CKM angle measurements
CP violation in charm

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for the LHCb collaboration

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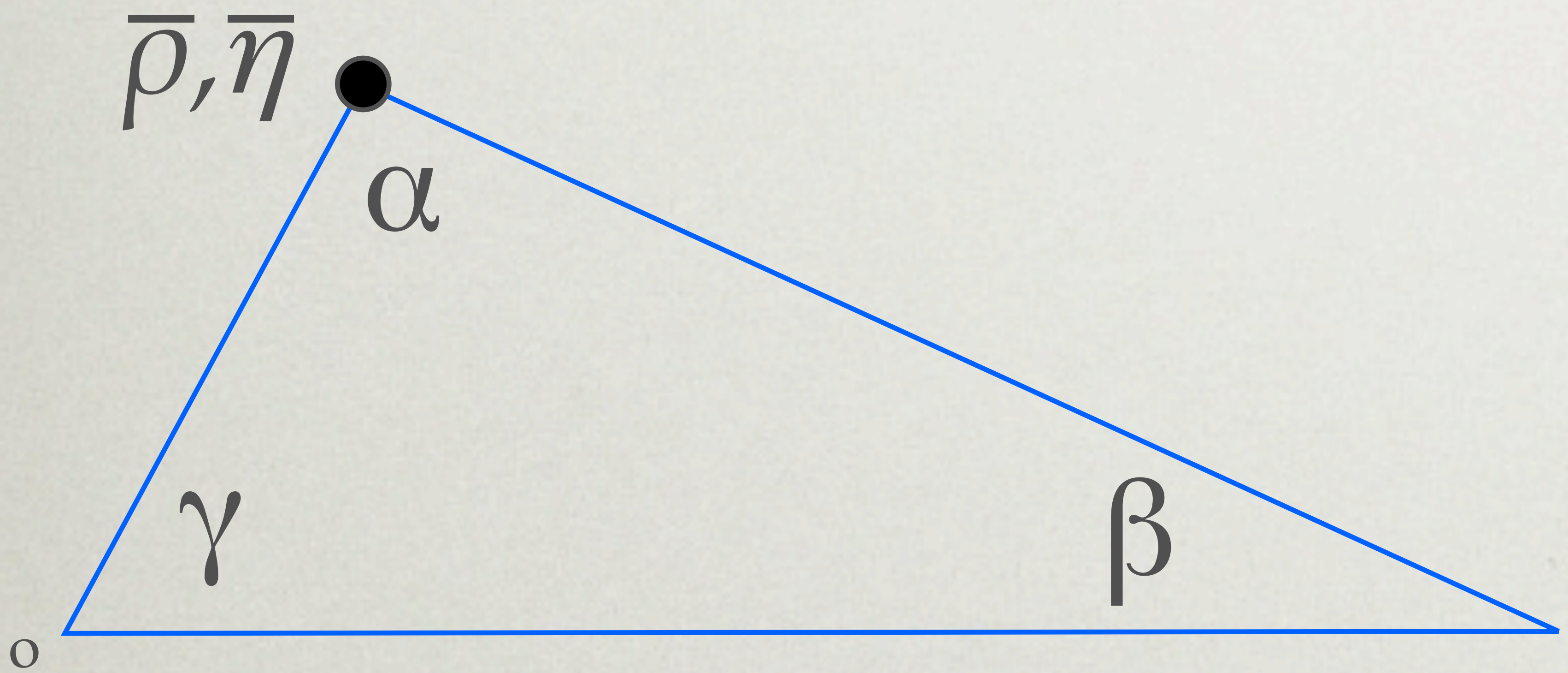
Quark couplings to the weak current

$$V_{CKM} = \begin{matrix} & d & s & b \\ u \\ c \\ t \end{matrix} \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta + \frac{i}{2}\eta\lambda^2) \\ -\lambda & 1-\frac{1}{2}\lambda^2 - i\eta A^2\lambda^4 & A\lambda^2(1+i\eta\lambda^2) \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^6)$$

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

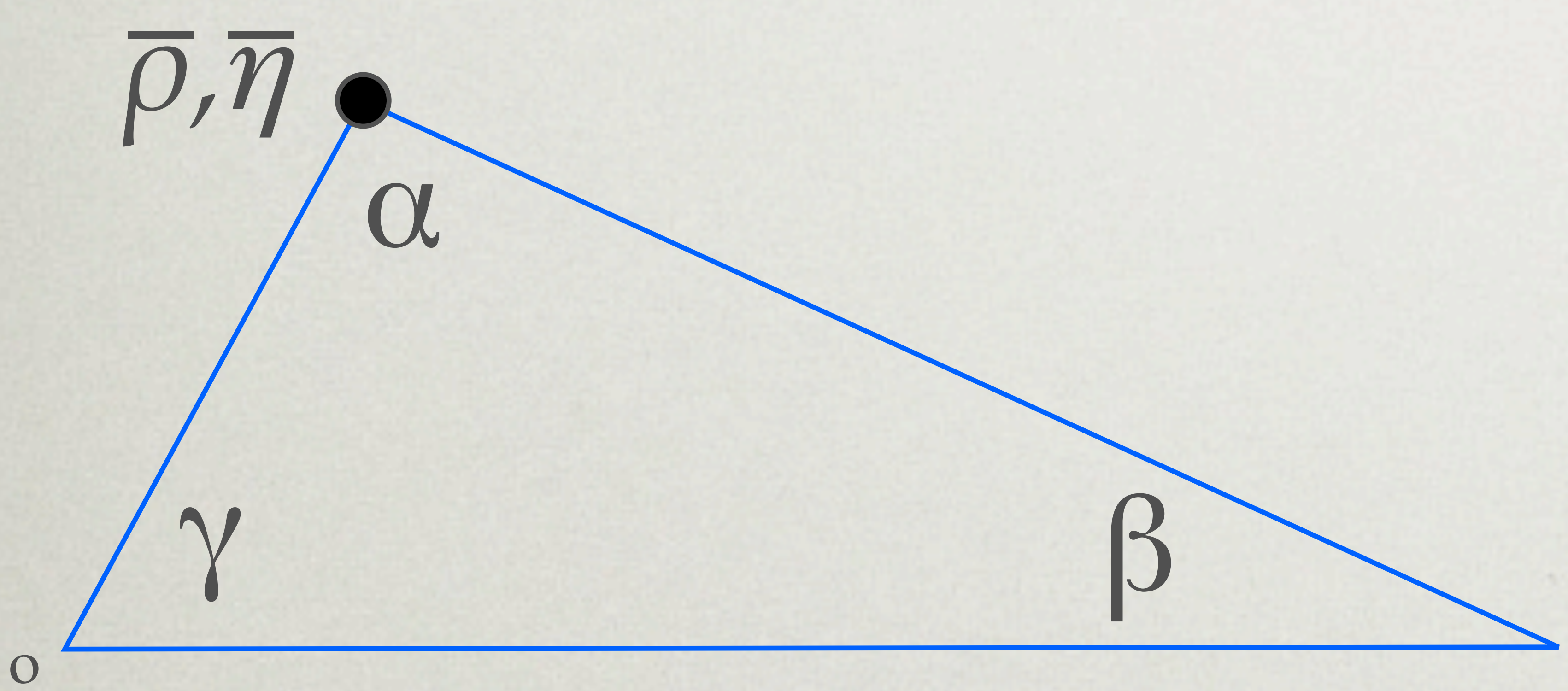


primarily B_u , B_d decays

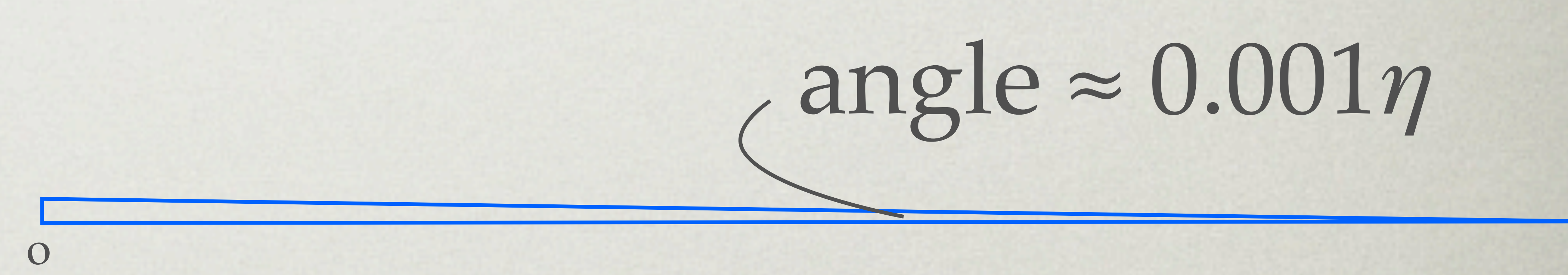
Quark couplings to the weak current

$$V_{CKM} = \begin{array}{c} \\ u \\ c \\ t \end{array} \begin{pmatrix} d & s & b \\ 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta + \frac{i}{2}\eta\lambda^2) \\ -\lambda & 1-\frac{1}{2}\lambda^2 - i\eta A^2\lambda^4 & A\lambda^2(1+i\eta\lambda^2) \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^6)$$

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



B_u,B_d decays

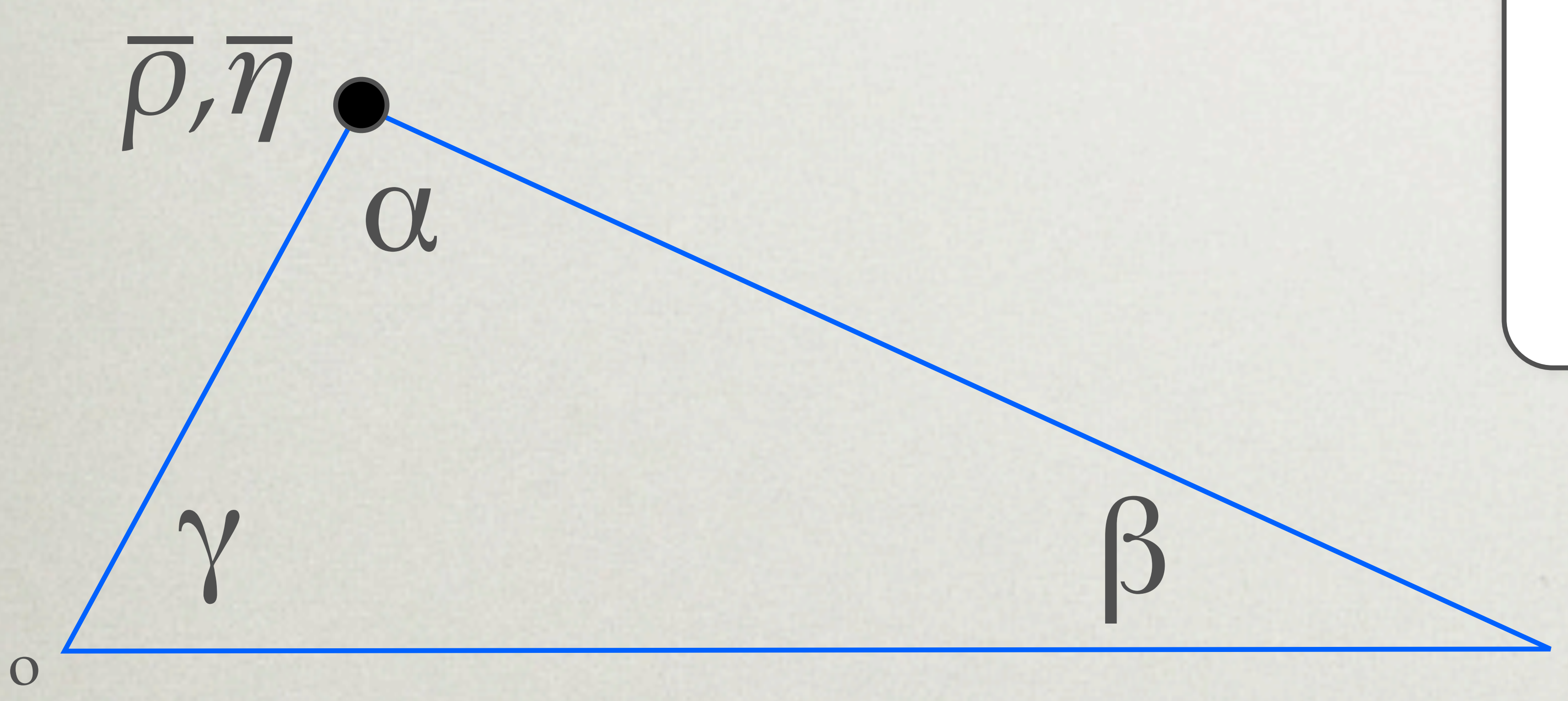


charm decays

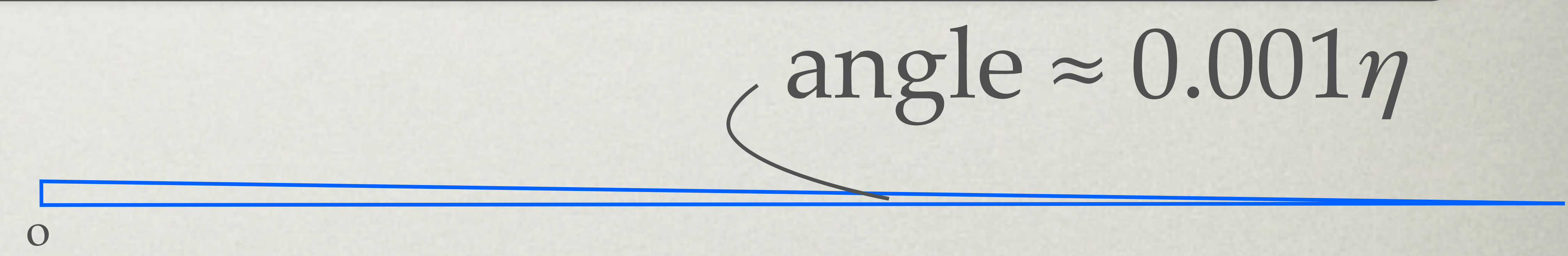
Quark couplings to the weak current

$$
V_{CKM} = \begin{array}{c} \\ u \\ c \\ t \end{array}
\begin{array}{c}
\begin{array}{ccc} d & s & b \end{array} \\
\begin{pmatrix}
1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta + \frac{i}{2}\eta\lambda^2) \\
-\lambda & 1-\frac{1}{2}\lambda^2 - i\eta A^2\lambda^4 & A\lambda^2(1+i\eta\lambda^2) \\
A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1
\end{pmatrix}
\end{array} + \mathcal{O}(\lambda^6)
$$

