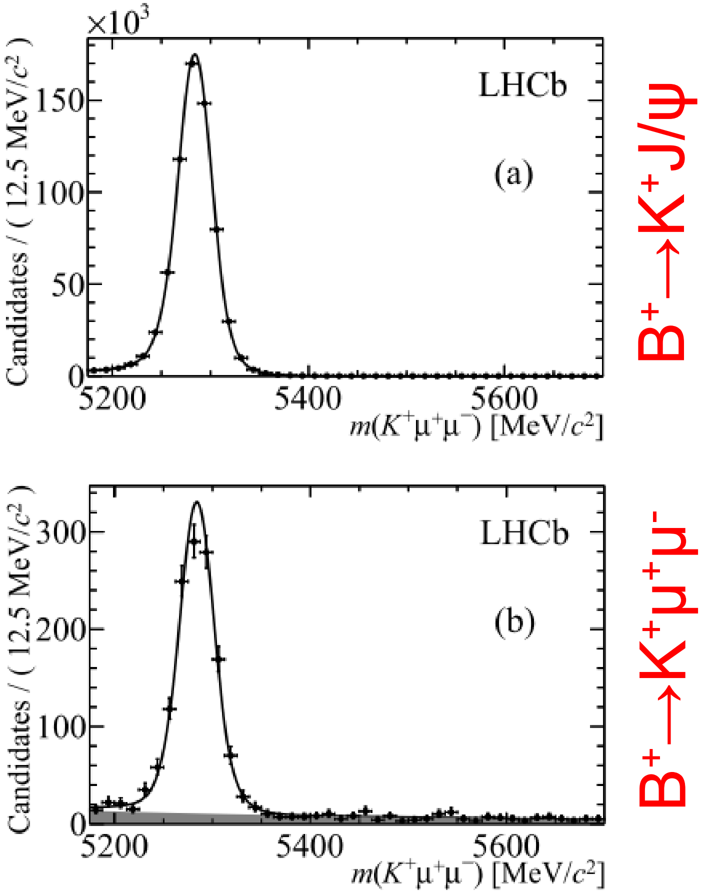
LHCb : PRL113, 151601 (2014)

Lepton universality test in $B^+\to K^+l^+l^-$

Due to lepton universality, the $B\to K\mu\mu$ and $B\to Kee$ decays should have same BF to within a factor 10^{-3}

The ratio

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



Sensitive to lepton flavour violating NP

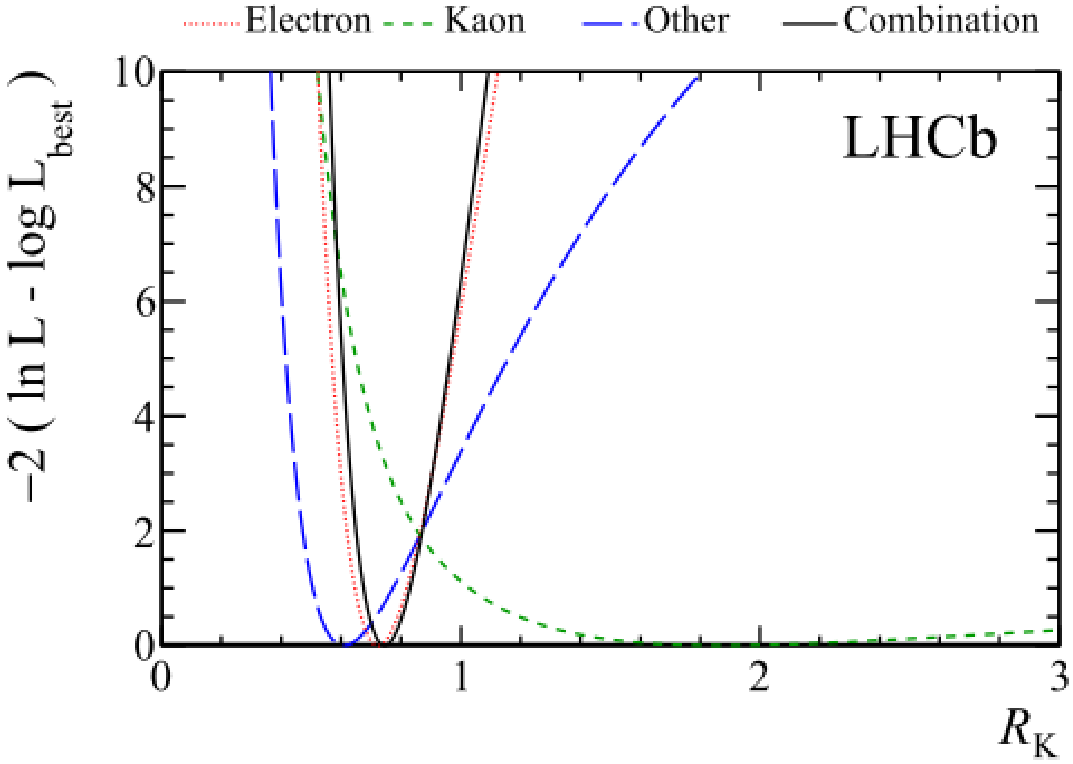
Look in $q^2 < 6\ \mathrm{GeV}^2$ region

Muon mode and its control mode $B^+\to K^+J/\psi$, $J/\psi\to\mu\mu$ are easy

LHCb : PRL113, 151601 (2014)

Lepton universality test in $B^+ \to K^+ l^+ l^-$

For the electron channel, analysis divided up in categories



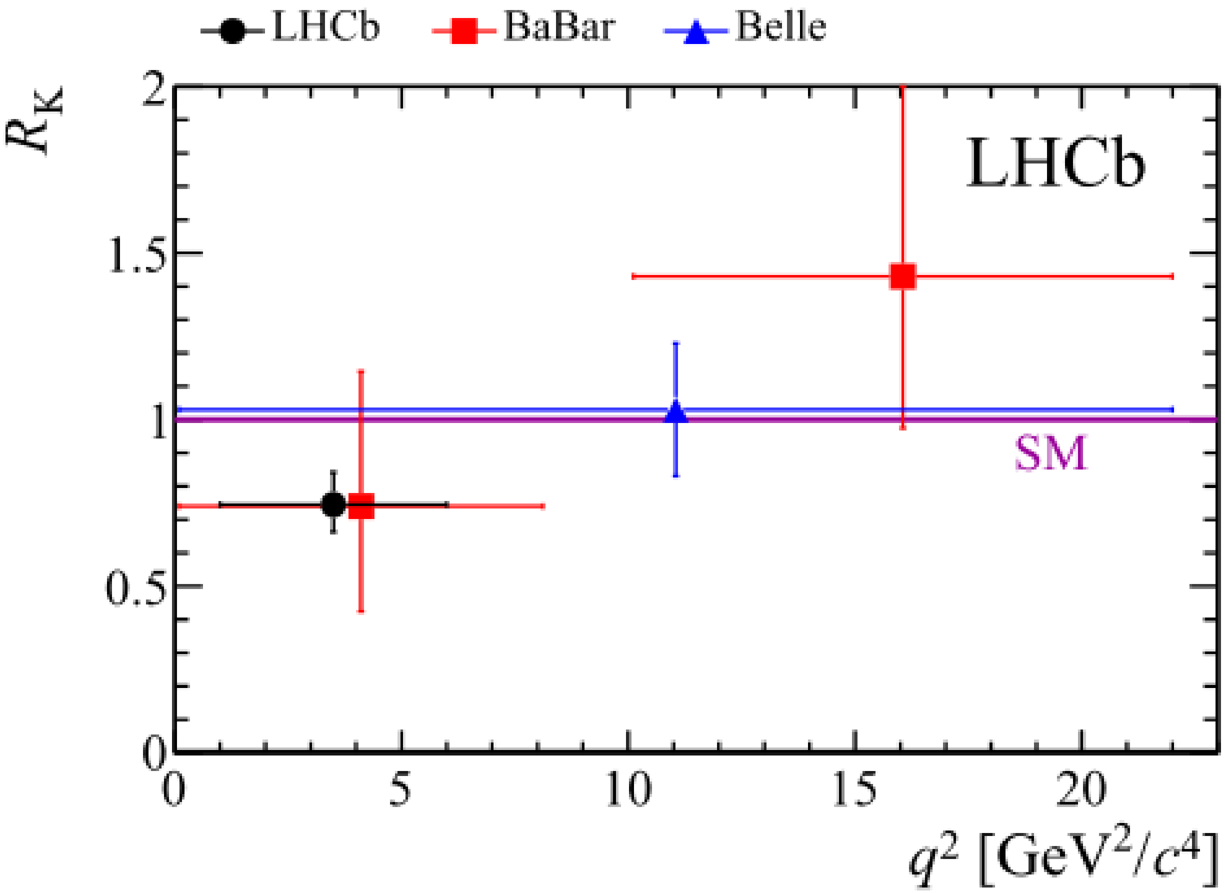
Electron mode control overall uncertainty

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

LHCb : PRL113, 151601 (2014)

Lepton universality test in $B^+ \to K^+l^+l^-$

Measurement is compatible with earlier, but less precise measurements



Interpretations

To understand the different anomalies, different approaches have gained some traction

- There is a problem with the uncertainties
  - Experimental side most like for lepton non-universality measurements
  - Theory side more likely for electroweak penguin angular analysis
- Introduce a leptoquark sector
  - Provides straight forward explanation of lepton non-universality
- Introduce a Z' that allows for flavour changing neutral currents at tree level
  - Aims mainly at $B \to K^* \mu^+ \mu^-$ but can also explain R_K

Problem with the uncertainties

- That the “NP” shows up in C9 is somewhat problematic
  - Most of the Standard Model uncertainties are there as well
  - Traditional fix is $C_9 \rightarrow C_9 + Y(q^2)$ to take charm loops into account
- From S. Jäger

SJ, Martin Camalich 1412.3183

Example

manifestly form-factor-scheme-independent

$$P_5' = P_5'|_\infty \left(1 + \frac{\boxed{a_{V_-} - a_{T_-}}}{\xi_\perp} \frac{m_B}{|\vec{k}|} \frac{m_B^2}{q^2} C_7^{\text{eff}} \frac{C_{9,\perp} C_{9,\parallel} - C_{10}^2}{(C_{9,\perp}^2 + C_{10}^2)(C_{9,\perp} + C_{9,\parallel})} \right.$$

$$+ \frac{\boxed{a_{V_0} - a_{T_0}}}{\xi_\parallel} 2\, C_7^{\text{eff}} \frac{C_{9,\perp} C_{9,\parallel} - C_{10}^2}{(C_{9,\parallel}^2 + C_{10}^2)(C_{9,\perp} + C_{9,\parallel})}$$

$$\left. + 8\pi^2 \frac{\tilde{h}_-}{\xi_\perp} \frac{m_B}{|\vec{k}|} \frac{m_B^2}{q^2} \frac{C_{9,\perp} C_{9,\parallel} - C_{10}^2}{C_{9,\perp} + C_{9,\parallel}} + \text{further terms} \right) + \mathcal{O}(\Lambda^2/m_B^2)$$

