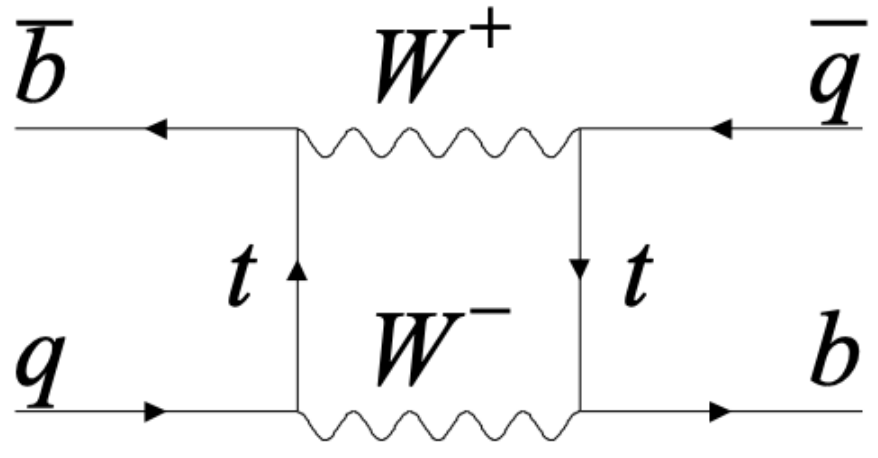
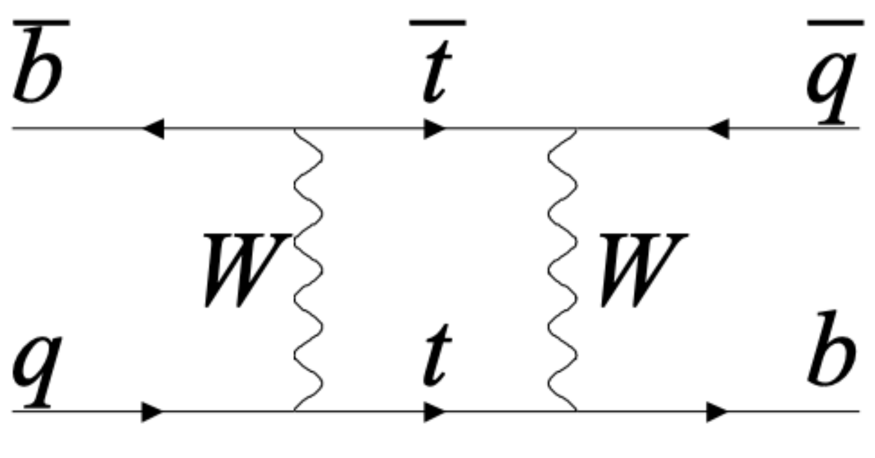
More than a ~~feeling~~ lifetime

Ozlem Ozcelik
CERN





Outlook

- Experimental strategies to measure lifetimes.
- Some of the results for the lifetimes at LHCb (<u>selective choice</u>)

$\rightarrow$ Effective lifetimes

$\rightarrow$ Ratio of the lifetimes

$\rightarrow \Delta\Gamma_s$ measurements

Why lifetime?

- Connected to decay width : $\tau \equiv 1/\Gamma$
- Important to probe both **weak interactions and non-perturbative QCD**

$\longrightarrow$

- Inputs for the CP violation measurements $(\Delta\Gamma, A_{CP}, \phi_s)$
- Precision flavour physics
- Important for testing HQE (Heavy Quark Expansion)

Heavy Quark Expansion

$$\Gamma = \Gamma_0 + \frac{\Lambda^2}{m_q^2}\Gamma_2 + \frac{\Lambda^3}{m_q^3}\Gamma_3 + \ldots.$$

m_q : the heavy quark mass

$\Lambda \sim \Lambda_{QCD}$: ~300–500MeV.

Works well for $m_q \gg \Lambda_{QCD}$

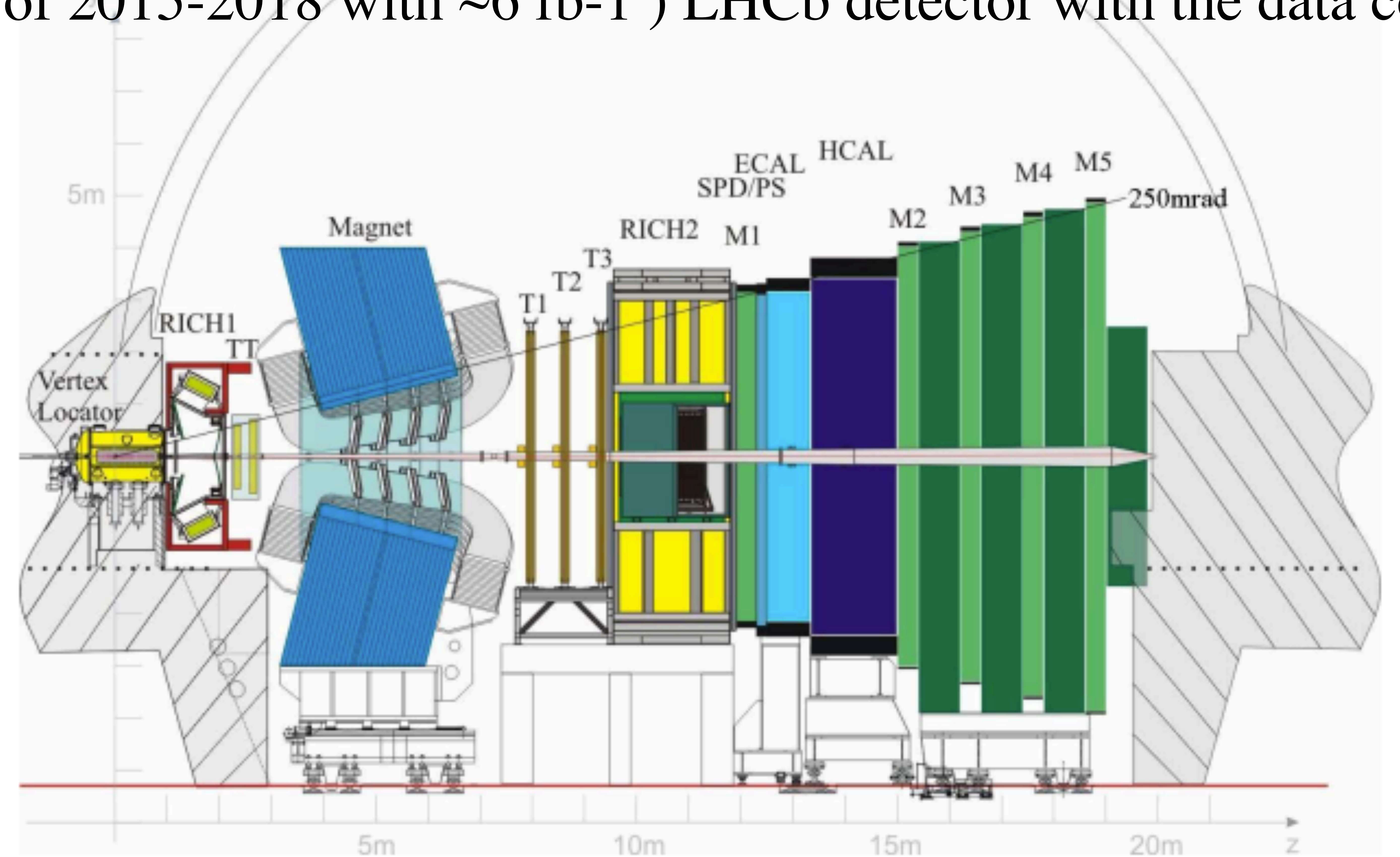
- Γ_0 : Free quark expansion, the leading contribution to the decay width

  $\rightarrow$ Lifetime would be same for all the hadrons having a same heavy-quark, if the expansion would stop here
- Γ_2 : Spin and kinetic corrections
- Higher orders: spectator effects (Pauli interference, W-exchange, etc.)

  $\rightarrow$ especially interesting for the ratio measurements

LHCb Detector

- Unique forward coverage in the pseudo rapidity range $2 < \eta < 5$ designed for studying particles including *b* and *c* quarks
- Run2 (data taking years of 2015-2018 with ~6 fb-1) LHCb detector with the data collected at $\sqrt{s} = 13$ TeV

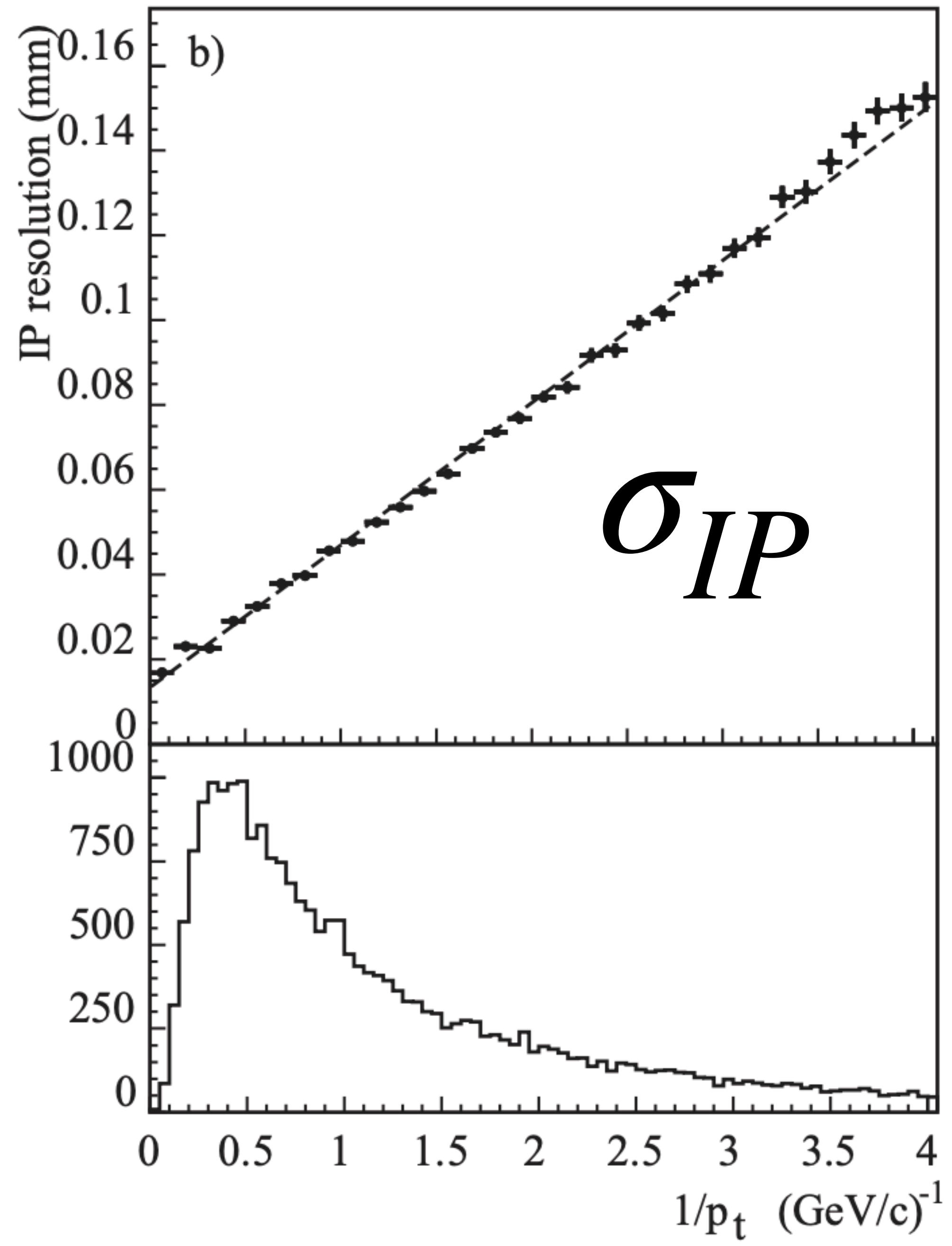


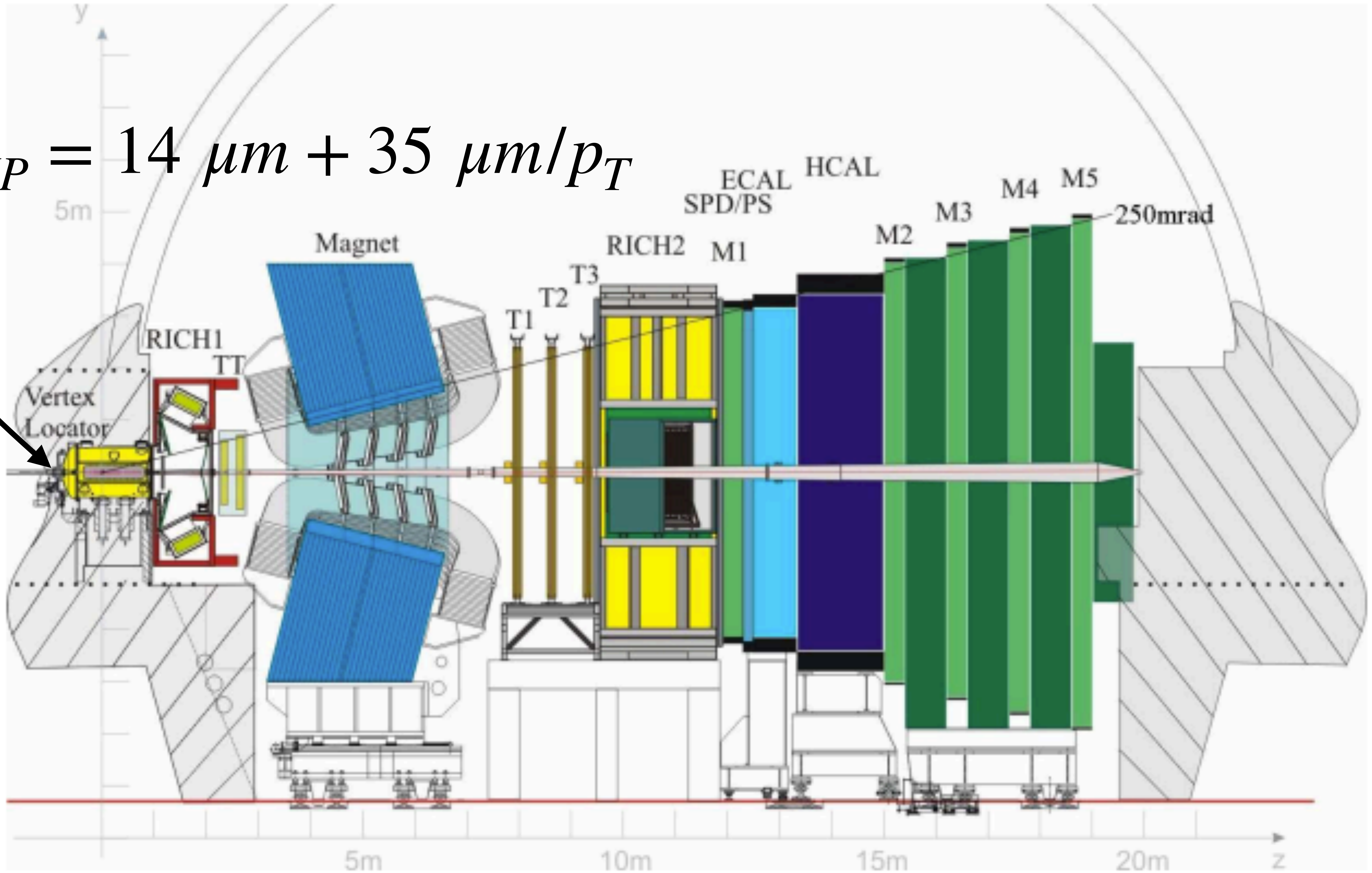
LHCb Detector

VELO (vertex) detector

→ Vertex resolution of ~10 μm

→ Impact parameter resolution $\sigma_{IP} = 14\ \mu m + 35\ \mu m/p_T$



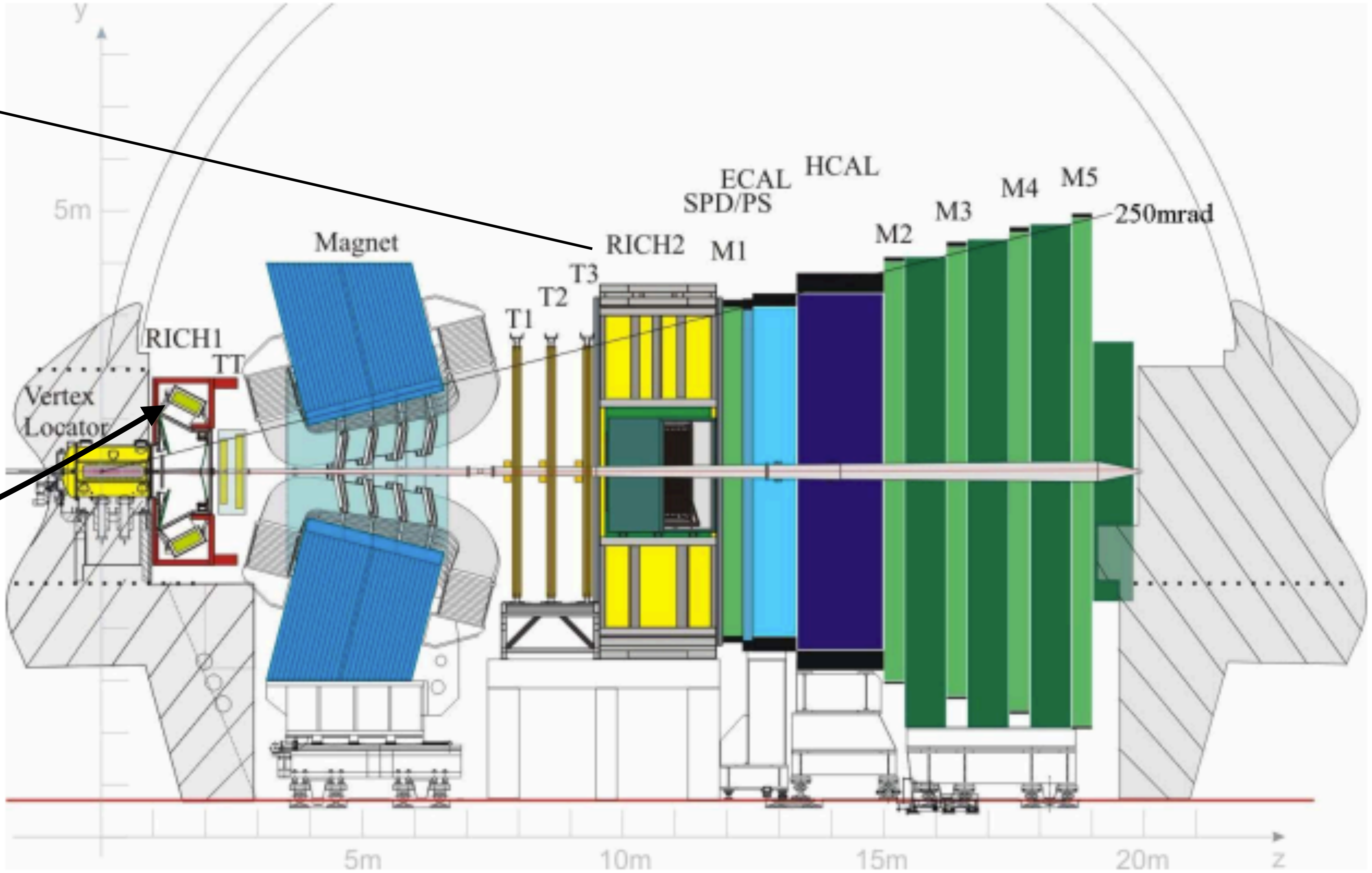


LHCb Detector

RICH detector(s)

