Flavour oscillations and CP violation in neutral mesons

(a.k.a. a biased introduction to heavy flavour physics)

Mirco Dorigo (EPFL)
mirco.dorigo@cern.ch

Part 1.b

Roma — May 31st & Jun 1st, 2016

So far (so good?)

- ★ No primordial antimatter observed, universe matter dominated
- ★ Need breaking of CP symmetry to explain this
- ★ C and P are violated by weak interactions (CP looks still healthy…)
- ★ Matter-antimatter oscillations: K^0 can turn into anti-K^0; the physical states are not the flavour eigenstates.
- ★ Using flavour-specific decays we can observe the flavour oscillations

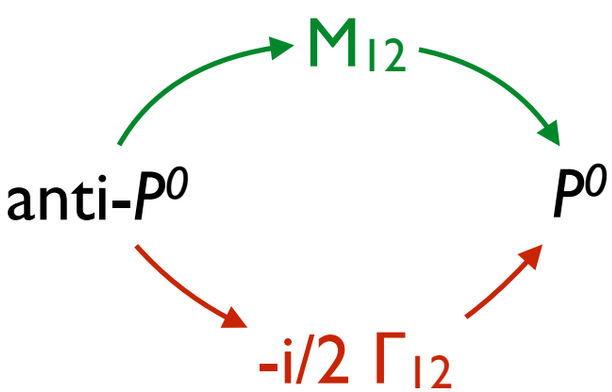
Mixing: who can?

	u	c	t
$\overline{u}$	$\times$	D^0	$\diamond$
$\overline{c}$	$\overline{D^0}$	$\times$	$\diamond$
$\overline{t}$	$\diamond$	$\diamond$	$\times$

	d	s	b
$\overline{d}$	$\times$	K^0	B^0
$\overline{s}$	$\overline{K^0}$	$\times$	B_s
$\overline{b}$	$\overline{B^0}$	$\overline{B_s}$	$\times$

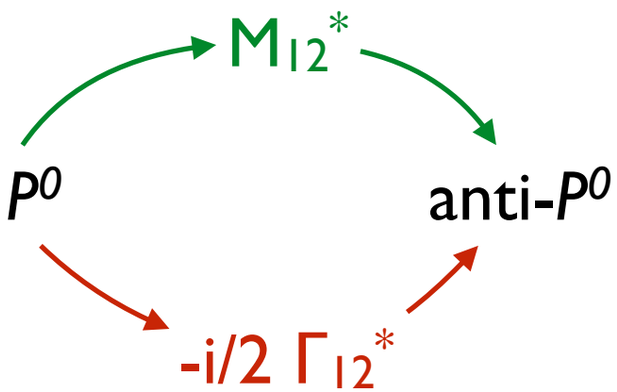
- Need to be neutral and have distinct anti-particle (x)
- Needs to have a non-zero lifetime: top is so heavy, it decays long before it can even form a meson ($\diamond$)
- That leaves four distinct cases...

What do M_{12} and Γ_{12} represent?

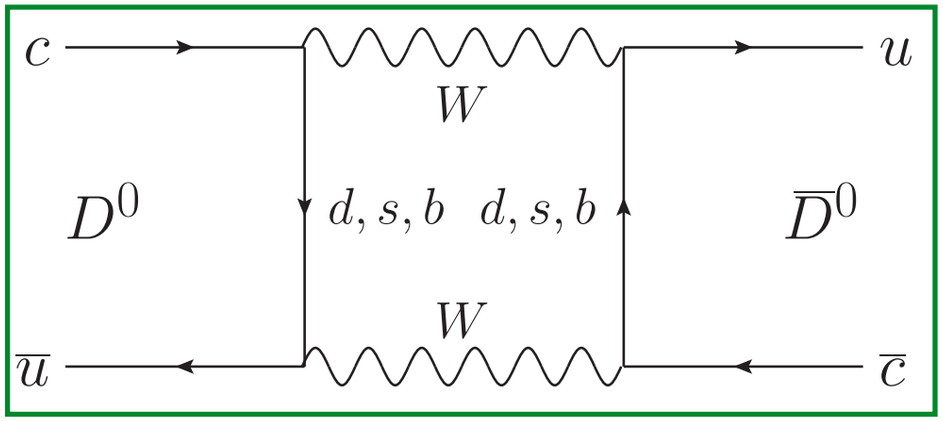


M_{12} describes oscillations via *virtual* states

Γ_{12} describes oscillations via *real* states, e.g. $\pi\pi$

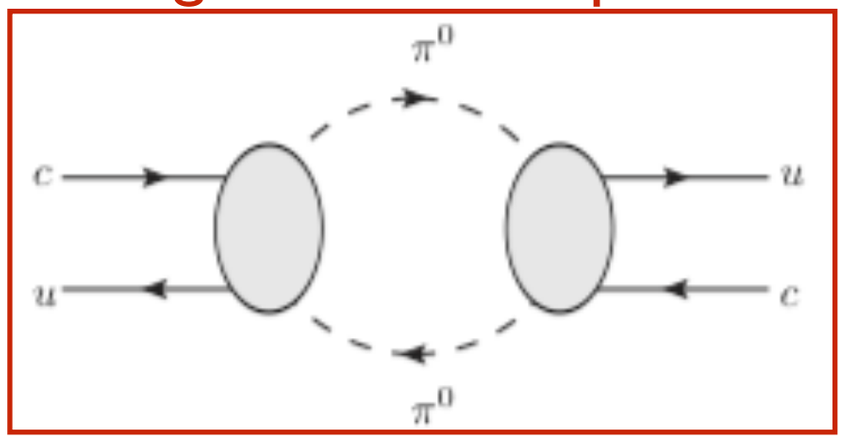


"short" distance amplitude



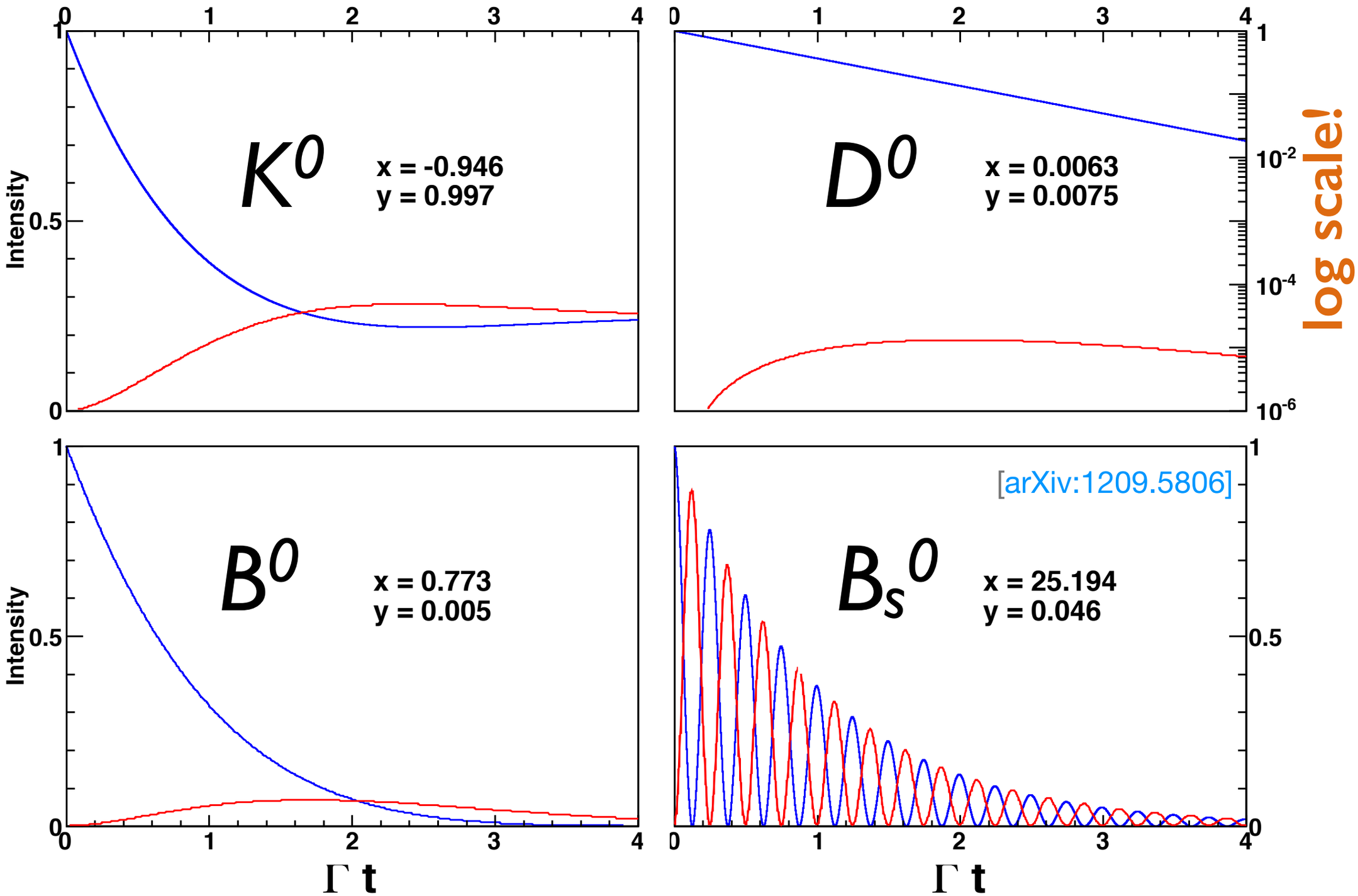
Will see discuss in the 2nd part this "box" diagram

"long" distance amplitude



Non-perturbative QCD: much more difficult to calculate! More relevant for K and D mesons.

Mixing phenomenology



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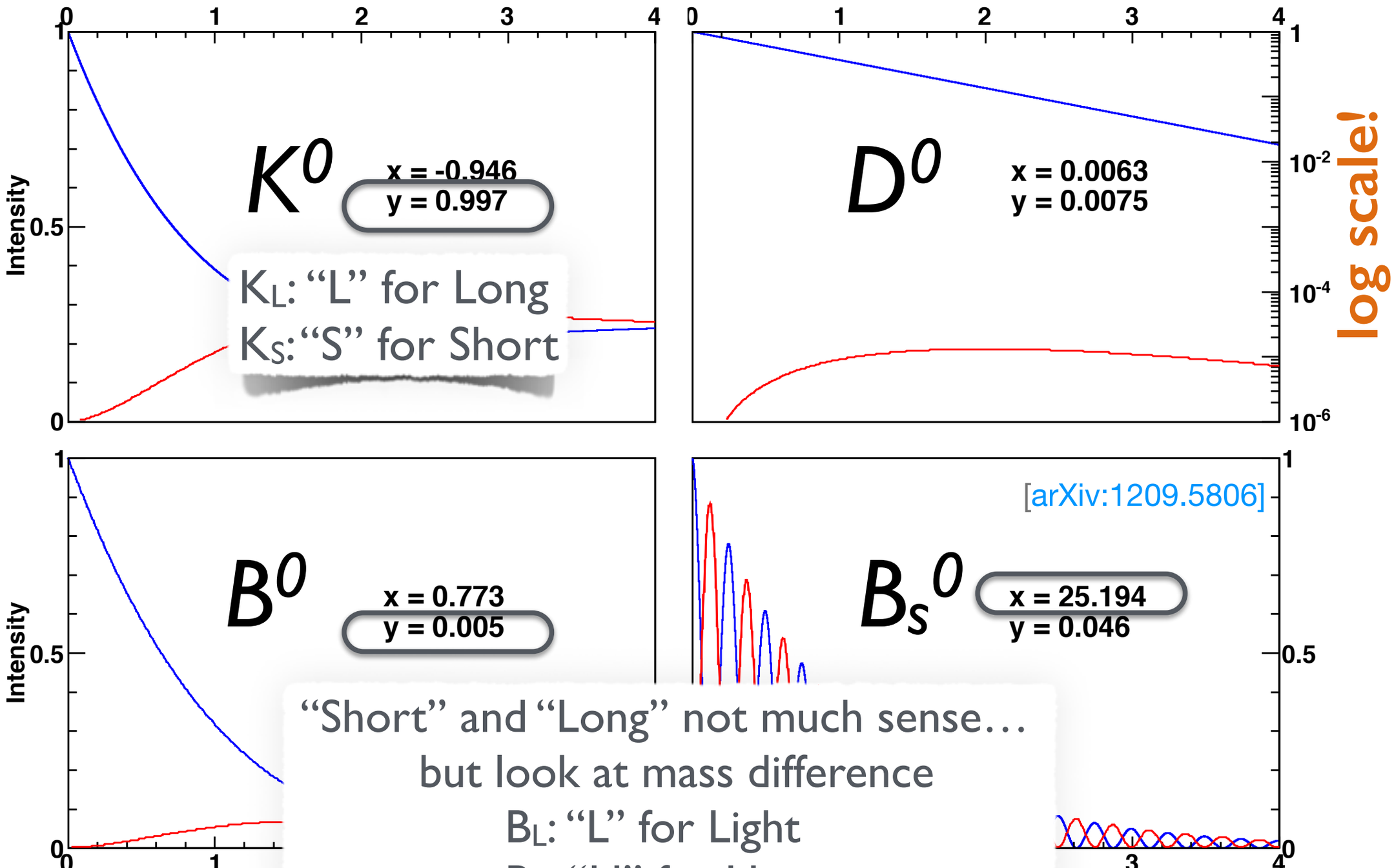

K_L: "L" for Long
K_S: "S" for Short

"Short" and "Long" not much sense…
but look at mass difference
B_L: "L" for Light
B_H: "H" for Heavy

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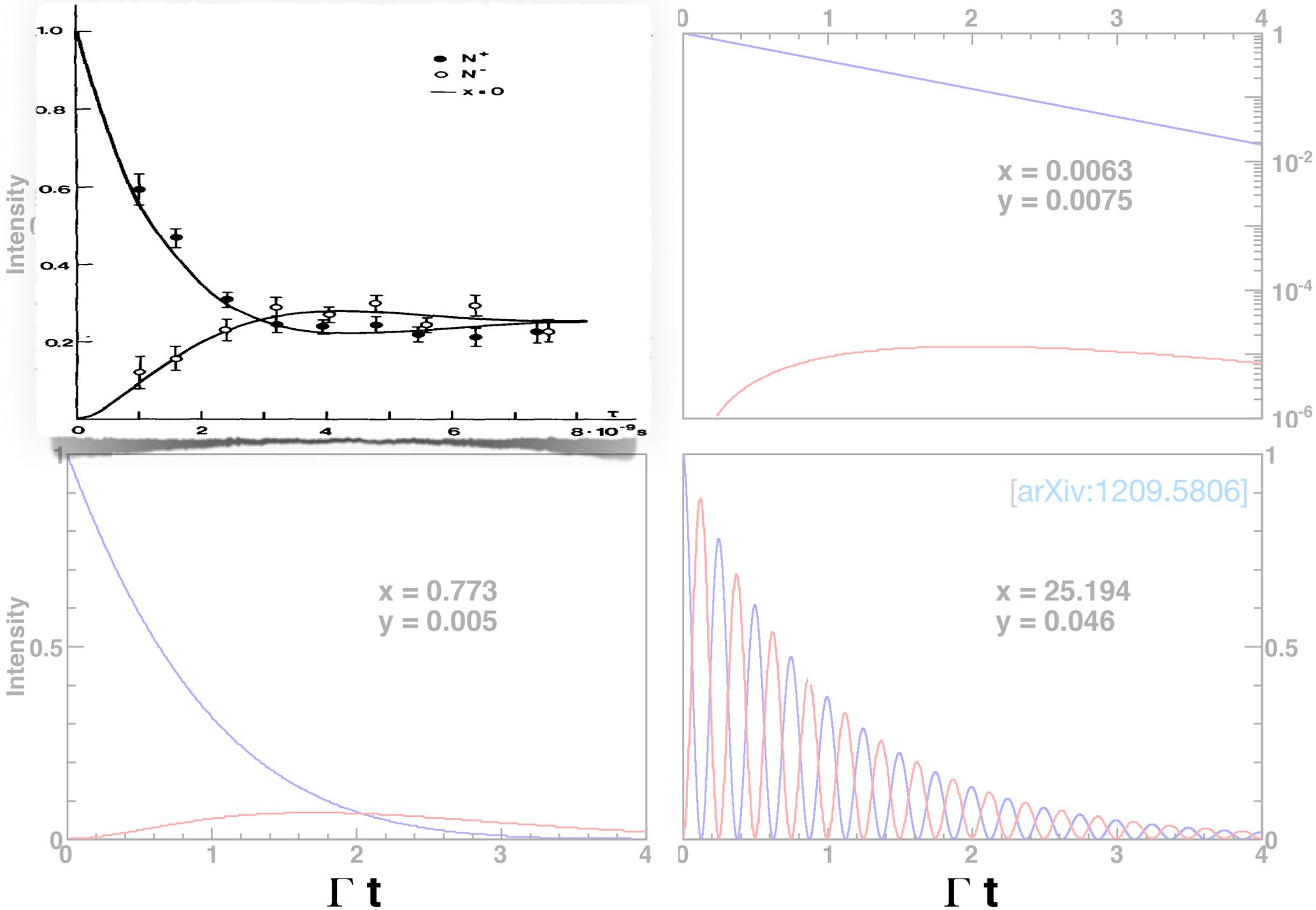

