Measurements of *CP* violation and mixing in Charm decays at LHCb

Olli Lupton on behalf of the LHCb collaboration

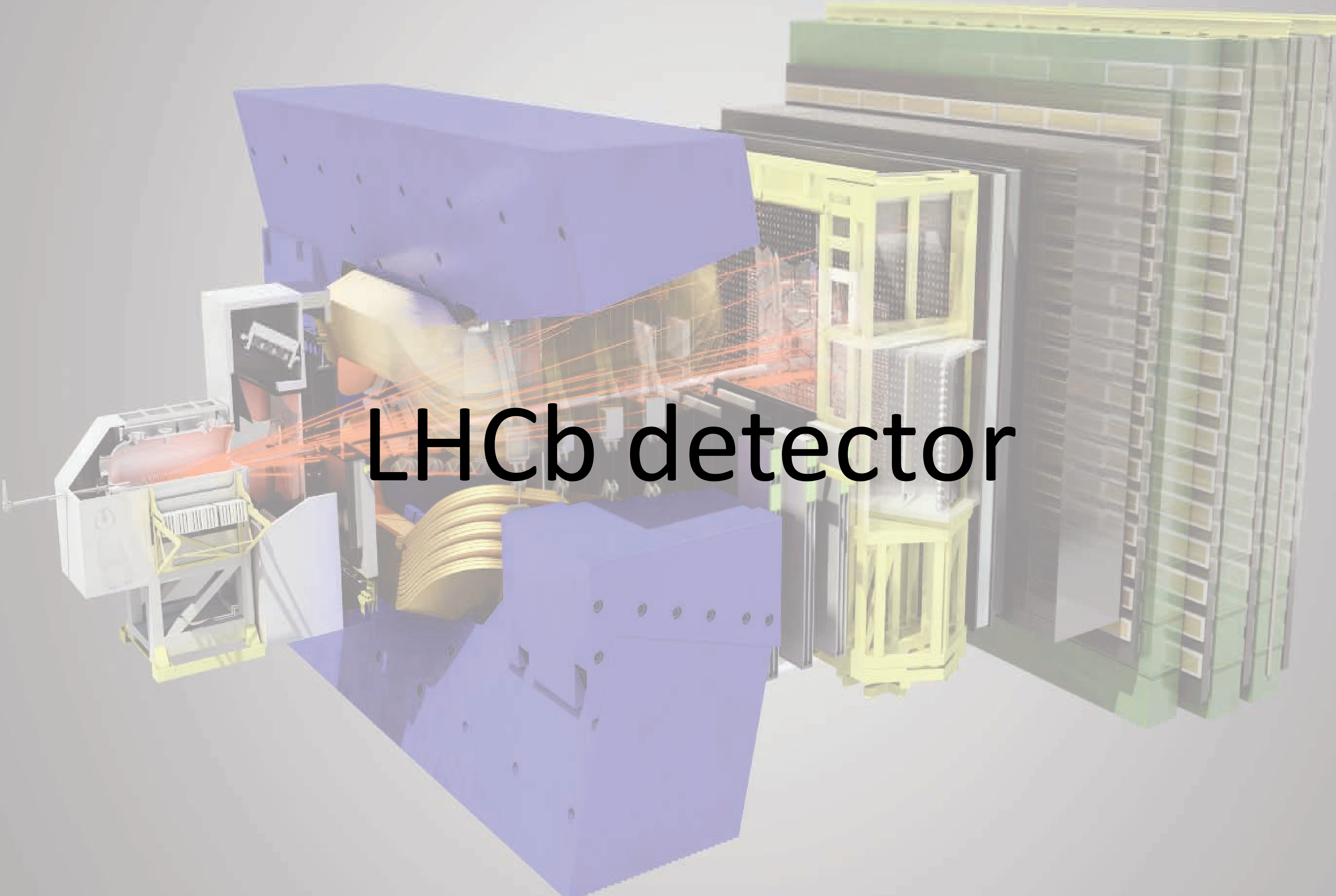
XXVIIth Rencontres de Blois

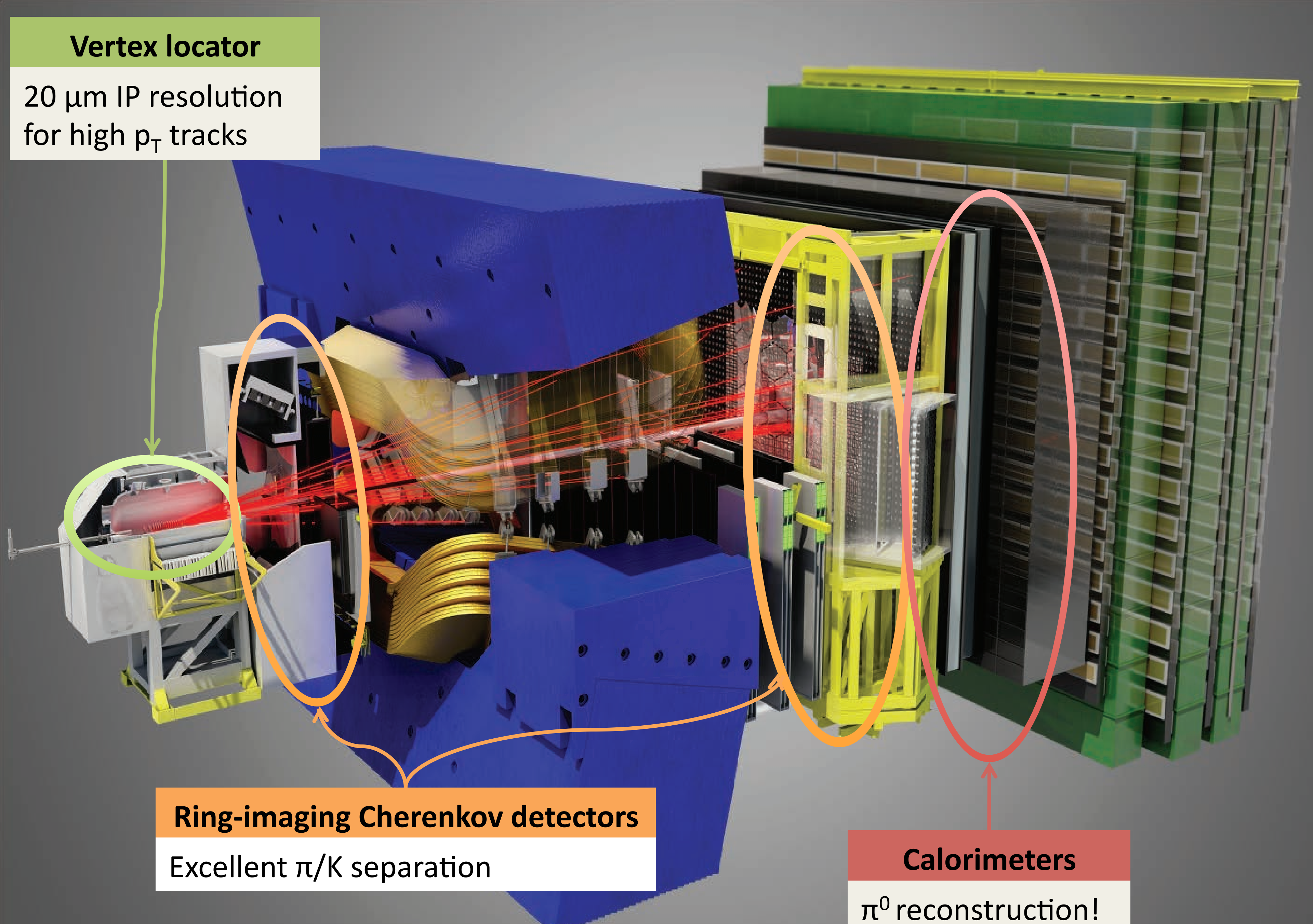
Overview

- LHCb detector
- Direct *CP* violation:
  - Model-independent: $D^0 \to \pi^+\pi^-\pi^0$
  - Model-dependent: $D^0 \to K_S^0 K^\pm \pi^\mp$ **(NEW)**
- Indirect / time-dependent *CPV*:
  - A_Γ with $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$
- Summary

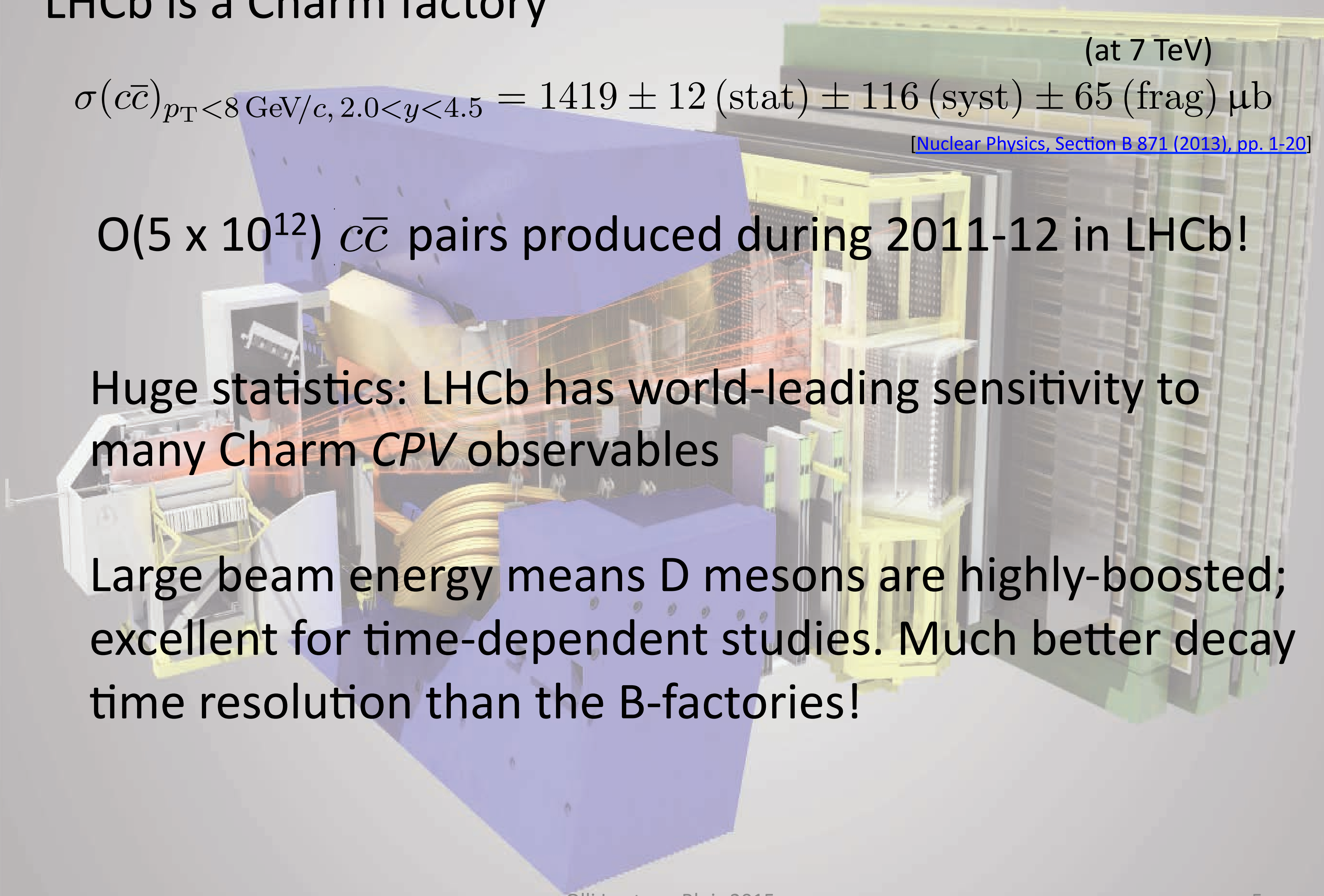
Just a selection of **recent** LHCb results, many already published and lots more to come!

