Search for a Strange Phase in Beautiful Oscillations

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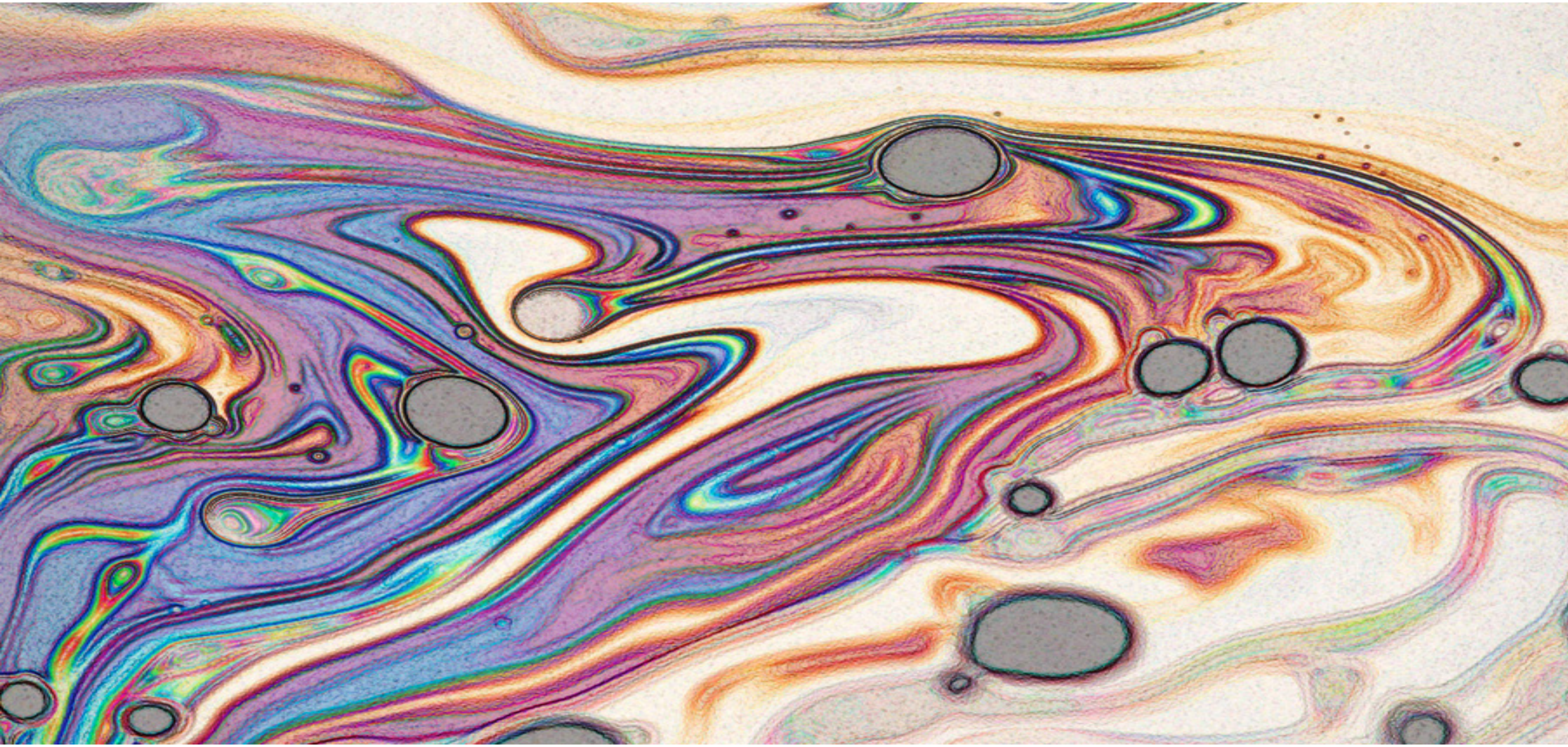
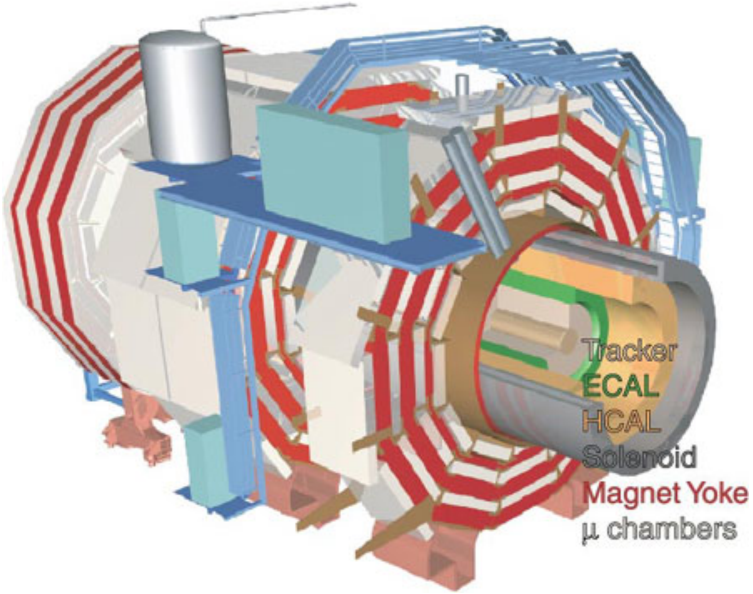
at IIHE(VUB/ULB), Brussels
20 January 2011



Simplistic: “direct” vs “indirect”

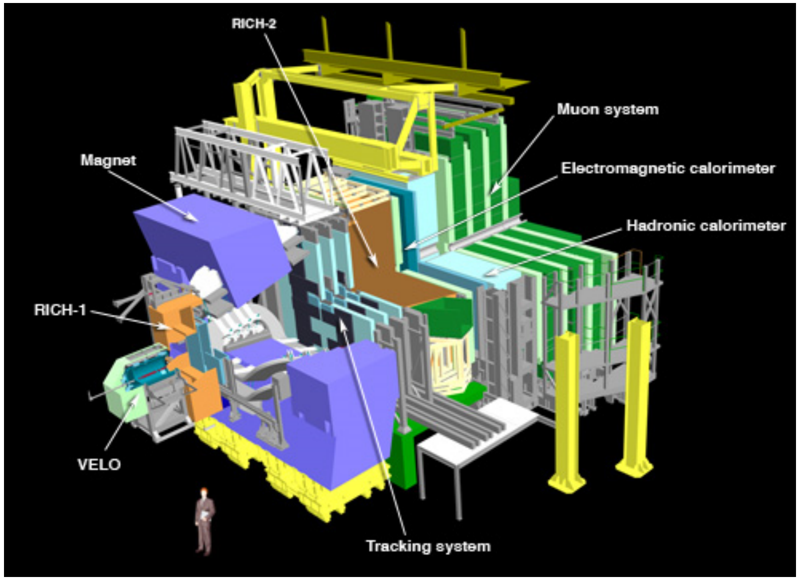
Direct: CMS

- Collide as hard as possible to produce yet undiscovered particle



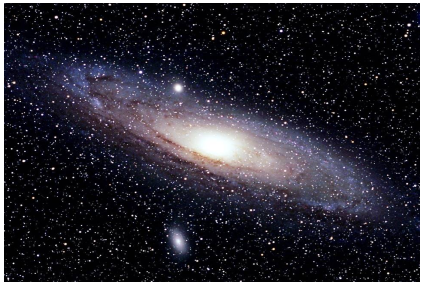
Indirect: LHCb

- Make many known particles (B_d,B_s,…) and study behavior
  - Off-shell BSM

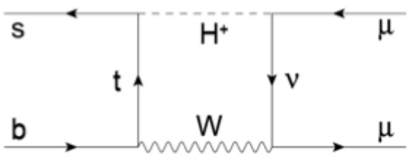


Why B-physics?

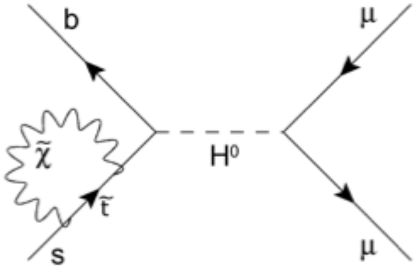
- CP violation
  - Baryogenesis
  - Too small in SM
  - BSM CP-violation needed



- Complementary to direct searches
  - Off-shell contributions
  - Measure couplings

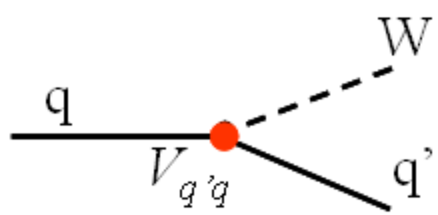


- Model-independent searches
  - Overconstraining CKM model



B-physics

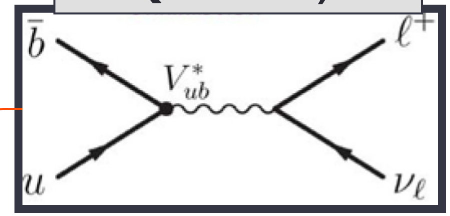
- Study CKM-matrix

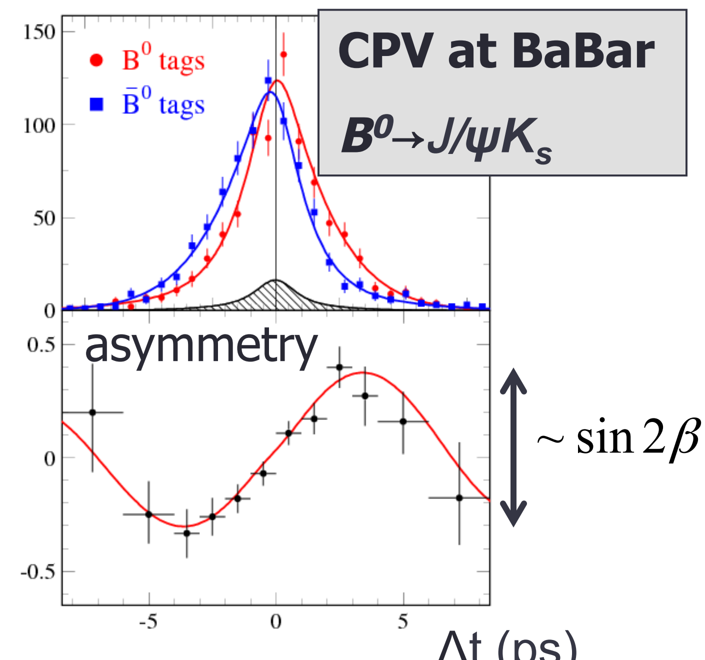


$$V_{CKM} \approx \begin{pmatrix} V_{ud} & V_{us} & |V_{ub}|e^{-i\gamma} \\ V_{cd} & V_{cs} & V_{cb} \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & V_{tb} \end{pmatrix}$$

- BR's & CPV

BR($B^+ \to \tau^+ \nu$)





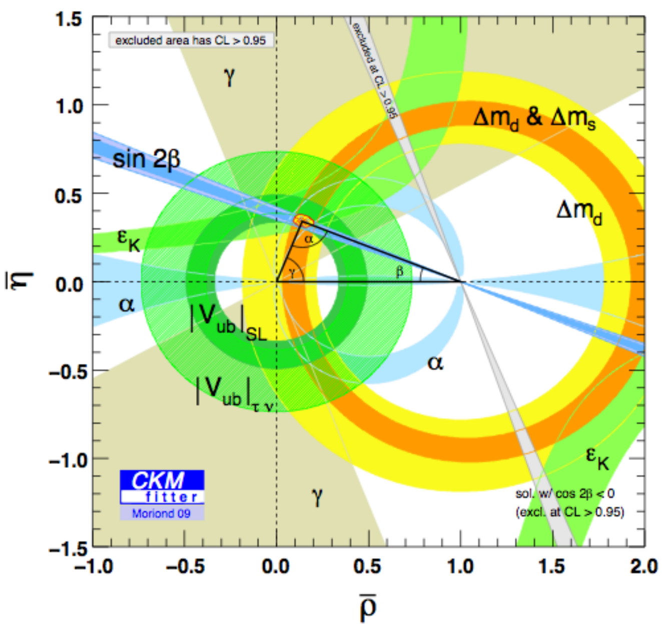
CKM matrix constraints

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

Parameter constraints

- Unitarity: $V_{CKM}V^{\dagger}_{CKM} = \mathbf{1}$
- 4 free parameters
  - One complex phase
    - Complex phase: CP violation

➢ Perform different measurements to overconstrain CKM matrix



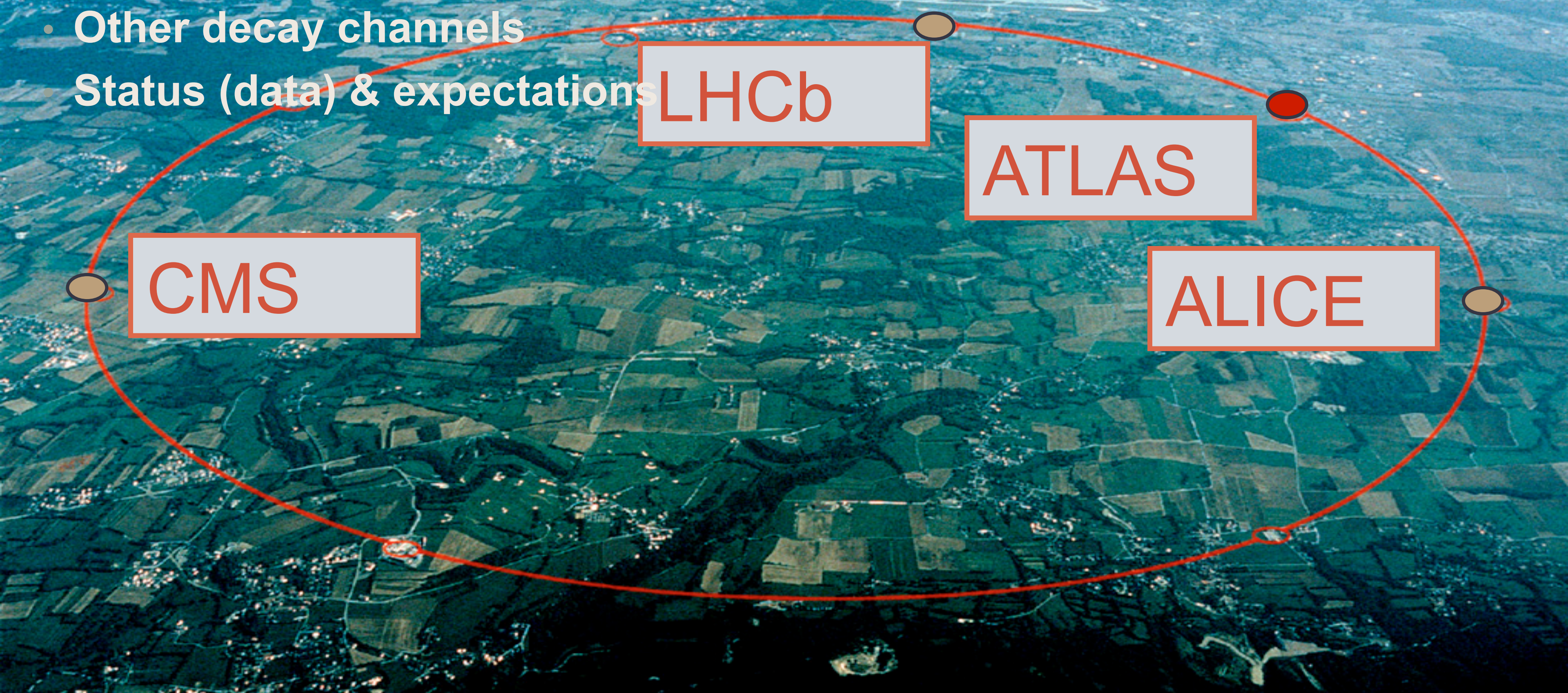
Current status

- SM CKM mechanism explanation of CP violation
  - No significant inconsistencies
  - Uncertainty γ, φ_s large
- Some interesting deviations
  - β^{eff} (penguins)
  - $|V_{ub}|(B^+ \to \tau\nu)$ vs β
  - "$K\pi$ puzzle"
  - φ_s

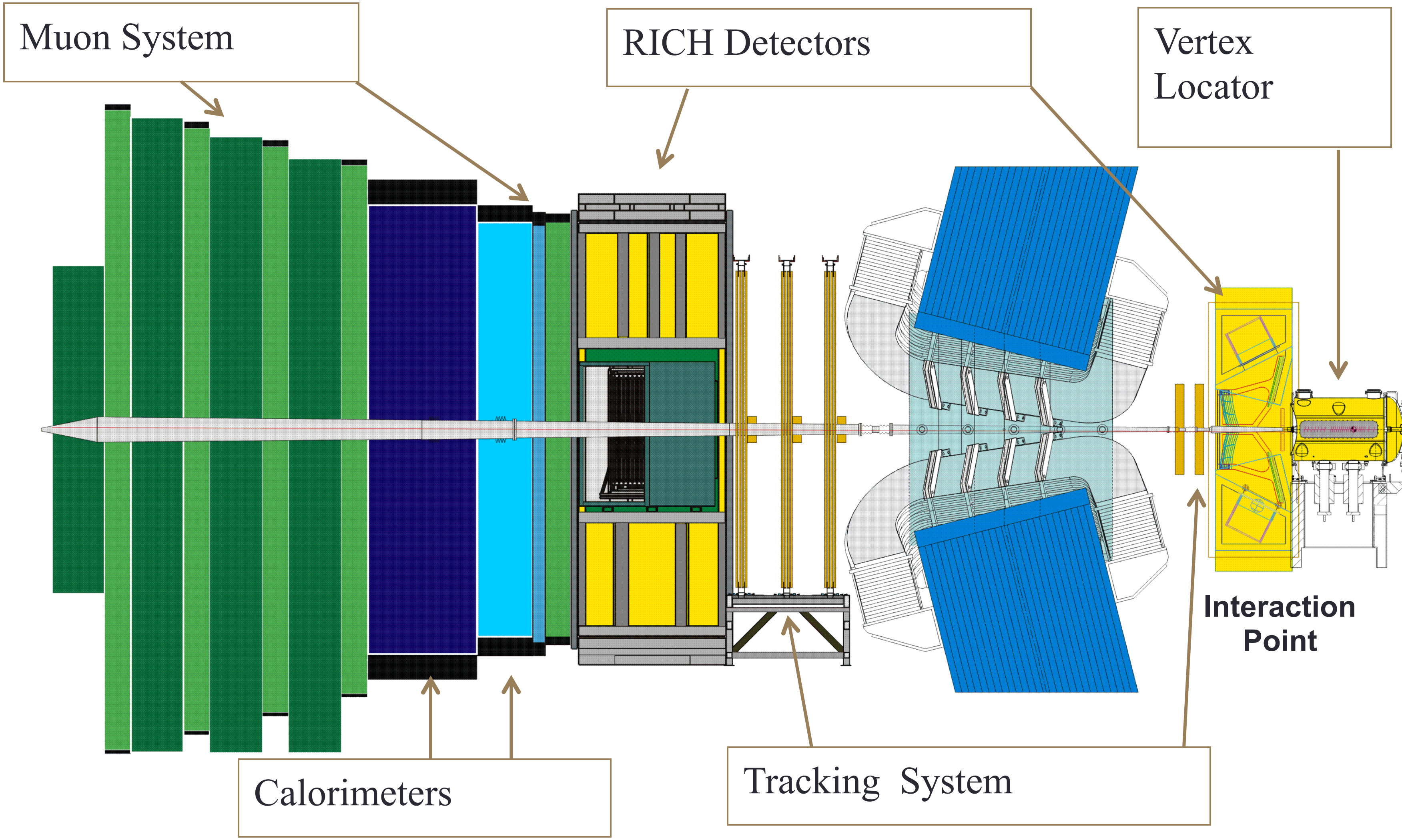
➢ Stronger contraints needed: LHCb!

Overview

- LHCb detector
- Time-dependent CP-asymmetry in $B_s \rightarrow J/\psi\varphi$
  - Analysis: selection & fit methods (MC)
- Other decay channels
- Status (data) & expectations



The LHCb Detector


Muon System
RICH Detectors
Vertex
Locator
Interaction
Point
Calorimeters
Tracking System

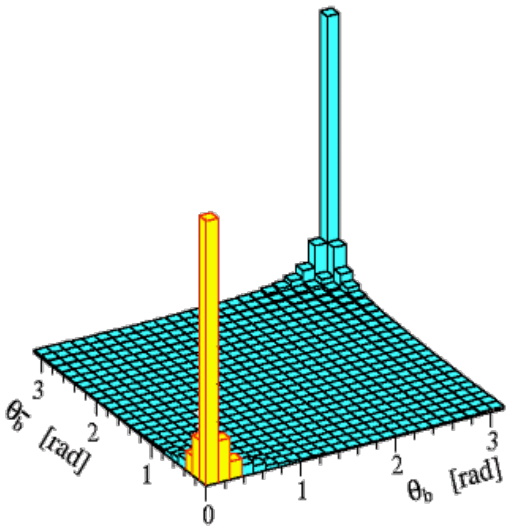
LHCb

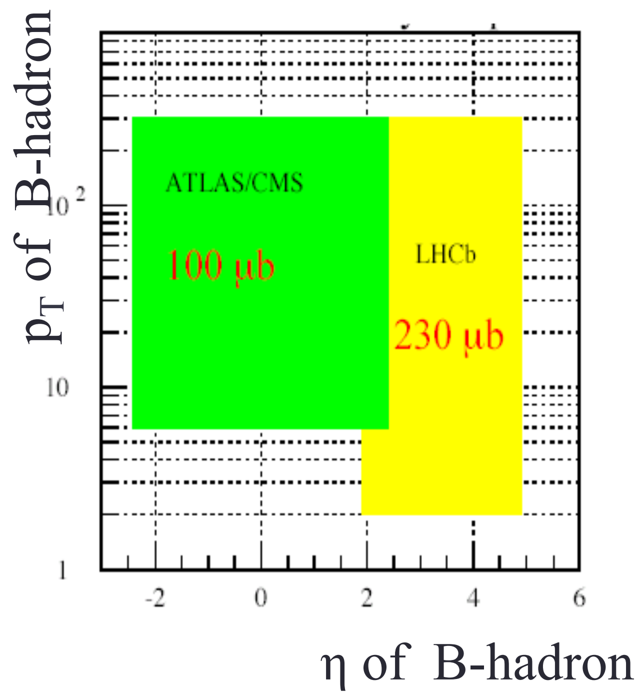
- Forward arm spectrometer
- ~20m x 10m x 10m
- L = (2-5) x 10^{32} cm^{-2} s^{-1}

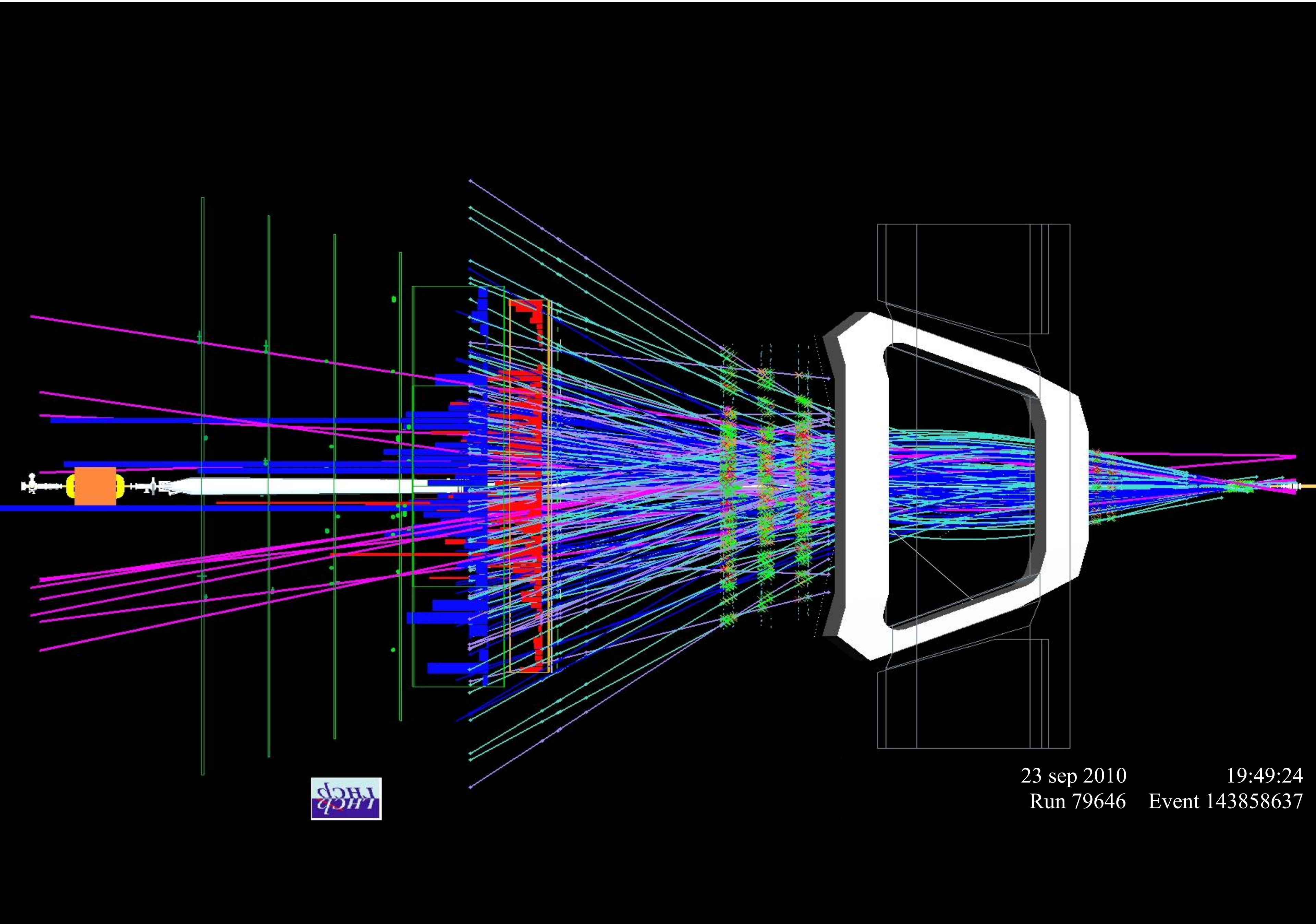
- σ_{bb} ~ 500 μb (10% B_s)
- ‘1 year’ = 2.0 fb^{-1}
- ➢ Produce O(10^{11}) B_s‘s per year
- ➢ Reconstruct O(100k) $B_s \rightarrow J/\psi\varphi$ per year

Advantages

- Number of B_s’s
- Proper time resolution
- Mass resolution
- Particle identification






23 sep 2010
19:49:24
Run 79646
Event 143858637

Some cool plots here

Discovery box

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

DESY 87-029
April 1987

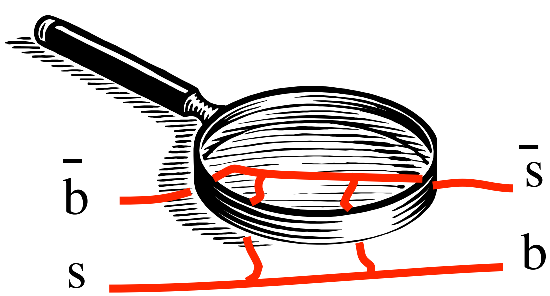
OBSERVATION OF B^0 - $\overline{B}^0$ MIXING

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-$\overline{B}^0$ mixing has been observed and is substantial.