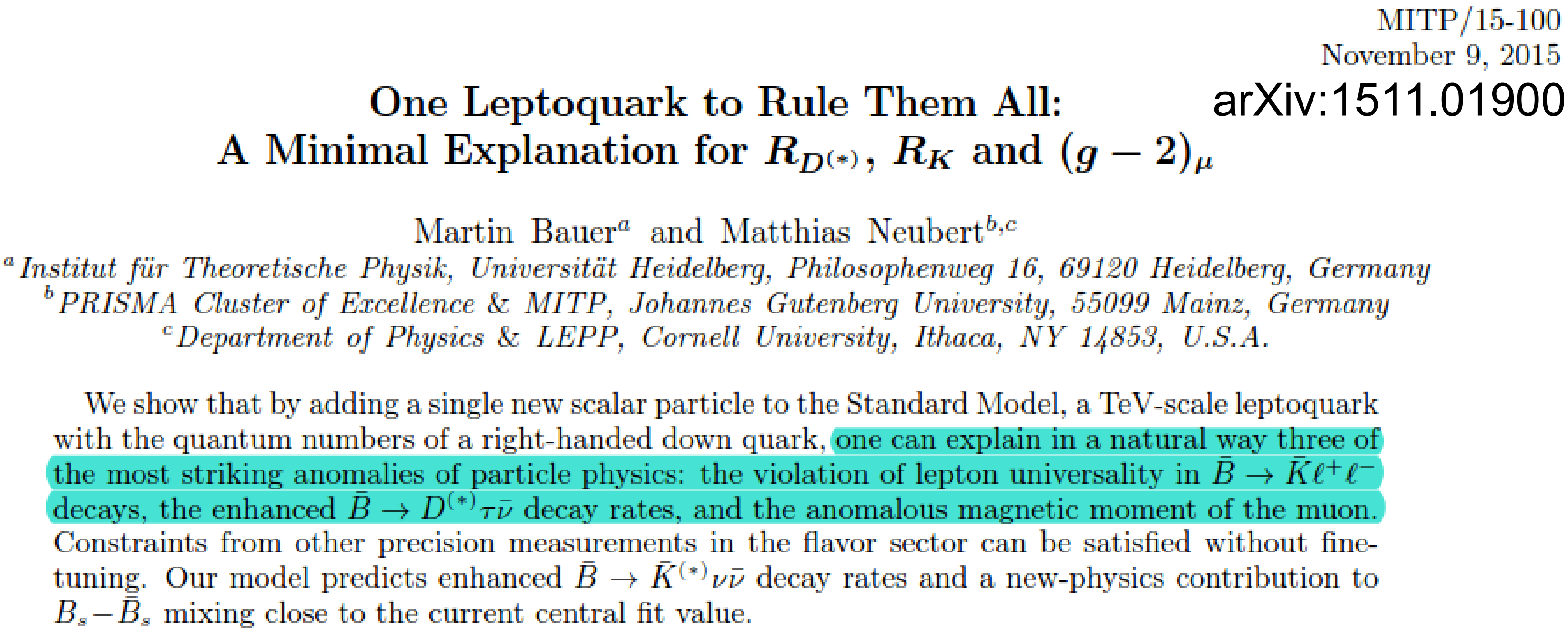
heavy-quark-limit result

(“charm loop” power correction)

(**truncated** after 3 out of 11 independent power-correction terms!)

Leptoquarks

- Latest attempt on leptoquarks attempts to explain nearly all anomalies
  - Assumes hierarchical coupling matrices



MITP/15-100
November 9, 2015

arXiv:1511.01900

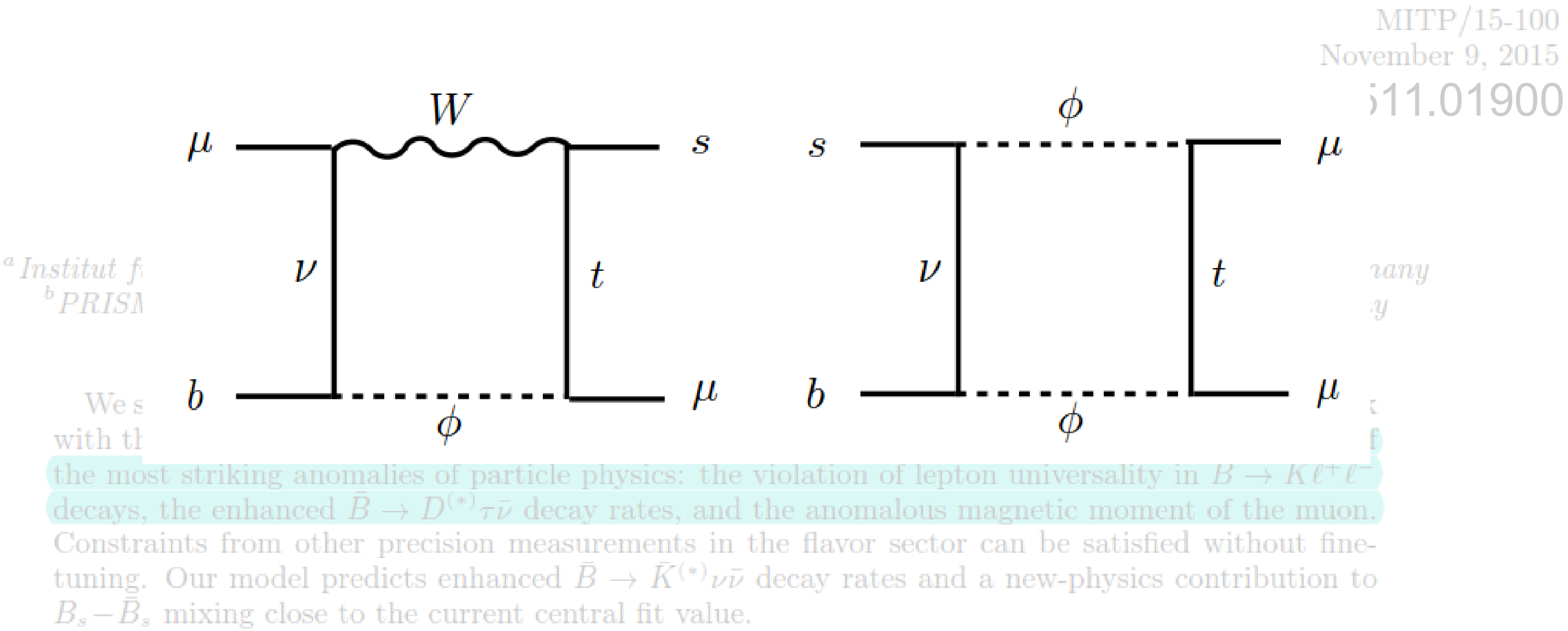
One Leptoquark to Rule Them All: A Minimal Explanation for $R_{D^{(*)}}$, R_K and $(g-2)_\mu$

Martin Bauer[a] and Matthias Neubert[b,c]
[a] *Institut für Theoretische Physik, Universität Heidelberg, Philosophenweg 16, 69120 Heidelberg, Germany*
[b] *PRISMA Cluster of Excellence & MITP, Johannes Gutenberg University, 55099 Mainz, Germany*
[c] *Department of Physics & LEPP, Cornell University, Ithaca, NY 14853, U.S.A.*

We show that by adding a single new scalar particle to the Standard Model, a TeV-scale leptoquark with the quantum numbers of a right-handed down quark, one can explain in a natural way three of the most striking anomalies of particle physics: the violation of lepton universality in $\bar{B} \to \bar{K}\ell^+\ell^-$ decays, the enhanced $\bar{B} \to D^{(*)}\tau\bar{\nu}$ decay rates, and the anomalous magnetic moment of the muon. Constraints from other precision measurements in the flavor sector can be satisfied without fine-tuning. Our model predicts enhanced $\bar{B} \to \bar{K}^{(*)}\nu\bar{\nu}$ decay rates and a new-physics contribution to $B_s - \bar{B}_s$ mixing close to the current central fit value.

Leptoquarks

- Latest attempt on leptoquarks attempts to explain nearly all anomalies
  - Assumes hierarchical coupling matrices
  - Loop diagrams explain R_K



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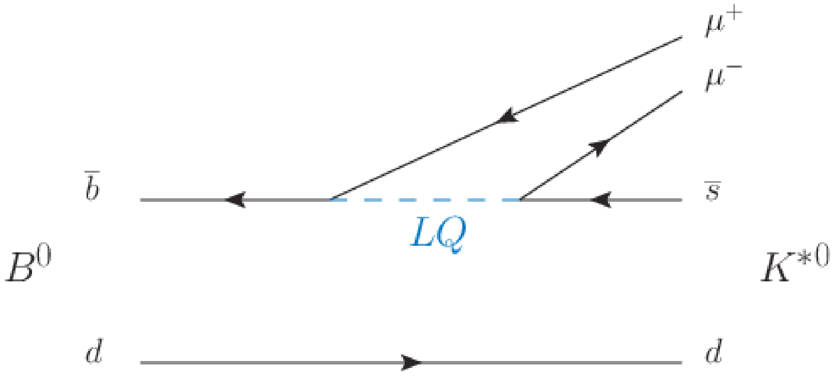
the most striking anomalies of particle physics: the violation of lepton universality in $B \to K\ell^+\ell^-$ decays, the enhanced $\bar{B} \to D^{(*)}\tau\bar{\nu}$ decay rates, and the anomalous magnetic moment of the muon. Constraints from other precision measurements in the flavor sector can be satisfied without fine-tuning. Our model predicts enhanced $\bar{B} \to \bar{K}^{(*)}\nu\bar{\nu}$ decay rates and a new-physics contribution to $B_s - \bar{B}_s$ mixing close to the current central fit value.

