Searching for BSM physics in heavy flavor loop decays at LHCb

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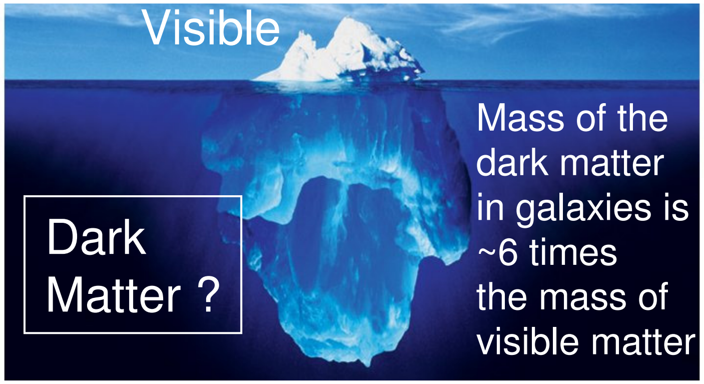
In this talk

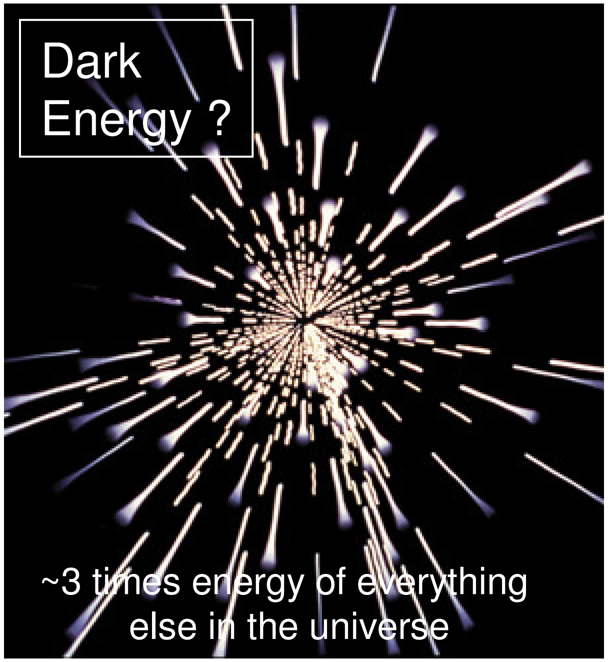
(BSM = Beyond Standard Model = New Physics = ***NP****)*

Evidence for Beyond Standard Model physics



Dark Matter ?

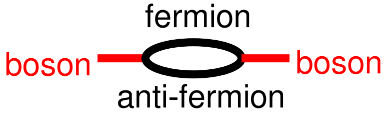
Mass of the dark matter in galaxies is ~6 times the mass of visible matter

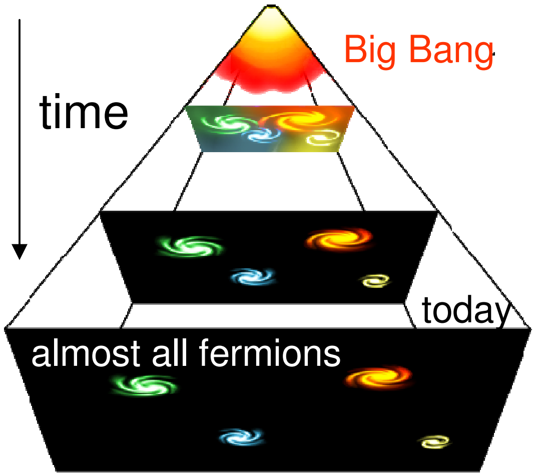


Dark Energy ?

~3 times energy of everything else in the universe

Baryogensis ?





Hierarchy problem ?
$M_H << M_{Planck}$

GUT?
How does gravity fits in?

end of 19th centaury → atoms, QED

	IA	IIA											IIIA	IVA	VA	VIA	VIIA	VIIIA
1	H																	He
2	Li	Be											B	C	N	O	F	Ne
3	Na	Mg	III B	IVB	VB	VIB	VIIB		VIII B		IB	IIB	Al	Si	P	S	Cl	Ar
4	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
5	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
6	Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
7	Fr	Ra	Ac															
					Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
					Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

mid 20th centaury → quarks, QCD

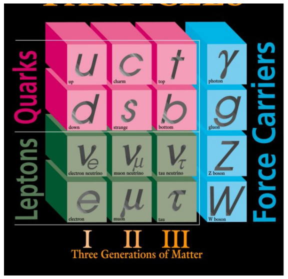
	$Q= -1$	$Q= 0$	$Q=+1$
$S=+1$		K^0	K^+
$S= 0$	π^+	π^0 ,η	π^+
$S= -1$	K^+	K^0	

	$Q= -1$	$Q= 0$	$Q=+1$
$S= 0$		n	p
$S= -1$	Σ^-	Σ^0 ,Λ	Σ^+
$S= -2$	Ξ^+	Ξ^0	

	$Q=-1$	$Q= 0$	$Q=+1$	$Q=+2$
$S= 0$	Δ^-	Δ^0	Δ^+	Δ^{++}
$S= -1$	Σ^{*-}	Σ^{*0}	Σ^{*+}	
$S= -2$	Ξ^{*-}	Ξ^{*0}		
$S= -3$	Ω^-			

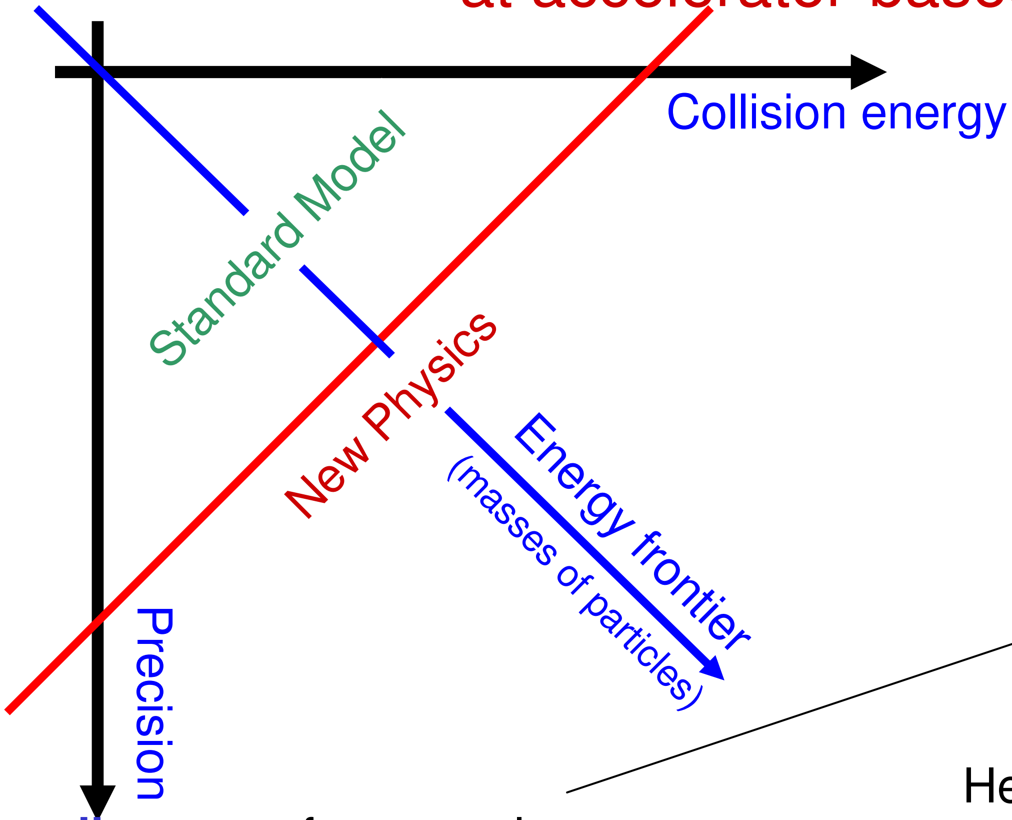
Generation problem ?

now → ?



- Unknown particles and forces exist, likely hiding at higher energy scales

Two complementary ways of advancing "energy frontier" at accelerator-based experiments



Collision energy

Standard Model

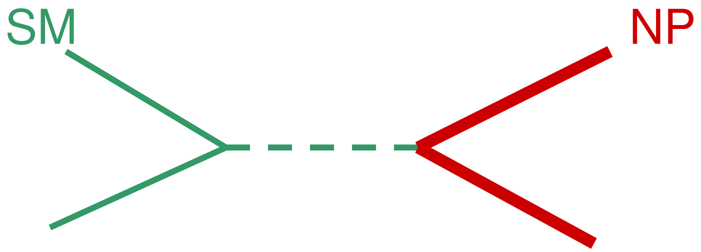
New Physics

Energy frontier

(masses of particles)

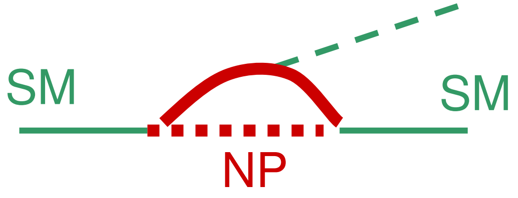
Precision

Tree diagrams, for example



Want high CM energy to exceed the production threshold

Loop diagrams, for example

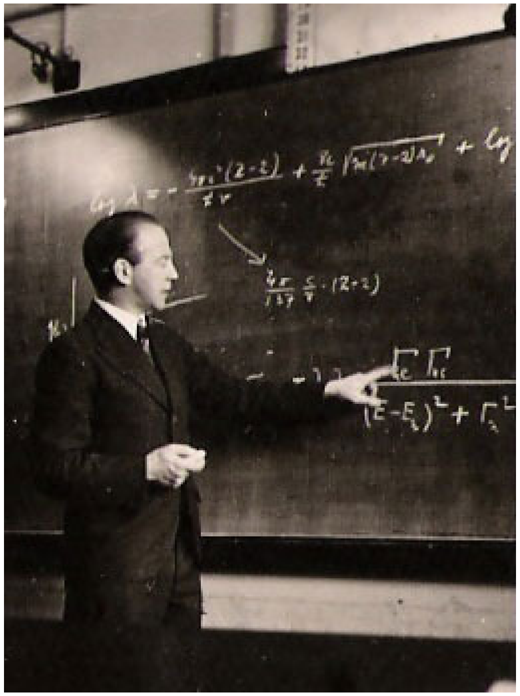


Want high precision since NP particles are highly virtual here, thus probabilities small

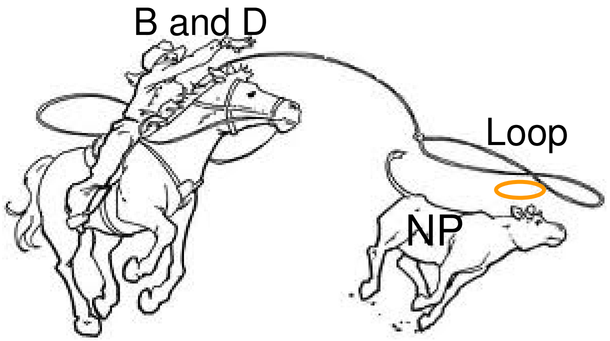
Heisenberg's uncertainty principle:

$$\Delta E \, \Delta t = \hbar/2$$

i.e. $\Delta m \, \Delta t = \hbar/2$

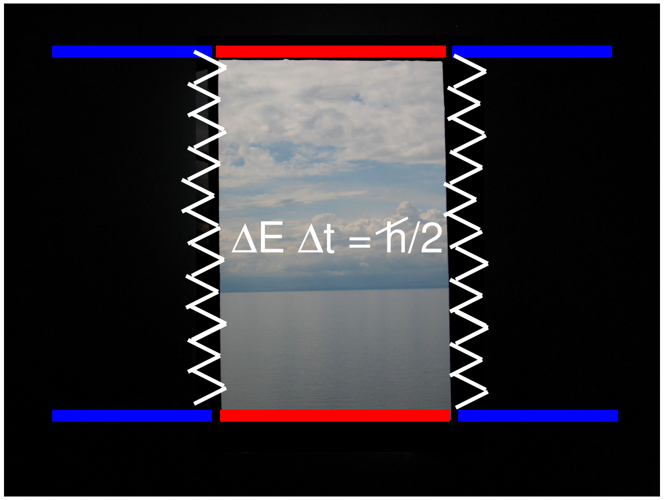


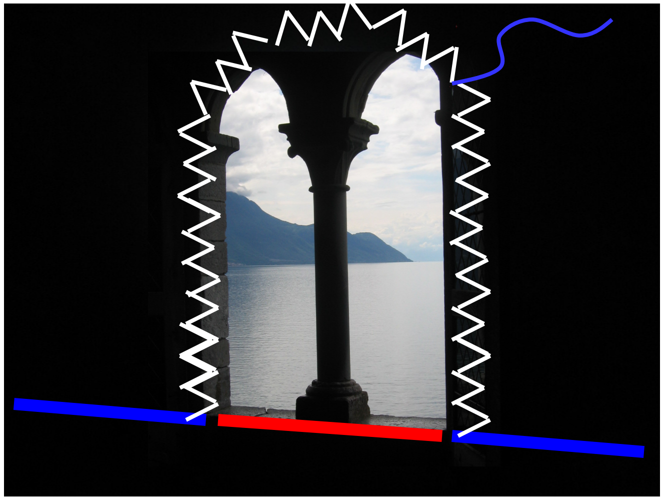
LHCb Physics Program



Not enough time to cover entire scope of the LHCb experiment
- selection of topics has been unavoidable.

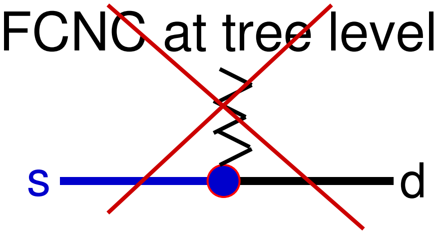
Loops as low energy windows to high energy physics



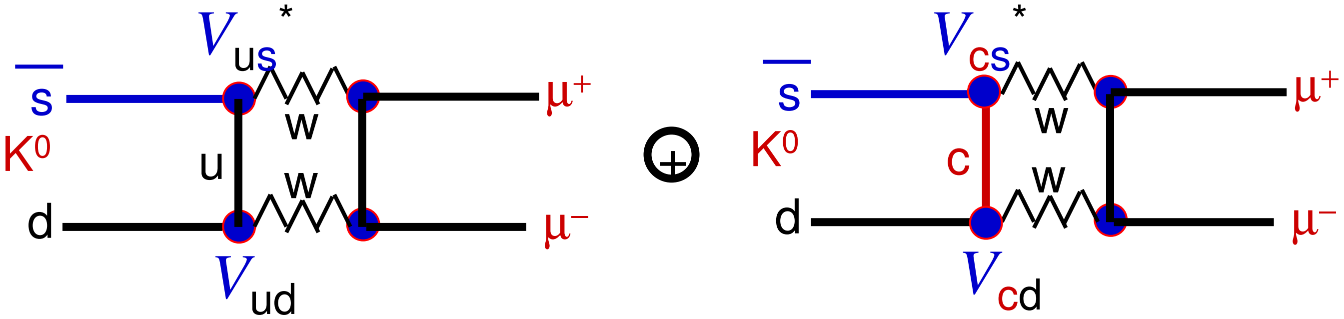


- Some spectacular successes in the past:
  - Lack of tree level FCNC, suppression of $K^0_L \to \mu^+\mu^-$ and GIM mechanism (1970):
    - prediction of charm quark 4 years before its discovery

FCNC at tree level



FCNC at loop level



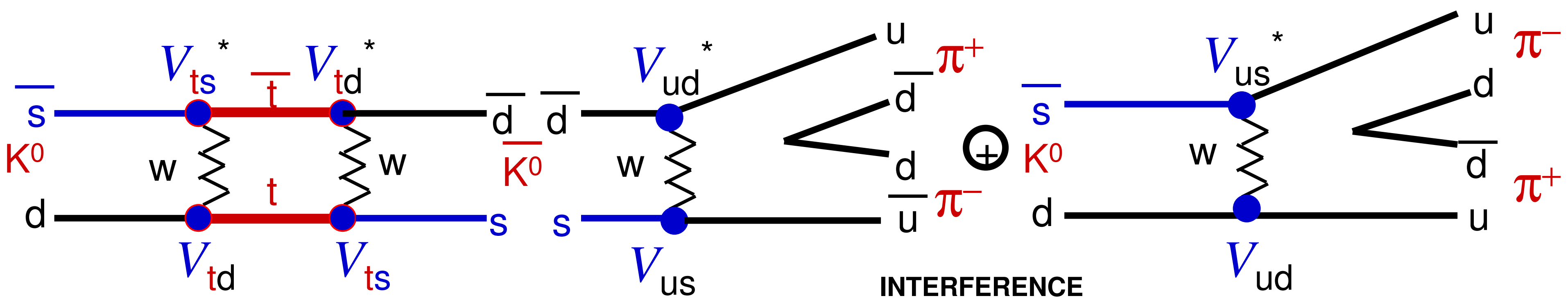
BR ~ 10^{-4} (rare decay!)
Not detected at expected rate

NEGATIVE INTERFERENCE BR « 10^{-4}

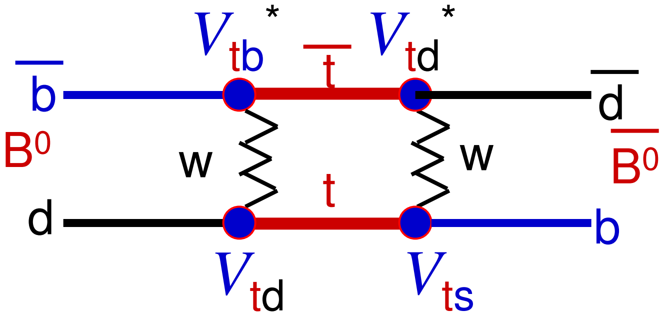
Observed in 1973 with BR ~ 10^{-8}

Loops as low energy windows to high energy physics

- CPV in $K^0_L \to \pi^+\pi^-$ decays (1964) + Kobayashi-Maskawa hypotheses (1972):
  - prediction of 3rd quark generation 5 years before its discovery
  - first glimpse of top quark 31 years before its discovery

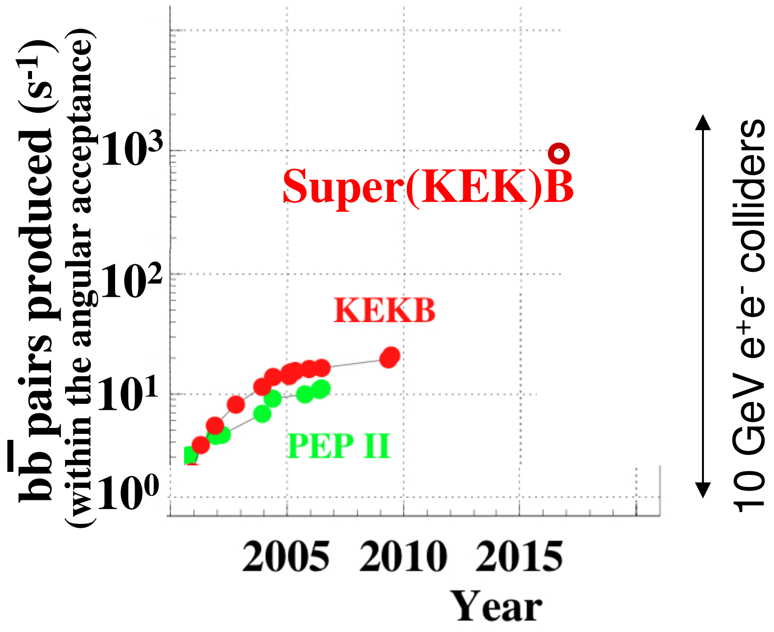


INTERFERENCE
produces
INDIRECT CPV proportional to relative complex phase (need 3 generations)



