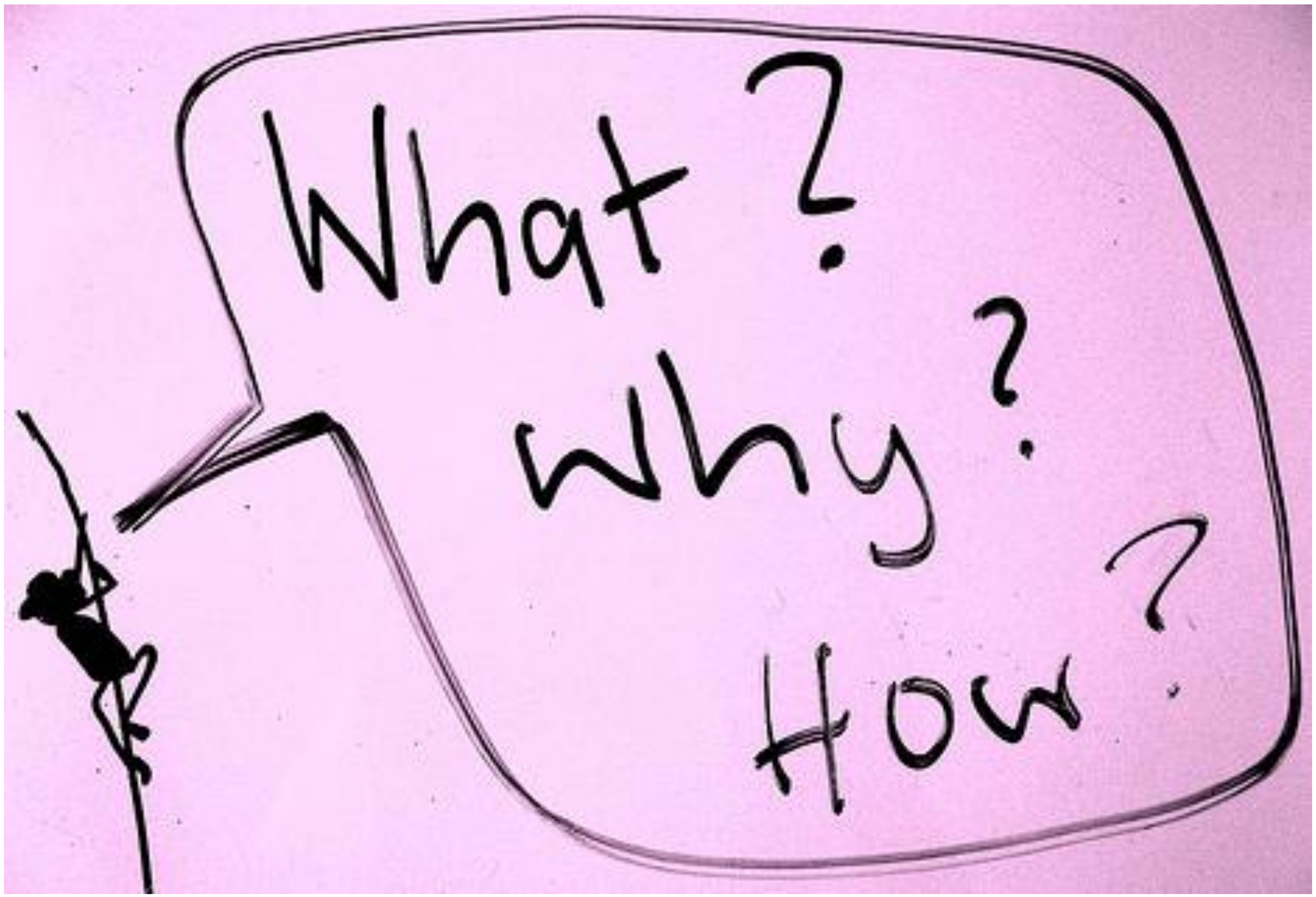
Heavy Flavour Physics at the LHC

Niels Tuning (Nikhef)
23 July 2012

On behalf of the LHCb collaboration
including results from ATLAS and CMS

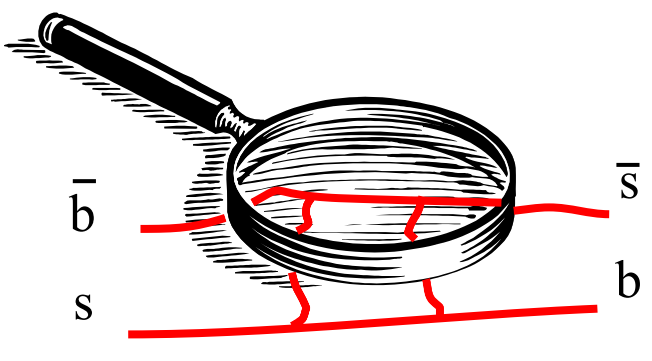
Why Flavour Physics??



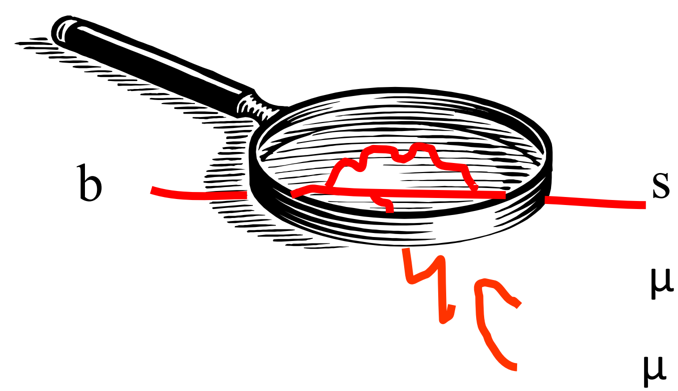
Motivation 1: New Physics in loop diagrams?

- Precision measurements
- Find deviations from the Standard Model
- Sensitive to heavy particles in loop diagrams

"Box" diagram: ΔB=2



"Penguin" diagram: ΔB=1



Flavour physics for discoveries

$K^0 \to \mu\mu$ pointed to the **charm** quark:

GIM, Phys.Rev.D2,1285,1970

Weak Interactions with Lepton-Hadron Symmetry*

S. L. Glashow, J. Iliopoulos, and L. Maiani†
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139
(Received 5 March 1970)

We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Milis theory is discussed.

• • •

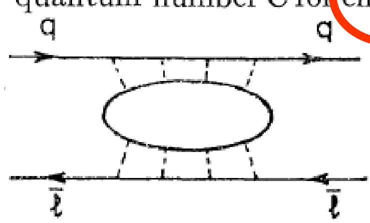
splitting, beginning at order $G(G\Lambda^2)$, as well as contributions to such unobserved decay modes as $K_2 \to \mu^+ + \mu^-$, $K^+ \to \pi^+ + l + \bar{l}$, etc., involving neutral lepton

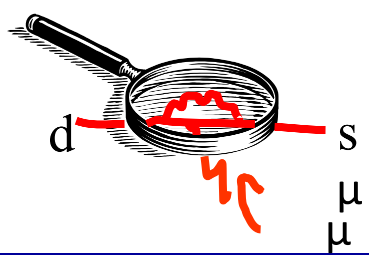
• • •

We wish to propose a simple model in which the divergences are properly ordered. Our model is founded in a quark model, but one involving four, not three, fundamental fermions; the weak interactions are modi-

• • •

new quantum number $\mathcal{C}$ for charm.





B^0 mixing pointed to heavy **top** quark:

ARGUS Coll, Phys.Lett.B192:245,1987

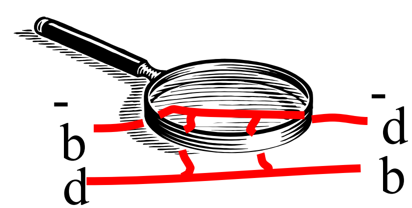
DESY 87-029
April 1987

OBSERVATION OF B^0-$\bar{B}^0$ MIXING

The ARGUS Collaboration

In summary, the combined evidence of the investigation of B^0 meson pairs, lepton pairs and B^0 meson-lepton events on the $\Upsilon(4S)$ leads to the conclusion that B^0-$\bar{B}^0$ mixing has been observed and is substantial.

Parameters	Comments
$r > 0.09$ 90%CL	This experiment
$x > 0.44$	This experiment
$B^{\frac{1}{2}} f_B \approx f_\pi < 160$ MeV	B meson (≈ pion) decay constant
$m_b < 5\mathrm{GeV}/c^2$	b-quark mass
$\tau_b < 1.4 \cdot 10^{-12}$s	B meson lifetime
$\lvert V_{td}\rvert < 0.018$	Kobayashi-Maskawa matrix element
$\eta_{QCD} < 0.86$	QCD correction factor [17]
$m_t > 50\mathrm{GeV}/c^2$	t quark mass



Motivation 2: at the heart of the SM

$$\mathcal{L}_{SM} = \mathcal{L}_{kinetic} + \mathcal{L}_{Higgs} + \mathcal{L}_{Yukawa}$$

$$i\bar{\psi}(D^{\mu}\gamma_{\mu})\psi$$

$$(D_{\mu}\phi)^{\dagger}(D^{\mu}\phi) - \mu^2\phi^{\dagger}\phi - \lambda(\phi^{\dagger}\phi)^2$$

$$Y_{ij}\overline{\psi_{Li}}\,\phi\,\psi_{Rj}$$

Charged current:
flavour diagonal

$$\frac{g}{\sqrt{2}}\overline{u_{iL}^{I}}\gamma_{\mu}W^{-\mu}d_{iL}^{I}$$

Yukawa couplings:
mix between generations

$$Y_{ij}^{d}\overline{Q_{Li}^{I}}\,\phi\,d_{Rj}^{I} + Y_{ij}^{u}\overline{Q_{Li}^{I}}\,\tilde{\phi}\,u_{Rj}^{I}$$

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Diagonalize Yukawa matrix:

Off diagonal in CC — Mass terms

$$\begin{aligned} u_i^I &= u_j \\ d_i^I &= V_{CKM} d_j \end{aligned}$$

$$\frac{g}{\sqrt{2}} \overline{u_{iL}} (V_L^u V_L^{d\dagger})_{ij} \gamma_\mu W^{-\mu} d_{iL}$$

$$\overline{d_{Li}} \, (M_{ij}^d)_{diag} \, d_{Rj} + \overline{u_{Li}} \, (M_{ij}^u)_{diag} \, u_{Rj}$$

$$V_{CKM} = (V_L^u V_L^{d\dagger})_{ij}$$

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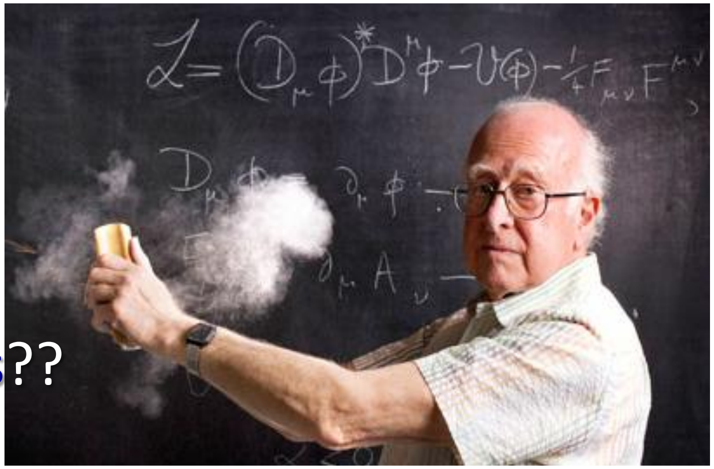
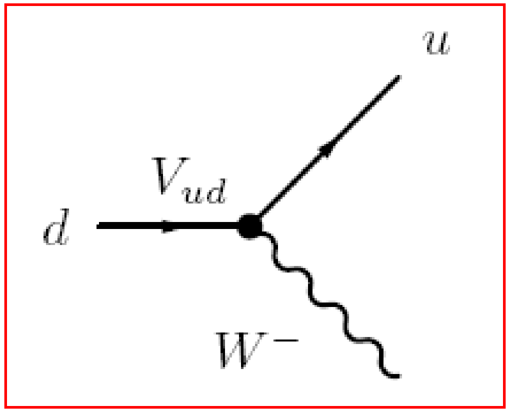


- Flavour physics closely connected to Higgs??

Motivation 3: CKM magnitude mysterious



CKM matrix:

- Coupling strength of charged current
- Completely different hierarchy !

$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = \begin{bmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{bmatrix}\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix} \quad \text{vs} \quad \begin{bmatrix}|d'\rangle\\ |s'\rangle\\ |b'\rangle\end{bmatrix} = \begin{bmatrix}V_{ud} & V_{us} & V_{ub}\\ V_{cd} & V_{cs} & V_{cb}\\ V_{td} & V_{ts} & V_{tb}\end{bmatrix}\begin{bmatrix}|d\rangle\\ |s\rangle\\ |b\rangle\end{bmatrix}.$$

flavour → mass ; flavour → mass

$$U_{MNSP} \approx \begin{pmatrix} 0.85 & 0.53 & 0\\ -0.37 & 0.60 & 0.71\\ -0.37 & 0.60 & -0.71\end{pmatrix}$$

$$V_{CKM} = \begin{pmatrix} 0.97428 & 0.2253 & 0.00347\\ 0.2252 & 0.97345 & 0.0410\\ 0.00862 & 0.0403 & 0.999152\end{pmatrix}$$

Motivation 3: CKM magnitude mysterious

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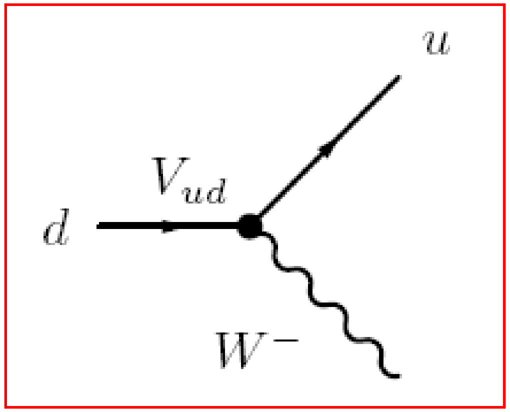

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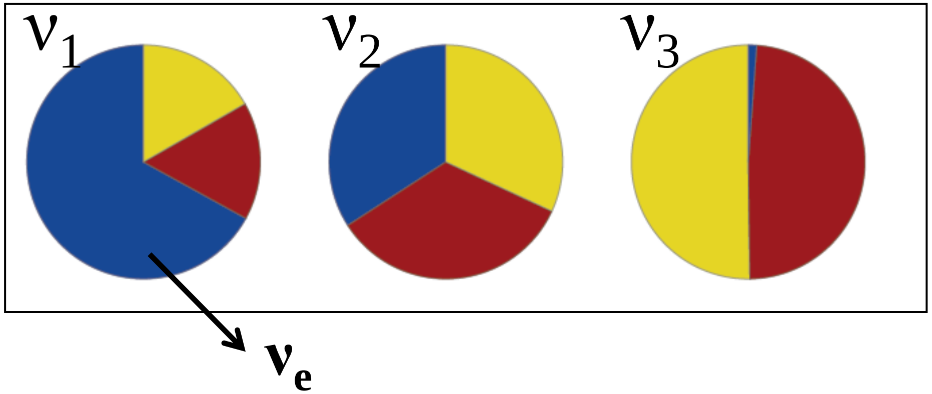
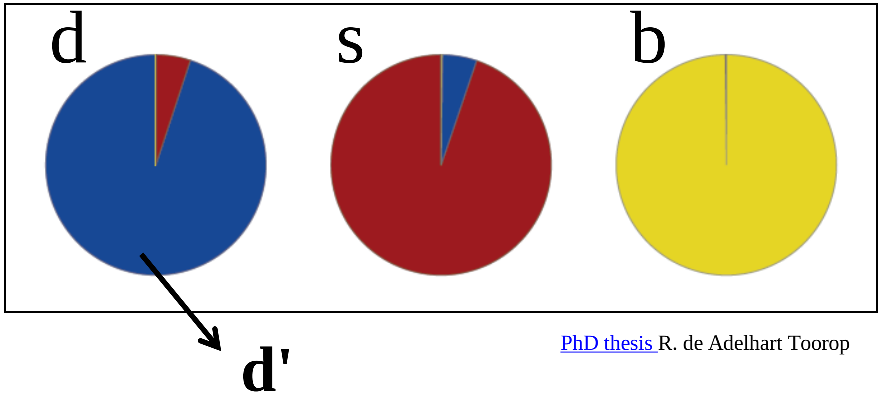
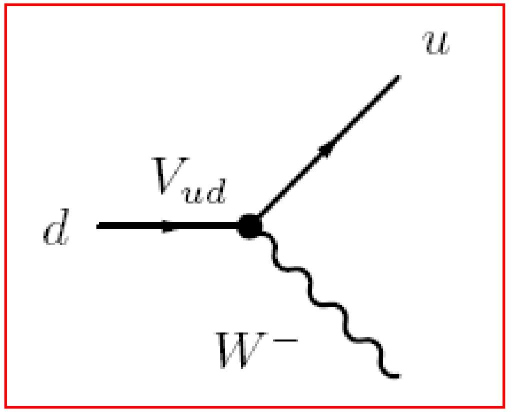
flavour — mass — flavour — mass





PhD thesis R. de Adelhart Toorop

CKM matrix: phases



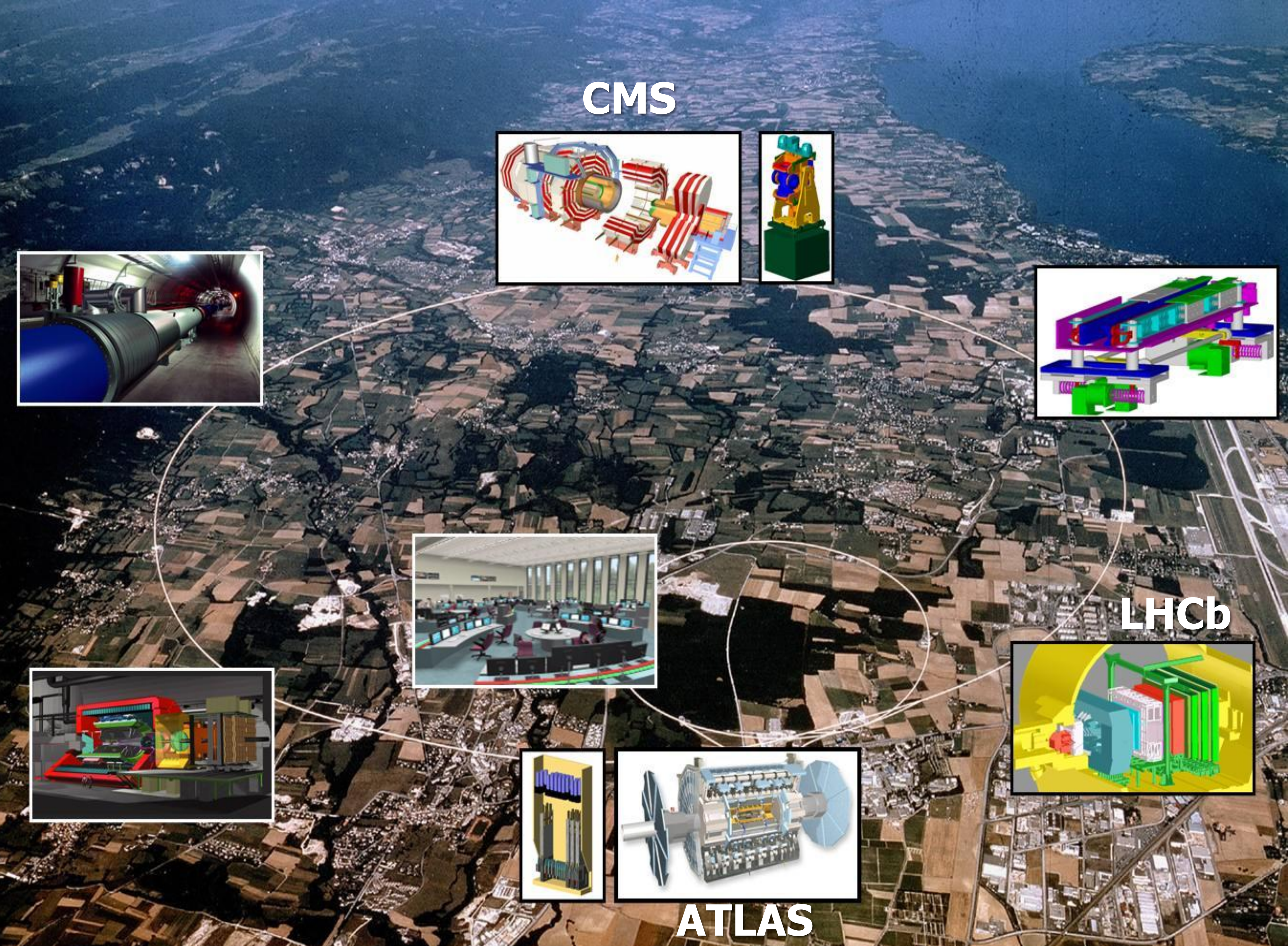
CKM matrix:

- Coupling strength of charged current
- Complex matrix: phases!

$$V_{CKM,\text{Wolfenstein}} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

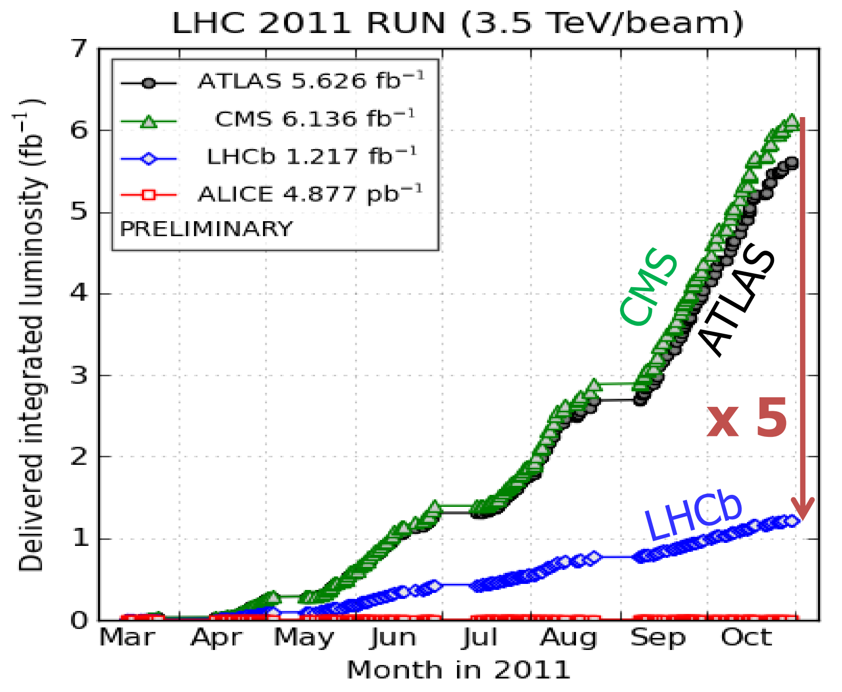
$$\frac{g}{\sqrt{2}}\overline{u_{iL}}(V_L^u V_L^{d\dagger})_{ij}\gamma_\mu W^{-\mu} d_{iL}$$

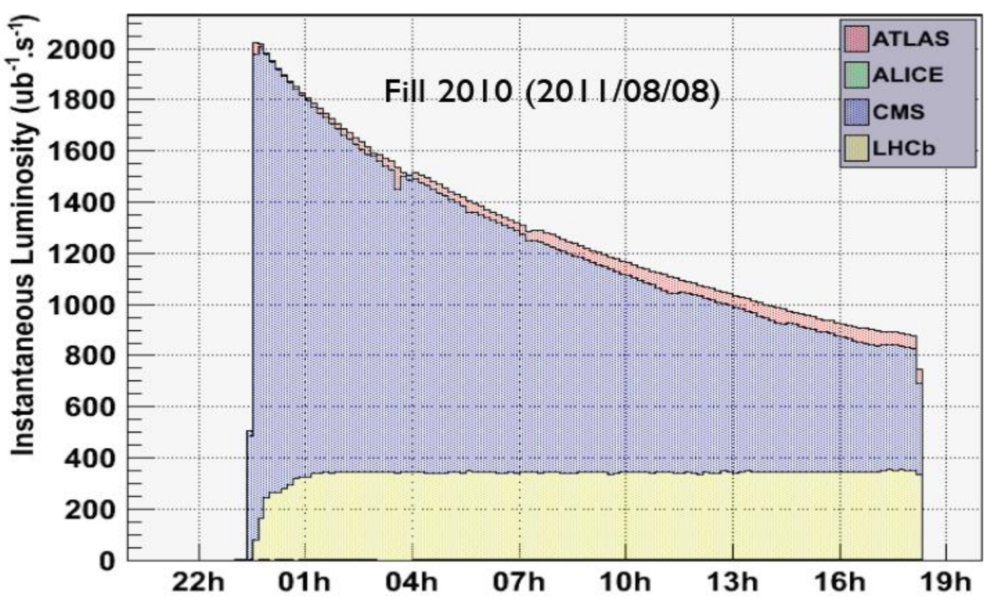
$$V_{CKM} = (V_L^u V_L^{d\dagger})_{ij}$$


CMS
LHCb
ATLAS

LHC

- LHC and experiments show excellent performance
- LHCb collected 1 fb^{-1} in 2011
- Aim for 2.2 fb^{-1} in 2012 (now 0.7 fb^{-1})
- 10^{12} $b\bar{b}$-pairs produced!



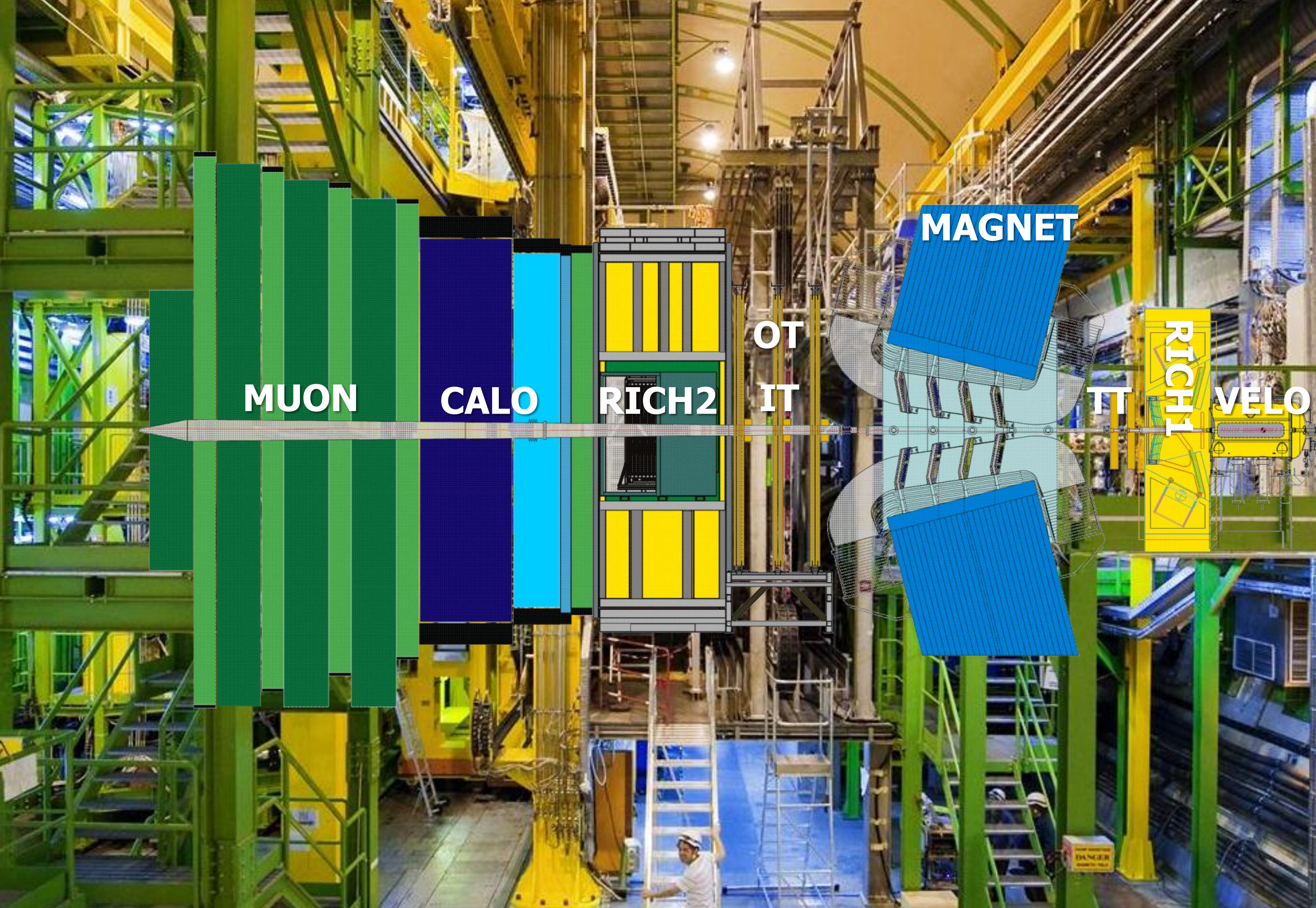


- Optimal use of LHC beam:
  - "Lumi levelling" at 4 x 10^{32}
    Design was 2 x 10^{32} with half the #bunches
  - Max. luminosity for entire fill
    With maximum detector occupancy

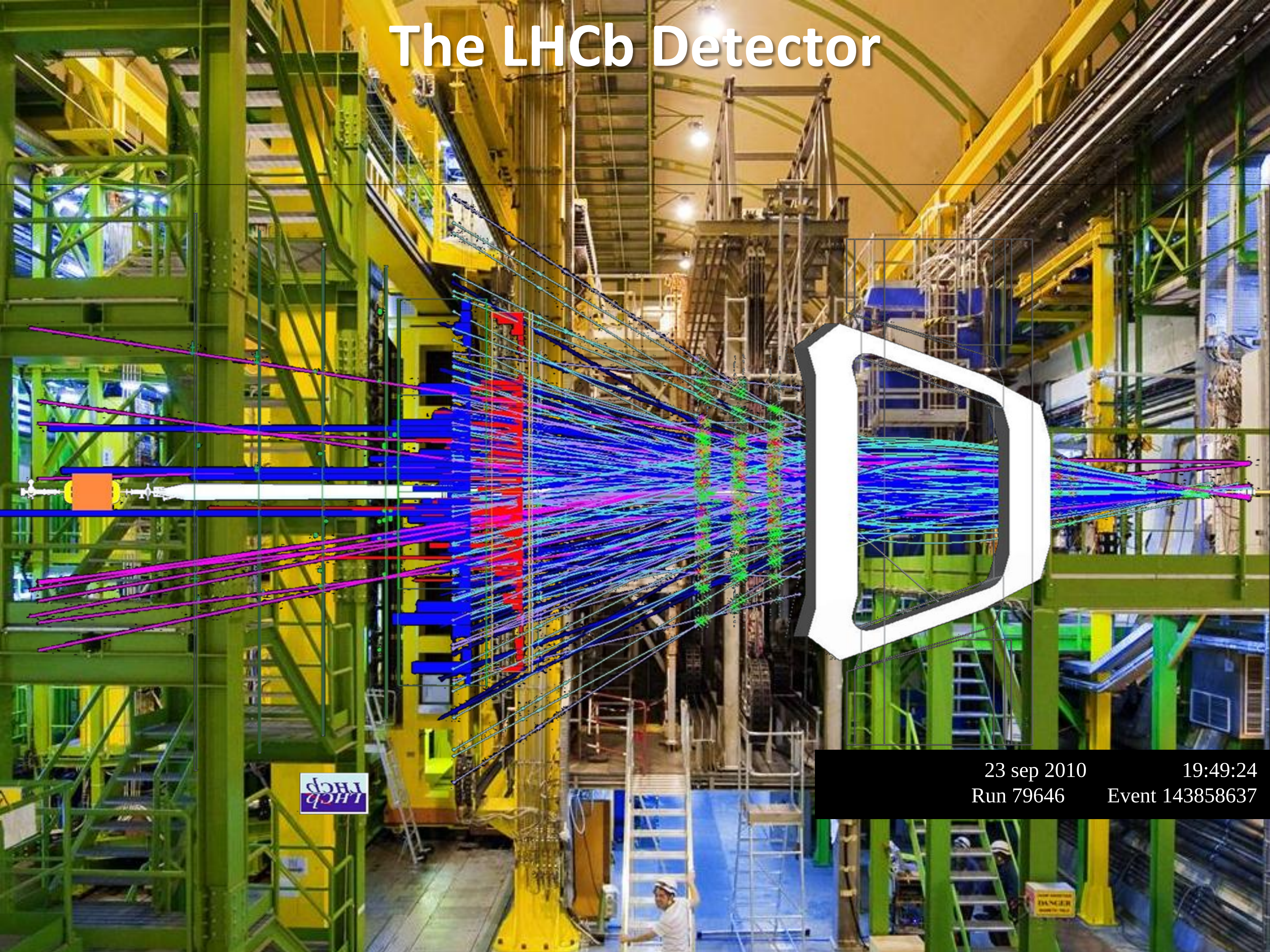
Disclaimer:
Most results shown, from LHCb

