Flavour physics at a hadron collider: part III

- Charm physics (mostly direct CPV).
- New physics with rare decays.
  - The NA62 experiment.
  - Search for the ultra rare decay B_s^0—>μμ
  - Semileptonic b—>sll transitions

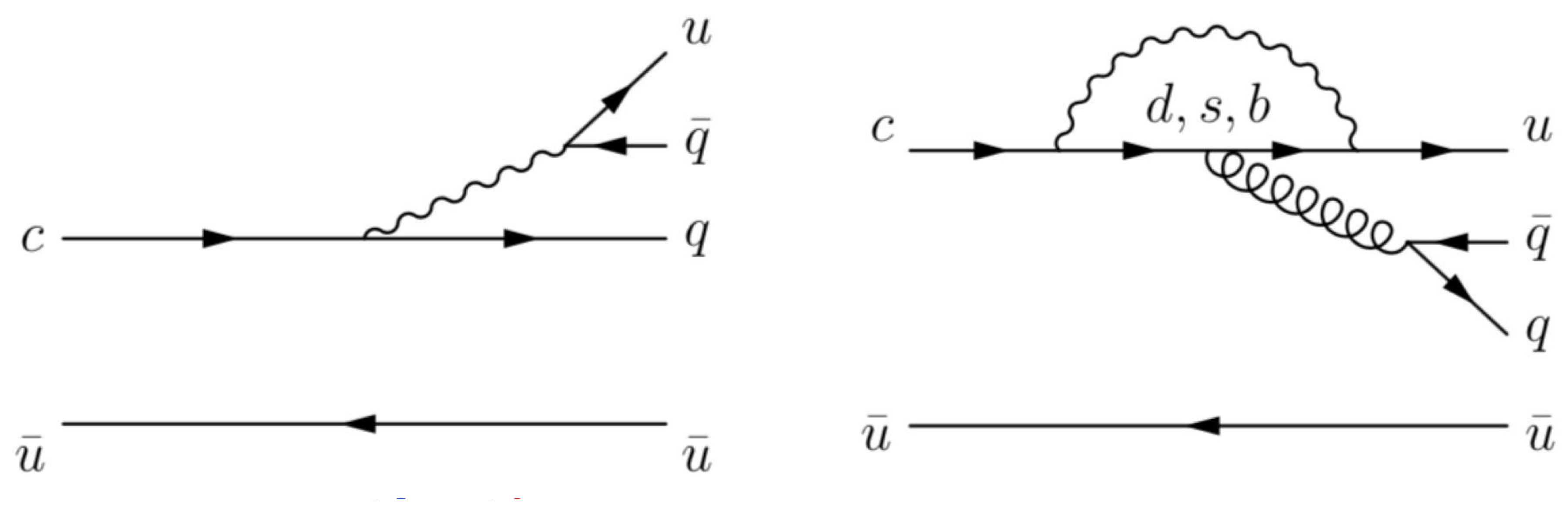
Patrick Owen

01/09/21

CPV in charm decays

- While CPV in B mesons/kaons has long been established, it had never been seen in charm quarks.
- The tree and penguin sizes were too different: $A^T >> A^P$

D—>hh



- Therefore expect CPV to be very small.

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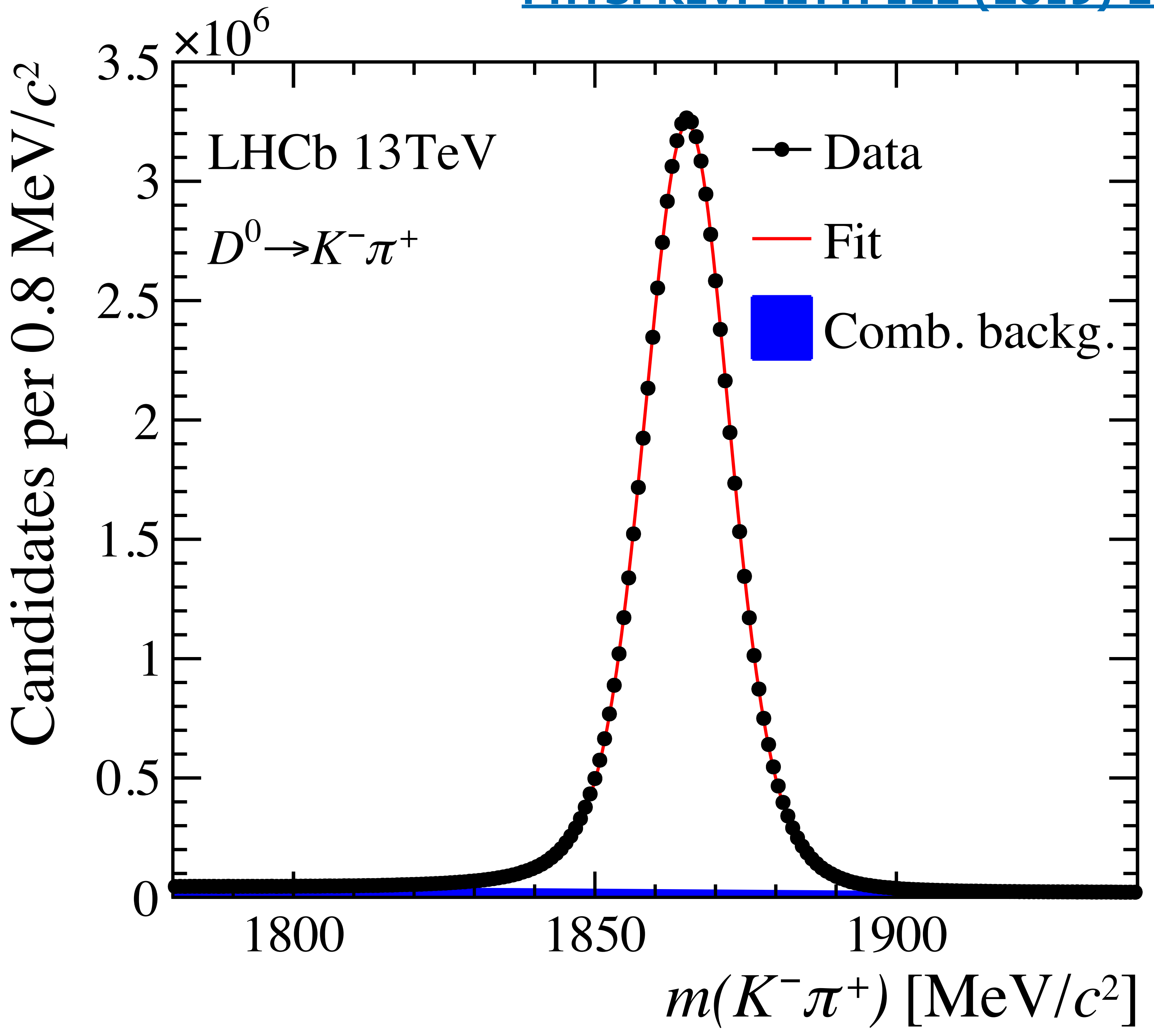
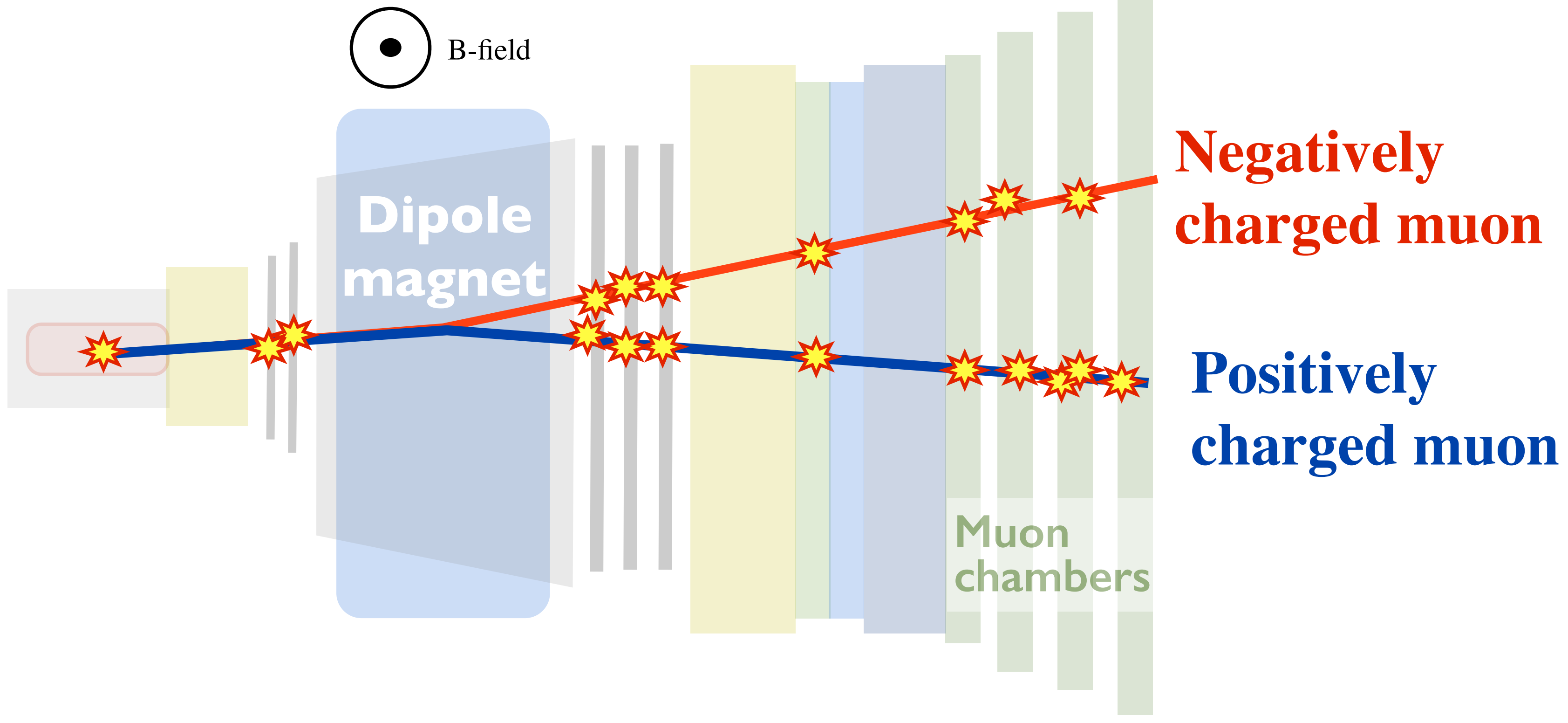


- Fortunately have millions of signal.

Aside: Detection asymmetries

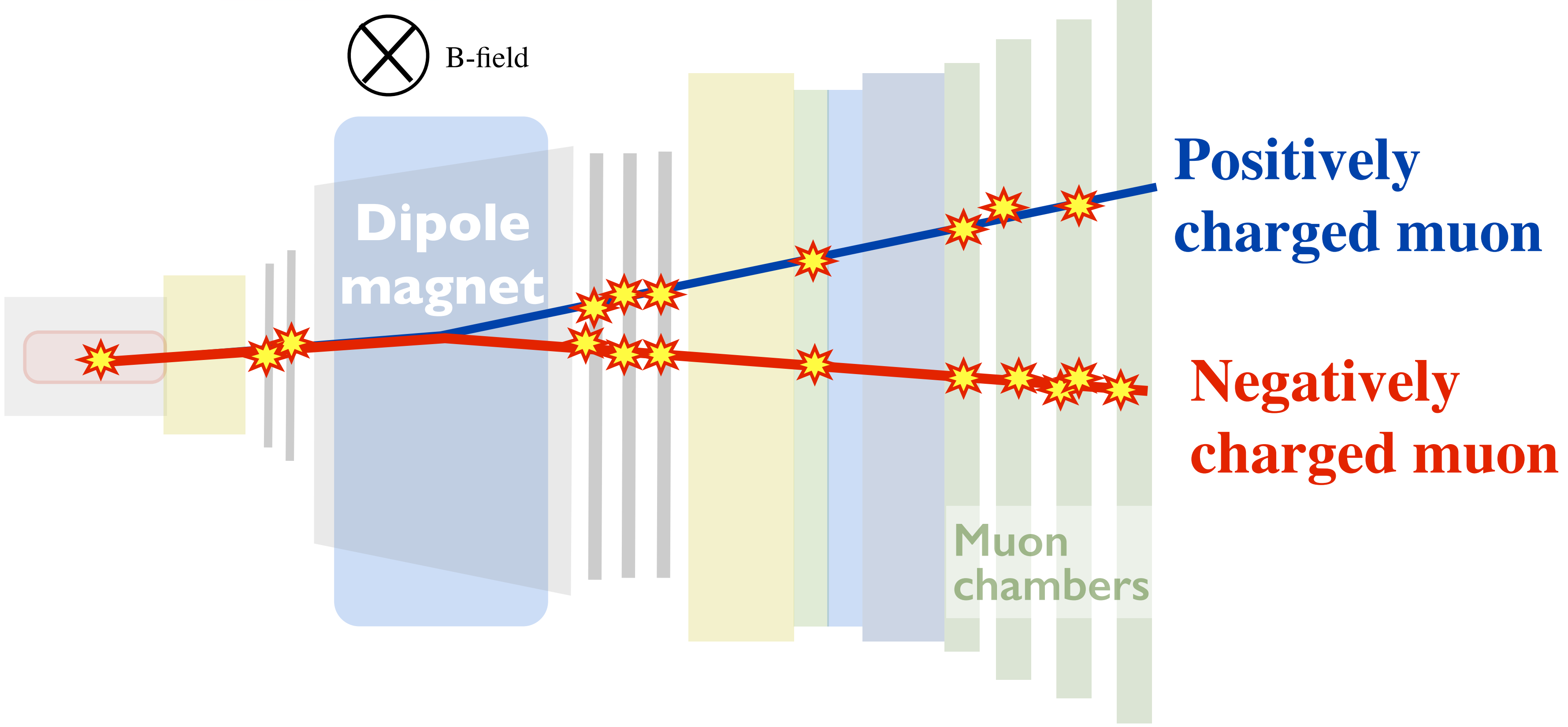
- If we had a perfect detector, the CP asymmetry would be given by $$A_{CP} = \frac{N - \bar{N}}{N + \bar{N}}$$
- In reality, there is a different efficiency for the two CP states $$A_{\text{raw}} = \frac{\epsilon N - \bar{\epsilon}\bar{N}}{\epsilon N + \bar{\epsilon}\bar{N}} \approx A_{CP} + A_{\text{det}}$$
- Where does this come from?

$$A_D = \frac{\varepsilon(f) - \varepsilon(\overline{f})}{\varepsilon(f) + \varepsilon(\overline{f})}$$



$$A_D = \frac{\varepsilon(f) - \varepsilon(\overline{f})}{\varepsilon(f) + \varepsilon(\overline{f})}$$

Reversed magnet polarity



- Controlled with a combination of data and simulation. We are interested in CP asymmetries at the 10^{-4} level - the details really matter here.

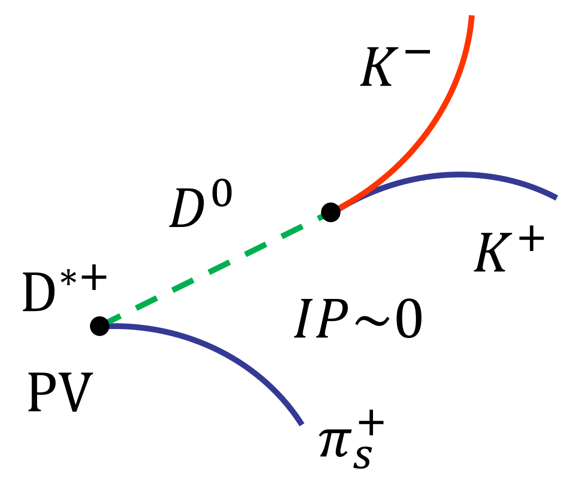
LHCb analysis

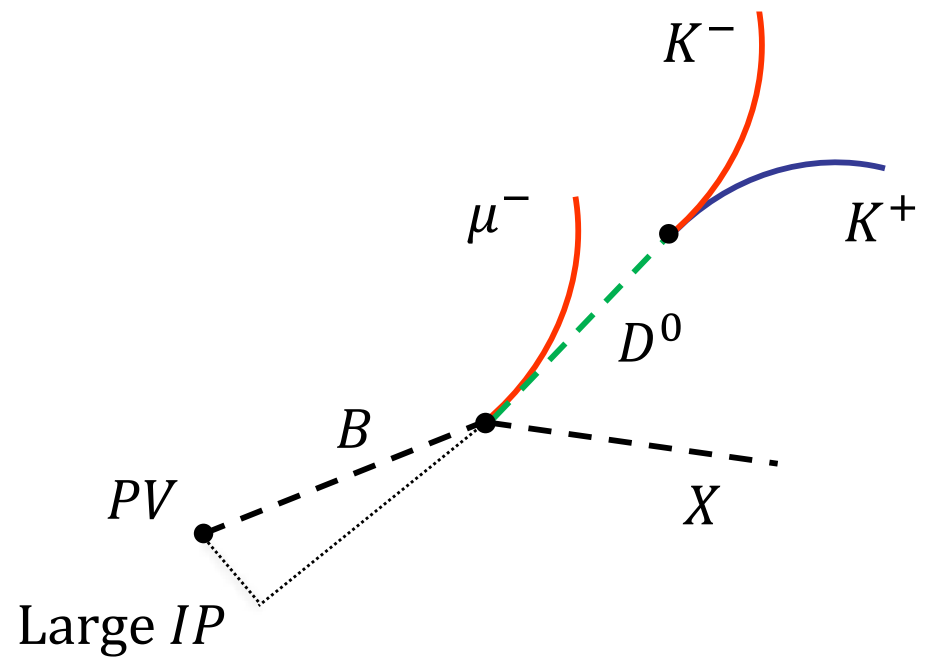
Those interested can look at Angelo Carbone's CERN seminar

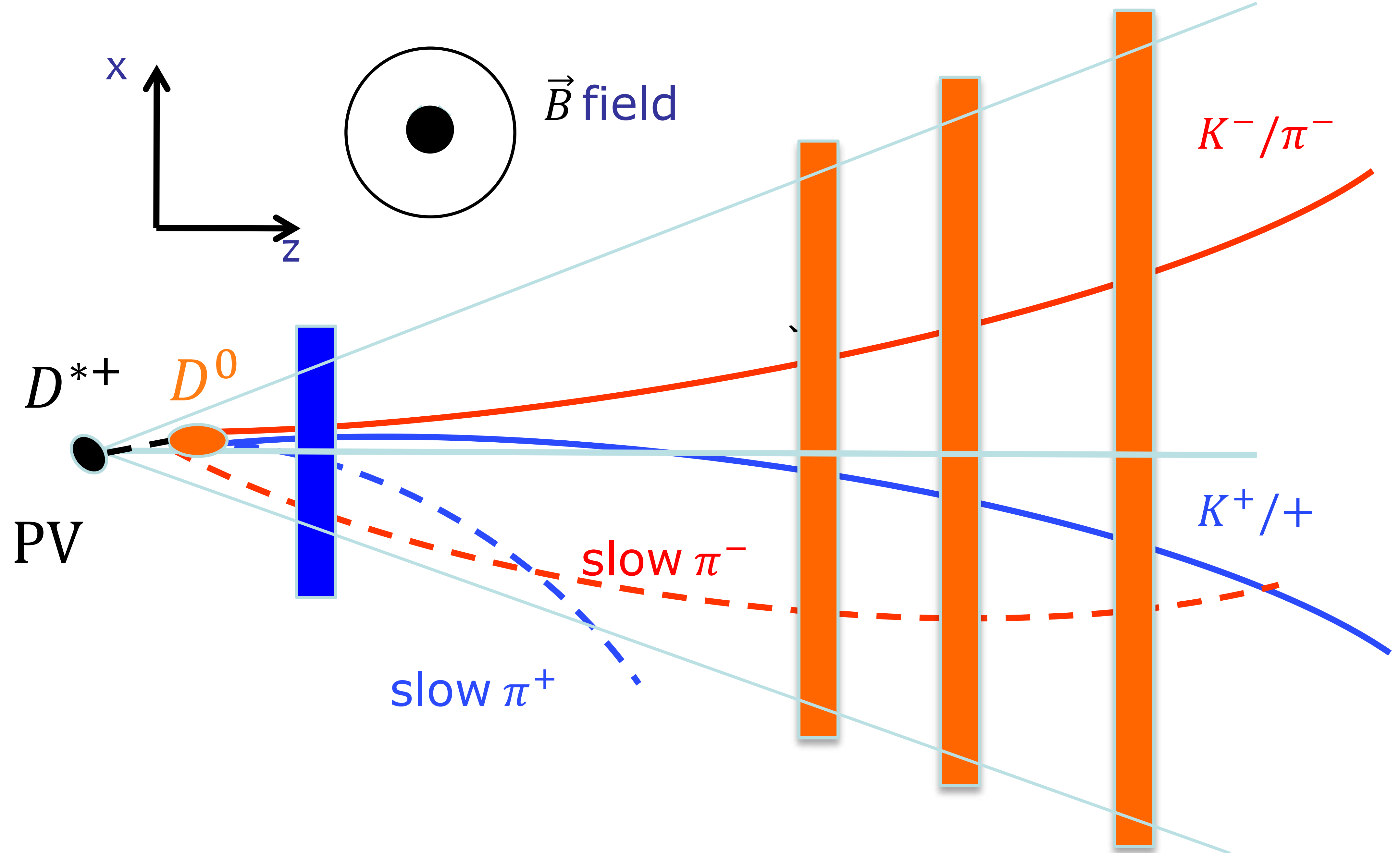
- In early 2019, we analysed our full dataset and looked for CP violation in $D^0 \rightarrow h^+h^-$ decays.
- In order to control detection asymmetries, compare two decays: $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$.

$$\Delta A_{CP} \equiv A_{raw}(KK) - A_{raw}(\pi\pi) = A_{CP}(KK) - A_{CP}(\pi\pi)$$

- The flavour of the D meson is determined from:
  - The charge of the excited D^{*+} state.
  - The charge of an accompanying muon.







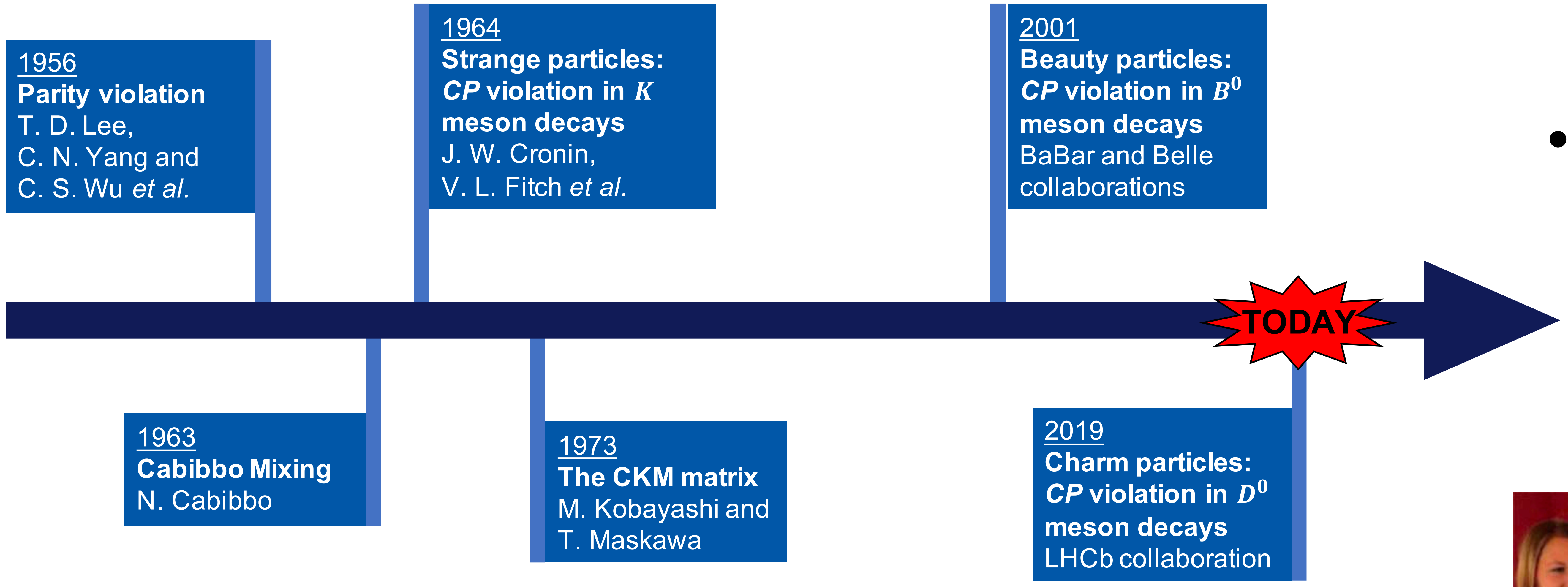
Discovery of CPV in charm

PHYS. REV. LETT. 122 (2019) 211803

- We measured this difference to be non-zero by 5.3 standard deviations.

$$\Delta a_{CP}^{\mathrm{dir}} = (-15.6 \pm 2.9)\times 10^{-4}$$

First time discovered!



- Presented at Moriond 2019 for the first time.

- The conference organisers were kind enough to provide a celebratory drink to the LHCb members.

Interpretation

- Interpretation is complicated by QCD uncertainties (size depends on strong phase).
- The charm quark is not very heavy - QCD is strong. Non-perturbative techniques are needed.

New physics explanation

News & Views | Published: 08 May 2019

PARTICLE PHYSICS

Charming clue for our existence

Alexander Lenz

Nature Reviews Physics **1**, 365–366(2019) | Cite this article

97 Accesses | **10** Altmetric | Metrics

The Large Hadron Collider beauty experiment (LHCb) collaboration announced the observation of charge parity (CP) violation in the decays of the D^0 meson, the lightest particle containing charm quarks, which might provide clues to why there is more matter than antimatter in the Universe and lead to a deeper understanding of the theory of the strong interaction.

QCD explanation

$SU(3)_F$ breaking through final state interactions and CP asymmetries in $D \to PP$ decays

Franco Buccella (INFN, Naples), Ayan Paul (DESY & Humboldt U., Berlin), Pietro Santorelli (INFN, Naples & Naples U.)