- Complementary probes of the CKM prescription:
  - Are the triangles closed?
    - *relates directly to the unitarity of the matrix.*
  - Do the have the same area?
    - *does the charm triangle have any area?*
- High statistics are needed to probe further



primarily B_u , B_d decays



charm decays

LHCb

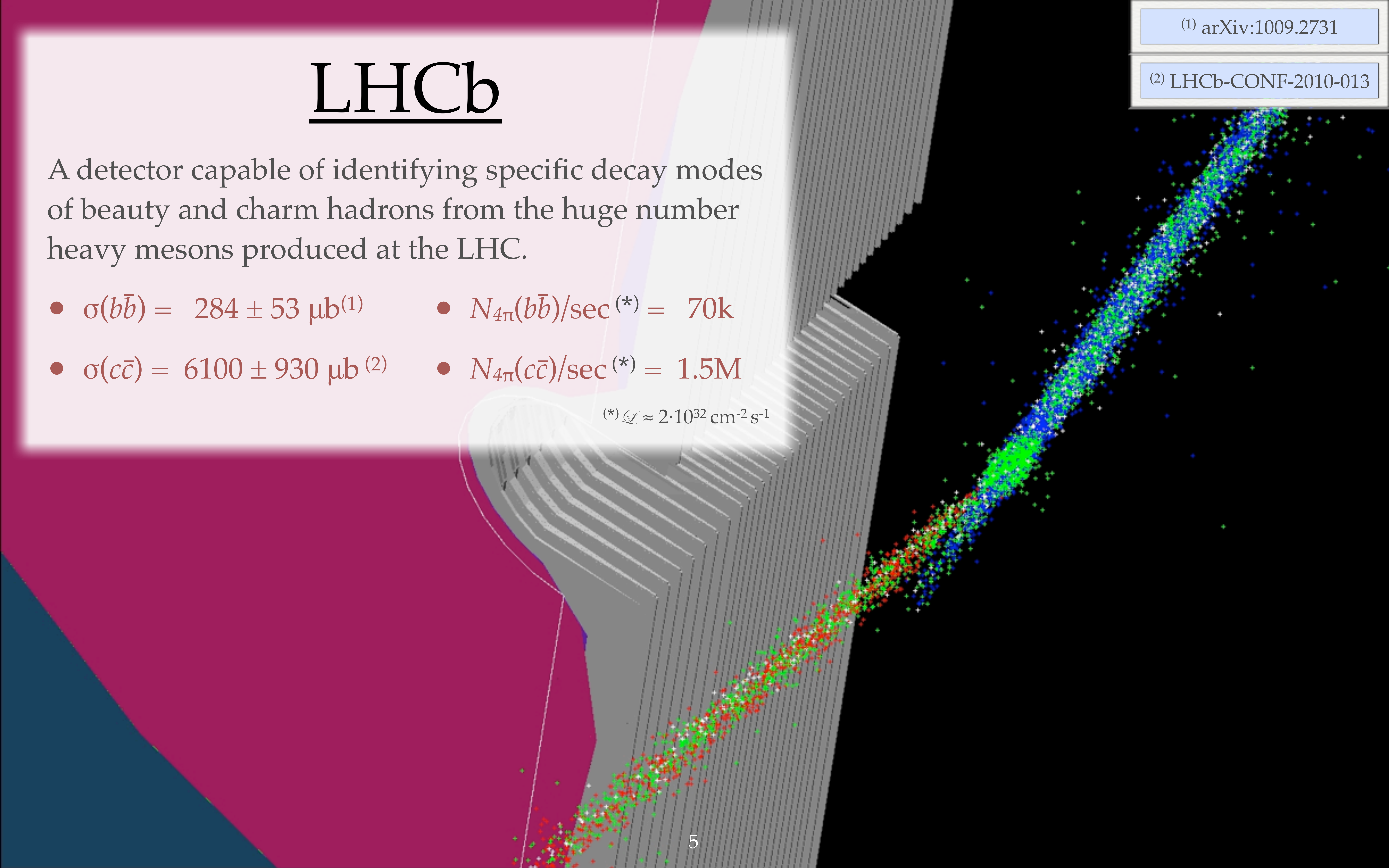
A detector capable of identifying specific decay modes of beauty and charm hadrons from the huge number heavy mesons produced at the LHC.

- $\sigma(b\bar{b}) = 284 \pm 53\ \mu b$ [1]
- $\sigma(c\bar{c}) = 6100 \pm 930\ \mu b$ [2]
- $N_{4\pi}(b\bar{b})/\mathrm{sec}^{(*)} = 70\mathrm{k}$
- $N_{4\pi}(c\bar{c})/\mathrm{sec}^{(*)} = 1.5\mathrm{M}$

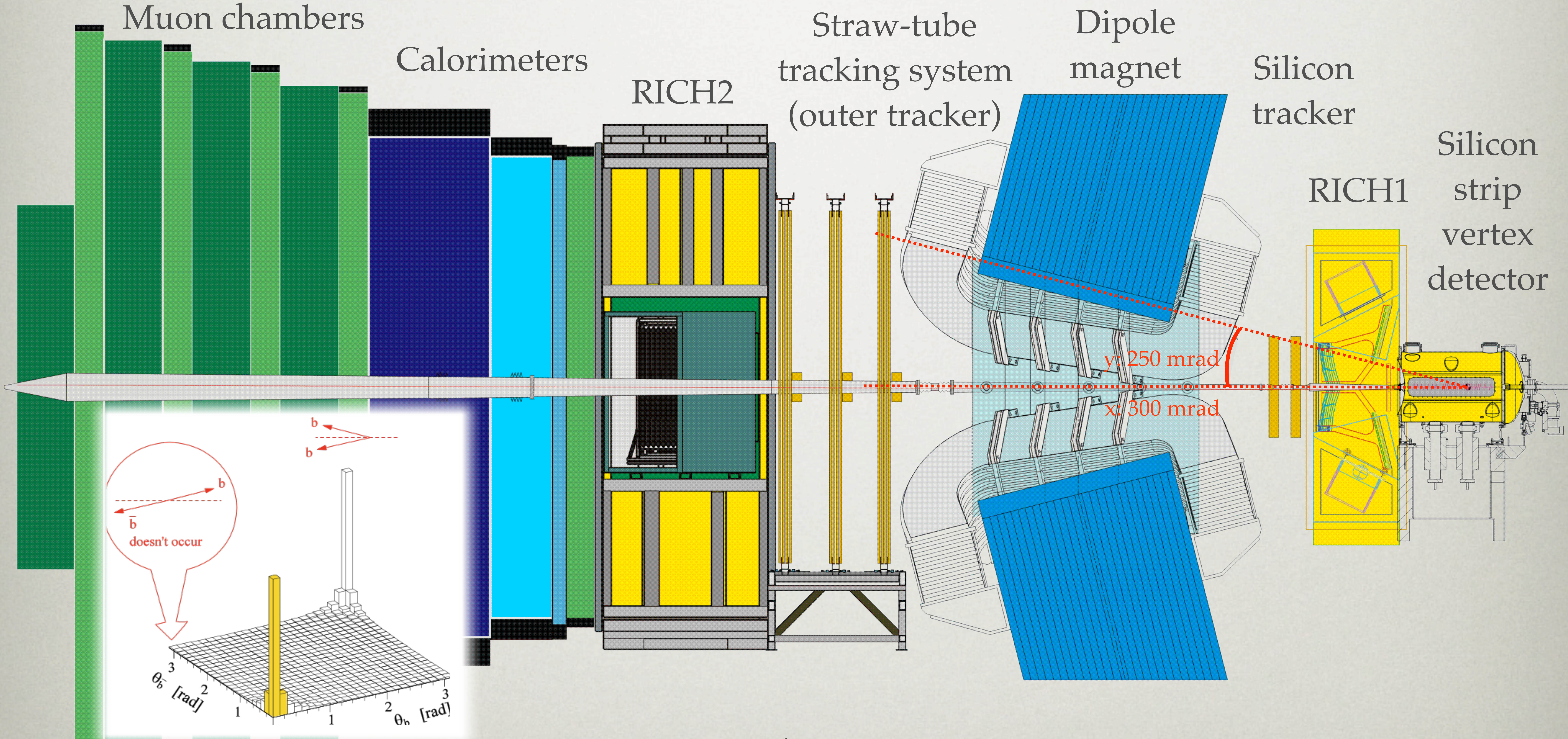
(*) $\mathscr{L} \approx 2\cdot10^{32}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