The LHCb Detector

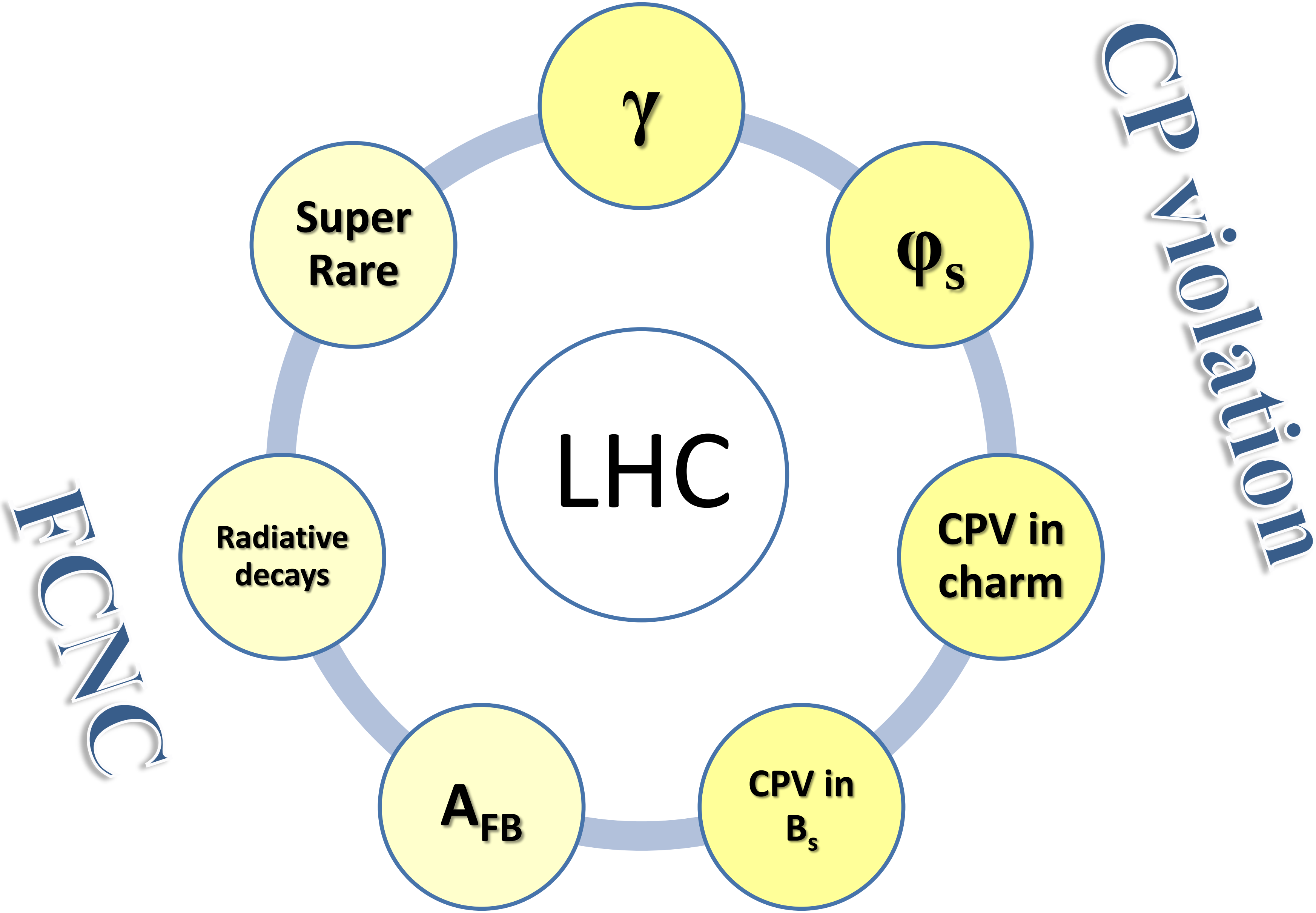
The LHCb Detector

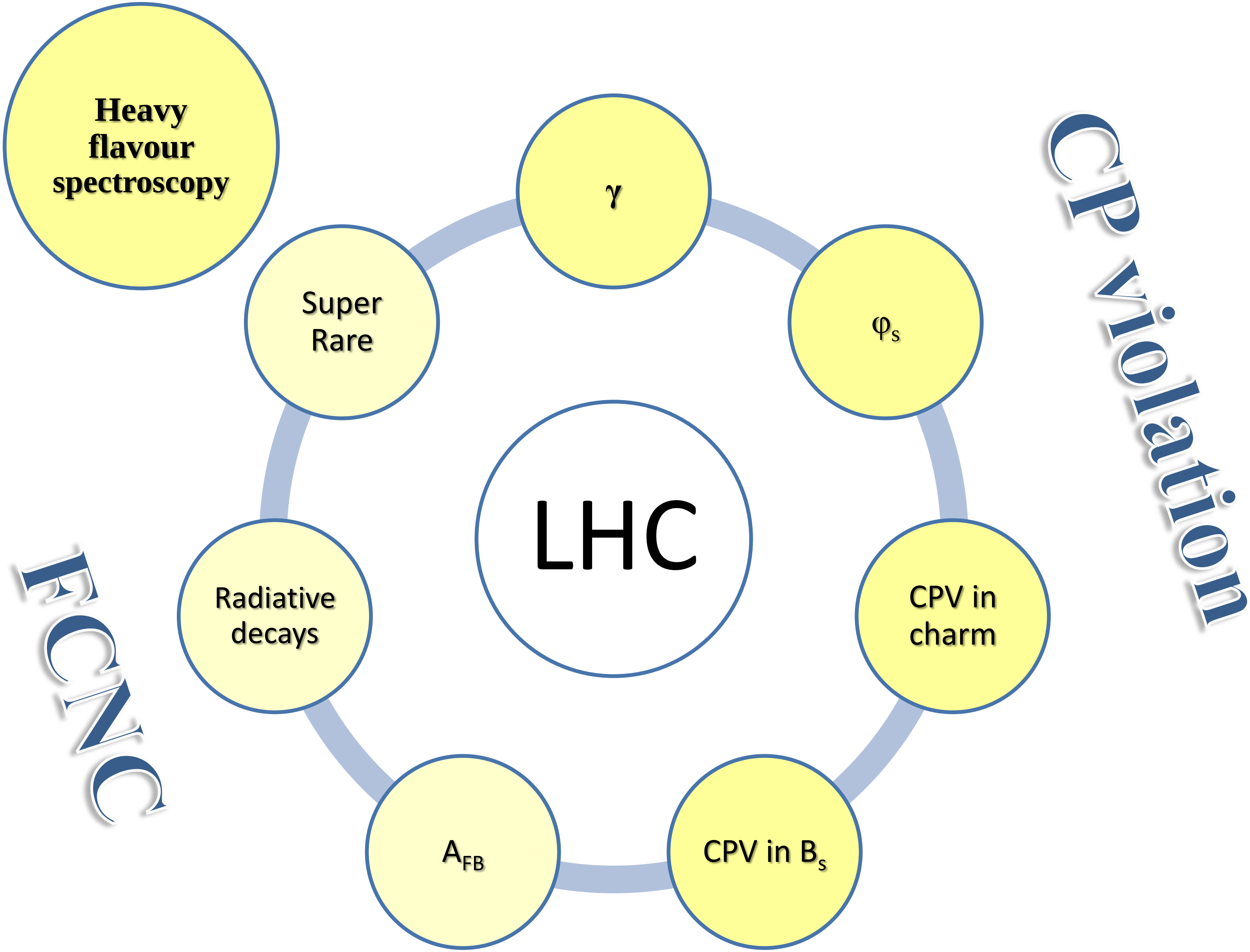


The LHCb Detector

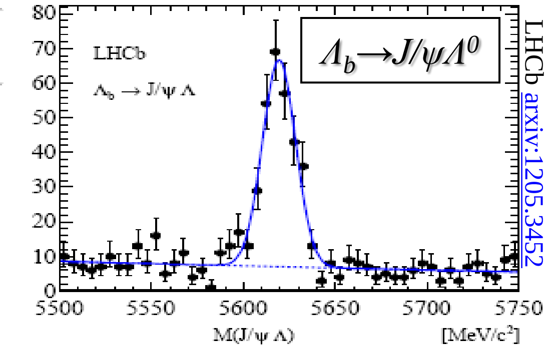


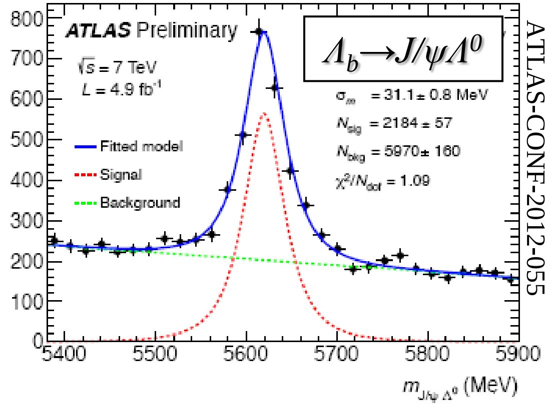
Outline

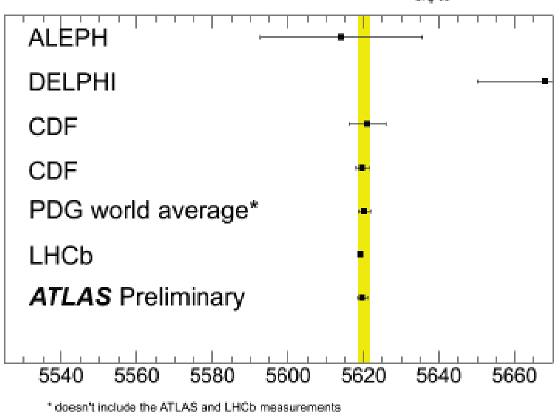

γ
φ_s
CPV in charm
CPV in B_s
A_{FB}
Radiative decays
Super Rare
LHC
CP violation
FCNC


Heavy flavour spectroscopy
γ
Super Rare
φ_s
LHC
Radiative decays
CPV in charm
A_{FB}
CPV in B_s
FCNC
CP violation

Heavy Flavour Spectroscopy







LHCb:

$m(\Xi_b^-)$=5796.5±1.2±1.2MeV

$m(\Omega_b^-)$=6050.3±4.5±2.2MeV

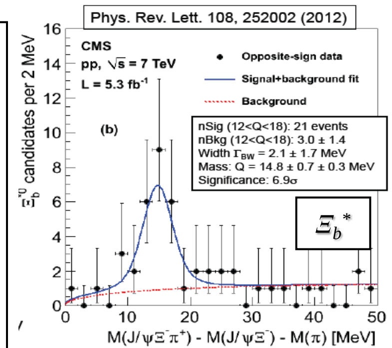
$m(\Xi_b^0)$=5802.0±5.5±1.7MeV

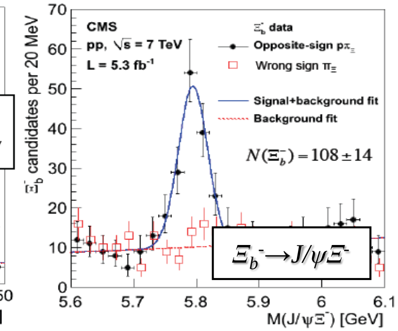
$m(\Lambda_b^0{}_{(5912)})$=5911.95±0.7MeV

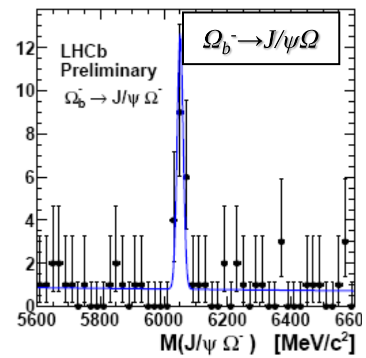
$m(\Lambda_b^0{}_{(5920)})$=5919.76±0.7MeV

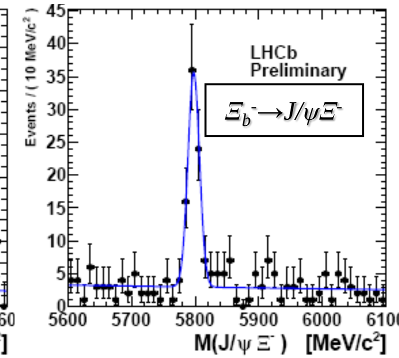
CMS:

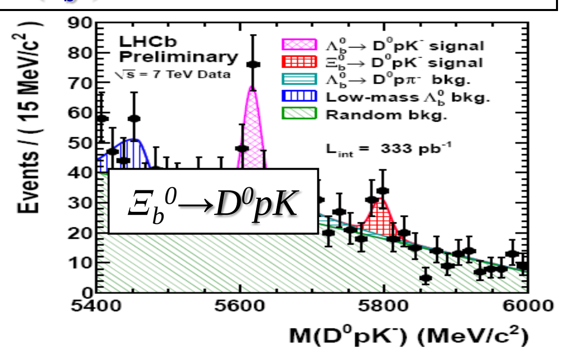
$m(\Xi_b^*)$=5945.0±0.7±0.3±2.7MeV

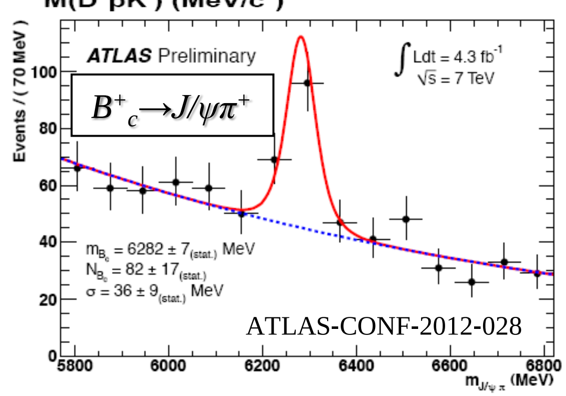


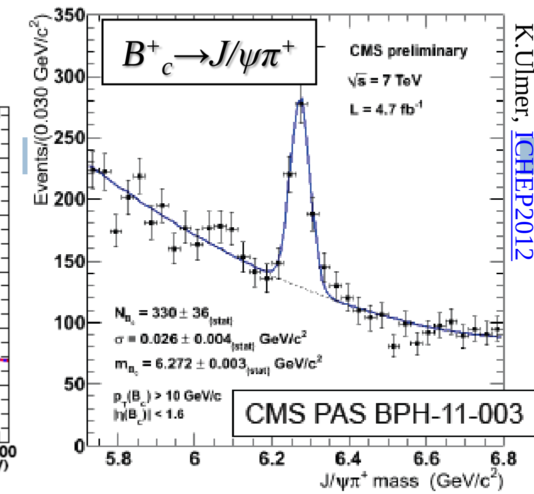




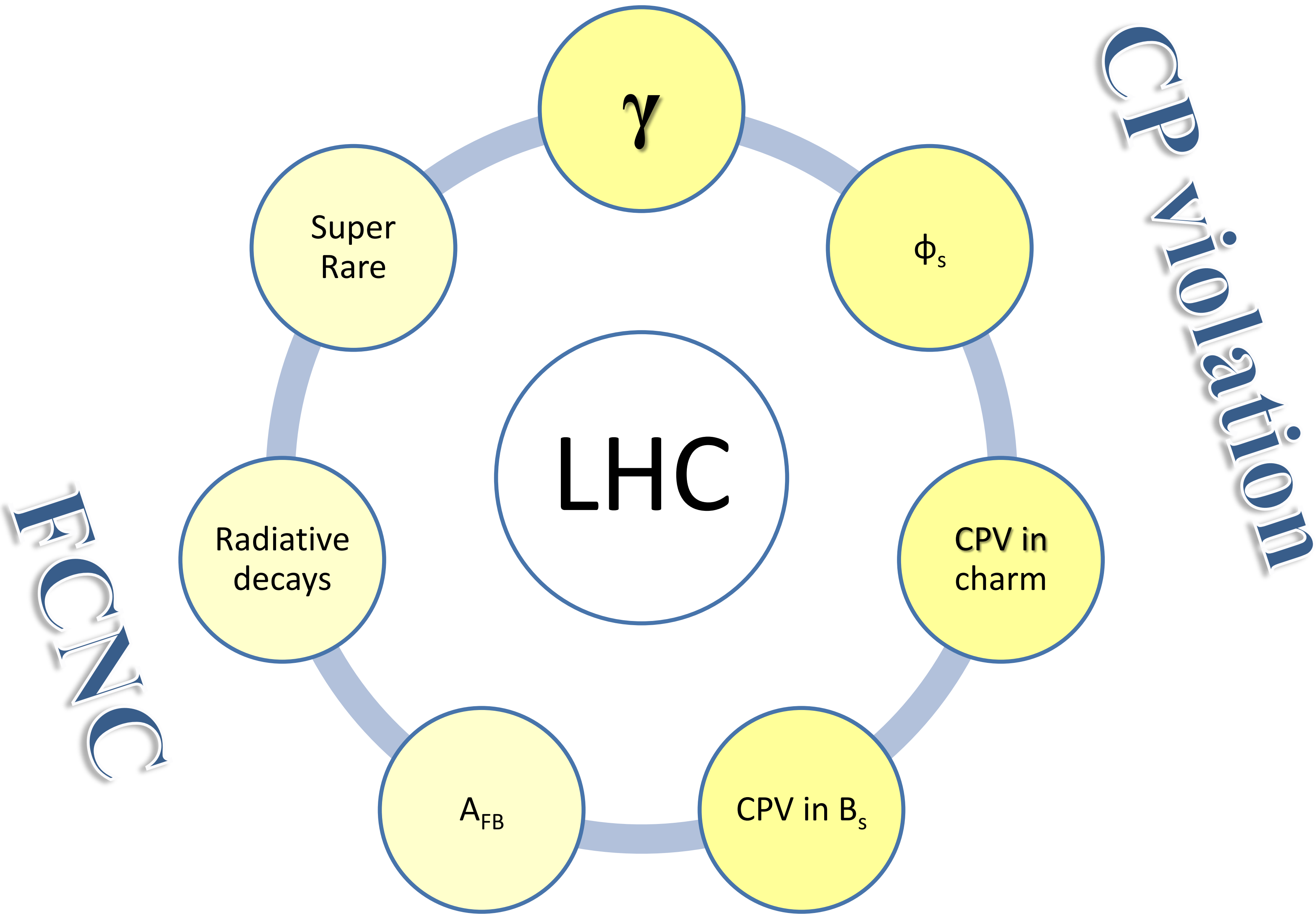




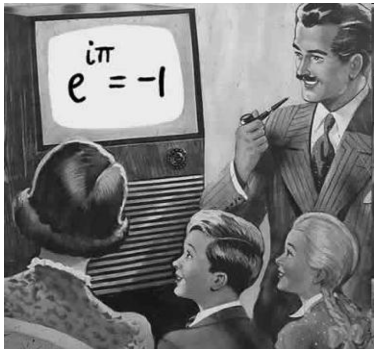




K.Ulmer, ICHEP2012


γ
φs
CPV in charm
CPV in Bs
AFB
Radiative decays
Super Rare
LHC
CP violation
FCNC

How to measure a phase??

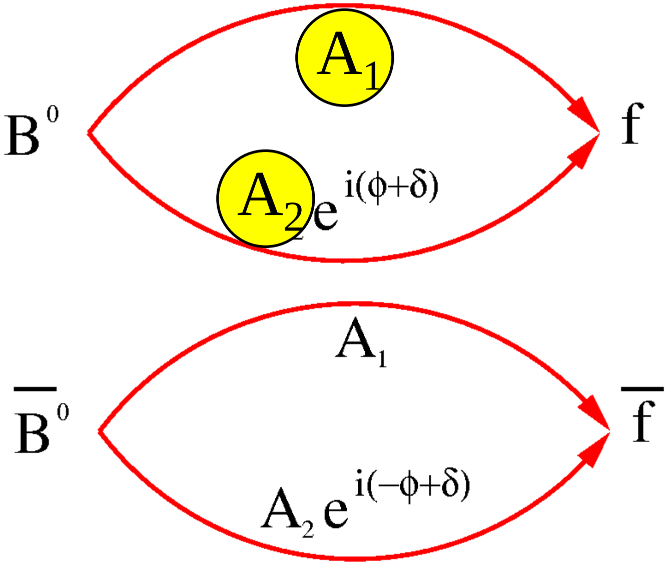


$$\Gamma(B \rightarrow f) = |A_1 + A_2 e^{i(\varphi+\delta)}|^2$$

$$\Gamma(\bar{B} \rightarrow \bar{f}) = |A_1 + A_2 e^{i(-\varphi+\delta)}|^2$$

Necessary ingredients for CP violation:

1) Two (interfering) amplitudes
2) Phase difference between amplitudes
   - one CP conserving phase ('strong' phase)
   - one CP violating phase ('weak' phase)



$$V_{CKM,\text{Wolfenstein}} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

γ

$$\gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$

1) $B^- \rightarrow \overset{(-)}{D}{}^0 K^-$ (Time integrated)
2) $B_s^0 \rightarrow D_s^{\pm} K^{+-}$ (Time dependent)

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

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γ (GLW)

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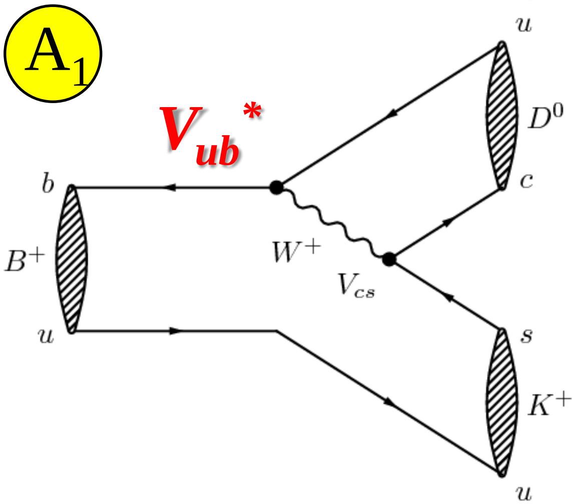
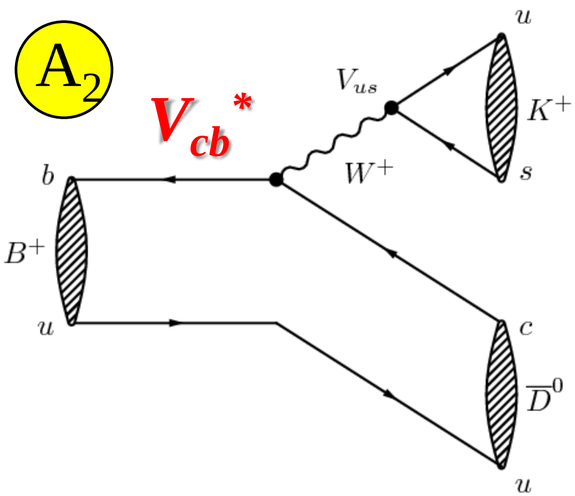




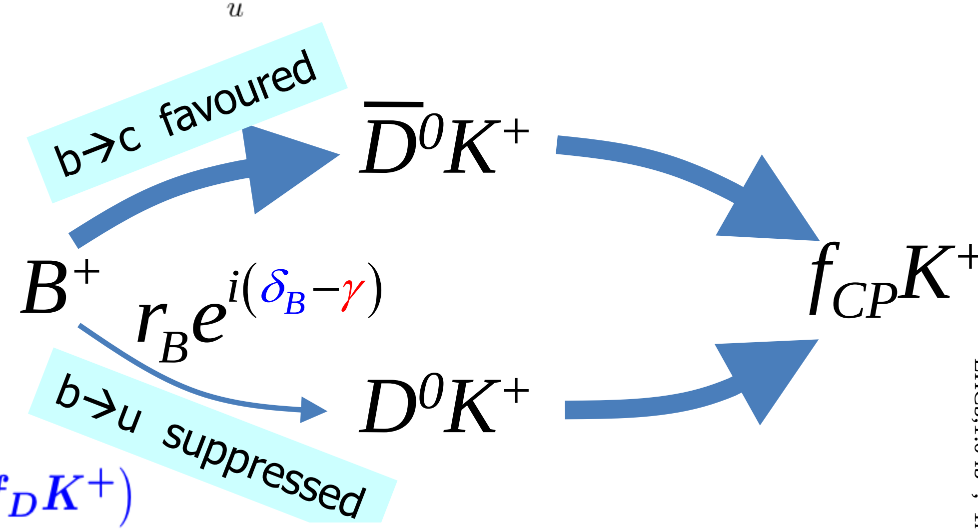
$B^- \rightarrow \overset{(-)}{D}{}^0 K^-$

- Relative phase: γ

Gronau, London, Wyler, [PL B265 (1991) 172.]

GLW:

CP eigenstate: $D^0 \rightarrow K^+K^-(\pi\pi)$



$$A_{CP+} = \frac{\Gamma\left(B^- \rightarrow f_D K^-\right) - \Gamma\left(B^+ \rightarrow f_D K^+\right)}{\Gamma\left(B^- \rightarrow f_D K^-\right) + \Gamma\left(B^+ \rightarrow f_D K^+\right)}$$

$$A_{CP+} \; = \; < A_K^{KK}, A_K^{\pi\pi} >$$

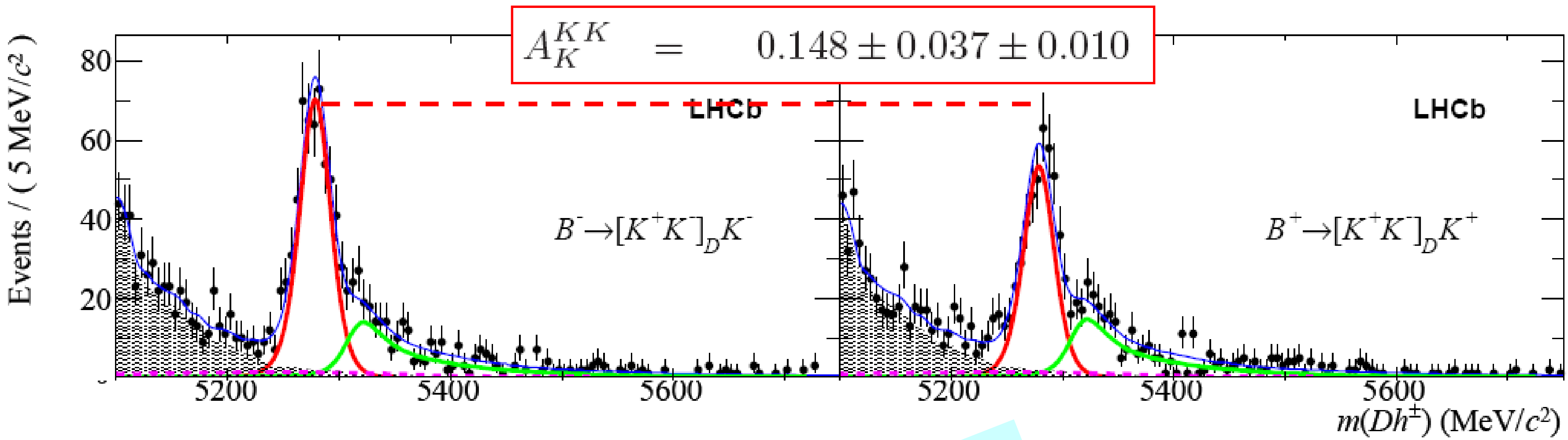
$$R_{CP+} = \frac{\Gamma\left(B^- \rightarrow f_D K^-\right) + \Gamma\left(B^+ \rightarrow f_D K^+\right)}{\Gamma\left(B^- \rightarrow D^0 K^+\right)}$$

$$R_{CP+} \; \approx \; < R_{K/\pi}^{KK}, R_{K/\pi}^{\pi\pi} > / R_{K/\pi}^{K\pi}$$

LHCb,1.0 fb^{-1}, 3h [LHCb-CONF-2012-021]
LHCb,1.0 fb^{-1}, 1h [PL B712 (2012) 203]

γ (GLW)

$$A_K^{KK} = 0.148 \pm 0.037 \pm 0.010$$



GLW:

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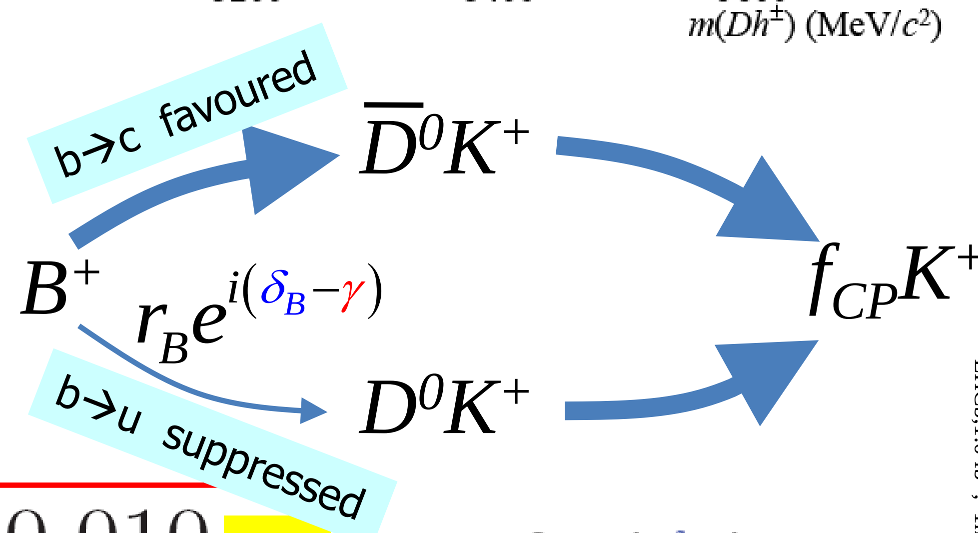


$$A_{CP+} = 0.145 \pm 0.032 \pm 0.010$$ **4.5σ**

$$R_{CP+} = 1.007 \pm 0.038 \pm 0.012$$

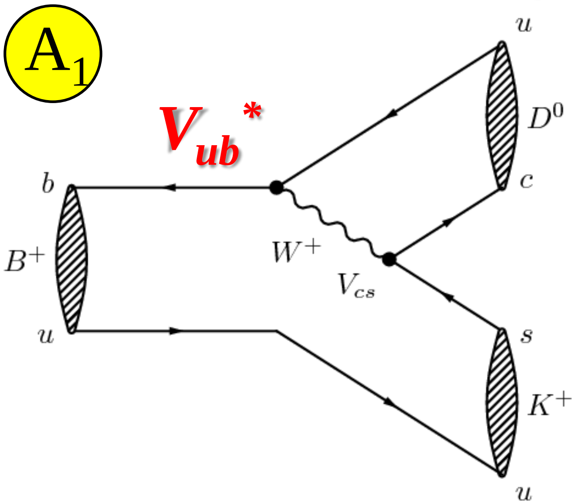
$$A_{CP+} = \frac{2\kappa r_B \sin\delta_B \sin\gamma}{R_{CP+}}$$

