The SM and beyond at LHCb

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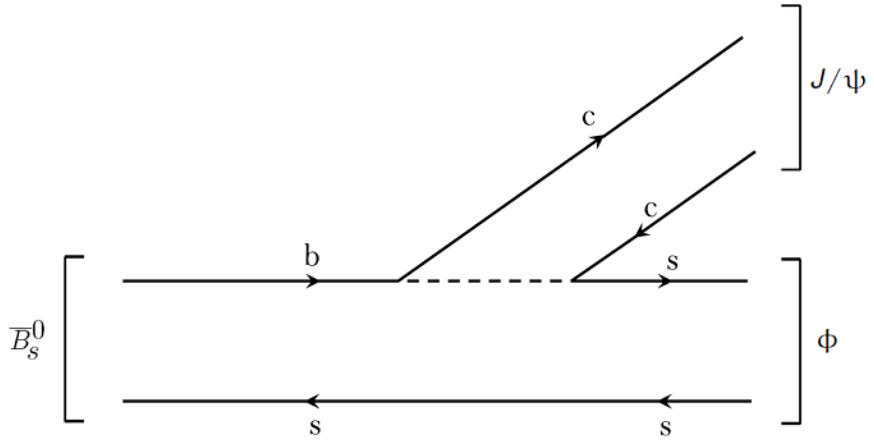
Outline

- Why LHCb?
- Insides in LHCb ←
- Angular Measurement

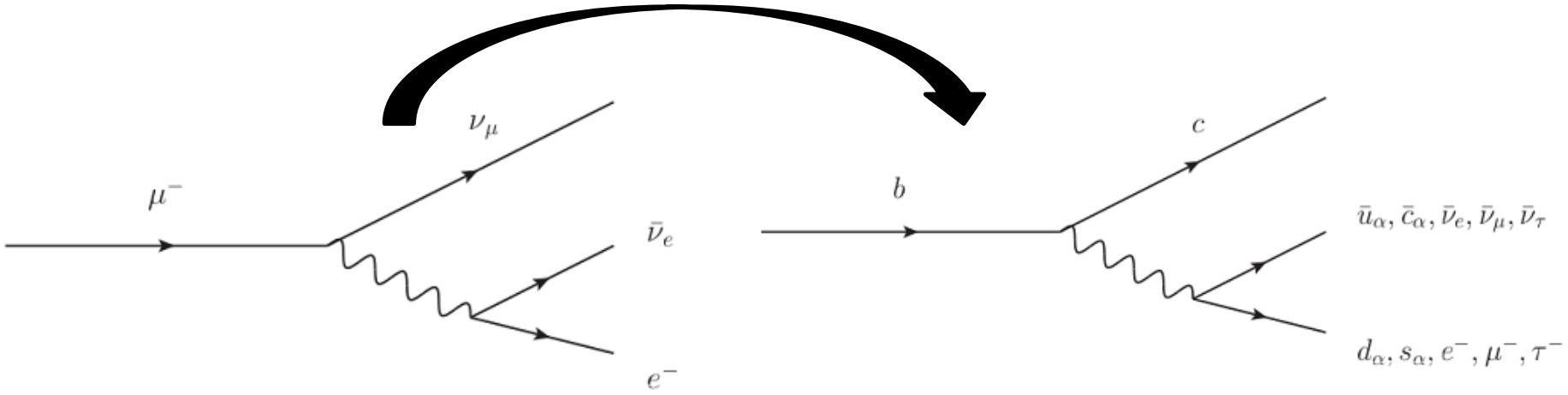
principles of experimental
particle physics

example:
precision lifetime measurements
of b hadrons at LHCb

b-hadron lifetime – spectator model

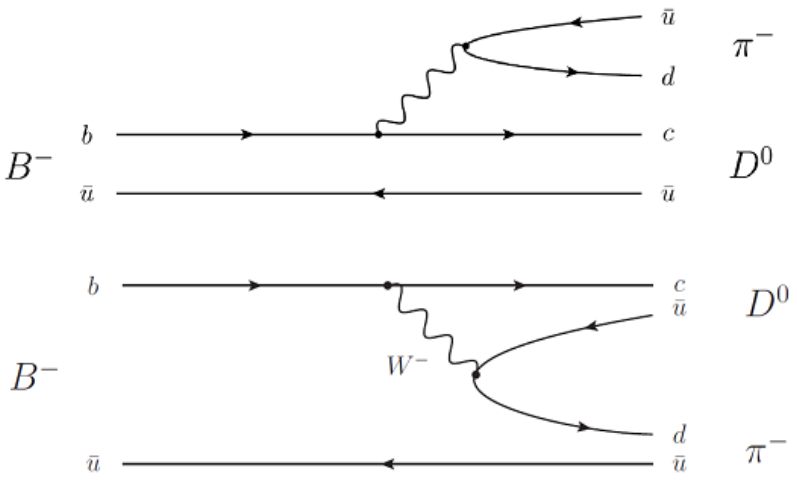


use for lifetime estimation

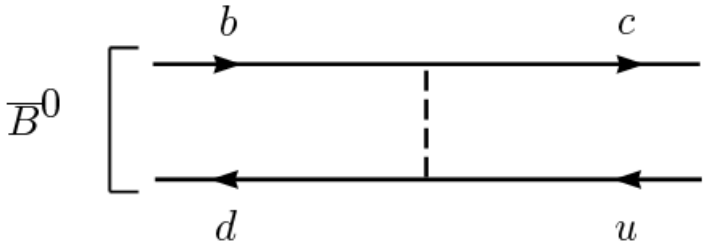


Influence of spectator quarks

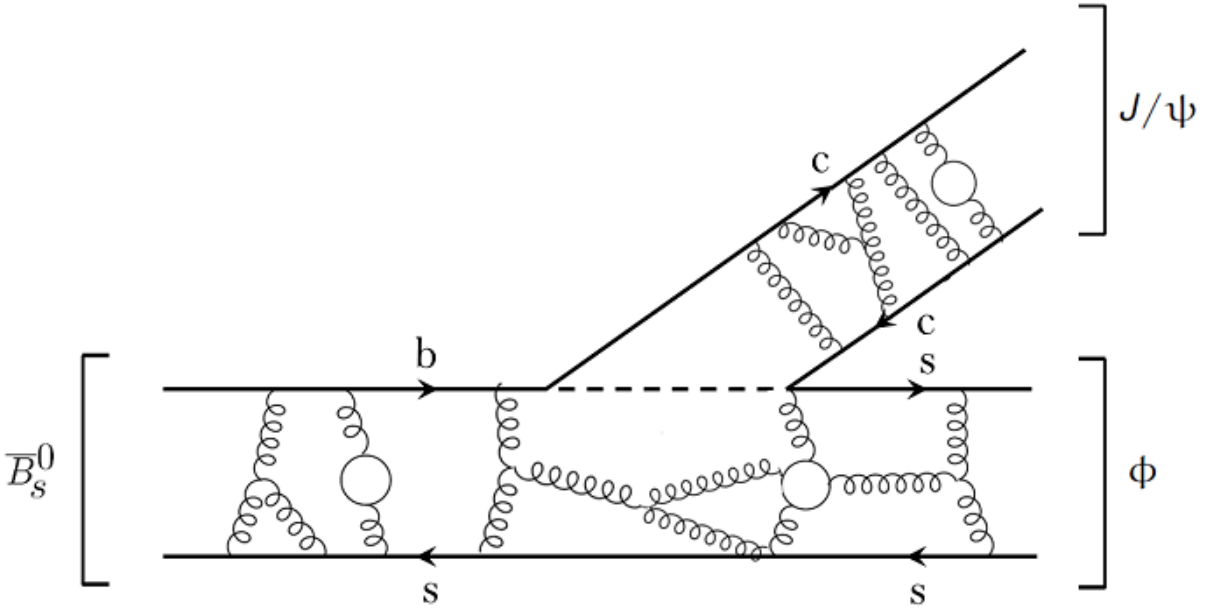
destructive Pauli interference



W exchange



Theoretical calculation



→ Heavy Quark Expansion (HQE)

Heavy Quark Expansion

$$\Gamma(H_b \to X_f) = \frac{G_F^2 m_b^5}{192\pi^3} \left\{ c_3^f \left(1 - \frac{\mu_\pi^2(H_b) - \mu_G^2(H_b)}{2m_b^2} \right) + 2c_5^f \frac{\mu_G^2(H_b)}{m_b^2} + \dots \right\}. \tag{89}$$

$$\frac{\tau(B^-)}{\tau(B^0)} = 1 + O(1/m_b^3)\,,$$

$$\frac{\tau(B_s)}{\tau(B_d)} = (1.00 \pm 0.01) + O(1/m_b^3)\,,$$

$$\frac{\tau(\Lambda_b)}{\tau(B^0)} = 1 + \frac{\mu_\pi^2(\Lambda_b) - \mu_\pi^2(B)}{2m_b^2} - c_G \frac{\mu_G^2(B)}{m_b^2} + O(1/m_b^3)$$

$$\approx 0.98 + O(1/m_b^3)\,,$$

$\tau(B^+)/\tau(B_d) = 1.04^{+0.05}_{-0.01} \pm 0.02 \pm 0.01$ $\qquad$ $\tau(B_s)/\tau(B_d) = 1.001 \pm 0.002$

$\tau(\Lambda_b)/\tau(B_d) = 0.935 \pm 0.054$

[A. Lenz, 2014 , arXiv:1405.3601]

Current World averages

b-hadron species	average lifetime	average lifetime relative to B^0 average lifetime
B^0	**1.519 ± 0.005 ps**	
B^+	**1.638 ± 0.004 ps**	1.076 ± 0.004
B_s	**1.512 ± 0.007 ps**	0.995 ± 0.006
B_c	**0.500 ± 0.013 ps**	
Λ_b	**1.451 ± 0.013 ps**	0.955 ± 0.009

HFAG

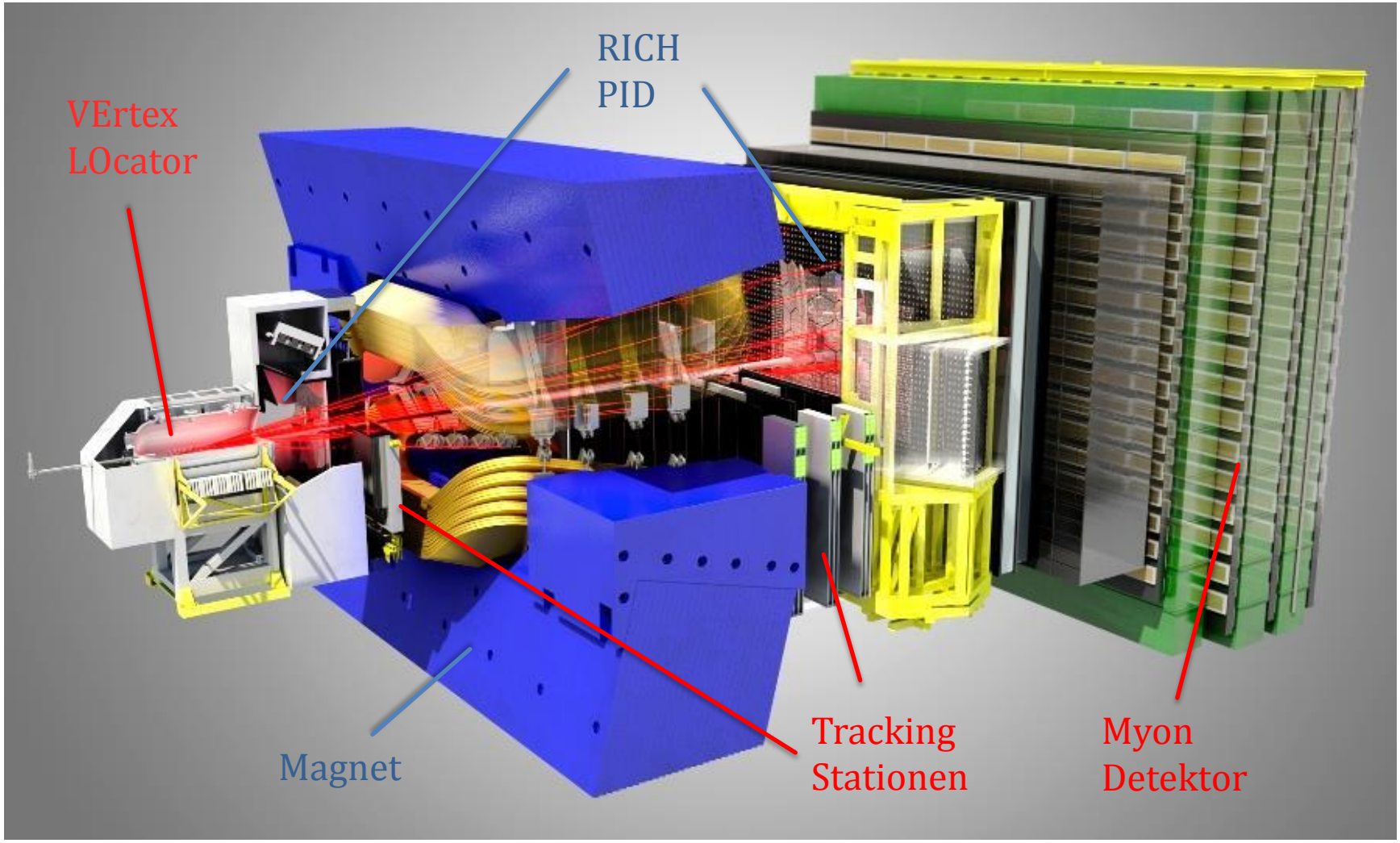
Recent results

CDF : $\tau^{\text{eff}}_{B_s^0 \to J/\psi\phi}$ = 1.528 ± 0.019(stat) ± 0.009(syst) ps - arXiv:1208.2967