Interpretation of results

Alternatively a leptoquark would contribute equally to 0_9 (vector) and O_{10} (pseudo-vector)



Would naturally expect Lepton Flavour Violation

e.g. $B^+ \to K^+ e^+ \mu^-$

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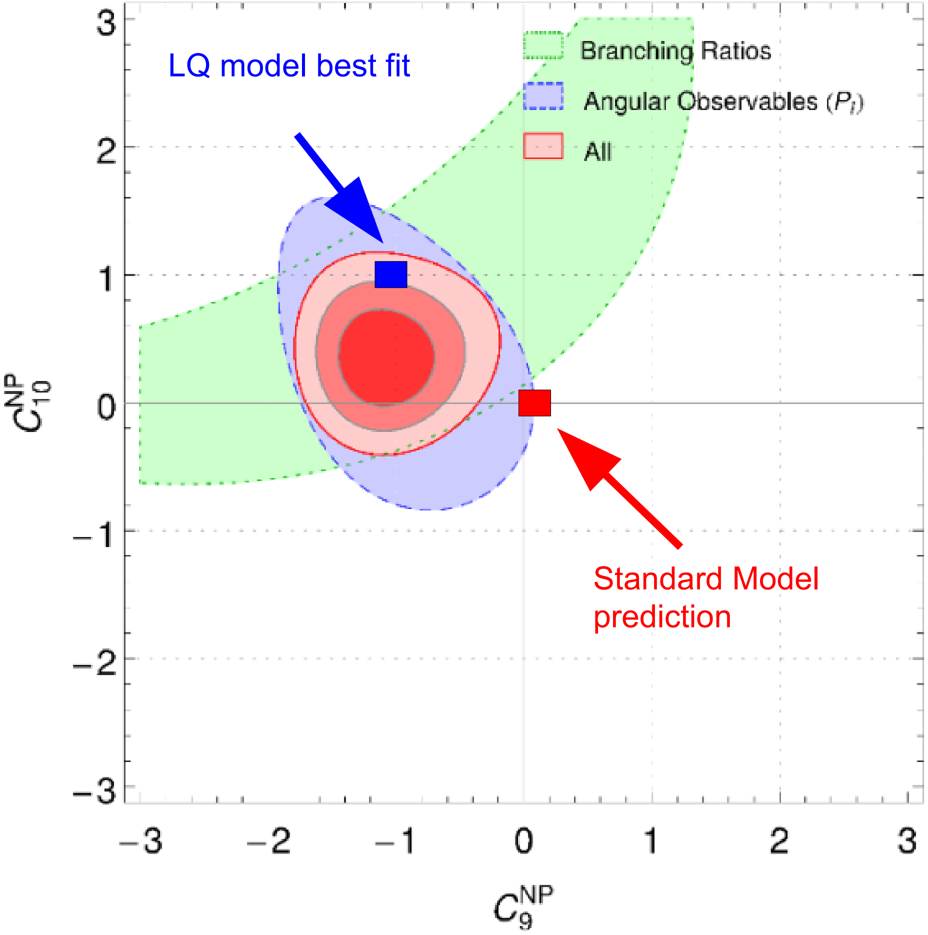
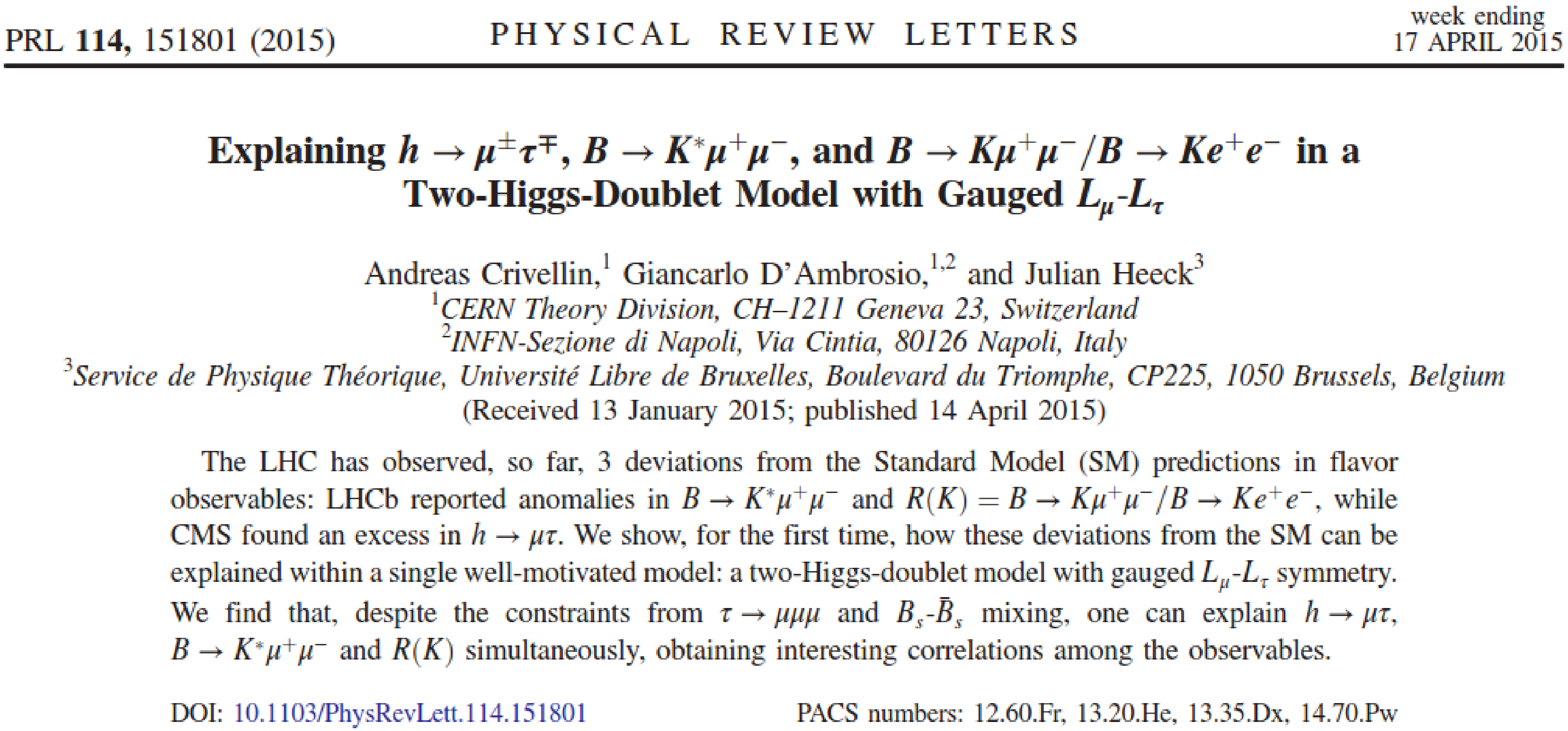


LQ model best fit

Standard Model prediction

Z' models

- Many variations of Z' models have been proposed
  - The example below tries to include the CMS H→μτ result as well



PRL **114,** 151801 (2015) PHYSICAL REVIEW LETTERS week ending 17 APRIL 2015

Explaining $h \to \mu^{\pm}\tau^{\mp}$, $B \to K^{*}\mu^{+}\mu^{-}$, and $B \to K\mu^{+}\mu^{-}/B \to Ke^{+}e^{-}$ in a Two-Higgs-Doublet Model with Gauged L_{μ}-L_{τ}

Andreas Crivellin,[1] Giancarlo D'Ambrosio,[1,2] and Julian Heeck[3]
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[2]*INFN-Sezione di Napoli, Via Cintia, 80126 Napoli, Italy*
[3]*Service de Physique Théorique, Université Libre de Bruxelles, Boulevard du Triomphe, CP225, 1050 Brussels, Belgium*

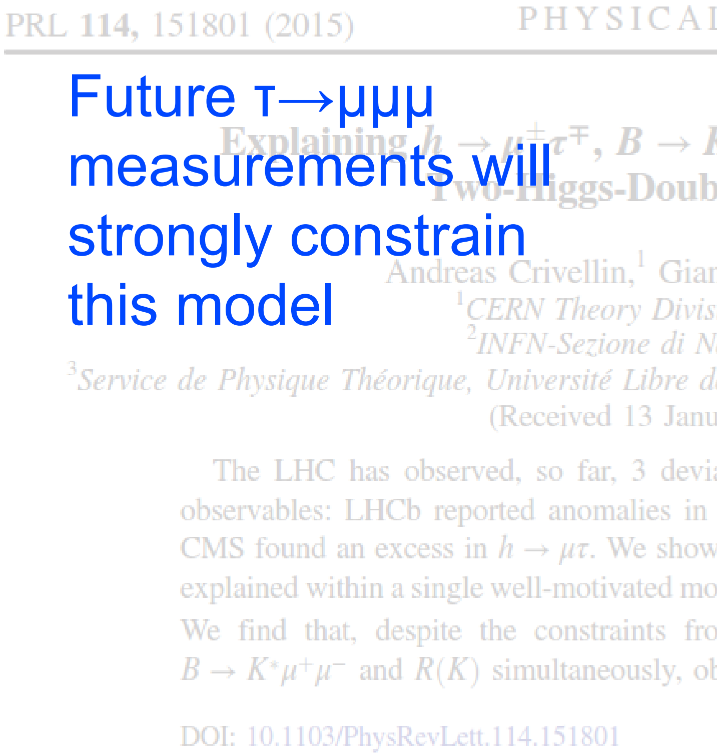
(Received 13 January 2015; published 14 April 2015)

The LHC has observed, so far, 3 deviations from the Standard Model (SM) predictions in flavor observables: LHCb reported anomalies in $B \to K^{*}\mu^{+}\mu^{-}$ and $R(K) = B \to K\mu^{+}\mu^{-}/B \to Ke^{+}e^{-}$, while CMS found an excess in $h \to \mu\tau$. We show, for the first time, how these deviations from the SM can be explained within a single well-motivated model: a two-Higgs-doublet model with gauged L_{μ}-L_{τ} symmetry. We find that, despite the constraints from $\tau \to \mu\mu\mu$ and B_s-$\bar{B}_s$ mixing, one can explain $h \to \mu\tau$, $B \to K^{*}\mu^{+}\mu^{-}$ and $R(K)$ simultaneously, obtaining interesting correlations among the observables.

