

Precision flavor physics:

**Recent measurements of the
CKM angle γ at LHCb**

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Particle Physics Seminar Marseille
09.03.2015



LHC, CERN, Geneva

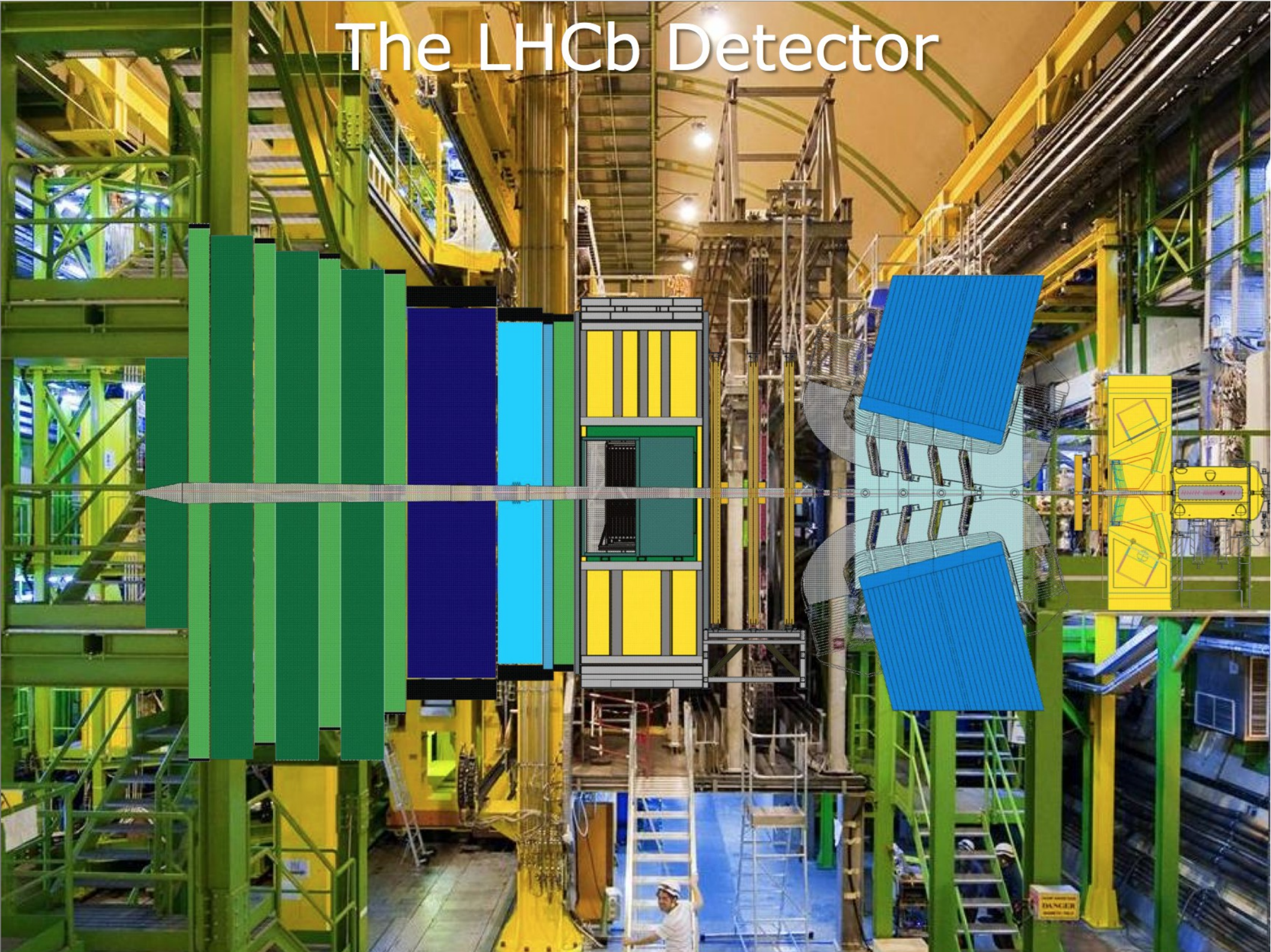


pp collisions at 7-8 TeV
Long Shutdown 1: 2013-2015
then: 13-14 TeV

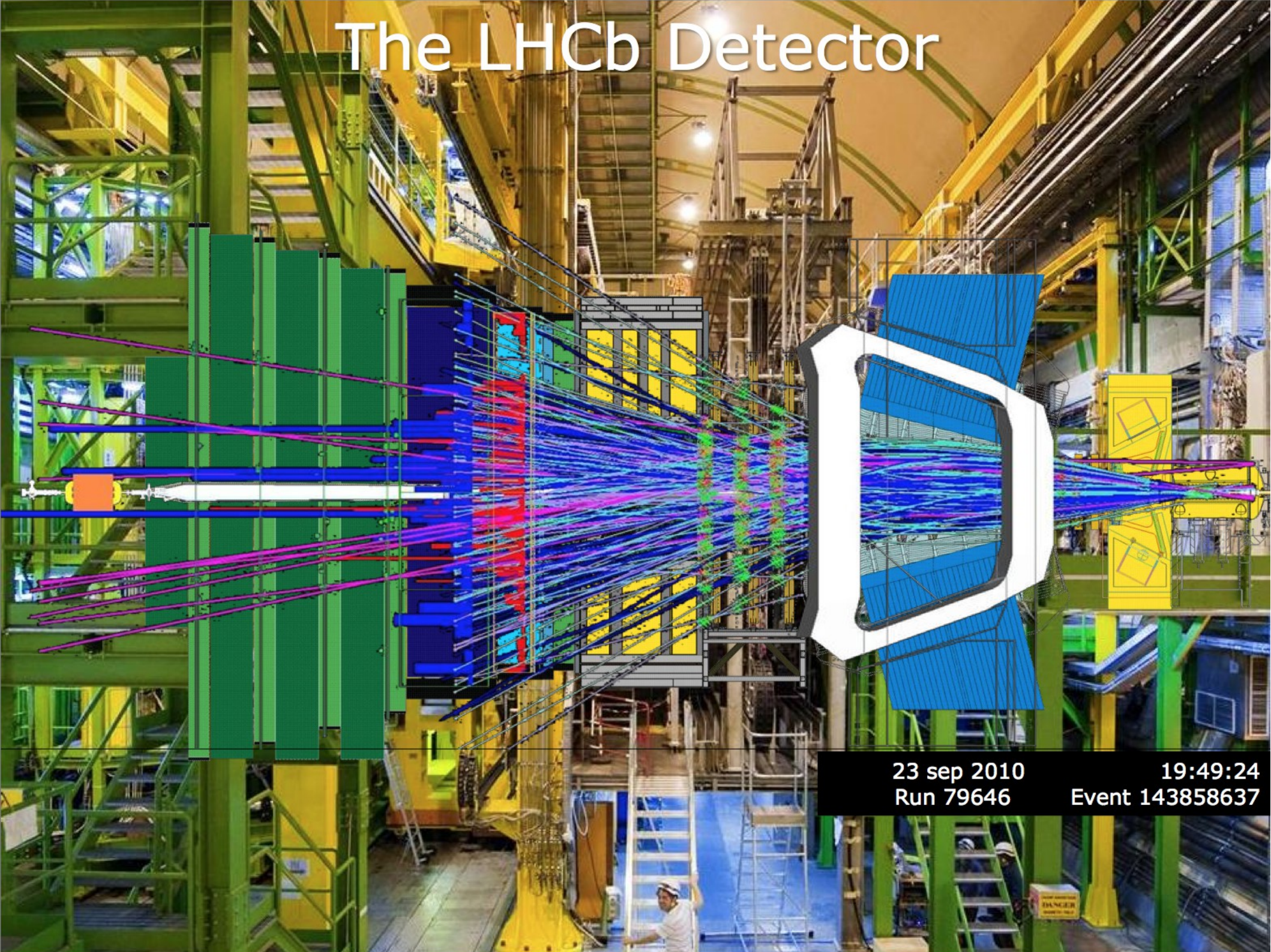
The LHCb Detector



The LHCb Detector



The LHCb Detector

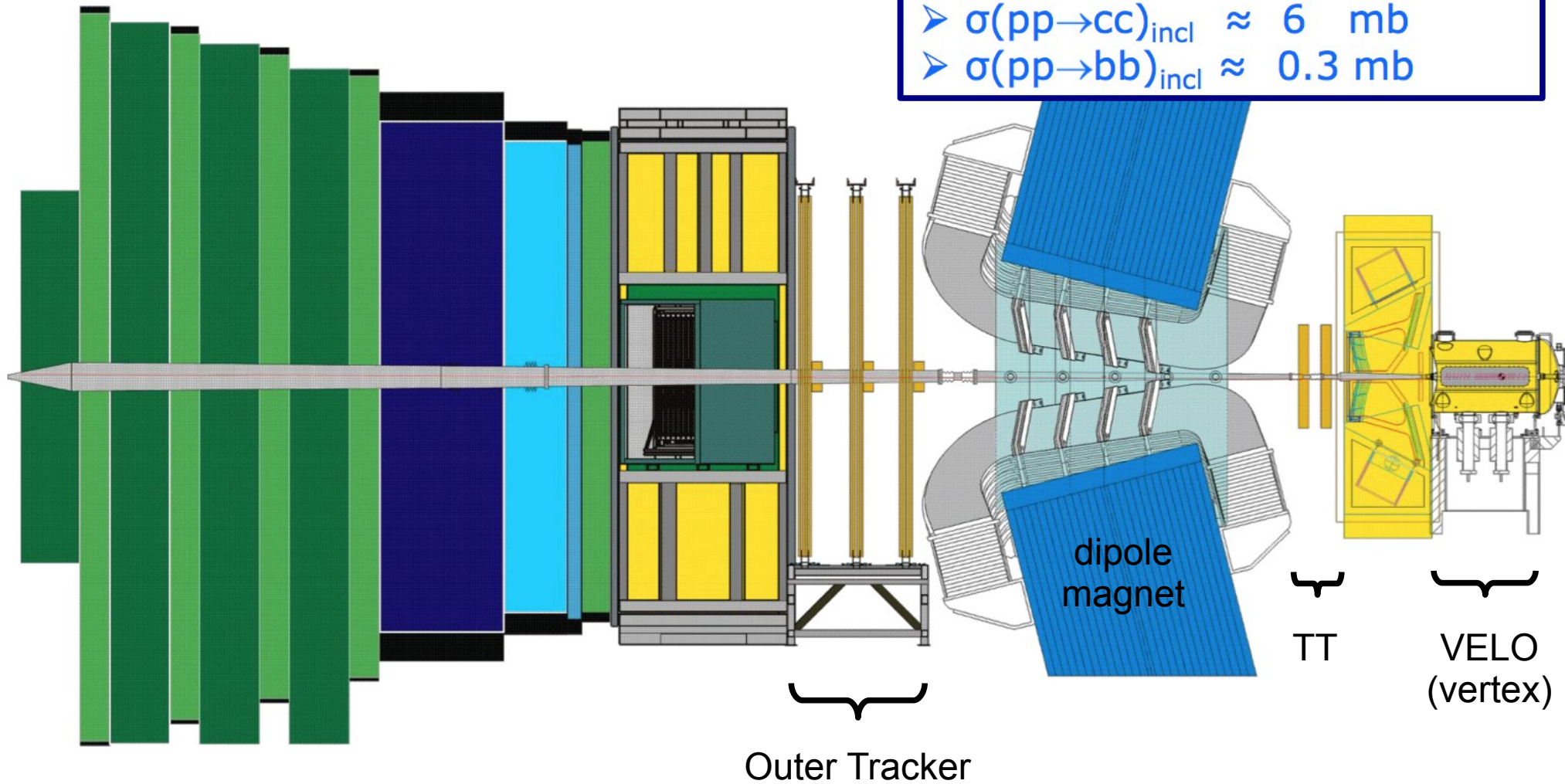


23 sep 2010
Run 79646

19:49:24
Event 143858637

Forward arm spectrometer

- $2 < \eta < 5$
- $\sigma(pp \rightarrow X)_{\text{inel}} \approx 60 \text{ mb}$
- $\sigma(pp \rightarrow cc)_{\text{incl}} \approx 6 \text{ mb}$
- $\sigma(pp \rightarrow bb)_{\text{incl}} \approx 0.3 \text{ mb}$



Outer Tracker

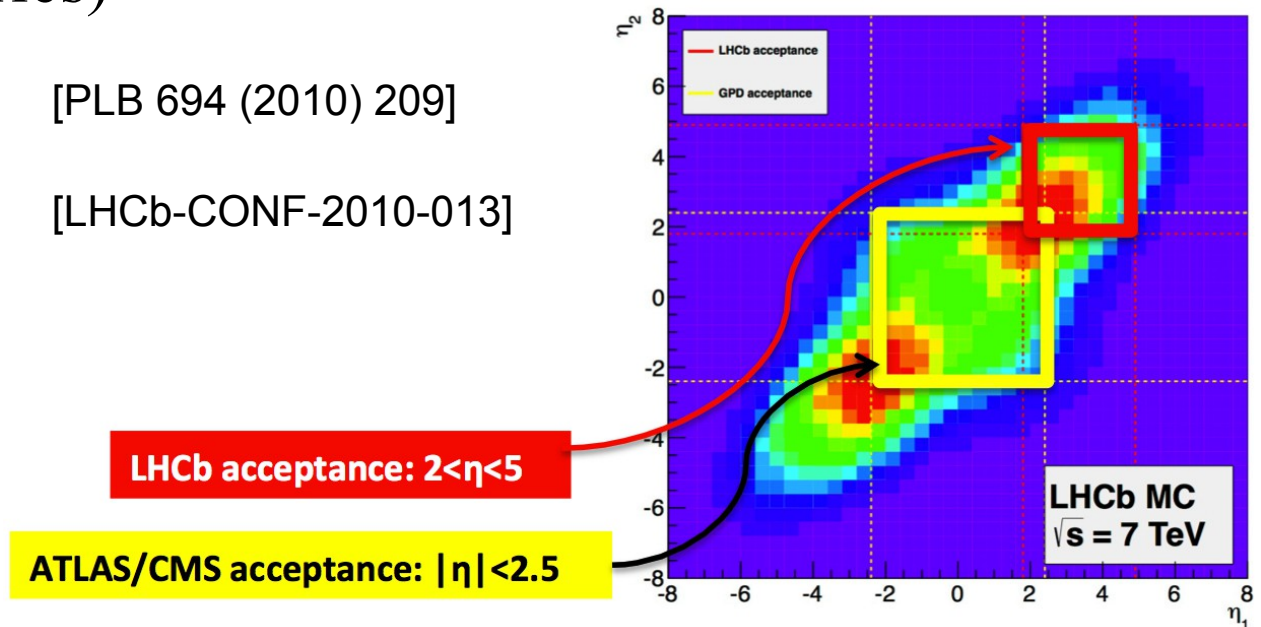
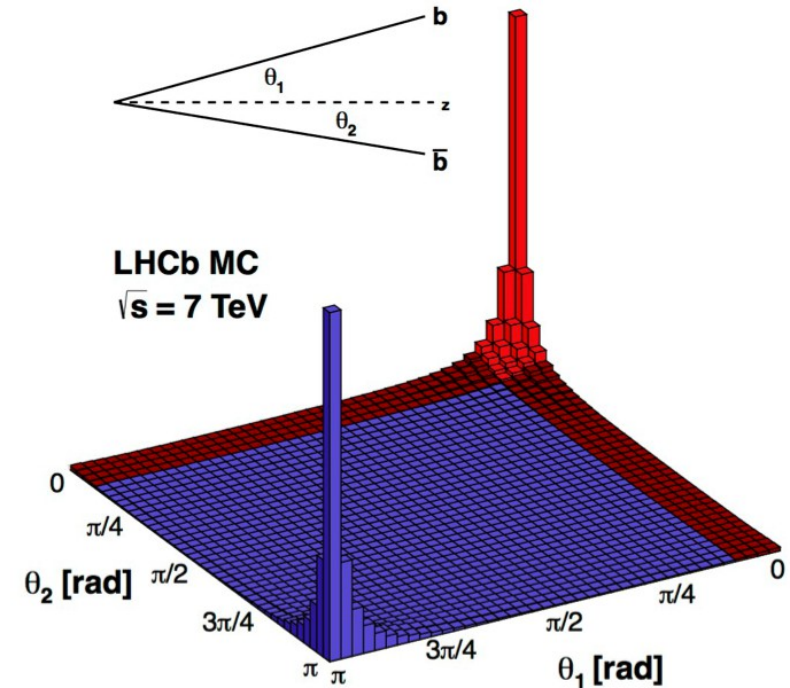


LHCb

- one arm forward spectrometer
- b pair production angles strongly correlated
- covers $1.9 < \eta < 4.9$
- 100'000 $b\bar{b}$ pairs produced per second ($10^4 \times B$ factories)

$$\sigma(b\bar{b}) = 284 \pm 53 \mu\text{b} \quad [\text{PLB 694 (2010) 209}]$$

$$\sigma(c\bar{c}) \approx 20 \times \sigma(b\bar{b}) \quad [\text{LHCb-CONF-2010-013}]$$

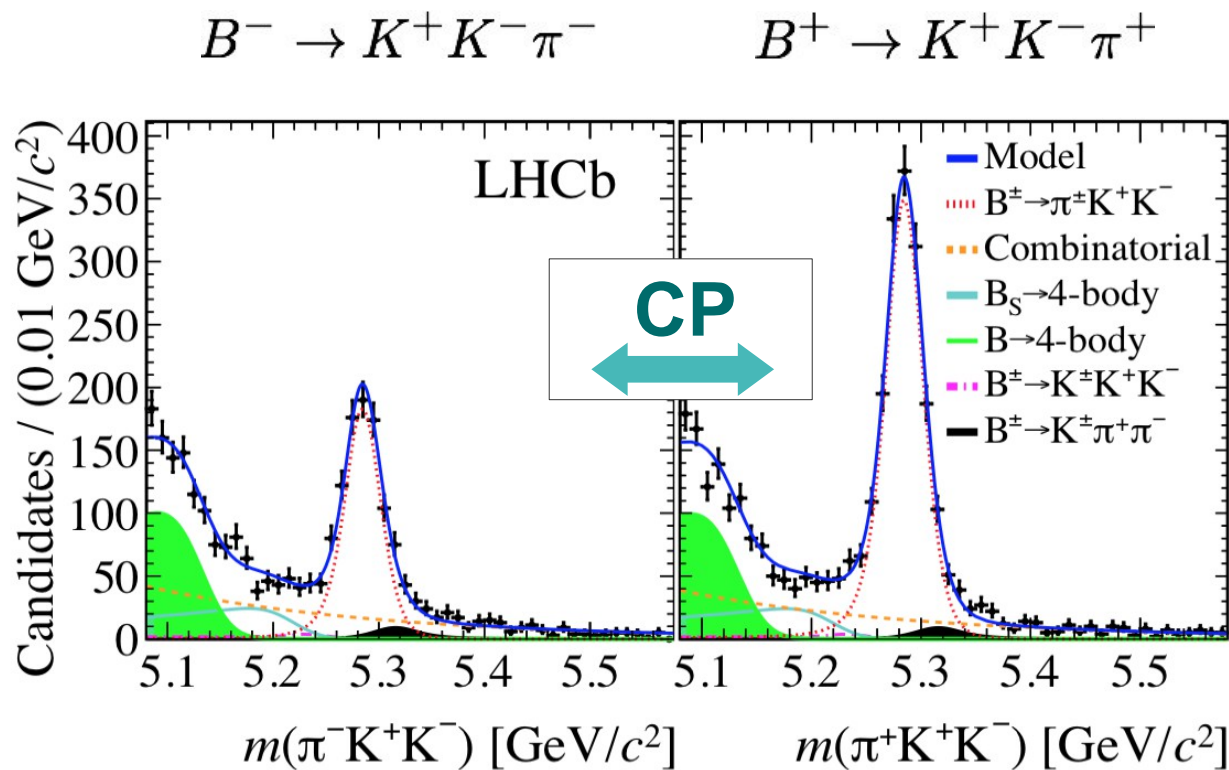


CP violation

- Matter/Antimatter, baryon genesis
- CP violation is one crucial ingredient (Sacharov)
- The CKM matrix is the one place in the SM with CP violation.

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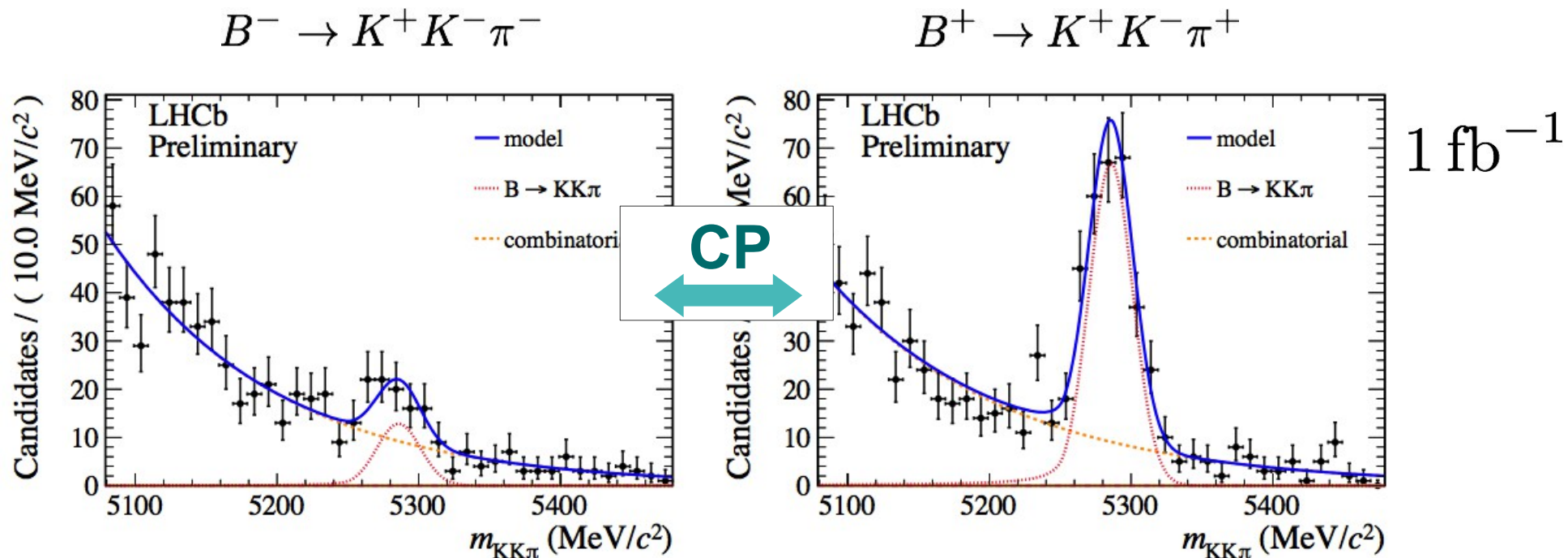


3 fb^{-1}

PRDD90 (2014) 112004
arXiv:1408.5373

CP violation

- Matter/Antimatter, baryon genesis
- CP violation is one crucial ingredient (Sacharov)
- The CKM matrix is the one place in the SM with CP violation.



CP asymmetry in $B \rightarrow KK\pi$ in **selected kinematic** range [LHCb-CONF-2012-028]

CP Violation in the SM: CKM matrix

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

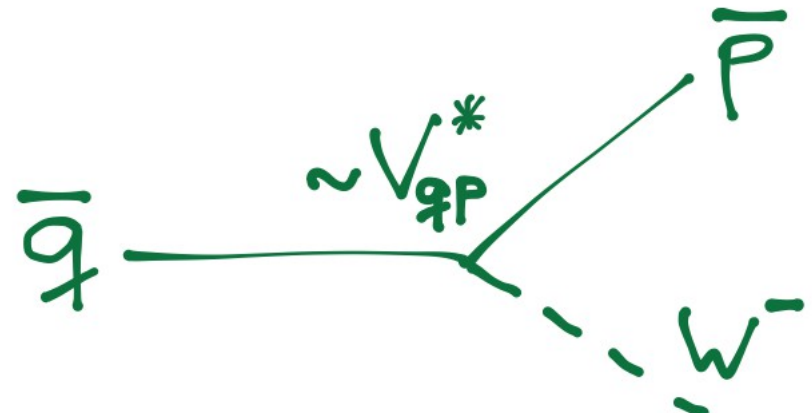
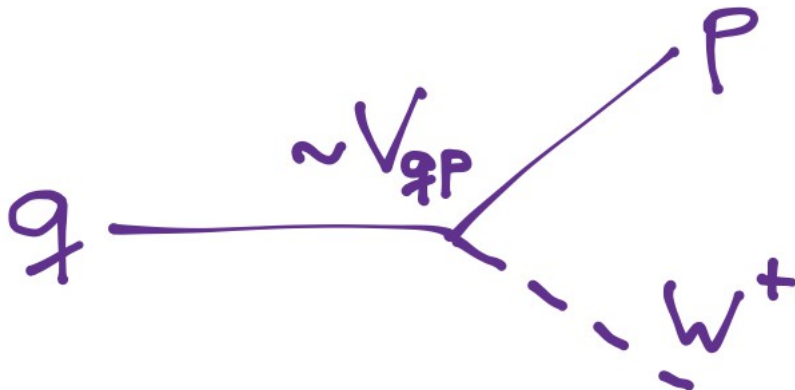
flavor eigenstates mass eigenstates

$$\begin{pmatrix} \bigcirc & \bigcirc & \cdot \\ \bigcirc & \bigcirc & \bigcirc \\ \cdot & \bigcirc & \bigcirc \end{pmatrix} \begin{matrix} u \\ c \\ t \end{matrix}$$

$d \quad s \quad b$

Cabibbo
Kobayashi
Maskawa

matrix elements determine transition probabilities:



CP Violation in the SM: CKM matrix

Unitarity condition

$$V^\dagger V = 1$$

implies

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

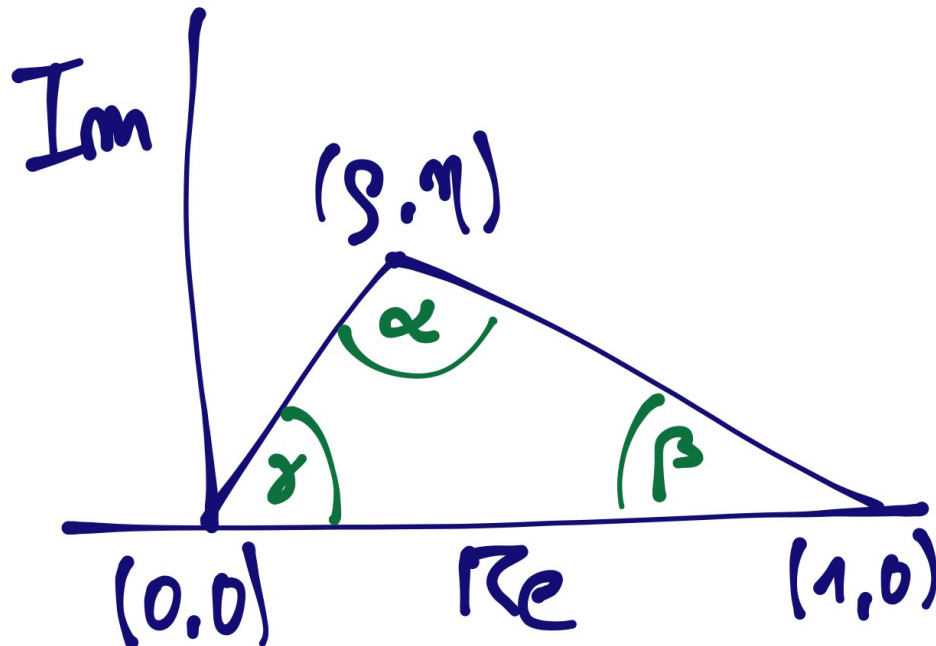
normalize it:

$$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + 1 + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = 0$$

CP Violation in the SM: CKM matrix

$$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + 1 + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = 0$$

Triangle in the complex plane.

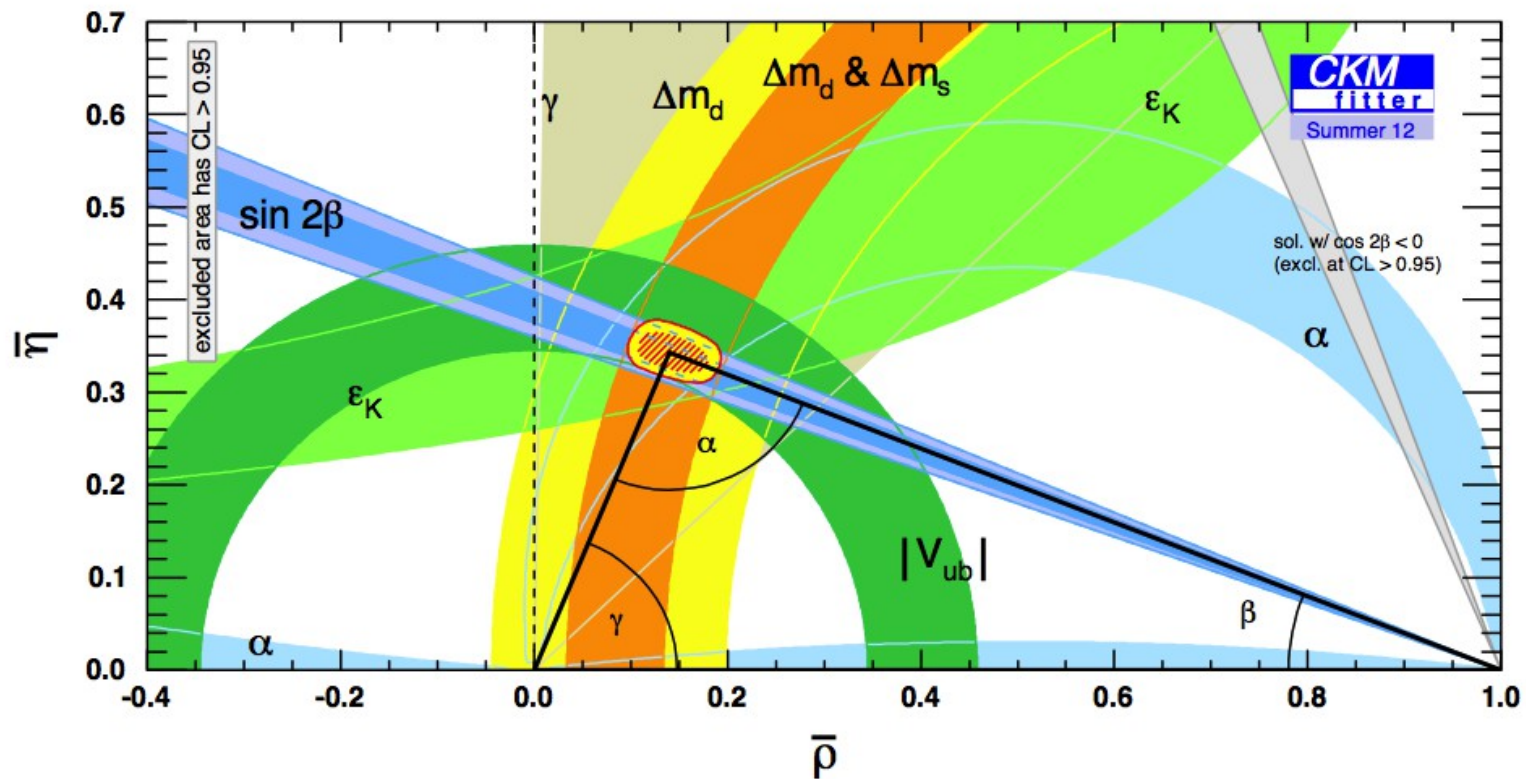


$$\gamma = \arg \left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right)$$

Area corresponds
to the **total CP violation**
in the Standard Model.

