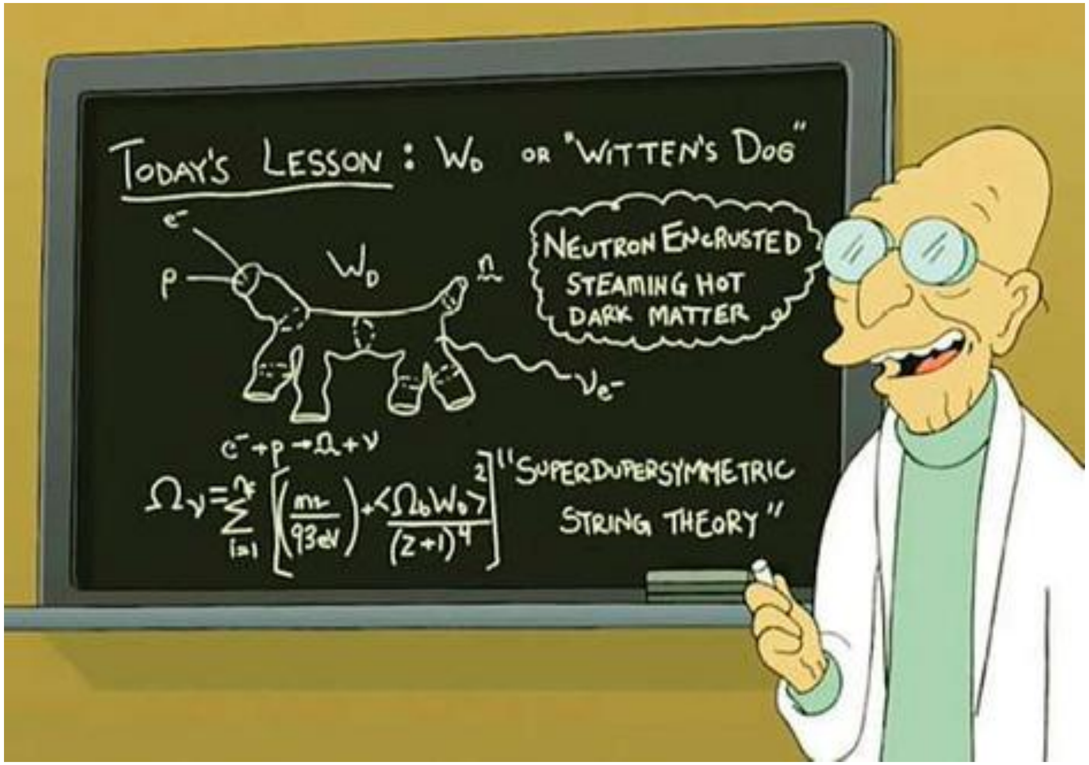
Recent results from rare decays



Recap of last weeks

What we have learned before:

- Neutral mesons (K,D,B_d,B_s) mix and oscillate.
    - Beautiful example of (fast) B_s oscillations: Δm_s=17.77 ± 0.10(stat) ± 0.07 (sys) ps^{-1}
    - Requires good proper time resolution and tagging of B flavour at production.
- There are three types of CP violation:
    - CPV in mixing
        - Small in SM (<1%), only observed so far in kaon decays
    - CPV in decay
        - Often difficult to extract weak phases due to unknown strong phases and T/P ratio.
    - CPV in interference between mixing and decay
        - Large effects and clean determination of weak angles possible.
- Example: LHCb's measurement of sin($2\beta_s$)
    - Measured value: $2\beta_s$=0.002 ± 0.087
    - SM value: $2\beta_s$=0.036 ± 0.002
    - No large phase from new physics…

Probes for New Physics searches

The aim of heavy flavour physics is to study *B* and *D* decays and to look for anomalous effects beyond the Standard Model.

Requirements to look for New Physics effects:
- Should not be ruled out by existing measurements.
- Prediction from SM should be well known.

These requirements are fulfilled for these processes:
- CP violation
- Rare decays

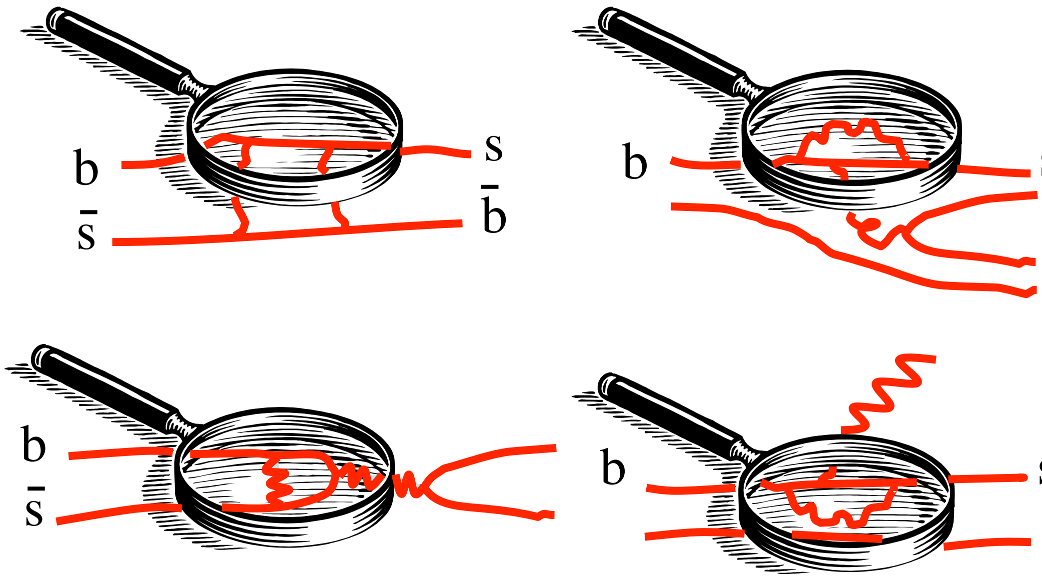
→ CP violation and rare decays of *B* and *D* hadrons are the main focus of LHCb.

Today: Rare decays

Introduction to rare decays

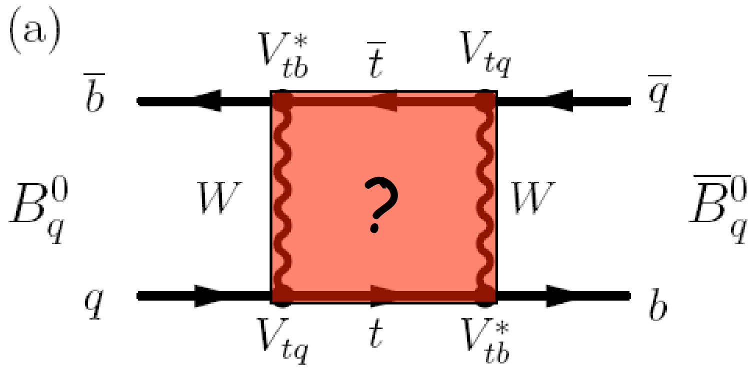
- Flavour changing neutral currents (FCNC) forbidden in SM at tree level.
  - Suppressed at higher-order due to GIM mechanism
- FCNC decays good testing ground for SM.
  - Corresponding decays are always rare (B-mesons < 10^{-5})
- New particles can appear as virtual particles in box and penguin diagrams.
  - Indirect searches have a high sensitivity to effects from new particles.
- Good testing ground: b → s transitions.
  - B_s oscillations → box diagram
  - $B_s \to \phi\gamma$
  - $B_{d,s} \to \mu^+\mu^-$
  - $B_d \to K^*\mu^+\mu^-$

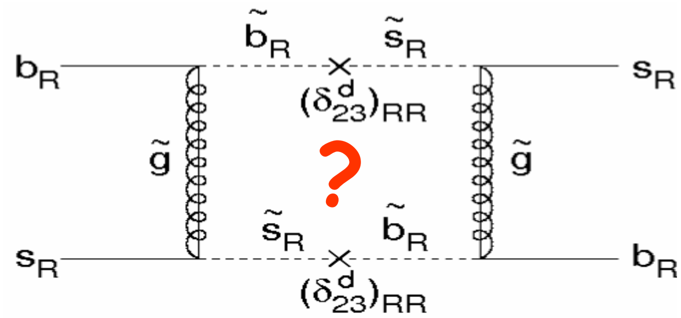
  } → Penguin diagrams



Example: Box diagrams (recap)

New particles could enter in the B_s box diagram





Could affect both amplitude and phase:

$\Delta m_s = \Delta m_s^{SM} + \Delta m_s^{NP}$

$\beta_s = \beta_s^{SM} + 2\beta_s^{NP}$

LHCb's measurements:

Preliminary

$\Delta m_s = 17.725 \pm 0.041(\text{stat}) \pm 0.025\ (\text{sys})\ \text{ps}^{-1}$

SM: $\Delta m_s = 17.3 \pm 2.6\ \text{ps}^{-1}$

$2\beta_s = -0.002 \pm 0.083(\text{stat}) \pm 0.027\ (\text{sys})$

SM: $2\beta_s = 0.036 \pm 0.002$

No hints (yet) for new physics in box diagrams, but still some room left.

But there are penguins on the horizon!

The story about penguins

Quoting John Ellis (Wikipedia):

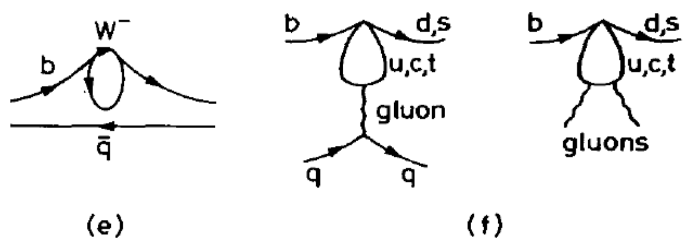
> Mary K. [Gaillard], Dimitri [Nanopoulos] and I first got interested in what are now called penguin diagrams while we were studying CP violation in the Standard Model in 1976... The penguin name came in 1977, as follows.
>
> In the spring of 1977, Mike Chanowitz, Mary K and I wrote a paper on GUTs predicting the b quark mass before it was found. When it was found a few weeks later, Mary K, Dimitri, Serge Rudaz and I immediately started working on its phenomenology. That summer, there was a student at CERN, Melissa Franklin who is now an experimentalist at Harvard. One evening, she, I, and Serge went to a pub, and she and I started a game of darts. We made a bet that if I lost I had to put the word penguin into my next paper. She actually left the darts game before the end, and was replaced by Serge, who beat me. Nevertheless, I felt obligated to carry out the conditions of the bet.
>
> For some time, it was not clear to me how to get the word into this b quark paper that we were writing at the time. Then, one evening, after working at CERN, I stopped on my way back to my apartment to visit some friends living in Meyrin where I smoked some illegal substance. Later, when I got back to my apartment and continued working on our paper, I had a sudden flash that the famous diagrams look like penguins. So we put the name into our paper, and the rest, as they say, is history.

