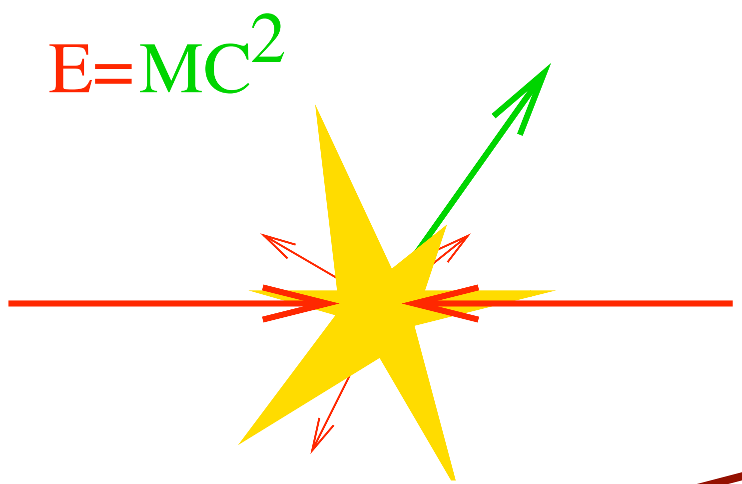
Seeing beyond the energy frontier with precision flavour physics at LHCb

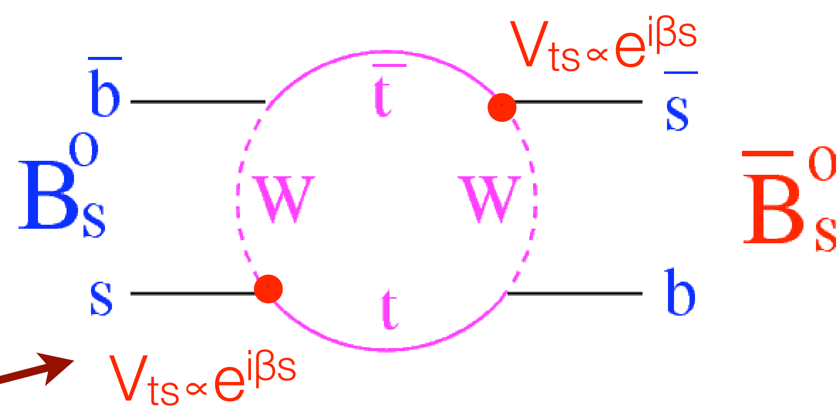
Jonas Rademacker (University of Bristol, UK, LHCb)

Two Roads to New Physics

Direct observation



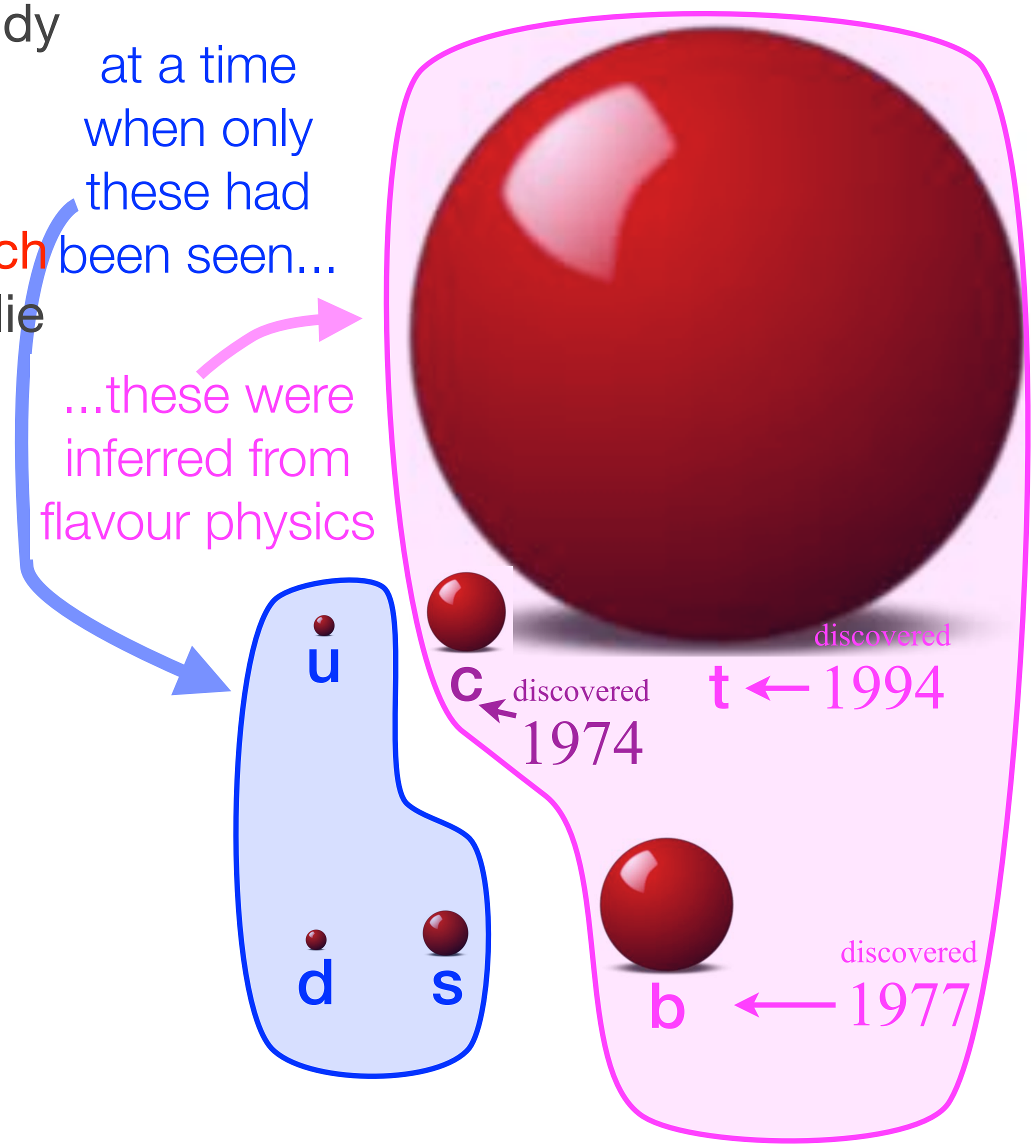
Effects of virtual particles



This approach is sensitive to particles far heavier than those directly produced in a collider. It is what flavour physics is about.

Flavour physics as a tool to discover New Physics

- Quark Flavour physics is the precision study of quark transitions.
- Sensitive to new particles that can be much heavier than those directly produced (i.e. lie beyond the energy frontier).
- Very successful in the past:
    - Charm quark predicted based on the suppression Flavour Changing Neutral Currents (FCNC).
    - Top/bottom quark predicted based on the observation of CP violation.



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Nobelprize.org

The Nobel Prize in Physics 2008

"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"

"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

Photo: SCANPIX

Yoichiro Nambu

1/2 of the prize

USA

Enrico Fermi Institute, University of Chicago
Chicago, IL, USA

b. 1921

Photo: Kyodo/Reuters

Makoto Kobayashi

1/4 of the prize

Japan

High Energy Accelerator Research Organization (KEK)
Tsukuba, Japan

b. 1944

Photo: Kyoto University

Toshihide Maskawa

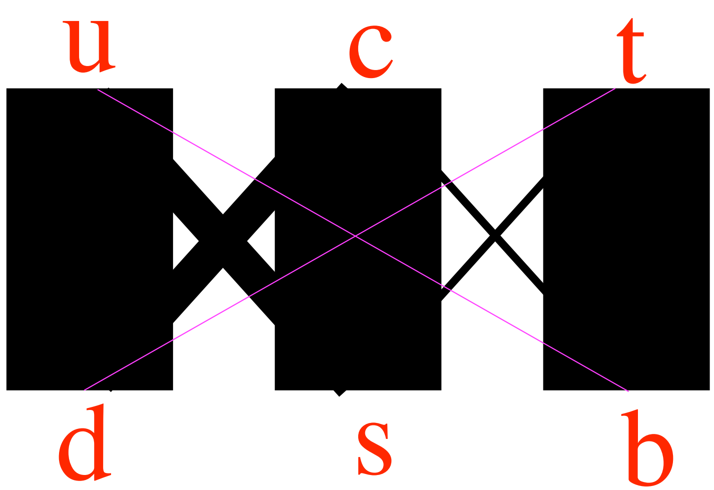
1/4 of the prize

Japan

Yukawa Institute for Theoretical Physics (YITP), Kyoto University
Kyoto, Japan

b. 1940

CKM matrix, CP violation



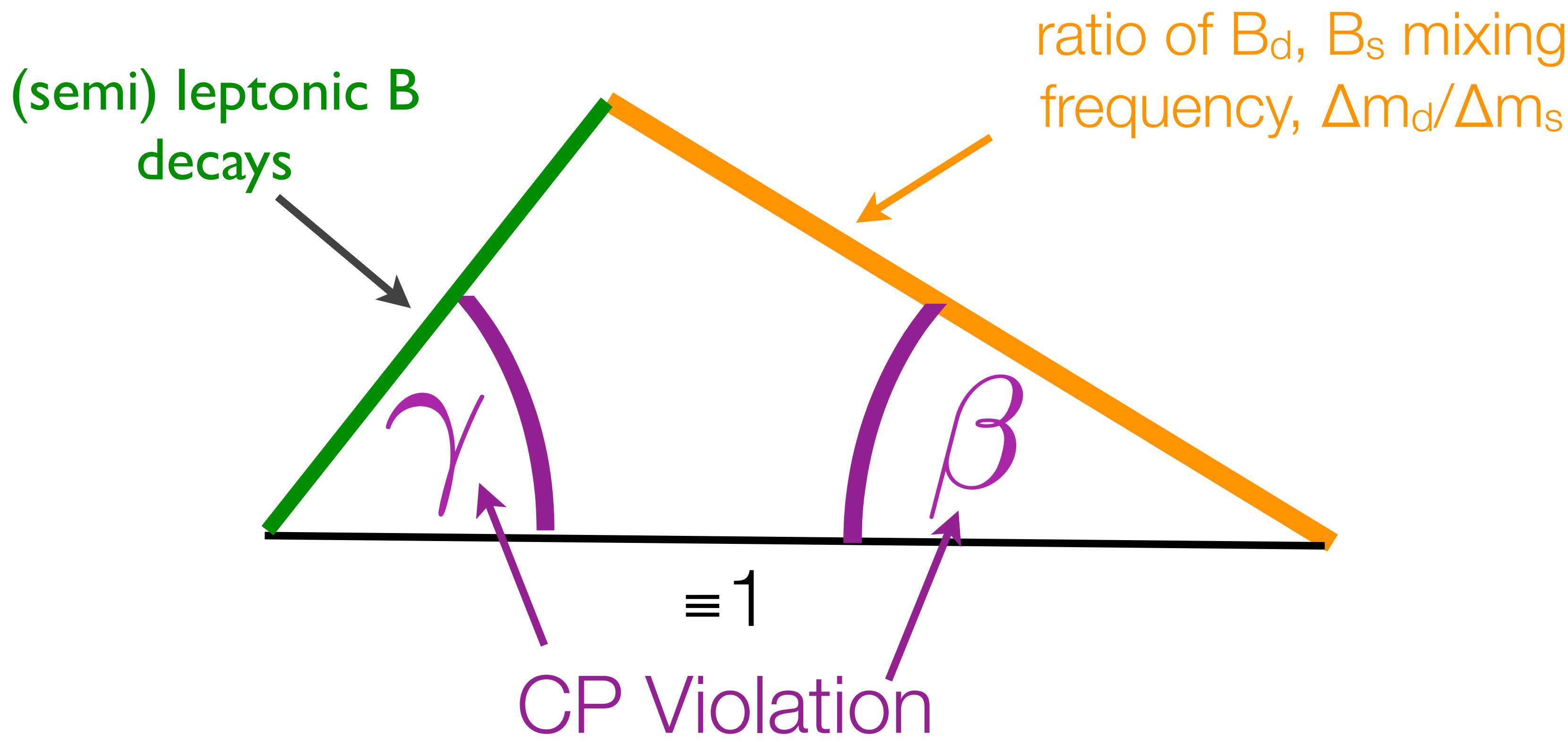
$$V_{CKM} \approx \begin{array}{c} \\ d \\ s \\ b \end{array} \begin{array}{c} \begin{array}{ccc} u & c & t \end{array} \\ \begin{pmatrix} 1 & \lambda & \lambda^3 e^{-i\beta} \\ -\lambda & 1 & \lambda^2 \\ \lambda^3 e^{-i\gamma} & -\lambda^2 & 1 \end{pmatrix} \end{array}$$

where λ=0.22

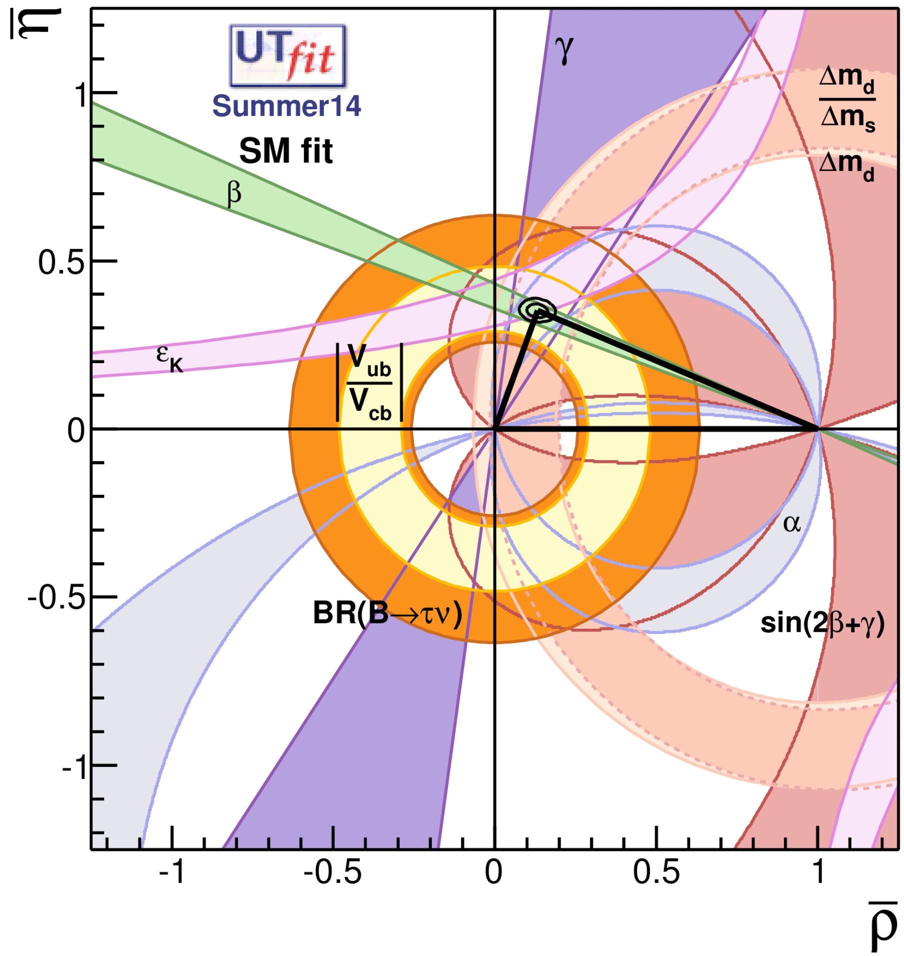
structure of the quark mixing matrix

- Elements of the CKM matrix = transition amplitudes between quarks.
- Operation of CP corresponds to complex-conjugating these -> need complex elements to get CP violation.
- Turns out: Only possible with at least three generations of quarks.

Unitarity triangle

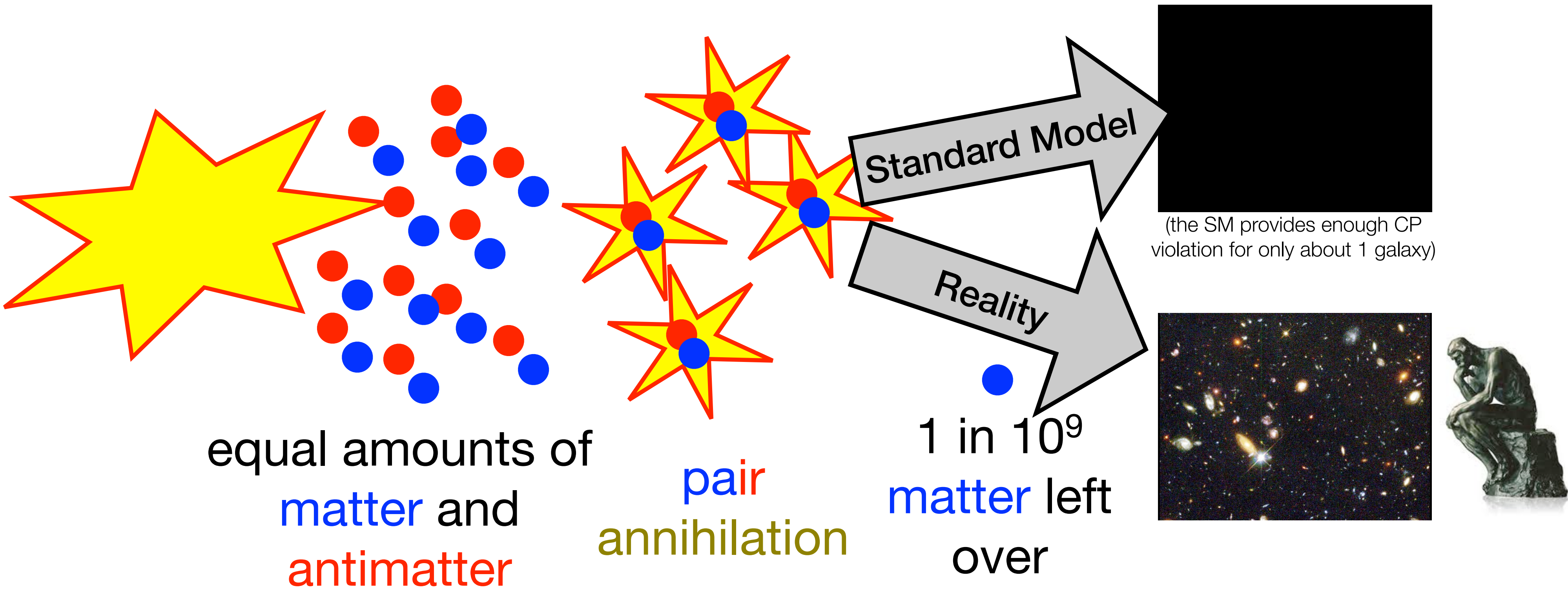


Constraints on the apex of the UT



CP violation and New Physics

- While there is O(10%) agreement between the SM description of CP violation, and recent measurements, there are several orders of magnitude disagreement between CPV in the SM and CPV in the universe.

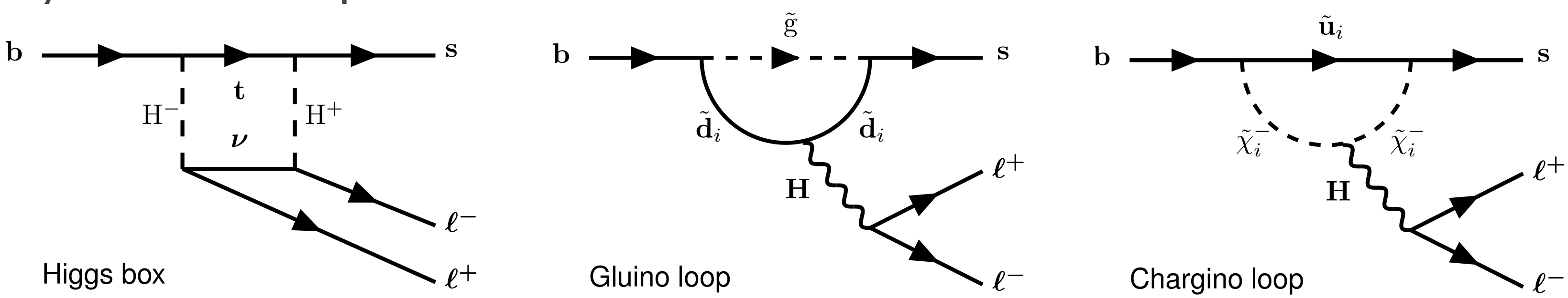


- There must be new sources of CP violation.

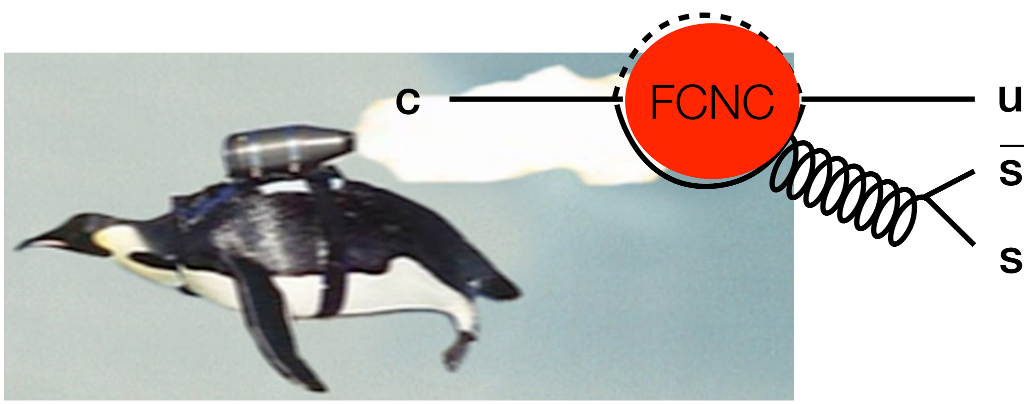
FCNC and New Physics

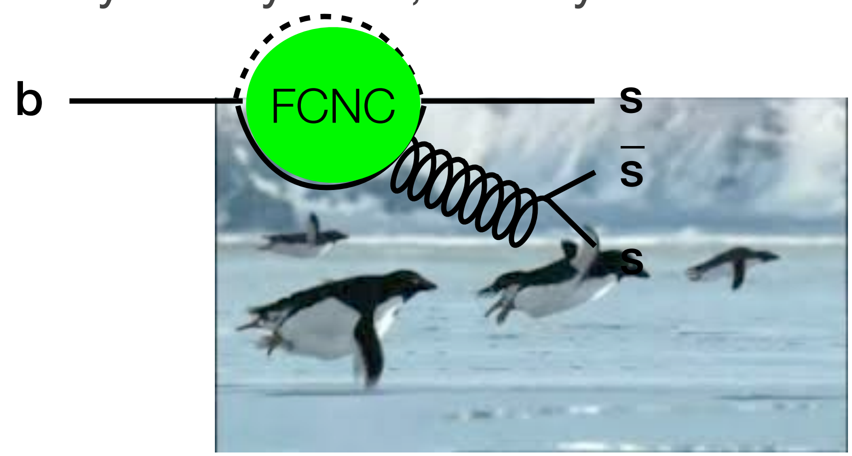
- The suppression of FCNC is an "accidental" symmetry of the SM. There is no fundamental reason why it should exist in models beyond the SM.

- Many NP models predict new sources of FCNCs.



- NP can affect up and down-type quarks differently. Study both, beauty & charm!



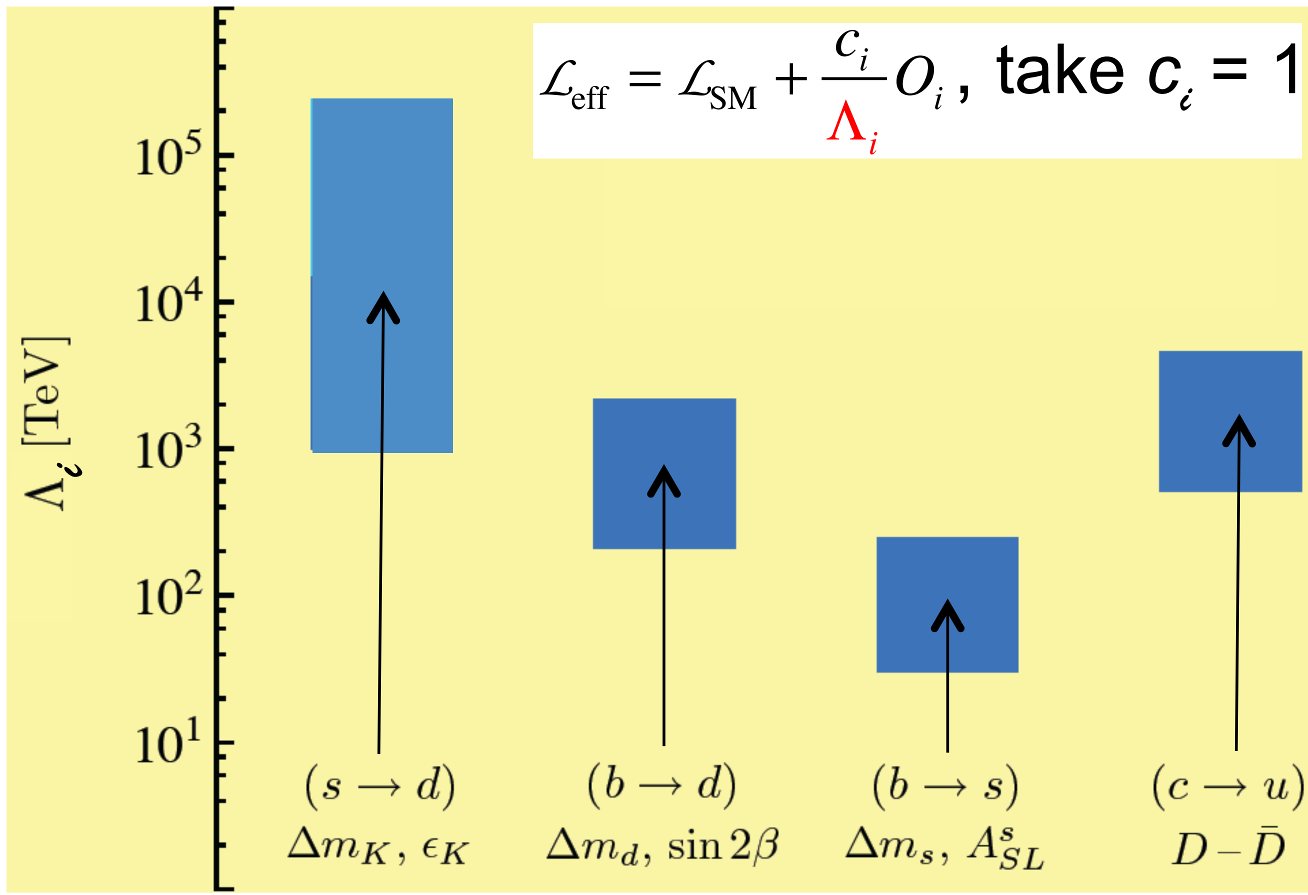


Sensitivity of FCNC to NP mass scales

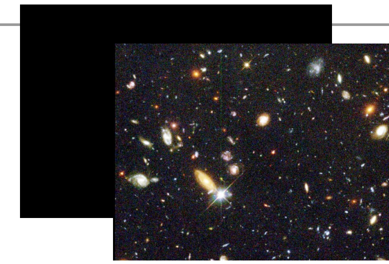
Ann.Rev.Nucl.Part.Sci.60:355,2010

plot from M. Neubert at EPS-HEP 2011

- "Simple" NP models ruled out up to PeV-scale, by Flavour Physics.
- Flavour physics imposes severe constraints on the structure and mass scale of NP



Outline

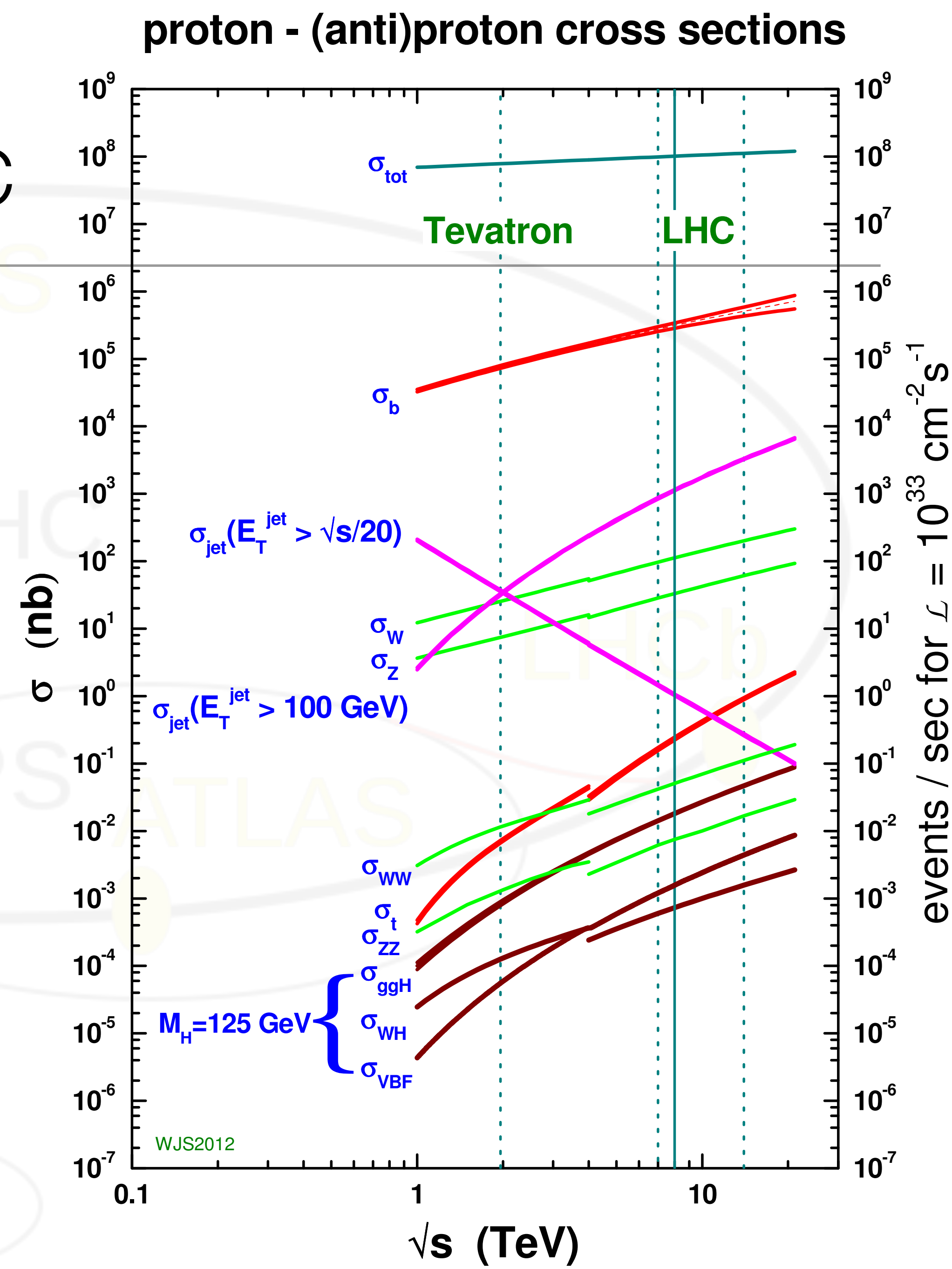


- CP violation & mixing (much of which probes FCNC)

- Rare decays, probing FCNC and other New Physics.
- … leaving out many other exciting measurements …
- Future prospects

Flavour physics at the LHC

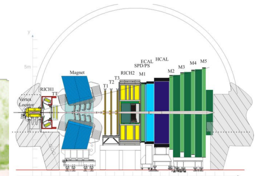
- Huge b cross section, even huger (20×) charm cross section.
- All types of b and c hadrons (like B^0, B_s, B_c, Λ_b, …).
- The world's largest heavy flavour samples, and a dedicated flavour physics detector (LHCb).
- Best place to do heavy flavour physics, today.



Eur.Phys.J. C63 (2009) 189-285

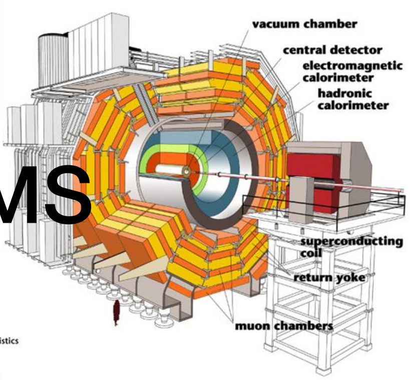
http://www.hep.ph.ic.ac.uk/~wstirlin/plots/plots.html

Heavy flavour physics at the LHC



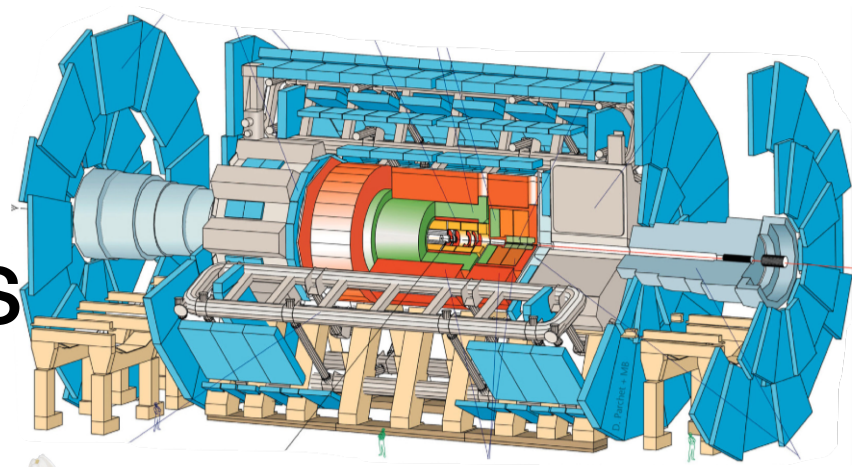
LHCb

(the dedicated flavour physics experiment at the LHC)