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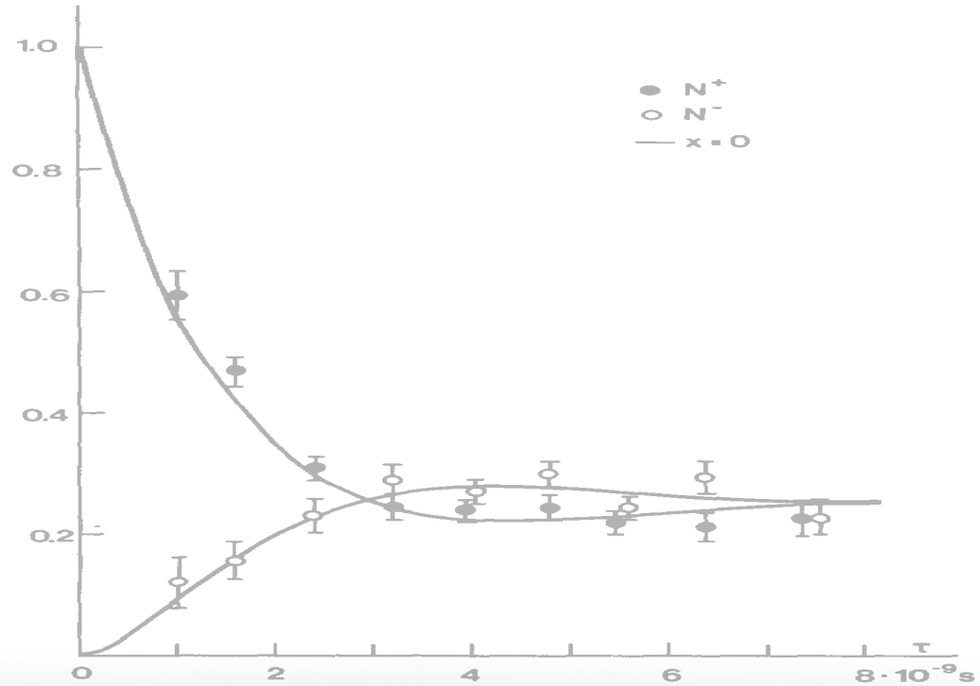
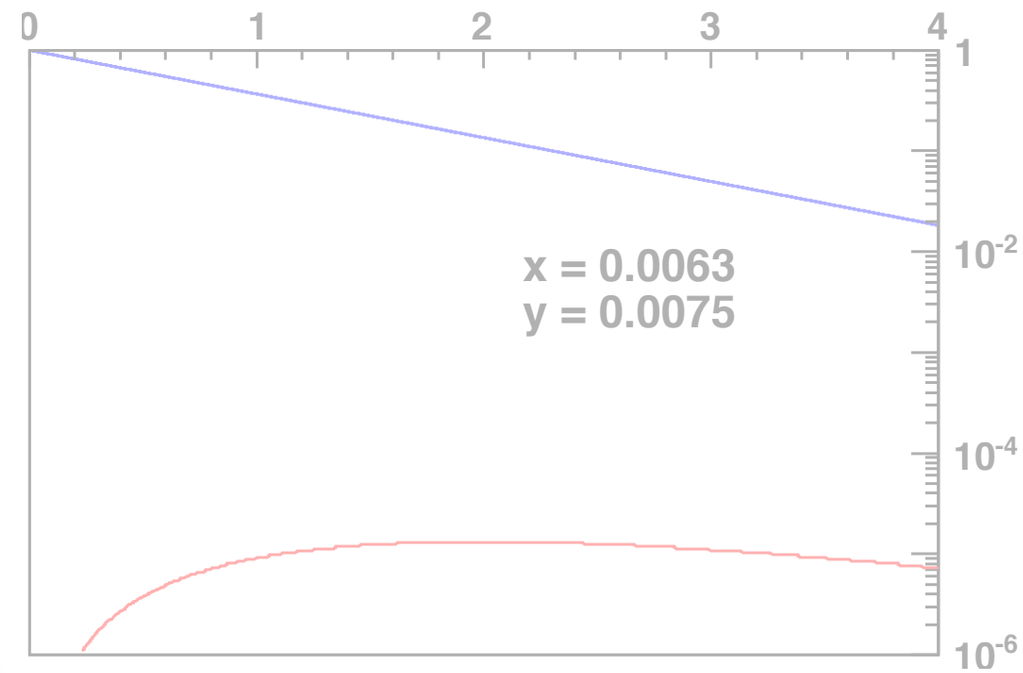




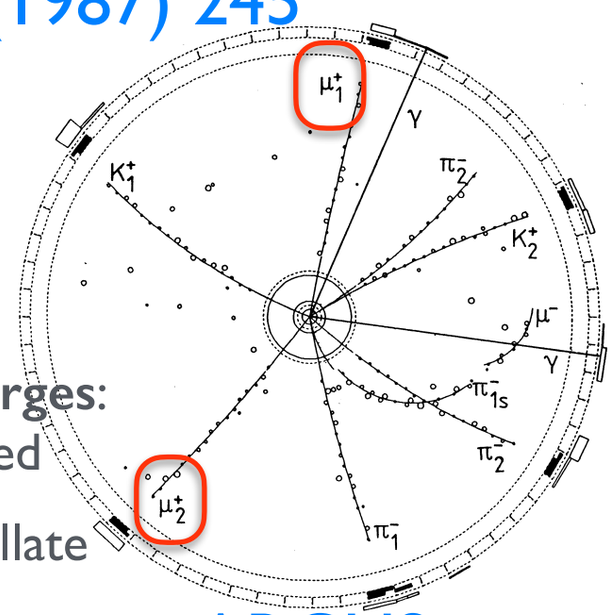
Phys. Lett. B 192 (1987) 245

$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^0 \text{anti-}B^0$

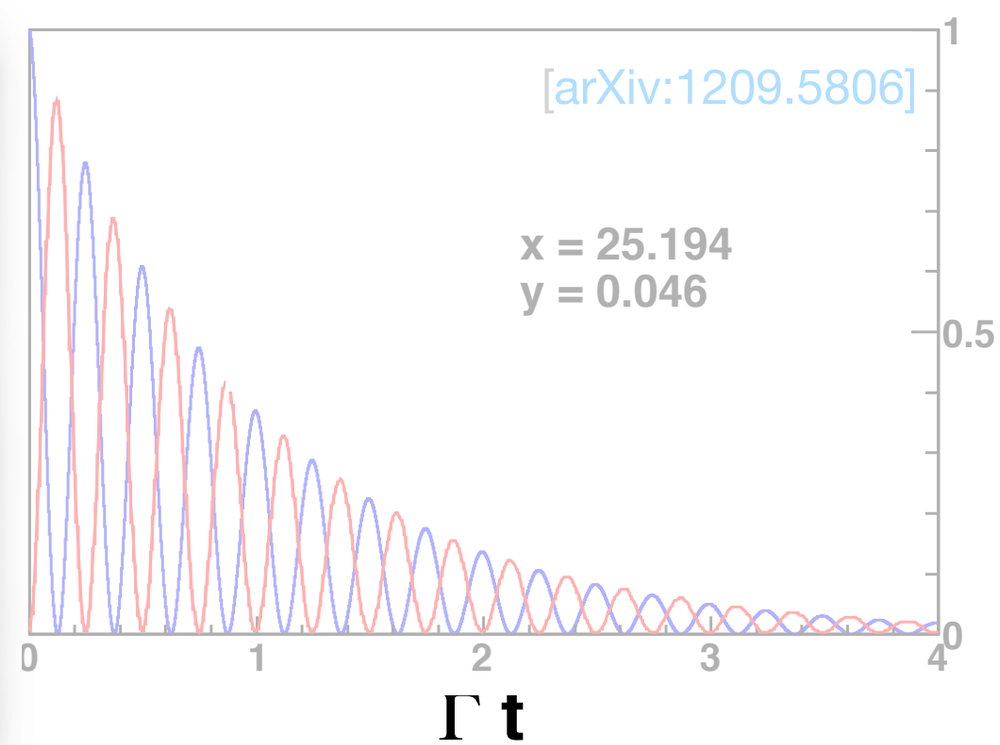
Look at semi-muonic decays (flavour-specific)

Search for events with **two muon of same charges:** one of the B has oscillated

About 17% of the B oscillate before they decay



ARGUS



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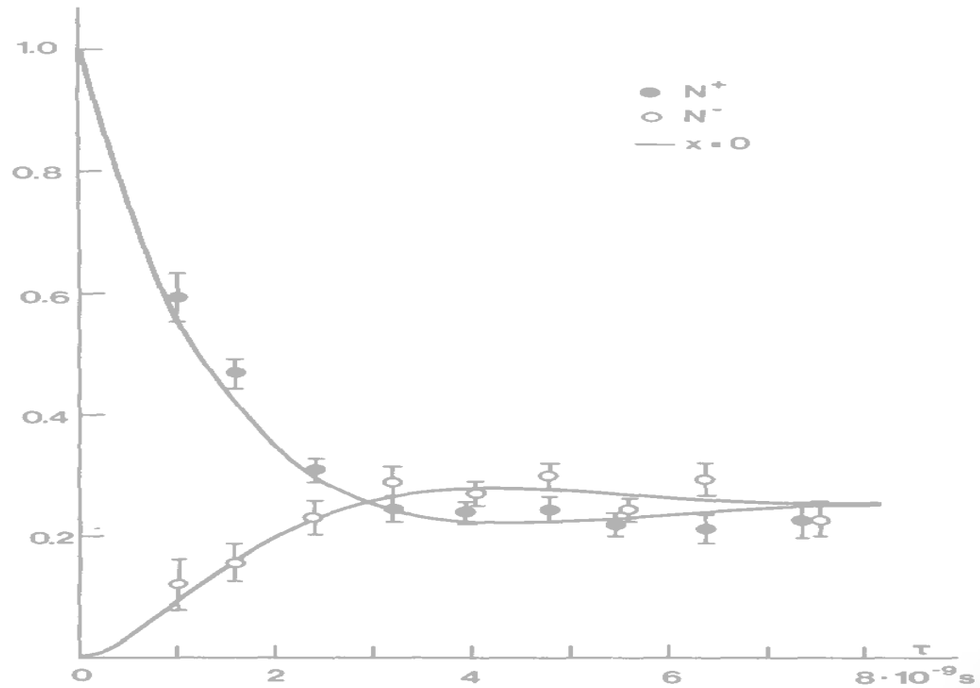

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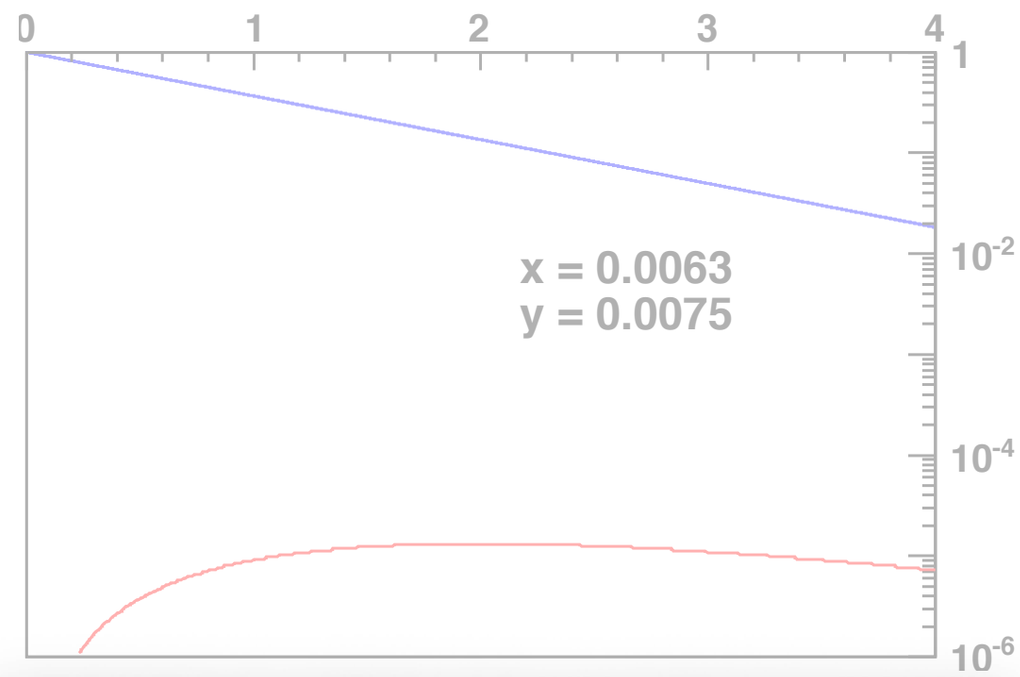