Feb 14, 2019 - 20 pages

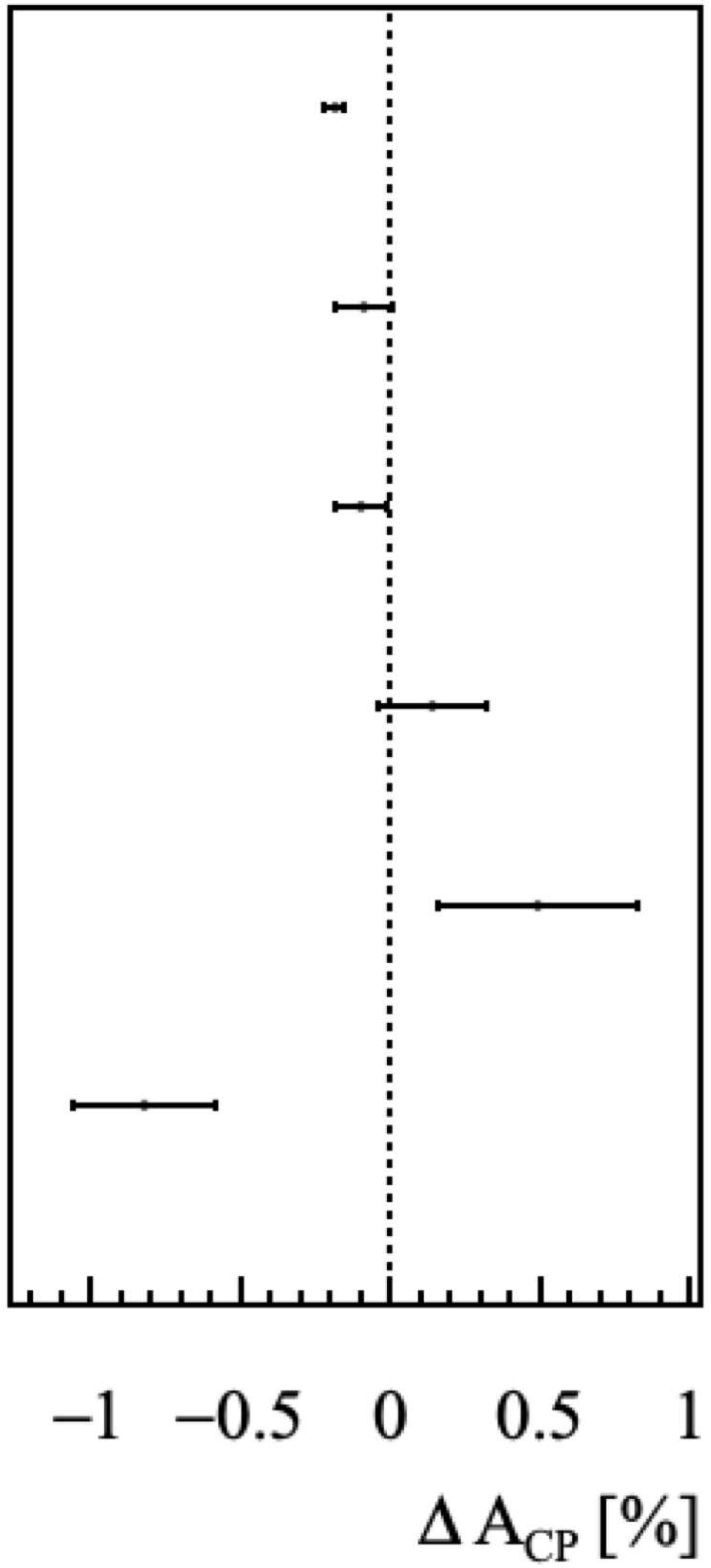
Phys.Rev. D99 (2019) no.11, 113001
(2019-06-11)
DOI: 10.1103/PhysRevD.99.113001
DESY-19-025, DESY 19-025
e-Print: arXiv:1902.05564 [hep-ph] | PDF

Abstract (APS)
We analyze D decays to two pseudoscalars (π,K) assuming the dominant source of SU(3)F breaking lies in final state interactions. We obtain an excellent agreement with experimental data and are able to predict CP violation in several channels based on current data on branching ratios and ΔACP. We also make predictions for δKπ and the branching fraction for the decay Ds+→K+KL.
Abstract (arXiv)

Note: 21 pages. Updated with the 2019 measurement of ΔA_{CP} from LHCb
Keyword(s): INSPIRE: symmetry breaking: flavor | symmetry breaking: SU(3) | final-state interaction | D: decay | decay: asymmetry | asymmetry: CP | CP: violation | D: branching ratio | D/s+ --> K+ K0(L)
Author supplied: Electroweak interactions

- Direct CPV often has interpretation issues due to the strong part needed to generate such effects.

The road to discovery is often not straight

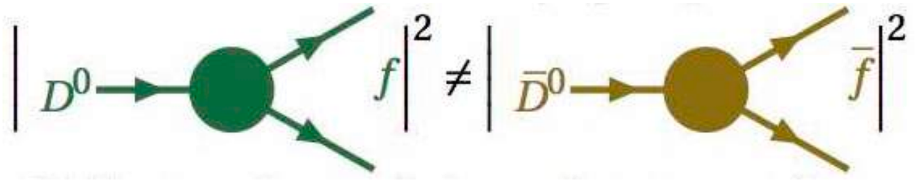


π-tagged (6 fb^{-1})	LHCb-PAPER-2019-006
μ-tagged (6 fb^{-1})	LHCb-PAPER-2019-006
π-tagged (3 fb^{-1})	Phys. Rev. Lett. 116 (2016)
μ-tagged (3 fb^{-1})	JHEP 07 041 (2014)
μ-tagged (1 fb^{-1})	Phys. Lett. B723 33 (2013)
π-tagged (0.62 fb^{-1})	Phys. Rev. Lett. 108 (2012)

Indirect CPV in charm

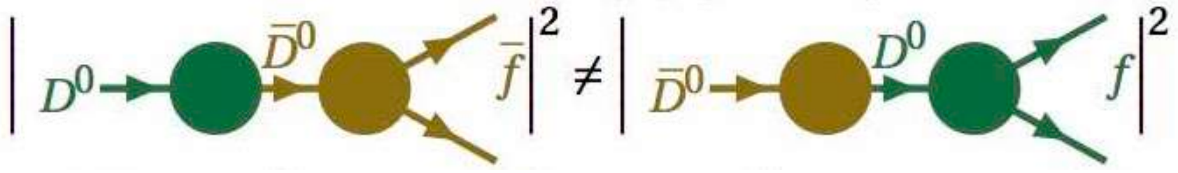
- Reminder of types of CPV:

1. ***CPV in the decay***



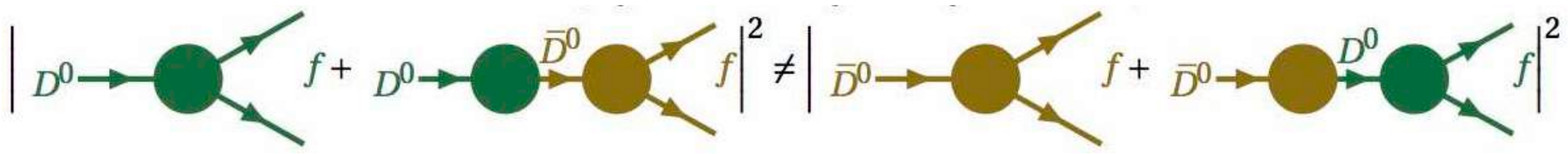
$$a_f^d \equiv \frac{|A_f|^2 - |\bar{A}_{\bar{f}}|^2}{|A_f|^2 + |\bar{A}_{\bar{f}}|^2}$$

2. ***CPV in the mixing***



$$P(D^0 \to \overline{D}^0) \neq P(\overline{D}^0 \to D^0)$$
$$\phi_{12} \equiv \arg(M_{12}/\Gamma_{12}) \neq 0$$

3. ***CPV in the interference***
   (of mixing and decay)



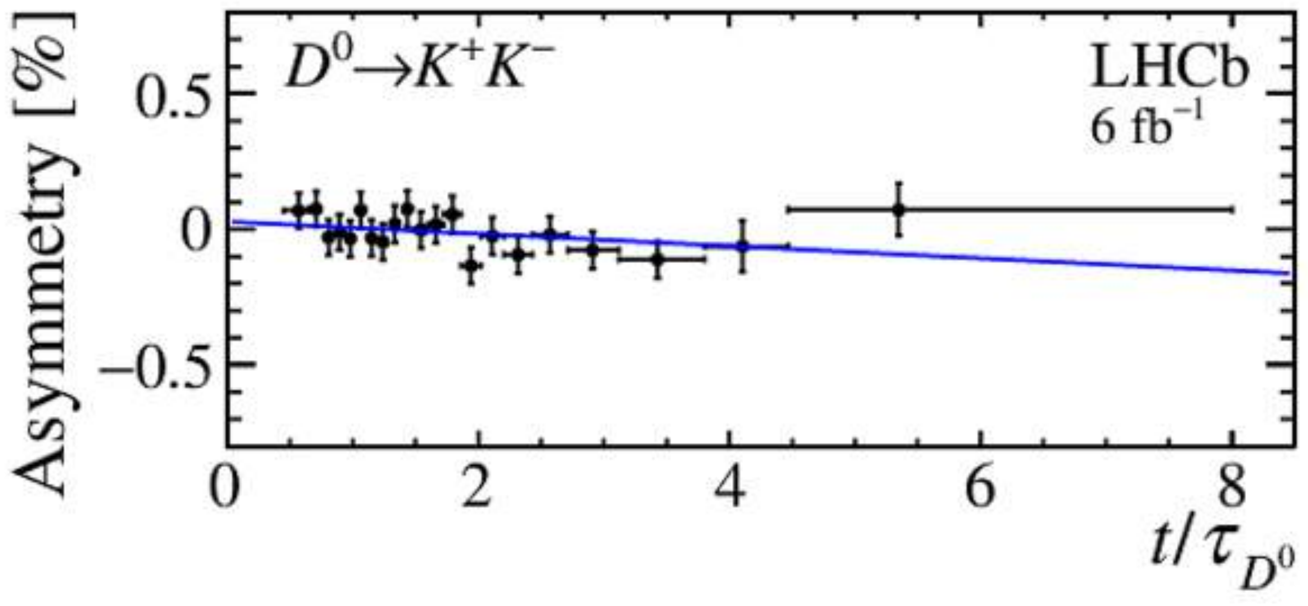
- Similarly to sin(2β), measure CP asymmetry as a function of time.

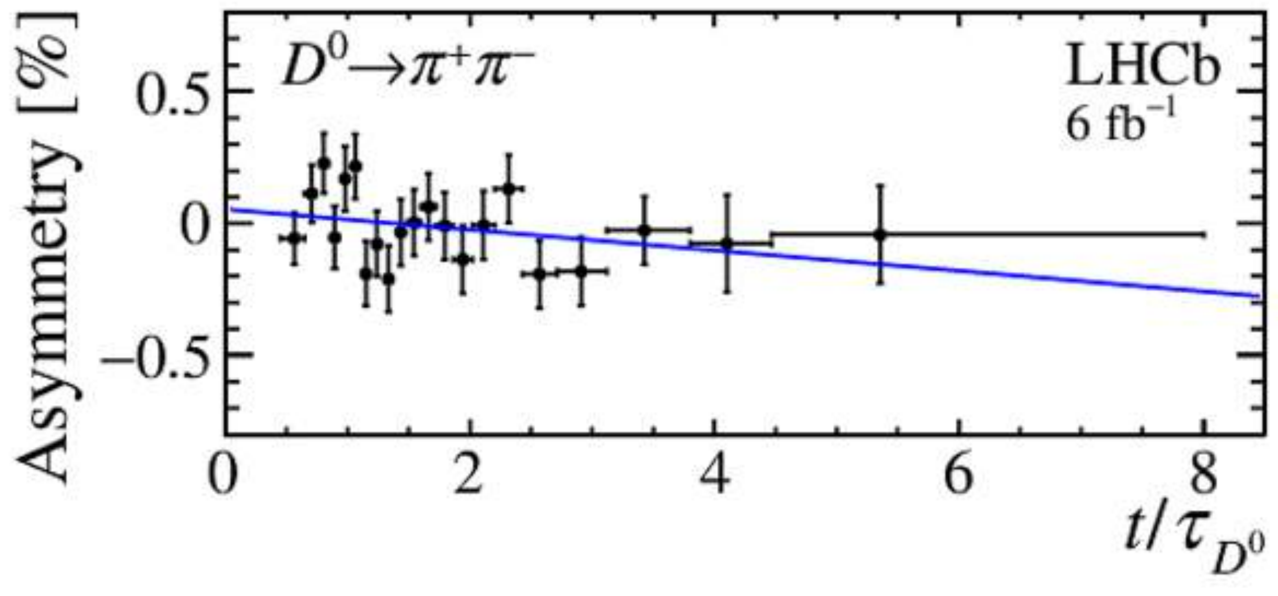
$$A_{CP}(f,t) \equiv \frac{\Gamma(D^0 \to f,t) - \Gamma(\overline{D}^0 \to f,t)}{\Gamma(D^0 \to f,t) + \Gamma(\overline{D}^0 \to f,t)} \approx a_f^d + \Delta Y_f \frac{t}{\tau_{D^0}}$$

Direct CPV

- Also parameterised as A_Γ, is sensitive to CPV in mixing and the decay.

ARXIV:2105.09889



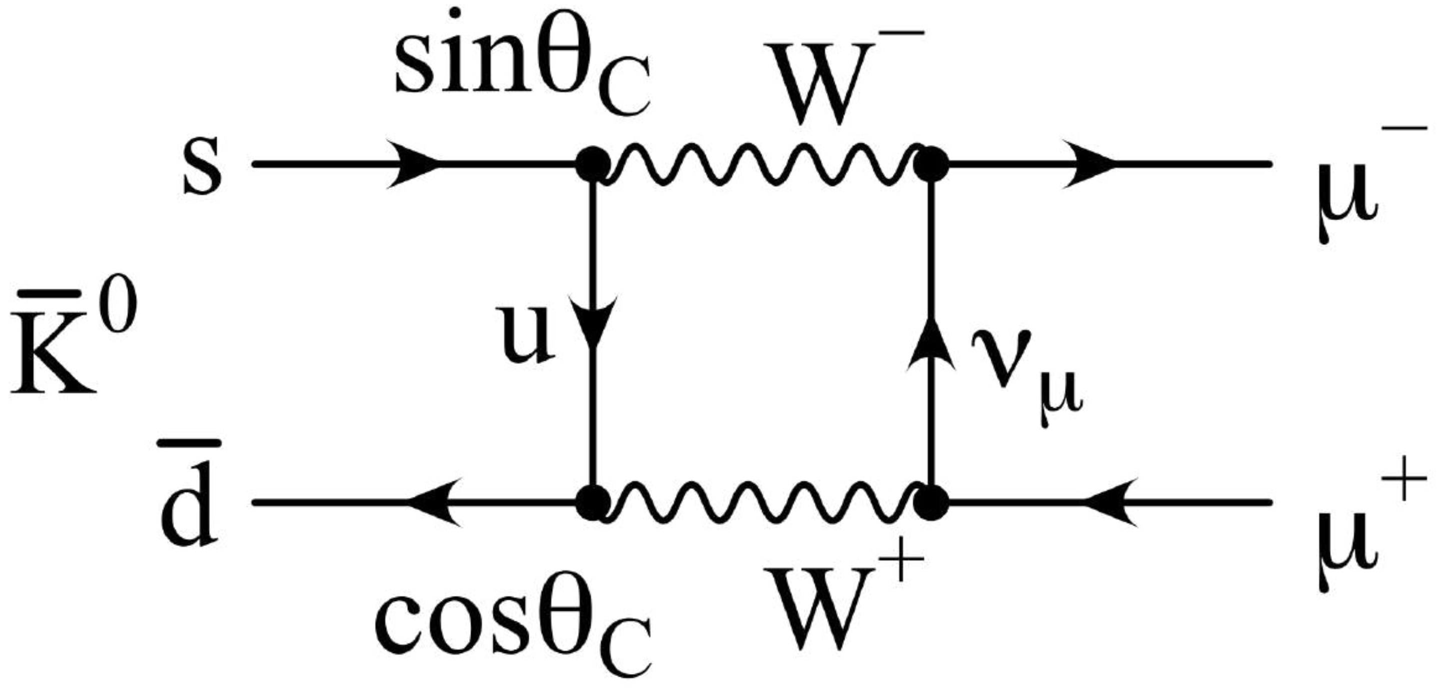


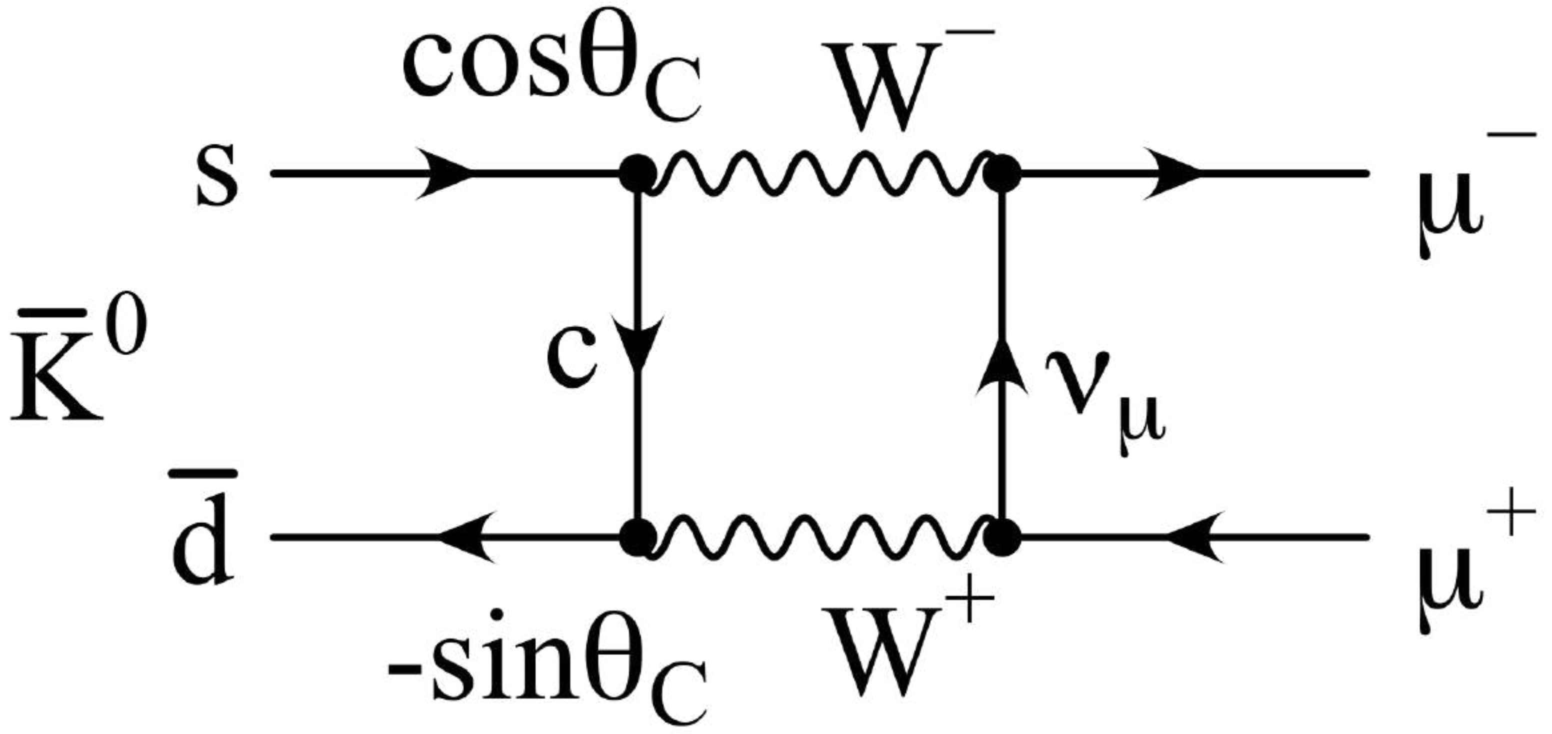
Incredible precision! Consistent with no CPV

$$\Delta Y_{K^+K^-} = (-2.3 \pm 1.5 \pm 0.3) \times 10^{-4}$$
$$\Delta Y_{\pi^+\pi^-} = (-4.0 \pm 2.8 \pm 0.4) \times 10^{-4}$$

Flavour changing neutral currents

- Decays which are either highly suppressed or forbidden in the SM are highly sensitive to new physics.
- The canonical example are **flavour changing neutral currents (FCNCs).** Examples that we will look at are s—>d and b—>s transitions.
- FCNCs have played a big part in our construction of the SM.



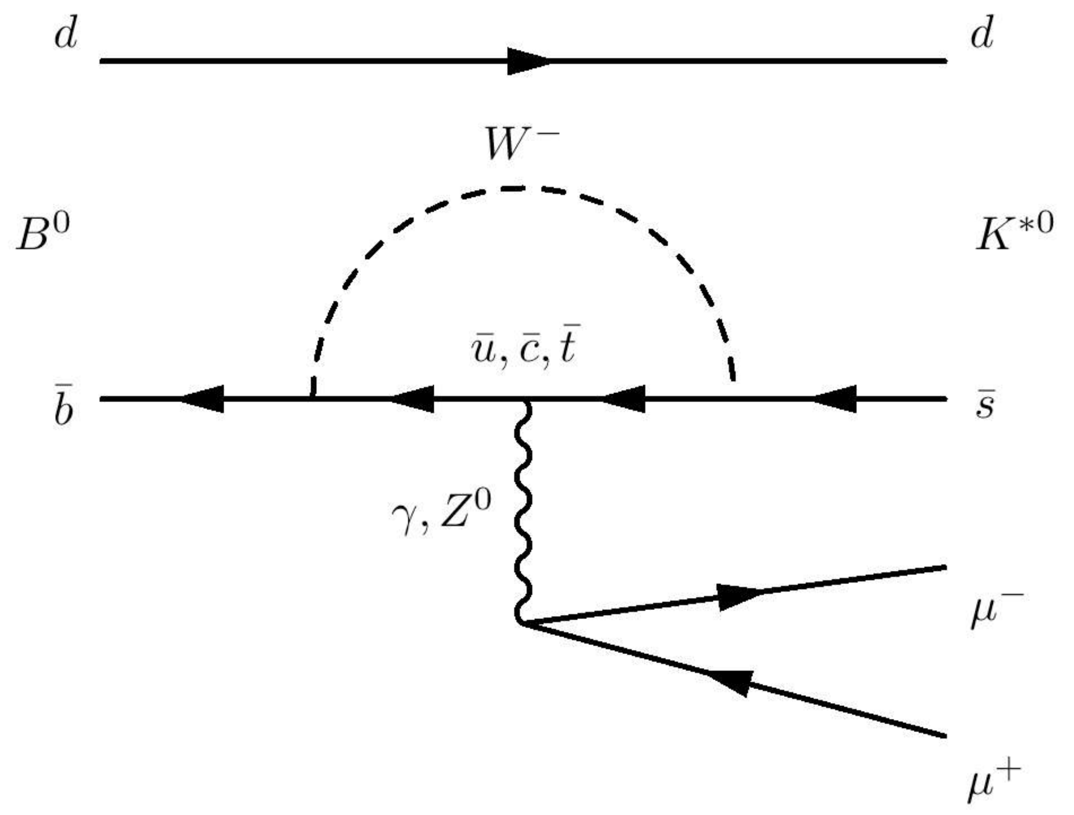


- The smallness of $K_L^0 \rightarrow \mu^+\mu^-$ led to the GIM mechanism and the prediction of the charm quark years before it was discovered.
- Can FCNCs do the same again but with new physics?

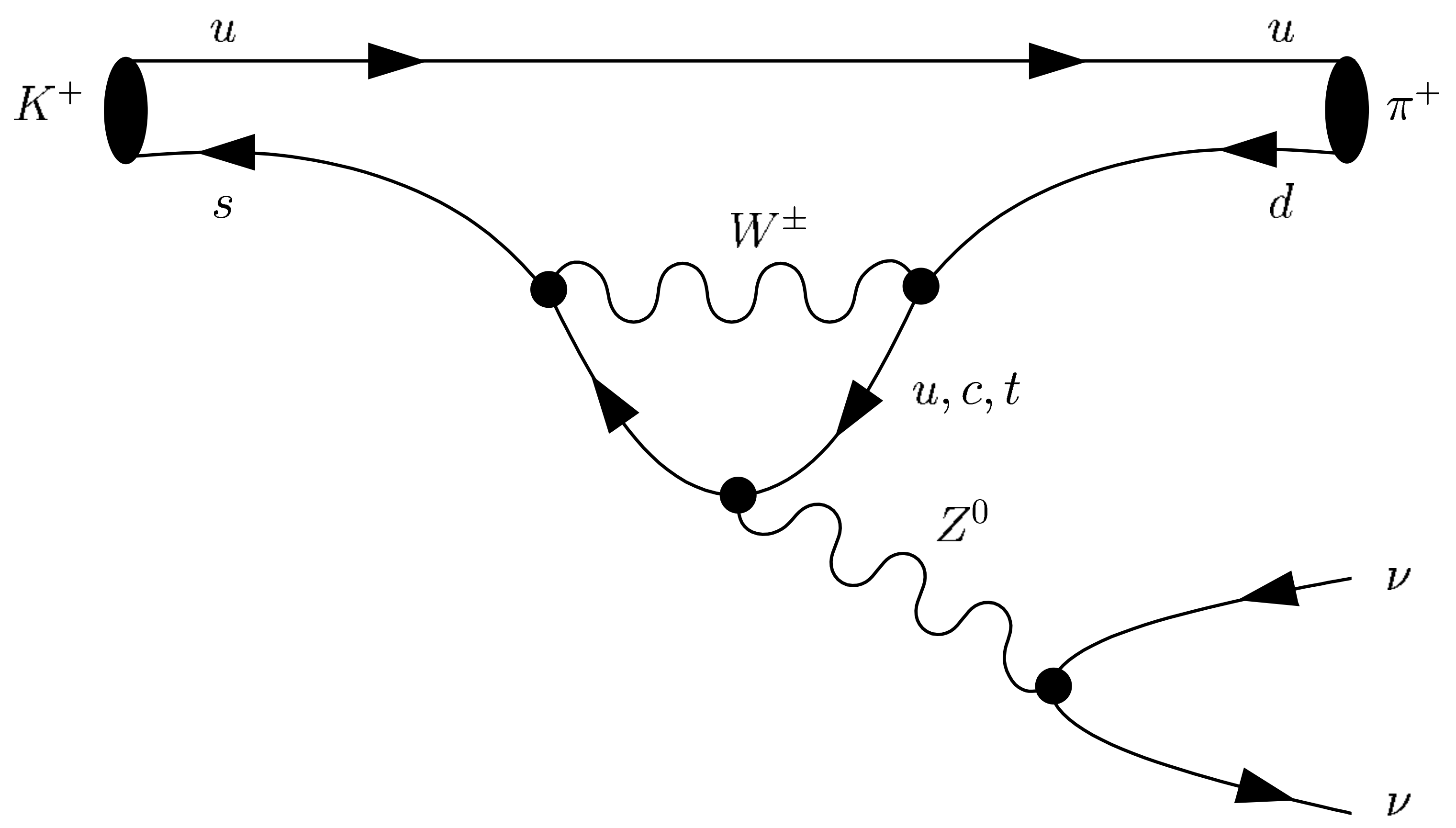
B mesons vs Kaons

- Let's compare FCNCs between B meson decays and kaons

$\mathcal{B} \sim 10^{-6}$



$\mathcal{B} \sim 10^{-10}$



- Kaons much more suppressed due to CKM elements involved.
- Why do we reconstruct charged leptons for B meson decays but neutrinos for the kaon?
  - Unfortunately decays such as $K^+ \to \pi^+ \ell^+ \ell^-$ are dominated by long distance contributions.
  - B decays still mostly short distance, even with charged leptons.
- The decay $K^+ \to \pi^+ \nu \bar{\nu}$ can be predicted with good precision in the SM.