LHCb detector




Vertex locator
20 μm IP resolution
for high p_T tracks
Ring-imaging Cherenkov detectors
Excellent π/K separation
Calorimeters
π^0 reconstruction!

LHCb is a Charm factory



(at 7 TeV)

$$\sigma(c\bar{c})_{p_{\mathrm{T}}<8\,\mathrm{GeV}/c,\,2.0<y<4.5} = 1419 \pm 12\,(\mathrm{stat}) \pm 116\,(\mathrm{syst}) \pm 65\,(\mathrm{frag})\,\mu\mathrm{b}$$

[Nuclear Physics, Section B 871 (2013), pp. 1-20]

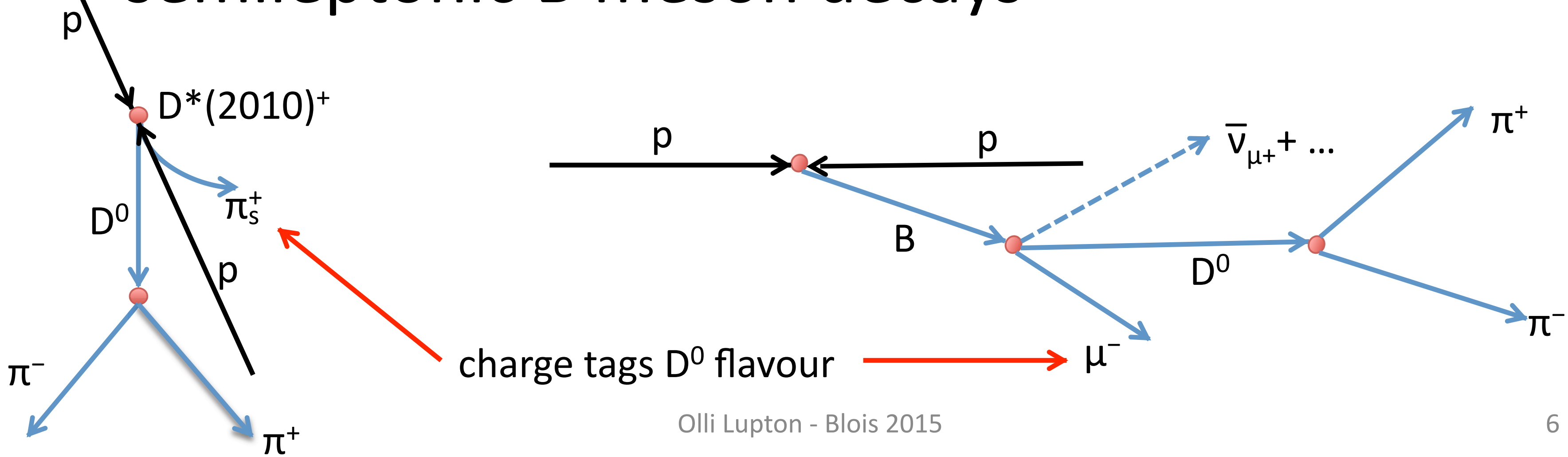
O(5 x 10^{12}) $c\bar{c}$ pairs produced during 2011-12 in LHCb!

Huge statistics: LHCb has world-leading sensitivity to many Charm *CPV* observables

Large beam energy means D mesons are highly-boosted; excellent for time-dependent studies. Much better decay time resolution than the B-factories!

CP violation in Charm

- Standard Model predictions are small; large *CP* violation would be a strong hint of New Physics
- Complementary to energy-frontier searches
- *CP* violation searches clearly want to tag D^0 flavour; at LHCb we do this with D*(2010)+ or semileptonic B meson decays

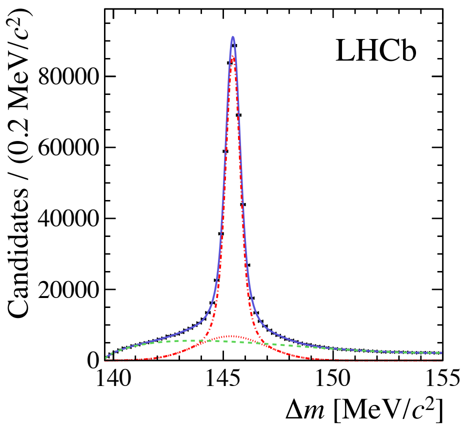


Direct CP violation

I.E. $|D^0 \rightarrow f|^2 \; != \; |\bar{D}^0 \rightarrow \bar{f}|^2$

- Today: time-integrated measurements looking for local asymmetries in multibody D^0 decays
- Interesting places to search for *CPV* because of interference effects in the Dalitz plots (difficult though!)
- Singly Cabbibo suppressed (SCS) decays are expected to be the best places to find **direct** *CPV*
- Several techniques: full-blown amplitude analysis, binned (e.g. "Miranda") techniques, unbinned metrics, triple-product asymmetries, …
- We'll see more about the highlighted ones…

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



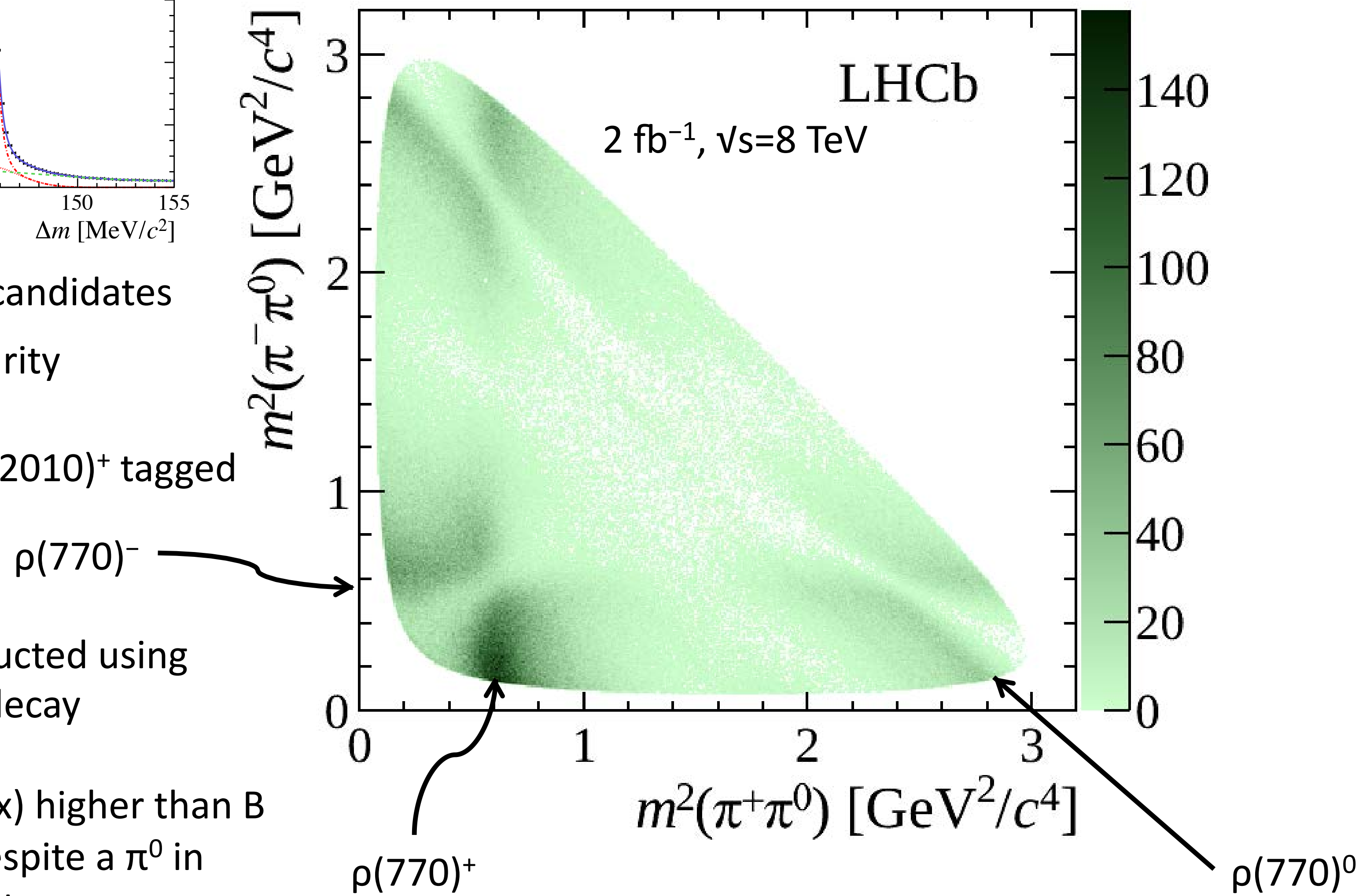
~6.6 x 10^5 candidates

O(85%) purity

Prompt, $D^*(2010)^+$ tagged D^0 decays

π^0 reconstructed using normal γγ decay

Yields O(10x) higher than B factories despite a π^0 in the final state…



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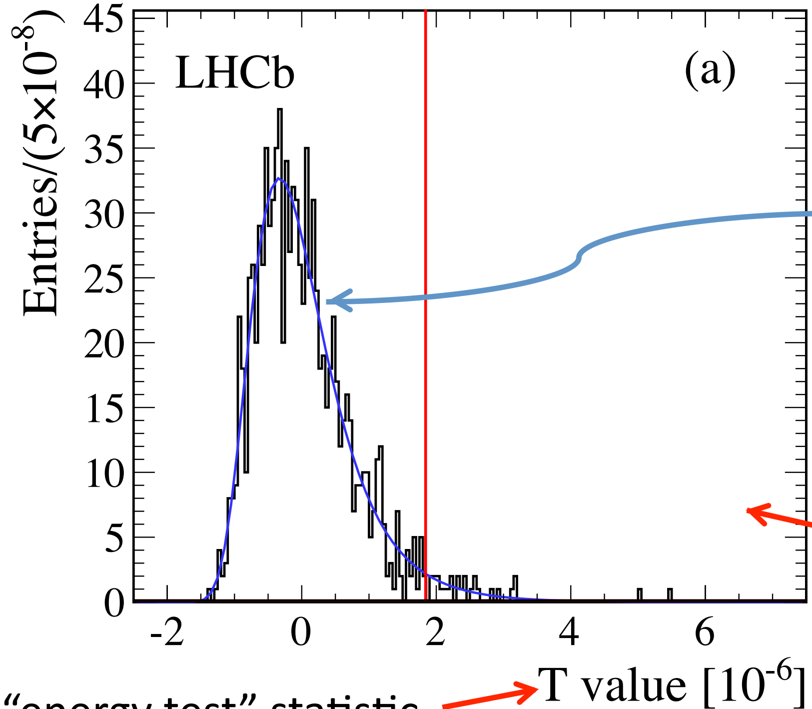
Search uses an unbinned model-independent test statistic