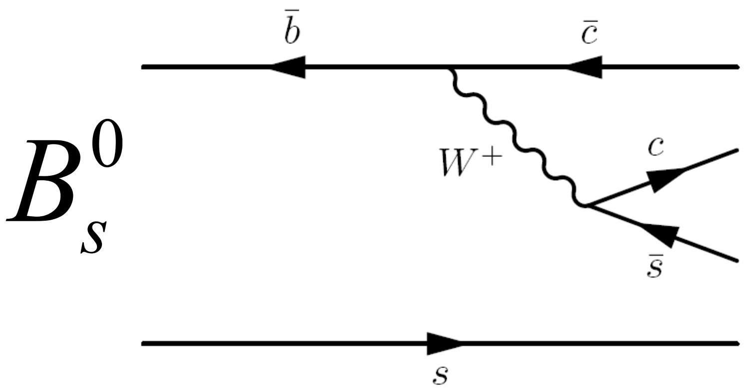
Parameters	Comments
$r > 0.09$ 90%CL	This experiment
$x > 0.44$	This experiment
$B^{\frac{1}{2}} f_B \approx f_\pi < 160$ MeV	B meson ($\approx$ pion) decay constant
$m_b < 5\mathrm{GeV}/c^2$	b-quark mass
$\tau_b < 1.4 \cdot 10^{-12}$s	B meson lifetime
$\lvert V_{td} \rvert < 0.018$	Kobayashi-Maskawa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

- Example: limit on the top-mass from $B_d \leftrightarrow$ anti-B_d mixing



The B_s mixing phase β_s

Equivalent of β in B_d system

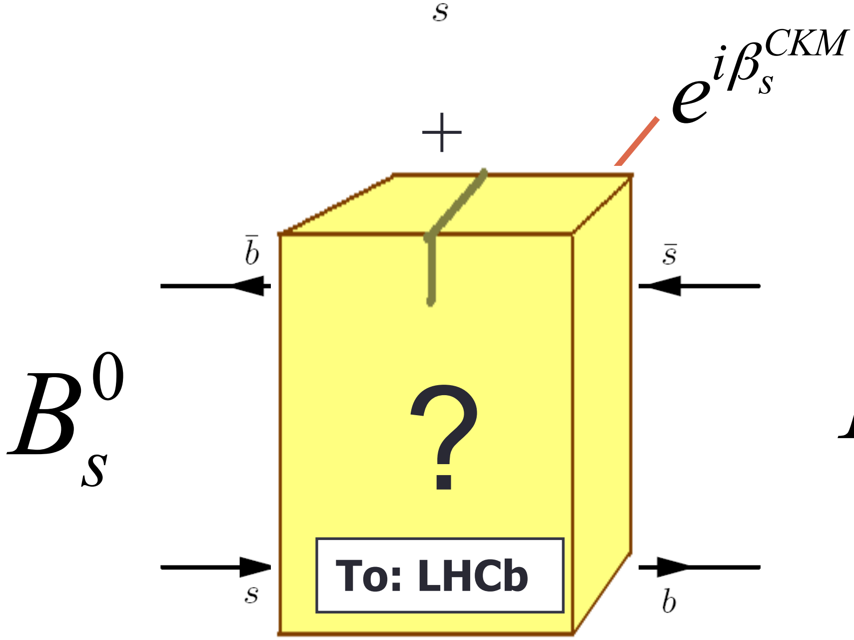


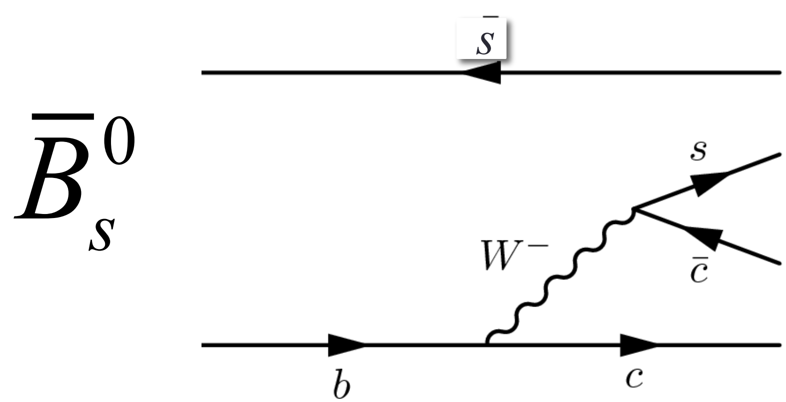
$$A_{\mathrm{CP}} = \frac{N_{B\to f} - N_{\bar{B}\to f}}{N_{B\to f} + N_{\bar{B}\to f}}$$

$$= \sin(-2\beta_s^{\mathrm{CKM}} + \phi_s^{\mathrm{NP}}) \sin \Delta m_s t$$

If $\Delta\Gamma_s$=0:
(in general $\Delta\Gamma_s \neq 0$)

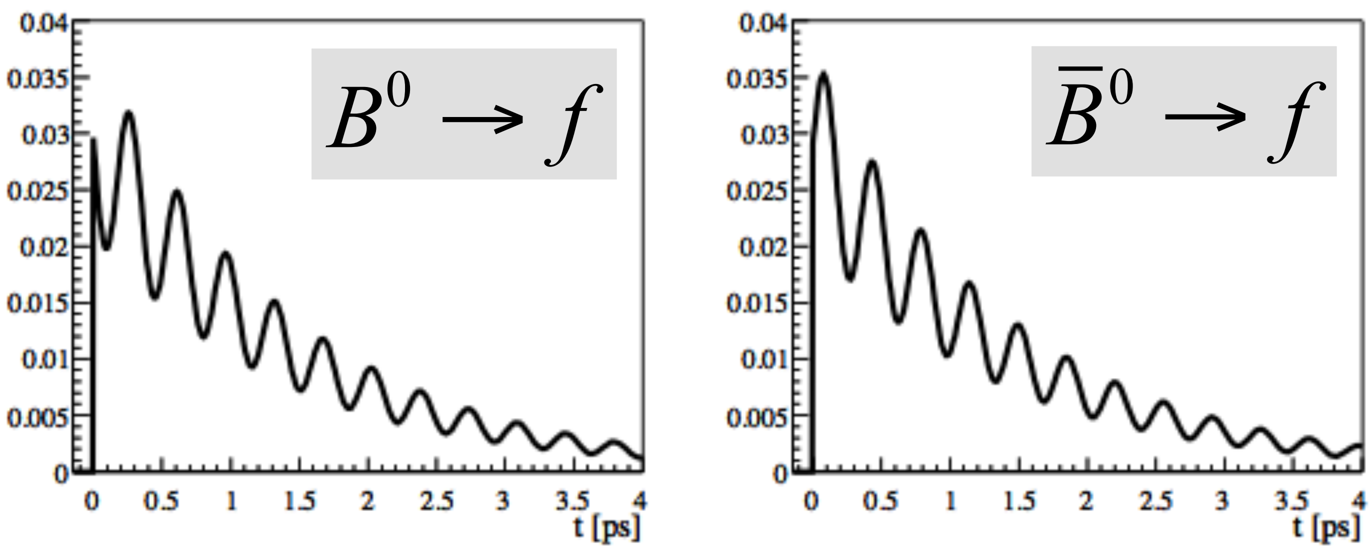
"φ_s"



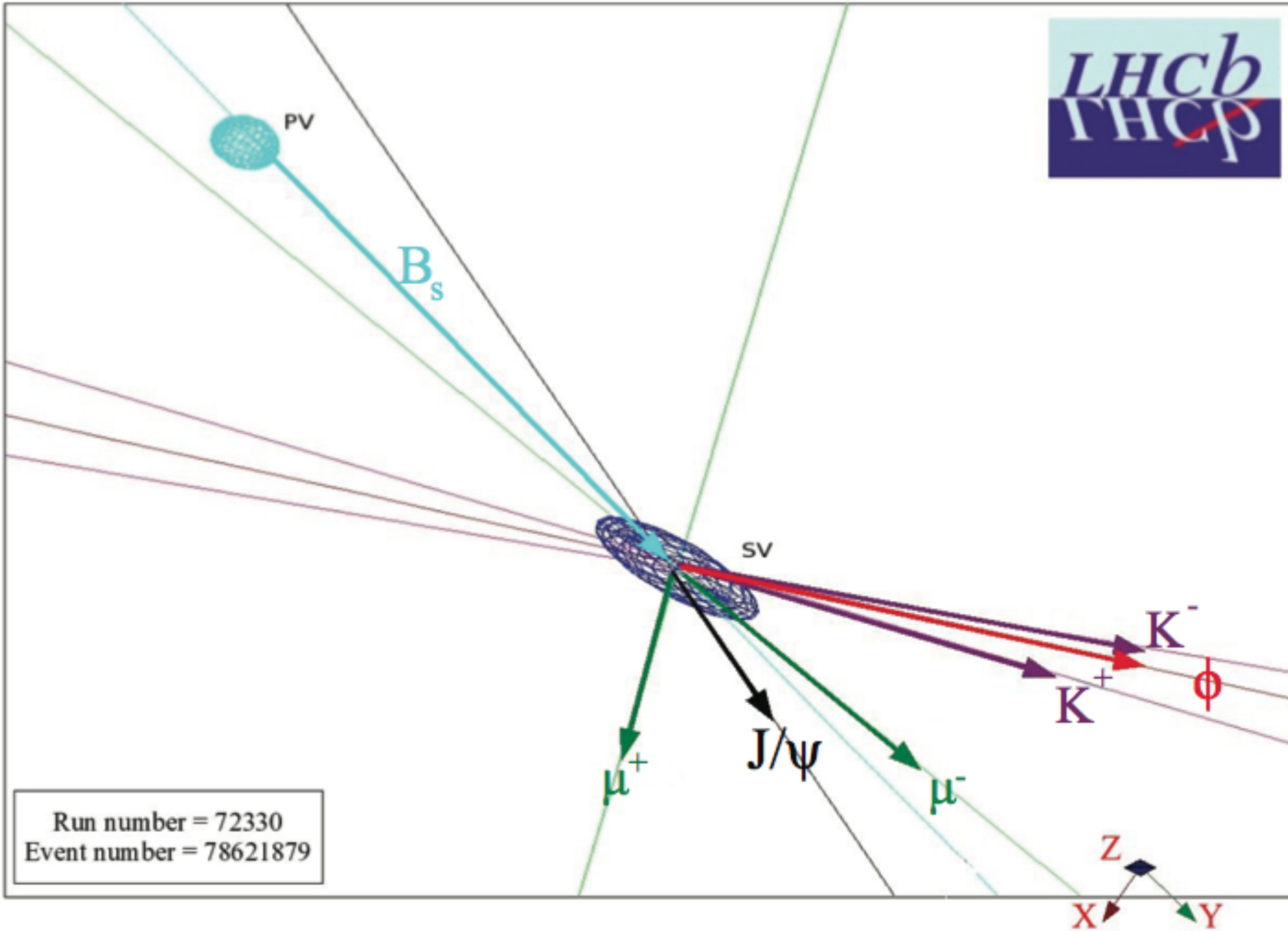


Time dependent CP violaton

- Time-dependent decay rate *B* and anti-*B* differ
  - Measure amplitude
    - Amplitude SM expectation: $\sin(\varphi_s)$~0
    - Frequency: $\sin(\Delta m_s t)$



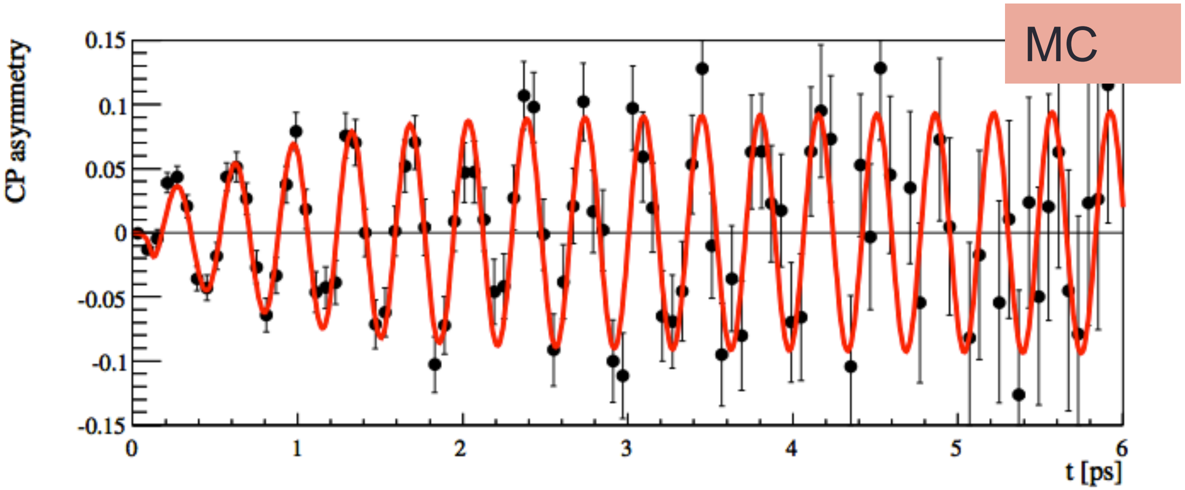
➢ To measure asymmetry, measure lifetime accurately



LHCb
PV
Bs
SV
K-
K+
φ
J/ψ
μ+
μ-
Run number = 72330
Event number = 78621879
Z
X
Y

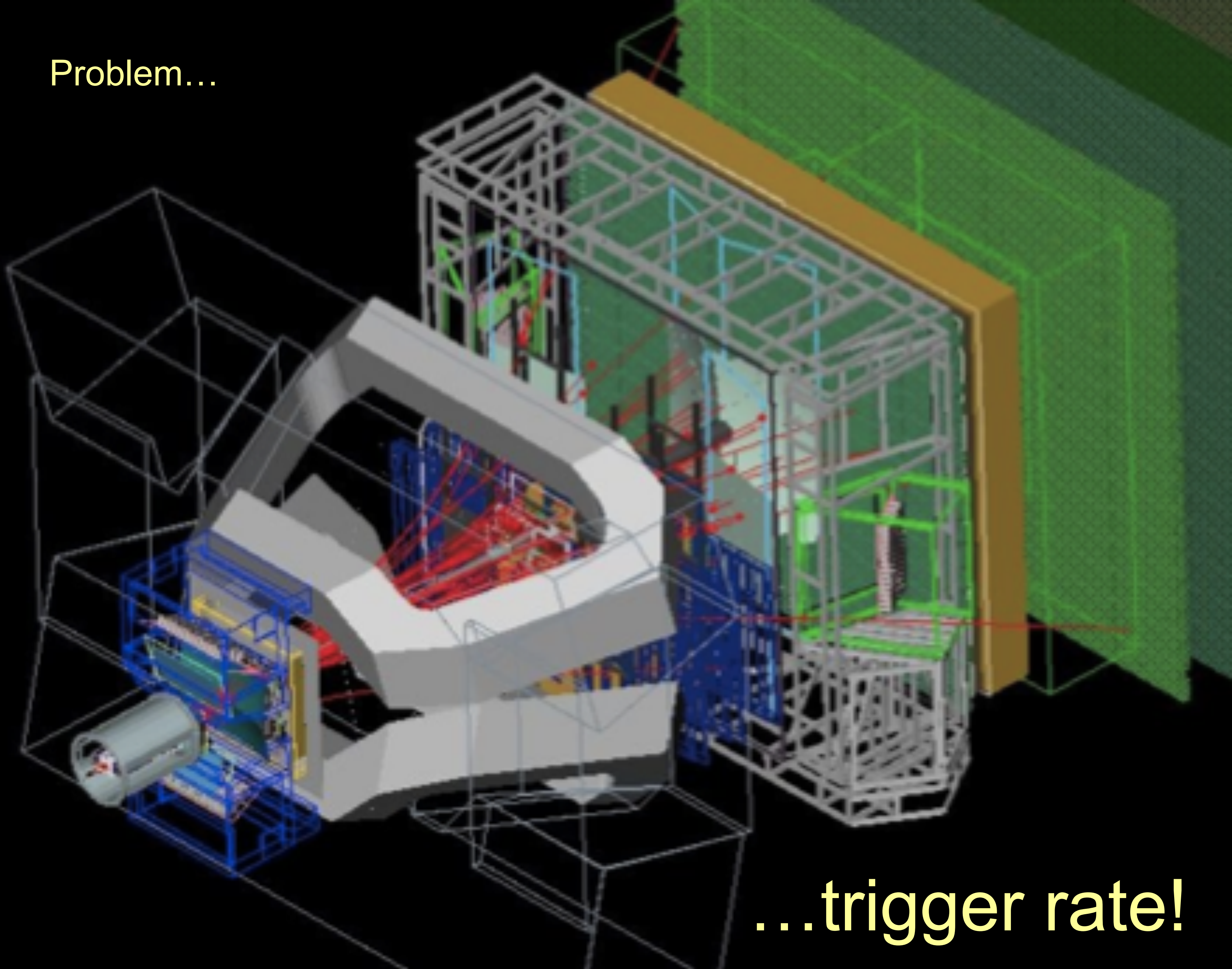
CP-asymmetry

- Goal: measure CP-asymmetry
  - Frequency: $\sin(\Delta m_s t)$
- Proper time resolution important
  - $B_s \rightarrow J/\psi\varphi$ at LHCb: ~40 fs



- SM amplitude: $\sin(\varphi_s)$ ~ 0
- Amplitude ≠ 0? ➔ BSM contributions!

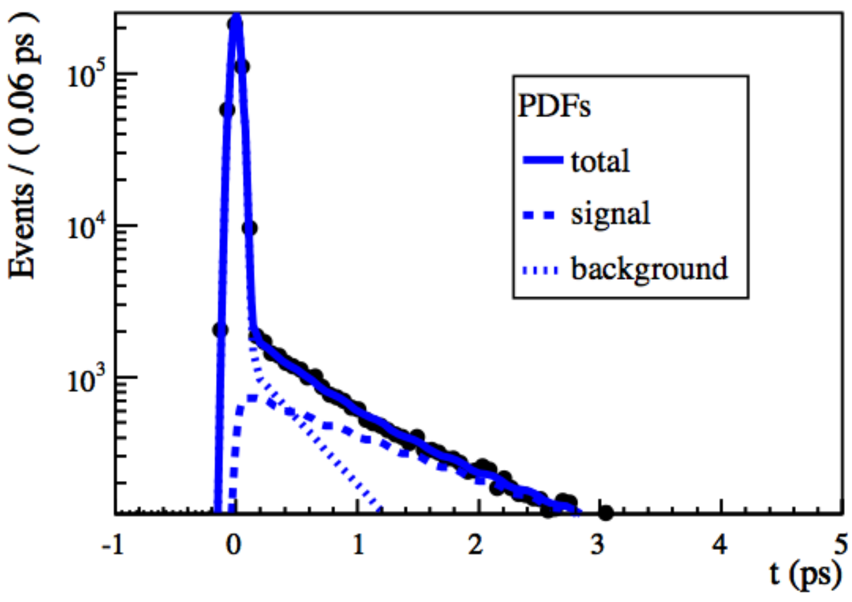
Problem…



…trigger rate!

