Recent results from rare decays

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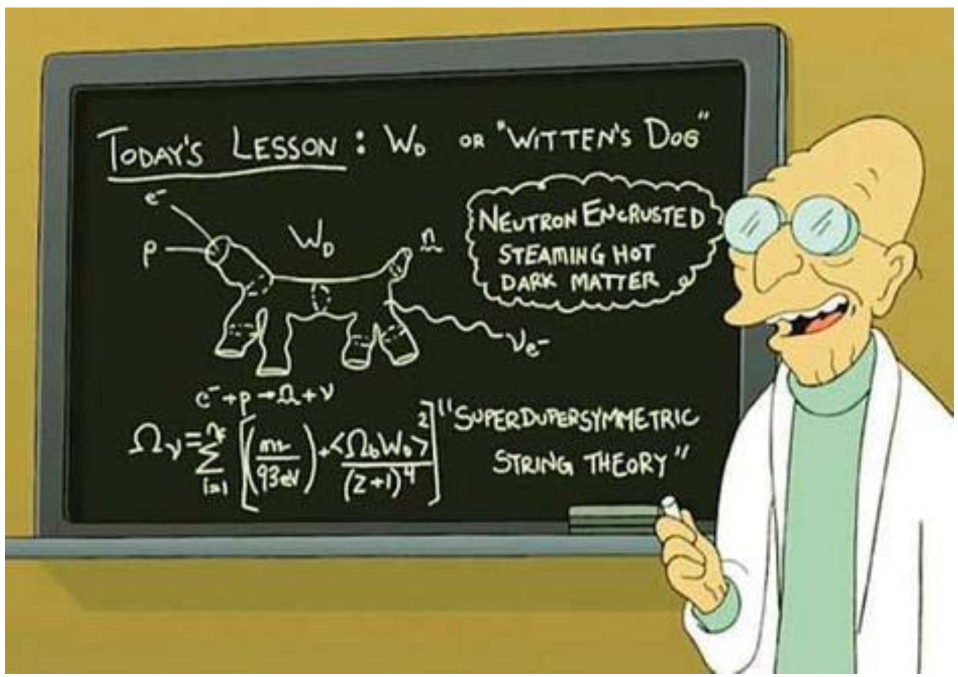


Don’t worry about the number of slides:
Only half of them is “new”

Recap of last week

<u>What we have learned last week:</u>

- 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
        - 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(2β_s)
    - Measured value: ϕ_s=-0.03 ± 0.16(stat) ± 0.07 (sys)
    - SM value: ϕ_s=-0.036
    - 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

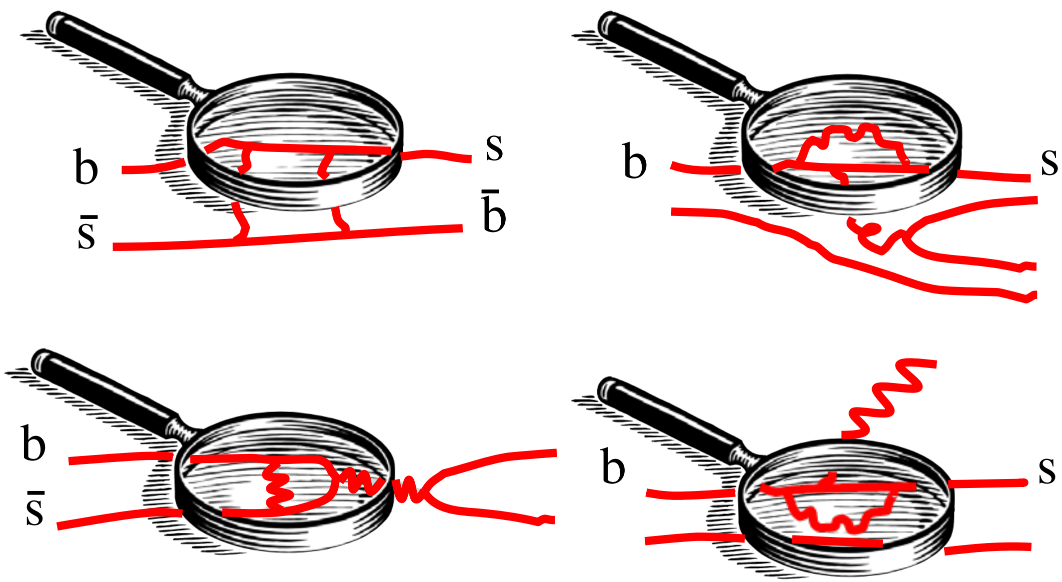
→ CP violation and rare decays of *B* and *D* hadrons are the main focus of LHCb.

Today: Rare decays

Introduction to rare decays

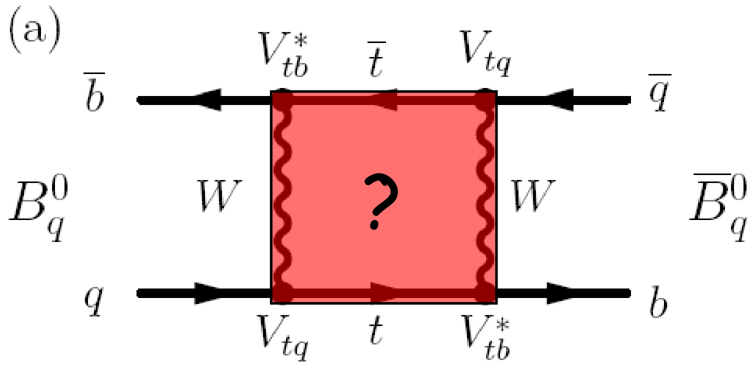
- Flavour changing neutral currents (FCNC) forbidden in SM at tree level.
  - Suppressed at higher order due to GIM mechanism
- FCNC decays good testing ground for SM.
  - Corresponding decays are always rare (B-mesons < 10^{-5})
- New particles can appear as virtual particles in box and penguin diagrams.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

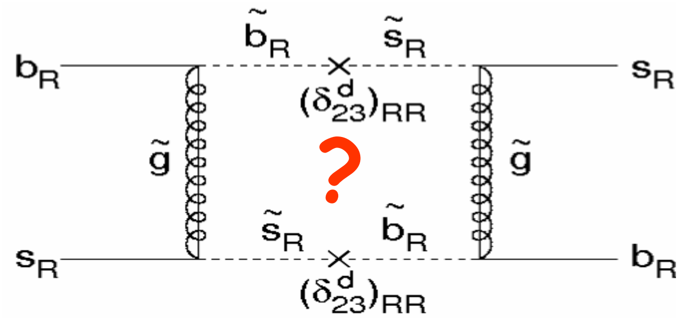
  ($B_s \to \phi\,\gamma$, $B_{d,s} \to \mu^+\mu^-$, $B_d \to K^*\mu^+\mu^-$) → Penguin diagrams



Example: Box diagrams (recap)

New particles could enter in the B_s box diagram





Could affect both amplitude and phase:

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

$\phi_s = \phi_s^{SM} + \phi_s^{NP}$

LHCb's measurements:

Preliminary

Δm_s=17.725 ± 0.041(stat) ± 0.025 (sys) ps^{-1}

SM: Δm_s=17.3 ± 2.6 ps^{-1}

ϕ_s = -0.03 ± 0.16(stat) ± 0.07 (sys)

SM: ϕ_s = -0.036 ± 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):

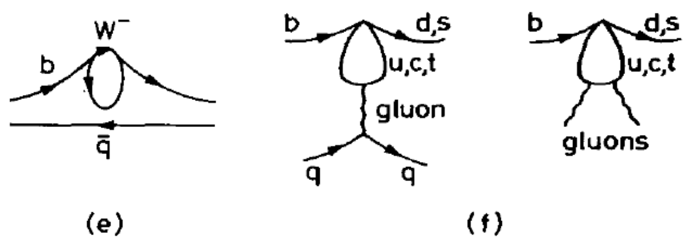
> Mary K. [Gaillard], Dimitri [Nanopoulos] and I first got interested in what are now called penguin diagrams while we were studying CP violation in the Standard Model in 1976... The penguin name came in 1977, as follows.
>
> In the spring of 1977, Mike Chanowitz, Mary K and I wrote a paper on GUTs predicting 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

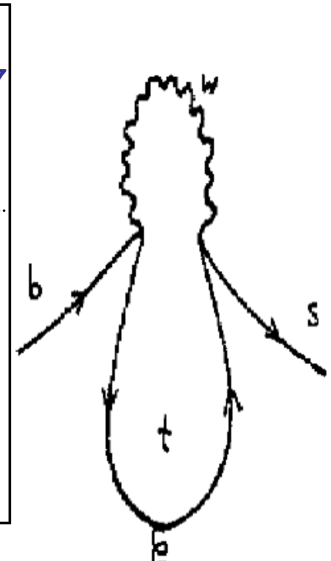
Nucl. Phys. B131:285 1977

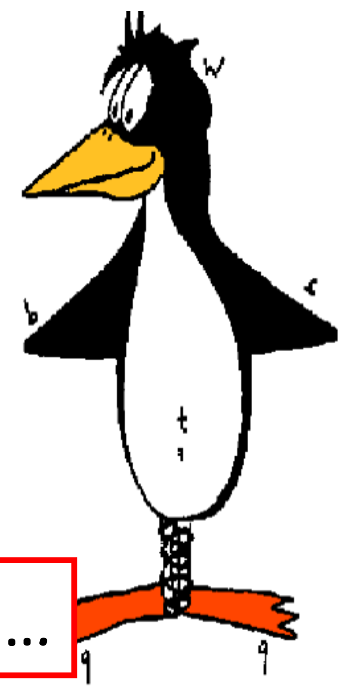
J. Ellis, M.K. Gaillard *), D.V. Nanopoulos +) and S. Rudaz ")

CERN - Geneva



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





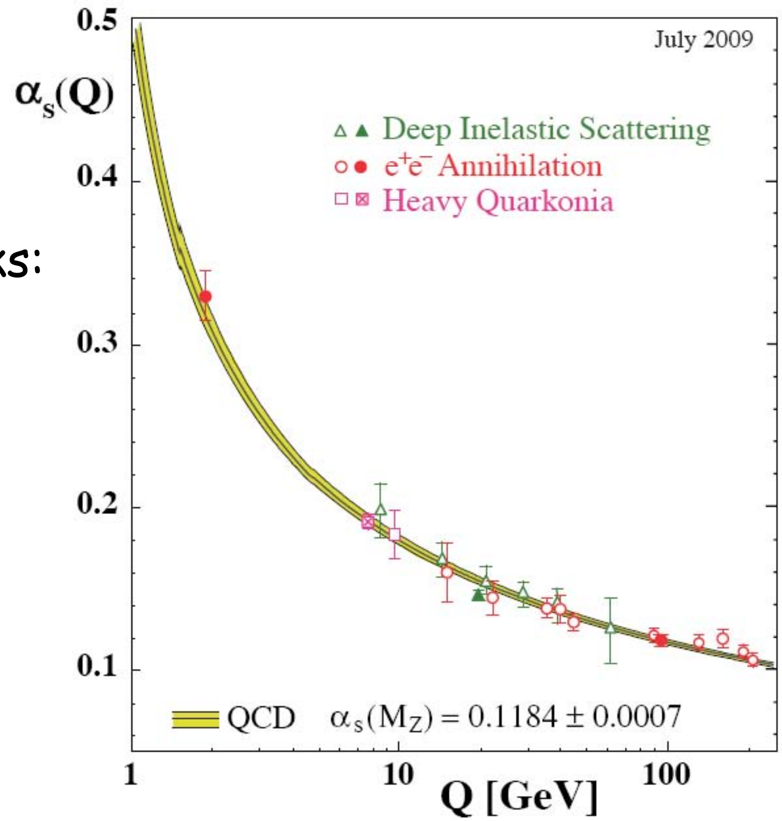
Don't try to beat Melissa Franklin at darts...