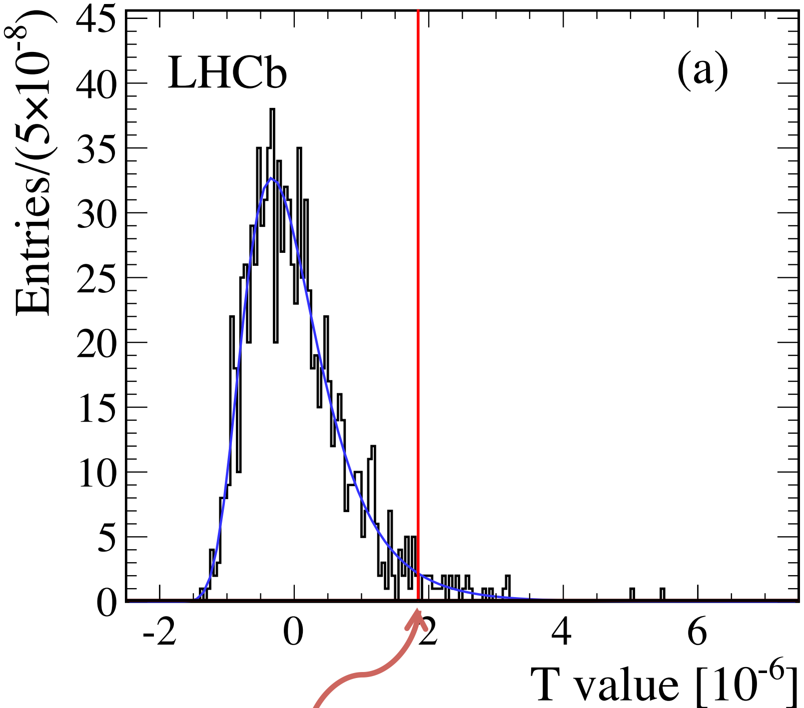


Expected no-*CPV* distribution obtained by repeatedly randomising flavour tags to generate no-*CPV* datasets

Calculate *p*-value for no-*CPV* hypothesis using this distribution

"energy test" statistic

Phys. Lett. B 740 (2015) 158
J. Stat. Comput. Simul. 75 (2005) 109
Nucl. Instrum. Meth. A537 (2005) 626
Phys. Rev. D84 (2011) 054015

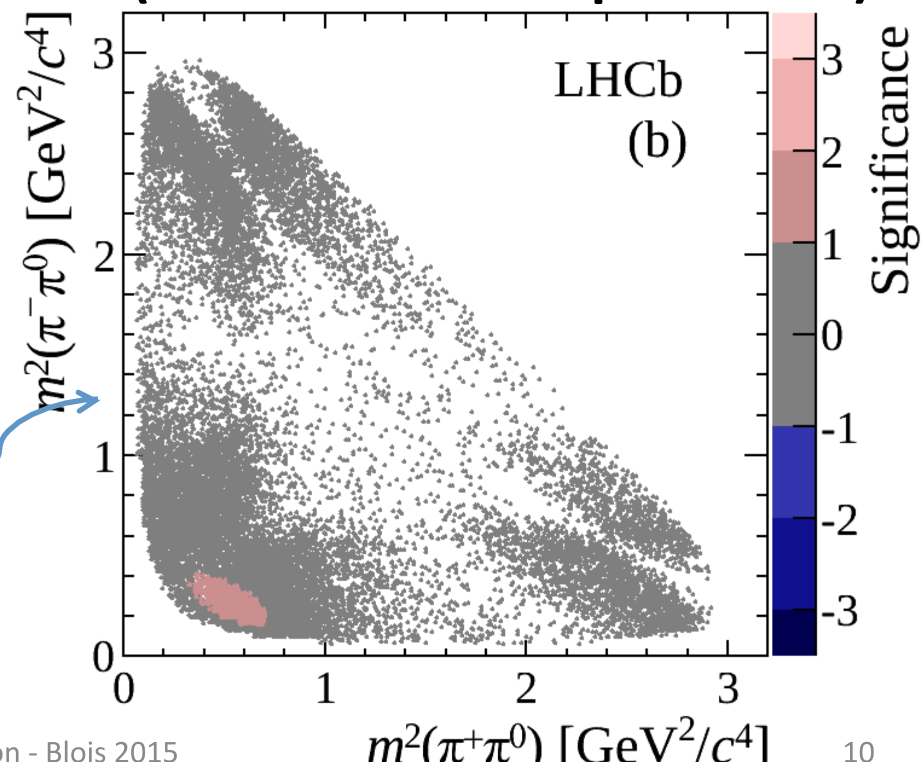


Measured value

Resulting p-value for no-CPV: (2.6±0.5)%

No evidence of *CP* violation

(but world's best precision!)



Visualisation of the local asymmetry

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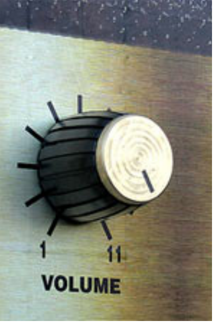
Nucl. Instrum. Meth. A537 (2005) 626

Phys. Rev. D84 (2011) 054015

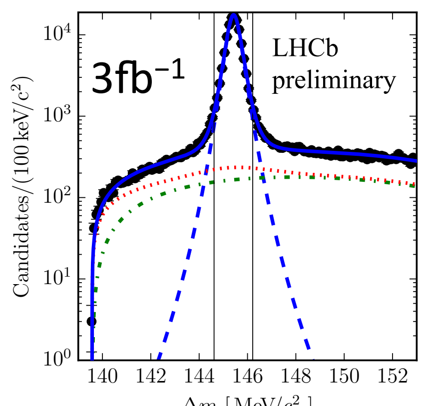
NEW

Amplitude analysis of $D^0 \to K_S^0 K^\pm \pi^\mp$



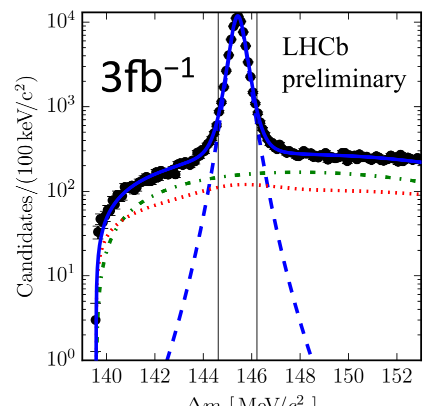
Two more SCS D^0 decays, but a rather different analysis

- More than a *CPV* search: isobar models (constructed assuming *CP*) useful for future measurements of mixing, and the *CP*-violating CKM angle γ
- Other interesting tests come direct from the models.
- **Here:** remove *CP* assumption and perform **model-dependent *CPV* search**
- World's most precise study; $O(10^2)$ higher statistics than previous best by CLEO



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

~113k



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

~76k

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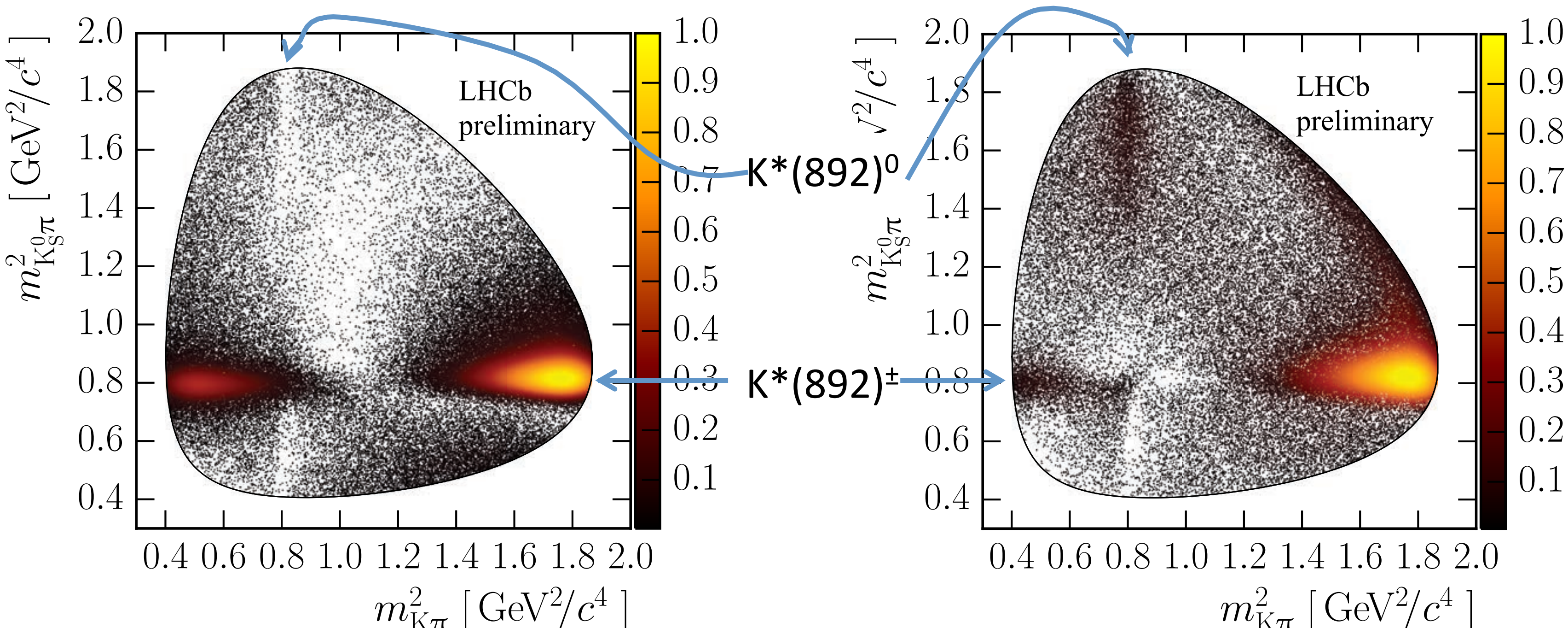
NEW

