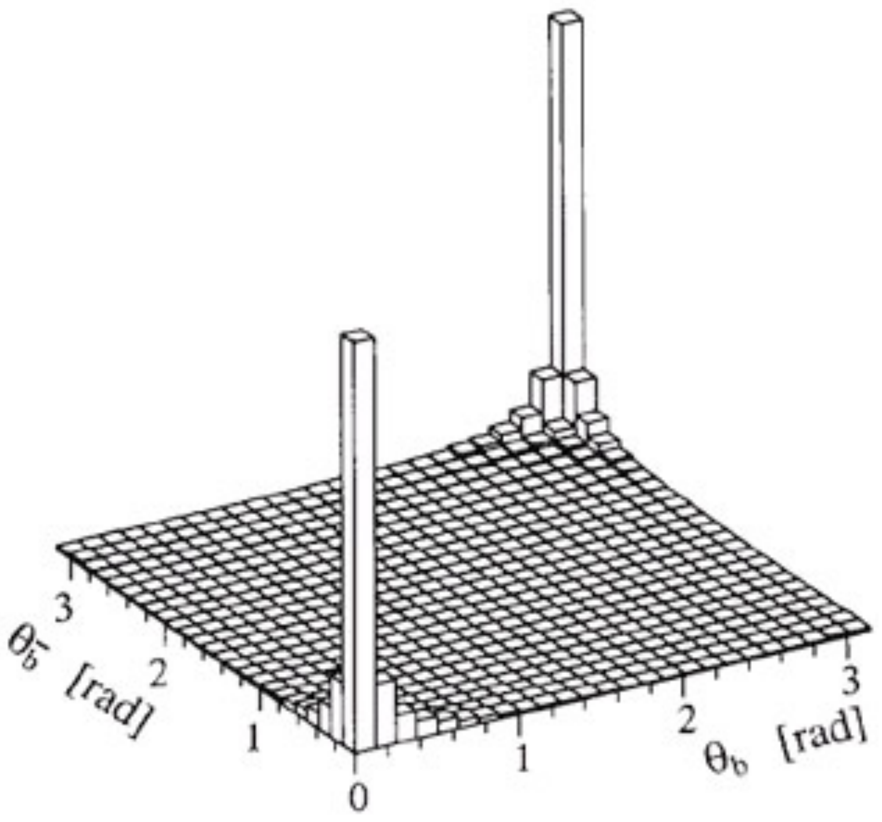
Looking beyond the Standard Model with the LHCb detector

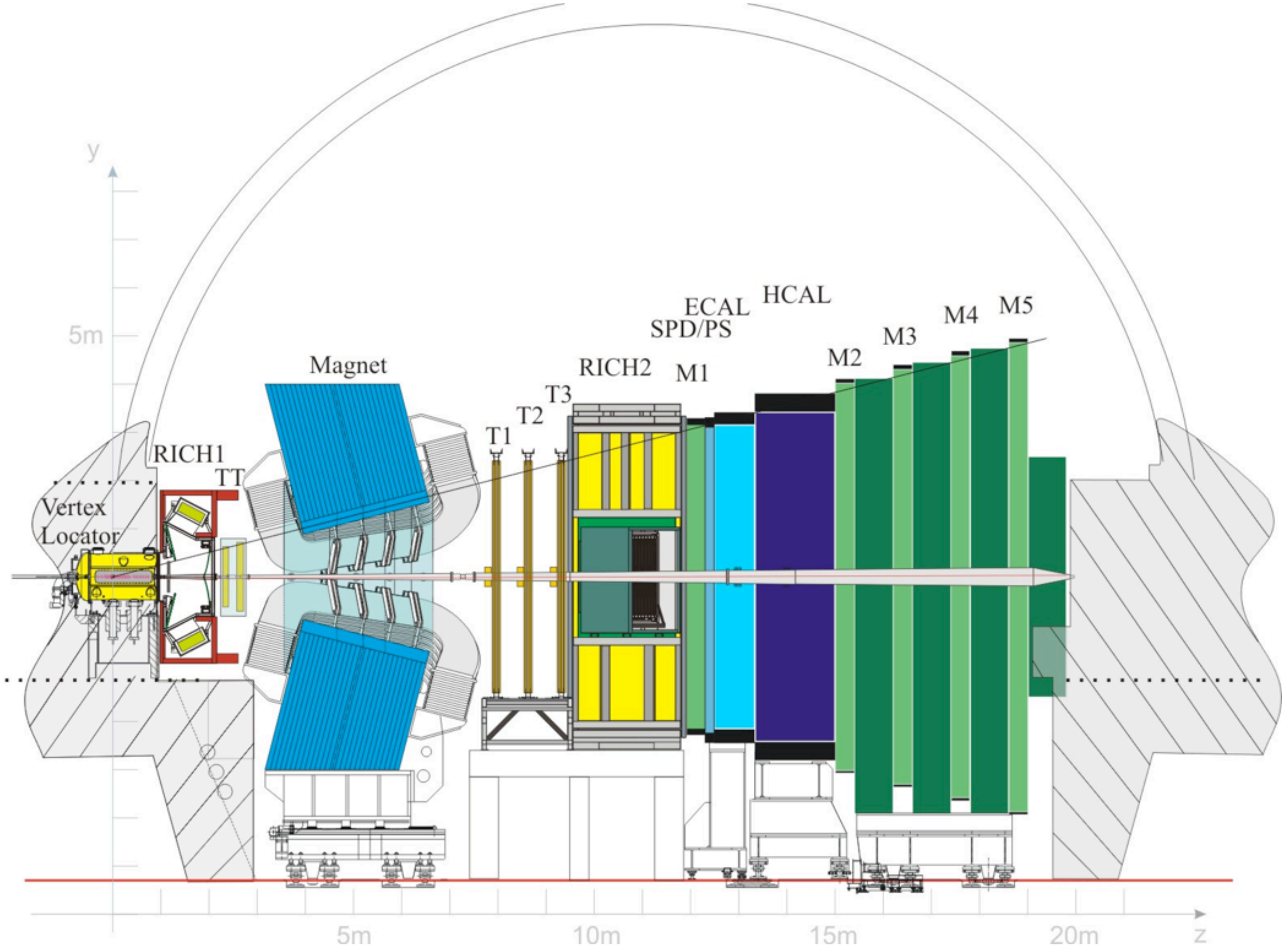
V.V. Gligorov, CERN

24th January 2014

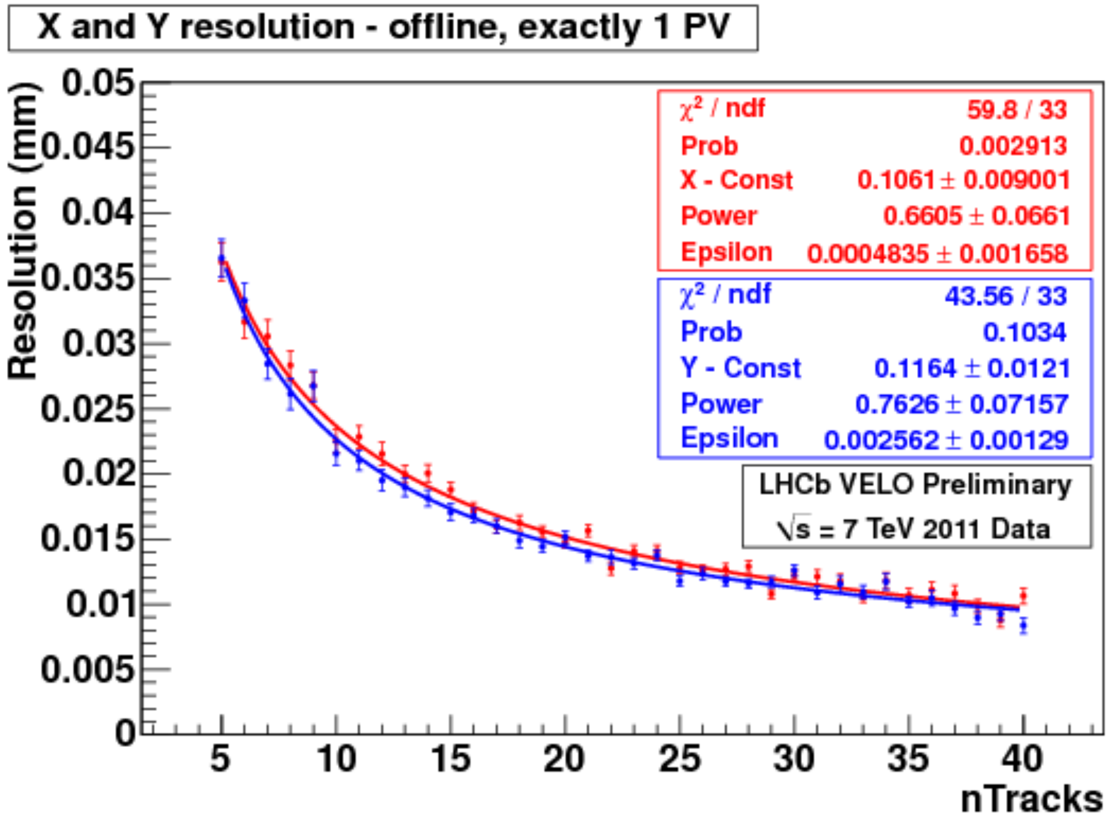
What is LHCb?

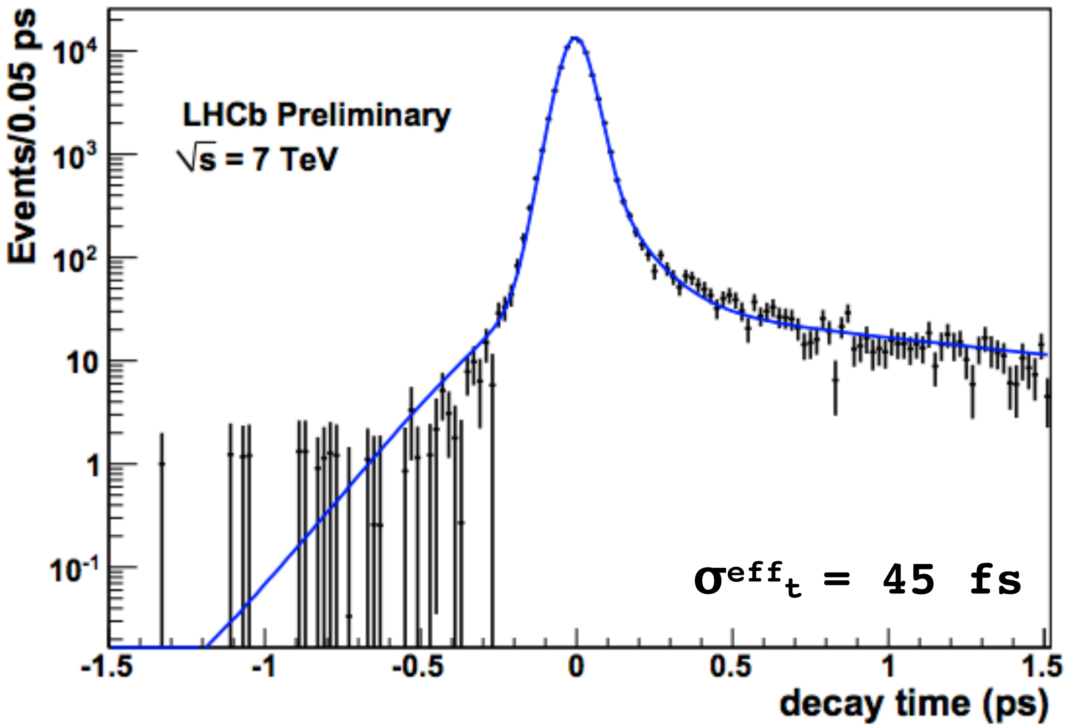
A forward spectrometer for the LHC

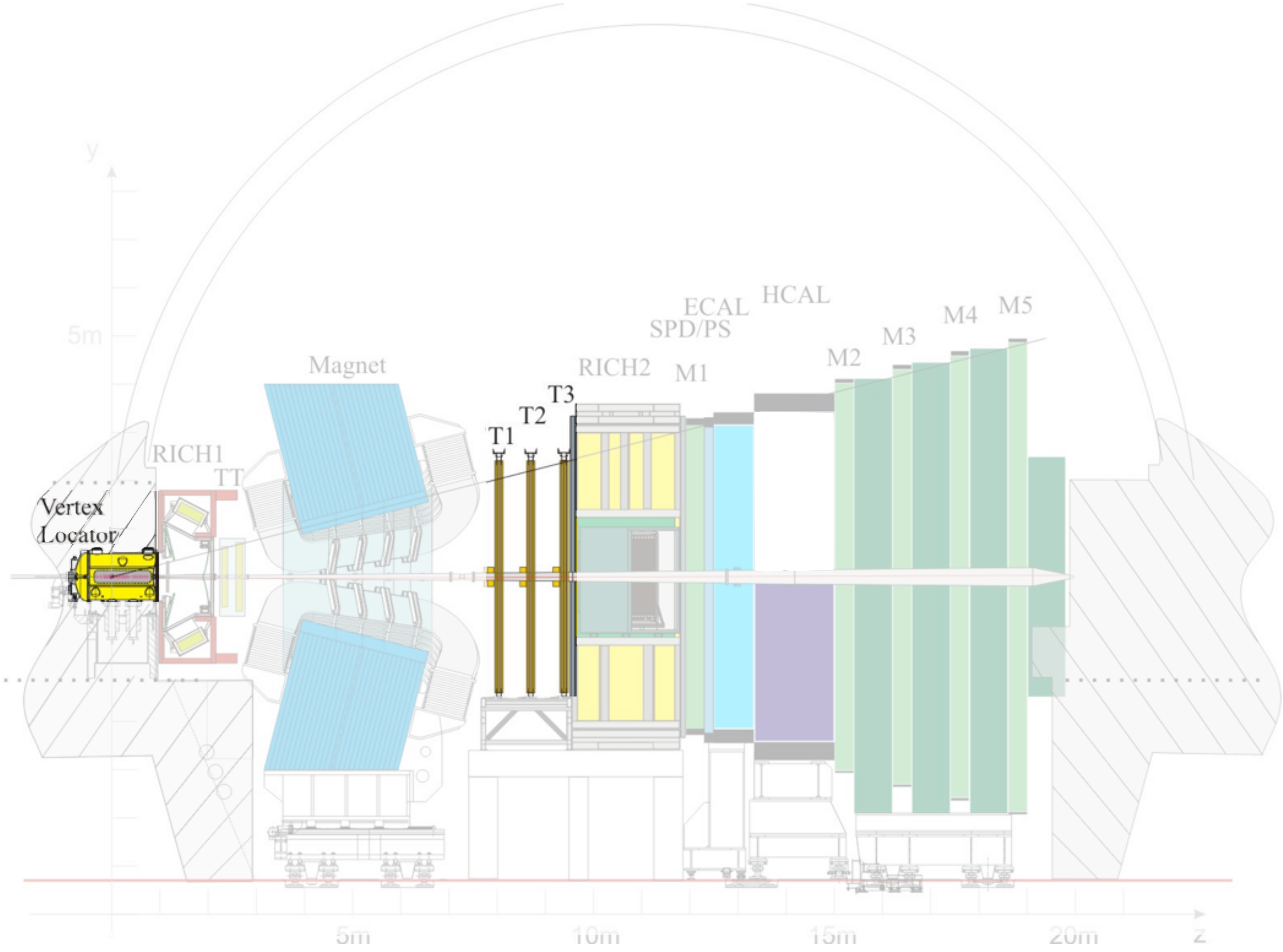




with excellent tracking resolution







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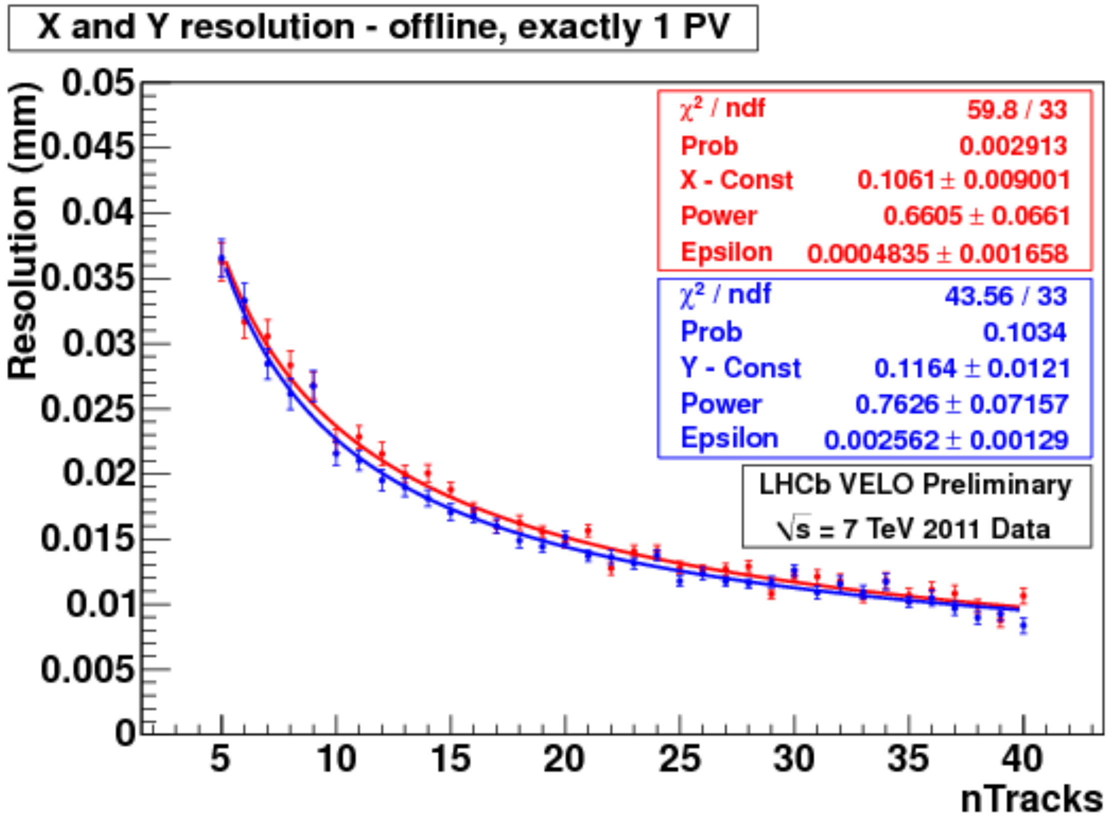
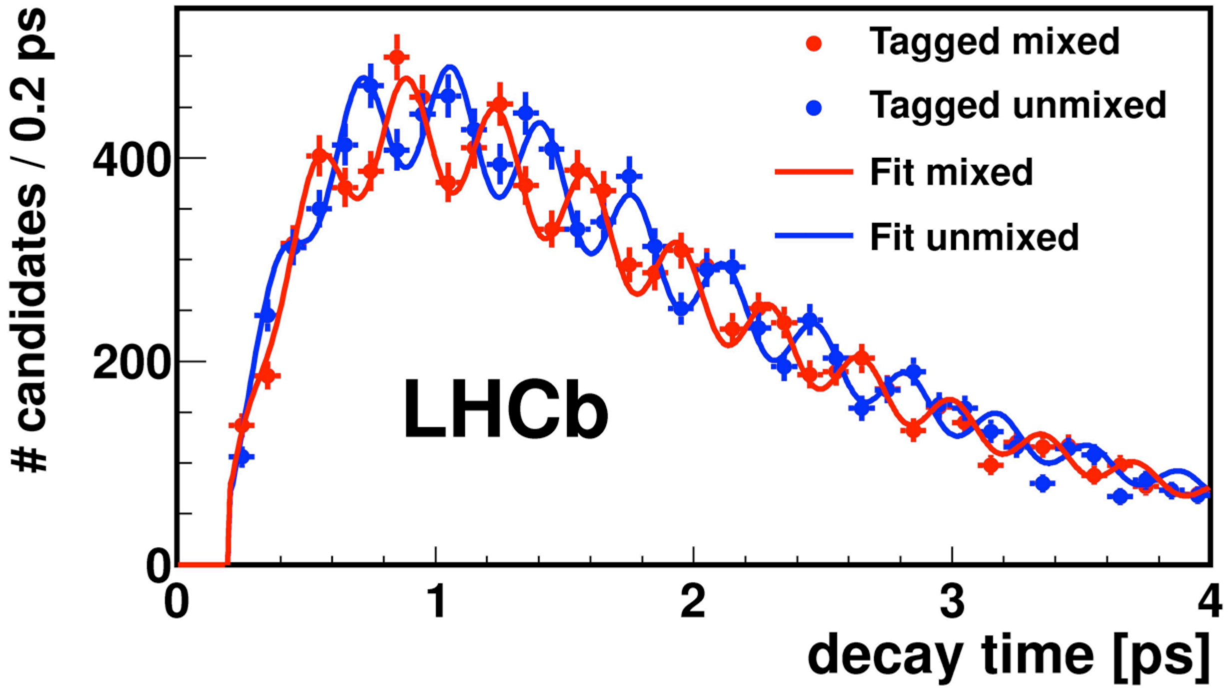
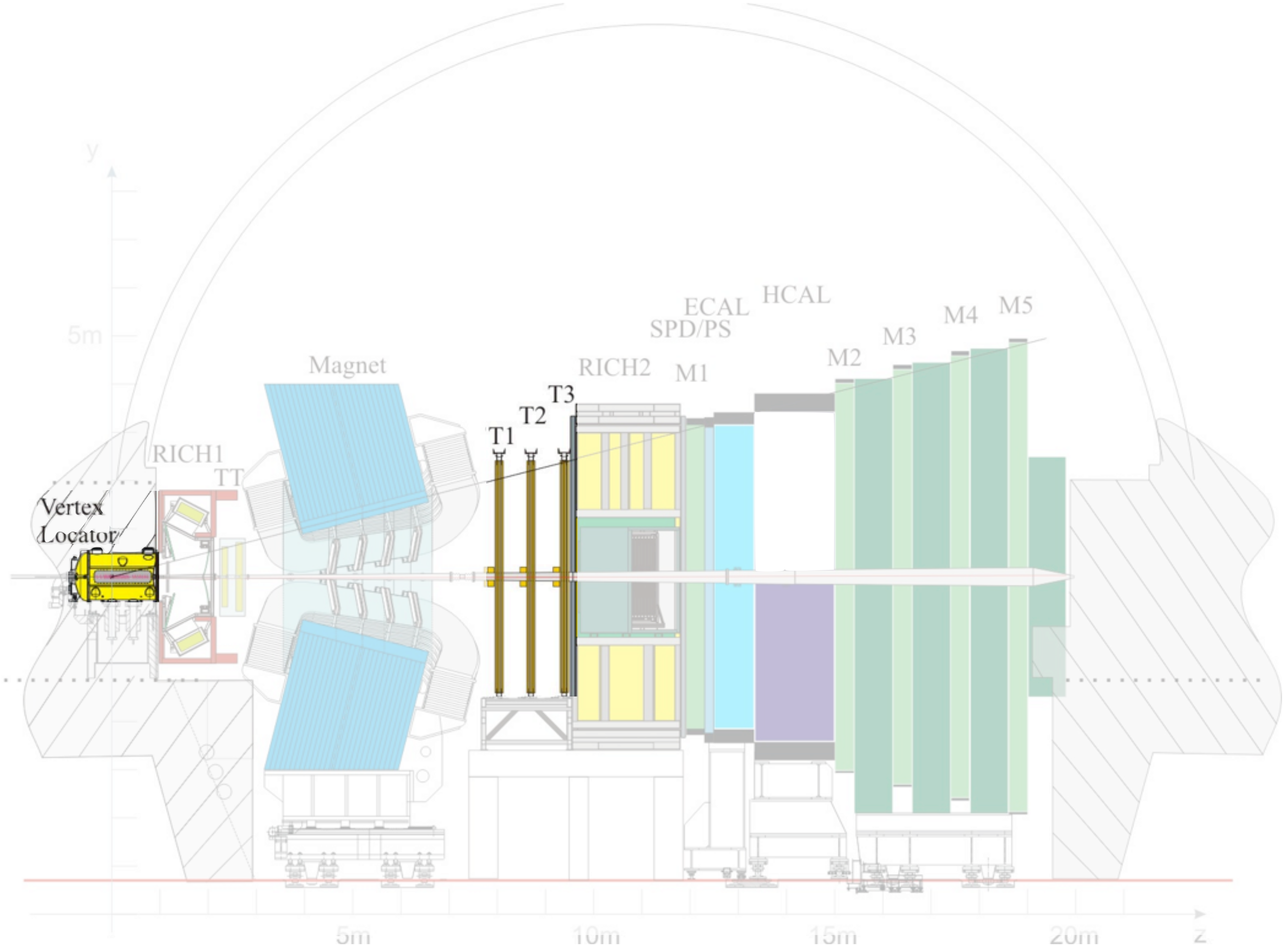
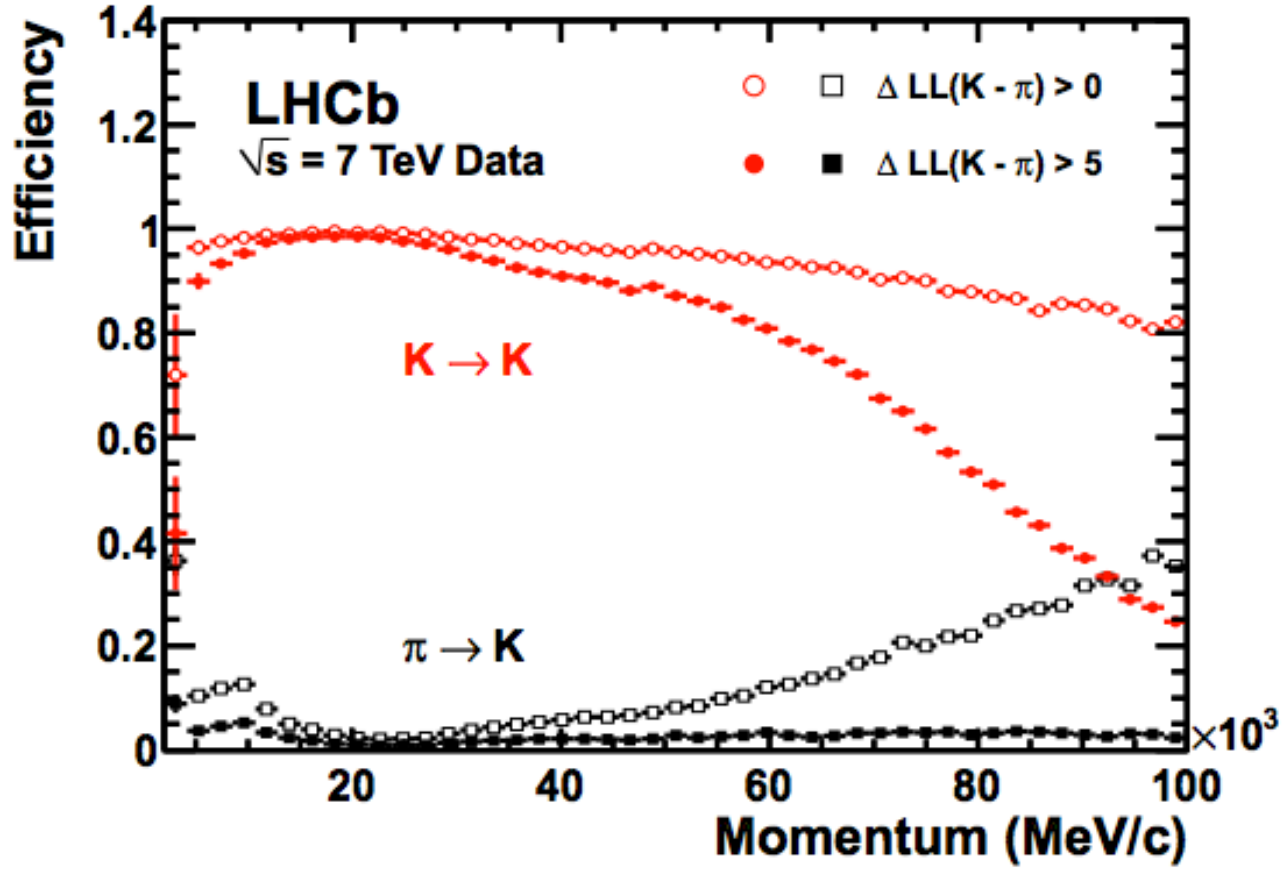


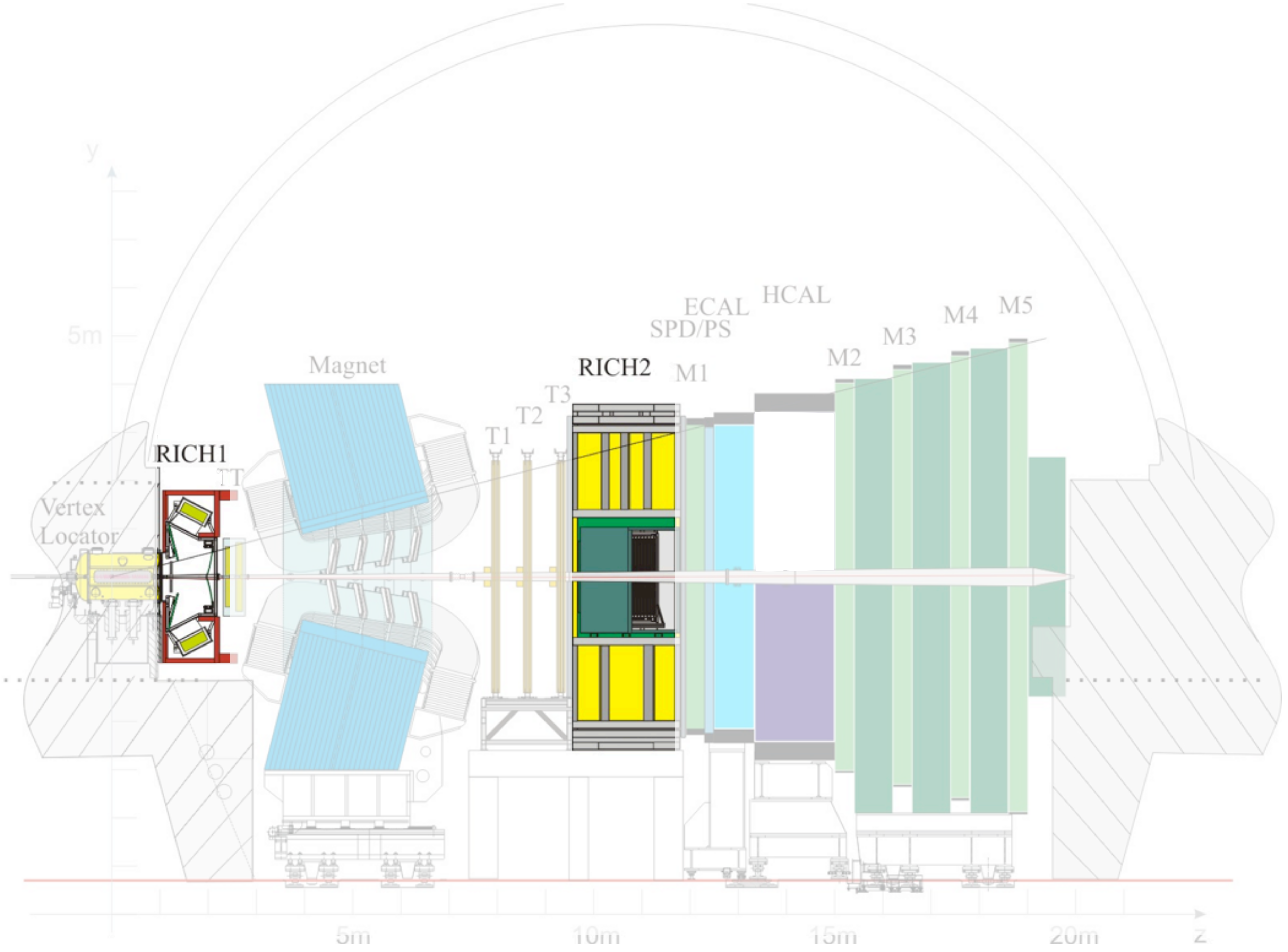




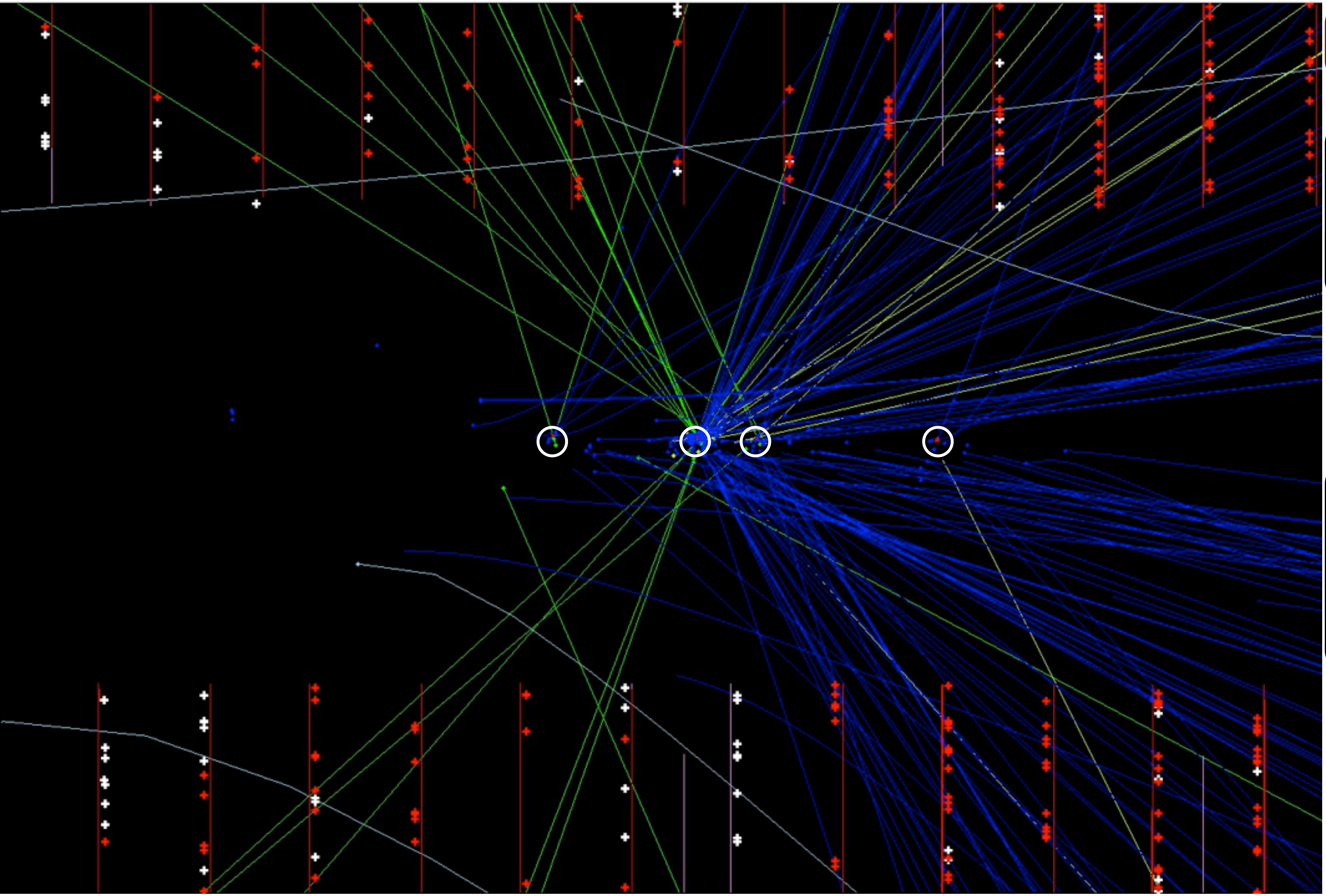
LHCb's is uniquely able to make high precision time-dependent B_s sector measurements

and charged hadron separation





The LHC environment



40 MHz bunch crossing rate

↓

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

450 kHz $h^{\pm}$	400 kHz $\mu/\mu\mu$	150 kHz e/γ

↓

Defer 20% to disk

↓

Software High Level Trigger

- **29000 Logical CPU cores**
- **Offline reconstruction tuned to trigger time constraints**
- **Mixture of exclusive and inclusive selection algorithms**

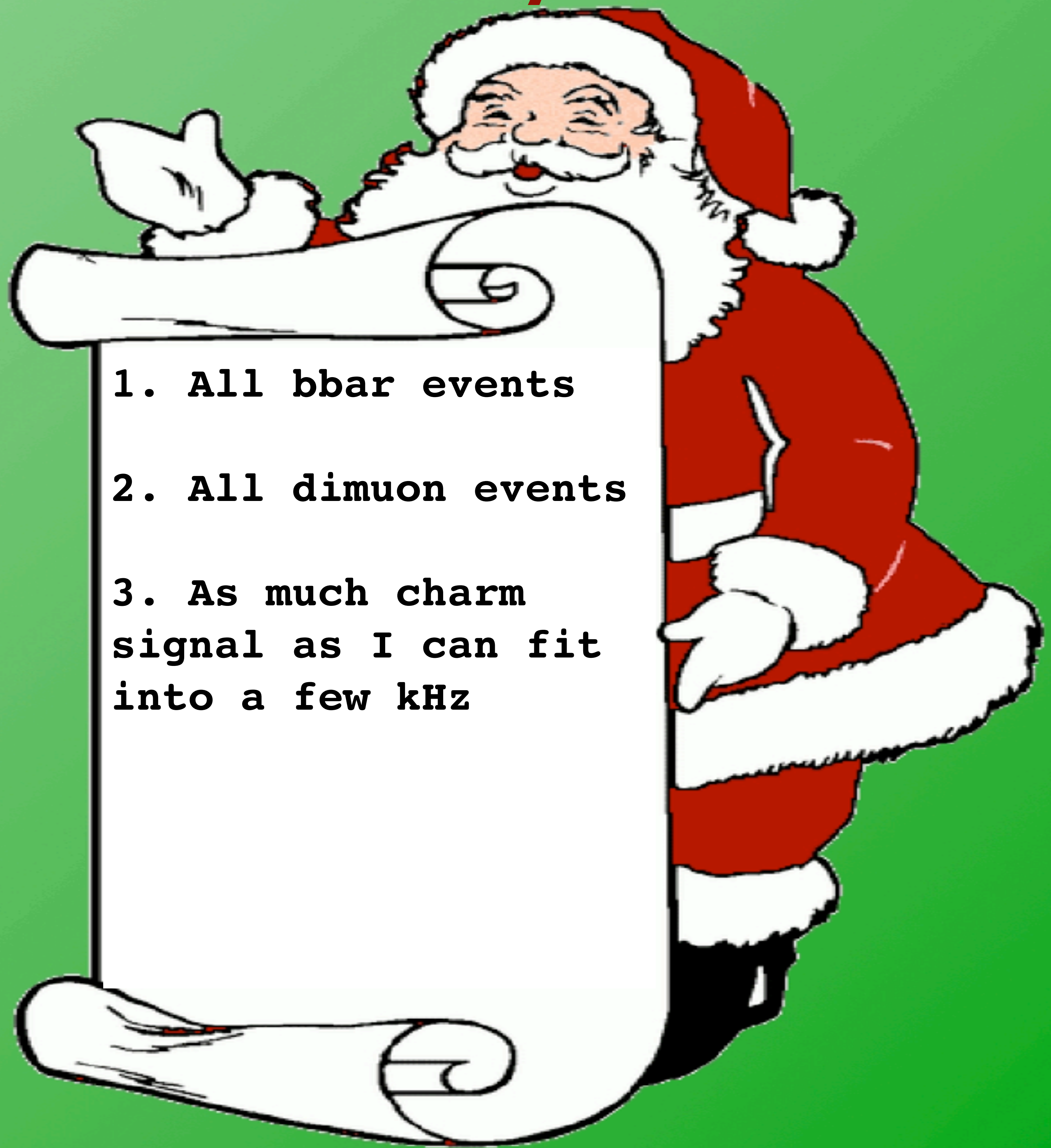
↓

5 kHz Rate to storage

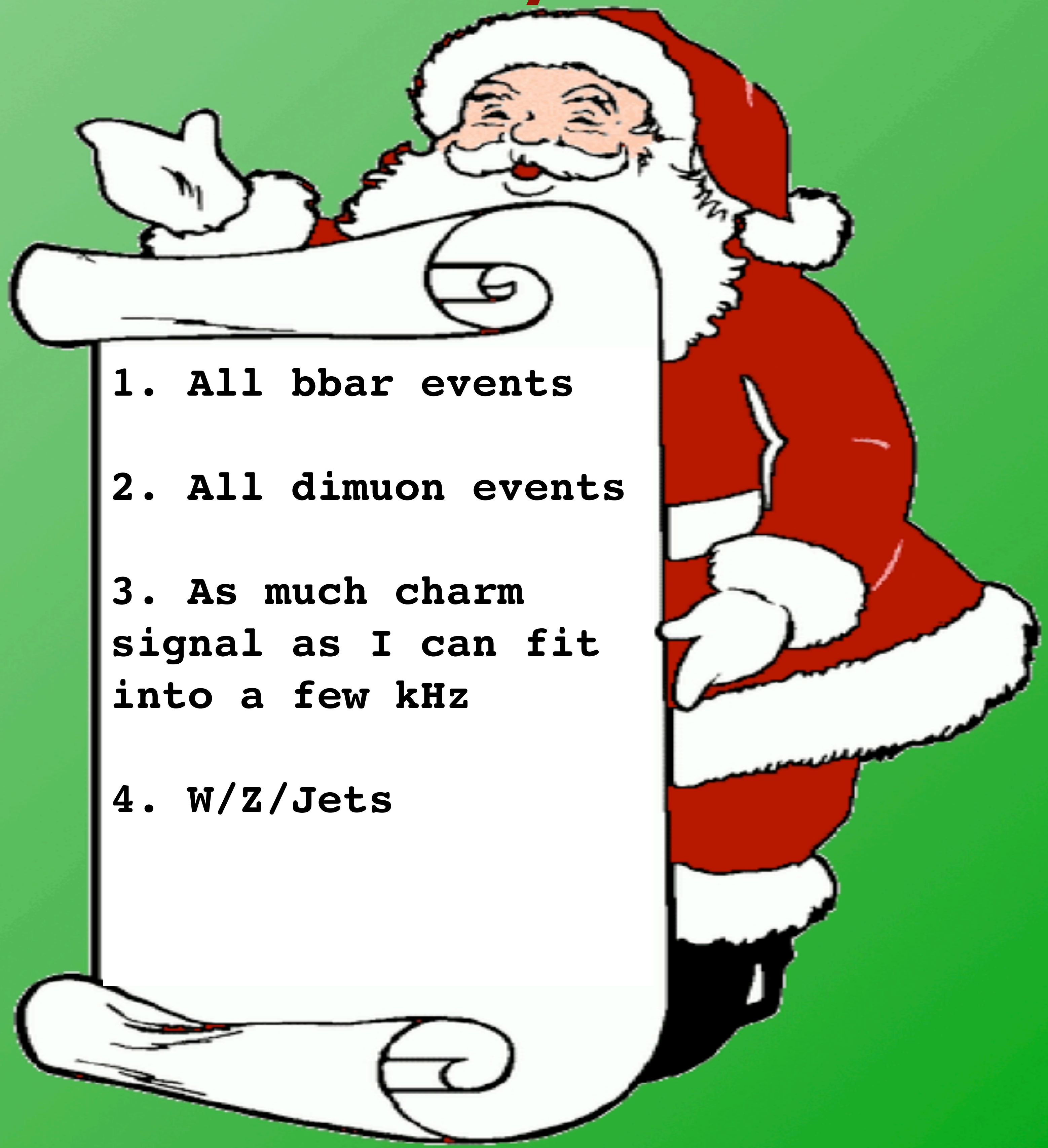
More than a B-factory

More than a B-factory

More than a B-factory

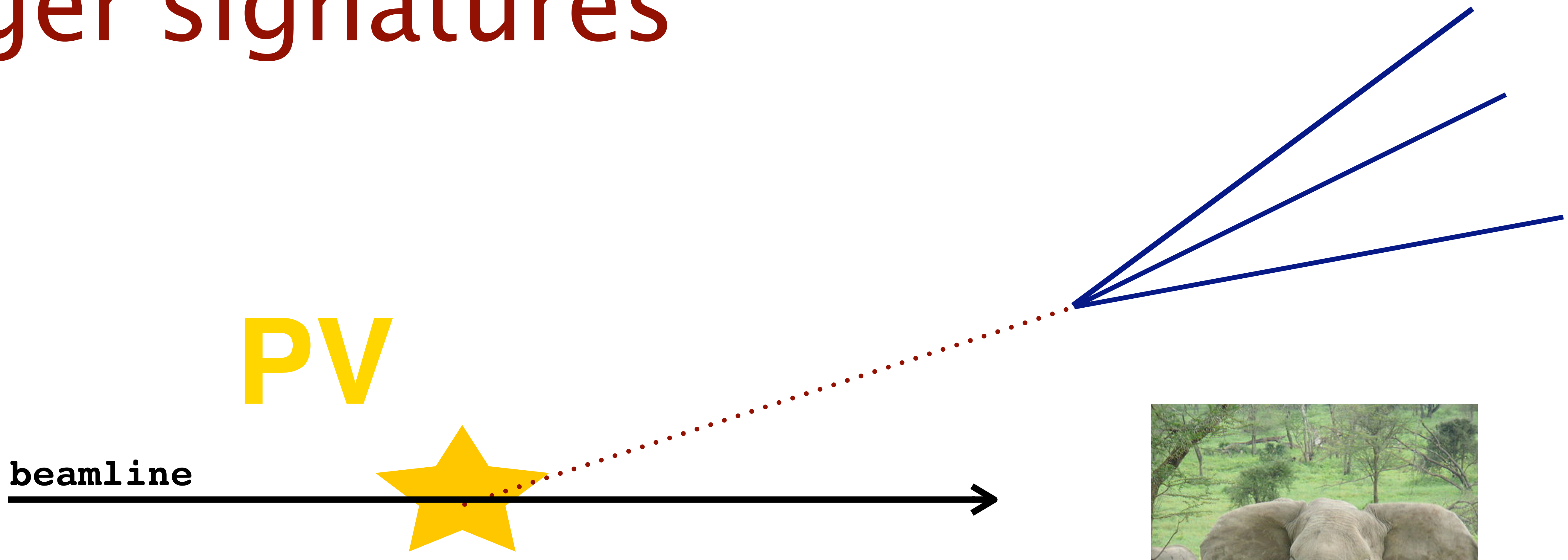


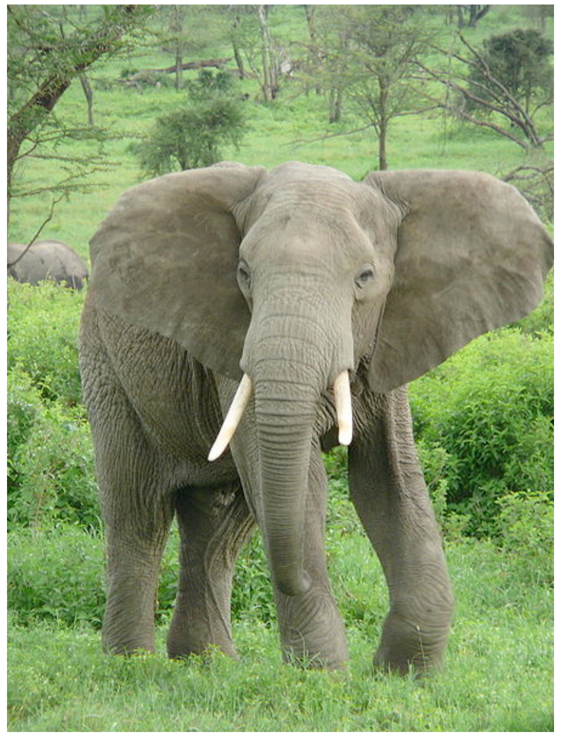
More than a B-factory



More than a B-factory

Trigger signatures





B meson signatures :

- Large child transverse momentum
- Large child impact parameter or vertex displacement
- DiMuon candidate

"A B is the elephant of the particle zoo: it is very heavy and lives a long time" -- T. Schietinger

Real time event selection

1. **Information gathering (“reconstruction”) stage**

Real time event selection

1.

Information gathering
("reconstruction") stage

⇒

Real time event selection

1. **Information gathering ("reconstruction") stage** ⇒ 

⇓

2. **Event selection stage**

Real time event selection

1. Information gathering ("reconstruction") stage ⇒ 

⇓

2. Event selection stage ⇒ Selected | Rejected

Real time event selection

1. Information gathering ("reconstruction") stage ⇒ 

⇓

2. Event selection stage ⇒ Selected | Rejected

⇓

3. Next reconstruction stage ⇒  

⇓

Displaced track trigger

1.

Full reconstruction of tracks in vertex locator

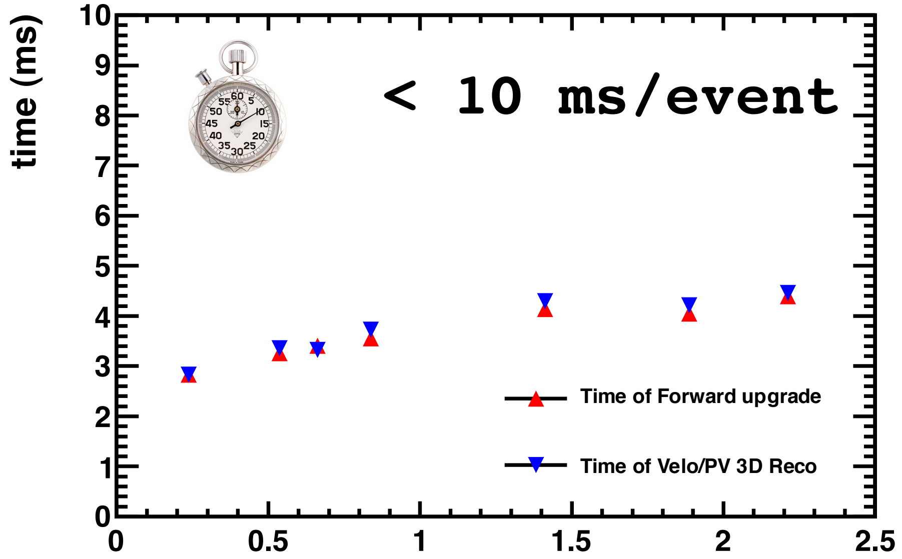
⇓

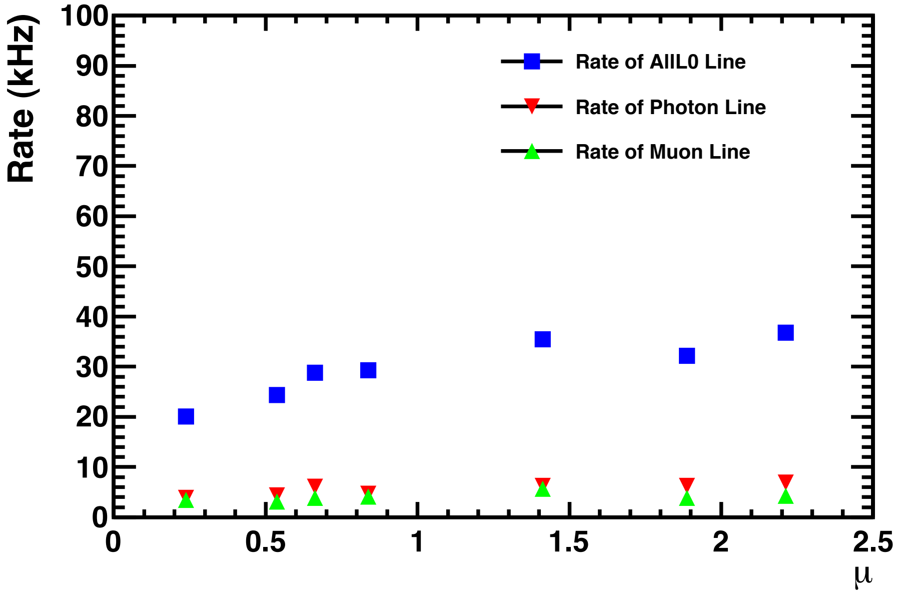
Select displaced tracks

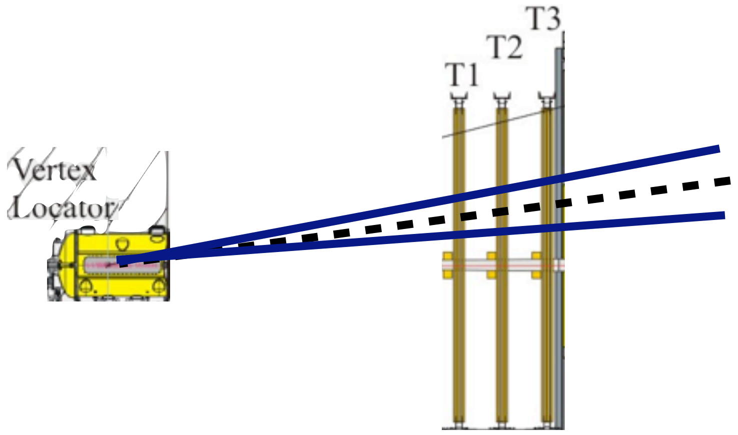
⇓

2.

Reconstruction of displaced tracks in regions of interest

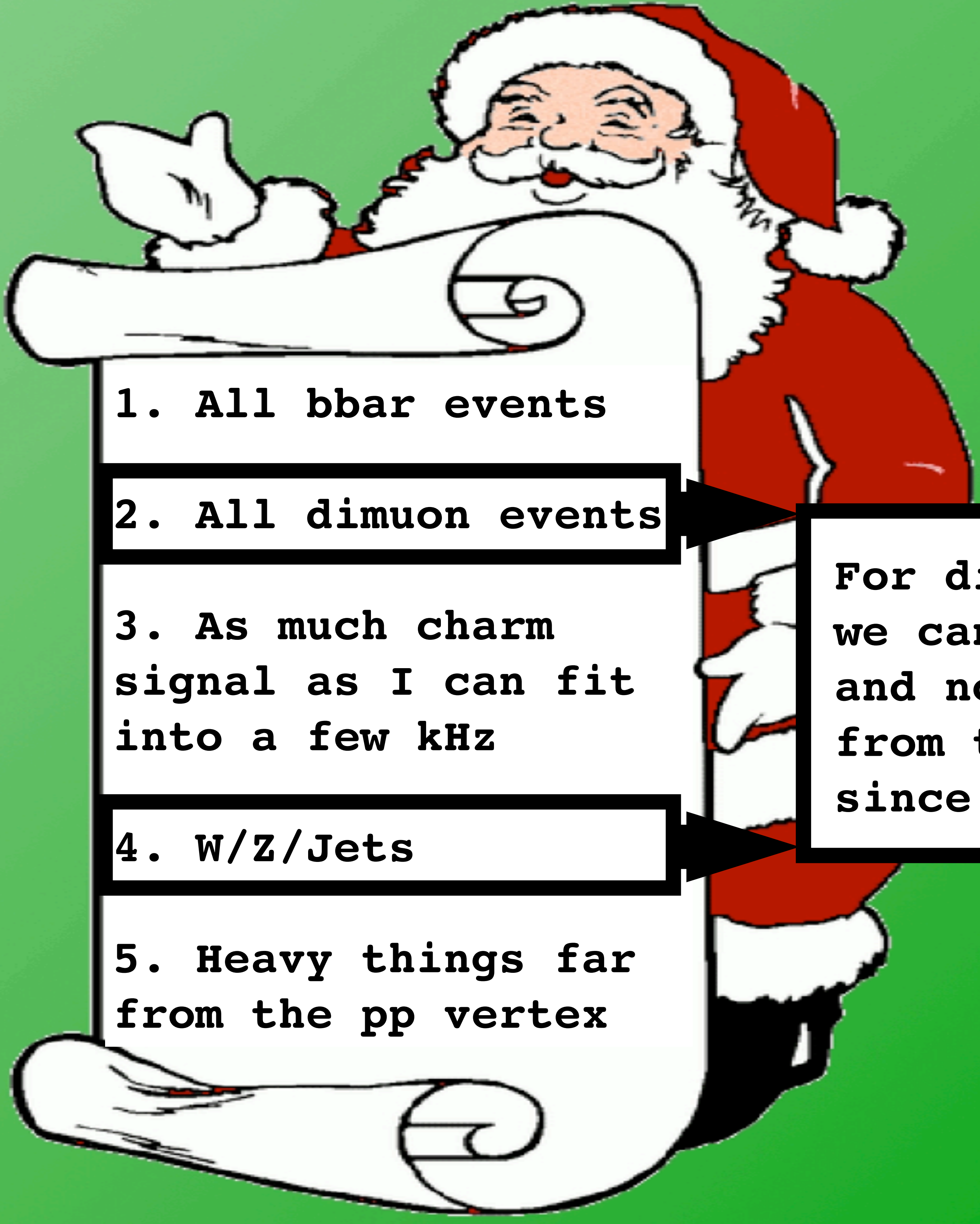






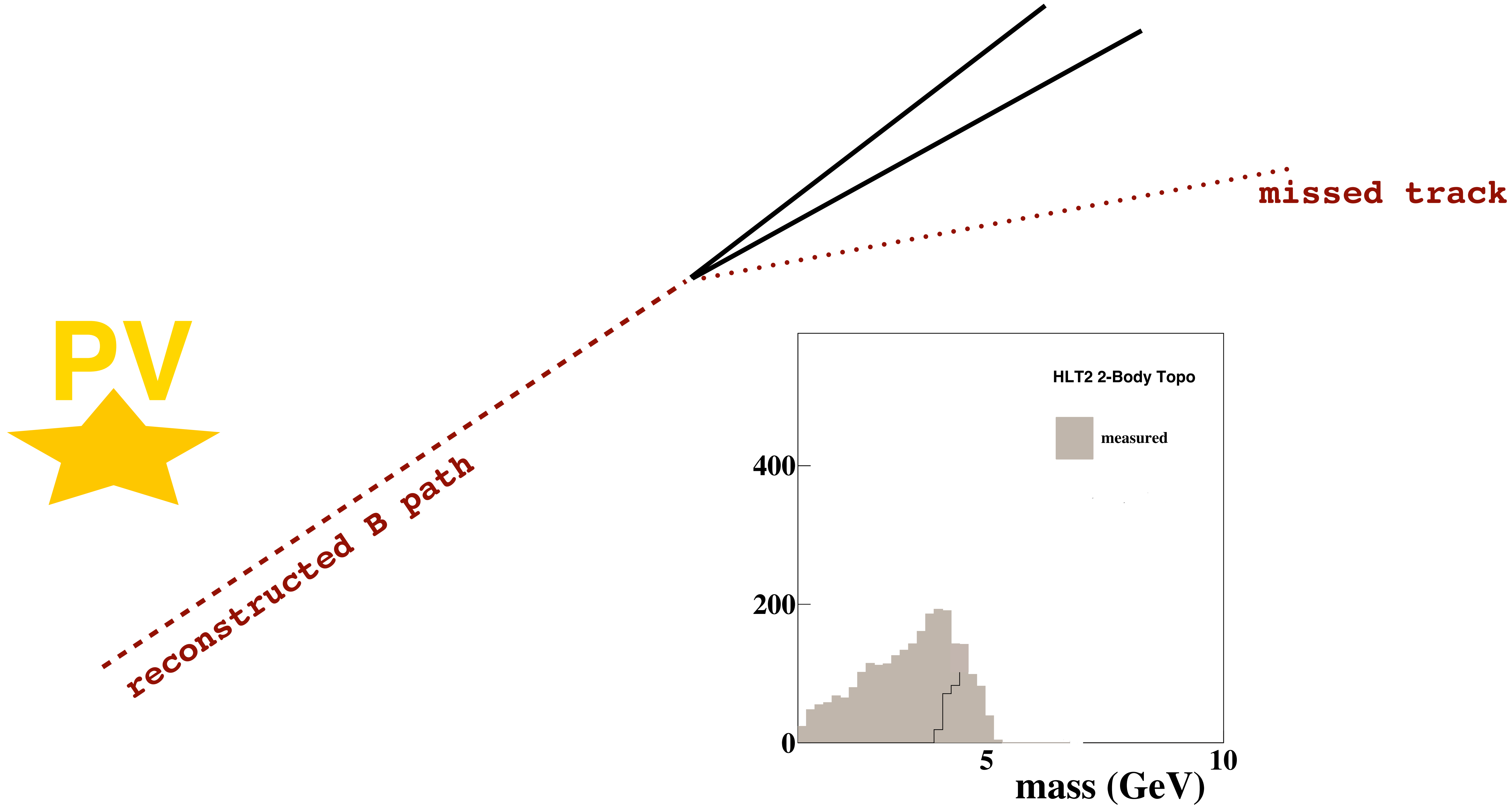
Region of interest defined by assumed track P&P_T

This satisfies almost all the wishlist

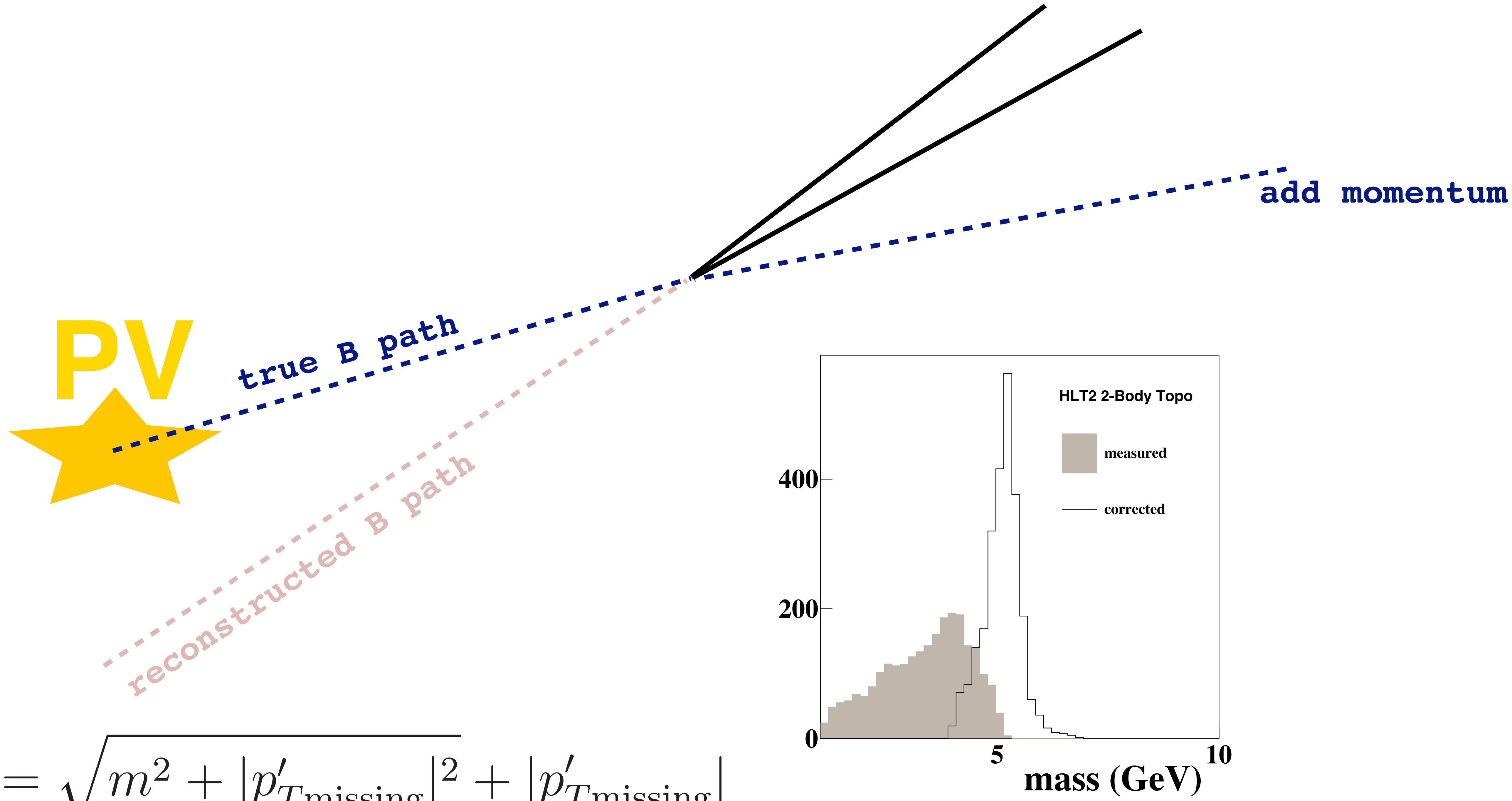


For dimuons and high p_T muons we can be even more inclusive and not require displacement from the primary pp vertex, since they are rare enough

A topological decision tree trigger



A topological decision tree trigger



$$m_{\text{corrected}} = \sqrt{m^2 + |p'_{T\text{missing}}|^2} + |p'_{T\text{missing}}|$$

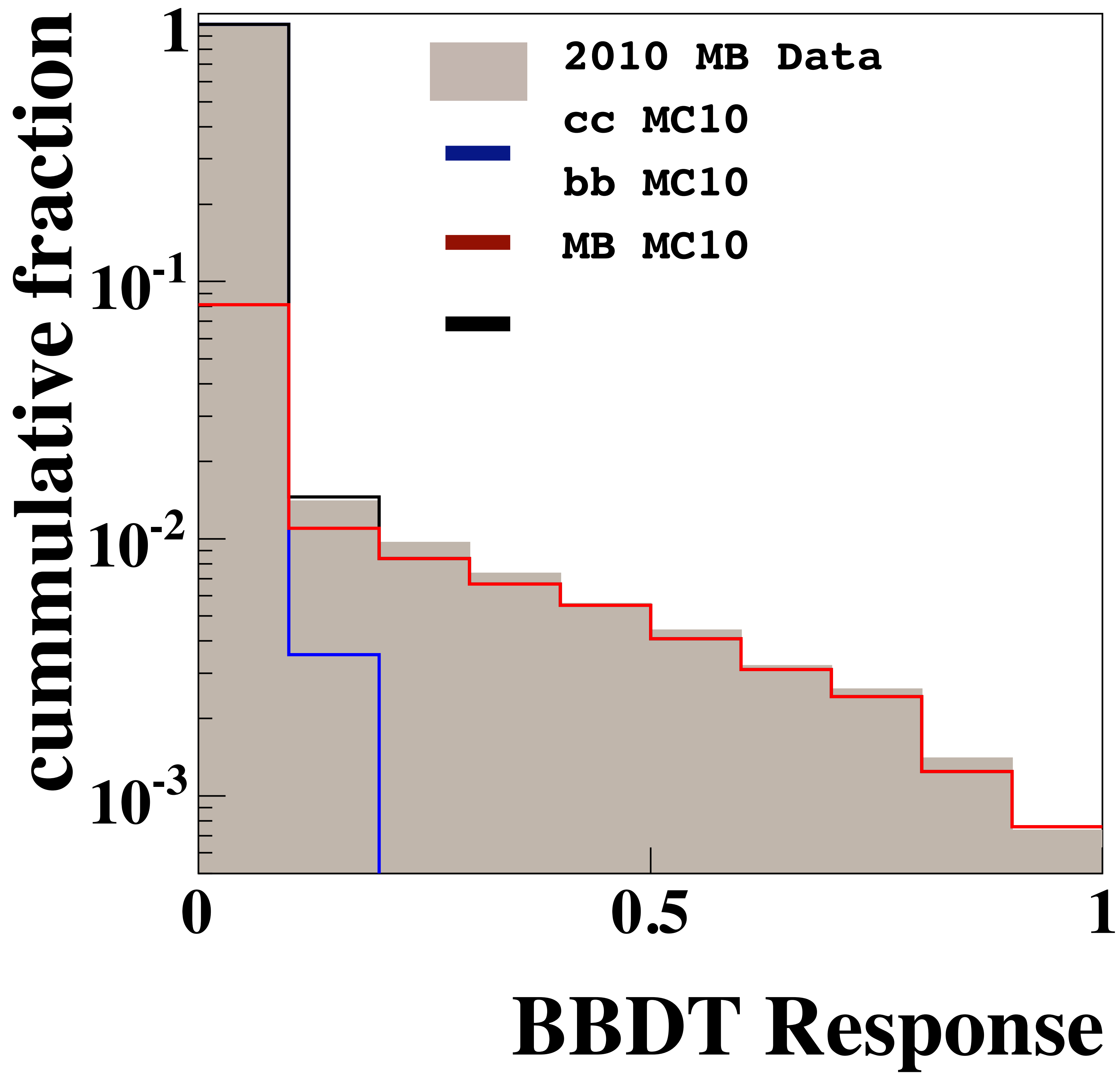
A topological decision tree trigger

The corrected mass goes into a multivariate algorithm to ensure both maximum background suppression and maximum inclusiveness.

For example, events with high enough p_T are always accepted.

Measured output is almost 100% consistent with bbar events.

We also have dedicated charm triggers, ask me if you want to know more about these!