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 for the individual quarks, so what is the problem?

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



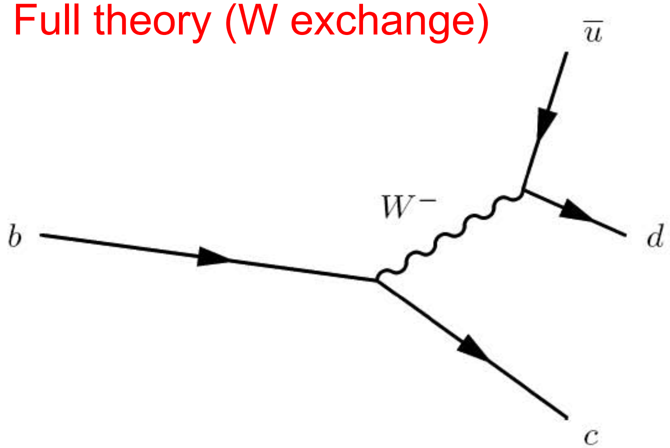
→ cannot use perturbation theory to calculate the (soft) QCD effects (hadronic effects)

OPE

Theoretical approach: Operator Product Expansion + renormalization group equations

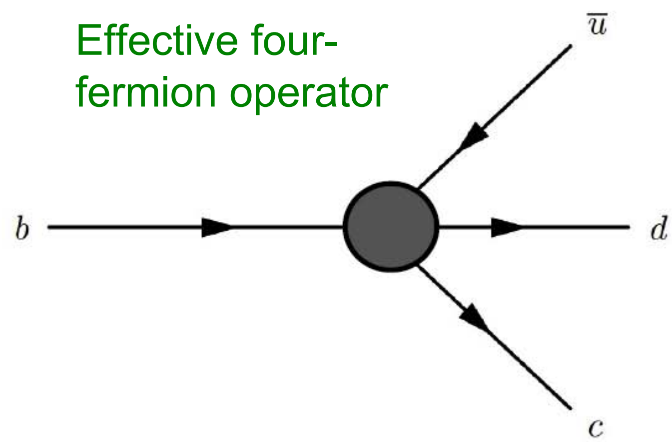
Basic idea:
Energy scale of weak decays is low compared to mass of W (propagator).
→ Absorb W exchange in effective Fermi theory (expansion of W propagator)

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)

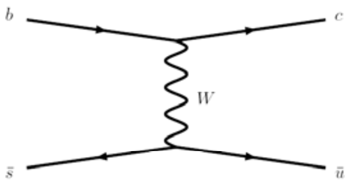
Energy scales:

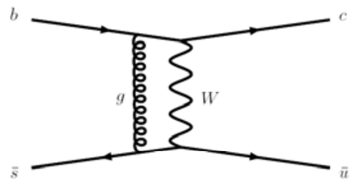
New physics	:	$\delta x \sim 1/\Lambda_{\mathrm{NP}}$
Electroweak interactions	:	$\delta x \sim 1/M_W$
Short-distance QCD(QED) corrections	:	$\delta x \sim 1/M_W \rightarrow 1/m_b$
Hadronic effects	:	$\delta x < 1/m_b$

} Wilson coefficients (New physics, Electroweak interactions, Short-distance QCD(QED) corrections)

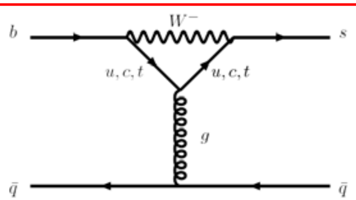
→ Operators (Hadronic effects):
decay constants, form factors
(large theory uncertainties)

Ordering the diagrams

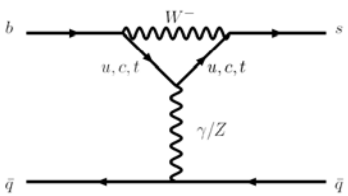


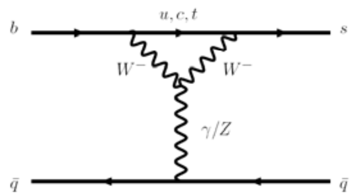


Current-current operators: Q_1, Q_2

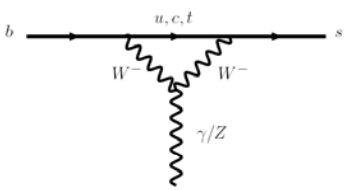


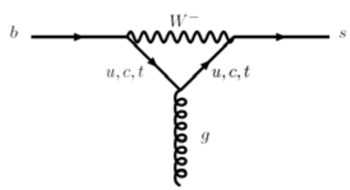
QCD penguins: Q_3, Q_4, Q_5, Q_6 small



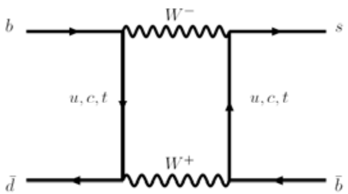


Electroweak penguins: Q_7, Q_8, Q_9, Q_{10}



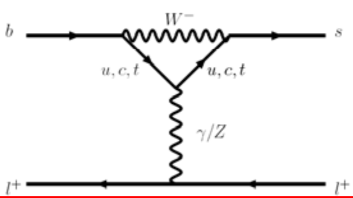


Electro/Chromo-magnetic penguins: Q_7^{γ}, Q_8^{g}



Box operators: $Q_{\Delta S=2}$, $Q_{\Delta B=2}$

FCNC operators



Semi-leptonic operators: Q_{9V}, Q_{10A}

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%)	$(5.7\pm2.0)\text{x}10^{-5}$	γ polarisation
$B_d \to K^* \mu^+ \mu^-$	$Q_7{}^\gamma, Q_9, Q_{10}$		$(1.05\pm0.15)\text{x}10^{-6}$	Angular distributions
$B_s \to \mu^+ \mu^-$	Q_{10}	$(3.2\pm0.2)\text{x}10^{-9}$	$< 1.1\text{x}10^{-9}$ (95%)	BR

→ Focus of today

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

Expected BRs

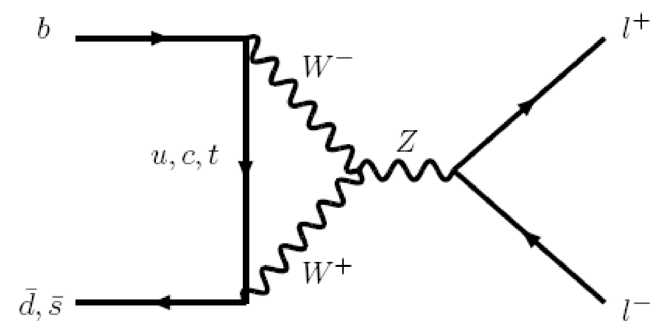
Numbers not up-to-date

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

Increasing BR

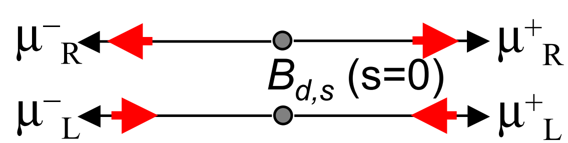
Why are the B_d decays suppressed relative to B_s?

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



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

Decays are helicity suppressed.
Spin of $B_{d,s}$ is zero. One lepton needs helicity flip.



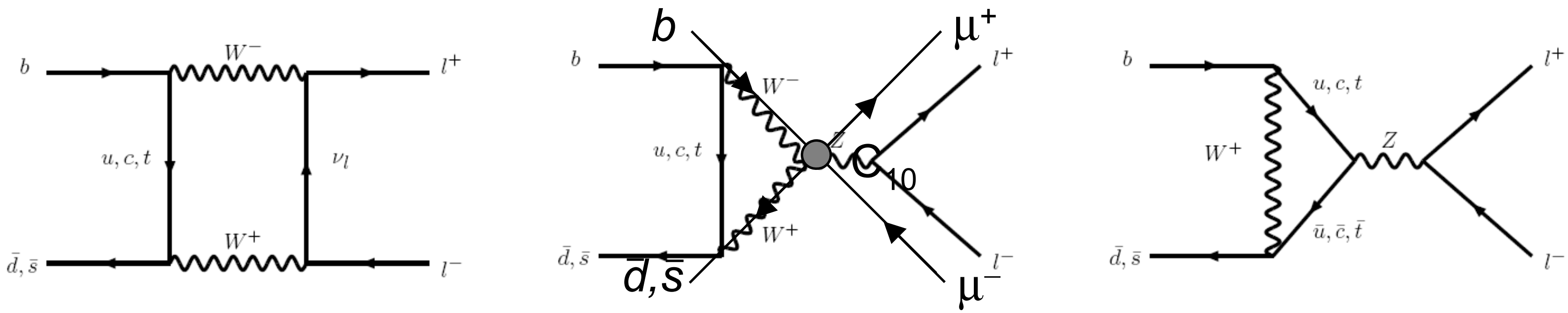
Why is the search for $B_{d,s} \to \mu^+\mu^-$ most popular?

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

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):

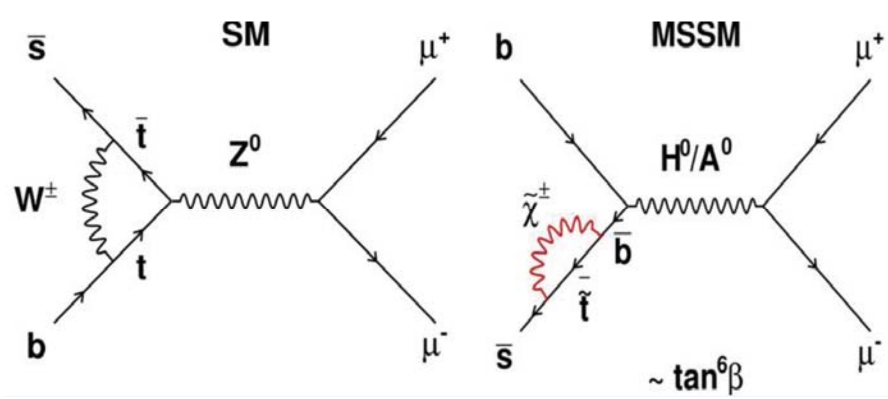


→ New physics could modify Wilson coefficients C_{10}, C_S, C_P (or introduce new operators).

