



Vista di Genova, Ambroise Louis Garneray (ca. 1810)

Violazione di CP nei decadimenti del charm a LHCb

Pietro Marino per la collaborazione LHCb
SNS & INFN-Pisa

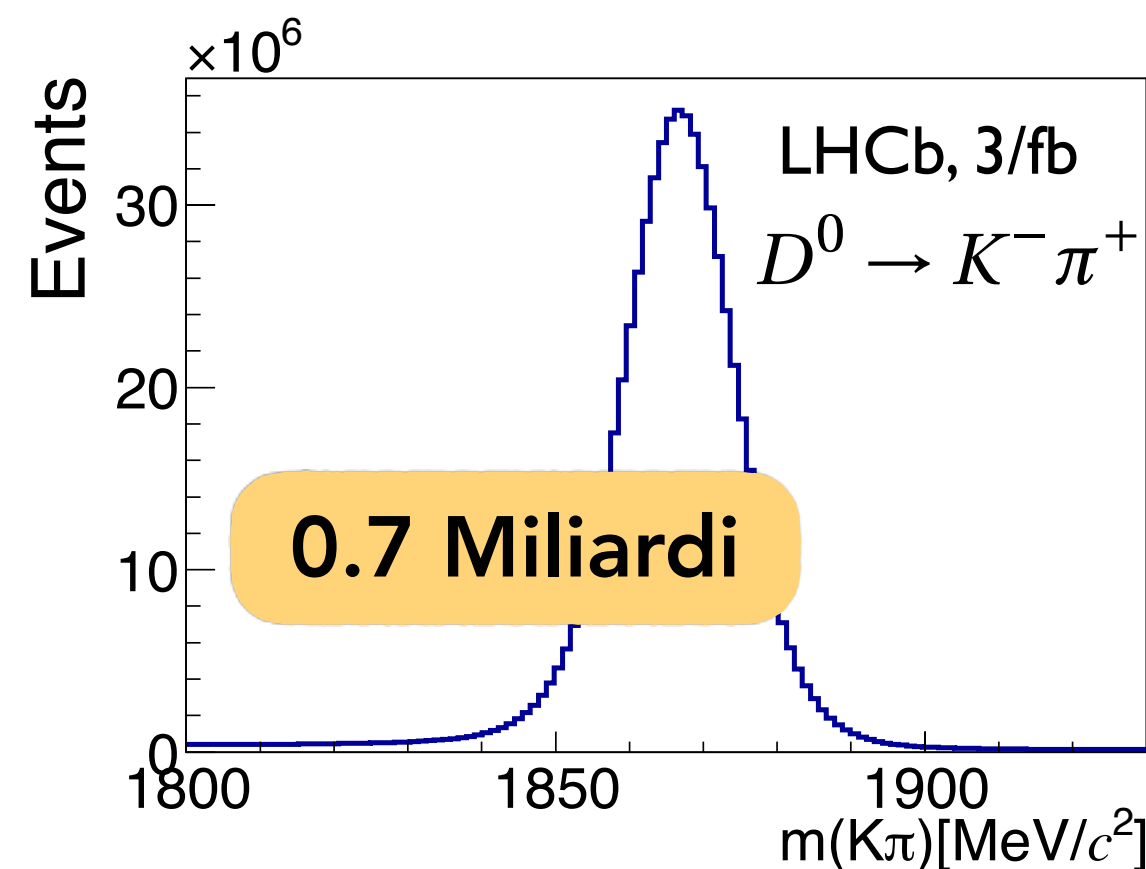
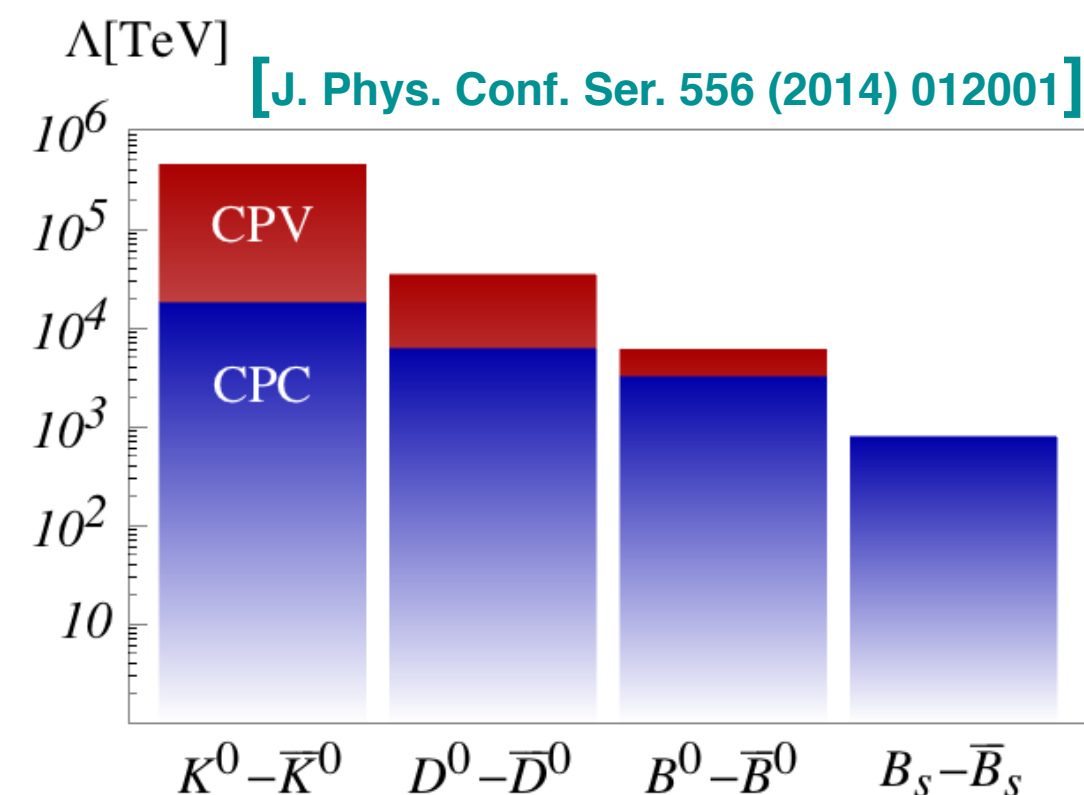


SCUOLA
NORMALE
SUPERIORE



● Perché il CHARM?

- Una sonda unica per la Fisica del sapore BSM.
- Unico quark di tipo up che oscilla:
 - ◆ complementare a sistemi B e K
 - ◆ i più stringenti limiti per un generico modello di NP dopo il mixing del sistema K
- Enormi campioni di dati (l'era del Gev),
 - ◆ LHCb ha i campioni i più grandi campioni di charm al mondo.
- Predizioni nel charm sono **complicate**:
 - ◆ sprona e aiuta la comprensione della QCD non perturbativa.



● Sistema dei mesoni D^0

- Sistema mesoni D^0 :

$$i \frac{\delta}{\delta t} \begin{pmatrix} |D^0(t)\rangle \\ |\bar{D}^0(t)\rangle \end{pmatrix} = \left[\begin{pmatrix} M_{11} & M_{12} \\ M_{12}^* & M_{22} \end{pmatrix} - \frac{i}{2} \begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{22} \end{pmatrix} \right] \begin{pmatrix} |D^0(t)\rangle \\ |\bar{D}^0(t)\rangle \end{pmatrix}$$

- Soluzione: due autostati di massa, combinazioni lineari degli autostati dell'interazione forte:

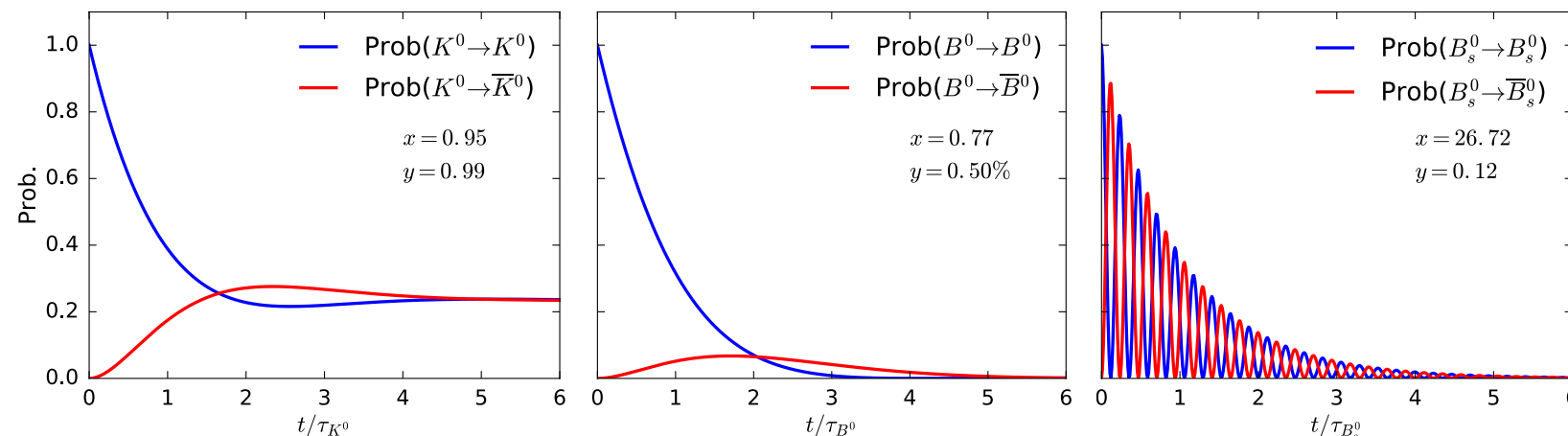
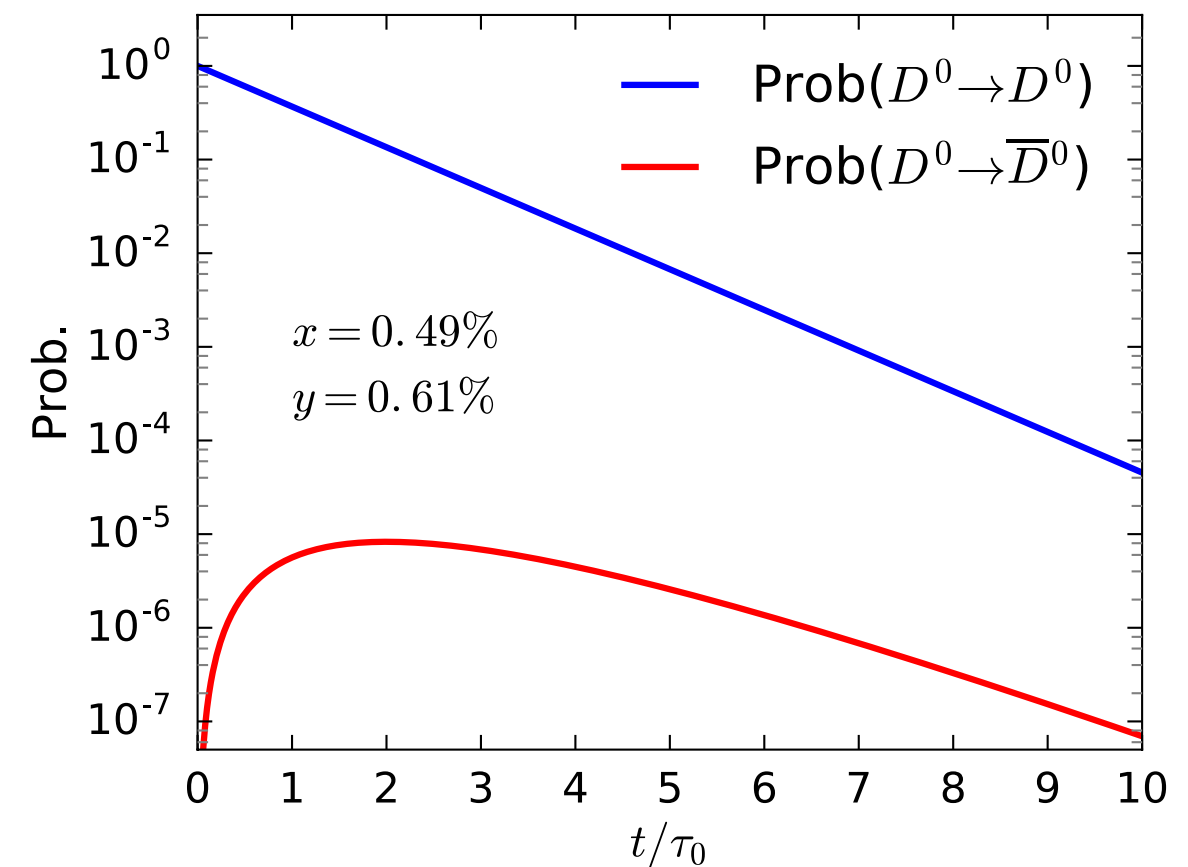
$$|D_{L,H}\rangle = p |D^0\rangle \pm q |\bar{D}^0\rangle$$

- Il sapore del mesone *oscilla* tra D^0 e \bar{D}^0

$$x \equiv \frac{m_H - m_L}{\Gamma}, \quad y \equiv \frac{\Gamma_H - \Gamma_L}{2\Gamma}$$

$$|\langle D^0(0) | D^0(t) \rangle|^2 \propto e^{-\Gamma t} [\cosh(y\Gamma t) + \cos(x\Gamma t)]$$

$$|\langle D^0(0) | \bar{D}^0(t) \rangle|^2 \propto e^{-\Gamma t} [\cosh(y\Gamma t) - \cos(x\Gamma t)]$$