Amplitude analysis of $D^0 \to K_S^0 K^{\pm}\pi^{\mp}$



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

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

$m^2_{K\pi}$ projection

NEW

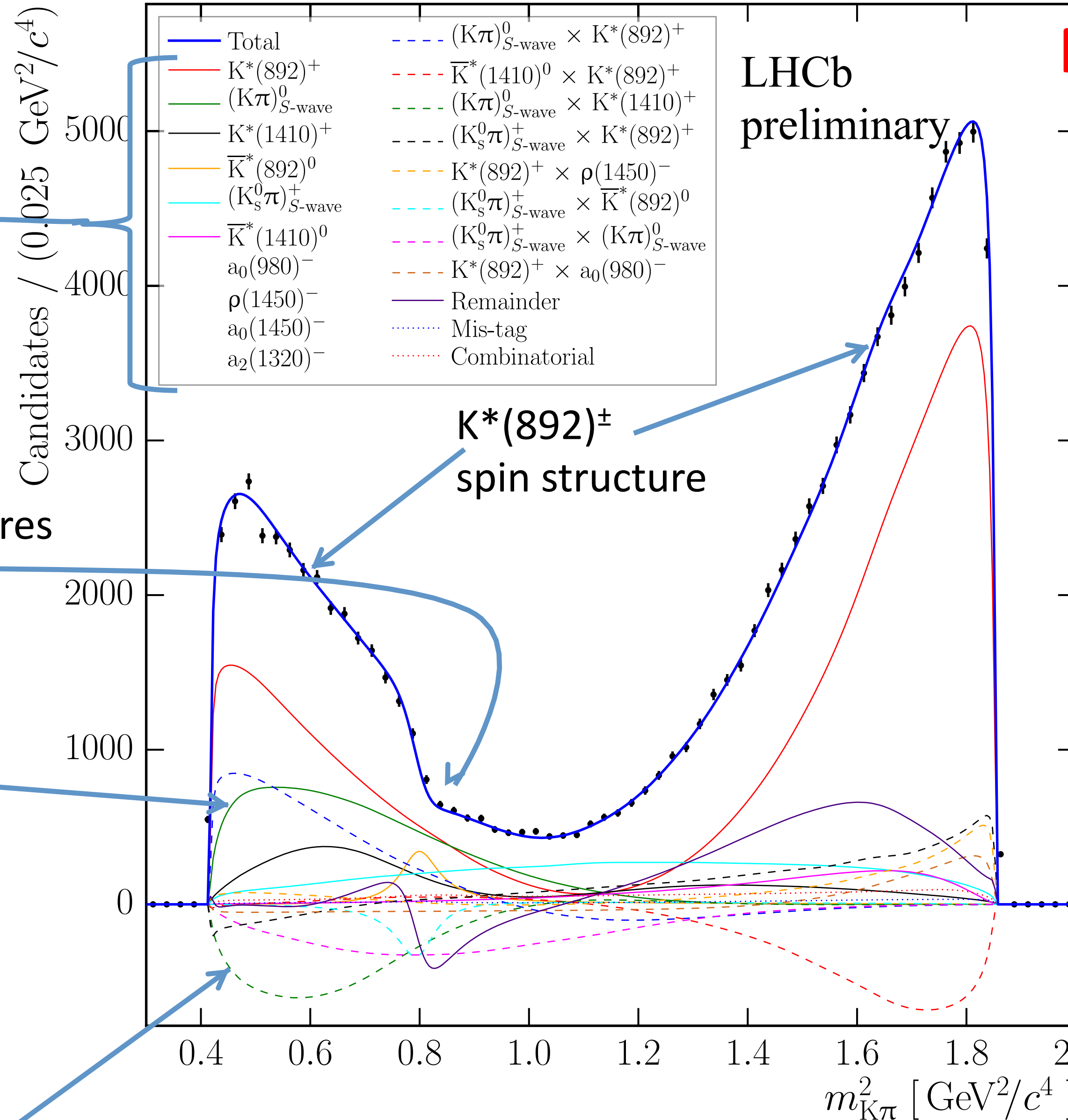
10 resonances in this model

K*(892)^0 interferes destructively

K*(892)$^\pm$ spin structure

Kπ *S*-wave plays a large role

Dashed lines are interference terms



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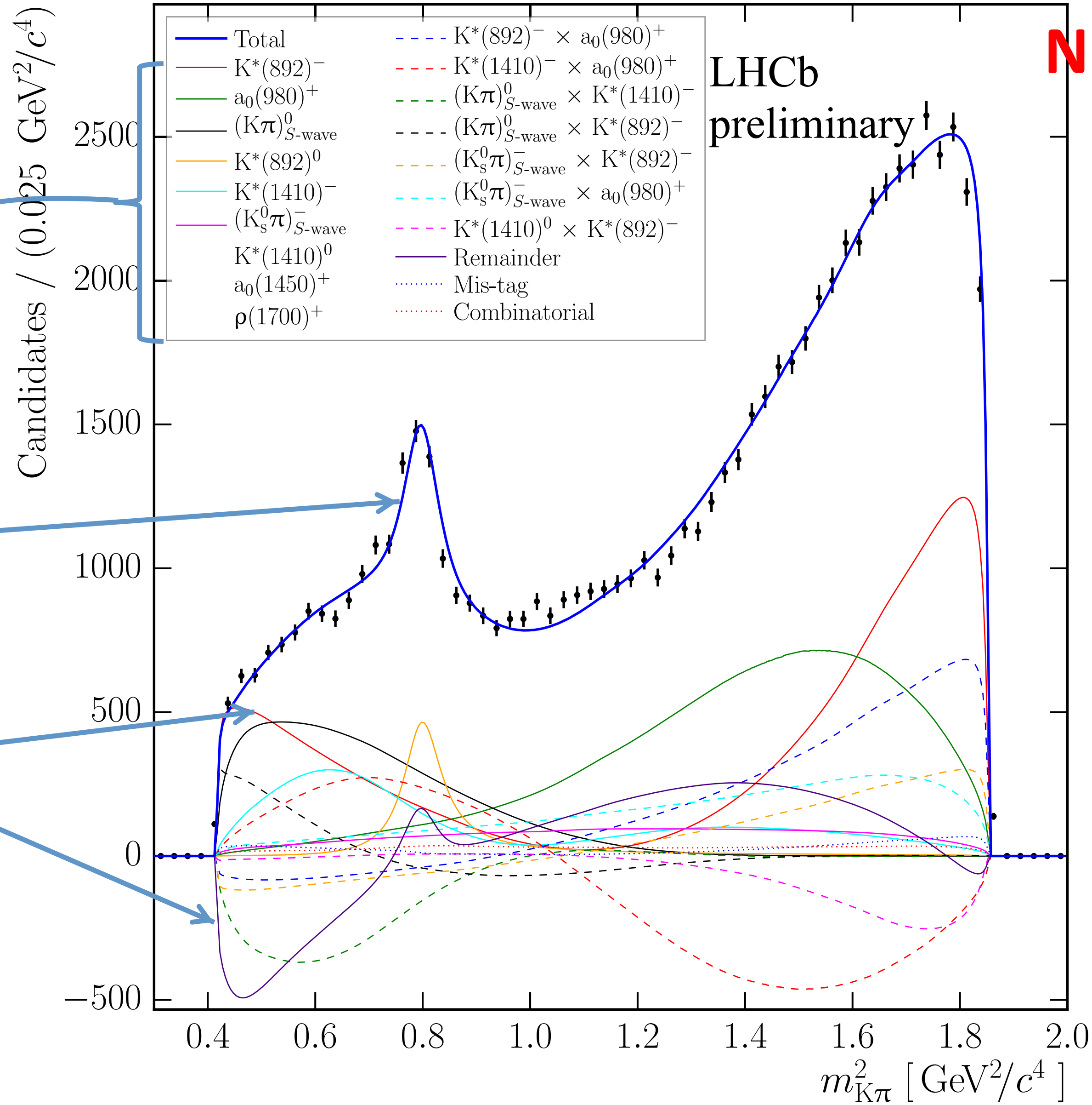
$D^0 \to K_S^0 K^+ \pi^-$

$m_{K\pi}^2$ projection

NEW

9 resonances in this model



K*(892)⁰ has a substantial mass peak in this mode

Interference terms suppress one lobe of the K*(892)± spin structure

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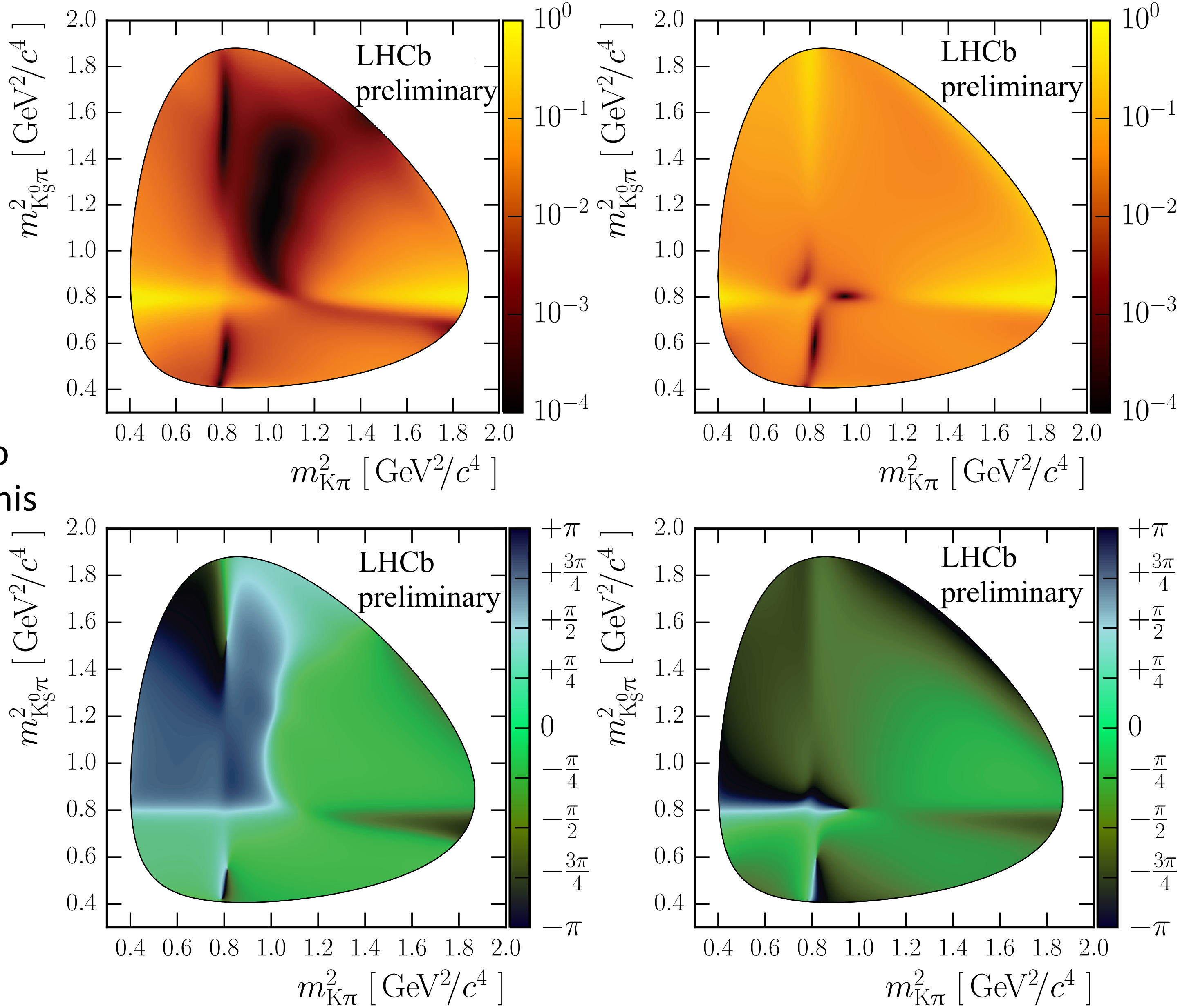
NEW

$|A|^2$

Fit this to extract this

$\arg(A)$



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

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NEW

Model-dependent *CPV* results

- Once you have an isobar model

$$A = \sum_R a_R e^{i\phi_R} A_R$$

Resonance `lineshape' (→ A_R)

Resonance amplitude (→ $a_R e^{i\phi_R}$)

- Substitute

$$A = \sum_R a_R (1 \pm \Delta a_R) e^{i(\phi_R \pm \Delta\phi_R)} A_R$$

- With the sign dependent on the D^0 flavour tag, and re-fit the models
- Perform χ^2 test w.r.t. no-*CPV* hypothesis ($\Delta = 0$)
- Find χ^2/ndf = 32.3/32 = 1.01, *p*-value 0.45

No evidence for *CP* violation

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Indirect *CPV* / mixing

I.E. $|D^0 \to \bar{D}^0 \to f|^2 \;!= |\bar{D}^0 \to D^0 \to f|^2$

- Time-dependent *CP* asymmetries…
- Charm mixing is the only up-type system where we can probe mixing and *CPV*
- Mixing now well-established (helped by LHCb 2-body results [Phys. Rev. Lett. 110, 101802, Phys. Rev. Lett. 111, 251801, JHEP 1204 (2012) 129]!)...but *CPV* is not