Background rate

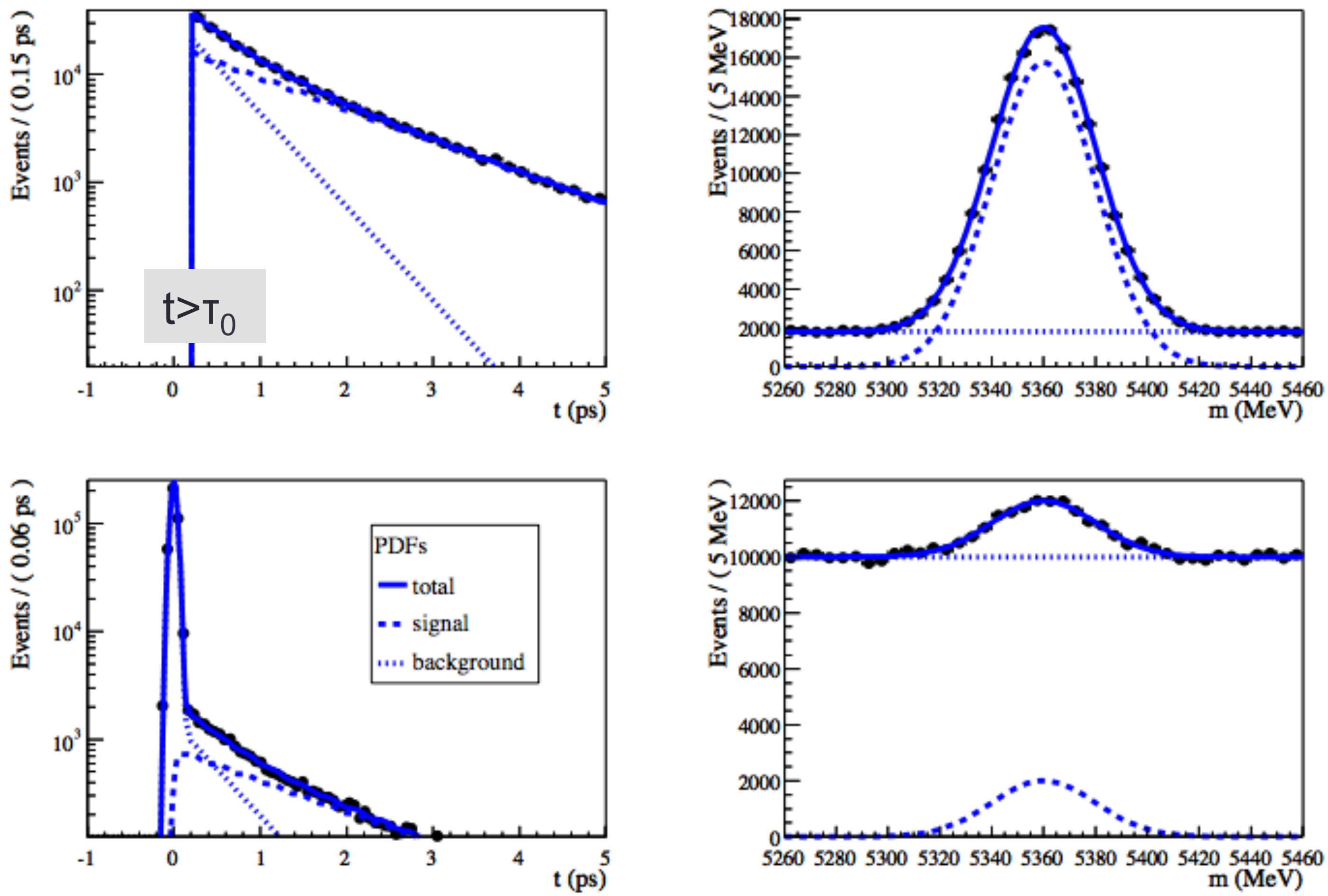
- Most background prompt background
  - Combinations of $K^+K^-\mu^+\mu^-$ produced at *pp*-interaction point
- Events around t=0 contribute to rate, not to sensivity
  - Rate >1 Hz
- ➢ How to get rid of these events while understanding the resolution/efficiency?
  - ➢ Time resolution is determined from prompt peak…



Previous solution

- Many cuts
  - ➢ Many systematic effects
  - ➢ Sub-optimal
- Trigger rate not flexible

Solution: detached (up) & prescaled (down)



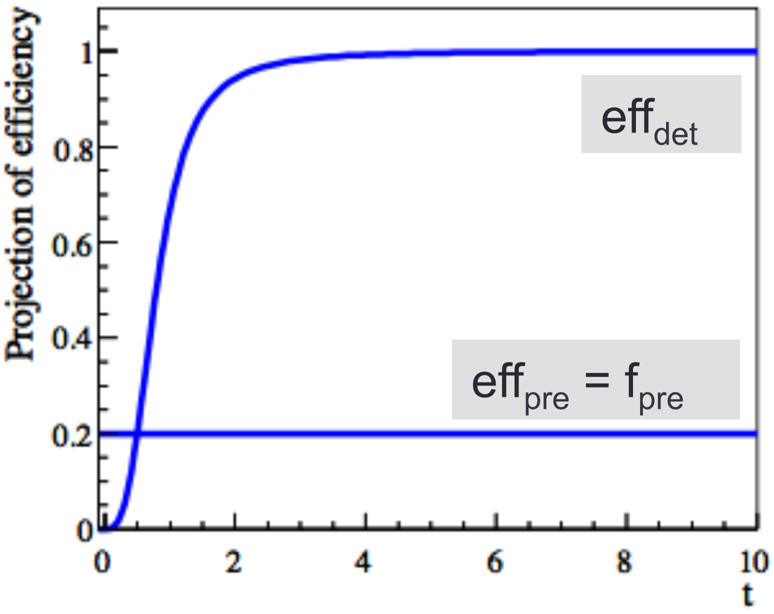
"signal sample"

"control sample"

Prescaled & detached

- Detached sample
  - Cut on lifetime
    - Online
  - Removes prompt background
  - Almost pure signal

- Prescaled sample
  - Mostly background
  - Control sample
    - Proper time resolution
    - Efficiency turn-on curve
    - Don’t need all events, so can be prescaled



- Adjusting prescale factor and lifetime-cut
  - Flexibly adjust trigger rate!
  - No loss of sensitvity, no extra systematic effects!!!

Selection optimization

Now we can use detached sample to optimize selection

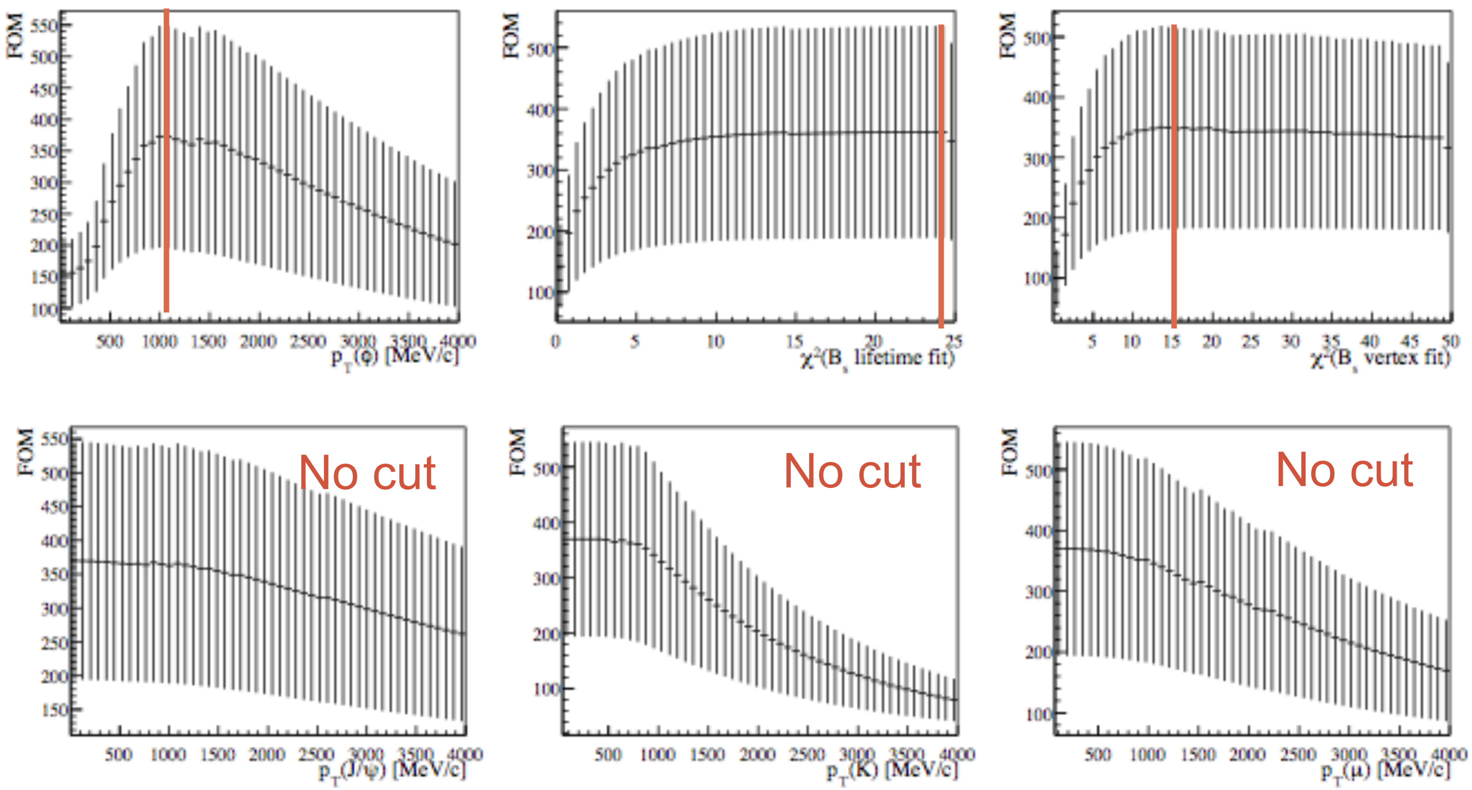
- Almost pure signal sample!

Goal optimization:

- Maximize sensitivity to φ_s
- Simple selection
  - Few orthogonal cuts
- Understandable selection
  - Optimize by hand
- Ignore cuts if unnecessary/unwanted

Optimization example

- Maximize figure of merit FOM ~ 1/σ(φ_s) ~ 1/σ(S)
- Do this for few, mostly orthogonal variables
- Ignore unnecessary/unwanted cuts



Selection criteria

Variable	Selection criterium
$X^2(B_s$ vertex)	< 16
$X^2(B_s$ lifetime fit)	< 9
$p_T(\varphi)$	> 1100 MeV/c
ΔlogL(K/π)	> -5
ΔlogL(μ/π)	> -5

"Real" selection: 5 cuts

Variable	Selection criterium
M(φ)	Wide enough
M(J/ψ)	Wide enough
$M(B_s)$	Wide enough
Prescaled factor (f_{pre})	Adjustable
Lifetime cut (τ_0)	Ajdustable

No limit on sideband study

Flexible trigger rate

- 170k $B_s \rightarrow J/\psi\varphi$ events per 2 fb^{-1}
  - Sensitivity improvement of ~20% compared to existing selection!

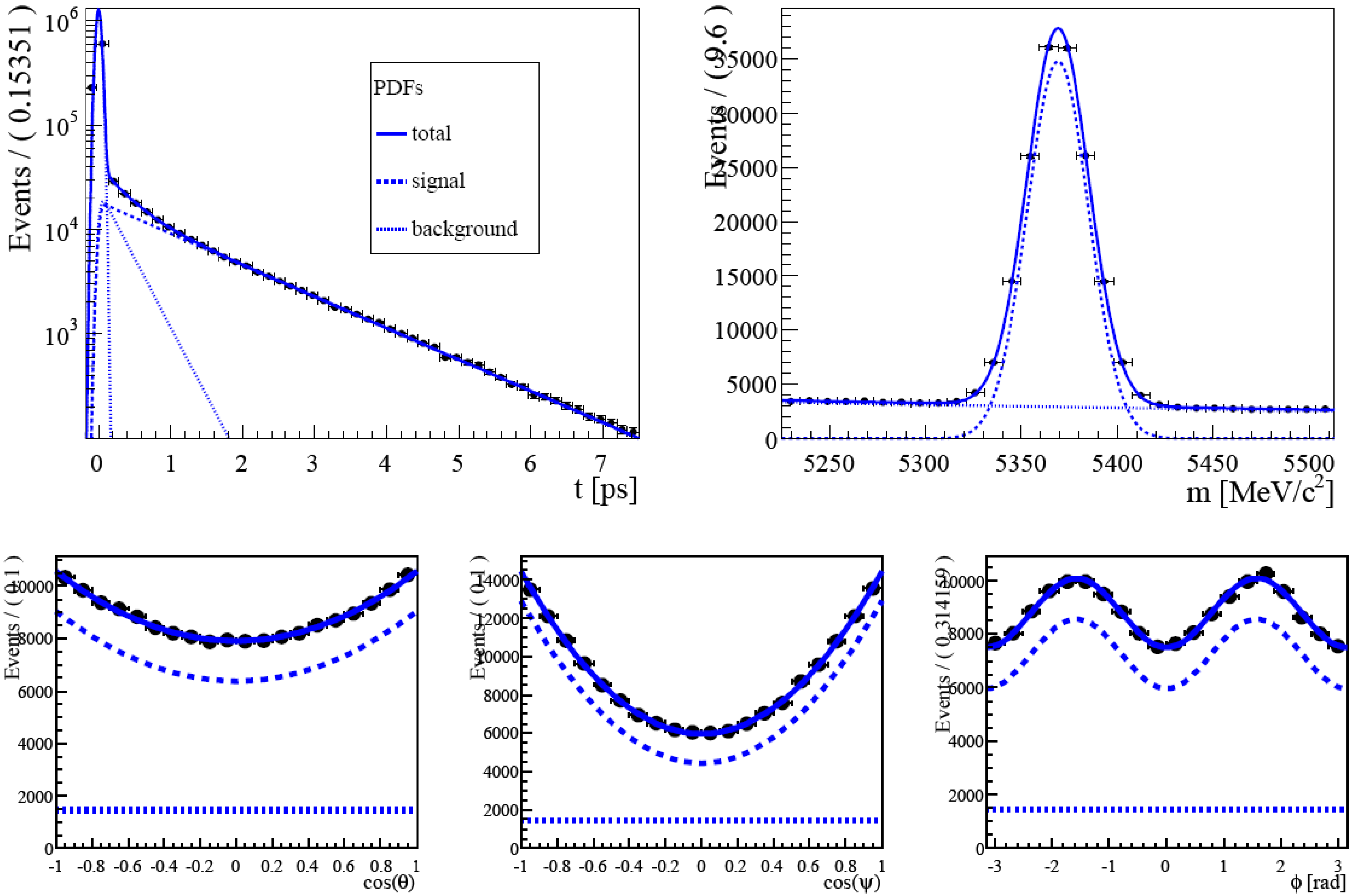
What else?

Final state not a pure CP-eigenstate

i	$f_i(\cos\theta,\cos\psi,\phi)$	$A_i(t\|\lambda)$	$A_i(t\|\lambda)$
1	$2\cos^2\psi[1-\sin^2\theta\cos^2\phi]$	$\|A_0(t)\|^2$	$\|\bar{A}_0(t)\|^2$
2	$\sin^2\psi[1-\sin^2\theta\sin^2\phi]$	$\|A_\parallel(t)\|^2$	$\|\bar{A}_\parallel(t)\|^2$
3	$\sin^2\psi\sin^2\theta$	$\|A_\perp(t)\|^2$	$\|\bar{A}_\perp(t)\|^2$
4	$-\sin^2\psi\sin 2\theta\sin\phi$	$\mathrm{Im}(A_\parallel^*(t)A_\perp(t))$	$\mathrm{Im}(\bar{A}_\parallel^*(t)\bar{A}_\perp(t))$
5	$\frac{1}{\sqrt{2}}\sin 2\psi\sin^2\theta\sin 2\phi$	$\mathrm{Re}(A_\parallel^*(t)A_0(t))$	$\mathrm{Re}(\bar{A}_\parallel^*(t)\bar{A}_0(t))$
6	$\frac{1}{\sqrt{2}}\sin 2\psi\sin 2\theta\cos\phi$	$\mathrm{Im}(A_0^*(t)A_\perp(t))$	$\mathrm{Im}(\bar{A}_0^*(t)\bar{A}_\perp(t))$

$$
\begin{aligned}
A_1 &= |A_0(0)|^2 e^{-\Gamma_s t}[\cosh(\Delta\Gamma_s t/2) - \cos\phi_s \sinh(\Delta\Gamma_s t/2) + \sin\phi_s \sin(\Delta m_s t)] \\
A_2 &= |A_\parallel(0)|^2 e^{-\Gamma_s t}[\cosh(\Delta\Gamma_s t/2) - \cos\phi_s \sinh(\Delta\Gamma_s t/2) + \sin\phi_s \sin(\Delta m_s t)] \\
A_3 &= |A_\perp(0)|^2 e^{-\Gamma_s t}[\cosh(\Delta\Gamma_s t/2) + \cos\phi_s \sinh(\Delta\Gamma_s t/2) - \sin\phi_s \sin(\Delta m_s t)] \\
A_4 &= |A_\parallel(0)||A_\perp(0)| e^{-\Gamma_s t}[\sin(\delta_\perp - \delta_\parallel)\cos(\Delta m_s t) - \cos\phi_s \cos(\delta_\perp - \delta_\parallel)\sin(\Delta m_s t) \\
&\qquad - \sin\phi_s \cos(\delta_\perp - \delta_\parallel)\sinh(\Delta\Gamma_s t/2)] \\
A_5 &= |A_\parallel(0)||A_0(0)|\cos(\delta_\parallel - \delta_0) \\
&\qquad \times e^{-\Gamma_s t}[\cosh(\Delta\Gamma_s t/2) - \cos\phi_s \sinh(\Delta\Gamma_s t/2) + \sin\phi_s \sin(\Delta m_s t)] \\
A_6 &= |A_0(0)||A_\perp(0)| e^{-\Gamma_s t}[\sin(\delta_\perp - \delta_0)\cos(\Delta m_s t) - \cos\phi_s \cos(\delta_\perp - \delta_0)\sin(\Delta m_s t) \\
&\qquad - \sin\phi_s \cos(\delta_\perp - \delta_0)\sinh(\Delta\Gamma_s t/2)].
\end{aligned}
$$

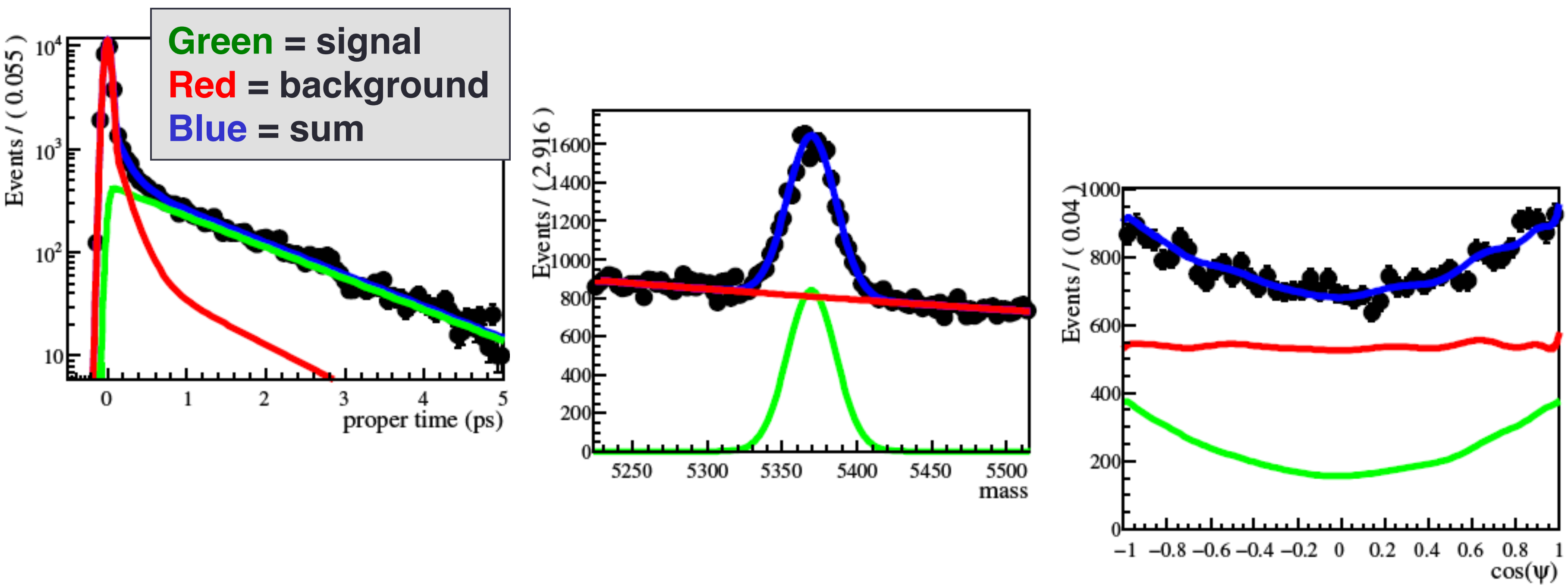
- Every event: measure time, 3 angles, mass, flavor…



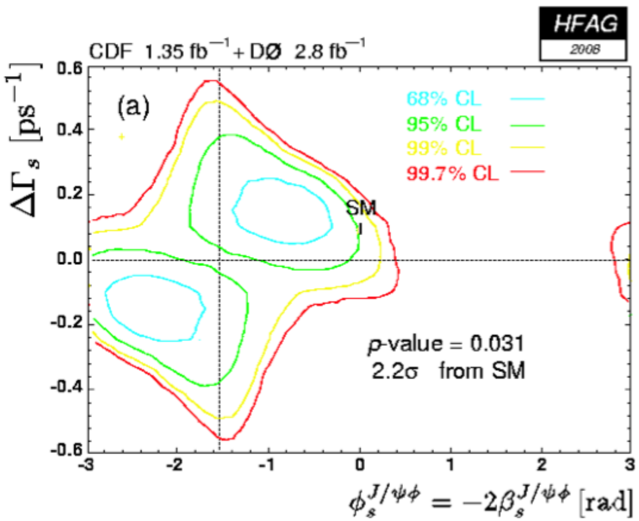
Events / (0.15351)
PDFs
total
signal
background
t [ps]
Events / (9.6)
m [MeV/c²]
Events / (0.1)
cos(θ)
Events / (0.1)
cos(ψ)
Events / (0.314159)
φ [rad]

Fit

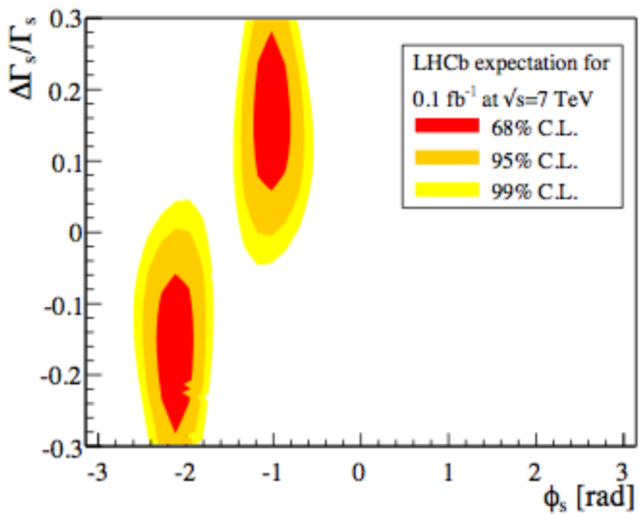
- Simultaneous likelihood analysis in mass, time, angles and tagging flavour
- Including efficiencies and resolutions using control samples
- Using mass sideband to model background

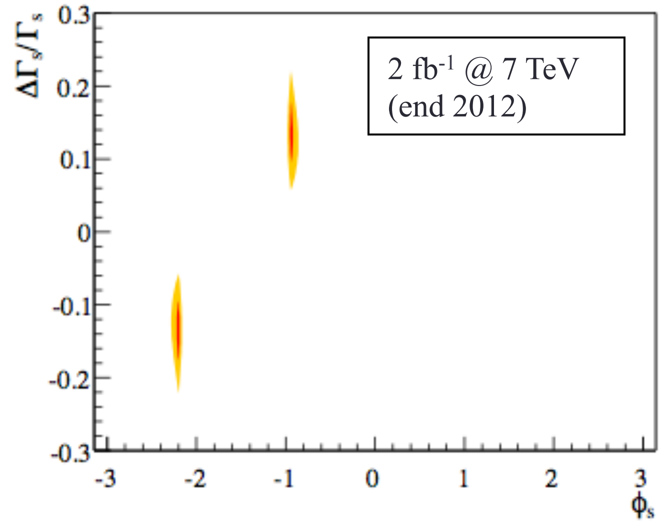


Sensitivity expectation…with MC



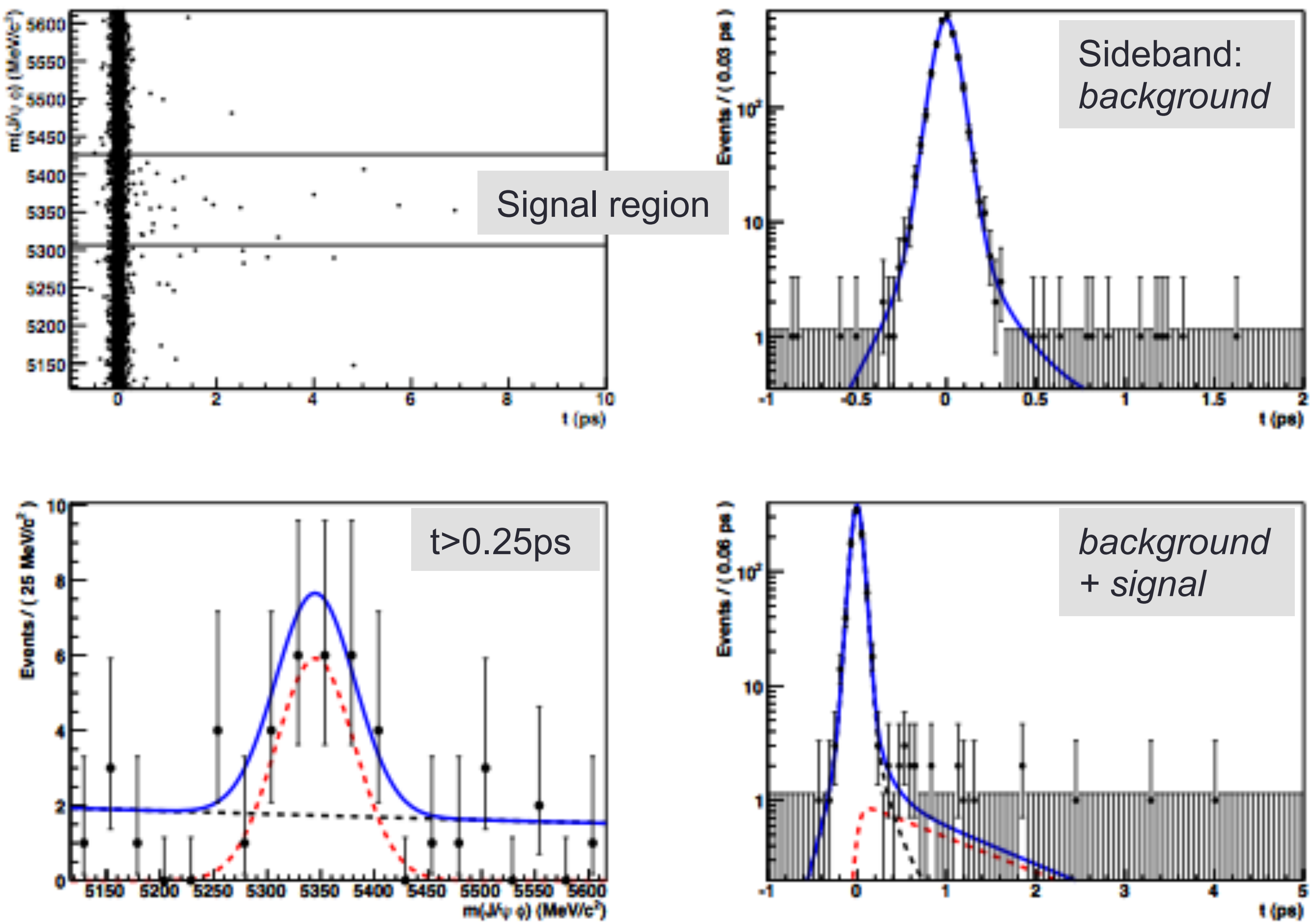
- Overtake Tevatron after 0.1-0.2 fb^{-1}
  - Next spring
- Very accurate measurement before shutdown!