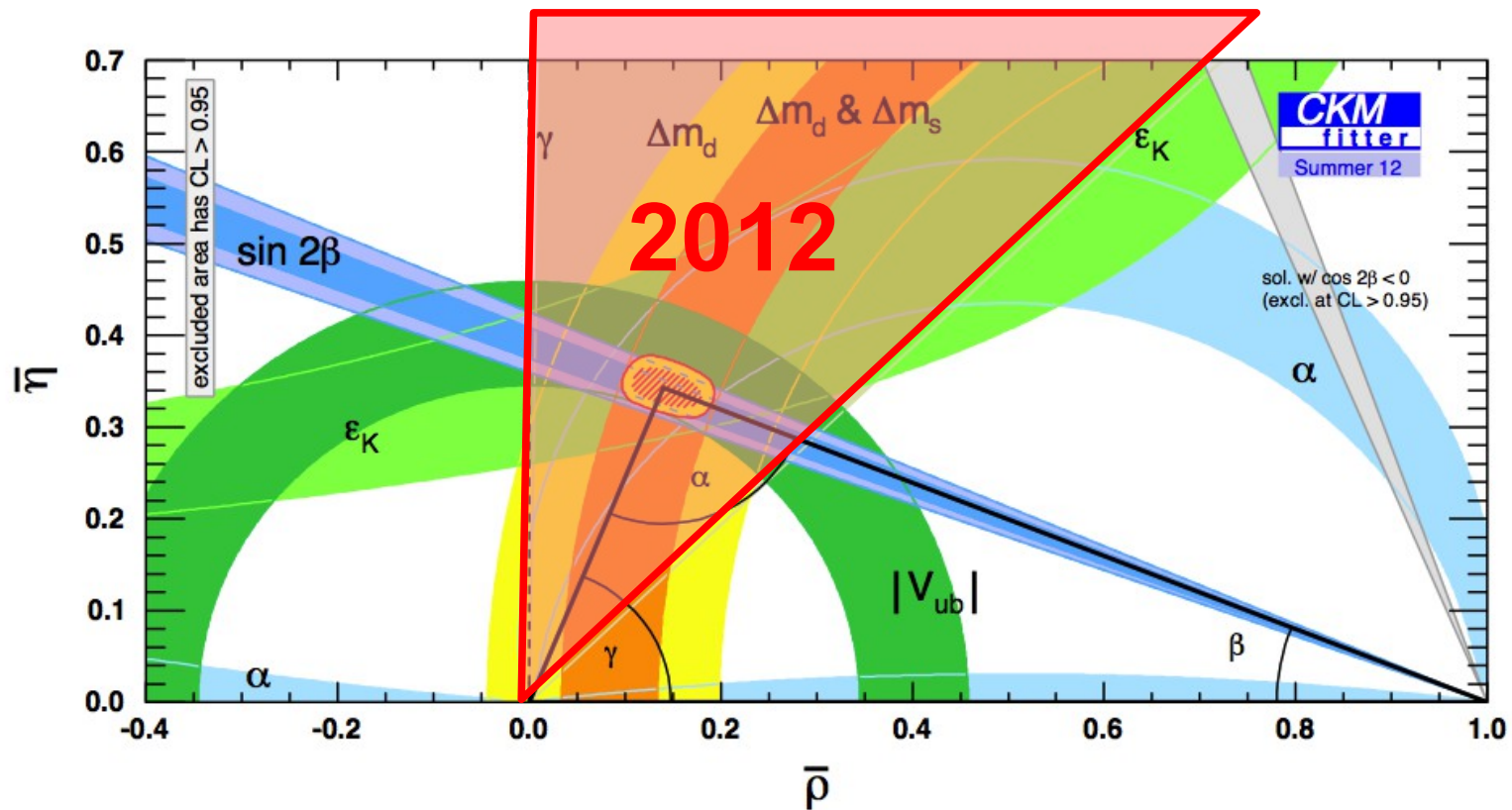
CKM angle γ

This is the *least well known* angle of the unitarity triangle.



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“combined γ measurements”

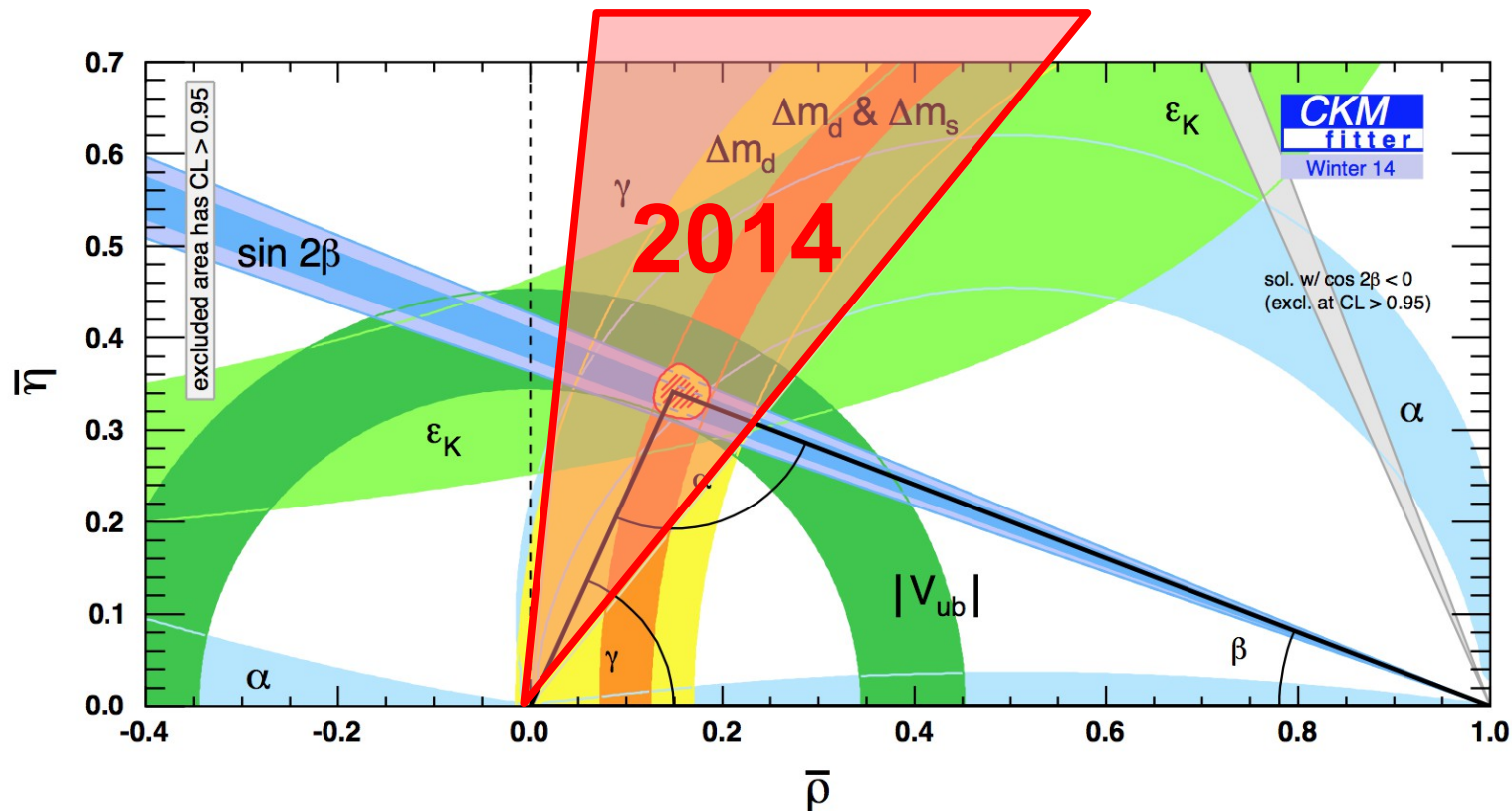
$$\gamma = (73.2^{+6.3}_{-7.0})^\circ$$

CKMfitter CKM2014

“ γ meas. not in triangle fit”

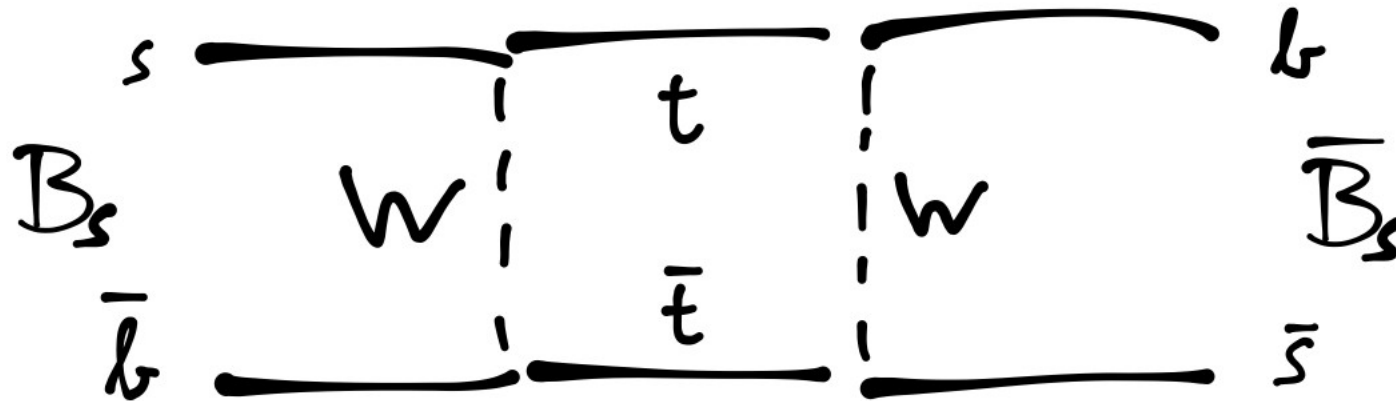
$$\gamma = (66.4^{+1.3}_{-3.3})^\circ$$

CKMfitter Moriond 2014



New Physics in particle oscillation?

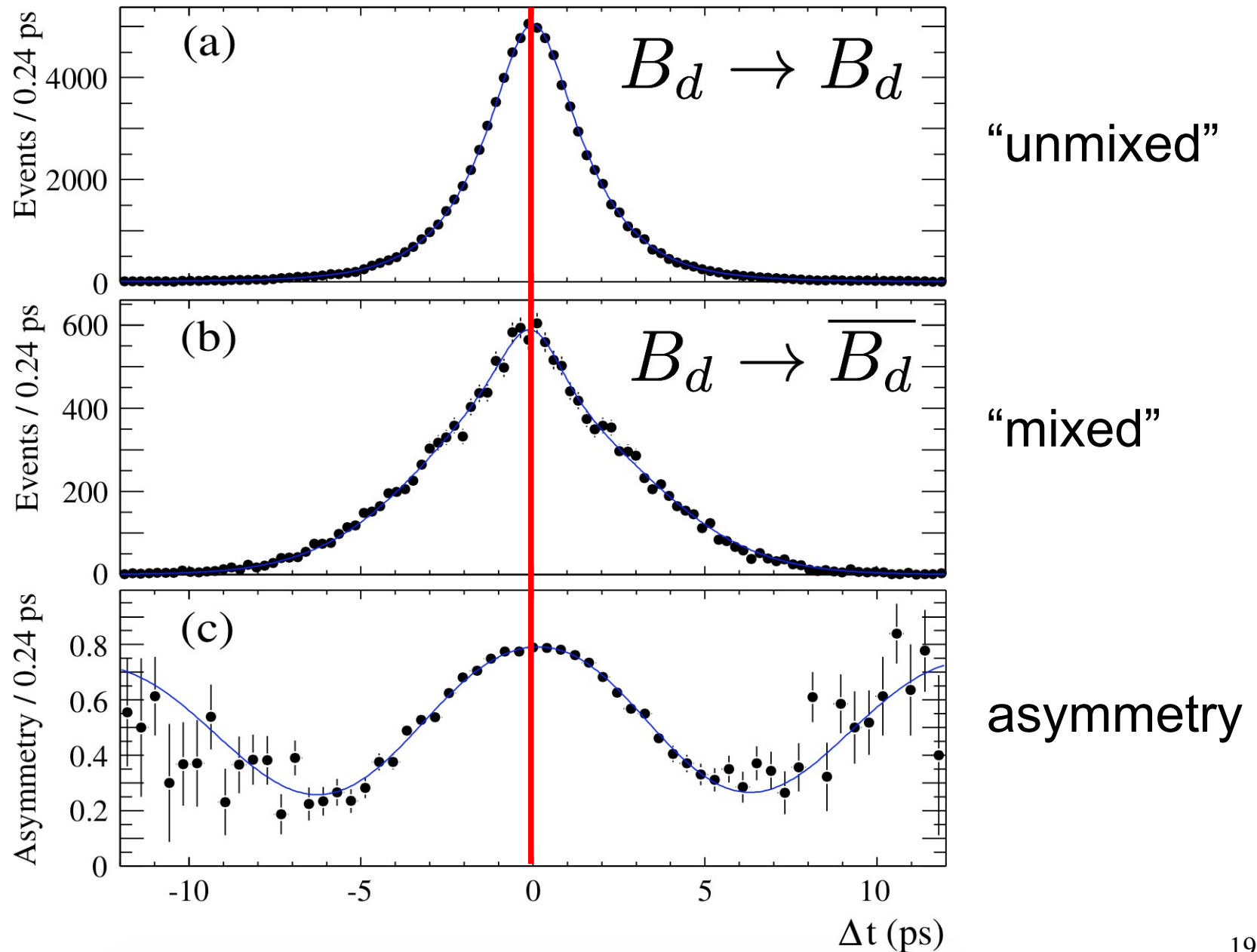
Some neutral particles can transition into their own anti-particle (mixing):



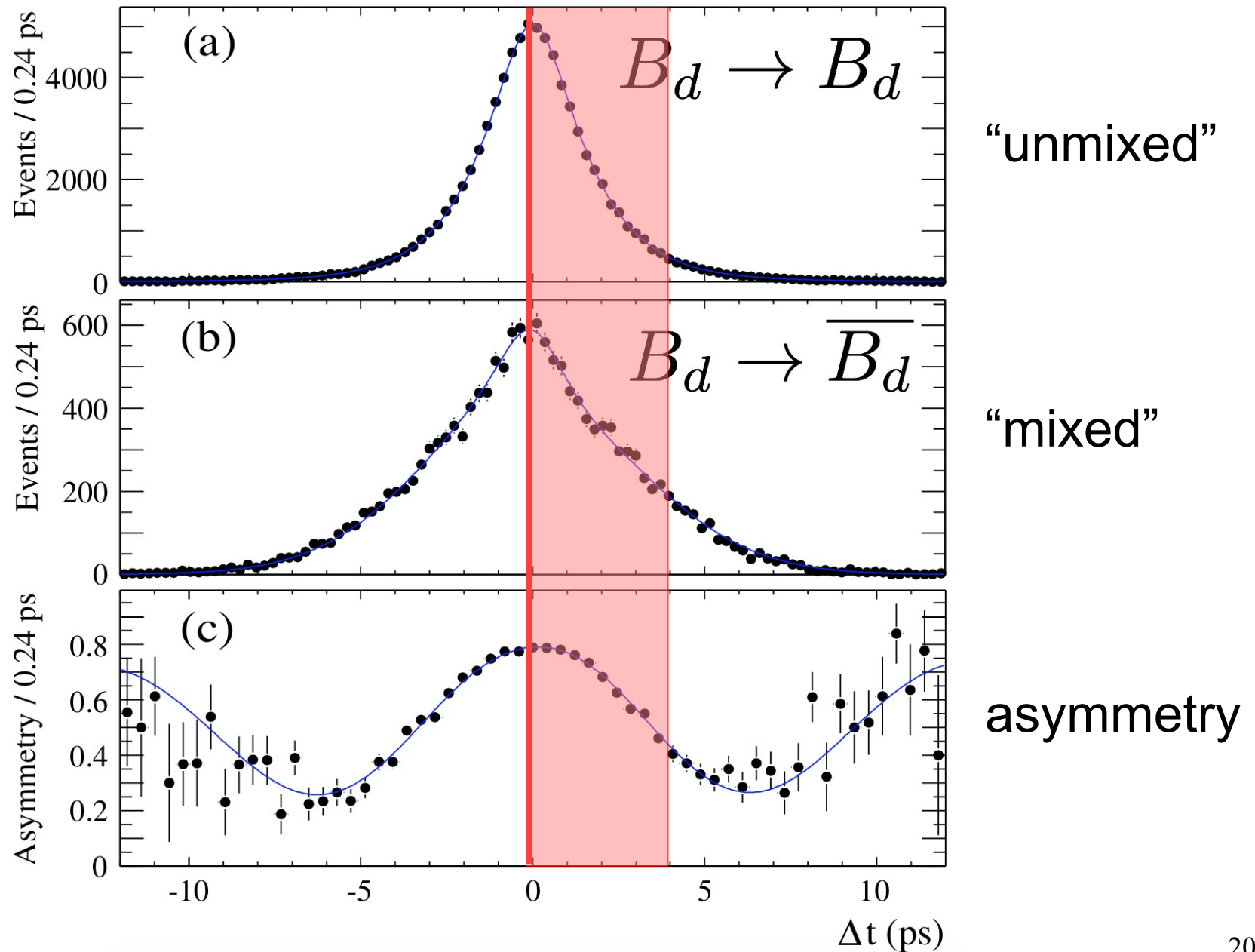
There are only 4 particles that can oscillate:

- D^0 mesons: *very, very* slowly
- K^0 mesons: very slowly
- B_d mesons: slowly
- B_s mesons: fast!

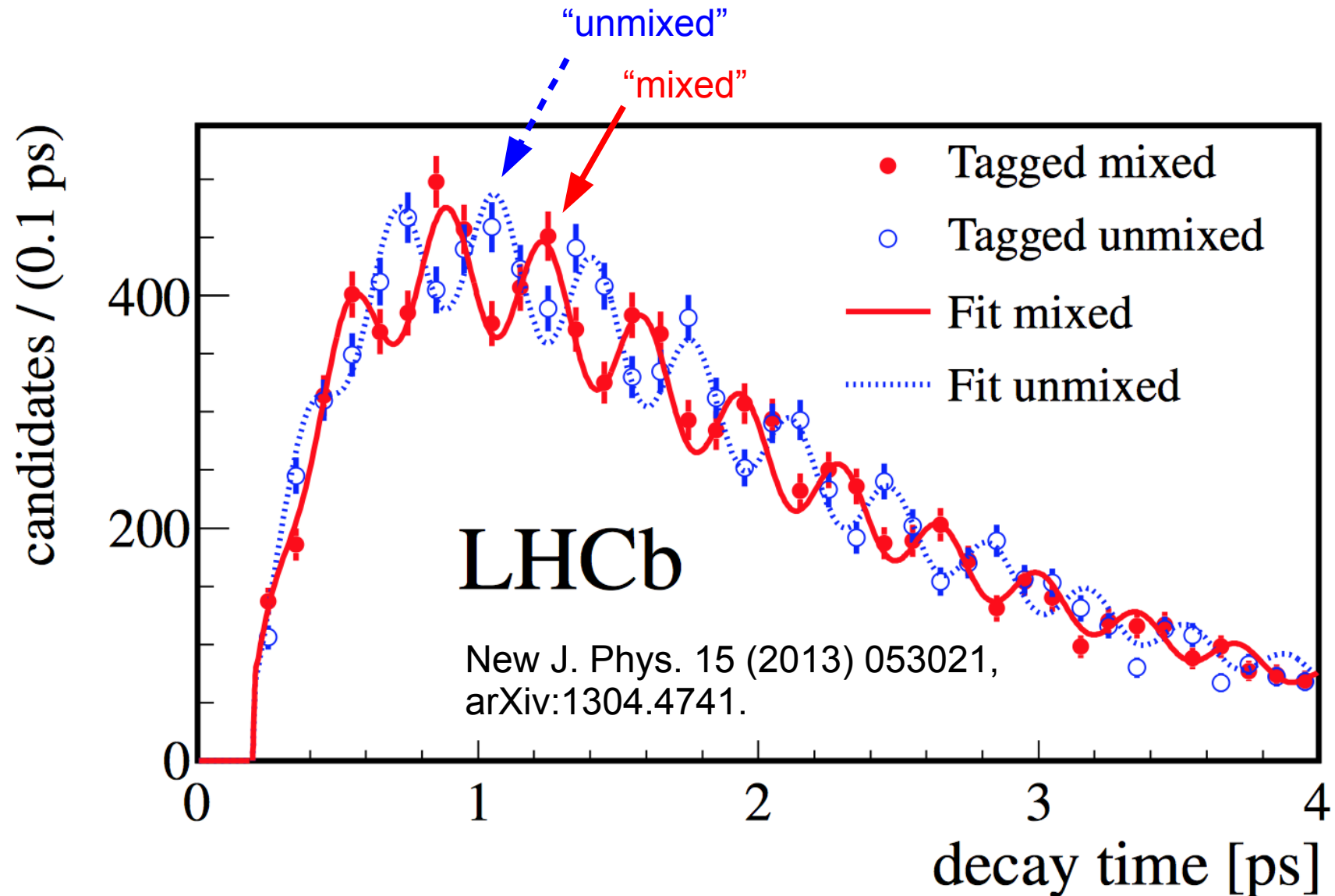
New Physics in particle oscillation?



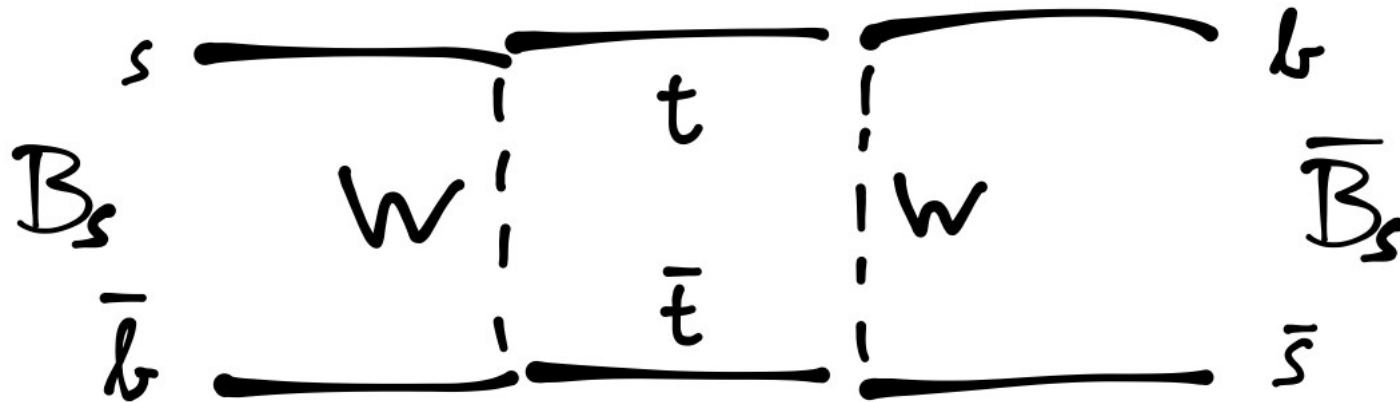
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New Physics in particle oscillation?

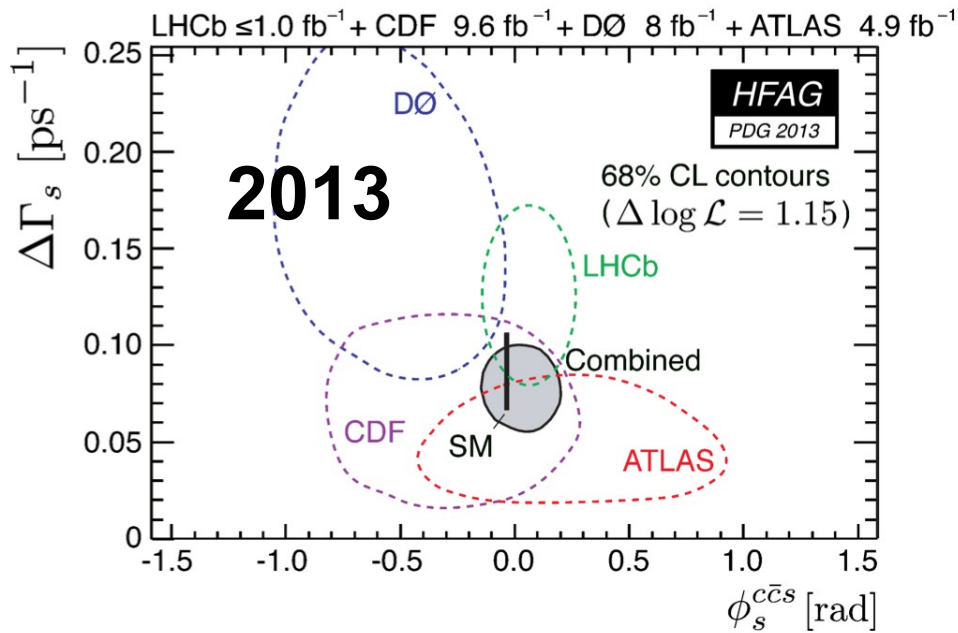


New Physics in particle oscillation?



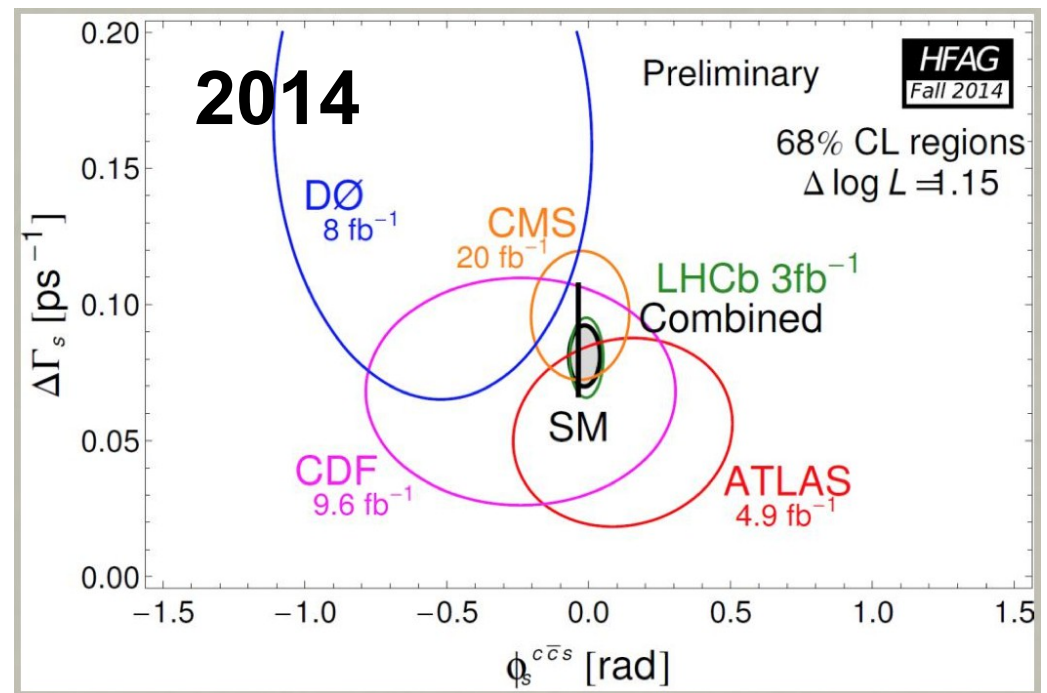
- mixing introduces a weak mixing phase $2\beta_s$
- the mixing phase could (have been...) easily affected by new physics!

New Physics in particle oscillation?

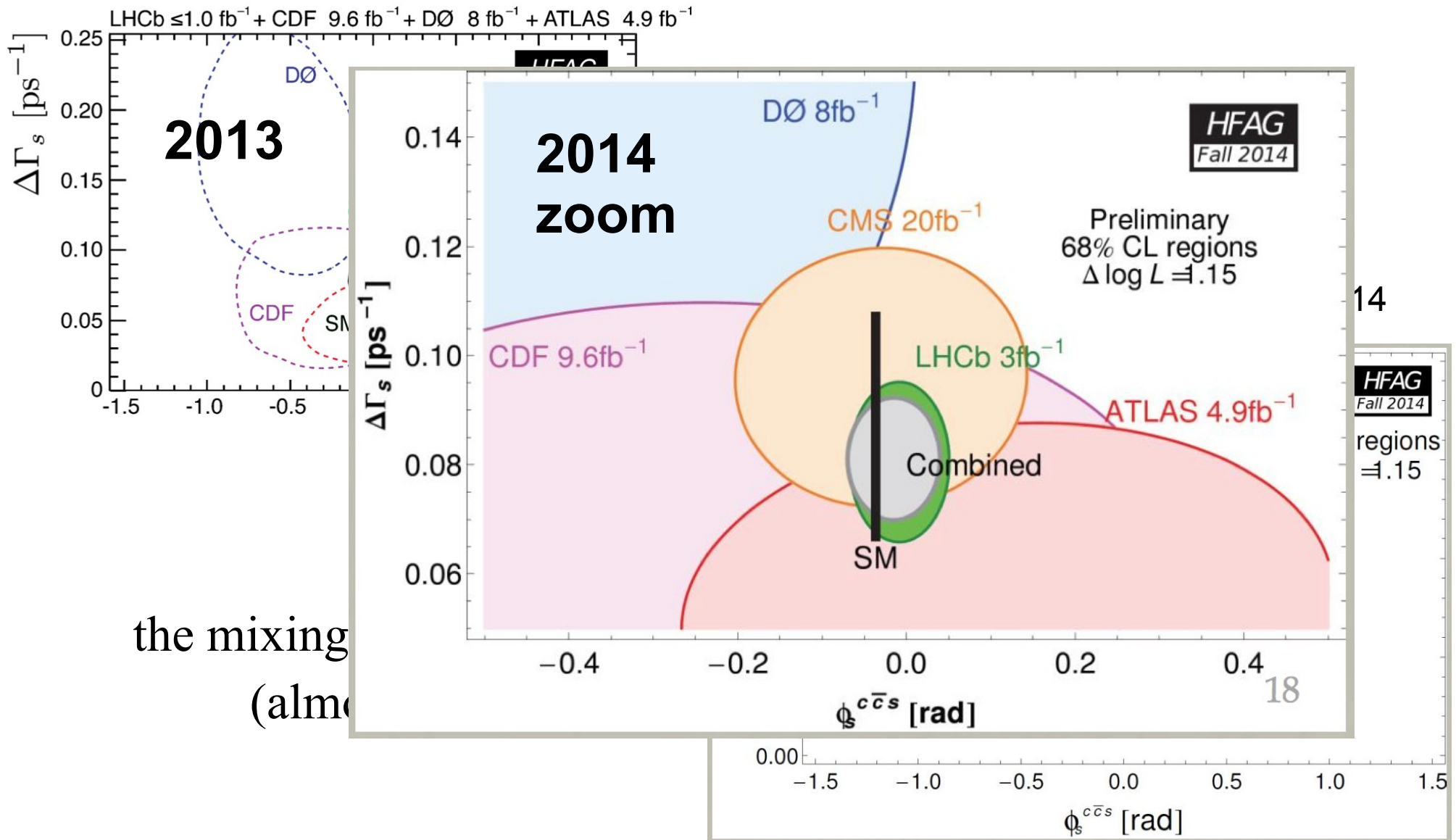


the mixing phase $2\beta_s$
(almost!)

