Messung von γ in Tree-Zerfällen bei LHCb

Till Moritz Karbach
CERN

moritz.karbach @ cern.ch

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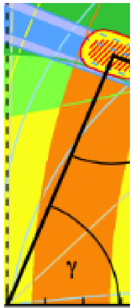


Plan

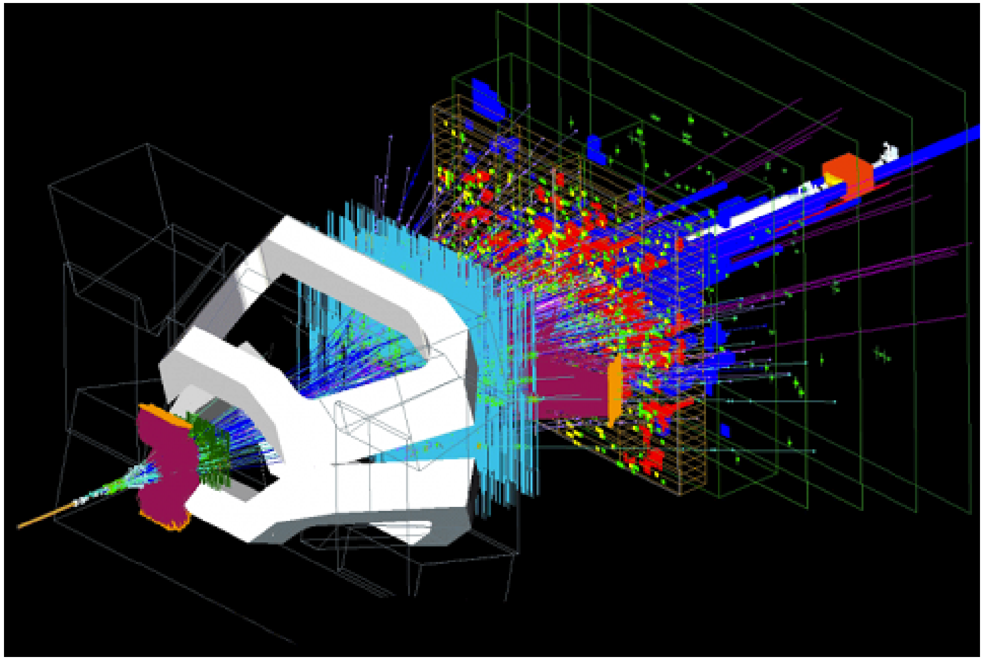
- Part I: introduction
- Part II: time *integrated* γ measurements
- Part III: combination of time int. meas.
- Part IV: time *dependent* γ measurement

LHCb

- LHCb is a forward spectrometer at LHC.
- Operating in collider mode.

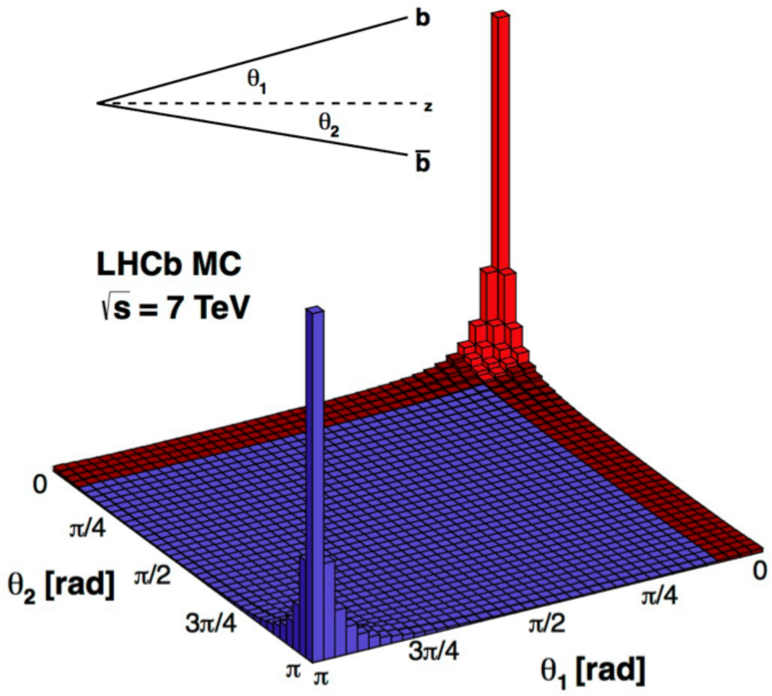
- It is dedicated to precision measurements of b and c physics ...
  … a general purpose spectrometer in the forward region!

- CP violation, rare decays



LHCb

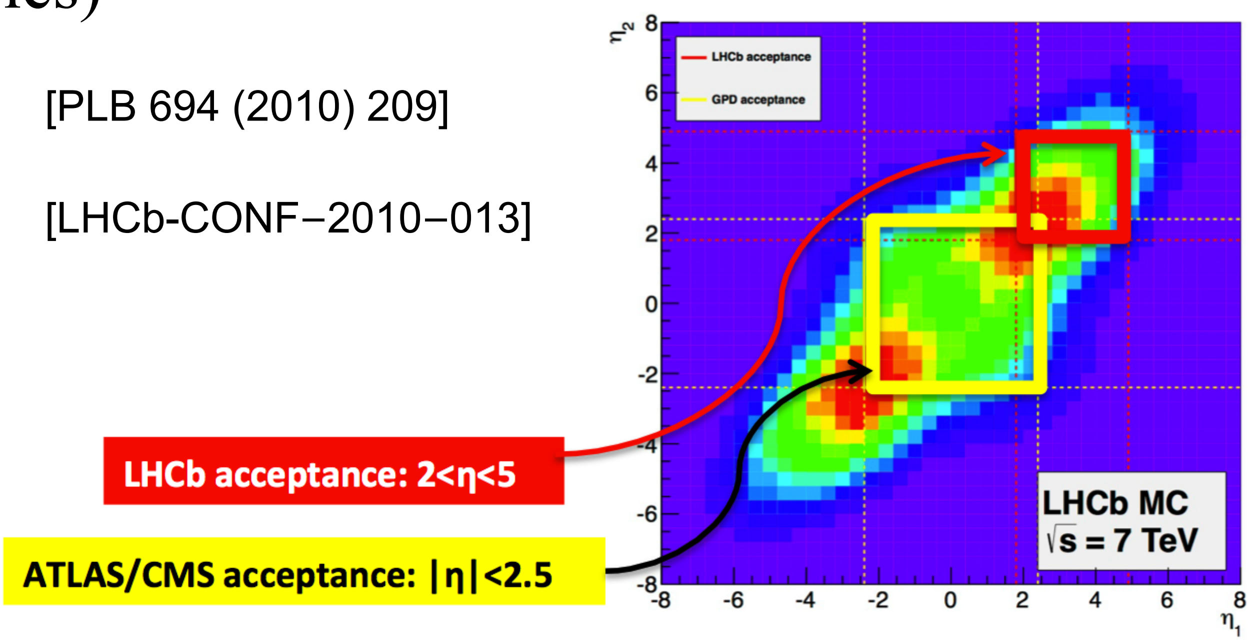
- one arm forward spectrometer
- b pair production angles strongly correlated
- covers **1.9 < η < 4.9**
- 100'000 bb pairs produced per second (10^4 x B factories)



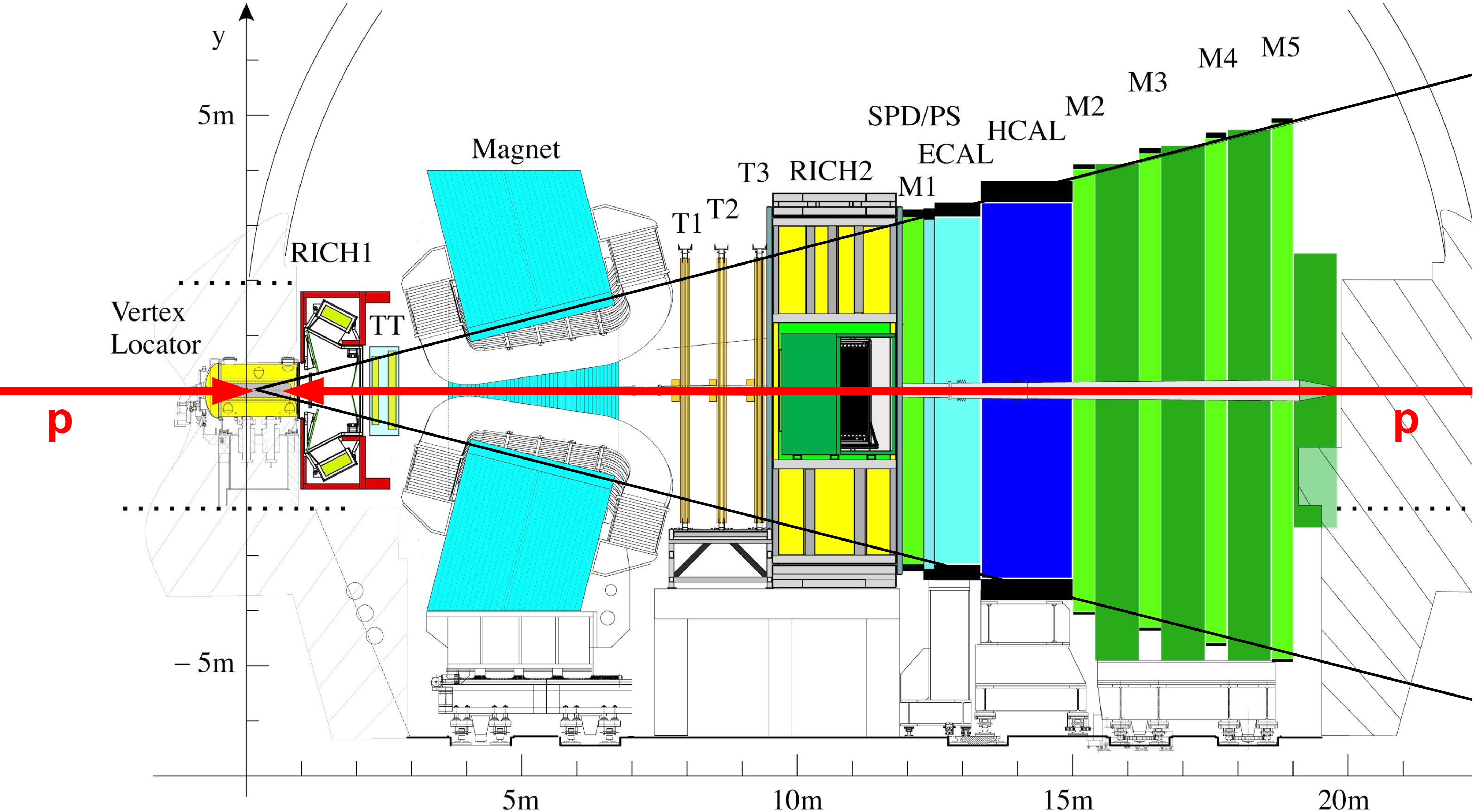
$$\sigma(b\bar{b}) = 284 \pm 53\mu\text{b}$$ [PLB 694 (2010) 209]

