

Misura della vita media del mesone B_c^+ nello stato finale inclusivo $J/\psi \mu^+$ con il rivelatore LHCb al CERN

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Nel Modello Standard ci sono

- 3 quark leggeri q (u, d, s) e
- 3 quark pesanti Q (c, b, t).

Stati legati $Q\bar{Q}$ (*quarkonia*)

- $c\bar{c}$ (i.e. J/ψ , $\psi(2S)$, χ_{cJ} , $h_c\dots$)
Scoperti in collisioni e^+e^- nel 1969
- $b\bar{b}$ (i.e. $\Upsilon(1S)$, $\Upsilon(4S)$, χ_{bJ}
Collisioni p su bersaglio fisso nel 1977
- $c\bar{b}$ – Osservato solo lo stato fondamentale B_c^+
Collisioni $p\bar{p}$ nel 1998 (CDF)
- t ha vita media troppo corta per creare stati legati.

L'unico mesone carico nel MS composto da due quark pesanti è $c\bar{b}$.

Solo i decadimenti deboli sono permessi.

Vita media

Decadimento debole dei quark b e c competitivo, ma $c \rightarrow s$ è Cabibbo Favorito, $b \rightarrow c$ è soppresso: vita media attesa simile ad altri adroni *charmati*.

Stime **teoriche** individuano l'intervallo

$$0.4 \div 0.7 \text{ ps.}$$

[hep-ph/9601249v1, hep-ph/9812514, hep-ph/0002127, hep-ph/0007162]

Sperimentalmente, la vita media è stata misurata da CDF e D0 (TeVatron). La combinazione delle misure ottenute nei vari canali è

$$(0.452 \pm 0.033) \text{ ps.}$$

L'incertezza sulla vita media introduce l'errore sistematico dominante in molte misure su

- sezione d'urto di produzione;
- rapporti di decadimento

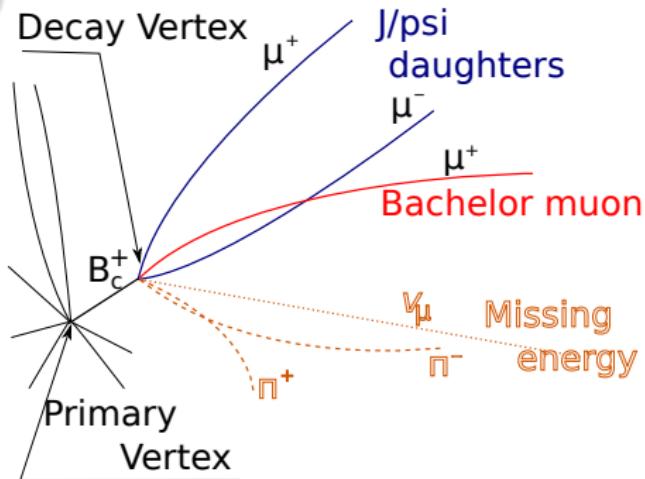
$$B_c^+ \rightarrow J/\psi \mu^+ \nu X \quad \text{con} \quad J/\psi \rightarrow \mu^+ \mu^-$$

Pro

- Nessun taglio di distaccamento dal PV; selezione indipendente dal tempo di decadimento
- Elevato rapporto di decadimento eccellente statistica

Contro

- Decadimento semileptonico,
⇒ nessun picco di massa
- Fondo di misidentificazione $h \rightarrow \mu$
- Dipendenza dal modello:
correzione per l'energia del neutrino;



Il valore della vita media è ottenuto da un fit bidimensionale

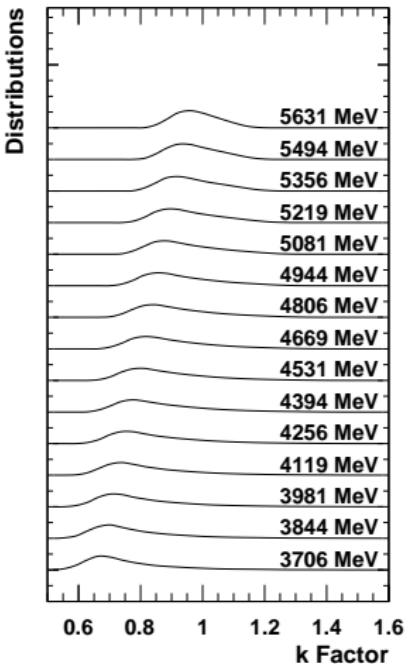
$$m(J/\psi \mu^+) \perp t_{ps}$$

$t_{ps} \equiv$ tempo di decadimento nel sistema di riferimento con $p(J/\psi \mu) = 0$

- **Massa.** Per conservazione dell'energia,

$$M_{J/\psi} + M_\mu < M_{J/\psi\mu} < M_{B_c^+}$$

$$3.2 \text{ GeV}/c^2 < M_{J/\psi\mu} < 6.25 \text{ GeV}/c^2$$



- **Tempo di decadimento**

La vita media è il la media del tempo di decadimento **nel sistema di riferimento** del B_c^+ .

Determinare il sistema di riferimento richiede conoscere $\gamma(B_c^+)$.

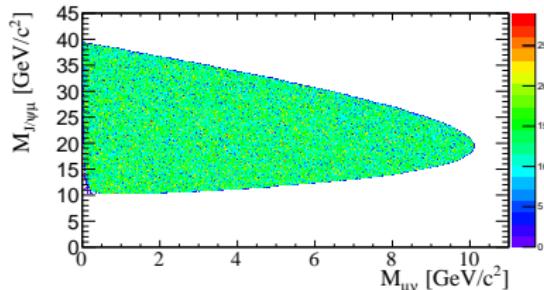
Ma come si determina $\gamma(B_c^+)$ senza il neutrino?

$$\frac{t}{\gamma(B_c^+)} = t_p \quad ; \quad \frac{t}{\gamma(J/\psi\mu^+)} = t_{ps} \quad \left| \begin{array}{ll} t_p = & \text{Tempo proprio, } p(B_c^+) = 0 \\ t_{ps} = & \text{Tempo pseudo-proprio, } p(J/\psi\mu) = 0 \end{array} \right.$$

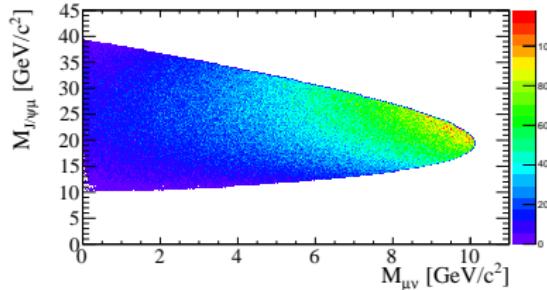
$\frac{t_{ps}}{t_p} = k$ -factor: correzione statistica basata su **simulazione**. In bin di massa.