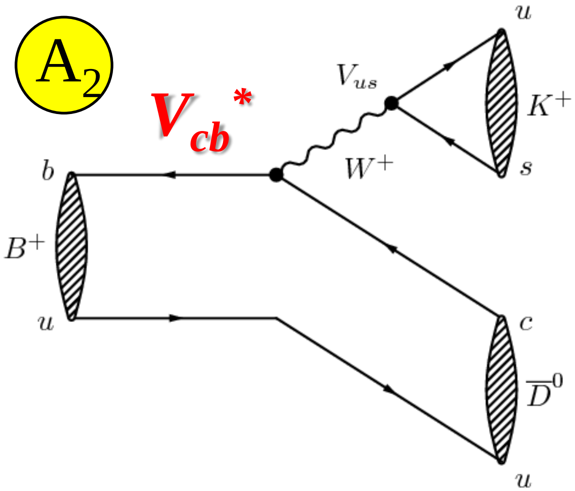
$$R_{CP+} = 1 + r_B{}^2 + 2\kappa r_B \cos\delta_B \cos\gamma$$

LHCb,1.0 fb^{-1}, 3h LHCb-CONF-2012-021
LHCb,1.0 fb^{-1}, 1h PL B712 (2012) 203

γ (ADS)

$$\gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$





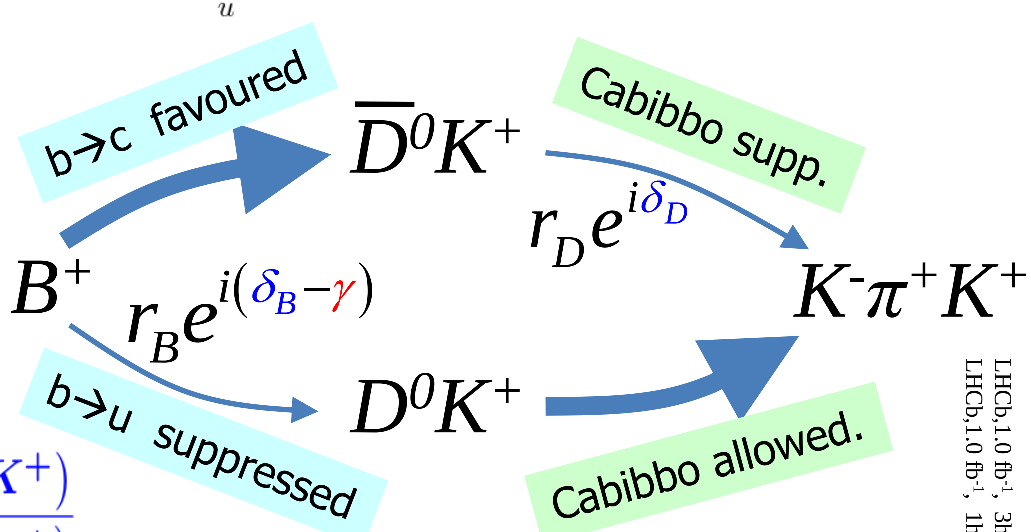
$B^- \to \overset{(-)}{D}{}^0 K^-$

- Relative phase: γ

Atwood, Dunietz, Soni , PRL 78 (1997) 3257

ADS:

B or D Cabibbo favoured: $D^0 \to K^+\pi^-$



$$A_{ADS} = \frac{\Gamma\left(B^- \to f_D K^-\right) - \Gamma\left(B^+ \to \overline{f_D} K^+\right)}{\Gamma\left(B^- \to f_D K^-\right) + \Gamma\left(B^+ \to \overline{f_D} K^+\right)}$$

"Difference in suppression"

$$R_{ADS} = \frac{\Gamma\left(B^- \to f_D K^-\right) + \Gamma\left(B^+ \to \overline{f_D} K^+\right)}{\Gamma\left(B^- \to \overline{f_D} K^-\right) + \Gamma\left(B^+ \to f_D K^+\right)}$$

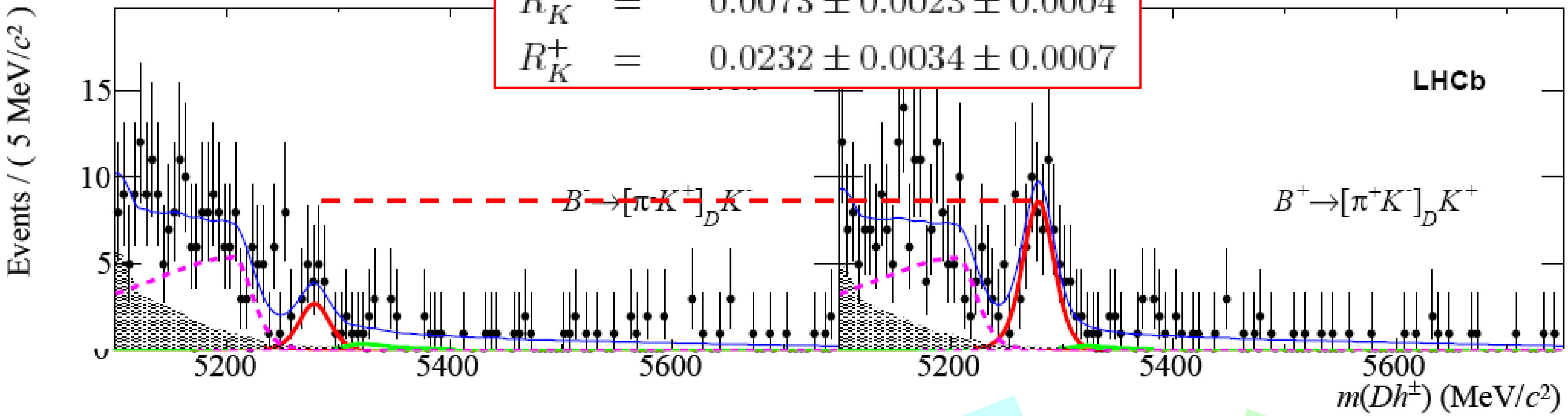
"Average suppression"

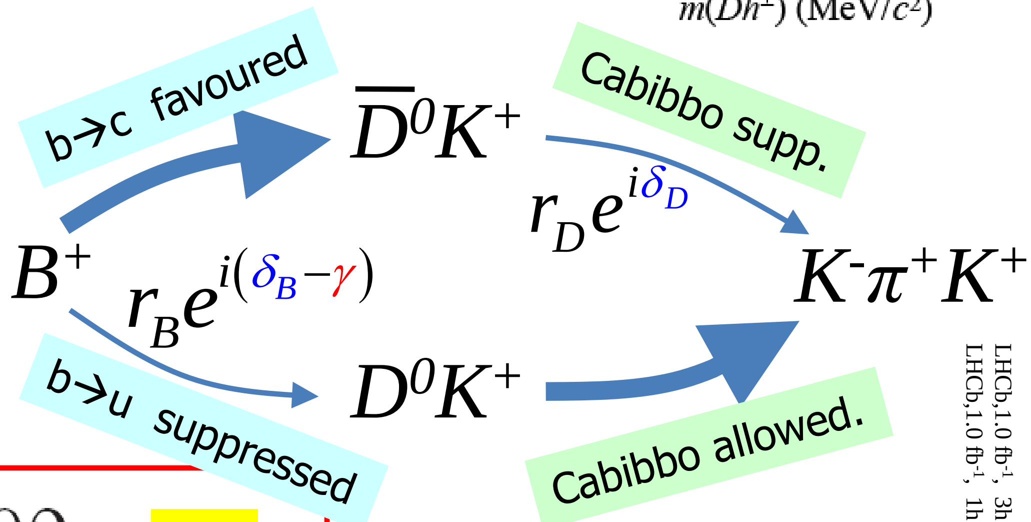
LHCb,1.0 fb^{-1}, 3h LHCb-CONF-2012-021
LHCb,1.0 fb^{-1}, 1h PL B712 (2012) 203

γ (ADS)

Suppressed mode for the B^- is relatively more suppressed than for the B^+…

$$R_K^- = 0.0073 \pm 0.0023 \pm 0.0004$$
$$R_K^+ = 0.0232 \pm 0.0034 \pm 0.0007$$





ADS:

B or D Cabibbo favoured: $D^0 \to K^+\pi^-$

BR~ 2 x 10^{-7}

First observation of suppressed mode

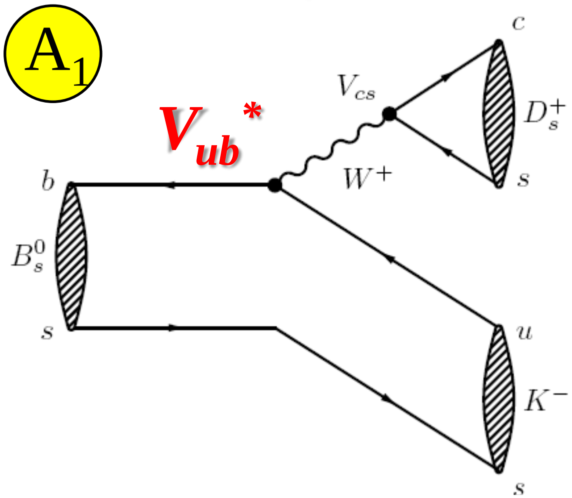
$$A_{ADS} = -0.52 \pm 0.15 \pm 0.02 \quad \textbf{4.0}\sigma$$
$$= 2\kappa r_B r \sin(\delta_B + \delta_D)\sin\gamma / \mathcal{R}_s^{ADS}$$

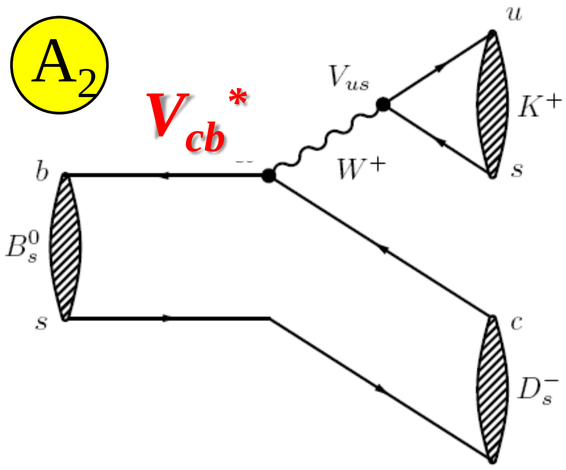
$$R_{ADS} = 0.0152 \pm 0.0020 \pm 0.0004$$
$$= r_B^2 + r_D^2 + 2\kappa r_B r_D \cos(\delta_B + \delta_D)\cos\gamma$$

LHCb,1.0 fb^{-1}, 3h LHCb-CONF-2012-021
LHCb,1.0 fb^{-1}, 1h PL B712 (2012) 203

γ (Time dependent)

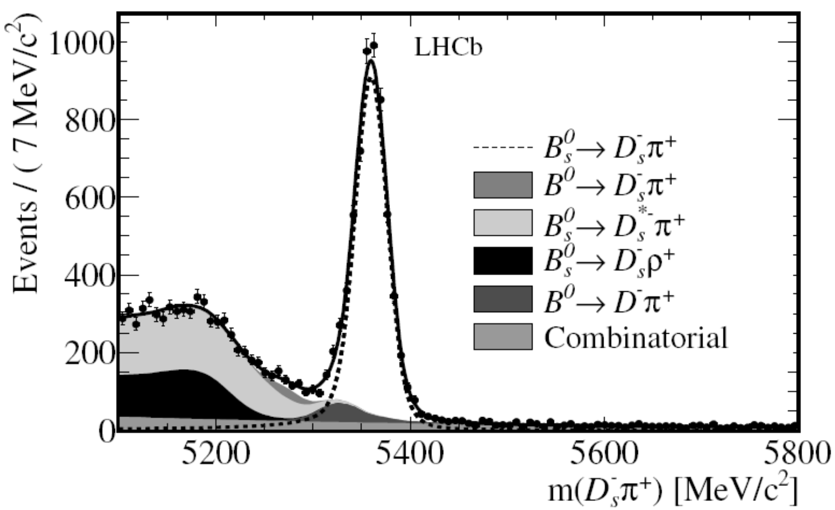
$$\gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$

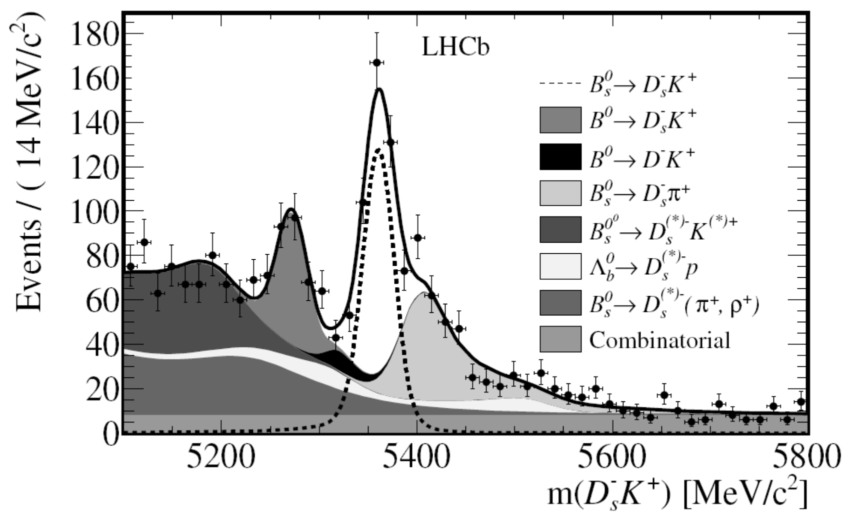




$B^0_s \rightarrow D_s^+ K^-$

- Relative phase: γ
- First step: BR!





$$\mathcal{B}(B_s^0 \to D_s^-\pi^+) = (2.95 \pm 0.05 \pm 0.17^{+0.18}_{-0.22}) \times 10^{-3}$$
$$\mathcal{B}(B_s^0 \to D_s^\mp K^\pm) = (1.90 \pm 0.12 \pm 0.13^{+0.12}_{-0.14}) \times 10^{-4}$$

(best known B^0_s decay!)

LHCb, 0.37fb^{-1}, JHEP06(2012)115

Intermezzo: how many B^0_s are produced? f_d/f_s

- To determine any B_s^0 BR, need to know how many are produced
- Relative to B^0 or B^+ decay
- e.g.:

$$\mathrm{BR}(B_s^0 \to \mu^+\mu^-) = \mathrm{BR}(B_q \to X) \frac{f_q}{f_s} \frac{\epsilon_X}{\epsilon_{\mu\mu}} \frac{N_{\mu\mu}}{N_X}$$

Measured f_d/f_s at LHCb:

- Hadronic:
  - Compare yields of $B^0_s \to D_s^+\pi^-$ and $B^0 \to D^+K^-$
  - Theoretically we can estimate ratio of BR!

$$\frac{f_d}{f_s} = 12.88 \times \frac{\tau_{B_s}}{\tau_{B_d}} \times \left[\mathcal{N}_a \mathcal{N}_F \frac{\epsilon_{D_s\pi}}{\epsilon_{D_dK}} \frac{N_{D_dK}}{N_{D_s\pi}}\right]$$

Fleischer, Serra, **NT,** PRD 82, 034038 (2010)
Fleischer, Serra, **NT,** PRD 83, 014017 (2011)

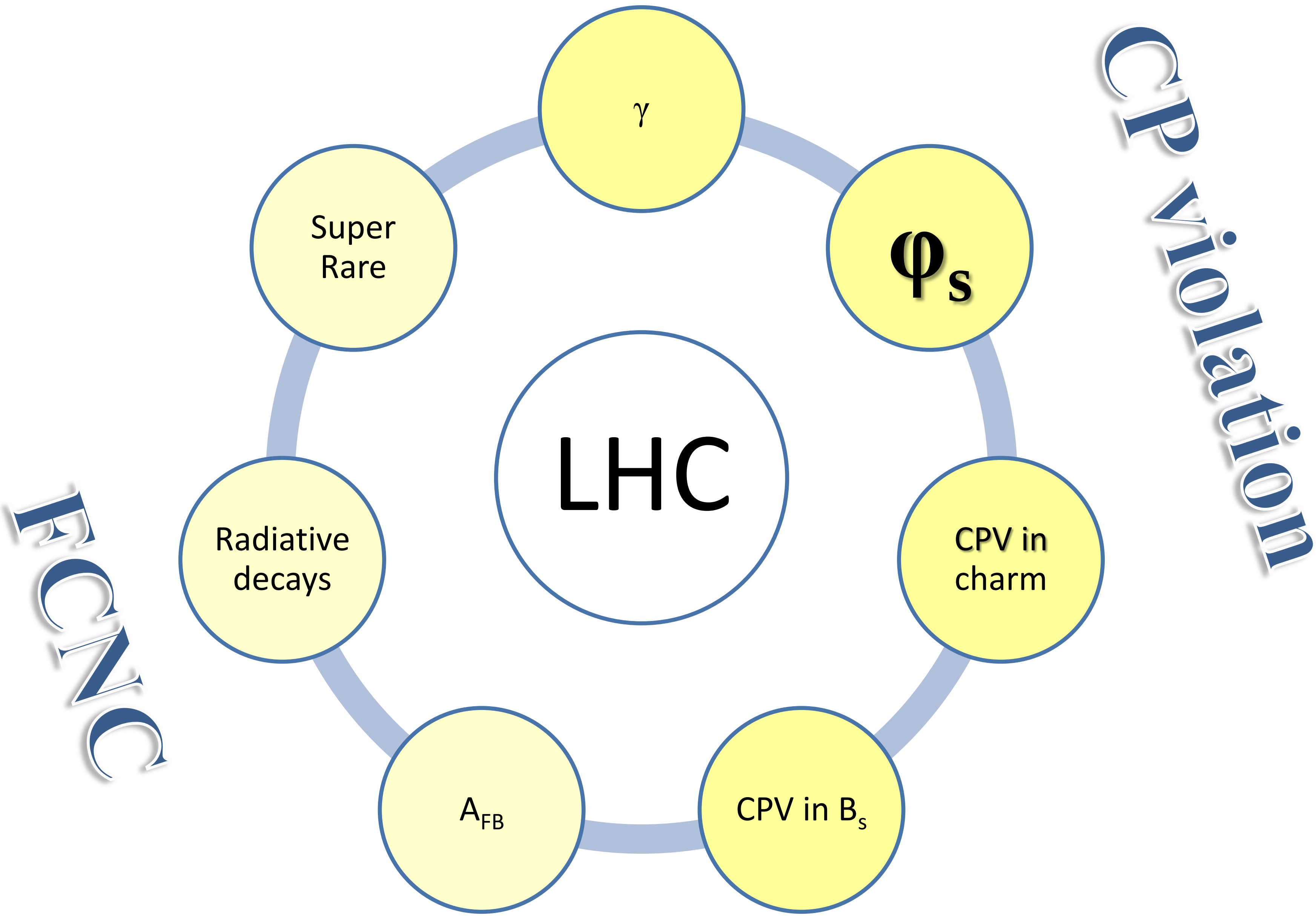
- Semi-leptonic
  - Compare yields of $B^0_s \to D_s^+X\mu\nu$ and $B^0 \to DX\mu\nu$

$$\frac{f_s}{f_u + f_d} = \frac{n_{\mathrm{corr}}(\overline{B}_s^0 \to D\mu)}{n_{\mathrm{corr}}(B \to D^0\mu) + n_{\mathrm{corr}}(B \to D^+\mu)} \frac{\tau_{B^-} + \tau_{\overline{B}^0}}{2\tau_{\overline{B}_s^0}}$$

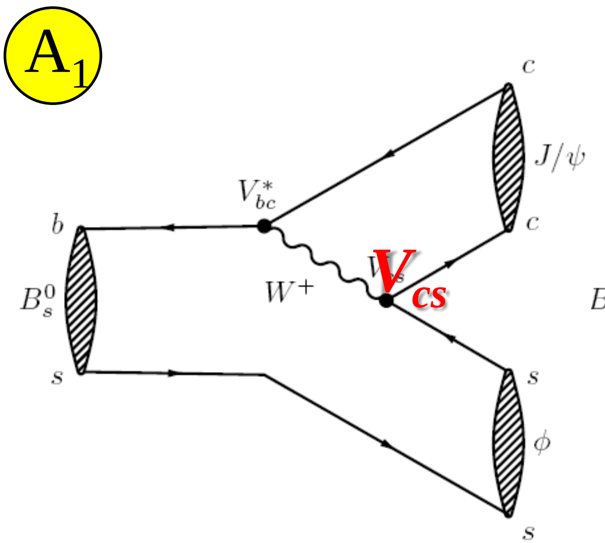
➢ Measure:

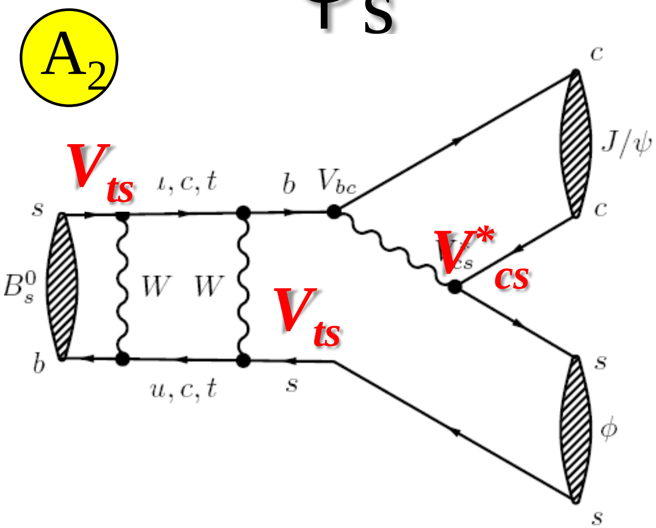
$$f_s/f_d = 0.267^{+0.021}_{-0.020}$$

LHCb PRL 107,(2011) 211801
LHCb PRD 85 (2012) 032008


LHC
γ
φ_s
CPV in charm
CPV in B_s
A_{FB}
Radiative decays
Super Rare
CP violation
FCNC

φ_s





$$\beta_s \equiv \arg\left[-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right]$$

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

$B^0_s \to J/\psi\varphi$

- Relative phase: φ_s

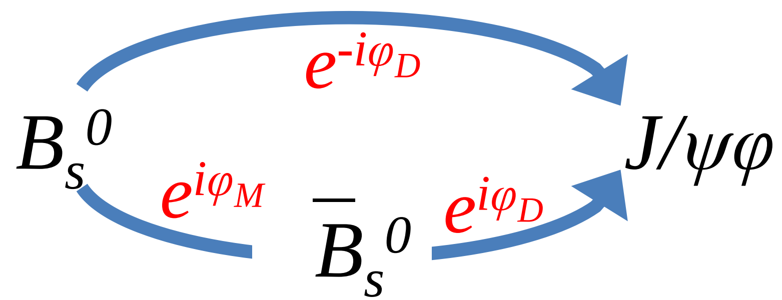
A.Lenz (SM prediction), arXiv:1205.1444

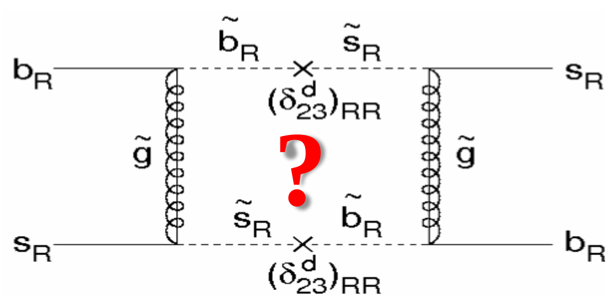
1) $B_s^0 \to J/\psi\varphi$

- $\varphi_s = \varphi_M - 2\varphi_D$
- $\varphi_s^{SM} = -2\beta_s = -0.036 \pm 0.002$ rad

(Neglecting penguin contributions)

➢ New physics can affect φ_M

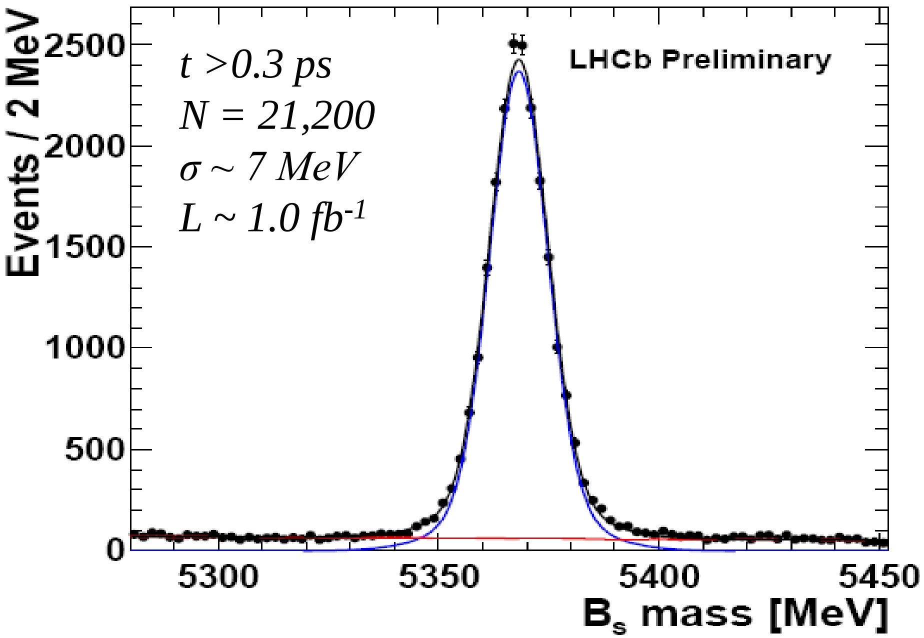


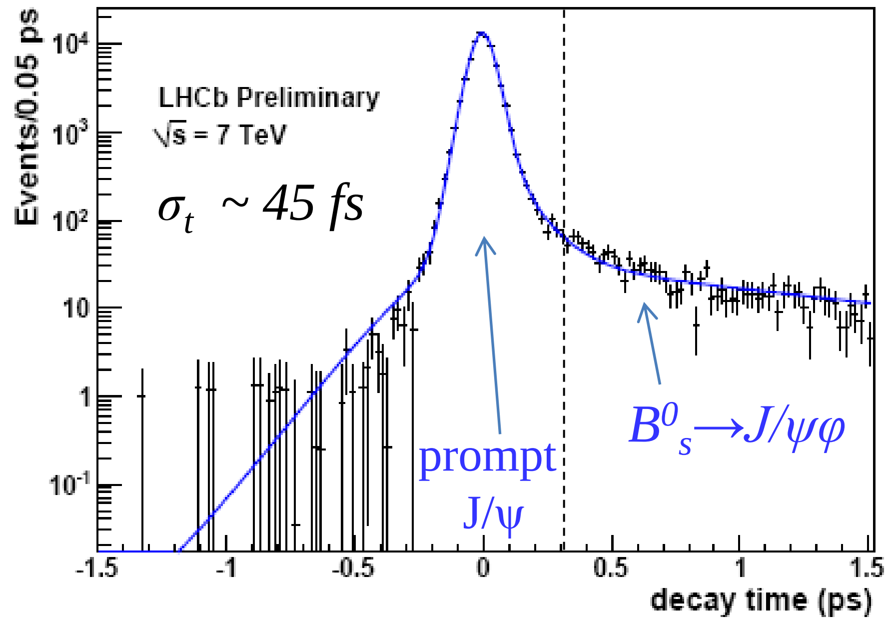


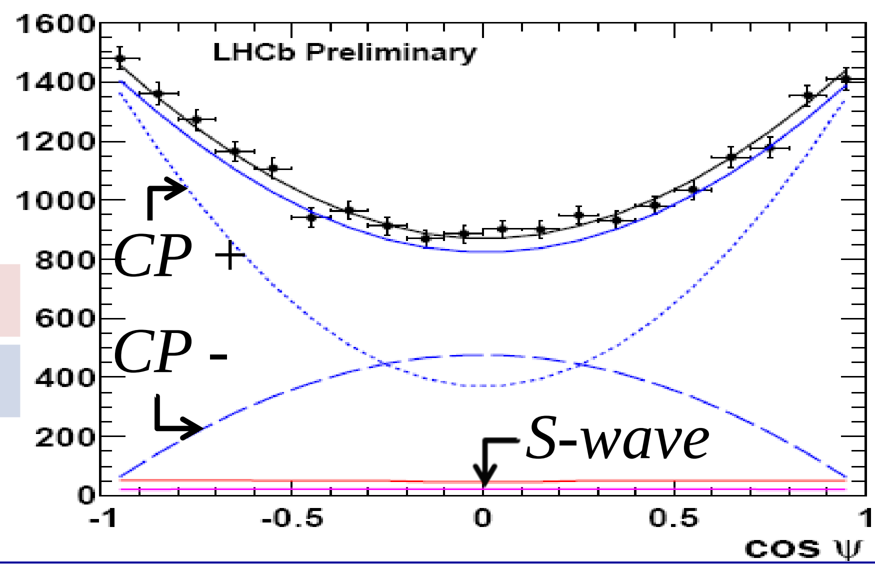
LHCb, 1.0fb^{-1}, φ_s, LHCb-CONF-2012-002
LHCb, 1.0fb^{-1}, $J/\psi\ \pi\pi$, arXiv:1204.5675
LHCb, 1.0fb^{-1}, $\tau_{J/\psi\ f0}$ arXiv:1207.0878
LHCb, 1.0fb^{-1}, amb, PRL. 108 (2012) 241801

LHCb: φ_s

$B^0_s \to J/\psi\varphi$







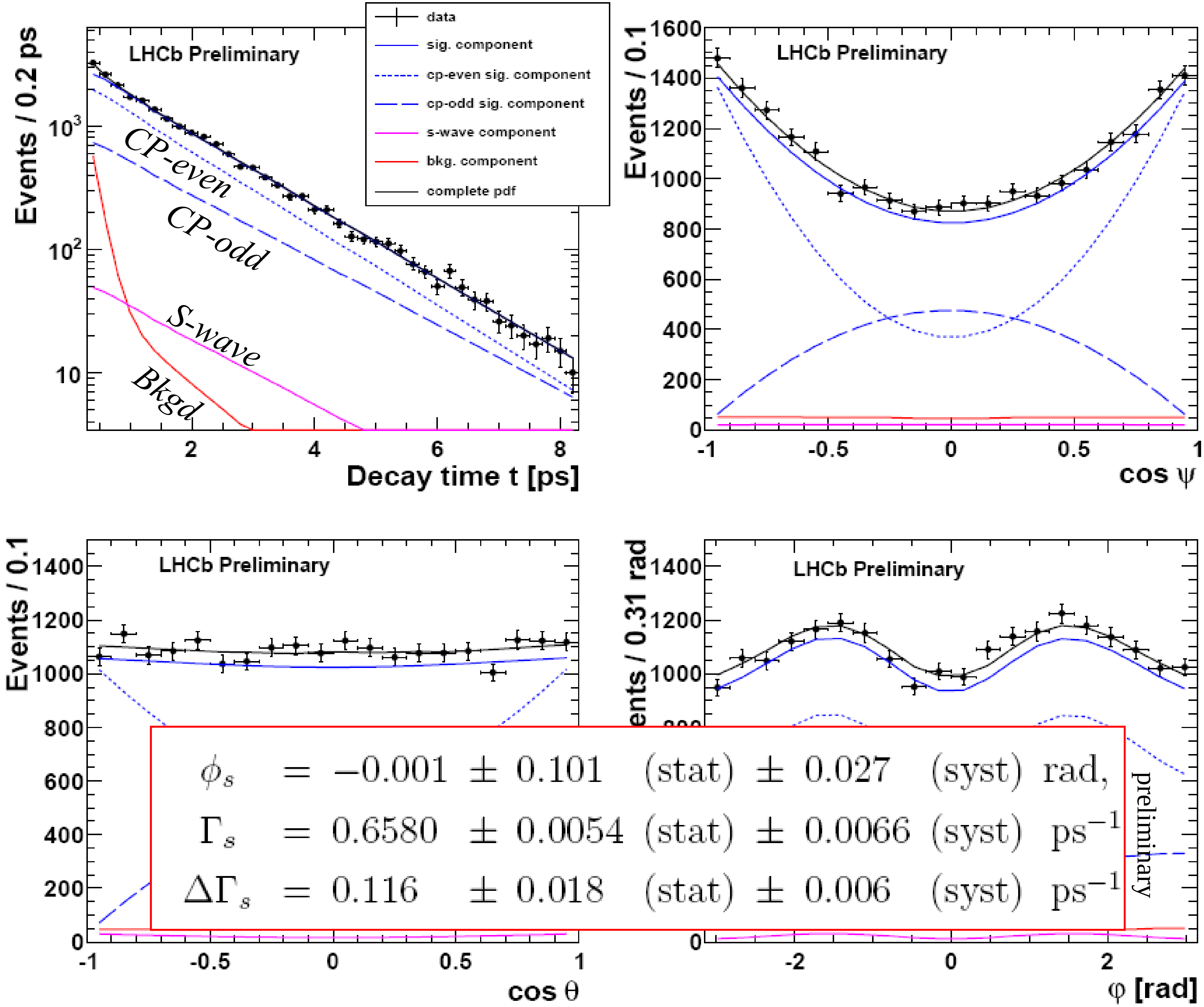
LHCb, 1.0fb^{-1}, φ_s, LHCb-CONF-2012-002