NP example: MSSM

Operators Q_S, Q_P will enhance BR:

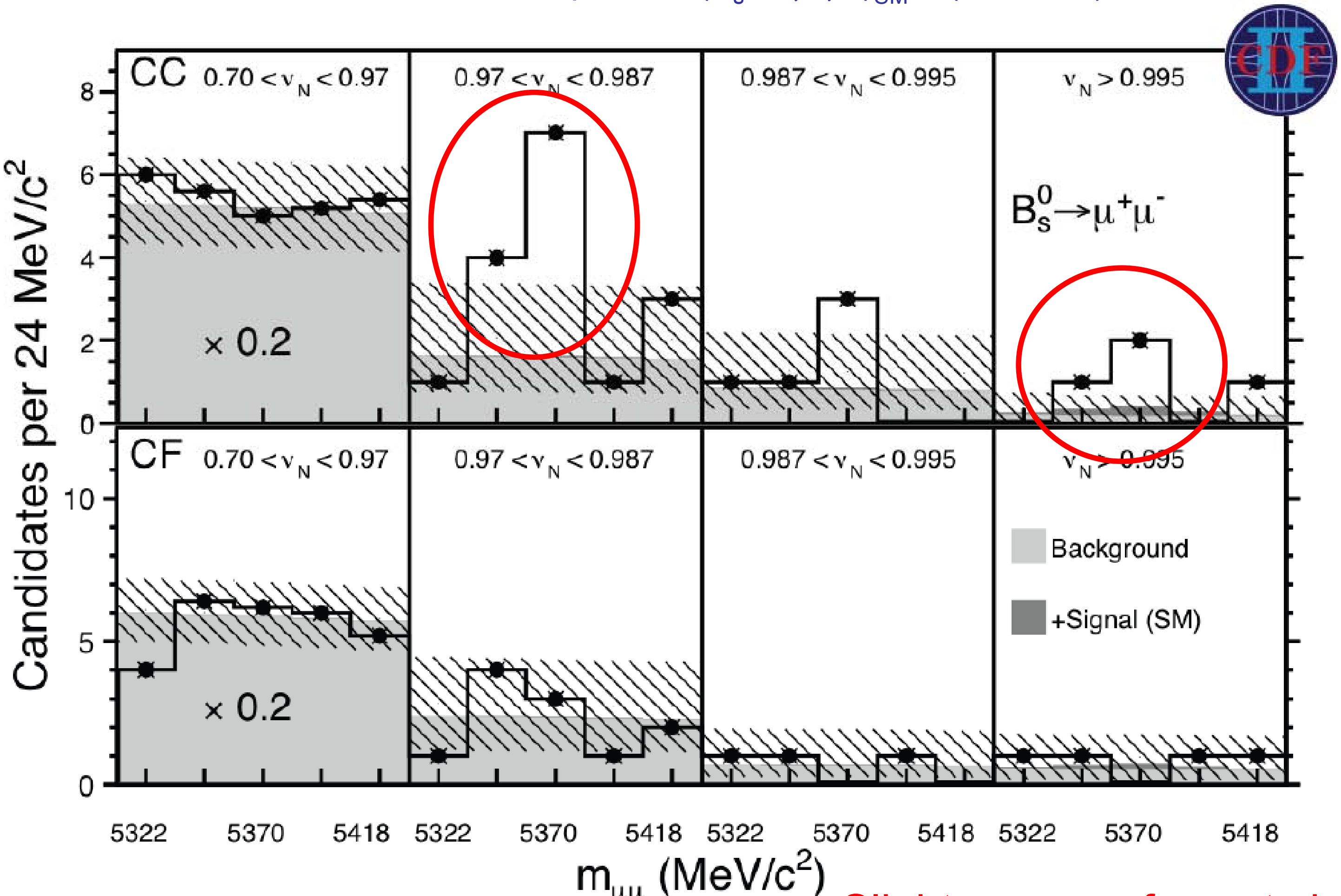
$$\mathrm{BR}(B_{d,s} \to \mu^+\mu^-) \sim \frac{\tan^6\beta}{M_A^4}$$



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

Recent excitement from CDF measurement (2011):
$BR(B_s \to \mu^+\mu^-) = (18^{+11}_{-9})\times10^{-9}$ arXiv:1107.2304

Compare $BR(B_s \to \mu^+\mu^-)_{SM} = (3.2 \pm 0.2)\times10^{-9}$



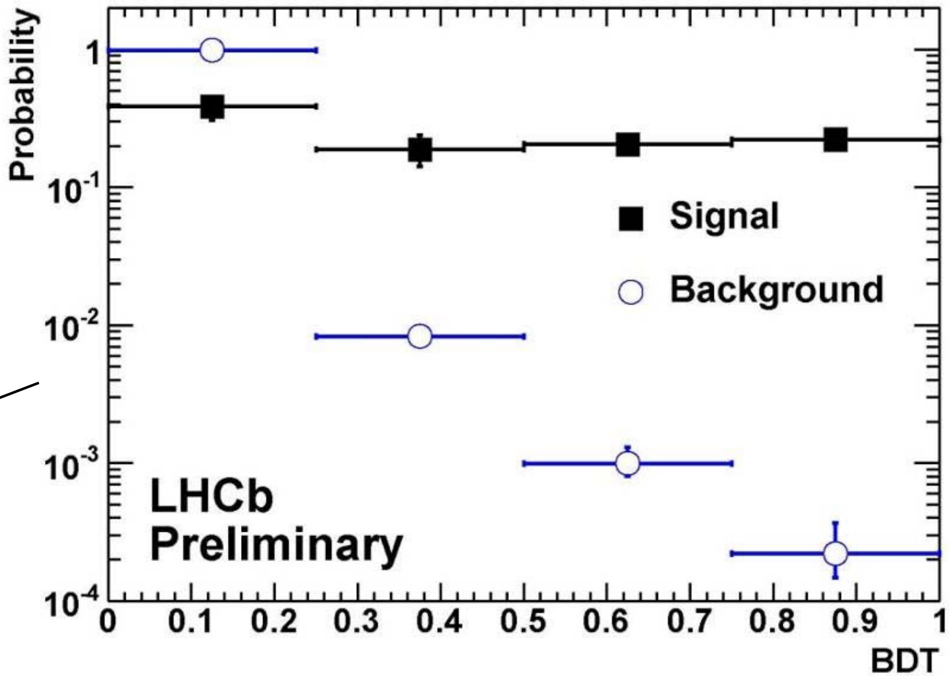
Slight excess of events in two bins

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

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

[LHCb-CONF-2011-037]

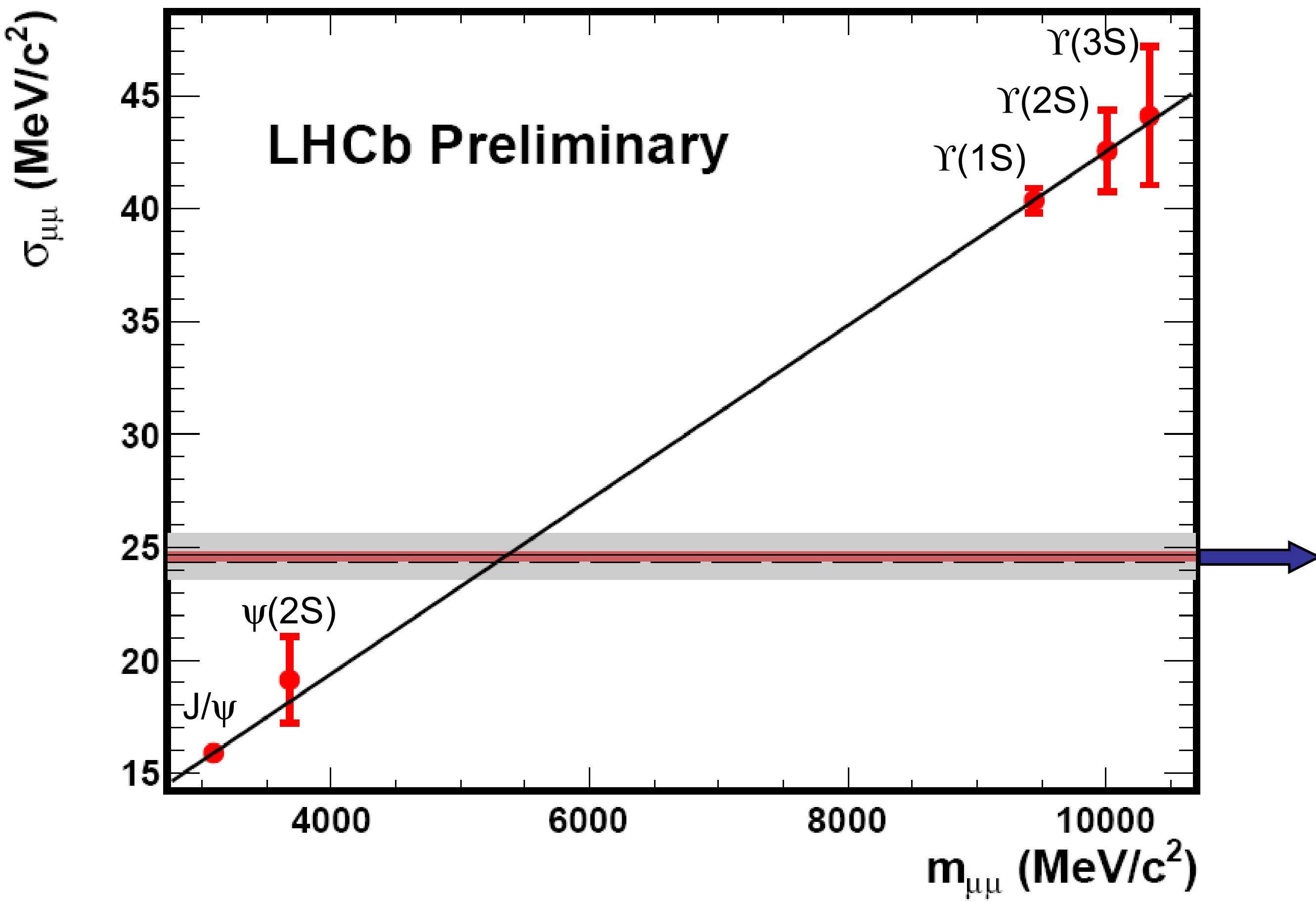


Next: Look at invariant mass spectrum in each of the 4 bins

Least sensitive bin → Most sensitive bin

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

Expected mass resolution obtained from interpolation of dimuon resonances
→ Procedure verified with $B \to hh$ events