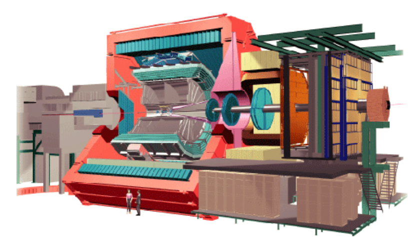


CMS

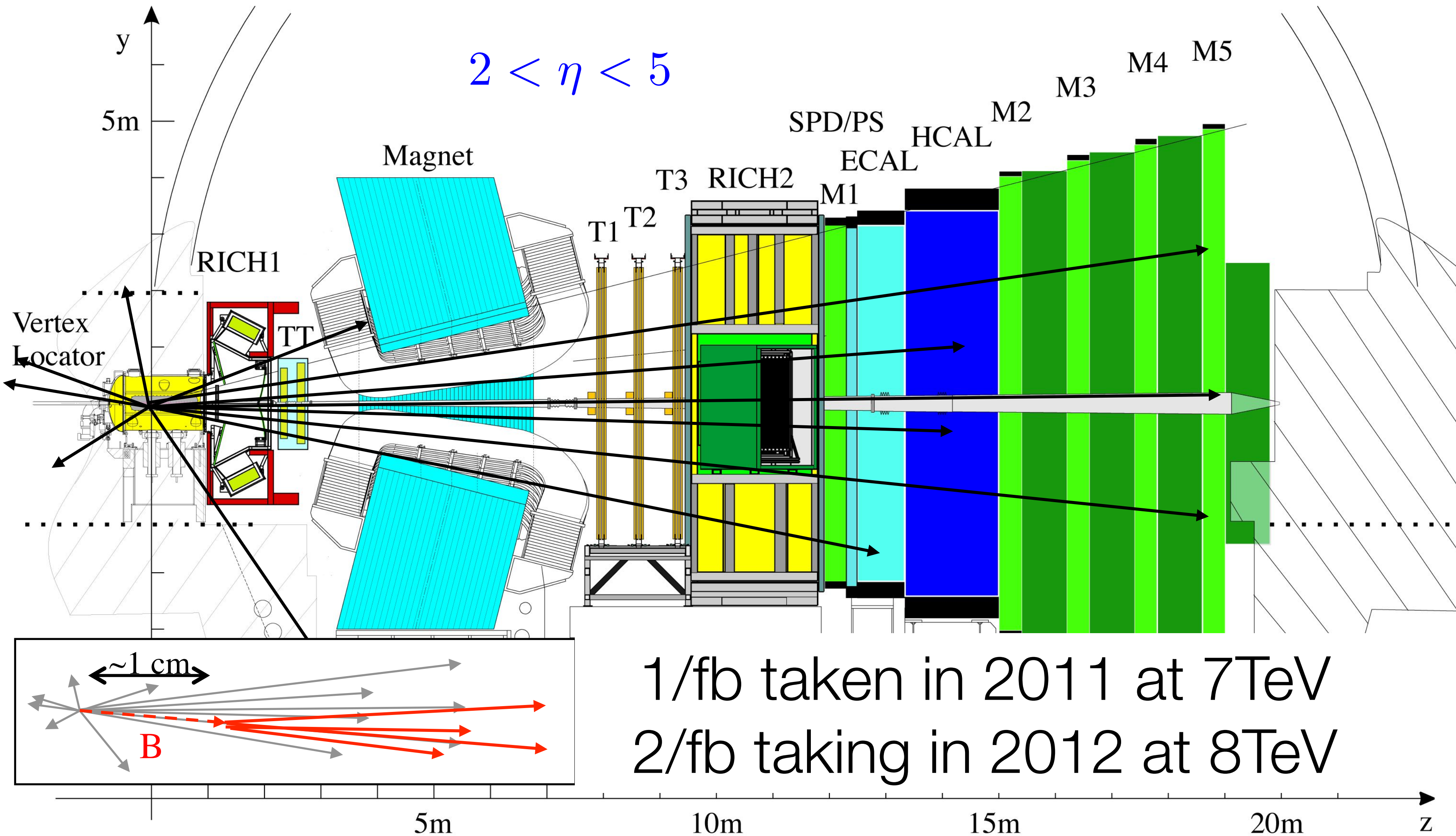
ATLAS



ALICE



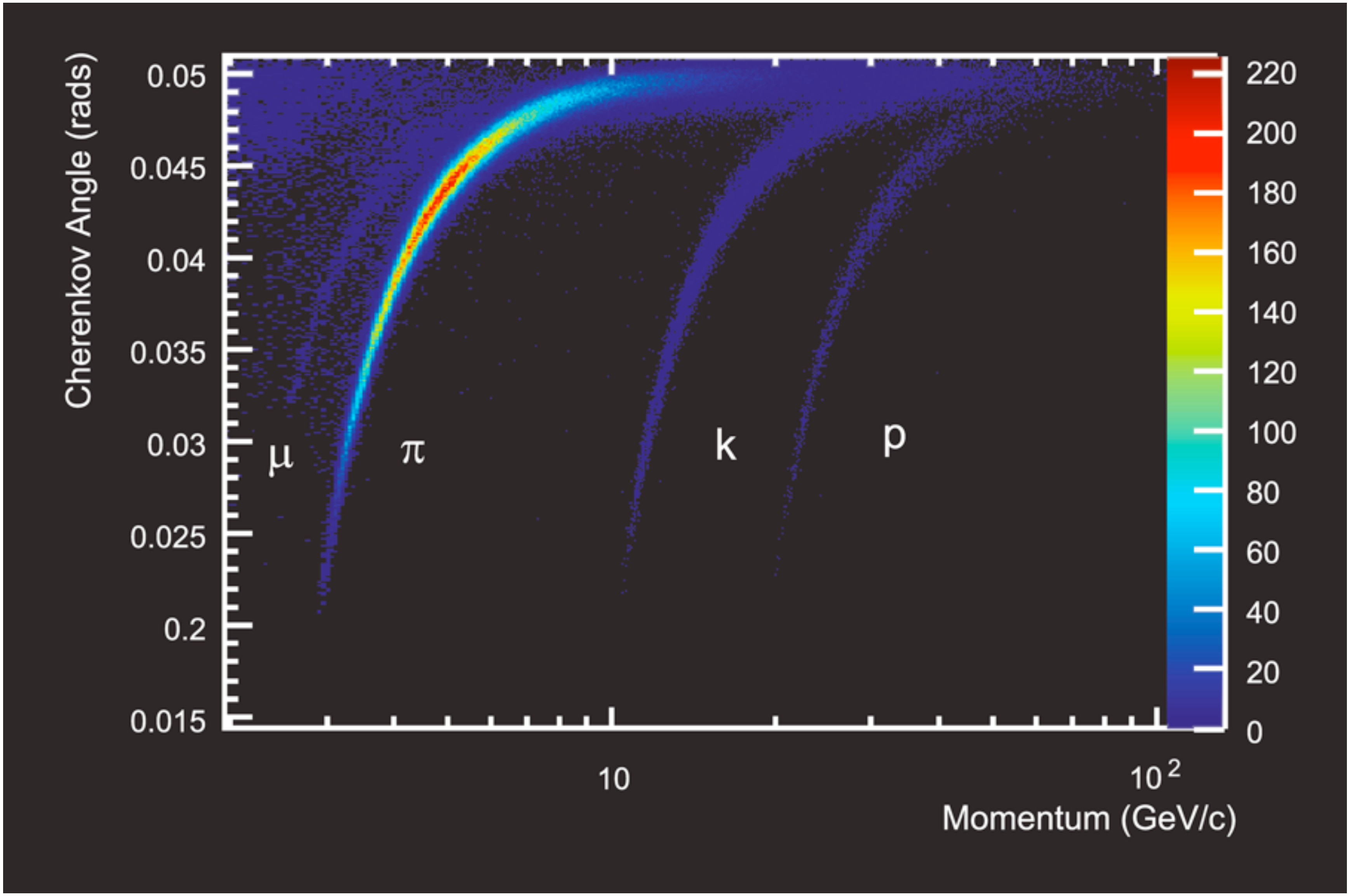
The LHCb Detector



1/fb taken in 2011 at 7TeV
2/fb taking in 2012 at 8TeV

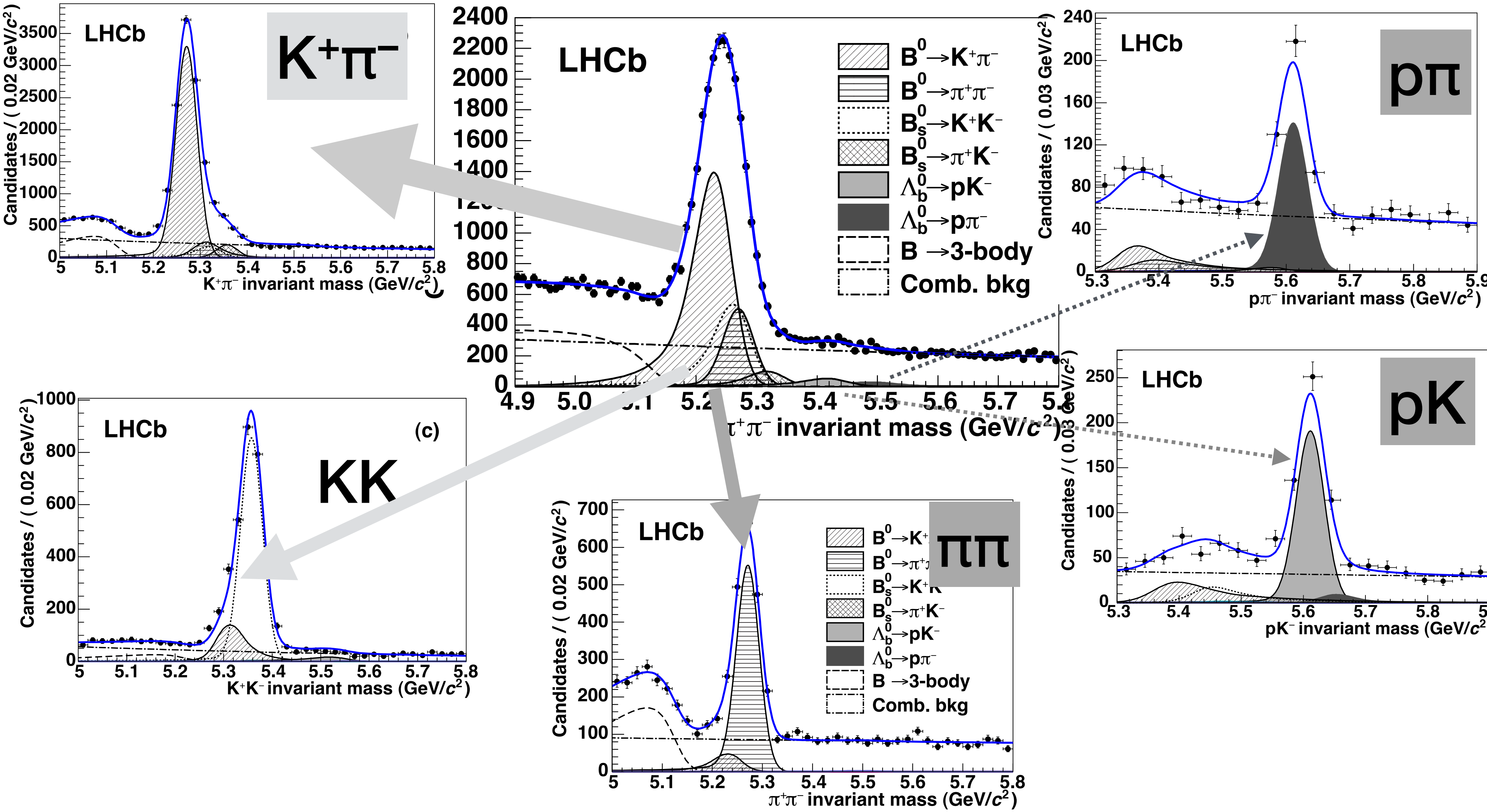
Particle ID with the LHCb RICH

LHCb: EPJ C 73:2431 (2013)



LHCb RICH particle ID in action

LHCb: JHEP 1210 (2012) 037



Direct CP violation in $B^o_{(s)} \to K\pi$

LHCb: PRL 110 (2013) 221601

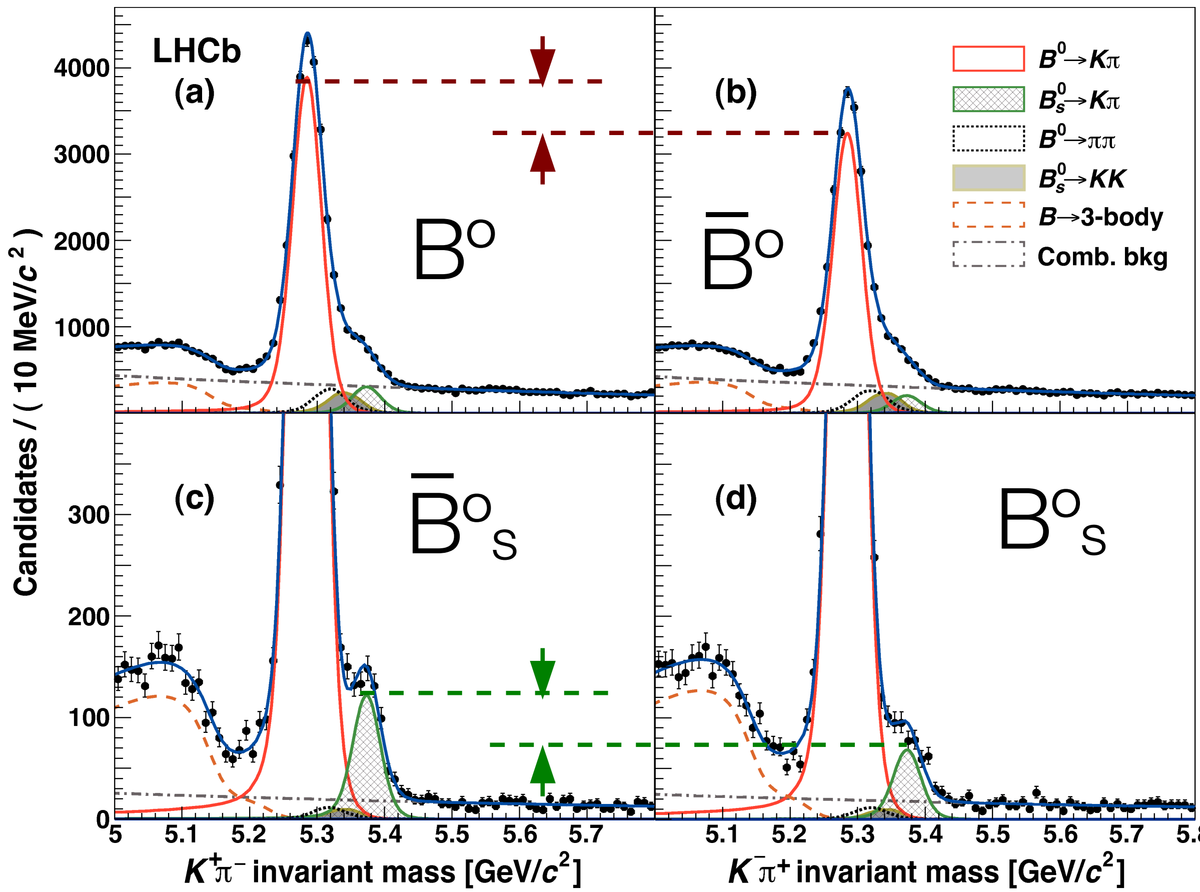
- Define

$$A_{CP} \equiv \frac{N(B^0_{(s)}) - N(\overline{B}^0_{(s)})}{N(B^0_{(s)}) + N(\overline{B}^0_{(s)})}$$

- For $B^o \to K^+\pi^-$, $\bar{B}^o \to K^-\pi^+$:
  $A_{CP} = -0.080 \pm 0.007 \pm 0.003$

- For $B_s \to K^-\pi^+$, $\bar{B}_s \to K^+\pi^-$
  $A_{CP} = 0.27 \pm 0.04 \pm 0.01$

- First observation of CPV in B_s decays!

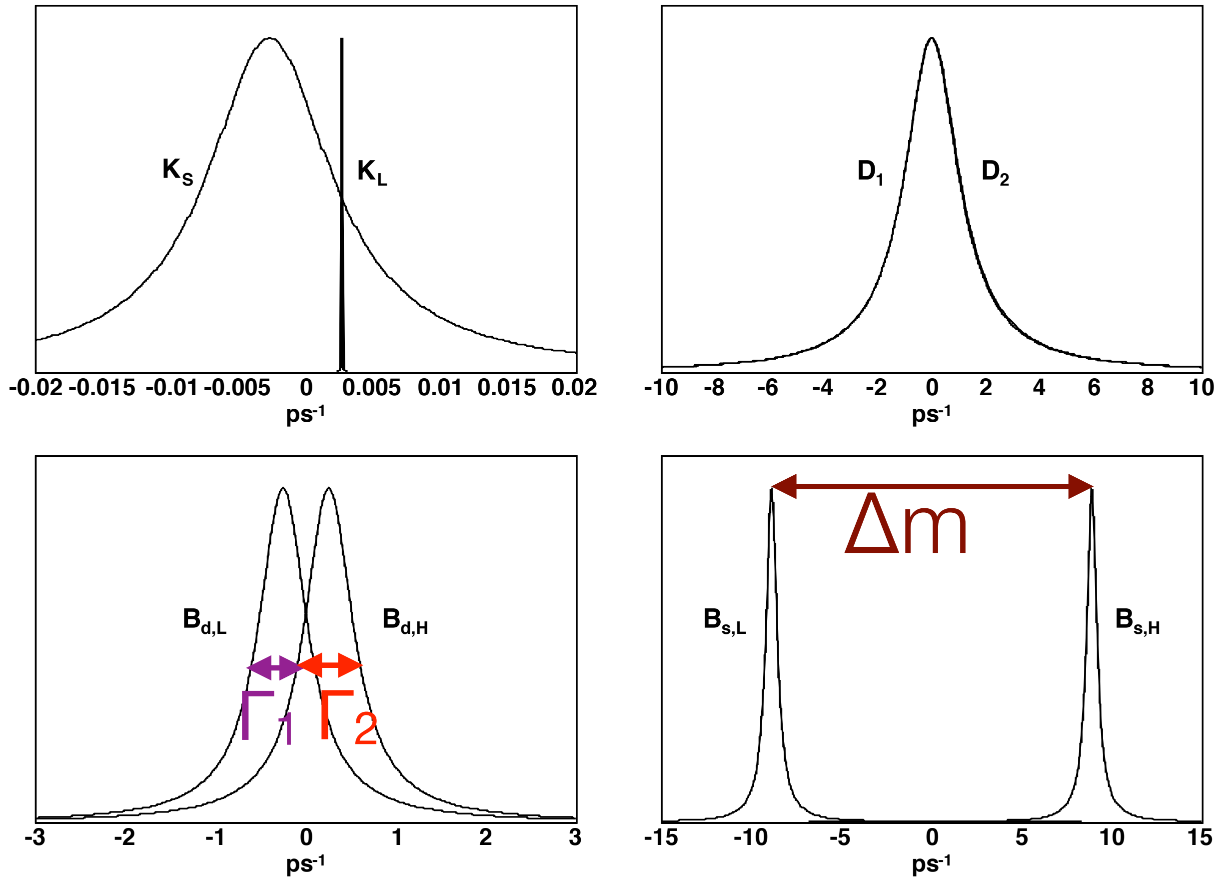


Mixing in neutral meson systems

$$|M_{1,2}\rangle = p|M^0\rangle \pm q|\overline{M}^0\rangle$$

$$\Delta\Gamma = \Gamma_2 - \Gamma_1$$

$$\Delta m = m_2 - m_1$$



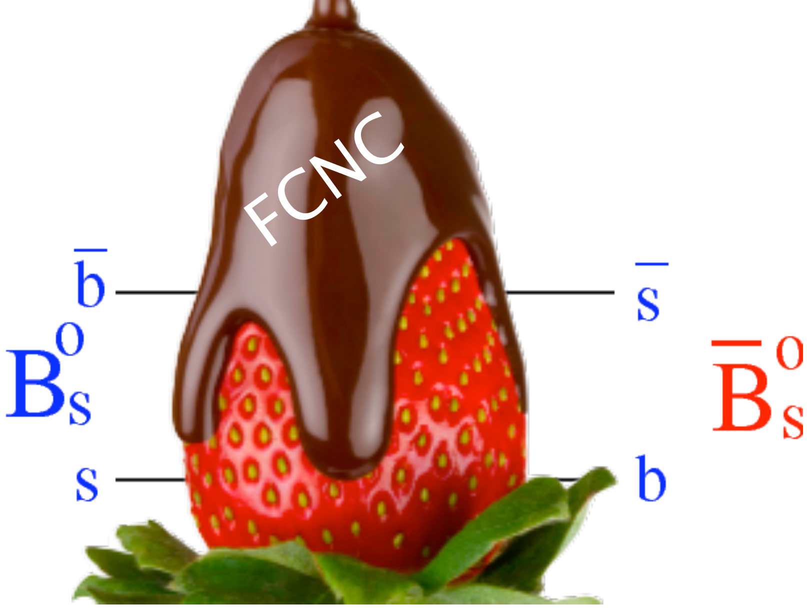
$$P(M^0 \to \overline{M}^0)(t) = \frac{1}{2}\left|\frac{q}{p}\right|^2 e^{-\Gamma t}\left(\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\left(\Delta m\, t\right)\right)$$

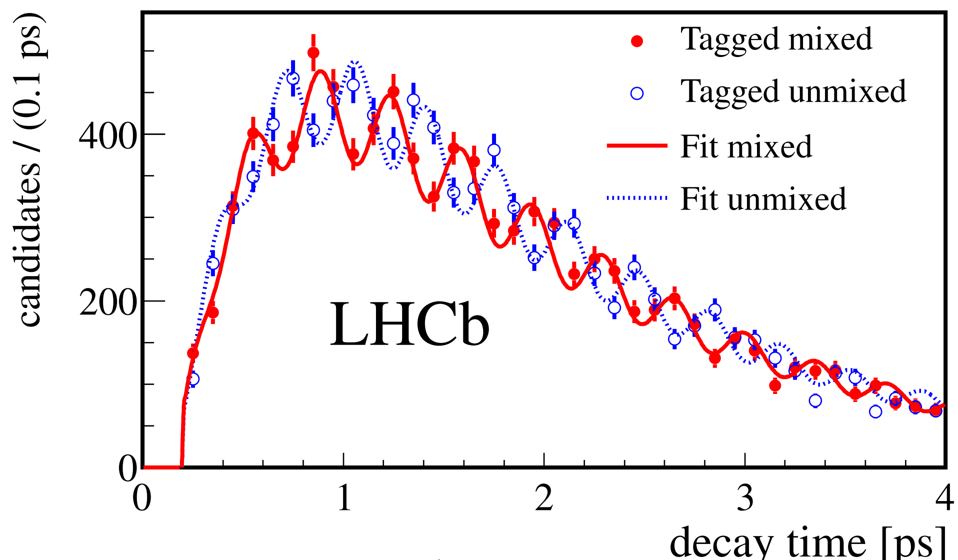
B_s O

New J.Phys. 15 (2013) 053021

(1st observed by CDF, Phys.Rev.Lett. 97 (2006) 062003, Phys.Rev.Lett. 97 (2006) 242003.)

B_s oscillations at LHCb



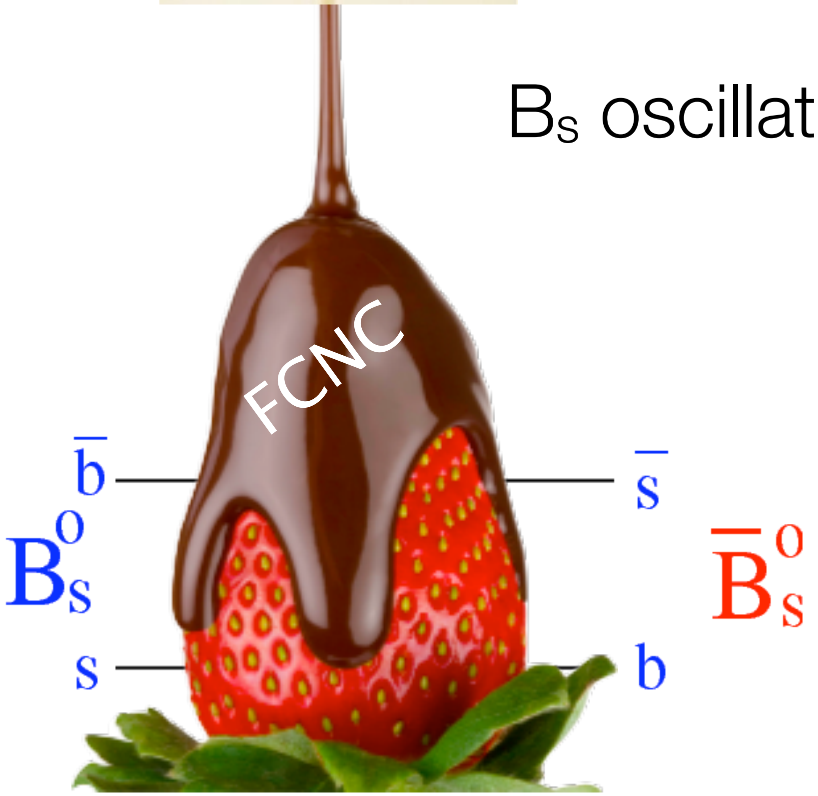


$$\Delta m_s = 17.768 \pm 0.023 \pm 0.006 \ ps^{-1}$$

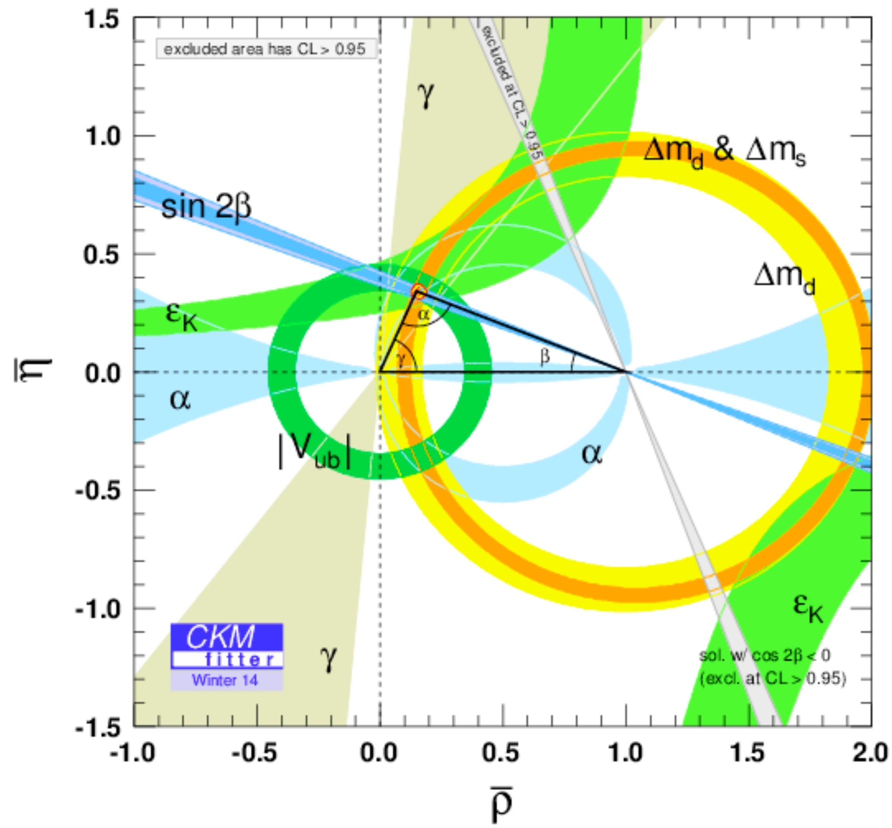
world's most precise measurement of Δm_s

New J.Phys. 15 (2013) 053021

B_s Oscillations



B_s oscillations



$$\Delta m_s = 17.768 \pm 0.023 \pm 0.006 \ ps^{-1}$$

world's most precise measurement of Δm_s

Nobel Mixing

- For neutral meson systems:

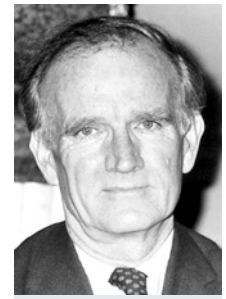
  Mixing → CP violation → Nobel Prize (~20 years)

- For 2 out of 4 mixing meson systems, we only just got started:
  - B_s: Mixing discovered in 2006 (no mixing-induced CPV, yet).
  - D^0: Mixing discovered in 2007 (no CPV, yet).
  - In both systems, the prize is in finding non-SM CP violation (in the case of D^o, this is any CPV)

The Nobel Prize in Physics 1980

"for the discovery of violations of fundamental symmetry principles in the decay of neutral K-mesons"

James Watson Cronin



Val Logsdon Fitch

½ Nobel Prize in Physics 2008

"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

© The Nobel Foundation Photo: U. Montan

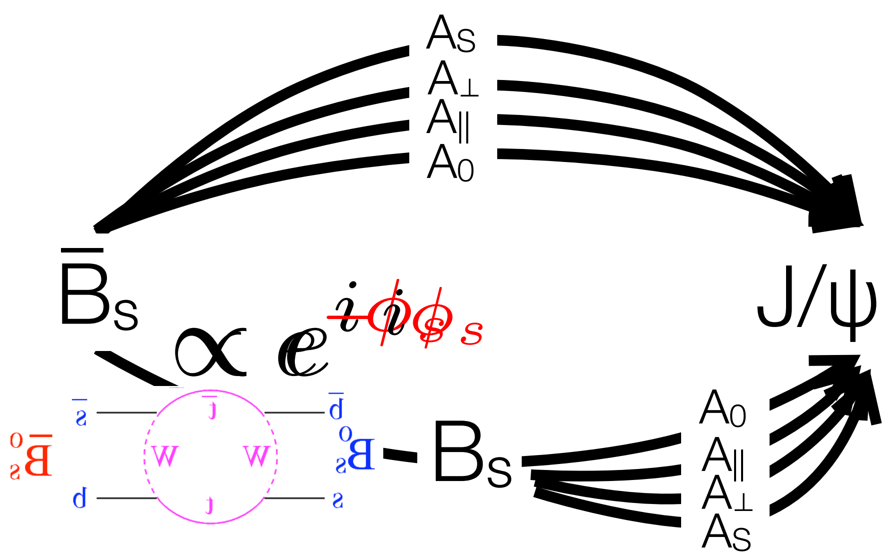
Makoto Kobayashi

© The Nobel Foundation Photo: U. Montan

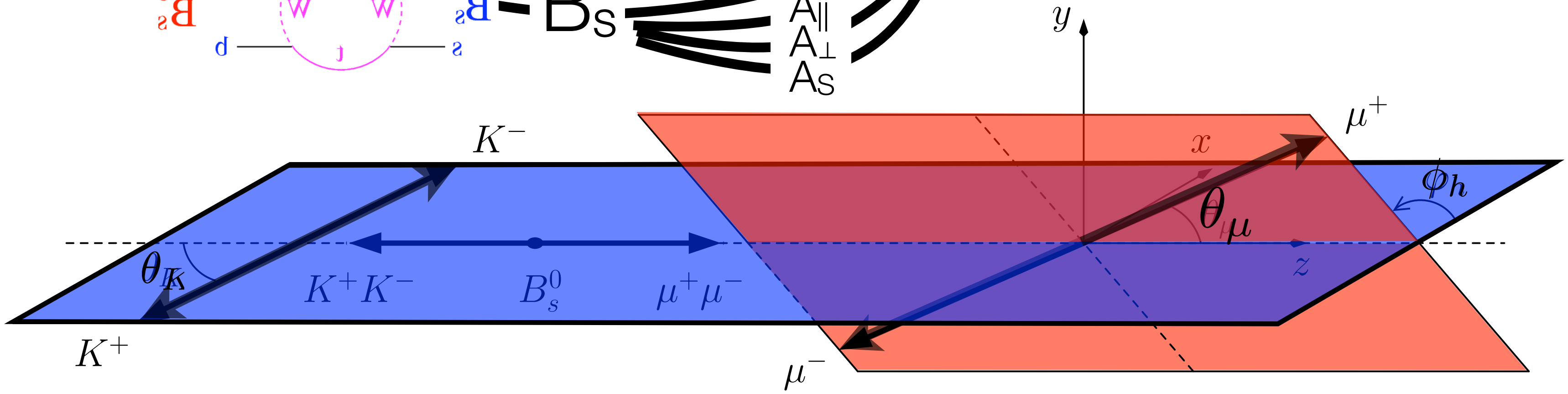
Toshihide Maskawa

$B_s \to J/\psi\, KK$ for ϕ_s

Need to disentangle CP even and CP odd amplitudes



J/ψ KK = J/ψ φ+ S-wave



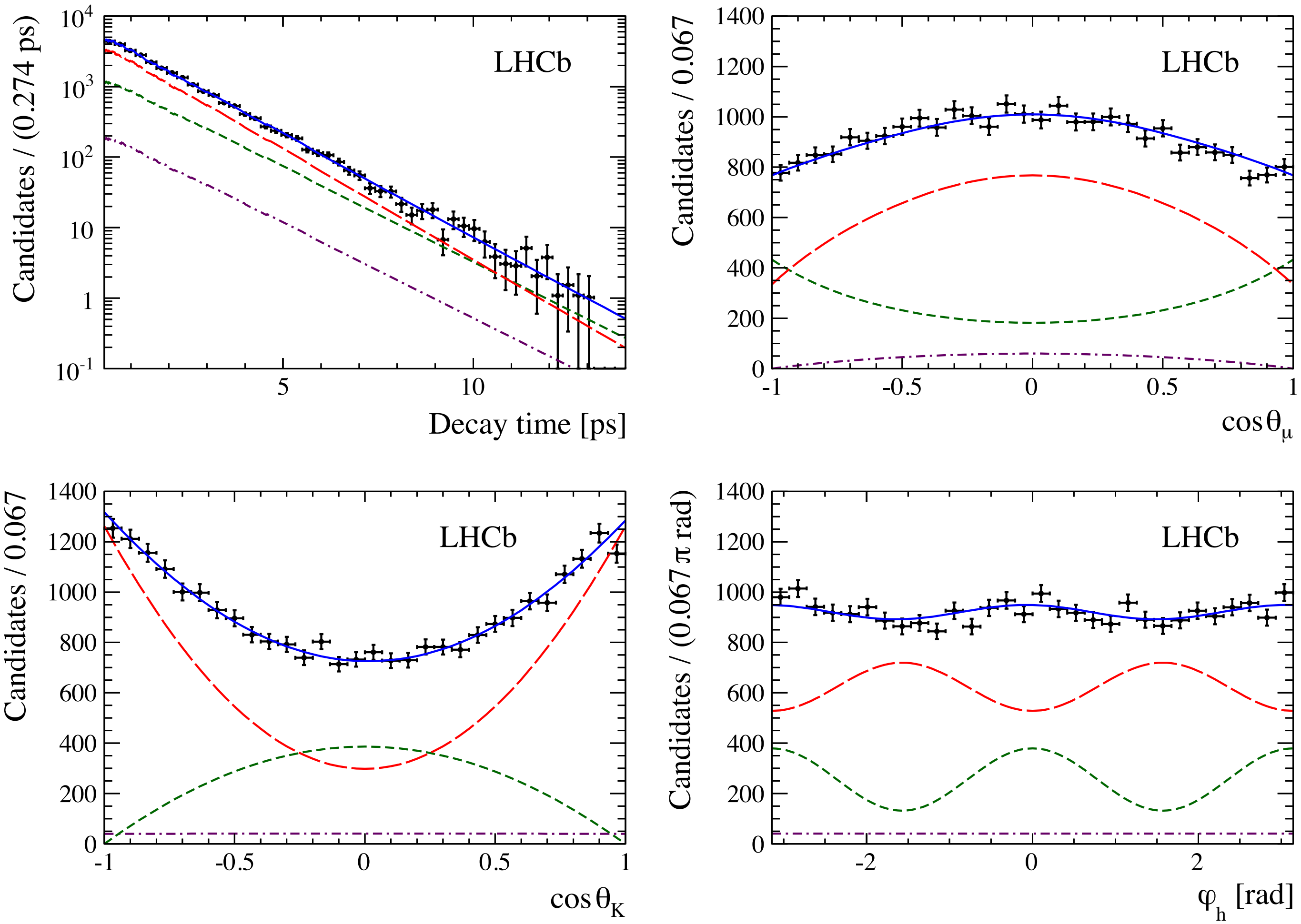
Precisely predicted in SM $\phi_s = (-0.036 \pm 0.002)$ rad

Hope to measure a different value!

$B_s \to J/\psi\, KK$ for ϕ_s

LHCb: Phys.Rev. D87 (2013) 112010

Fit projections*



*Fit done in 4-D (not just projections)

Total

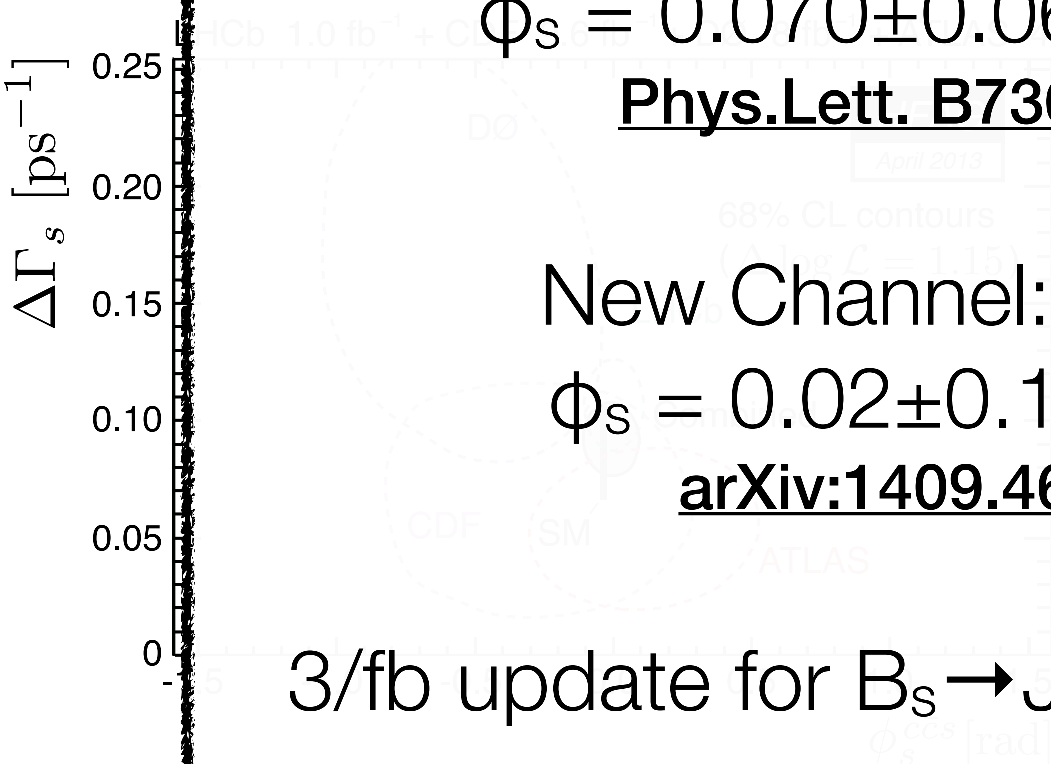
CP-even

CP-odd

S-wave

background-subtracted data

Combined $B_s \to J/\psi$ KK and $B_s \to J/\psi\ \pi\pi$ for ϕ_s



Since then:

Updated LHCb results for 3/fb, $B_s \to J/\psi\ \pi\pi$

$\phi_s = 0.070 \pm 0.068 \pm 0.008$ rad

Phys.Lett. B736 (2014) 186

New Channel: $B_s \to D_s^+ D_s^-$

$\phi_s = 0.02 \pm 0.17 \pm 0.02$ rad

arXiv:1409.4619 (2014)

3/fb update for $B_s \to J/\psi$ KK in progress.

12010

s B 713 (2012) 378)

But

...

sive

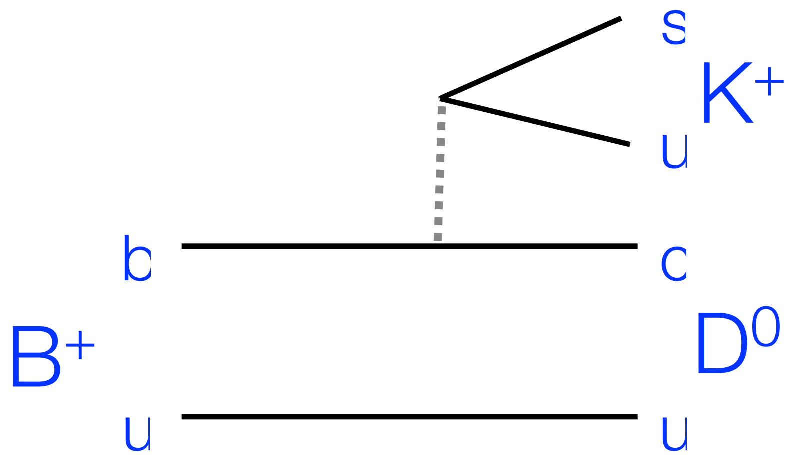
$$
\begin{aligned}
\text{SM:} \quad & \phi_s^{SM} &= -0.036 \pm 0.002 \\
\text{Experiment:} \quad & \phi_s &= 0.00 \pm 0.07
\end{aligned}
$$

← plenty of room left for NP.