Problema: il formalismo del k -factor introduce dipendenza dal modello teorico

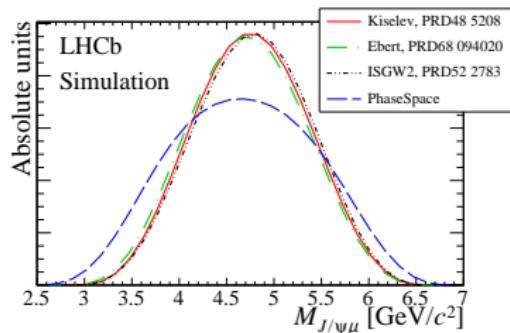
Spazio delle fasi



Modello corretto con fattori di forma



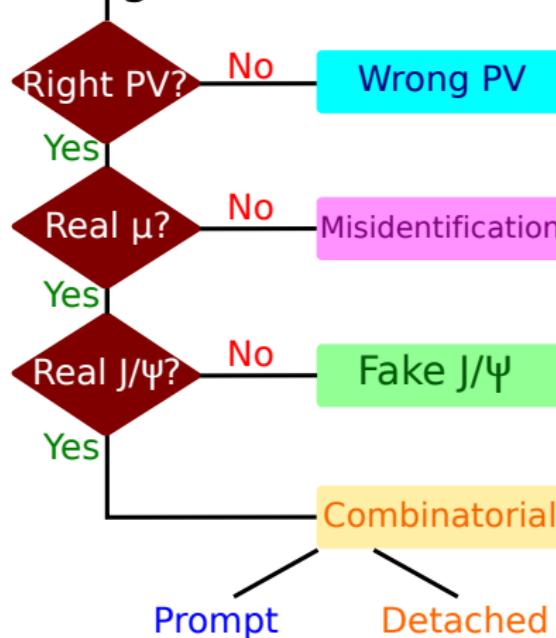
$$\frac{d\Gamma}{dM_{J/\psi\mu}^2 dM_{\mu\nu}^2} = \frac{1}{(2\pi)^3} \frac{1}{32M_{B_c}^3} \underbrace{|\mathcal{M}(M_{J/\psi\mu}^2, M_{\mu\nu}^2)|^2}_{\text{fattori di forma}}$$



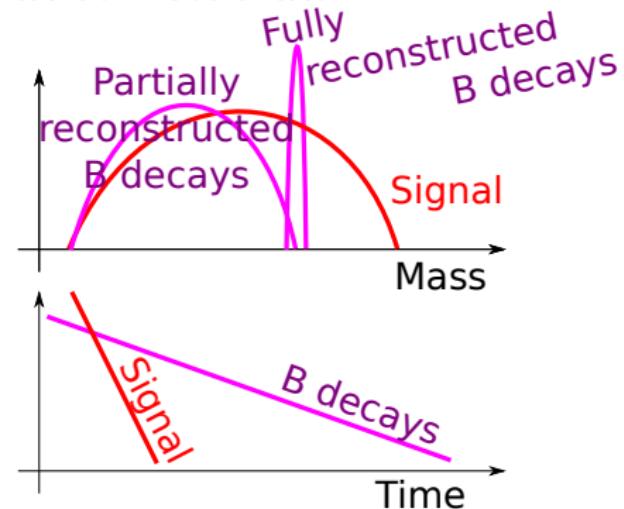
- Effetto diretto sul k -factor;
- indiretto sulla distribuzione di massa:
il k -factor è descritto in bin di massa
 \Rightarrow il peso dei bin dipende dal modello.

Effetto sulla vita media ottenuta nel fit piuttosto rilevante.

Background



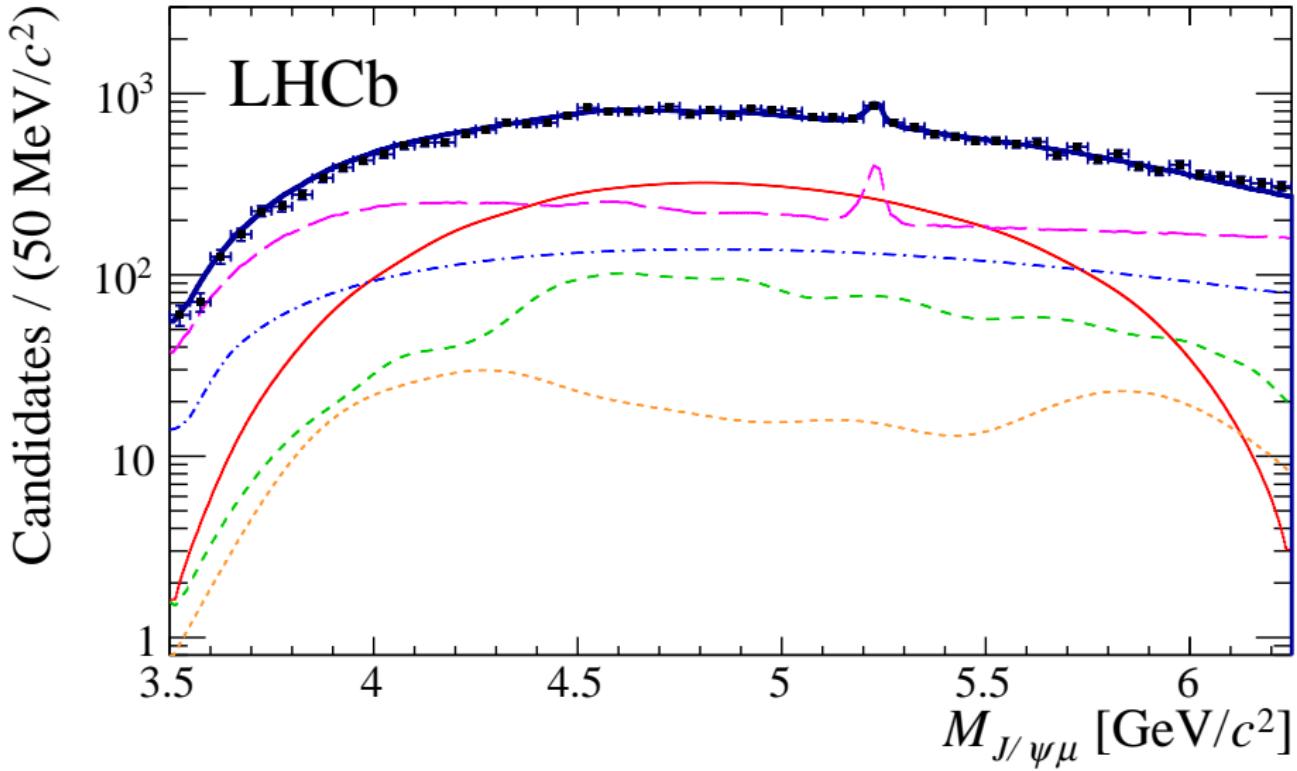
Il fondo è dominato da eventi con muone *bachelor* misidentificato.