● Violazione di CP nel Charm

- Non ancora osservata sperimentalmente!
- Valore aspettato dal SM $\mathcal{O}(V_{ub}V_{cb}^*/V_{us}V_{cs}^*) \sim \mathcal{O}(10^{-3})$
 - ♦ ottimo luogo dove cercare NP (buon rapporto segnale(NP)/fondo(SM))

CPV nel decadimento $\left| D^0 \rightarrow \text{[Vertex]} \rightarrow f \right|^2 \neq \left| \bar{D}^0 \rightarrow \text{[Vertex]} \rightarrow \bar{f} \right|^2 \quad \left| \frac{A_f}{\bar{A}_{\bar{f}}} \right| \neq 1$

CPV nel mixing $\left| D^0 \rightarrow \text{[Vertex]} \rightarrow \bar{D}^0 \rightarrow \text{[Vertex]} \rightarrow \bar{f} \right|^2 \neq \left| \bar{D}^0 \rightarrow \text{[Vertex]} \rightarrow D^0 \rightarrow \text{[Vertex]} \rightarrow f \right|^2 \quad \left| \frac{q}{p} \right| \neq 1$

CPV nel interferenza $\left| D^0 \rightarrow \text{[Vertex]} \rightarrow f + D^0 \rightarrow \text{[Vertex]} \rightarrow \bar{D}^0 \rightarrow \text{[Vertex]} \rightarrow f \right|^2 \quad \arg\left(\frac{qA_f}{p\bar{A}_{\bar{f}}}\right) \neq 0$

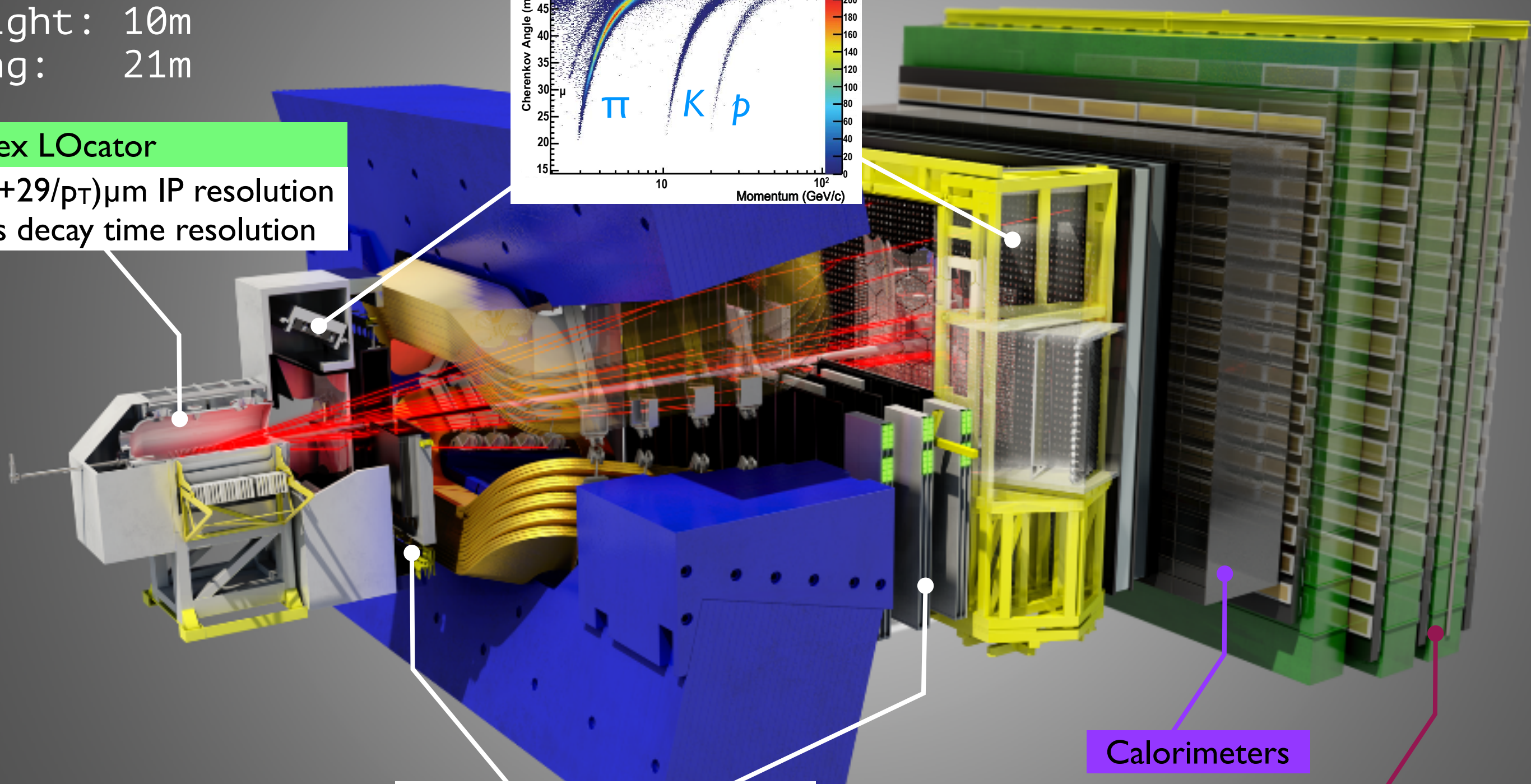
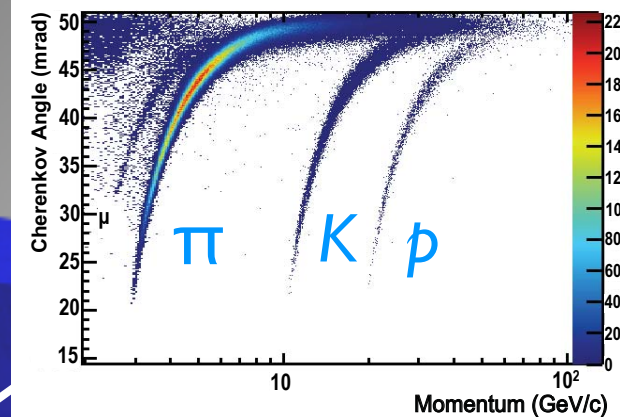
● LHCb

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

VERtex LOcator

$\sim (15 + 29/p_T) \mu\text{m}$ IP resolution
 $\sim 45\text{fs}$ decay time resolution

RICH



$\sigma_p/p \sim 0.5-1\% @ 5-200 \text{ GeV}/c$
Tracking system

Calorimeters

Muon system

● Fisica del Charm a LHCb

Study of $D_{sJ}^{(*)+}$ mesons decaying to $D^{*+}K_S^0$ and $D^{*0}K^+$ final states



The LHCb collaboration

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ABSTRACT: A search is performed for $D_{sJ}^{(*)+}$ meson $pp \rightarrow D^{*0}K^+X$ using data collected at centre-of-mass energies of 7 and 8 TeV by the LHCb detector. For the $D^{*+}K_S^0$ final state, $D^{*+} \rightarrow D^0\pi^+$ and $D^0 \rightarrow K^-\pi^+\pi^+\pi^-$ are used. For the $D^{*0}K^+$ final state, $D^{*0} \rightarrow D^0\pi^0$ and $D^0 \rightarrow K^-\pi^+\pi^+\pi^-$ are used. A prominent $D_{s1}(2536)^+$ resonance is observed. The resonances $D_{s1}(2700)^+$ and $D_{s1}(2860)^+$ are also observed. Their properties, such as their masses, widths, and branching fractions, are determined. The $D_{s1}(2700)^+$ is observed for the first time.



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Search for the decay $D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$

LHCb Collaboration

Measurement of the difference of time-integrated CP asymmetries in $D^0 \rightarrow K^-K^+$ and $D^0 \rightarrow \pi^-\pi^+$ decays

9 Feb 2016

Search for the doubly charmed baryon Ξ_{cc}^+



Physics Letters B 728 (2014) 585–595

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Search for CP violation in the decay $D^+ \rightarrow \pi^-\pi^+\pi^+$

Search for the rare decay $D^0 \rightarrow \mu^+\mu^-$

The LHCb collaboration[†]

Abstract

A search for the rare decay $D^0 \rightarrow \mu^+\mu^-$ is performed using a data sample, corresponding to an integrated luminosity of 0.9 fb^{-1} , of pp collisions collected at a centre-of-mass energy of 7 TeV by the LHCb experiment. The observed number of events is consistent with the background expectations and corresponds to an upper limit of $B(D^0 \rightarrow \mu^+\mu^-) < 6.2 (7.6) \times 10^{-9}$ at 90% (95%) confidence level. This result represents an improvement of more than a factor twenty with respect to previous measurements.

ABSTRACT

Search for CP violation in the phase space of the decay $D^+ \rightarrow \pi^-\pi^+\pi^+$ is reported using pp collision data corresponding to an integrated luminosity of 1.0 fb^{-1} , collected by the LHCb experiment at a centre-of-mass energy of 7 TeV. The Dalitz plot distributions for 3.1×10^6 D^+ and D^- candidates are compared using unbinned model-independent techniques. No evidence for CP violation is found.
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Search for the lepton-flavour violating decay $D^0 \rightarrow e^\pm\mu^\mp$

LHCb Collaboration

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ABSTRACT

A search for the lepton-flavour violating decay $D^0 \rightarrow e^\pm\mu^\mp$ is made with a dataset corresponding to an integrated luminosity of 3.0 fb^{-1} of proton-proton collisions at centre-of-mass energies of 7 TeV and 8 TeV, collected by the LHCb experiment. Candidate D^0 mesons are selected using the decay $D^{*+} \rightarrow D^0\pi^+$ and the $D^0 \rightarrow e^\pm\mu^\mp$ branching fraction is measured using the decay mode $D^0 \rightarrow K^-\pi^+$ as a normalization channel. No significant excess of $D^0 \rightarrow e^\pm\mu^\mp$ candidates over the expected background is seen, and a limit is set on the branching fraction, $B(D^0 \rightarrow e^\pm\mu^\mp) < 1.3 \times 10^{-8}$, at 90% confidence level. This is an order of magnitude lower than the previous limit and it further constrains the parameter space in some leptoquark models and in supersymmetric models with R-parity violation.
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mixing parameters in the $D^0 \rightarrow K_S^0\pi^+\pi^-$ decays

contributions due to $D^0 \rightarrow K_S^0\pi^+\pi^-$ decays

First observation of $D^0-\bar{D}^0$ oscillations in $D^0 \rightarrow K^+\pi^-\pi^+\pi^-$ decays and measurement of the associated coherence parameters

The LHCb collaboration[†]

Model-independent measurement of mixing parameters in $D^0 \rightarrow K_S^0\pi^+\pi^-$ decays

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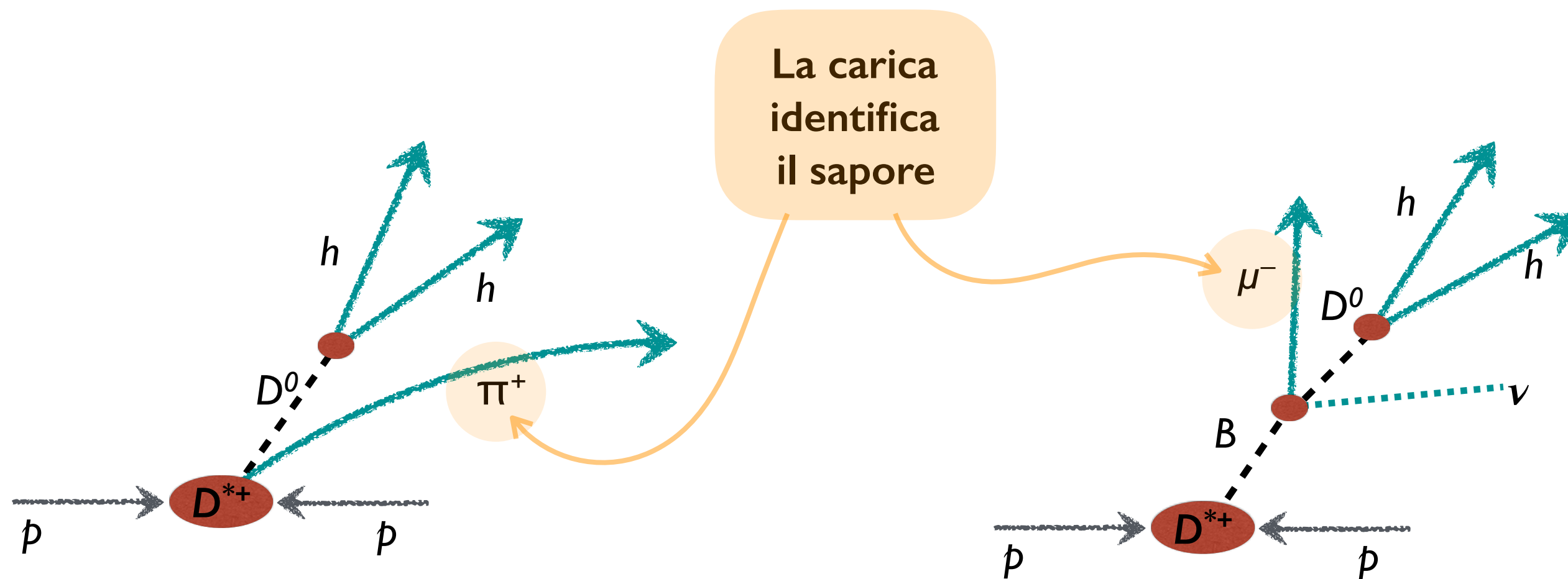
Tanta fisica del Charm a LHCb, qui solo i “golden modes” ($D^0 \rightarrow hh$).