THE PHENOMENOLOGY OF THE NEXT LEFT - HANDED QUARKS

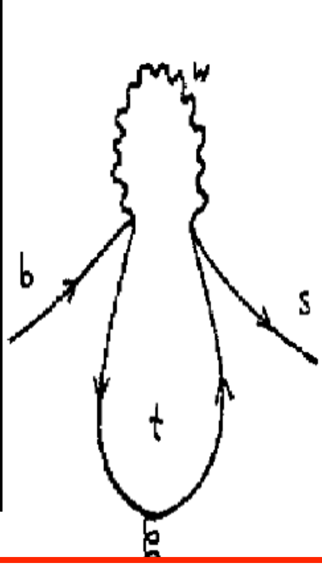
Nucl. Phys. B131:285 1977

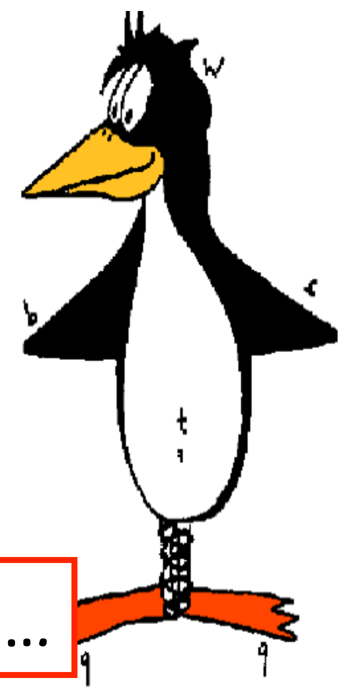
J. Ellis, M.K. Gaillard *), D.V. Nanopoulos +) and S. Rudaz ")

CERN - Geneva



We now turn to the "penguin" diagrams of figs. 2e and 2f.





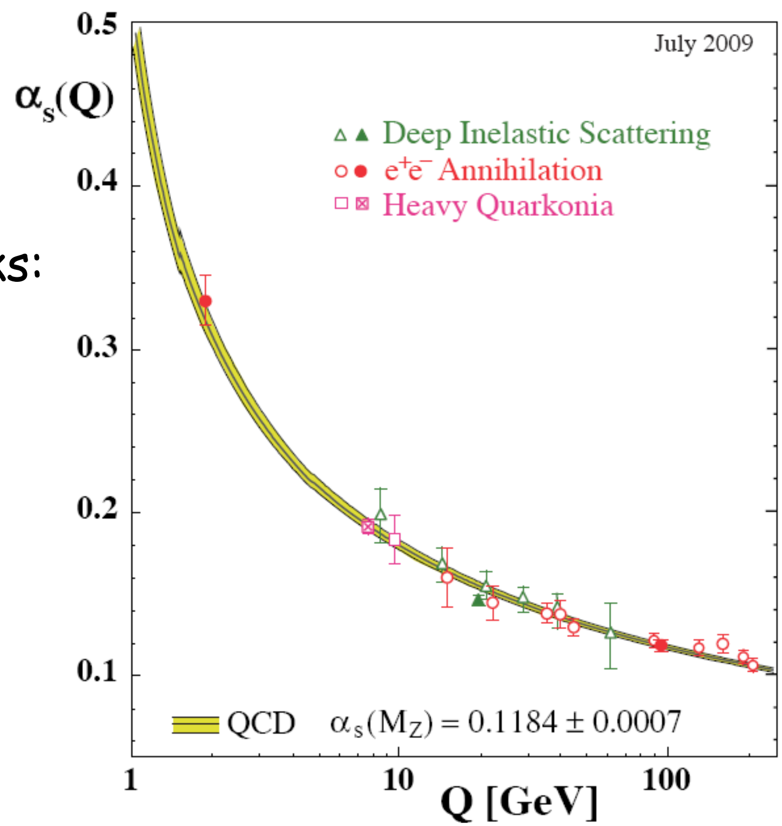
Don't try to beat Melissa Franklin at darts…

Rare decays

Just as in the box diagram, new particles can easily enter in the penguin diagram.
We can measure branching ratio, polarization, angular distributions.
→ compare with theoretical prediction from SM (if deviation: NP)

No problem to calculate the SM Feynman diagrams at quark level, so what is the problem?

We don't measure the individual quarks: we measure only hadrons.



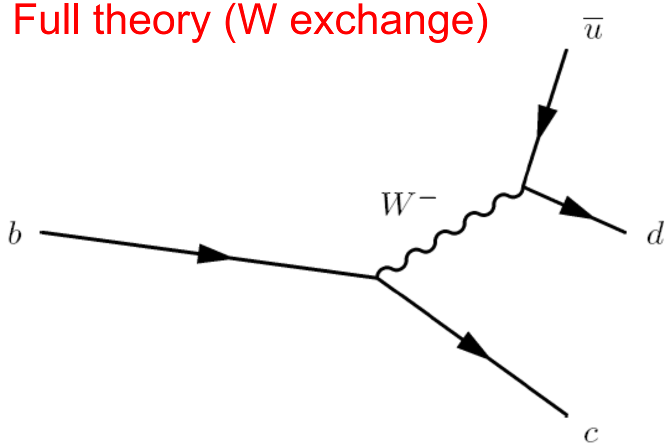
→ cannot use perturbation theory to calculate the (soft) QCD effects (hadronic effects)

OPE

Theoretical approach: Operator Product Expansion + renormalization group equations

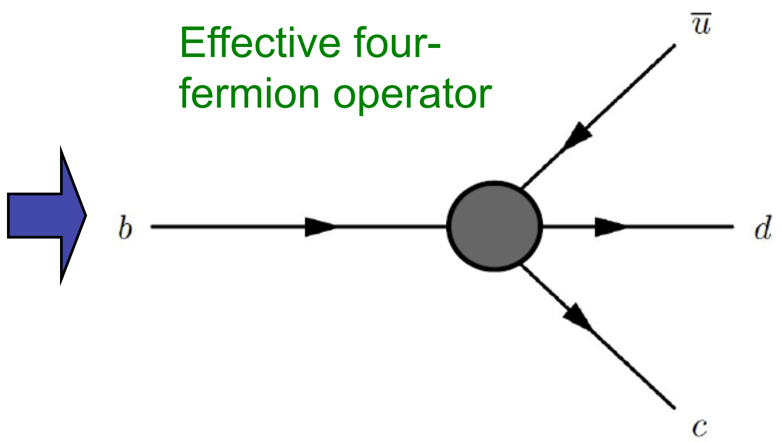
Basic idea:
Energy scale of weak decays is low compared to mass of W (propagator).
→ Absorb W exchange in effective Fermi theory (expansion of W propagator)

Full theory (W exchange)



Fermi theory

Effective four-fermion operator



Allows to separate low-energy effects (non-pertubative QCD) and high-energy effects (pertubative QCD + weak interactions + new physics).

Effective Hamiltonian

$$\langle f|\mathcal{H}_{eff}|B\rangle = \frac{4G_F}{\sqrt{2}}\lambda_{CKM}\sum_i C_i(\mu)\langle f|Q_i(\mu)|B\rangle$$

$$\frac{g^2}{8M_W^2} \longrightarrow \frac{G_F}{\sqrt{2}}$$

CKM elements: for b→s : $V_{ts}^{*} V_{tb}$

Wilson coefficients (high energy)

Low-energy operators

Renormalization scale (μ)
(Unphysical) border between the two regimes
→ for B decays: a few GeV (around b-quark mass)

Energy scales:

New physics	:	$\delta x \sim 1/\Lambda_{NP}$
Electroweak interactions	:	$\delta x \sim 1/M_W$
Short-distance QCD(QED) corrections	:	$\delta x \sim 1/M_W \rightarrow 1/m_b$
Hadronic effects	:	$\delta x < 1/m_b$

} Wilson coefficients

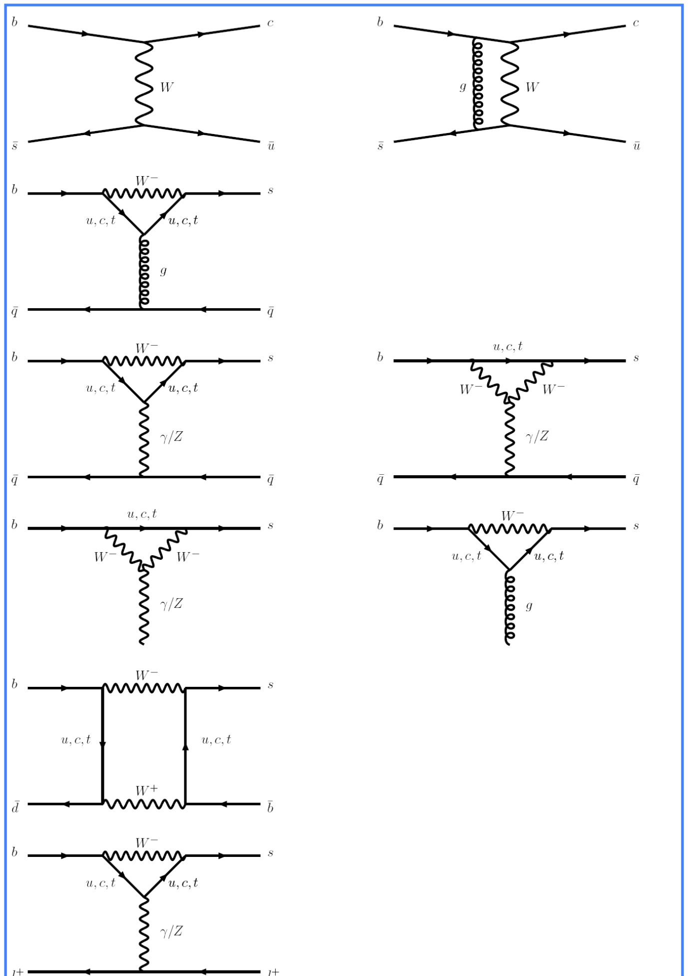
→ Operators:
decay constants, form factors
(large theory uncertainties)

Ordering the diagrams

(Lorentz structure)

$$\langle f|\mathcal{H}_{eff}|B\rangle = \frac{4G_F}{\sqrt{2}}\lambda_{CKM}\sum_i C_i(\mu)\langle f|Q_i(\mu)|B\rangle$$

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



New physics in $b \to s$

New physics could show up as:

- Modified Wilson coefficients
  → new particles in the penguin loop
- New operators
  → e.g. right-handed currents

Three interesting channels:

	SM operators	BR (SM)	BR (exp)	@ LHCb
$B_s \to \phi \gamma$	$Q_{7\gamma}$	Large theory uncertainties O(20%)	$(5.7\pm2.0)\times10^{-5}$	γ polarisation
$B_d \to K^{*}\mu^{+}\mu^{-}$	$Q_{7}^{\gamma}, Q_9, Q_{10}$		$(1.05\pm0.15)\times10^{-6}$	Angular distributions
$B_s \to \mu^{+}\mu^{-}$	Q_S, Q_P	$(3.2\pm0.2)\times10^{-9}$	$< 1.1\times10^{-9}$ (95%)	BR

→ Focus of today

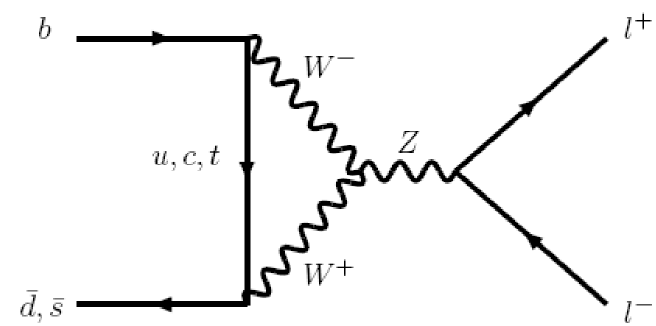
Search for $B_{d,s} \rightarrow \mu^+\mu^-$

Expected BRs

Numbers not up-to-date

	$\mathcal{B}(B_d^0 \rightarrow \ell^+\ell^-)$	$\mathcal{B}(B_s^0 \rightarrow \ell^+\ell^-)$
$\ell = e$	$(2.40 \pm 0.34) \times 10^{-15}$	$(8.15 \pm 1.29) \times 10^{-14}$
$\ell = \mu$	$(1.00 \pm 0.14) \times 10^{-10}$	$(3.42 \pm 0.54) \times 10^{-9}$
$\ell = \tau$	$(2.90 \pm 0.41) \times 10^{-8}$	$(9.86 \pm 1.55) \times 10^{-7}$

Increasing BR



Why are the B_d decays suppressed relative to B_s?