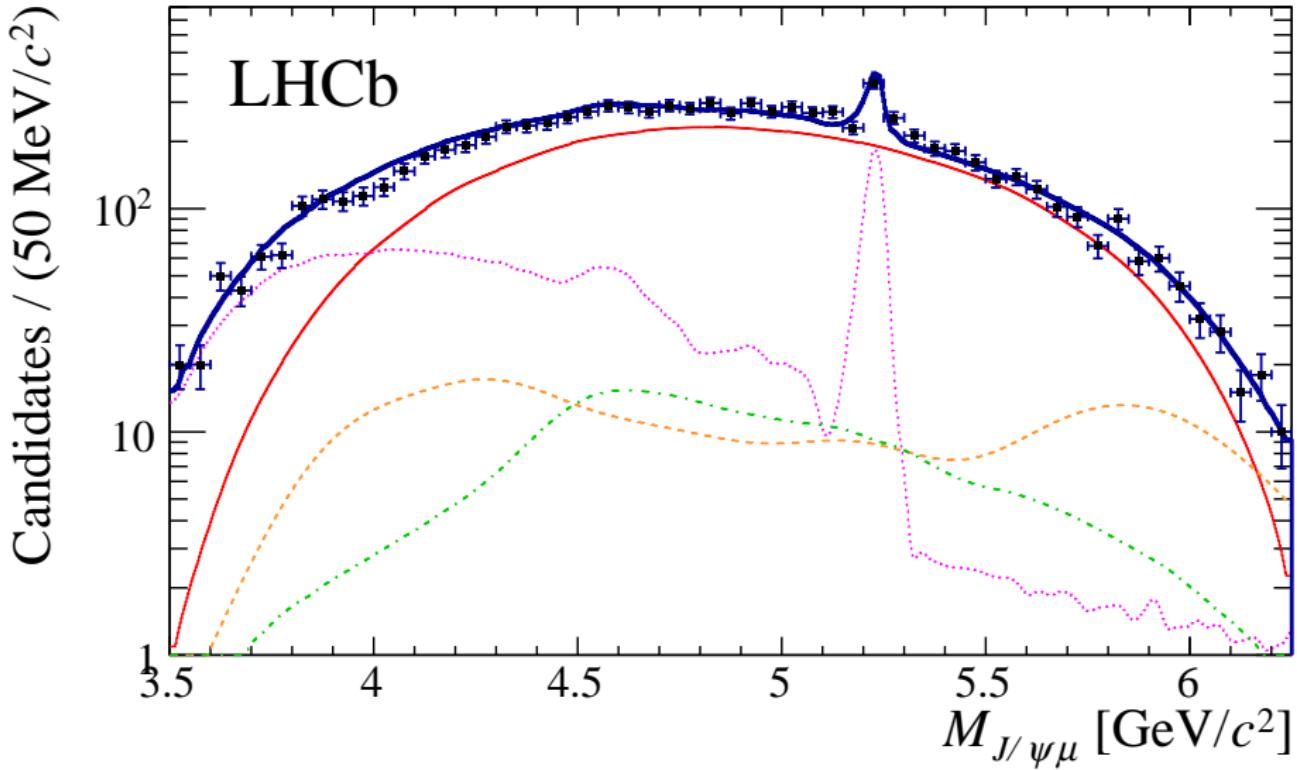
Ricostruzione totale: $B^+ \rightarrow J/\psi K^+$

Ricostruzione parziale: $B^0 \rightarrow J/\psi K^+(\pi^-)$

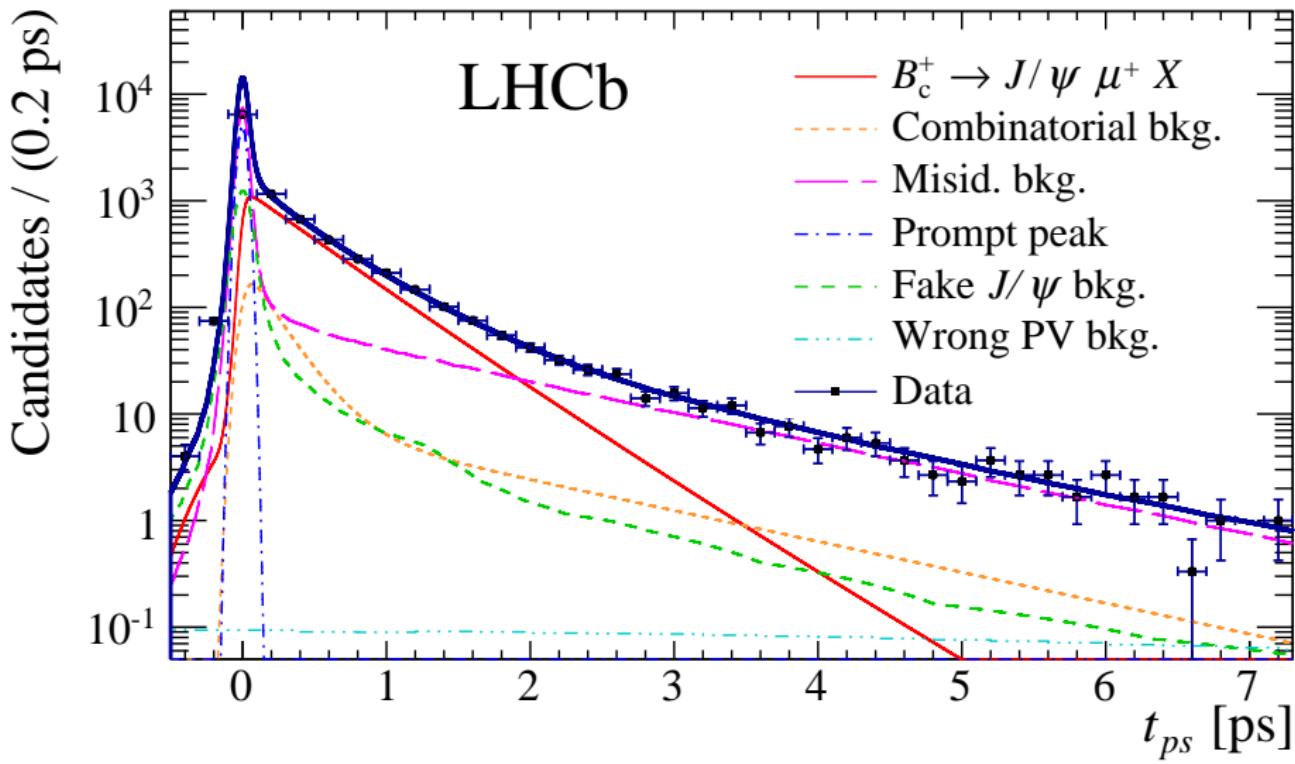
Utilizzo della simulazione limitato al (piccolo) fondo combinatorio.