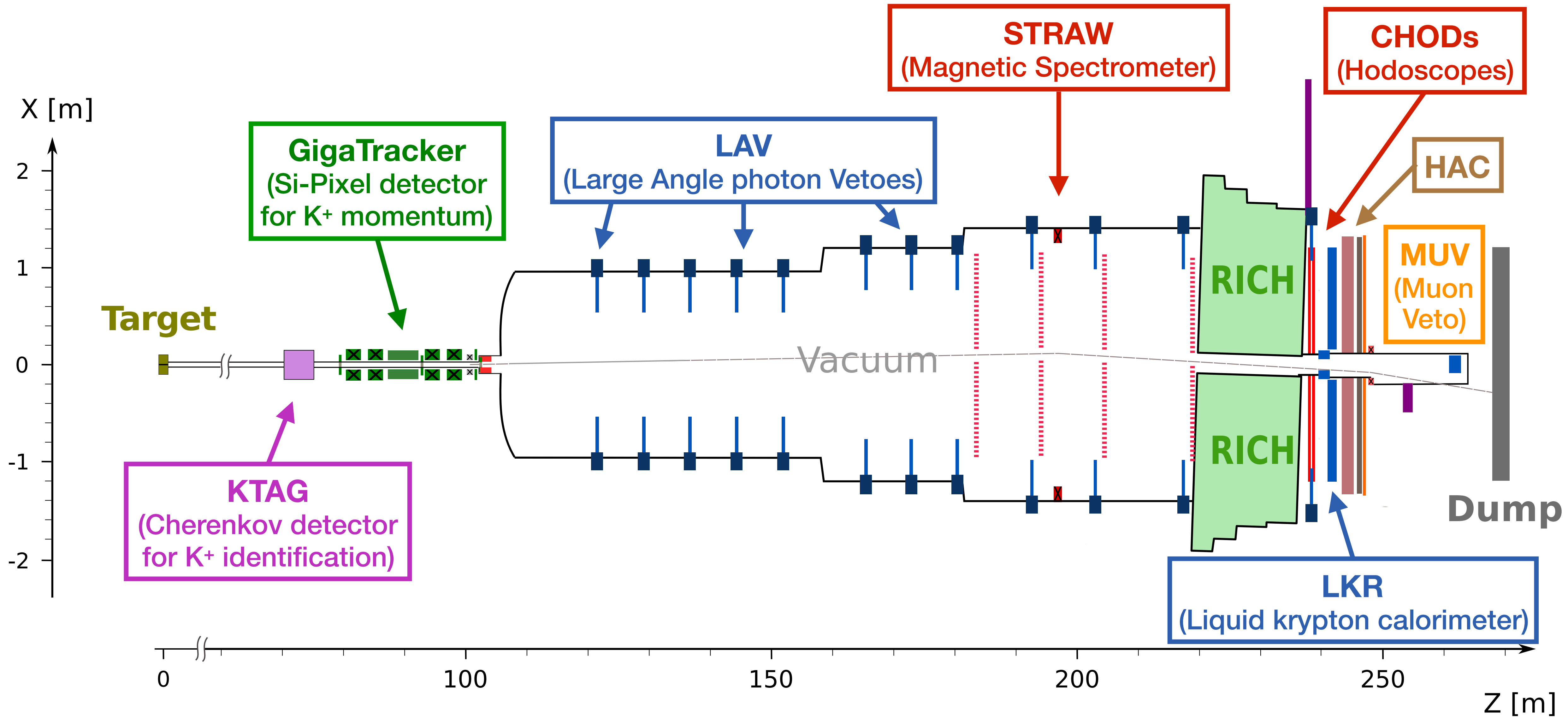
$\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$

[Buras et al., JHEP 1511 (2015) 033]

The NA62 experiment

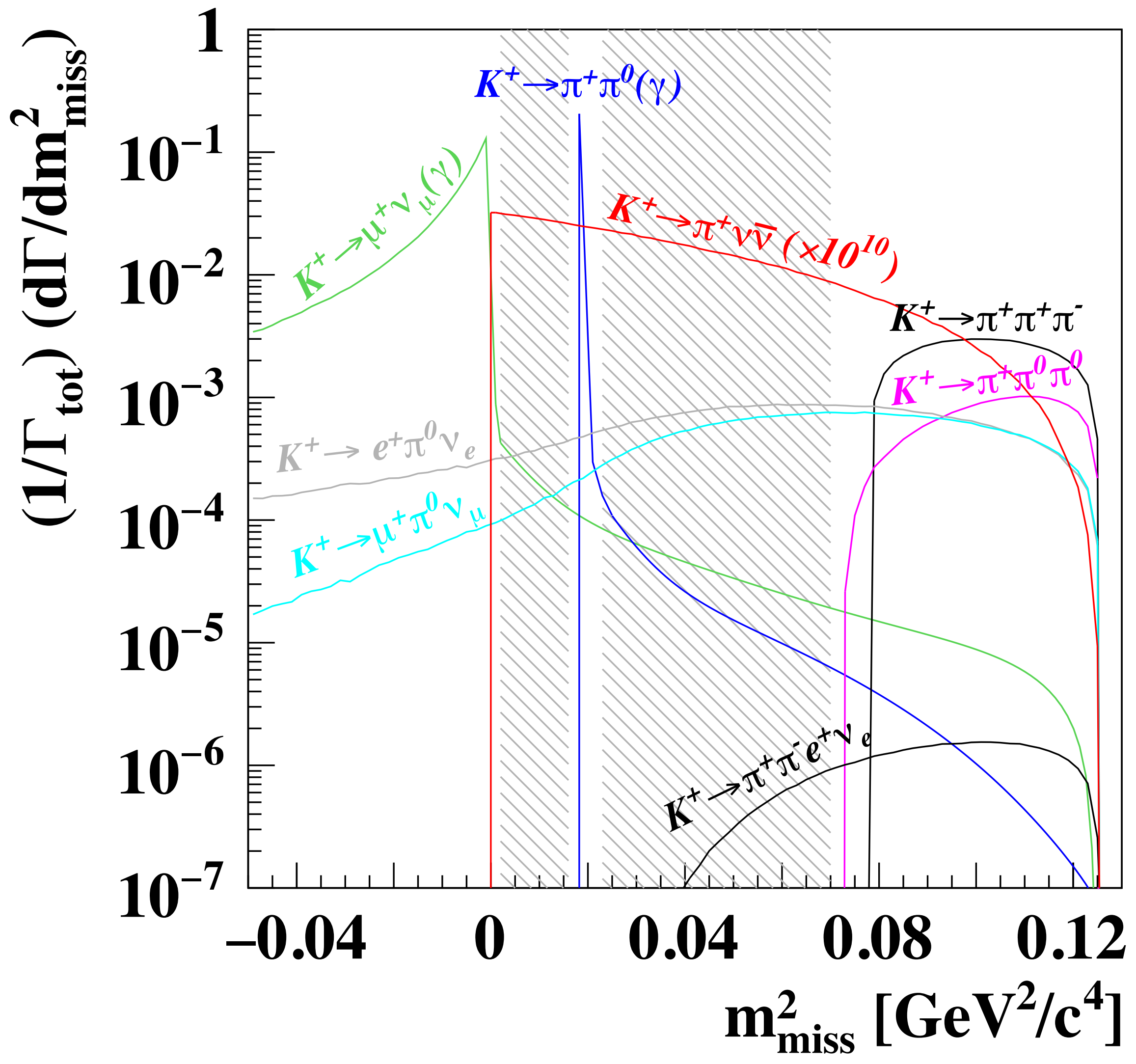
- Experiment dedicated to a precise measurement of the $K^+ \to \pi^+ \nu \bar{\nu}$ branching fraction.

- Key features:
  - Huge beam intensity from SPS: 10^{12} pot/sec.
  - 100ps timing to match beam/decay particles.
  - Precise kinematic constraints.
  - Efficient photon detection.
  - Excellent PID.



- Main backgrounds:

Decay mode	Branching fraction
$K^+ \to \mu^+ \nu_\mu (\gamma)$	63.5%
$K^+ \to \pi^+ \pi^0 (\gamma)$	20.7%
$K^+ \to \pi^+ \pi^+ \pi^-$	5.6%
$K^+ \to \pi^+ \pi^- e^+ \nu_e$	4.3×10^{-5}

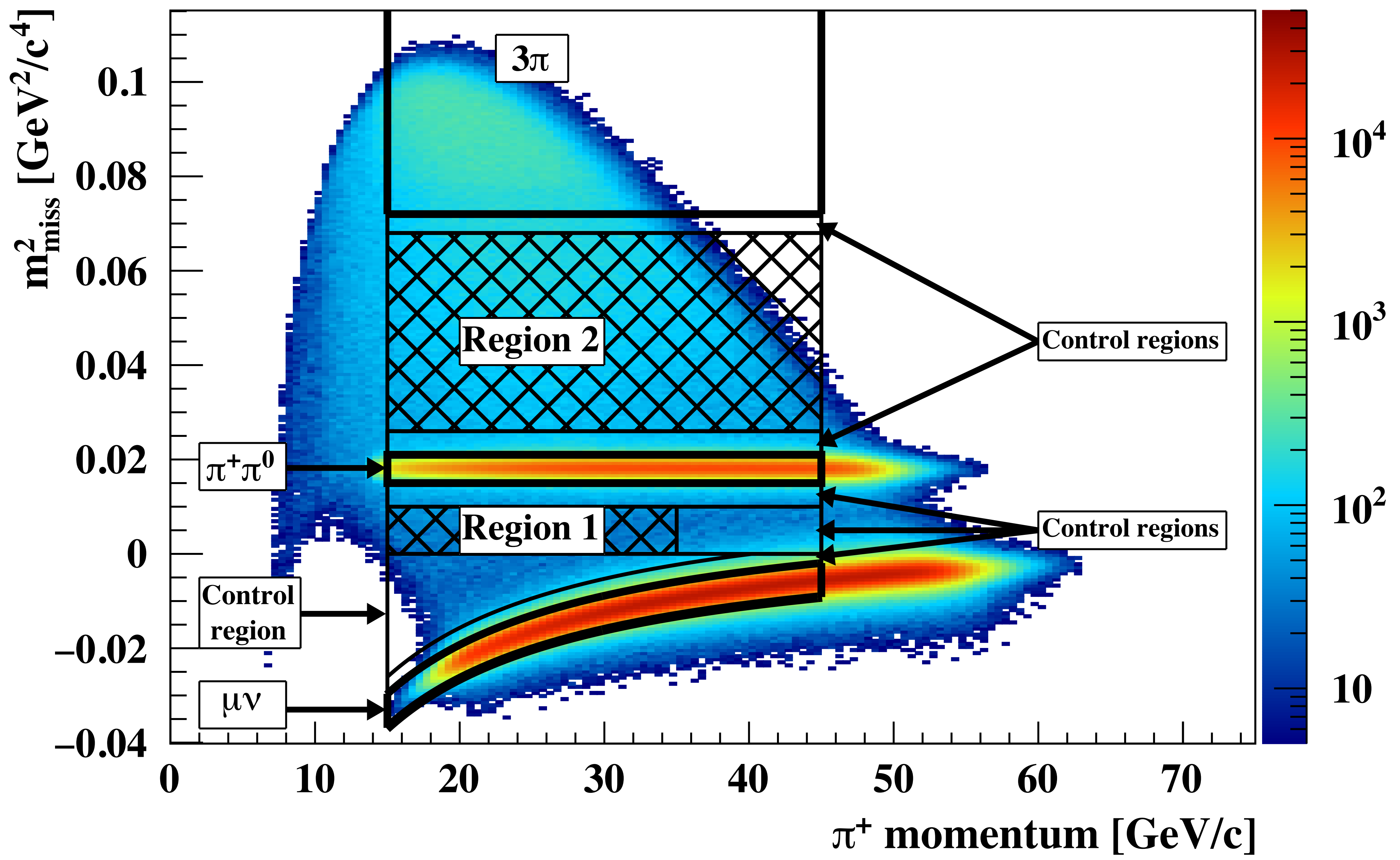


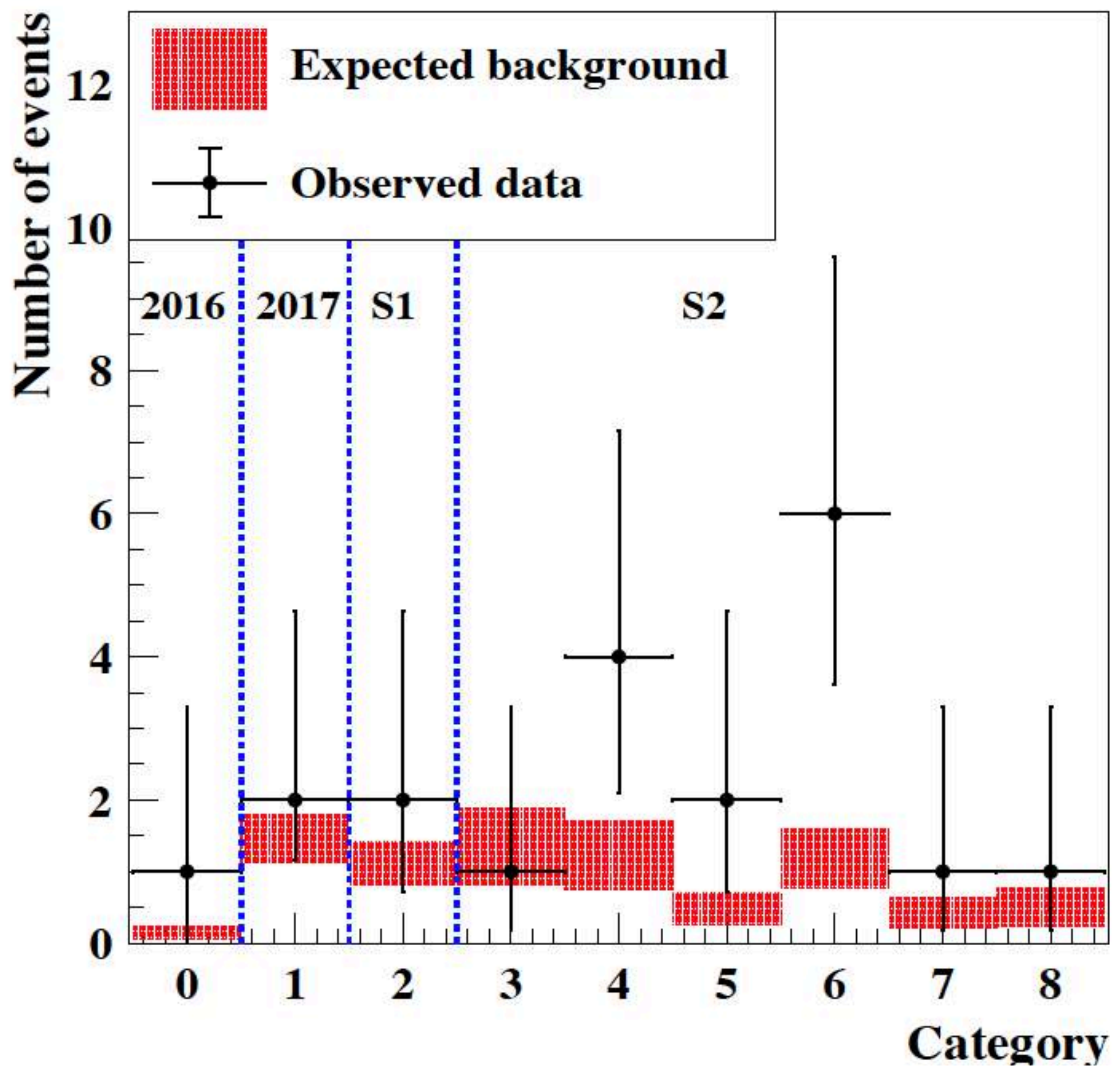
10.1007/JHEP11(2020)042

Latest results

10.1007/JHEP06(2021)093

- Select signal region kinematically to avoid main backgrounds.
- Observation of 20 events with 7 background expected.
  - Evidence for signal at the level of 3.4σ.

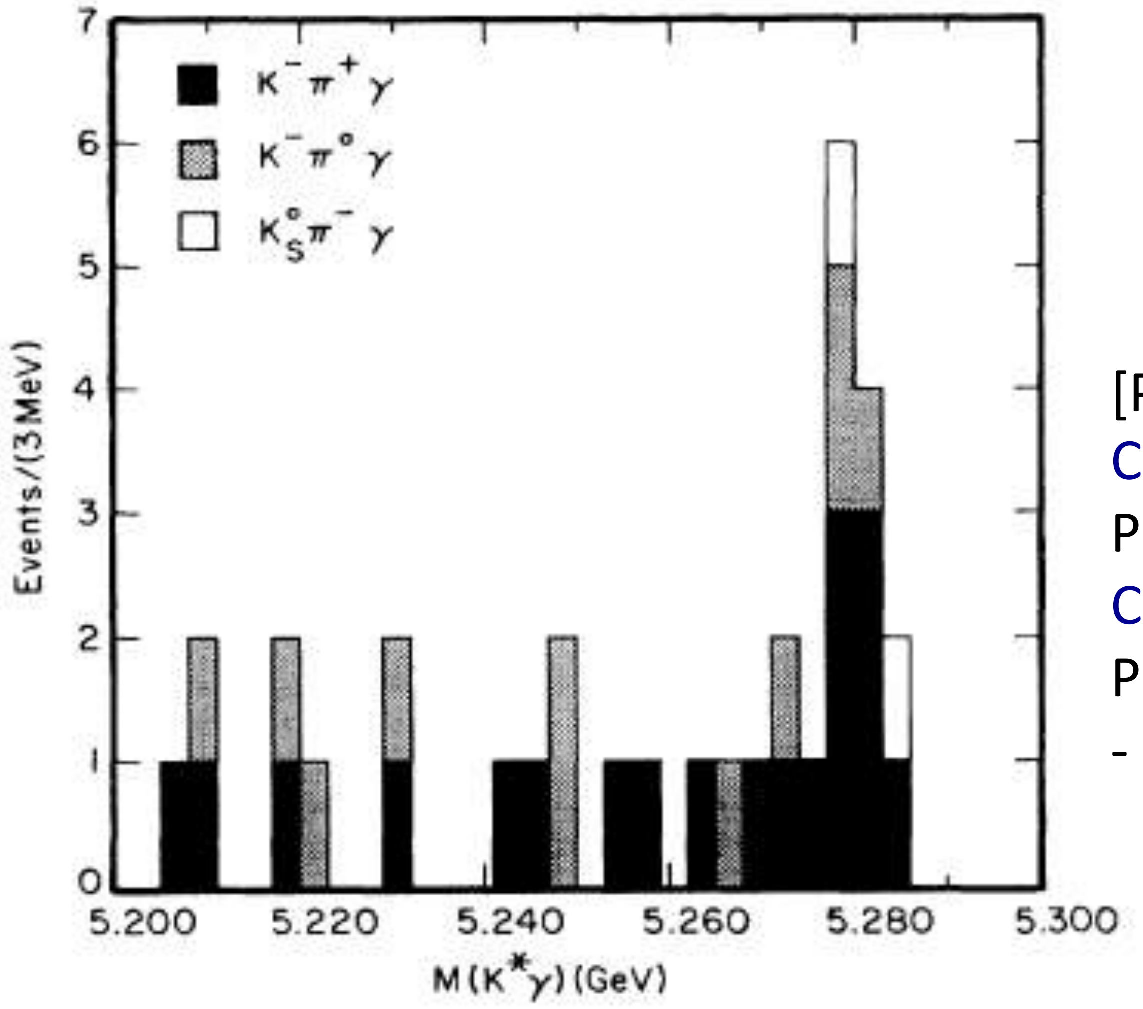




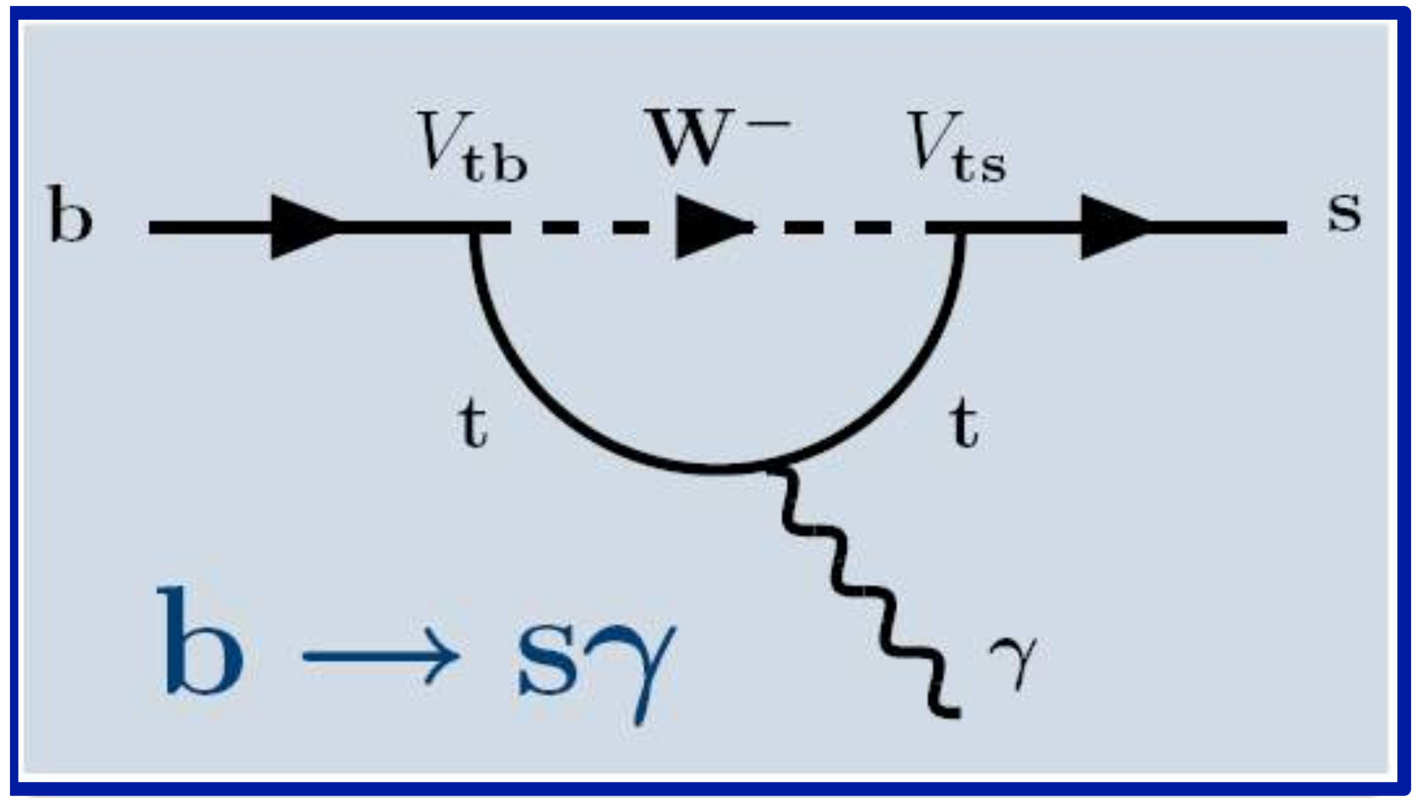
- Most precise value to date: $\mathrm{BR}(K^+ \to \pi^+ \nu \bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{\mathrm{stat}} \pm 0.9_{\mathrm{syst}}) \times 10^{-11}$ and compatible with SM.
- Run II will be important for even more precise determination.

b—>s transitions

- The first b—>s transition was discovered in 1993 by the CLEO collaboration.