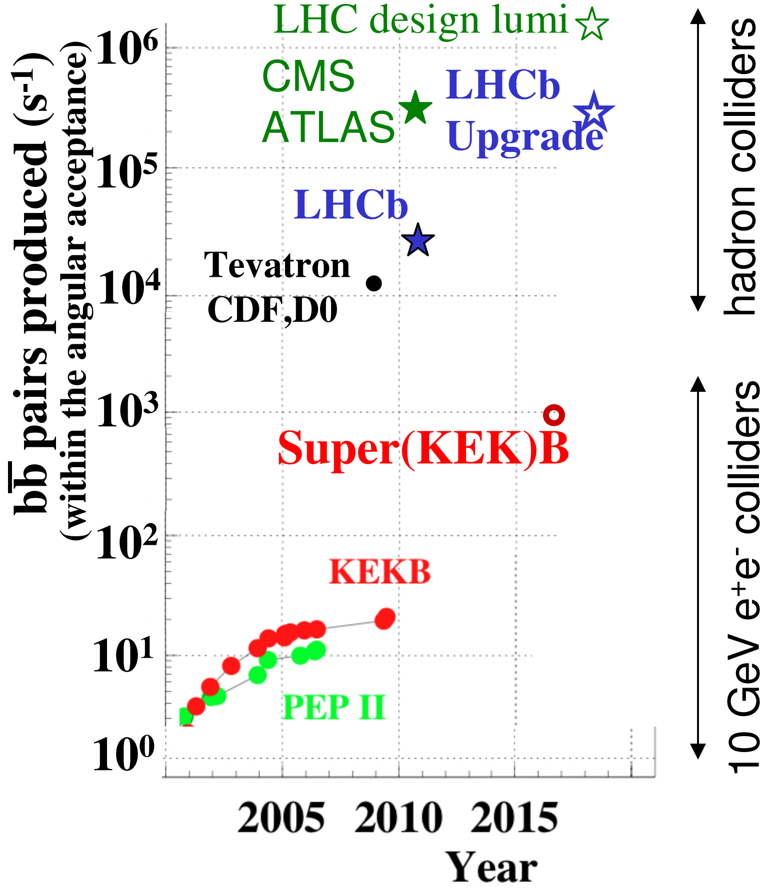
- Large B^0-$\overline{B^0}$ mixing at ARGUS (1987):
  - lower limit on top mass puts 5 higher energy colliders (PETRA,PEP,TRISTRAN,SLC,LEP) out of business in quest for top discovery,
  - but makes CPV measurements in B^0 easier

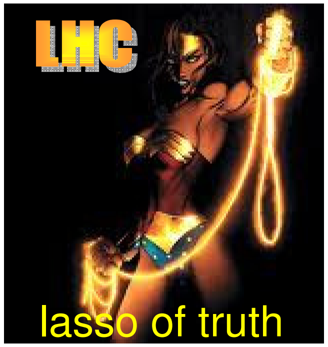
Colliders and $b\bar{b}$ rates



- The past decade has been a golden age of 10 GeV e^+e^- b-factories
- Super b-factories are being pursued in Japan and Italy, with luminosity upgrade by almost 2 orders of magnitude

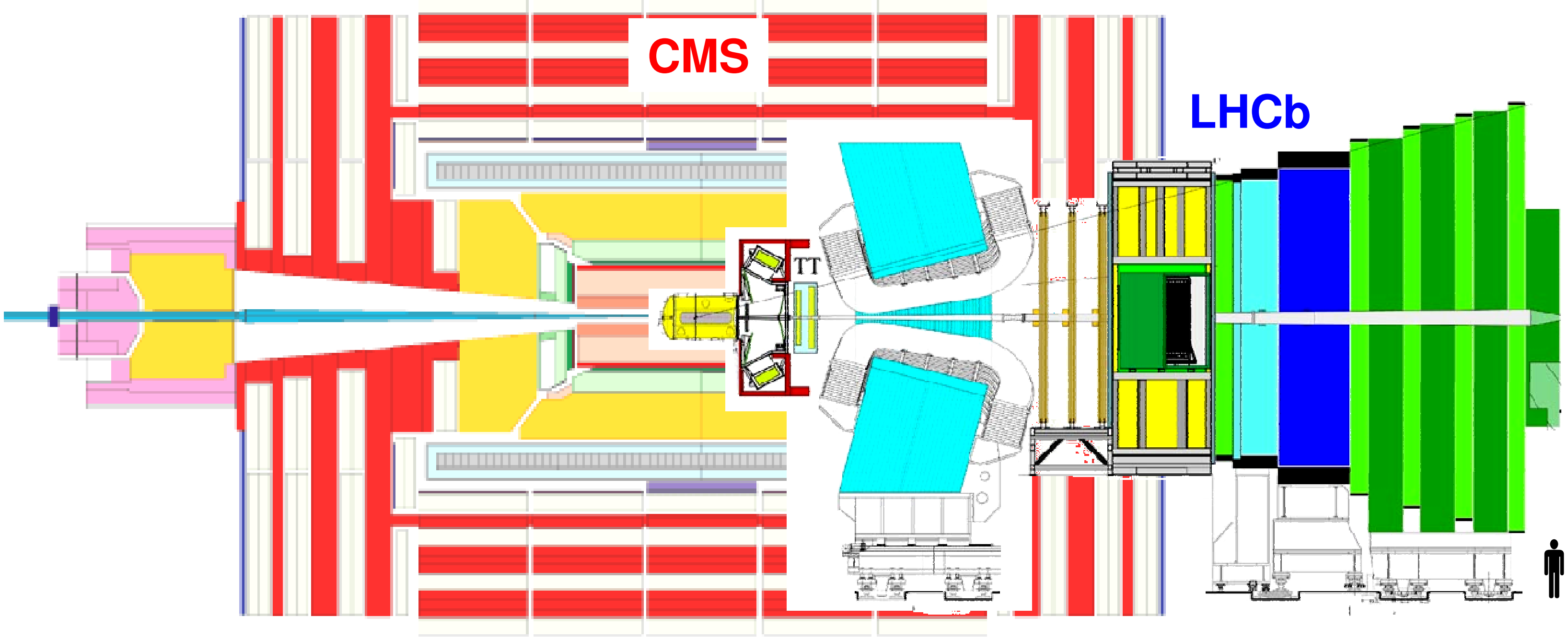
Colliders and $b\bar{b}$ rates





- Tremendous rate potential at hadron colliders
  - **physics reach determined by the detector capabilities not by the machine**
- Collect all b-hadron species at the same time:
  - **additional gain by a factor of ~10-100 in integrated B_s rates at hadronic colliders**
  - **time dependent CPV studies of B_s possible**
  - **also get Λ_b, B_c which are out of reach of the 10 GeV e^+e^- factories**
- Charm rates factor of 10 higher than beauty rates:
  - **nuisance and great physics opportunity at the same time**

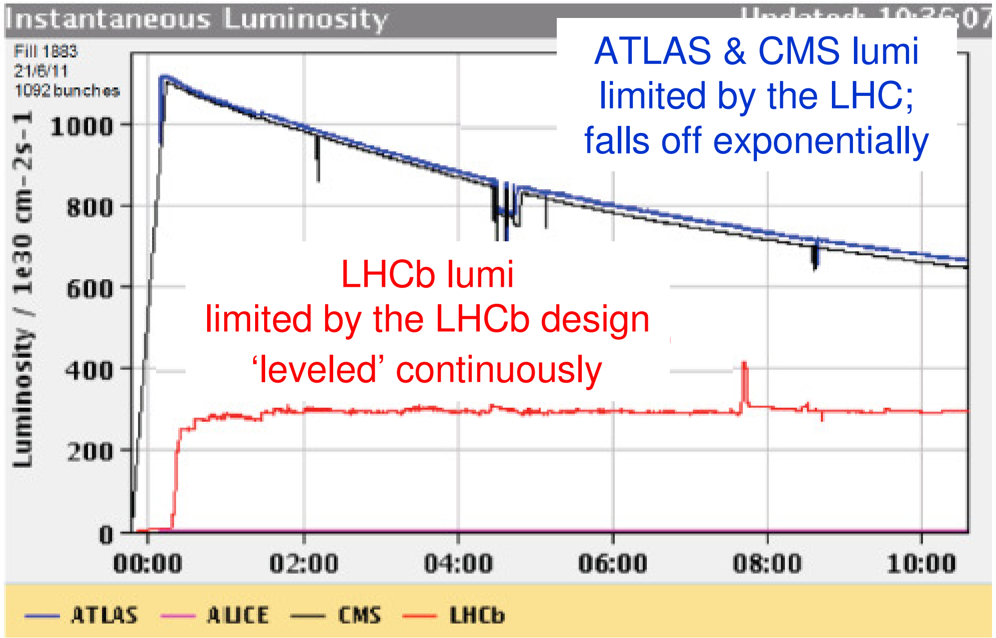
LHCb vs central detectors



- Advantages of LHCb (forward spectrometer):
  - comparable b cross-section in much smaller solid angle; smaller number of electronic channels; smaller event size; much larger trigger bandwidth to tape (~3.5 kHz)
  - b and c physics dominate the trigger bandwidth (e.g. CMS b-trigger rate ~25 Hz; 2 orders of magnitude less than LHCb)
  - large p for small p_T (in central region $p \sim p_T$); can identify muons to lower p_T values
  - large bandwidth important for triggering on purely hadronic final states (GDPs limited to dimuon trigger)
  - large bandwidth important for collecting very large charm samples
  - space for RICH detectors: K/π separation; crucial for background suppression in many channels; increased flavor tagging
- Limitation of LHCb:
  - luminosity limited by the detector readout capabilities (see next)

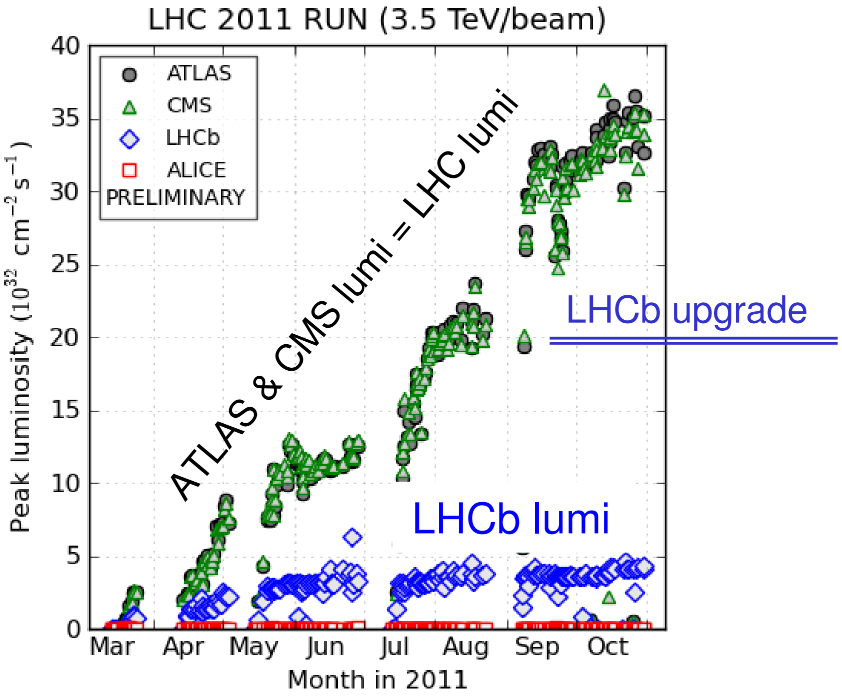
LHCb luminosity at its upgrade

- Maximal value of luminosity for safe LHCb operations ~ $4x10^{32}$ $cm^{-2}s^{-1}$
- Beams are intentionally misaligned at LHCb to stay below this limit.
- Luminosity is “leveled” over run duration.



ATLAS & CMS lumi limited by the LHC; falls off exponentially

LHCb lumi limited by the LHCb design ‘leveled’ continuously



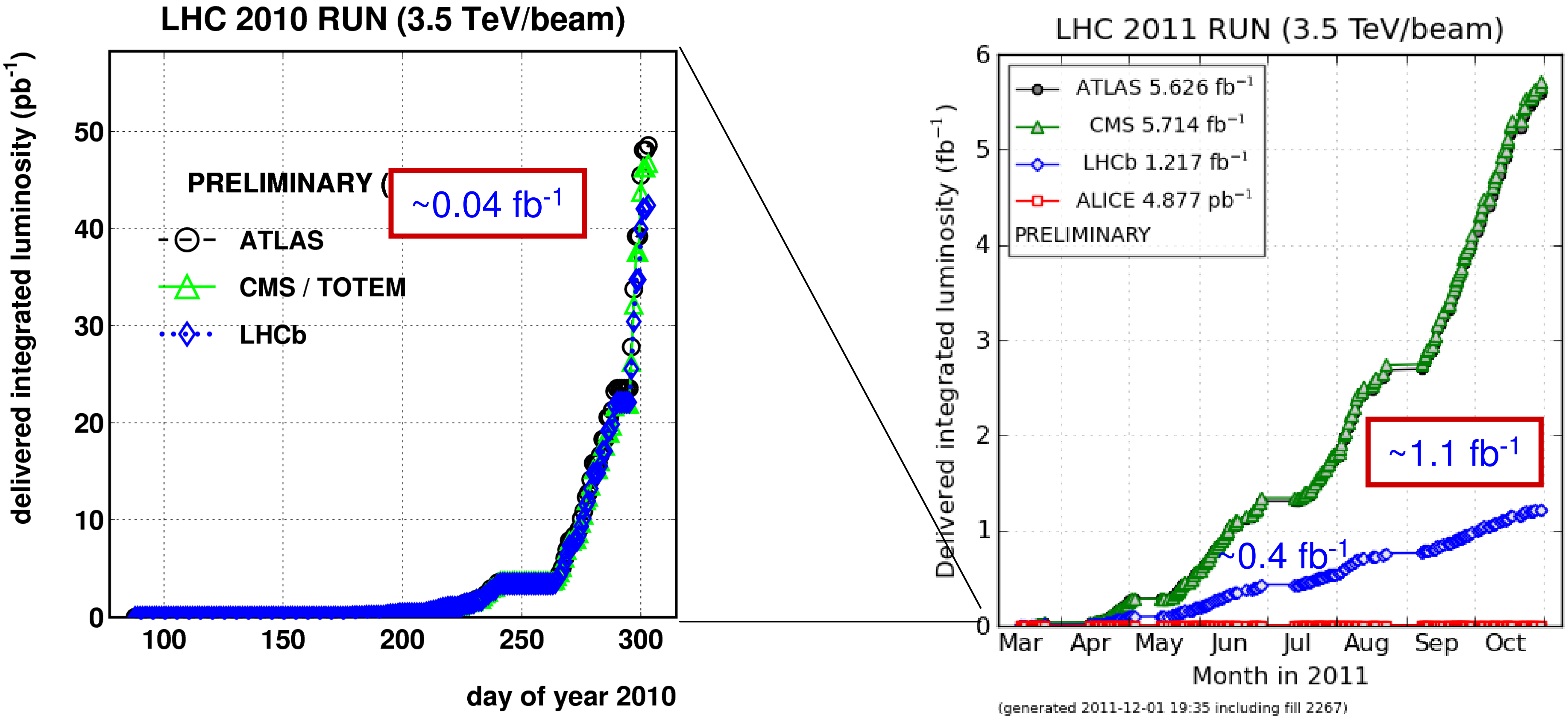
ATLAS & CMS lumi = LHC lumi

LHCb upgrade

LHCb lumi

- The main luminosity limitation comes from 1MHz L0 bandwidth imposed by the readout speed.
- **upgrade: (2018-)** instantenous luminosity up to ~ $20x10^{32}$ $cm^{-2}s^{-1}$
  - Readout all detectors at 40 MHz. Do all triggering in the computer farm. Increase output bandwidth to 20-30 kHz to cope with the increased physics rate
  - Factor of ~2 improvement in hadronic trigger efficiencies. Muon trigger efficiencies stay the same.

LHCb data samples



- Statistically 2010 data are insignificant (0.04 fb^{-1}), but some analyses published only on this statistics so far.
- Most of 2011 results were based on “summer” statistics (~0.4 fb^{-1}). Still being published.
- Many new results at winter conferences 2012 (~1 fb^{-1}). More to come in summer.