- Angular analysis
  - Pseudo-scalar → 2 vectors
  - CP ~ $(-1)^L$

L=1	$A_\perp$	CP= -
L=0,2	A_0,$A_\parallel$	CP=+

- Tagging: εD^2 = 2.29±0.27%

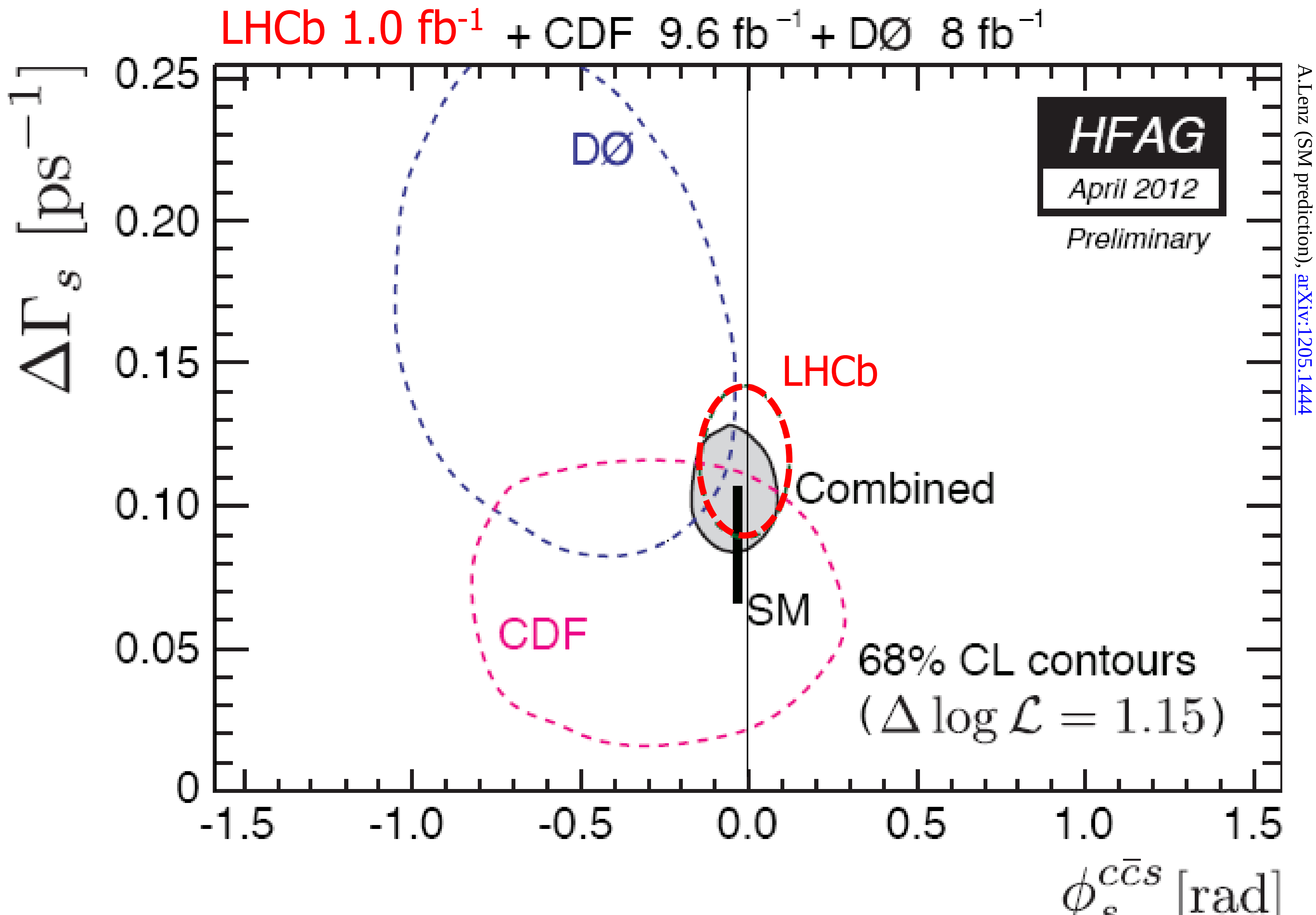
LHCb, EPJ C (2012) 72:2022



$$\phi_s = -0.001 \pm 0.101 \ (\mathrm{stat}) \pm 0.027 \ (\mathrm{syst}) \ \mathrm{rad},$$
$$\Gamma_s = 0.6580 \pm 0.0054 \ (\mathrm{stat}) \pm 0.0066 \ (\mathrm{syst}) \ \mathrm{ps}^{-1}$$
$$\Delta\Gamma_s = 0.116 \pm 0.018 \ (\mathrm{stat}) \pm 0.006 \ (\mathrm{syst}) \ \mathrm{ps}^{-1}$$

LHCb, $1.0\,\mathrm{fb}^{-1}$, ϕ_s, LHCb-CONF-2012-002

φ_s



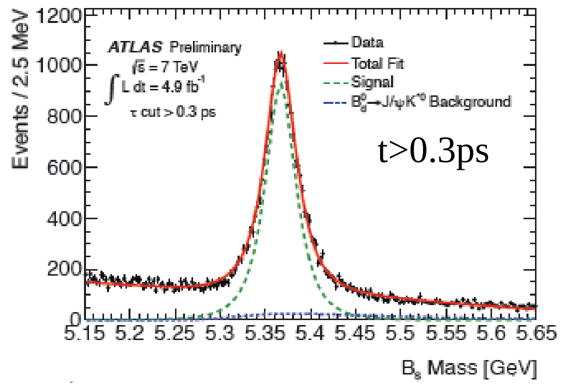
LHCb 1.0 fb-1 + CDF 9.6 fb-1 + DØ 8 fb-1
DØ
HFAG
April 2012
Preliminary
LHCb
Combined
SM
CDF
68% CL contours
(Δ log ℒ = 1.15)
ΔΓs [ps−1]
0.25
0.20
0.15
0.10
0.05
0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
φs ccs [rad]
A.Lenz (SM prediction), arXiv:1205.1444

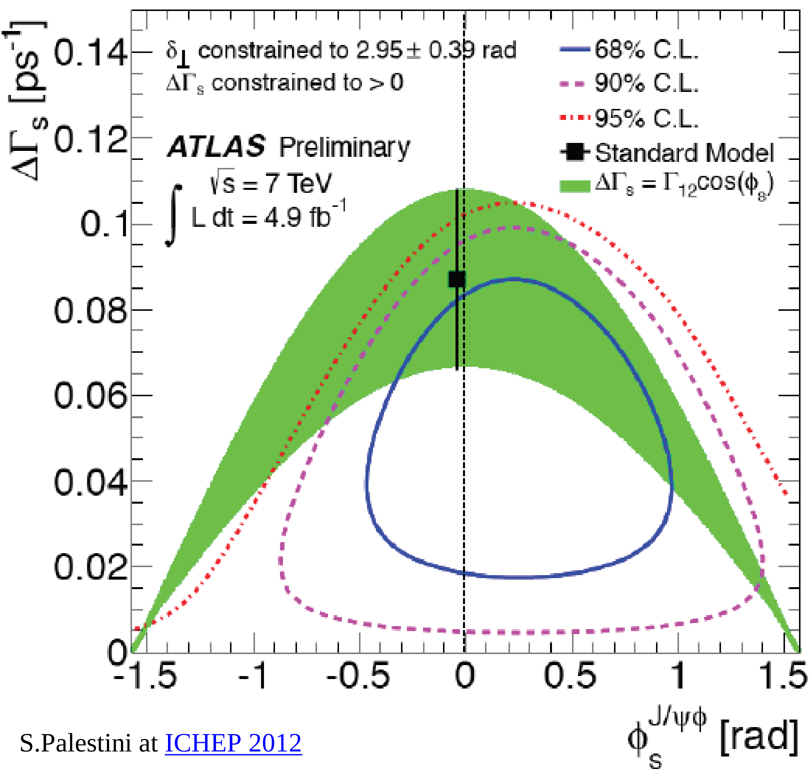
ATLAS: φ_s

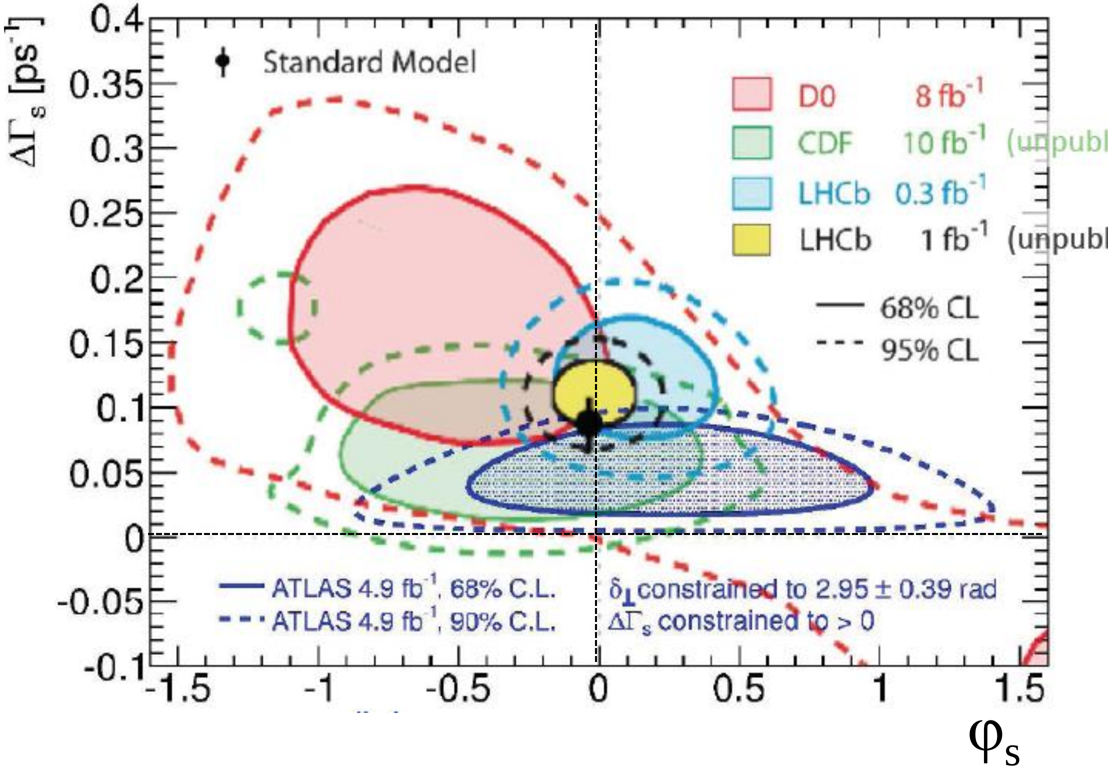
Avg: 5.6 overlapping pp!

- Luminosity: 4.9 fb^{-1}
- P_t^{μ}>4 GeV

$$\phi_s = 0.22 \pm 0.41 \text{ (stat.)} \pm 0.10 \text{ (syst.) rad}$$
$$\Delta\Gamma_s = 0.053 \pm 0.021 \text{ (stat.)} \pm 0.008 \text{ (syst.) ps}^{-1}$$







S.Palestini at ICHEP 2012

φ_s

- $B^0_s \to J/\psi\pi\pi$: *CP eigenstate*
  - *Pure CP-odd, only long living B^0_s*
  - *No angular analysis needed*
  - *Data sample smaller compared to $J/\psi\varphi$*
  - *Hadronic effects might shift φ_s differently*

1) Combined fit:

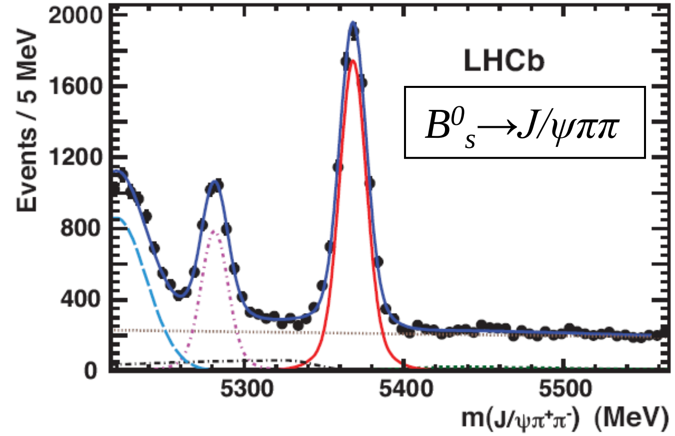
- Decrease statistical unc from 0.101 to 0.083:

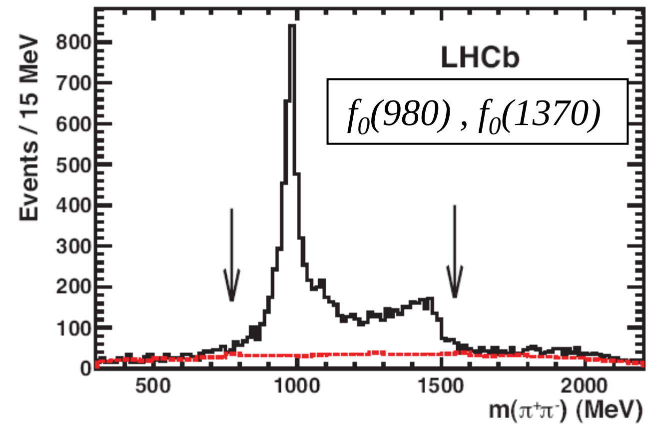
$$\phi_s = -0.002 \pm 0.083 \pm 0.027\,\text{rad}$$

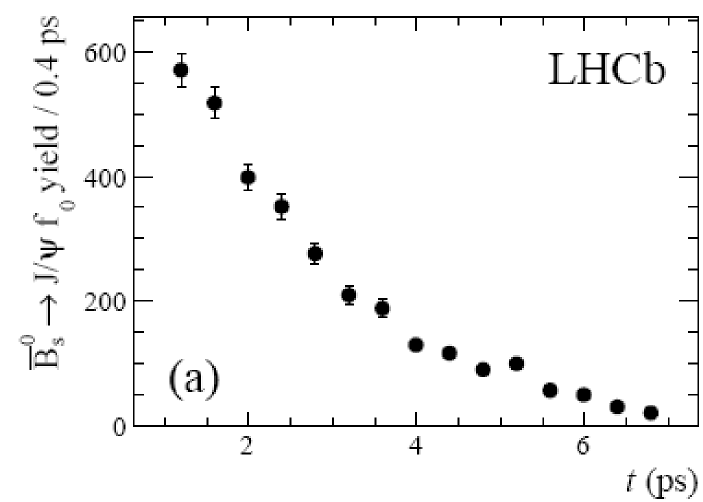
2) Effective lifetime:

$$\Gamma\left(B^0_s \to f_-\right) + \Gamma\left(\overline{B}^0_s \to f_-\right) = \mathcal{N} e^{-t/\tau_{J/\psi\, f_0}}$$

$$\tau_{J/\psi\, f_0} = 1.700 \pm 0.040 \pm 0.026\,\text{ps}$$





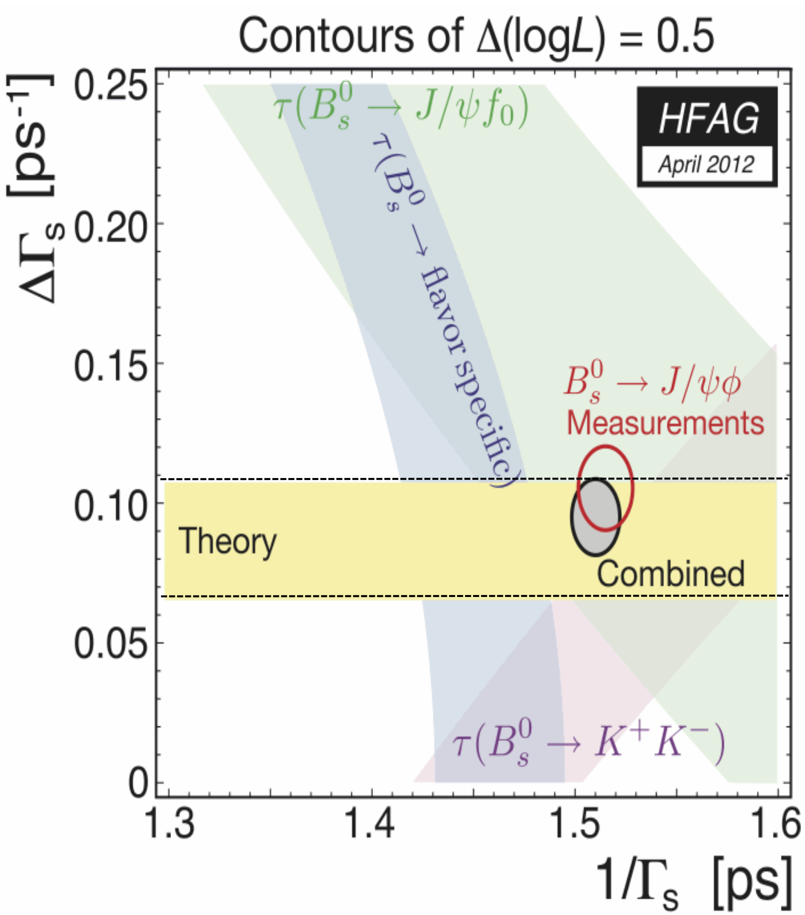


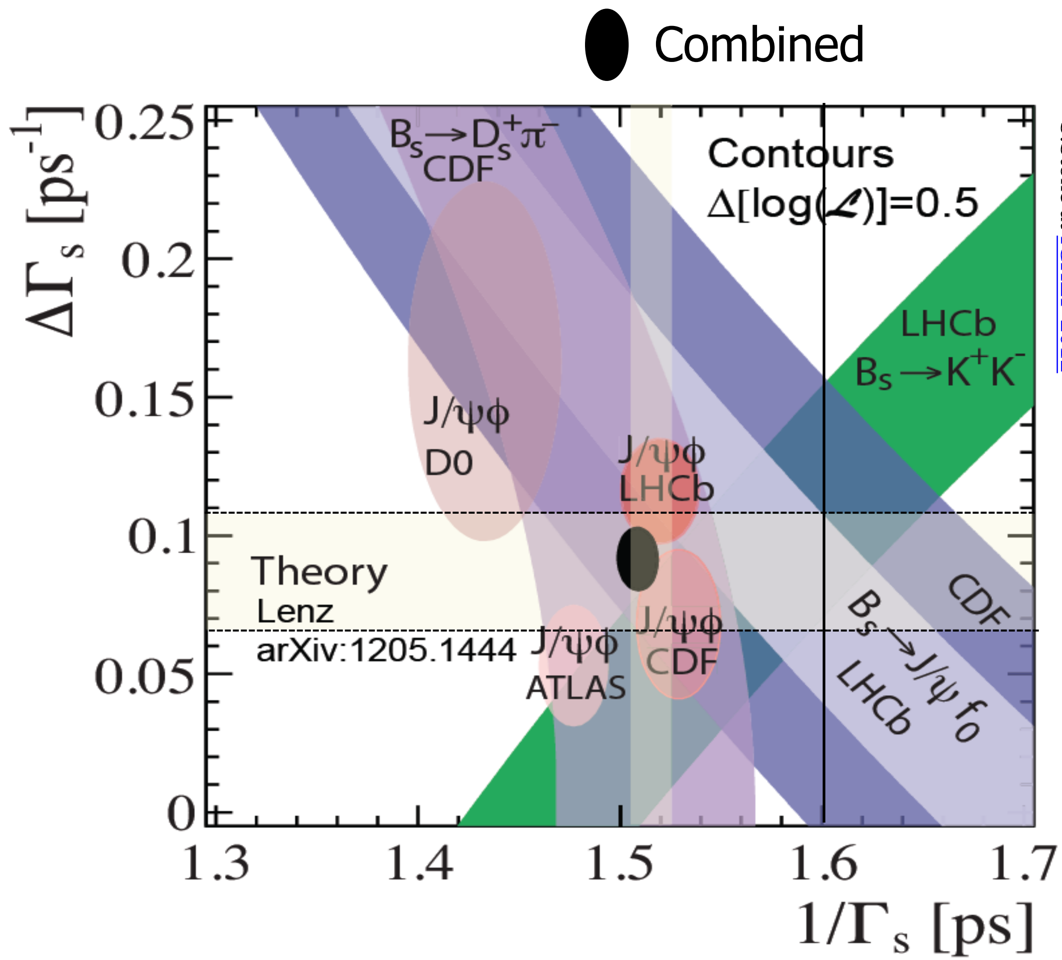
LHCb, 1.0fb^{-1}, φ_s, LHCb-CONF-2012-002
LHCb, 1.0fb^{-1}, $J/\psi\,\pi\pi$, arXiv:1204.5675
LHCb, 1.0fb^{-1}, $\tau_{J/\psi\, f0}$ arXiv:1207.0878

B_s^0 Lifetime

CP	mass	lifetime	example
+	L	short	$B^0_s \to KK$
-	H	long	$B^0_s \to J/\psi f_0$

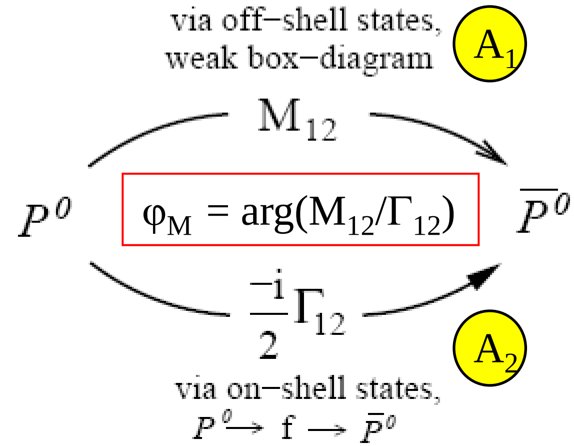
LHCb, 1.0fb^{-1}, amb, PRL. 108 (2012) 241801





S.Stone at ICHEP 2012

Mixing Phase



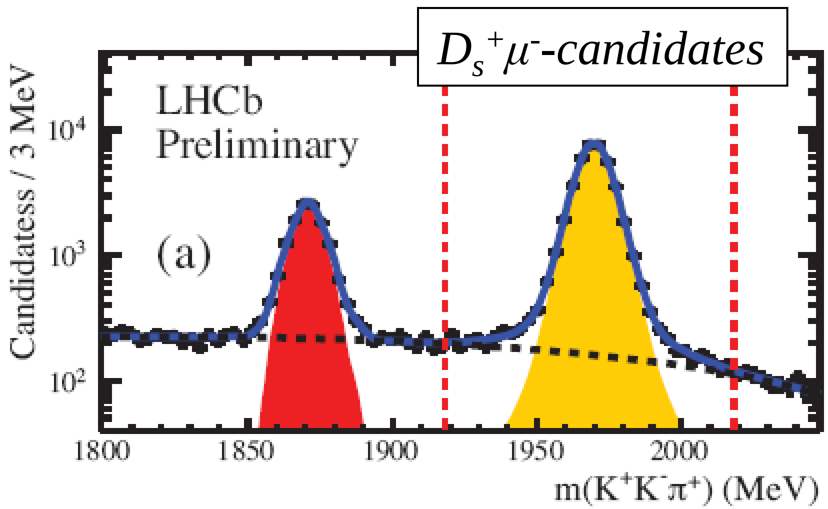
$B_s^0 \to D_s^- X \mu^+ \nu$

- $\varphi_s = \varphi_M - 2\varphi_D$
- $\varphi_s^{SM} = -2\beta_s = -0.036 \pm 0.002$ rad
- $\varphi_M^{SM} = 0.0035$ rad

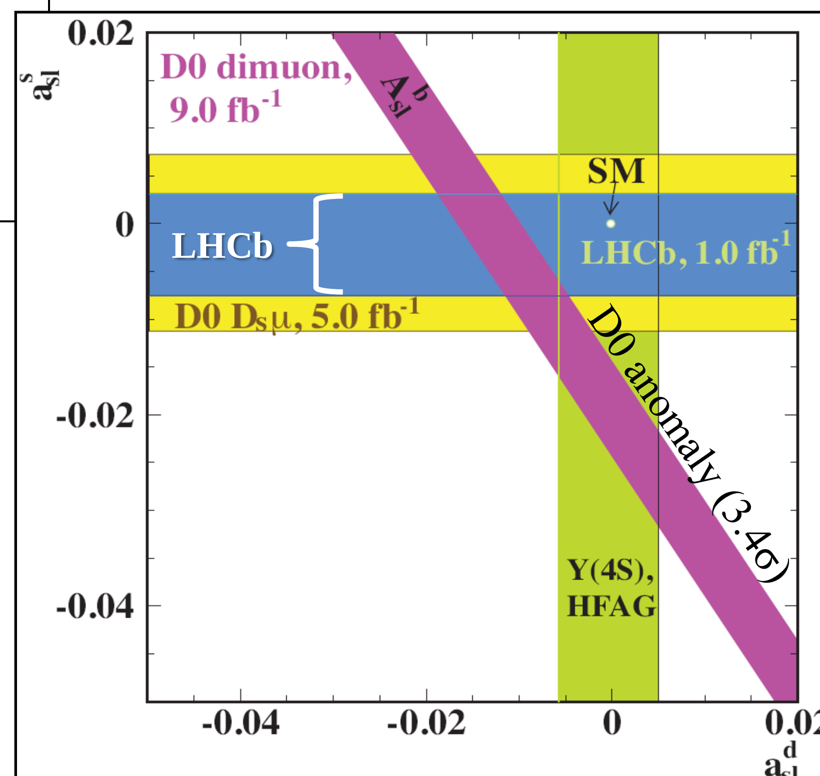
- New physics can affect φ_M
- Measure: $A_{\rm meas} = \dfrac{\Gamma[D_s^- \mu^+] - \Gamma[D_s^+ \mu^-]}{\Gamma[D_s^- \mu^+] + \Gamma[D_s^+ \mu^-]}$

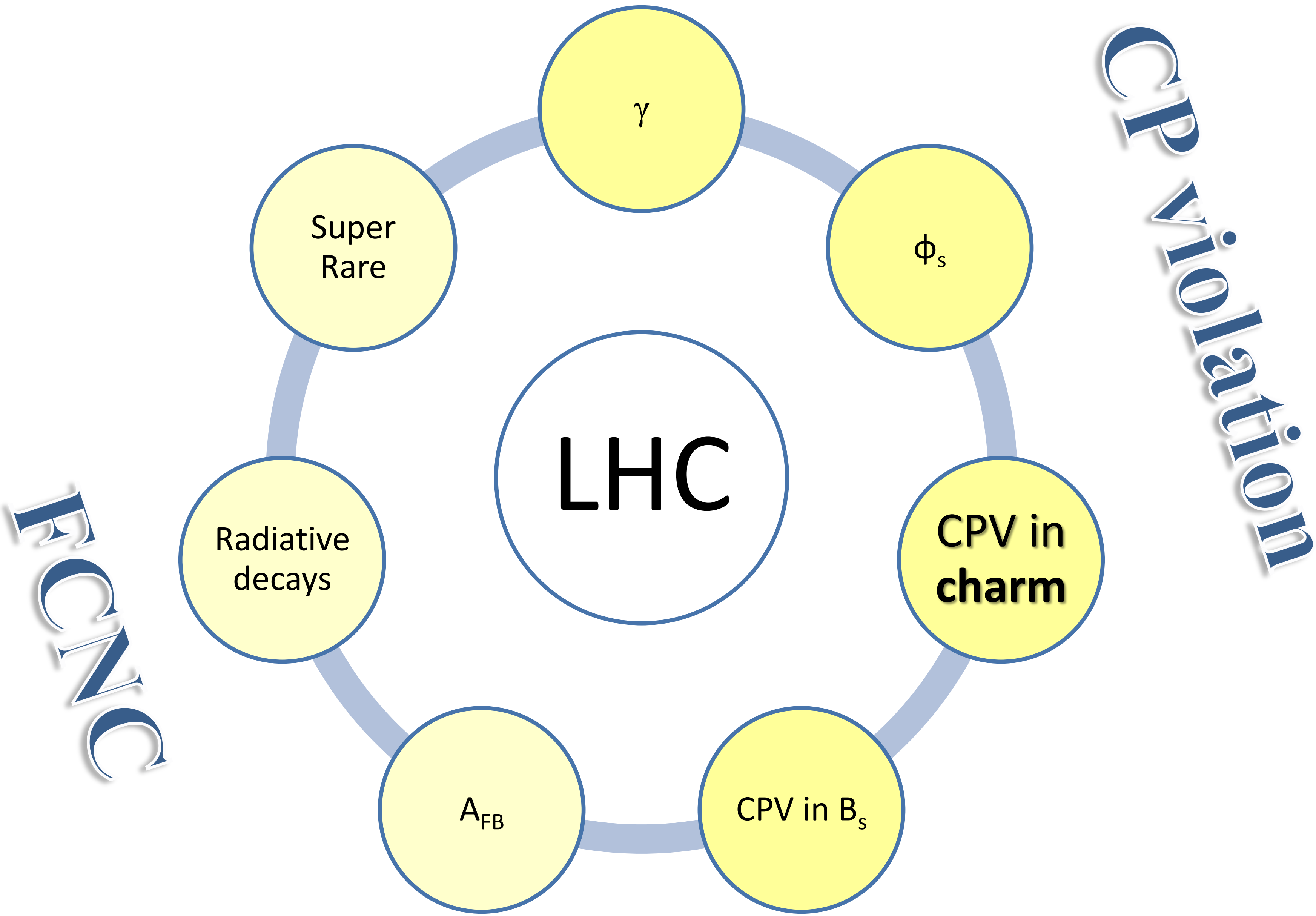
$$a_{\rm sl} = \frac{\Gamma\left(\overline{B}(t) \to f\right) - \Gamma\left(B(t) \to \overline{f}\right)}{\Gamma\left(\overline{B}(t) \to f\right) + \Gamma\left(B(t) \to \overline{f}\right)} = \frac{\Delta\Gamma}{\Delta M} \tan \varphi_M$$

➢ LHCb in agreement with SM *and* D0



LHCb, 1.0fb^{-1}, LHCb-CONF-2012-022





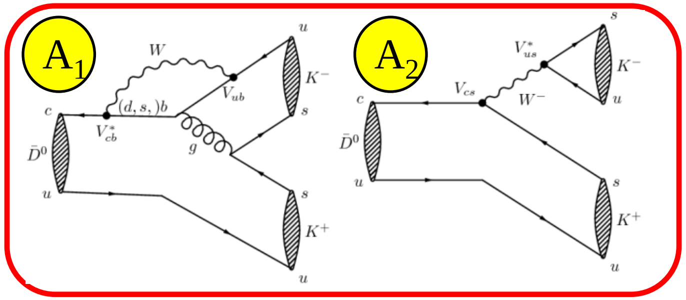
LHC
γ
φs
CPV in charm
CPV in Bs
AFB
Radiative decays
Super Rare
CP violation
FCNC