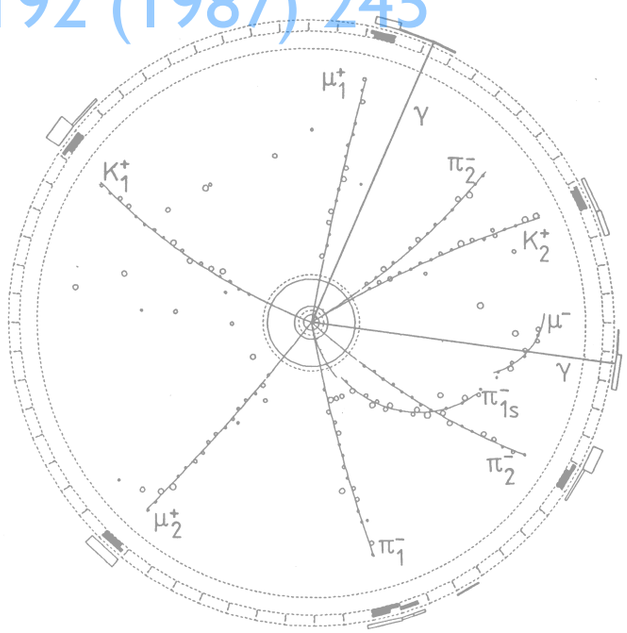

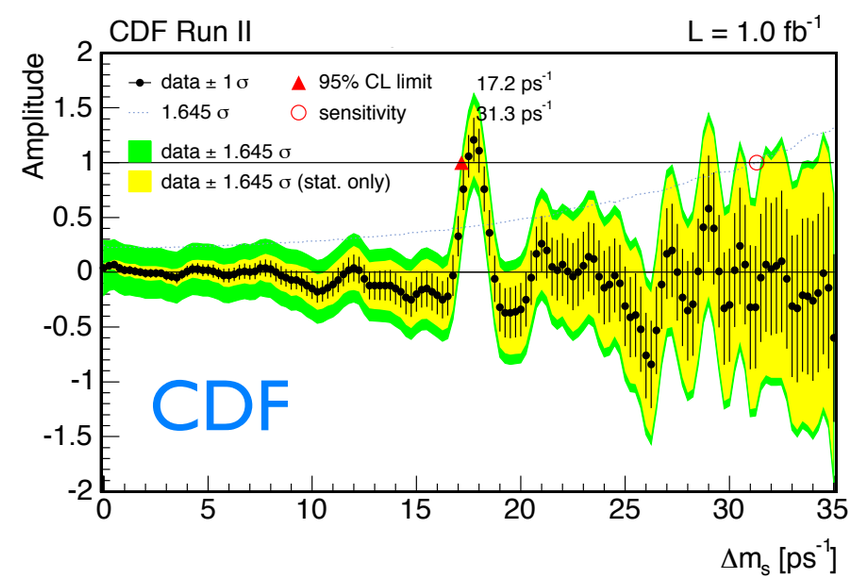

Phys. Rev. Lett. 97 (2006) 242003

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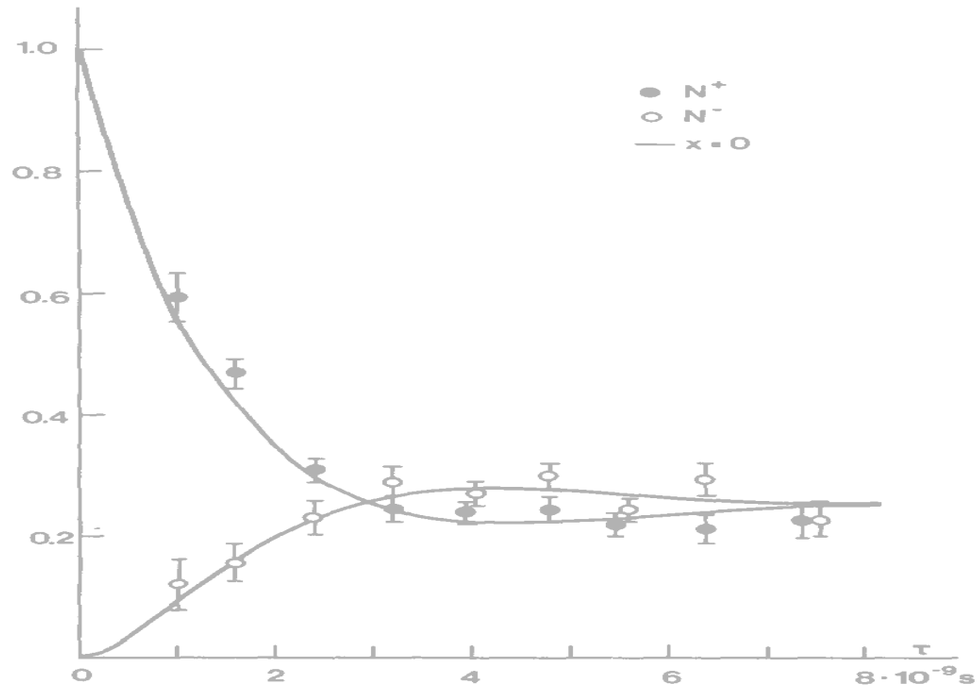

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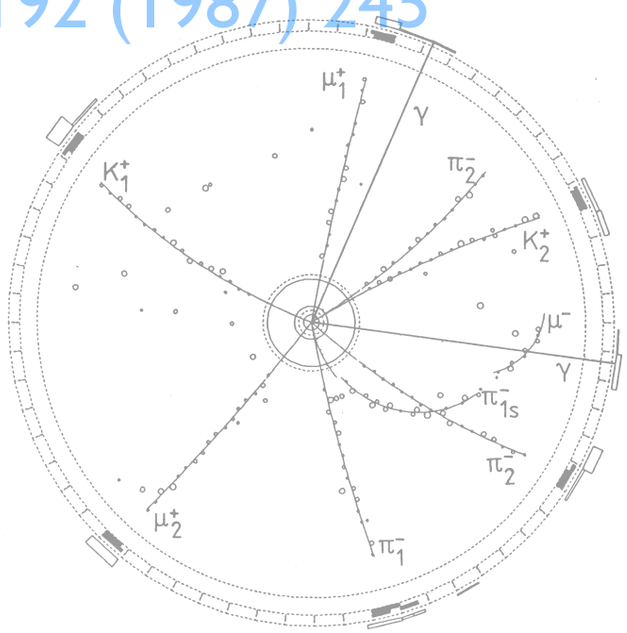

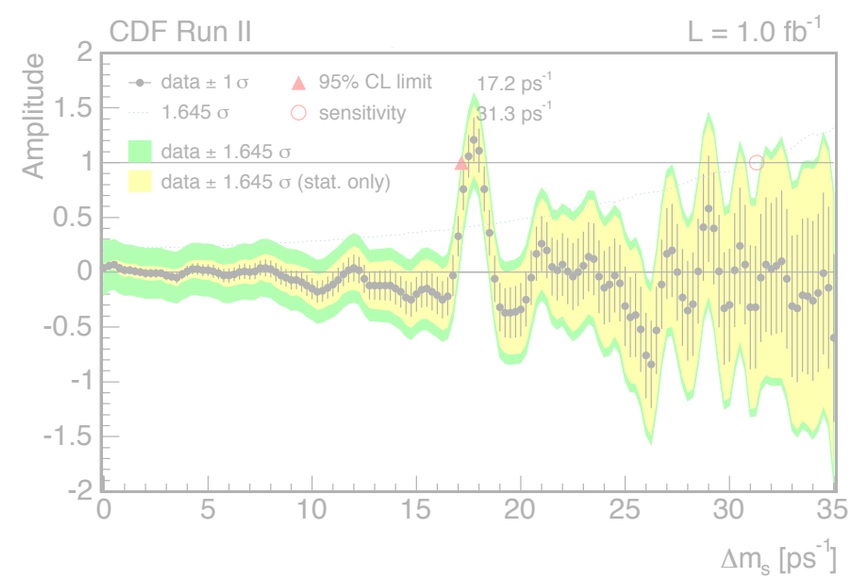

Phys. Rev. Lett.

Charm mixing

Flavour at production for D^0 determined by (soft) pion from D^* (strong) decays

$$D^{*+} \rightarrow \mathbf{D^0}\, \pi^+ \qquad\qquad D^{*-} \rightarrow \mathbf{\bar{D}^0}\, \pi^-$$

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This is the dominant decay for a D^0.
We call it **Right Sign (RS)**

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$$\bar{D}^0 \rightarrow K^+ \pi^-$$

This is the CP conjugate decay

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A **Wrong Sign (WG)** is observed when the D^0 has oscillated before it decays

A WS decay can happen also for the D^0, but it's very rare (why?)

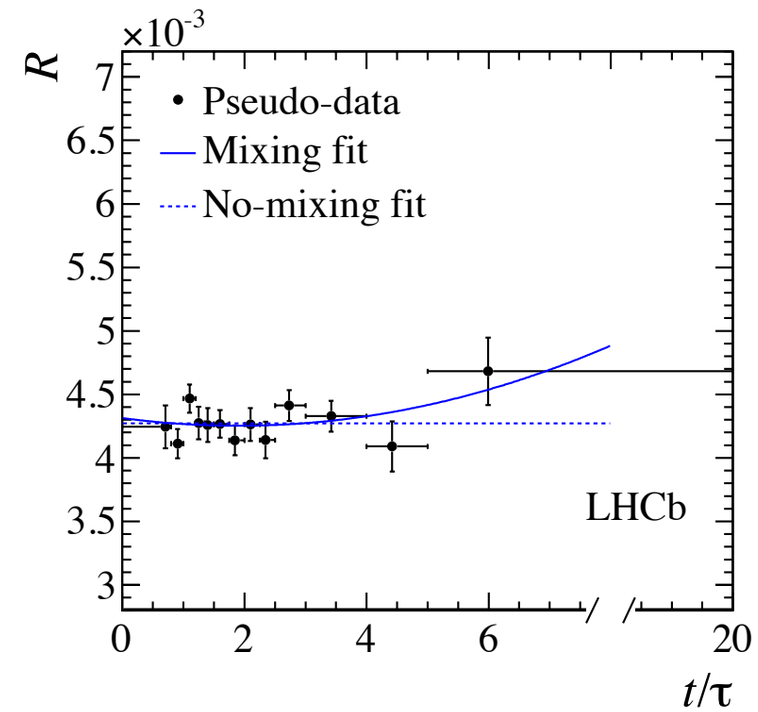
The idea

Count WS and RS decays in bins of decay time of the D^0.
The ratio WG/RS is:

- independent from time

$$R(t) = \frac{N_{WS}(t)}{N_{RS}(t)} = R_D$$

if there is **NO MIXING**
(it's the ratio of the rate of rare and dominant decays)

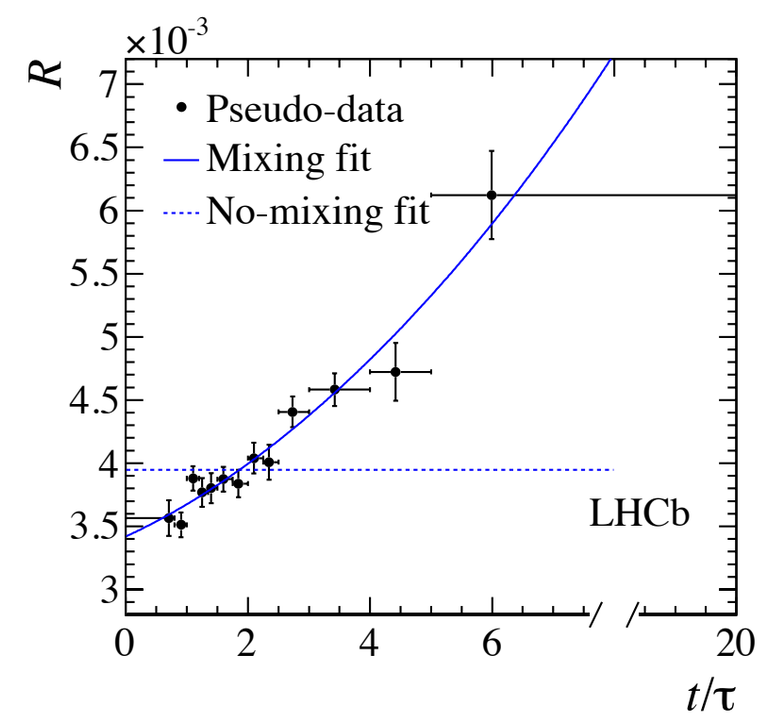


- dependent on time

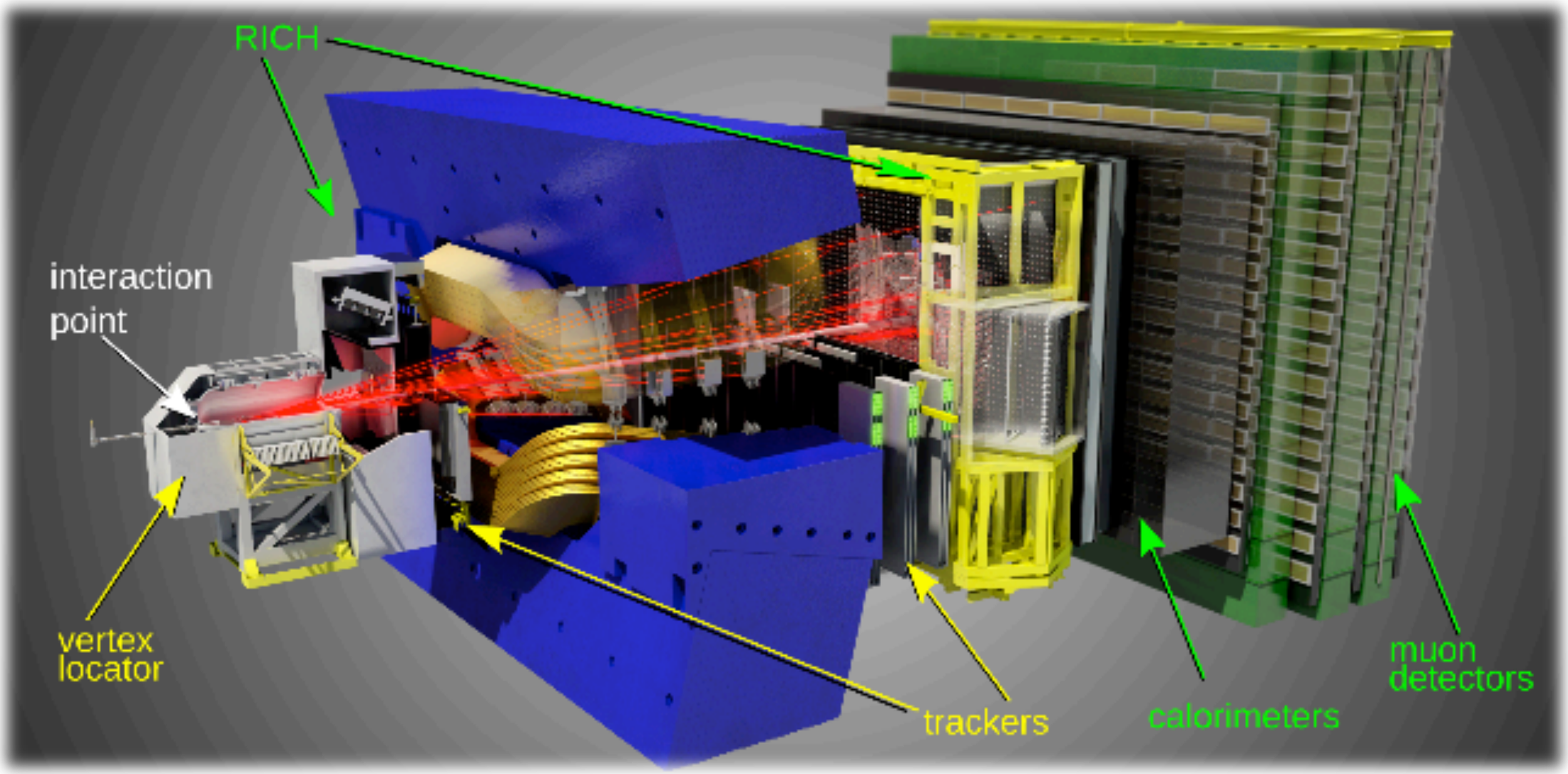
$$R(t) = \frac{N_{WS}(t)}{N_{RS}(t)} = R_D + \sqrt{R_D}y't + \frac{x'^2 + y'^2}{4}t^2$$

