Heavy Flavour Physics, an introduction and review

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Question 1:
Where to start?

What is Recent?

EXPERIMENT

Rutherford: Proton
Chadwick: Neutron
Gell-Mann: Strange
AGS : CPV in Kaons
SLAC: Up+Down
SLAC: Charm
E288: Bottom
Argus: B-mixing
DØ + CDF: Top

1815 1919 1920 1932 1953 1963 1964 1968 1970 1973 1974 1977 1987 1995

Prout: Proton
Rutherford: Neutron
Cabbibo: angle
Gell-Mann: 8-fold way
Anderson: EWSB
Guralnik-Hagen-Kibble-
Brout-Englert-Higgs-
GIM: charm
CKM: 3rd Generation

THEORY

1815-1990

Not-too distant history…

- Last 20 years dominated by the *B*-factories and TeVatron

- Many experiments, hundreds of amazing papers...

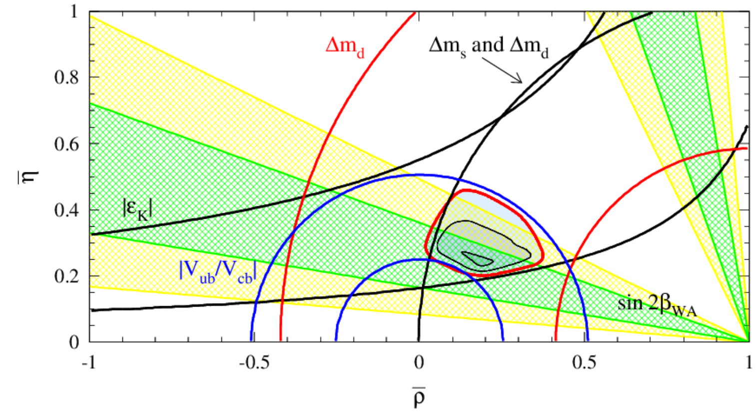
1990-2010

A pretty picture?

- The new millennium perfected our picture of flavour in the SM

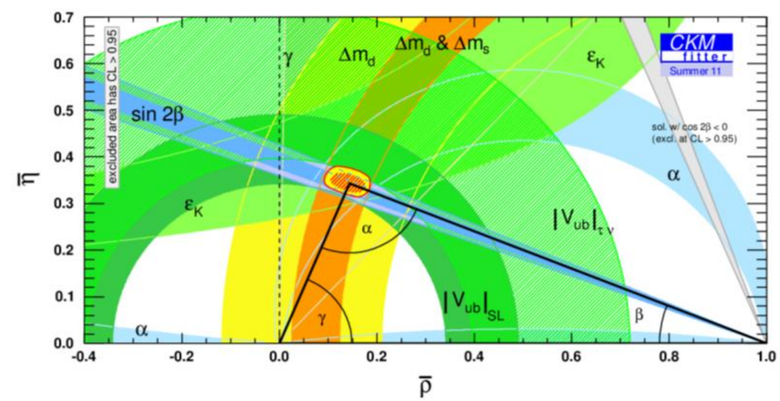
Mass of Top quark is known,
B_d known to oscillate
CKM matrix looks… OK

2001



B_d and B_s known to oscillate
CKM matrix works amazingly!

2011



- To understand why that is important we must go back further..
  - …… muuuuch further ….

1990-2010

Outline

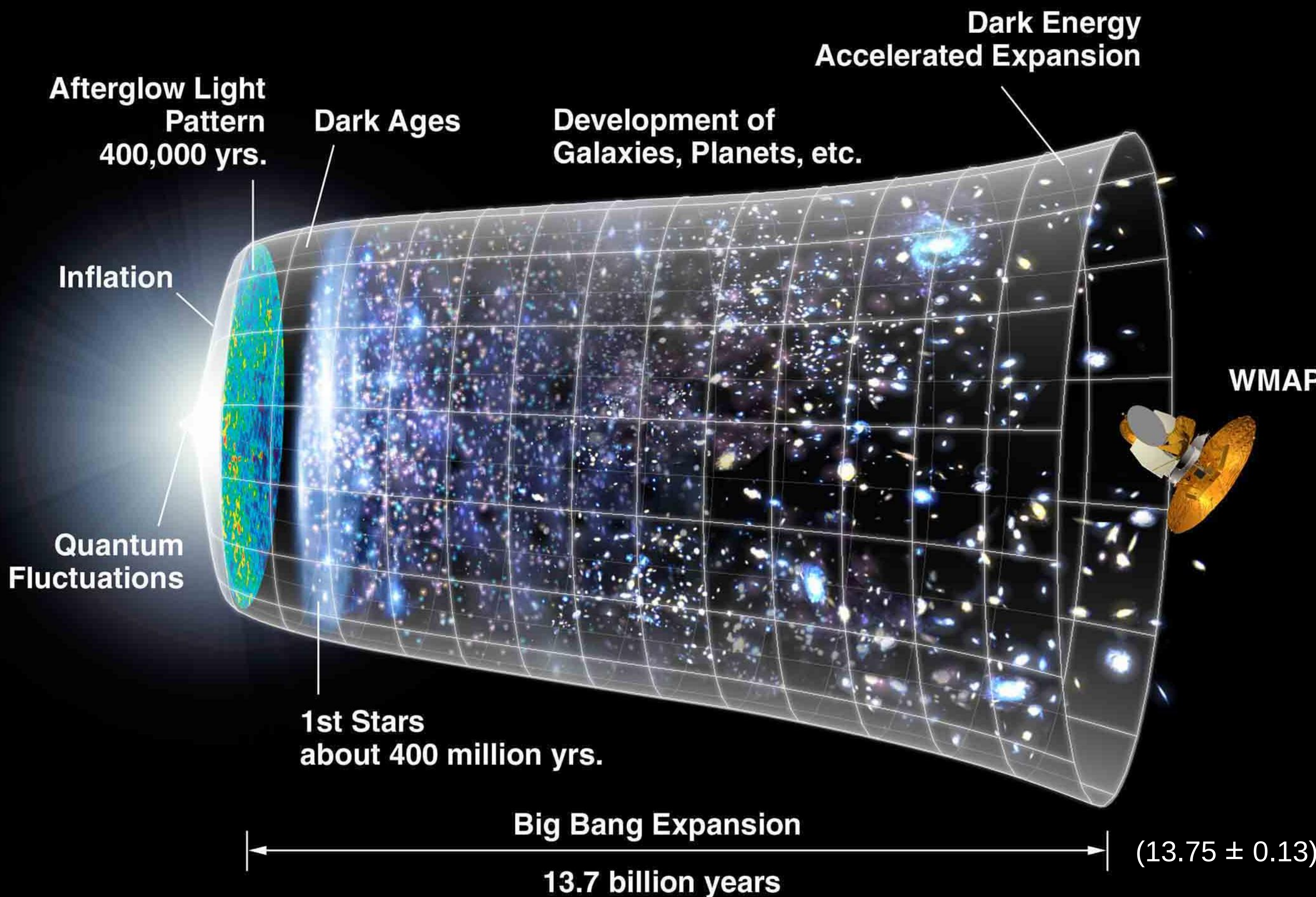
1. Welcome to our universe
   - Did you forget how awesome it was?

2. Introduction to flavour physics
   - What has that got to do with flavour physics?
   - Where can we look for new physics?
   - What are the observables?
   - What is Mixing?

3. 2011 results, the hottest new physics searches

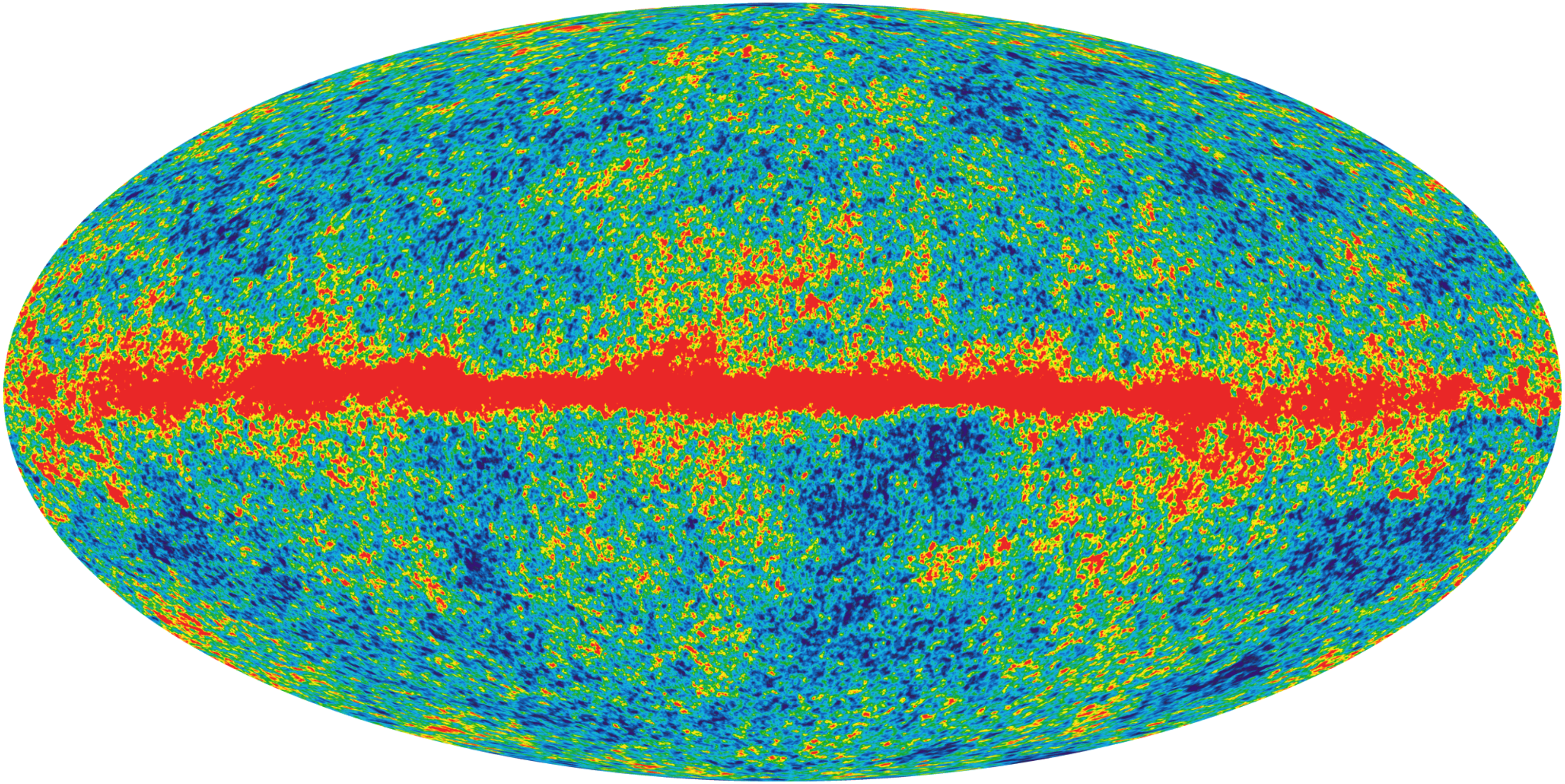
4. Summary and Outlook

Gravity



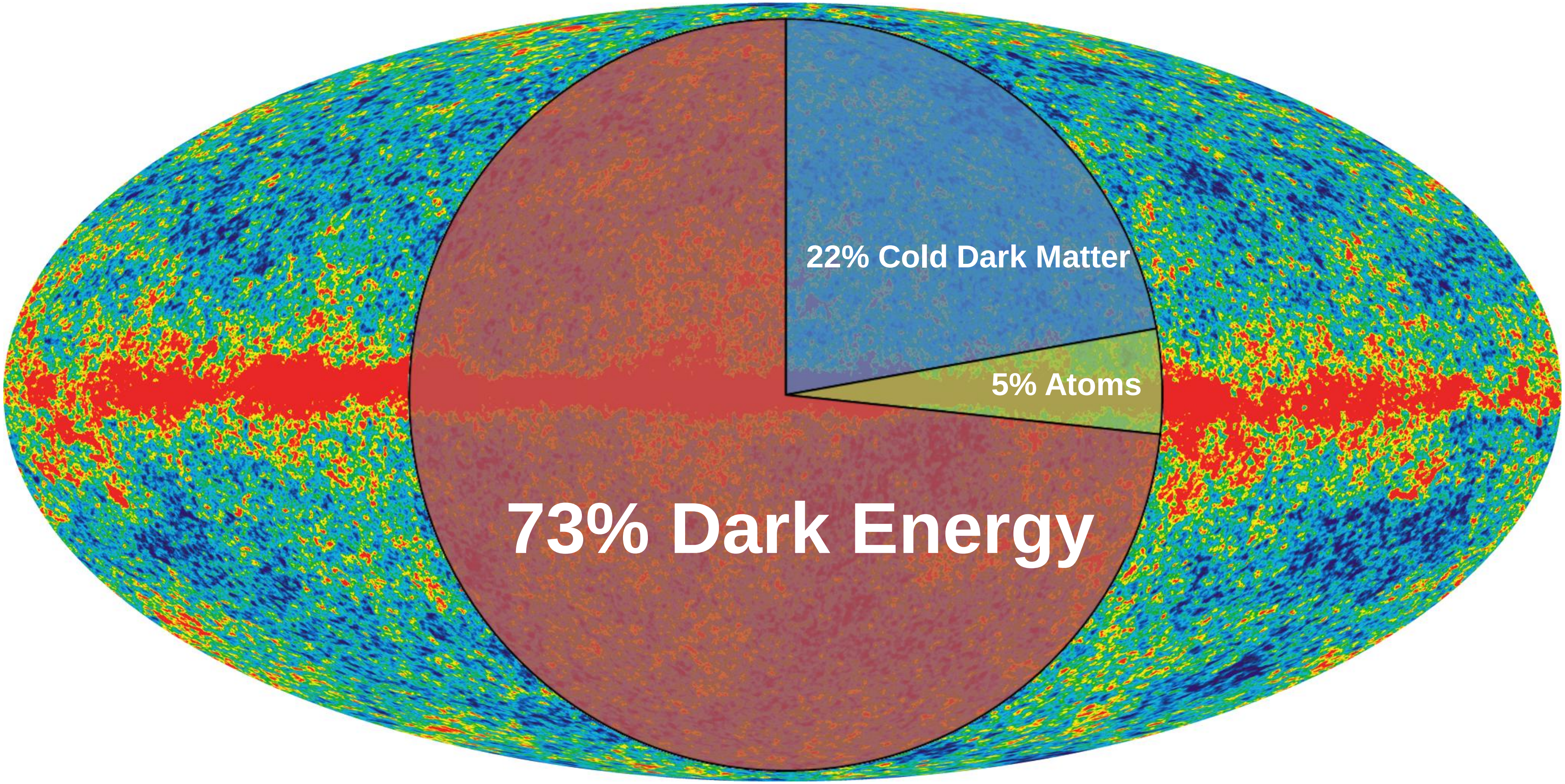
(13.75 ± 0.13) Gyr

Light

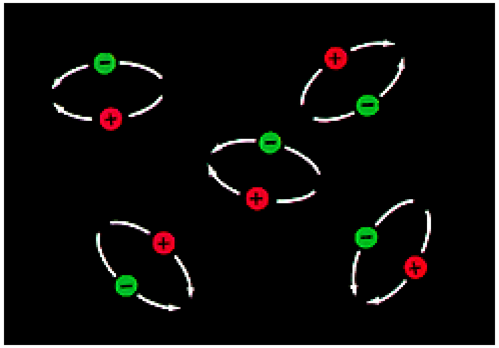


(13.75 ± 0.13) Gyr

Matter and …?