Expected future data samples

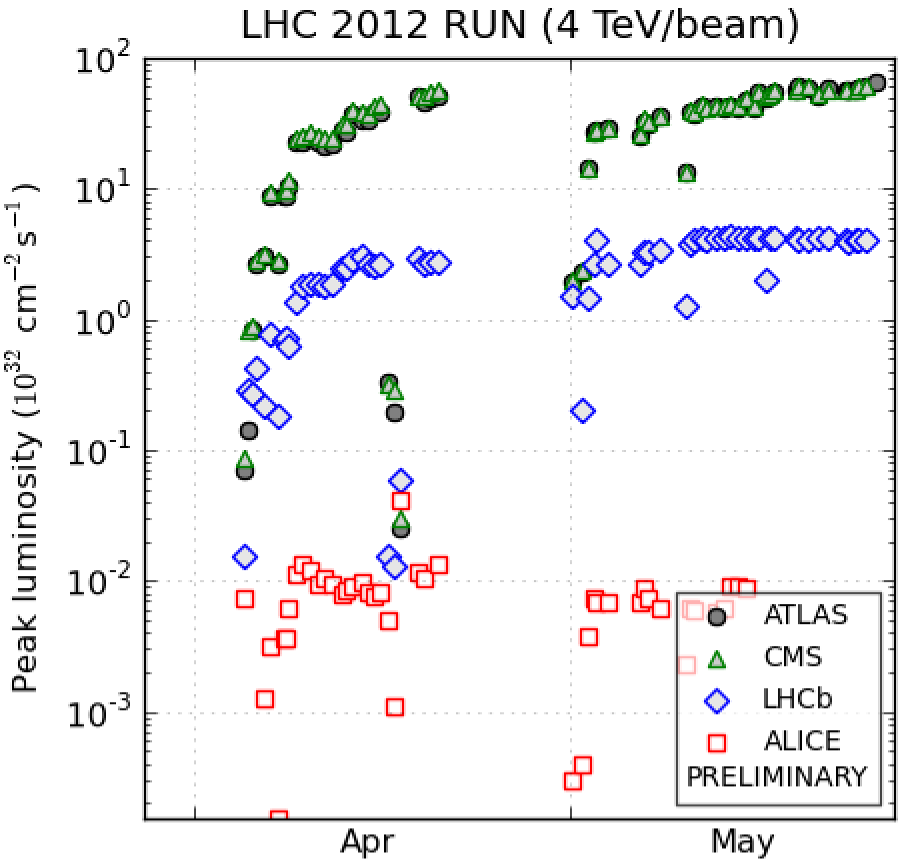
Run	CM Energy [TeV]	Integrated luminosity (all data together) [fb^{-1}]	
		LHCb	LHC (Atlas,CMS)
2011	7	**1**	5
2012	8	**2**	20
2015-17	14	**5**	95
2019-…	14	**50**	200

~50% higher $b\bar{b}$ cross section at 14 TeV

LHCb will collect ~1fb^{-1} a year until upgrade

LHCb upgrade

2012 run so far



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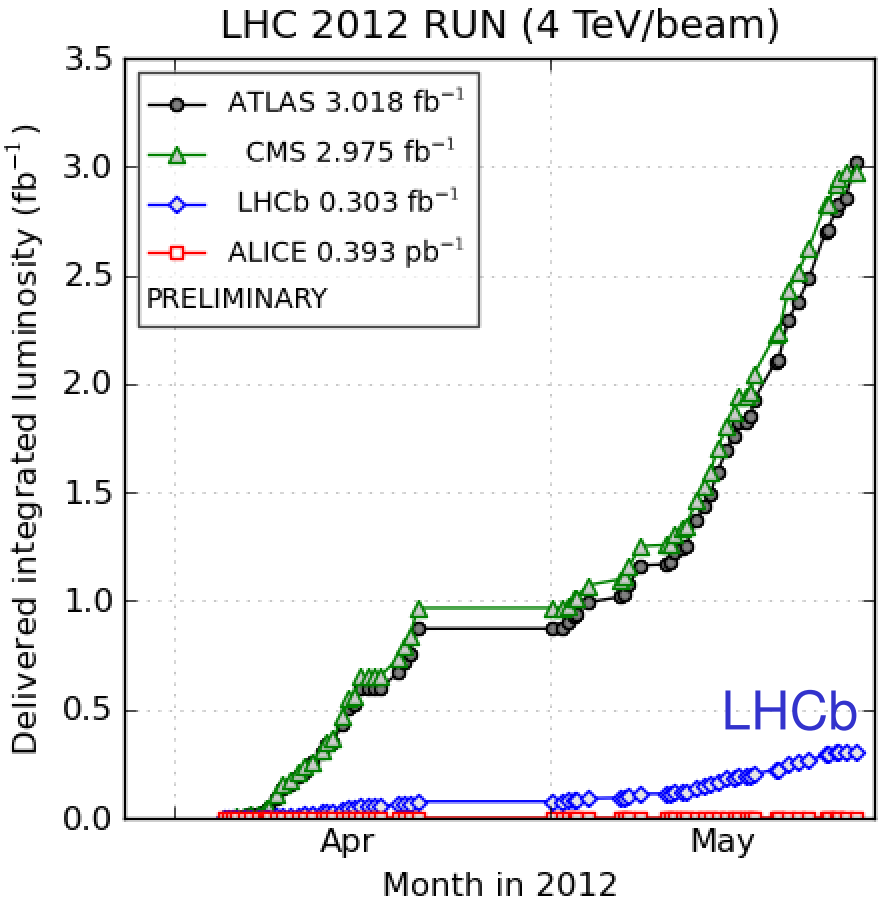
LHC ~70x10^{32} cm^{-2}s^{-1}

LHCb 4x10^{32} cm^{-2}s^{-1}



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Quark flavor transitions – CKM matrix

- Described by CKM matrix in SM
- A complex phase in 3-generation matrix gives a rise to CPV
- Wolfenstein's parameterization depicts the measured structure of CKM well

λ=0.226±0.001 ($\sin\theta_C$)

A=0.81±0.02

ρ,η see next

Good to λ^3~1%

$$\begin{array}{cc} & \begin{array}{ccc} \quad d \quad & \quad\quad s \quad\quad & \quad\quad b \quad \end{array} \\ \begin{array}{c} u \\ \\ c \\ \\ t \end{array} & V = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \delta V \end{array}$$

$$\delta V = \begin{pmatrix} 0 & 0 & 0 \\ -iA^2\lambda^5\eta & 0 & 0 \\ A\lambda^5(\rho+i\eta)/2 & -A\lambda^4(1/2-\rho-i\eta) & 0 \end{pmatrix}$$

Complex phase η

mostly in V_{td}, V_{ub} (λ^3)

then a bit in V_{ts} (λ^4)

even less in V_{cd} (λ^5)

$\lambda^0 = 1$

$\lambda^1 = 0.23$

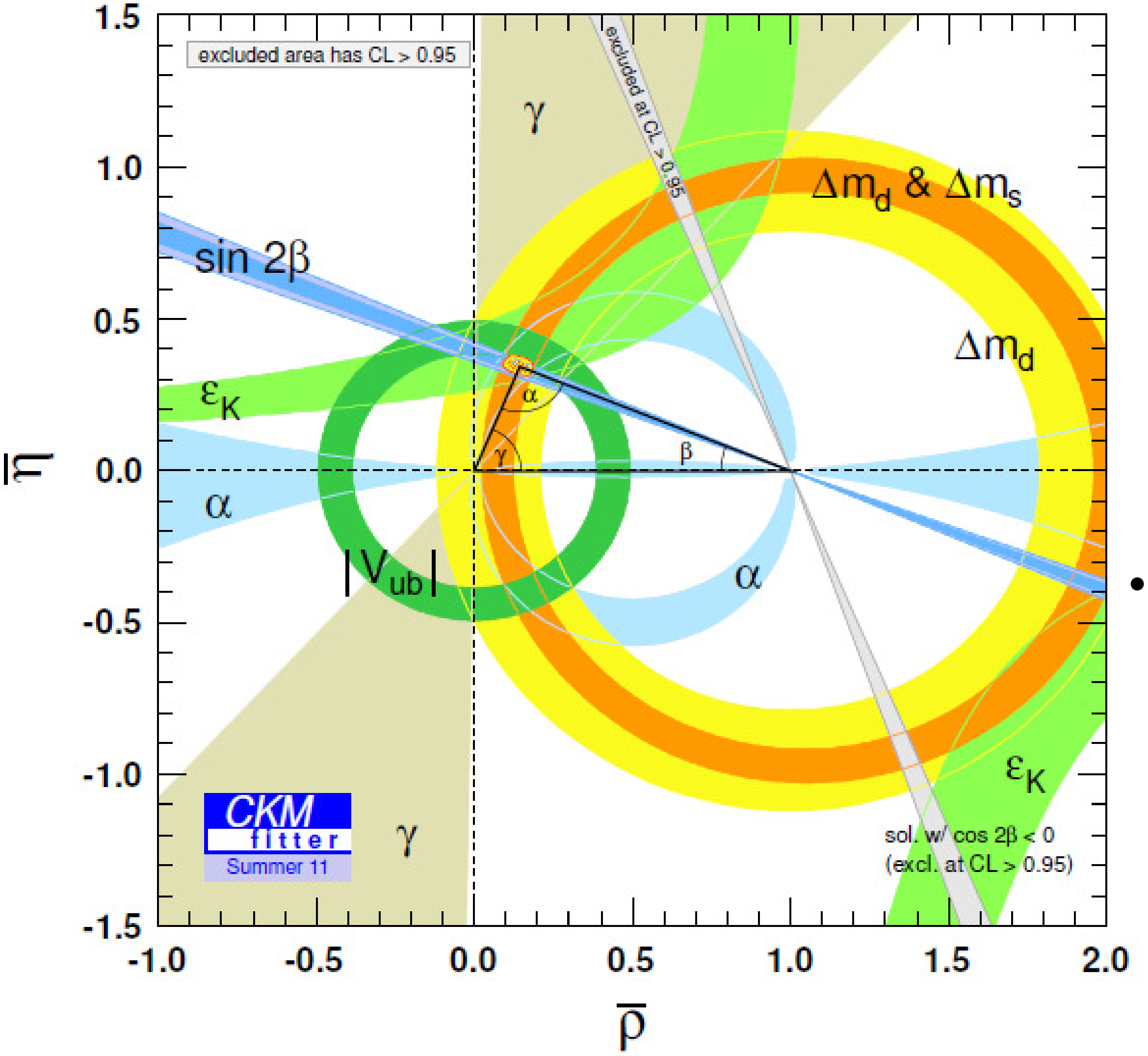
$\lambda^2 = 0.051$

$\lambda^3 = 0.012$

$\lambda^4 = 0.0026$

$\lambda^5 = 0.0006$

Quark flavor transitions – unitarity triangle



- After a decade of e^+e^- B-factory experiments the KM hypothesis is well verified

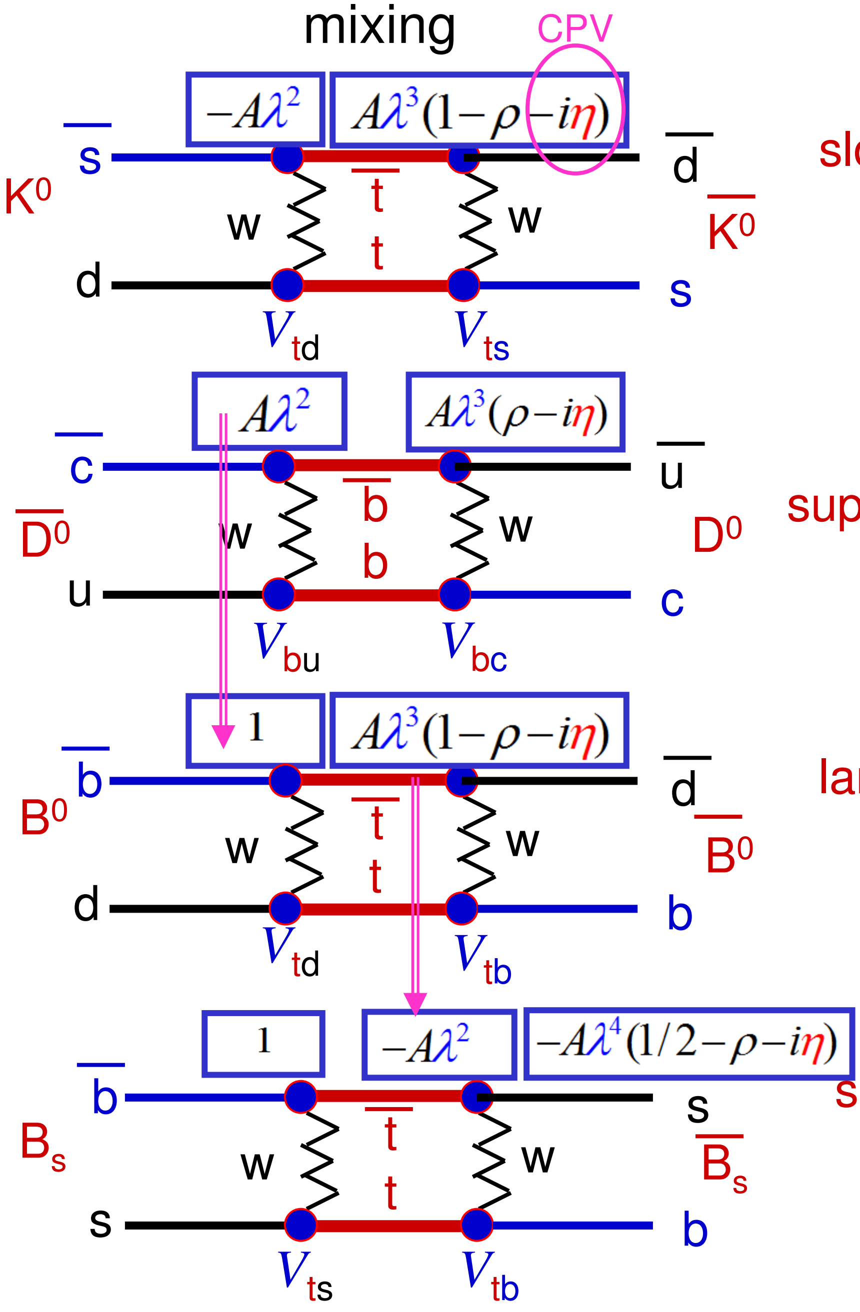
Kobayashi & Maskawa
Nobel Prize 2008

- The game now is looking for NP in corrections to CKM picture

Note: $\bar{\rho} = \rho(1-\lambda^2/2)$
$\bar{\eta} = \eta(1-\lambda^2/2)$

Trees: γ, V_{ub}
Loops: everything else

Importance of B_s physics: example indirect CPV



slow mixing, small CPV

CPV discovery
KM hypothesis

super slow mixing, very small CPV

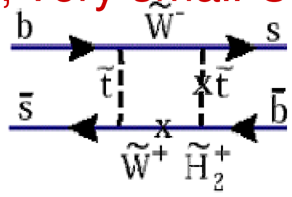
long distance diagrams can come into play
good place to look for non-SM CPV, but SM "background" not well predicted

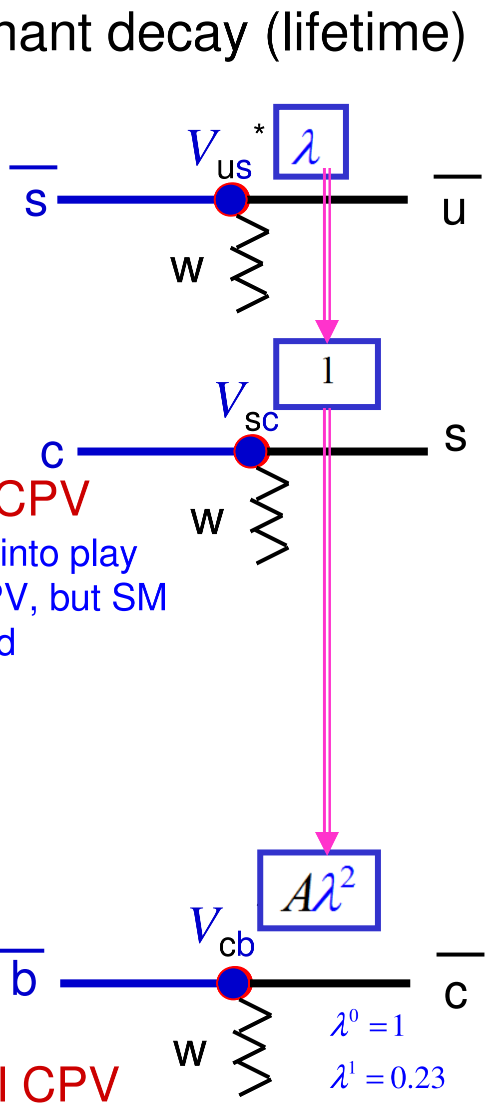
large mixing, large CPV

good place
to test SM CPV

super fast mixing, very small CPV

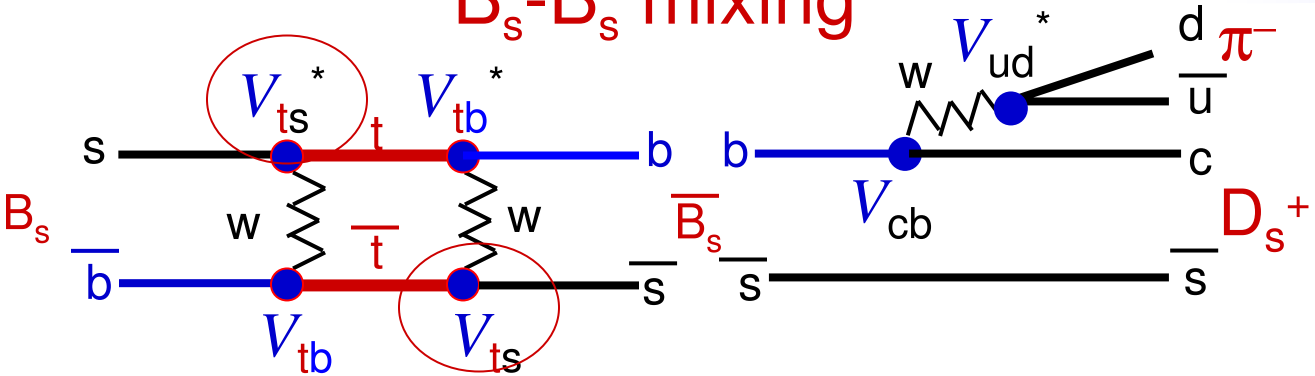
good place
to look for
non-SM CPV





$\lambda^0 = 1$
$\lambda^1 = 0.23$
$\lambda^2 = 0.051$
$\lambda^3 = 0.012$
$\lambda^4 = 0.0026$
$\lambda^5 = 0.0006$

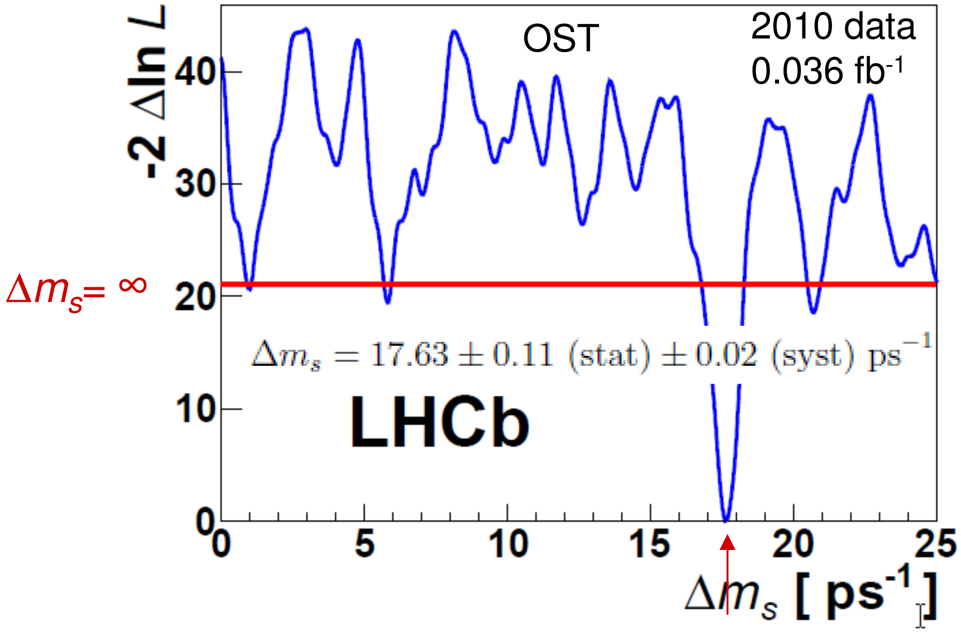
B_s-$\overline{B}_s$ mixing



- First measured by CDF in 2006
- LHCb (world best!):

Measure Δm_s with $B_s \rightarrow D_s(KK\pi)(3)\pi$

σ_t^{LHCb} ~ 44 (36) fs for $D_s(3)\pi$



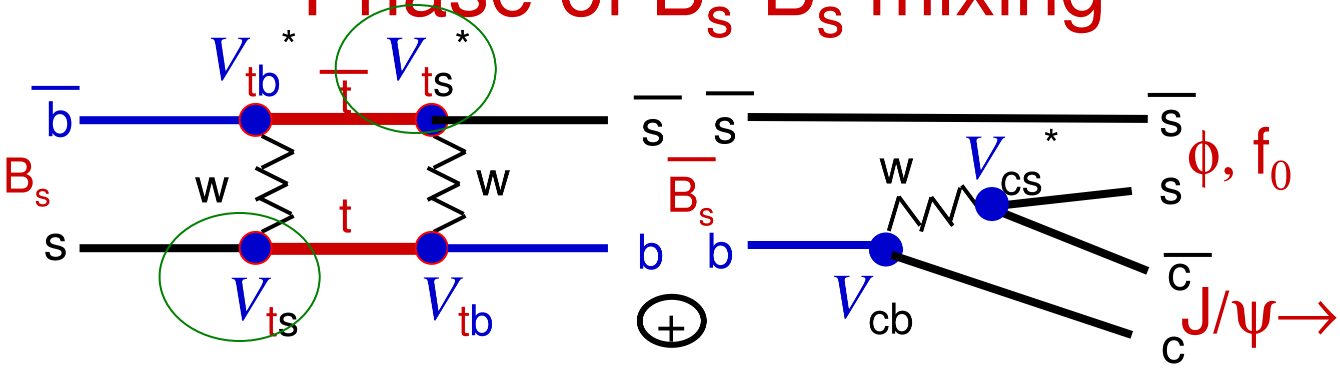
arxiv:1112.4311 submitted to PLB

$\Delta m = M_L - M_S$ frequency of oscillations sensitive to $|V_{ts}|$

Final state determines B_s flavor at the decay (no interference of mixing & decay). Also need to determine ("tag") B_s flavor at the production point.