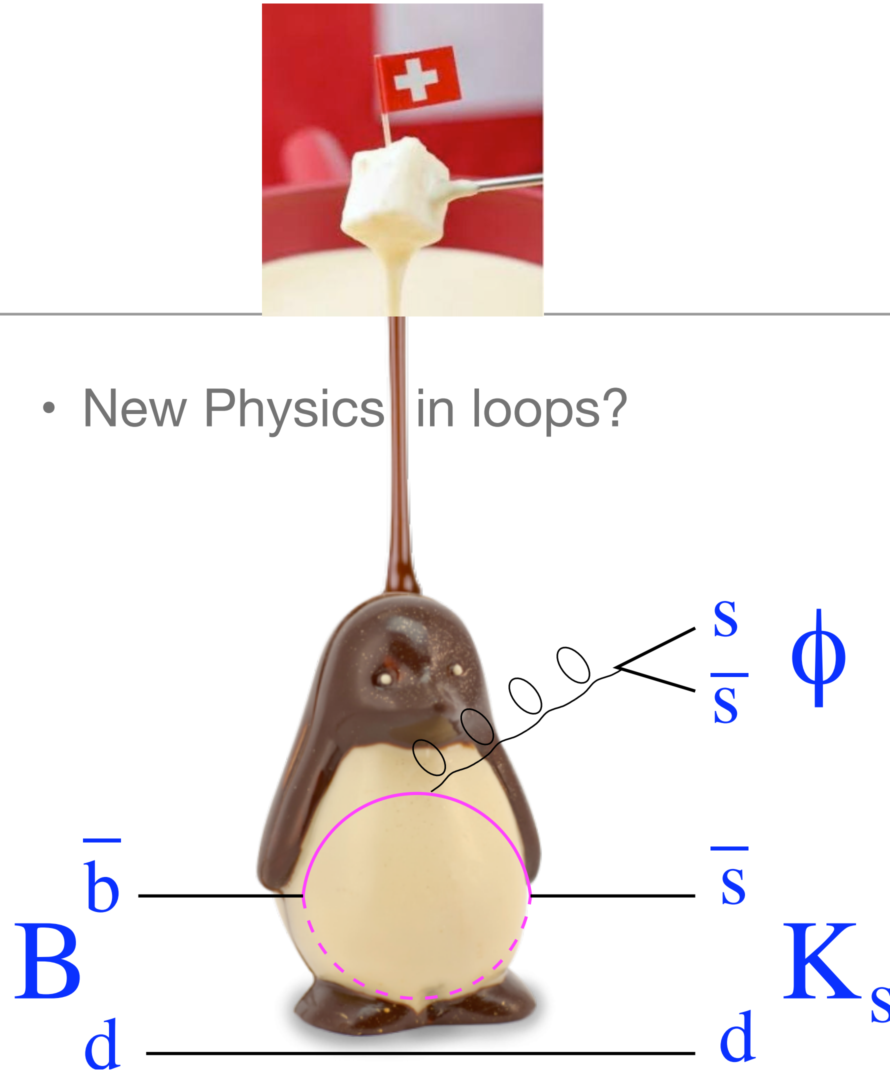
SM: http://ckmfitter.in2p3.fr

Loops vs Trees

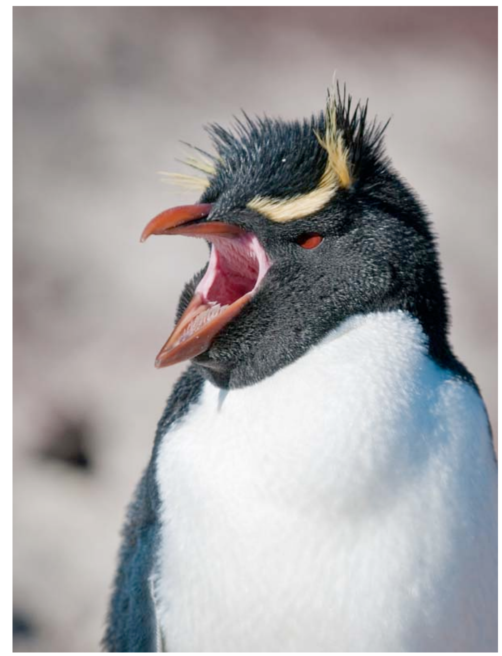
- Expect no New Physics in Trees



- New Physics in loops?



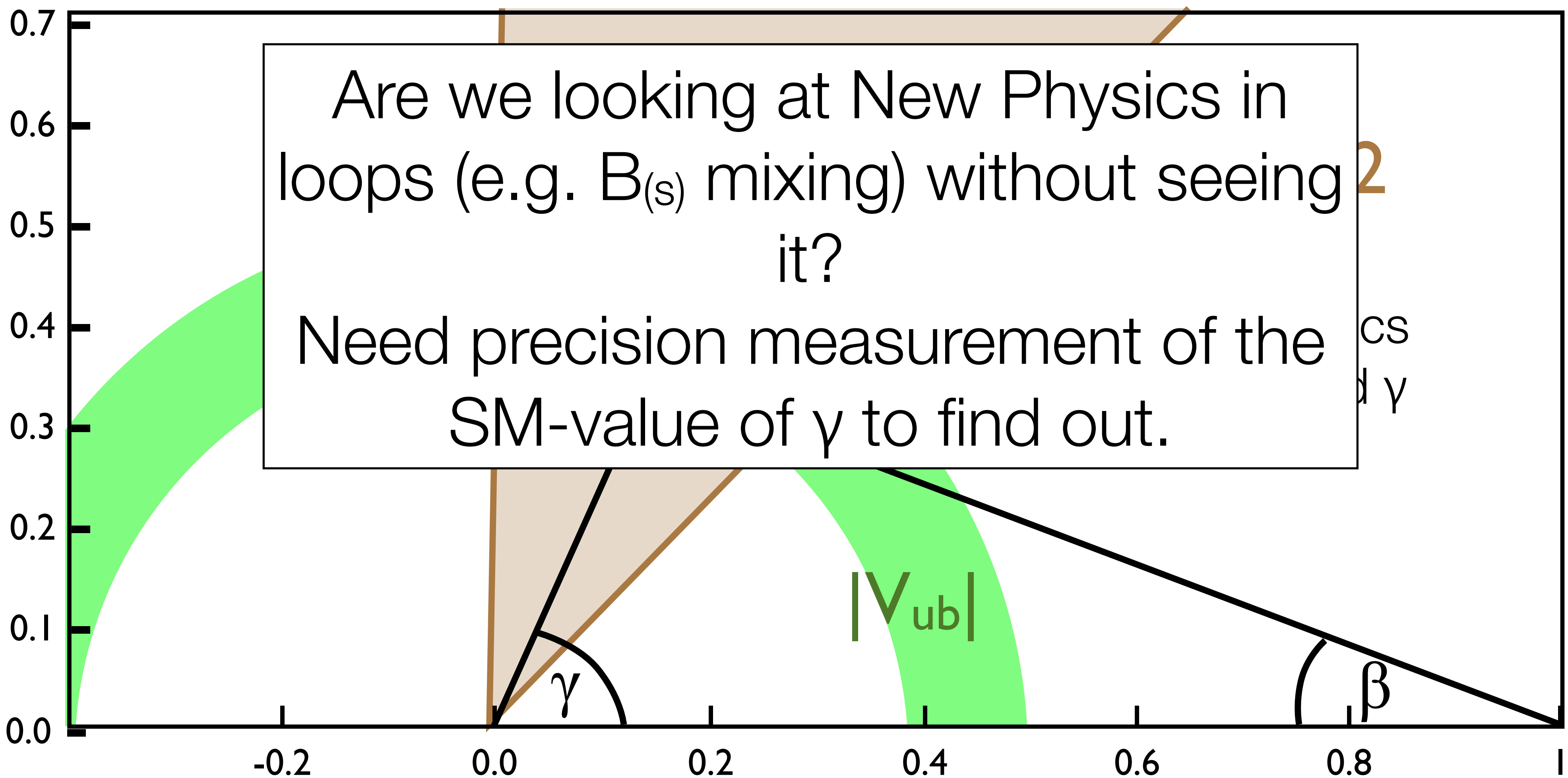
Can penguins be bad?



They can.

The "Unitarity Triangle" represents key parameters of the Standard Model description of CP violation.

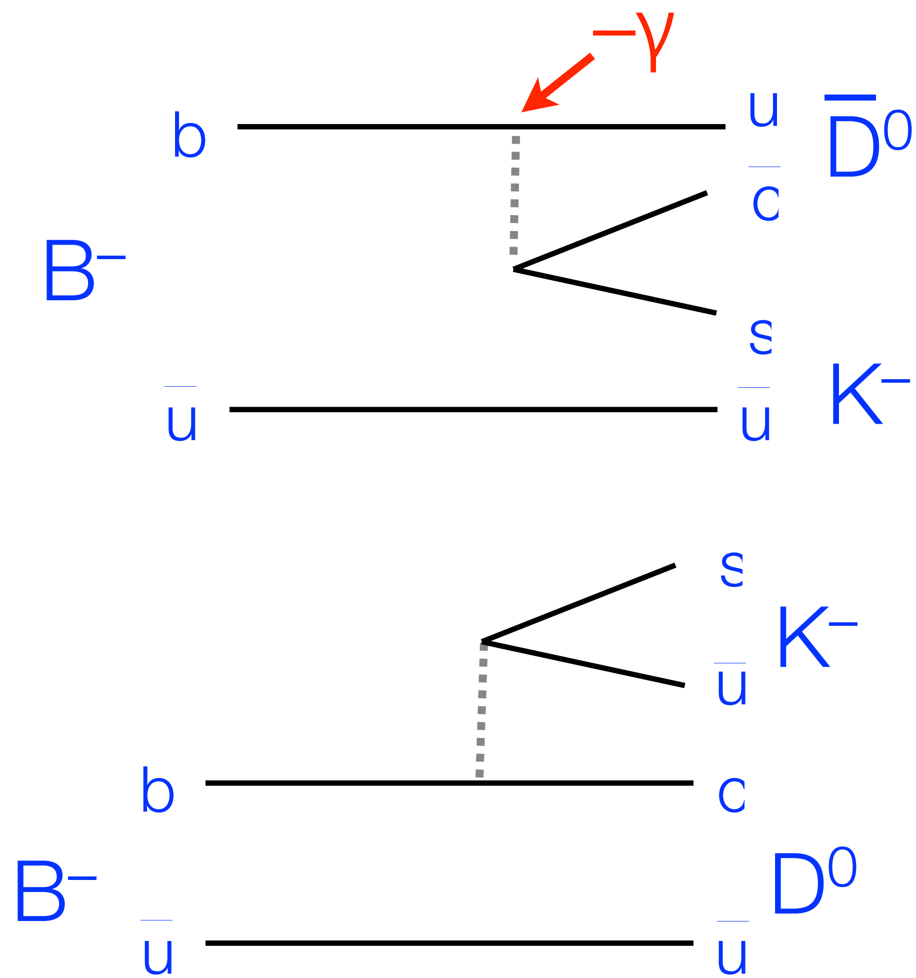
If the Standard Model is correct, we should get consistent constraints on the apex of the triangle.
Shaded areas identify constraints from different sources (95% CL). (Yellow: "loops", others "trees".)

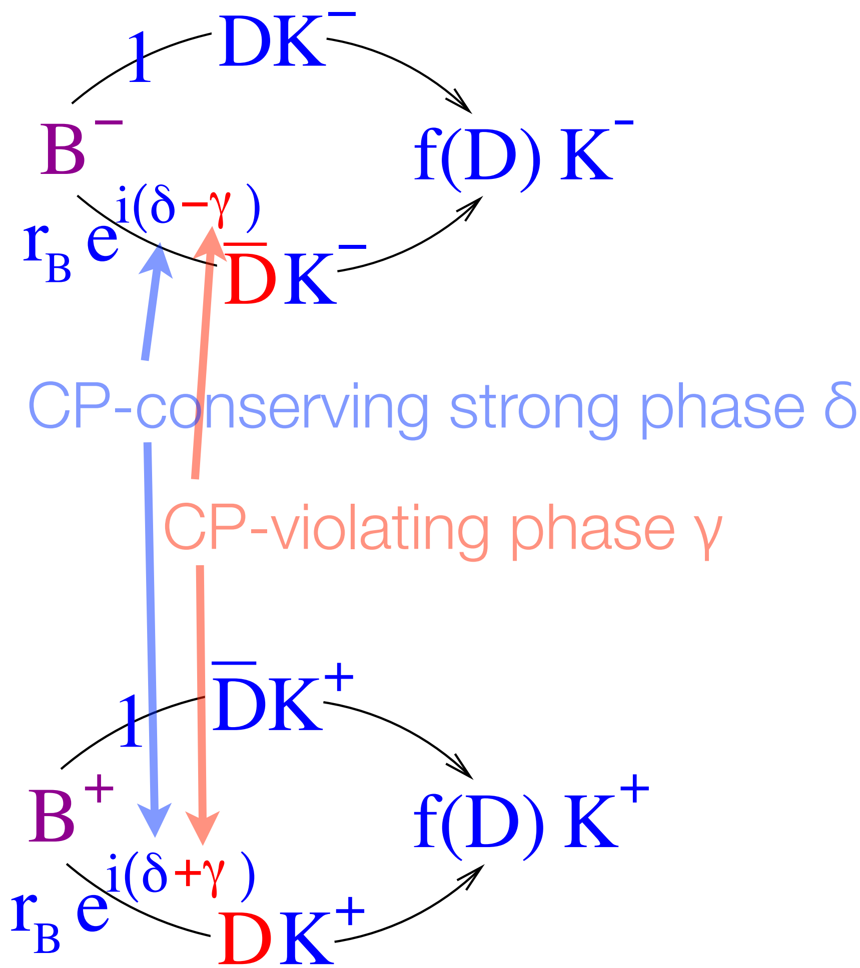


Are we looking at New Physics in loops (e.g. $B_{(s)}$ mixing) without seeing it?

Need precision measurement of the SM-value of γ to find out.

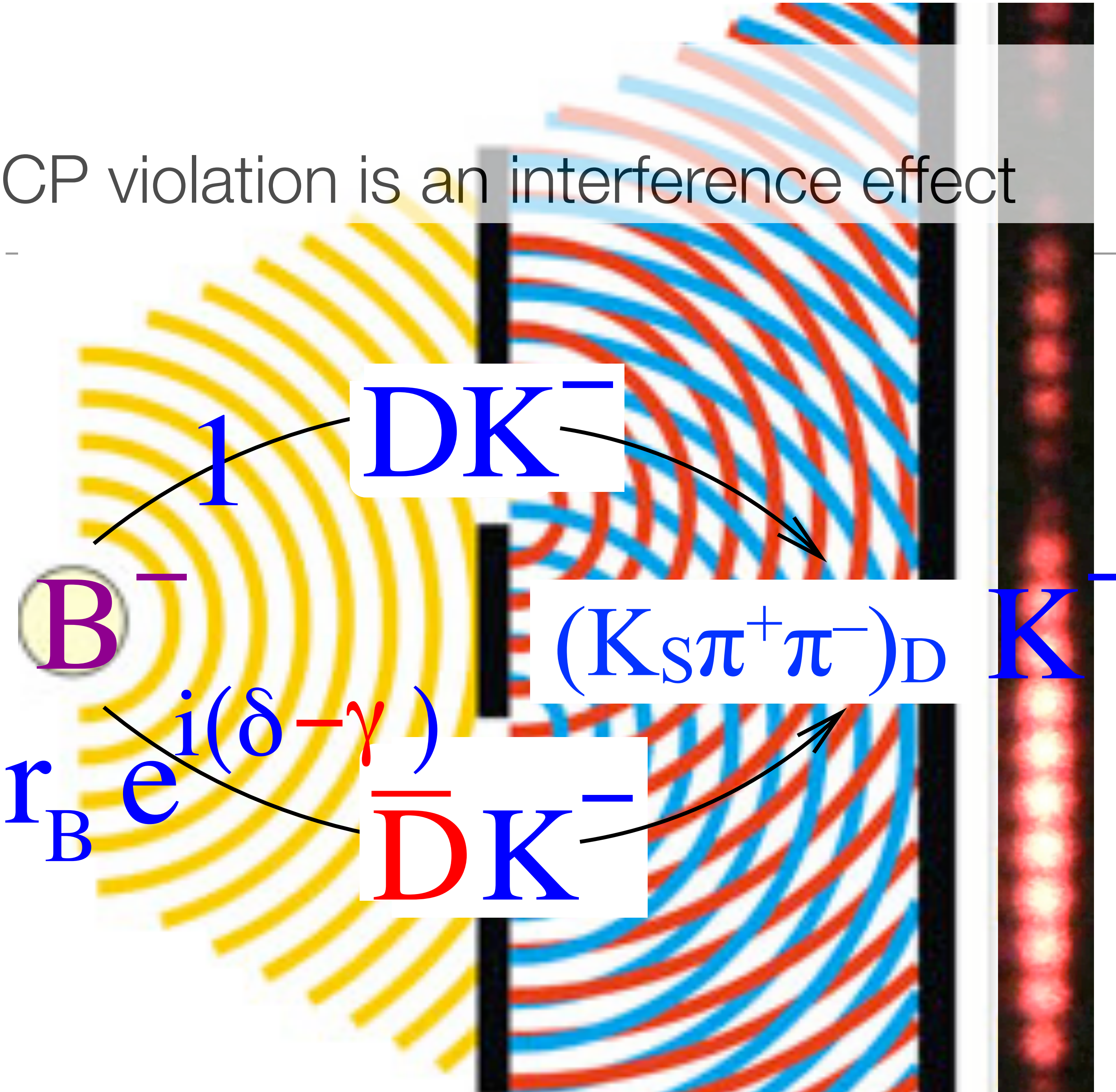
$B^\pm \rightarrow DK^\pm$





Gronau, Wyler Phys.Lett.B265:172-176,1991, (GLW), Gronau, London Phys.Lett.B253:483-488,1991 (GLW) Atwood, Dunietz and Soni Phys.Rev.Lett. 78 (1997) 3257-3260 (ADS) Giri, Grossman, Soffer and Zupan Phys.Rev. D68 (2003) 054018 Belle Collaboration Phys.Rev. D70 (2004) 072003

CP violation is an interference effect



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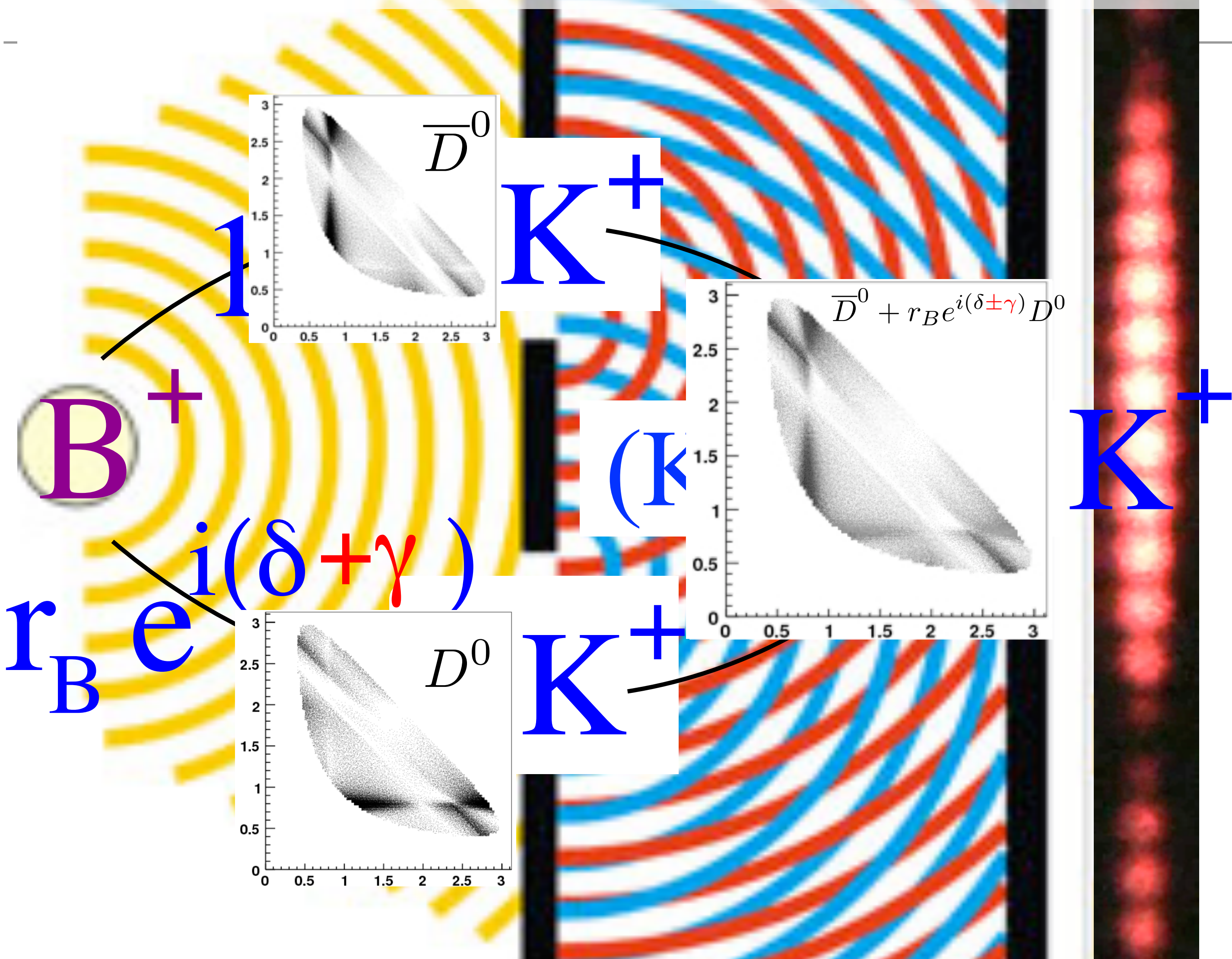
CP violation is an interference effect



- For D→3-body decays, the interference takes place in a 2-D Dalitz plot
- Analysing the Dalitz plot of the D decay, in D's that come from $B^{\pm}$'s, gives access to γ

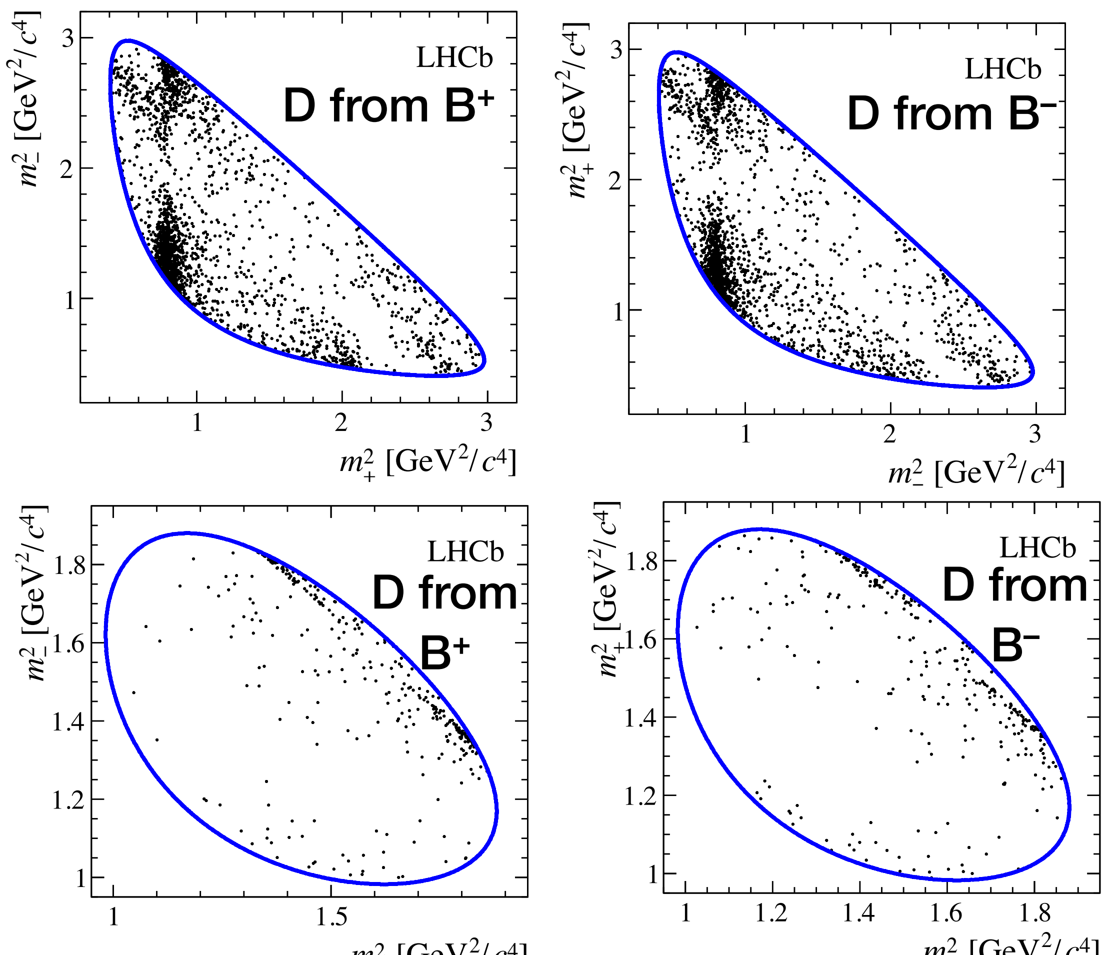
Gronau, Wyler Phys.Lett.B265:172-176,1991, (GLW), Gronau, London Phys.Lett.B253:483-488,1991 (GLW) Atwood, Dunietz and Soni Phys.Rev.Lett. 78 (1997) 3257-3260 (ADS) Giri, Grossman, Soffer and Zupan Phys.Rev. D68 (2003) 054018 Belle Collaboration Phys.Rev. D70 (2004) 072003

LHCb model-independent γ from $B^\pm \to (K_S\pi\pi)_D K$ and $B^\pm \to (K_S KK)_D K$

JHEP 1410 (2014) 97

- Binned, model-independent analysis using CLEO-c input. Phys. Rev. D 82 112006.
- Plots show LHCb 2012 data
- Result of combined analysis (2011 & 2012 data, $K_S\pi\pi$ & $K_S KK$):

$$\gamma = (62\,^{+15}_{-14})^\circ$$



CLEO-c input:: Phys. Rev. D 82 112006.
Model-independent method: Giri, Grossmann, Soffer, Zupan, Phys Rev D 68, 054018 (2003).
Optimal binning: Bondar, Poluektov hep-ph/0703267v1 (2007)
BELLE's first model-independent γ measurement: PRD 85 (2012) 112014

LHCb's γ 2013 combination

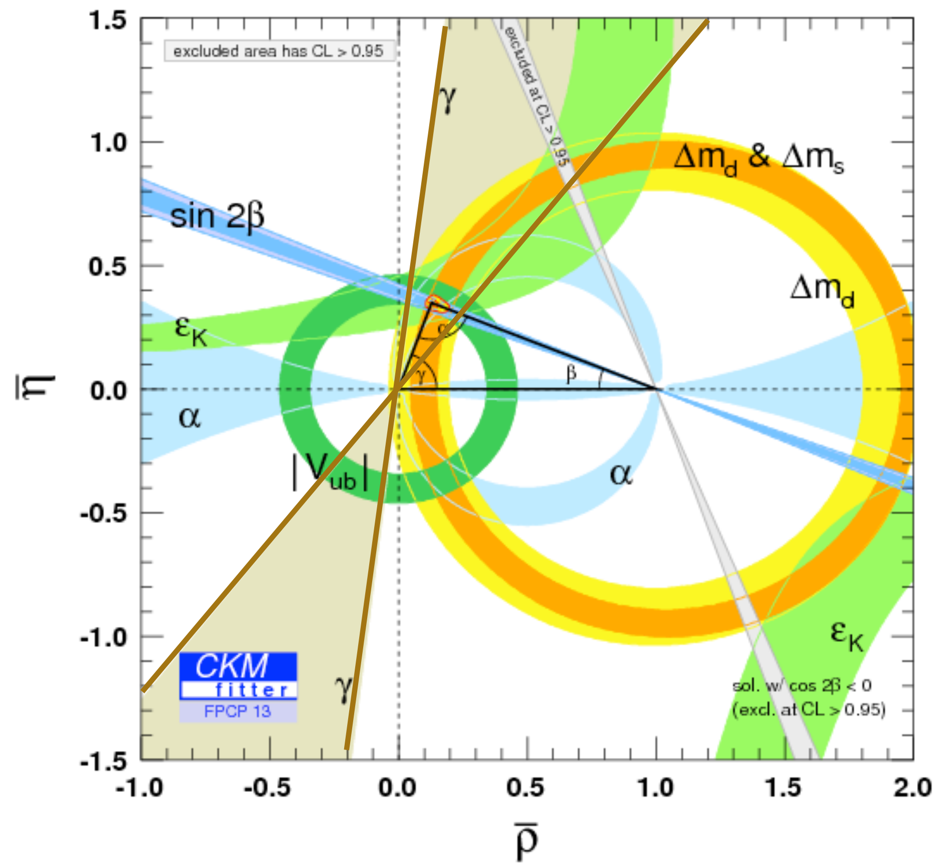
technique & 2011 data: Phys. Lett. B726 (2013) 151

2012 data: LHCb-CONF (2013-006)

- LHCb combines inputs from
  $B^\pm \to (hh')_D K^\pm$
  $B^\pm \to (K_S\pi\pi)_D K^\pm$
  $B^\pm \to (K_S KK)_D K^\pm$
  $B^\pm \to (K\pi\pi\pi)_D K^\pm$

- Result:
  $$\gamma = (67.2 \pm 12)^o$$

World averages by CKM Fitter



previous world average (Moriond 2012): $\gamma = 68^\circ \pm 12^\circ$ → LHCb: γ=67.2°±12° → $\gamma = 68^{\circ}{}^{+8.0^\circ}_{-8.5^\circ}$

technique & 2011 data: Phys. Lett. B726 (2013) 151

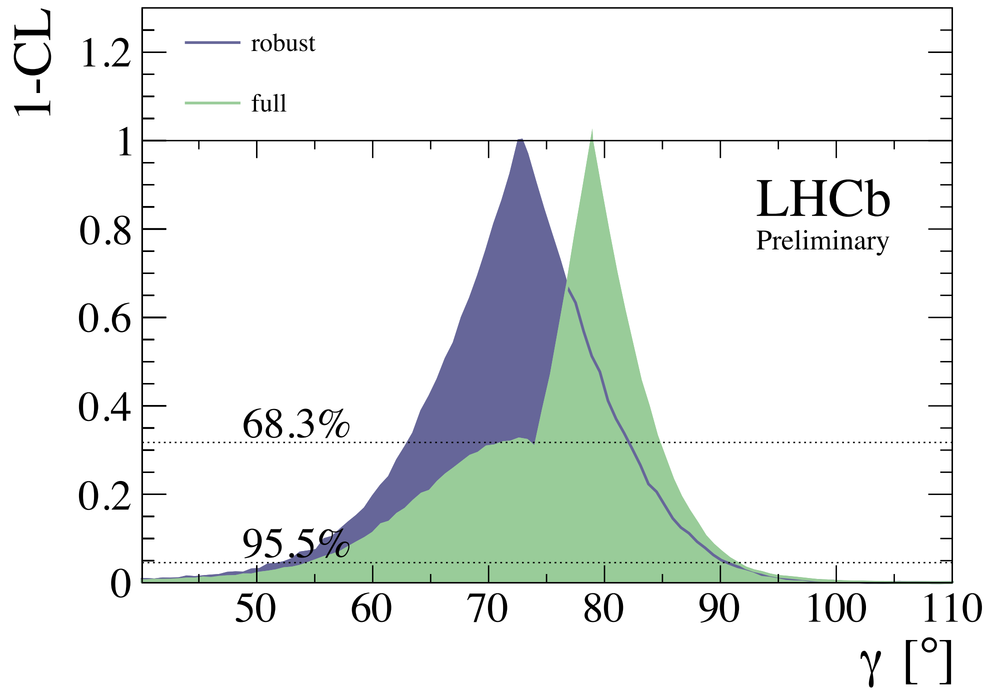
LHCb's 2014 γ combination

2014 combination: LHCB-CONF-2014-004

- LHCb combines inputs from
  $B^{\pm}\to DK^{\pm}$, $B^{\pm}\to D\pi^{\pm}$, $B^0\to DK^*$,
  LHCB-PAPER-2014-028

  where $D\to K_S\pi\pi$, K_SKK, $K_SK\pi$, $K\pi\pi\pi$.
  JHEP 1410 (2014) 97 arXiv:1402.2982 (2014)
- Also: $B_s^0\to D_s^{\mp}K^{\pm}$ (time-dependent)
  arXiv:1407.6127 (2014)
- Combined result:
  - all modes $\gamma = 78^{\circ}{}^{+5.8^{\circ}}_{-7.4^{\circ}}$
  - "robust" (only $B^{\pm}\to DK^{\pm}$ modes, theoretically cleanest)

$$\gamma = 73^{\circ}{}^{+9^{\circ}}_{-10^{\circ}}$$

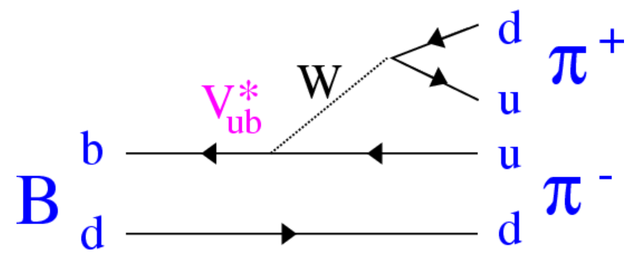


Expect substantial progress in Run II, and <1° with upgrade. (Theory error negligible).

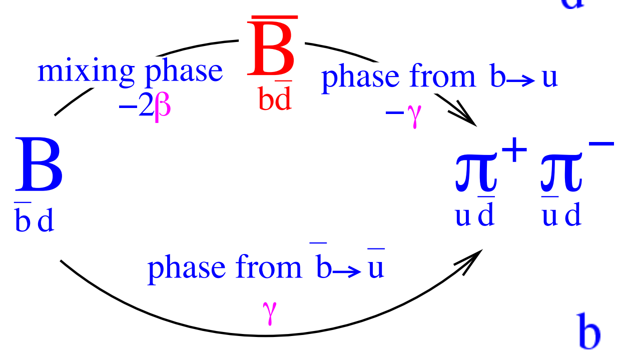
γ with loops from $B^0\to\pi\pi$, $B_s\to KK$

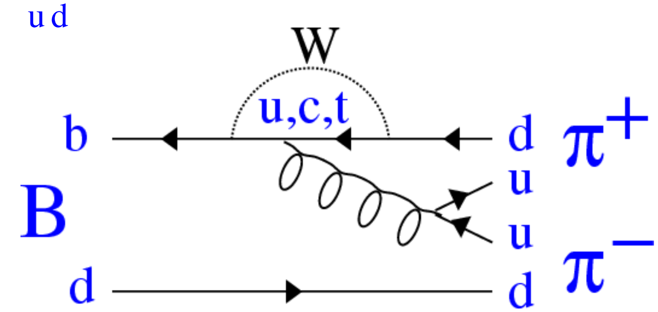
arXiv:1408.4368 (2014)

- If there were only the tree-contribution, $B^0\to\pi\pi$ would measure $2\beta + 2\gamma$, $B_s\to KK$ would measure $-\phi_s + 2\gamma$.



- But there are penguins. They complicate things, but provide sensitivity to new physics.





- Disentangle Penguin and Tree contribution. Assumes U-spin ($d \leftrightarrow s$) symmetry of strong interaction. Allows for up to 50% U-spin breaking.