→ Good particle **identification** over the entire momentum range (π/K/p separation)

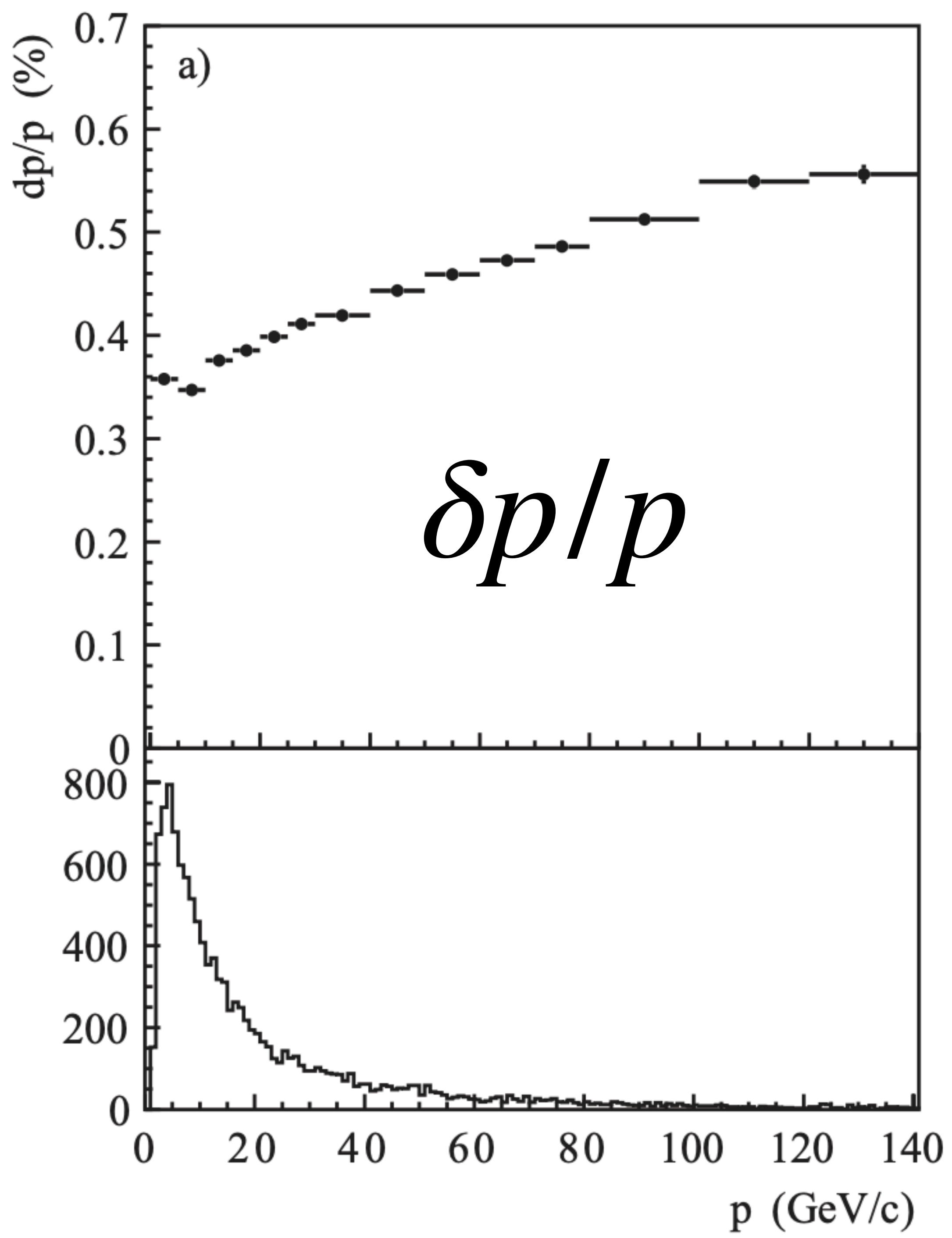
→ ~ 30 GeV/c , (mis)identification probability ~97% (5%)



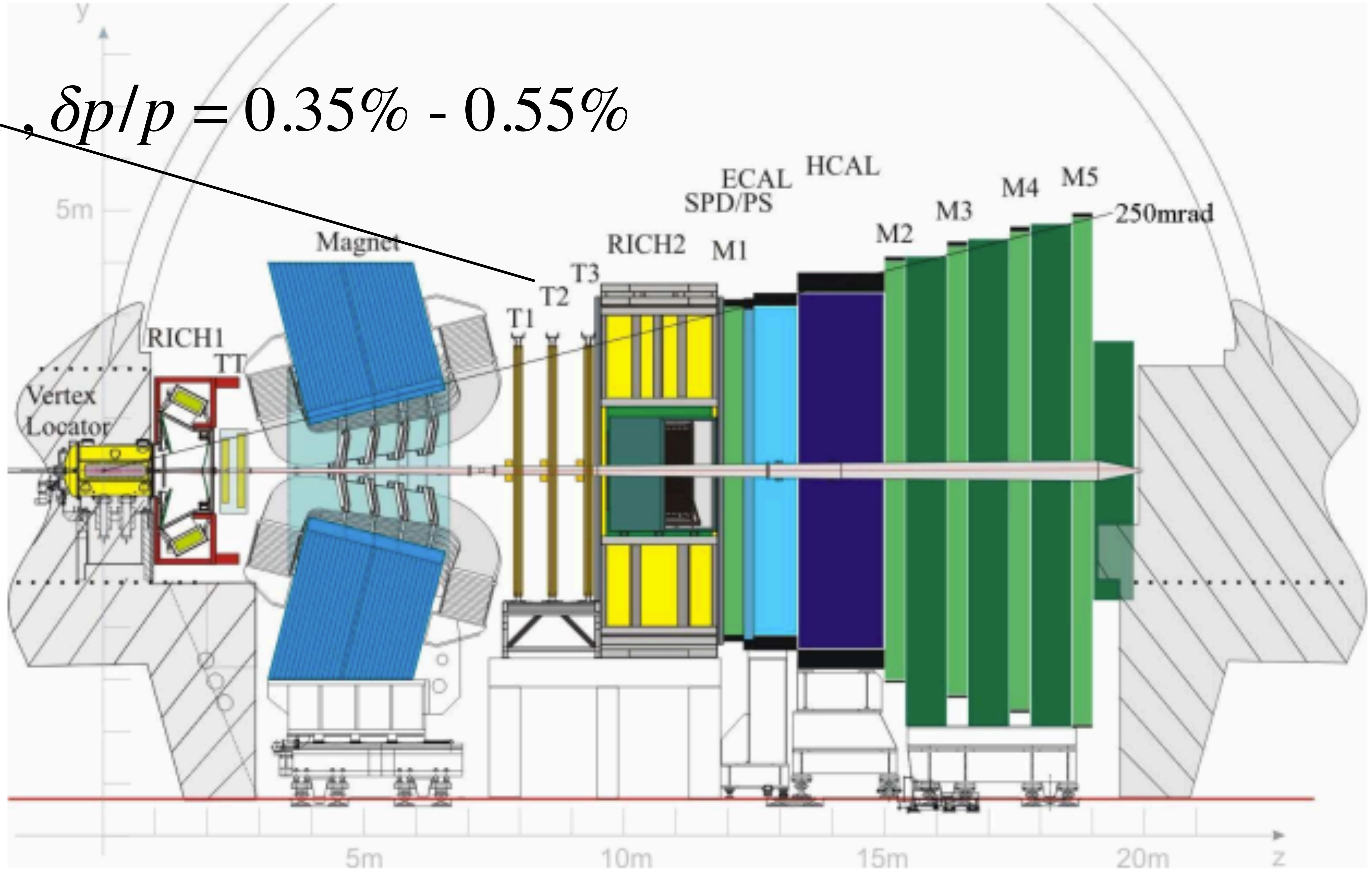
LHCb Detector

Tracking detectors

→ Excellent momentum resolution , $\delta p/p$ = 0.35% - 0.55%



$\delta p/p$

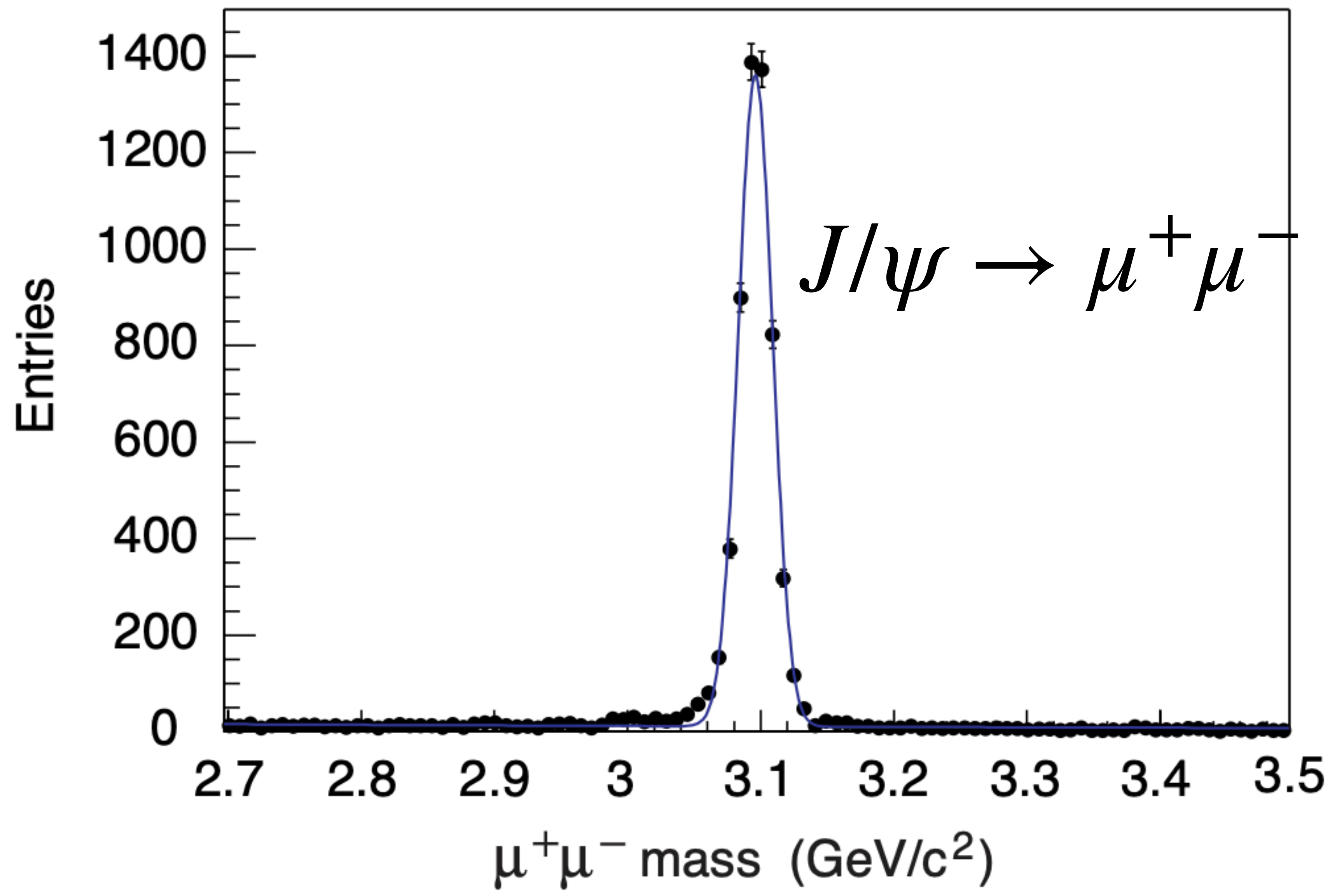


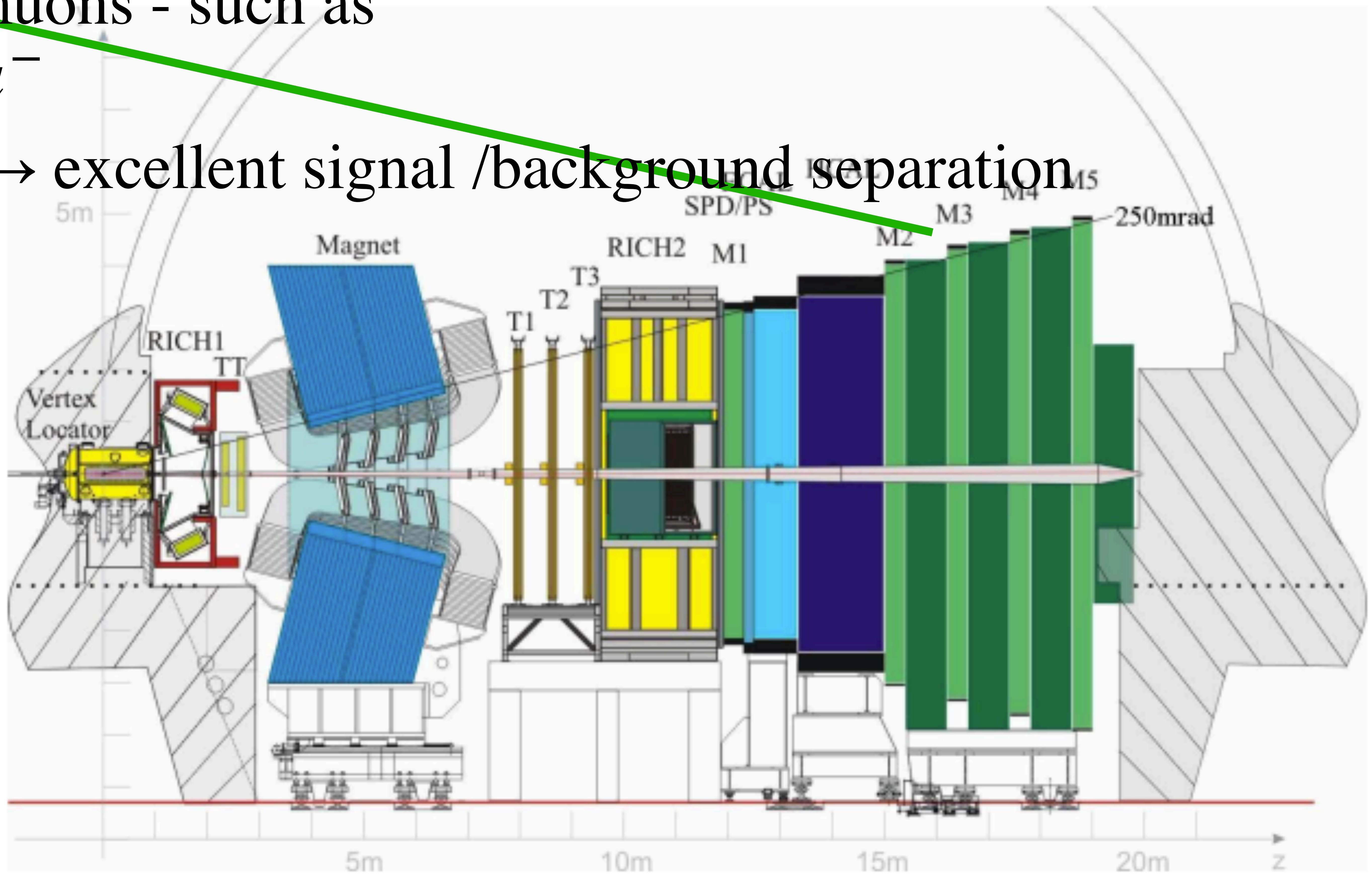
LHCb Detector

Muon detectors

→ Many golden channels includes muons - such as $B_s \to J/\psi\phi, B^0 \to J/\psi K_s, B_s \to \mu^+\mu^-$

→ Excellent particle identification → excellent signal /background separation $\varepsilon(\mu \to \mu)$=93% and $\varepsilon(\mu \to \pi) = 1\%$





Experimental Strategy

- Reconstruct decay vertex (SV) and primary vertex (PV)

  → Exploit from the excellent momentum and vertex resolution.