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

- particle identification by two RICH detectors



LHCb



y
5m
– 5m
Magnet
RICH1
Vertex
Locator
TT
T1
T2
T3
RICH2
M1
SPD/PS
ECAL
HCAL
M2
M3
M4
M5
p
p
5m
10m
15m
20m

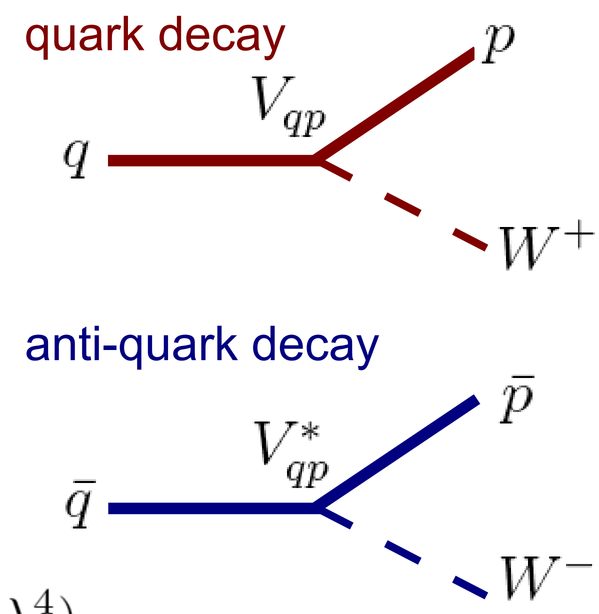
CKM matrix

Cabibbo
Kobayashi
Maskawa

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

flavor eigenstates

mass eigenstates

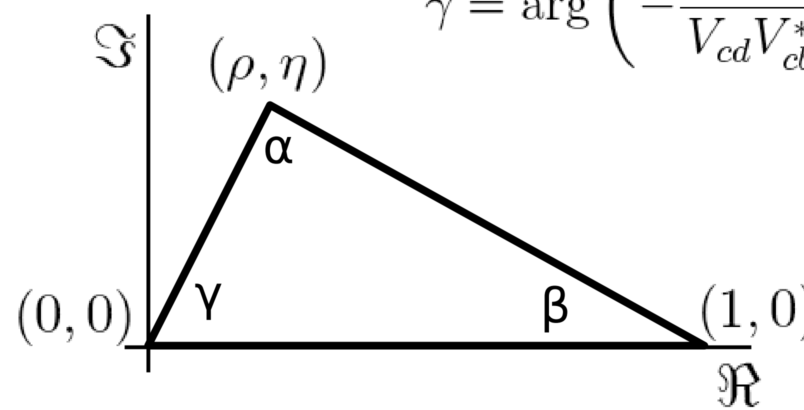


$$V_{\mathrm{CKM}} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & \lambda^3 A(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & \lambda^2 A \\ \lambda^3 A(1-\rho-i\eta) & -\lambda^2 A & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

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

unitarity condition: $V^\dagger V = 1$

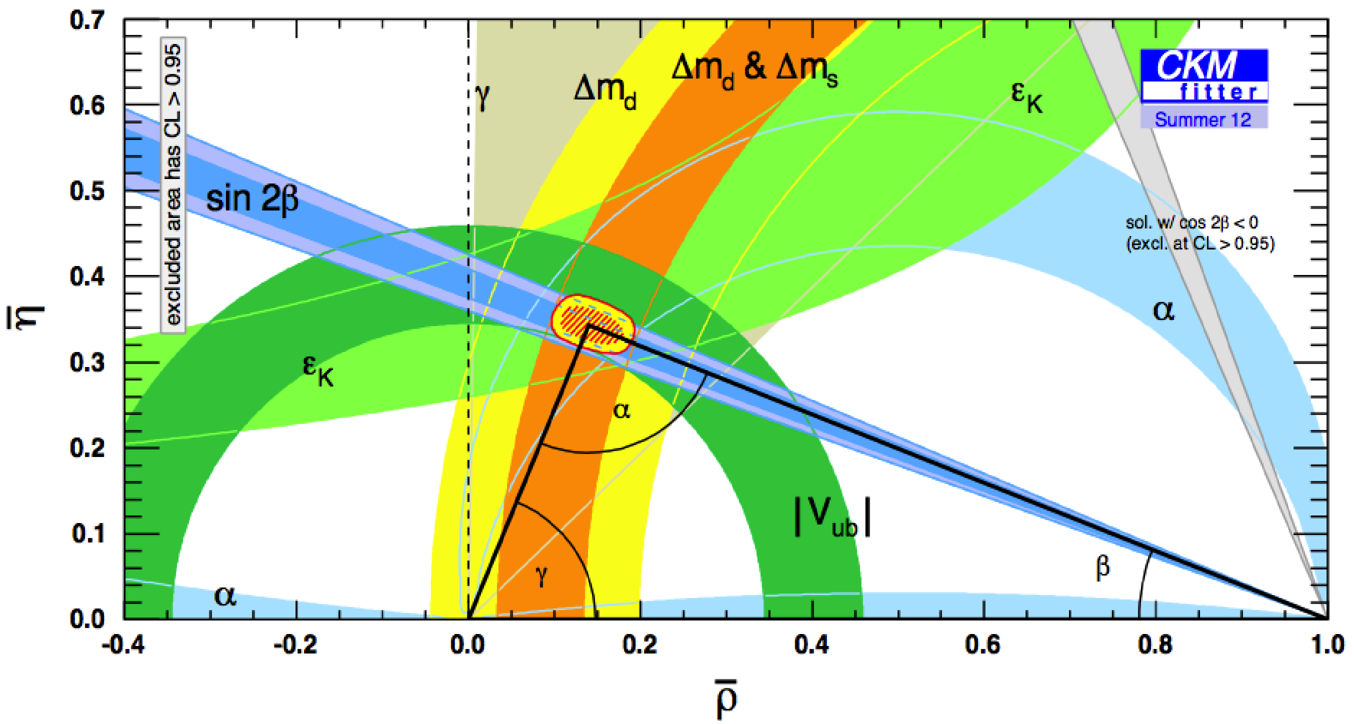
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



angle γ

γ is the least well known angle of the unitarity triangle.

"combined γ measurements"		**"γ meas. not in triangle fit"**
$\gamma = (66^{+12}_{-12})^\circ$	CKMfitter ICHEP 2012	$\gamma = (68.0^{+4.1}_{-4.6})^\circ$
$\gamma = (75.5 \pm 10.5)^\circ$	UTfit pre-ICHEP 2012	$\gamma = (67.8 \pm 3.2)^\circ$



angle γ

- Difficult to measure, as the decay rates are small.