Results $B_s \rightarrow J/\psi\varphi$ at LHCb

Data summer 2010



Status $B_s \to J/\psi\varphi$ at LHCb

This summer

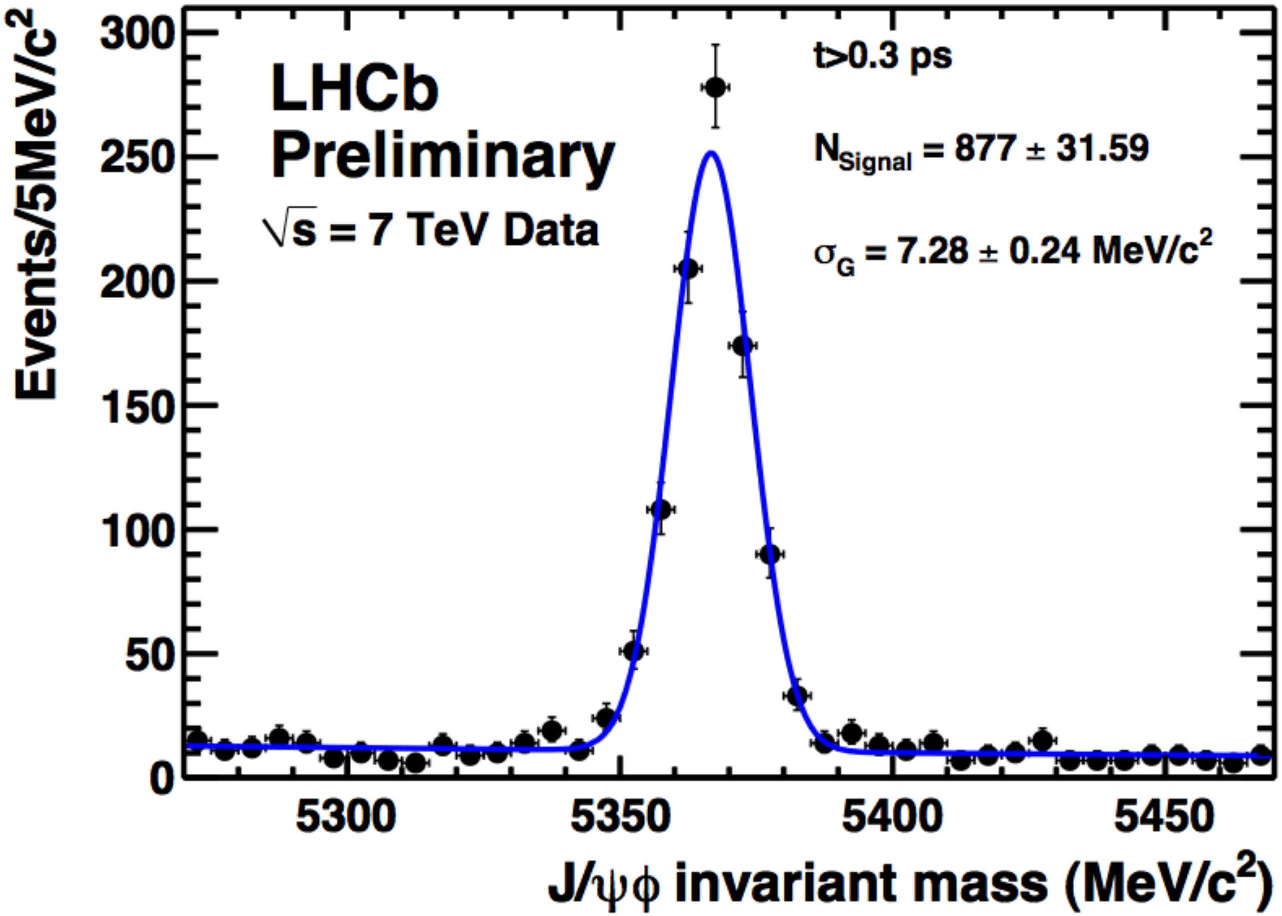
- Yields as expected
- Mass resolution as expected from MC
- Proper time resolution factor ~two worse
  - Misalignment
- Flavour tagging OK

➢ No showstoppers!

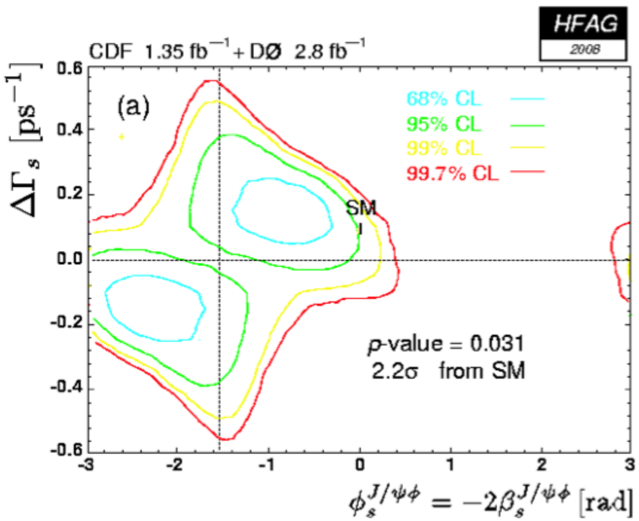
- Summer 2010: (23 ± 5) events
- Winter 2010-2011: ~870 events

Most recent results

Data 2010



Sensitivity expectation $B_s \rightarrow J/\psi\varphi$



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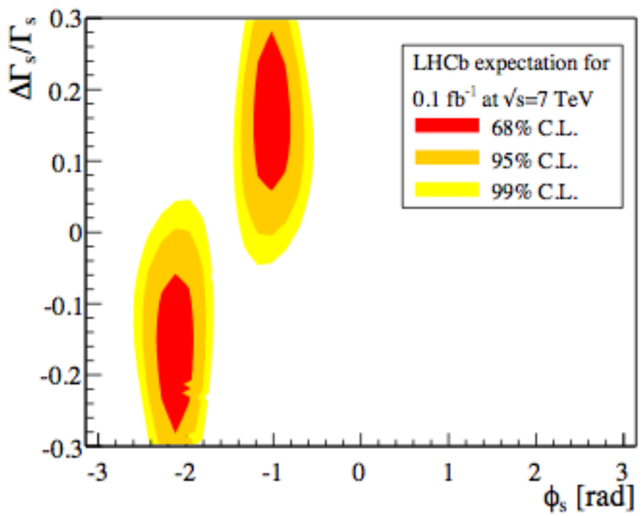
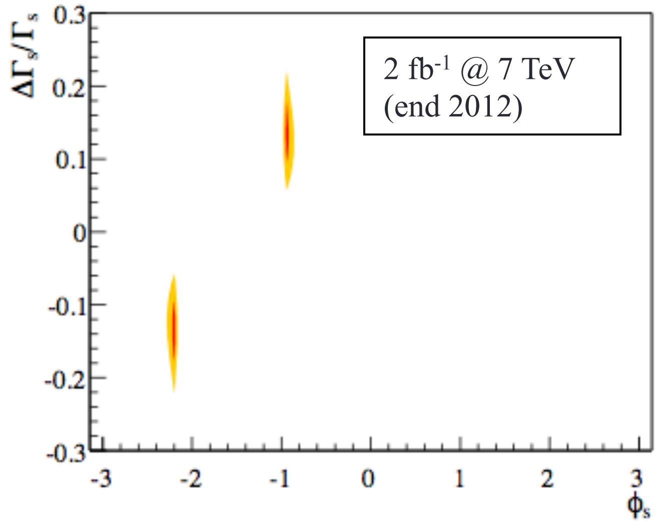
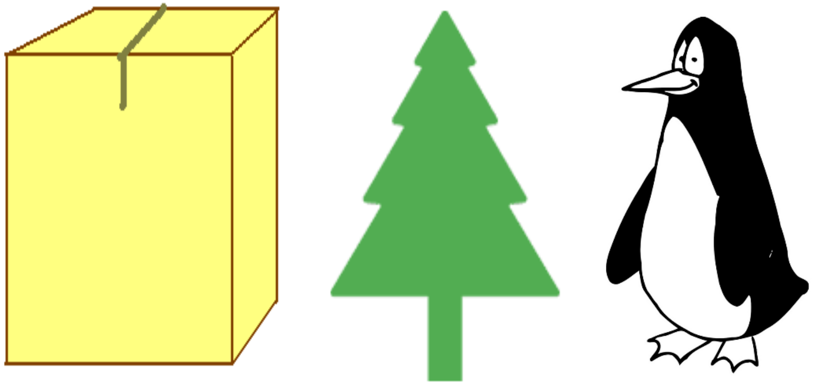


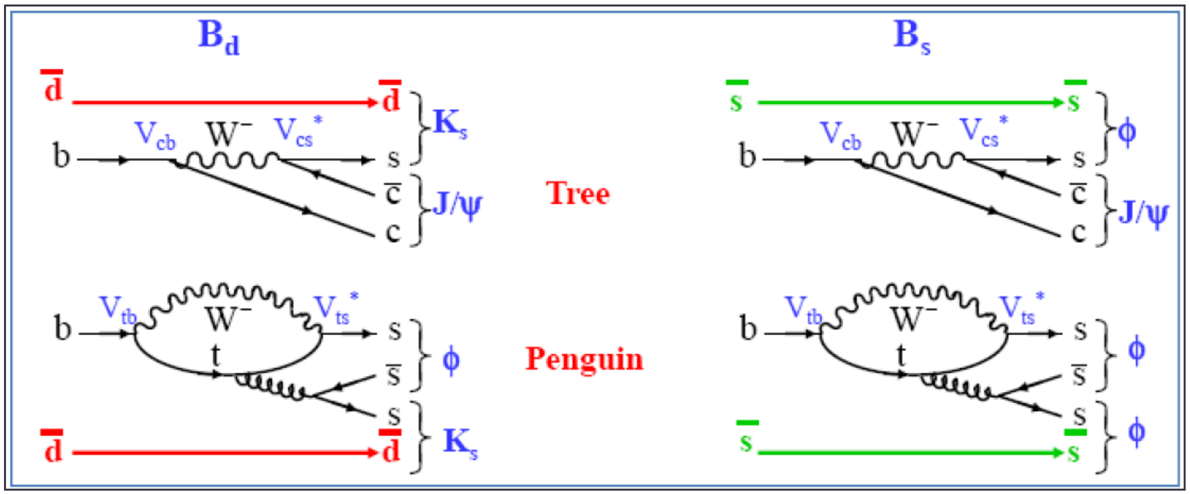


OTHER CPV DECAY CHANNELS AT LHCB



$B_s \to \varphi\varphi$

- Compare: phase(tree) & phase(penguin)



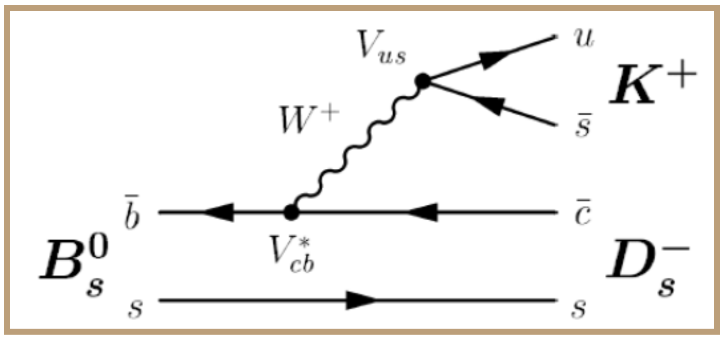
$$\Phi_{\phi K_s} = 2\beta^{mix} + 2\beta_s^{decay} \approx 2\beta(SM)$$

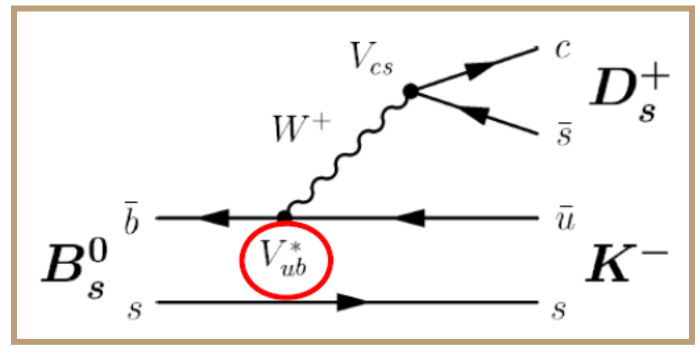
$$\Phi_{\phi\phi} = \Phi_s^{mix} + 2\beta_s^{decay} \approx 0(SM)$$

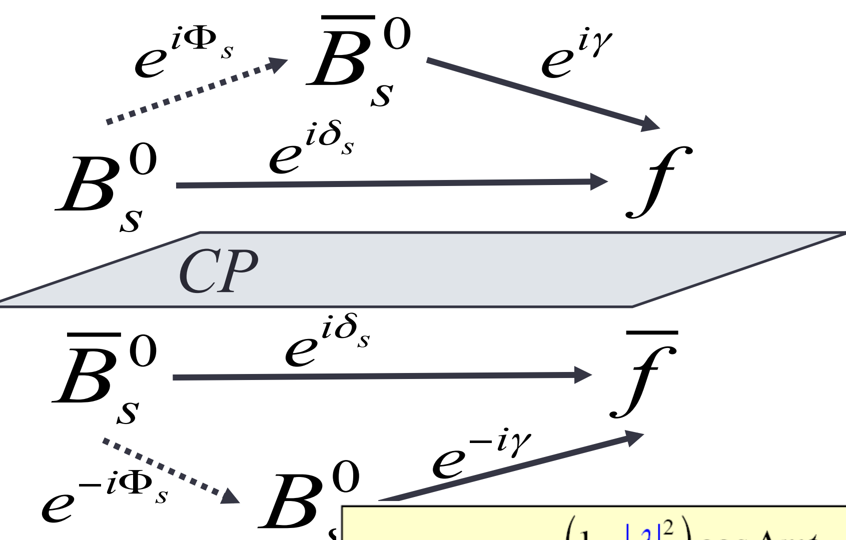
- $B_s \to \varphi\varphi$ angular analysis à la $B_s \to J/\psi\varphi$

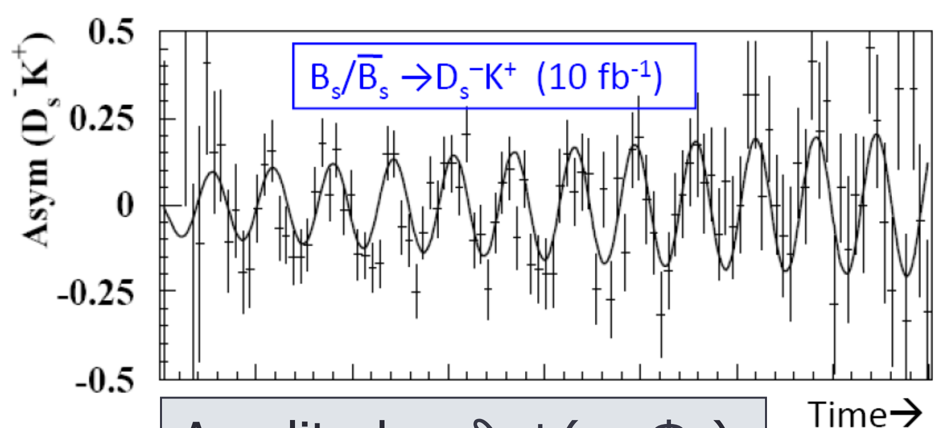
Channel	Yield (2 fb^{-1})	B/S	Weak phase precision
$B \to \phi K_s$	920	0.3 < B/S < 1.1	$\sigma(\sin(\Phi_{\varphi Ks}))=0.23$
$B_s \to \phi\phi$	3.1 k	< 0.8	**$\sigma(\Phi_{\varphi\varphi})=4.6^o$**

γ: time-dependent oscillation









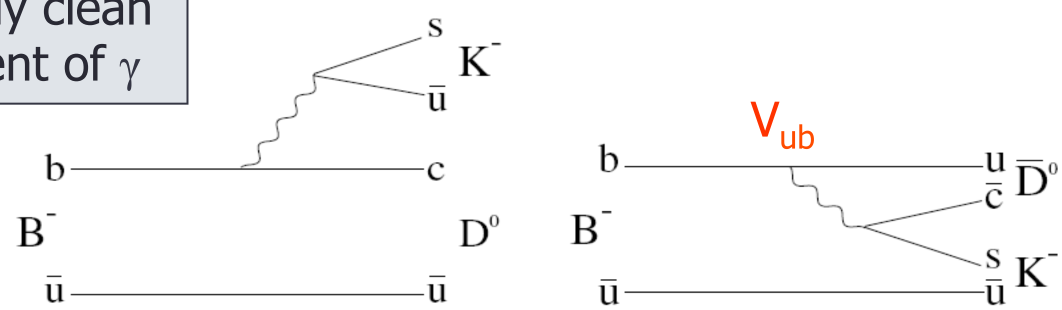
Amplitude: $\delta_s \pm (\gamma + \Phi_s)$

$$A^{B/\overline{B}}_{D_s^{\mp}K^{\pm}} = \frac{\left(1-|\lambda|^2\right)\cos\Delta m t - 2|\lambda|\sin\left(\delta_s \mp (\gamma+\phi_s)\right)\sin(\Delta m t)}{\left(1+|\lambda|^2\right)\cosh\frac{\Delta\Gamma t}{2} - 2|\lambda|\cos\left(\delta_s \mp (\gamma+\phi_s)\right)\sinh\left(\frac{\Delta\Gamma t}{2}\right)}$$

With 2.0fb^{-1}:
$\sigma(\gamma+\Phi_s)=9^o\text{-}12^o$

γ: decay time independent CPV

Theoretically clean measurement of γ



- $\sim V_{cb}V_{us}^{*}$
- D^0

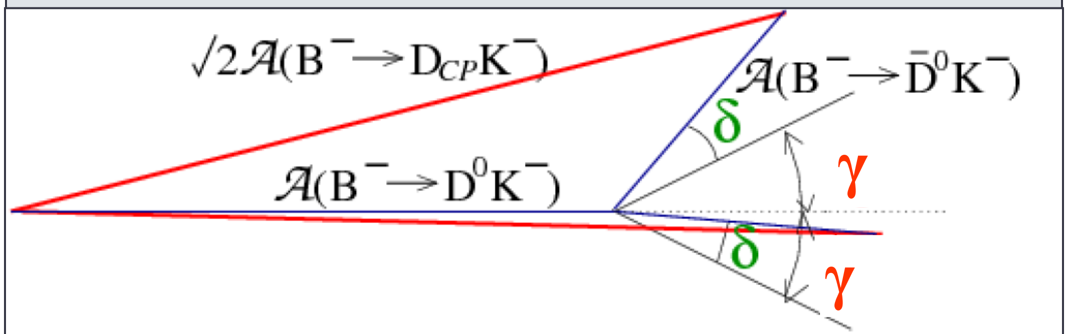
- $\sim V_{ub}V_{cs}^{*}$
- D^0

- Sum of amplitudes leads to CPV
  - Relative strong phase δ
  - Relative weak phase γ

➢ For interference: need a common final D^0&$\overline{D^0}$ state

γ (2)

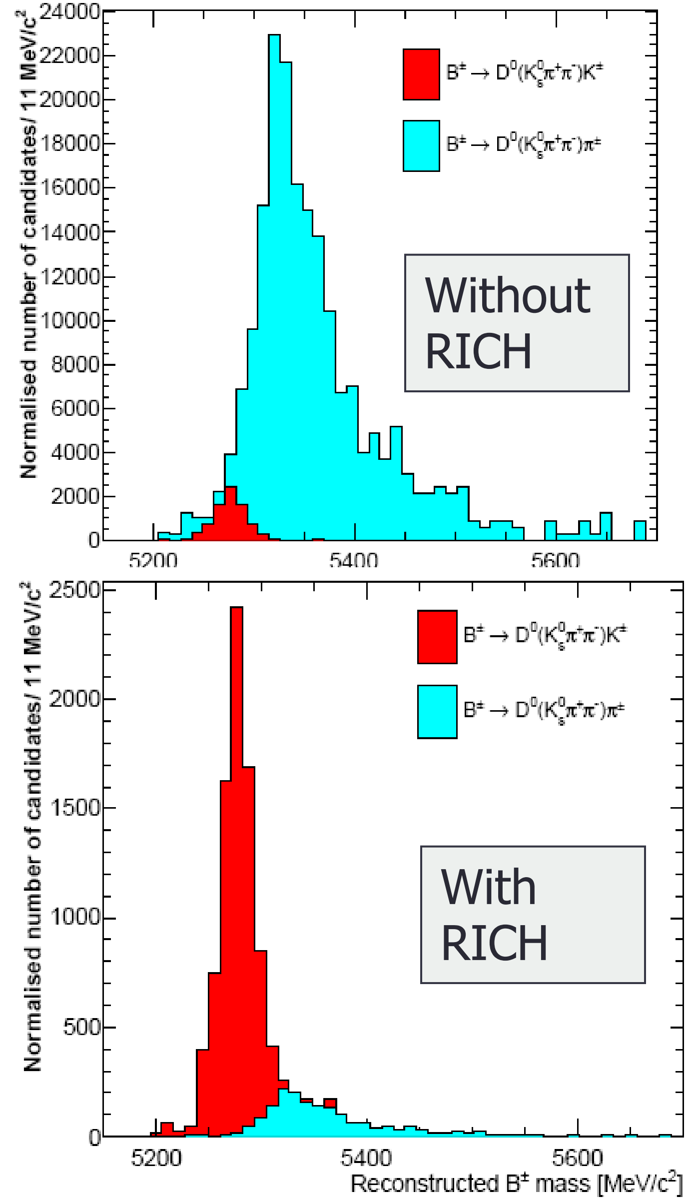
- GLW: Choose CP-even final state
  - $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$
  - D_{CP} is CP-even D^0-$\bar{D}^0$ mixture



- Rates → δ+γ
- Rates (CP-conjugated) → δ-γ
- ➢ The combination gives two solutions of γ

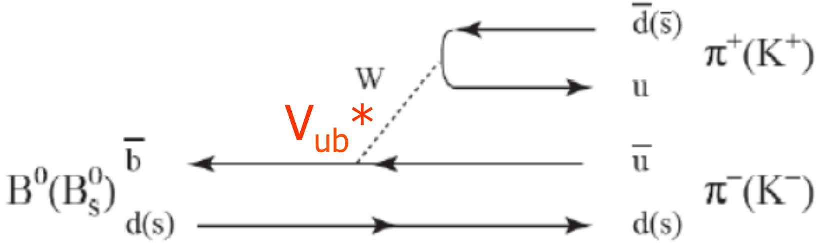
Combination of all methods after 2.0 fb⁻¹:
σ(γ) = 4-5º