if there is **MIXING** (eq. valid for |x|, |y| << 1) with

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

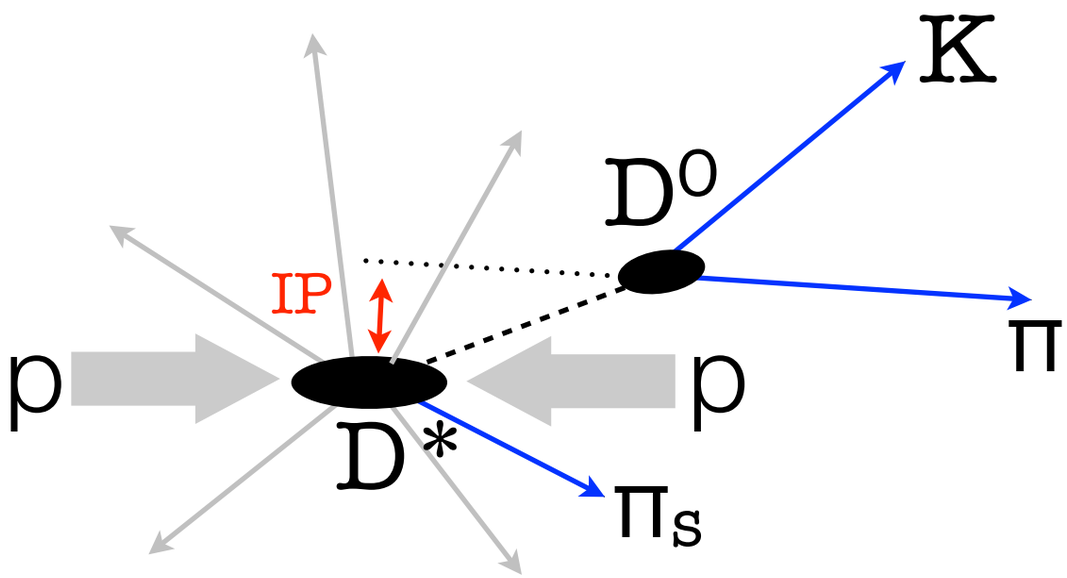


LHCb detector



LHCb detector performance paper

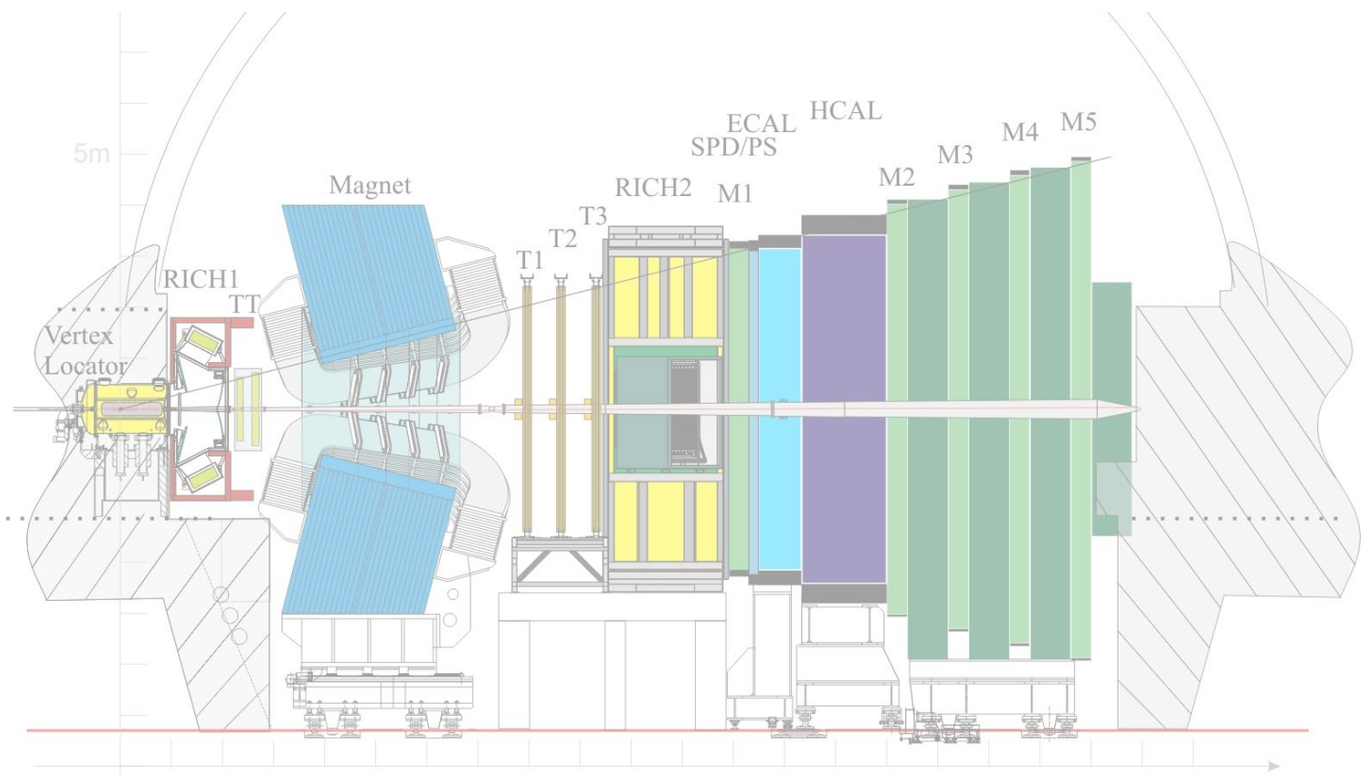
Hadronic charm decays at LHCb



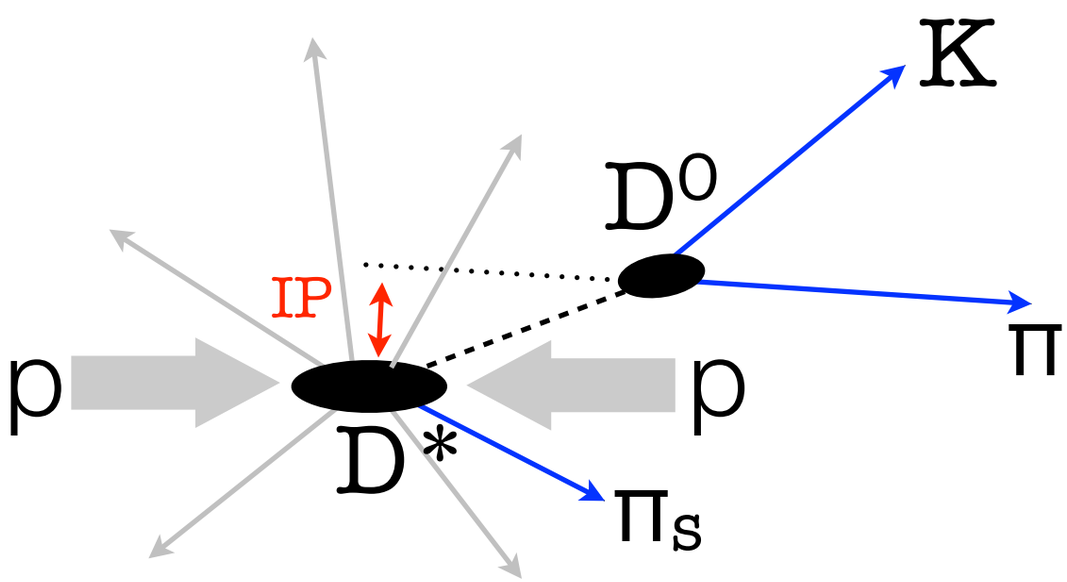
The D^* is produced in the pp interaction and decays promptly

The D^0 has lifetime ~0.4 ps, at LHCb it flights about 5 mm before decays.

It's impact parameters is (on average) different from 0.



VELO



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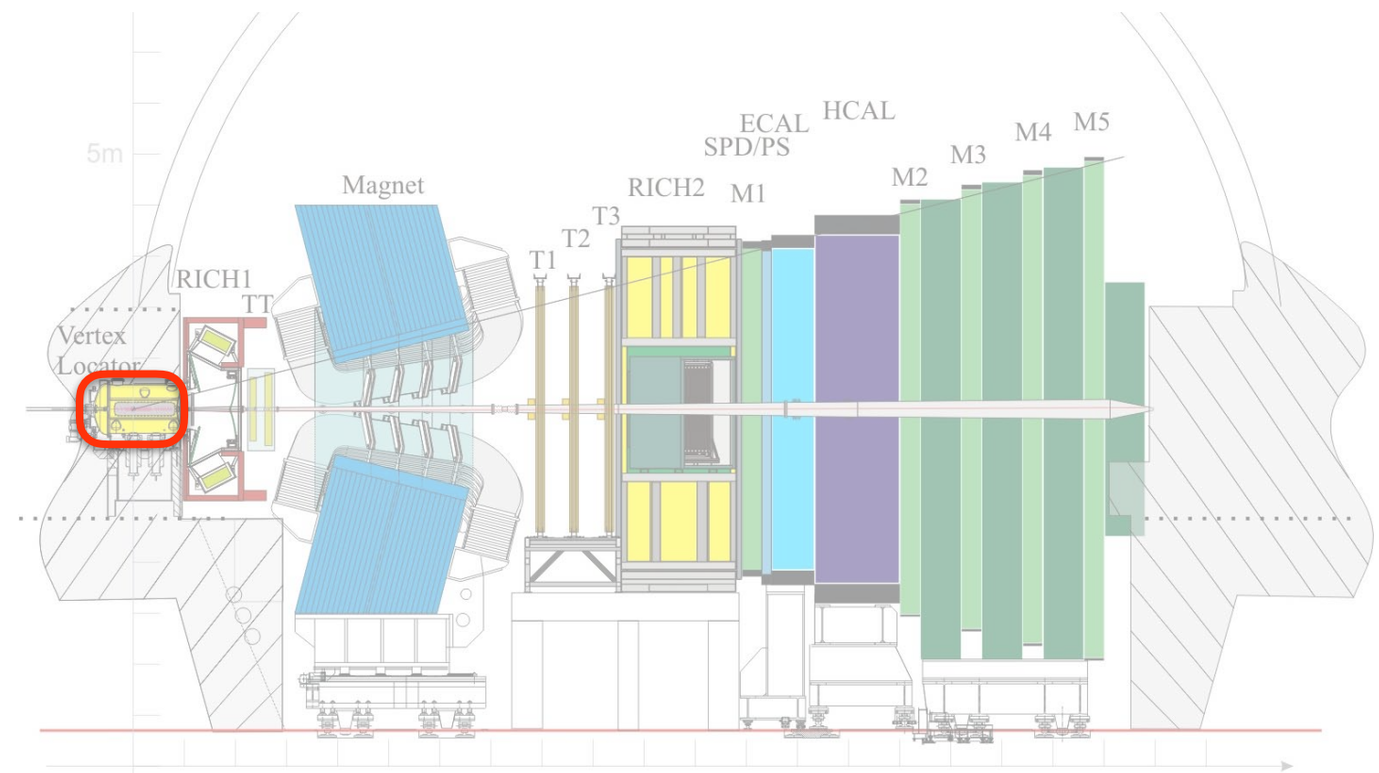
Silicon Vertex Locator
20 μm IP resolution,
corresponds to ~0.1τ decay-time resolution for a 2-body charm decay



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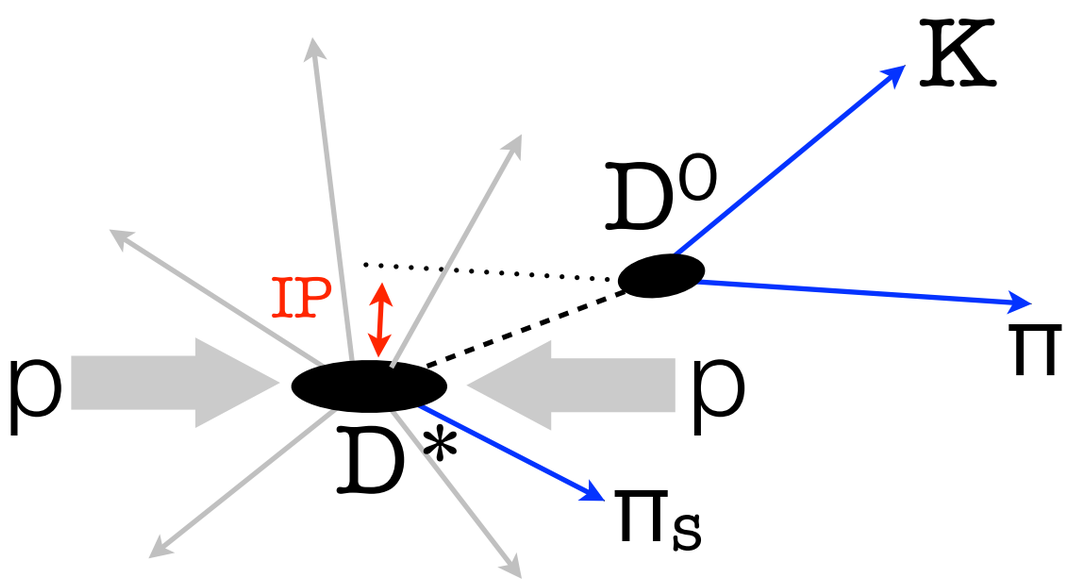

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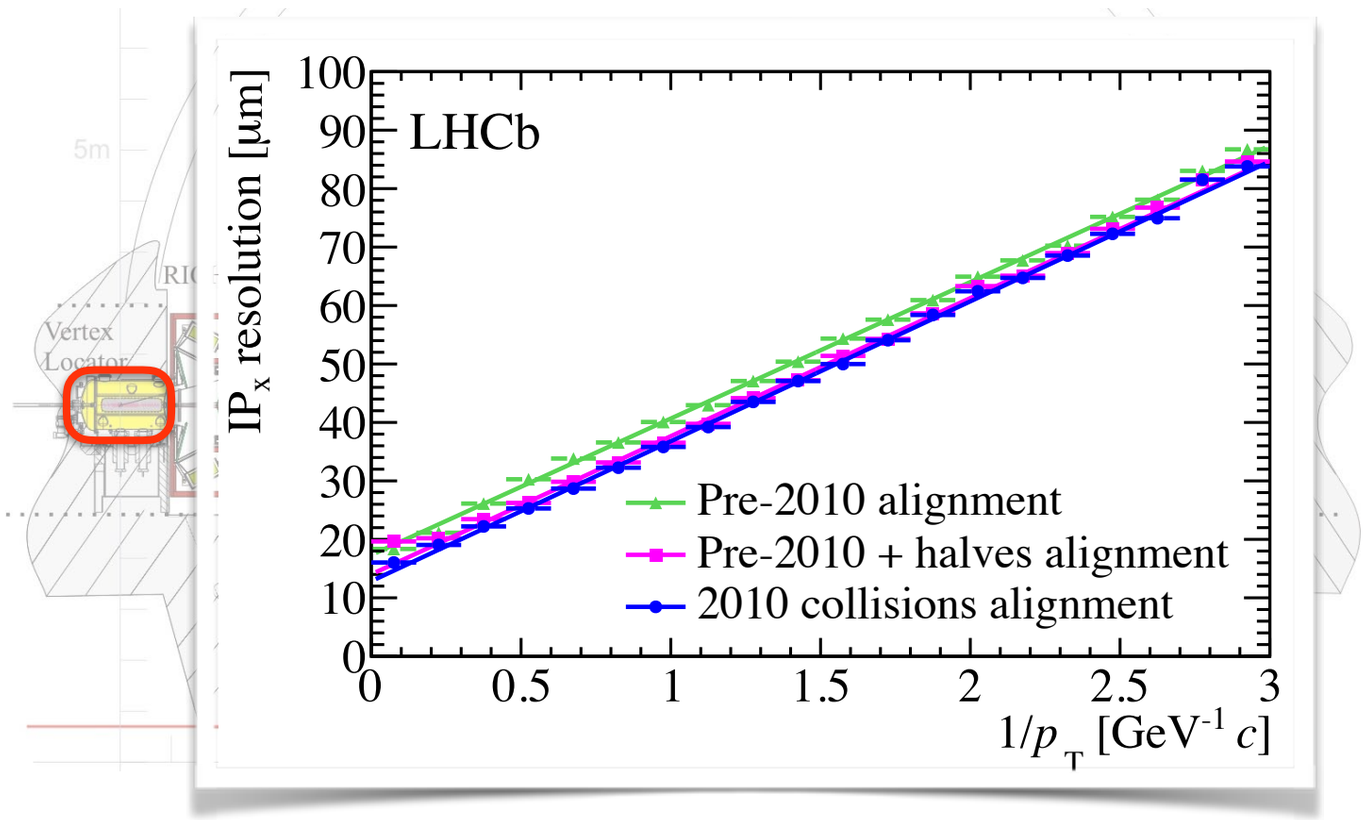
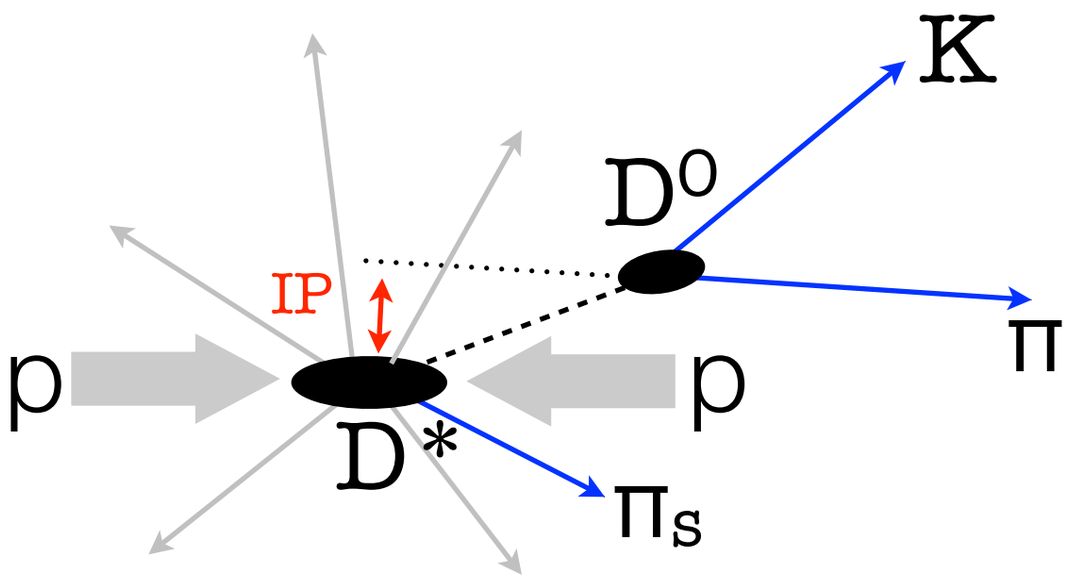
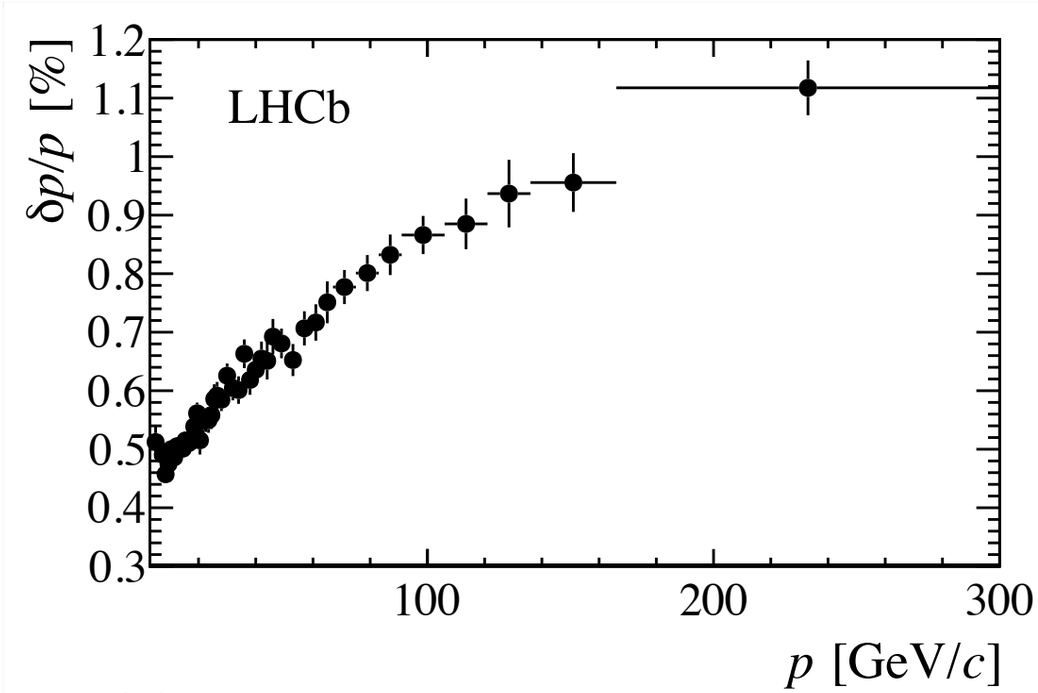


