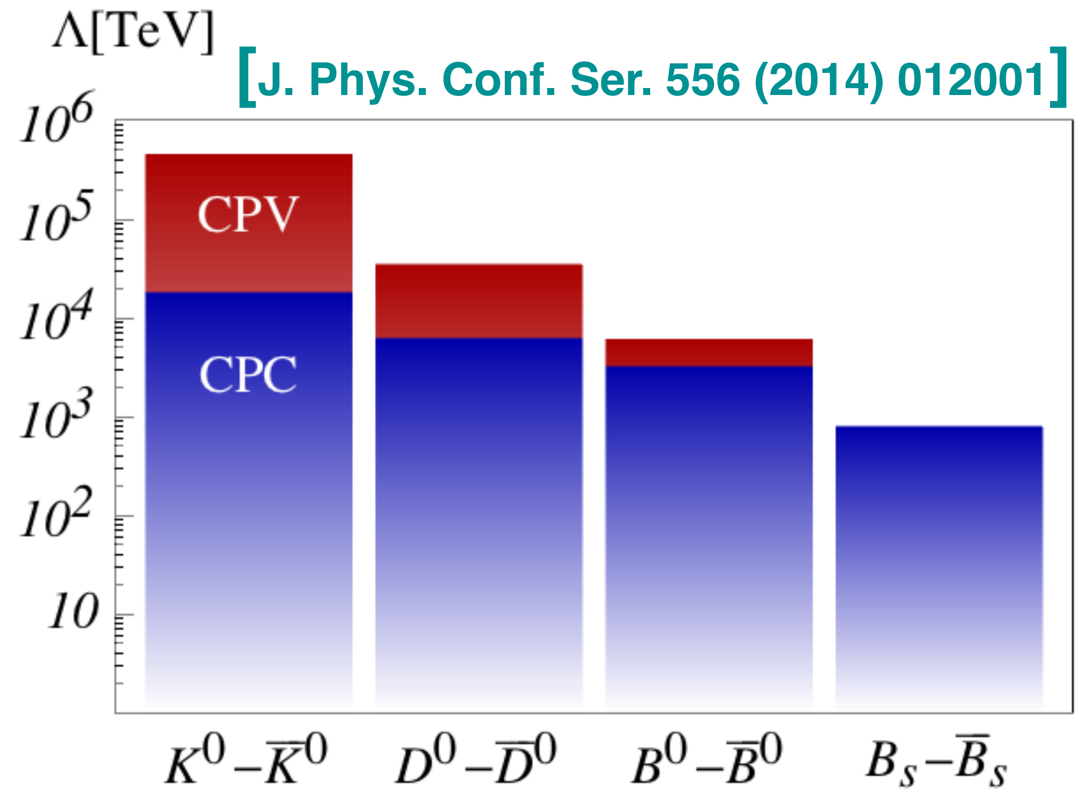
View of Hamburg, Elias Galli (ca. 1680)

Charm CP violation @ LHCb

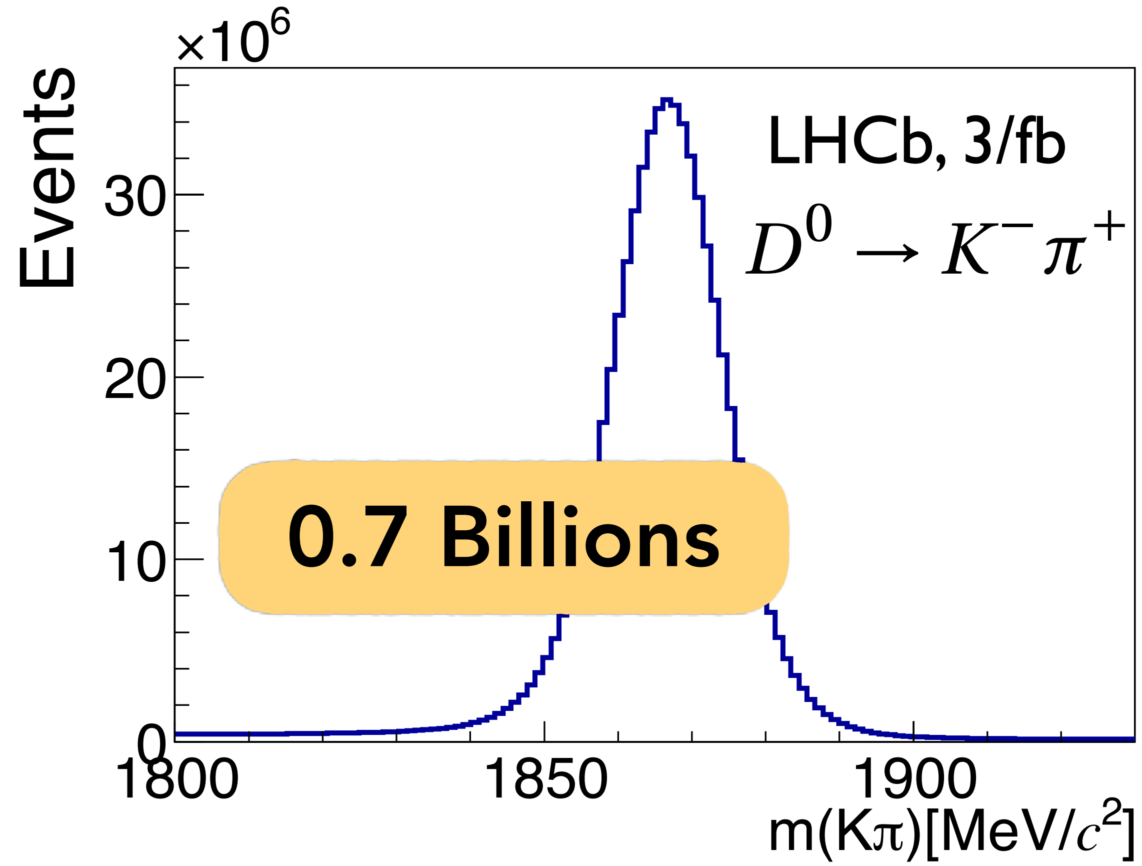
Pietro Marino on behalf of LHCb collaboration
SNS & INFN-Pisa

Why is charm charming?

- Unique and powerful probe of BSM flavour effects.
- Charm is an up-type quark:
  - complementary to *B* and *K*;
  - best bounds on a generic new physics model after the kaon mixing.



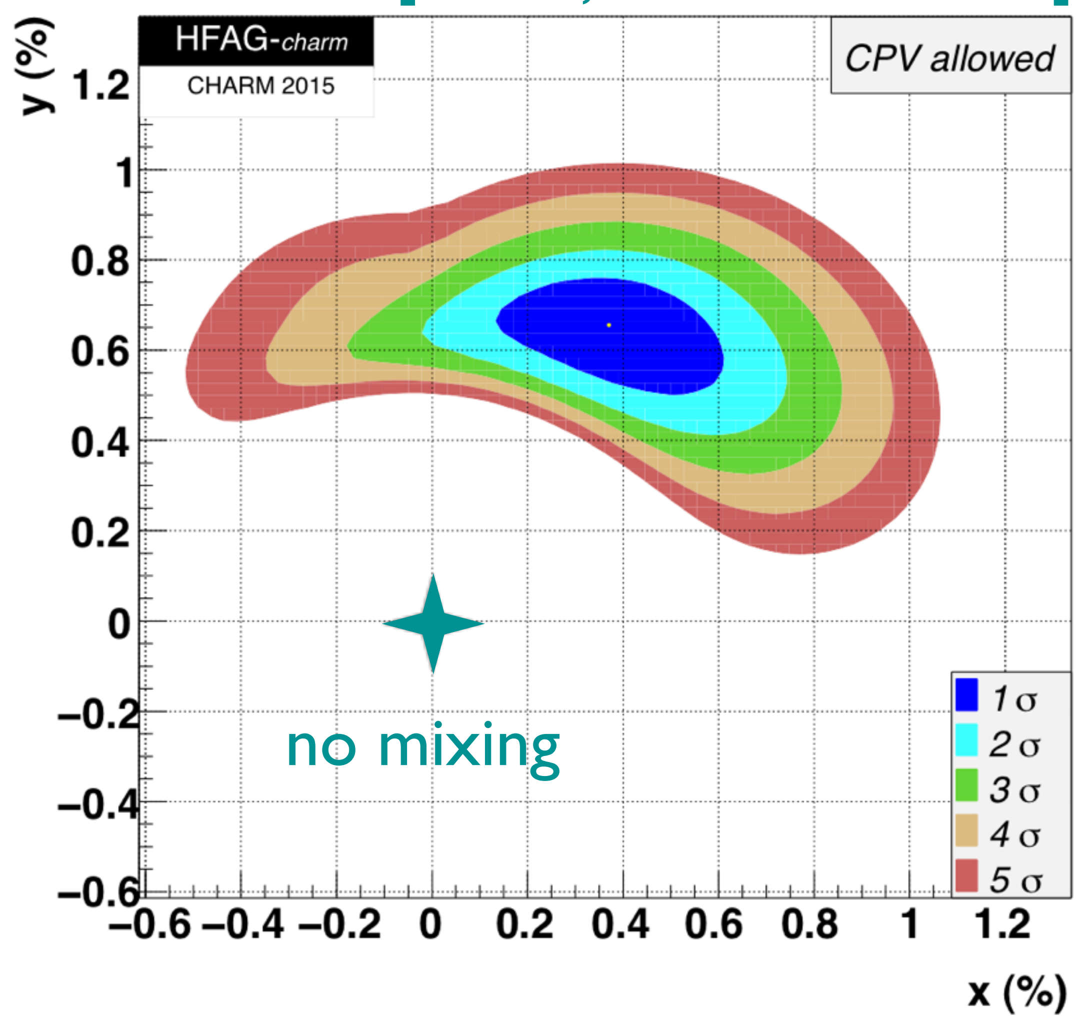
- **Huge data samples,**
  - LHCb has the opportunity to exploit fully the charm sector as a probe for new physics.
- Charm predictions are **complicated**:
  - QCD not perturbative.



Charm mixing and CP violation

- D^0 mixing is established.
- CP violation yet unobserved!
  - Small value expected from SM $\mathcal{O}(V_{ub}V_{cb}^*/V_{us}V_{cs}^*) \sim \mathcal{O}(10^{-3})$
  - Sensitivity close to possible BSM contribution (yields ~ $\mathcal{O}(10^6)$)

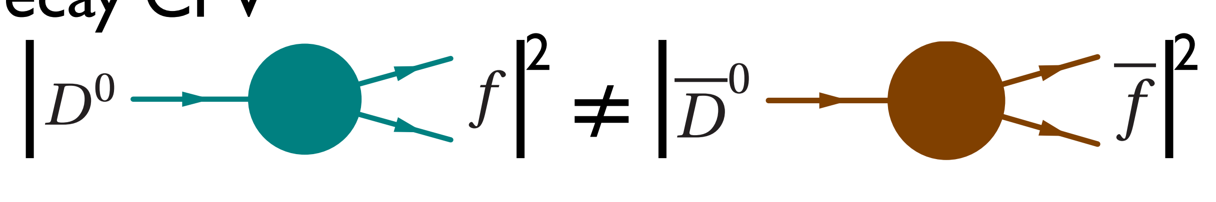
[HFAG, arXiv:1412.7515]



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

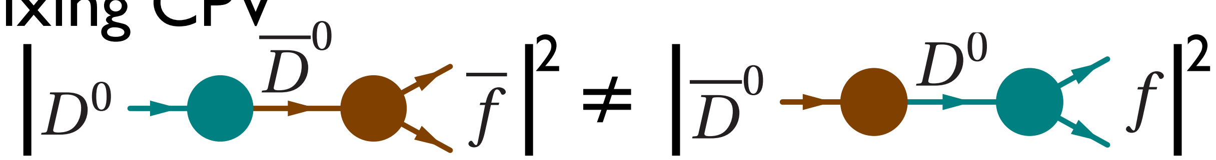
$$x \equiv \frac{m_1 - m_2}{\Gamma}, \quad y \equiv \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$

