Flavour physics.

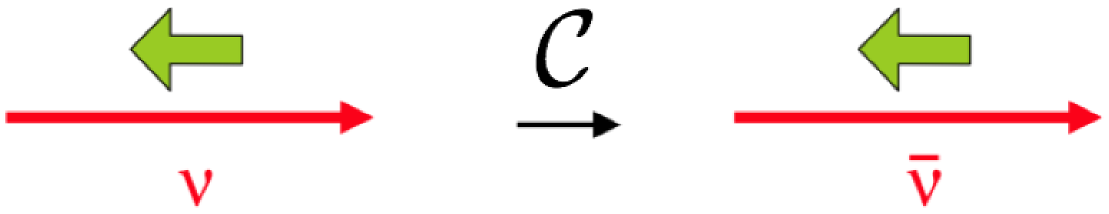
DESY Summer Student Lectures 2018

Sam Cunliffe
24.08.2018

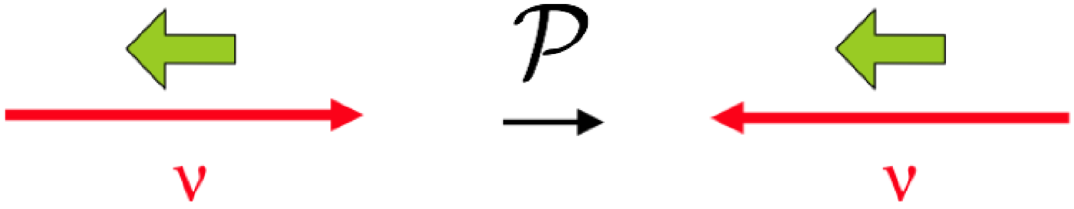
What?
Experiments
Observables
A touch of CP violation
Rare decays and anomalies
The field in 2018

C and P transformations

- “C” = charge conjugation. Replace particle with antiparticle.
  - For example: a left-handed neutrino becomes a left-handed antineutrino



- “P” = parity transformation. Mirror flip of spatial coordinates (angular momentum unchanged).
  - For example: a left-handed neutrino becomes a right-handed neutrino.



C and P ~~transformations~~ violation

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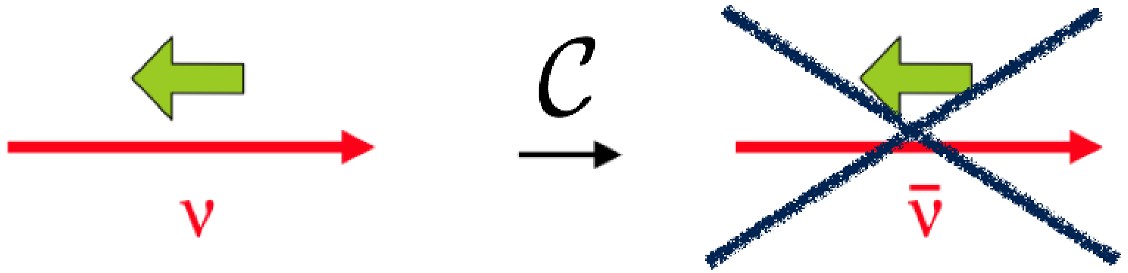
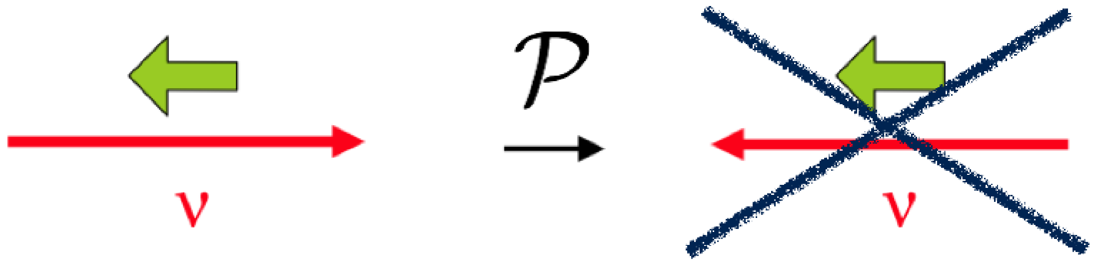
  - For example: a left-handed neutrino becomes a **left-handed antineutrino**



- "P" = parity transformation. Mirror flip of spatial coordinates (angular momentum unchanged).
  - For example: a left-handed neutrino becomes a **right-handed neutrino**.



Neither of these are seen to interact via the weak interaction (maybe don't exist?).

→ **Weak interaction violates C and P separately in the Standard model.**

CP violation then?

- Neutrinos seem to be OK with CP transformation. Both at once changes a left-handed neutrino into a right-handed antineutrino. (All good.)

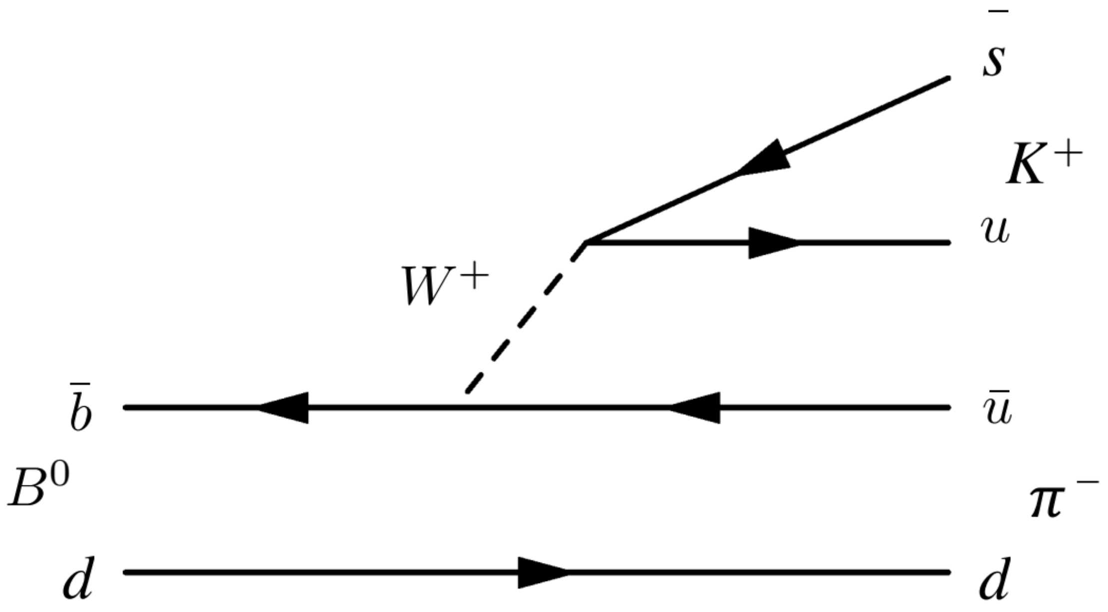
- What about CP violation? Well, it does happen.
  - First discovered with kaons.

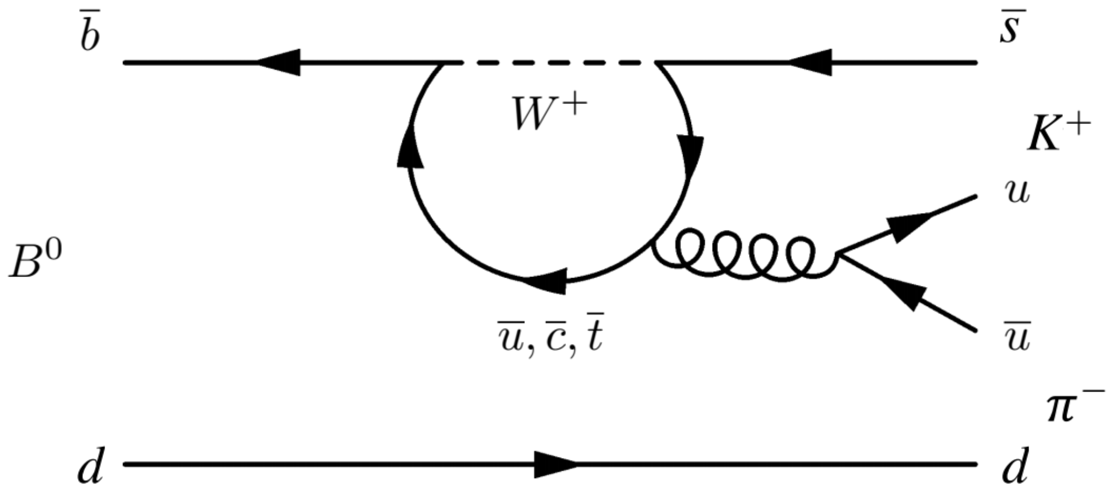
- I want to show some more recent b-physics…
  - It’s a good first b-physics analysis to look at. And it’s very dramatic.

How to measure CP violation

Matter vs. antimatter in B decays

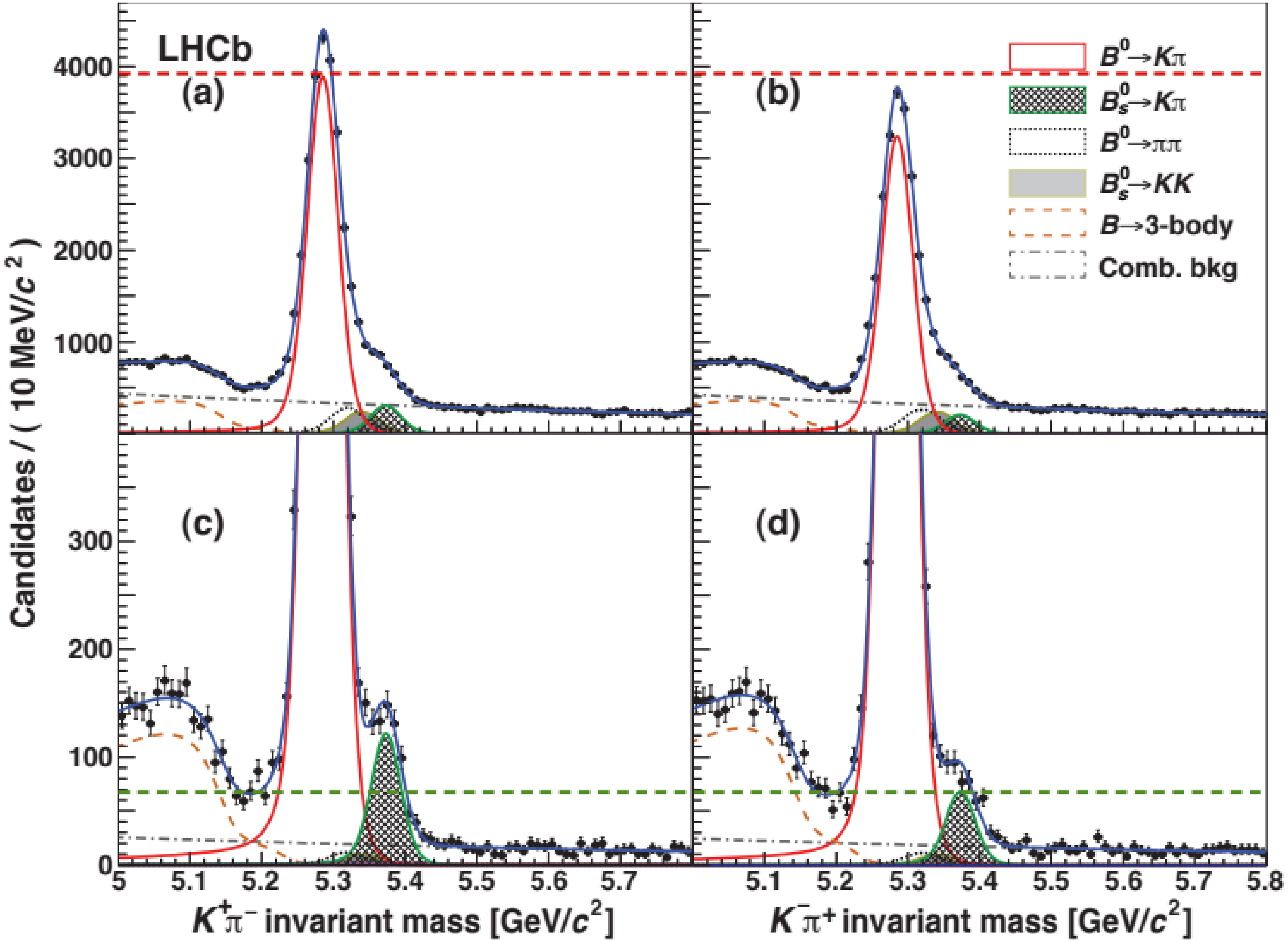
- You need to find some decay (initial state to final state: i → f) where you have reason to suspect the rate will be different than it’s CP conjugate.
- [Hint] two diagrams + weak interaction + phases.
- Like $B^0 \to K^+\pi^-$…





$A_{CP}[\, B \to K\pi \,]$

Phys.Rev.Lett.110, 221601



- Can see the difference by eye!
- A_{CP} is measured, basically from these plots:

  -0.080 ± 0.0076

$$\frac{\Gamma(\bar{B}^0 \to K^-\pi^+) - \Gamma(B^0 \to K^+\pi^-)}{\Gamma(\bar{B}^0 \to K^-\pi^+) + \Gamma(B^0 \to K^+\pi^-)}$$

Homework*

*worth nothing apart from your own happiness

- Find this paper.
- Read it.
- I hope you will be able to get the **<u>gist</u>** of what's going on, based on what I've told you.
- What do they measure? What to they make a histogram of? Why is it significant? Can you draw a Feynman diagram of it?
- Bonus question: could this bring about CP violation?