Tracking





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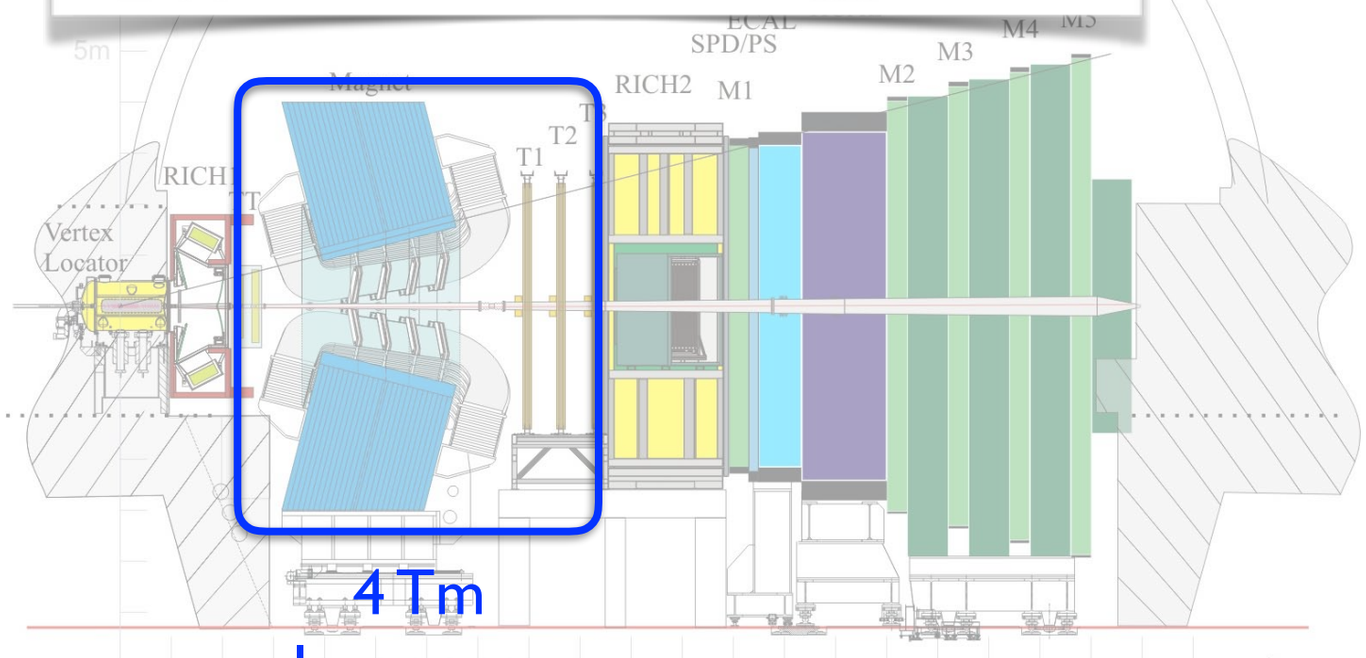
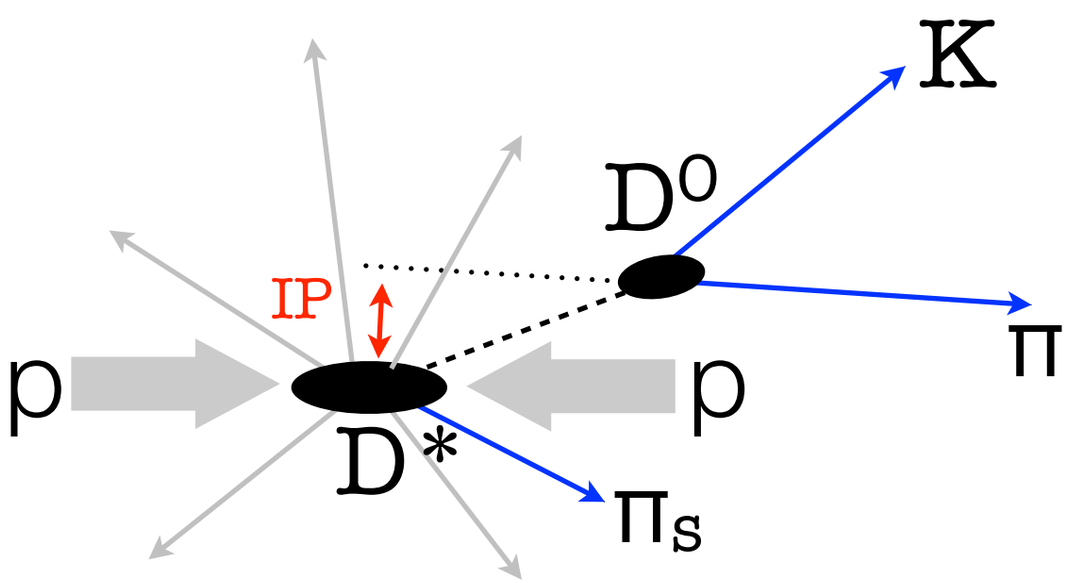
Excellent tracking:
$\Delta p/p$ = 0.5-0.8% at 5-100 GeV/c,

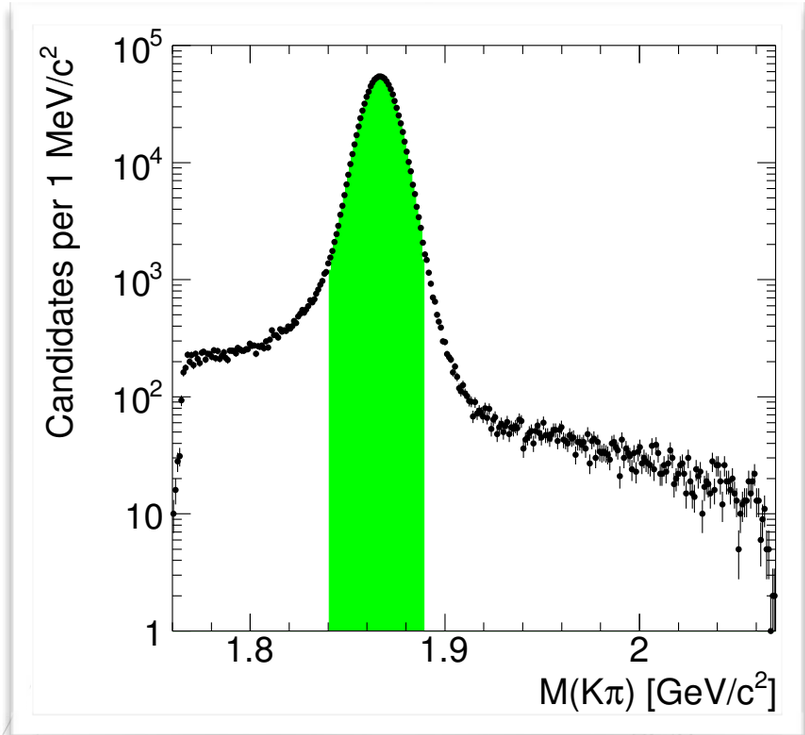
corresponds to ~8 MeV/c^2 mass
resolution for a 2-body charm decay



4 Tm
lever-arm

Tracking





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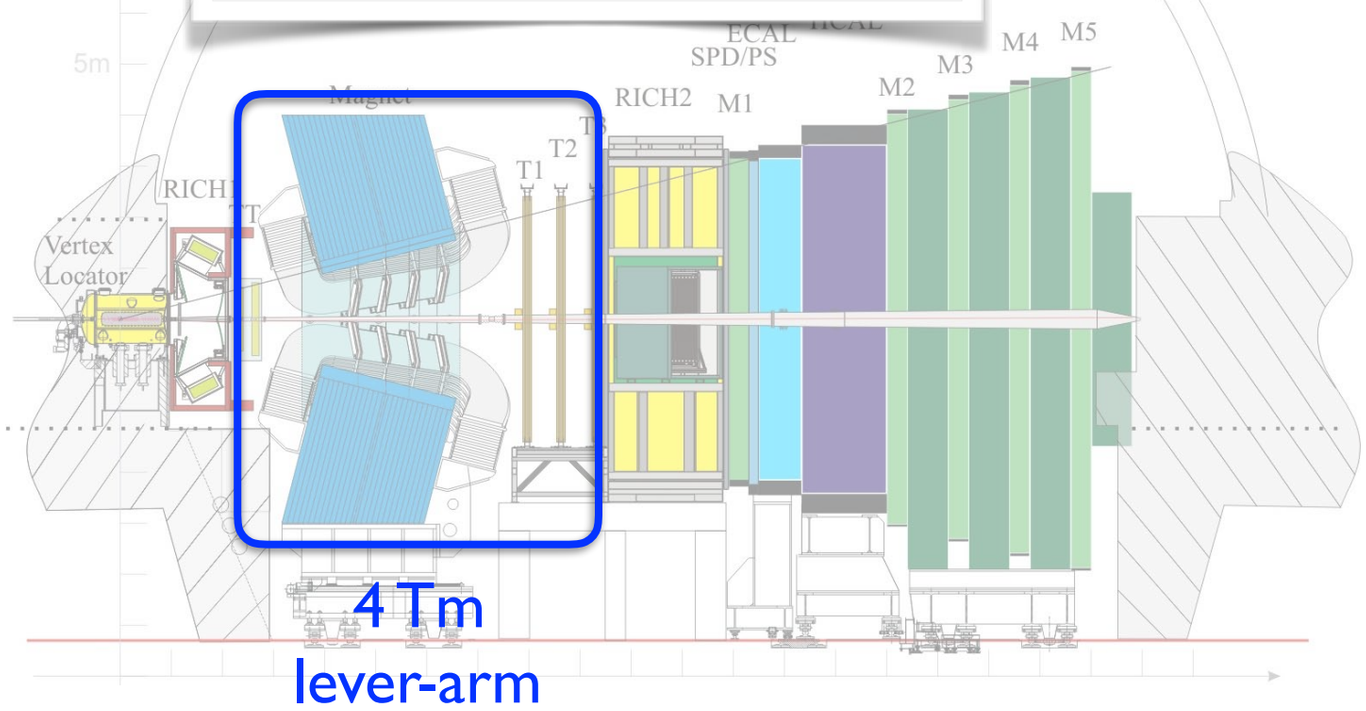

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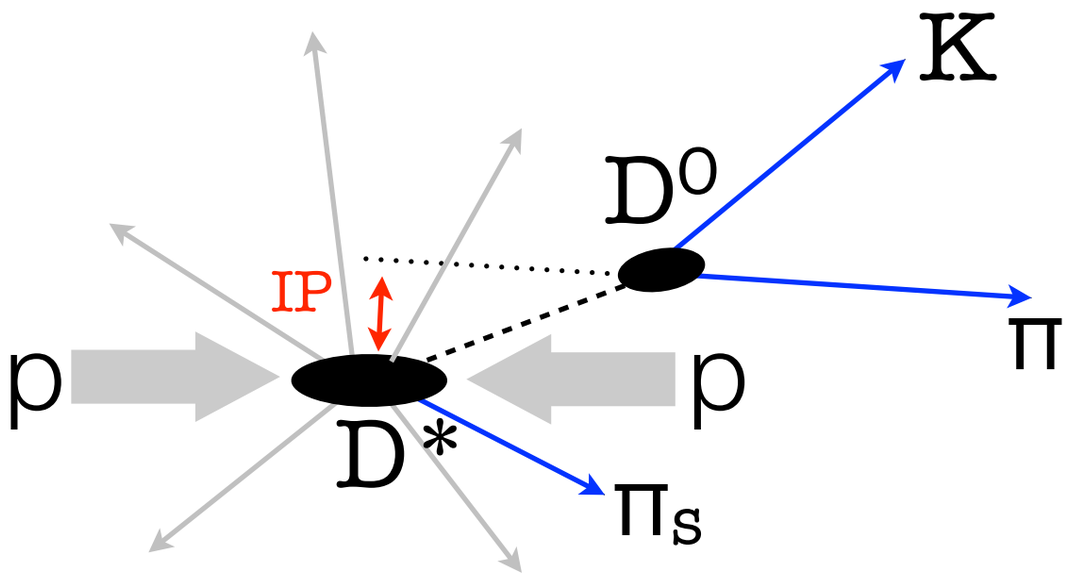
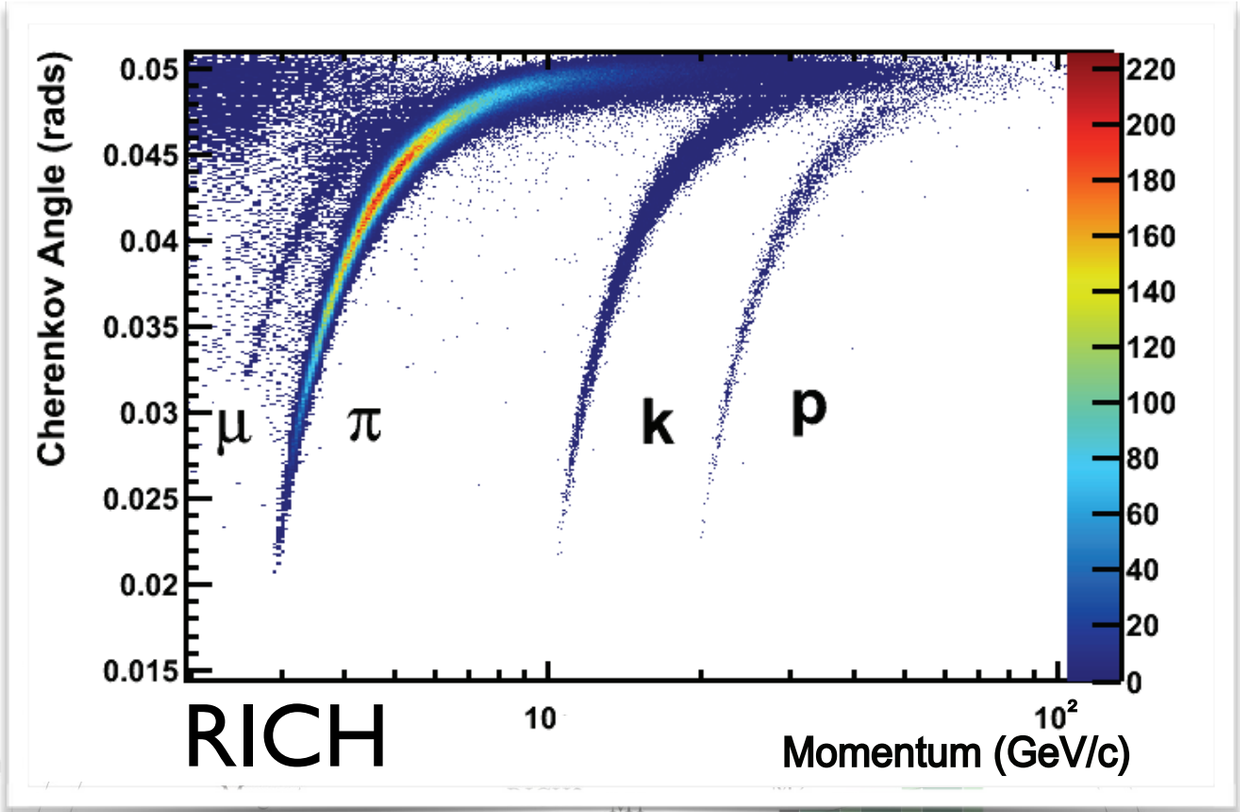
PID