See also LHCb public notes and trigger publications
LHCb-PUB-2011-002,003,016
http://arxiv.org/abs/1310.8544
http://arxiv.org/abs/1211.3055

Gligorov&Williams http://arxiv.org/abs/1210.6861

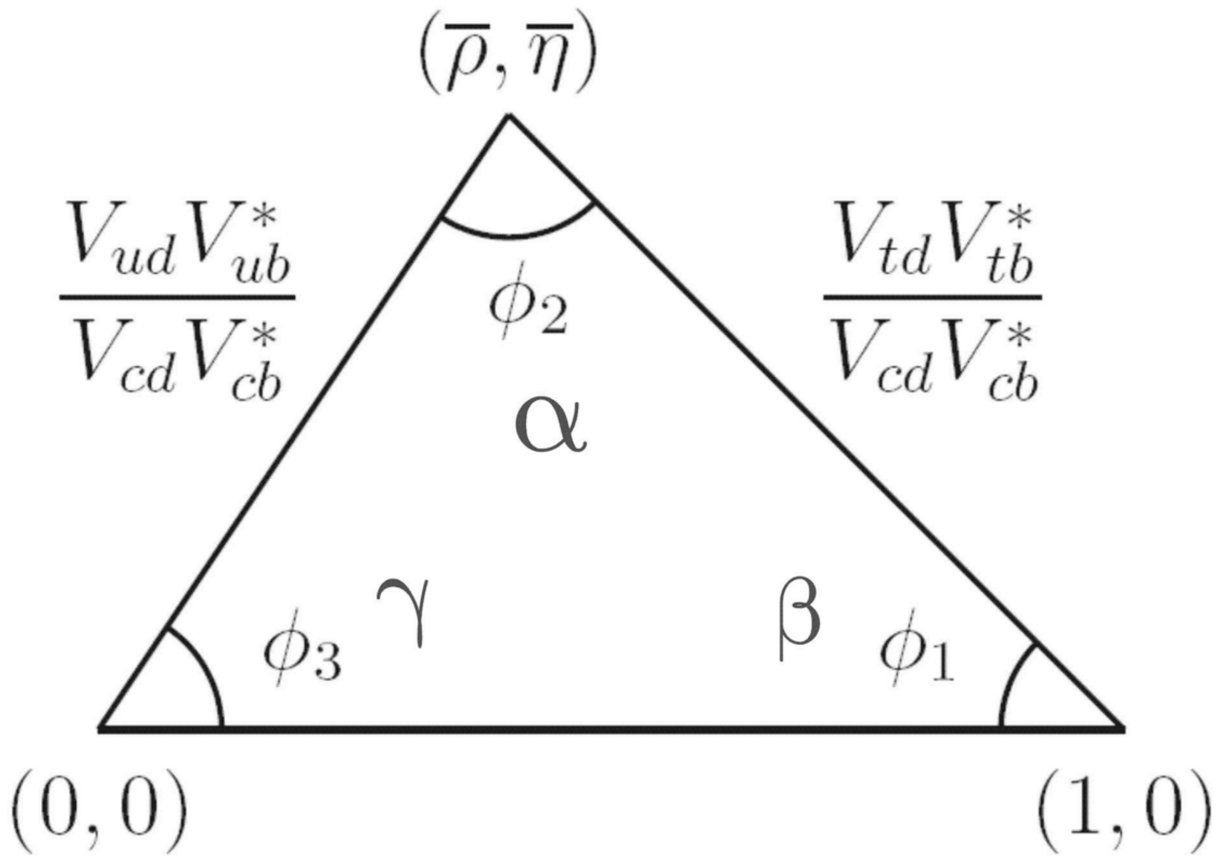
The CKM matrix aka finding Waldo

The CKM matrix

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

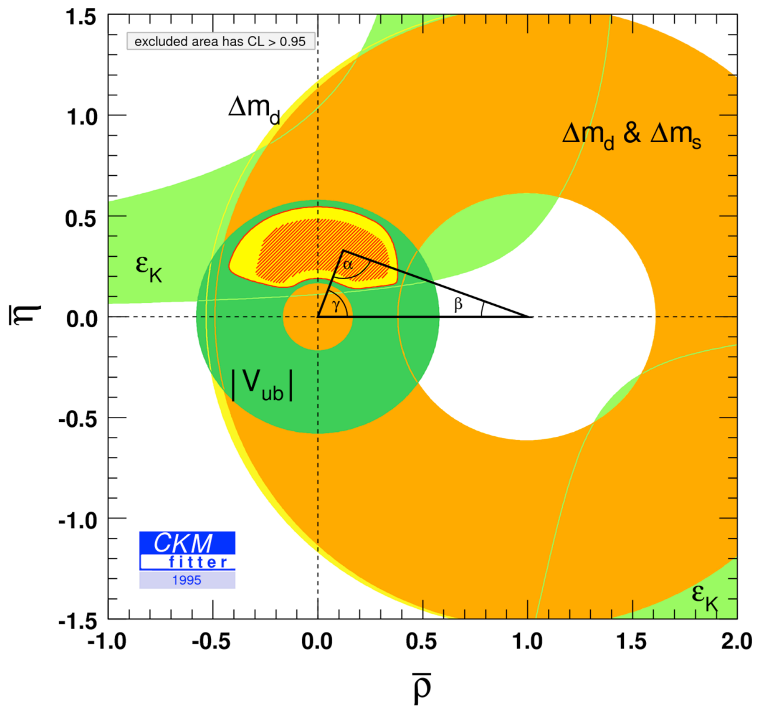
$$\mathbf{V_{CKM}} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \sum_{n=4}^{N} O(\lambda^n)$$

As a triangle



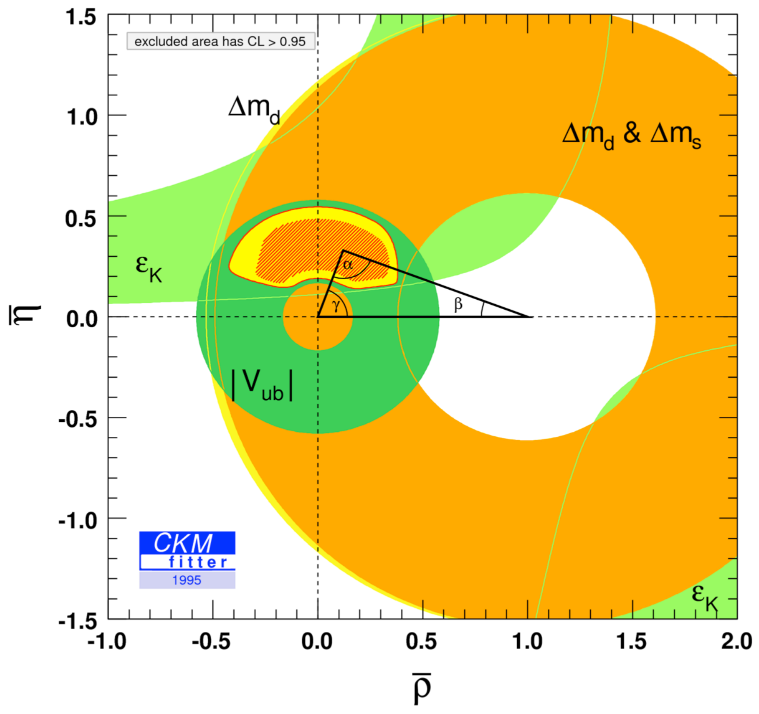
Experimental status through the years

1995

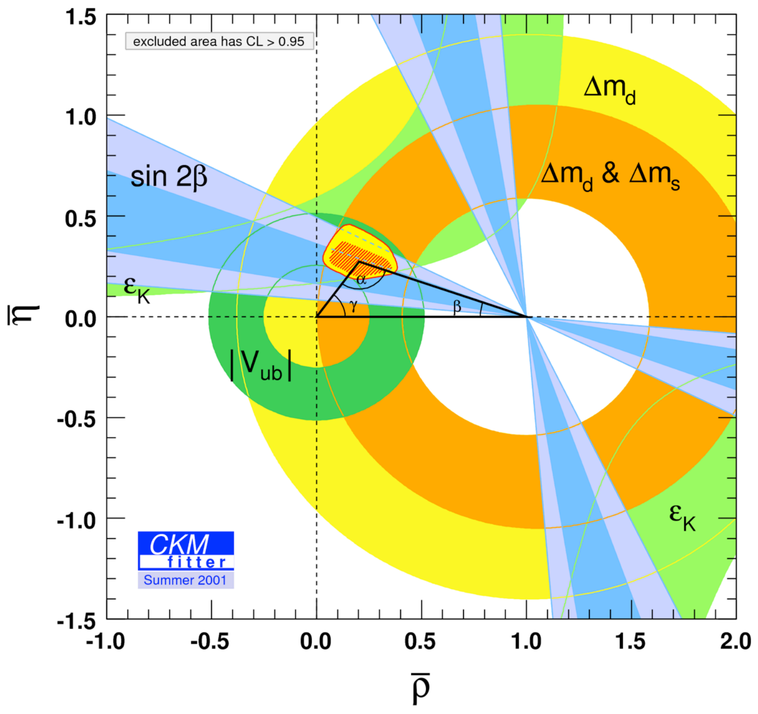


Experimental status through the years

1995

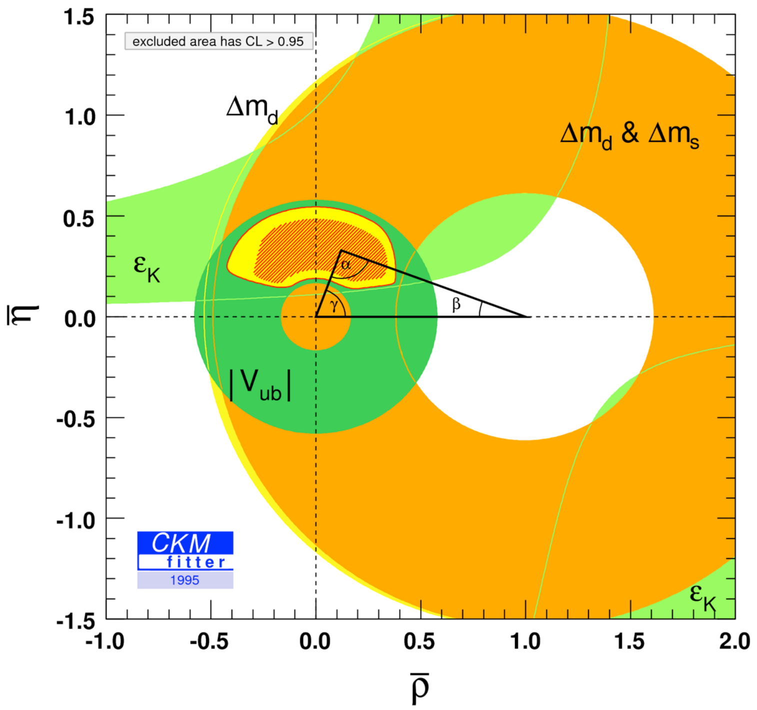


2001

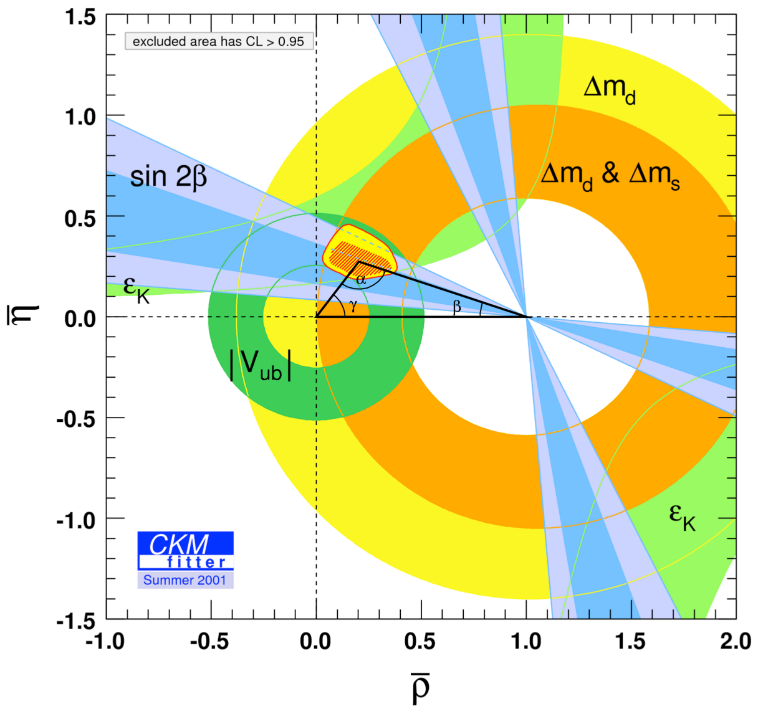


Experimental status through the years

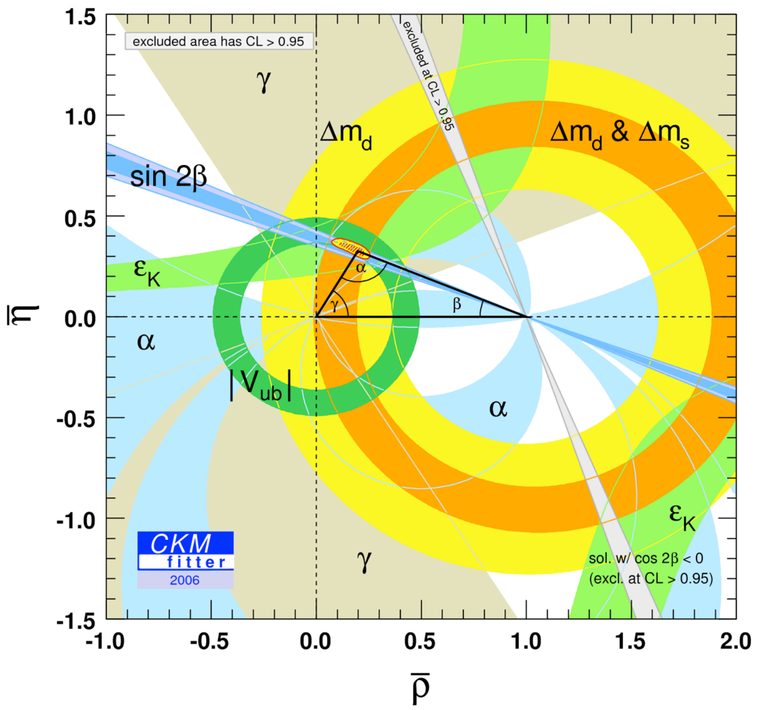
1995



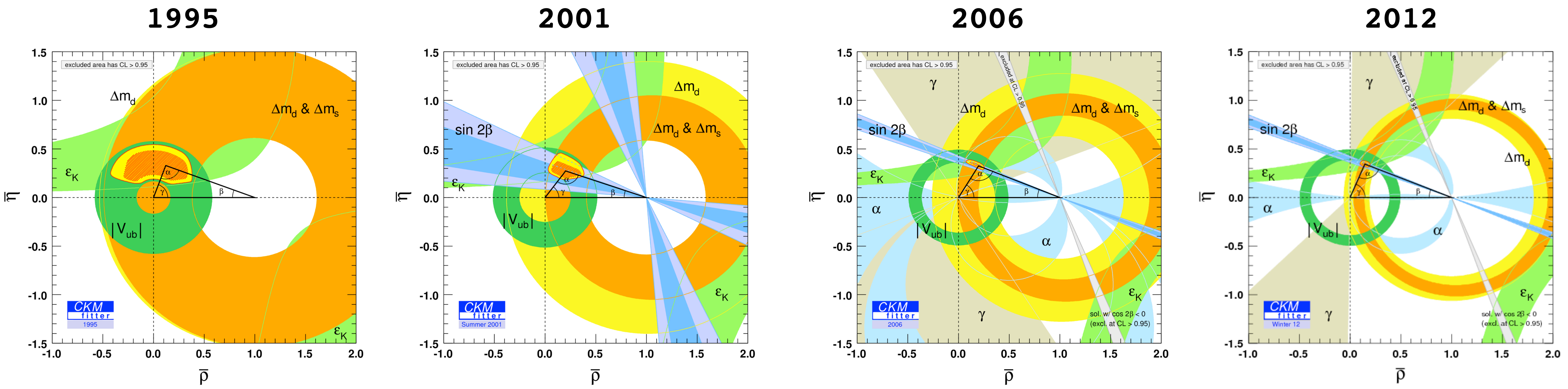
2001



2006

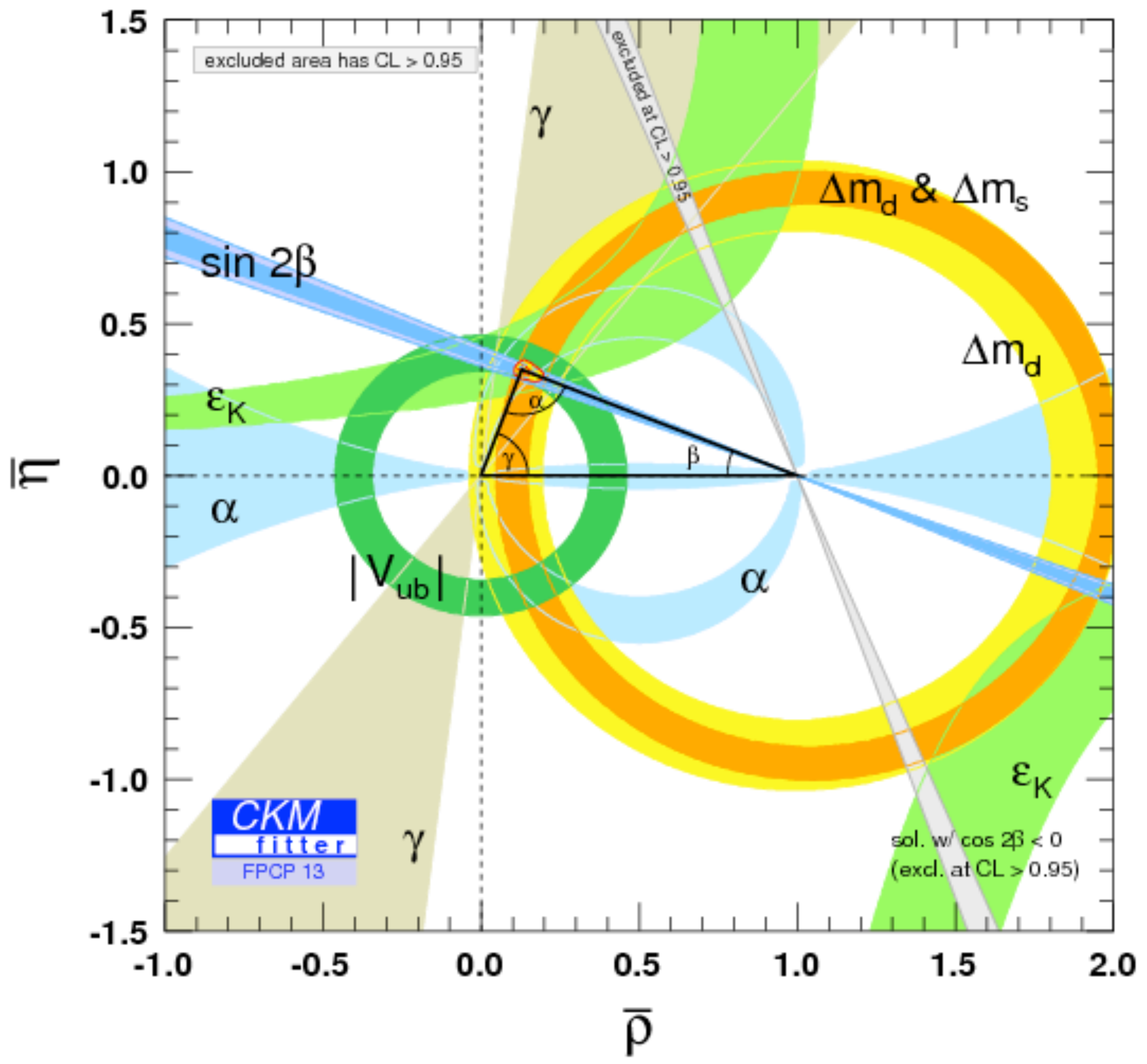


Experimental status through the years

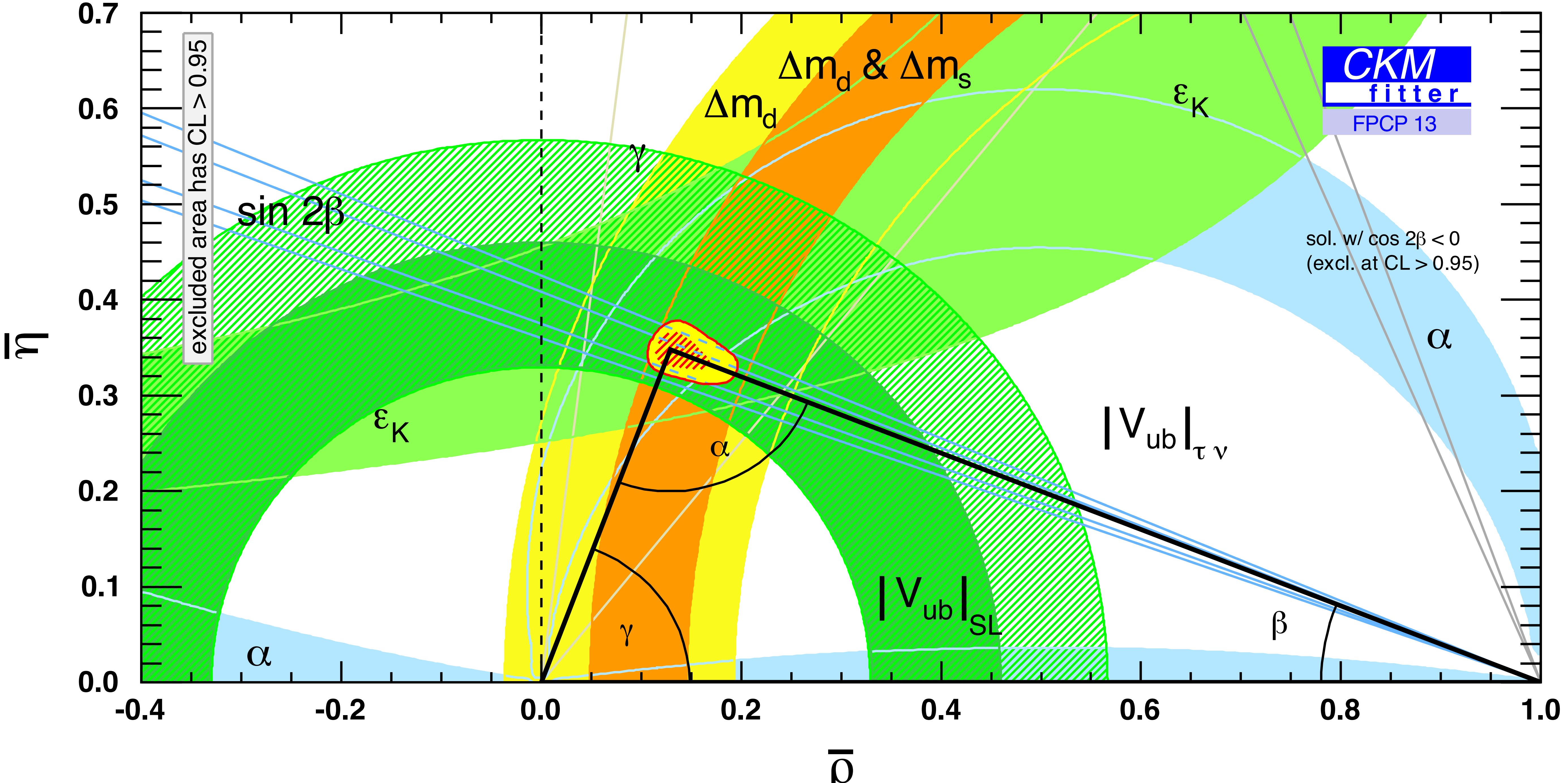


Further "experimental" evidence for interest in CKM matrix : Nobel prize...

The CKM triangle “state of the art”…



Zooming in on the apex



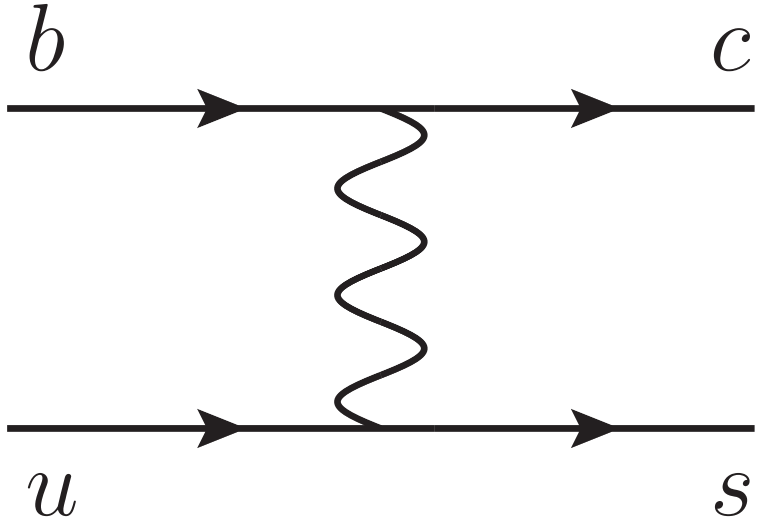
Why does the apex matter?

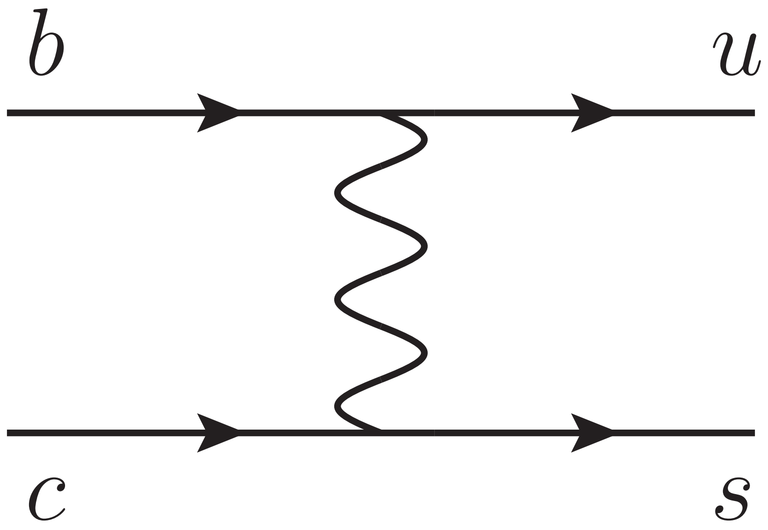
1. We know that Standard Model CP violation (through CKM matrix) cannot explain baryogenesis : we need new sources of CP violation.

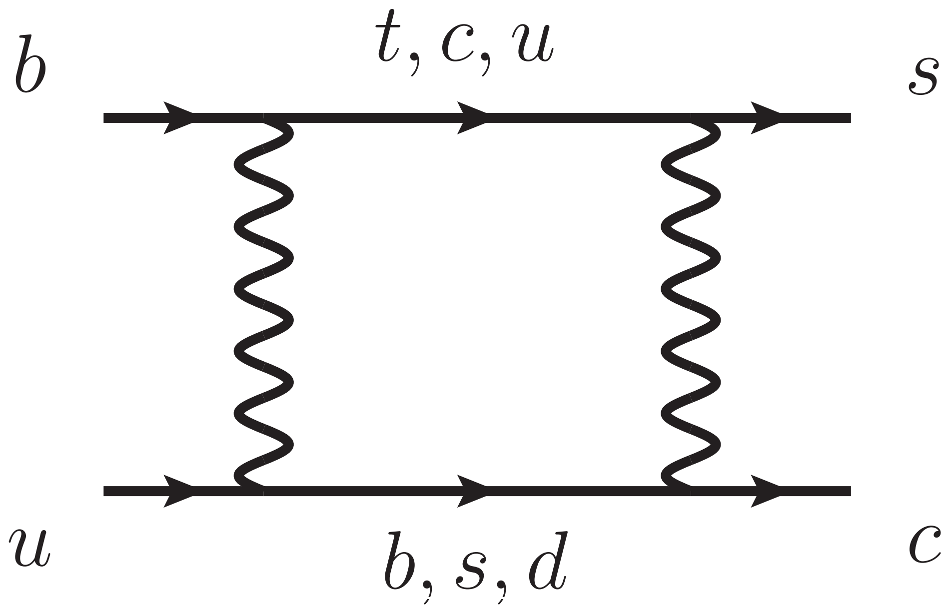
2. These new sources should (generally) affect different observables in different ways.

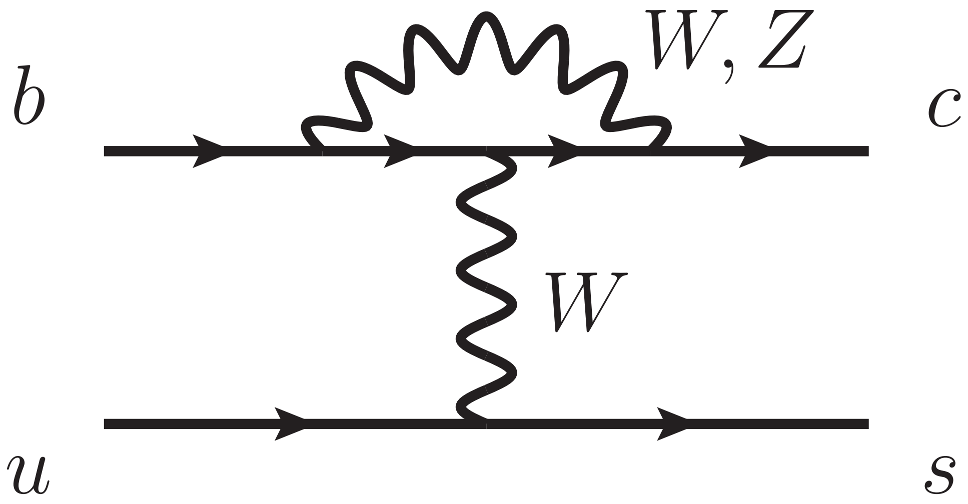
3. Overconstraining the apex therefore tests the consistency of the Standard Model picture of CP violation : we want to know at what level it breaks down.

Ultimate theory error on γ









Zupan, http://arxiv.org/pdf/1101.0134.pdf

What scales does γ probe?

$$|\delta\gamma| \lesssim \mathcal{O}(10^{-7})$$

Probe	Λ_{NP} for (N)MFV NP	Λ_{NP} for gen. FV NP	$B\overline{B}$ pairs
γ from $B \to DK$ [1]	$\Lambda \sim \mathcal{O}(10^2\ \text{TeV})$	$\Lambda \sim \mathcal{O}(10^3\ \text{TeV})$	$\sim 10^{18}$
$B \to \tau\nu$ [2]	$\Lambda \sim \mathcal{O}(\ \text{TeV})$	$\Lambda \sim \mathcal{O}(30\ \text{TeV})$	$\sim 10^{13}$
$b \to ss\bar{d}$ [3]	$\Lambda \sim \mathcal{O}(\ \text{TeV})$	$\Lambda \sim \mathcal{O}(10^3\ \text{TeV})$	$\sim 10^{13}$
β from $B \to J/\psi K_S$ [4]	$\Lambda \sim \mathcal{O}(50\ \text{TeV})$	$\Lambda \sim \mathcal{O}(200\ \text{TeV})$	$\sim 10^{12}$
$K - \overline{K}$ mixing [5]	$\Lambda > 0.4$ TeV (6 TeV)	$\Lambda > 10^{3(4)}$ TeV	now

Zupan, http://arxiv.org/pdf/1101.0134.pdf

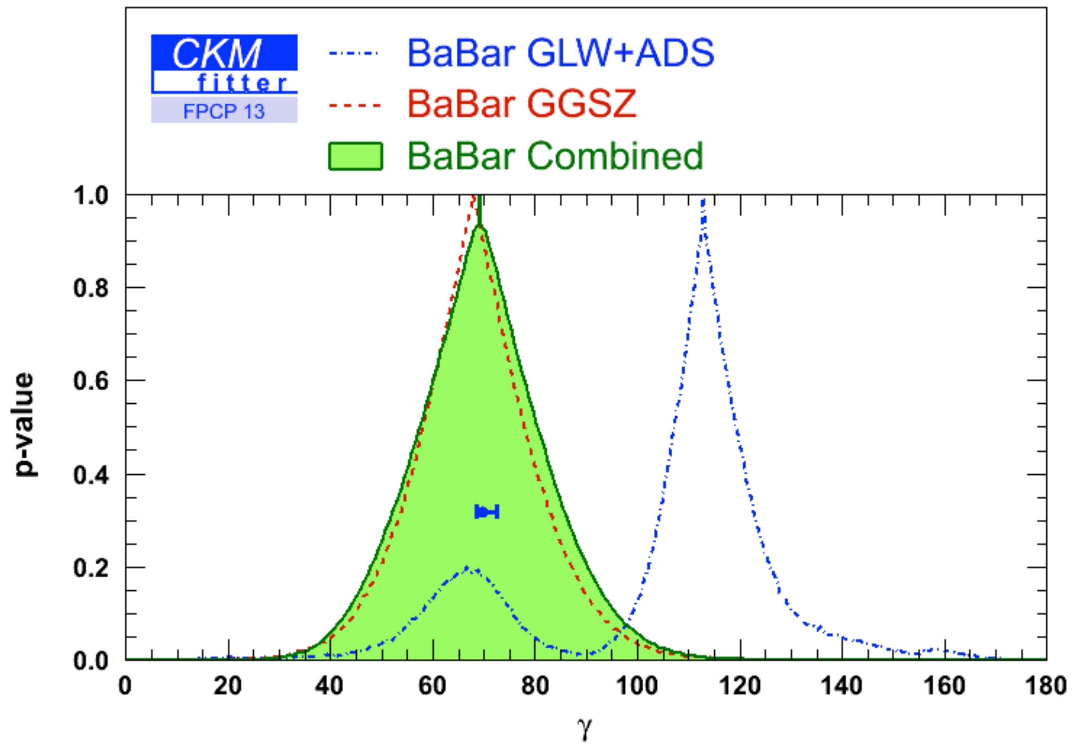
Back to the apex

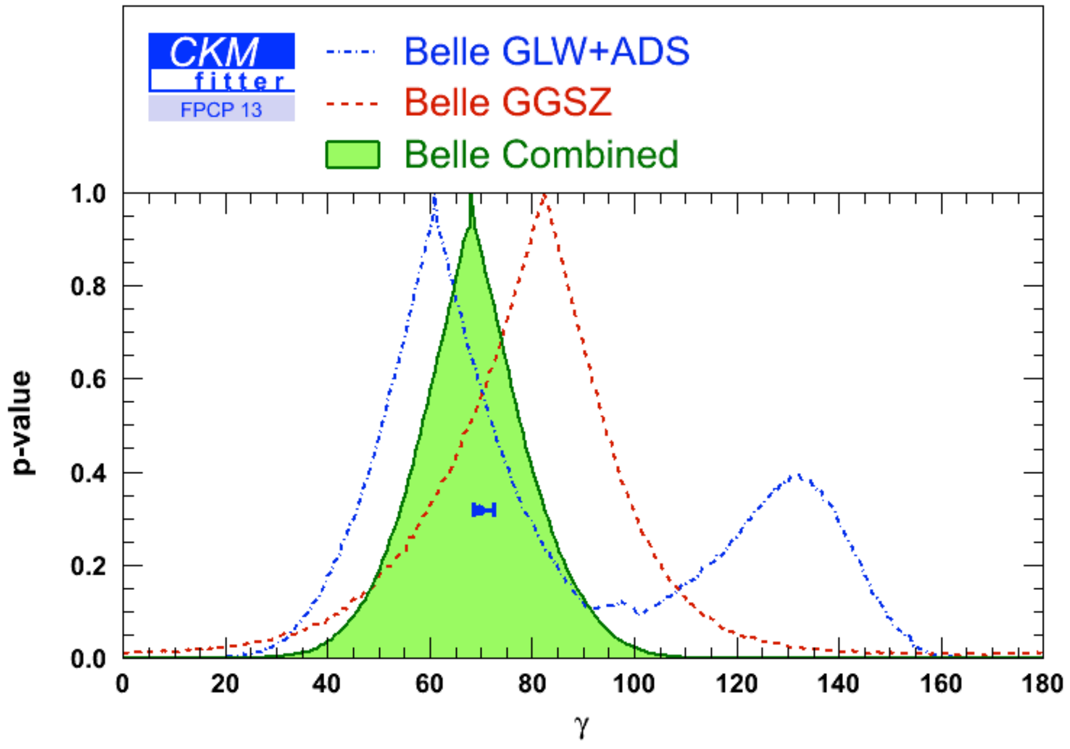
1. Gamma from B→DK measures the tree-level apex.

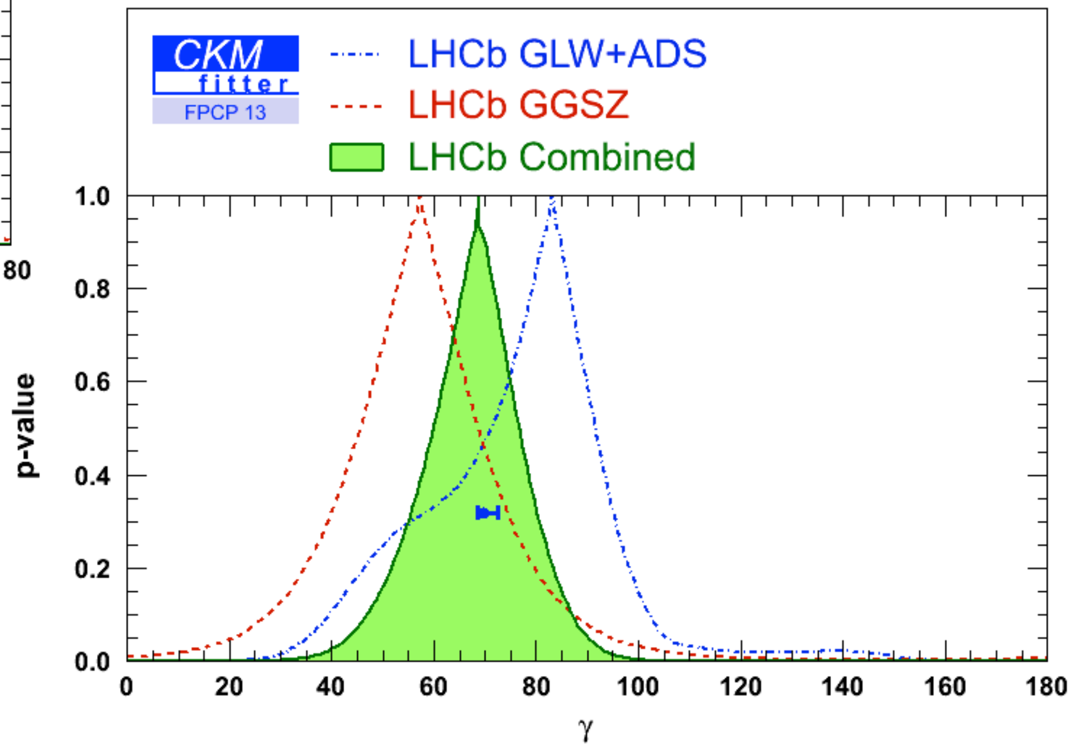
2. Other measurements (including measurements of gamma, e.g. from B→hh) are sensitive to loop diagrams.

=> Any discrepancy allows us to learn about the scale (and maybe the nature) of physics Beyond the Standard Model.

The many faces of γ

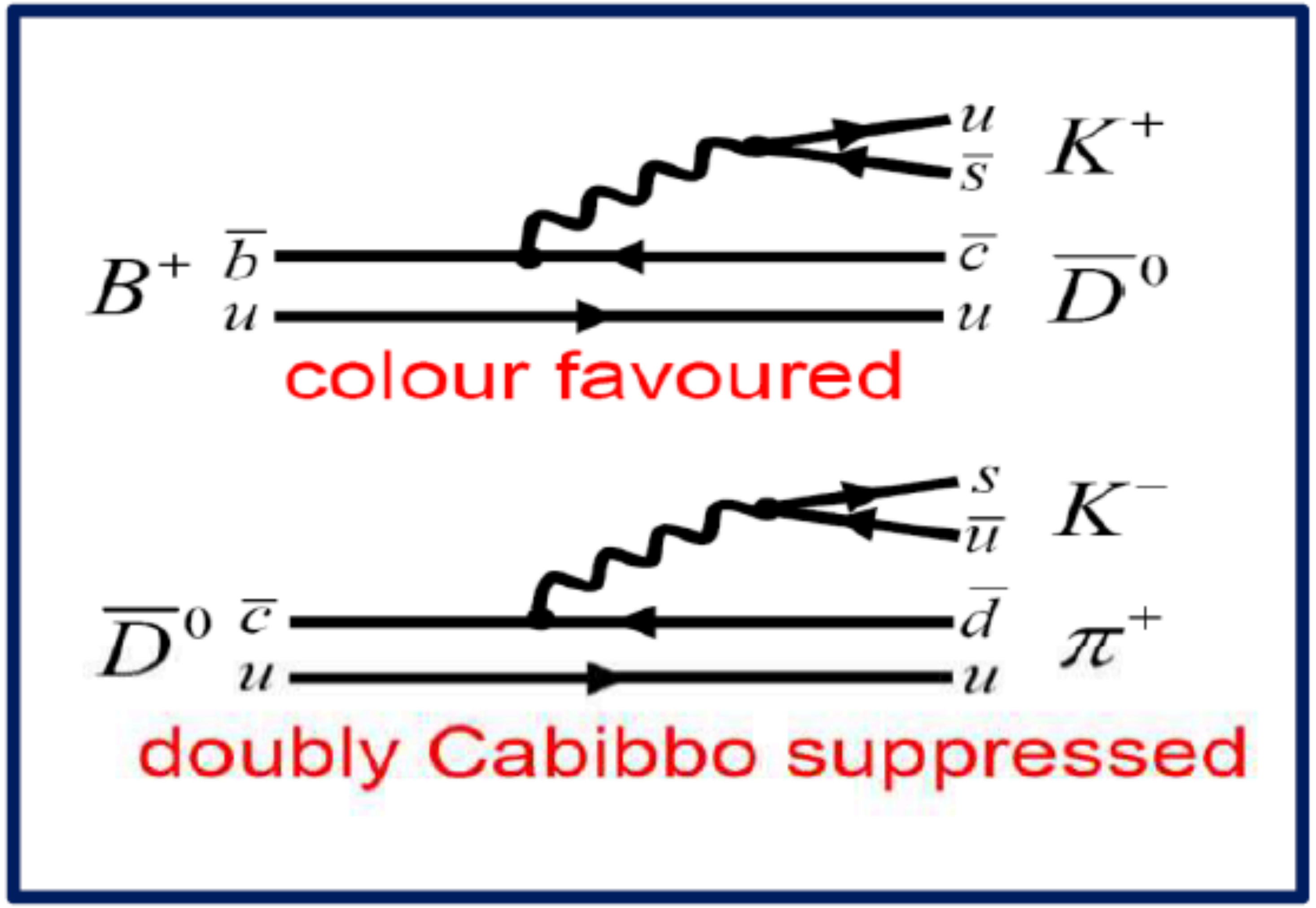


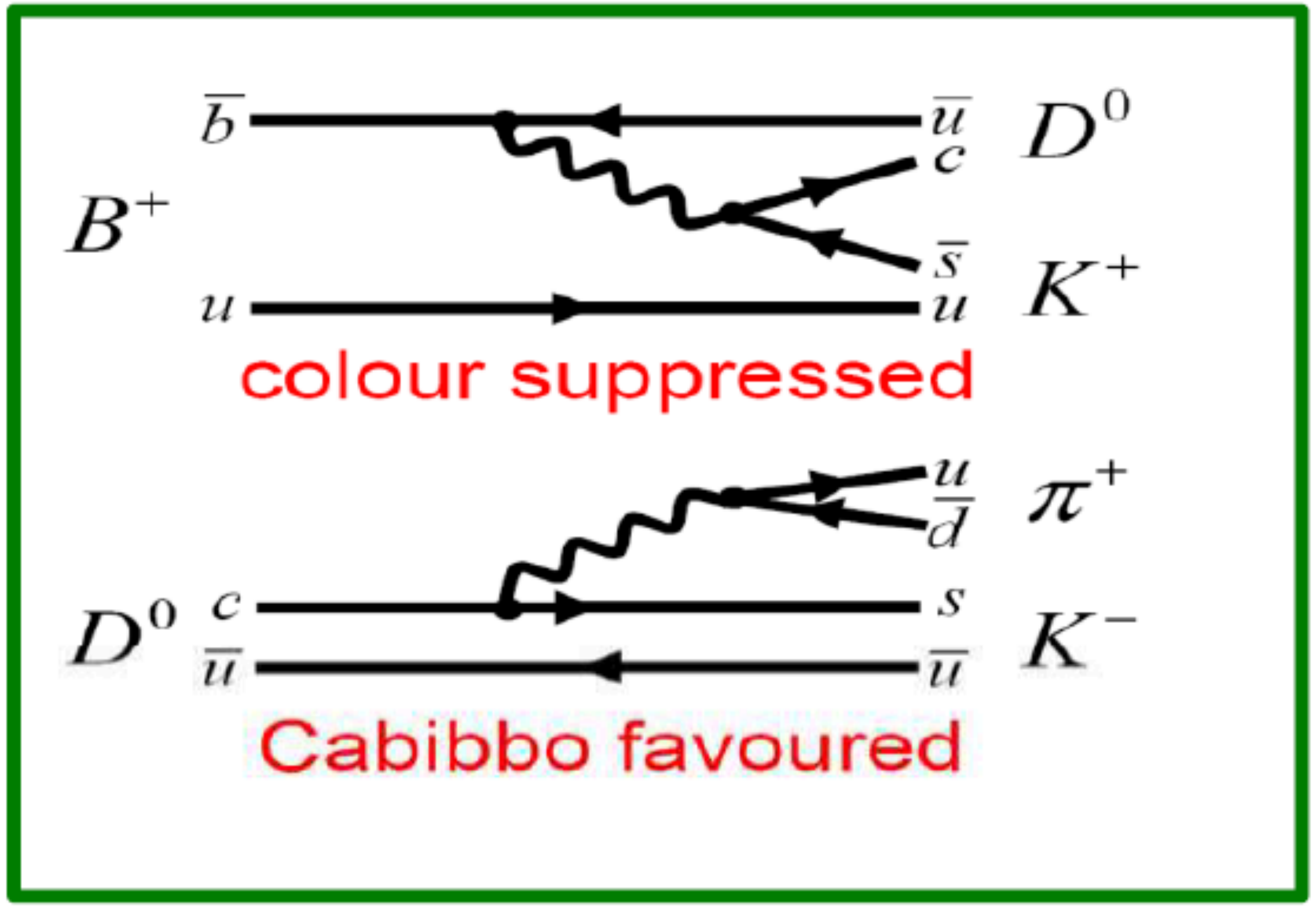




The number of ways in which it is being measured is growing...

But the same basic idea

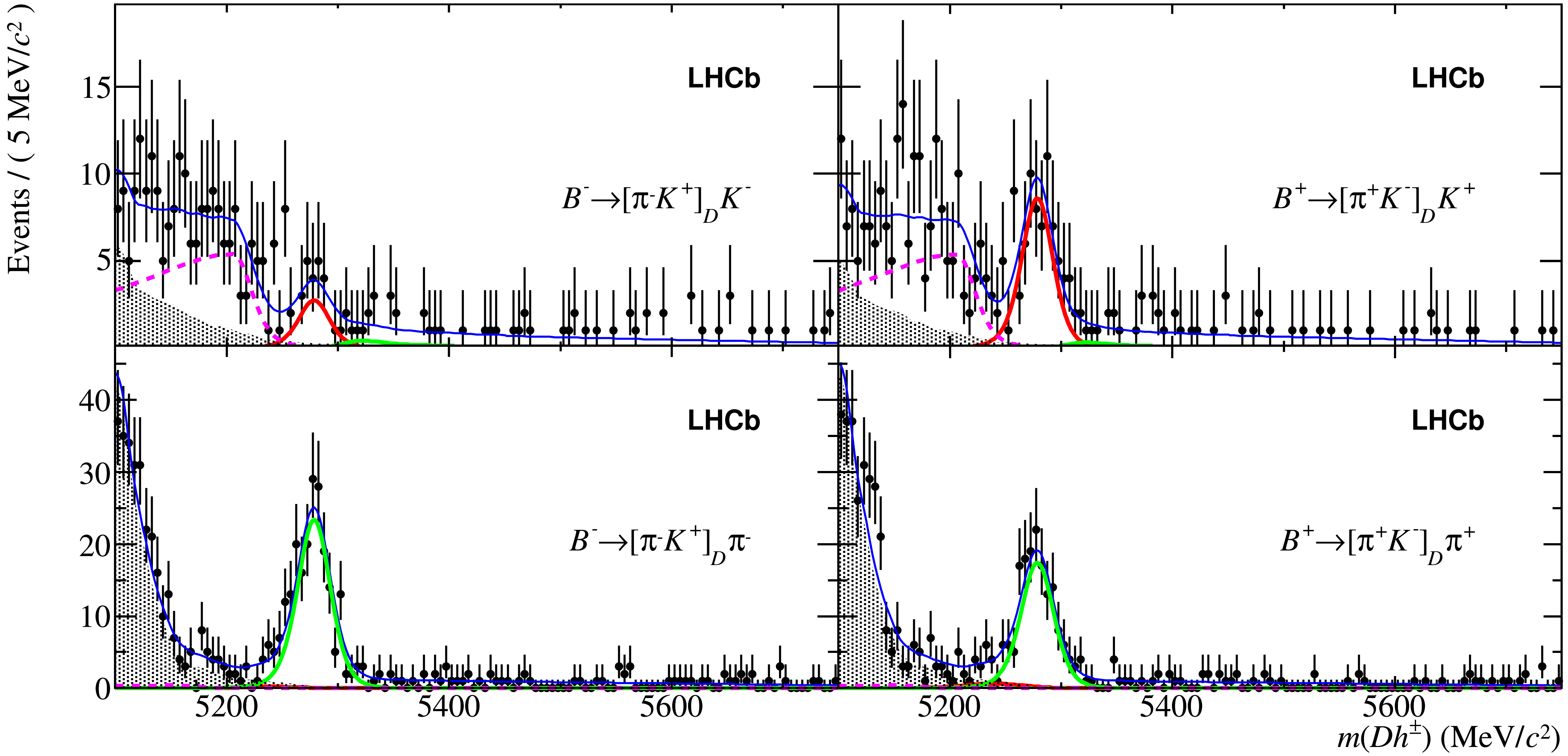




But they all involve interfering V_{ub} and V_{cb} decays to the same final state

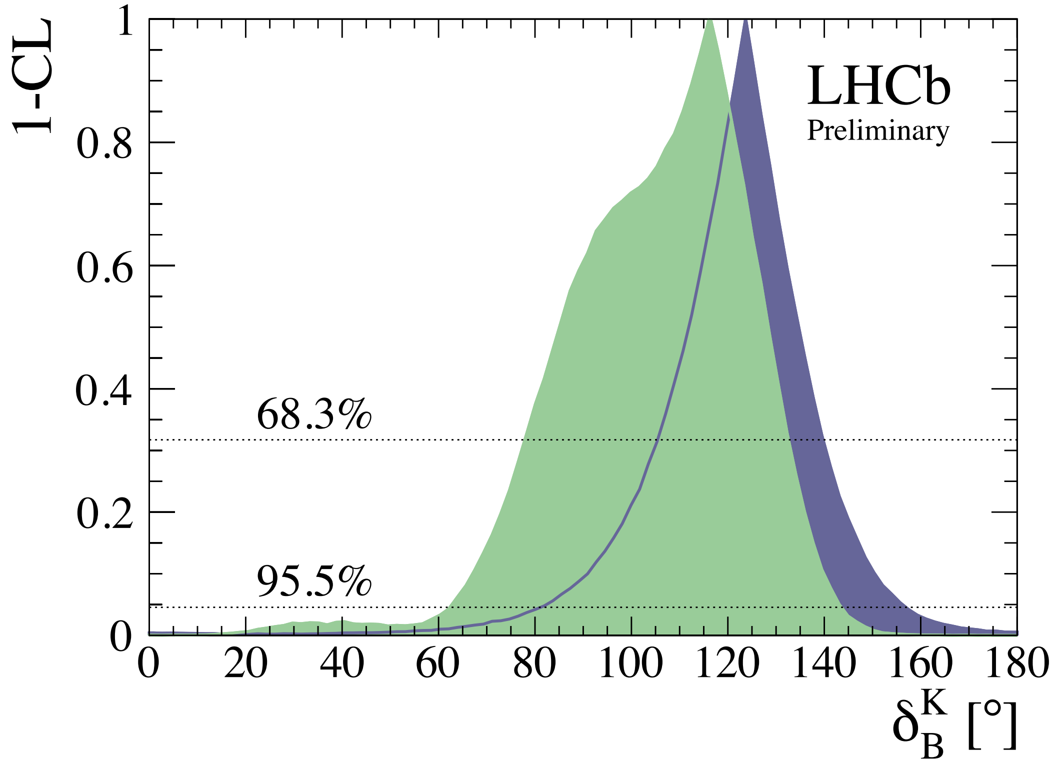
How clean are our signals?

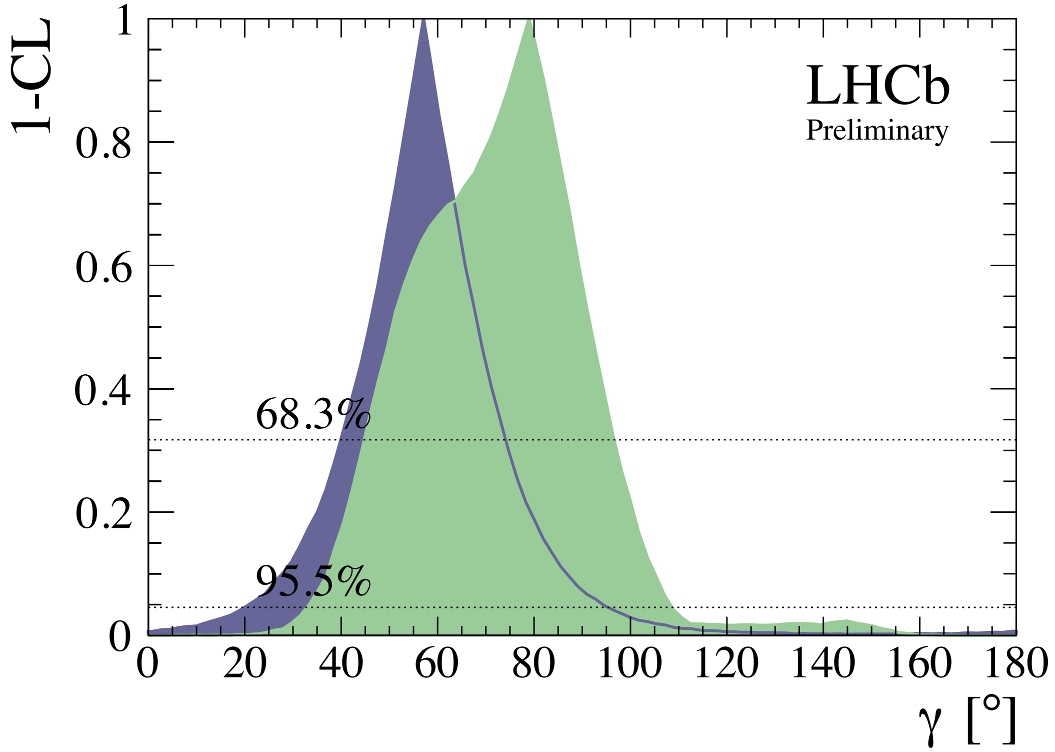
The "ADS" B→DK decay mode, total branching fraction O(10^{-7})

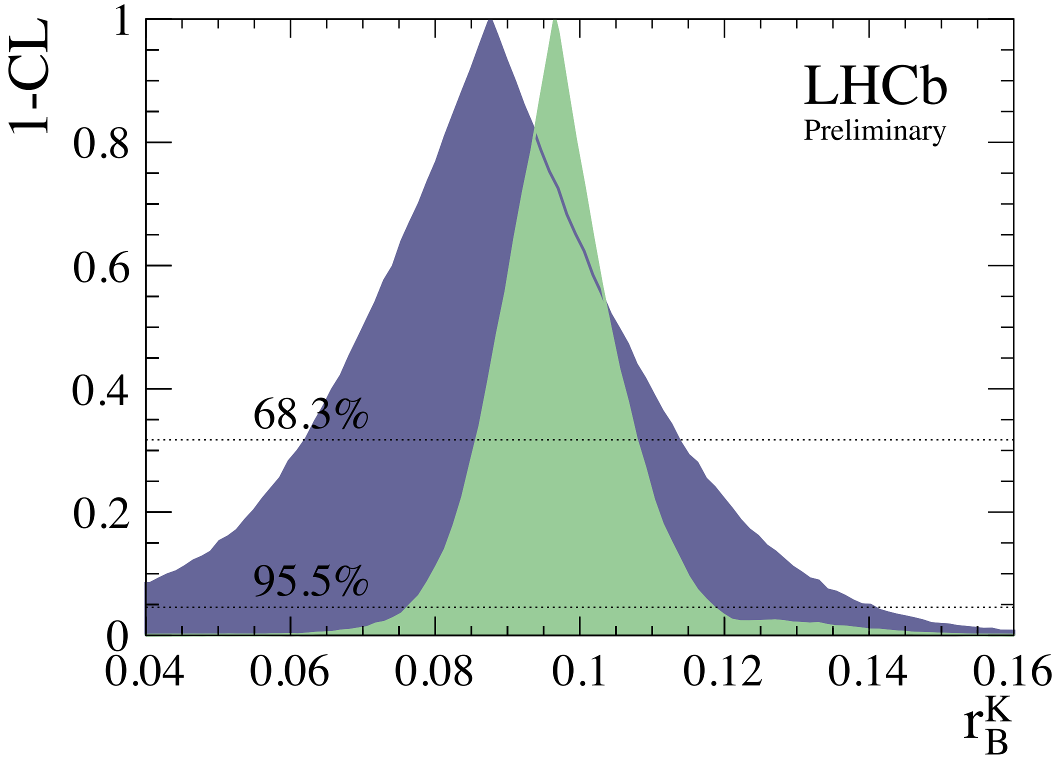


LHCB-PAPER-2012-001

Combining the individual measurements







- ADS/GLW 1 fb^{-1} analysis
- GGSZ 3 fb^{-1} analysis

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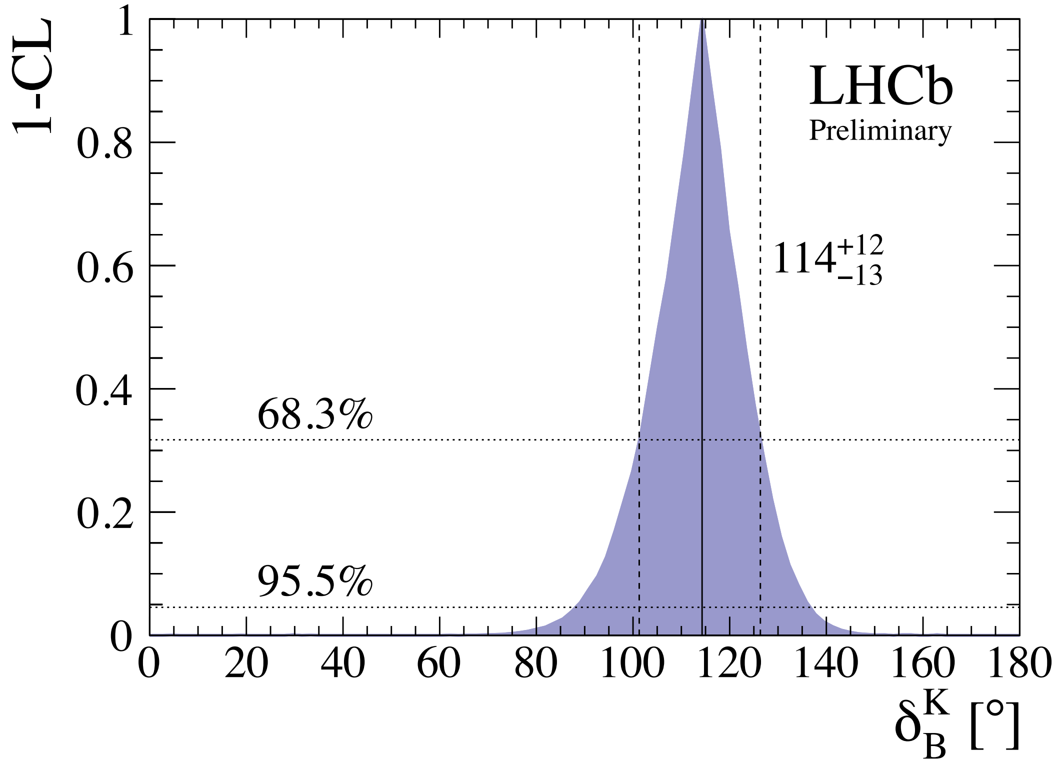
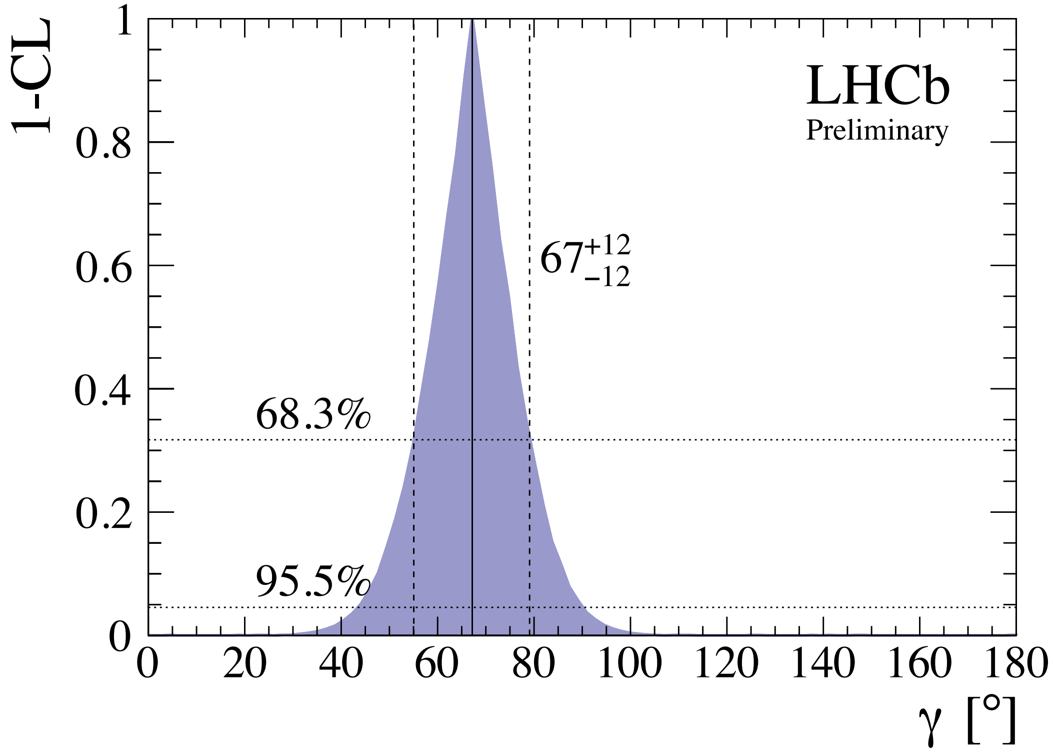
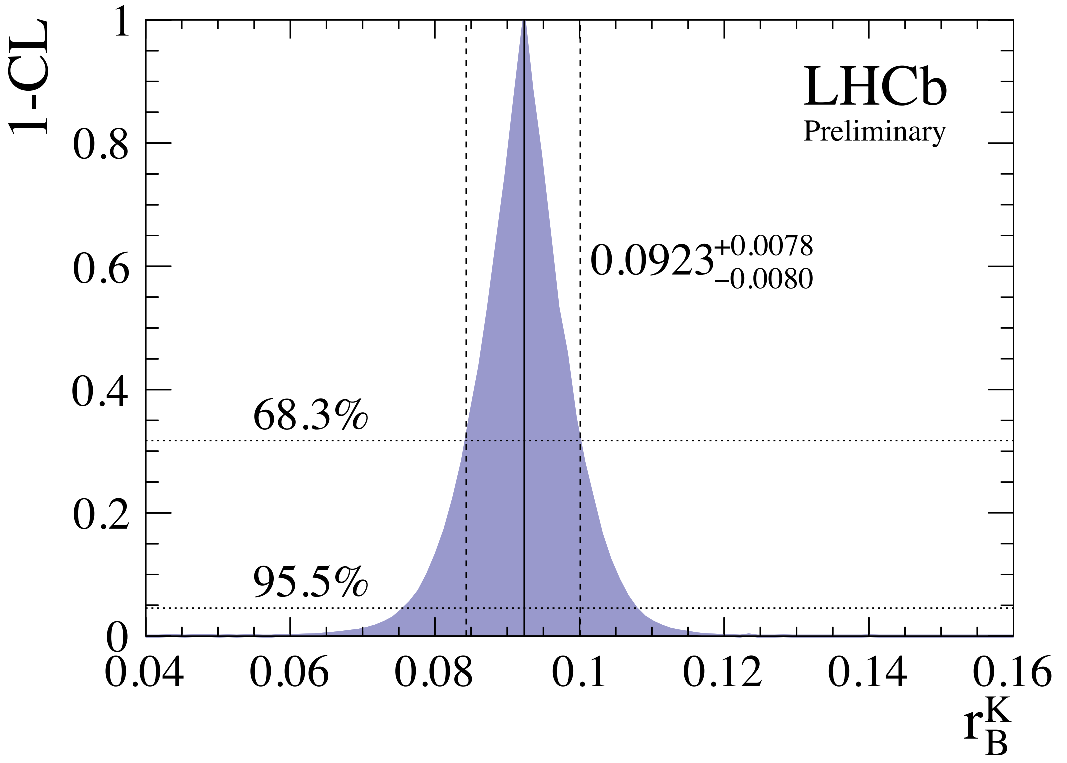
Combining the individual measurements



- Combined 3 fb^{-1} analysis



$\gamma = (67 \pm 12)°$



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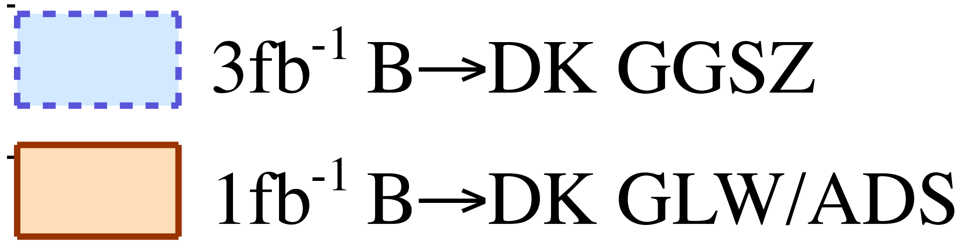
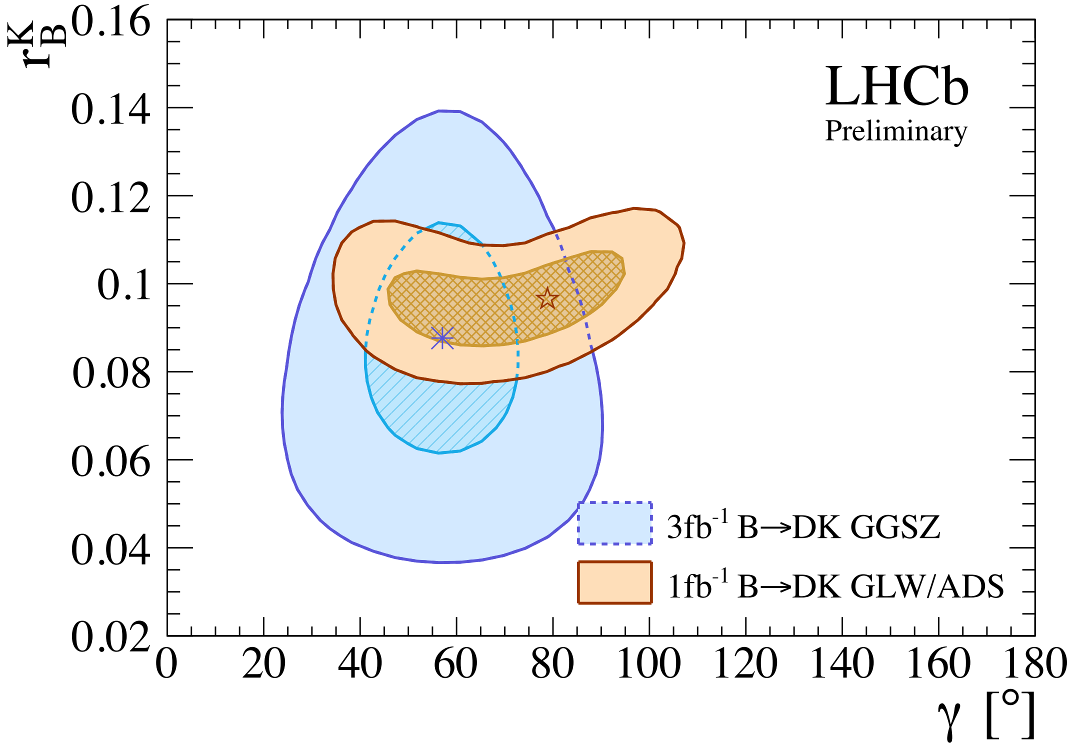
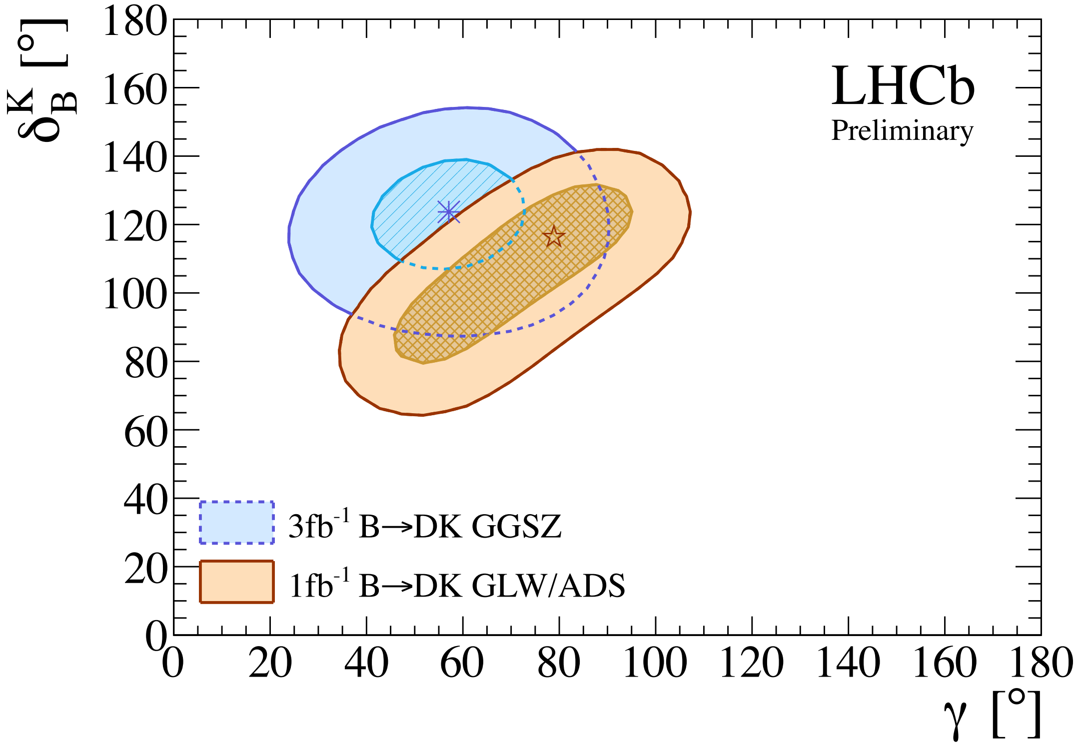
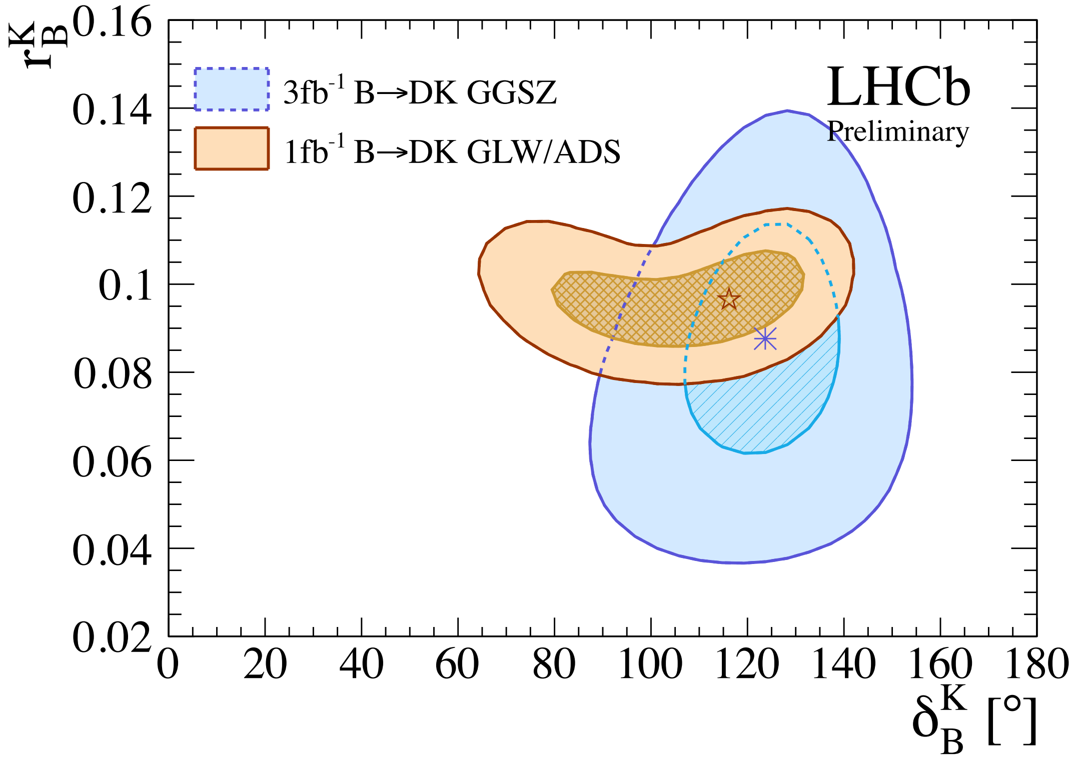
What about the 2D likelihoods?