31/3/2016

P. Marino (SNS & INFN-Pi)

● Identificazione del sapore

- Nelle misure del mixing e della violazione di CP è necessario determinare il sapore del D^0 .
- Due metodi vengono sfruttati a LHCb:
 - ♦ $D^{*+} \rightarrow D^0 \pi^+$ (decadimento forte: la carica del pione identifica il sapore del D^0)
 - ♦ decadimenti semi-leptonici del B



● CPV diretta in $D^0 \rightarrow h^+ h^-$

- Asimmetria di CP integrata nel tempo:

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

- Sperimentalmente misuriamo gli yields:

$$\begin{aligned} A_{\text{raw}}(f) &= \frac{N(D^{*+} \rightarrow D^0(\rightarrow f)\pi^+) - N(D^{*-} \rightarrow \bar{D}^0(\rightarrow f)\pi^-)}{N(D^{*+} \rightarrow D^0(\rightarrow f)\pi^+) + N(D^{*-} \rightarrow \bar{D}^0(\rightarrow f)\pi^-)} \\ &\approx A_{CP}(f) + A_D(f) + A_D(\pi) + A_P(D^*) \end{aligned}$$

dove $\begin{cases} A_D(f) & \text{asimmetria di detector dello stato finale } f = K^+ K^-, \pi^+ \pi^- \\ A_D(\pi) & \text{asimmetria di detector del pione soffice (tag)} \\ A_P(D^*) & \text{asimmetria di produzione del } D^* \end{cases}$

● CPV diretta in $D^0 \rightarrow h^+ h^-$

- Asimmetria di CP integrata nel tempo:

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

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

- Sperimentalmente misuriamo gli yields:

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

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

- Parametri, difficilmente misurabili (a queste precisioni), che non ci interessano per la CPV, si sfrutta la differenza $A_{CP}(KK)$ e $A_{CP}(\pi\pi)$:

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

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

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

● ΔA_{CP} in $D^0 \rightarrow h^+ h^-$

Poster Federico Betti

- Misure precedenti:

- ◆ usando 0.6/fb (D^* -tag): $\Delta A_{CP} = (-0.82 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.}))\%$ [PRL 108 (2012) 111602]

- ◆ 3/fb (tag semi-leptonico): $\Delta A_{CP} = (+0.14 \pm 0.16(\text{stat.}) \pm 0.08(\text{syst.}))\%$ [JHEP 07 (2014) 041]

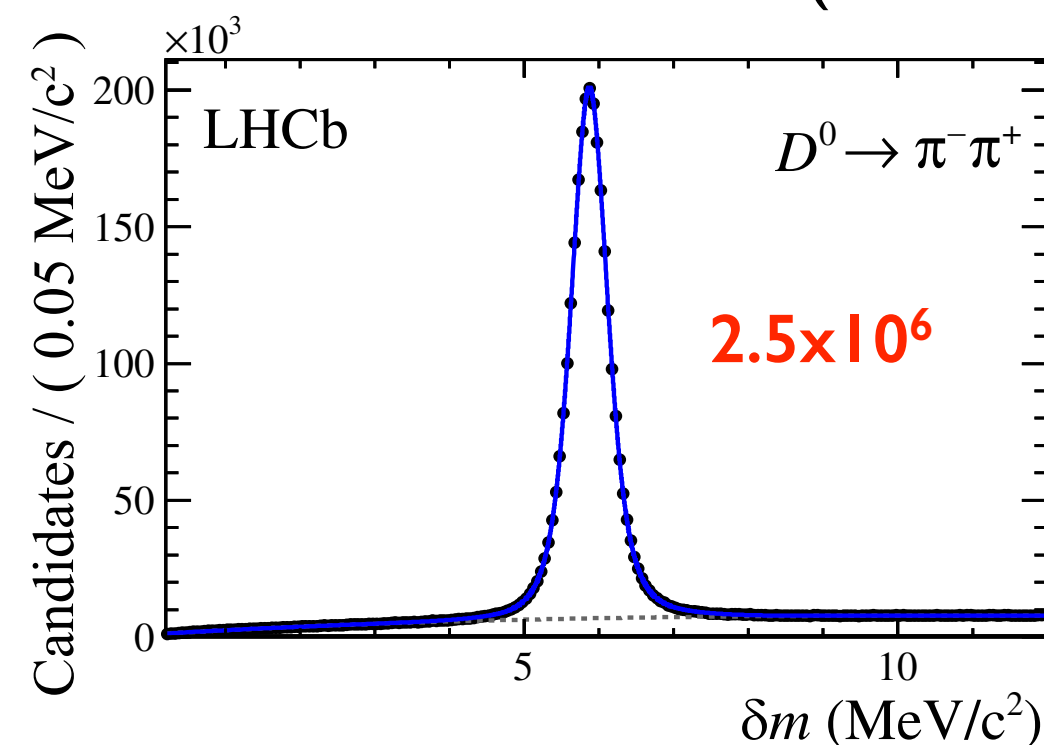
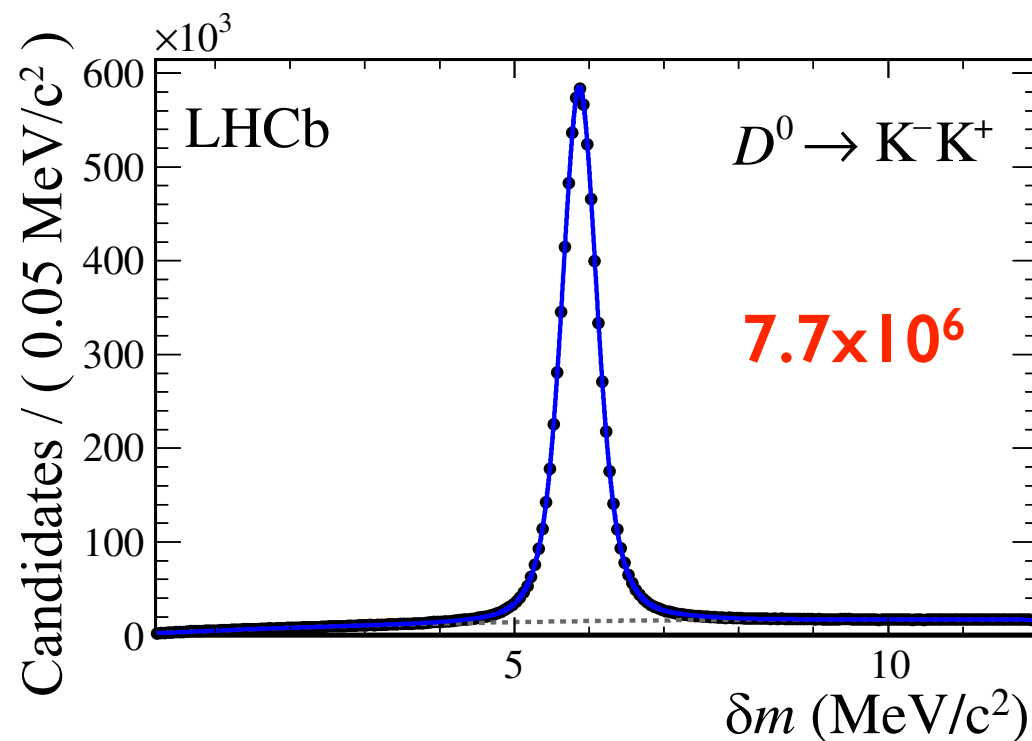
- Nuova misura con tutto il campione del Run1 di LHCb 3/fb:

- ◆ decadimenti del D^0 identificando il sapore dal D^{*+} .

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

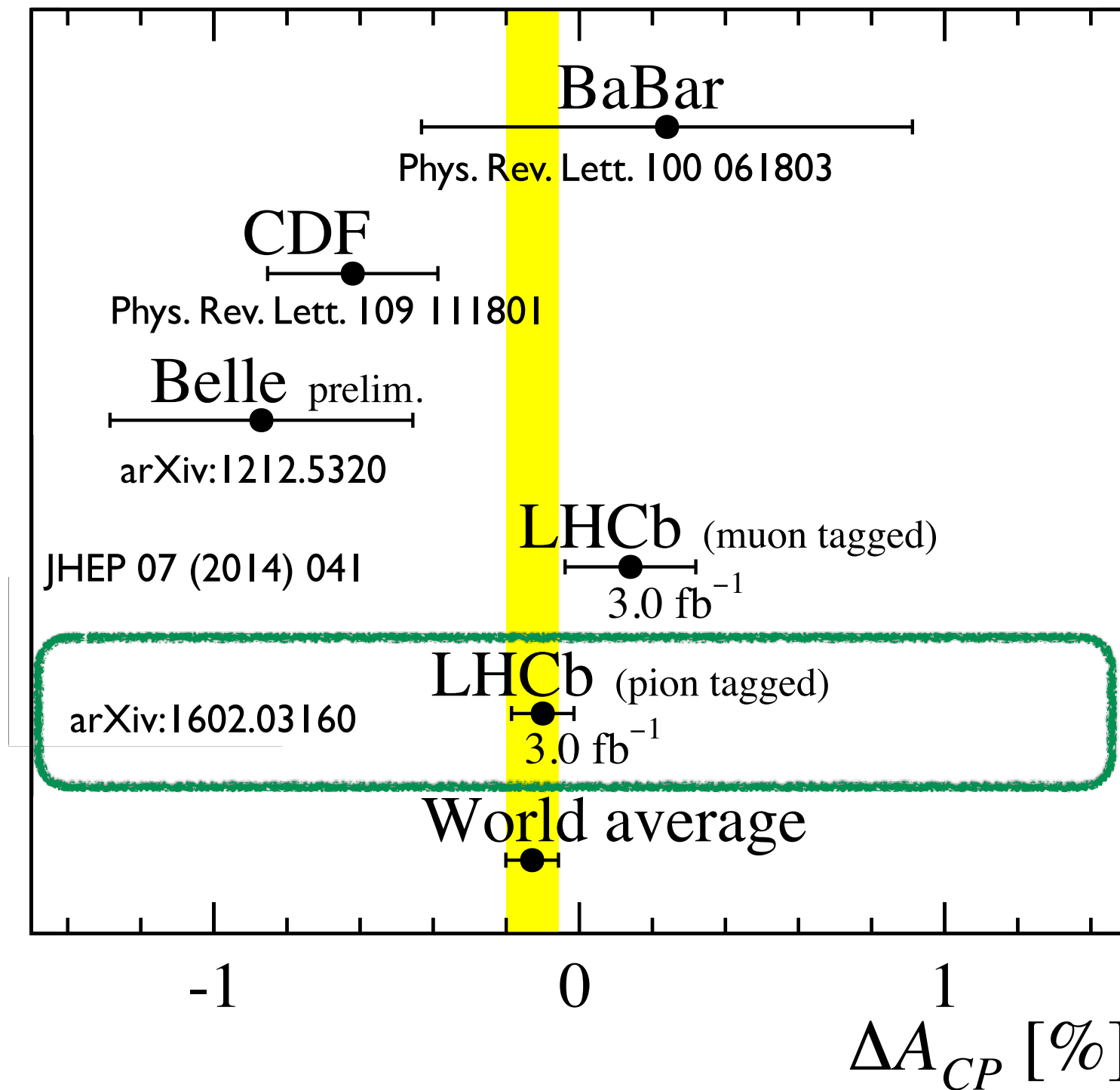
[arXiv:1602.03160]

(submitted to PRL)



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

● Stato dell'arte su ΔA_{CP}



Media (ignorando il contributo della CPV indiretta) = $(-0.129 \pm 0.072)\%$

● A_Γ : violazione indiretta di CP $D^0 \rightarrow h^+ h^-$

- Asimmetria di CP dipendente dal tempo:

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

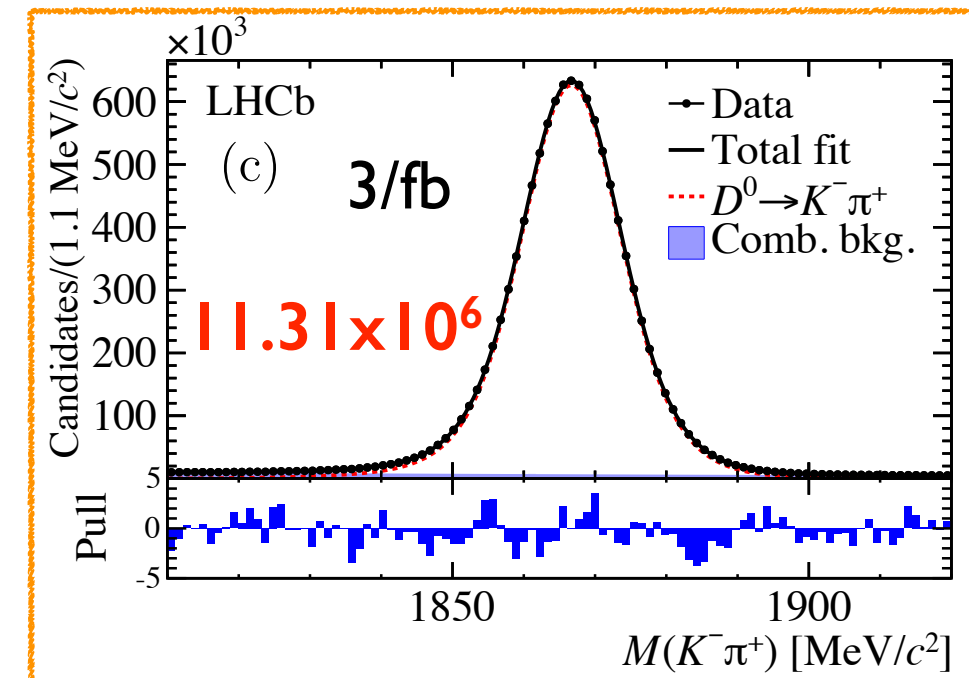
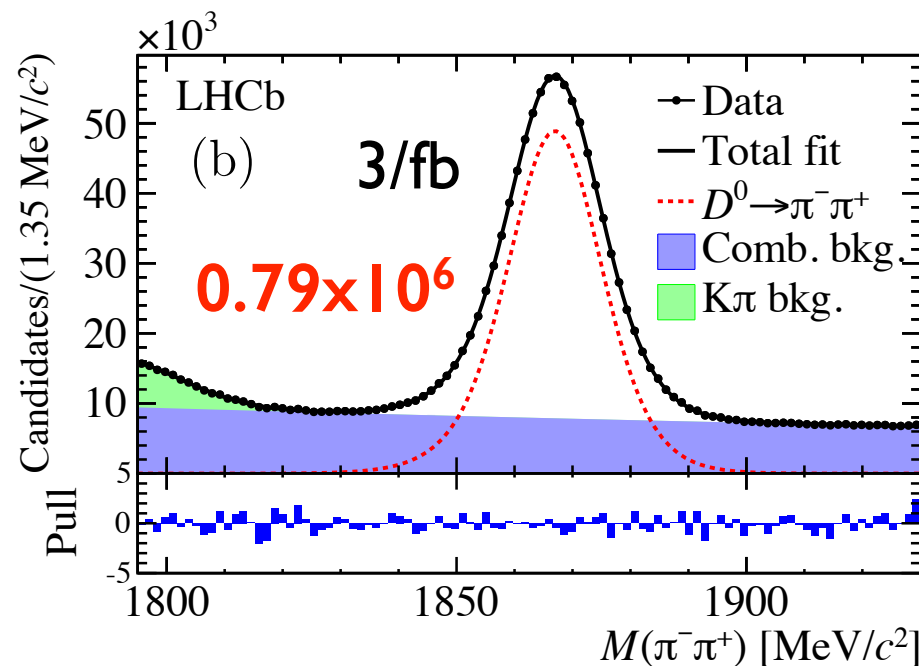
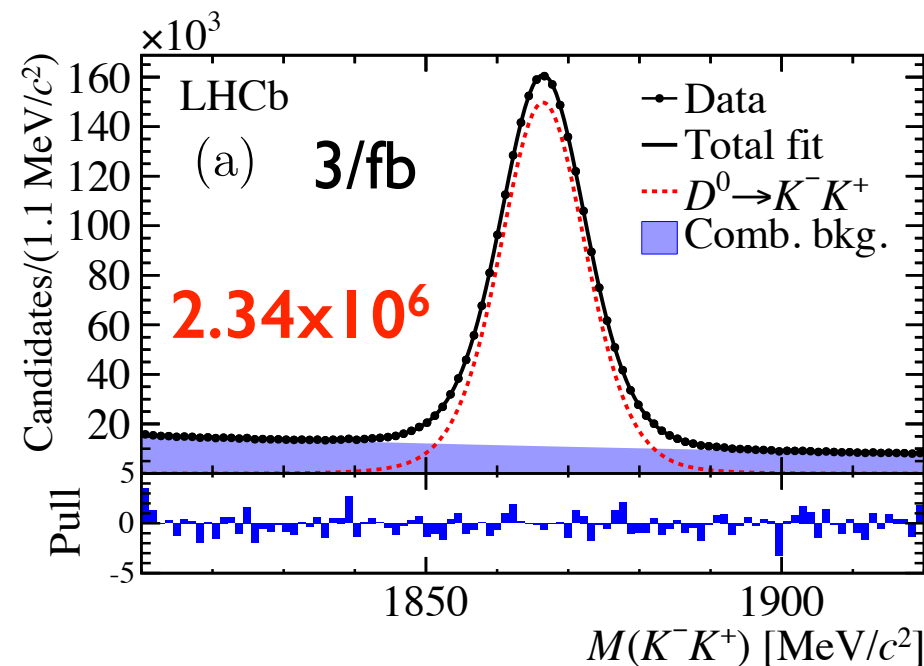
A_Γ è collegata alla violazione di CP nel mixing (A_m) e nel decadimento (A_d):

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

- Misura dell'asimmetria in m bin del tempo di decadimento del D^0 :

$$A_{\text{raw}}^i = \frac{n_i(D^0 \rightarrow f) - n_i(\bar{D}^0 \rightarrow f)}{n_i(D^0 \rightarrow f) + n_i(\bar{D}^0 \rightarrow f)}; \quad i = 1, \dots, m$$

campione di controllo $D^0 \rightarrow K\pi$
pseudo- $A_\Gamma(D^0 \rightarrow K\pi) = 0$



[JHEP 1504 (2015) 043]

● A_Γ : violazione indiretta di CP $D^0 \rightarrow h^+ h^-$

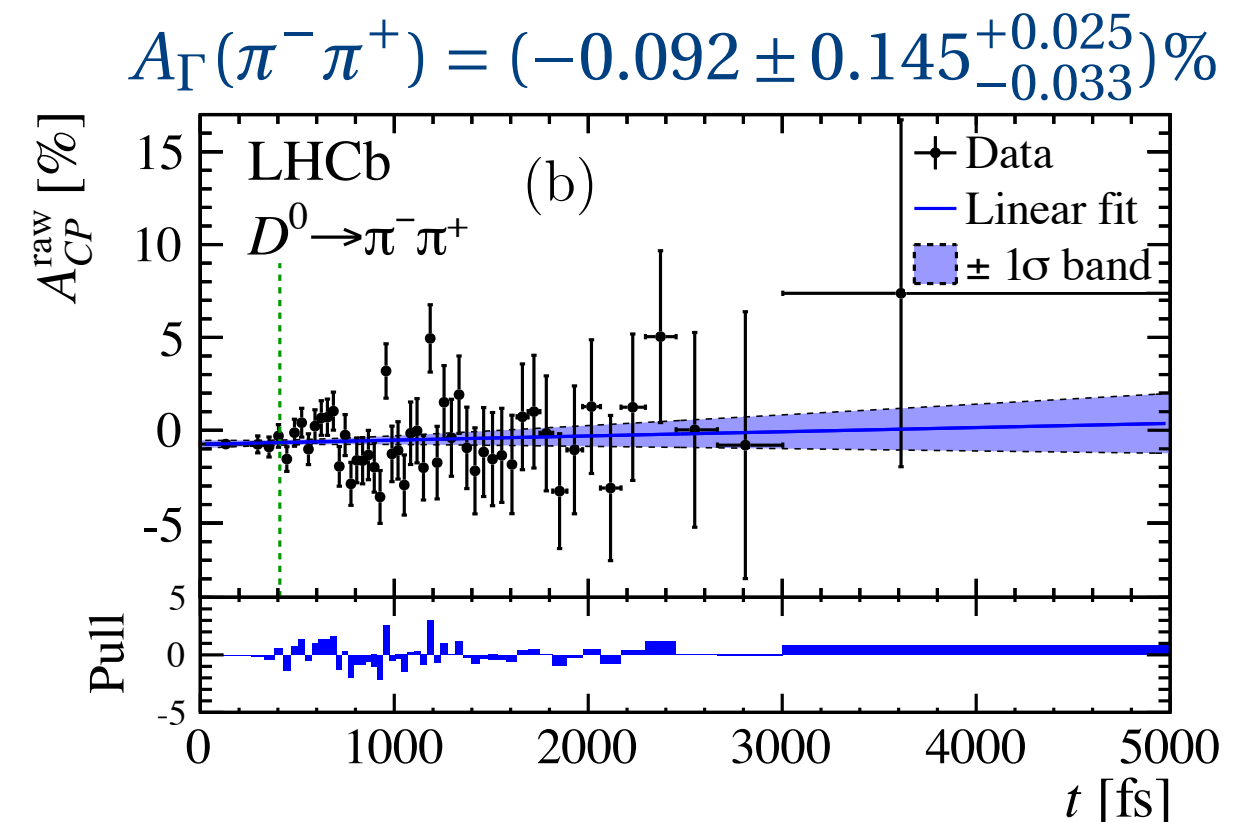
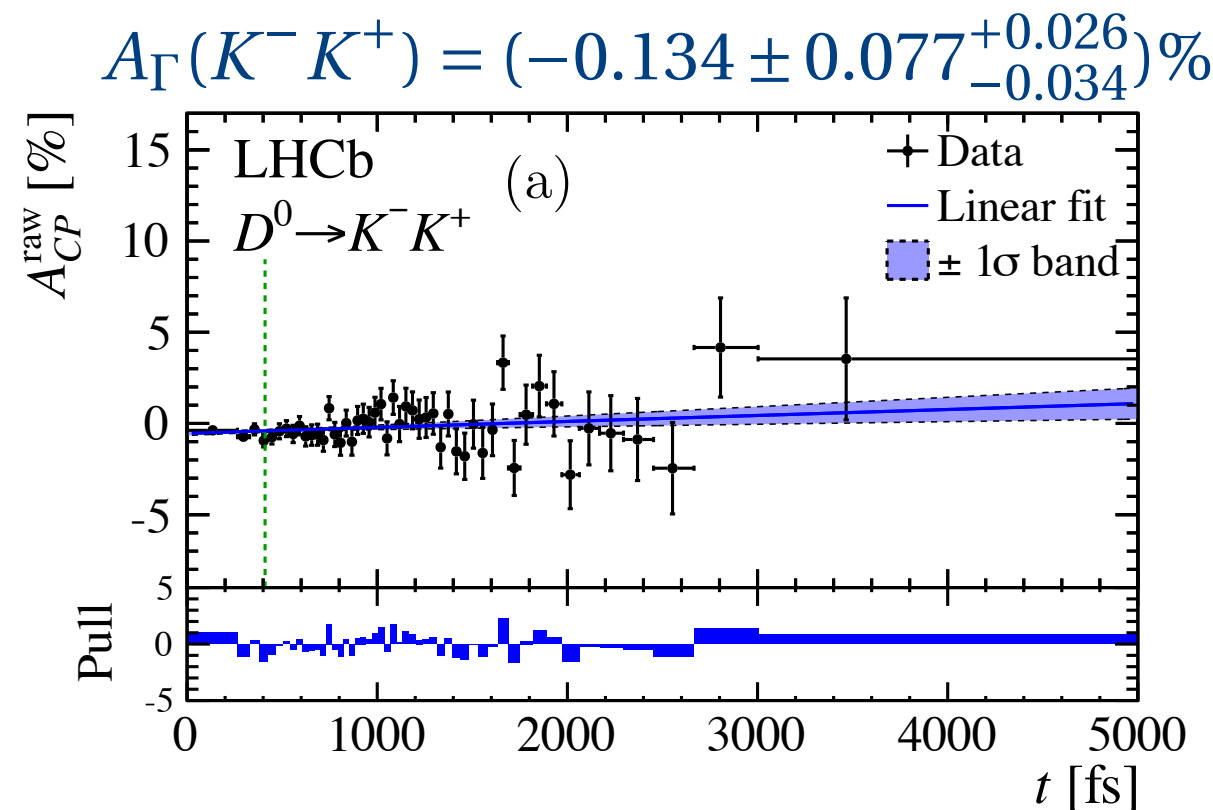
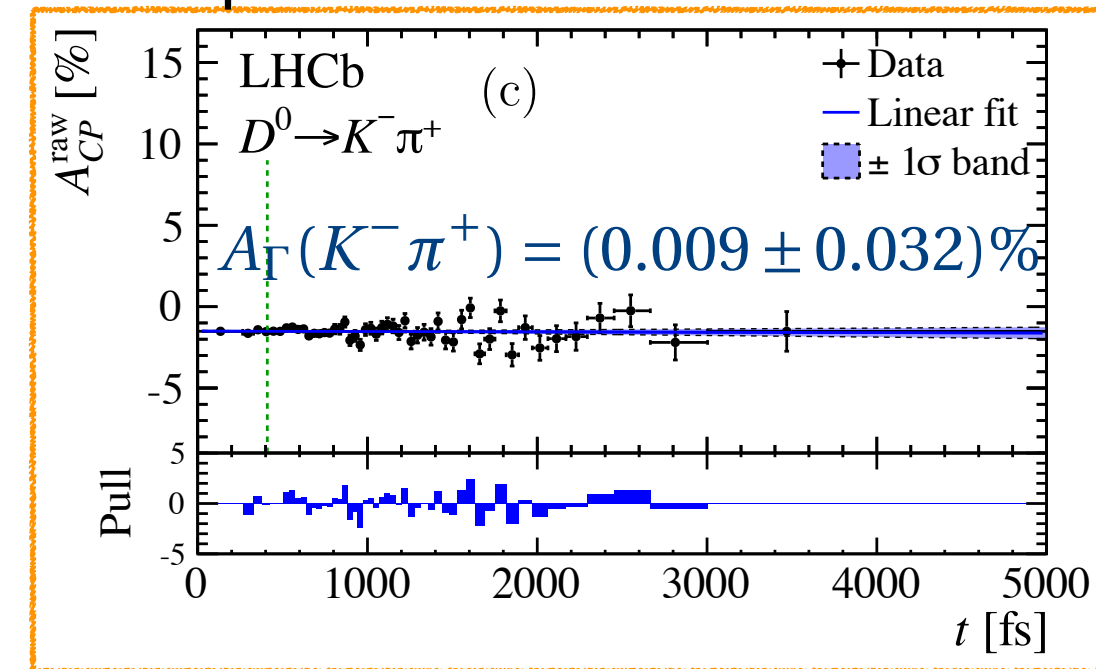
- Fit dell'asimmetria in funzione di