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

OBSERVATION OF B^0–$\bar{B}^0$ MIXING

ARGUS Collaboration

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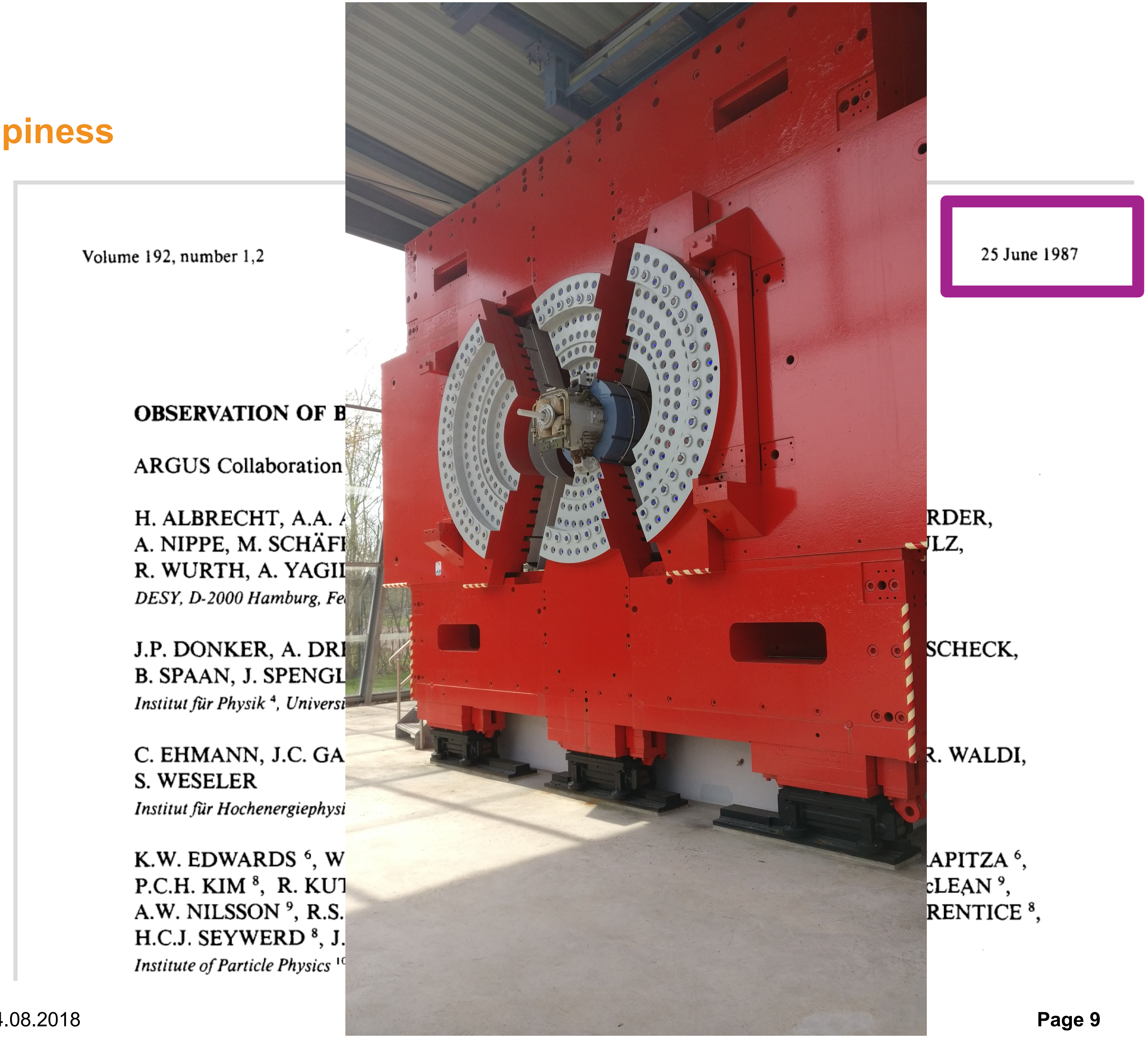

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OBSERVATION OF B

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Some pre-questions this time

- Can you draw the Feynman diagram for a $b \to s$ quark transition.

  [Hint: you can look back at slide 26 or so of the part 1 slides.]

- How about $b \to s$ with two generic leptons (this is kind of famous, it's called "$b \to sll$") ?
- Can you draw the full Feynman diagram for a B_s^0 (sb) meson decaying into two leptons?

Photo: Godot13 / Wikimedia Commons


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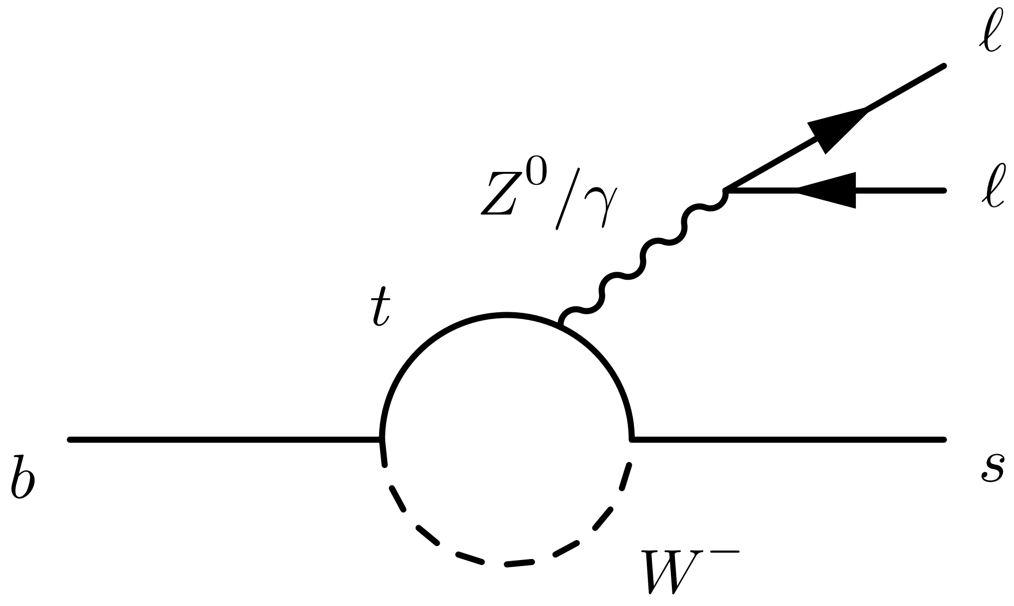
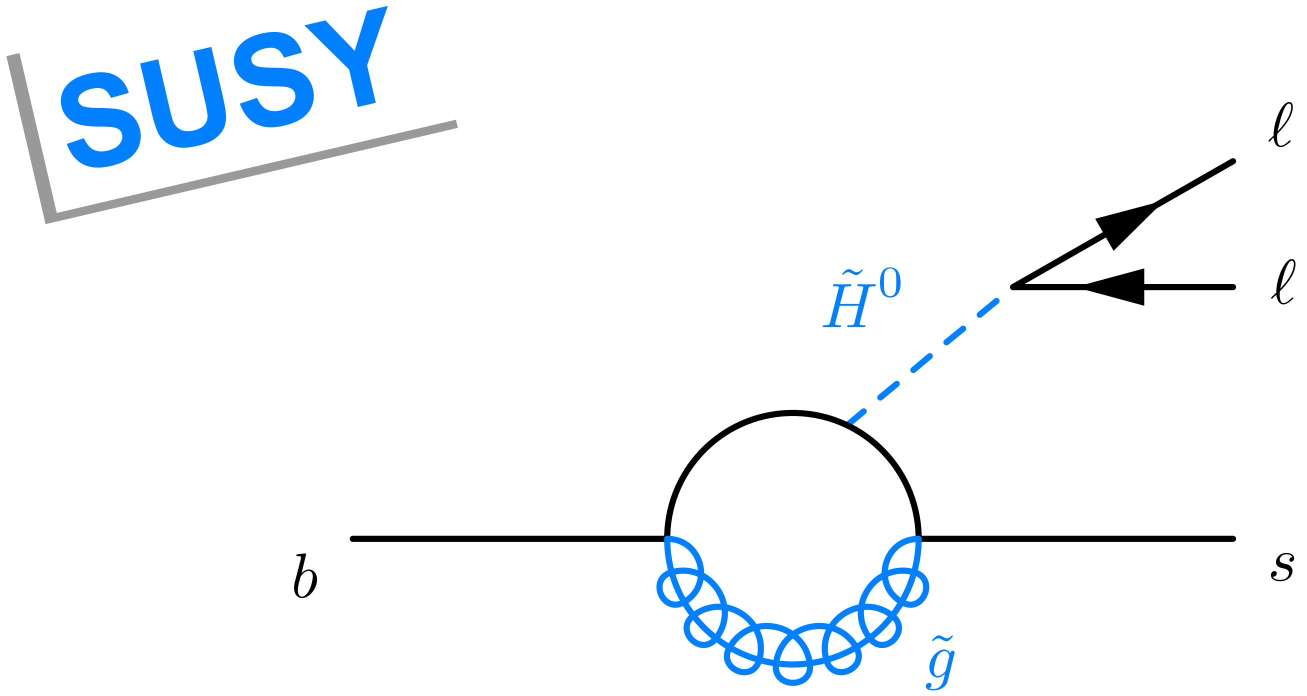
b → sll

A hot topic



$b \to sll$

A hot topic



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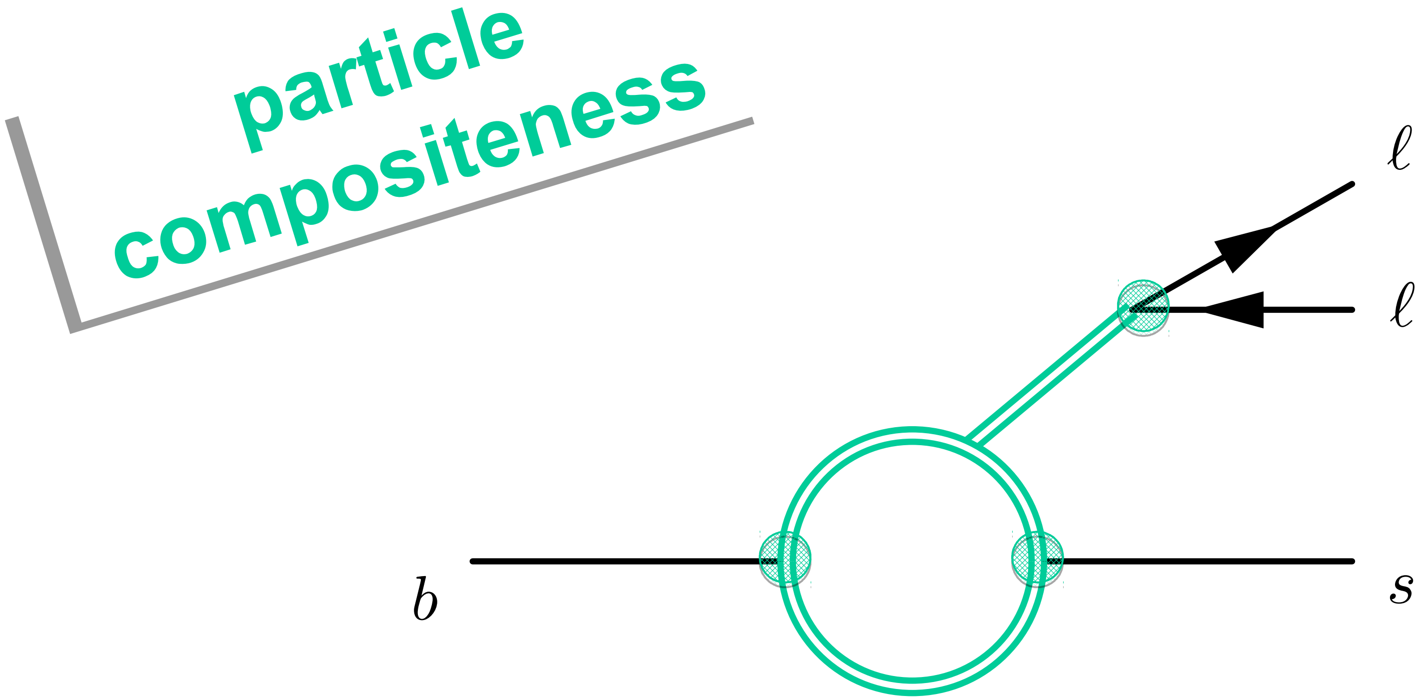