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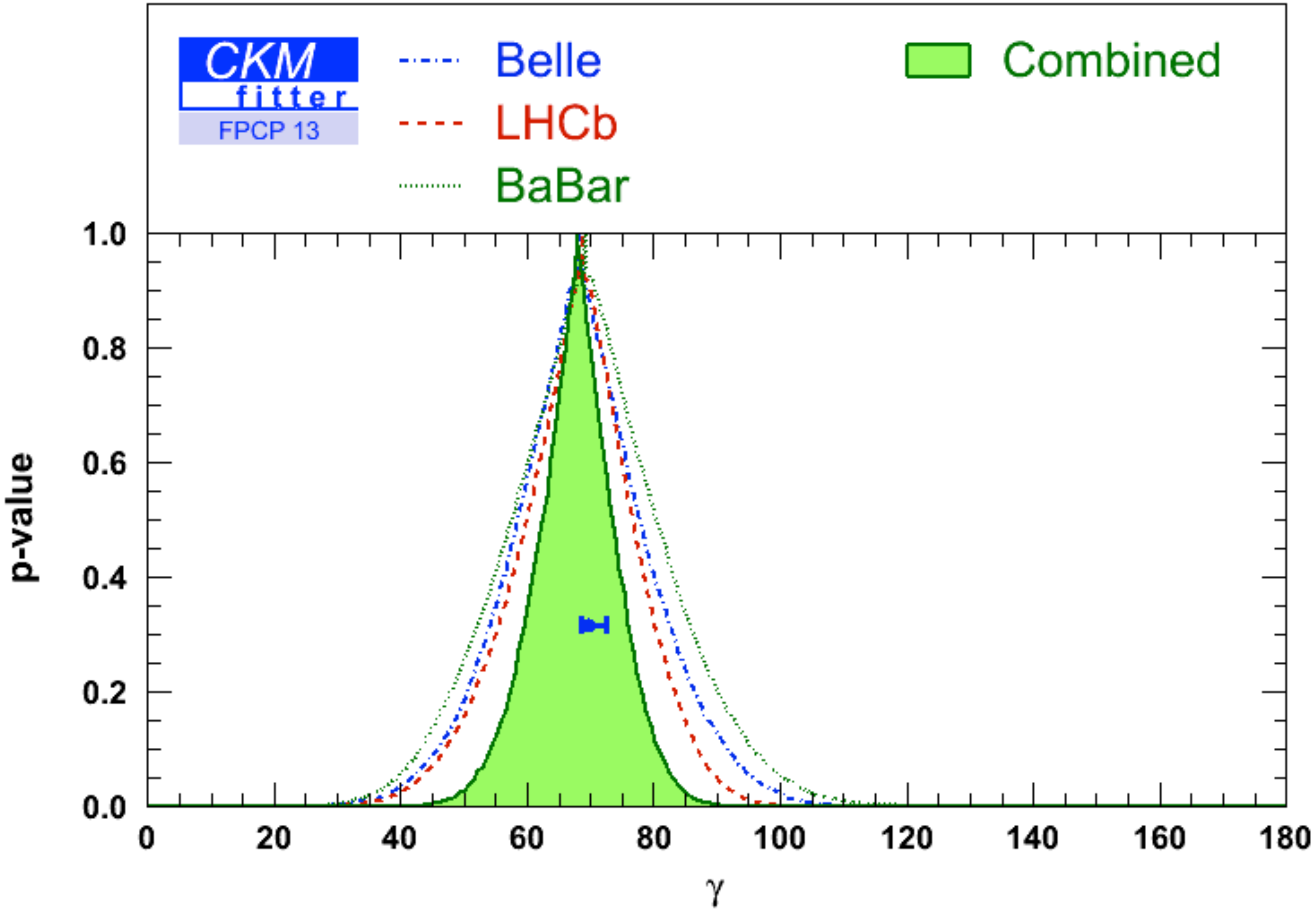
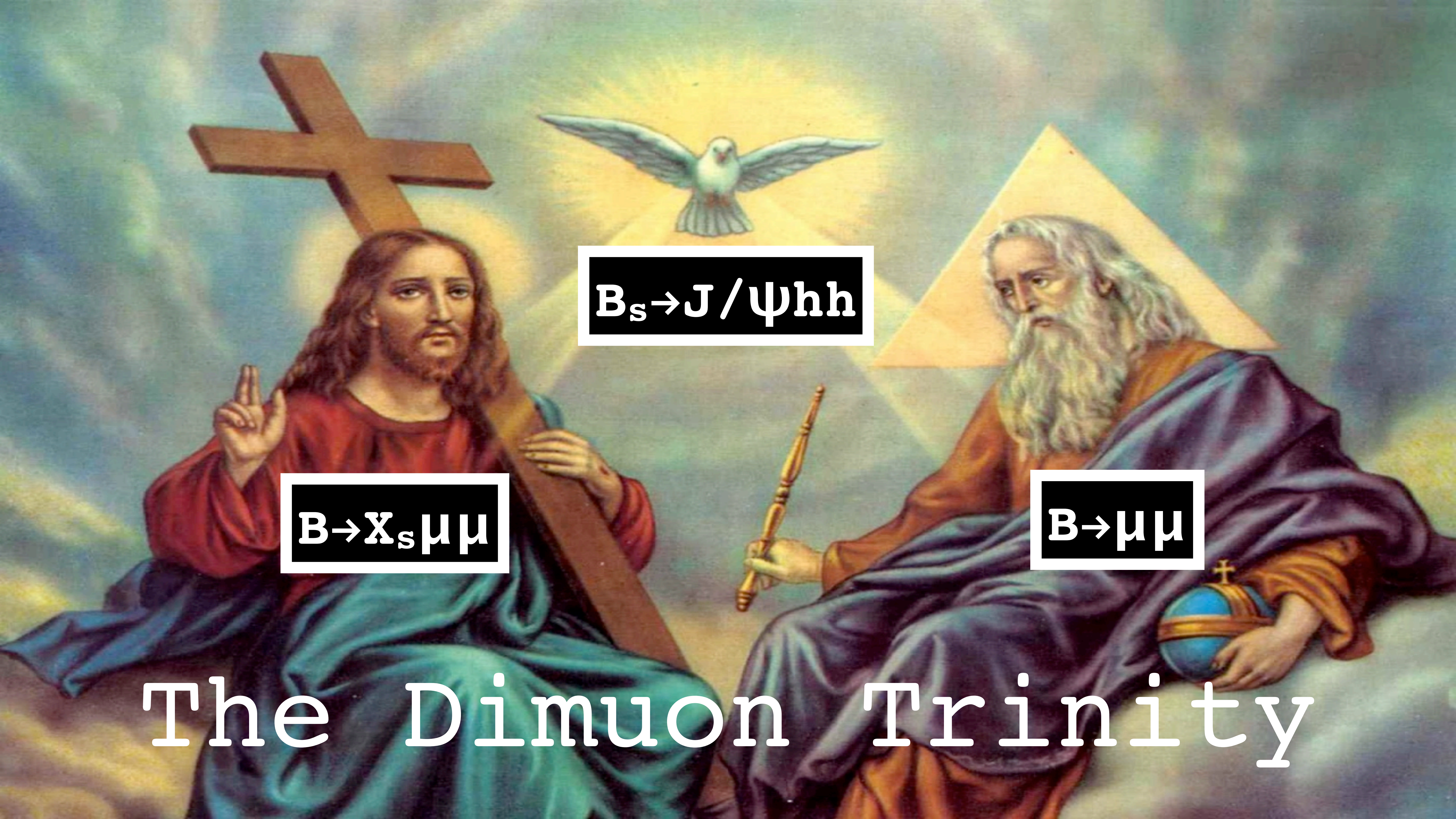
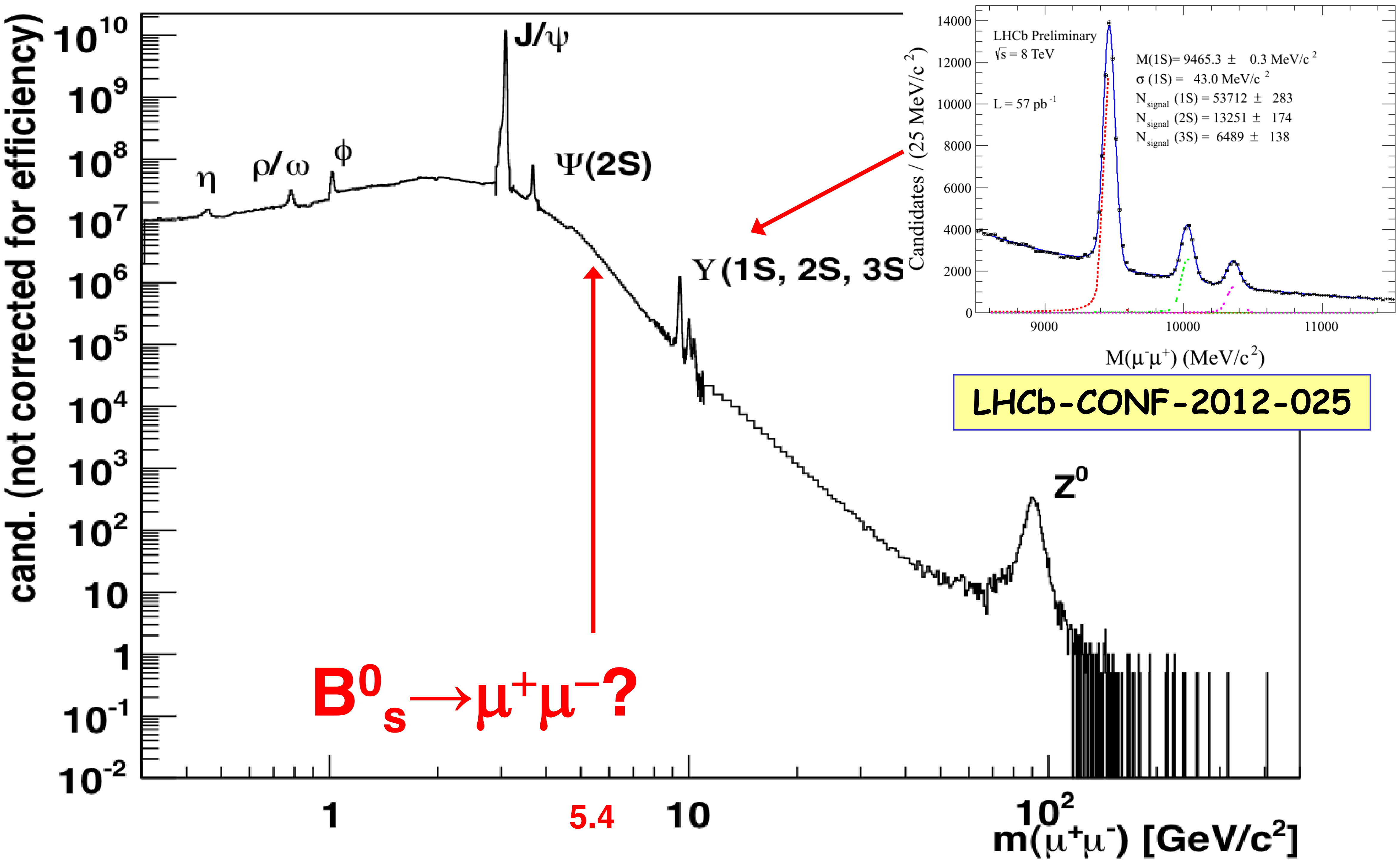
Compared to the B-factories

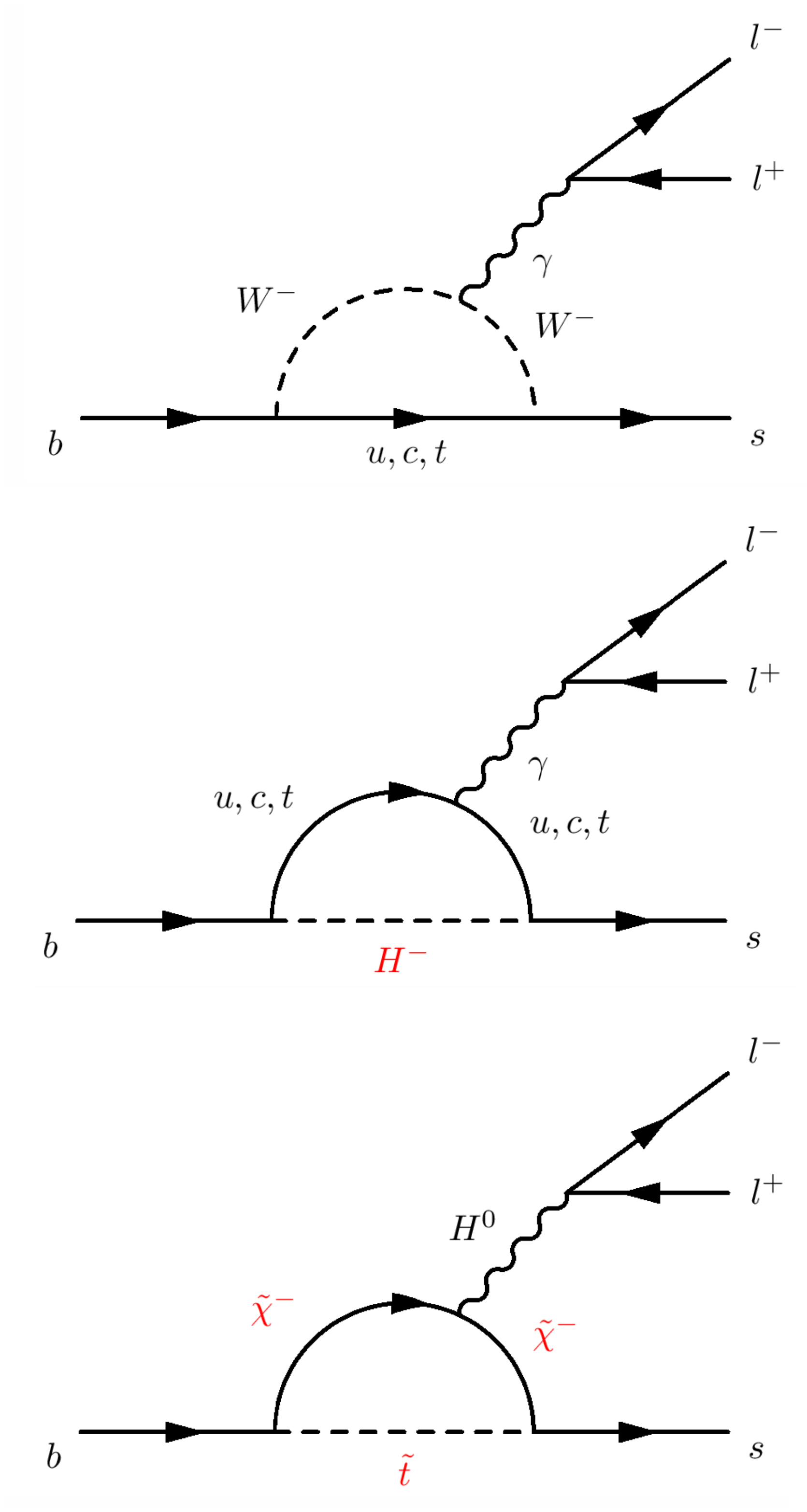



$B_s \to J/\psi hh$
$B \to X_s \mu\mu$
$B \to \mu\mu$
The Dimuon Trinity

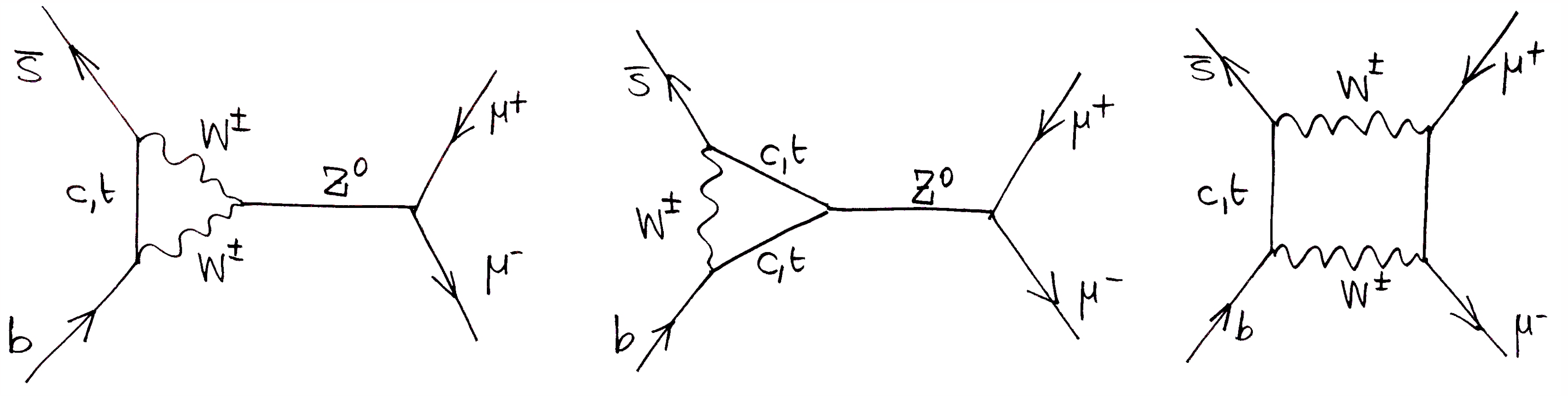
We love dimuons



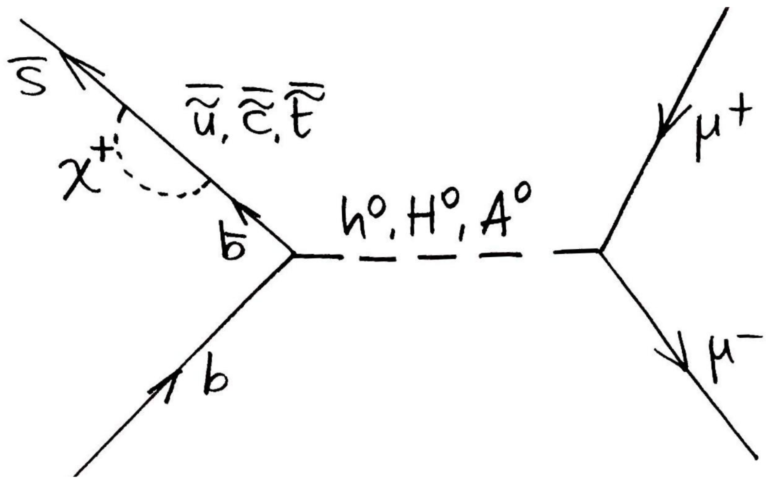
And we love loop diagrams



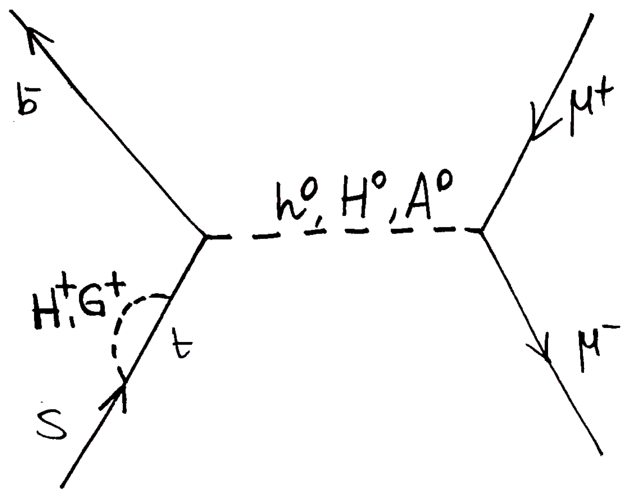
SM



MSSM



2HDM-II



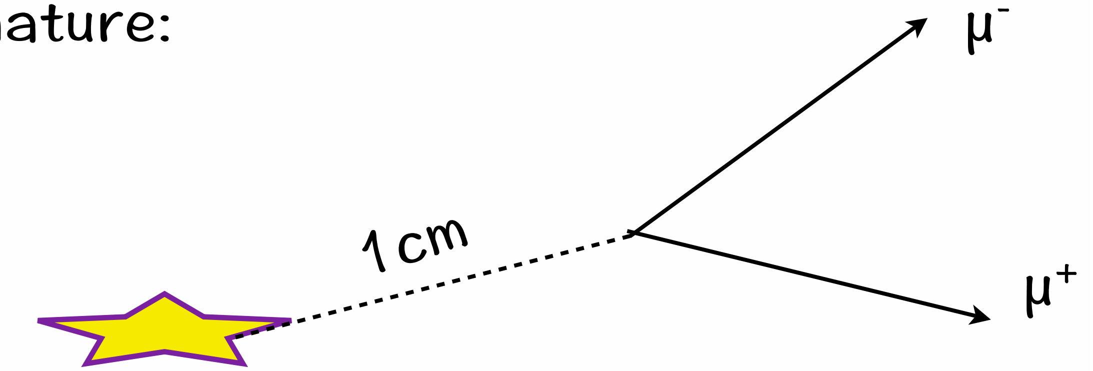
B→μμ, the father of all dimuons

Precise SM predictions due to decay diagrams

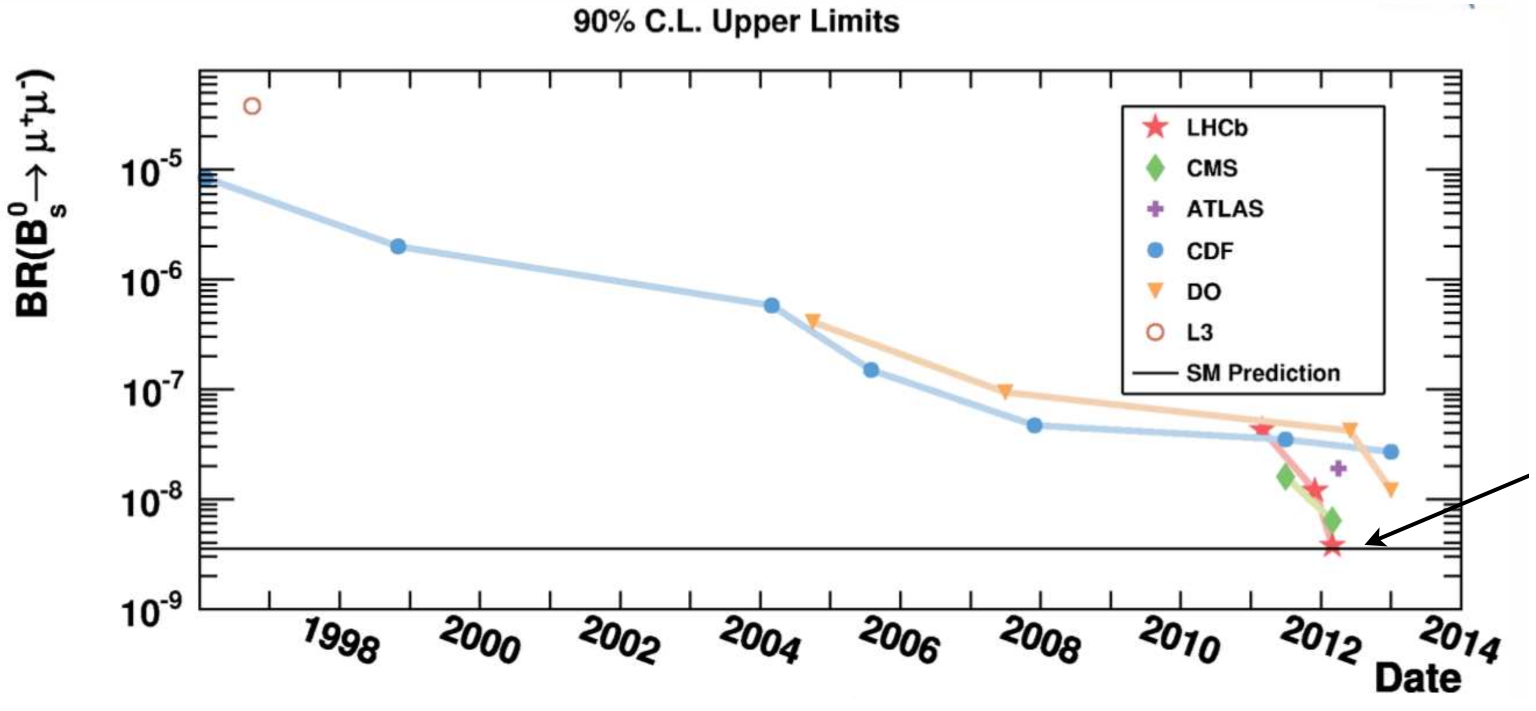
- $Br(B_d\text{->}\mu\mu) = (1.1 \pm 0.2)\ 10^{-10}$
- $Br(B_s\text{->}\mu\mu) = (3.5 \pm 0.2)\ 10^{-9}$

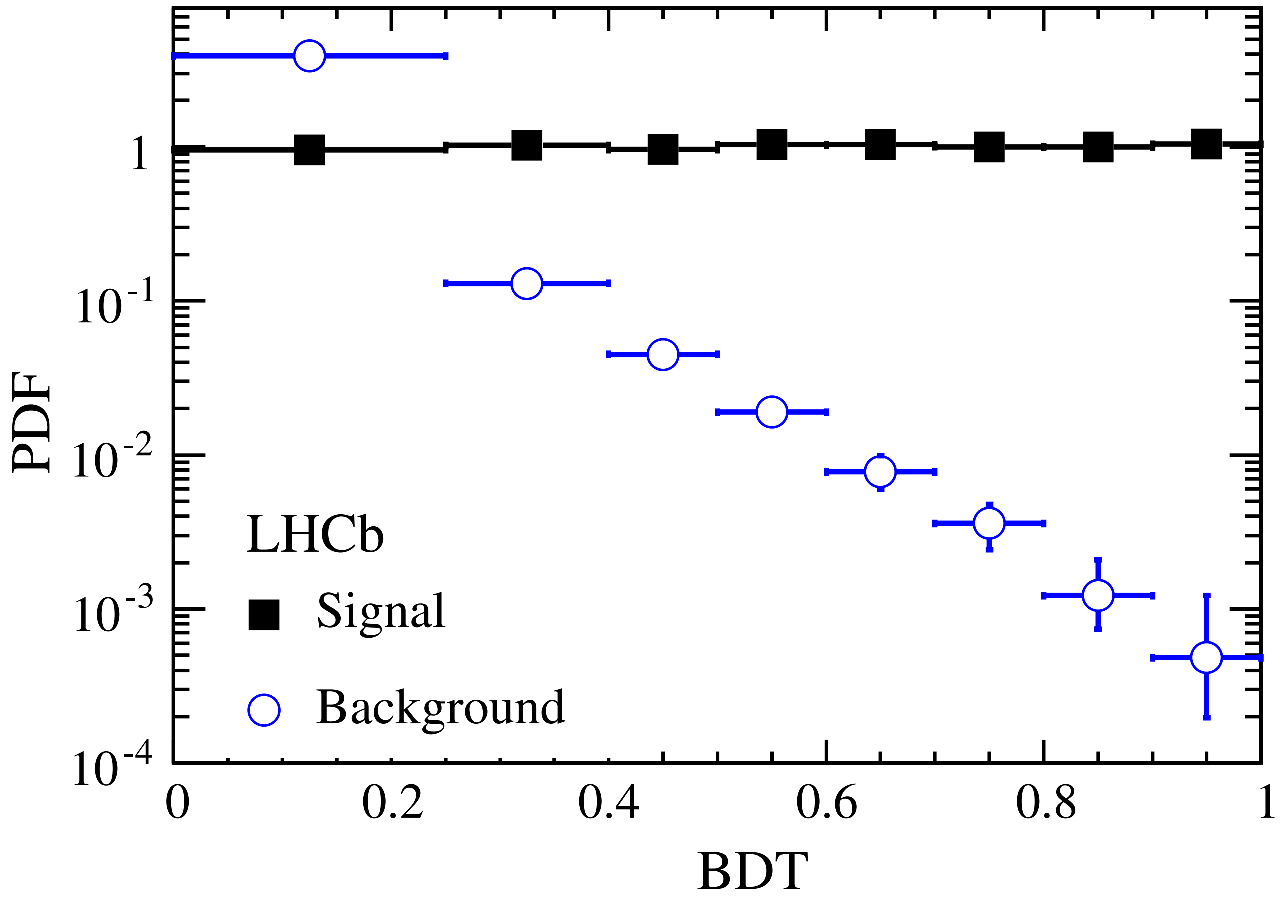
Buras et al, EPJ C72 (2012) 2172; see also PRL109 (2012) 041801

Signature:



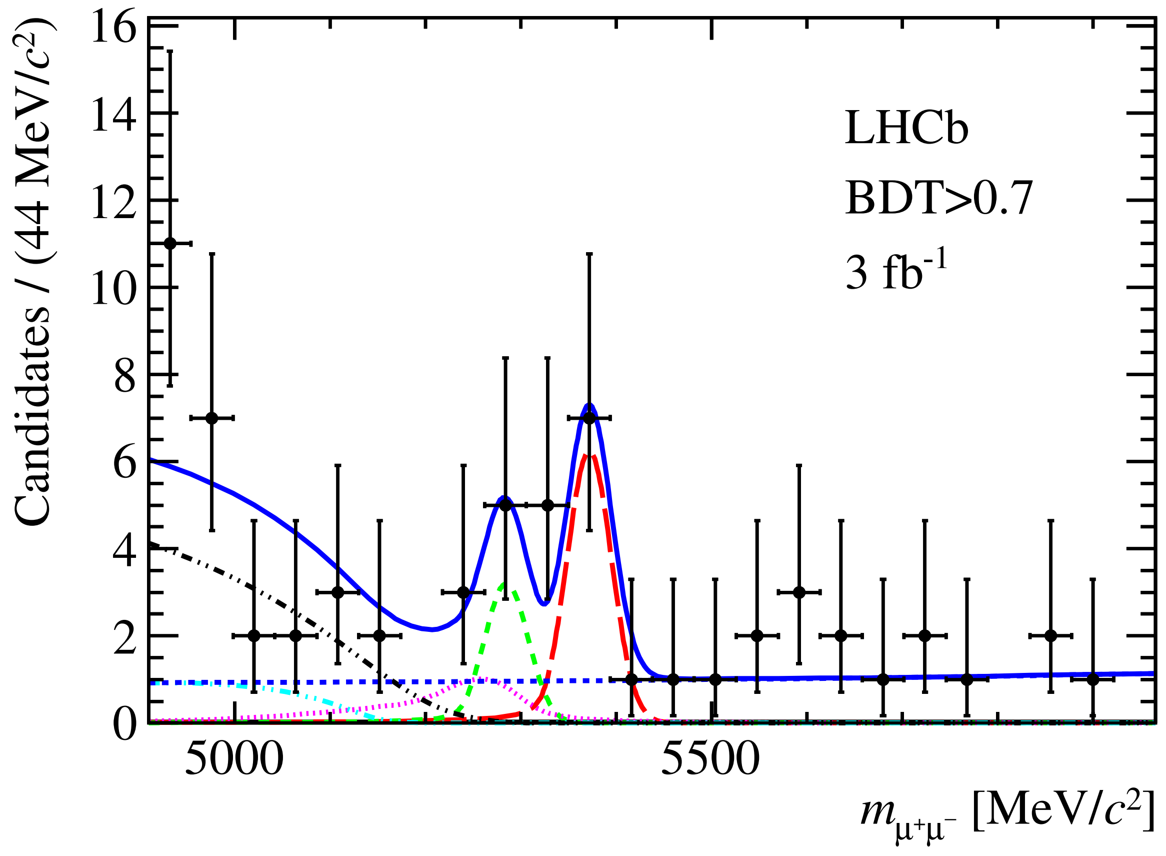
A quest of decades...





LHCb and CMS, united we stand

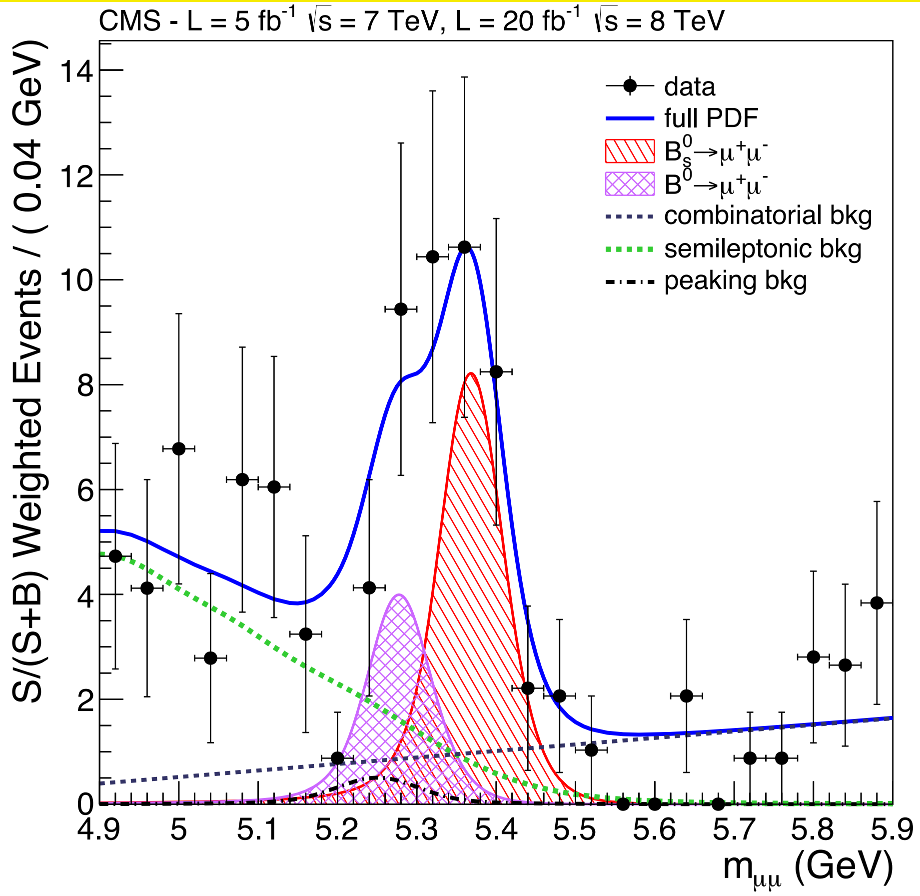
LHCb: arXiv:1307.5024, PRL.111.101805 (2013)



$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(2.9\,^{+1.1}_{-1.0}\right) \times 10^{-9},$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(3.7\,^{+2.4}_{-2.1}\right) \times 10^{-10}$$

--> 4.0σ

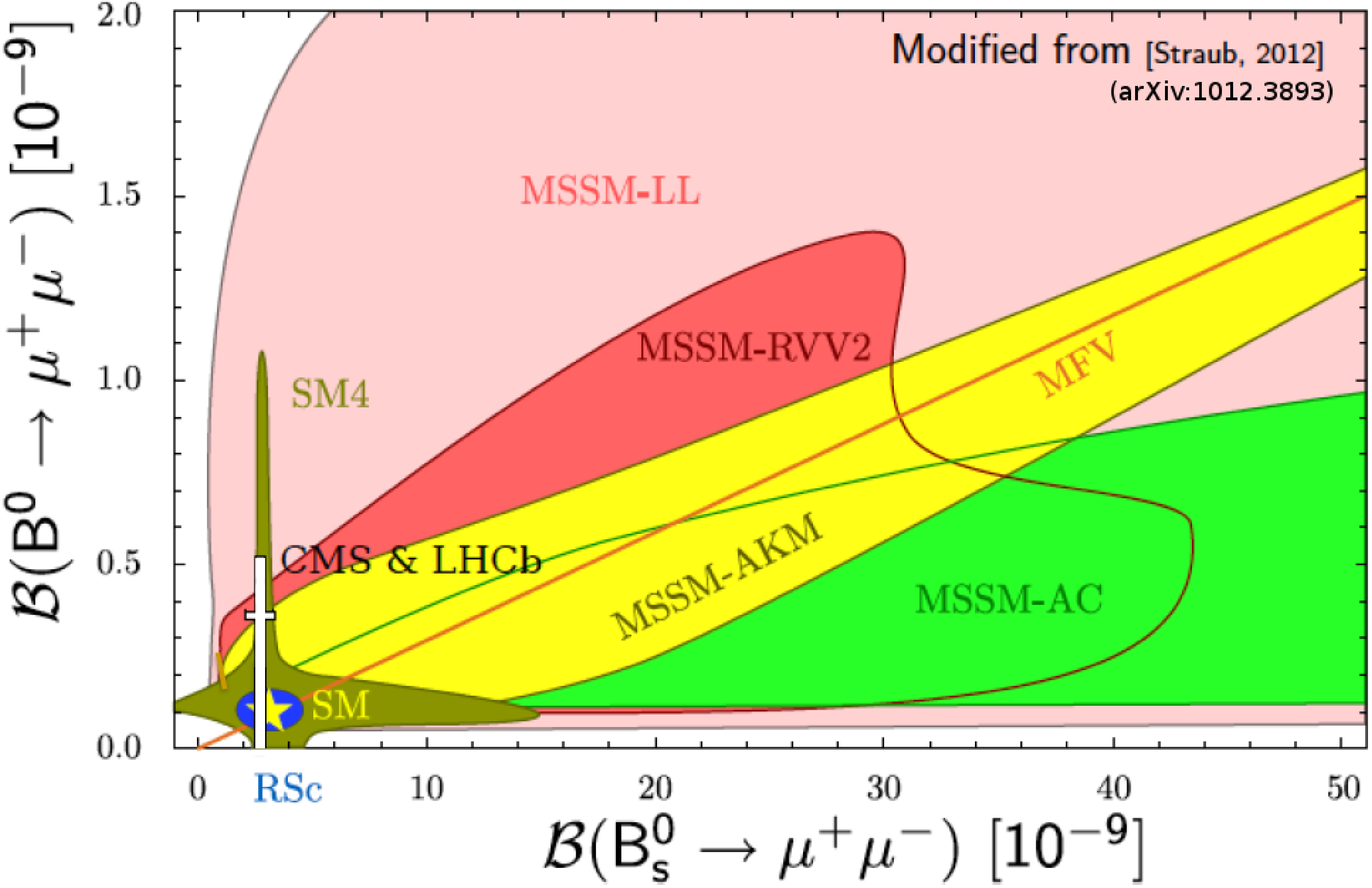
CMS: arXiv:1307.5025, PRL. 111.101804 (2013)



$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(3.0\,^{+1.0}_{-0.9}\right) \times 10^{-9},$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(3.5\,^{+2.1}_{-1.8}\right) \times 10^{-10}$$

--> 4.3σ

$B^0/B^0_s \to \mu\mu$, the golden ratio

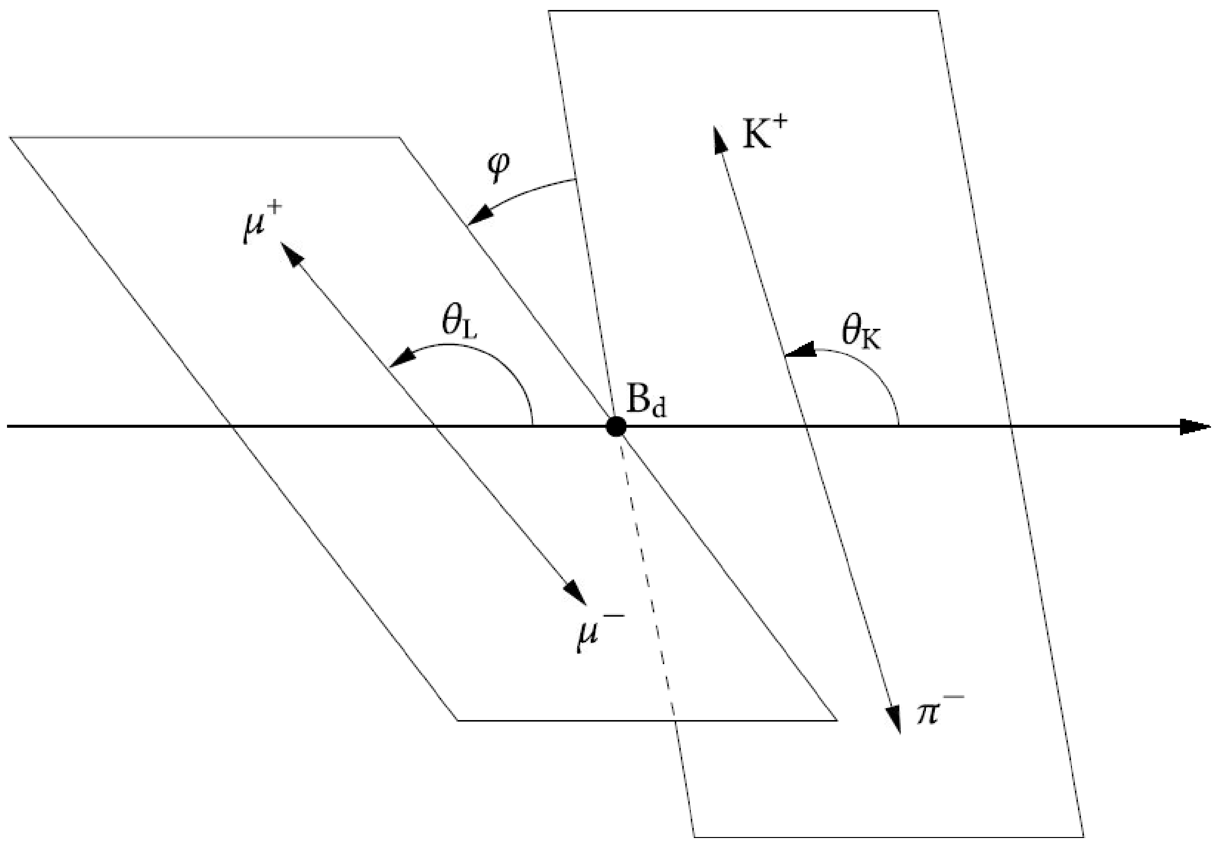


$B \to X_s \mu\mu$

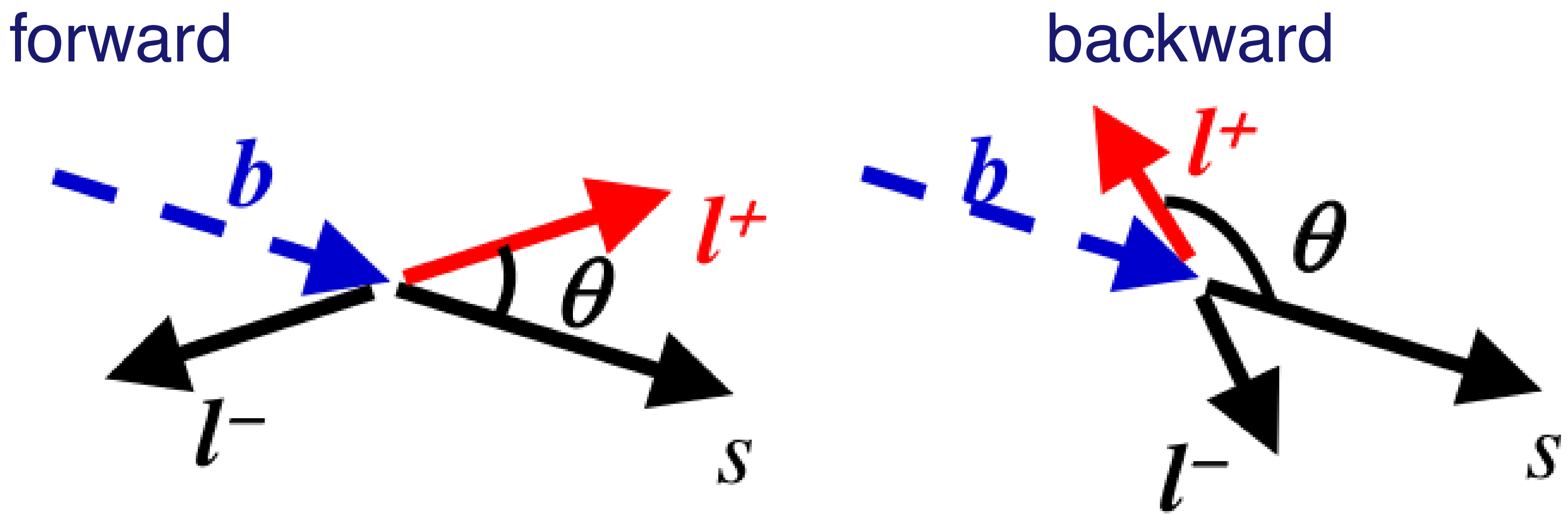
$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\theta_l d\theta_K d\varphi dq^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_l$$
$$- F_L\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\varphi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_l\cos\varphi + S_5\sin 2\theta_K\sin\theta_l\cos\varphi$$
$$+ S_6^s\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\varphi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_l\sin\varphi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\varphi\Big]$$

Altmannshofer et al, JHEP 01 (2009) 019

q^2 = dimuon invariant mass^2

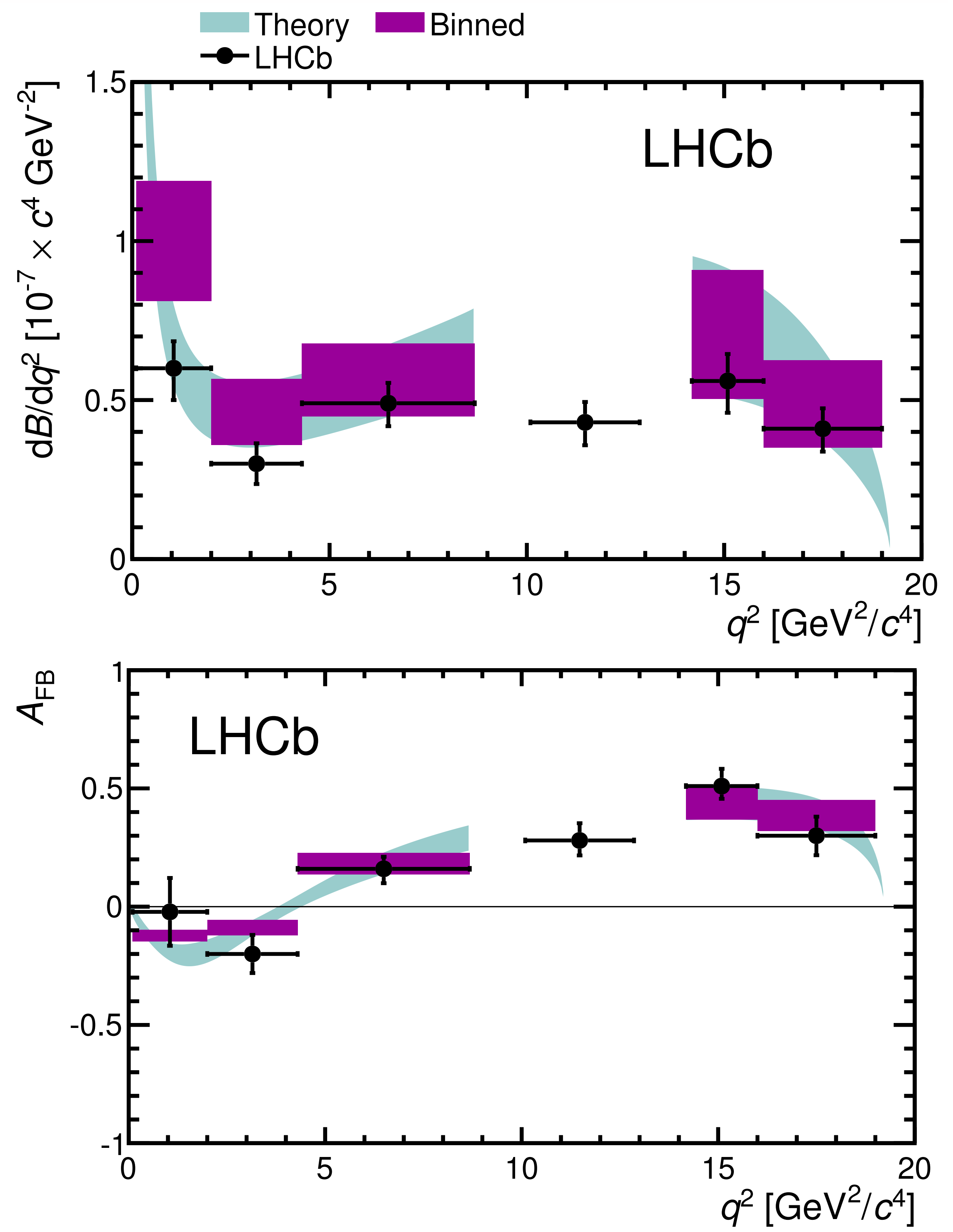


Example observables : forward backward asymmetry (sensitive to S_6), K^{*0} longitudinal polarization...

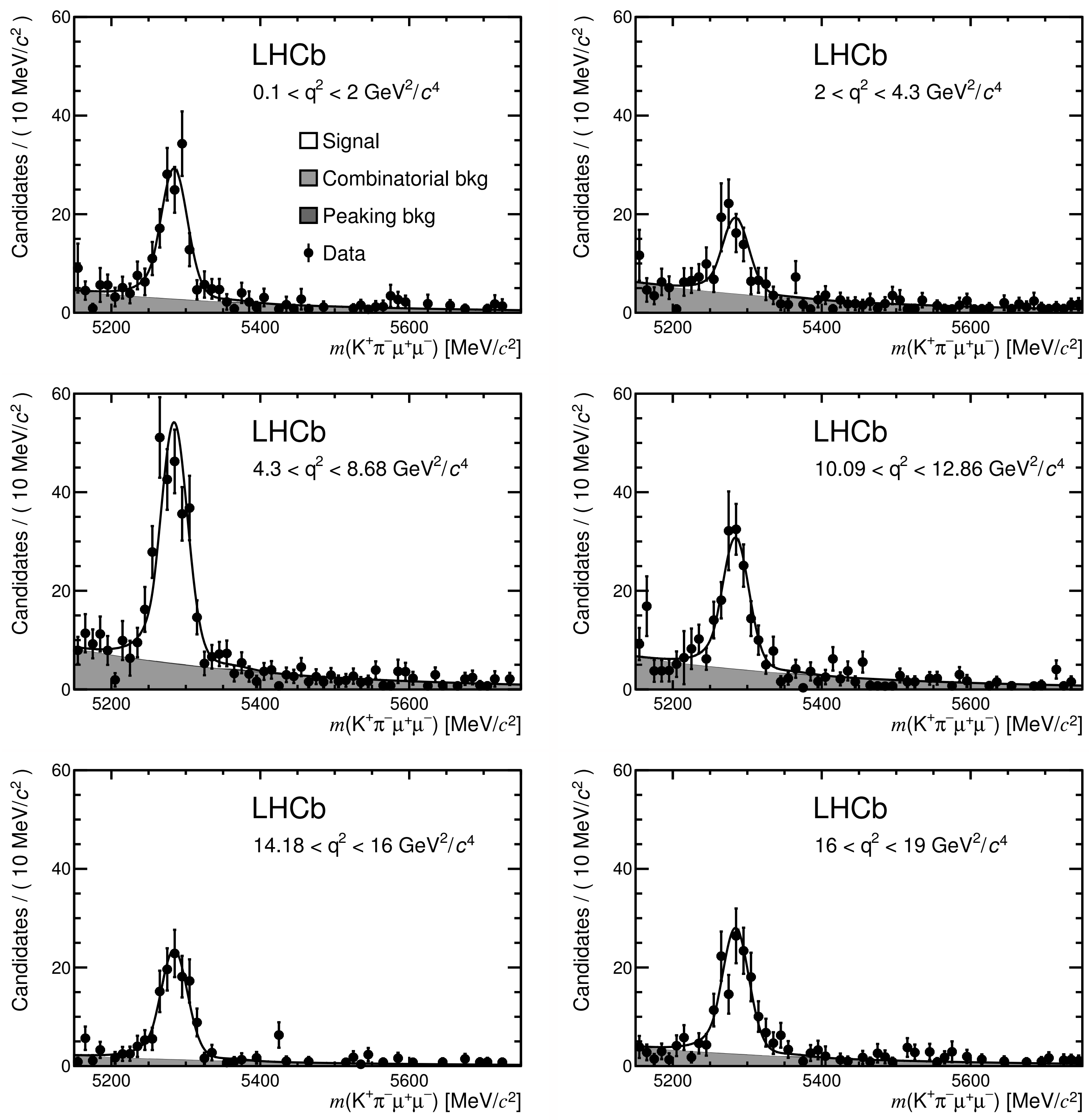


$B^0 \to K^* \mu\mu$ angular analysis

JHEP 08 (2013) 131

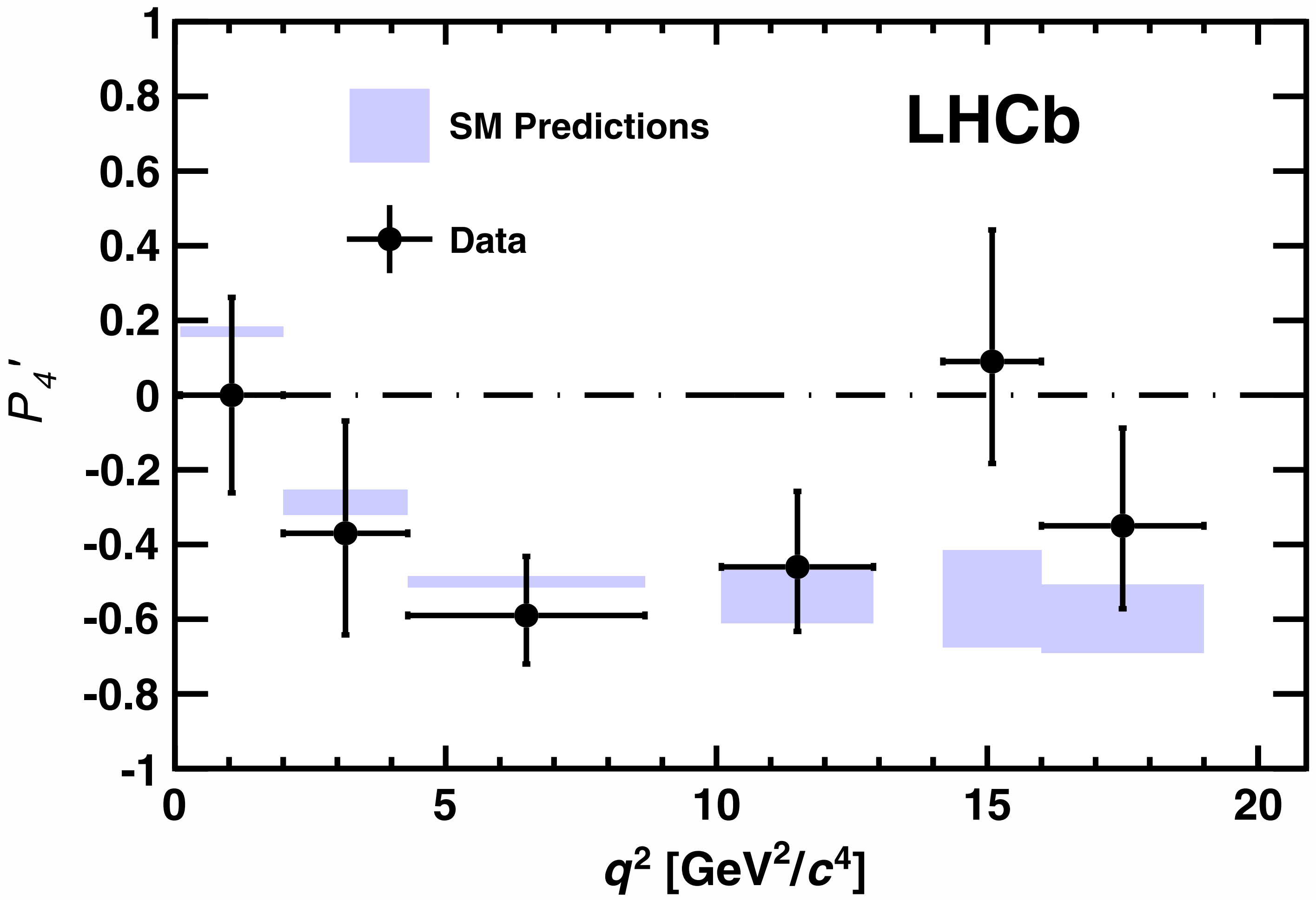


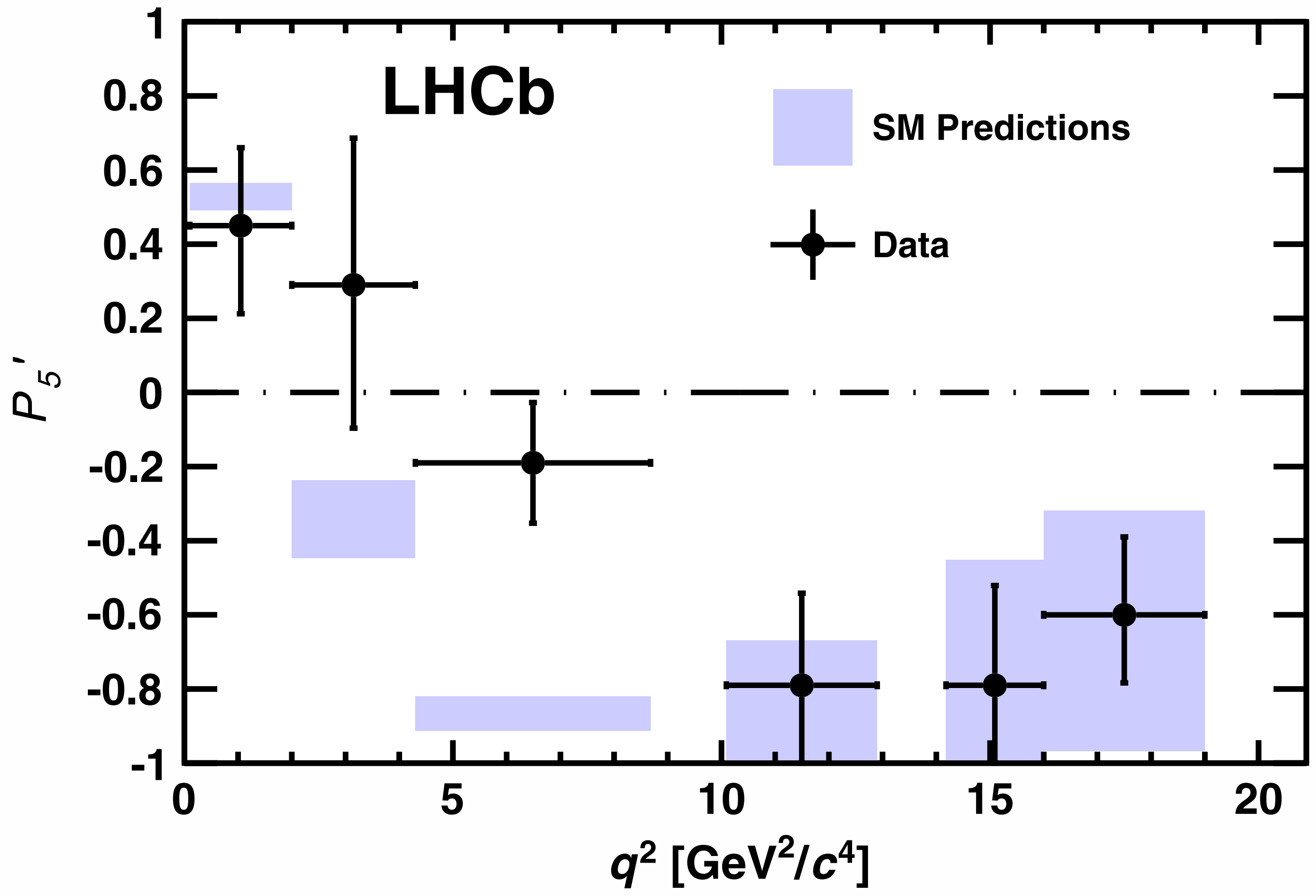
B candidate mass in bins of q^2
(in total: 883±34 candidates in 1/fb)



We also love tensions

JHEP 08 (2013) 131
PRL 111 (2013) 191801

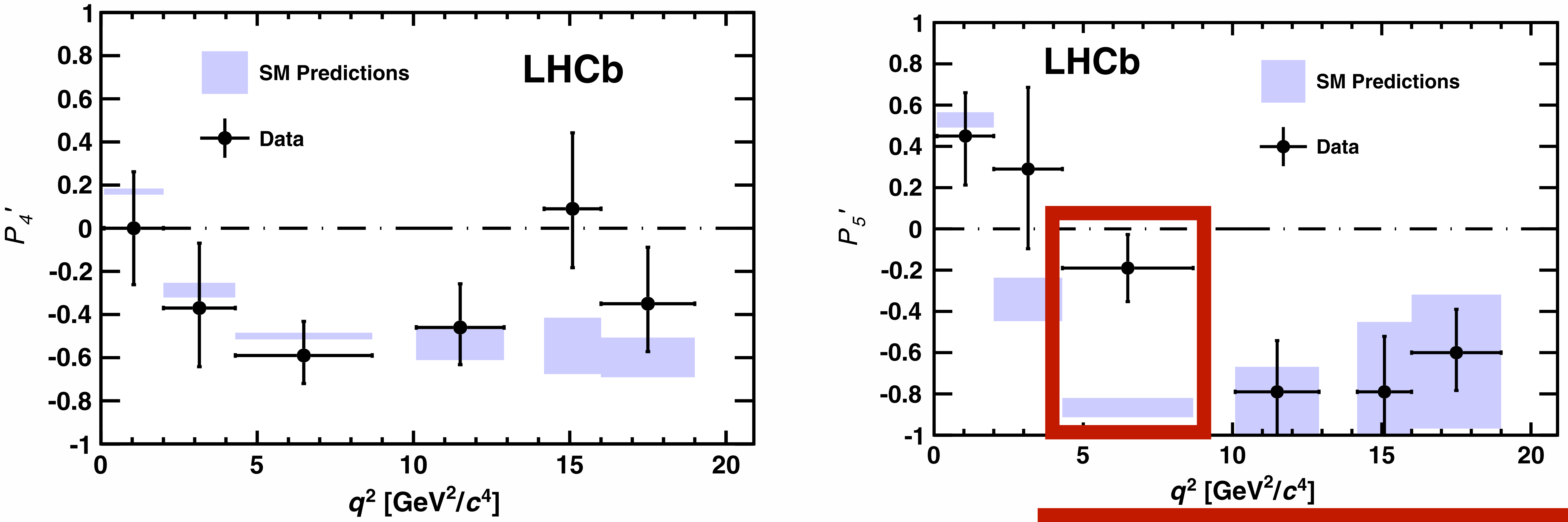




- at low q^2, ratios $P'_{i=4,5,6,8} = \frac{S_{i=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$ largely free of FF uncertainties, while sensitivity to NP remains (Descotes-Genon, Hurth, Matias, Virto, arXiv:1303.5794)

We also love tensions

JHEP 08 (2013) 131
PRL 111 (2013) 191801



2.8σ global significance : 3 fb^{-1} result coming soon!

- at low q^2, ratios $P'_{i=4,5,6,8} = \frac{S_{i=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$ largely free of FF uncertainties, while sensitivity to NP remains (Descotes-Genon, Hurth, Matias, Virto, arXiv:1303.5794)

The isospin puzzle

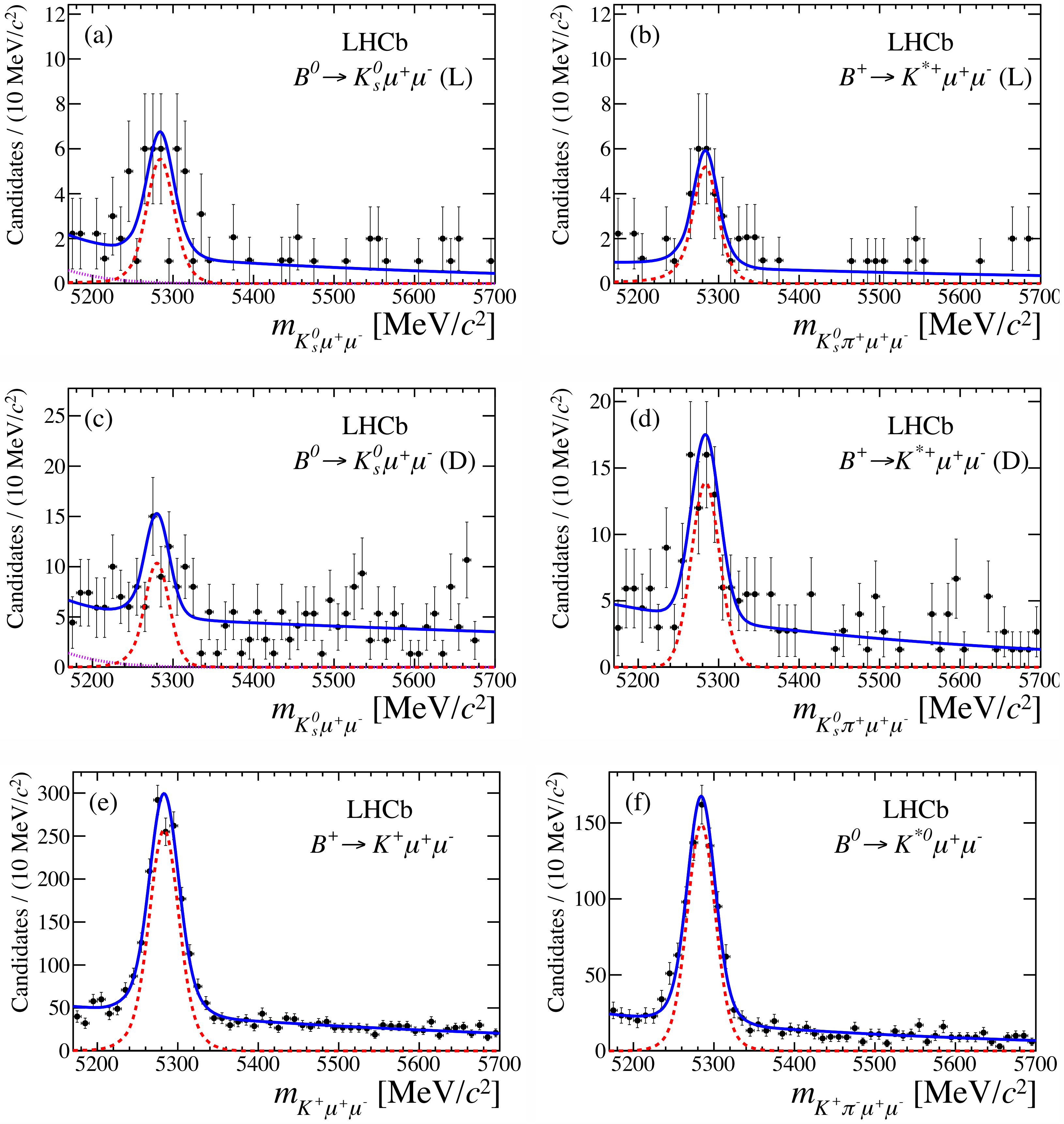
JHEP 07 (2012) 133

$$A_{\rm I} = \frac{\Gamma(B^0 \to K^{(*)0}\mu^+\mu^-) - \Gamma(B^+ \to K^{(*)+}\mu^+\mu^-)}{\Gamma(B^0 \to K^{(*)0}\mu^+\mu^-) + \Gamma(B^+ \to K^{(*)+}\mu^+\mu^-)}$$

SM prediction : basically 0

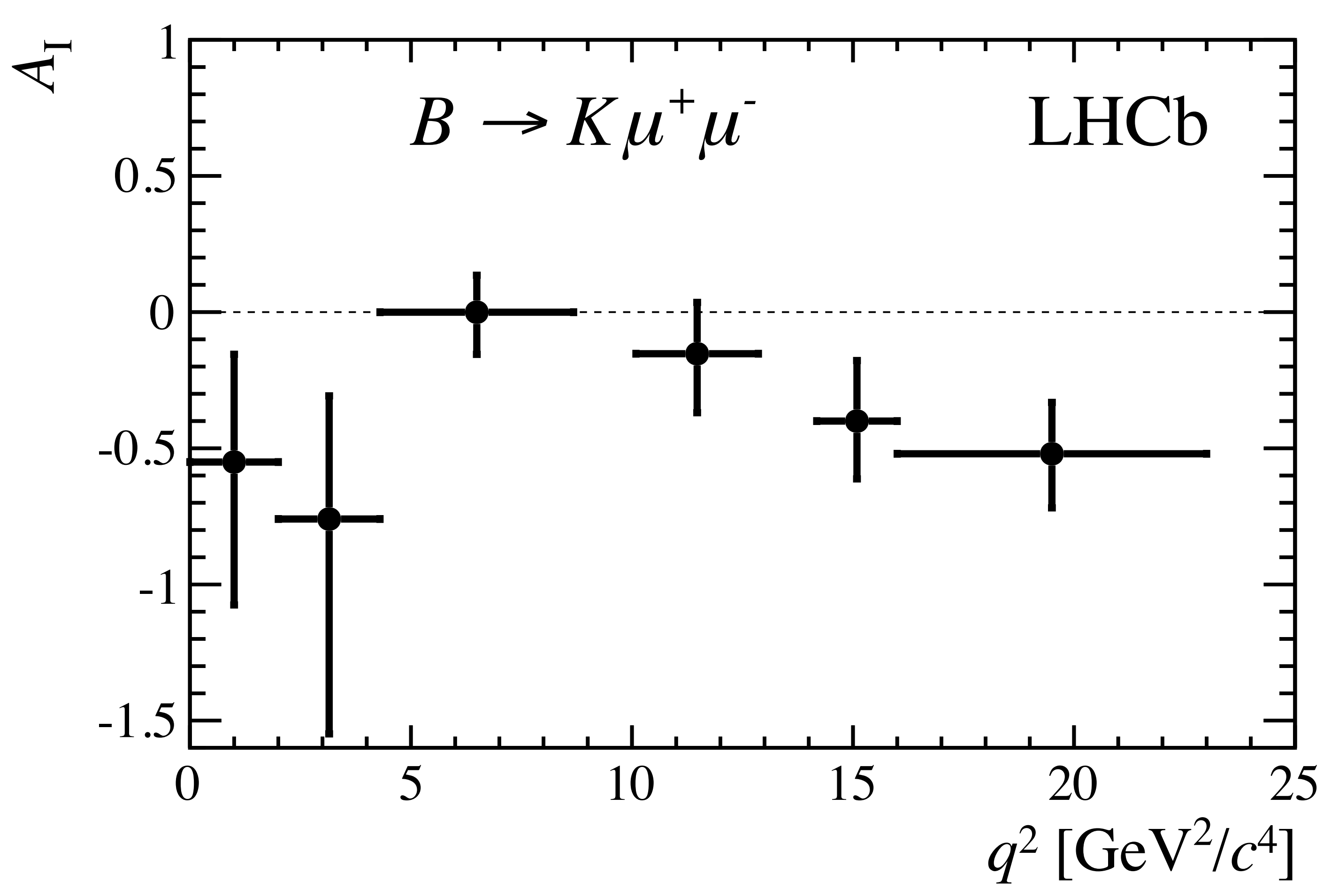
$$B^0 \to K^0\mu^+\mu^- \to K_s\mu^+\mu^-$$
$$B^+ \to K^+\mu^+\mu^-$$

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

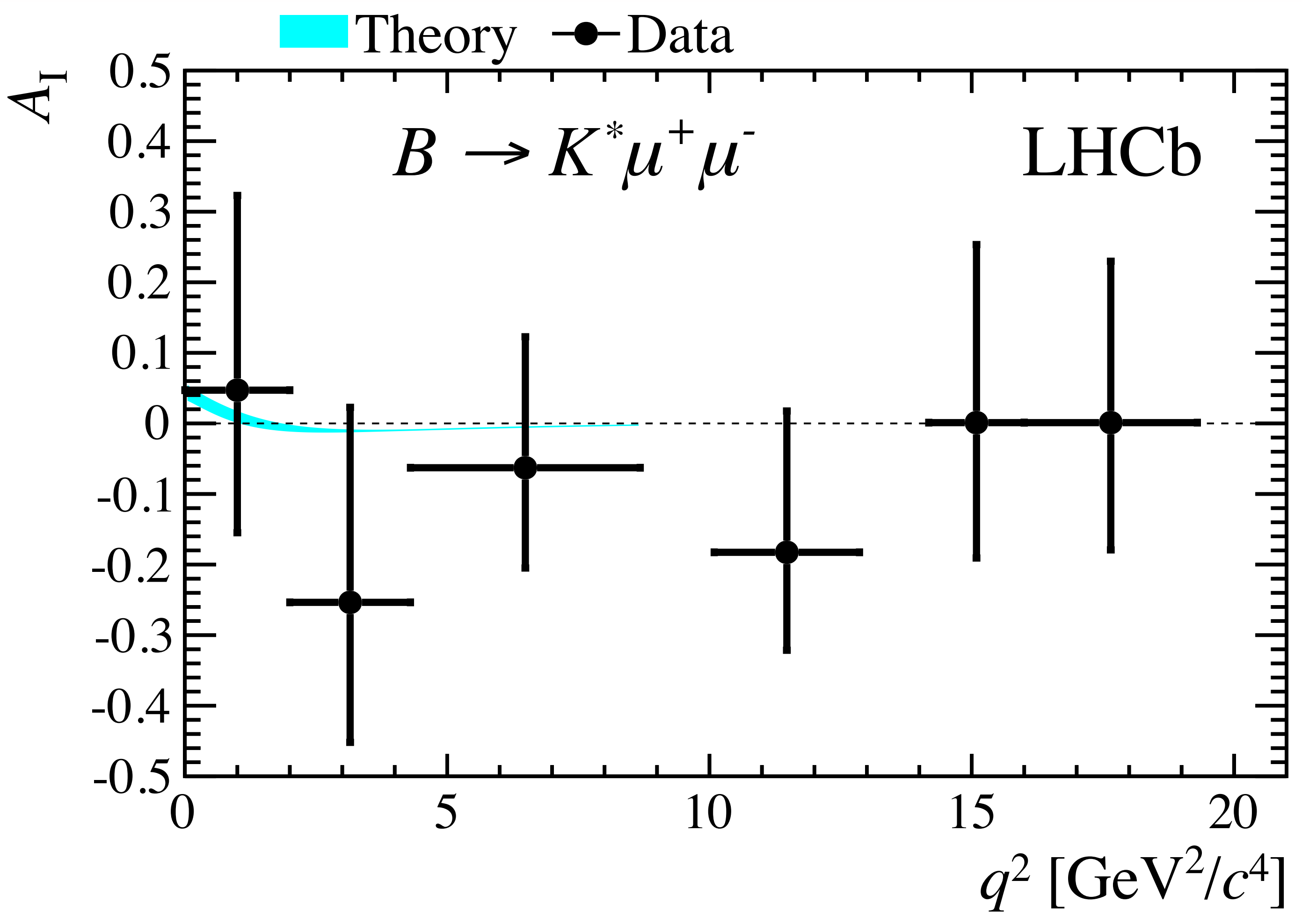


The isospin puzzle

JHEP 07 (2012) 133

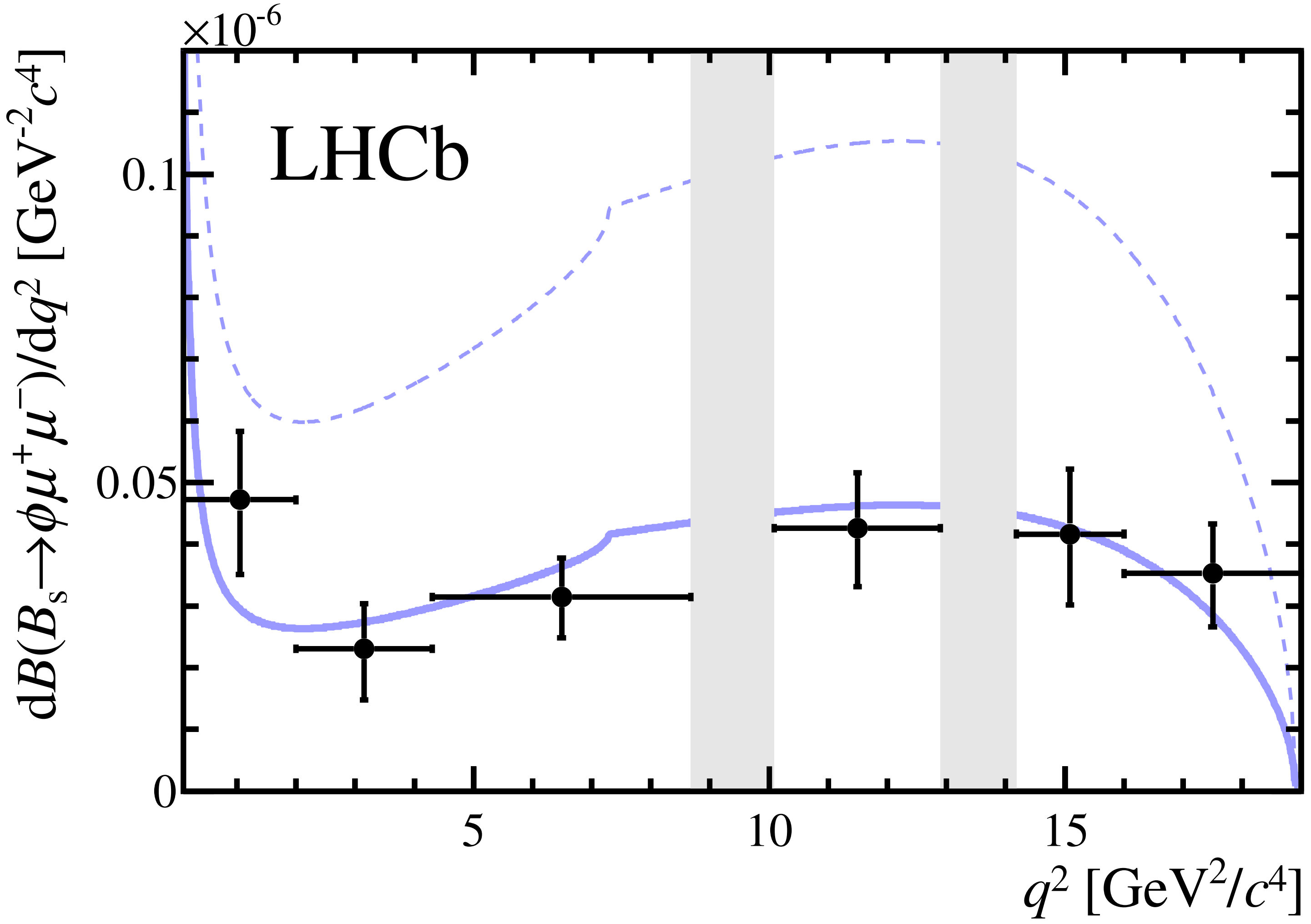


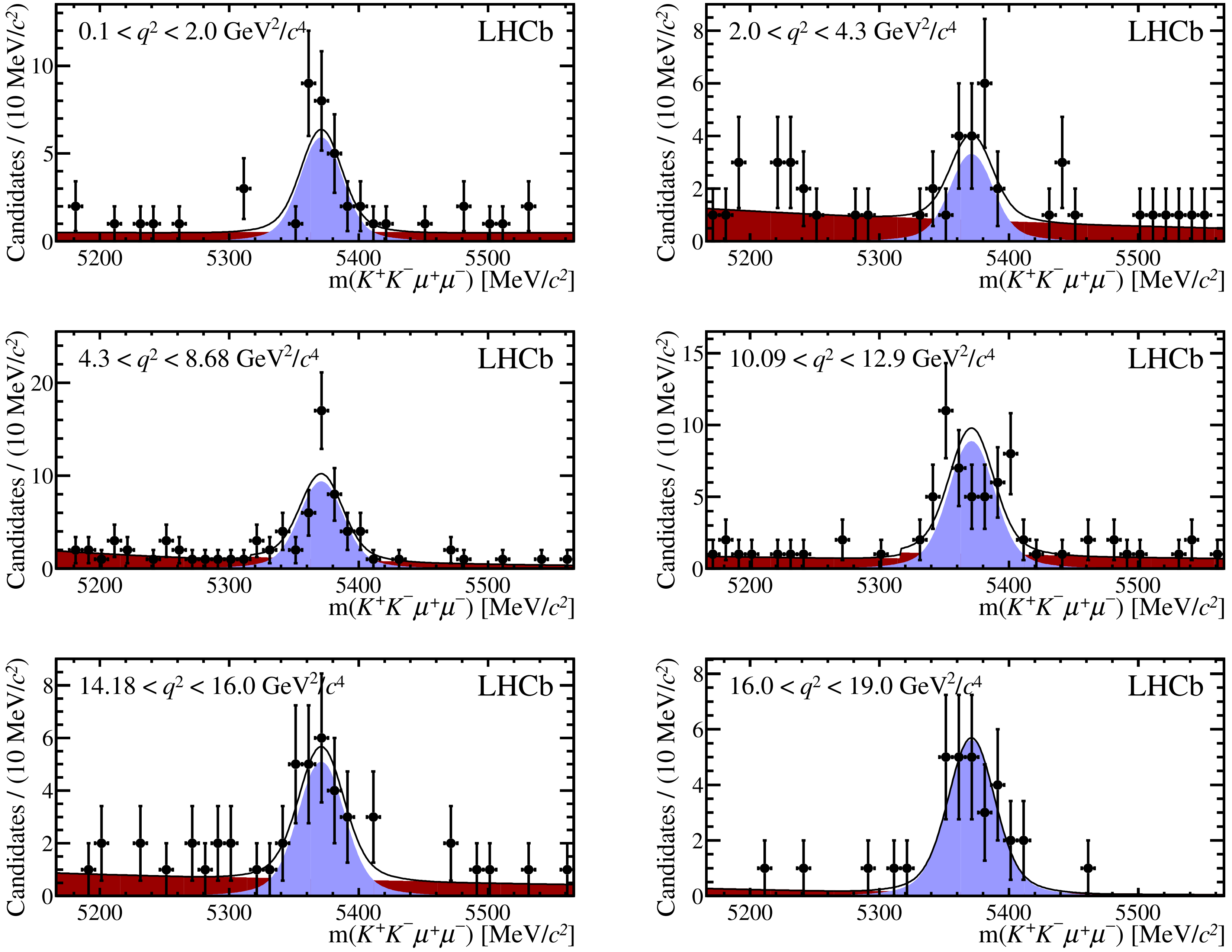
4.4σ says "not 0". What gives?
Again, $3fb^{-1}$ result coming soon!