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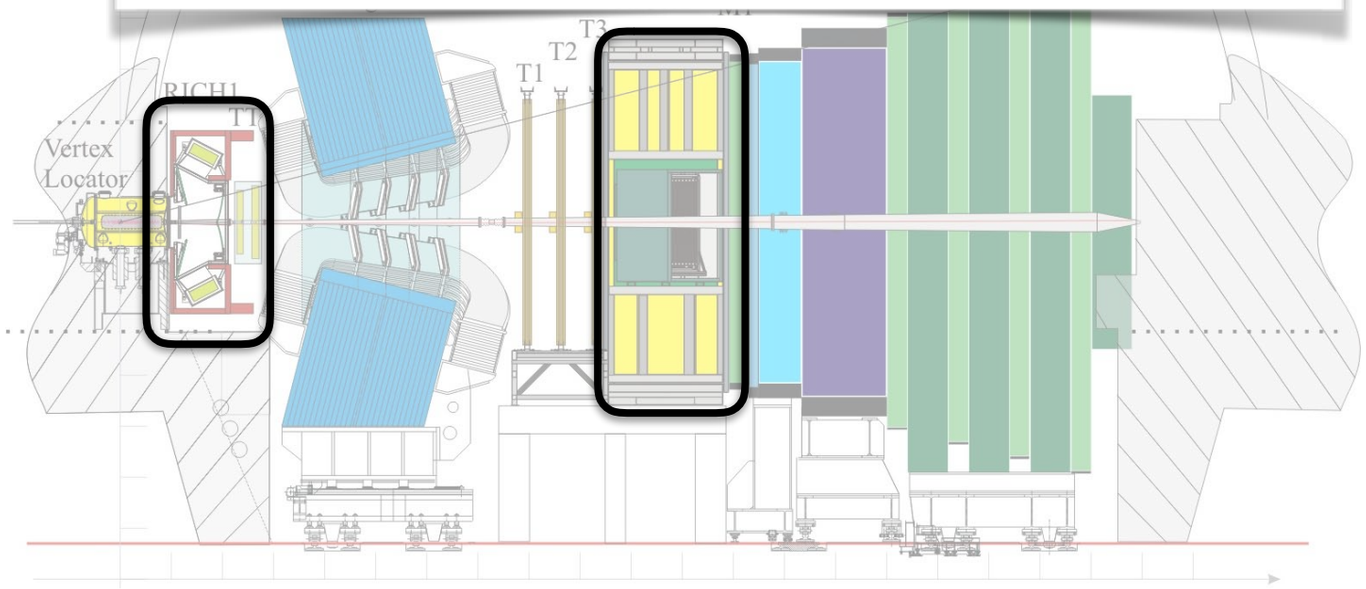

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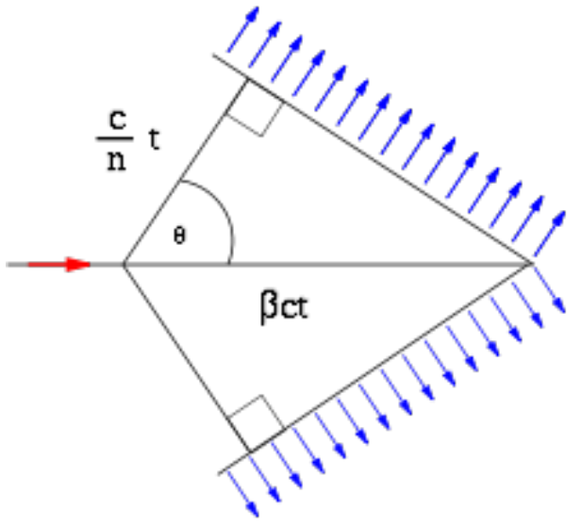
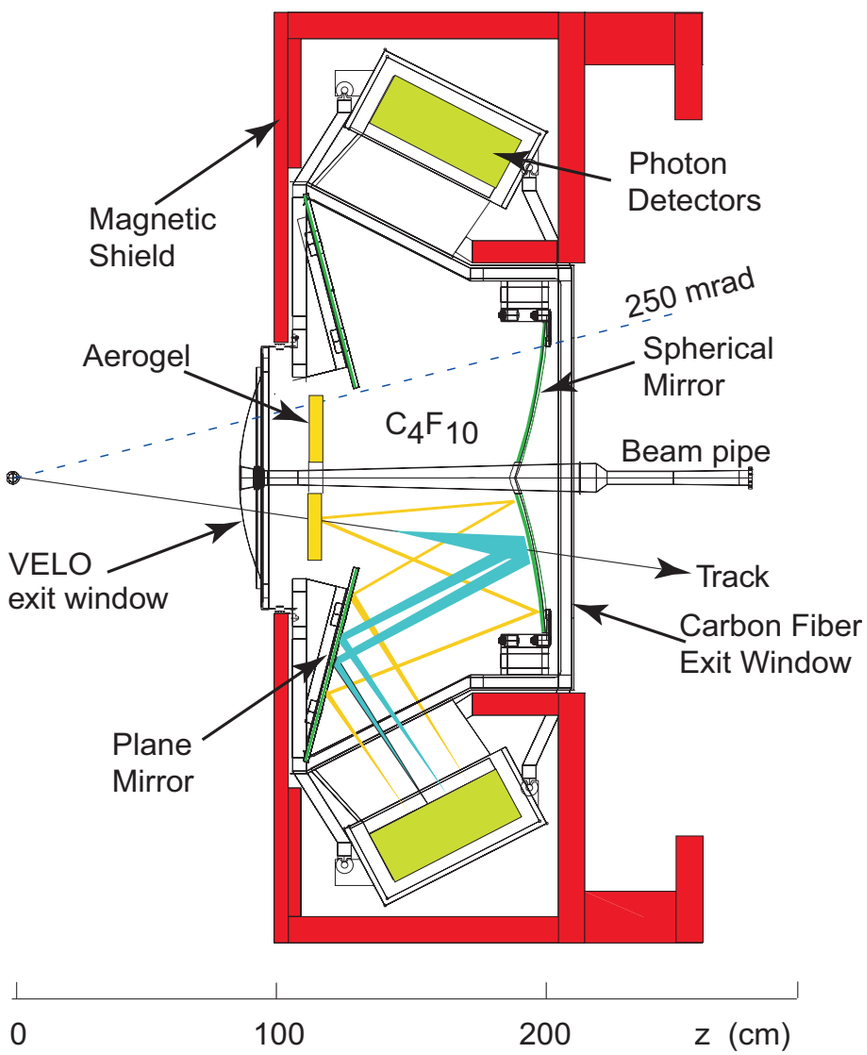
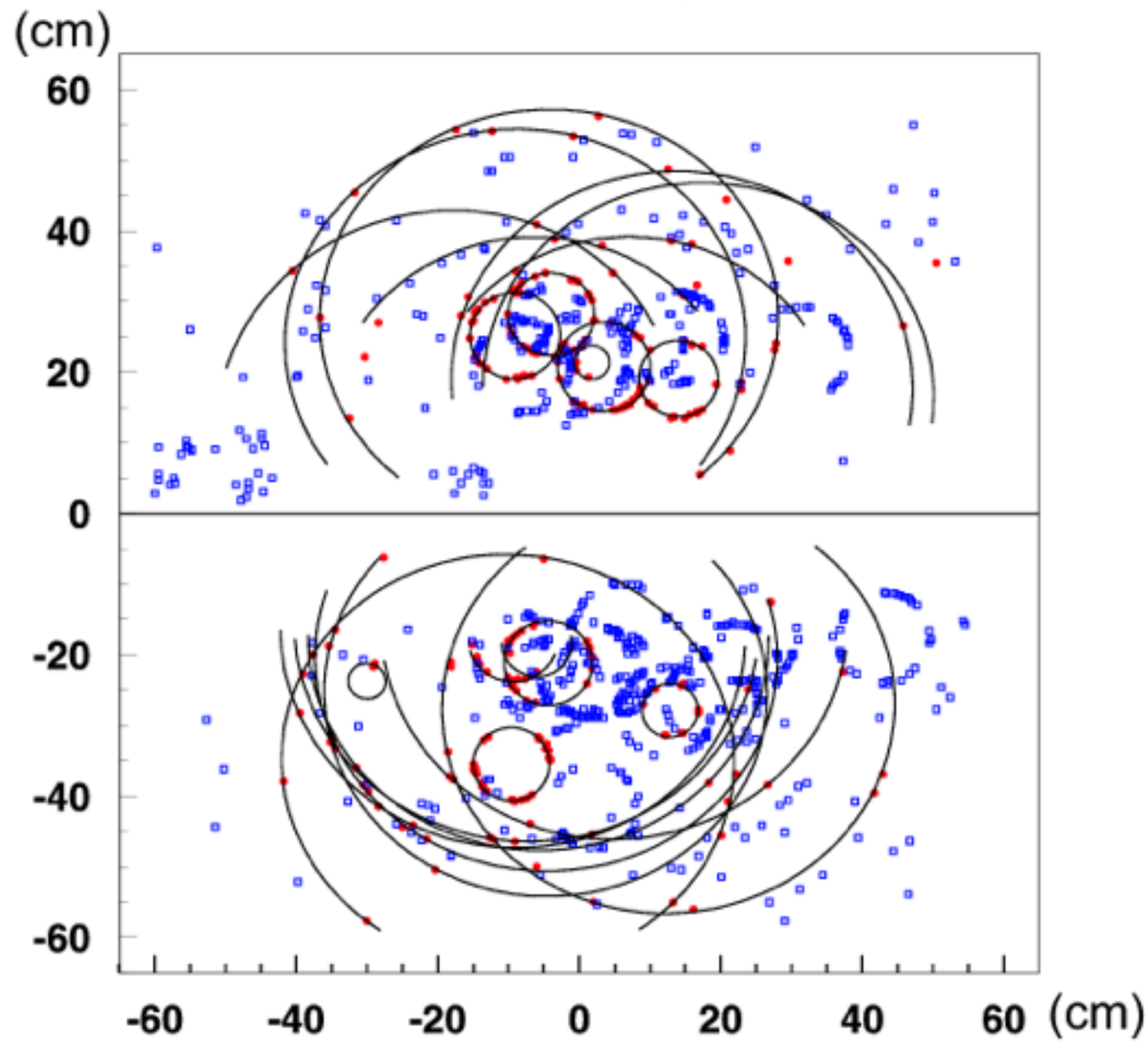
RICH



$$\cos\theta = \frac{1}{n\beta}$$





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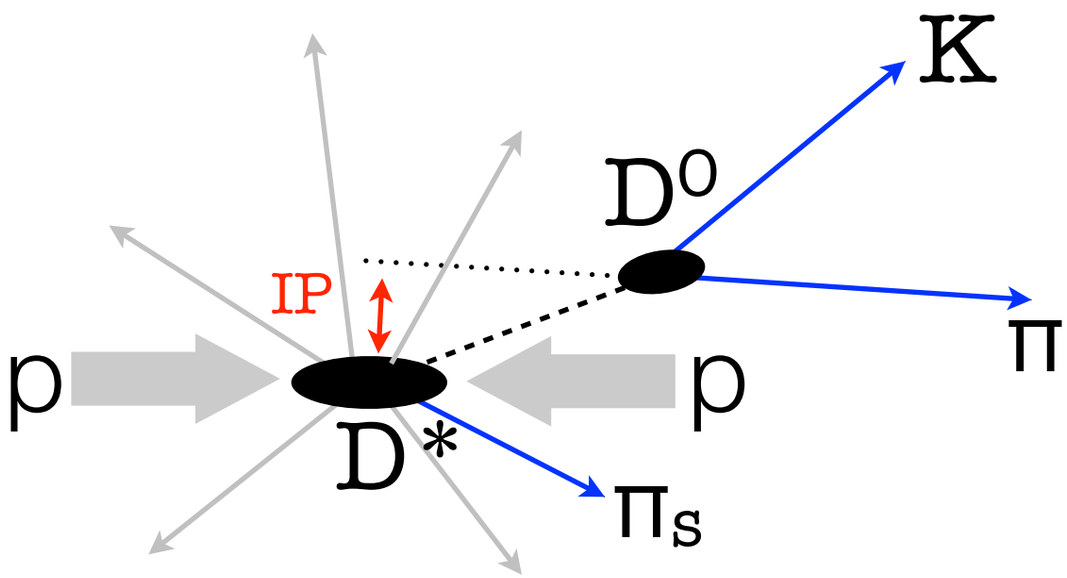
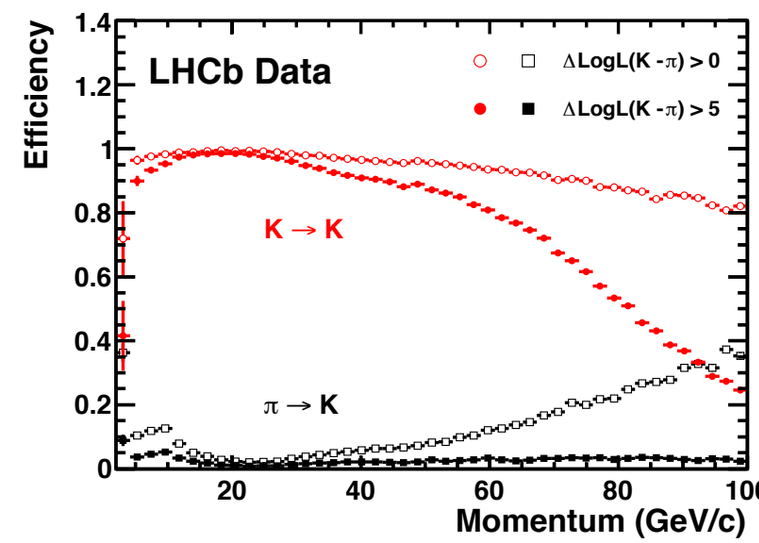