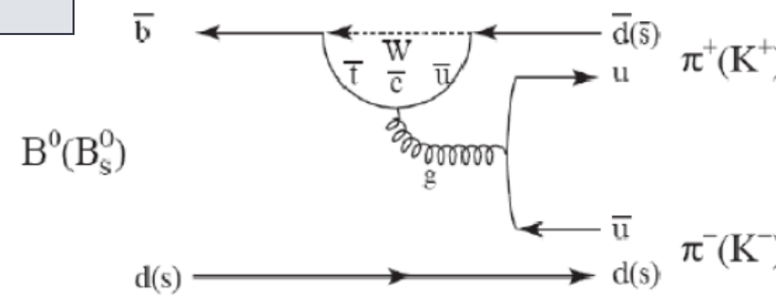
PID by RICH important



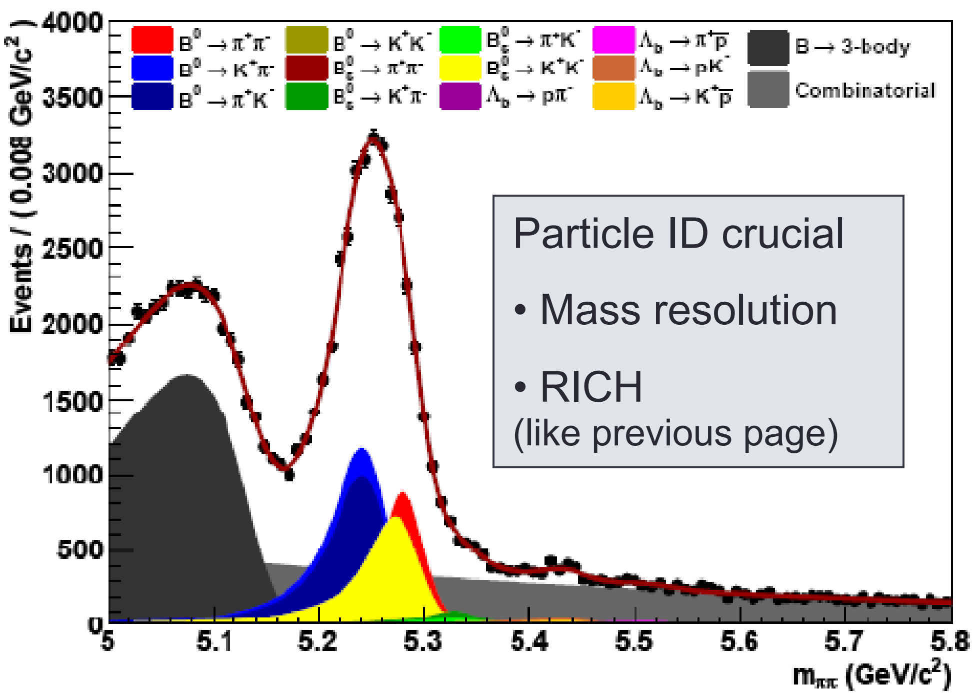
γ with loops: B→hh

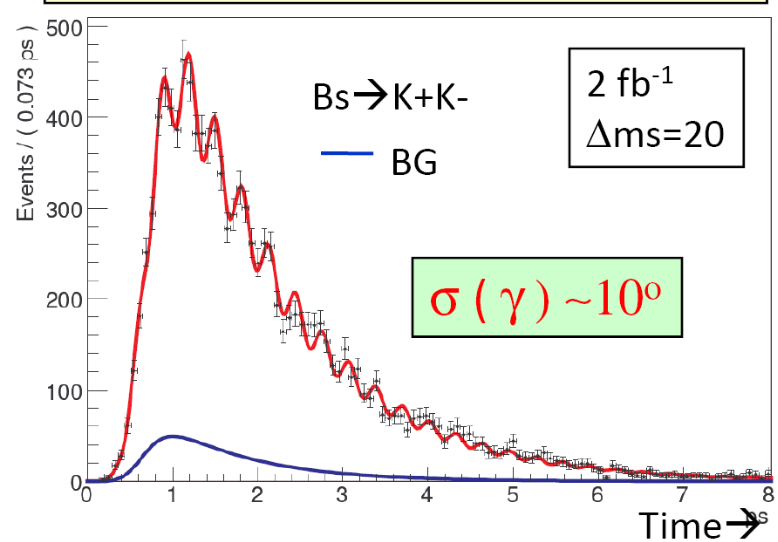
Interfere b→u tree diagram with penguins:





$$A_f^{CP}(t) = \frac{A_f^{dir}\cos\Delta mt + A_f^{mix}\sin\Delta mt}{\cosh\left(\frac{\Delta\Gamma t}{2}\right) - A_f^{\Delta}\sinh\left(\frac{\Delta\Gamma t}{2}\right)}$$





LHCb with 2 fb^{-1}

Brown = box
Green = tree
Black = penguin

γ with time dependent osc
- $B_s \rightarrow D_s K$
- $B \rightarrow D^*\pi$

$\sigma(\gamma-\Phi_s) = 9^o-12^o$

γ with direct CPV
- $B \rightarrow DK$ (glw)
- $B \rightarrow DK$ (ads)
- More bodies

$\sigma(\gamma) = 4\text{-}5^o$

γ with loops
- $B \rightarrow hh$

$\sigma(\gamma) = 7^o$

$\sigma(\Phi_s) =$ 2.8°-3.4°

Φ_s
- $B_s \rightarrow J/\psi\ \phi$

$\sigma(\Phi_s) = 1.8^o$

Φ_s with penguins
- $B_s \rightarrow \phi\ \phi$

$\sigma(\Phi_{\varphi\varphi}) = 4.6^o$

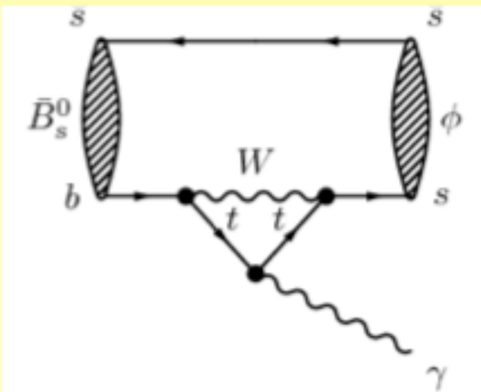
Compare with current constraints:
$\sigma(\gamma) = 30°$, $\sigma(\phi_s) = 2*(20°)$

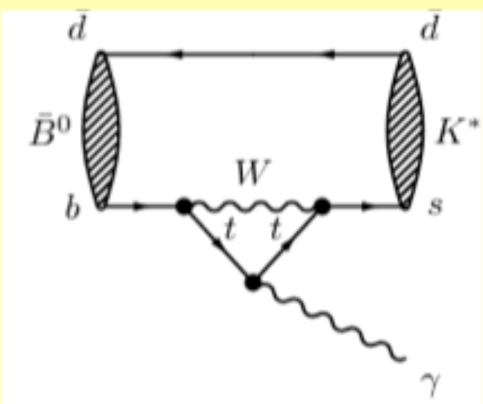
Advantages of LHCb
- Number of B_s's
- Proper time and mass resolution
- Particle ID

Other LHCb topics, not covered today:

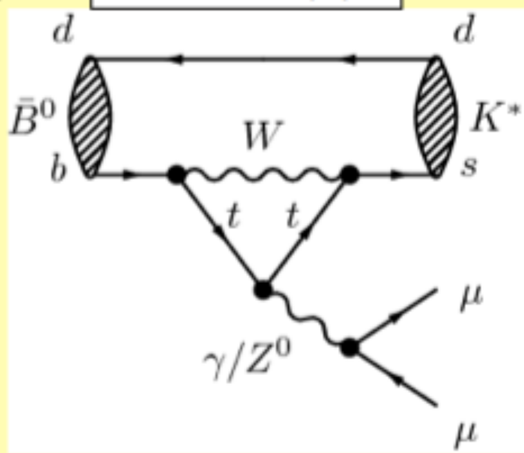
Rare decays

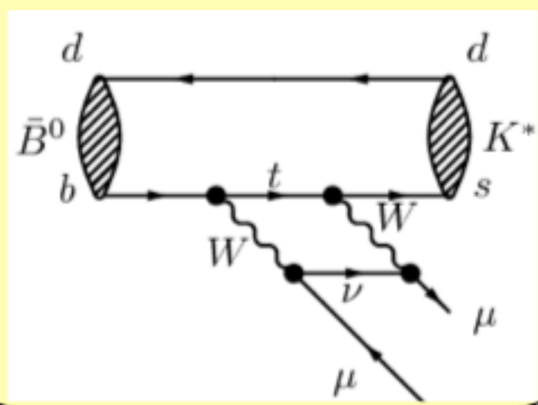
$B^0_{(s)} \rightarrow K^*(\varphi)\gamma$



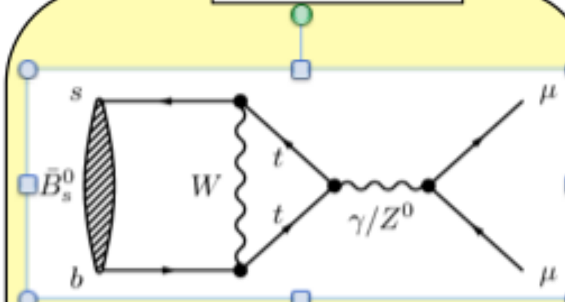


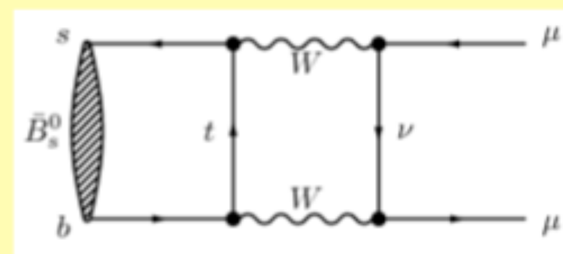
$B^0 \rightarrow K^*\mu\mu$





$B^0_s \rightarrow \mu\mu$

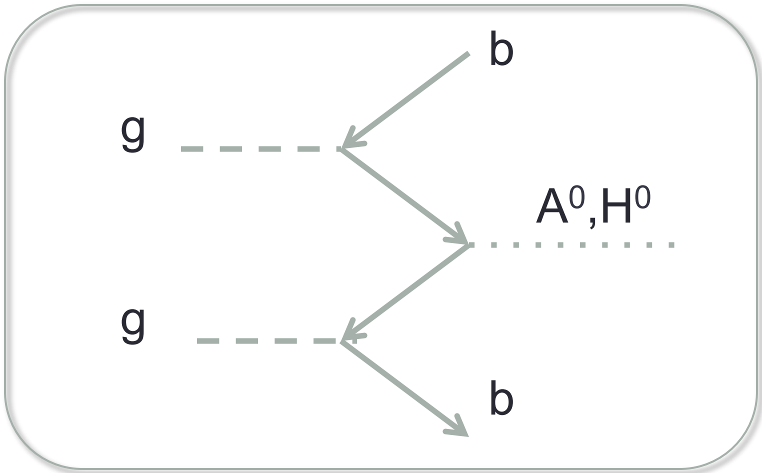


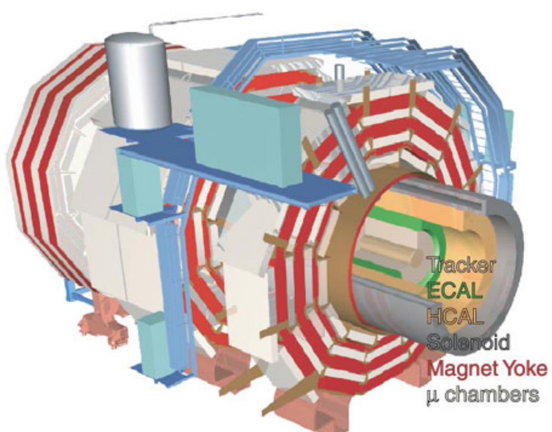


Wolf and sheep *can* work together!

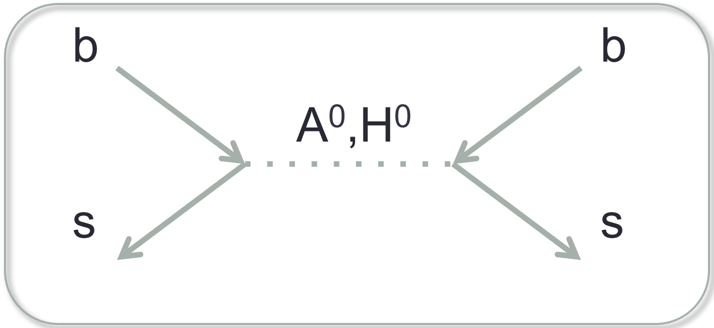
Dream scenario for 2011/2012…2HDM

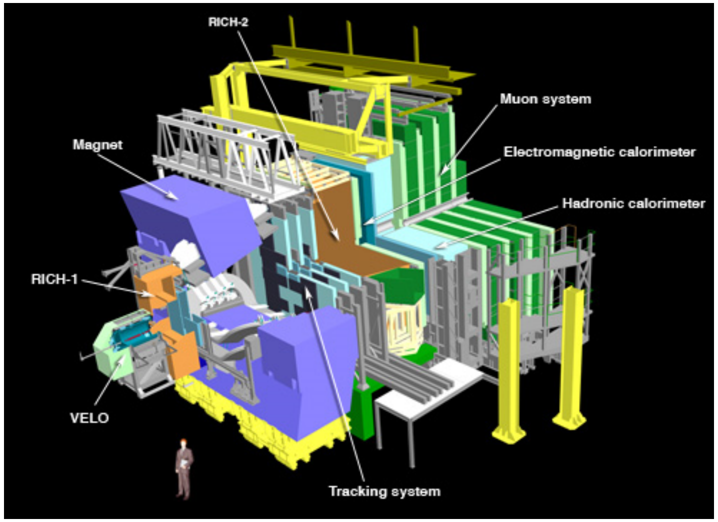
- CMS: direct





- LHCb: indirect





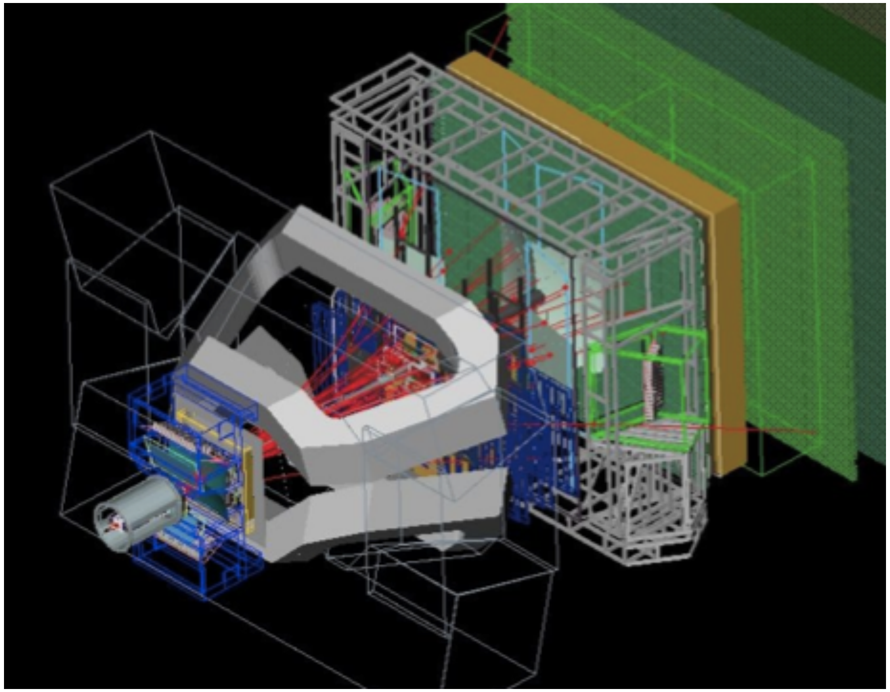
e.g. arxiv/1012.1981

Conclusions

- *B*-physics complementary to direct BSM searches
- LHCb: a dedicated *B*-physics experiment
- $B_s \rightarrow J/\psi\varphi$ sensitive to off-shell processes in $B_s \leftrightarrow$anti-B_s mixing
  - LHCb's advantages: #B_s's, mass & proper time resolution, particle identification
  - Optimized selection: few cuts, trigger rate flexibly adjustable
  - Multi-dimensional likelihood fit
- Many other probes to γ, φ_s
  - Sensitive to different diagrams
- Expectation LHCb for $B_s \rightarrow J/\psi\varphi$
  - Overtake Tevatron at ~0.2 fb^{-1}
- If different from SM…
  - new sources of CPV, BSM particles…and their couplings!

➢ Stay tuned for the upcoming results!

Search like Sherlock Holmes…



…pay attention to the indirect evidence!

BACKUP!

Discussion

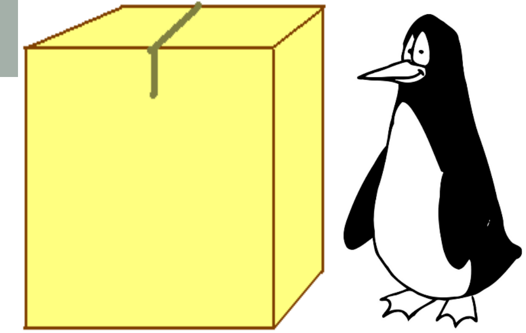
CMS

- Have to know SM QCD accurately
- Don't know where new physics will pop up
  - Search benchmark points and pray…
- Cross section NP small
  - Much background

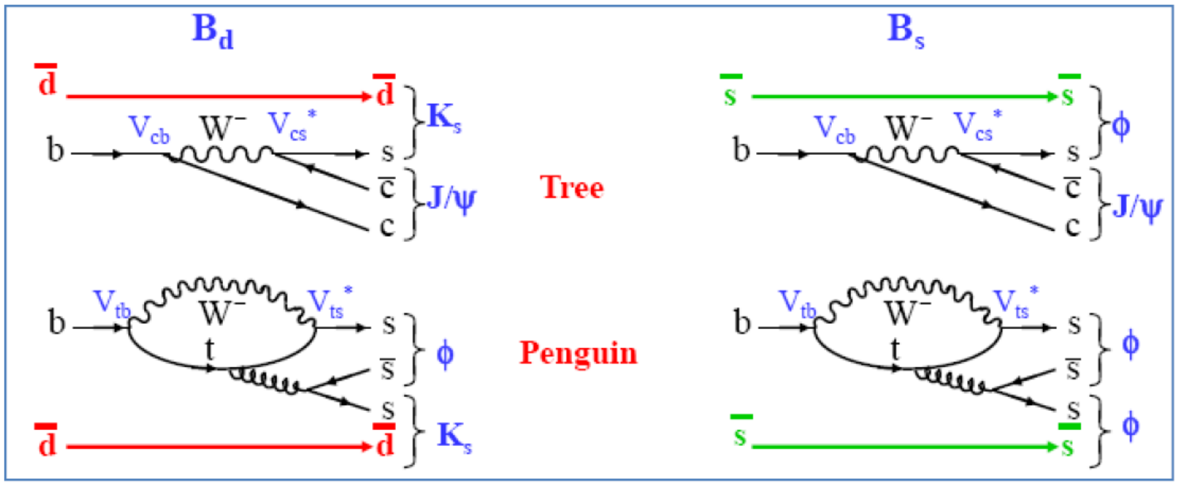
LHCb

- Can choose
  - Theoretically clean channel
  - Experimentally clean channel
  - Channel with large x-sec/br
- 'Independent' of new physics channel
- Don't need large lumi/high COM-energy
  - Especially handy coming years

$B_s \rightarrow \varphi\varphi$



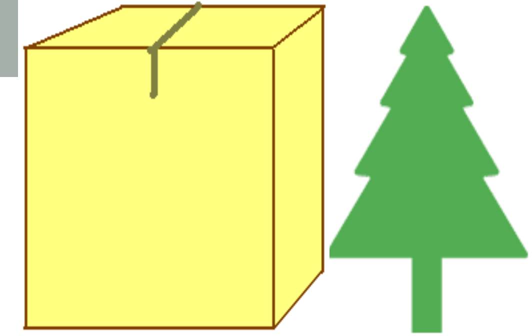
- Compare: phase(tree) & phase(penguin)



$$\Phi_{\phi K_s} = 2\beta^{mix} + 2\beta_s^{decay}$$
$$\approx 2\beta(SM)$$

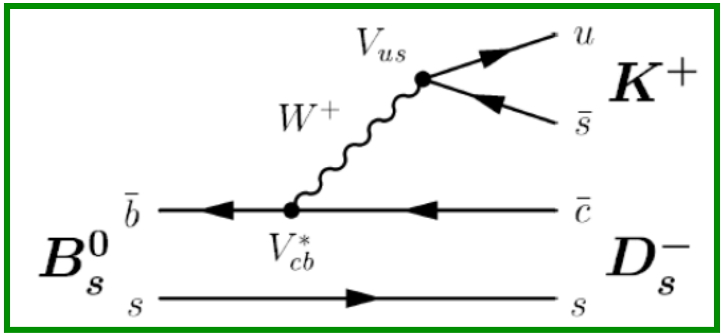
$$\Phi_{\phi\phi} = \Phi_s^{mix} + 2\beta_s^{decay}$$
$$\approx 0(SM)$$

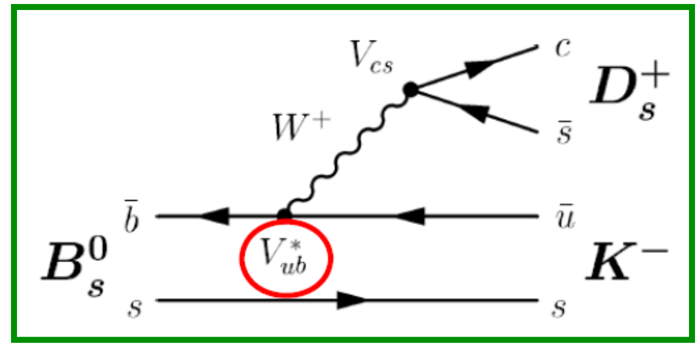
Channel	Yield (2 fb^{-1})	B/S	Weak phase precision
$B \rightarrow \phi K_s$	920	0.3 < B/S < 1.1	$\sigma(\sin(\Phi_{\varphi Ks}))=0.23$
$B_s \rightarrow \phi\ \phi$	3.1 k	< 0.8	$\sigma(\Phi_{\varphi\varphi})=4.6^o$

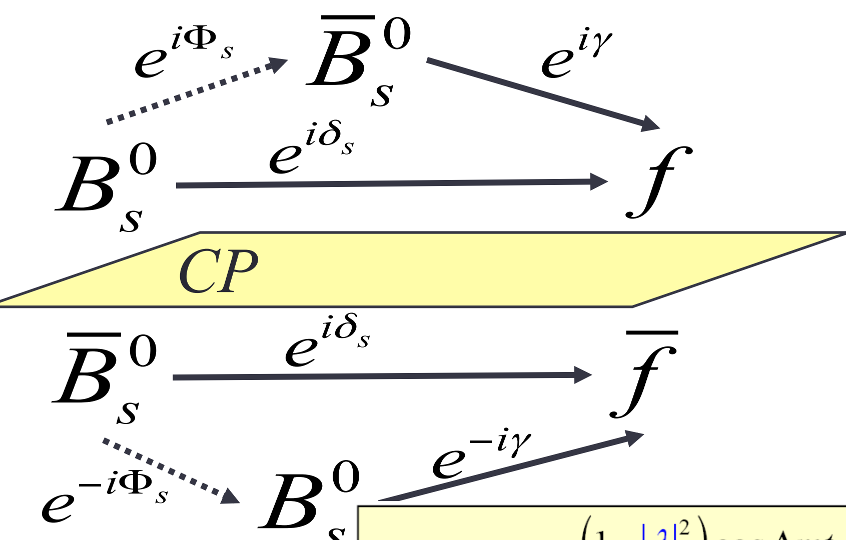


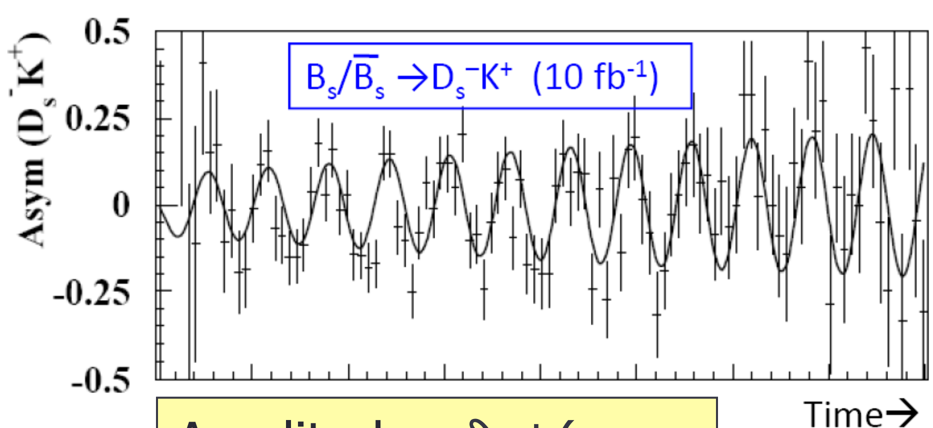
γ with trees (1)

