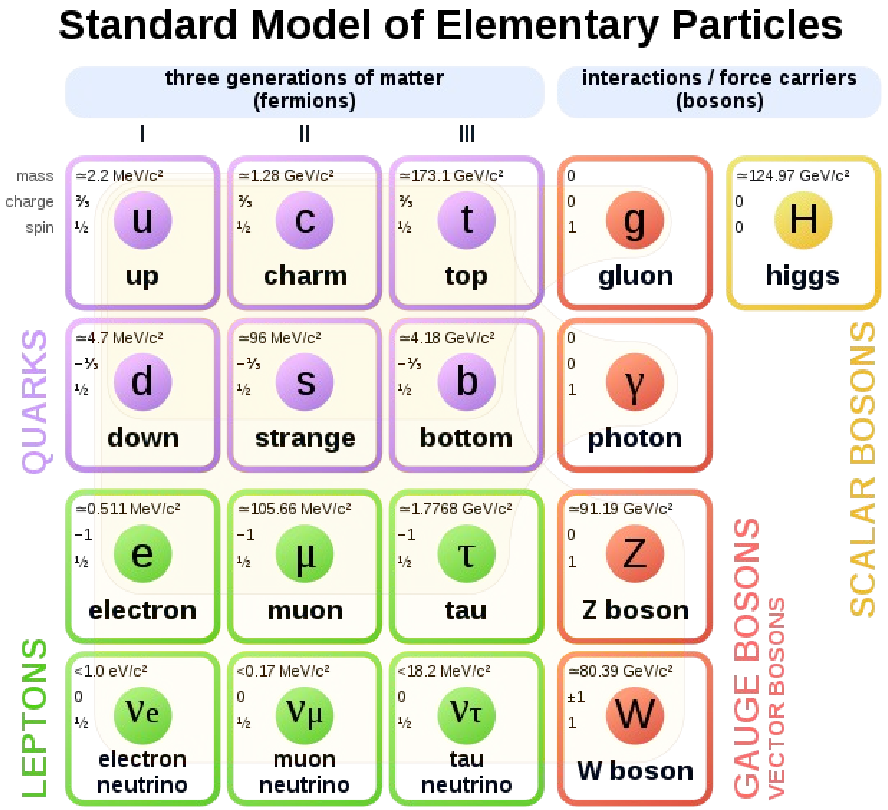
Searching for new physics through precision measurements of the $B^0 \to K^{*0}\mu^+\mu^-$ decay

Ulrik Egede, Monash University

10 June 2025

Flavour anomalies

- What IS flavour?
  - Described, but not understood within the Standard Model
- A reason for 3 families?
- Any other force carrying particles
- Is the Higgs the only scalar



Flavour **anomalies**

- What do we mean by an anomaly?

Collins dictionary

anomaly | English: anomaly | American: anomaly | anomaly | Example sentences | COBUILD Collocations | Trends

Definition of 'anomaly'

anomaly

Collins COBUILD

Word Frequency

(ənɒməli)

Word forms: plural anomalies

COUNTABLE NOUN

If something is an anomaly, it is different from what is usual or expected.

[*formal*]

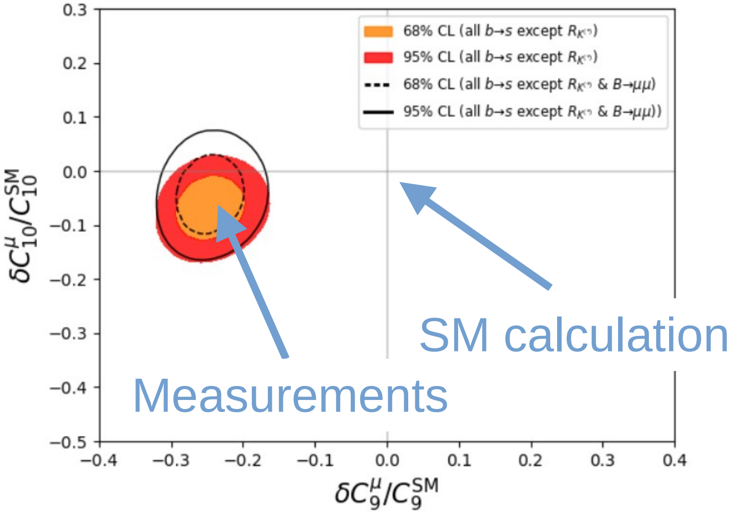
The computer's software detected an anomaly caused by a virus.

Synonyms: irregularity, departure, exception, abnormality More Synonyms of anomaly

Flavour **anomalies**

- Within the Standard Model framework, we can calculate the probability of a decay or a differential kinematic distribution of daughters in a decay
- If the measured distributions (within uncertainties) are not in agreement with the calculated ones, we have an anomaly
- So what! With loads of measurements and predictions, some of them are bound to be wrong?
- But what if nearly all (>100!) point in the same direction? Do we see signs of a new fundamental force, new vector bosons, …??

arXiv:2104.10058



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Flavour anomalies at **LHCb**

- The Large Hadron Collider is the largest producer in the world of b-hadrons
  - These are great for studying as they have $O(10^4)$ different decays that each give information
  - About 10^{13} b-hadrons per year
  - One year of LHCb Upgrade I data already recorded
  - Next publications will have twice as much data

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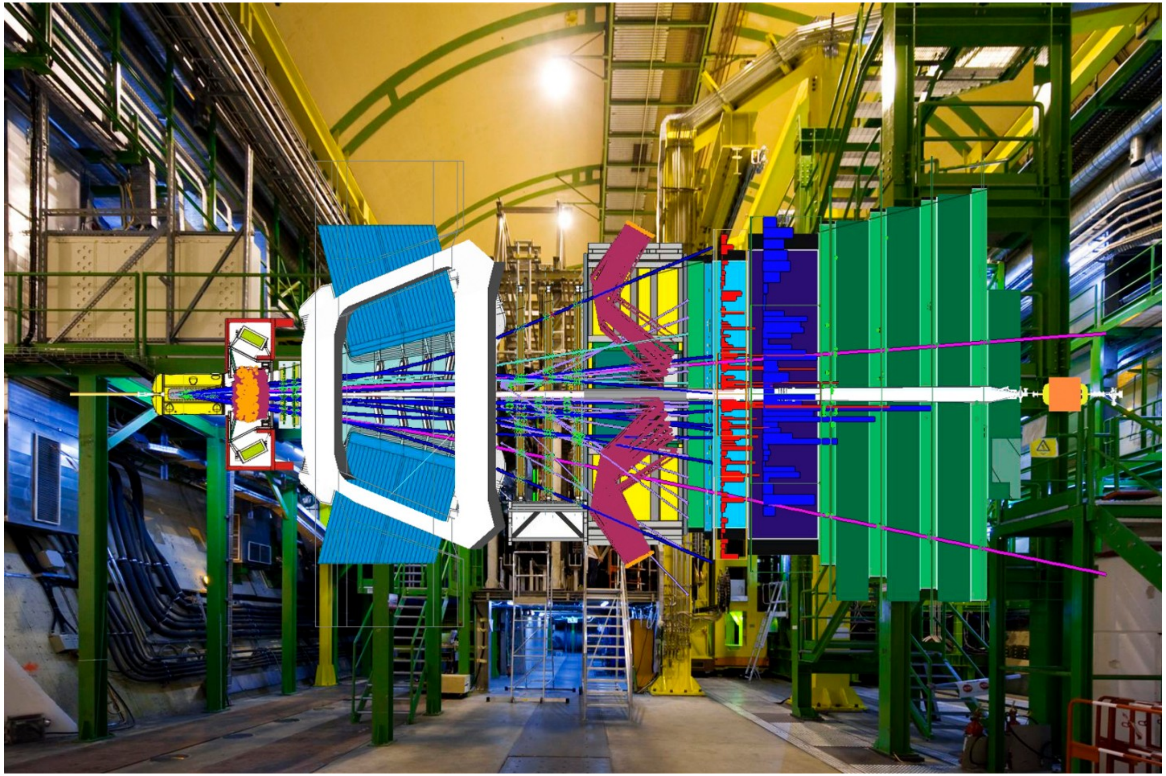

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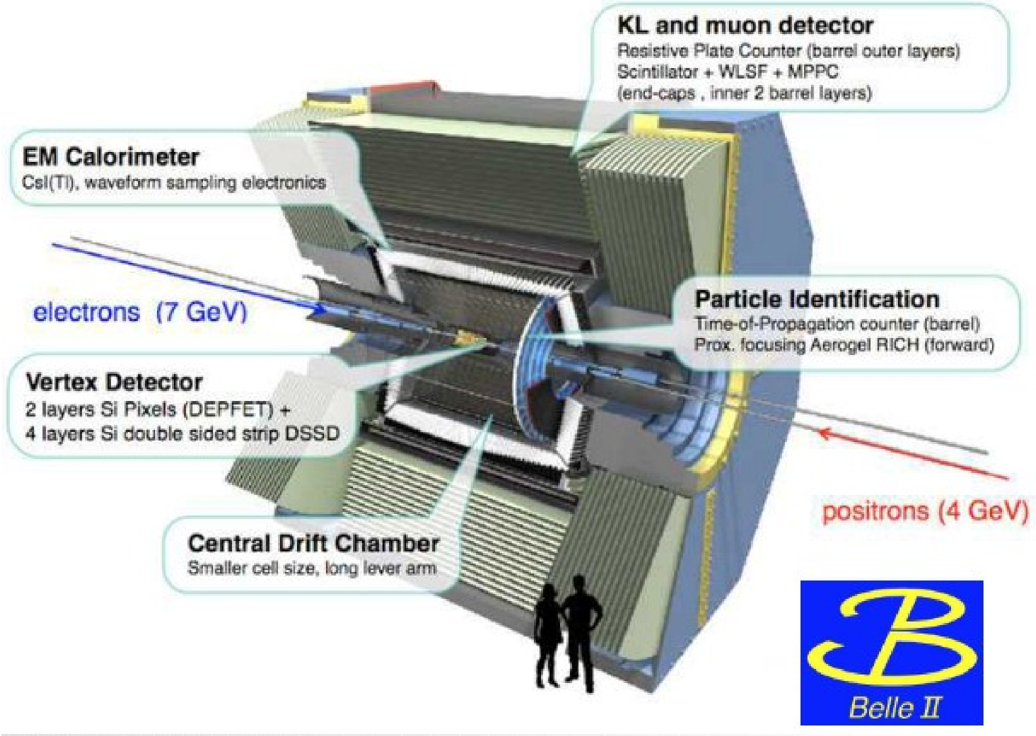
… and at **Belle II**

- The Belle II detector detect B^+ and B^0 mesons produced from Υ(4S) decays
  - Simplicity of environment allows for inclusive reconstruction
  - Capability to detect final states with multiple neutral particles
  - One result from Belle II plays an important part in this story



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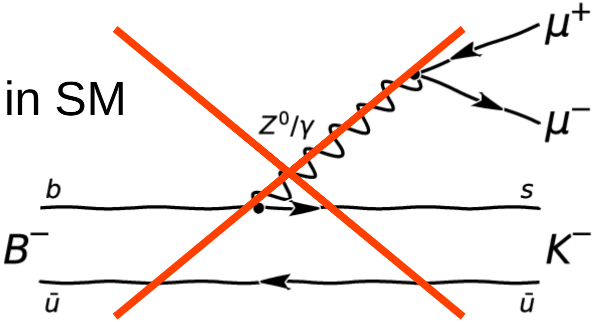
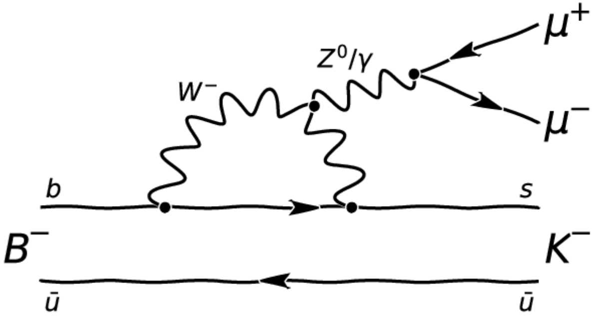
Look for the rare

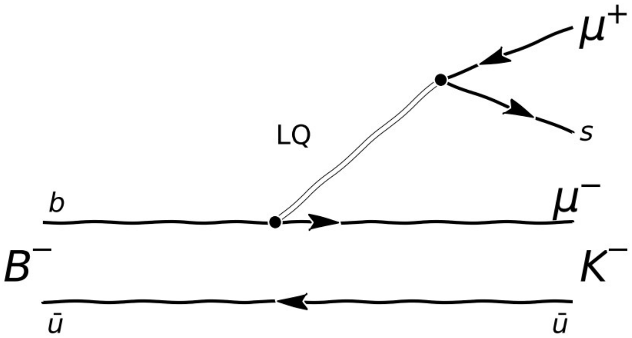
- If a decay of a b-hadron is predicted as really rare within the Standard Model, it is easier to spot an effect from something beyond the SM

Not allowed in SM





Allowed in SM
but suppressed



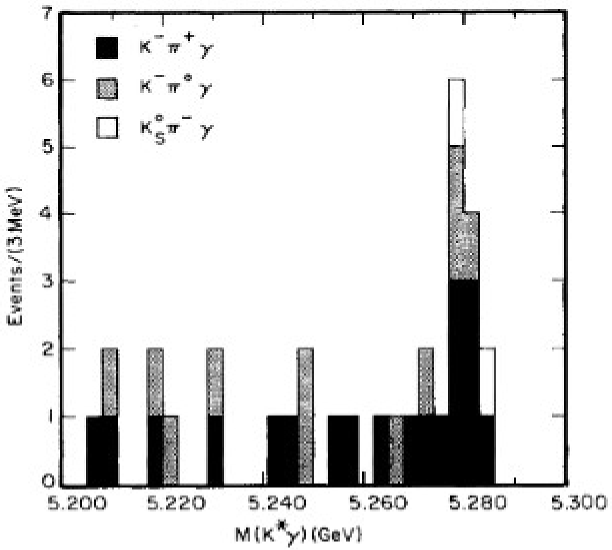
Some new force carrier
that allows same final state??