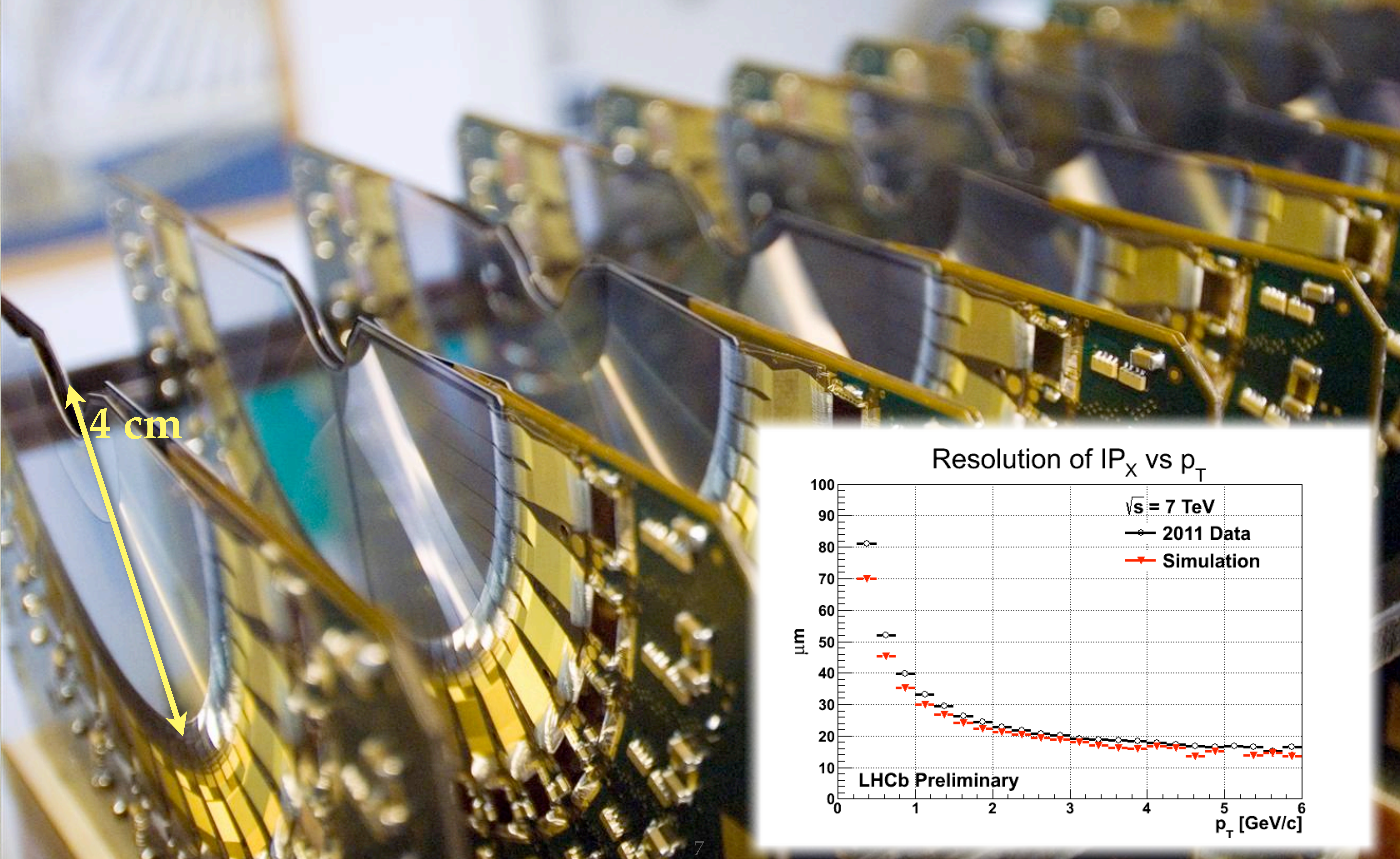
(1) arXiv:1009.2731

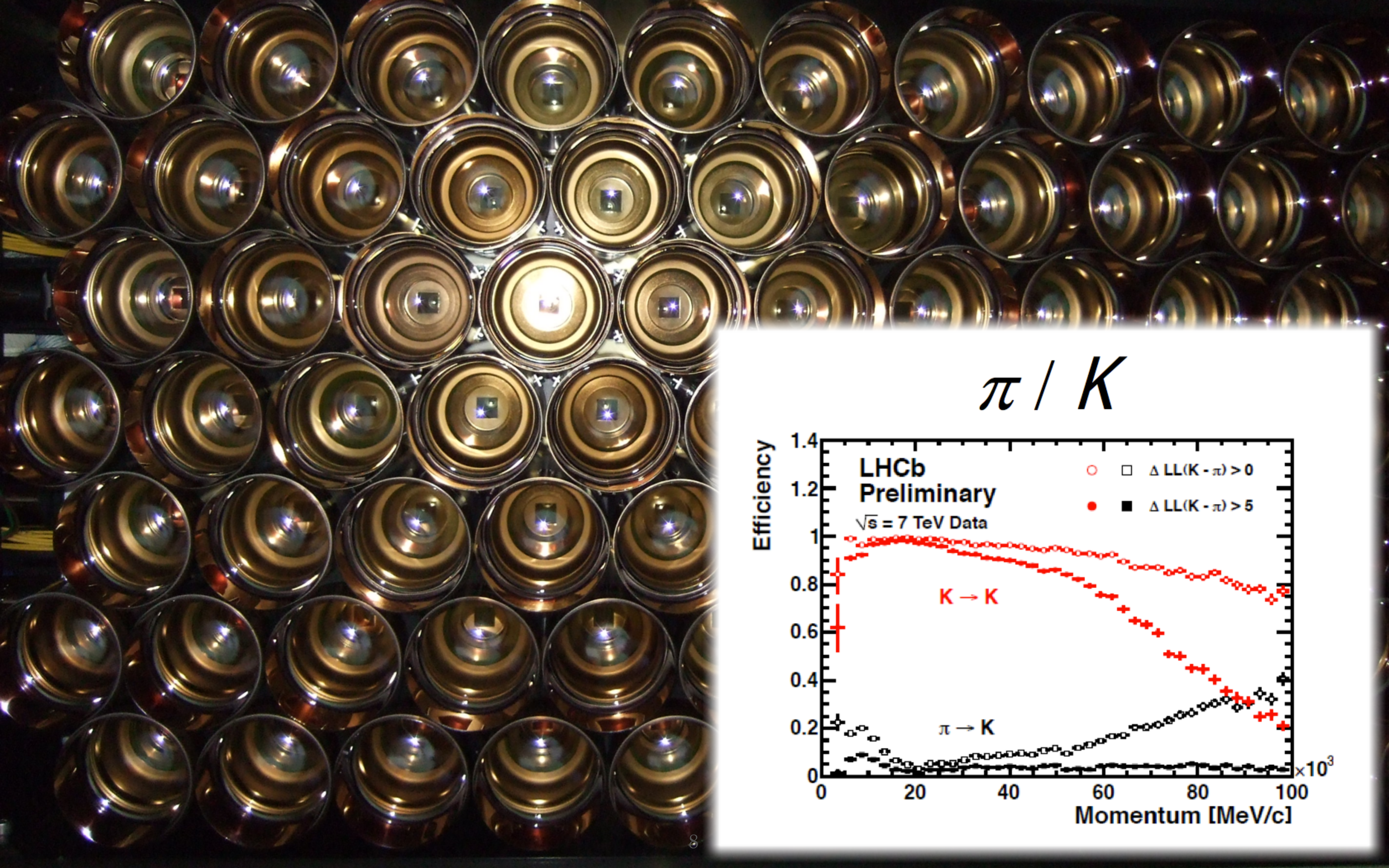
(2) LHCb-CONF-2010-013

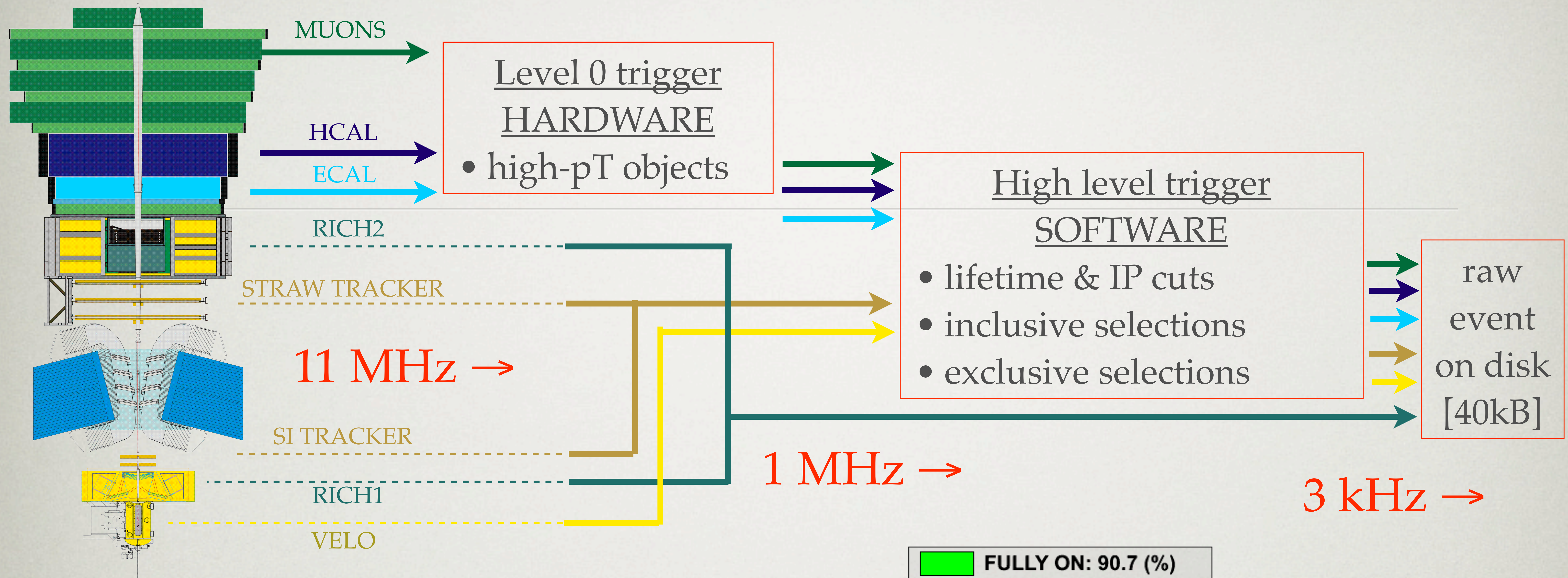


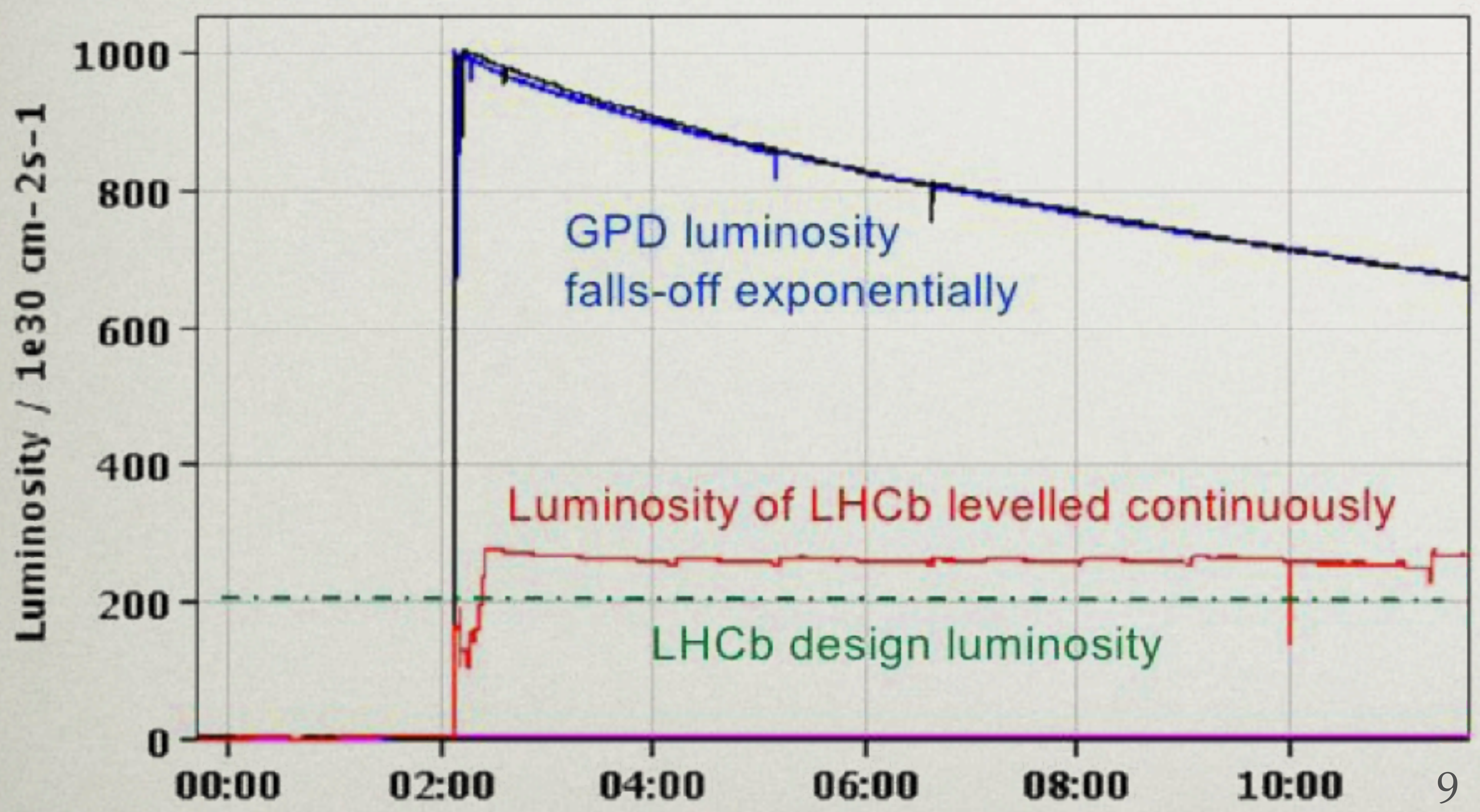
LHCb instruments $2<\eta_{LHC}<5$

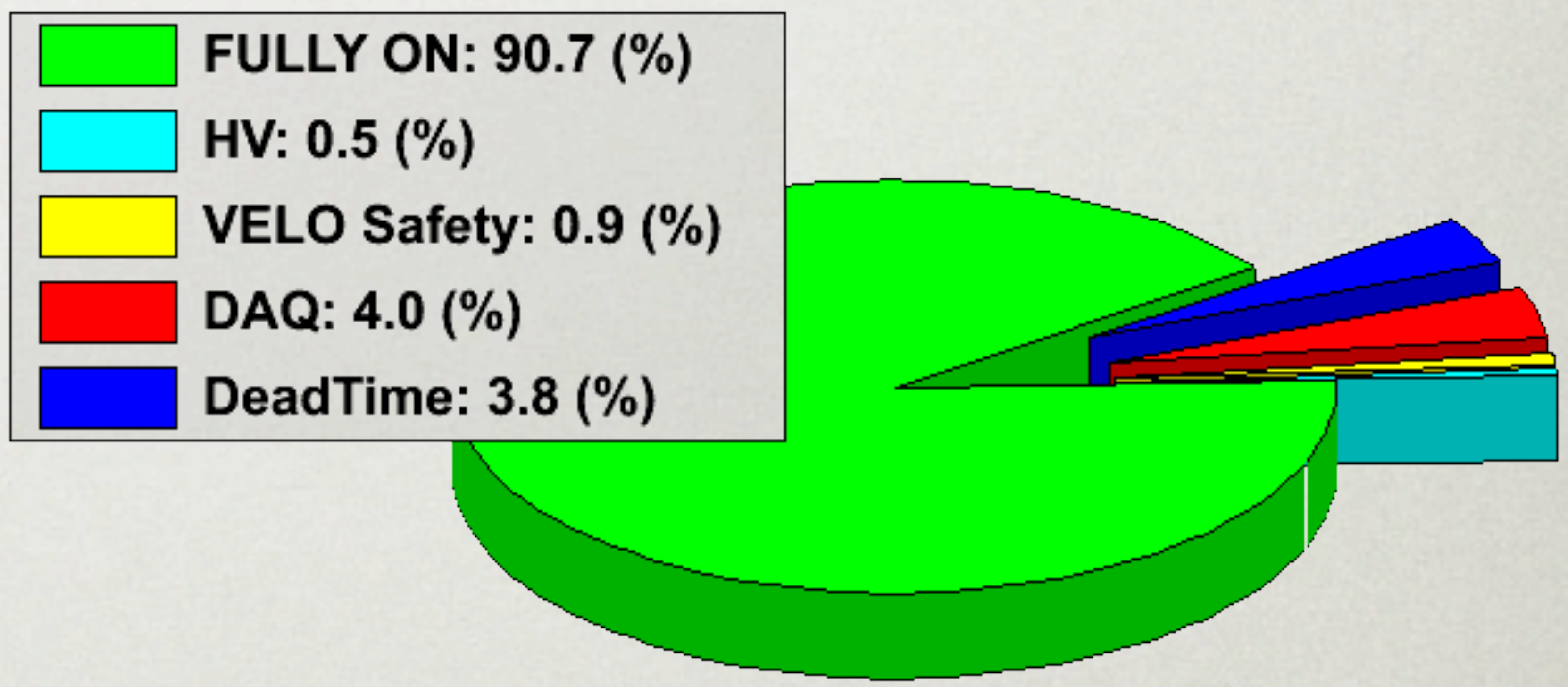



4 cm
Resolution of IPX vs pT
√s = 7 TeV
2011 Data
Simulation
LHCb Preliminary
μm
pT [GeV/c]
0
10
20
30
40
50
60
70
80
90
100
1
2
3
4
5
6


π / K
LHCb
Preliminary
√s = 7 TeV Data
Δ LL(K - π) > 0
Δ LL(K - π) > 5
Efficiency
1.4
1.2
1
0.8
0.6
0.4
0.2
0
K → K
π → K
0
20
40
60
80
100
×10^3
Momentum [MeV/c]





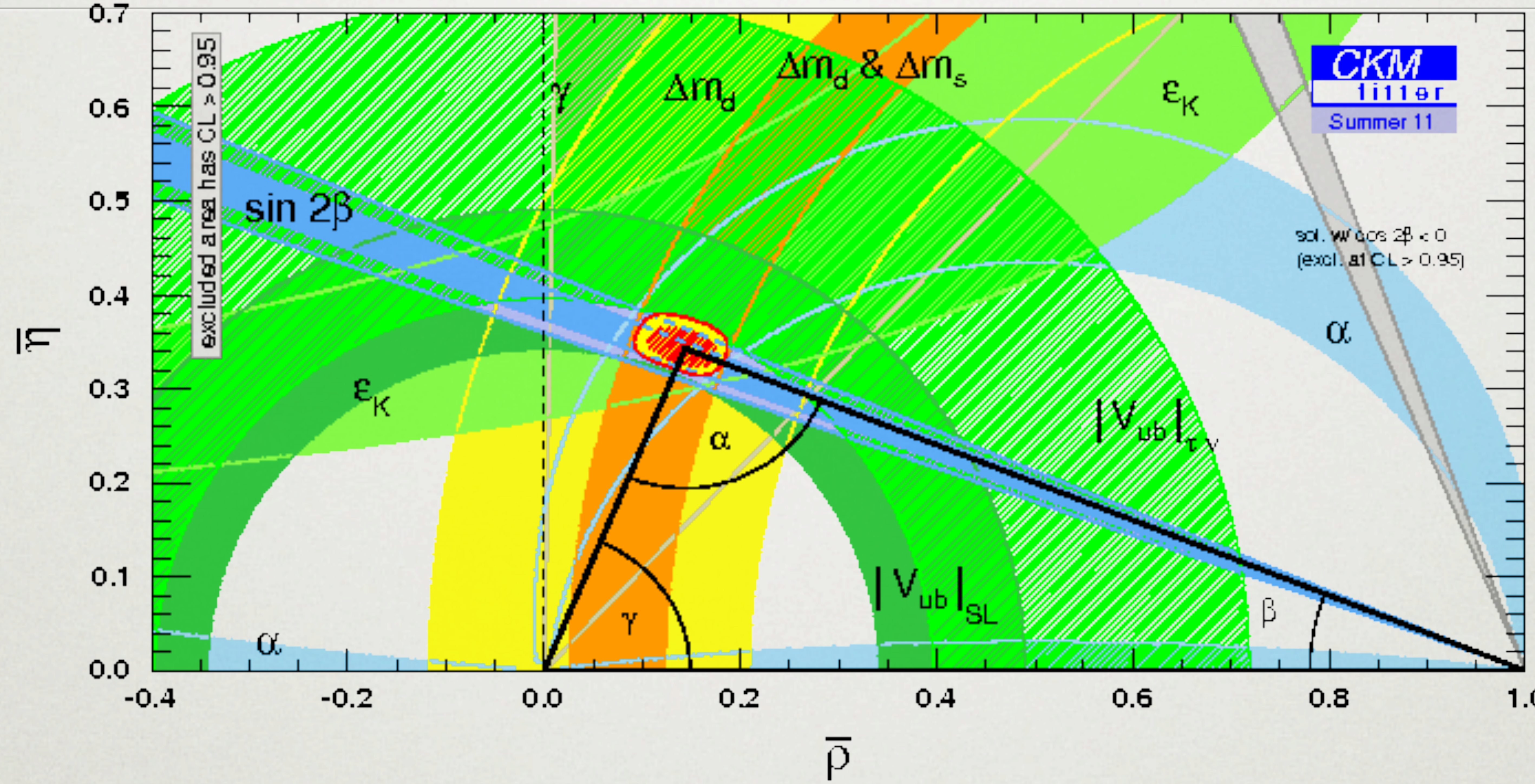


- 2010 dataset ≈ 37 pb^{-1}
- 2011 “summer” dataset ≈ 350 pb^{-1}
- 2011 final dataset > 1 fb^{-1}

CKM angles

CKM angles: the story so far

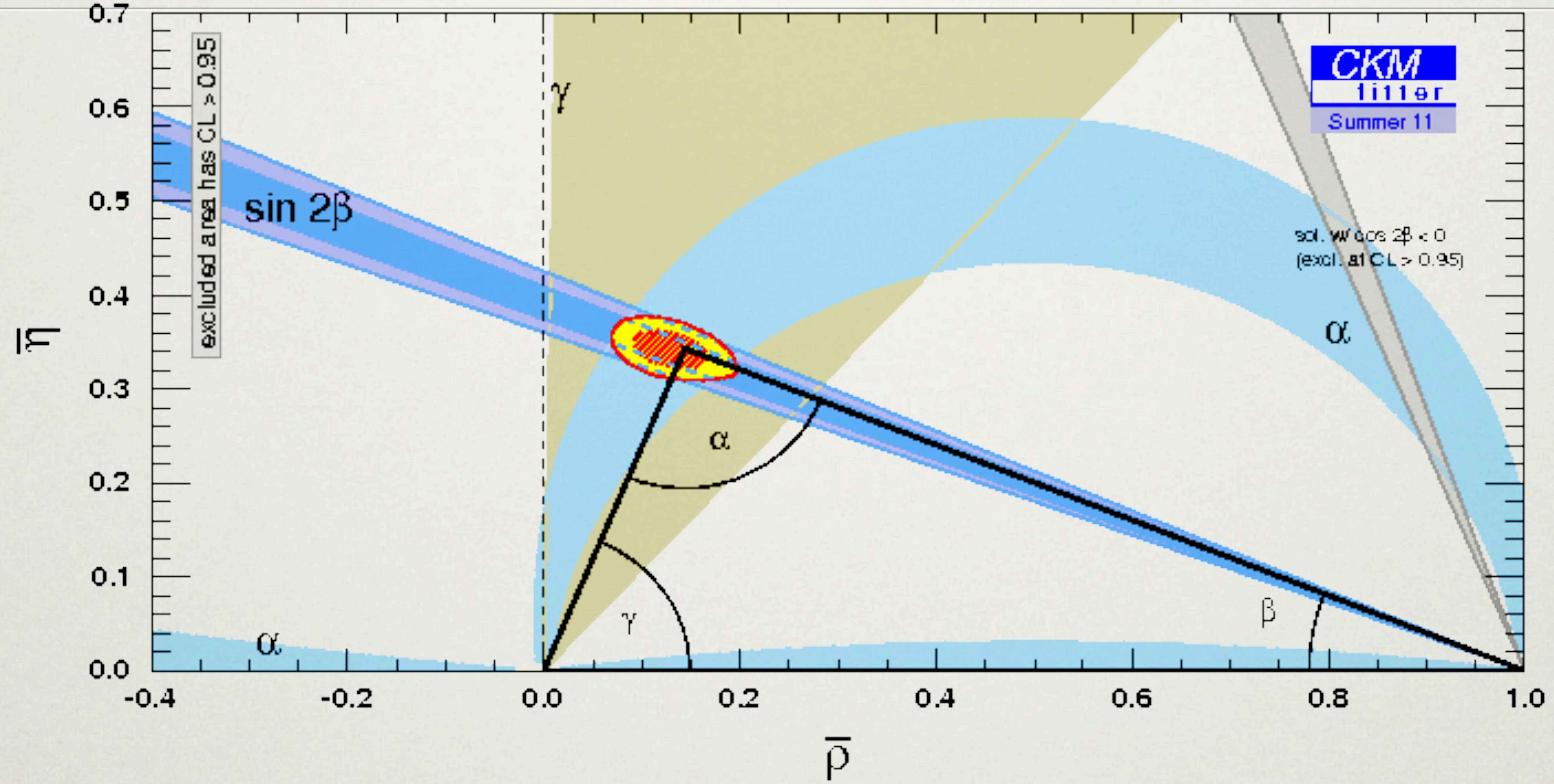
(courtesy of CKMFitter)



- Large CP violation is seen in B decays. A decade of excellence from the B-factories.