J. High Energy Phys. 04 (2015) 043

LHCb A_Γ results

- Let's see LHCb's most recent result: full 3 fb^{-1} using D^0 tagged with semileptonic B decays
- D^0 decays to *CP* eigenstate: K^+K^- or $\pi^+\pi^-$, and we measure the time-dependent asymmetry

$$A_{CP}(t) \equiv \frac{\Gamma(D^0 \to f;t) - \Gamma(\overline{D}^0 \to f;t)}{\Gamma(D^0 \to f;t) + \Gamma(\overline{D}^0 \to f;t)} \approx A_{CP}^{\mathrm{dir}} - A_\Gamma \frac{t}{\tau}$$

- Straight line fit gives A_Γ, which is sensitive to indirect *CP* violation

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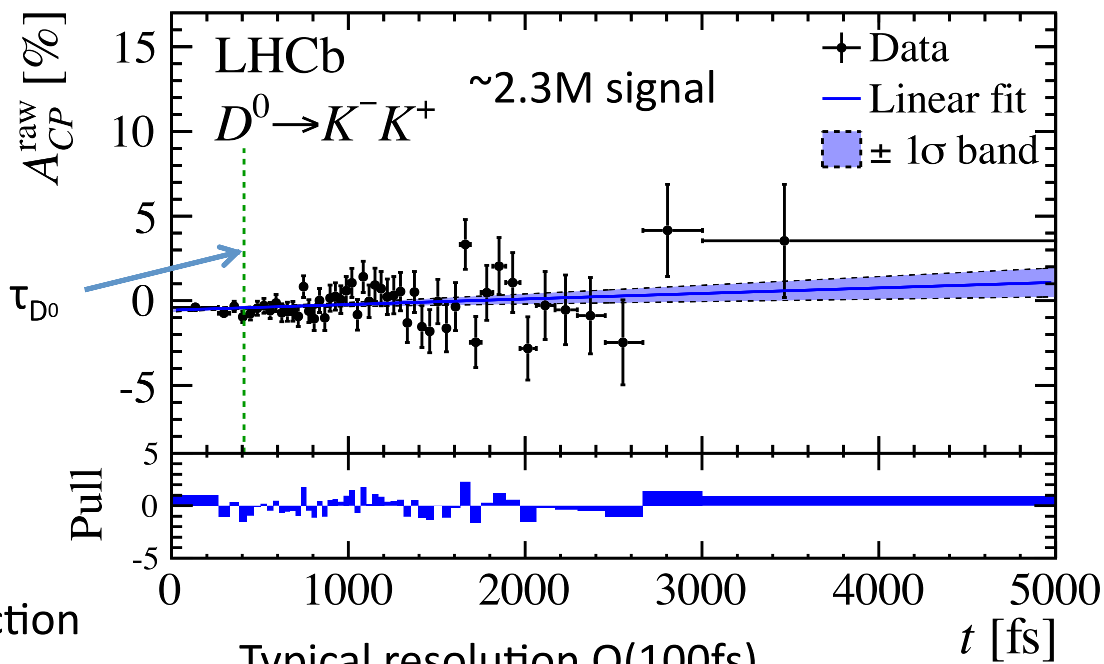
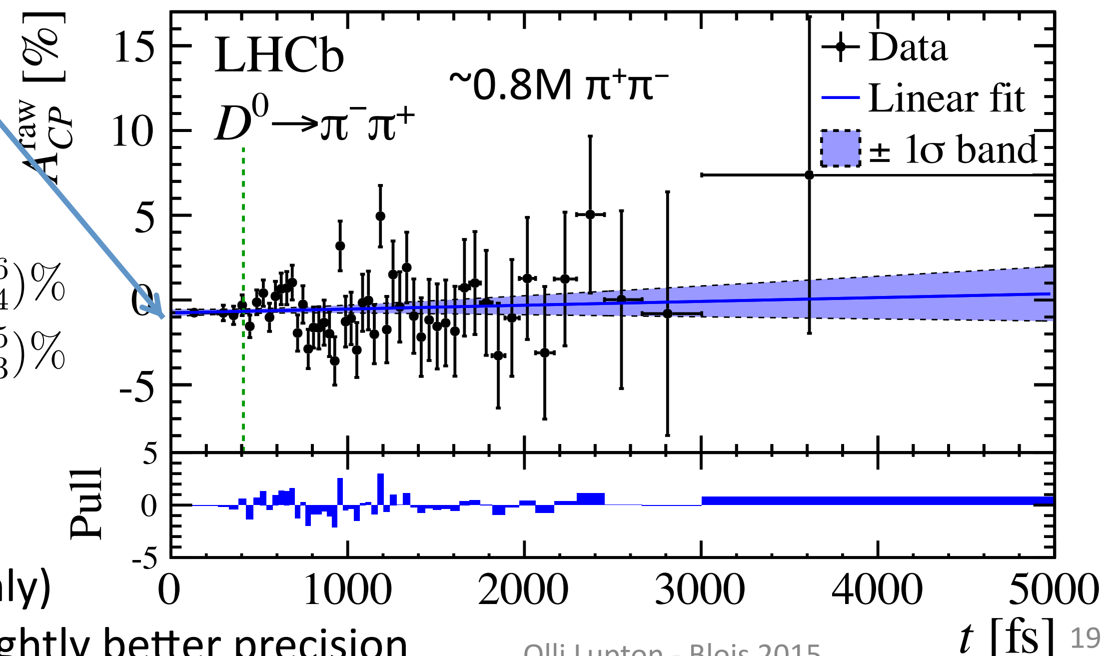
50 bins in D^0 decay time, approx. optimised to have equal sensitivity



Typical resolution O(100fs)

D^0 production asymmetry, muon detection asymmetry etc. all contribute to non-zero intercept, but only negligibly to A_Γ



$$A_\Gamma(K^-K^+) = (-0.134 \pm 0.077 \,^{+0.026}_{-0.034})\%$$
$$A_\Gamma(\pi^-\pi^+) = (-0.092 \pm 0.145 \,^{+0.025}_{-0.033})\%$$

(statistically limited)

There is also a previous LHCb result using promptly produced D^0 (2011 only) [Phys. Rev. Lett. 112, 041801] with slightly better precision

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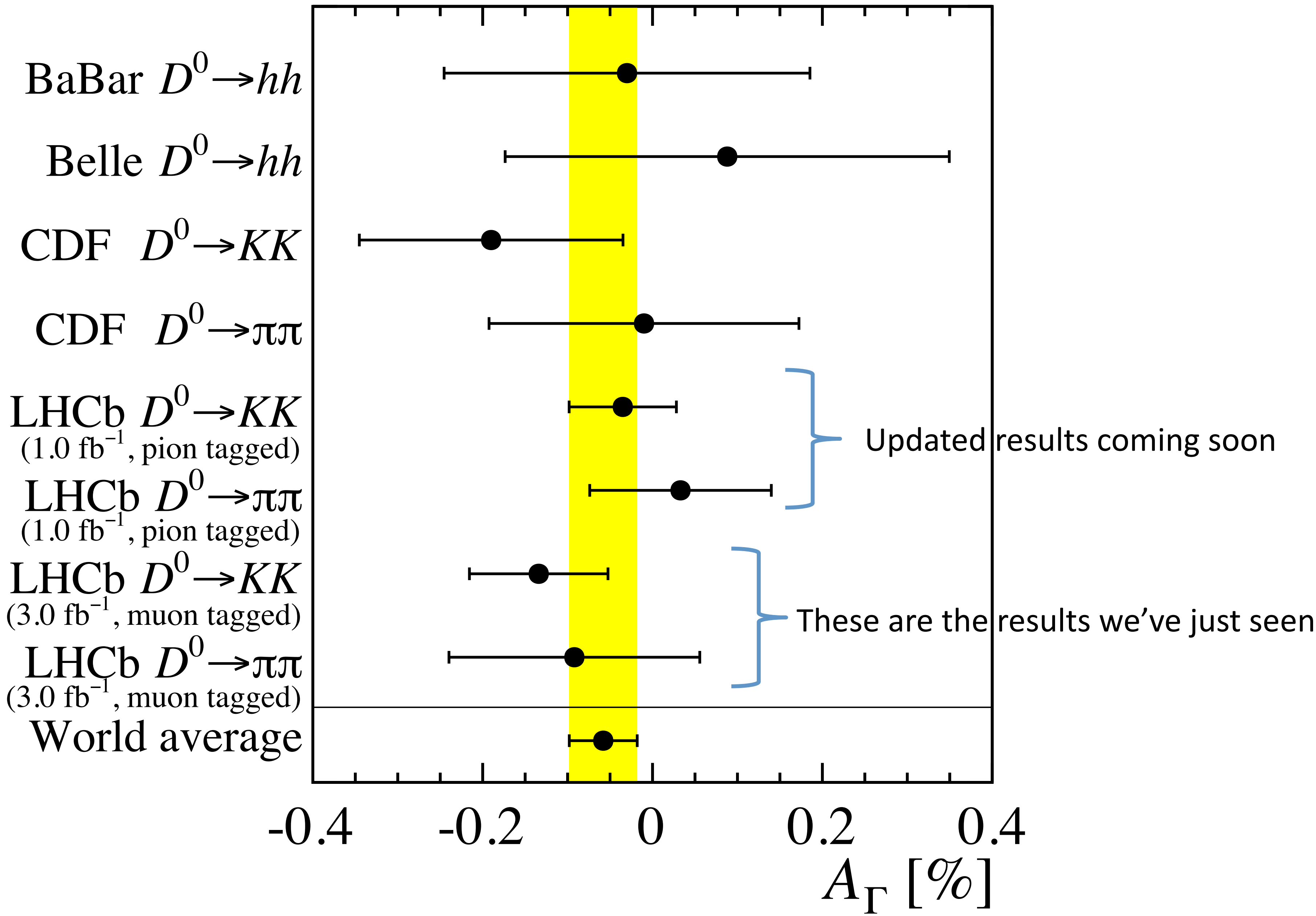

Summary

- Lots of activity in LHCb searching for *CPV* in Charm
- Many different methods; have presented a selection with recent results.
- Complementary measurements from semi-leptonic B meson decays and promptly produced Charm
- Lots more Run 1 results to come soon: 3 fb^{-1} prompt A_{Γ}, mixing with $D^0 \to K_S^0 \pi^+ \pi^-$, …
- …and Run 2 of the LHC is just starting, with even higher charm production cross sections at 13 TeV
- Huge data samples; exciting opportunities!