Decay CPV



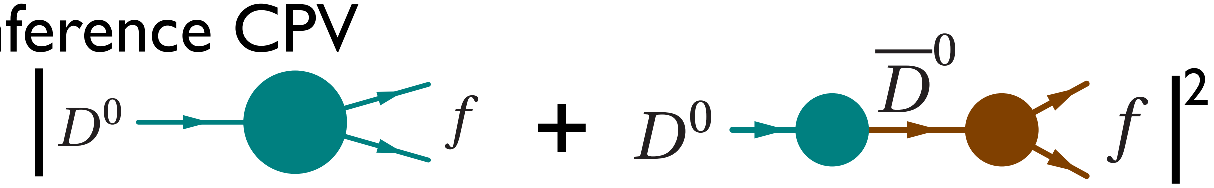
$\leftrightarrow \left|\frac{A_f}{\overline{A}_{\overline{f}}}\right| \neq 1$

Mixing CPV



$\leftrightarrow \left|\frac{q}{p}\right| \neq 1$

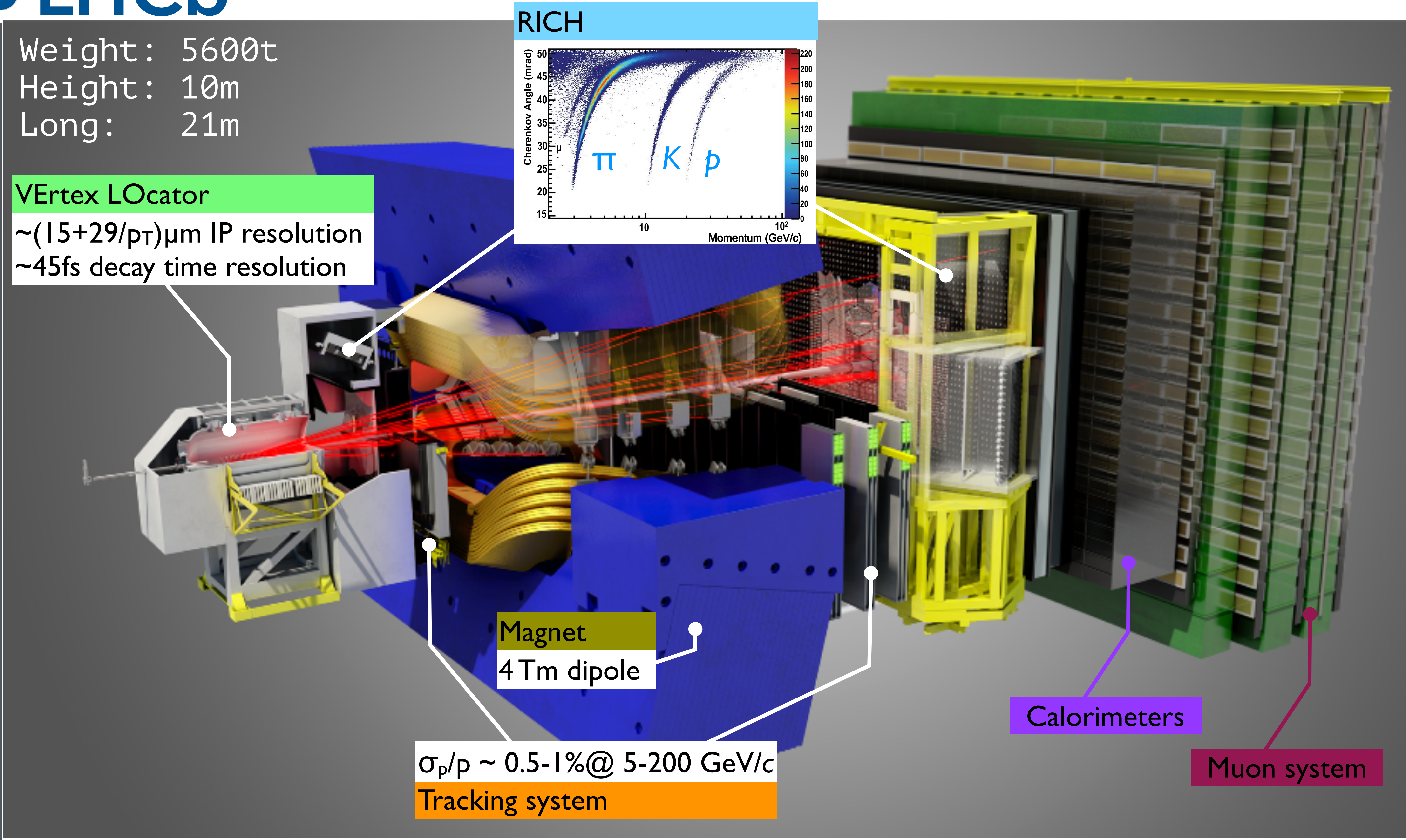
Inference CPV



$\leftrightarrow \arg\left(\frac{qA_f}{p\overline{A}_{\overline{f}}}\right) \neq 0$

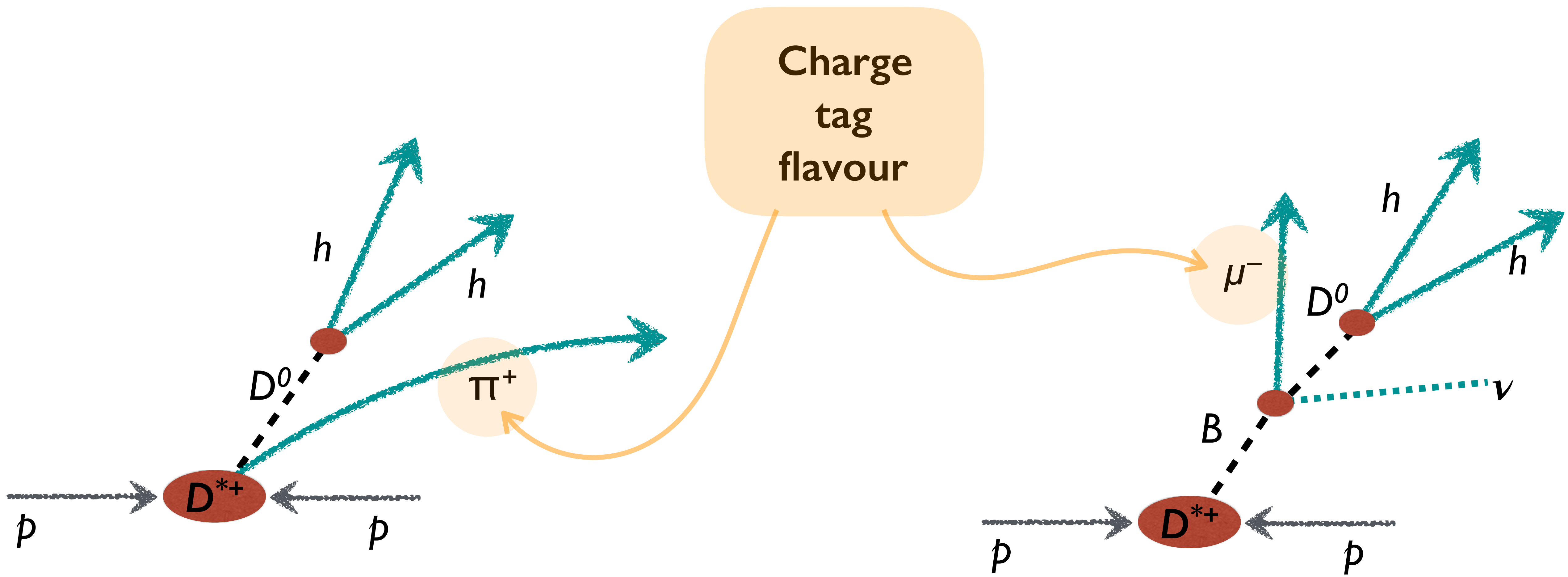
LHCb

Weight: 5600t
Height: 10m
Long: 21m



Charm flavour tagging

- In order to measure mixing and CPV, it is necessary to identify the flavour of the D^0 meson.
- LHCb exploits two decays:
  - $D^{*+} \to D^0 \pi^+$ decays
  - semi-leptonic *B*-decays



First observation of D^0-$\overline{D}^0$ oscillation in $D^0 \to K^+\pi^-\pi^+\pi^-$

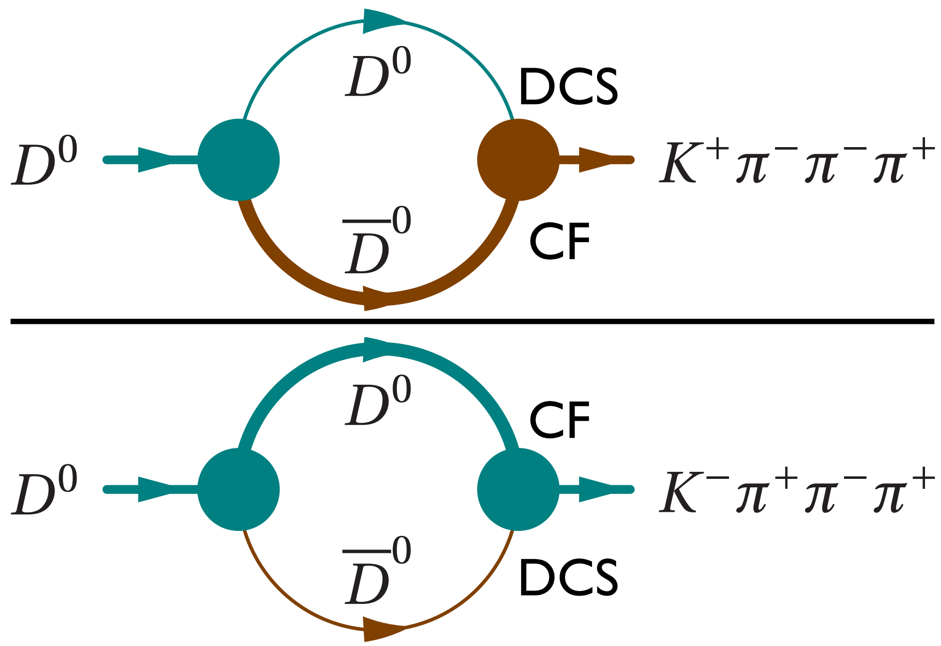
First observation of D^0 mixing in a multi-body decay

D^0 mixing with $D^0 \to K^+\pi^-\pi^+\pi^-$

[arXiv:1602.07224]

- Full Run I data sample (3/fb)
- Challenges:
  - Five-dimensional phase space parametrisation.
  - Higher combinatorial background.