Theory: Fleischer, Phys. Lett. B459 (1999) 306; Ciuchini, Franco, Mishima, Silvestrini: JHEP 10 (2012) 0

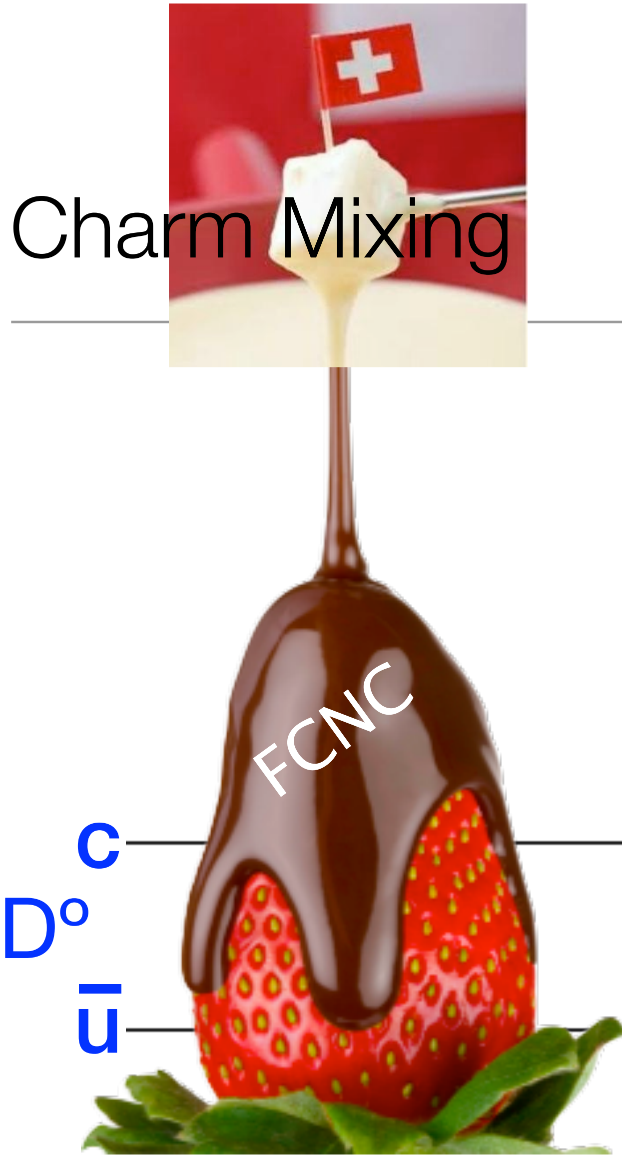
$$\gamma = \left(63.5^{+7.2}_{-6.7}\right)^\circ$$

compare to

$$\gamma = 73^{\circ}{}^{+9^\circ}_{-10^\circ}$$ or $$\gamma = 78^{\circ}{}^{+5.8^\circ}_{-7.4^\circ}$$

Charm Mixing

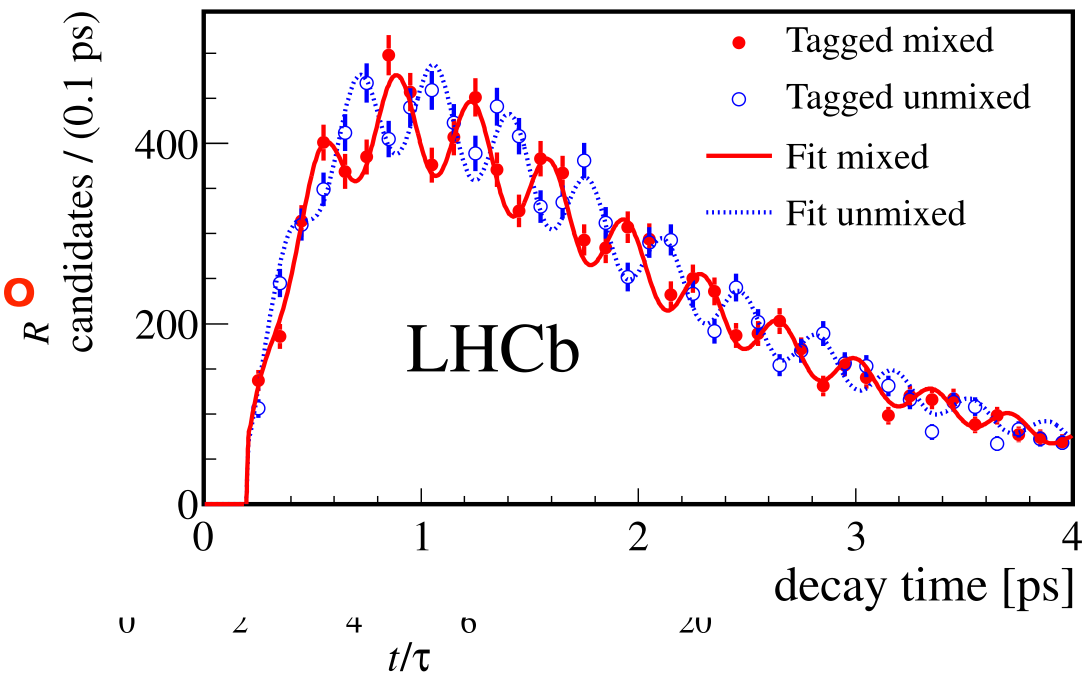
New J.Phys. 15 (2013) 053021



$$\frac{\Gamma(D^0 \to K^+\pi^-)}{\Gamma(D^0 \to K^-\pi^+)}(t)$$

numerator: mixing amplitude $D^o \to \bar{D}^o \to K^+\pi^-$ significant

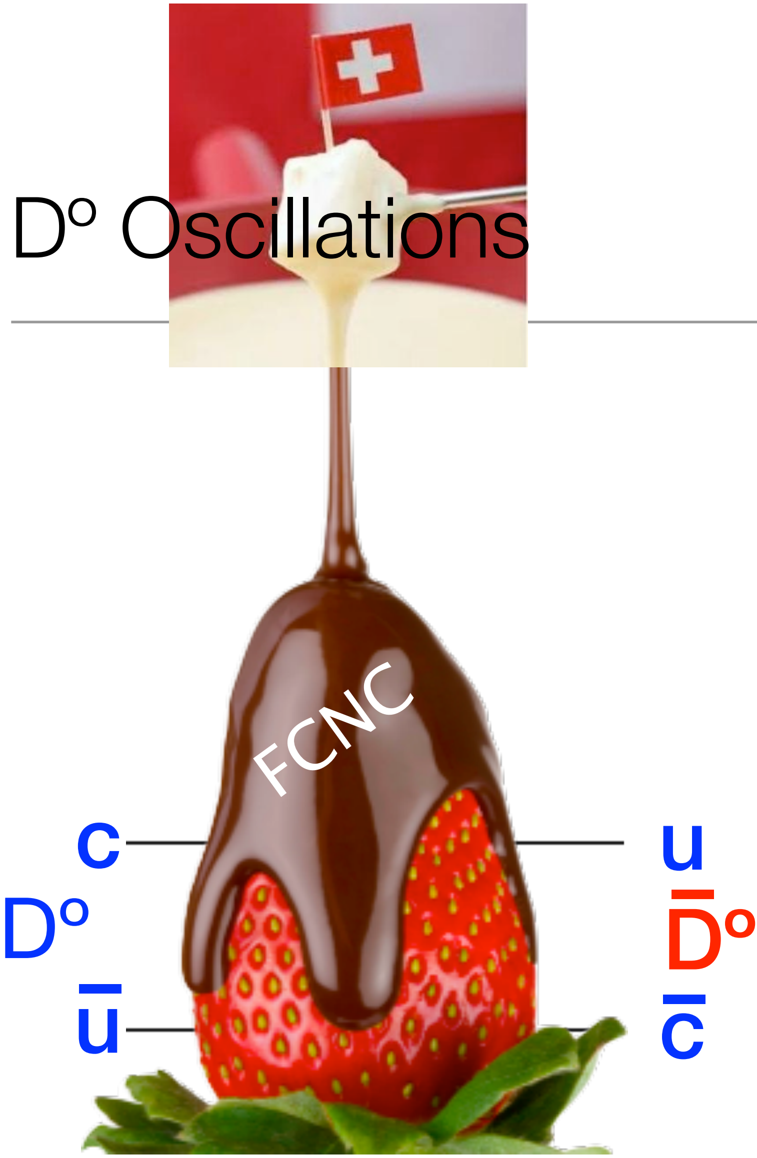
denominator: for normalisation (mixing negligible)



First single measurement with >5σ observation of charm mixing.

New J.Phys. 15 (2013) 053021

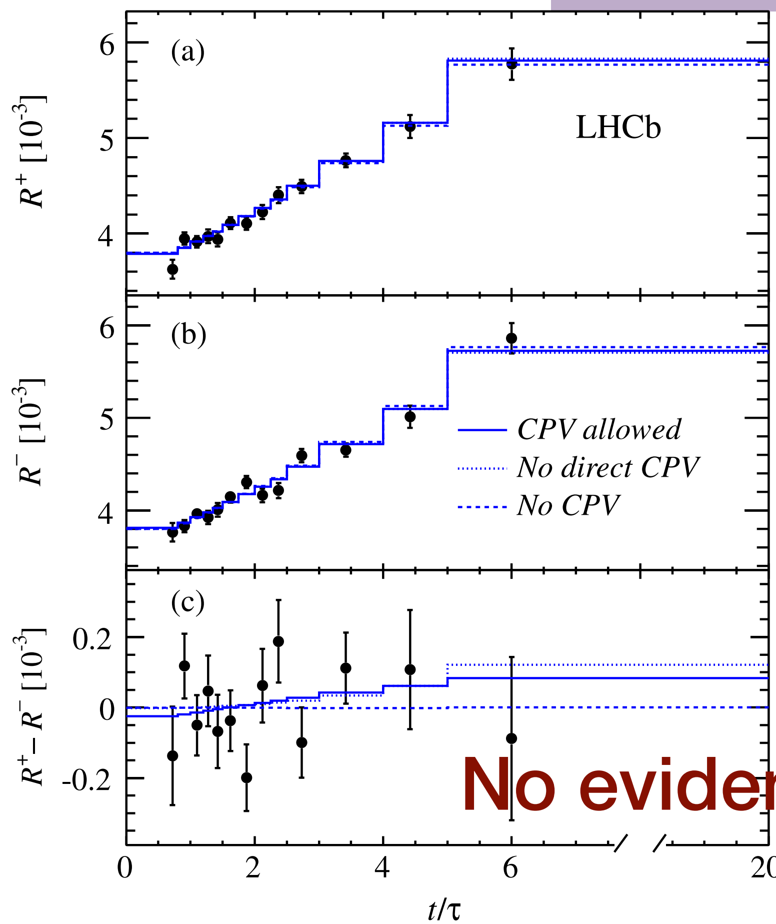
D° Oscillations



$$\frac{\Gamma(D^0 \to K^+\pi^-)}{\Gamma(D^0 \to K^-\pi^+)}(t)$$

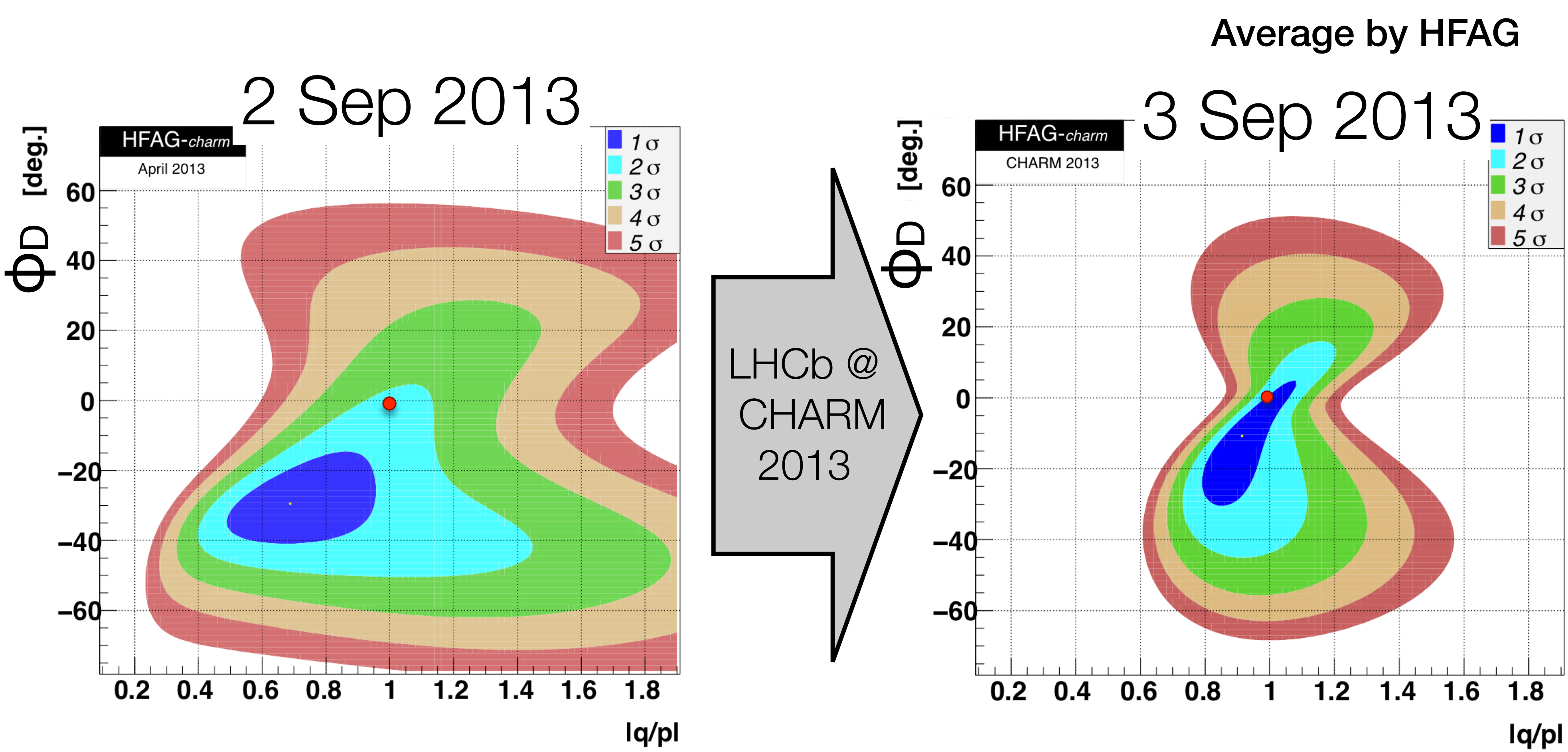
numerator: mixing amplitude D°→D̄°→K⁺π⁻ significant

denominator: for normalisation (mixing negligible)



No evidence for CPV

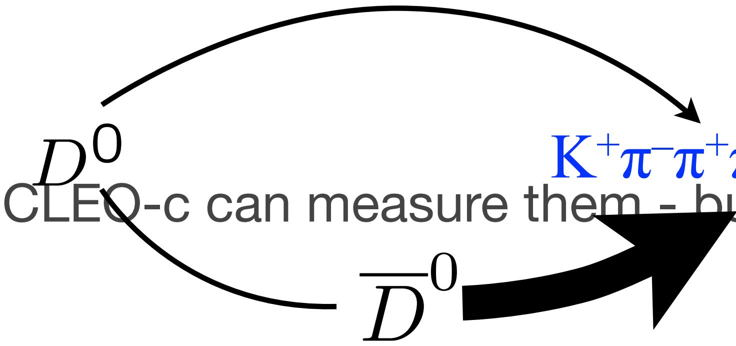
Impact on world average for CPV in mixing & interference between mixing and decay.

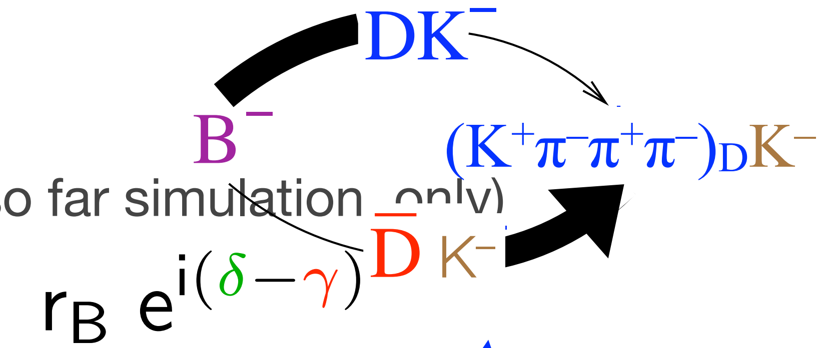


Again, no evidence of CP violation or new physics - but a very impressive improvement in our knowledge

D^0 Mixing as input to γ from $B^{\pm}\rightarrow DK^{\pm}$

- CLEO-c can measure them - but so can we (so far simulation only)

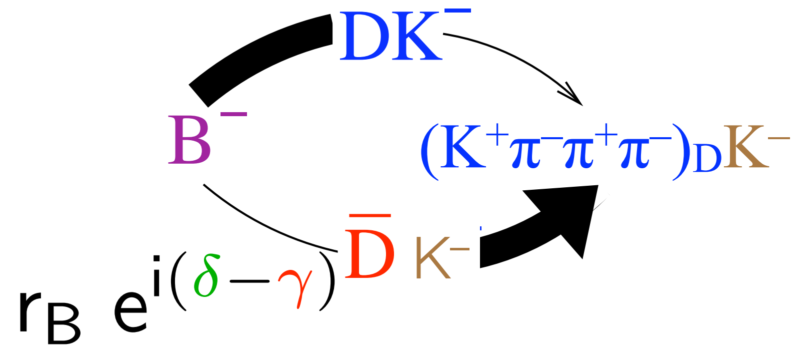




This process is sensitive to the same D-$\overline{\text{D}}$ interference effects that pollute this measurement.

Phys.Lett. B728 (2014) 296-302

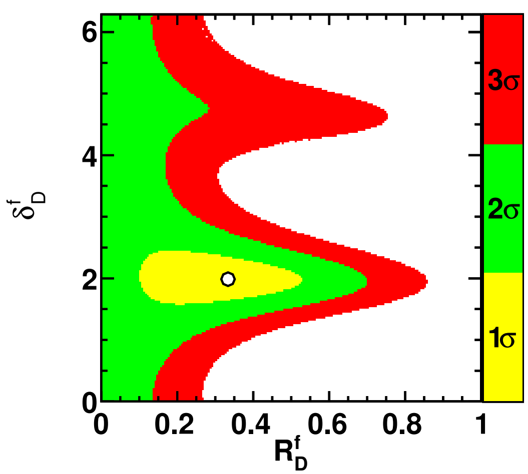
Mixing as input to γ from



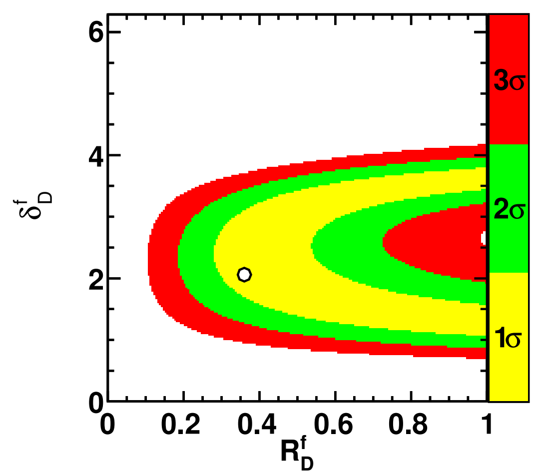
Use interference effects in charm mixing as input to γ

$$\Gamma\left(B^- \to \left(K^+3\pi\right)_D K^-\right) \propto r_B^2 + \left(r_D^{K3\pi}\right)^2 + 2R_{K3\pi} r_B r_D^{K3\pi} \cdot \cos\left(\delta_B + \delta_D^{K3\pi} - \gamma\right)$$

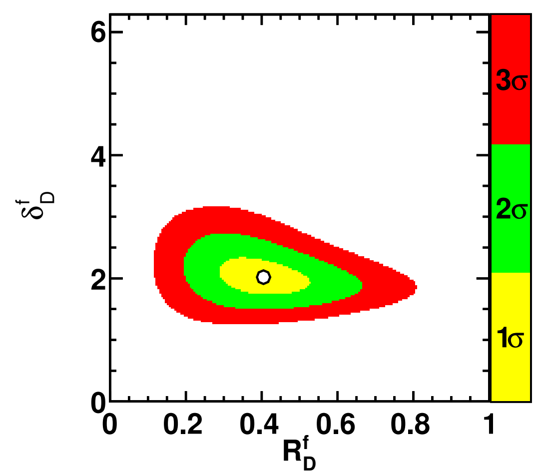
from D-$\bar{D}$ superpositions at CLEO-c



Input from charm mixing. Toy **simulation** with 8M CF+DCS events



Combination:CLEO-c and mixing simulation (with real data, soon).



<u>CLEO-c input theory</u>: Atwood, Soni: Phys.Rev. D68 (2003) 033003
<u>CLEO-c input: </u>Phys.Rev.D80:031105,2009, update
LHCb/mixing theory: arXiv:1309.0134 (2013)

<u>Phys.Lett. B728 (2014) 296-302</u>

Searches for CPV by comparing binned Dalitz plots

- Compare yields in CP-conjugate bins

$$S_{CP} = \frac{N_i - \alpha \overline{N}_i}{\sigma(N_i - \alpha \overline{N}_i)}$$

$$\alpha = \frac{N_{\text{total}}}{\overline{N}_{\text{total}}}$$

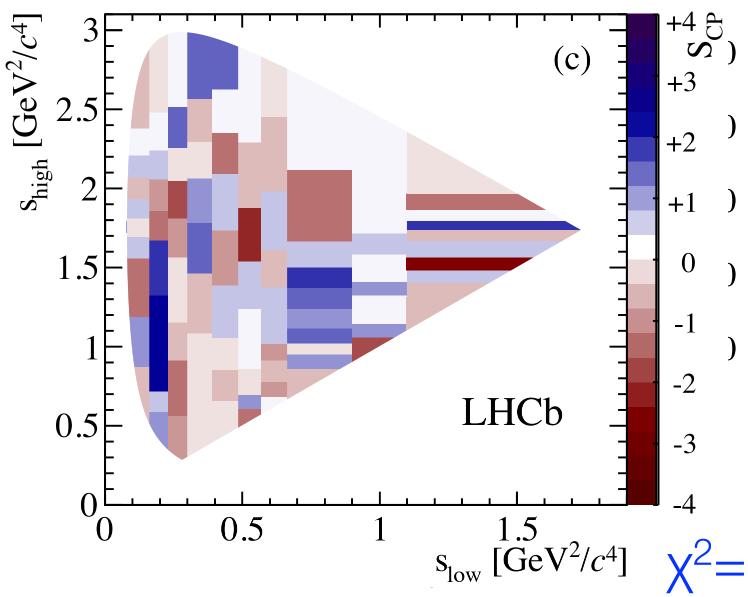
- Calculate p-value for no-CPV hypothesis based on

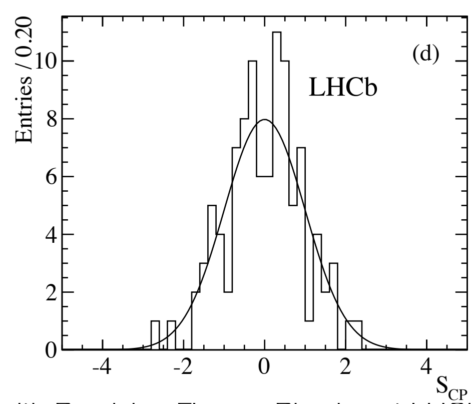
$$\chi^2 = \sum_i (S_{CP}^i)^2$$

- Model independent. Many production and detection effects cancel.

3.1M D±→πππ in 1/fb

Phys.Lett. B728 (2014) 585-595





χ^2=89.1 for 100 bins - compatible with CP conservation at

p=75%

(other binning schemes lead to similar result)

Phys.Lett. B728 (2014) 585-595
Phys. Lett. B 723 (2013) 33-43
LHCb-CONF-2013-003 (2013)
JHEP 1306 (2013) 112
Phys.Lett. B726 (2013) 623-633
PhysRevD.84.112008 (2011)

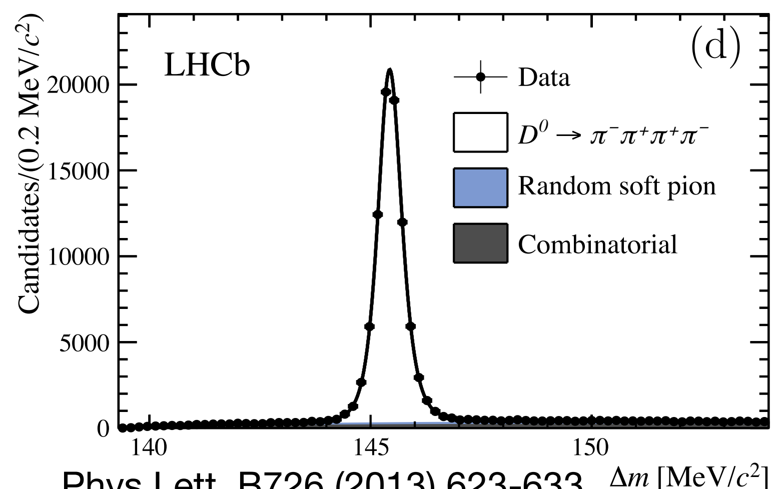
More CPV in charm.

- Compare D→f yields with $\overline{\text{D}}$→$\overline{\text{f}}$.
- Looking for tiny signals. LHCb uses huge data samples, and data-driven methods to control systematics.
- Looked at hundreds of millions of clean signal events in various singly Cabibbo suppressed decay channels (the ones with penguins).
- Sadly, no evidence for direct CPV.

LHCb charm data are amazingly clean.

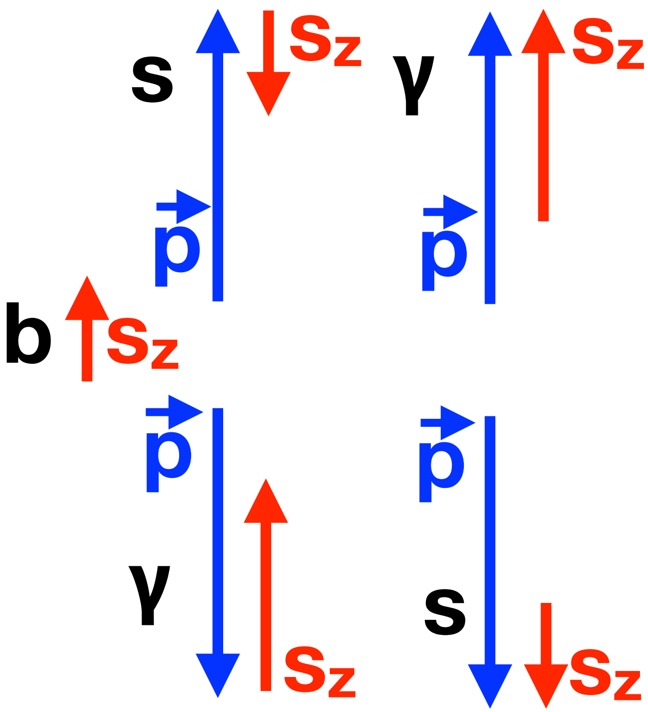
Example below: 330k $D^{*+}\to D^o\pi$, $D^o\to\pi\pi\pi\pi$ in 1/fb for CPV.

This is a Cabibbo-suppressed decay. We have to reconstruct a 5-pion final state at a hadron collider. And we see hardly any background.



Phys.Lett. B726 (2013) 623-633

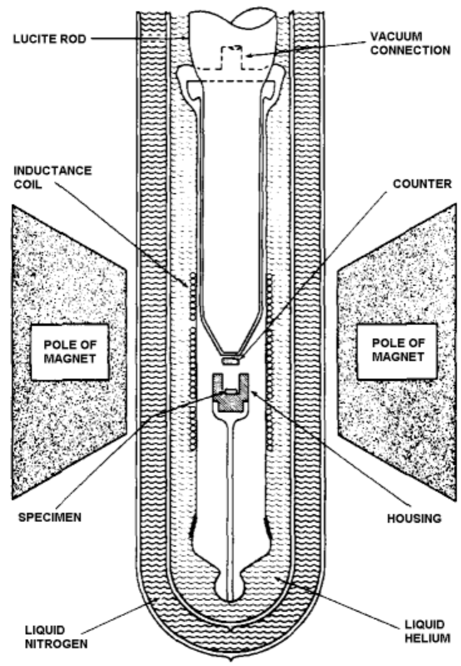
Photon polarisation in b→sγ



OK

wrong helicity, highly suppressed

But: why repeat Madame Wu's experiment?

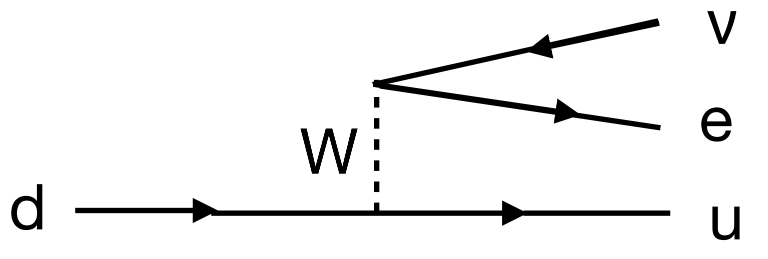


Phys. Rev. 105, 1413 (1957)

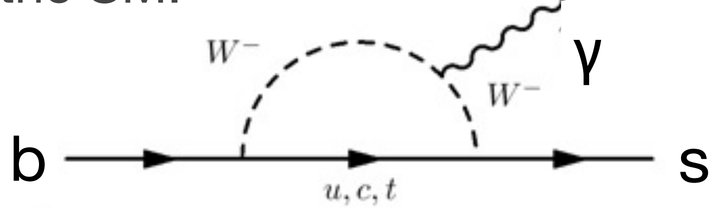
Photon from b→s transitions in the SM are, up to $0(m_s/m_b)^2$ corrections, left-handed.

Photon polarisation in b→sγ

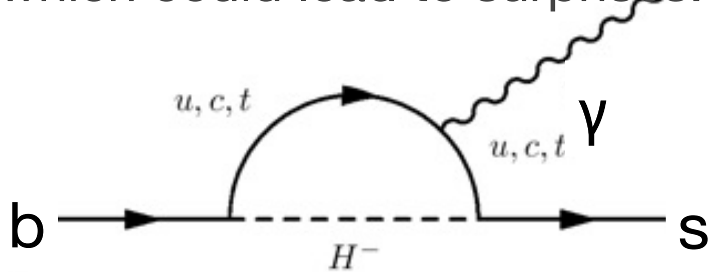
- Mme Wu studied a tree-level decay:



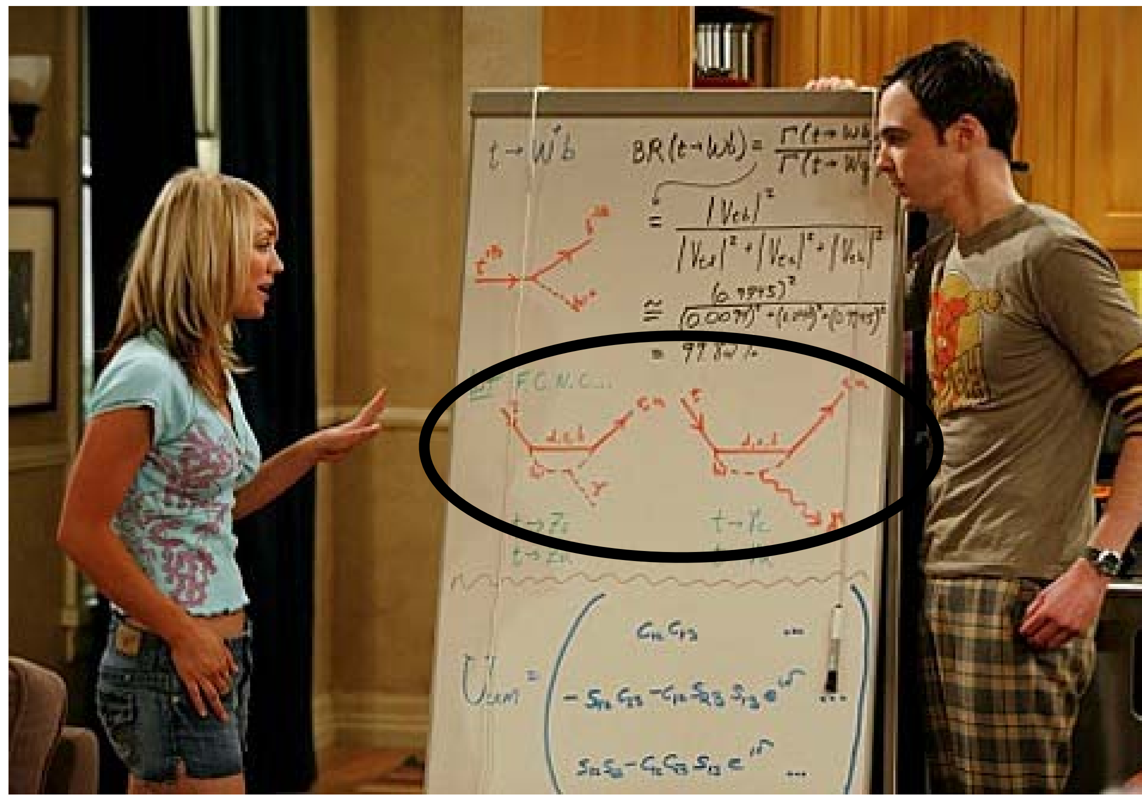
- b→sγ is a loop-mediated FCNC in the SM:



- which could lead to surprises:

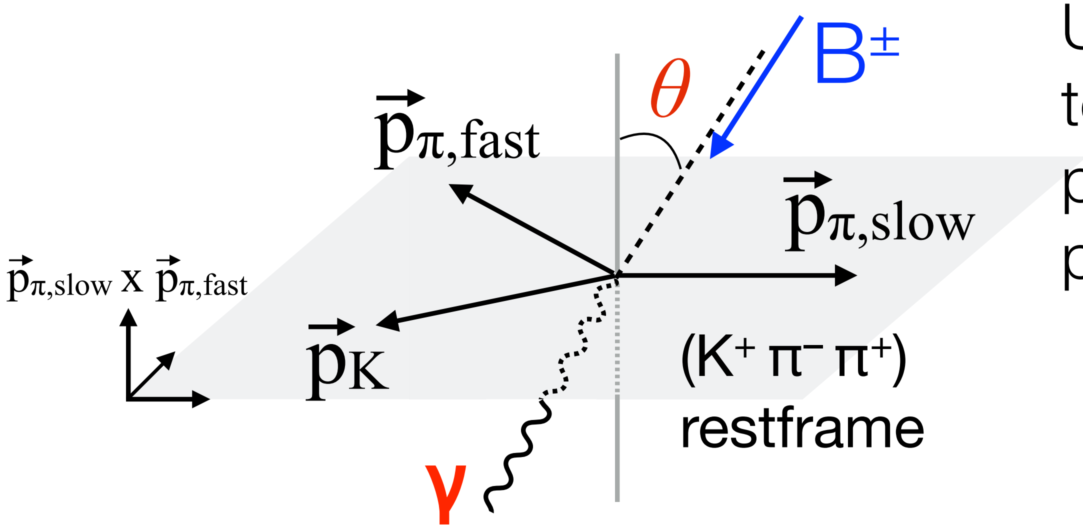


But: why repeat Madame Wu's experiment?



LHCb: arXiv:1402.6852 (2014)

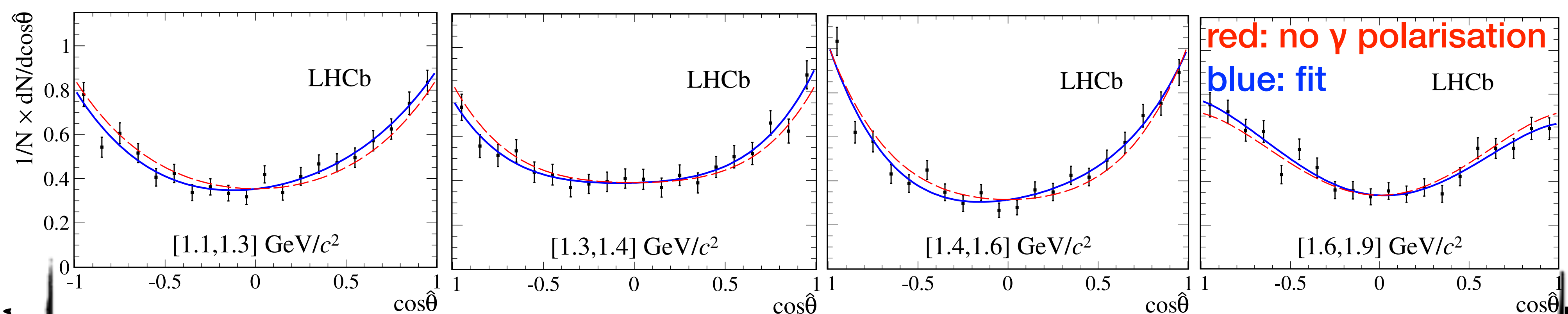
Photon polarisation in b→sγ with $B^\pm \to K^+ \pi^- \pi^+ \gamma$



Up-down asymmetry relative to (oriented) $K^+ \pi^- \pi^+$ decay plane is proportional to photon polarisation λ_γ.

$$\cos\hat{\theta} = \text{sign}(\text{charge}) B^\pm \cos\theta$$

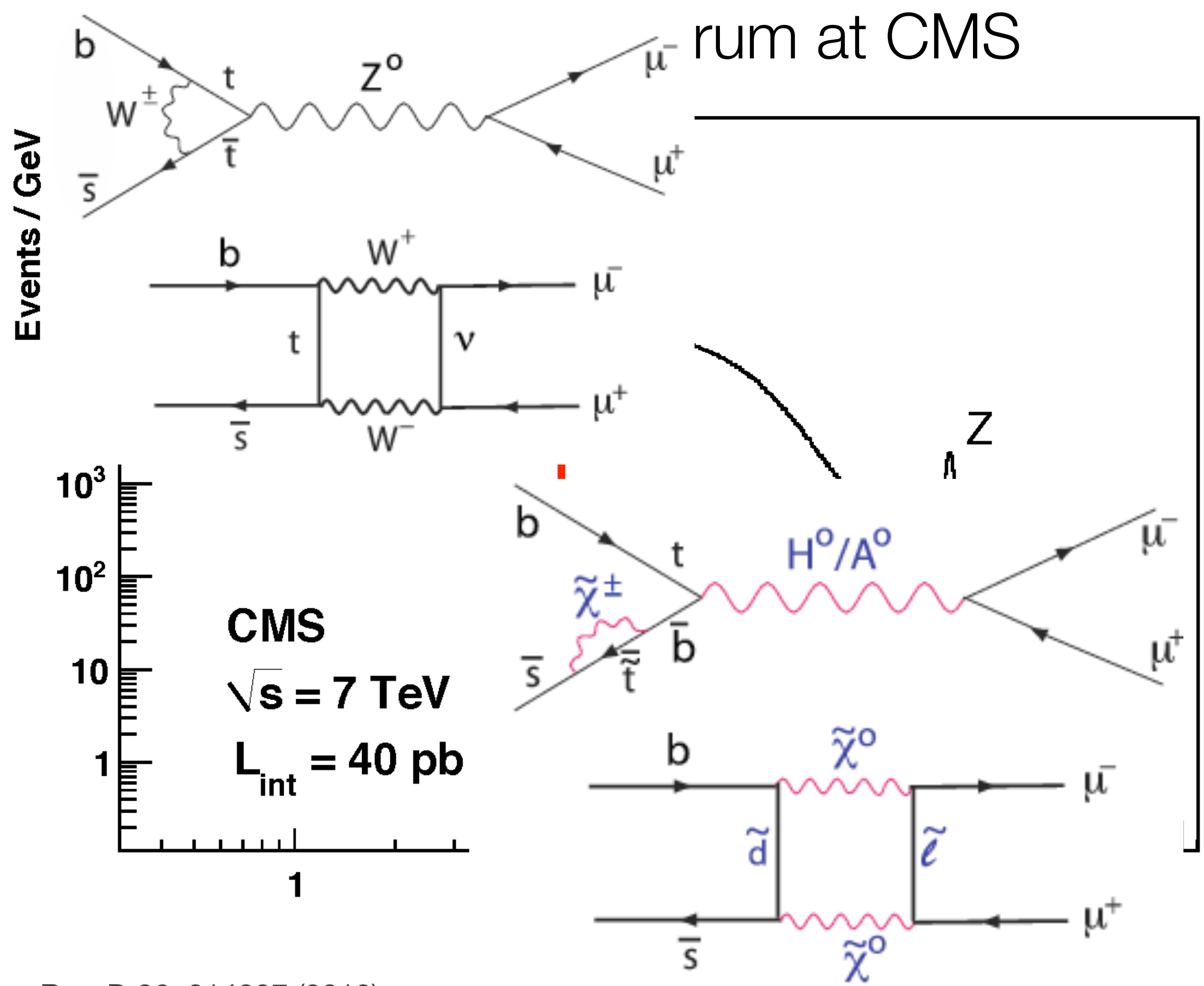
in bins of $(K^+ \pi^- \pi^+)$ mass



First observation of P violation in radiative decays.