$$A_{\text{raw}}(t) = A_0 - \frac{t}{\tau_{D^0}} A_\Gamma;$$

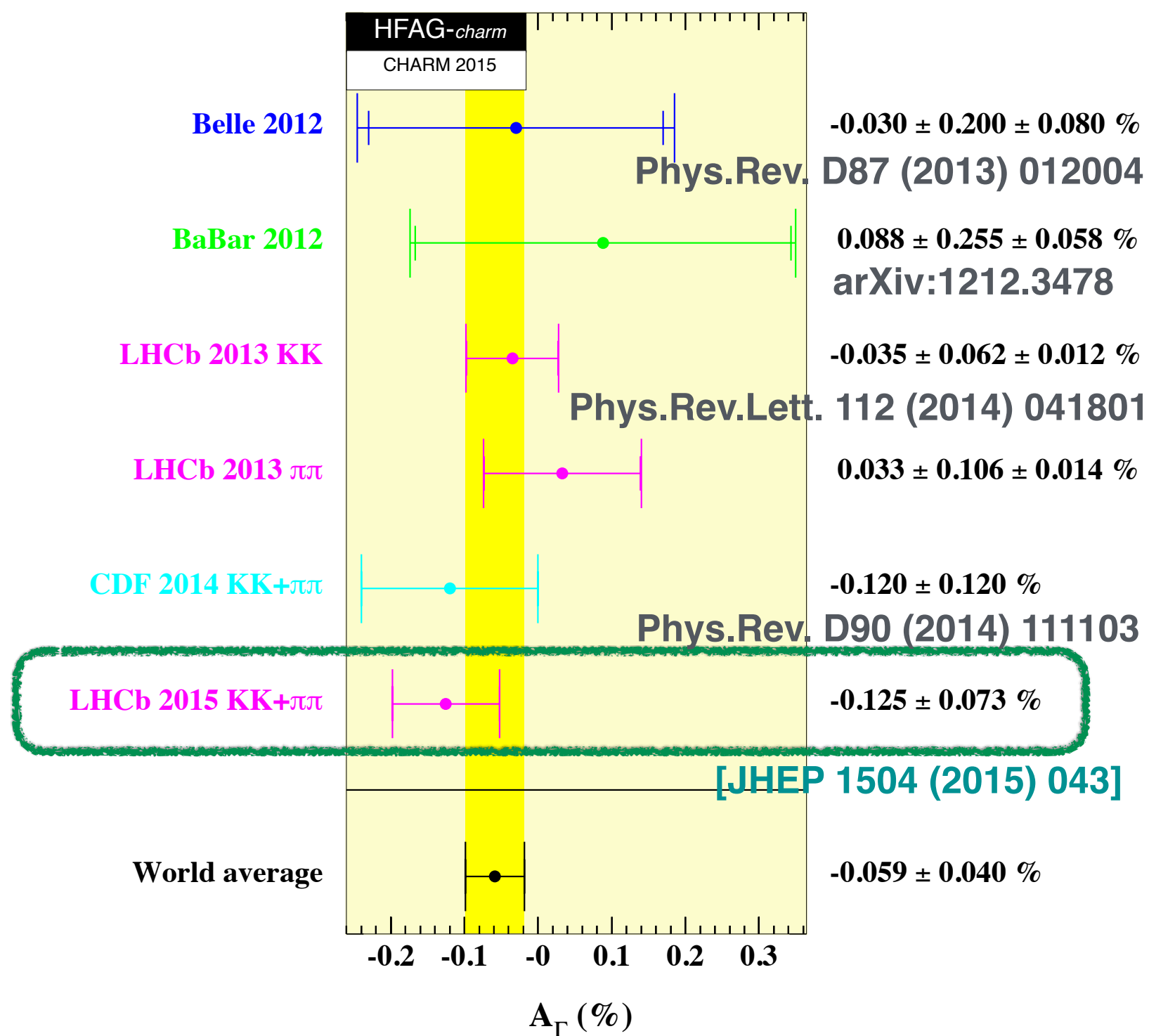
termine noto:
asimmetria globale (indipendente dal tempo di decadimento)

pendenza della retta:
asimmetria dipendente dal tempo di decadimento

campione di controllo $D^0 \rightarrow K\pi$



● Stato dell'arte su A_Γ



- La misura migliore è di LHCb D^* -tag su 1/fb.

● Violazione di CP in $D^0 \rightarrow K_s^0 K_s^0$

- L'ampiezza di decadimento è dominata da “long-distance contribution”:

- ◆ i termini “short-distance” si cancellano visto $V_{cd}V_{ud}^* \simeq -V_{cs}V_{us}^*$,

- ◆ i termini di interferenza possono dare un grosso contributo $\mathcal{O}(1\%)$

[Phys. Rev. D87 (2013) 014024]

[Phys. Rev. D92 (2015) 054036]

- ◆ aiuta la comprensione del contributo dei diagrammi a pinguino

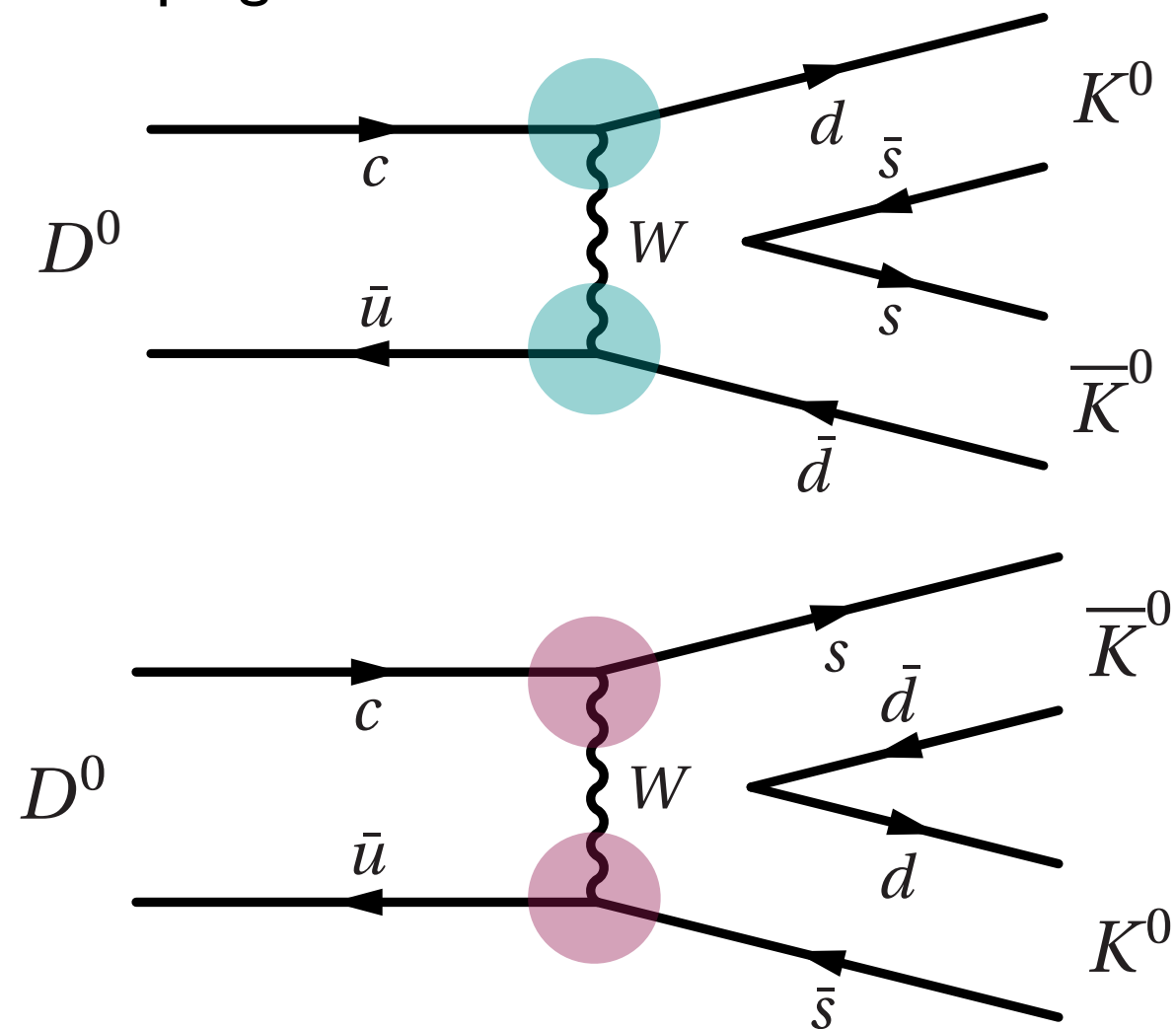
- Sperimentalmente complicata: ricostruzione di vertici di particelle a **lunga** vita media ($K_s^0 \rightarrow \pi^+ \pi^-$), anche fuori la regione del VELO.

- ◆ Difficile da “triggerare”

- Solo una misura precedente da CLEO:

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

[PRD 63 (2011) 071101]



● A_{CP} in $D^0 \rightarrow K_s^0 K_s^0$

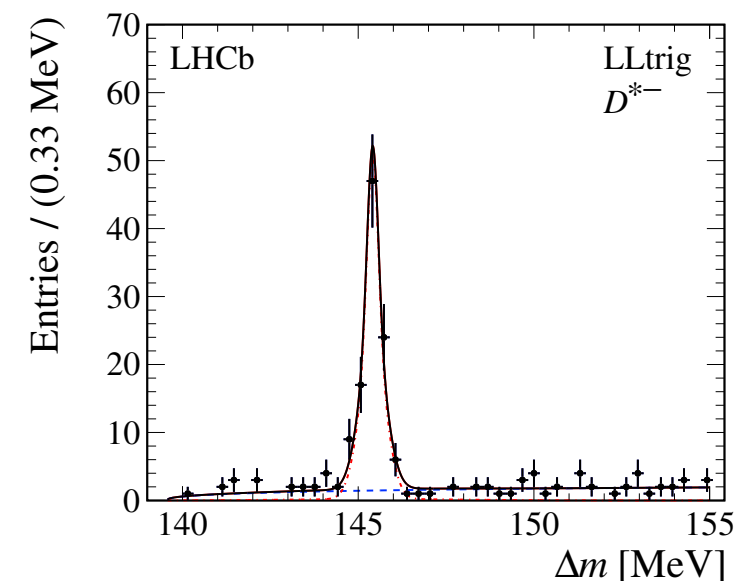
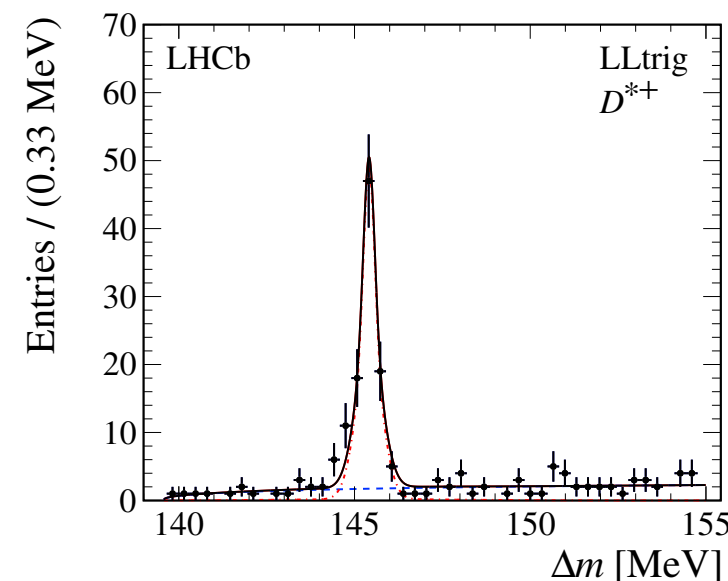
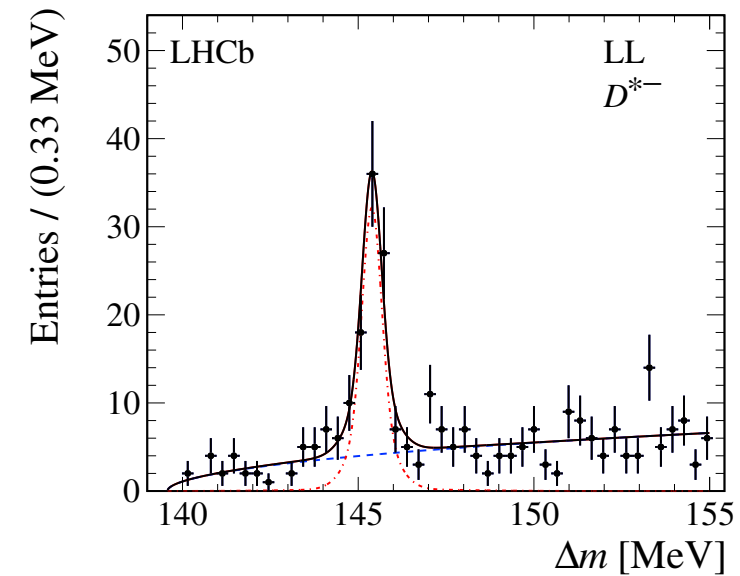
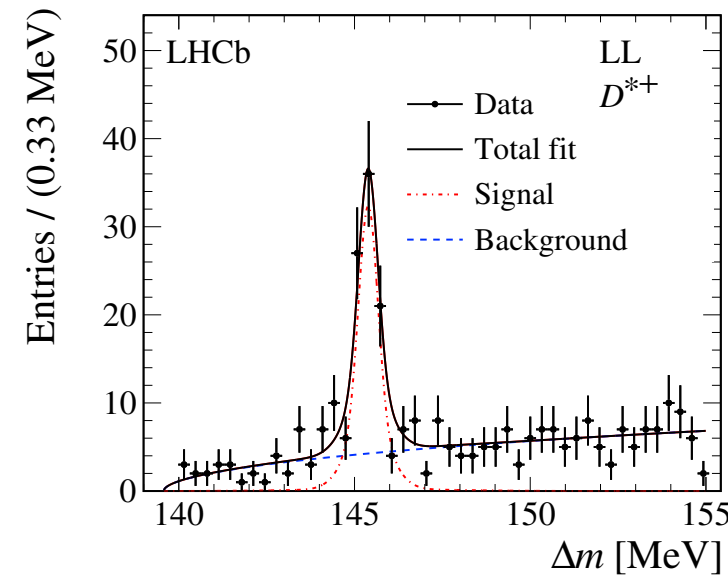
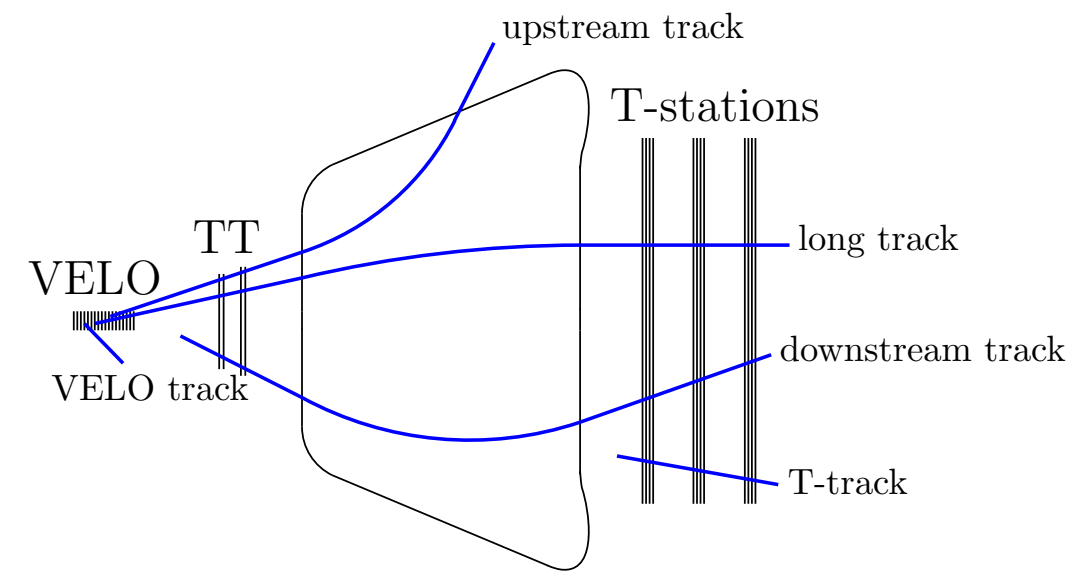
- Misura dell'asimmetria di CP