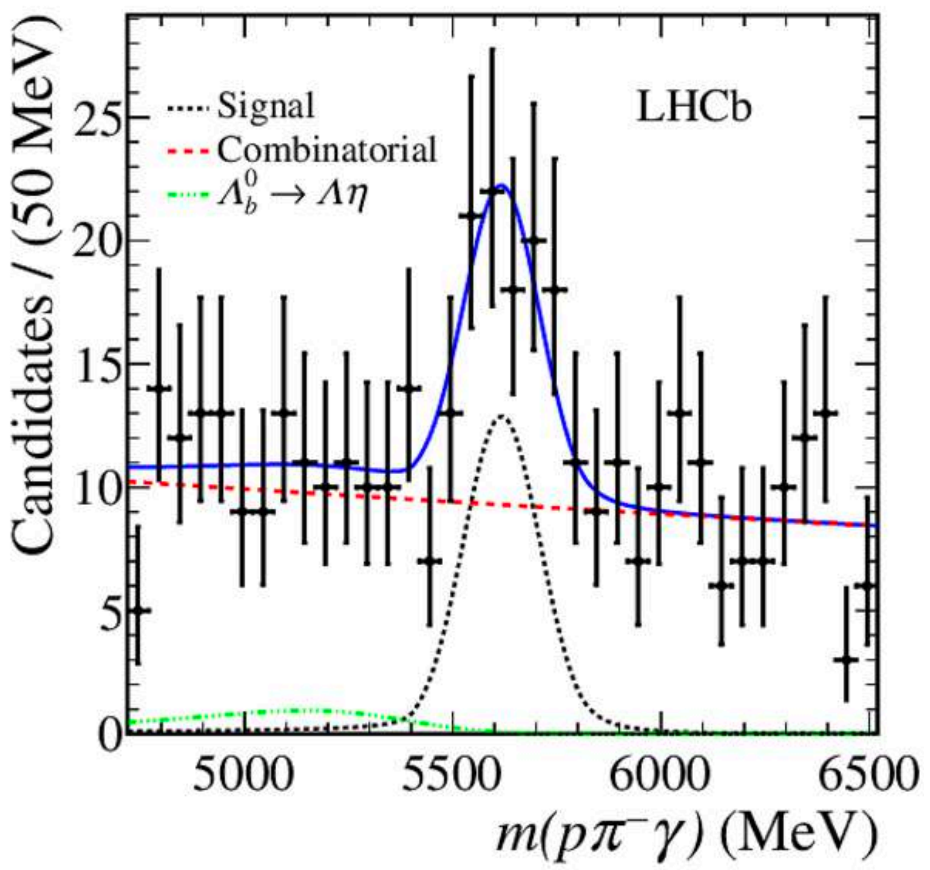


[Phys.Rev.Lett. 71 (1993) 674 - Cited by 605 records
Phys.Rev.Lett. 74 (1995) 2885 - Cited by 836 records
Phys.Rev.Lett. 87 (2001) 251807 - Cited by 565 records]



- At LHCb we focus more on B_s^0 and Λ_b^0 decays:
  - time-dependent CP asymmetry of $B_s^0 \text{—>} \phi\gamma$
  - Branching fraction of $\Lambda_b^0 \text{—>} \Lambda^0\gamma$

PHYS. REV. LETT. 123 (2019) 031801



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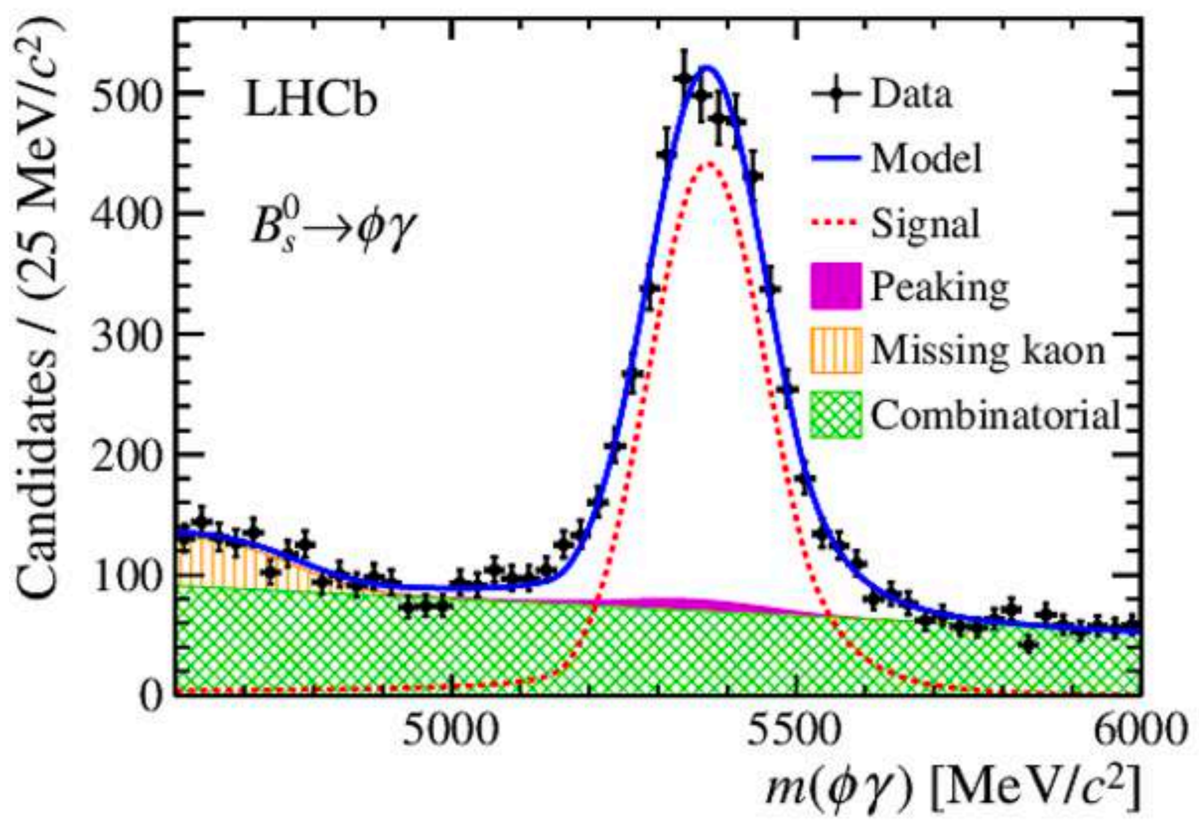
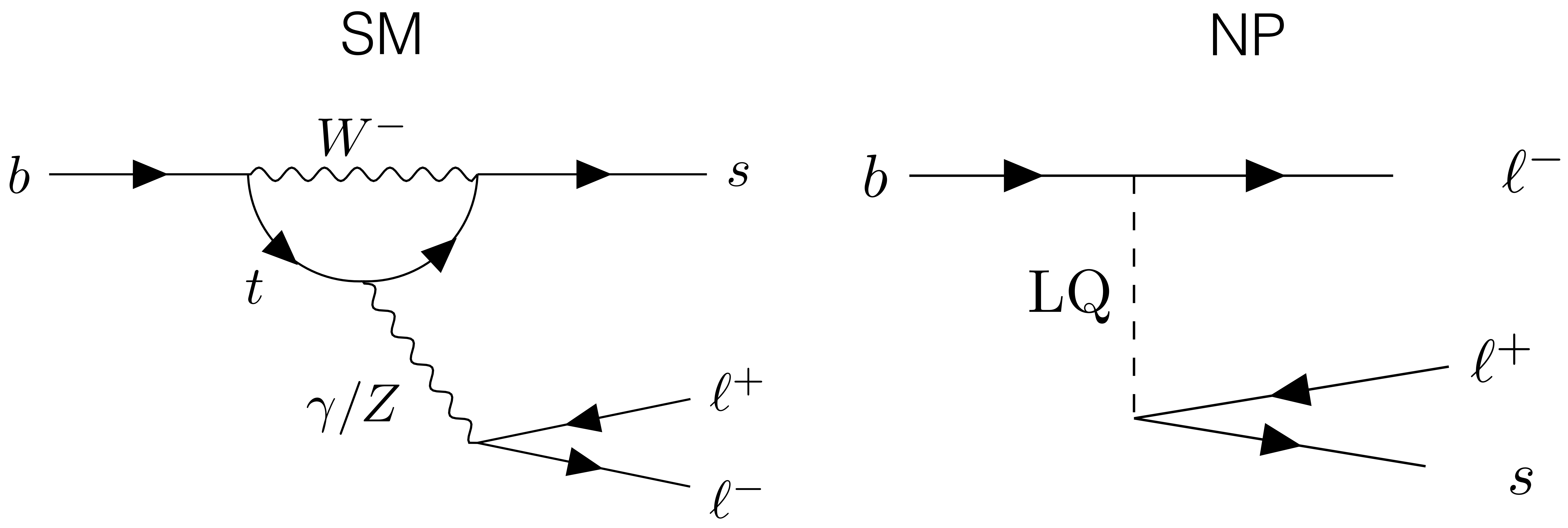


- $b \text{—>} s\gamma$ transitions difficult at hadron collider due to neutral photon.

$b \to s\ell\ell$ transitions

- The idea is that because these are loop suppressed, NP can compete quite easily with the SM decay amplitude.



- If NP couples strongly and is light enough, it will significantly alter the behaviour compared to the SM expectation.

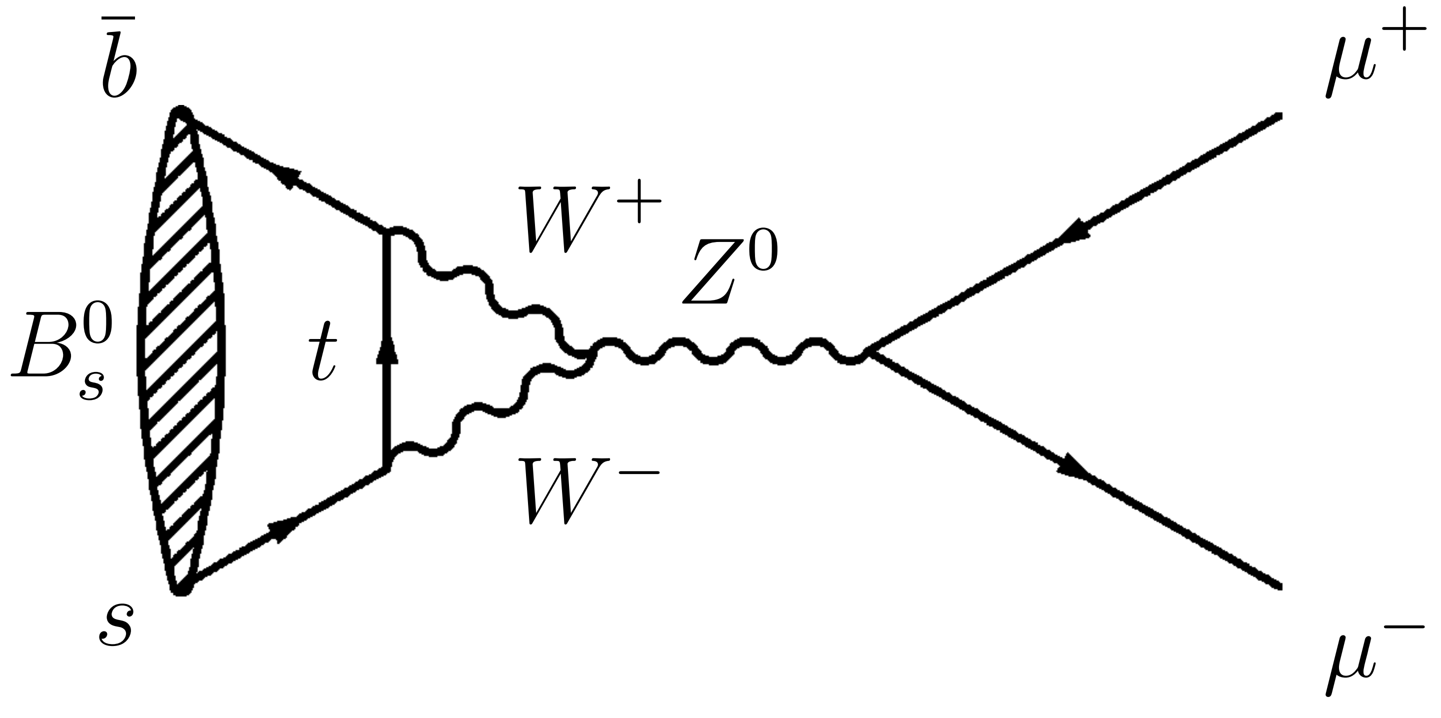
The ultra rare decay $B_s^0 \to \mu^+\mu^-$

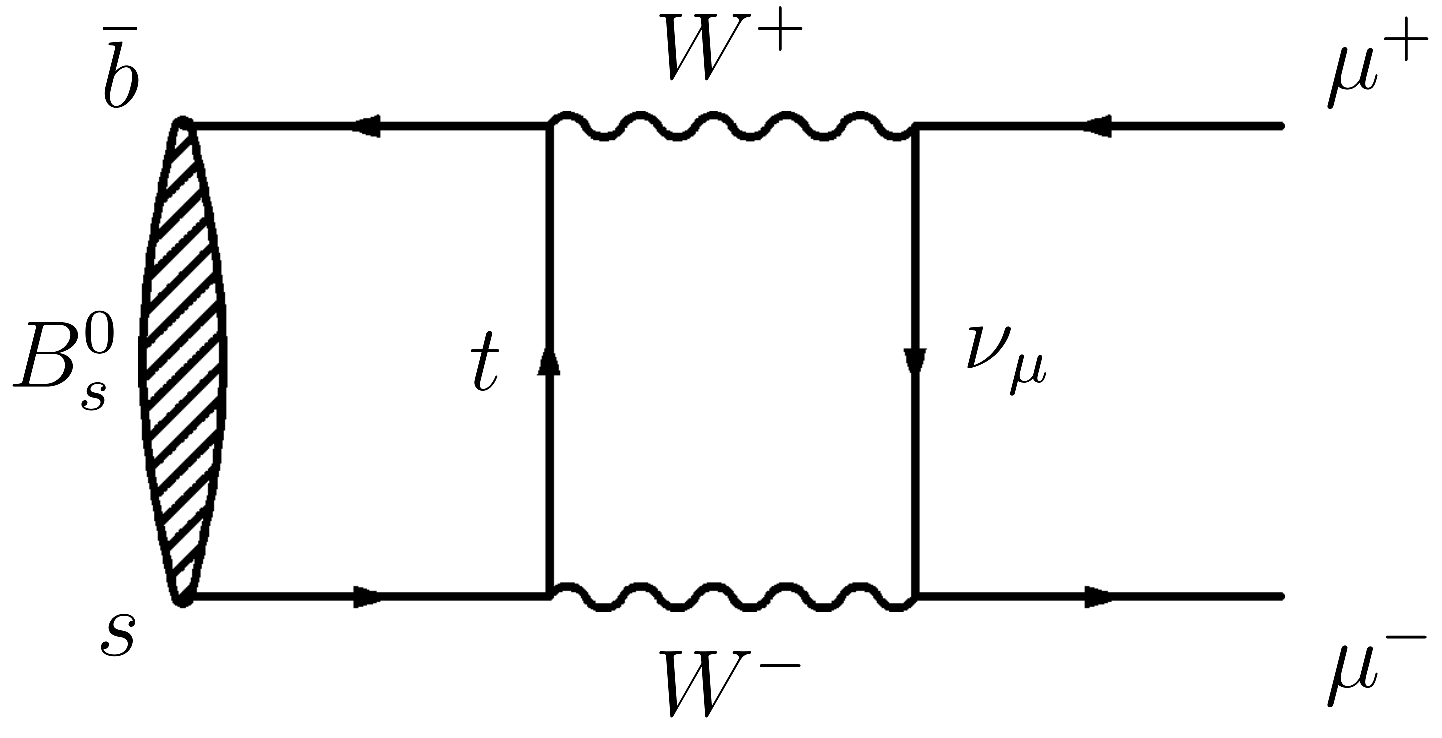
- When LHCb started taking data $B_s^0 \to \mu^+\mu^-$ was THE flagship measurement of the experiment.

- Helicity and GIM suppressed, resulting in a SM BF of

$$\mathscr{B}(B_s^0 \to \mu^+\mu^-)_{\text{SM}} = (3.66 \pm 0.14) \times 10^{-9}$$

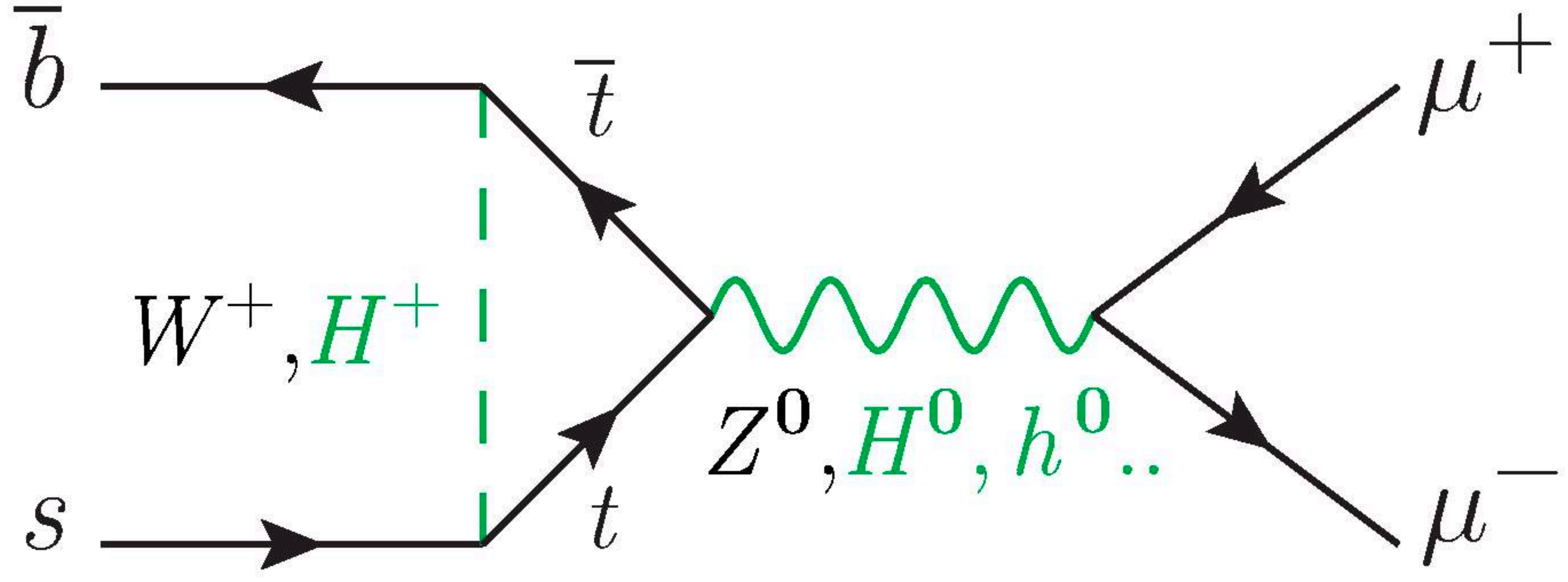
[JHEP 10 (2019) 232]





- Suppressed to the level of rare kaon decays, and very well predicted, a golden channel for new physics.

- The initial focus on new physics was on scalar NP breaking the helicity suppression (e.g. 2HDM with large tan(β)).



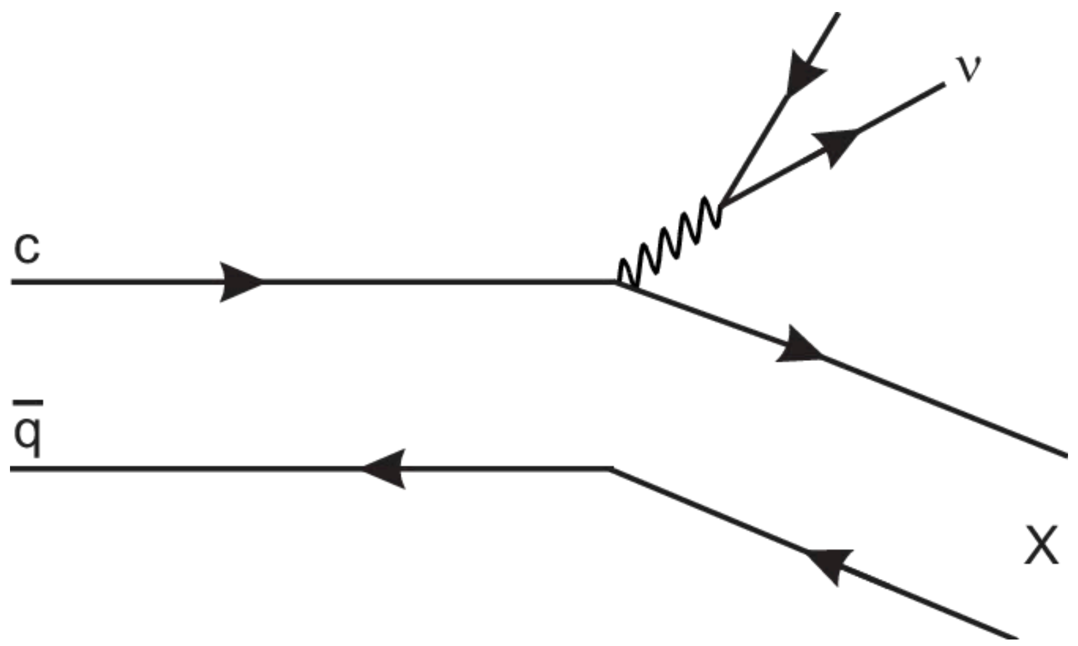
One important ingredient: f_s/f_d

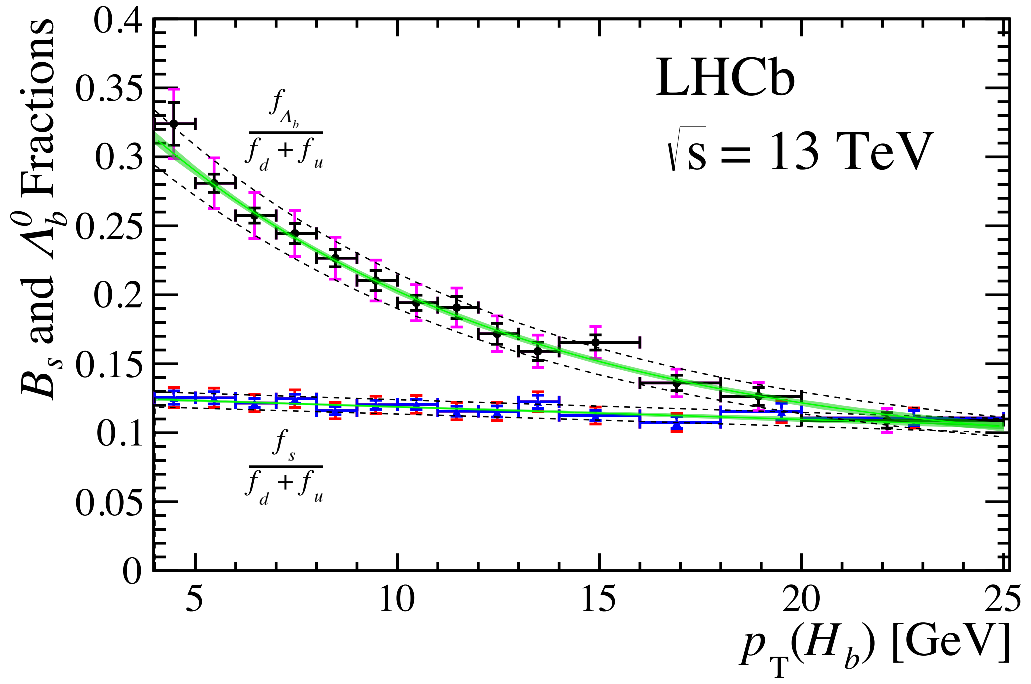
- All branching fraction measurements in LHCb are normalised to a known decay mode.
- The most precise branching fractions are measured by the B-factories - B^+ and B^0 decays.
- Measuring B_s^0 decays therefore requires the production fraction ratio f_s/f_d. Two ways:

Semileptonic decays	Hadronic decays

Semileptonic decays

- Use equality of partial widths (from HQET) and compare semileptonic decay rates from B_s and $B^{0/+}$ decays.