CKM angles: the story so far

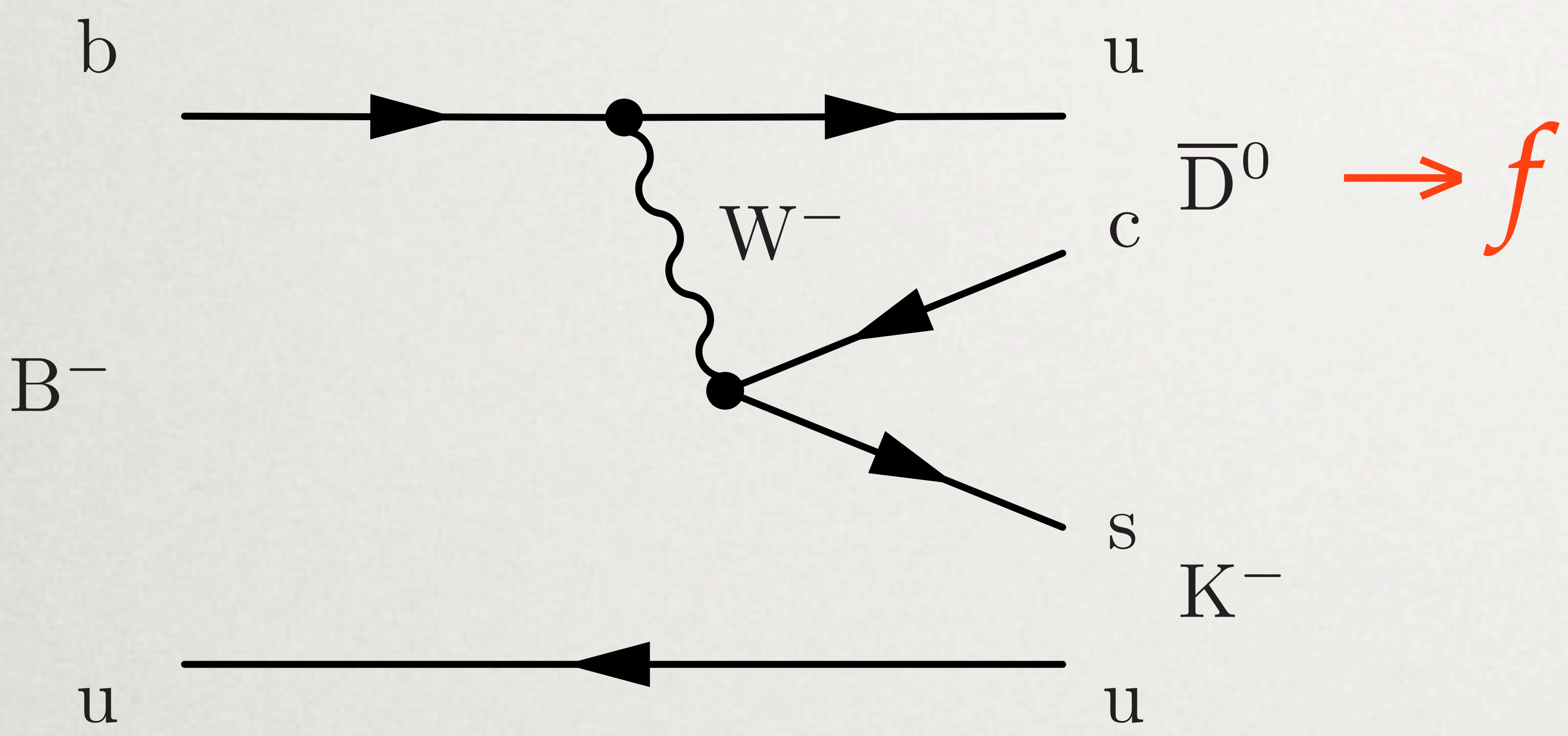
(courtesy of CKMFitter)

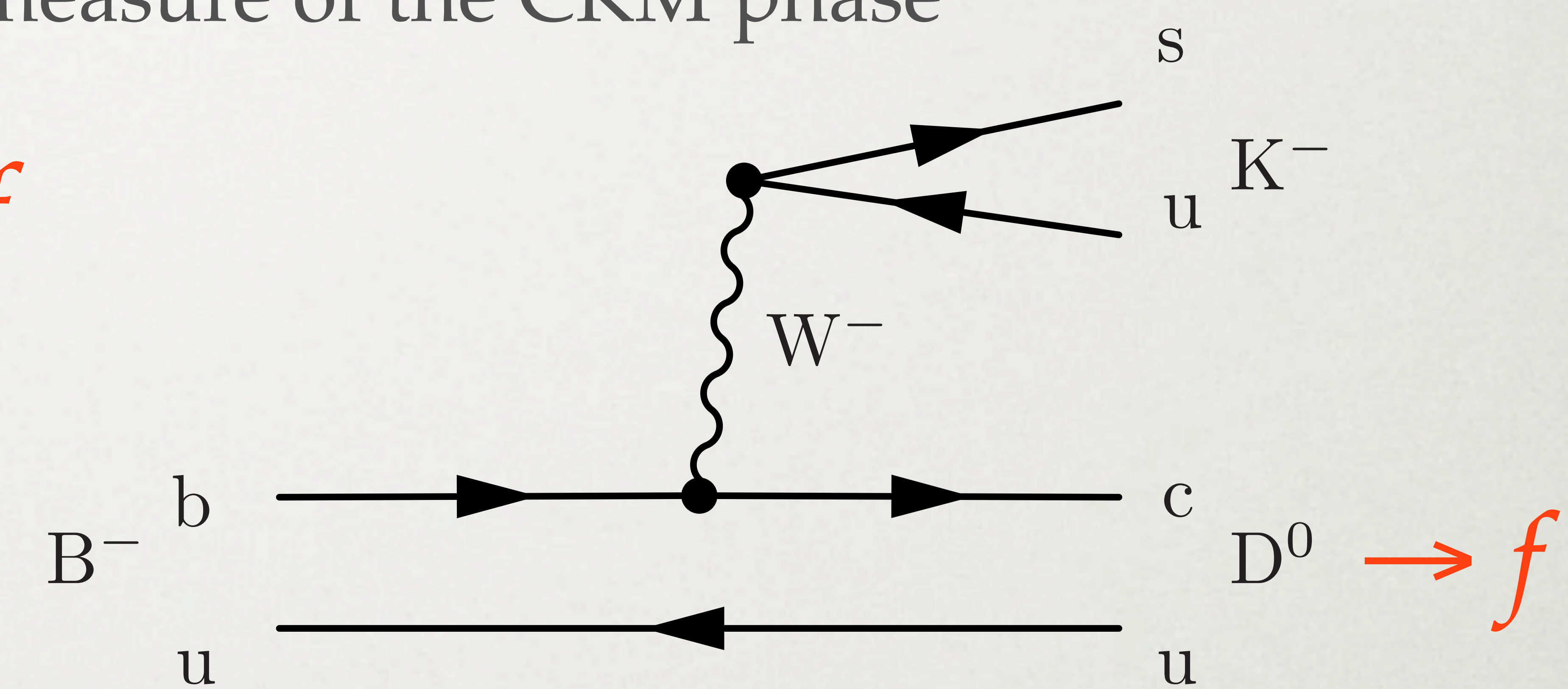


- Large CP violation is seen in B decays. A decade of excellence from the B-factories.
  - $\beta = 21.38^{+0.79}_{-0.77}$ primarily from studying *CP* violation in $B \rightarrow J/\psi K_S{}^0$
  - α is also well measured: $89.0^{+4.4}_{-4.2}$
  - γ not well known; due to the rarity of the modes which are sensitive: *amplitude* $\propto V_{ub}$

γ_{CKM}

- Tree-level (no penguin, theoretically clean) measure of the CKM phase





where f can be:

CP eigenstate
- K^+K^-, $\pi^+\pi^-$

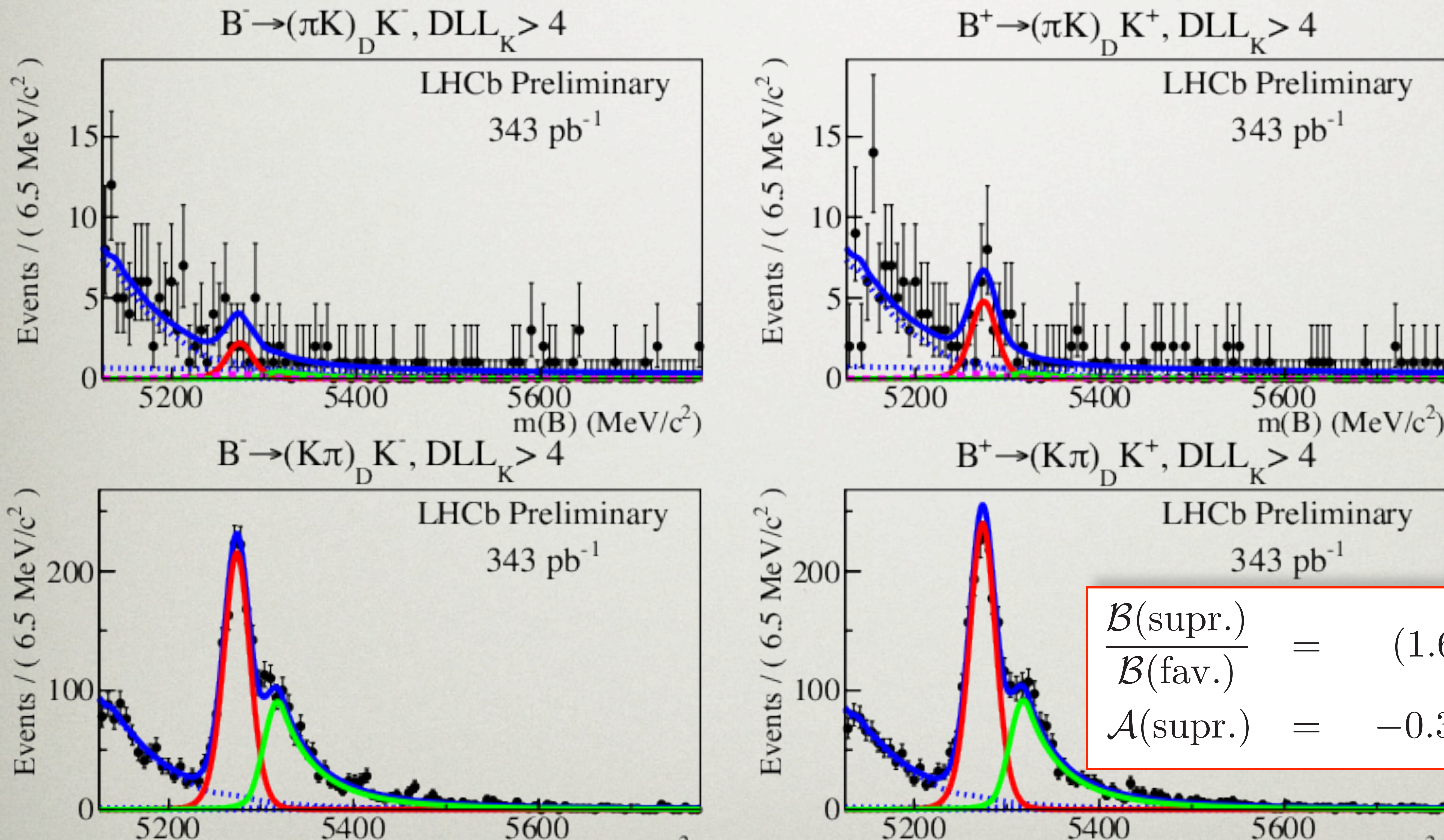
DCS D-decay mode
- $K^+\pi^-$, $K^+\pi^-\pi^+\pi^-$, $K^+\pi^-\pi^0$

SCS multi-body state
- $K_S\,\pi^+\pi^-$, $K_S\,K^+K^-$, $K^+K^-\pi^+\pi^-$

- Sensitivity to γ stems from interference between $b\rightarrow u$ and $b\rightarrow c$ transitions
- Small branching fraction but large asymmetries are possible.
- Many modes to be exploited
- Precision of less than 5° expected by end 2012

$B^+ \to (\pi^+ K^-)_D K^+$

- Leading mode for the extraction of γ
  - 4 σ excess observed in 350 pb^{-1} .



$B \to DK$

$B \to D\pi$

$$\frac{\mathcal{B}(\text{supr.})}{\mathcal{B}(\text{fav.})} = (1.66 \pm 0.39 \pm 0.24) \times 10^{-2}$$

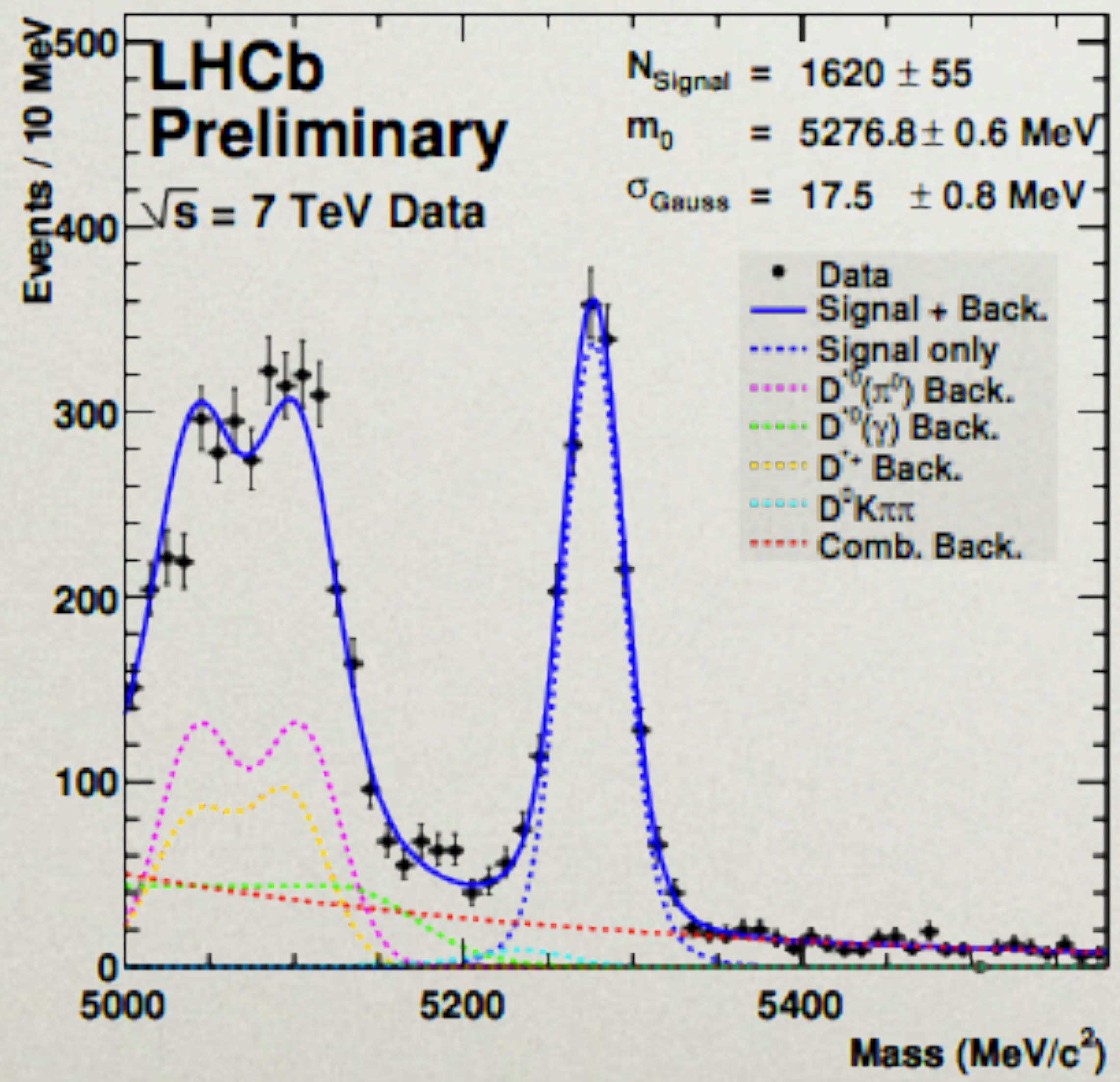
$$\mathcal{A}(\text{supr.}) = -0.39 \pm 0.17 \pm 0.02$$