R(t) =

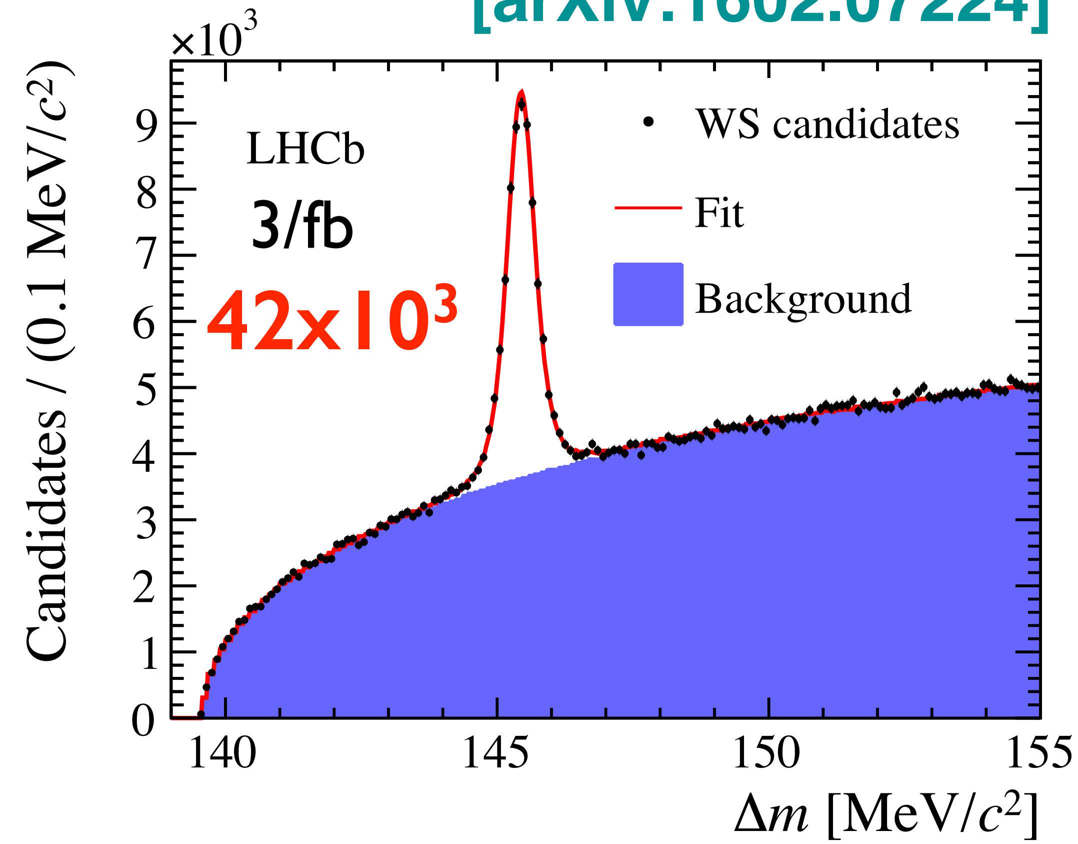


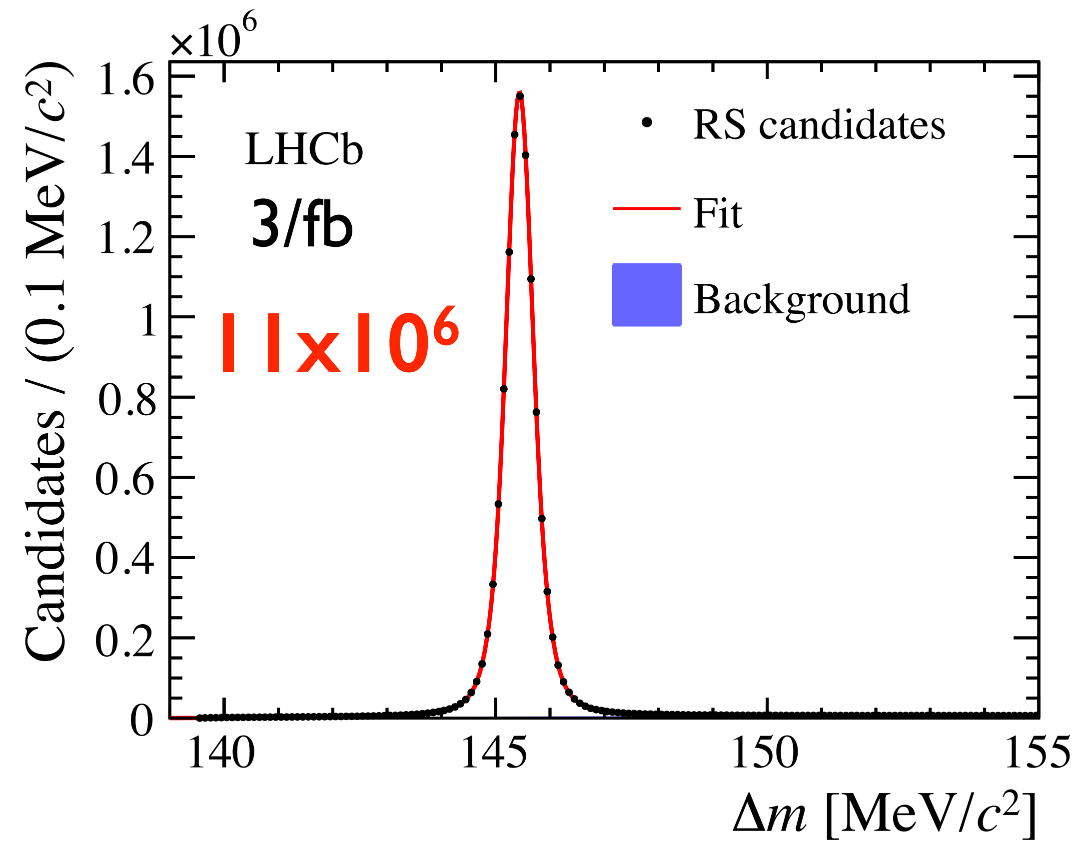
$$\approx r_D^2 - r_D R_D y' \frac{t}{\tau} + \frac{x^2+y^2}{4}\left(\frac{t}{\tau}\right)^2$$

$$R_D e^{-i\delta} = \langle\cos\delta\rangle + i\langle\sin\delta\rangle$$

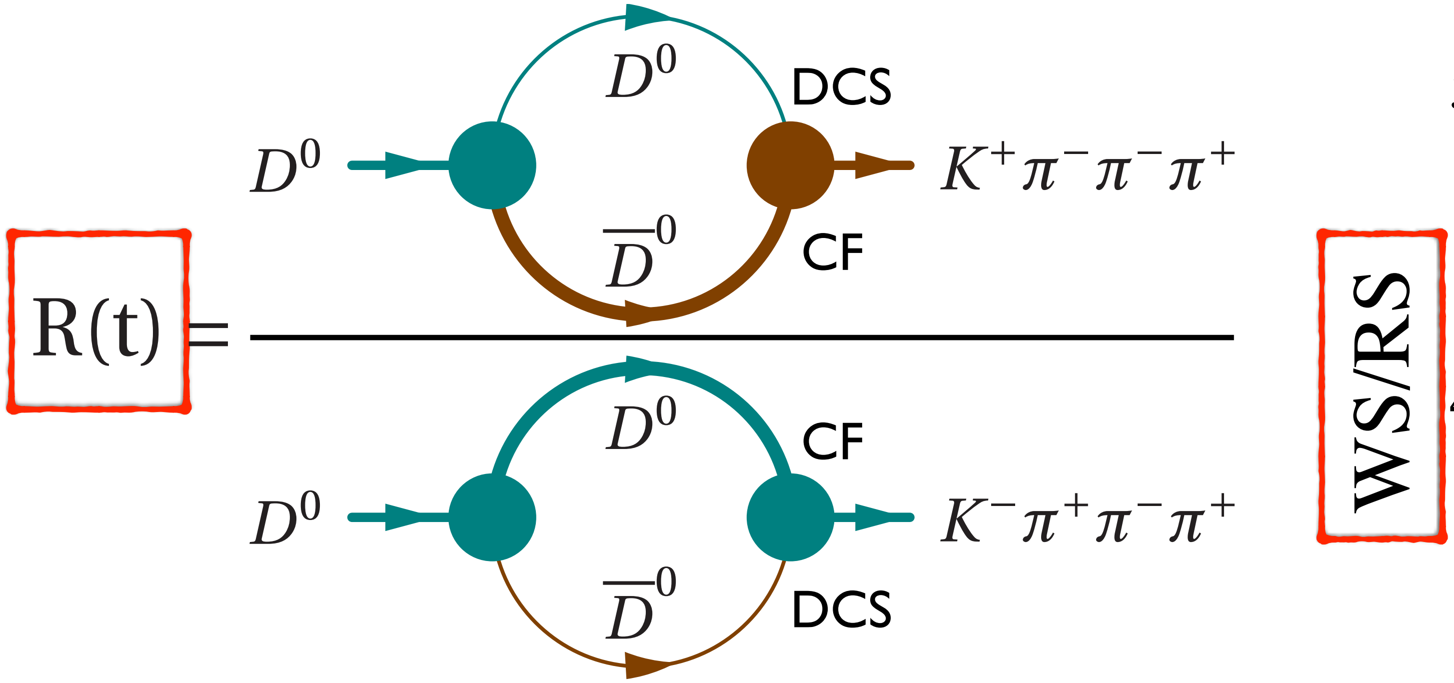
$$y' = y\cos\delta - x\sin\delta$$

$r_D =$ phase space average DCS/CF ratio amplitudes



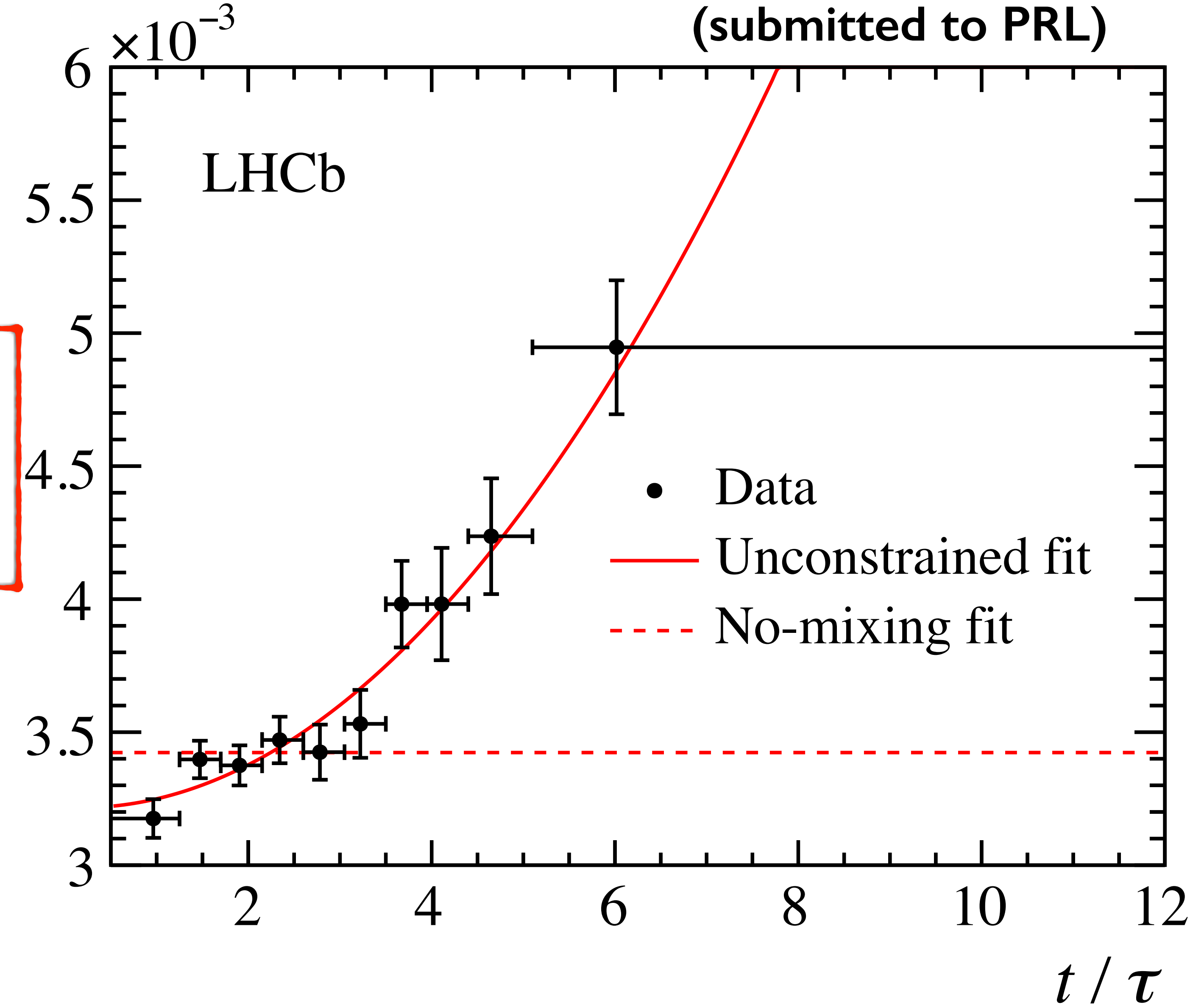


D^0 mixing with $D^0 \to K^+\pi^-\pi^+\pi^-$



$$\approx r_D^2 - r_D R_D y' \frac{t}{\tau} + \frac{x^2 + y^2}{4}\left(\frac{t}{\tau}\right)^2$$

[arXiv:1602.07224]
(submitted to PRL)



$$r_D = (5.67 \pm 0.12) \times 10^{-2}$$
$$R_D y' = (0.3 \pm 1.8) \times 10^{-3}$$

[arXiv:1602.07224]

No mixing hypothesis reject at 8.2σ

Difference of time-integrated CP asymmetries (a.k.a. ΔA_{CP})

Direct CPV in $D^0 \to h^+ h^-$

[arXiv:1602.03160]

- Time-integrated CP asymmetry:

$$A_{CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to f)}$$

- Experimentally yields are measured:

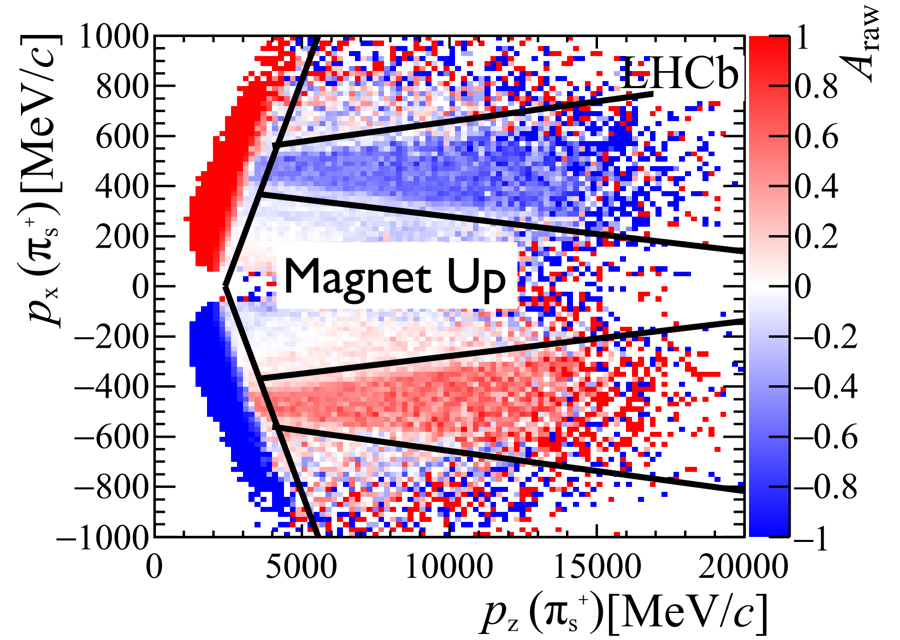
$$A_{\rm raw}(f) = \frac{N(D^{*+} \to D^0(\to f)\pi^+) - N(D^{*-} \to \overline{D}^0(\to f)\pi^-)}{N(D^{*+} \to D^0(\to f)\pi^+) + N(D^{*-} \to \overline{D}^0(\to f)\pi^-)}$$

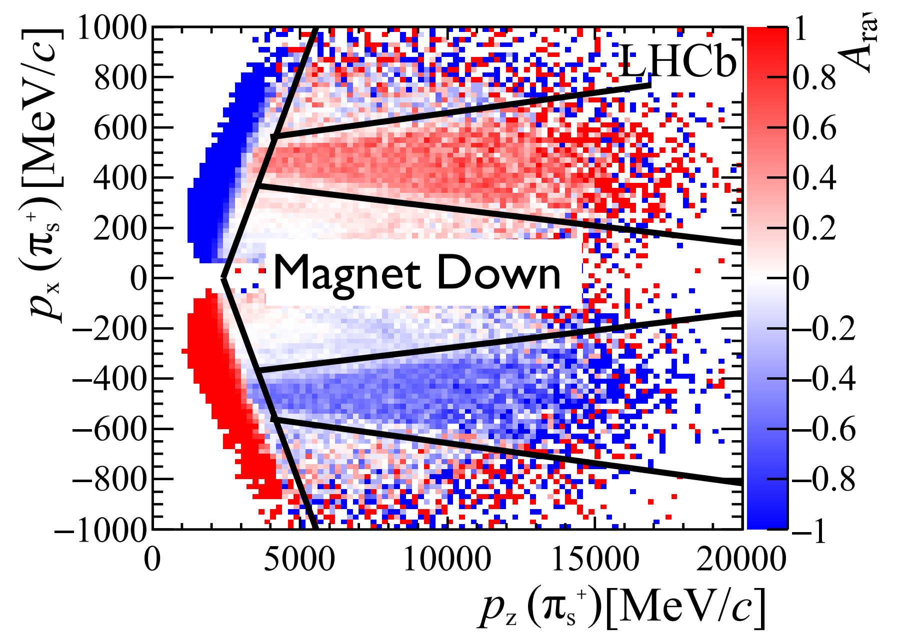
$$\approx A_{CP}(f) + A_D(f) + A_D(\pi) + A_P(D^*)$$

where

- $A_D(\pi)$ soft-pion (tag) detection asymmetry
- $A_P(D^*)$ D^* production asymmetry
- $A_D(f)$ final state detection asymmetry, zero for $f = K^+K^-, \pi^+\pi^-$

Fiducial cuts on soft-pion kinematics





Direct CPV in $D^0 \to h^+h^-$

- Time-integrated CP violation:

$$A_{CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to f)}$$

- Experimentally yields are measured:

$$A_{\text{raw}}(f) = \frac{N(D^{*+} \to D^0(\to f)\pi^+) - N(D^{*-} \to \overline{D}^0(\to f)\pi^-)}{N(D^{*+} \to D^0(\to f)\pi^+) + N(D^{*-} \to \overline{D}^0(\to f)\pi^-)}$$

$$\approx A_{CP}(f) + A_D(f) + A_D(\pi) + A_P(D^*)$$

- Challenging keep under control A_D and A_P to $\mathcal{O}(10^{-3})$. In order to access the CP asymmetry the difference between $A_{CP}(KK)$ and $A_{CP}(\pi\pi)$ is exploited:

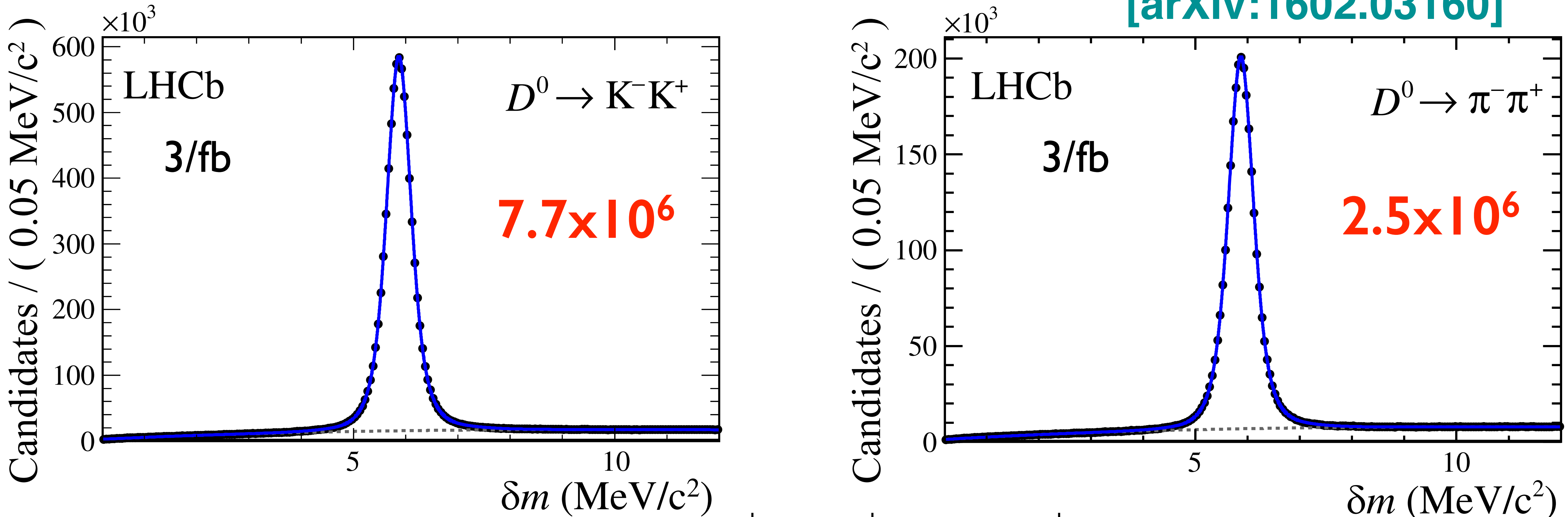
$$A_{\text{raw}}(KK) \approx A_{CP}(KK) + A_D(\pi) + A_P(D^*)$$

$$A_{\text{raw}}(\pi\pi) \approx A_{CP}(\pi\pi) + A_D(\pi) + A_P(D^*)$$

$$\Delta A_{CP} = A_{\text{raw}}(KK) - A_{\text{raw}}(\pi\pi) = A_{CP}(KK) - A_{CP}(\pi\pi)$$

ΔA_{CP} in $D^0 \to h^+ h^-$ decays

[arXiv:1602.03160]



$$\delta m = m(h^+ h^- \pi^+) - m(h^+ h^-) - m_\pi$$

- **New** measurement with full Run I data sample (3/fb, D^*-tagged):

$$\Delta A_{CP} = (-0.10 \pm 0.08(\text{stat.}) \pm 0.03(\text{syst.}))\%$$

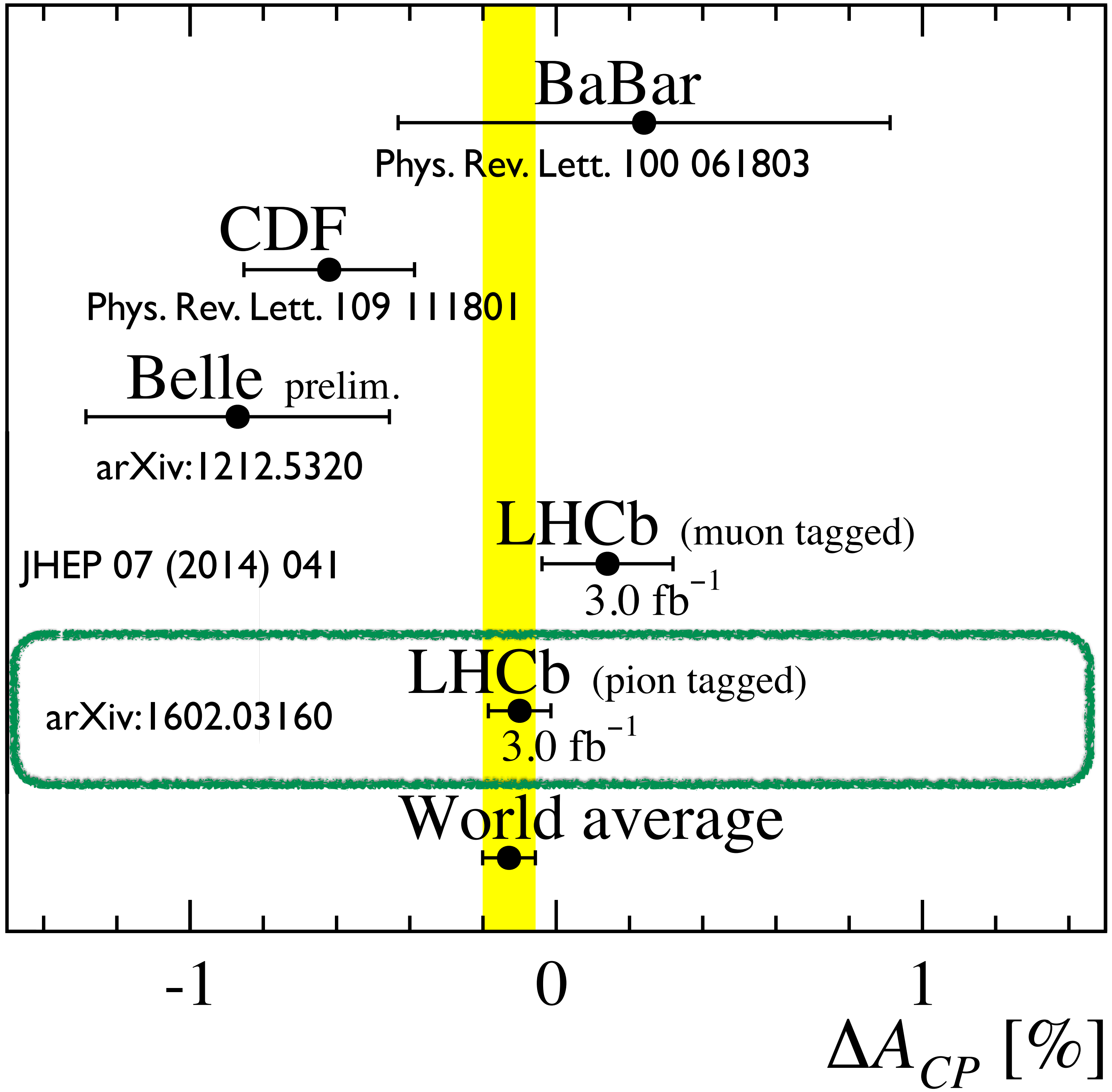
[arXiv:1602.03160]
(submitted to PRL)