DOI: 10.1103/PhysRevLett.114.151801 PACS numbers: 12.60.Fr, 13.20.He, 13.35.Dx, 14.70.Pw

Z' models

- Many variations of Z' models have been proposed
  - The example below tries to include the CMS H→μτ result as well



PRL **114,** 151801 (2015) PHYSICAI

Explaining $h \to \mu^\pm\tau^\mp$, $B \to$ I

Two-Higgs-Doub

Andreas Crivellin,[1] Giar

[1]CERN Theory Divis

[2]INFN-Sezione di N

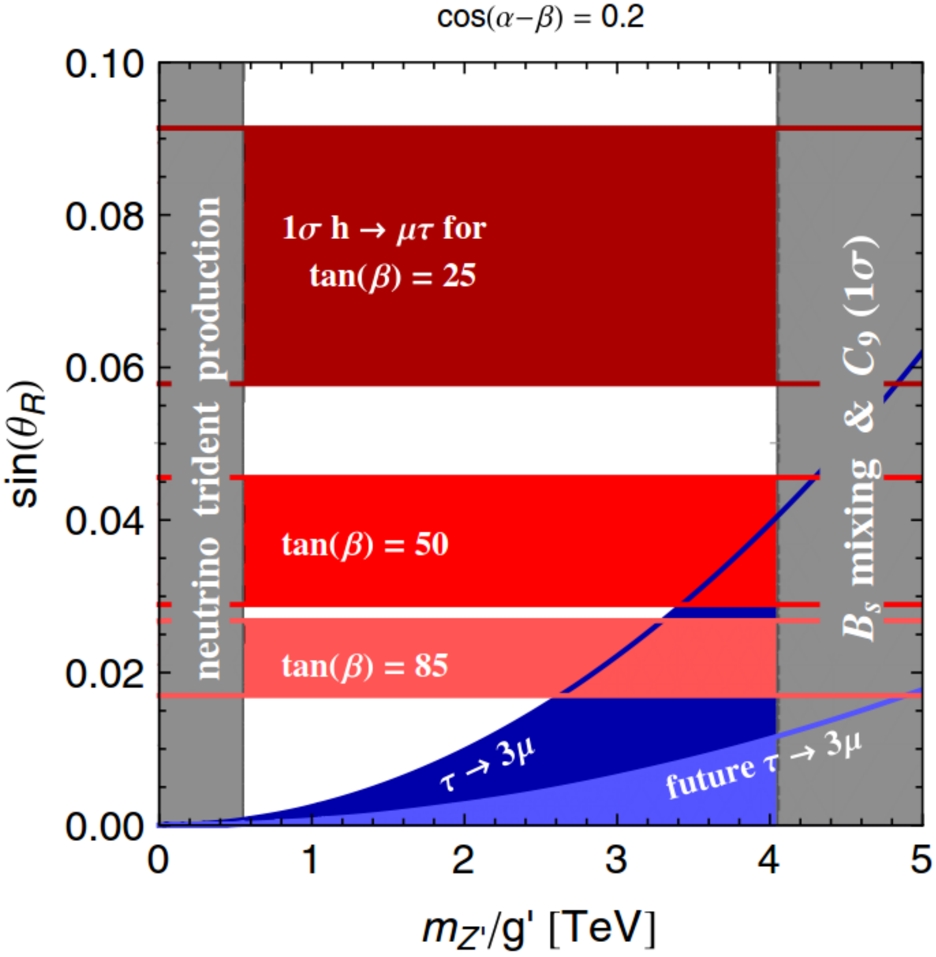
[3]Service de Physique Théorique, Université Libre d

(Received 13 Janu

The LHC has observed, so far, 3 devi observables: LHCb reported anomalies in CMS found an excess in $h \to \mu\tau$. We show explained within a single well-motivated mo We find that, despite the constraints fro $B \to K^*\mu^+\mu^-$ and $R(K)$ simultaneously, ol

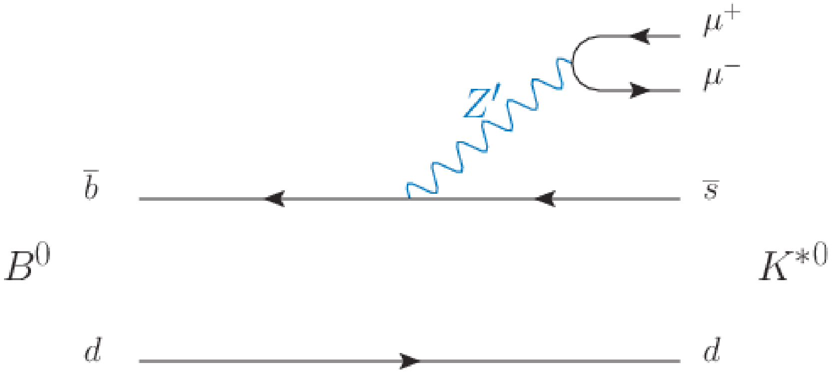
DOI: 10.1103/PhysRevLett.114.151801

- Future τ→μμμ measurements will strongly constrain this model



Interpretation of results

A new vector boson, Z’, would only contribute to the O_9 operator



Direct observation of new boson would be fantastic

… but maybe out of reach of LHC

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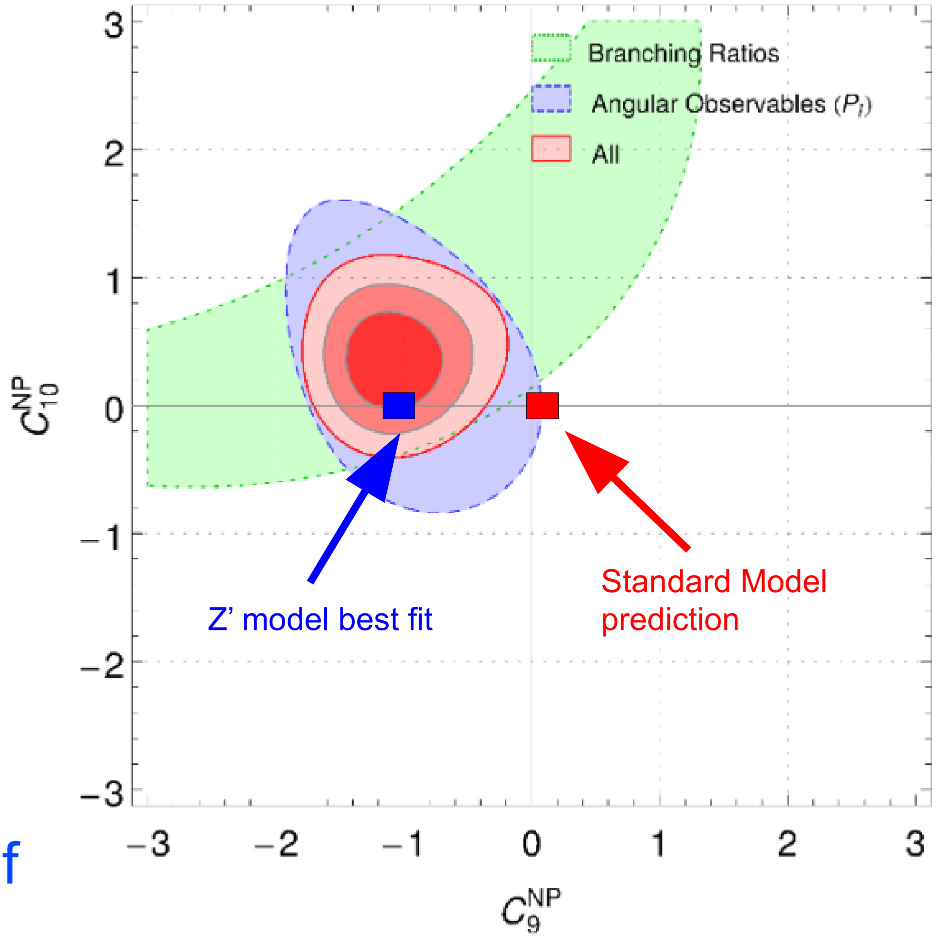
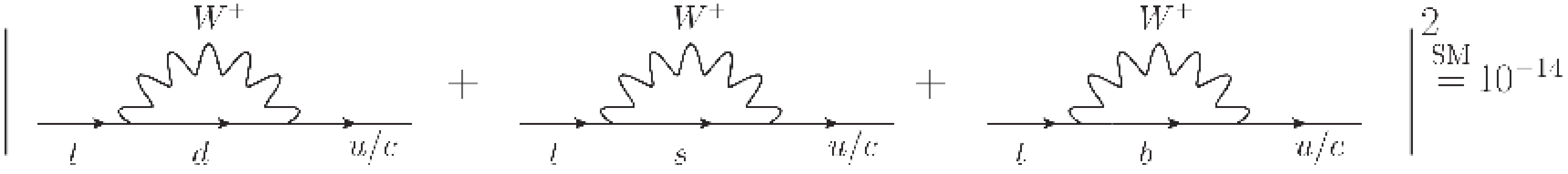


Z’ model best fit

Standard Model prediction

Flavour changing neutral currents in top

With massless quarks, flavour changing neutral current decays are forbidden in the SM (GIM mechanism)



Comparing to the top mass, all other quarks **are** nearly massless

FCNC for top ($t \rightarrow c\,X$, $t \rightarrow u\,X$) are suppressed by huge factor in SM

Not the case for many NP models

arXiv: 1311.2028

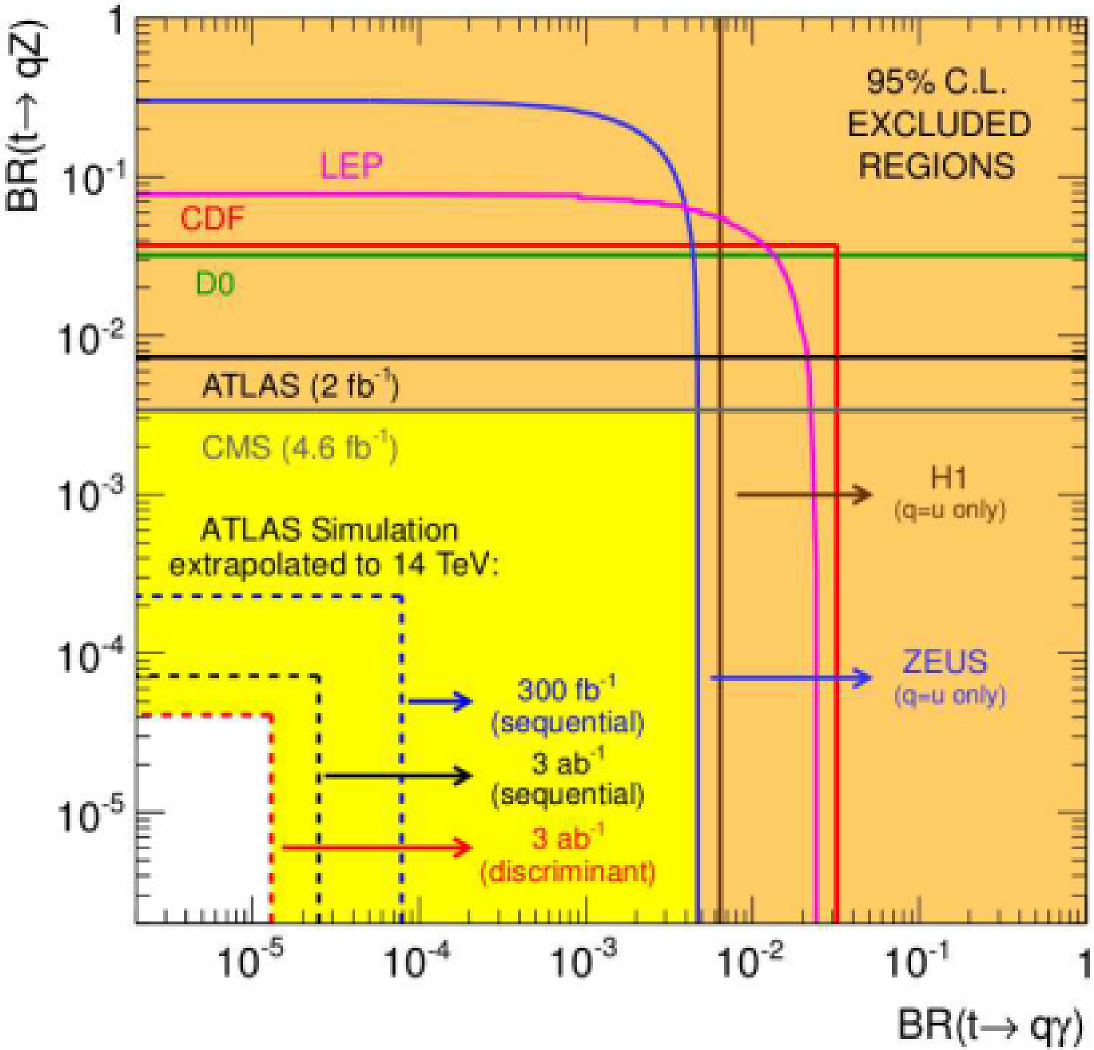
	2HDM	MSSM	RS
$t \to cZ$	$\lesssim 10^{-6}$	$\lesssim 10^{-7}$	$\lesssim 10^{-5}$
$t \to c\gamma$	$\lesssim 10^{-7}$	$\lesssim 10^{-8}$	$\lesssim 10^{-9}$
$t \to cg$	$\lesssim 10^{-5}$	$\lesssim 10^{-7}$	$\lesssim 10^{-10}$
$t \to ch$	$\lesssim 10^{-2}$	$\lesssim 10^{-5}$	$\lesssim 10^{-4}$