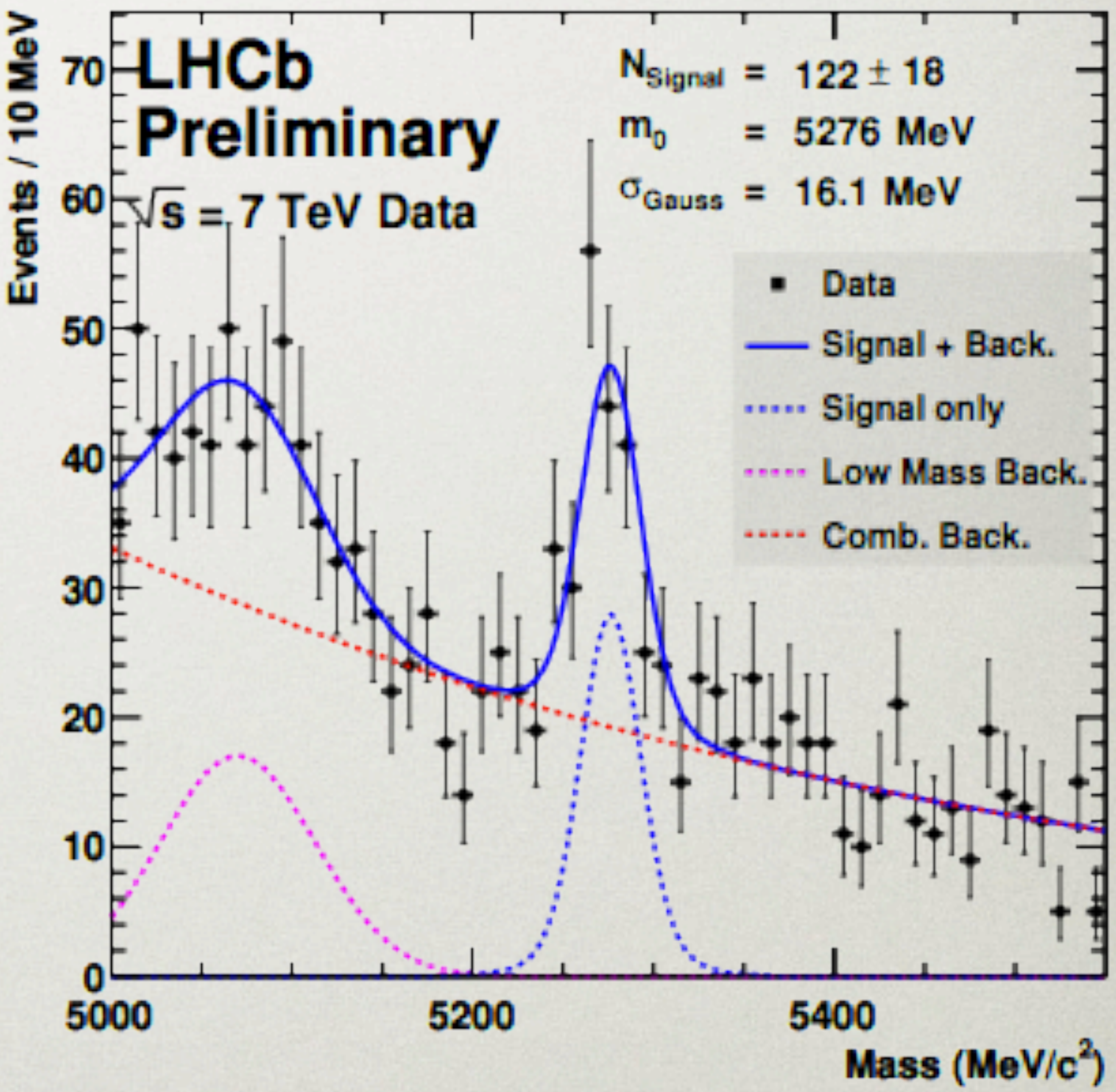
B→Dπππ and B→DKππ decays

- First observation of the Cabibbo-suppressed, five-track final states
  - The Cabibbo-suppressed decays hold similar promise for γ as B → DK (but ¼ statistics)

$$\frac{\mathcal{B}(B^- \to D^0 K^- \pi^+ \pi^-)}{\mathcal{B}(B^- \to D^0 \pi^- \pi^+ \pi^-)} = (9.6 \pm 1.5(\text{stat}) \pm 0.8(\text{syst})) \times 10^{-2}$$

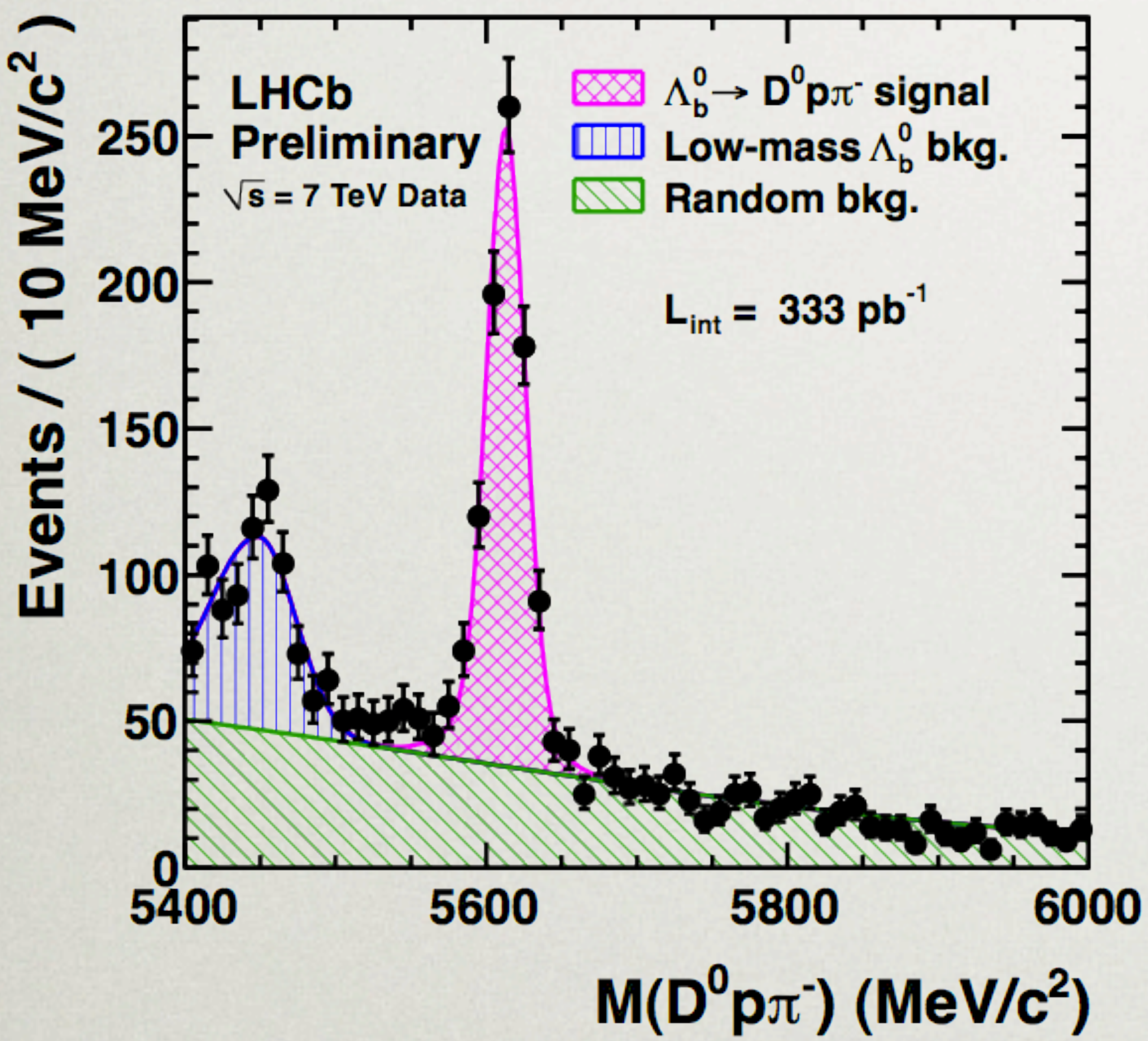
$$\frac{\mathcal{B}(B^- \to D^0 \pi^- \pi^+ \pi^-)}{\mathcal{B}(B^- \to D^0 \pi^-)} = 1.26 \pm 0.07(\text{stat}) \pm 0.12(\text{syst})$$

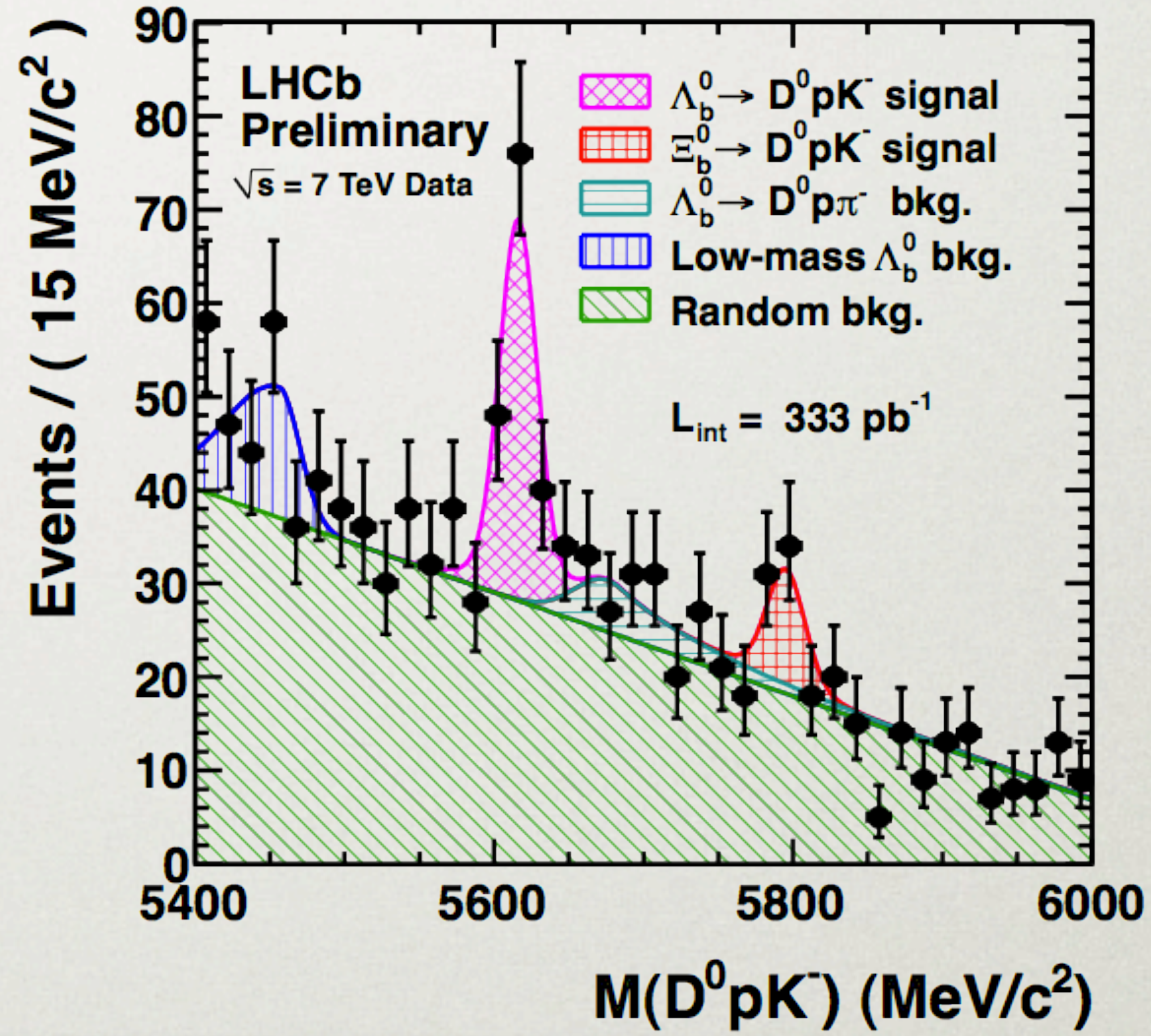




$\Lambda_b \to D^0 pK$

- These baryon decays exhibit similar quark-level interference and eventual sensitivity to γ
    - First step taken: observation of the 'favoured', Cabibbo-suppressed transition *(right)*

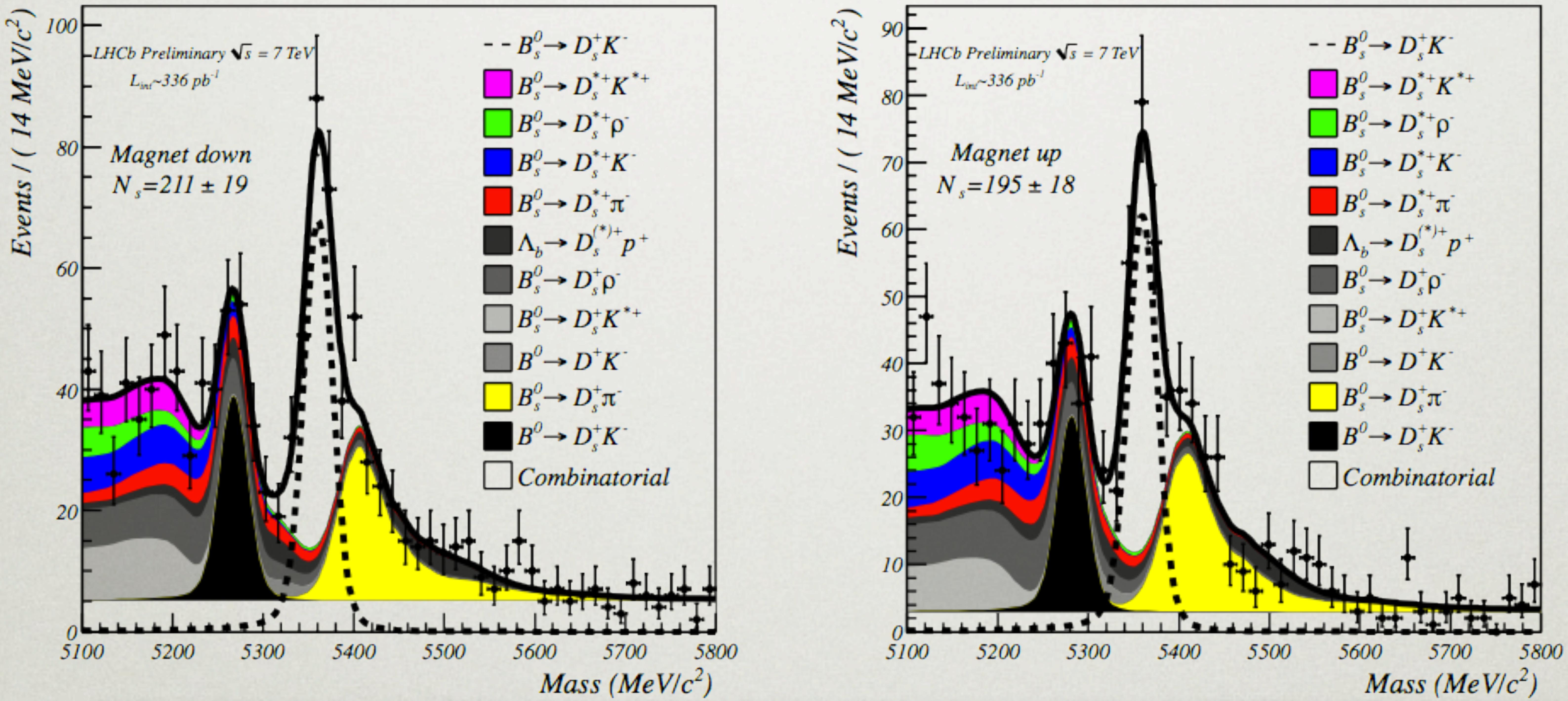




$$R_{D^0pK^-} = \frac{\mathcal{B}(\Lambda_b^0 \to D^0pK^-)}{\mathcal{B}(\Lambda_b^0 \to D^0p\pi^-)} = 0.112 \pm 0.019\,^{+0.011}_{-0.014}$$