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

LHCb first observation
with ~100 events

- γ can be determined entirely from **tree decays**.
  - this is a unique property among all CP violation parameters
  - negligible theoretical uncertainty (J. Zupan): $\delta\gamma/\gamma = \mathcal{O}(10^{-6})$
  - hadronic parameters can all be determined from the data
  - provides an important Standard Model set point ("standard candle")

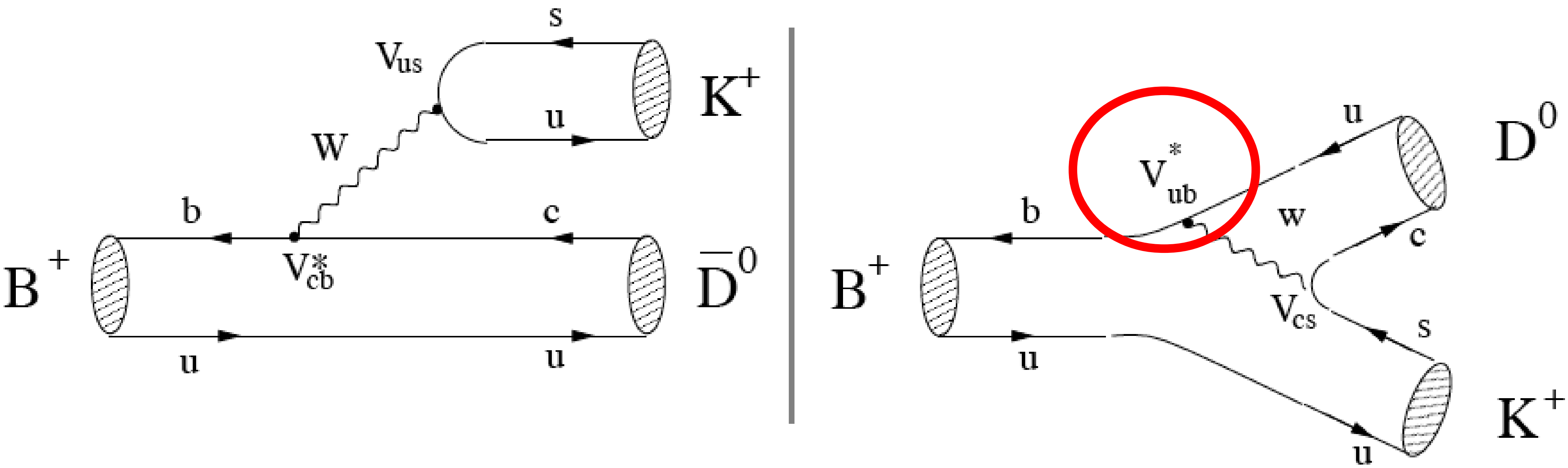
- γ can probe for new physics at extremely **high energy scales** (J. Zupan)
  - (N)MFV new physics scenarios: ~O(10^2 TeV)
  - gen. FV new physics senarios: ~O(10^3 TeV)

arXiv:1208.3355

Part II:

time integrated measurements

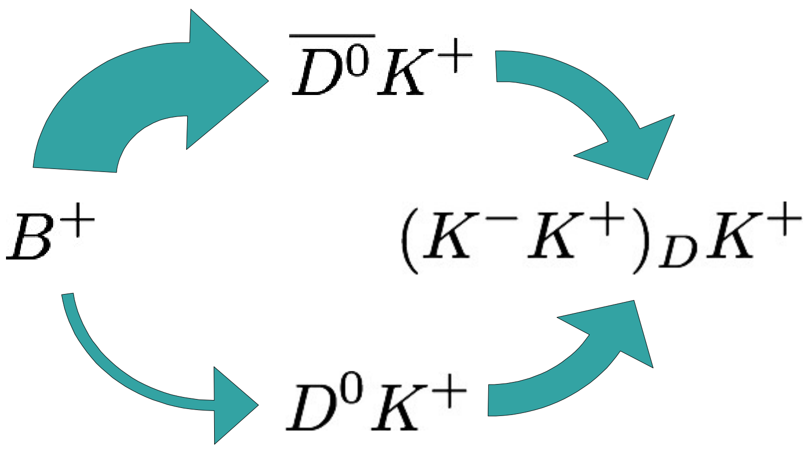
$B \to DK$



- This was, and still is, the most important channel to measure γ.
- We need to reconstruct the $D/\overline{D}$ meson in a final state accessible to both to achieve interference.
- **Also possible: $\mathbf{B \to D\pi}$!** But little sensitivity.
- Choice of final state labels the "method": GLW, ADS, GGSZ

$B \to DK$

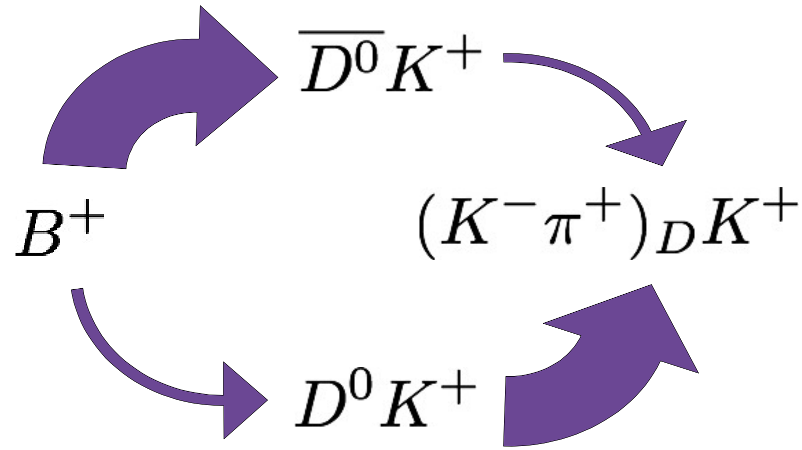
"GLW"



Phys.Lett. B253 (1991) 483
Phys.Lett. B265 (1991) 172

Gronau, London, Wyler

"ADS", "suppressed"



Phys.Rev.Lett 78 (1997) 3257
Phys.Rev. D63 (2001) 036005

Atwood, Dunietz, Soni

"GGSZ", "Dalitz"

- Use 3-body self-conjugate modes such as $\mathbf{D \to K_S \pi^+ \pi^-}$
- hadronic D parameters vary across Dalitz plot

Giri, Grossman, Soffer, Zupan, hep-ph/0303187

ARXIV:1203.3662

B → Dh: Observables

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

- Charge **asymmetries**:

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

- **Kaon/pion** ratio:

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

Form a system of equations.
Need more observables than parameters!
→ many different D decays

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

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

B → Dh: Observables

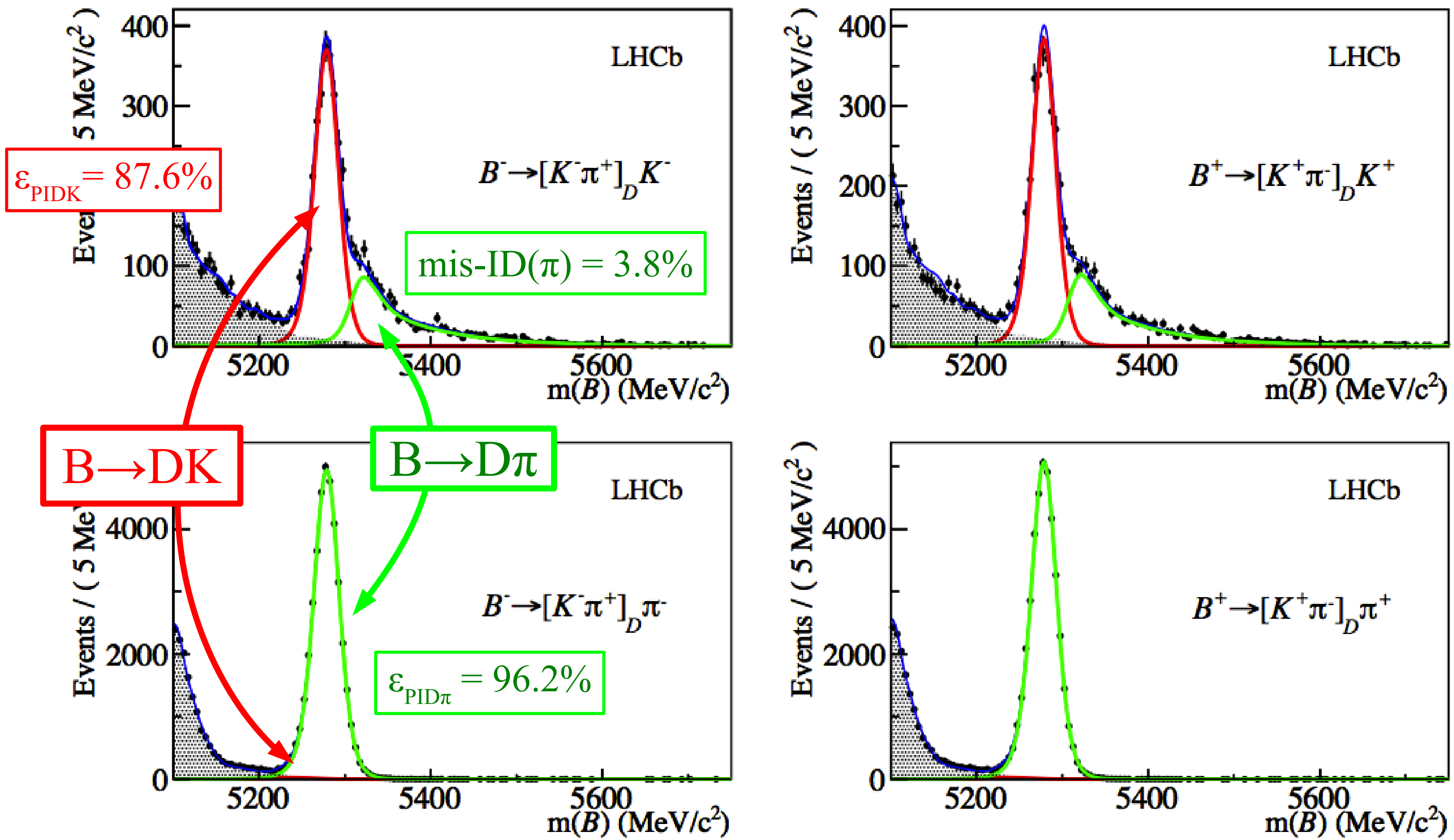
- Reconstructing neutral particles is difficult, so we miss the GLW CP- states.
- We also suffer in D → $K_S\pi\pi$.
- At LHCb, we chose a more **"factory like" approach**.
- We use **all** reasonable ratios, including the asymmetry of the ADS favored modes.