ATLAS : τ_{Λ_b} = 1.449 ± 0.036(stat) ± 0.017(syst) ps - arXiv:1207.2284

LHCb : τ_{Λ_b} = 1.479 ± 0.009(stat) ± 0.010(syst) ps - arXiv:1402.6242

CMS : τ_{Λ_b} = 1.503 ± 0.052(stat) ± 0.031(syst) ps - arXiv:1304.7495


RICH
PID
VErtex
LOcator
Magnet
Tracking
Stationen
Myon
Detektor

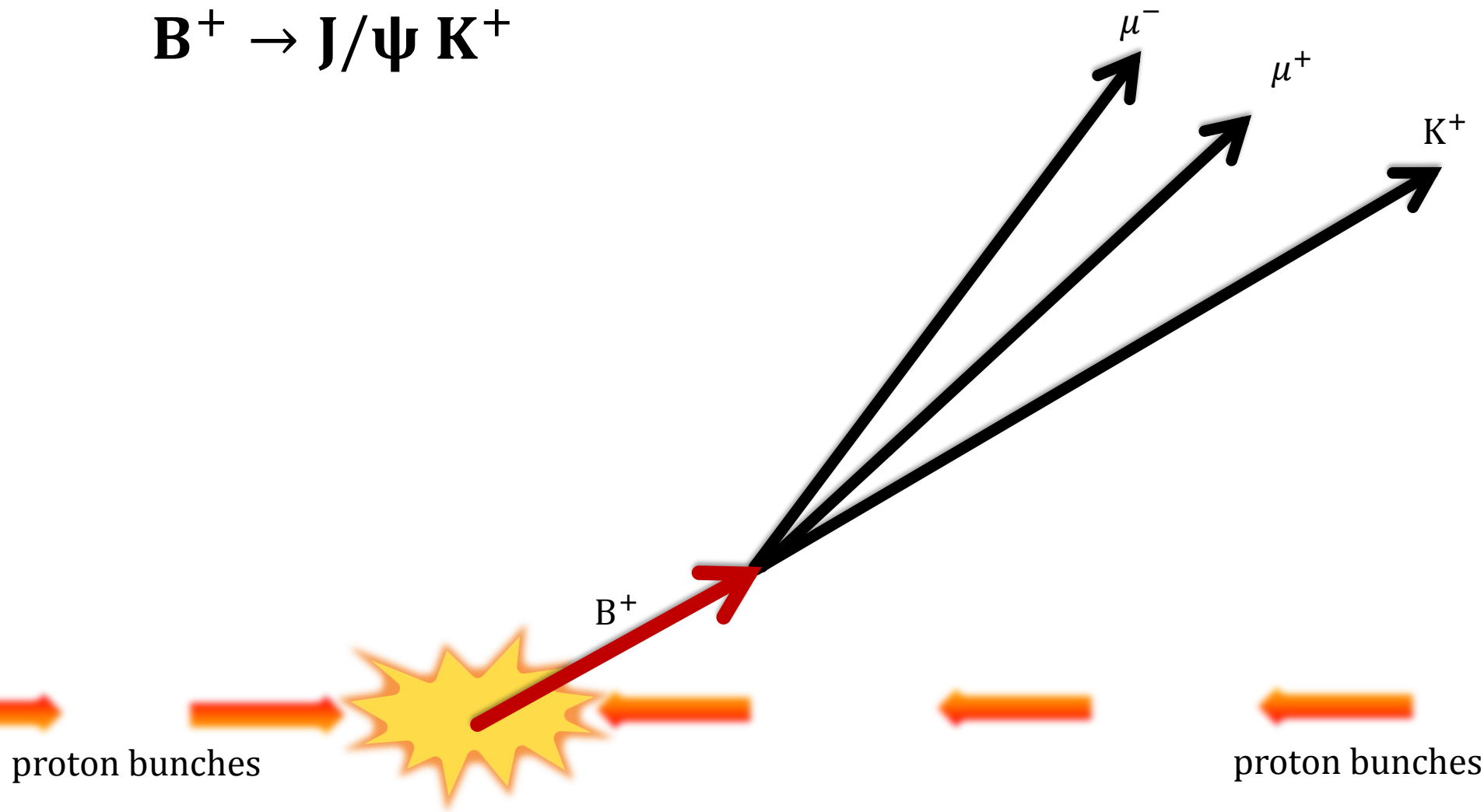
$\mathbf{B^+ \rightarrow J/\psi\, K^+}$

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

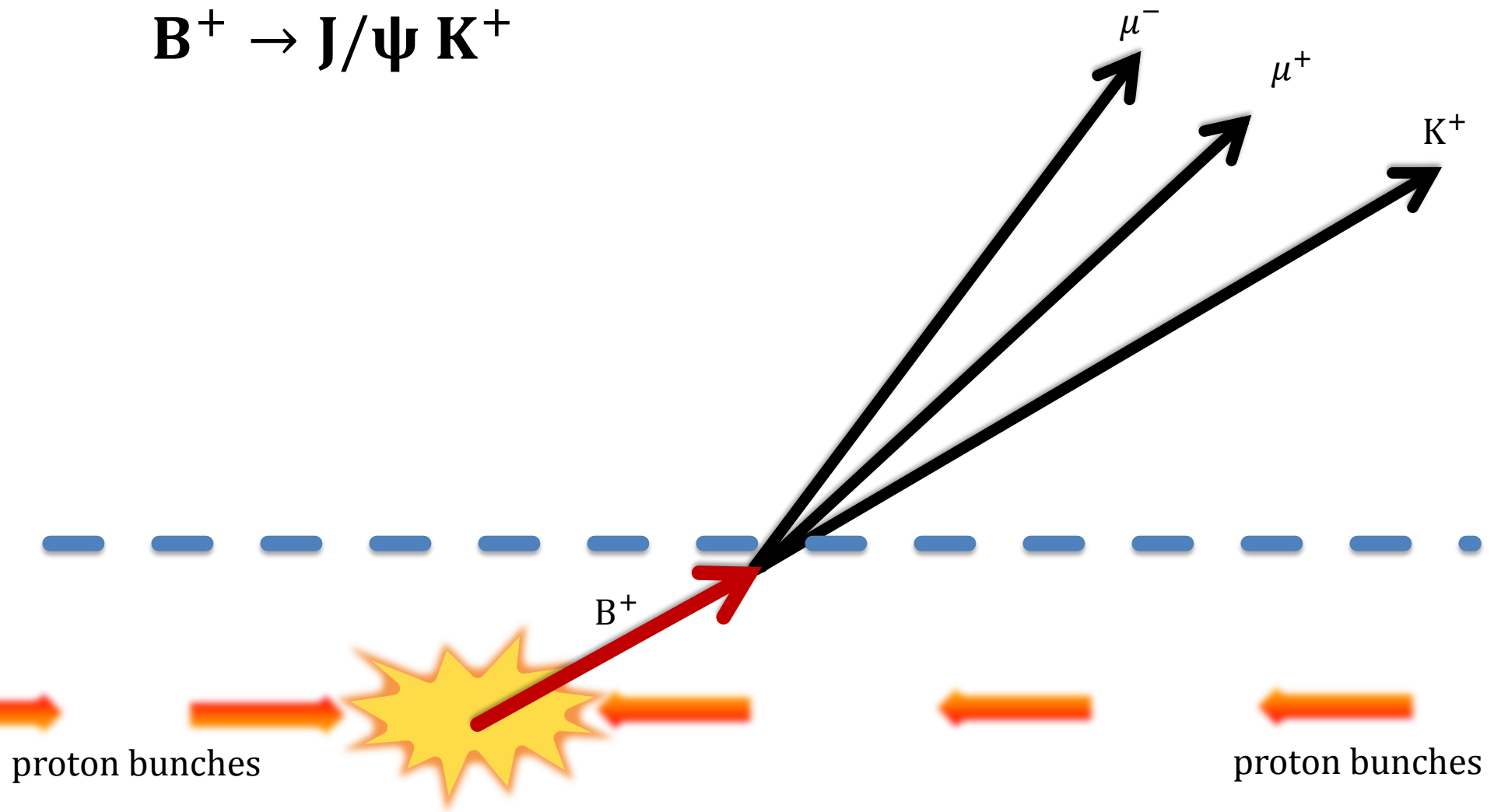
proton bunches

proton bunches

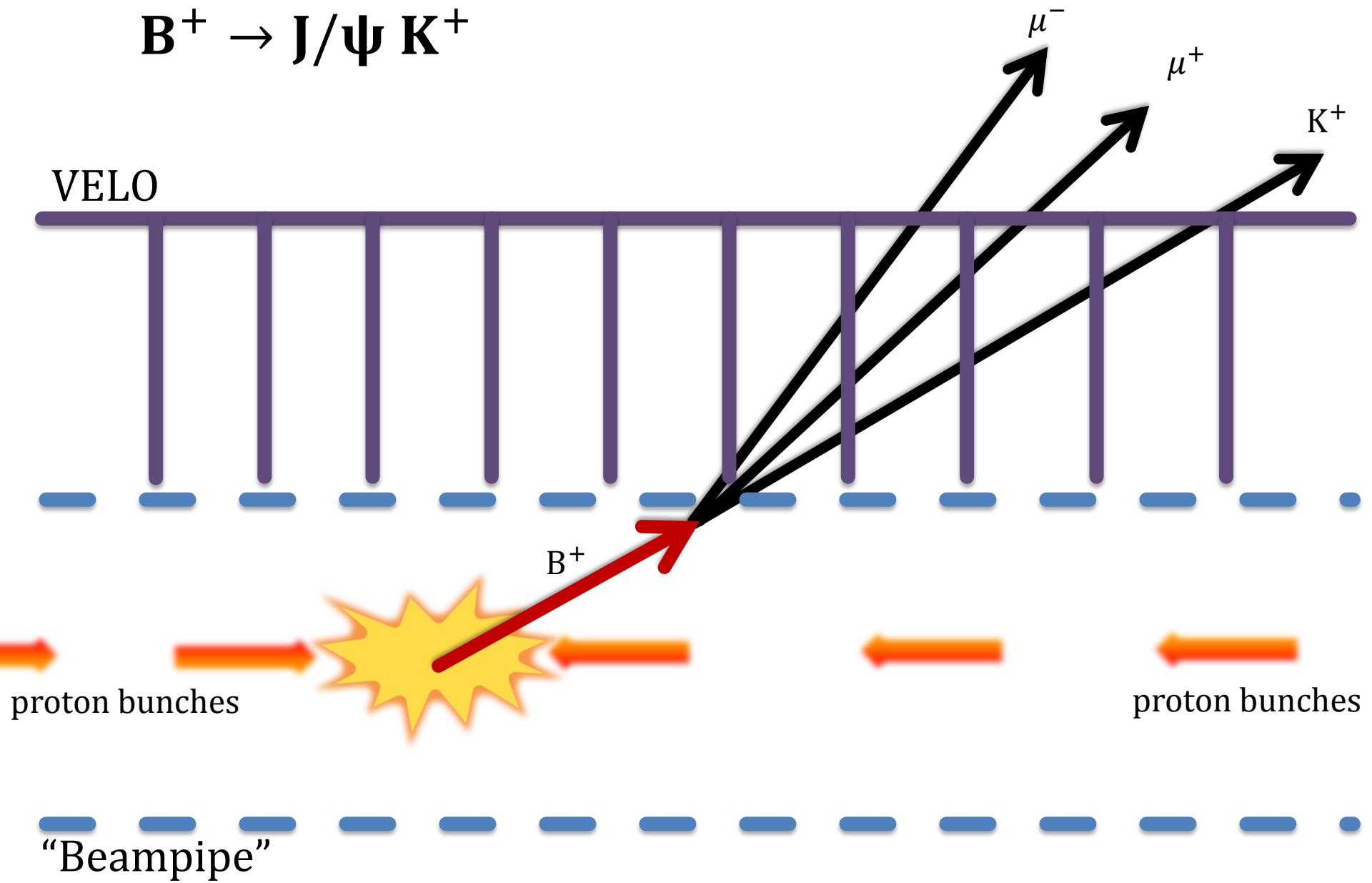
$B^+ \rightarrow J/\psi\, K^+$



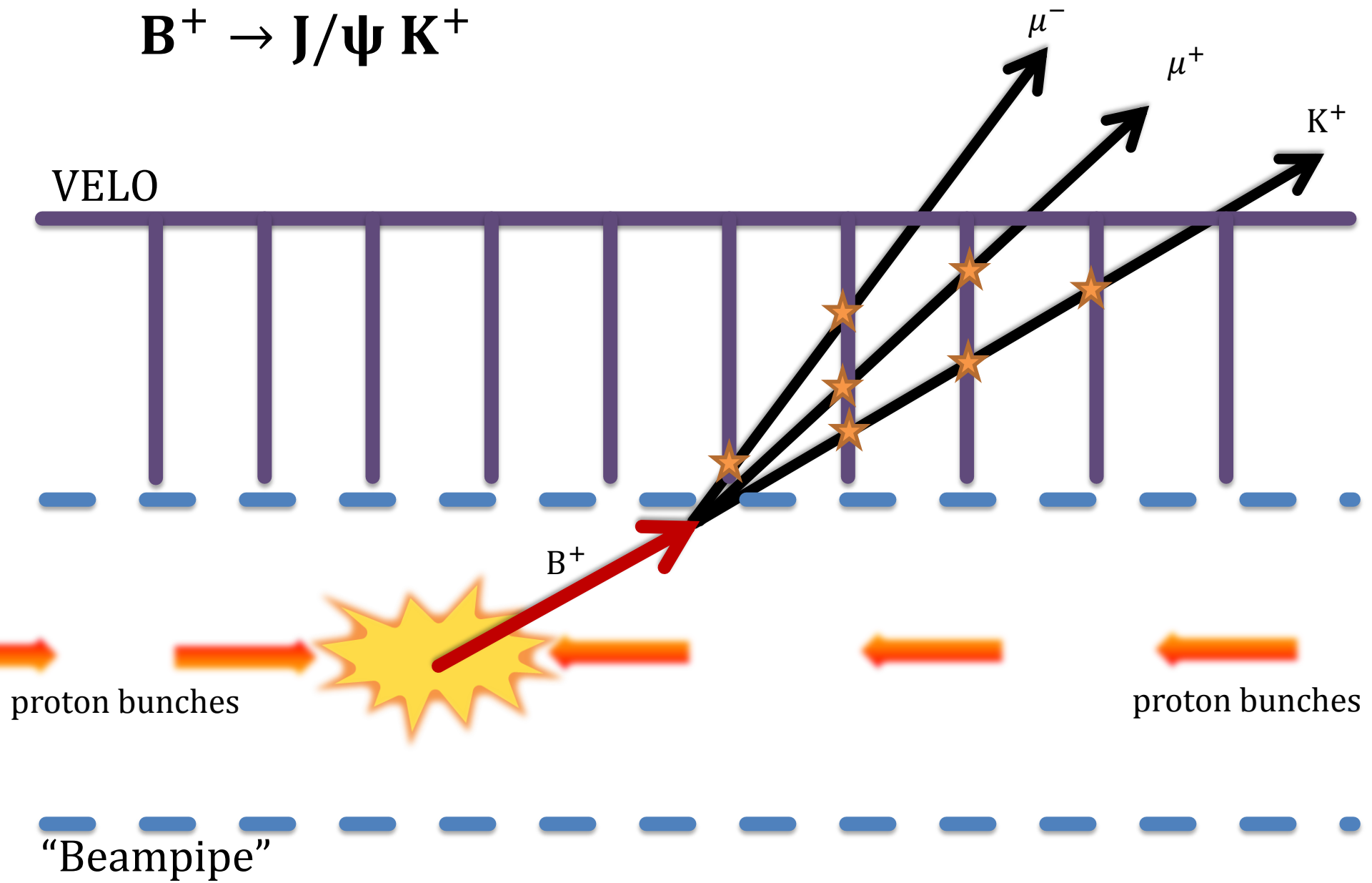
$B^+ \rightarrow J/\psi\, K^+$

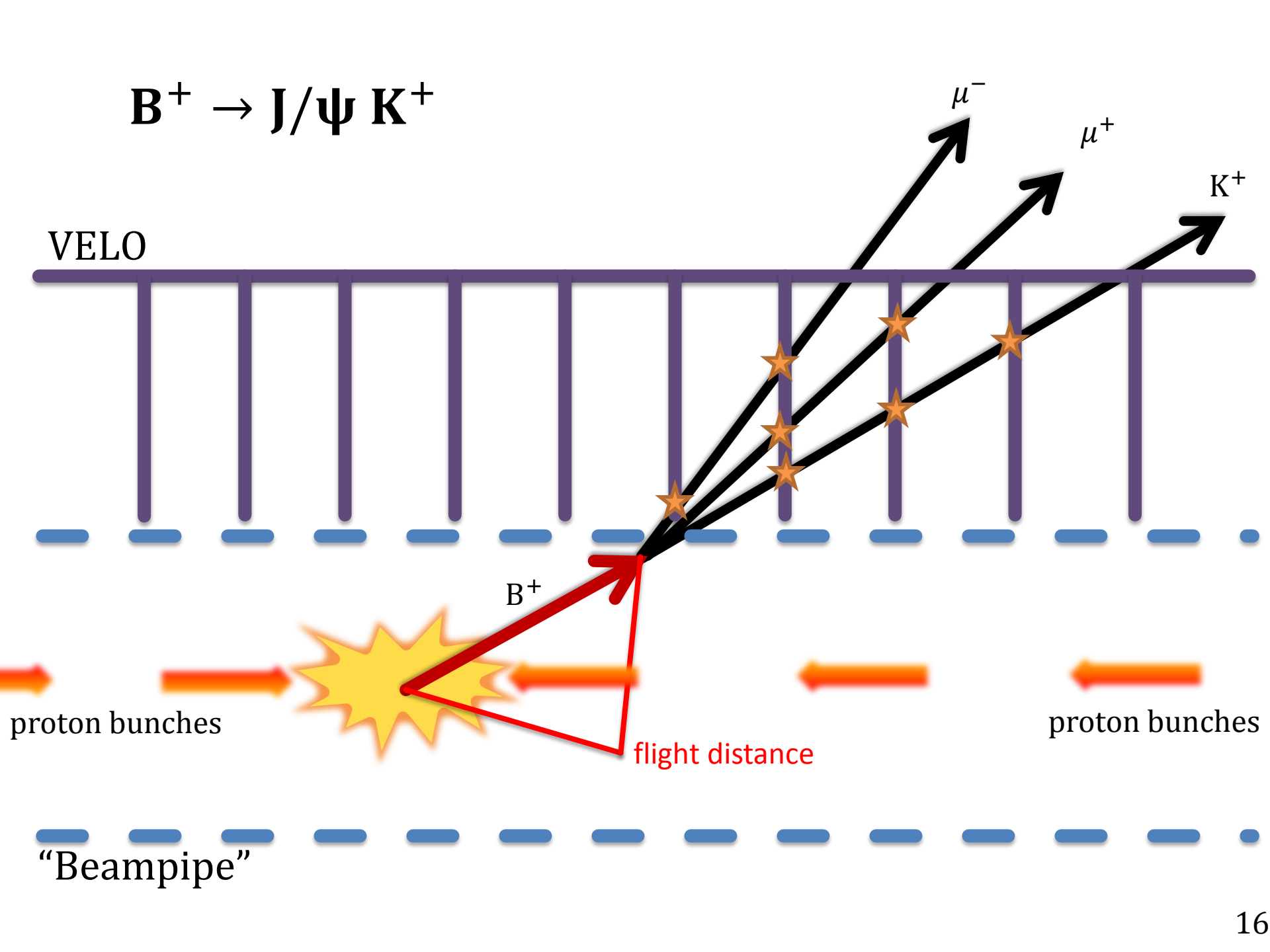


$B^+ \rightarrow J/\psi\, K^+$