$B_s \rightarrow D_s K^{\pm}$

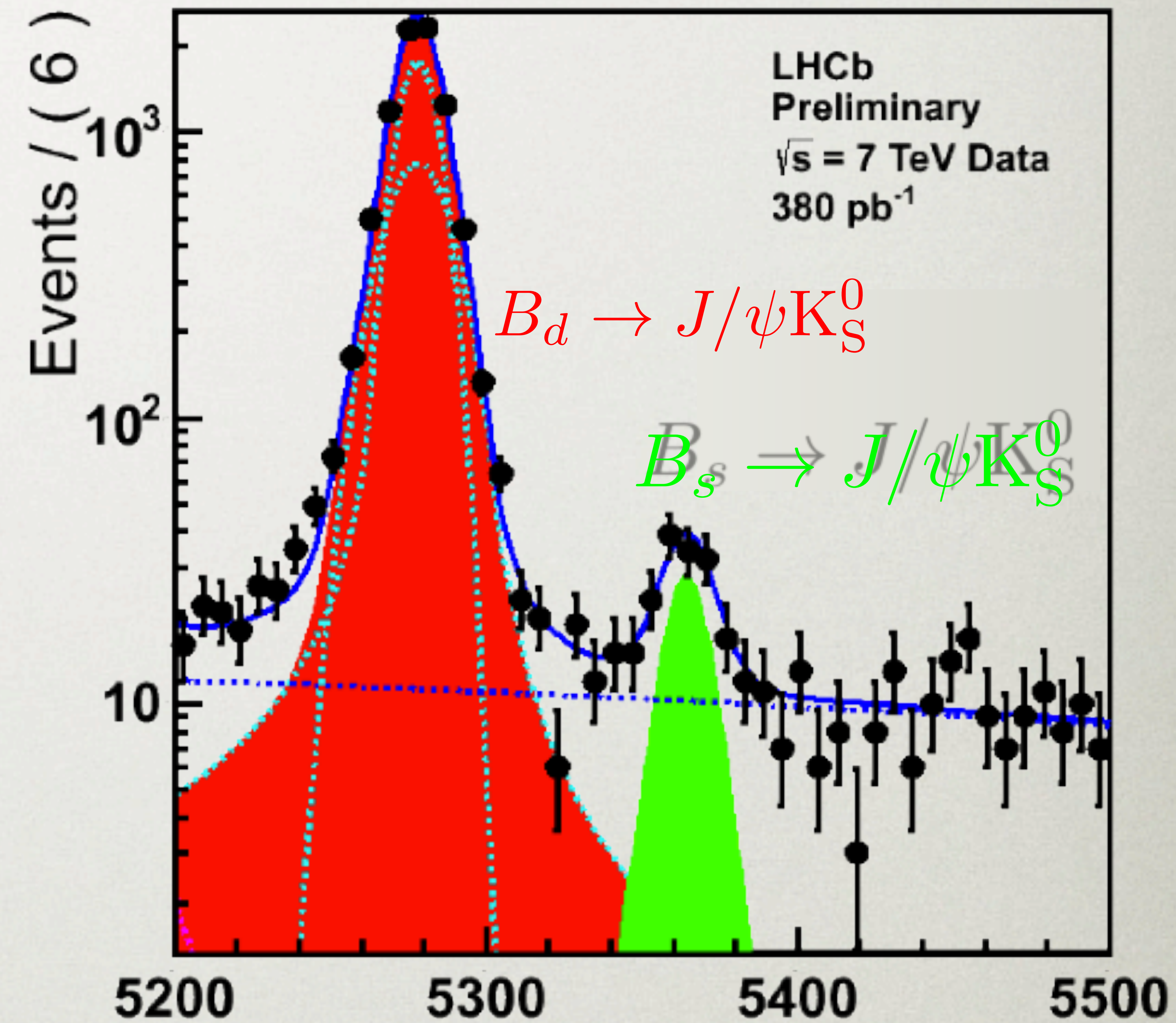
- γ can be extracted B_s decays with this mode
  - Both $b \rightarrow c$ and $b \rightarrow u$ diagrams are colour allowed
  - But the B_s oscillates so a time dependant analysis is required (also need B_s mixing phase)

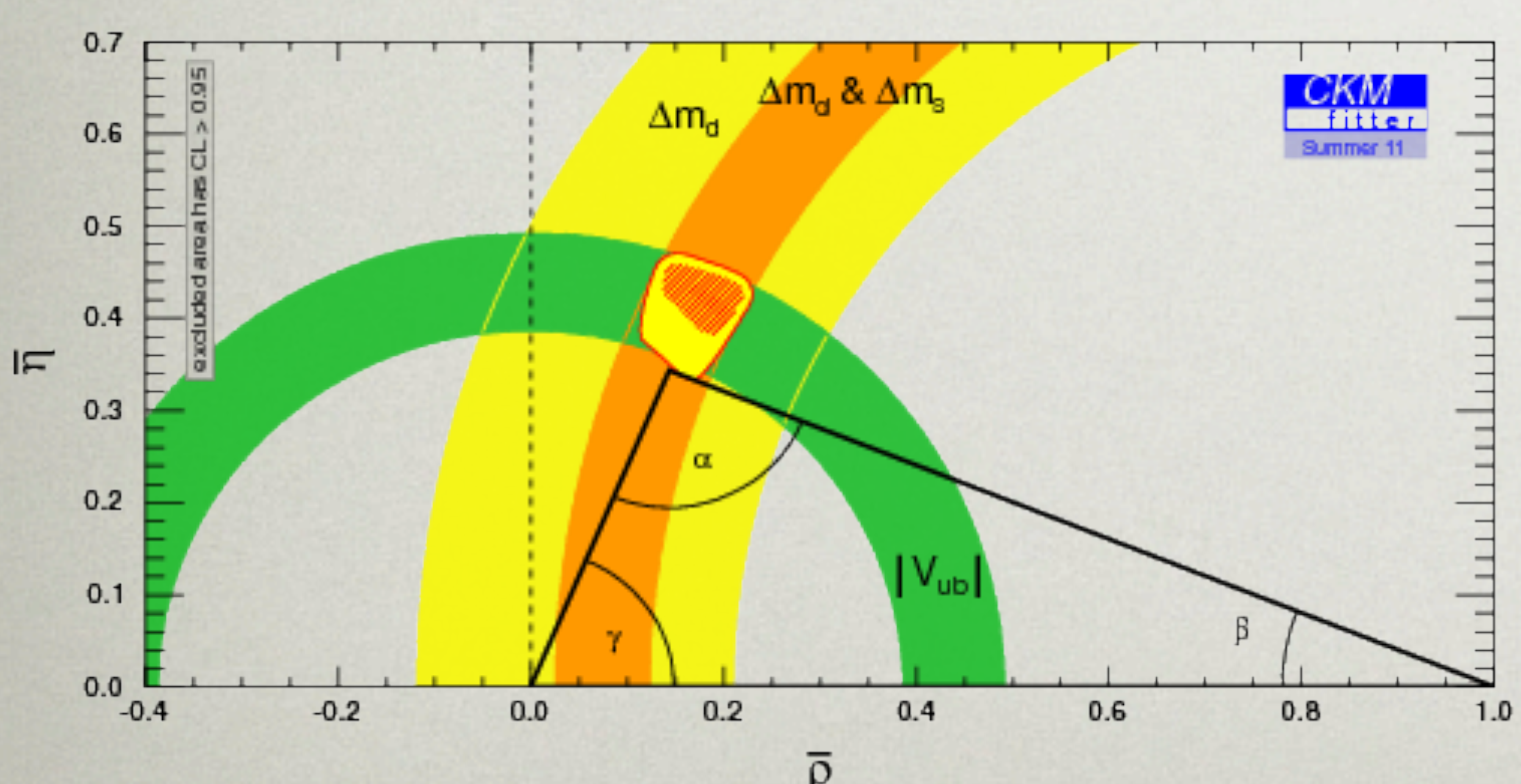


$$\mathcal{B}(B_s^0 \rightarrow D_s^{\mp} K^{\pm}) = (1.97 \pm 0.18\ (\text{stat.})\ ^{+0.19}_{-0.20}\ (\text{syst.})\ ^{+0.11}_{-0.10}\ (f_s/f_d)) \times 10^{-4}$$

Future of sin(2β): $B_s \to J/\psi K_S^0$

- The unitarity triangle shows some tension between $|V_{ub}|$ and sin(2β).
- How much of "sin(2β)" is sin(2β)? How large are the hadronic penguin contributions?
- Could be eventually deduced by comparing $B_d \to J/\psi K_S^0$ and its U-spin partner: $B_s \to J/\psi K_S^0$
  arXiv:1010.0089
- First step: confirmation in LHCb dataset.





$$\frac{\mathcal{B}(B_s \to J/\psi \mathrm{K_S^0})}{\mathcal{B}(B_d \to J\psi \mathrm{K_S^0})} = (3.78 \pm 0.58 \pm 0.20 \pm 0.30) \times 10^{-2}$$

CP violation in charm

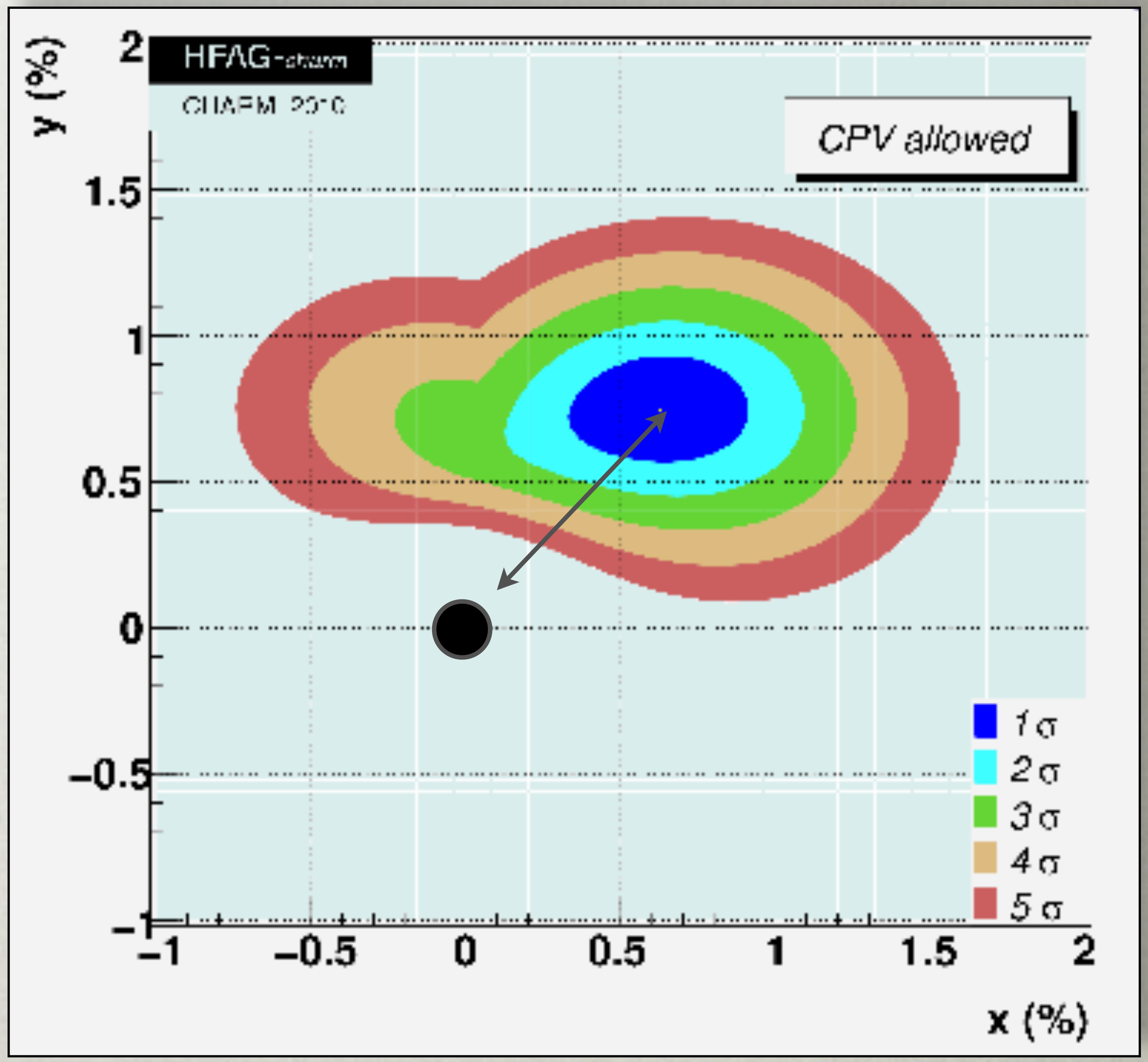
CP violation in charm

- Generically speaking, one can look for CP violation in:
  - Mixing: $\Gamma(\bar{D}^0 \to D^0) \neq \Gamma(D^0 \to \bar{D}^0)$ — "Indirect"
  - Decay: $A(D^0 \to f) \neq A(\bar{D}^0 \to f)$
  - Interference of the two — "Direct"
- Mixing is the D system is establish, though no single 5σ measurement