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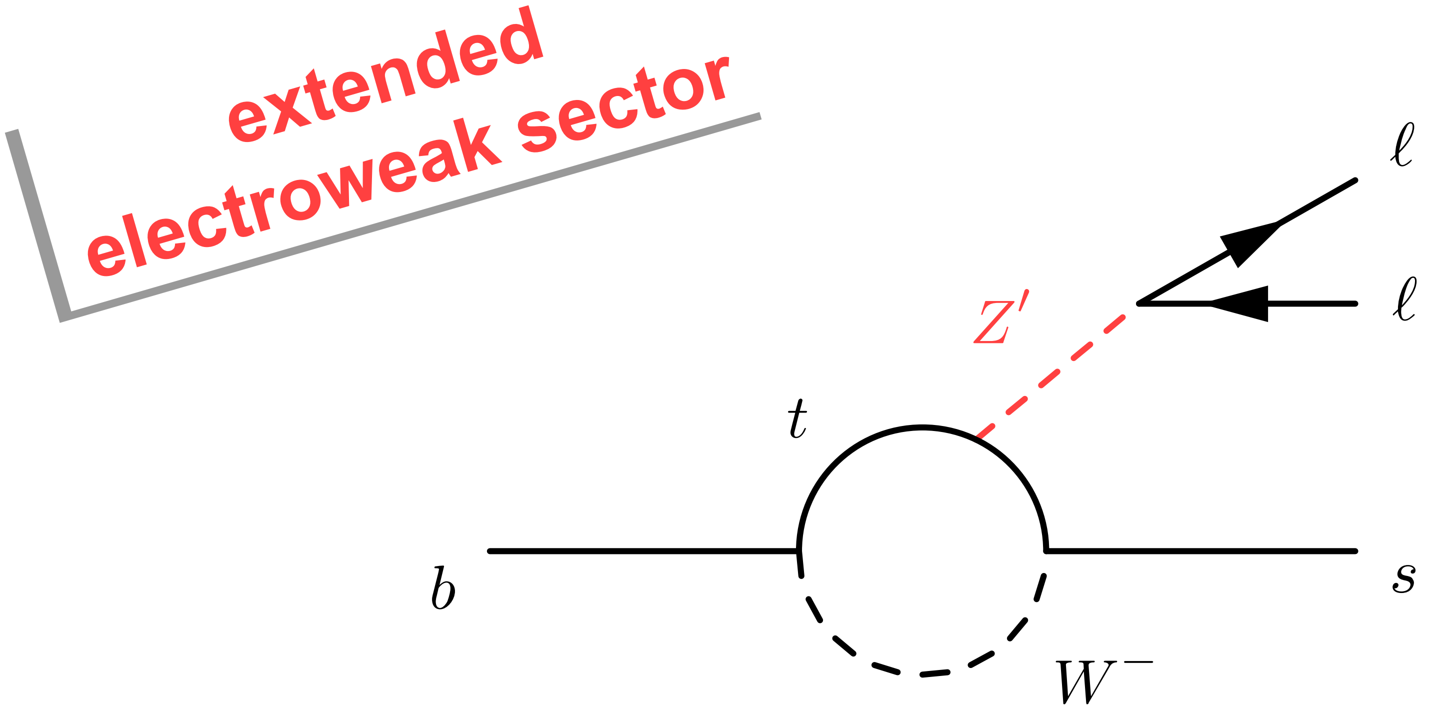

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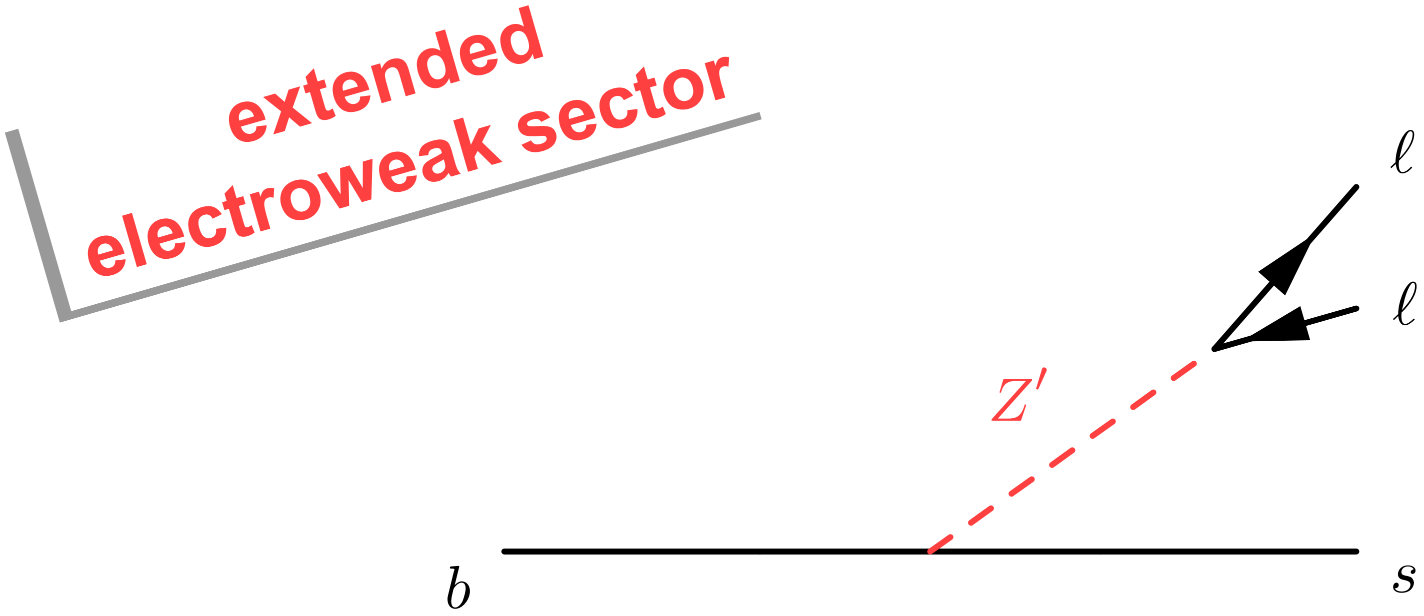
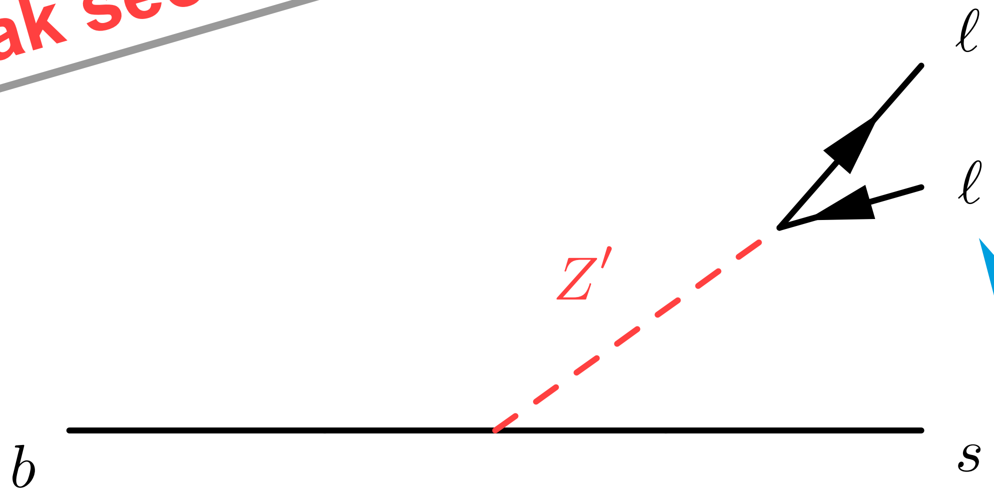
A hot topic



b → sll

A hot topic

extended electroweak sector

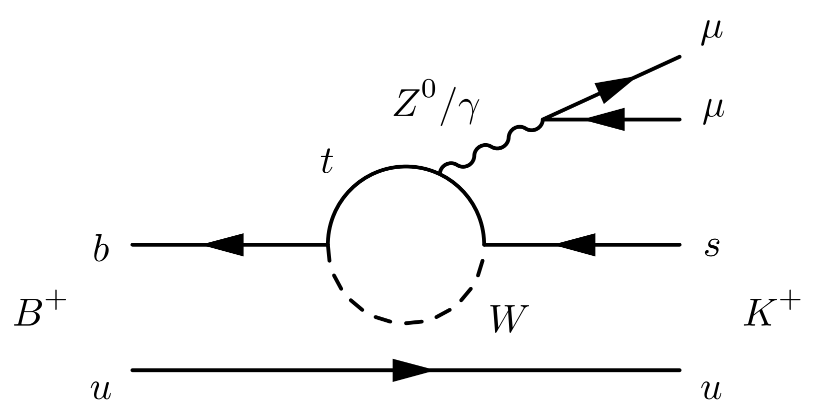


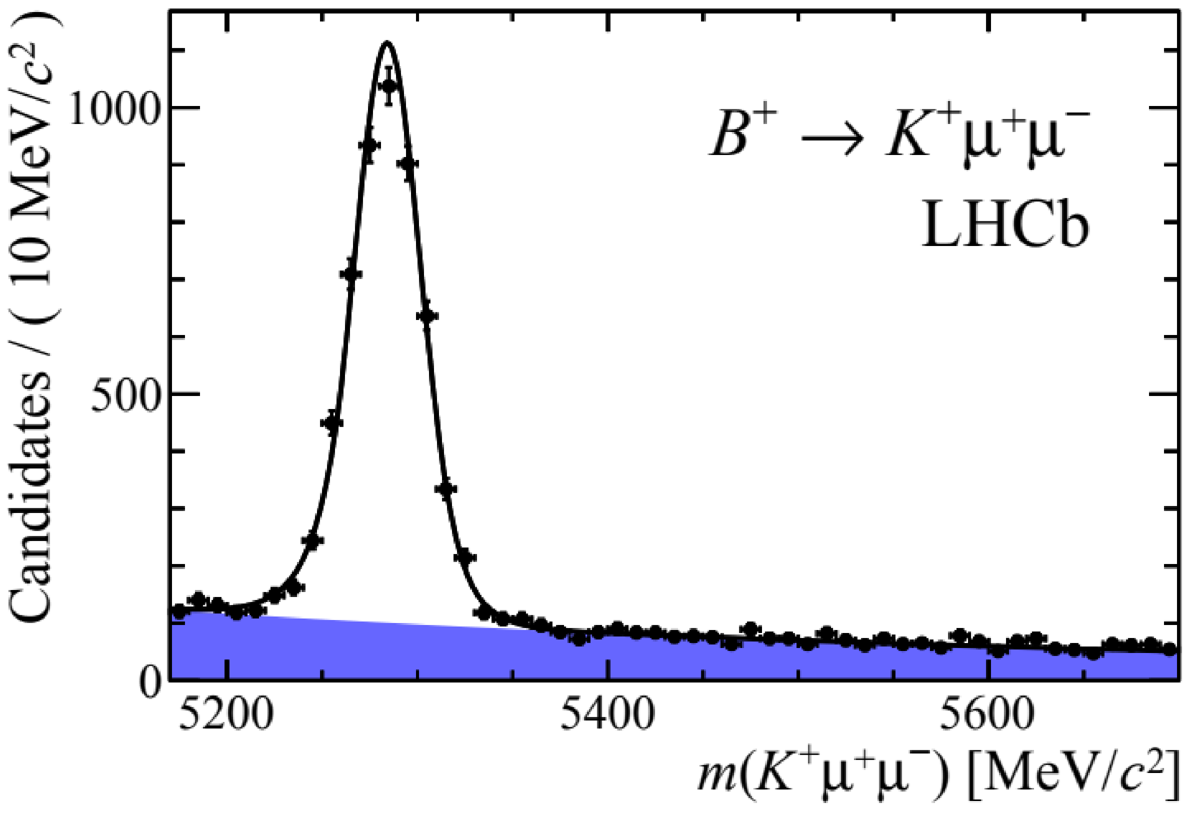
p.s. q^2 is the squared invariant mass of the two leptons.
$q^2 = m_{\mu\mu}^2$