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

- Tag dal decadimento del D^* .
- Asimmetrie di detector, $A_D(\pi)$, e produzione $A_P(D^*)$, determinate da campioni di controllo ($D^0 \rightarrow K\pi$), entrambi dell' $\mathcal{O}(1\%)$.
- Circa **600 eventi** nell'intero campione del Run1:

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

- Significativo miglioramento rispetto alla misura precedente (circa un fattore 4).
- Run2 trigger dedicato.

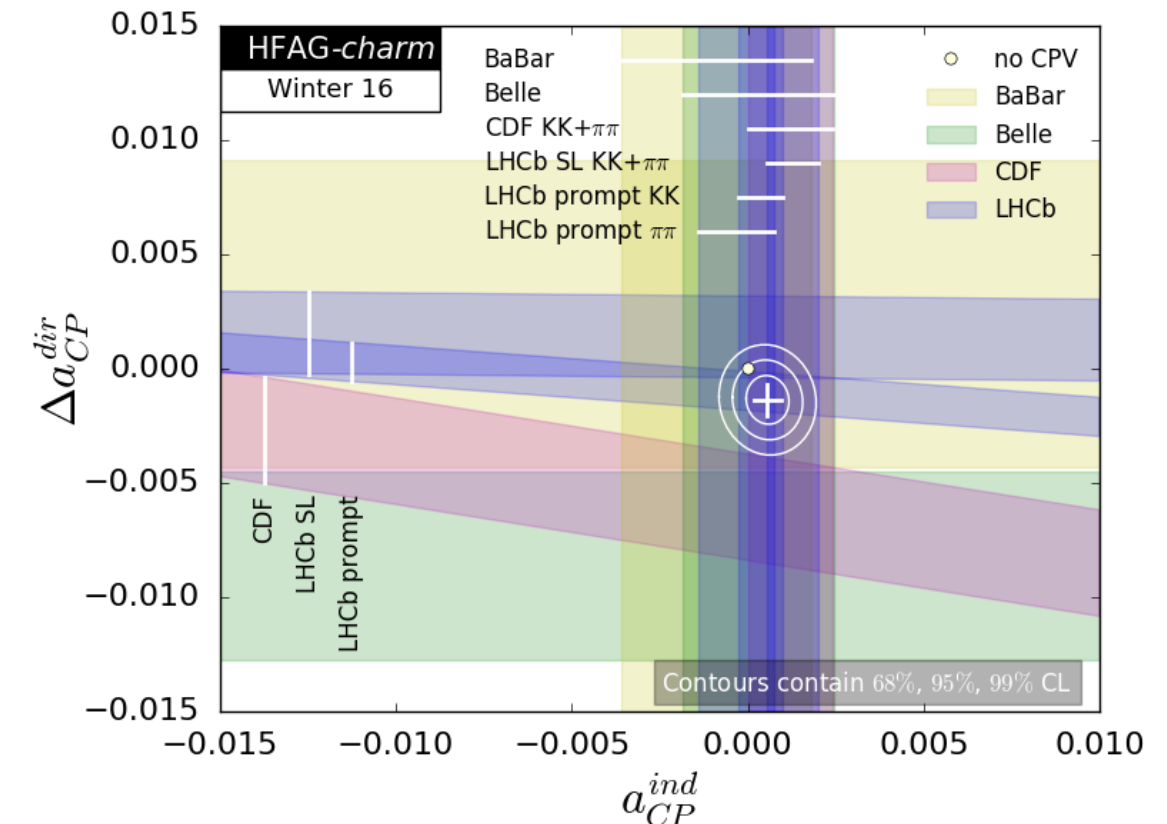


● Sommario e prospettive per il futuro

- Misure di precisione sul charm con gli enormi campioni di LHCb del RunI
 - ✦ La violazione di CP nel charm ancora non osservata;
 - ✦ vicini ai valori aspettati dalla teoria.
- Alcune analisi di punta in fase di preparazione sul RunI.
 - ✦ Presto $A_\Gamma(D^*\text{-tag})$ su 3/fb: precisione $A_\Gamma(D^0 \rightarrow KK) \sim 4 \times 10^{-4}$
- Ancora più charm nel RunII e nell'upgrade di LHCb.

[White paper of CSN1]

Analysis	Obs.	LHCb (3 fb^{-1})	LHCb (50 fb^{-1})
$K_S^0 \pi^+ \pi^-$	x	2×10^{-3}	4×10^{-4}
	y	2×10^{-3}	4×10^{-4}
	$ q/p $	0.2	0.04
	φ	15°	3°
$K^+ K^-$, $\pi^+ \pi^-$	y_{CP}	3×10^{-4}	2×10^{-5}
	A_Γ	3×10^{-4}	2×10^{-5}
$K^+ \pi^-$	x'^2	5×10^{-5}	1×10^{-5}
	y'	1×10^{-3}	2×10^{-4}
	$ q/p $	0.25	0.05
	A_D	0.02	4×10^{-3}
	φ	-	-