$B \to X_s \mu\mu$, the B_s sector

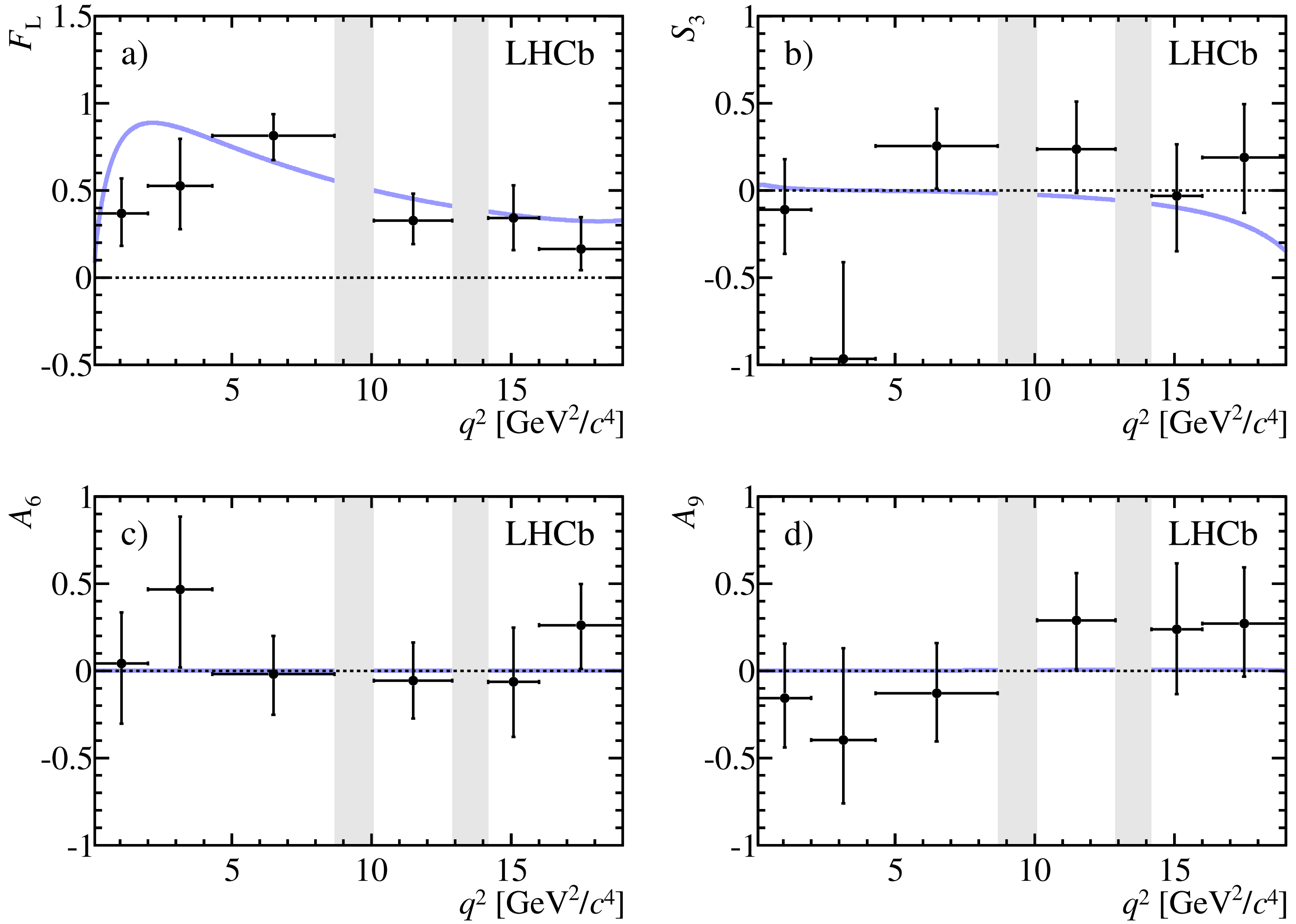
JHEP 07 (2012) 084

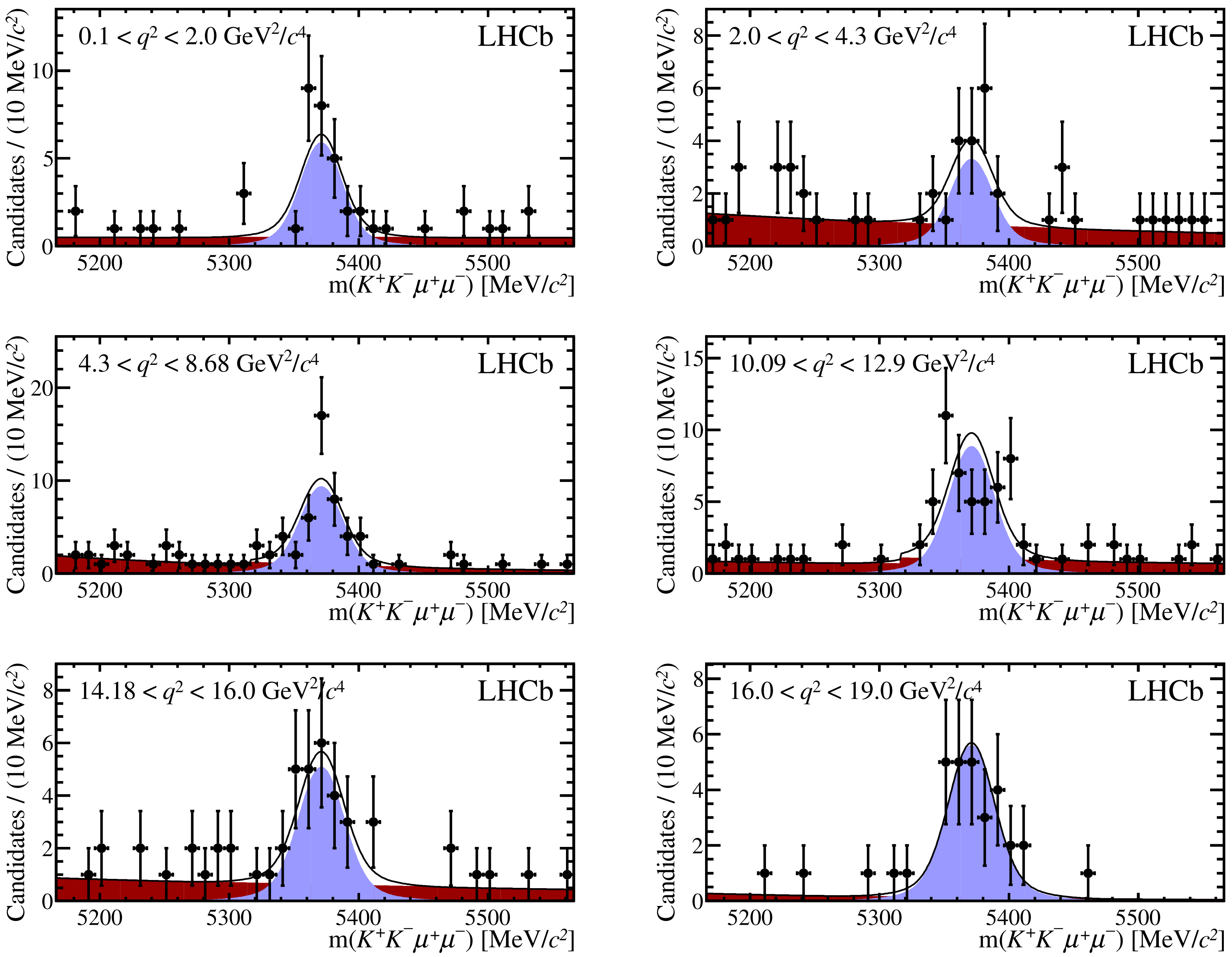




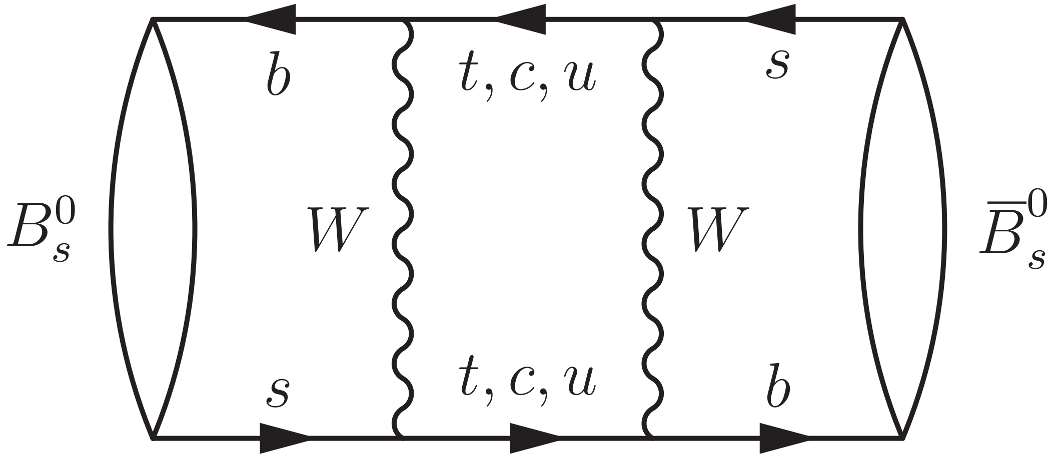
B→$X_s\mu\mu$, the B_s sector

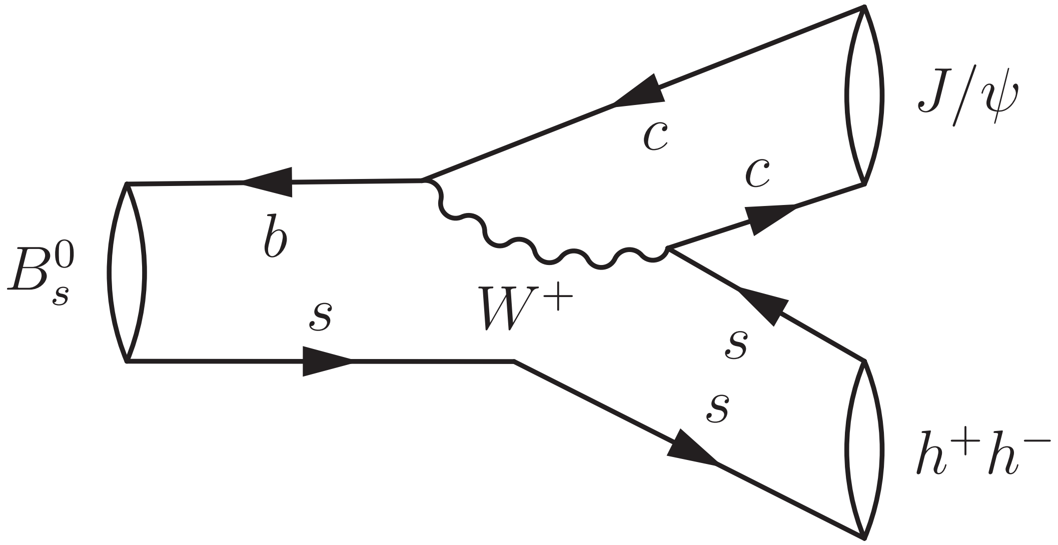
JHEP 07 (2012) 084

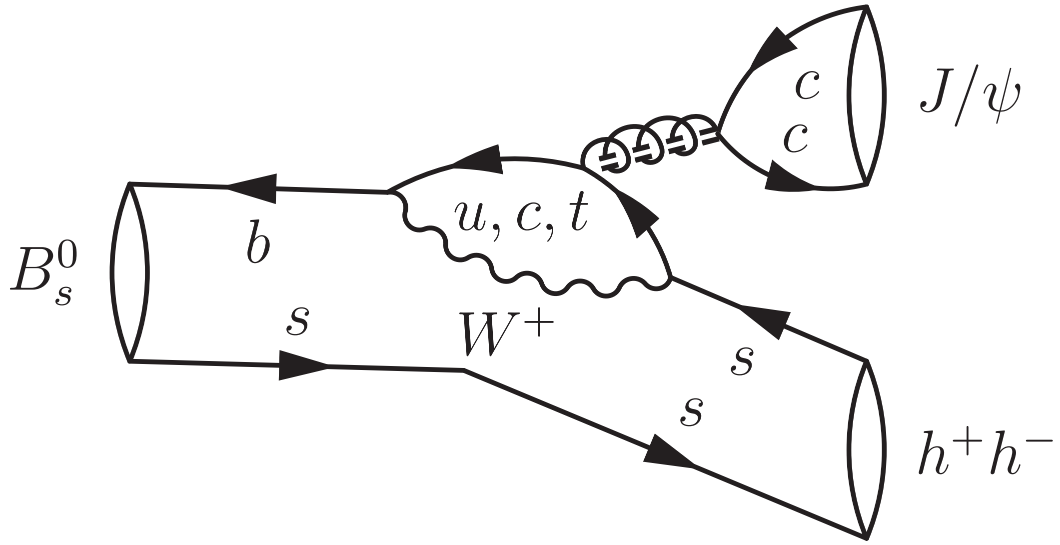


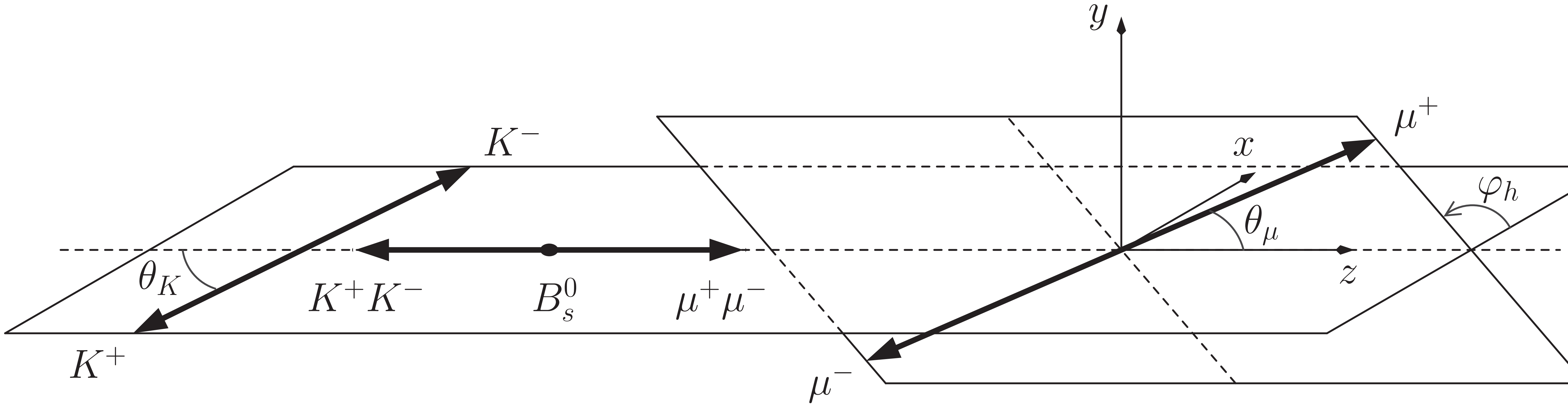


$B_s \to J/\psi\pi\pi$ and $B_s \to J/\psi KK$

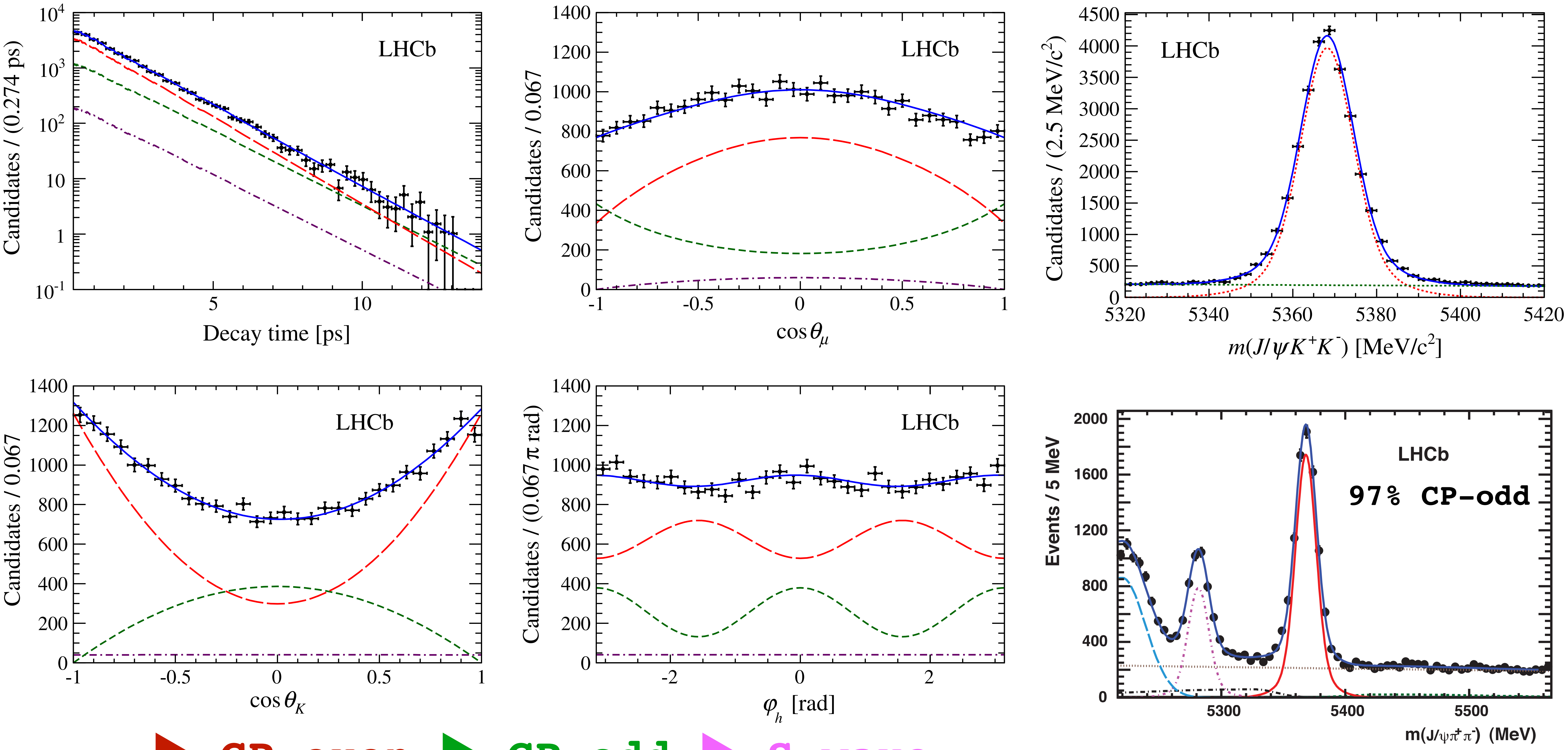






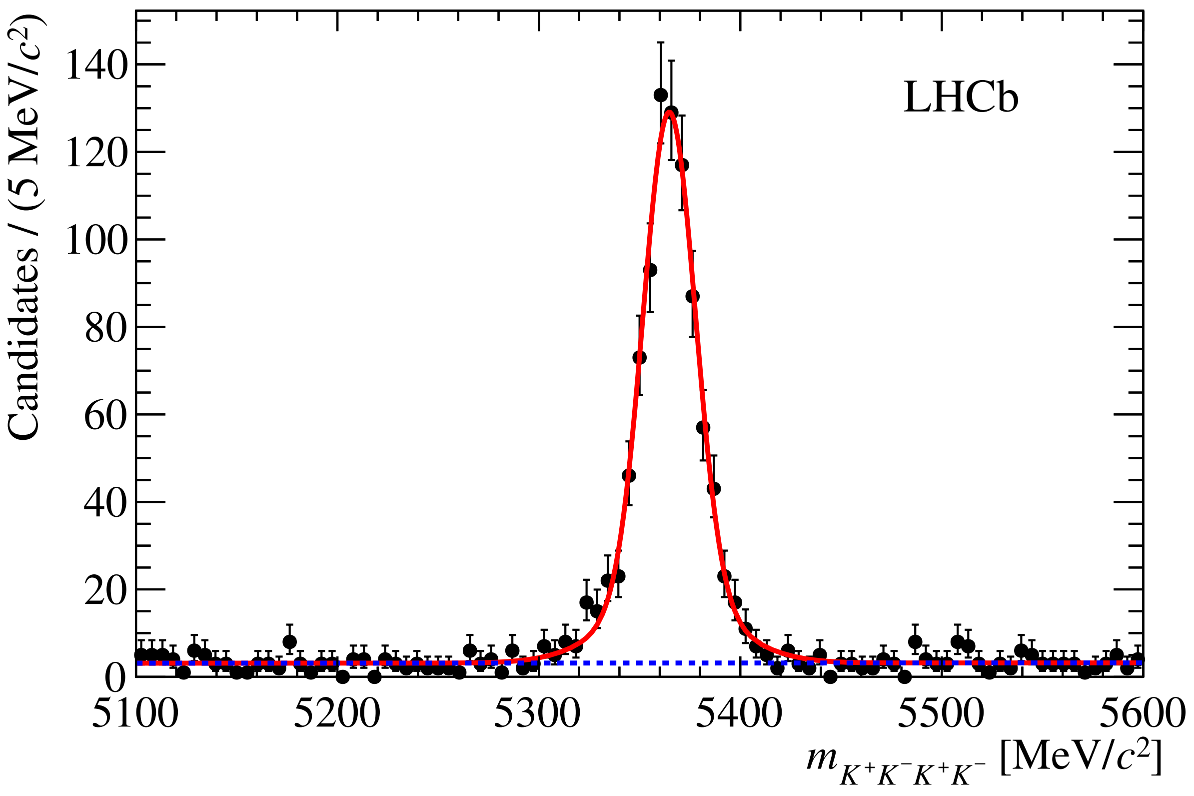


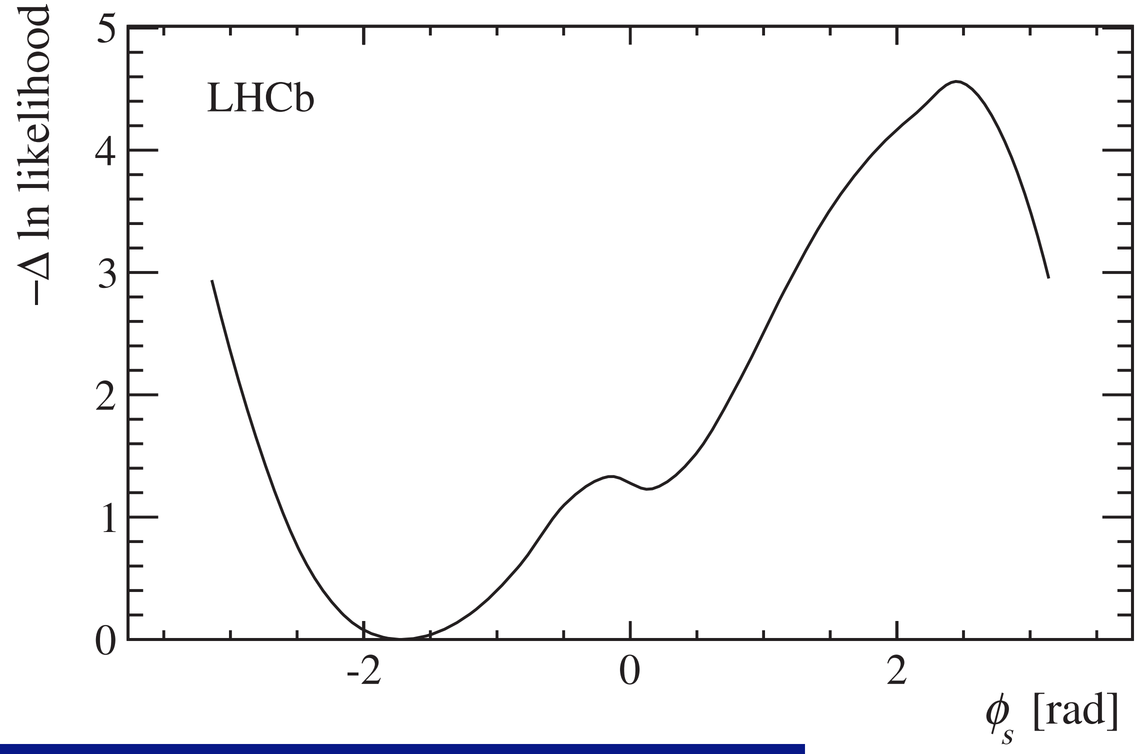
Simultaneous lifetime/angular fit

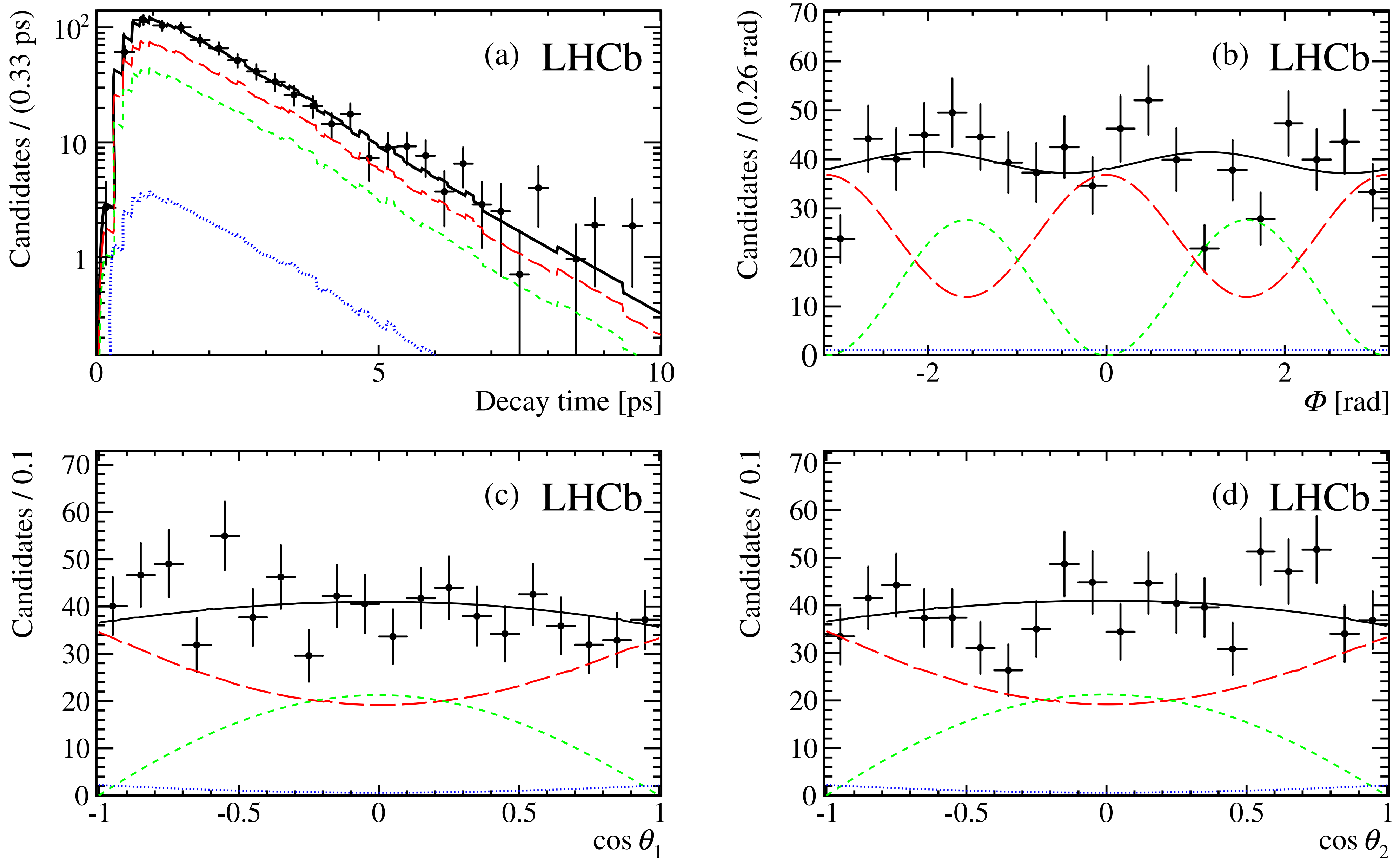


▶ **CP-even** ▶ **CP-odd** ▶ **S-wave**

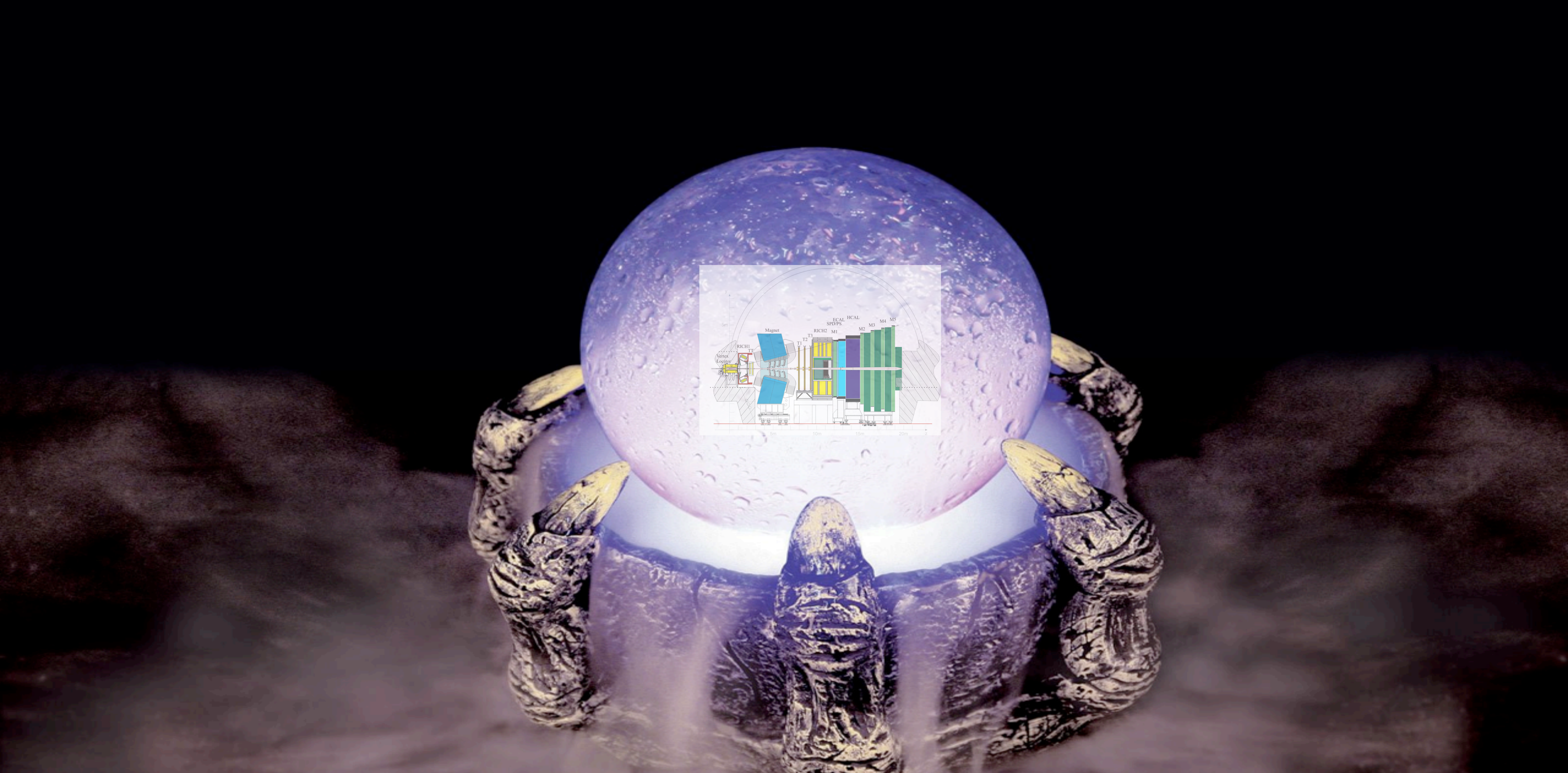
$B_s \rightarrow \varphi\varphi$ (ok, not a dimuon, but…)







PRL 110, 241802 (2013)



What of the future?

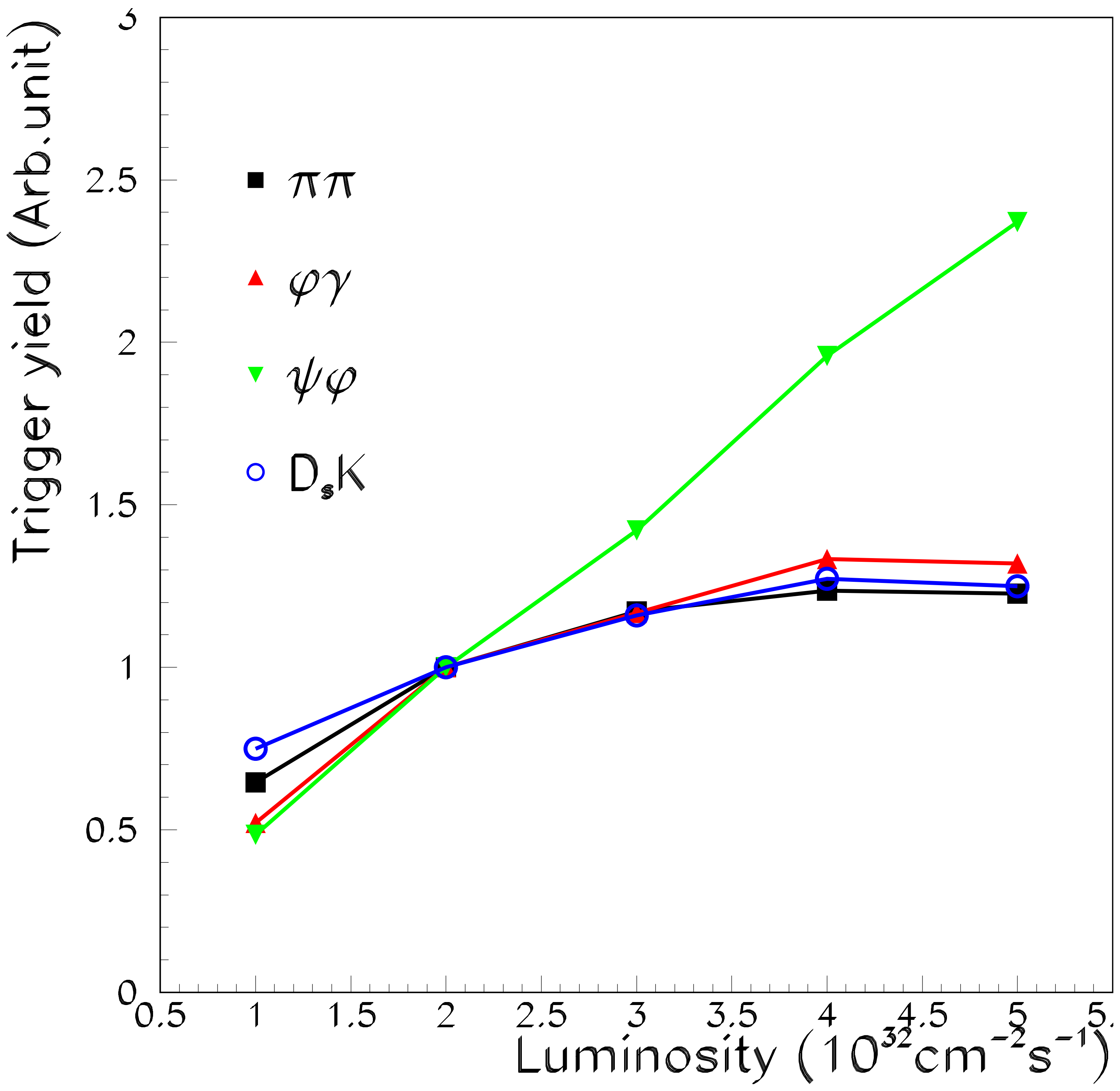
Building an experiment 101

LHCb Management

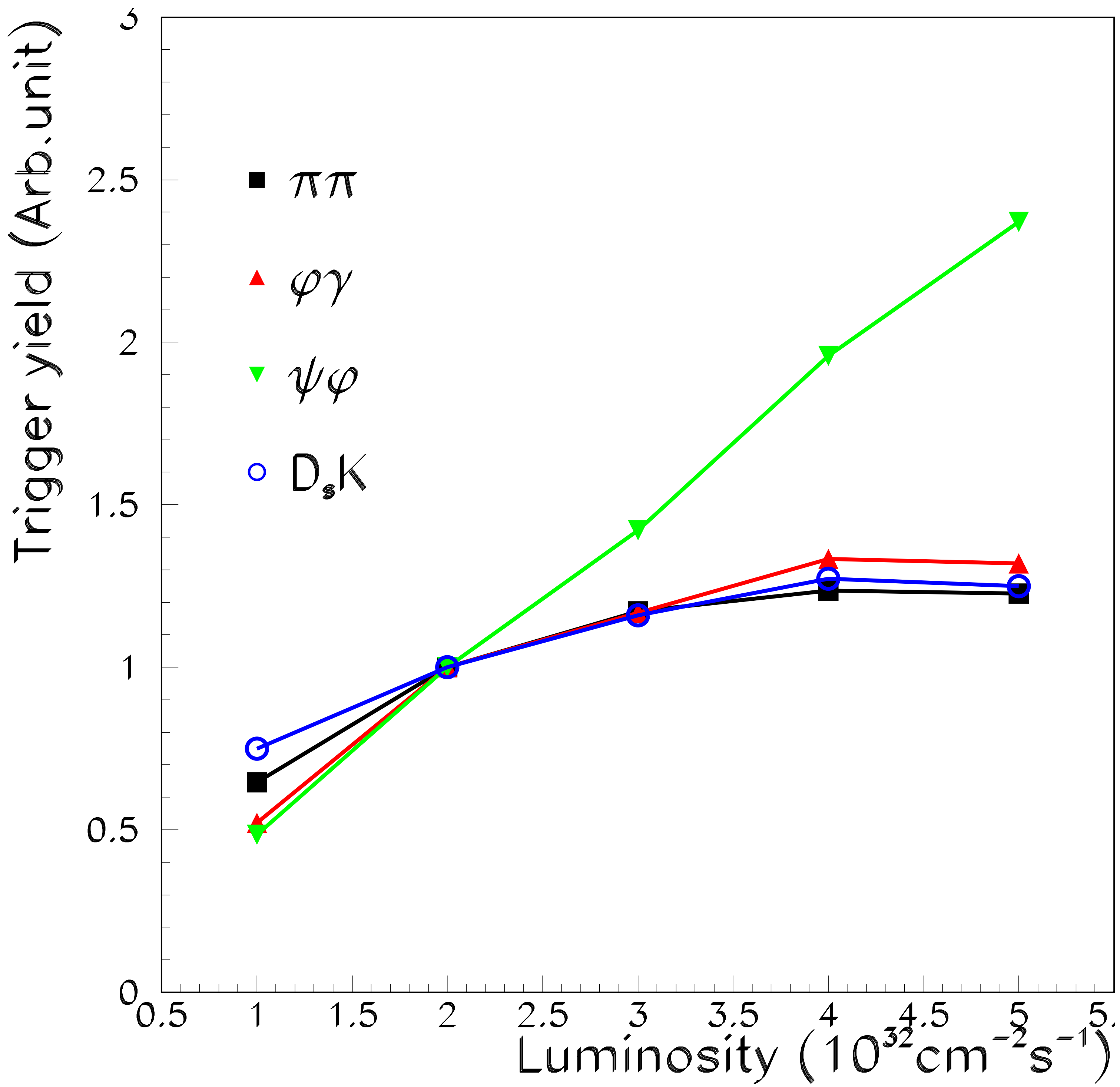
Funding agencies

Let’s be optimists

What is our upgrade all about?



What is our upgrade all about?



Only being able to read out the full detector at 1 MHz severely limits the event yields for hadronic modes

To run at higher luminosity we must remove this bottleneck

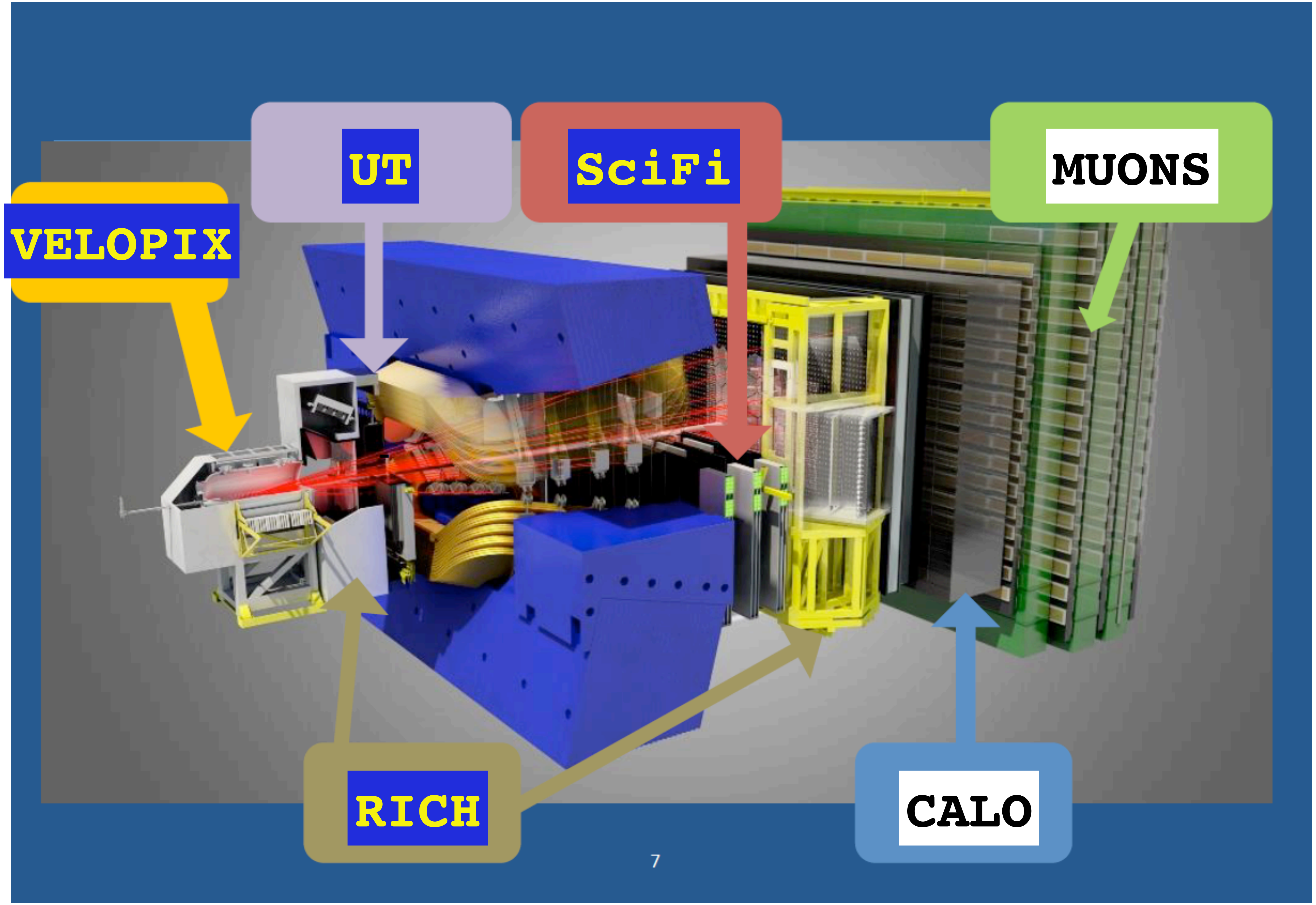
=> Full 40 MHz detector readout

=> All software trigger

=> Keep a hardware LLT (low-level trigger) as a backup for early running before the full farm is purchased

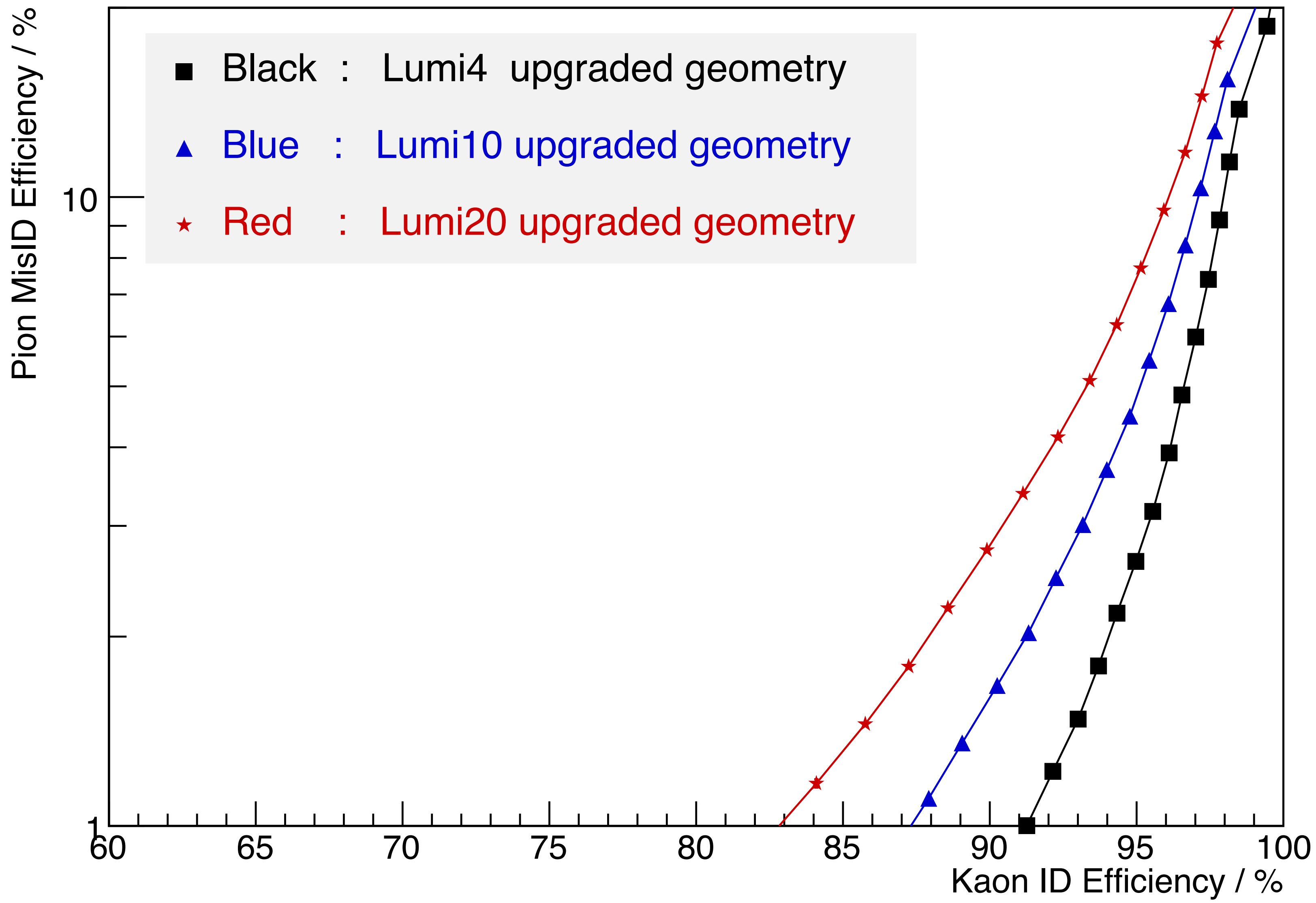
=> Run at $2\cdot10^{33}$ $cm^{-2}s^{-1}$

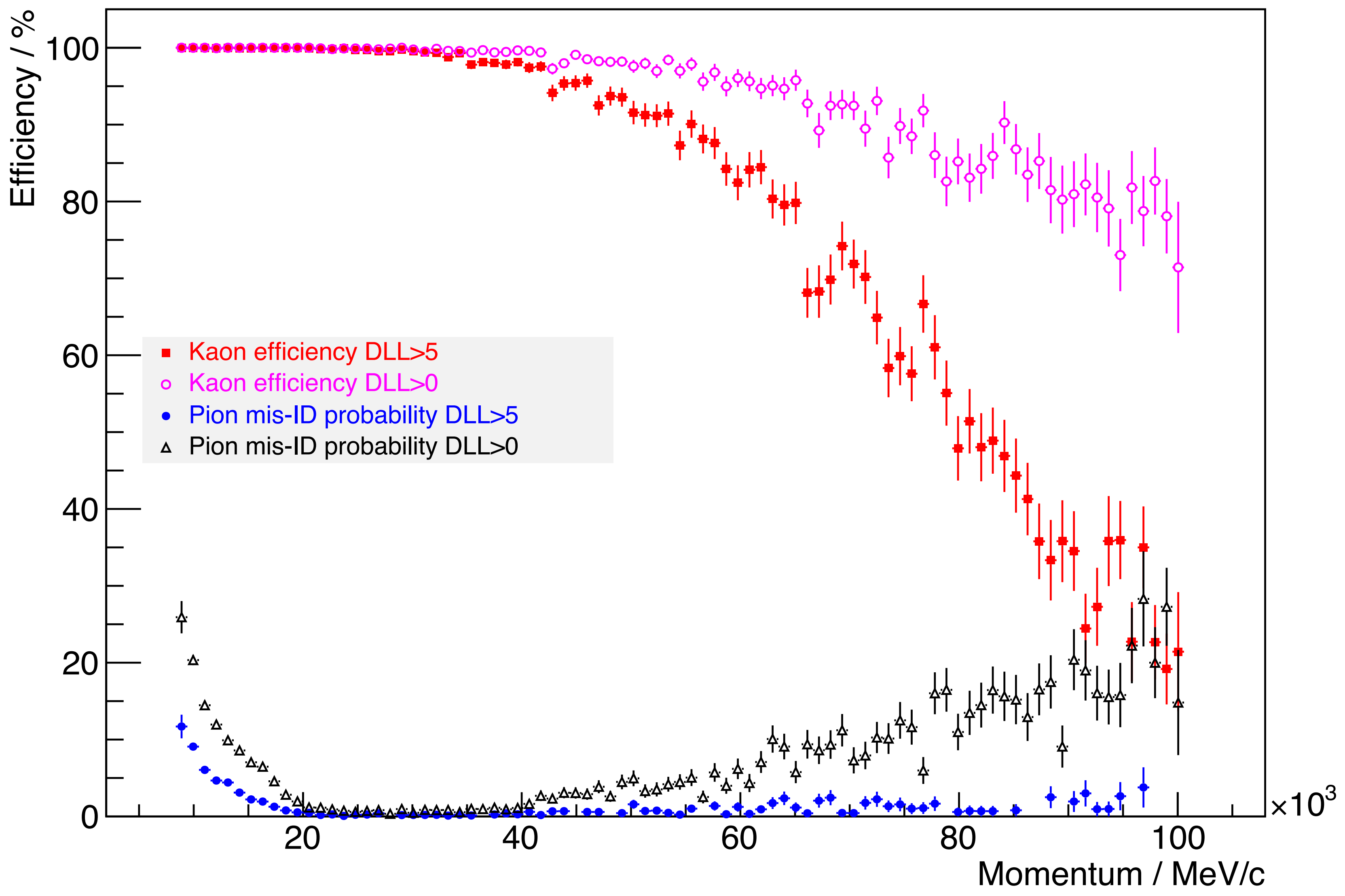
Also improve some subdetectors



UPGRADED
RETAINED

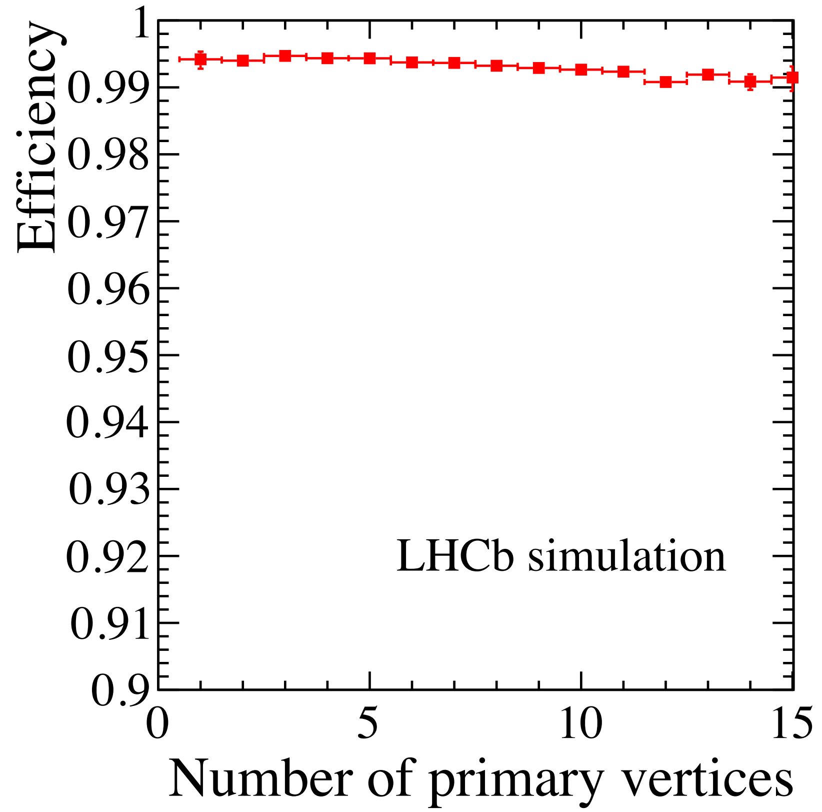
PID performance in the upgrade

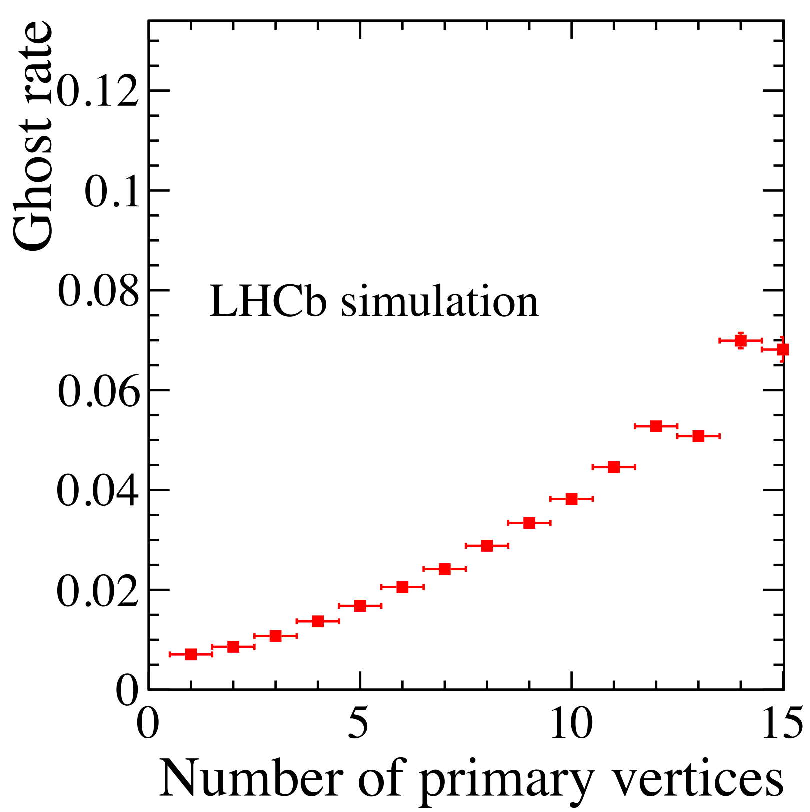




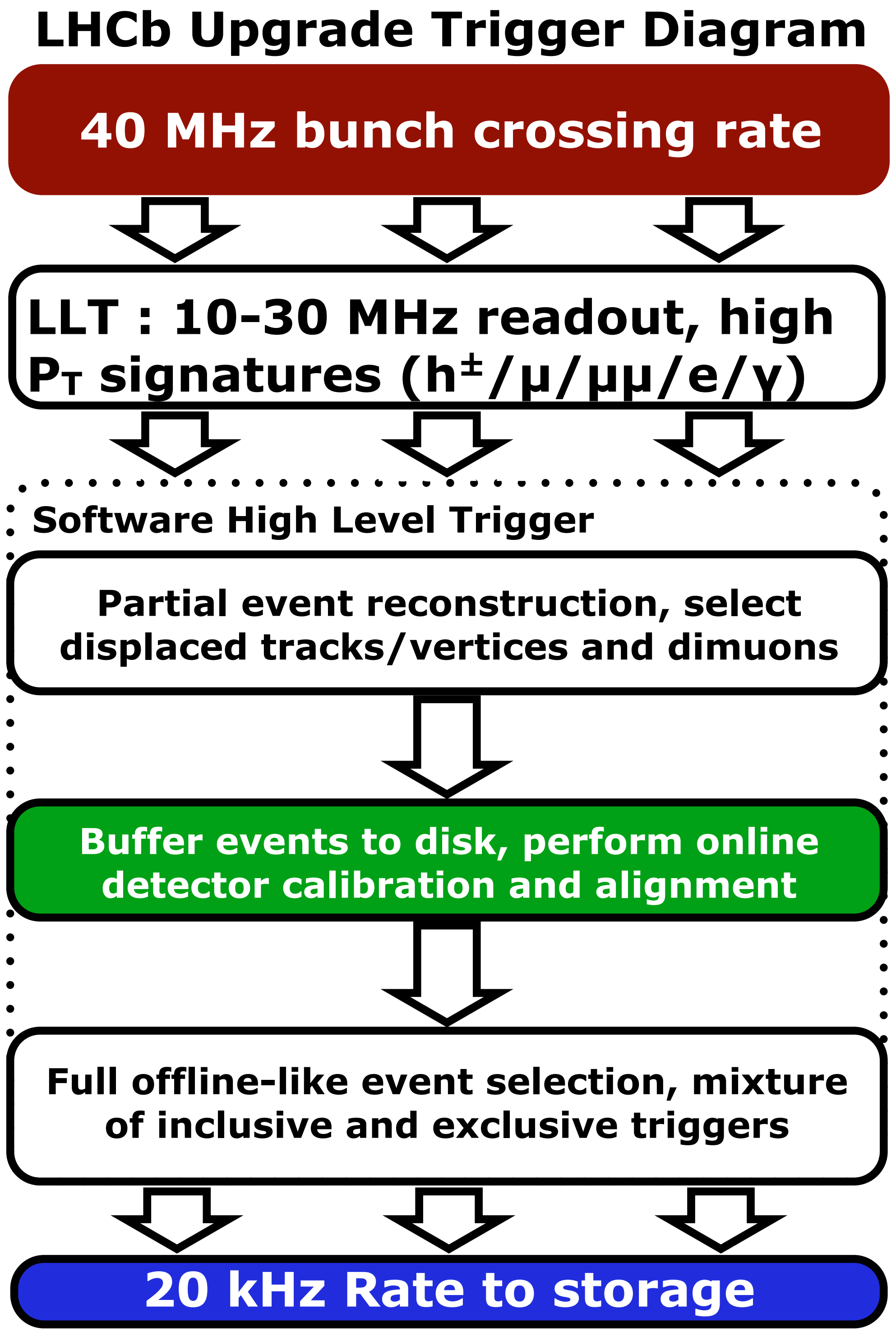
VELOPIX performance in the upgrade

	Existing VELO [%] $\nu = 2$	$\nu = 7.6$	Upgraded VELO [%] $\nu = 7.6$
Ghost rate	6.2	25.0	2.5
Clone rate	0.7	0.9	1.0
Reconstruction efficiency			
VELO, $p > 5\,\text{GeV}/c$	95.0	92.7	98.9
long	97.9	93.7	99.4
long, $p > 5\,\text{GeV}/c$	98.6	95.7	99.6
b-hadron daughters	99.0	95.4	99.6
b-hadron daughters, $p > 5\,\text{GeV}/c$	99.1	96.6	99.8



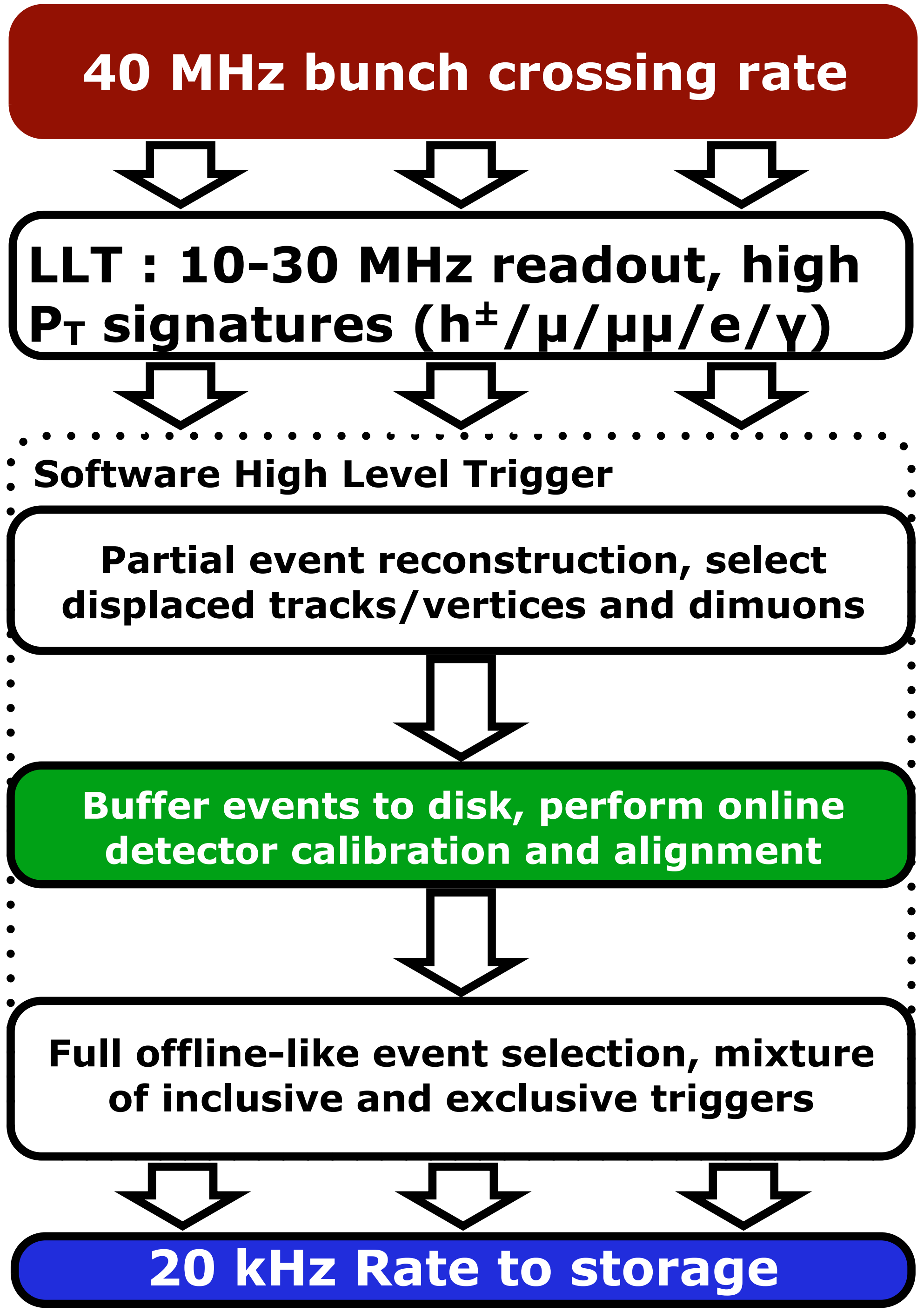


The all-software trigger



The all-software trigger

LHCb Upgrade Trigger Diagram

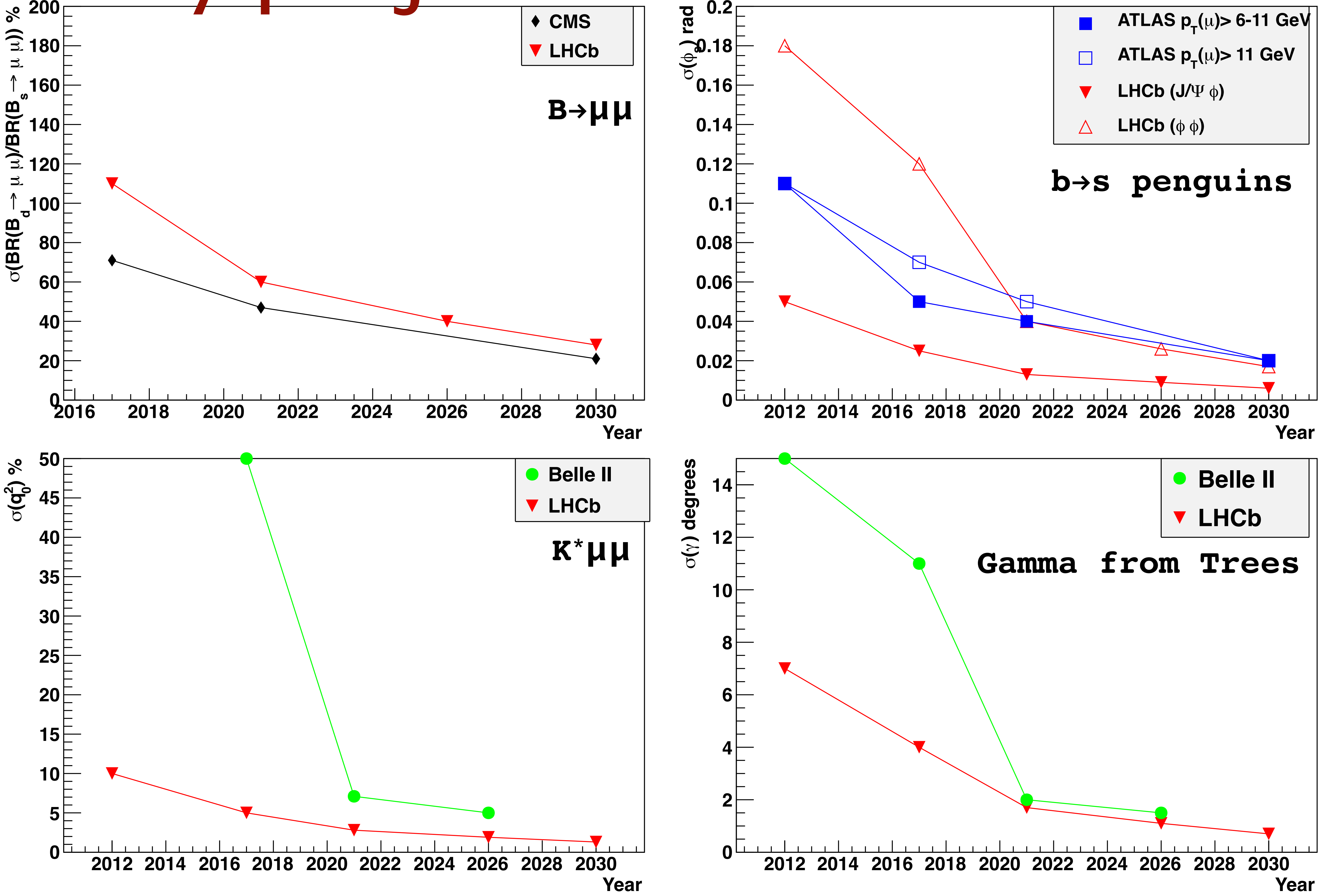


	Run 3 2019–21	Run 4 2024–26	Run 5+ 2028–30+
LLT rate (MHz)	10	15	15
E_T cut (GeV)	3.2	2.4	2.4
$\phi_s(B_s^0 \to \phi\phi)$	1.35	1.6	1.6
$\gamma(B^+ \to DK^+)$	1.35	1.6	1.6
$A_\Gamma(D^0 \to K^+K^-)$	1.4	2.1	2.1

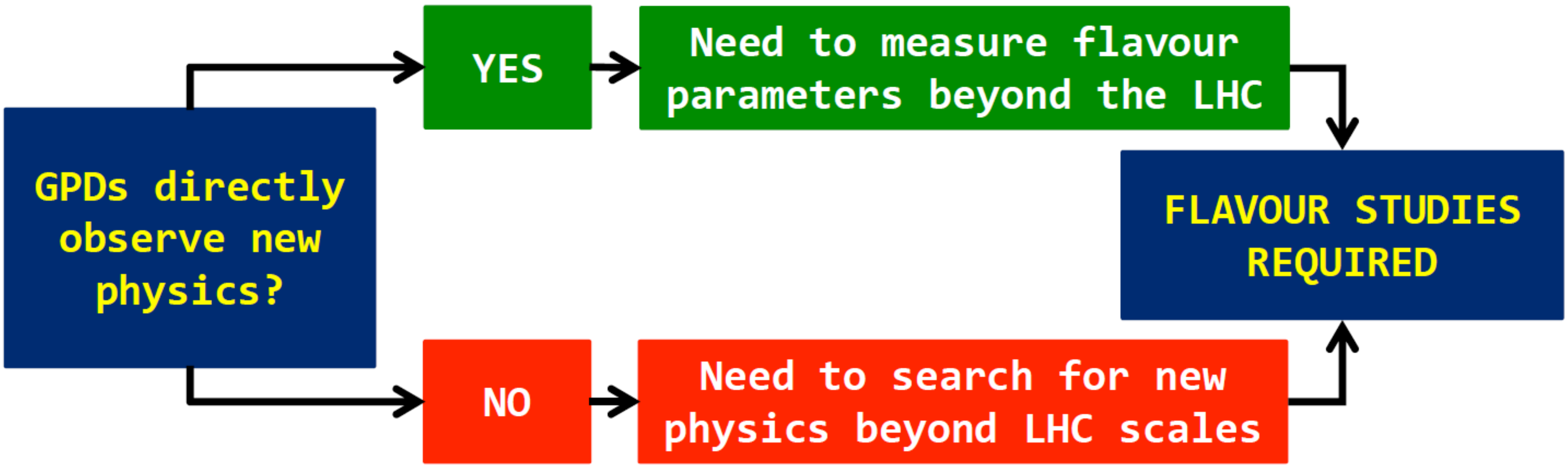
Gain 50-100% efficiency for hadronic final states

Aim to eventually run "quasi-triggerless" : implement offline reconstruction and selections in the trigger for any final state which can be reconstructed by the detector.