$B_s \to \mu\mu$

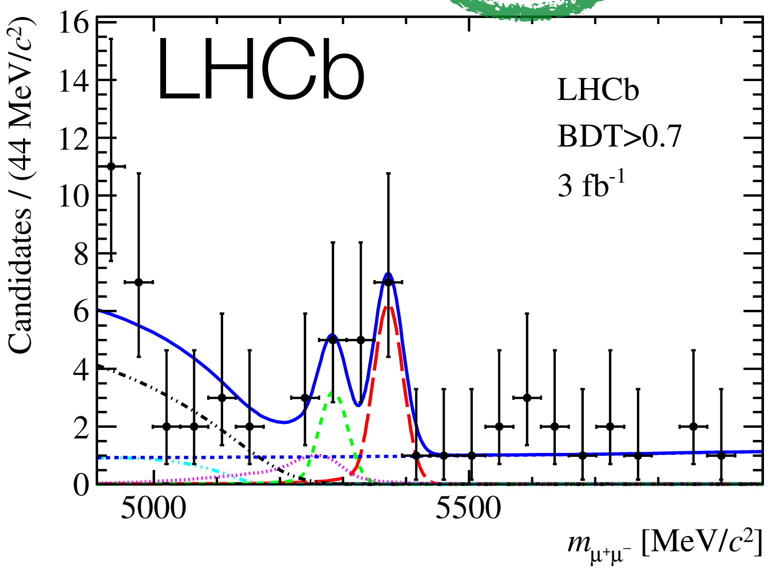
- Helicity-suppressed FCNC - very rare in SM!
- SM prediction [1]*:
  $BF(B_s \to \mu^+\mu^-) = (3.56 \pm 0.30) \cdot 10^{-9}$
  $BF(B_d \to \mu^+\mu^-) = (1.07 \pm 0.05) \cdot 10^{-10}$
- Large enhancements in many SUSY models, $\propto \tan^6\beta$



[1] Eur. Phys. J. C72 (2012) 2172 and Phys. Rev. D 86, 014027 (2012)
*) this BF refers to the time-integrated value, which differs from the one at t=0 due to the lifetime difference between the two B_s mass eigenstates. See Phys. Rev. D 86, 014027 (2012).

$B_{(s)} \to \mu^+\mu^-$

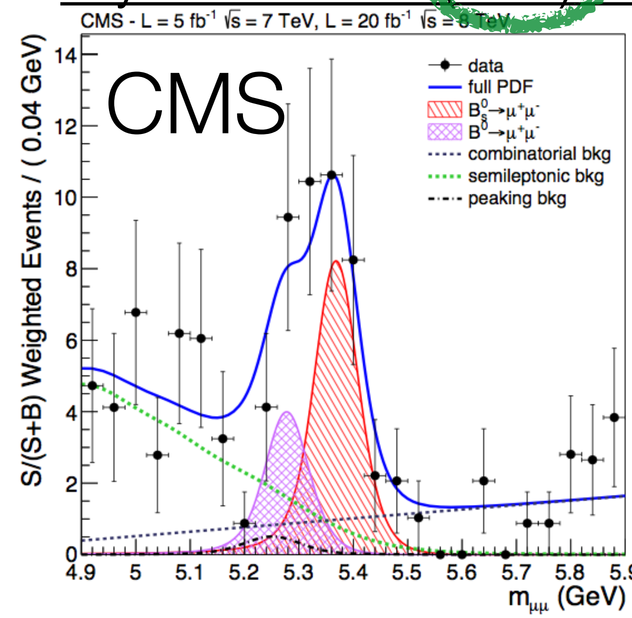
Phys.Rev.Lett. 111 (2013) 101805



$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9^{+1.1+0.3}_{-1.0-0.1}) \times 10^{-9}$$

$$\mathcal{B}(B_d^0 \to \mu^+\mu^-) = (3.7^{+2.4+0.6}_{-2.1-0.4}) \times 10^{-10}$$

Phys.Rev.Lett. 111 (2013) 101804



$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.7^{+1.0}_{-0.9}) \times 10^{-9}$$

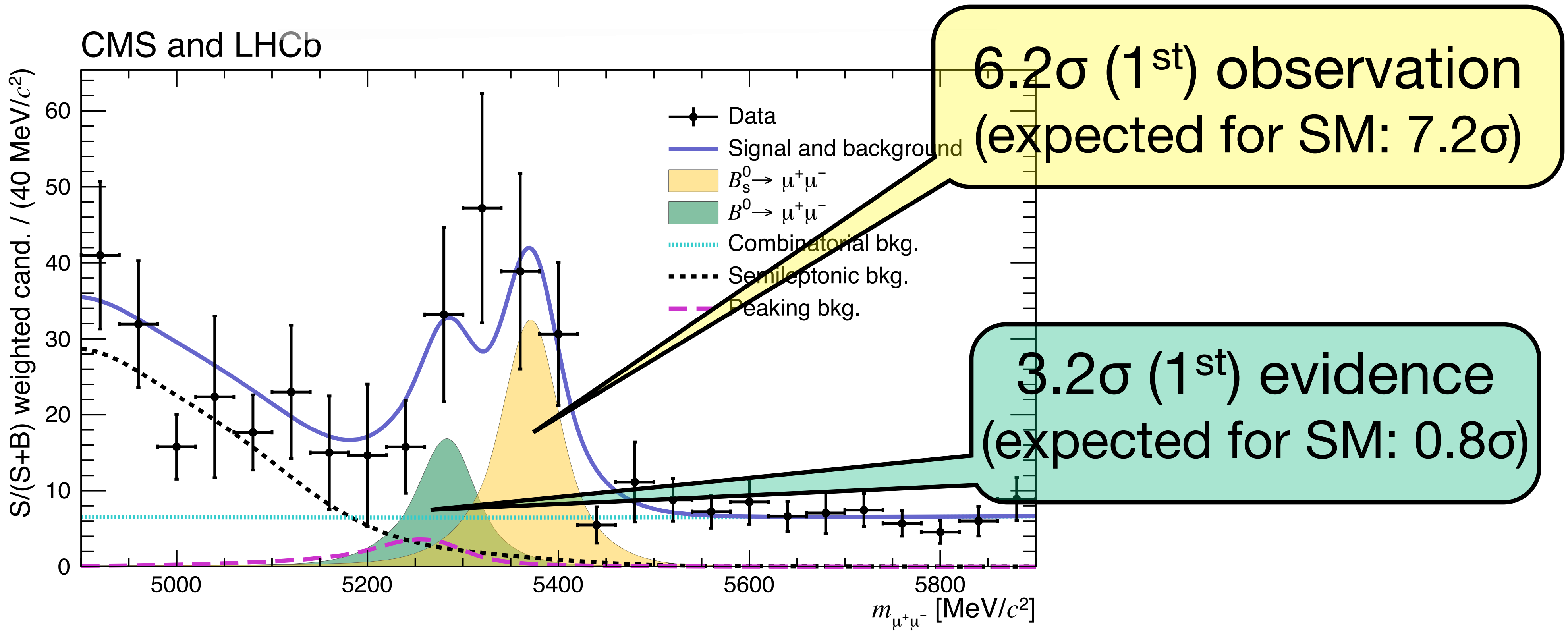
$$\mathcal{B}(B_d^0 \to \mu^+\mu^-) = (3.5^{+2.1}_{-1.8}) \times 10^{-10}$$

[LHCb-CONF-2013-012] [CMS-PAS-BPH-13-007]

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9} \qquad \mathrm{SM:} (3.2 \pm 0.2) \times 10^{-9}$$

$$\mathcal{B}(B_d^0 \to \mu^+\mu^-) = (3.6^{+1.6}_{-1.4}) \times 10^{-10} \qquad \mathrm{SM:} (1.0 \pm 0.1) \times 10^{-10}$$

2014 Combination of CMS & LHCb

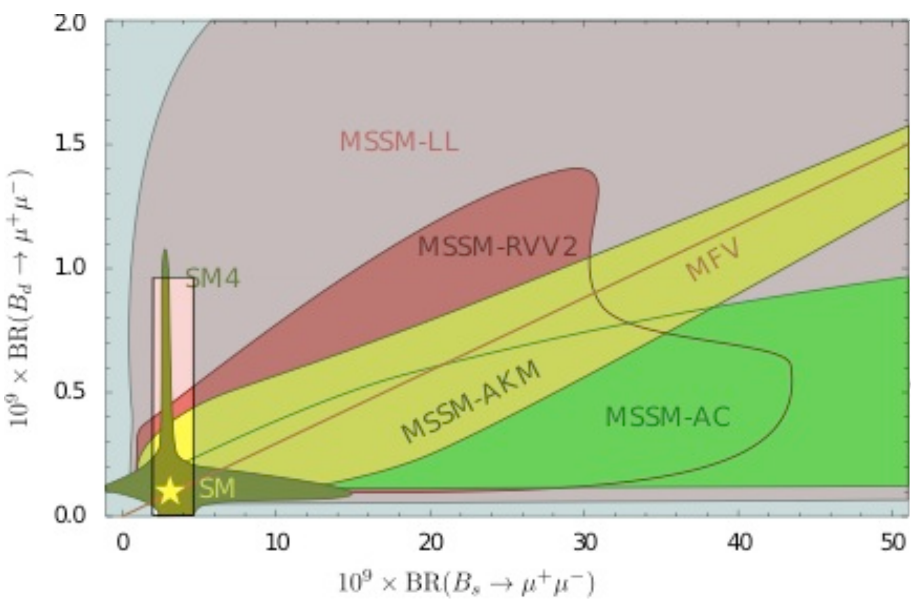


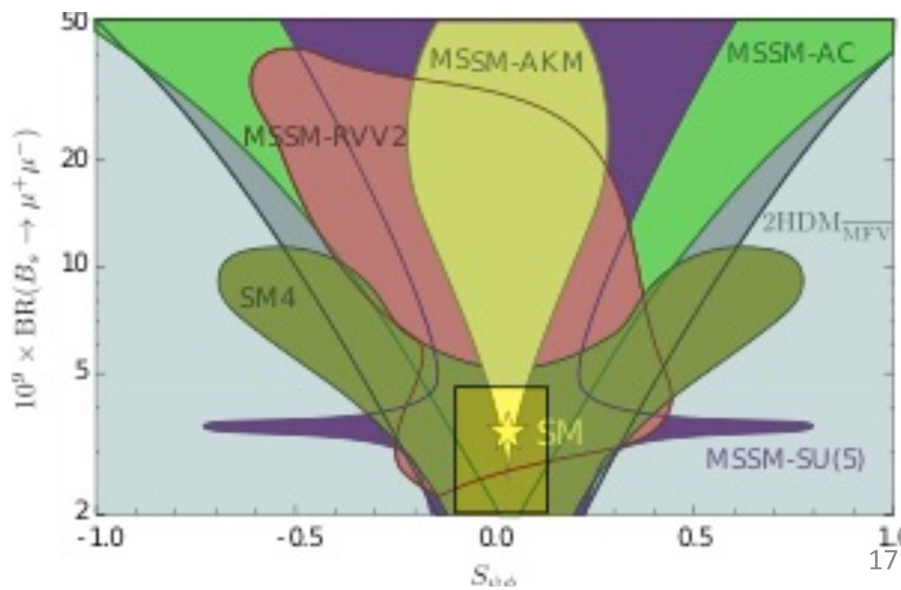
$$\mathcal{BR}(B_s \to \mu^+\mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$$

$$\mathcal{BR}(B_d \to \mu^+\mu^-) = 3.9^{+1.6}_{-1.4} \times 10^{-10}$$

$B_{(s)} \rightarrow \mu^+\mu^-$ - ~~Golden decay channel for New Physics~~ SUSY killer

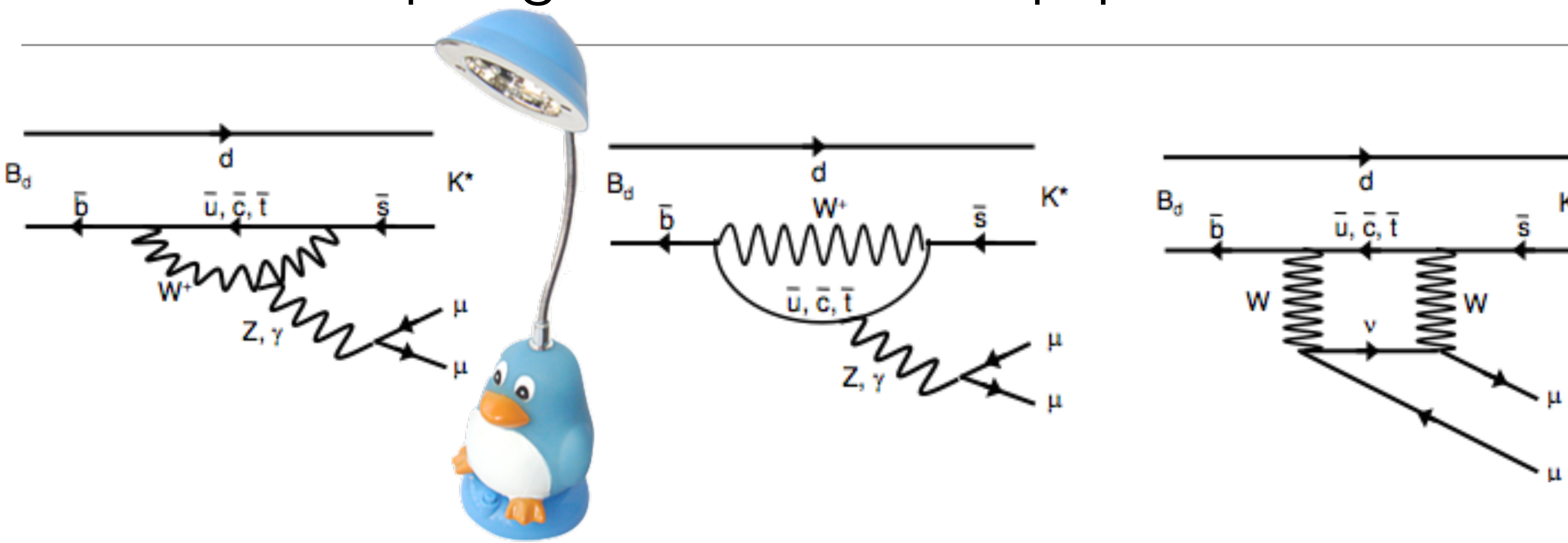
adapted from
D.Straub arXiv:1205.6094



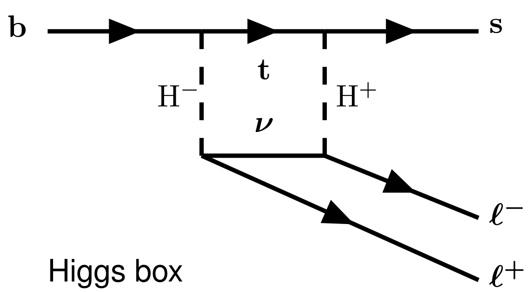


(OK, SUSY is not really dead, but it's definitely looking a bit under the weather)

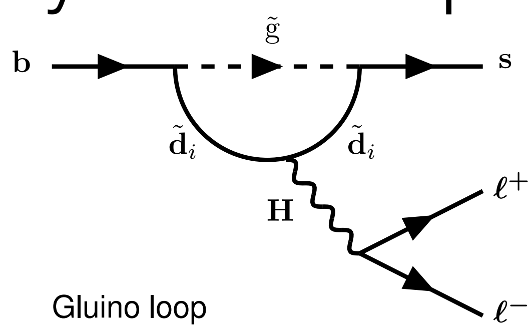
Electroweak penguins with B→K*μ+μ−



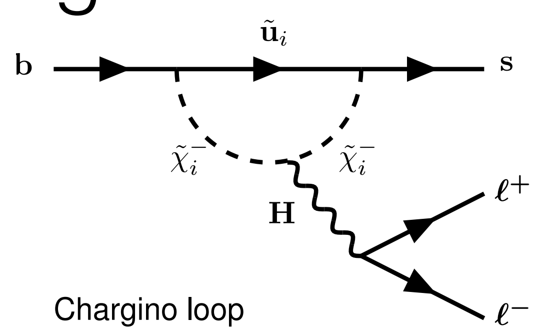
sensitive to New Physics in loops, e.g.



Higgs box



Gluino loop

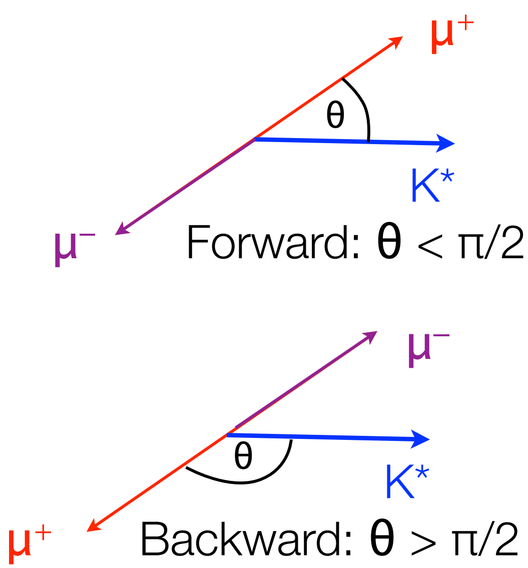


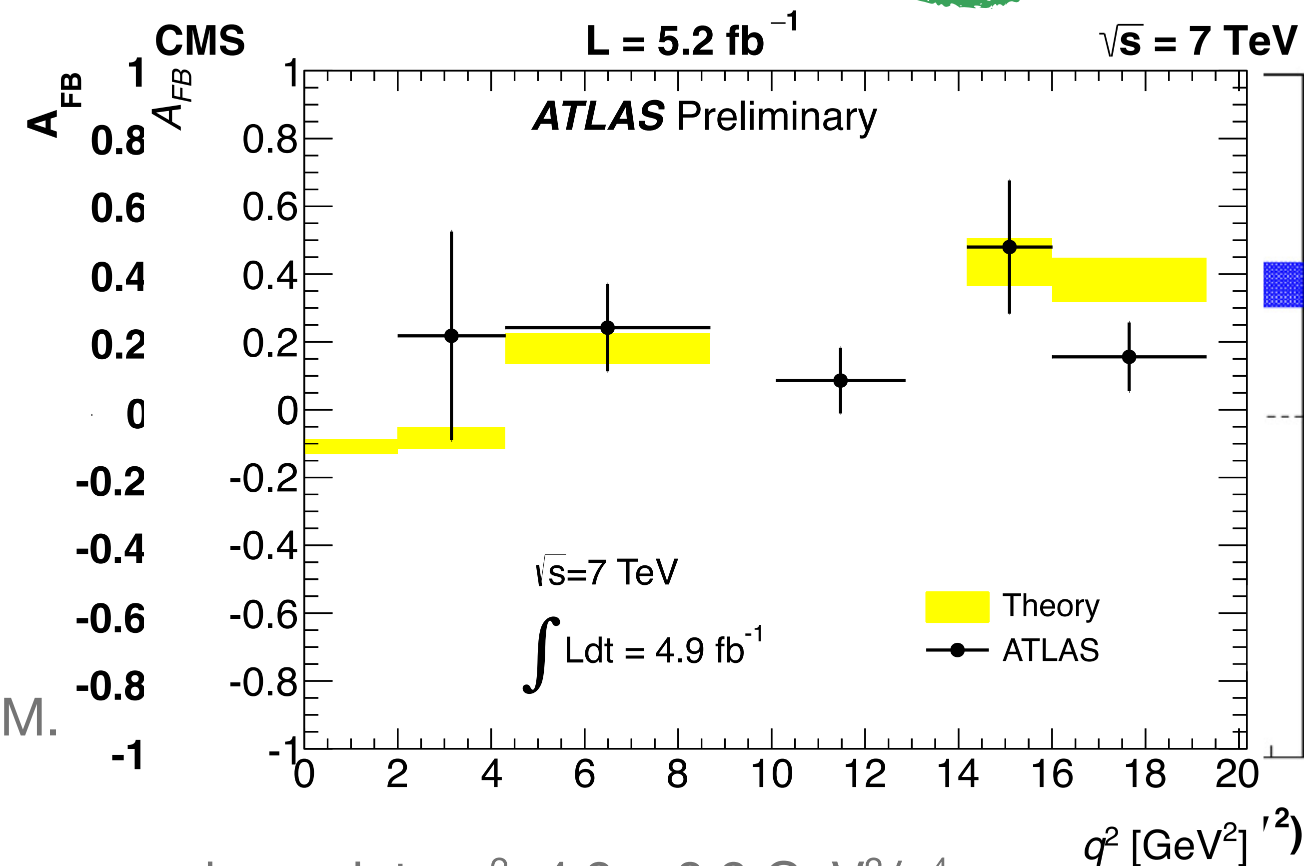
Chargino loop

$B \to K^* \mu^+ \mu^-$: Forward-backward asymmetry

ATLAS-CONF-2013-038
CMS: Physics Letters B 727 (2013) 77–100
LHCb: JHEP 1308 (2013) 131
Theory: Phys.Rev. D87 (2013) 034016

- Forward-backward asymmetry as function of $q^2 = m^2(\mu\mu)$



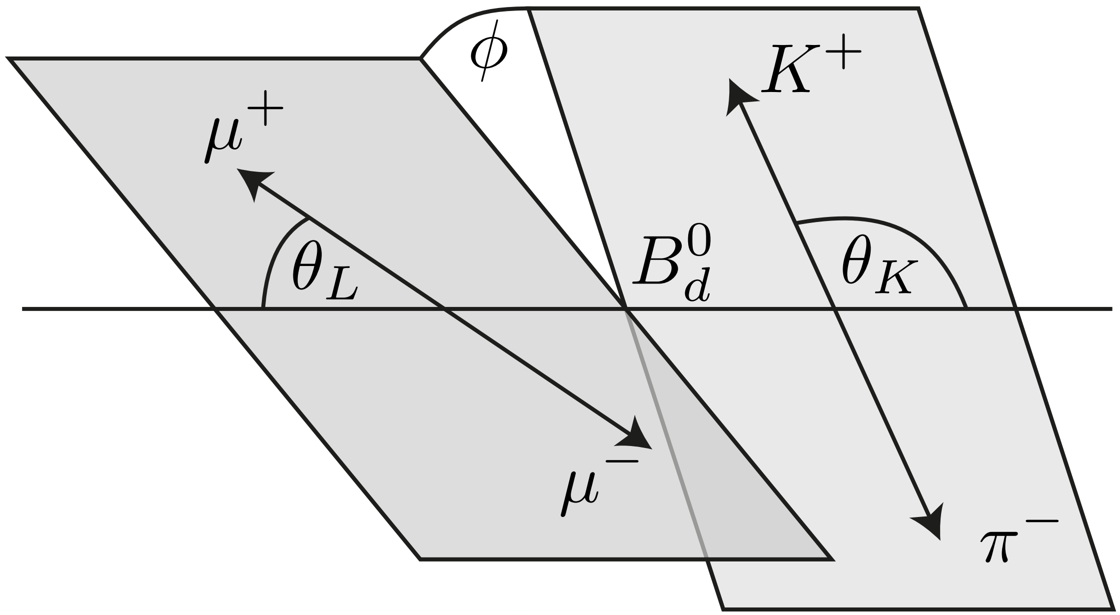


- Good agreement with SM.

- First measurement of zero-crossing point: $q_0^2 = 4.9 \pm 0.9$ GeV^2/c^4

$B \to K^* \mu^+ \mu^-$: P'5

Phys.Rev.Lett. 111 (2013) 191801



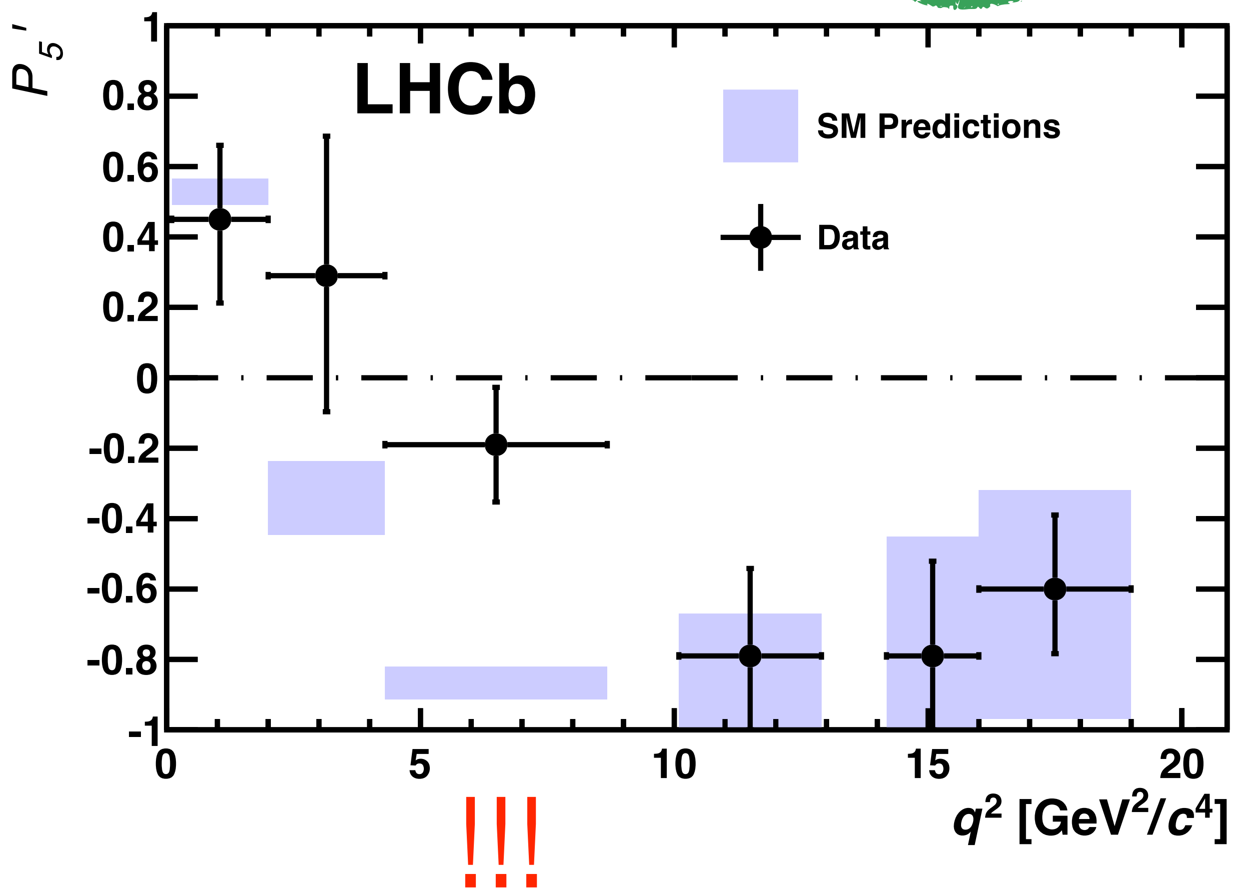
$$\frac{1}{\Gamma}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + \frac{1}{2}(1-F_L)A_T^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi +$$
$$\sqrt{F_L(1-F_L)}P_4'\sin 2\theta_K\sin 2\theta_\ell\cos\phi + \sqrt{F_L(1-F_L)}P_5'\sin 2\theta_K\sin\theta_\ell\cos\phi +$$
$$(1-F_L)A_{Re}^T\sin^2\theta_K\cos\theta_\ell + \sqrt{F_L(1-F_L)}P_6'\sin 2\theta_K\sin\theta_\ell\sin\phi +$$
$$\sqrt{F_L(1-F_L)}P_8'\sin 2\theta_K\sin 2\theta_\ell\sin\phi + (S/A)_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

$B \to K^* \mu^+ \mu^-$: P'5

LHCb: Phys.Rev.Lett. 111 (2013) 191801

Theory: JHEP 05 (2013) 137

- Might seem an abstract variable but it is theoretically better understood than A_{FB}, as it is less sensitive to form factors.
- 3.7 σ discrepancy in the region $4.3 < q^2 < 8.68$ GeV^2
- 0.5% probability (2.8σ) to observe such a deviation given 24 independent measurements (several other variables probed, each in several bins of q^2).

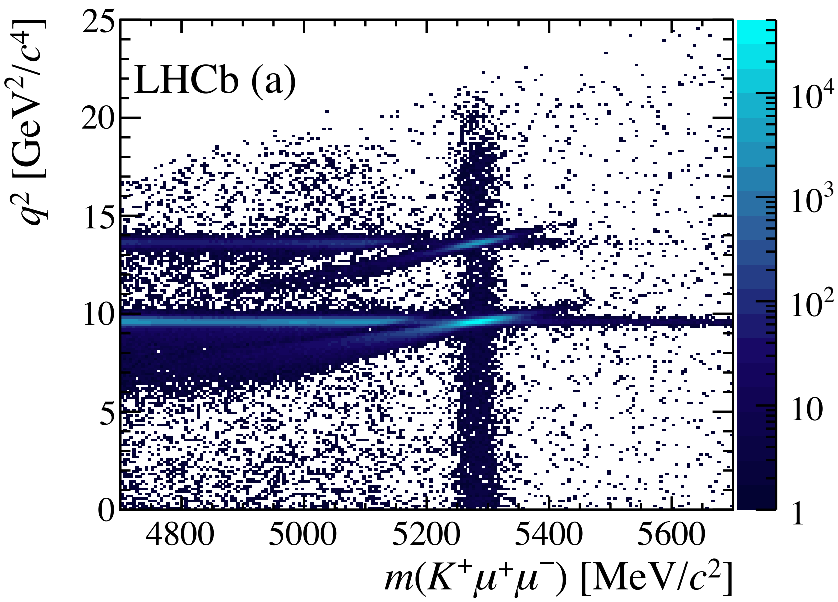


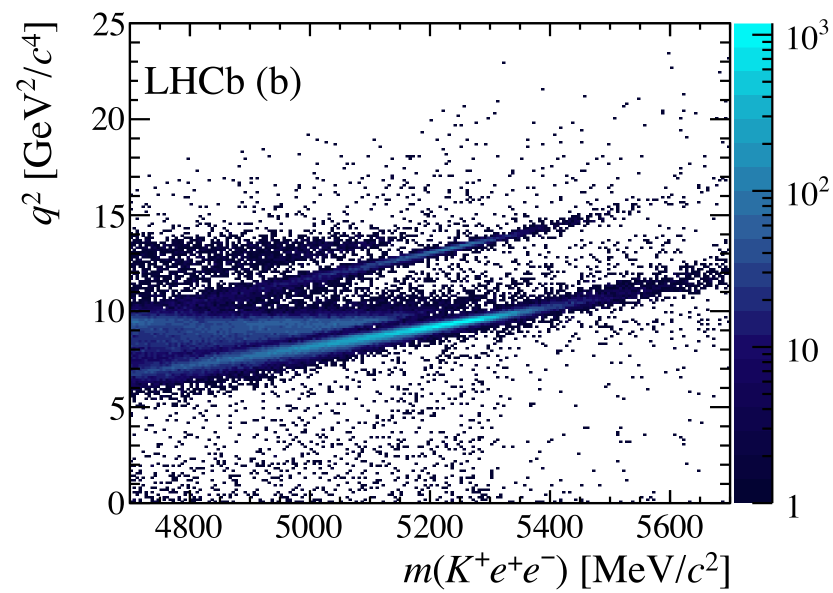
Possible explanations include models with flavour changing Z'. Or that non-factorisable QCD effects are more important than thought. **(See JHEP 1305 (2013) 043)**

Lepton (non?) Universality with B⁺→K⁺μ⁺μ⁻, K⁺e⁺e⁻.

Phys.Rev.Lett. 113 (2014) 151601

$R_K \equiv \Gamma(B^+ \to K^+\mu^+\mu^-) / \Gamma(K^+e^+e^-)$ for $q^2 \in [1\text{GeV}, 6\text{ GeV}]$





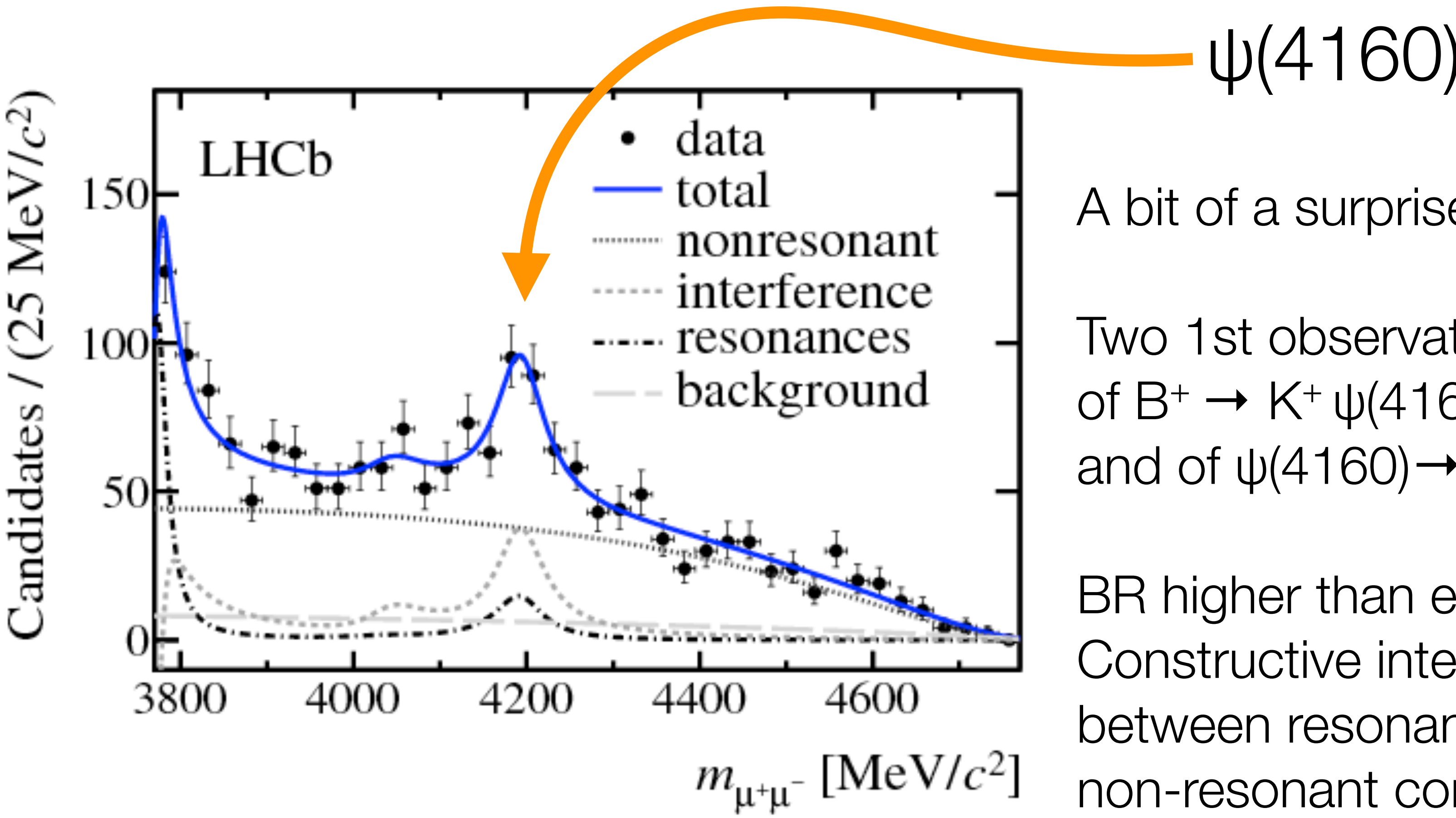
In SM: $R_K = 1.000(1)$

At LHCb: $R_K = 0.745^{+0.090}_{-0.074}\,(\text{stat}) \pm 0.036\,(\text{syst})$

2.6σ

$\mu^+\mu^-$ mass distribution in $B^+ \to K^+\mu^+\mu^-$

Phys.Rev.Lett. 111 (2013) 112003 (2013)



A bit of a surprise.

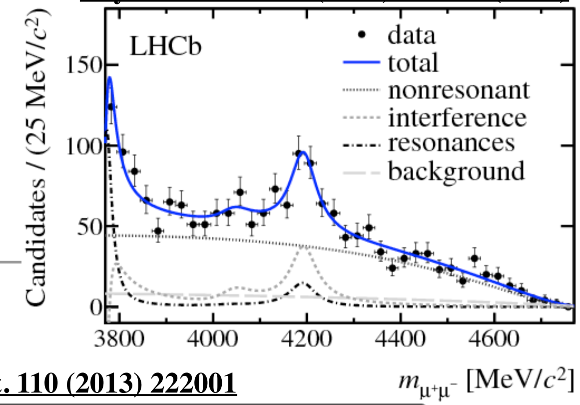
Two 1st observations:
of $B^+ \to K^+ \psi(4160)$,
and of $\psi(4160) \to \mu^+\mu^-$)

BR higher than expected.
Constructive interference between resonance and non-resonant component.

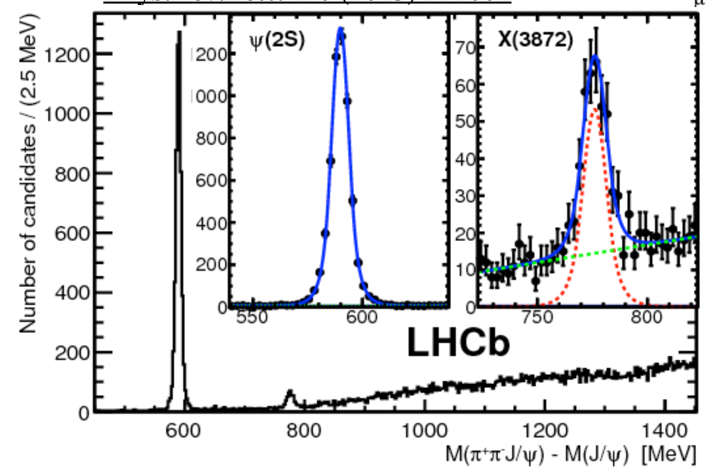
And there’s much more!

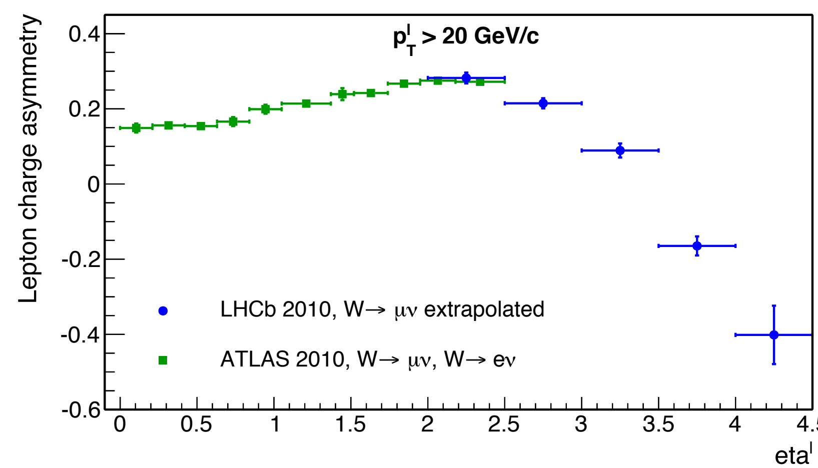
- New resonances and quantum numbers of recently discovered ones, e.g. X(3872), Z(4430), several D_J^*.
- Precision measurements of masses, lifetimes, branching fractions.
- Production measurements in p-p and p-A collisions
- …and many, many more.