Tagging	εD^2
Opposite Side	2.1±0.2 %
Same Side Kaon	1.3±0.4 %

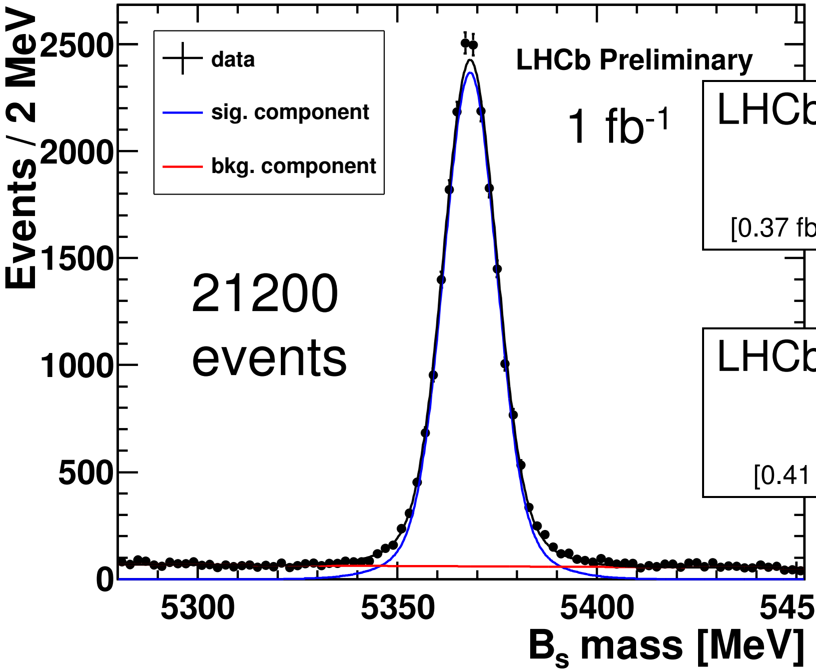
Phase of B_s-$\overline{B}_s$ mixing



Interference of mixing and decay produces **indirect CPV.**

No SM phase in the lowest order. Small V_{ts} phase suppressed by λ^2

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



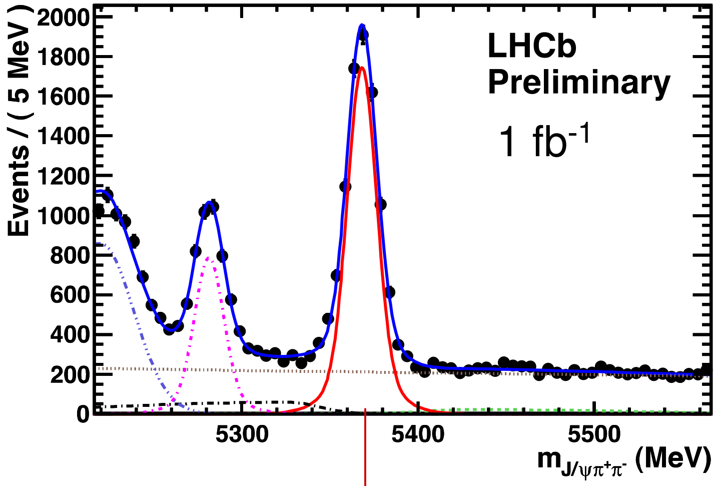
LHCb-CONF-2012-002 (Moriond)

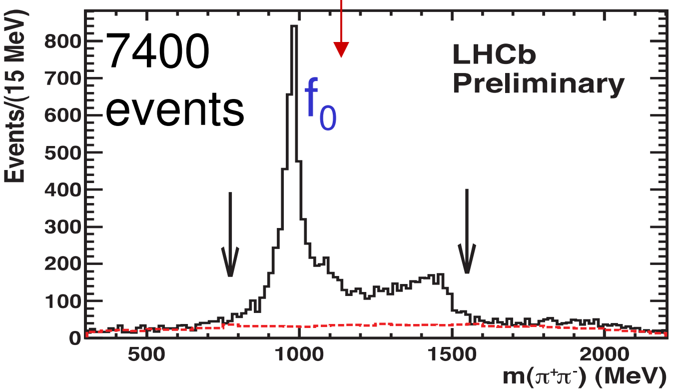
[0.37 fb^{-1} PRL 108, 101803 (2012)]

LHCb-CONF-2012-006 (Moriond)

[0.41 fb^{-1} PL B707, 497 (2012)]

$B_s \to J/\psi\ \pi^+\pi^-$



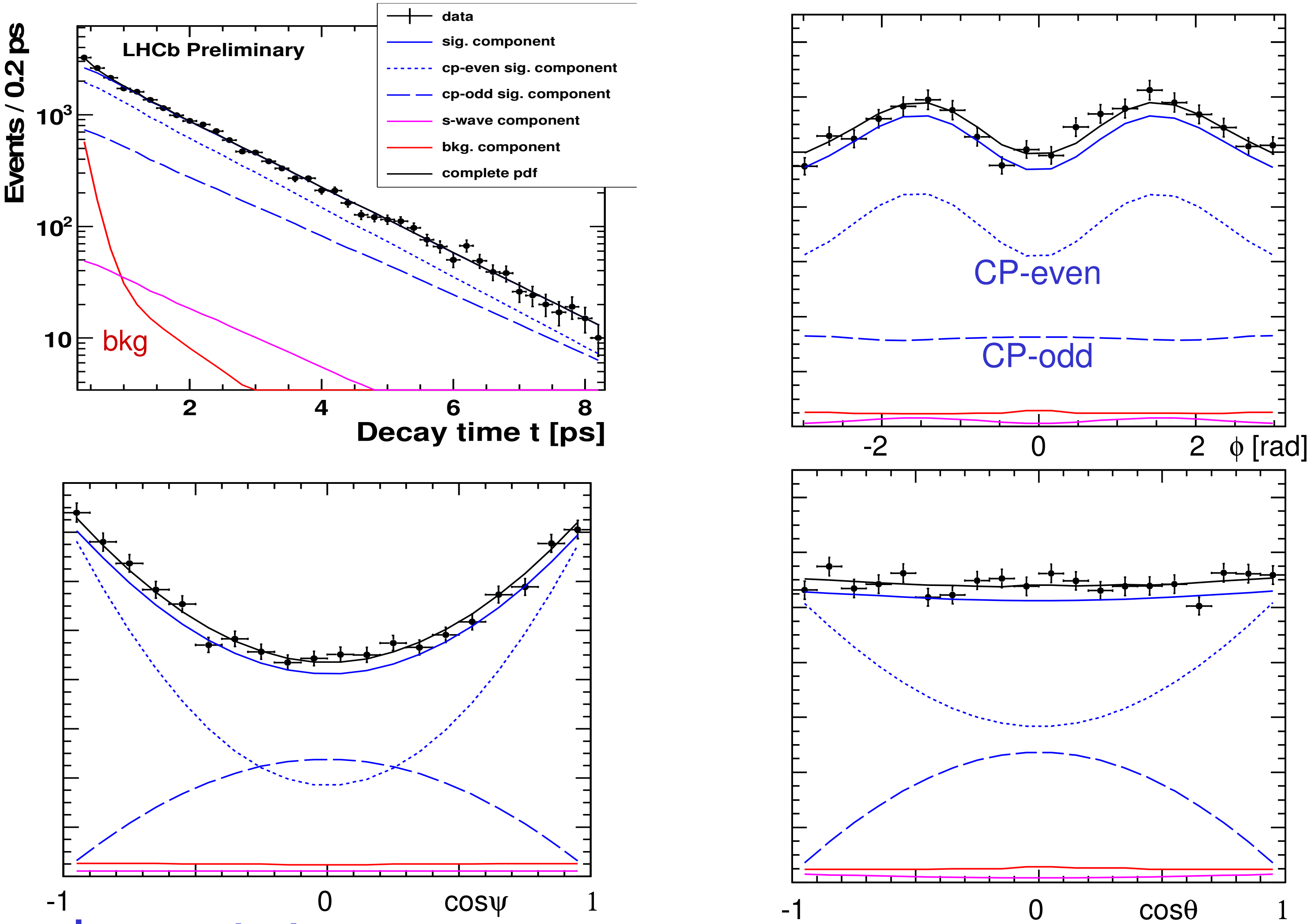


Phase of B_s-$\overline{B_s}$ mixing

$B_s \to J/\psi\ \phi$: not an eigenstate; need angular analysis

(σ_t~45 fs)

Opposite side flavor tags only: εD^2 = 2.3±0.3 %



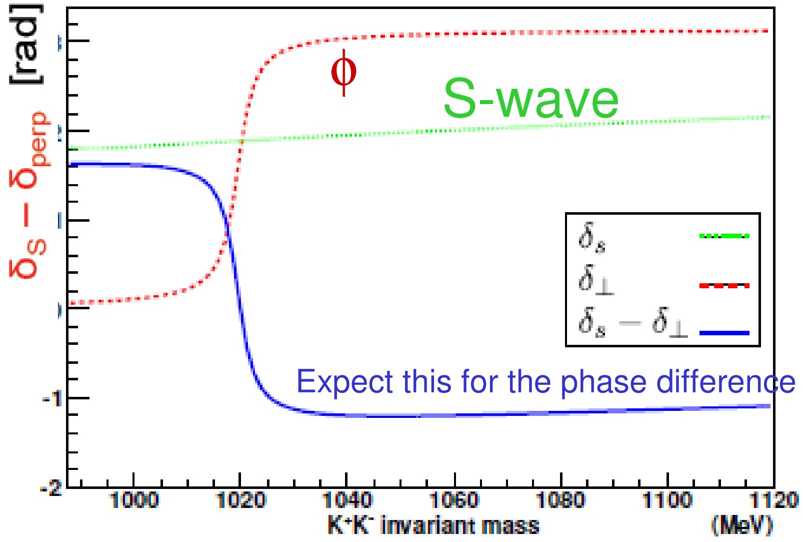
$B_s \to J/\psi\pi^+\pi^-$: eigenstate (LHCb-PAPER-2012-005); no need for angular analysis

Resolving fit ambiguity (sign of $\Delta\Gamma_s$)

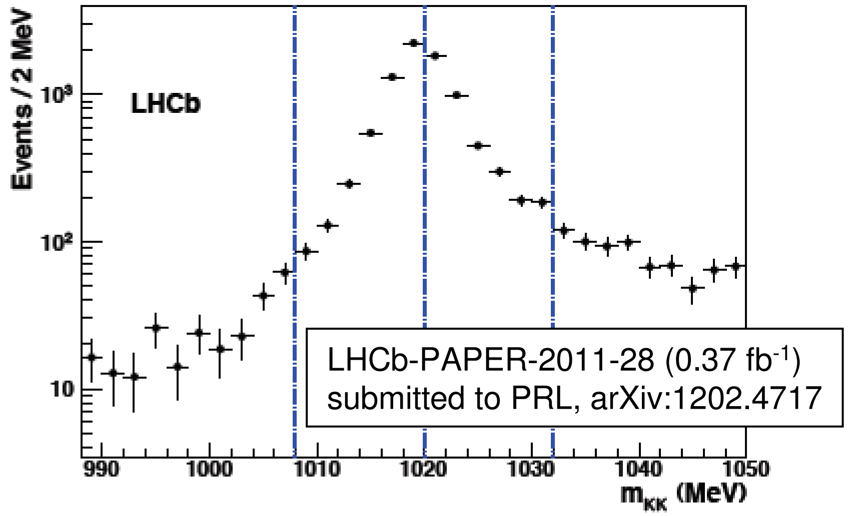
Solution I		Solution II
$\delta_\parallel - \delta_0$		$\delta_0 - \delta_\perp$
$\delta_\perp - \delta_0$		$\pi + \delta_0 - \delta_\perp$
$\delta_s - \delta_0$	$\Leftrightarrow$	$\delta_0 - \delta_s$
ϕ_s		$\pi - \phi_s$
$\Delta\Gamma_s$		$-\Delta\Gamma_s$

To resolve the ambiguity look at interference of the ϕ resonance (P-wave) and small S-wave component

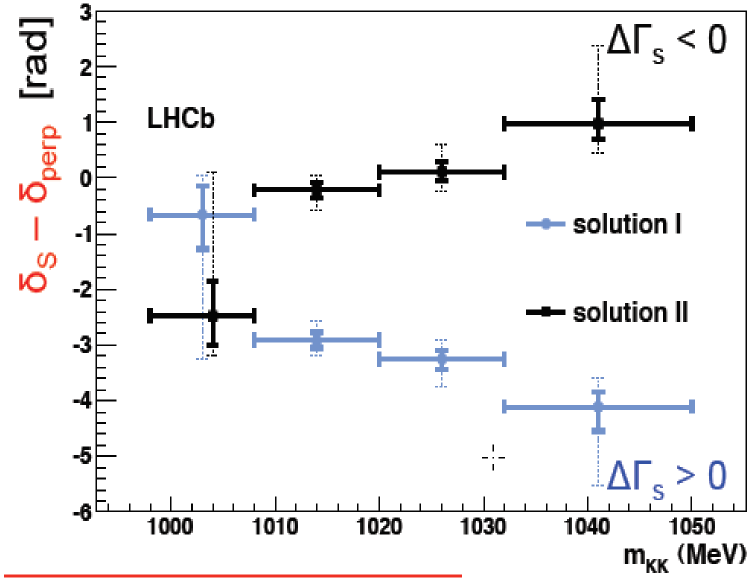
Expected for the right solution:



Expect this for the phase difference



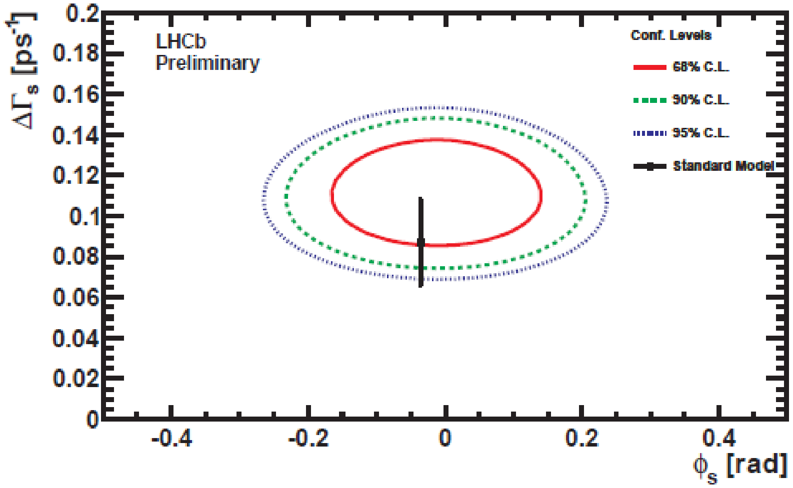
LHCb-PAPER-2011-28 (0.37 fb^{-1})
submitted to PRL, arXiv:1202.4717



Solution I chosen (4.5σ away from flat)

Phase of B_s-$\overline{B}_s$ mixing

- Profile likelihood contour in $\Delta\Gamma_s$-ϕ_s plane:



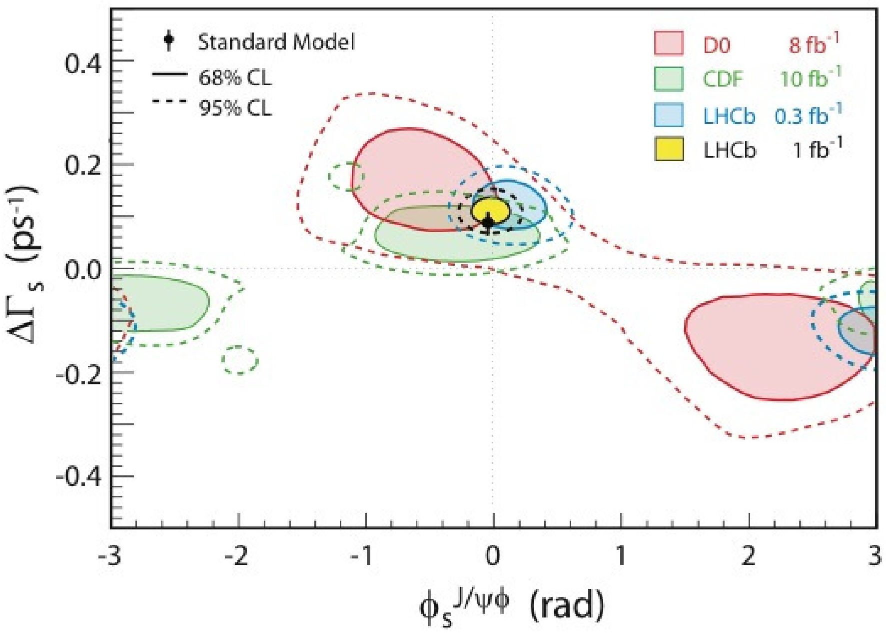
- Result, LHCb 1 fb^{-1}(Preliminary)

$$\begin{array}{rcllllll}
\Gamma_s & = & 0.6580 & \pm & 0.0054(\text{stat.}) & \pm & 0.0066(\text{syst.}) & \text{ps}^{-1} \\
\Delta\Gamma_s & = & 0.116 & \pm & 0.018(\text{stat.}) & \pm & 0.006(\text{syst.}) & \text{ps}^{-1} \\
\phi_s & = & \text{-}0.001 & \pm & 0.101(\text{stat.}) & \pm & 0.027(\text{syst.}) & \text{rad}
\end{array}$$

- Simultaneous fit to both $\mathrm{B}_s^0 \to \mathrm{J}/\psi\pi^+\pi^-$, $\mathrm{B}_s^0 \to \mathrm{J}/\psi\phi$:

$$\phi_s \quad = \quad \text{-}0.002 \quad \pm \quad 0.083(\text{stat.}) \quad \pm \quad 0.027(\text{syst.}) \quad \text{rad}$$

Phase of Bs-$\overline{\text{Bs}}$ mixing



- First significant observation of $\Delta\Gamma_s$, sign determined
- SM not challenged yet.
- Plenty of room for improved NP searches: SM uncertainty on ϕ_s~0.003
- LHCb will measure ϕ_s to ±0.02 with 5 fb^{-1}.
- Upgraded LHCb will measure ϕ_s to ±0.006 with 50 fb^{-1}.