$\sigma(B_s) = (24.6 \pm 0.2 \pm 1.0)$ MeV/c²

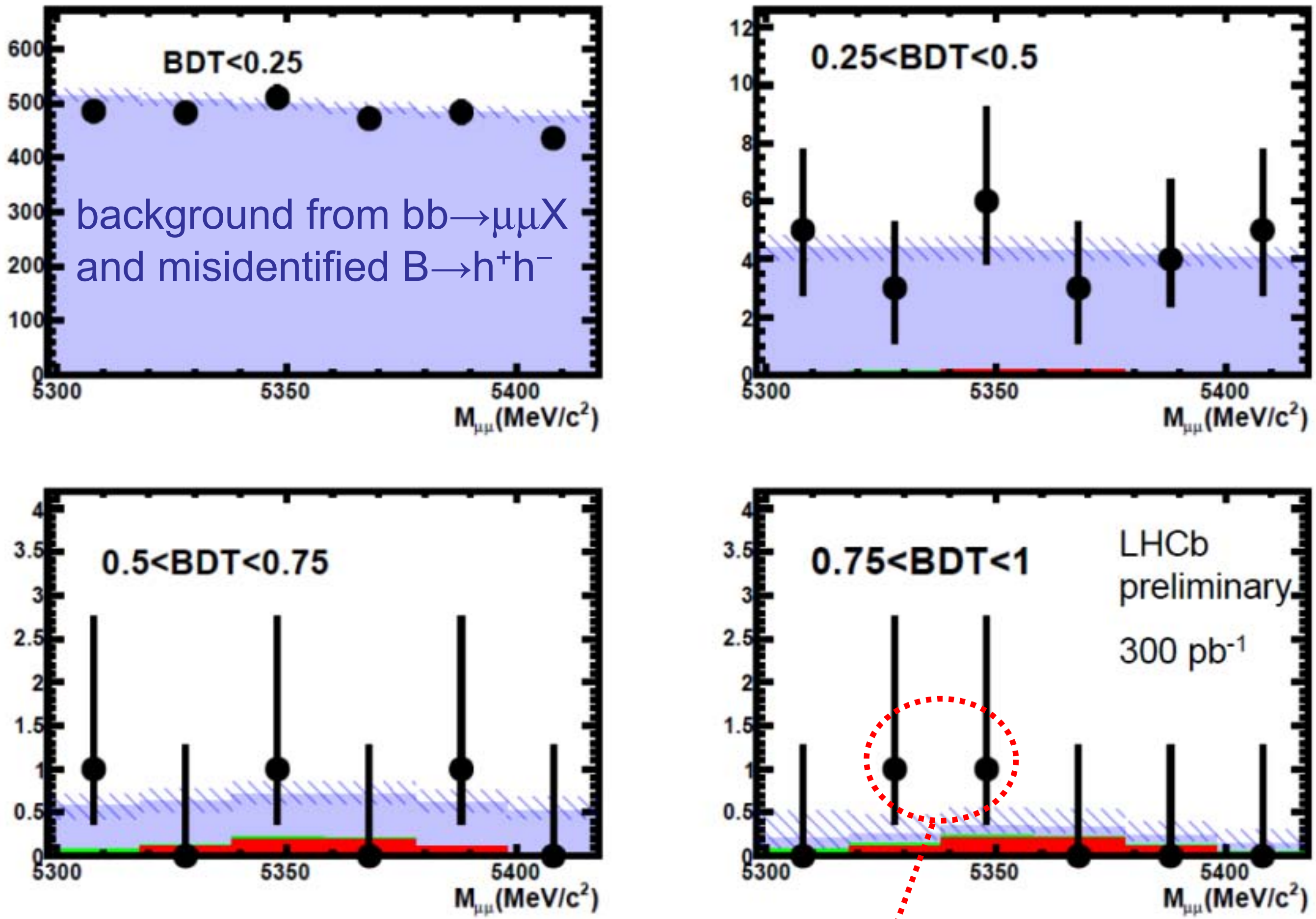
$\sigma(B_d) = (24.3 \pm 0.2 \pm 1.0)$ MeV/c²

[LHCb-CONF-2011-037]

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

$M_{\mu\mu}$ for signal region in 4 bins of BDT

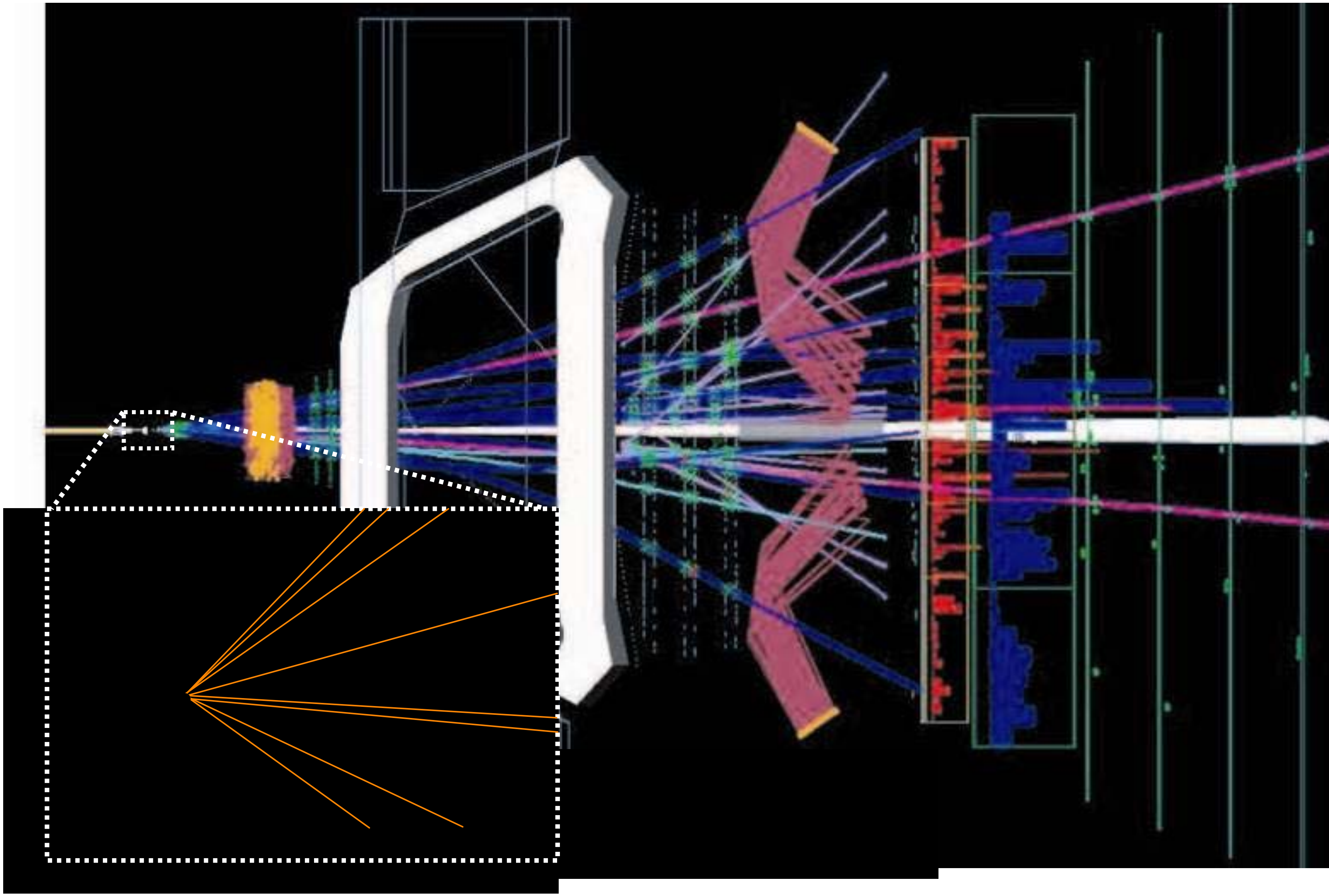
Expect ~ 1 event in each bin from SM.



[LHCb-CONF-2011-037]

Small excess (2 events) in most sensitive bin, compatible with SM.

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



[LHCb-CONF-2011-037]

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

[LHCb-CONF-2011-037]

Normalization

The final branching ratio can be calculated as:

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

Three complementary normalization channels with very different systematics:

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

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

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

	$\mathcal{B}$ $(\times 10^{-5})$	N_{cal}	$\alpha^{cal}_{B_d\to\mu^+\mu^-}$ $(\times 10^{-10})$	$\alpha^{cal}_{B_s\to\mu^+\mu^-}$ $(\times 10^{-9})$
$B^+ \to J/\psi K^+$	6.01 ± 0.21	107358 ± 1759	2.58 ± 0.16	0.966 ± 0.096
$B_s^0 \to J/\psi\phi$	3.4 ± 0.9	5919 ± 84	3.39 ± 0.98	1.27 ± 0.35
$B^0 \to K^+\pi^-$	1.94 ± 0.06	5732 ± 506	2.47 ± 0.57	0.92 ± 0.22

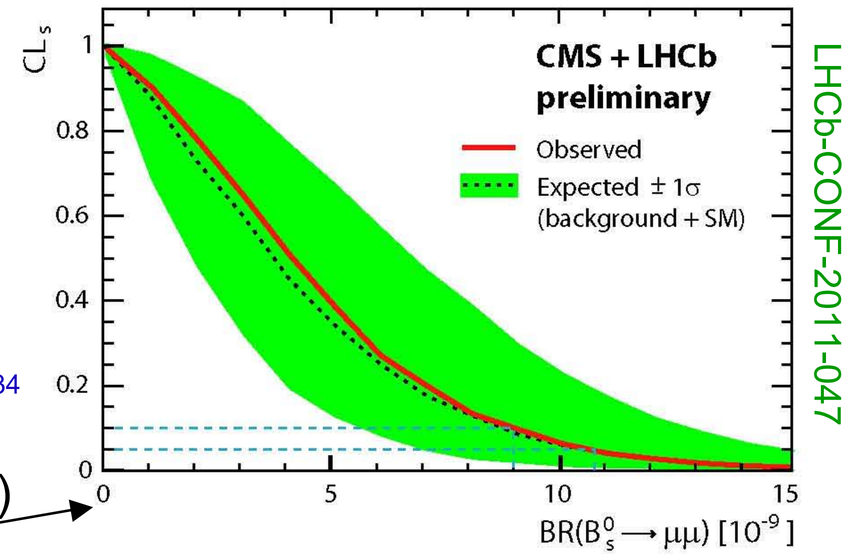
Values for α very compatible

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

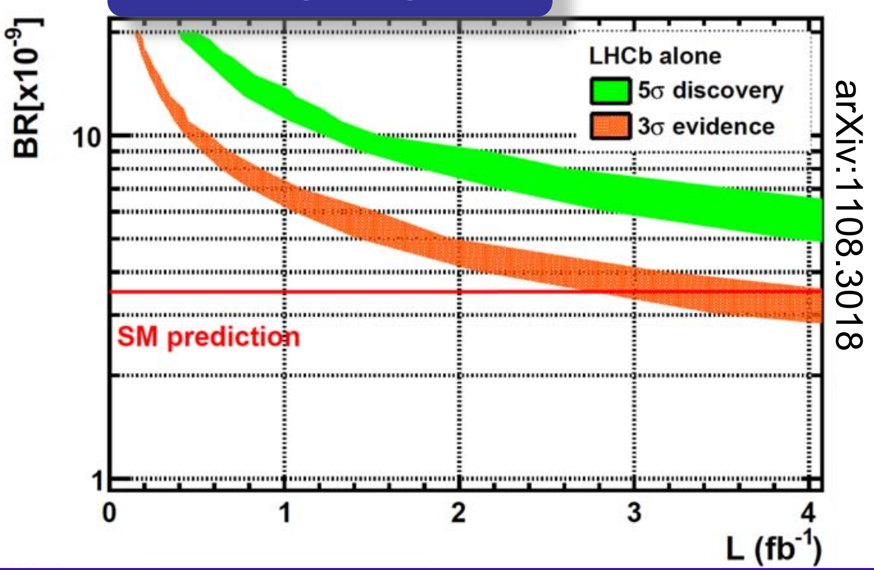
- No significant excess observed in 0.3 fb^{-1}
- Upper limits: arXiv:1112.1600
  - $BR(B_s \to \mu^+\mu^-) < 1.5 \times 10^{-8}$ (95% CL)
  - $BR(B_d \to \mu^+\mu^-) < 5.2 \times 10^{-9}$ (95% CL)

- CMS also set a limit this Summer with 1.1 fb^{-1}
  - $BR(B_s \to \mu^+\mu^-) < 1.9 \times 10^{-8}$ (95% CL) arXiv:1107.5834

- LHCb + CMS analyses combined (preliminary)
  - $BR(B_s \to \mu^+\mu^-) < 1.1 \times 10^{-8}$ (95% CL)
- This is ~ 3.4 × SM value
- Most probable value ~ 4 × 10^{-9}
- Excess over SM not confirmed.