- Semi-leptonic tagged measurement (3/fb):

$$\Delta A_{CP} = (+0.14 \pm 0.16(\text{stat.}) \pm 0.08(\text{syst.}))\%$$

[JHEP 07 (2014) 041]

• ΔA_{CP} state-of-the-art



World best measurement

Naive average (neglecting indirect CPV contribution) = (-0.129 ± 0.072)%

Time dependent CP asymmetry (a.k.a. A_Γ)

A_Γ: indirect *CPV in $D^0 \to h^+h^-$* decays

- Time-dependent CP asymmetry:

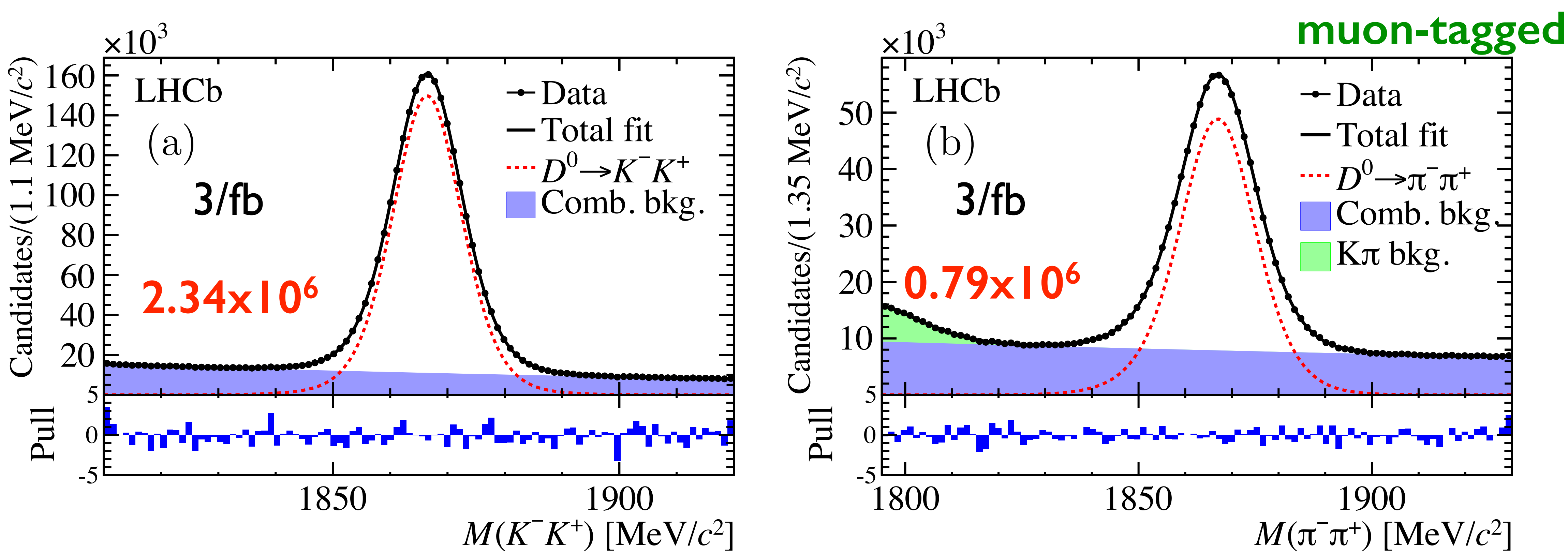
$$A_{CP}(t) = \frac{\Gamma(D^0(t) \to f) - \Gamma(\overline{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\overline{D}^0(t) \to f)} \simeq a_{CP}^{dir} - \frac{t}{\tau_{D^0}} A_\Gamma$$

$$A_m = \left|\frac{q}{p}\right|^2 - 1$$

- A_Γ measures CPV in the mixing (A_m) e in the decay (A_d):

$$A_\Gamma \simeq \left[\frac{1}{2}(A_m + A_d) y \cos\phi - x \sin\phi\right]$$

$$A_d = \left|\frac{\overline{A}_f}{A_f}\right|^2 - 1$$



[JHEP 1504 (2015) 043]

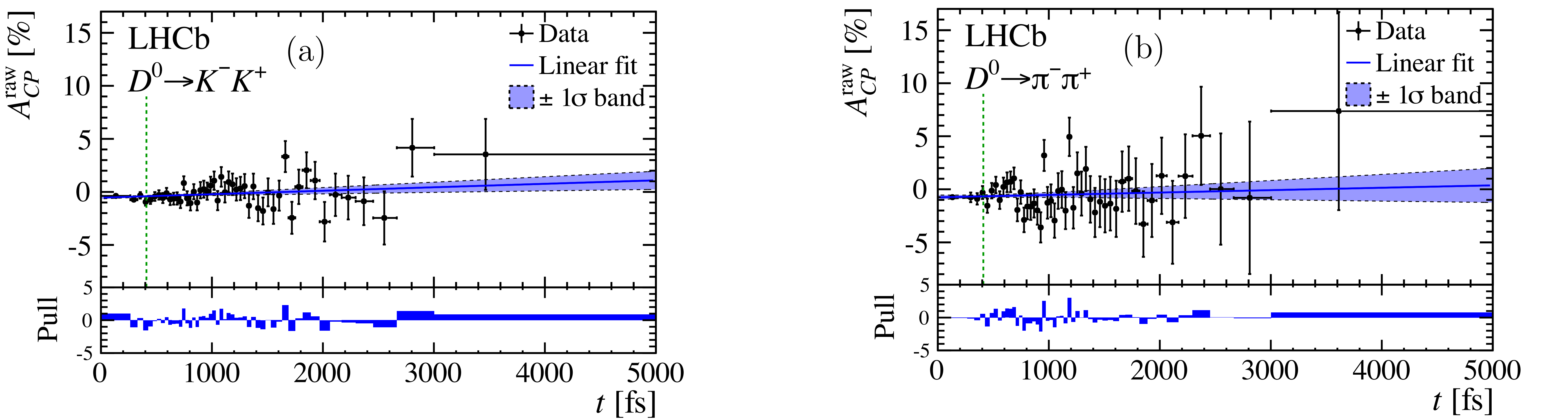
A_Γ: indirect *CPV in $D^0 \to h^+h^-$* decays

- Measure yields asymmetry in various bin of D^0 proper decay time:

$$A^i_{\rm raw} = \frac{n_i(D^0 \to f) - n_i(\overline{D}^0 \to f)}{n_i(D^0 \to f) + n_i(\overline{D}^0 \to f)}; \qquad i = 1, \dots, m$$

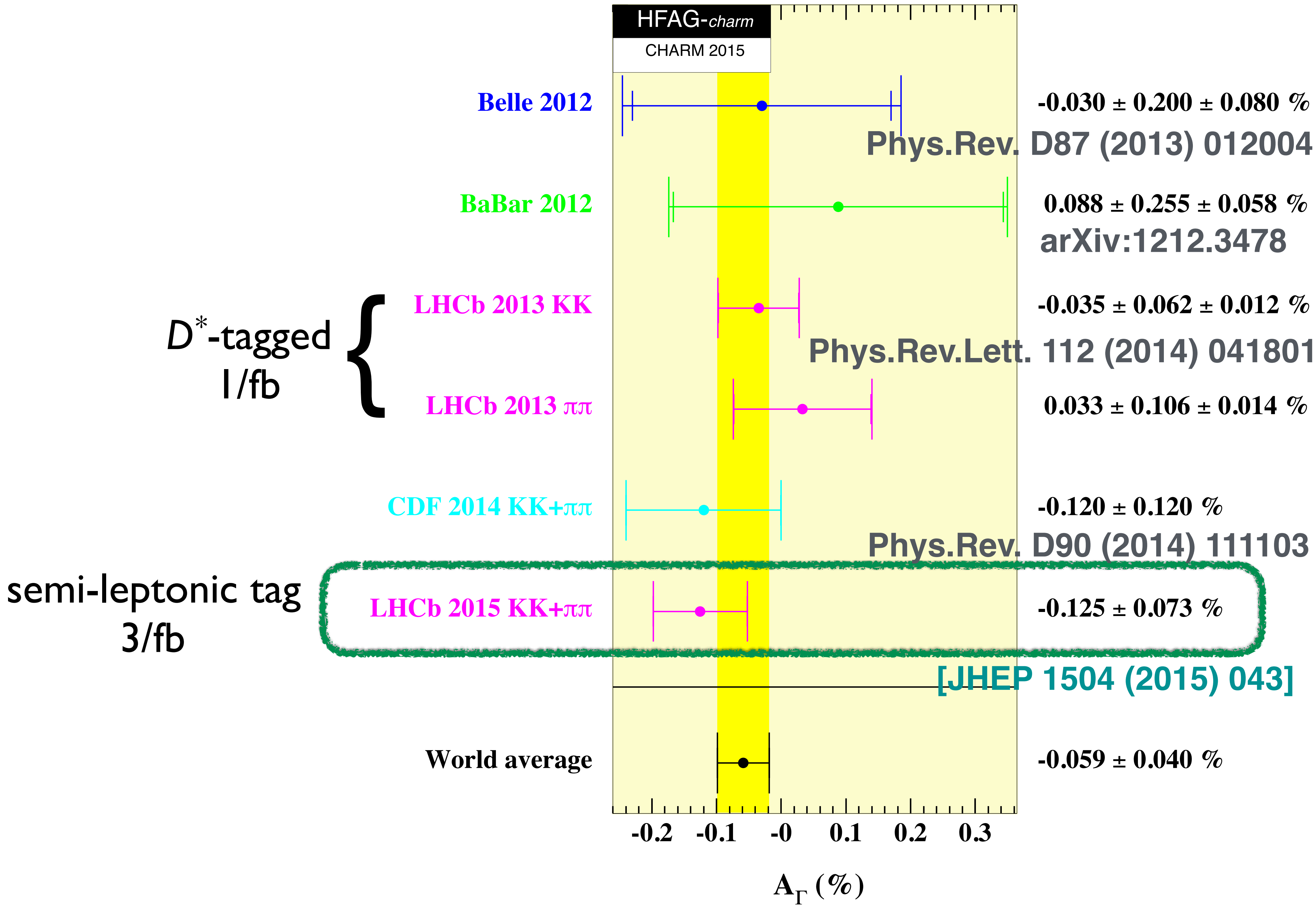
- Straight line fit of the asymmetry as function of decay time: $A_{\rm raw}(t) = A_0 - \frac{t}{\tau_{D^0}} A_\Gamma;$
- control sample: $D^0 \to K\pi$, where pseudo-$A_\Gamma(D^0 \to K\pi) = 0$. $A_\Gamma(K^-\pi^+) = (0.009 \pm 0.032)\%$

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



[JHEP 1504 (2015) 043]

A_Γ state-of-the-art



- World best measurement from LHCb D^{*}-tagged using 1/fb of integrated luminosity.