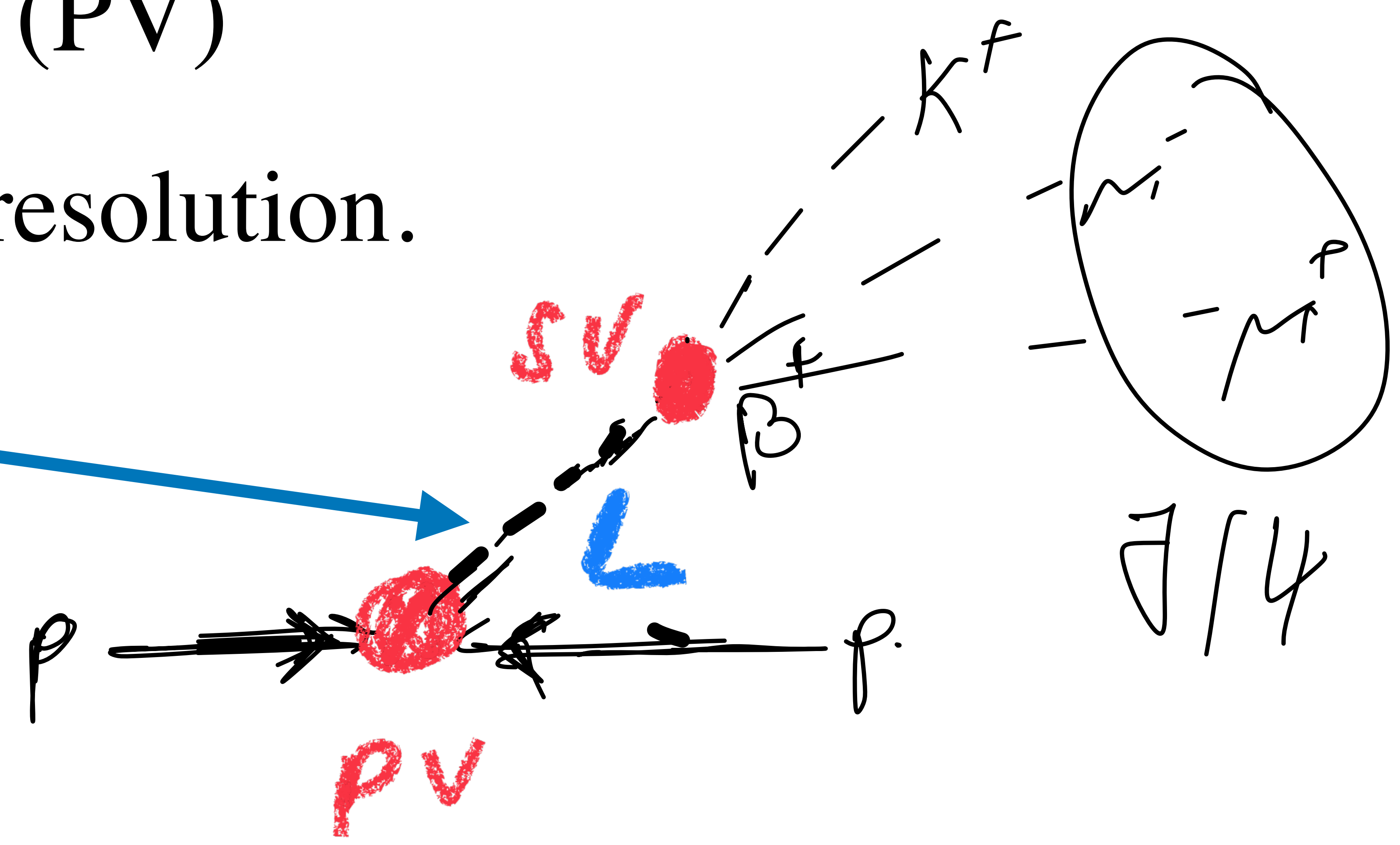
- Measure momentum **p** and decay length , L

- **Proper time** measurement:

$$t = \frac{L \cdot m_B}{p}$$

Invariant mass

Momentum



But is that really how we measure lifetime?
Almost..

Experimental Strategy - 2

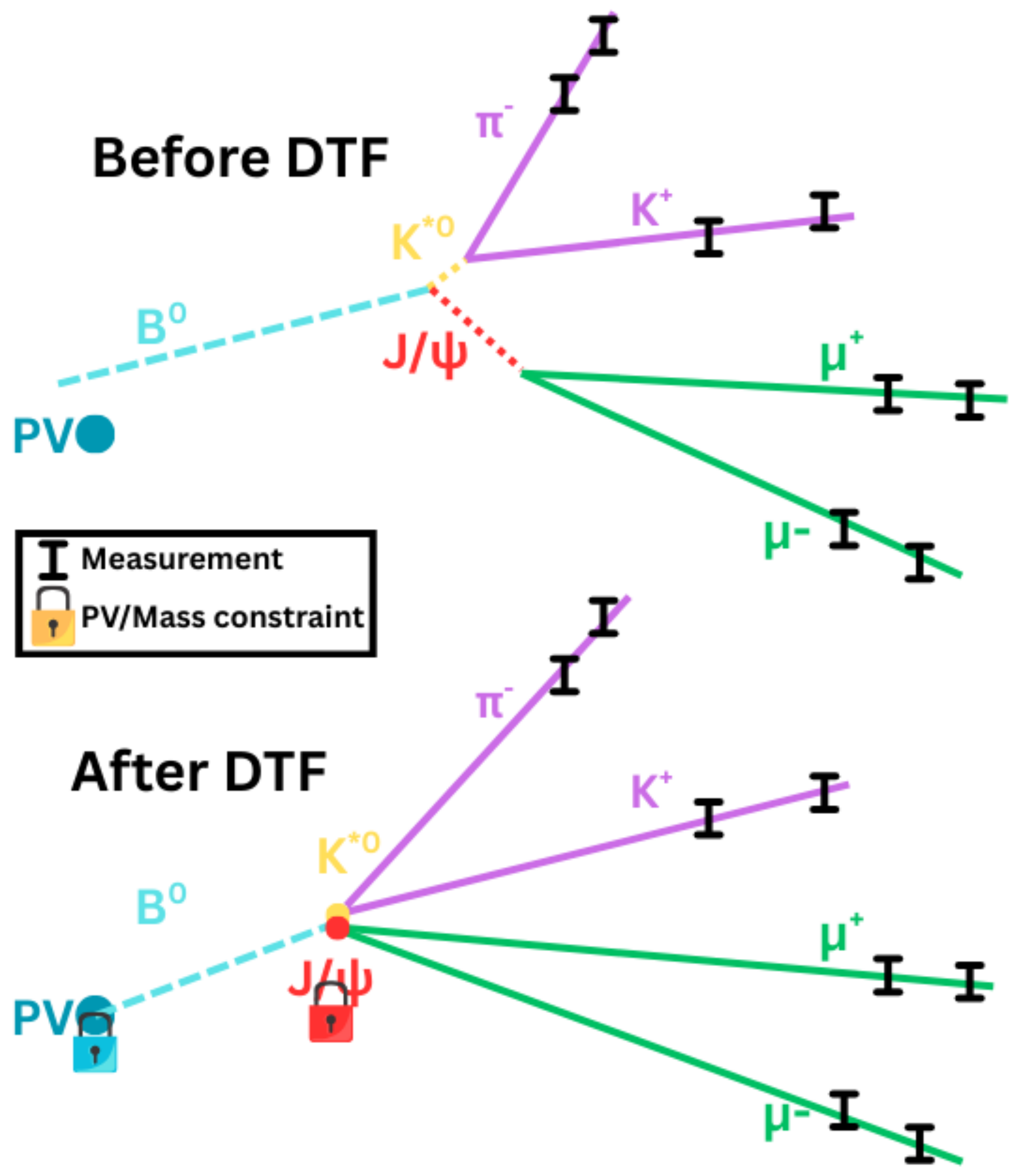
How can we improve the momentum and vertexing strategy even more?

→ Kinematic fitting tool - DecayTreeFitter (DTF)

- Refit the full decay chain of a particle using measured track parameters, such as position and momentum of the particles, and some physics constraints (PV vertex, mass constraints).

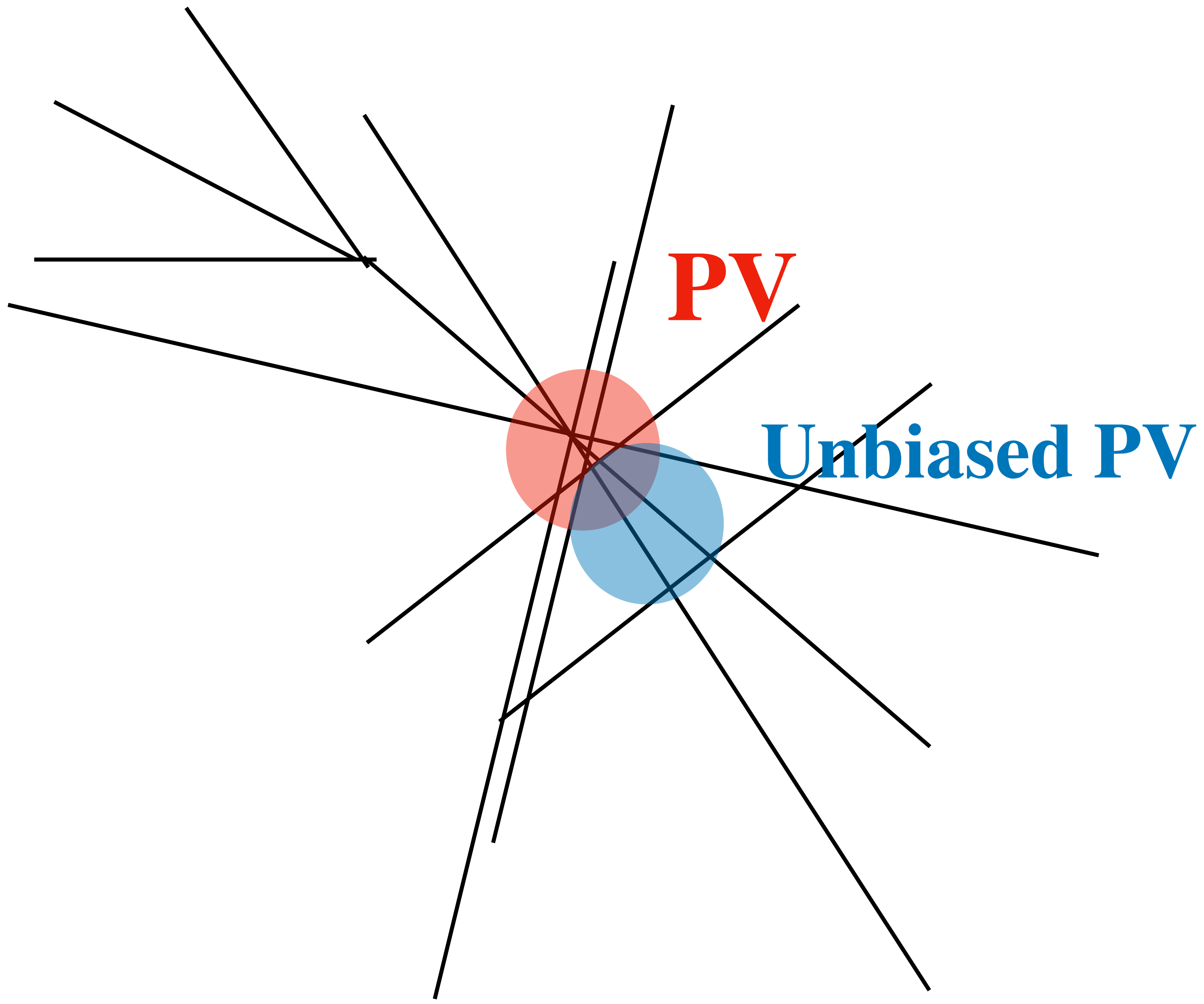
→ Make sure tracks from same vertex -> Better momentum resolution → mass resolution

→ Mass constraint -> Better momentum resolution → mass resolution

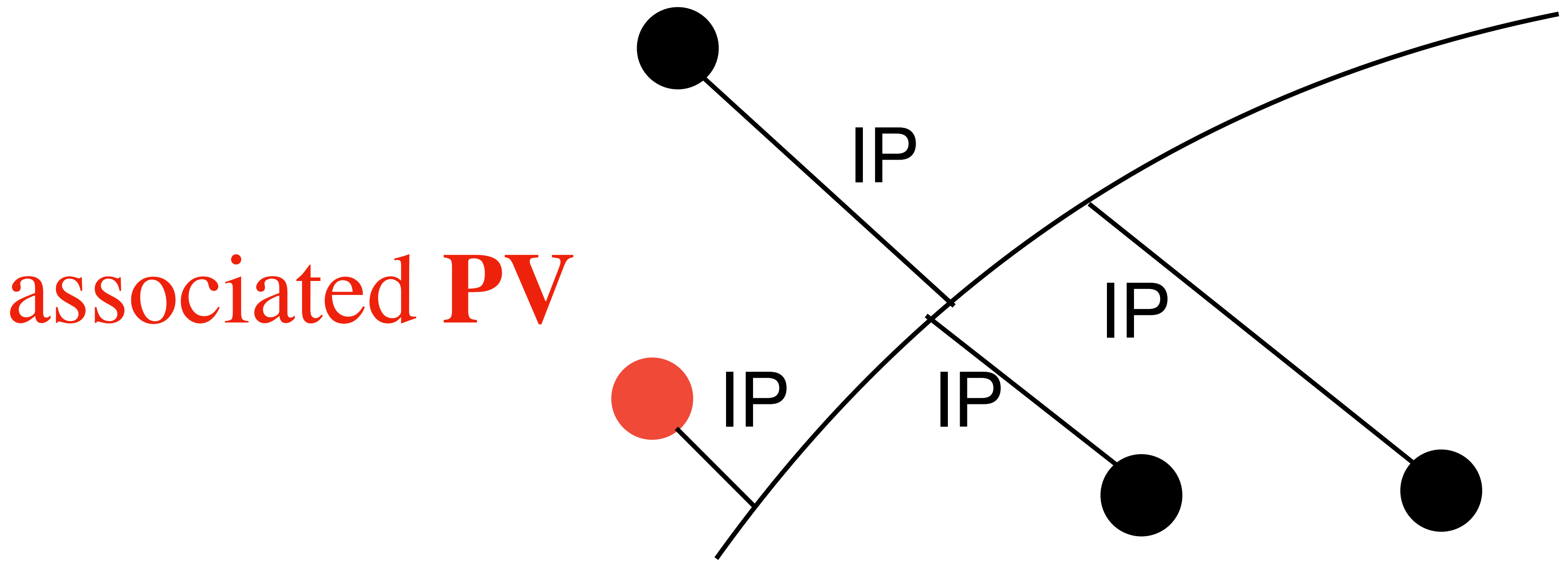


Experimental Strategy - 3

How do we know we do not bias the measurement by the “associated” **PV**?

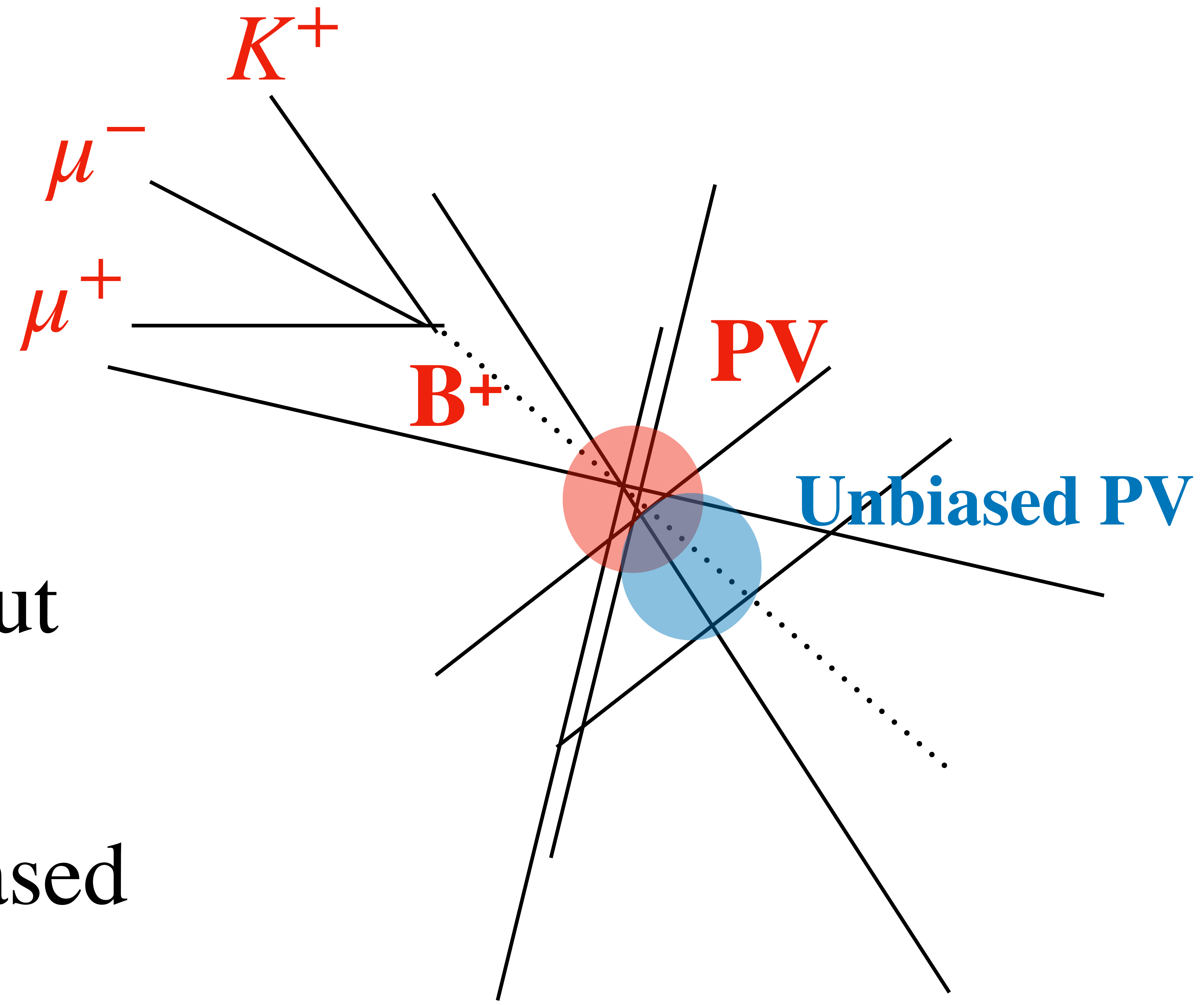


→ Tracks are **associated with the PV** that minimises their **impact Parameter** χ^2_{IP}