Future prospects

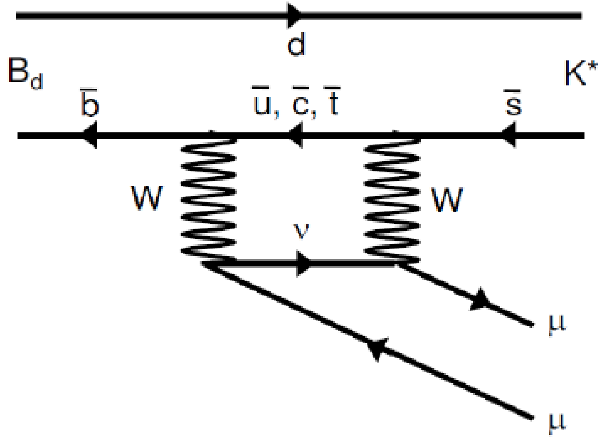


Angular distributions in $B_d \to \mu^+\mu^- K^*$

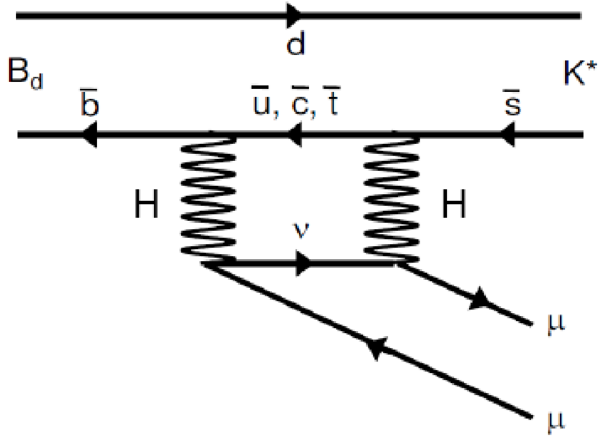
$B_d \to \mu^+\mu^- K^*$ rare decay in the SM.

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

Example of SM diagram:
W exchange



Example of NP diagram:
Charged Higgs exchange



> W± is spin 1 particle, while H± is spin 0.
> → Modifies the angular distributions of the muons.

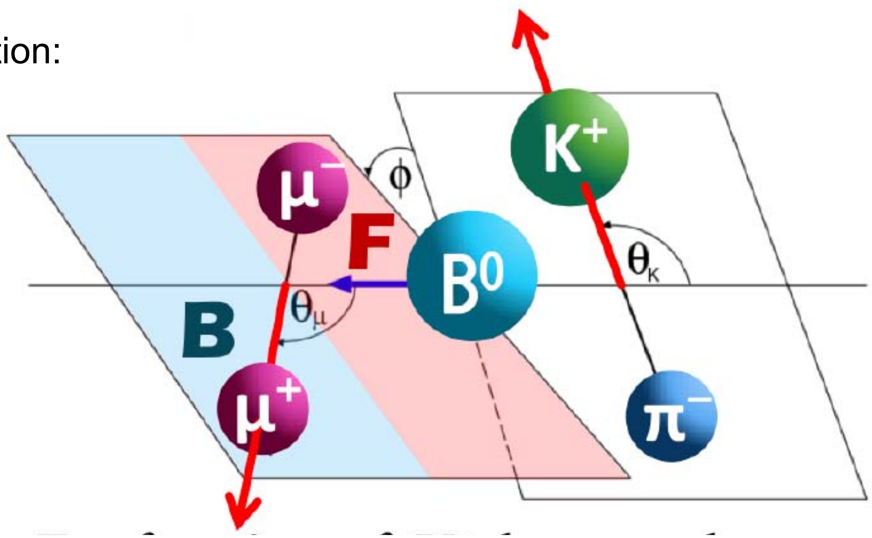
Generally, angular distributions contain a lot of information.

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

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

A_{FB}: μ forward-backward asymmetry

Definition:



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

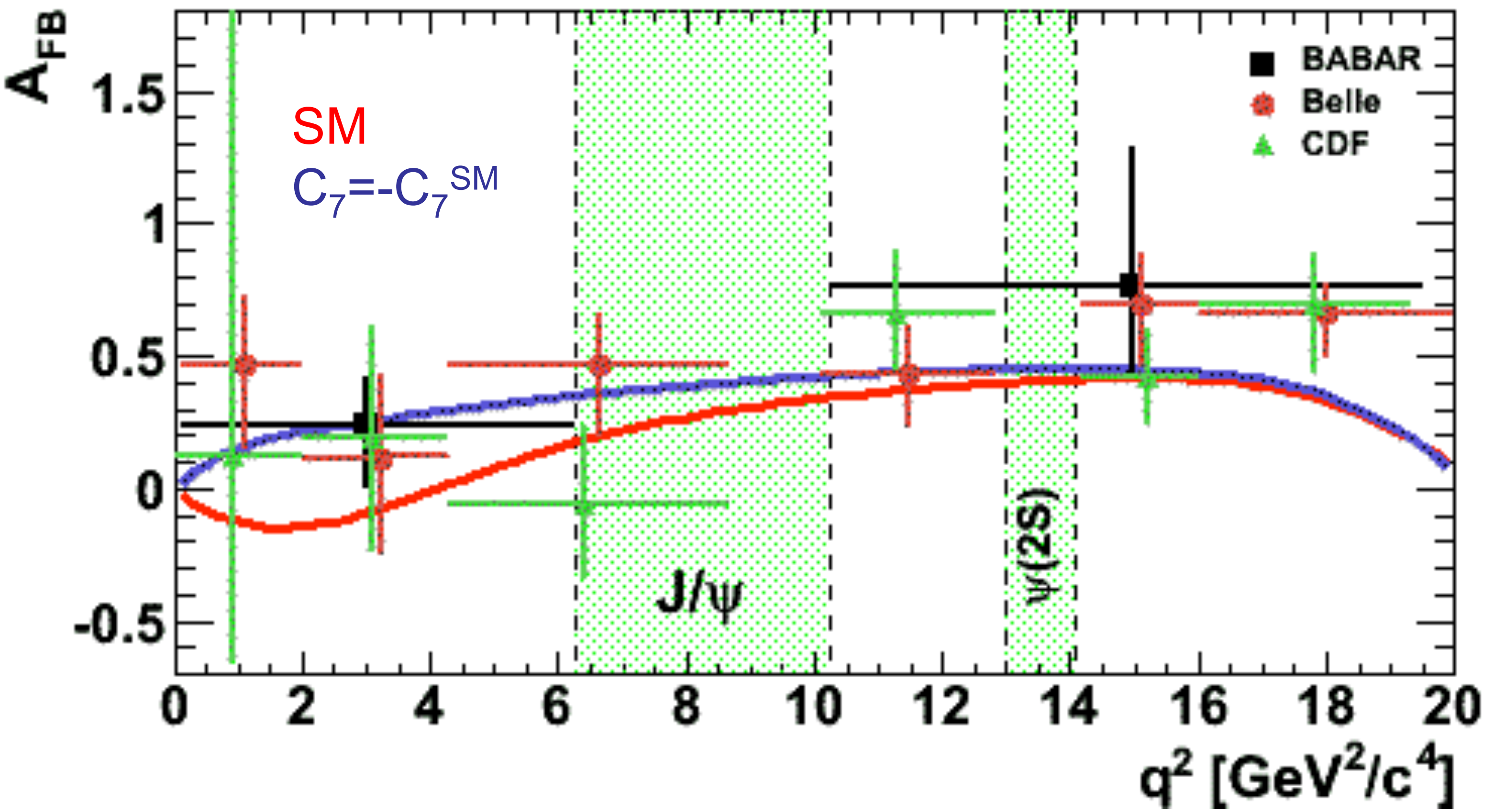
→ Zero crossing point of $A_{FB}(q^2)$ well predicted in SM

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

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

Previous results from CDF & B-factories show intriguing behaviour at low q^2 :
→ however, precision is limited.

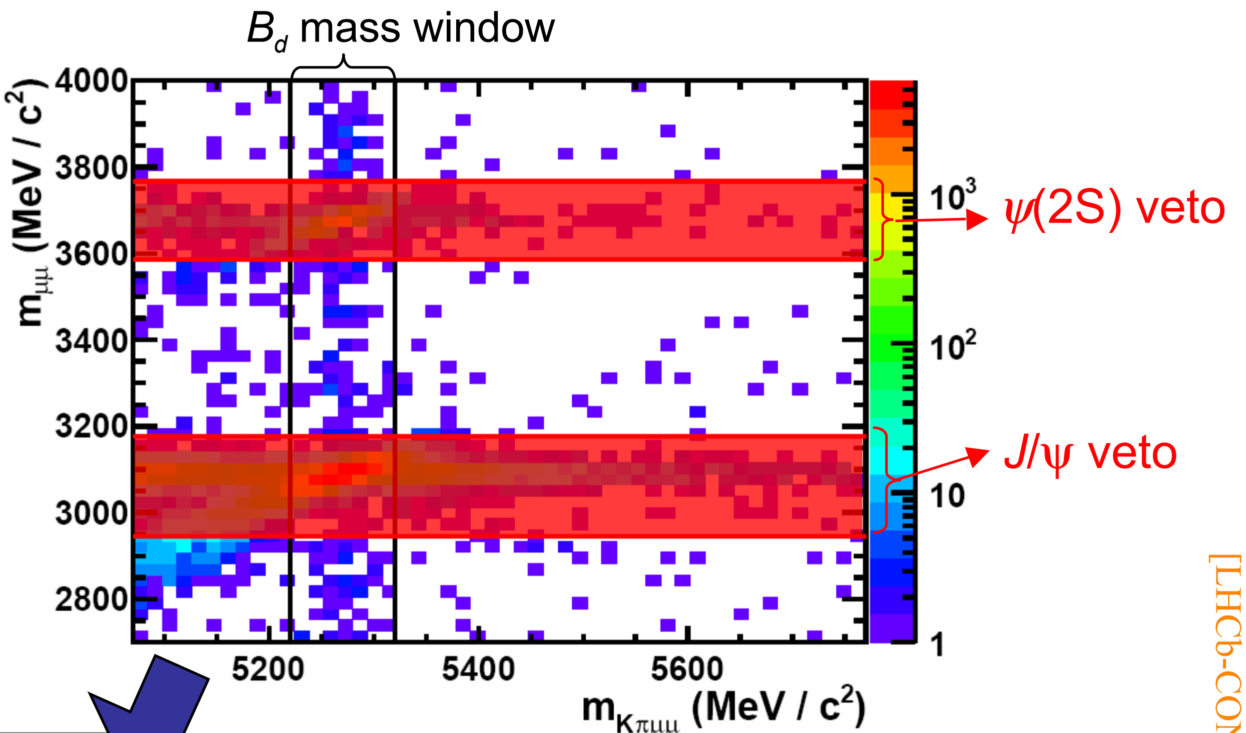
[arXiv:1101.0470]