LHCb state-of-the-art on $D^0 \to h^+h^-$ CPV

- ΔA_{CP} can be expressed as:

$$\Delta A_{CP} = \Delta a_{CP}^{\text{dir}} \left(1 + \frac{\overline{\langle t \rangle}}{\tau(D^0)}\right) y_{CP} + \frac{\Delta\langle t \rangle}{\tau(D^0)} a_{CP}^{\text{ind}}$$

$$\frac{\Delta\langle t \rangle}{\tau(D^0)} = 0.1153 \pm 0.0007(\text{stat}) \pm 0.0018(\text{syst})$$

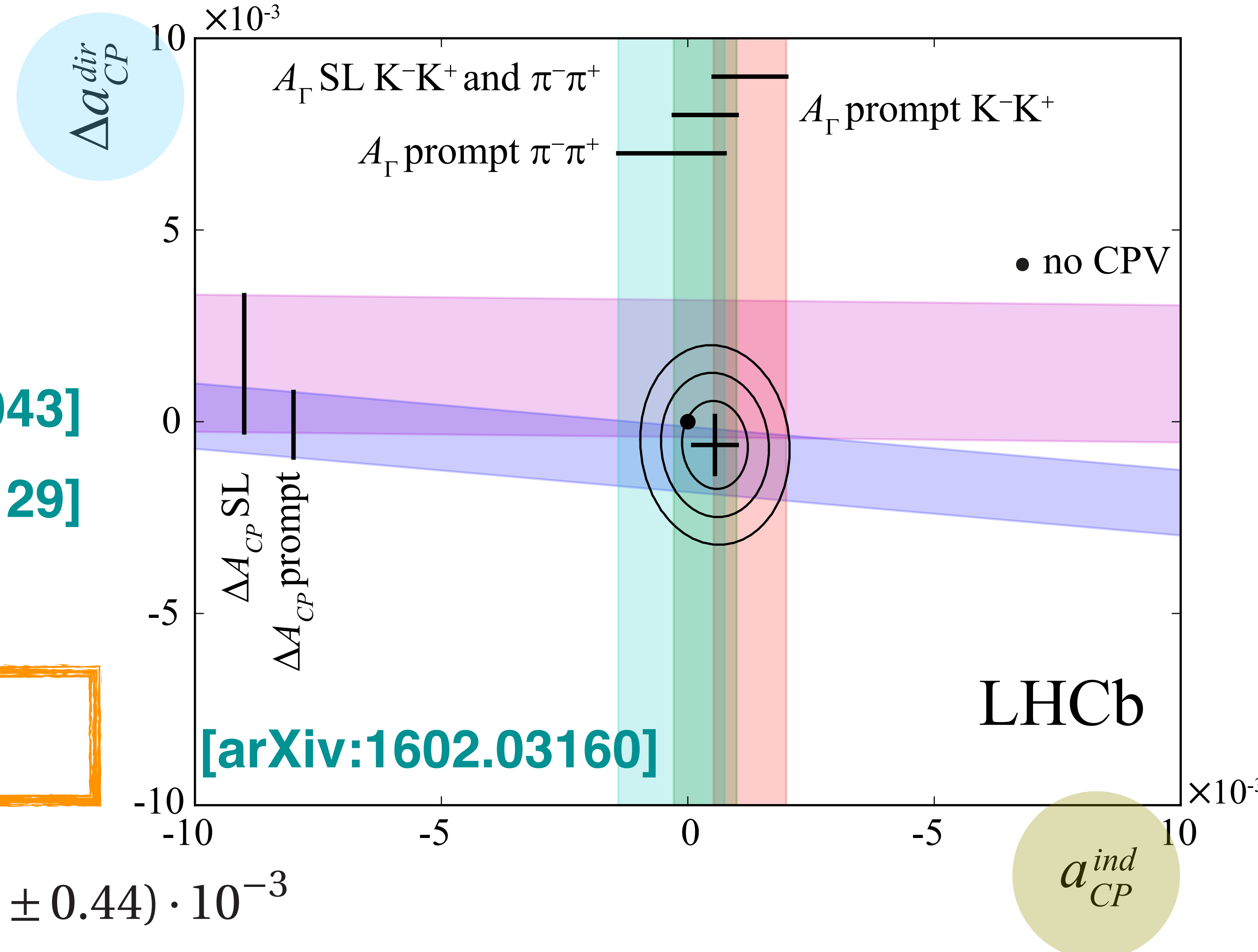
$$\frac{\overline{\langle t \rangle}}{\tau(D^0)} = 2.0949 \pm 0.0004(\text{stat}) \pm 0.0159(\text{syst})$$

- Using LHCb measurement for:

$$A_\Gamma \simeq -a_{CP}^{\text{ind}}$$ [JHEP 04 (2015) 043]

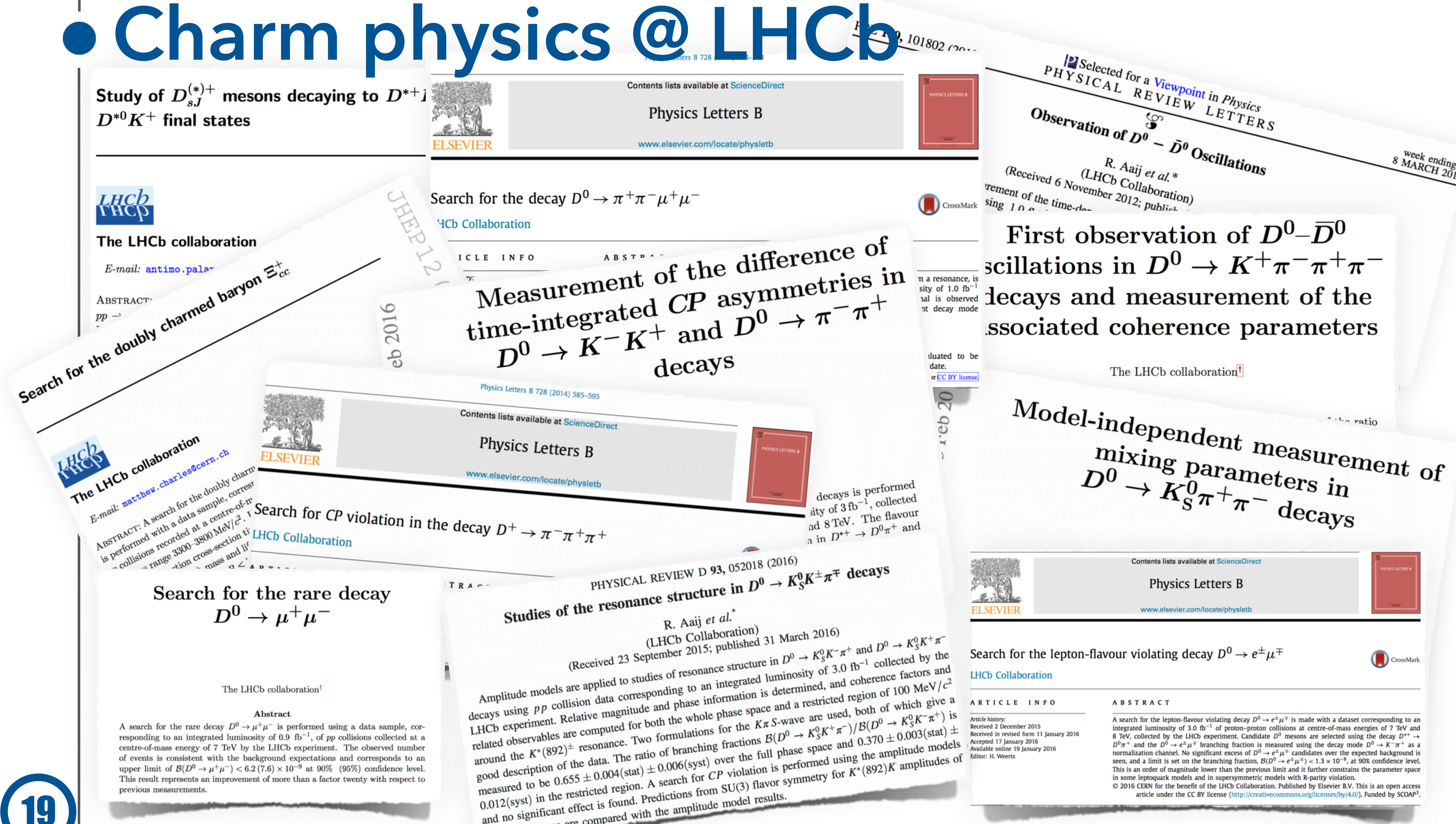
$$y_{CP} = \frac{\Gamma(D^0 \to h^+h^-)}{\Gamma(D^0 \to K^-\pi^+)} - 1$$ [JHEP 04 (2012) 129]

No CPV hypothesis: p-value 0.32



$$\Delta a_{CP}^{\text{dir}} = (-0.61 \pm 0.76) \cdot 10^{-3} \qquad a_{CP}^{\text{ind}} = (-0.58 \pm 0.44) \cdot 10^{-3}$$