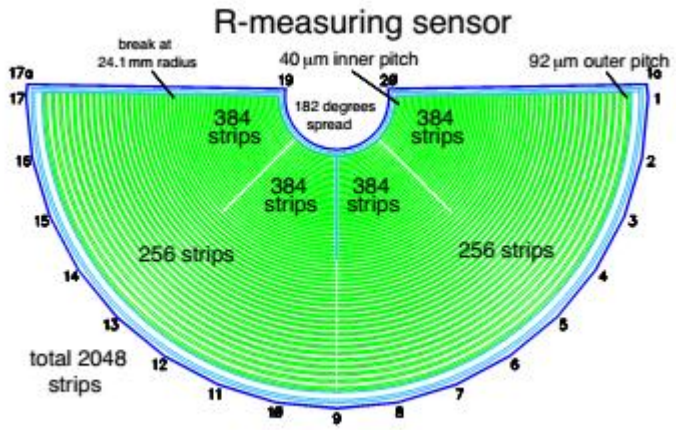


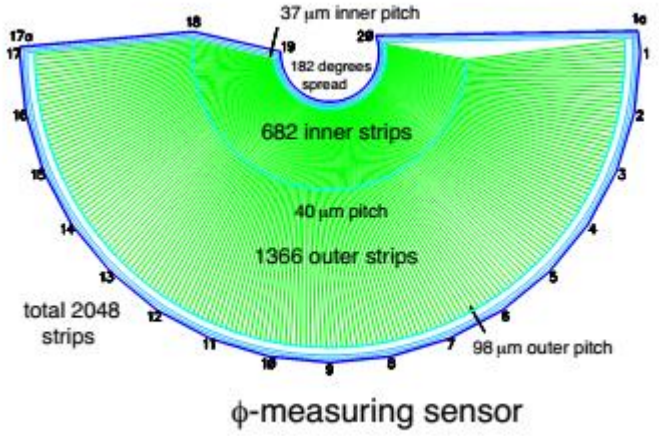
$B^+ \rightarrow J/\psi K^+$



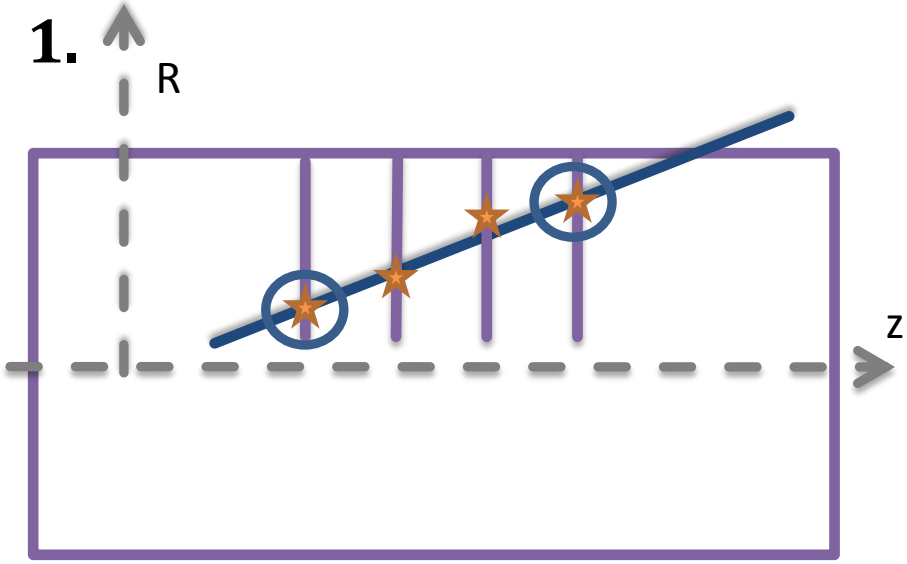

$B^+ \rightarrow J/\psi\, K^+$
μ^-
μ^+
K^+
VELO
B^+
proton bunches
proton bunches
flight distance
"Beampipe"

VELO Tracking

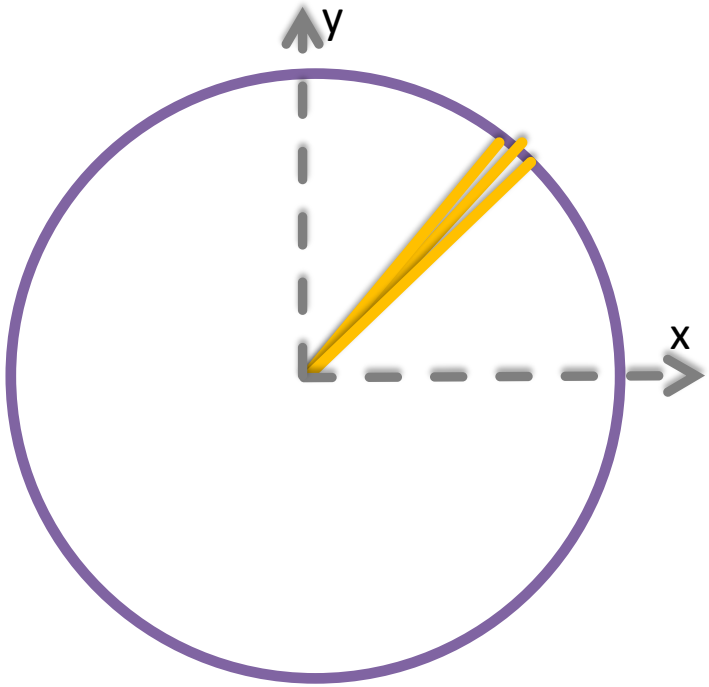




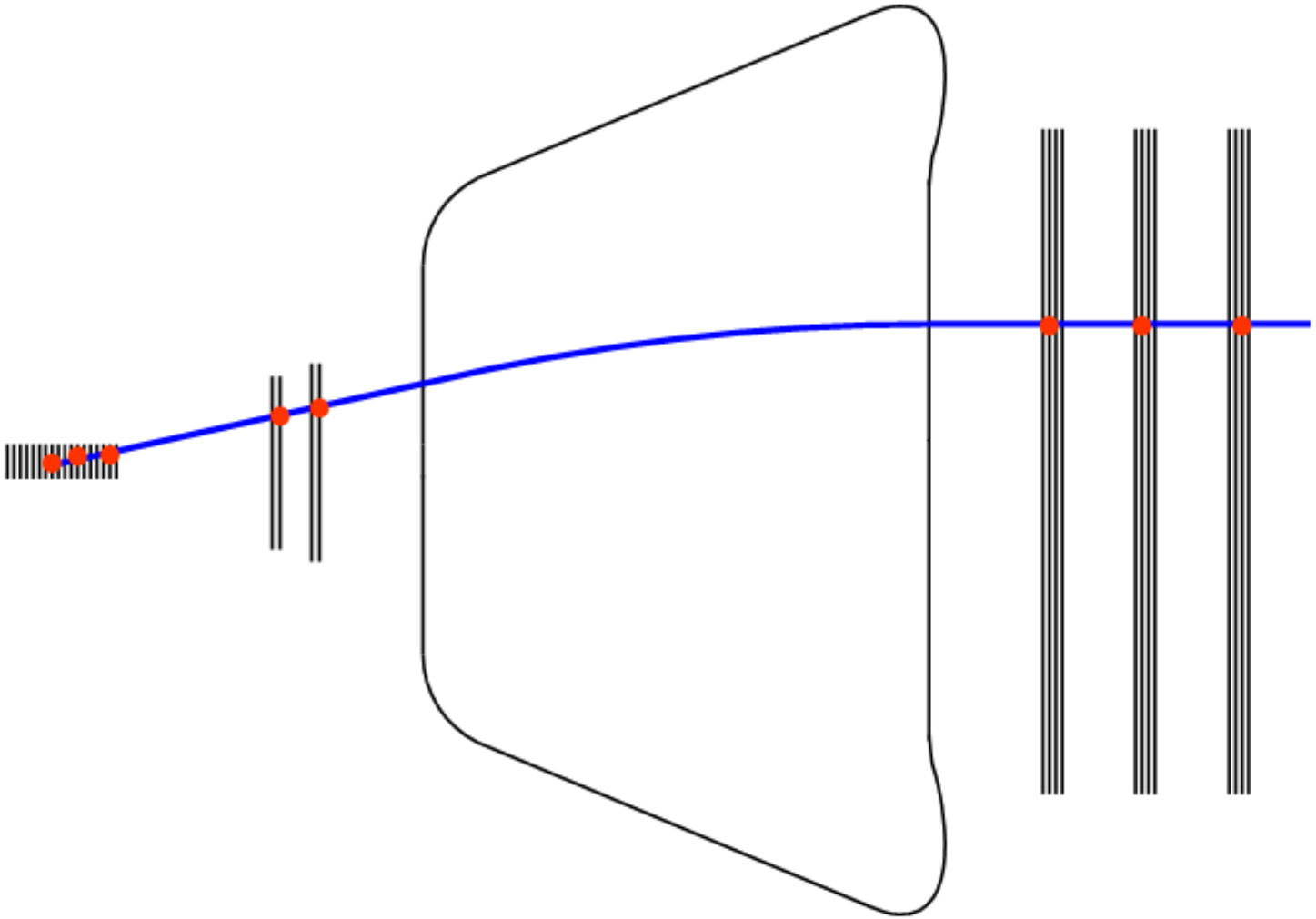
1.



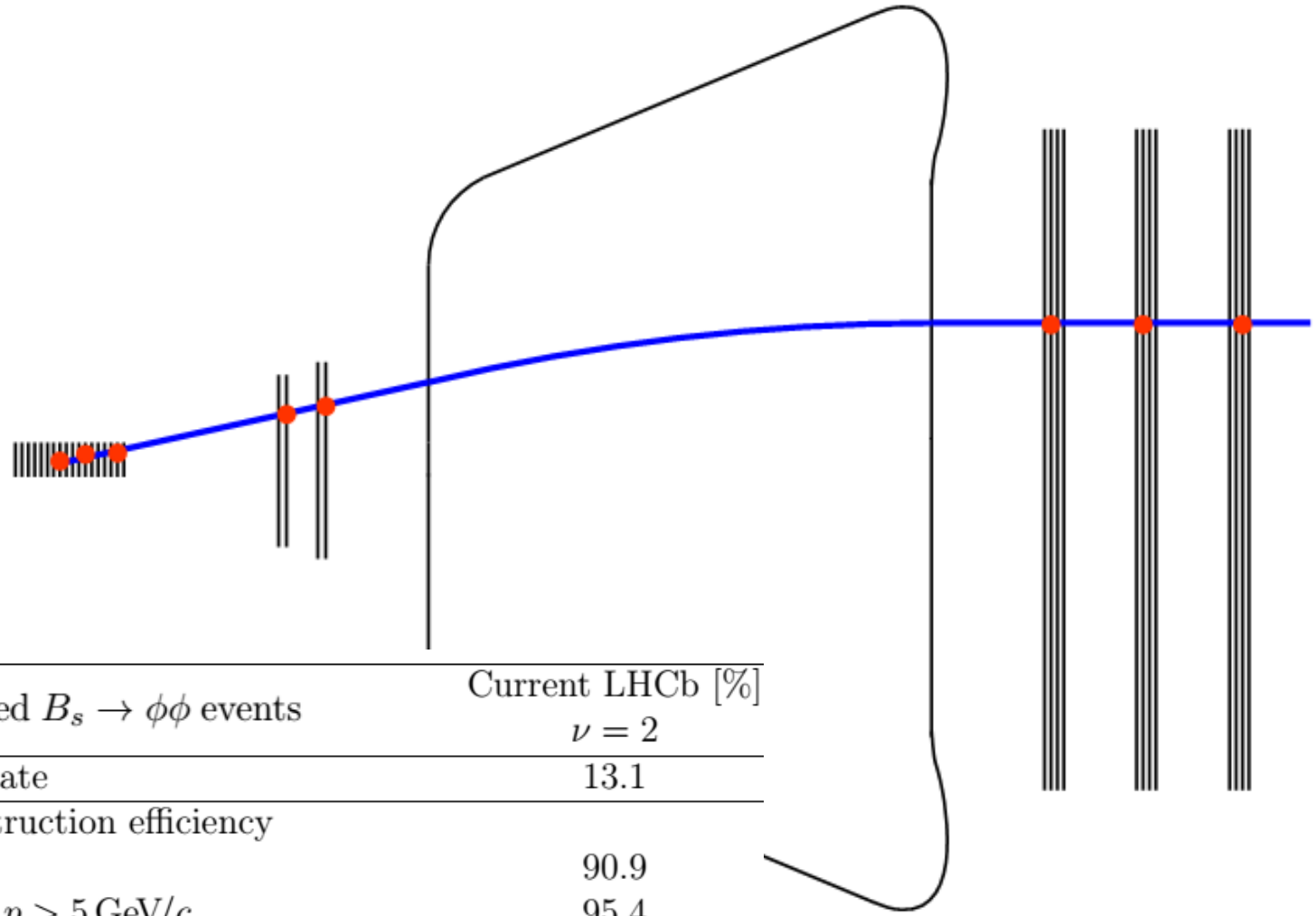
2.



Long Track

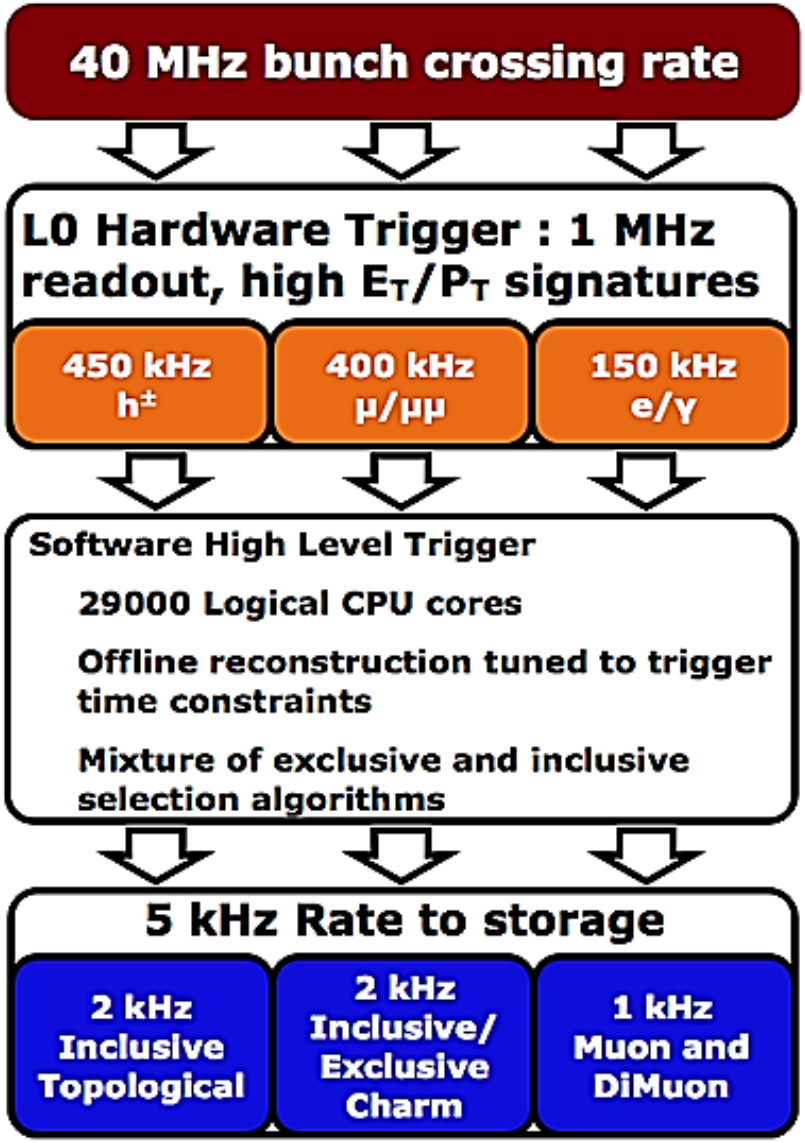


Long Track



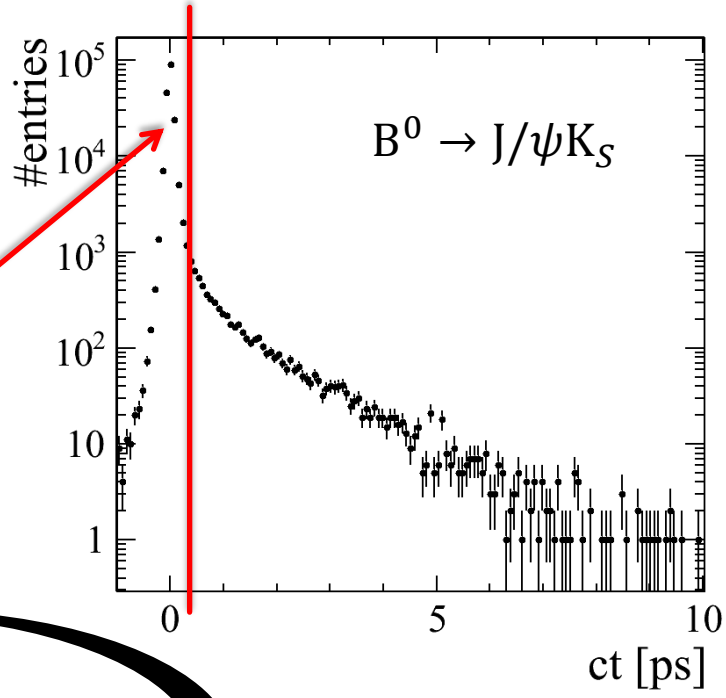
simulated $B_s \to \phi\phi$ events	Current LHCb [%] $\nu = 2$
Ghost rate	13.1
Reconstruction efficiency	
long	90.9
long, $p > 5\,\mathrm{GeV}/c$	95.4
b-hadron daughters	93.9
b-hadron daughters, $p > 5\,\mathrm{GeV}/c$	96.1