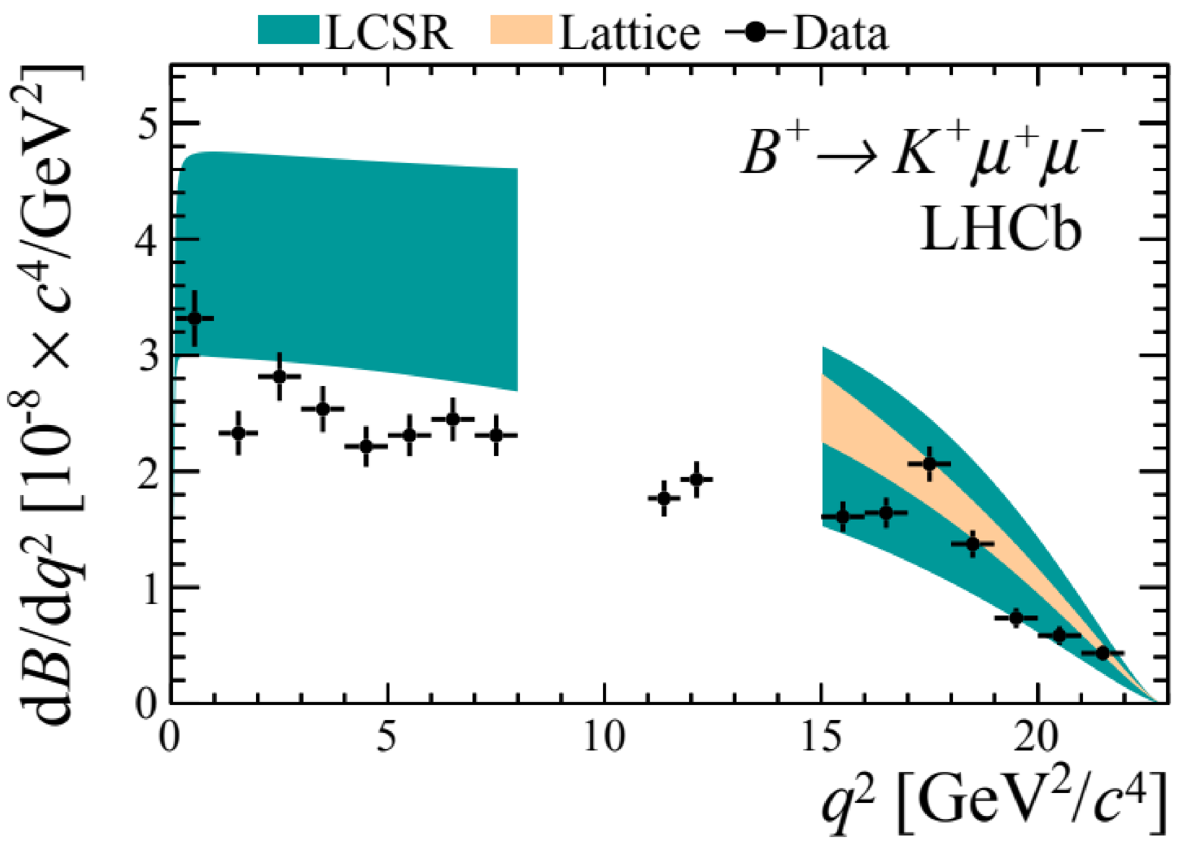
$B^+ \to K^+\mu^+\mu^-$

JHEP06(2014)133

- Take the $b \to s\mu^+\mu^-$ diagram
- … add a spectator u…
- Make invariant mass ($m_{K\mu\mu}$) plot,
- Fit to extract signal yield.
- Measurement is low wrt SM predictions at low q^2.







$B^0 \to K_S^0 \mu^+ \mu^-$

JHEP06(2014)133

- Take the $b \to s\mu^+\mu^-$ diagram
- … add a spectator d…
- Make invariant mass ($m_{\pi\pi\mu\mu}$) plot,
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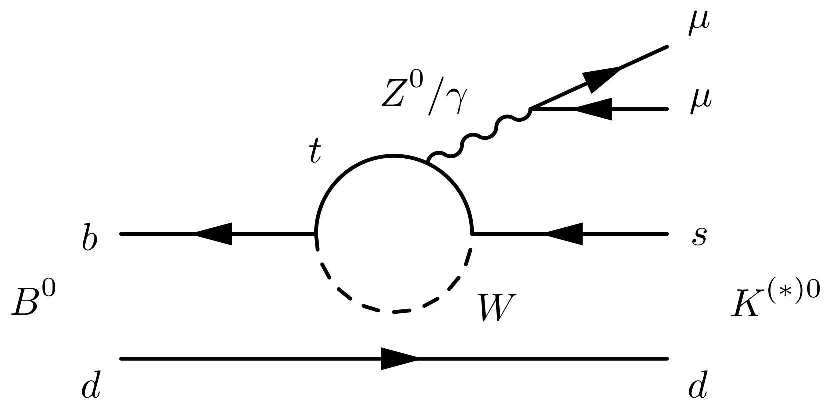
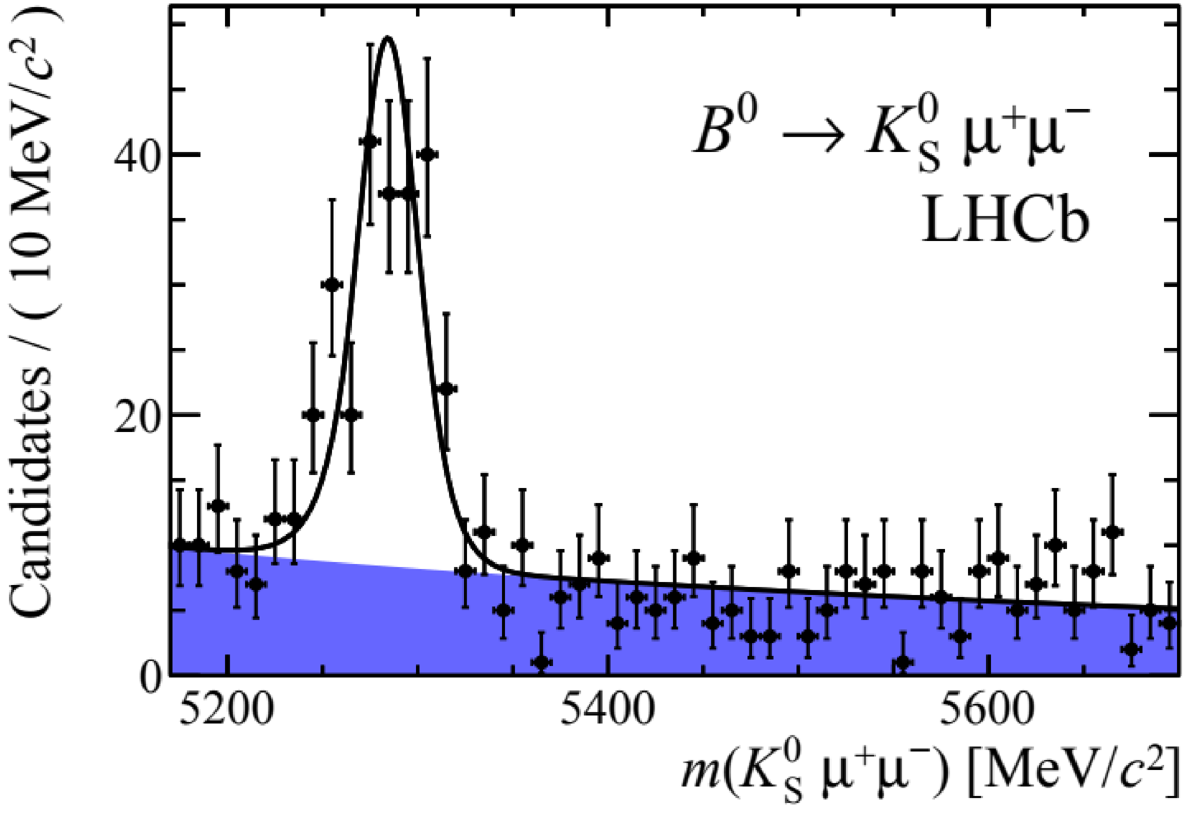
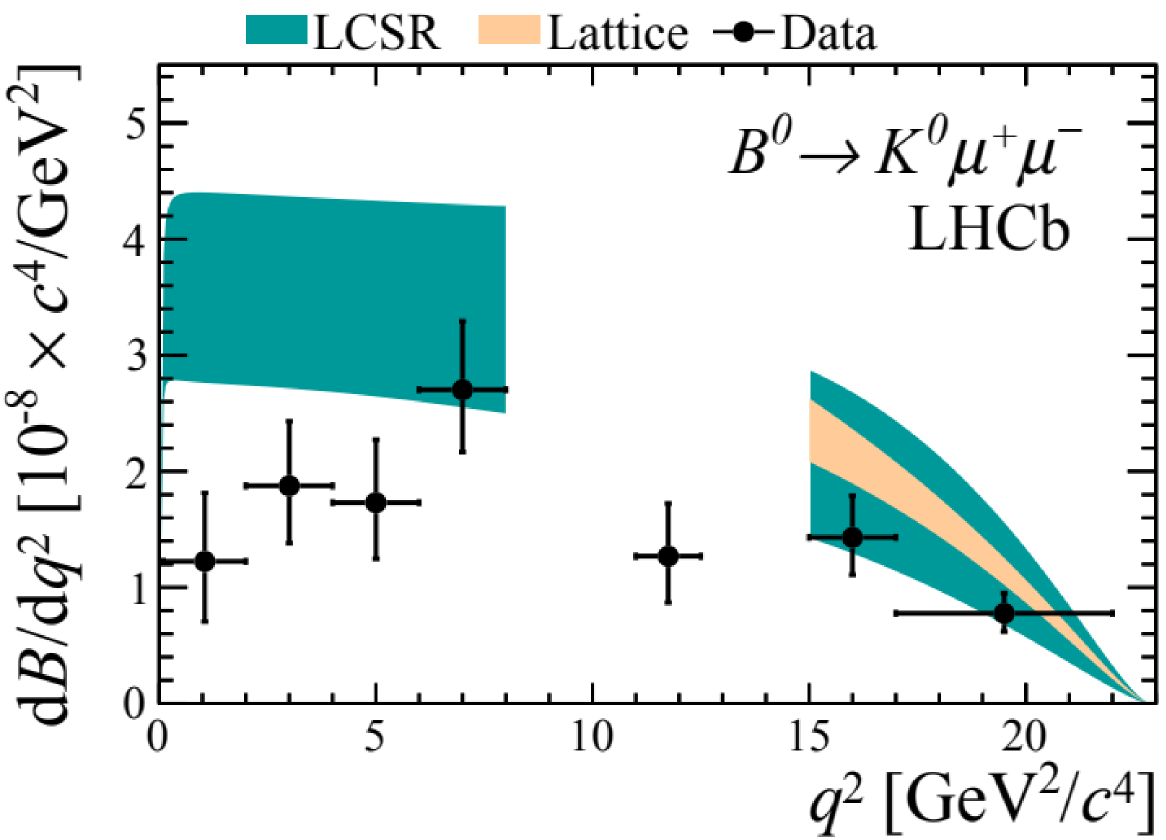