$$a_{CP}^{ind} = (+0.56 \pm 0.40) \times 10^{-3}$$

$$\Delta a_{CP}^{dir} = (-1.37 \pm 0.70) \times 10^{-3}$$

HFAG

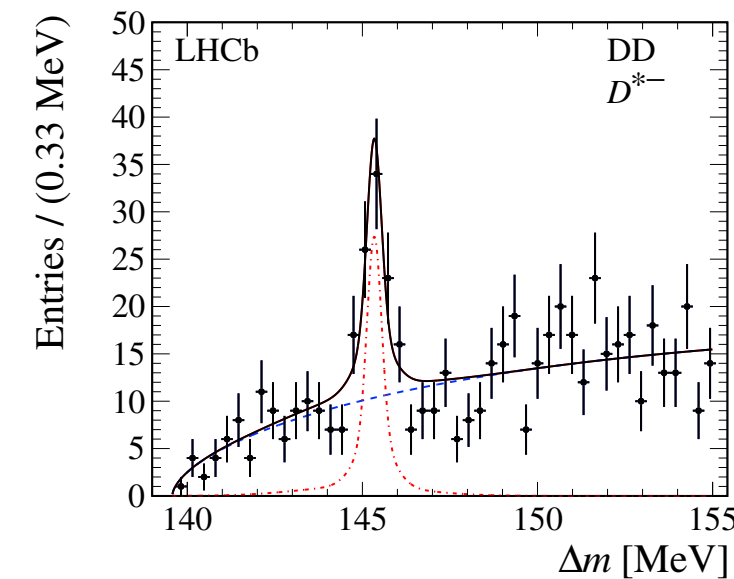
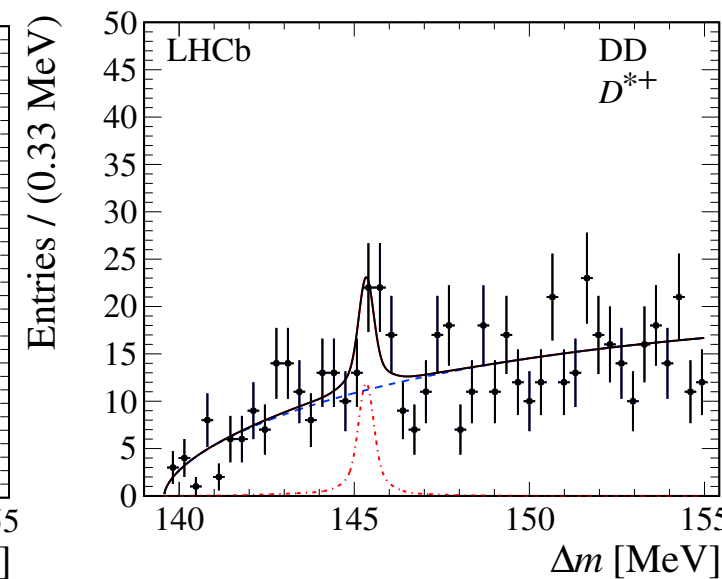
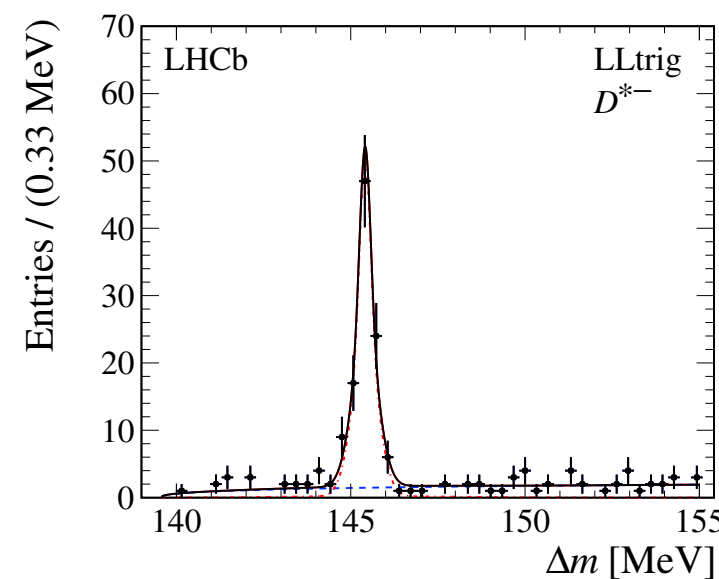
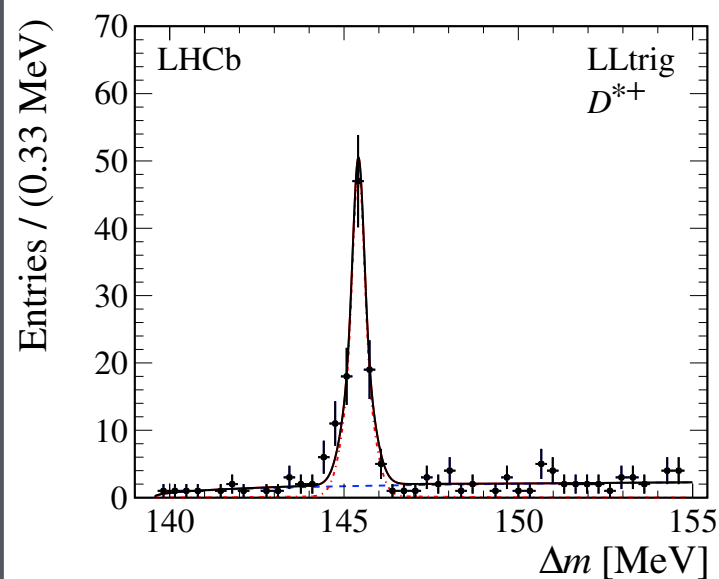
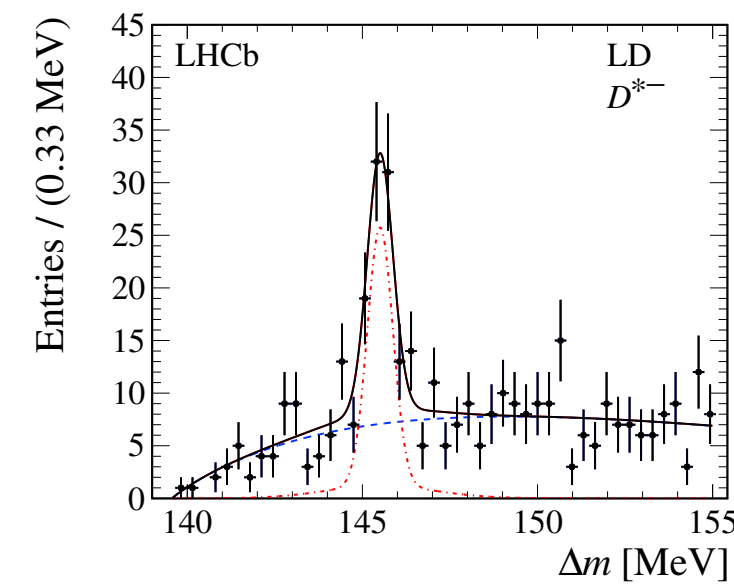
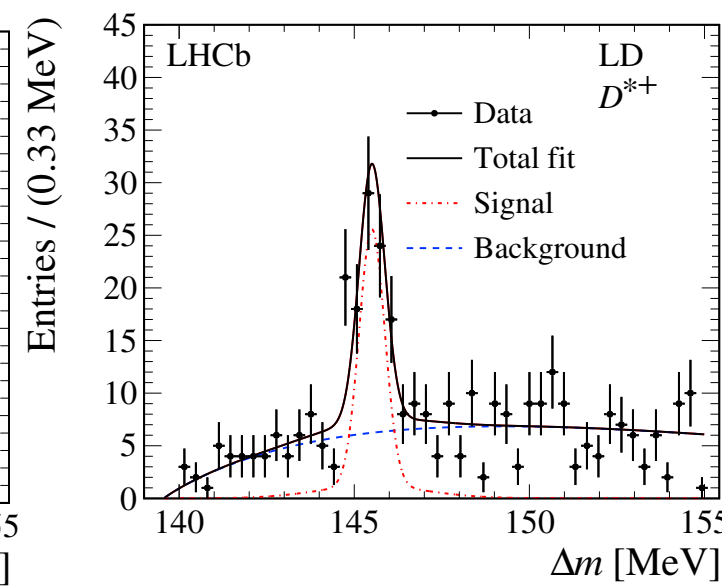
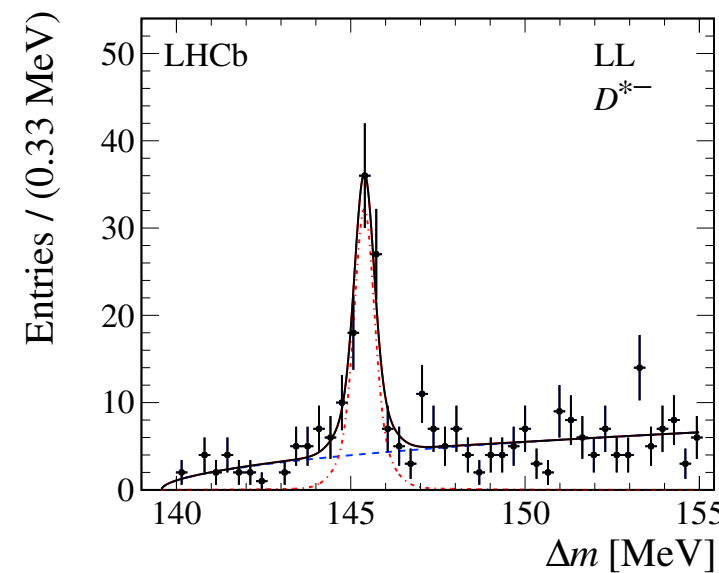
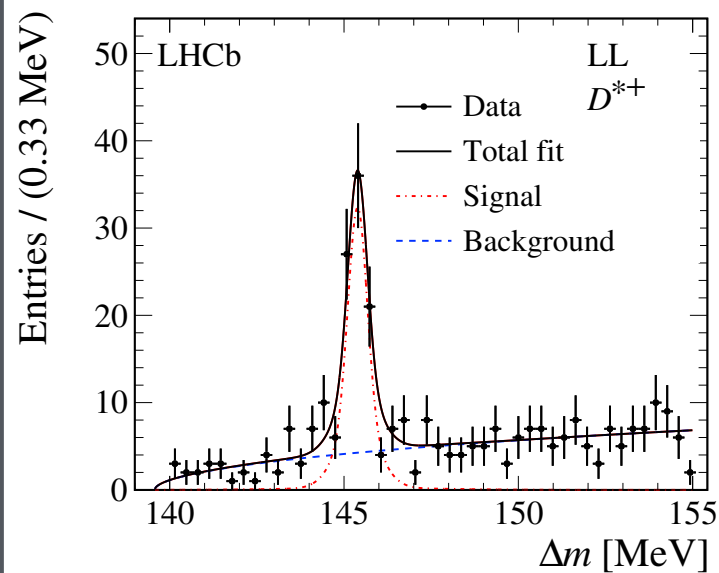
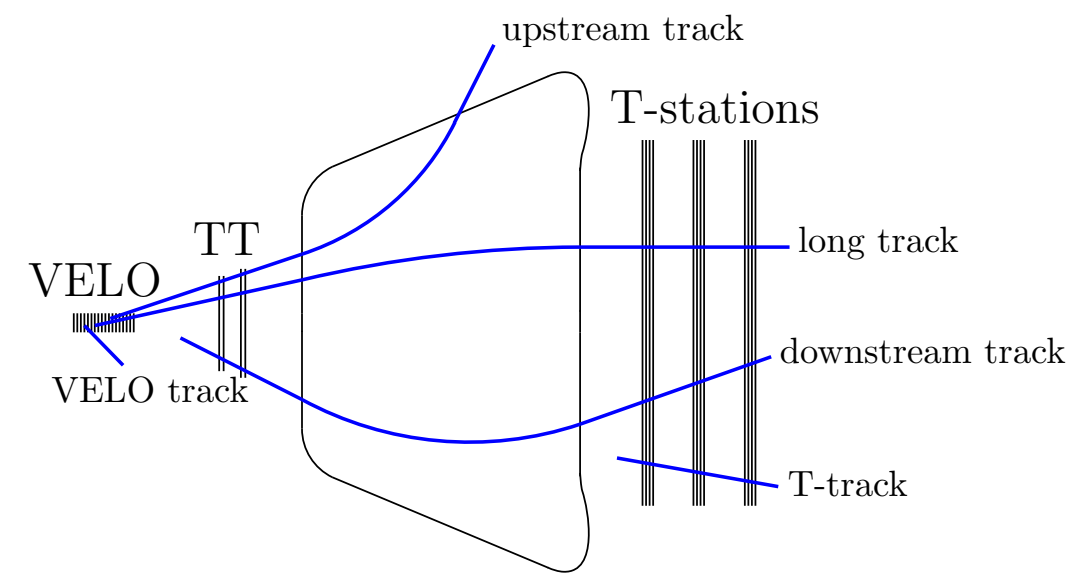
- Backup

● Prospettive per il futuro

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

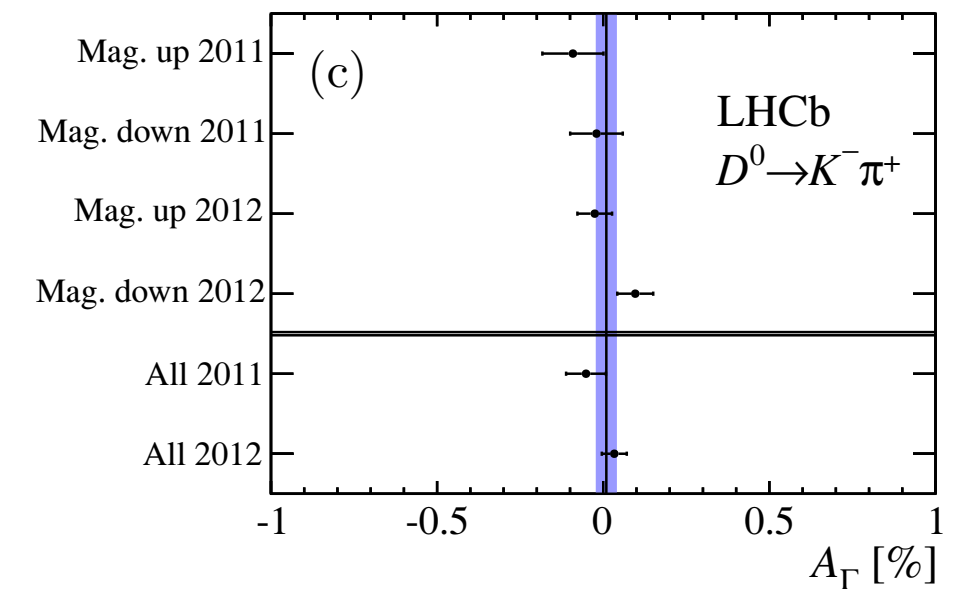
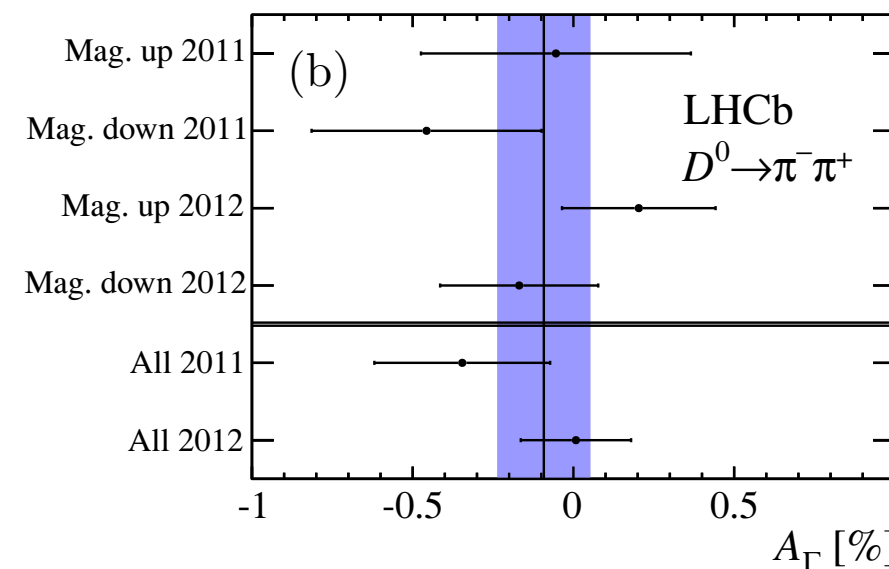
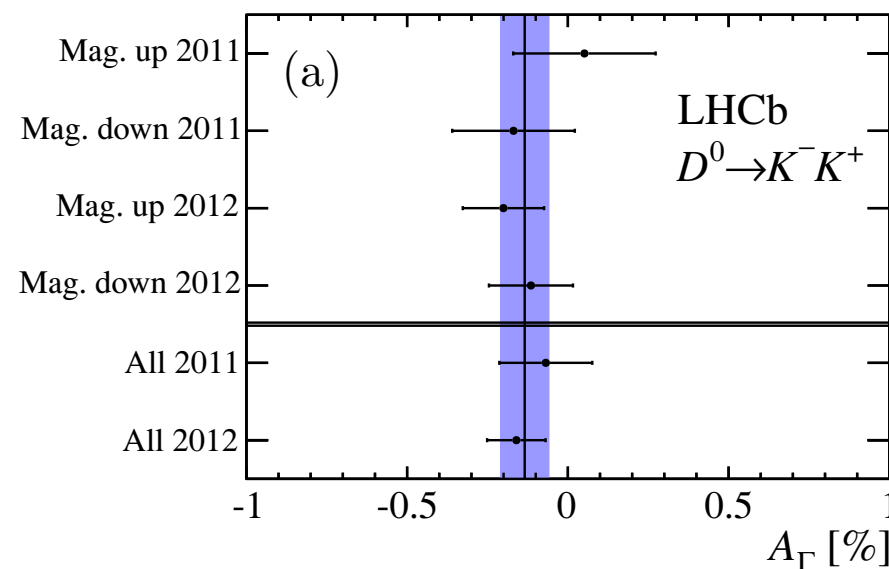
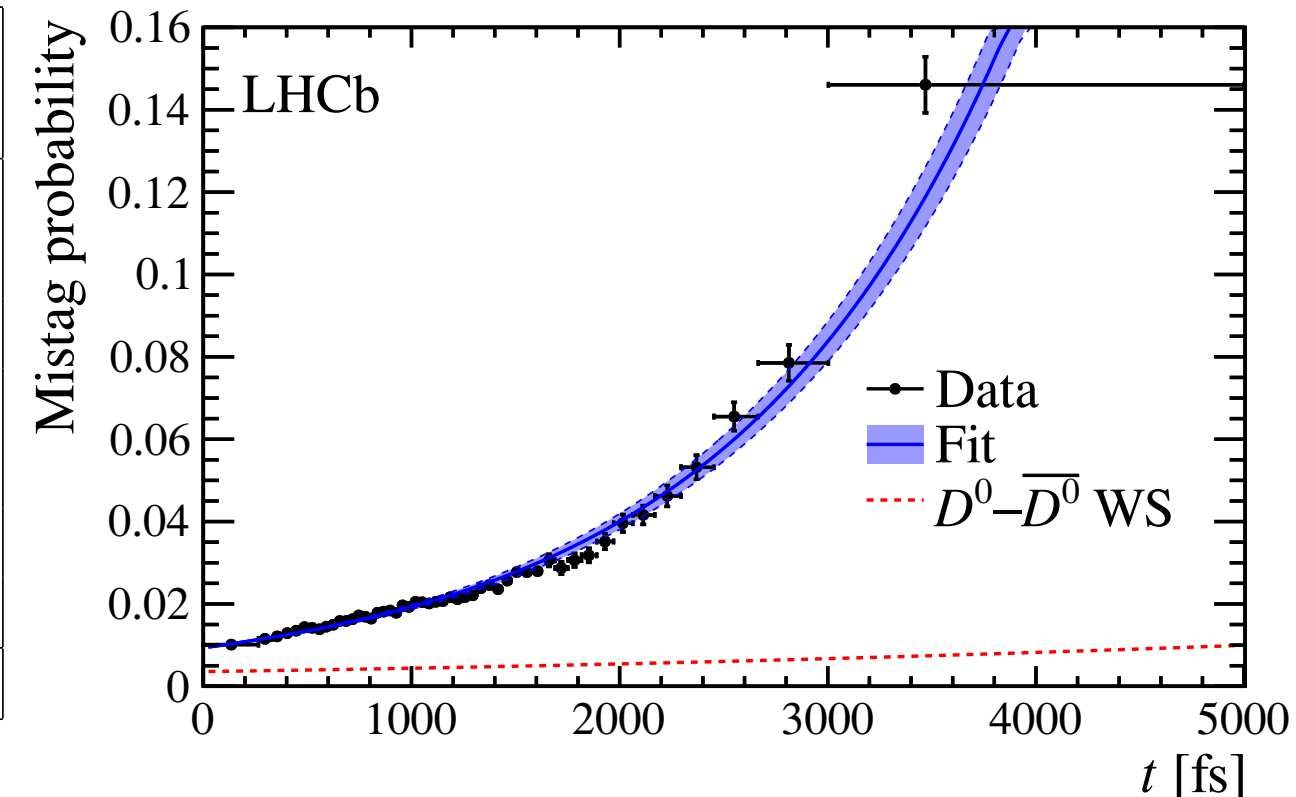
$D^0 \rightarrow K_s^0 K_s^0$