$B_s \to D_s K$: time-dependent oscillation









Amplitude: $\delta_s \pm (\gamma + \Phi_s)$

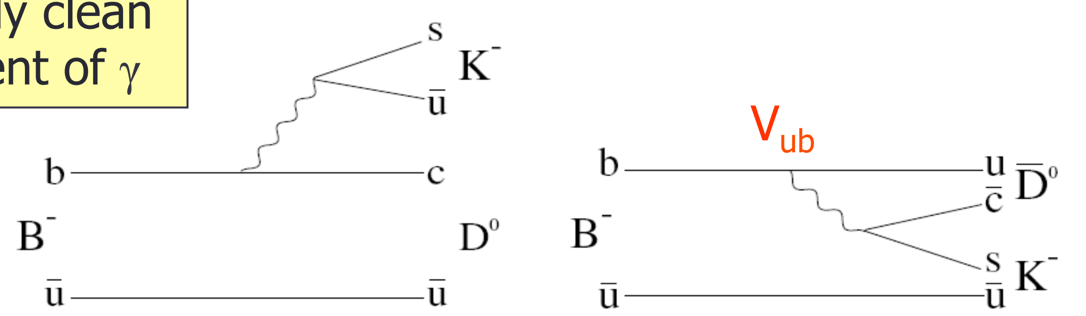
$$A^{B/\overline{B}}_{D_s^{\mp} K^{\pm}} = \frac{\left(1-|\lambda|^2\right)\cos\Delta m t - 2|\lambda|\sin\left(\delta_s \mp (\gamma+\phi_s)\right)\sin\left(\Delta m t\right)}{\left(1+|\lambda|^2\right)\cosh\frac{\Delta\Gamma t}{2} - 2|\lambda|\cos\left(\delta_s \mp (\gamma+\phi_s)\right)\sinh\left(\frac{\Delta\Gamma t}{2}\right)}$$

With 2.0fb^{-1}:
$\sigma(\gamma+\Phi_s)$ =9°-12°

γ with trees (2)

Decay time independent CPV in B→DK

Theoretically clean measurement of γ



- $\sim V_{cb} V_{us}^*$
- D^0

- $\sim V_{ub} V_{cs}^*$
- D^0

- Sum of amplitudes leads to CPV
  - Relative strong phase δ
  - Relative weak phase γ

➢ For interference: need a common final D^0&$\bar{D}^0$ state

Status CP-violating observables

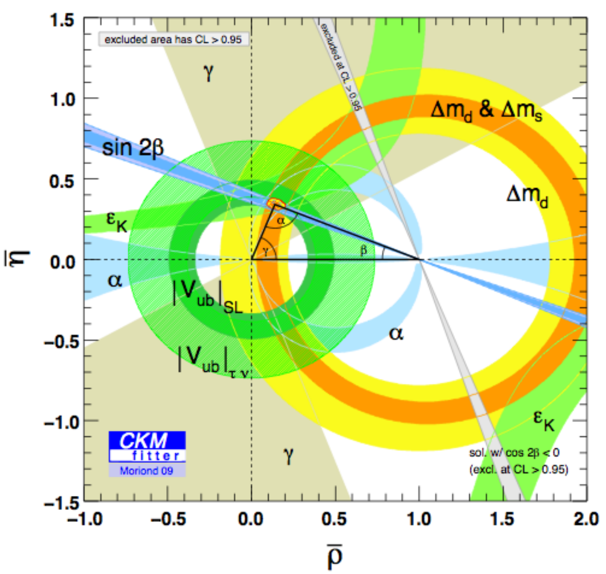
$\beta \equiv \arg[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}]$

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

CP angle	Indirect measurements (°)	Direct measurements (°)
α	$95.6^{+3.3}_{-8.8}$	$89.0^{+4.4}_{-4.2}$
β	$27.4^{+1.3}_{-1.9}$	$21.07^{+0.90}_{-0.88}$
γ	$67.8^{+4.2}_{-3.9}$	70^{+27}_{-30}
β_s	$1.032^{+0.049}_{-0.046}$	22 ± 10 or 68 ± 10

β: $B_d \leftrightarrow$ anti-B_d

β_s: $B_s \leftrightarrow$ anti-B_s



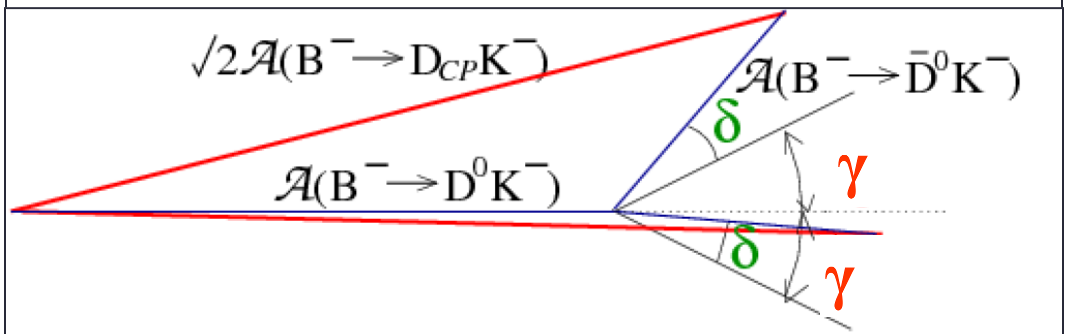
- All measurements consistent
- $B_d \leftrightarrow$ anti-B_d mixing phase known very accurately
- $B_s \leftrightarrow$ anti-B_s mixing phase not yet known very accurately
- 2-3 σ deviations in β_s

➢ Stronger constraints needed… LHCb!

γ with trees (2)

Decay time independent CPV

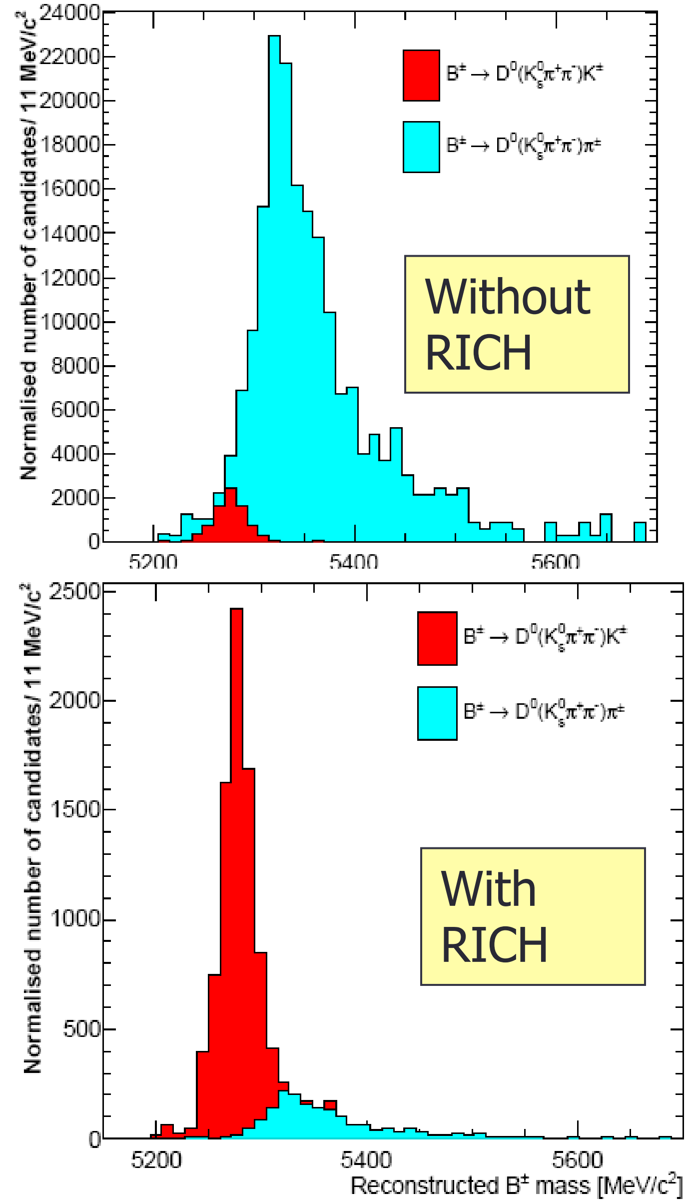
- GLW: Choose CP-even final state
  - $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$
  - D_{CP} is CP-even D^0-$\bar{D^0}$ mixture



- Rates → δ+γ
- Rates (CP-conjugated) → δ-γ
- ➢ The combination gives two solutions of γ

Combination of all methods after 2.0 fb^{-1}:
$\sigma(\gamma)$ = 4-5º

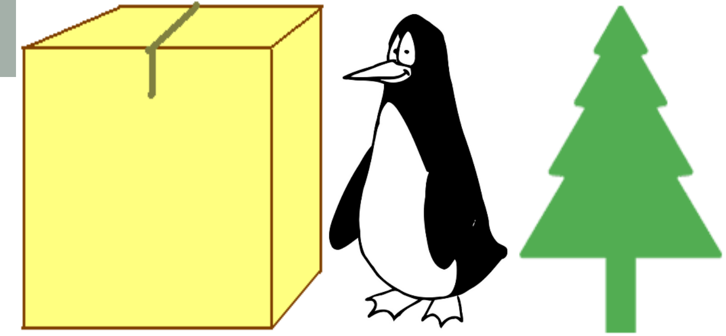
PID by RICH important

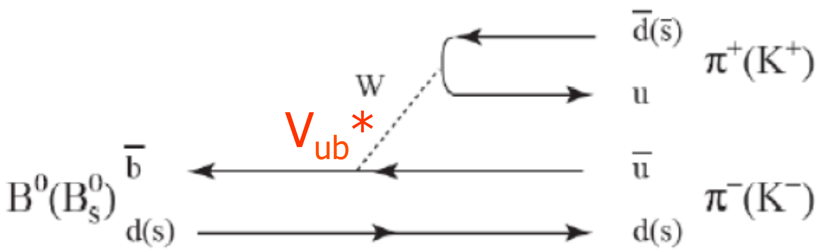


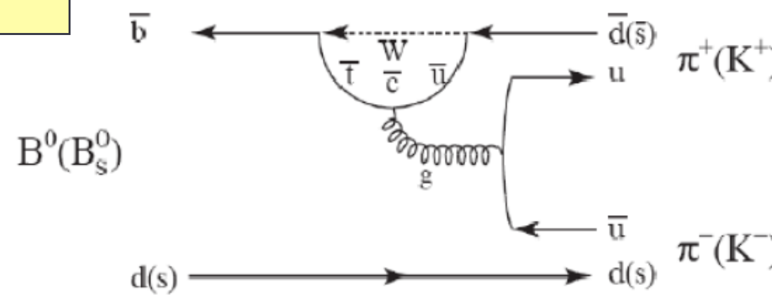
γ with loops

B→hh

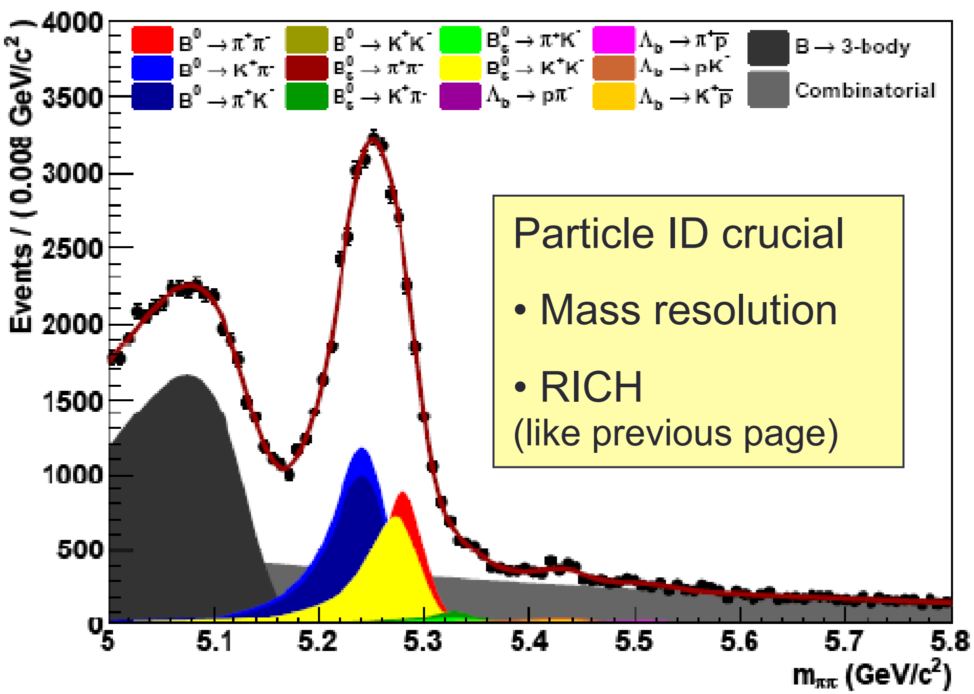
Interfere b→u tree diagram with penguins:





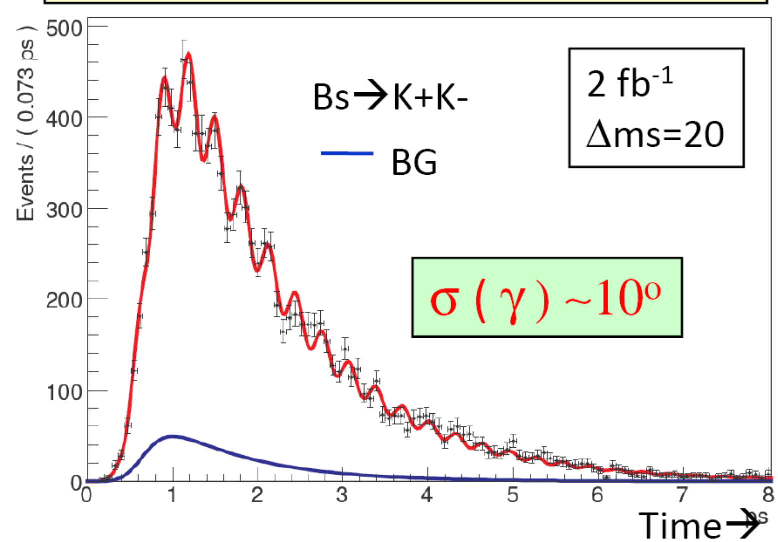


$$A_f^{CP}(t) = \frac{A_f^{dir}\cos\Delta mt + A_f^{mix}\sin\Delta mt}{\cosh\left(\frac{\Delta\Gamma t}{2}\right) - A_f^{\Delta}\sinh\left(\frac{\Delta\Gamma t}{2}\right)}$$

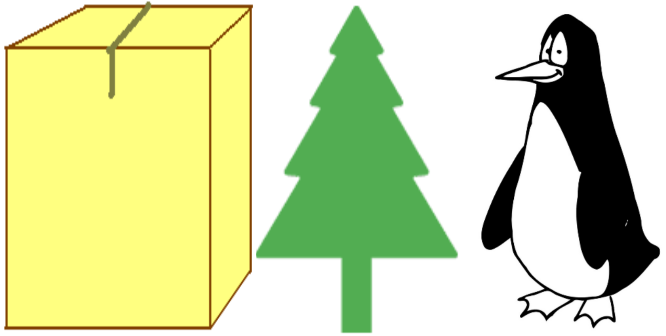


Particle ID crucial

- Mass resolution
- RICH
(like previous page)



Conclusions



- CKM model successful in describing CP violation
  - …but γ and β_s poorly constrained
  - …and inconsistencies at the horizon?
- Many different methods to study diagrams
  - Standard model diagrams (trees)
  - Possible new physics contributions (boxes, penguins)
- LHCb will drastically improve the sensitivity to the CKM angles γ and β_s

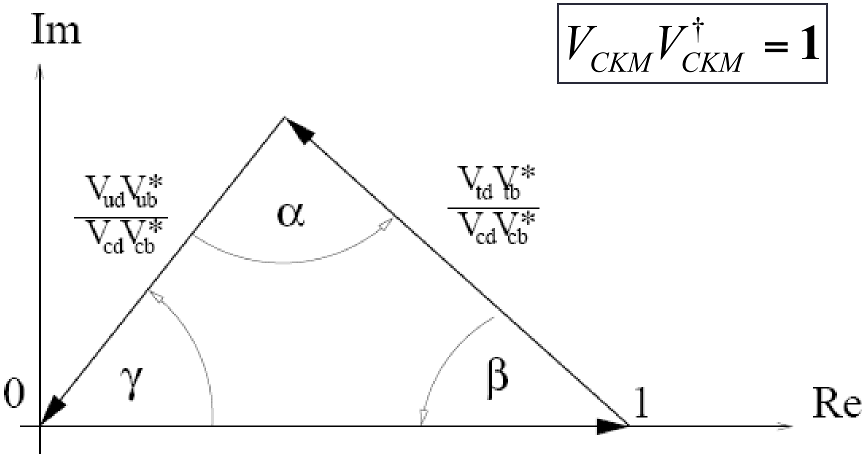
SOMETHING NEW IN THE BOX OF $B_S \rightarrow J/\Psi\varphi$?

BACK-UP

Unitarity Triangle

- Constraints following from unitarity of CKM matrix
  - Three complex numbers add up to zero

$$V_{CKM} V_{CKM}^{\dagger} = \mathbf{1}$$



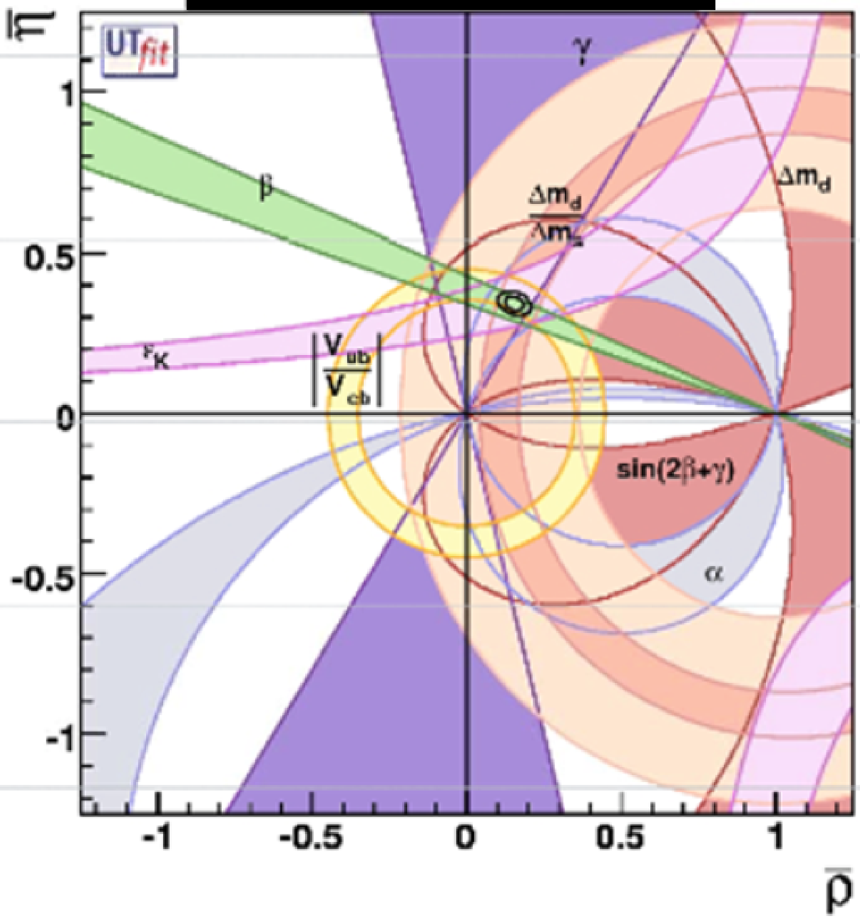
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- Performing different measurements, overconstrain 4 free parameters in CKM matrix
  - To test consistency of CKM model
  - Inconsistency (e.g. triangle doesn’t close) → new physics

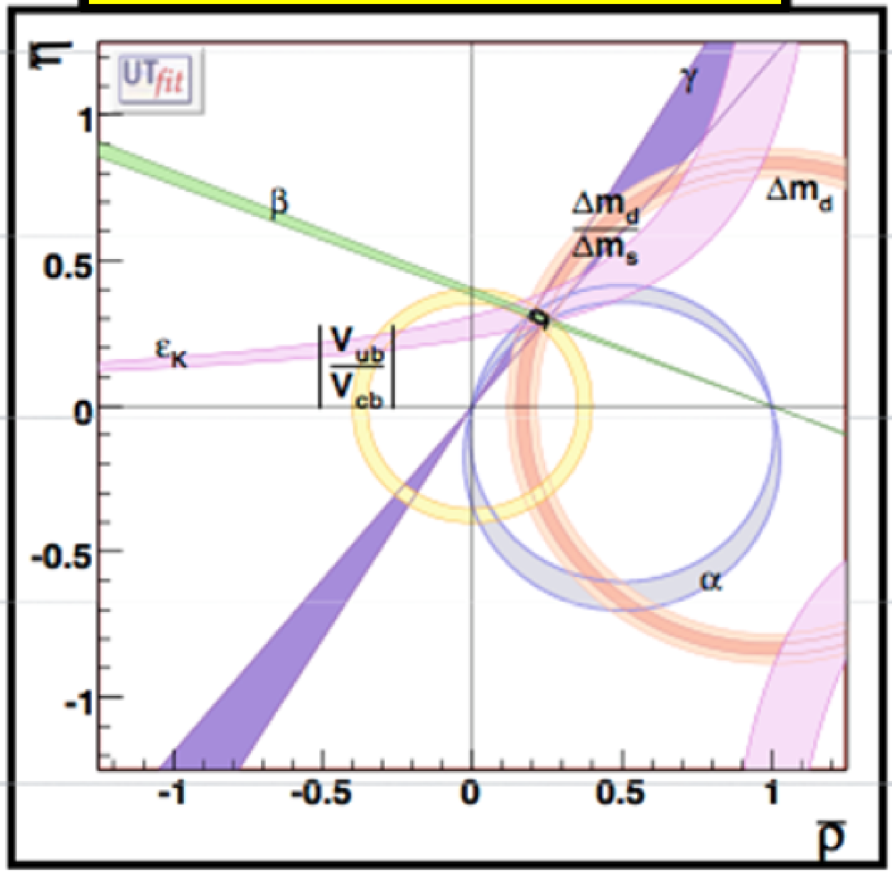
UT after 5 years of LHCb

in case of no new physics

Winter 2009



LHCb at L=10fb^{-1}

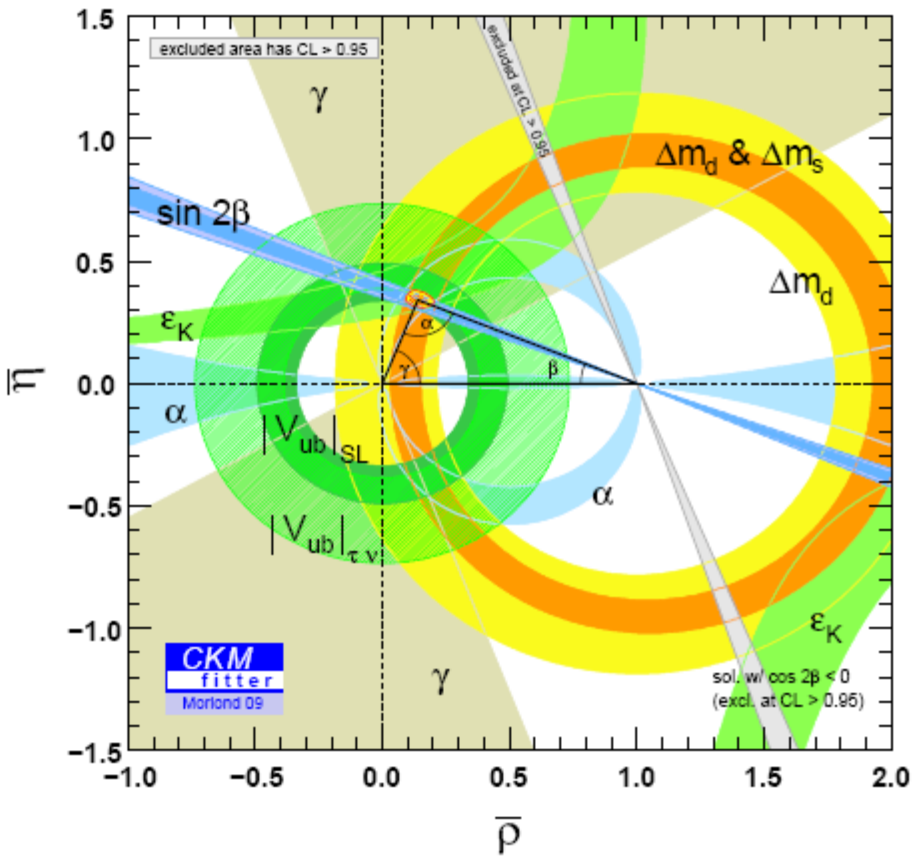


Lattice QCD improvements assumed: $\sigma(\xi)/\xi = 1.5\%$

$\sigma(\sin(2\beta)) = 0.01$; $\sigma(\gamma) = 2.4°$; $\sigma(\alpha) = 4.5°$

Current status UT

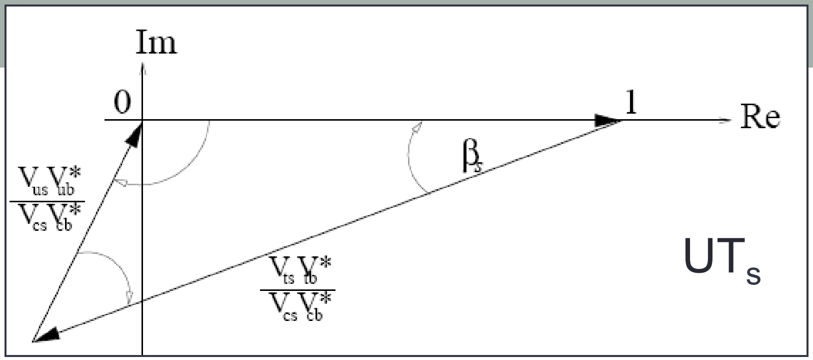
experimental constraints on unitary CKM matrix