Phys.Rev.Lett. 111 (2013) 112003 (2013)



Phys.Rev.Lett. 110 (2013) 222001





The flavour puzzle

- The measurements shown are highly sensitive to New Physics
- If there really are all these new particles at O(TeV), the Standard model description should fail.
- Why is the flavour structure not much richer and more complex than predicted by the SM?
- New symmetries that enforce an “alignment” of SM and NP phases (MFV)? Unnaturally tiny couplings between NP and SM? Or no new particles at O(TeV)?

New Physics promises this:

So far, all we got is this:

Historical Note

- A historical note (from L. B. Okun: "Spacetime and vacuum as seen from Moscow", Int.J.Mod.Phys. A17S1 (2002) 105-118):

> A special search at Dubna was carried out by E. Okonov and his group. They have not found a single $K_L^0 \to \pi^+\pi^-$ event among 600 decays of K_L^0 into charged particles [13] (Anikina et al., JETP, 1962). At that stage the search was terminated by administration of the Lab. The group was unlucky.
>
> Approximately at the level 1/350 the effect was discovered by J.Christensen, J.Cronin, V.Fitch and R.Turlay [14] at Brookhaven in 1964 in an experiment[...]

- Don't give up once you've excluded New Physics at the few% level.
- A successful past is no impediment to a successful future.
- Discrete symmetries are usually broken (C, P, CP,... MFV?)

How Precise is Precise enough?

- Increasing precision pays off as long as it significantly increases our understanding of physics.

- There are two scenarios when we might argue that we have reached sufficient experimental precision:

  - We have seen New Physics, fully understand the theory underlying it, and have measured all its fundamental parameters.

  - When precision is limited by the precision of theory calculations. Improving fast through faster computers and cleverer algorithms.

- We need to identify theoretically clean measurements with high sensitivity and discriminating power for New Physics models.

A selected list NP-sensitive flavour variables

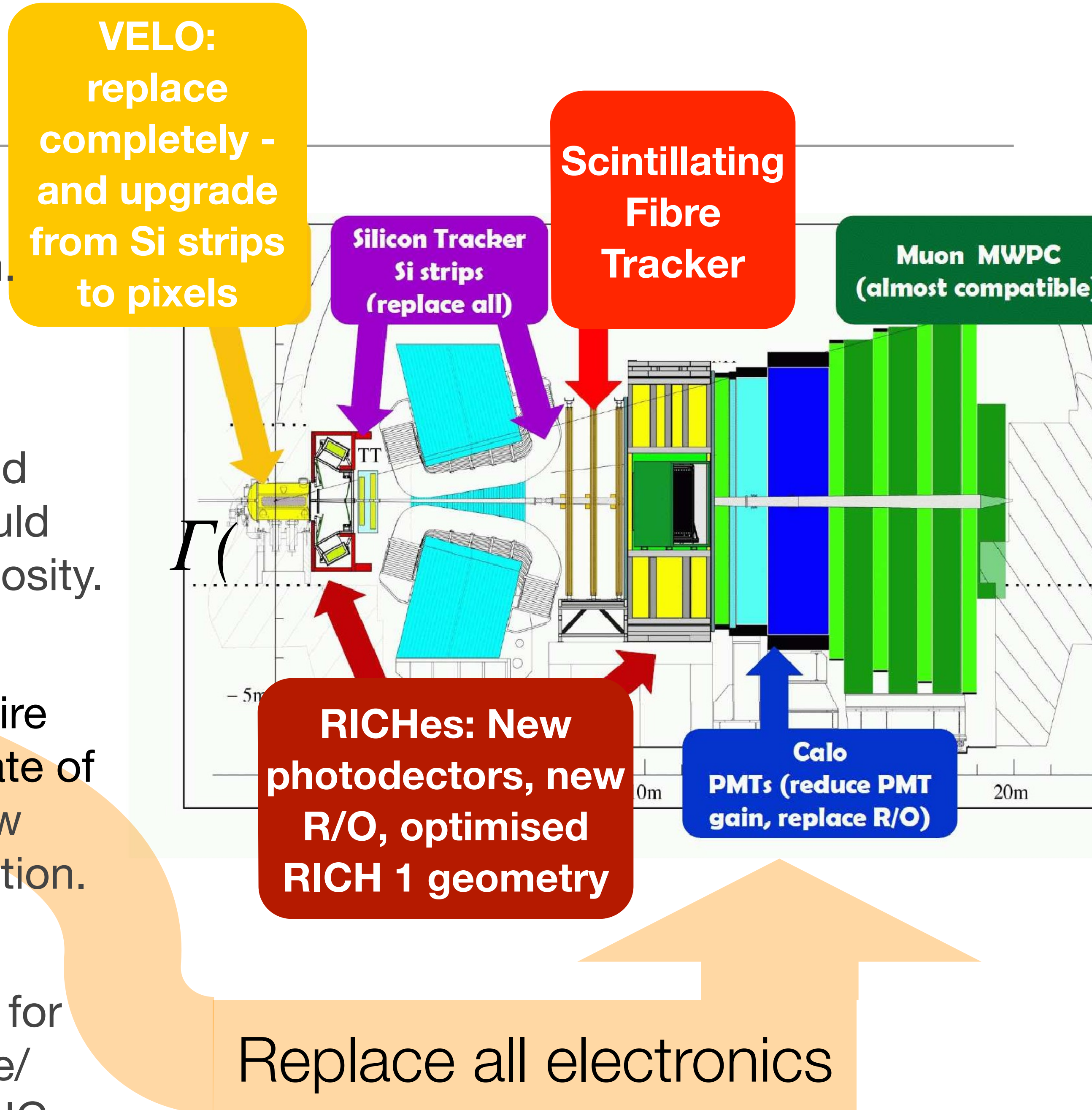
Type	Observable	Current precision	LHCb 2018	**Upgrade** ($50\,\mathrm{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing					~ 0.003
					~ 0.01
					0.03×10^{-3}
Gluonic penguins					0.02
					< 0.02
					0.02
Right-handed currents					< 0.01
					$0.2\,\%$
Electroweak penguins					0.02
					$7\,\%$
					~ 0.02
					$\sim 10\,\%$
Higgs penguins					0.3×10^{-9}
					$\sim 5\,\%$
Unitarity triangle angles					negligible
					negligible
					negligible
Charm CP violation					–
					–

- Plenty of theoretically clean channels with high sensitivity and discriminating power for New Physics models
- Theoretical uncertainties in many cases far better than current experimental sensitivity (and improving).
- Lots of room for New Physics to hide - and opportunity to find it!
- Need (even) better experimental precision to fully exploit flavour physics' sensitivity to physics beyond the SM.

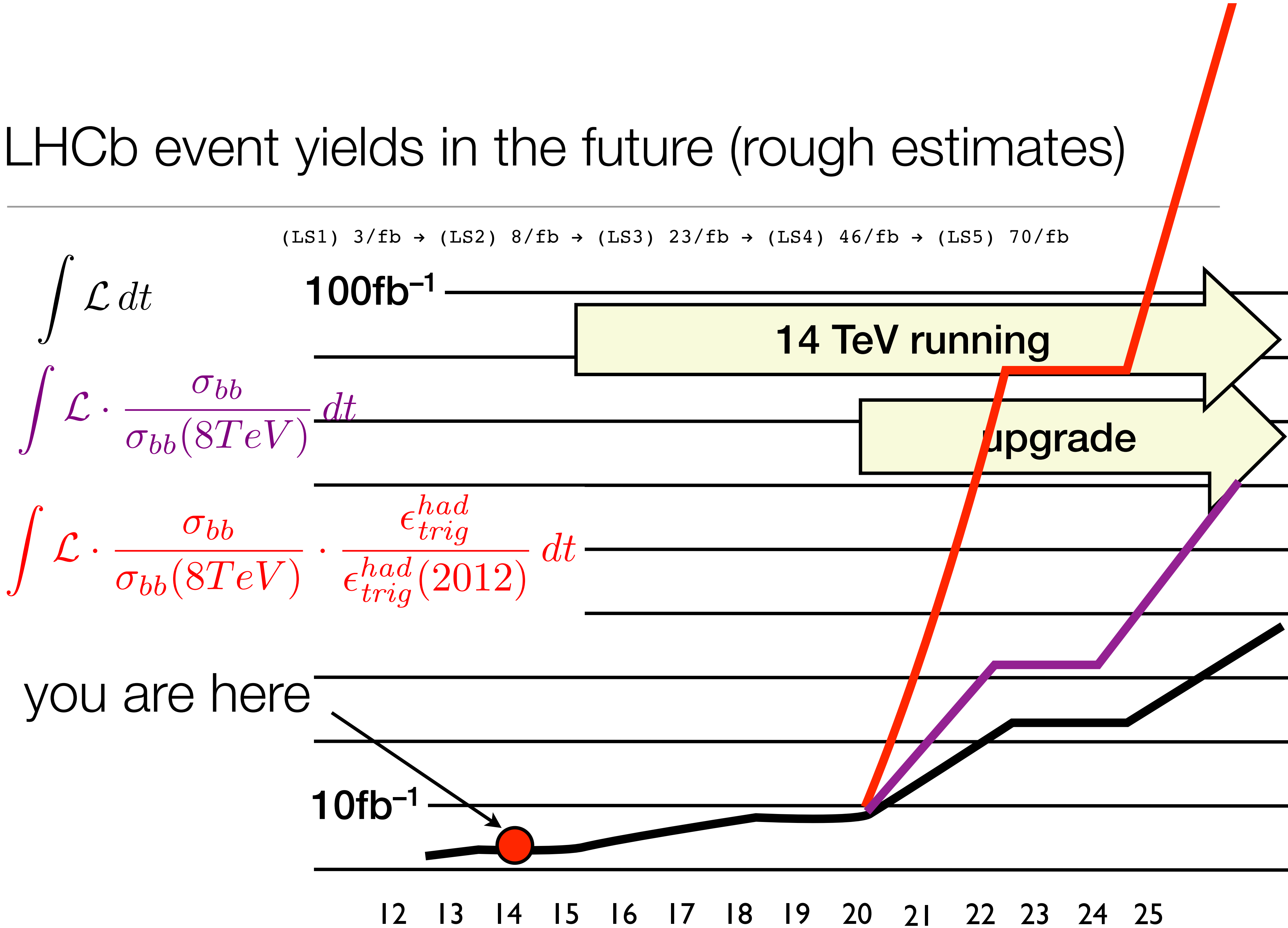
Eur.Phys.J. C73 (2013) 2373

The LHCb upgrade

- Higher luminosity $\Longrightarrow$ higher precision $\Longrightarrow$ better NP reach.
- Trigger is at the heart of the upgrade. Current trigger would “choke”, the signal yields would not increase in line with luminosity.
- For upgrade, read out the entire detector at bunch-crossing rate of 40MHz, fully customisable s/w trigger, with full event information.
- Doubles the trigger efficiency for hadronic modes. Most flexible/ customisable trigger at the LHC.

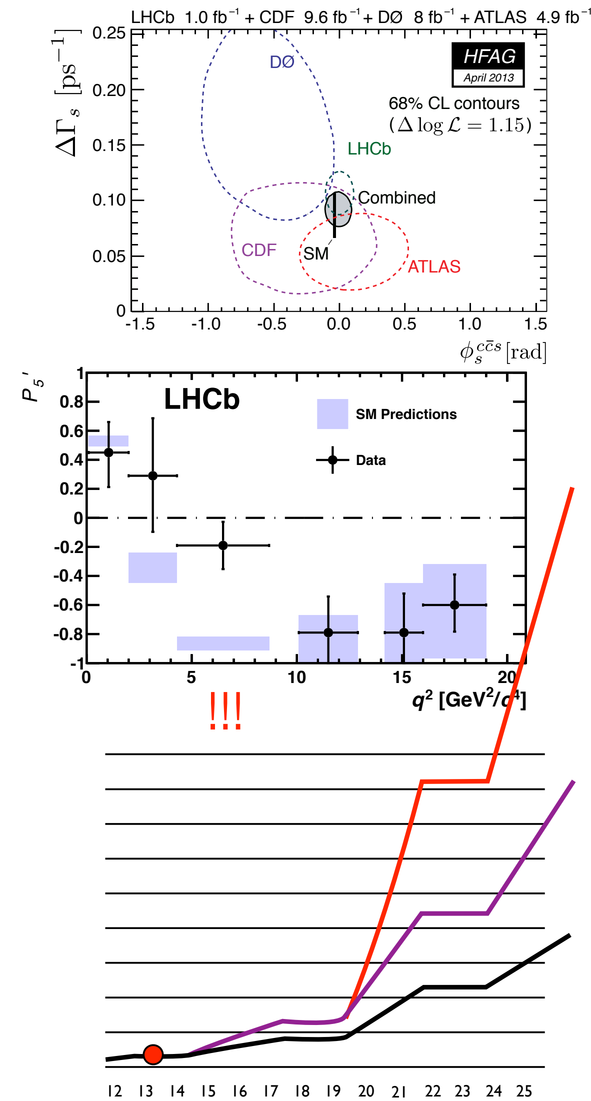


LHCb event yields in the future (rough estimates)



Conclusions

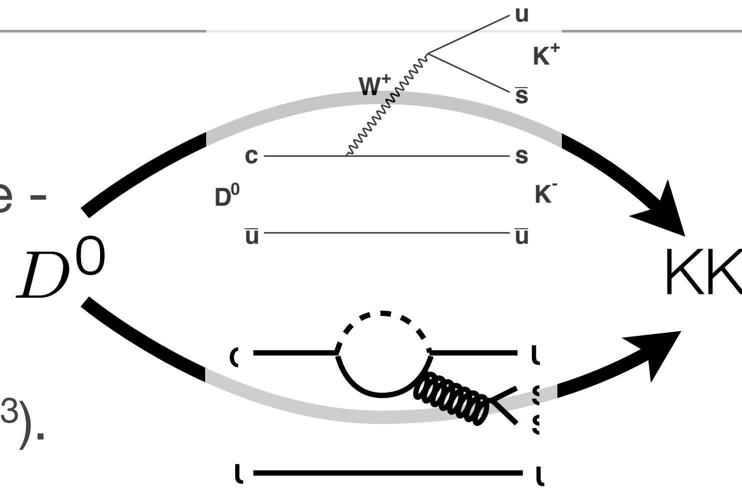
- Flavour physics is sensitive to physics at very high mass scales.
- The LHC is the world's most copious source of heavy flavour. LHCb, designed to exploit this, has huge, clean signals in a cornucopia of final states - unprecedented precision. ATLAS, CMS contribute in di-muon channels.
- So far we have used that sensitivity to rule out many NP models. But we know there must be NP…. and there are intriguing hints.
- This is just the beginning.



BBC, http://www.youtube.com/watch?v=9dfWzp7rYR4

Backup

CPV in charm. Looking for tiny signals.



- CPV is an interference effect - need ≥2 amplitudes, ideally of comparable magnitude - effects most likely in SCS decays.
- Looking for tiny effects (in SM up to few×10^{-3}). Careful with systematics!

$$A_{raw} = A_{CP} + A_{prod} + A_{det}$$

- Typical analysis measures ΔA_{CP} in decays to similar final states:

$$\Delta A_{CP} = A_{CP}(D \to f_1) - A_{CP}(D \to f_2) \approx A_{raw}(D \to f_1) - A_{raw}(D \to f_2)$$

Production and detection asymmetries cancel to first order.

A SCS decay

Could be a CF decay with $A_{CP} \approx 0$ or another SCF decay as in f_1=KK and f_2=ππ where $A_{CP}(D \to KK) \approx -A_{CP}(D \to \pi\pi)$

Direct CPV in D→KK, D→ππ

$$A_{CP}(K^+K^-) \equiv \frac{\Gamma(D^0 \to K^+K^-) - \Gamma(\overline{D}^0 \to K^+K^-)}{\Gamma(D^0 \to K^+K^-) + \Gamma(\overline{D}^0 \to K^+K^-)}$$

$$A_{CP}(\pi^+\pi^-) \equiv \frac{\Gamma(D^0 \to \pi^+\pi^-) - \Gamma(\overline{D}^0 \to \pi^+\pi^-)}{\Gamma(D^0 \to \pi^+\pi^-) + \Gamma(\overline{D}^0 \to \pi^+\pi^-)}$$

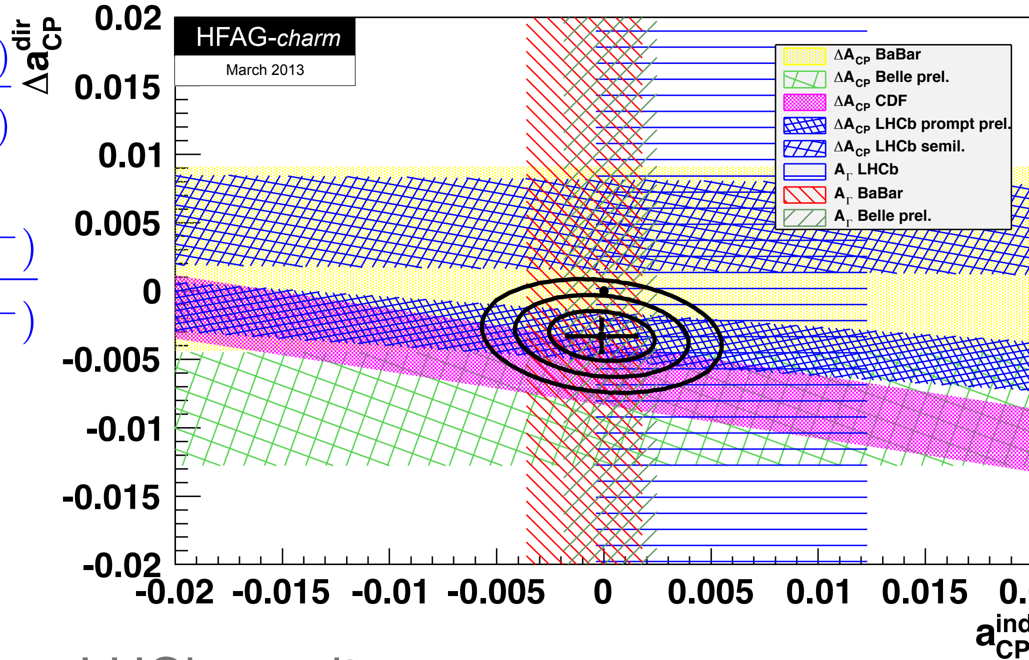
- Tag initial state as D° or $\overline{D}$° using either

$$D^{*-} \to \overline{D}^0 \pi_s^- \quad D^{*+} \to D^0 \pi_s^+$$

or:
$$b \to D^0 \ell^- + \ldots$$
$$\overline{b} \to \overline{D}^0 \ell^+ + \ldots$$

- Measure

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$

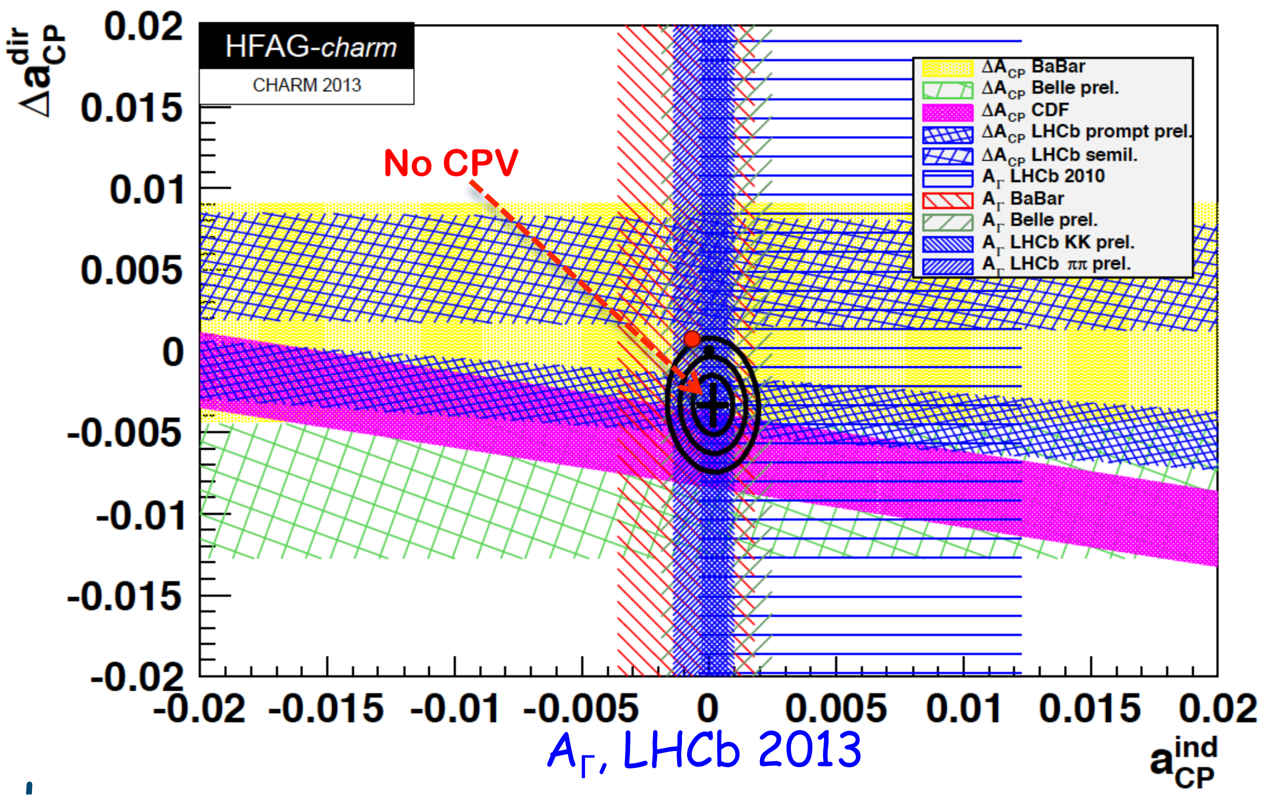


- LHCb results:

$$\Delta A_{CP} = (-0.34 \pm 0.15\,(\text{stat.}) \pm 0.10\,(\text{syst.}))\,\%$$
$$\Delta A_{CP} = (+0.49 \pm 0.30\,(\text{stat.}) \pm 0.14\,(\text{syst.}))\,\%$$
$$\Delta A_{CP} = (-0.15 \pm 0.16)\,\%$$

- World average:

$$\Delta A_{CP}^{dir} = (-0.329 \pm 0.121)\%$$



HFAG-charm
CHARM 2013
No CPV
ΔA_{CP} BaBar
ΔA_{CP} Belle prel.
ΔA_{CP} CDF
ΔA_{CP} LHCb prompt prel.
ΔA_{CP} LHCb semil.
A_Γ LHCb 2010
A_Γ BaBar
A_Γ Belle prel.
A_Γ LHCb KK prel.
A_Γ LHCb $\pi\pi$ prel.
Δa_{CP}^{dir}
a_{CP}^{ind}
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
A_Γ, LHCb 2013

Searches for CPV by comparing binned Dalitz plots

- Compare yields in CP-conjugate bins

$$S^i_{CP} = \frac{N_i - \alpha \overline{N}_i}{\sigma_i}$$

$$\alpha = \frac{N_{\text{total}}}{\overline{N}_{\text{total}}}$$

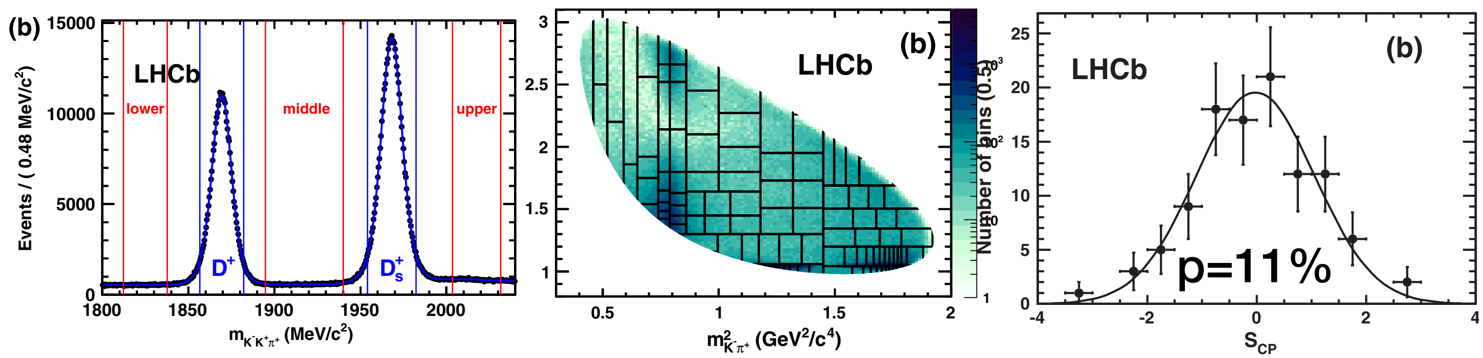
- Calculate p-value for no-CPV hypothesis based on

$$\chi^2 = \sum_i (S^i_{CP})^2$$

- Model independent. Many production and detection effects cancel.

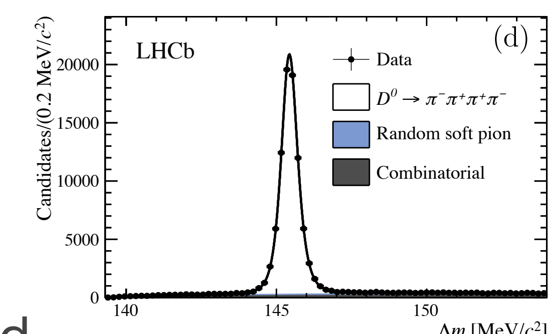
PhysRevD.84.112008

330k $D^+ \rightarrow K^-K^+\pi^+$ in 35/pb

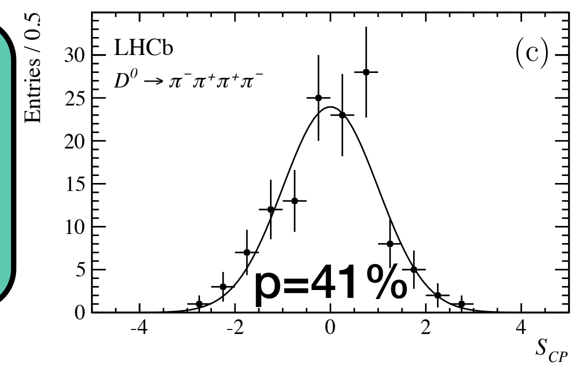


330k $D^{*+} \rightarrow D^o\pi$, $D^o \rightarrow \pi\pi\pi\pi$ in 1/fb

LHCb 1fb⁻¹ arXiv:1308.3189 (2013)



5-dim. “Dalitz” plot, binned.



also 57k $D^{*+} \rightarrow D^o\pi$, $D^o \rightarrow KK\pi\pi$ in 1/fb (p=9%)

$B_s \to J/\psi$ KK for ϕ_s

$$\frac{d^4\Gamma(B_s^0 \to J/\psi K^+K^-)}{dt\, d\Omega} \propto \sum_{k=1}^{10} h_k(t)\, f_k(\Omega)$$

$$h_k(t) = N_k e^{-\Gamma_s t}\left[a_k \cosh\left(\tfrac{1}{2}\Delta\Gamma_s t\right) + b_k \sinh\left(\tfrac{1}{2}\Delta\Gamma_s t\right) + c_k \cos(\Delta m_s t) + d_k \sin(\Delta m_s t)\right]$$

CPV-related parameters:

C : direct CPV and CPV in mixing (very small)

$S \approx -\sin\phi_s$

$D \approx -\cos\phi_s$

(no such approximation is made in the fit)

k	$f_k(\theta_\mu, \theta_K, \varphi_h)$	N_k	a_k	b_k	c_k	d_k
1	$2\cos^2\theta_K \sin^2\theta_\mu$	$\lvert A_0\rvert^2$	1	D	C	$-S$
2	$\sin^2\theta_K\left(1-\sin^2\theta_\mu\cos^2\varphi_h\right)$	$\lvert A_\parallel\rvert^2$	1	D	C	$-S$
3	$\sin^2\theta_K\left(1-\sin^2\theta_\mu\sin^2\varphi_h\right)$	$\lvert A_\perp\rvert^2$	1	$-D$	C	S
4	$\sin^2\theta_K \sin^2\theta_\mu \sin 2\varphi_h$	$\lvert A_\parallel A_\perp\rvert$	$C\sin(\delta_\perp-\delta_\parallel)$	$S\cos(\delta_\perp-\delta_\parallel)$	$\sin(\delta_\perp-\delta_\parallel)$	$D\cos(\delta_\perp-\delta_\parallel)$
5	$\frac{1}{2}\sqrt{2}\sin 2\theta_K \sin 2\theta_\mu \cos\varphi_h$	$\lvert A_0 A_\parallel\rvert$	$\cos(\delta_\parallel-\delta_0)$	$D\cos(\delta_\parallel-\delta_0)$	$C\cos(\delta_\parallel-\delta_0)$	$-S\cos(\delta_\parallel-\delta_0)$
6	$-\frac{1}{2}\sqrt{2}\sin 2\theta_K \sin 2\theta_\mu \sin\varphi_h$	$\lvert A_0 A_\perp\rvert$	$C\sin(\delta_\perp-\delta_0)$	$S\cos(\delta_\perp-\delta_0)$	$\sin(\delta_\perp-\delta_0)$	$D\cos(\delta_\perp-\delta_0)$
7	$\frac{2}{3}\sin^2\theta_\mu$	$\lvert A_S\rvert^2$	1	$-D$	C	S
8	$\frac{1}{3}\sqrt{6}\sin\theta_K \sin 2\theta_\mu \cos\varphi_h$	$\lvert A_S A_\parallel\rvert$	$C\cos(\delta_\parallel-\delta_S)$	$S\sin(\delta_\parallel-\delta_S)$	$\cos(\delta_\parallel-\delta_S)$	$D\sin(\delta_\parallel-\delta_S)$
9	$-\frac{1}{3}\sqrt{6}\sin\theta_K \sin 2\theta_\mu \sin\varphi_h$	$\lvert A_S A_\perp\rvert$	$\sin(\delta_\perp-\delta_S)$	$-D\sin(\delta_\perp-\delta_S)$	$C\sin(\delta_\perp-\delta_S)$	$S\sin(\delta_\perp-\delta_S)$
10	$\frac{4}{3}\sqrt{3}\cos\theta_K \sin^2\theta_\mu$	$\lvert A_S A_0\rvert$	$C\cos(\delta_0-\delta_S)$	$S\sin(\delta_0-\delta_S)$	$\cos(\delta_0-\delta_S)$	$D\sin(\delta_0-\delta_S)$

A_{SL}

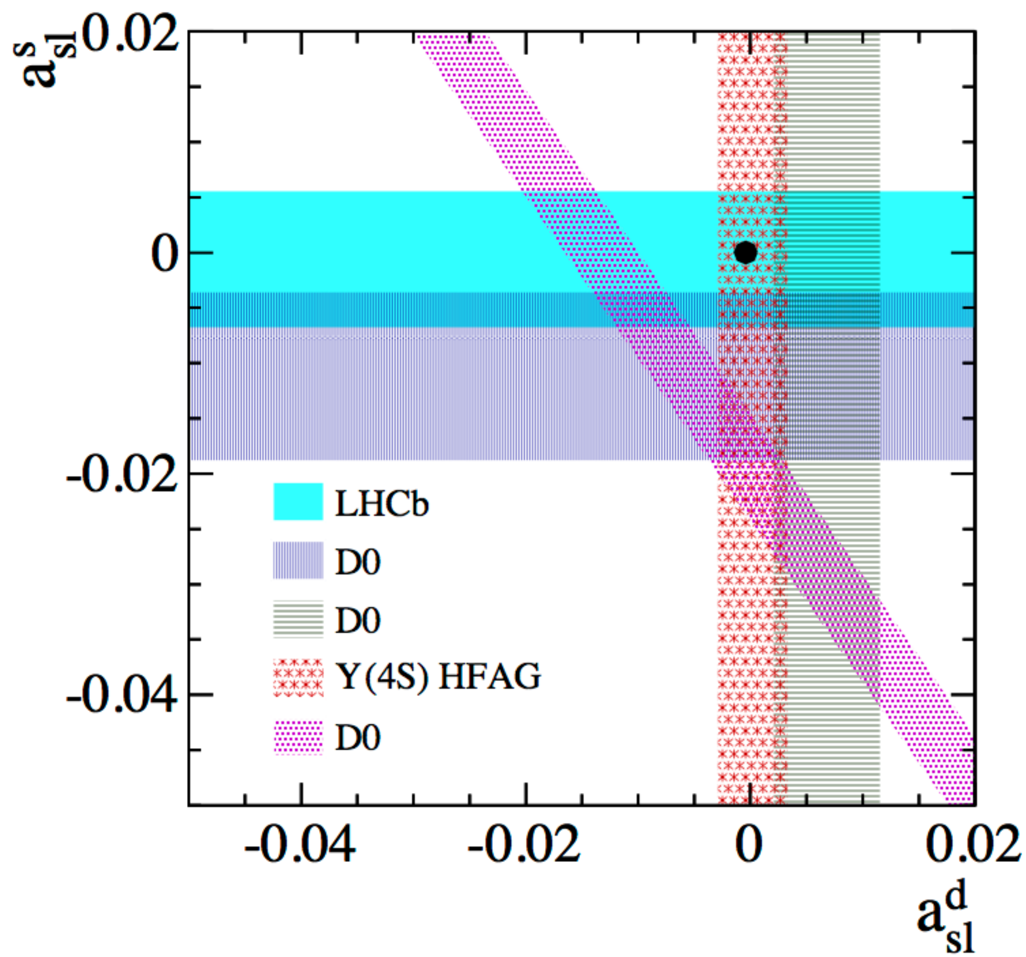
arXiv:1308.1048 (2013)

$$A_{\text{meas}} \equiv \frac{\Gamma[D_s^- \mu^+] - \Gamma[D_s^+ \mu^-]}{\Gamma[D_s^- \mu^+] + \Gamma[D_s^+ \mu^-]} = \frac{a_{\text{sl}}^s}{2} + \left[a_{\text{P}} - \frac{a_{\text{sl}}^s}{2}\right] \frac{\int_{t=0}^{\infty} e^{-\Gamma_s t} \cos(\Delta M_s\, t)\epsilon(t)dt}{\int_{t=0}^{\infty} e^{-\Gamma_s t} \cosh(\frac{\Delta\Gamma_s\, t}{2})\epsilon(t)dt}$$

- CP violation in mixing - tiny in the SM in both B_s and B_d
- There were some recent hints of non-zero Asl at D0.
- Latest LHCb results:

$$a_{\text{sl}}^s = (-0.06 \pm 0.50 \pm 0.36)\%$$

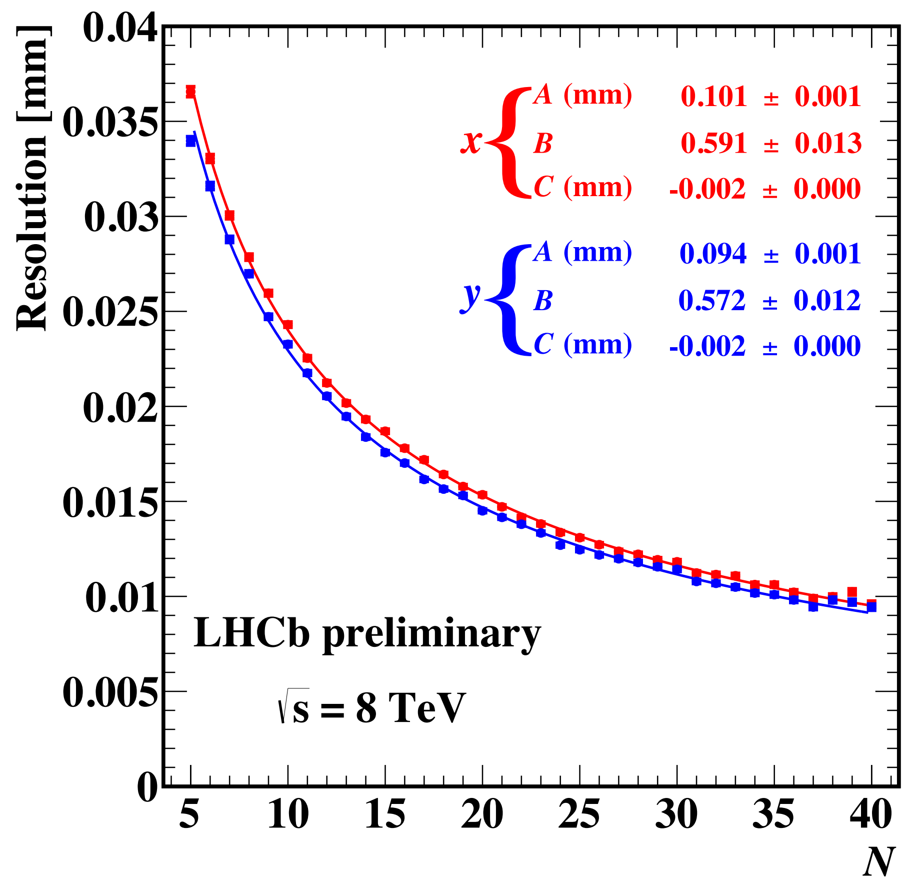
are (sadly) compatible with the SM.