Thanks

Credit: francehexagone.blogspot.co.uk

Backup

Phys. Lett. B 740 (2015) 158
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The energy test

$$d_{ij}^2 = \left|(\Delta m^2_{\pi^+\pi^-}, \Delta m^2_{\pi^0\pi^-}, \Delta m^2_{\pi^+\pi^0})\right|^2$$

$$\psi_{ij} \equiv \psi(d_{ij}) = e^{-d_{ij}^2/2\sigma^2}$$

- Unbinned test statistic:

$$T = \underbrace{\sum_{i,j>i}^{n} \frac{\psi_{ij}}{n(n-1)}}_{D^0 \leftrightarrow D^0} + \underbrace{\sum_{i,j>i}^{\overline{n}} \frac{\psi_{ij}}{\overline{n}(\overline{n}-1)}}_{\overline{D^0} \leftrightarrow \overline{D^0}} - \underbrace{\sum_{i,j}^{n,\overline{n}} \frac{\psi_{ij}}{n\overline{n}}}_{D^0 \leftrightarrow \overline{D^0}},$$

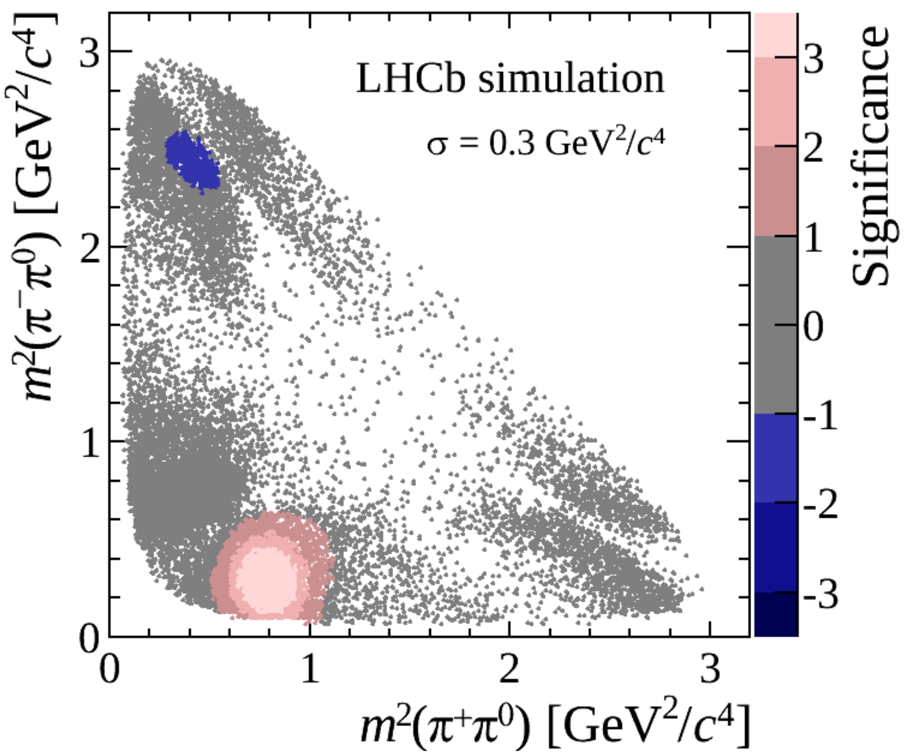
Mean metric-weighted distances between candidates in the Dalitz plot.

- No *CPV* gives $T \approx 0$

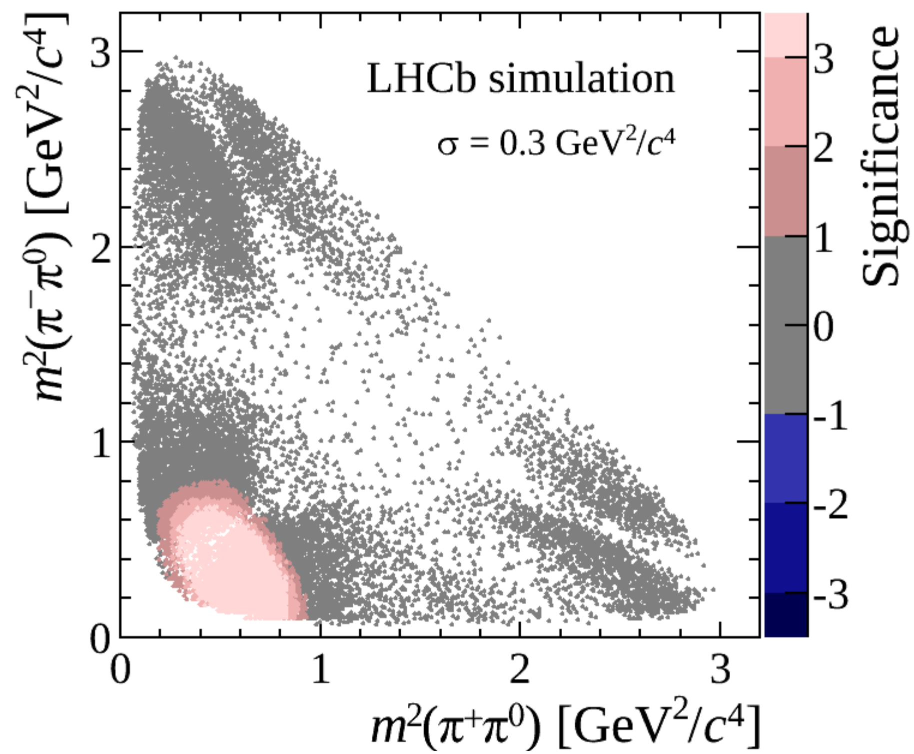
Sensitivity studies

Table 1: Overview of sensitivities to various CP violation scenarios. ΔA and $\Delta\phi$ denote, respectively, change in amplitude and phase of the resonance R.

R (ΔA, $\Delta\phi$)	p-value (fit)	Upper limit
ρ^0 (4%, 0°)	$3.3^{+1.1}_{-3.3} \times 10^{-4}$	4.6×10^{-4}
ρ^0 (0%, 3°)	$1.5^{+1.7}_{-1.4} \times 10^{-3}$	3.8×10^{-3}
ρ^+ (2%, 0°)	$5.0^{+8.8}_{-3.8} \times 10^{-6}$	1.8×10^{-5}
ρ^+ (0%, 1°)	$6.3^{+5.5}_{-3.3} \times 10^{-4}$	1.4×10^{-3}
ρ^- (2%, 0°)	$2.0^{+1.3}_{-0.9} \times 10^{-3}$	3.9×10^{-3}
ρ^- (0%, 1.5°)	$8.9^{+22}_{-6.7} \times 10^{-7}$	4.2×10^{-6}



1° *CP* violation in the ρ^+ phase



2% amplitude CP violation for the ρ^+

Sensitivity study for the energy test method

Cross-check for local asymmetries in the Cabbibo-favoured control mode

This confirms that there is no indication of local asymmetries in these samples.

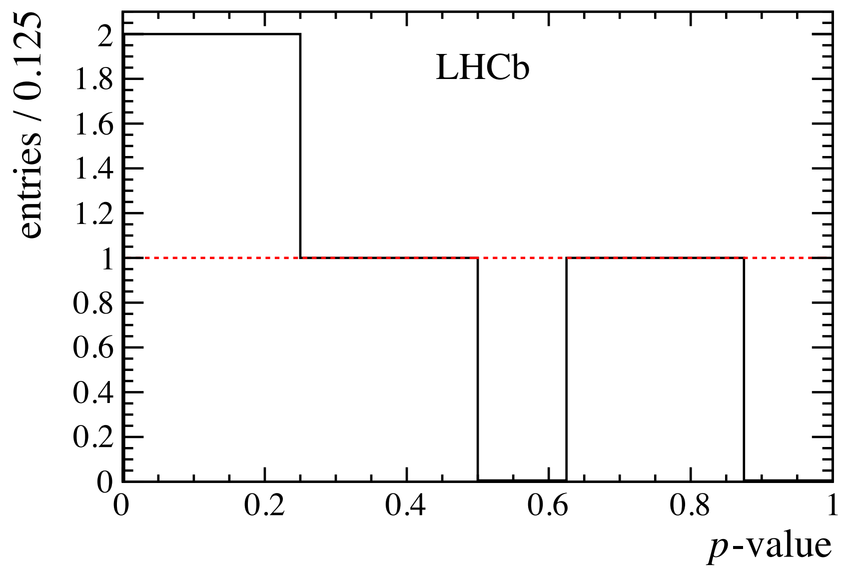
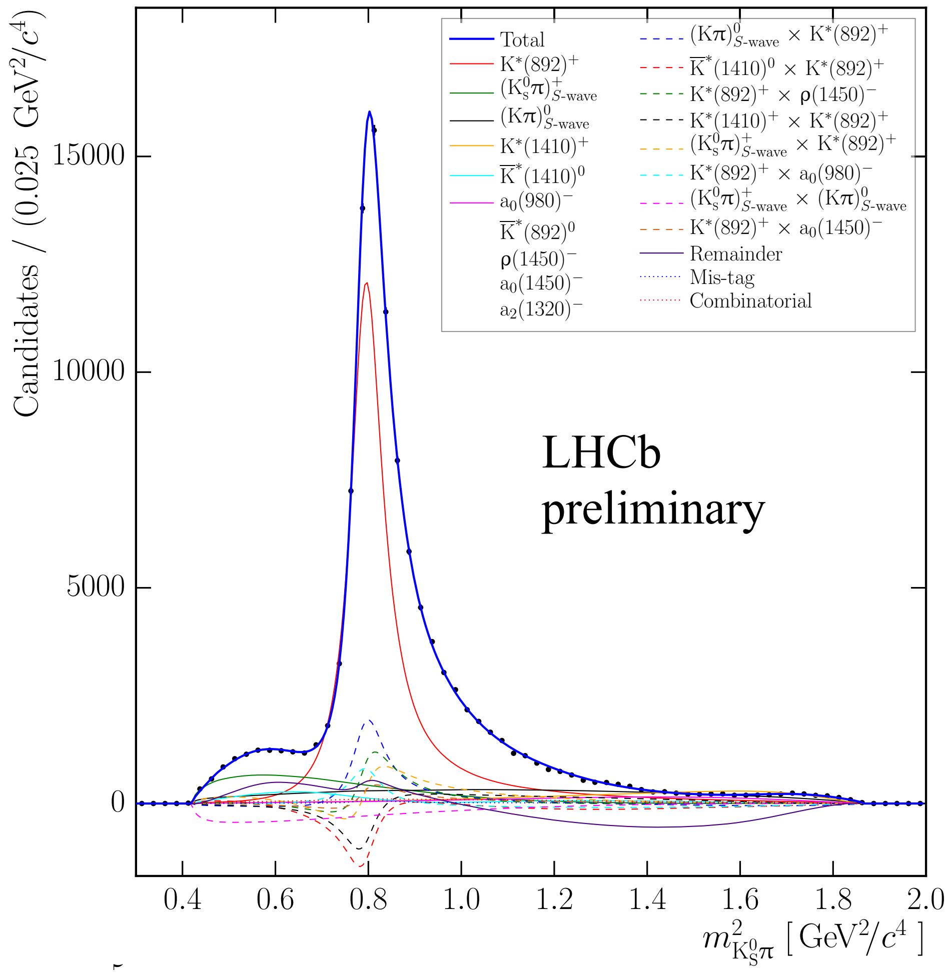
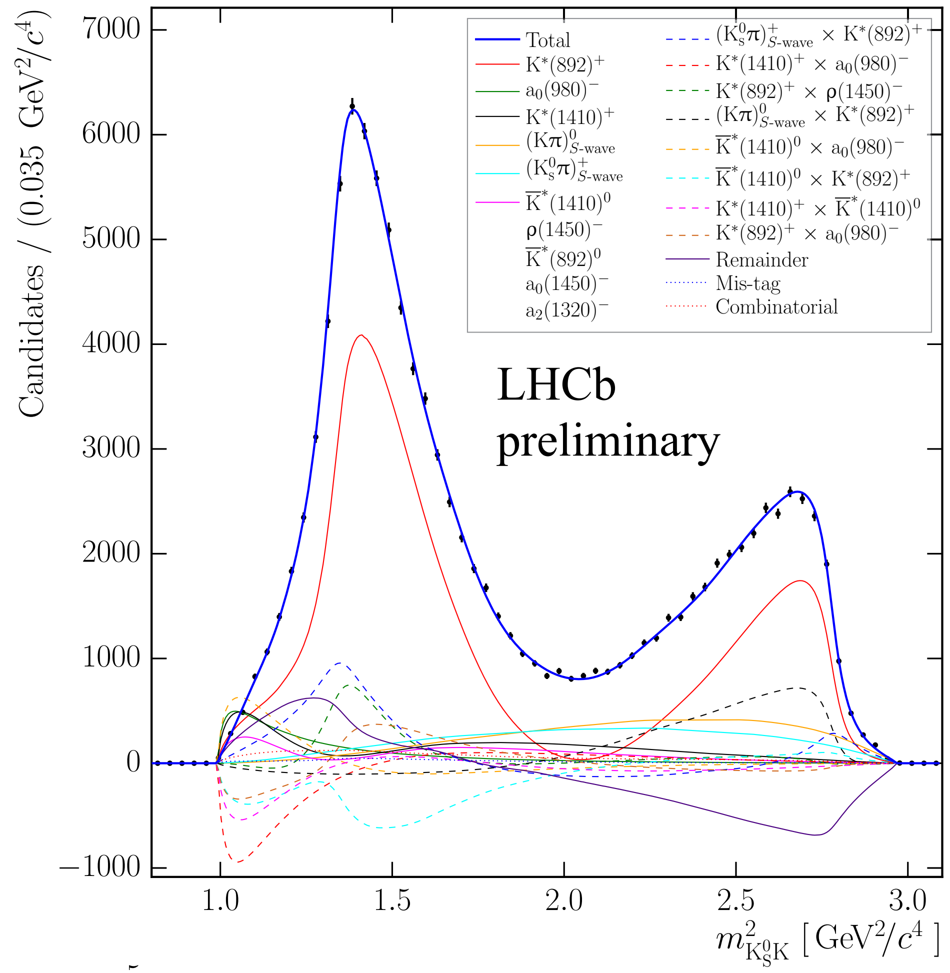
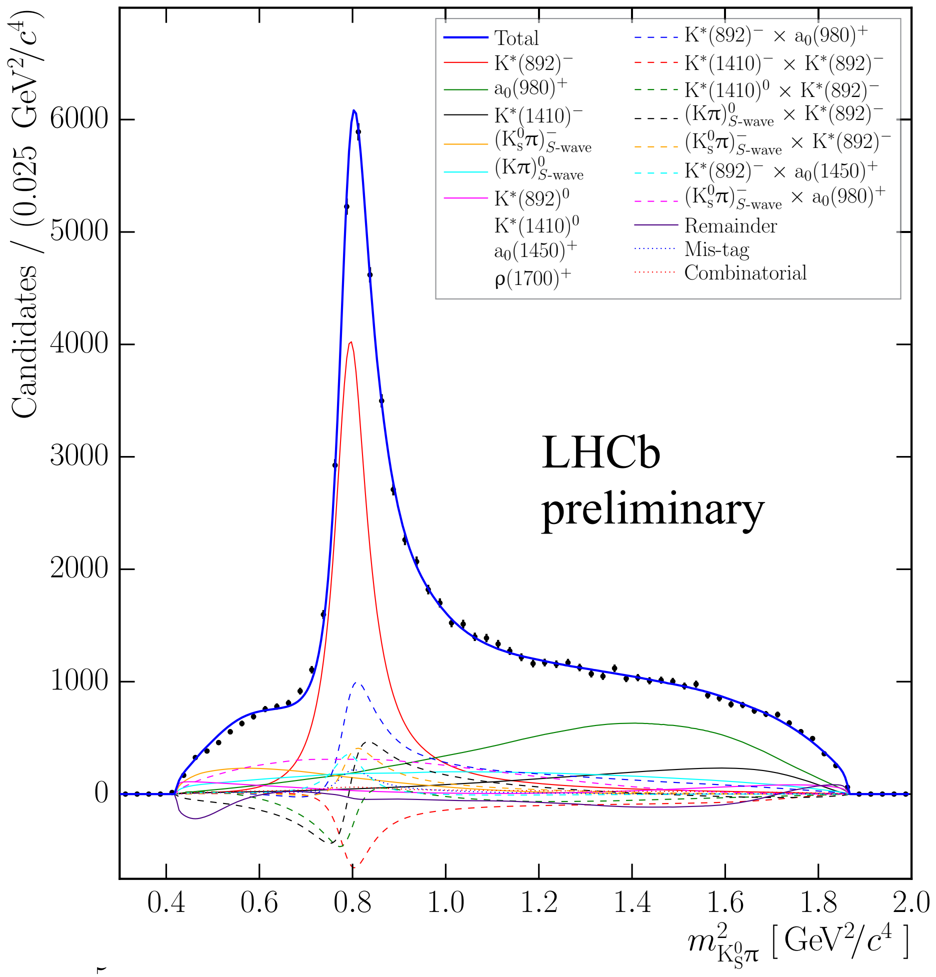