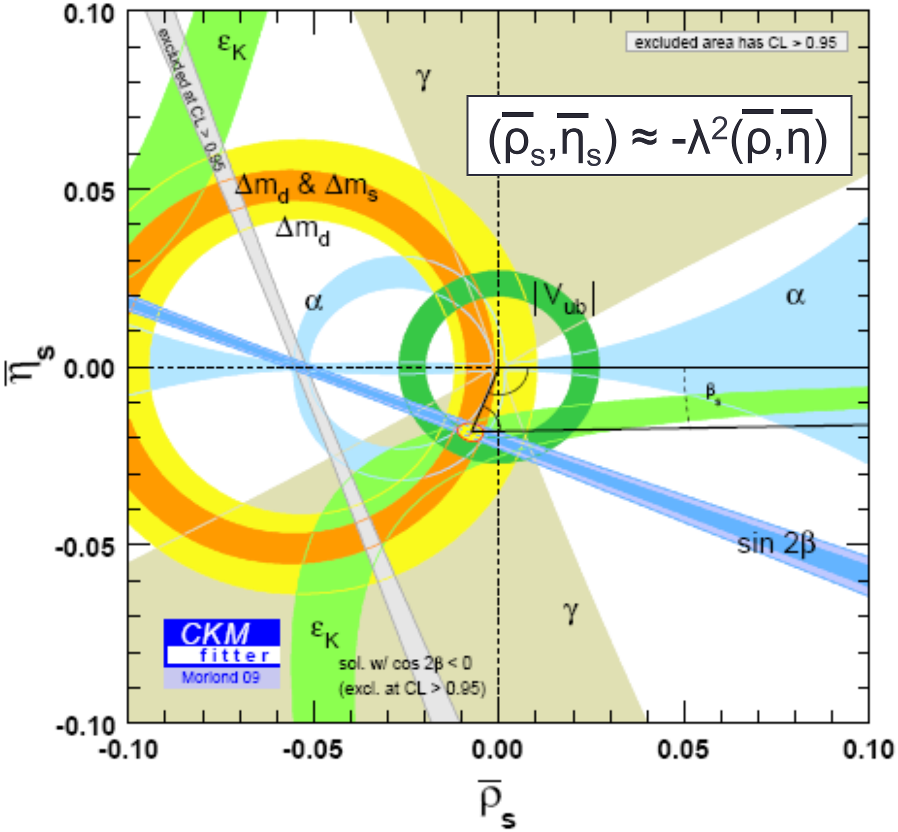


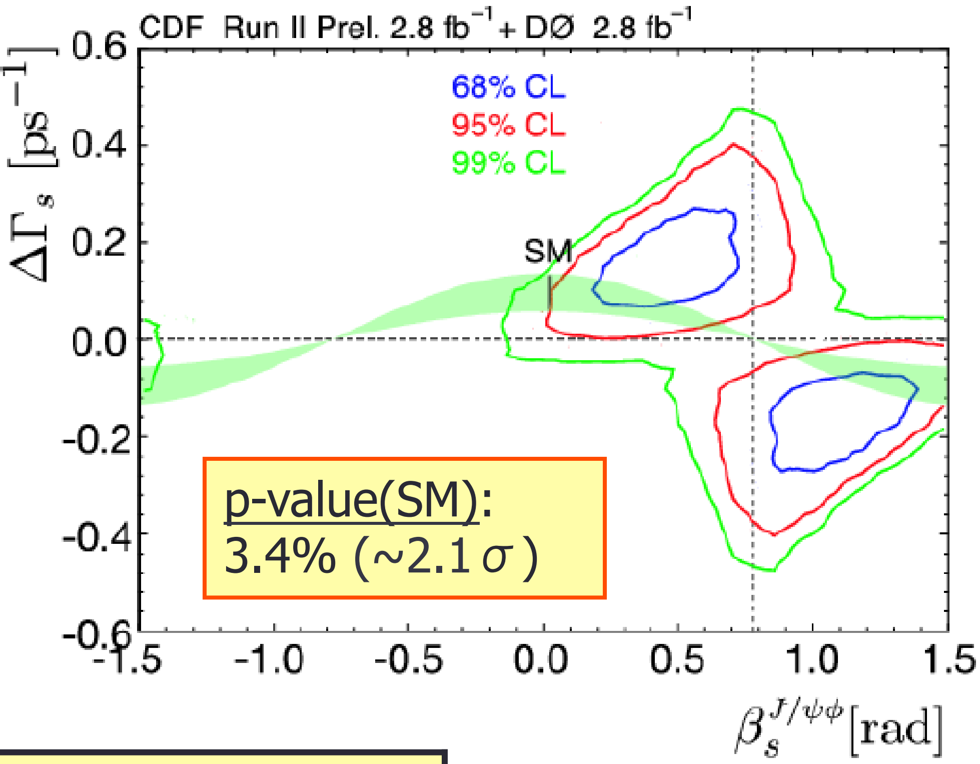
- CKM mechanism explanation of CPV
  - No significant inconsistencies
- Some interesting deviations
  - β^{eff} (penguins)
  - $B \to \tau\nu$ vs β
  - "Kπ puzzle"
  - β_s ← Subject today
- Biggest uncertainty in γ ← Subject today
- ➢ Stronger constraints needed!
  - To constrain CKM & discover NP

CP angle	Indirect measurements (°)	Direct measurements (°)
α	$95.6^{+3.3}_{-8.8}$	$89.0^{+4.4}_{-4.2}$
β	$27.4^{+1.3}_{-1.9}$	$21.07^{+0.90}_{-0.88}$
γ	$67.8^{+4.2}_{-3.9}$	70^{+27}_{-30}

Present status β_s





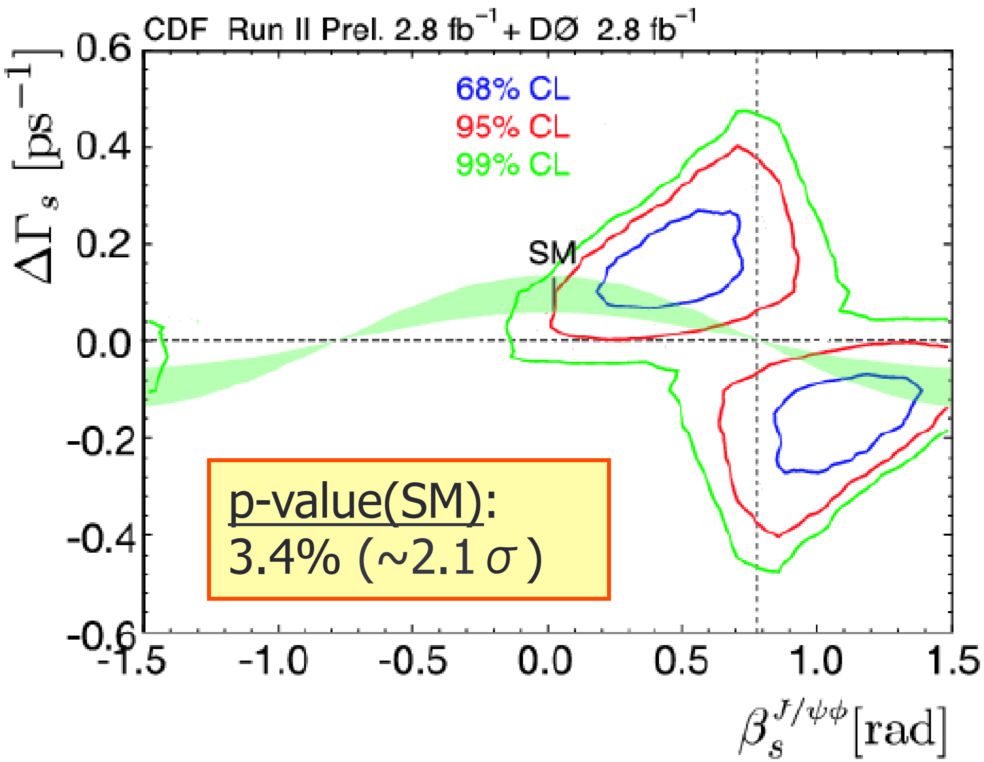


p-value(SM):
3.4% (~2.1 σ)

	Left: Indirect (UT$_s$)	Right: Direct ($B_s \to J/\psi\ \phi$ TeVatron)
β_s	1.03°±0.05°	[15°-34°]U[56°-75°] @68%CL

2.0 fb^{-1} LHCB:
$\sigma(\beta_s) \sim 0.9°$

Present status Φ_s

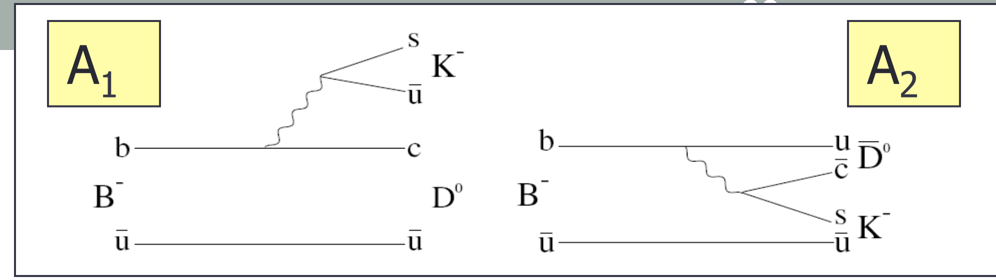


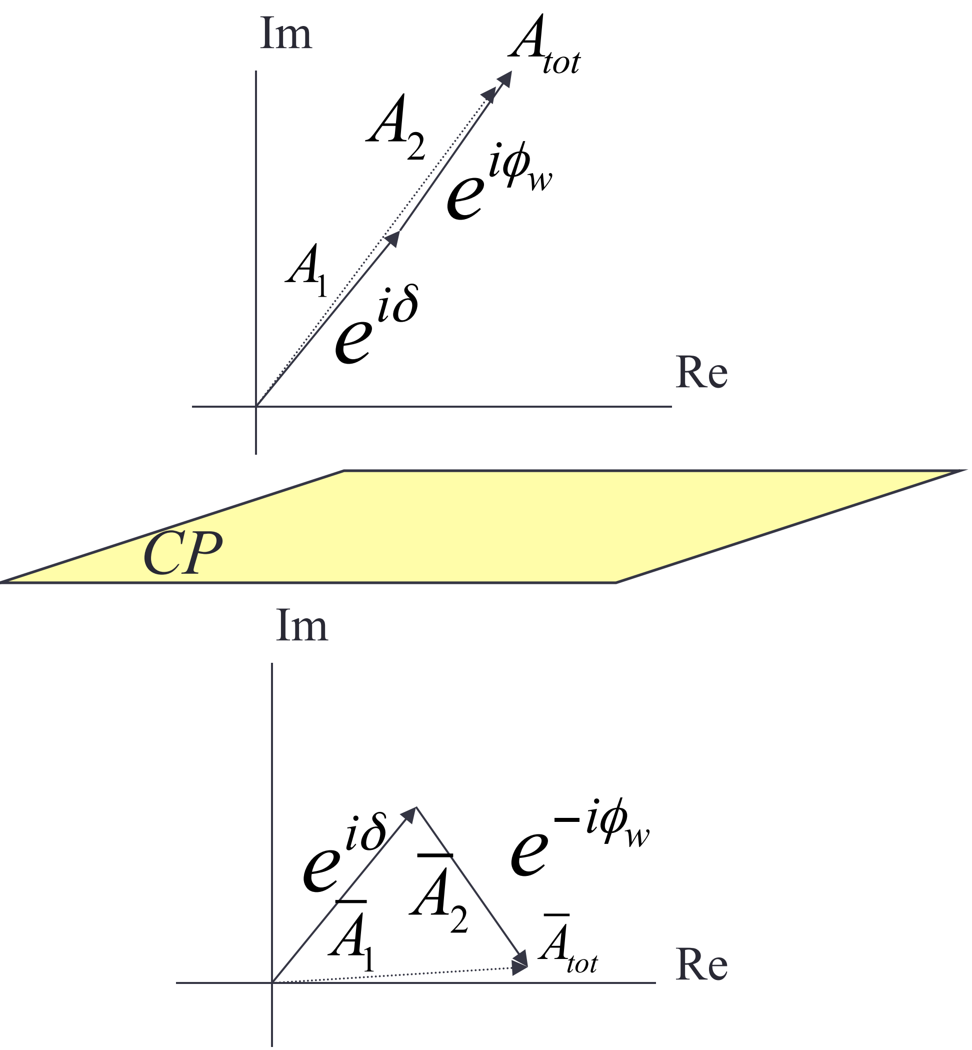
	Indirect (CKM fit)	Direct ($B_s \to J/\psi\ \phi$ TeVatron)
Φ_s	-2.1°±0.1°	[-30°,-68°]U[-112°,-150°] @68%CL

2.0 fb^{-1} LHCB:

$\sigma(\Phi_s)$ ~ 1.8°

Example
CP violation





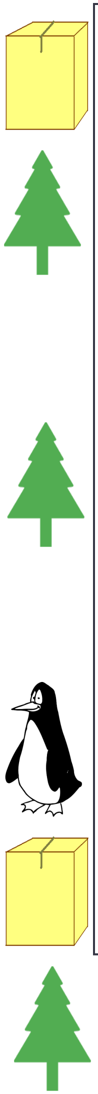
2 amplitudes

- Relative weak phase φ_w
  - Flips sign under CP
- Relative strong phase δ
  - Does not flip sign under CP
- $|A_{tot}|^2 = |A_1+A_2|^2$
- Need both nonzero δ and φ_w for CP asymmetry:

$$|A_{tot}|^2 - |\bar{A}_{tot}|^2 = -4|A_1||A_2|\sin\delta\sin\varphi_w$$

Brown = box
Green = tree
Black = penguin

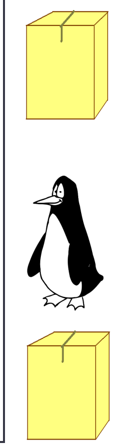
CP violation at LHCb



γ with time dependent osc
- $B_s \rightarrow D_s K$
- $B \rightarrow D^*\pi$

γ with direct CPV
- $B \rightarrow DK$ (glw)
- $B \rightarrow DK$ (ads)
- More bodies

γ with loops
- $B \rightarrow hh$



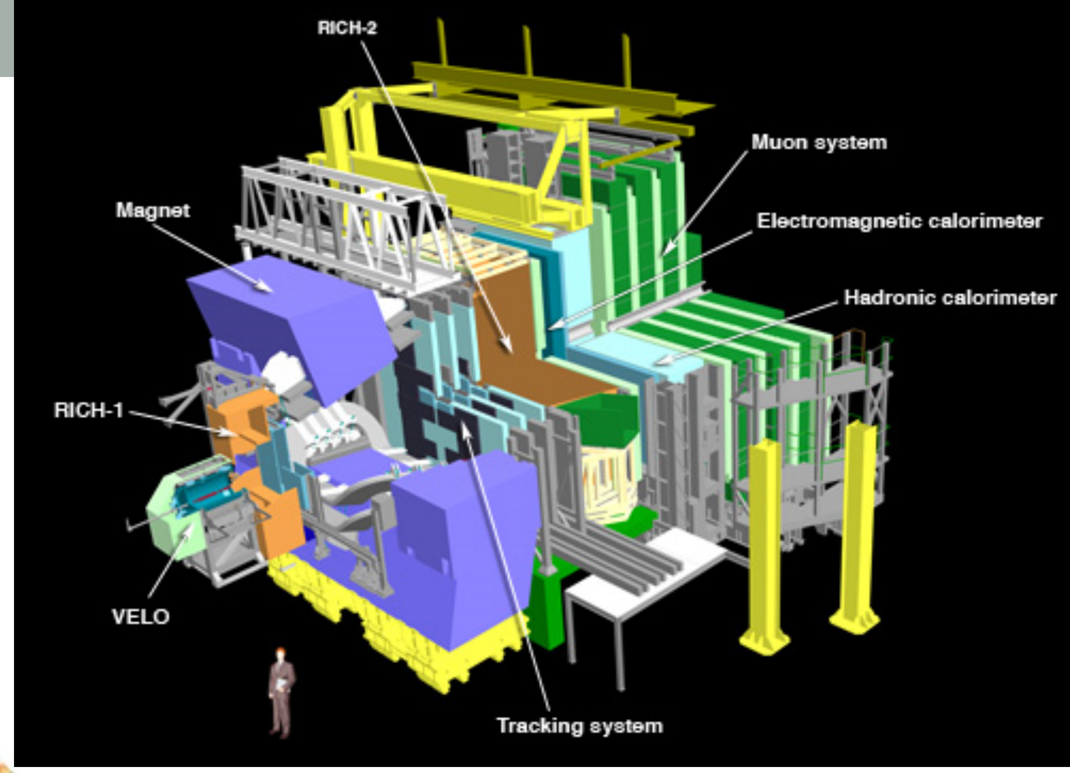
Φ_s
- $B_s \rightarrow J/\psi\ \phi$

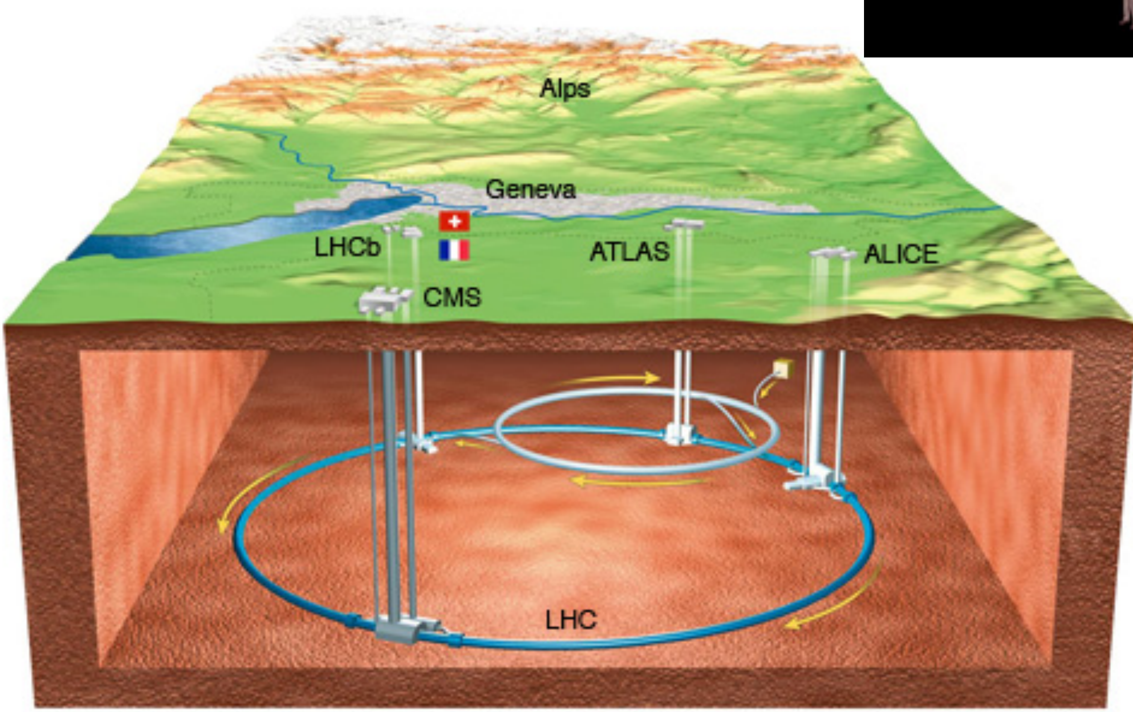
Φ_s with penguins
- $B_s \rightarrow \phi\ \phi$

Advantages of LHCb
- Number of B_s's
- Proper time and mass resolution
- Particle ID

LHC

- 27 km
- Proton-proton
- $\sqrt{s}$ = 14 TeV?
- Re-start this fall





HCb

L = $(2\text{-}5)\times10^{32}\,cm^{-2}s^{-1}$

σ_{bb}~500μb (10% B_s)

'1 year' = 2.0fb^{-1}

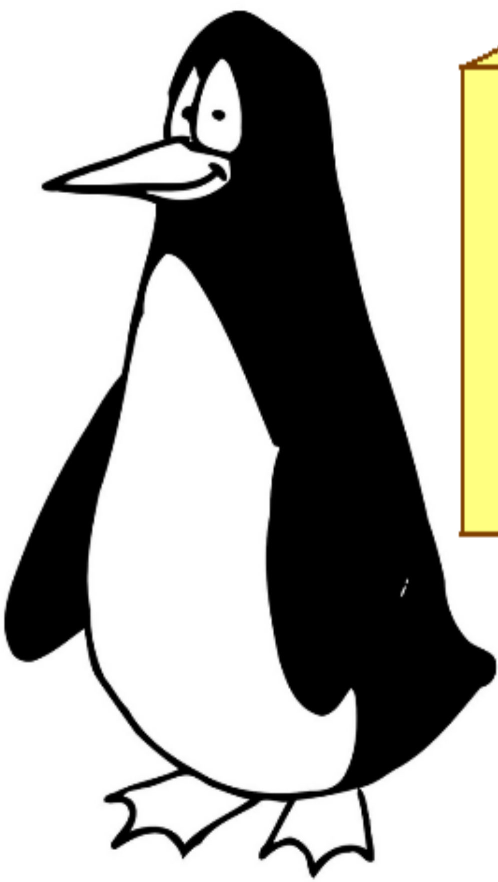
Produce $O(10^{11})$ B_s per y.

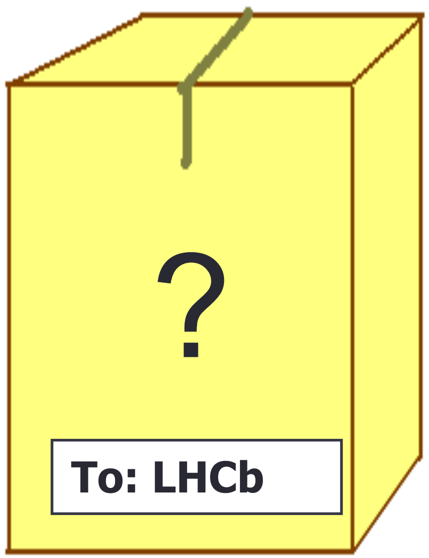
Expect to reconstruct:

O(100k) $B_s \rightarrow J/\psi\phi$ per y.