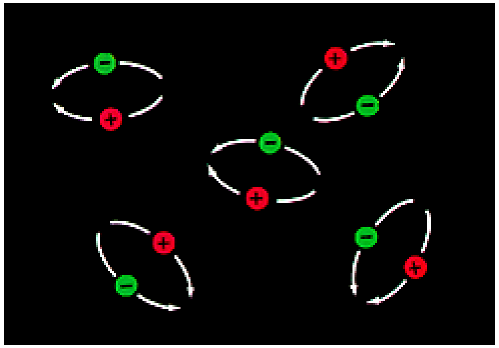


Antimatter



Matter + Antimatter = photons

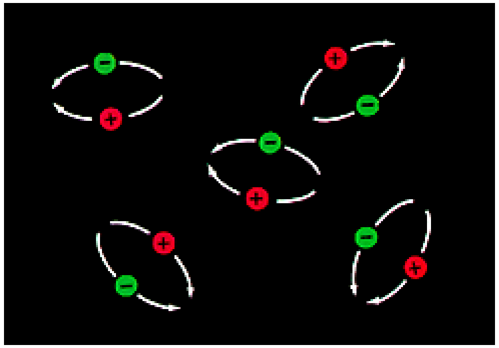
Antimatter



Matter + Antimatter = photons ± CP-violation, CPV

observable difference between matter and antimatter

Antimatter



Matter + Antimatter = photons ± CP-violation, CPV

observable difference between matter and antimatter

REALITY

$$\frac{n_{baryon}}{n_\gamma} = (5.5 \pm 0.5) \times 10^{-10}$$

You Are Here

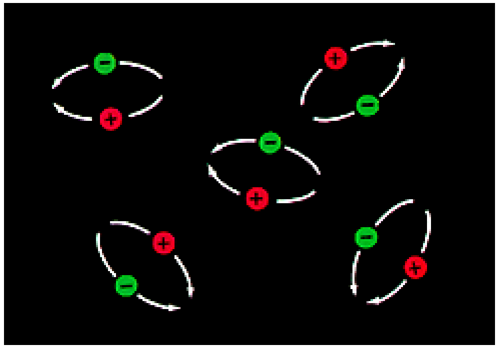
SM (maximal CPV)

$$\frac{n_{baryon}}{n_\gamma} < 10^{-20}$$

Where did you go?

Guys…? Guys…??

Antimatter



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REALITY

$$\frac{n_{baryon}}{n_\gamma} = (5.5 \pm 0.5) \times 10^{-10}$$

SM (maximal CPV)

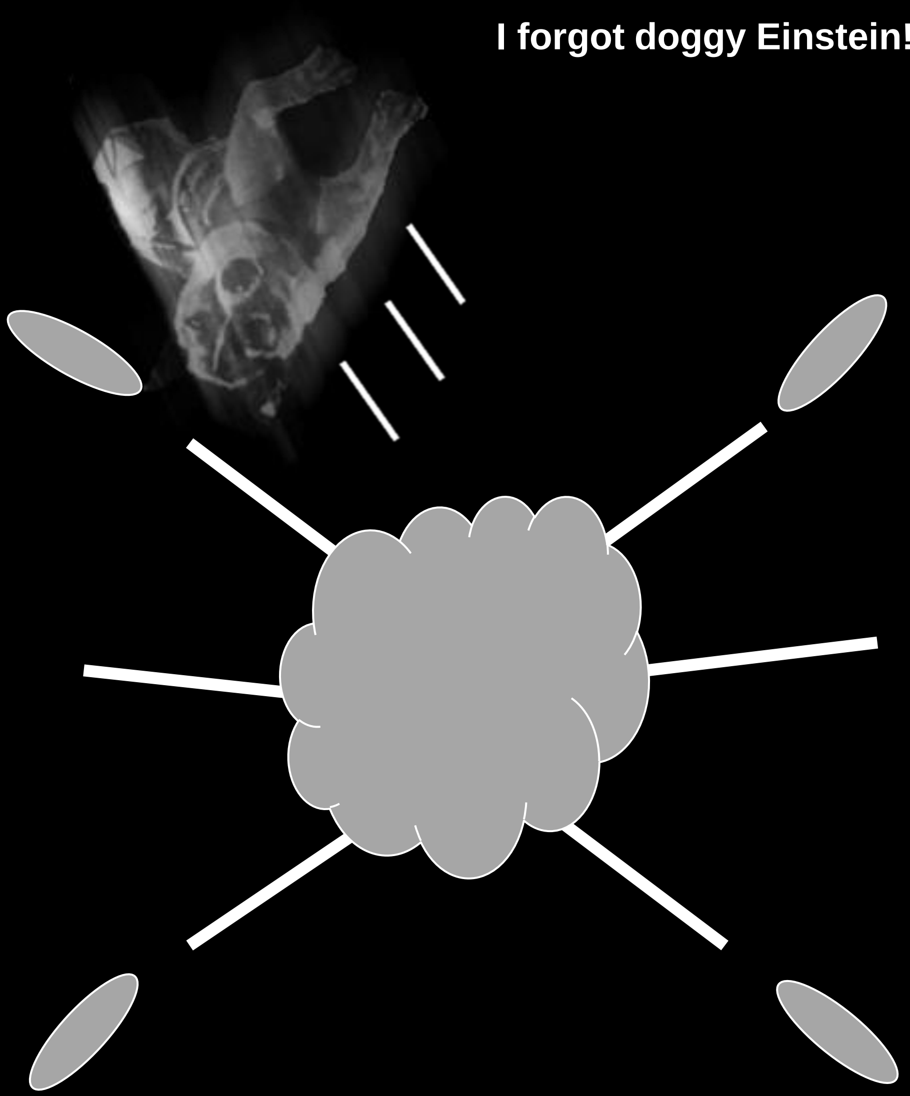
$$\frac{n_{baryon}}{n_\gamma} < 10^{-20}$$

Mass of entire solar system: 2x10^{30} kg → **Mass of largest asteroid, Ceres: 10^{21} kg**

Area ~ (Northwest+Nunavut): Population ~ one small dog

Woof?

Gravity fail.



Bad news for the SM

- *The SM is awesome*, but it fails to cover the most obvious features of our universe!!

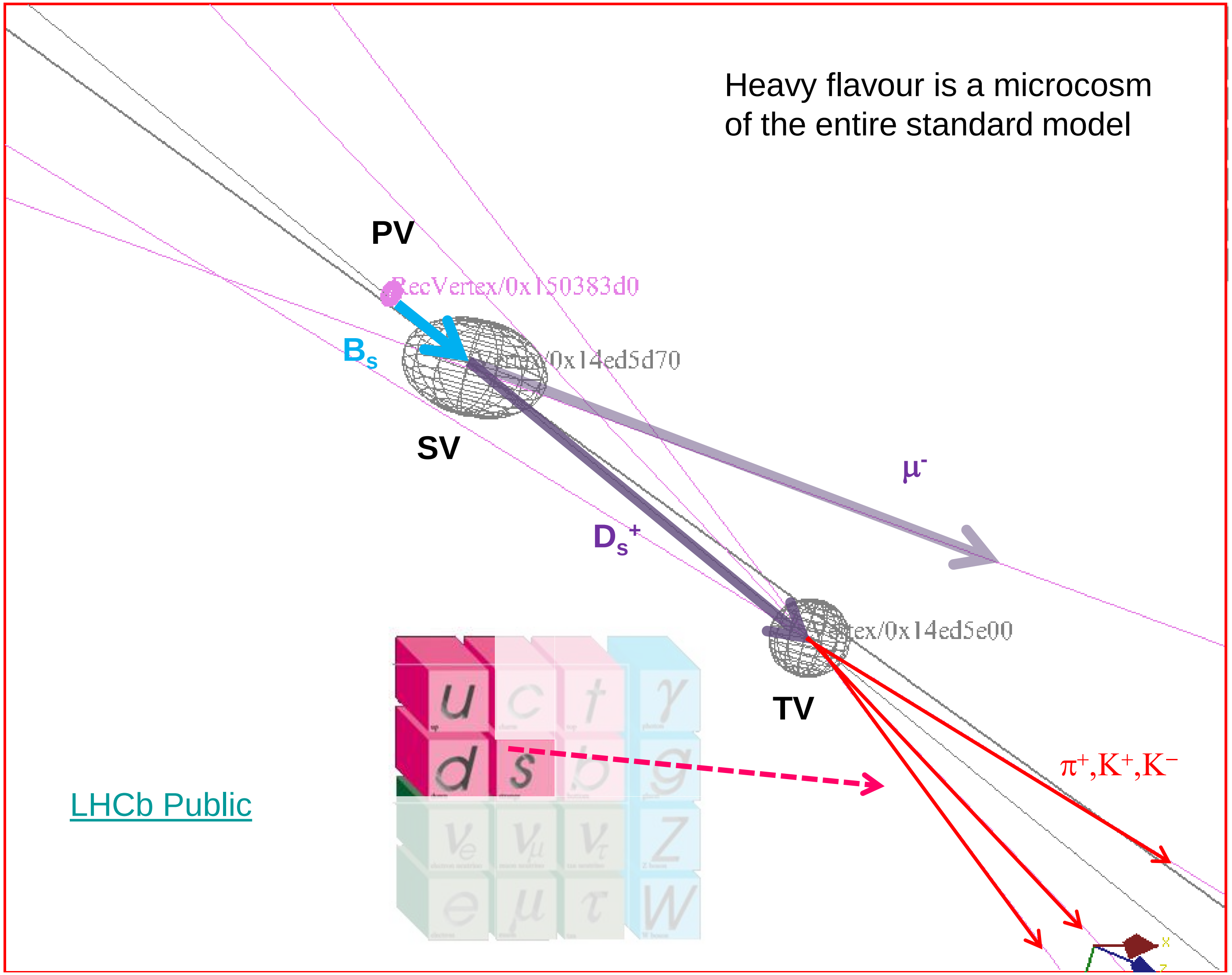
1. Gravity
2. Inflation (Anisotropy)
3. 95% of stuff in the universe (dark energy and dark matter)
4. Why the 5% of baryonic matter even exists (CPV)
5. Why three generations?
6. Why is only one of them light?

- Apologies to the SM, but it is a poor approximation of reality!

Question 2:
What does that have to do with heavy flavour physics?

A beautiful image

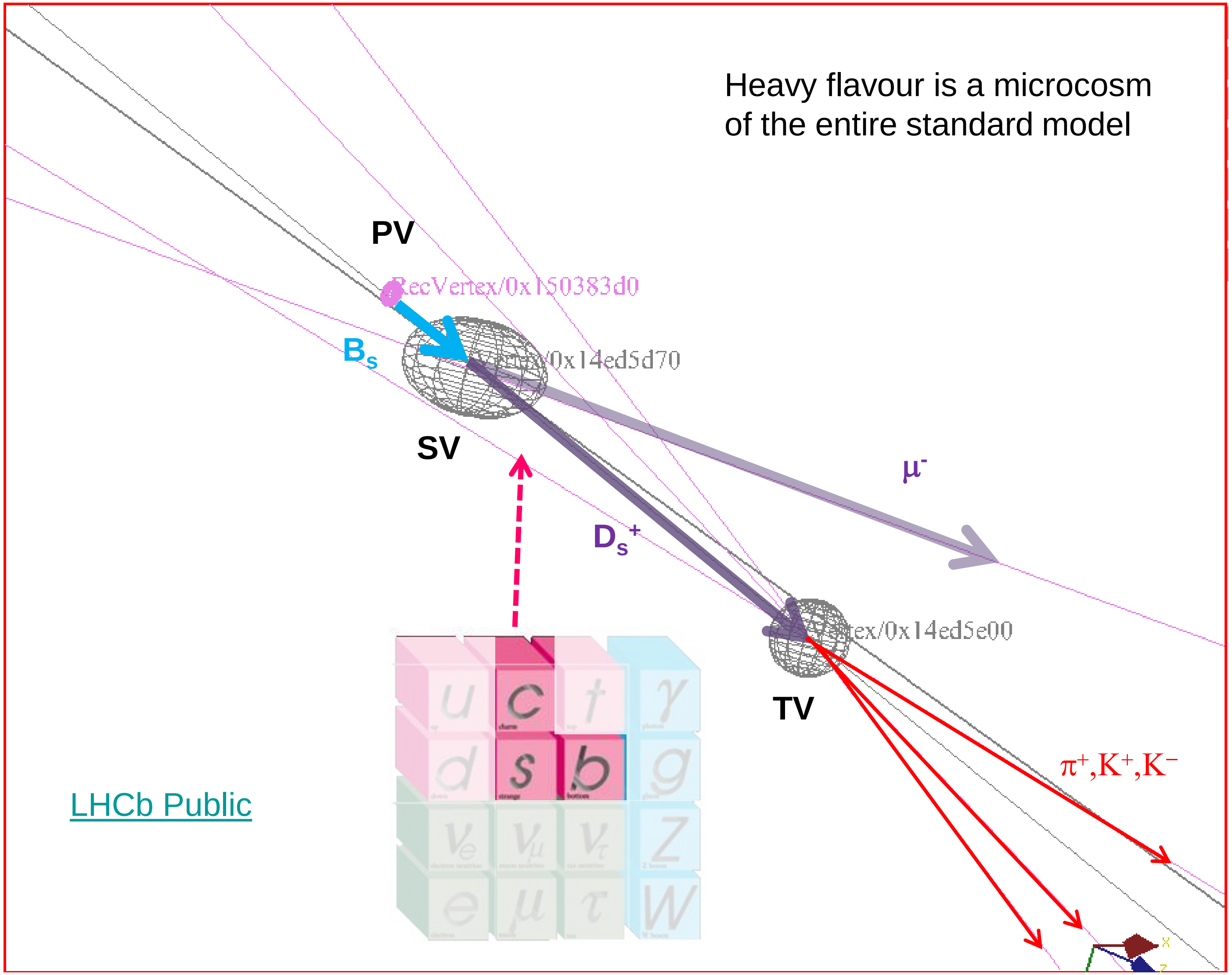
Heavy flavour is a microcosm of the entire standard model