$$
\begin{aligned}
R^{K\pi}_{K/\pi} &= 0.0774 \pm 0.0012 \pm 0.0018 \\
R^{KK}_{K/\pi} &= 0.0773 \pm 0.0030 \pm 0.0018 \\
R^{\pi\pi}_{K/\pi} &= 0.0803 \pm 0.0056 \pm 0.0017 \\
A^{K\pi}_{\pi} &= -0.0001 \pm 0.0036 \pm 0.0095 \\
A^{K\pi}_{K} &= 0.0044 \pm 0.0144 \pm 0.0174 \\
A^{KK}_{K} &= 0.148 \pm 0.037 \pm 0.010 \\
A^{\pi\pi}_{K} &= 0.135 \pm 0.066 \pm 0.010 \\
A^{KK}_{\pi} &= -0.020 \pm 0.009 \pm 0.012 \\
A^{\pi\pi}_{\pi} &= -0.001 \pm 0.017 \pm 0.010 \\
R^{-}_{K} &= 0.0073 \pm 0.0023 \pm 0.0004 \\
R^{+}_{K} &= 0.0232 \pm 0.0034 \pm 0.0007 \\
R^{-}_{\pi} &= 0.00469 \pm 0.00038 \pm 0.00008 \\
R^{+}_{\pi} &= 0.00352 \pm 0.00033 \pm 0.00007 \;.
\end{aligned}
$$

13 observables, all part of same analysis!

final states $[f]_D$:
KK, ππ
Kπ, πK

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



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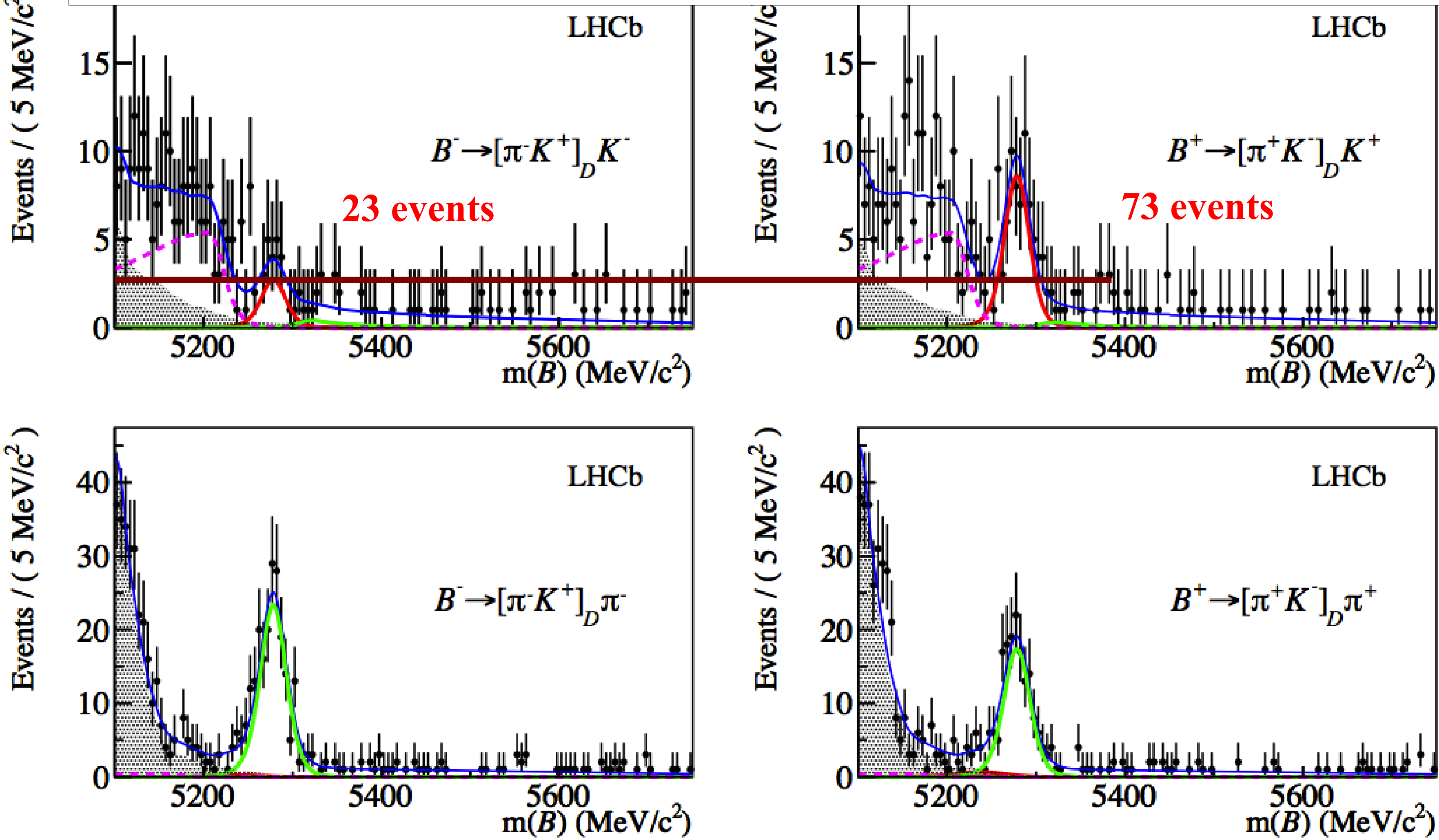
B → D(πK)h: suppressed ADS mode

$\mathcal{B}(B^{\pm} \to D_{ADS}K^{\pm}) \approx 2 \cdot 10^{-7}$ $A_{CP} = -0.520 \pm 0.150 \pm 0.021$



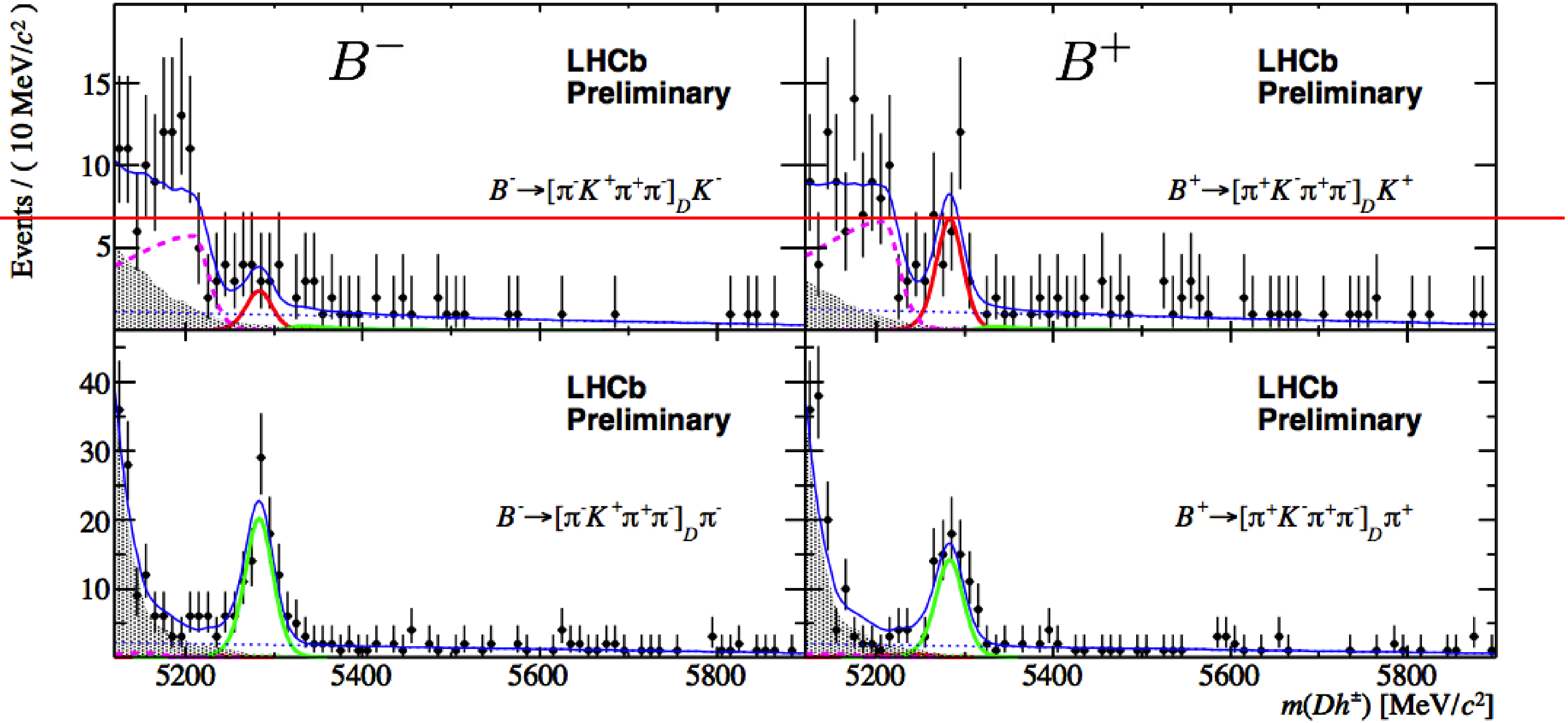
ARXIV:1203.3662

four-body ADS

$B \to Dh$ followed by $D \to K\pi\pi\pi$

First observations of these decay modes!