Trigger

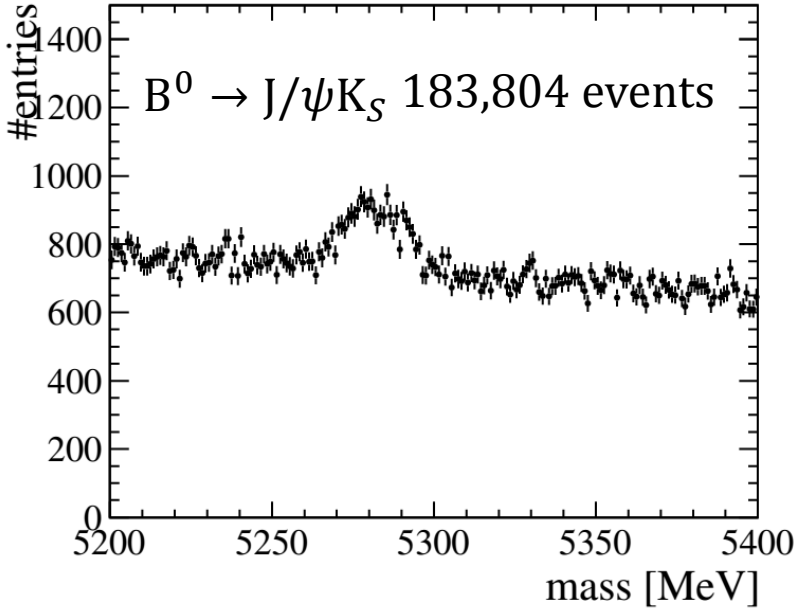

40 MHz bunch crossing rate
L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures
450 kHz $h^{\pm}$
400 kHz μ/μμ
150 kHz e/γ
Software High Level Trigger
29000 Logical CPU cores
Offline reconstruction tuned to trigger time constraints
Mixture of exclusive and inclusive selection algorithms
5 kHz Rate to storage
2 kHz Inclusive Topological
2 kHz Inclusive/ Exclusive Charm
1 kHz Muon and DiMuon

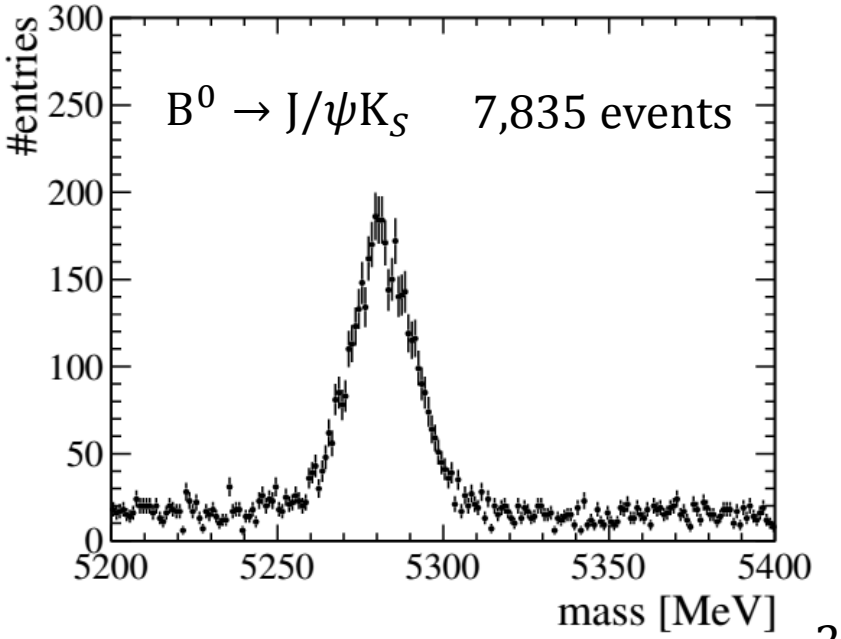
How to reduce the rate?

prompt background

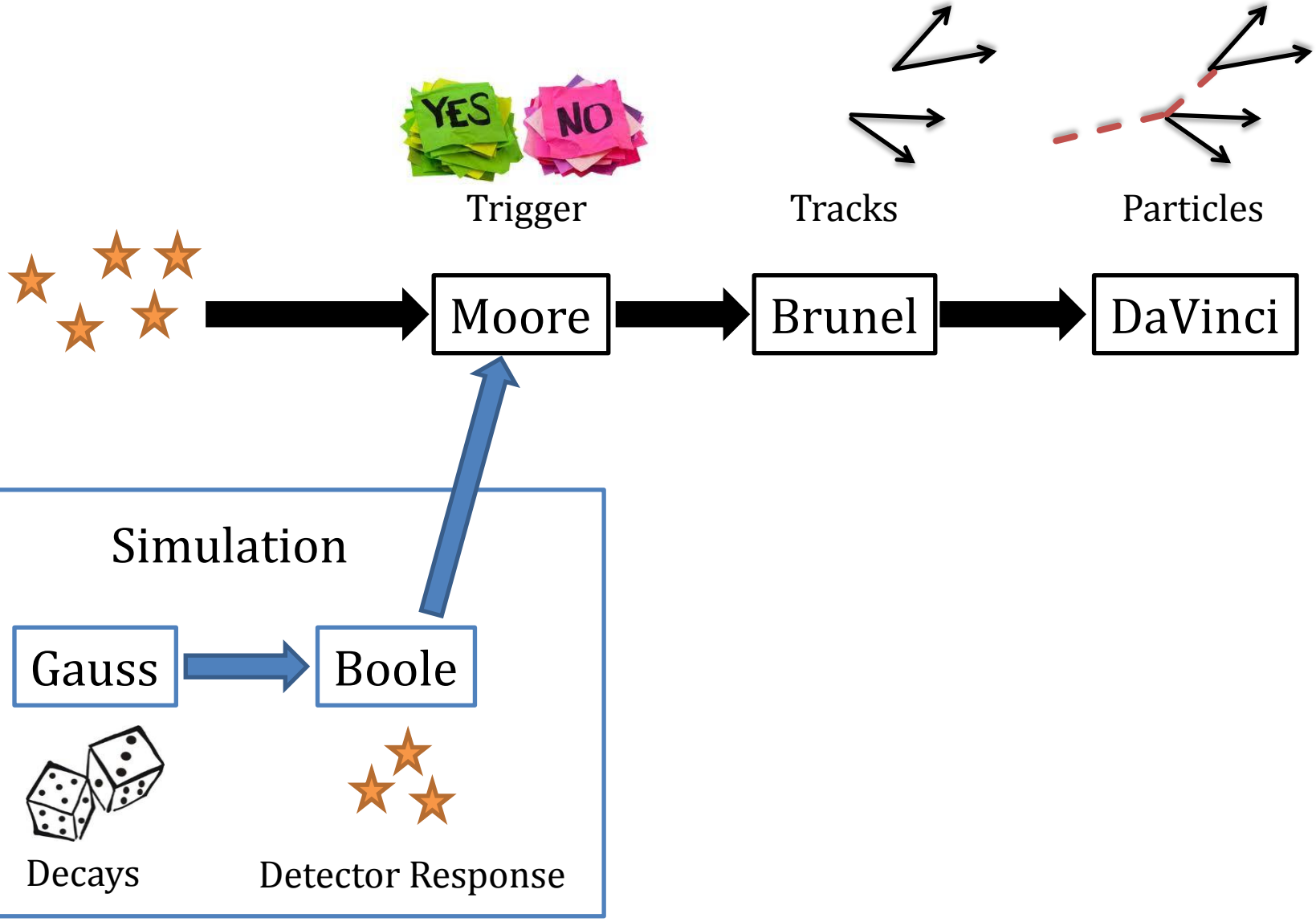


decay time cut of 0.3 ps (τ = 1.5 ps)





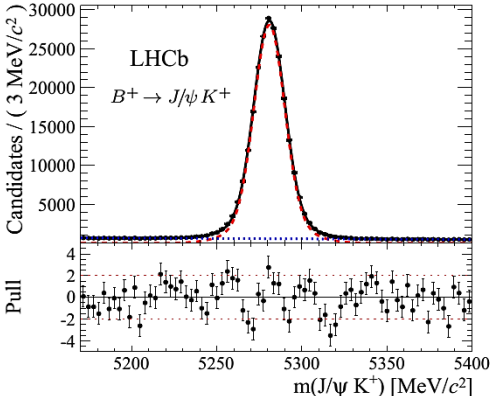
Data Processing

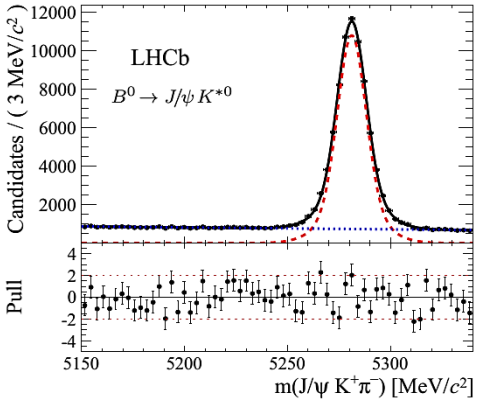


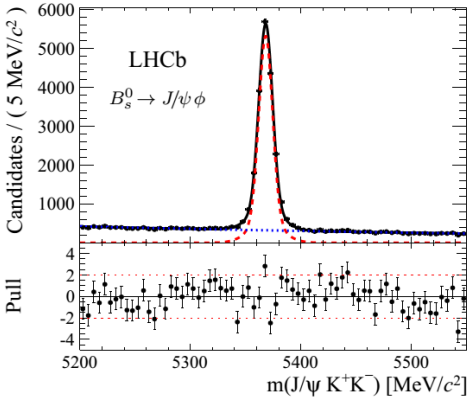
Data Samples

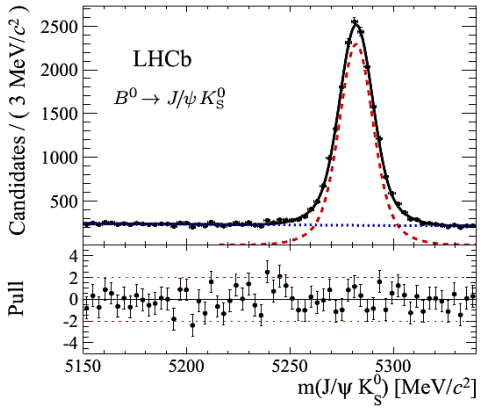
Reconstructed Signal candidates:

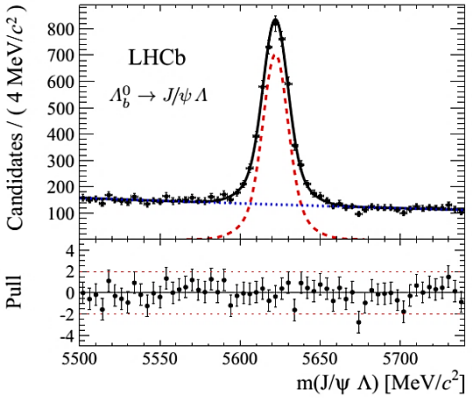
229.000	$B^+ \to J/\psi\, K^+$
71.000	$B^0 \to J/\psi\, K^*$,
17.000	$B^0 \to J/\psi K_S$,
19.000	$B_s^0 \to J/\psi\, \phi$,
3.900	$\Lambda_b^0 \to J/\psi\, \Lambda$,



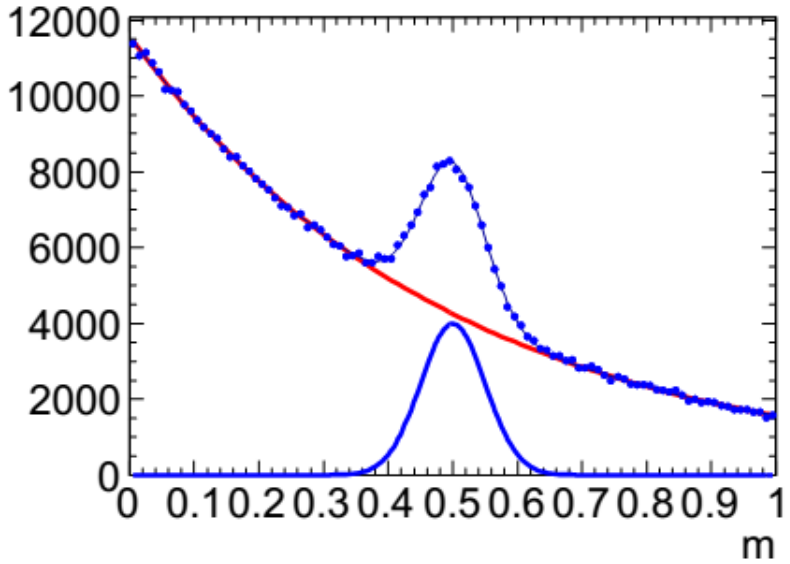


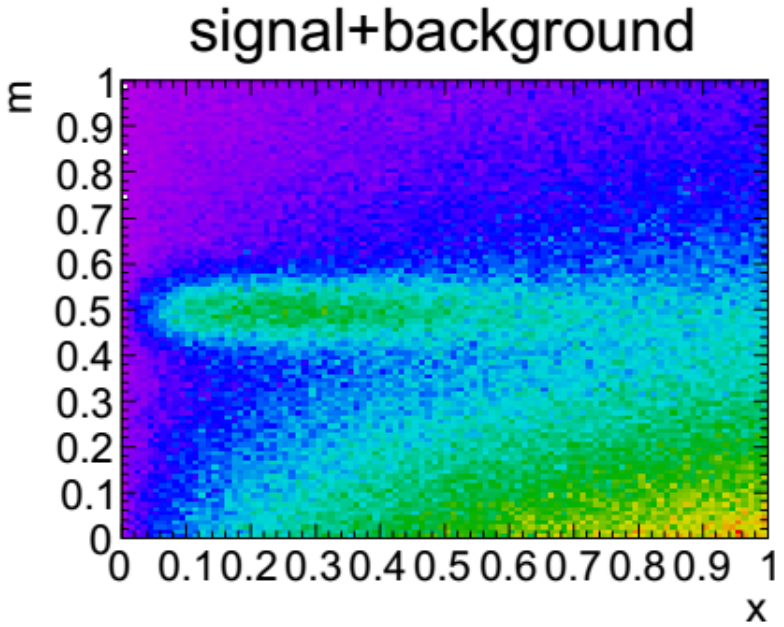


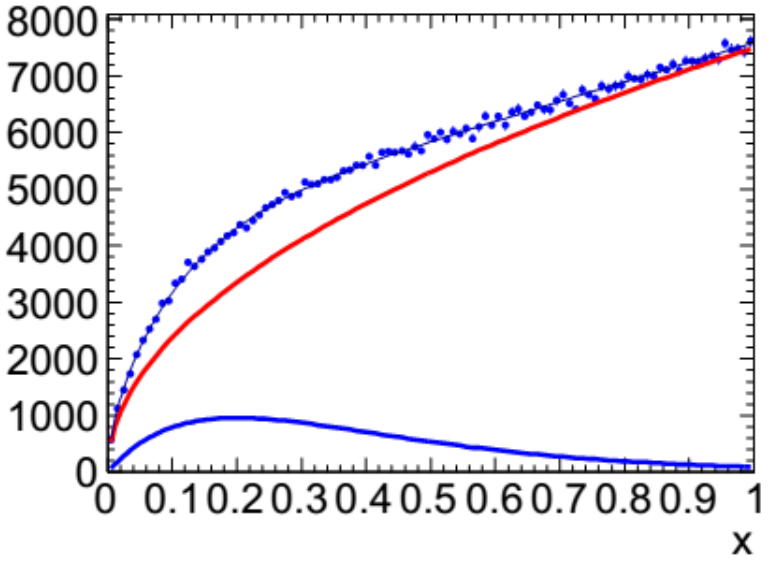




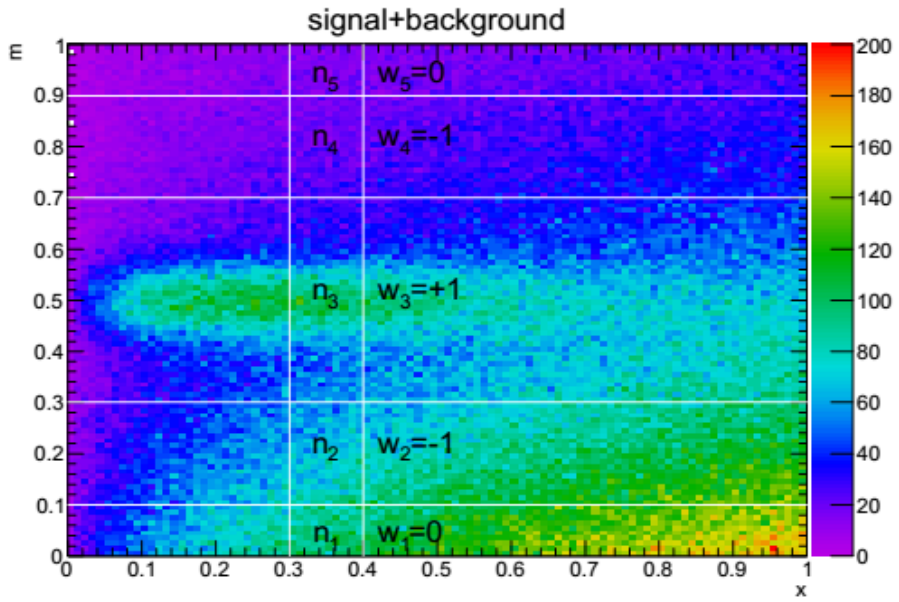
How to separate signal and background?