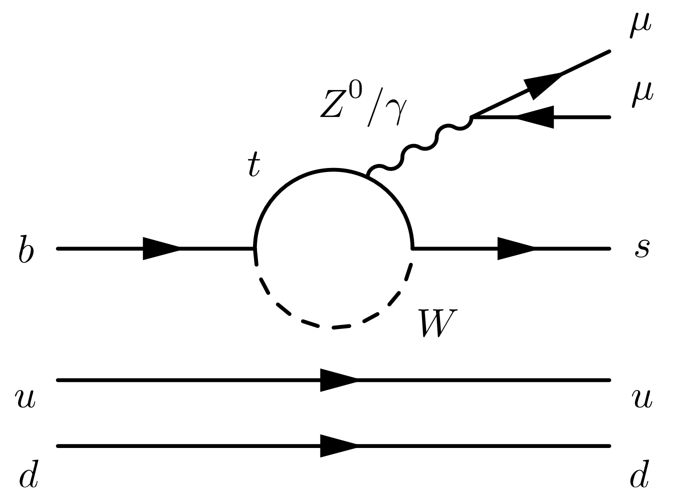


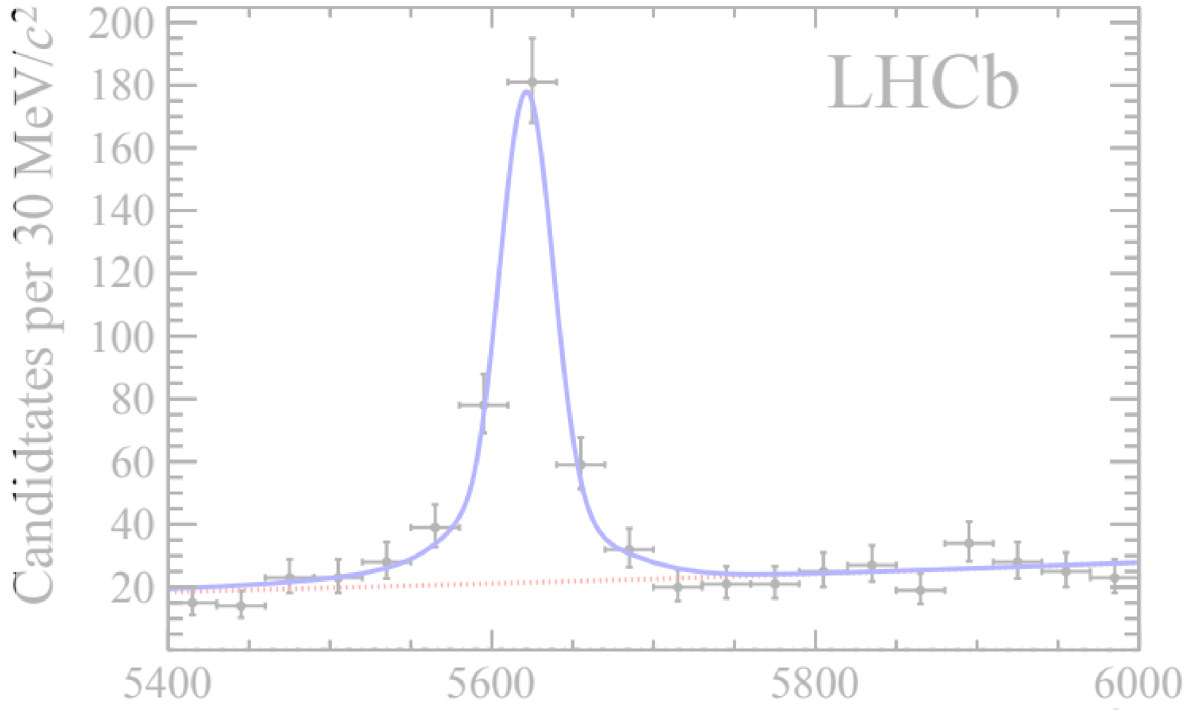


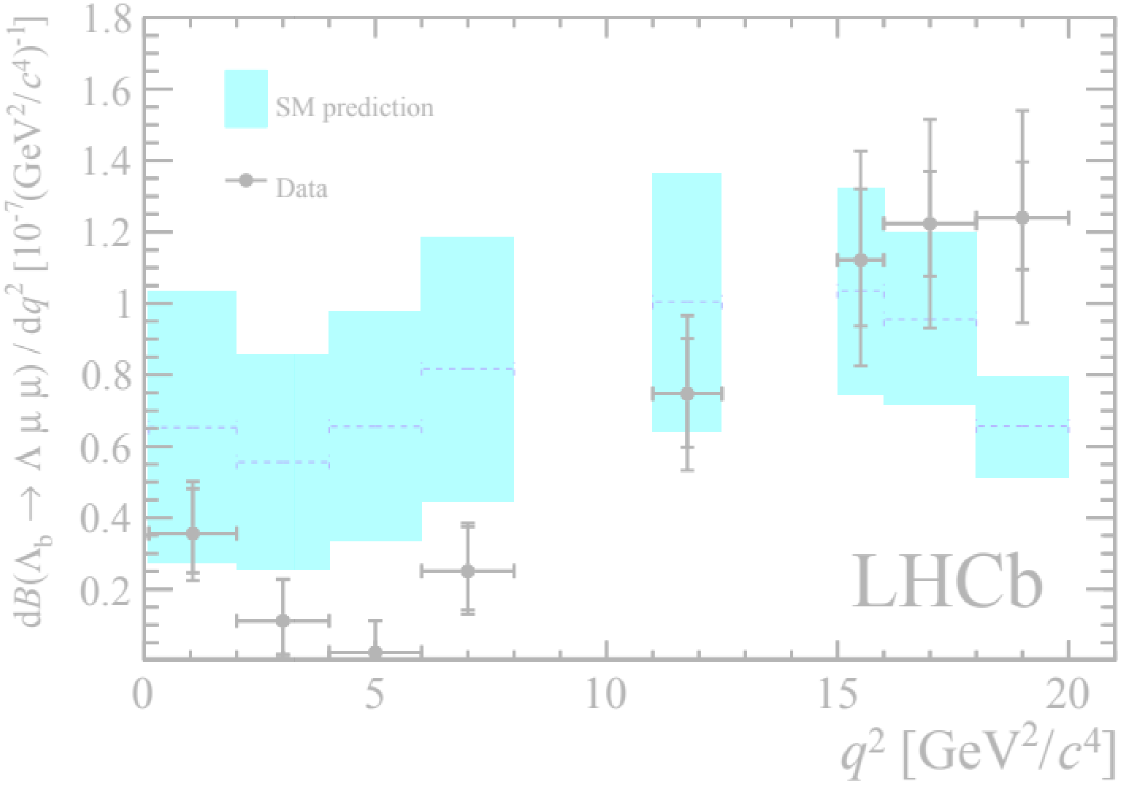
?→?μ⁺μ⁻

JHEP06(2015)115

- Take the b → sμ⁺μ⁻ diagram
- … add two spectators and flip the b quark direction …
- Make invariant mass ($m_{p\pi\mu\mu}$) plot,
- Fit to extract signal yield.
- Measurement is low wrt SM predictions at low q^2.







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

JHEP06(2015)115

- Take the $b \rightarrow s\mu^+\mu^-$ diagram
- … add two spectators and flip the b quark direction …
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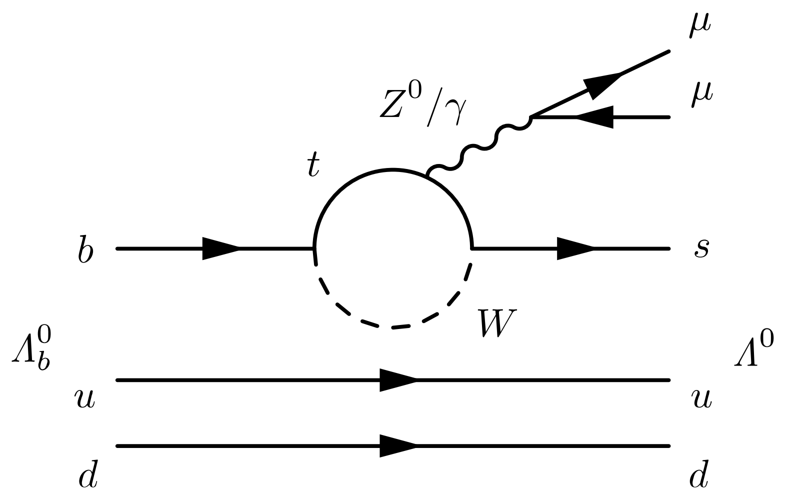
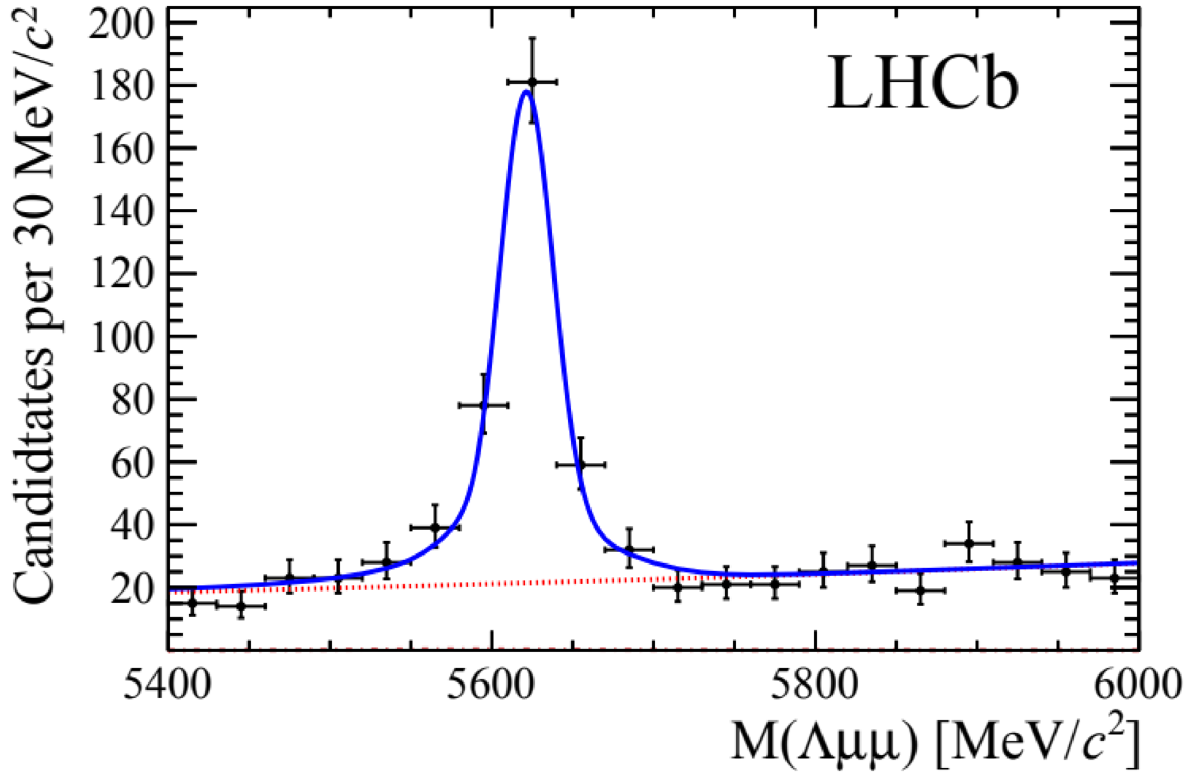
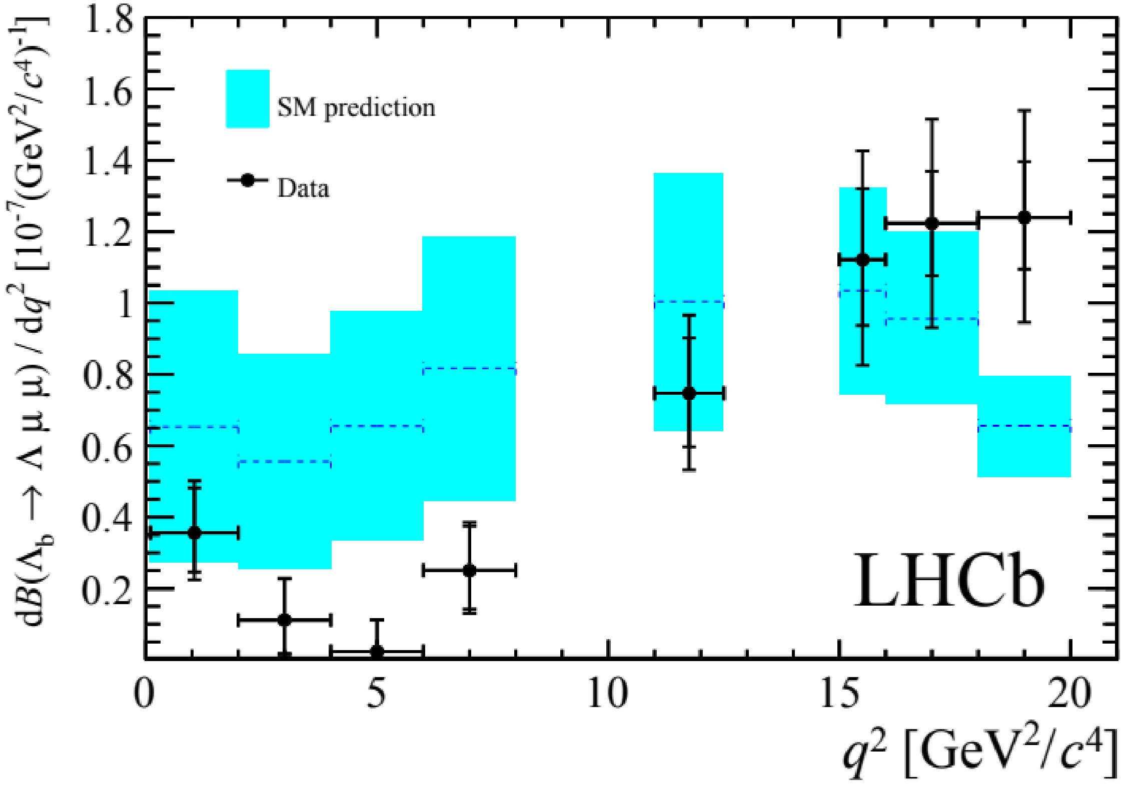