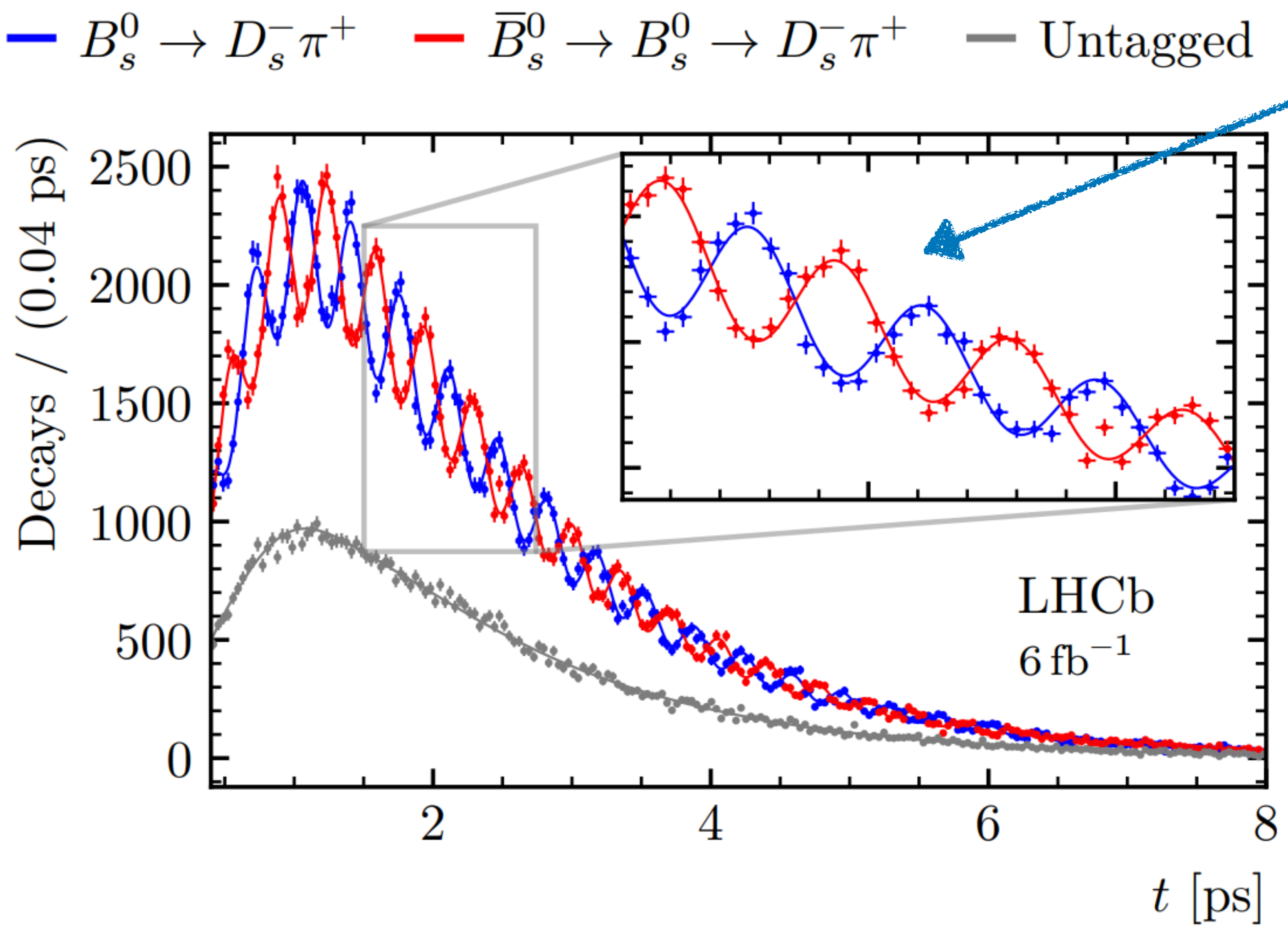
Experimental Strategy - 3

How do we know we do not bias the measurement by the “associated” PV?



- **Unbiased PV** remove the b-tracks and refit the **PV** without them.
- Choose the (new) PV with the minimum χ^2_{IP} wrt the unbiased PV

What we measure?



- The (**tagged**) decay-time distribution of neutral mesons by **mixing** and the **two heavy/light mass eigenstates** with different lifetimes:

$$\Gamma(t) \propto e^{\Gamma_s . t}\left(\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + A^f_{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + C\cos(\Delta m_s t) - S(\Delta m_s t)\right)$$

$$\Gamma_s = (\Gamma_L + \Gamma_H)/2$$

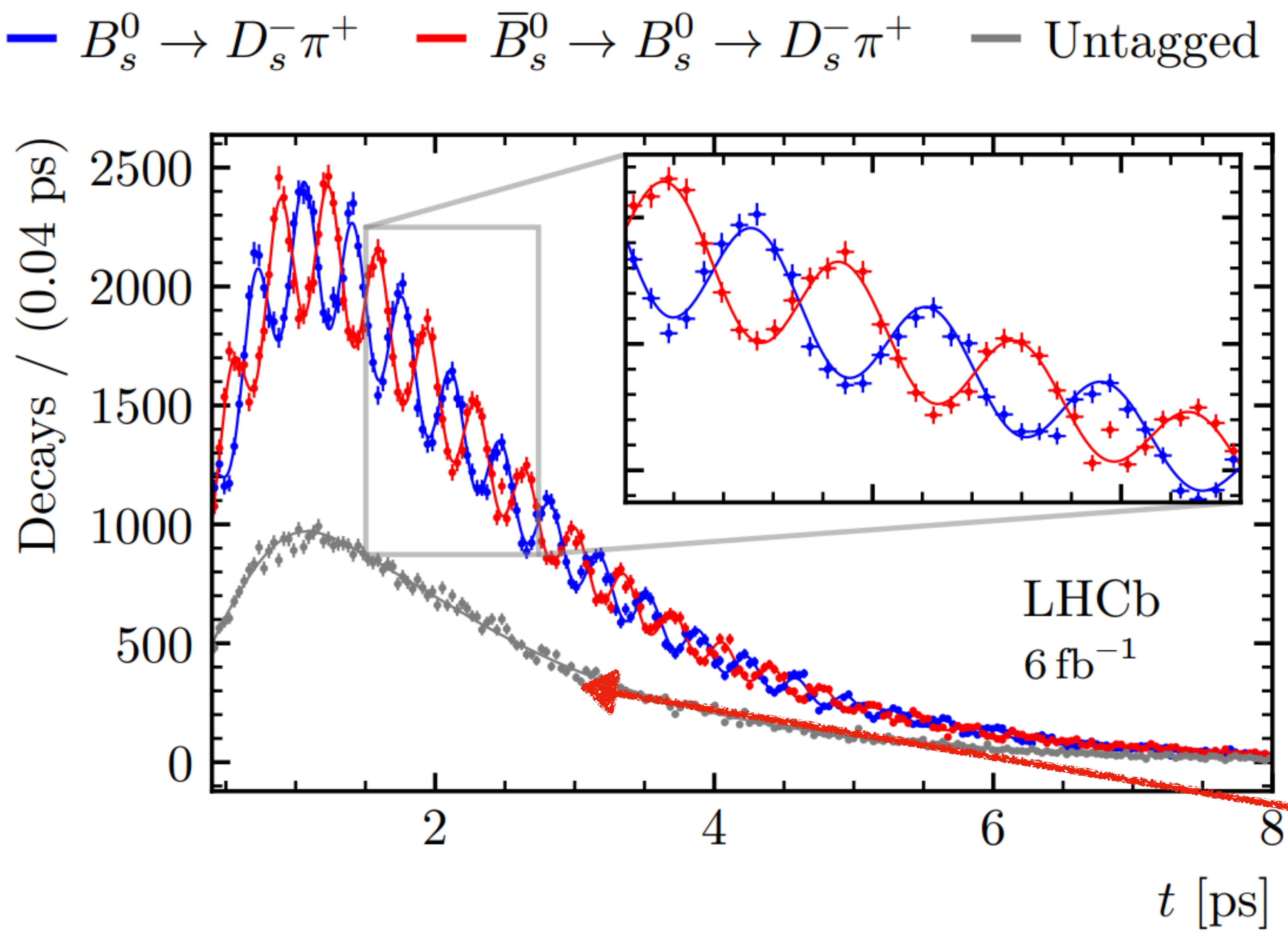
$$\Delta\Gamma_s = \Gamma_L - \Gamma_H$$

$$A^f_{\Delta\Gamma} \equiv \frac{R^f_H - R^f_L}{R^f_H + R^f_L}$$

- Requires **tagged** information

  → initial flavour of the neutral mesons at production

What we measure?



- The (**untagged**) decay-time distribution of neutral mesons by **mixing** and the **two heavy/light mass eigenstates** with different lifetimes:

$$\Gamma(t) \propto e^{\Gamma_s \cdot t}\left(\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + A^f_{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right)\right)$$

$\Gamma_s = (\Gamma_L + \Gamma_H)/2$

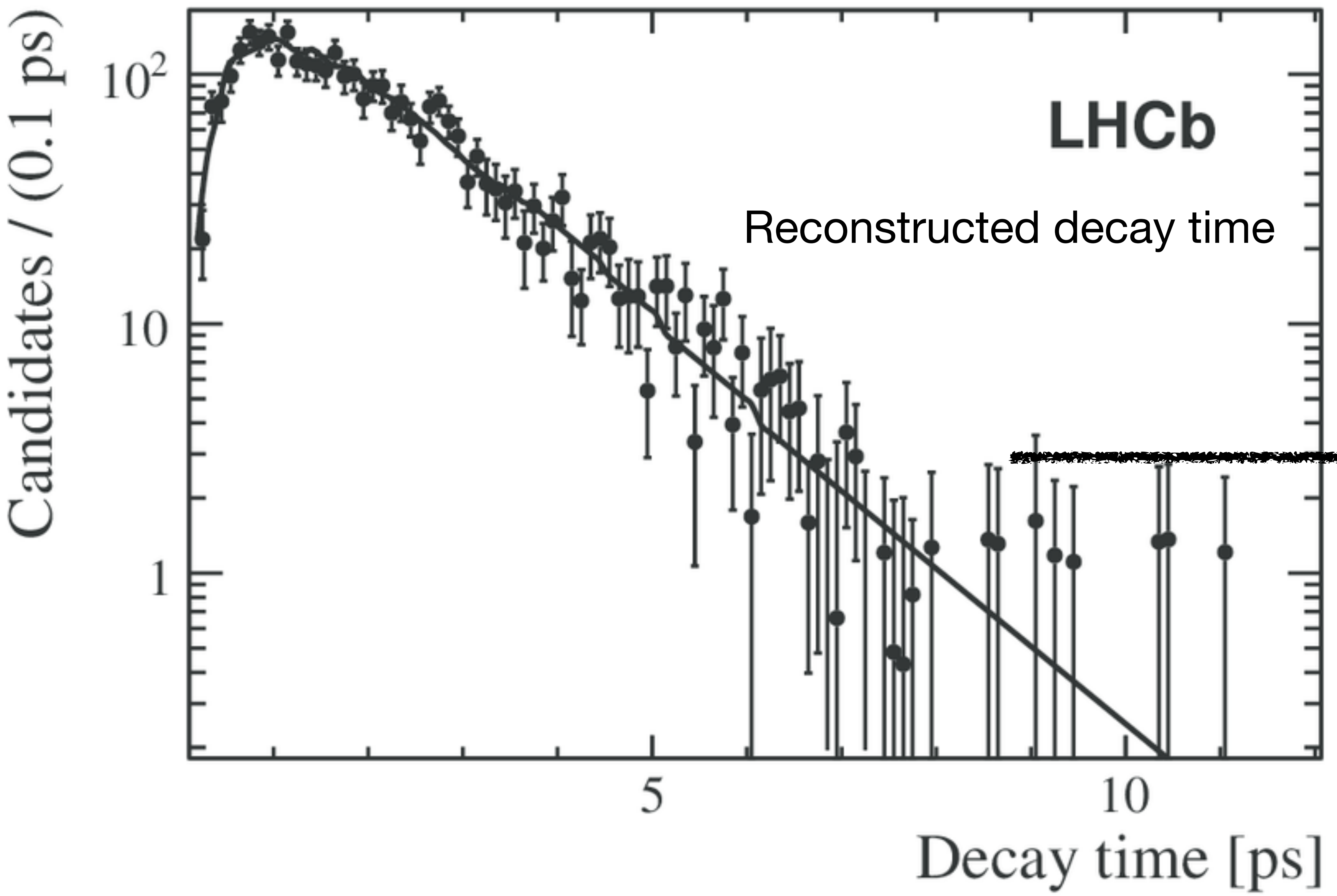
$\Delta\Gamma_s = \Gamma_L - \Gamma_H$

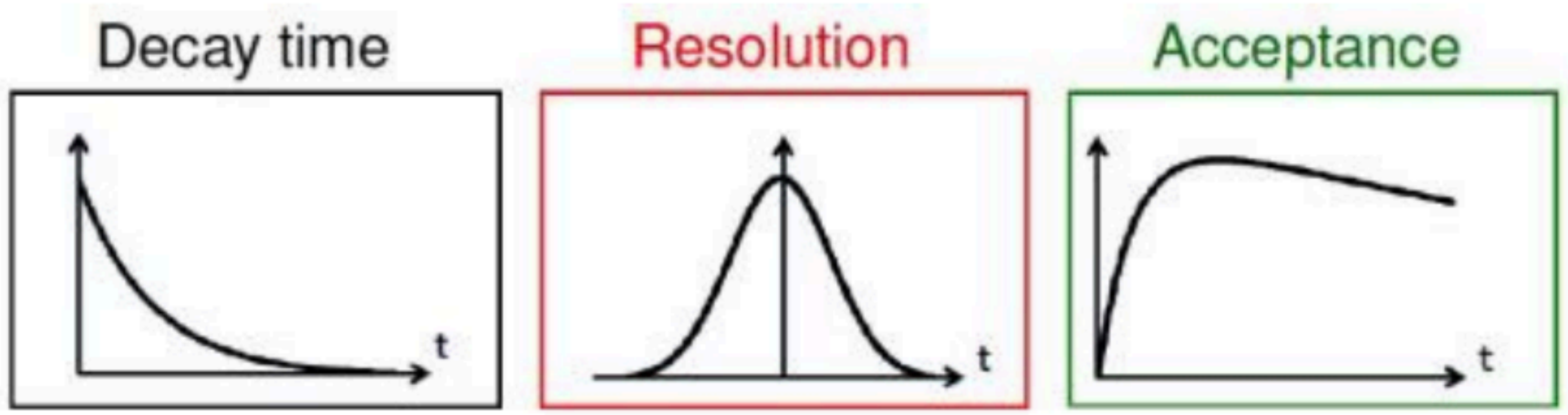
$$A^f_{\Delta\Gamma} \equiv \frac{R^f_H - R^f_L}{R^f_H + R^f_L}$$

- In **untagged measurements** , (today's focus)

$$N(t) \propto e^{-t/\tau_{eff}}$$: effective lifetime behaviour of the decaying system

How do we measure?

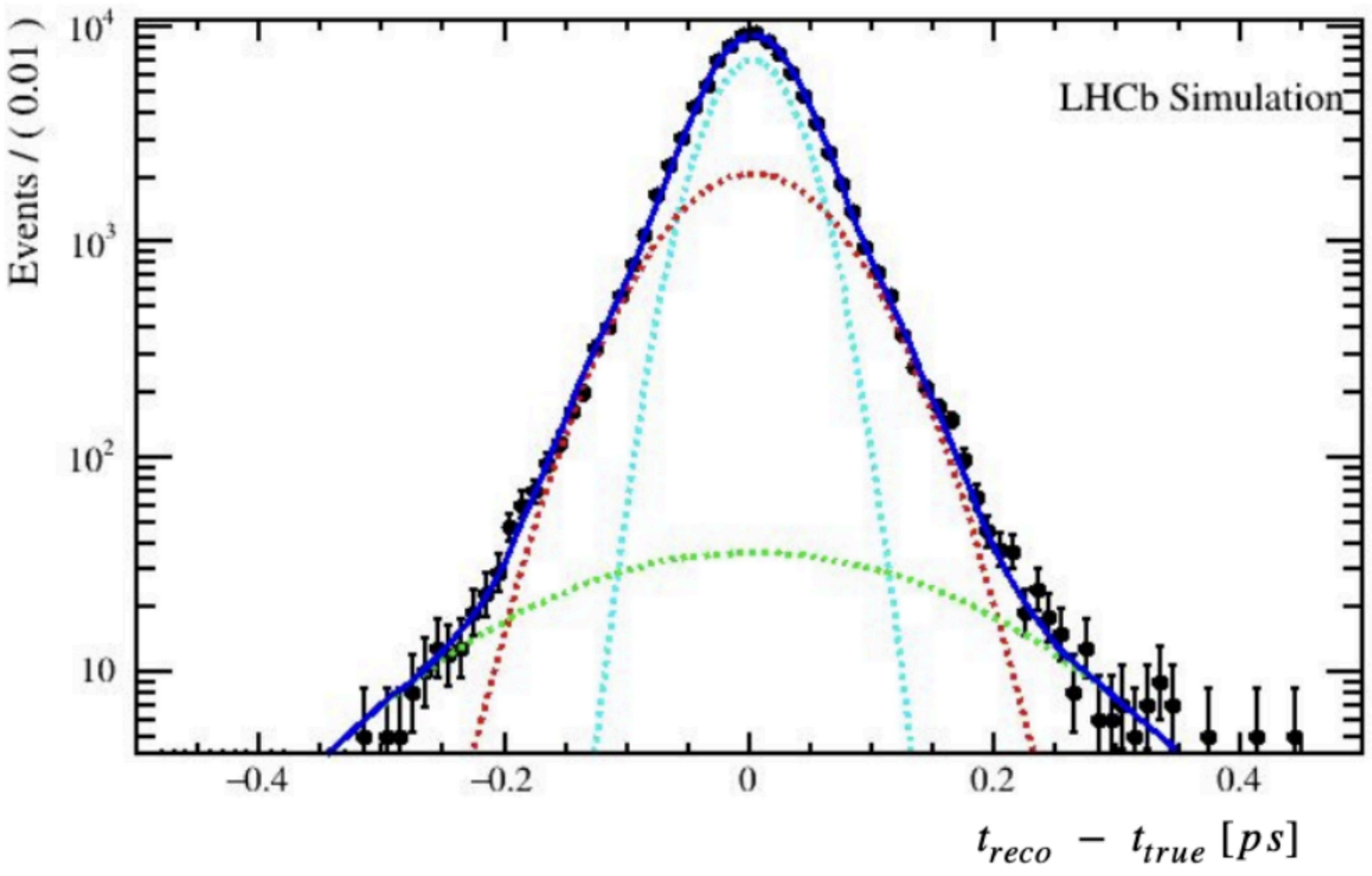




Measured distribution $= \left[e^{\frac{-t}{\tau}} \otimes \mathrm{Res}(t, t')\right] \cdot \mathrm{Acc}(t')$

$$P(t) = \left((\frac{1}{\tau} e^{-t/\tau}) \otimes \mathcal{R}(t) \right) . \mathcal{A}(t)$$