Flavour changing neutral currents in top

ATLAS/CMS searches in

- single top
- t→Zq decays

ATL-PHYS-PUB-2013-007



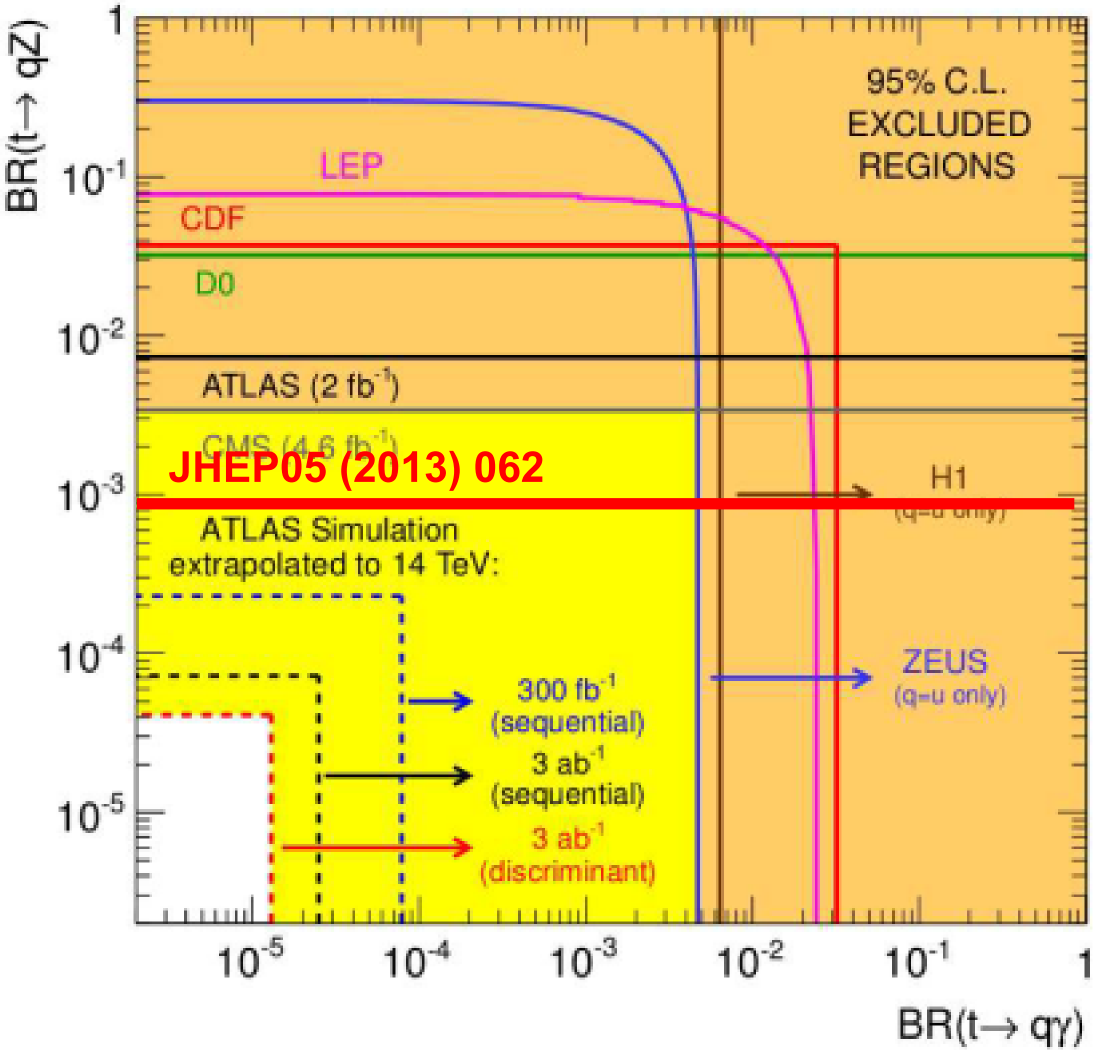
Flavour changing neutral currents in top

ATLAS/CMS searches in

- single top
- t→Zq decays

But at the moment effects on B penguin decays sets a better limit (LHCb)

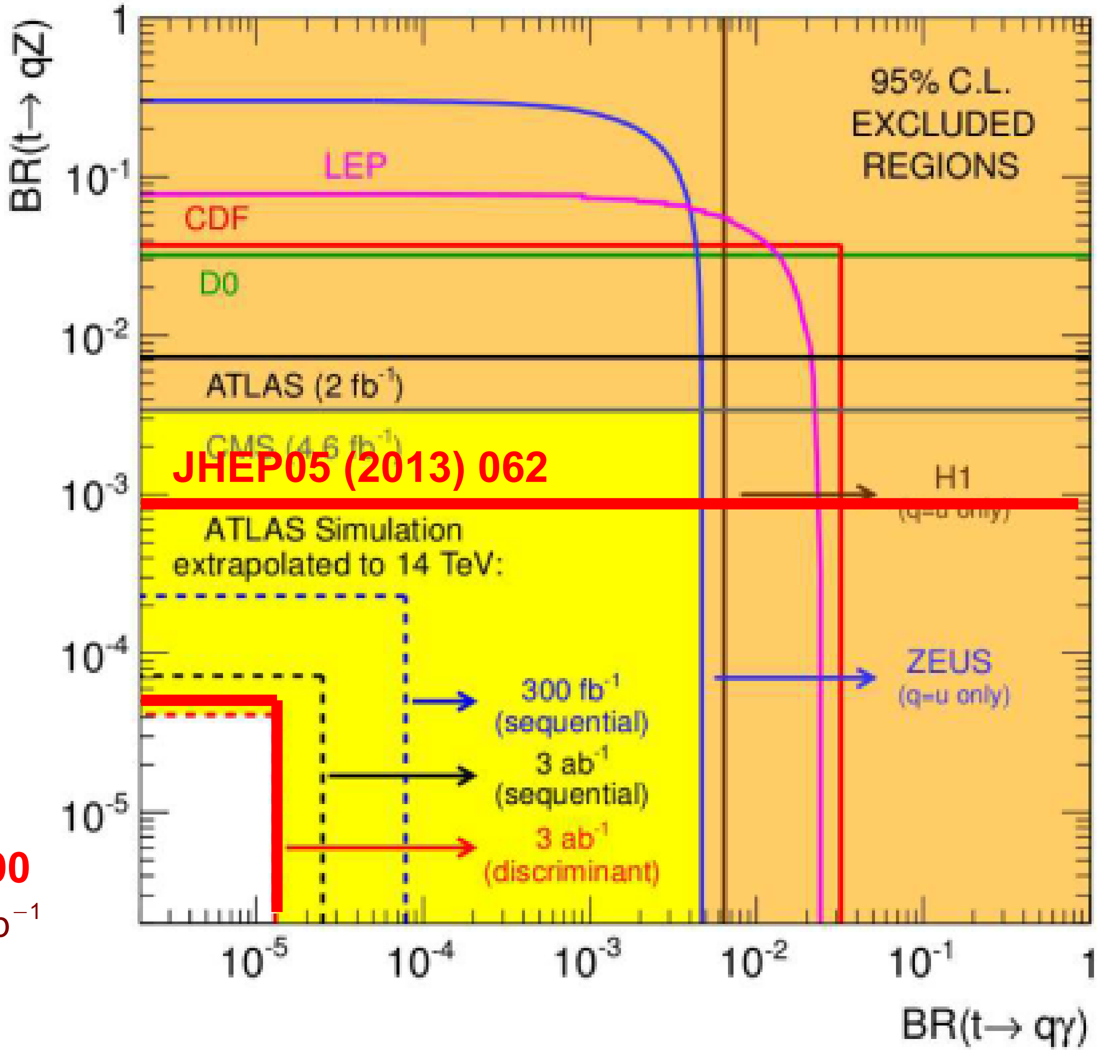
ATL-PHYS-PUB-2013-007



JHEP05 (2013) 062

Flavour changing neutral currents in top

- ATLAS/CMS searches in
  - single top
  - t→Zq decays
- But at the moment effects on B penguin decays sets a better limit (LHCb)
- But TLEP is also very competitive