If necessary, we can control penguin pollution in $B_s \rightarrow J/\psi\phi$ with measurement of direct-CPV in $B_s \rightarrow J/\psi K^{*0}$

Also plan to study indirect CPV in $B_s \rightarrow [\psi(2S),\eta_c,\chi_{c1}]\phi$, $J/\psi\eta^{(')}$, D_sD_s

~10% of J/$\psi\phi$

~1500 events in 1 fb^{-1}

Why is LHCb with 1/10th of CDF luminosity doing a factor of 4 better than CDF?

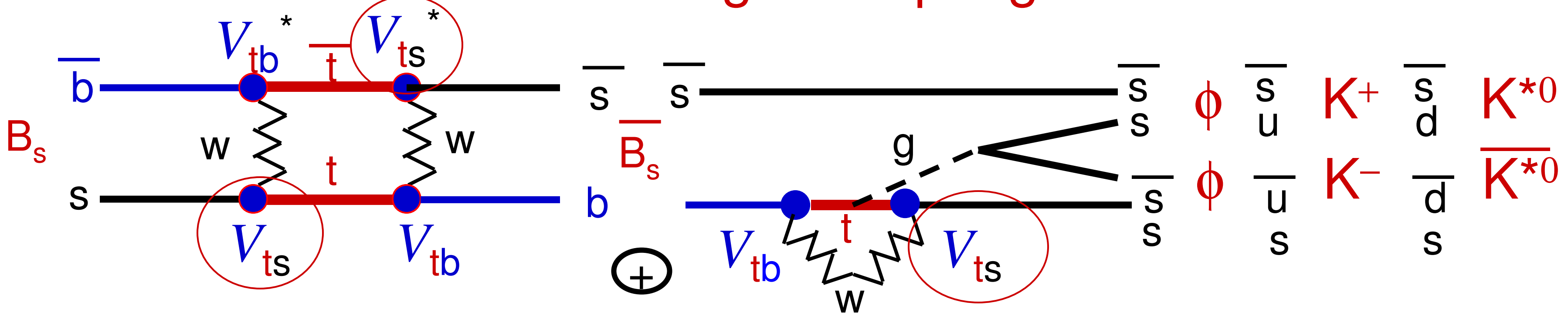
Higher b$\bar{\text{b}}$-cross section at LHC helps, but only by a factor of sqrt(3)=1.7

B trigger happy!

	CDF	LHCb
Bunch crossing rate	**2 350 kHz**	**20 000 kHz**
Bunch spacing	396 ns	50 ns
Interactions / crossing	***(at 3 10^{32}) 10.0***	**(at 3.5 10^{32}) 2.4**
Stage 1	L1	L0
Output rate	**30 kHz**	**1 000 kHz**
Latency	5.5 μs	4.0 μs
Type	**Hardware** (tracks,mu,ecal)	**Hardware** (hcal,mu,ecal)
Single μ	Pt>4 GeV	Pt>1.3 GeV
Dimoun	Pt1>2.0 & Pt2>2.0 GeV	Pt1+Pt2>1.3 GeV
Stage 2	L2	HLT1
Output rate	**1 kHz**	**30 kHz**
Execution time	20 μs	~5 000 μs
Type	**Hardware** (tracks, IP)	**Computer Farm** (tracks,IP)
Stage 3	L3	HLT2
Output rate	**150 Hz**	**3 500 Hz**
Event size	250 kB	45 kB
Type	**Computer farm**	**Computer Farm** (full event reco)
Fraction of bandwidth for heavy flavors	small	all

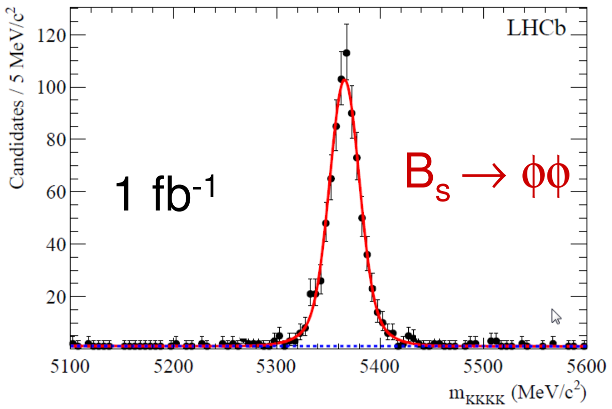
- LHCb is the first dedicated hadron collider b-experiment

Indirect CPV via box-gluonic penguin interference

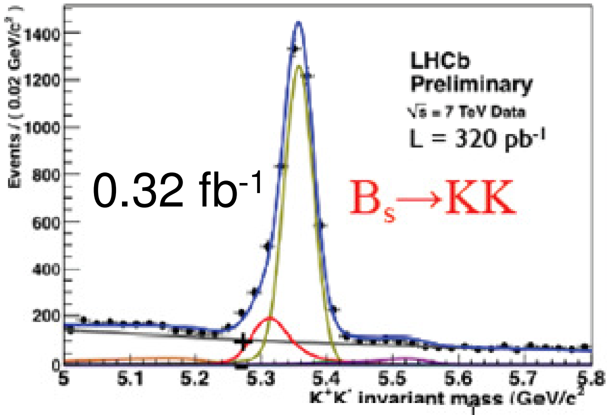


No SM phase in the lowest and second order: small V_{ts} phase cancels between the mixing and decay diagrams.

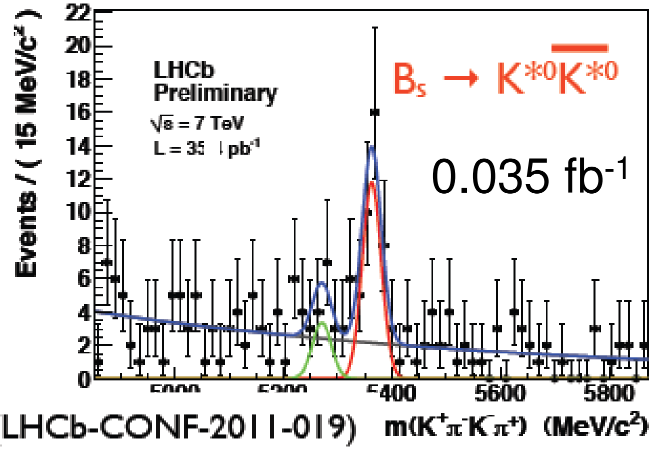
NP can enter also through the penguin diagram.



LHCb-PAPER-2012-12
submitted to PLB, arXiv:1204.2813



(LHCb-CONF-2011-042)



(LHCb-CONF-2011-019)

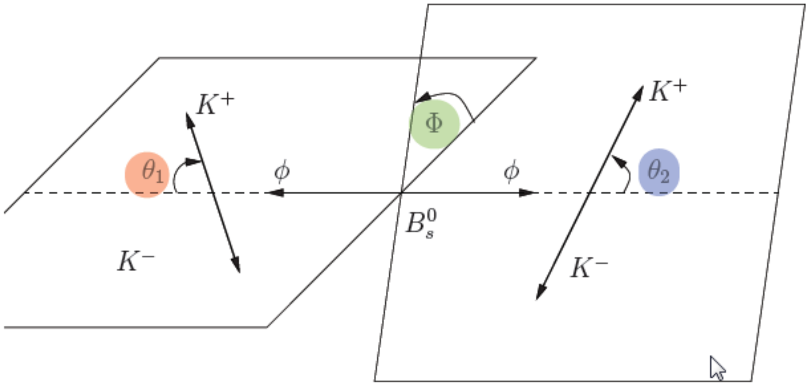
arXiv:1111.4183 submitted to PLB

- Purely hadronic final states – at LHC only LHCb can trigger on them

Indirect CPV with $B_s \to \phi\phi$

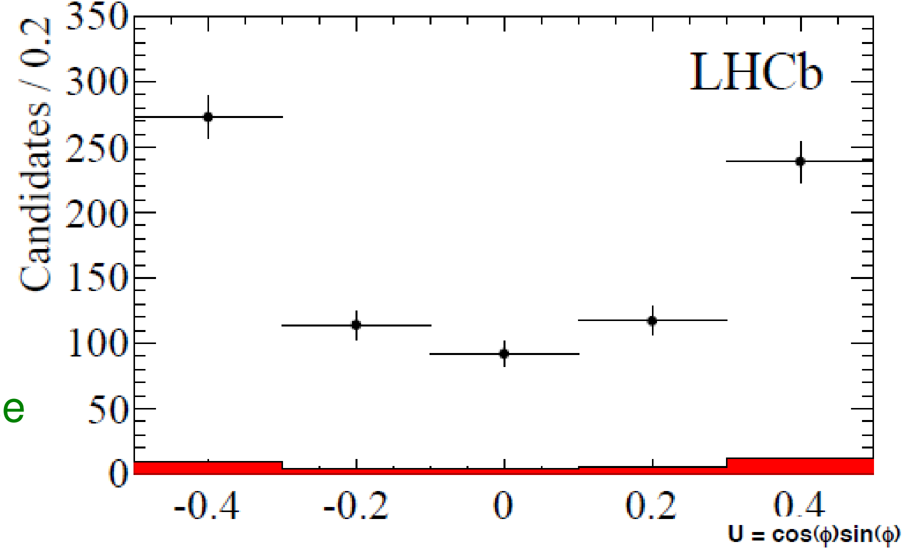
T-odd triple product asymmetries

Phys.Lett.B701(2011),357, arXiv:1107.1232

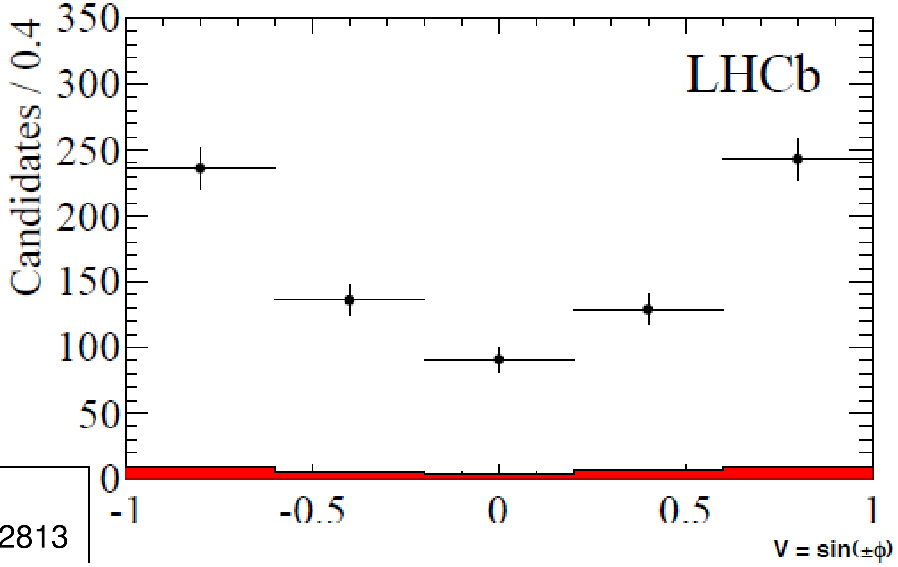


- These flavor untagged asymmetries must be zero unless there is a difference between phase of CP even/odd amplitudes (not in SM!)
- LHCb results based on 801±29 events in 1 fb^{-1} consistent with the SM and with less precise measurements by the CDF (arXiv:1107.4999 295±20 events in 2.9 fb^{-1})
- Future improvements:
  - Full angular analysis
  - **Flavor-tagged time-dependent analysis with more data**
- CPV phase of this process will be measured by LHCb to ±0.04 with 5 fb^{-1}; to ±0.01 with 50 fb^{-1} and upgraded detector (improved hadronic triggers!) reaching the theoretical uncertainty

$$A_U = -0.055 \pm 0.036\,(\mathrm{stat}) \pm 0.018\,(\mathrm{syst})$$



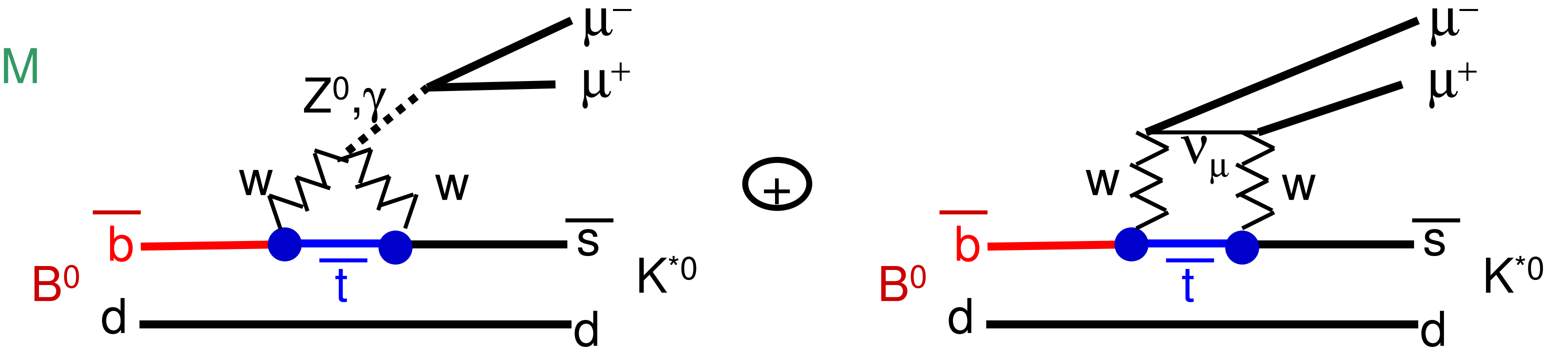
$$A_V = 0.010 \pm 0.036\,(\mathrm{stat}) \pm 0.018\,(\mathrm{syst})$$



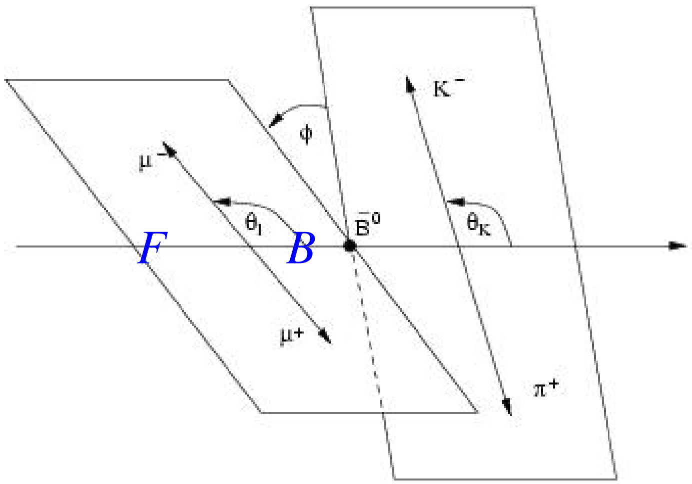
LHCb-PAPER-2012-12
submitted to PLB, arXiv:1204.2813

$B^0 \to K^{*0}\mu^+\mu^-$

SM



- Look for interference of these SM diagrams. NP diagrams can contribute.
- Need to eliminate effect of form-factors – various observables related to angular correlations. Most famous A_{FB}



$$A_{FB}\left(q^2\right) = \frac{N_F - N_B}{N_F + N_B}$$

$B^0 \rightarrow K^{*0}\mu^+\mu^-$

Before summer 2011:

Babar, Belle and CDF

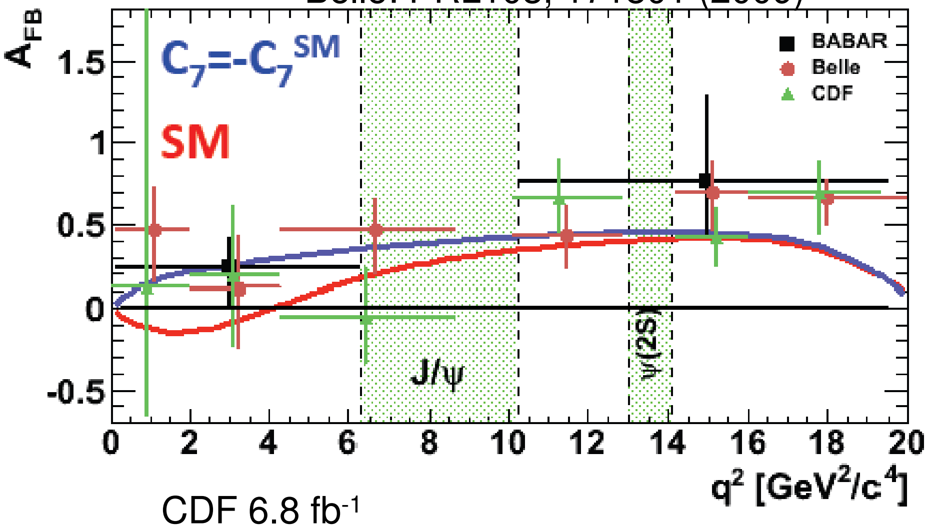
- Babar 60 events with B/S=0.3
- Belle 247 0.25
- CDF 100 (4.4 fb^{-1}) 0.4

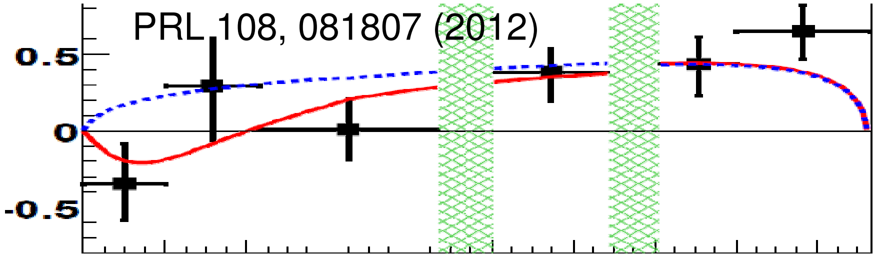
New results:

- CDF 164 (6.8 fb-1) 0.4
- LHCb 900 (1.0 fb-1) 0.25

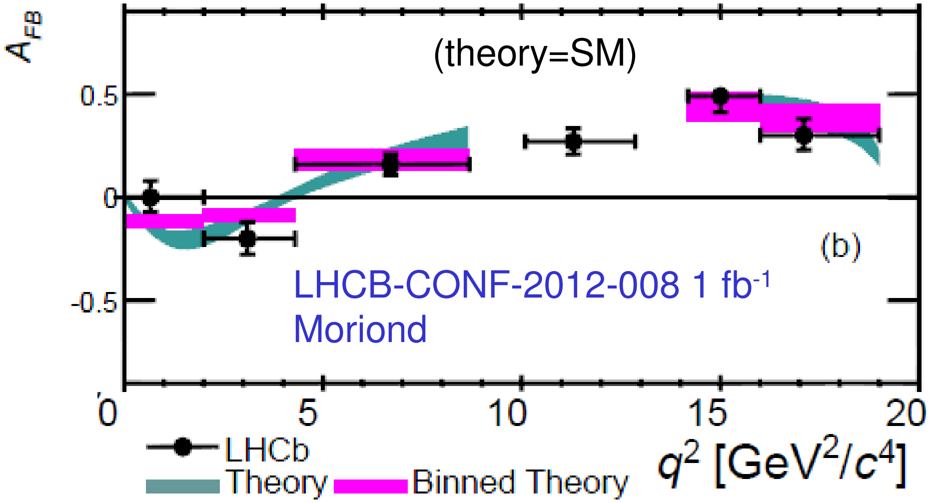
- So far no challenge to SM
- LHCb already has the most sensitive measurement:
  - 5 times more data by 2018
  - 50 times more data with upgrade
- LHCb upgrade will have better sensitivity than super e^+e^- factories in this exclusive channel (e^+e^- can also do inclusive measurement)