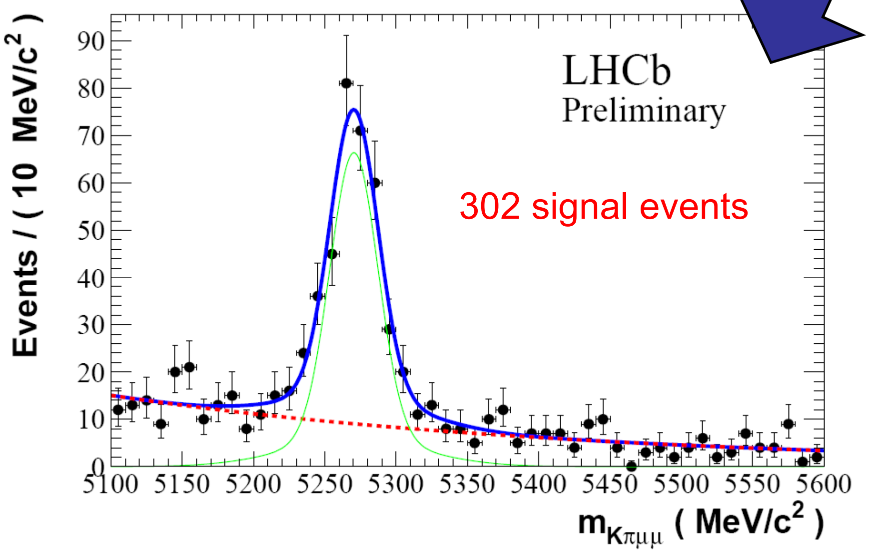


Angular distributions in $B_d \to \mu^+\mu^- K^*$

Event selection

309 pb^{-1} in 2011





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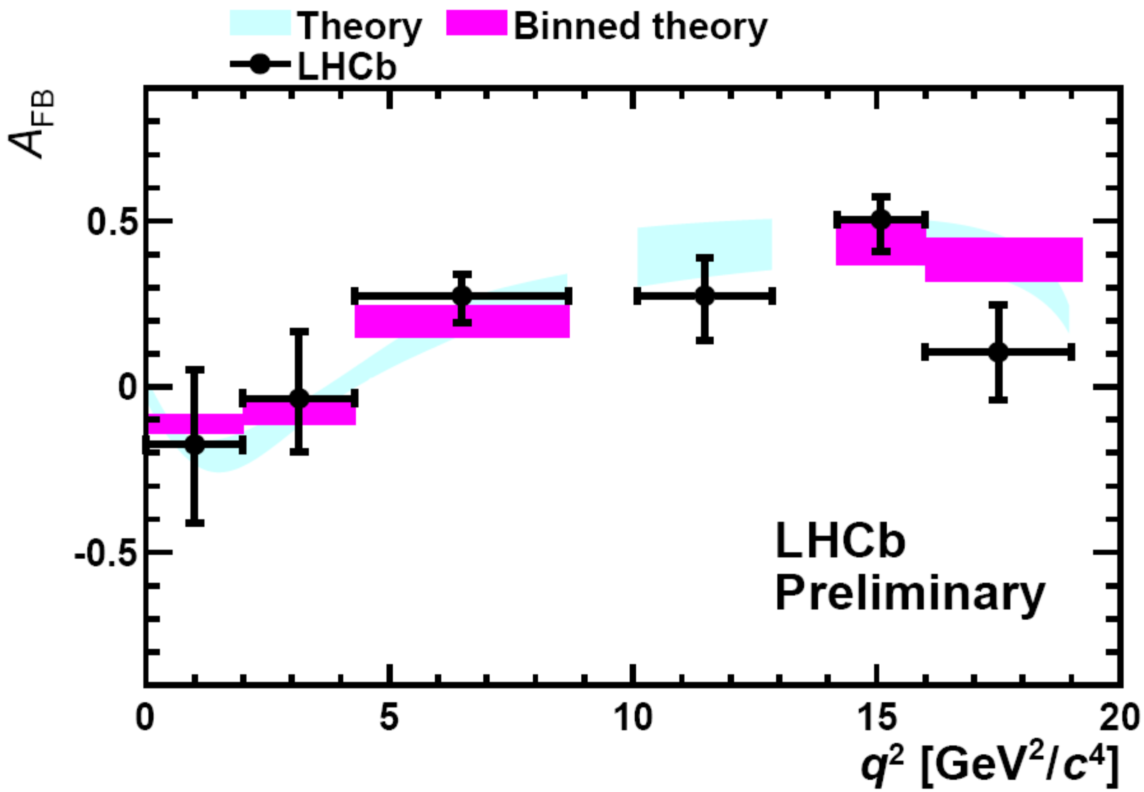
Angular distributions in $B_d \to \mu^+\mu^- K^*$



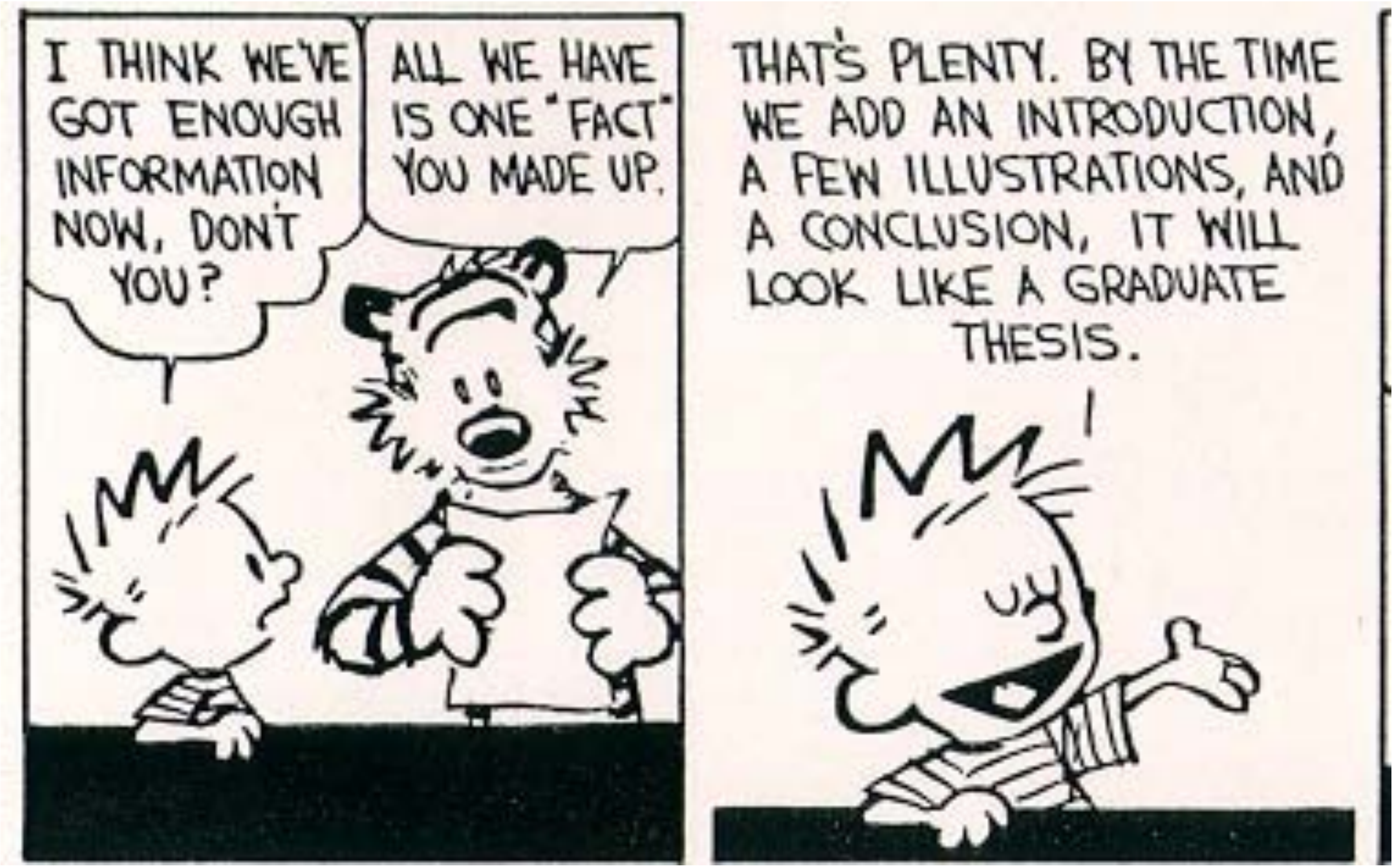
Already effective in constraining NP
arXiv:1111.1257

Data consistent with SM predictions at present sensitivity and indicate that A_{FB} is changing sign as predicted by the SM

(most recent CDF result also has negative first bin: arXiv:1108.0695)

Next steps
- Determine zero-crossing point in $A_{FB}(q^2)$
- Include full 2011 data set.
- With > 2 fb^{-1} do full angular analysis

Cartoon

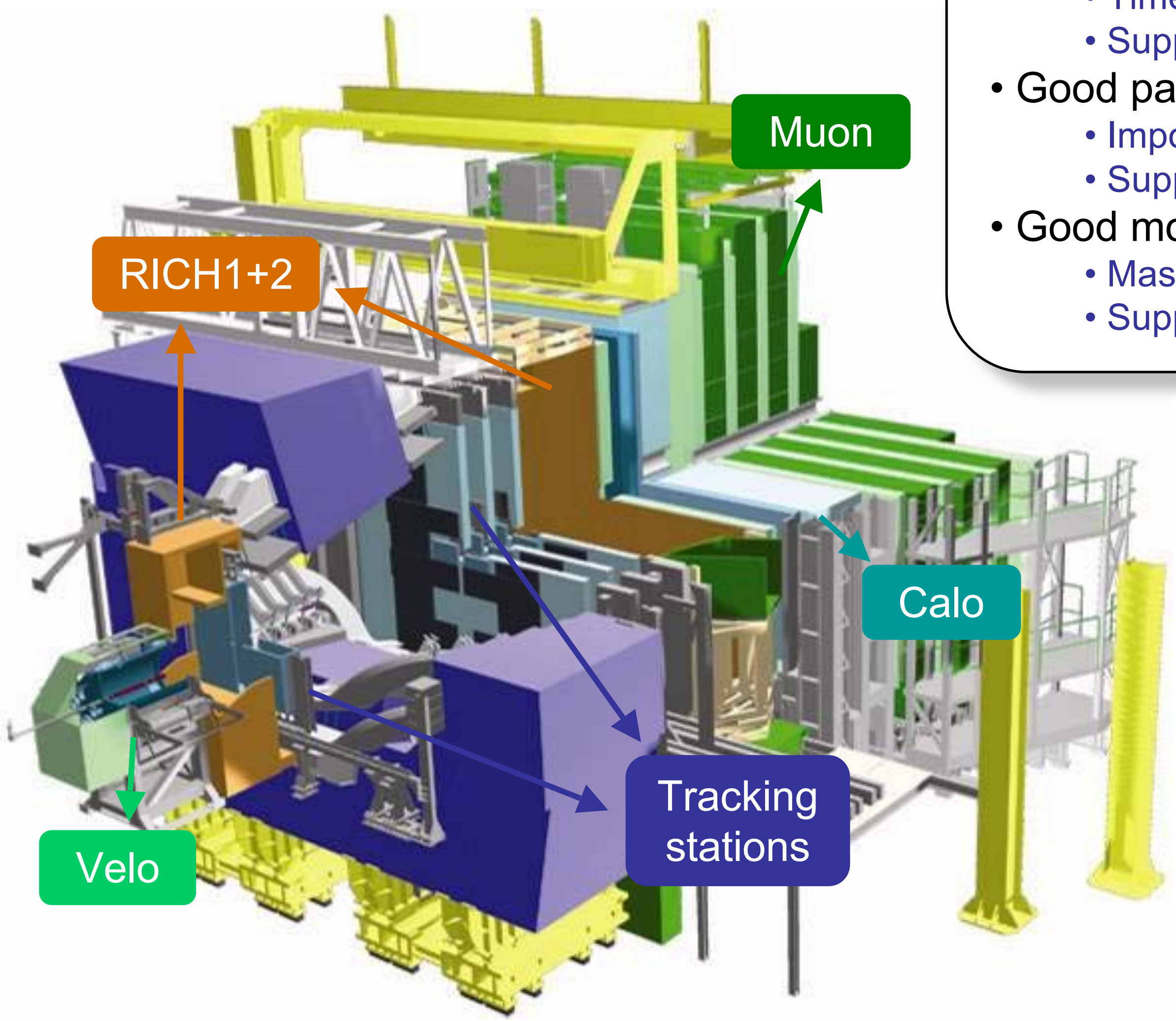


I THINK WE'VE GOT ENOUGH INFORMATION NOW, DON'T YOU?
ALL WE HAVE IS ONE "FACT" YOU MADE UP.
THAT'S PLENTY. BY THE TIME WE ADD AN INTRODUCTION, A FEW ILLUSTRATIONS, AND A CONCLUSION, IT WILL LOOK LIKE A GRADUATE THESIS.