Stat uncertainty projections

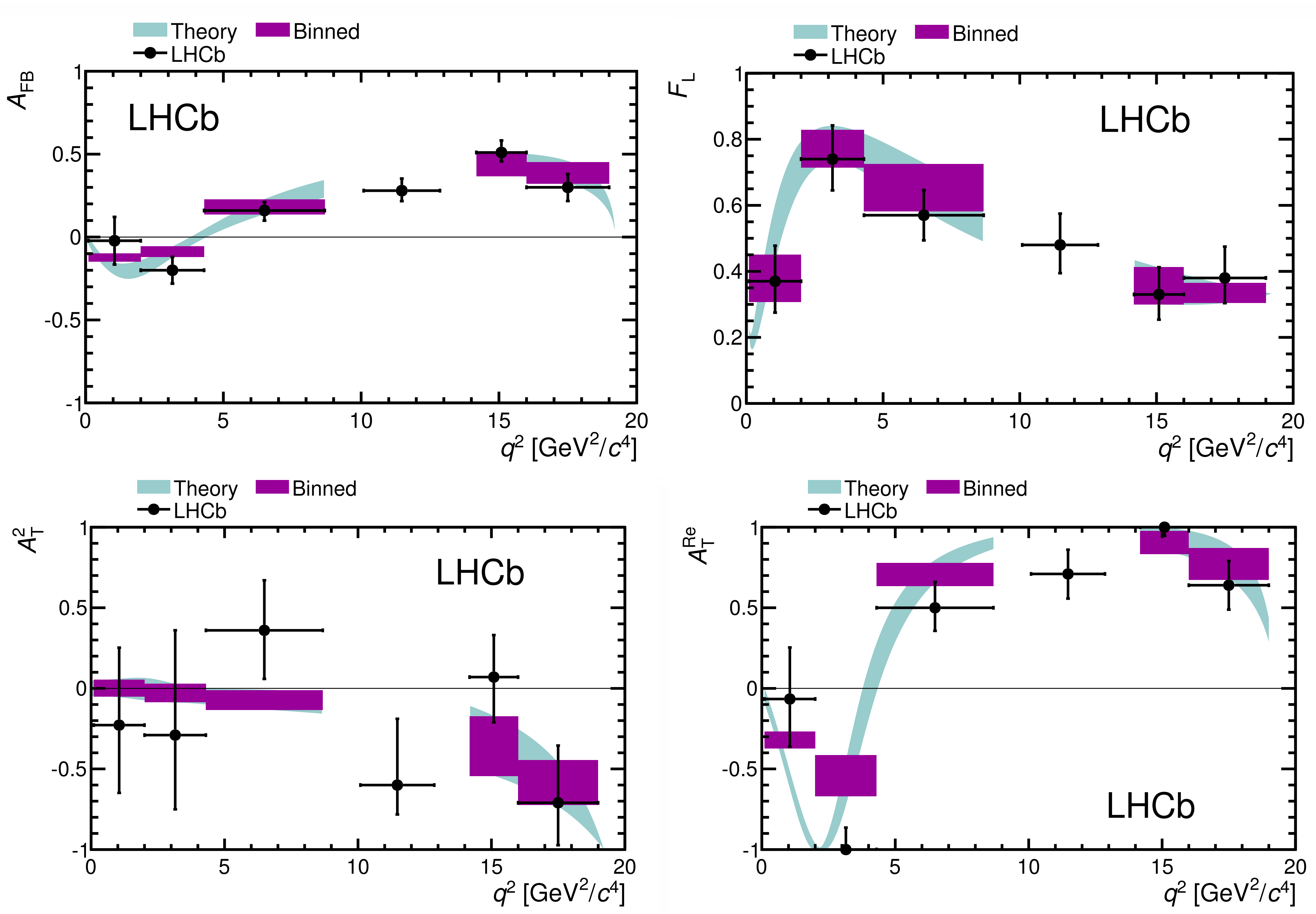


Tremendous reach whatever happens

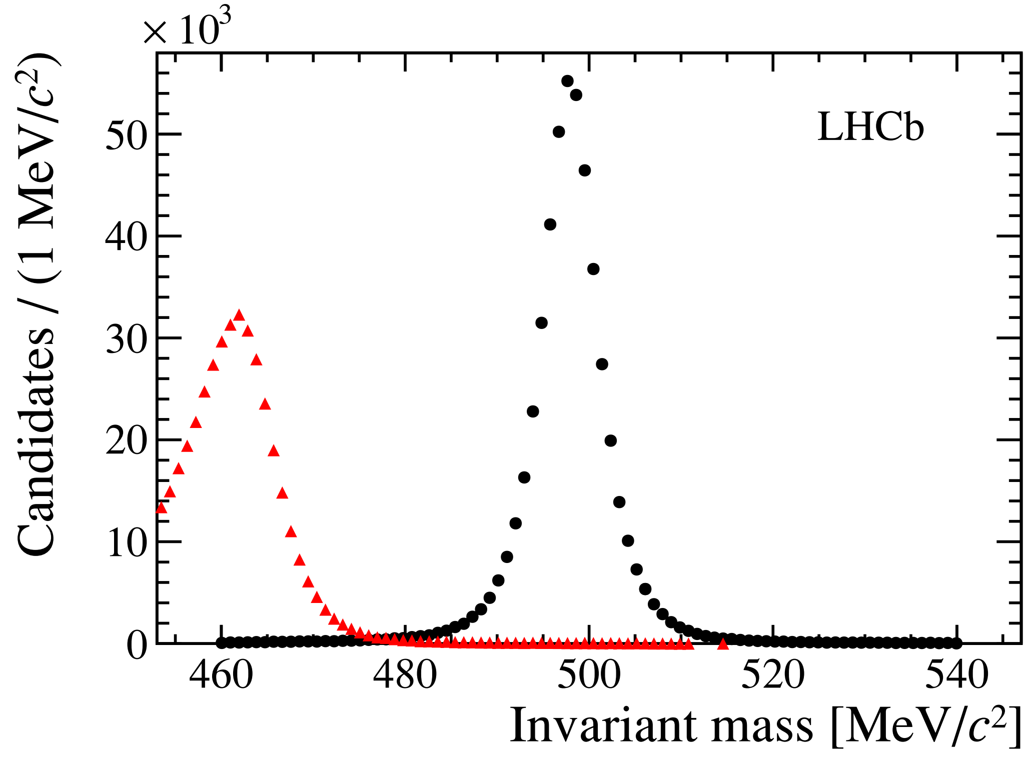


Backups

More $B^0 \rightarrow K^{*}\mu\mu$ angular analysis



$K_S \rightarrow \mu\mu$



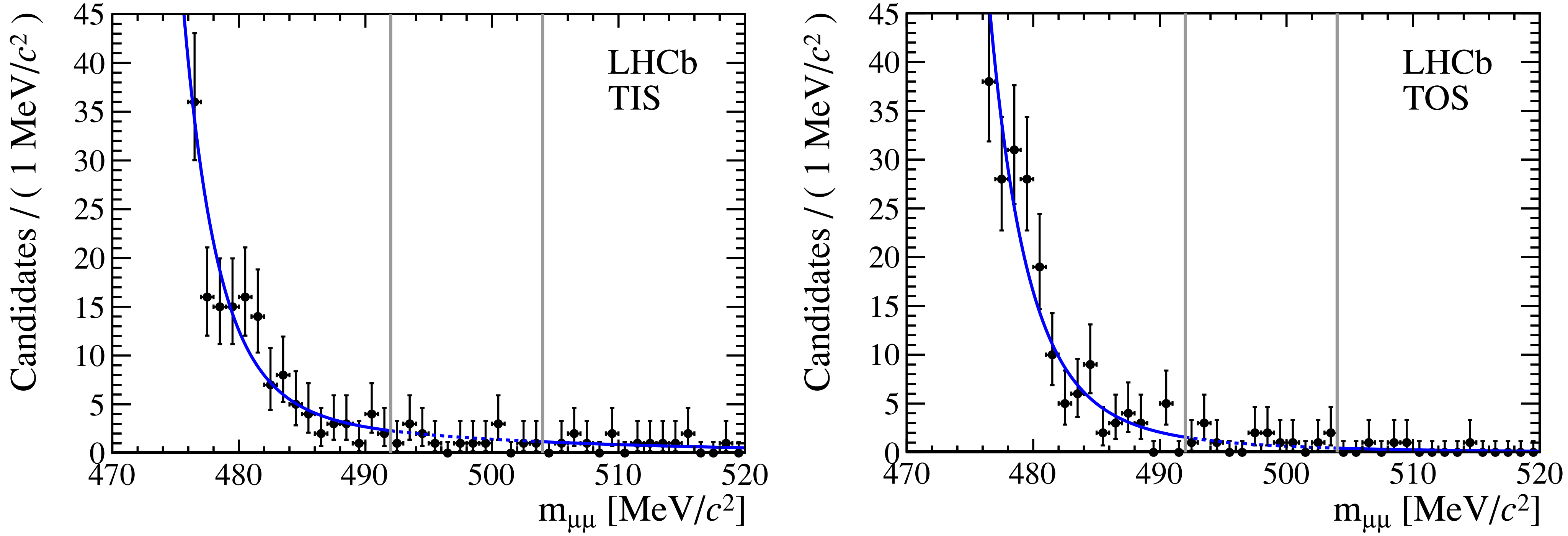
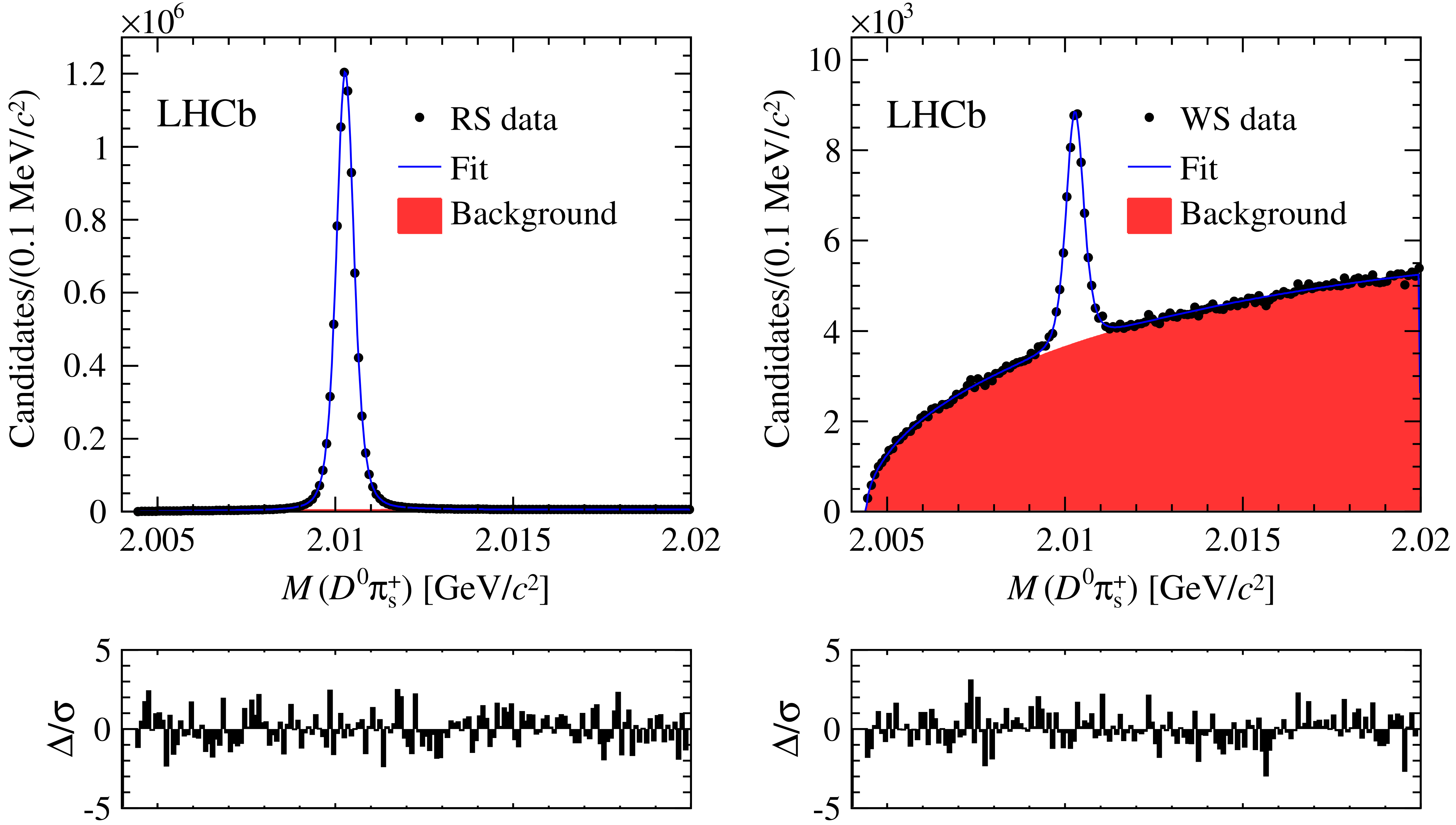


Figure 3. Background model fitted to the data separated along (left) TIS and (right) TOS trigger categories. The vertical lines delimit the search window.

$$\mathcal{B}(K^0_S \rightarrow \mu^+\mu^-) < 11(9) \times 10^{-9}$$

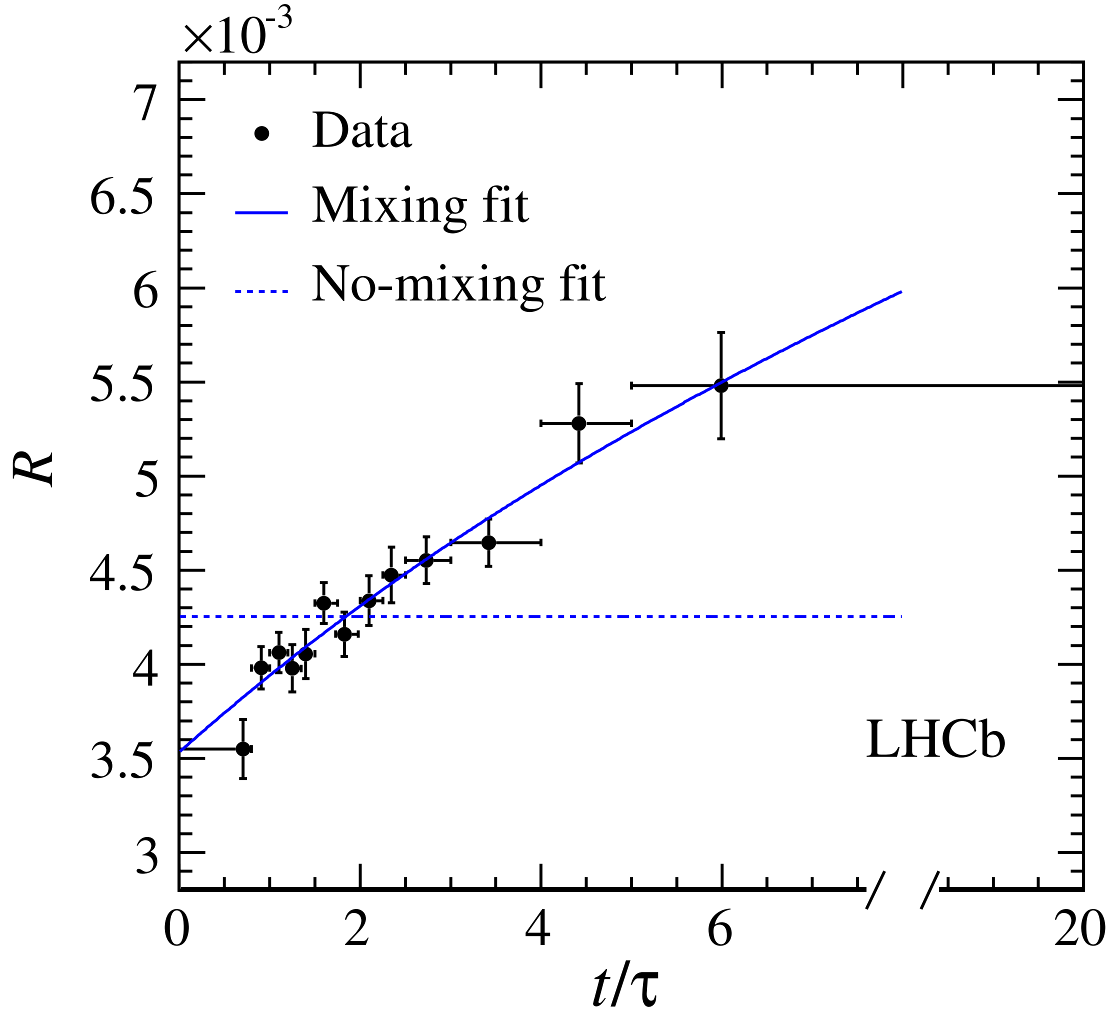
JHEP01(2013)090

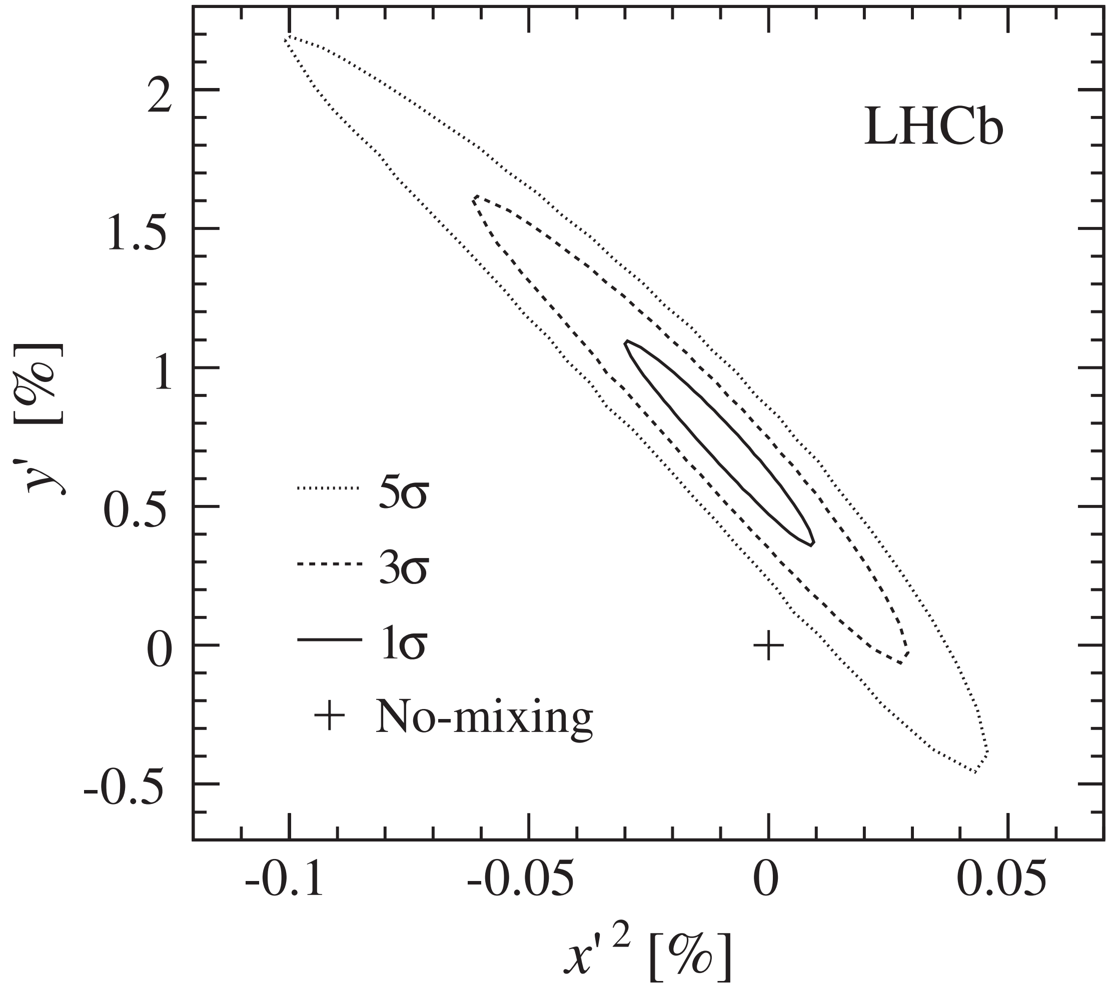
D^0 mixing



PRL 110 (2013) 101802

D^0 mixing



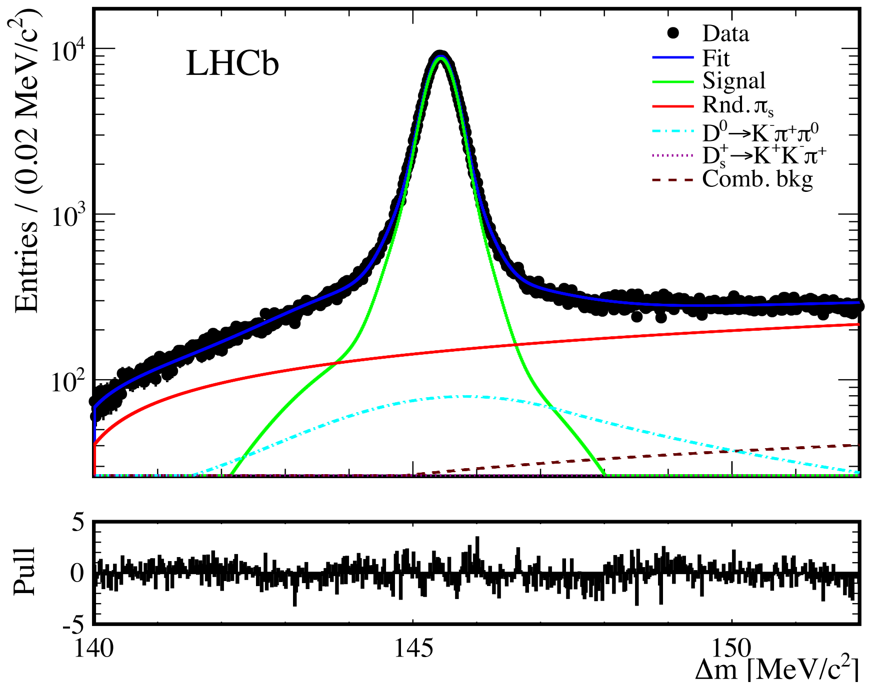


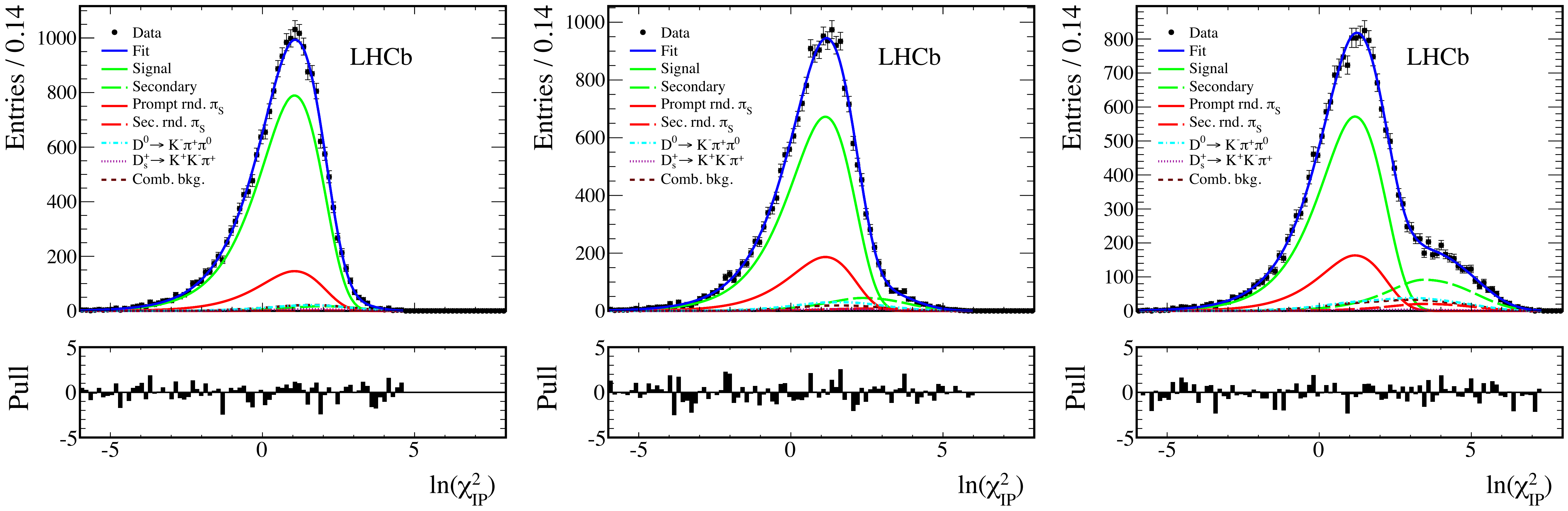
Fit type (χ^2/ndf)	Parameter	Fit result (10^{-3})	Correlation coefficient R_D	y'	x'^2
Mixing (9.5/10)	R_D	3.52 ± 0.15	1	-0.954	$+0.882$
	y'	7.2 ± 2.4		1	-0.973
	x'^2	-0.09 ± 0.13			1
No mixing (98.1/12)	R_D	4.25 ± 0.04			

PRL 110 (2013) 101802

A_Γ

$$A_\Gamma \equiv \frac{\hat{\Gamma} - \hat{\bar{\Gamma}}}{\hat{\Gamma} + \hat{\bar{\Gamma}}} \approx \eta_{CP}\left(\frac{A_m + A_d}{2} y\cos\phi - x\sin\phi\right)$$





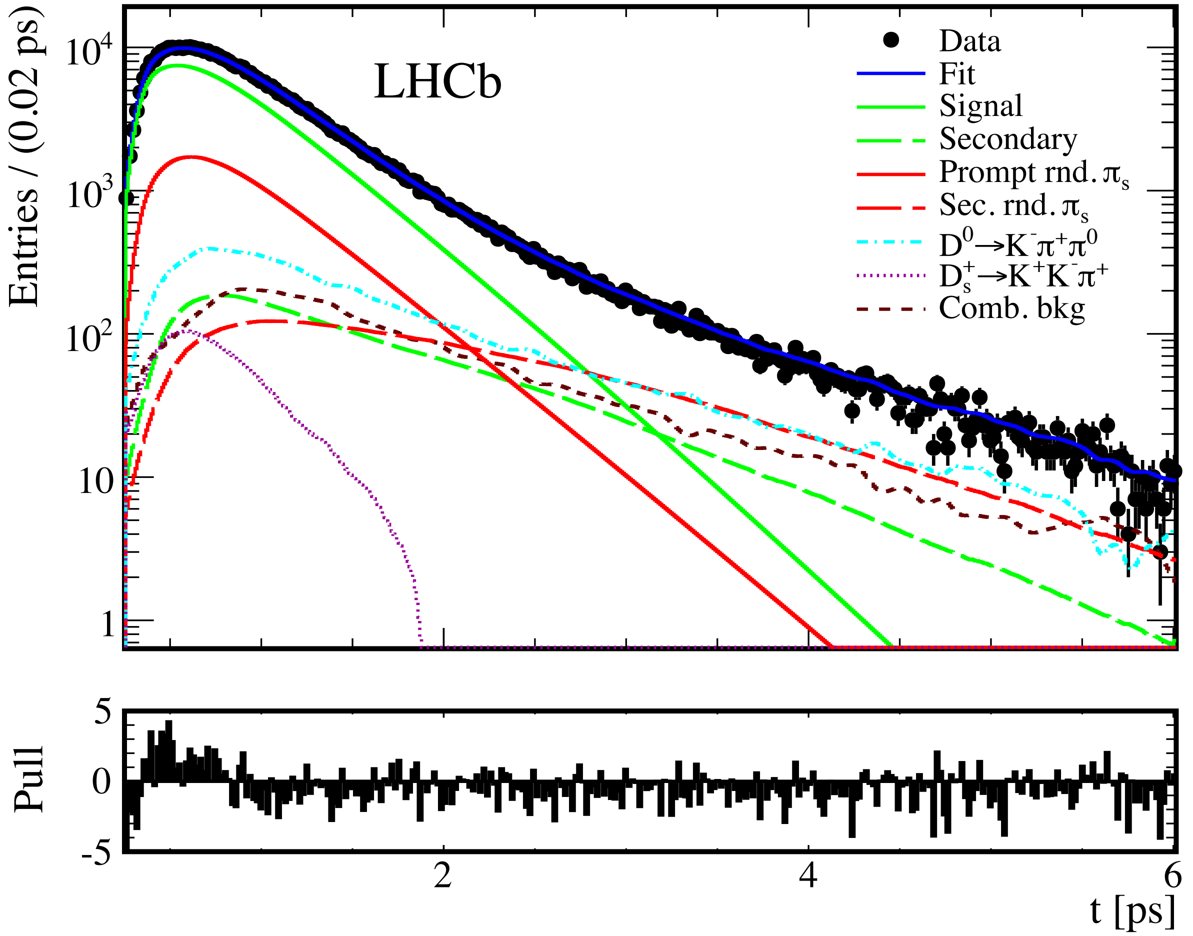
arXiv:1310.7201v1

A_Γ

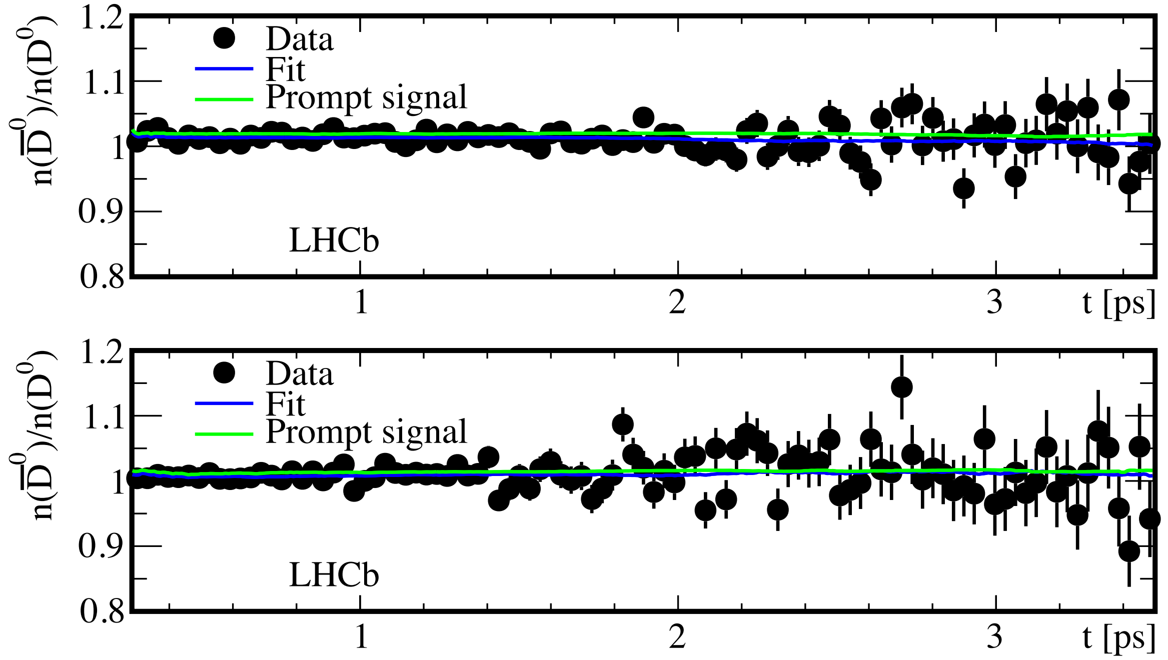
$$A_\Gamma \equiv \frac{\hat{\Gamma} - \hat{\bar{\Gamma}}}{\hat{\Gamma} + \hat{\bar{\Gamma}}} \approx \eta_{CP} \left(\frac{A_m + A_d}{2} y \cos\phi - x \sin\phi \right)$$

A_Γ(KK) = (-0.35 ± 0.62 ± 0.12)•10^{-3}

$A_\Gamma(\pi\pi)$ = (0.33 ± 1.06 ± 0.14)•10^{-3}

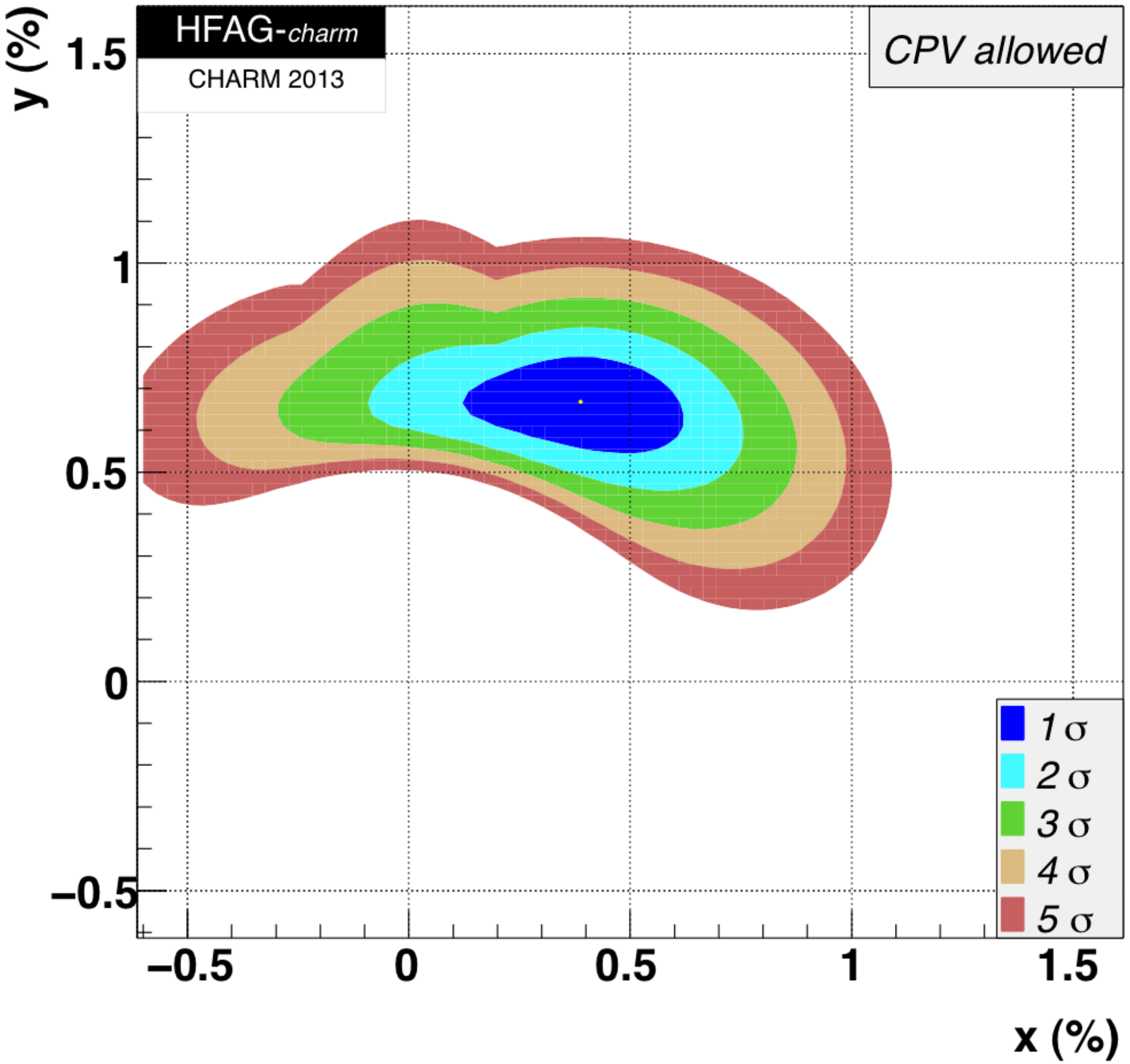


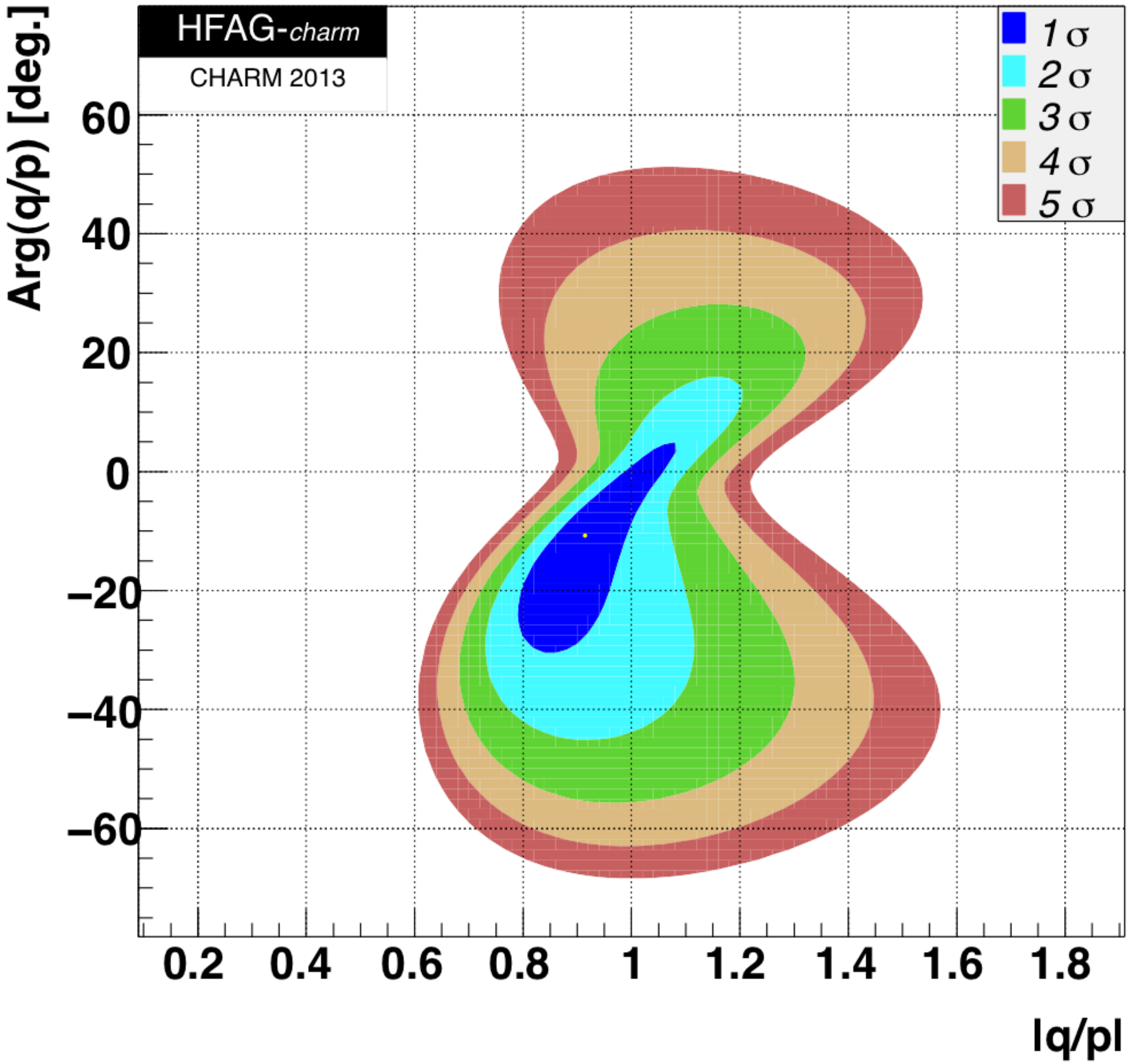
Source	$A_\Gamma^{unb}(KK)$	$A_\Gamma^{bin}(KK)$	$A_\Gamma^{unb}(\pi\pi)$	$A_\Gamma^{bin}(\pi\pi)$
Partially reconstructed backgrounds	±0.02	±0.09	±0.00	±0.00
Charm from b decays	±0.07	±0.55	±0.07	±0.53
Other backgrounds	±0.02	±0.40	±0.04	±0.57
Acceptance function	±0.09	—	±0.11	—
Magnet polarity	—	±0.58	—	±0.82
Total syst. uncertainty	±0.12	±0.89	±0.14	±1.13



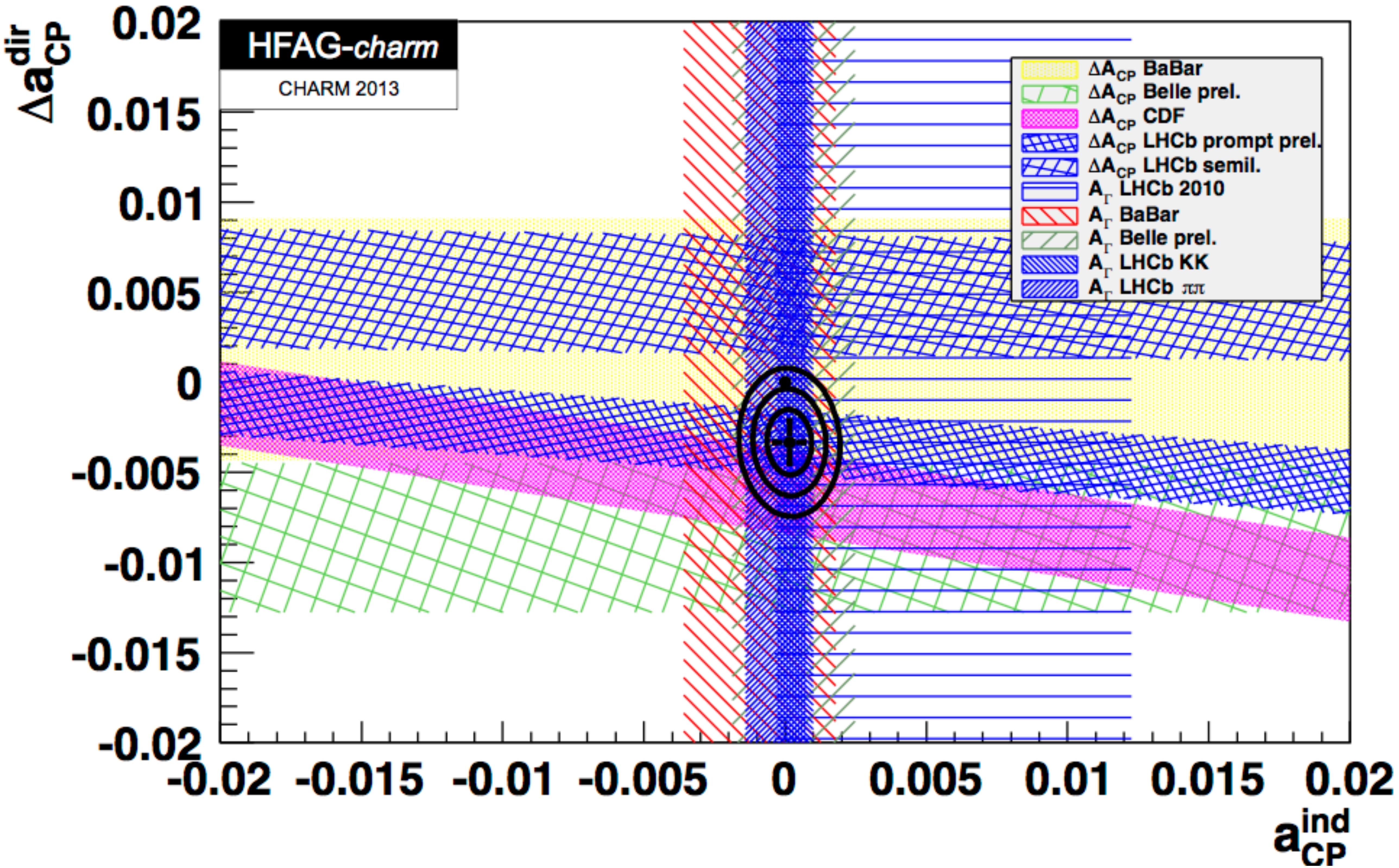
arXiv:1310.7201v1

HFAG charm latest

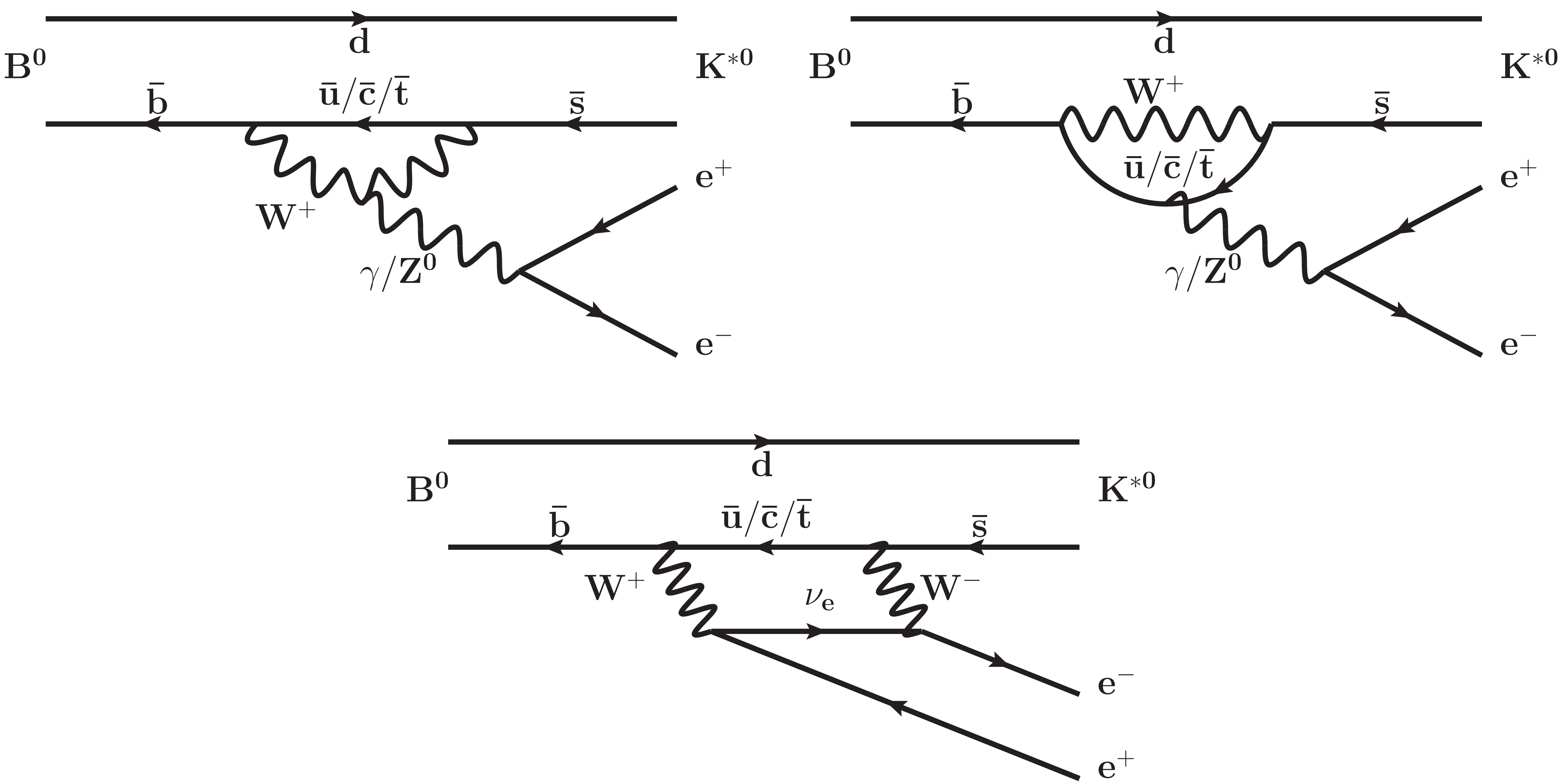




HFAG charm latest



$K^{*0}ee$ in the low q^2 region



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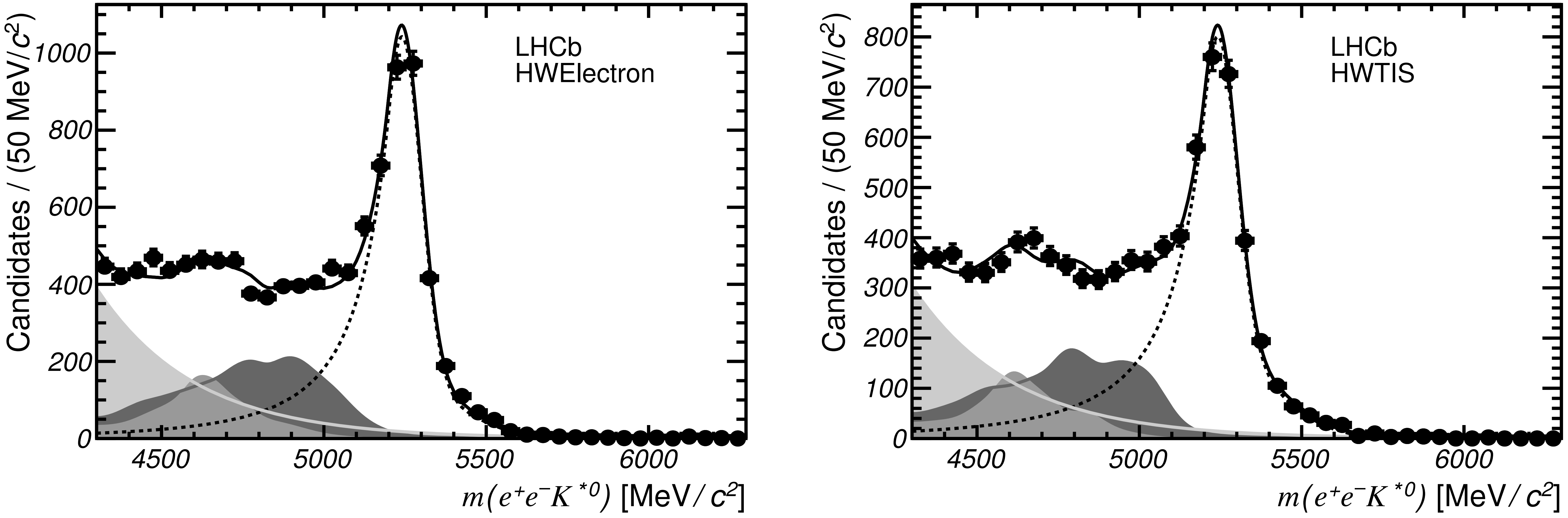
$K^{*0}ee$ in the low q^2 region



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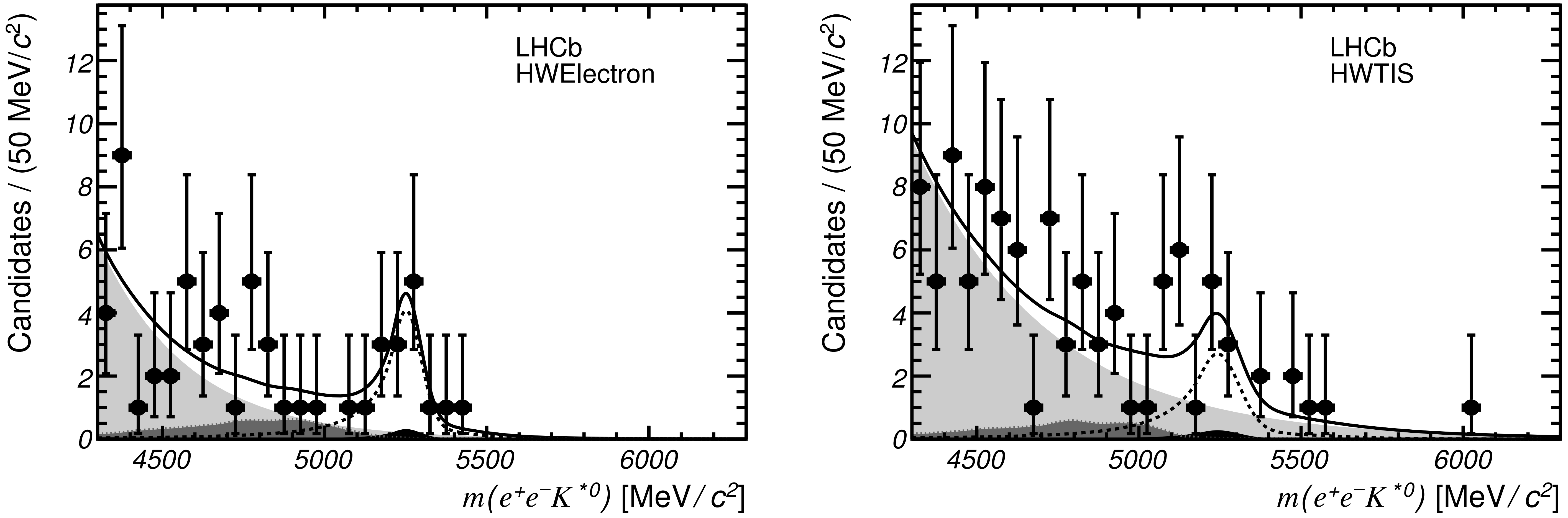
$K^{*0}ee$ in the low q^2 region



$$\mathcal{B}(B^0 \to K^{*0}e^+e^-)^{30-1000\,\mathrm{MeV}/c^2} = (3.1\,^{+0.9}_{-0.8}\,^{+0.2}_{-0.3} \pm 0.2) \times 10^{-7}.$$

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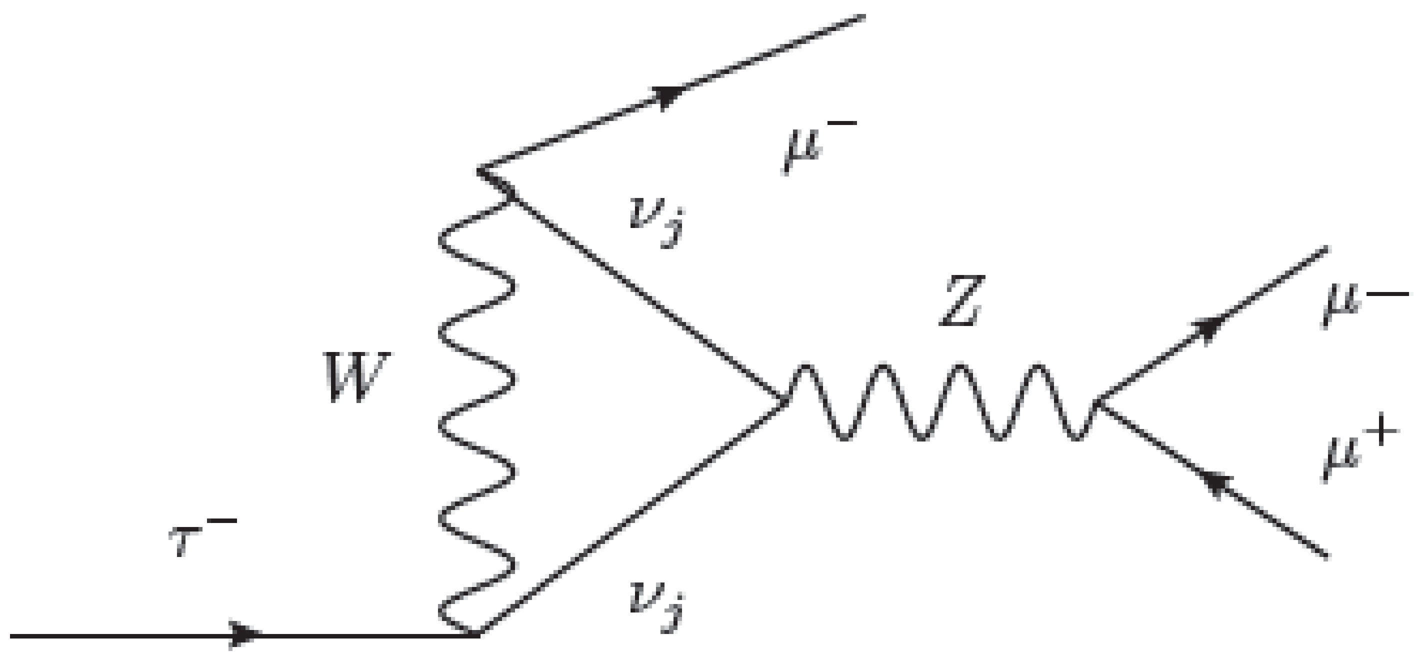
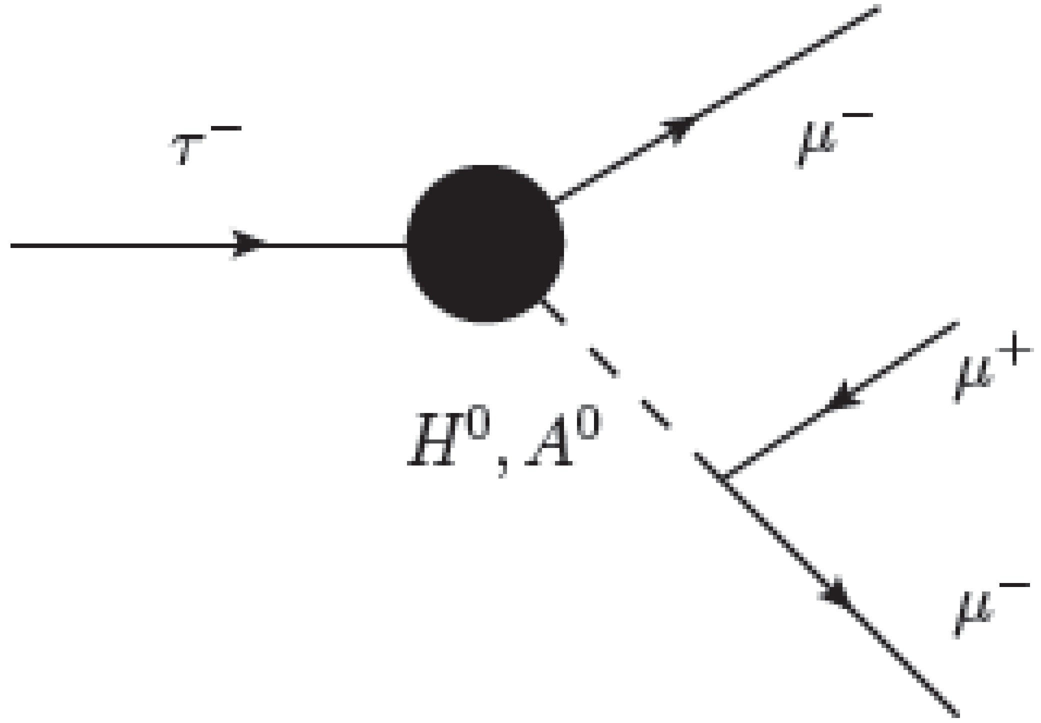
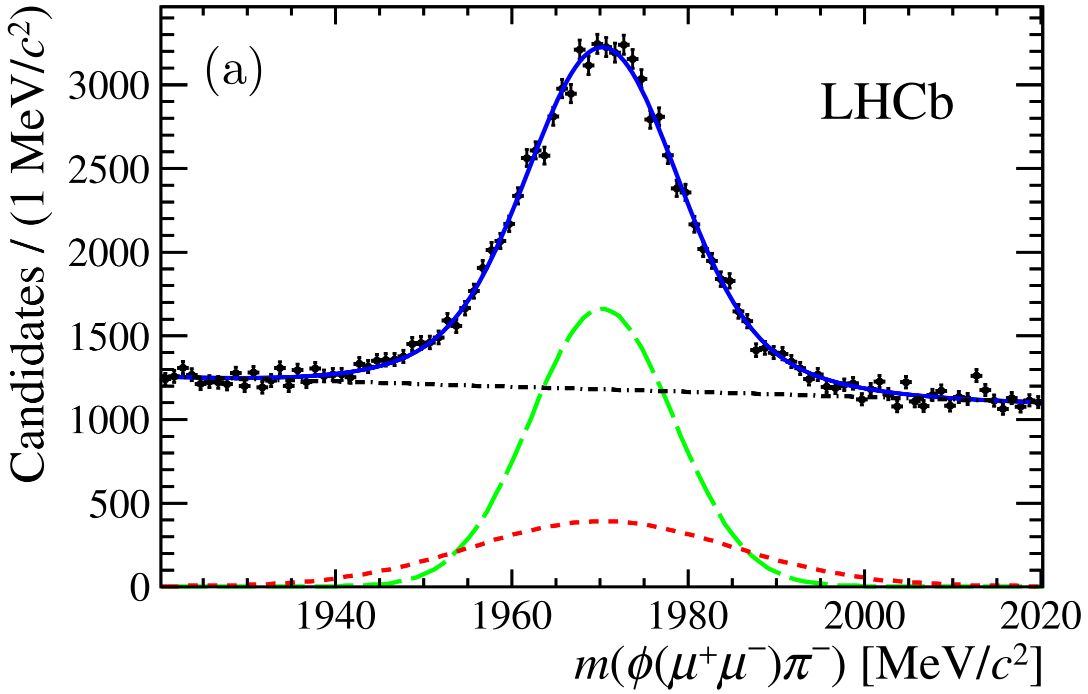
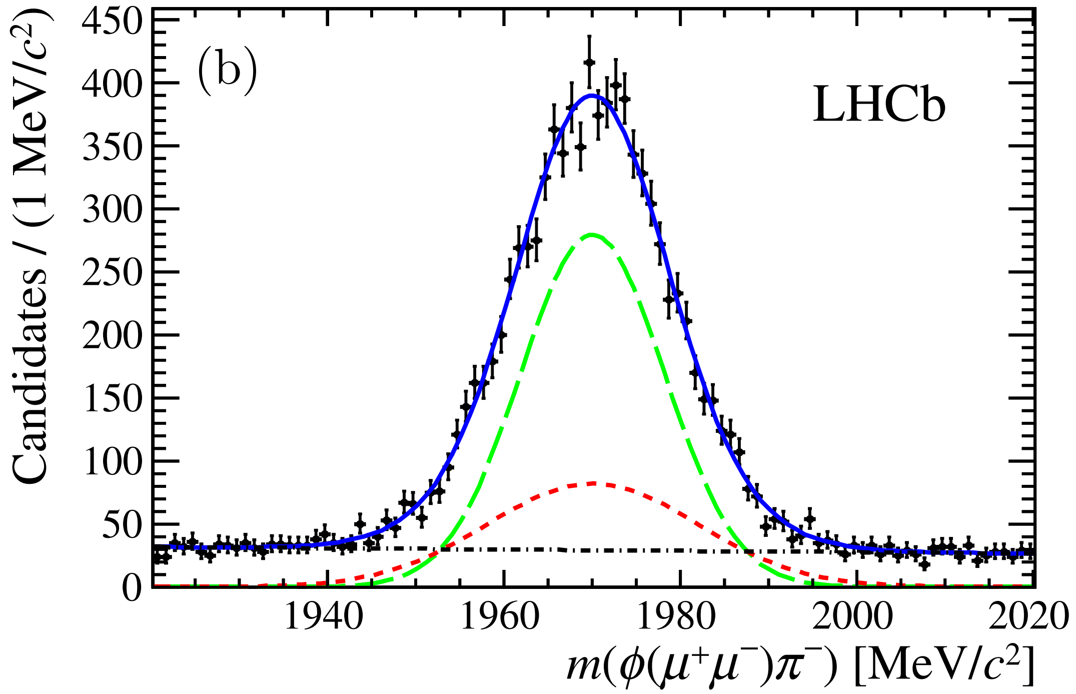
LFV searches



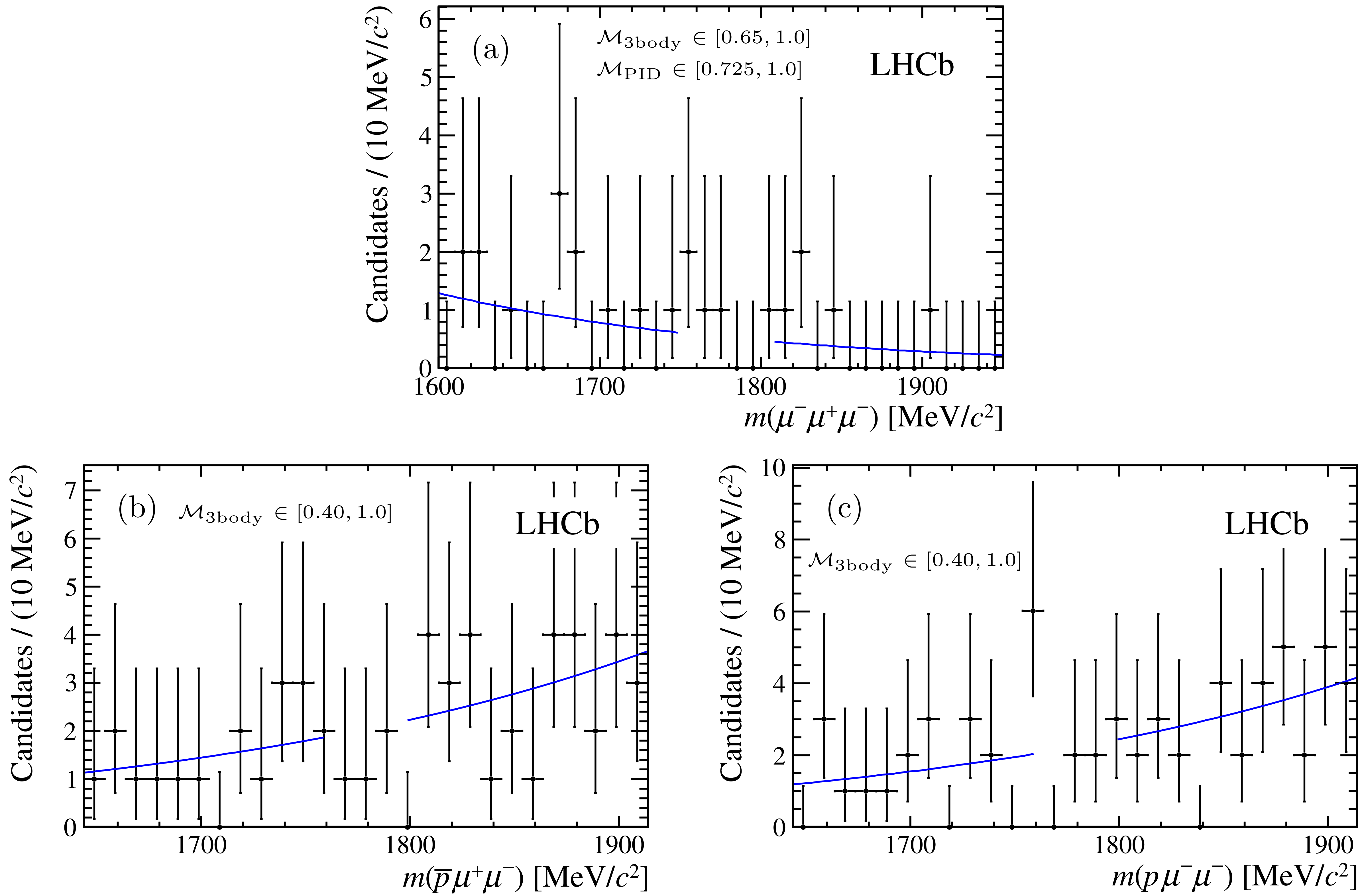






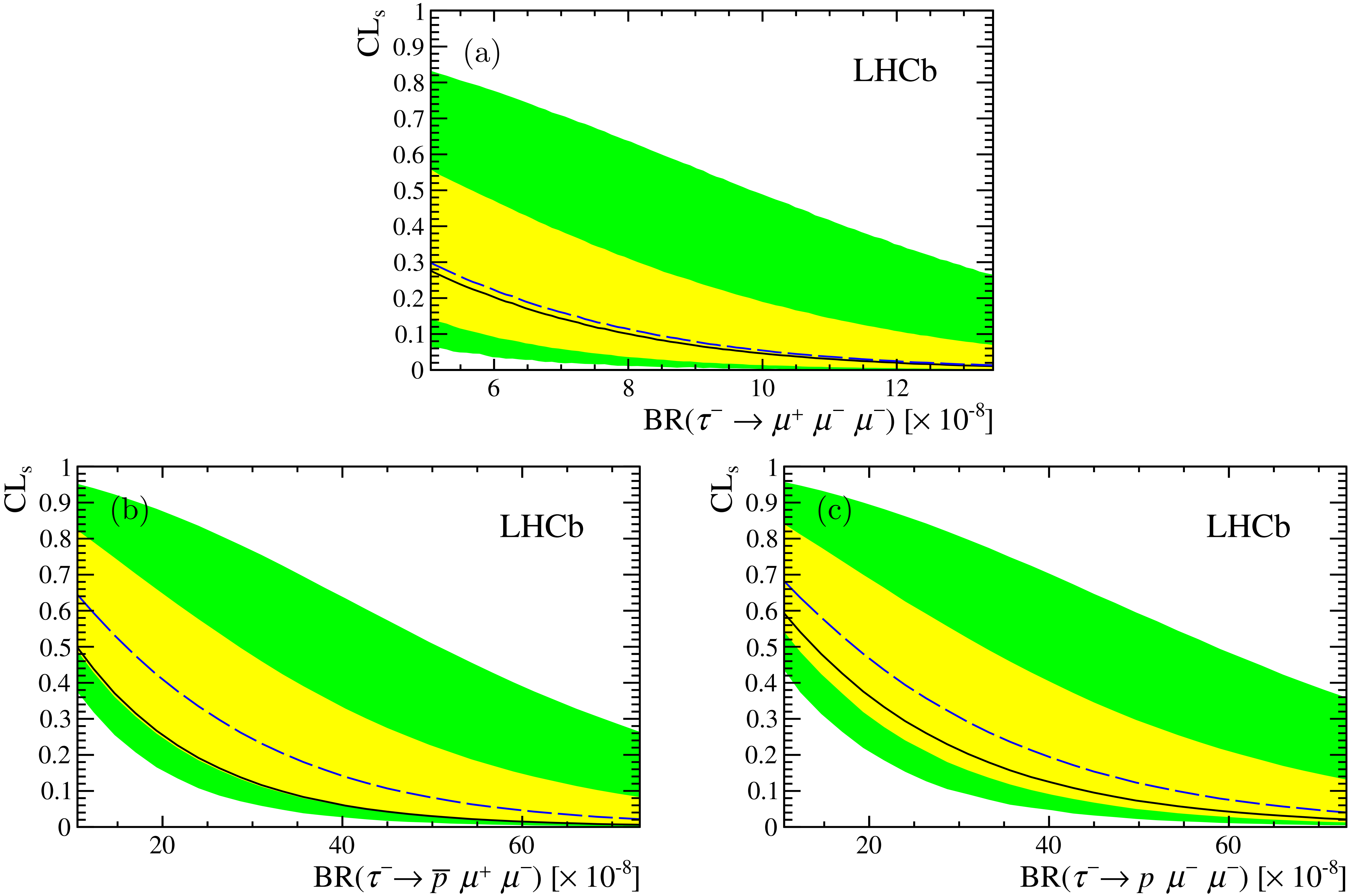
PLB 724 (2013) 36-45

LFV searches



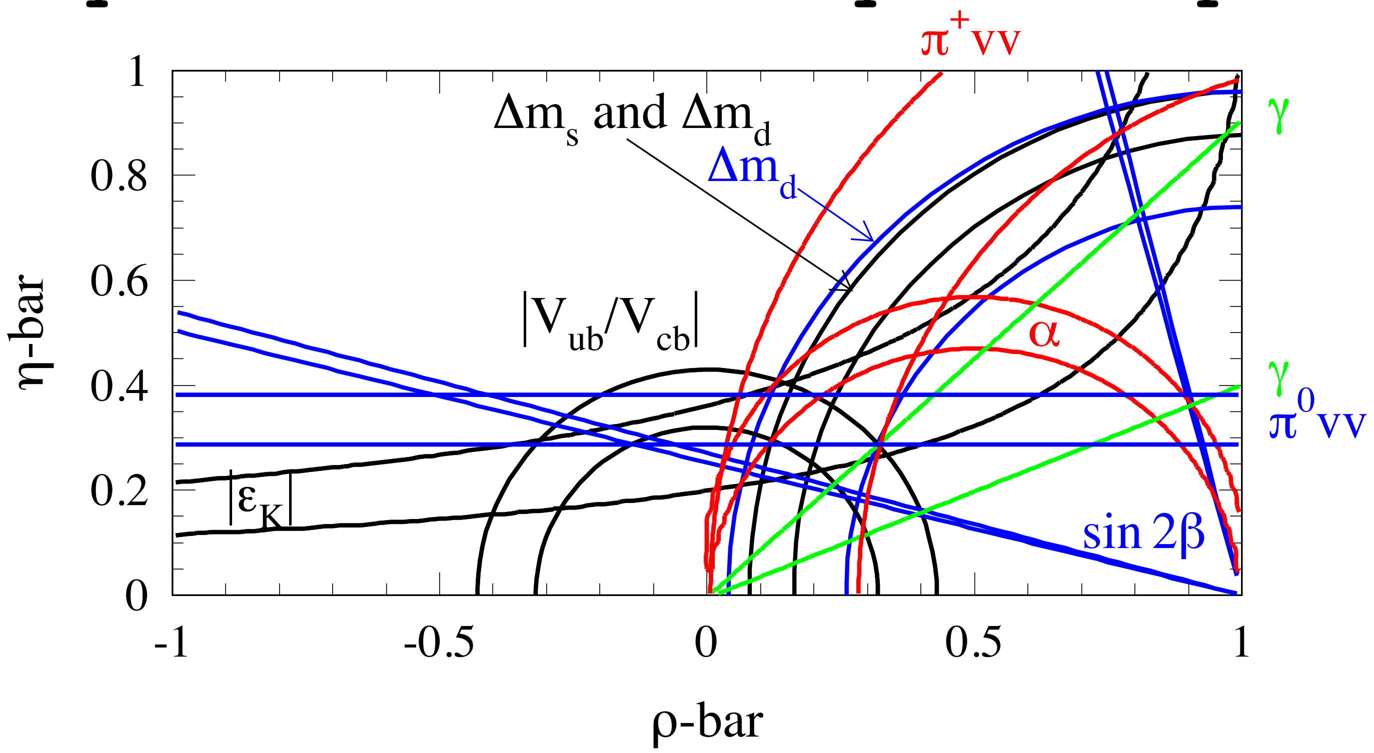
PLB 724 (2013) 36-45

LFV searches

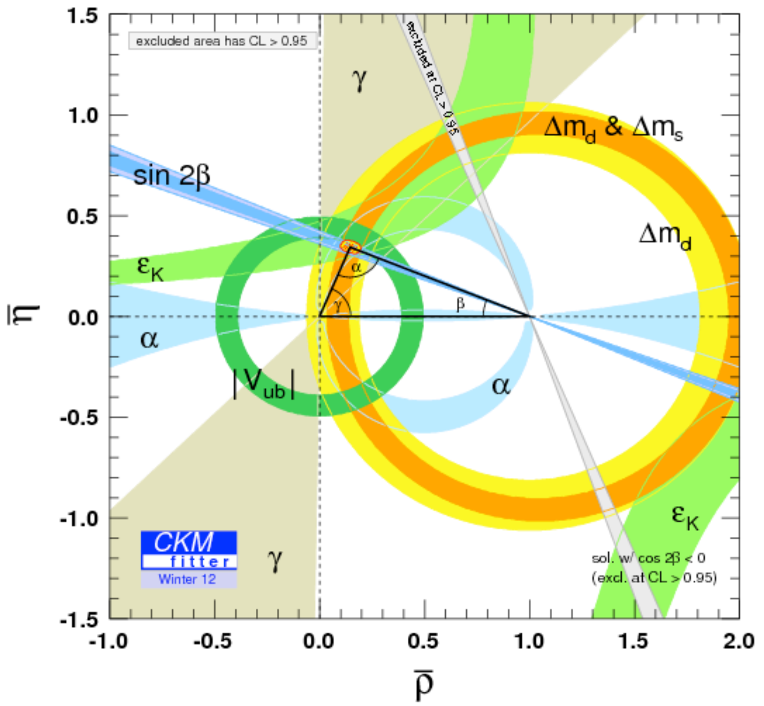


PLB 724 (2013) 36-45

Prophecy for 2010 -- clearly a bit optimistic!