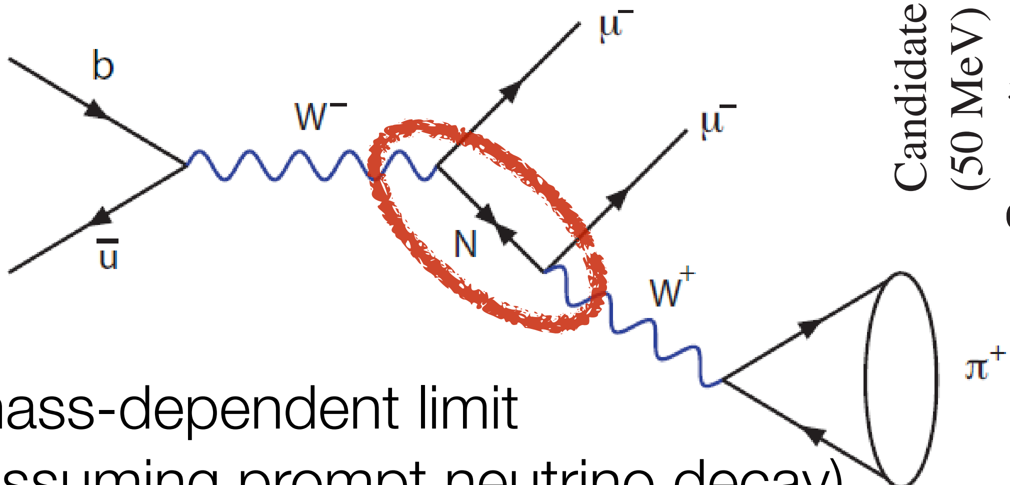
VELO

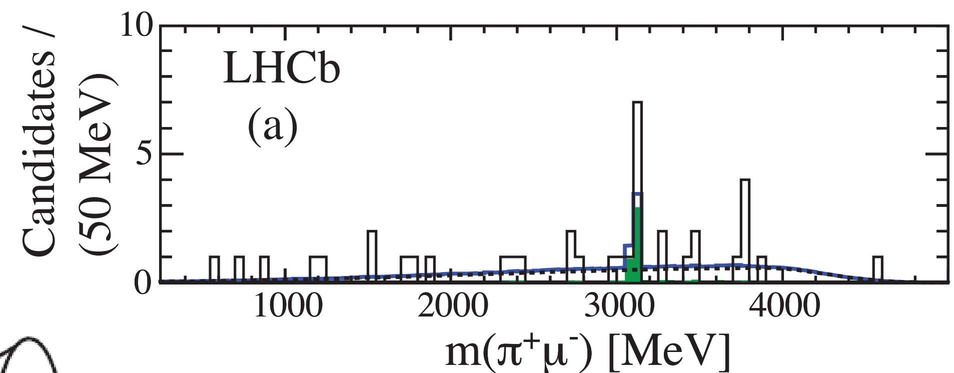
- The VELO gives LHCb the best vertex resolution at the LHC.
- This is crucial for our trigger, that selects B decays based on their characteristic detached vertices. LHCb is the only experiment at the LHC whose B trigger can efficiently select fully hadronic B decays.
- Also important time-dependent measurements (see later).

Vertex resolution (vs number of tracks)

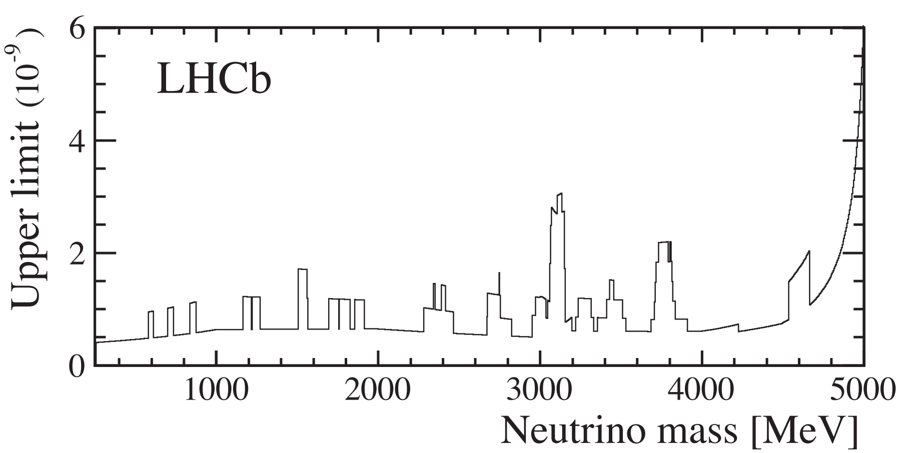


Long-lived Majorana neutrinos in $B^+ \to \pi^+ \mu^- \mu^-$ arXiv:1401.5361

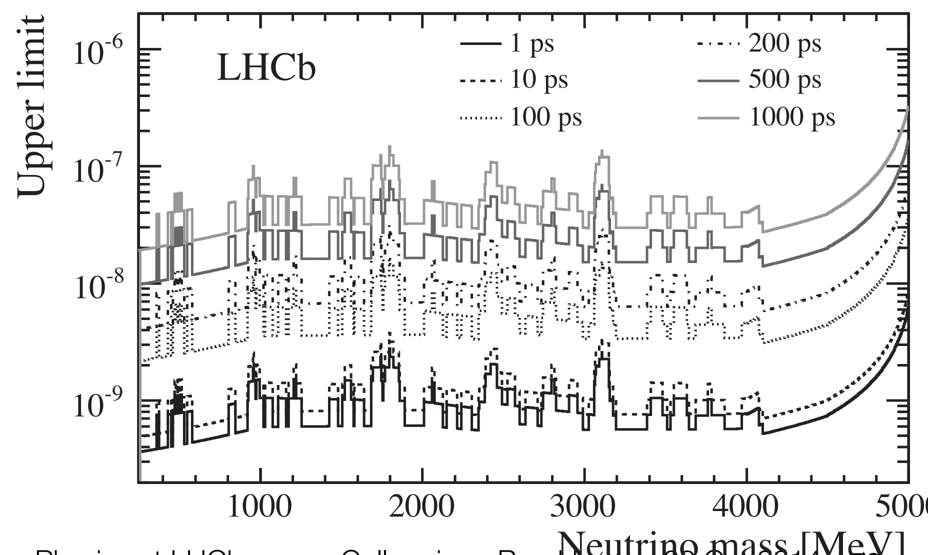




mass-dependent limit
(assuming prompt neutrino decay)

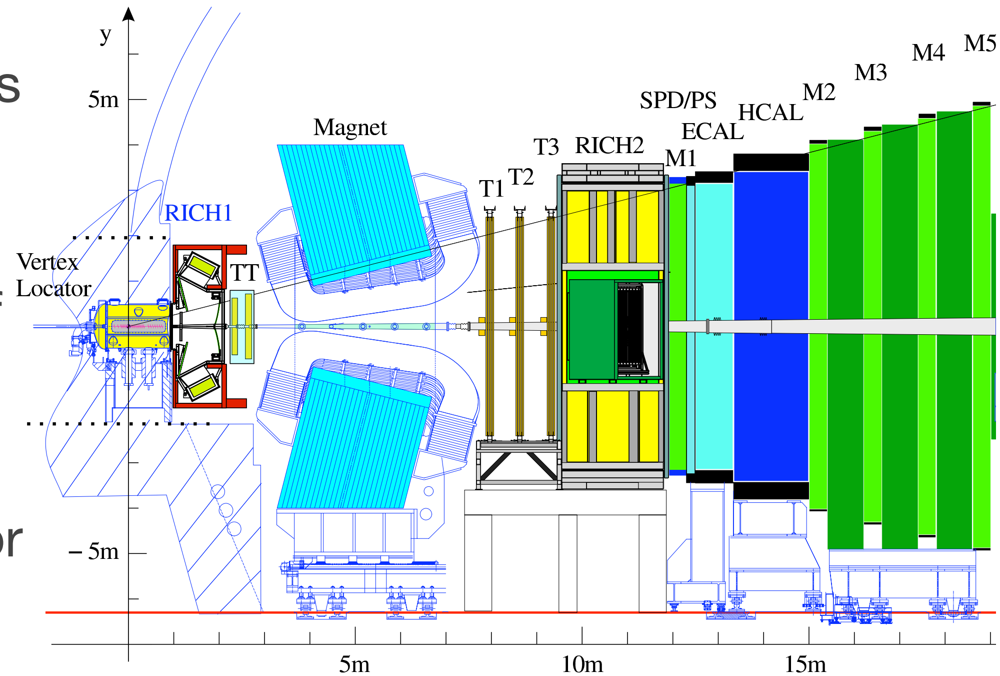


mass-dependent limit
For different lifetimes

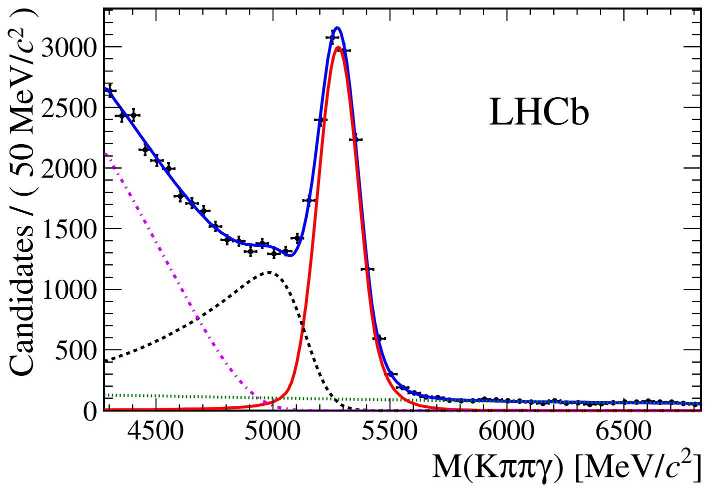


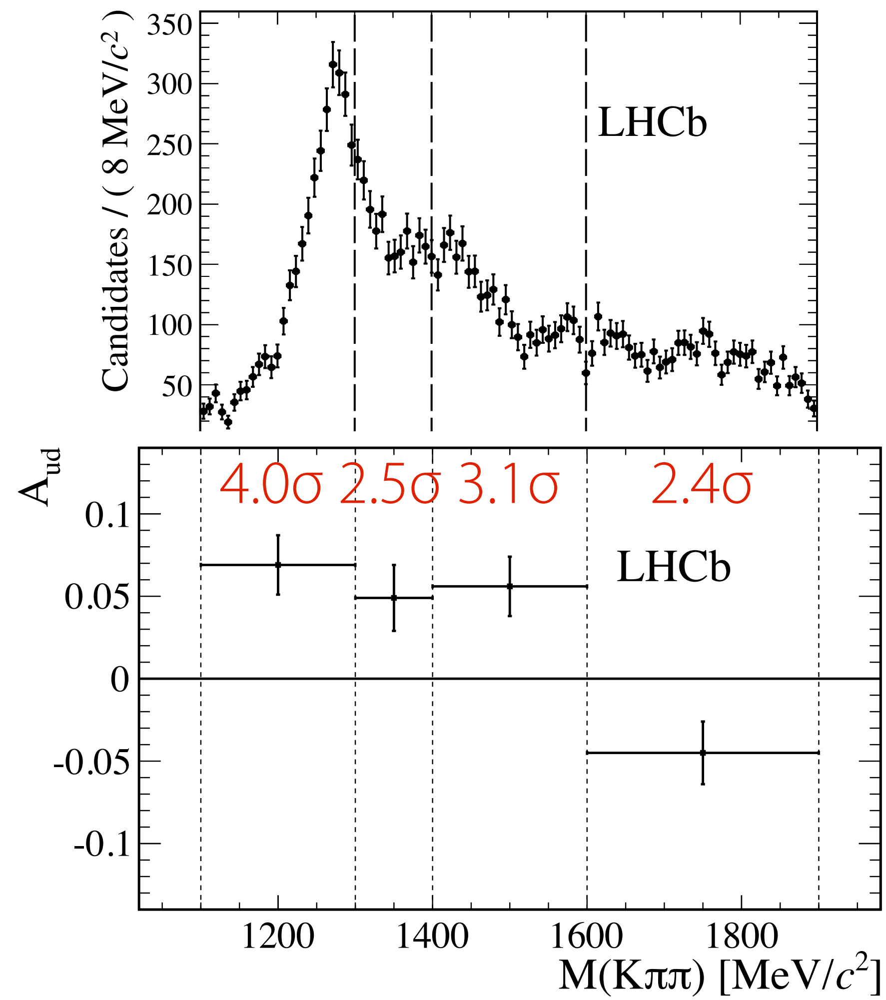
LHCb

- ca 100,000 b-bbar pairs per second at 14 TeV. Produce all types of B-hadrons (B_d, B_s, $B^{\pm}$, B_c, Λ_b,...). Even more c-cbar pairs for charm physics.
- Special geometry to capture as many of them as possible.
- Vertex detector INSIDE the beampipe for extra precision
- Ring Imaging Cherenkov detector (RICH) that provides particle identification.
- Trigger on displaced vertices - captures all types of B decays.



Photon polarisation in $b \to s\gamma$ with $B^{\pm} \to K^{+} \pi^{-} \pi^{+} \gamma$





- First observation of P violation in radiative decays.
- Need more theory input to turn this into a precision test of the SM.
- Future: $B \to \phi\gamma$ (time-dependent) very promising, theoretically clean.

CPV in charm - time-dependent measurements

CP even

4.8M D→KK

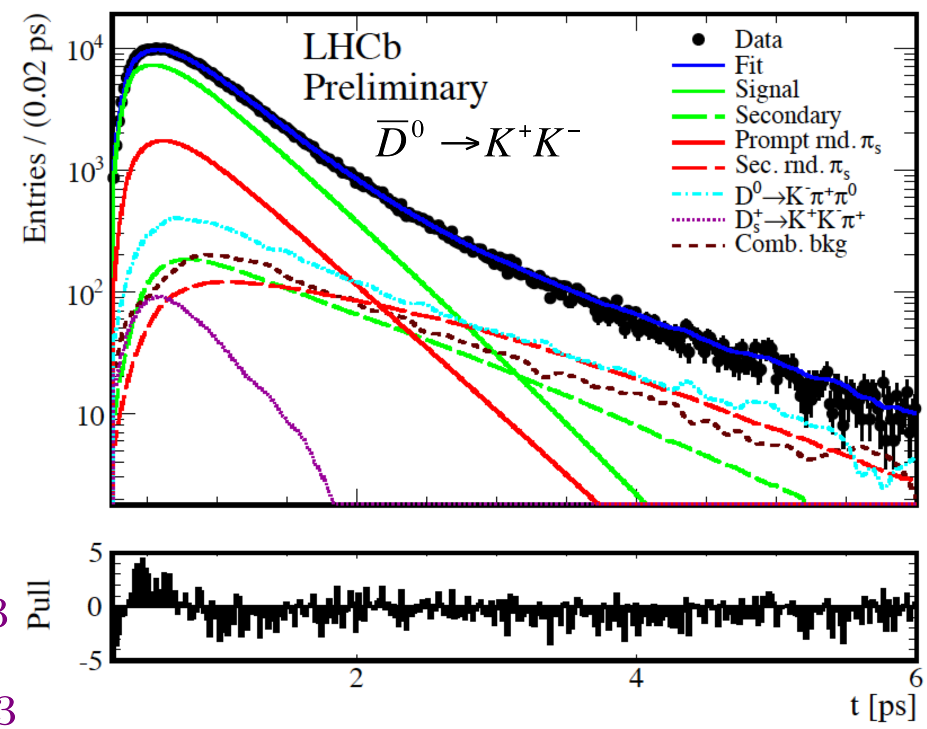
1.6M D→ππ

34.1M D→Kπ

control channel

signal purity > 90% for all modes

[Phys. Rev. Lett. 112 (2014) 041801]

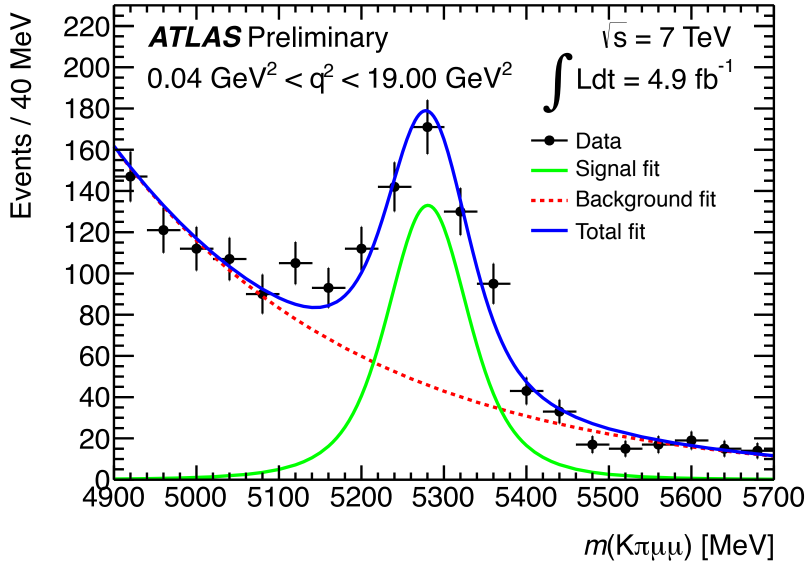


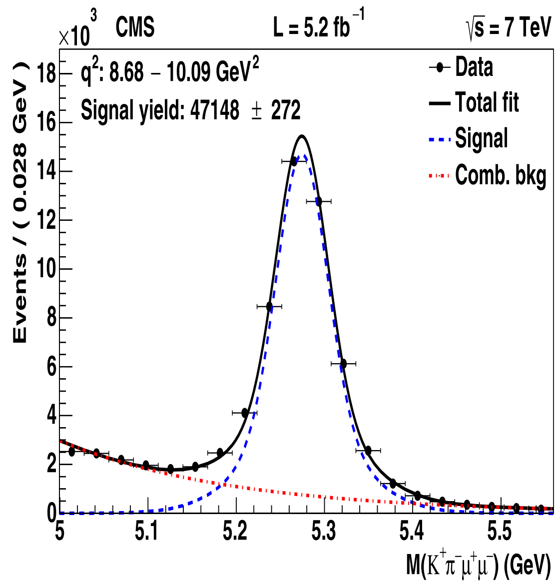
$$A_\Gamma(\pi\pi) = (+0.33 \pm 1.06 \pm 0.14) \cdot 10^{-3}$$

$$A_\Gamma(\pi\pi) = (-0.33 \pm 0.62 \pm 0.12) \cdot 10^{-3}$$

Results are consistent with no CP violation, and with each other. They are by far the most precise results for this quantity.

$B \to K^*\mu^+\mu^-$ at ATLAS, CMS and LHCb





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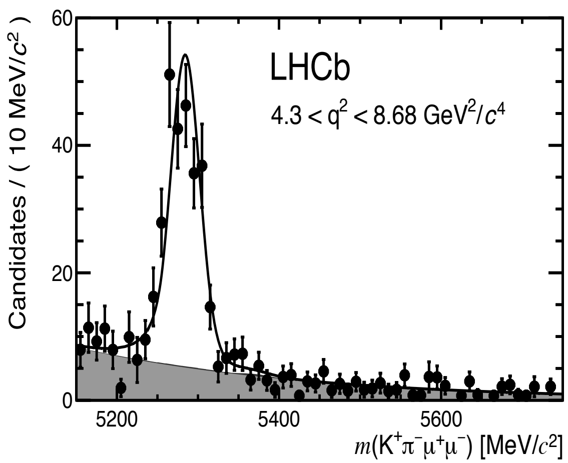

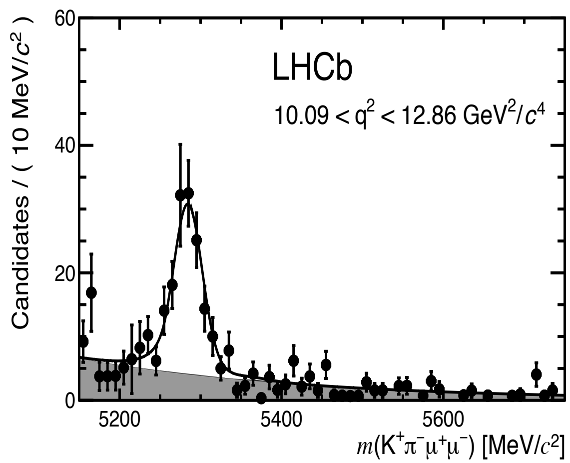

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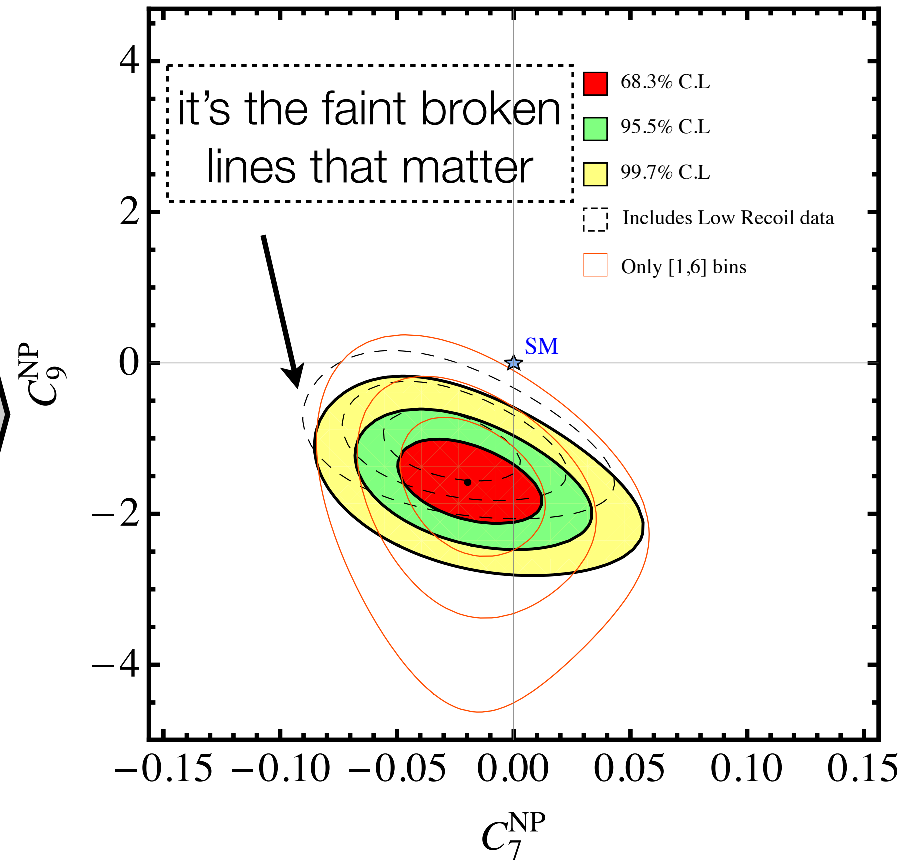
B→K*μ⁺μ⁻: interpretation

Descotes-Genon, JMatias, Virto: arXiv:1307.5683 (2013)

- Combining the K*μμ observables, and other flavour physics observables such as $B_s \to \mu\mu$.
- 3.7σ difference* from SM C_9
- Several theorists suggest a flavour changing Z’ gauge boson as a possible explanation

$$\mathcal{H}(b \to s\ell^+\ell^-) = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1}^{10} C_i(\mu)\mathcal{O}_i(\mu)$$

Observable	Experiment	SM prediction	Pull
$\langle P_1\rangle_{[0.1,2]}$	$-0.19^{+0.40}_{-0.35}$	$0.007^{+0.043}_{-0.044}$	-0.5
$\langle P_1\rangle_{[2,4.3]}$	$-0.29^{+0.65}_{-0.46}$	$-0.051^{+0.046}_{-0.046}$	-0.4
$\langle P_1\rangle_{[4.3,8.68]}$	$0.36^{+0.30}_{-0.31}$	$-0.117^{+0.056}_{-0.052}$	$+1.5$
$\langle P_1\rangle_{[1,6]}$	$0.15^{+0.39}_{-0.41}$	$-0.055^{+0.041}_{-0.043}$	$+0.5$
$\langle P_2\rangle_{[0.1,2]}$	$0.03^{+0.14}_{-0.15}$	$0.172^{+0.020}_{-0.021}$	-1.0
$\langle P_2\rangle_{[2,4.3]}$	$0.50^{+0.00}_{-0.07}$	$0.234^{+0.060}_{-0.086}$	$+2.9$
$\langle P_2\rangle_{[4.3,8.68]}$	$-0.25^{+0.07}_{-0.08}$	$-0.407^{+0.049}_{-0.037}$	$+1.7$
$\langle P_2\rangle_{[1,6]}$	$0.33^{+0.11}_{-0.12}$	$0.084^{+0.060}_{-0.078}$	$+1.8$
$\langle P_4'\rangle_{[0.1,2]}$	$0.00^{+0.52}_{-0.52}$	$-0.342^{+0.031}_{-0.026}$	$+0.7$
$\langle P_4'\rangle_{[2,4.3]}$	$0.74^{+0.54}_{-0.60}$	$0.569^{+0.073}_{-0.063}$	$+0.3$
$\langle P_4'\rangle_{[4.3,8.68]}$	$1.18^{+0.26}_{-0.32}$	$1.003^{+0.028}_{-0.032}$	$+0.6$
$\langle P_4'\rangle_{[1,6]}$	$0.58^{+0.32}_{-0.36}$	$0.555^{+0.067}_{-0.058}$	$+0.1$
$\langle P_5'\rangle_{[0.1,2]}$	$0.45^{+0.21}_{-0.24}$	$0.533^{+0.033}_{-0.041}$	-0.4
$\langle P_5'\rangle_{[2,4.3]}$	$0.29^{+0.40}_{-0.39}$	$-0.334^{+0.097}_{-0.113}$	$+1.6$
$\langle P_5'\rangle_{[4.3,8.68]}$	$-0.19^{+0.16}_{-0.16}$	$-0.872^{+0.053}_{-0.041}$	$+4.0$
$\langle P_5'\rangle_{[1,6]}$	$0.21^{+0.20}_{-0.21}$	$-0.349^{+0.088}_{-0.100}$	$+2.5$
$\langle P_6'\rangle_{[0.1,2]}$	$0.24^{+0.23}_{-0.20}$	$-0.084^{+0.034}_{-0.044}$	$+1.6$
$\langle P_6'\rangle_{[2,4.3]}$	$-0.15^{+0.38}_{-0.36}$	$-0.098^{+0.043}_{-0.056}$	-0.1
$\langle P_6'\rangle_{[4.3,8.68]}$	$0.04^{+0.16}_{-0.16}$	$-0.027^{+0.060}_{-0.063}$	$+0.4$
$\langle P_6'\rangle_{[1,6]}$	$0.18^{+0.21}_{-0.21}$	$-0.089^{+0.042}_{-0.052}$	$+1.3$
$\langle P_8'\rangle_{[0.1,2]}$	$-0.12^{+0.56}_{-0.56}$	$0.037^{+0.037}_{-0.030}$	-0.3
$\langle P_8'\rangle_{[2,4.3]}$	$-0.30^{+0.60}_{-0.58}$	$0.070^{+0.045}_{-0.034}$	-0.6
$\langle P_8'\rangle_{[4.3,8.68]}$	$0.58^{+0.34}_{-0.38}$	$0.020^{+0.054}_{-0.055}$	$+1.5$
$\langle P_8'\rangle_{[1,6]}$	$0.46^{+0.36}_{-0.38}$	$0.063^{+0.042}_{-0.033}$	$+1.0$
$\langle A_{\rm FB}\rangle_{[0.1,2]}$	$-0.02^{+0.13}_{-0.13}$	$-0.136^{+0.051}_{-0.048}$	$+0.8$
$\langle A_{\rm FB}\rangle_{[2,4.3]}$	$-0.20^{+0.08}_{-0.08}$	$-0.081^{+0.055}_{-0.069}$	-1.1
$\langle A_{\rm FB}\rangle_{[4.3,8.68]}$	$0.16^{+0.06}_{-0.05}$	$0.220^{+0.138}_{-0.113}$	-0.5
$\langle A_{\rm FB}\rangle_{[1,6]}$	$-0.17^{+0.06}_{-0.06}$	$-0.035^{+0.037}_{-0.034}$	-2.0
$\langle P_1\rangle_{[14.18,16]}$	$0.07^{+0.26}_{-0.28}$	$-0.352^{+0.697}_{-0.468}$	$+0.6$
$\langle P_1\rangle_{[16,19]}$	$-0.71^{+0.36}_{-0.26}$	$-0.603^{+0.589}_{-0.315}$	-0.2
$\langle P_2\rangle_{[14.18,16]}$	$-0.50^{+0.03}_{-0.00}$	$-0.449^{+0.136}_{-0.041}$	-1.1
$\langle P_2\rangle_{[16,19]}$	$-0.32^{+0.08}_{-0.08}$	$-0.374^{+0.151}_{-0.126}$	$+0.3$
$\langle P_4'\rangle_{[14.18,16]}$	$-0.18^{+0.54}_{-0.70}$	$1.161^{+0.190}_{-0.332}$	-2.1
$\langle P_4'\rangle_{[16,19]}$	$0.70^{+0.44}_{-0.52}$	$1.263^{+0.119}_{-0.248}$	-1.1
$\langle P_5'\rangle_{[14.18,16]}$	$-0.79^{+0.27}_{-0.22}$	$-0.779^{+0.328}_{-0.363}$	$+0.0$
$\langle P_5'\rangle_{[16,19]}$	$-0.60^{+0.21}_{-0.18}$	$-0.601^{+0.282}_{-0.367}$	$+0.0$
$\langle P_6'\rangle_{[14.18,16]}$	$0.18^{+0.24}_{-0.25}$	$0.000^{+0.000}_{-0.000}$	$+0.7$
$\langle P_6'\rangle_{[16,19]}$	$-0.31^{+0.38}_{-0.39}$	$0.000^{+0.000}_{-0.000}$	-0.8
$\langle P_8'\rangle_{[14.18,16]}$	$-0.40^{+0.60}_{-0.50}$	$-0.015^{+0.009}_{-0.013}$	-0.6
$\langle P_8'\rangle_{[16,19]}$	$0.12^{+0.52}_{-0.54}$	$-0.008^{+0.005}_{-0.007}$	$+0.2$
$\langle A_{\rm FB}\rangle_{[14.18,16]}$	$0.51^{+0.07}_{-0.05}$	$0.404^{+0.199}_{-0.191}$	$+0.5$
$\langle A_{\rm FB}\rangle_{[16,19]}$	$0.30^{+0.08}_{-0.08}$	$0.360^{+0.205}_{-0.172}$	-0.3
$10^4\,\mathcal{B}_{B\to X_s\gamma}$	3.43 ± 0.22	3.15 ± 0.23	$+0.9$
$10^6\,\mathcal{B}_{B\to X_s\mu^+\mu^-}$	1.60 ± 0.50	1.59 ± 0.11	$+0.0$
$10^9\,\mathcal{B}_{B_s\to\mu^+\mu^-}$	2.9 ± 0.8	3.56 ± 0.18	-0.8
$A_I(B \to K^*\gamma)$	0.052 ± 0.026	0.041 ± 0.025	$+0.3$
$S_{K^*\gamma}$	-0.16 ± 0.22	-0.03 ± 0.01	-0.6

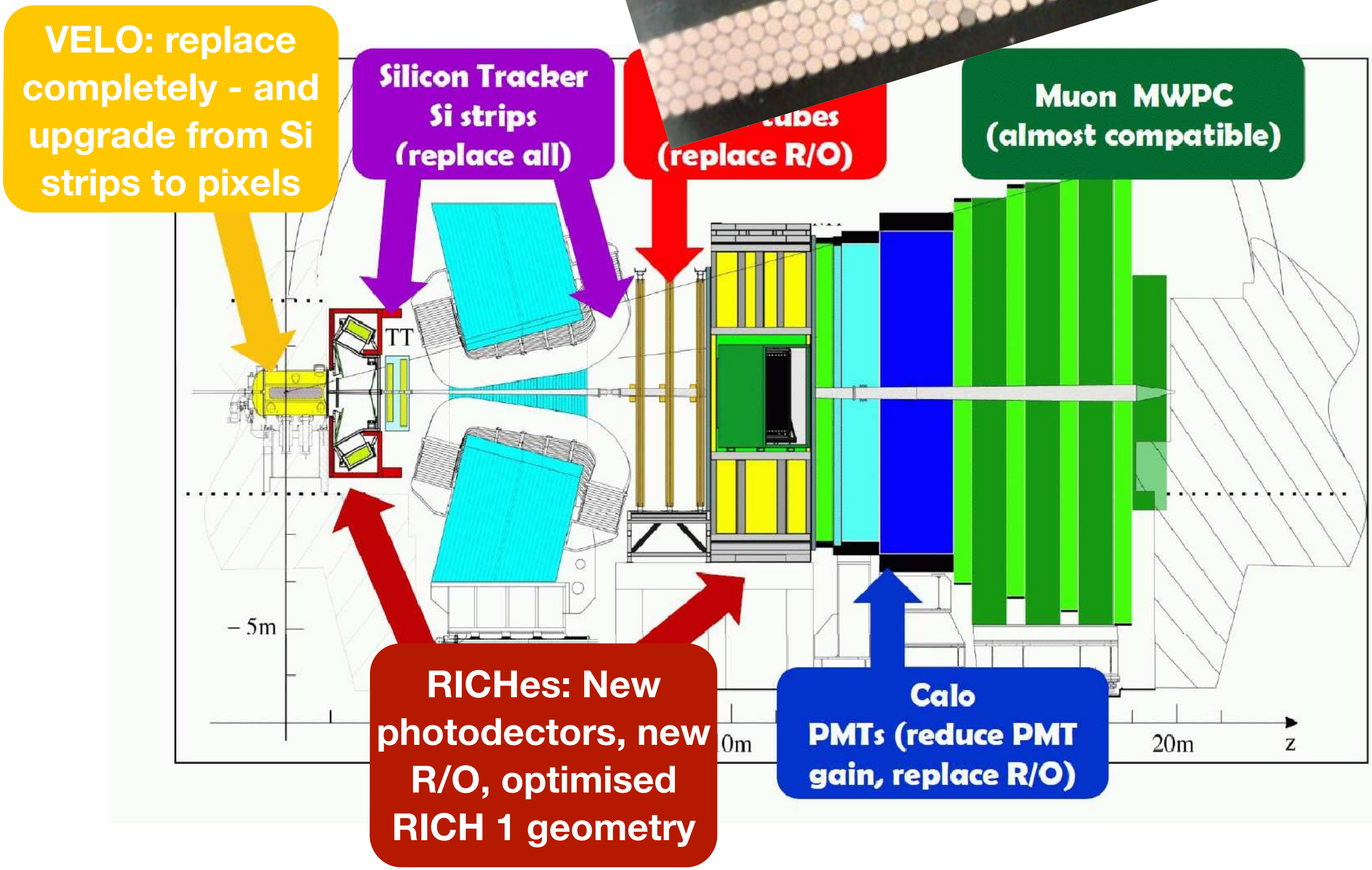


*) Even 4.6σ if we consider only the low q^2 region, which is the theoretically best understood.

The Future: LHCb upgrade

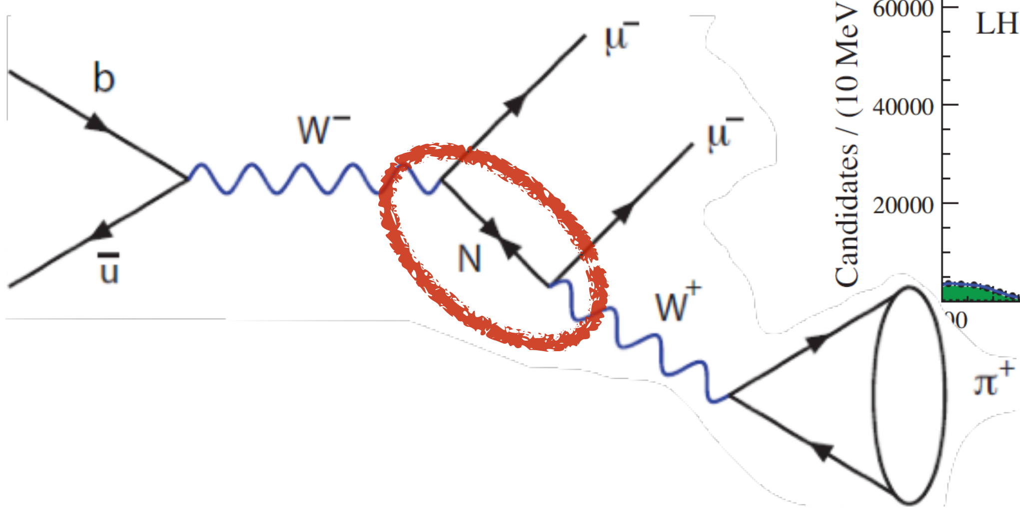
- We need (even) more precision. Need: More luminosity, better trigger.
- Trigger upgrade is crucial as the current trigger would “choke”, the signal yields would not increase in line with the increased luminosity.
- For the LHCb upgrade we will read out the entire detector at the bunch-crossing rate at 40MHz, and then use a fully customisable software trigger. Effectively, the trigger will use the same information as the offline selection!
- This doubles the trigger efficiency for hadronic modes, and provides the most flexible trigger at the LHC - we’ll be able to react quickly to any new discoveries. This will be fantastic for flavour, but go far beyond it - we will have a true general purpose detector for the forward region.

Changing the trigger is not all.