LHCb Public

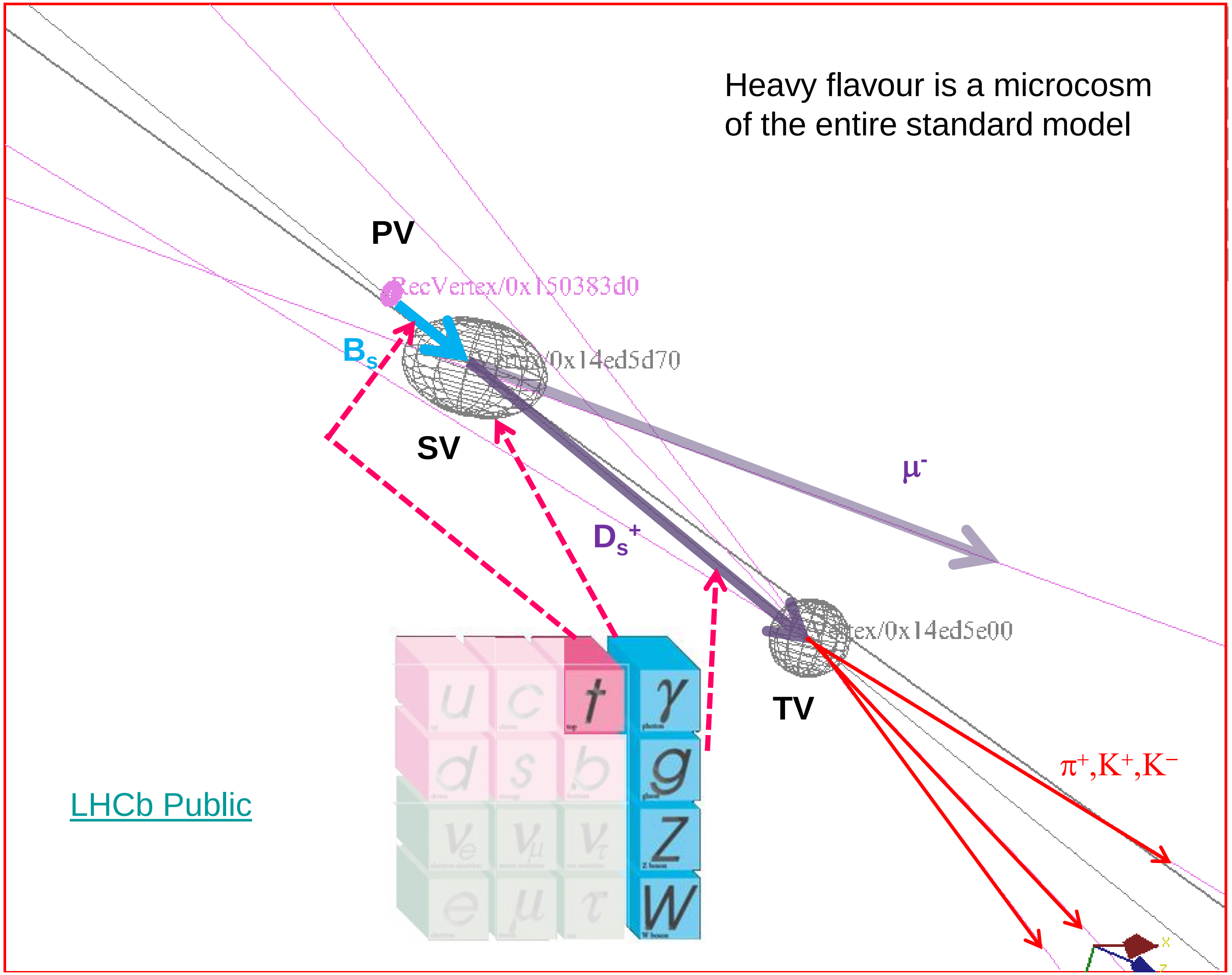
A beautiful image

Heavy flavour is a microcosm of the entire standard model

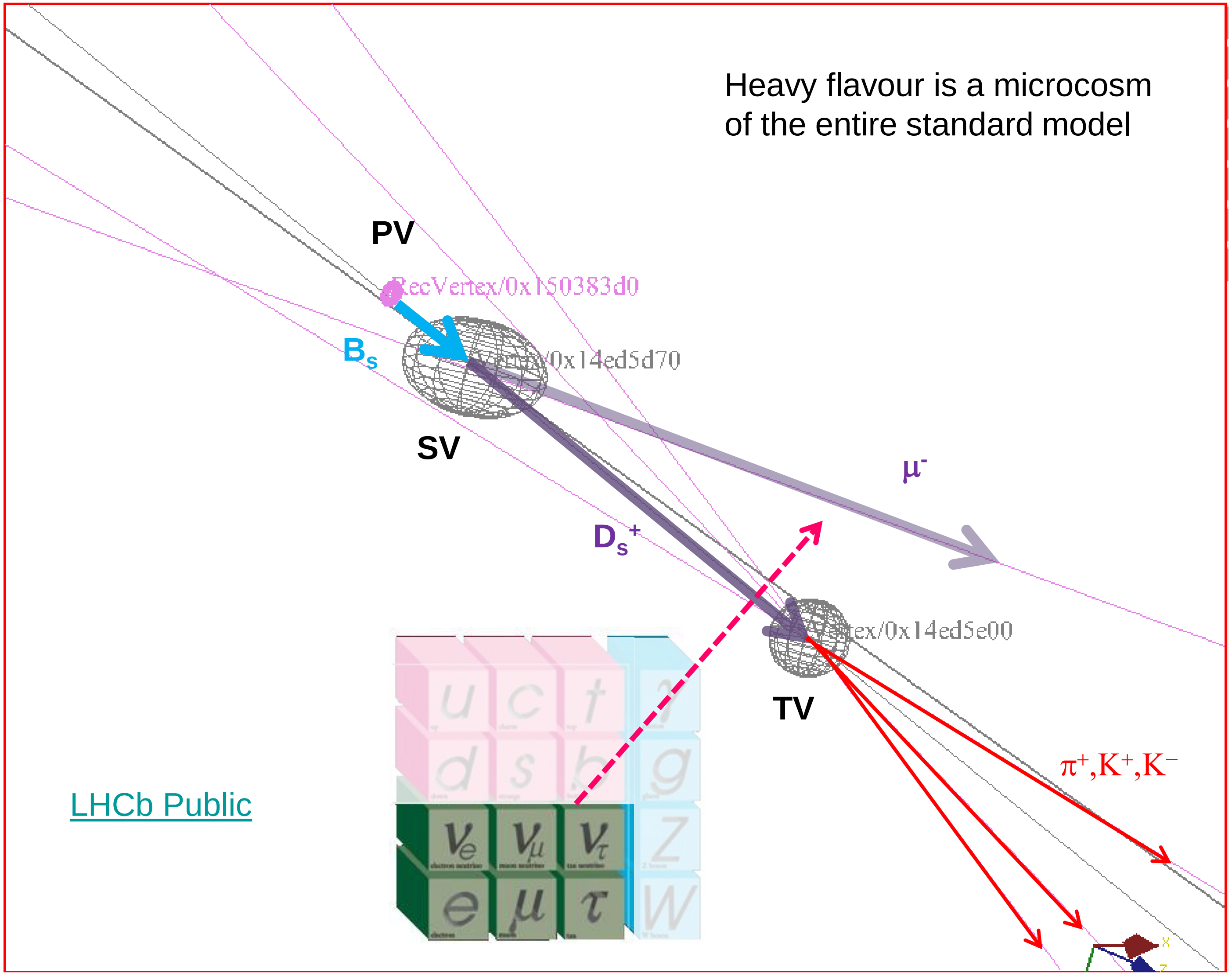


LHCb Public

A beautiful image



A beautiful image

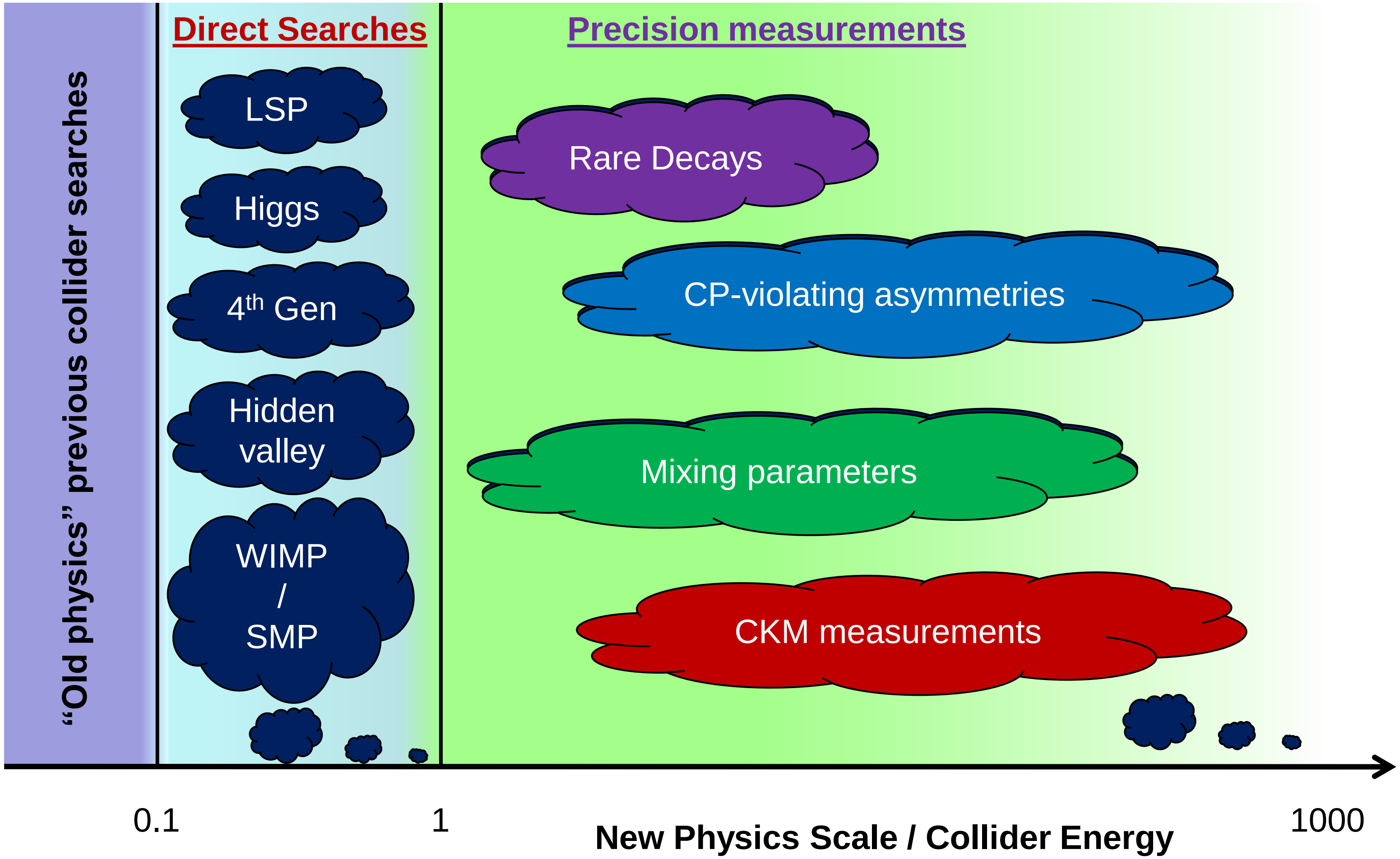


LHCb Public

Question 3:
Where can we look for new physics?