Good PID:
K-π separation in
wide range of momentum



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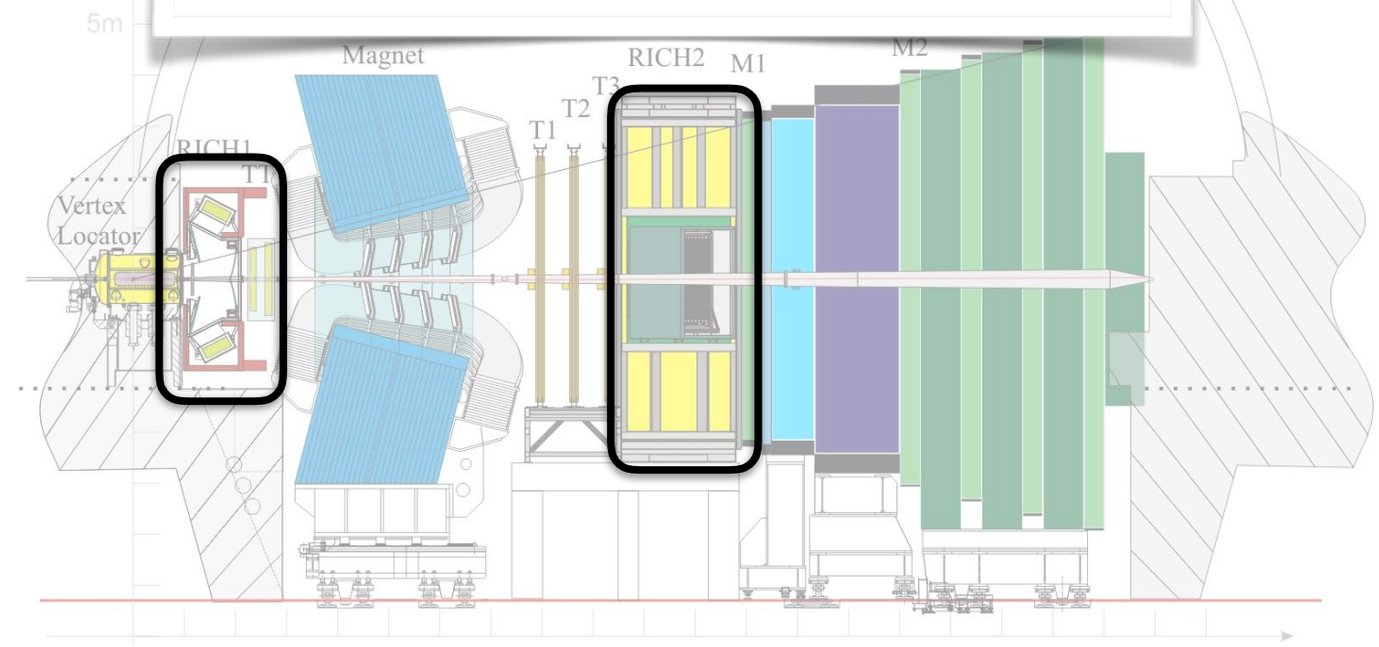

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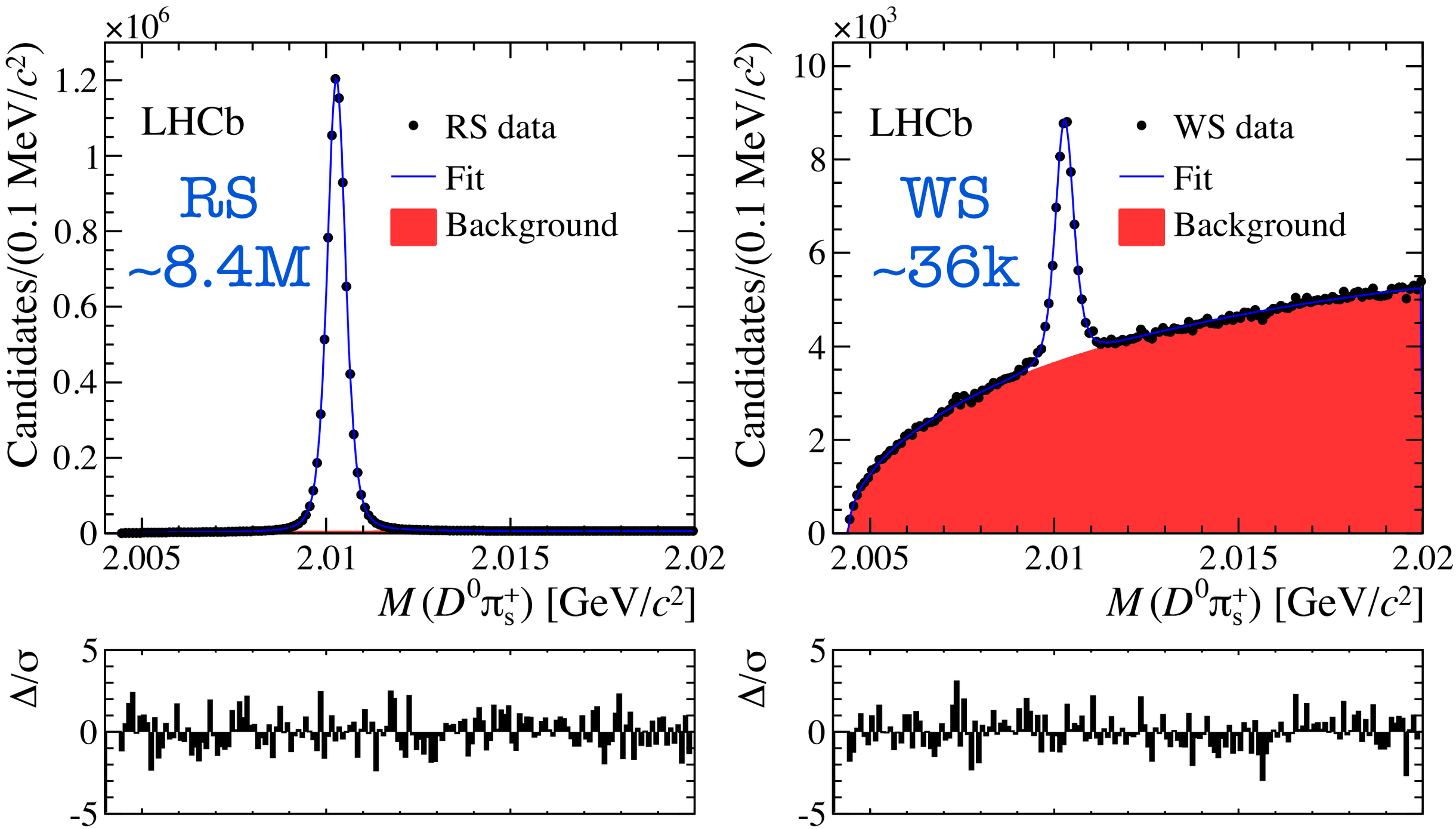
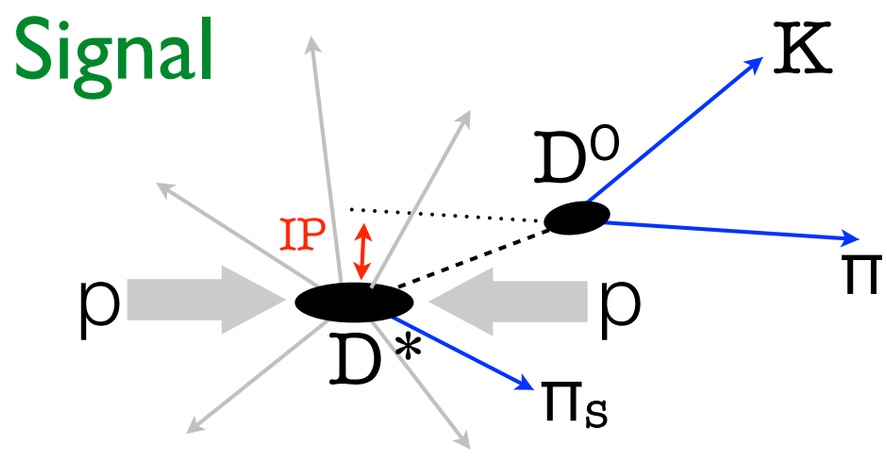
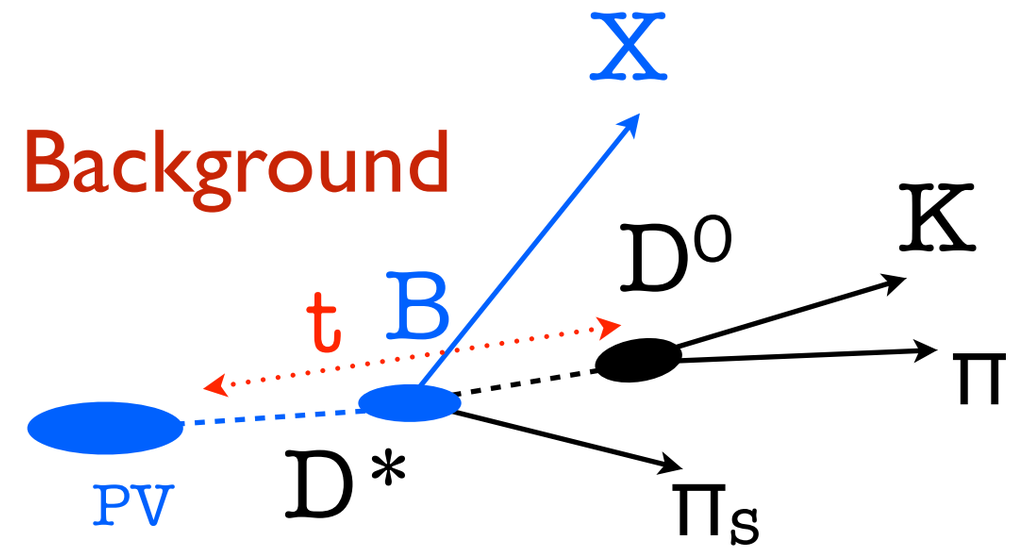
Signal Yields



Phys. Rev. Lett. 110 (2013) 101802

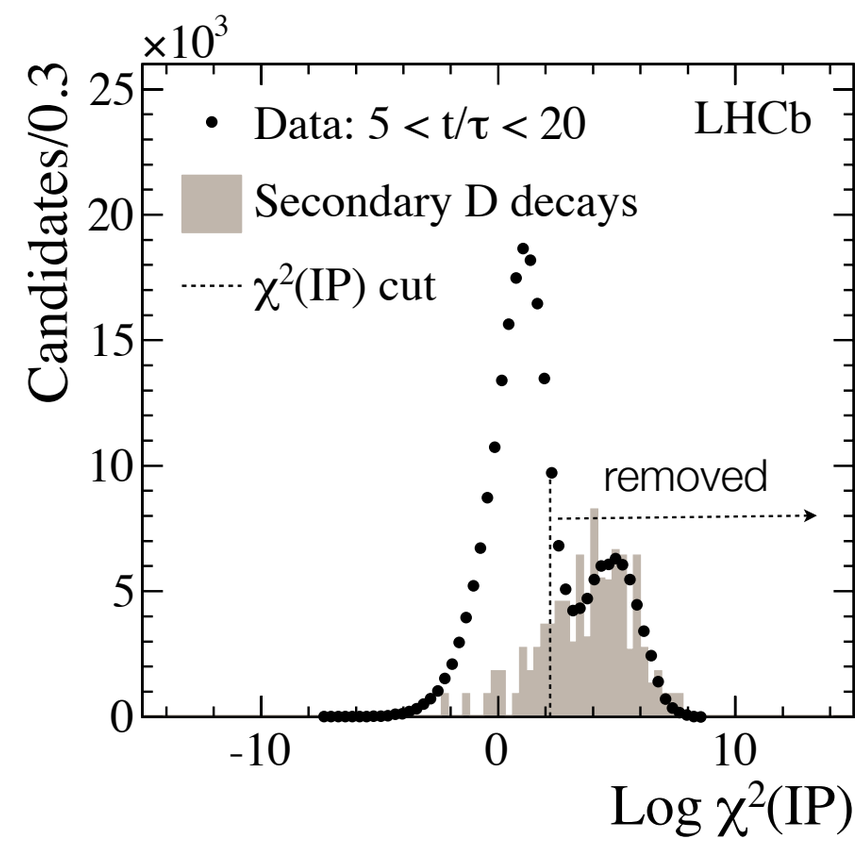
A residual background





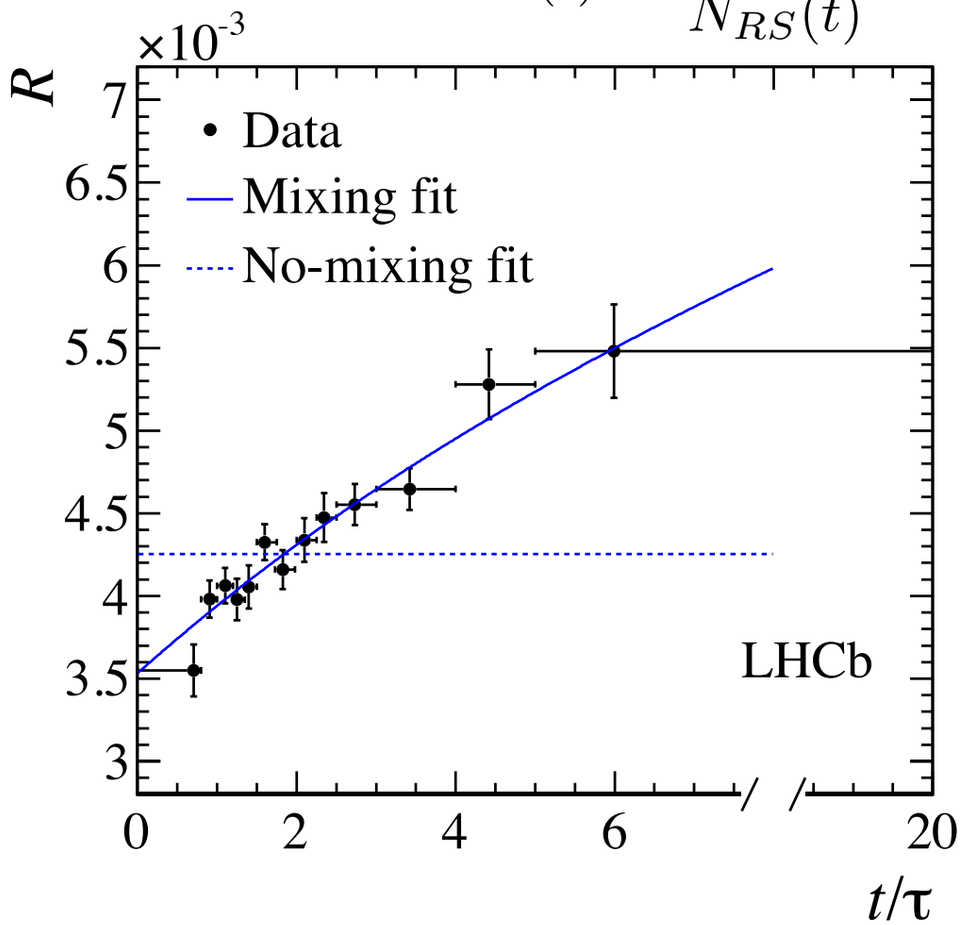
D from B decays have wrong decay time. Neglecting the secondary component could induce a time-dependent bias.