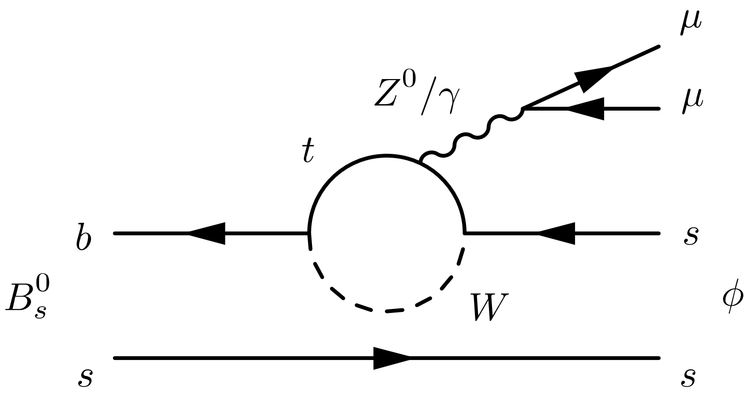


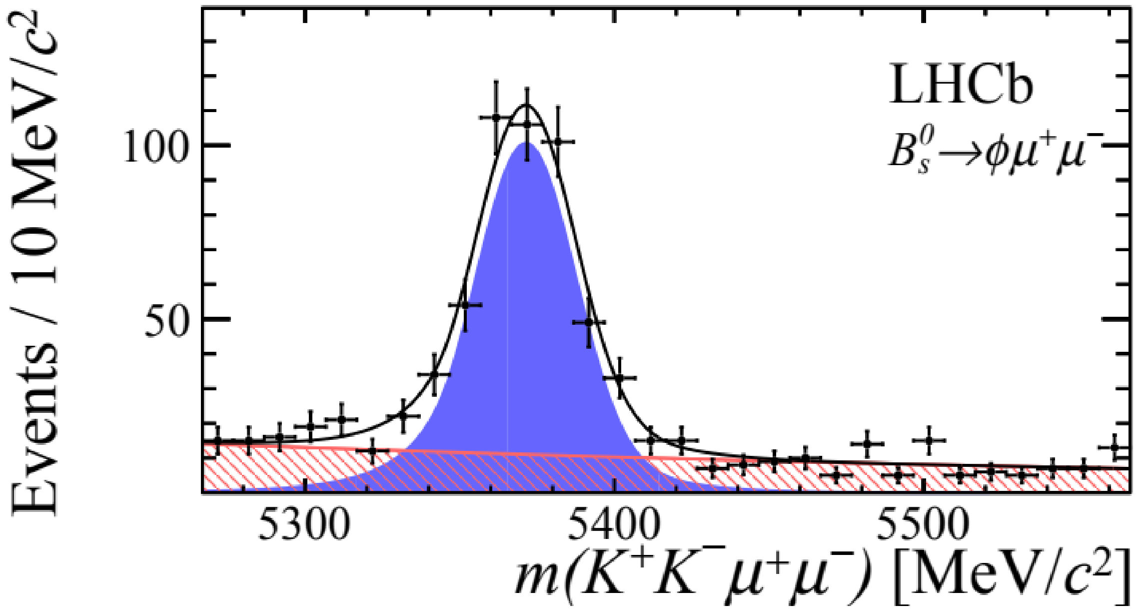


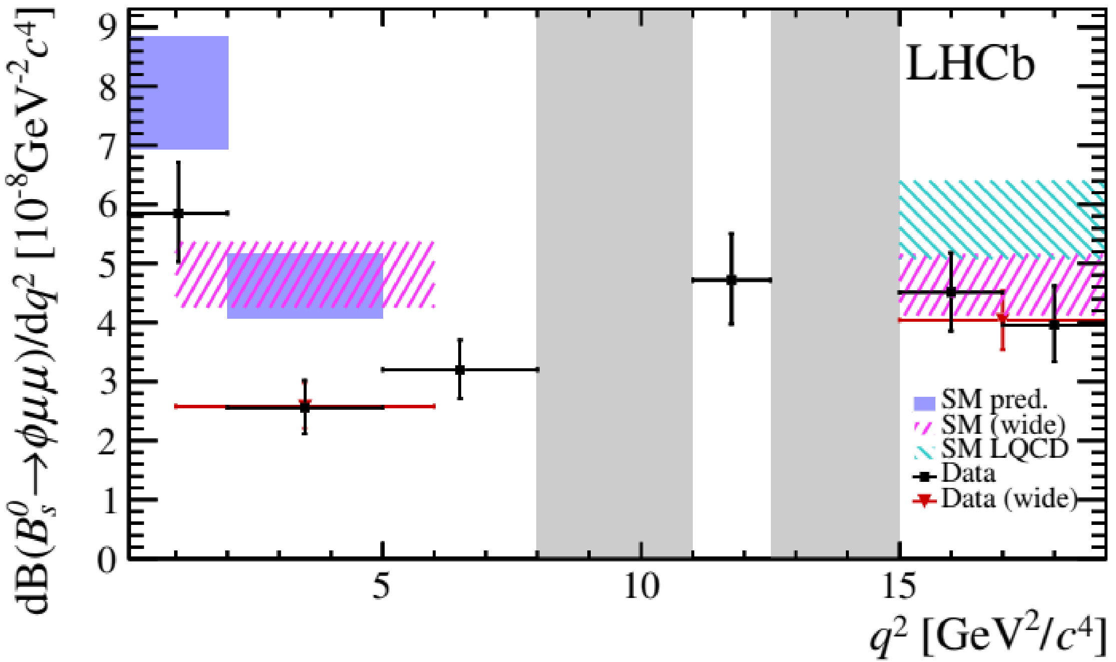
$B_s \rightarrow \phi^0\mu^+\mu^-$

JHEP09(2015)179

- Take the $b \rightarrow s\mu^+\mu^-$ diagram
- … add a spectator s…
- Make invariant mass ($m_{KK\mu\mu}$) plot,
- Fit to extract signal yield.
- Measurement is low wrt SM predictions at low q^2.







What's so great about muons?

Lepton flavour

- Every sentence has started "take the $b \to s\mu^+\mu^-$ diagram".
- But the transition is $b \to sll$ … what about electrons, taus, and neutrinoes!?
- Well $l=\tau$ has never been seen. They are difficult because we have to reconstruct them from:
  - $\tau \to \pi\pi\pi\nu$ "three prong"
  - $\tau \to \mu\nu\nu$ "one prong"

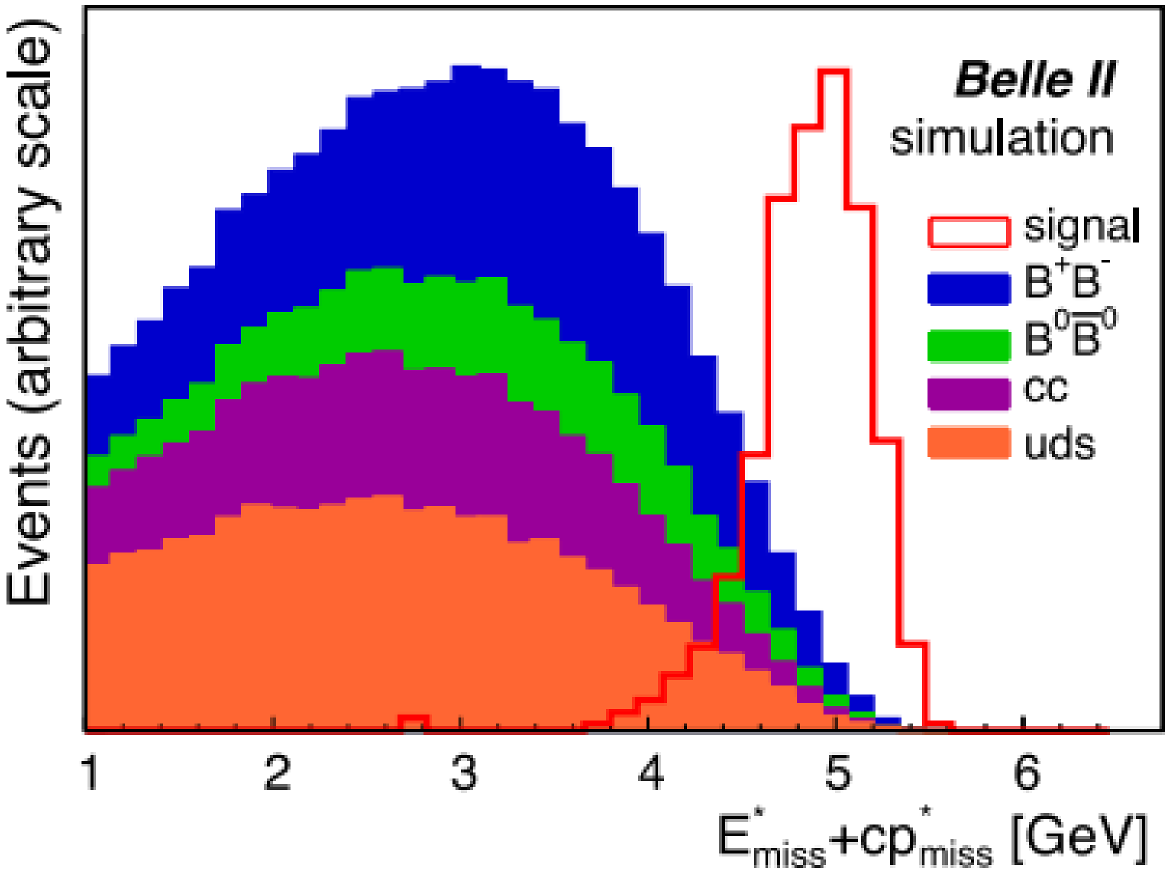
  these tracks tend to have low momentum and there is either many tracks or a lot of missing energy.

  And there are two taus. So the possible wrong combinations of tracks becomes a bit boggling.
  $\to$ Belle II will probably not observe a $b \to s\tau^+\tau^-$ transition. But we will try.
- $l=e$ and $l=\nu$, on the other hand is cool, interesting, and do-able. 😎

$B \rightarrow K^{(*)}\nu\nu$

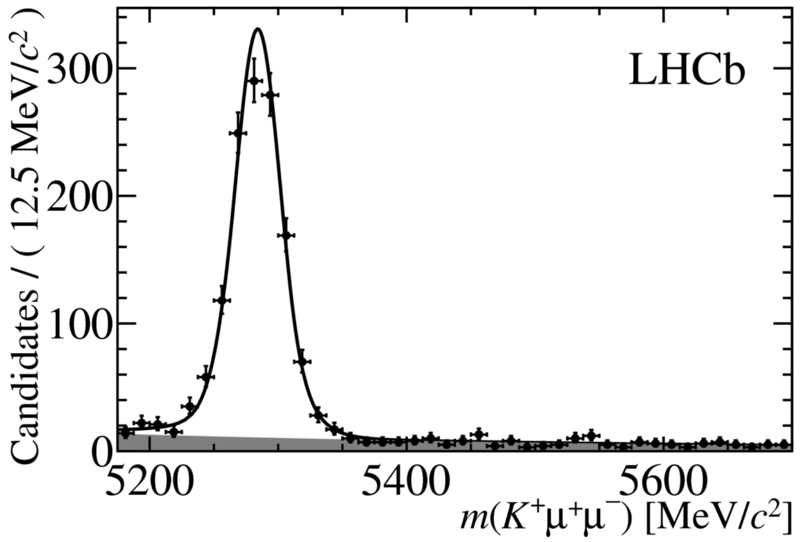
Belle II

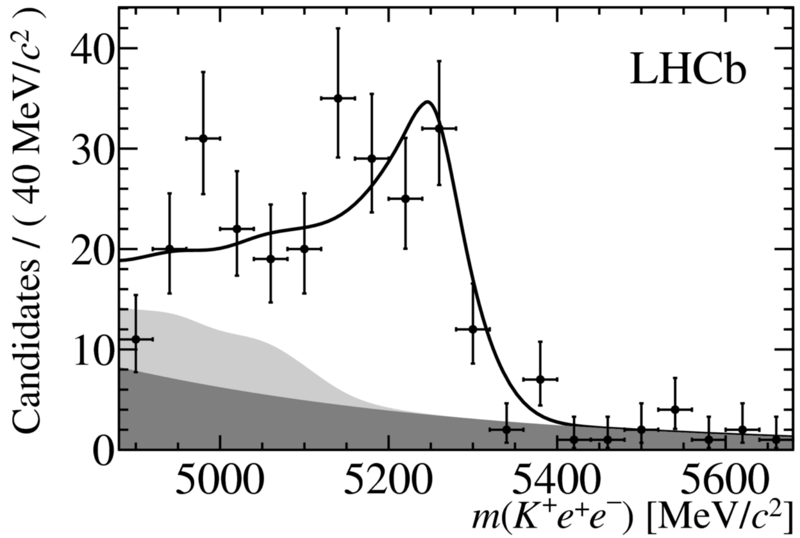
- Measurement that hasn't happened yet.
- Belle II expected to observe the K* and K version of this process
  - the K* is a little bit easier, because $K^* \rightarrow K\pi$ is helpful … can you figure out why?
- Assuming Belle II stays on schedule: sometime between 2021 – 2022.
- Mock up a histogram with fake data to see how it looks. (Do a pretend measurement)
  - Histogram variable is a little bit different: the sum of missing energy and the missing 3 momentum in the centre-of-momentum frame.