Time resolution

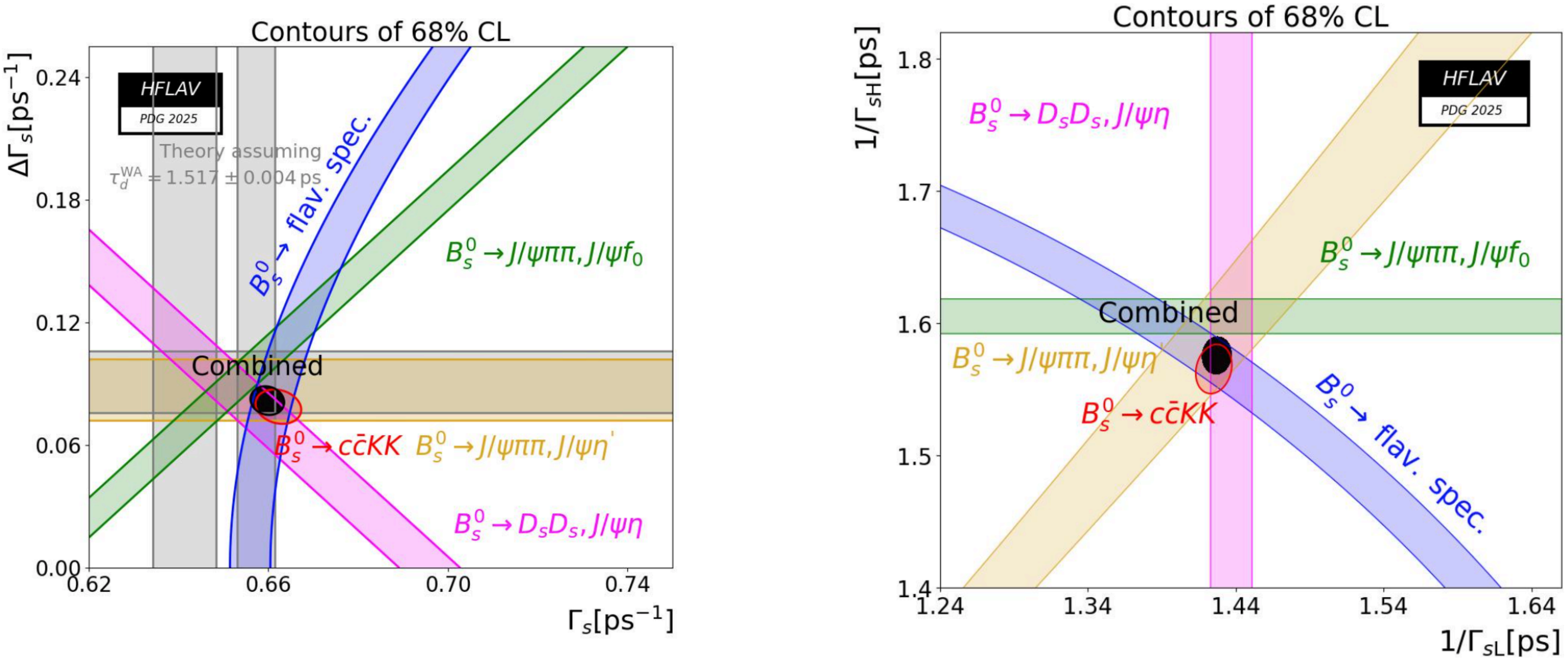


$$\mathcal{R}(t_{\text{reco}} - t_{\text{true}}) = \frac{1}{\sqrt{2\pi}\sigma_t} \exp\left(-\frac{t_{\text{reco}} - t_{\text{true}}}{2\sigma_t^2}\right)$$

- Due to detector vertexing, tracking, alignment, we do NOT measure true decay time in LHCb.
- It is usually the RMS of the $\sigma_t = t_{\text{reco}} - t_{\text{true}}$
- The decay time resolution shape is usually Gaussian model obtained from simulation.
- It is $\sigma_t \approx$ ~45-50 fs for Run 2 that it is possible to measure neutral B meson oscillation period $T \approx 350$ fs ($\Delta m_s \approx 17.8\ \text{ps}^{-1}$).

→ Thanks to excellent vertexing and tracking!

The state of the art



Absolute Measurements

Measurement of τ_L with $B_s^0 \to J/\psi\eta$ - Method

$$\Gamma(B_s^0(t) \to f) \approx e^{\Gamma_s . t}\left(\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma_s t}{2}\right)\right)$$

- Experiment is compatible with SM prediction of $\phi_s \sim -0.036\text{rad} \to$ very small
  $\to$ Mass eigenstates are also CP-eigenstates .

$$\boxed{\to \ \tau_{eff}(B_s \to f_{CP-even(odd)}) \approx \tau_{L(H)}}$$

SM prediction of $\Delta\Gamma_s$ and measured Γ_s :

$\tau_L = 1.42 \pm 0.01$ ps

Lenz/10.1007/JHEP07(2020)177

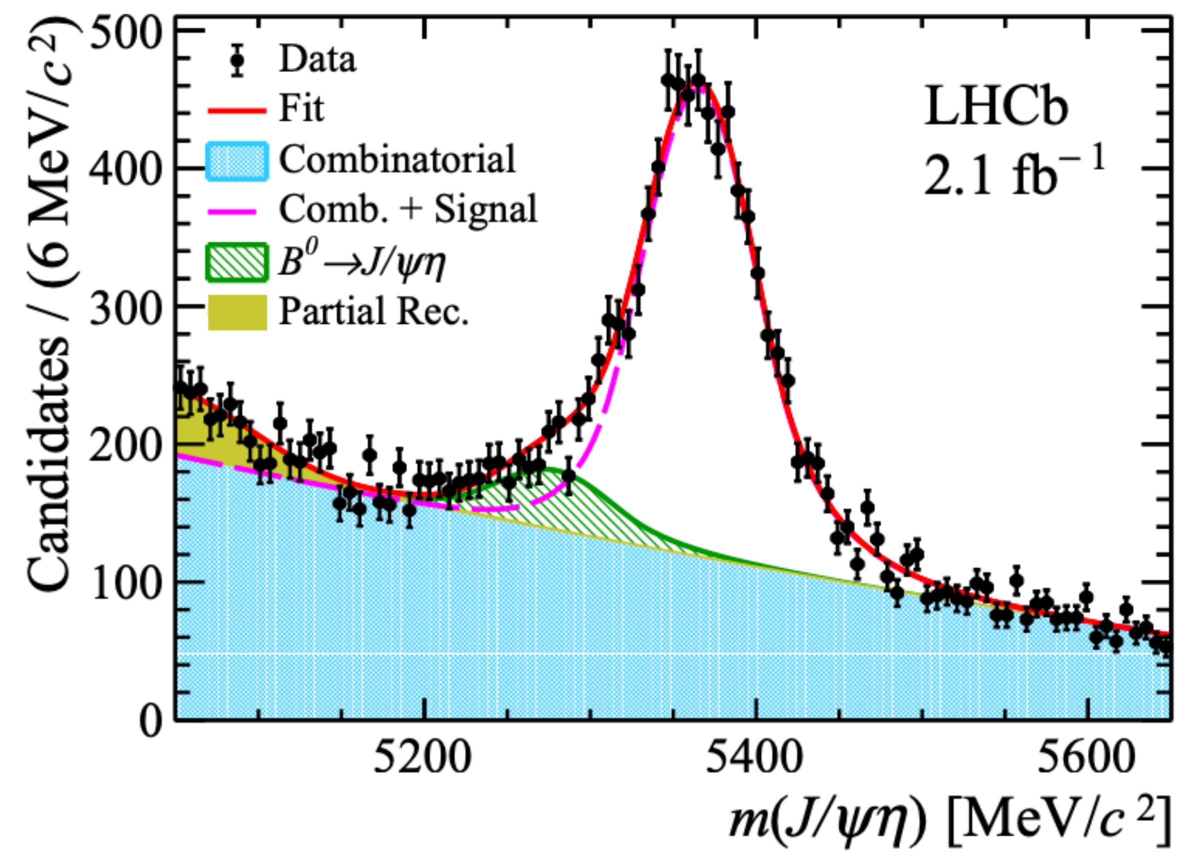
- $\tau_{eff} \approx \tau_{L(H)}$ important for the stringent tests of the direct measurements of $\Delta\Gamma$, such as from $B_s \to J/\psi\phi$.
- Important inputs for HQE theory.

Eur. Phys. J/C83(2023)/629

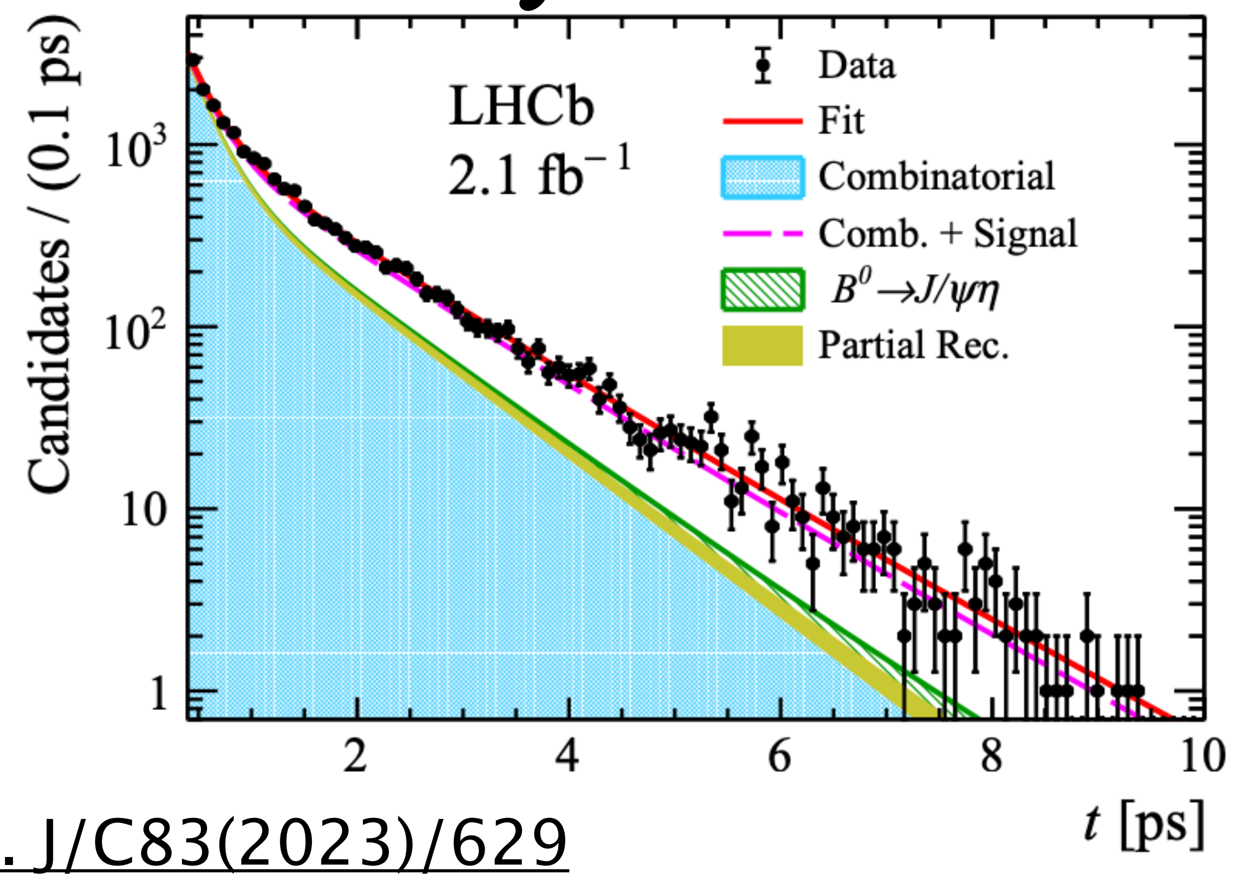
Measurement of τ_L with $B_s^0 \to J/\psi\eta$ - Fit strategy

- It requires the reconstruction of $B_s^0 \to J/\psi\eta$ where $J/\psi \to \mu^+\mu^-$ and $\eta \to \gamma\gamma$ ($\sim\mathcal{O}(10)$ of $\eta \to \pi^+\pi^-\pi^0$ mode)
  - $\to$ mass resolution is relatively poor but B_s/B_d separation is well-known and it is constrained, $M(B_s) - M(B_d)$=87.22 ± 0.16 MeV/c^2.
- 2D unbinned maximum likelihood fit to invariant mass and decay time.
  - $\to$ Simultaneous fit to 4 categories - data-taking years of 2015-2018

Invariant mass



Decay time



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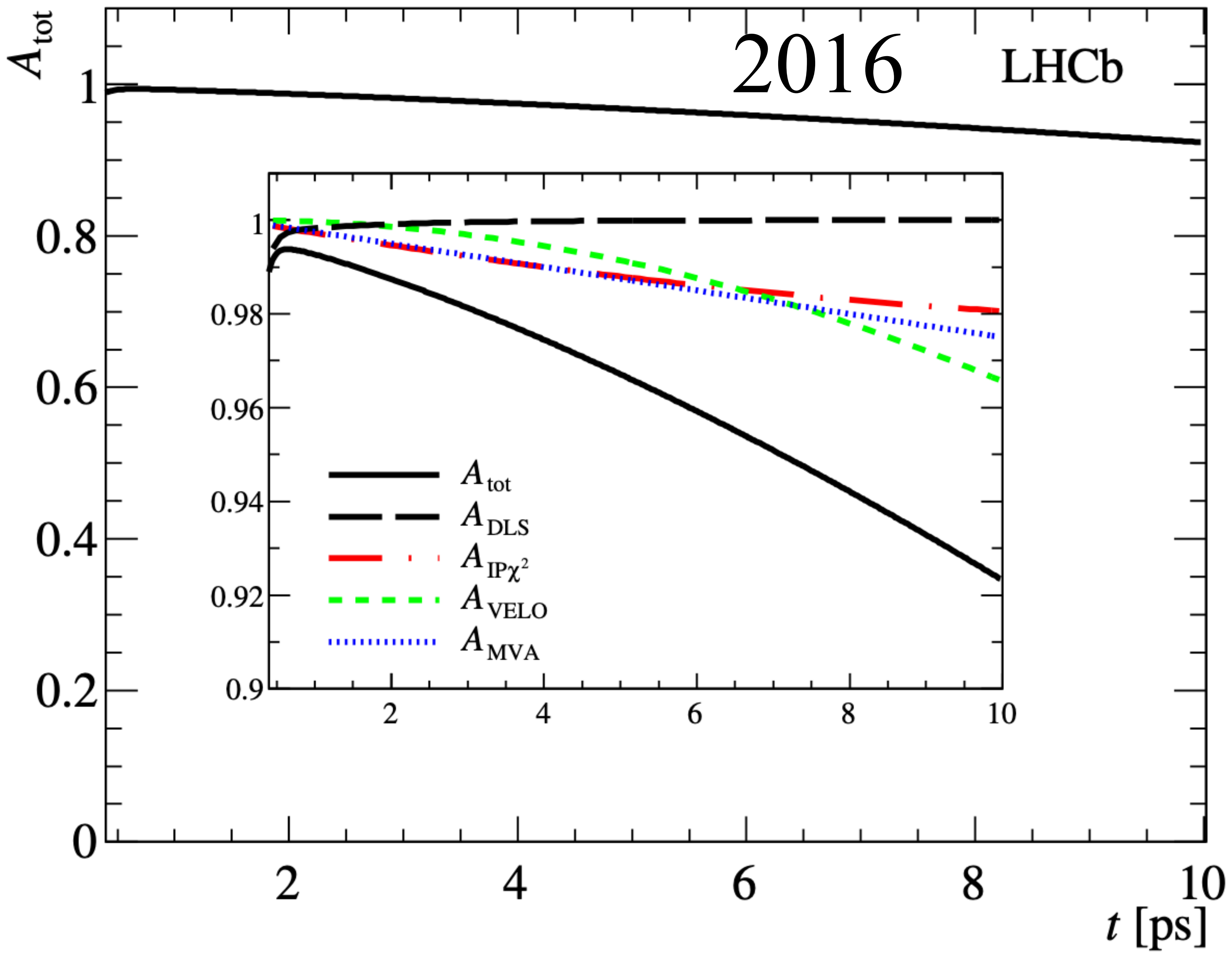
Measurement of τ_L with $B_s^0 \to J/\psi\eta$ - Acceptance

Eur. Phys. J/C83(2023)/629

- Total acceptance correction function is a product of various components fully obtained from simulation.

  $\rightarrow A_{VELO} \times A_{DLS} \times A_{IP\chi^2} \times A_{MVA}$

- VELO misalignment
- Decay length significance (DLS) cut on the trigger
- Requirement on the B_s candidate $IP\chi^2$
- Lifetime biasing cuts in the multivariate analysis (MVA).



If the data was not corrected the bias on the τ_L is ~18 fs!