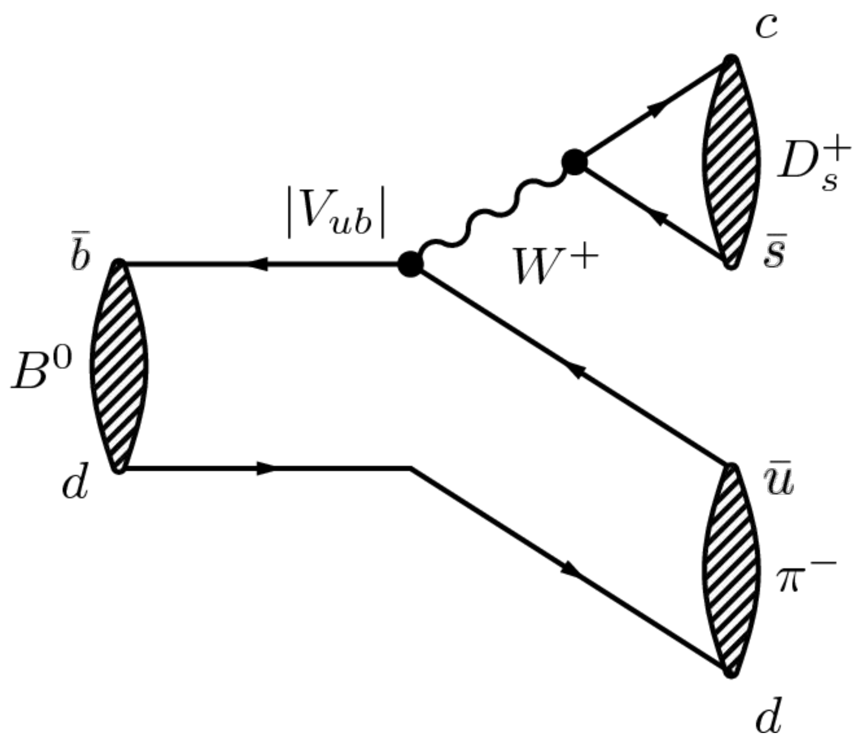




B-fractions analysis, Phys.Rev. D100 (2019) no.3, 031102

Hadronic decays

- Compare $B_s^0 \rightarrow D_s^+\pi^-$ and $B^0 \rightarrow D^-\pi^+$ decays



- Ratio assuming SU(3) is

$$r_{D\pi} = \tan\theta_c \frac{f_{D^+}}{f_{D_s^+}} \sqrt{\frac{\mathcal{B}(B^0 \to D_s^+\pi^-)}{\mathcal{B}(B^0 \to D^-\pi^+)}}$$

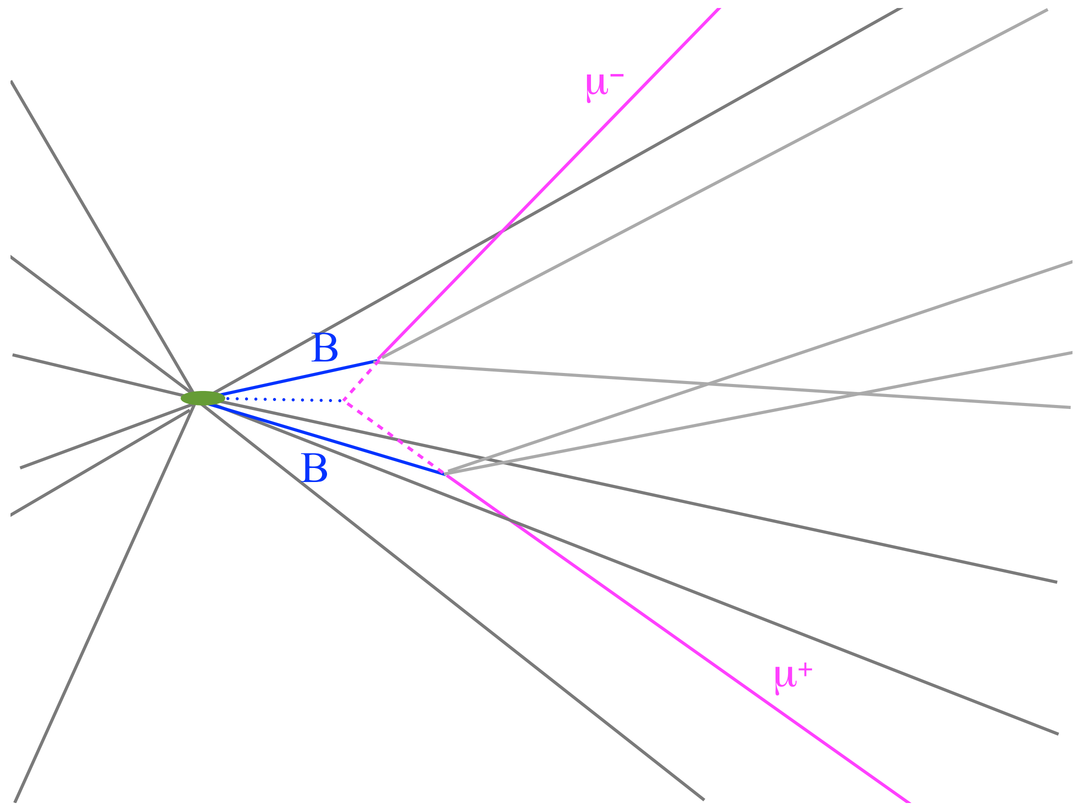
- Perhaps there is also a puzzle here too:

10.1140/epjc/s10052-020-08512-8

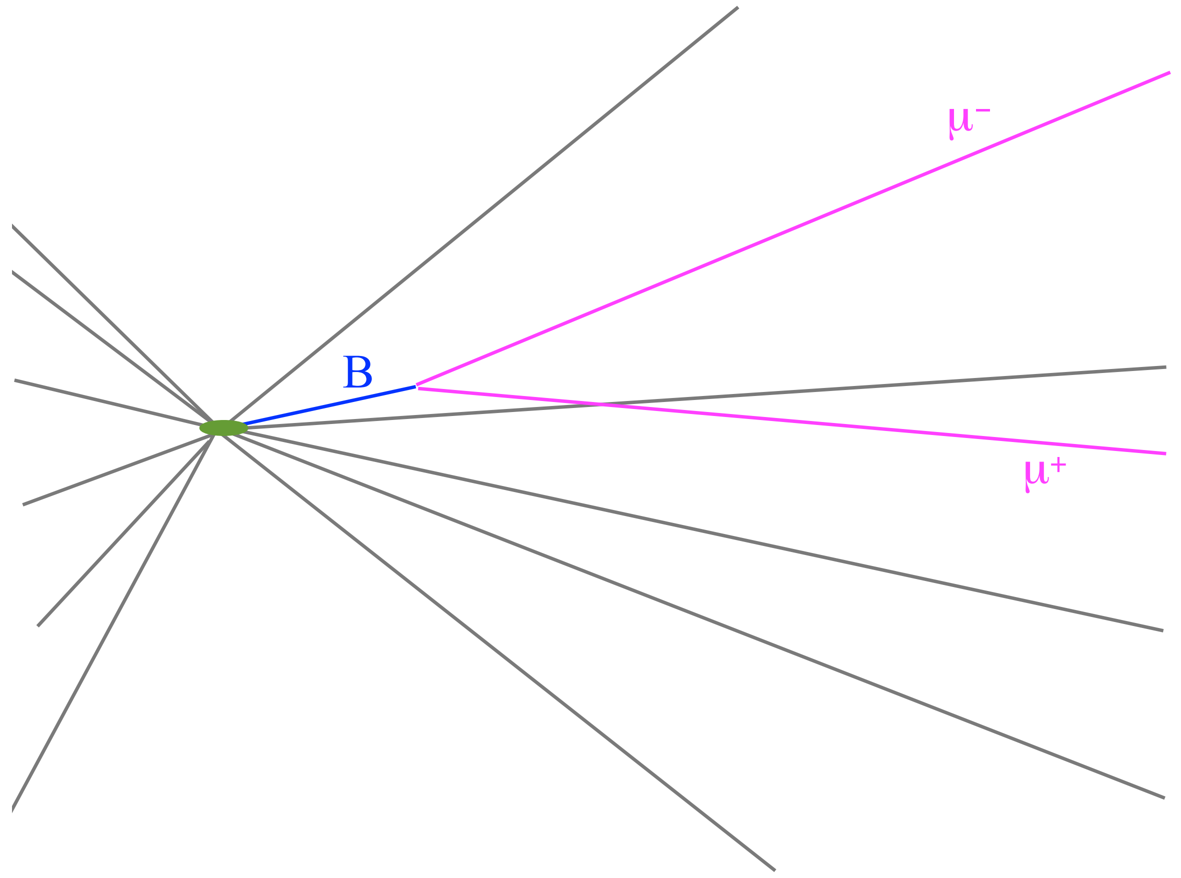
Background reduction

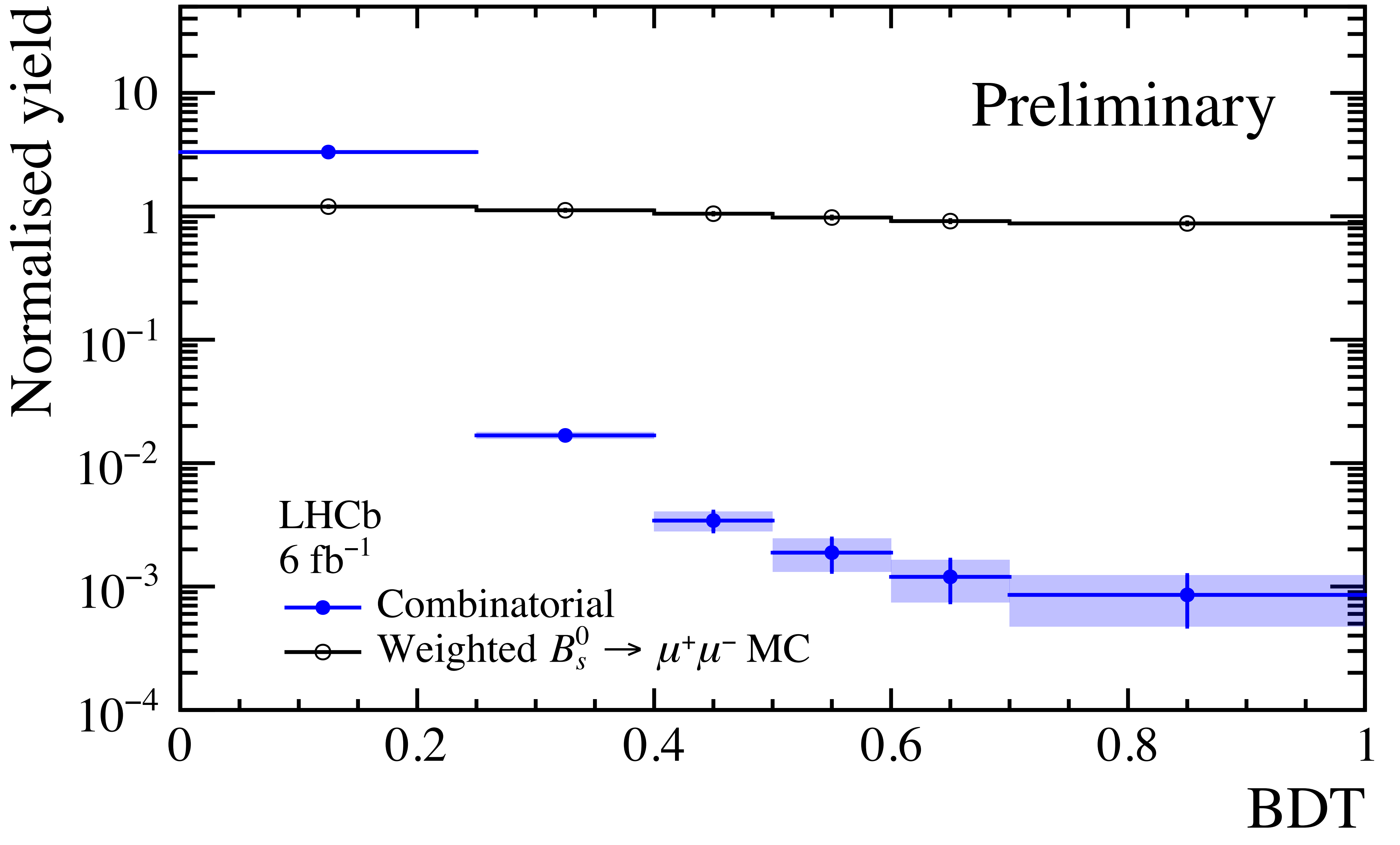
- Main background arises from so-called combinatorial background: Accidental combinations of two muons from different decays.

Combinatorial



Signal





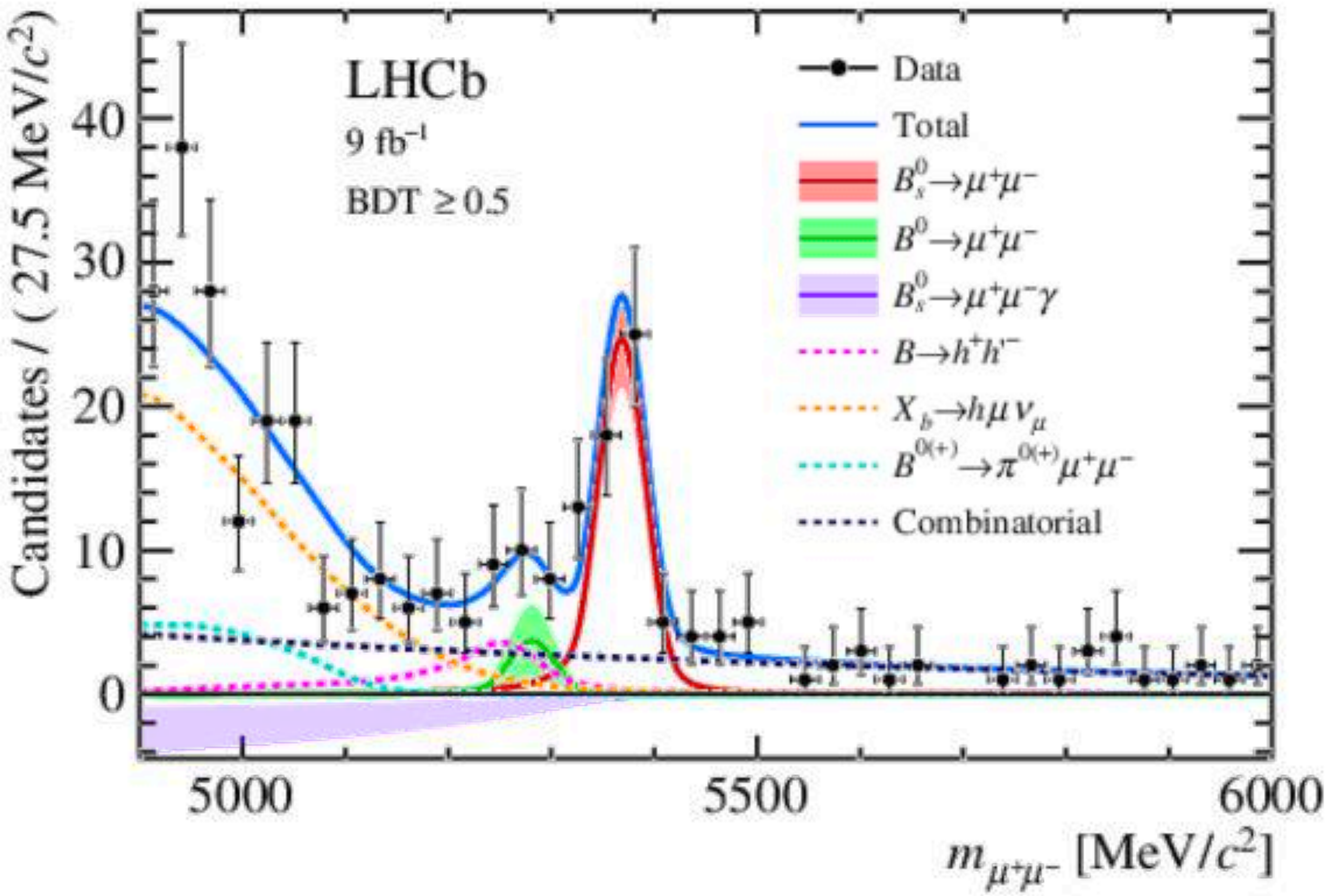
- Other specific backgrounds include b—>u semileptonic decays and misidentified charmless decays.

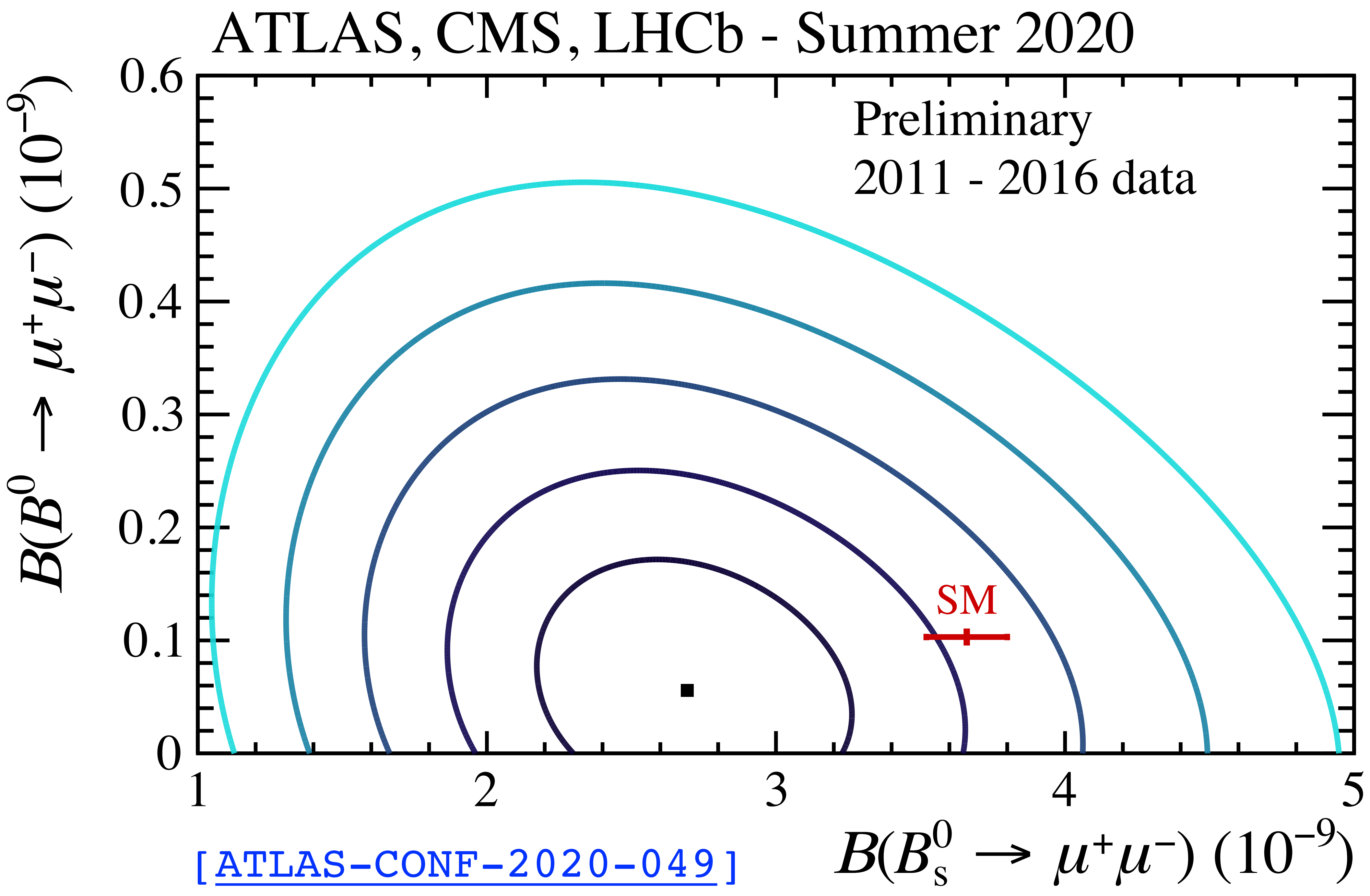
Latest results

- Latest results with full run II data includes precise f_s/f_d combination

$$f_s/f_d\ (7\ \text{TeV}) = 0.239 \pm 0.008,\ \ f_s/f_d\ (13\ \text{TeV}) = 0.254 \pm 0.008$$ [LHCb-PAPER-2020-046]

ARXIV:2108.09284

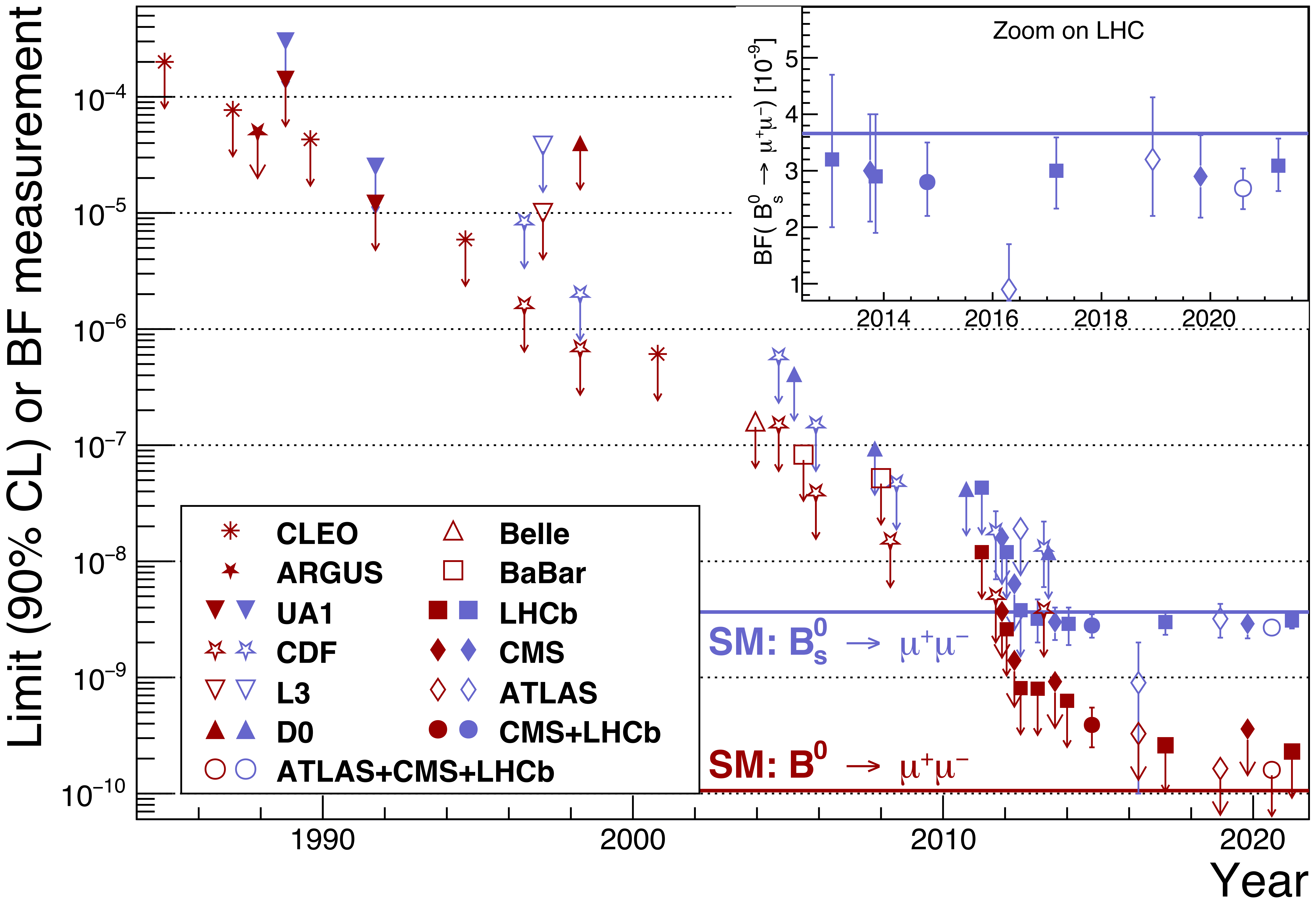




[ATLAS-CONF-2020-049]

- Results consistent with SM, but combination with ATLAS/CMS ~ 2 σ below SM prediction.
  - Combination to be updated with new f_s/f_d and latest LHCb result.

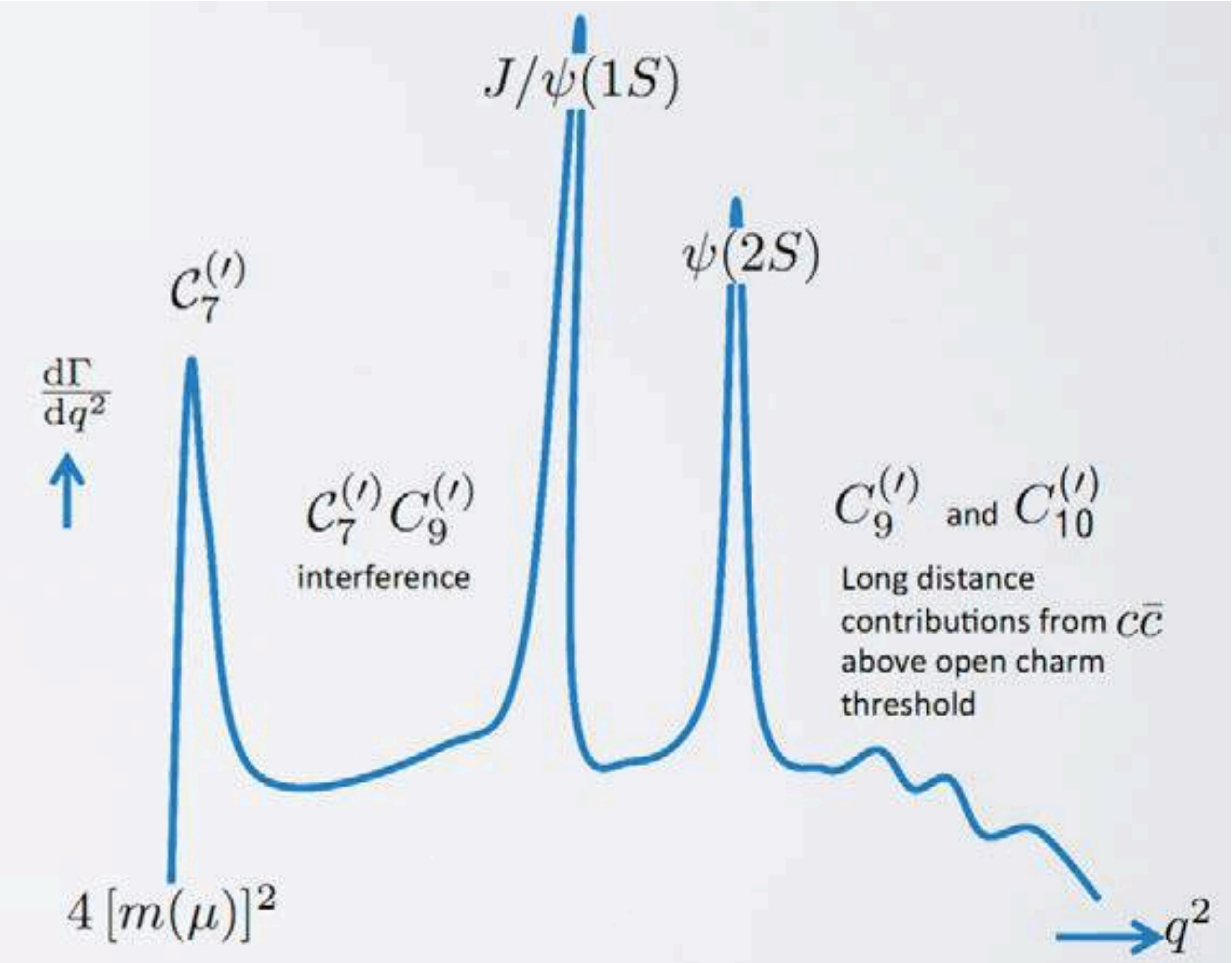
A long history - still room for NP!



Semileptonic $b \to s\ell\ell$

- Example decays should result in low energy hadrons in order to get good theory predictions.