The first penguins

- CLEO found evidence of B → K*γ with BF~5 x 10^{-5} in 1993

VOLUME 71, NUMBER 5 PHYSICAL REVIEW LETTERS 2 AUGUST 1993

Evidence for Penguin-Diagram Decays: First Observation of $B \to K^*(892)\gamma$



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Many penguins have followed

- We are now looking at many penguins and in many different ways
- What do we want from the studies
  - Cross check current results from experimental and theoretical view
  - Look for “forbidden” decays
  - Clarify if current anomalies are due to New Physics
  - Improve our understanding of QCD in non-pertubative regime

Penguin studies on Macquarie island, 1968

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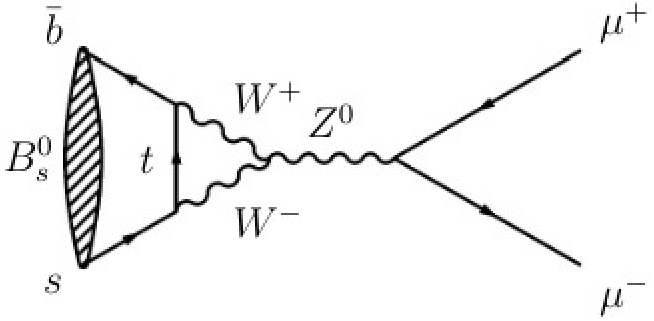
The $B^0_s \to \mu^+\mu^-$ decay

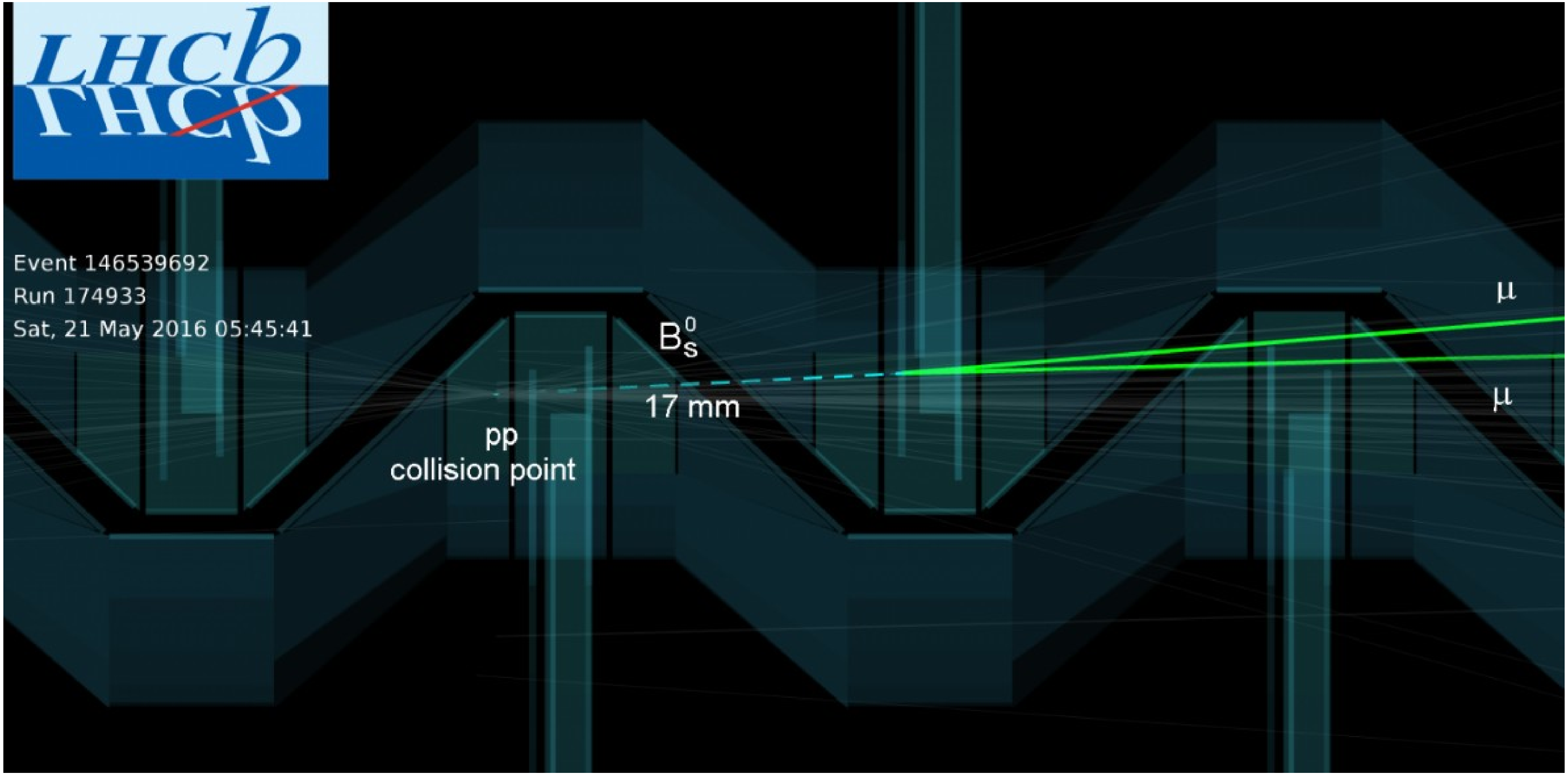
- Conceptually the easiest of all these rare decays to look at



$$\mathcal{B}(B^0_s \to \mu^+\mu^-)_{SM} = \frac{\tau_{B_q} G_F^4 M_W^4 \sin^4\theta_W}{8\pi^5} |C_{10}^{SM} V_{tb} V_{ts}^*|^2 f_{B_s}^2 m_{B_s} m_\mu^2 \sqrt{1 - \frac{4m_\mu^2}{m_{B_s}^2}} = (3.66 \pm 0.14) \times 10^{-9}$$

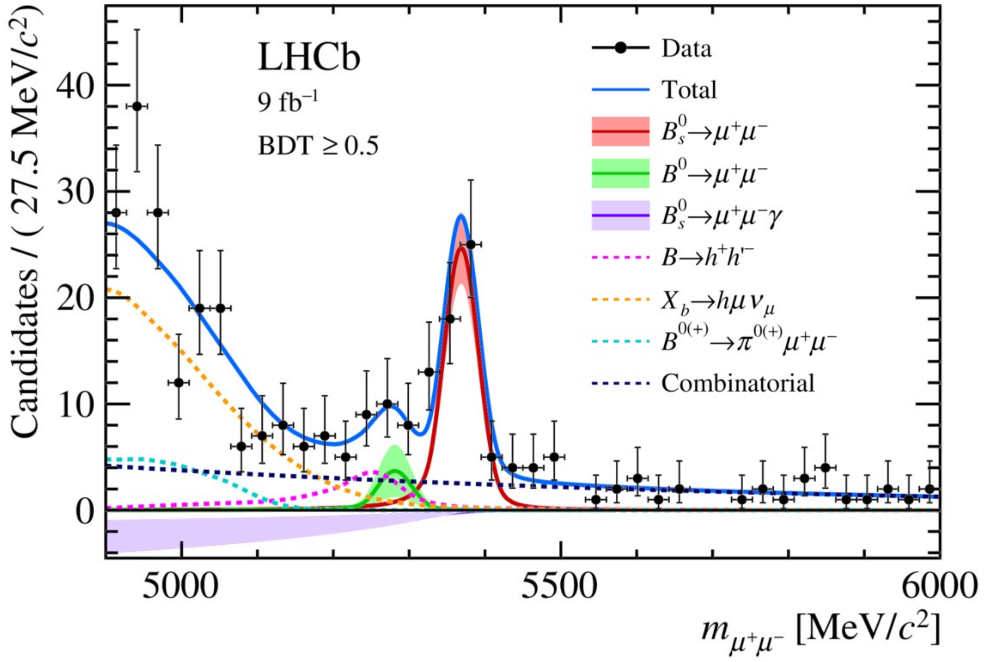
- Very precise prediction in the Standard Model

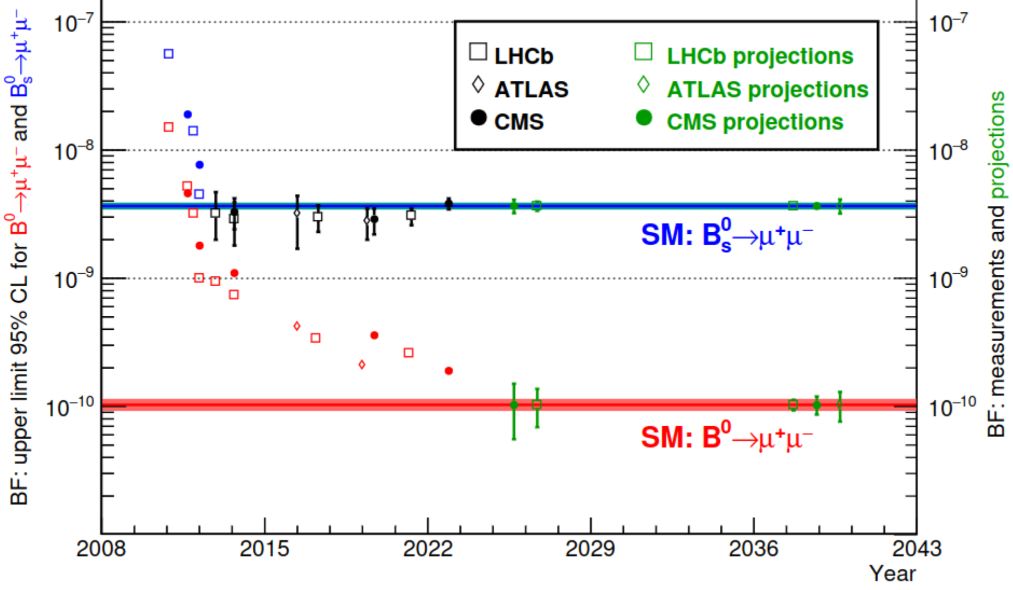
The $B^0_s \rightarrow \mu^+\mu^-$ decay



The $B^0_s \to \mu^+\mu^-$ decay

- Very complex endeavour to identify a decay at the *part-per-billion* level
- Eventually fit can be made to mass distribution of the two muons





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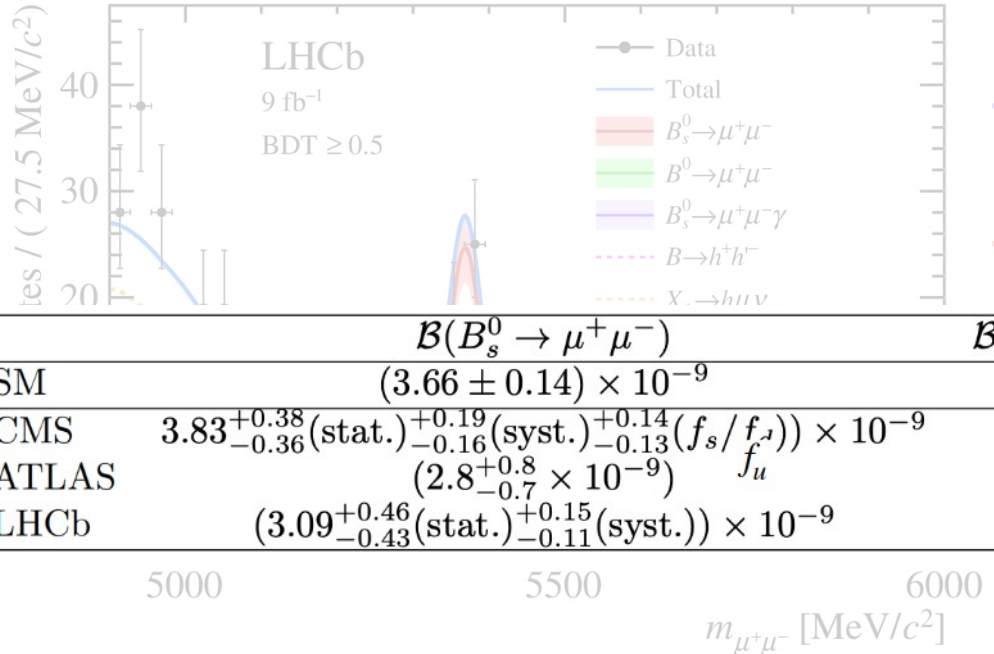
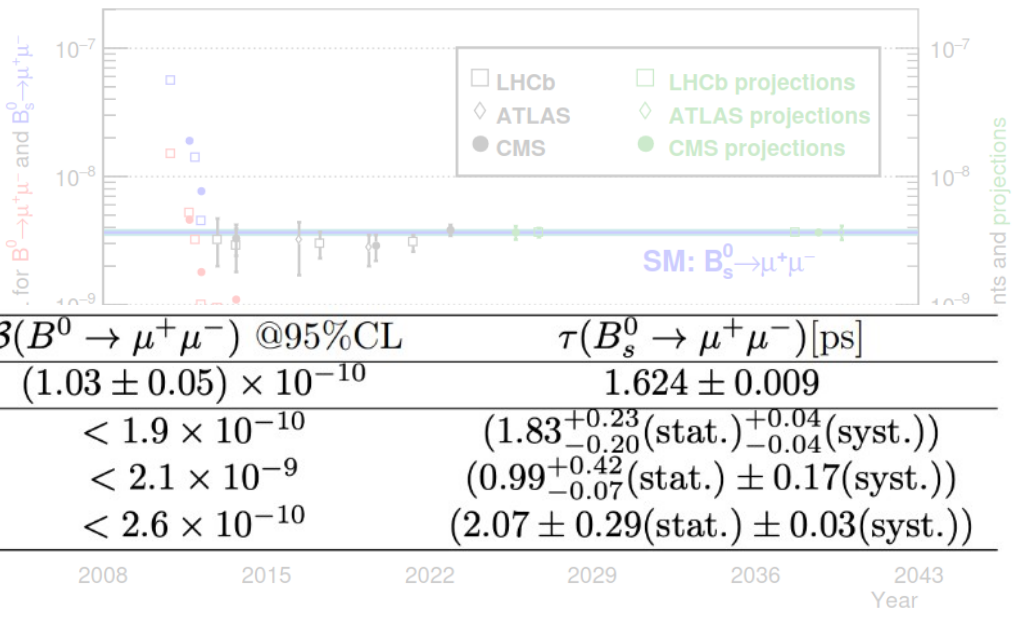
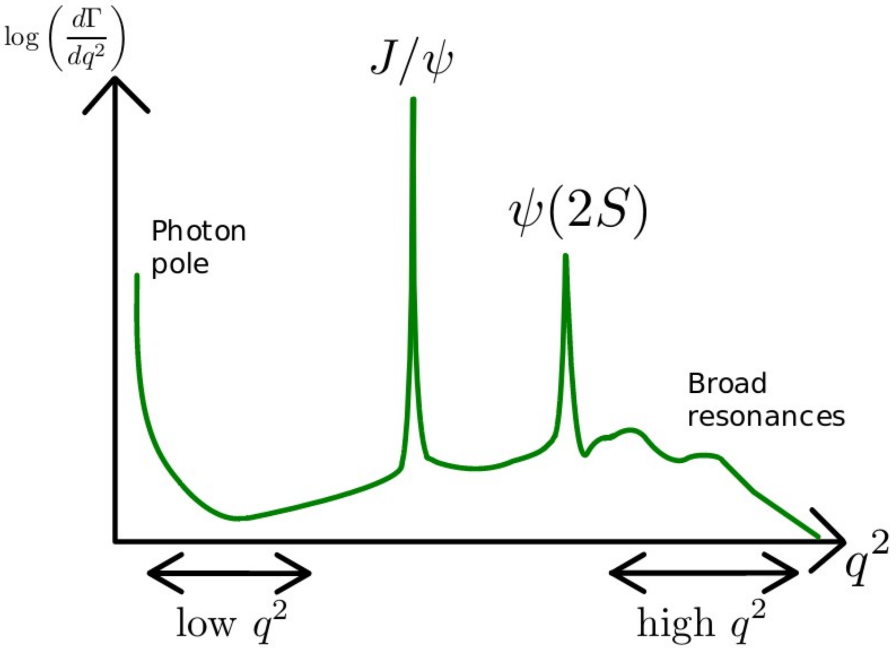




	$\mathcal{B}(B^0_s \rightarrow \mu^+\mu^-)$	$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-)$ @95%CL	$\tau(B^0_s \rightarrow \mu^+\mu^-)$[ps]
SM	$(3.66 \pm 0.14) \times 10^{-9}$	$(1.03 \pm 0.05) \times 10^{-10}$	1.624 ± 0.009
CMS	$3.83^{+0.38}_{-0.36}(\text{stat.})^{+0.19}_{-0.16}(\text{syst.})^{+0.14}_{-0.13}(f_s/f_u)) \times 10^{-9}$	$< 1.9 \times 10^{-10}$	$(1.83^{+0.23}_{-0.20}(\text{stat.})^{+0.04}_{-0.04}(\text{syst.}))$
ATLAS	$(2.8^{+0.8}_{-0.7} \times 10^{-9})$	$< 2.1 \times 10^{-9}$	$(0.99^{+0.42}_{-0.07}(\text{stat.}) \pm 0.17(\text{syst.}))$
LHCb	$(3.09^{+0.46}_{-0.43}(\text{stat.})^{+0.15}_{-0.11}(\text{syst.})) \times 10^{-9}$	$< 2.6 \times 10^{-10}$	$(2.07 \pm 0.29(\text{stat.}) \pm 0.03(\text{syst.}))$

Topology of $B^0 \rightarrow K^{*0}\mu^+\mu^-$

- The local (high energy) amplitudes interferes with the non-local tree level $B \rightarrow K^{*0}(c\bar{c})$ followed by $(c\bar{c}) \rightarrow \mu^+\mu^-$
- Gives multiple regions in $q^2 = m^2_{\mu\mu}$
- Interference only relevant for vector current (C_9)



Observables

- So called “observables” were developed to categorise the decay
- F_L, fraction of decay produced with a longitudinally polarised K* seems to be the first

Volume 175, number 3 PHYSICS LETTERS B

RARE DECAYS OF THE B MESON

Patrick J. O'DONNELL[1]
CERN, CH-1211 Geneva 23, Switzerland

Received 11 April 1986

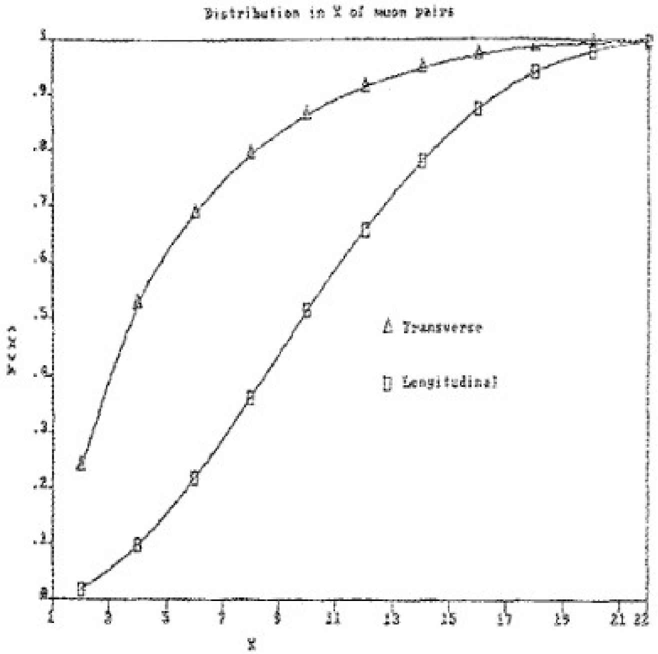


Fig. 1. The distribution functions $F(X)$ give the fraction of events for which the pairs produced have a value smaller than X. (Here X denotes the value of x in units of $2m_\mu$.) The fraction has been calculated separately for the distinct decay modes $B \to K^* \mu^+ \mu^-$ and $B \to K \mu^+ \mu^- X$. If only $\mu^+ \mu^-$ pairs are observed then F_T and F_L should be multiplied by $[\rho_T/(\rho_T + \rho_L)]$ and $[\rho_L/(\rho_T + \rho_L)]$, respectively.