$B_c^+ \rightarrow J/\psi\mu^+X$ fondo di misidentificazione ($h \rightarrow \mu$) fondo combinatorio pronto
 fondo da fake J/ψ fondo combinatorio distaccato da PV.



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Incertezza statistica: 8 fs.

Incertezza totale PDG: 33 fs

Modello del segnale

- Spettri delle variabili cinematiche di produzione del B_c^+ ;
- Modelli dei fattori di forma; \leftarrow **OGGI**
- Decadimenti di *feed-down*;
- Modello della risoluzione sperimentale sul tempo di decadimento.

Modello di fondo

- Forma e normalizzazione di ciascuna componente

Ricostruzione e tecnica di fit

- Bias dello stimatore
- Calibrazione e allineamento del rivelatore
- Efficienza in funzione del tempo

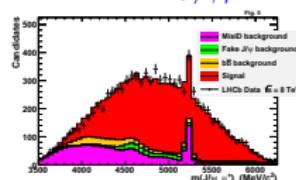
Dipendenza dal modello teorico: deformazione del Dalitz plot

Deformazione del modello teorico:

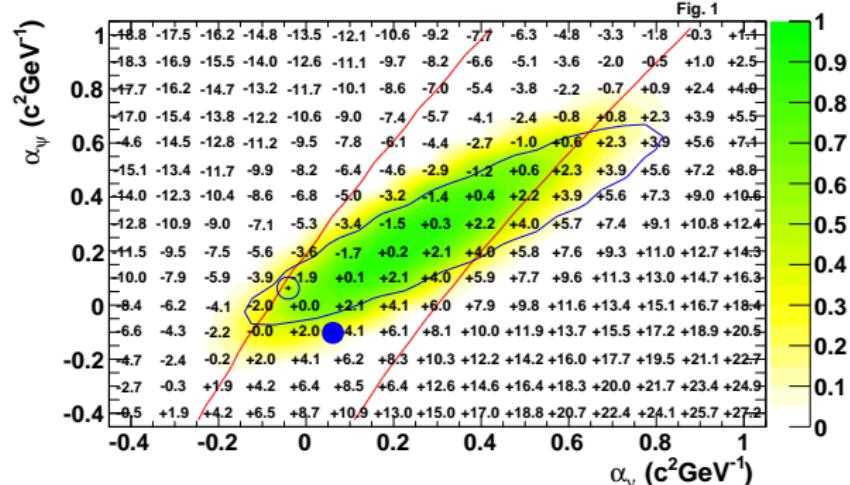
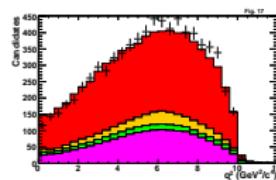
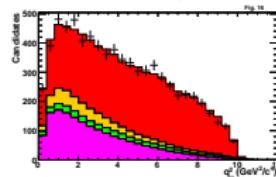
$$DeformedDalitz(M_{J/\psi\mu}^2, M_{\mu\nu}^2) = NominalDalitz(M_{J/\psi\mu}^2, M_{\mu\nu}^2) e^{(\alpha_\psi M_{J/\psi\mu} + \alpha_\nu M_{\mu\nu})}$$

Quindi si cercano i parametri α_ψ e α_ν che preservano buon accordo coi dati.

Distribuzione $M_{J/\psi\mu}$



Distribuzione $M_{\mu\nu}$ (2 soluzioni)



Model-independent uncertainty on lifetime ± 5 fs

Lista delle incertezze sistematiche

Source	Assigned systematic [fs]
B_c^+ production model	1.0
B_c^+ decay model	5.0
Signal resolution model	1.3
Prompt background model	6.4
Fake J/ψ background yield	0.4
Fake J/ψ background shape	2.3
Combinatorial background yield	3.4
Combinatorial background shape	7.3
Misid. background yield	0.8
Misid. background shape	1.2
Length scale calibration	1.3
Momentum scale calibration	0.2
Acceptance function	2.6
Wrong association to PV	1.8
Multiple candidates	1.0
Fit validation	0.5
Quadratic sum	12.4

$$\Delta\tau_{B_c^+} = 8(\text{stat}) \oplus 12(\text{syst}) \text{ fs}$$

Conclusioni

La vita media del mesone B_c^+ è stato misurato utilizzando i decadimenti semileptonici

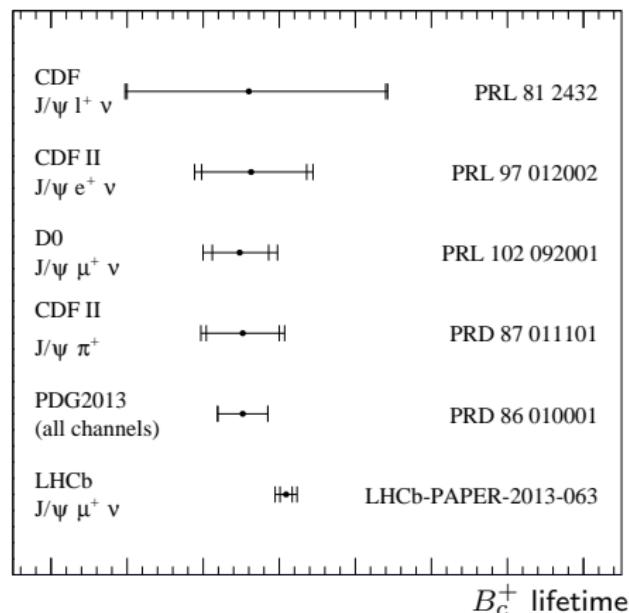
$$B_c^+ \rightarrow J/\psi \mu^+ X.$$

Il fondo atteso è modellizzato utilizzando metodi basati su dati reali ovunque possibile.

L'incertezza sistematica dovuta alla dipendenza dal modello è ben controllata e non risulta dominante.

Il risultato ottenuto per la vita media del mesone B_c^+ ,

$$\tau = 509 \pm 8 \text{ (stat)} \pm 12 \text{ (syst)} \text{ fs}$$

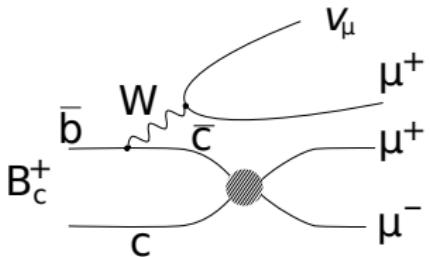


è in buon accordo con la media mondiale, e ne migliora la precisione di un fattore 2.

Articolo disponibile su [arXiv:1401.6932](https://arxiv.org/abs/1401.6932), e presto su EPJC.