Measurement of τ_L with $B_s^0 \to J/\psi\eta$

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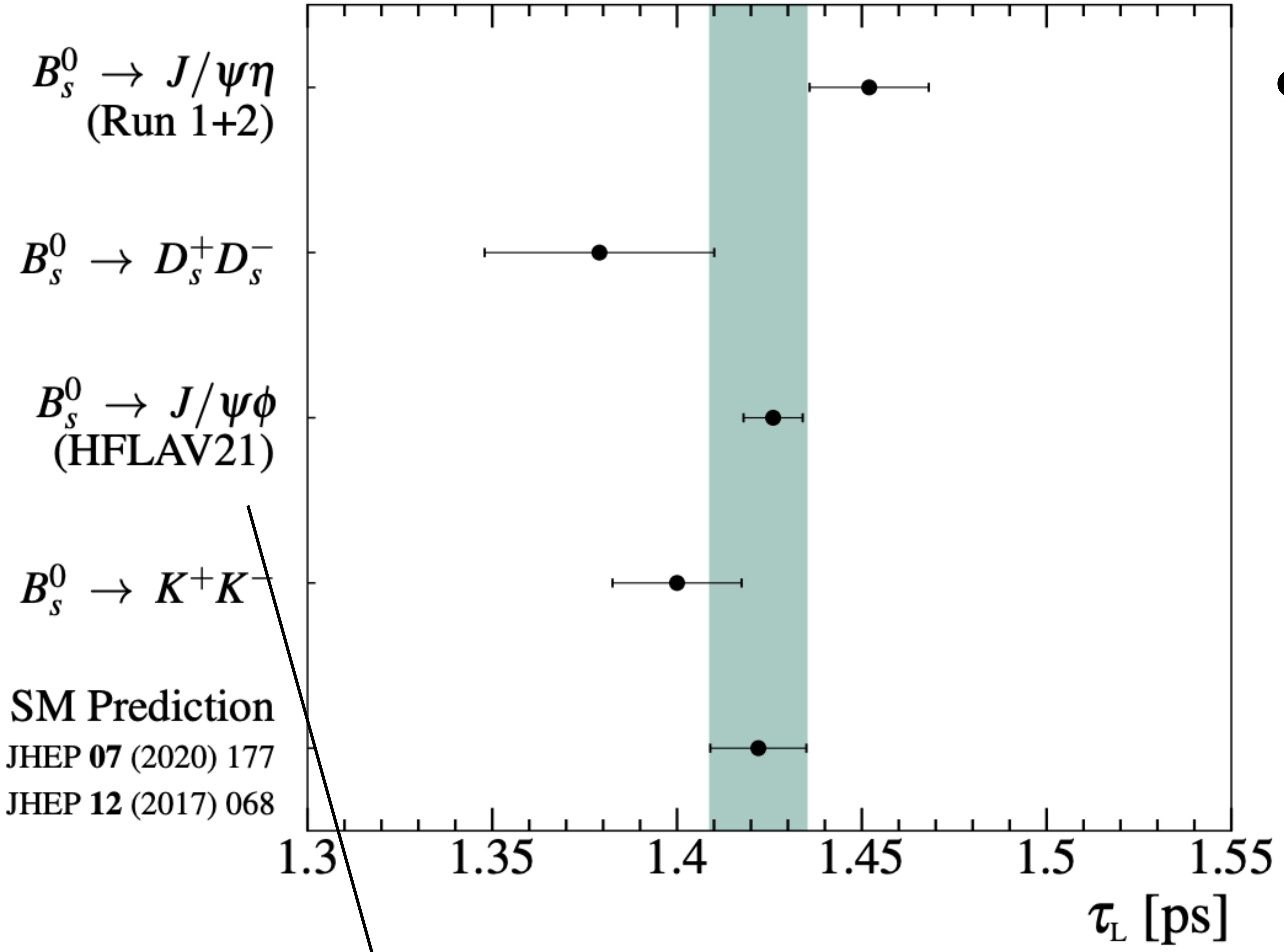


- Results :

$\rightarrow$ [Run 2] $\tau_L = 1.445 \pm 0.016(\text{stat}) \pm 0.008(\text{syst})$ ps

$\rightarrow$ [Run 1+2] $\tau_L = 1.452 \pm 0.014 \pm 0.007 \pm 0.002\ ps$

Correlated

Uncorrelated

*No significant change in HFLAV 25 : $\tau_L = 1.426 \pm 0.009$ ps

Relative Measurements (ratio of the lifetimes)

Precision measurement of Ξ_b baryon

arXiv:2507.12402
submitted to PRD

- Decays through the $\Lambda_b^0(\Xi_b) \to \Lambda_c^+(\Xi_c)\pi^-$ where $\Lambda_c^+(\Xi_c^+) \to pK^-\pi^+$
- Provides important tests for the HQE due to interactions of the spectator quarks.
- Measures the lifetime ratio $\tau_{\Xi_b}/\tau_{\Lambda_b}$

$\to$ The ratio of the efficiency corrected yields

$$R(t) \equiv \frac{N[\Xi_b \to \Xi_c^+\pi^-](t)}{N[\Lambda_b \to \Lambda_c^+\pi^-](t)} \cdot \frac{\varepsilon[\Lambda_b \to \Lambda_c^+\pi^-](t)}{\varepsilon[\Xi_b \to \Xi_c^+\pi^-](t)} = R_0 \exp(\lambda t)$$

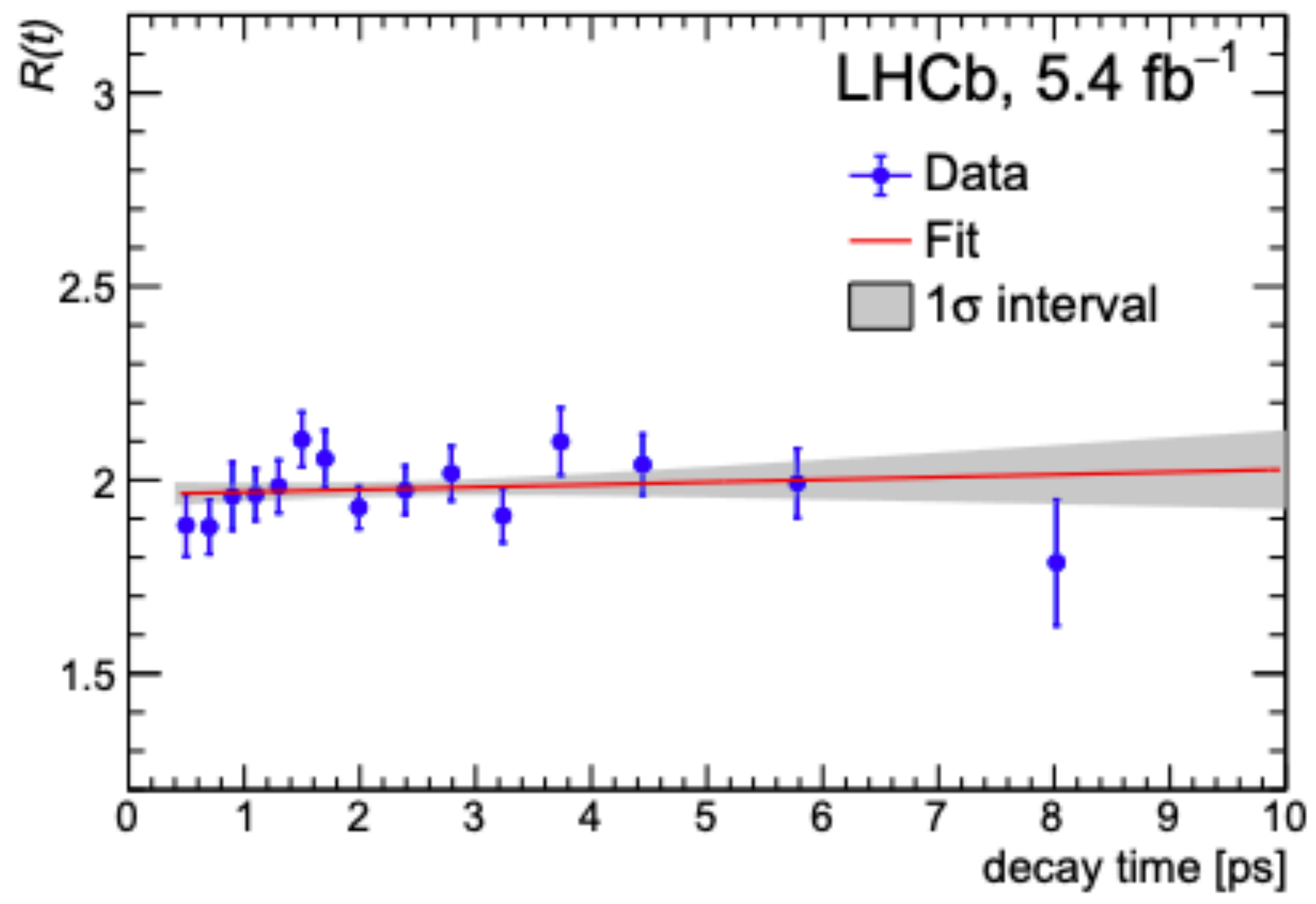
$$\lambda \equiv \frac{1}{\tau_{\Lambda_b^0}} - \frac{1}{\tau_{\Xi_b^0}}$$

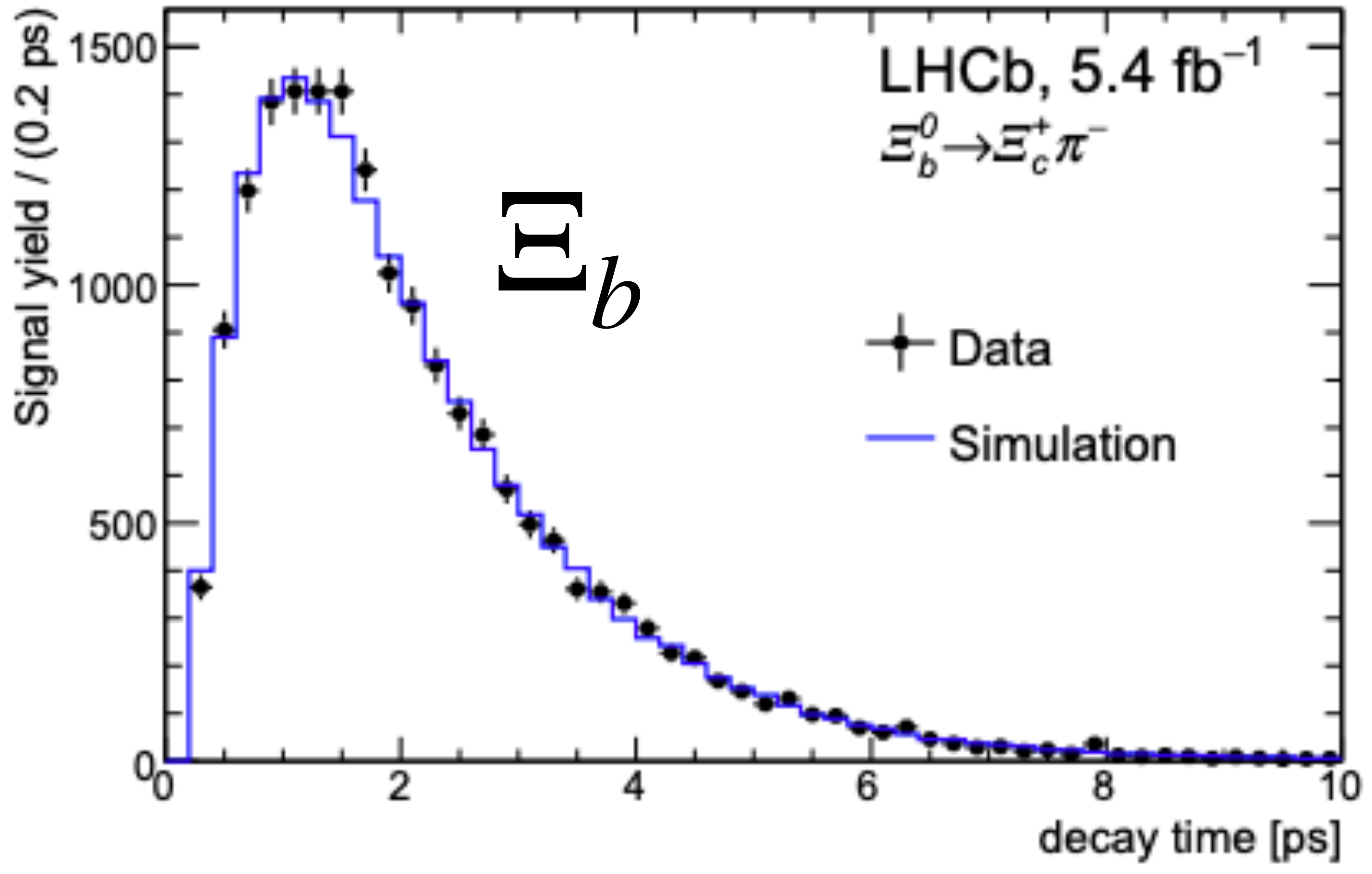
$$r_\tau \equiv \frac{\tau_{\Xi_b^0}}{\tau_{\Lambda_b^0}} = \frac{1}{1-\lambda\tau_{\Lambda_b}}$$

With the input of $\tau_{\Lambda_b} = 1.468 \pm 0.009$ ps :

$$r_\tau = 1.004 \pm 0.009 \pm 0.006$$

$$\tau_{\Xi_b^0} = 1.473 \pm 0.014 \pm 0.009 \pm 0.009 \text{ ps}$$

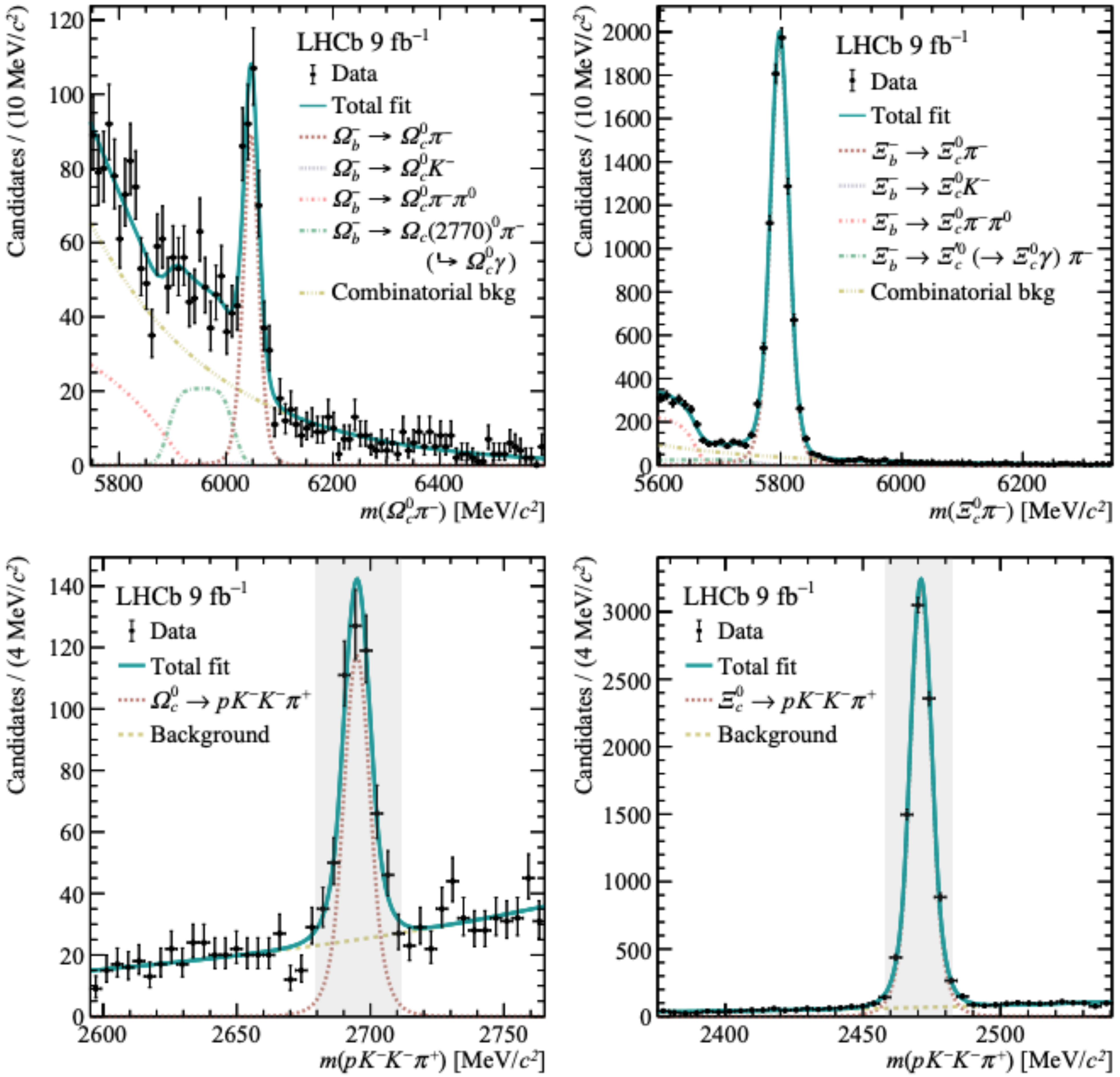




Lifetime measurements of Ξ_c^0 and Ω_c^0

arXiv:2506.13334
Submitted to JHEP

- Motivation
  - Charm baryon lifetimes to probe higher order effects in HQE, such as Pauli interference and W-exchange.
  - Recent lifetime measurements of Ω_c and Ξ_c by BelleII/ LHCb (semileptonic and prompt samples) in tension between the previous averages.
  - New hadronic-mode measurements provide (statistically) independent confirmation.
- Fully reconstructed charm baryons produced in b -decays normalised to a similar decay mode.
  - Signal : $\Omega_b^- \to \Omega_c(\to pK^-K^-\pi^+)\pi^-$
  - Signal : $\Xi_b^- \to \Xi_c(pK^-K^-\pi^+)\pi^-$
  - Normalisation : $B \to D^0(\to K^-K^+\pi^-\pi^+)\pi^-$



Lifetime measurements of Ξ_c^0 and Ω_c^0 -2

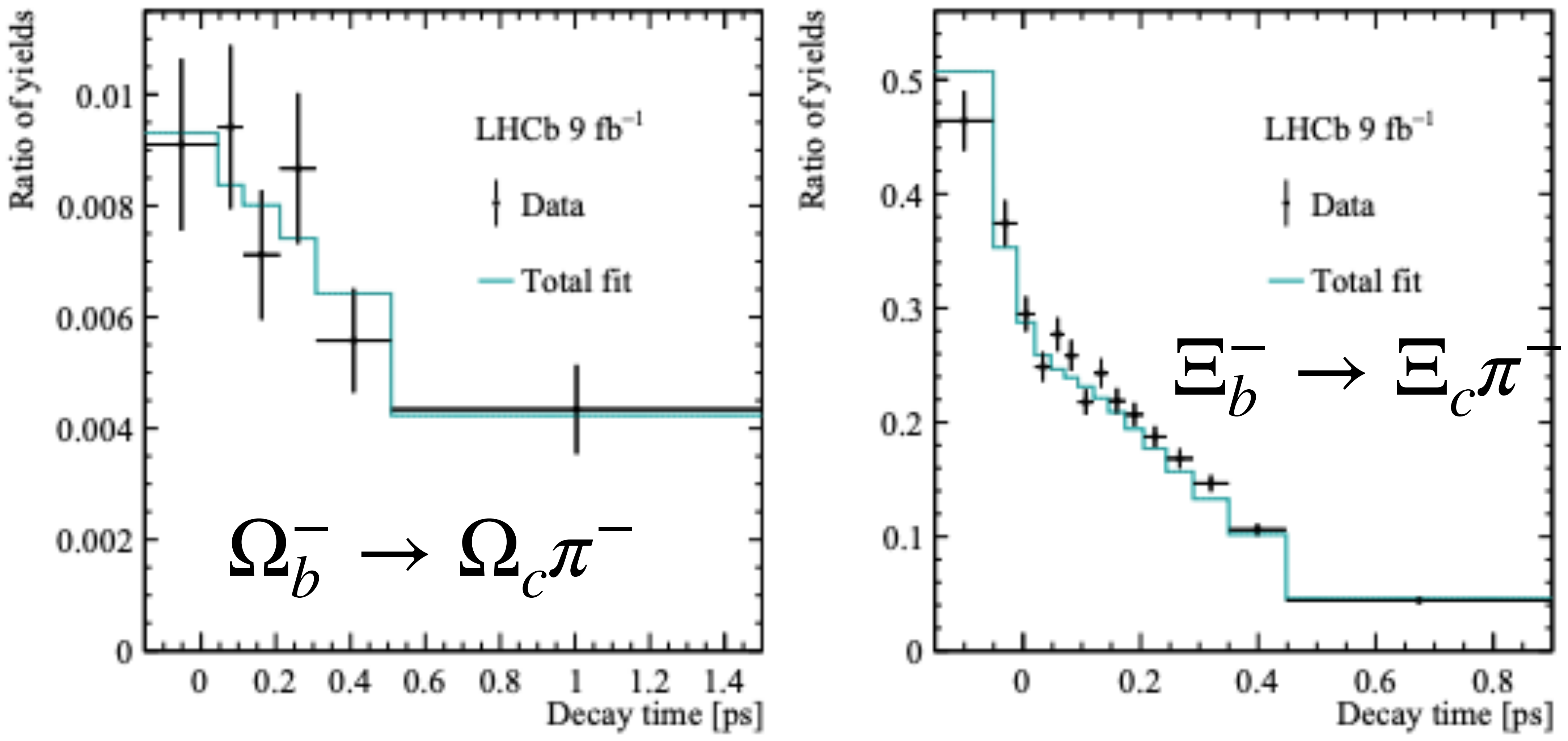
arXiv:2506.13334
Submitted to JHEP

- The ratio of yields in decay time bins (bins are chosen to have similar number of events)

$$r_i \equiv \frac{\int_{t_i}^{t_{i+1}} A_{\Omega_c^0,\Xi_c^0}(t) \cdot \left(e^{-t/\tau_{\Omega_c^0,\Xi_c^0}} * R_{\Omega_c^0,\Xi_c^0}(t)\right) \mathrm{d}t}{\int_{t_i}^{t_{i+1}} A_{D^0}(t) \cdot \left(e^{-t/\tau_{D^0}} * R_{D^0}(t)\right) \mathrm{d}t},$$

Decay-time resolution

Acceptance



- Two independent methods that well agreed:
  - **Binned method**: Extract yield in bins of decay time.
  - **sPlot-like method**: Uses covariance of mass fits to weight each candidate's decay time distribution.

$$r_{\Omega_c^0} = 276.3 \pm 19.4(stat) \pm 1.8(syst) \pm 0.7(\tau_{D^0})\ \text{fs},$$

$$r_{\Xi_c^0} = 149 \pm 2.5(stat) \pm 0.9(syst) \pm 0.4(\tau_{D^0})\ \text{fs},$$

A mixture of CP eigenstates..