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Optimised observables

- The observables were refined to minimise the effect of uncertainties in form factors
- In particular the P' observables have gained traction

JHEP05(2013)137

Optimizing the basis of $B \to K^* \ell^+ \ell^-$ observables in the full kinematic range

Sébastien Descotes-Genon,[a] Tobias Hurth,[b] Joaquim Matias[c] and Javier Virto[c]

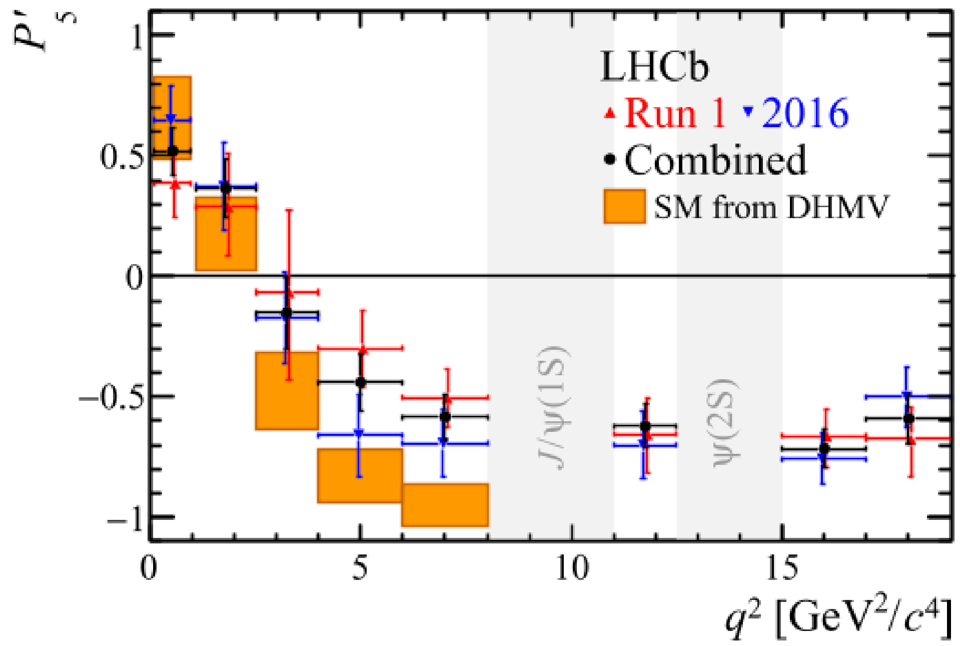
$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi\, dq^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi$$
$$+ S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big],$$

$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}.$$

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

- Results based on data from 2011 – 2016 from LHCb
- P_5' is a derived parameter from the angular distribution
- This fit excludes the largest resonance regions
- Leaves it to subsequent interpretation to deal with non-local effects

LHCb, Phys. Rev. Lett. 125 (2020) 011802



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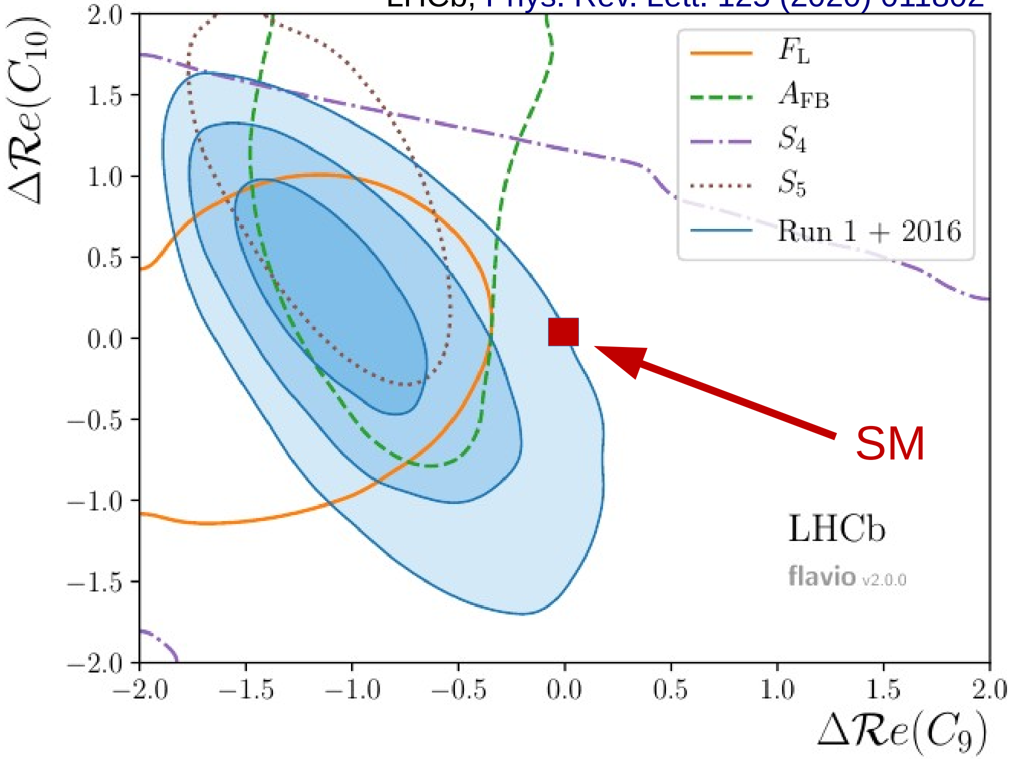
Measurement of observables

- All the angular observables from the $B^0 \rightarrow K^{*0}\mu^+\mu^-$ can be translated into constraints in the effective theory
- But the translation from experimental measurements to Wilson coefficients still depend on our “estimates” of low energy QCD effects.

LHCb, Phys. Rev. Lett. 125 (2020) 011802



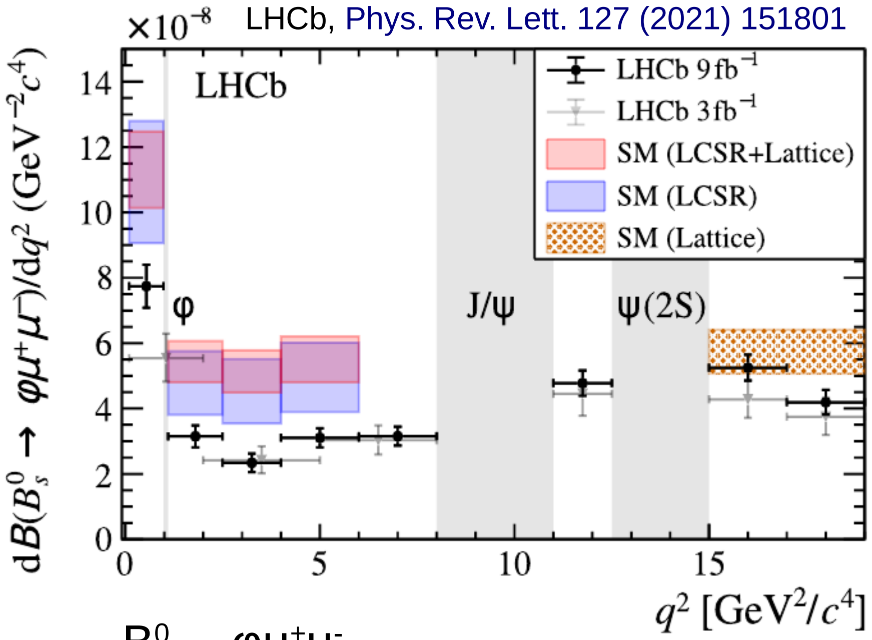
How to work around QCD limitations

- To be able to make firm statements about a signal of something new we need to get beyond the current limitation from QCD uncertainties
- Several directions to follow
  - Exploit that there is only one fundamental theory
  - Compare final states where only the leptons differ
  - Extract the QCD effects using a data driven method
  - Look for matter-antimatter difference (e.g. CP violation) in the decays
  - Final states with neutrinos

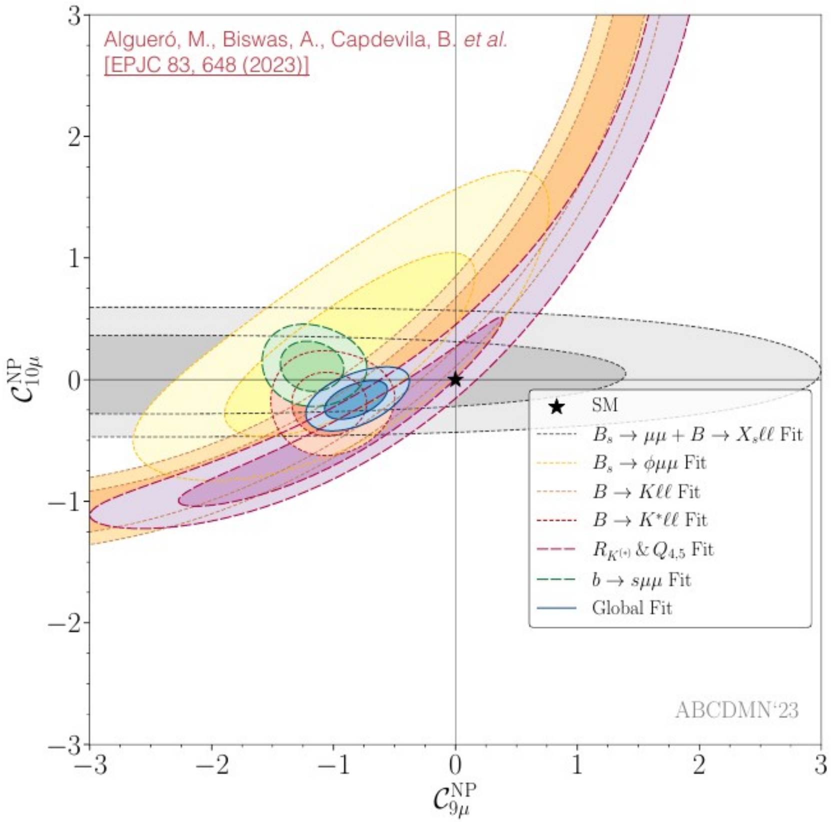
Exploit that there is only one fundamental theory

- For a given 4-fermion coupling there should only be one type of New Physics

LHCb, Phys. Rev. Lett. 127 (2021) 151801

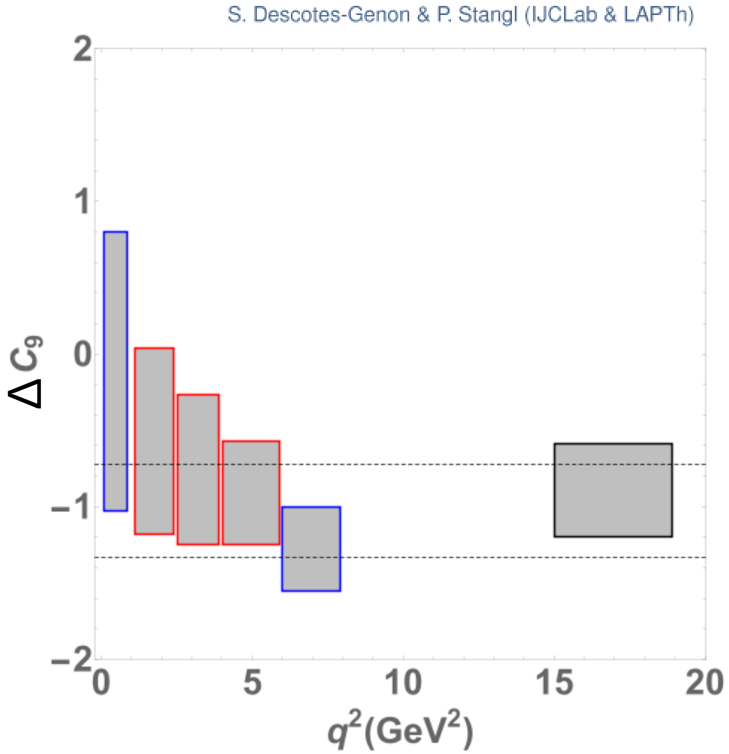


$B^0_s \rightarrow \phi\mu^+\mu^-$



Exploit that there is only one fundamental theory

- Any potential new physics should affect all regions in q^2
  - We can't have two different values of C_9
- We can fit the $B^0 \rightarrow K^{*0}\mu^+\mu^-$ in bins
  - Good agreement between different regions
  - Match between low q^2 (LCSR) and high q^2 (Lattice QCD) is encouraging
  - Sensitivity of comparison still quite poor



Fit anomalies and QCD simultaneously

- Use expression of dispersion relation to parametrise $B \to K^{*0}\mu\mu$ ($K^{*0} \to K^{+}\pi^{-}$)

$$A_0^{L,R}(q^2) = N_0 \left\{ \left[\left(\mathcal{C}_9^{(\mathrm{eff}),0}(q^2) - \mathcal{C}_9' \right) \mp \left(\mathcal{C}_{10} - \mathcal{C}_{10}' \right) \right] A_{12}(q^2) + \frac{m_b}{m_B + m_{K^*}} \left(\mathcal{C}_7^{(\mathrm{eff}),0} - \mathcal{C}_7' \right) T_{23}(q^2) \right\},$$

$$A_\parallel^{L,R}(q^2) = N_\parallel \left\{ \left[\left(\mathcal{C}_9^{(\mathrm{eff}),\parallel}(q^2) - \mathcal{C}_9' \right) \mp \left(\mathcal{C}_{10} - \mathcal{C}_{10}' \right) \right] \frac{A_1(q^2)}{m_B - m_{K^*}} + \frac{2m_b}{q^2} \left(\mathcal{C}_7^{(\mathrm{eff}),\parallel} - \mathcal{C}_7' \right) T_2(q^2) \right\},$$

$$A_\perp^{L,R}(q^2) = N_\perp \left\{ \left[\left(\mathcal{C}_9^{(\mathrm{eff}),\perp}(q^2) + \mathcal{C}_9' \right) \mp \left(\mathcal{C}_{10} + \mathcal{C}_{10}' \right) \right] \frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2} \left(\mathcal{C}_7^{(\mathrm{eff}),\perp} - \mathcal{C}_7' \right) T_1(q^2) \right\},$$

$$A_t(q^2) = N_t \left\{ 2 \left[\mathcal{C}_{10} - \mathcal{C}_{10}' \right] A_0(q^2) \right\},$$

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Fit anomalies and QCD simultaneously