Top quark is dominating in the loop.
Cabibbo suppression by factor $|V_{td}/V_{ts}|^2$

Why is the search for $B_{d,s} \rightarrow \mu^+\mu^-$ most popular?

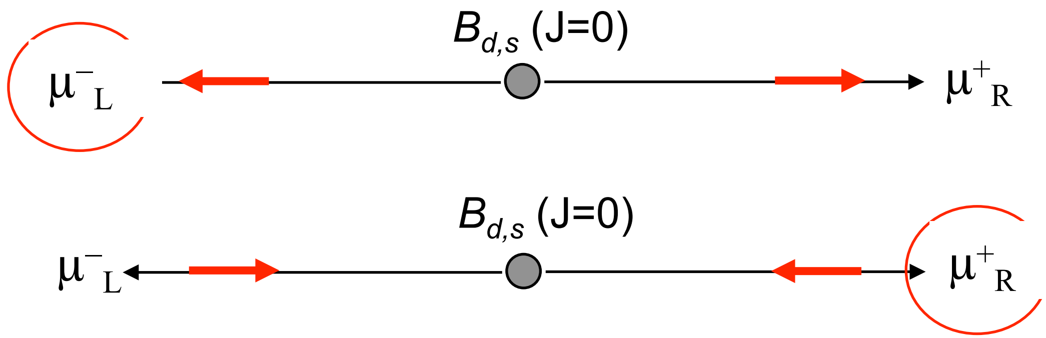
Muons are easiest to reconstruct (taus always give a neutrino)

Why is the BR for taus so much larger than for electrons?

Decays are helicity suppressed.

Helicity suppression

Two decay options:
(Spin of B is zero. Total spin is conserved)



In the mass-less limit this would be a left-handed anti-muon.

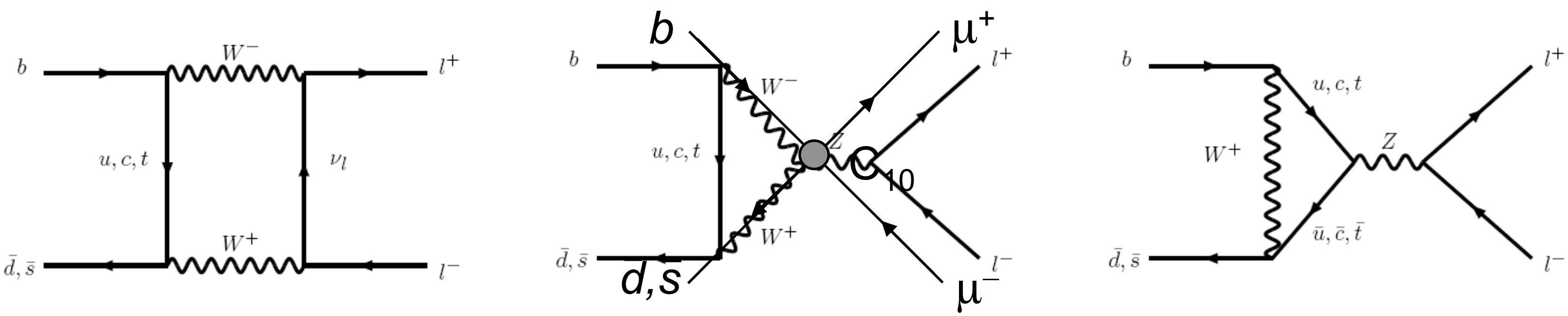
No right-handed particles or left-handed anti-particles produced in weak interaction.
→ One lepton has to undergo a helicity flip.
→ This is easier have the heavy tau than for the light electron.

In other words, this decay can only happen due to the Higgs field

Search for $B_{d,s} \to \mu^+\mu^-$

The decay $B_{d,s} \to \mu^+\mu^-$ provides sensitive probe for New Physics

SM diagrams: Only semi-leptonic operator Q_{10} (C_S and C_P are suppressed):

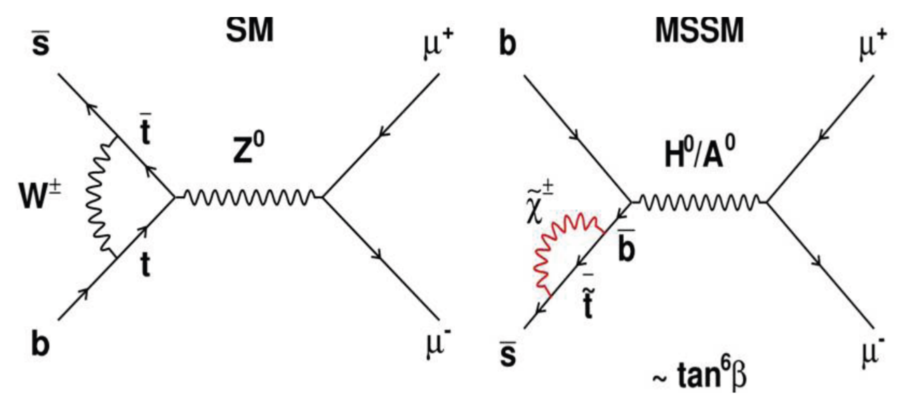


→ New physics could modify Wilson coefficients C_{10}, C_S, C_P (or introduce new operators).

NP example: MSSM

Operators Q_S, Q_P will enhance BR:

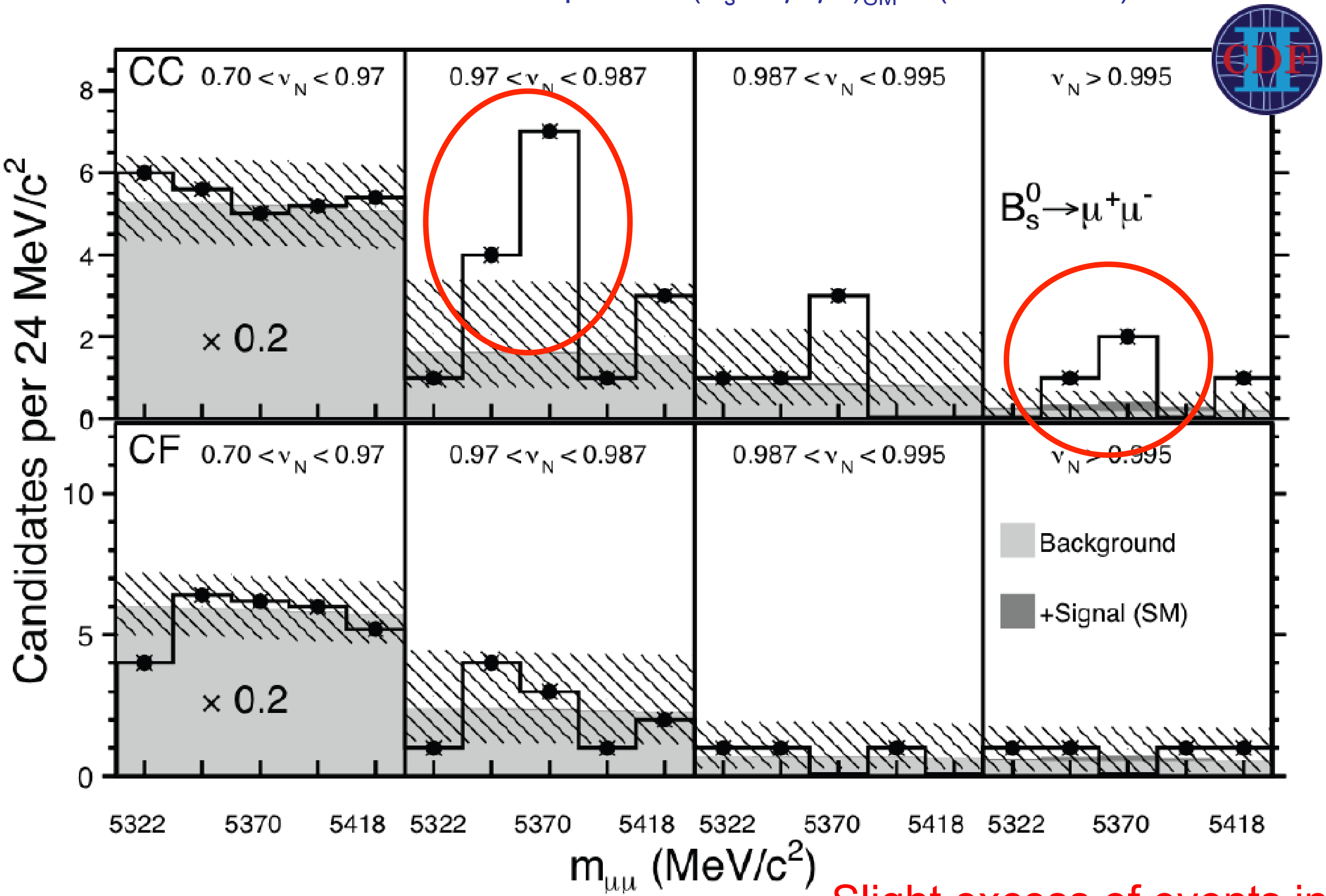
$$\mathrm{BR}(B_{d,s} \to \mu^+\mu^-) \sim \frac{\tan^6\beta}{M_A^4}$$



Search for $B_{d,s} \to \mu^+\mu^-$

In 2011 there was some excitement from CDF:
$BR(B_s \to \mu^+\mu^-) = (18\,^{+11}_{-9})\text{x}10^{-9}$ arXiv:1107.2304

Compare $BR(B_s \to \mu^+\mu^-)_{SM} = (3.54 \pm 0.30)\text{x}10^{-9}$



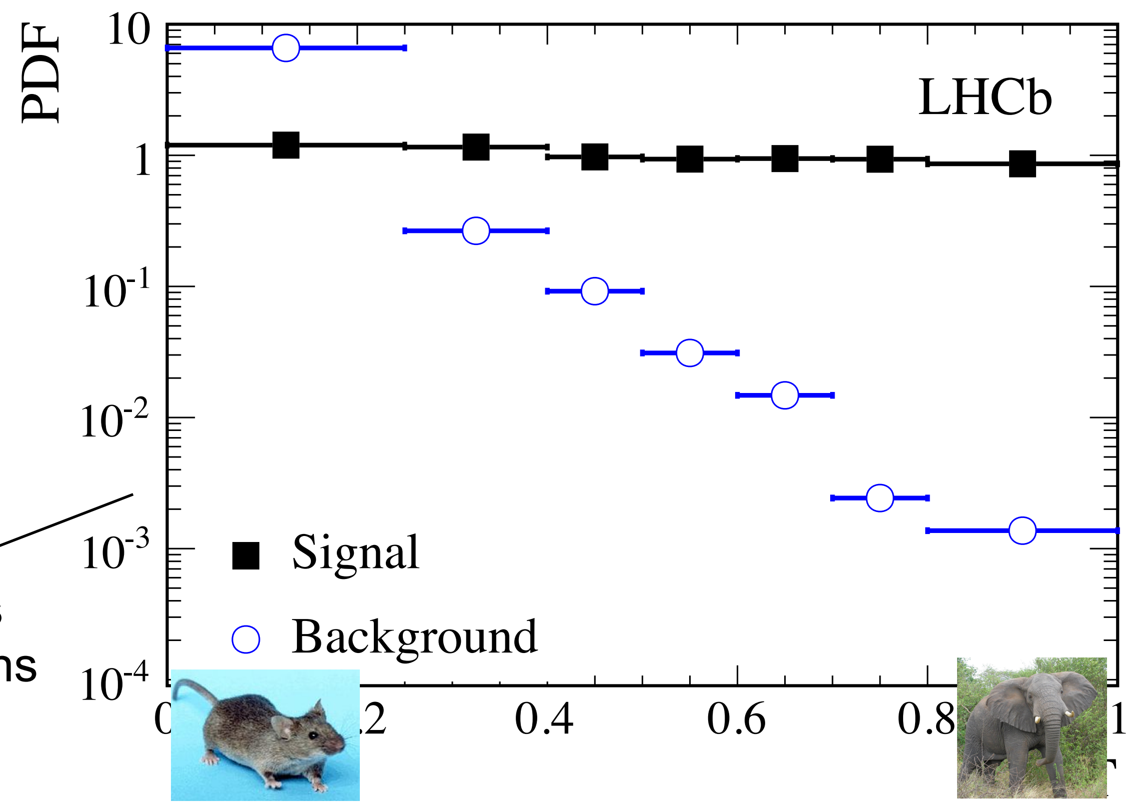
Slight excess of events in two bins

Search for $B_{d,s} \to \mu^+\mu^-$

Back to the analysis in LHCb:

Evaluate signal/background in a 2D-space of
- Invariant mass $m_{\mu\mu}$
- MVA classifier BDT combining kinematic and geometrical variables

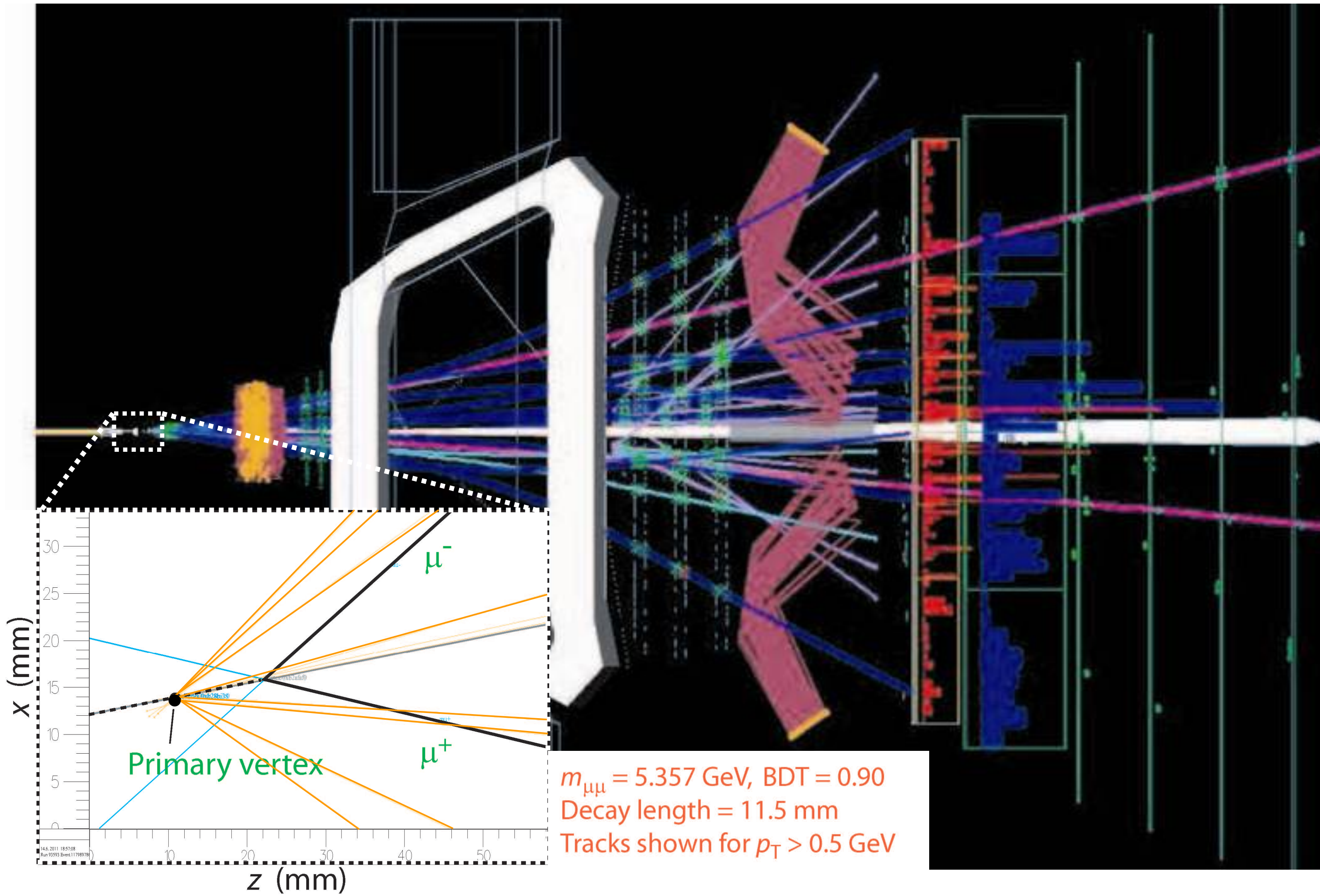
→ Remember the elephant



Next: Look at invariant mass spectrum in each of the 7 bins

Least sensitive bin → Most sensitive bin

Search for $B_{d,s} \to \mu^+\mu^-$



$m_{\mu\mu}$ = 5.357 GeV, BDT = 0.90
Decay length = 11.5 mm
Tracks shown for p_T > 0.5 GeV

Search for $B_{d,s} \to \mu^+\mu^-$

Normalization

The final branching ratio can be calculated as:

$$\mathrm{BR}(B_q^0 \to \mu^+\mu^-) = \mathrm{BR}_{\mathrm{cal}} \times \frac{\varepsilon_{\mathrm{cal}}}{\varepsilon_{\mathrm{sig}}} \times \frac{f_{\mathrm{cal}}}{f_{B_q^0}} \frac{N_{B_q^0 \to \mu^+\mu^-}}{N_{\mathrm{cal}}} = \alpha_{\mathrm{cal}} \times N_{B_q^0 \to \mu^+\mu^-}$$

Two complementary normalization channels with very different systematics:

$$B^+ \to J/\psi(\mu^+\mu^-)K^+$$

$$B^0 \to K^+\pi^-$$

Values for α very compatible

	$\mathcal{B}$ $(\times 10^{-5})$	$\frac{\epsilon^{\mathrm{rec}}_{\mathrm{norm}}\epsilon^{\mathrm{sel\|rec}}_{\mathrm{norm}}}{\epsilon^{\mathrm{rec}}_{\mathrm{sig}}\epsilon^{\mathrm{sel\|rec}}_{\mathrm{sig}}}$	$\frac{\epsilon^{\mathrm{trg\|sel}}_{\mathrm{norm}}}{\epsilon^{\mathrm{trg\|sel}}_{\mathrm{sig}}}$	N_{norm}	$\alpha^{\mathrm{norm}}_{B^0\to\mu^+\mu^-}$ $(\times 10^{-11})$	$\alpha^{\mathrm{norm}}_{B^0_s\to\mu^+\mu^-}$ $(\times 10^{-10})$
$B^+ \to J/\psi K^+$	6.01 ± 0.21	0.548 ± 0.018	0.932 ± 0.012	$424\,200 \pm 1500$	7.24 ± 0.39	2.83 ± 0.27
$B^0 \to K^+\pi^-$	1.94 ± 0.06	0.908 ± 0.031	0.057 ± 0.002	$14\,600 \pm 1100$	6.93 ± 0.67	2.71 ± 0.34

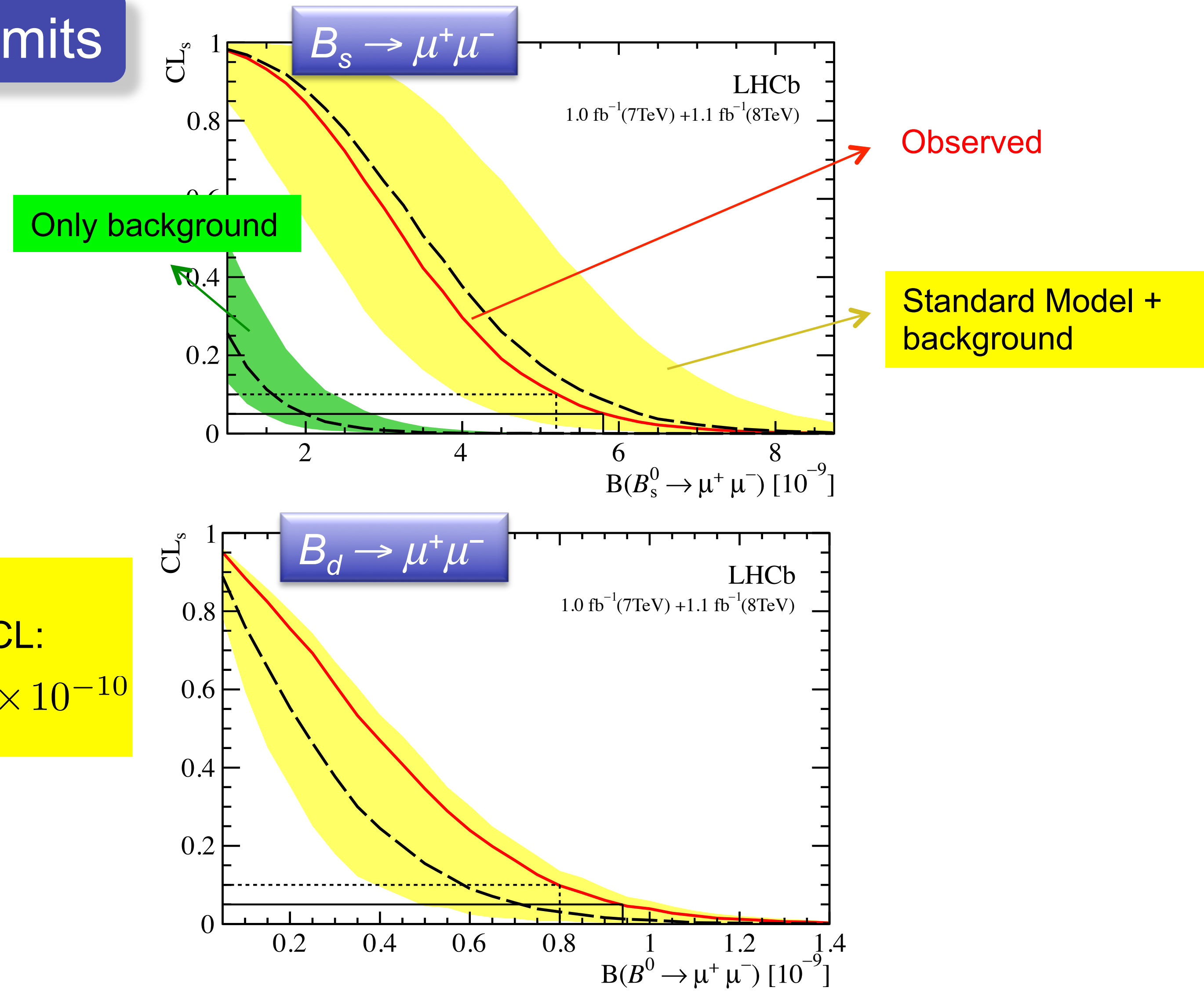
Search for $B_{d,s} \to \mu^+\mu^-$

CLs exclusion limits

B_s
incompatible with background-only hypothesis

B_d
Exclusion limit at 95% CL:

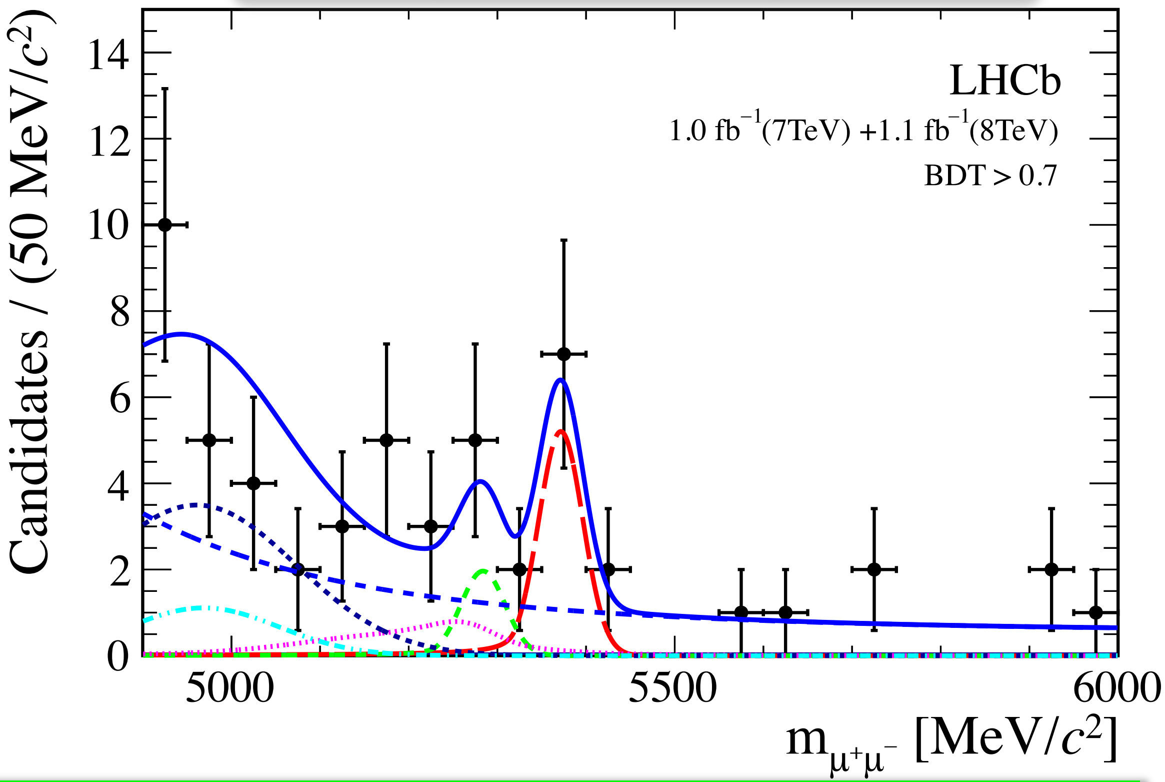
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 9.4 \times 10^{-10}$$



First evidence of $B_s \to \mu^+\mu^-$

Small peak already visible!

[arXiv:1211.2674]



$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.2\,^{+1.4}_{-1.2}(\text{stat})\,^{+0.5}_{-0.3}(\text{syst})) \times 10^{-9}$$

3.5σ significance

Compare BR($B_s \to \mu^+\mu^-$)$_{SM}$ = (3.54 ± 0.30)x10^{-9}

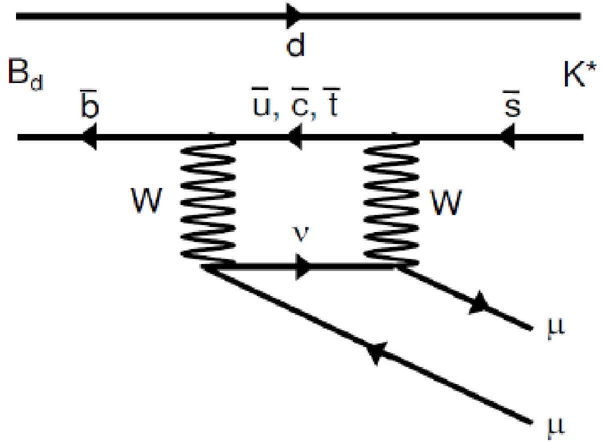
Measurement puts strong constraints on SUSY models.

Angular distributions in $B_d \rightarrow \mu^+\mu^- K^*$

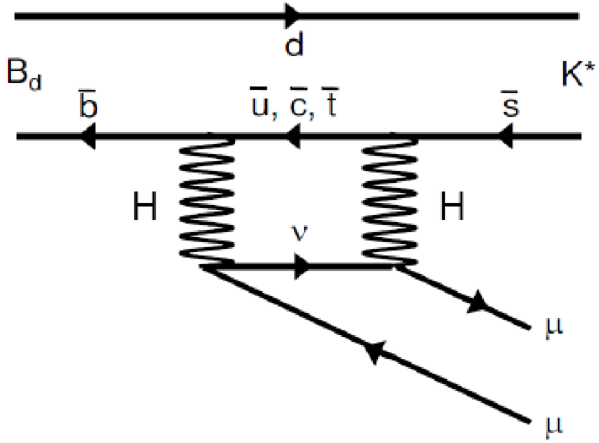
$B_d \rightarrow \mu^+\mu^- K^*$ rare decay in the SM.

- BR ($B_d \rightarrow l^+l^- K^*$) ~ 1.0×10^{-6}

Example of SM diagram:
W exchange



Example of NP diagram:
Charged Higgs exchange



$W^\pm$ is spin 1 particle, while $H^\pm$ is spin 0.
→ Modifies the angular distributions of the muons.

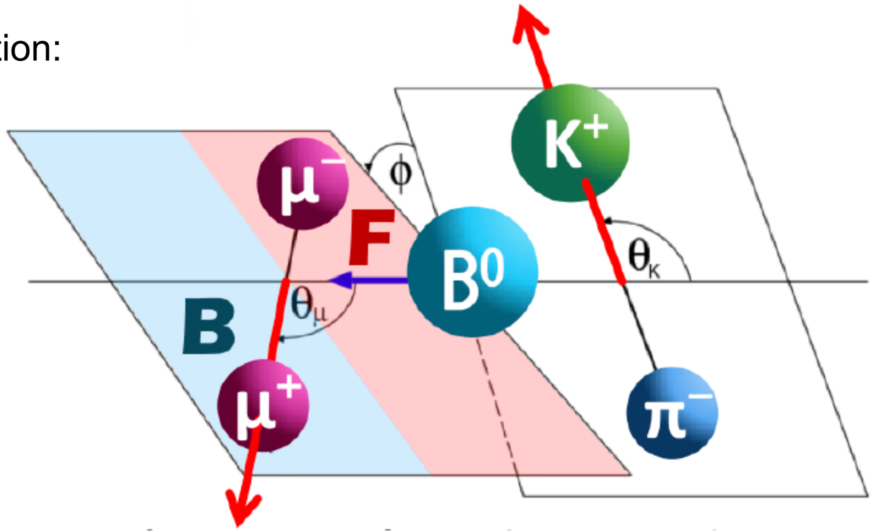
Generally, angular distributions contain a lot of information.

- Sensitive to SUSY, graviton exchanges, extra dimensions…
- Many observables which probe helicity structure of NP
- Best known example: A_{FB} (see next slide)

Angular distributions in $B_d \to \mu^+\mu^- K^*$

A_{FB}: μ forward-backward asymmetry

Definition:



Idea: Measure A_{FB} as a function of invariant mass of muon pair (q^2).

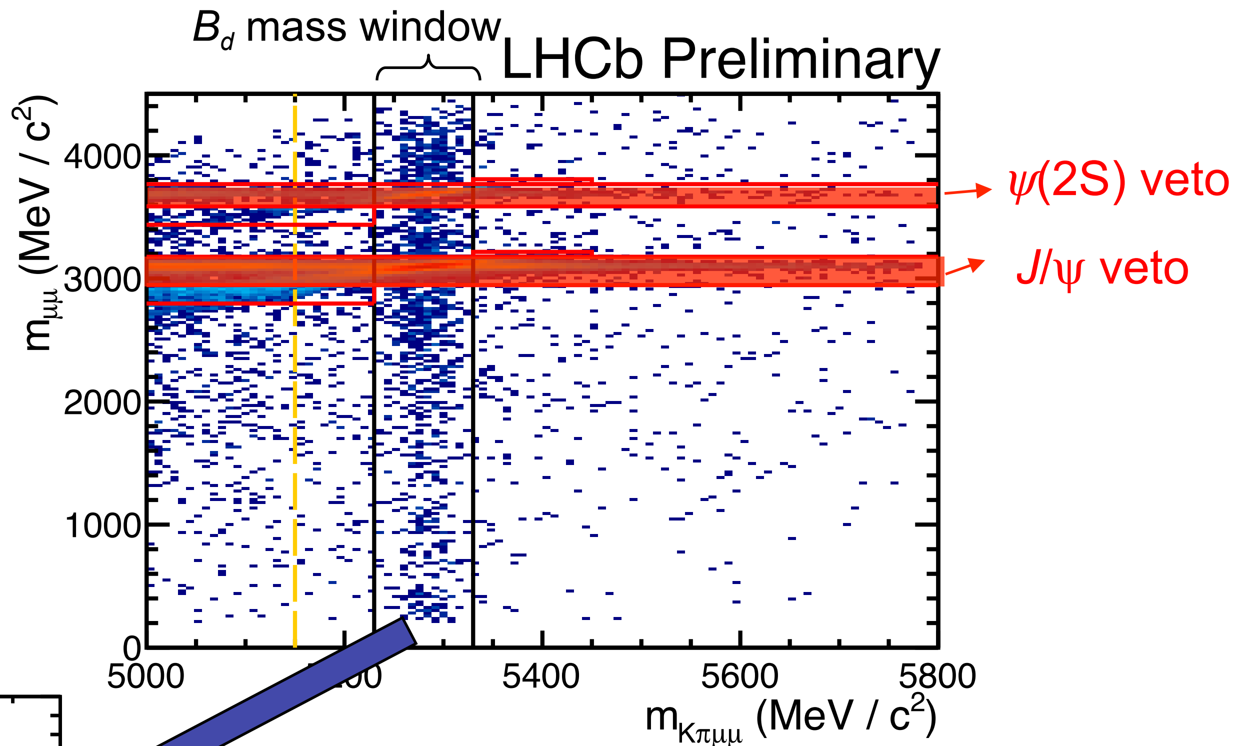
→ Zero crossing point of $A_{FB}(q^2)$ well predicted in SM

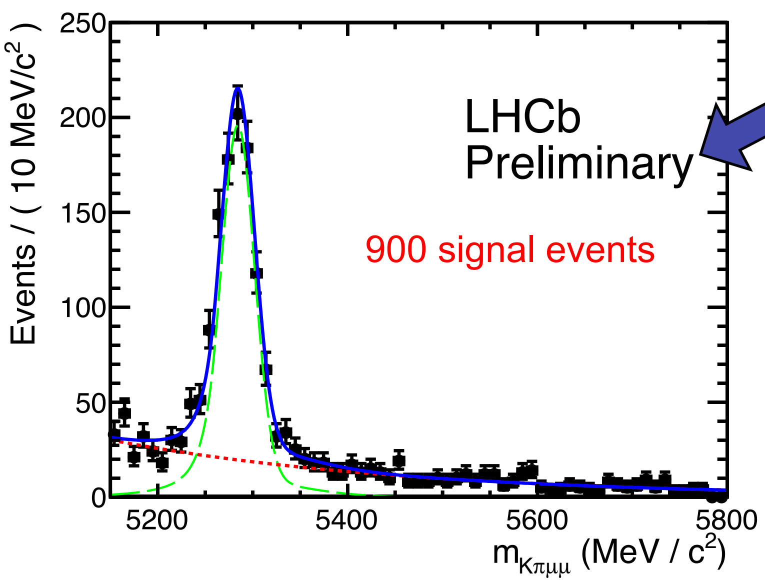
- Hadronic uncertainties are minimized
- Measures ratio Wilson coefficients C_9/C_7.
- $C_{7\gamma}$ constrained by $B_s \to \phi\gamma$ but not its sign.