Charm physics @ LHCb



More Run I results to come … more charm in Run II and Upgrade

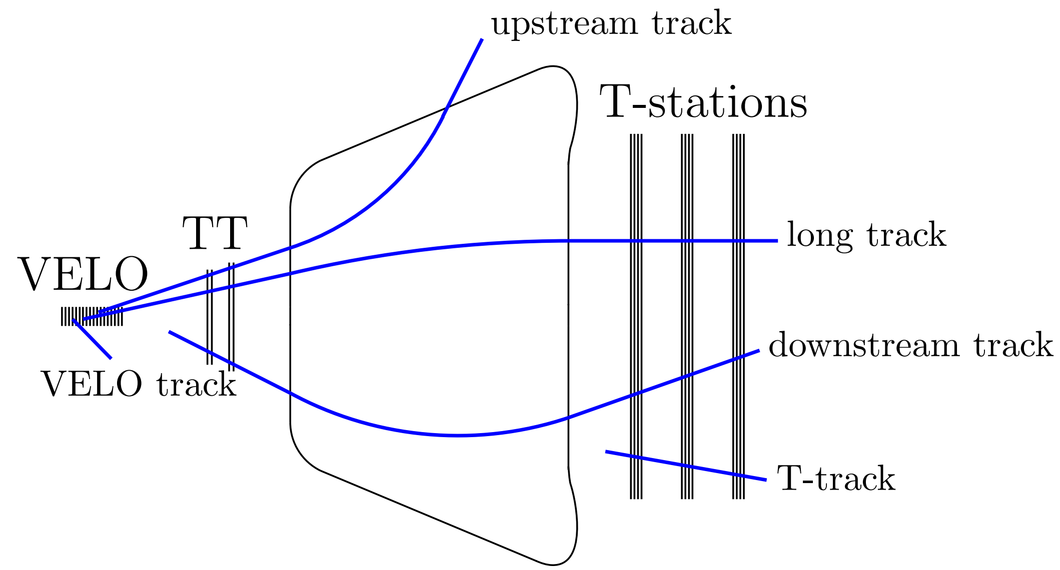
Backup

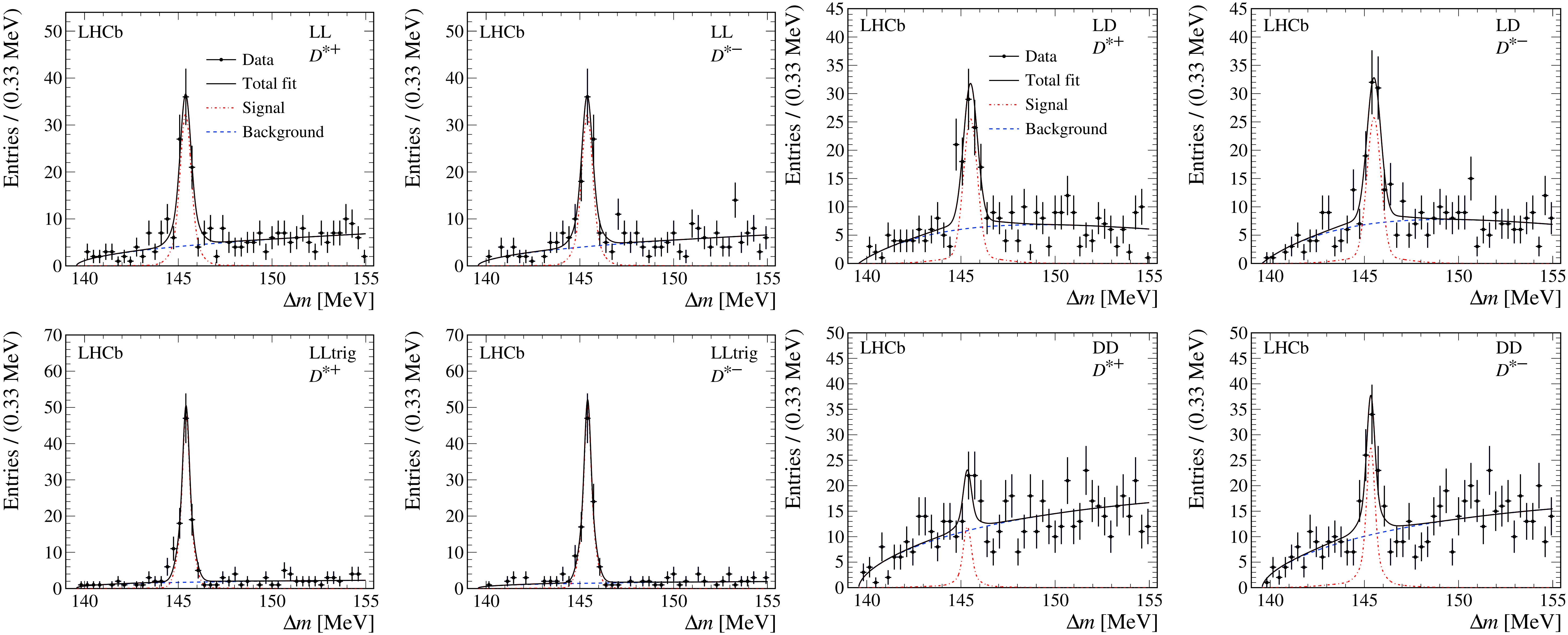
LHCb benchmarks

Type	Observable	Current precision	LHCb 2018	**Upgrade** (50 fb^{-1})	Theory uncertainty
B_s^0 mixing	$2\beta_s$ ($B_s^0 \to J/\psi\ \phi$)	0.10 [138]	0.025	0.008	~ 0.003
	$2\beta_s$ ($B_s^0 \to J/\psi\ f_0(980)$)	0.17 [214]	0.045	0.014	~ 0.01
	$a_{\rm sl}^s$	6.4×10^{-3} [43]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguins	$2\beta_s^{\rm eff}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$	0.17 [43]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\rm eff}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguins	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.08 [67]	0.025	0.008	0.02
	$s_0\ A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [67]	6 %	2 %	7 %
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.25 [76]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [85]	8 %	2.5 %	~ 10 %
Higgs penguins	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [13]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	γ ($B \to D^{(*)}K^{(*)}$)	~ 10–12° [244, 258]	4°	0.9°	negligible
	γ ($B_s^0 \to D_sK$)	–	11°	2.0°	negligible
	β ($B^0 \to J/\psi\ K_{\rm S}^0$)	0.8° [43]	0.6°	0.2°	negligible
Charm CP violation	A_Γ	2.3×10^{-3} [43]	0.40×10^{-3}	0.07×10^{-3}	–
	$\Delta\mathcal{A}_{CP}$	2.1×10^{-3} [18]	0.65×10^{-3}	0.12×10^{-3}	–

$D^0 \to K_s^0 K_s^0$

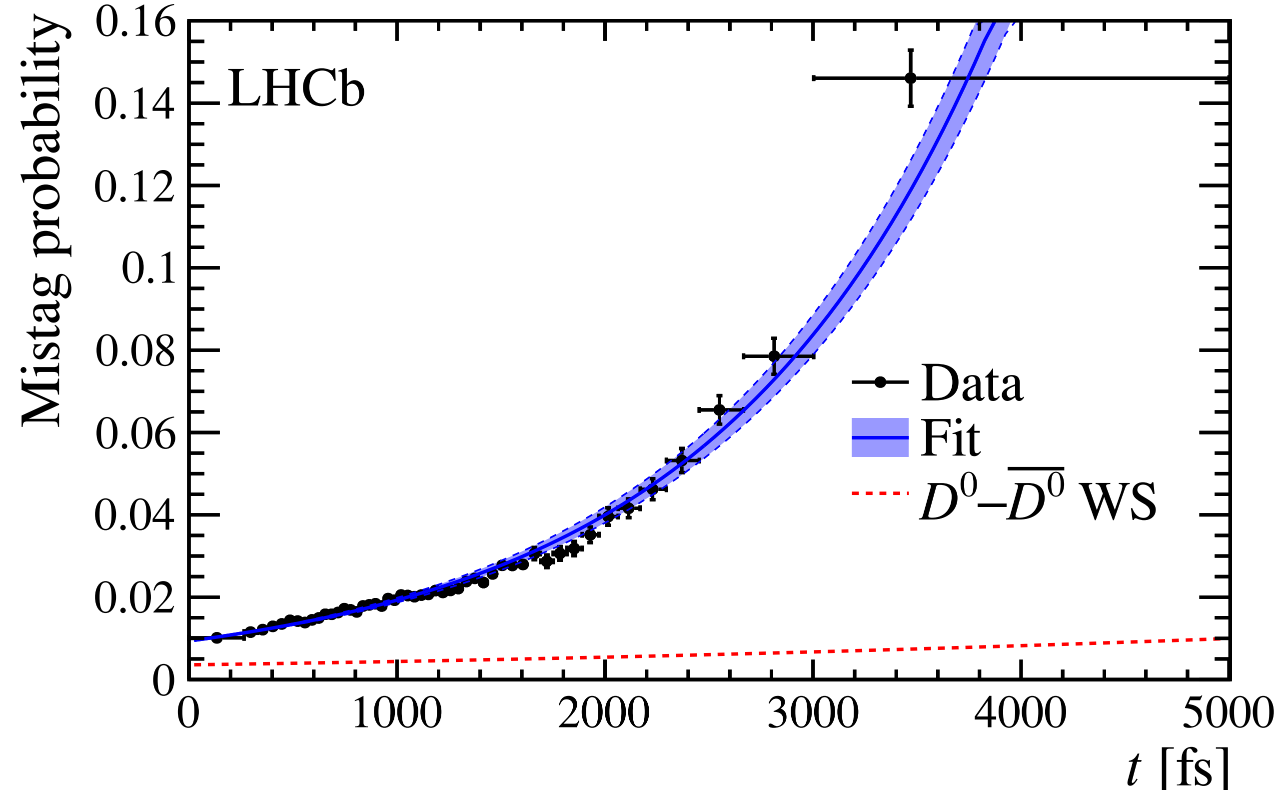
Category	N^+	N^-	$\mathcal{A}_{CP}$
LL	86 ± 11	86 ± 12	0.00 ± 0.09
LD	82 ± 14	83 ± 13	-0.00 ± 0.11
DD	29 ± 14	66 ± 14	-0.39 ± 0.23
LLtrig	96 ± 11	99 ± 11	-0.02 ± 0.08
combined			-0.029 ± 0.052

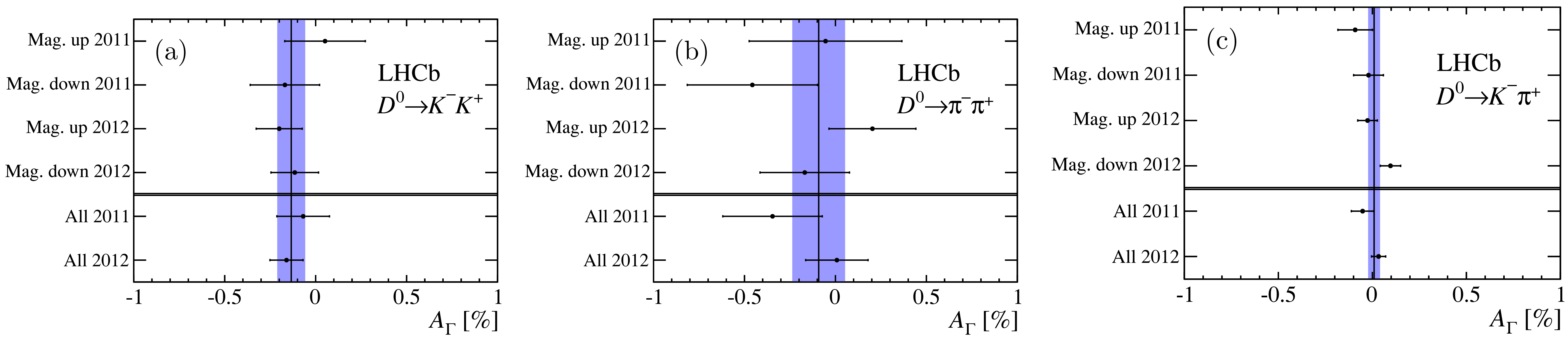




A_Γ: indirect $D^0 \to h^+h^-$ CPV, systematics

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

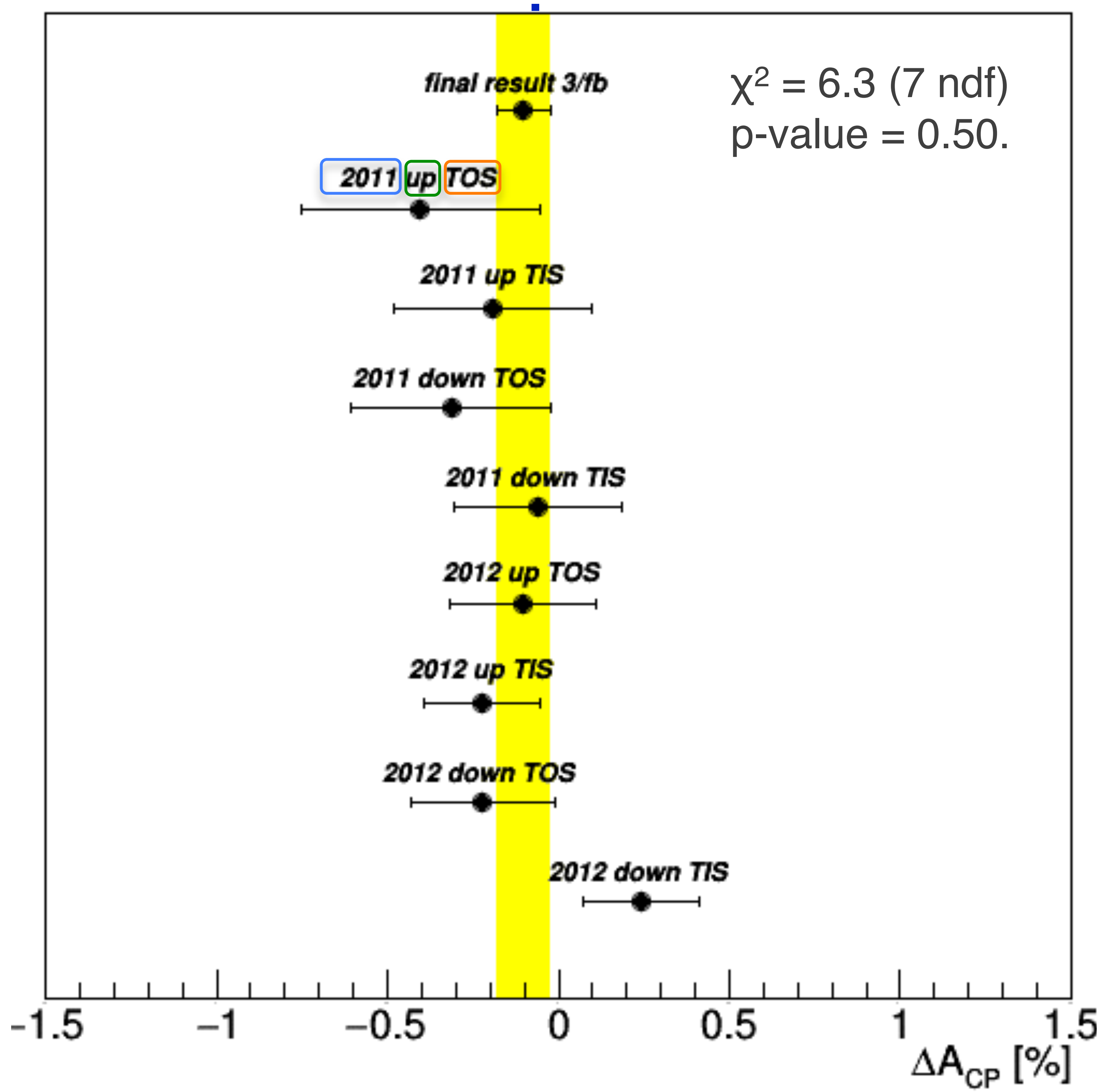




Cross-checks

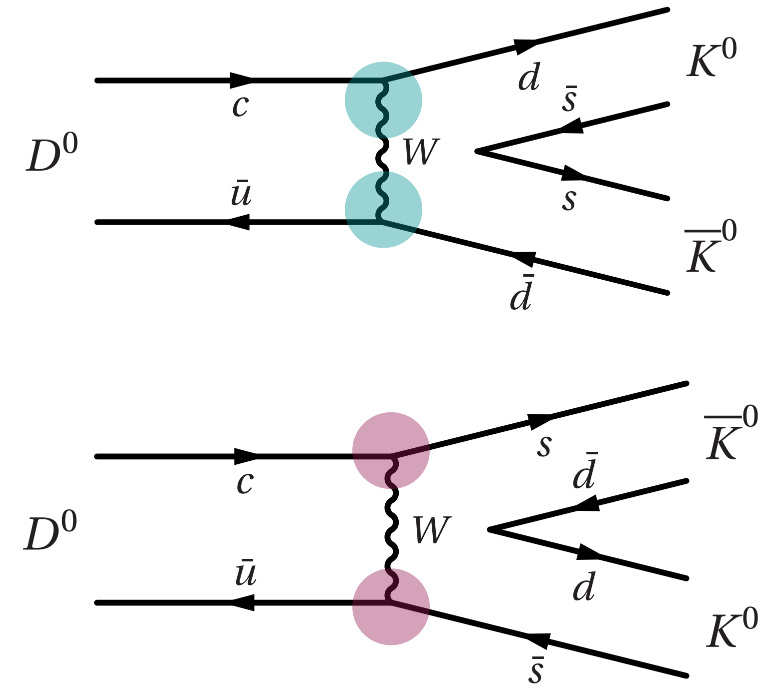
- Data taking year (= different energy 7/8 TeV)
- Magnet Polarity
- Trigger configuration
  - TOS: trigger on signal
  - TIS: trigger independent from signal