Lifetime with $B_s^0 \to J/\psi K^+K^-$

- $B_s \to J/\psi\phi$ is a "golden channel" for time-dependent analyses.

  $\to$ High statistics $\to$ lower uncertainties

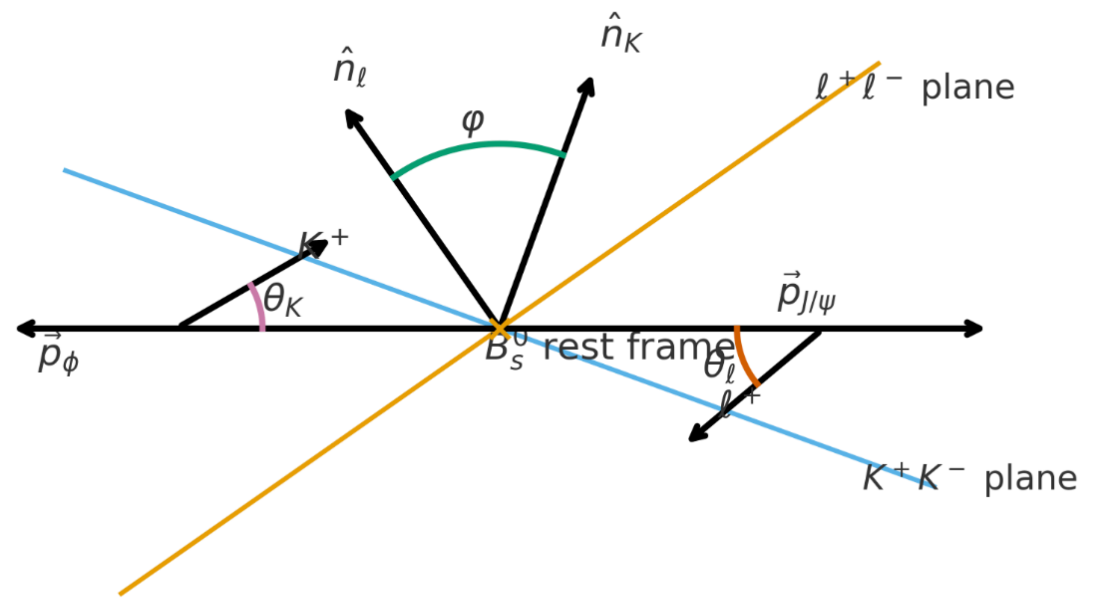
  $\to$ Sensitive to too many observables, $\Delta\Gamma_s$, Γ_s, CP violating phase ($\phi_s \approx -2\beta_s$)

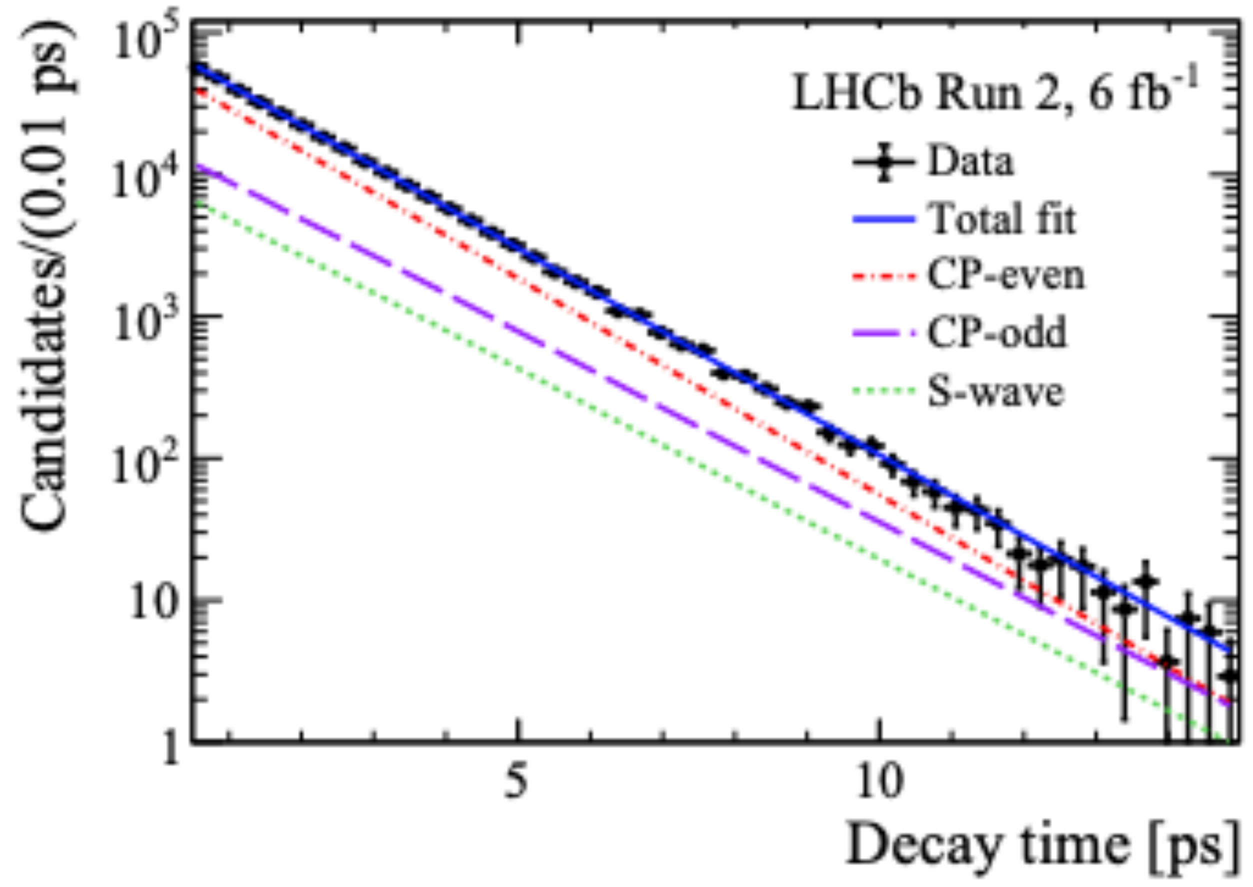
- $B \to VV$ states are a mixture of CP-even and CP-odd

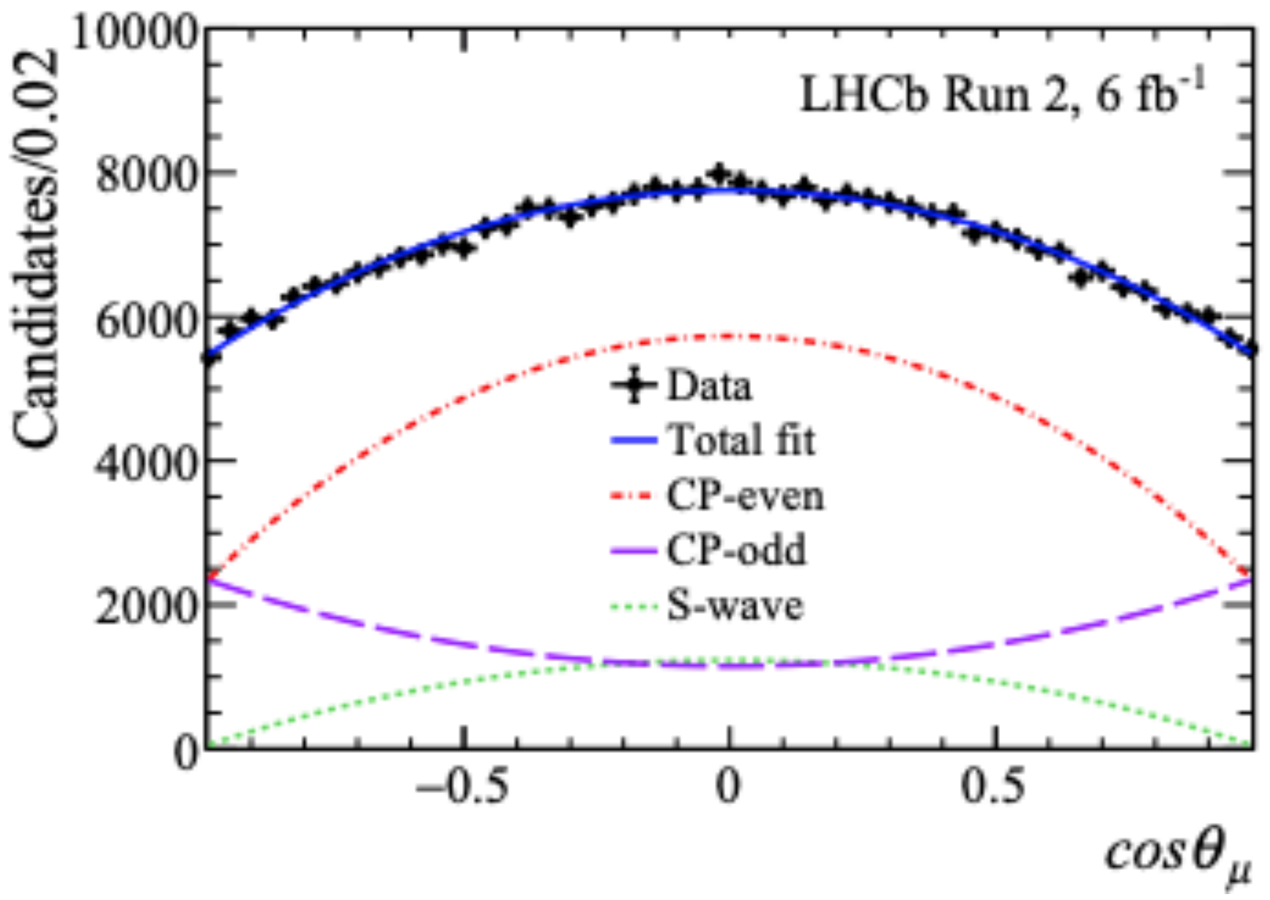
  $\to$ Angular analysis needed to extract the $\Delta\Gamma_s$

  $\to$ Gives indirect access to τ_L and τ_H

$$\Delta\Gamma_s = 0.0845 \pm 0.0044 \pm 0.0024\ ps$$







An alternative approach..

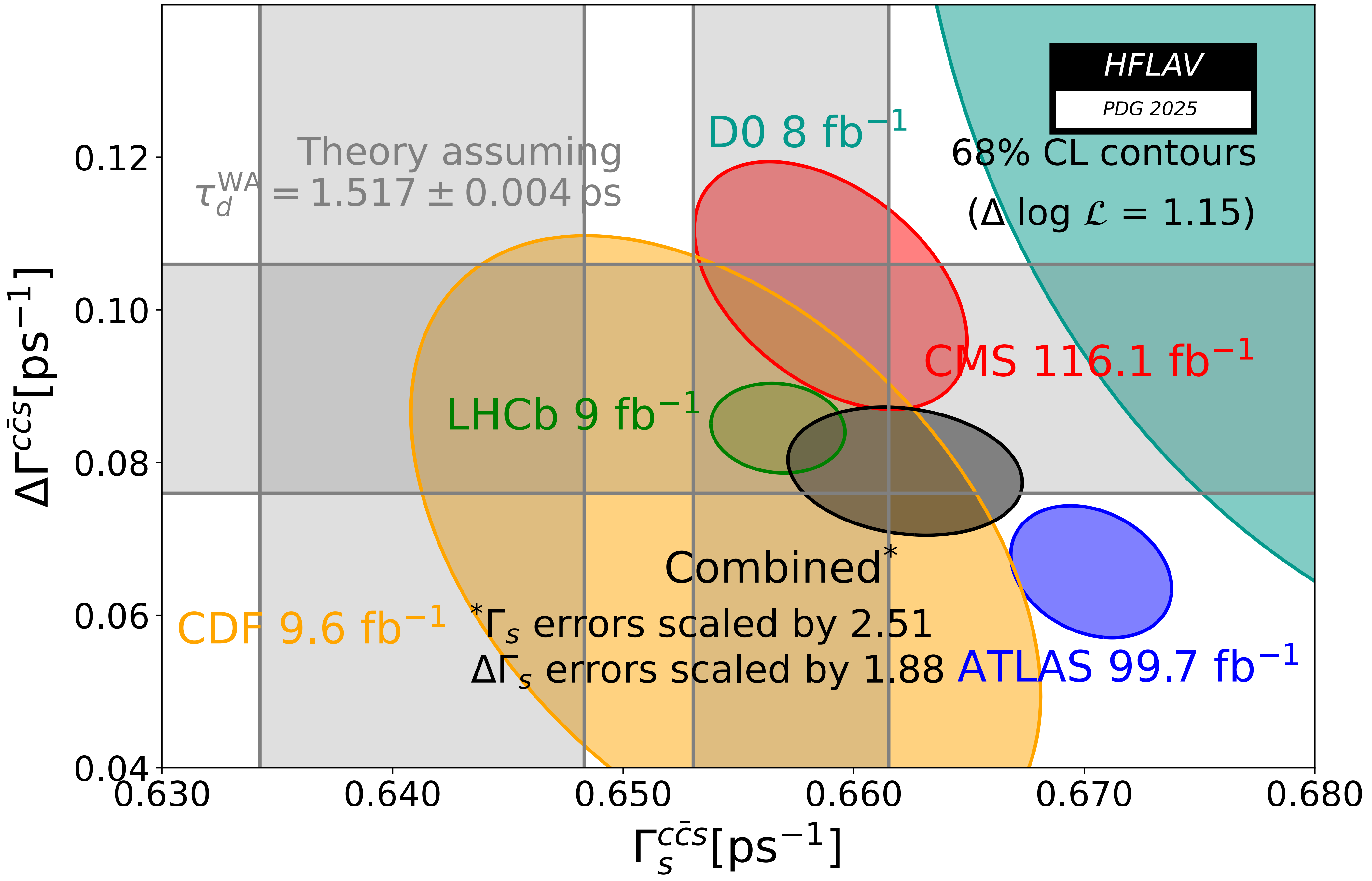
A measurement of $\Delta\Gamma_s$ (motivation)

- Though precise, there is a tension within the LHC experiments.

  → motivates independent measurements

- $B \rightarrow VV$ states can provide $\Delta\Gamma_q$ but needs angular analysis to separate the CP-even/odd states
- Another approach is to combine the effective lifetime of the pure CP-even ($\tau_{eff} = 1/\Gamma_L$) and pure CP-odd modes ($\tau_{eff} = 1/\Gamma_H$) Fleischer and Knegjens

  →In the price of the small statistics.