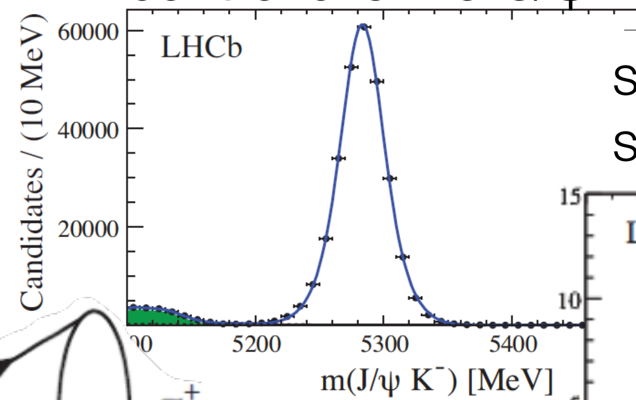


Majorana neutrinos in $B^+ \to \pi^+\mu^-\mu^-$

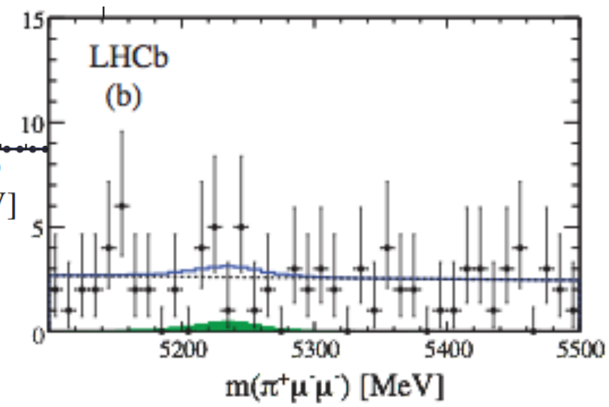
LHCb arXiv:1401.5361 (2014)



control channel J/ψK



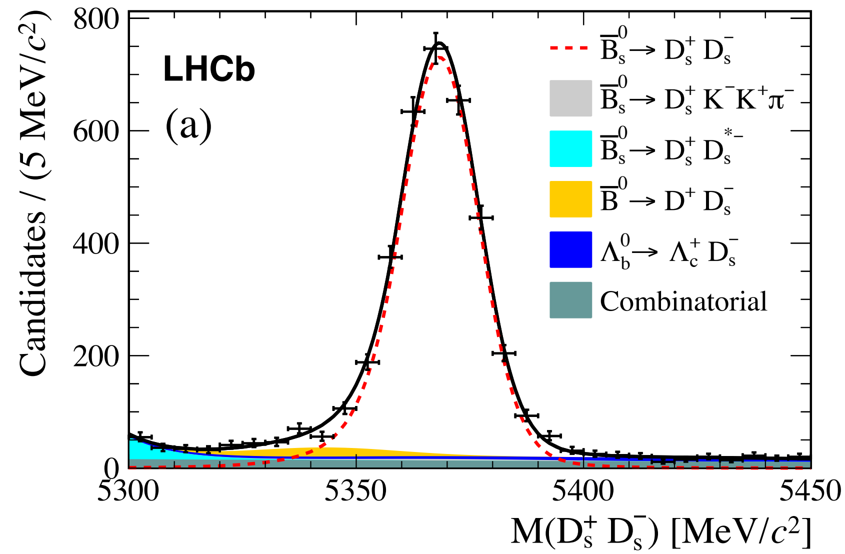
signal window (for short-lived N)



CLEO	BR(B⁻
Babar	BR(B⁻
LHCb (0.41fb	BR(B⁻
LHCb 3 fb	**BR(B**

Additional results are available for long-lived N, and as function of N mass.

ϕ_s from other B_s decay modes*



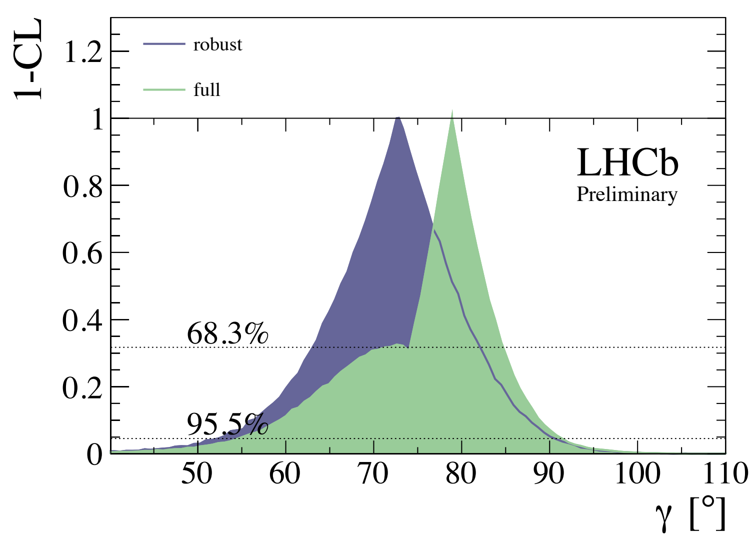
$$\phi_s = 0.02 \pm 0.17\,(\text{stat}) \pm 0.02\,(\text{syst})\,\text{rad}$$

arXiv:1409.4619 (2014)

*) Although closely related, there are subtle differences in the definitions of these ϕ_s. They share that they are ~0 in the SM, and sensitive to the same NP effects in the Bs mixing box diagram.

gamma combination

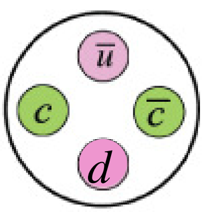
- $B^+ \to Dh^+$, $D \to hh$, GLW/ADS, $1\,\mathrm{fb}^{-1}$ [3]
- $B^+ \to Dh^+$, $D \to K\pi\pi\pi$, ADS, $1\,\mathrm{fb}^{-1}$ [4]
- $B^+ \to DK^+$, $D \to K^0_S hh$, model-independent GGSZ, $3\,\mathrm{fb}^{-1}$ [5]
- $B^+ \to DK^+$, $D \to K^0_S K\pi$, GLS, $3\,\mathrm{fb}^{-1}$ [6]
- $B^0 \to DK^{*0}$, $D \to hh$, GLW/ADS, $3\,\mathrm{fb}^{-1}$ [7]
- $B^0_s \to D^{\mp}_s K^{\pm}$, time-dependent, $1\,\mathrm{fb}^{-1}$ [8],



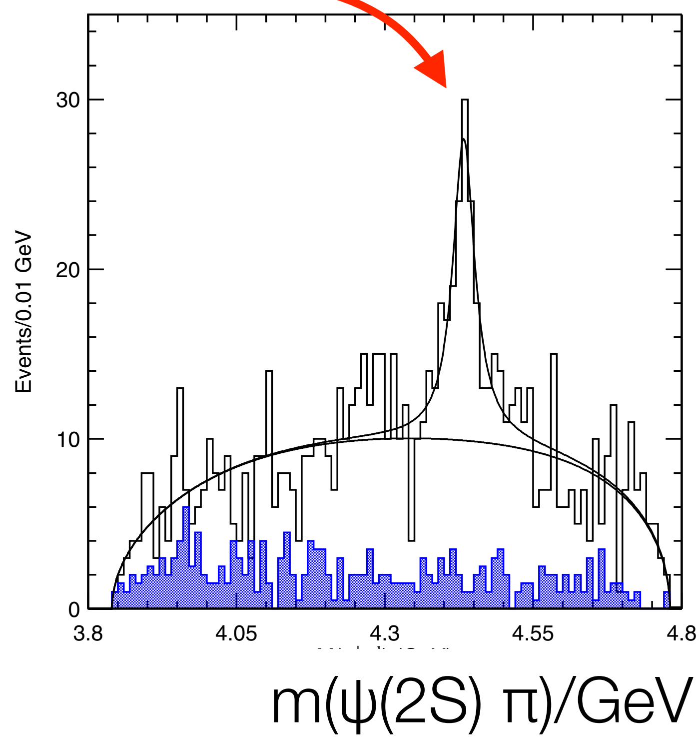
The Z(4430) question:

Is this peak in the $\psi(2S)\pi^-$ invariant mass, seen first by BELLE in 2008 when analysing $B \to \psi(2S)\pi^- K^+$, really a resonance?

Big thing - charged 4-quark state



The problem is that this is just the 1-D projection of a 4-D distribution…

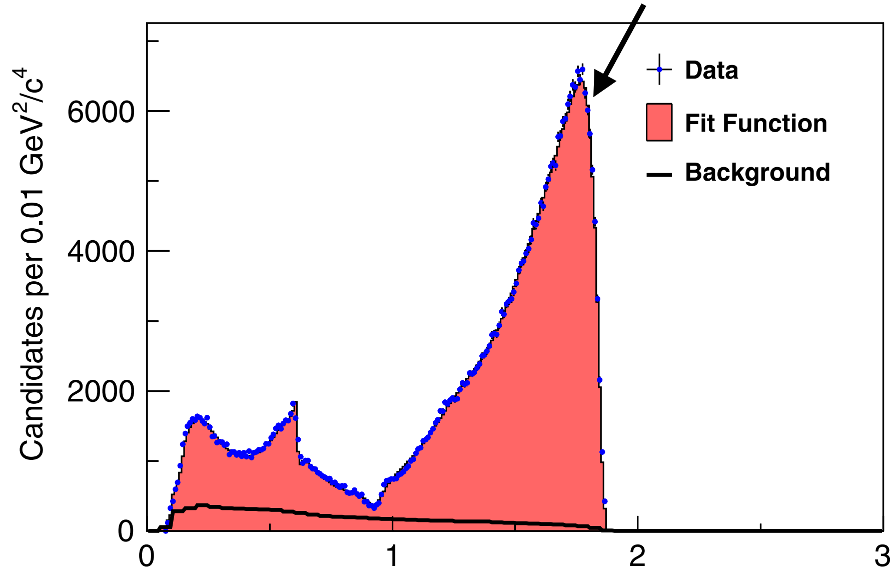


BELLE, Phys. Rev. Lett. 100 (2008) 142001, arXiv:0708.1790.

The 2-D illustration of this 4-D question

$D^o \rightarrow K_S \pi\pi$

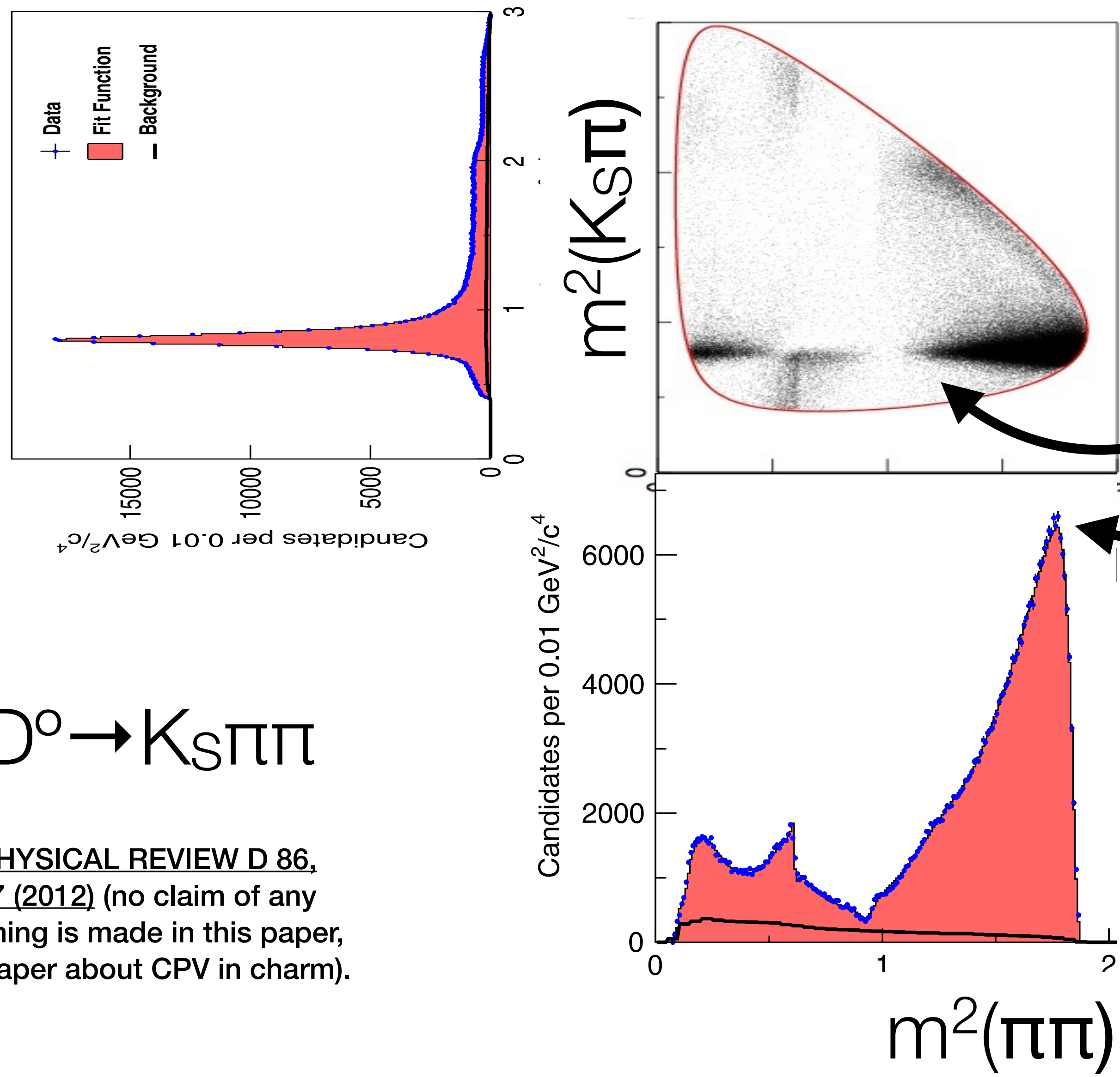
ππ resonance near 2GeV^2?



$m^2(\pi\pi)/GeV^2$

CDF PHYSICAL REVIEW D 86, 032007 (2012) (no claim of any such thing is made in this paper, it's a paper about CPV in charm).

The 2-D illustration of this 4-D question



Structure due to angular distribution in $D \to K^*(K_S\pi)\pi$

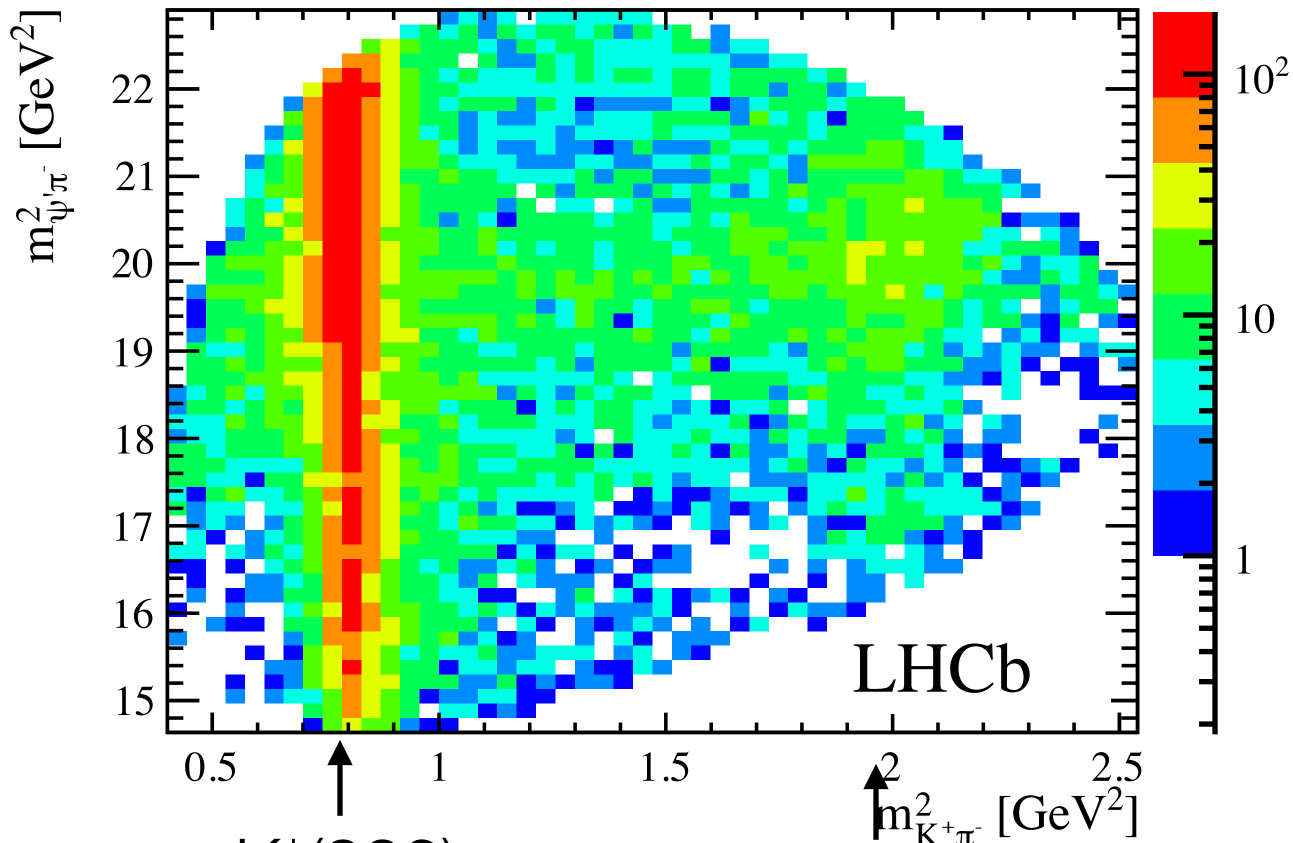
Not a (new) $\pi\pi$ resonance

$D^0 \to K_S\pi\pi$

CDF PHYSICAL REVIEW D 86, 032007 (2012) (no claim of any such thing is made in this paper, it's a paper about CPV in charm).

Z(4430)→ψ(2S)π⁻ in B→ψ(2S)π⁻ K⁺?

Z(4430)?→



plus helicity angles

K*(893)

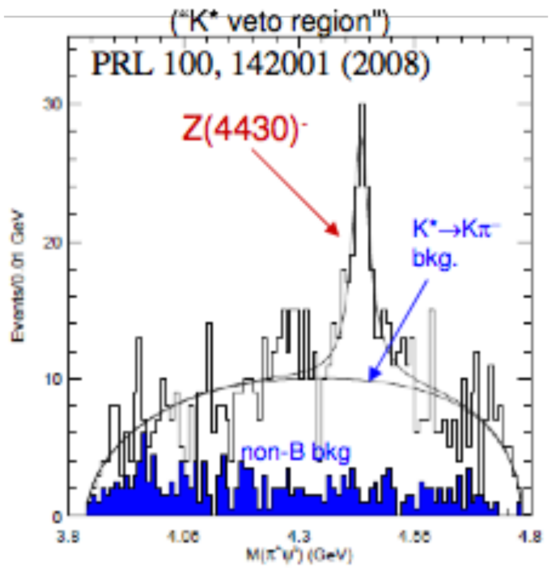
K^*_2(1430)

…and many other K* resonances

Z(4430)→ψ(2S)π⁻ in B→ψ(2S)π⁻ K⁺?

Belle 2008

1D



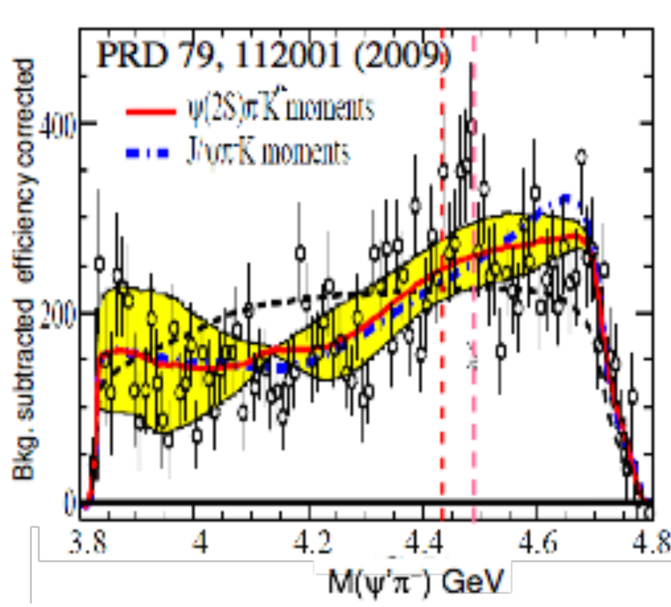
$M(Z) = 4433 \pm 4 \pm 2$ MeV

$\Gamma(Z) = 45^{+18}_{-13}{}^{+30}_{-13}$ MeV

significance 6.5σ

BaBar 2009

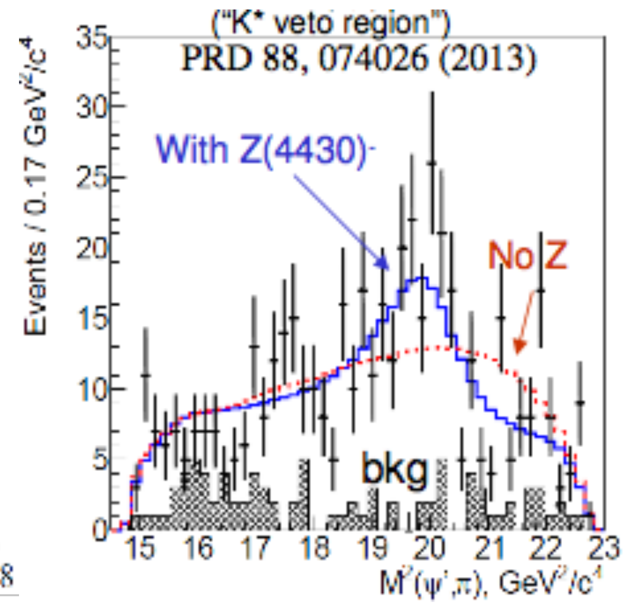
model-independent



Takes Kπ mass distribution as is (no K* model) and attempts to reproduce structure in ψ(2S)π⁻. from angular momentum effects. Works within statistics.

Belle 2013

4D



$M(Z) = 4485^{+22}_{-22}{}^{+28}_{-11}$ MeV

$\Gamma(Z) = 200^{+41}_{-46}{}^{+26}_{-35}$ MeV

6.4σ (5.6σ with sys.)

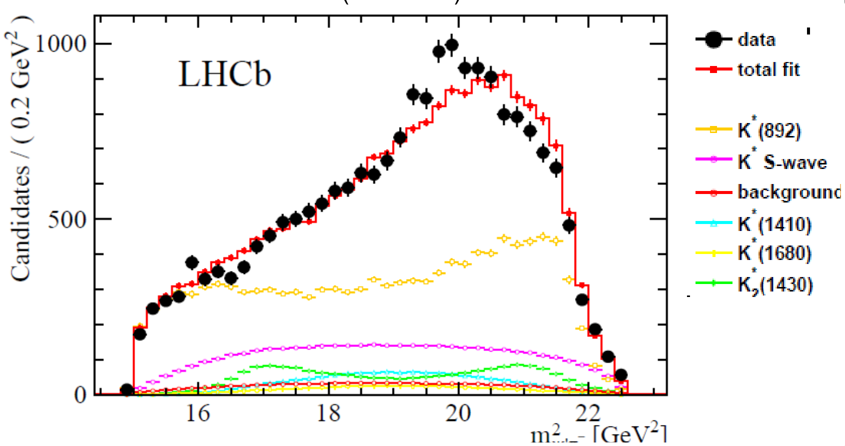
$J^P = 1^+$ preferred by $>3.4\sigma$

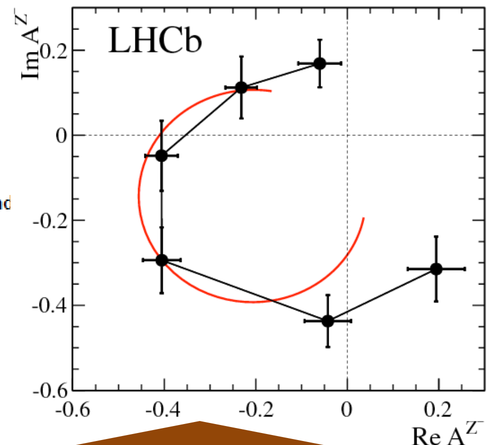
LHCb's evidence for the Z(4430) in $B \to \psi(2S)\pi^- K^+$

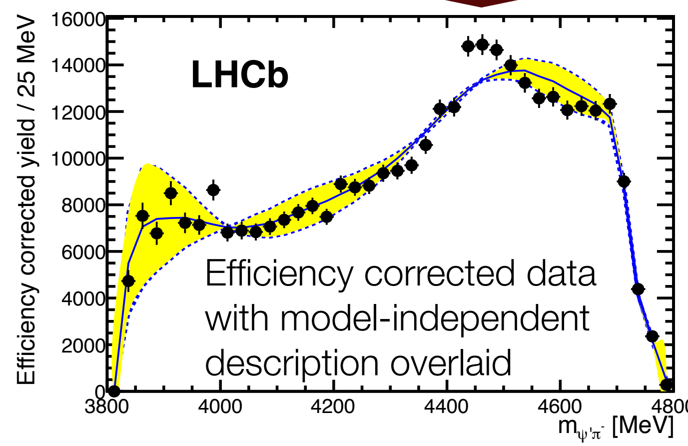
Amplitude fit:
>13.9σ in amplitude fit for Z(4430) (and >9.7σ for 1^+ relative other J^P assignments)

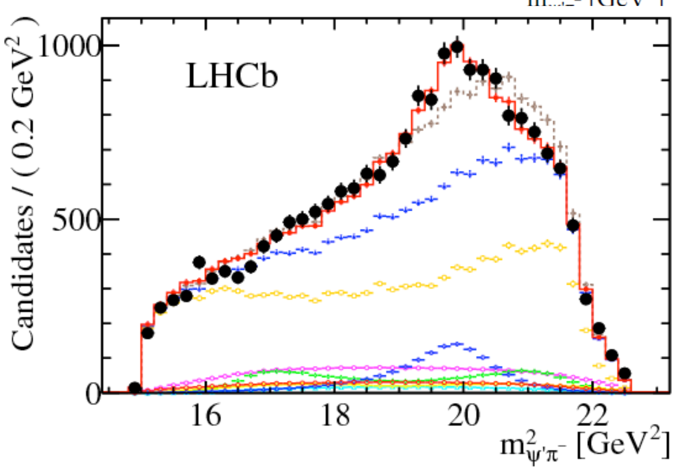
Model-independent
Model-indep. description of K* resonances (w/o Z) incompatible with data, clear excess in Z(4430) region

("all data")









Phase Motion
Fit where K* amplitudes are allowed to float, but Z amplitude is described model-independently by complex numbers in 6 bins of m(ψ(2S)π) confirms resonance-like phase motion

Tetraquark candidate travels around the world:

LHCb confirms existence of exotic hadrons

How CERN's Discovery of Exotic Particles May Affect Astrophysics
by BRIAN KOBERLEIN *on* APRIL 10, 2014

大型强子对撞机捕获到神秘粒子Z (4430)
或许成为物质形式 "四夸克态" 存在的有力证据

2014/04/13 15:46
LHCb実験を行っている国際研究チームが、4個のクォークが結合した粒子である「Z(4430)⁻」を合成したと発表した。Z(4430) としては、初発見から7年目にしてようやく別の研究チームが存在を立証した事になる。

นักฟิสิกส์ยืนยันพบฮาดรอนสองคว้ากสองแอนตีคว้าก

WRITTEN BY NATTY_SCI ON APRIL 13, 2014. POSTED IN ฟิสิกส์, วิทยาศาสตร์

ล่าสุด เครื่อง LHCb ได้มีการศึกษาอีกครั้งและใช้ข้อมูลอนุภาคจากเครื่องโดยตรงมาวิเคราะห์ แต่นำเอาเทคนิคการวิเคราะห์ของศูนย์ปฏิบัติการวิจัยเบลล์และ BaBar มาใช้ ศาสตราจารย์ชวาร์นิคกี้และทีมงานได้ยืนยันแล้วว่า Z(4430) นั้นมีอยู่จริง และ exotic hadron ก็มีอยู่จริงด้วย

Nowa forma materii: potwierdzono istnienie egzotycznych hadronów
13-04-2014 13:08 TO TRZECI RODZAJ HADRONÓW, DOTYCHCZAS WYRÓŻNIANO BARIONY I MEZONY

confirmada l´existència d´una nova partícula subatòmica

"המובהקות לאותות של Z (4430) מדהימה – לפחות 13.9 סיגמה – דבר המאשר את קיומו של מצב זה" אמר דובר LHCb פיירולואיג'י קמפנה. "ניתוח ה- LHCb חשף את הטבע המהדהד של המבנים הנצפים, והוכיח כי זהו באמת חלקיק, ולא תכונה מיוחדת של הנתונים".

Эксперимент LHCb окончательно доказал реальность экзотического мезона Z(4430)

PISTOLA FUMANTE DI UNA PARTICELLA A QUATTRO QUARK

LHCb kinnitas tetrakvargi olemasolu

LHC Beauty Tangkap Z (4430) Mungkin Tetraquark

SU professors test boundaries of 'new physics' with discovery of four-quark hadron
Physicist Tomasz Skwarnicki confirms existence of exotic hadron with two quarks, two anti-quarks
Apr 10, 2014 | Article by: Rob Enslin

Mystisk partikel udfordrer fysikernes kvarkmodel

Các nhà nghiên cứu tại LHC xác nhận sự tồn tại của hạt Tetraquark: tổ hợp tạo thành từ 4 quark
Thảo luận trong 'Khoa học' bắt đầu bởi ndminhduc, 15/4/14.

De LHCb heeft 't bevestigd: er bestaan exotische hadronen
10 APRIL 2014 DOOR ARIE NOUWEN • REAGEER

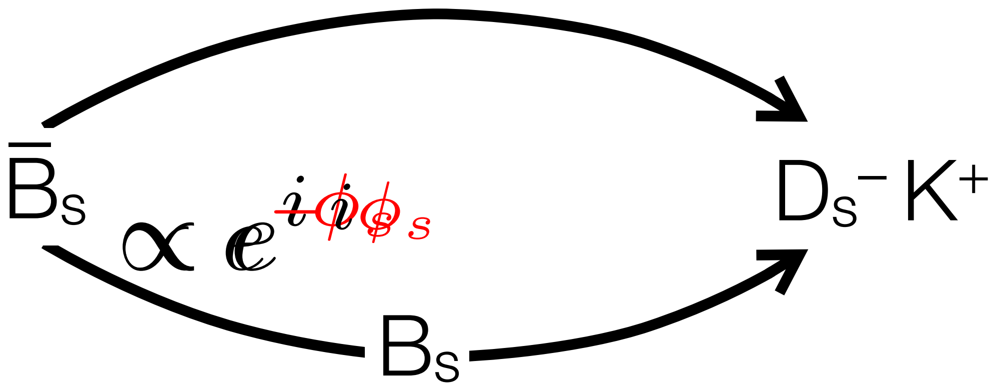
تاکنون کشف ذره (4430)Z در سال 2007 بشدت جنجال برانگیز بود و فیزیکدانان بر سر موجودیت یا عدم موجودیت آن اختلاف نظر داشتند

تائید کنونی ذره با استفاده از آشکارساز LHCb ماورای هرگونه تردید منطقی موجود است.

LHCb confirma la existencia de la partícula Z(4430) formada por cuatro quarks

Παρασκευή, 11 Απριλίου 2014

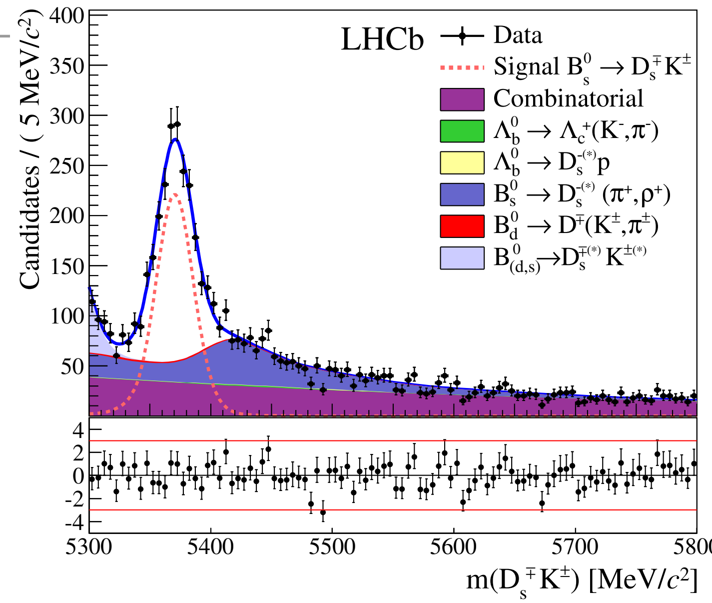
Ο LHCb επιβεβαιώνει την ύπαρξη εξωτικού σωματιδίου, LHCb confirms existence of exotic hadrons

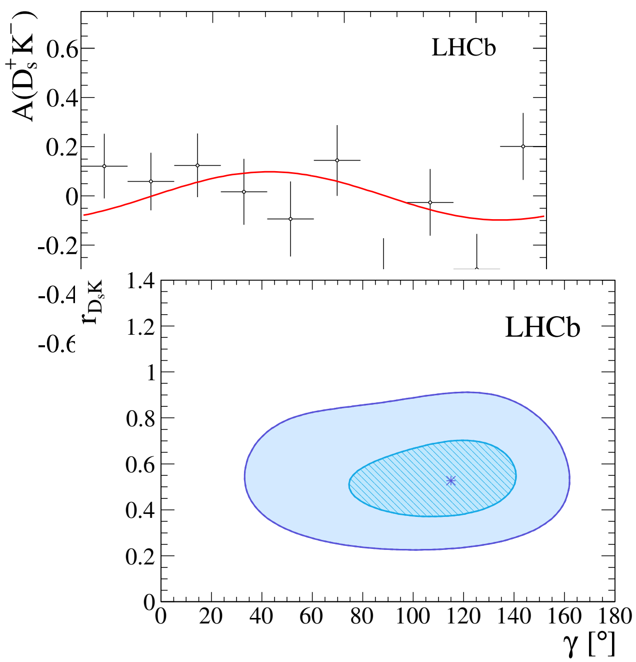

$\bar{B}_s$
$\propto e^{i\phi_s}$
$D_s^- K^+$
B_s

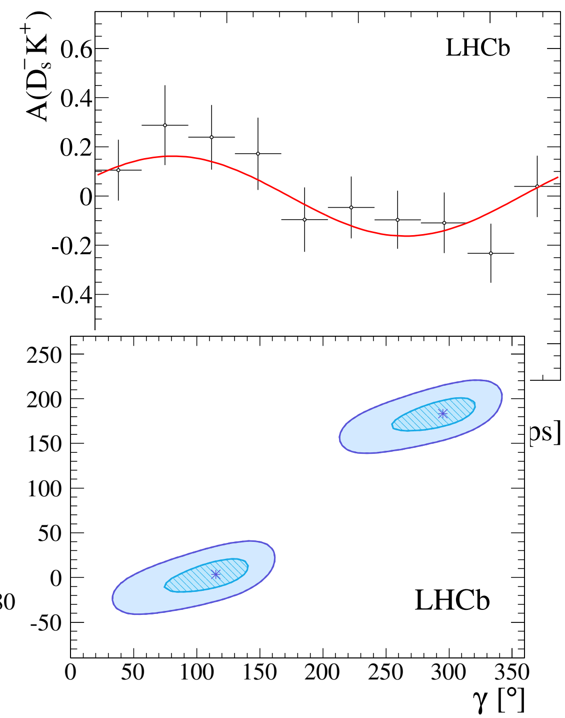
Bs->DsK, 1/fb

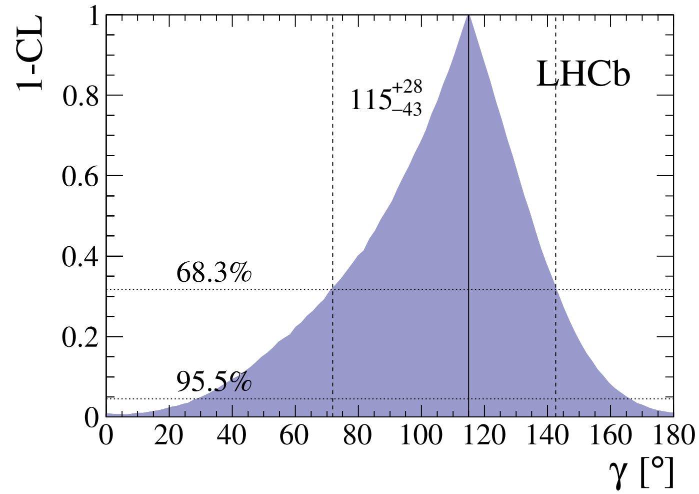
Event type	ε_{tag} [%]	ε_{eff} [%]
OS-only	19.80 ± 0.23	1.61 ± 0.03 ± 0.08
SSK-only	28.85 ± 0.27	1.31 ± 0.22 ± 0.17
OS-SSK	18.88 ± 0.23	2.15 ± 0.05 ± 0.09
Total	67.53	5.07

arXiv:1407.6127 (2014)



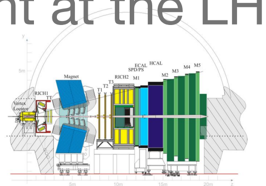






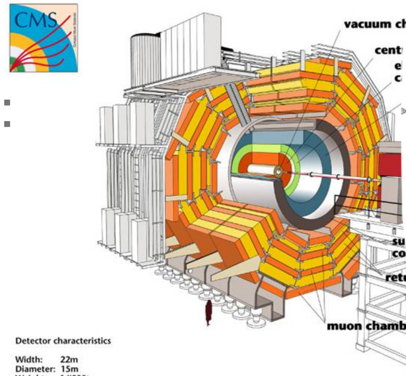
Heavy flavour physics at the LHC

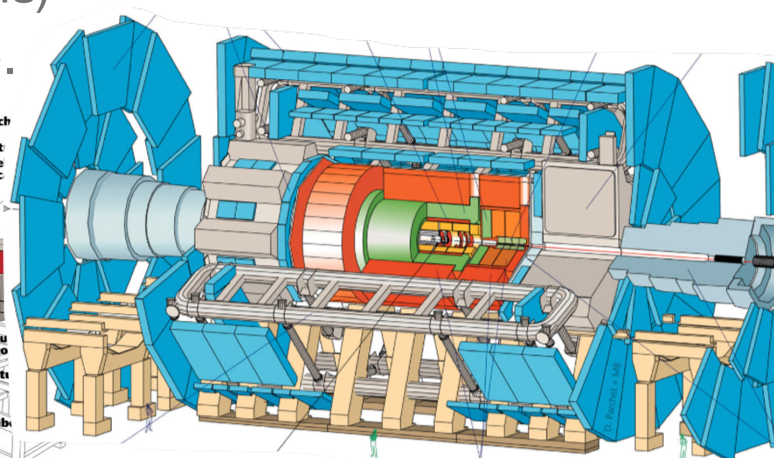
- LHCb: Dedicated flavour physics experiment at the LHC:
  - Optimised geometry
  - RICH particle ID (K/π separation)
  - Most precise vertexing at LHC
  - Dedicated heavy flavour trigger (incl B→hadrons)
  - Best mass resolution at LHC (for heavy flavour).



small & mighty

- ATLAS, CMS' heavy flavour skills:
  - good μ coverage,
  - efficient di-muon trigger,
  - maximal luminosity.
  - Good at rare dimuon decays such as $B_{(s)} \to \mu\mu$.





- ALICE: Cleanly reconstructs heavy flavour decays, focussed on using this to study quark-gluon plasma.