- cross-checks:
  - π-soft, D^0 kinematics
  - run number
  - PID requirements
  - D^* vertex quality
  - …



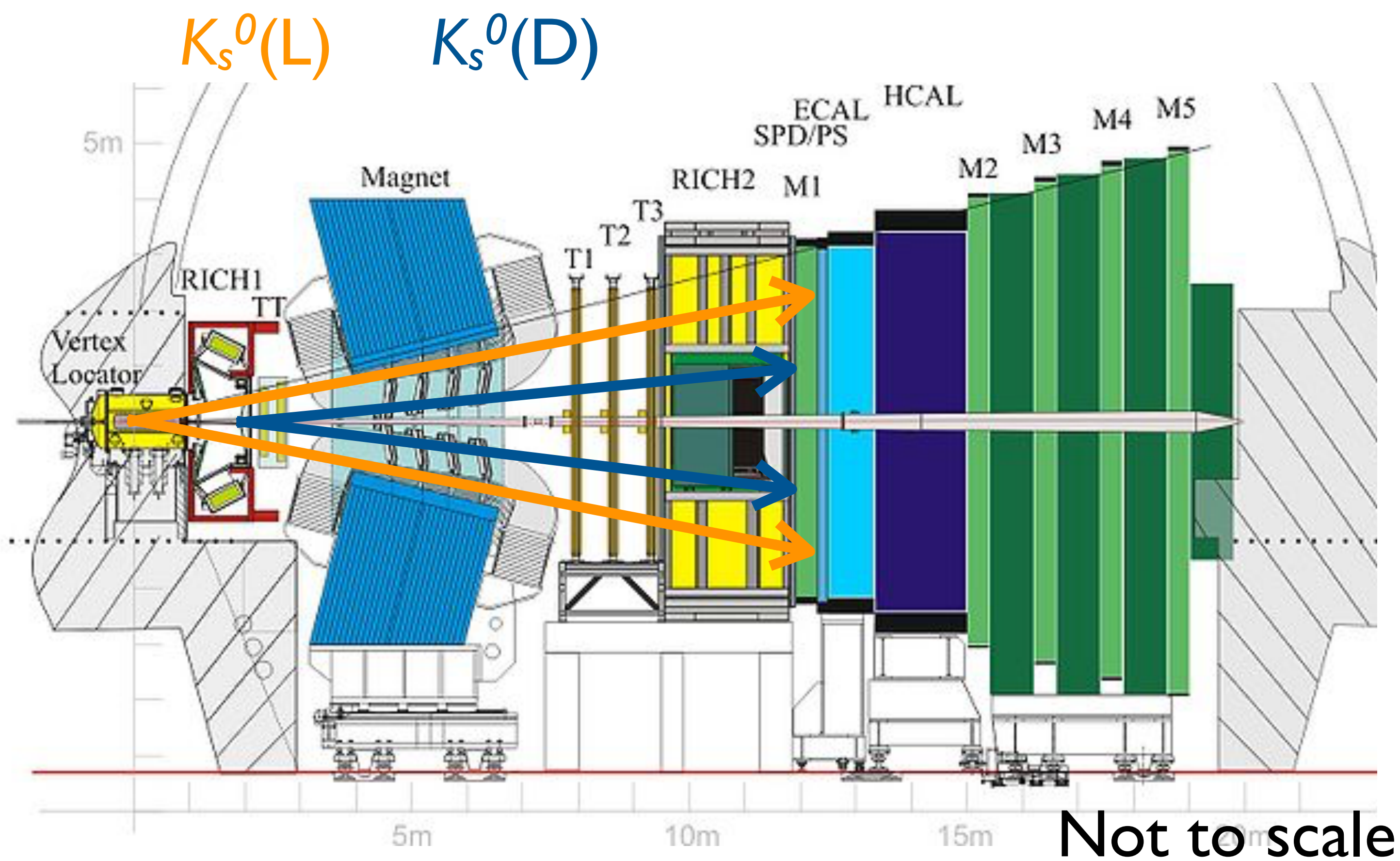
arXiv:1602.03160

CPV in $D^0 \to K_s^0 K_s^0$ decays



- Decay dominated by long-distance contributions:
  - short-distance contributions cancel since $V_{cd}V_{ud}^* \simeq -V_{cs}V_{us}^*$,
  - interference terms could give a large contribution to CPV $\mathcal{O}(1\%)$;

    [Phys. Rev. D87 (2013) 014024] [Phys. Rev. D92 (2015) 054036]



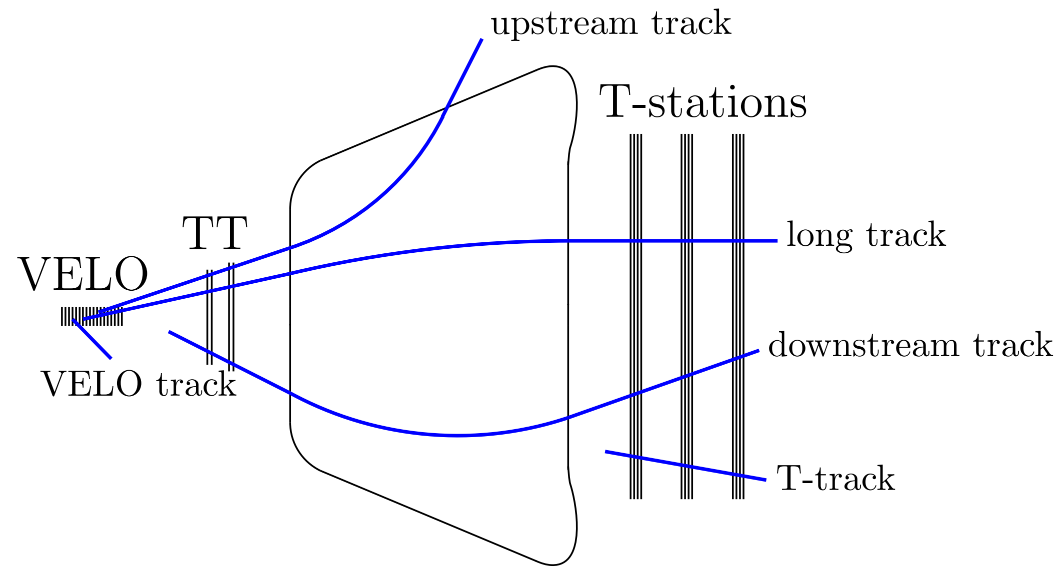
- Challenge: reconstruction of **long-lived** particles, $K_s^0 \to \pi^+\pi^-$, decaying mainly outside the region of vertex detector (VELO)

- Only one previous measurement from CLEO:

$$A_{CP} = (23 \pm 19)\%$$

[PRD 63 (2011) 071101]

A_{CP} in $D^0 \to K_s^0 K_s^0$



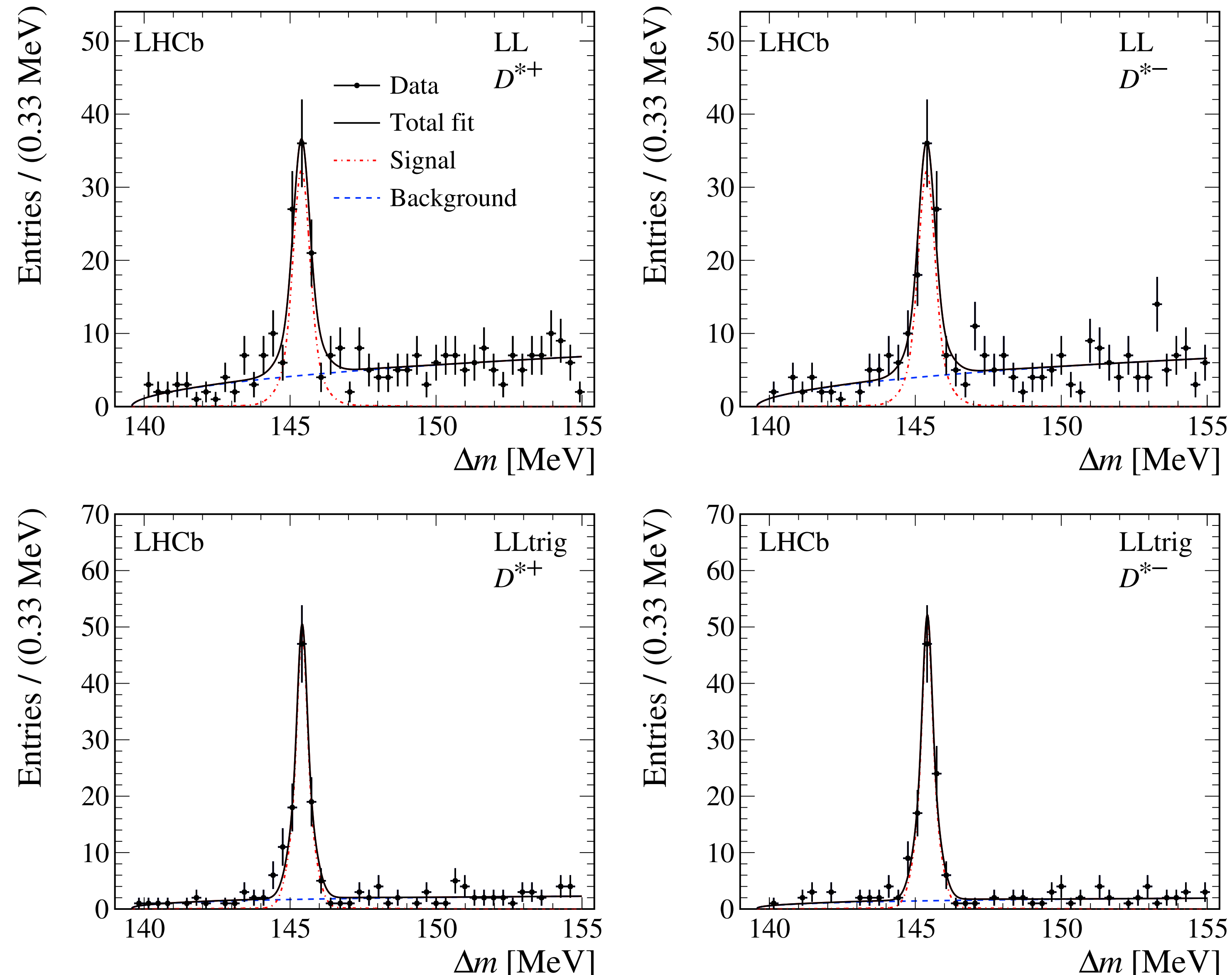
- Measurement of *CP* asymmetry:

$$A_{\text{raw}}(K_s^0 K_s^0) \approx A_{CP}(K_s^0 K_s^0) + A_D(\pi) + A_P(D^*)$$

- D^*-tagged decays.
- Detection, $A_D(\pi)$, and production, $A_P(D^*)$, asymmetries kept under control using $D^0 \to K\pi$ control sample;
  - both $\mathcal{O}(1\%)$.
- **600 events** with the full RunI data sample:

$$A_{CP} = -0.029 \pm 0.052(\text{stat.}) \pm 0.022(\text{syst.})$$

- Large improvement with respect to the previous measurement (~ factor 4).
- Dedicate trigger in Run2.



$$\Delta m = m(K_s^0 K_s^0 \pi) - m(K_s^0 K_s^0)$$

[JHEP 10 (2015) 055]