BaBar: PRD 79, 031102 (2009)
Belle: PRL103, 171801 (2009)





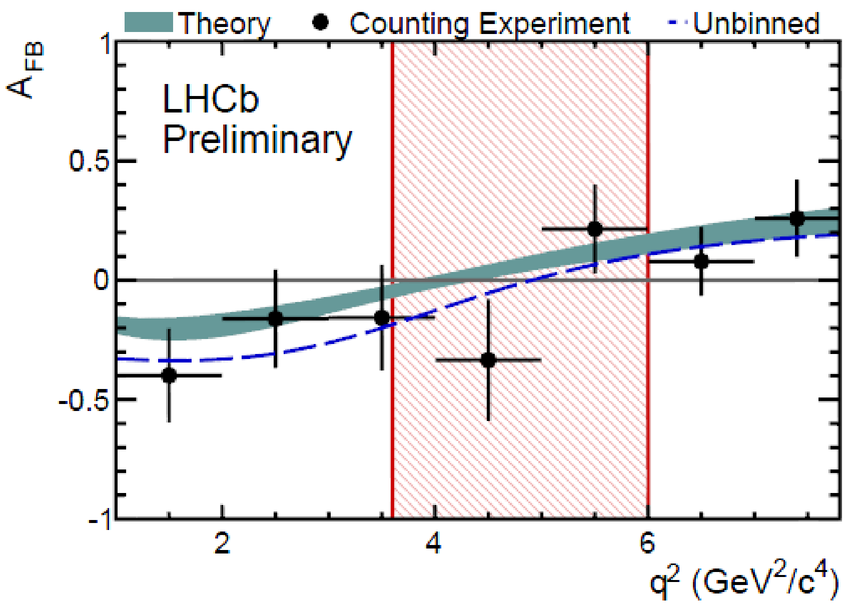
CDF 6.8 fb^{-1}
PRL 108, 081807 (2012)



LHCB-CONF-2012-008 1 fb^{-1}
Moriond

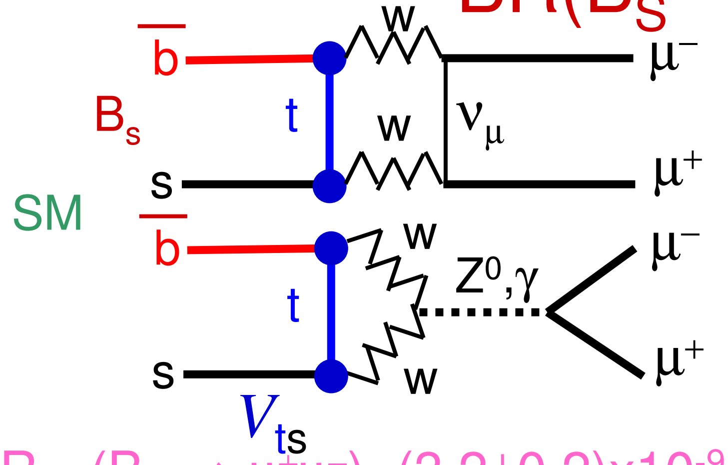
First measurement of A_{FB} zero-crossing point

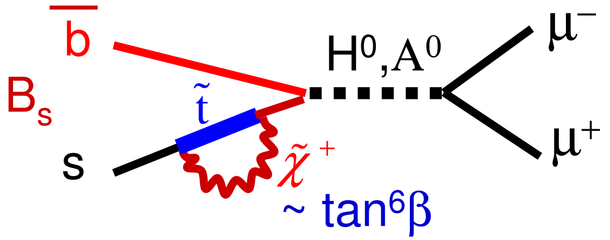
- The SM predicts A_{FB} to change sign at a well defined point in q^2
- This zero-crossing point q_0^2 is largely free from form-factor uncertainties
- Extracted through a 2D fit to the foward- and backward-going m_{B^0} and q^2 distributions



- The worlds first measurement of q_0^2, at $q_0^2 = 4.9^{+1.1}_{-1.3}\ \mathrm{GeV}^2/c^4$ [preliminary]
- This is consistent with SM predictions which range from $4 - 4.3\ \mathrm{GeV}^2/c^4$

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





NP

e.g. SUSY

~ $\tan^6\beta$

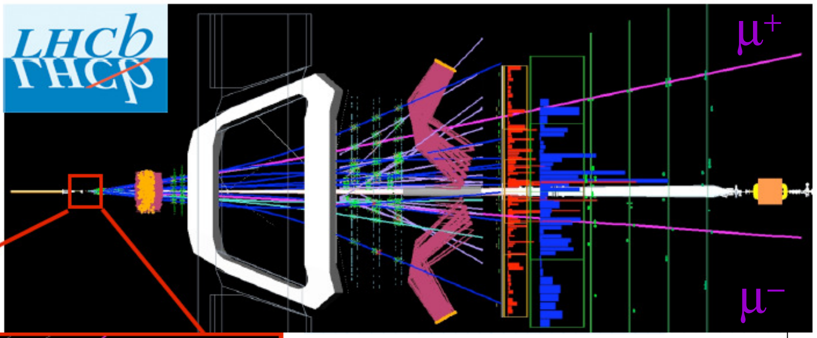
Could be strongly enhanced.

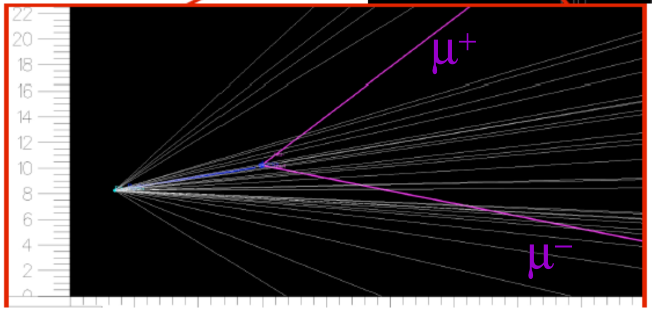
In some models negative interference with the SM.

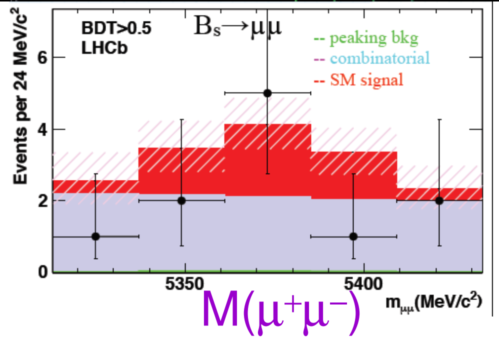
$BR_{SM}(B_S \to \mu^+\mu^-)=(3.2\pm0.2)\text{x}10^{-9}$ JHEP 1010, 009 (2010) Small with small theoretical error!

CDF 7 fb^{-1} 7/12/11 PRL 107,191801(2011)	$(1.8^{+1.1}_{-0.9})\times10^{-8}$	$< 4.0\times10^{-8}$ (95% CL)
CDF 9.6 fb^{-1} 3/5/12	$(1.3^{+0.9}_{-0.7})\times10^{-8}$	$< 3.1\times10^{-8}$
LHCb 0.37 fb^{-1} 7/21/11 PL B707,497 (2012)		$< 1.4 \text{ x } 10^{-8}$
CMS 5 fb^{-1} 2/28/12 CMS-BPH-11-020		$< 0.77 \text{ x } 10^{-8}$
ATLAS 2.4 fb^{-1} 3/2/12 ATLAS-CONF-2012-010		$< 2.2 \text{ x } 10^{-8}$
LHCb 1 fb^{-1} 3/21/12 LHCB-PAPER-2012-007		$< 0.45 \text{ x } 10^{-8}$

2.1σ evidence for NP







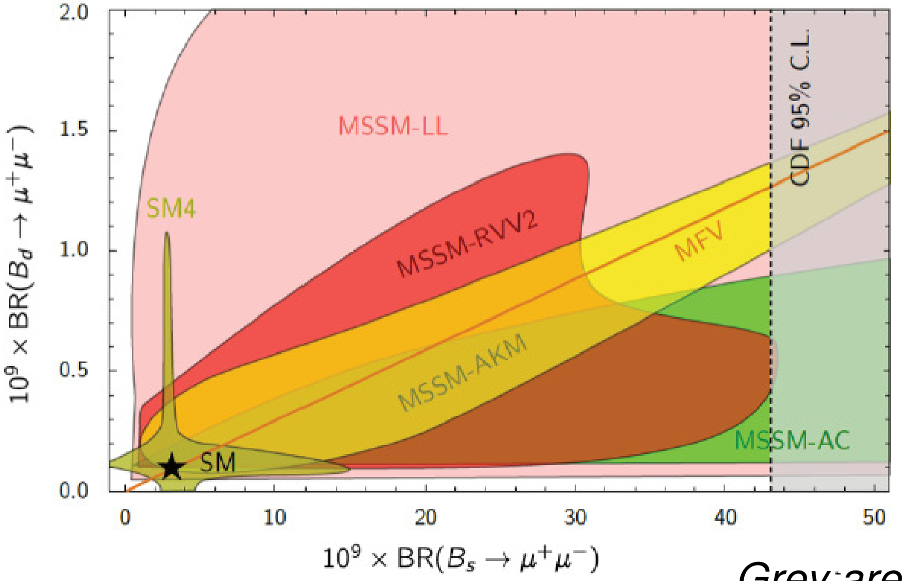
No excess of events over the expected background + expected SM signal

BR($B_S \to \mu^+\mu^-$) and BR($B^0 \to \mu^+\mu^-$)

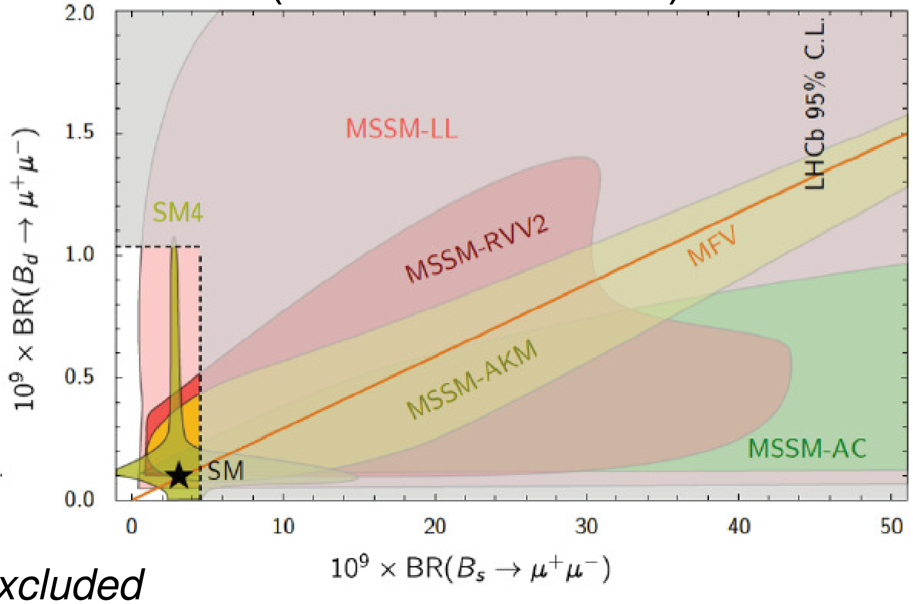
- Together more sensitive probe for NP

New results in 2012	[Moriond E.W.]	CDF	CMS	ATLAS	LHCb	SM
	Luminosity (fb^{-1})	10	4.9	2.4	**1**	
BR($B^0 \to \mu^+\mu^-$)	95% CL upper limit (10^{-9})	4.6	1.8		**1.03**	0.10 ± 0.01
BR($B_s \to \mu^+\mu^-$)	95% CL upper limit (10^{-9}) Value (10^{-9})	**31** **13^{+9}_{-7}**	**7.7**	**22**	**4.5** **$0.8^{+1.8}_{-1.3}$**	3.2 ± 0.2

(status after CDF 7 fb^{-1} results)



(now LHCb 1 fb^{-1})



Grey area excluded

SM has survived an order of magnitude improvement in experimental senitivity

room left for NP (in some models negative interference with the SM)

Future LHC samples and $B_s \to \mu^+\mu^-$ prospects

Run	CM Energy [TeV]	Integrated luminosity (all data together) [fb^{-1}]	
		LHCb	CMS
2011	7	**1**	5
2012	8	**2**	20
2015-17	14	**5**	95
2019-…	14	**50**	200

At present CMS limits ~ 1.7 x LHCb limits

If CMS manages to retain present trigger and analysis efficiencies, it will lead in sensitivity for this channel until LHCb upgrade.

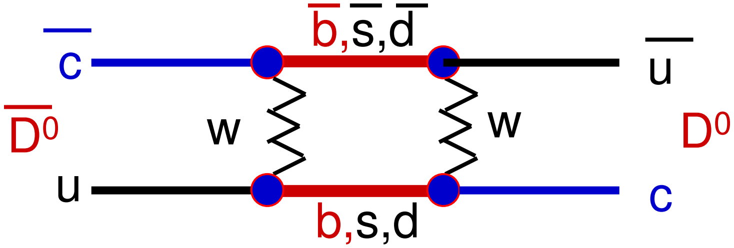
If no NP found earlier, the SM value will be observed during 2015-17 run.

After 2019-21 run the experimental errors will become comparable to the SM theoretical uncertainty (<10%), closing this window to NP.

$BR(B^0 \to \mu^+\mu^-)/BR(B_s \to \mu^+\mu^-)$ ~ 1/30 in SM; ~5% theor. error will also be measured to ~35% accuracy by the upgraded LHCb

Charm mixing

Short distance



b: CKM-suppressed:

$|A^2\lambda^5(\rho - i\eta)|^2$ ~10^{-8}

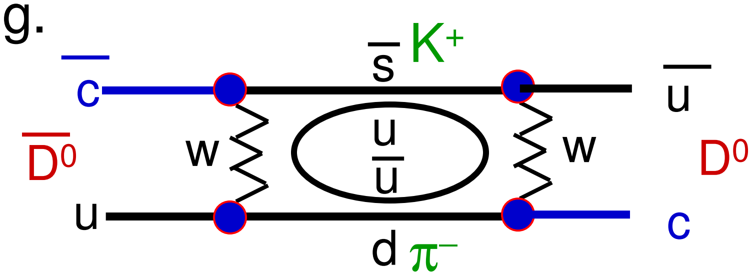
s,d: GIM-cancellations:

$(m_s^2 - m_d^2)/m_c^2$ ~10^{-5}

phase is CKM-suppressed: $A^2\lambda^5 i\eta$

Long distance

e.g.



Many intermediate states can contribute:

Kπ, KK, ππ, πππ,…

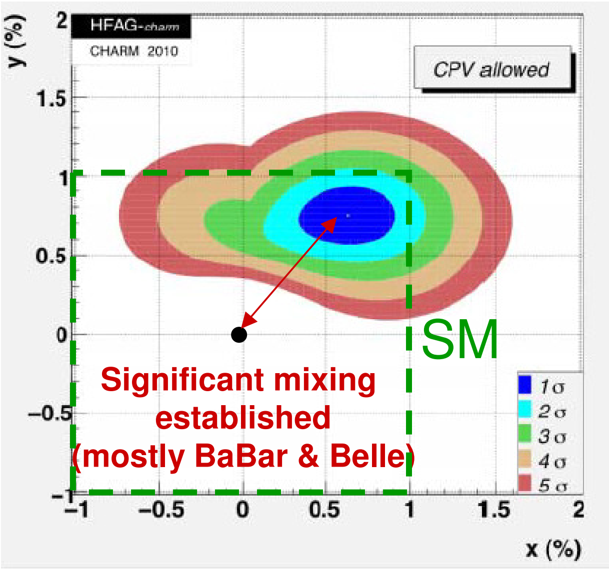
with difficult to predict magnitudes & phases.

Mixing with |x|<1%, |y|<1% in SM possible.

1,2-mass eigenstates $|D_{1,2}> = p|D^0> \pm q|\bar{D}^0>$

- Mixing observed by the previous experiments at the level of the largest SM predictions. It is a bit of surprise, but can't prove NP contributions.
- SM CPV phase is strongly CKM-suppressed. Expect indirect CPV to be tiny ~10^{-8} (« 10^{-3}); good place to look for NP.