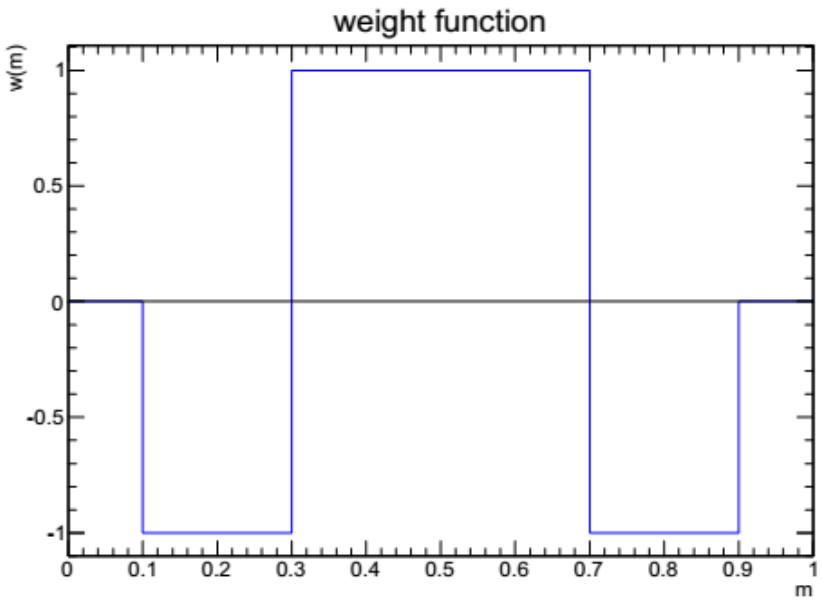




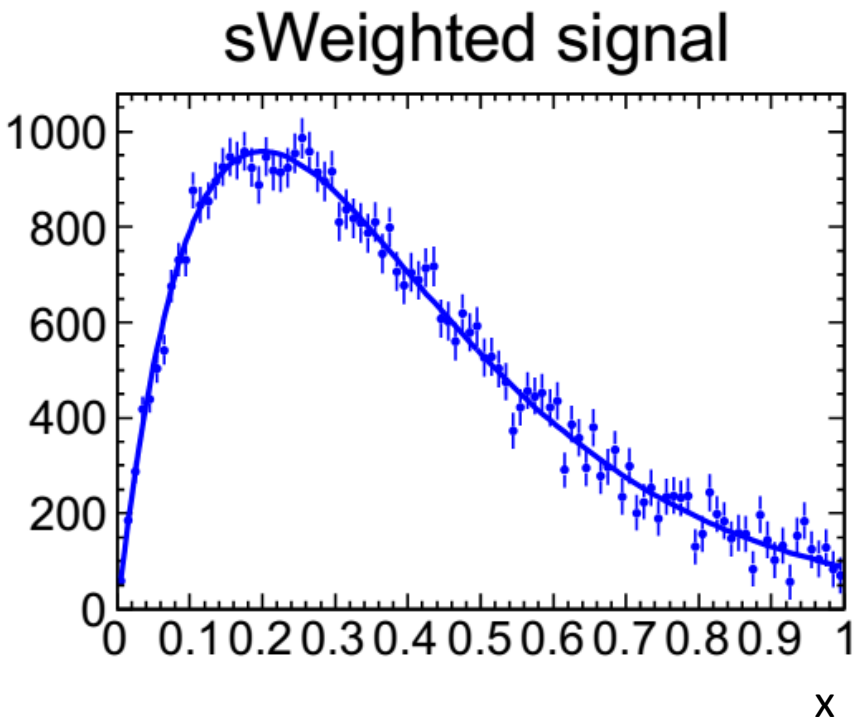


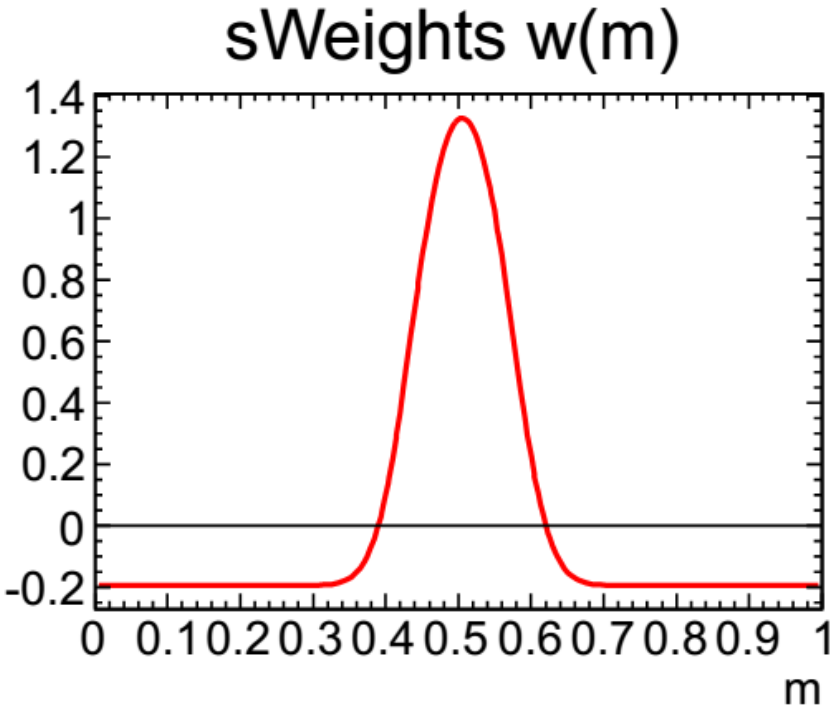
Sideband Subtraction



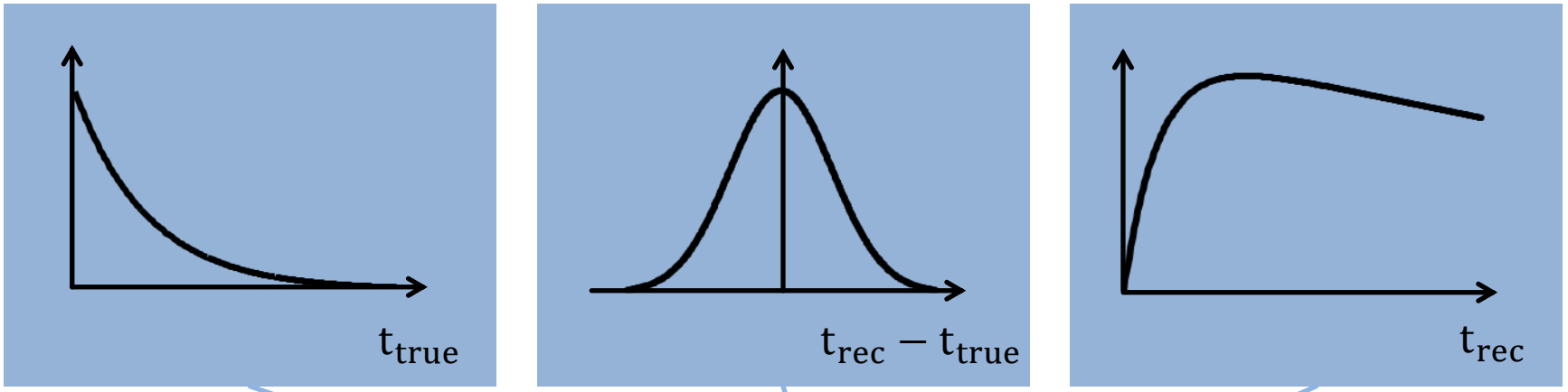


m and x must be uncorrelated!


sWeighted signal
1000
800
600
400
200
0
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
x


sWeights w(m)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
m

Lifetime Measurements



$$PDF = \exp(-t/\tau) \otimes Res(t,t') \cdot Acc(t')$$

$Res(t,t')$: Decay Time Resolution
$Acc(t)$: Reconstruction & Selection Efficiency

Lifetime Measurement

1. Why not rely on simulation

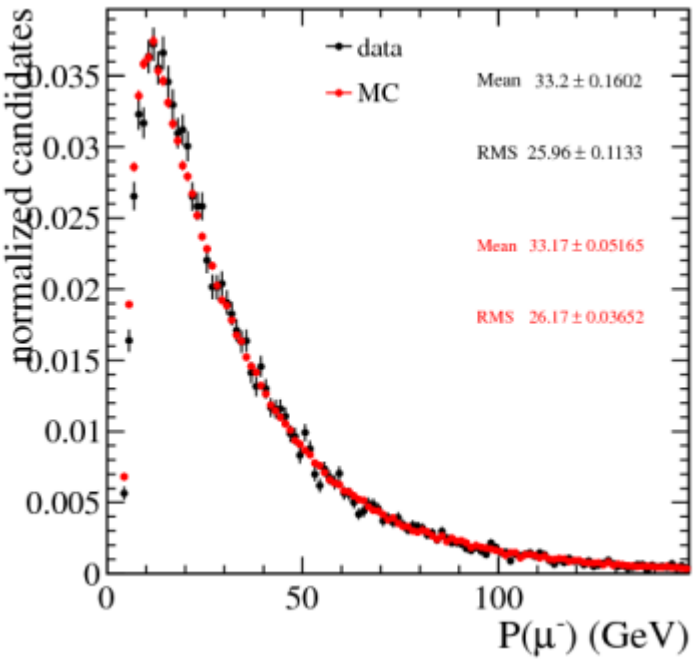
2. Data driven method to measure decay time resolution

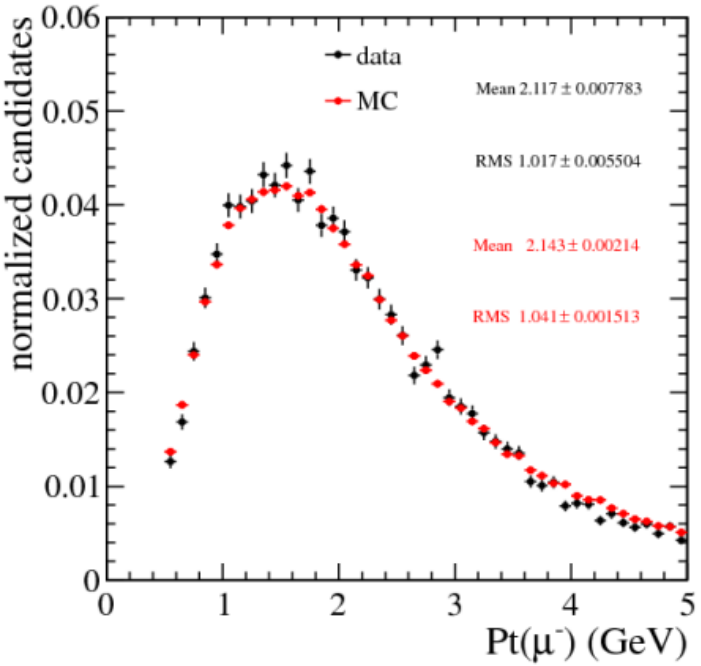
3. Data driven method to measure decay time dependent reconstruction efficiency:
   Tag and Probe

1. Fit

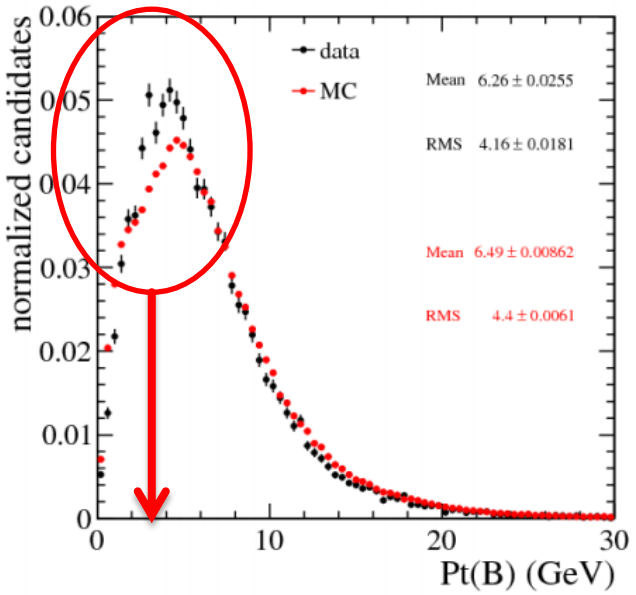
Why not just trust simulation?

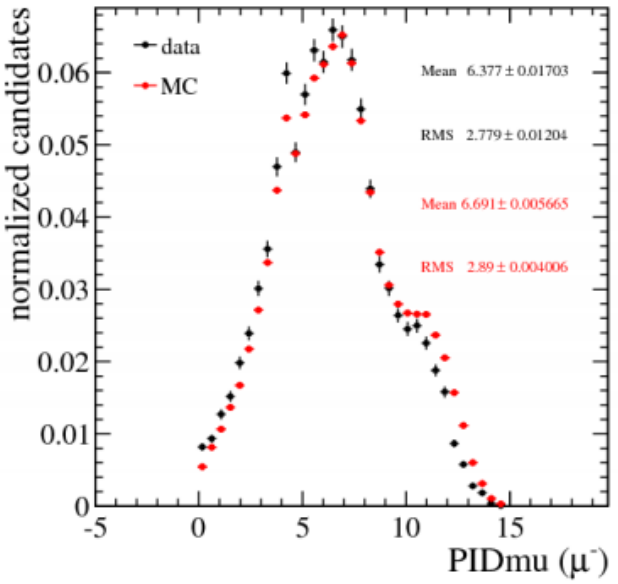
The good…





...,the bad...

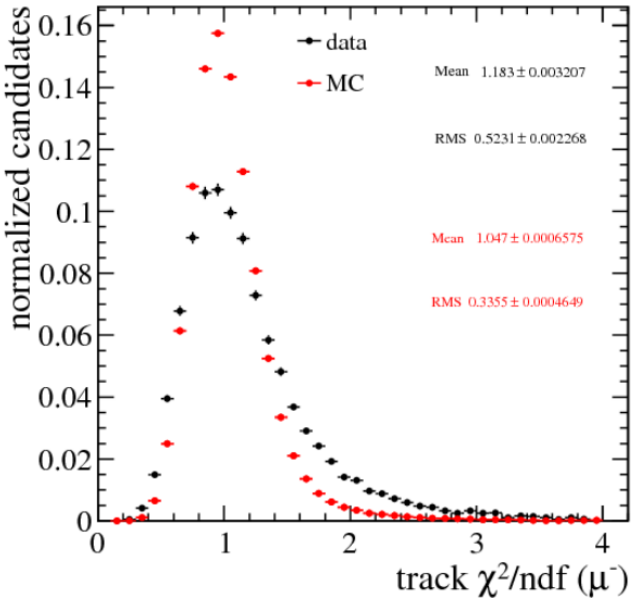


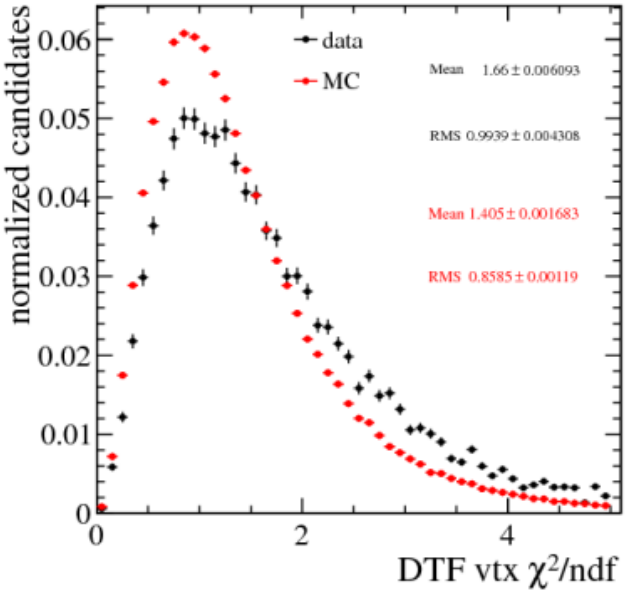


low energetic particles:

- much multiple scattering
- 10% uncertainty on material
- Misalignment of the detector

... and the ugly



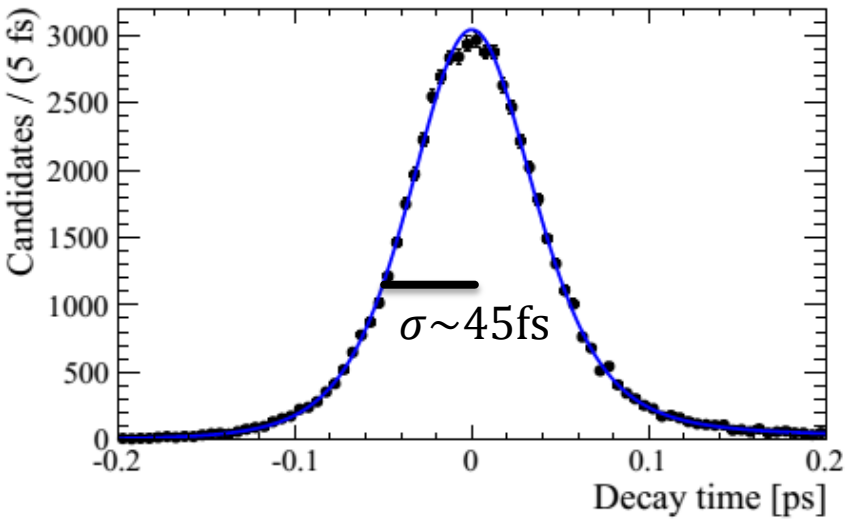


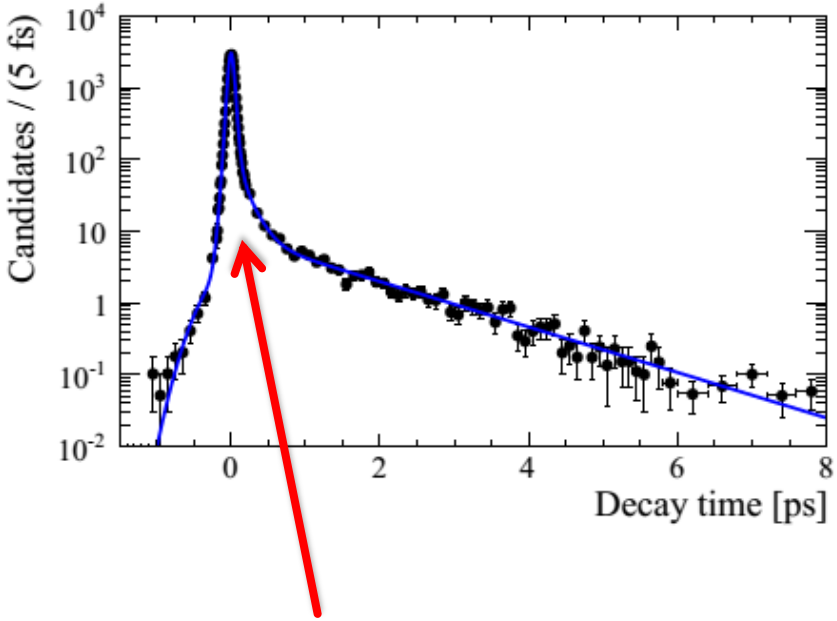
low energetic particles:

- much multiple scattering
- 10% uncertainty on material
- Misalignment of the detector

Decay Time Resolution

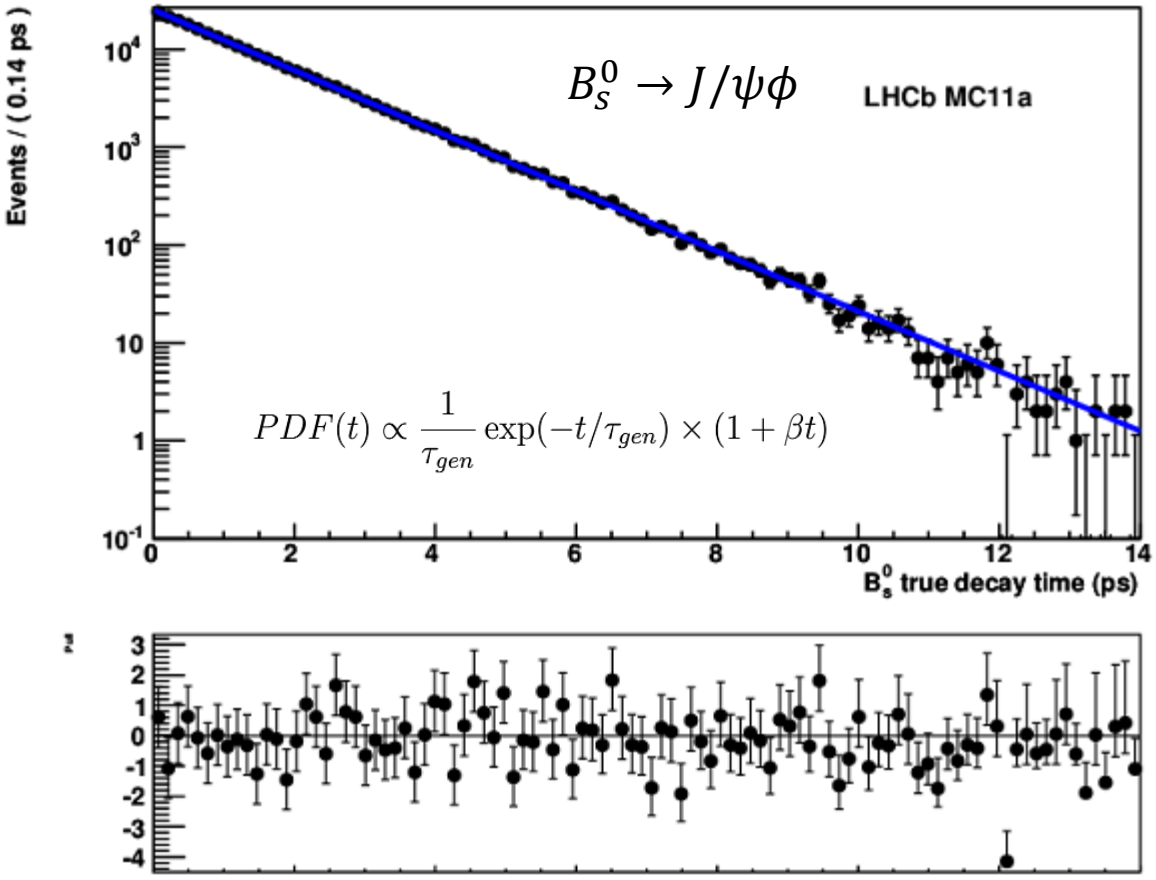
Prompt J/ψK^+K^- candidates





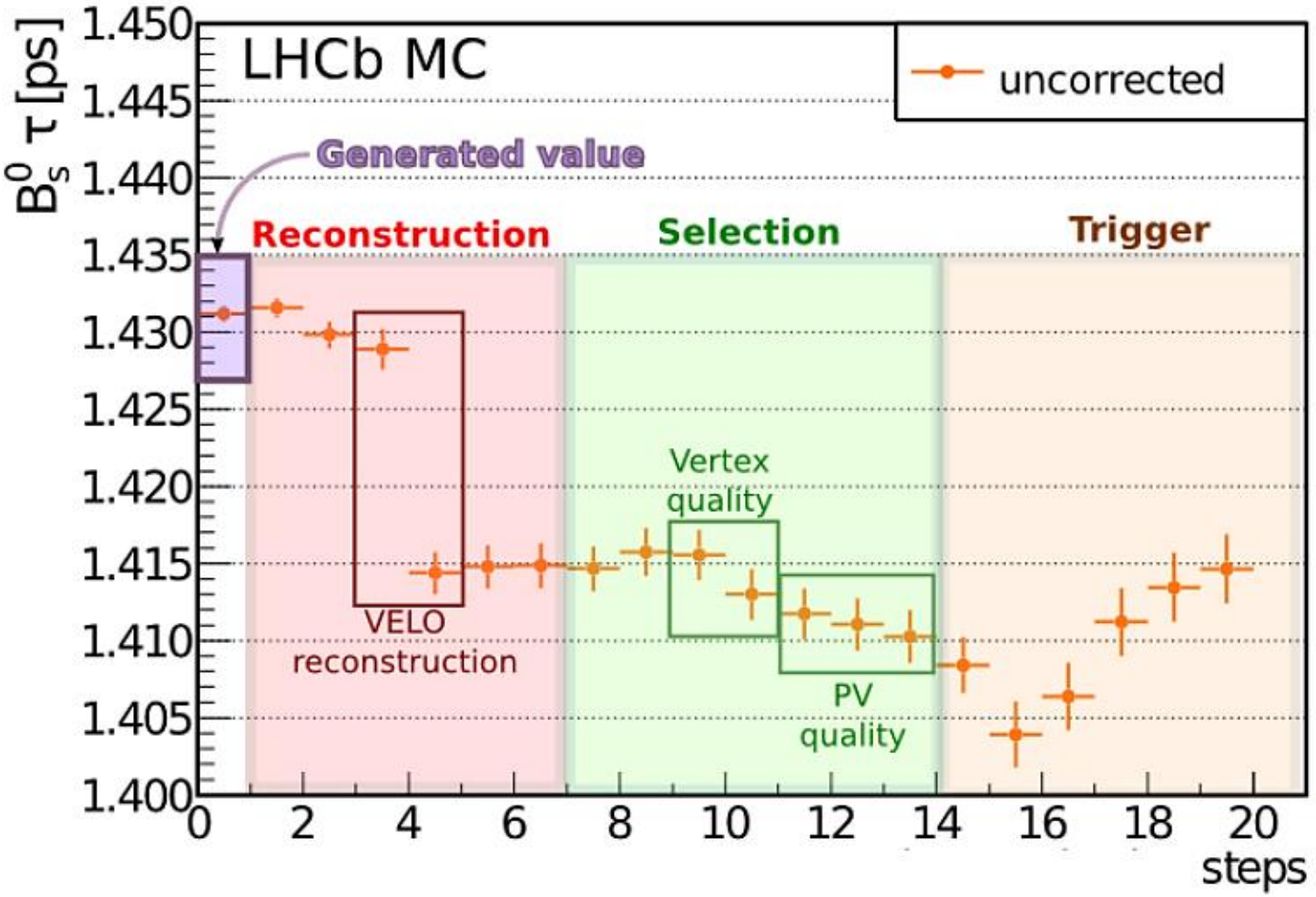
true J/ψ + random kaons

Decay Time Acceptance



$\beta \sim \mathcal{O}(10^{-2}) \mathrm{ps}^{-1} \to \Delta\tau \sim 20$ fs

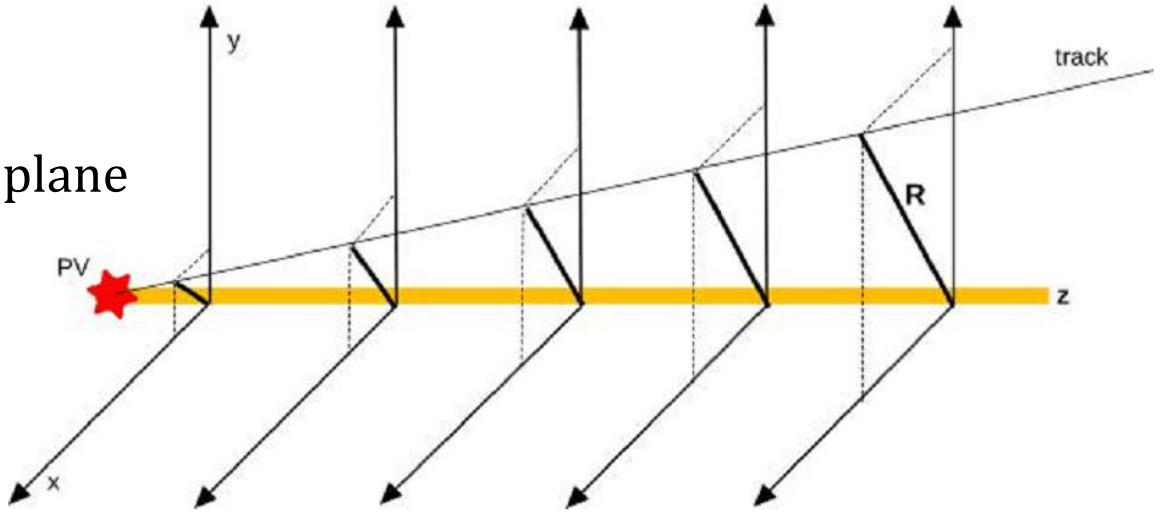
Measured lifetime after different
Selection and Reconstruction steps