Angular distributions in $B_d \to \mu^+\mu^- K^*$

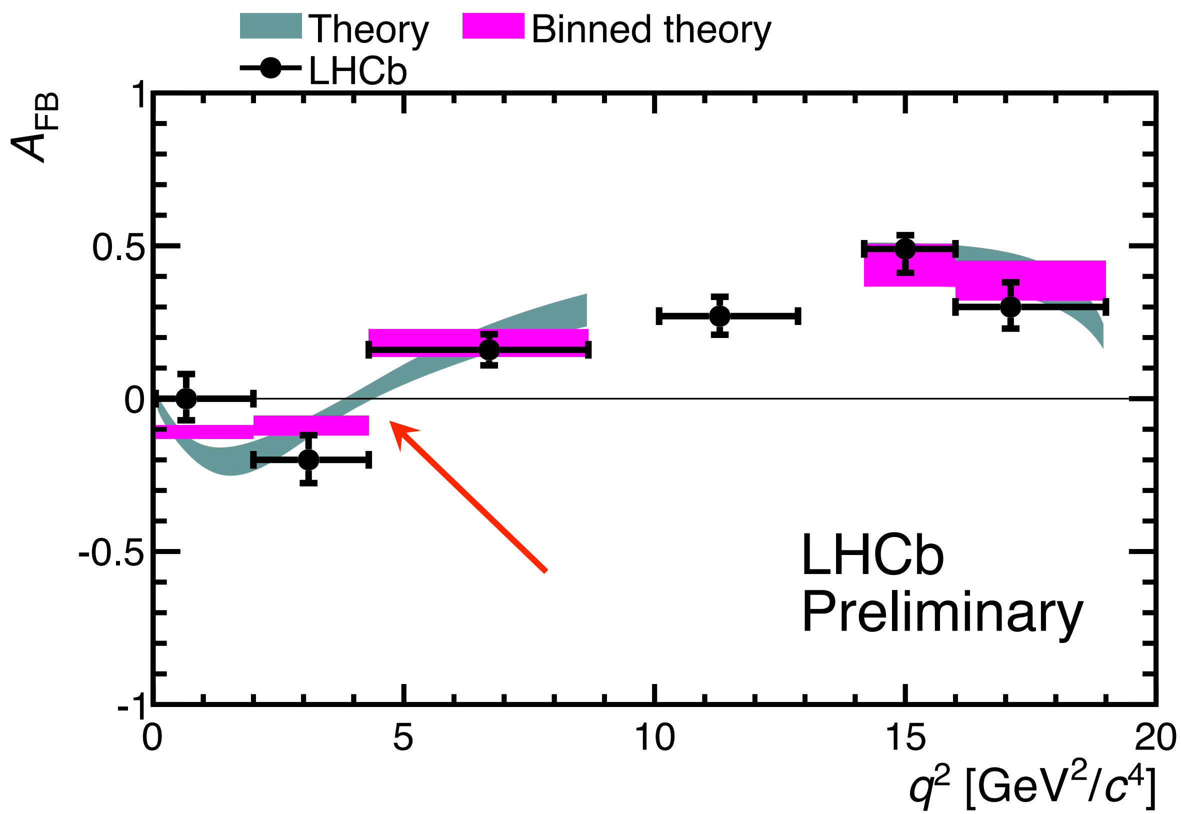
Event selection

$1.0\ fb^{-1}$ in 2011





Angular distributions in $B_d \rightarrow \mu^+\mu^- K^*$



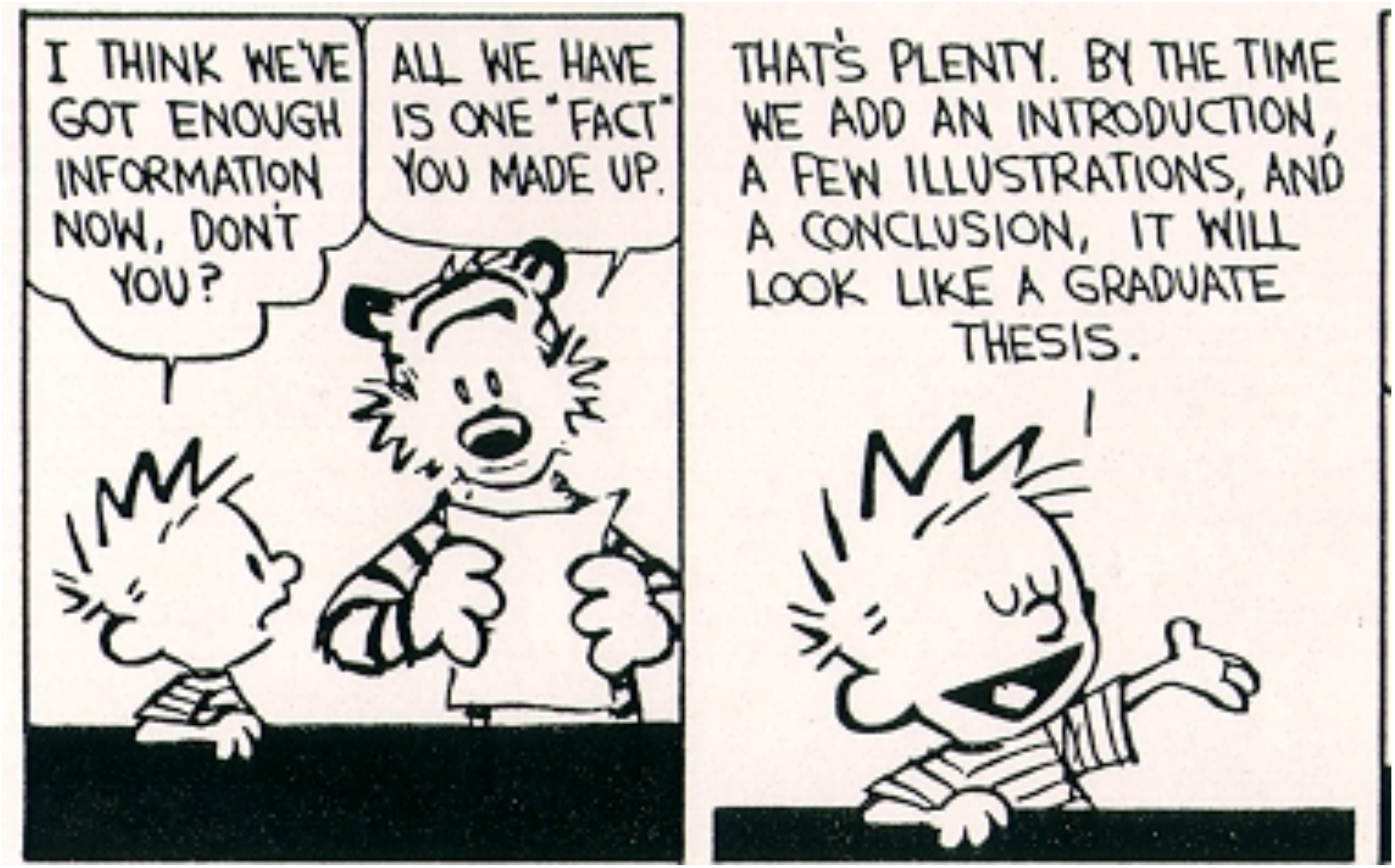
LHCb has performed the world's first measurement of the zero-crossing point:

$$q_0^2 = 4.9\,^{+1.1}_{-1.3}\ \text{GeV}^2$$

consistent with SM prediction: 4-4.3 GeV^2 [Eur. Phys. J C 41 (2005) 173-188]

Still many more angular distributions to analyse

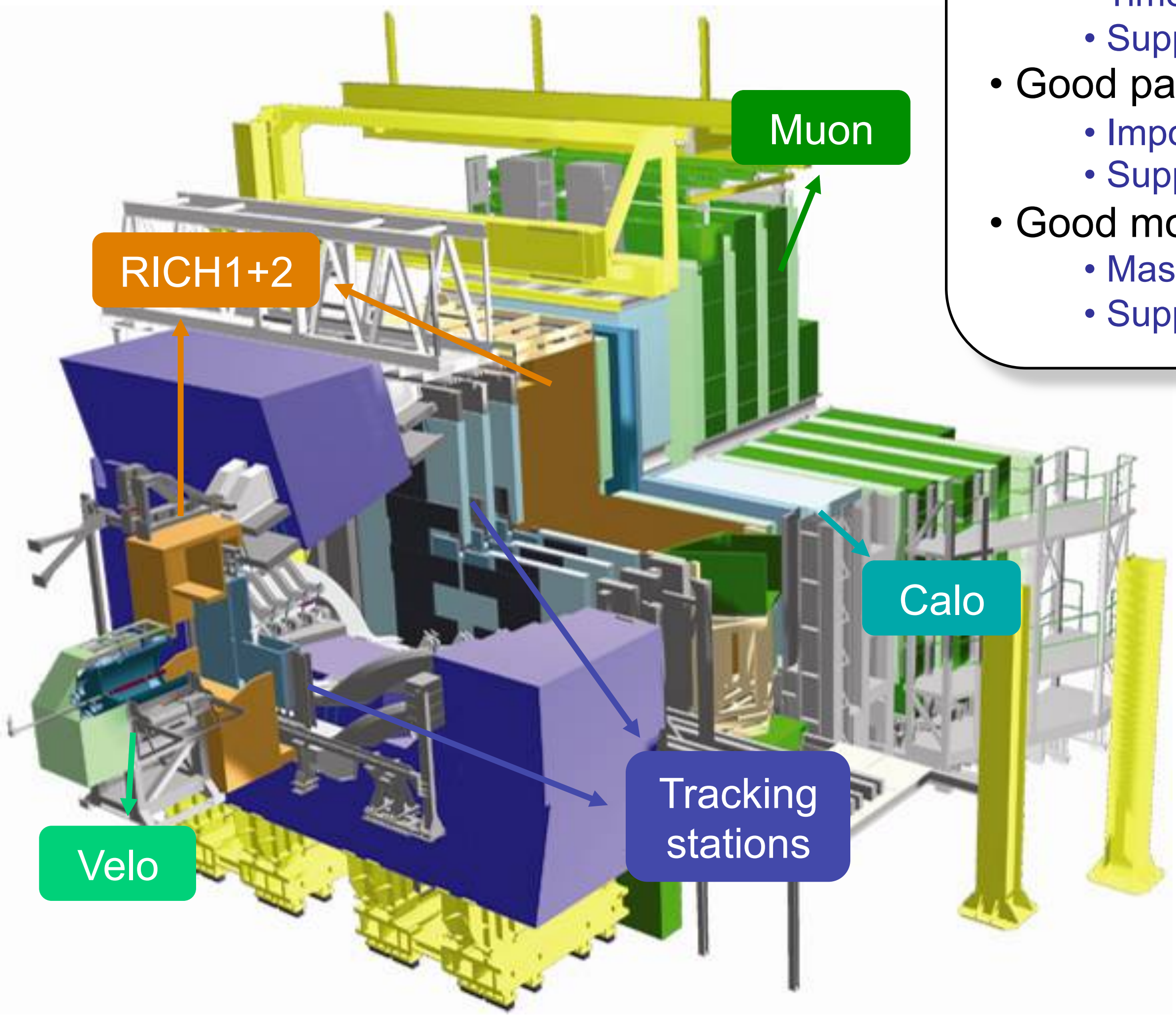
Cartoon


I THINK WE'VE GOT ENOUGH INFORMATION NOW, DON'T YOU?
ALL WE HAVE IS ONE "FACT" YOU MADE UP.
THAT'S PLENTY. BY THE TIME WE ADD AN INTRODUCTION, A FEW ILLUSTRATIONS, AND A CONCLUSION, IT WILL LOOK LIKE A GRADUATE THESIS.