$y=(\Gamma_1-\Gamma_2)/(2\Gamma)$



Significant mixing established (mostly BaBar & Belle)

$\Gamma=(\Gamma_1+\Gamma_2)/2$

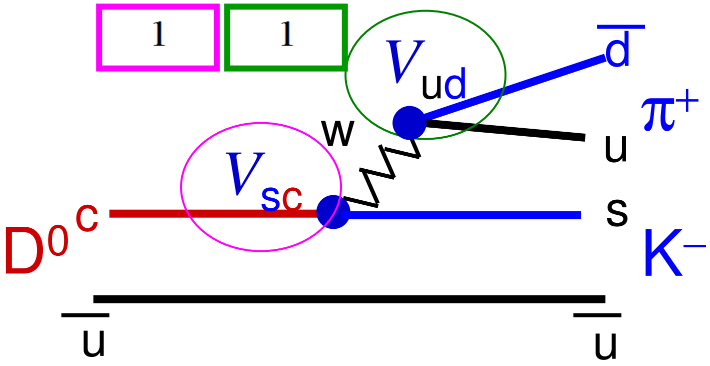
$x=(m_1-m_2)/\Gamma$

Charm mixing and CPV via effective lifetimes

Measure effective lifetimes (effective = fit simple exponential decay) for $D^0 \to K^-\pi^+$ and $D^0 \to K^+K^-$

$D^0 \to K^-\pi^+$,
$\overline{D^0} \to K^+\pi^-$

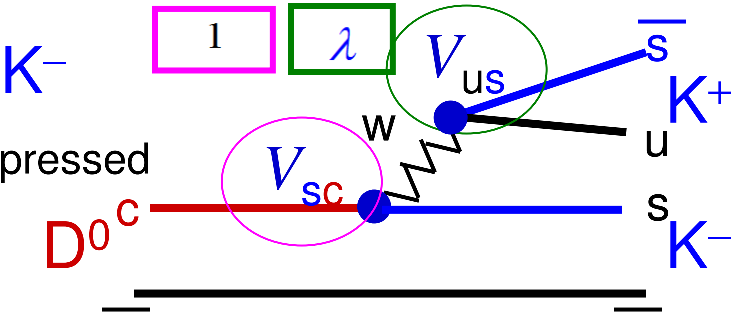
Cabibbo Favored
BR ~ 0.04



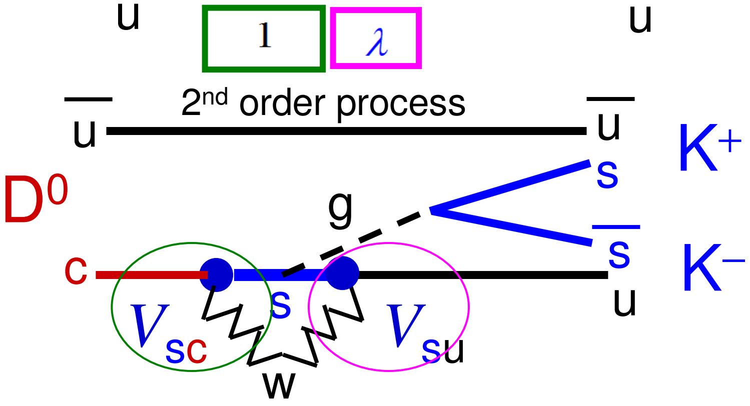
Not a CP eigenstate
(averages over CP states)

$D^0, \overline{D^0} \to K^+K^-$

Single Cabibbo Suppressed
BR ~ 0.004



CP eigenstate (CP= -1)
Sensitivity to CPV in mixing, and in interference of mixing and decay (indirect CPV)



Interference of the tree and penguin decays can produce small direct CPV

NP can enter via mixing or penguin processes

Charm mixing and CPV via effective lifetimes

Measure effective lifetimes (effective = fit simple exponential decay)

$$\boxed{y_{CP} = \frac{\tau_{K\pi}}{\tau_{KK}} - 1}$$

$$\boxed{A_\Gamma = \frac{\tau_{\bar{D}^0\to K^+K^-} - \tau_{D^0\to K^+K^-}}{\tau_{\bar{D}^0\to K^+K^-} + \tau_{D^0\to K^+K^-}}}$$

$$y_{CP} \approx (1+\frac{1}{8}A_m{}^2)\,y\cos\phi - \frac{1}{2}A_m\,x\sin\phi$$

$$A_\Gamma \approx \frac{1}{2}(A_m + A_d)\,y\cos\phi - x\sin\phi$$

$$|D_{1,2}> = p\,|D^0> \pm q\,|\bar{D}^0>$$

$$A_m \approx \left(\frac{q}{p}\right)^2 - 1$$

CPV in mixing itself ("indirect CPV")

$$A_d \approx \left(\frac{A_{\bar{D}^0\to K^+K^-}}{A_{D^0\to K^+K^-}}\right)^2 - 1$$

CPV in decay ("direct CPV")

$$\phi = \arg\left(\frac{q}{p}\frac{A_{\bar{D}^0\to K^+K^-}}{A_{D^0\to K^+K^-}}\right)$$

CPV in interference of mixing and decay ("indirect CPV")

For no CPV

$$A_m \to 0, \phi \to 0$$

$$y_{CP} \to y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$

$$A_m \to 0, \phi \to 0, A_d \to 0$$

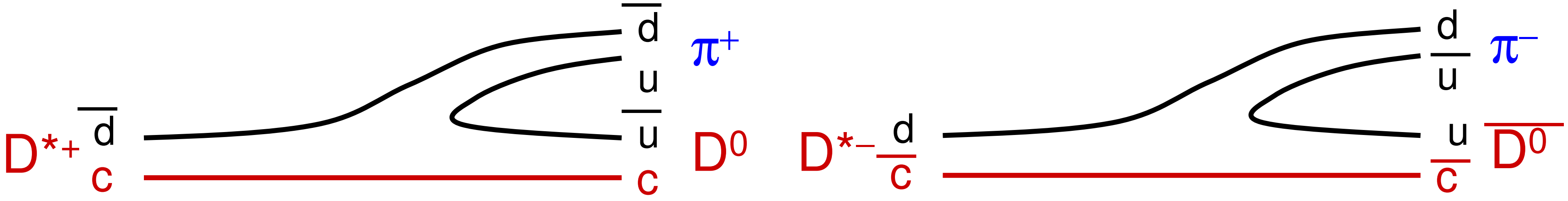
$$A_\Gamma \to 0$$

$y_{CP} \neq y$ is a sign of indirect CPV

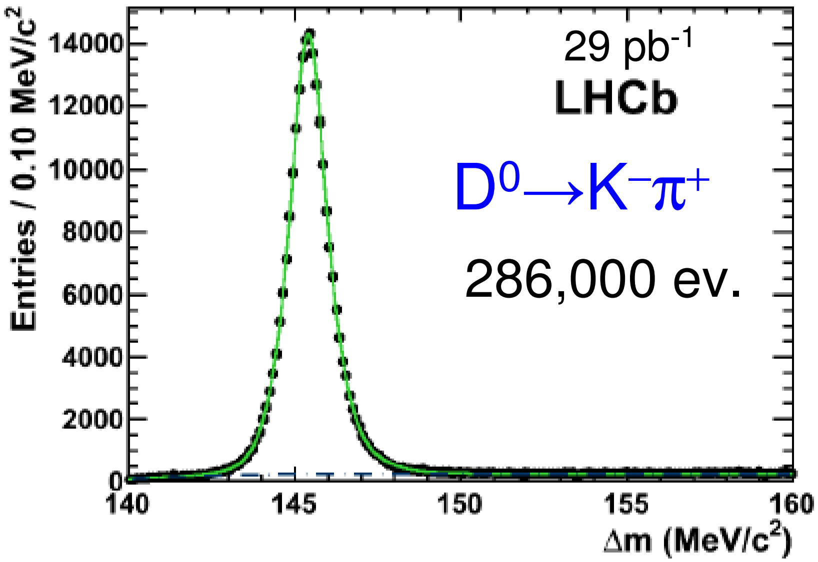
$A_\Gamma \neq 0$ is a sign of indirect or direct CPV

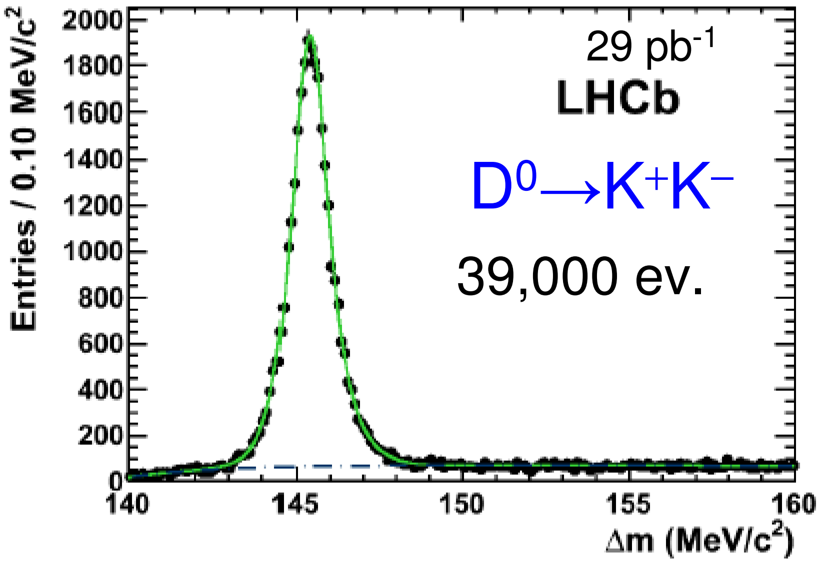
Charm mixing and CPV via effective lifetimes

arXiv:1112.4698 submitted to JHEP; 2010 data (29 pb^{-1})



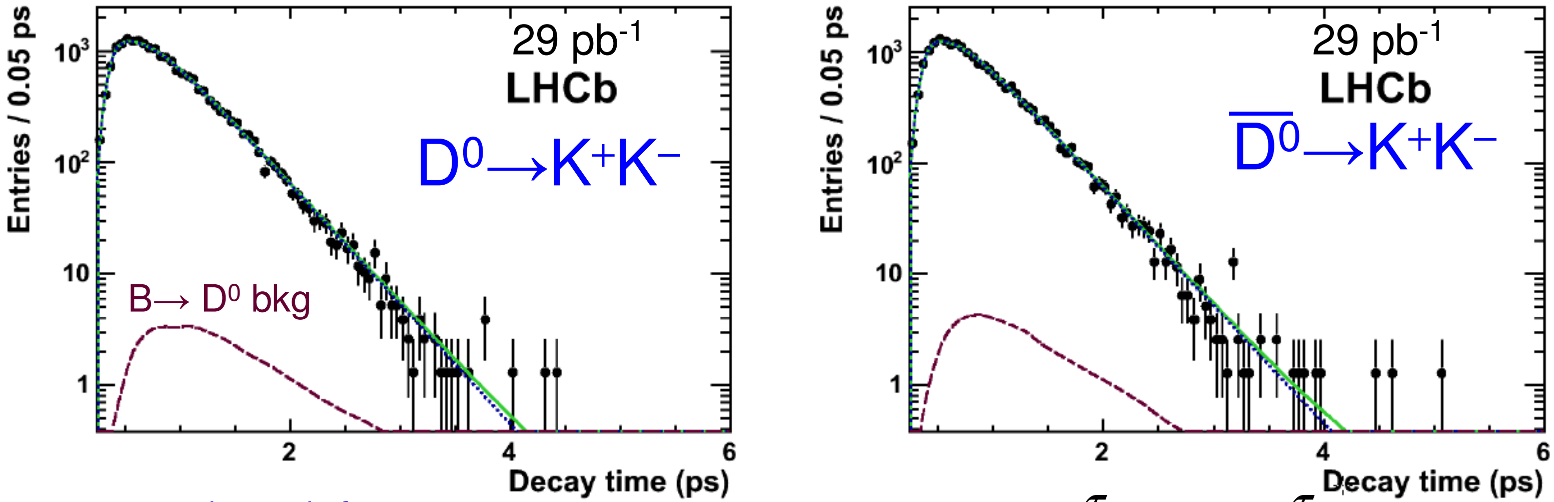
- Charge of the (strong interactions) transition π tags the D^0 flavor
- D^{*+} detection also helps the background suppression





$$\Delta m = M(D^0\pi^\pm) - m(D^0)$$

Charm mixing and CPV via effective lifetimes



$\tau_{K+\pi-}$=410.2±0.9 (stat.) fs vs 410.1±1.5 fs PDG

τ_{K+K-}=408.0±2.4 (stat.) fs

$$y_{CP} = \frac{\tau_{K\pi}}{\tau_{KK}} - 1 = (5.5 \pm 6.3 \pm 4.1) \times 10^{-3}$$

$$A_\Gamma = \frac{\tau_{\bar{D}^0 \to K^+K^-} - \tau_{D^0 \to K^+K^-}}{\tau_{\bar{D}^0 \to K^+K^-} + \tau_{D^0 \to K^+K^-}} = (-5.9 \pm 5.9 \pm 2.1) \times 10^{-3}$$

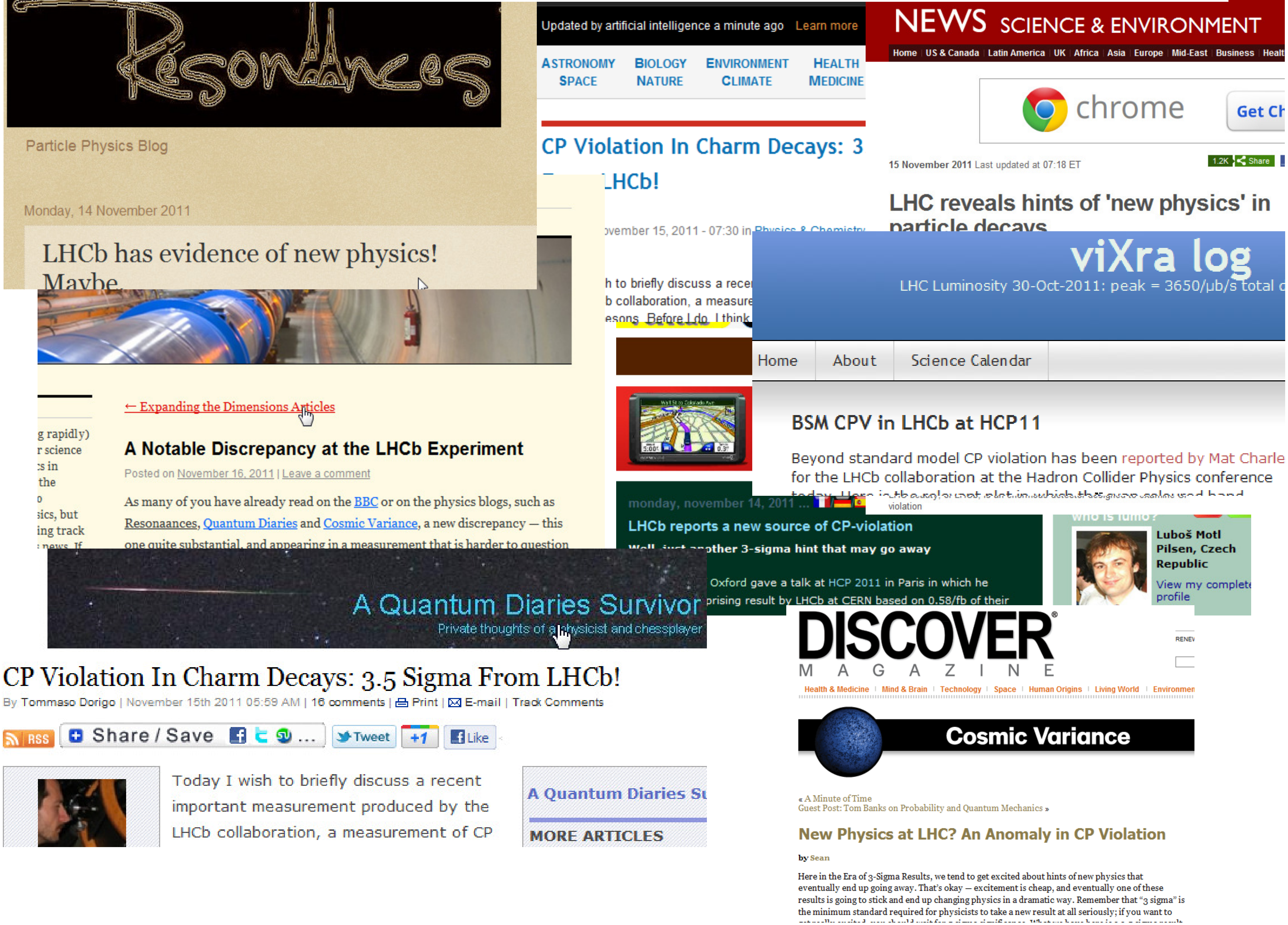
BaBar	$(11.2 \pm 2.2 \pm 1.8) \times 10^{-3}$	PRD78,01105(2008) PRD80,071103(2009)	$(2.6 \pm 3.6 \pm 0.8) \times 10^{-3}$
Belle	$(13.1 \pm 3.2 \pm 2.5) \times 10^{-3}$	PRL 98,211803(2007)	$(0.1 \pm 3.0 \pm 1.5) \times 10^{-3}$

HFAG $y = (7.5 \pm 1.2) \times 10^{-3}$

$y_{CP} \approx y$ No evidence for CPV in mixing $A_\Gamma \approx 0$

- First measurements at hadron collider.
- Not yet competitive with e$^+$e$^-$. With 2011 data (1.1 fb^{-1}) statistical errors will be 1x10^{-3}. Need to improve background systematics. Most sensitive measurements expected.
- Expected statistical errors on A_Γ with 5 fb^{-1} (upgraded LHCb 50 fb^{-1}) ~4x10^{-4} (1x10^{-4})

Direct CPV in charm decays via time integrated rates



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Beyond standard model CP violation has been reported by Mat Charle… for the LHCb collaboration at the Hadron Collider Physics conference today…

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monday, november 14, 2011 ...
LHCb reports a new source of CP-violation
Well, just another 3-sigma hint that may go away
… Oxford gave a talk at HCP 2011 in Paris in which he … prising result by LHCb at CERN based on 0.58/fb of their …
Luboš Motl
Pilsen, Czech Republic
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A Quantum Diaries Survivor
Private thoughts of a physicist and chessplayer
CP Violation In Charm Decays: 3.5 Sigma From LHCb!
By Tommaso Dorigo | November 15th 2011 05:59 AM | 16 comments | Print | E-mail | Track Comments
Today I wish to briefly discuss a recent important measurement produced by the LHCb collaboration, a measurement of CP…
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New Physics at LHC? An Anomaly in CP Violation
by Sean
Here in the Era of 3-Sigma Results, we tend to get excited about hints of new physics that eventually end up going away. That's okay — excitement is cheap, and eventually one of these results is going to stick and end up changing physics in a dramatic way. Remember that "3 sigma" is the minimum standard required for physicists to take a new result at all seriously; if you want to…

Direct CPV in charm decays via time integrated rates

LHCb 0.62 fb^{-1} LHCB-PAPER-2011-023; PRL 108, 111602 (2012)

$$\boxed{A_{CP}(f)=\frac{\Gamma_{D^0\to f}-\Gamma_{\bar{D}^0\to f}}{\Gamma_{D^0\to f}+\Gamma_{\bar{D}^0\to f}}}$$

f – CP eigenstate

Γ ~ # of events

$$\boxed{a^{dir}_{CP}(f)=\frac{|A_{D^0\to f}|^2-|A_{\bar{D}^0\to f}|^2}{|A_{D^0\to f}|^2+|A_{\bar{D}^0\to f}|^2}}\approx-\frac{1}{2}A_d$$

$$A_{CP}(f)\approx a^{dir}_{CP}(f)-A_\Gamma(f)\frac{<t>}{\tau}$$

$<t>$ - average decay time of candidates after cuts

For experimental reasons (see next) we measure:

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

$D^0\to\pi^+\pi^-$ also SCS, similar BR

In case of U-spin symmetry: $A_{CP}(K^+K^-) = -A_{CP}(\pi^+\pi^-)$

universal

assumed universal

$$a^{ind}_{CP}=-\frac{1}{2}A_m y\cos\phi+x\sin\phi$$

$$\Delta A_{CP}\approx\Delta a^{dir}_{CP}-\Delta\left(A_\Gamma\frac{<t>}{\tau}\right)$$

$$\Delta A_{CP}\approx\Delta a^{dir}_{CP}+a^{ind}_{CP}\frac{\Delta<t>}{\tau}$$

$$\frac{\Delta<t>}{\tau}=0.098\pm0.002\pm0.001$$

(LHCb specific)

$$\boxed{\Delta A_{CP}\approx\Delta a^{dir}_{CP}}$$

ΔA_{CP}

For any D^*-tagged decay $D^0 \rightarrow f$:

$$A_{RAW}(f)^* \equiv \frac{N(D^{*+} \to D^0(f)\pi^+) - N(D^{*-} \to \overline{D}^0(\bar{f})\pi^-)}{N(D^{*+} \to D^0(f)\pi^+) + N(D^{*-} \to \overline{D}^0(\bar{f})\pi^-)}$$

$$A_{RAW}(f)^* = \underbrace{\boxed{A_{CP}(f)}}_{\text{physics CP asymmetry}} + \underbrace{\boxed{A_D(f)}}_{\text{Detection asymmetry of } D^0} + \underbrace{\boxed{A_D(\pi_s)}}_{\text{Detection asymmetry of soft pion}} + \underbrace{\boxed{A_P(D^{*+})}}_{\text{Production asymmetry}}$$

For a two-body decay of a spin-0 particle to a self-conjugate final state, no D^0 detector efficiency asymmetry, i.e.