LHCb Implications Workshop Oct 2014



New Physics in (anti)particle oscillation?



New Physics in particle oscillation?

- Example: model independent analysis of the room for new physics in meson mixing (Ligeti et al. 2013):

$$M_{12}^{d,s} = (M_{12}^{d,s})_{\text{SM}} \times (1 + h_{d,s} e^{2i\sigma_{d,s}})$$

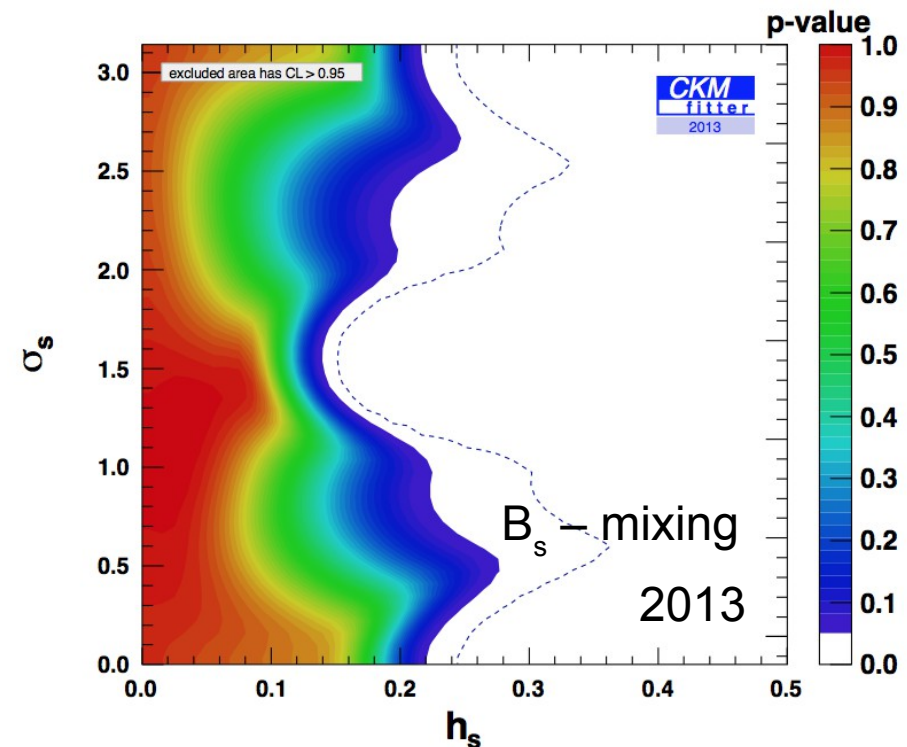
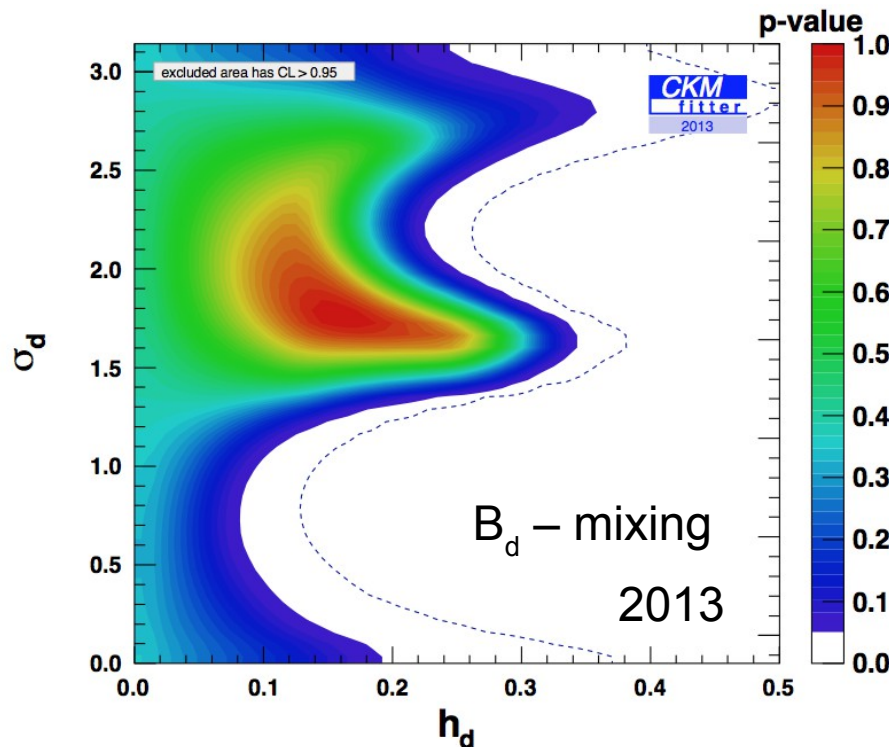
mixing operator

NP magnitude

NP phase

plots assume this value:

$$\gamma = (68^{+8.0}_{-8.5})^\circ$$



New Physics in particle oscillation?

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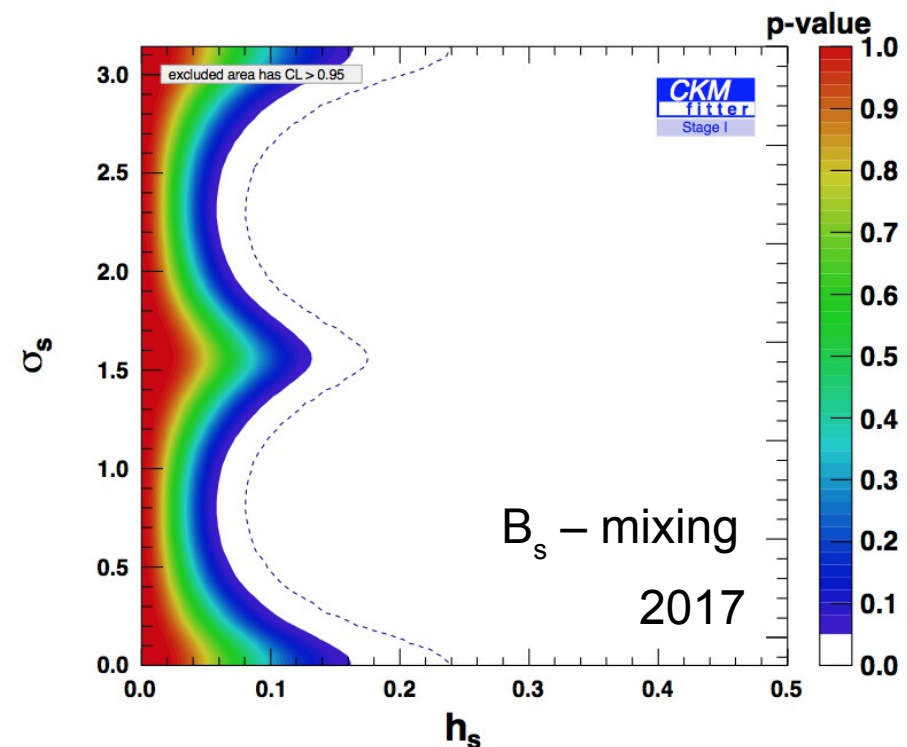
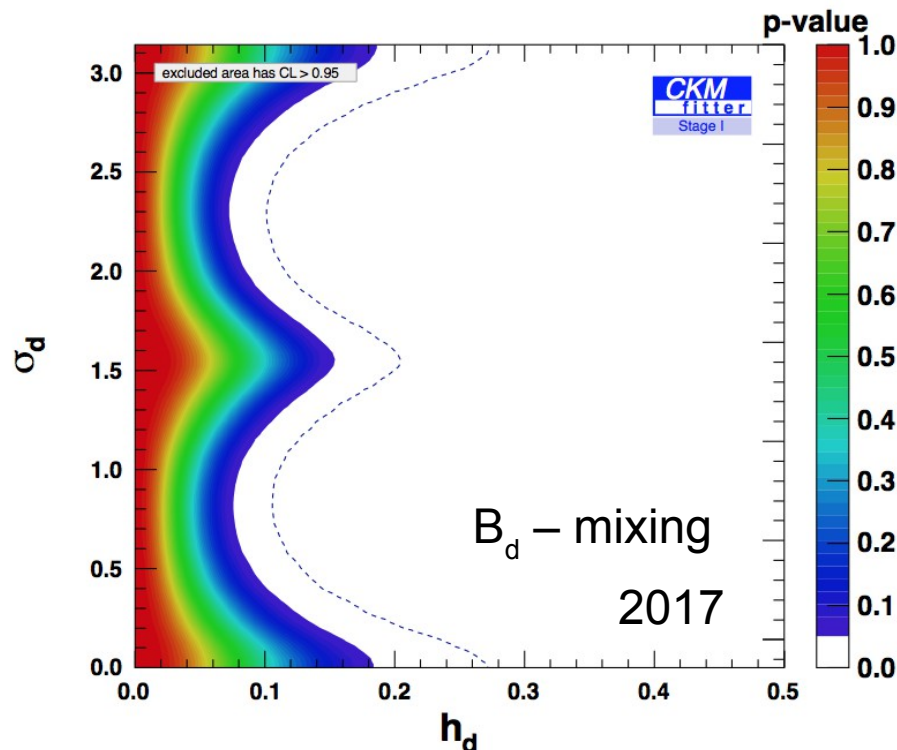
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New Physics in particle oscillation?

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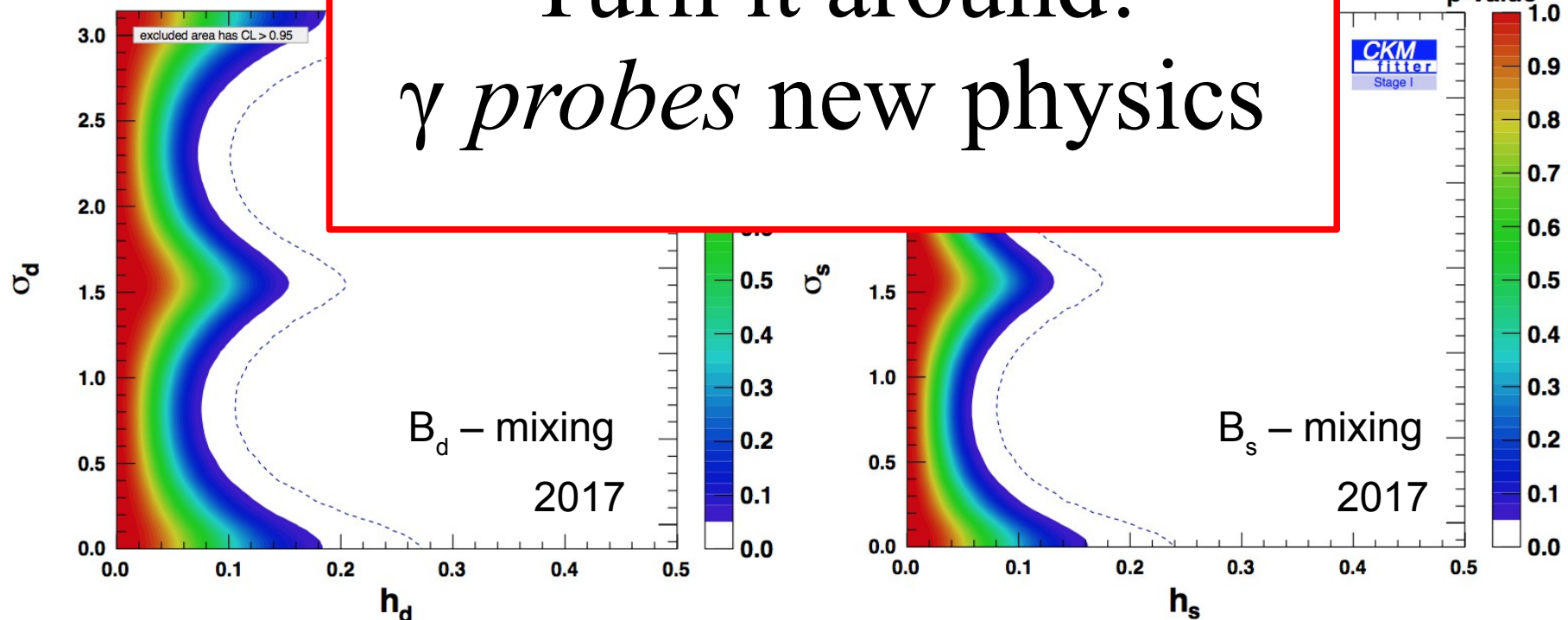
$$M_{12}^{d,s} = (M_{12}^{d,s})_{\text{SM}} \times (1 + h_{d,s} e^{2i\sigma_{d,s}})$$

mixing operator

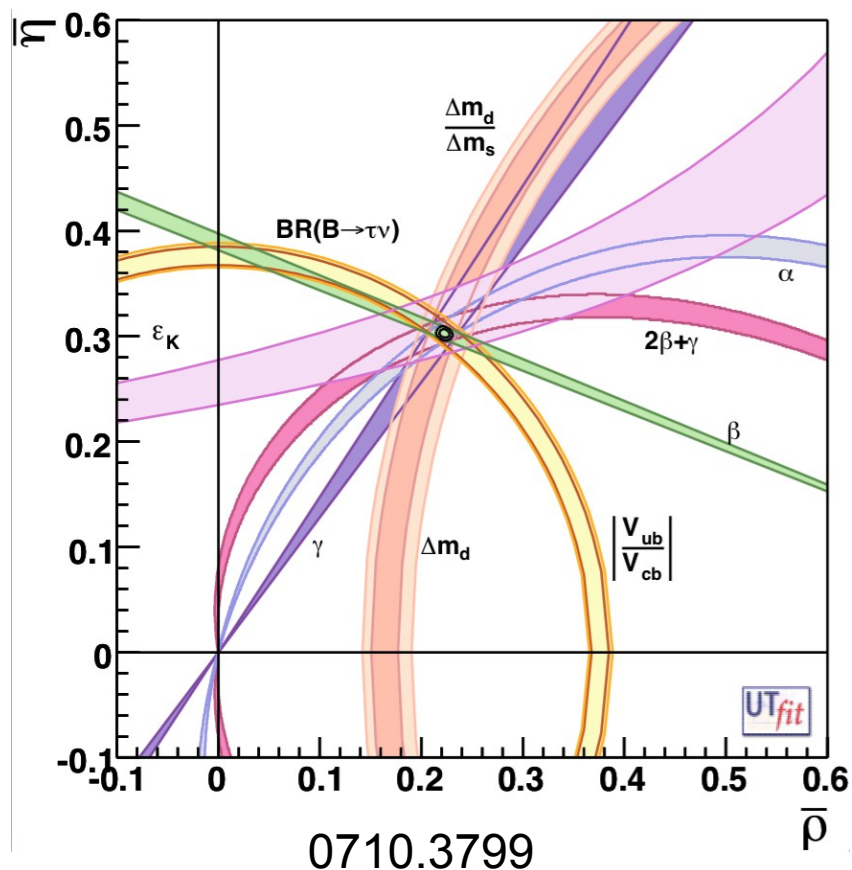
plots assume this value:

$$(68^{+4.0}_{-4.0})^\circ$$

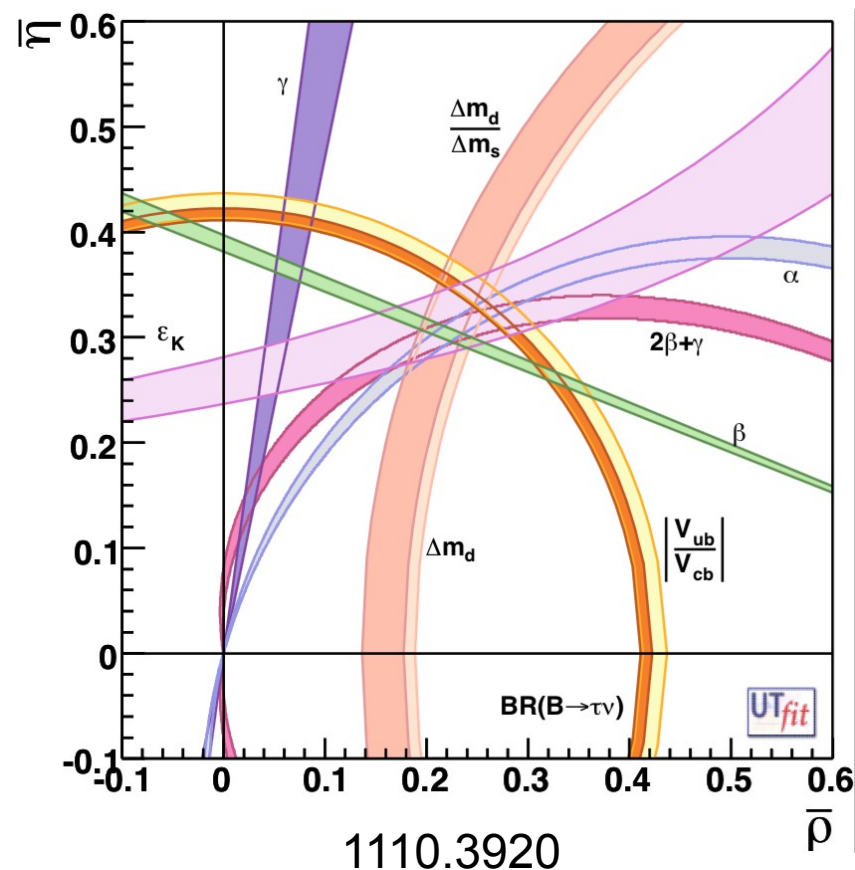
Turn it around!
 γ probes new physics



the ultimate test

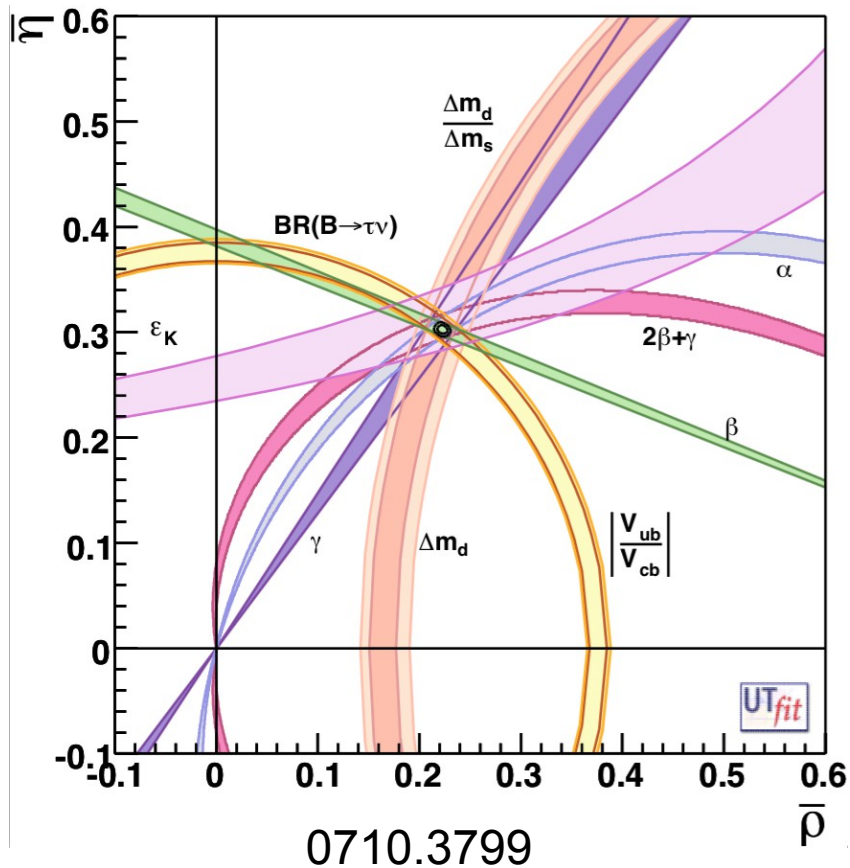


“the nightmare”

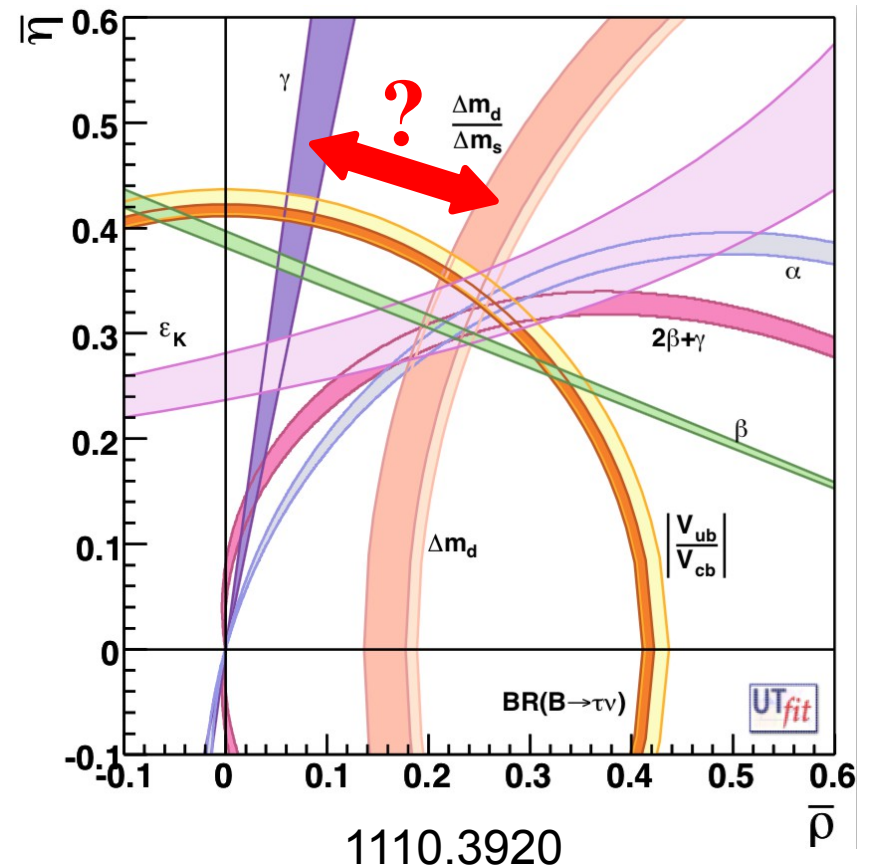


“the dream”

the ultimate test

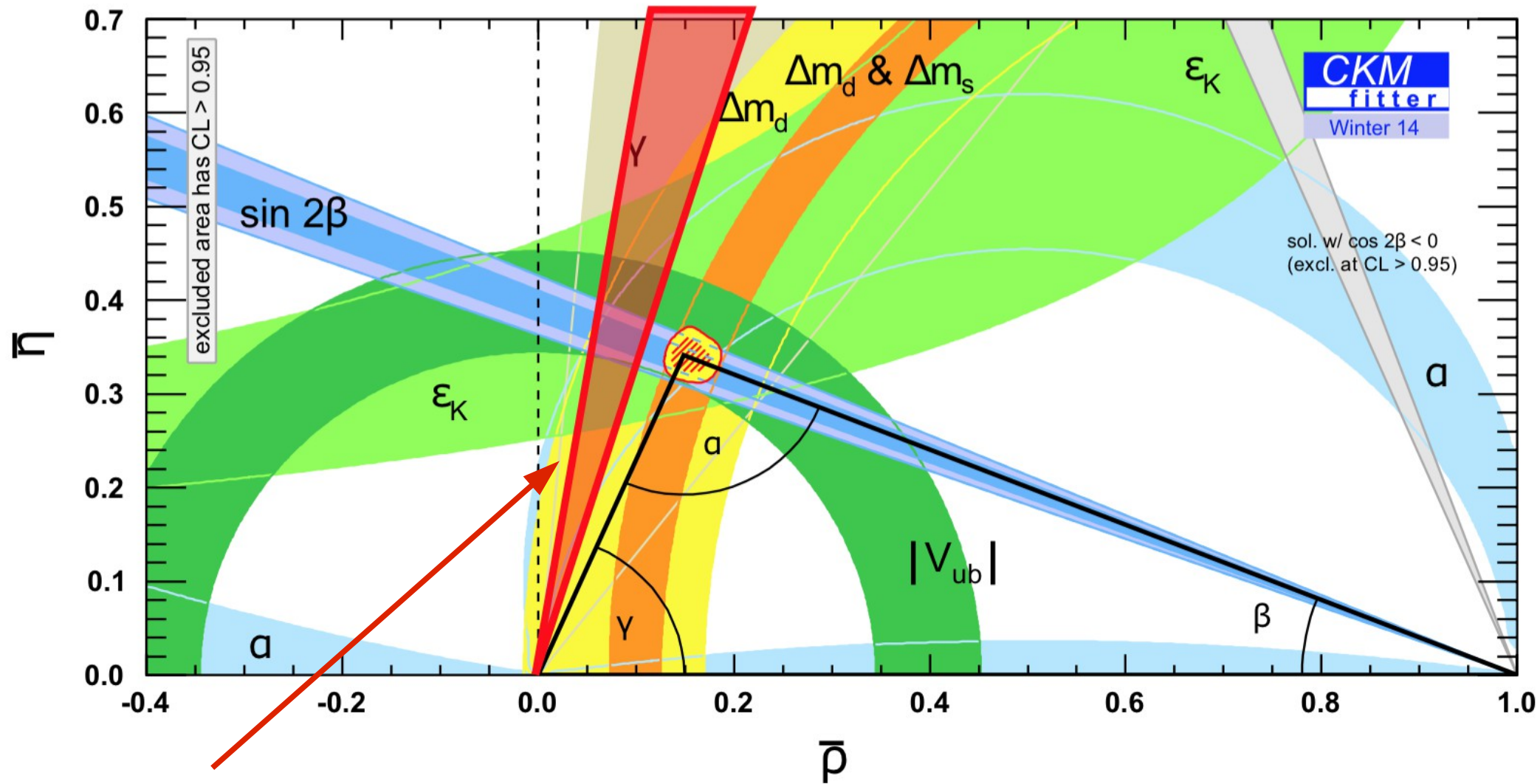


“the nightmare”



“the dream”

the ultimate test



LHCb precision in 2020

γ is known very well

theory

- γ can be determined entirely from **tree decays**.
 - this is a **unique** property among all CP violation parameters
 - hadronic parameters can all be **determined from the data**
 - **negligible** theoretical uncertainty (Zupan and Brod 2013):

$$\delta\gamma/\gamma \approx \mathcal{O}(10^{-7})$$

JHEP 1401 (2014) 051,
arXiv:1308.5663.

- γ can probe for new physics at extremely **high energy scales** (Zupan)
 - (N)MFV new physics scenarios: $\sim \mathcal{O}(10^2 \text{ TeV})$
 - gen. FV new physics scenarios: $\sim \mathcal{O}(10^3 \text{ TeV})$

γ is **not** known very well *experiment*

it is quite challenging to measure!

- The decay rates are small.

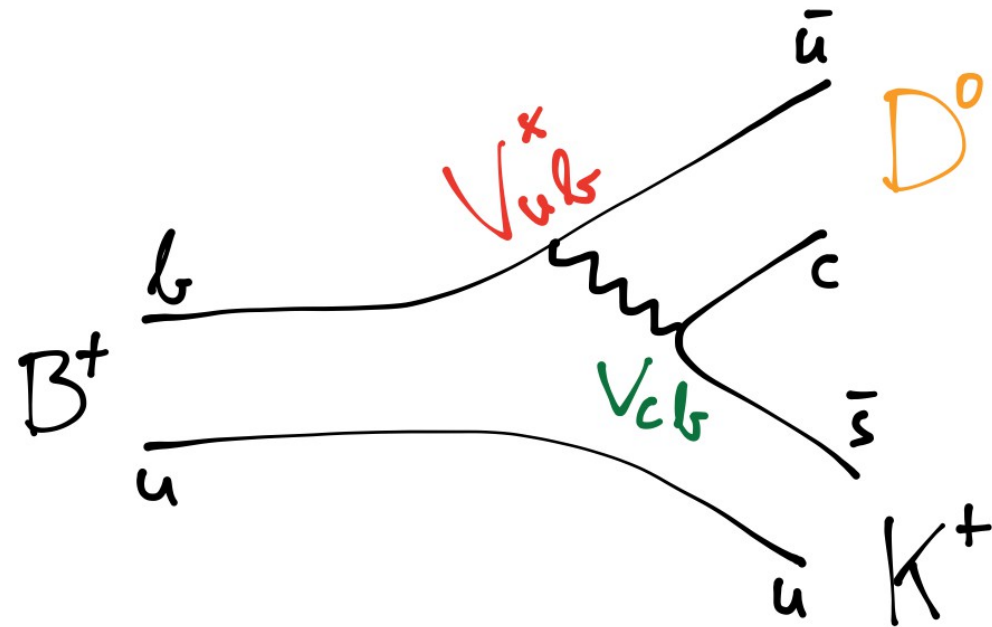
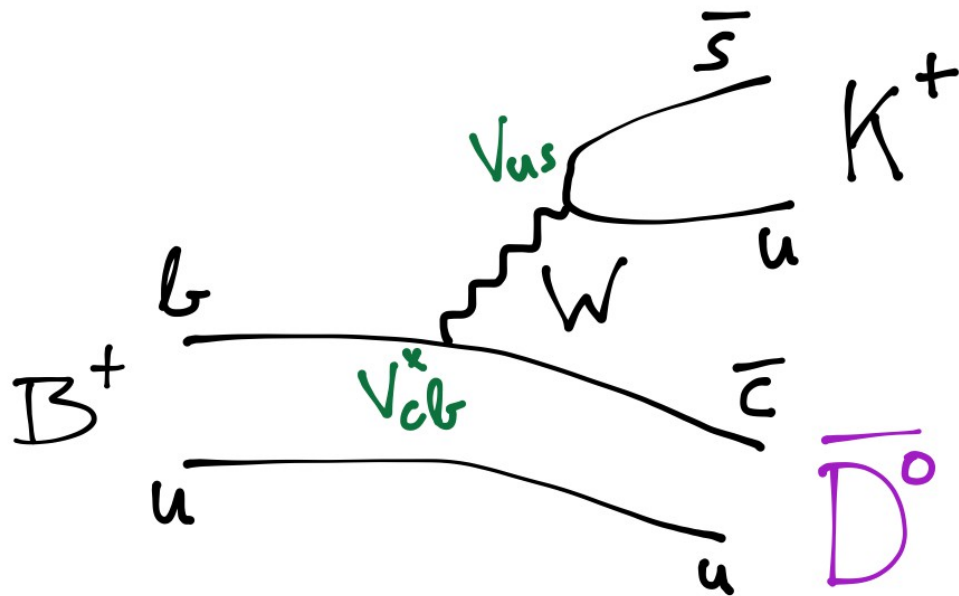
$$\text{BR}(B^- \rightarrow DK^-, D \rightarrow \pi K) \approx 2 \times 10^{-7}$$

- Low interference effects of typically 10%.
- Fully hadronic decays – hard to trigger on.
- Many channels contain a K_S in the final state – low efficiency.
- Many channels contain a π^0 in the final state – very challenging at LHCb.
- Many decay channels involved.
- Many observables – statistically challenging.