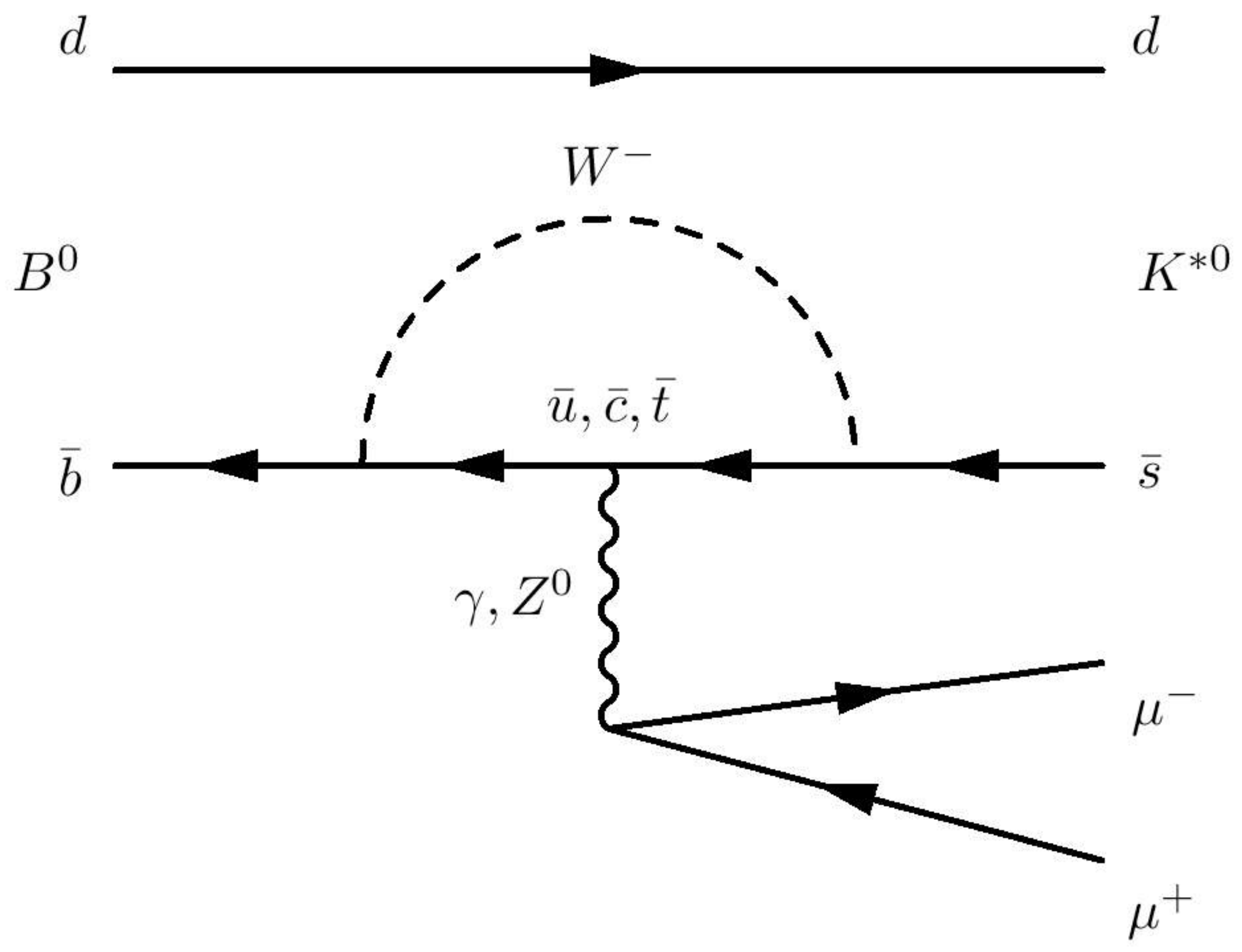
- e.g.
  - $B^+ \to K^+\mu^+\mu^-$
  - $\Lambda_b^0 \to \Lambda^0\mu^+\mu^-$
  - $B_s^0 \to \phi\mu^+\mu^-$
  - $B^0 \to K^{*0}\mu^+\mu^-$

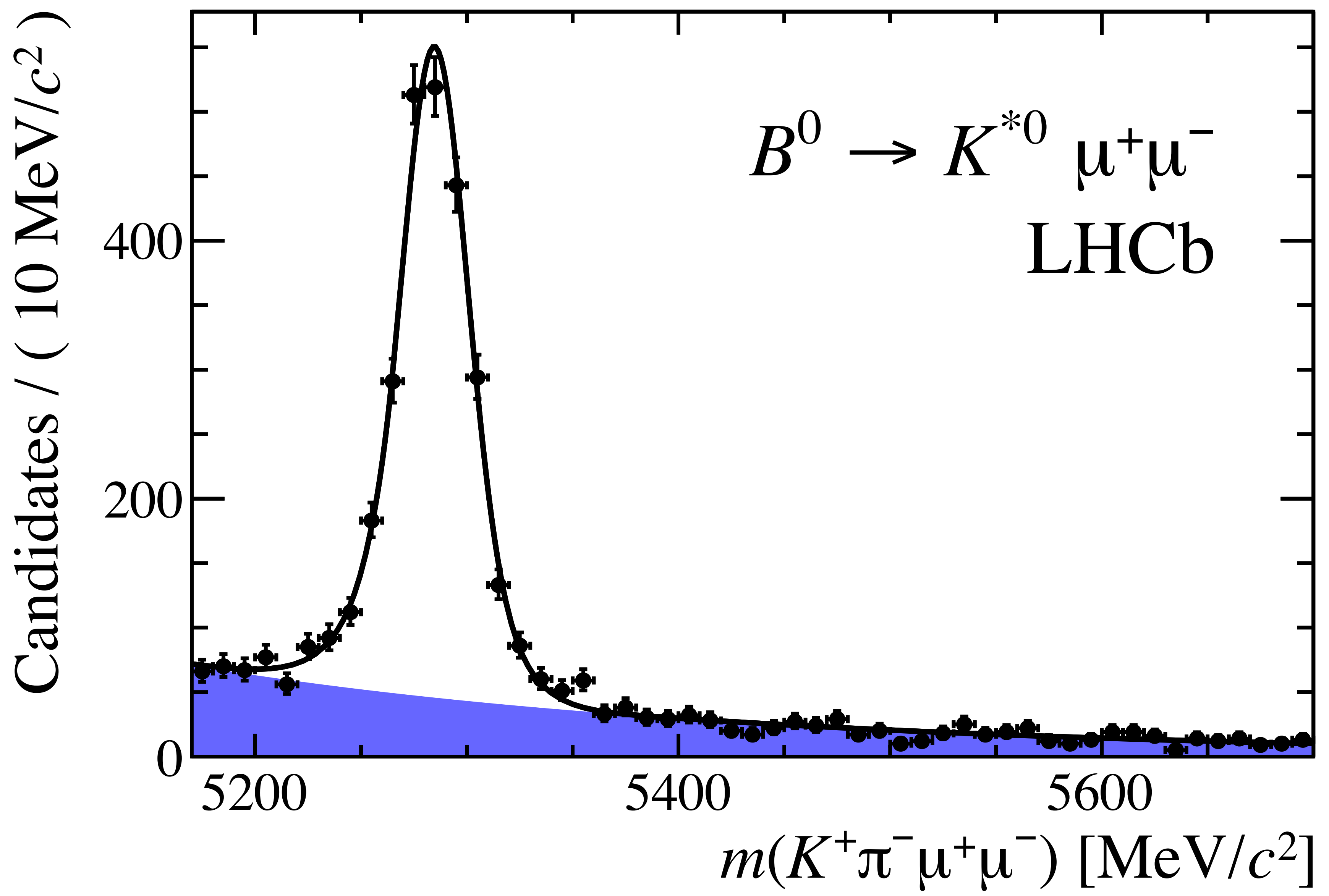


- Get spikes in the distribution, typically we veto these so that we are dominated by the semileptonic decay.

Branching fraction

- Is NP affecting the rate of these decays?
  - Measure the branching fraction as a function of q².





- Take the most experimentally appealing signature (muons and charged hadrons).

Normalisation

- At LHCb we normalise to the corresponding J/ψ decay mode.

$$\frac{d\mathcal{B}}{dq^2} = \frac{N(B\to K^{(*)}\mu^+\mu^-)}{N(B\to J/\psi\, K^{(*)})} \cdot \frac{\varepsilon(B\to J/\psi\, K^{(*)})}{\varepsilon(B\to K^{(*)}\mu^+\mu^-)} \cdot \frac{\mathcal{B}(B\to J/\psi\, K^{(*)})\mathcal{B}(J/\psi \to \mu^+\mu^-)}{(q^2_{\max} - q^2_{\min})}$$

- This vastly simplifies systematic uncertainties, as both signal and normalisation have the same final state.

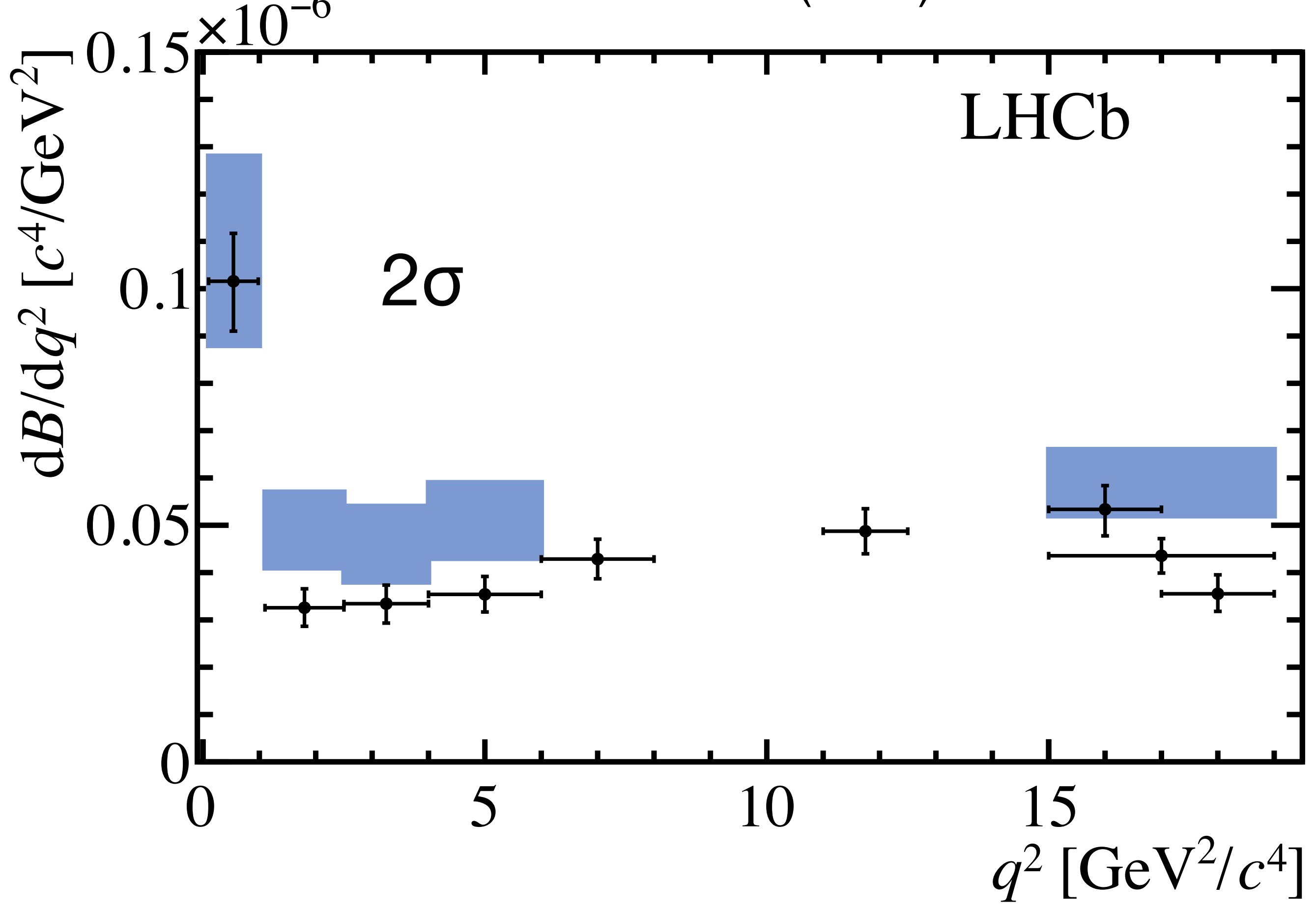
- But: we are limited by the uncertainty on $\mathcal{B}(B \to J/\psi K^{(*)})$

- Good information for B^+ and B^0 mesons from B-factories, for B_s^0 and Λ_b^0 branching fractions we have to do a bit more work.

Branching fraction results

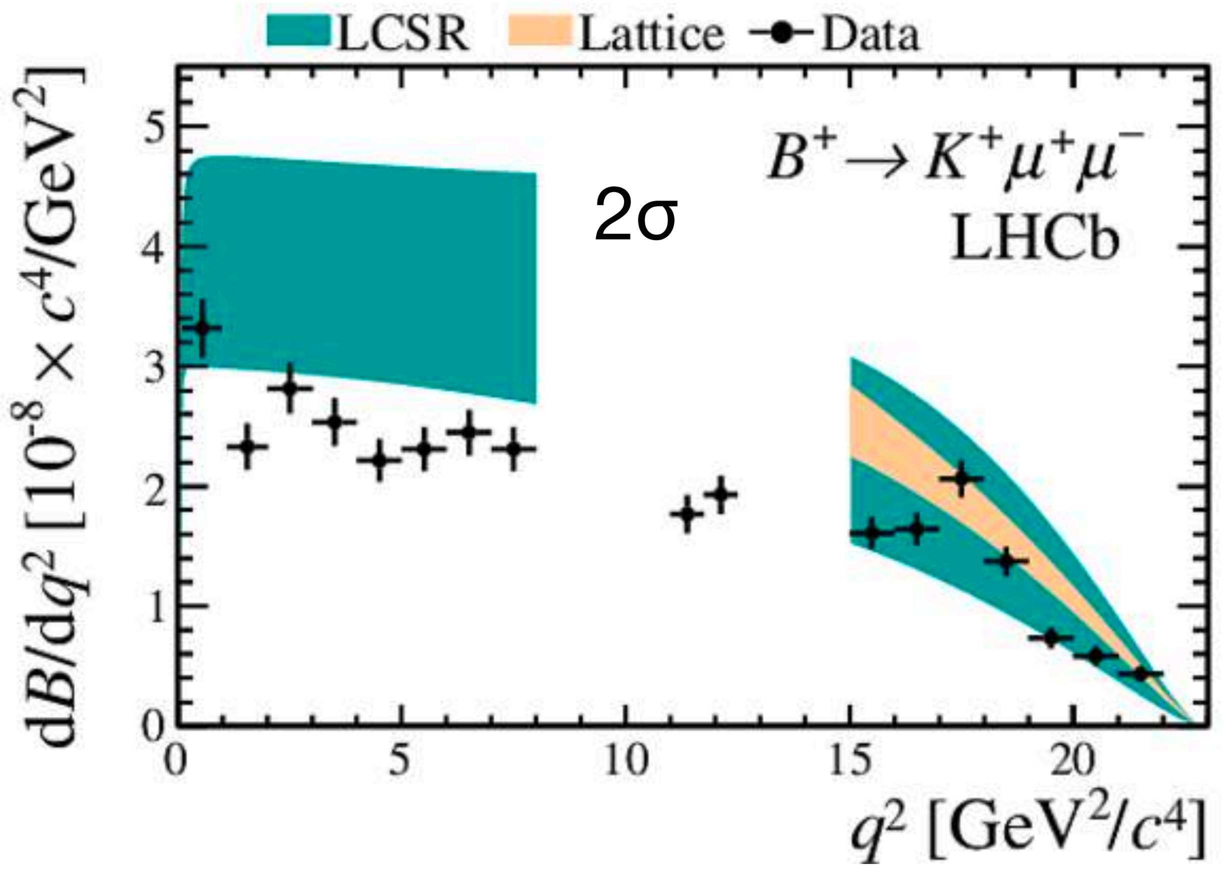
$B^0 \to K^{*0}\mu^+\mu^-$

JHEP 02 (2016) 104



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

[JHEP 06 (2014) 133](https://doi.org/10.1007/JHEP06(2014)133)



$B_s^0 \to \phi\mu^+\mu^-$

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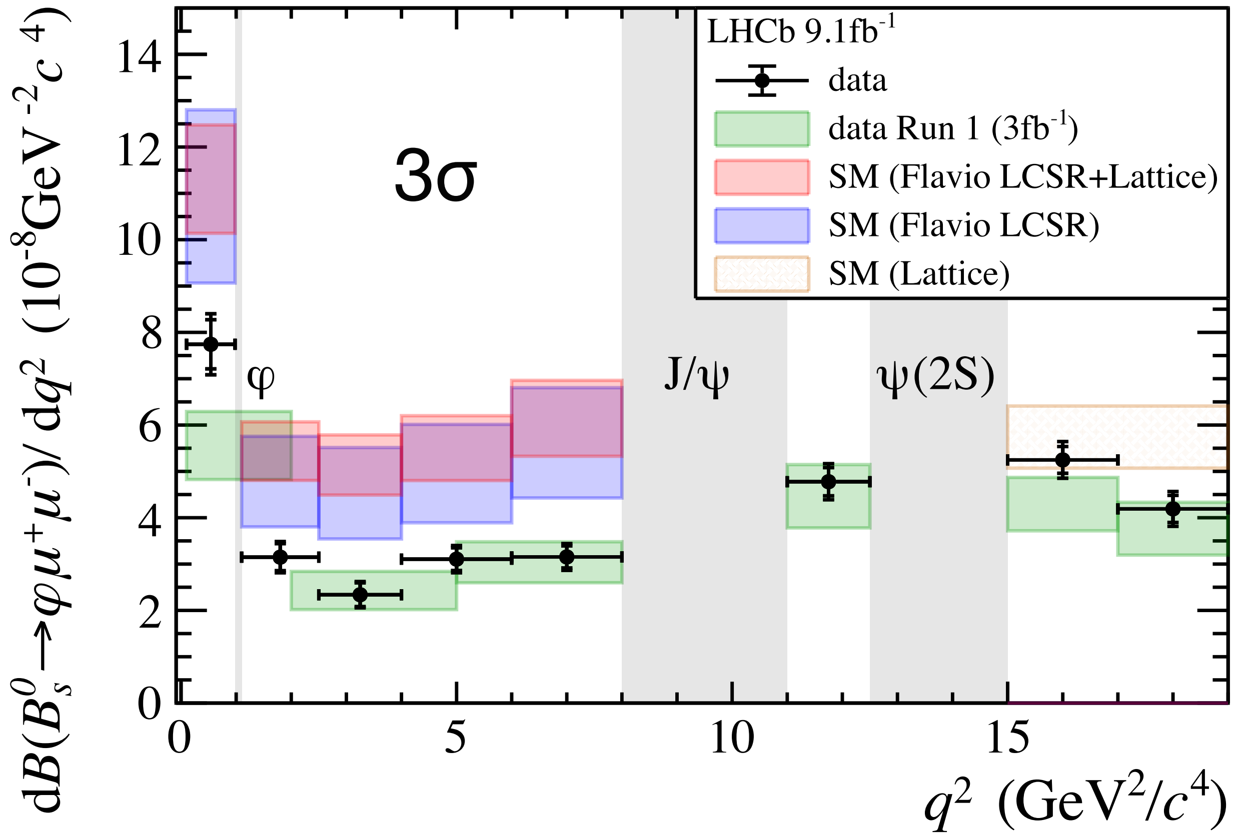
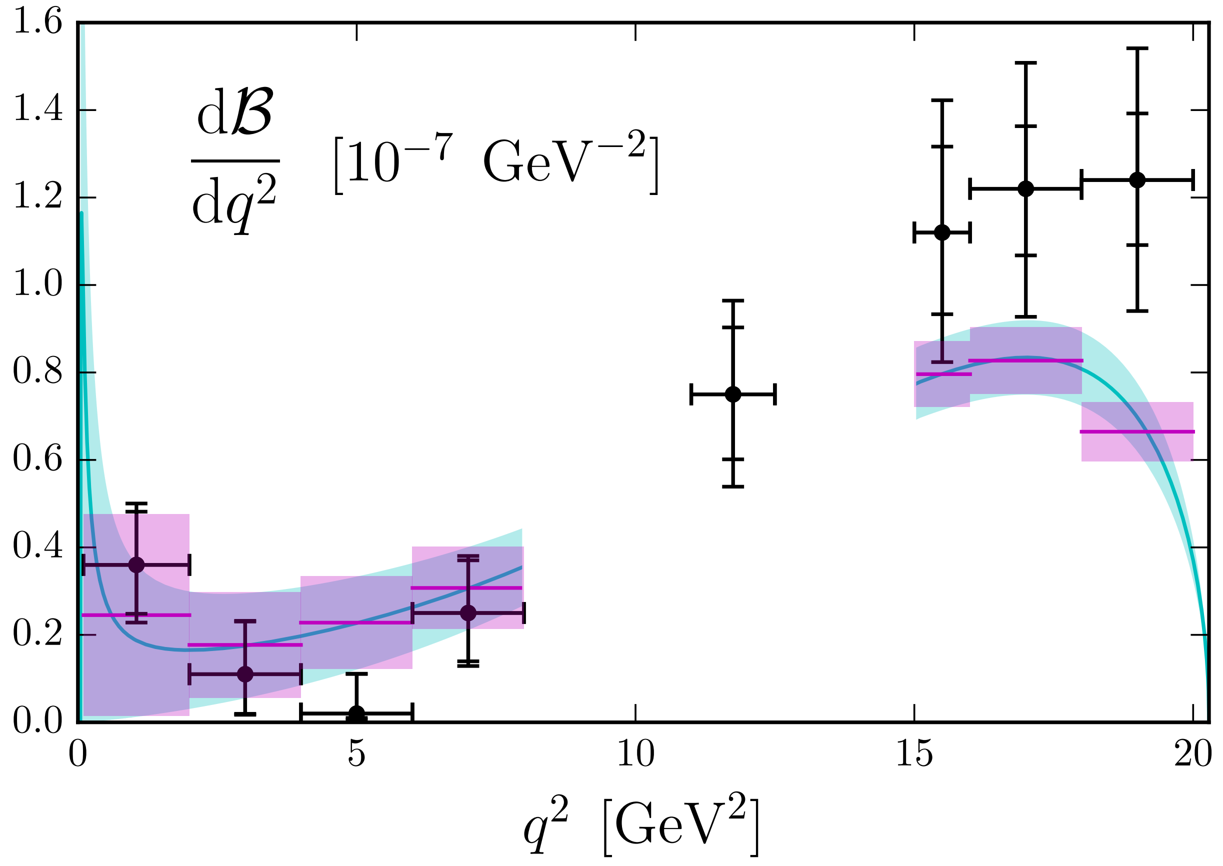


$\Lambda_b^0 \to \Lambda^0\mu^+\mu^-$

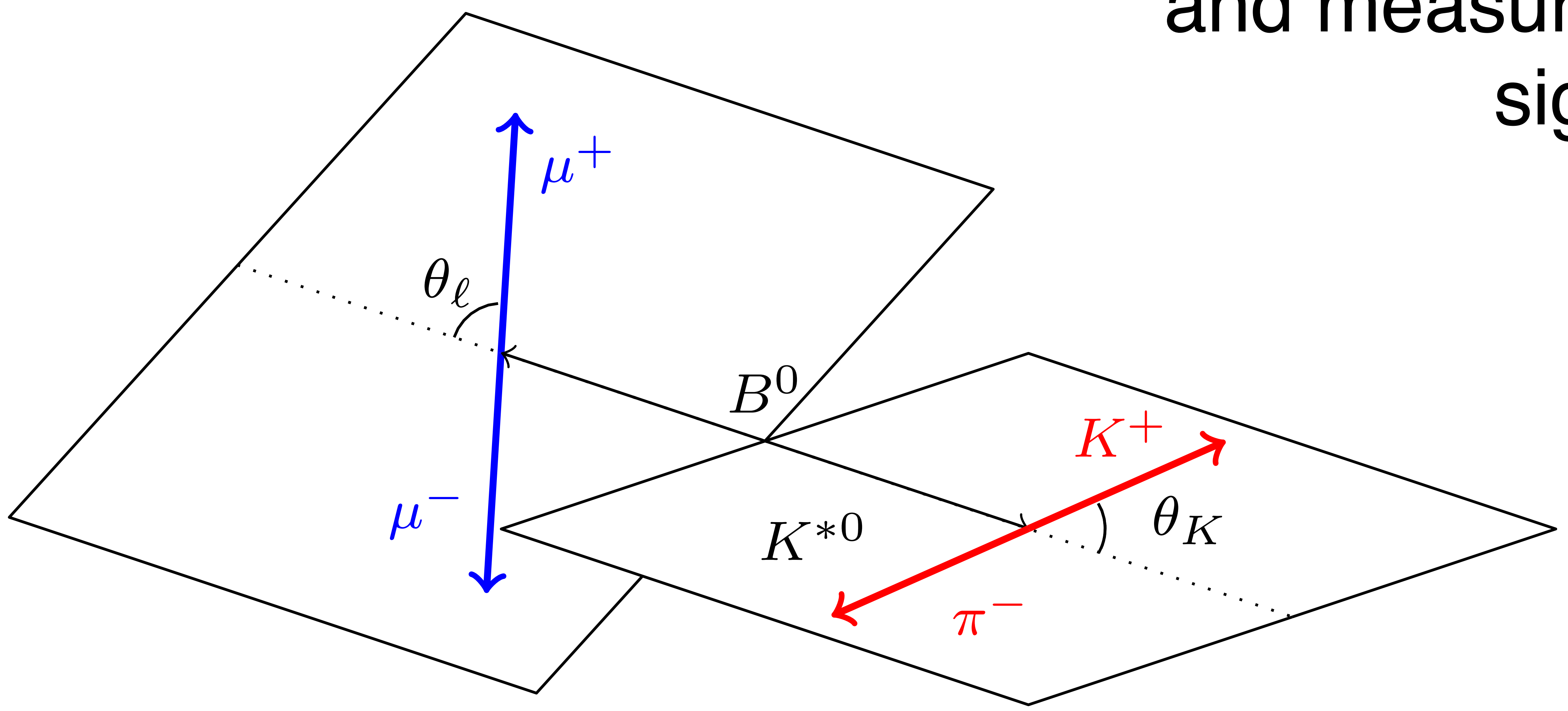


- Everything is below the SM, with the notable exception of $\Lambda_b^0 \to \Lambda^0\mu^+\mu^-$

However, this one appears to be a problem with the normalisation: [10.1103/PhysRevD.101.035023](https://doi.org/10.1103/PhysRevD.101.035023)

Beyond branching fractions

- If NP is indeed changing the branching fractions of these decays, expect it also to change the angular distribution.