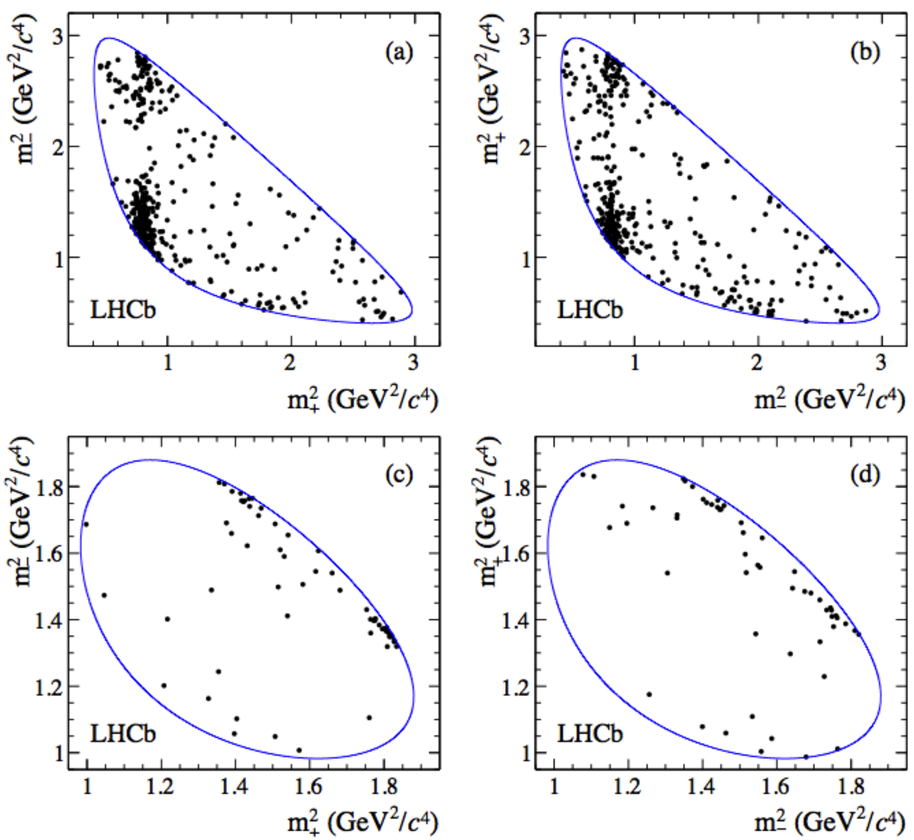
$$A_{CP} = -0.42 \pm 0.22$$



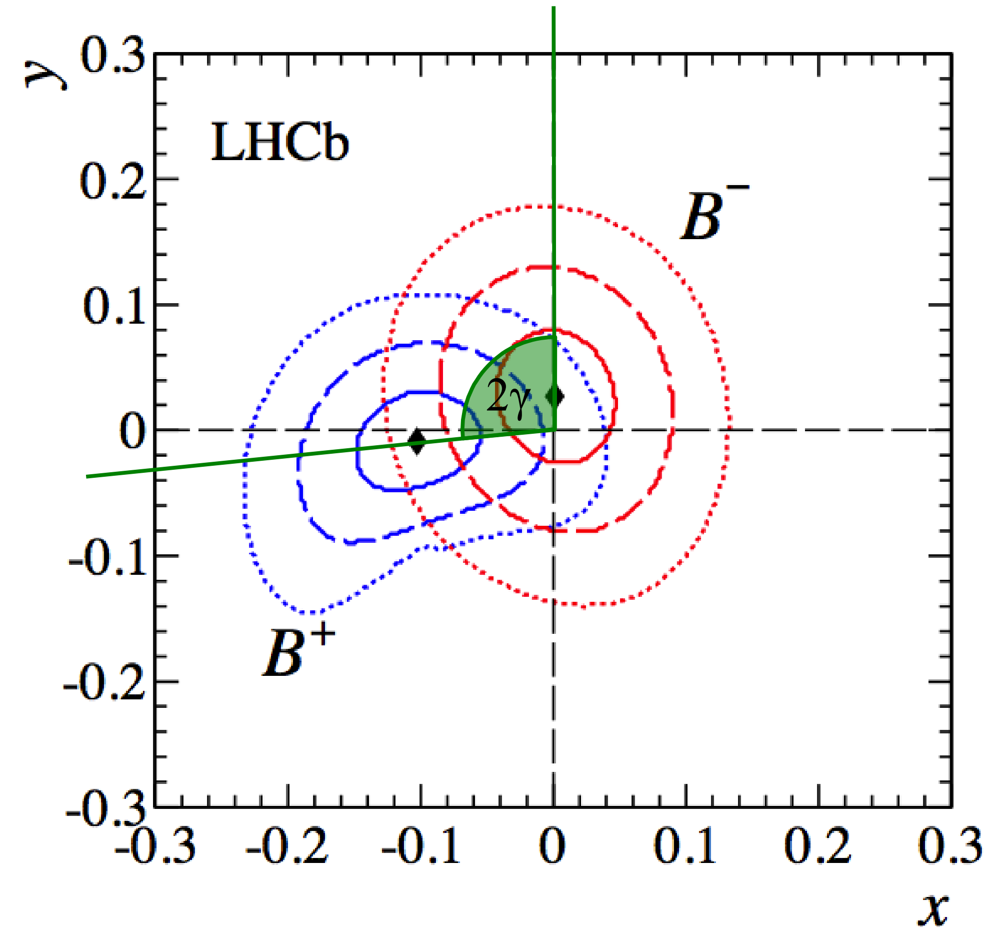
ARXIV:1209.5869

model independent GGSZ

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



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



Observables: "cartesian coordinates"

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

$$x_- = (0.0 \pm 4.3 \pm 1.5 \pm 0.6) \times 10^{-2}$$
$$y_- = (2.7 \pm 5.2 \pm 0.8 \pm 2.3) \times 10^{-2}$$
$$x_+ = (-10.3 \pm 4.5 \pm 1.8 \pm 1.4) \times 10^{-2}$$
$$y_+ = (-0.9 \pm 3.7 \pm 0.8 \pm 3.0) \times 10^{-2}$$

Part III:

gamma combination

Combination

- We now have measured a total of **24 γ-related observables**. What does it mean for γ?
- At the CKM2012 conference, both Babar and Belle presented their legacy combinations.
- LHCb showed first results!
  - frequentist procedure
  - for the first time including the $B \to D\pi$ system
  - considering CP violation in charm decays
  - partially considering charm mixing
- Combined likelihood:

$$\mathcal{L}(\vec{y}) = \frac{1}{N} \exp\left(-\frac{1}{2}(\vec{y} - \vec{y_{\mathrm{t}}})^T V_{\mathrm{cov}}^{-1} (\vec{y} - \vec{y_{\mathrm{t}}})\right)$$

$$\chi^2(\vec{y}) = -2 \ln \mathcal{L}(\vec{y}) \; .$$

statistical treatment

- The combined likelihood has a very rich structure:
  - many **nuisance parameters**
  - many trigonometrical functions, thus **many local minima**
  - **varying dimensionality** of the likelihood, if depends on the value of the nuisance parameters, potentially affecting the coverage

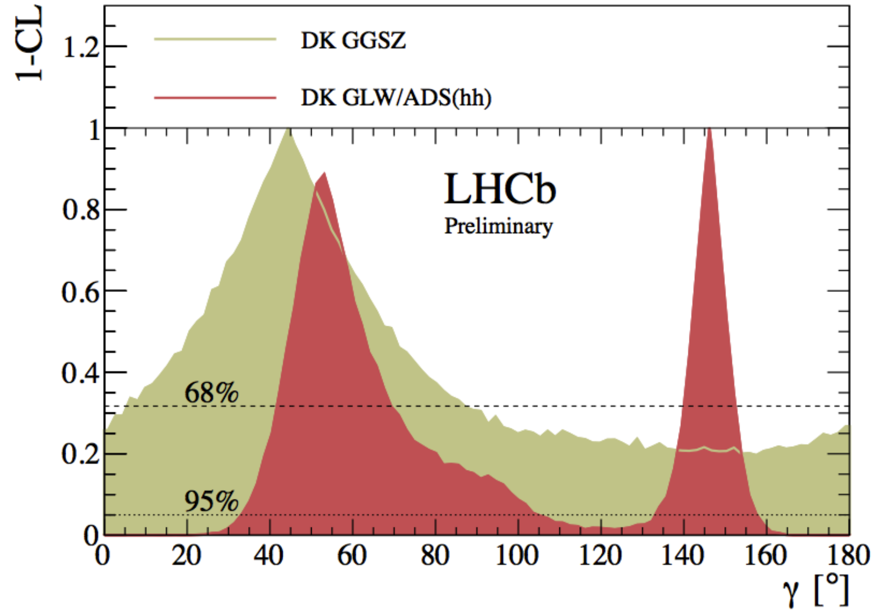
direct product of rB and angular terms:
$x_\pm = r_B \cos(\delta_B \pm \gamma)$