First^(*) method to measure γ

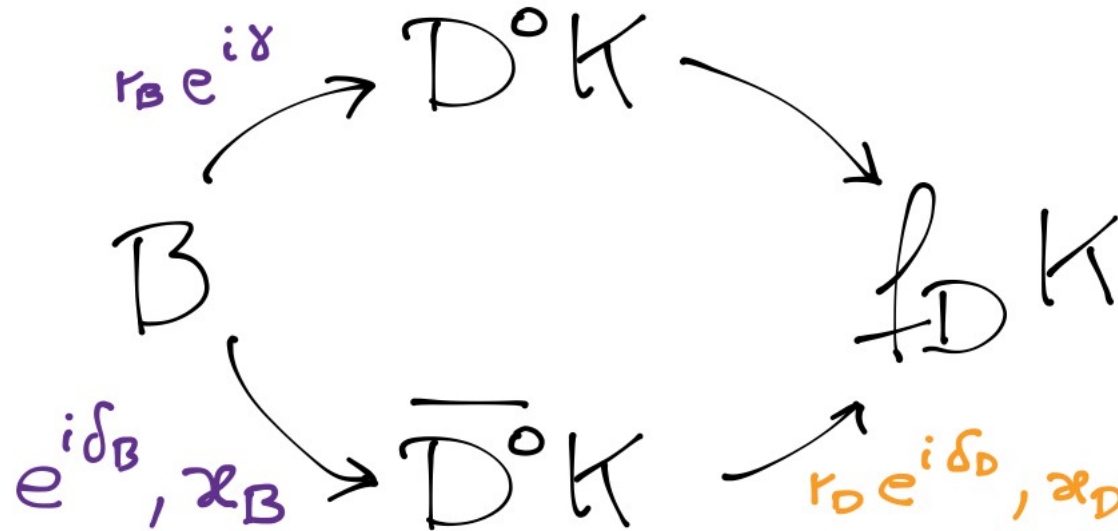
^(*) of this talk

first method to measure γ



We need to reconstruct the $D/\bar{D}$ meson in a final state accessible to both to achieve interference.

first method to measure γ



Depending on the final state f_D the method is called:

“GLW”

Gronau, London, Wyler (1991)

Phys. Lett. B253 (1991) 483

Phys. Lett. B265 (1991) 172

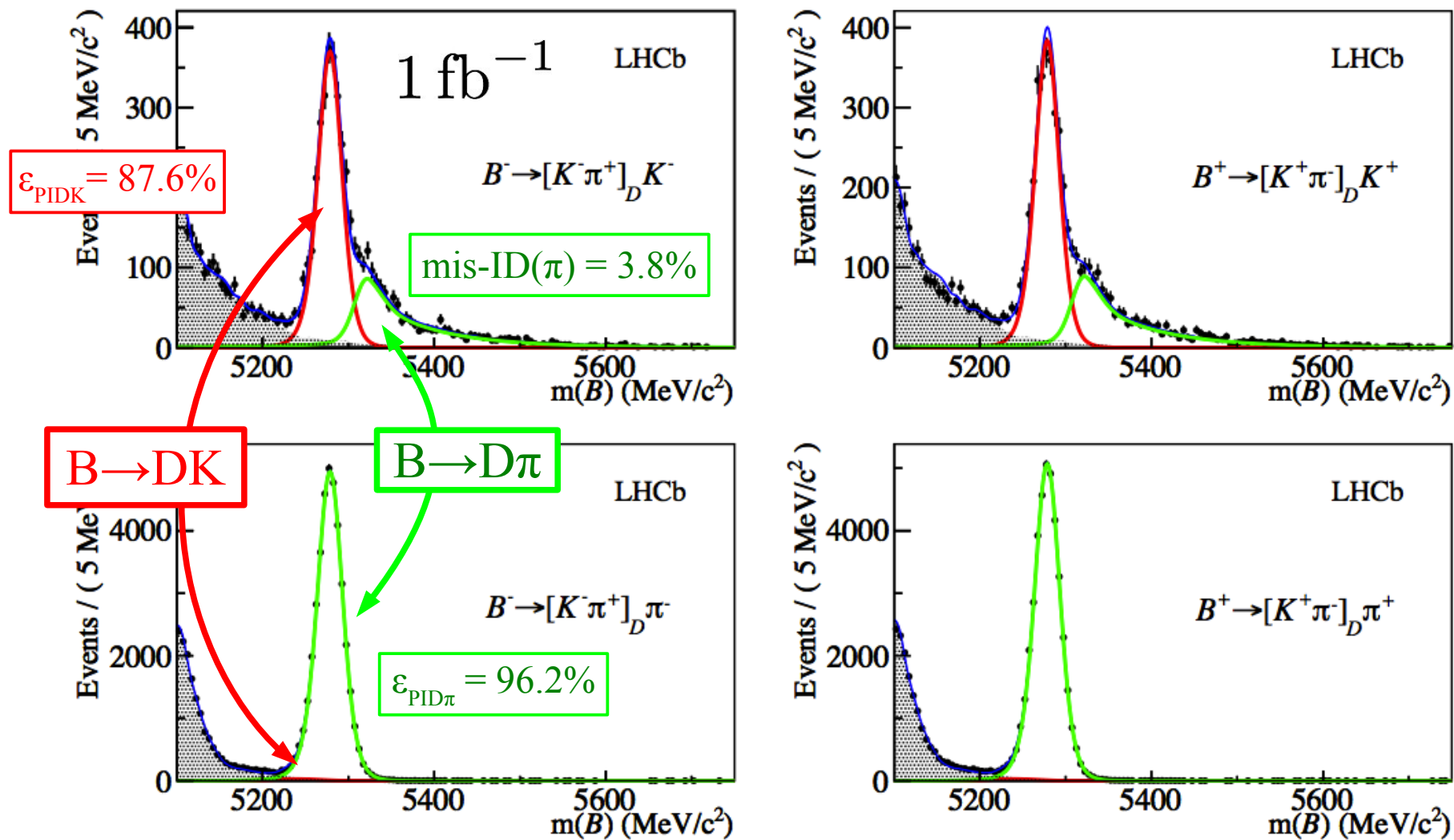
“ADS”

Atwood, Dunietz, Soni (1997, 2001)

Phys. Rev. D63 (2001) 036005

Phys. Rev. Lett. 78 (1997) 3257

$B \rightarrow D(K\pi)h$: ADS favored mode

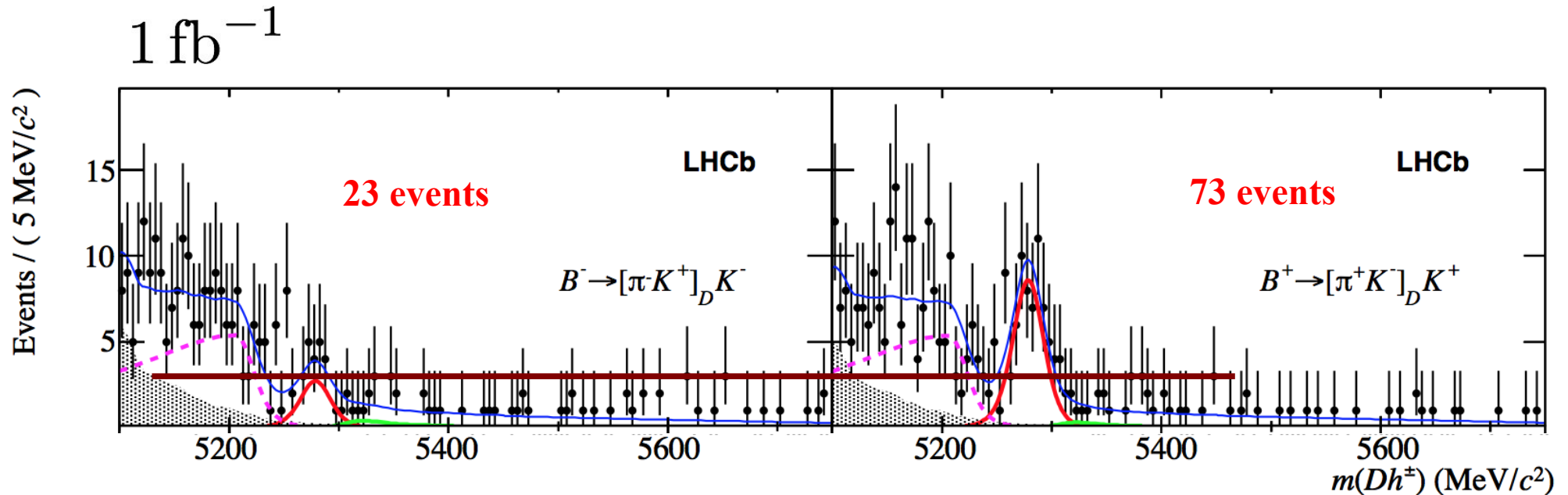


Phys. Lett. B712 (2012) 203, arXiv:1203.3662.

$B \rightarrow D(\pi K)K$: ADS **suppressed** mode

$$\mathcal{B}(B^\pm \rightarrow D_{ADS} K^\pm) \approx 2 \cdot 10^{-7} \quad (!!)$$

$$A_{CP} = -0.520 \pm 0.150 \pm 0.021$$



Phys. Lett. B712 (2012) 203, arXiv:1203.3662.

first method to measure γ

- Define observables as **yield ratios** (many systematics cancel).
- Charge **asymmetries**:

$$A_h^f = \frac{\Gamma(B^- \rightarrow [f]_D h^-) - \Gamma(B^+ \rightarrow [f]_D h^+)}{\Gamma(B^- \rightarrow [f]_D h^-) + \Gamma(B^+ \rightarrow [f]_D h^+)}$$

- Kaon/pion** ratio:

$$R_{K/\pi}^f = \frac{\Gamma(B^\pm \rightarrow [f]_D K^\pm)}{\Gamma(B^\pm \rightarrow [f]_D \pi^\pm)}$$

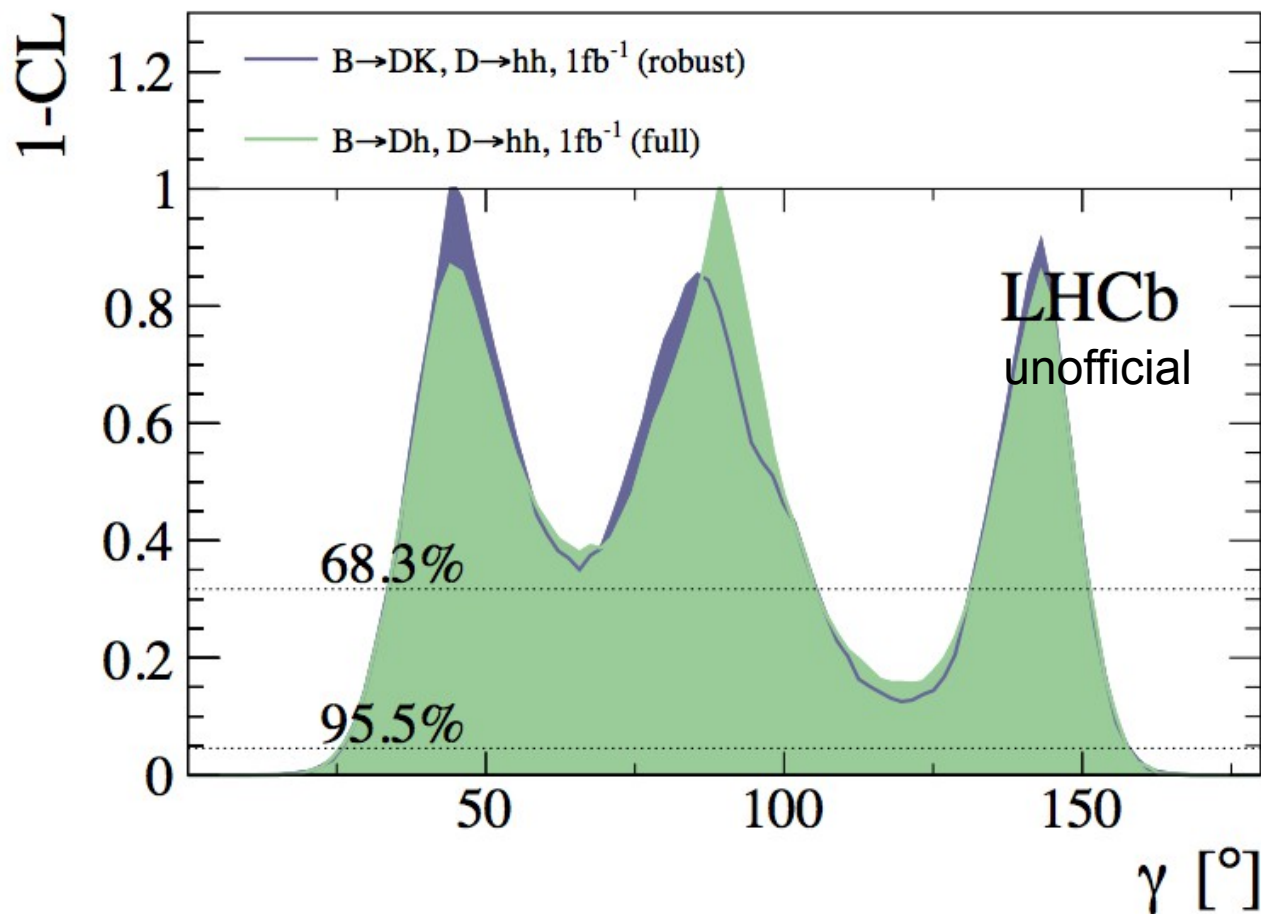
Form a system of equations.
Need more observables than
parameters!

→ many different D decays

- Suppressed/favored** decay ratio (2-body example):

$$\begin{aligned} R_h^\pm &= \frac{\Gamma(B^\pm \rightarrow [\pi^\pm K^\mp]_D h^\pm)}{\Gamma(B^\pm \rightarrow [K^\pm \pi^\mp]_D h^\pm)} \\ &= r_B^2 + r_D^2 + 2r_B r_D \cos(\underbrace{(\pm\gamma) + \delta_B + \delta_D}_{\text{strong phase diff.}}) \end{aligned}$$

first method to measure γ



Second method to measure γ

second method: “GGSZ”

- **Idea:** perform an GLW/ADS type analysis in every bin of the D decay phase space
- GGSZ uses $B \rightarrow DK$ followed by self-conjugate three-body final states

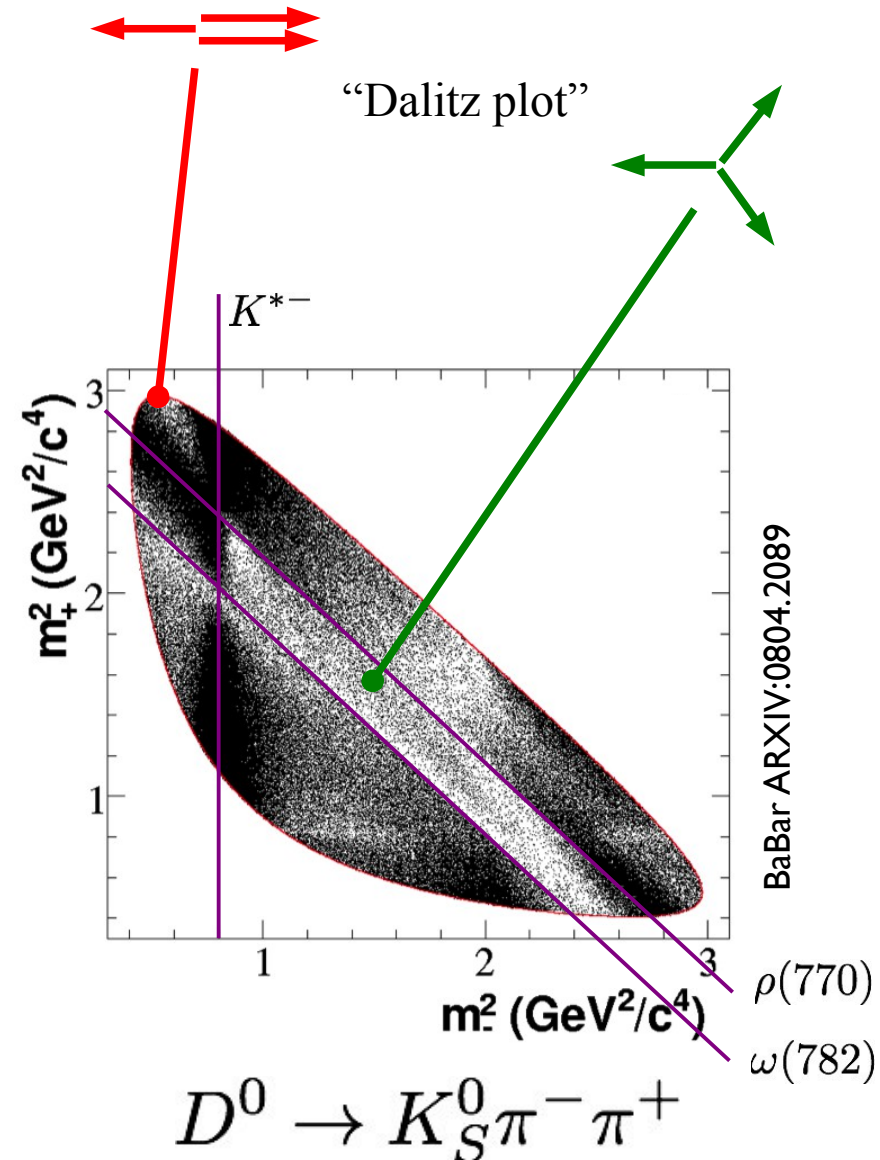
$$D^0 \rightarrow K_S^0 \pi^- \pi^+$$

$$D^0 \rightarrow K_S^0 K^- K^+$$

- Most precise at B-factories.
- Observables: the “cartesian coordinates”

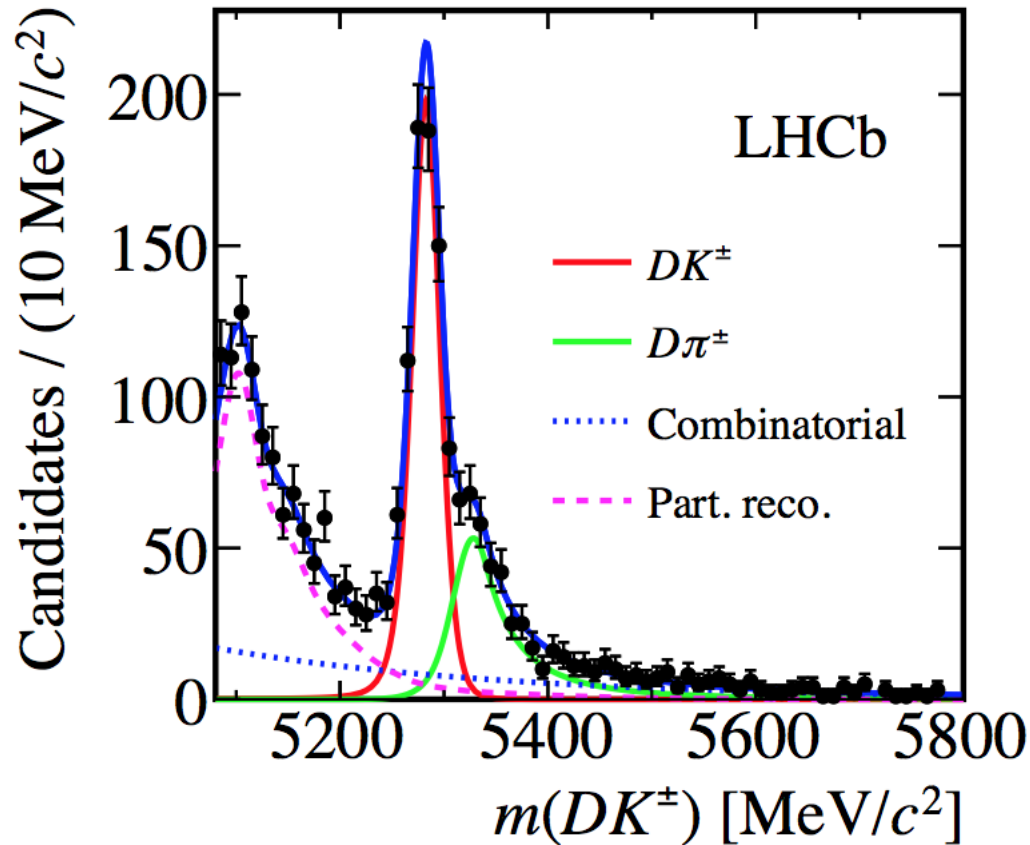
$$x_{\pm} = r_B \cos(\delta_B \pm \gamma)$$

$$y_{\pm} = r_B \sin(\delta_B \pm \gamma)$$

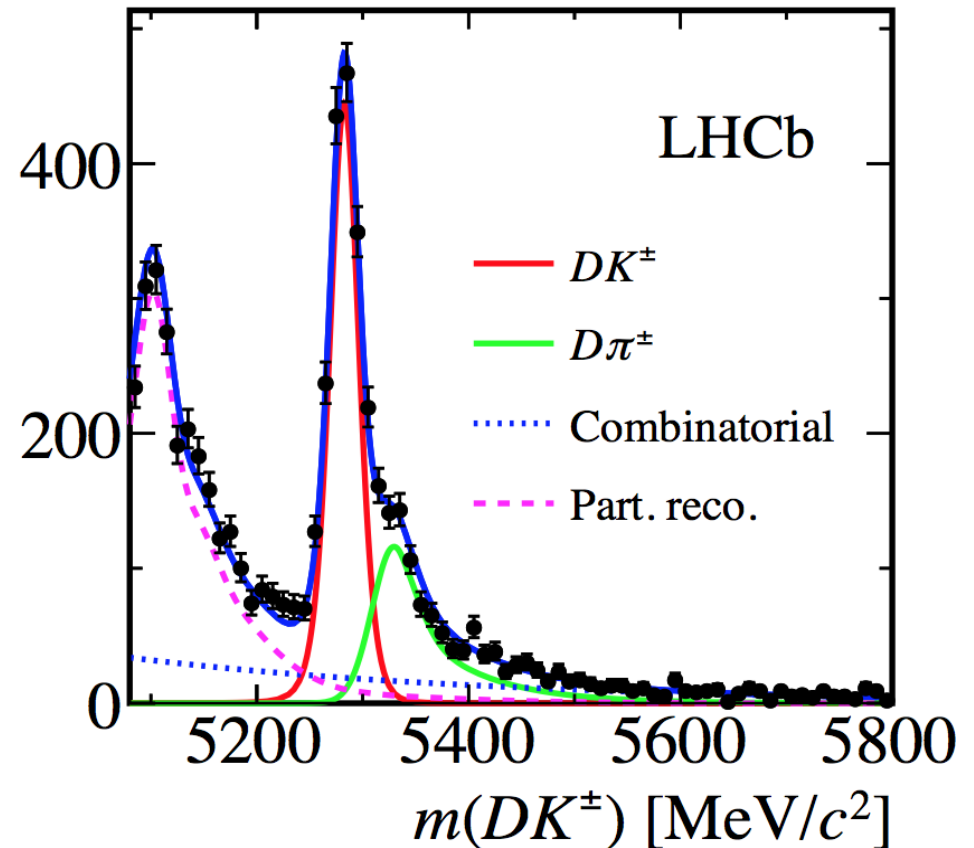


second method: “GGSZ”

“long K_S ” (N~700)

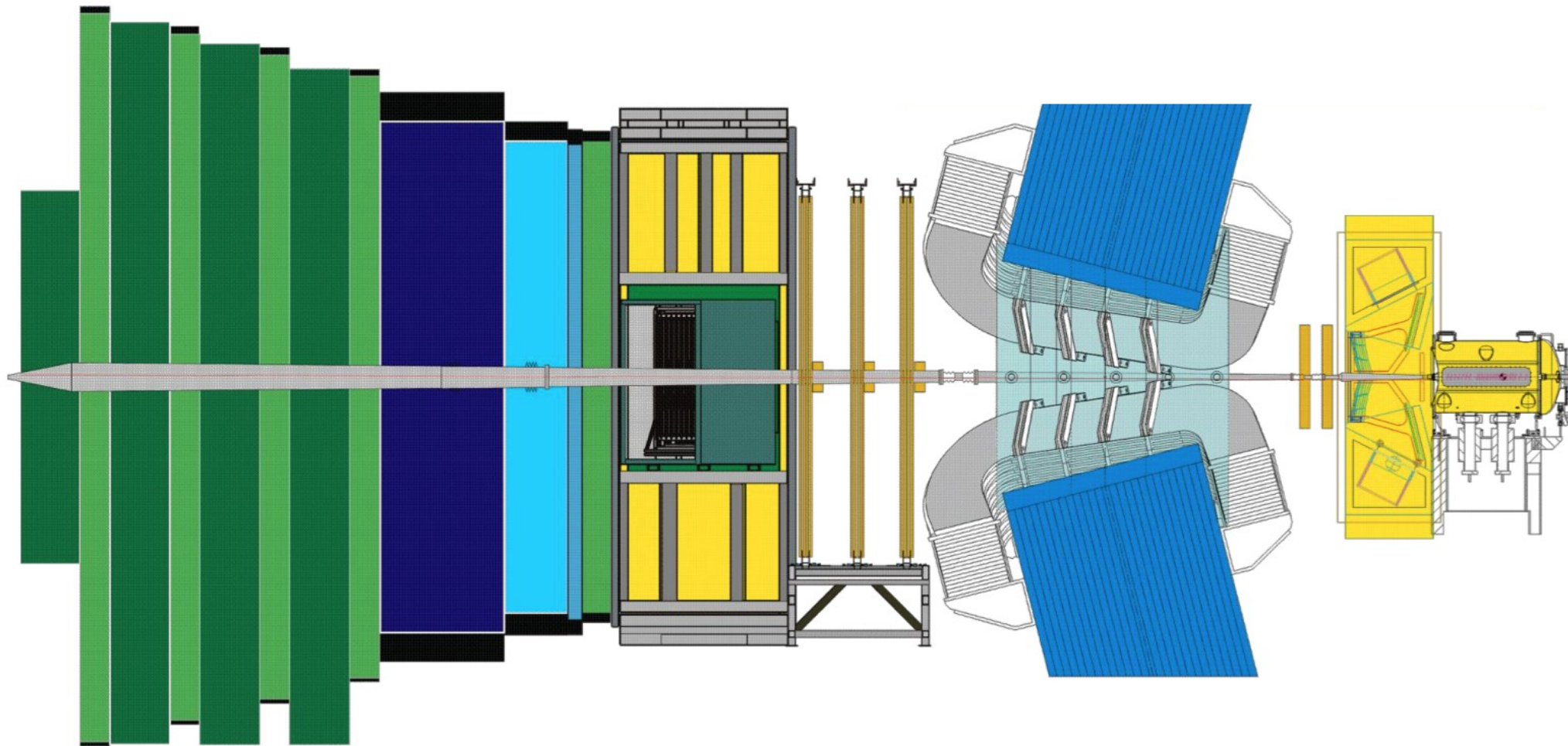


“downstream K_S ” (N~1600)

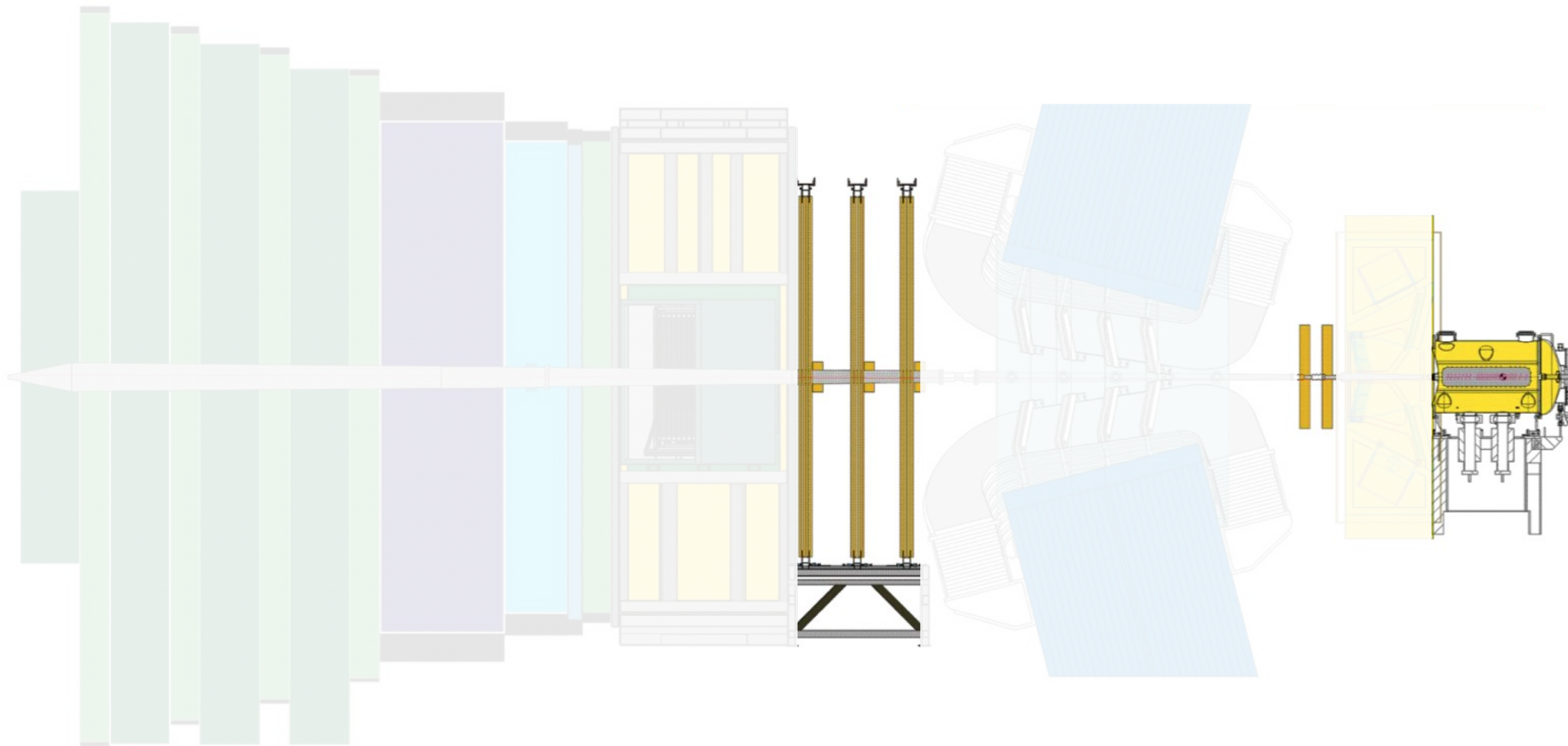


JHEP 1410 (2014) 97, arXiv:1408.2748.