ATL-PHYS-PUB-2013-007

JHEP05 (2013) 062

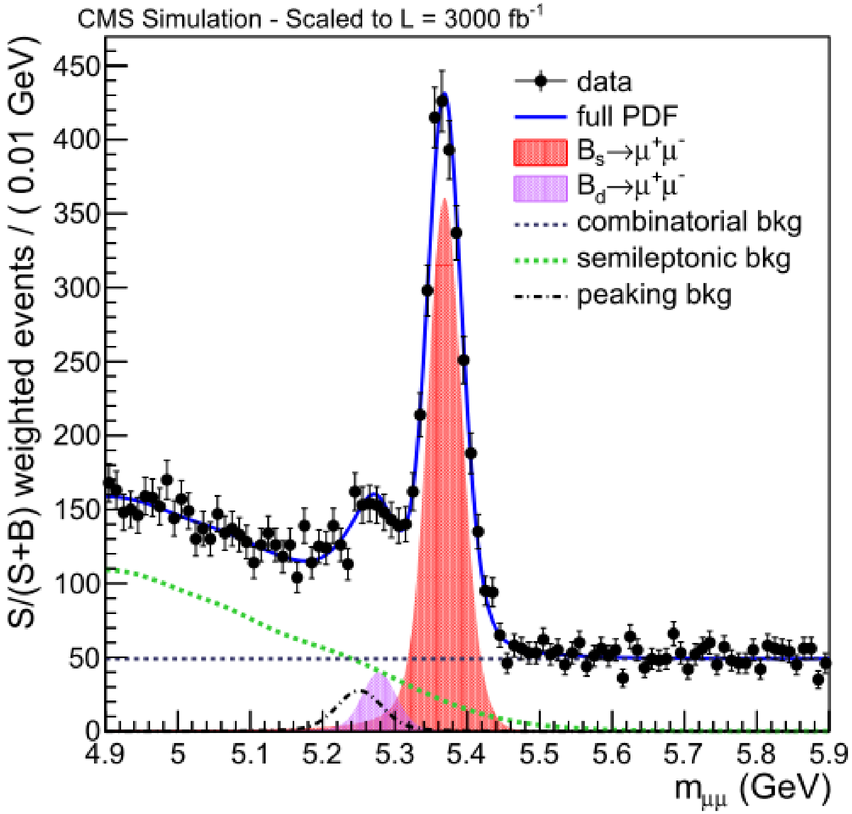
arXiv:1408.2090

$\sqrt{s}=350\,\text{GeV},\ \int L=100\,\text{fb}^{-1}$

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

- For Run II, the clear goal is observation of $B^0 \to \mu^+\mu^-$
  - In the SM suppressed by $|V_{ts}|^2/|V_{td}|^2 \sim 25$
  - LHCb upgrade expect to measure the ratio to a 35% accuracy
  - CMS upgrade at full 3 ab^{-1} expected to reduce this to 21%
    - Depends critically on ability to keep peaking backgrounds under control
- $B^0_s \to \tau^+\tau^-$ an interesting opportunity for TLEP
  - Would need **huge** enhancemer to be visible in LHCb

CMS PAS FTR-13-016



B→$\mu^+\mu^-$

- Is the decay $B^0_s \rightarrow \mu^+\mu^-$ *CP*-even or *CP*-odd?
  - The two weak eigenstates of the B^0_s differ by about 12% in effective lifetime ($\Delta\Gamma/\Gamma \sim 0.12$)
  - The two states are almost purely CP-even and CP-odd
  - Thus measurement of effective lifetime in $B^0_s \rightarrow \mu^+\mu^-$ is a measure of the CP of the decay.
- A measurement like this was made for $B^0 \rightarrow K^+K^-$
  - [PLB 736 (2014) 446]
  - 10k candidates gives resolution of 16 fs
  - Current LHCb $B^0_s \rightarrow \mu^+\mu^-$ is about 10 events equivalent
  - Need a factor 200 higher yield, 300 fb^{-1}

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

- Direct *CP* violation in $B^0_s \to \mu^+\mu^-$ is another challenging measurement
  - Requires that the flavour of the B^0_s is known (B^0_s or $\overline{B}^0_s$)
  - Efficiencies for this are approaching 6% in LHCb
  - To measure a 25% direct CPV with 5σ will require 25 times current dataset times flavour tagging efficiency, 400 fb^{-1}
- For a **long** time the measurement of $|V_{ts}|/|V_{td}|$ from $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ will be the only new result.

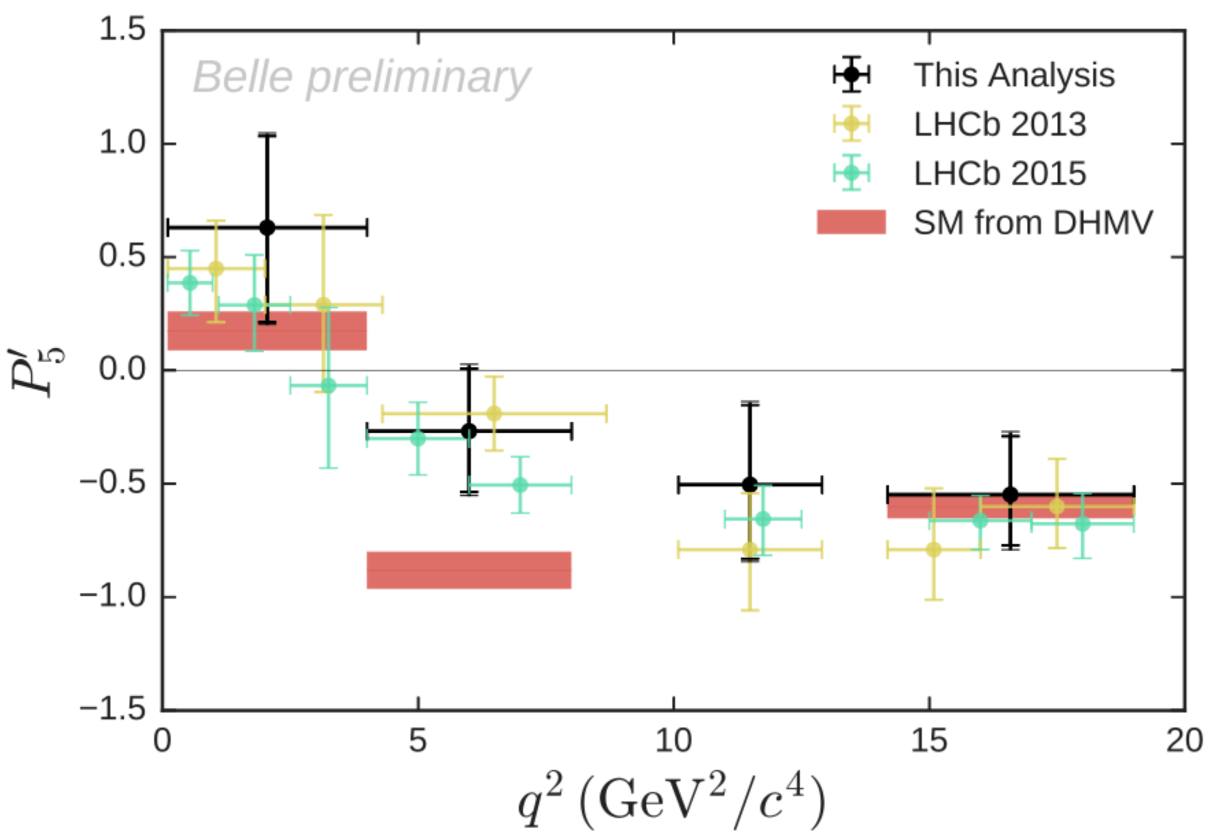
$B^0 \to K^{*0}\mu^+\mu^-$ angular analysis

- The Wilson coefficients describe the effective couplings from a higher energy scale
- The matrix element of the decay is controlled by the K^{*0} polarisation amplitudes
  - These are functions of the Wilson coefficients as well as the form factors arising from hadronic effects
    - The form factors can be calculated using light cone sum rules (mainly at low q^2) or lattice QCD (mainly large q^2)

$$A_\perp^{L,R} = N\sqrt{2}\lambda^{1/2}\left[\left\{(\mathcal{C}_9^{(\mathrm{eff})} + \mathcal{C}_9^{\prime(\mathrm{eff})}) \mp (\mathcal{C}_{10}^{(\mathrm{eff})} + \mathcal{C}_{10}^{\prime(\mathrm{eff})})\right\}\frac{V(q^2)}{m_B + m_{K^*}} + \right. \\ \left. + \frac{2m_b}{q^2}(\mathcal{C}_7^{(\mathrm{eff})} + \mathcal{C}_7^{\prime(\mathrm{eff})})T_1(q^2)\right],$$

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

Results Run-I LHCb and full Belle dataset



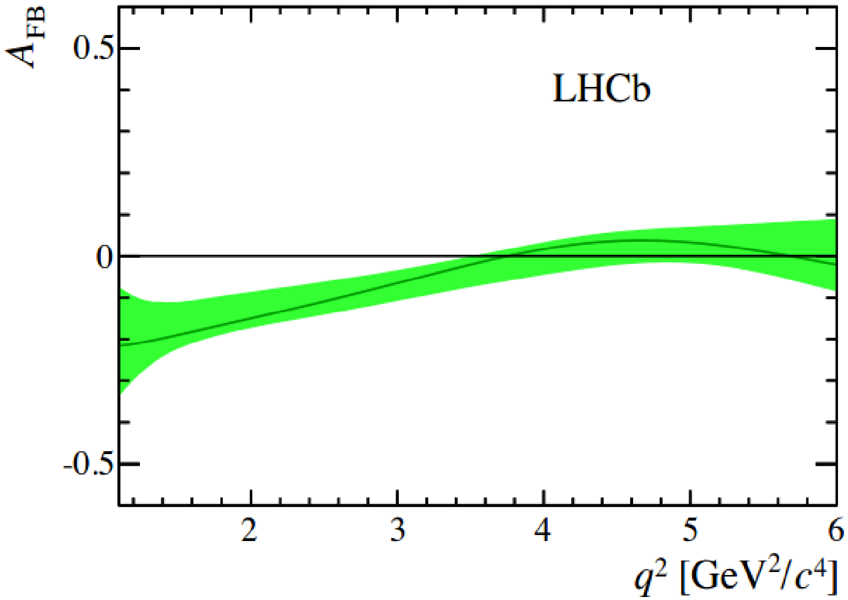
How do we progress from here?

LHCb : ArXiv: 1512.04442

$B^0 \rightarrow K^{*0}\mu^+\mu^-$ angular analysis

Unbinned fit result in region $1<q^2< 6$ GeV^2

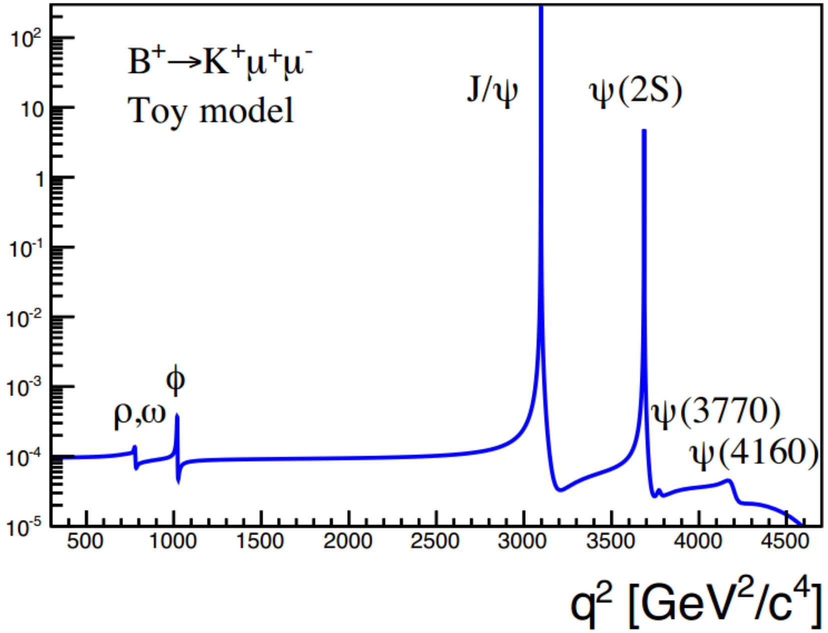
[JHEP 06 (2015) 084 for method]



$q_0^2(S_5) \in [2.49, 3.95]$ GeV^2/c^4 @ 68% CL

$q_0^2(A_{FB}) \in [3.40, 4.87]$ GeV^2/c^4 @ 68% CL

$B \rightarrow K\mu\mu$ fit in full q^2 toy fit (P. Owen)



Full angular fit, unbinned in q^2, might give us a better understanding of charm contributions.