JHEP05(2024)253

A measurement of $\Delta\Gamma_s$ (method)

- If CP is conserved, the time-dependent decay rate to a CP-eigenstate final state $\rightarrow$ $A_{\Delta\Gamma_s} = \pm 1$

- For pure CP-odd mode : $B_s \rightarrow J/\psi\eta'$ where $J/\psi \rightarrow \mu^+\mu^-, \eta' \rightarrow \rho^0\gamma$

$$\Gamma(B_s^0(t) \rightarrow f) \approx e^{\Gamma_s.t}\left(\cosh\left(\frac{\Delta\Gamma_s \mathrm{t}}{2}\right) - \sinh\left(\frac{\Delta\Gamma_s t}{2}\right)\right)$$

- For pure CP-even mode : $B_s \rightarrow J/\psi\pi^+\pi^-$ where $J/\psi \rightarrow \mu^+\mu^-$

$$\Gamma(B_s^0(t) \rightarrow f) \approx e^{\Gamma_s.t}\left(\cosh\left(\frac{\Delta\Gamma_s \mathrm{t}}{2}\right) + \sinh\left(\frac{\Delta\Gamma_s t}{2}\right)\right)$$

JHEP05(2024)253

A measurement of $\Delta\Gamma_s$ (method)

- If CP is conserved, the time-dependent decay rate to a CP-eigenstate final state, f, integrating over a time interval ,

•For pure CP-odd $$N_H \approx \int_{t_1}^{t_2} e^{\Gamma_s . t} \left(\cosh\left(\frac{\Delta\Gamma_s \mathrm{t}}{2}\right) - \sinh\left(\frac{\Delta\Gamma_s t}{2}\right)\right) dt$$

•For pure CP-even $$N_L \approx \int_{t_1}^{t_2} e^{\Gamma_s . t} \left(\cosh\left(\frac{\Delta\Gamma_s \mathrm{t}}{2}\right) + \sinh\left(\frac{\Delta\Gamma_s t}{2}\right)\right) dt$$

$$\frac{N_L}{N_H} = \frac{\left[e^{\Gamma_s t(1+y)}\right]_{t_1}^{t_2}}{\left[e^{\Gamma_s t(1-y)}\right]_{t_1}^{t_2}} \cdot \frac{1-y}{1+y}$$ where $$2y = \frac{\Delta\Gamma_s}{\Gamma_s}$$ JHEP05(2024)253

A measurement of $\Delta\Gamma_s$ (method)

- If CP is conserved, the time-dependent decay rate to a CP-eigenstate final state, f, integrating over a time interval ,

$$\frac{N_L}{N_H} = \frac{\left[e^{\Gamma_s t(1+y)}\right]_{t_1}^{t_2}}{\left[e^{\Gamma_s t(1-y)}\right]_{t_1}^{t_2}} \cdot \frac{1-y}{1+y} \qquad \text{where} \qquad 2y = \frac{\Delta\Gamma_s}{\Gamma_s}$$

- Experimentally we measure $R_i = A_i \,.\, \dfrac{N_L^{\mathrm{RAW}}}{N_H^{\mathrm{RAW}}}$ where $A_i = \dfrac{\varepsilon_H^i}{\varepsilon_L^i}$

i : decay time bins

$\rightarrow \chi^2$ minimisation to determine $\Delta\Gamma_s$

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A measurement of $\Delta\Gamma_s$ (strategy)

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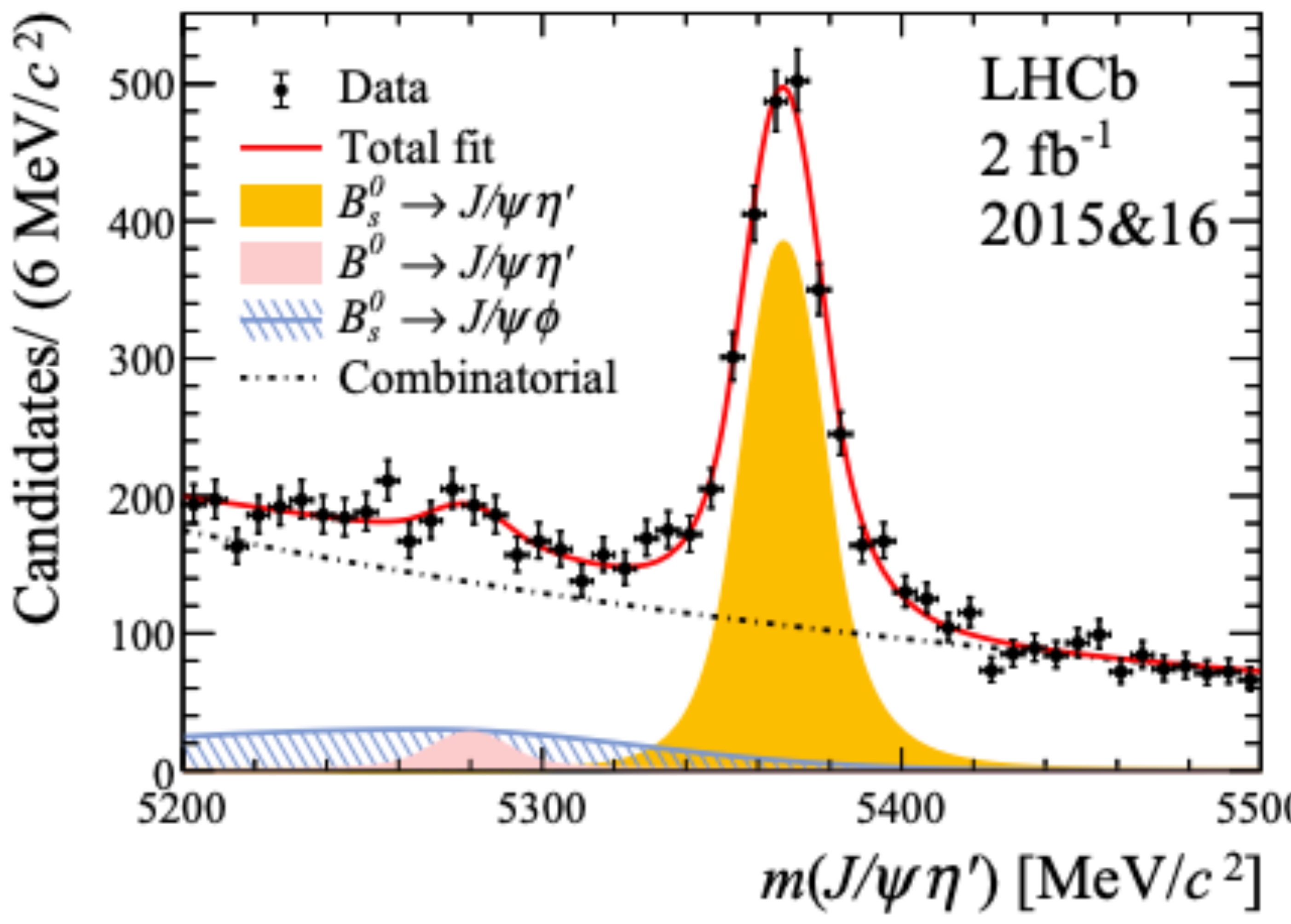
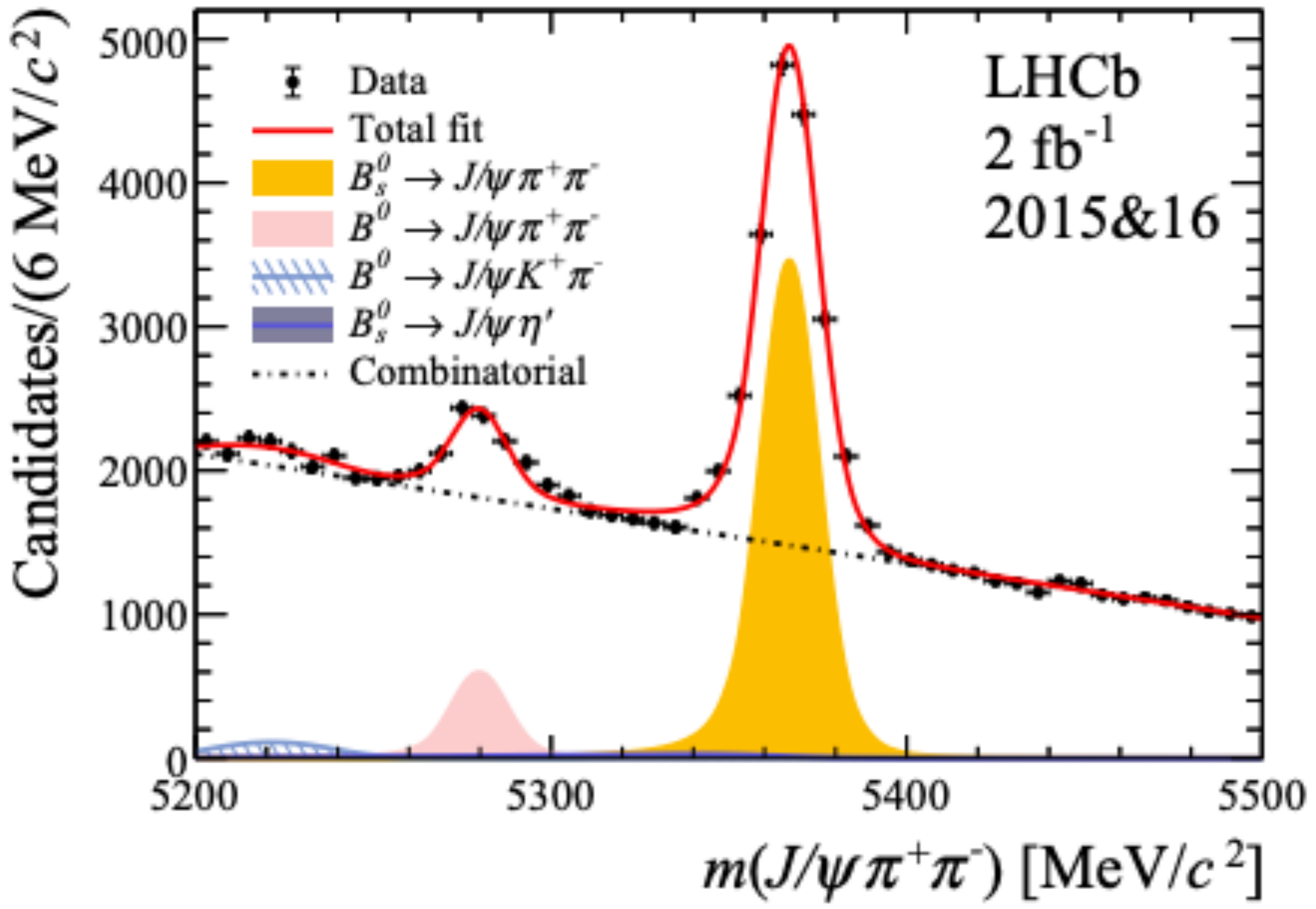
- To obtain the yields in each decay time bin, simultaneous unbinned maximum likelihood fits are performed to $J/\psi\eta'$ and $J/\psi\pi^+\pi^-$ invariant masses.

- Due to the similar final states, acceptance largely cancel in the ratio. Relative acceptance correction function in the form of $A_r(t) = 1 - \beta t$





A measurement of $\Delta\Gamma_s$ (results)

Results obtained from χ^2 fits in decay time bins :

$$\rightarrow \ \Delta\Gamma_s = 0.087 \pm 0.012 \pm 0.009 \text{ ps}^{-1}$$

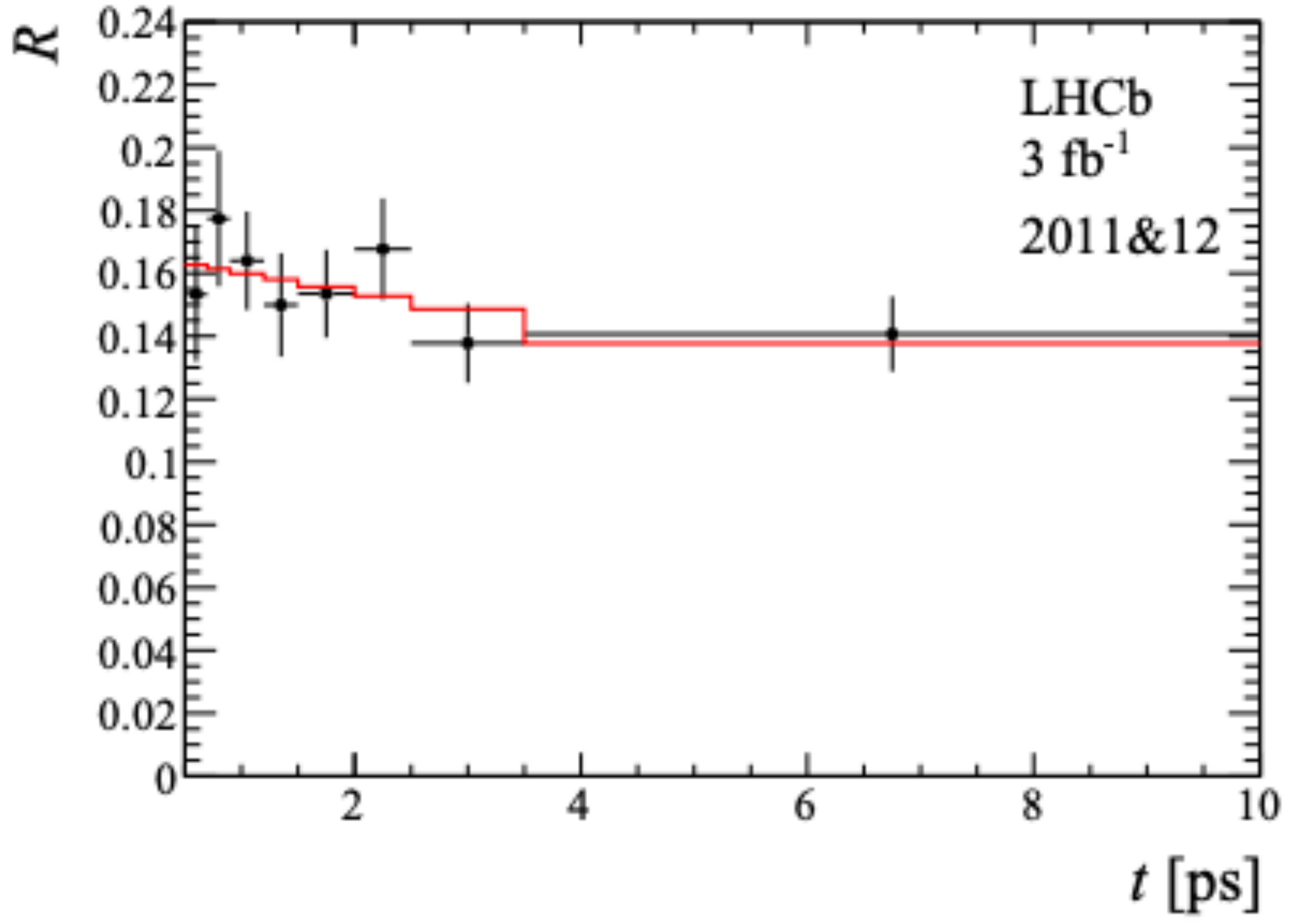
It is good agreement with

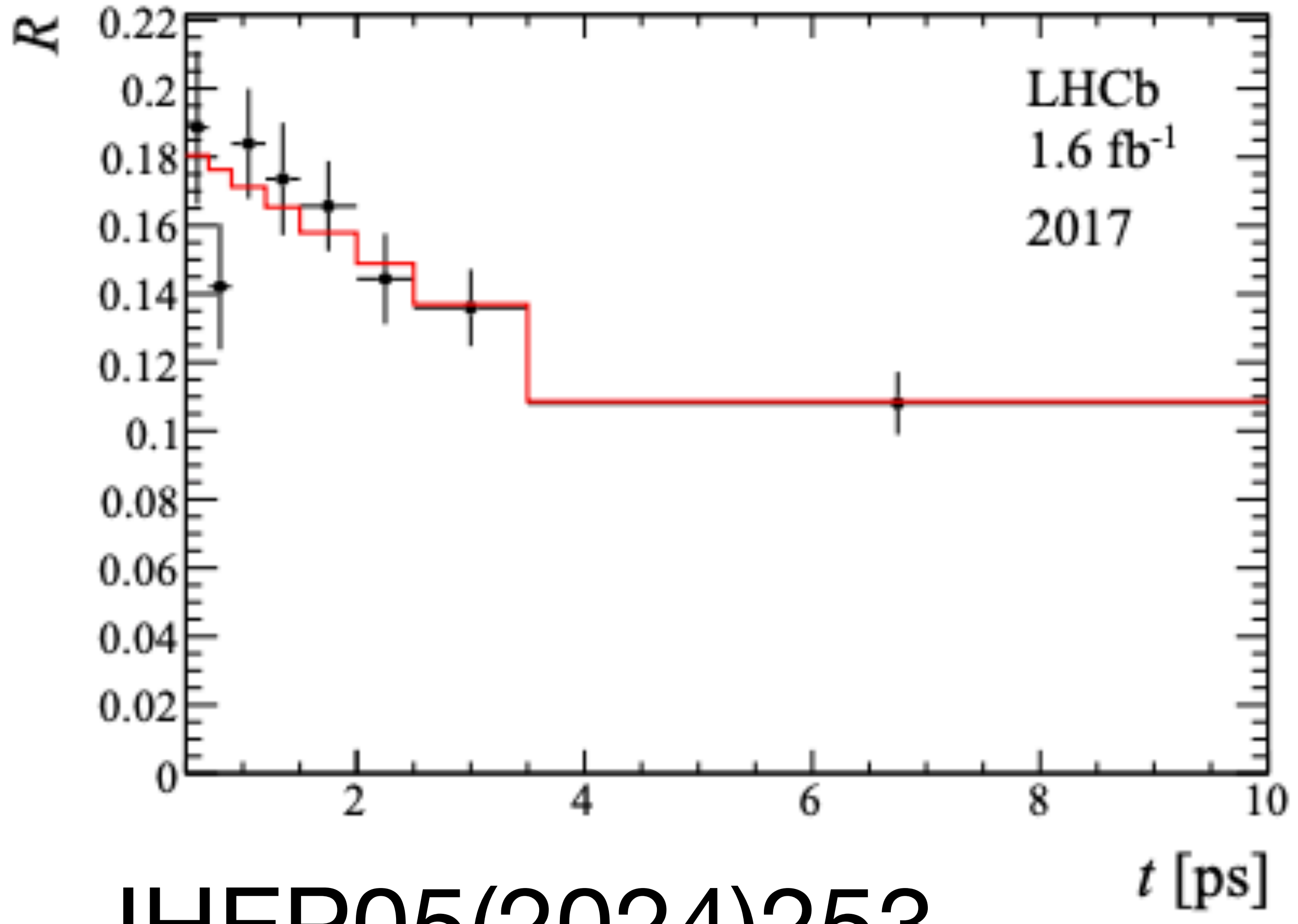
✓ the latest LHCb results from $B_s \rightarrow J/\psi K^+ K^-$,

$\Delta\Gamma_s = 0.0845 \pm 0.0044 \pm 0.0024 \ \text{ps}^{-1}$

✓ HFLAV average of $\Delta\Gamma_s = 0.076 \pm 0.006 \text{ ps}^{-1}$

→ It offers unique approach to measure $\Delta\Gamma$ to help to resolve the observed tensions between LHC measurements.





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Summary and Outlook

- LHCb is pursuing a broad programme of lifetime measurements — both **tagged and untagged**.
- We continue to focus on improving the **precision** of lifetime determinations.

→ Ongoing efforts include channels like

$B^+ \to J/\psi K^+$,

$B^0 \to J/\psi K^*$,

$B_s \to J/\psi \phi$,

And $\Delta\Gamma_d$ measurements and many more…

- With the upgraded LHCb detector we are well-equipped for even more precise and differential studies.
- And we promise.. these measurements will not take **more than a lifetime**.. :)