Backup slides

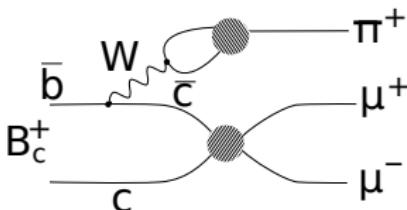
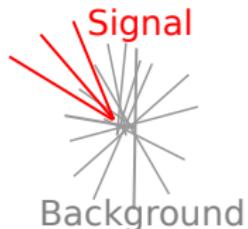
Canale adronico o semileptonico?



Decadimento semileptonico (SL)

$$B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu$$

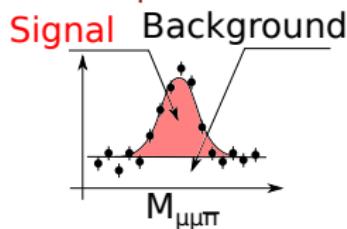
- Alta statistica, $\sim 20\times$ rispetto a $J/\psi\pi$;
- Vertice di 3μ , piuttosto raro.
- Impossibile ricostruire massa del B_c^+
- Include contributi $c\bar{c} \rightarrow J/\psi X$ (feed-down)



Decadimento non-leptonico (NL)

$$B_c^+ \rightarrow J/\psi \pi^+$$

- Modello di fondo più semplice;
- Analisi indipendente dal modello;
- Fondo irriducibile dal vertice primario
- Tagli di distaccamento hanno efficienza dipendente dal tempo



Competitive and complementary analyses

Essential Ingredients

Signal model

- ▶ t_{ps} -independent acceptance
- ▶ Resolution
- ▶ k-factor (dynamics)
- ▶ feed-down decays
- ▶ Different t_{ps} slope for different $M_{J/\psi\mu}$

Background

Rejection

- ▶ Good vertex
- ▶ High p_T
- ▶ Tight MuonID
- ▶ Narrow J/ψ mass window

Model

- ▶ Background subtraction
- ▶ Data-driven
- ▶ pdf
- ▶ yield

Probability of observing each i -th event with a decay time t and invariant mass m :

$$P^{(i)}(t, m; \tau_{B_c^+}, \dots) = P_{\text{sig}}^{(i)}(t, m; \tau_{B_c^+}, \dots) + P_{\text{bkg}}^{(i)}(t, m; \dots)$$

Many events \Rightarrow Likelihood function:

$$\mathcal{L} = \prod_i P^{(i)}(t, m; \tau_{B_c^+}, \dots)$$

The best estimation for the B_c^+ lifetime $\tau_{B_c^+}$ maximizes \mathcal{L} .

Putting all together: the Signal model

Theoretical pdf for decays, weighted on k -factor distribution $h(k)$.

$$f_{th}^*(t^*) = \int_{-\infty}^{+\infty} \frac{1}{\tau k} \theta(t^*/k) \exp\left(-\frac{t^*}{k\tau}\right) h(k) dk$$

Assuming a Gaussian resolution model, with width $\sigma_{t^*}^*$, the resolved pdf becomes

$$\begin{aligned} f(t^*) &= f_{th}^*(t^*) * G(t^*; \sigma_{t^*}) \\ &= \int_{-\infty}^{+\infty} dt' \int_{-\infty}^{+\infty} dk h(k) \frac{1}{\tau k} \theta(t') \exp\left(-\frac{t'}{k\tau}\right) \frac{1}{\sqrt{2\pi\sigma_{t^*}^2}} \exp\left(-\frac{(t^* - t')^2}{2\sigma_{t^*}^2}\right) \\ &= \int_{-\infty}^{+\infty} dk h(k) \int_0^{+\infty} dt' \frac{1}{\tau k} \exp\left(-\frac{t'}{k\tau}\right) \frac{1}{\sqrt{2\pi\sigma_{t^*}^2}} \exp\left(-\frac{(t^* - t')^2}{2\sigma_{t^*}^2}\right) \\ &= \frac{1}{2\tau} \int_{-\infty}^{+\infty} dk h(k) \exp\left(\frac{\sigma_{t^*}^2/\tau - 2t^*}{2\tau}\right) \operatorname{erfc}\left(\frac{\sigma_{t^*}^2/\tau - t^*}{\sigma\sqrt{2}}\right) \end{aligned}$$

The integral is evaluated numerically using k -factor distribution from Monte Carlo.

$$f(t_{ps}, M_{J/\psi\mu}) = \sum_i h(k_i; M_{J/\psi\mu}) w_i \exp\left(\frac{\sigma_{t^*}^2/\tau - 2t_{ps}}{2\tau}\right) \operatorname{erfc}\left(\frac{\sigma_{t^*}^2/\tau - t_{ps}}{\sigma\sqrt{2}}\right) \otimes f(M_{J/\psi\mu})$$

For integral operator linearity, using a 3 Gaussian resolution function is trivial:

$$f(t^*) = \sum_{i=1}^3 g_i f_i(t^*; \sigma_{t^*}^{(i)})$$

Reconstruction effect: decay time resolution

- Resolution function studied on Simulation;
- Four Gaussian model;

$$G(\Delta t) = \sum_{i=1}^4 g_i \exp\left(-\frac{(\Delta t - t_0)}{2\sigma_i^2}\right)$$

- Smallest Gaussian accounts for wrong PV association and is removed in the final fit;
- Fitted parameters are checked on data studying events with a reconstructed $t_{ps} < 0$.

Only for comparison, not used in the analysis:

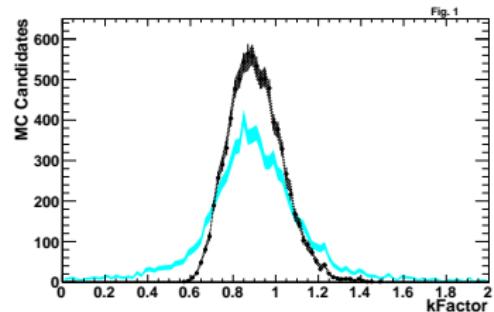
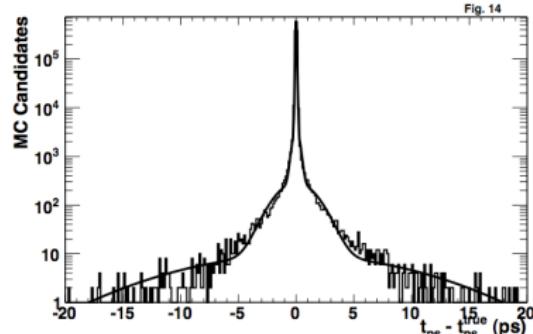
- k*-factor distribution with resolution effects**

compared to

- k*-factor without resolution effects**

on a small sub-sample of simulated data.