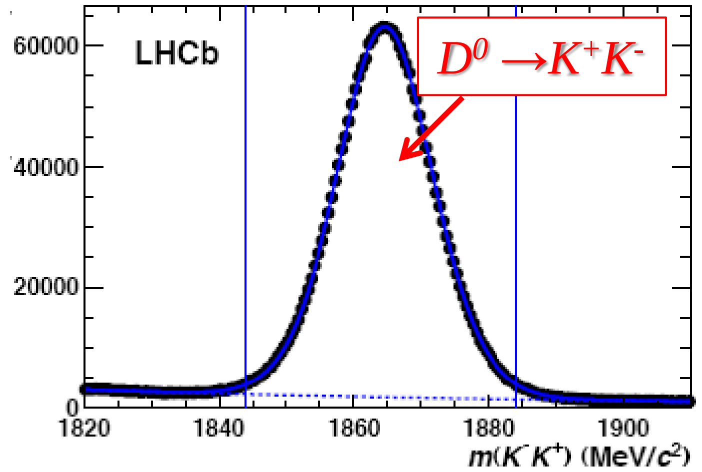
Charm

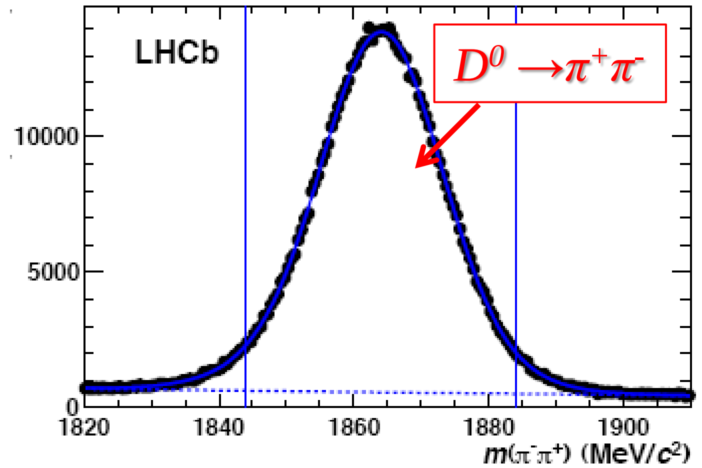
- Measure difference of CP asymmetry
  - CP violation from *mixing* largely cancels
  - *Direct* CP violation expected to be small

$$A_{\rm raw}(f) = A_{CP}(f) + A_{\rm D}(f) + A_{\rm D}(\pi_{\rm s}^{+}) + A_{\rm P}(D^{*+})$$

$$A_{\rm raw}(f) \equiv \frac{N(D^{*+} \to D^0(f)\pi_s^+) - N(D^{*-} \to \overline{D}^0(f)\pi_s^-)}{N(D^{*+} \to D^0(f)\pi_s^+) + N(D^{*-} \to \overline{D}^0(f)\pi_s^-)}$$

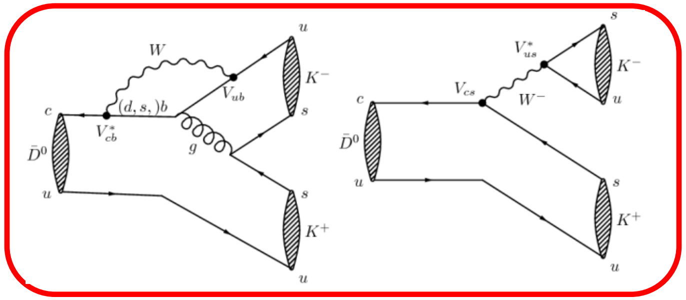






LHCb, 0.6 fb^{-1}, PRL 108, 111602 (2012)

Charm



- Measure difference of CP asymmetry
  - CP violation from *mixing* largely cancels
  - *Direct* CP violation expected to be small

$$A_{\rm raw}(f) = A_{CP}(f) + A_{\rm D}(f) + A_{\rm D}(\pi_{\rm s}^+) + A_{\rm P}(D^{*+})$$

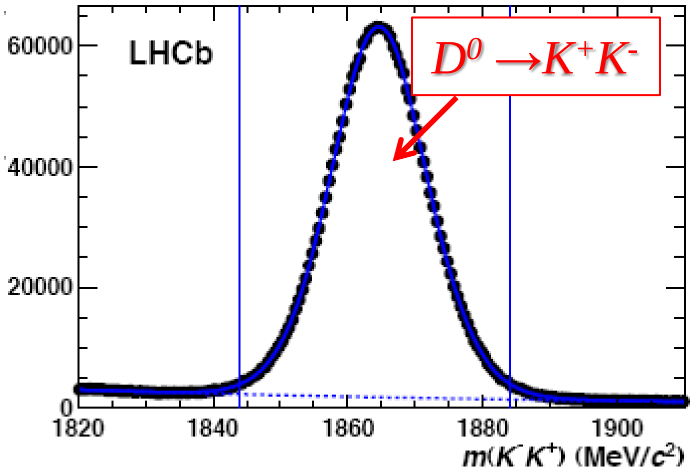
Cancel production and detector asymmetries

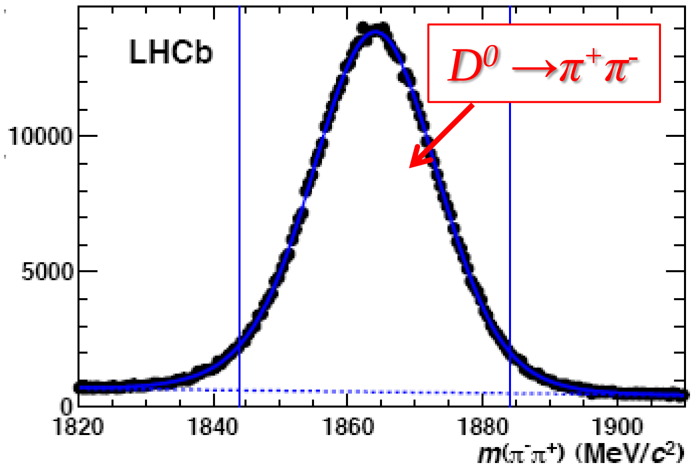
- Compare $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$
- ➢ Same production and detector asymmetry
- ➢ Charge symmetric final state: $A_D(f)=0$

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

$$\Delta A_{CP} = [-0.82 \pm 0.21({\rm stat.}) \pm 0.11({\rm syst.})]\,\%$$

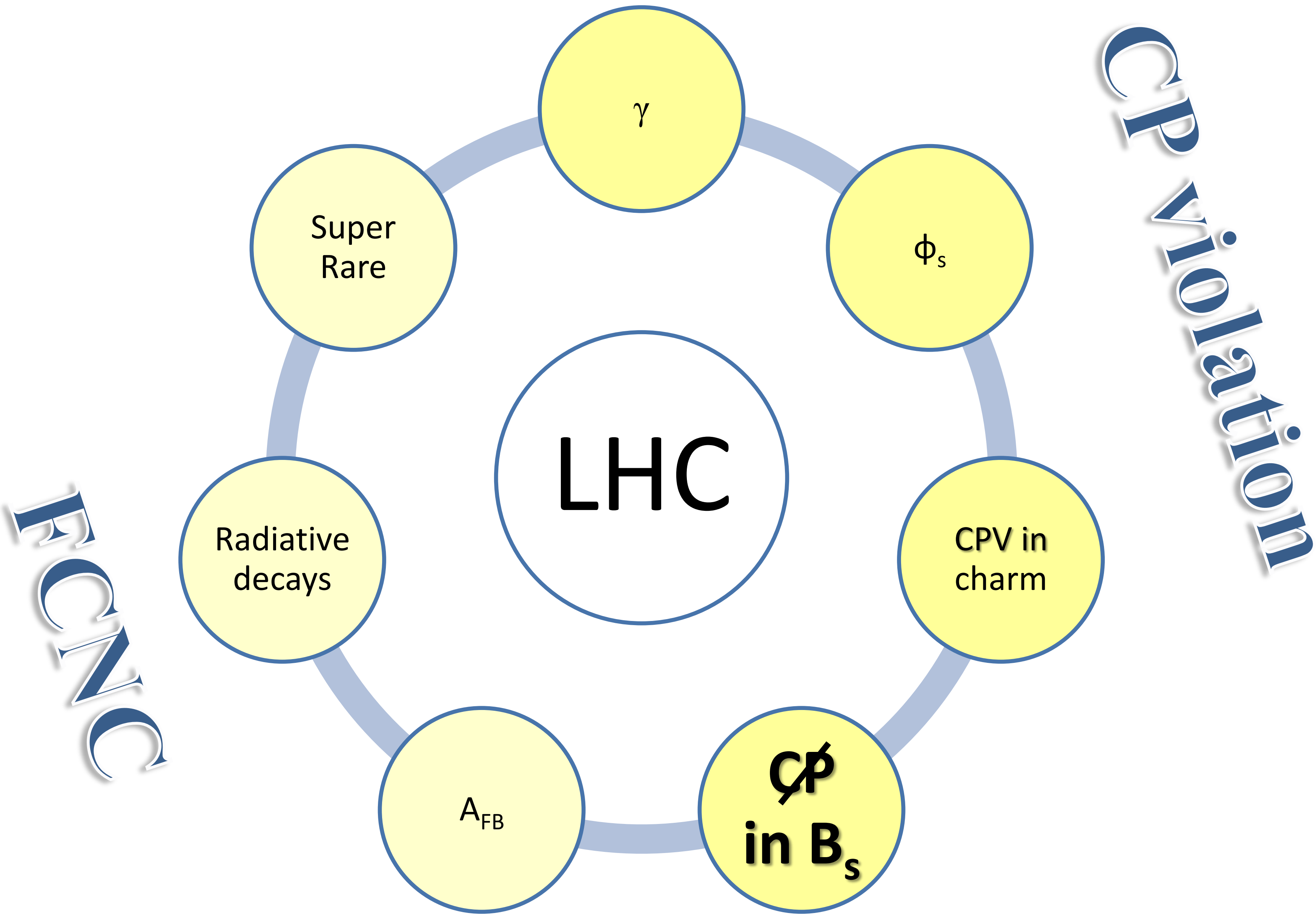
3.5σ



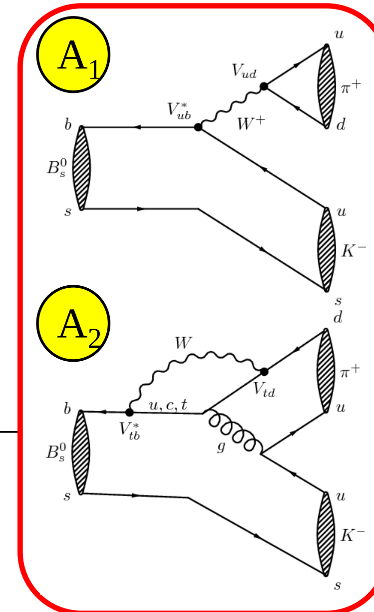


➢ First evidence for CP violation in charm

LHCb, 0.6 fb^{-1}, PRL 108, 111602 (2012)

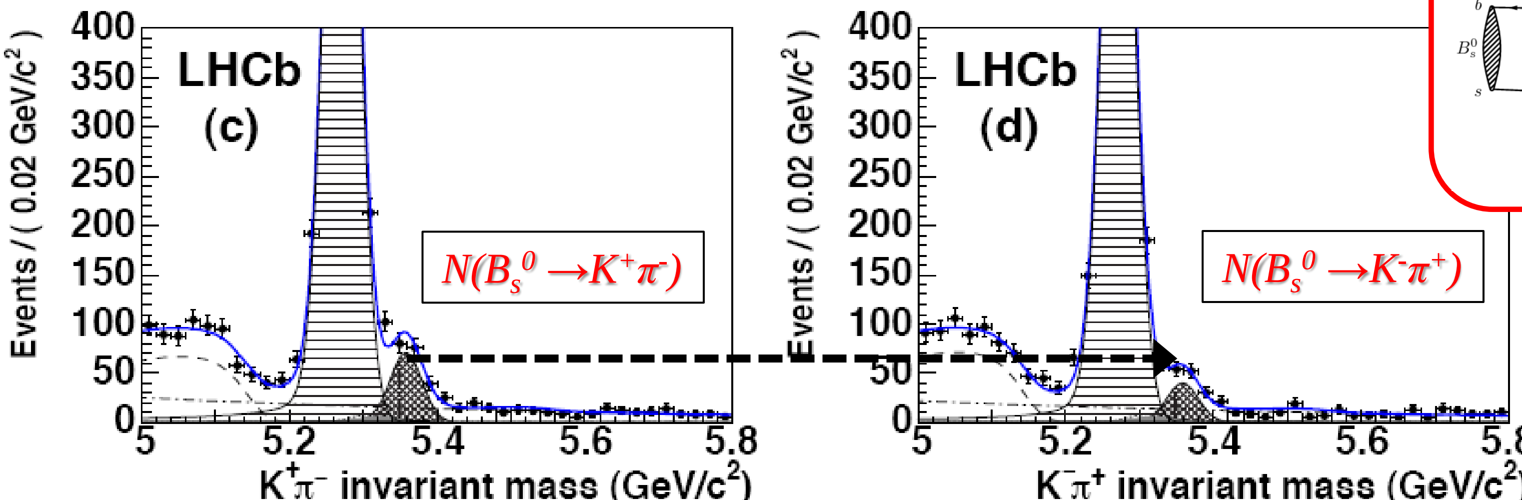

γ
Super Rare
ϕ_s
Radiative decays
LHC
CPV in charm
A_{FB}
CP in B_s
FCNC
CP violation

CP violation in B_s decays



1) First observation of direct CP violation in B^0_s decays

- $N(B_s^0 \to K^+\pi^-) \neq N(\overline{B}_s^0 \to K^-\pi^+)$!
- Interference of tree and penguin diagrams



$N(B_s^0 \to K^+\pi^-)$

$N(B_s^0 \to K^-\pi^+)$

$$A_{CP}(B^0_s \to K\pi) = 0.27 \pm 0.08\,(\text{stat}) \pm 0.02\,(\text{syst}).$$

3.3σ

LHCb, Phys. Rev. Lett. 108 (2012) 201601

2) Measurement of time dependent CP:

- Interference of mixing and decay

preliminary

$$A^{\text{dir}}_{\pi\pi} = 0.11 \pm 0.21 \pm 0.03$$
$$A^{\text{mix}}_{\pi\pi} = -0.56 \pm 0.17 \pm 0.03$$
$$A^{\text{dir}}_{KK} = 0.02 \pm 0.18 \pm 0.04$$
$$A^{\text{mix}}_{KK} = 0.17 \pm 0.18 \pm 0.05$$

3.2σ

LHCb, 0.7fb^{-1}, CP TD, LHCb-CONF-2012-007

LHCb, 1.0fb^{-1}, BR, arXiv:1206.2794

Historical?

1) $P(K^0 \rightarrow \overline{K}^0) \neq P(\overline{K}^0 \rightarrow K^0)$

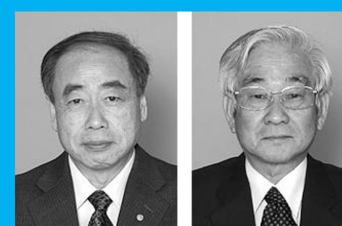
1964 Discovery
1980 Nobel Prize

J. Cronin, V. Fitch

Phys.Rev.Lett. 13 (1964) 138-140

2) $P(B^0 \,(\rightarrow \overline{B}^0) \rightarrow f) \neq P(\overline{B}^0 \,(\rightarrow B^0) \rightarrow f)$

1972 Prediction
2001 Observation
2008 Nobel Prize

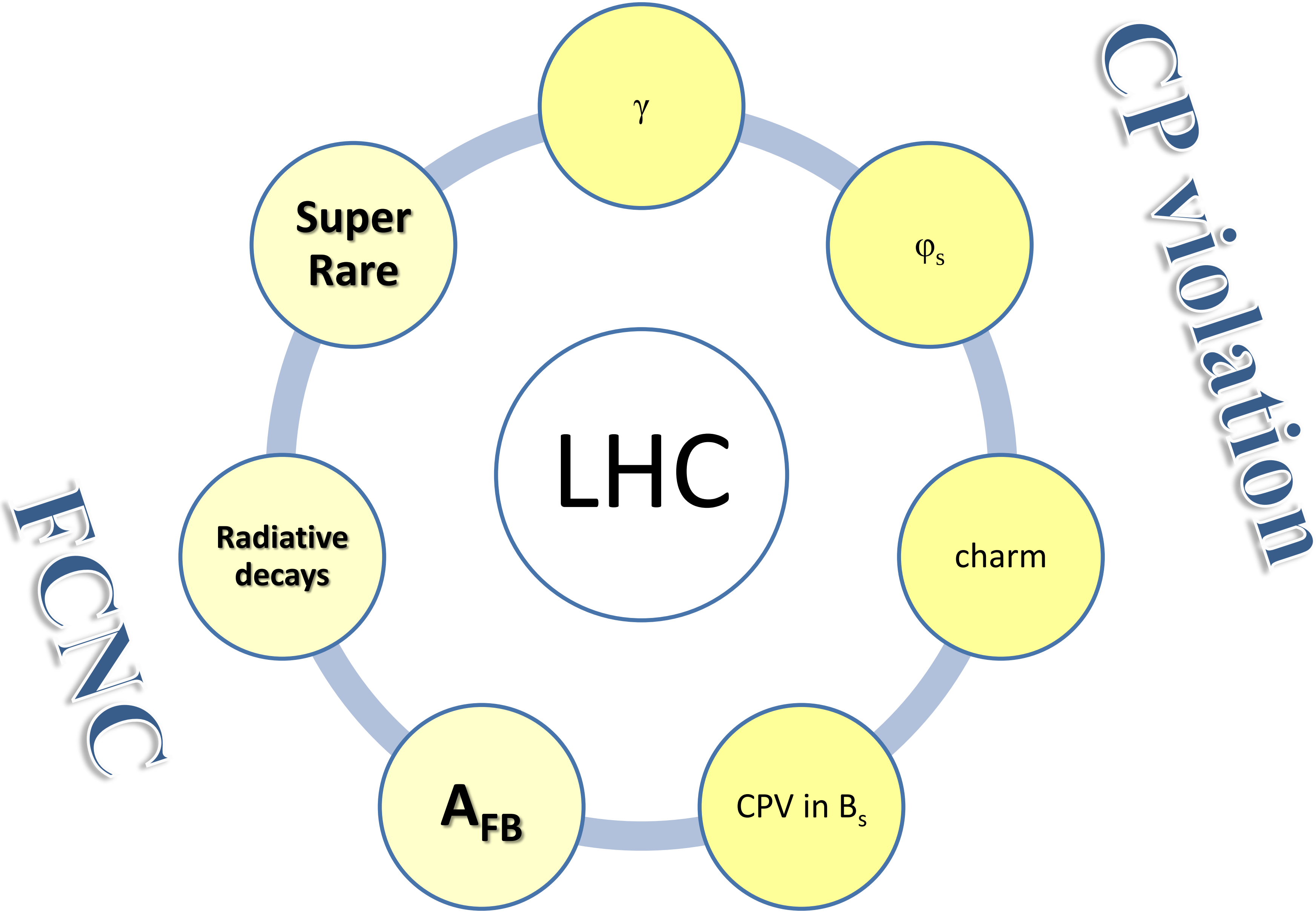


M. Kobayashi, T. Maskawa

Prog.Theor.Phys. 49 (1973) 652-657

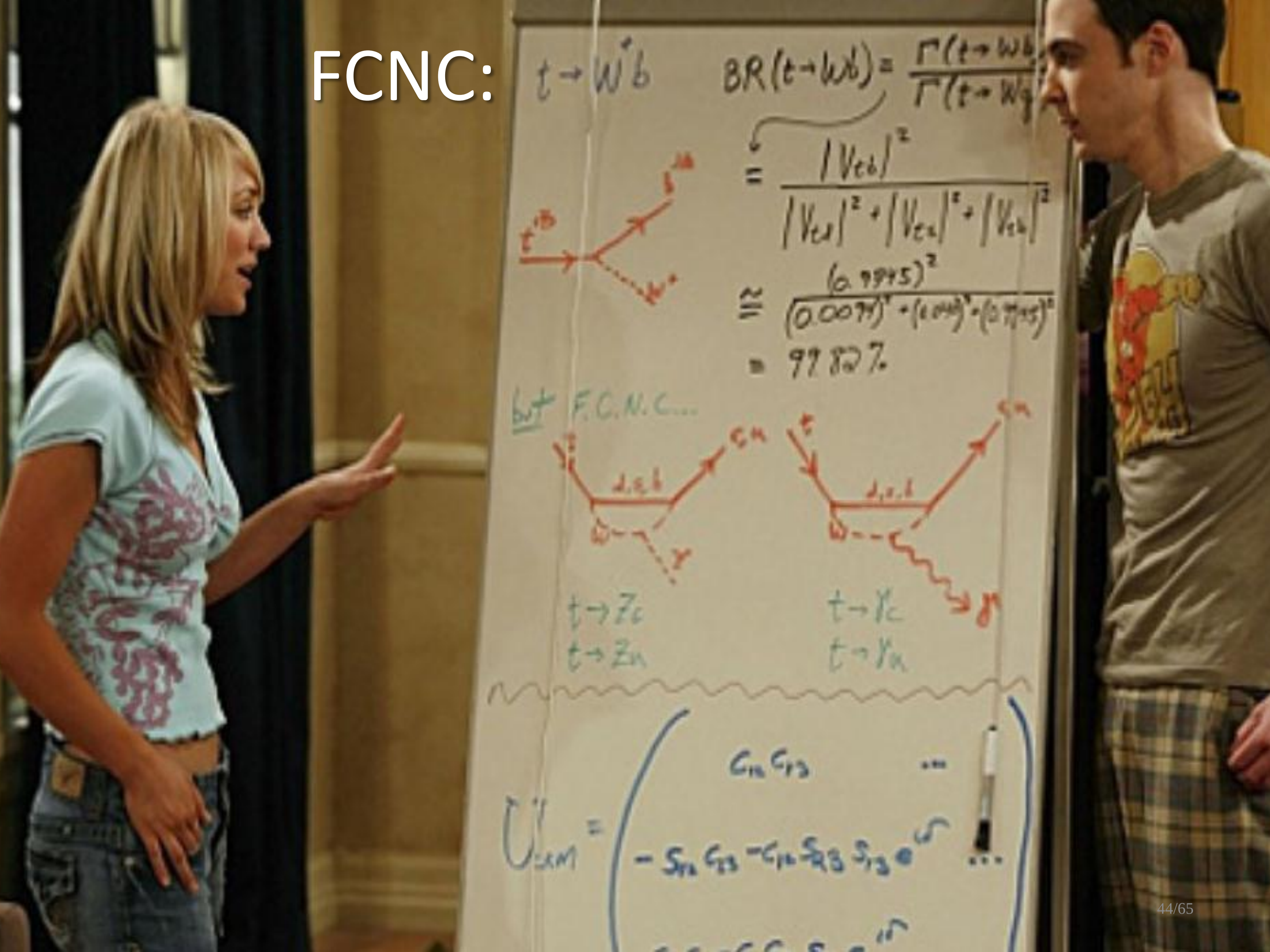
1964: CP violation in K^0-mesons (sd)
2001: CP violation in B^0-mesons (bd)
2011: CP violation in D^0-mesons (cu)
2012: CP violation in B_s^0-mesons (bs)

FCNC

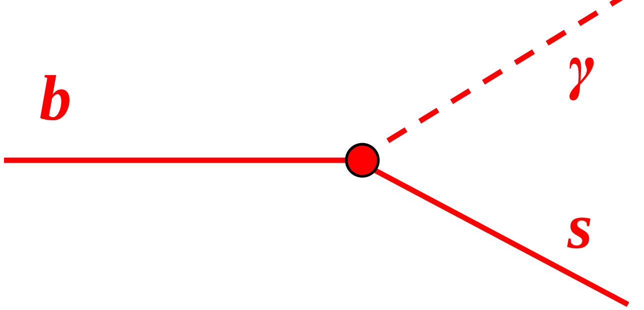


γ
φ_s
charm
CPV in B_s
A_{FB}
Radiative decays
Super Rare
LHC
CP violation
FCNC

FCNC:

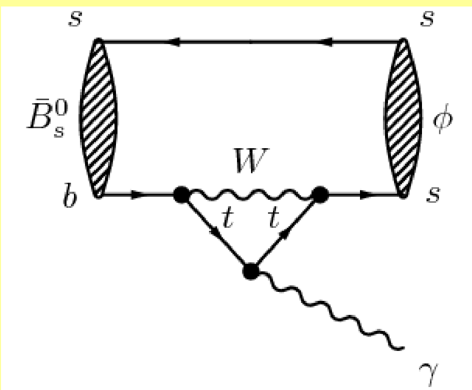


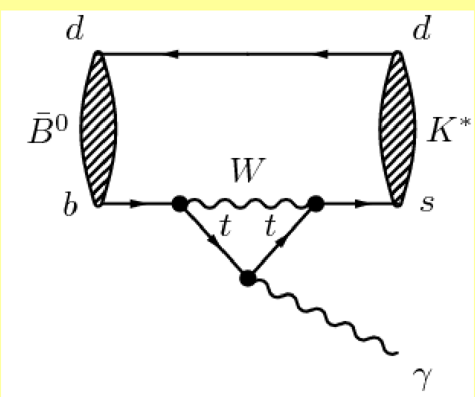
FCNC



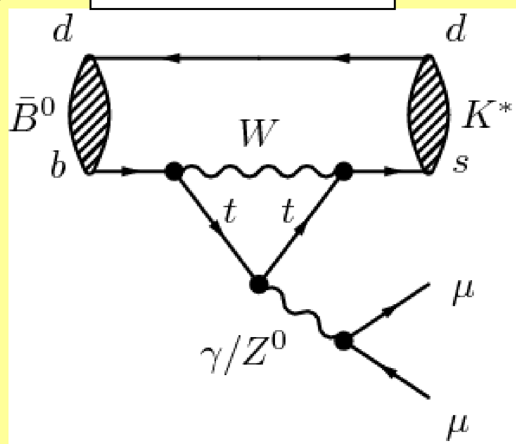
- **Flavour Changing Neutral Current**
  - Also known as “rare decays”

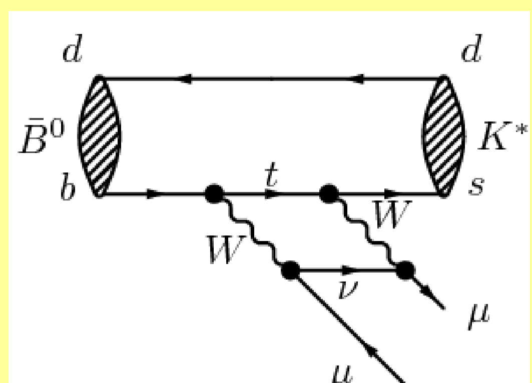
$B^0_{(s)} \to K^*(\varphi)\gamma$



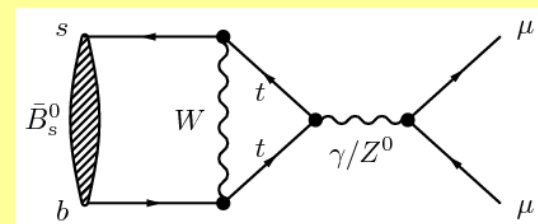


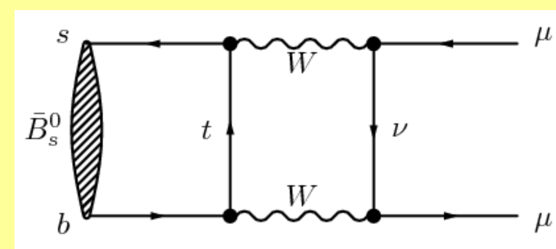
$B^0 \to K^*\mu\mu$



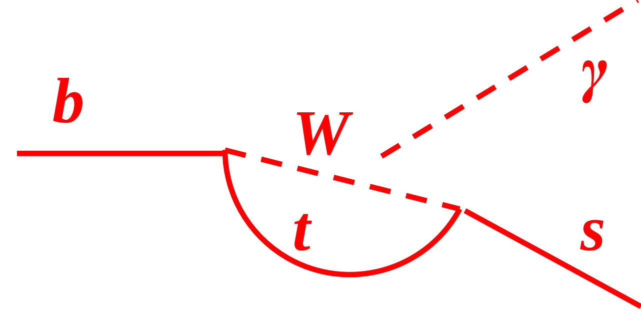


$B^0_s \to \mu\mu$



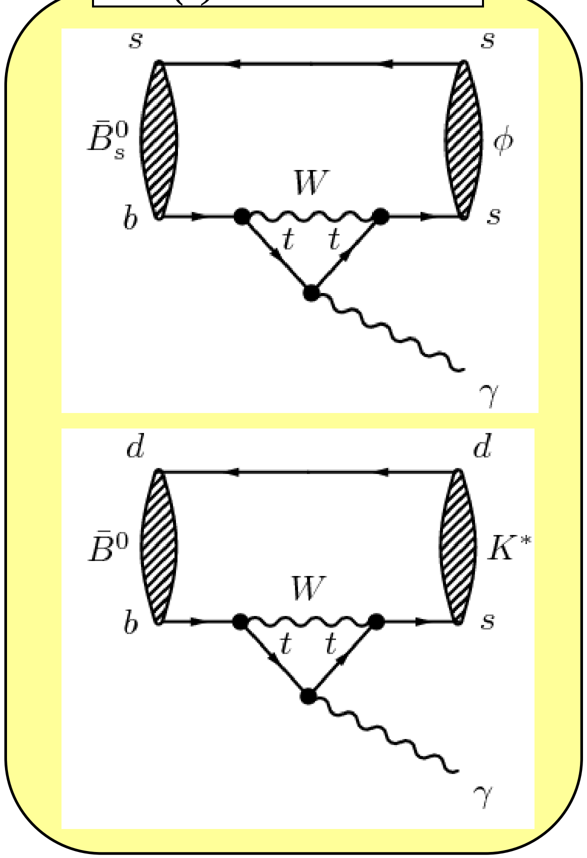


FCNC

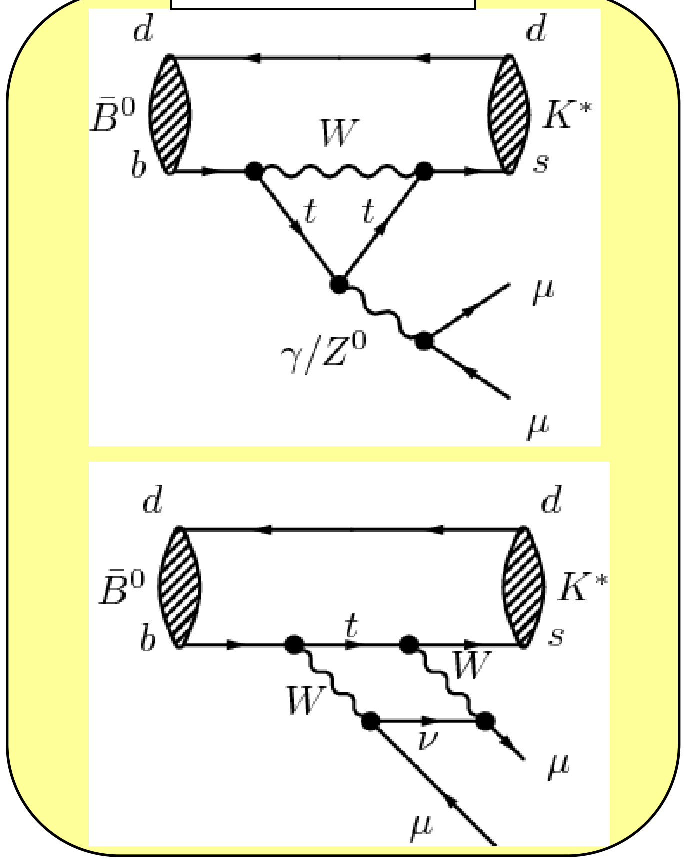


- Flavour Changing Neutral Current
- Occur in SM only through loop diagrams
- New Physics can appear at same order as SM