NP Searches

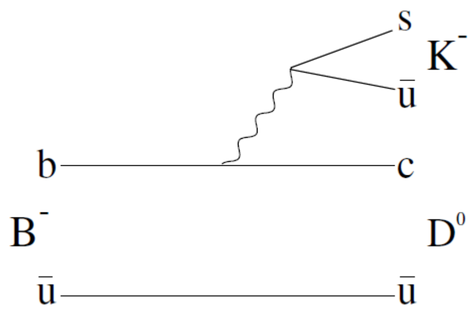
➢ There are in general two types of new physics searches



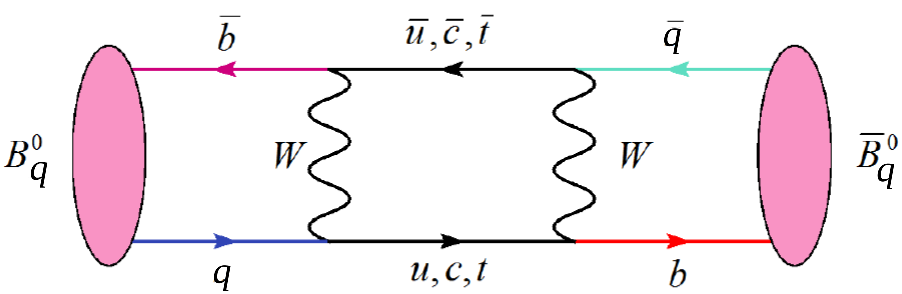
Precision Searches

1. Find a place where new physics is unlikely
2. Precisely measure well-predicted observables
3. Find a place where new physics could enter
4. Precisely measure related observables

Unlikely: tree-level decays



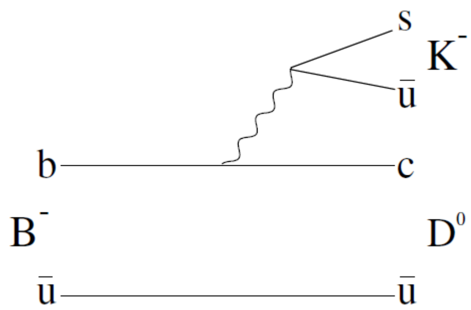
Likely: loops and penguins



NP in loops

1. Find a place where new physics is unlikely
2. Precisely measure well-predicted observables
3. Find a place where new physics could enter
4. Precisely measure related observables

Unlikely: tree-level decays



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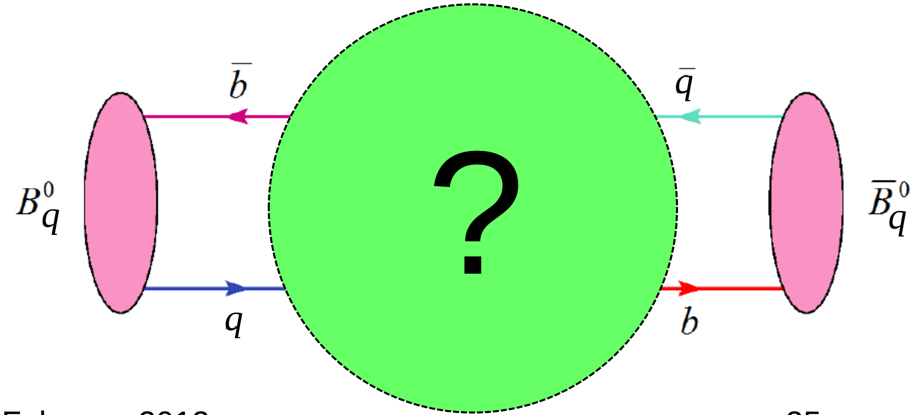


Question 4:
What Are “The Observables”?

CPV observables

- SM has only one source of CPV, from the CKM, a phase

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

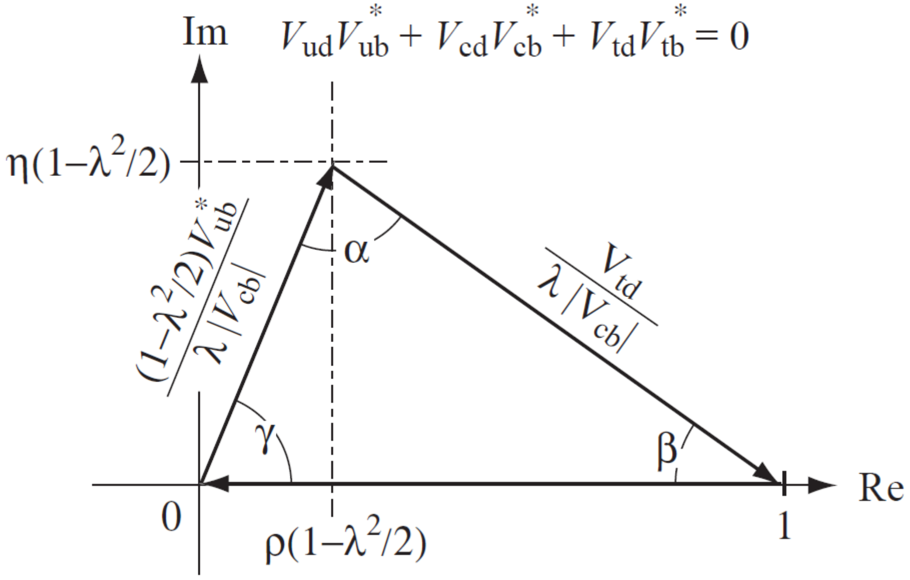
$$\overline{\rho} + i\overline{\eta}$$

- Observe this and any NP phase with interference:
  - Need observables with two competing amplitudes

- SM phase manifests most obviously in the *b*-quark system

Unitarity Triangles

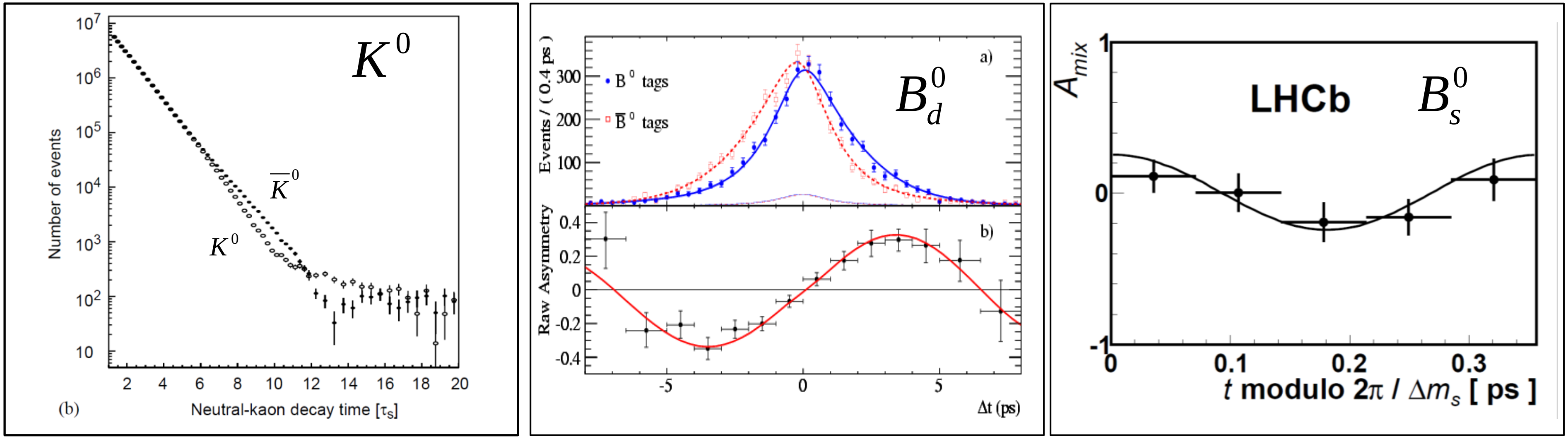
- Product of rows and columns are constrained by unitarity
- Of the nine relationships, six form a unitarity triangle
- The most well-known triangle is:



- A lot of phases are neatly accessible through Mixing

Question 5:
What Is Mixing?

Neutral mesons are *weird*



(CPLear) (Babar) (LHCb)

- ➢ *"mass eigenstates are not the flavour eigenstates"*
  - Probably the weirdest phenomenon in physics!
- ➢ *"neither of those are the CP-eigenstates"*
  - CP-violation is very weird in itself
  - Observation of CPV in Kaons in 1964, before any predictions!

QM with a broad brush!

- Evolution of a state is governed by the Hamiltonian:

$$\left|X(t)\right\rangle = e^{-iHt}\left|X(0)\right\rangle = e^{(-i\Re\{H\}+\Im\{H\})t}\left|X(0)\right\rangle$$

Wave-like propagation
(e^{ix} -> cos(x) …)

Decay if Im{H}<0
$e^{-\Gamma t}$

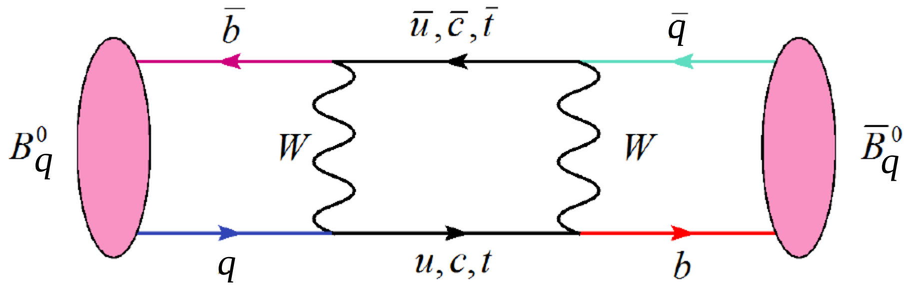
- Leads to the most basic Hamiltonian of anything

$$H\left|X\right\rangle = i\frac{d}{dt}\left|X\right\rangle = \left(M_X - \frac{i}{2}\Gamma_X\right)\left|X\right\rangle$$

- X is an eigenstate, with a mass and a lifetime

Mixing

- In the *b*-system we have two coupled states



- Simplest one-line Hamiltonian is now a matrix

$$i\frac{d}{dt}\begin{pmatrix} \left|B_q^0(t)\right\rangle \\ \left|\bar{B}_q^0(t)\right\rangle \end{pmatrix} = \left(\underline{\underline{M}}_q - \frac{i}{2}\underline{\underline{\Gamma}}_q\right)\begin{pmatrix} \left|B_q^0(t)\right\rangle \\ \left|\bar{B}_q^0(t)\right\rangle \end{pmatrix}$$

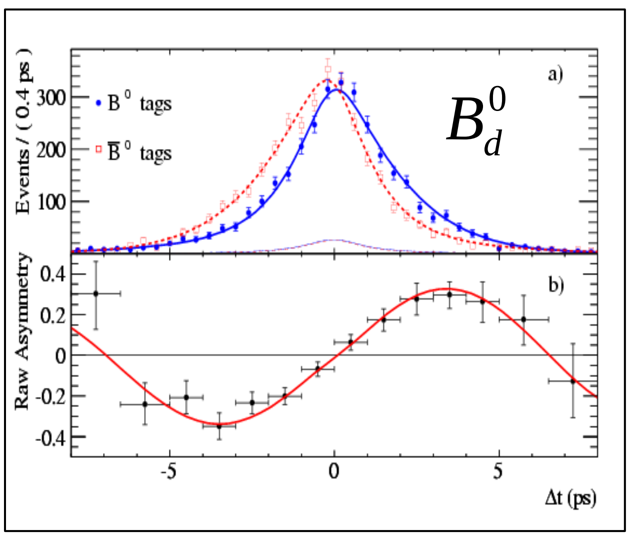
- Off-diagonal elements encode mixing and interference (!=0)

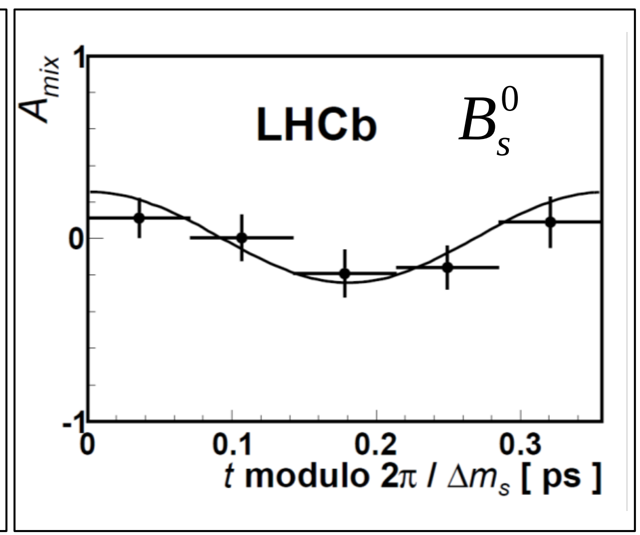
Mass and lifetime

- Diagonalize to find the "propagating" states, with a "simple" *H*

$$H\left|B_{L/H}\right\rangle = i\frac{d}{dt}\left|B_{L/H}\right\rangle = \left(M_{L/H} - \frac{i}{2}\Gamma_{L/H}\right)\left|B_{L/H}\right\rangle$$