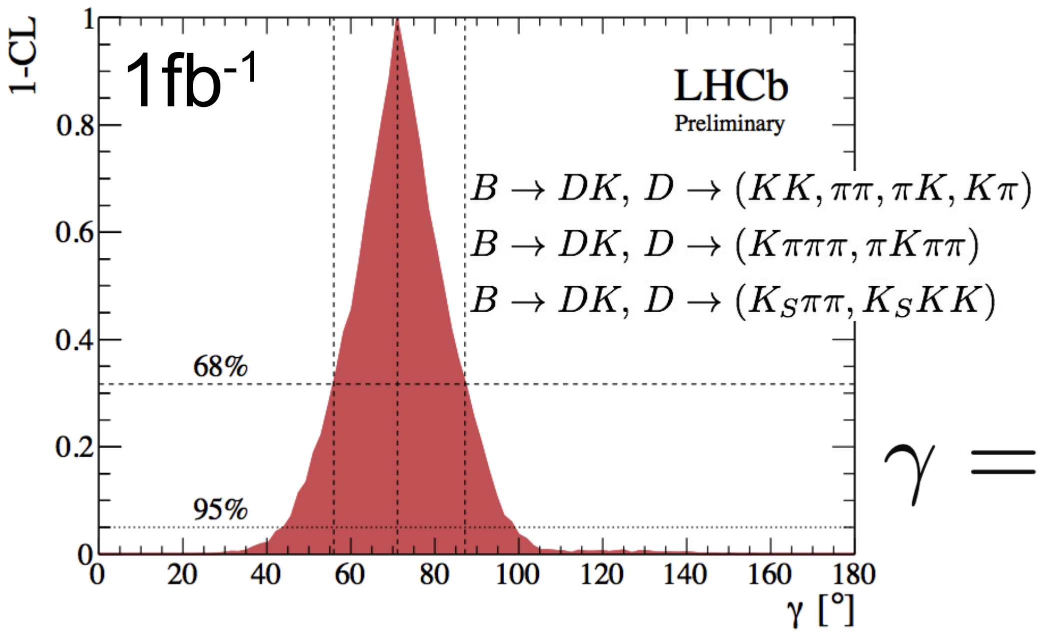
- Use a Feldman-Cousins based frequentist method (likelihood ratio ordering).
- Compute the actual distribution of the test statistic ($\Delta\chi^2$) using toy Monte Carlo ("plug-in" method).
- **Test the coverage** at the best-fit point.

coverage test:

D^0K & $D^0\pi$	α
$\eta = 0.6827$	0.6616 ± 0.0067
$\eta = 0.9545$	0.9586 ± 0.0028
$\eta = 0.9973$	0.9958 ± 0.0009

B → DK only

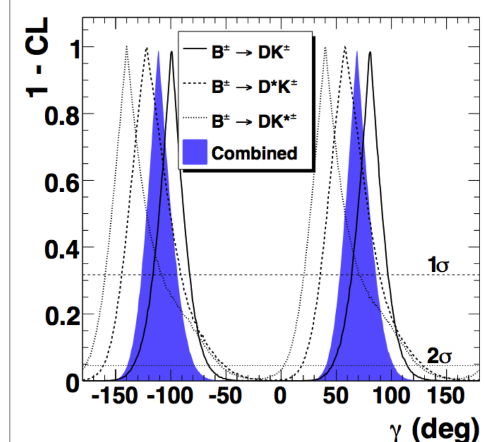




$$\gamma = (71.1\,^{+16.6}_{-15.7})^\circ$$

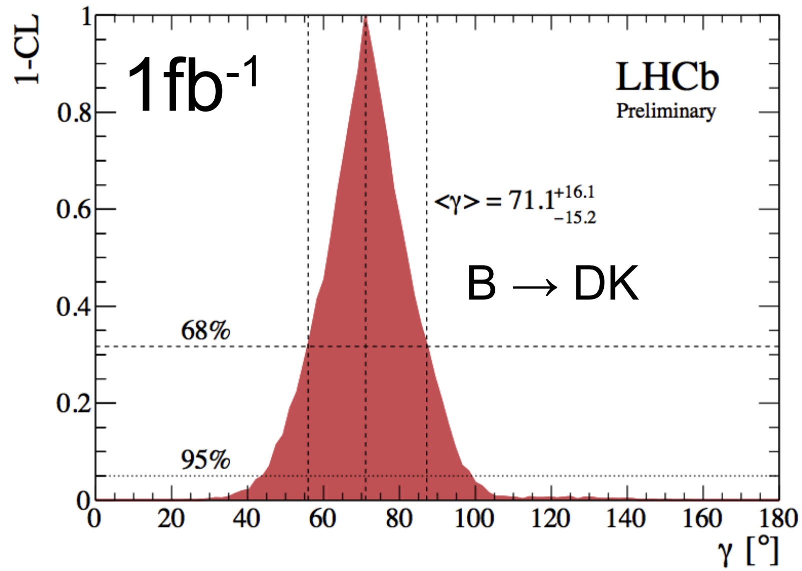
This is about as precise as the B-factory legacy combinations!

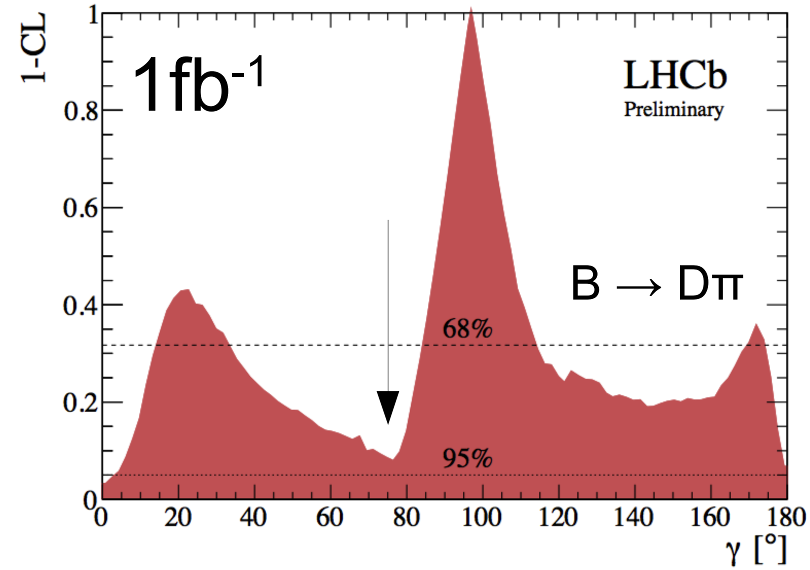
BaBar: $\gamma = 69^{+17}_{-16}$



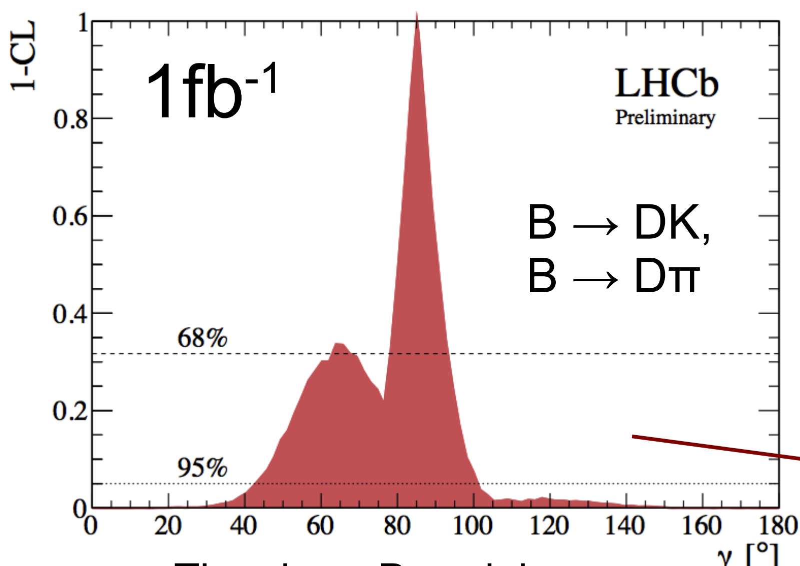
ARXIV:1301.1029

adding B → Dπ

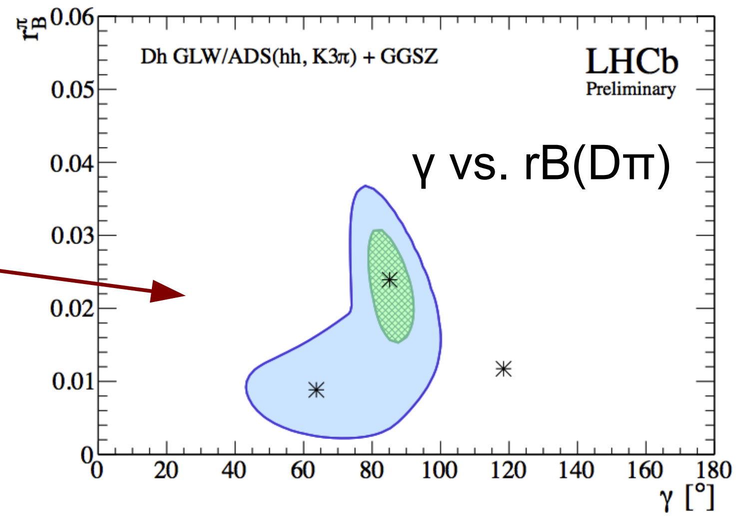




B → Dπ is more precise than expected.
But (almost) no constraint at 2σ.



The sharp Dπ minimum
affects the full combination!