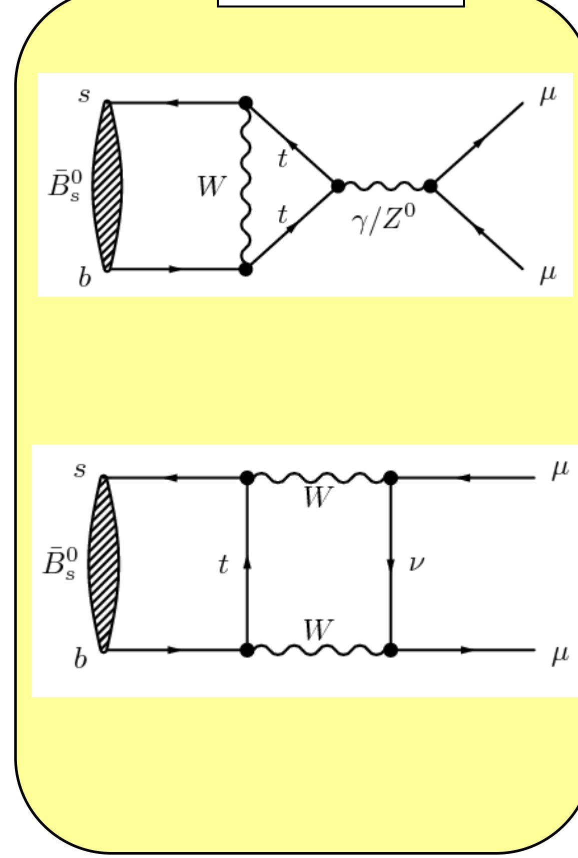
$B^0_{(s)} \to K^*(\varphi)\gamma$

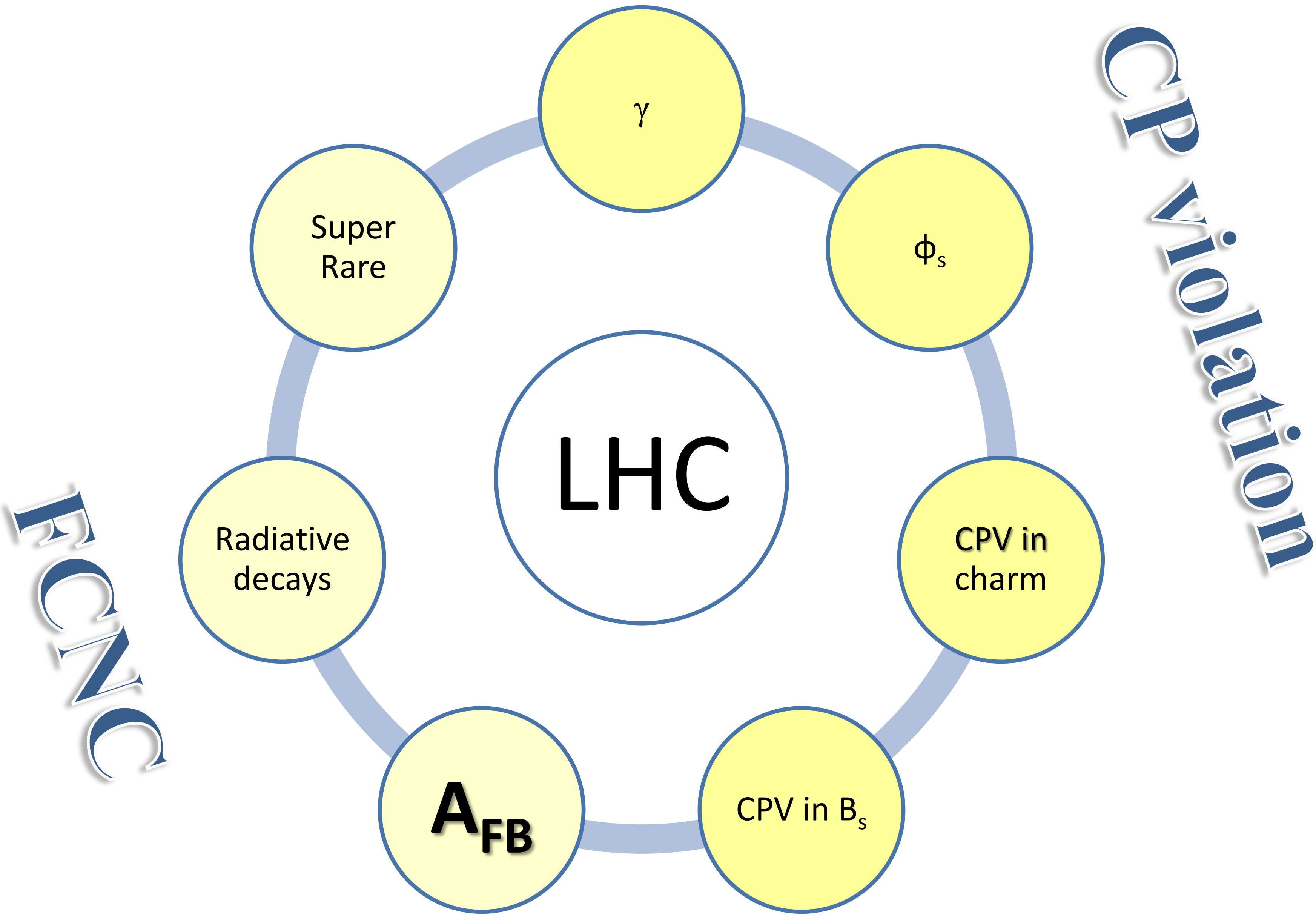


$B^0 \to K^*\mu\mu$

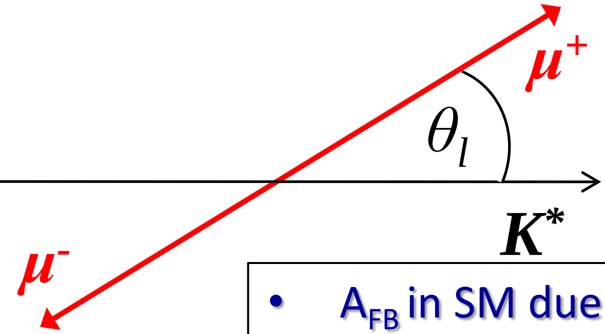


$B^0_s \to \mu\mu$

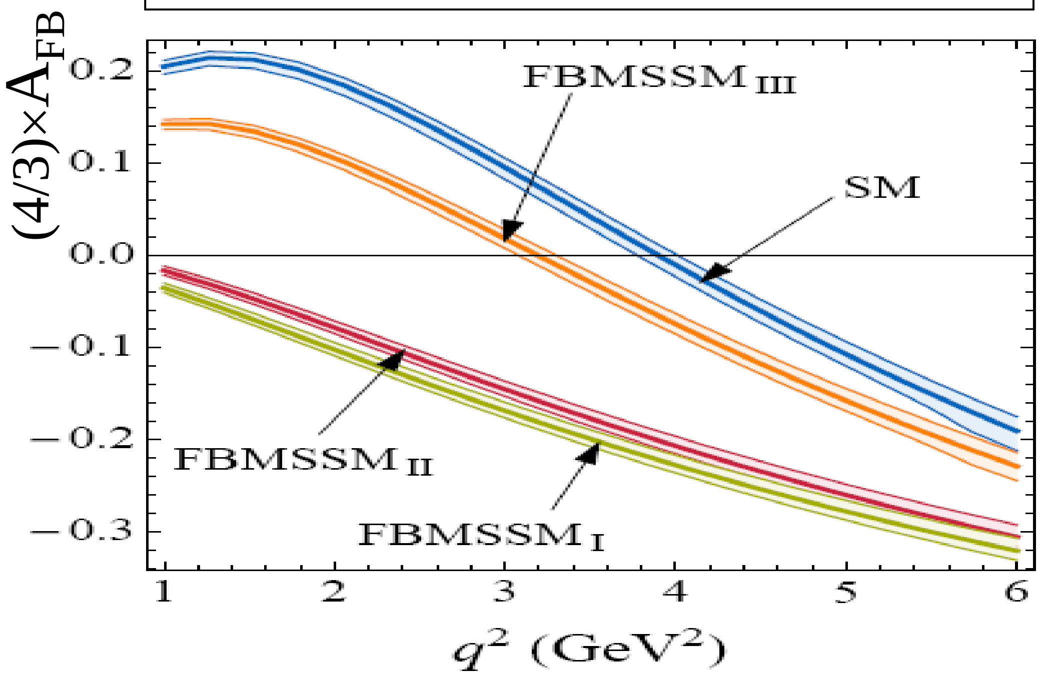



LHC
γ
φs
CPV in charm
CPV in Bs
AFB
Radiative decays
Super Rare
CP violation
FCNC

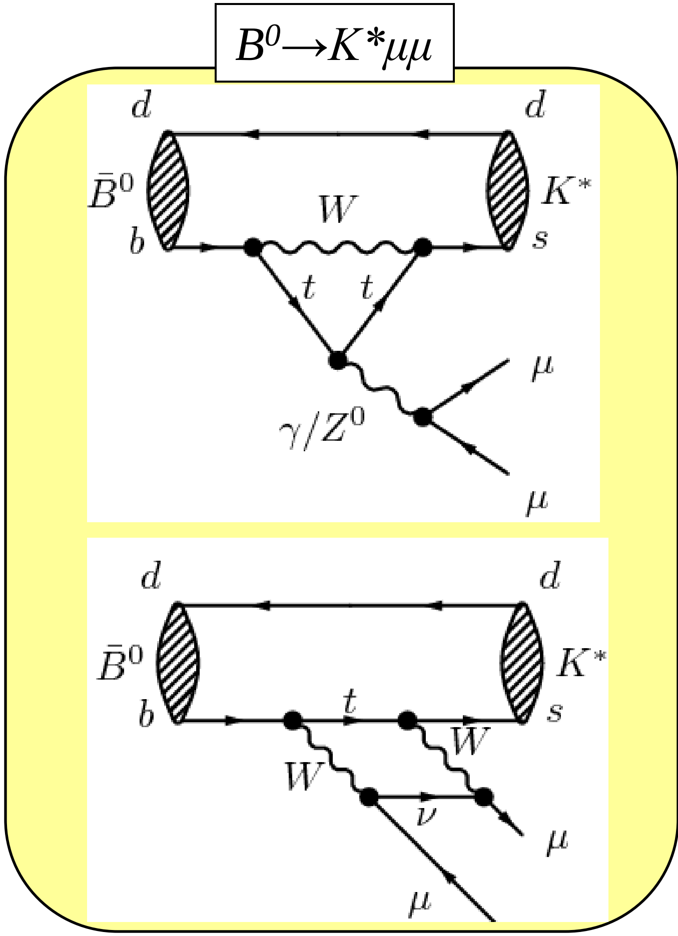
FCNC: $B^0 \rightarrow K^* \mu\mu$



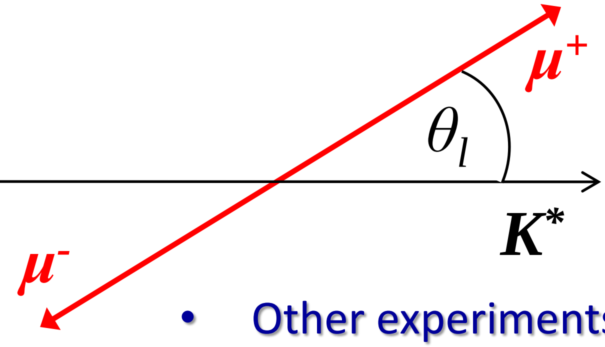
- A_{FB} in SM due to V-A coupling
- Hadronic uncertainties cancel in forward-backward asymmetry A_{FB}
- Sensitive to many NP models
  - Example:



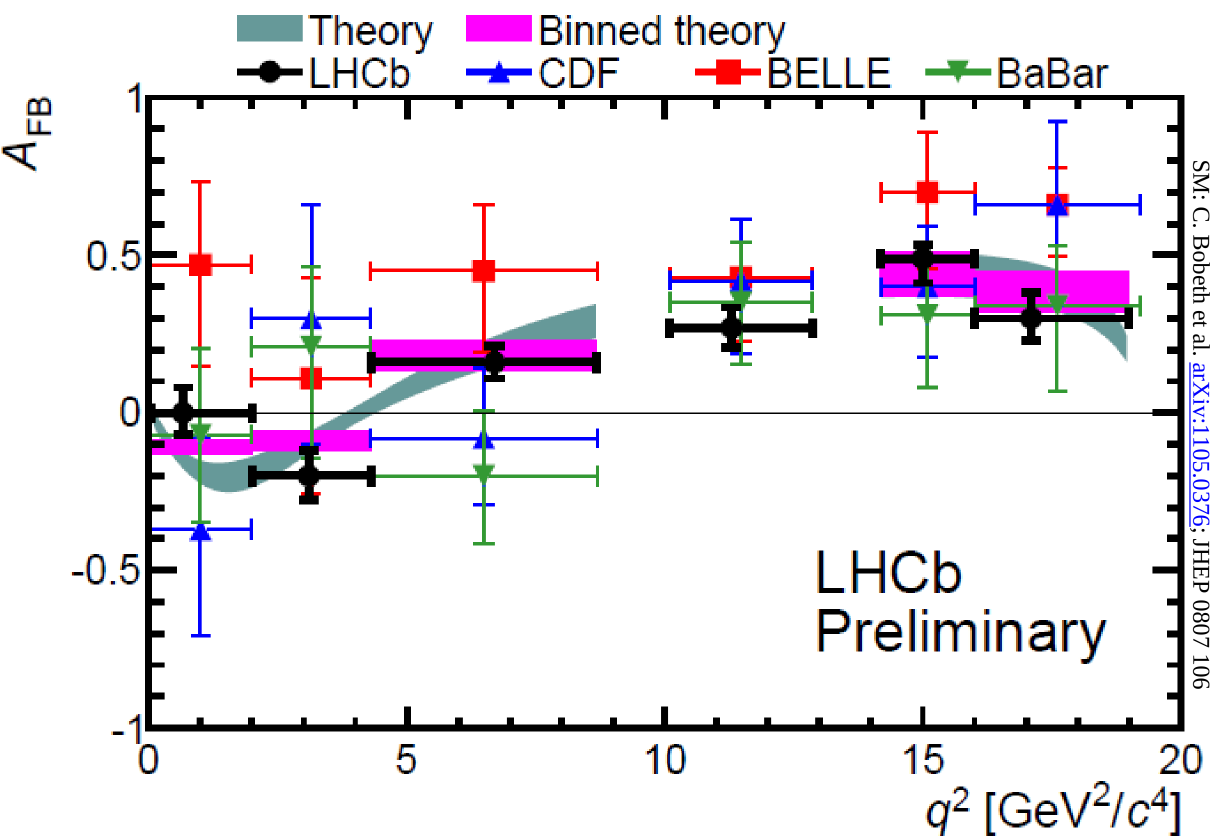
W.Altmannshofer *et al.*, JHEP 0901:019,2009

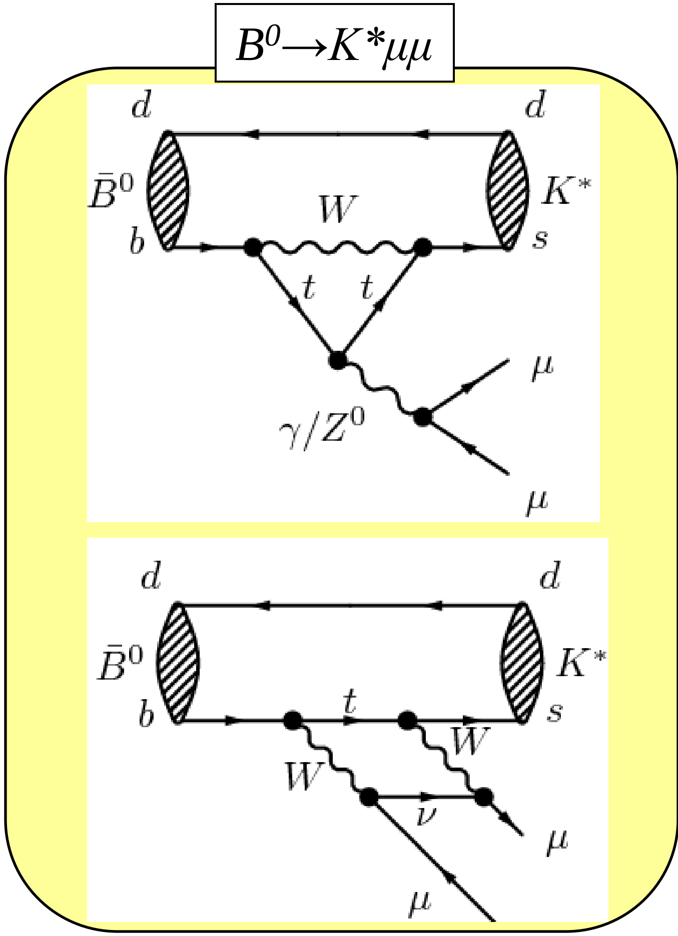


FCNC: $B^0 \to K^* \mu\mu$



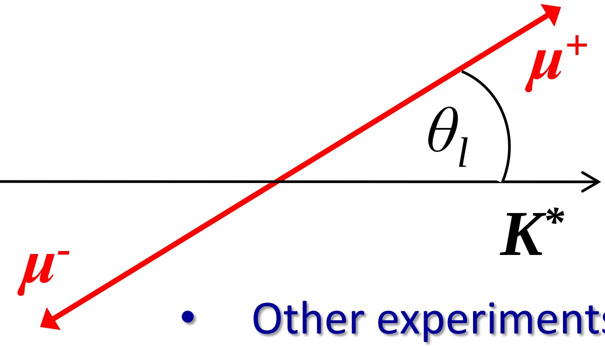
- Other experiments show $A_{FB}>0$ at low q^2





$A_{FB}(K^* \mu\mu)$ LHCb-CONF-2012-008

FCNC: $B^0 \to K^* \mu\mu$



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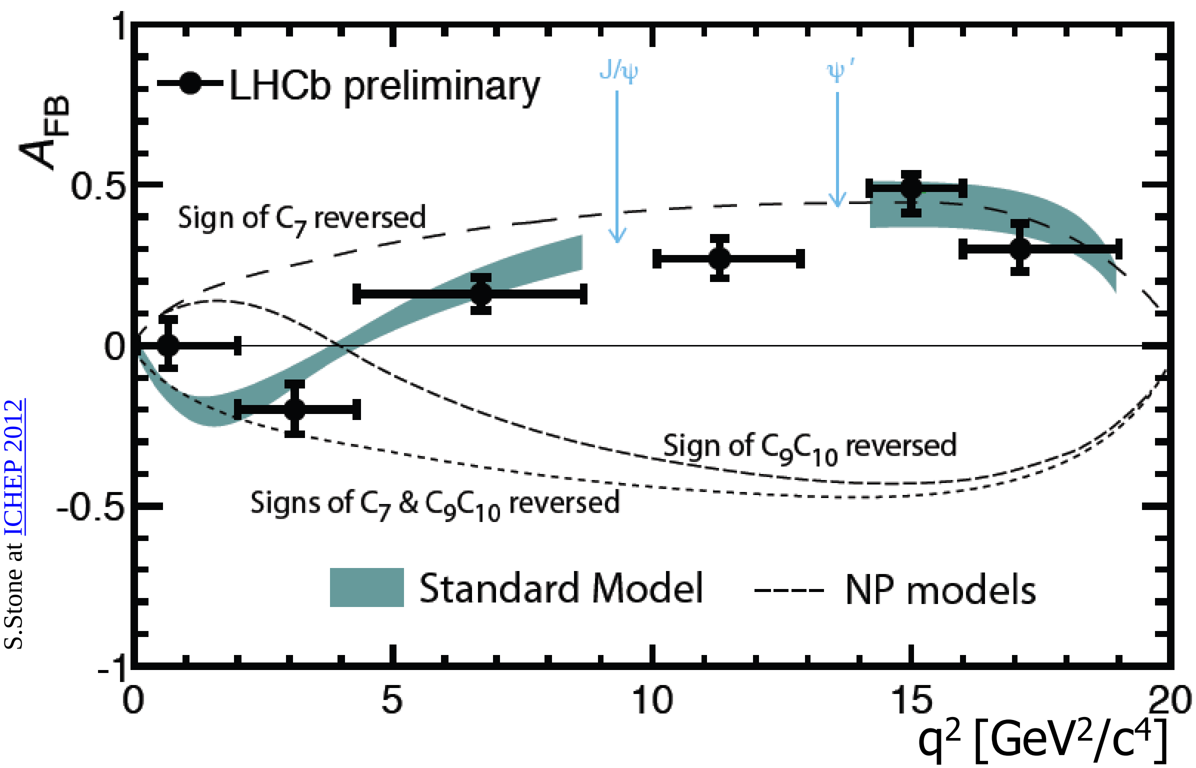
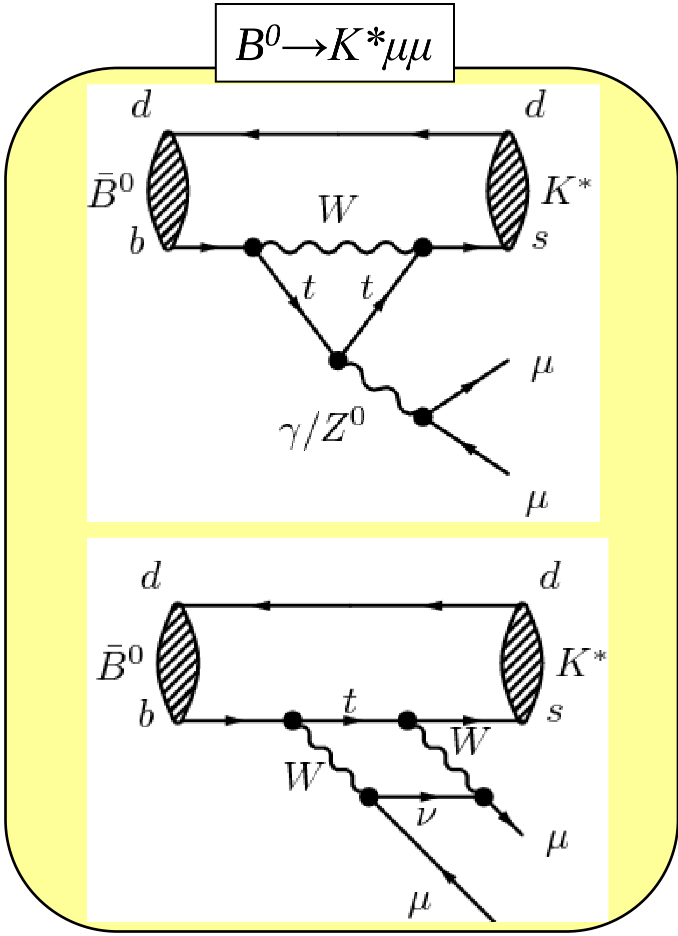
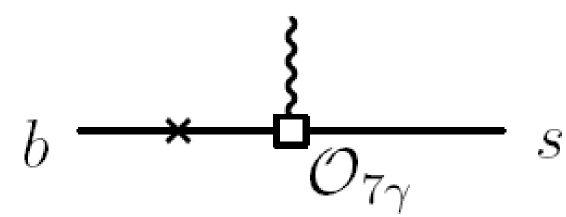


S.Stone at ICHEP 2012

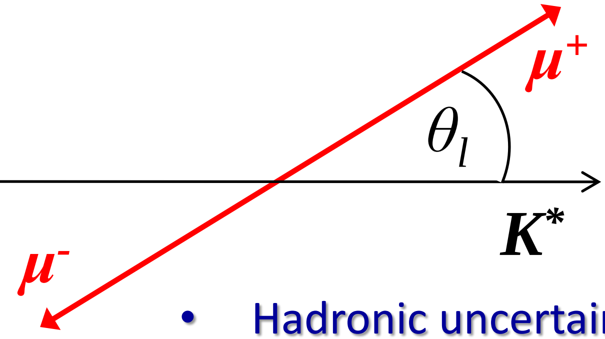




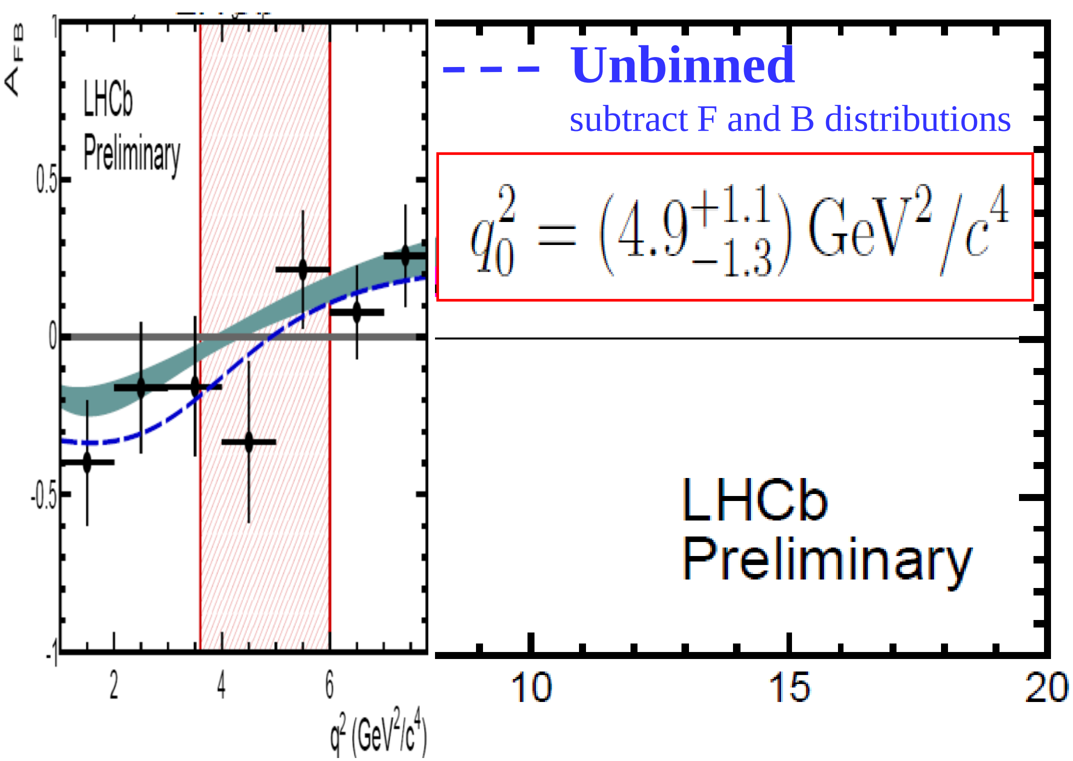
NB: *Size* of C_7 constrained by $BR(B^0 \to K^*\gamma)$ but not the *sign*.

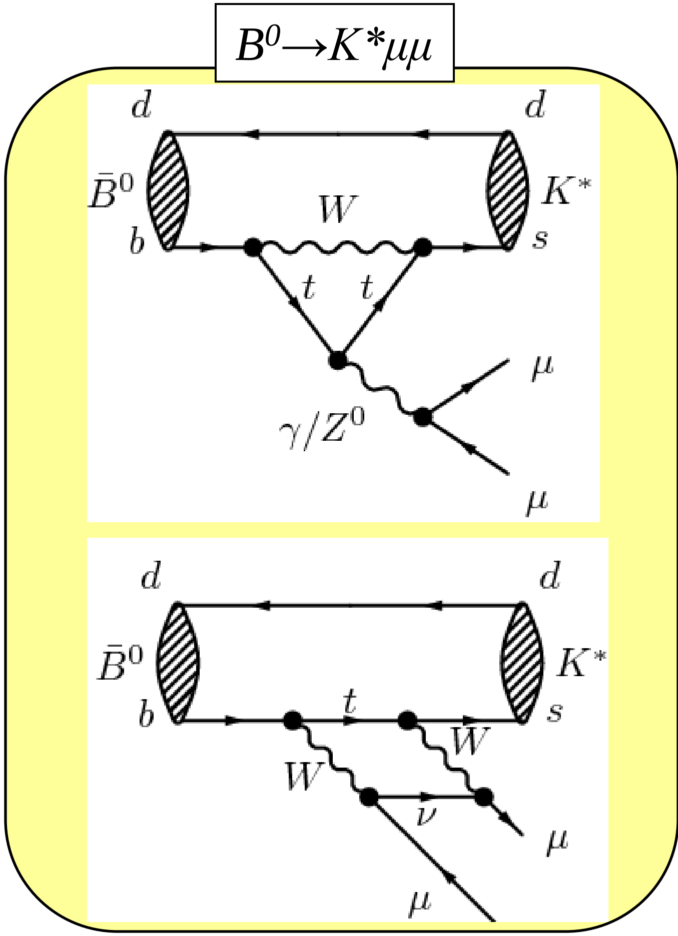
$A_{FB}(K^* \mu\mu)$ LHCb-CONF-2012-008

FCNC: $B^0 \to K^*\mu\mu$



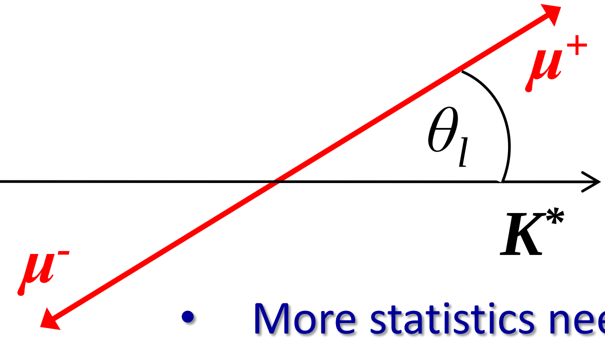
- Hadronic uncertainties cancel in forward-backward asymmetry A_{FB}
- First measurement of zero-crossing point



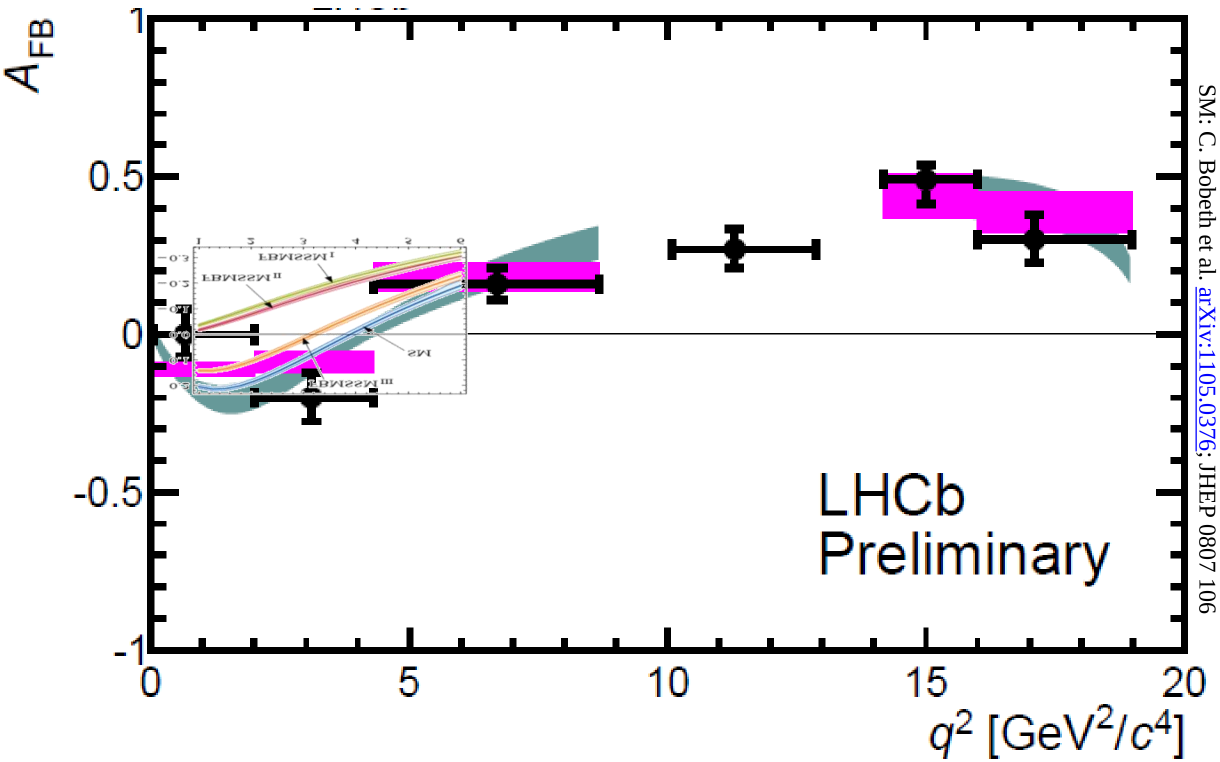


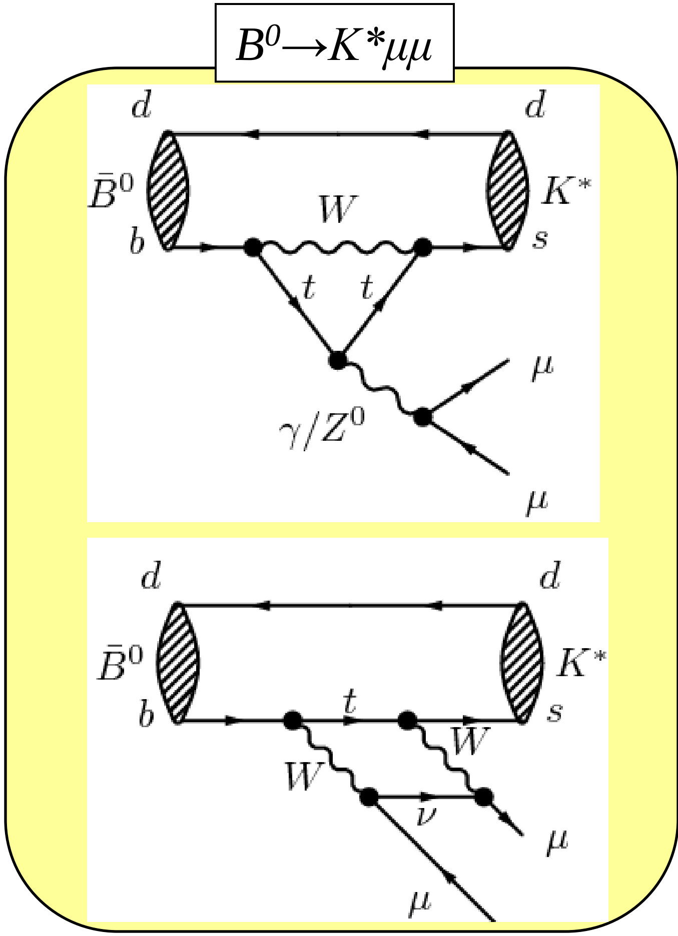
$A_{FB}(K^*\mu\mu)$ LHCb-CONF-2012-008

FCNC: $B^0 \to K^* \mu\mu$



- More statistics needed to distinguish NP models!