- Not flavour states - time-dependent mixtures of probabilities





Observables

- Four simple observables:
  1. Average width $\bar{\Gamma}, \Gamma_{11} + \Gamma_{22}$
  2. Average mass $\bar{M}, M_{11} + M_{22}$
  3. Width Difference $\Delta\Gamma_q = \left(\Gamma_H^q - \Gamma_L^q\right) = 2\left|\Gamma_{12}^q\right| \arg\left\{\frac{\Gamma_{12}^q}{M_{12}^q}\right\}$
  4. Mass Difference $\Delta m_q = \left(M_H^q - M_L^q\right) = 2\left|M_{12}^q\right|$
- And we also have **a phase**, which violates CP:

$$\phi_q = \arg\left\{-\frac{M_{12}^q}{\Gamma_{12}^q}\right\}$$

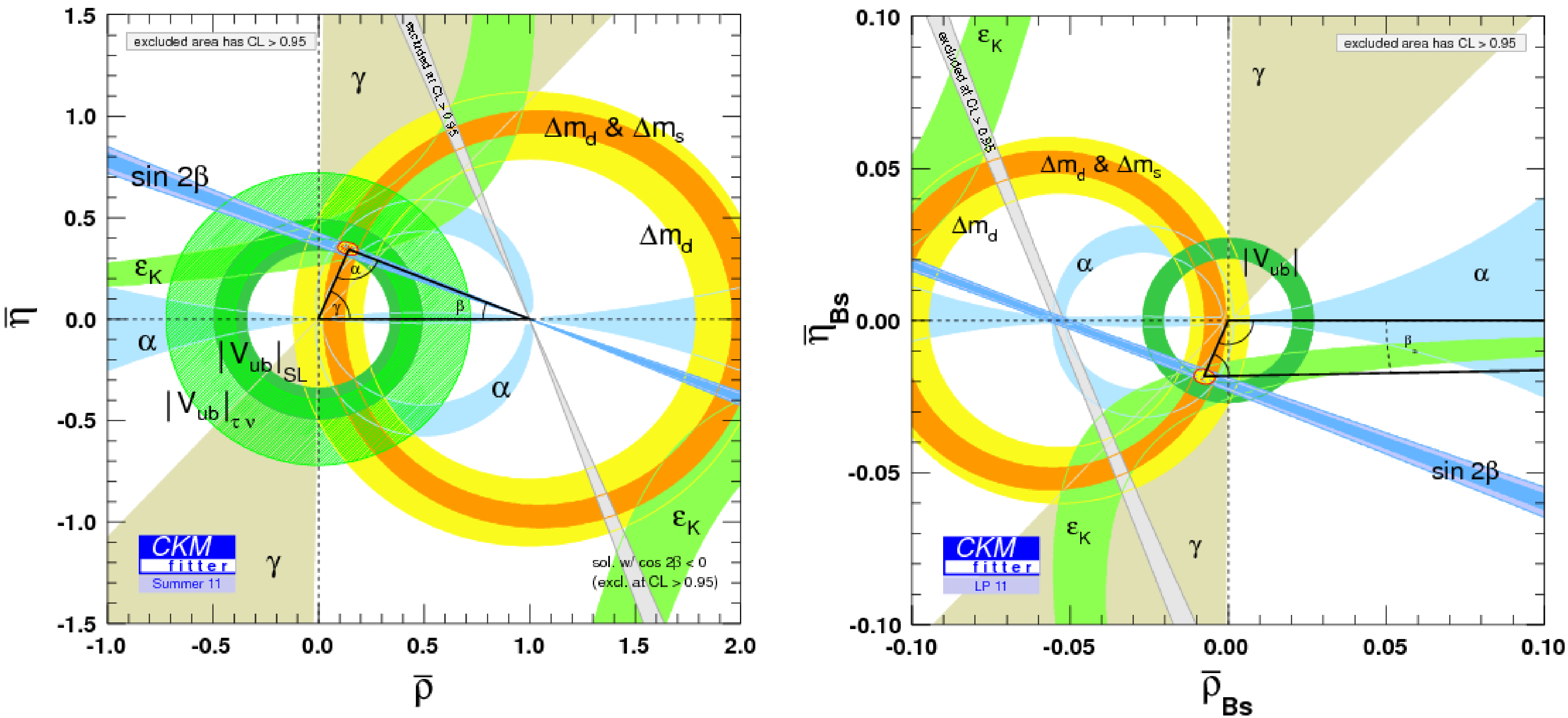
and/or

$$a_{fs}^q = \mathrm{Im}\left\{\frac{\Gamma_{12}^q}{M_{12}^q}\right\}$$

- All very predictable observables in the SM, related to the CKM

CKM - status

- Plot everything together on a single graph
- Everything is consistent ... so far ...



All work and no play makes Jack a dull boy;
Aol work and no play makes Jack a dull boy.
All work and no play makes Jack a dull boy.
All work and no play makes Jack a dullboy.
All work and no play makes Jack a dull boy.
All work and no play makes Jack a dull boy.
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…no play makes Jack a dull boy.
…d no play makes Jack a dull boy.
…and no play makes Jack a dull boy.
…l work and no play makes Jack a dull boy.
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All work and no play makes Jack a dull boy.
All work and no play makes Jack a dull boy.
All work and no play makes Jack a dull boy.
…no play makes Jack audll boy.

Pit Stop

➢ Intermission, intermezzo, break, pause, rest, deep breath

A. **What to take away so far?**
   - -13730000000 -> 1815: ☹ Standard Model ☹
   - 1815 -> 1990: ☺ Electro-weak, quarks, CKM ☺
   - 1990 -> 2010: ☺ QCD, CPV, Mixing ☺

B. **Theory?**
   - Mixing is a simple QM process, you can understand it!
   - Mixing and other variables can accurately measure CPV
   - The only source of CPV in the SM is a single phase in the CKM

C. **So: What's left? What's interesting? What's new?**

Status of example searches (as of the end of 2011)

So many results …

- LHCb 31 papers, most are on heavy flavour
  - See here
  - Four great examples:
    - Differential branching fraction and angular analysis of the decay $B^0 \to K^{*0} \mu^+ \mu^-$
    - Measurement of the CP violating phase ϕ_s in $B_s \to J/\psi\ f^0(980)$
    - Search for the rare decays $B_s \to \mu^+ \mu^-$ and $B^0 \to \mu^+ \mu^-$
    - Measurement of the effective $B^0_s \to K^+ K^-$ lifetime
- CMS, 9 papers on heavy flavour
  - See here
  - e.g. Search for B(s) and B to dimuon decays in pp collisions at 7 TeV
- ATLAS, 3 papers on heavy flavour
  - See here
  - e.g.: Observation of a new χ_b state in radiative transitions to $\Upsilon(1S)$ and $\Upsilon(2S)$

Recent Results

- Three key results with major updates in 2011

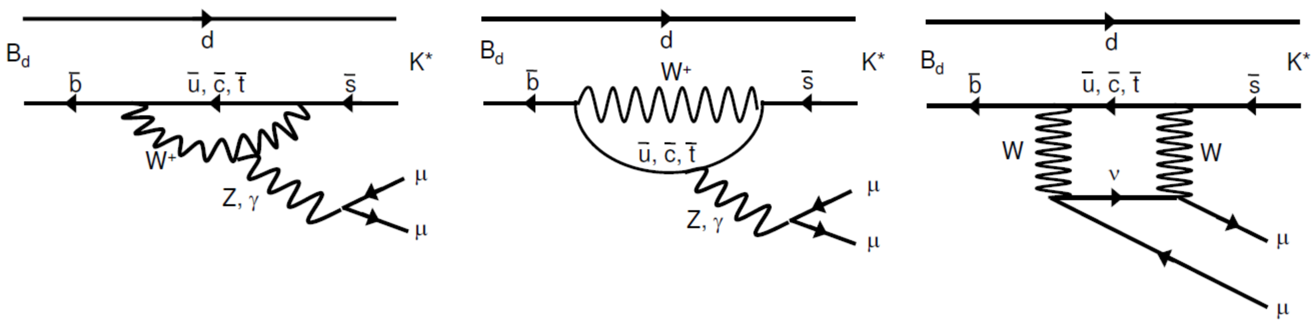
1. B^0 -> K^{*0} μ+ μ-
   - Model-independent test of classes of NP
2. B_s -> μ+ μ- and B^0 -> μ+ μ-
   - Direct constraints on SUSY models and mass scales
3. Phase ϕ_s in B_s -> J/ψ f^0(980) and B_s -> J/ψ Φ
   - Determine CPV in the B_s system

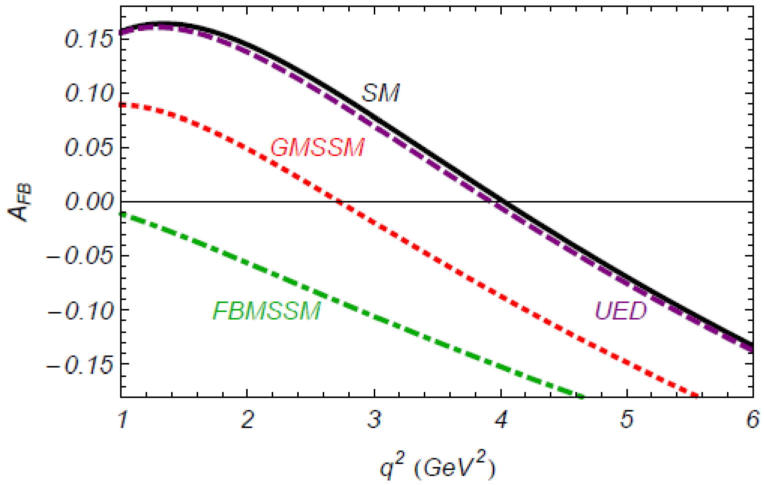
- … more updates coming soon (Moriond … next few weeks)!
- … even more where the LHC hasn’t yet made a statement!

K*μμ Motivation

- $B_d \rightarrow K^*\mu\mu$ has both loops and penguins!
- Amongst many observables A_{fb} is sensitive to SUSY

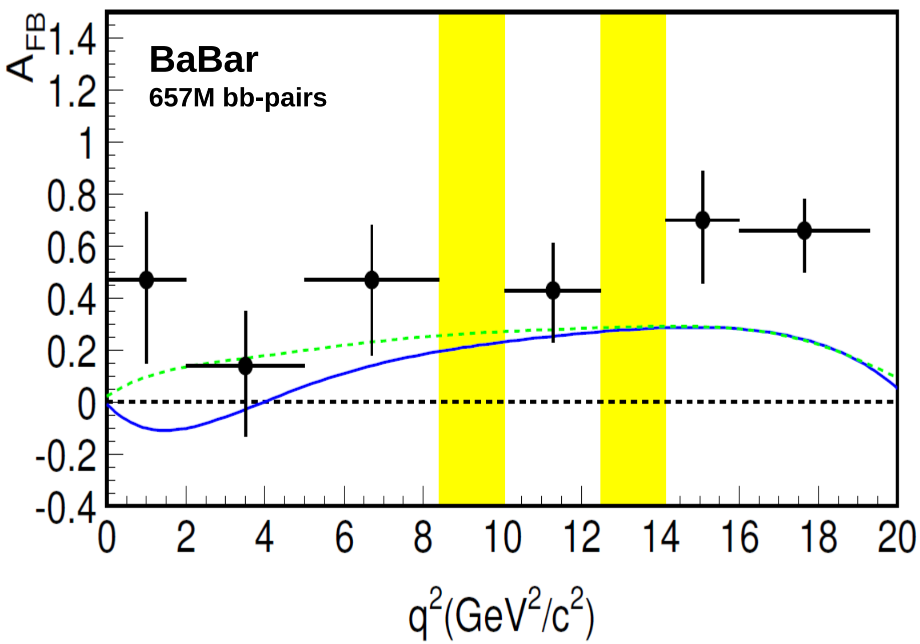
e.g.

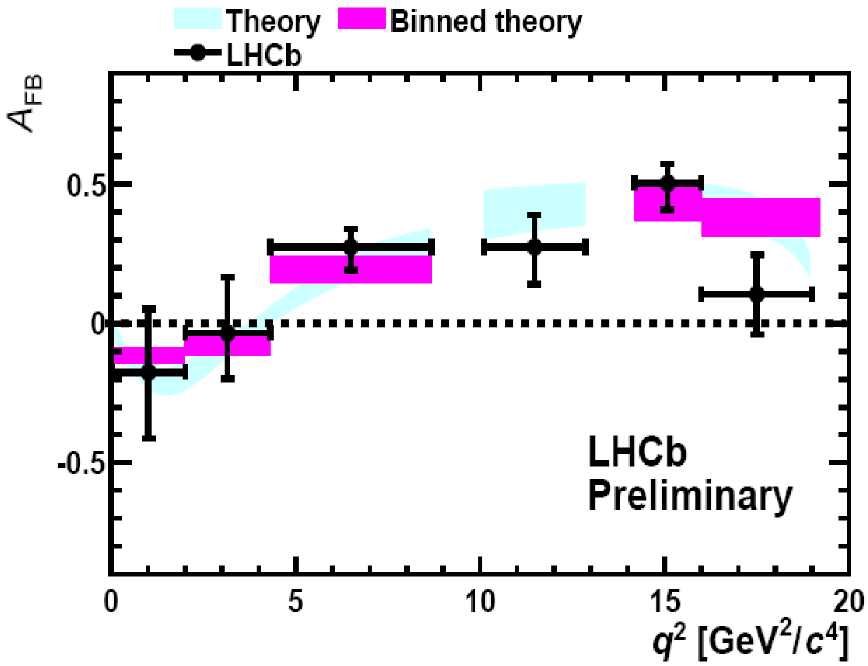




K*μμ Recently

2010 → **2011**

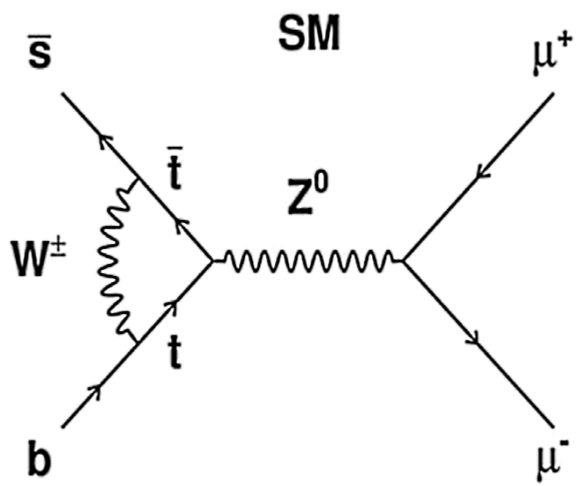


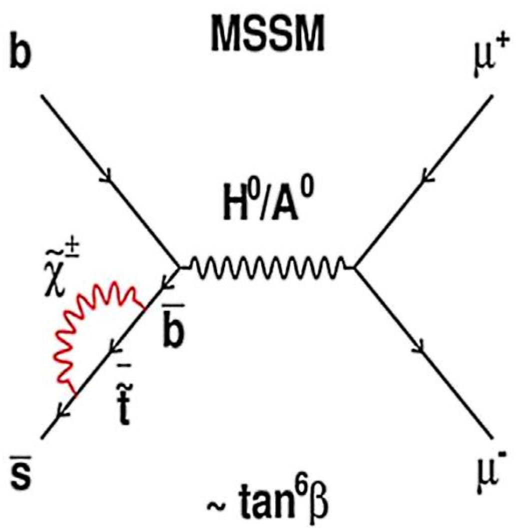


Bμμ Motivation

- Very rare decays, where SM BR predictions are very good
- In the case of $B_{s/d}\rightarrow\mu\mu$, the rate is very sensitive to SUSY

e.g.