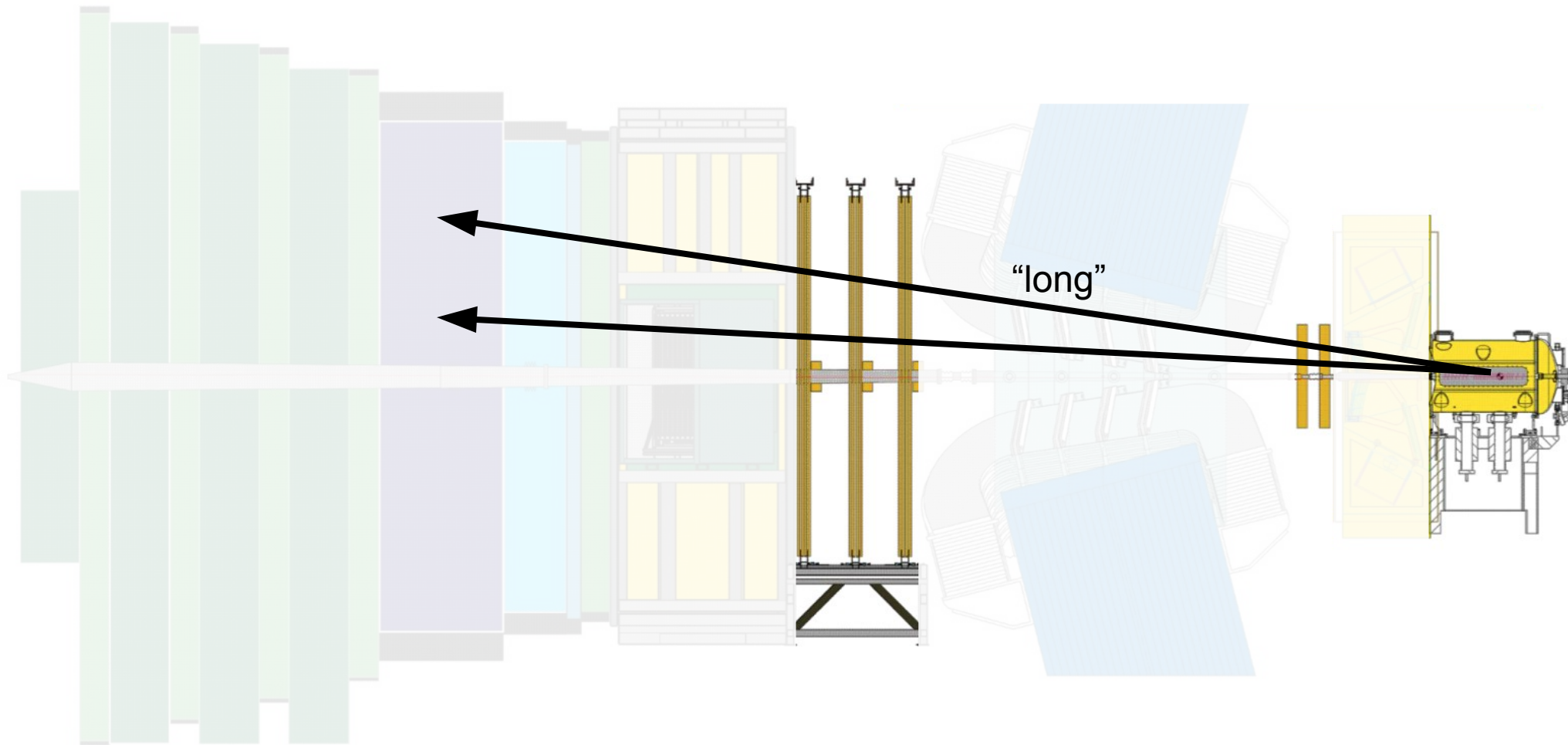
K_S reconstruction



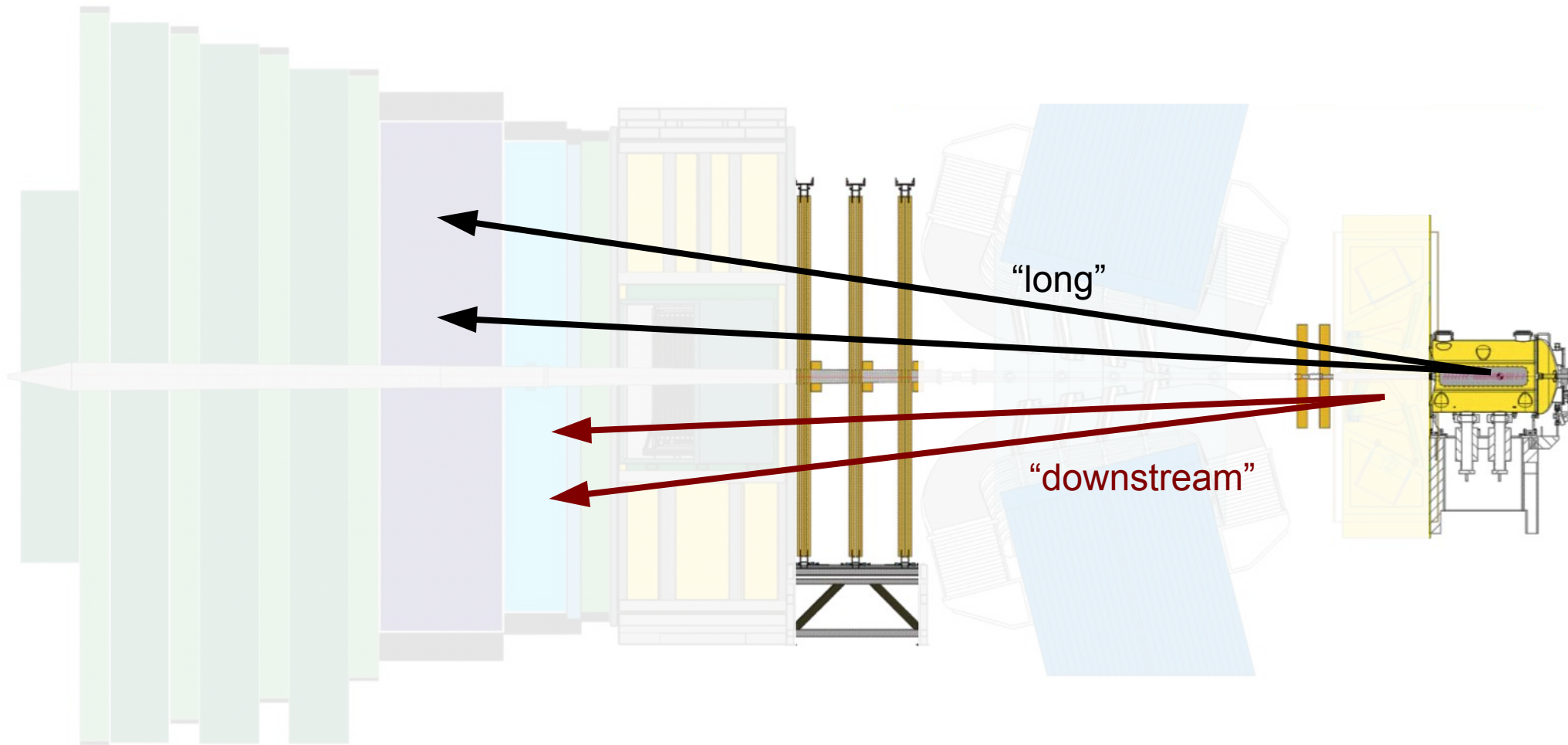
K_S reconstruction



K_S reconstruction

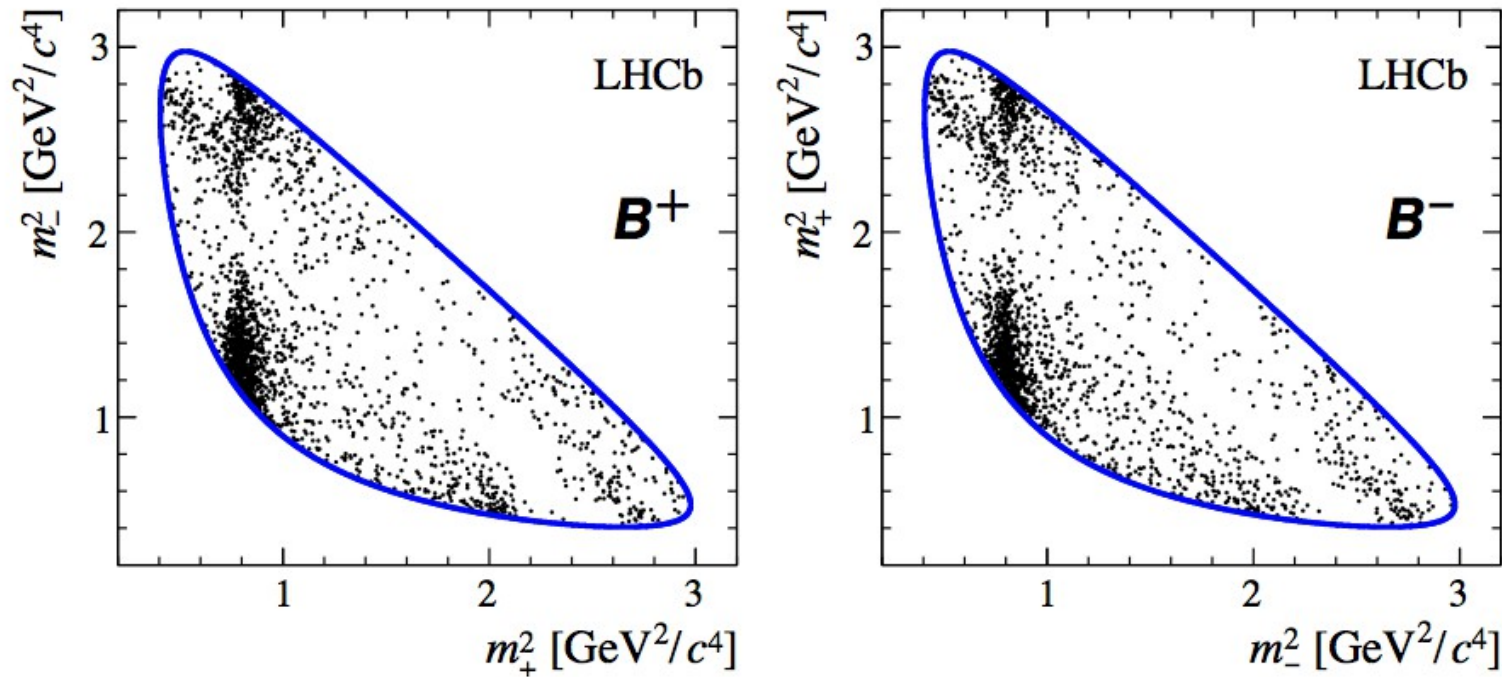


K_S reconstruction



second method: “GGSZ”

$K_S^0 \pi^+ \pi^-$ data (~ 2600 candidates):

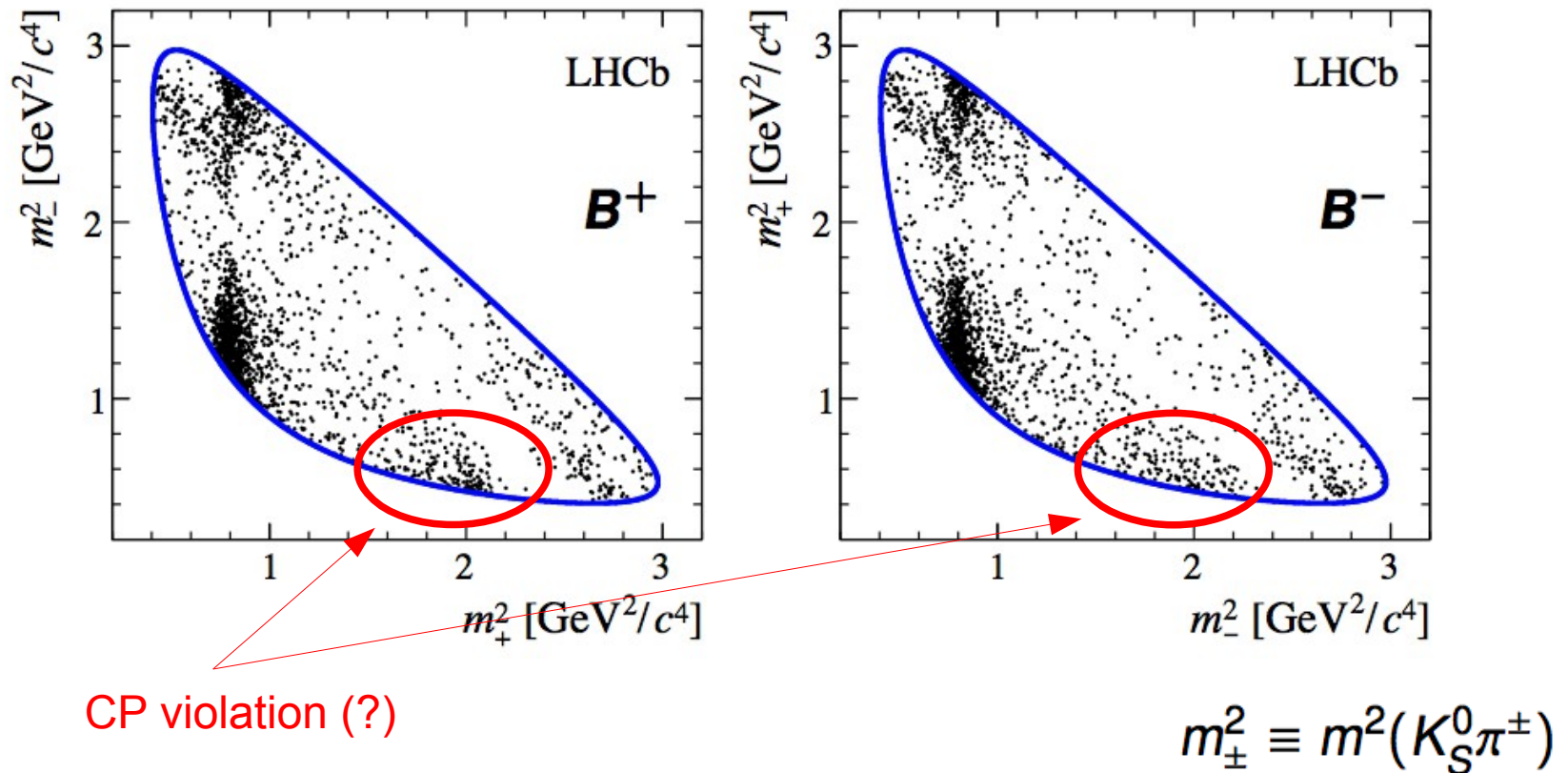


$$m_{\pm}^2 \equiv m^2(K_S^0 \pi^{\pm})$$

JHEP 1410 (2014) 97, arXiv:1408.2748.

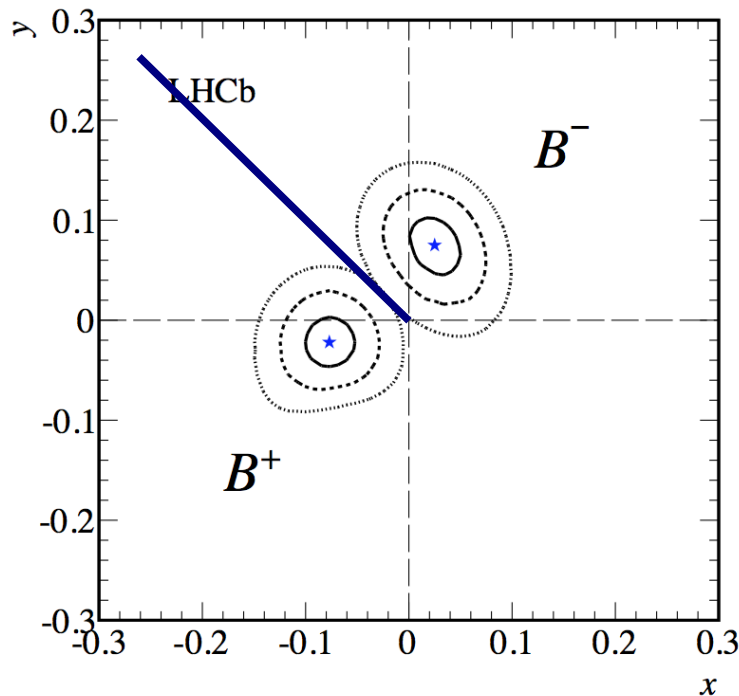
second method: “GGSZ”

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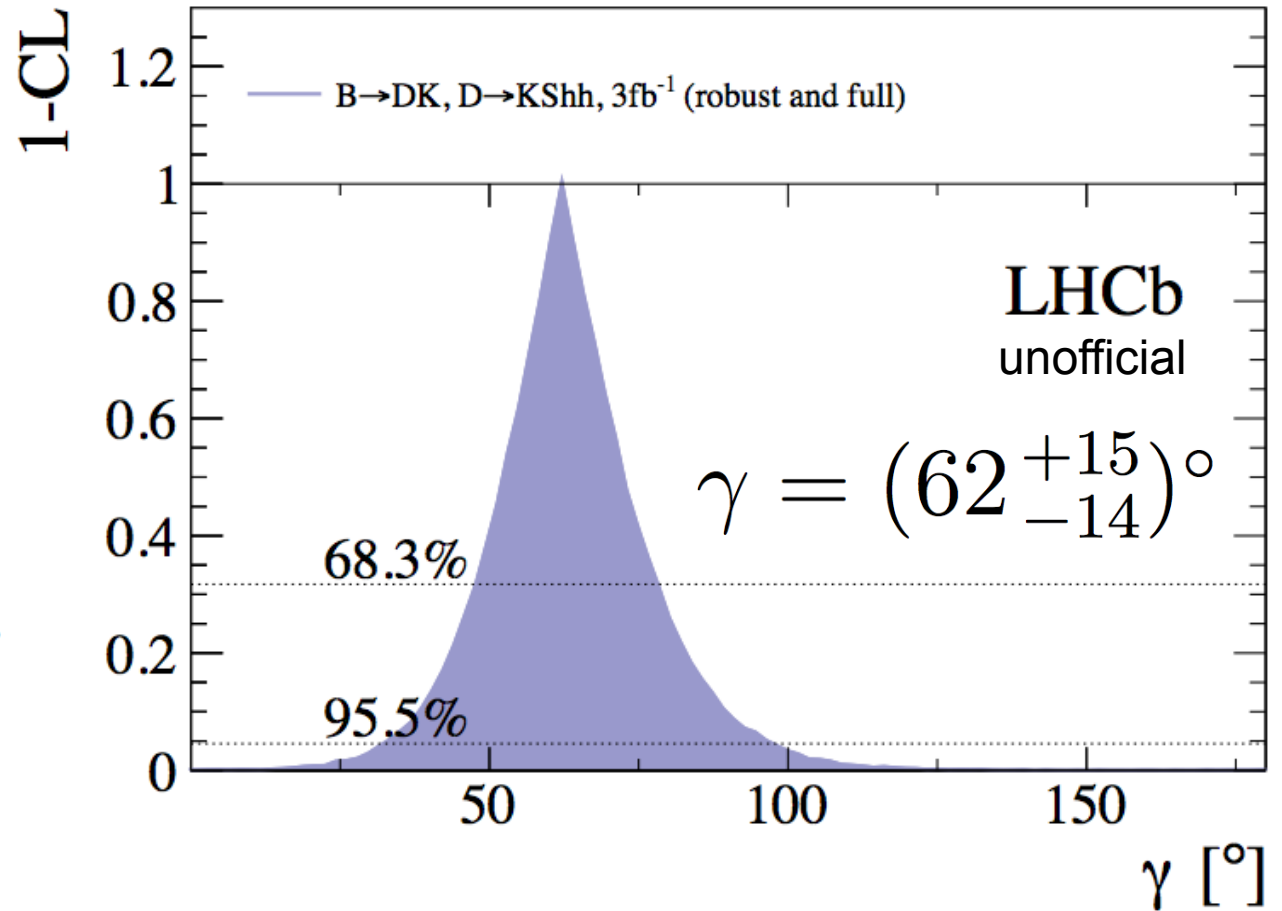
second method: “GGSZ”



$$x_{\pm} = r_B \cos(\delta_B \pm \gamma)$$

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JHEP 1410 (2014) 97,
arXiv:1408.2748.



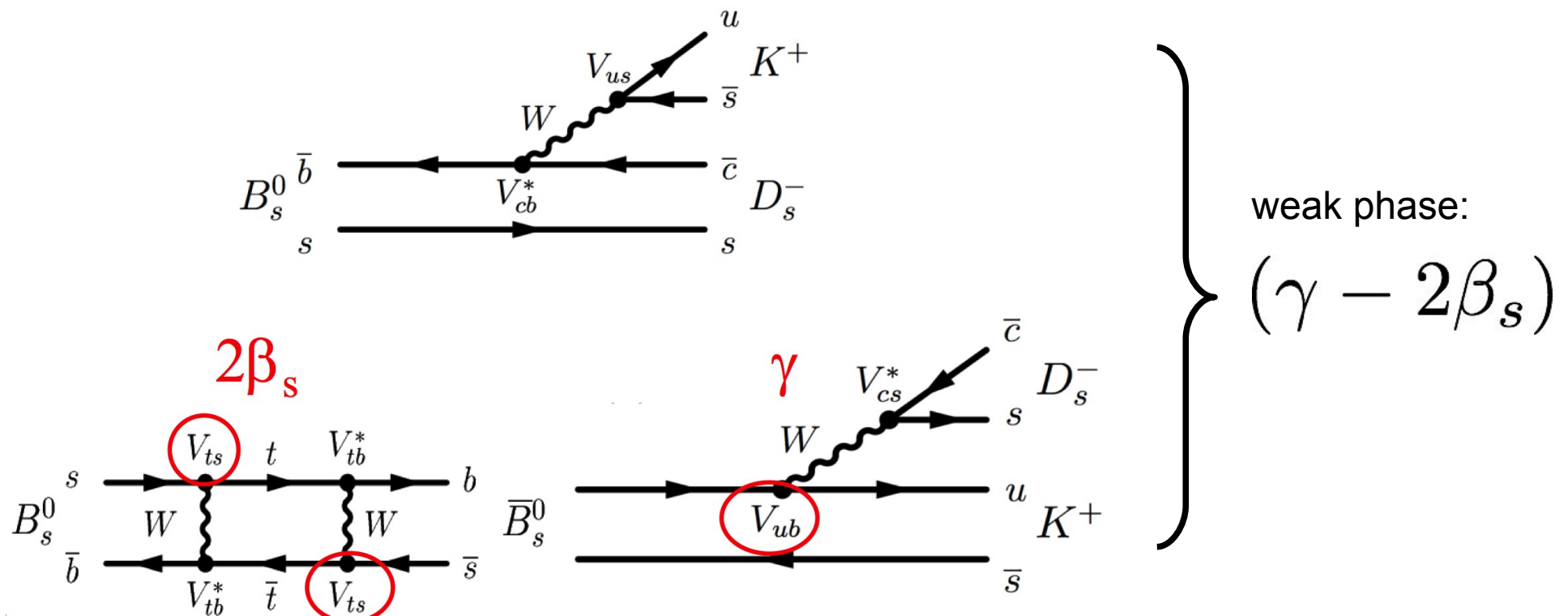
World's most precise *single* measurement!

Third method to measure γ

third method: time-dependent

Using charged-particle final states, interference is achieved through **mixing**.

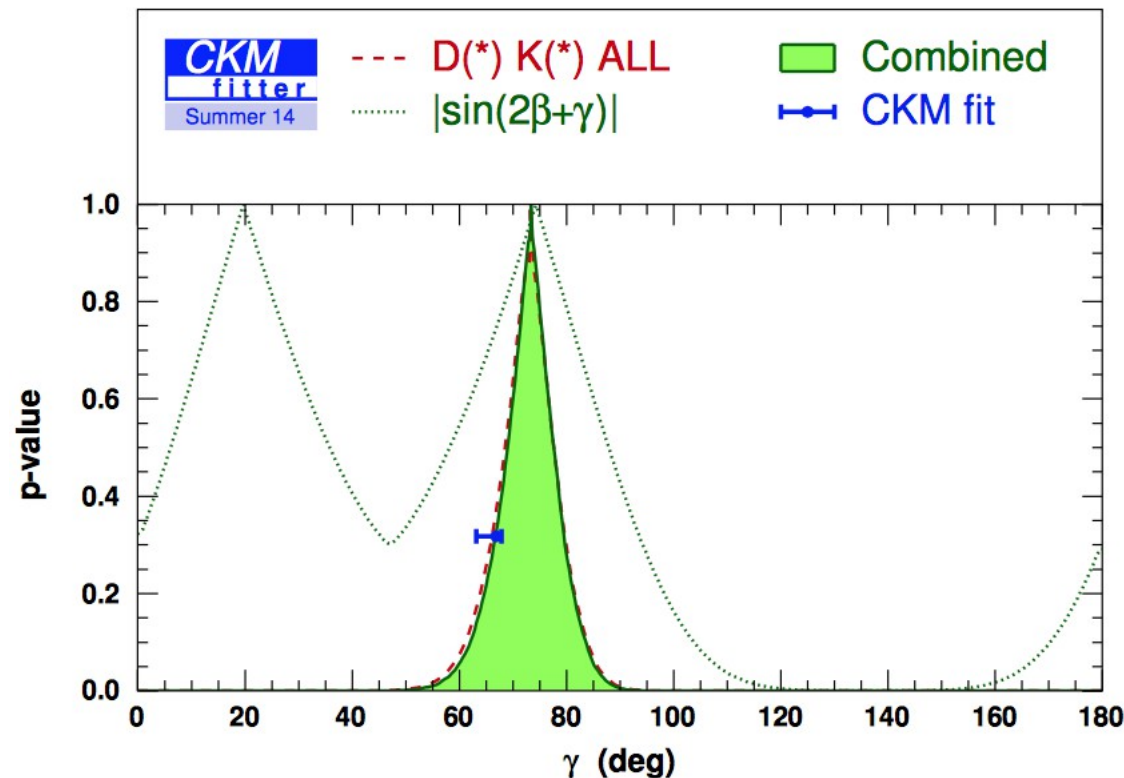
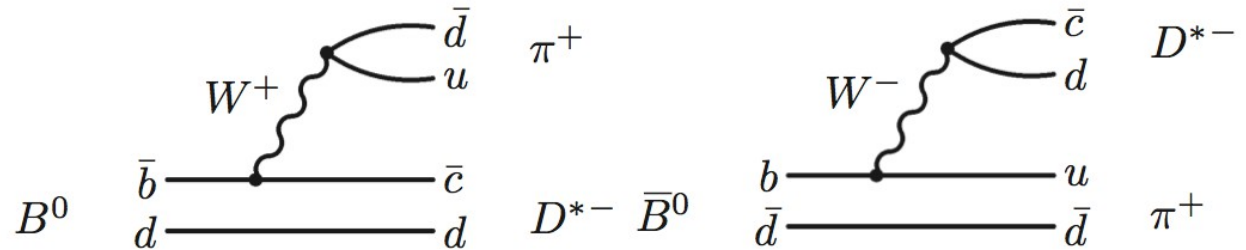
$$B_s \rightarrow D_s^\pm K^\mp$$



Phys. Lett. B387 (1996) 361, arXiv:hep-ph/9605221.

third method: time-dependent

B-factories performed
such measurements
with $B^0 \rightarrow D^+ \pi^-$,
constraining $\sin(2\beta+\gamma)$



BaBar 2005,
hep-ex/0504035

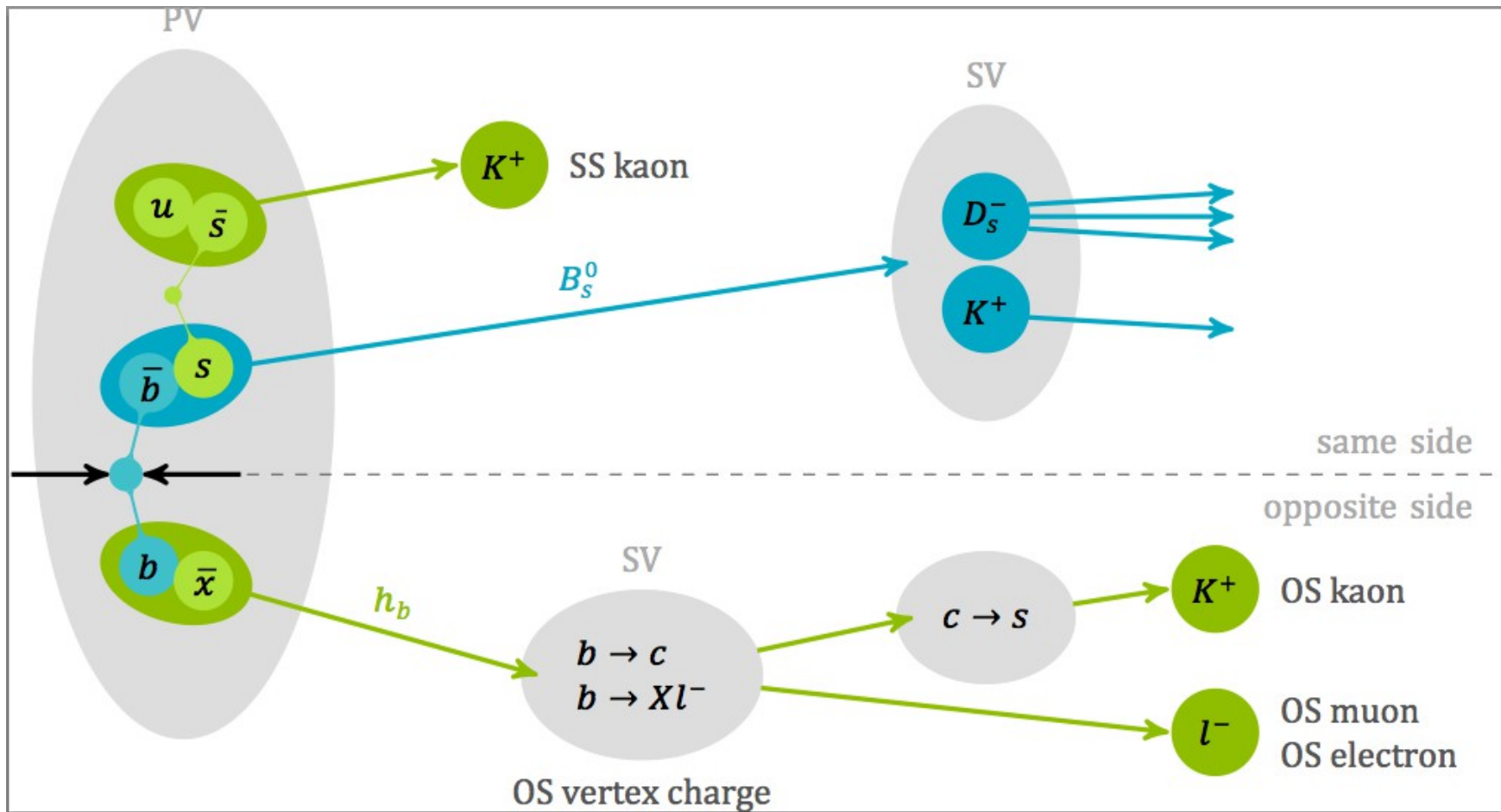
Belle 2011,
arXiv:1102.0888

CKMfitter 2015,
arXiv:1501.05013

third method: time-dependent

- B_s is much better suited than B_d !
- expected **large interference** effects of $\sim 40\%$
- finite decay width difference adds sensitivity:
 $\Delta\Gamma_s = 0.091 \pm 0.011 \text{ ps}^{-1}$ (HFAG fall 2012)
- It is still a pure, **clean tree decay**.
- **Only possible at LHCb:**
 - B_s statistics: large b-quark production cross section
 - fully hadronic: full real-time reconstruction on trigger level
 - time resolution: $\sigma(t) \sim 50\text{fs}$
 - flavor tagging: distinguish B_s from anti- B_s (tagging power $\sim 5\%$)

flavor tagging

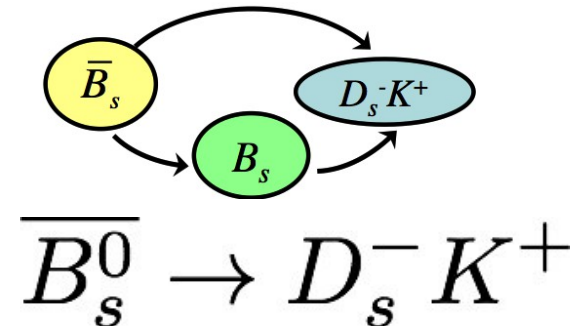
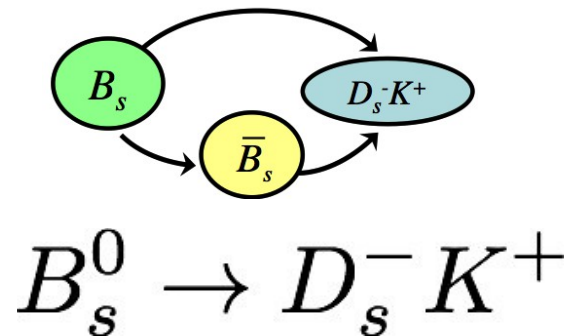
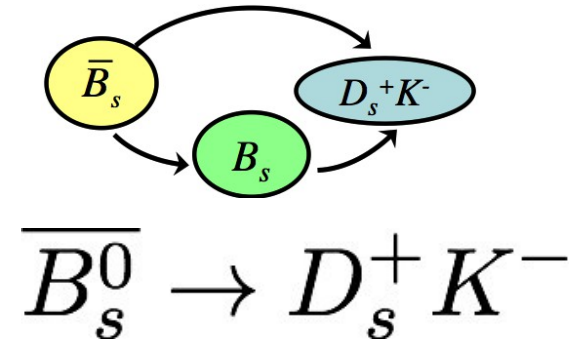
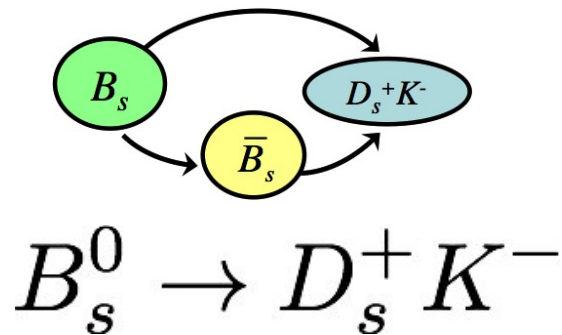


$$\varepsilon_{\text{eff}} = \varepsilon(1 - 2\omega)^2$$

$$\varepsilon_{\text{eff}} = 5.07\% \text{ (for } B_s \rightarrow D_s K \text{)}$$

$$\sigma \propto 1/\sqrt{\varepsilon_{\text{eff}}}$$

third method: time-dependent



each has their own time dependence ...