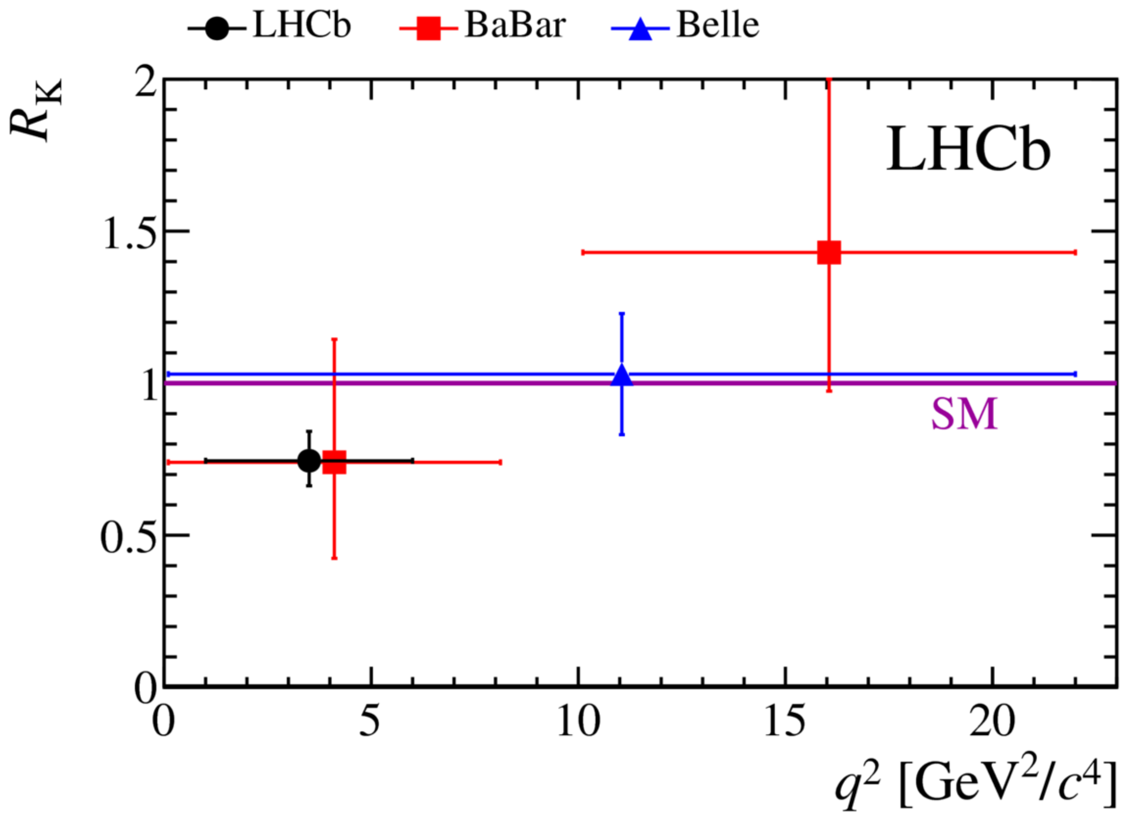
$R_K = \mathcal{B}[B^+ \rightarrow K^+\mu^+\mu^-] / \mathcal{B}[B^+ \rightarrow K^+e^+e^-]$

Phys.Rev.Lett.113,151601





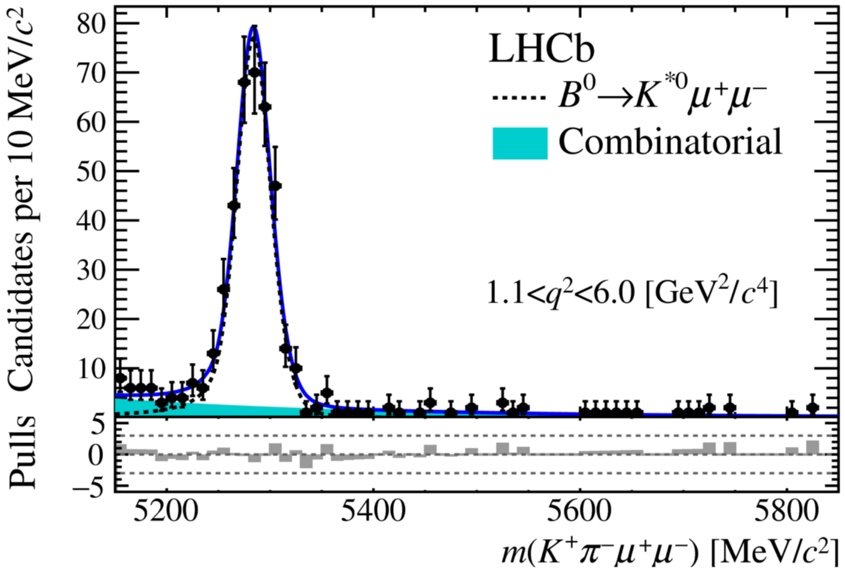
- Remember why ratios are a good idea?
- Look at the x labels of the hisograms, which is which mode?
- R_K in nature seems to be about 0.7… does this make sense based on the number of entries in the histograms? Why not? What information are you missing?

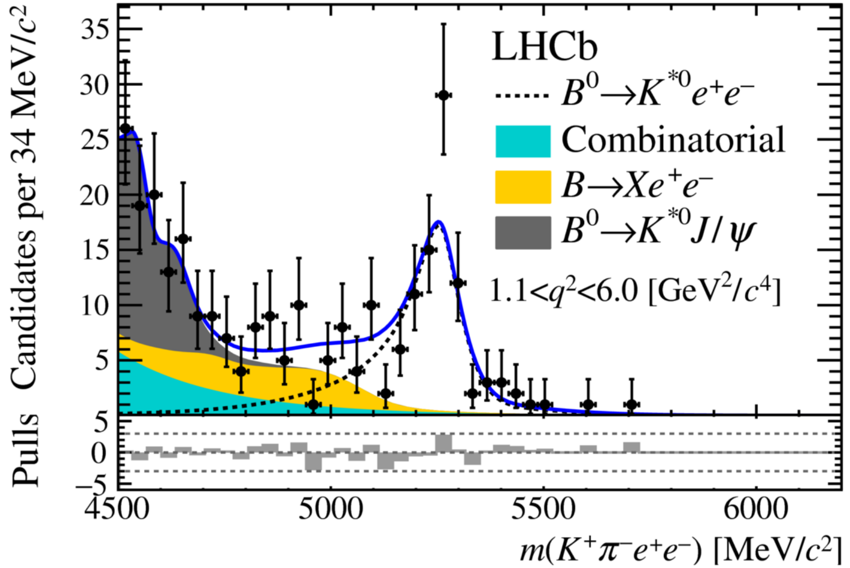


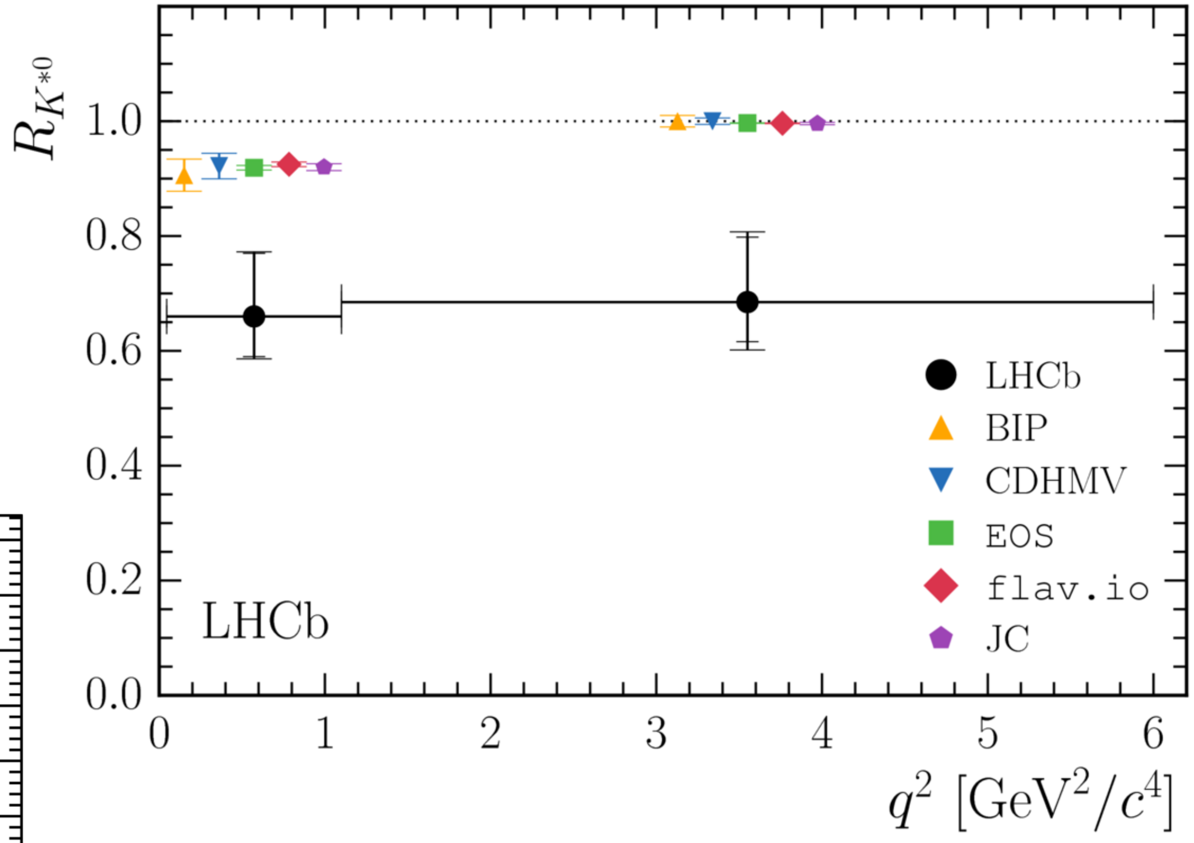
$R_{K^*} = \mathcal{B}[B^0 \to K^{*0}\mu^+\mu^-] / \mathcal{B}[B^0 \to K^{*0}e^+e^-]$

JHEP08(2017)055

- Same story.





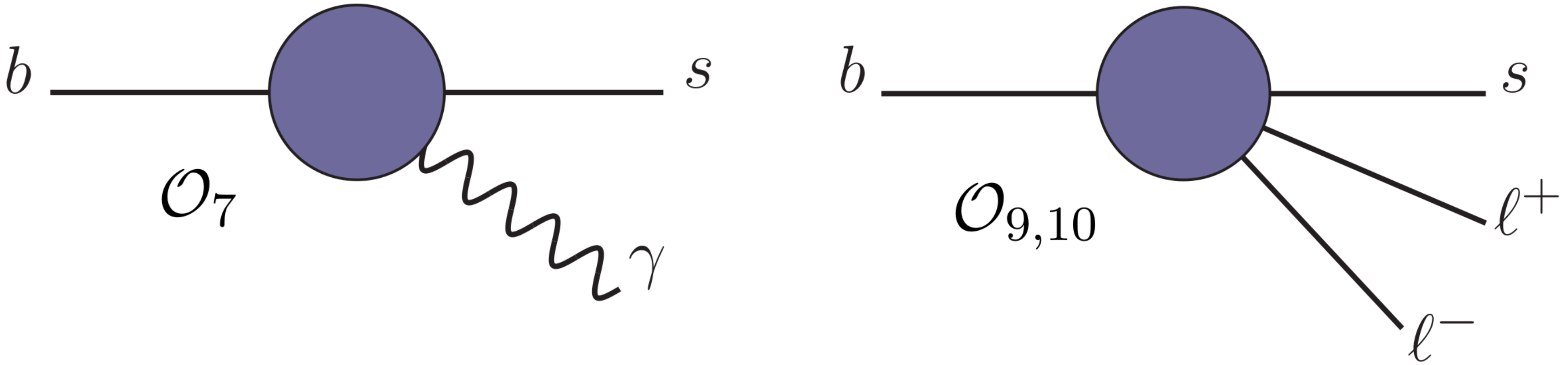


Everybody take a deep breath.

How to understand it all?

Global fit phenomenology

- Make a Standard Model prediction for these observables → many of them are slightly different.
- Now what? Do we have to make a prediction in every model? (**SUSY**, **particle compositeness**, **extended electroweak sector**, … probably others)
- (Re) express all of these observable quantities in terms of an effective field theory.
  - A phenomenologist's trick.



Remember this?

Precision of statement

- An effective relativistic quantum field theory gauge invariant under SU(3) . SU(2) . U(1).
- A Lagrangian density which is the closest we've come to finding the Lagrangian density of nature.
- A collection of quantum fields
- A collection of quantum fields
- ✔ A collection of different types c
- A framework for theorists to ca
- ✔ A table of particles on wikiped
- A set of rules for really small a

Amount of QF

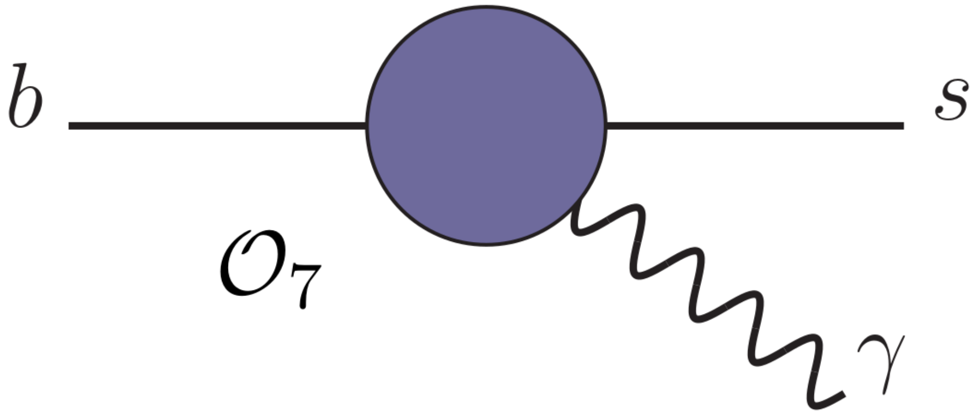
How to understand it all?