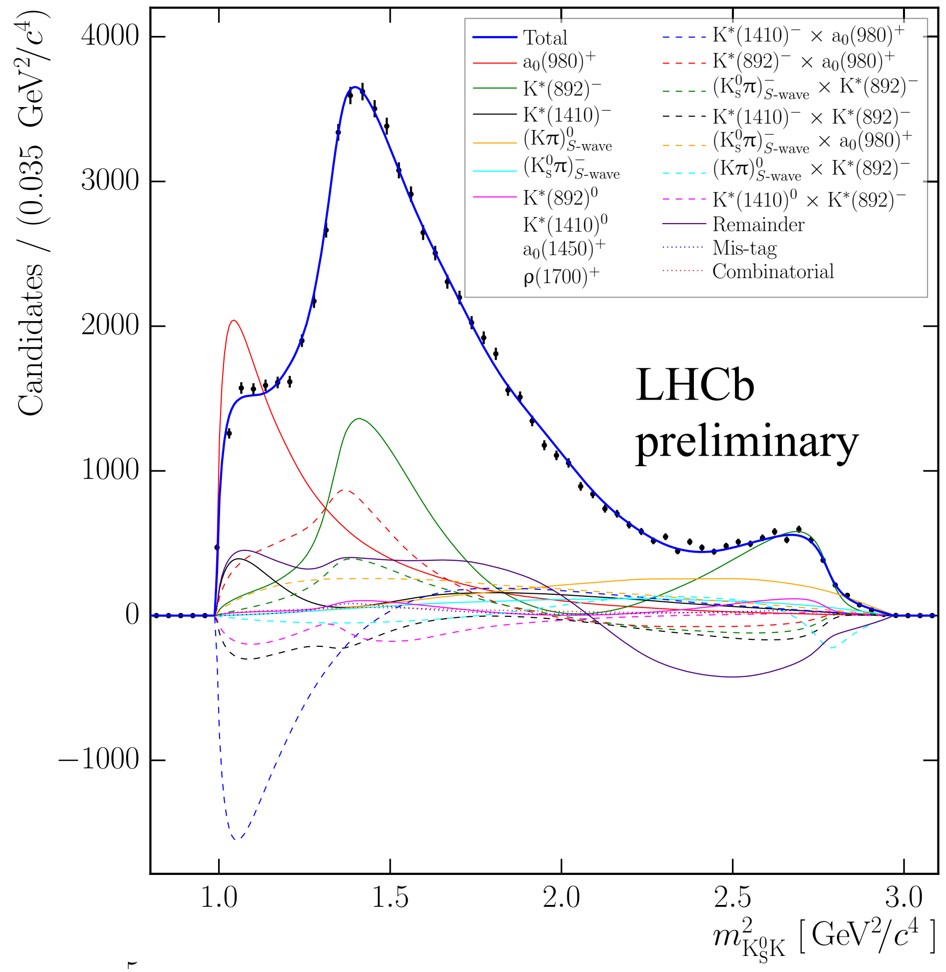
Figure 6: Distribution of p-values for the eight subsamples of the control channel $D^0 \to K^-\pi^+\pi^0$. The dashed line indicates the expected distribution.



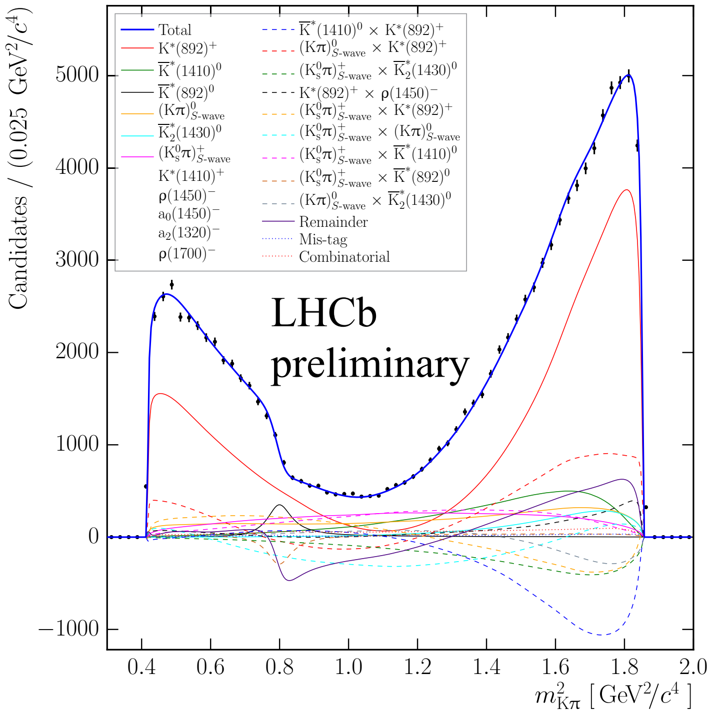


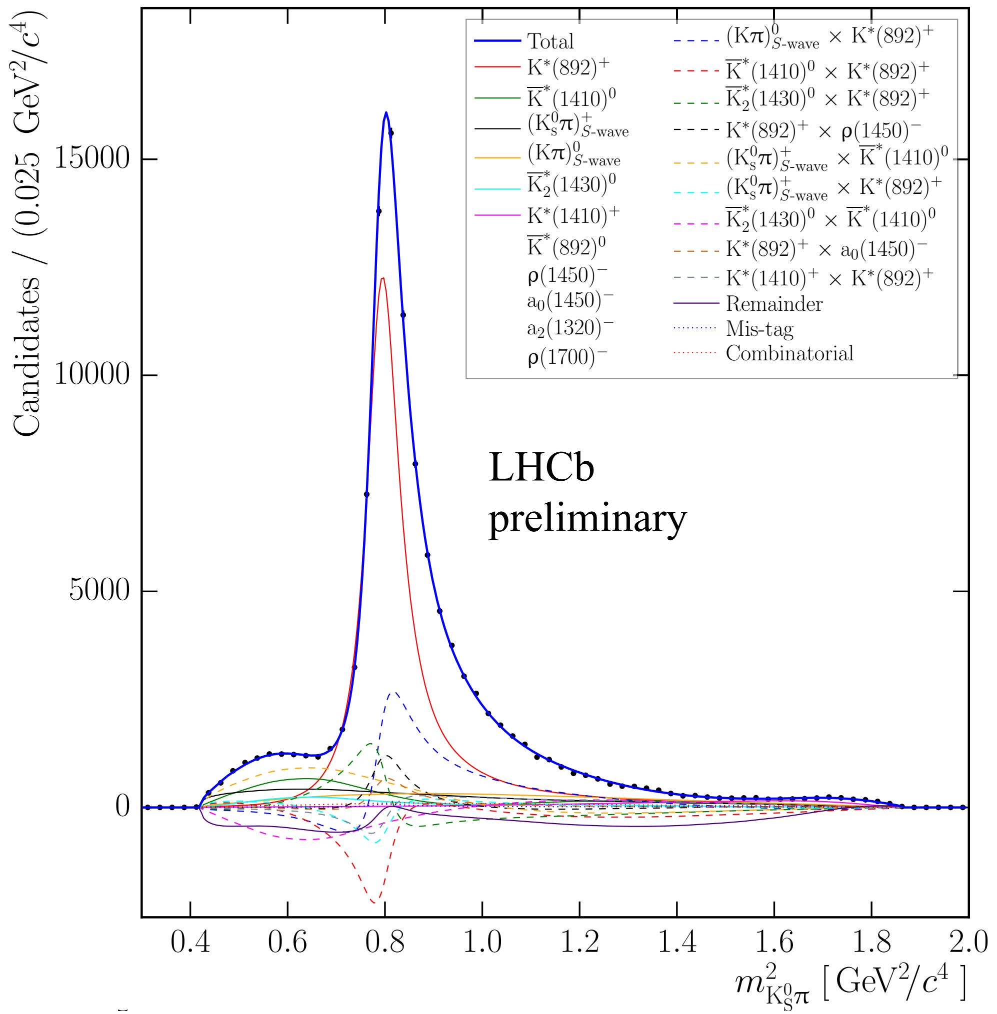
Other projections for $D^0 \rightarrow K_S^0 K^- \pi^+$