third method: time-dependent

$$\frac{d\Gamma_{B_s^0 \rightarrow f}(t)}{dt e^{-\Gamma_s t}} = \frac{1}{2}|A_f|^2(1 + |\lambda_f|^2) \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + D_f \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + C_f \cos(\Delta m_s t) - S_f \sin(\Delta m_s t) \right] \quad (1)$$

$$\frac{d\Gamma_{\bar{B}_s^0 \rightarrow f}(t)}{dt e^{-\Gamma_s t}} = \frac{1}{2}|A_f|^2 \left| \frac{p}{q} \right|^2 (1 + |\lambda_f|^2) \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + D_f \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - C_f \cos(\Delta m_s t) + S_f \sin(\Delta m_s t) \right] \quad (2)$$

$$\frac{d\Gamma_{\bar{B}_s^0 \rightarrow \bar{f}}(t)}{dt e^{-\Gamma_s t}} = \frac{1}{2}|\bar{A}_{\bar{f}}|^2(1 + |\bar{\lambda}_{\bar{f}}|^2) \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + D_{\bar{f}} \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + C_{\bar{f}} \cos(\Delta m_s t) - S_{\bar{f}} \sin(\Delta m_s t) \right] \quad (3)$$

$$\frac{d\Gamma_{B_s^0 \rightarrow \bar{f}}(t)}{dt e^{-\Gamma_s t}} = \frac{1}{2}|\bar{A}_{\bar{f}}|^2 \left| \frac{q}{p} \right|^2 (1 + |\bar{\lambda}_{\bar{f}}|^2) \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + D_{\bar{f}} \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - C_{\bar{f}} \cos(\Delta m_s t) + S_{\bar{f}} \sin(\Delta m_s t) \right] \quad (4)$$

third method: time-dependent

$$\frac{d\Gamma_{B_s^0 \rightarrow f}(t)}{dt e^{-\Gamma_s t}} = \frac{1}{2}|A_f|^2(1 + |\lambda_f|^2) \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + D_f \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + C_f \cos(\Delta m_s t) - S_f \sin(\Delta m_s t) \right] \quad (1)$$

$$\frac{d\Gamma_{\bar{B}_s^0 \rightarrow f}(t)}{dt e^{-\Gamma_s t}} = \frac{1}{2}|A_f|^2 \left| \frac{q}{p} \right|^2 (1 + |\lambda_f|^2) \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + D_f \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - C_f \cos(\Delta m_s t) + S_f \sin(\Delta m_s t) \right] \quad (2)$$

$$\frac{d\Gamma_{\bar{B}_s^0 \rightarrow \bar{f}}(t)}{dt e^{-\Gamma_s t}} = \frac{1}{2}|\bar{A}_{\bar{f}}|^2(1 + |\bar{\lambda}_{\bar{f}}|^2) \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + D_{\bar{f}} \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + C_{\bar{f}} \cos(\Delta m_s t) - S_{\bar{f}} \sin(\Delta m_s t) \right] \quad (3)$$

$$\frac{d\Gamma_{B_s^0 \rightarrow \bar{f}}(t)}{dt e^{-\Gamma_s t}} = \frac{1}{2}|\bar{A}_{\bar{f}}|^2 \left| \frac{q}{p} \right|^2 (1 + |\bar{\lambda}_{\bar{f}}|^2) \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + D_{\bar{f}} \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - C_{\bar{f}} \cos(\Delta m_s t) + S_{\bar{f}} \sin(\Delta m_s t) \right] \quad (4)$$

third method: time-dependent

$$\frac{d\Gamma_{B_s^0 \rightarrow f}(t)}{dt e^{-\Gamma_s t}} = \frac{1}{2}|A_f|^2(1 + |\lambda_f|^2) \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + D_f \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + C_f \cos(\Delta m_s t) - S_f \sin(\Delta m_s t) \right] \quad (1)$$

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$$\frac{d\Gamma_{\bar{B}_s^0 \rightarrow \bar{f}}(t)}{dt e^{-\Gamma_s t}} = \frac{1}{2}|\bar{A}_{\bar{f}}|^2(1 + |\bar{\lambda}_{\bar{f}}|^2) \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + D_{\bar{f}} \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + C_{\bar{f}} \cos(\Delta m_s t) - S_{\bar{f}} \sin(\Delta m_s t) \right] \quad (3)$$

$$\frac{d\Gamma_{B_s^0 \rightarrow \bar{f}}(t)}{dt e^{-\Gamma_s t}} = \frac{1}{2}|\bar{A}_{\bar{f}}|^2 \left| \frac{q}{p} \right|^2 (1 + |\bar{\lambda}_{\bar{f}}|^2) \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + D_{\bar{f}} \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - C_{\bar{f}} \cos(\Delta m_s t) + S_{\bar{f}} \sin(\Delta m_s t) \right] \quad (4)$$

third method: time-dependent

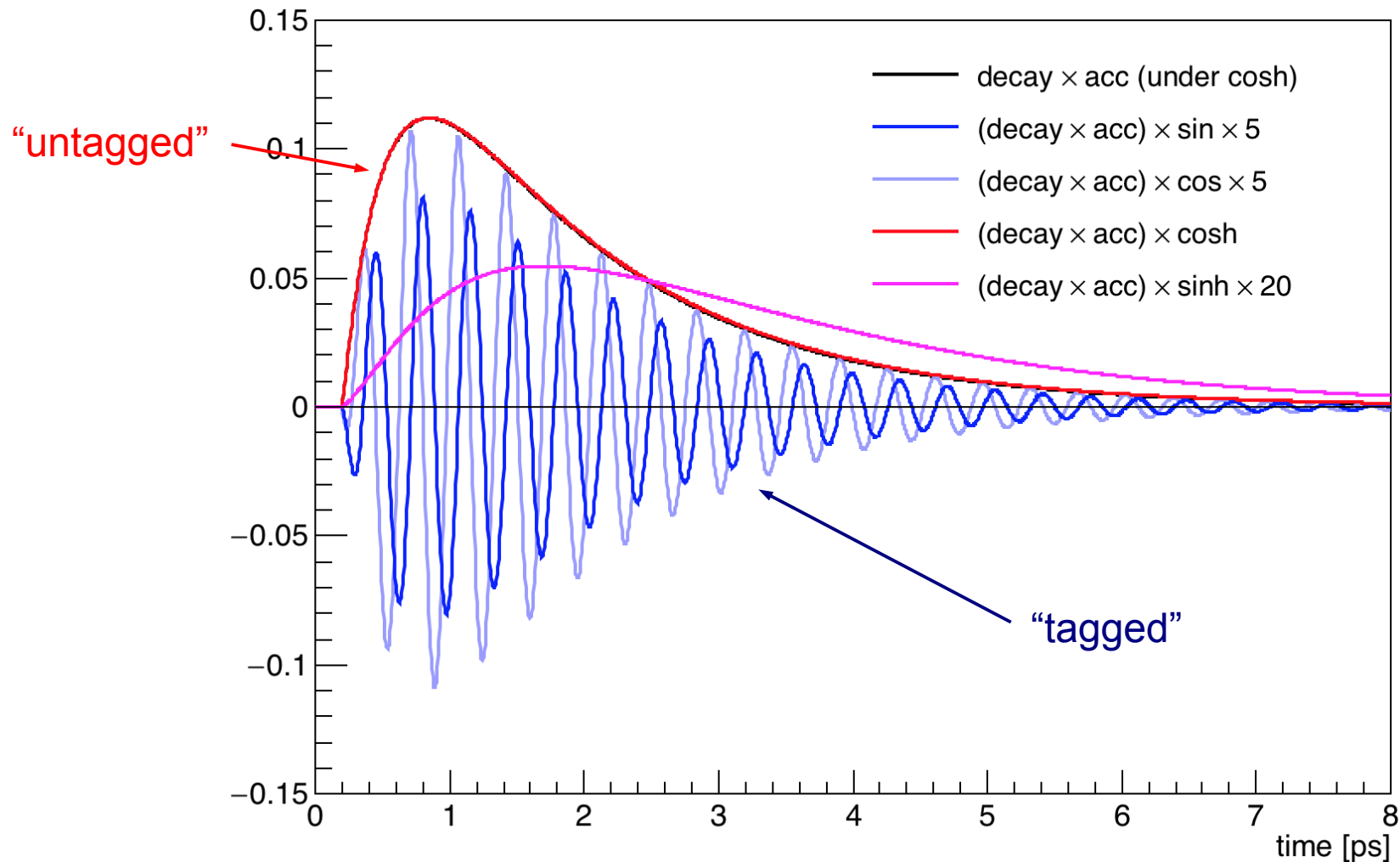
$$\frac{d\Gamma_{B_s^0 \rightarrow f}(t)}{dt e^{-\Gamma_s t}} = \frac{1}{2}|A_f|^2(1 + |\lambda_f|^2) \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + D_f \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + C_f \cos(\Delta m_s t) - S_f \sin(\Delta m_s t) \right] \quad (1)$$

$$\frac{d\Gamma_{\bar{B}_s^0 \rightarrow f}(t)}{dt e^{-\Gamma_s t}} = \frac{1}{2}|A_f|^2 \left| \frac{p}{q} \right|^2 (1 + |\lambda_f|^2) \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + D_f \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - C_f \cos(\Delta m_s t) + S_f \sin(\Delta m_s t) \right] \quad (2)$$

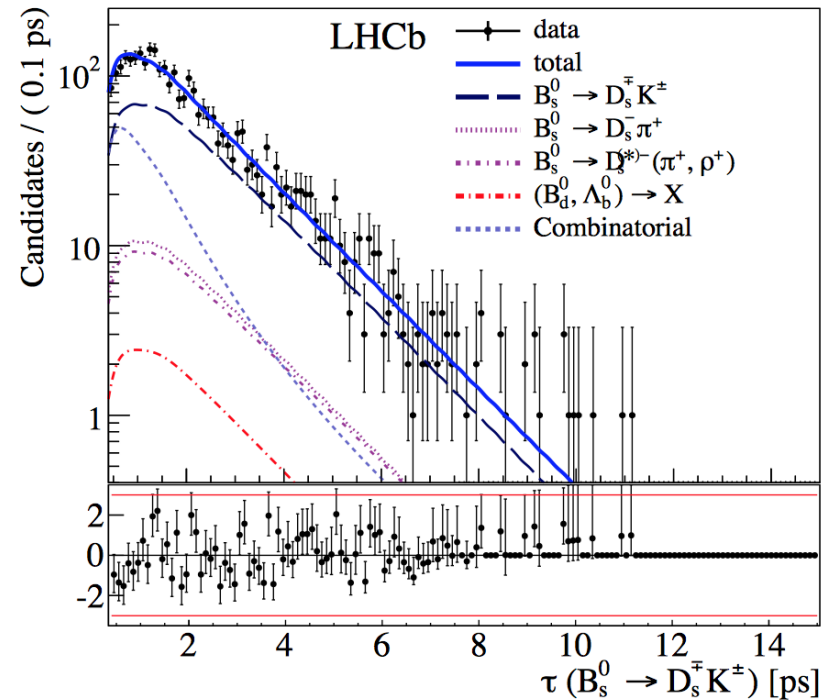
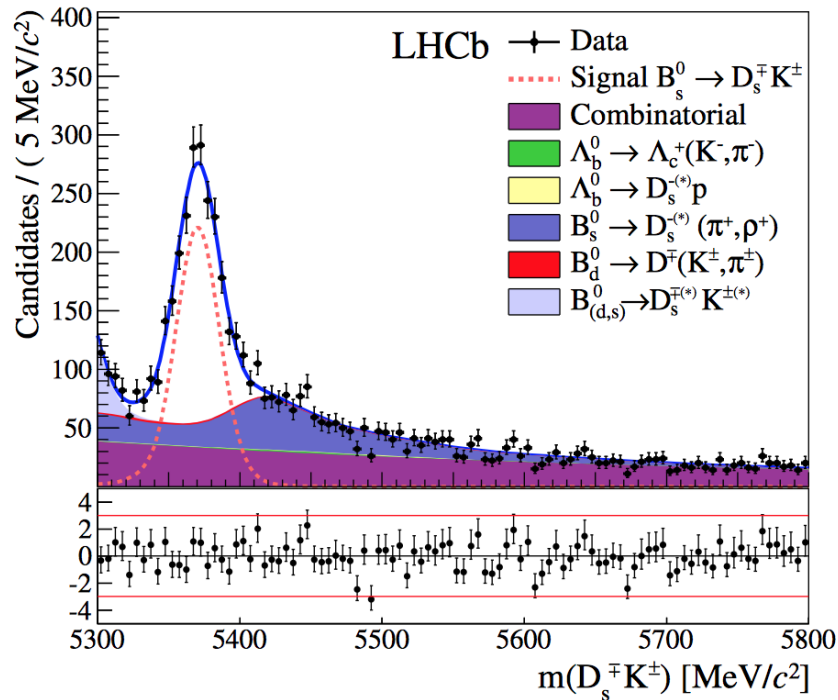
$$\frac{d\Gamma_{\bar{B}_s^0 \rightarrow \bar{f}}(t)}{dt e^{-\Gamma_s t}} = \frac{1}{2}|\bar{A}_{\bar{f}}|^2(1 + |\bar{\lambda}_{\bar{f}}|^2) \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + D_{\bar{f}} \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + C_{\bar{f}} \cos(\Delta m_s t) - S_{\bar{f}} \sin(\Delta m_s t) \right] \quad (3)$$

$$\frac{d\Gamma_{B_s^0 \rightarrow \bar{f}}(t)}{dt e^{-\Gamma_s t}} = \frac{1}{2}|\bar{A}_{\bar{f}}|^2 \left| \frac{q}{p} \right|^2 (1 + |\bar{\lambda}_{\bar{f}}|^2) \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + D_{\bar{f}} \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - C_{\bar{f}} \cos(\Delta m_s t) + S_{\bar{f}} \sin(\Delta m_s t) \right] \quad (4)$$

third method: time-dependent



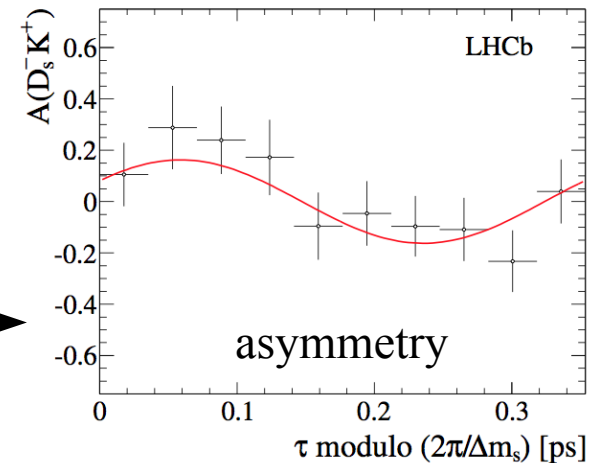
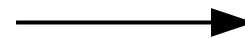
third method: time-dependent



$$N_{\text{sig}} \sim 1770 (1 \text{ fb}^{-1})$$

JHEP 1411 (2014) 060,
arXiv:1407.6127.

hint of an oscillation!



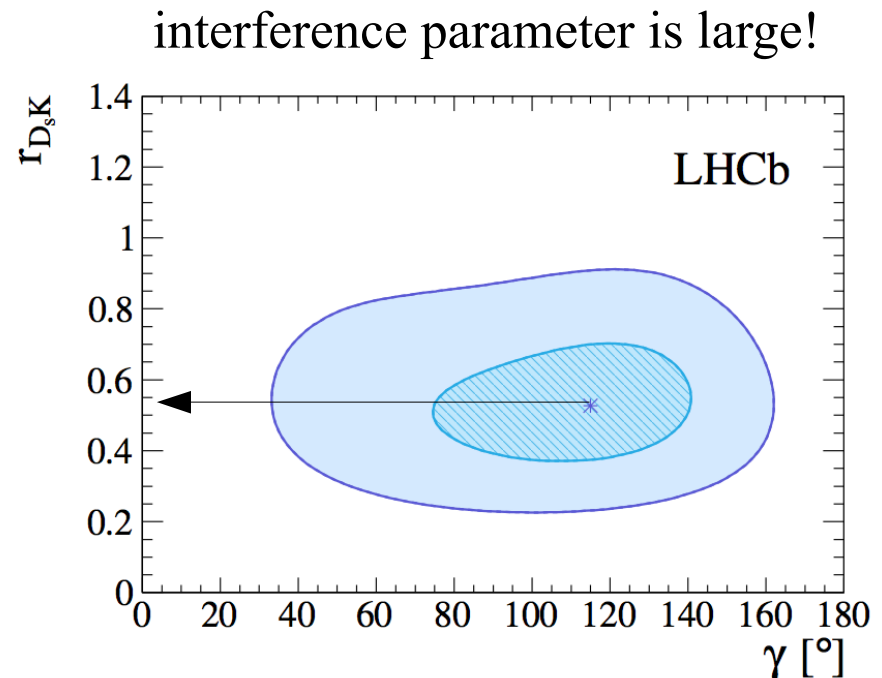
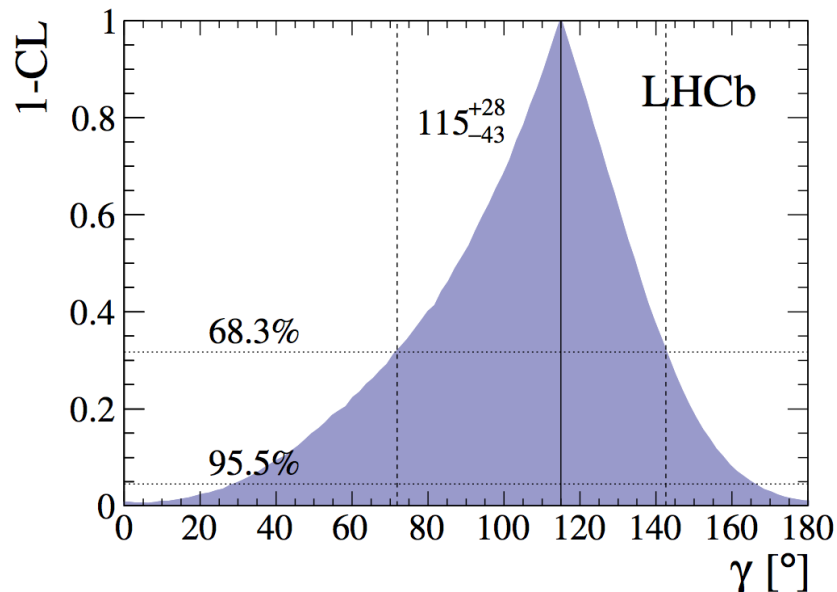
third method: time-dependent

Assuming the B_s mixing phase to be (LHCb, arXiv:1304.2600)

$$\phi_s = 0.01 \pm 0.07 \text{ (stat)} \pm 0.01 \text{ (syst) rad}$$

we constrain γ (arXiv:1407.6127):

$$\gamma = (115^{+28}_{-43})^\circ$$



Combining all LHCb tree-level γ measurements

γ combination

Two combinations:

robust	$B \rightarrow DK\text{-like}$
full	$B \rightarrow DK\text{-like and } B \rightarrow D\pi$

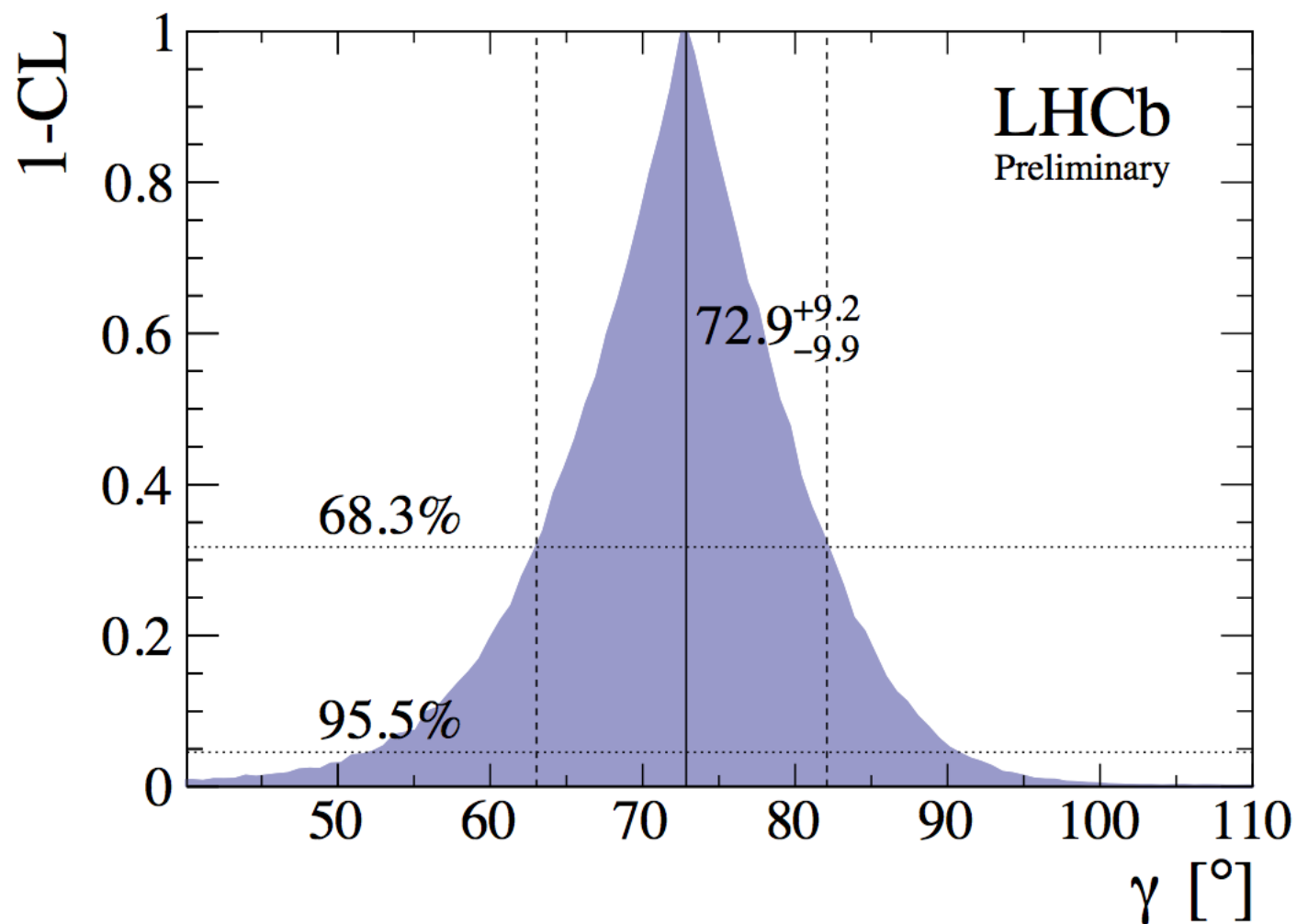
Inputs:

- ▶ $B^+ \rightarrow Dh^+, D \rightarrow hh$, GLW/ADS, 1 fb^{-1} 1203.3662
- ▶ $B^+ \rightarrow Dh^+, D \rightarrow K\pi\pi\pi$, ADS, 1 fb^{-1} 1303.4646
- ▶ **updated:** $B^+ \rightarrow DK^+, D \rightarrow K_s^0 hh$, model-ind. GGSZ, 3 fb^{-1} 1408.2748
- ▶ **new:** $B^+ \rightarrow DK^+, D \rightarrow K_s^0 K\pi$, GLS, 3 fb^{-1} 1402.2982
- ▶ **new:** $B^0 \rightarrow D^0 K^{*0}, D \rightarrow hh$, GLW/ADS, 3 fb^{-1} 1407.8136
- ▶ **new:** $B_s^0 \rightarrow D_s^\mp K^\pm$, 1 fb^{-1} 1407.6127

γ combination

LHCb-CONF-2014-004

Frequentist (plugin-method)



γ combination

Table: Summary of results for γ from the B factories BaBar and Belle, and from LHCb, and combiners. Errors correspond to 68% confidence or credibility.

experiment	result	date
BaBar	$(69^{+17}_{-16})^\circ$	Jan 2013
Belle	$(68^{+15}_{-14})^\circ$	Jan 2013
LHCb $1\text{--}3\text{ fb}^{-1}$ prelim.	$(67 \pm 12)^\circ$	Apr 2013
LHCb 1 fb^{-1}	$(72.6^{+9.7}_{-17.2})^\circ$	Aug 2013
LHCb $1\text{--}3\text{ fb}^{-1}$ prelim.	$(72.9^{+9.2}_{-9.9})^\circ$	Sep 2014
UTfit	$(68.3 \pm 7.5)^\circ$	post Moriond 2014
CKMfitter	$(70.0^{+7.7}_{-9.0})^\circ$	Moriond / Jun 2014
CKMfitter	$(73.2^{+6.3}_{-7.0})^\circ$	Sep 2014

Outlook

What's next?

Update the existing measurements to the full dataset:

$$1\text{fb}^{-1} \rightarrow 3\text{fb}^{-1}$$

There are many more possibilities:

$$B^+ \rightarrow Dh^+, D \rightarrow K\pi\pi^0 \quad \text{ADS}$$

$$B^+ \rightarrow Dh^+, D \rightarrow \pi\pi\pi^0 \quad \text{GLW}$$

$$B^+ \rightarrow Dh^+, D \rightarrow KK\pi\pi \quad \text{GGSZ}$$

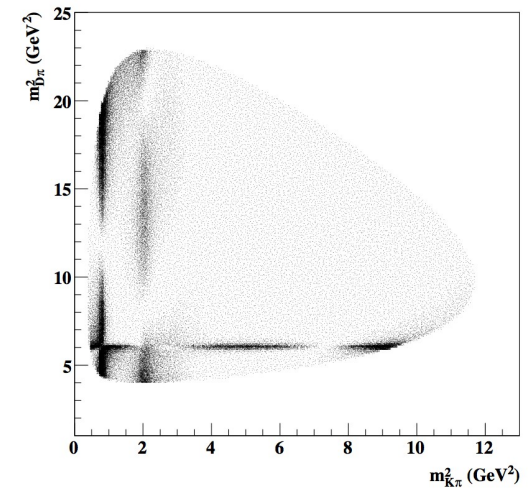
$$B^0 \rightarrow DK^{*0}, D \rightarrow Khh \quad \text{GGSZ}$$

$$B^+ \rightarrow DK\pi\pi, D \rightarrow hh, Khh \quad \text{GLW/ADS/GGSZ}$$

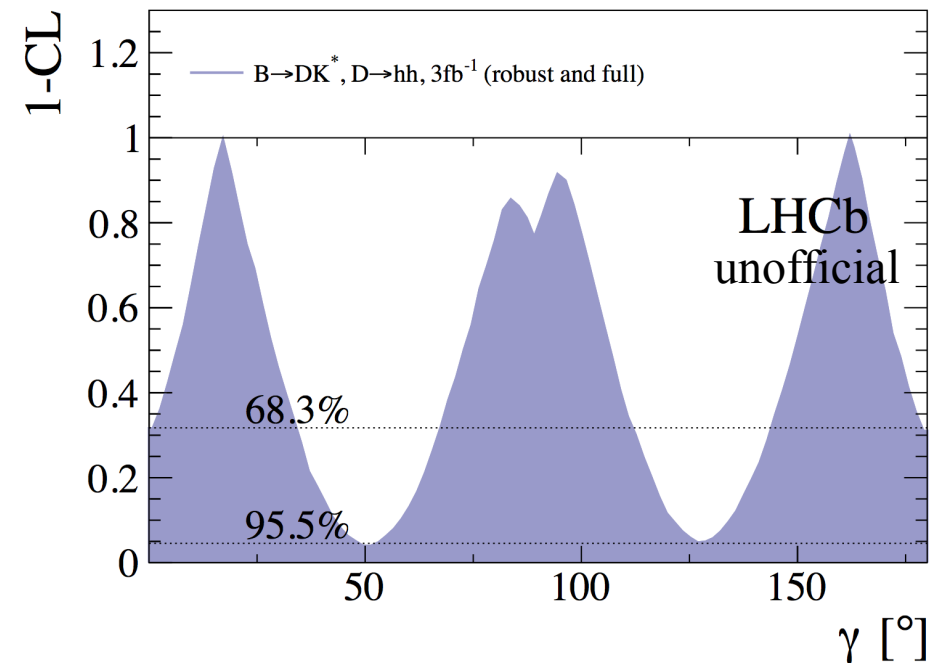
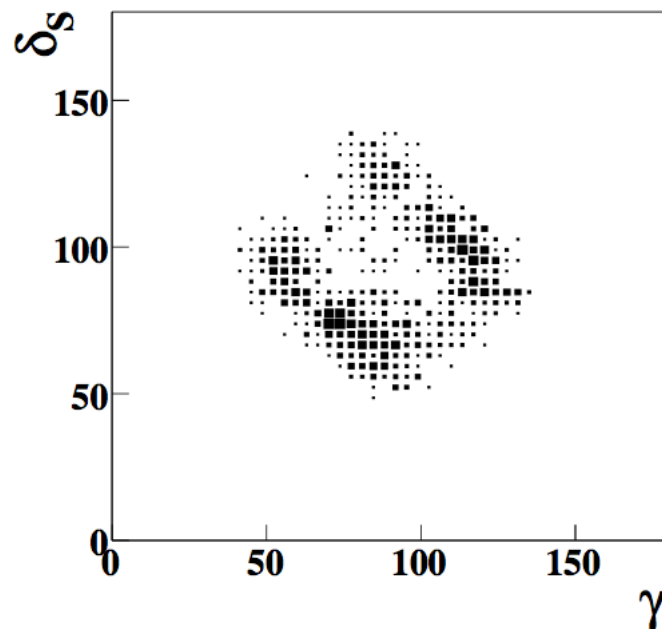
...