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

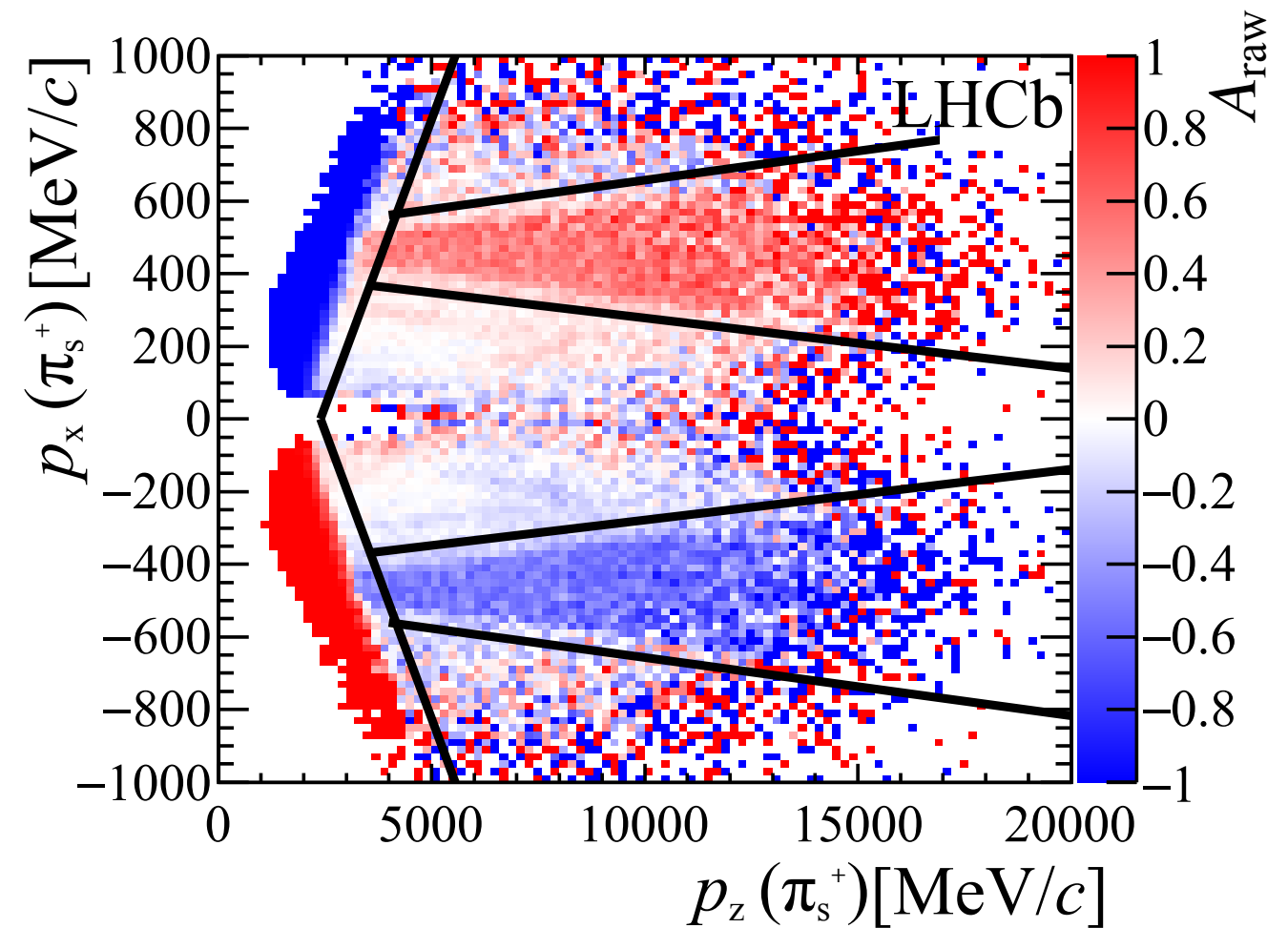
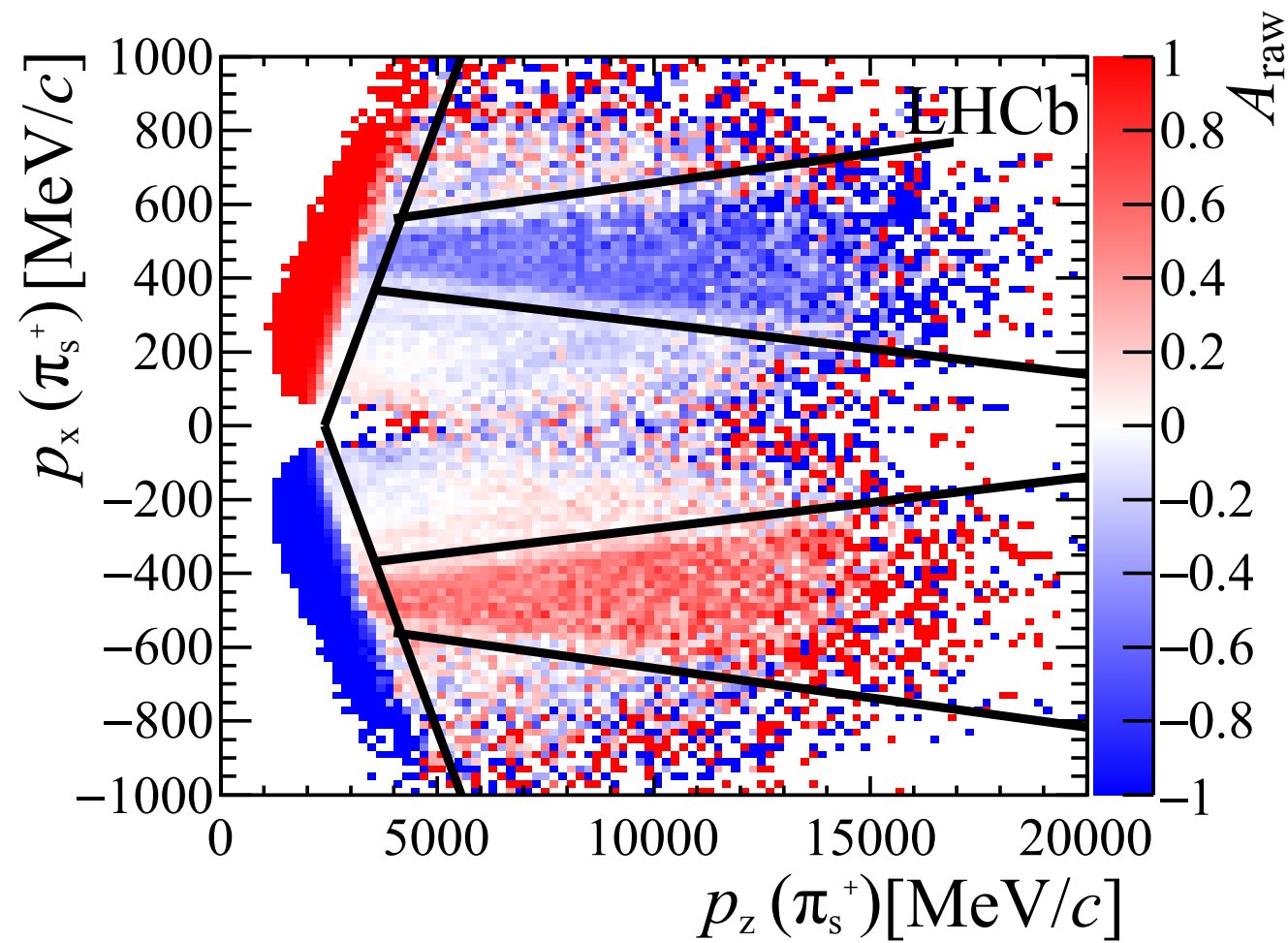


● A_Γ : CPV indiretta $D^0 \rightarrow h^+ h^-$: sistematici

Source of uncertainty	$D^0 \rightarrow K^- K^+$		$D^0 \rightarrow \pi^- \pi^+$	
	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
$B^0 - \bar{B}^0$ mixing	0.007%		0.007%	
Quadratic sum	0.026%	0.10	0.025%	0.09

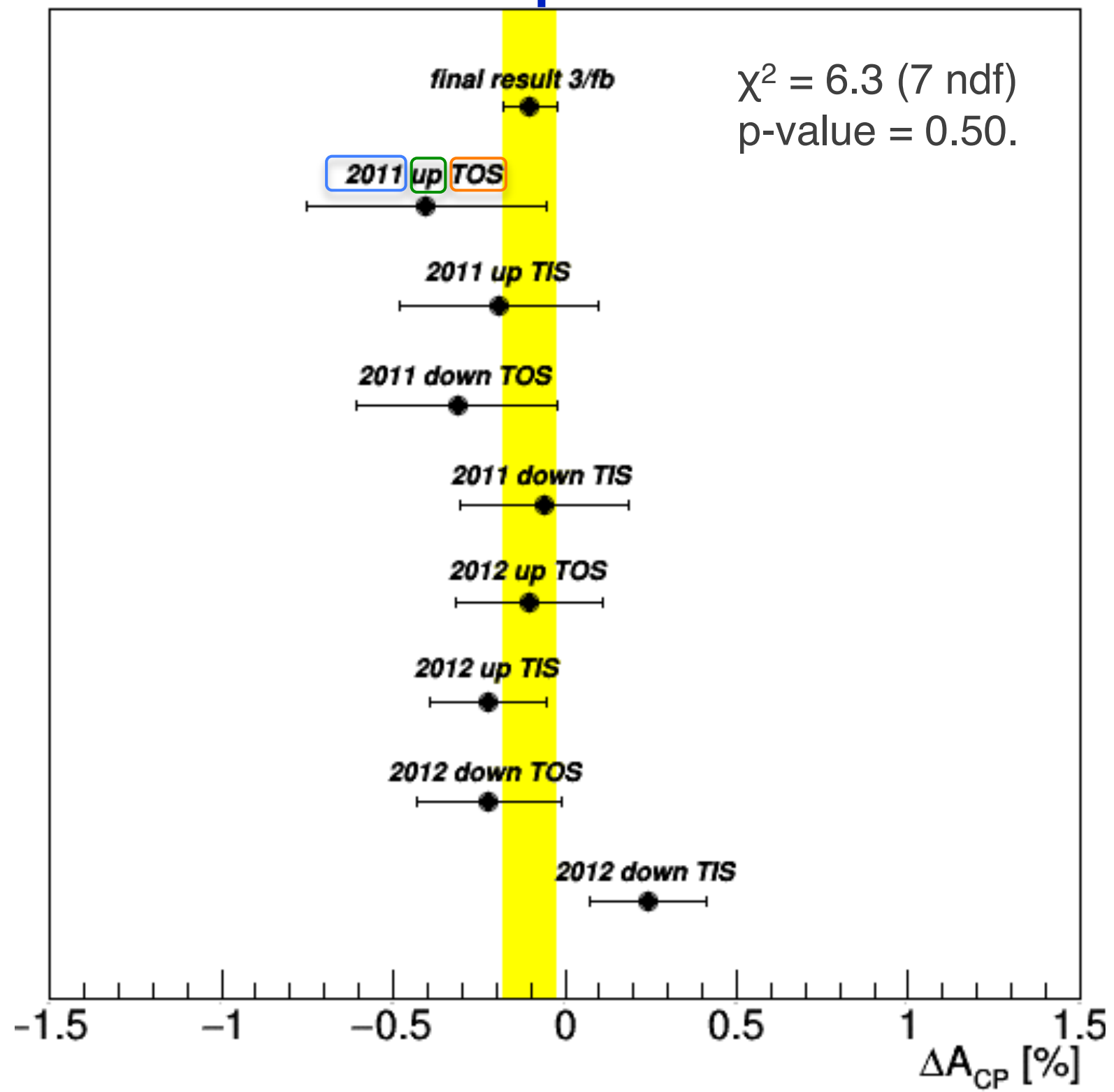


● Tagli fiduciali



● Cross-checks

- Anno di presa dati (= differente energia 7/8 TeV)
- Polarità del magnete
- Configurazione del trigger
 - ◆ TOS: trigger on signal
 - ◆ TIS: trigger independent from signs
- Vari cross-checks:
 - ◆ cinematica π -soft, D0
 - ◆ run numbers
 - ◆ richieste di PID
 - ◆ qualità del vertice del D^*
 - ◆ ...



arXiv:1602.03160