Concluding slides

What is the minimum you should take home from these 4 lectures?

LHCb detector



LHCb made for Heavy Flavour physics

- Good vertex resolution
  - Time-dependent measurements.
  - Suppress background from prompt decays.
- Good particle identification
  - Important for trigger, flavour tagging
  - Suppress background.
- Good momentum resolution
  - Mass resolution of heavy flavours.
  - Suppress background.

The power of indirect searches

GIM Mechanism

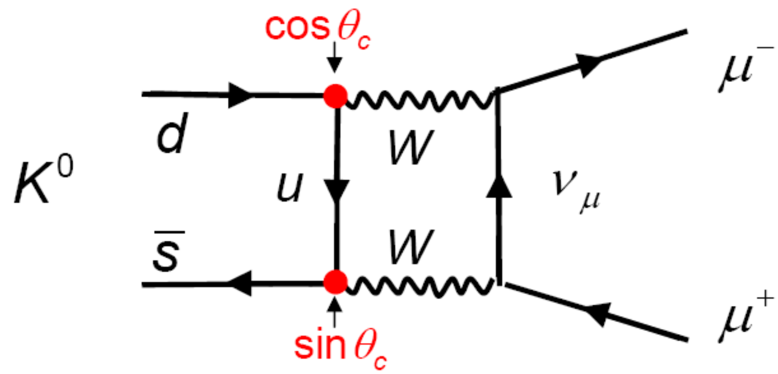
Observed branching ratio $K^0 \to \mu\mu$

$$\frac{BR(K_L \to \mu^+\mu^-)}{BR(K_L \to all)} = (7.2 \pm 0.5) \cdot 10^{-9}$$

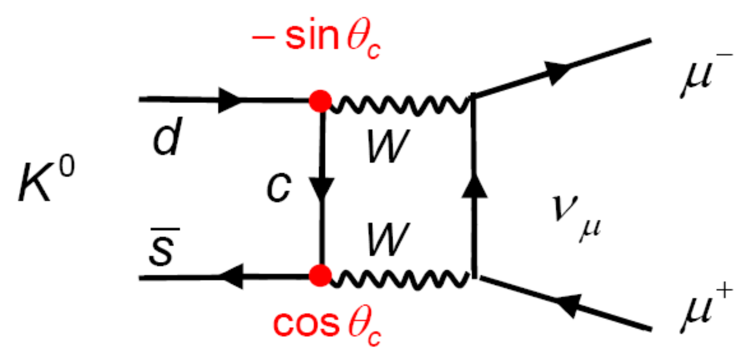
In contradiction with theoretical expectation in the 3-Quark Model

Glashow, Iliopolus, Maiani (1970):

Prediction of a 2nd up-type quark, additional Feynman graph cancels the “u box graph”.

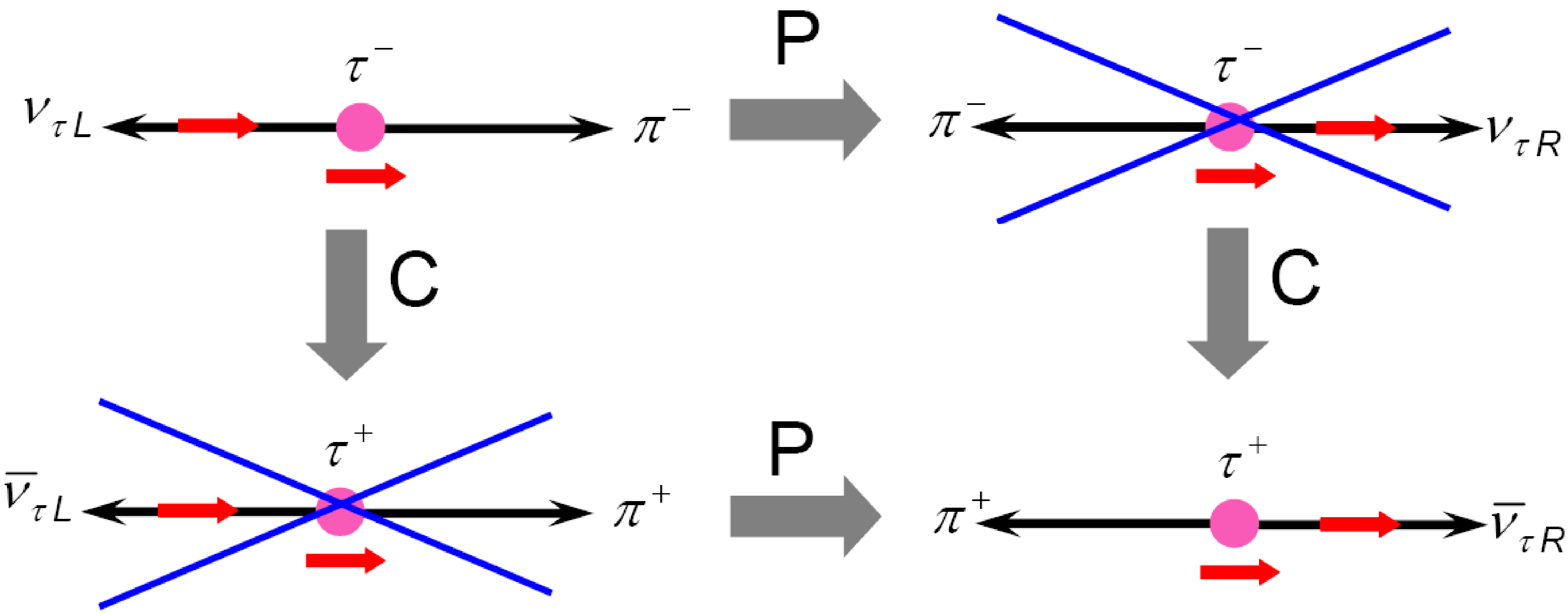


$$M \sim \sin\theta_c \cos\theta_c$$



$$M \sim -\sin\theta_c \cos\theta_c$$

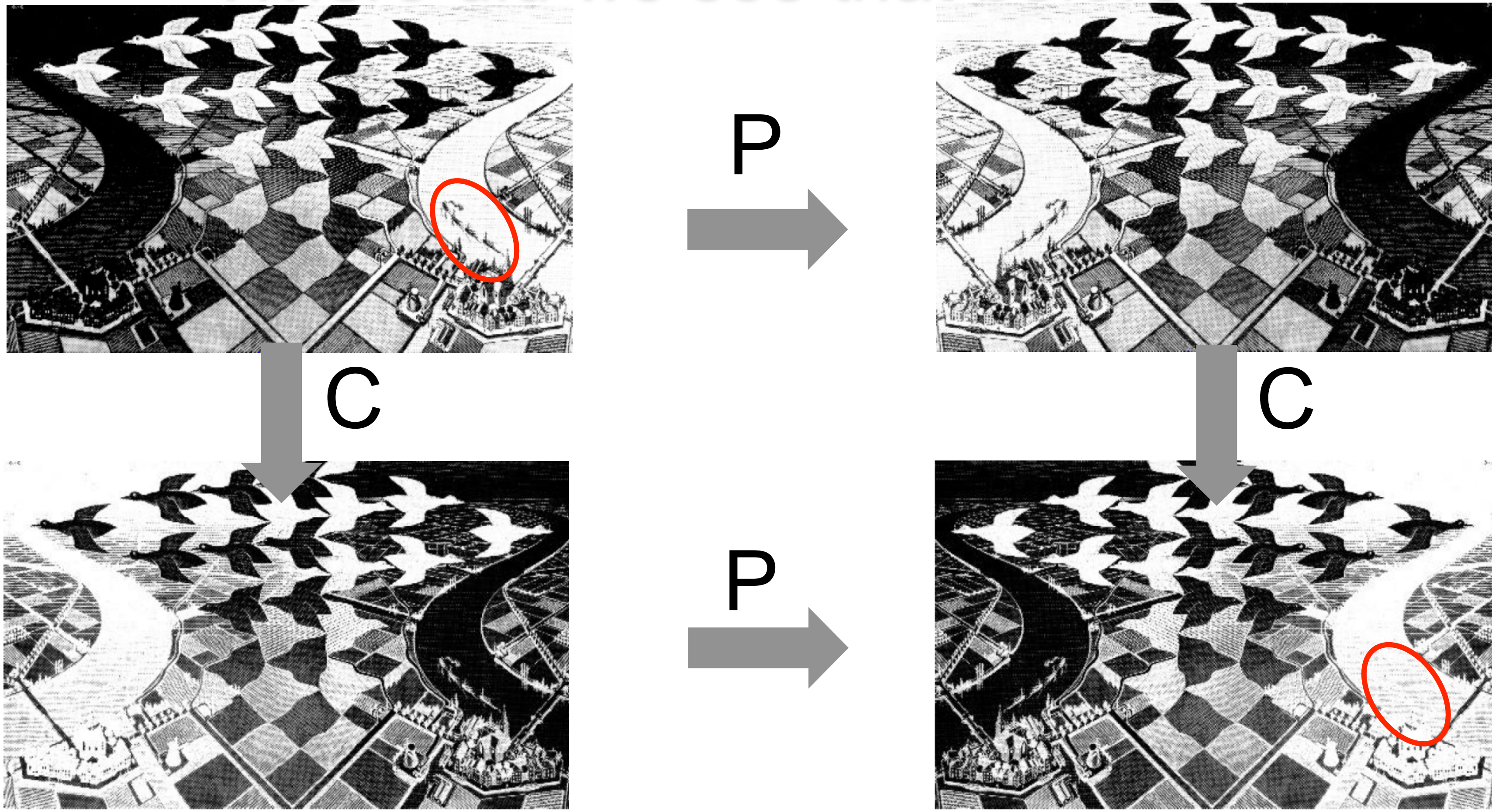
C, P and CP in weak interactions



The weak interaction violates C and P maximally.
But CP was thought to be a good symmetry, until 1964 when it was experimentally found to be broken.

Where did we see that before?

Color ↓ anti-color



Left → right

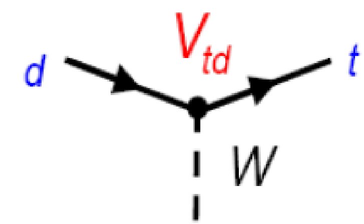
Escher's (Dutch artist) impression of C, P and CP violation.

Where is the CP violation?