$A_D(K^-K^+) = A_D(\pi^-\pi^+) = 0$

Then:

cancel

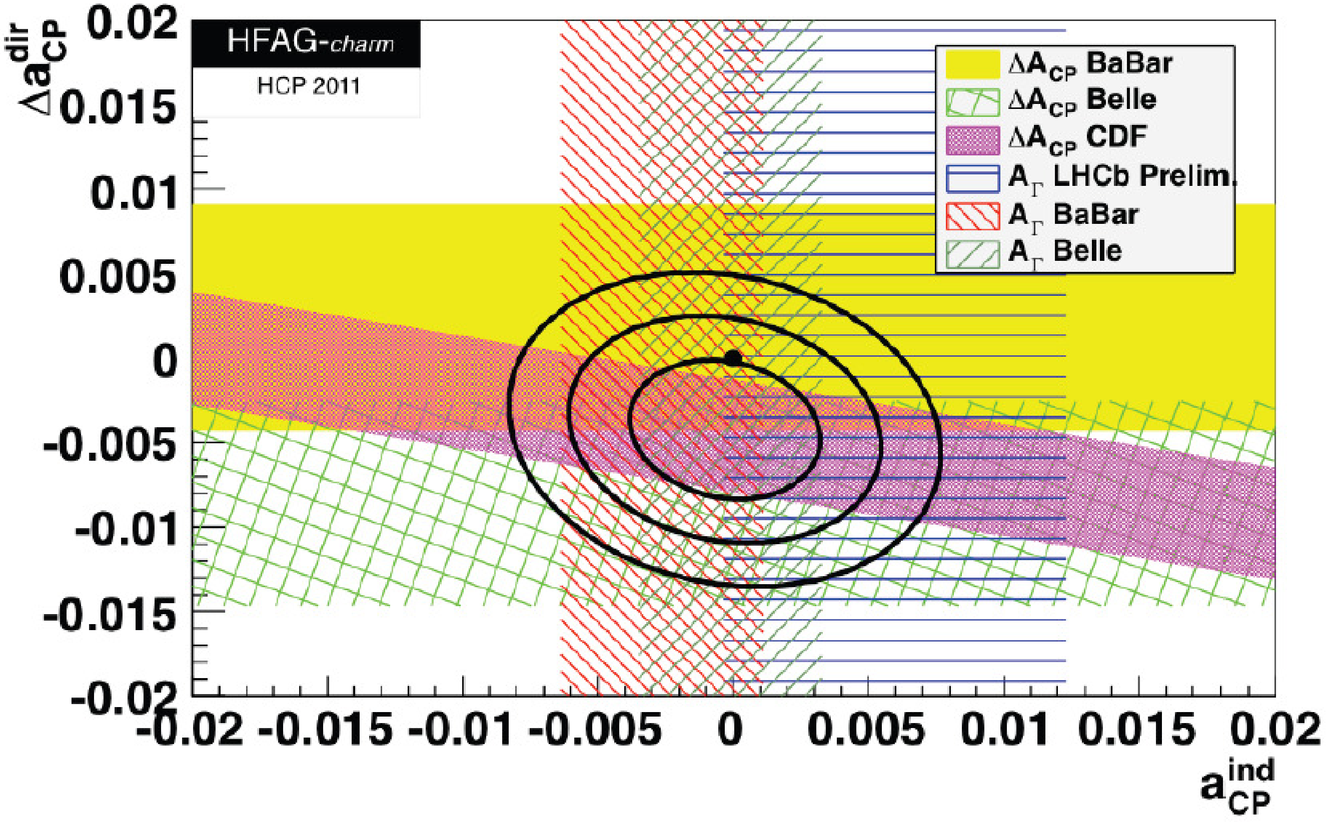
$$A_{RAW}(K^-K^+)^* = A_{CP}(K^-K^+) + A_D(\pi_s) + A_P(D^{*+})$$

$$A_{RAW}(\pi^-\pi^+)^* = A_{CP}(\pi^-\pi^+) + A_D(\pi_s) + A_P(D^{*+})$$

$$\boxed{\Rightarrow A_{RAW}(K^-K^+)^* - A_{RAW}(\pi^-\pi^+)^* = A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)}$$

Δa_{CP} previous measurements

- Different measurements are sensitive to different combinations of direct and indirect asymmetries



HFAG averages:

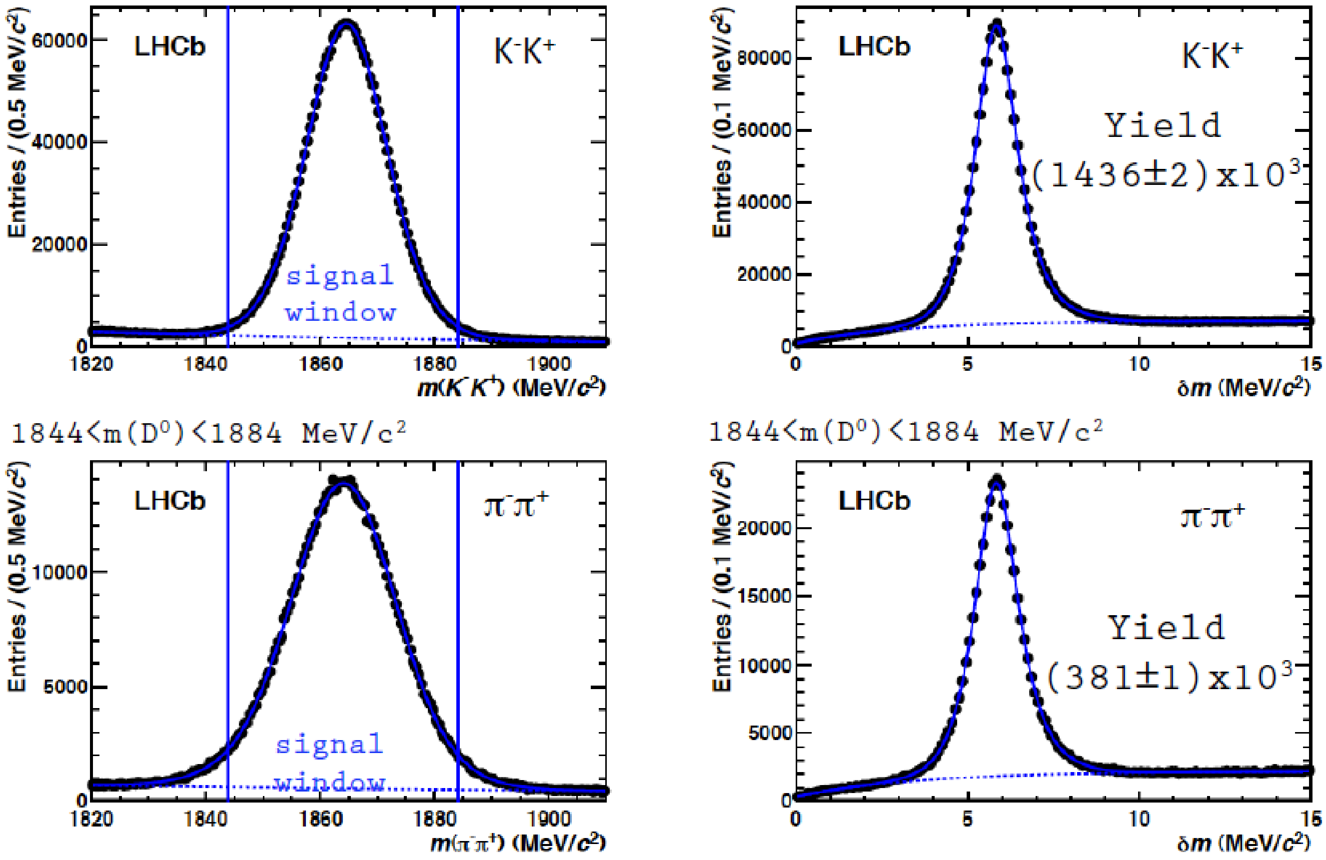
$\Delta a_{CP}^{dir}=(-0.42\pm0.27)\%$

1.6σ away from zero

$a_{CP}^{ind}=(-0.03\pm0.23)\%$

ΔA_{CP}: LHCb data

- Based on 60% of 2011 data



$$\delta m = M(D^0\pi^\pm) - m(D^0) - M(\pi^\pm)$$

ΔA_{CP}: LHCb result

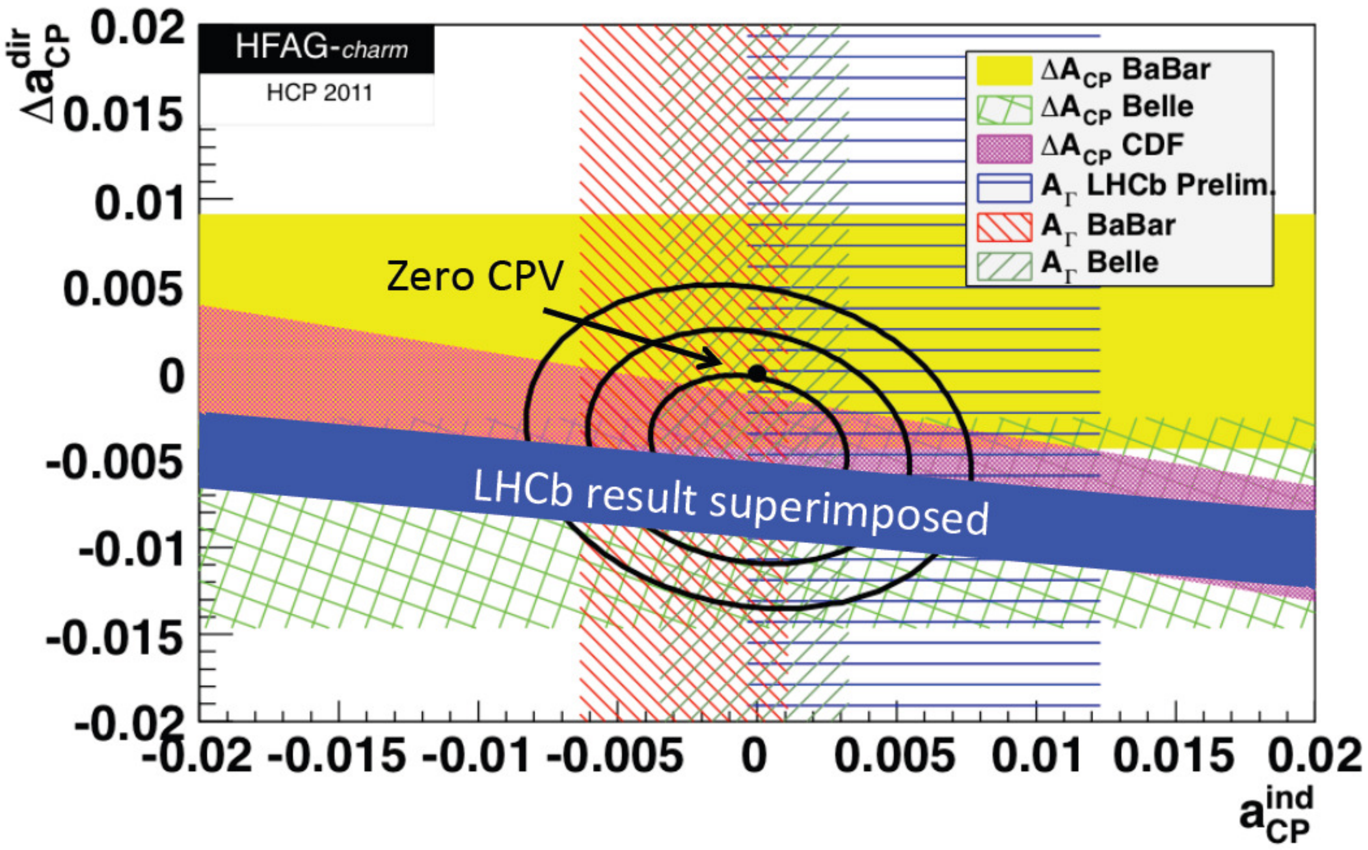
$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (0.82 \pm 0.21 \pm 0.11)\%$$

$$= a_{CP}^{dir}(K^+K^-) - a_{CP}^{dir}(\pi^+\pi^-) + (0.098 \pm 0.002 \pm 0.001) a_{CP}^{ind}$$

$$\text{SM } \Delta A_{CP} < \sim 0.1\%$$

Our result is consistent with the previous measurements (~1.1σ) but more precise

3.5σ away from no CPV



HFAG averages including LHCb:

$\Delta a_{CP}^{dir} = (-0.65 \pm 0.18)\%$

3.6σ away from zero

$a_{CP}^{ind} = (-0.02 \pm 0.23)\%$

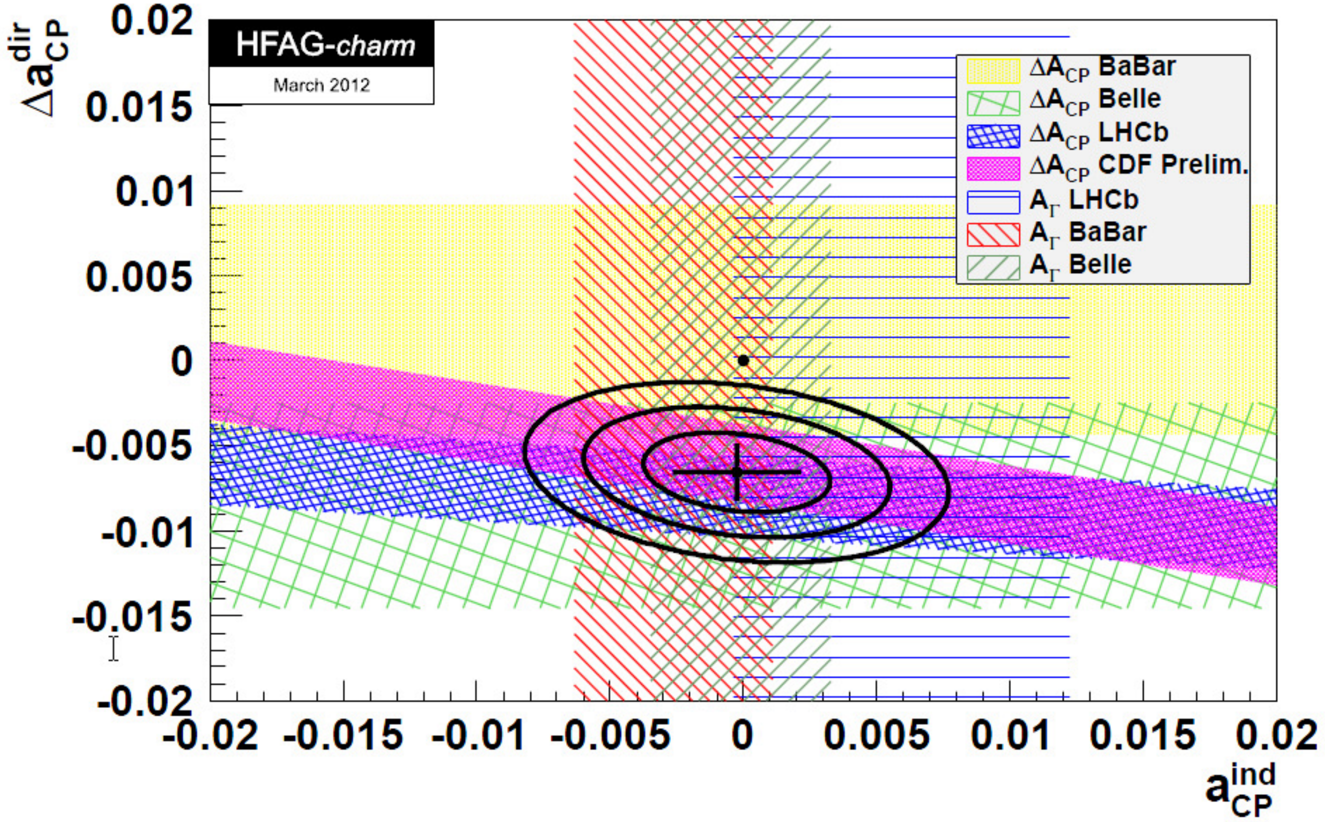
ΔA_{CP} recent developments: CDF 9.6 fb^{-1}

- CDF Public Note 10784, 2/28/12, similar analysis to LHCb

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (0.62 \pm 0.21 \pm 0.10)\%$$

$$= a_{CP}^{dir}(K^+K^-) - a_{CP}^{dir}(\pi^+\pi^-) + (0.26 \pm 0.01) a_{CP}^{ind}$$

CDF
2.7σ from no-CPV



HFAG averages including new CDF:

Δa_{CP}^{dir}=(–0.66±0.15)%

4.4σ away from zero

a_{CP}^{ind}=(–0.03±0.23)%

ΔA_{CP} recent developments: theory

- Before the LHCb results:
  - ΔA_{CP} ~O(1%) would be a sign of NP
- A large number of theoretical papers has been published since then
- Now:
  - it may be possible to accommodate such asymmetry within the SM via interference of decays mediated by tree and penguin diagrams; see e.g.
    - T.Feldman,S.Nandi,A.Soni arXiV: 1202.3795,
    - J. Brod, Y. Grossman, A.L. Kagan, J.Zupan arXiv: 1203.6659
- More measurements of direct and indirect CPV in charm decays are needed to distinguish between SM and NP scenarios

ΔA_{CP}: future prospects in LHCb

- The present LHCb result is based on 0.6 fb^{-1}; update to 1 fb^{-1} in preparation
- Further future:
  - LHCb 5 fb^{-1}: ΔA_{CP} to ±0.04%
  - LHCb upgrade 50 fb^{-1}: to ± 0.005%
- Related measurements:
  - Measure ΔA_{CP} with D^0 from B semileptonic decays
  - Look for direct CPV in other SCS modes, especially 3 body ones

LHCb upgrade – opportunity to contribute

- The collaboration is of BaBar size:
  - 800 Physicists
  - 54 Institutes
  - 15 Countries
- Upgrade work is still in early stages:
  - R&D on various technologies -2012
  - TDR in 2013, prototypes
  - Production 2013-17
  - Installation 2018

- On-going and future physics program are very broad (many topics not covered in this talk)
- Cutting edge in sensitivity in many beauty and charm topics – NP discovery potential
- Opportunity for significant scientific impact

Conclusions

- LHC is a beauty and charm factory for foreseeable future:
  - Unique reach in B_s physics. Best sensitivity in many $B_{d,u}$ measurements.
- LHCb is the first hadron collider experiment dedicated to heavy flavor physics
  - The recent results have proven that a broad beauty and charm physics program at a hadronic collider is possible with quality of results matching the e^+e^- factories.
  - Reaching new levels of sensitivity (i.e. higher energy scales) in many key measurements:
    - No indication of NP in beauty decays yet. **Plenty of room left for NP before theoretical limitations are reached. Probing smaller deviations from SM means probing high energy scales.**
    - More data to be collected in next few years
  - Channels with many neutrals, neutrino(s) and inclusive processes will remain exclusive domain of the e^+e^- factories.
- Have we just seen a glimpse of NP in charm decays?
  - More data and more measurements in charm sector soon
- Physics reach limited by the detector capabilities not the collider:
  - LHCb upgrade in 2018**.** Opportunity to get involved.