Dispersion Relation

Local / Non-local contributions

$$C_9^{\mathrm{eff},\lambda}(q^2) = C_9^{\mu} + Y_{c\bar{c}}^{(0),\lambda} + Y_{c\bar{c}}^{1P,\lambda}(q^2) + Y_{\mathrm{light}}^{1P,\lambda}(q^2) + Y_{c\bar{c}}^{2P,\lambda}(q^2) + Y_{\tau\bar{\tau}}(q^2)$$

$$C_7^{\mathrm{eff},\lambda}(q^2) = C_7^{\mu} + \epsilon^{\lambda} e^{i\omega^0}$$

C. Cornella, G. Isidori, M. König, S. Liechti, P. Owen, N. Serra [Eur.Phys.J.C 80 (2020) 12, 1095]

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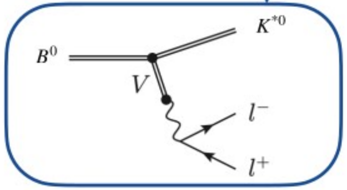

1-particle contributions

Includes:

$\omega(782)$, $\rho(770)$, $\phi(1020)$, J/ψ, $\psi(2S)$, $\psi(3770)$, $\psi(4040)$, $\psi(4160)$

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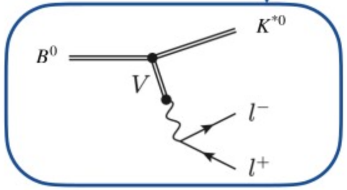

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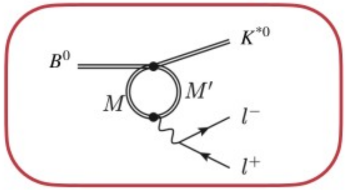

2-particle contributions

Includes:
$D\bar{D}$, $D^*\bar{D}$, $D^*\bar{D}^*$

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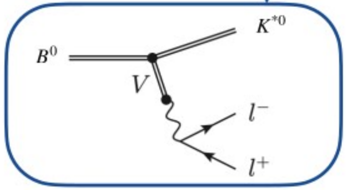

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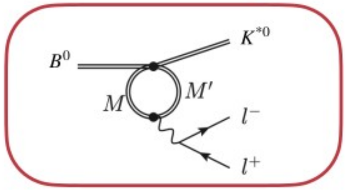

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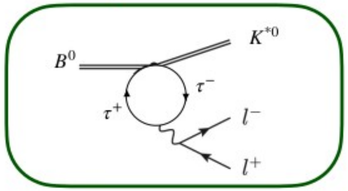

Tau loop contribution

Sensitive to C_9^{τ}

C. Cornella, G. Isidori, M. König, S. Liechti, P. Owen, N. Serra [Eur.Phys.J.C 80 (2020) 12, 1095]

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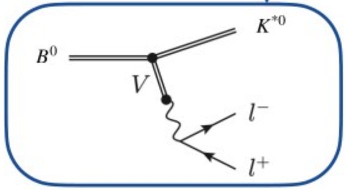
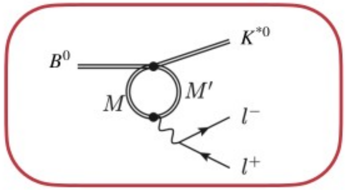
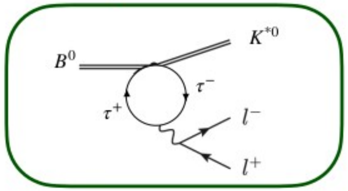
$$C_7^{\text{eff},\lambda}(q^2) = C_7^\mu + \epsilon^\lambda e^{i\omega^0}$$

This is determined theoretically at negative q^2 values







Subtraction term

Asatrian, Greub, Virto [JHEP 04 (2020) 012]

Negligible impact from light quarks

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$$C_9^{\text{eff},\lambda}(q^2) = C_9^{\mu} + Y_{c\bar{c}}^{(0),\lambda} + Y_{c\bar{c}}^{1P,\lambda}(q^2) + Y_{\text{light}}^{1P,\lambda}(q^2) + Y_{c\bar{c}}^{2P,\lambda}(q^2) + Y_{\tau\bar{\tau}}(q^2)$$

$$C_7^{\text{eff},\lambda}(q^2) = C_7^{\mu} + \epsilon^{\lambda} e^{i\omega^0}$$

ΔC_7^{λ}

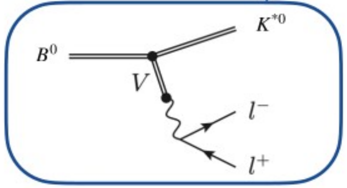
Polarisation dependent shift to C_7

This is determined theoretically at negative q^2 values

Subtraction term

Asatrian, Greub, Virto [JHEP 04 (2020) 012]

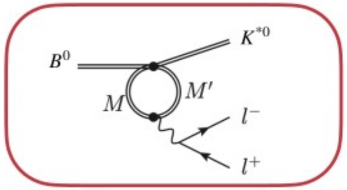
Negligible impact from light quarks



1-particle contributions

Includes:

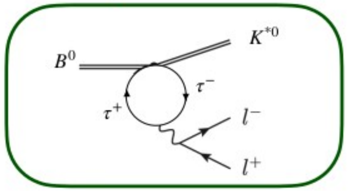
$\omega(782)$, $\rho(770)$, $\phi(1020)$, J/ψ, $\psi(2S)$, $\psi(3770)$, $\psi(4040)$, $\psi(4160)$



2-particle contributions

Includes:

$D\bar{D}$, $D^*\bar{D}$, $D^*\bar{D}^*$



Tau loop contribution

Sensitive to C_9^{τ}

C. Cornella, G. Isidori, M. König, S. Liechti, P. Owen, N. Serra [Eur.Phys.J.C 80 (2020) 12, 1095]

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Fit anomalies and QCD simultaneously

Dispersion Relation

Local — Non-local contributions

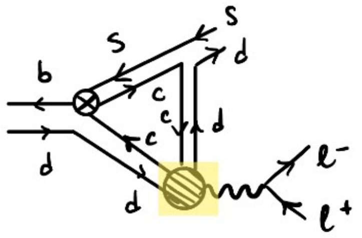
$$C_9^{\text{eff},\lambda}(q^2) = C_9^{\mu} + Y_{c\bar{c}}^{(0),\lambda} + Y_{c\bar{c}}^{1P,\lambda}(q^2) + Y_{\text{light}}^{1P,\lambda}(q^2) + Y_{c\bar{c}}^{2P,\lambda}(q^2) + Y_{\tau\bar{\tau}}(q^2)$$

$$C_7^{\text{eff},\lambda}(q^2) = C_7^{\mu} + \epsilon^{\lambda} e^{i\omega^0}$$

Rescattering terms not implemented

Ciuchini et al,
Phys.Rev.D 107 (2023) 5, 055036

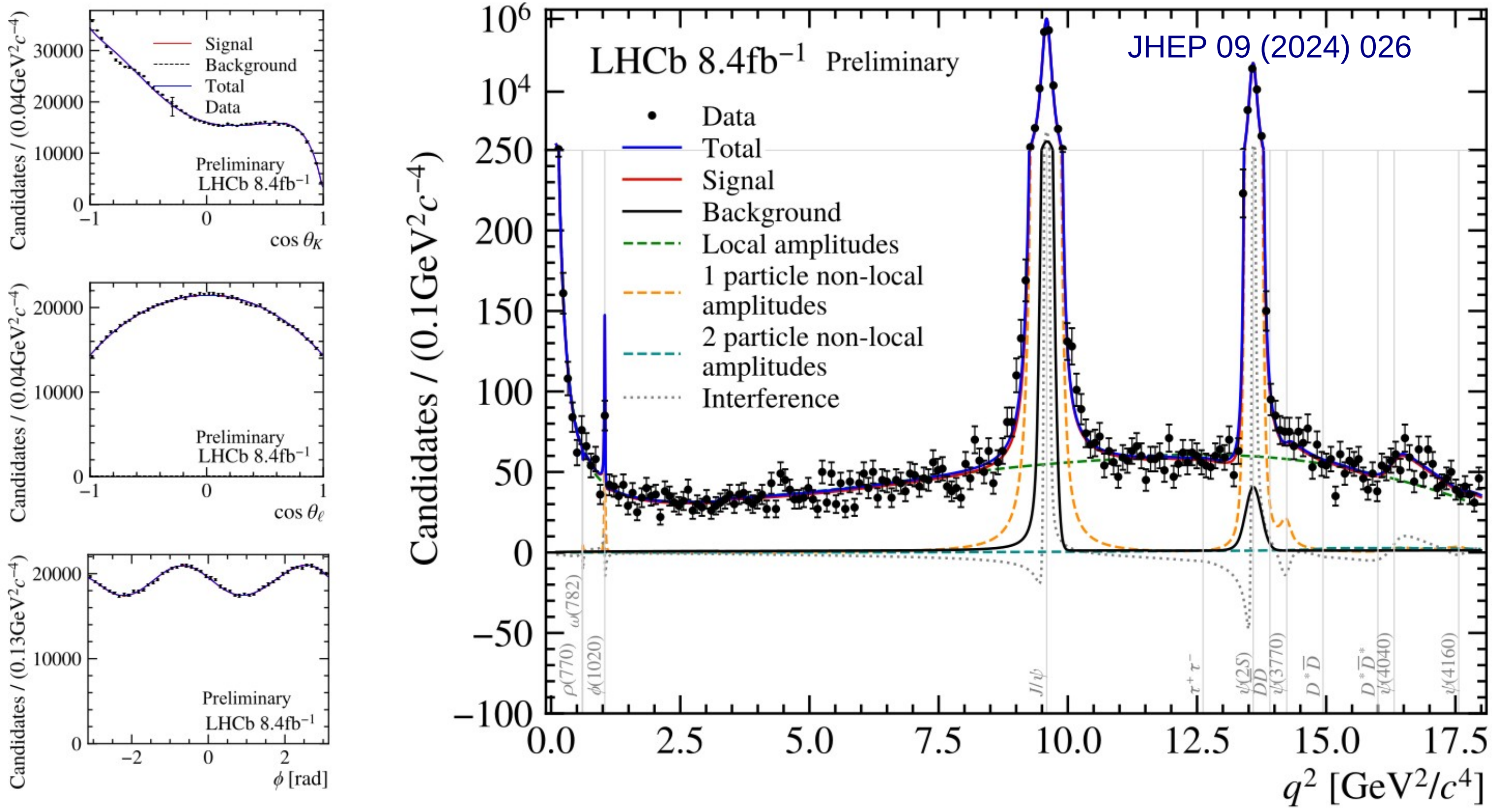
Isidori, Polonsky, Tinari
Phys.Rev.D 111 (2025) 9, 093007



C. Cornella, G. Isidori, M. König, S. Liechti, P. Owen, N. Serra [Eur.Phys.J.C 80 (2020) 12, 1095]

Fit anomalies and QCD simultaneously

- An unbinned analysis in the dimuon mass - In total 150 parameters



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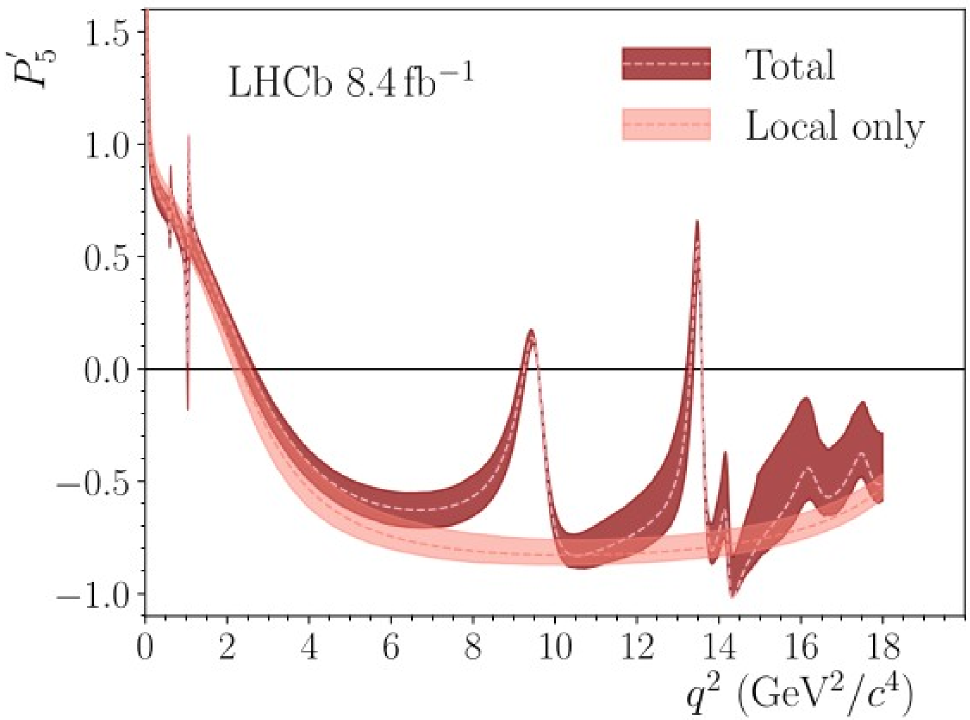
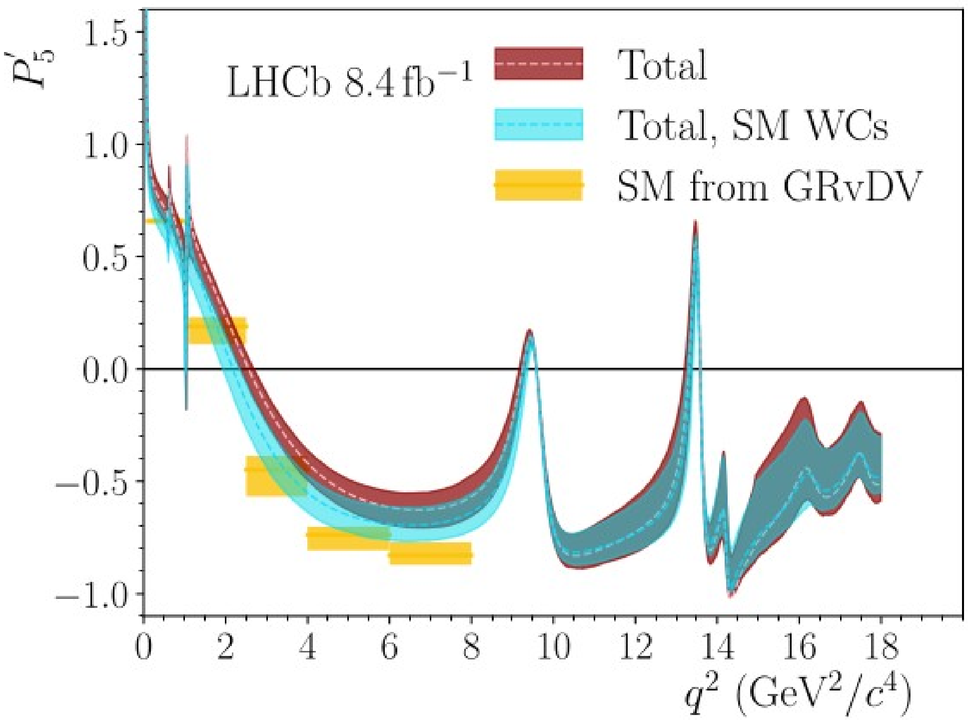
Fit anomalies and QCD simultaneously

- We now **measure** the non-local effects from charm loops!