Boost into the rest frame of the B, and measure these angles for every signal candidate.

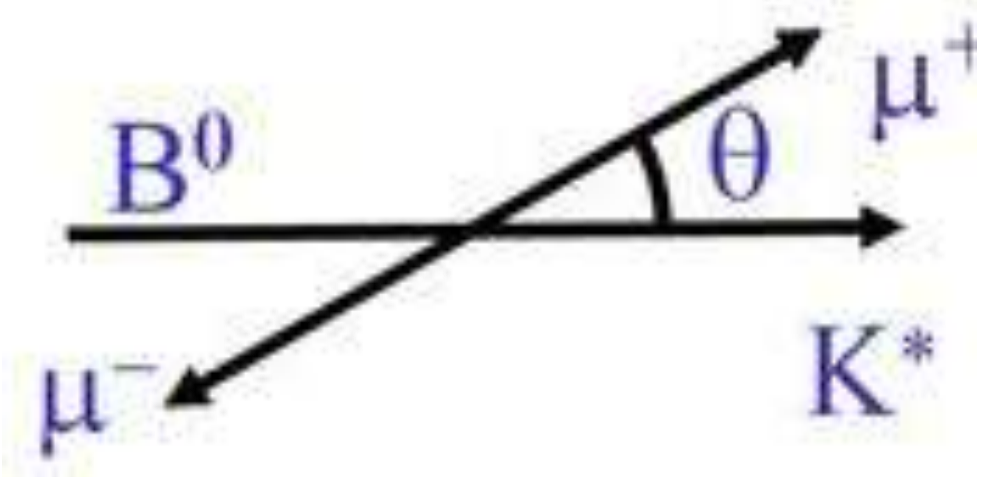
- The main decay is $B \to K^* \mu^+ \mu^-$, why not $B \to K \mu^+ \mu^-$ or $B_s^0 \to \phi \mu^+ \mu^-$?

First we write down the PDF

- The $B^0 \to K^{*0}\ell^+\ell^-$ angular distribution can be written down as follows

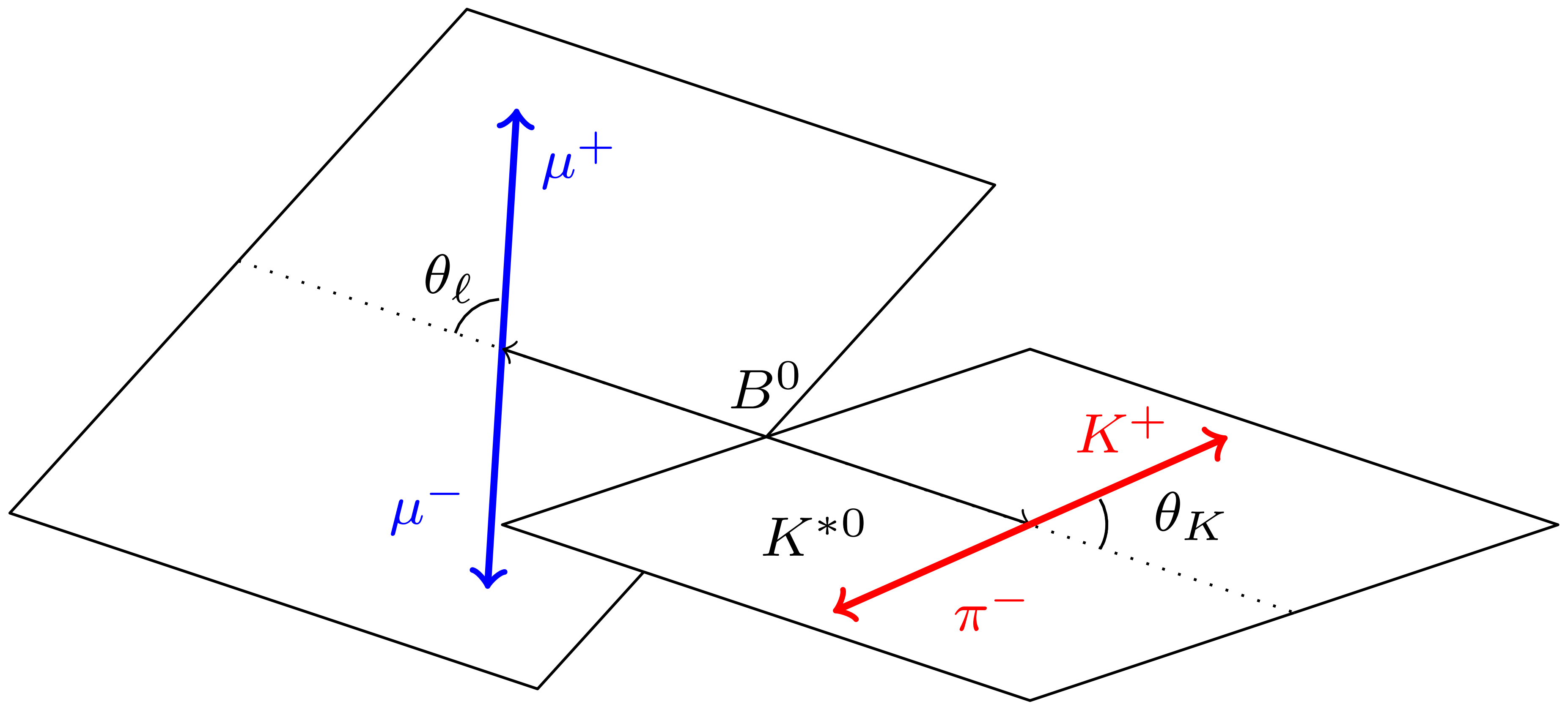
$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l$$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

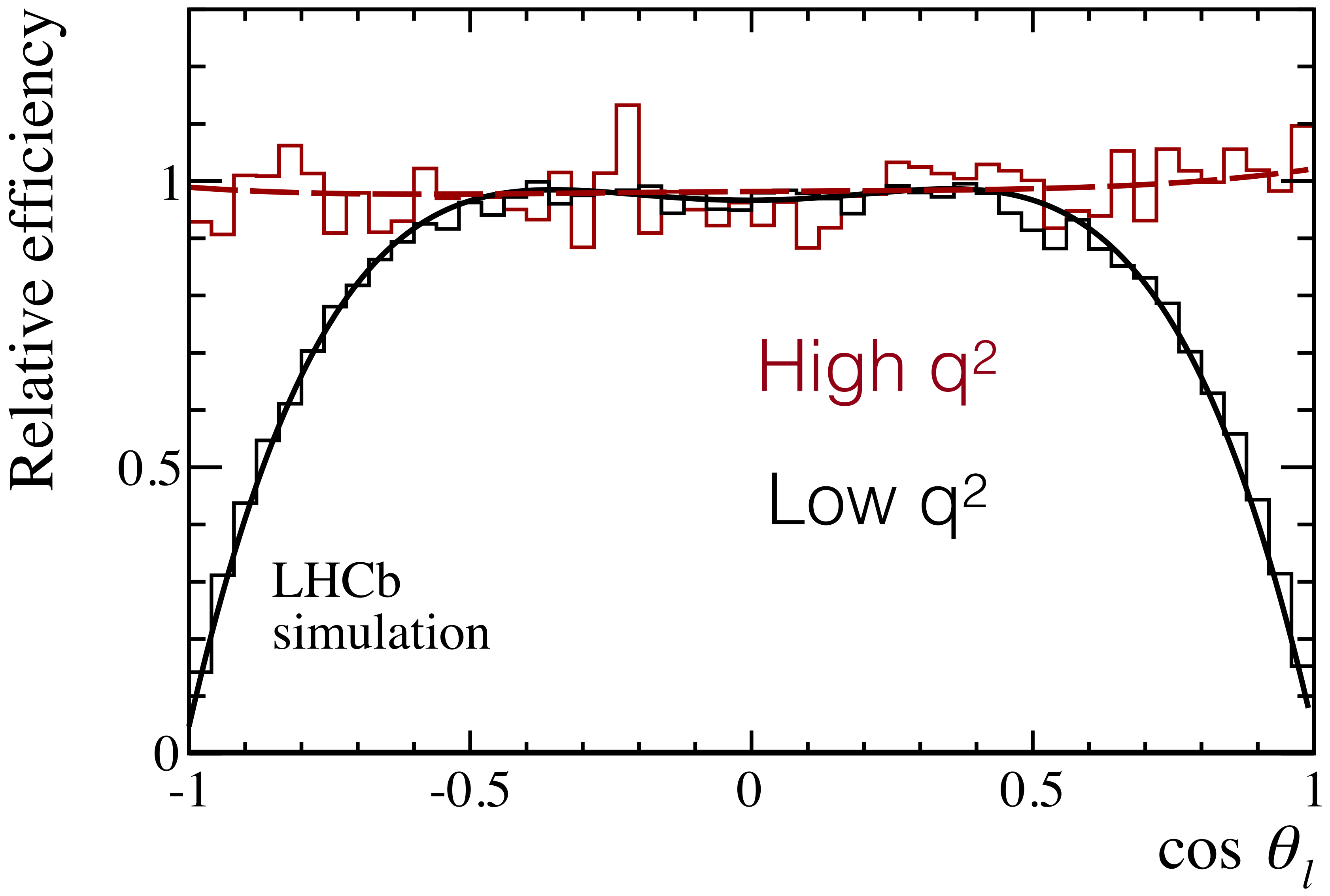
Probe observables such as the forward-backward asymmetry (A_{FB}) and and the fraction of longtitundal polarisation of the K* (F_L)



Need to correct for angular acceptance

- The requirements that the decay is reconstruction will bias the angular distribution.

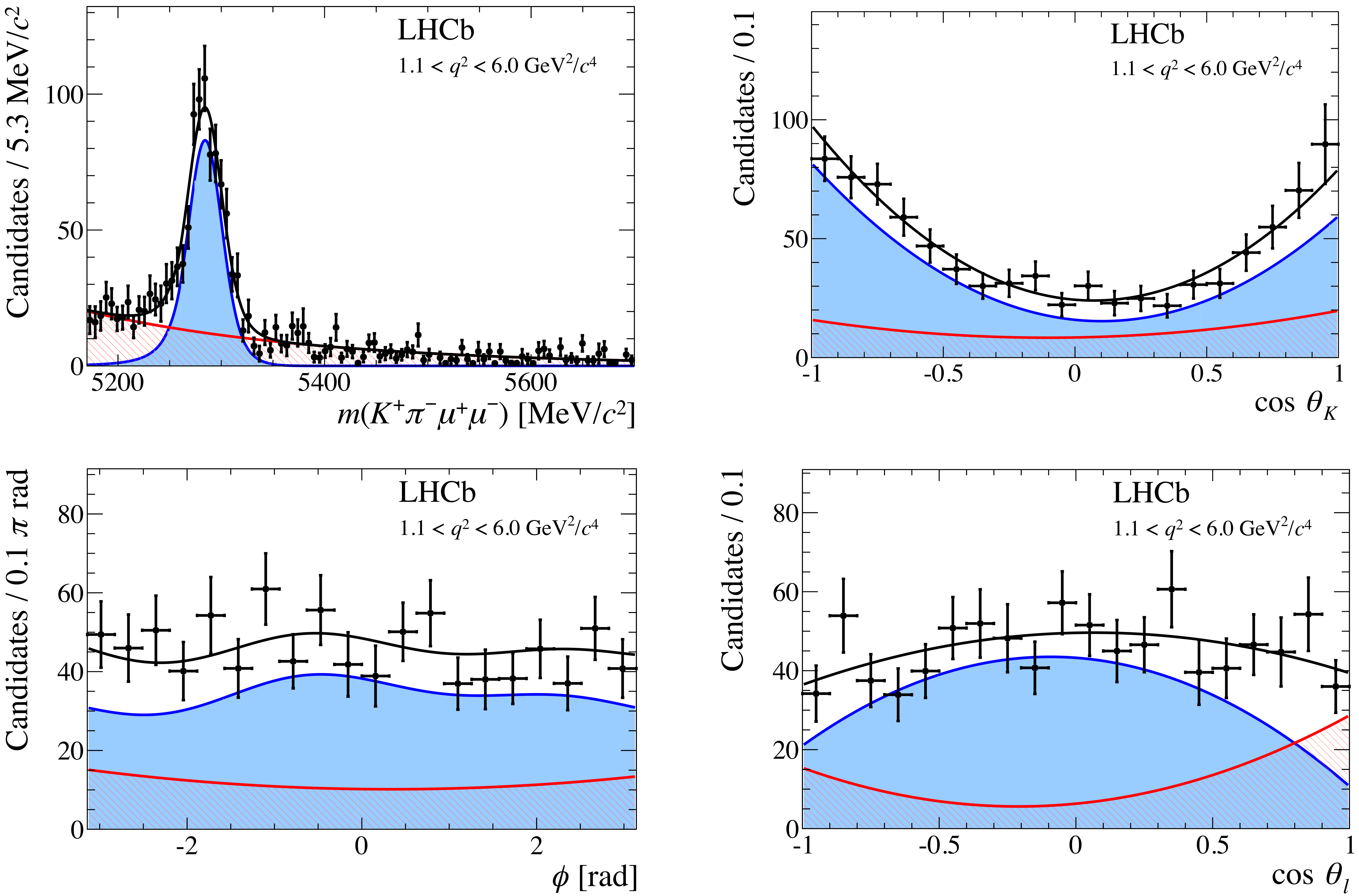




- This is corrected using simulation.

Then we fit the distribution

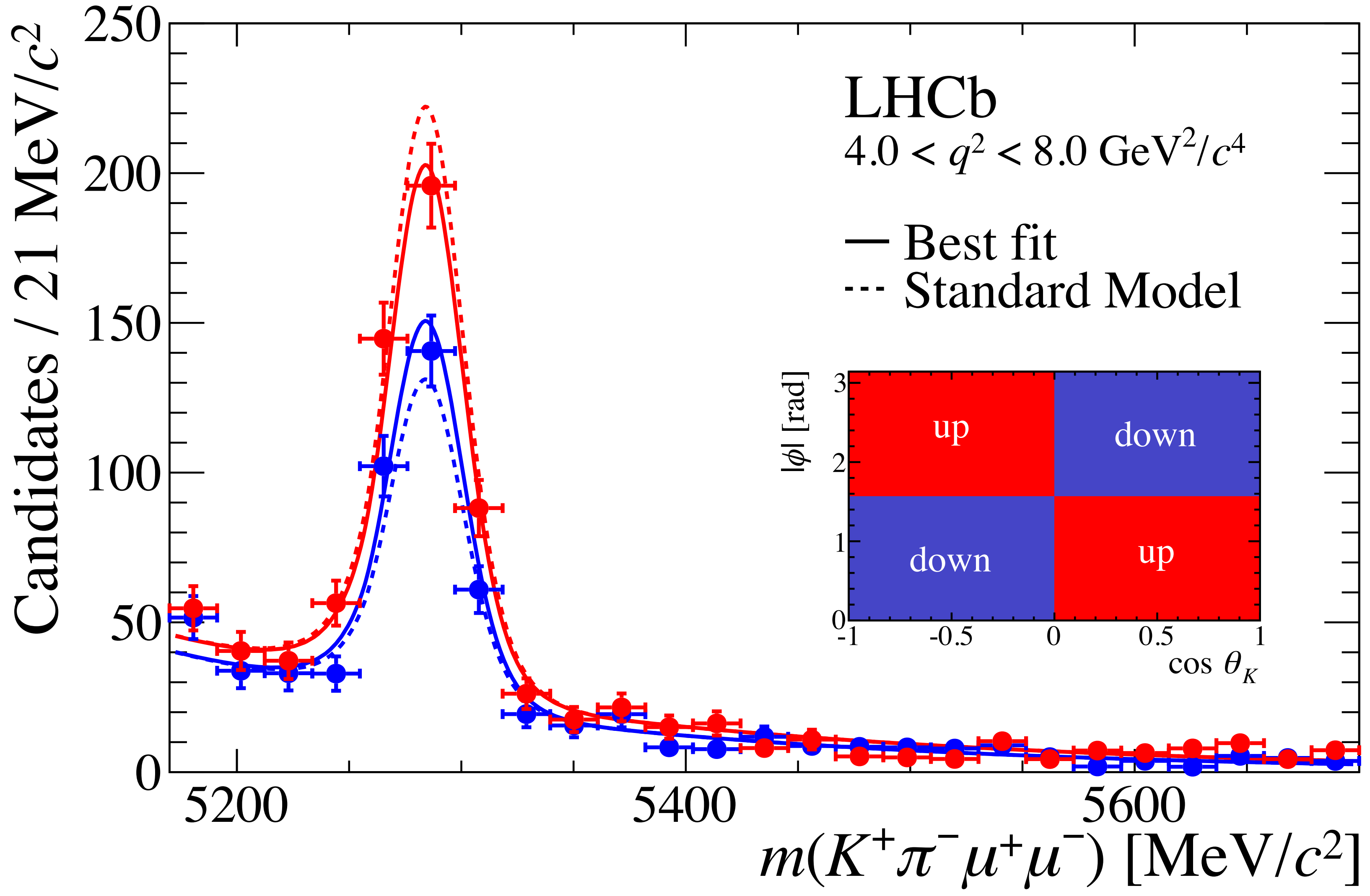
- Fit the 4D distribution of mass, three angles in bins of q².

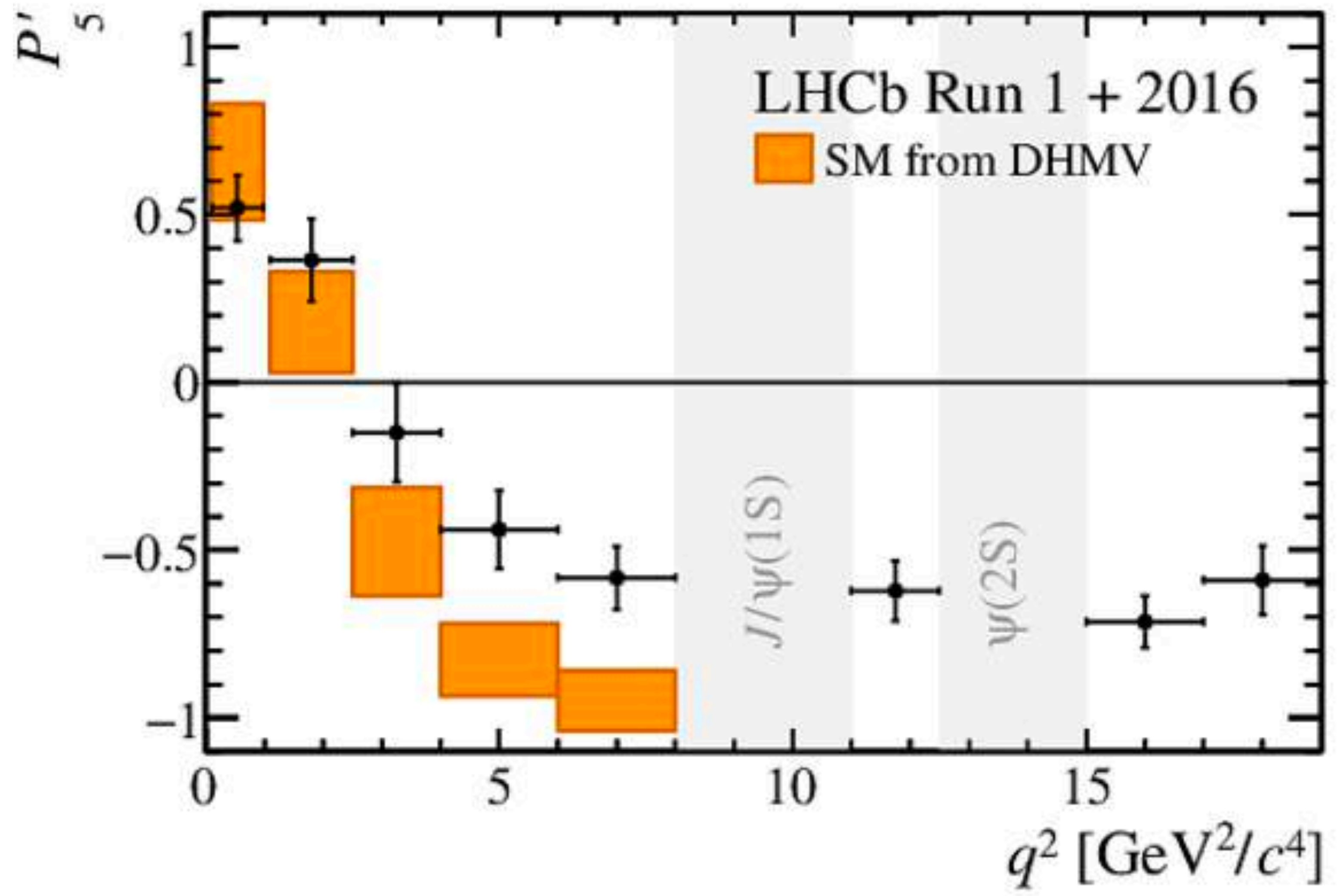


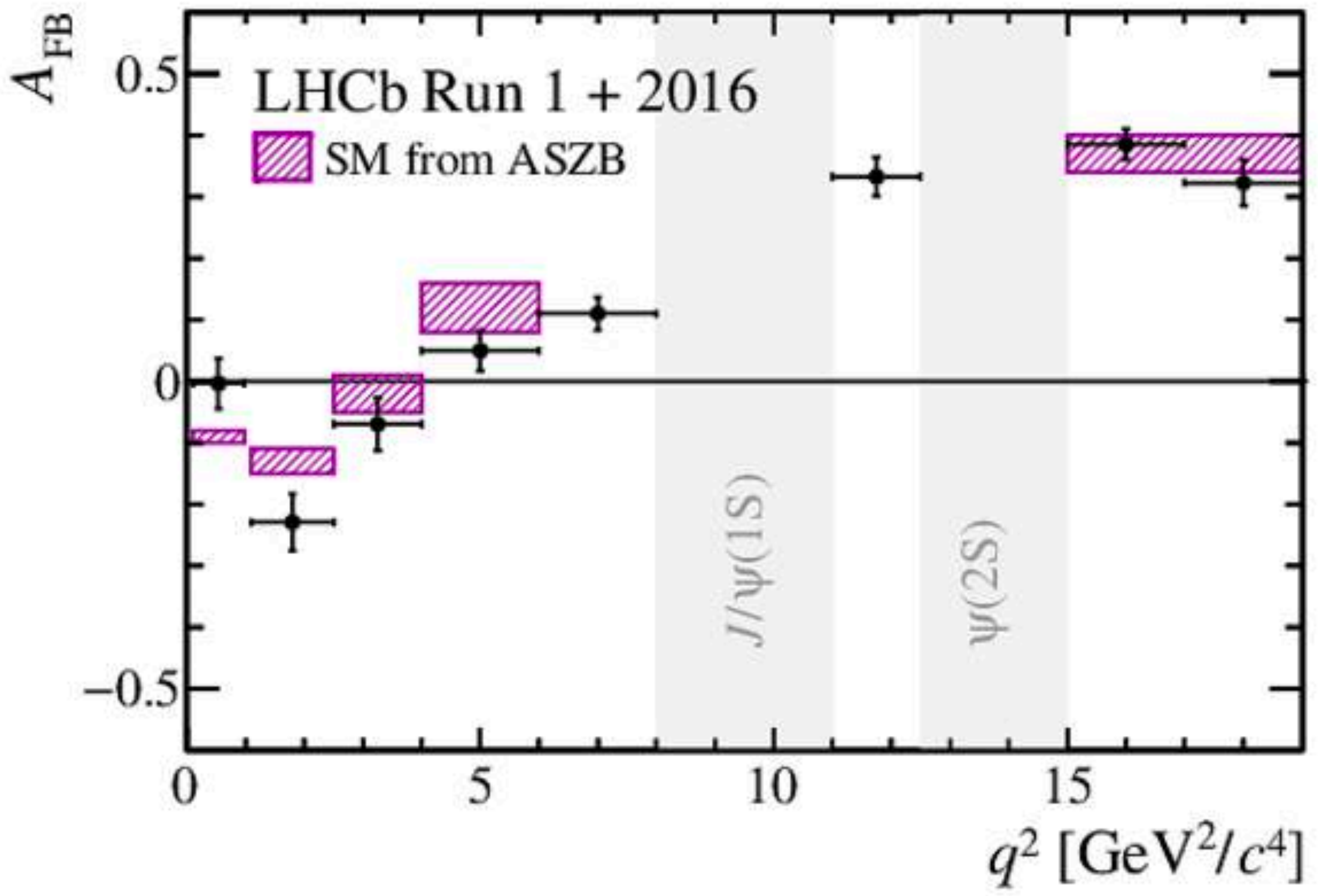
Angular discrepancy

- Cancel leading form factor uncertainties by constructing ‘optimised observables’ (P observables).