2012



A decade of overachievement…

BELLE ADS

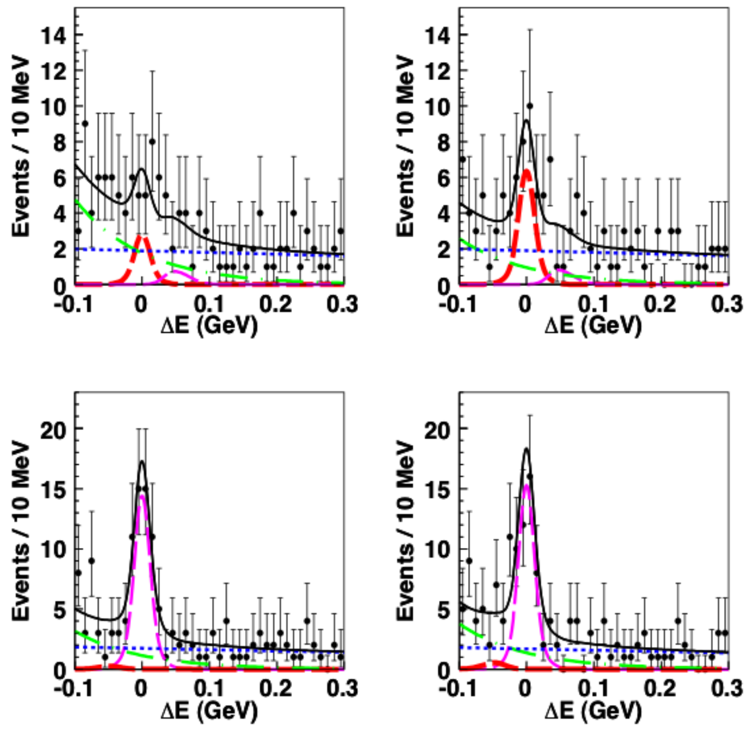


FIG. 2: ΔE distributions ($NB > 0.9$) for $[K^+\pi^-]_D K^-$ (left upper), $[K^-\pi^+]_D K^+$ (right upper), $[K^+\pi^-]_D \pi^-$ (left lower), and $[K^-\pi^+]_D \pi^+$ (right lower). The curves show the same components as in Fig. 1.

BABAR ADS

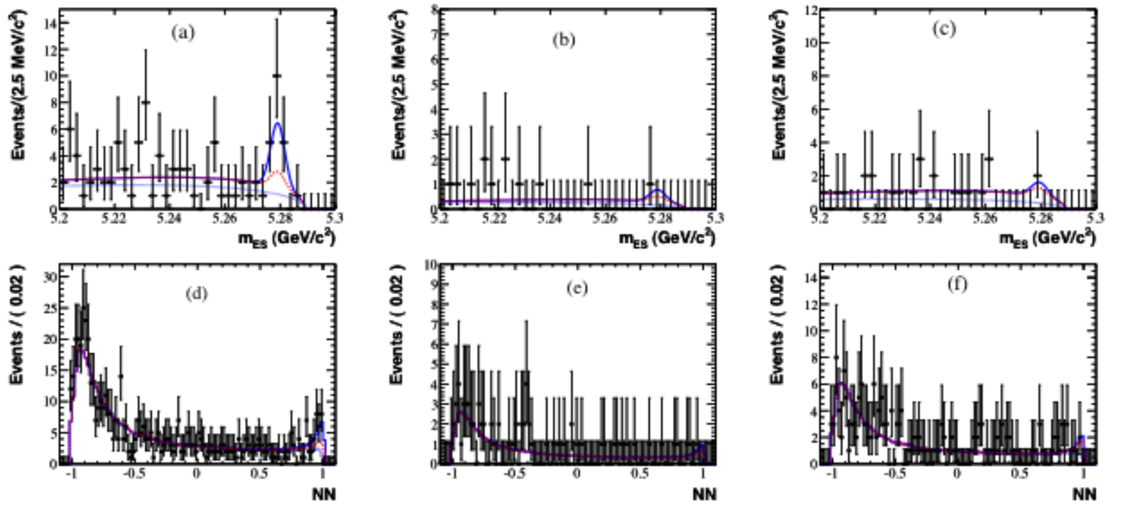


FIG. 8: (color online). Projections on m_{ES} (a, b, c) and NN (d, e, f) of the fit results for DK^+ (a, d), $D^*_{D\pi^0}K^+$ (b, e) and $D^*_{D\gamma}K^+$ (c, f) WS decays, for samples enriched in signal with the requirements $NN > 0.94$ (m_{ES} projections) or $5.2725 < m_{ES} < 5.2875$ GeV/c^2 (NN projections). The points with error bars are data. The curves represent the fit projections for signal plus background (solid), the sum of all background components (dashed), and $q\bar{q}$ background only (dotted).

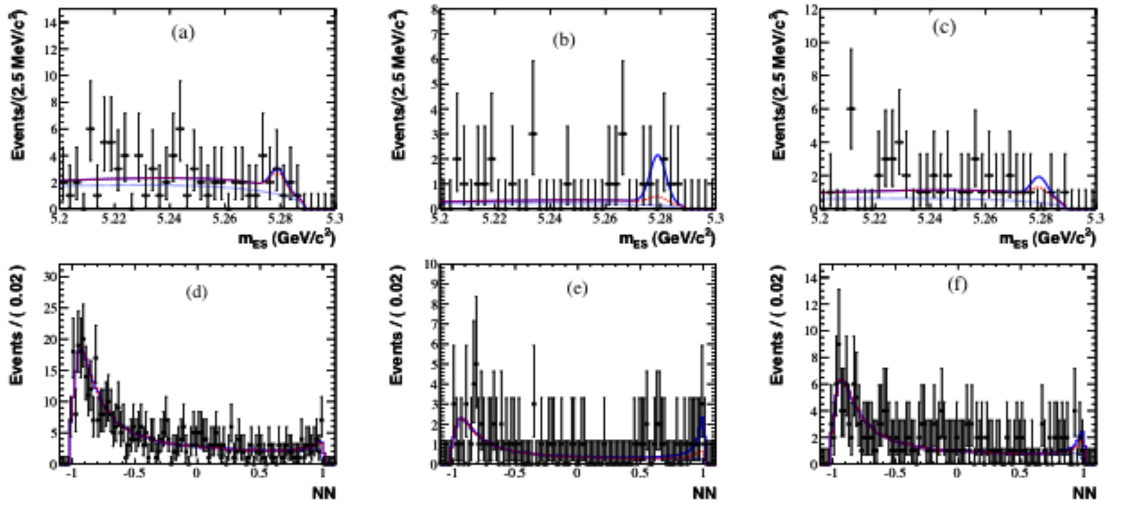


FIG. 9: (color online). Projections on m_{ES} (a, b, c) and NN (d, e, f) of the fit results for DK^- (a, d), $D^*_{D\pi^0}K^-$ (b, e) and $D^*_{D\gamma}K^-$ (c, f) WS decays, for samples enriched in signal with the requirements $NN > 0.94$ (m_{ES} projections) or $5.2725 < m_{ES} < 5.2875$ GeV/c^2 (NN projections). The points with error bars are data. The curves represent the fit projections for signal plus background (solid), the sum of all background components (dashed), and $q\bar{q}$ background only (dotted).

CDF ADS

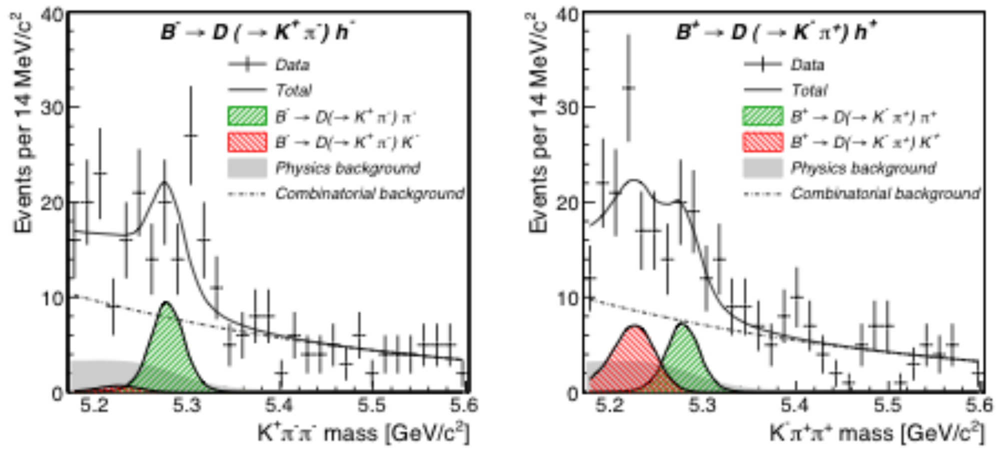


FIG. 1: Invariant mass distributions of $B^\pm \to Dh^\pm$ for the suppressed mode (bottom meson on the left and antibottom on the right). The pion mass is assigned to the charged track from the B candidate decay vertex. The projections of the common likelihood fit (see text) are overlaid.

Left to right :

arXiv:1103.5951v2

PRD 82 072006 (2010)

arXiv:1108.5765v2

What has this enabled LHCb to produce?

GLW/ADS in $B \to DK, D\pi$ with $D \to hh$

ADS in $B \to DK, D\pi$ with $D \to hhhh$

GGSZ in $B \to DK$ with $D \to K_S hh$

GLW in $B \to DK^{0*}$

GLW in $B \to Dhhh$

Frequentist γ combination

Time dependent CPV in $B_S \to D_S K$

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GLW in $B \to Dhhh$

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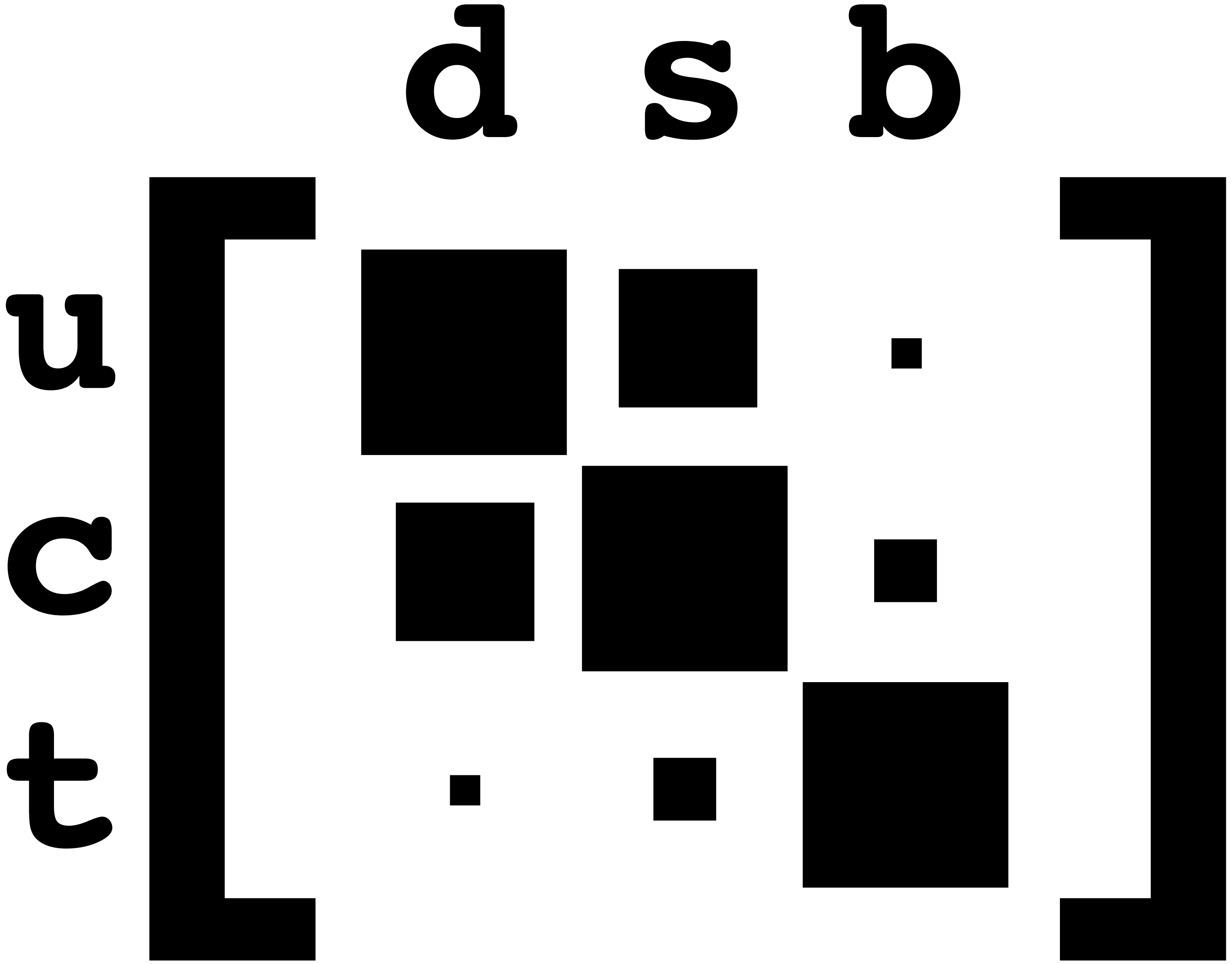
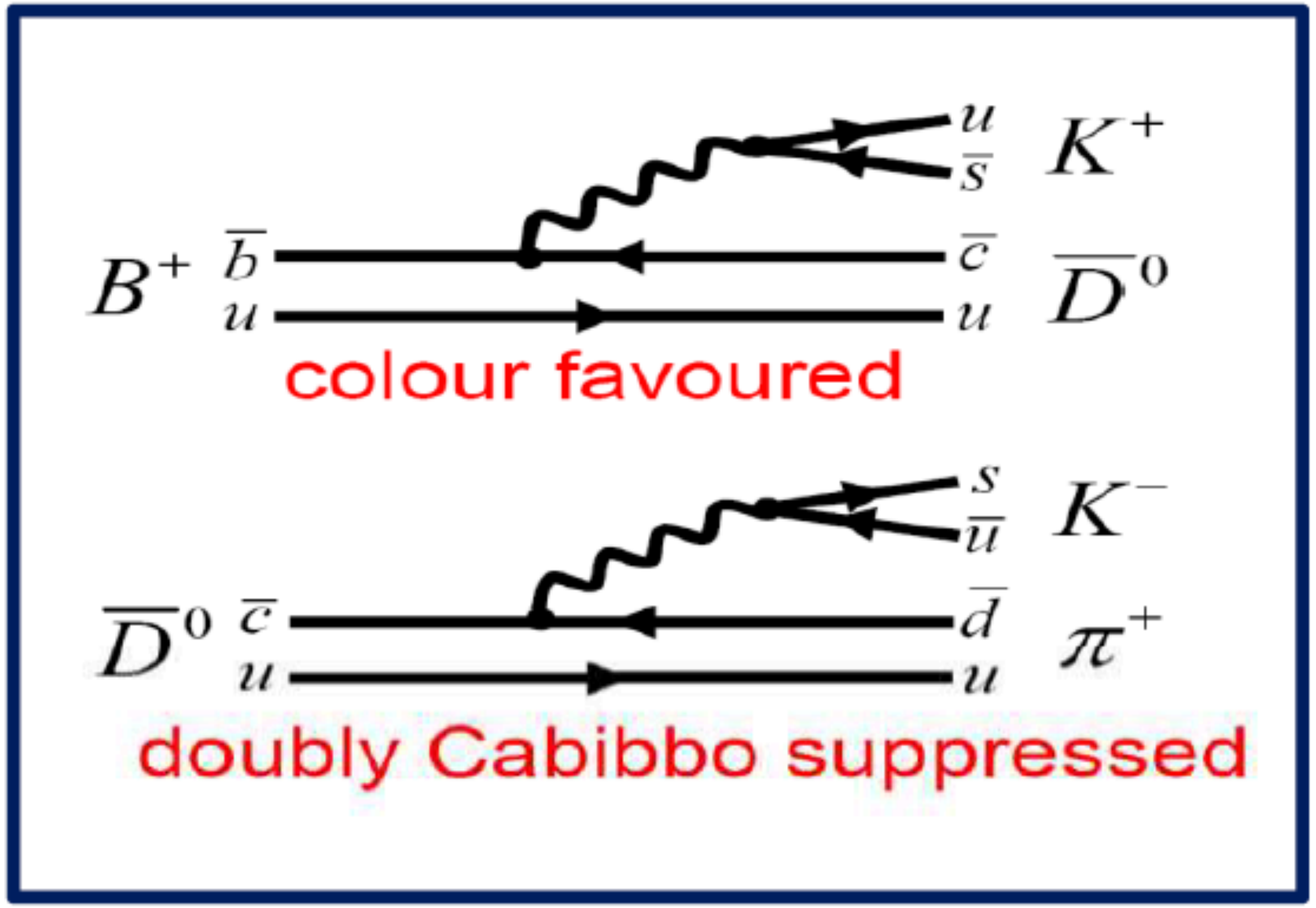
Time dependent CPV in $B_S \to D_S K$

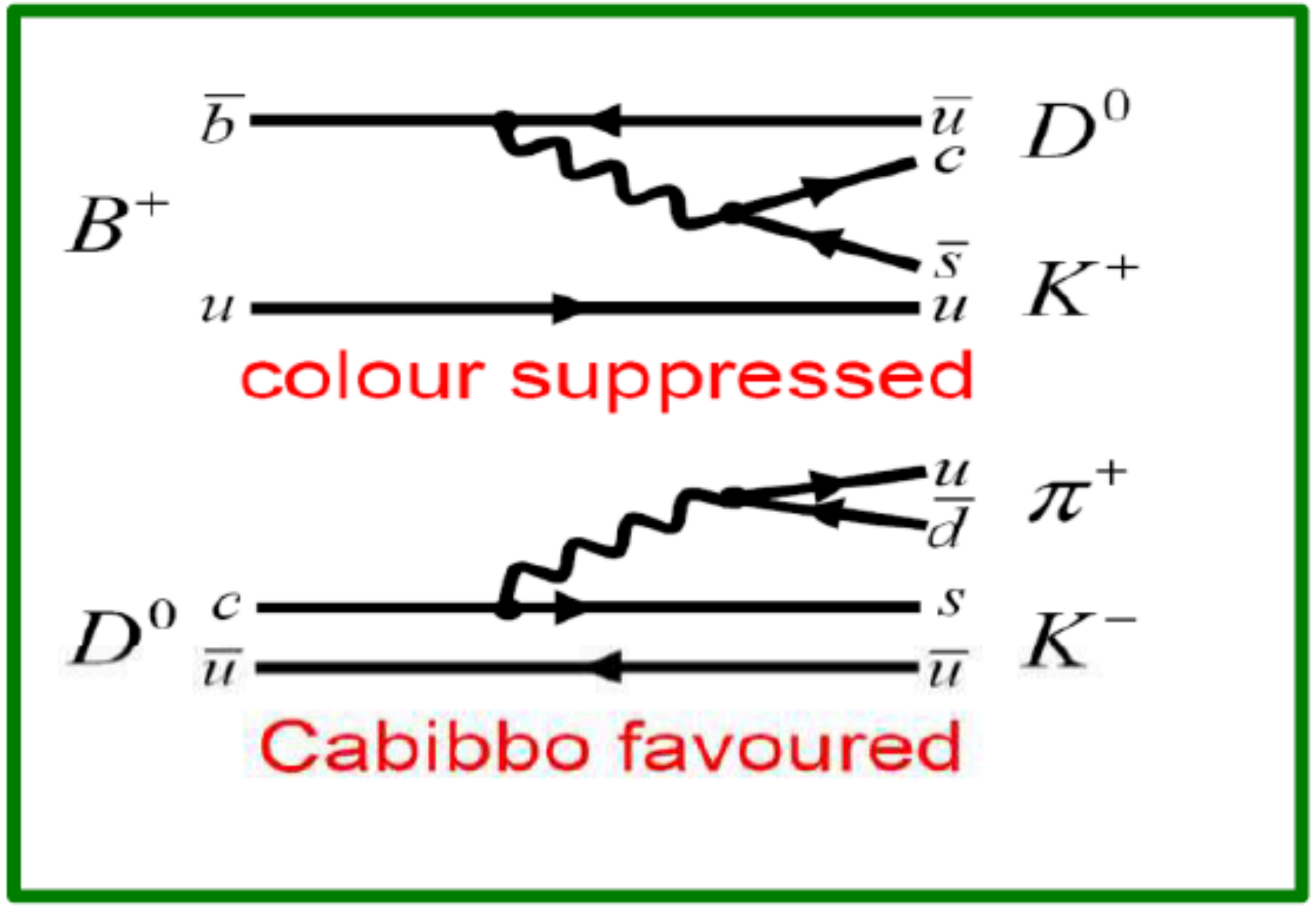
Aside on the CKM matrix structure



Bigger box == stronger coupling
(not to scale)

Observables ⇔ physics parameters





Observables ⇔ physics parameters

$$
\begin{aligned}
R^{K\pi}_{K/\pi} &= R\,\frac{1+(r_B r_D)^2+2r_B r_D\cos(\delta_B-\delta_D)\cos\gamma}{1+(r^\pi_B r_D)^2+2r^\pi_B r_D\cos(\delta^\pi_B-\delta_D)\cos\gamma} \\
R^{KK}_{K/\pi} = R^{\pi\pi}_{K/\pi} &= R\,\frac{1+{r_B}^2+2r_B\cos\delta_B\cos\gamma}{1+{r^\pi_B}^2+2r^\pi_B\cos\delta^\pi_B\cos\gamma} \\
A^{Fav} &= \frac{2r_B r_D\sin(\delta_B-\delta_D)\sin\gamma}{1+(r_B r_D)^2+r_B r_D\cos(\delta_B-\delta_D)\cos\gamma} \\
A^{Fav}_\pi &= \frac{2r^\pi_B r_D\sin(\delta^\pi_B-\delta_D)\sin\gamma}{1+(r^\pi_B r_D)^2+r^\pi_B r_D\cos(\delta^\pi_B-\delta_D)\cos\gamma} \\
A^{KK} = A^{\pi\pi} &= \frac{2r_B\sin\delta_B\sin\gamma}{1+{r_B}^2+r_B\cos\delta_B\cos\gamma} \\
A^{KK}_\pi = A^{\pi\pi}_\pi &= \frac{2r^\pi_B\sin\delta^\pi_B\sin\gamma}{1+{r^\pi_B}^2+r^\pi_B\cos\delta^\pi_B\cos\gamma} \\
R^{ADS} &= \frac{{r_B}^2+{r_D}^2+2r_B r_D\cos(\delta_B+\delta_D)\cos\gamma}{1+(r_B r_D)^2+2r_B r_D\cos(\delta_B-\delta_D)\cos\gamma} \\
A^{ADS} &= \frac{2r_B r_D\sin(\delta_B+\delta_D)\sin\gamma}{{r_B}^2+{r_D}^2+2r_B r_D\cos(\delta_B+\delta_D)\cos\gamma} \\
R^{ADS}_\pi &= \frac{{r^\pi_B}^2+{r_D}^2+2r^\pi_B r_D\cos(\delta^\pi_B+\delta_D)\cos\gamma}{1+(r^\pi_B r_D)^2+2r^\pi_B r_D\cos(\delta^\pi_B-\delta_D)\cos\gamma} \\
A^{ADS}_\pi &= \frac{2r^\pi_B r_D\sin(\delta^\pi_B+\delta_D)\sin\gamma}{{r^\pi_B}^2+{r_D}^2+2r^\pi_B r_D\cos(\delta^\pi_B+\delta_D)\cos\gamma}
\end{aligned}
$$

Observables ⇔ physics parameters

r_B, δ_B are the amplitude ratio and relative strong phase of the interfering B decays

$$R^{K\pi}_{K/\pi} = R\,\frac{1+(r_B r_D)^2+2r_B r_D\cos(\delta_B-\delta_D)\cos\gamma}{1+(r_B^\pi r_D)^2+2r_B^\pi r_D\cos(\delta_B^\pi-\delta_D)\cos\gamma}$$

$$R^{KK}_{K/\pi} = R^{\pi\pi}_{K/\pi} = R\,\frac{1+{r_B}^2+2r_B\cos\delta_B\cos\gamma}{1+{r_B^\pi}^2+2r_B^\pi\cos\delta_B^\pi\cos\gamma}$$

$$A^{Fav} = \frac{2r_B r_D\sin(\delta_B-\delta_D)\sin\gamma}{1+(r_B r_D)^2+r_B r_D\cos(\delta_B-\delta_D)\cos\gamma}$$

$$A^{Fav}_\pi = \frac{2r_B^\pi r_D\sin(\delta_B^\pi-\delta_D)\sin\gamma}{1+(r_B^\pi r_D)^2+r_B^\pi r_D\cos(\delta_B^\pi-\delta_D)\cos\gamma}$$

$$A^{KK} = A^{\pi\pi} = \frac{2r_B\sin\delta_B\sin\gamma}{1+{r_B}^2+r_B\cos\delta_B\cos\gamma}$$

$$A^{KK}_\pi = A^{\pi\pi}_\pi = \frac{2r_B^\pi\sin\delta_B^\pi\sin\gamma}{1+{r_B^\pi}^2+r_B^\pi\cos\delta_B^\pi\cos\gamma}$$

$$R^{ADS} = \frac{{r_B}^2+{r_D}^2+2r_B r_D\cos(\delta_B+\delta_D)\cos\gamma}{1+(r_B r_D)^2+2r_B r_D\cos(\delta_B-\delta_D)\cos\gamma}$$

$$A^{ADS} = \frac{2r_B r_D\sin(\delta_B+\delta_D)\sin\gamma}{{r_B}^2+{r_D}^2+2r_B r_D\cos(\delta_B+\delta_D)\cos\gamma}$$

$$R^{ADS}_\pi = \frac{{r_B^\pi}^2+{r_D}^2+2r_B^\pi r_D\cos(\delta_B^\pi+\delta_D)\cos\gamma}{1+(r_B^\pi r_D)^2+2r_B^\pi r_D\cos(\delta_B^\pi-\delta_D)\cos\gamma}$$

$$A^{ADS}_\pi = \frac{2r_B^\pi r_D\sin(\delta_B^\pi+\delta_D)\sin\gamma}{{r_B^\pi}^2+{r_D}^2+2r_B^\pi r_D\cos(\delta_B^\pi+\delta_D)\cos\gamma}$$

Observables ⇔ physics parameters

r_B, δ_B are the amplitude ratio and relative strong phase of the interfering B decays

r_D, δ_D are hadronic parameters describing the $D^0 \to K\pi(\pi K)$ decays

- r_D is the amplitude ratio of the CF to DCS D^0 decays
- δ_D is the relative strong phase between the CF and DCS decays

Both are taken from CLEO measurements

$$R^{K\pi}_{K/\pi} = R\,\frac{1+(r_B r_D)^2+2r_B r_D\cos(\delta_B-\delta_D)\cos\gamma}{1+(r_B^\pi r_D)^2+2r_B^\pi r_D\cos(\delta_B^\pi-\delta_D)\cos\gamma}$$

$$R^{KK}_{K/\pi} = R^{\pi\pi}_{K/\pi} = R\,\frac{1+{r_B}^2+2r_B\cos\delta_B\cos\gamma}{1+{r_B^\pi}^2+2r_B^\pi\cos\delta_B^\pi\cos\gamma}$$

$$A^{Fav} = \frac{2r_B r_D\sin(\delta_B-\delta_D)\sin\gamma}{1+(r_B r_D)^2+r_B r_D\cos(\delta_B-\delta_D)\cos\gamma}$$

$$A^{Fav}_\pi = \frac{2r_B^\pi r_D\sin(\delta_B^\pi-\delta_D)\sin\gamma}{1+(r_B^\pi r_D)^2+r_B^\pi r_D\cos(\delta_B^\pi-\delta_D)\cos\gamma}$$

$$A^{KK} = A^{\pi\pi} = \frac{2r_B\sin\delta_B\sin\gamma}{1+{r_B}^2+r_B\cos\delta_B\cos\gamma}$$

$$A^{KK}_\pi = A^{\pi\pi}_\pi = \frac{2r_B^\pi\sin\delta_B^\pi\sin\gamma}{1+{r_B^\pi}^2+r_B^\pi\cos\delta_B^\pi\cos\gamma}$$

$$R^{ADS} = \frac{{r_B}^2+{r_D}^2+2r_B r_D\cos(\delta_B+\delta_D)\cos\gamma}{1+(r_B r_D)^2+2r_B r_D\cos(\delta_B-\delta_D)\cos\gamma}$$

$$A^{ADS} = \frac{2r_B r_D\sin(\delta_B+\delta_D)\sin\gamma}{{r_B}^2+{r_D}^2+2r_B r_D\cos(\delta_B+\delta_D)\cos\gamma}$$

$$R^{ADS}_\pi = \frac{{r_B^\pi}^2+{r_D}^2+2r_B^\pi r_D\cos(\delta_B^\pi+\delta_D)\cos\gamma}{1+(r_B^\pi r_D)^2+2r_B^\pi r_D\cos(\delta_B^\pi-\delta_D)\cos\gamma}$$

$$A^{ADS}_\pi = \frac{2r_B^\pi r_D\sin(\delta_B^\pi+\delta_D)\sin\gamma}{{r_B^\pi}^2+{r_D}^2+2r_B^\pi r_D\cos(\delta_B^\pi+\delta_D)\cos\gamma}$$

Observables ⇔ physics parameters

r_B,δ_B are the amplitude ratio and relative strong phase of the interfering B decays

r_D,δ_D are hadronic parameters describing the $D^0 \to K\pi(\pi K)$ decays

- **r_D is the amplitude ratio of the CF to DCS D^0 decays**

- **δ_D is the relative strong phase between the CF and DCS decays**

Both are taken from CLEO measurements

Notice that ADS asymmetries are enhanced by the absence of a "1 +" term in the denominator compared to the GLW ones

$$R^{K\pi}_{K/\pi} = R\,\frac{1+(r_B r_D)^2+2r_B r_D\cos(\delta_B-\delta_D)\cos\gamma}{1+(r^\pi_B r_D)^2+2r^\pi_B r_D\cos(\delta^\pi_B-\delta_D)\cos\gamma}$$

$$R^{KK}_{K/\pi} = R^{\pi\pi}_{K/\pi} = R\,\frac{1+{r_B}^2+2r_B\cos\delta_B\cos\gamma}{1+{r^\pi_B}^2+2r^\pi_B\cos\delta^\pi_B\cos\gamma}$$

$$A^{Fav} = \frac{2r_B r_D\sin(\delta_B-\delta_D)\sin\gamma}{1+(r_B r_D)^2+r_B r_D\cos(\delta_B-\delta_D)\cos\gamma}$$

$$A^{Fav}_\pi = \frac{2r^\pi_B r_D\sin(\delta^\pi_B-\delta_D)\sin\gamma}{1+(r^\pi_B r_D)^2+r^\pi_B r_D\cos(\delta^\pi_B-\delta_D)\cos\gamma}$$

$$A^{KK} = A^{\pi\pi} = \frac{2r_B\sin\delta_B\sin\gamma}{1+{r_B}^2+r_B\cos\delta_B\cos\gamma}$$

$$A^{KK}_\pi = A^{\pi\pi}_\pi = \frac{2r^\pi_B\sin\delta^\pi_B\sin\gamma}{1+{r^\pi_B}^2+r^\pi_B\cos\delta^\pi_B\cos\gamma}$$

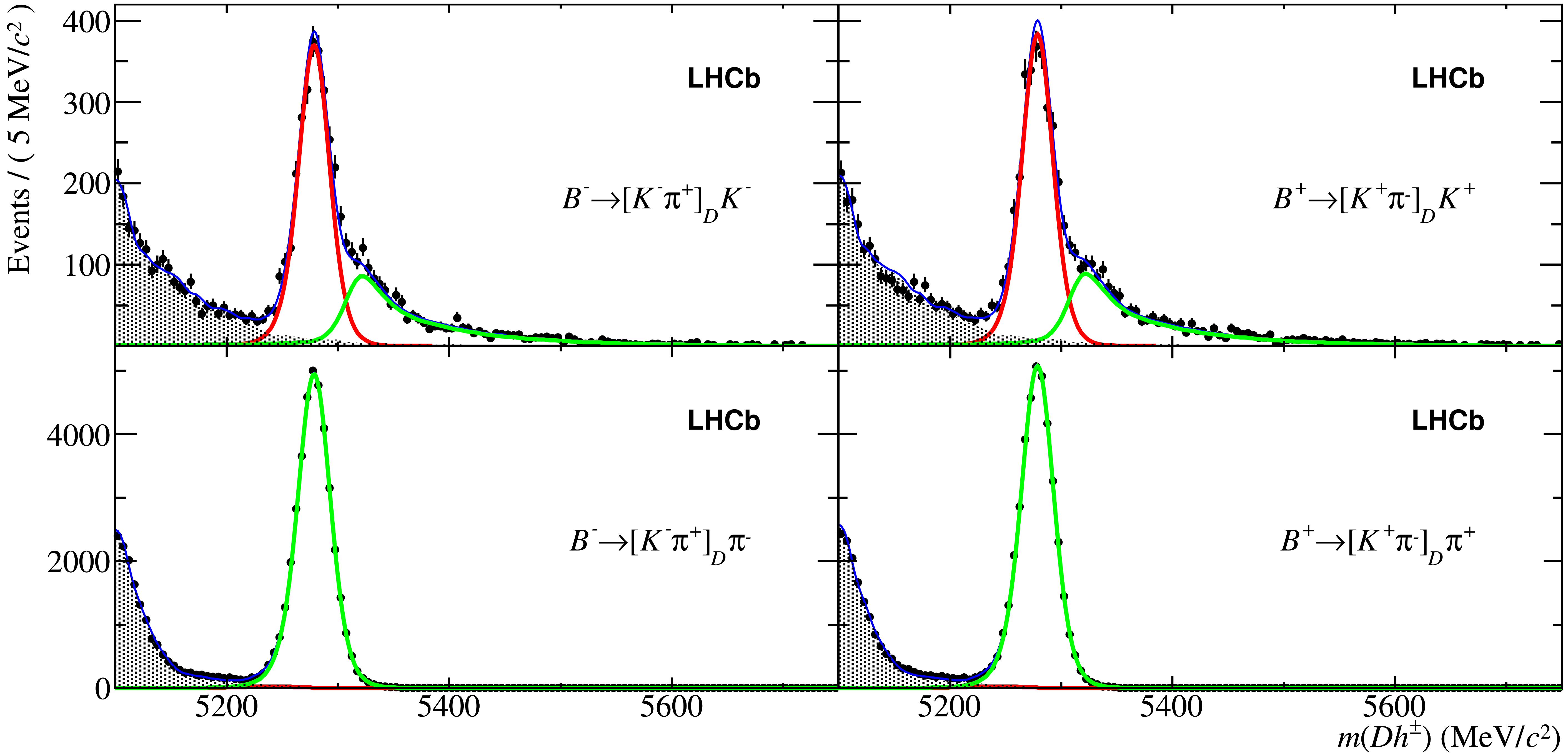
$$R^{ADS} = \frac{{r_B}^2+{r_D}^2+2r_B r_D\cos(\delta_B+\delta_D)\cos\gamma}{1+(r_B r_D)^2+2r_B r_D\cos(\delta_B-\delta_D)\cos\gamma}$$

$$A^{ADS} = \frac{2r_B r_D\sin(\delta_B+\delta_D)\sin\gamma}{{r_B}^2+{r_D}^2+2r_B r_D\cos(\delta_B+\delta_D)\cos\gamma}$$

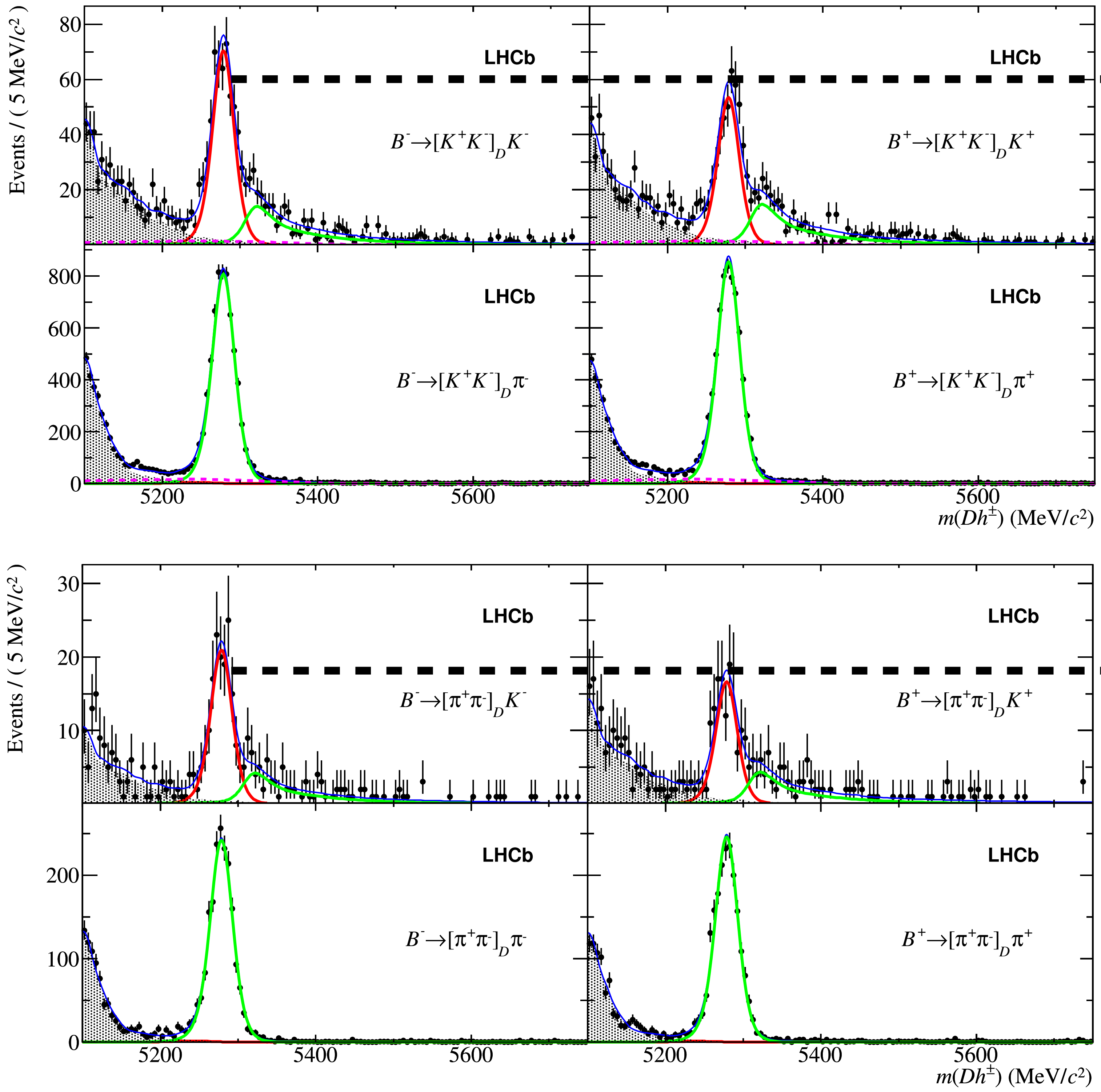
$$R^{ADS}_\pi = \frac{{r^\pi_B}^2+{r_D}^2+2r^\pi_B r_D\cos(\delta^\pi_B+\delta_D)\cos\gamma}{1+(r^\pi_B r_D)^2+2r^\pi_B r_D\cos(\delta^\pi_B-\delta_D)\cos\gamma}$$

$$A^{ADS}_\pi = \frac{2r^\pi_B r_D\sin(\delta^\pi_B+\delta_D)\sin\gamma}{{r^\pi_B}^2+{r_D}^2+2r^\pi_B r_D\cos(\delta^\pi_B+\delta_D)\cos\gamma}$$

The Cabbibo-favoured signals



The singly Cabbibo-Suppressed signals



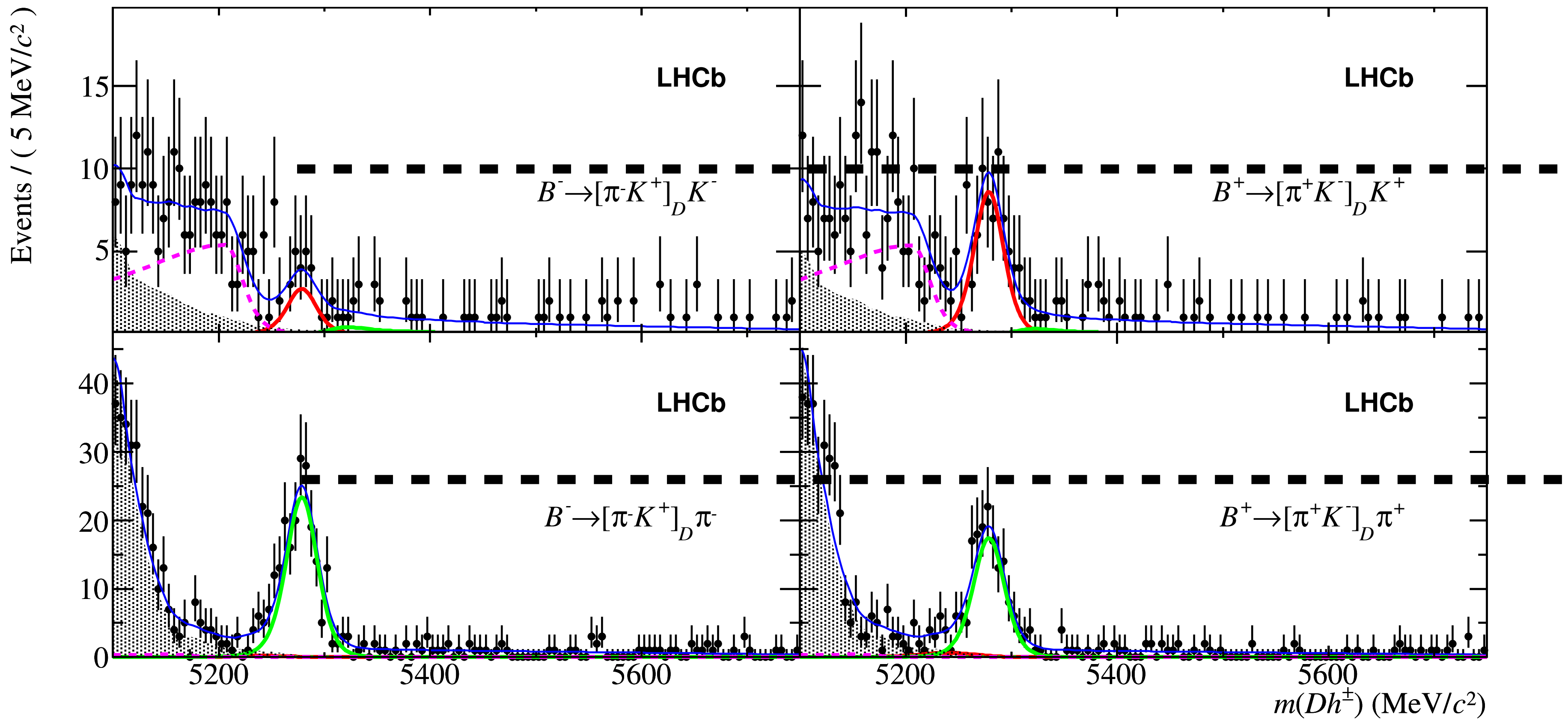
KK and ππ show similar-sized CP asymmetries, in the same direction

$$A_{CP+} = < A_K^{KK}, A_K^{\pi\pi} > \quad = \quad 0.145 \pm 0.032 \pm 0.010$$

Branching fraction ratios consistent with CF D^0 decay mode

$$R_{CP+} = \frac{< R_{K/\pi}^{KK}, R_{K/\pi}^{\pi\pi} >}{R_{K/\pi}^{Kpi}} \quad = \quad 1.007 \pm 0.038 \pm 0.012$$

The ADS signals



The Kaon mode shows a large CP asymmetery

$$A_{ADS(K)} = \frac{R_K^- - R_K^+}{R_K^- + R_K^+} = -0.520 \pm 0.150 \pm 0.021$$

And there is also a hint of something in the pion mode!

$$A_{ADS(\pi)} = \frac{R_\pi^- - R_\pi^+}{R_\pi^- + R_\pi^+} = 0.1426 \pm 0.0621 \pm 0.0110$$

ADS modes established at >5σ significance

Combining all two body modes, direct CPV is observed at 5.8σ significance

LHCb-PAPER-2012-001

What has this enabled us to produce?

GLW/ADS in $B \to DK, D\pi$ with $D \to hh$

ADS in $B \to DK, D\pi$ with $D \to hhhh$

GGSZ in $B \to DK$ with $D \to K_S hh$

GLW in $B \to DK^{0*}$

GLW in $B \to Dhhh$

Frequentist γ combination

Time dependent CPV in $B_S \to D_S K$

Observables ⇔ physics parameters

$$\Gamma(B^\pm \to D(K^\pm\pi^\mp\pi^+\pi^-)K^\pm) \propto 1 + (r_B r_D^{K3\pi})^2 + 2\boxed{R_{K3\pi}} r_B r_D^{K3\pi} \cos(\delta_B - \delta_D^{K3\pi} \pm \gamma),$$

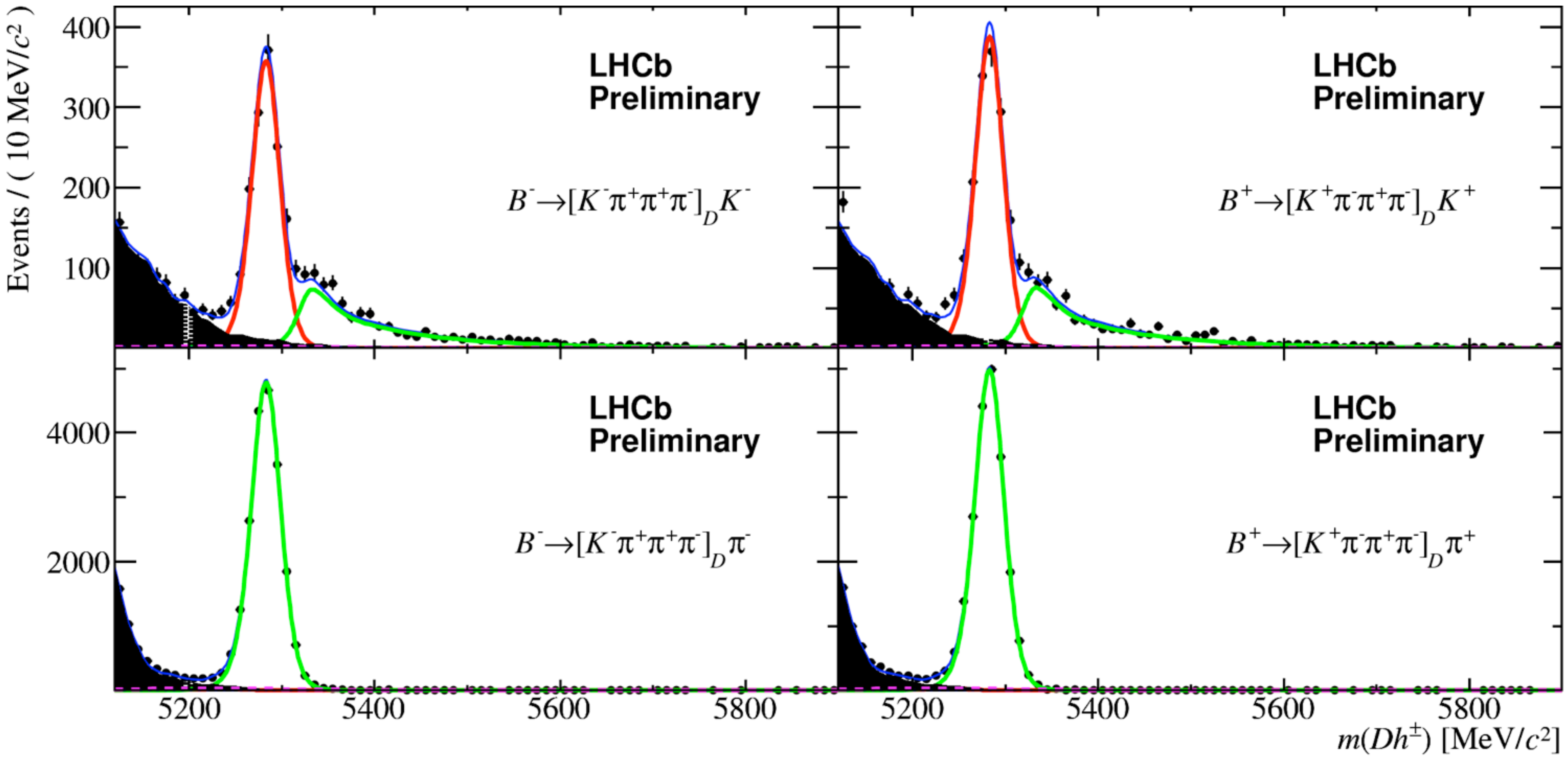
$$\Gamma(B^\pm \to D(K^\mp\pi^\pm\pi^+\pi^-)K^\pm) \propto r_B^2 + (r_D^{K3\pi})^2 + 2\boxed{R_{K3\pi}} r_B r_D^{K3\pi} \cos(\delta_B + \delta_D^{K3\pi} \pm \gamma),$$

Same formalism as for the two-body case, except for the coherence factor $R_{K3\pi}$. This is necessary because the D^0 decay is a sum of amplitudes varying across the Dalitz plot; when we perform an analysis integrating over these amplitudes, we lose sensitivity from the way in which they interfere.

$R_{K3\pi}$ has been measured at CLEO and is small (~0.33) which indicates that these modes have a smaller sensitivity to γ when treated in this integrated manner than the two-body modes. However, they can still provide a good constraint on r_B.

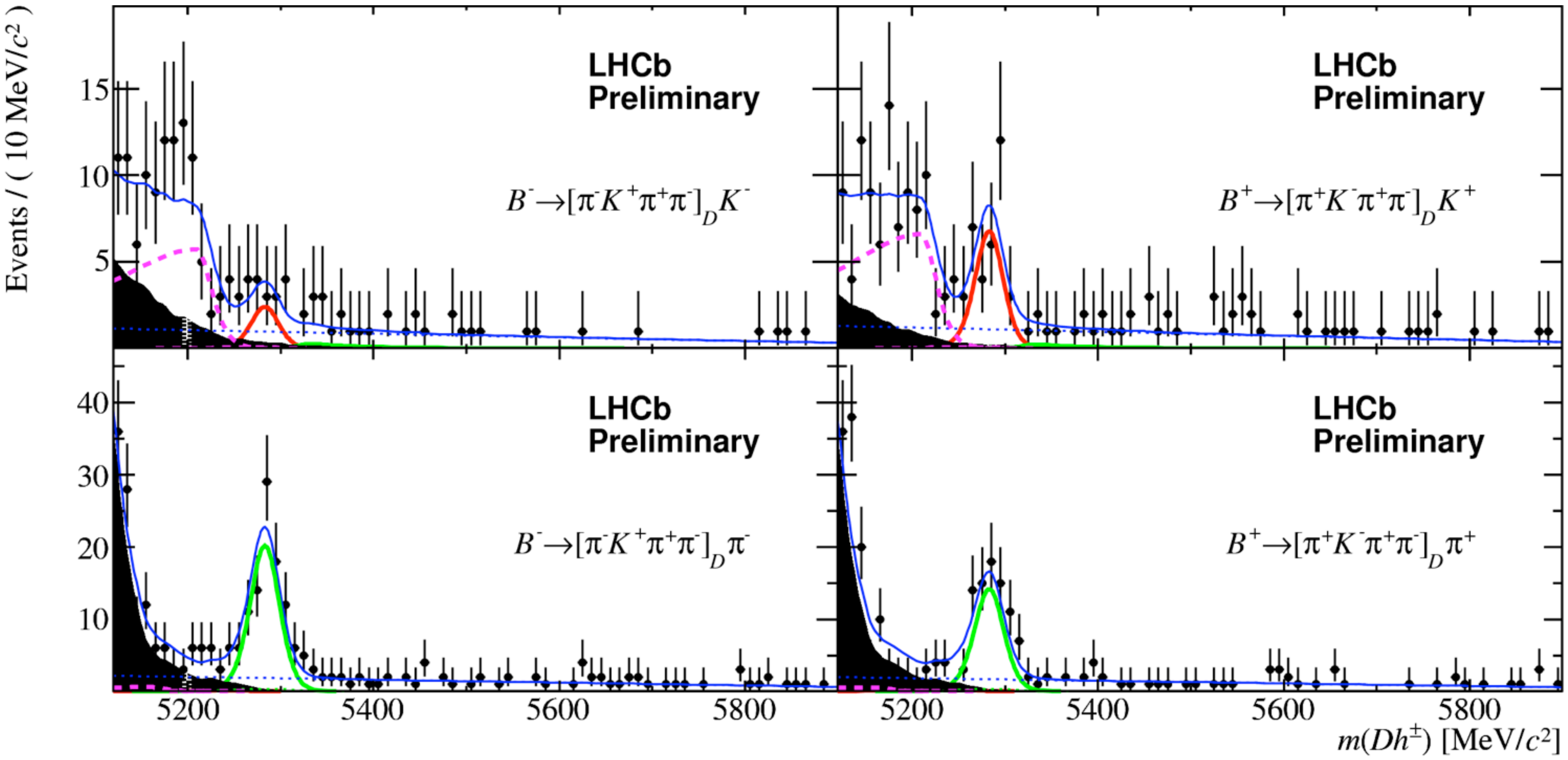
LHCb-PAPER-2012-055

The Cabbibo-favoured signals



LHCb-PAPER-2012-055

The ADS signals



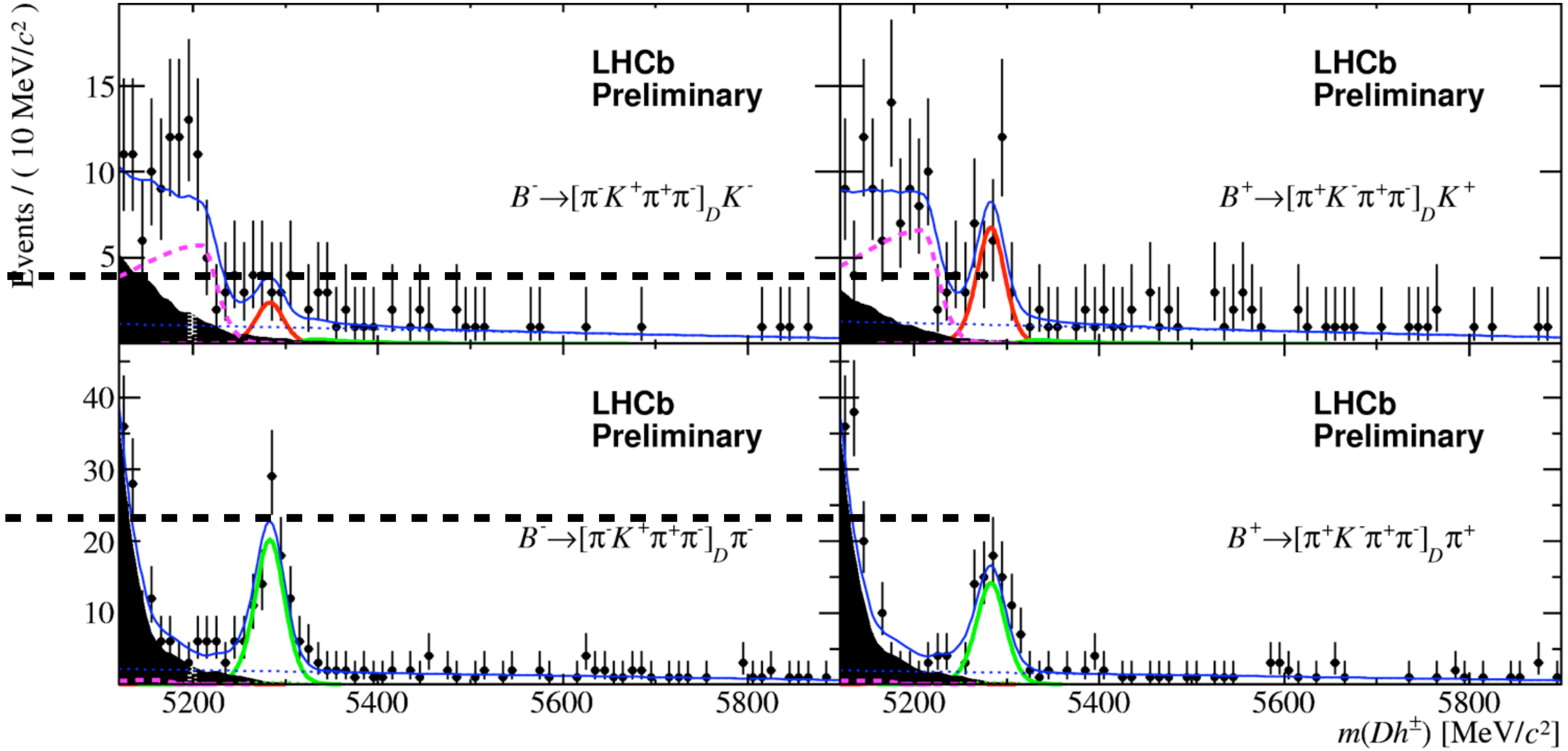
The ADS signals

Once again, indications of CP asymmetries in both the Kaon and the Pion modes

And again, going in the same direction as for the two-body modes.

$$A^{K3\pi}_{\mathrm{ADS}(K)} = (R^{K3\pi,-}_{K} - R^{K3\pi,+}_{K})/(R^{K3\pi,-}_{K} + R^{K3\pi,+}_{K}) = -0.42 \pm 0.22$$

$$A^{K3\pi}_{\mathrm{ADS}(\pi)} = (R^{K3\pi,-}_{\pi} - R^{K3\pi,+}_{\pi})/(R^{K3\pi,-}_{\pi} + R^{K3\pi,+}_{\pi}) = +0.13 \pm 0.10,$$



ADS modes established at >5σ significance!

LHCb-PAPER-2012-055

What has this enabled LHCb to produce?

GLW/ADS in $B\to DK, D\pi$ with $D\to hh$

ADS in $B\to DK, D\pi$ with $D\to hhhh$

GGSZ in $B\to DK$ with $D\to K_S hh$

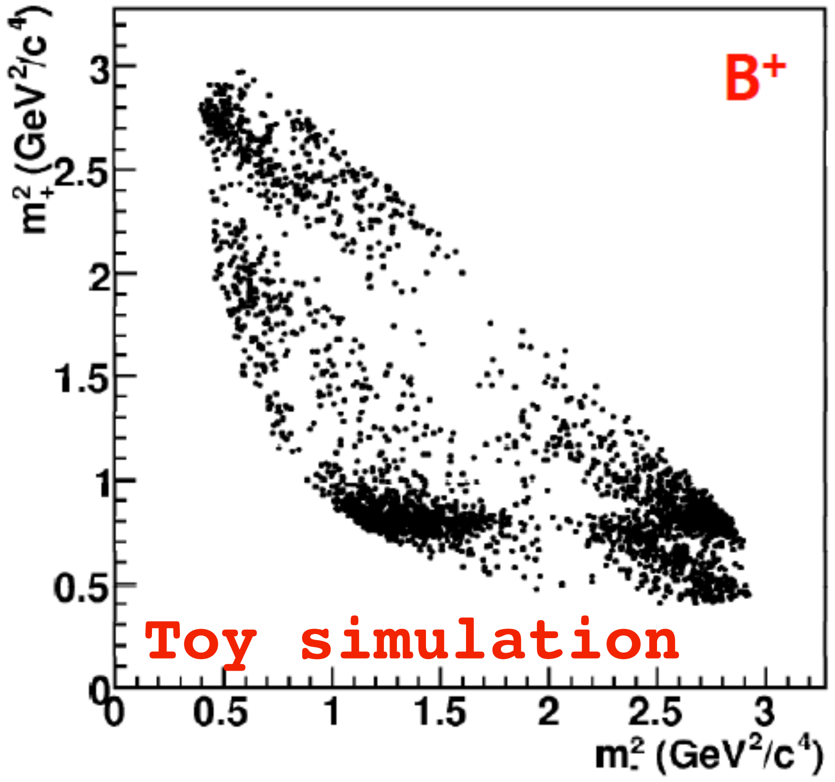
GLW in $B\to DK^{0*}$

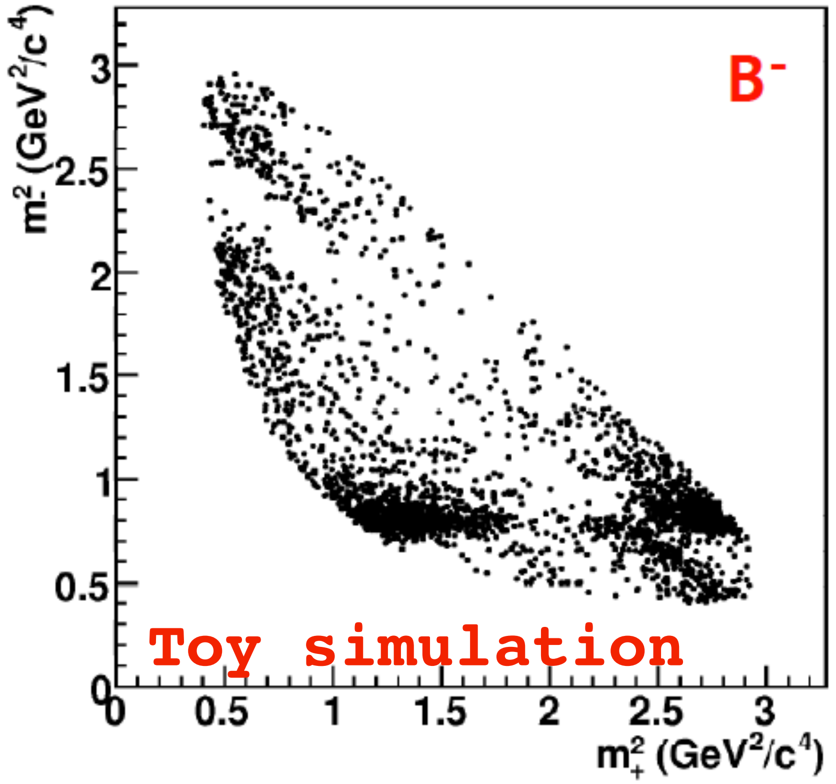
GLW in $B\to Dhhh$

Frequentist γ combination

Time dependent CPV in $B_S\to D_S K$

Observables ⇔ physics parameters



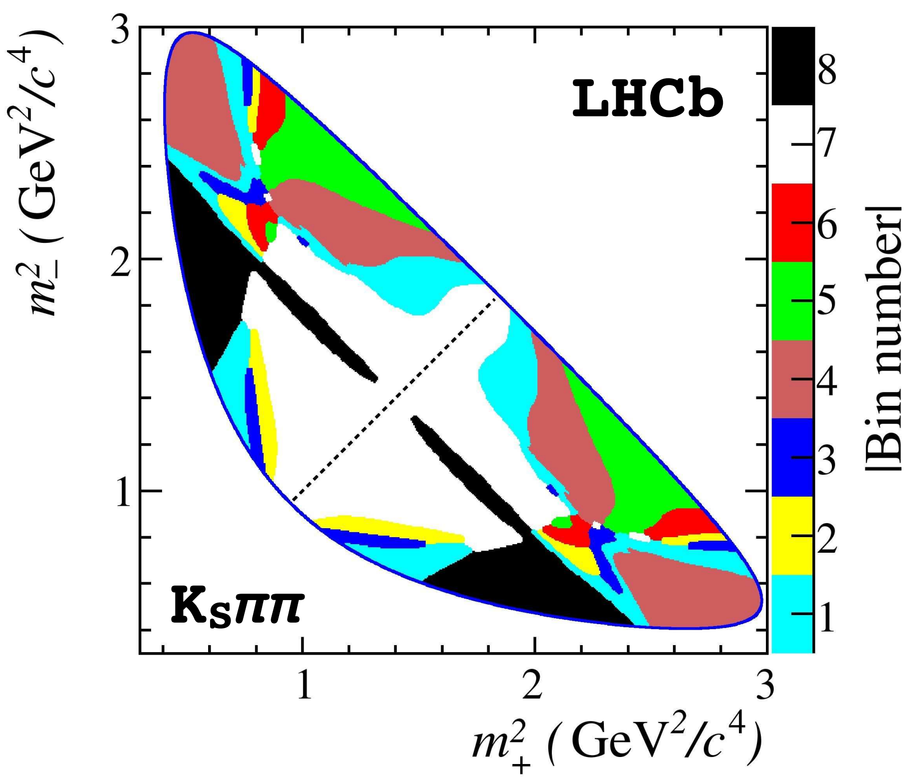


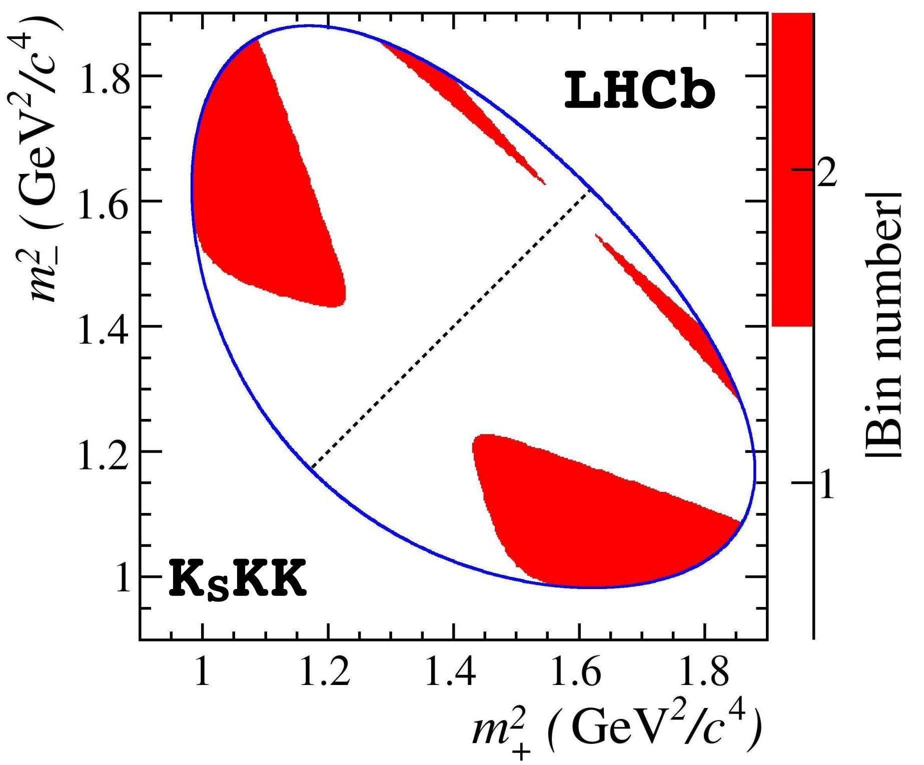
Here the decay chain is $B\to D^0K$, with $D^0\to K_S\pi\pi/K_SKK$

The D^0 decays proceed through many interfering amplitudes, some of which are Cabbibo-favoured, some singly Cabbibo-suppressed, and some doubly Cabbibo-suppressed

You are effectively doing a simultaneous ADS/GLW analysis, as long as you understand how the amplitudes and their phases vary across the Dalitz plot.

Observables ⇔ physics parameters





Here the decay chain is $B \to D^0 K$, with $D^0 \to K_S\pi\pi / K_SKK$

The D^0 decays proceed through many interfering amplitudes, some of which are Cabbibo-favoured, some singly Cabbibo-suppressed, and some doubly Cabbibo-suppressed

You are effectively doing a simultaneous ADS/GLW analysis, as long as you understand how the amplitudes and their phases vary across the Dalitz plot.