A new method

- Idea: analyze the B^0 Dalitz plot in $B^0 \rightarrow D^0 K \pi$
- Gershon, Williams [arXiv:0909.1495]
- This resolves ambiguities!
- A 10deg error on γ seems not unreasonable! (Dalitz model unknown).

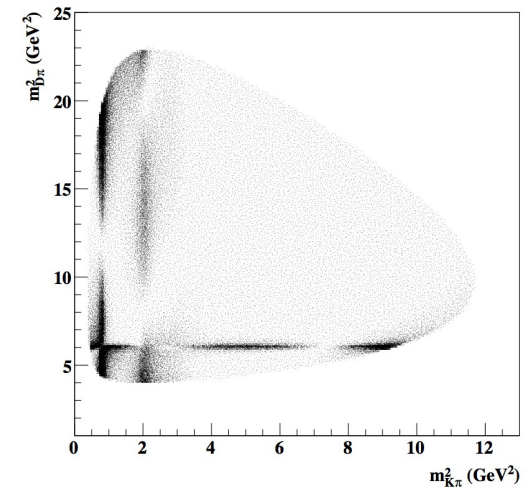


$B^0 \rightarrow D^0 K^{*0} \rightarrow D^0 K \pi$
already contributes now!

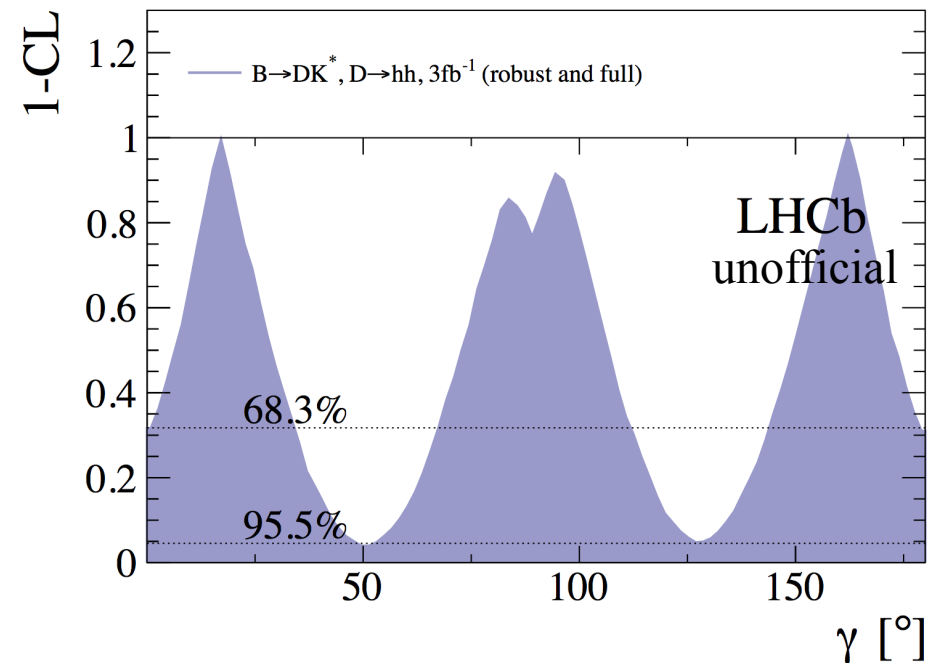
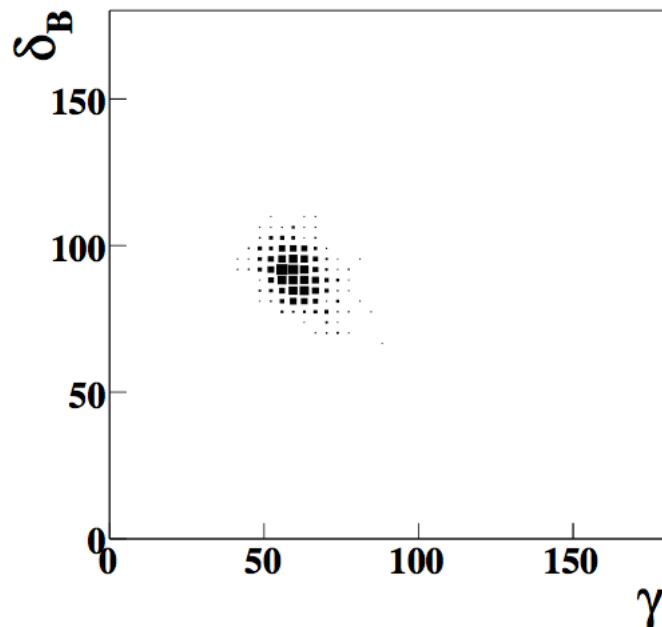


A new method

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- This resolves ambiguities!
- A 10deg error on γ seems not unreasonable! (Dalitz model unknown).



$B^0 \rightarrow D^0 K^{*0} \rightarrow D^0 K \pi$
already contributes now!



expected sensitivities

$\sigma(\gamma)$ [deg]	2018	2022	2025?
LHCb	4 (8fb ⁻¹)	1.0 (50fb ⁻¹)	LHCb Run4?
Belle-II	startup	3 (20ab ⁻¹)	1.5 (50ab ⁻¹)

Sources

LHCb: arXiv:1208.3355

Belle-II: <https://belle2.cc.kek.jp/~twiki/bin/view/Public/B2TIPGoldenModes>
(20ab-1 point scaled)

current systematic effects

Tree-level measurements of γ will **not be limited** by systematics for a long time (not at **100 times** the current dataset).

going well beyond
LHCb upgrade!

- **first method** ($B \rightarrow DK$ GLW/ADS)
 - instrumental charge asymmetries
(known to the per-mille level,
 $B \rightarrow J/\psi K$ asymmetry needed as input, magnet polarity flip)
 - calibration of particle identification

example result:

$$A_{CP} = 0.0849 \pm 0.0201(\text{stat.}) \pm 0.0010(\text{syst.})$$

current systematic effects

Tree-level measurements of γ will **not be limited** by systematics for a long time (not at **100 times** the current dataset).

going well beyond
LHCb upgrade!

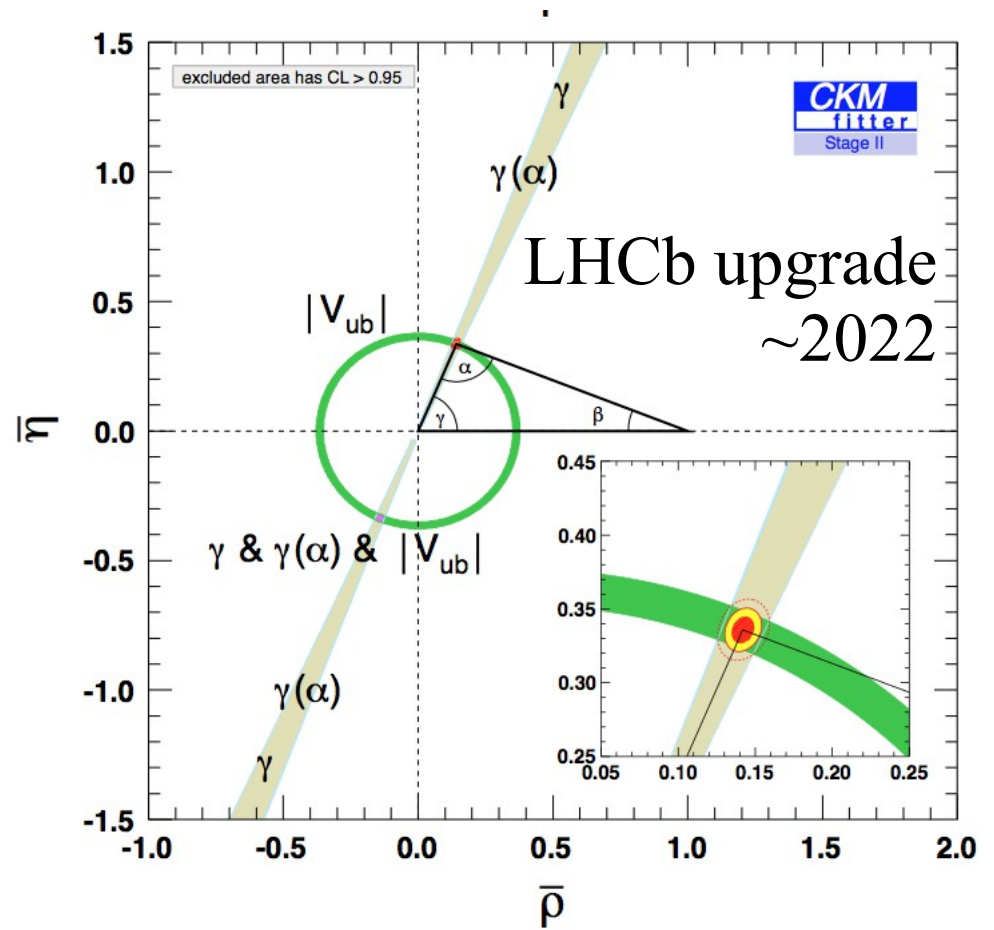
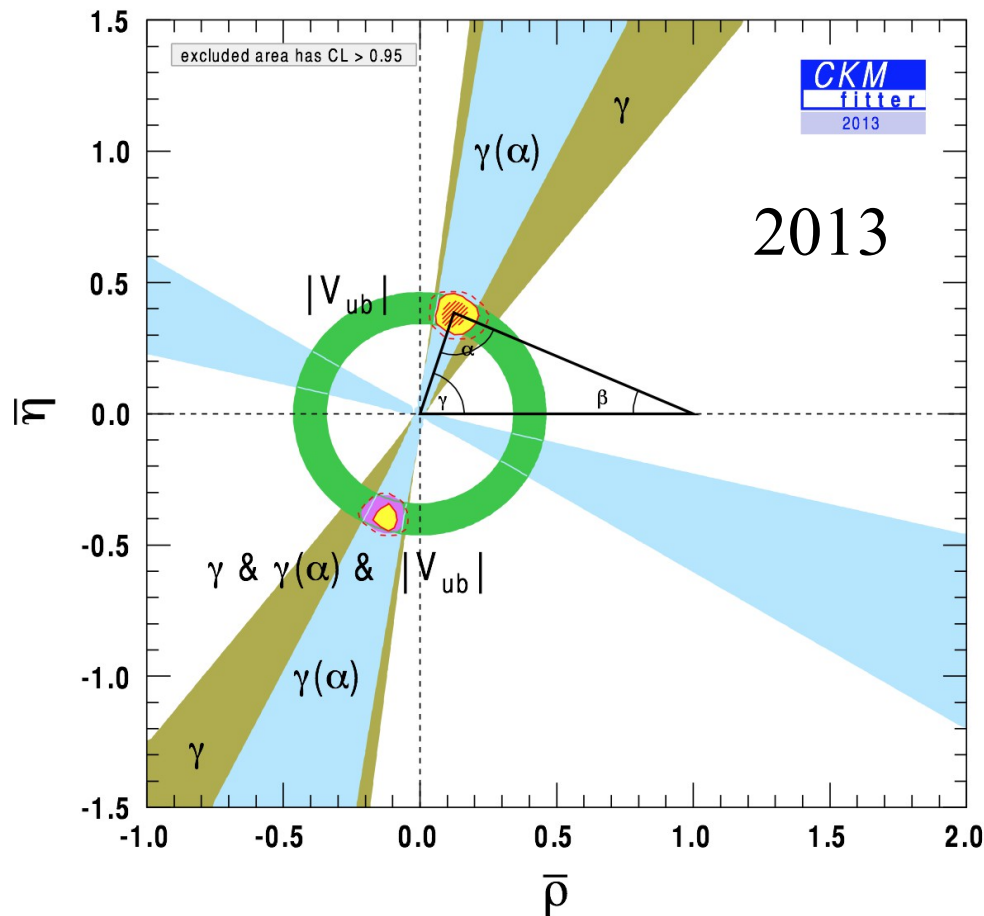
- **first** method ($B \rightarrow DK$ GLW/ADS)
 - instrumental charge asymmetries (known to the per-mille level, $B \rightarrow J/\psi K$ asymmetry needed as input, magnet polarity flip)
 - calibration of particle identification
- **second** method ($B \rightarrow DK$ GGSZ)
 - efficiency corrections over the Dalitz plot
- **third** method ($B_s \rightarrow D_s K$ time dependent)
 - decay time resolution
 - decay time acceptance
 - knowledge of $\Delta m_s, \Delta \Gamma_s, \Gamma_s$

} completely different sources!

Conclusion

Conclusion

LHCb is getting closer to a tree-level precision measurement of the CKM triangle!
(Might need a little help with $|V_{ub}|$ though!)



Ligeti et al., 1309.2293

GammaCombo

Combination framework:

fork me on github.com!

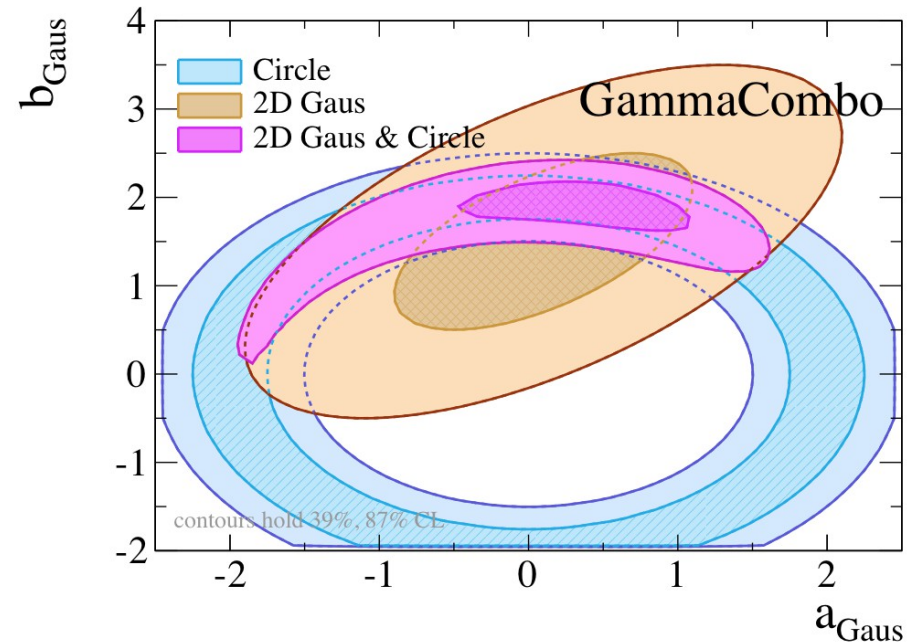
[GammaCombo Manual \(pdf\)](#)

Dependencies:

git, cmake, C++11
boost, ROOT, RooFit

Installation:

```
git clone https://github.com/mkarbach/gammacombo.git
cd gammacombo
mkdir build; cd build
cmake ..
make install -j4
cd ../tutorial
```



TMK, Matt Kenzie, Max Schlupp,
Florian Bernlochner

just released!

Backup

LHCb Run2 expectations

Table 28: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the expected sensitivity is given for the integrated luminosity accumulated by the end of LHC Run 1, by 2018 (assuming 5fb^{-1} recorded during Run 2) and for the LHCb Upgrade (50fb^{-1}). An estimate of the theoretical uncertainty is also given – this and the potential sources of systematic uncertainty are discussed in the text.

	Type	Observable	LHC Run 1	LHCb 2018	LHCb upgrade	Theory
☺ ☺ (☺) ☺ ☺ ☺ ☺ ☺ ☺ ☺	B_s^0 mixing	$\phi_s(B_s^0 \rightarrow J/\psi \phi)$ (rad)	0.050	0.025	0.009	~ 0.003
		$\phi_s(B_s^0 \rightarrow J/\psi f_0(980))$ (rad)	0.068	0.035	0.012	~ 0.01
		$A_{\text{sl}}(B_s^0)$ (10^{-3})	2.8	1.4	0.5	0.03
	Gluonic penguin	$\phi_s^{\text{eff}}(B_s^0 \rightarrow \phi \phi)$ (rad)	0.15	0.10	0.023	0.02
		$\phi_s^{\text{eff}}(B_s^0 \rightarrow K^{*0} \bar{K}^{*0})$ (rad)	0.19	0.13	0.029	< 0.02
		$2\beta^{\text{eff}}(B^0 \rightarrow \phi K_S^0)$ (rad)	0.30	0.20	0.04	0.02
	Right-handed currents	$\phi_s^{\text{eff}}(B_s^0 \rightarrow \phi \gamma)$	0.20	0.13	0.030	< 0.01
		$\tau^{\text{eff}}(B_s^0 \rightarrow \phi \gamma)/\tau_{B_s^0}$	5%	3.2%	0.8%	0.2 %
	Electroweak penguin	$S_3(B^0 \rightarrow K^{*0} \mu^+ \mu^-; 1 < q^2 < 6 \text{ GeV}^2/c^4)$	0.04	0.020	0.007	0.02
		$q_0^2 A_{\text{FB}}(B^0 \rightarrow K^{*0} \mu^+ \mu^-)$	10%	5%	1.9%	$\sim 7\%$
		$A_1(K \mu^+ \mu^-; 1 < q^2 < 6 \text{ GeV}^2/c^4)$	0.09	0.05	0.017	~ 0.02
		$\mathcal{B}(B^+ \rightarrow \pi^+ \mu^+ \mu^-)/\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)$	14%	7%	2.4%	$\sim 10\%$
	Higgs penguin	$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$ (10^{-9})	1.0	0.5	0.19	0.3
		$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)/\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$	220%	110%	40%	$\sim 5\%$
☺ (☺ ☺) ☺ ☺ (☺ ☺)	Unitarity triangle	$\gamma(B \rightarrow D^{(*)} K^{(*)})$	7°	4°	1.1°	negligible
		$\gamma(B_s^0 \rightarrow D_s^\mp K^\pm)$	17°	11°	2.4°	negligible
	angles	$\beta(B^0 \rightarrow J/\psi K_S^0)$	1.7°	0.8°	0.31°	negligible
	Charm	$A_{\Gamma}(D^0 \rightarrow K^+ K^-)$ (10^{-4})	3.4	2.2	0.5	–
	CP violation	ΔA_{CP} (10^{-3})	0.8	0.5	0.12	–

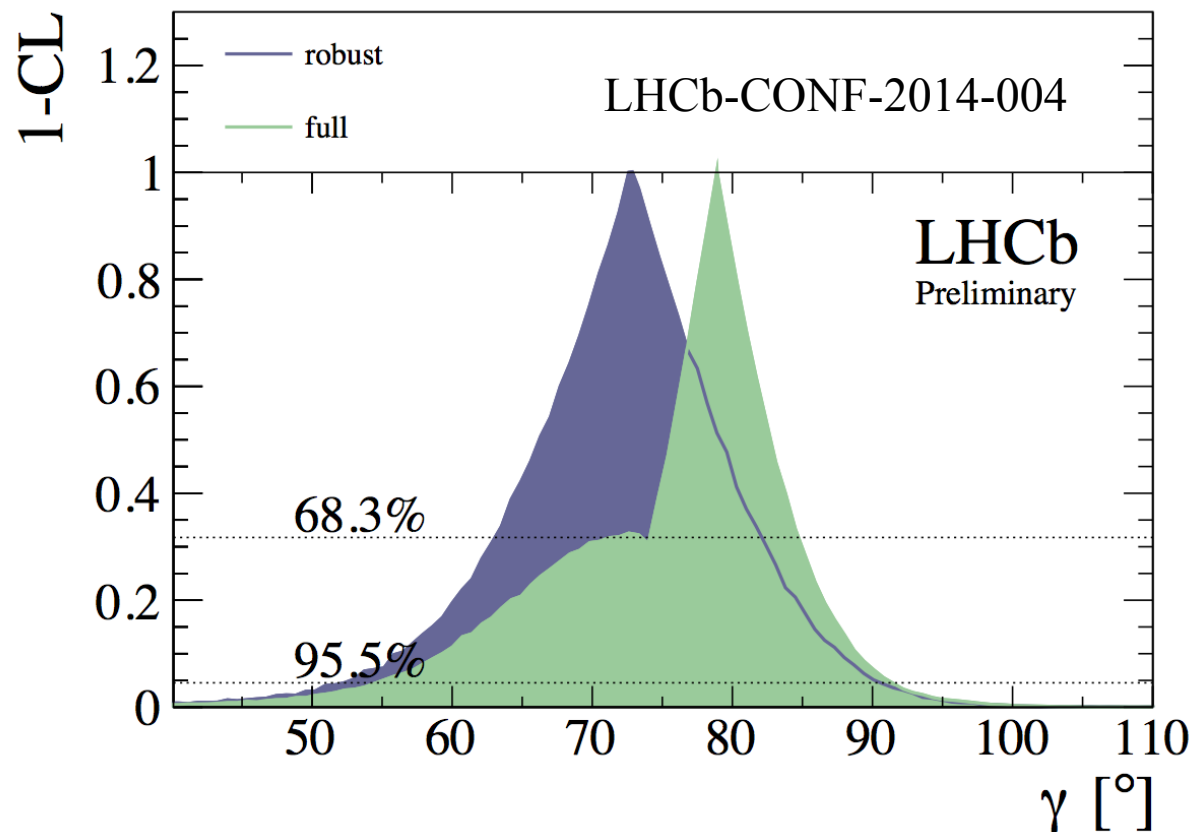
Smileys indicate “on trackness”, added by Tim Gershon (LHCb Implications Workshop Oct 2014)

content of LHCb γ (CKM2014)

- ▶ $B^+ \rightarrow Dh^+, D \rightarrow hh$, GLW/ADS, 1 fb^{-1} 1203.3662
- ▶ $B^+ \rightarrow Dh^+, D \rightarrow K\pi\pi\pi$, ADS, 1 fb^{-1} 1303.4646
- ▶ **updated:** $B^+ \rightarrow DK^+, D \rightarrow K_s^0 hh$, model-ind. GGSZ, 3 fb^{-1} 1408.2748
- ▶ **new:** $B^+ \rightarrow DK^+, D \rightarrow K_s^0 K\pi$, GLS, 3 fb^{-1} 1402.2982
- ▶ **new:** $B^0 \rightarrow D^0 K^{*0}, D \rightarrow hh$, GLW/ADS, 3 fb^{-1} 1407.8136
- ▶ **new:** $B_s^0 \rightarrow D_s^\mp K^\pm$, 1 fb^{-1} 1407.6127

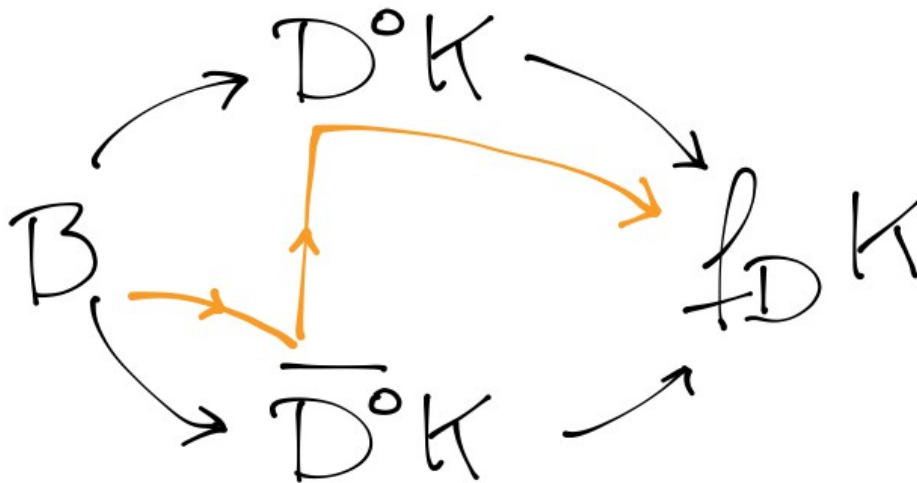
on the way to the degree precision

- We add another channel: $B \rightarrow D^0\pi$, “full combination”
- Less sensitivity to γ , but larger statistics
- A fluctuation causes much increased apparent sensitivity, and highly non Gaussian behavior – to be interpreted with care!



on the way to the degree precision

- The effect of D^0 mixing does affect the determination of γ .
- Already accounted for in the LHCb combination!
- Next up: also K^0 mix ...



$$\Delta \approx \sqrt{x_D^2 + y_D^2 / r_B}$$

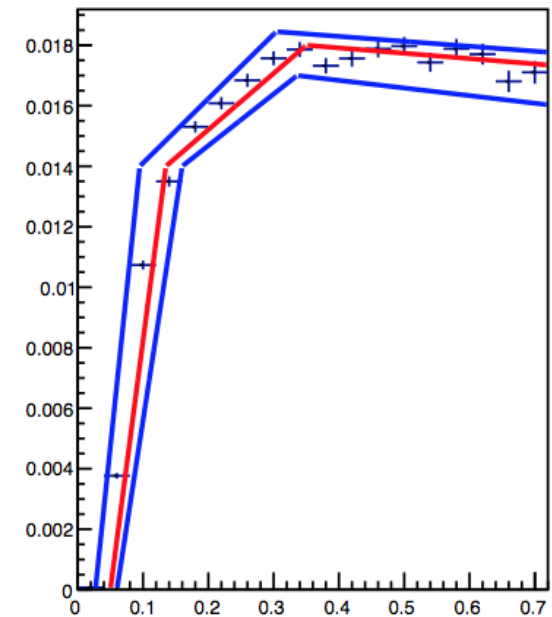
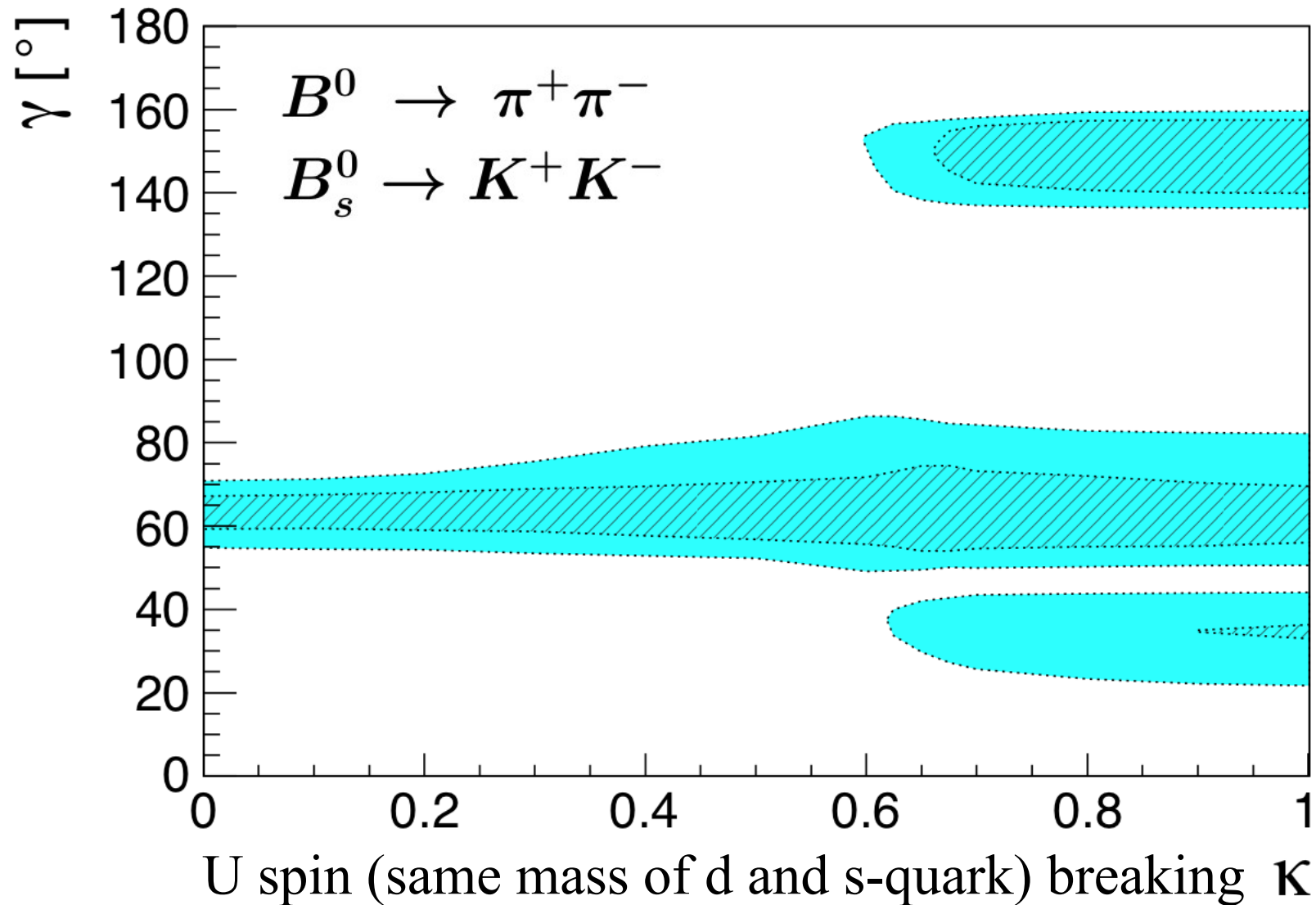
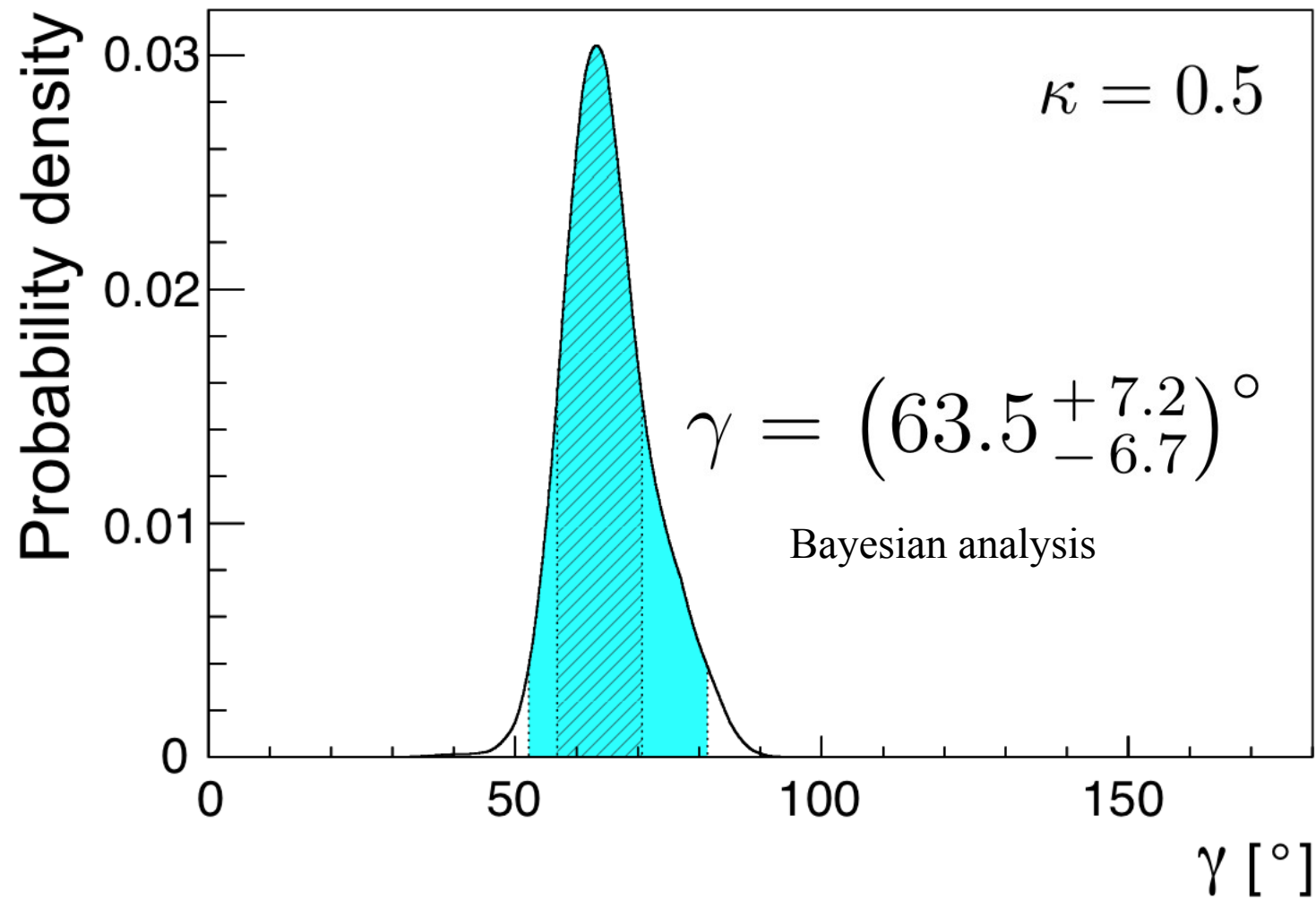


Figure: LHCb D^0 decay time acceptance for $B^+ \rightarrow DK^+$, $D \rightarrow hh$.