PHYS. REV. LETT. 125 (2020) 011802







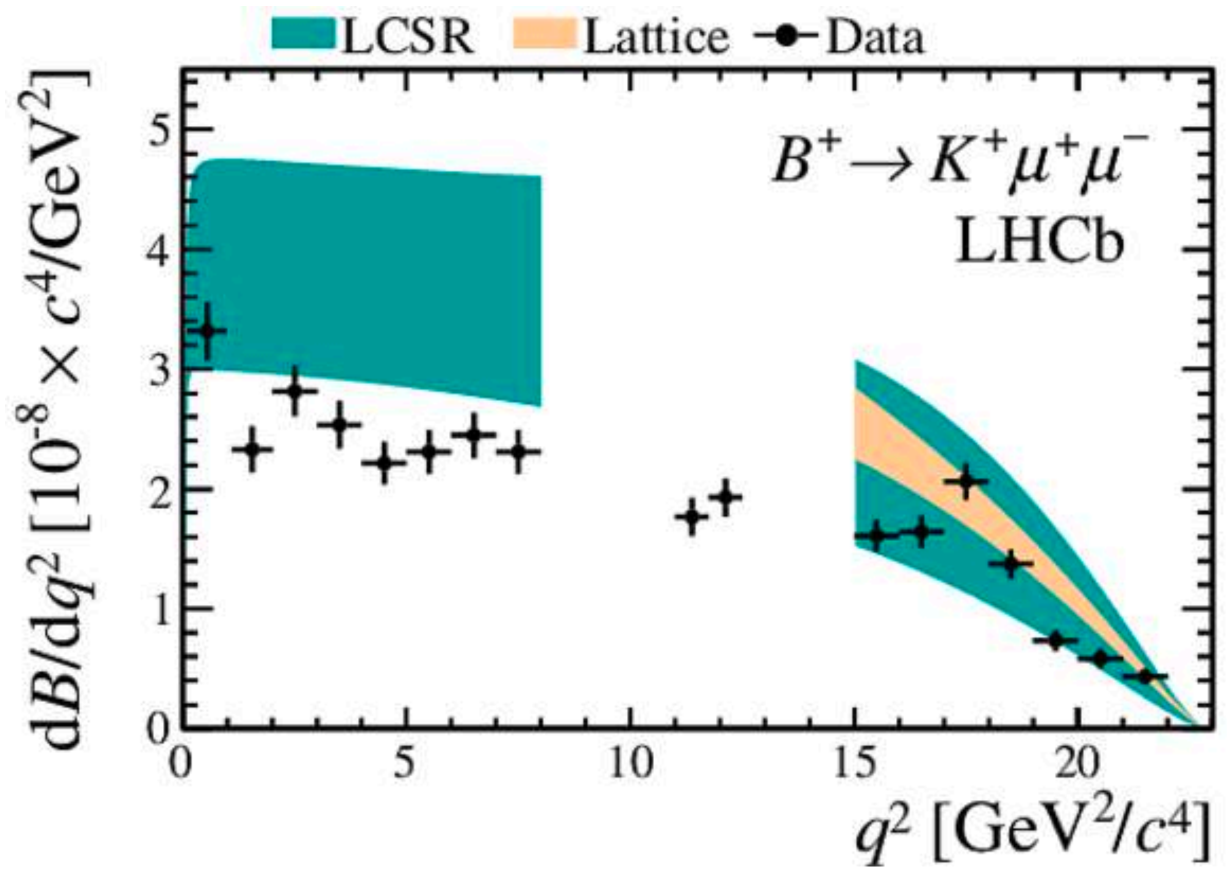
$$P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_L(1-F_L)}},$$

- Discrepancy just below the J/ψ peak. Combined significance is around 3.3σ.
  - People wrongly assume this only comes from P_5'. Tensions in A_{FB} and F_L all point in the same direction.

Coherent pattern?

- If the P_5' discrepancy is due to NP, it would also cause the branching fractions to be lower than the SM.

JHEP 06 (2014) 133



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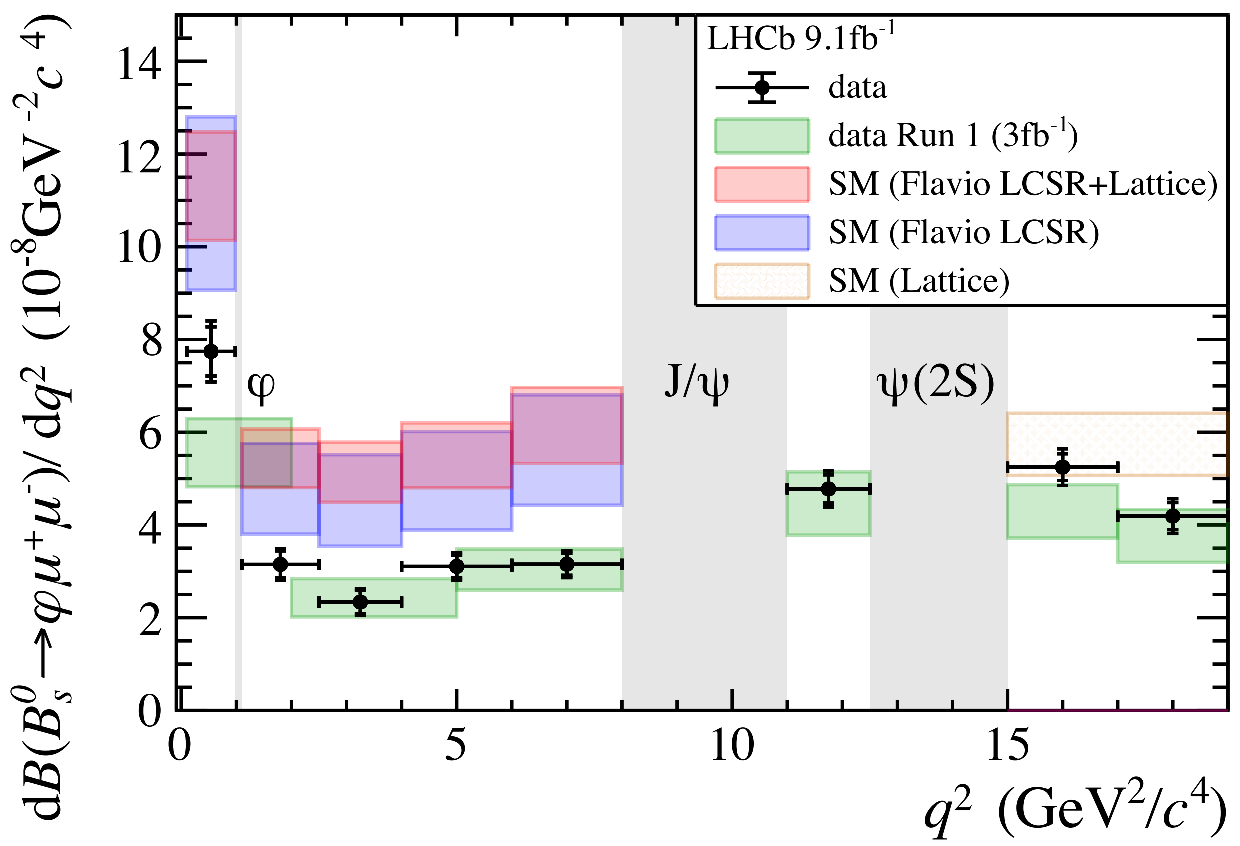
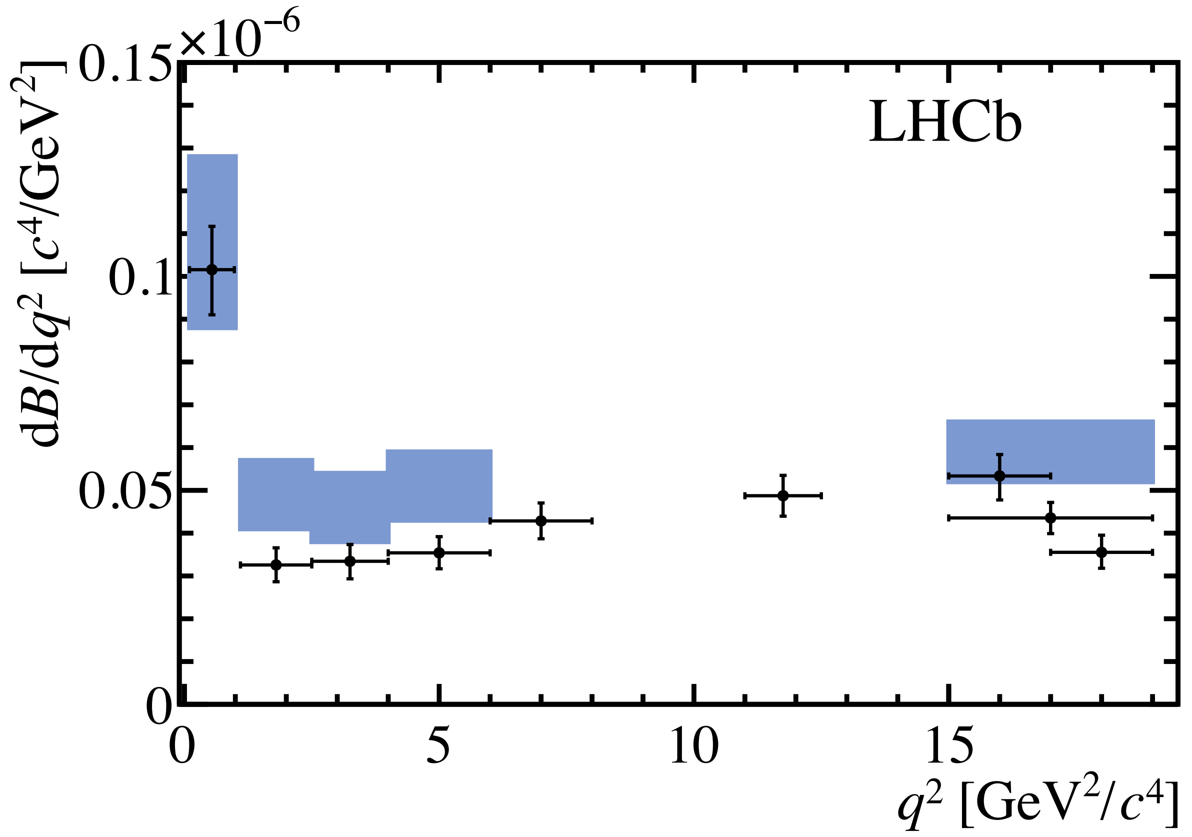
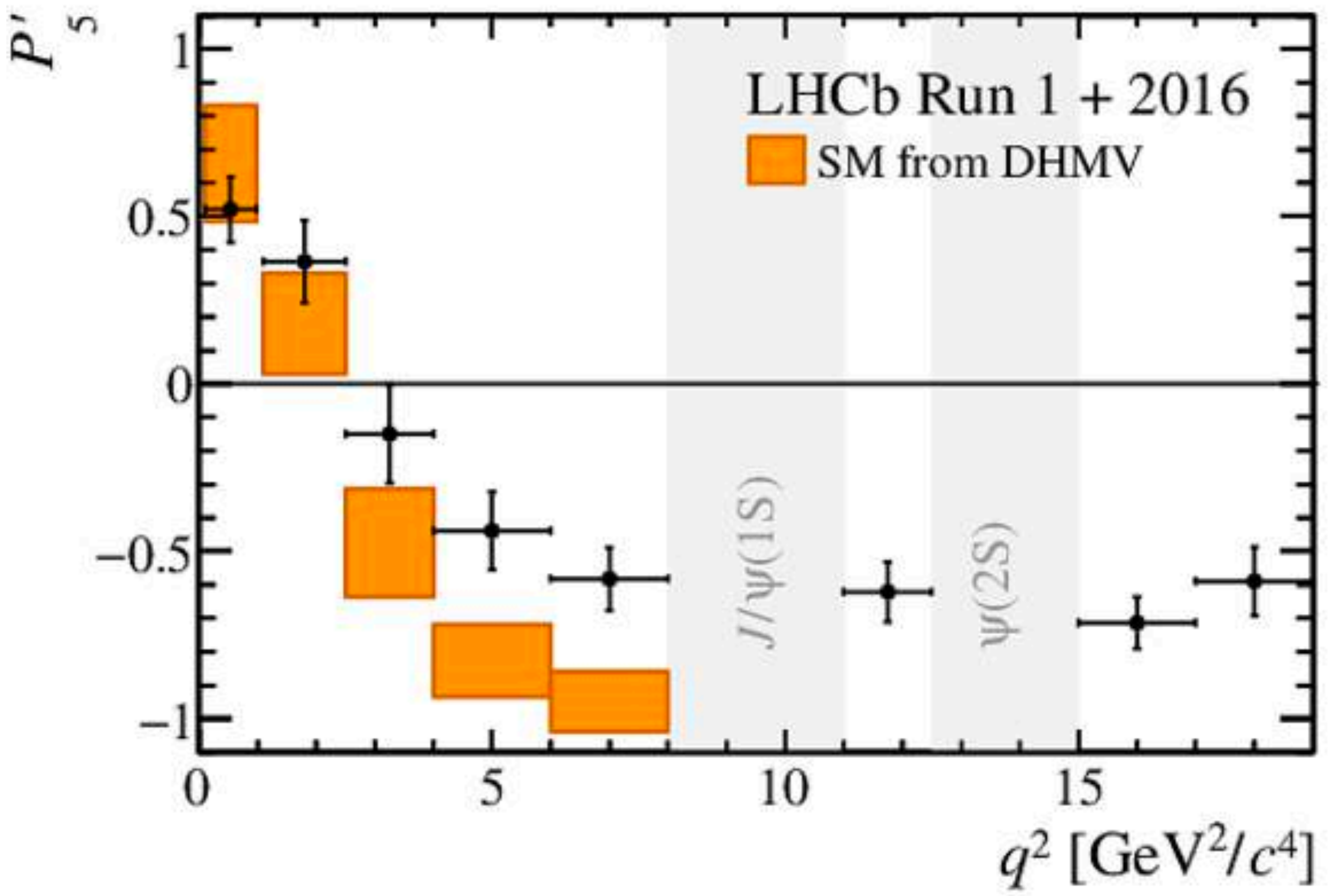


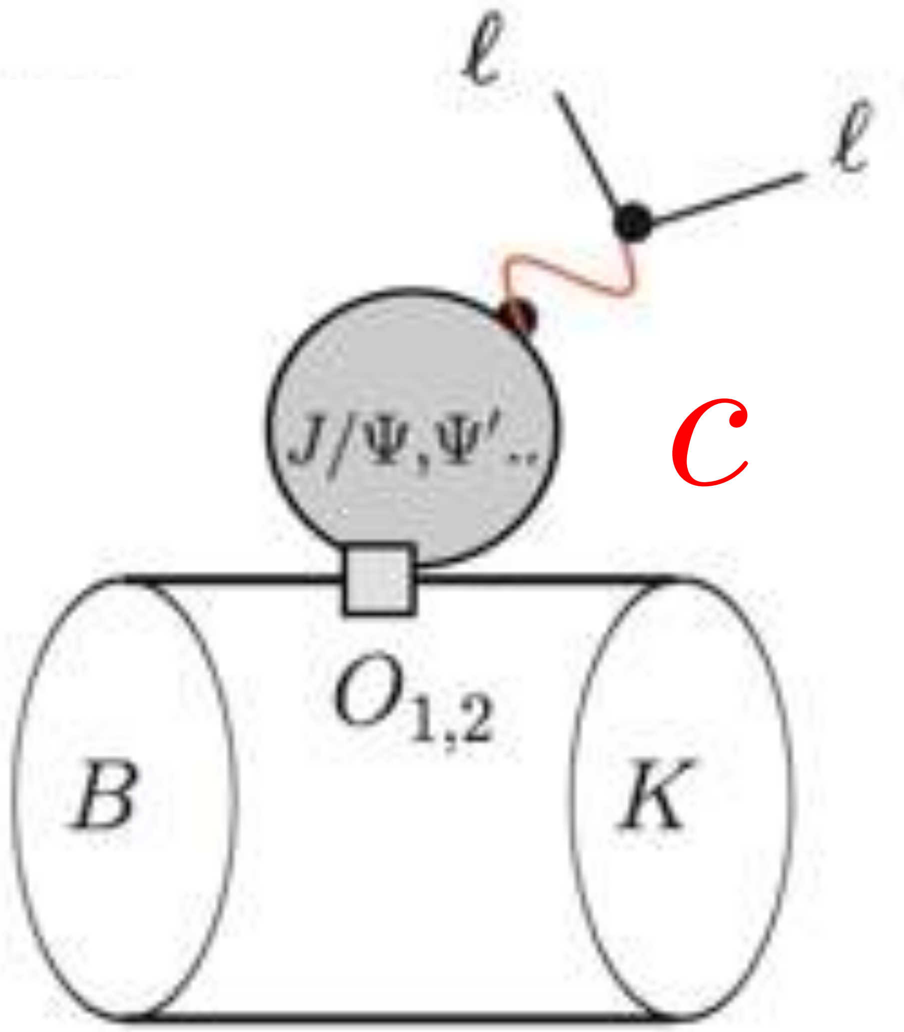


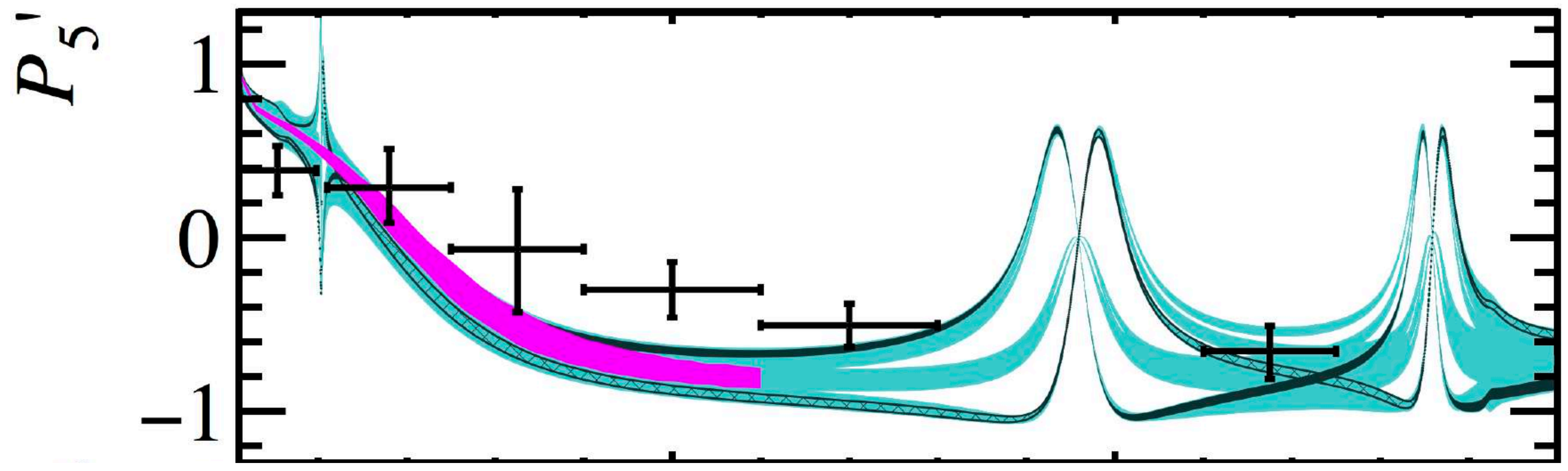


- Something appears to be negatively interfering with the SM b->sll decay amplitude, with a vector like coupling to the leptons.

A SM complication

- Unfortunately, there is also a SM contribution which can negatively interfere with the semileptonic amplitude.





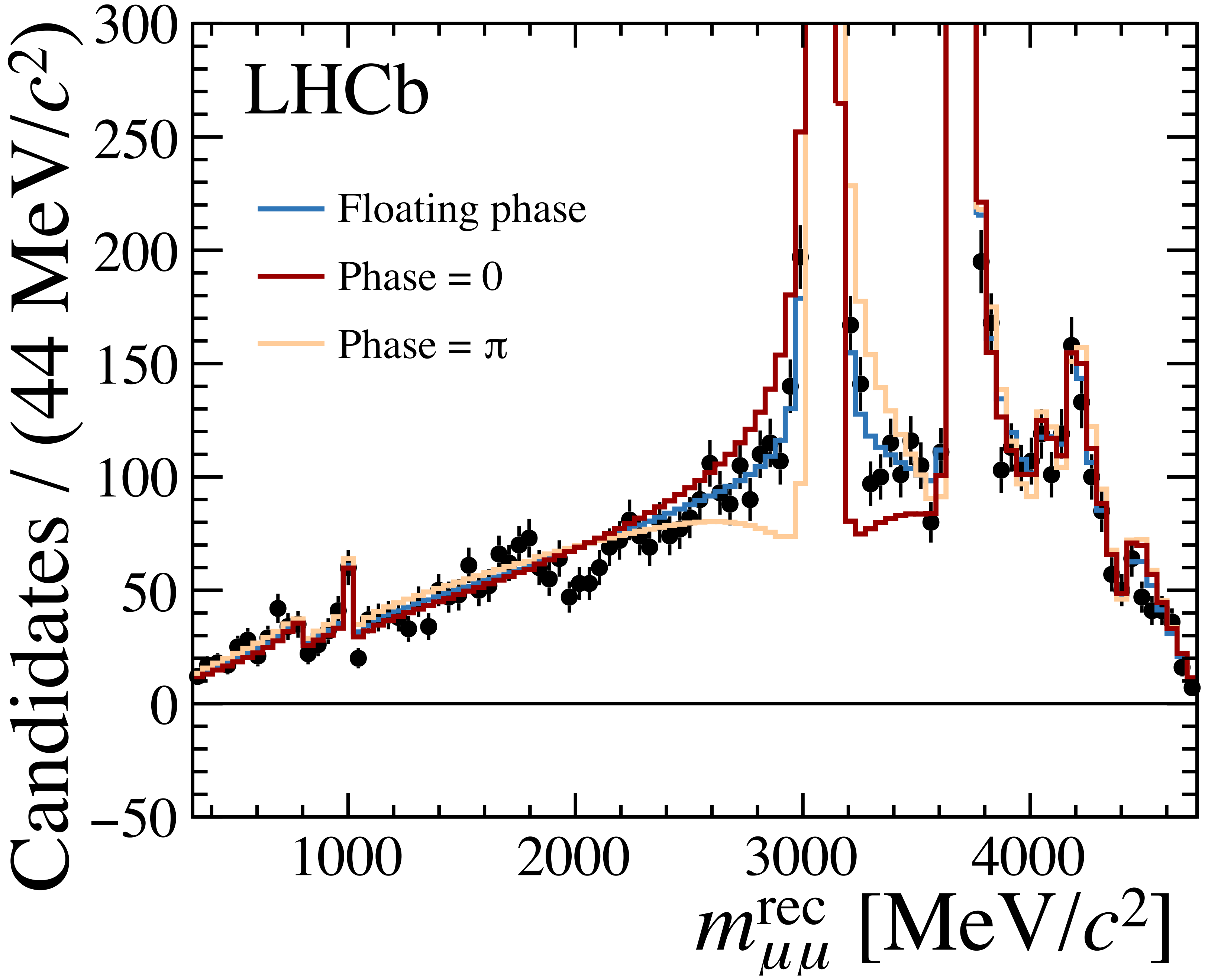
Blake et al, Eur. Phys. J. C (2018) 78: 453

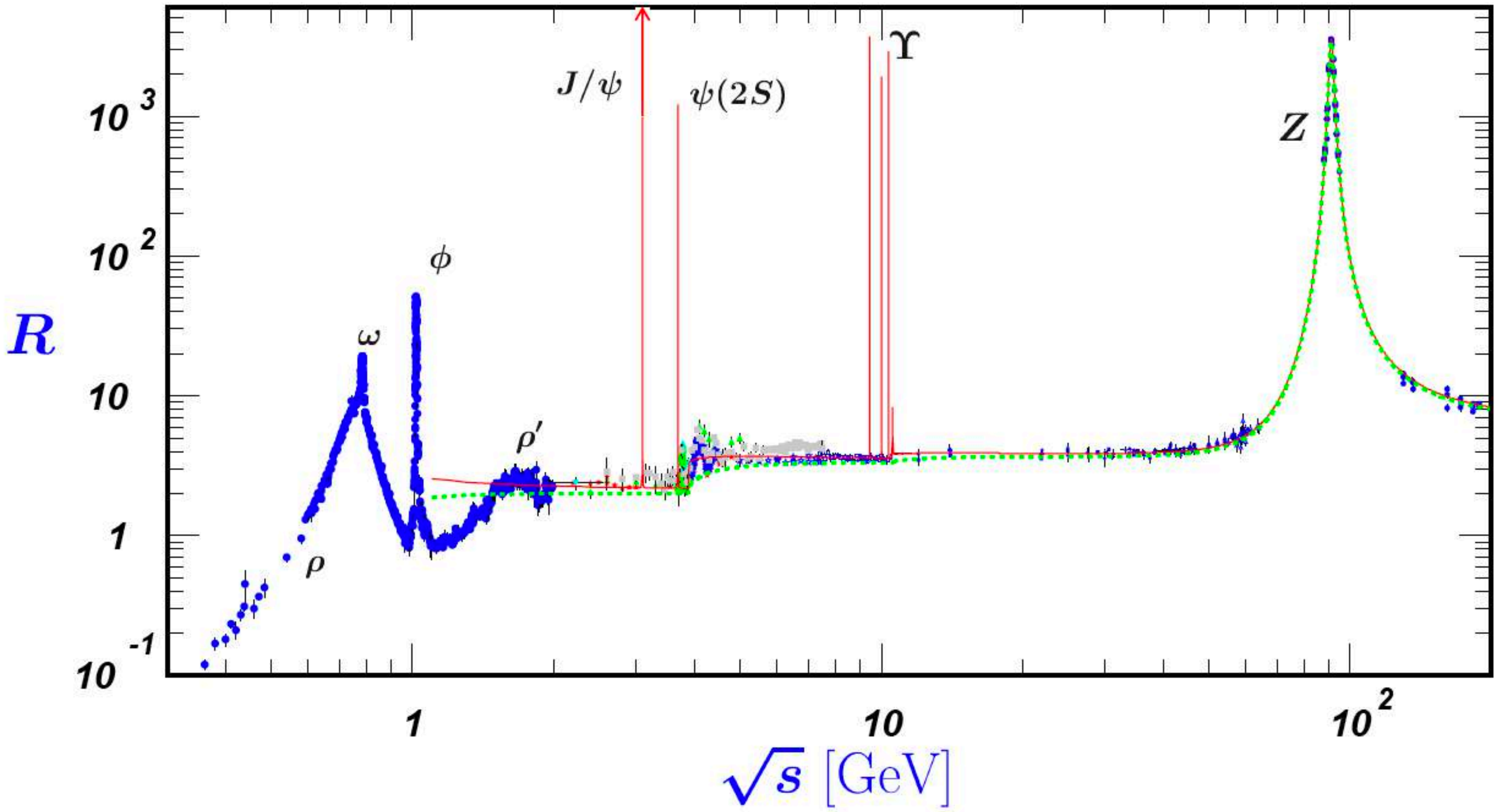
- This contribution is very difficult to calculate as it is fully hadronic.

Handles with data

- We have tried experimentally to control this in $B \to K\mu^+\mu^-$ decays.

Eur. Phys. J. C77 (2017) 161





- No big effect from charmonium resonances seen, but model does have some assumptions which are being tested for next round.
  - Other approaches to be tested soon (e.g. arXiv:1707.07305) will help clarify this issue.

What if it can’t be solved?

- If we can’t figure out these hadronic effects, can we cancel them somehow?

Test lepton universality!!!