Trees, penguins and boxes at LHCb

Prospects for CP violation measurements at LHCb





Tristan du Pree (Nikhef)

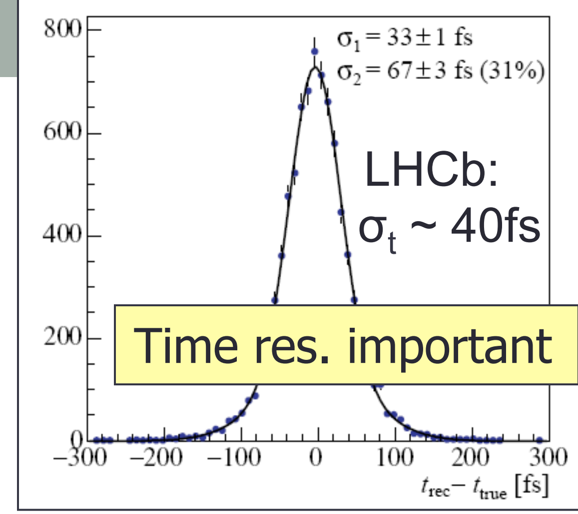
On behalf of the LHCb collaboration

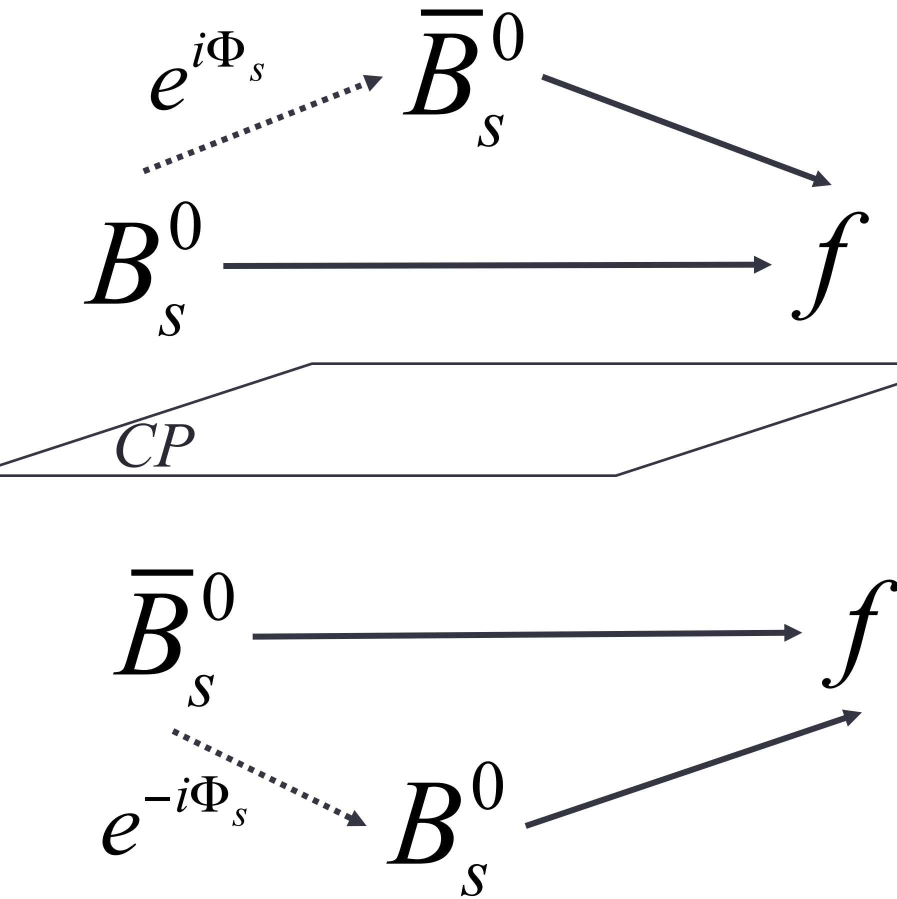
14th Lomonosov conference

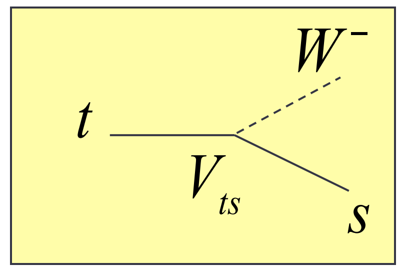
19-25 Aug 2009, Moscow

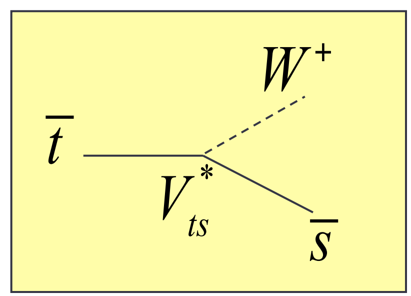
Time dependent CPV

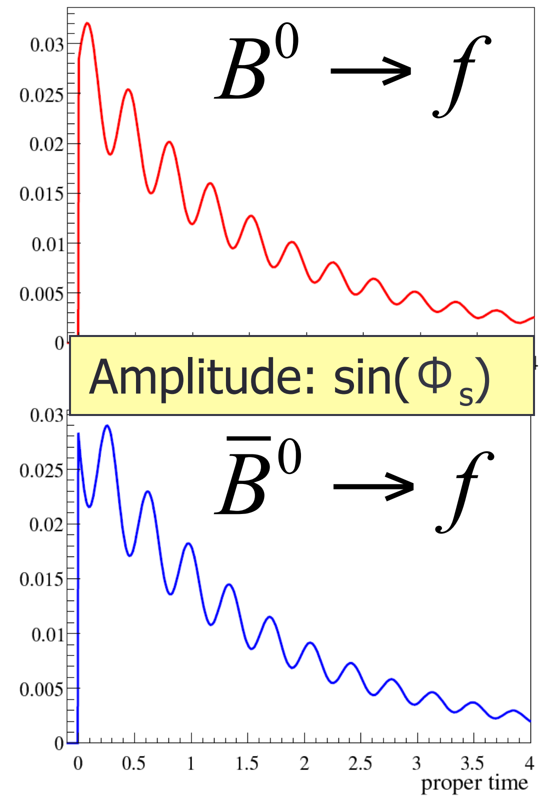
- Final state *f* is a $c\bar{c}s\bar{s}$ CP-eigenstate











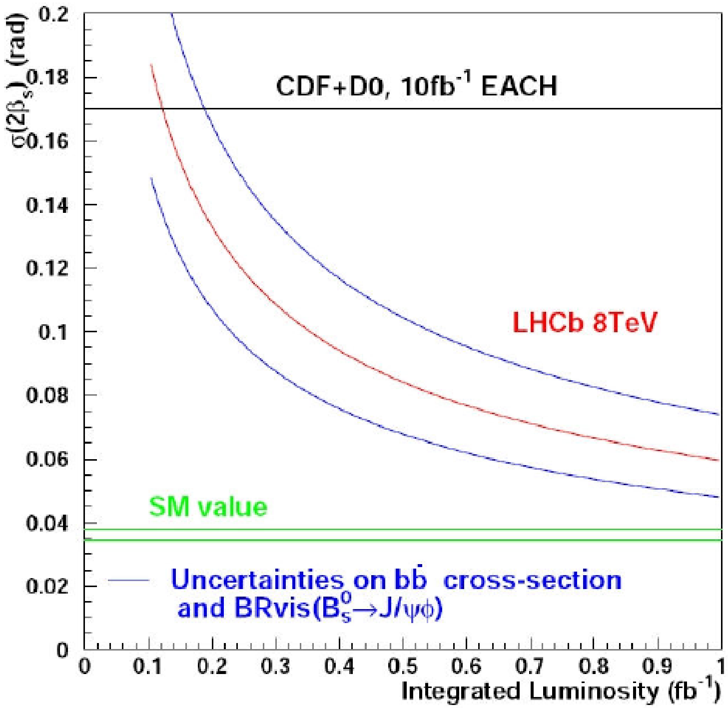
Sensitivity: $\sigma(\Phi_s)$

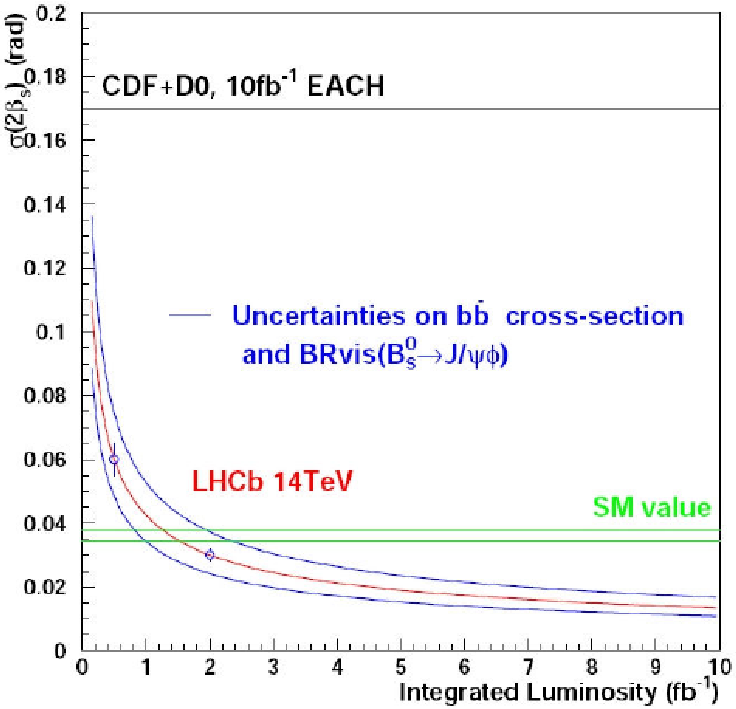
0.2 fb^{-1} (8 TeV):

- $\sigma_{LHCb}(\Phi_s) < \sigma_{TeVatron}(\Phi_s)$

2.0 fb^{-1} (14 TeV):

- **If** $\Phi_{TeVatron} = \Phi_{true}$:
  LHCb 5 σ discovery!

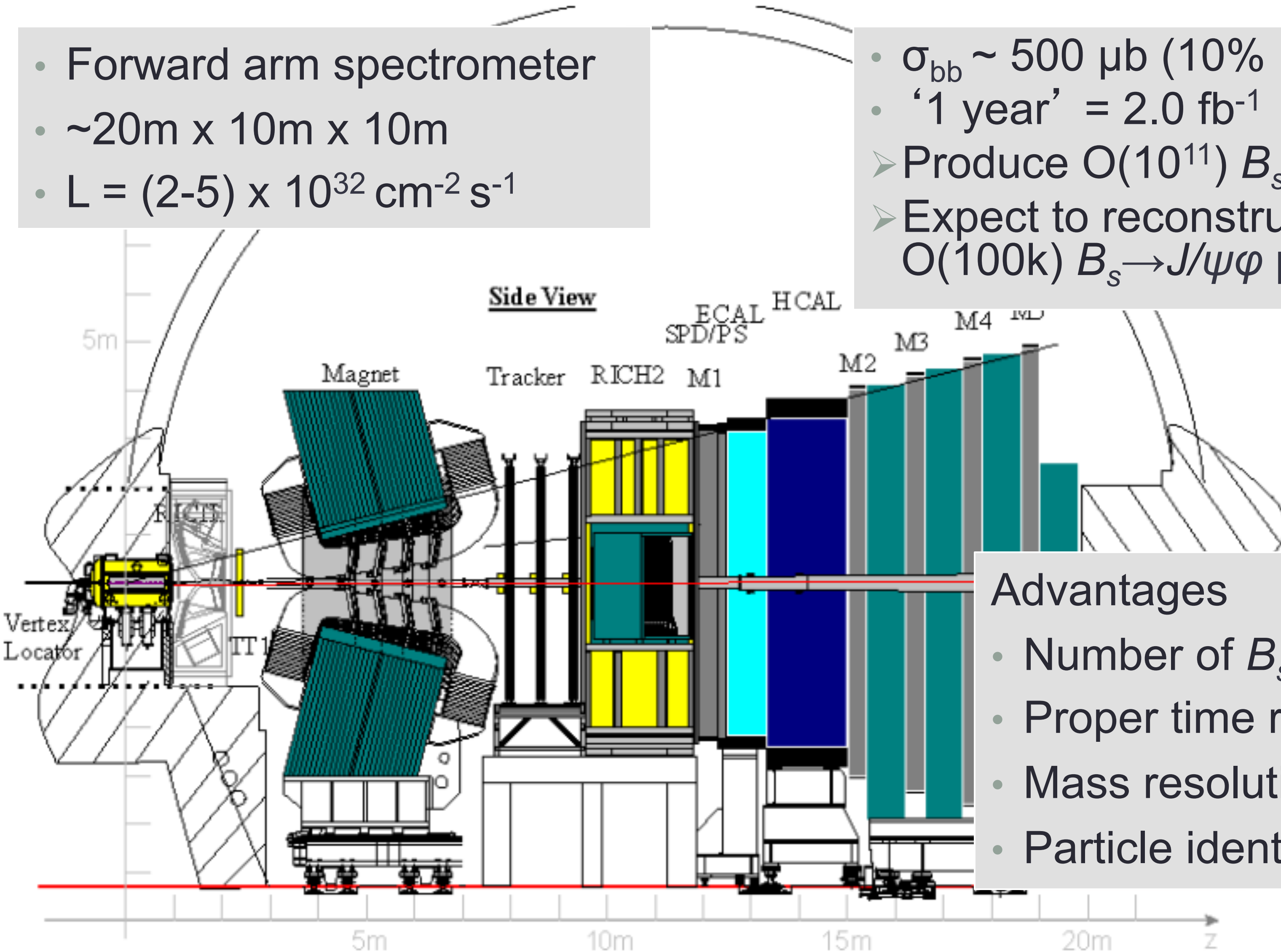




LHCb

- Forward arm spectrometer
- ~20m x 10m x 10m
- L = (2-5) x 10^{32} cm^{-2} s^{-1}

- σ_{bb} ~ 500 μb (10% B_s)
- ‘1 year’ = 2.0 fb^{-1}
- ➢ Produce O(10^{11}) B_s per year
- ➢ Expect to reconstruct: O(100k) $B_s \to J/\psi\varphi$ per year



Advantages

- Number of B_s's
- Proper time resolution
- Mass resolution
- Particle identification

CMS

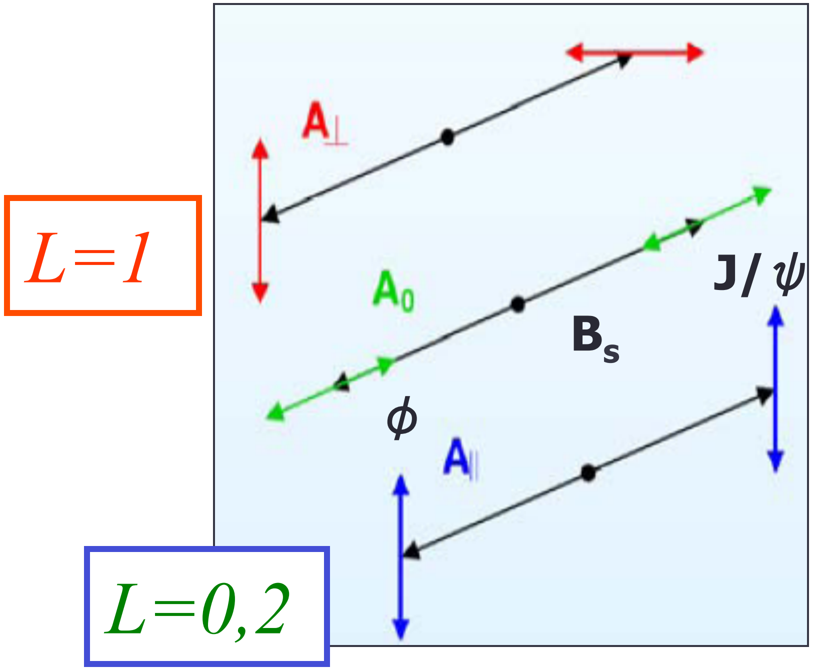
- Have to know SM QCD accurately
- Don't know where new physics will pop up
  - Search benchmark points and pray…
- Cross section NP small
  - Much background

LHCb

- Can choose theoretically clean channel
- 'Independent' of new physics channel
- Can choose channel with large x-sec/br
- Don't need large lumi/high COM-energy
  - Especially handy coming years

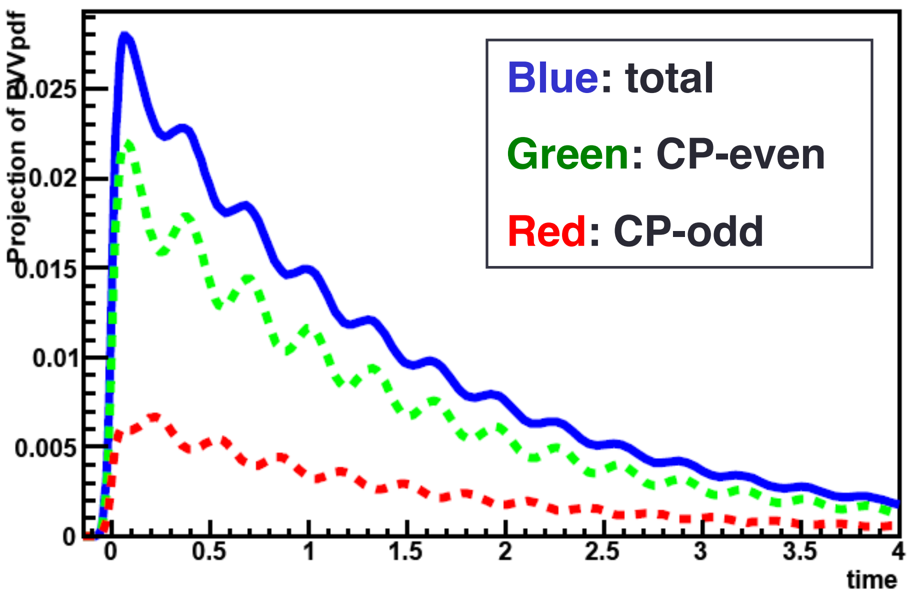
CP-even vs CP-odd

- Initial B_s: J=0
- Different final spin states
  - Different angular momenta L in final states
  - Different CP: factor $(-1)^L$
  - CP-even and CP-odd opposite proper time behaviour



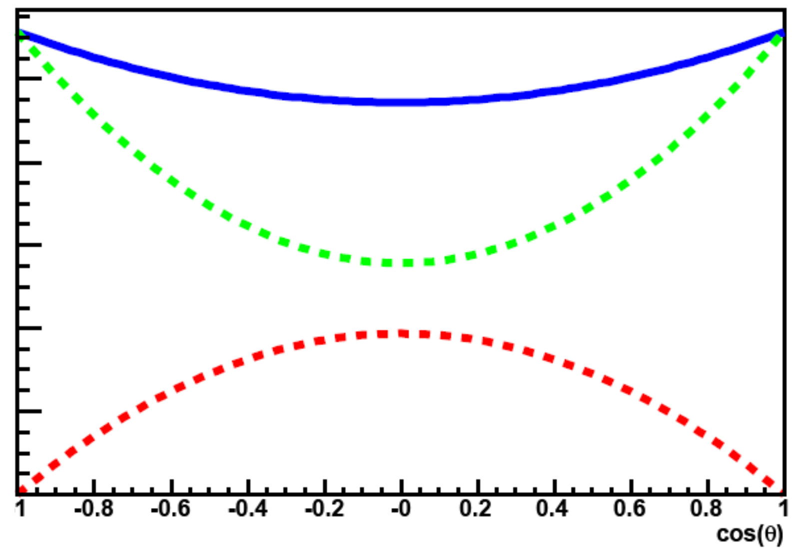
If $\Delta\Gamma_s=0$:
(simplified expression, in general $\Delta\Gamma_s\neq0$)

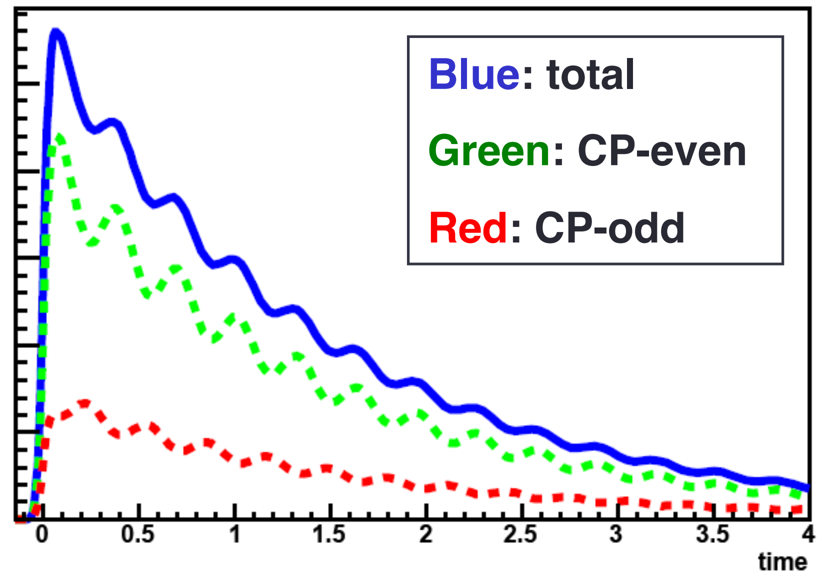
$$A_{CP} \sim |A_{even}|^2 \sin\Phi_s \sin\Delta m_s t - |A_{odd}|^2 \sin\Phi_s \sin\Delta m_s t$$



Angular analysis

- 4 particles: 3 decay angles
- Angles of daughter particles in rest frame parents
- Angular distribution: information about spin polarizations
  - ➢ CP states different angular distributions
  - ➢ Perform angular analysis to separate CP-even & CP-odd





If $\Delta\Gamma_s=0$:
(simplified expression, in general $\Delta\Gamma_s \neq 0$)

$$A_{CP} \sim |A_{even}|^2 \sin\Phi_s \sin\Delta m_s t\,(1+\cos^2\theta)/2$$
$$-|A_{odd}|^2 \sin\Phi_s \sin\Delta m_s t\,(1-\cos^2\theta)$$

Fit methods

Now describe all observables, including all experimental distortions, using control samples as much as possible

- Observables
  - Time + angles + tagging flavor + mass
- Experimental effects
  - Resolutions + inefficiencies + backgrounds
- Control samples
  - MC sample only used for angular efficiency
  - $B_d \rightarrow J/\psi K^*$ + mass-sidebands + prescaled sample

LHCb with 2 fb^{-1}

Brown = box
Green = tree
Black = penguin

γ with time dependent osc
- $B_s \rightarrow D_s K$
- $B \rightarrow D^*\pi$

$\sigma(\gamma\text{-}\Phi_s)$ = 9º-12º

γ with direct CPV
- $B \rightarrow DK$ (glw)
- $B \rightarrow DK$ (ads)
- More bodies

$\sigma(\gamma)$ = 4-5º

γ with loops
- $B \rightarrow hh$

$\sigma(\gamma)$ = 7º

$\sigma(\Phi_s)$ = 2.8º-3.4º

Φ_s
- $B_s \rightarrow J/\psi\, \phi$

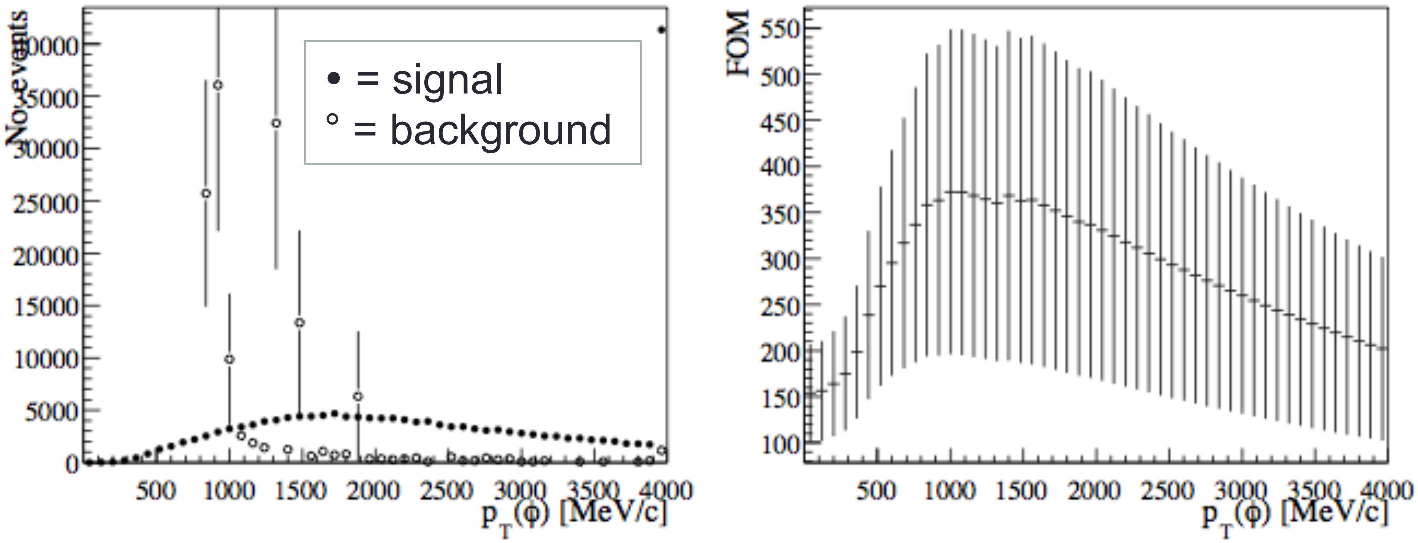
$\sigma(\Phi_s)$ = 1.8º

Φ_s with penguins
- $B_s \rightarrow \phi\, \phi$

$\sigma(\Phi_{\varphi\varphi})$ = 4.6º

Advantages of LHCb
- Number of B_s's
- Proper time and mass resolution
- Particle ID

Example *S*, *B* & FOM



- Construct figure of merit to optimize correct variable
  - FOM ~ $\sigma^{-1}(\varphi_s) \sim S/\sqrt{(S+B^*)} \sim \sigma^{-1}(S)$
    - Determine FOM from toy MC or extended likelihood fit
- Choose maximal FOM plateau by eye
  - Stable and understandable

Summary selection

- Simple selection
  - Few orthogonal cuts
- Understandable selection
  - Cuts chosen by eye
    - Ignored cut if possible
  - Stable plateaus
- 170k $B_s \rightarrow J/\psi\varphi$ events per 2 fb^{-1}!
  - Sensitivity improvement of ~20% compared to existing selection
  - Equivalent to yield improvement of ~50%
- Trigger rates flexible!