"Model-independent" : Bin the Dalitz plot and fit for yield of B^+ and B^- in each bin of the Dalitz plot, plugging in the strong phase in each bin from a CLEO measurement.

$$N^+_{+i} = n_{B^+}[K_{-i} + (x_+^2 + y_+^2)K_{+i} + 2\sqrt{K_{+i}K_{-i}}(x_+ c_{+i} - y_+ s_{+i})]$$

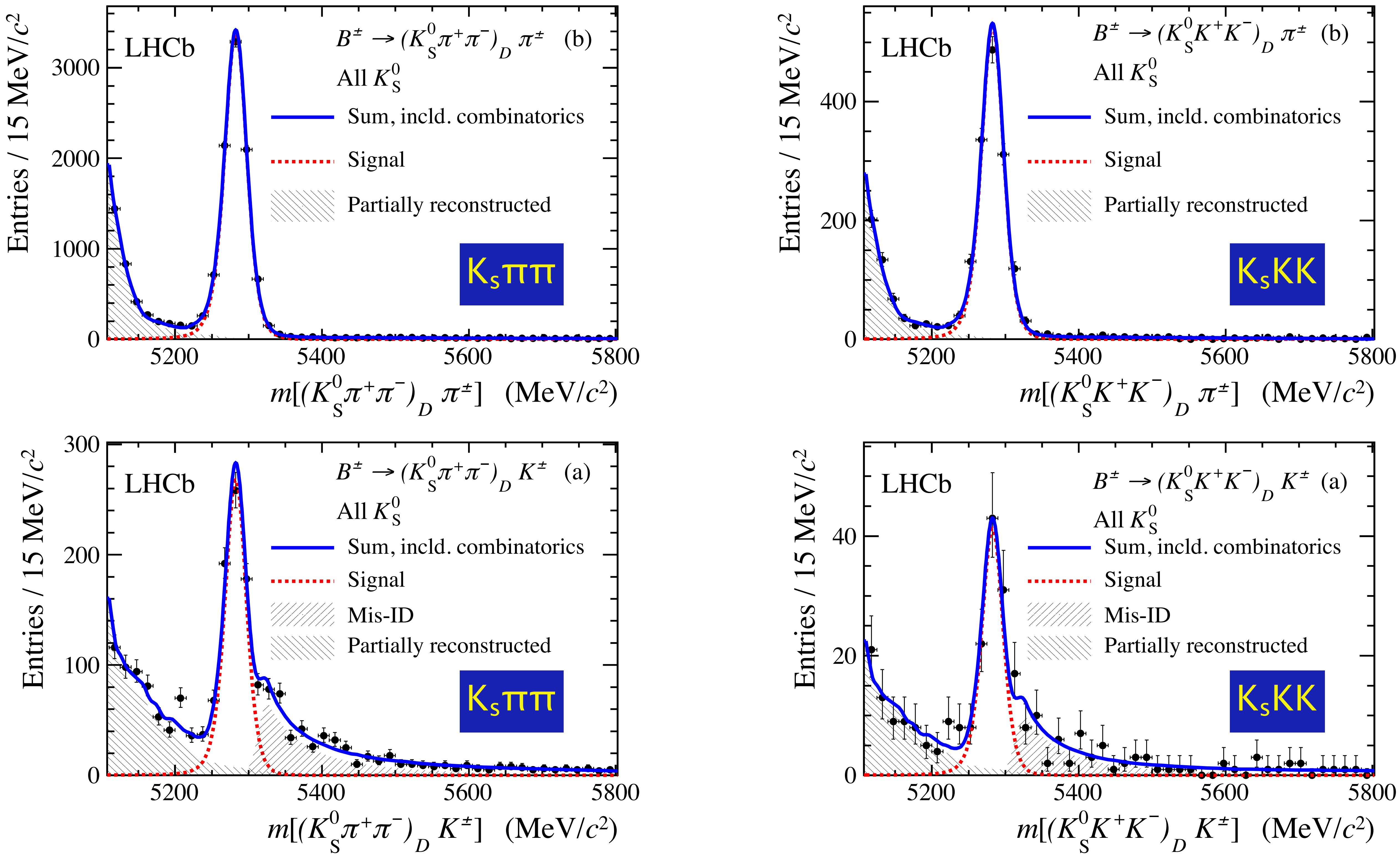
$$x_\pm = r_B \cos(\delta_B \pm \gamma), y_\pm = r_B \sin(\delta_B \pm \gamma)$$

c_i, s_i are the CLEO inputs

K_i are the yields of tagged D^0 decays in each bin

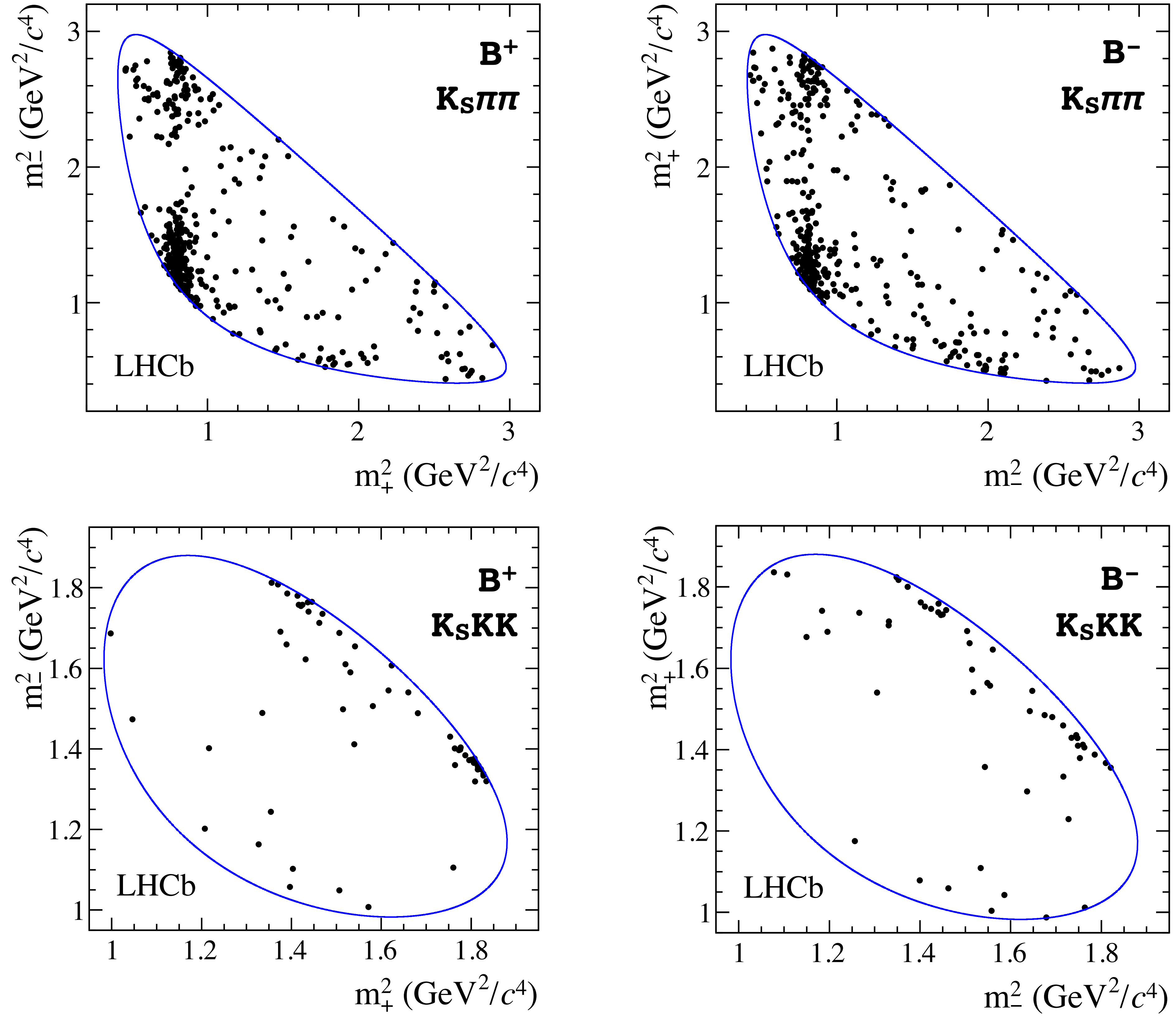
LHCb-PAPER-2012-027

$K_S\pi\pi$ and K_SKK signals for 1 fb^{-1}



LHCb-PAPER-2012-027

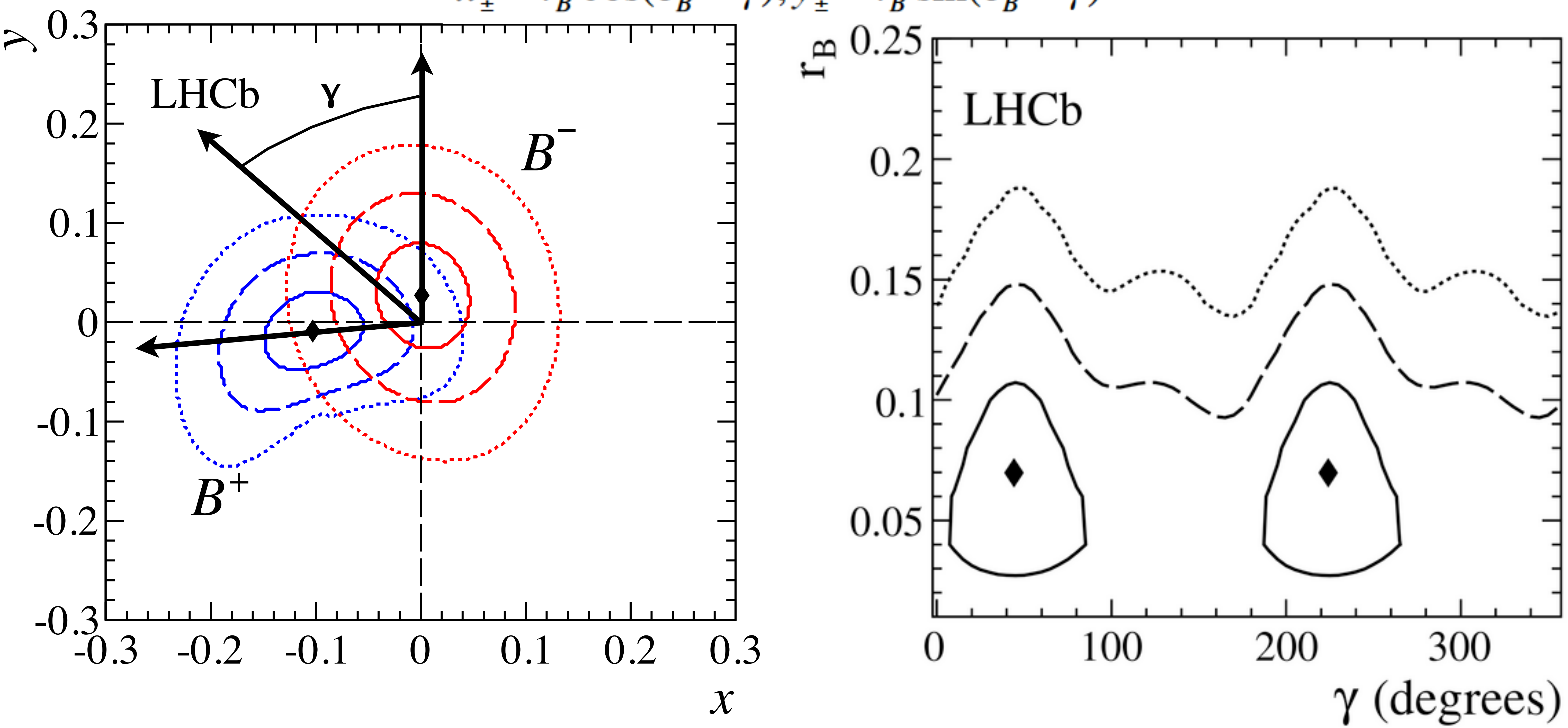
Dalitz distributions for 1 fb^{-1}



LHCb-PAPER-2012-027

$x^{\pm}, y^{\pm}$ for 1 fb^{-1}

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

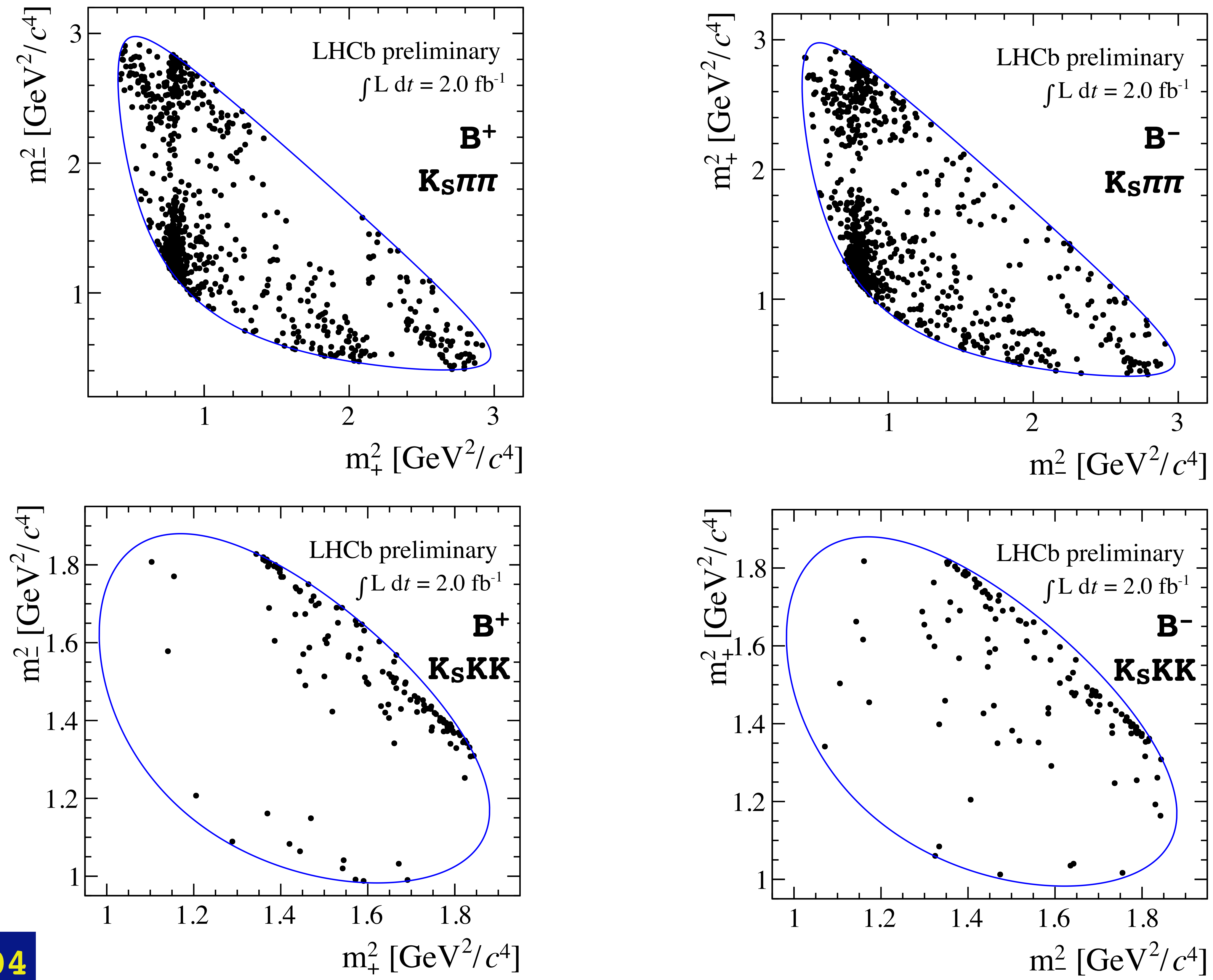


Largest systematic arises from the assumption of no CPV in the control mode Dπ

Little stand-alone sensitivity due to "unlucky" fluctuation of r_B

LHCb-PAPER-2012-027

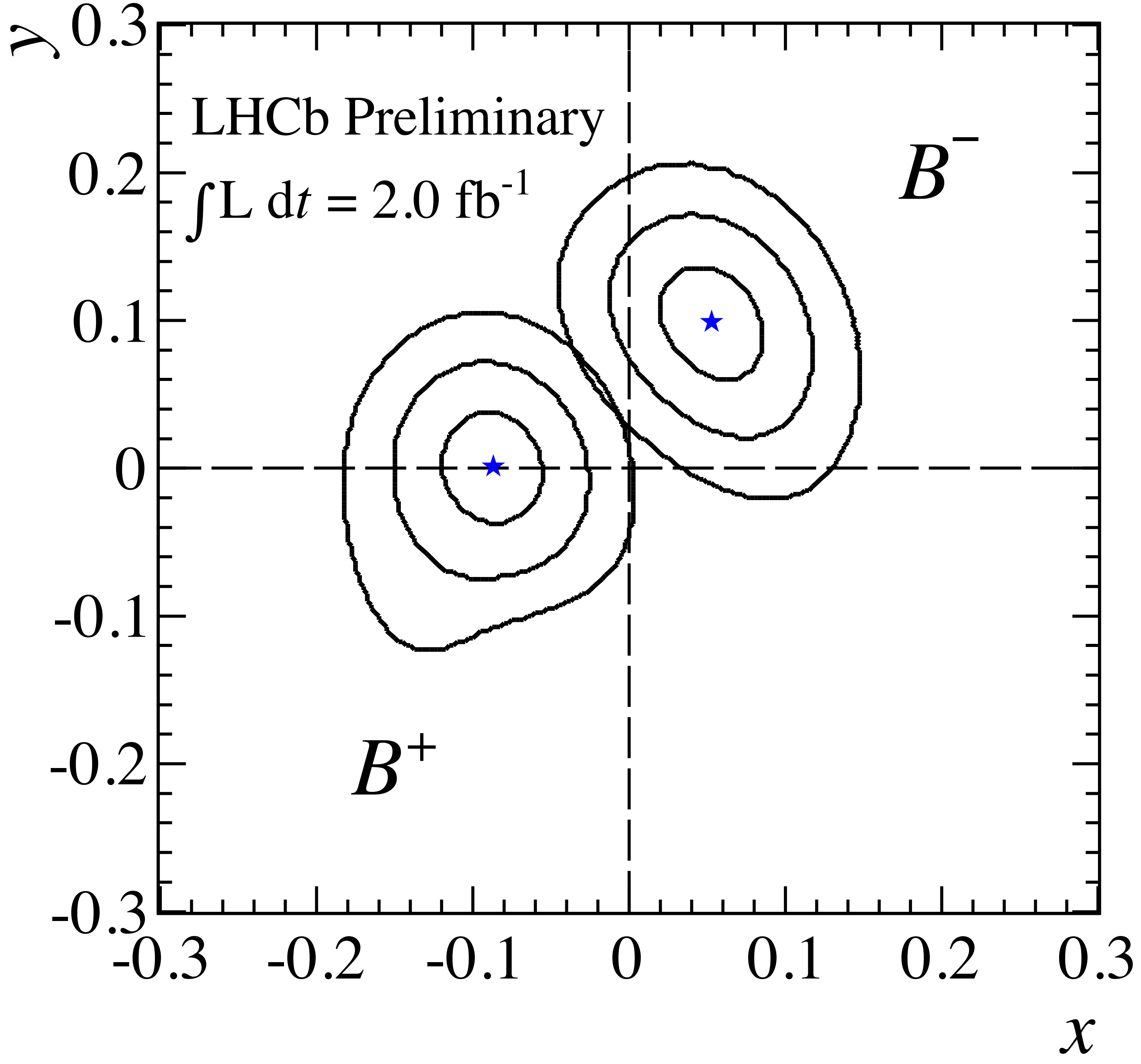
Dalitz distributions for 2 fb^{-1}

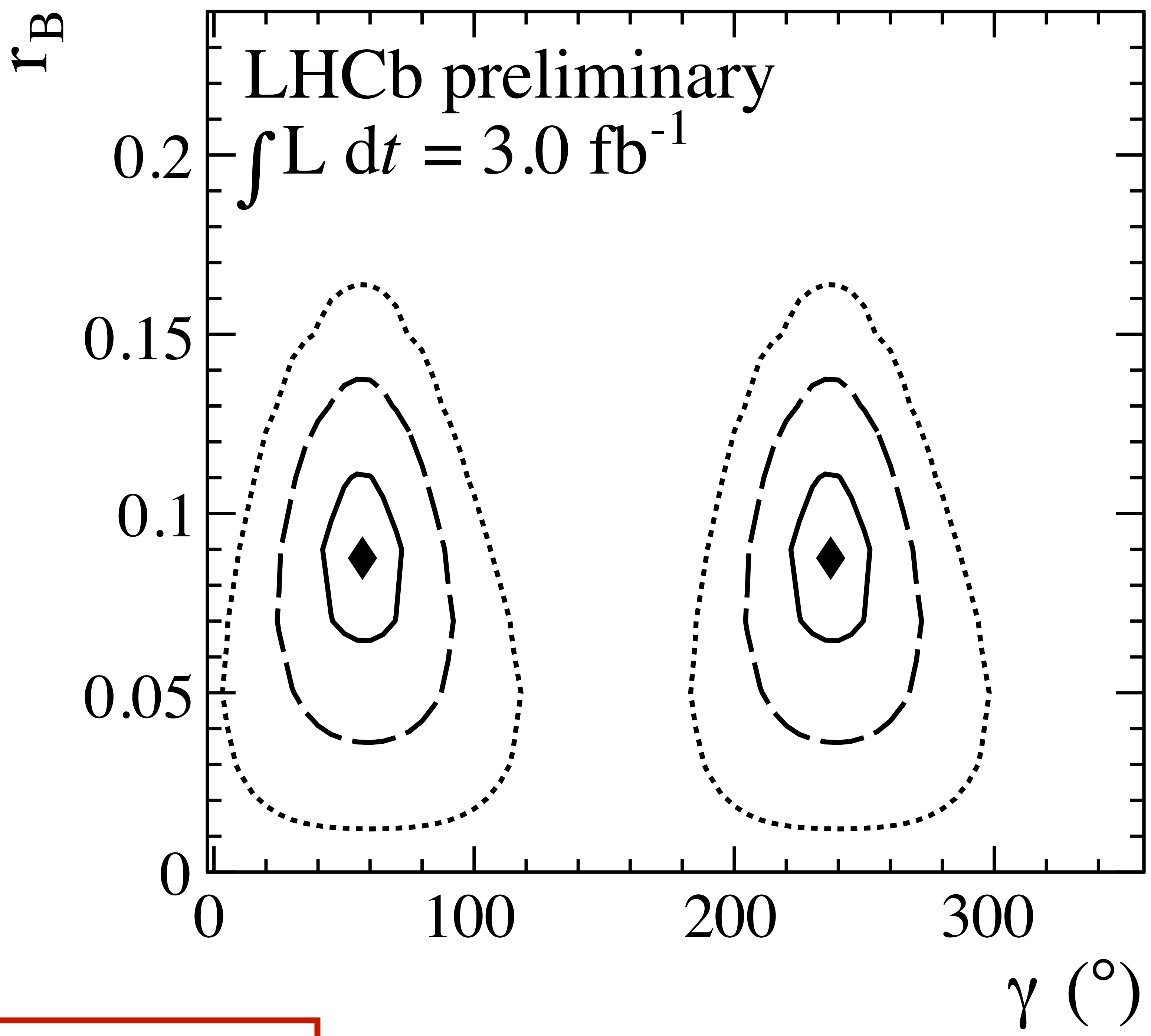


LHCb-CONF-2013-004

$x^{\pm}, y^{\pm}$ for 2 fb^{-1}

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

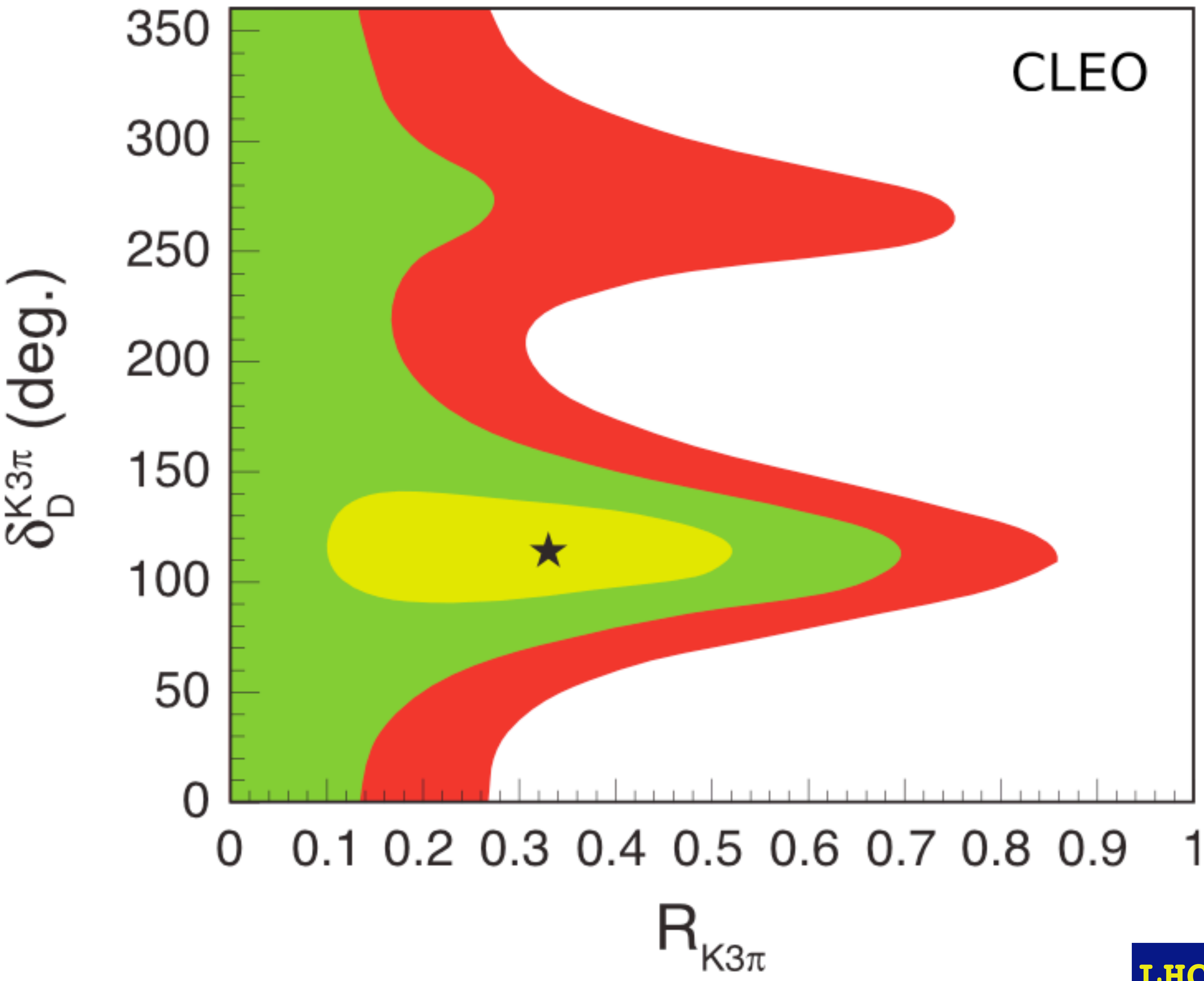




$\gamma = (57 \pm 16)°$

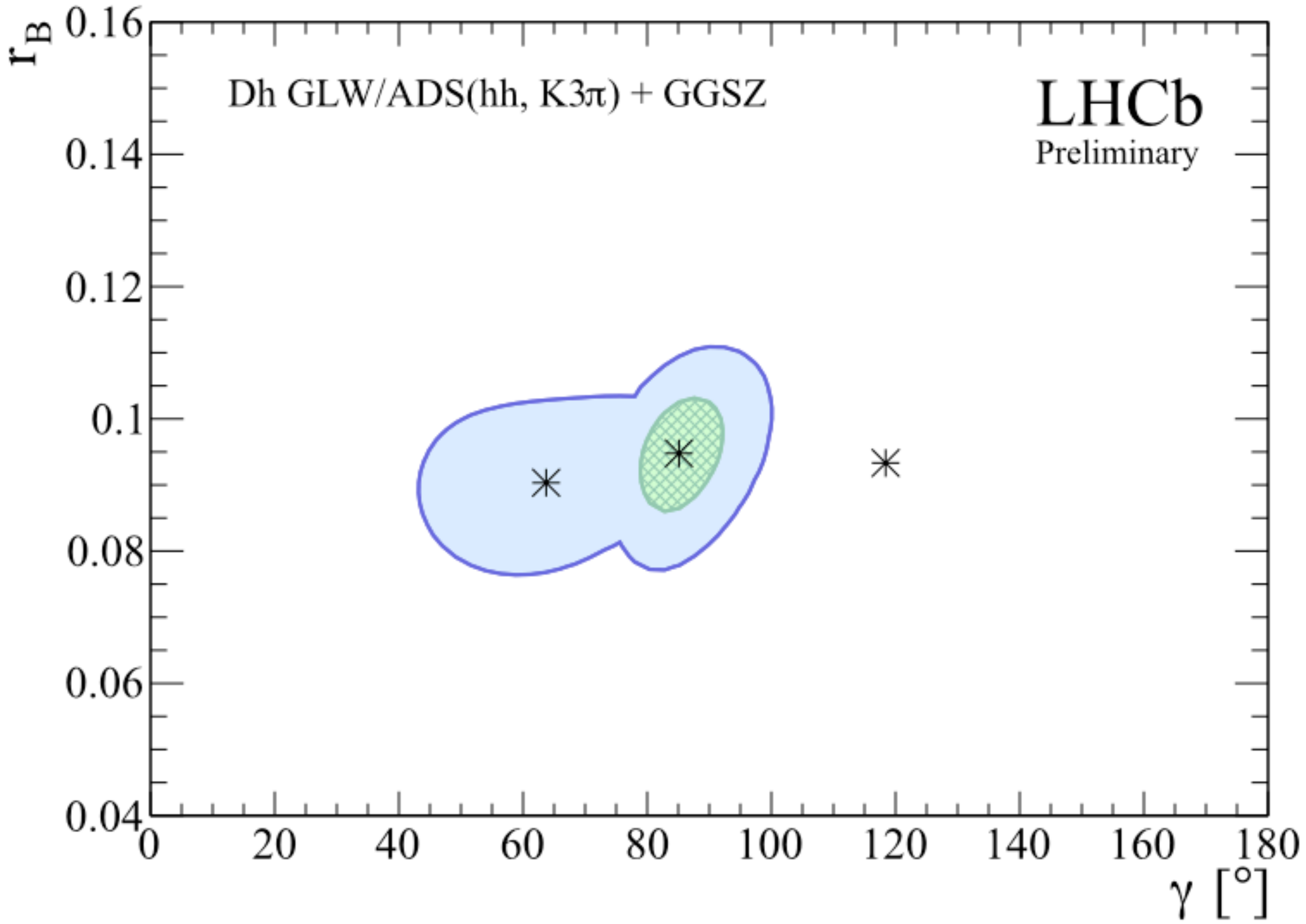
LHCb-CONF-2013-004

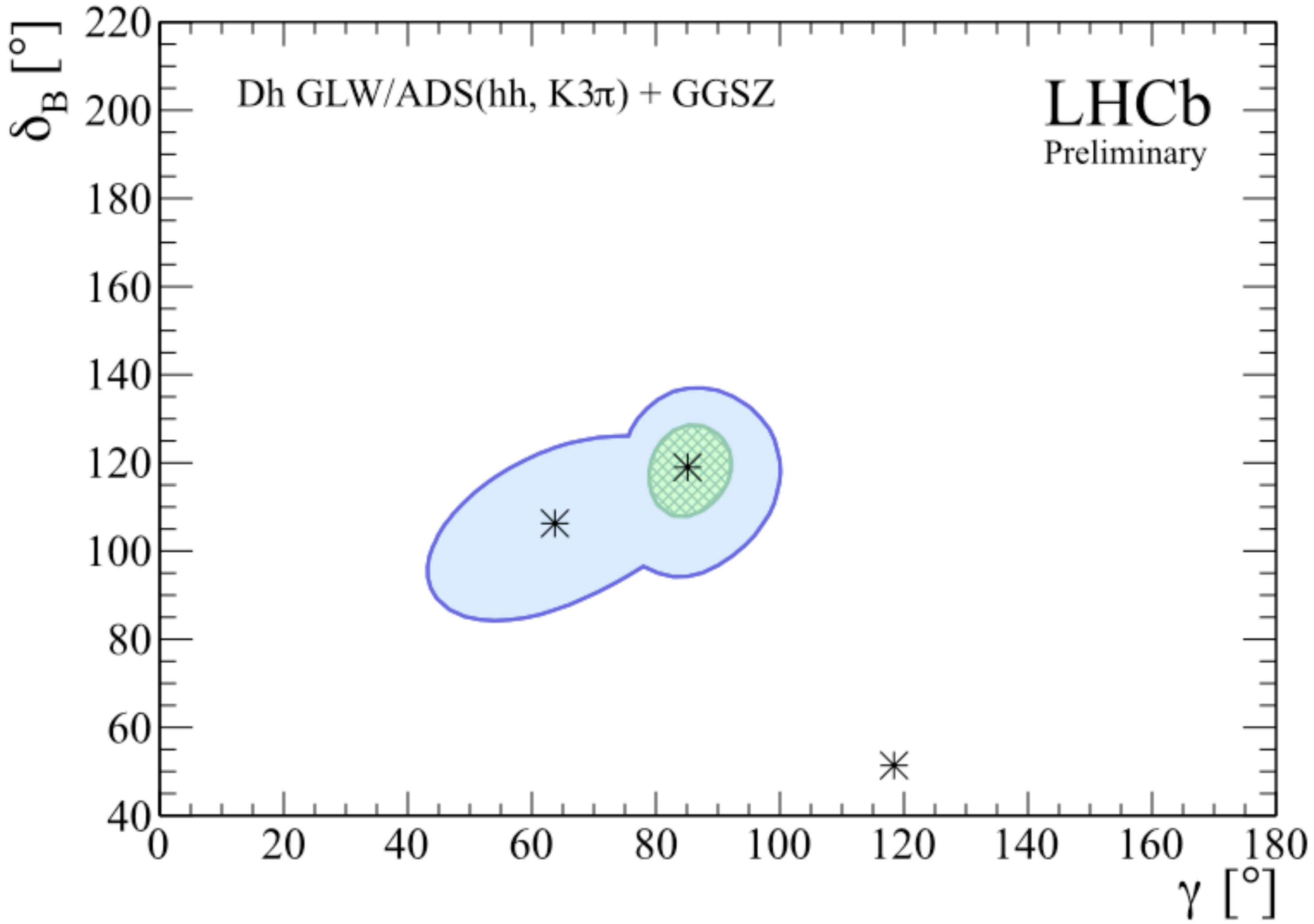
CLEO inputs



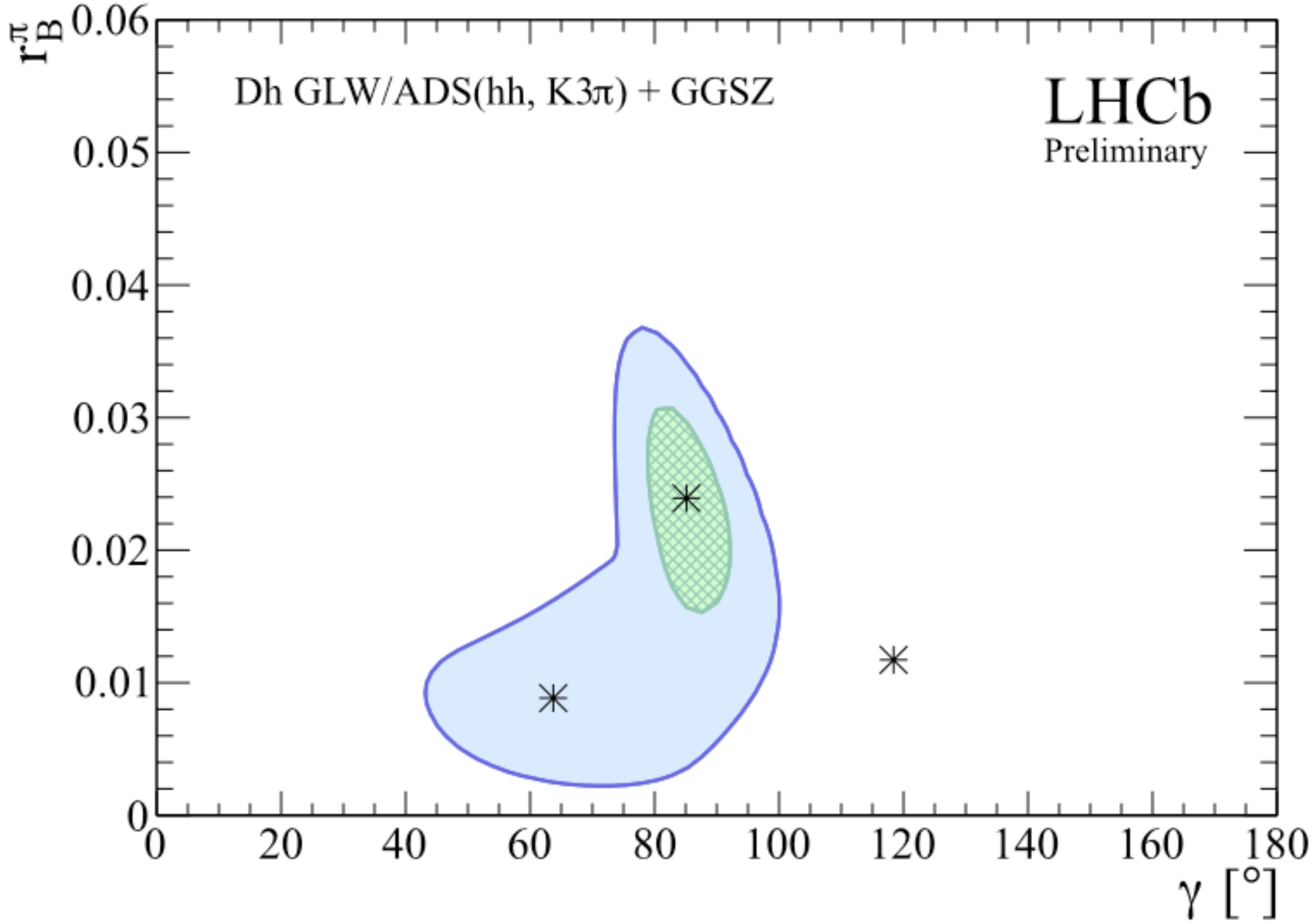
LHCb-CONF-2012-032

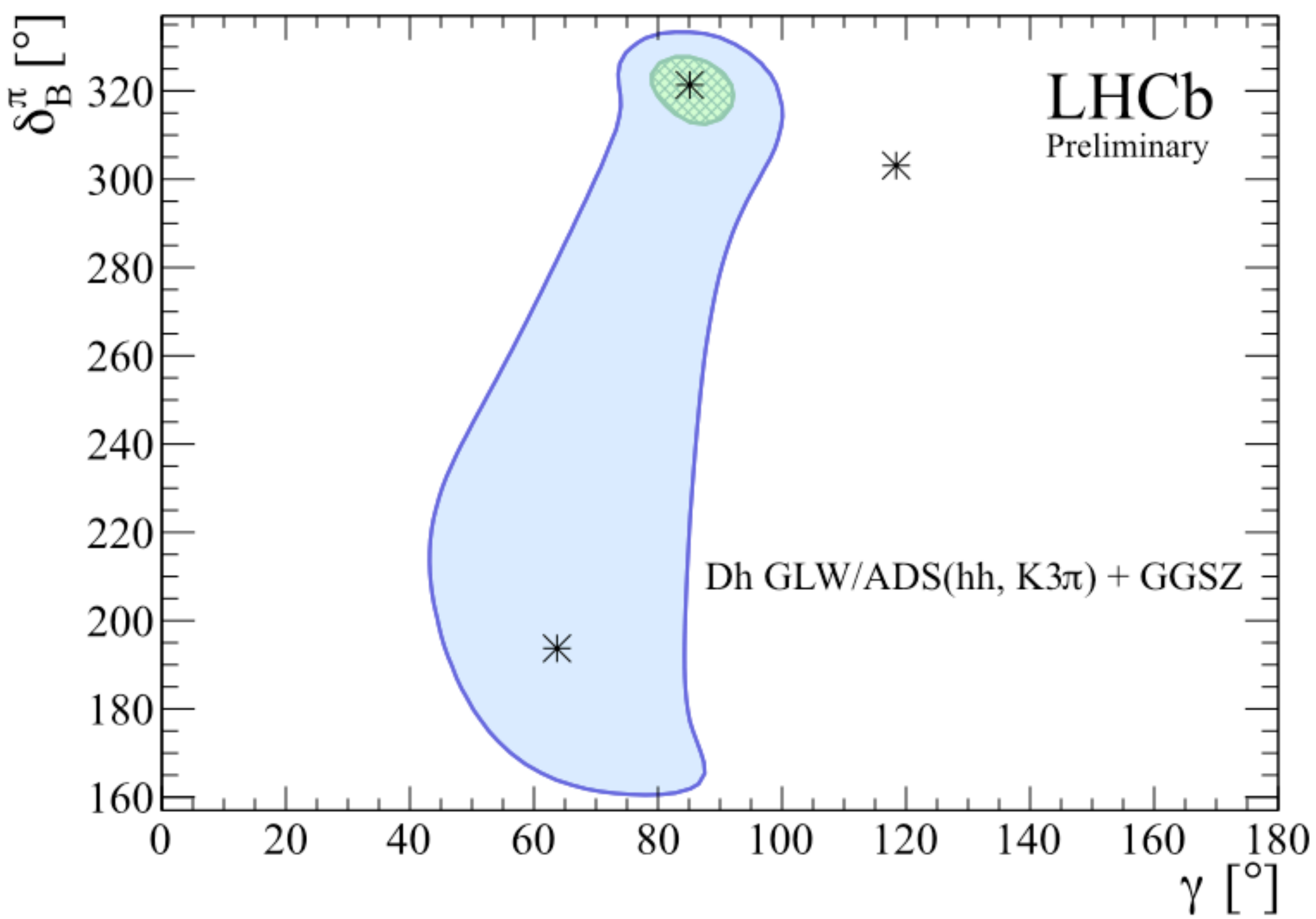
GLW/ADS 2D plots



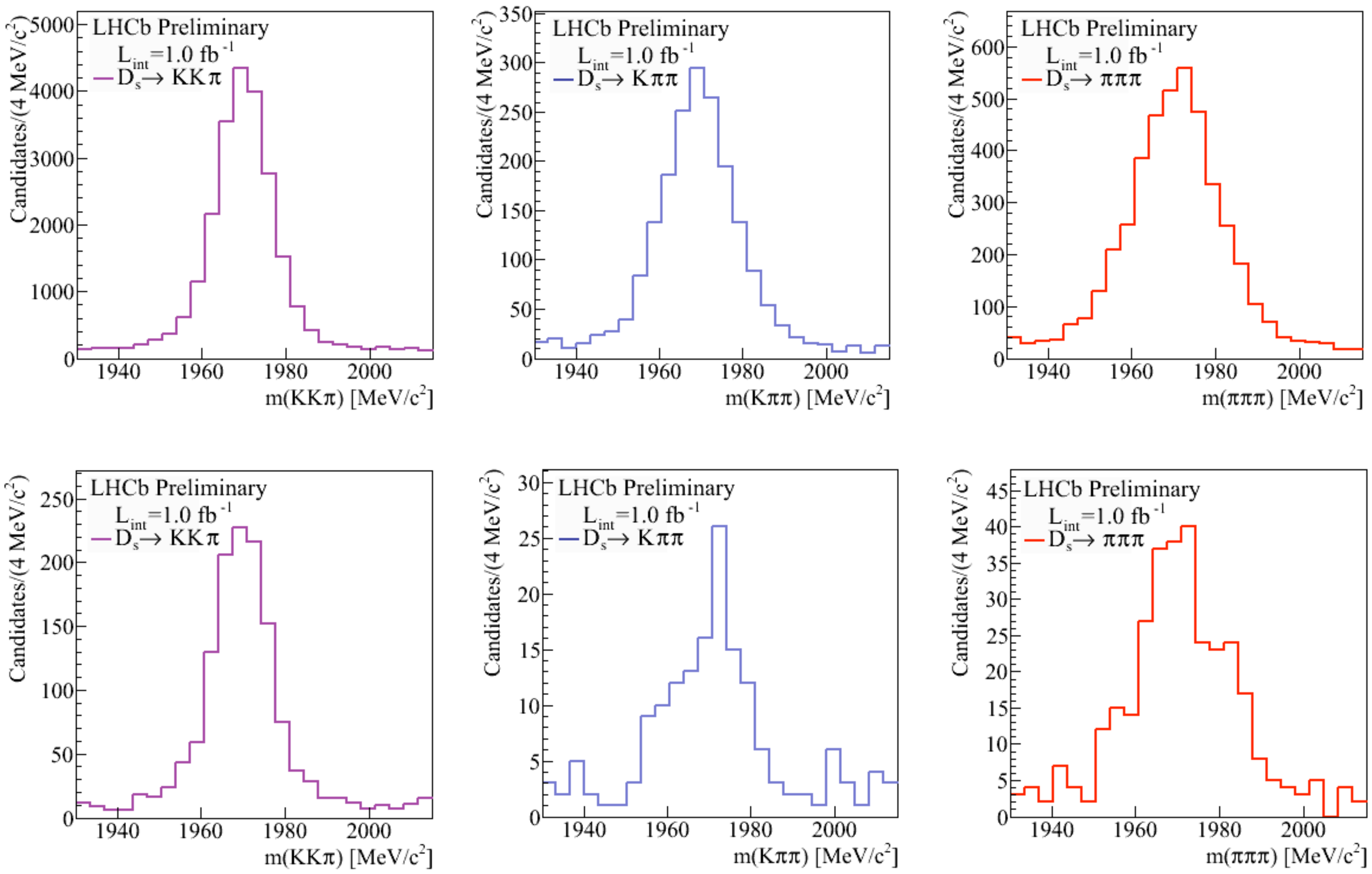


GLW/ADS 2D plots

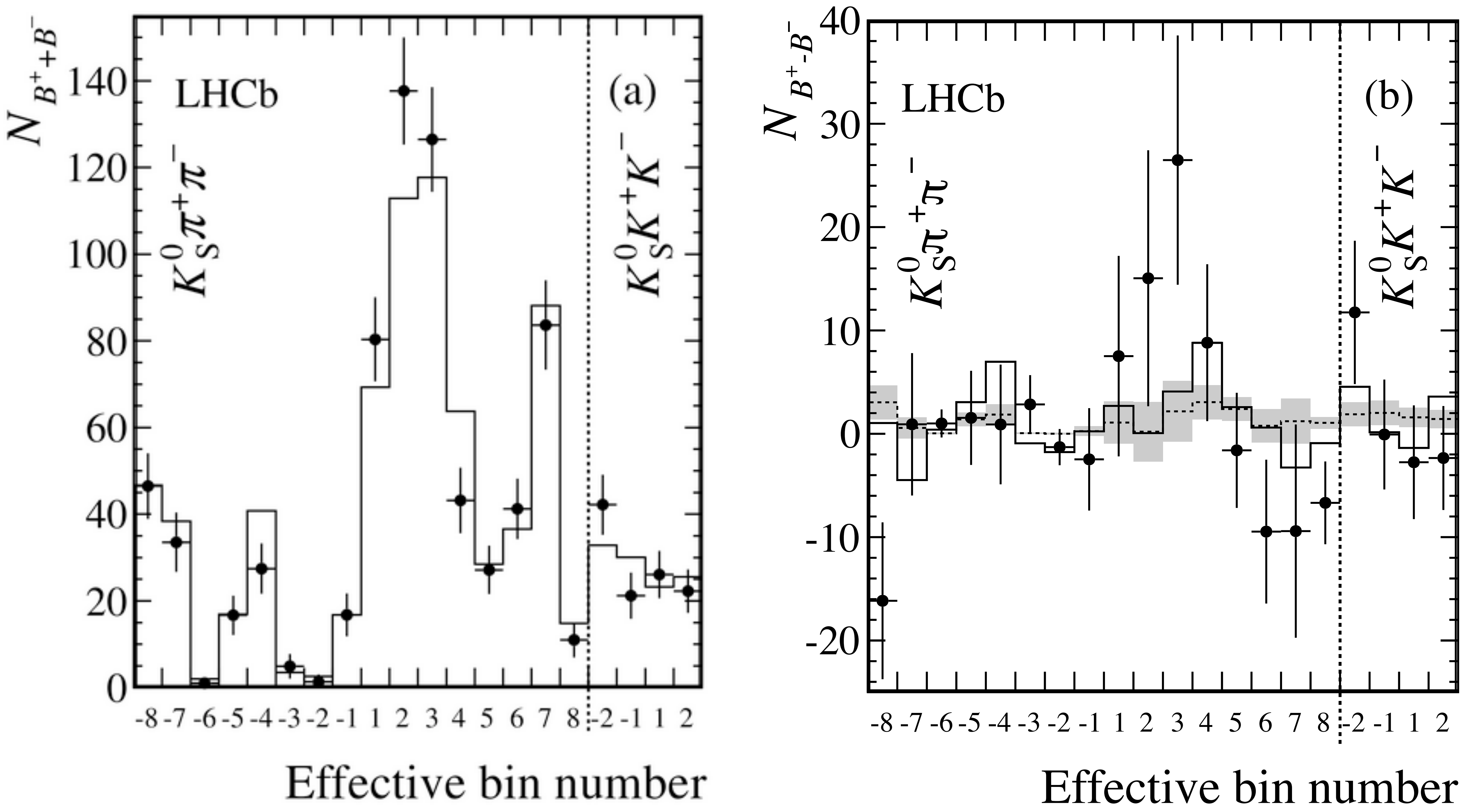




D_sK charm signals



GGSZ asymmetries per bin 1fb^{-1}



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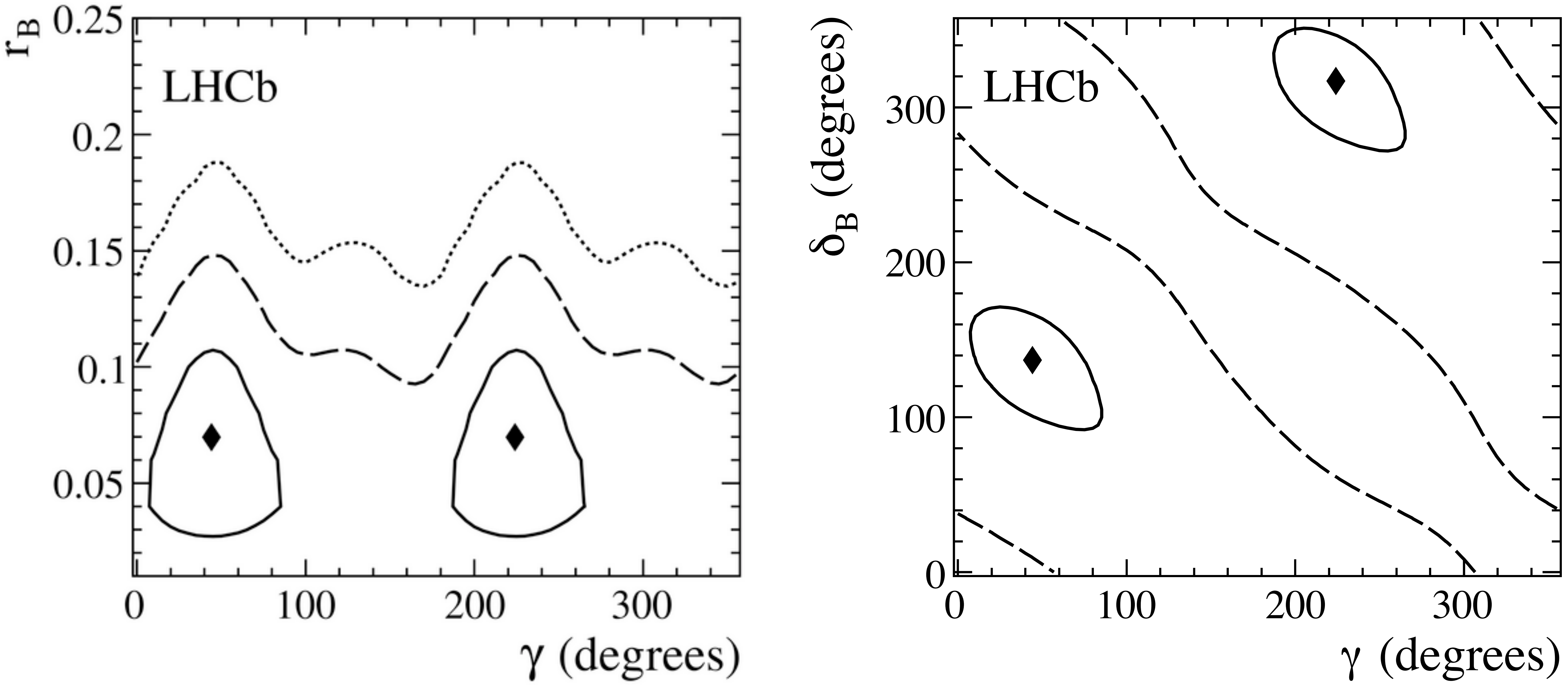
GGSZ only extractions 1fb^{-1}



LHCb-PAPER-2012-027

GLW/ADS full results

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

Table 2: Systematic uncertainties on the observables. PID refers to the fixed efficiency of the $\mathrm{DLL}_{K\pi}$ cut on the bachelor track. PDFs refers to the variations of the fixed shapes in the fit. "Sim" refers to the use of simulation to estimate relative efficiencies of the signal modes which includes the branching fraction estimates of the Λ^0_b background. $A_{\text{instr.}}$ quantifies the uncertainty on the production, interaction and detection asymmetries.

$\times 10^{-3}$	PID	PDFs	Sim	$A_{\text{instr.}}$	Total
$R^{K\pi}_{K/\pi}$	1.4	0.9	0.8	0	1.8
$R^{KK}_{K/\pi}$	1.3	0.8	0.9	0	1.8
$R^{\pi\pi}_{K/\pi}$	1.3	0.6	0.8	0	1.7
$A^{K\pi}_{\pi}$	0	1.0	0	9.4	9.5
$A^{K\pi}_{K}$	0.2	4.1	0	16.9	17.4
A^{KK}_{K}	1.6	1.3	0.5	9.5	9.7
$A^{\pi\pi}_{K}$	1.9	2.3	0	9.0	9.5
A^{KK}_{π}	0.1	6.6	0	9.5	11.6
$A^{\pi\pi}_{\pi}$	0.1	0.4	0	9.9	9.9
R^{-}_{K}	0.2	0.4	0	0.1	0.4
R^{+}_{K}	0.4	0.5	0	0.1	0.7
R^{-}_{π}	0.01	0.03	0	0.07	0.08
R^{+}_{π}	0.01	0.03	0	0.07	0.07

LHCb-PAPER-2012-001

GLW/ADS 4h full results

Table 2: Systematic uncertainties on the observables. PID refers to the fixed efficiency for the bachelor $\mathrm{DLL}_{K\pi}$ requirement which is determined using the $D^{*\pm}$ calibration sample. PDFs refers to the variations of the fixed shapes in the fit. Sim refers to the use of simulation to estimate relative efficiencies of the signal modes. $A_{\text{instr.}}$ quantifies the uncertainty on the production, interaction and detection asymmetries.

$\times 10^{-3}$	PID	PDFs	Sim	$A_{\text{instr.}}$	Total
$R_{K/\pi}^{K3\pi}$	1.7	1.2	1.5	0.0	2.6
$A_{\pi}^{K3\pi}$	0.2	1.3	0.1	9.9	10.0
$A_{K}^{K3\pi}$	0.6	4.4	0.3	17.1	17.7
$R_{K}^{K3\pi,-}$	0.4	0.7	0.1	0.1	0.8
$R_{K}^{K3\pi,+}$	0.4	0.9	0.2	0.1	1.0
$R_{\pi}^{K3\pi,-}$	0.02	0.09	0.01	0.06	0.11
$R_{\pi}^{K3\pi,+}$	0.04	0.08	0.02	0.06	0.11

$$
\begin{aligned}
R_{K/\pi}^{K3\pi} &= 0.0771 \pm 0.0017 \pm 0.0026 \\
A_{K}^{K3\pi} &= -0.029 \pm 0.020 \pm 0.018 \\
A_{\pi}^{K3\pi} &= -0.006 \pm 0.005 \pm 0.010 \\
R_{K}^{K3\pi,-} &= 0.0072 \ {}^{+0.0036}_{-0.0032} \pm 0.0008 \\
R_{K}^{K3\pi,+} &= 0.0175 \ {}^{+0.0043}_{-0.0039} \pm 0.0010 \\
R_{\pi}^{K3\pi,-} &= 0.00417 \ {}^{+0.00054}_{-0.00050} \pm 0.00011 \\
R_{\pi}^{K3\pi,+} &= 0.00321 \ {}^{+0.00048}_{-0.00045} \pm 0.00011
\end{aligned}
$$

GGSZ full results 1fb^{-1}

Table 3: Results for $x_\pm$ and $y_\pm$ from the fits to the data in the case when both $D \to K^0_S\pi^+\pi^-$ and $D \to K^0_S K^+K^-$ are considered and when only the $D \to K^0_S\pi^+\pi^-$ final state is included. The first, second, and third uncertainties are the statistical, the experimental systematic, and the error associated with the precision of the strong-phase parameters, respectively. The correlation coefficients are calculated including all sources of uncertainty (the values in parentheses correspond to the case where only the statistical uncertainties are considered).

Parameter	All data	$D \to K^0_S\pi^+\pi^-$ alone
x_- [$\times 10^{-2}$]	$0.0 \pm 4.3 \pm 1.5 \pm 0.6$	$1.6 \pm 4.8 \pm 1.4 \pm 0.8$
y_- [$\times 10^{-2}$]	$2.7 \pm 5.2 \pm 0.8 \pm 2.3$	$1.4 \pm 5.4 \pm 0.8 \pm 2.4$
corr(x_-,y_-)	-0.10 (-0.11)	-0.12 (-0.12)
x_+ [$\times 10^{-2}$]	$-10.3 \pm 4.5 \pm 1.8 \pm 1.4$	$-8.6 \pm 5.4 \pm 1.7 \pm 1.6$
y_+ [$\times 10^{-2}$]	$-0.9 \pm 3.7 \pm 0.8 \pm 3.0$	$-0.3 \pm 3.7 \pm 0.9 \pm 2.7$
corr(x_+,y_+)	0.22 (0.17)	0.20 (0.17)

LHCb-PAPER-2012-027

What has this enabled us to produce?

GLW/ADS in B→DK,Dπ with D→hh

ADS in B→DK,Dπ with D→hhhh

GGSZ in B→DK with D→$K_S$hh

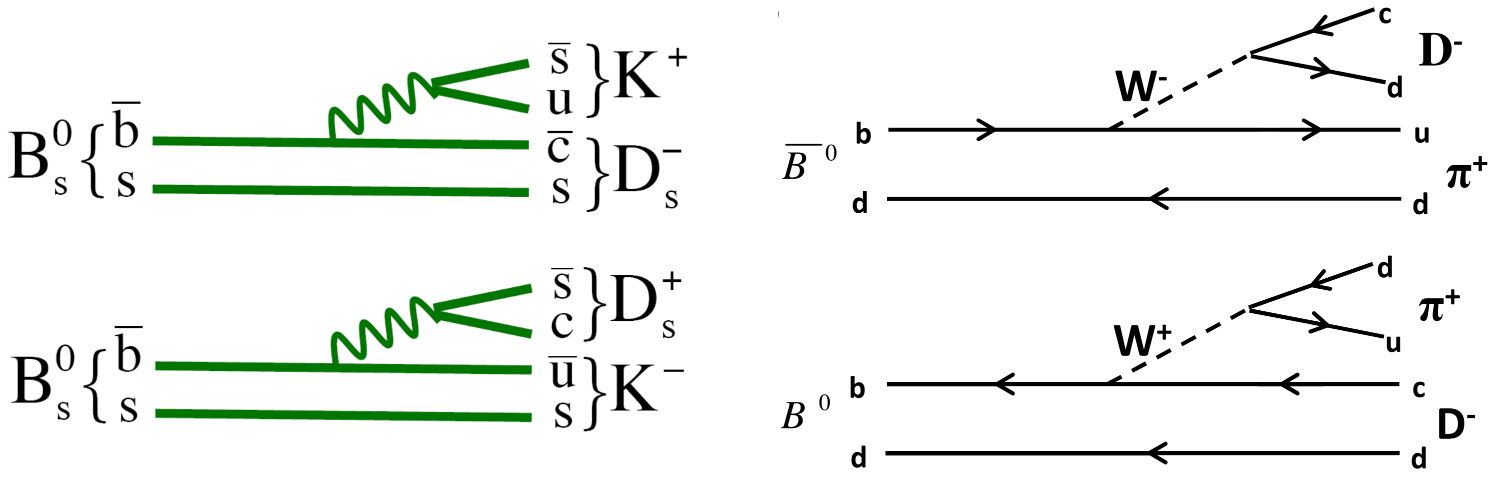
GLW in B→DK^{0*}

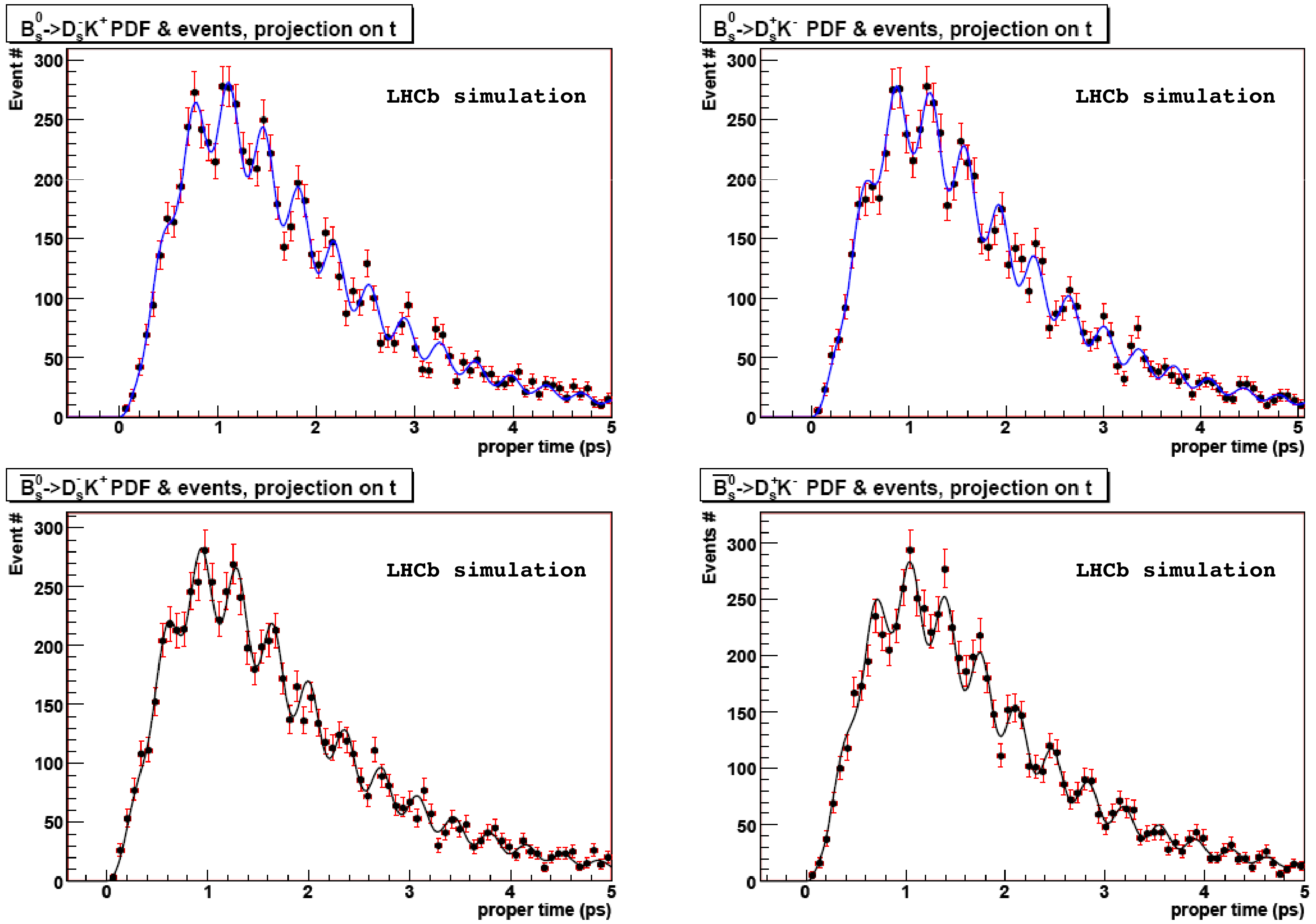
GLW in B→Dhhh

Frequentist γ combination

Time dependent CPV in B_S→D_SK

Observables ⇔ physics parameters





Sensitivity to γ comes from the time-dependent interference of the V_{ub} and V_{cb} decay rates.

Can perform both flavour tagged and flavour untagged measurements.

The sizes of the interfering diagrams are expected to be similar, leading to large interference and good per-event sensitivity to γ.

Observables ⇔ physics parameters

$$A\left(B_q^0 \rightarrow D_q \bar{u}_q\right) = \frac{C\cos(\Delta m\tau) + S\sin(\Delta m\tau)}{\cosh(\Delta\Gamma_q t/2) - A_{\Delta\Gamma}\sinh(\Delta\Gamma_q t/2)}$$

$$C = -\frac{1 - x_q^2}{1 + x_q^2}$$

Ratio of CKM-suppressed to CKM-favoured amplitudes, **~0.4 in $B_s \rightarrow D_s K$**

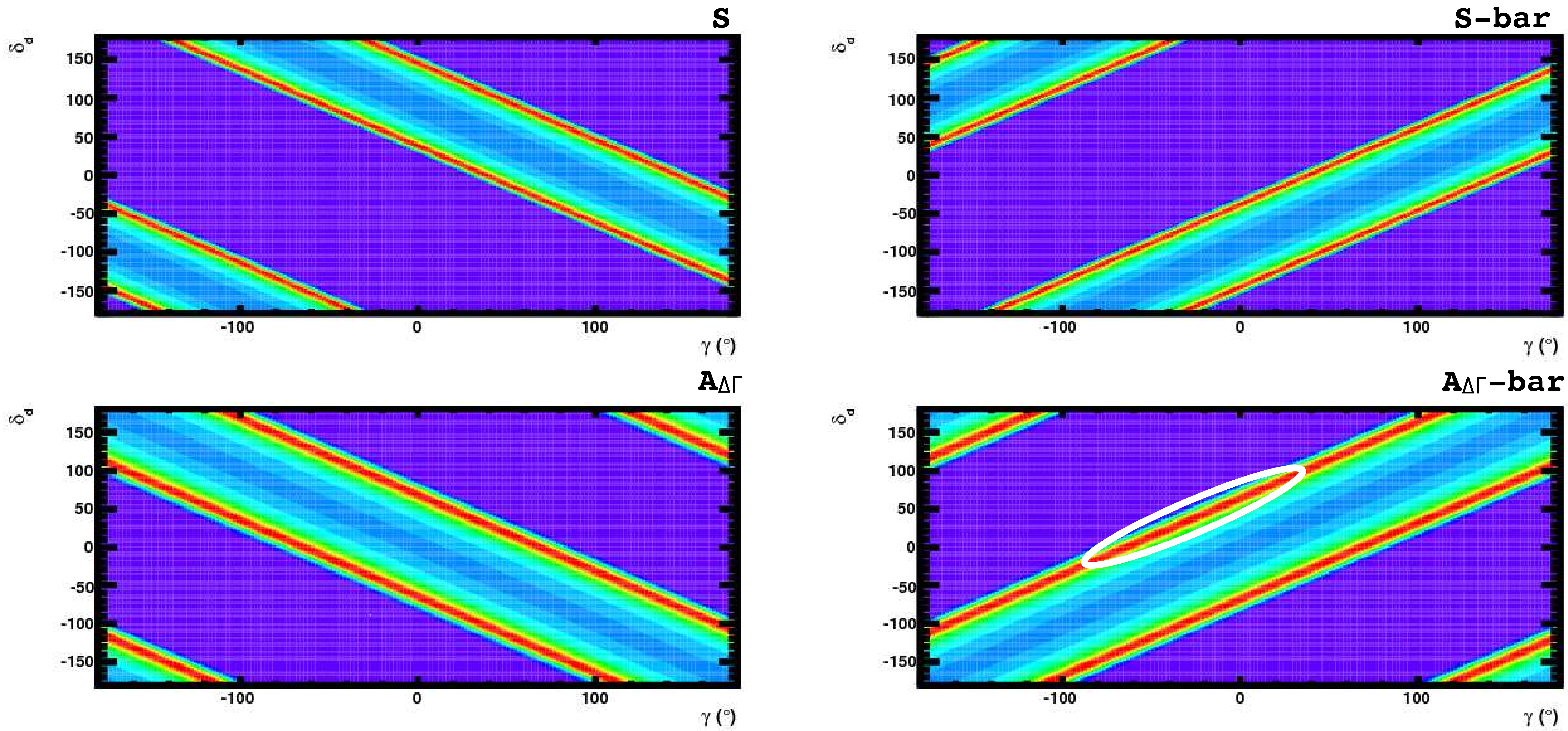
$$S = \frac{2x_q \sin(\gamma + \delta_q + \phi_q)}{(x_q^2 + 1)}$$

$$A_{\Delta\Gamma} = \frac{2x_q \cos(\gamma + \delta_q + \varphi_q)}{(x_q^2 + 1)}$$

Strong phase (δ_q)

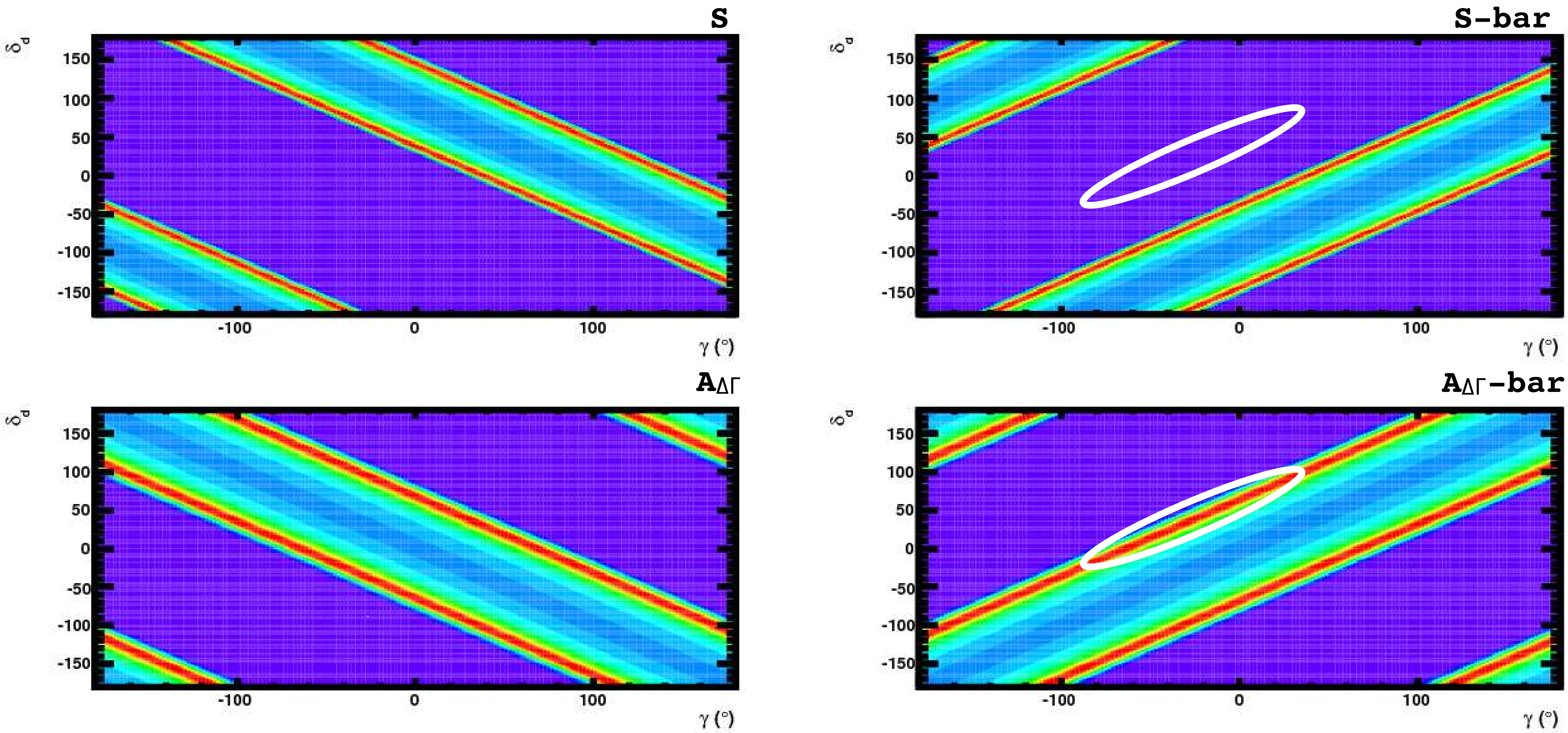
Weak mixing phase (φ_q)

Observables ⇔ physics parameters



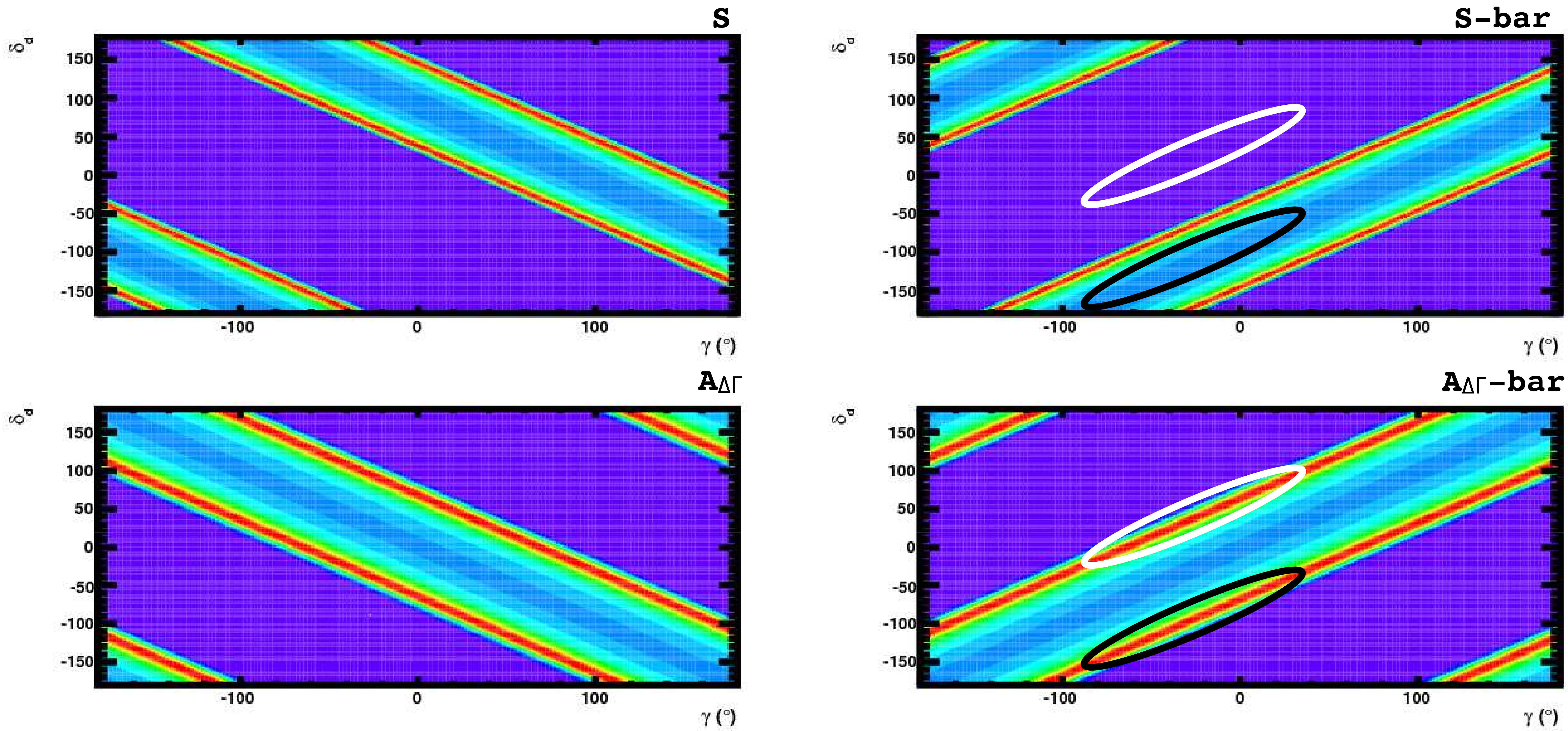
TOY SIMULATION

Observables ⇔ physics parameters



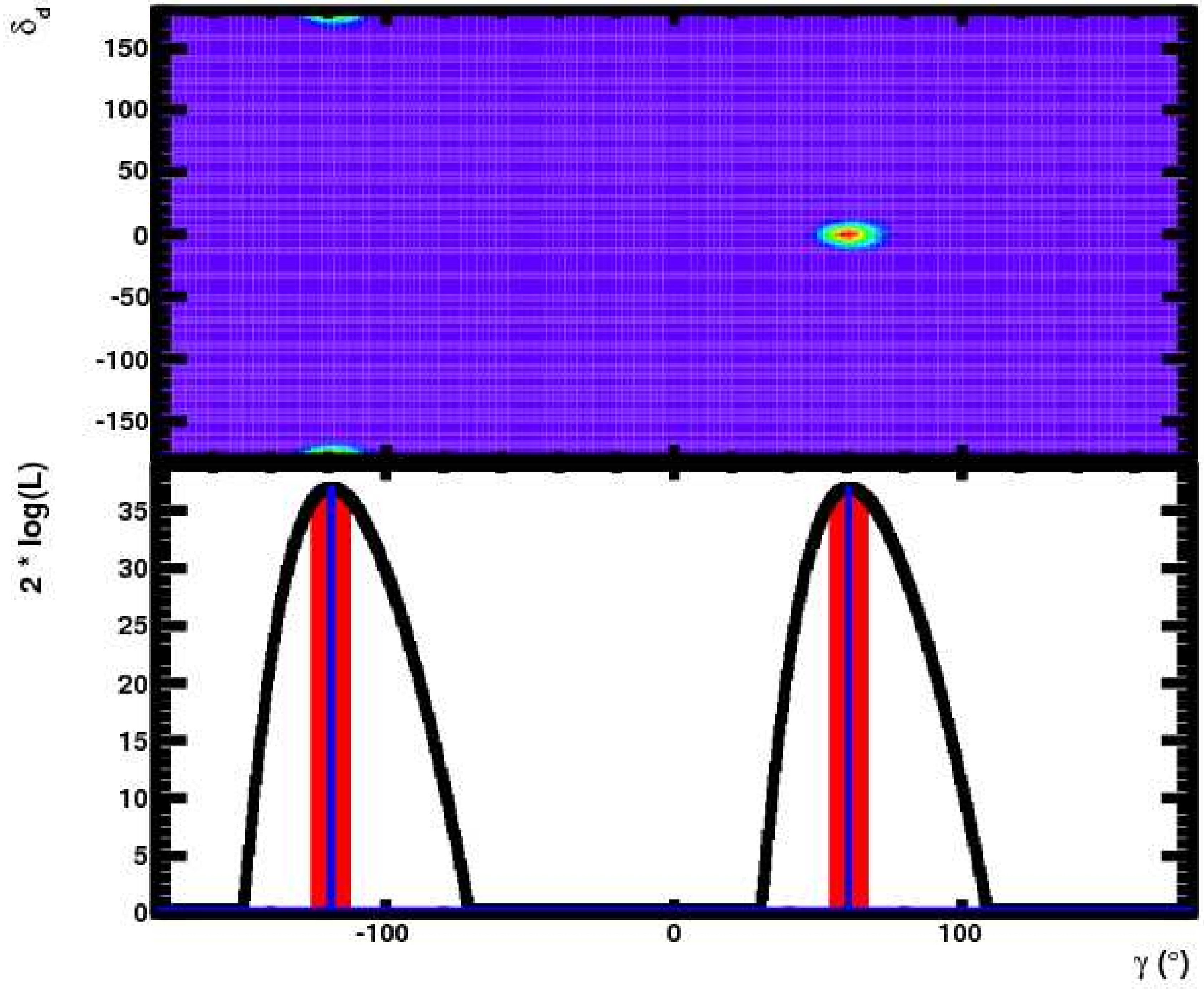
TOY SIMULATION

Observables ⇔ physics parameters



TOY SIMULATION

Observables ⇔ physics parameters



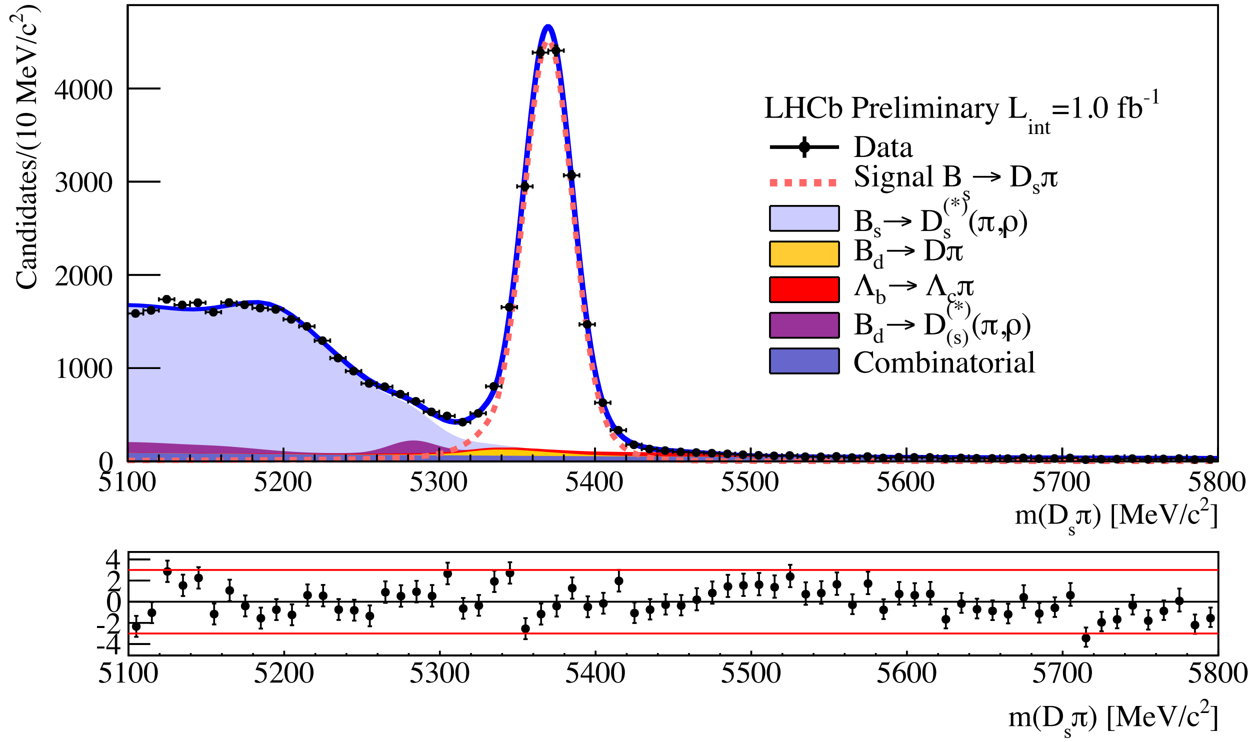
In the limit of large statistics, the different observables combine in such a way as to give only a twofold ambiguity on the angle γ

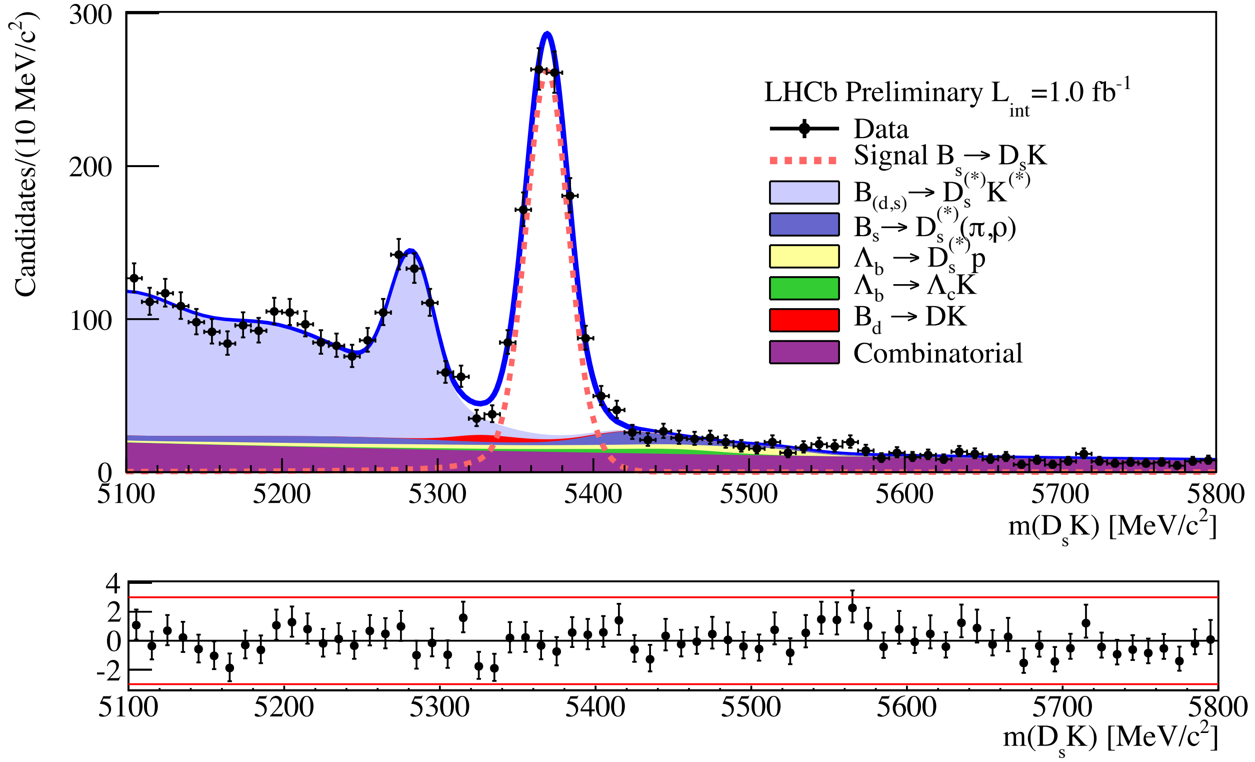
This relies on having both the "tagged" and "untagged" observables

Luckily nature has been kind with a large value of $\Delta\Gamma_S/\Gamma_S$ ~ 15.9%!