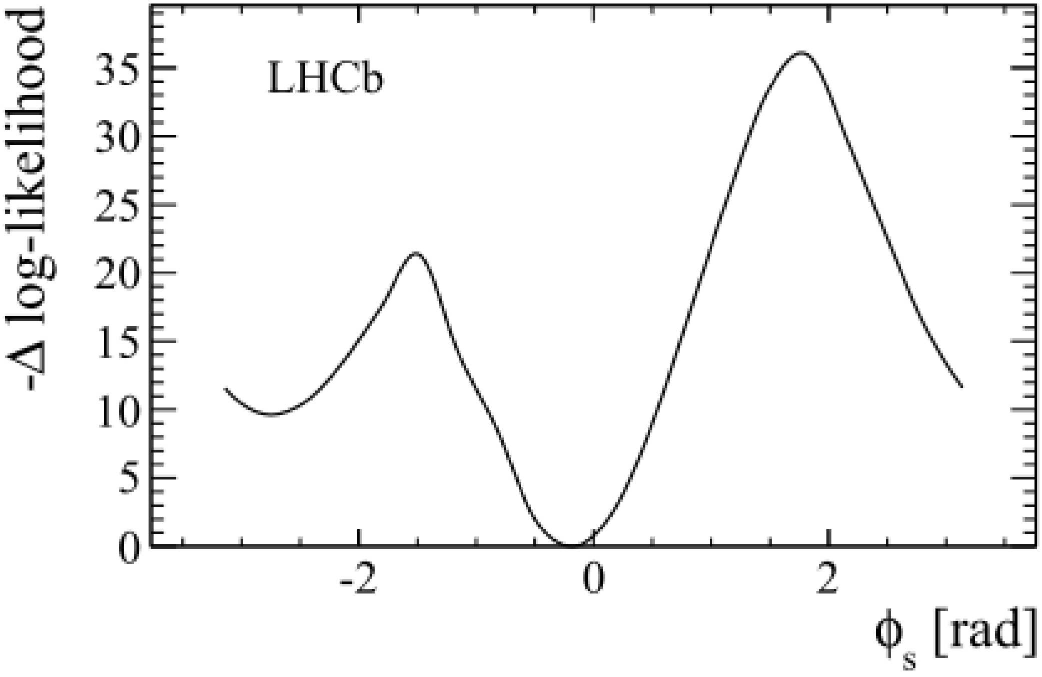
Lepton non-universality

- Can also consider to test b→u transitions
  - Experimentally tricky as $X_b \to X_u \mu^+ \nu$ are already hard
  - Looking at $X_b \to X_u \tau^+ \nu$ will just be even harder
  - Best prospects might be in decays that are more kinematically constrained (high mass of X_u)
    - $B^+ \to p\bar{p}\mu^+\nu$ vs. $B^+ \to p\bar{p}\tau^+\nu$
    - Form factors obviously unknown but can restriction of phase space (to let μ look like τ) help us.
    - Does $B+ \to \tau^+\nu$ already put severe restrictions on finding LNU?
  - Can careful selection of fiducial region reduce the theoretical uncertainties from form factors?

LHCb : PRD 90 (2014) 5, 052011

CP violation in $B^0_s \rightarrow \varphi\varphi$

Current status of LHCb $B^0_s \rightarrow \varphi\varphi$ measurement



No significant CP violation observed

$$\phi_s = -0.17 \pm 0.15\,(\mathrm{stat}) \pm 0.03\,(\mathrm{syst})\ \ \mathrm{rad}$$

LHCb : PRD 90 (2014) 5, 052011

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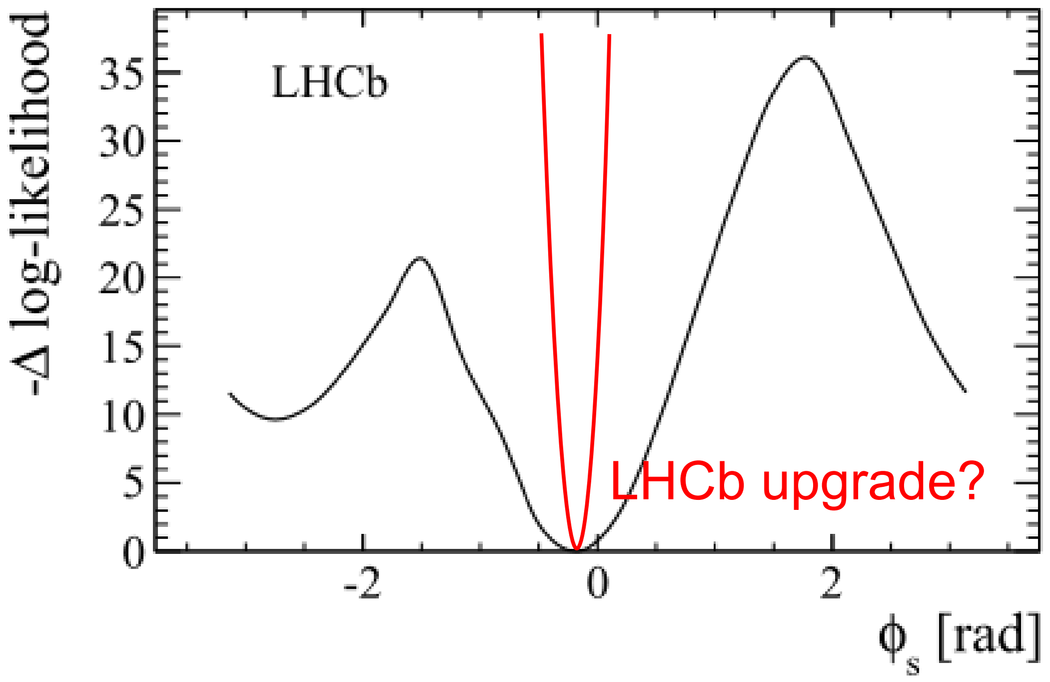


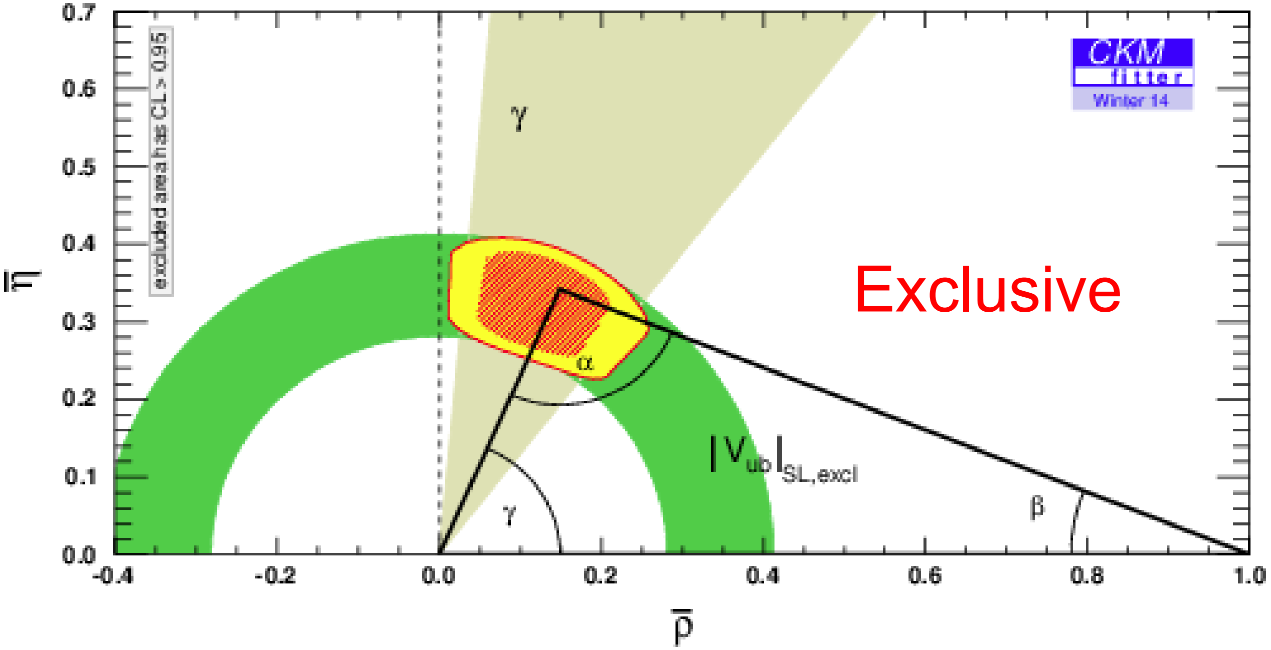
LHCb upgrade will bring precision on this down to 0.02

- Same level as the current theoretical uncertainty

The need to resolve the problem with $|V_{ub}|$

The measurement of $|V_{ub}|$ hides and internal inconsistency between

- Exclusive measurement: $B^0 \to \pi^- \mu^+ \upsilon$
- Inclusive measurement : $B^0/B^+ \to X_u\ \mu^+ \upsilon$