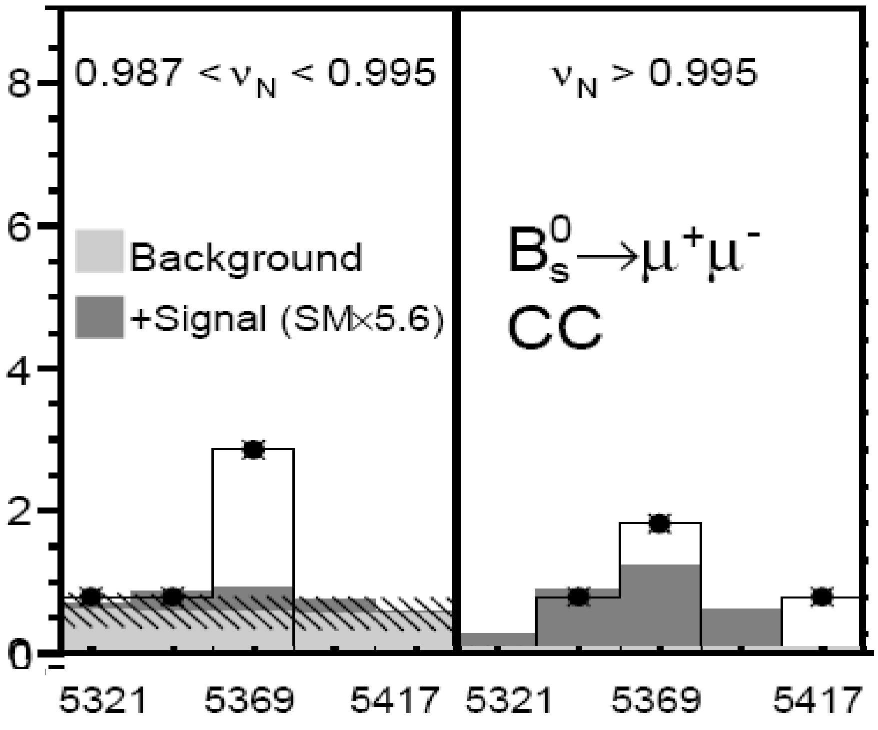


BR($B^0_s\rightarrow\mu\mu$)= (0.32 ± 0.02)x **10^{-8}** → ?

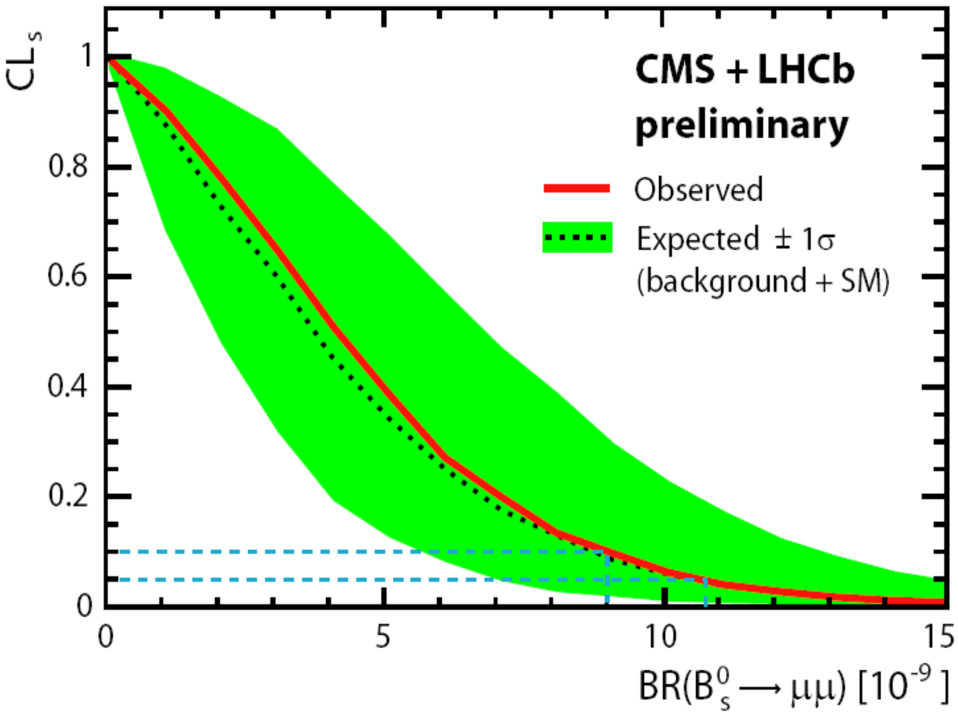
Bμμ Recently

2010 → **2011**

CDF @ TeVatron



CMS+LHCb @ LHC



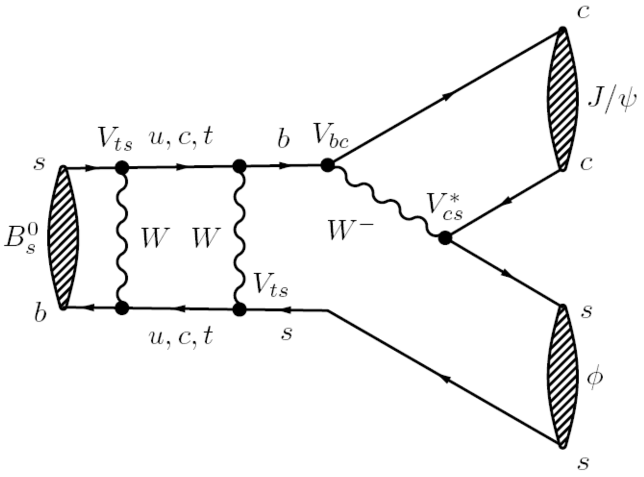
BR($B^0_s \rightarrow \mu\mu$)<4.3 x **10^{-8}** @95%CL

BR($B^0_s \rightarrow \mu\mu$)<1.08 x **10^{-8}** @95%CL

ϕ_s Motivation

- B_s -> J/ψ Φ and B_s -> J/ψ $f^0(980)$
  - Flavour-symmetric, charge-symmetric, final states
  - e.g. (K+K-μ+μ-), through resonances

- ✓ Can be reached by B_s *and* $\bar{B}_s$
  - ✓ Mixing, decay, interference
  - ✓ Maximum chance for CPV



- B_s -> J/ψ Φ requires separating out CP-odd and CP-even
  - Tagged, time-dependent angular analysis

- B_s -> J/ψ $f^0(980)$ has a lower BR, but is essentially CP-odd
  - No angular component required

Complex analysis!

$$\frac{d^4\Gamma(B_s^0 \to J/\psi\phi)}{dt\; d\cos\theta\; d\varphi\; d\cos\psi} \equiv \frac{d^4\Gamma}{dt\; d\Omega} \propto \sum_{k=1}^{10} h_k(t) f_k(\Omega)\,.$$

k	$h_k(t)$	$f_k(\theta,\psi,\varphi)$
1	$\lvert A_0\rvert^2(t)$	$2\cos^2\psi\,(1-\sin^2\theta\cos^2\phi)$
2	$\lvert A_\parallel(t)\rvert^2$	$\sin^2\psi\,(1-\sin^2\theta\sin^2\phi)$
3	$\lvert A_\perp(t)\rvert^2$	$\sin^2\psi\sin^2\theta$
4	$\Im(A_\parallel(t)\,A_\perp(t))$	$-\sin^2\psi\sin 2\theta\sin\phi$
5	$\Re(A_0(t)\,A_\parallel(t))$	$\frac{1}{2}\sqrt{2}\,\sin 2\psi\sin^2\theta\sin 2\phi$
6	$\Im(A_0(t)\,A_\perp(t))$	$\frac{1}{2}\sqrt{2}\,\sin 2\psi\sin 2\theta\cos\phi$
7	$\lvert A_s(t)\rvert^2$	$\frac{2}{3}(1-\sin^2\theta\cos^2\phi)$
8	$\Re(A_s^*(t)A_\parallel(t))$	$\frac{1}{3}\sqrt{6}\sin\psi\sin^2\theta\sin 2\phi$
9	$\Im(A_s^*(t)A_\perp(t))$	$\frac{1}{3}\sqrt{6}\sin\psi\sin 2\theta\cos\phi$
10	$\Re(A_s^*(t)A_0(t))$	$\frac{4}{3}\sqrt{3}\cos\psi(1-\sin^2\theta\cos^2\phi)$

$$|A_0|^2(t) = |A_0|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s\sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s\sin(\Delta m t)\right], \quad (4)$$

$$|A_\parallel(t)|^2 = |A_\parallel|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s\sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s\sin(\Delta m t)\right], \quad (5)$$

$$|A_\perp(t)|^2 = |A_\perp|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s\sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s\sin(\Delta m t)\right], \quad (6)$$

$$\Im(A_\parallel(t)\,A_\perp(t)) = |A_\parallel||A_\perp|e^{-\Gamma_s t}\left[-\cos(\delta_\perp-\delta_\parallel)\sin\phi_s\sinh\left(\frac{\Delta\Gamma}{2}t\right) - \cos(\delta_\perp-\delta\_\|)\cos\phi_s\sin(\Delta m t) + \sin(\delta_\perp-\delta_\parallel)\cos(\Delta m t)\right], \quad (7)$$

$$\Re(A_0(t)\,A_\parallel(t)) = |A_0||A_\parallel|e^{-\Gamma_s t}\cos(\delta_\parallel-\delta_0)\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s\sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s\sin(\Delta m t)\right], \quad (8)$$

$$\Im(A_0(t)\,A_\perp(t)) = |A_0||A_\perp|e^{-\Gamma_s t}\left[-\cos(\delta_\perp-\delta_0)\sin\phi_s\sinh\left(\frac{\Delta\Gamma}{2}t\right) - \cos(\delta_\perp-\delta_0)\cos\phi_s\sin(\Delta m t) + \sin(\delta_\perp-\delta_0)\cos(\Delta m t)\right], \quad (9)$$

$$|A_s(t)|^2 = |A_s|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s\sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s\sin(\Delta m t\right], \quad (10)$$

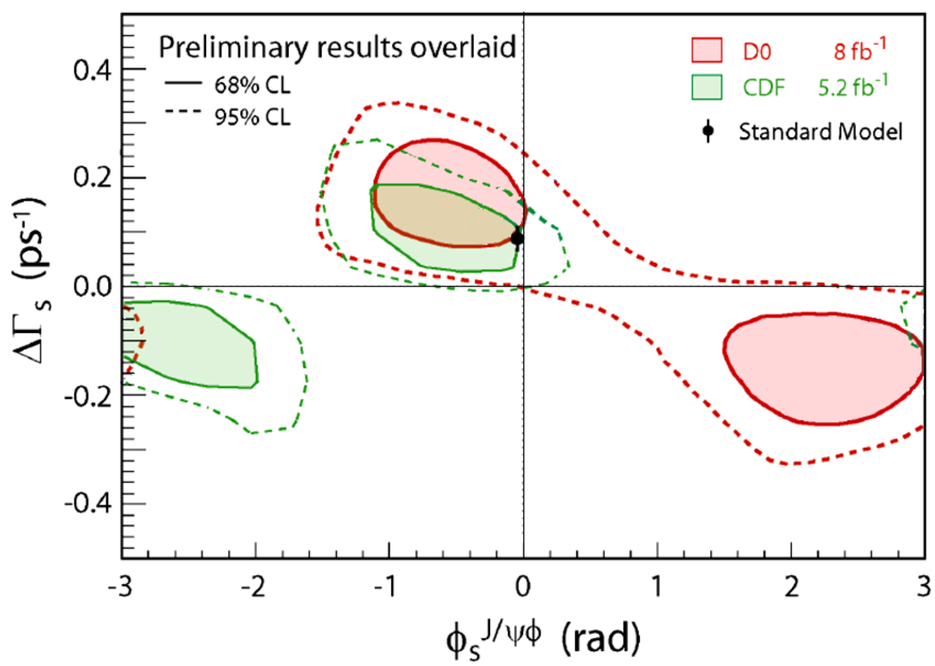
$$\Re(A_s^*(t)A_\parallel(t)) = |A_s||A_\parallel|e^{-\Gamma_s t}\left[-\sin(\delta_\parallel-\delta_s)\sin\phi_s\sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin(\delta_\parallel-\delta_s)\;\cos\phi_s\sin(\Delta m t) + \cos(\delta_\parallel-\delta_s)\cos(\Delta m t)\right], \quad (11)$$

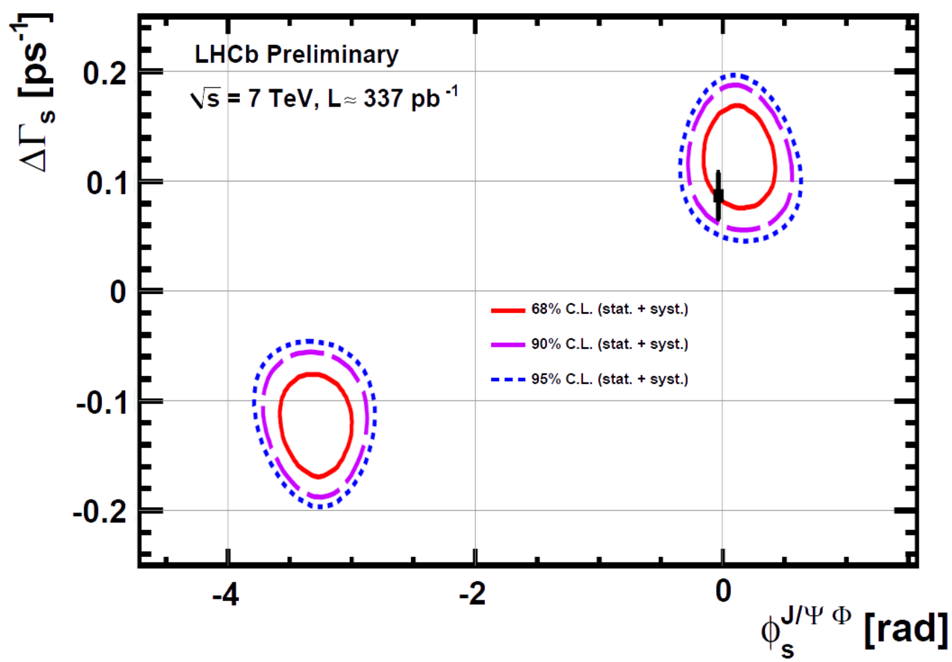
$$\Im(A_s^*(t)A_\perp(t)) = |A_s||A_\perp|e^{-\Gamma_s t}\sin(\delta_\perp-\delta_s)\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s\sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s\sin(\Delta m t)\right], \quad (12)$$

$$\Re(A_s^*(t)A_0(t)) = |A_s||A_0|e^{-\Gamma_s t}\left[-\sin(\delta_0-\delta_s)\sin\phi_s\sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin(\delta_0-\delta_s)\cos\phi_s\sin(\Delta m t) + \cos(\delta_0-\delta_s)\cos(\Delta m t)\right]. \quad (13)$$