The smearing of the reconstructed time is
dominated by *k*-factor



Muon identification

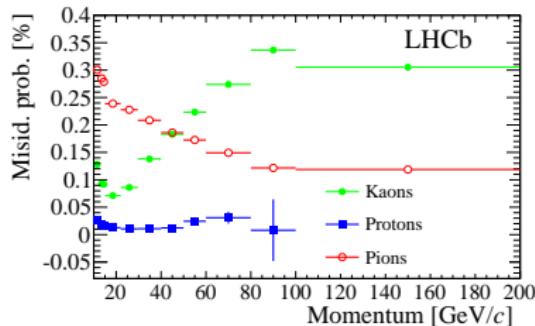
Signal-background separation relies on 3μ : $h \rightarrow \mu$ misidentification is dangerous.

$B \rightarrow J/\psi K(\pi)$ is very abundant and detached.

- Require muon hits in ≥ 4 muon stations;
- Reject K (and p) using RICH detectors;
- Reject K decaying to μ using track kink;
- Reject combinatorial association of muon hits to hadron tracks by
 - Performing a **Kalman filter** track fit using muon hits
 - Rejecting muon candidates with Kalman filter $\chi^2/\text{ndof} > 1.5$;
 - Requiring **each hit is used at most once**.

Average misidentification probability: 0.2%
Single muon identification efficiency: 87%

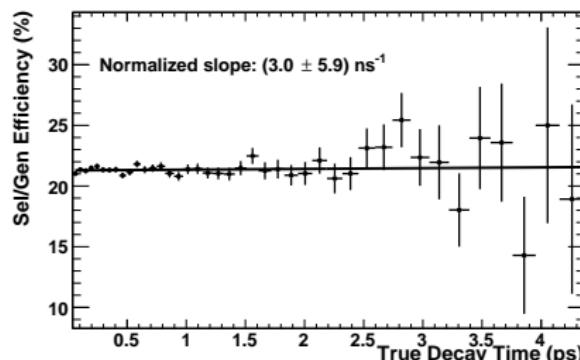
Dominating residual background from
decays in flight



Lifetime unbiased selection

Time dependence of the selection efficiency?

Simulated sample with 10 times the statistics available on data.



Real data:

- Selected 30 700 candidates;
- Expected signal yield:
~ 10 000 candidates.

The efficiency includes the simulated effect of:

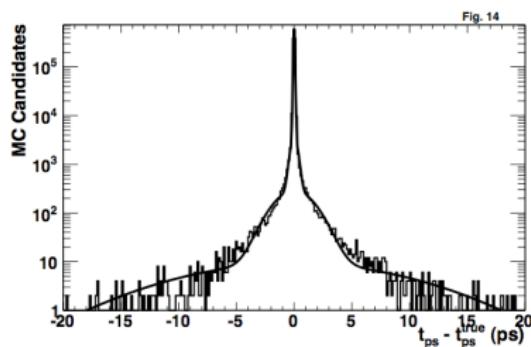
- Geometrical acceptance of the detector;
- Trigger fast-reconstruction algorithms as used in 2012;
- Reconstruction effects;
- Stripping and offline-refined selection.

No evidence of deviation from the flat hypothesis is observed confirming expectations.

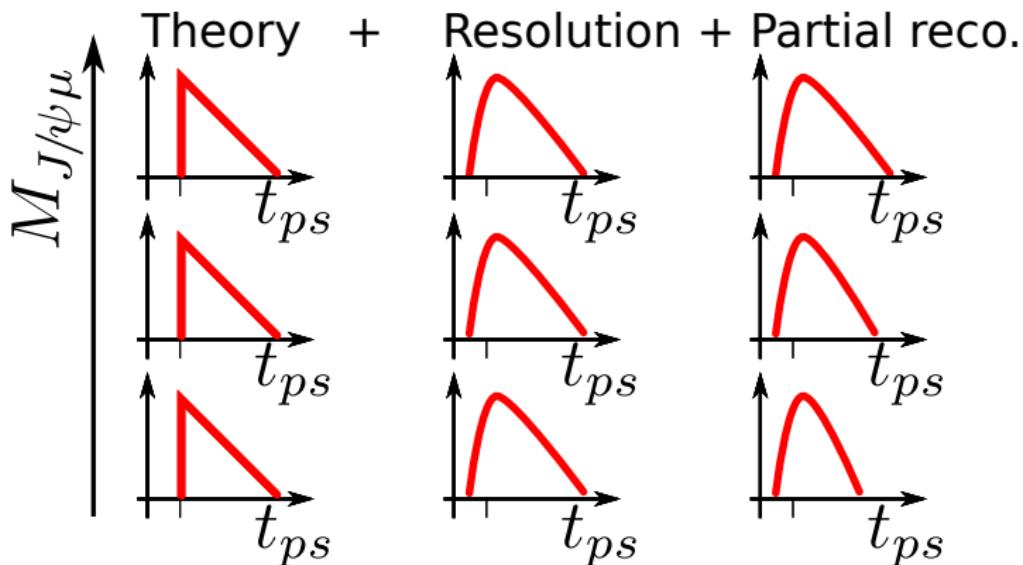
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The smearing of the reconstructed time is dominated by k -factor



Mass projection taken from full Simulation

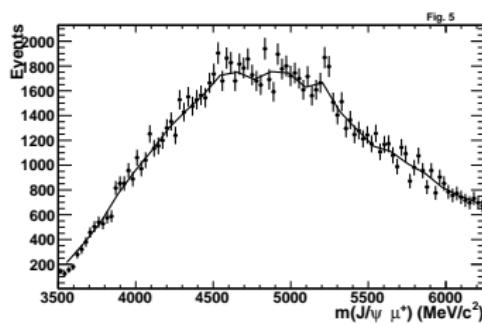
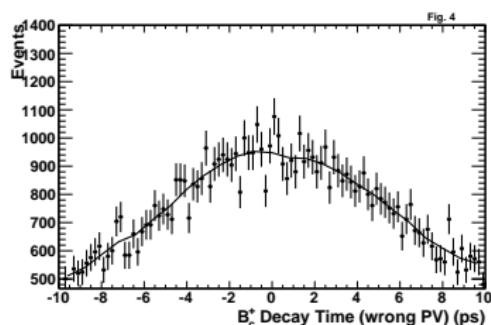
Maths in the backup

Association to the wrong PV is particularly relevant for SL decays.