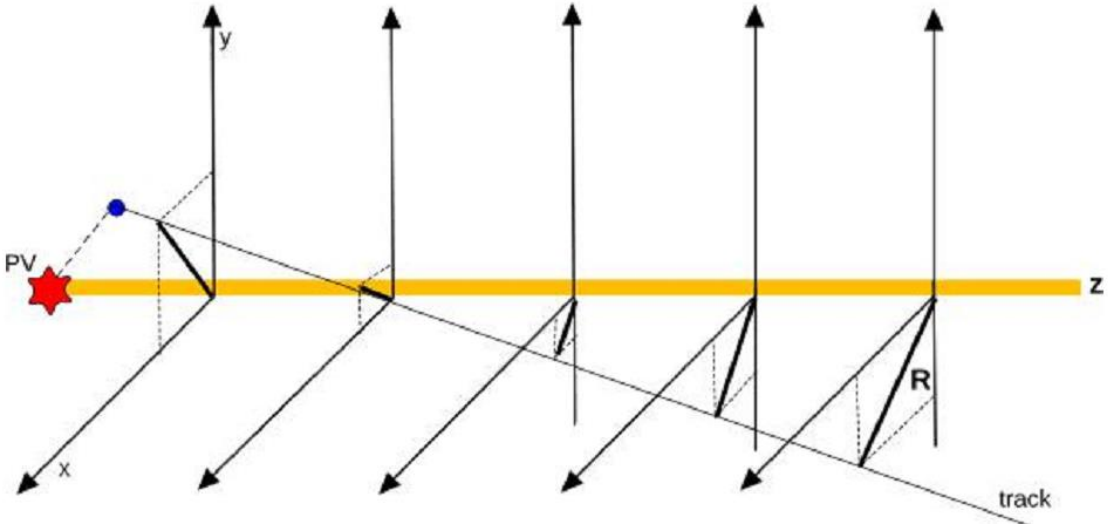
Reconstruction in the VELO

Track from origin

- straight line in R-z plane
- same ϕ

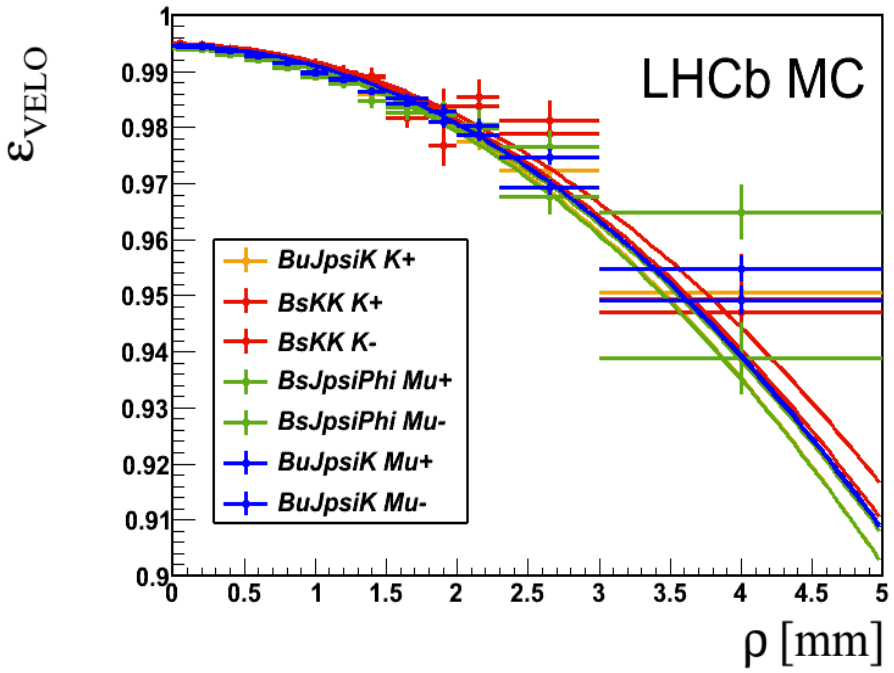


Track from B decay

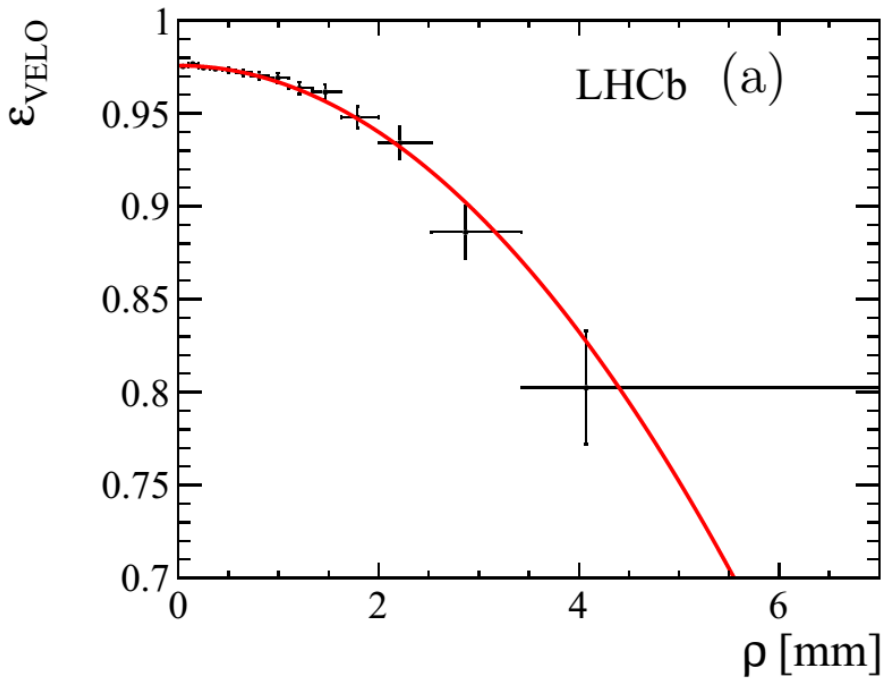


VELO reconstruction efficiency

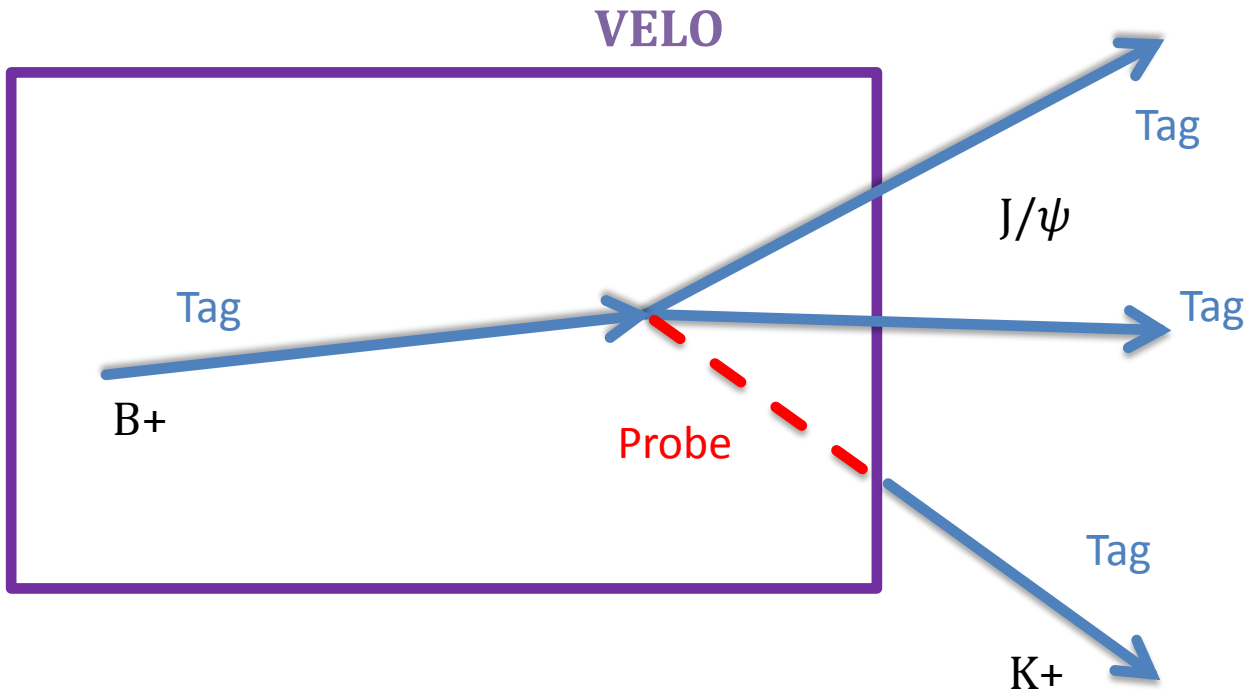
Simulation



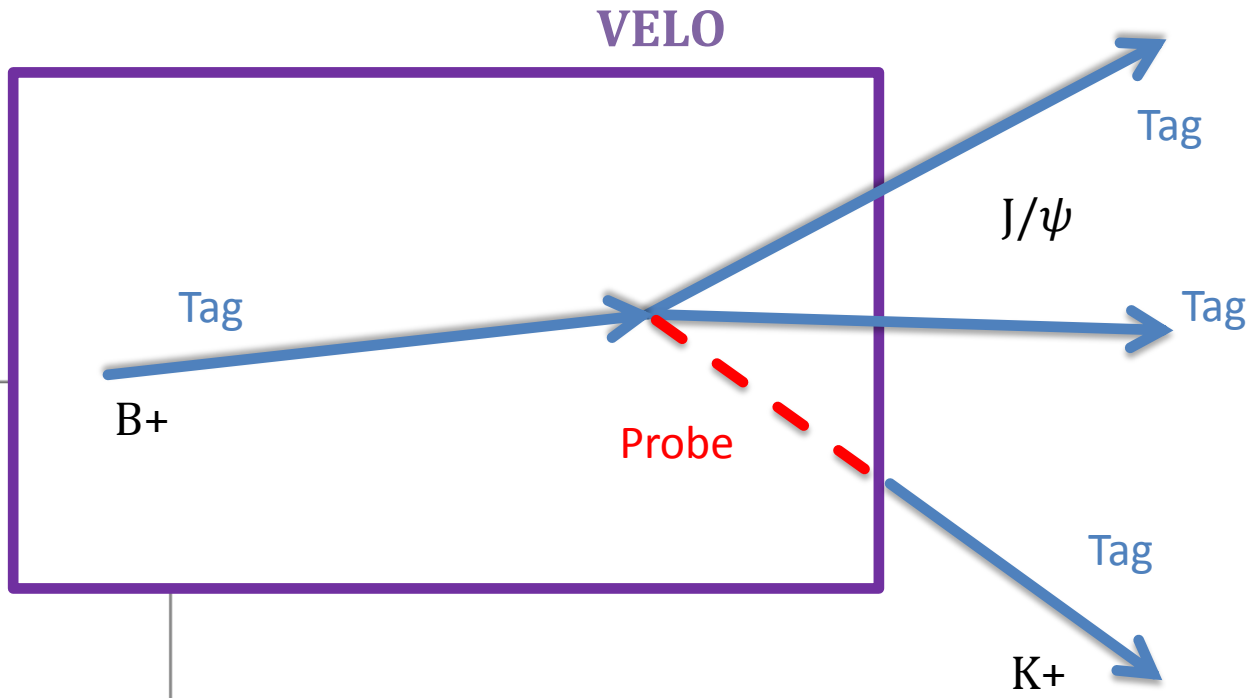
Data

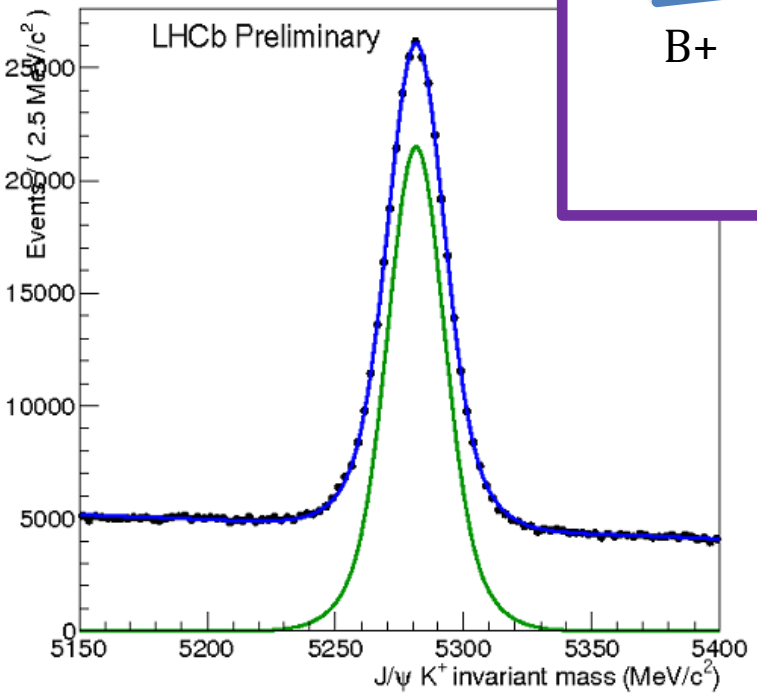


Tag and Probe



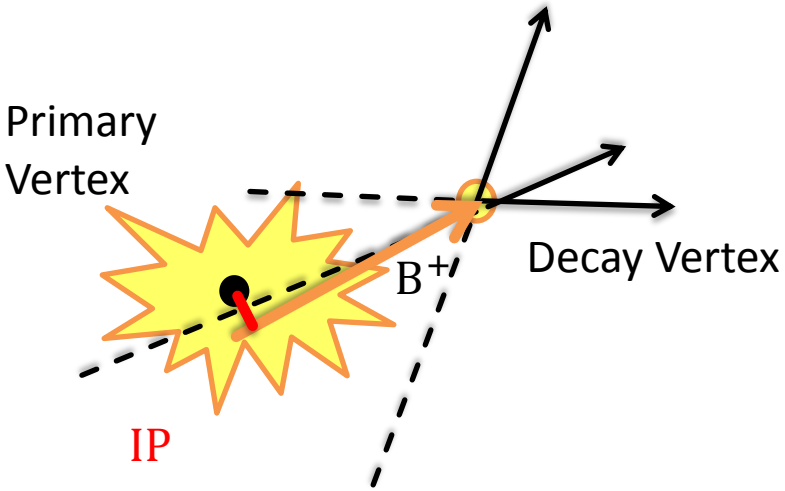
Tag and Probe

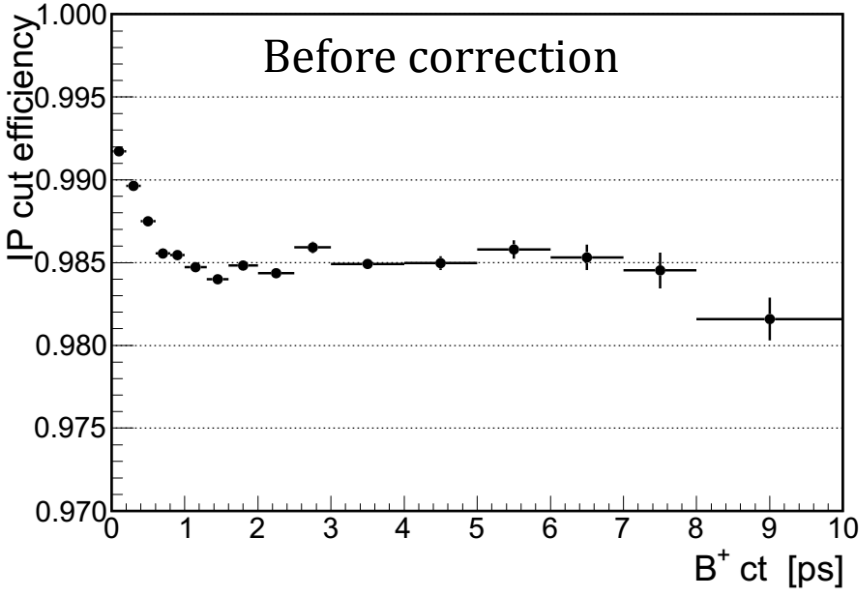


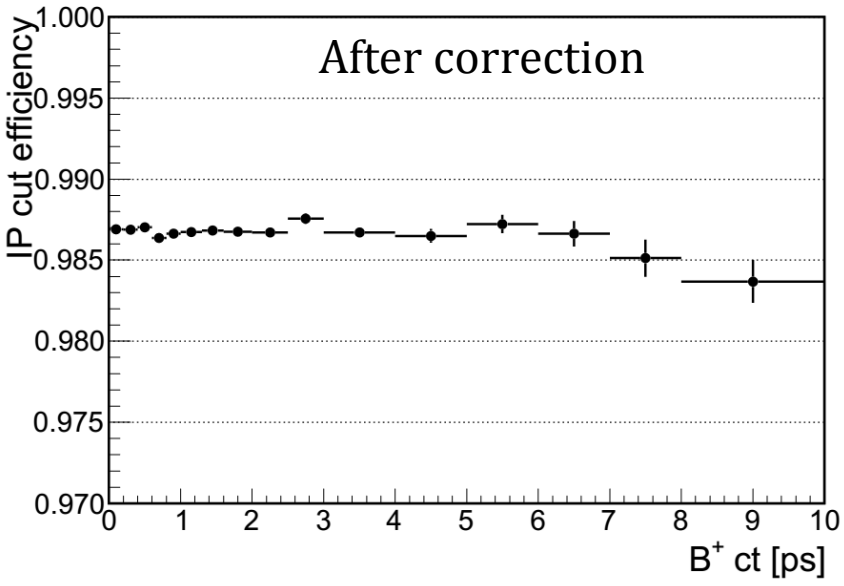


B mass without using VELO for K+ reconstruction

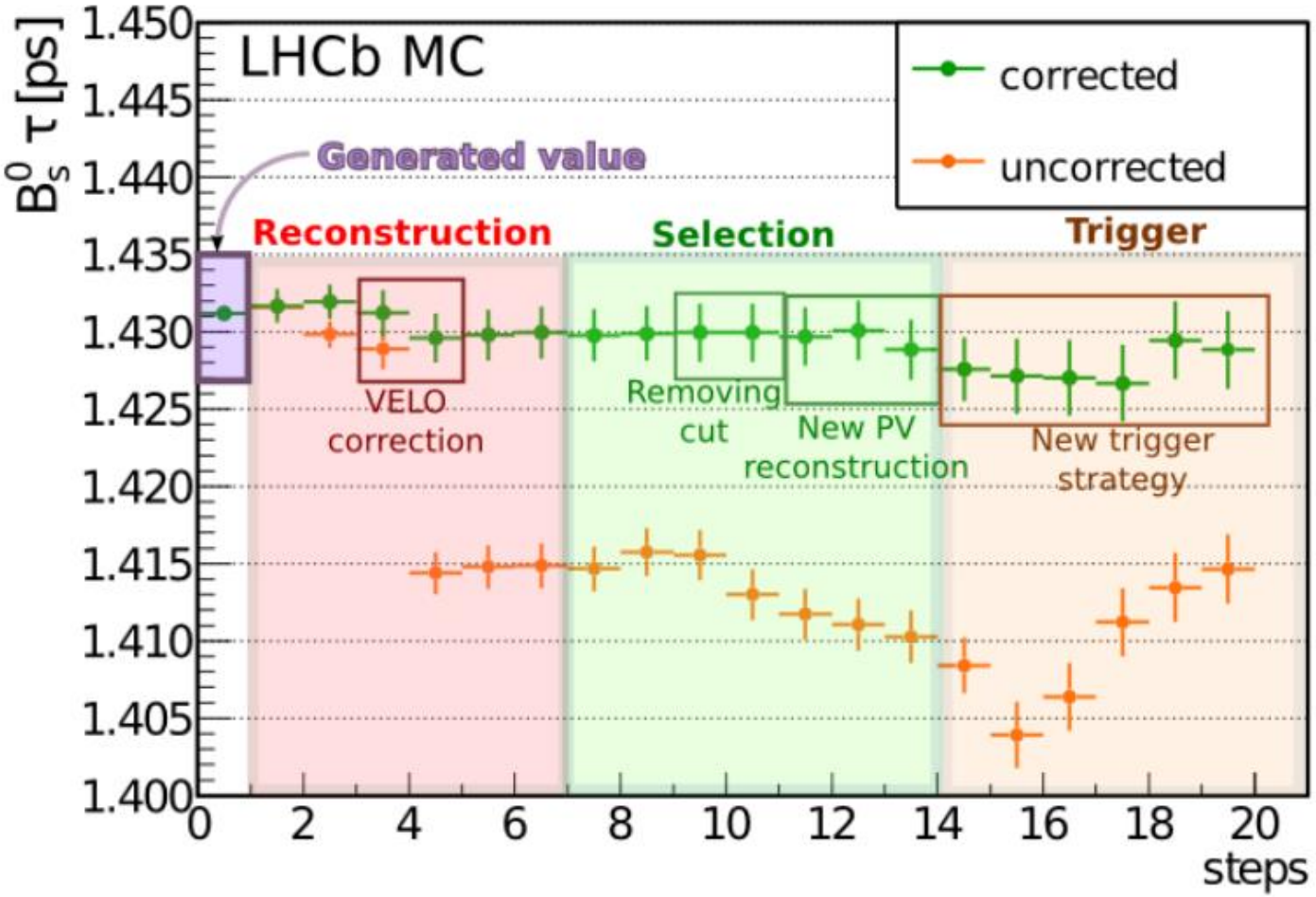
Correcting PV reconstruction

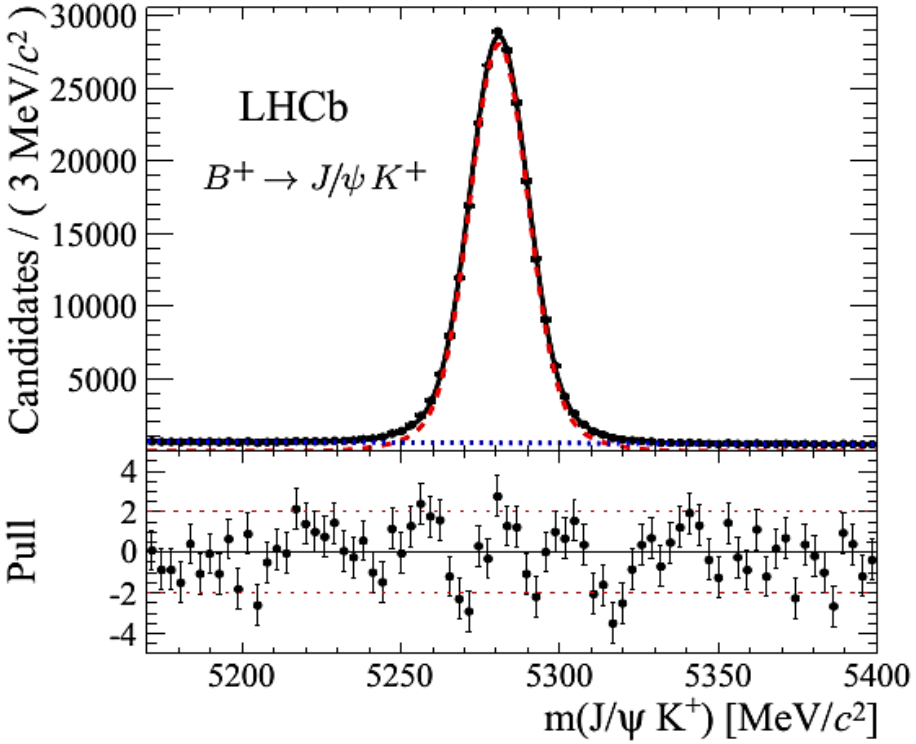


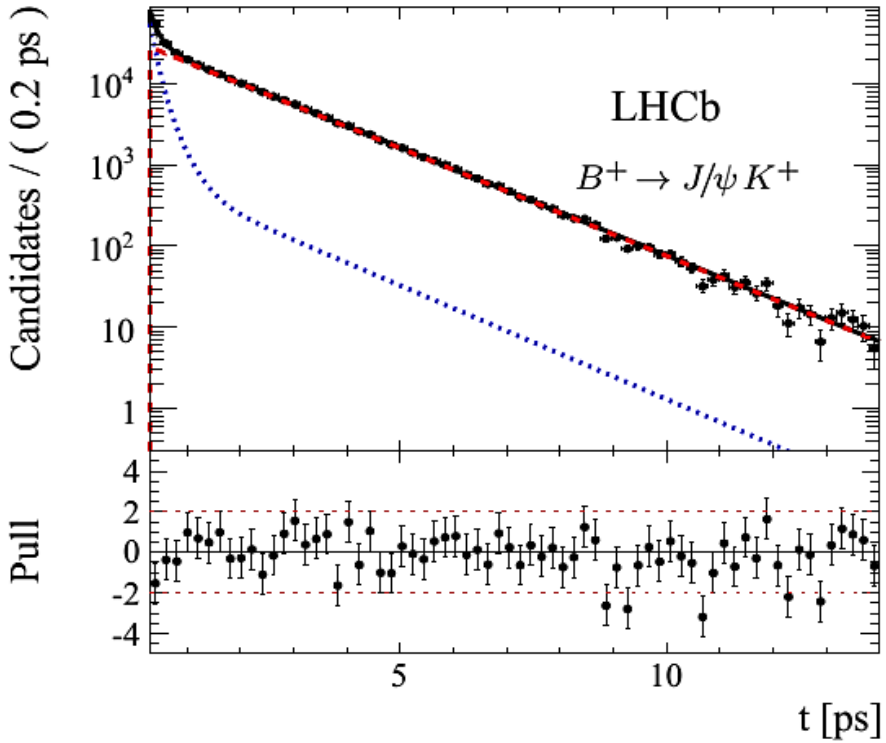


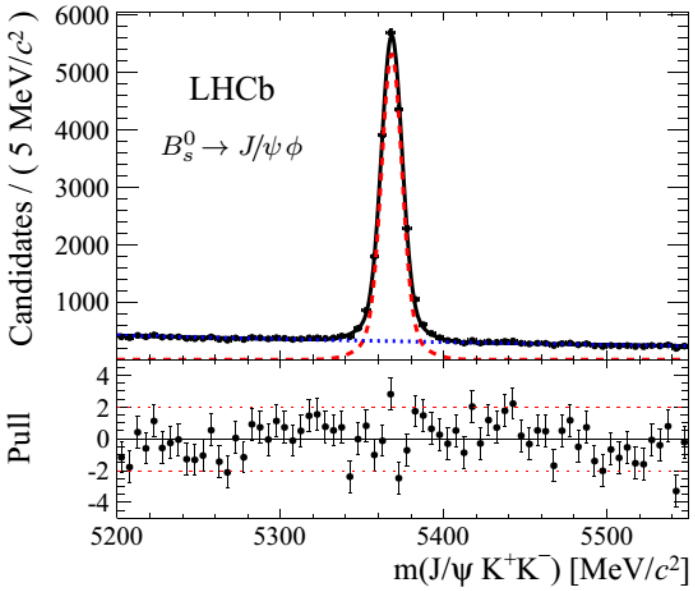


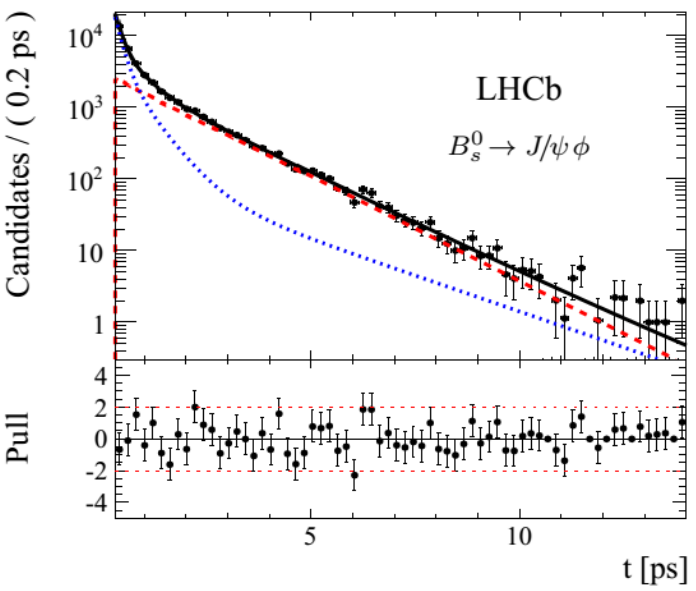
Corrected Lifetime acceptance

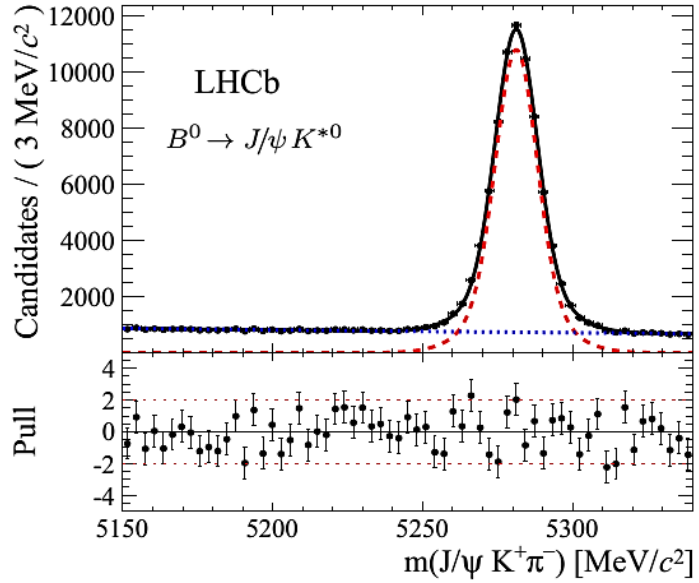


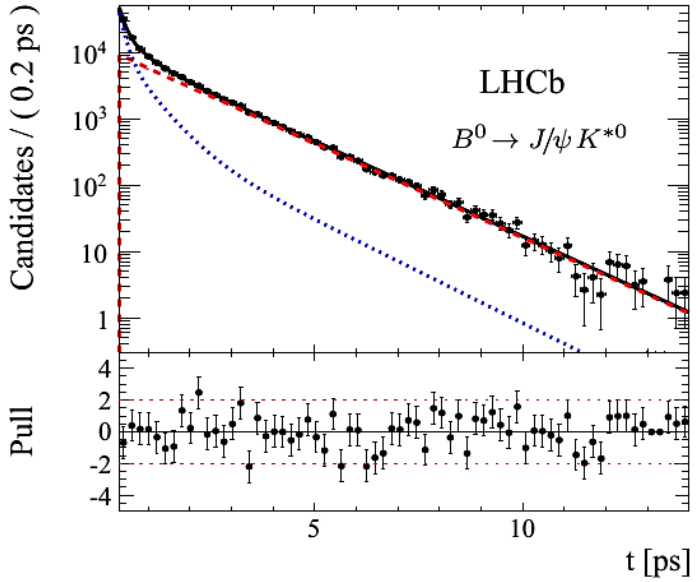

LHCb
$B^+ \to J/\psi K^+$
Candidates / (3 MeV/c^2)
Pull
m(J/ψ K$^+$) [MeV/c^2]

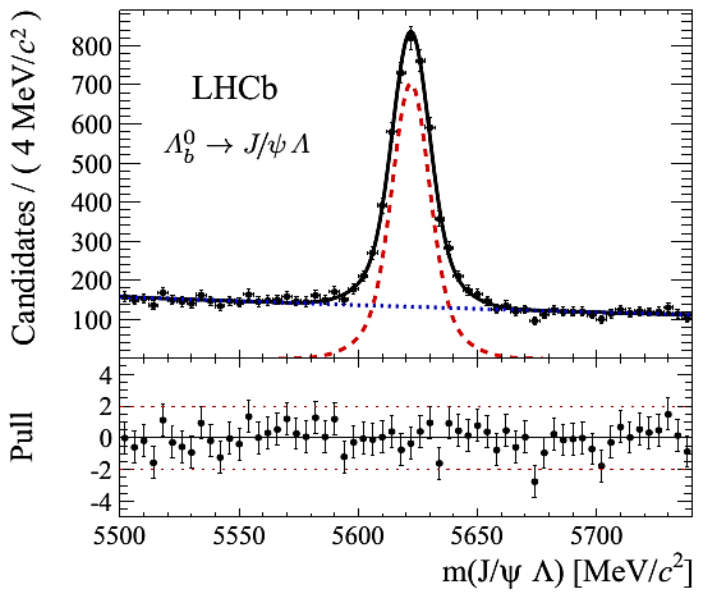

LHCb
$B^+ \to J/\psi K^+$
Candidates / (0.2 ps)
Pull
t [ps]

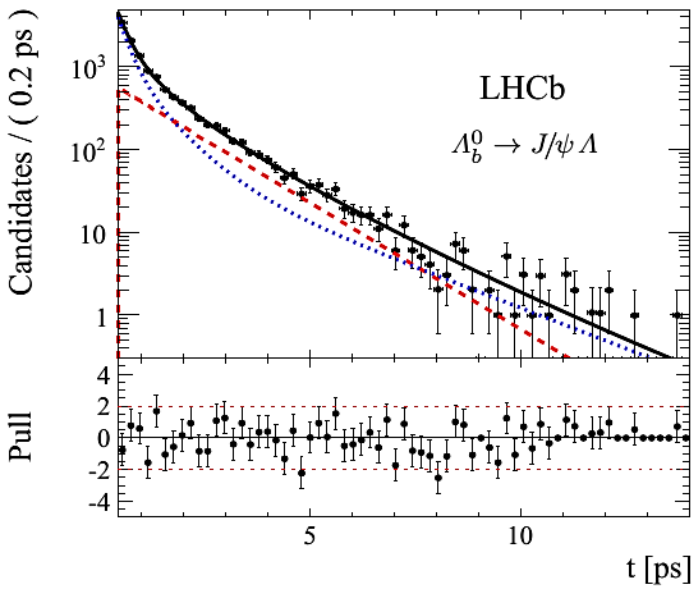

LHCb
$B_s^0 \to J/\psi\,\phi$
Candidates / (5 MeV/c^2)
Pull
m(J/ψ K^+K^-) [MeV/c^2]

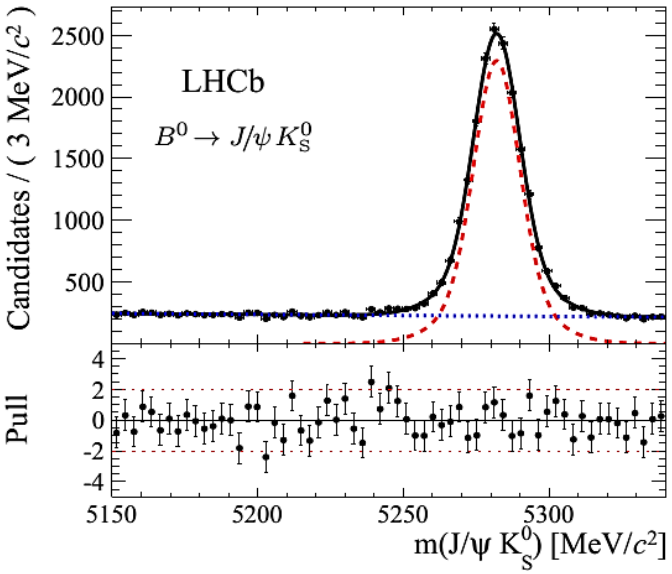

LHCb
$B_s^0 \to J/\psi\,\phi$
Candidates / (0.2 ps)
Pull
t [ps]

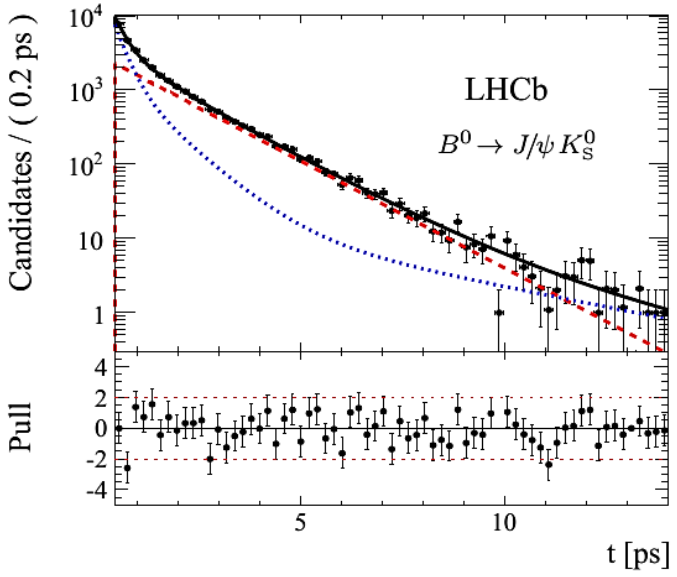

LHCb
$B^0 \to J/\psi\,K^{*0}$
Candidates / (3 MeV/c^2)
Pull
m(J/ψ $K^+\pi^-$) [MeV/c^2]


LHCb
$B^0 \to J/\psi\,K^{*0}$
Candidates / (0.2 ps)
Pull
t [ps]


LHCb
$\Lambda_b^0 \to J/\psi\,\Lambda$
Candidates / (4 MeV/c^2)
Pull
m(J/ψ Λ) [MeV/c^2]


LHCb
$\Lambda_b^0 \to J/\psi\,\Lambda$
Candidates / (0.2 ps)
Pull
t [ps]


LHCb
$B^0 \to J/\psi\,K^0_S$
Candidates / (3 MeV/c^2)
Pull
m(J/ψ K^0_S) [MeV/c^2]


LHCb
$B^0 \to J/\psi\,K^0_S$
Candidates / (0.2 ps)
Pull
t [ps]