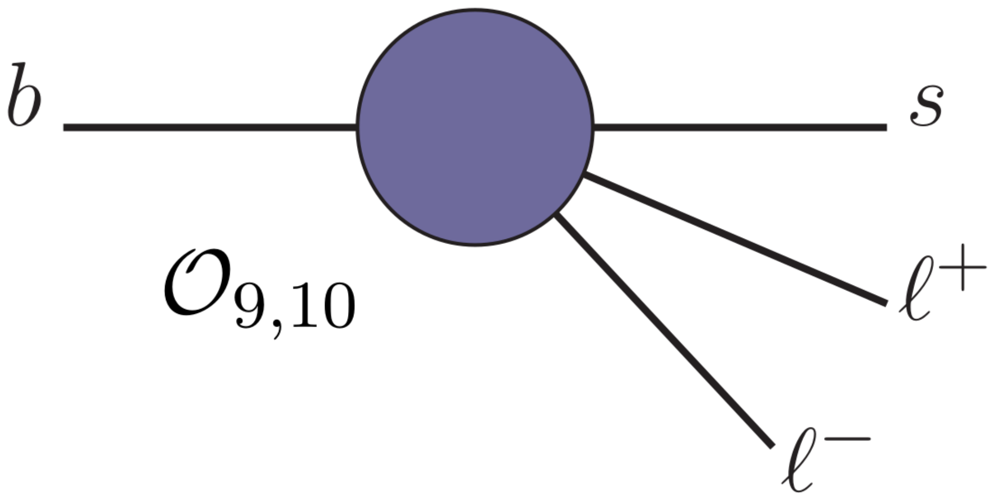
Global fit phenomenology

- If you like Lagrangian densities, then this is writing down all possible terms with their perturbative and non-perturbatively calculable parts separately.
- This is called an “Operator Product expansion”.

$$\mathcal{L}_{\text{eff}} = \sum_i C_i(\varrho)\mathcal{O}_i.$$

- You can just think of it as an alternative way to write down a general QFT (like the SM, or SUSY, or...)





Wilson Coefficients

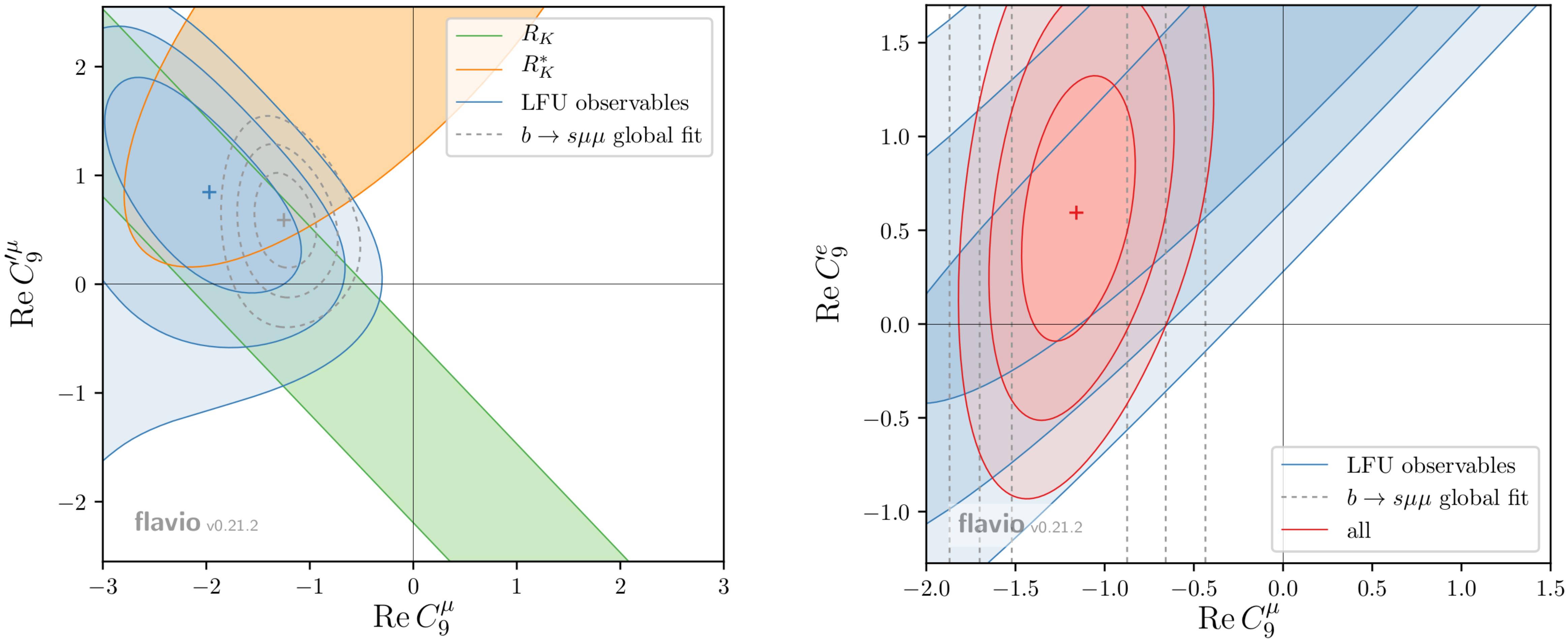
Global fit phenomenology

- The purple blobs all have an associated size (which we call “Wilson Coefficients”).
- You could think of them as a model-independent coupling to **the form** of the interaction.

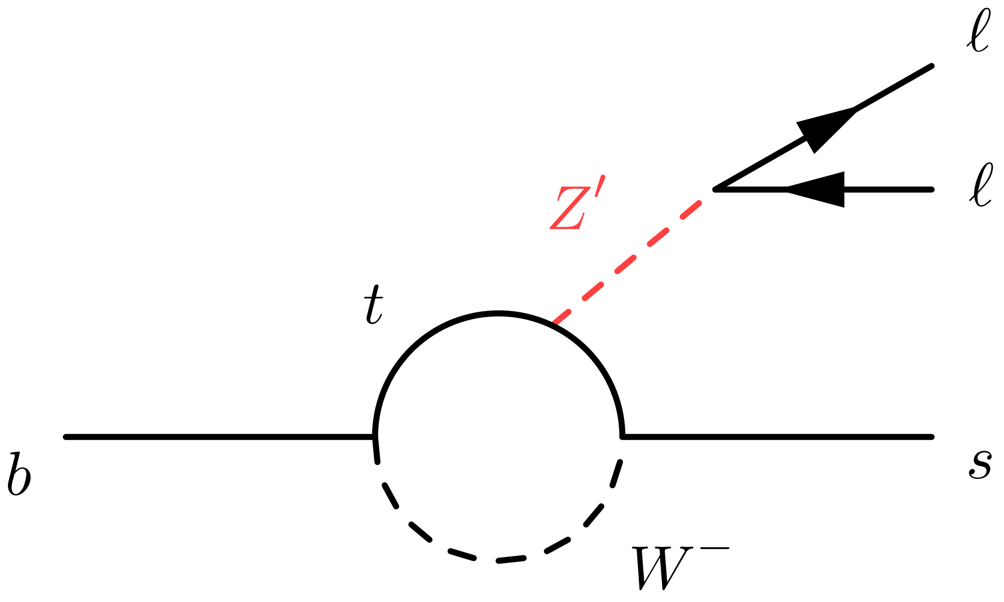
- … anyway! We re-express the results in terms of these coefficients (C_i). Then many observables constrain the same coefficient.
  - Run a fit to try and find them, based on all measured quantities that you think are relevant.
  - Interpret the results in terms of a general theory, and see which interactions are favored.

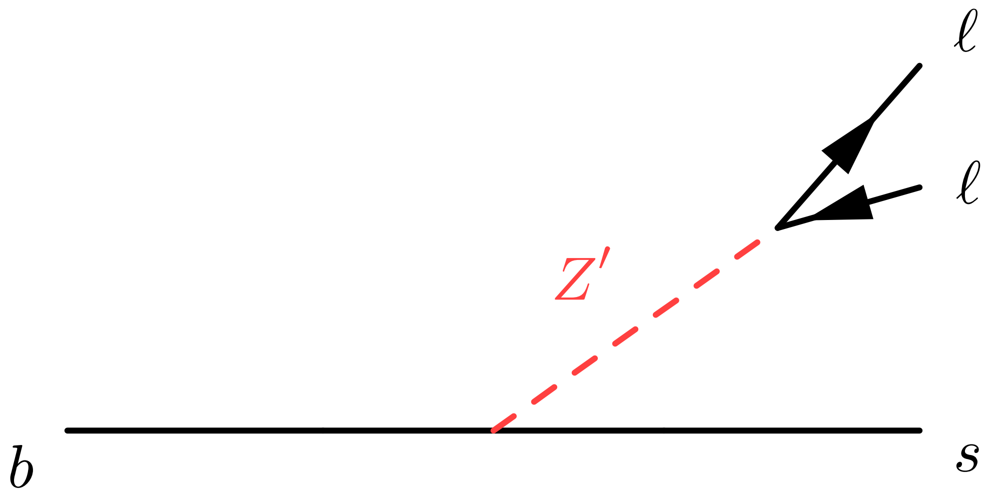
Lets take a look

Phys.Rev.D.96.055008



Is this the way the hints are pointing us?





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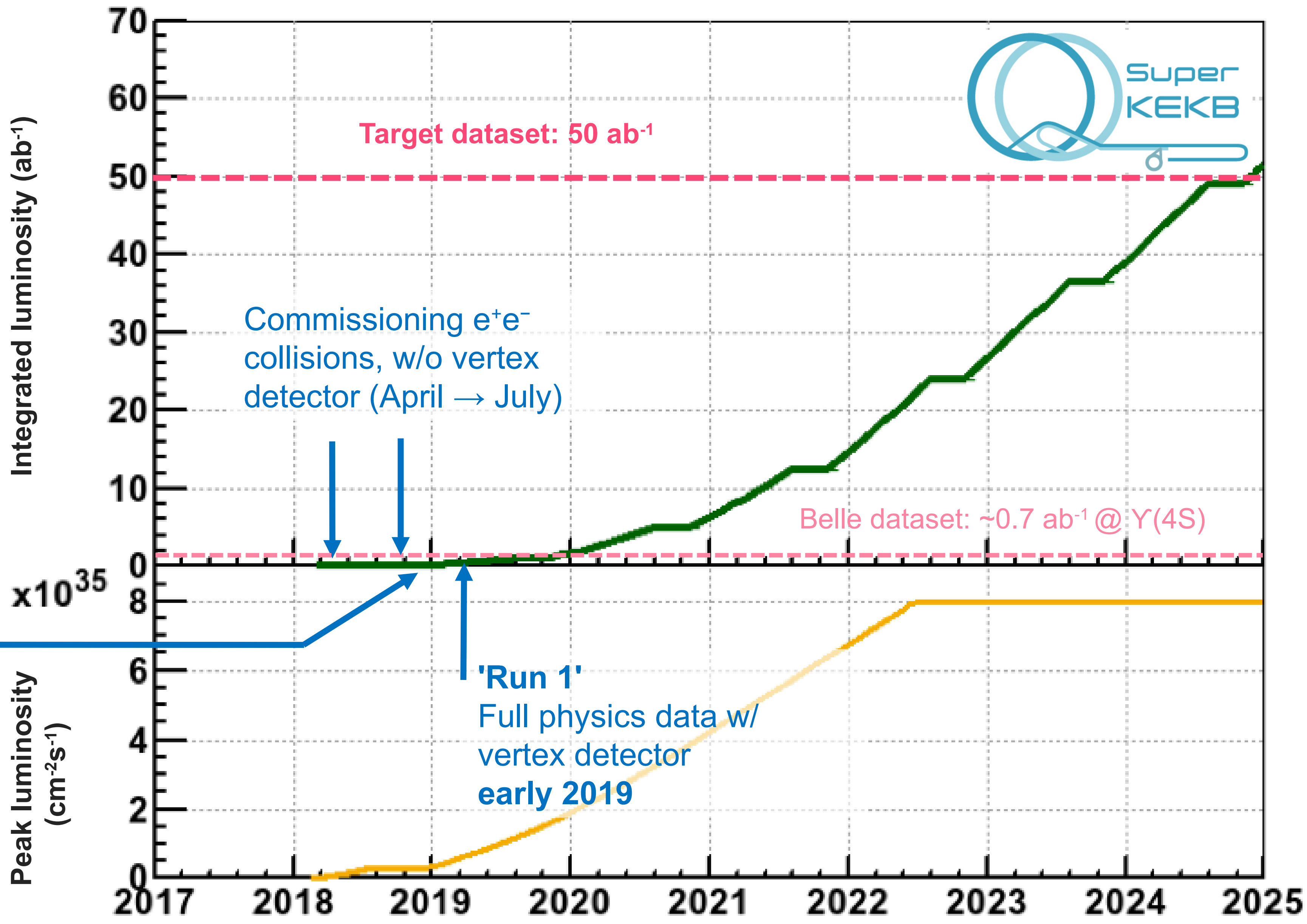
Belle II

...again



Right now: between our first run and the start of "real" data

… in summary

Only somewhat impartial overview

- There are plenty of things still to do!

- Belle II will soon start up (“real data”).
- LHCb is taking data (probably right now).

We need:
- Precision on rare B decays. Particularly ones with neutral particles.
- To measure things that require knowledge of the full event (remember the part about B factories).
- Very high statistics measurements of rare processes.

- I hope you consider a PhD in this (sub)field.
- If you don’t, at least be friends with us!
  Now you know a bit of the lingo.

LHCb

Belle II

Acknowledgements

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