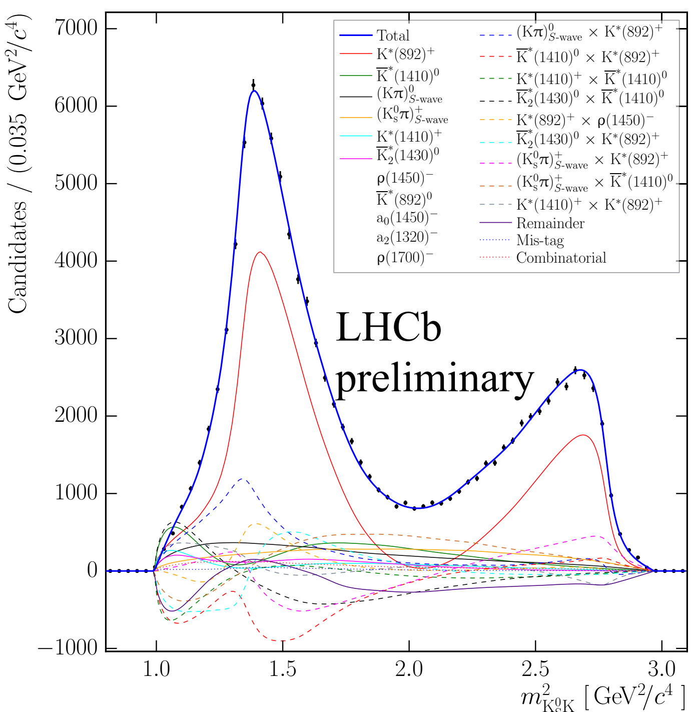




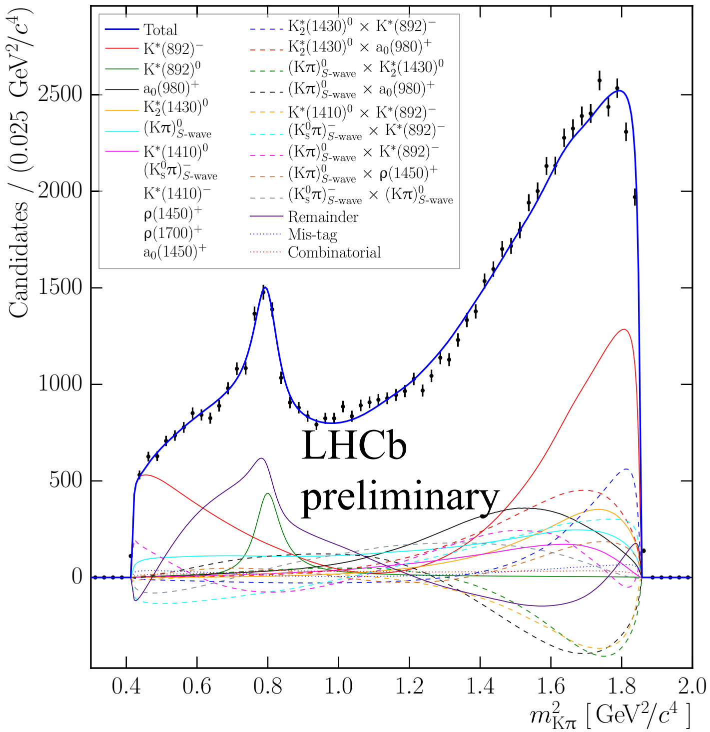
Other projections for $D^0 \to K_S^0 K^+ \pi^-$

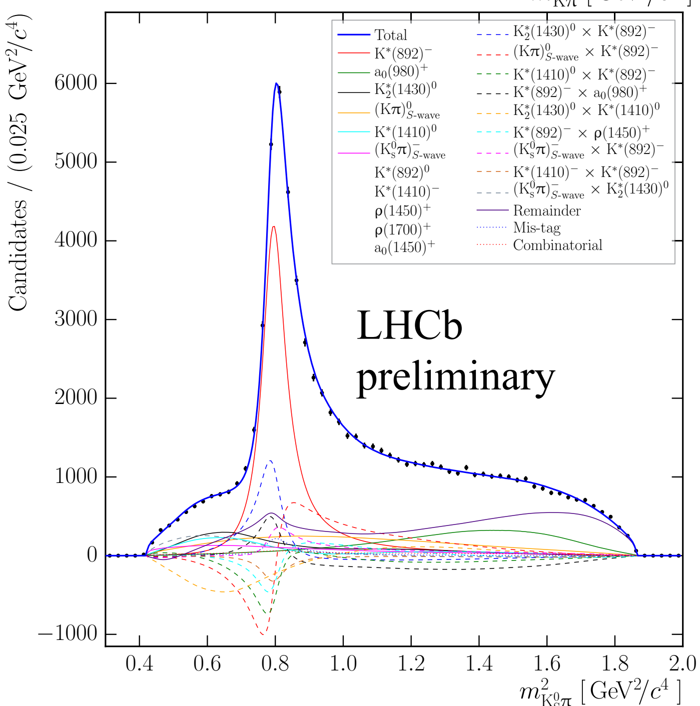


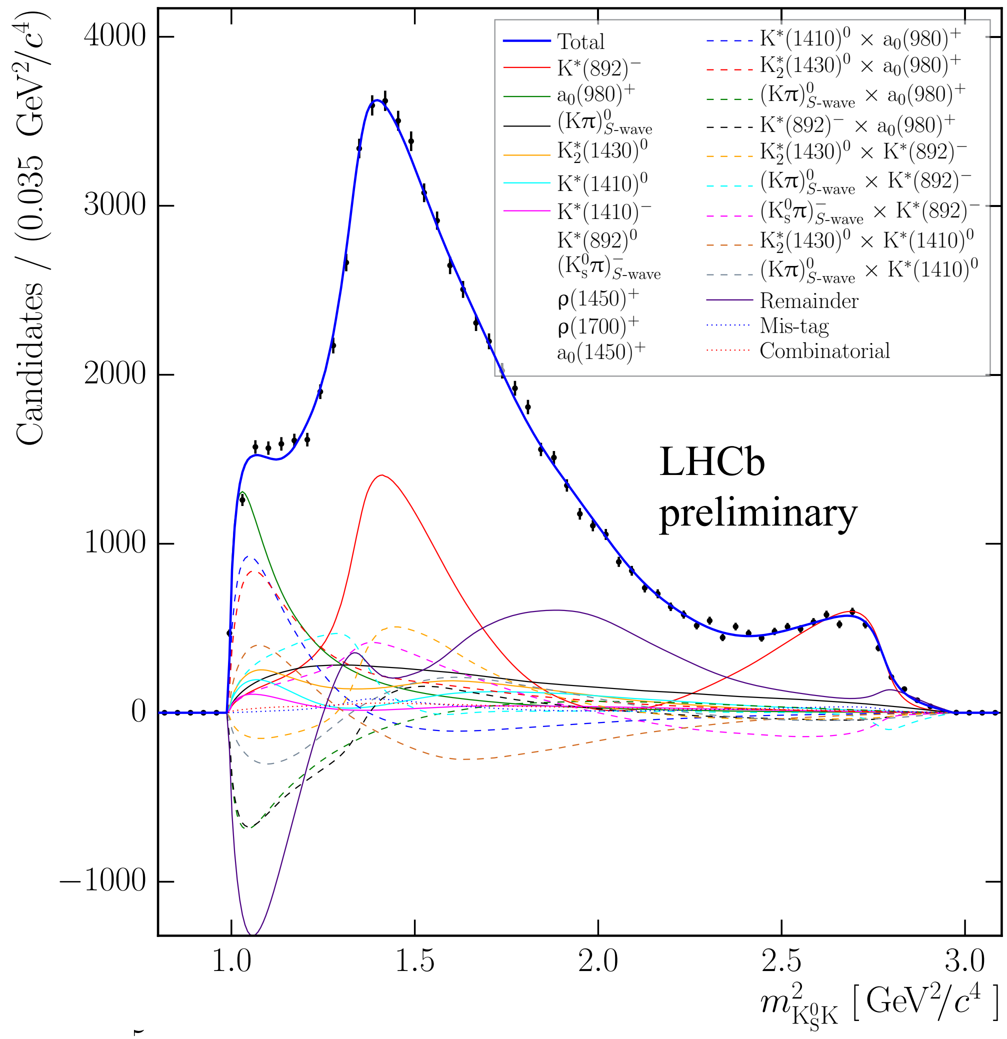




Alternative model for $D^0 \rightarrow K^0_S K^- \pi^+$







Alternative model for $D^0 \to K_S^0 K^+ \pi^-$

A_Γ formalism

$$A_\Gamma \equiv \frac{\hat{\Gamma}_{D^0} - \hat{\Gamma}_{\bar{D}^0}}{\hat{\Gamma}_{D^0} + \hat{\Gamma}_{\bar{D}^0}} \approx (A_{CP}^{\text{mix}}/2 - A_{CP}^{\text{dir}})\, y \cos\phi - x \sin\phi \;,$$

D^0 mixing parameters

weak phase
(decay mode specific)
describes interference between
mixing and decay

where $A_{CP}^{\text{mix}} = |q/p|^2 - 1$ describes CP violation in D^0–$\bar{D}^0$ mixing, with q and p the coefficients of the transformation from the flavour basis to the mass basis, $|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$. The weak phase ϕ describes CP violation in the interference between mixing and decay, and is specific to the decay mode. Finally, A_Γ receives a contribution from direct CP violation as well [16].

A_Γ systematic uncertainties

Table 1: Contributions to the systematic uncertainty of $A_\Gamma(K^-K^+)$ and $A_\Gamma(\pi^-\pi^+)$. The constant and multiplicative scale uncertainties are given separately.

Source of uncertainty	$D^0 \to K^-K^+$		$D^0 \to \pi^-\pi^+$	
	constant	scale	constant	scale
Mistag probability	0.006%	0.05	0.008%	0.05
Mistag asymmetry	0.016%		0.016%	
Time-dependent efficiency	0.010%		0.010%	
Detection and production asymmetries	0.010%		0.010%	
D^0 mass fit model	0.011%		0.007%	
D^0 decay-time resolution		0.09		0.07
B^0–$\overline{B}^0$ mixing	0.007%		0.007%	
Quadratic sum	0.026%	0.10	0.025%	0.09