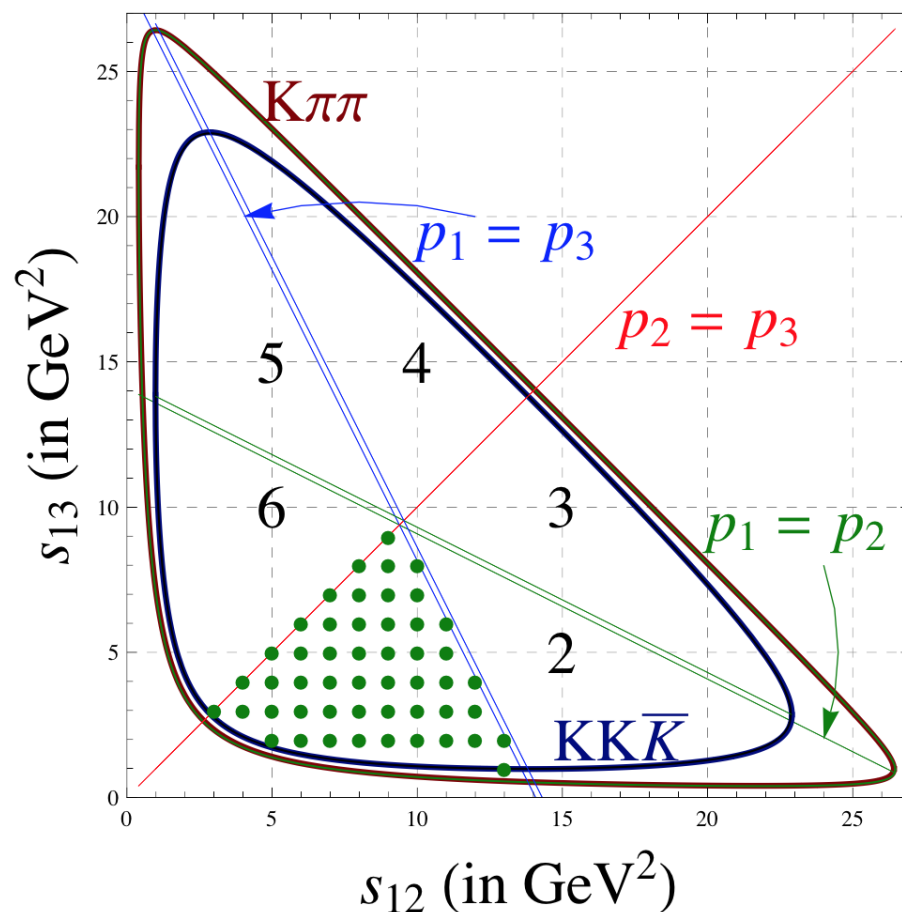
“ γ from loops”



“ γ from loops”



“ γ from loops”



New method by
London, Bhattacharya,
Imbeault, Rey-Le Lurier:

$$B \rightarrow hhh$$

$$h = K, \pi$$

$$\gamma = (77 \pm 3)^\circ$$

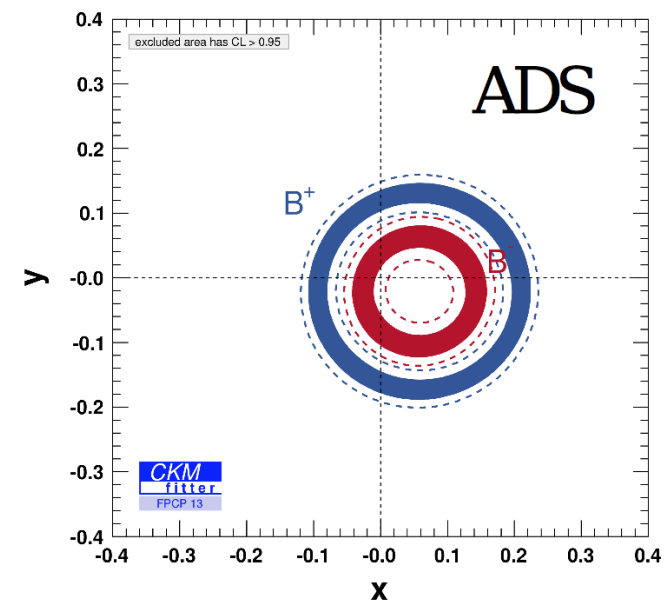
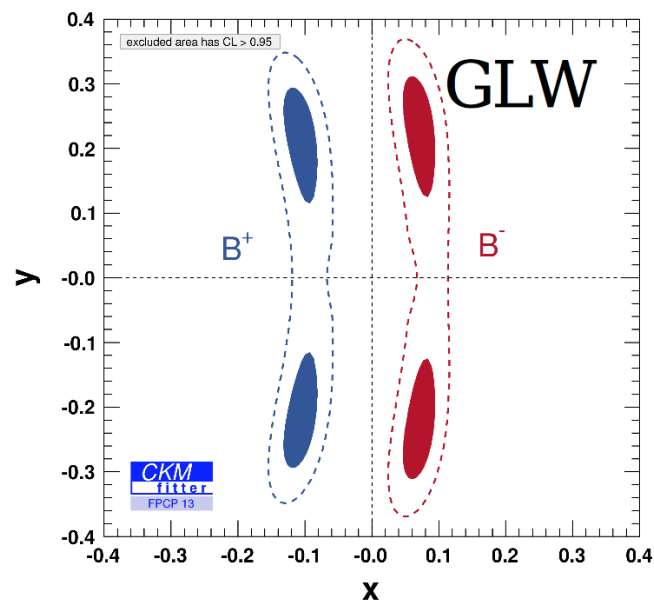
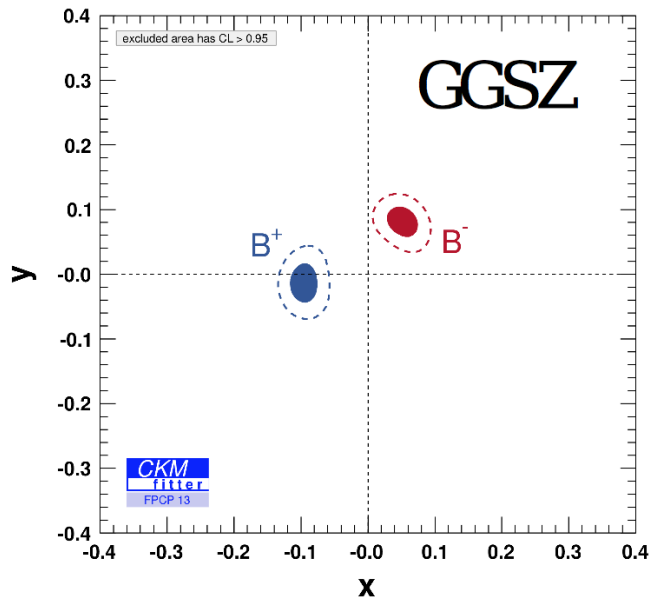
(take with a grain of salt)

FIG. 1: Kinematic boundaries and symmetry axes of $B \rightarrow K\pi\pi$ and $B \rightarrow KK\bar{K}$ Dalitz plots. The symmetry axes divide each plot into six zones, five of which are marked 2-6. The fifty dots in the region of overlap of the first of six zones from all Dalitz plots are used for the γ measurement.

**Well suited
for LHCb!**

GGSZ or the “Dalitz” method

illustration:



Karim Trabelsi, CKM2014

$$x_{\pm} = r_B \cos(\delta_B \pm \gamma) \quad y_{\pm} = r_B \sin(\delta_B \pm \gamma)$$

Combination

Table 2: Observables used in the robust combination.

LHCb Analysis	Observables
$B^+ \rightarrow DK^+, D \rightarrow hh$, GLW/ADS	$A_{CP}^{DK, KK}, A_{CP}^{DK, \pi\pi}, R_{K/\pi}^{KK}, R_{K/\pi}^{\pi\pi}, R_{K/\pi}^{K\pi}, A_{\text{fav}}^{DK, K\pi}, R_+^{DK, K\pi}, R_-^{DK, K\pi}$
$B^+ \rightarrow DK^+, D \rightarrow K\pi\pi\pi$, ADS	$R_+^{DK, K3\pi}, R_-^{DK, K3\pi}, A_{\text{fav}}^{DK, K3\pi}$
$B^+ \rightarrow DK^+, D \rightarrow K_s^0 hh$, model-independent GGSZ	x_-, x_+, y_-, y_+
$B^+ \rightarrow DK^+, D \rightarrow K_s^0 K\pi$, GLS	$R_{DK, \text{fav/sup}}^{K_S K\pi}, A_{\text{fav}}^{DK, K_S K\pi}, A_{\text{sup}}^{DK, K_S K\pi}$
$B^0 \rightarrow DK^{*0}$ GLW/ADS	$A_{CP}^{DK^{*0}, KK}, A_{\text{fav}}^{DK^{*0}, K\pi}, R_{CP}^{DK^{*0}, KK}, A_{CP}^{DK^{*0}, \pi\pi}, R_{CP}^{DK^{*0}, \pi\pi}, R_+^{DK^{*0}, K\pi}, R_-^{DK^{*0}, K\pi}$
$B_s^0 \rightarrow D_s^\mp K^\pm$	$C_f, A_f^{\Delta\Gamma}, A_{\bar{f}}^{\Delta\Gamma}, S_f, S_{\bar{f}}$
Auxiliary Input	Observables
CLEO-c	$\kappa_D^{K3\pi}, \delta_D^{K3\pi}$
Belle, CLEO	$R_{WS}(D \rightarrow K\pi\pi\pi)$
CLEO	$R_D^{K_S K\pi}, \kappa_D^{K_S K\pi}, \delta_D^{K_S K\pi}$
LHCb toy	$\kappa_B^{DK^{*0}}$
LHCb	ϕ_s
HFAG	$x_D, y_D, \delta_D^{K\pi}, R_D^{K\pi}, A_{CP}^{\text{dir}}(KK), A_{CP}^{\text{dir}}(\pi\pi)$

Combination

Table 3: Confidence intervals and central values for the robust combination.

quantity	robust combination
γ ($^\circ$)	72.9
68% CL ($^\circ$)	[63.0, 82.1]
95% CL ($^\circ$)	[52.0, 90.5]
r_B^{DK}	0.0914
68% CL	[0.0826, 0.0997]
95% CL	[0.0728, 0.1078]
δ_B^{DK} ($^\circ$)	126.8
68% CL ($^\circ$)	[115.3, 136.7]
95% CL ($^\circ$)	[101.6, 145.2]

Combination

Table 4: Observables used in the full combination in addition to those of the robust combination given in Table 2.

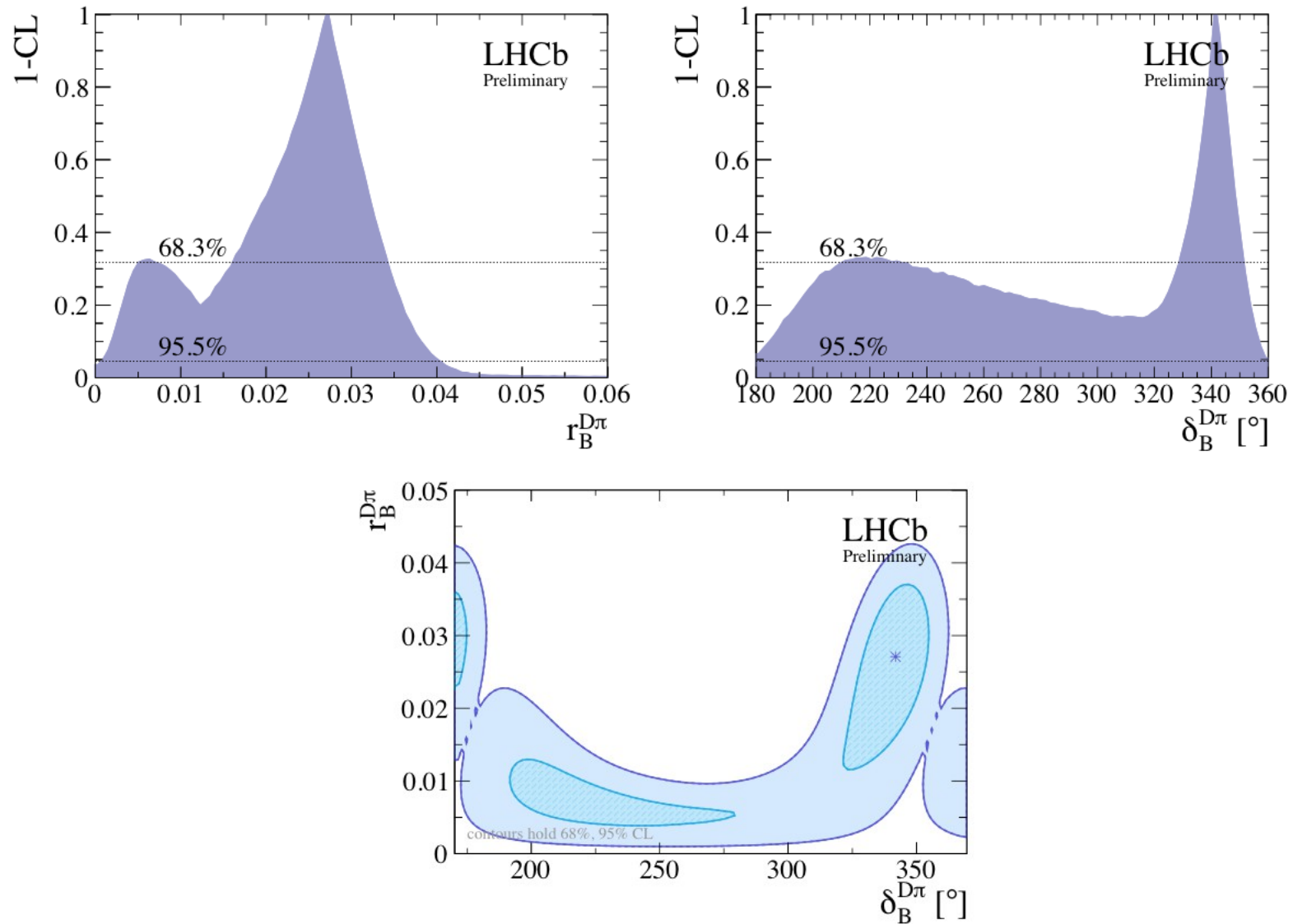
$B^+ \rightarrow DK^+, D \rightarrow hh, \text{GLW/ADS}$	$A_{CP}^{D\pi, KK}, A_{CP}^{D\pi, \pi\pi}, A_{\text{fav}}^{D\pi, K\pi}, R_+^{D\pi, K\pi}, R_-^{D\pi, K\pi}$
$B^+ \rightarrow DK^+, D \rightarrow K\pi\pi\pi, \text{ADS}$	$R_+^{D\pi, K3\pi}, R_-^{D\pi, K3\pi}, A_{\text{fav}}^{D\pi, K3\pi}, R_{K/\pi}^{K3\pi}$

Combination

Table 5: Confidence intervals and central values for the full combination. The two columns correspond to the two minima found by the fit. The most probable value is given in the left column, corresponding to a large value of $r_B^{D\pi}$.

quantity	full	
γ ($^\circ$)	78.9	72.8
68% CL ($^\circ$)	[71.5, 84.7]	
95% CL ($^\circ$)	[54.6, 91.4]	
r_B^{DK}	0.0928	
68% CL	[0.0845, 0.1008]	
95% CL	[0.0732, 0.1085]	
δ_B^{DK} ($^\circ$)	128.9	
68% CL ($^\circ$)	[118.9, 137.9]	
95% CL ($^\circ$)	[102.0, 145.9]	
$r_B^{D\pi}$	0.027	0.006
68% CL	[0.016, 0.034]	[0.005, 0.007]
95% CL	[0.001, 0.040]	
$\delta_B^{D\pi}$ ($^\circ$)	341.8	215.6
68% CL ($^\circ$)	[328.7, 351.4]	[210.2, 231.5]
95% CL ($^\circ$)	no constraint	

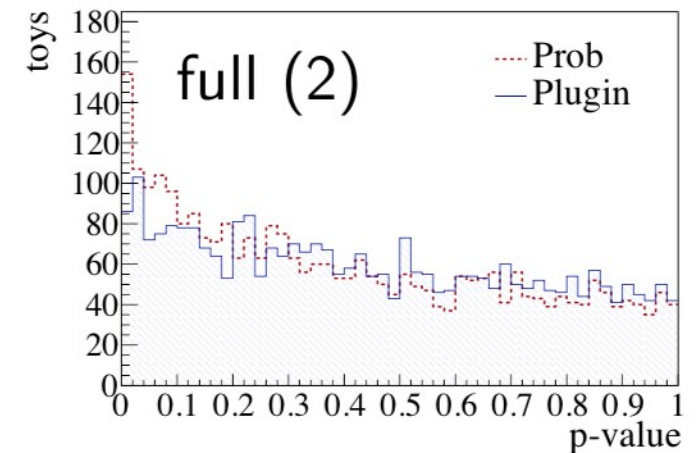
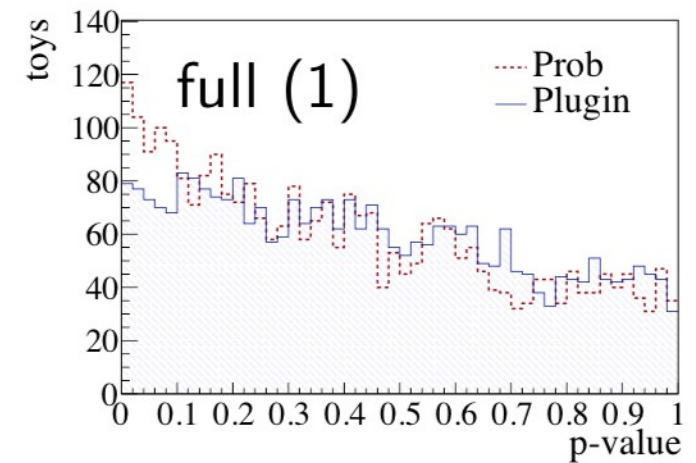
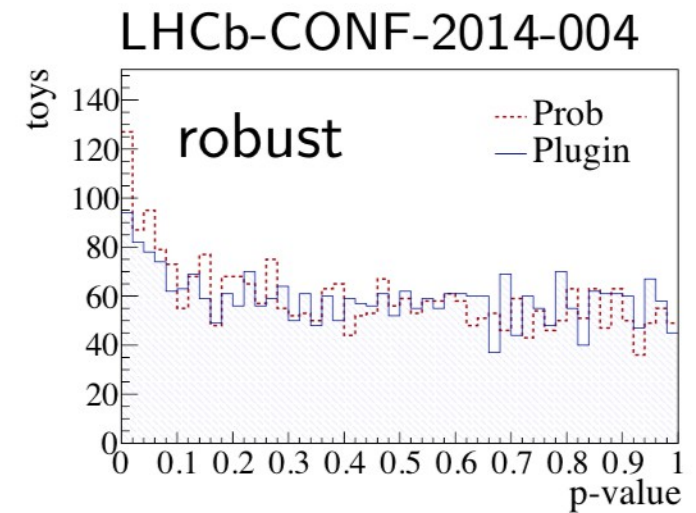
Combination



Coverage test

- ▶ We test the frequentist coverage at the minima of the combinations.
- ▶ We find that the profile likelihood construction undercovers quite a bit.
- ▶ The robust plugin method has good coverage.
- ▶ The coverage of the full combination is worse than of the robust. Expected due to the low value of $r_B^{D\pi}$.

$\eta = 0.683$	α (prof. LH.)	α (plugin)
robust	0.6158	0.6494
full (1), $r_B^{D\pi} = 0.027$	0.5593	0.6154
full (2), $r_B^{D\pi} = 0.006$	0.5454	0.6120



Auxiliary input from HFAG

comparing old and new

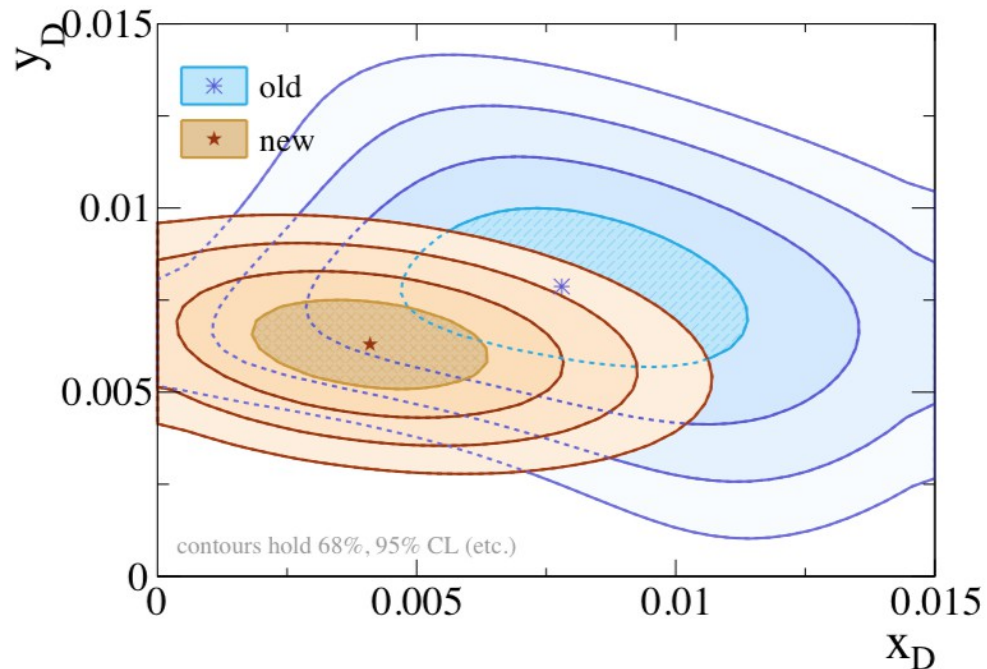
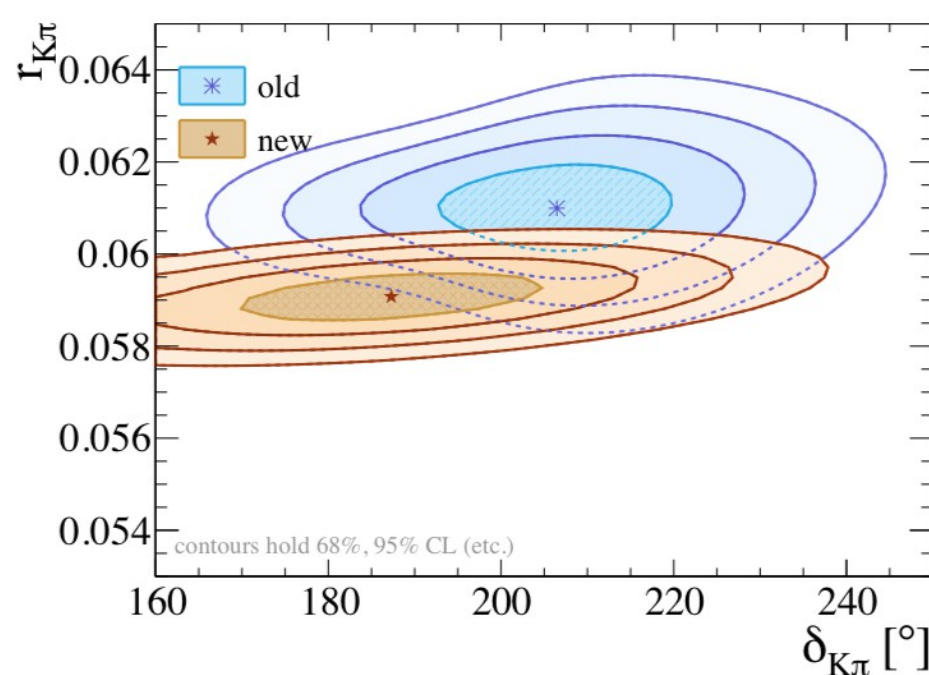


Figure: Profile likelihood contours: The “old” contour corresponds to what was used in the previous (2013) combination (the 2009 CLEO input [25] together with the 2013 LHCb charm mixing measurement [26]). The “new” contour is what is used in this combination (HFAG 2014). The contours are two-dimensional 1–4 σ contours.

Auxiliary input from HFAG

The parameter $R_D^{K\pi}$ is the squared ratio of the doubly-Cabibbo-suppressed amplitude $D^0 \rightarrow \pi^- K^+$ to the favored one $D^0 \rightarrow K^- \pi^+$. It is not the ratio of branching ratios. It gets often measured in time-dependent wrong-sign D^0 mixing measurements:

$$R_{WS} = R_D^{K\pi} + \sqrt{R_D^{K\pi}} \left(x \cos(\delta_D^{K\pi}) \pm y \sin(\delta_D^{K\pi}) \right) \frac{t}{\tau} + \frac{x_D^2 + y_D^2}{4} \left(\frac{t}{\tau} \right)^2$$

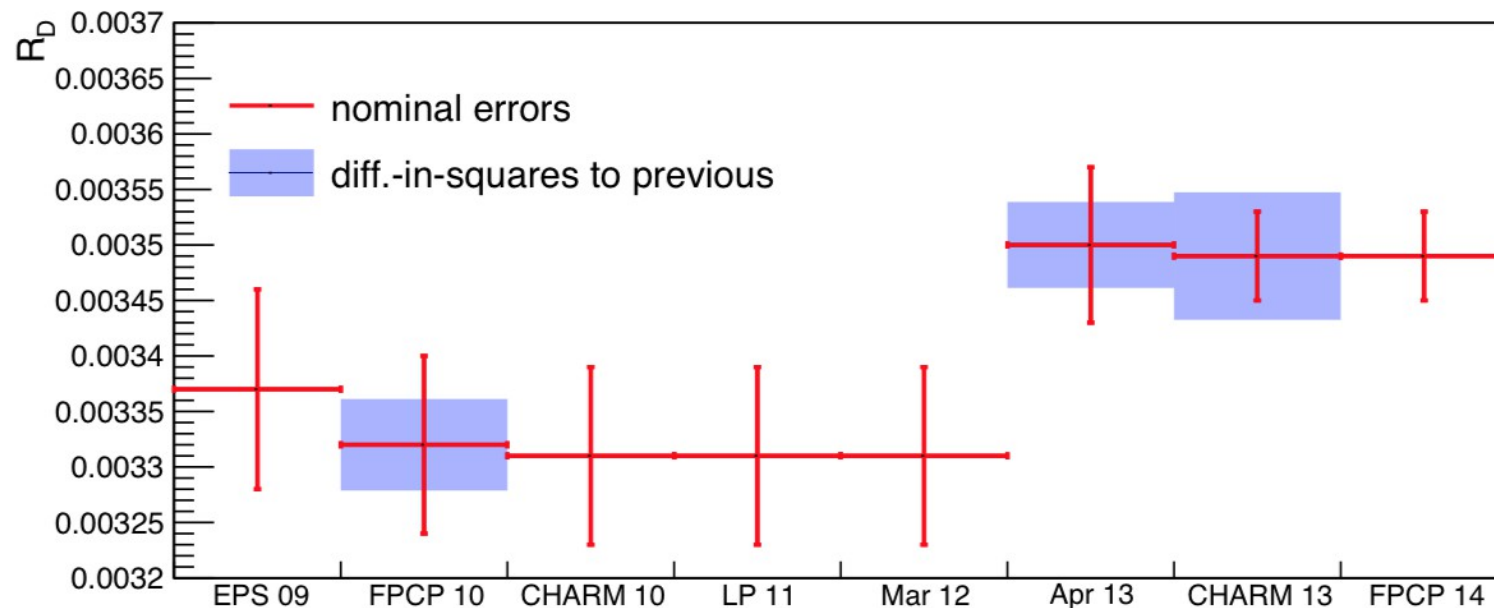


Figure: Evolution of HFAG results on $R_D^{K\pi}$.