TOY SIMULATION

Signals in the data



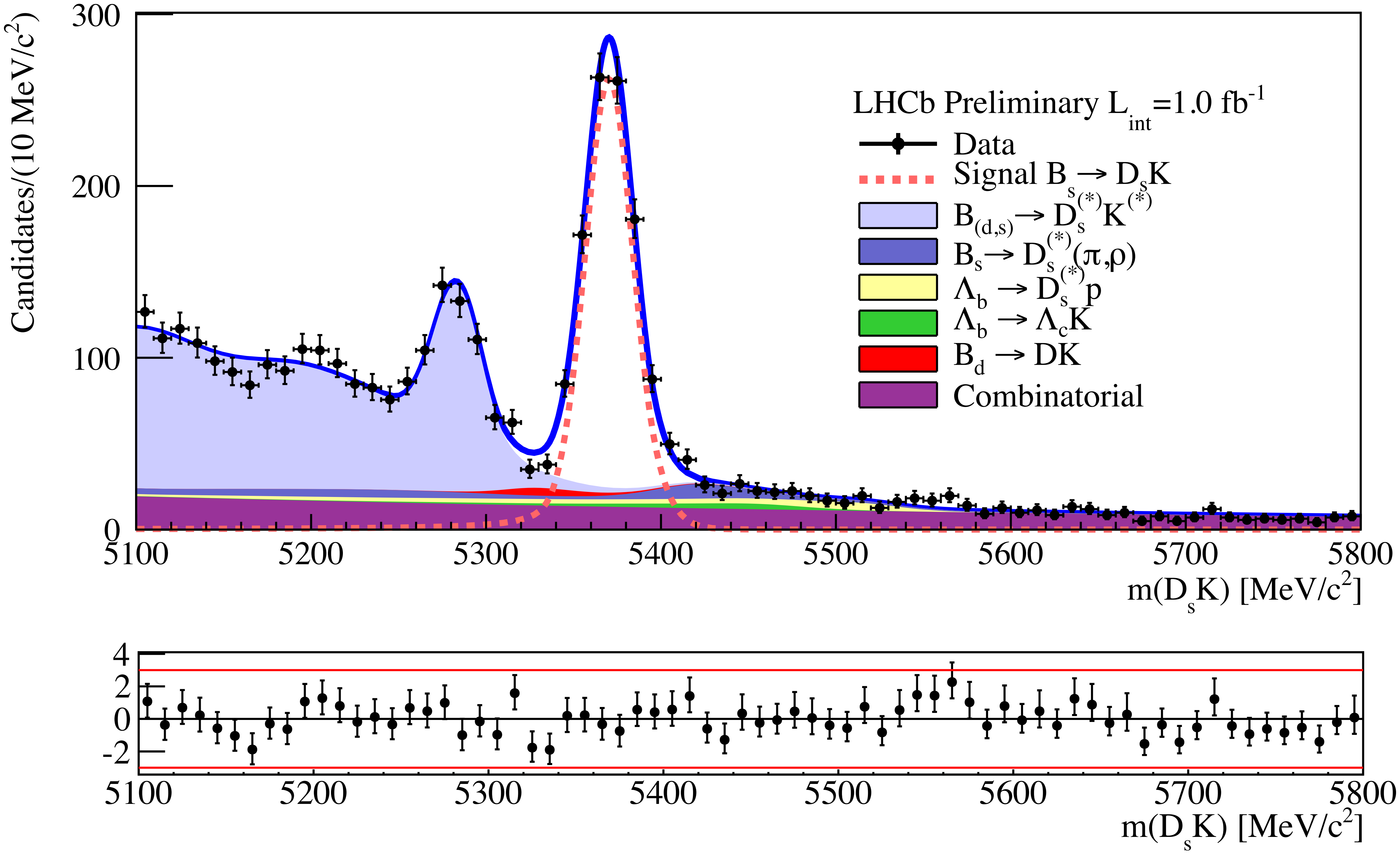


Clean high yield control mode $B_s \to D_s \pi$

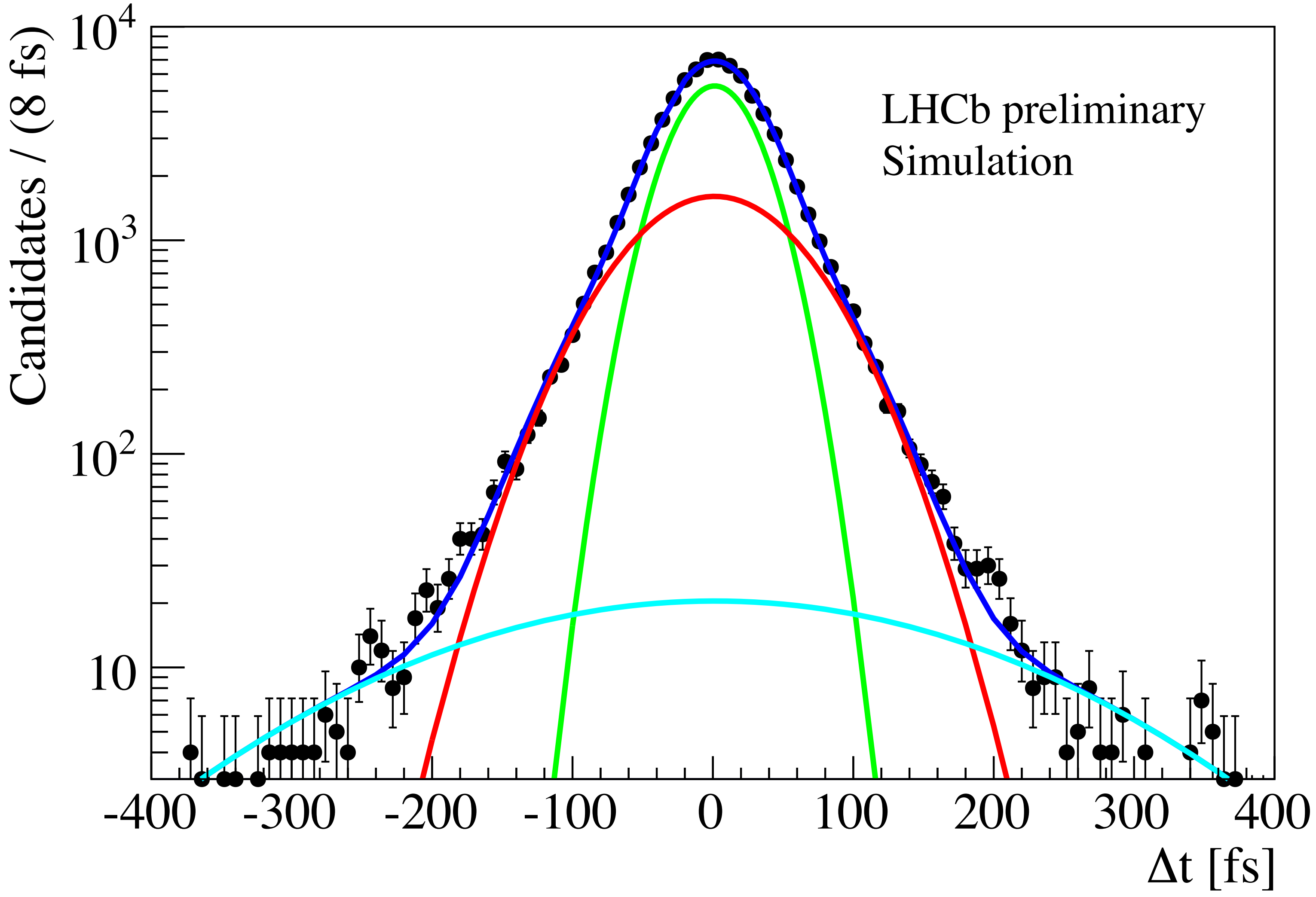
1) **Allows to constrain backgrounds in D_sK**

2) **Allows flavour tagging calibration**

Backgrounds in $D_S K$



Propertime resolution/acceptance



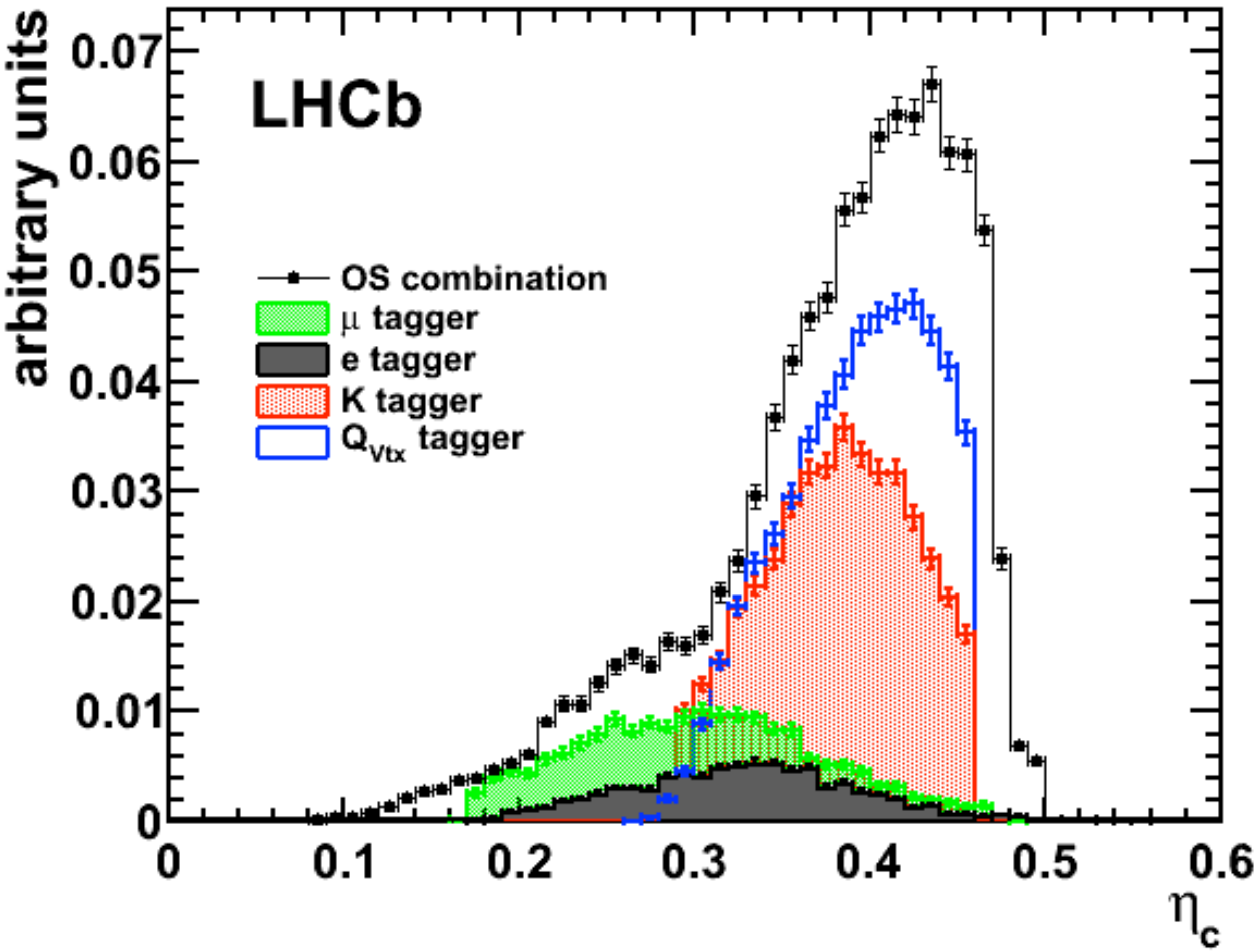
Propertime resolution taken from simulation scaled by the difference between simulation and data resolutions measured on a control channel (15%)

Effective propertime resolution is ~50 fs

Acceptance taken from a fit to the $B_s \to D_s \pi$ data fixing the lifetime and oscillation frequency to the WA values

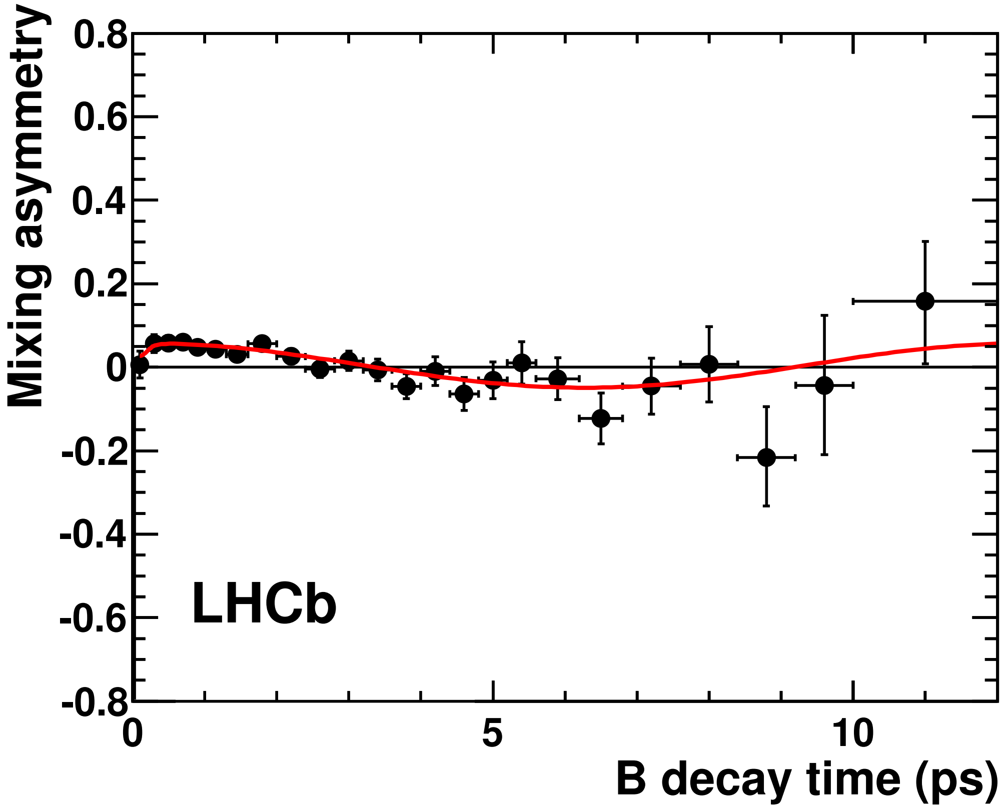
Corrected by the ratio of acceptances observed in the simulation

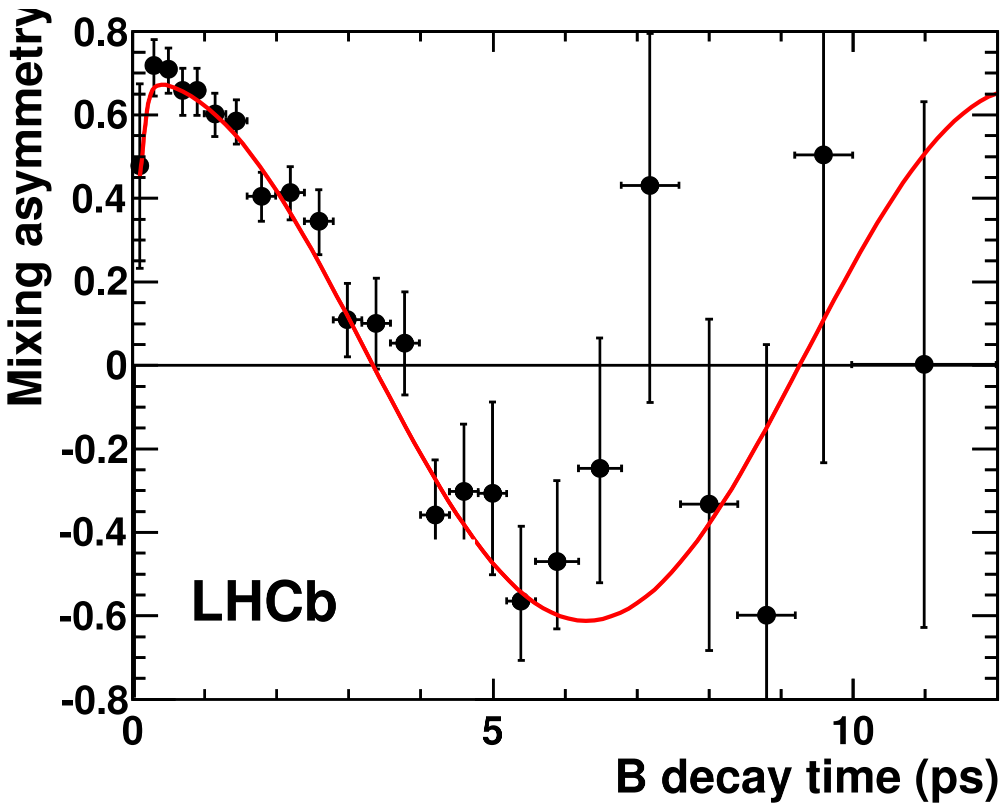
Mistag distributions



LHCb-PAPER-2011-027

Tagging





Tagging based on the "opposite-side" B decay

Mixture of

- **Single particle tag : e,μ,K**
- **Vertex charge tag**

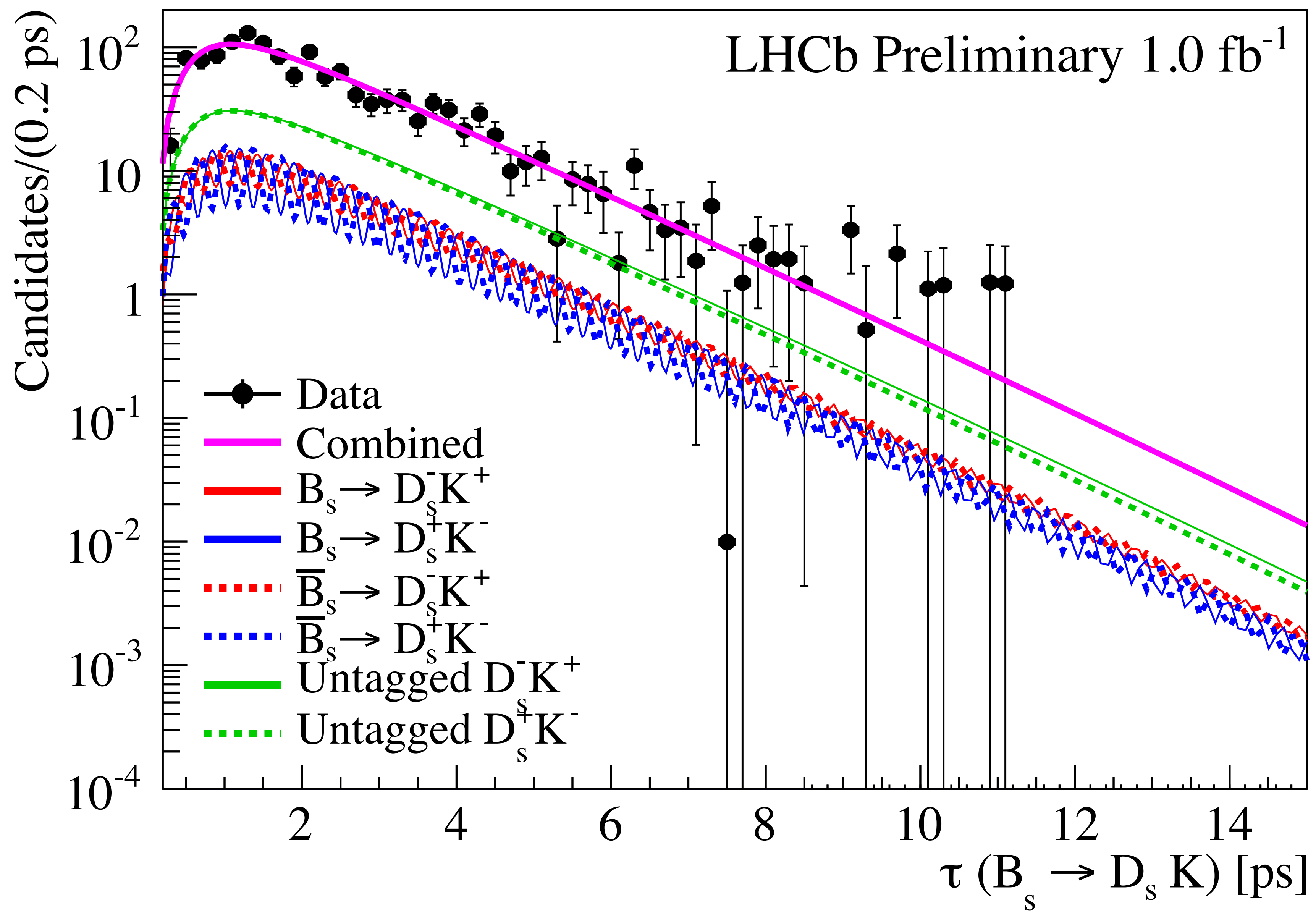
Combined using a Neural Network trained on simulated events

Tagging performance is calibrated on self tagging control channels in the data

Analysis uses the predicted per-event mistag to maximize sensitivity

LHCb-PAPER-2011-027, LHCb-CONF-2012-026

Time fit



The time uses a statistical background subtraction technique (the "sPlot" method) in order to avoid modelling the time dependence of the backgrounds

Fit performance verified in through studies of 2000 pseudoexperiment ensembles

Systematic uncertainties calculated from similar pseudoexperiment ensembles, varying fixed parameters and computing toy-by-toy differences between the nominal and modified fit.

See Arxiv physics.data_an 0402083, 0905.0724

Results

Table 4: Fitted values of the $B_s^0 \to D_s^{\mp} K^{\pm}$ CP-asymmetry observables with statistical and systematic uncertainties. All systematics are given as fractions of the statistical uncertainty. Systematics are added in quadrature under the assumption that they are uncorrelated.

	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

No extraction of γ for now because we did not have the time to evaluate the correlations between systematic uncertainties and we saw a non-negligible effect of including these on γ.

Will be done for the eventual paper.

LHCb-CONF-2012-029

What has this enabled us to produce?

GLW/ADS in $B \to DK, D\pi$ with $D \to hh$

ADS in $B \to DK, D\pi$ with $D \to hhhh$

GGSZ in $B \to DK$ with $D \to K_S hh$

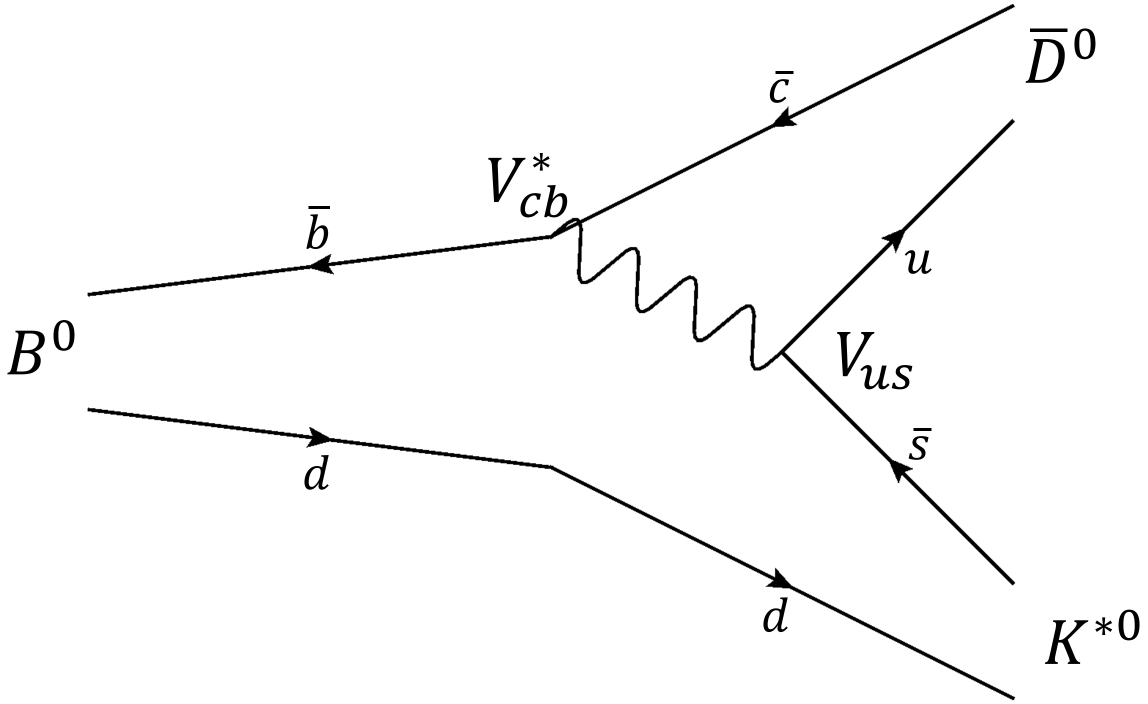
GLW in $B \to DK^{0*}$

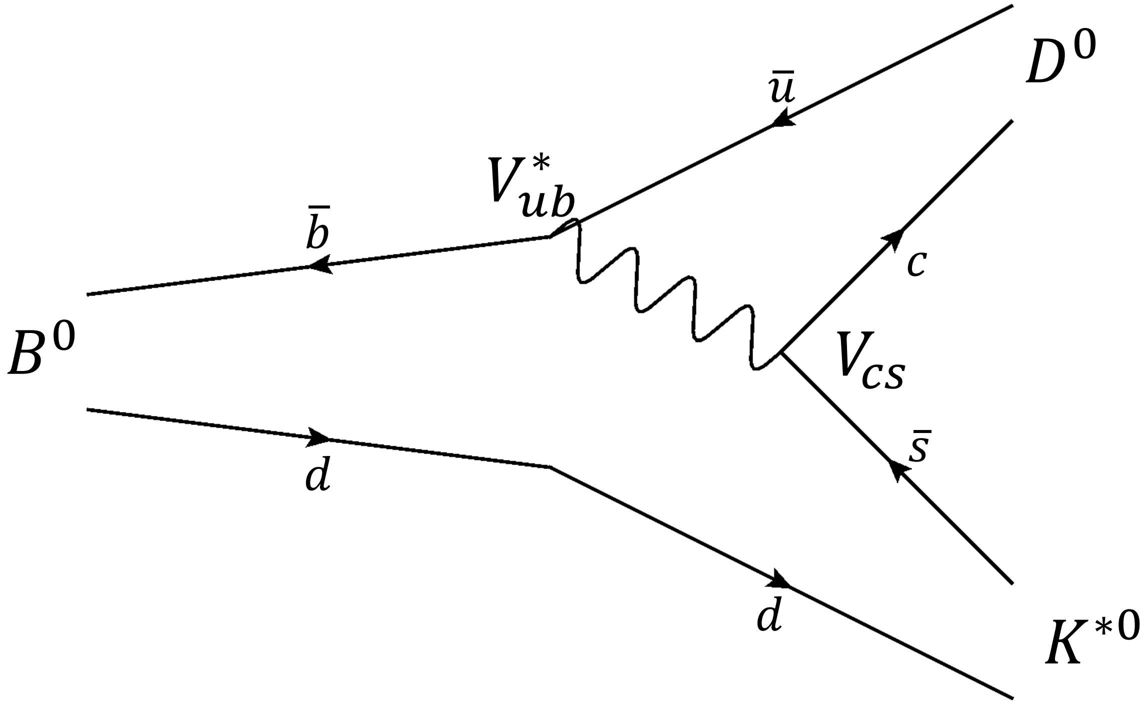
GLW in $B \to Dhhh$

Frequentist γ combination

Time dependent CPV in $B_S \to D_S K$

Observables ⇔ physics parameters

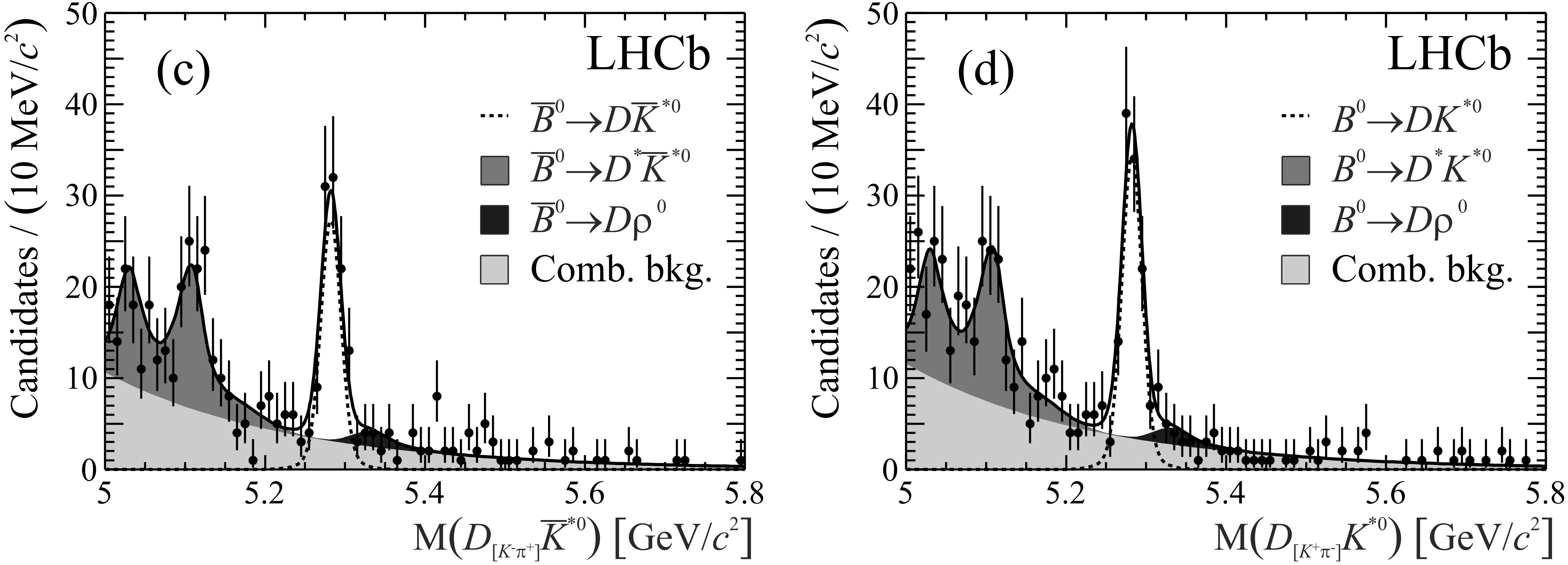




Quasi two-body approach : fewer events than DK, but bigger interference

LHCb-PAPER-2012-042

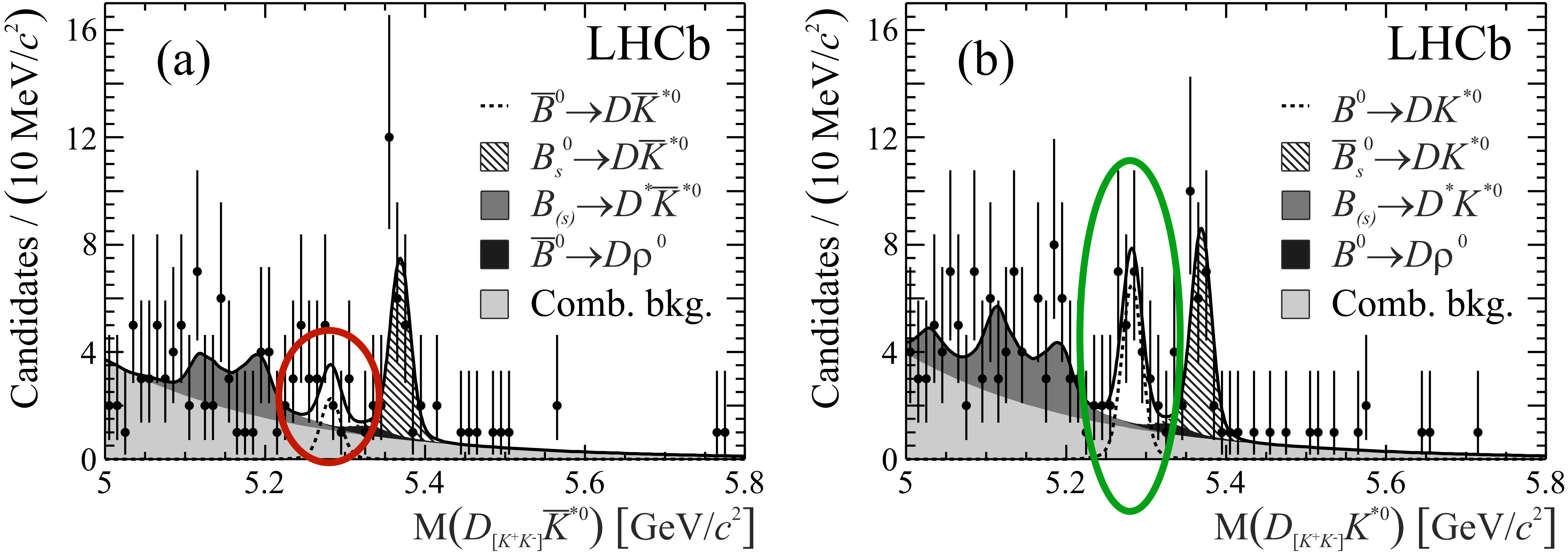
Cabibbo favoured normalization mode



Kaon from K^{*0} and from D^0 have the same sign, so no B_d contribution

LHCb-PAPER-2012-042

Cabibbo suppressed mode



$$\mathcal{A}_d^{KK} = -0.45 \pm 0.23\ (\text{stat}) \pm 0.02\ (\text{syst}),$$
$$\mathcal{A}_d^{\text{fav}} = -0.08 \pm 0.08\ (\text{stat}) \pm 0.01\ (\text{syst}),$$
$$\mathcal{A}_s^{KK} = 0.04 \pm 0.16\ (\text{stat}) \pm 0.01\ (\text{syst}),$$
$$\mathcal{R}_d^{KK} = 1.36^{+\ 0.37}_{-\ 0.32}\ (\text{stat}) \pm 0.07\ (\text{syst}).$$

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What has this enabled us to produce?

GLW/ADS in B→DK,Dπ with D→hh

ADS in B→DK,Dπ with D→hhhh

GGSZ in B→DK with $D \to K_S hh$

GLW in $B \to DK^{0*}$

GLW in B→Dhhh

Frequentist γ combination

Time dependent CPV in $B_S \to D_S K$

Observables ⇔ physics parameters

$$N(B^- \to D(K^-\pi^+)X_s^-) = N^{K\pi}(1 + (r_B r_D)^2 + 2\kappa r_B r_D \cos(\delta_B - \delta_D - \gamma))$$
$$N(B^+ \to D(K^+\pi^-)X_s^+) = N^{K\pi}(1 + (r_B r_D)^2 + 2\kappa r_B r_D \cos(\delta_B - \delta_D + \gamma))$$
$$N(B^- \to D(h^-h^+)X_s^-) = N^{hh}(1 + r_B^2 + 2\kappa r_B \cos(\delta_B - \gamma))$$
$$N(B^+ \to D(h^-h^+)X_s^+) = N^{hh}(1 + r_B^2 + 2\kappa r_B \cos(\delta_B + \gamma)).$$

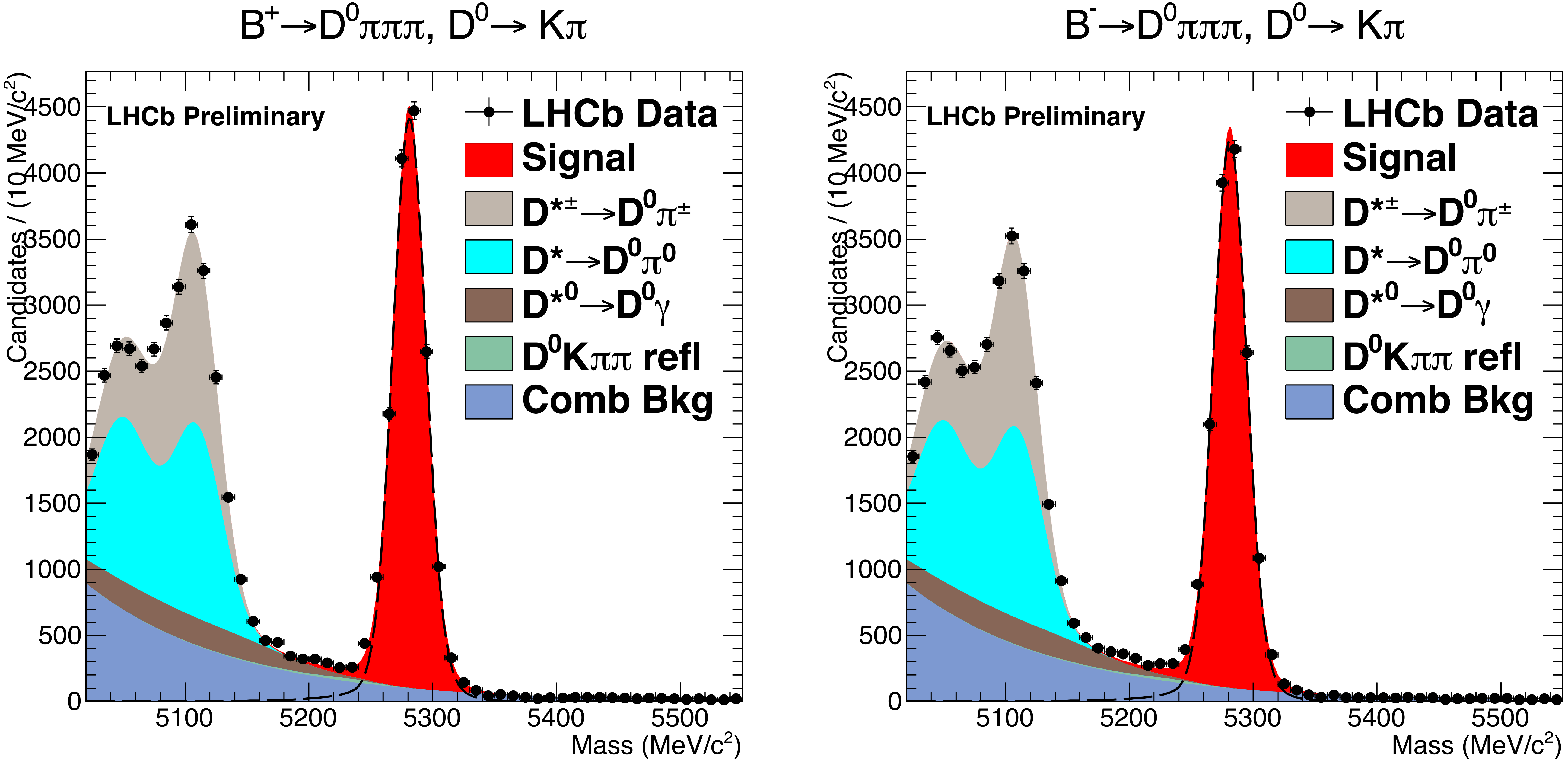
Same formalism as for the two-body case, except for the coherence factor κ.

This is necessary because the B decay is a sum of amplitudes varying across the Dalitz plot; when we perform an analysis integrating over these amplitudes, we lose sensitivity from the way in which they interfere.

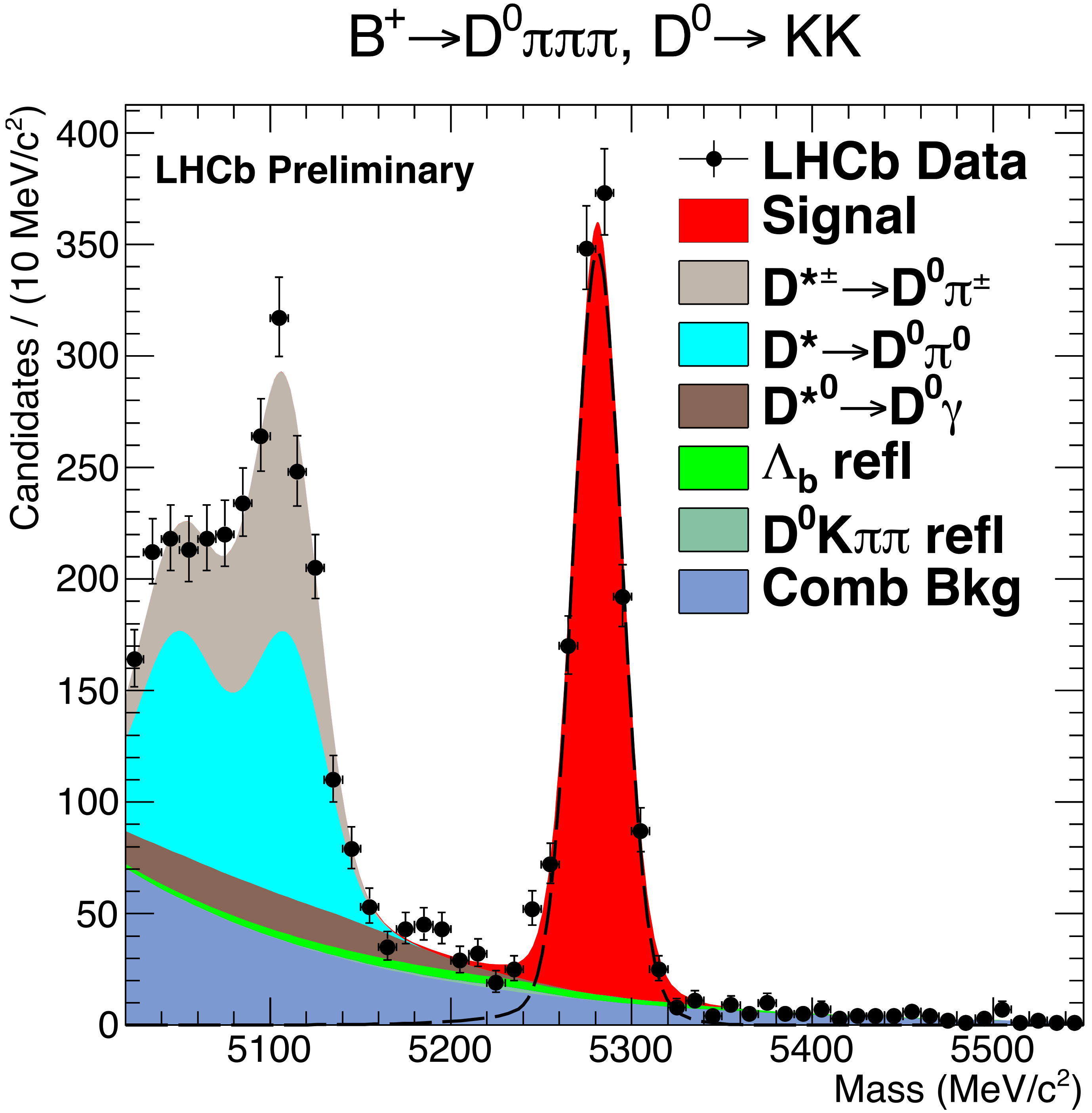
κ=1 means full sensitivity, κ=0 means no sensitivity.

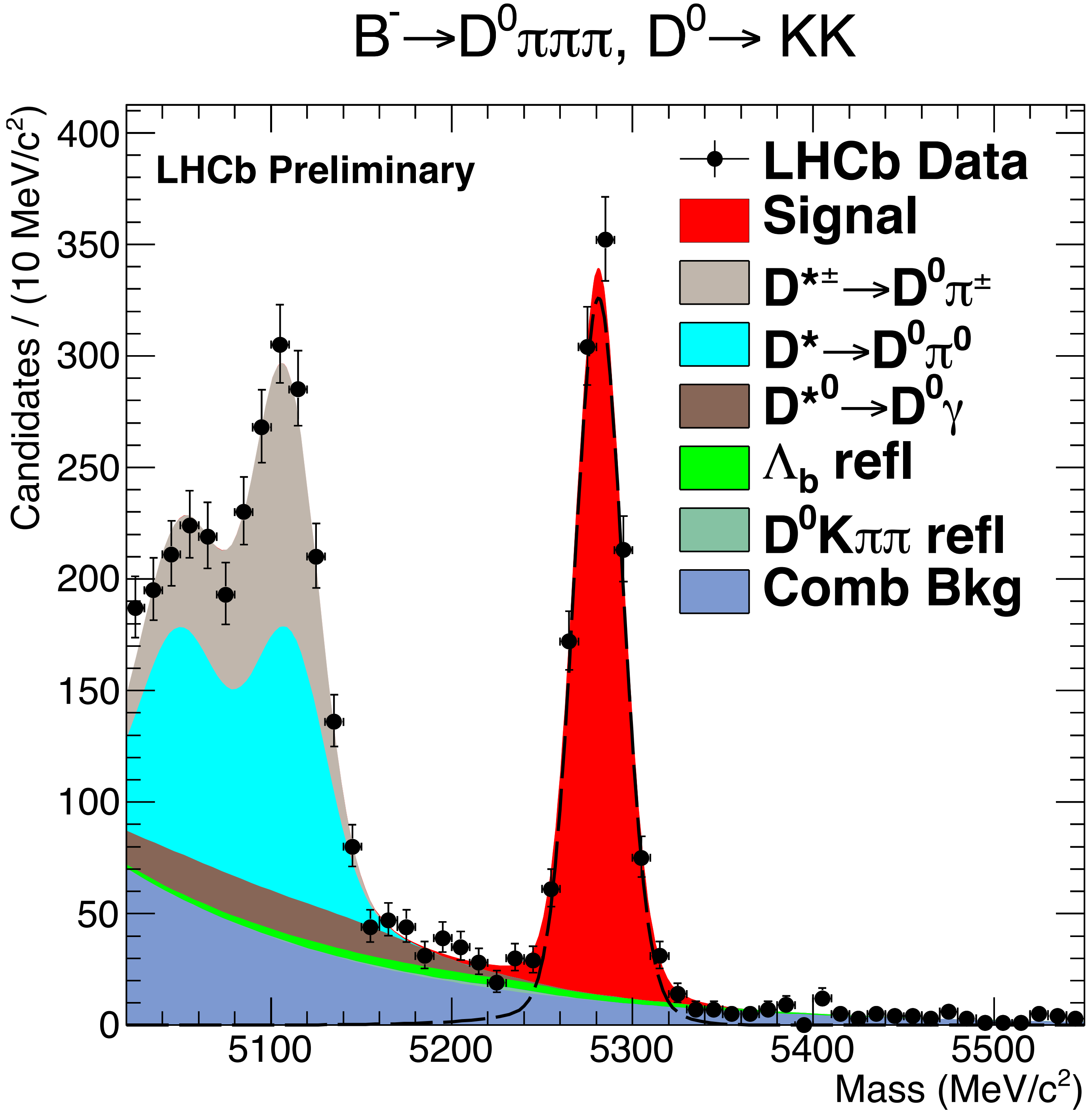
LHCb-CONF-2012-021

Signals, favoured B, D→Kπ



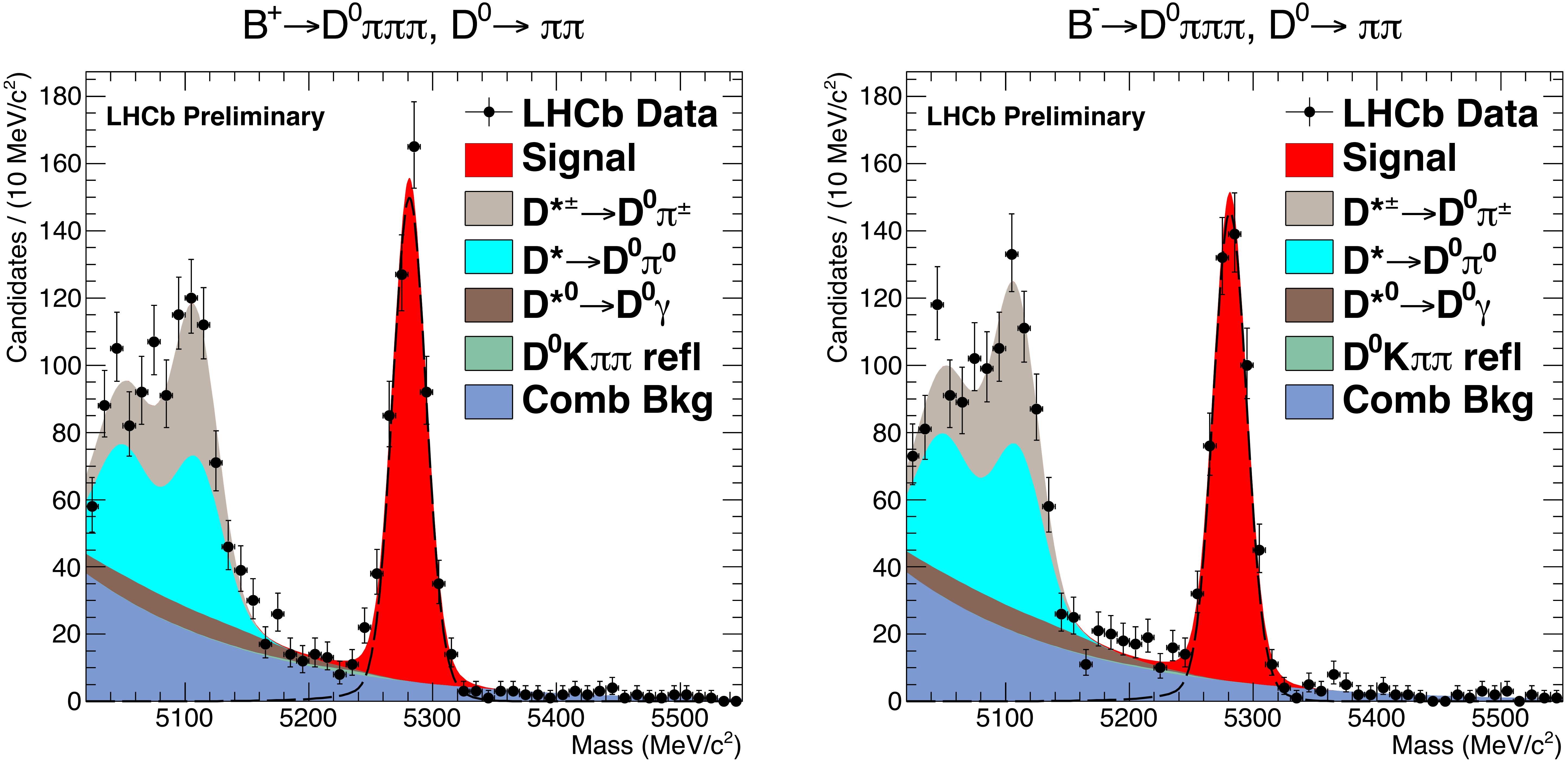
Signals, favoured B, D→KK



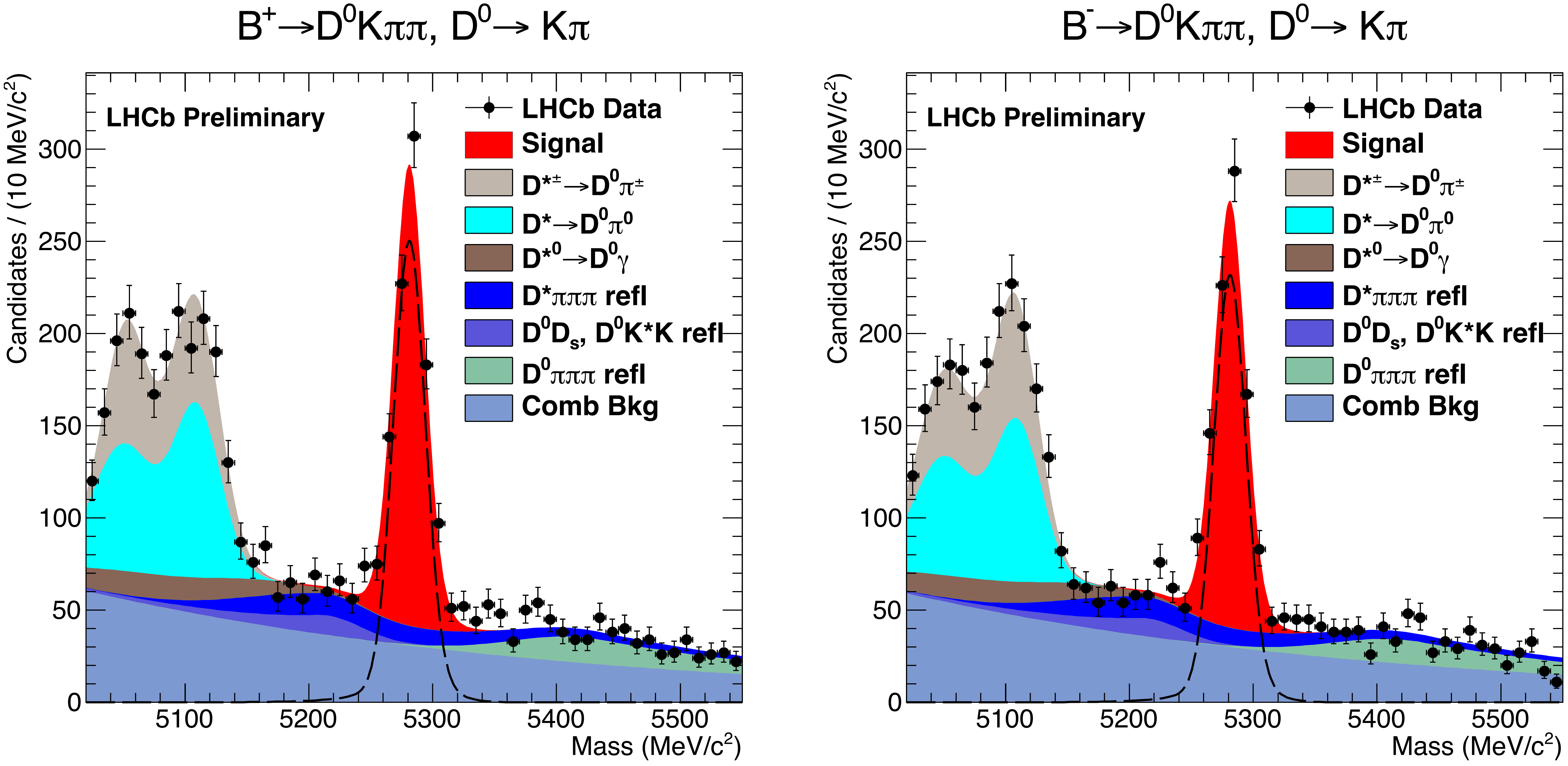


LHCb-CONF-2012-021

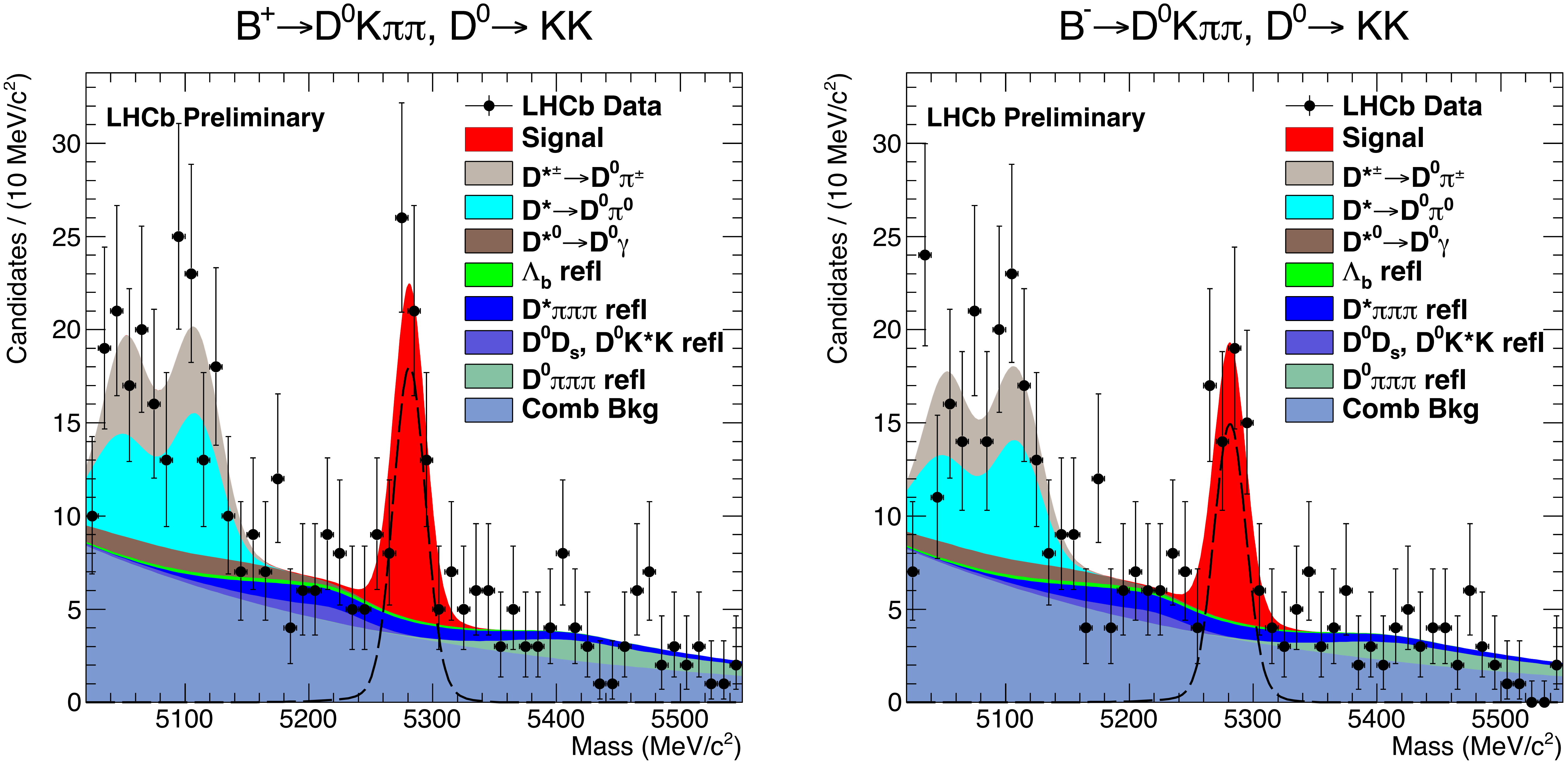
Signals, favoured B, D→ππ



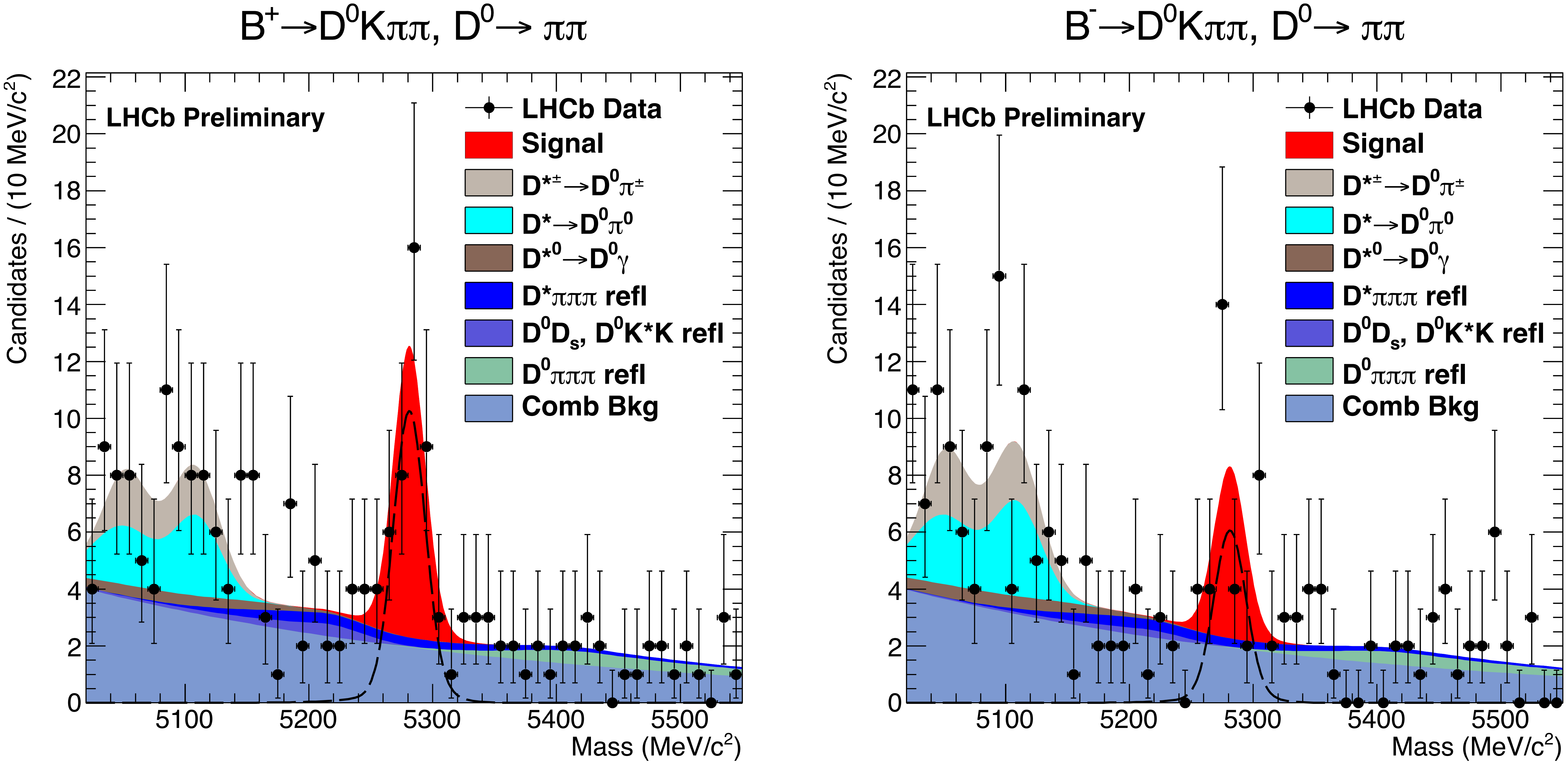
Signals, suppressed B, D→Kπ



Signals, suppressed B, D→KK



Signals, suppressed B, D→ππ



Results

The final results for the relative rate R_{CP+} and the asymmetries are

$$\begin{aligned} R_{CP+} &= \quad 0.95 \ \ \pm 0.11 \ \ (\text{stat}) \pm 0.02 \ \ (\text{syst}) \\ A_s^{CP+} &= -0.14 \ \ \pm 0.10 \ \ (\text{stat}) \pm 0.01 \ \ (\text{syst}) \\ A_s^{K^-\pi^+} &= -0.009 \pm 0.028 (\text{stat}) \pm 0.013 (\text{syst}) \end{aligned} \tag{14}$$

We also measure asymmetries in the corresponding Cabibbo-favored decays, and find:

$$\begin{aligned} A_d^{CP+} &= -0.018 \pm 0.018 (\text{stat}) \pm 0.007 (\text{syst}) \\ A_d^{K^-\pi^+} &= -0.006 \pm 0.006 (\text{stat}) \pm 0.010 (\text{syst}) \end{aligned} \tag{15}$$