JHEP 09 (2024) 026





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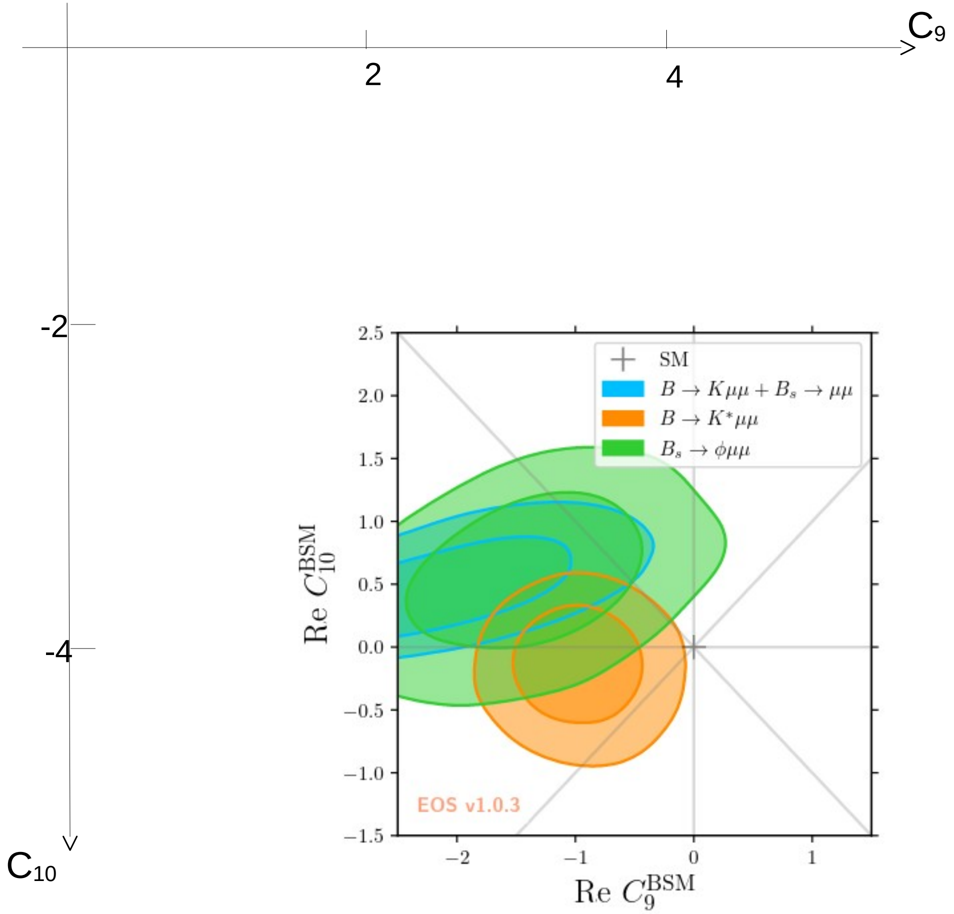
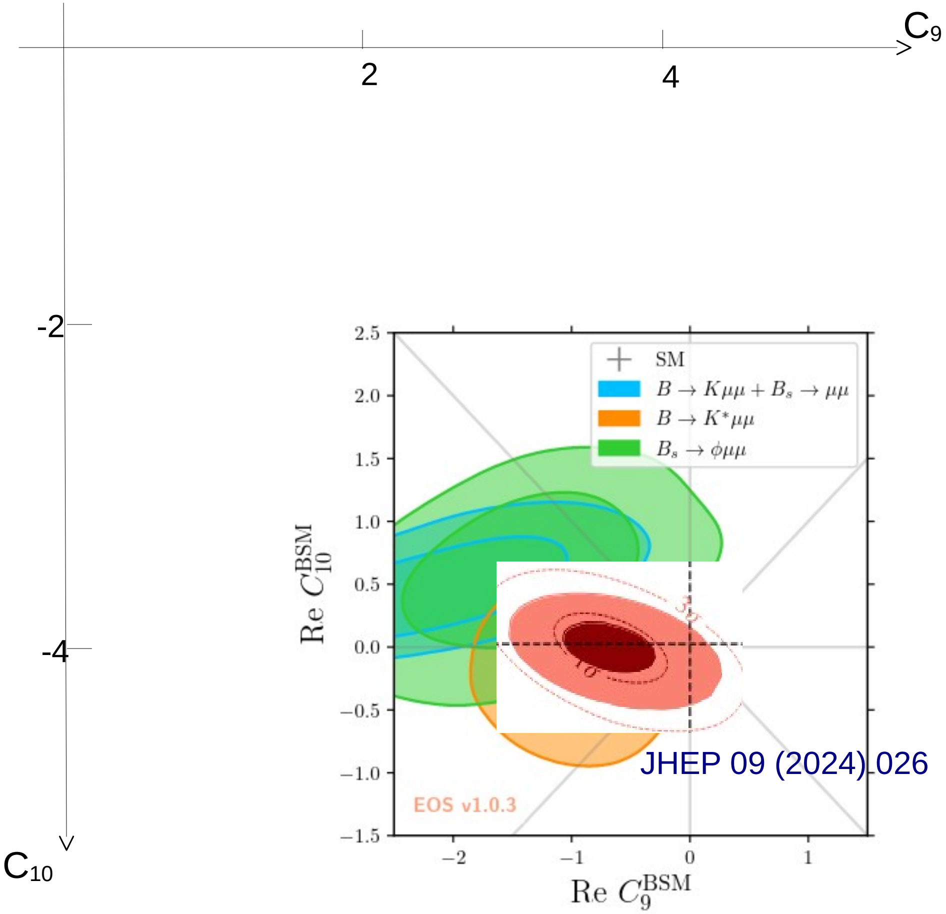
Improved precision from this measurement

- Orange is all knowledge from previous measurements of decay



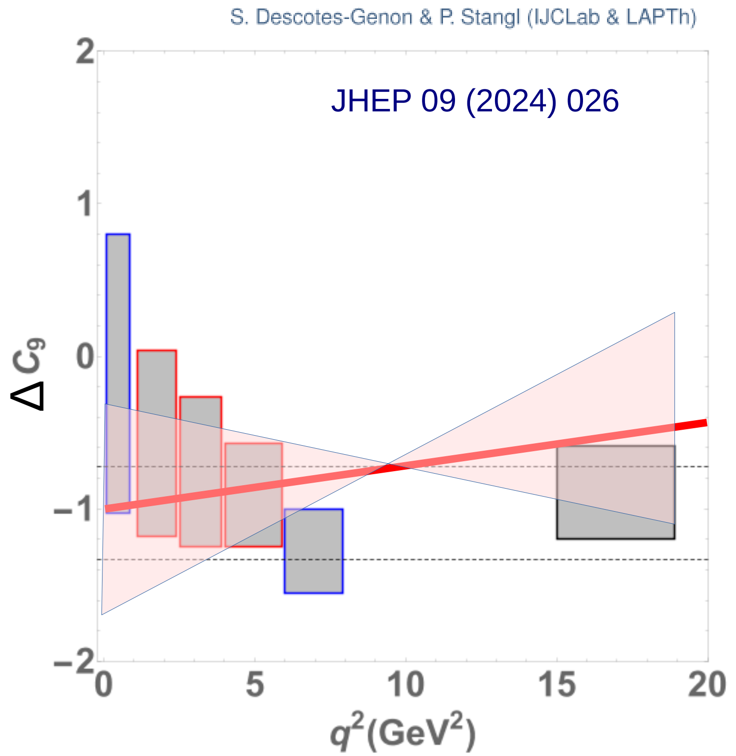
Improved precision from this measurement

- Orange is all knowledge from previous measurements of decay
- Shrinkage to red region is from a factor 2 more data and 7 years of work
- Even includes fit to C_9', C_{10}', $C_{9\tau}$ that were ignored before



Exploit that there is only one fundamental theory

- The unbinned fit can be extended to allow for an unphysical change of Wilson coefficient as function of q^2
- For vector current (C9), uncertainty is quite large due to resonances



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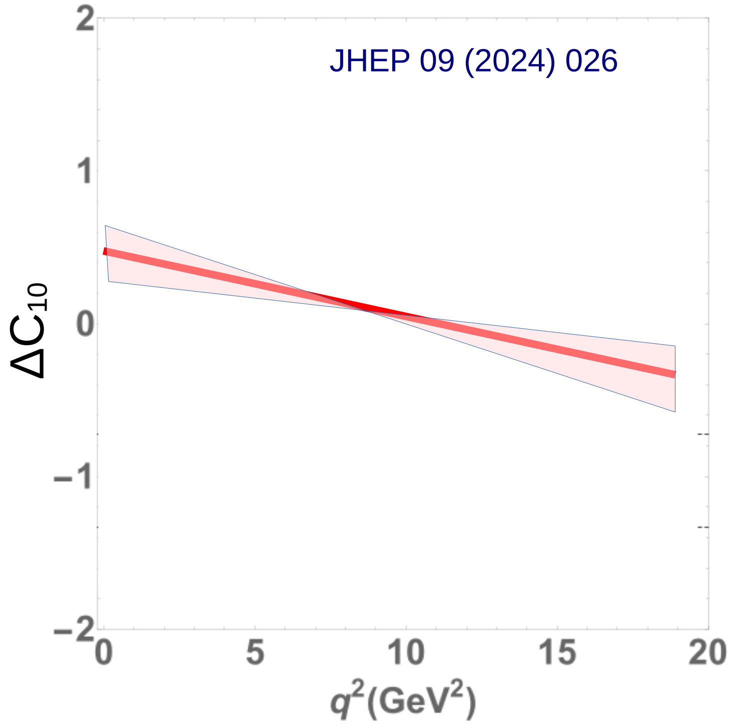
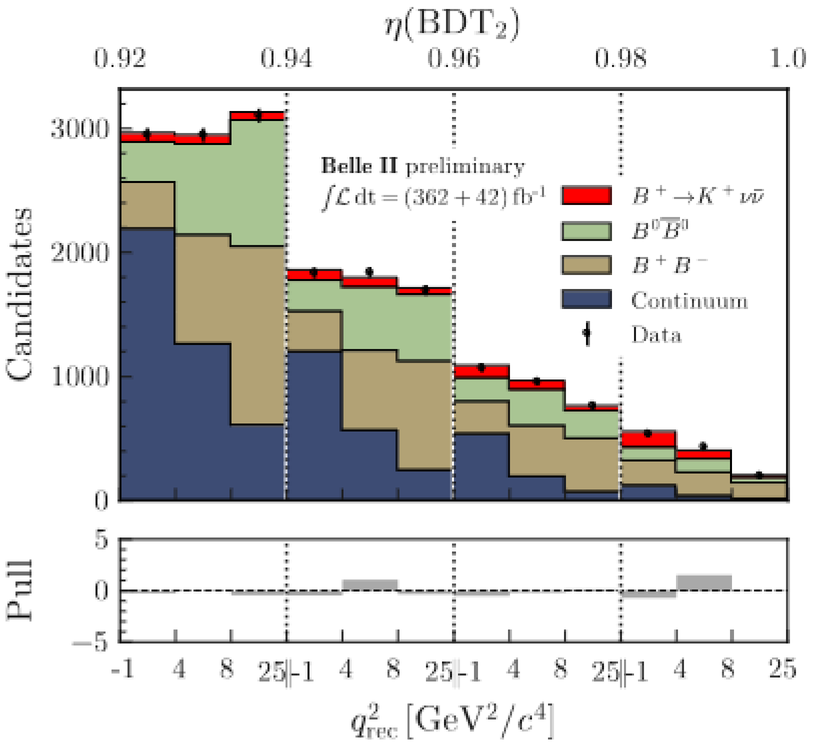
Exploit that there is only one fundamental theory

- The unbinned fit can be extended to allow for an unphysical change of Wilson coefficient as function of q^2
- For vector current (C9), uncertainty is quite large due to resonances
- For axial-vector, we see agreement with no slope at 2.2σ level. Issue with form factors?



Final states with neutrinos

- We can investigate decays with neutrinos, rather than charged leptons in final state
  - SM calculation is almost identical for differential decay rate, but no $c\bar{c}$ loops!
  - Final state $B \to K\nu\bar{\nu}$ impossible at hadron collider, but can be accessed at Belle II



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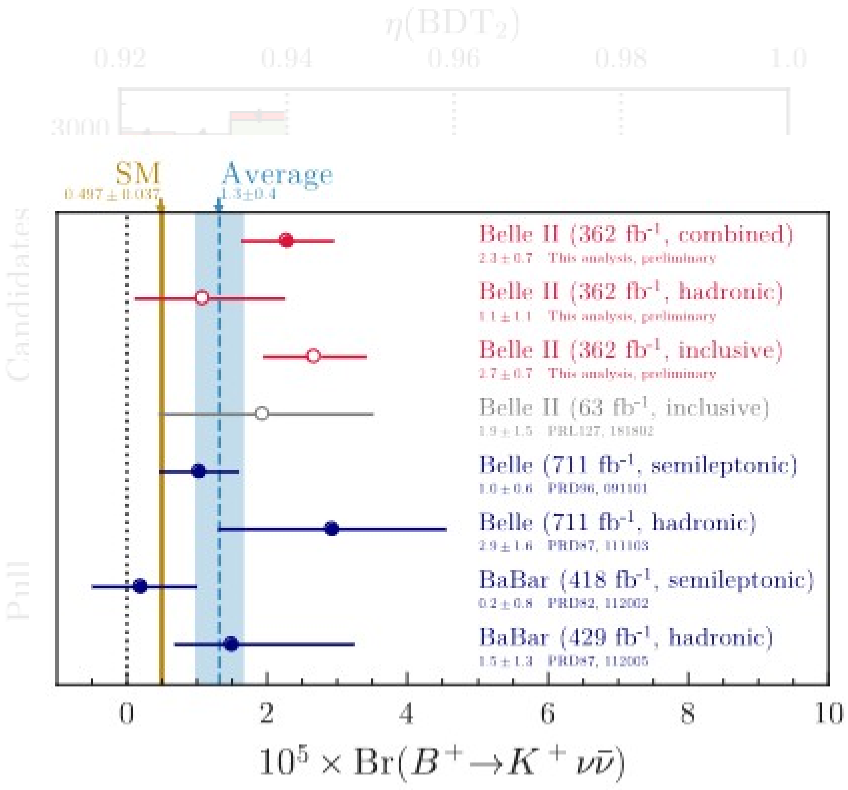
Final states with neutrinos

- We can investigate decays with neutrinos, rather than charged leptons in final state
  - SM calculation is almost identical for differential decay rate, but no $c\bar{c}$ loops!
  - Final state $B \rightarrow K\nu\bar{\nu}$ impossible at hadron collider, but can be accessed at Belle II
  - See evidence for decay at slightly above SM prediction



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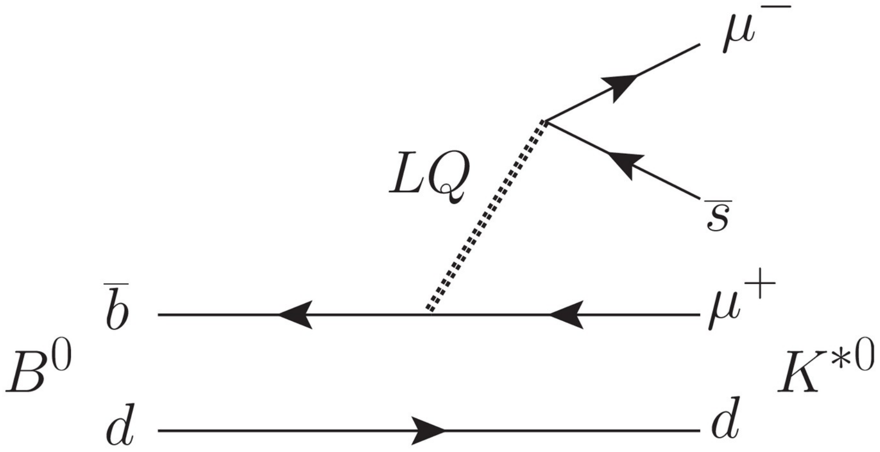
Conclusion