Exclusive

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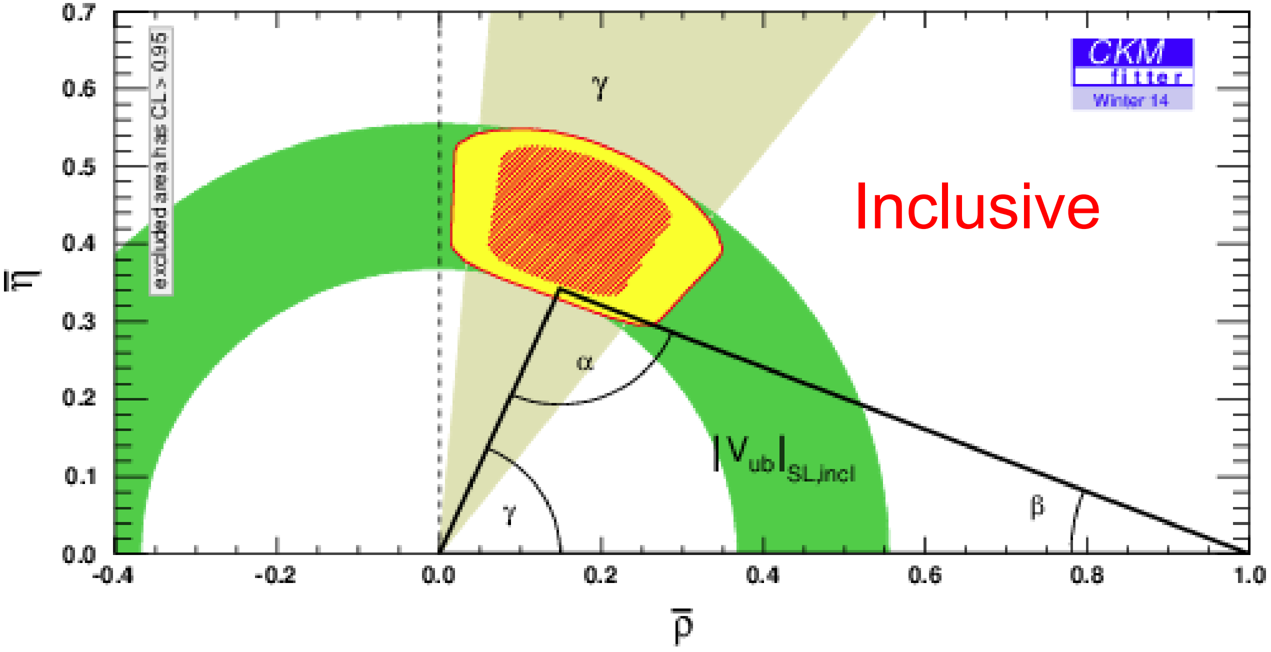

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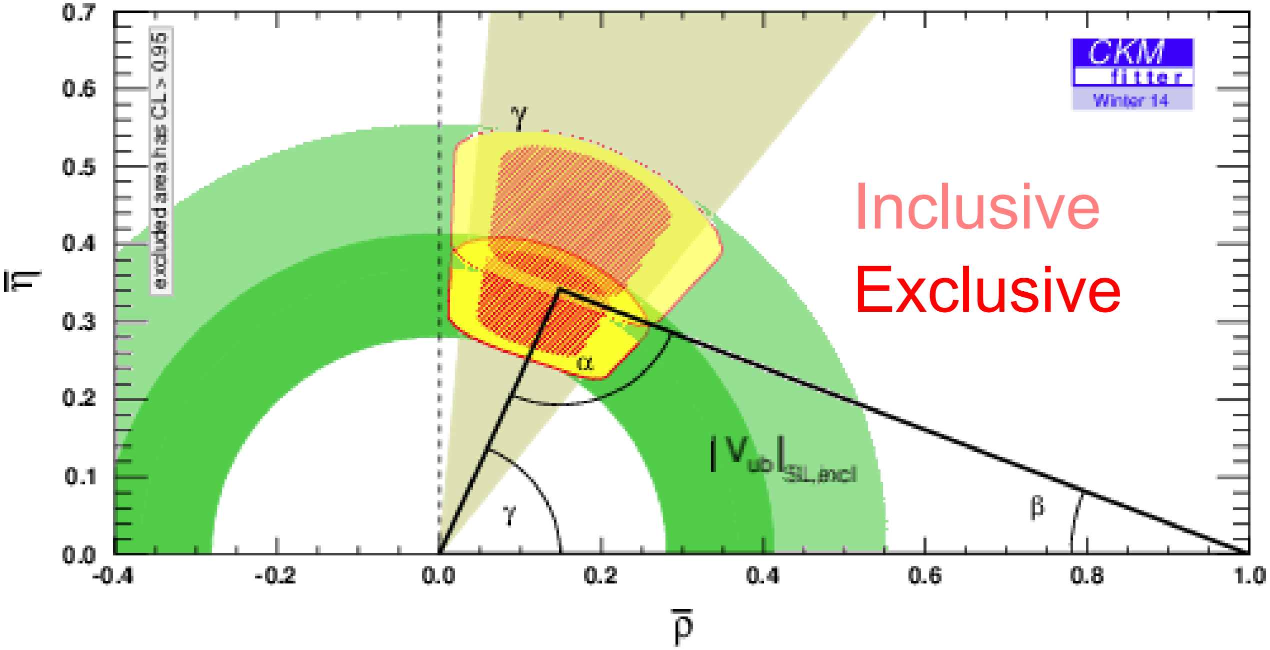


Inclusive

Exclusive

The need to resolve the problem with $|V_{ub}|$

Indicating that we do not fully understand QCD?

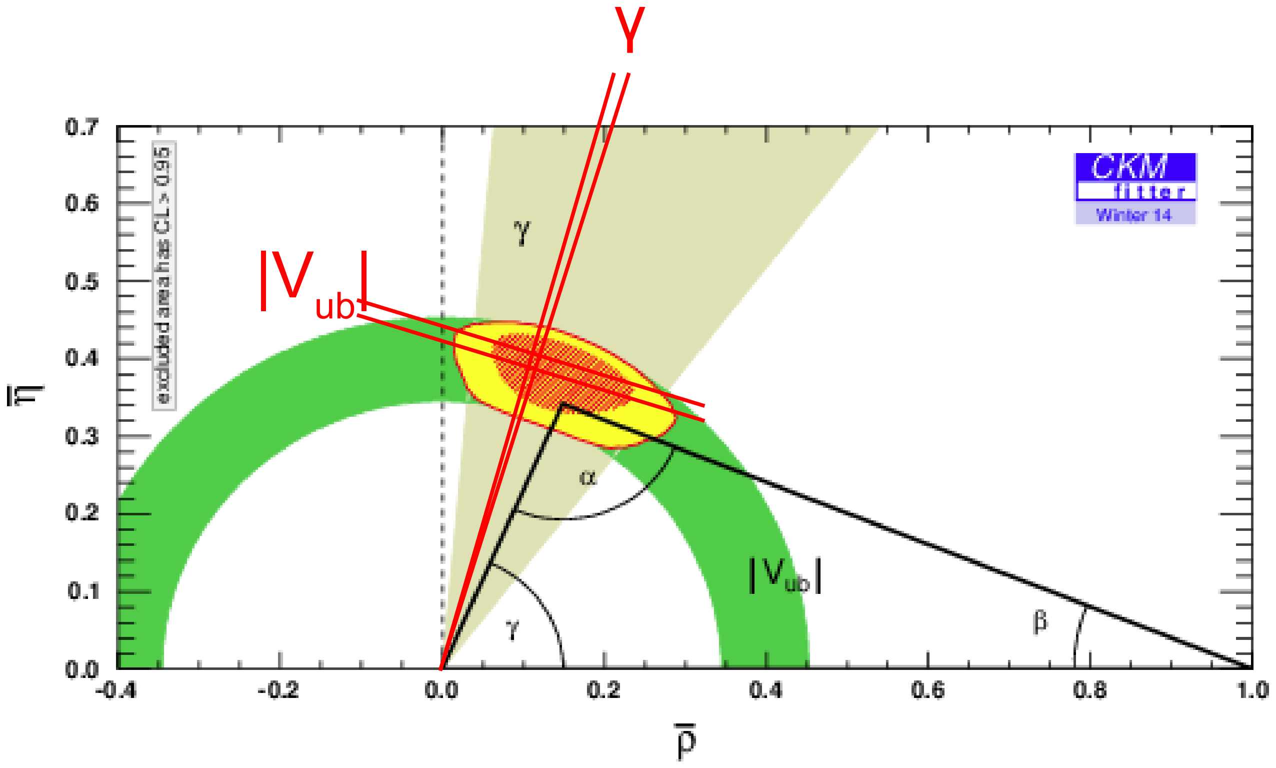
More independent measurements required

- $\Lambda_b \to p\,\mu^- \nu$
  - Sets constraints on $|V_{ub}|/|V_{cb}|$
- $B^+ \to \tau^+ \nu$
  - At the moment statistics limited, Belle-II will much improve
  - But maybe dangerous as it drags in LNU as well
- Inclusive measurement
  - Large gain in hadron tagged sample with Belle-II
- $B_c^+ \to X_c\,\mu^+ \nu$
  - Possible at LHCb or LHCb upgrade. Interesting?

$|V_{ub}|$ at a few percent level will be possible

Unitarity of CKM matrix

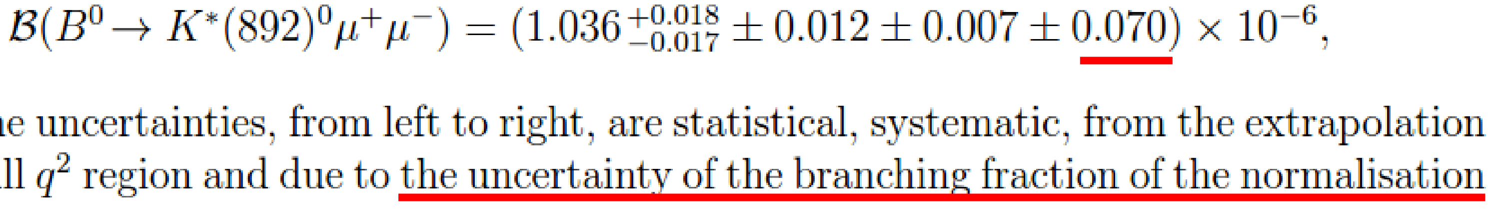
Left side ($|V_{ub}|/|V_{cb}|$) and the angle γ will be precision measurements in the future



Bread and butter work

- There are SM measurements that we need to prove
- Many of the experimental measurements depends on normalisation with respect to other modes
    - Often these normalisation modes are now imposing serious limits
- $B^0 \to J/\psi K^{*0}$, $B^0 \to J/\psi K^{*0}$
- Understanding of S-wave components

LHCb : arXiv:1606.04731



$$\mathcal{B}(B^0 \to K^*(892)^0 \mu^+ \mu^-) = (1.036\,^{+0.018}_{-0.017} \pm 0.012 \pm 0.007 \pm \underline{0.070}) \times 10^{-6},$$

where the uncertainties, from left to right, are statistical, systematic, from the extrapolation to the full q^2 region and due to the uncertainty of the branching fraction of the normalisation mode.

- $\Lambda_c^+ \to pK^+\pi^-$
    - Discrepancy between Belle and BES measurement a serious limitation on all Λ_c measurements