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 $K^0 \to \mu\mu$

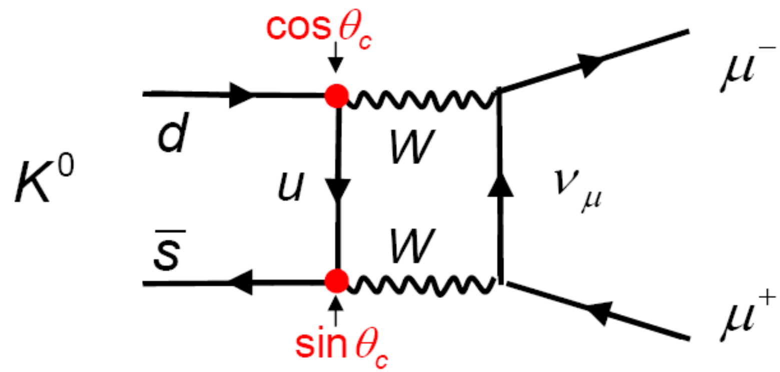
$$\frac{BR(K_L \to \mu^+\mu^-)}{BR(K_L \to all)} = (7.2 \pm 0.5) \cdot 10^{-9}$$

In contradiction with theoretical expectation in the 3-Quark Model

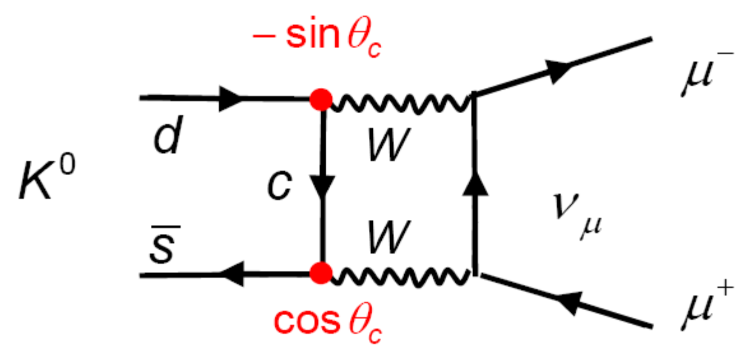
⬇

Glashow, Iliopolus, Maiani (1970):

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

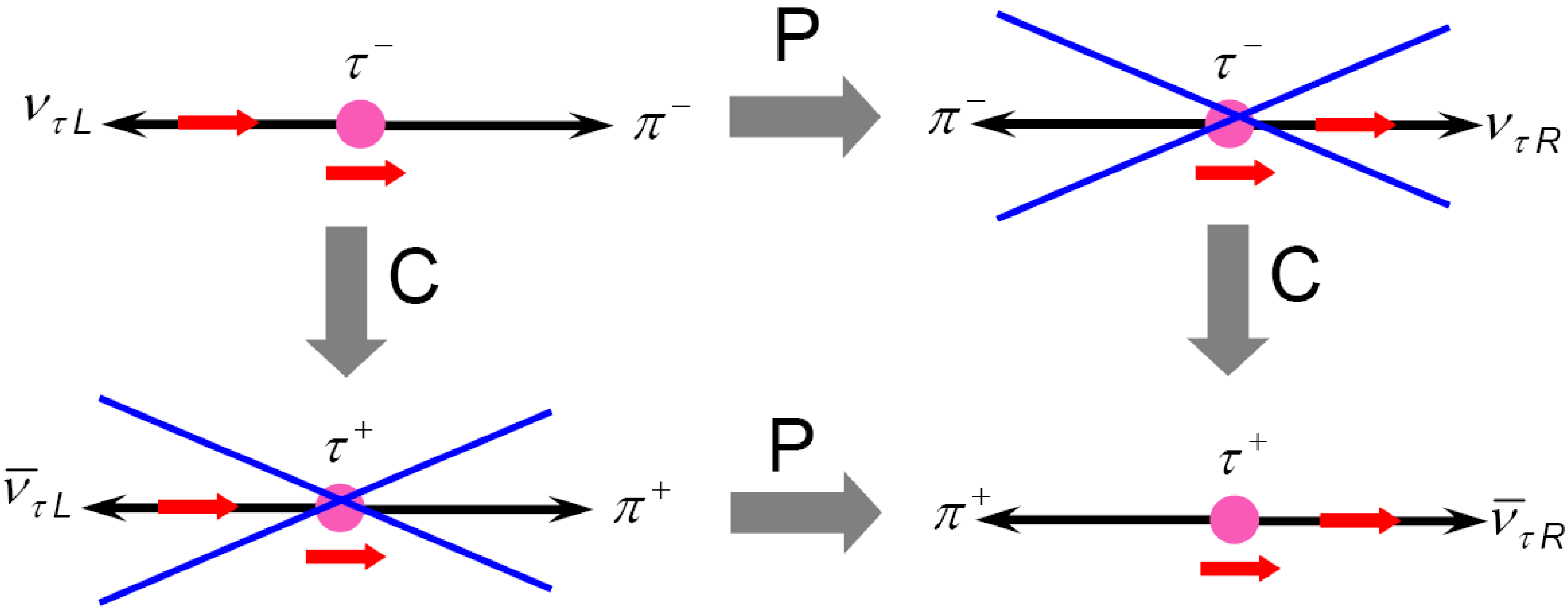


$$M \sim \sin\theta_c \cos\theta_c$$



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

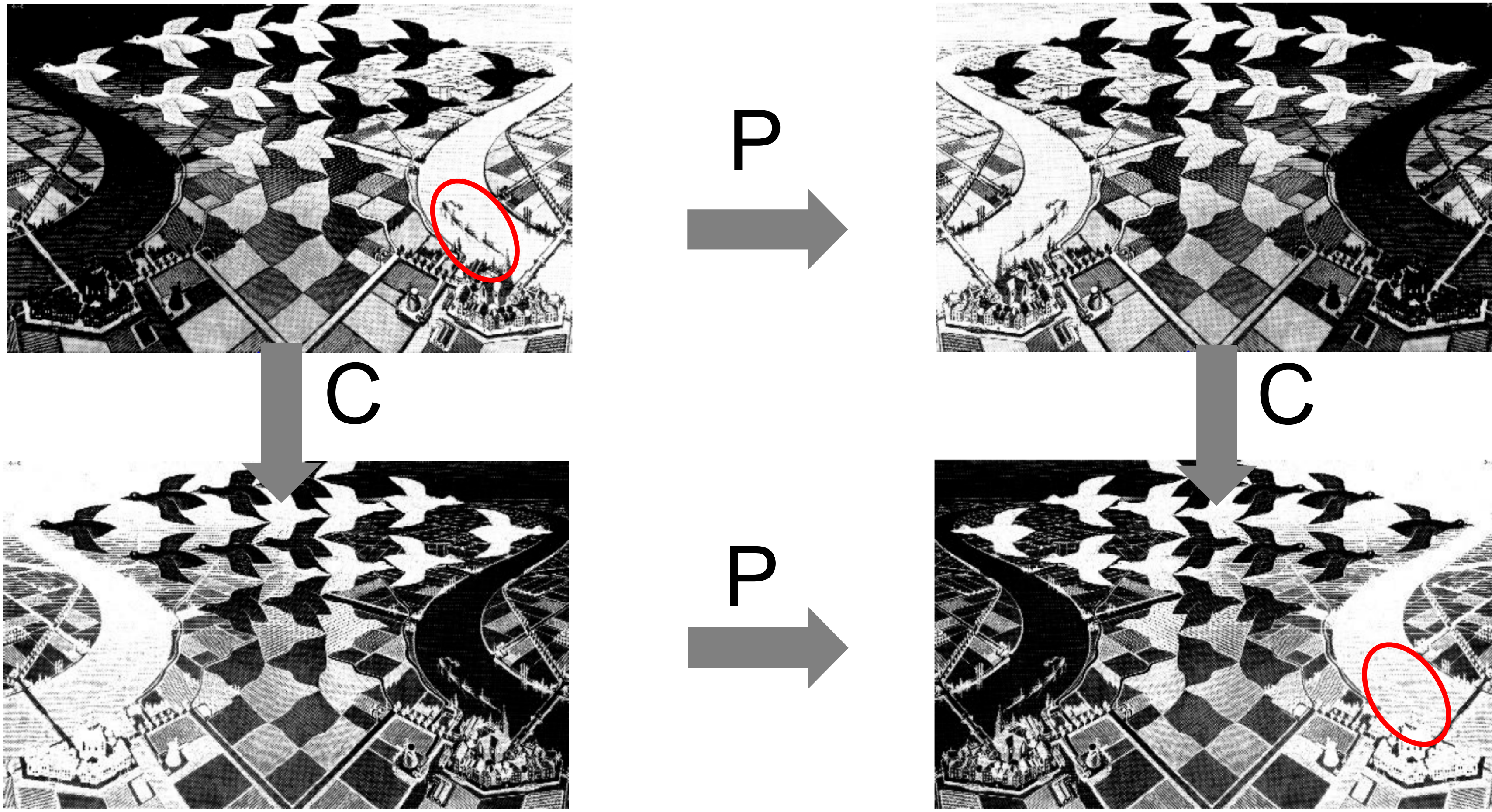
C, P and CP in weak interactions



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

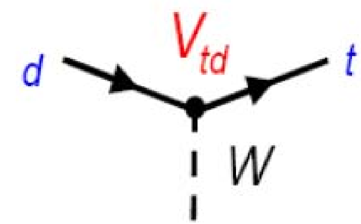
Escher's (Dutch artist) impression of C, P and CP violation.

Where is the CP violation?