With enough data, we **WILL** be able to distinguish New Physics from QCD

LHCb upgrade I (2024-31?) and Upgrade II (2034?-) will form big part of this



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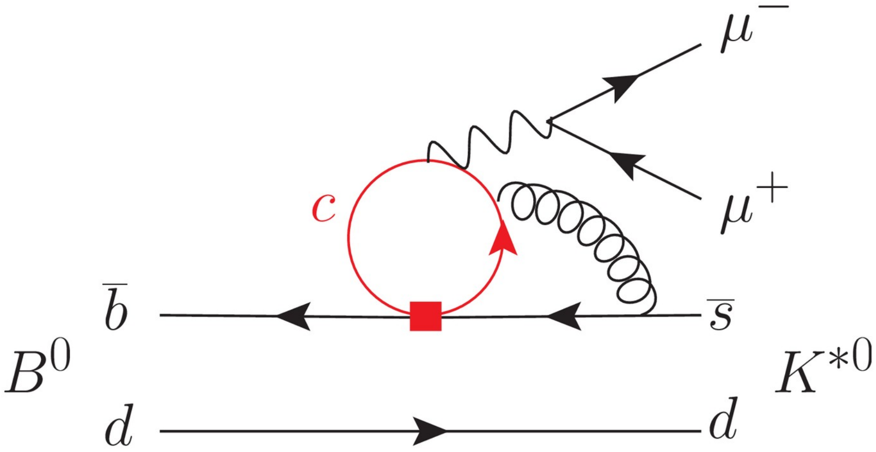
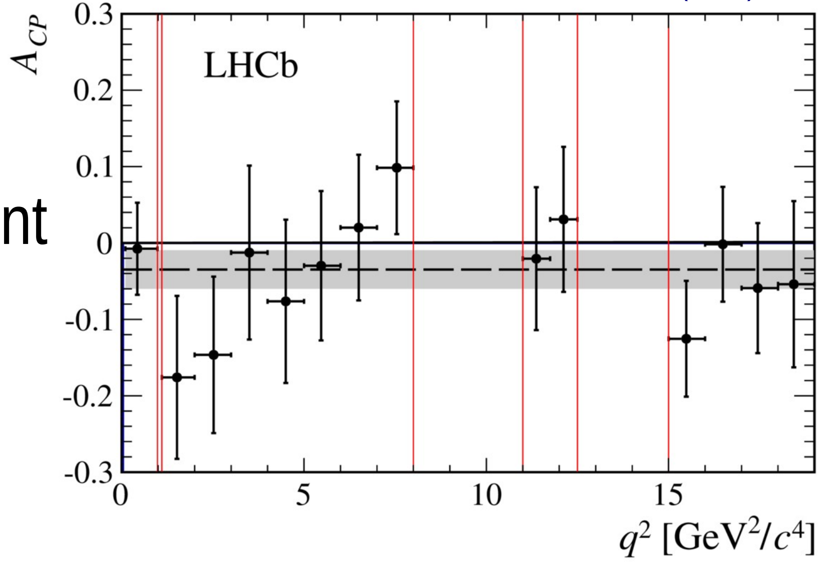


Look for matter-antimatter differences

- QCD treat matter and antimatter identically – no CP violation
  - An observation of CP violation would indicate new physics amplitudes
  - To observe it requires interference with SM amplitudes of different phase
  - Unfortunately existing measurement exactly avoids regions where we will have phase difference

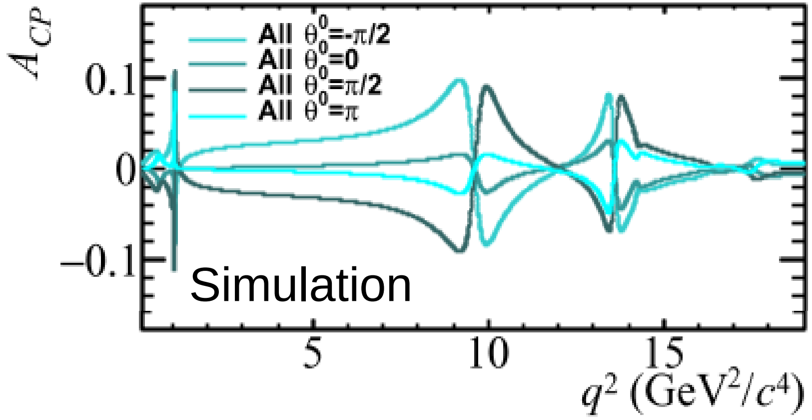
JHEP 09 (2014) 177



Look for matter-antimatter differences

- QCD treat matter and antimatter identically – no CP violation
  - An observation of CP violation would indicate new physics amplitudes
  - To observe it requires interference with SM amplitudes of different phase
  - Combining unbinned fit with CP violation analysis will allow for this

Eur.Phys.J.C 78 (2018) 6, 453



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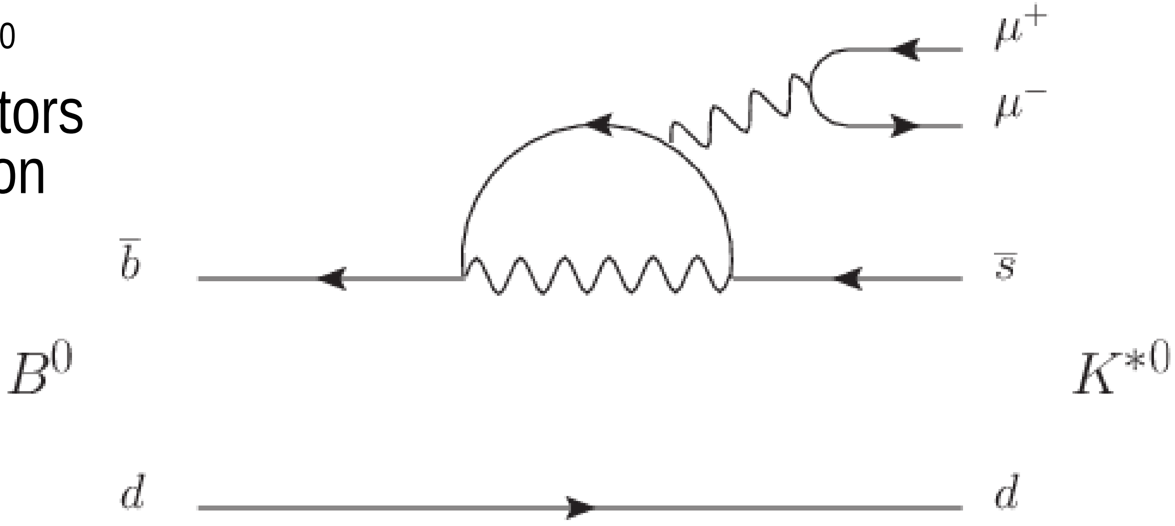
Final states where only the leptons differ

- Lepton universality is one of the key features of the Standard Model
- The only difference for decays with electrons, muons and taus is from their mass
  - Effect of this is easy to correct for in predictions
  - Discovery of lepton flavour non-universality is a key signature of New Physics
- Some serious drawbacks though
  - The experimental measurements of electrons, muons and taus is anything but universal
  - The measurements are only sensitive to effects that are not lepton universal

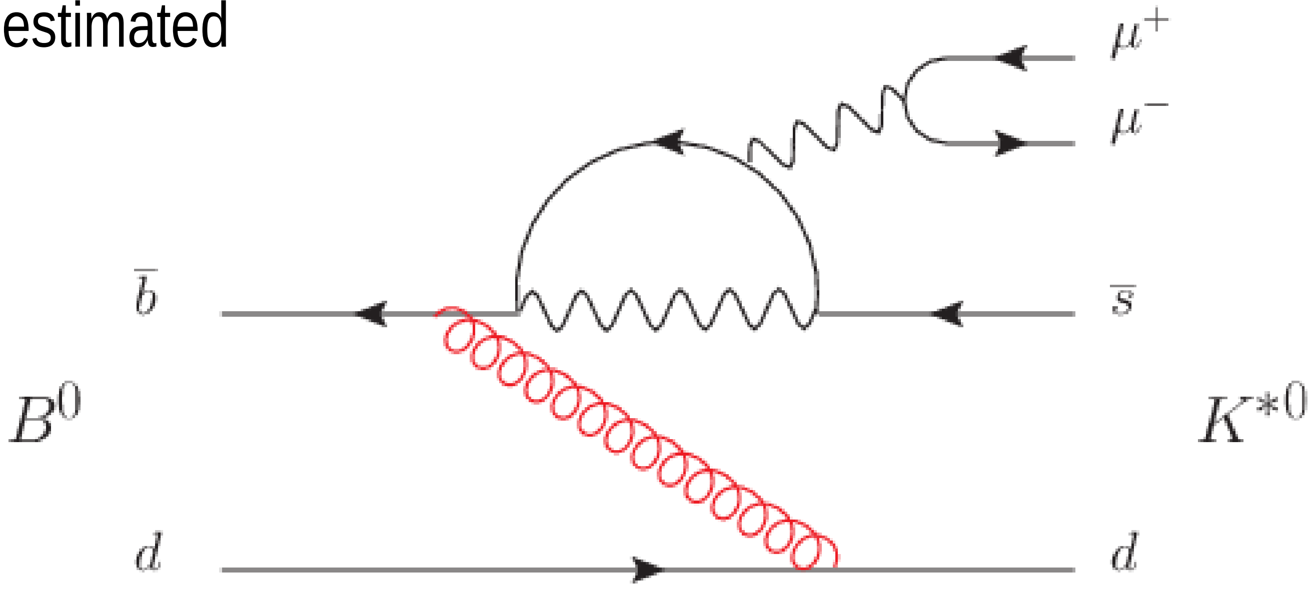
Theory at lowest order

- Decay can't proceed through tree level, so loop level weak decay is lowest order
  - Physics at high energy scale gives Wilson coefficients C_7, C_9, C_{10}
  - Theory provides the form factors that describe the hadornisation into the K*
- Combination gives prediction of angular distribution that can be compared to measurements



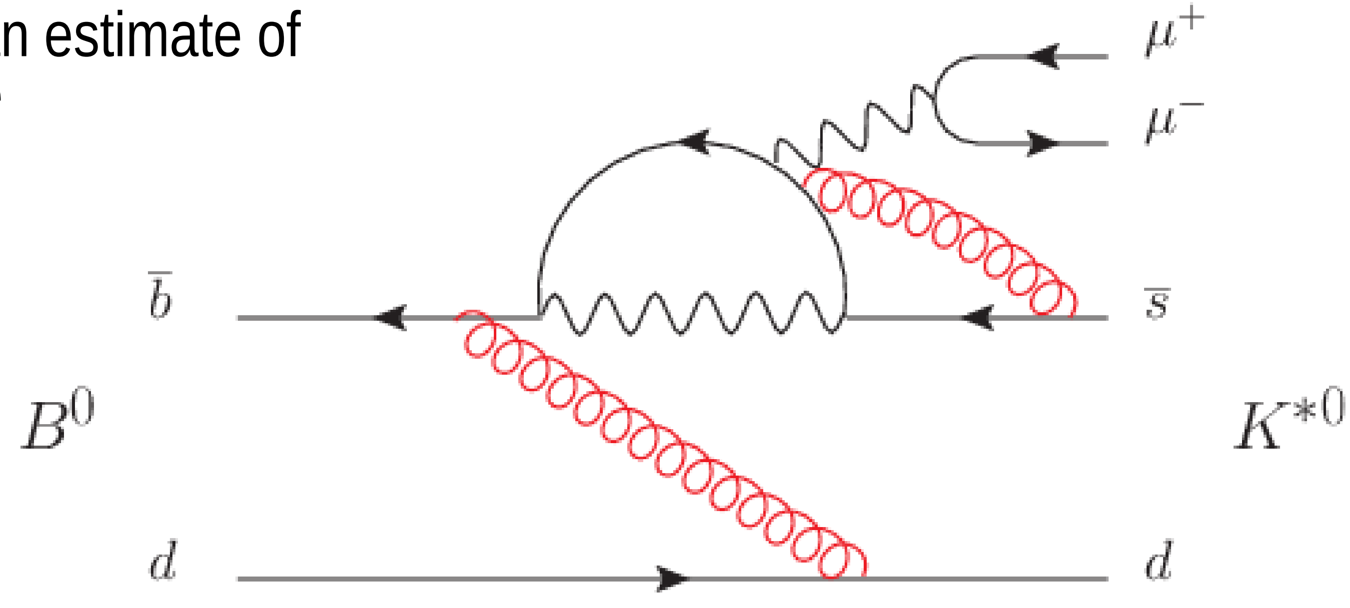
Factorisable corrections

- Strong interactions to the spectator quark can be dealt with through factorisation using Light Cone Sum Rule or Lattice QCD calculations
  - Uncertainties are at the few percent level and can be well estimated



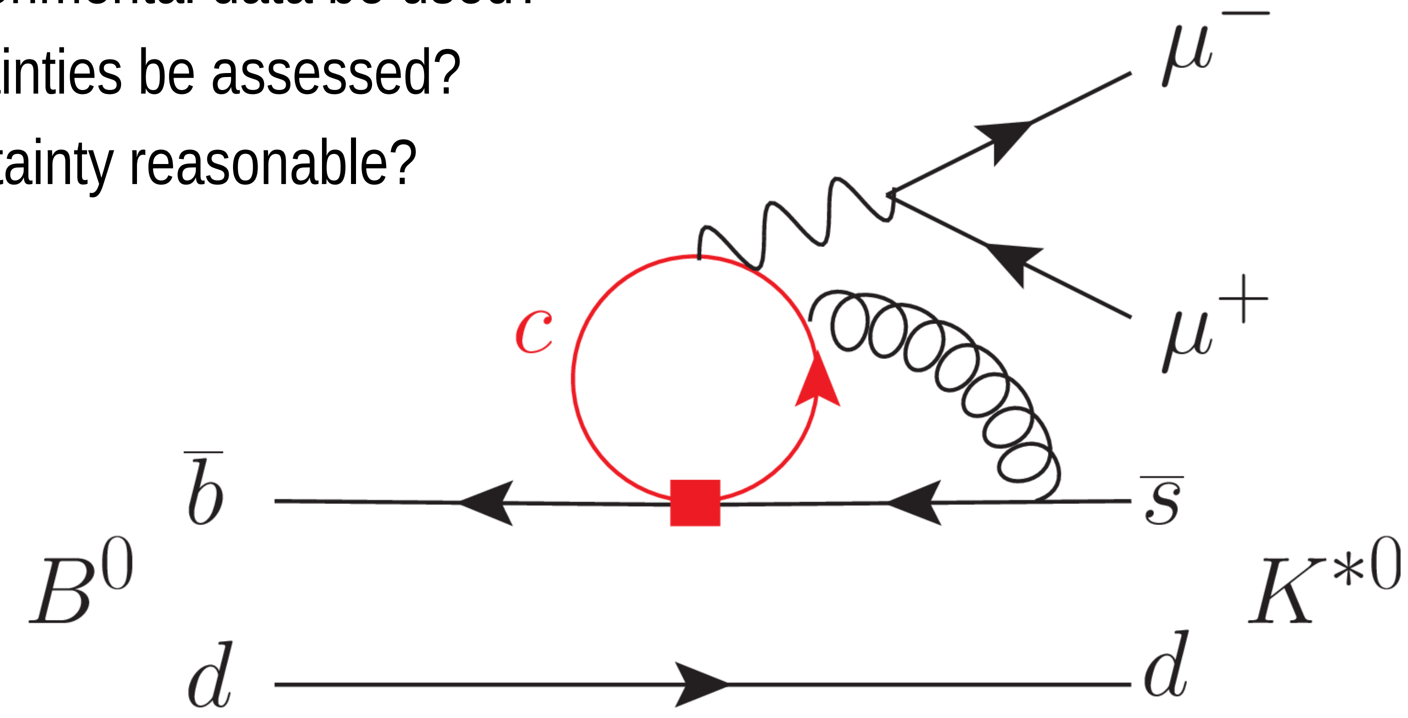
Non-factorisable corrections

- When the lepton system can no longer be regarded as isolated, the theoretical framework is much weaker
  - From looking at the size of this effect in hadronic decays, an estimate of O(10%) can be made



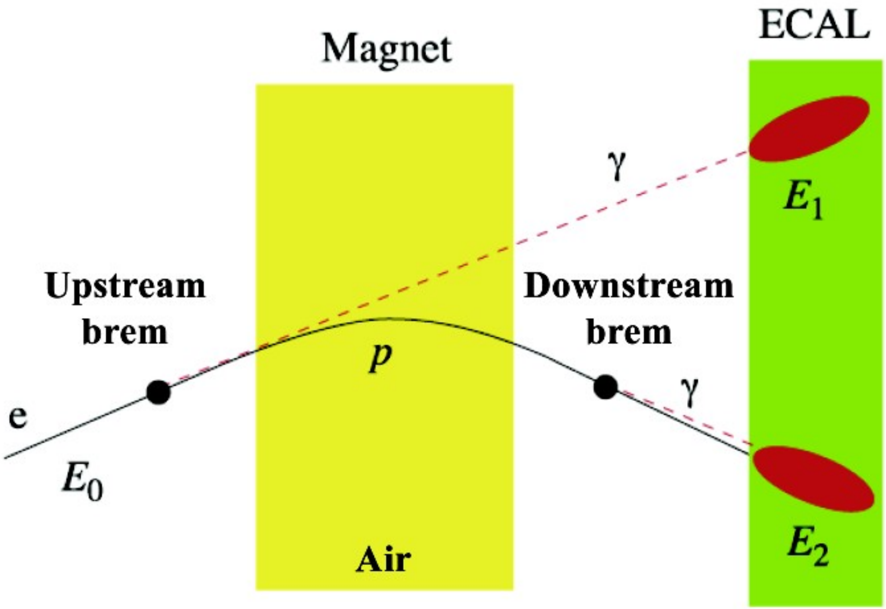
Charm loop corrections

- The most hotly debated area at the moment
  - How should experimental data be used?
  - How can uncertainties be assessed?
  - Is O(10%) uncertainty reasonable?