ϕ_s Recently

2010 → **2011**

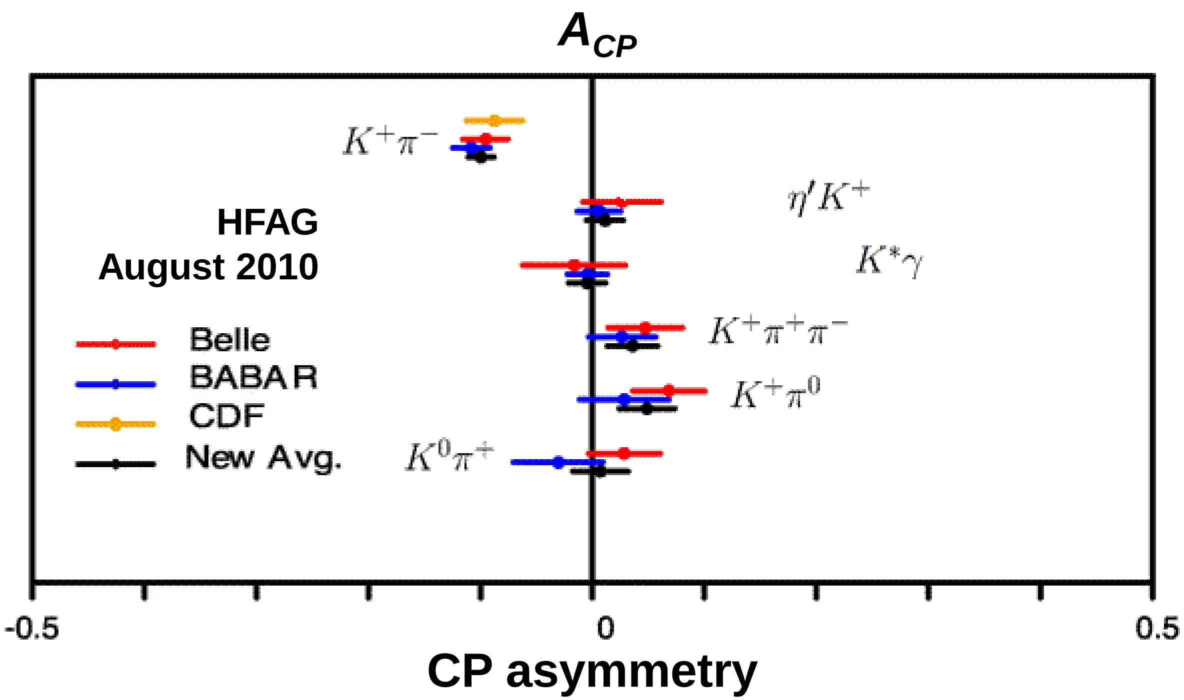




Upcoming very interesting results…

Upcoming (1)

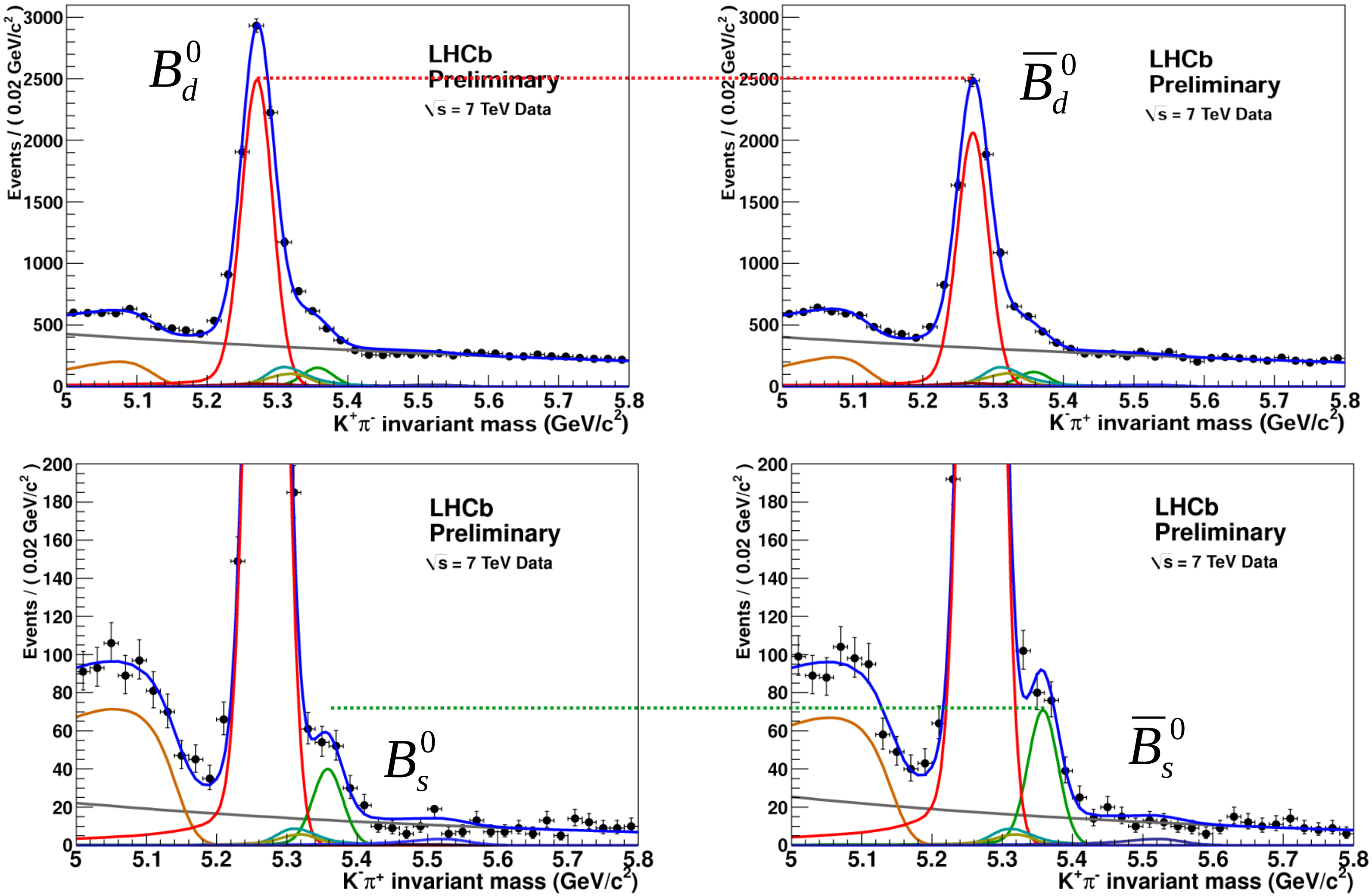
- CP-asymmetry in decays (Direct CP-violation)
- Interesting hint: the B→Kπ "puzzle"



- LHCb poised to make a similar measurement, keep watching!

CPV by eye

- From the LHCb public page



Upcoming (2)

Fermilab-Pub-10/114-E

Evidence for an anomalous like-sign dimuon charge asymmetry

V.M. Abazov,[36] B. Abbott,[74] M. Abolins,[63] B.S. Acharya,[29] M. Adams,[49] T. Adams,[47] E. Aguilo,[6] G.D. Alexeev,[36] G. Alkhazov,[40] A. Alton[a],[62] G. Alverson,[61] G.A. Alves,[2] L.S. Ancu,[35] M. Aoki,[48] Y. Arnoud,[14] M. Arov,[58] A. Askew,[47] B. Åsman,[41] O. Atramentov,[66] C. Avila,[8] J. BackusMayes,[81] F. Badaud,[13] L. Bagby,[48] B. Baldin,[48] D.V. Bandurin,[47] S. Banerjee,[29] E. Barberis,[61] A.-F. Barfuss,[15] P. Baringer,[56] J. Barreto,[2] J.F. Bartlett,[48] U. Bassler,[18] S. Beale,[6] A. Bean,[56] M. Begalli,[3] M. Begel,[72] C. Belanger-Champagne,[41] L. Bellantoni,[48] J.A. Benitez,[63] S.B. Beri,[27] G. Bernardi,[17] R. Bernhard,[22] I. Bertram,[42] M. Besançon,[18] R. Beuselinck,[43]

…

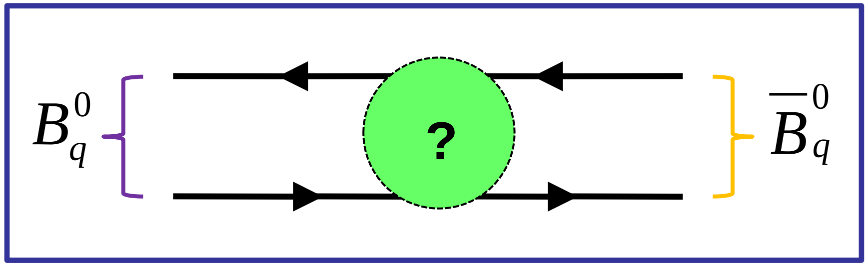
We measure the charge asymmetry A of like-sign dimuon events in 6.1 fb^{-1} of $p\overline{p}$ collisions recorded with the D0 detector at a center-of-mass energy $\sqrt{s} = 1.96$ TeV at the Fermilab Tevatron collider. From A, we extract the like-sign dimuon charge asymmetry in semileptonic b-hadron decays: $A^b_{\rm sl} = -0.00957 \pm 0.00251\ (\rm stat) \pm 0.00146\ (\rm syst)$. This result differs by 3.2 standard deviations from the standard model prediction $A^b_{\rm sl}(SM) = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}$ and provides first evidence of anomalous CP-violation in the mixing of neutral B mesons.

PACS numbers: 13.25.Hw; 14.40.Nd

Suprize!
… is it new physics?
First let's compare with other measurements…

NP & Mixing Recap

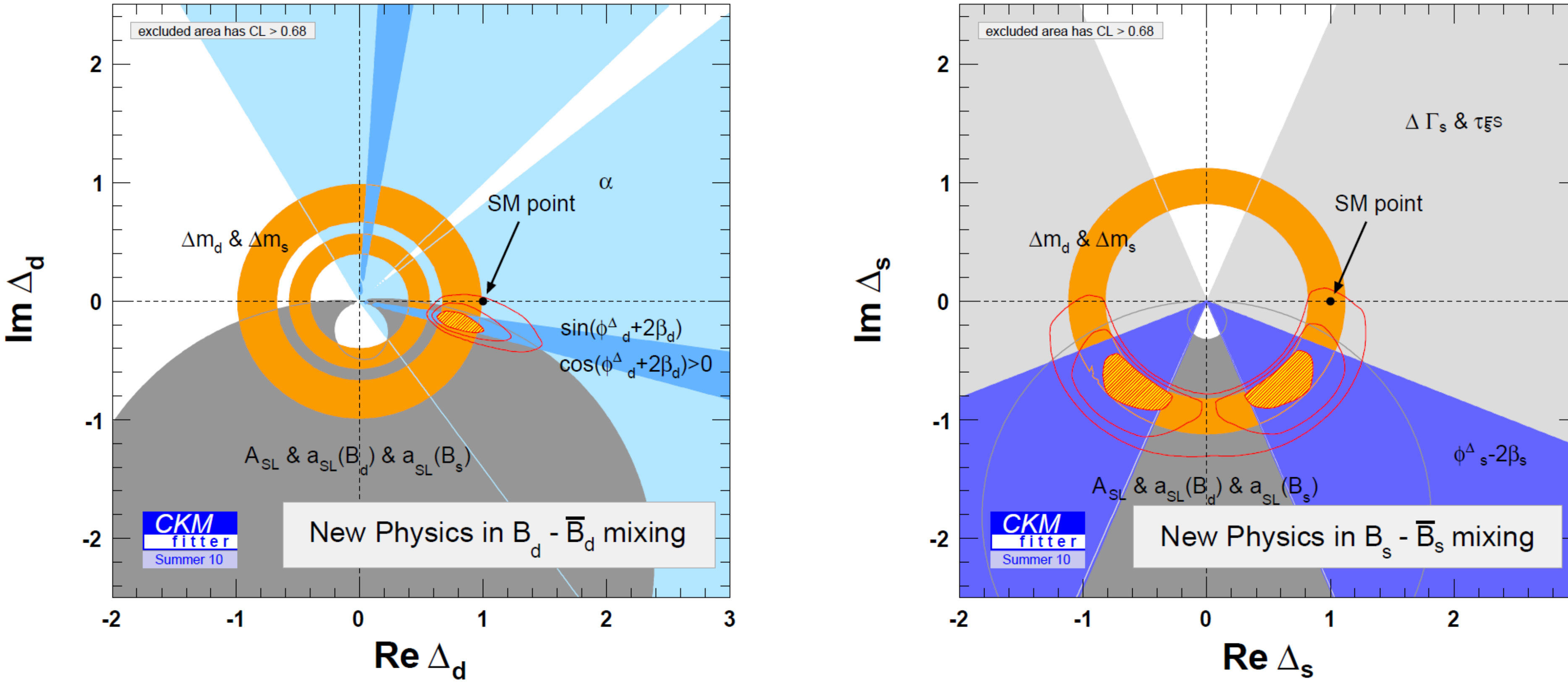
- Remember mixing is a loop-level process



- Mixing can be modified in both magnitude *and* phase
- Define a complex number parameter Δ_q for the new physics
- Just like we did with the CKM
  - Collect all the measurements together
  - Plot all at once in 2D (complex plane)

Status: NP in mixing?