Two options:

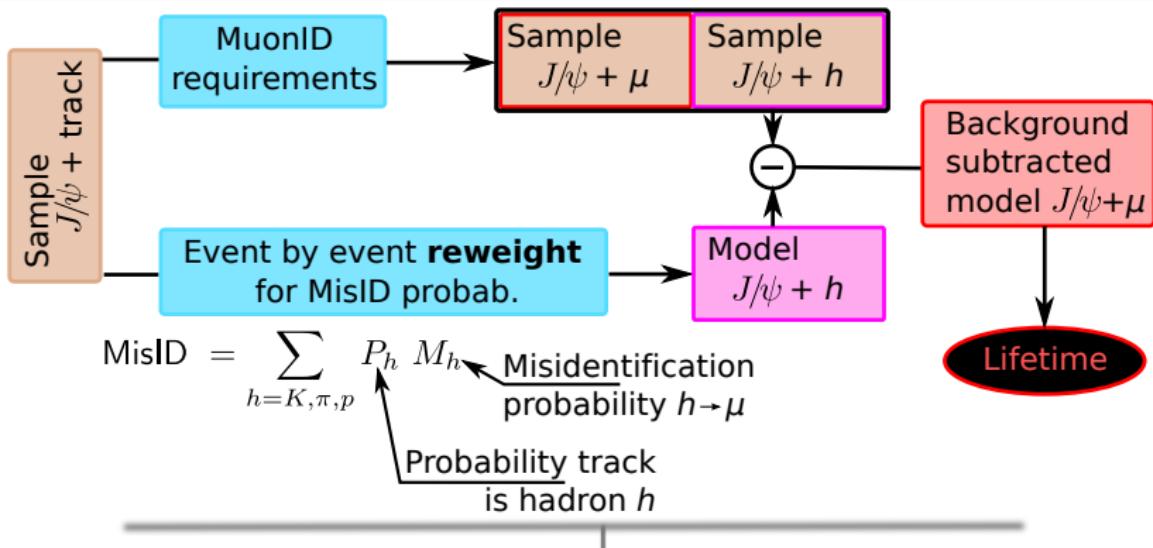
- Cut events with ambiguities in PV association
(found to have low efficiency → for systematics)
- Model events (as done for J/ψ cross-section measurement).

Pdf constructed by taking PVs from the previous event in nTuples and re-associating.

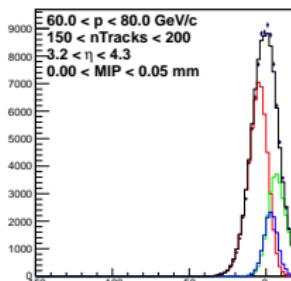


The global fit converges to 15 ± 6 wrong associated events (association efficiency $> 99\%$).

Misidentification background



$$P_h = P_h(p, \eta, \text{nTracks})$$



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$$M_h = M_h(p, \eta, \text{Impact parameter})$$

Calibration samples

- $D^{*+} \rightarrow D^0 \pi_s^+ \rightarrow (\text{K}^+ \text{ red} \pi^+ \text{ green})_D \pi_s^+$
Flavour tagged with the slow pion π_s .
- $\Lambda^0 \rightarrow p \pi^-$
Very wrong mass in case of
 $p \rightarrow \pi$ & $\pi \rightarrow p$.

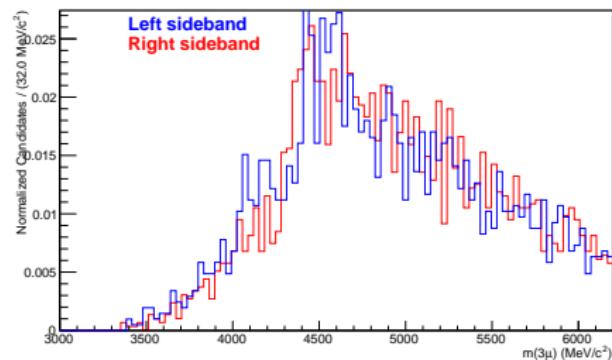
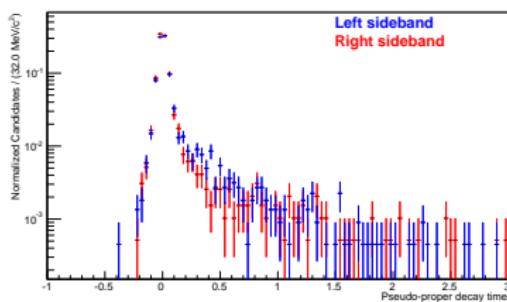
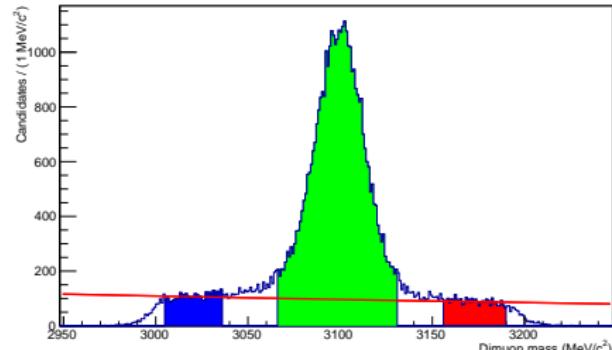
Fake J/ψ background

The **pdf** is taken from the events in far sidebands after having applied all the final-fit cuts.

The **normalization** is fixed to the integral of an exponential fit function (in red), in the signal region.

The pdf of the right and left sidebands are almost consistent.

Small deviations considered in systematic uncertainty assessment.



Combination of Kernel PDF and adaptive binning to model the contribution

A true J/ψ with a true μ^+ , but not from a B_c^+ .

Insidious background: very small, but very difficult to model.

- 18M event $B_{u,d,s} \rightarrow J/\psi X$ MC, truth-matched to ensure true $J/\psi +$ true μ^+ .
- Using LHCb detached J/ψ cross-section measurement at $\sqrt{s} = 8$ TeV to find expected event yield.

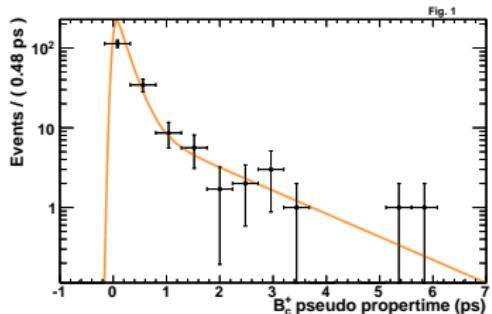


Fig. 1

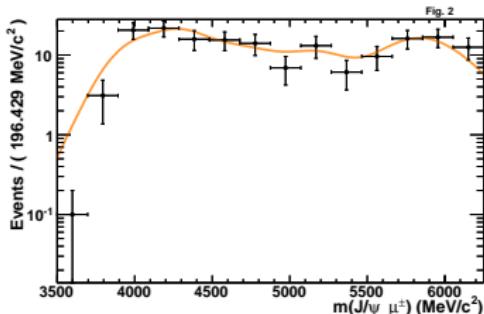
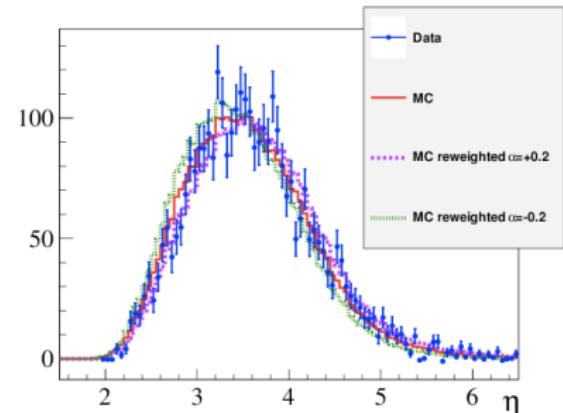