Electron identification is hard

- Electrons are very light
  - When they pass through material they emit bremsstrahlung
    - Curvature in magnetic field will measure too low momentum
  - Photons can convert and fake electrons
  - Background from $\pi^0 \rightarrow \gamma\gamma$ decay that can fake electrons
- Bremsstrahlung recovery can (partially) fix this



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

- The dependence on the efficiency of reconstructing electrons can be reduced through double ratio

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+J/\psi(\mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to K^+J/\psi(e^+e^-))}$$

$$= \frac{N(B^+ \to K^+\mu^+\mu^-)}{N(B^+ \to K^+J/\psi(\mu^+\mu^-))} \times \frac{\varepsilon_{B^+\to K^+J/\psi(\mu^+\mu^-)}}{\varepsilon_{B^+\to K^+\mu^+\mu^-}}$$

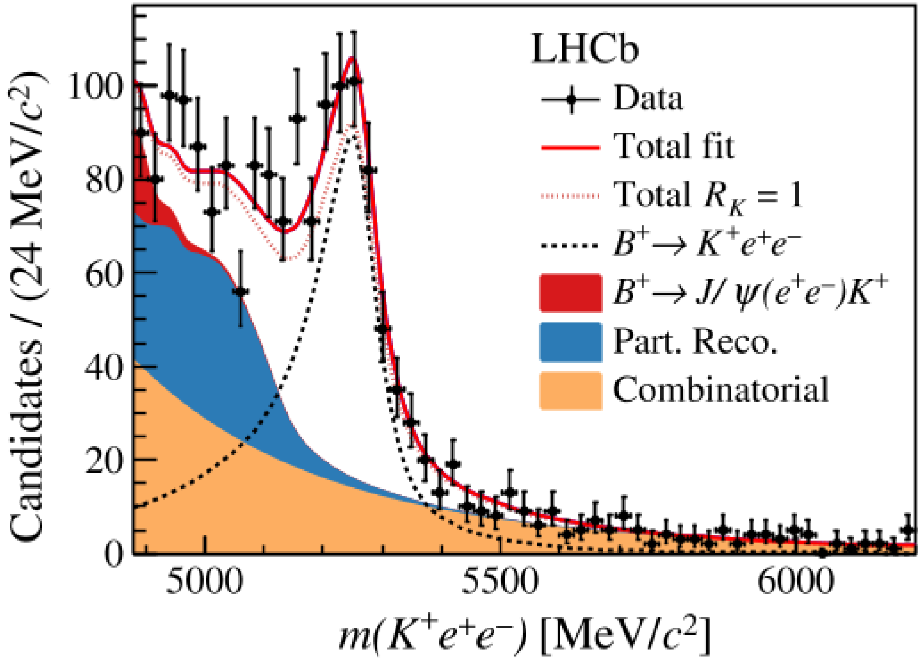
$$\times \frac{N(B^+ \to K^+J/\psi(e^+e^-))}{N(B^+ \to K^+e^+e^-)} \times \frac{\varepsilon_{B^+\to K^+e^+e^-}}{\varepsilon_{B^+\to K^+J/\psi(e^+e^-)}}$$

- J/ψ decay proceed through virtual photon which is measured to be lepton-universal at 0.4% level

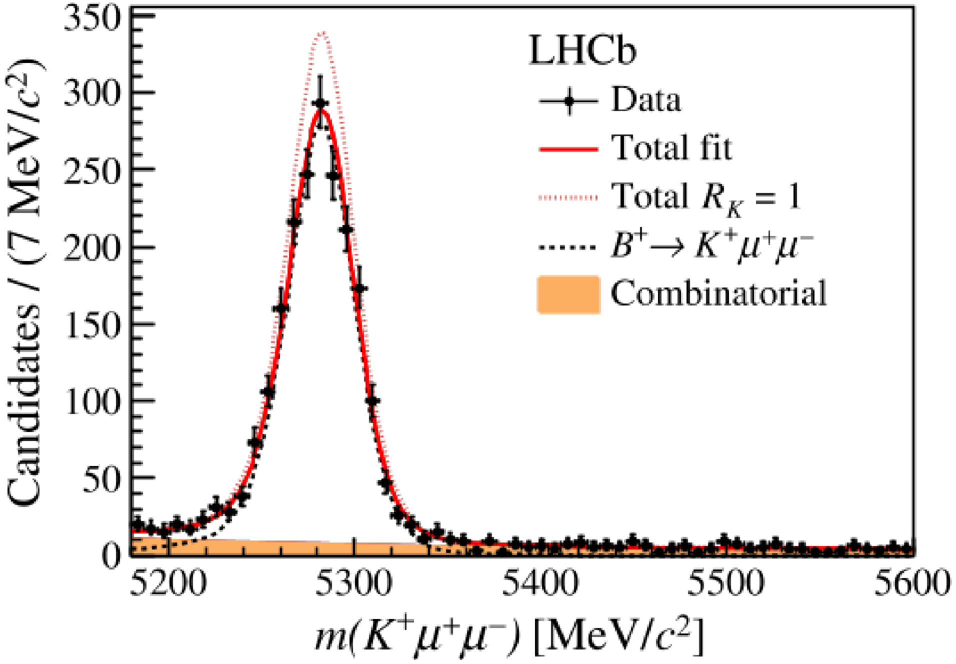
$B^+ \to K^+\mu^+\mu^-$ vs $B^+ \to K^+e^+e^-$

- Reconstructed peaks in the electron and muon modes

Electrons



Muons



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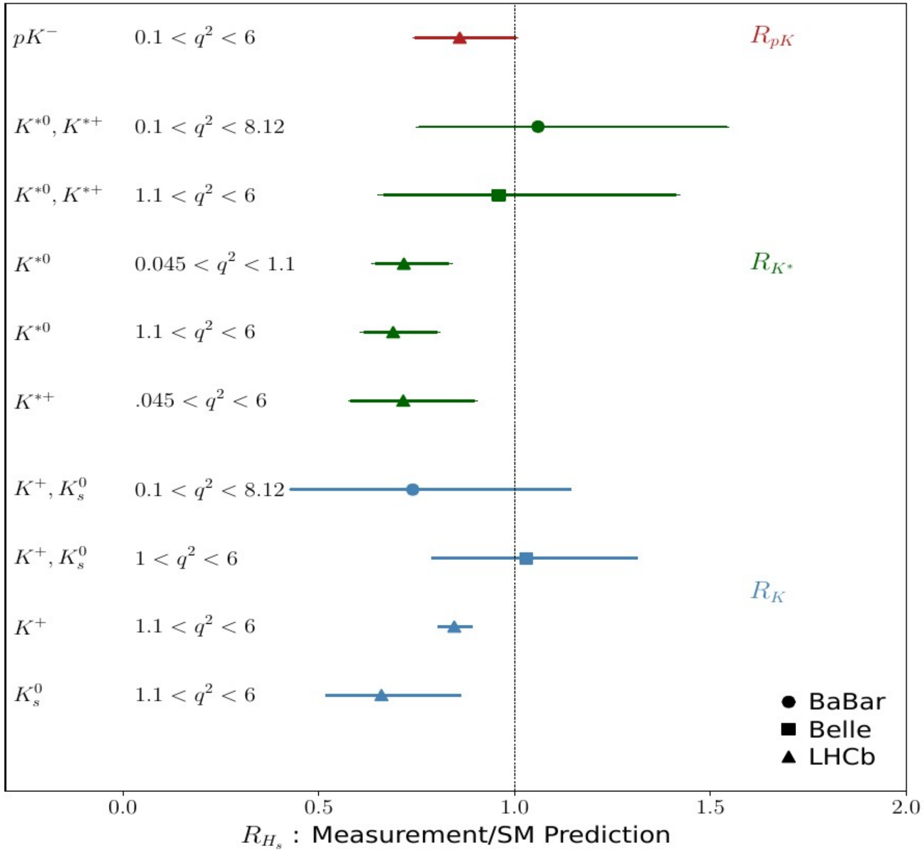
Many measurements of lepton non-universality

- Many of the measurements shows that that the muon final states are less common than the electron ones
- Several measurements are above 2σ below the SM expectation
- We need more data **AND** other experiments (Belle II) to do this



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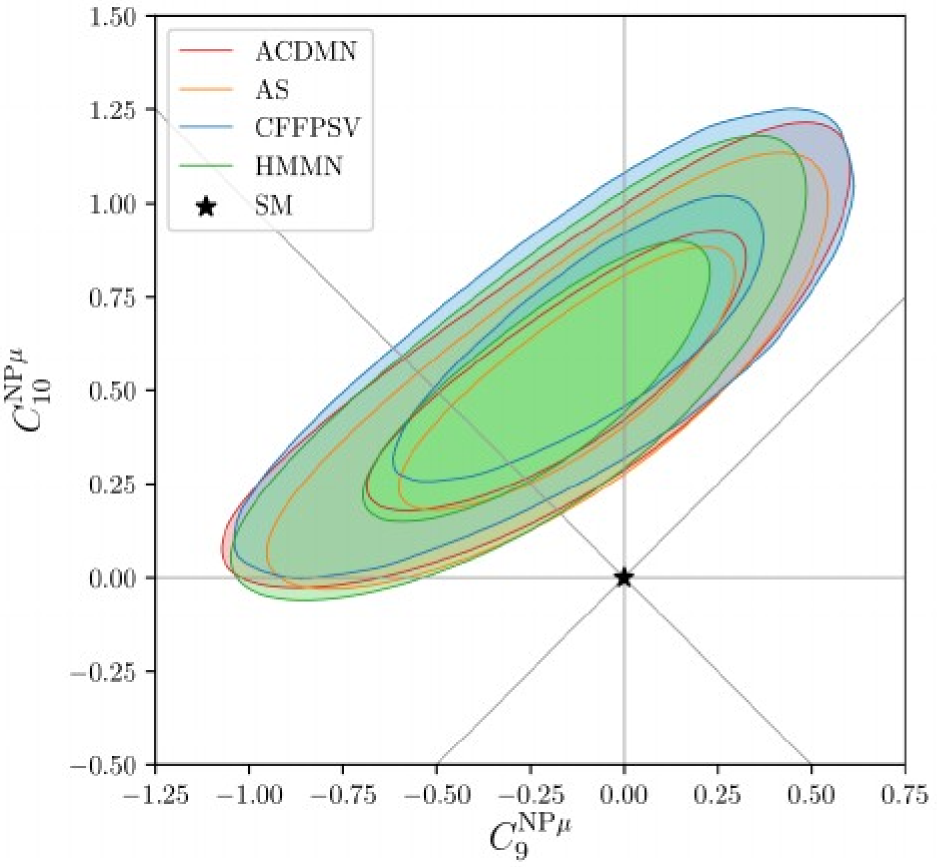
Many measurements of lepton non-universality

- Combine all lepton non-universality measurements with $B^0_s \rightarrow \mu^+\mu^-$ measurement
- All theoretical groups prefer a non-SM solution by around 3σ



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Extract the QCD effects using a data driven method

- With knowledge of the form factors, the branching fraction can tell about the Wilson coefficients – here for $B^+ \rightarrow K^+\mu^+\mu^-$

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 \alpha^2 |V_{tb}V_{ts}^*|^2}{128\pi^5} |\boldsymbol{k}|\beta \left\{ \frac{2}{3}|\boldsymbol{k}|^2\beta^2 \left| \mathcal{C}_{10} f_+(q^2) \right|^2 + \frac{4m_\mu^2(m_B^2 - m_K^2)^2}{q^2 m_B^2} \left| \mathcal{C}_{10} f_0(q^2) \right|^2 + |\boldsymbol{k}|^2 \left[1 - \frac{1}{3}\beta^2 \right] \left| \mathcal{C}_9 f_+(q^2) + 2\mathcal{C}_7 \frac{m_b + m_s}{m_B + m_K} f_T(q^2) \right|^2 \right\}$$

- The C_9 we measure has interference from vector resonances

$$\mathcal{C}_9^{\text{eff}} = \mathcal{C}_9 + \sum_j \eta_j e^{i\delta_j} A_j^{\text{res}}(q^2)$$

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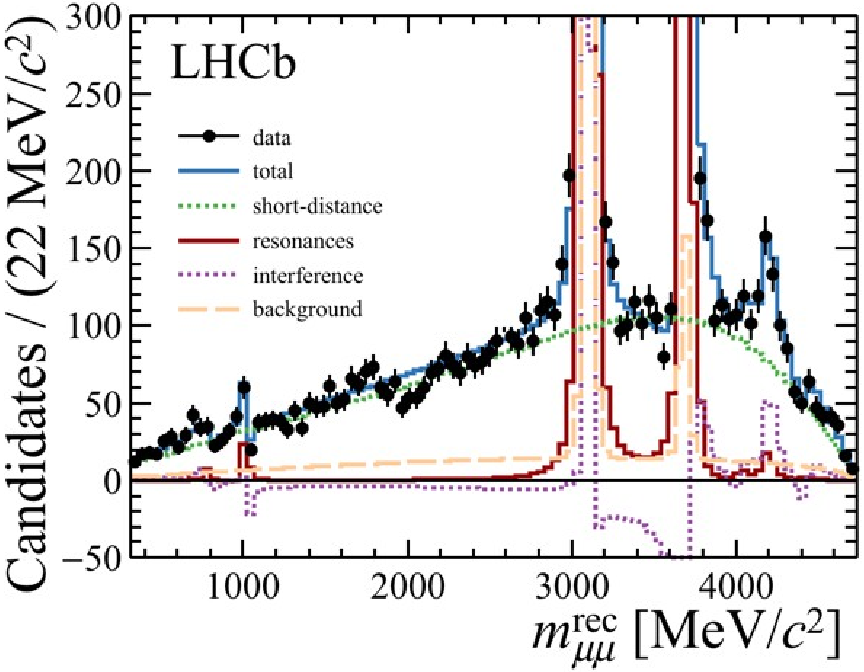
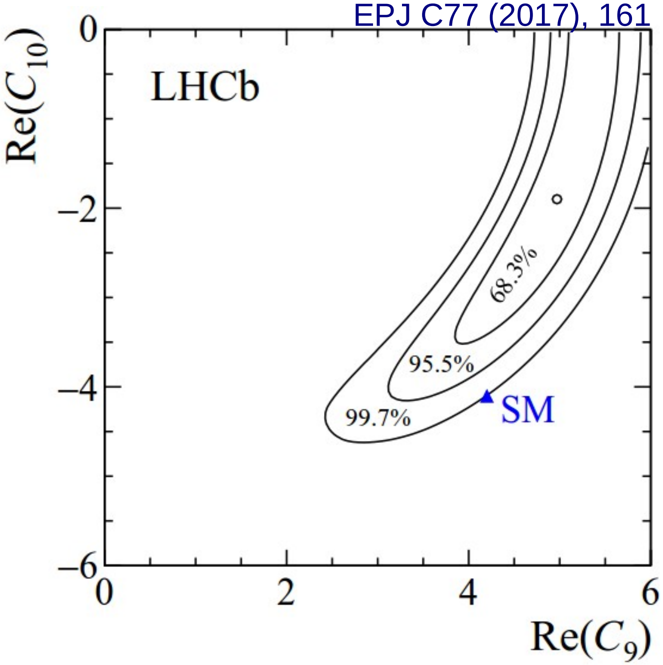
$B^+ \to K^+\mu^+\mu^-$ branching fraction