Lifetime	LHCb 1 fb^{-1}	World average (2013)
τ_{B^+}	1.637 ± 0.005 ps	1.641 ± 0.008 ps
$\tau_{B^0 \to J/\psi K^*}$	1.524 ± 0.007 ps	1.519 ± 0.007 ps
$\tau_{B^0 \to J/\psi K_S}$	1.499 ± 0.014 ps	1.519 ± 0.007 ps
$\tau_{B_s^0 \to J/\psi \phi}$	1.480 ± 0.012 ps	1.429 ± 0.088 ps
$\tau_{\Lambda_b^0}$	1.415 ± 0.027 ps	1.429 ± 0.024 ps

	Ratio	LHCb 1 fb^{-1}	Theory
Test HQE	τ_{B^+} / τ_{B^0}	1.074 ± 0.005 ± 0.003	$1.04^{+0.05}_{-0.02}$
	$\tau_{\Lambda_b^0} / \tau_{B^0}$	0.929 ± 0.018 ± 0.004	0.935 ± 0.054
	$\tau_{B_s^0 \to J/\psi \phi} / \tau_{B^0}$	0.971 ± 0.009 ± 0.004	-
Test CPT	τ_{B^+} / τ_{B^-}	1.002 ± 0.004 ± 0.002	1
	$\tau_{B^0} / \tau_{\bar{B}^0}$	1.000 ± 0.008 ± 0.009	1
	$\tau_{\Lambda_b^0} / \tau_{\bar{\Lambda}_b^0}$	0.940 ± 0.035 ± 0.006	1

Systematic Uncertainty

Uncertainty	Comment	Value				
		$B_s^0 \to J/\psi\,\phi$	$B^0 \to J/\psi K^*$	$B^+ \to J/\psi K^+$	$B_s^0 \to J/\psi K_S$	$\Lambda_b^0 \to J/\psi\,\Lambda$
VELO Reconstruction	Precision of efficiency measurement	2.3 fs	2.3 fs	2.0 fs	0.9 fs	0.5 fs
MC Statistic	Simulation sample size	2.4 fs	2.3 fs	1.7 fs	2.9 fs	3.7 fs
Trigger efficiency	Control sample size	2.5 fs	1.2 fs	1.1 fs	2.0 fs	2.0 fs
Mass-time correlation	Fit mass in different decay time bins	0.7 fs	1.8 fs	1.4 fs	2.1 fs	3.0 fs
Background modeling	Different fit models	0.4 fs	0.2 fs	0.1 fs	2.2 fs	2.1 fs
Mass modeling	Different fit models	0.5 fs	0.2 fs	0.1 fs	0.4 fs	0.2 fs
Peaking background	Misreconstructed decays	0.4 fs	-	-	0.3 fs	1.1 fs
Effective lifetime bias	Angular acceptance	1.6 fs	-	-	-	-
Prod. asymmetry	Proton collider	-	-	-	1.1 fs	-
LHCb length scale	VELO alignment	0.3 fs	0.3 fs	0.4 fs	0.3 fs	0.3 fs
Total systematic		**4.6 fs**	**3.9 fs**	**3.2 fs**	**4.9 fs**	**5.7 fs**
Statistical		**11.4 fs**	**6.1 fs**	**3.5 fs**	**12.8 fs**	**26.5 fs**

Summary

Showed precision measurement of lifetimes

Model independent test of QCD

Next lecture: NEW PHYSICS measurement
(with observed deviation!)