Fig. 2

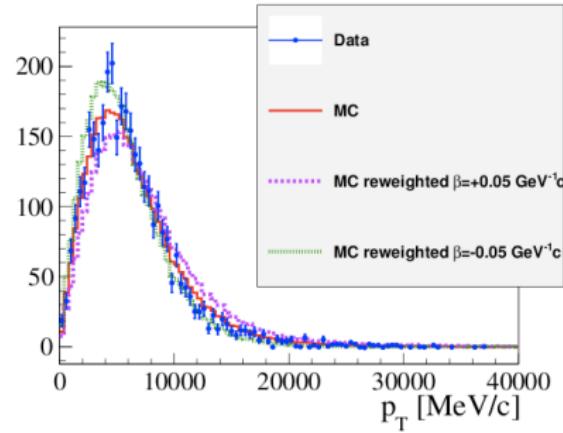
Expected yield: $978 \pm 168(\text{stat})$ events.

A bad simulation of the B_c^+ momentum spectrum can modify the simulated k -factor distribution, and thus the lifetime. **How much?**

Reweighting of the B_c^+ spectra (p_T and η) to assess systematic uncertainty due to data/simulation disagreement



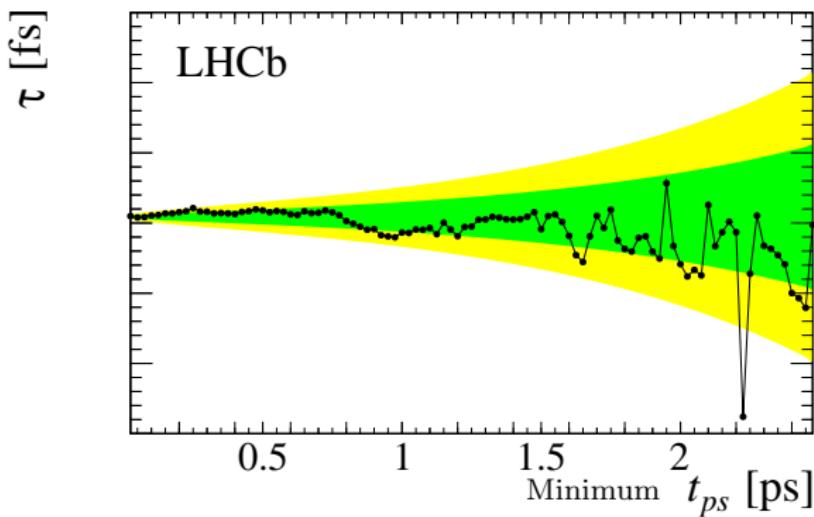
- using $B_c^+ \rightarrow J/\psi\pi^+$ distribution to compare data and Simulation
- reweighted signal pdf (including feed-down decays)



Small effect: $0.8(p_T) \oplus 0.6(\eta) = 1.0 \text{ fs}$

Systematic uncertainty on the prompt peak model

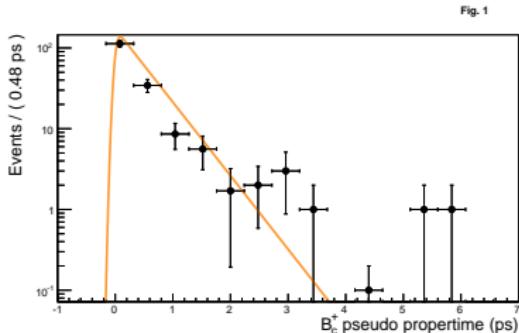
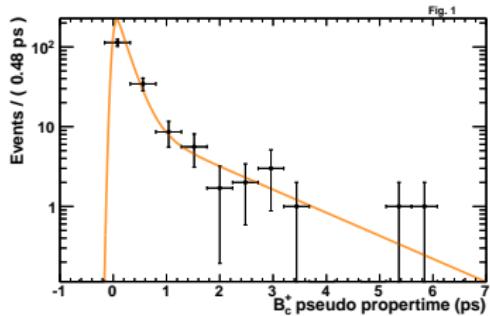
Prompt peak removed using only events with $t_{ps} > x$.



The results are consistent with statistical fluctuations.

Lifetime variation obtained at $t_{ps} > 150$ fs was used as systematic uncertainty: 6.4 fs

The Simulation statistics is low and the time-projection shape can be parametrized well with a single exponential instead of a double exponential.



The effect on the lifetime is quite large: 7.4 fs

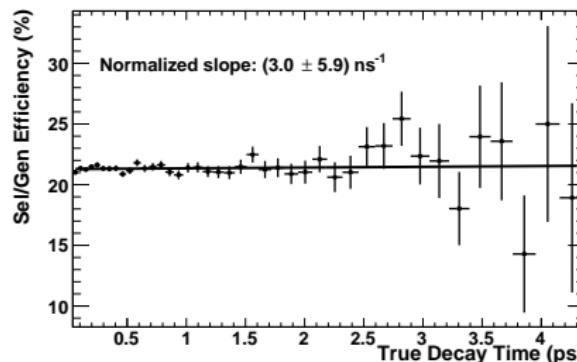
An uncertainty $\pm 50\%$ is set on the expected normalization.

The effect on the lifetime is ± 3.4 fs.

Acceptance function

Let's consider once again the acceptance function.

A fit to a straight line constrains the slope $\beta \in [-3, 9]$ (68% C.L.).



$$\begin{aligned}\exp\left(-\frac{t}{\tau + \Delta\tau}\right) &\approx \exp\left(-\frac{t}{\tau} + \frac{t}{\tau^2}\Delta\tau\right) = \exp\left(-\frac{t}{\tau}\right)\exp\left(\frac{t}{\tau^2}\Delta\tau\right) \approx \\ &\approx \left(1 + \frac{\Delta\tau}{\tau^2}t\right)\exp\left(-\frac{t}{\tau}\right) = (1 + \beta t)\exp\left(-\frac{t}{\tau}\right)\end{aligned}$$

Thus,

$$\beta = \frac{\Delta\tau}{\tau^2} \quad \Rightarrow \quad \Delta t = \tau^2\beta \quad \Rightarrow \quad \beta \in [-3, 9] \text{ ns}^{-1} \rightarrow \Delta\tau \in [-0.7, 2.6] \text{ fs}$$

± 2.6 fs assigned as systematic uncertainty.