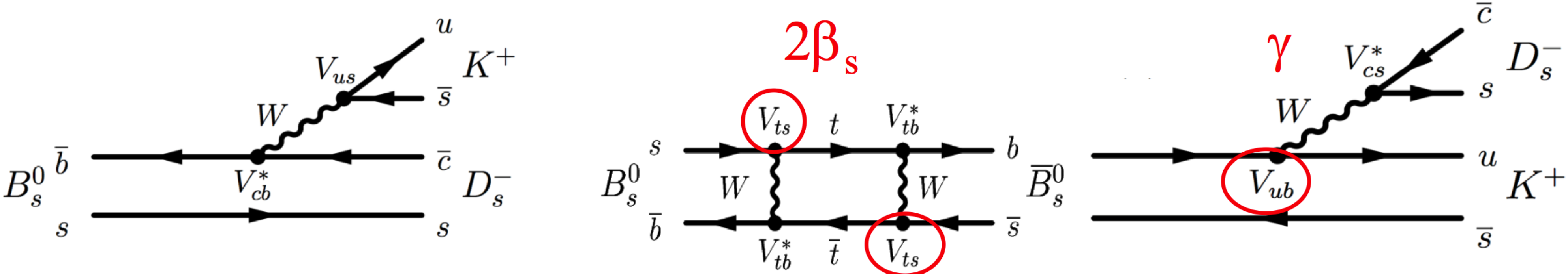


Part IV:

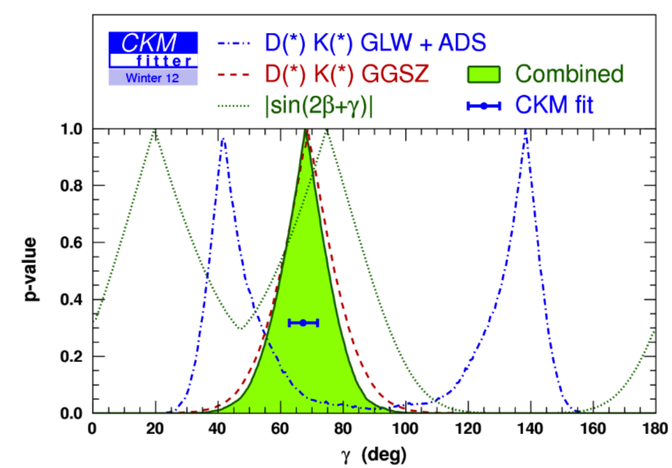
time dependent measurements

time dependent measurements

- It is also possible to use tree decays of neutral B mesons [1]!
- Using charged-particle final states, interference is achieved through mixing.



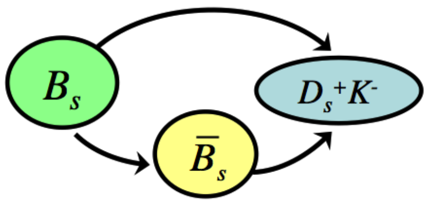
- B-factories performed such measurements with $B^0 \to D^+ \pi^-$, constraining $\sin(2\beta+\gamma)$



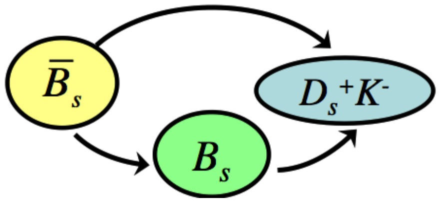
- **Much better sensitivity expected in $B_s \to D_s K$**, comparable to GGSZ, only really possible at LHCb
  - large amplitude ratio: r_{DsK}~0.4
  - finite decay width difference: $\Delta\Gamma = 0.091 \pm 0.011\ \text{ps}^{-1}$ (HFAG fall 2012)

[1] R. Fleischer. New strategies to obtain insights into CP violation through $B_{(s)} \to D^{\pm}_{(s)} K^{\mp}$, $D^{*\pm}_{(s)} K^{\mp}$, ... and $B_{(d)} \to D^{\pm}\pi^{\mp}$, $D^{*\pm}\pi^{\mp}$, ... decays. *Nucl.Phys.*, B671:459–482, 2003.

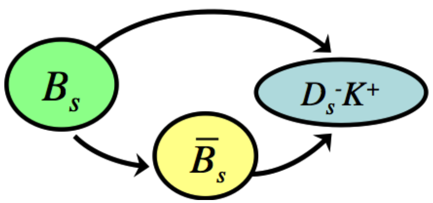
four decay rates



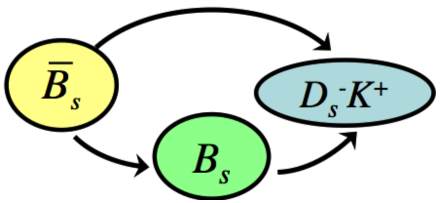
$$B_s^0 \to D_s^+ K^-$$



$$\overline{B_s^0} \to D_s^+ K^-$$



$$B_s^0 \to D_s^- K^+$$



$$\overline{B_s^0} \to D_s^- K^+$$

each has their own time dependence

four decay rates

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

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

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

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

observables

Five observables:

$$C = \frac{1 - r_{D_sK}^2}{1 + r_{D_sK}^2} \,,$$

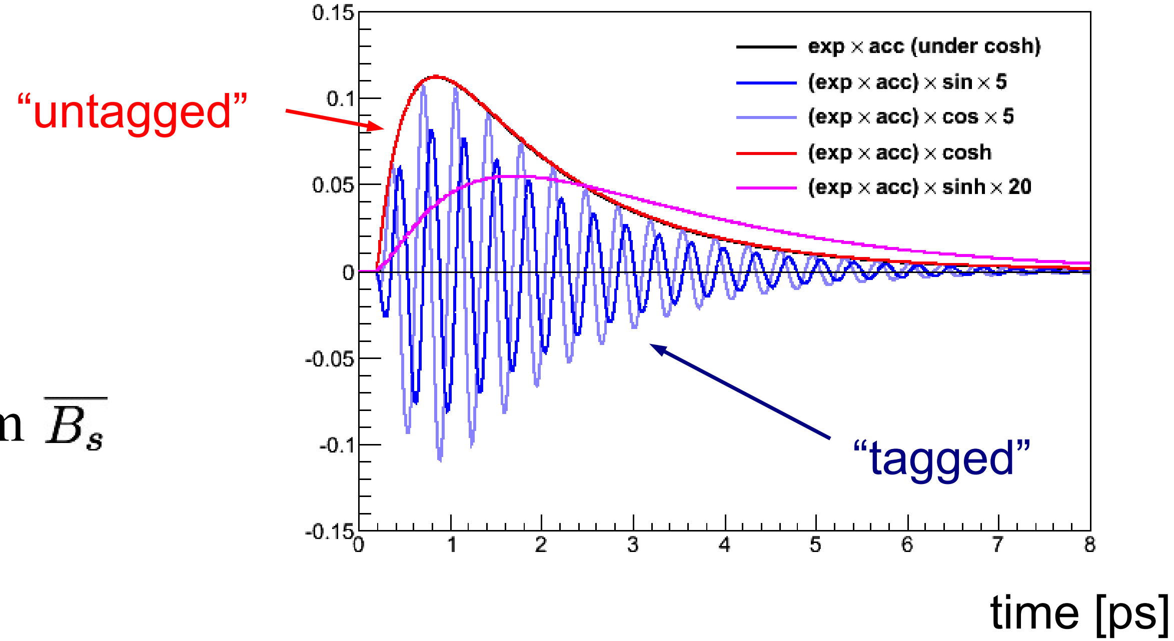
$$D_f = \frac{2r_{D_sK}\cos(\Delta - (\gamma - 2\beta_s))}{1 + r_{D_sK}^2} \,, \quad D_{\bar{f}} = \frac{2r_{D_sK}\cos(\Delta + (\gamma - 2\beta_s))}{1 + r_{D_sK}^2} \,,$$

$$S_f = \frac{2r_{D_sK}\sin(\Delta - (\gamma - 2\beta_s))}{1 + r_{D_sK}^2} \,, \quad S_{\bar{f}} = \frac{2r_{D_sK}\sin(\Delta + (\gamma - 2\beta_s))}{1 + r_{D_sK}^2} \,.$$

Measurement:

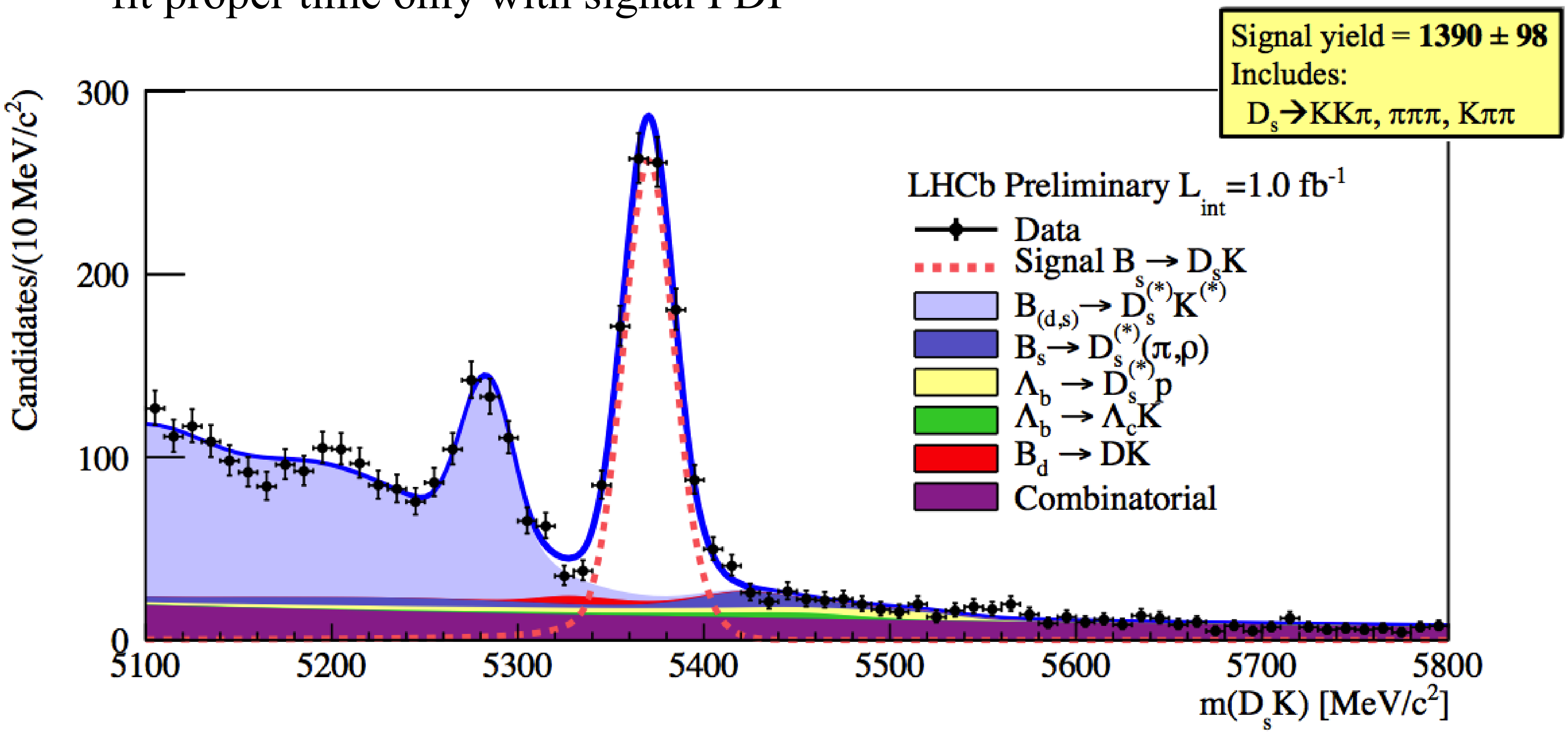
- excellent time resolution needed to resolve fast B_s oscillations
- flavor tagging to tell B_s from $\overline{B_s}$

$$\epsilon D^2 = 1.9\%$$

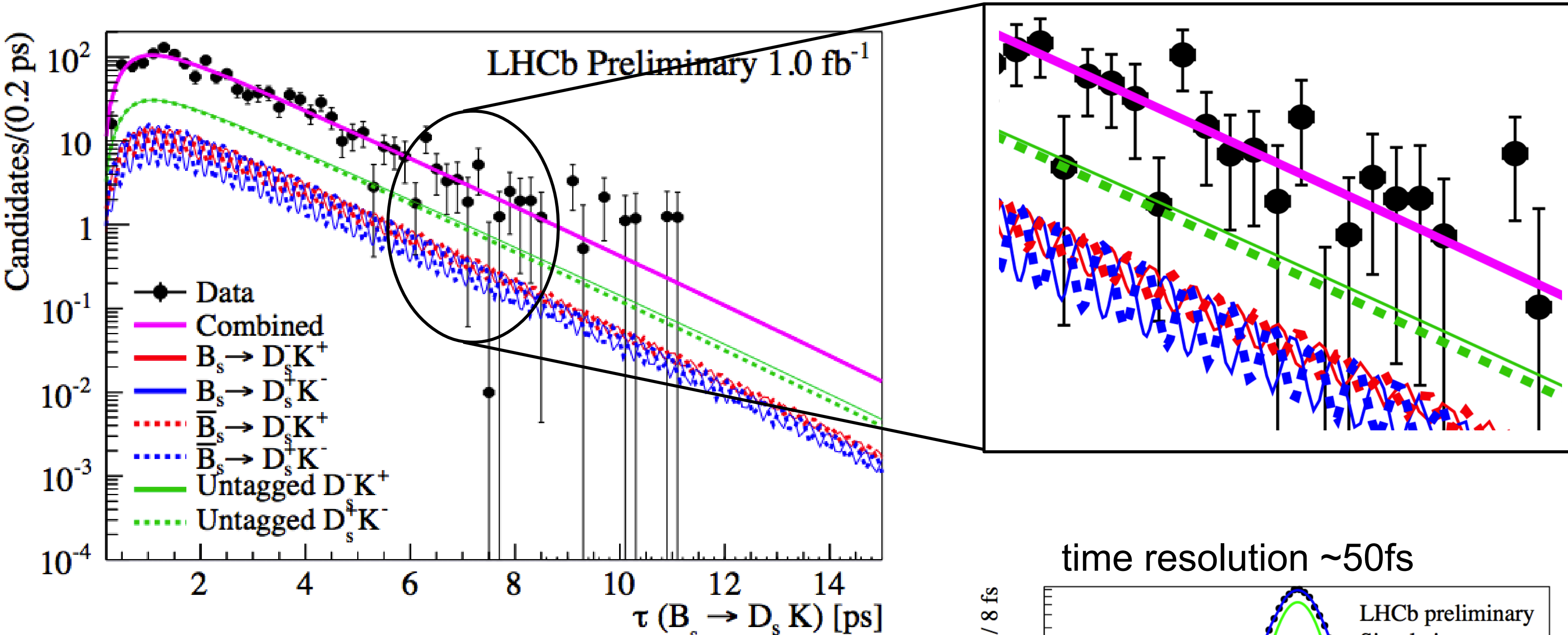


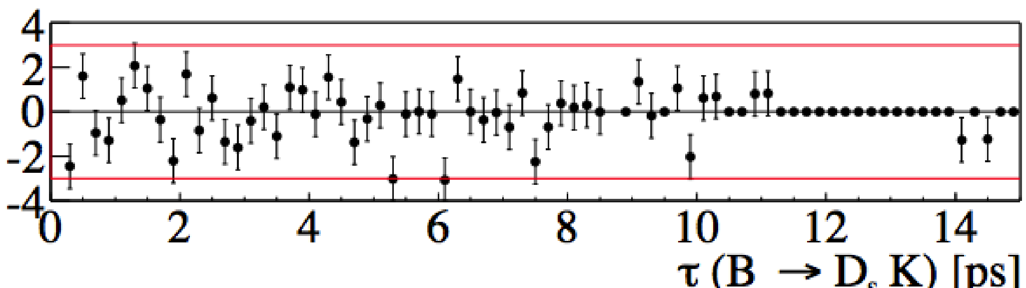
mass plot

- rich physics backgrounds – all could have different time structure!
- employ an "sFit" technique ("cFit" available):
  - use B_s mass as discriminating variable to compute per-event weights
  - fit proper time only with signal PDF

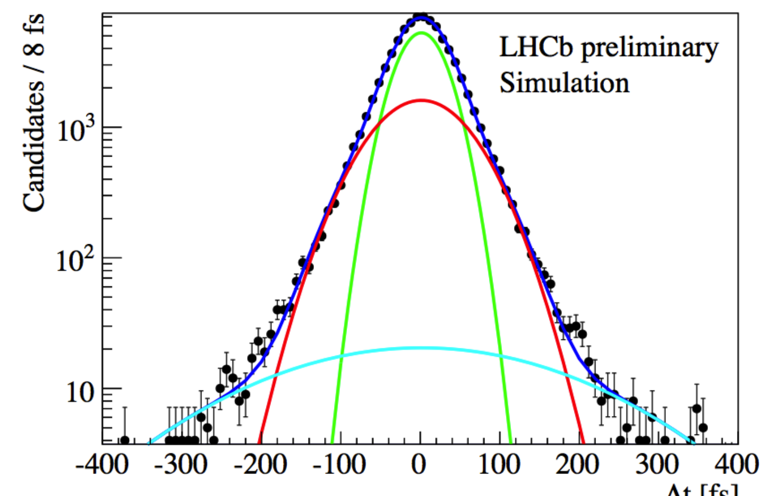


time dependent DsK





time resolution ~50fs



result

	C	S_f	$S_{\bar{f}}$	D_f	$D_{\bar{f}}$
Toy corrected central value	1.01	-1.25	0.08	-1.33	-0.81
Statistical uncertainty	0.50	0.56	0.68	0.60	0.56
Systematic uncertainties (σ_{stat})					
Decay-time bias	0.03	0.05	0.05	0.00	0.00
Decay-time resolution	0.11	0.08	0.09	0.00	0.00
Tagging calibration	0.23	0.17	0.16	0.00	0.00
Backgrounds	0.15	0.07	0.07	0.07	0.07
Fixed parameters	0.15	0.22	0.20	0.40	0.42
Asymmetries	0.12	0.01	0.04	0.00	0.02
Momentum/length scale	0.00	0.00	0.00	0.00	0.00
k-factors	0.27	0.27	0.27	0.08	0.08
Bias correction	0.03	0.03	0.03	0.03	0.03
Total systematic (σ_{stat})	0.46	0.50	0.35	0.43	0.46

- statistically limited, but non-negligible systematic errors
- no constraints on γ yet (warning: syst. correlations cannot be neglected)
- significant update planned

Conclusion

Conclusion

- In the era of precision flavor physics, γ provides a set point of the Standard Model because of its **negligible theoretical uncertainty** (tree decays).
  - does the unitarity triangle close?
  - can probe for new physics at very high energy scales
- First LHCb measurements are available.
  - been statistically lucky with $B \to D\pi$
- with $1fb^{-1}$ already at the precision of the B factories
- For the first time, attempt to measure γ in time-dependent analysis of $\mathbf{B_s \to D_s K}$ - high precision seems possible!

$$\gamma = (71.1\,^{+16.6}_{-15.7})^\circ$$

$B \to DK$ only, LHCb at CKM2012 preliminary

Backup

flavor tagging