$A_{FB}(K^* \mu\mu)$ LHCb-CONF-2012-008

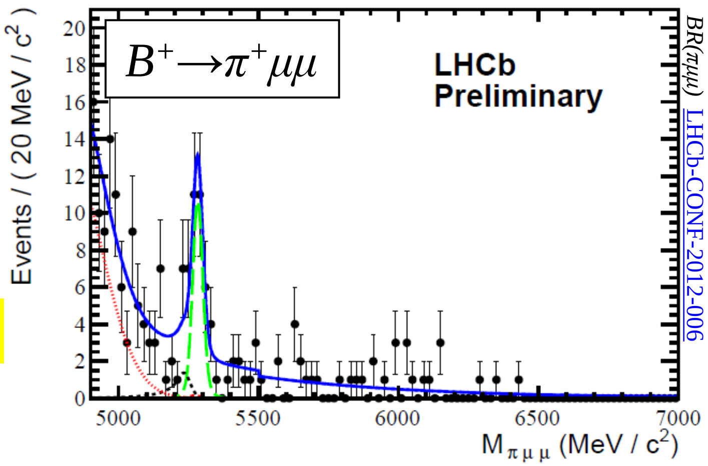
FCNC: $B^0 \to K^*\mu\mu$ and friends

1) First observation of $B^+ \to \pi^+\mu\mu$

- Prediction: $BR(B^+ \to \pi^+\mu\mu) = 1.96 \pm 0.21 \times 10^{-8}$ Song,Lu,Lu Com.Th.Phys. 50 (2008) 696
- Rarest B decay ever observed!

$$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-) = (2.4 \pm 0.6\ (\text{stat}) \pm 0.2\ (\text{syst})) \times 10^{-8}$$

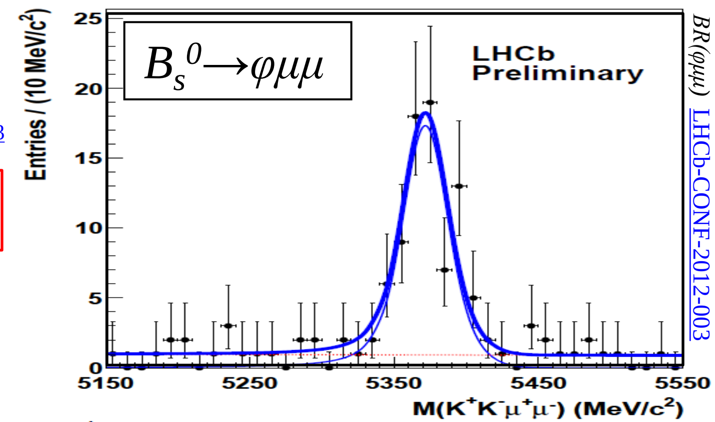
5.2σ



2) Observation of $B_s^0 \to \varphi\mu\mu$

- Prediction: $BR(B_s^0 \to \varphi\mu\mu) = 1.61 \times 10^{-6}$ Geng,Lui JPG29:1103,2003

$$\mathcal{B}(B_s^0 \to \phi\mu\mu) = (0.78 \pm 0.10(\text{stat}) \pm 0.06(\text{syst}) \pm 0.28(\mathcal{B})) \times 10^{-6}$$

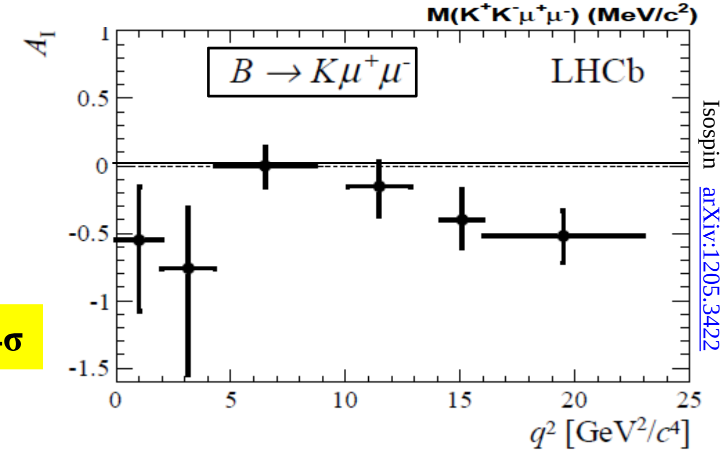


3) Isospin asymmetry: B^0 vs B^+ difference?

$$A_I = \frac{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) - \frac{\tau_0}{\tau_+}\mathcal{B}(B^+ \to K^{(*)+}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) + \frac{\tau_0}{\tau_+}\mathcal{B}(B^+ \to K^{(*)+}\mu^+\mu^-)}$$

- **No** isospin asymmetry in K^* channels
  - SM prediction: -1%
- Isospin asymmetry in K channels
  - Deficit in N($B^0 \to K_s^0\mu\mu$)
  - No precise SM prediction for A_I; expect close to zero…

4.4σ



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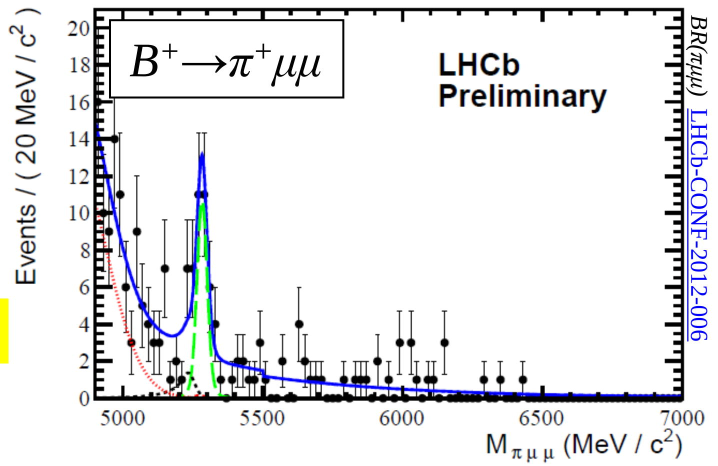

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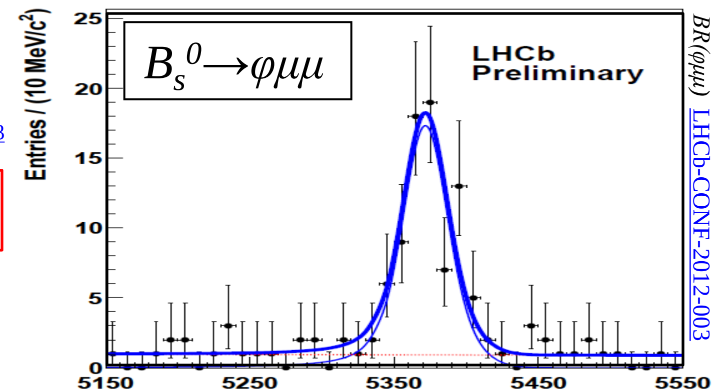

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- **No** isospin asymmetry in *K** channels
  - SM prediction: -1%
- Isospin asymmetry in *K* channels
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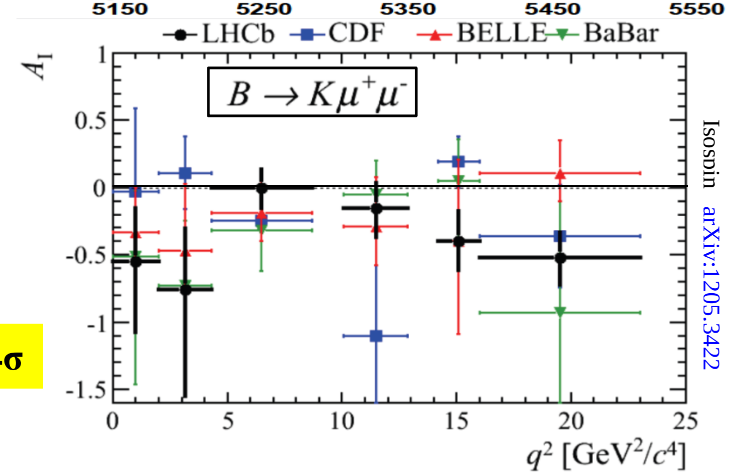
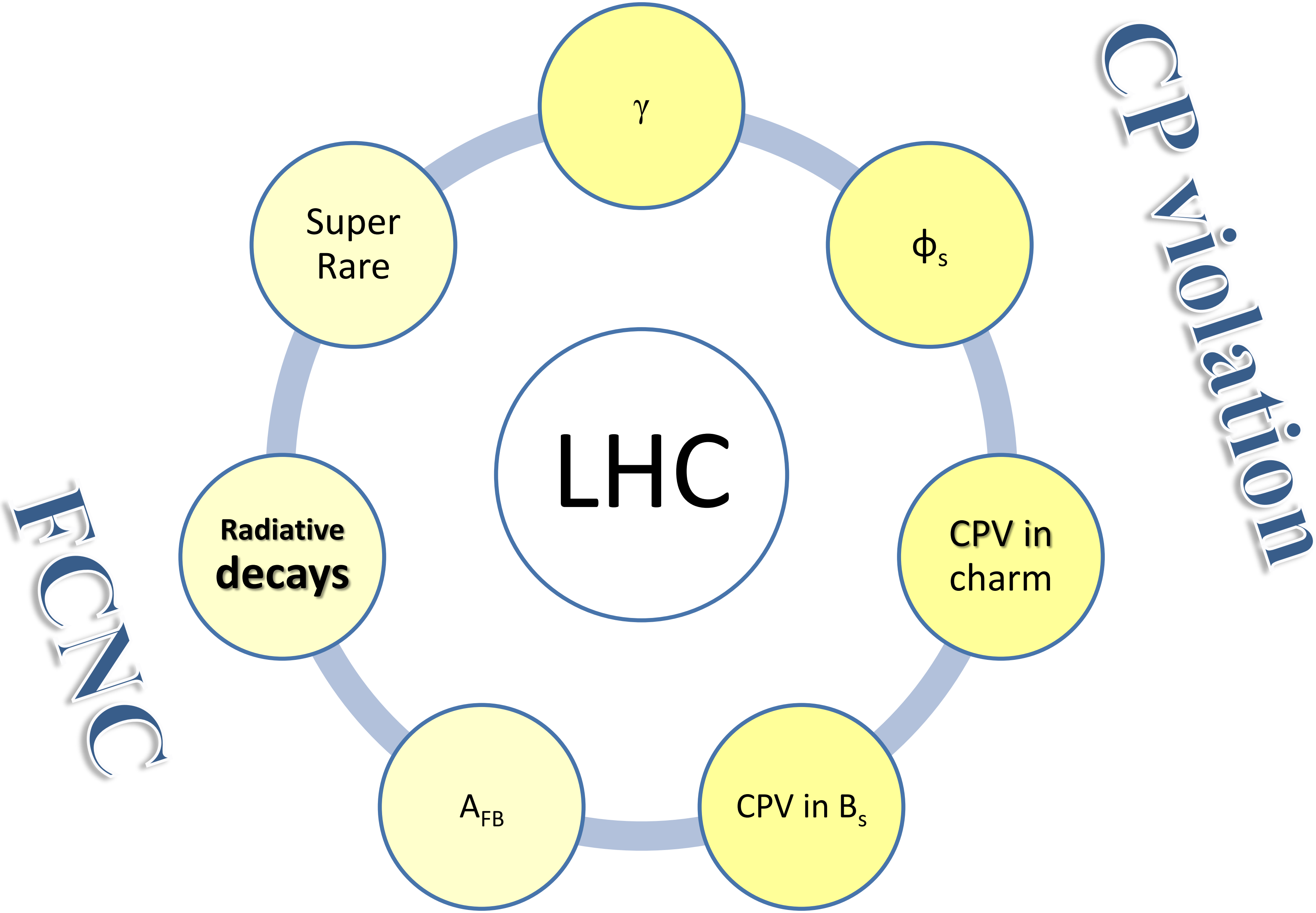


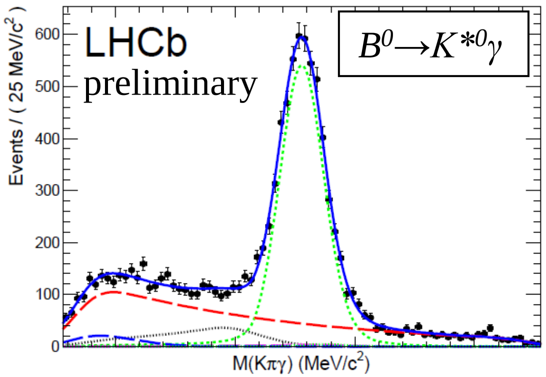

LHC
γ
ϕ_s
CPV in charm
CPV in B_s
A_{FB}
Radiative decays
Super Rare
CP violation
FCNC

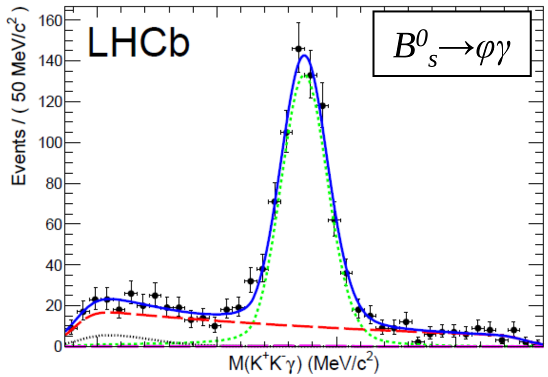
FCNC: radiative decays

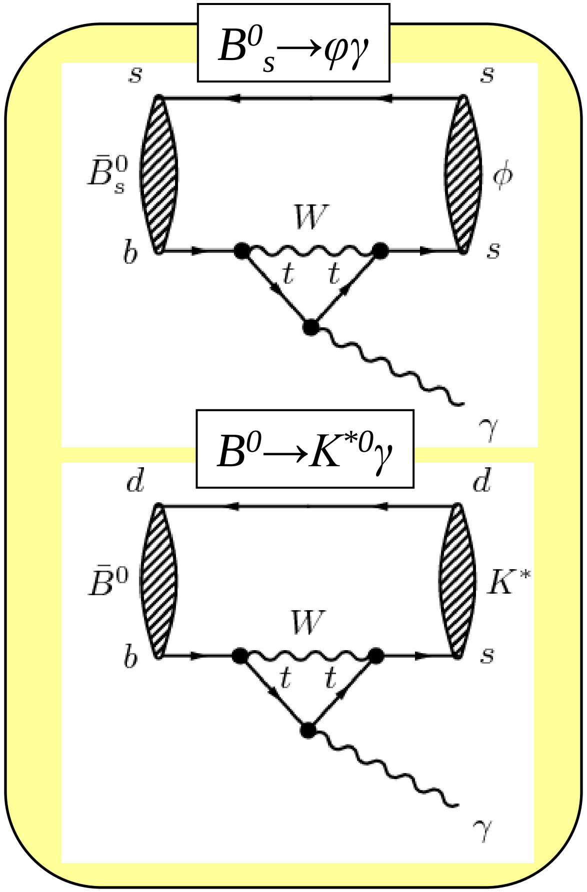
1) Measurement of BR($B^0_s \to \varphi\gamma$)

$$\mathcal{B}(B^0_s \to \phi\gamma) = (3.3 \pm 0.3) \times 10^{-5}$$

($BR^{SM} = (4.3 \pm 1.4) \times 10^{-5}$)
Ali et al, EPJ C55 (2008) 577



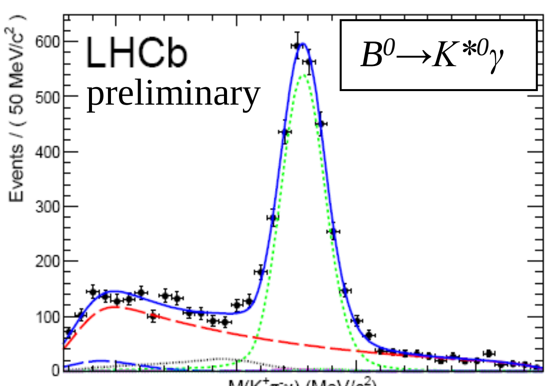


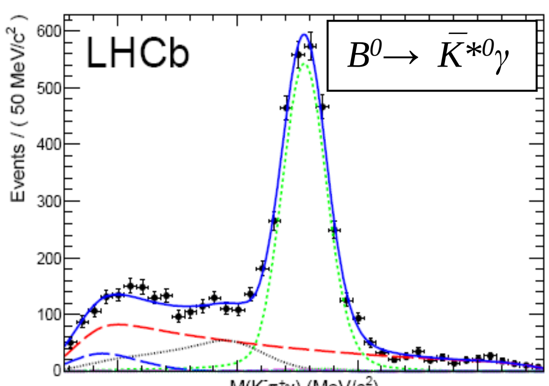


2) Direct CP asymmetry of $B^0 \to K^{*0}\gamma$

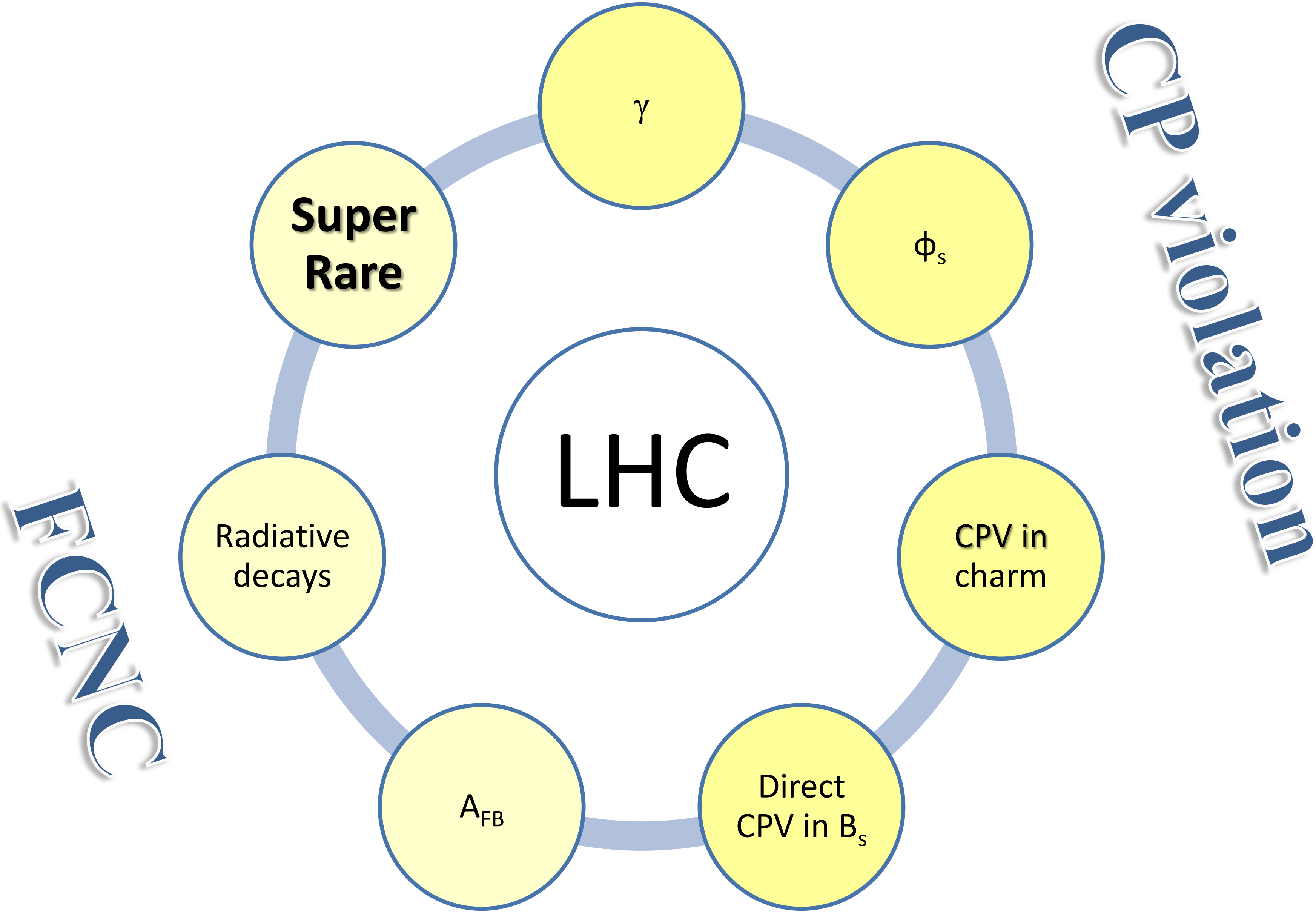
$$\mathcal{A}_{CP}(B^0 \to K^{*0}\gamma) = (0.8 \pm 1.7(\text{stat}) \pm 0.9(\text{syst}))\%$$

($A_{CP}^{SM} = (-0.61 \pm 0.43)\%$)
Matsumori et al, PRD72 (2005) 014013





LHCb 1 fb-1 LHCb-PAPER-2012-019



LHC
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ϕ_s
CPV in charm
Direct CPV in B_s
A_{FB}
Radiative decays
Super Rare
CP violation
FCNC

Super Rare: searches

- Search for non-resonant decay:
  - $BR(B_s^0 \to \mu^+\mu^-\mu^+\mu^-)_{\text{non-res}} < 1.3 \times 10^{-8}$
- Rare charm (@ 90% CL):
  - CMS: $BR(D^0 \to \mu^+\mu^-) < 5.4 \times 10^{-7}$
  - LHCb: $BR(D^0 \to \mu^+\mu^-) < 0.11 \times 10^{-7}$
- Rare? Forbidden!
  - $BR(\tau^+ \to \mu^+\mu^-\mu^+) < 7.8 \times 10^{-8}$
- Main focus: $B_s^0 \to \mu^+\mu^-$

LHCb 4mu LHCb-CONF-2012-010
LHCb D LHCb-CONF-2012-005
LHCb tau LHCb-CONF-2012-015
CMS D CMS PAS BPH-11-017
Babar D arXiv:1206.5419

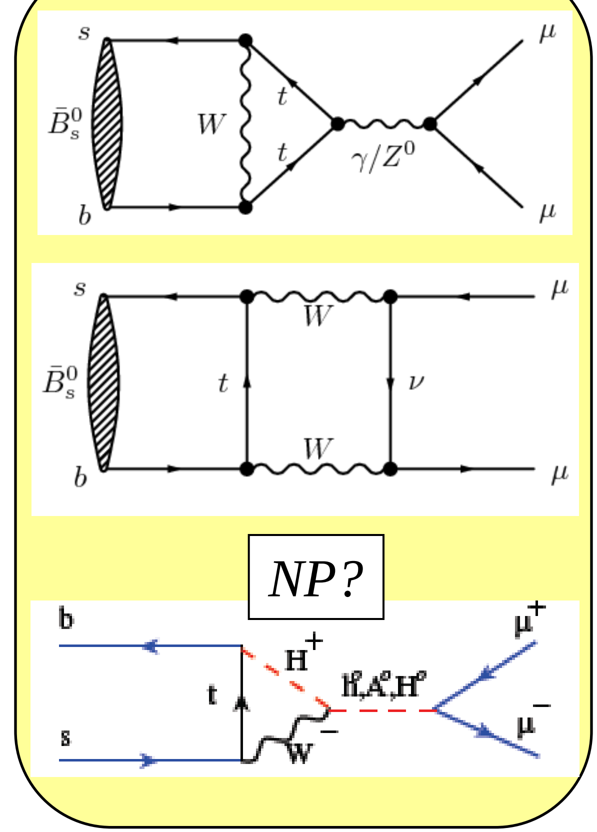
Super Rare: $B_s^0 \to \mu^+\mu^-$

- **Highly suppressed in the SM**
  - Higher order
  - Helicity suppressed
- SM: $BR(B_s^0 \to \mu^+\mu^-) = 3.2 \times 10^{-9}$
  - remember rarest to date: $BR(B^+ \to \pi^+\mu\mu) = 2.4 \times 10^{-8}$

- BR strongly enhanced in many models
- i.e. MSSM at large tanβ: $\propto \tan^6\beta / m_A^4$
  - ➢ Example: 10x higher BR for tanβ=50(20), m_{H+}=800(200) GeV

A.Buras, arXiv:1106.0998

$B^0_s \to \mu\mu$



Intermezzo: Subtlety regarding BR's

- Subtlety…:
  - We measure the <u>time-integrated</u> branching ratio
  - But the theoretical prediction holds at <u>t=0</u>

➢ Not equal if $\Delta\Gamma_s \neq 0$!

➢ Different by 8.8%* depending on CP eigenvalue:

($y_s = \Delta\Gamma_s/2\Gamma_s = 0.088 \pm 0.014$) LHCb-CONF-2012-002

$$\mathrm{BR}\left(B_s \to f\right)_{\mathrm{theo}} = \left[\frac{1-y_s^2}{1+\mathcal{A}^f_{\Delta\Gamma}\, y_s}\right] \mathrm{BR}\left(B_s \to f\right)_{\mathrm{exp}}$$

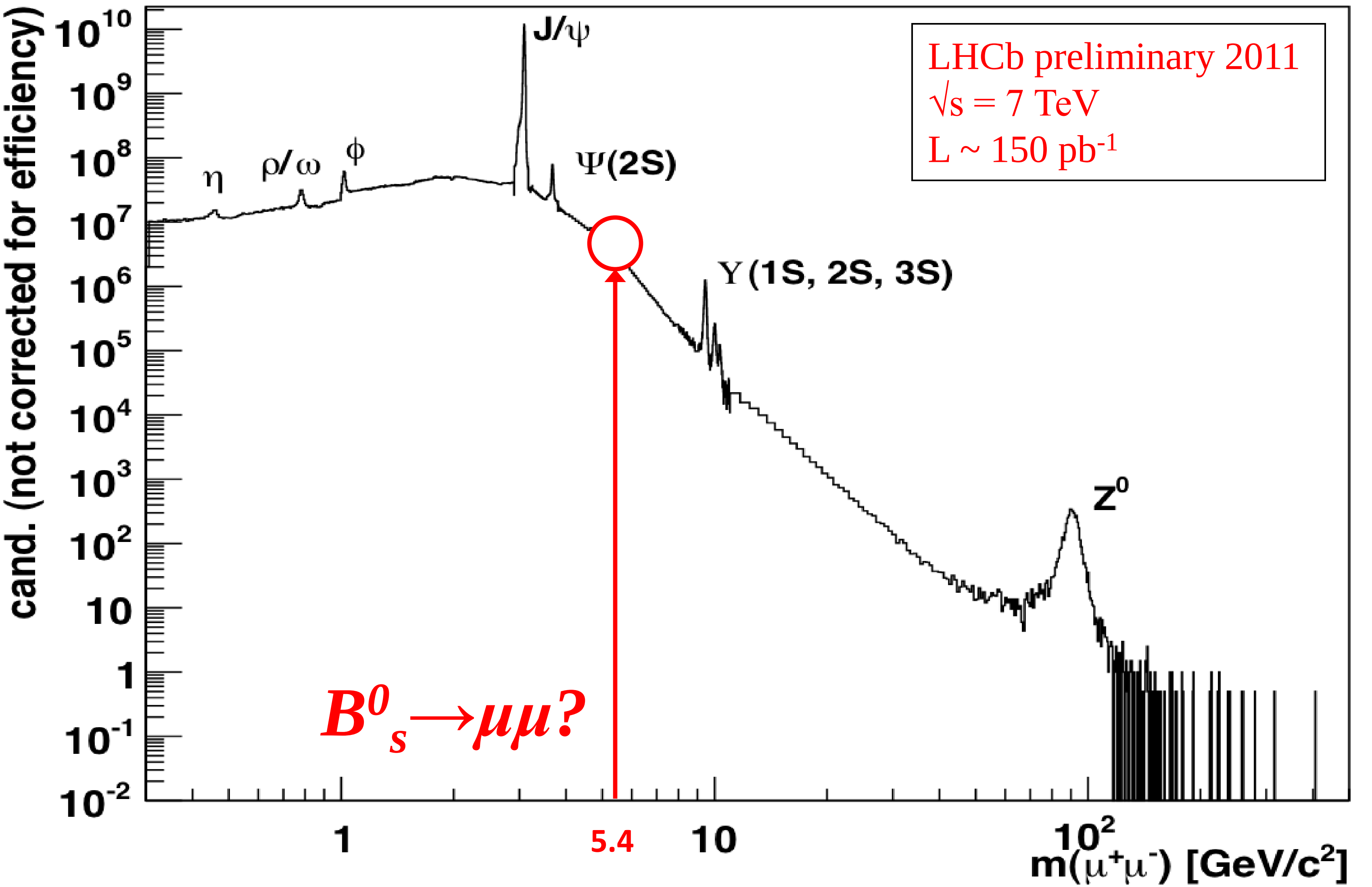
- Example: what is BR($K^0 \to \pi\pi$) ??
  - Quite different for t=0 (~100%)
  - Compared to time-integrated (~50%)

- $B_s^0 \to \mu^+\mu^-$ is CP-even
- Independent of μ-helicity
- Should compare to SM value of <u>3.5 x 10^{-9}</u> !