CP violation in the weak interaction

Quarks

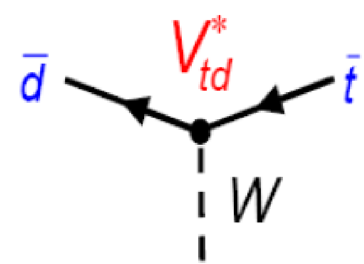
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



CP

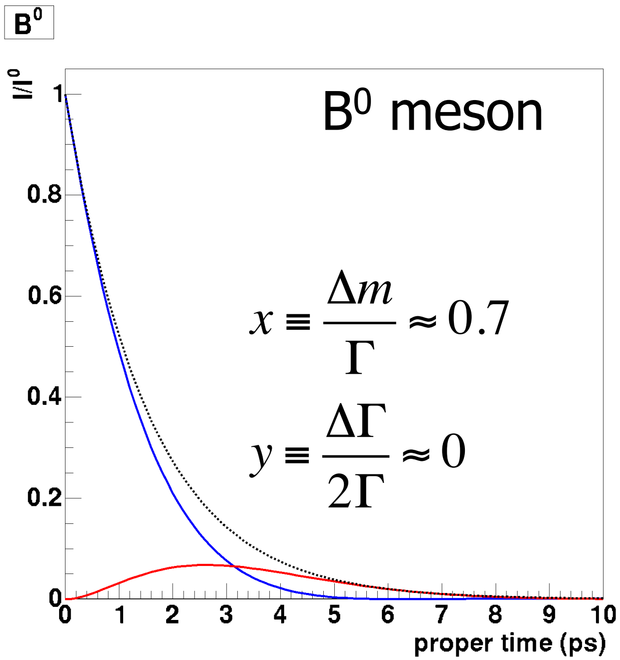
Anti-quarks:

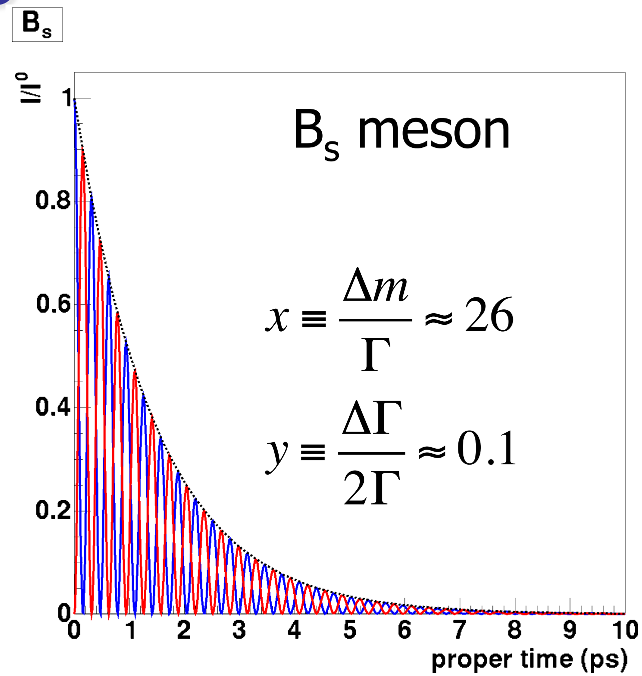
$$\begin{pmatrix} \bar{d}' \\ \bar{s}' \\ \bar{b}' \end{pmatrix} = \begin{pmatrix} V^*_{ud} & V^*_{us} & V^*_{ub} \\ V^*_{cd} & V^*_{cs} & V^*_{cb} \\ V^*_{td} & V^*_{ts} & V^*_{tb} \end{pmatrix} \begin{pmatrix} \bar{d} \\ \bar{s} \\ \bar{b} \end{pmatrix}$$



CP violation requires complex matrix elements.

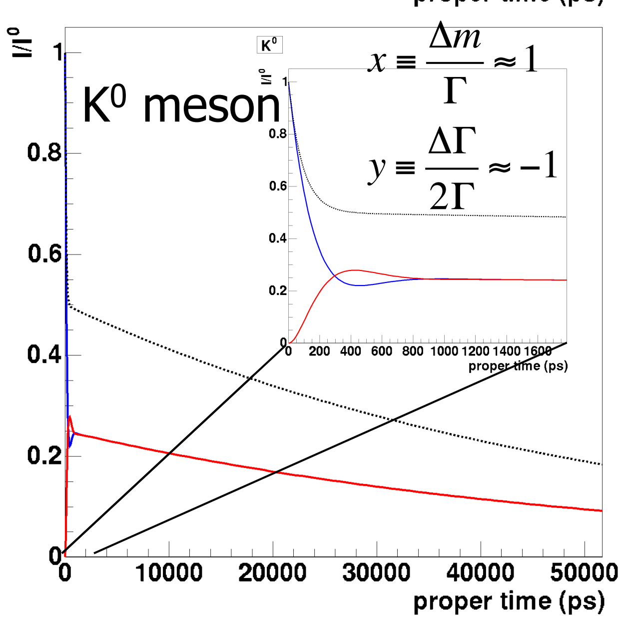
Mixing of neutral mesons

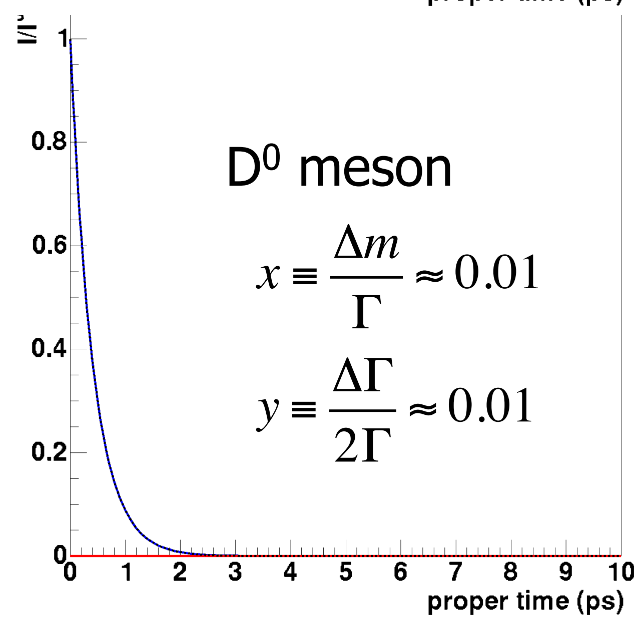




The 4 different neutral meson systems have very different mixing properties.

B_s system: very fast mixing





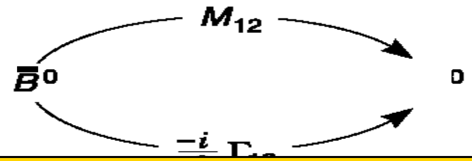
Kaon system: large decay time difference.

Charm system: very slow mixing

Overview: Types of CP violation

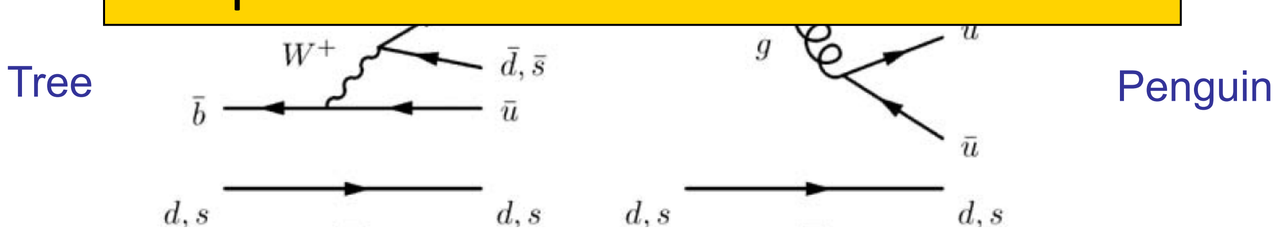
- Three types of CP violation (always two amplitudes!):

1. CP violation in mixing ("indirect" CP violation): $\left|\frac{q}{p}\right| \neq 1$

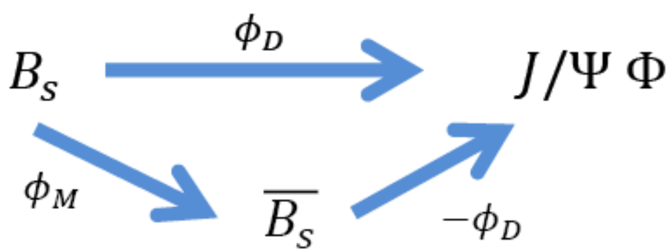


2. CP violat $\left|\bar{A}_{\bar{f}}\right|$

Note that in the SM all these effects are caused by a single complex parameter δ in the CKM matrix!

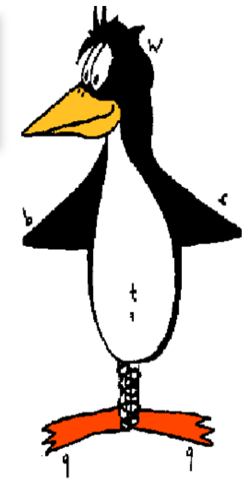


3. CP violation in the interference: $\arg\lambda_f + \arg\lambda_{\bar{f}} \neq 0$



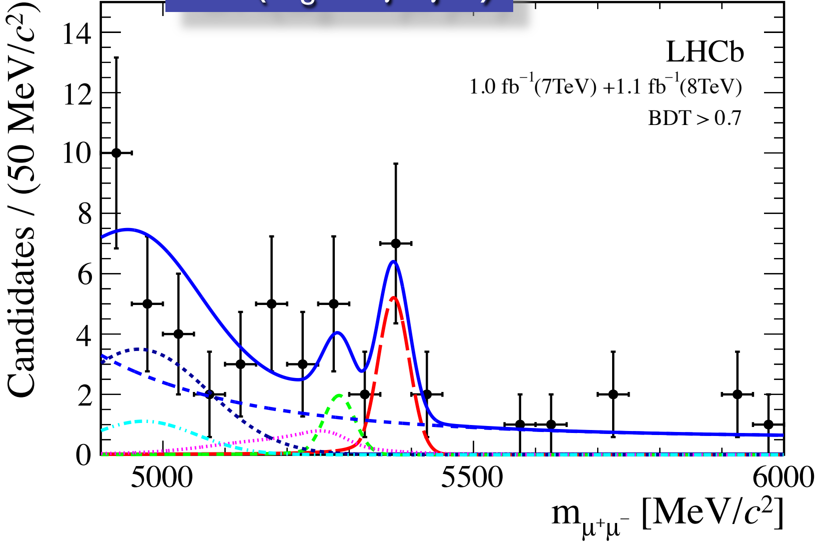
FCNC penguin decays

In FCNC decays new particles can enter *at same level* as SM particles.
→ Sensitive probes for new physics.

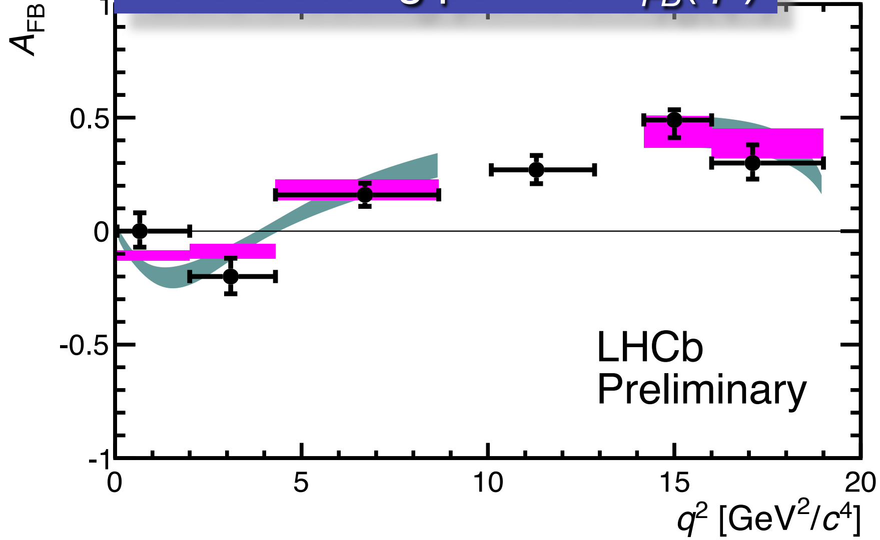


Two examples of quantities which can be well-predicted in SM:

BR($B_s \to \mu^+\mu^-$)



Zero crossing point of $A_{FB}(q^2)$



It's all about imaginary numbers

Conclusion

LHCb has just collected 3.2 fb^{-1} of data.
Waiting for you to be analysed!