CP violation in the weak interaction

Quarks

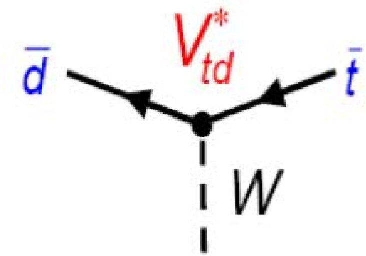
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



CP

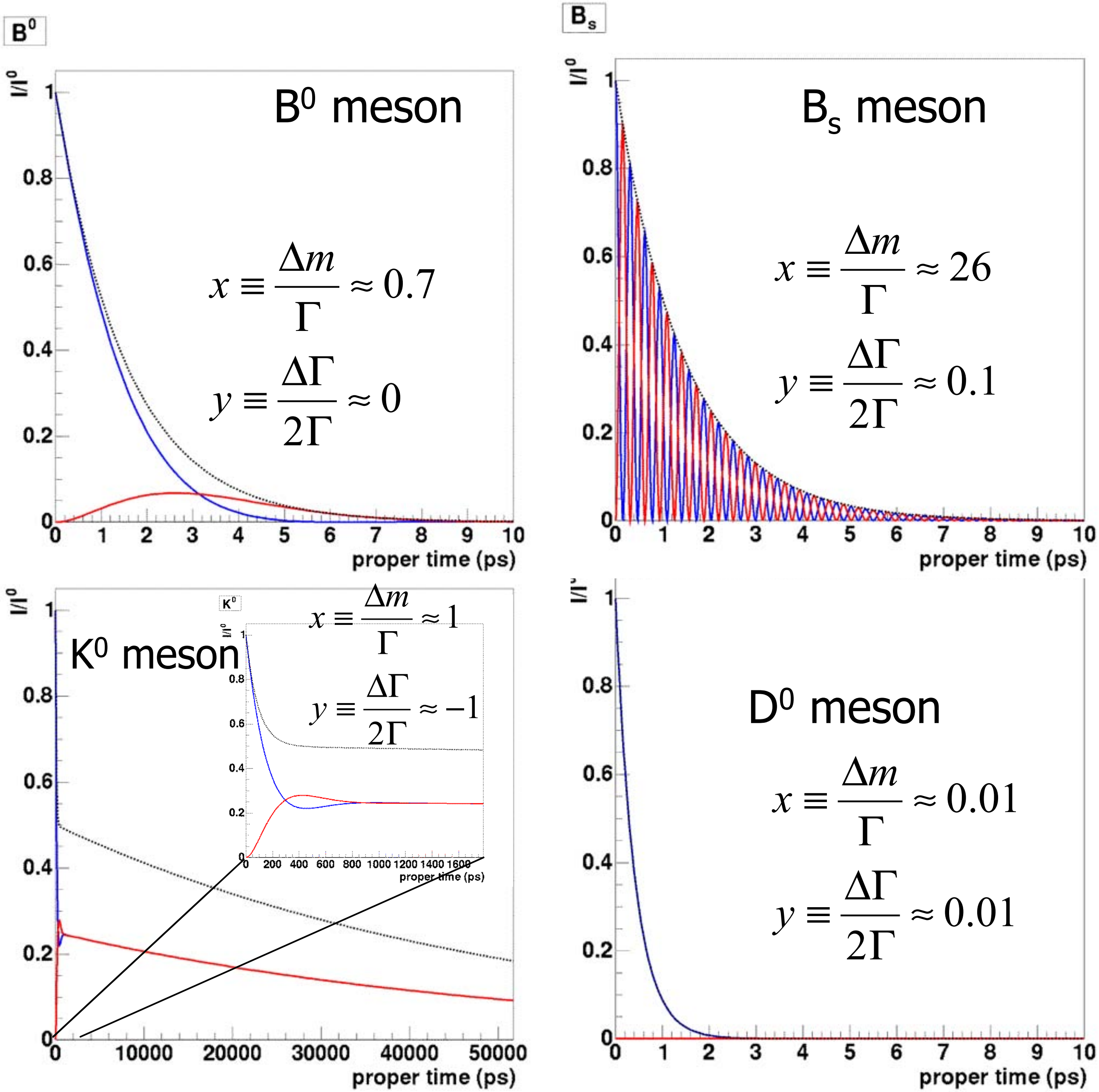
Anti-quarks:

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



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

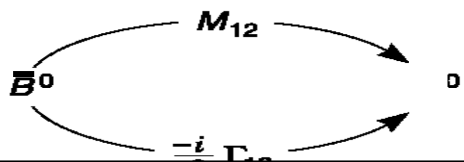
Kaon system: large decay time difference.

Charm system: very slow mixing

Overview: Types of CP violation

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

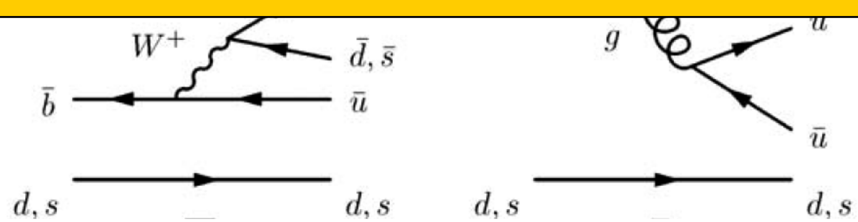
1. CP violation in mixing ("indirect" CP violation): $\left|\frac{q}{p}\right| \neq 1$



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

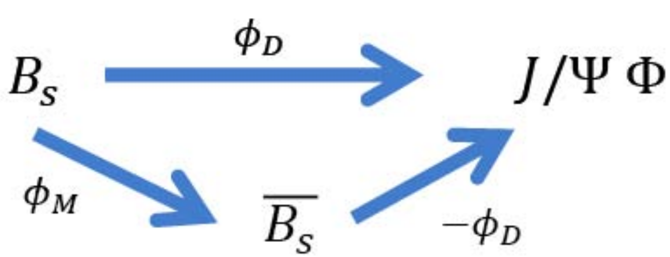
Note that in the SM all these effects are caused by a single complex parameter δ in the CKM matrix!

Tree



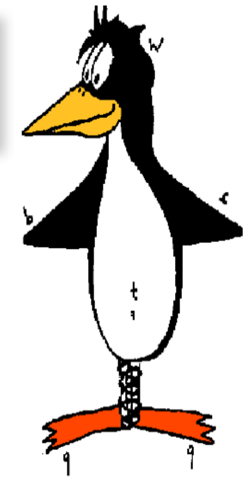
Penguin

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



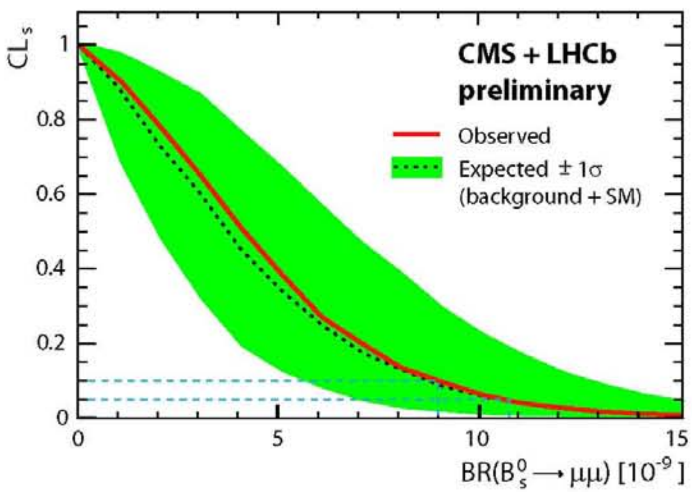
FCNC penguin decays

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

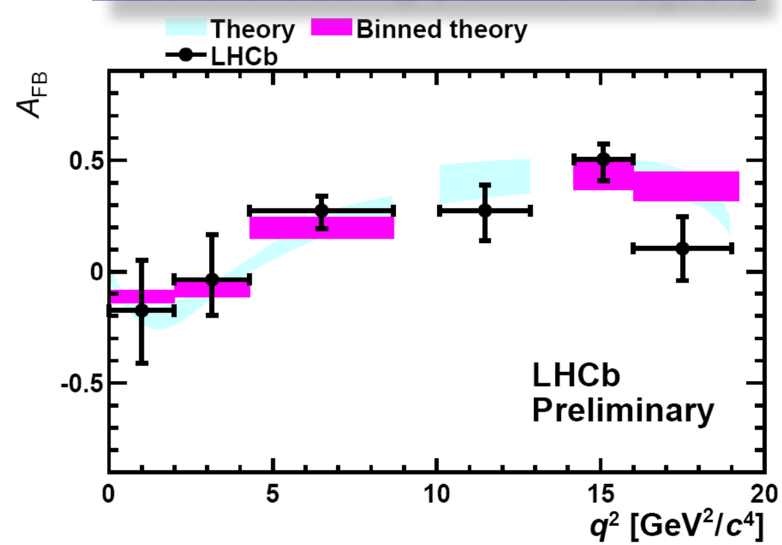


Two examples of quantities which can be well-predicted in SM:

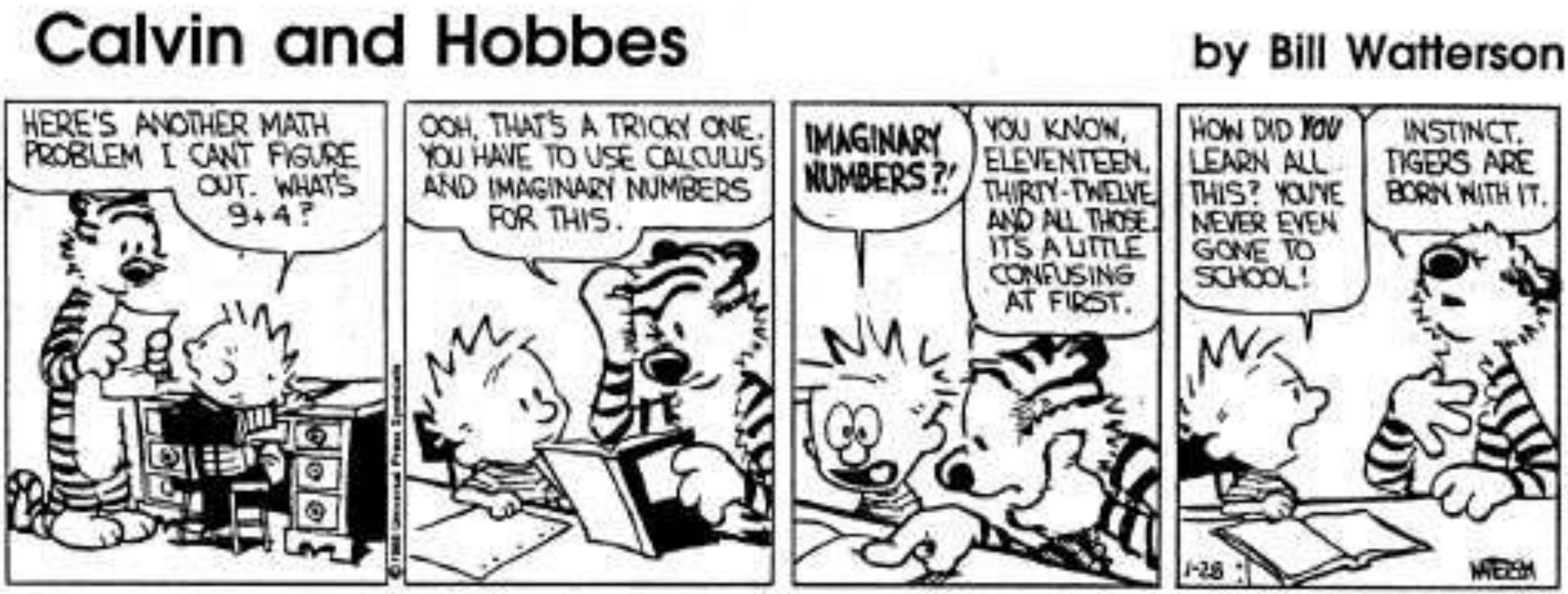
BR($B_s \to \mu^+\mu^-$)



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



It's all about imaginary numbers



Conclusion

LHCb has just collected 1.1 fb^{-1} of data.
Waiting for you to be analysed!