- SM was **disfavoured** by 3.6σ, due to DØ result….

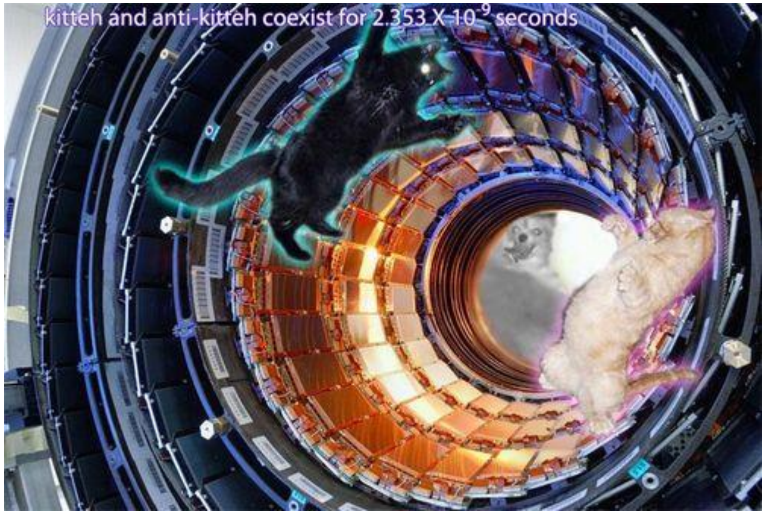


- LHCb poised to make a similar measurement, keep watching!

If it's true?

- Not just new physics
  - CP-violating new physics beyond any SM shoe-horning
  - Leptoquarks?
  - Unparticles?
  - Completely unexplored new physics?

Heeeere's
new physics!



- In a way it's exactly what we need!

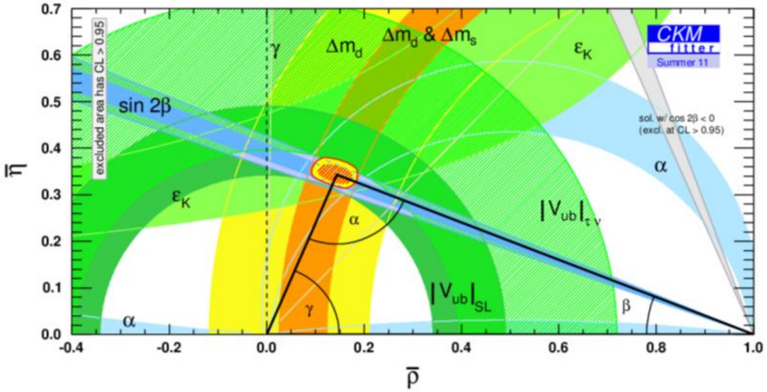
Woof?

Nobody has even invented the chew-toy!!!

Summary and Outlook

- What did we learn?
  - The SM is a poor description of reality
  - It is a surprize that the SM works so well in particle physics!
  - There ***must*** be new physics and it ***must*** violate CP
  - Precision experiments probe energy scales others cannot!
- The LHC is a heavy-flavour factory
  - The first year's results already rule out classes of NP models

2011 → **2012**



?

End

- Backups are often required

Further References

- LHCb:
  - $B_s \to \mu\mu$ first result: http://arxiv.org/abs/1103.2465
  - Detector paper: J. of Instrumentation (No. 3 pp. S08005P)
  - "Roadmap" of physics analyses: arXiv:0912.4179
    - Chapter 2: γ
    - Chapter 3: $B \to K\pi$
    - Chapter 5: $B_{s/d} \to \mu\mu$
    - Chapter 6: $K^* \mu\mu$
  - ΔA_{fs} studies:
    - R.W. Lambert, CERN-THESIS-2009-001
    - N. Brook *et al.*, CERN-LHCb-2007-054
- CPLear: Kaon mixing: Physics Reports, Volume 374, Issue 3, Pages 165-270 (January 2003)
- Experimental averages:
  - CKM fitter group : http://ckmfitter.in2p3.fr/
  - HFAG ($B \to K\pi$): http://www.slac.stanford.edu/xorg/hfag/rare/ichep10/acp/index.html
- More on $B \to K\pi$
  - Theory Status: S. Mishima from CKM 2010, arXiv:1101.1501
  - New Physics : S. Baek *et al.*, arXiv:hep-ph/0412086
- CDF $B_{s/d} \to \mu\mu$: CDF Public Note 9892 (preliminary)

Interesting reading…

- General texts:
  - The BaBar physics book, SLAC-R-504

- Recent papers:
  - DØ measurement of A^b, 3.2σ deviation from the SM (May 2010)
    Evidence for an anomalous like-sign dimuon charge asymmetry
    PRL. 105, 081801 (2010)
  - Nierste and Lenz B-mixing update (Feb 2011)
    Numerical updates of lifetimes and mixing parameters of B mesons
    hep-ph arxiv:1102.4274
  - WMAP 7-year sky maps (Feb 2011)
    Seven-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Sky Maps, Systematic Errors, and Basic Results
    Jarosik, N., et.al., 2011, ApJS, 192, 14

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- WMAP poster, WMAP and NASA
- Laika photo is public domain

A_{fs}?

Translate

1. $p\bar{p}$-interactions within a symmetric experiment
2. Correct all experimental biases (magnets, mis-id …)
3. Observe $N(\mu^+\mu^+) \neq N(\mu^-\mu^-)$
4. In the SM, the favoured way to make charge asymmetry is if:

$$b\bar{b} \longrightarrow \mu^+\mu^+ \neq b\bar{b} \longrightarrow \mu^-\mu^-$$

5. Which comes from B^0-mixing:

$$b\bar{b} \Rightarrow \bar{B}^0 B^0 \sim \bar{B}^0 \bar{B}^0 \rightarrow \mu^+\mu^+ X \neq b\bar{b} \Rightarrow \bar{B}^0 B^0 \sim B^0 B^0 \rightarrow \mu^-\mu^- X$$

- **In the standard model it is almost negligible**

$$A^b \approx \frac{a^s_{fs} + a^d_{fs}}{2} \qquad SM = (-2.0 \pm 0.3) \times 10^{-4} \qquad D\emptyset \approx (-1 \pm 0.3)\%$$

Discovery Potential

- a_{fs} is very sensitive to new physics (NP) even if:
  - Tree-level processes are SM-dominated
  - SM flavour structure
  - Unitary CKM
- With very weird scenarios (like *leptoquarks*)
  - Probe NP mixing, interference and/or decays
- Usual formula is modified:

$$a^{SM} \approx \mathrm{Im}\left\{\frac{\Gamma_{12}^{SM}}{M_{12}^{SM}}\right\}$$

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- With very weird scenarios (like *leptoquarks*)
  - Probe NP mixing, interference and/or decays
- If we allow a single NP phase in the mixing Θ

$$a^{NP} \approx \mathrm{Im}\left\{\frac{\Gamma_{12}^{SM}}{M_{12}^{SM}}\right\}\cos\Theta - \mathrm{Re}\left\{\frac{\Gamma_{12}^{SM}}{M_{12}^{SM}}\right\}\sin\Theta$$

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- With very weird scenarios (like *leptoquarks*)
  - Probe NP mixing, interference and/or decays
- If we allow a single NP phase in the mixing Θ
  - (first part is just the SM value)

$$a^{NP} \approx \quad a_{fs}^{SM} \quad \cos\Theta - \mathrm{Re}\left\{\frac{\Gamma_{12}^{SM}}{M_{12}^{SM}}\right\}\sin\Theta$$

Discovery Potential

- a_{fs} is very sensitive to new physics (NP) even if:
  - Tree-level processes are SM-dominated
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- With very weird scenarios (like *leptoquarks*)
  - Probe NP mixing, interference and/or decays
- If we allow a single NP phase in the mixing Θ
  - (first part is just the SM value)

$$a^{NP} \approx 2.1\times10^{-5}\cos\Theta + 4.0\times10^{-3}\sin\Theta$$

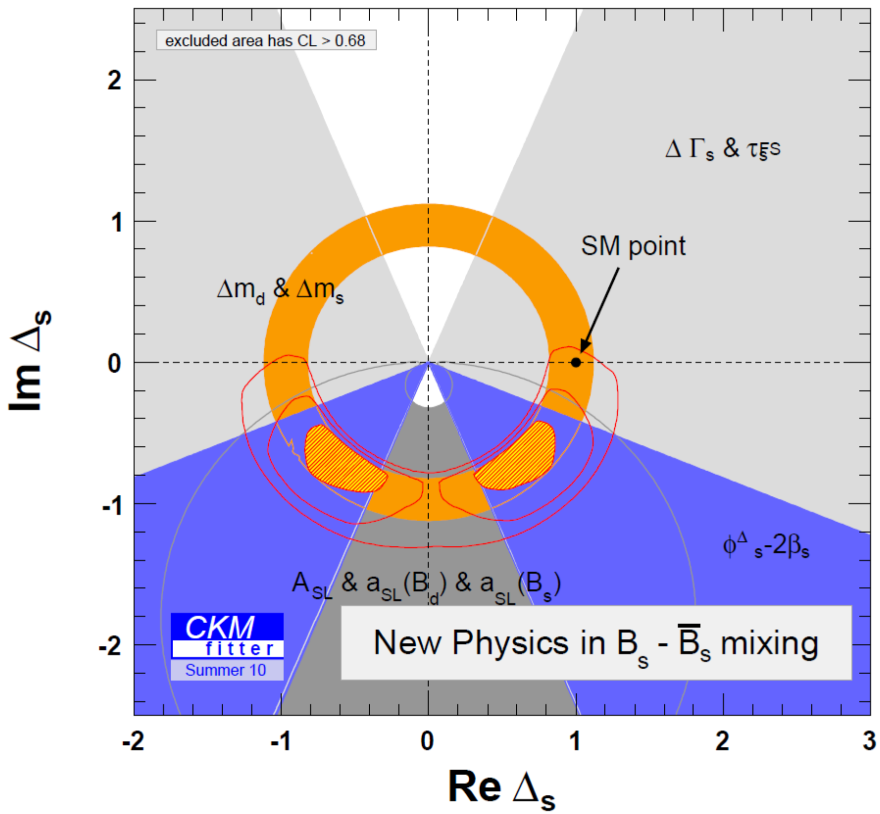
- Up to **200-times** the SM!!! [[[... still... < DØ measurement]]]

c.f. J/Ψ Φ

- $B_s^0 \to J/\psi\ \Phi$
  - Directly Measure sin ϕ_s
  - $\sigma(\phi_s) = 0.05^c$ in 1 fb^{-1}
- a_{fs}^s
  - Effectively Measures

$$\mathrm{Im}\left\{\frac{\Gamma_{12}}{M_{12}}\right\}\cos\Theta - \mathrm{Re}\left\{\frac{\Gamma_{12}}{M_{12}}\right\}\sin\Theta$$

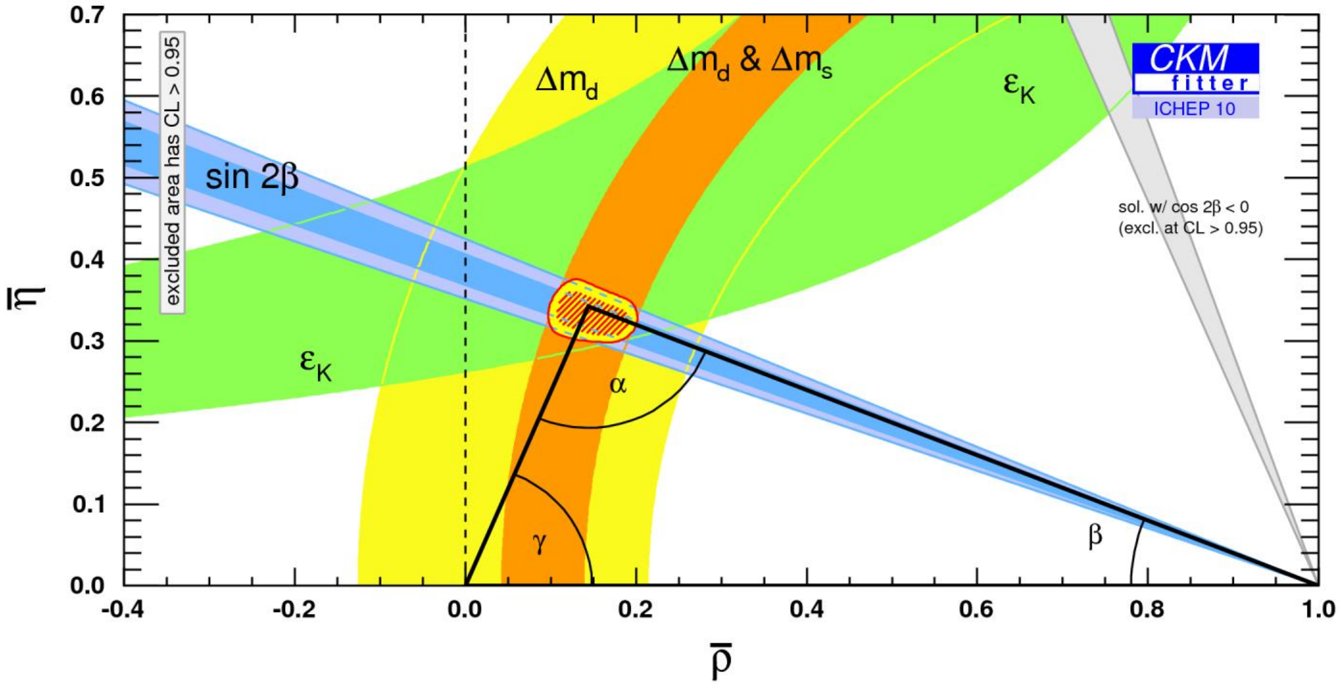
  - $\sigma(\Theta) = 0.5^c$ in 1 fb^{-1}



- But they constrain NP differently
  - Effective power enhanced
  - NB physical limit of a_{fs} is at 4×10^{-3} < current DØ result!

Looking for flavour (3)

- Check loop-level observables
- Would need a very accurate determination of dmd/dms



Penultimate slide

ACME™

Woof?