$$D_{1,2} = p|D^0\rangle \pm q|\bar{D}^0\rangle$$

$$x = (m_2 - m_1)/2\Gamma \qquad y = (\Gamma_2 - \Gamma_1)/2\Gamma$$

- No evidence yet of CP violation in the charm system

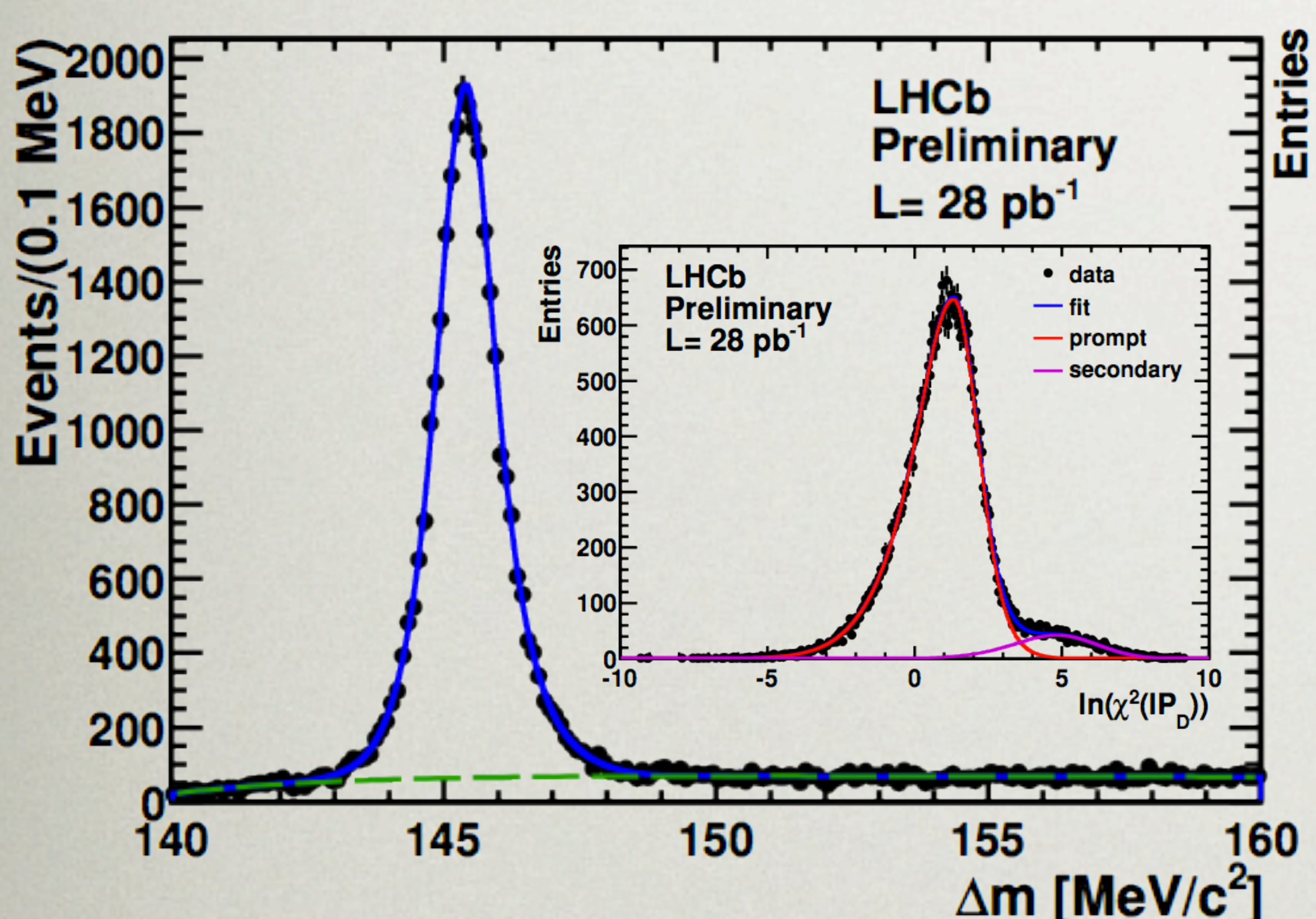


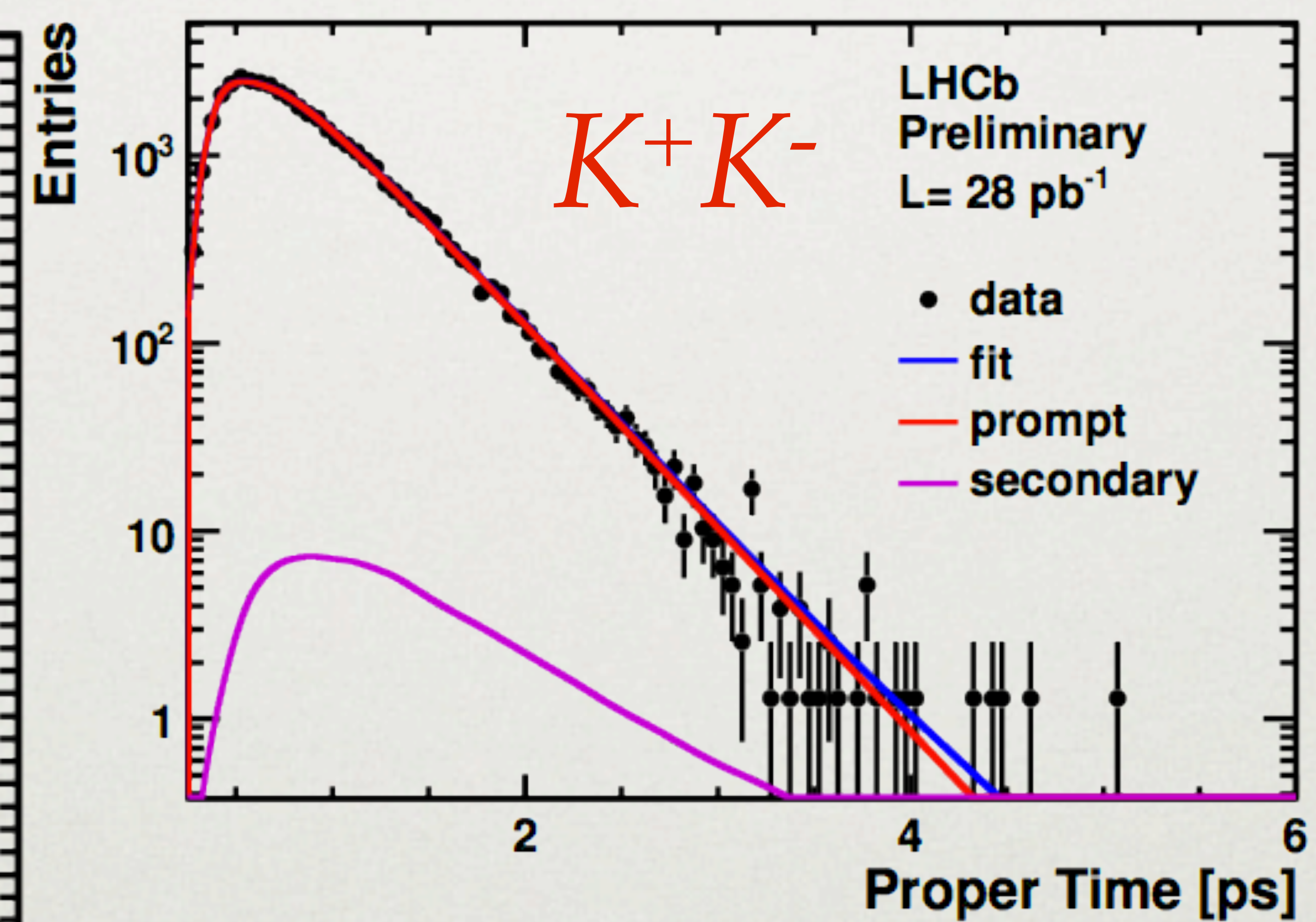
Pursuing CP violation in mixing

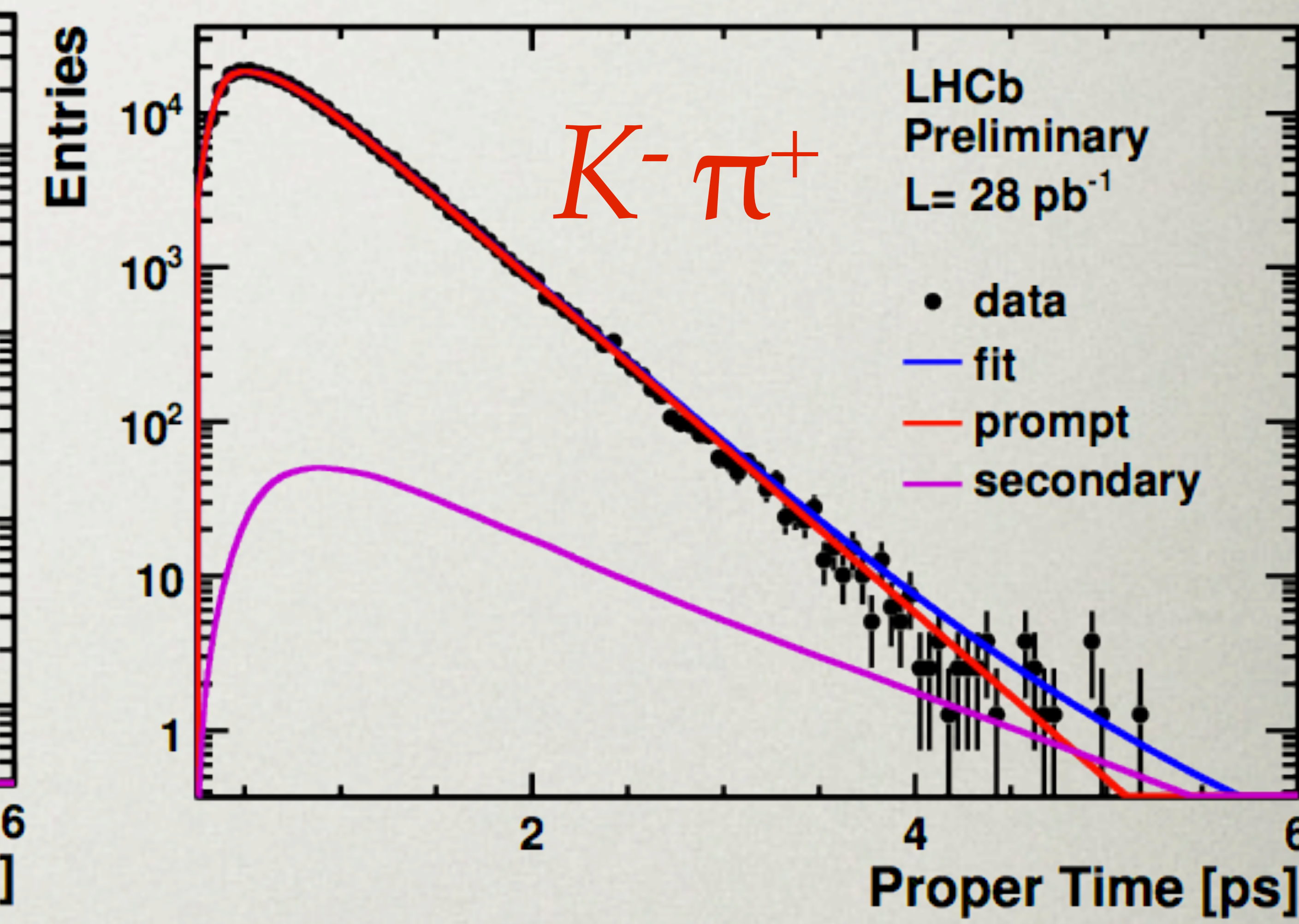
- Define

$$y_{CP} = \frac{\Gamma(D^0 \to K^+K^-)}{\Gamma(D^0 \to K^-\pi^+)} - 1$$

  - In the absence of CP violation, $y_{CP} = y$. Ultimately need both to demonstrate *CPV* in mixing







- With 28 pb^{-1}

$$y_{CP} = (5.5 \pm 6.3_{stat} \pm 4.1_{syst}) \times 10^{-3}.$$

$\mathrm{WA}_{\mathrm{HFAG}} = (1.11 \pm 0.22)\%$

Pursuing CP violation in mixing

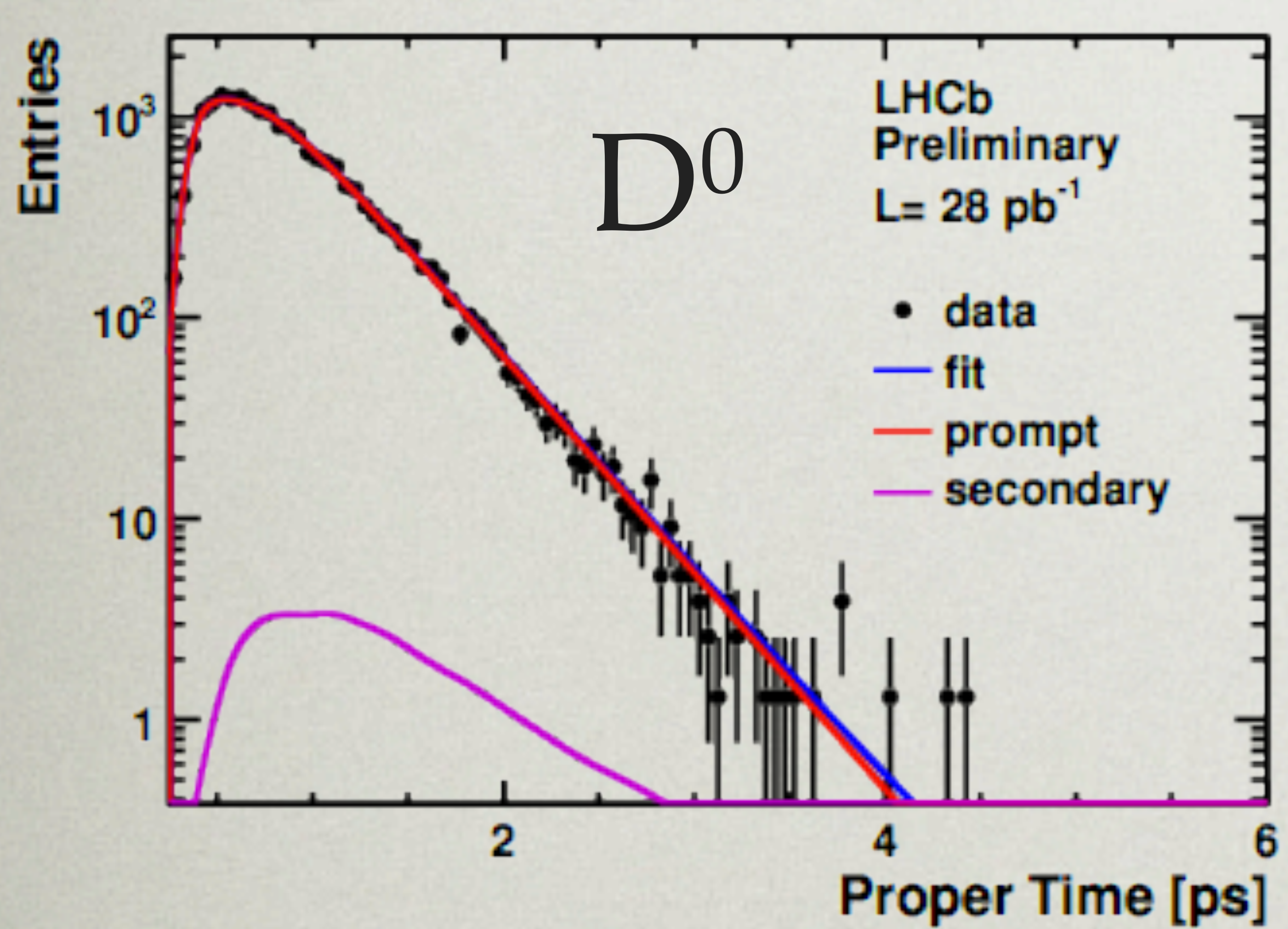
- Another interesting observable:

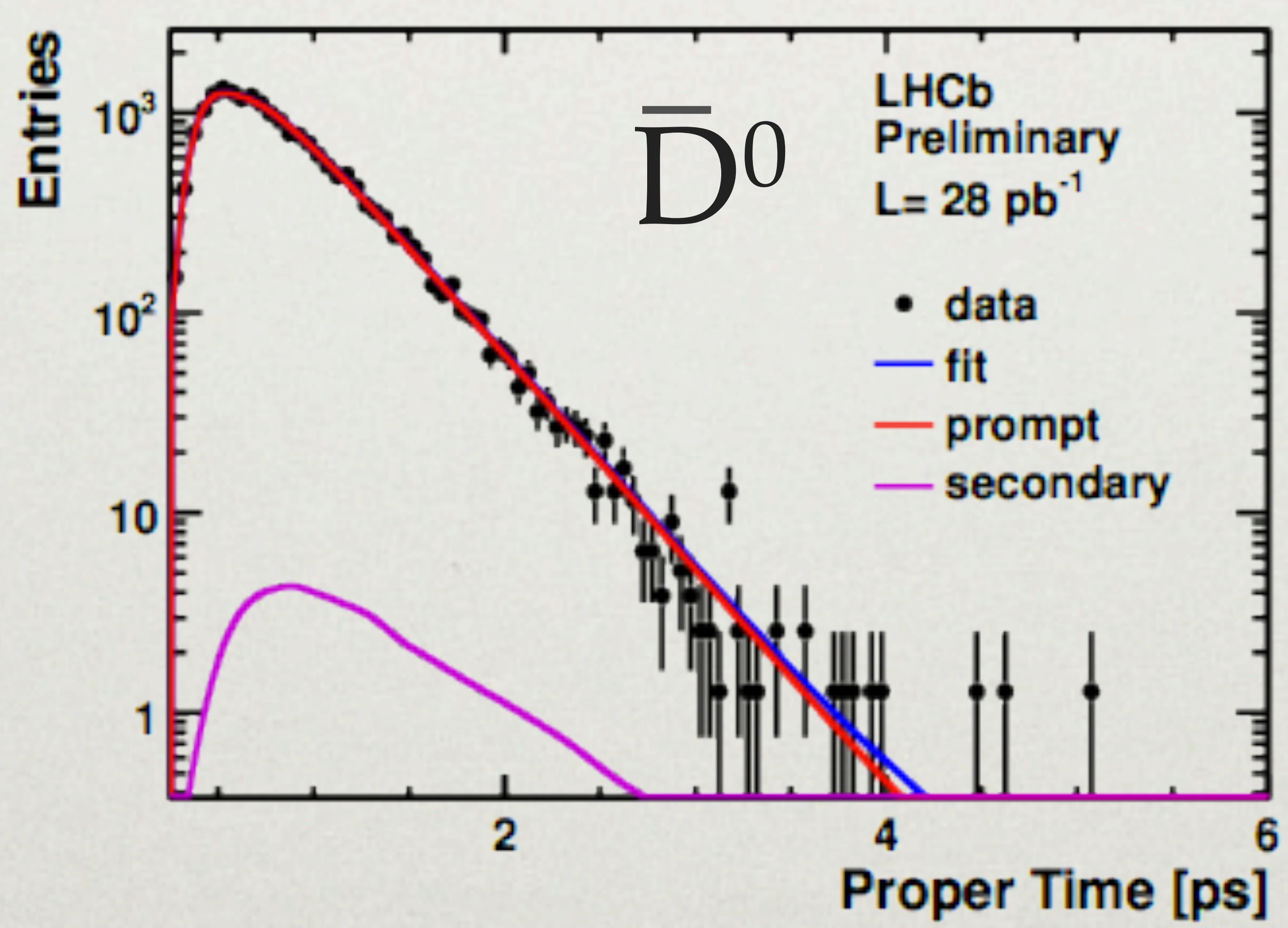
$$A_\Gamma = \frac{\Gamma(D^0 \to K^+K^-) - \Gamma(\bar{D}^0 \to K^+K^-)}{\Gamma(D^0 \to K^+K^-) + \Gamma(\bar{D}^0 \to K^+K^-)}$$

  - $A_\Gamma \neq 0$ would a clear sign of CP violation

- D* events used. Charge of slow pion tags the D flavour

- A "swimming" technique is used to estimate the trigger and acceptance lifetime bias





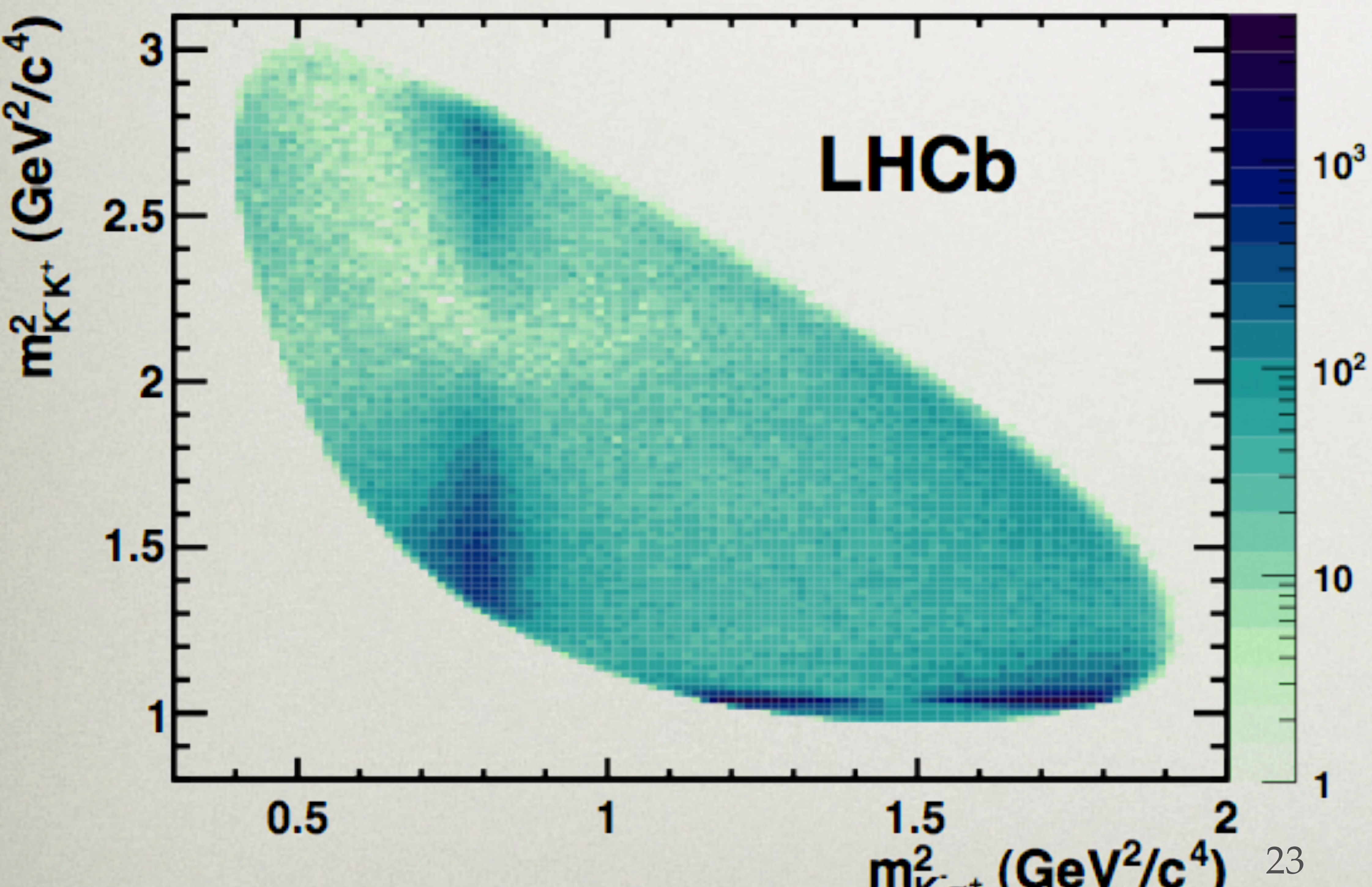
- With 2010 dataset, 28 pb^{-1}

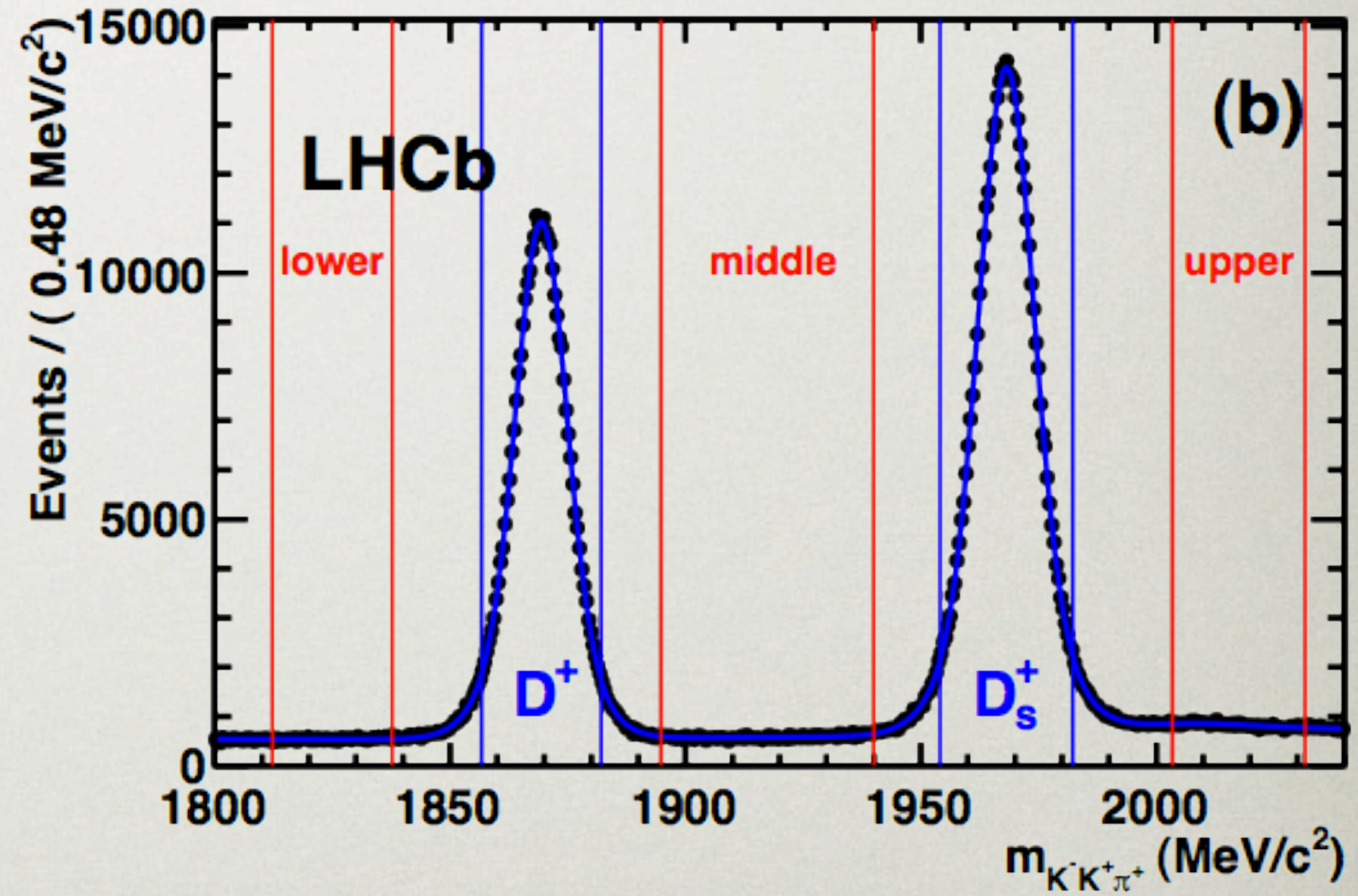
$$A_\Gamma = (-5.9 \pm 5.9_{\rm stat} \pm 2.1_{\rm syst}) \times 10^{-3}.$$

$WA_{HFAG} = (0.12 \pm 0.25)\%$

Direct CPV in charm

- $D^{\pm} \to K^{+}K^{-}\pi^{\pm}$ is a singly-Cabibbo suppressed where competing tree and penguin diagrams could be of similar magnitude.
    - Direct CPV is possible if two processes, with different weak and strong phases interfere
- $D_s \to K^{+}K^{-}\pi^{\pm}$ is used a a control channel (Cabibbo favoured). Blind signal.





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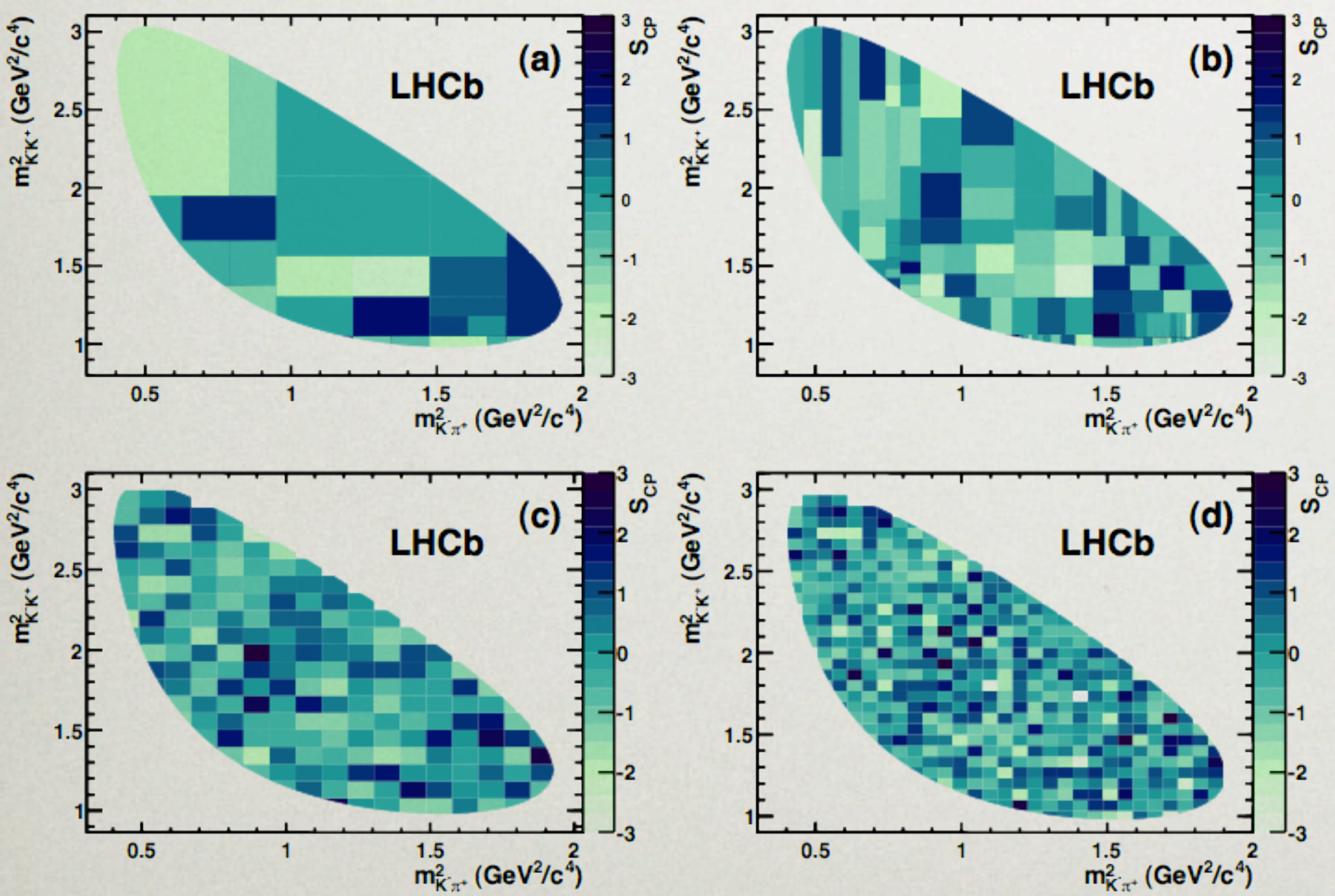

A range of binning schemes tried

Binning	Fitted mean	Fitted width	χ^2/ndf	p-value (%)
Adaptive I	0.01 ± 0.23	1.13 ± 0.16	32.0/24	12.7
Adaptive II	-0.024 ± 0.010	1.078 ± 0.074	123.4/105	10.6
Uniform I	-0.043 ± 0.073	0.929 ± 0.051	191.3/198	82.1
Uniform II	-0.039 ± 0.045	1.011 ± 0.034	519.5/529	60.5

Scatter consistent with random

No CPV observed with 2010 dataset

LHCb-CONF-2011-023

Direct CPV: ΔA_{CP}

- Another test of CP violation in charm:

$$\begin{aligned}\Delta A_{CP} &= A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) \\ &= A_{RAW}(D^* \to (K^+K^-)_D\pi_s) - A_{RAW}(D^* \to (\pi^+\pi^-)_D\pi_s)\end{aligned}$$

  - Experimentally, very robust. Nearly all systematics cancel (e.g. D* production)

- With 2010 dataset, 37 pb^{-1}

$$\Delta A_{CP} = (-0.28 \pm 0.70 \pm 0.25)\%$$

Null result

The 600 pb^{-1} update of this analysis is the last talk of today's session

- LHCb takes advantage of the unprecedented samples of heavy quark hadrons at the LHC

- There is considerable effort on CKM angle measurements, notably γ
    - Many complimentary modes in preparation

- Charm physics is providing as much excitement as the beauty program

- Most results here are on 37 pb^{-1}. Results using 1 fb^{-1} in preparation