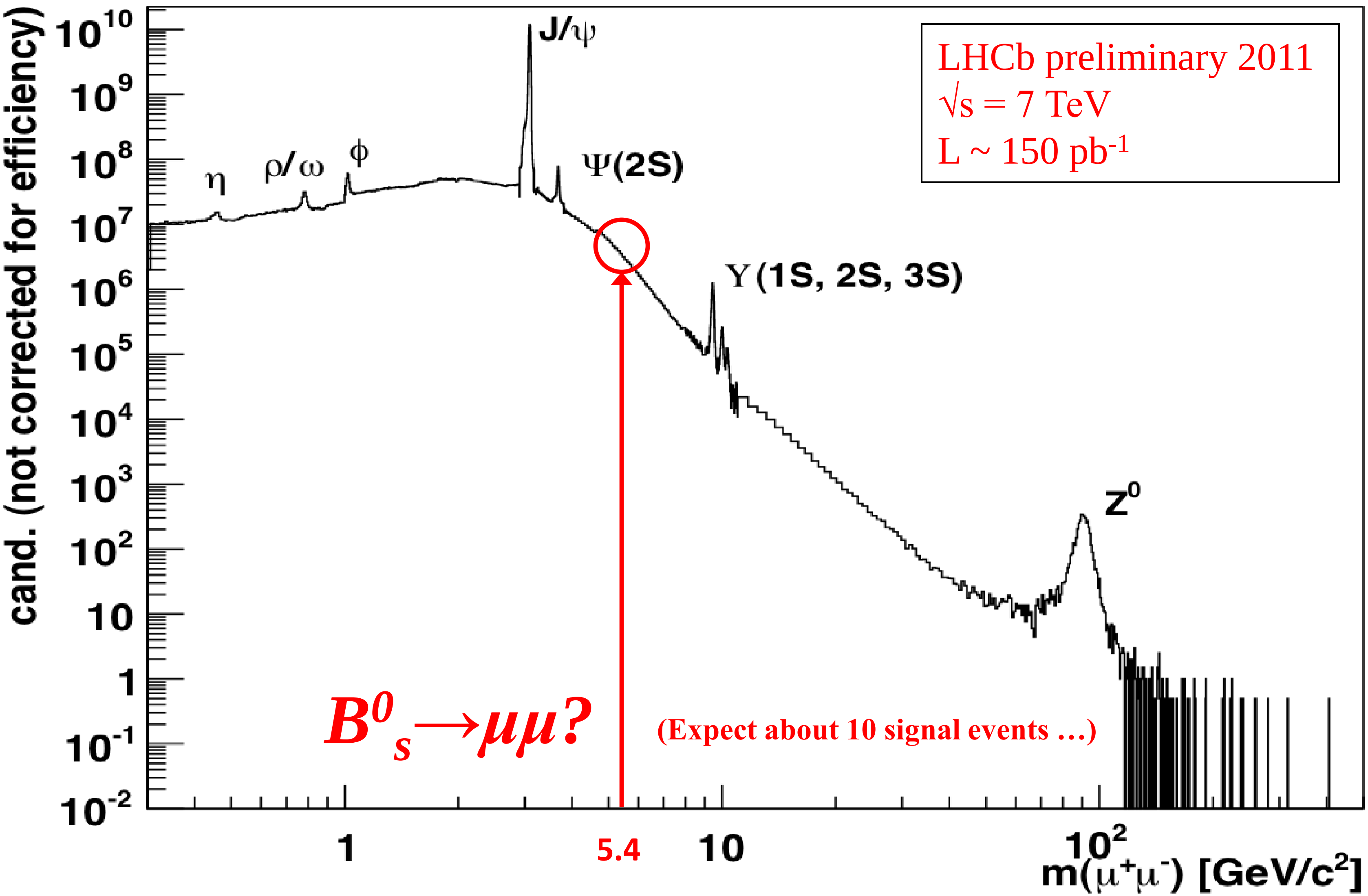
$B_s \to f$	$\mathrm{BR}(B_s \to f)_{\mathrm{exp}}$	$\mathcal{A}^f_{\Delta\Gamma}(\mathrm{SM})$	$\mathrm{BR}(B_s \to f)_{\mathrm{theo}}/\mathrm{BR}(B_s \to f)_{\mathrm{exp}}$ From Eq. (9)	From Eq. (11)
$J/\psi f_0(980)$	$(1.29^{+0.40}_{-0.28}) \times 10^{-4}$ [18]	0.9984 ± 0.0021 [14]	0.912 ± 0.014	0.890 ± 0.082 [6]
$J/\psi K_S$	$(3.5 \pm 0.8) \times 10^{-5}$ [7]	0.84 ± 0.17 [15]	0.924 ± 0.018	N/A
$D_s^- \pi^+$	$(3.01 \pm 0.34) \times 10^{-3}$ [9]	0 (exact)	0.992 ± 0.003	N/A
K^+K^-	$(3.5 \pm 0.7) \times 10^{-5}$ [18]	-0.972 ± 0.012 [13]	1.085 ± 0.014	1.042 ± 0.033 [19]
$D_s^+ D_s^-$	$(1.04^{+0.29}_{-0.26}) \times 10^{-2}$ [18]	-0.995 ± 0.013 [16]	1.088 ± 0.014	N/A
	$\mathrm{BR}(B_s \to f)_{\mathrm{exp}}$		$\mathrm{BR}(B_s \to f)_{\mathrm{theo}}$	
$\mu^+\mu^-$	3.5×10^{-9}	$+1$	3.2×10^{-9}	

De Bruyn, Fleischer, Knegjens, Koppenburg, Merk, Pellegino, NT, arXiv:1204.1735
arXiv:1204.1737 Accepted by PRL

Search for $B_s^0 \to \mu^+\mu^-$

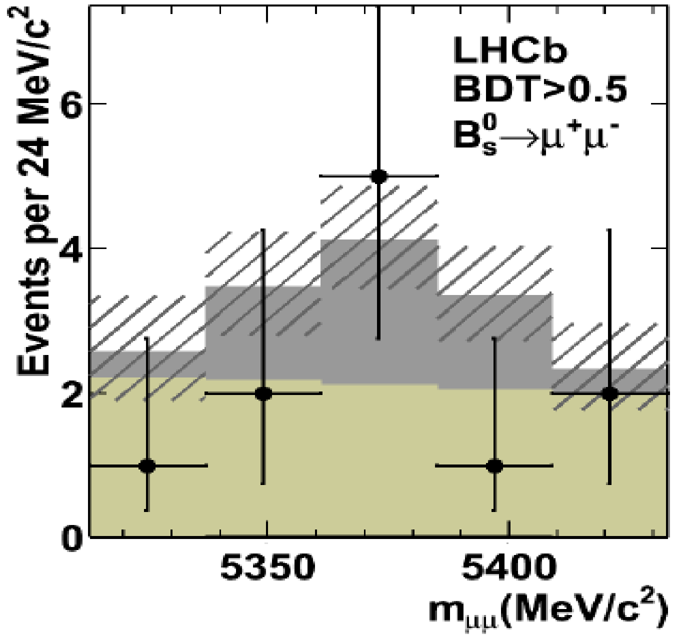


Search for $B_s^0 \to \mu^+\mu^-$

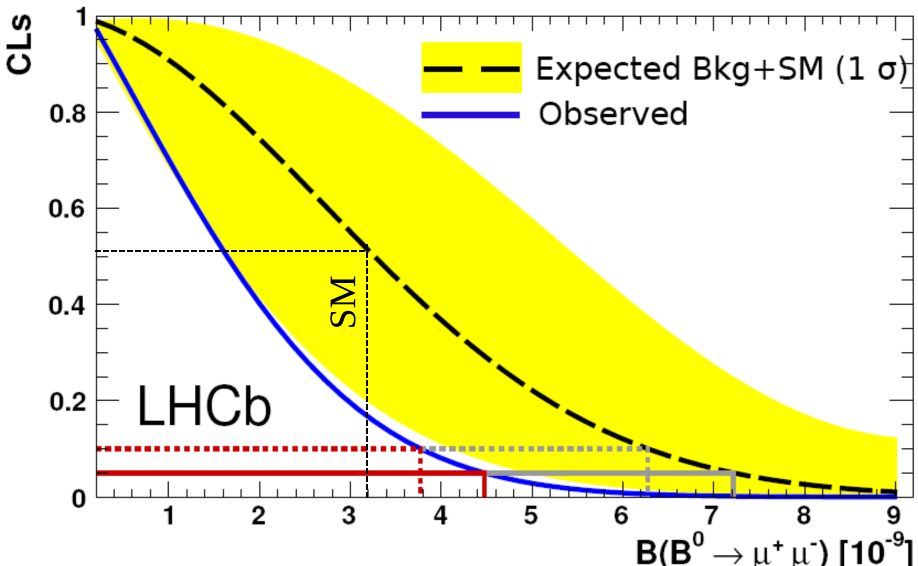


Search for $B_s^0 \to \mu^+\mu^-$: LHCb

- "Enriched" half of the sample, BDT>0.5
- Observe 11 events ($m_B \pm 60$ MeV), expect:
  - ~10.4 background
  - ~5.3 SM



➢ Few events, so strong limit:
  - Comparison with SM: compatible at 1σ
  - Comparison with bkgd only: p-value (1-CL_b)=18%



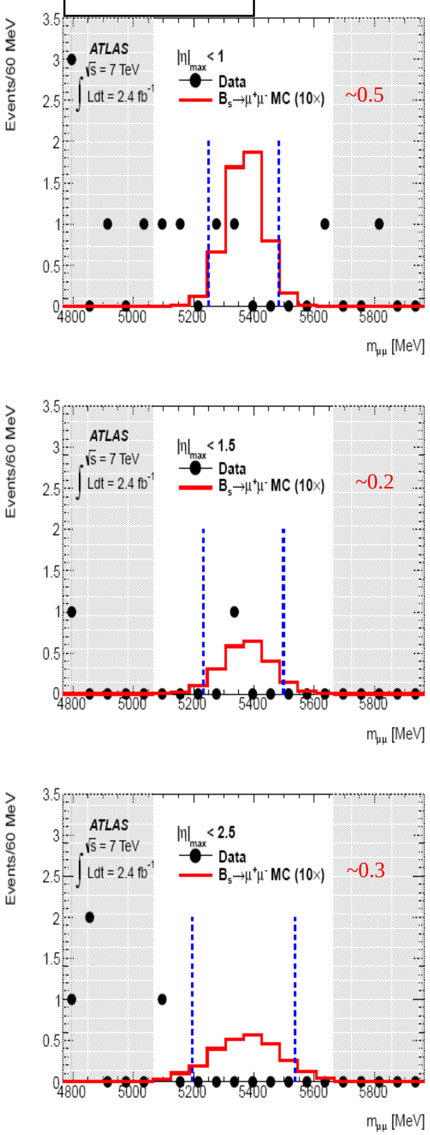
Mode	Limit	at 95 % CL
$B_s^0 \to \mu^+\mu^-$	Exp. bkg+SM	7.2×10^{-9}
	Exp. bkg	3.4×10^{-9}
	Observed	4.5×10^{-9}

➢ Close to the SM value!

LHCb 1 fb^{-1} PRL 108 (2012) 231801

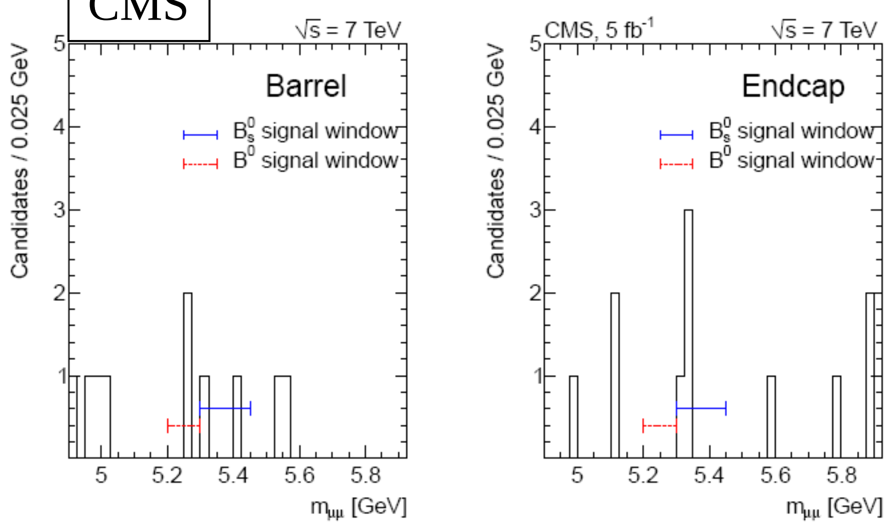
Search for $B_s^0 \rightarrow \mu^+\mu^-$: ATLAS, CMS, LHCb

ATLAS

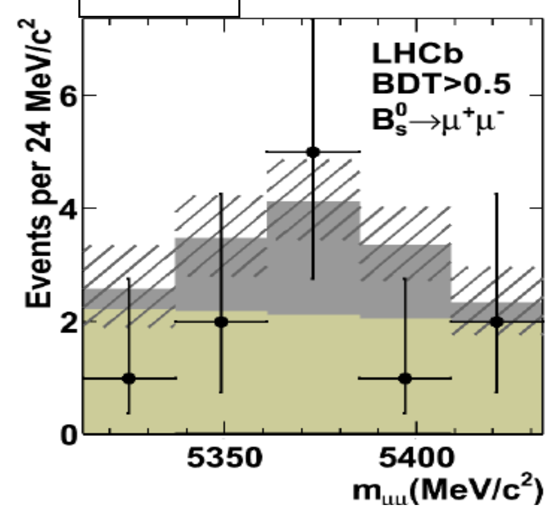


	ATLAS (bar+tr+endc)	CMS (bar+endc)	LHCb (BDT>0.5)
Lumi	2.4 fb^{-1}	5 fb^{-1}	1.0 fb^{-1}
$p^{\mu}_{T,min}$(GeV)	4 GeV	4 GeV	1.5 GeV
Mass window	~ ±130 MeV	±75 MeV	±60 MeV
N_{obs}	3	6	11
N_{exp}(sig)	~ 1 (estimated from histos, NT)	3.93	10.4
N_{exp}(bkgd)		1.99	5.3
Publication	PL B713 (2012) 387 arXiv:1204.0735	JHEP 04 033 (2012) arXiv:1203.3976	PRL 108, 231801 (2012) arXiv:1203.4493

CMS



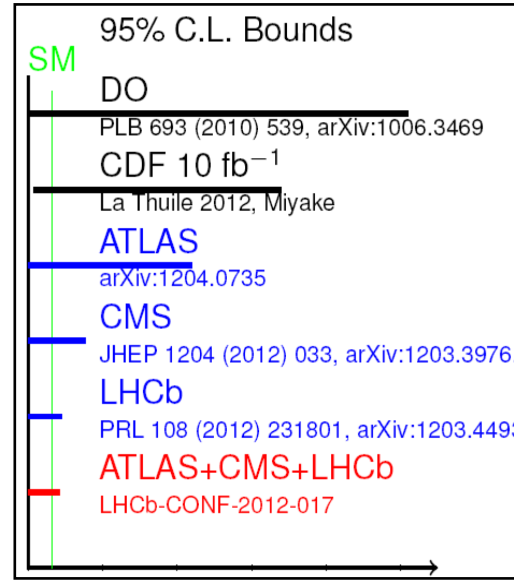
LHCb

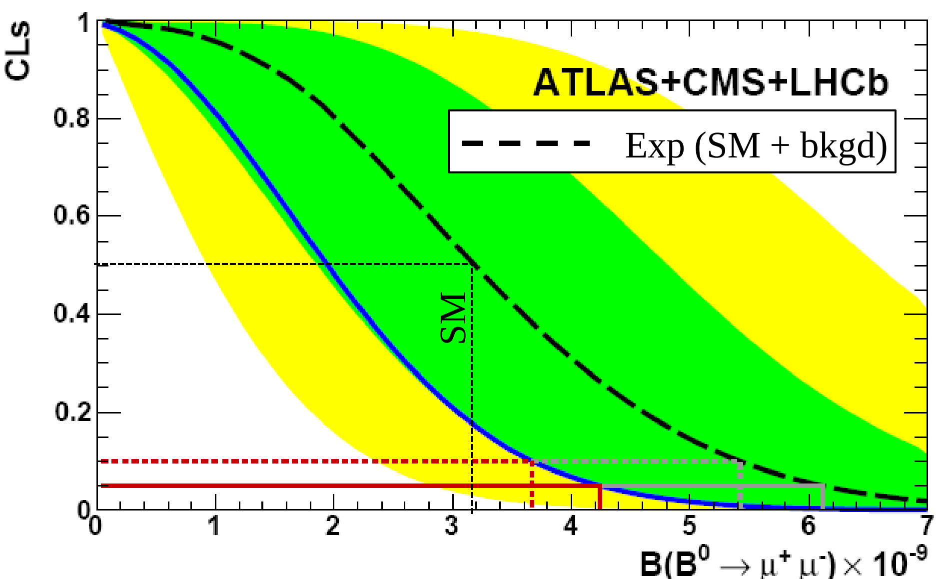


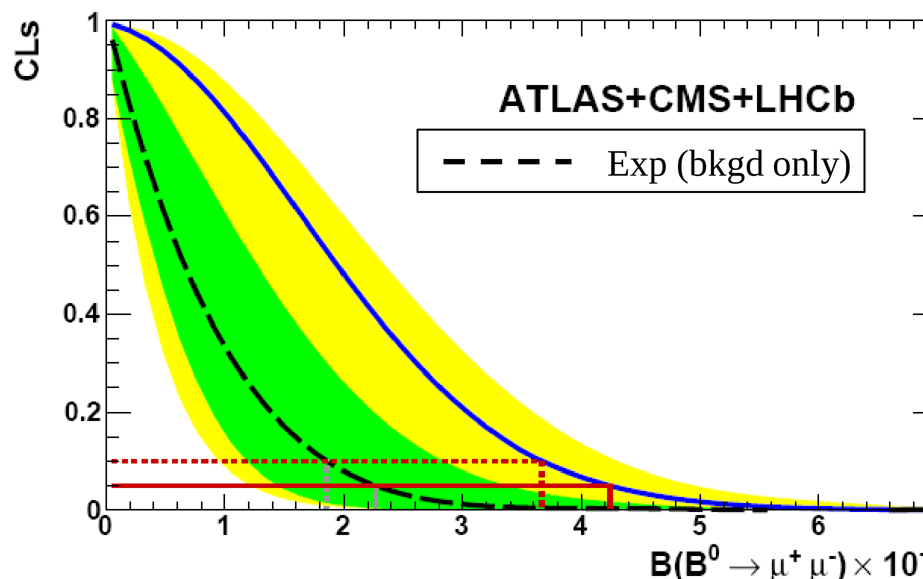
Search for $B_s^0 \rightarrow \mu^+ \mu^-$

- **Combination of LHCb, ATLAS and CMS**
  - **BR($B_s^0 \rightarrow \mu^+\mu^-$) < 4.2 x 10^{-9} @ 95% CL**
- Slight (2σ) 'excess' wrt bkd: p-value (1-CL_b) = 5%
- Compatible with SM within 1σ

Mode	Limit	ATLAS	CMS	LHCb 2010	LHCb 2011	Combined
$B_s^0 \rightarrow \mu^+\mu^-$ (10^{-9})	Bkg Only	23	(3.6)	65	3.4	2.3
	Bkg+SM		8.4		7.2	6.1
	Obs	22	7.7 (7.2)	56	**4.5**	**4.2**







Search for $B_s^0 \to \mu^+\mu^-$

- Combination of LHCb, ATLAS and CMS
  - **BR($B_s^0 \to \mu^+\mu^-$) < 4.2 x 10^{-9} @ 95% CL**
- Slight (2σ) 'excess' wrt bkd: p-value (1-CL_b) = 5%
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Mode	Limit	ATLAS	CMS	LHCb 2010	LHCb 2011	Combined
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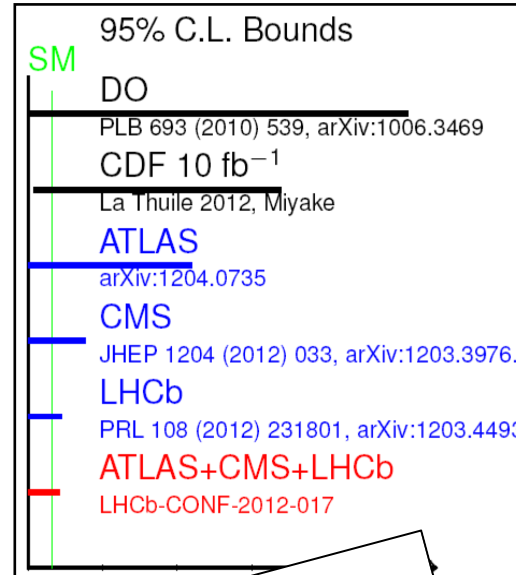
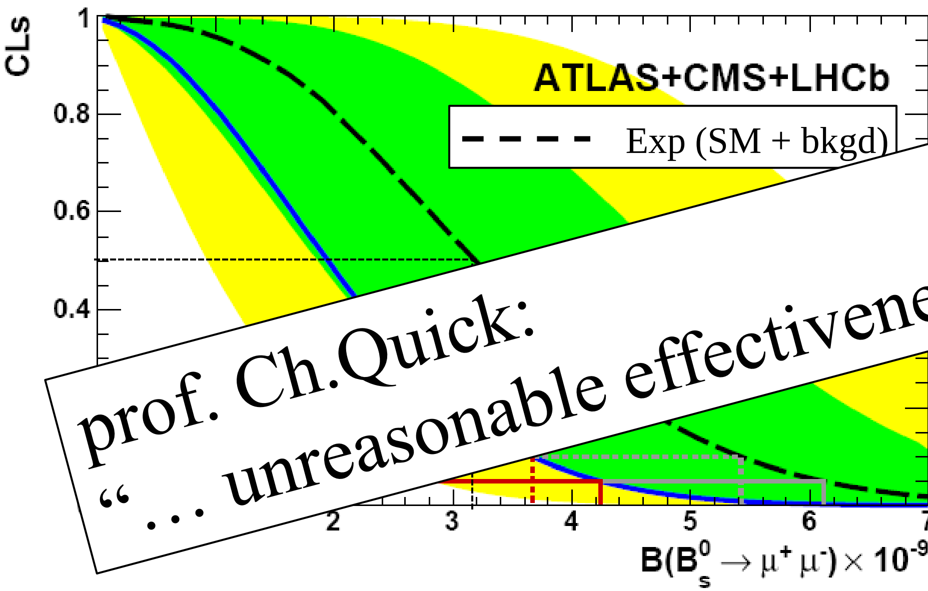
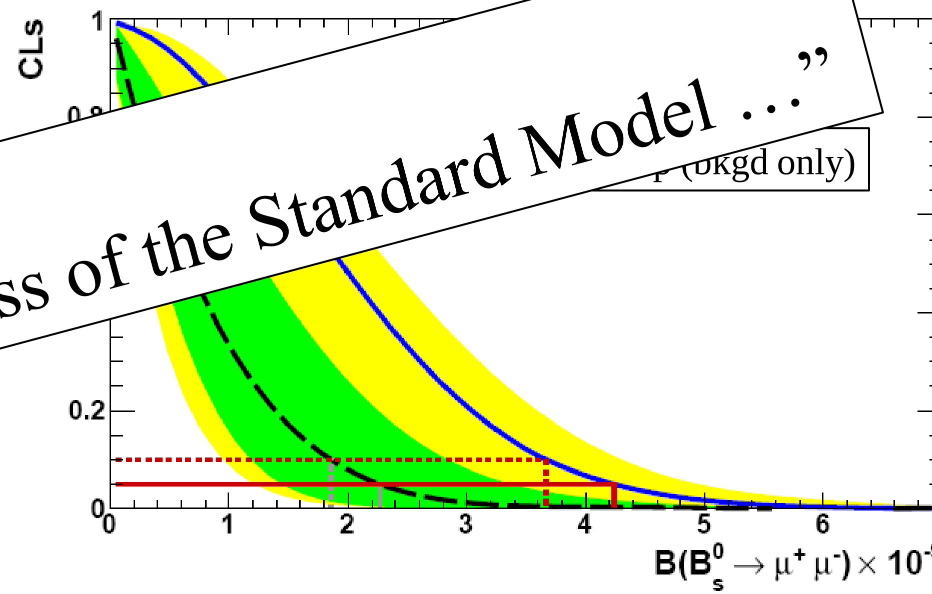
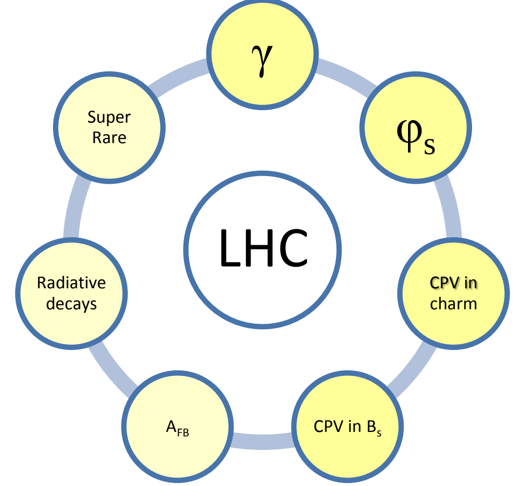






prof. Ch.Quick:
"… unreasonable effectiveness of the Standard Model …"

Conclusions



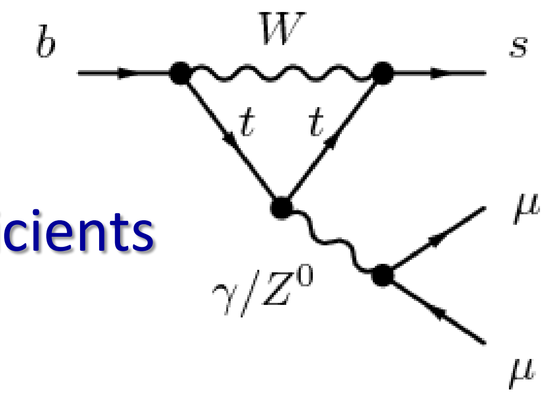
- **CP violation:**
  - LHCb made first step towards measuring γ
  - Best measurement of φ_s
  - Mixing asymmetry a_{sl} consistent with D0 and SM
  - First measurement of CP violation in charm
  - First measurement of CP violation in B_s^0
- **FCNC:**
  - A_{FB} in $B^0 \rightarrow K^{*0}\mu\mu$ consistent with SM
  - Isospin asymmetry in $B \rightarrow K\mu\mu$
  - Super rare decay $B_s^0 \rightarrow \mu\mu$ around the corner

➢ All results statistically limited!

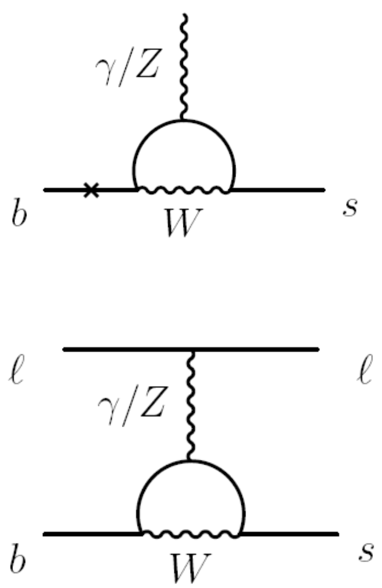
Thank you!

Backup: OPE

- Flavour changing neutral currents
- Probe V-A structure of SM
- In HQET expressed in terms of Wilson coeficients



$$H_{\text{eff}} = -\frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i(\mu, M_{heavy}) \mathcal{O}_i(\mu)$$



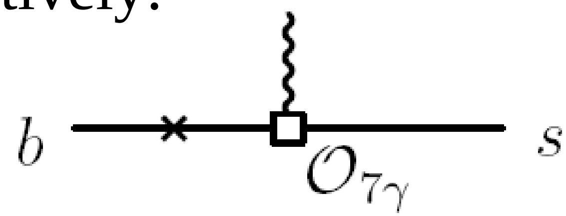
$B^0_{(s)} \to K^*(\varphi)\gamma$	$B^0 \to K^*\mu\mu$	$B^0_s \to \mu\mu$
$\mathcal{O}_{7\gamma}$	$\mathcal{O}_{7\gamma}, \mathcal{O}_{9V}, \mathcal{O}_{10A}, \mathcal{O}_S, \mathcal{O}_P$	$\mathcal{O}_{10A}, \mathcal{O}_S, \mathcal{O}_P$

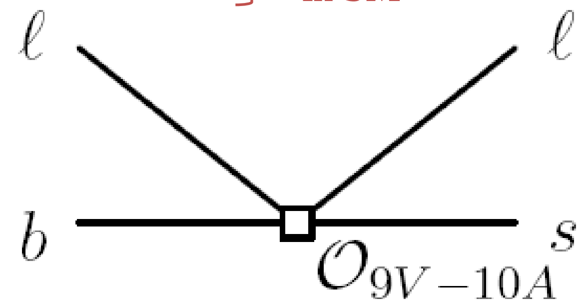
In principle both left- and righthanded, $\mathcal{O}_{7\gamma}$ and $\mathcal{O}_{7\gamma}$'

$\mathcal{O}_S$: Scalar current (Higgs)
$\mathcal{O}_P$: Pseudo-scalar

Highly suppressed in SM

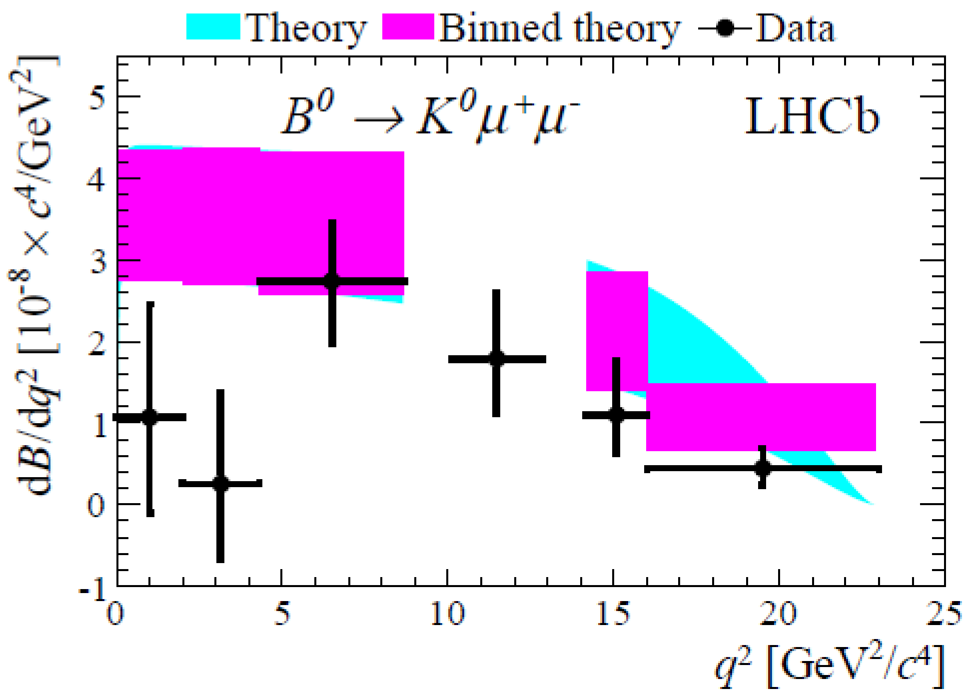
effectively:



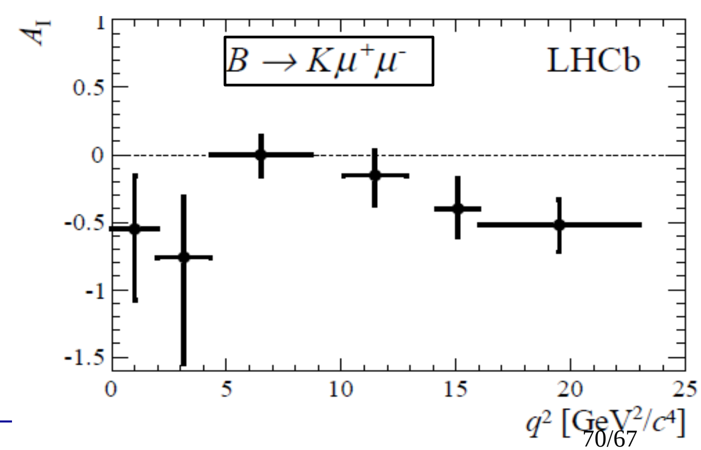


e.g. W.Altmannshofer et al., JHEP 0901:019,2009

Backup: Isospin asymmetry



- Isospin asymmetry: B^0 vs B^+ difference?



  - No isospin asymmetry in K^* channels
    - SM prediction: -1%
  - Deficit in N($B^0 \to K_s^0 \mu\mu$)
    - No precise SM prediction, expected close to zero…