EPJ C77 (2017), 161

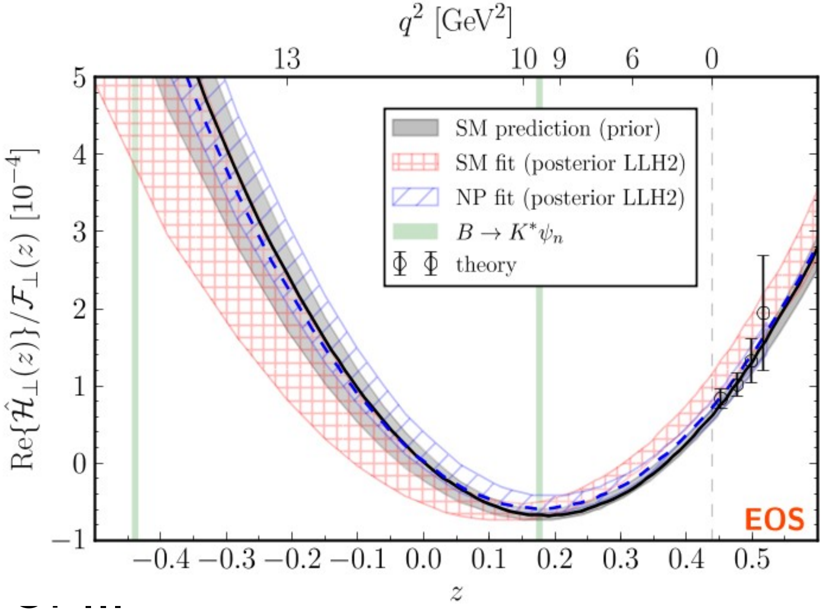




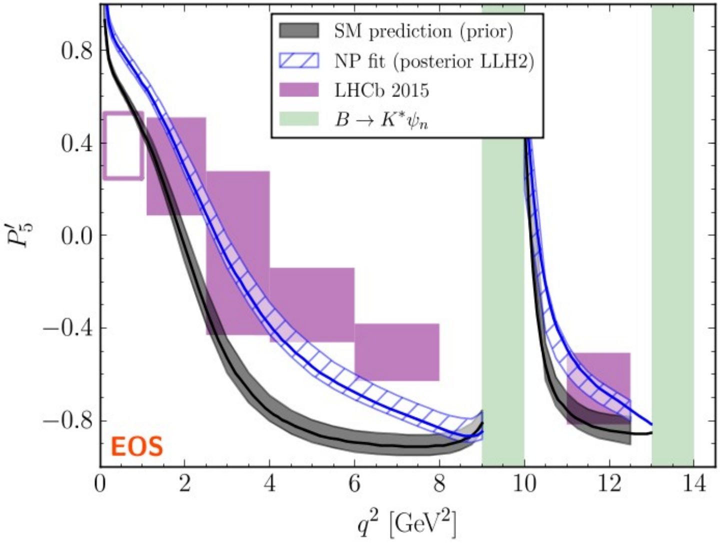
- Branching fraction is below SM expectation
  - This is seen in all other electroweak penguin decays with muons

Refine the data driven method

- Promising progress on work that utilise that scattering from initial to final state is described by analytical function in the complex plane
  - Leads to a dispersion relation that can be estimated from the theory side …



EPJ C78 (2018), 451



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Refine the data driven method

- Use expression of dispersion relation to parametrise $B \to K^{*0}\mu\mu$ $(K^{*0} \to K^+\pi^-)$
- Th

$$\mathcal{A}_0^{L,R}(q^2) = -8N\frac{m_B m_{K^*}}{\sqrt{q^2}}\left\{(C_9 \mp C_{10})A_{12}(q^2) + \frac{m_b}{m_B + m_{K^*}}C_7 T_{23}(q^2) + \mathcal{G}_0(q^2)\right\}$$

$$\mathcal{A}_\parallel^{L,R}(q^2) = -N\sqrt{2}(m_B^2 - m_{K^*}^2)\left\{(C_9 \mp C_{10})\frac{A_1(q^2)}{m_B - m_{K^*}} + \frac{2m_b}{q^2}C_7 T_2(q^2) + \mathcal{G}_\parallel(q^2)\right\}$$

$$\mathcal{A}_\perp^{L,R}(q^2) = N\sqrt{2\lambda}\left\{(C_9 \mp C_{10})\frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2}C_7 T_1(q^2) + \mathcal{G}_\perp(q^2)\right\},$$

Wilson Coefficients | Form Factors | Non-local hadronic contributions

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Modelling the hadronic contributions

$$Y^{q\bar{q},\lambda}(q^2) = Y^{q\bar{q}}(q_0^2) + \frac{q^2 - q_0^2}{\pi} \int_{q^2_{min}}^{\infty} \mathrm{d}s \frac{\rho^{q\bar{q},\lambda}(s)}{(s - q_0^2)(s - q^2 - i\varepsilon)}$$

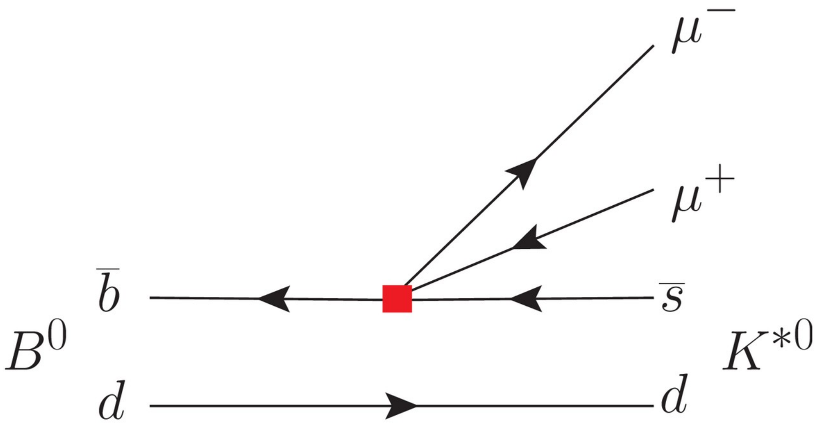
- Include φ, ρ, J/ψ, ψ(2S), ψ(3770), ψ(4040), ψ(4160), and $D^{(*)}D$ states

$$\begin{aligned}\rho^{q\bar{q},\lambda}(q^2) &= \rho_{1P}^{q\bar{q},\lambda}(q^2) + \rho_{2P}^{q\bar{q},\lambda}(q^2) \\ &= \sum_i \mathcal{A}_i^\lambda(B \to K^+\pi^- V_i)\delta(q^2 - m_i^2) + \\ &+ \sum_i \int \frac{\mathrm{d}p_i^2}{16\pi^2}\delta(q^2 - p_i^2) \int \frac{\mathrm{d}^3\vec{p}_{i1}}{E_{i1}} \frac{\mathrm{d}^3\vec{p}_{i2}}{E_{i2}} \mathcal{A}_i^\lambda(K^+\pi^- M_{i1} M_{i2})\delta^4(p_i - p_{i1} - p_{i2})\end{aligned}$$

- Leads to a (large) set of free parameters that we can simply fit for in data

An effective theory for describing decay

- As the W boson or any NP particle(s) are of a mass far above the b quark mass, we can treat decay in an effective theory.



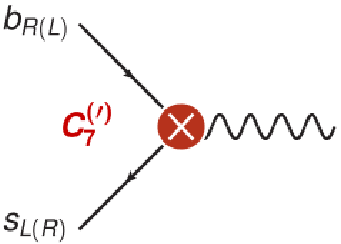
- This is the same idea as treating radioactive decay as a 4-fermion operator in Fermi theory

An effective theory for describing decay

- The effective theory needs to describe the different types of coupling

$$\mathcal{H}_{\text{eff}} = \mathcal{H}_{\text{eff}}^{\text{SM}} - \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i \left(C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \right)$$

magnetic dipole operators



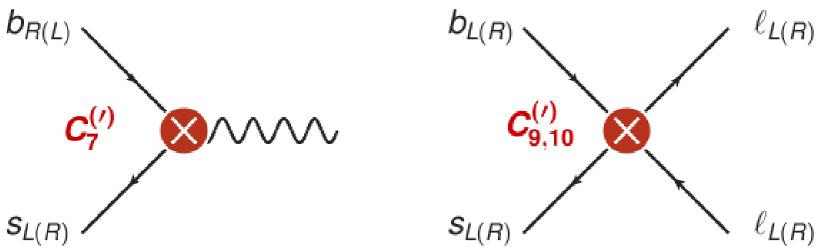
$$C_7^{(\prime)} (\bar{s} \sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$$

An effective theory for describing decay

- The effective theory needs to describe the different types of coupling

$$\mathcal{H}_{\text{eff}} = \mathcal{H}_{\text{eff}}^{\text{SM}} - \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i \left(C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \right)$$

magnetic dipole operators semileptonic operators



$$C_7^{(\prime)} (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu} \quad , \quad C_9^{(\prime)} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell)$$

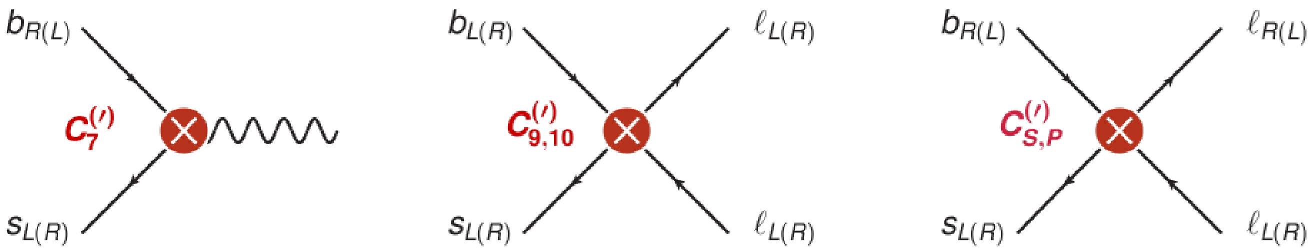
$$C_{10}^{(\prime)} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

An effective theory for describing decay

- The effective theory needs to describe the different types of coupling

$$\mathcal{H}_{\text{eff}} = \mathcal{H}_{\text{eff}}^{\text{SM}} - \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i \left(C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \right)$$

magnetic dipole operators | semileptonic operators | scalar operators



$C_7^{(\prime)}(\bar{s}\sigma_{\mu\nu}P_{R(L)}b)F^{\mu\nu}$, $C_9^{(\prime)}(\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\ell}\gamma^\mu \ell)$, $C_S^{(\prime)}(\bar{s}P_{R(L)}b)(\bar{\ell}P_{L(R)}\ell)$

$C_{10}^{(\prime)}(\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$

From Altmannshofer

Looking for New Physics

- Within the language of the effective theory, the determination of Wilson coefficients is how we can identify New Physics
- We then compare the measured values to the ones predicted from the parameters of the SM

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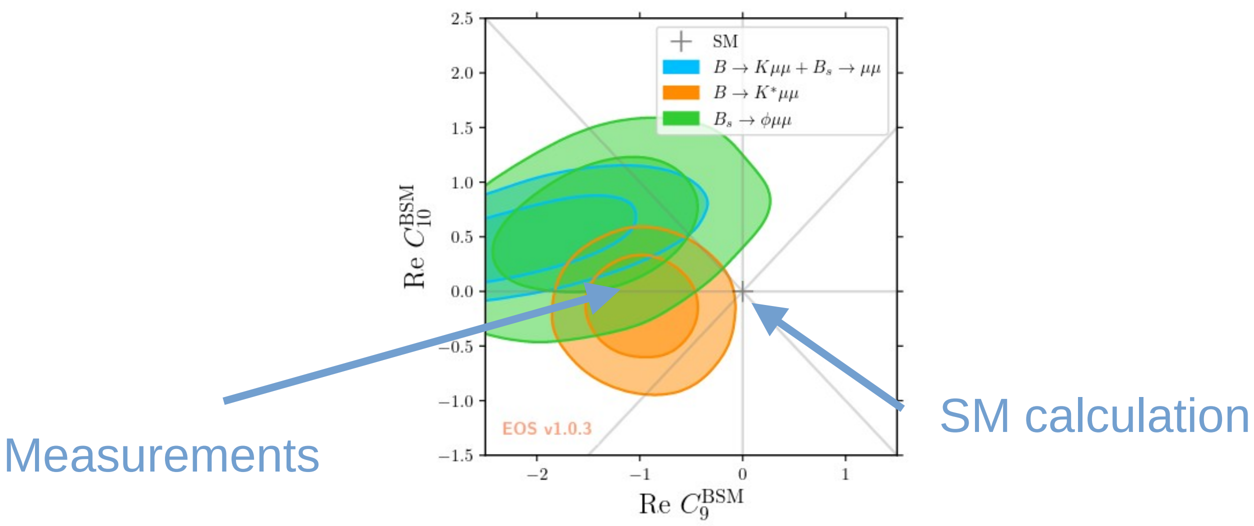

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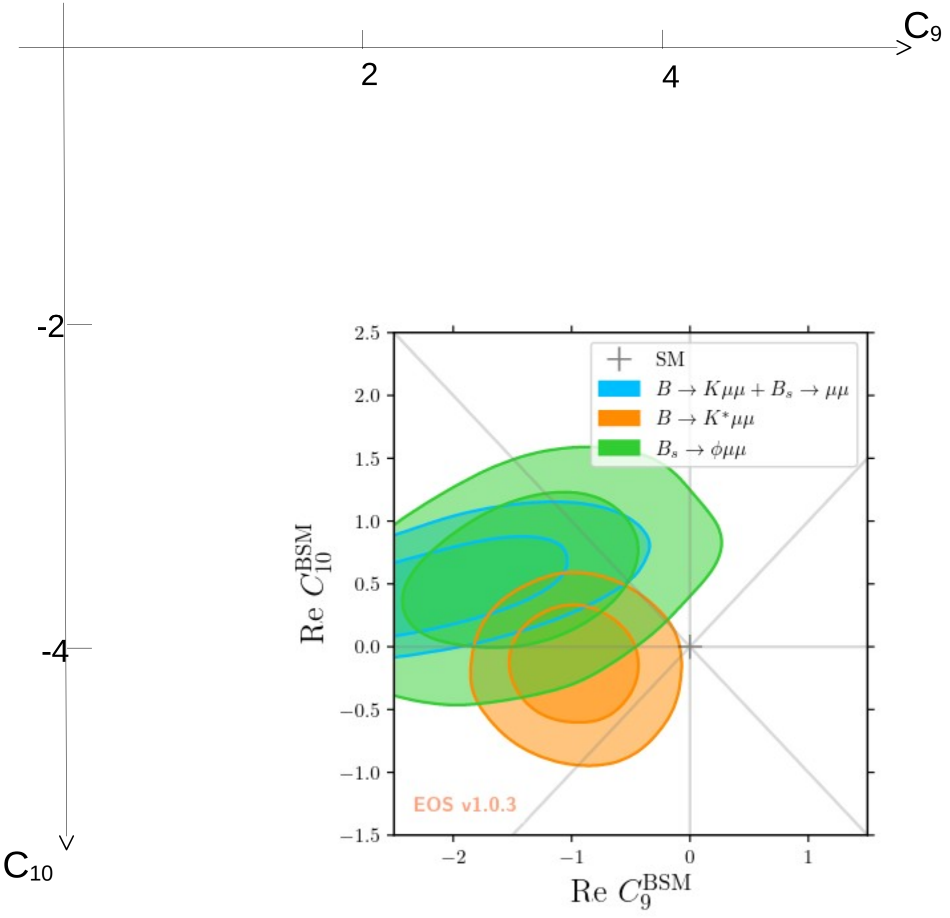
The need for high precision

- Plots are often made showing deviation from SM prediction
- We actually measure the absolute value of the Wilson coefficients
- High precision measurements are required



But potential gains are large

- We can try to estimate the mass scale of new physics
- For a tree-level mediated NP effect, we are sensitive to λ^2/M^2 in B decays

$$\frac{\lambda^2}{M^2} = 20\%\,\mathrm{SM} \sim 20\%\,\frac{g^4}{m_W^2}\frac{1}{16\pi^2}V_{tb}V_{ts}^* \sim \frac{1}{(30\,\mathrm{TeV})^2}$$

- Or in a minimal flavour violating model (where structure is the same as Higgs couplings to quarks)

$$\frac{\lambda^2}{M^2} = 20\%\,\mathrm{SM} \sim 20\%\,\frac{g^4}{m_W^2}\frac{1}{16\pi^2} \sim \frac{1}{(6\,\mathrm{TeV})^2}$$