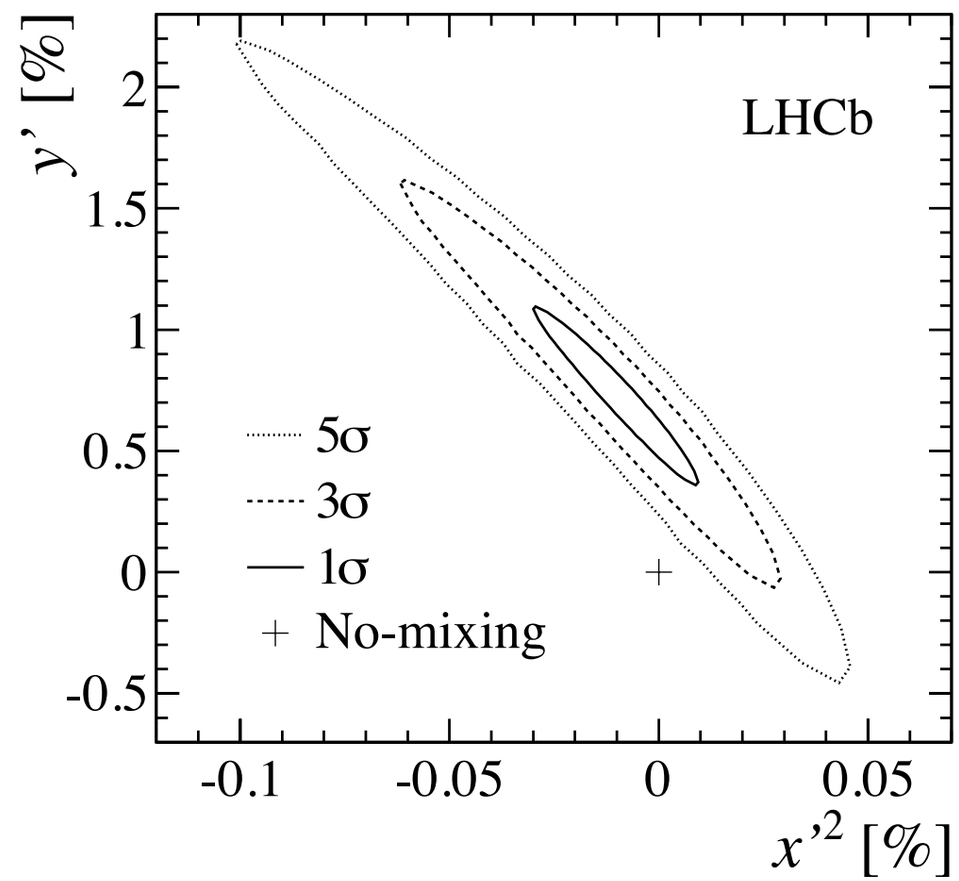
- B flights ~1 cm (τ~1.5 ps): large IP.
- Cut on χ^2(IP) removes most of them but still ~3% of our candidates are likely to come from a B decay
- Fit log χ^2(IP) vs decay time and extrapolate fraction below cut



First mixing observation!

$$R(t) = \frac{N_{WS}(t)}{N_{RS}(t)} = R_D + \sqrt{R_D}y't + \frac{x'^2 + y'^2}{4}t^2$$





Fit type (χ^2/ndf)	Parameter	Fit result (10^{-3})	Correlation coefficient R_D	y'	x'^2
Mixing (9.5/10)	R_D	3.52 ± 0.15	1	-0.954	$+0.882$
	y'	7.2 ± 2.4		1	-0.973
	x'^2	-0.09 ± 0.13			1
No mixing (98.1/12)	R_D	4.25 ± 0.04			

No-mixing hypothesis excluded at 9.1σ

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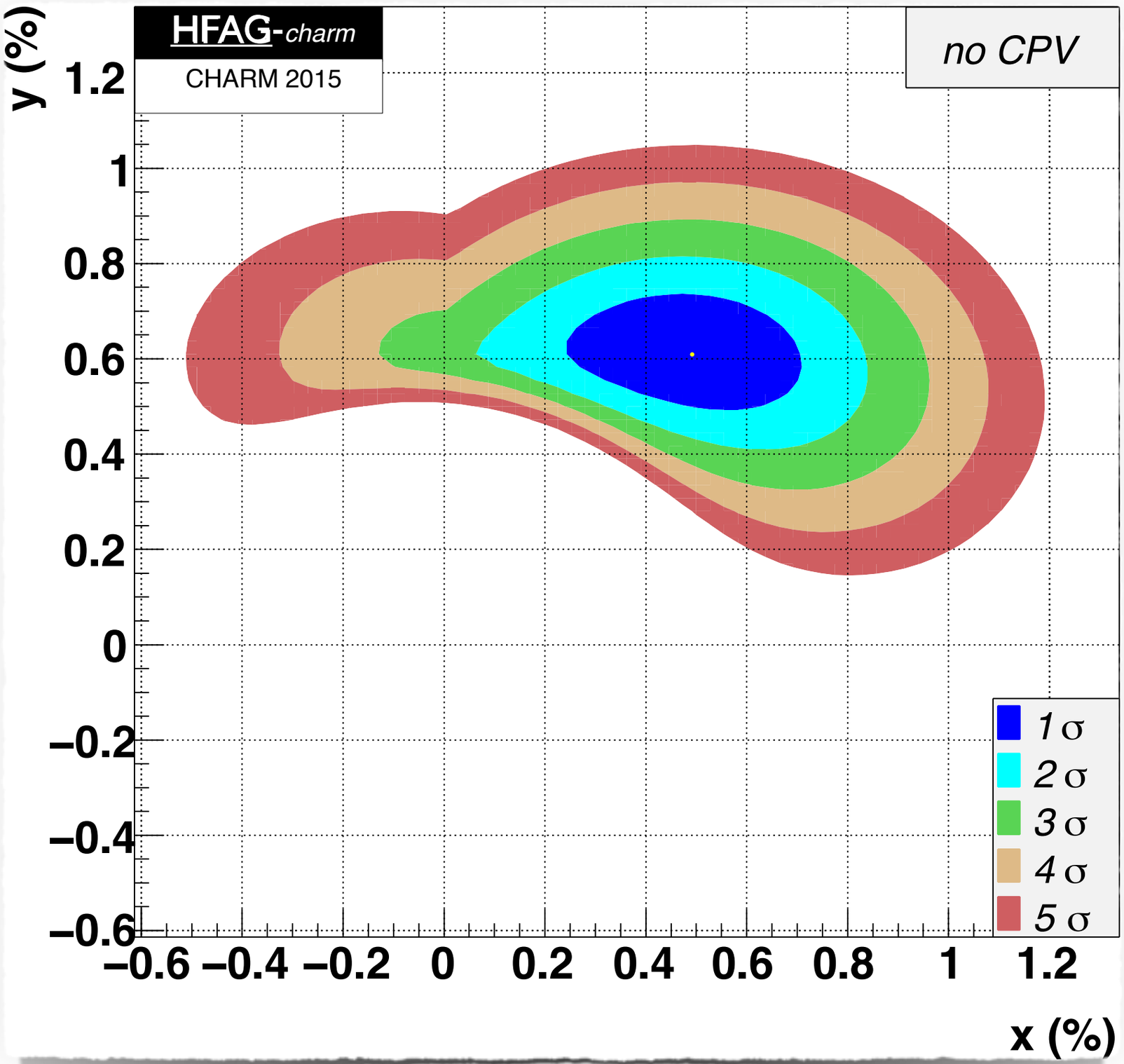
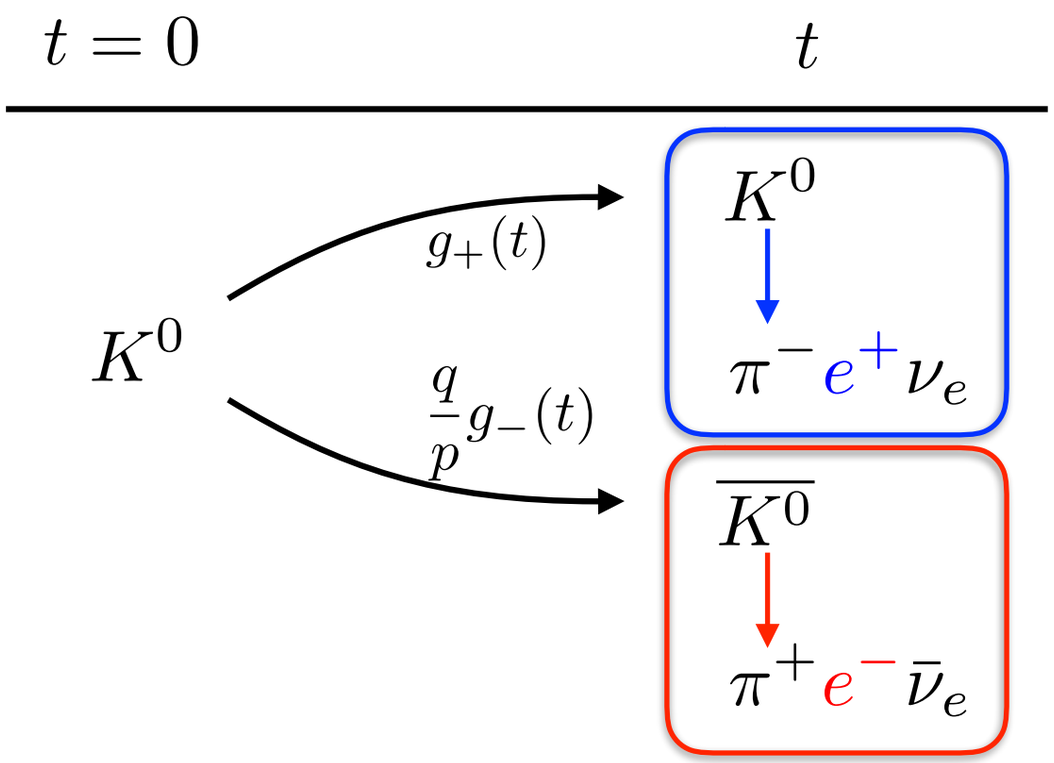
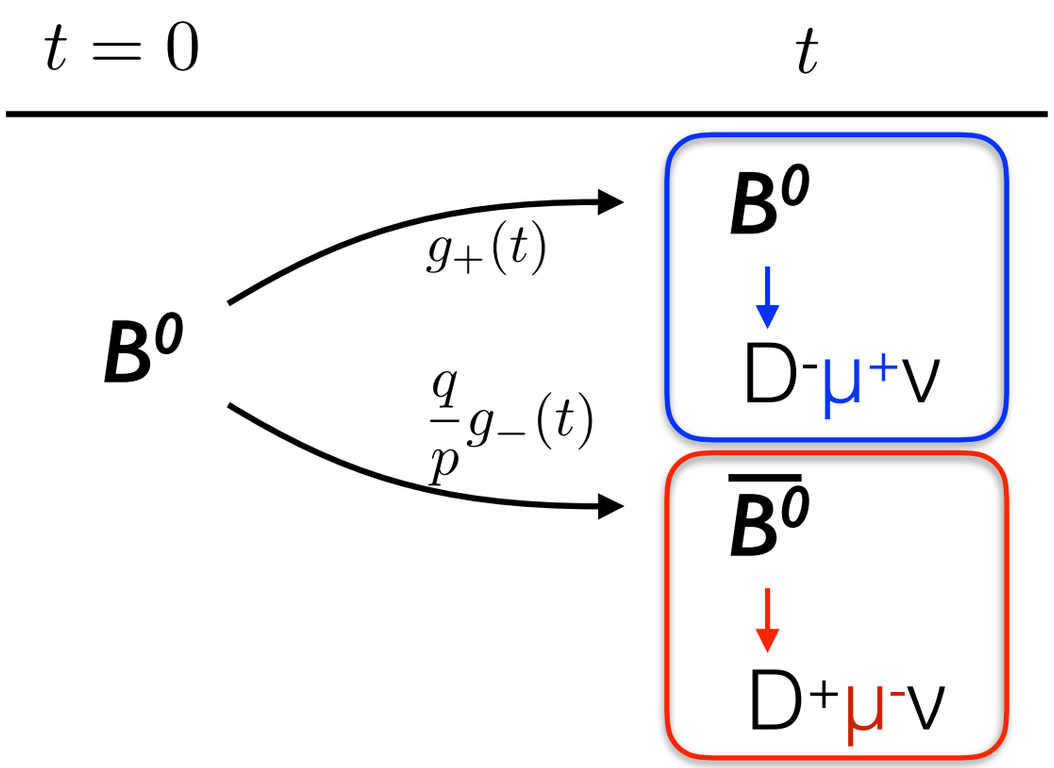
Charm, x and y

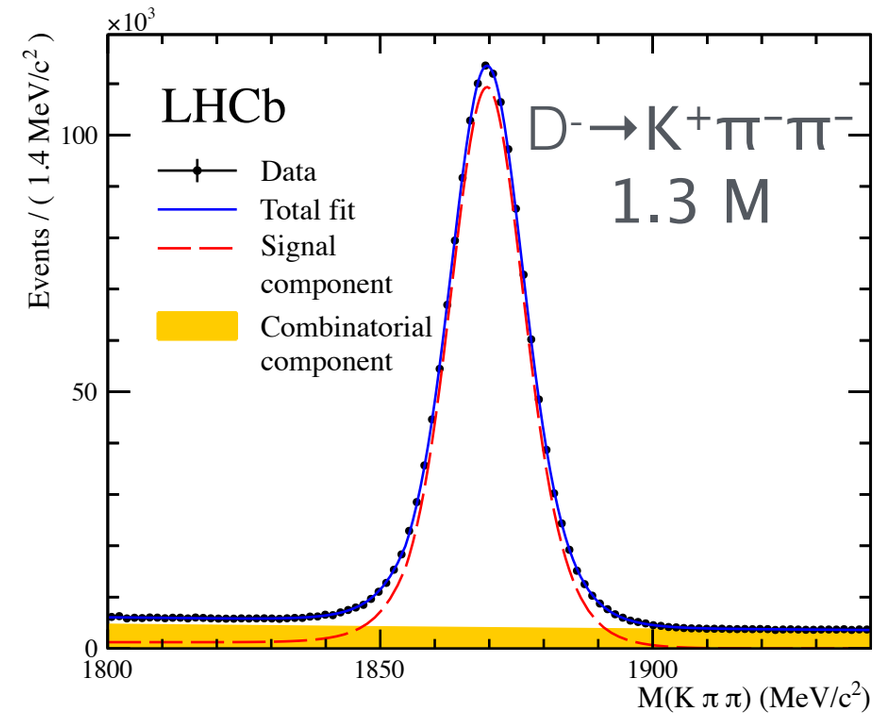

HFAG-charm
CHARM 2015
no CPV
y (%)
1.2
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.6 −0.4 −0.2 0 0.2 0.4 0.6 0.8 1 1.2
x (%)
1 σ
2 σ
3 σ
4 σ
5 σ

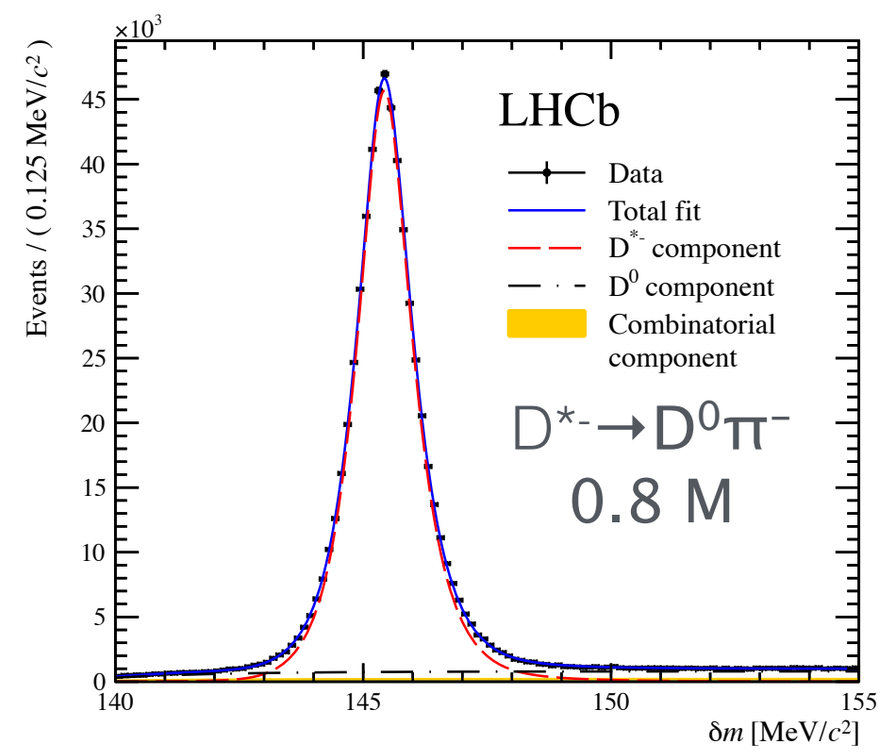
B^0 mixing at high precision



B^0 mixing at high precision



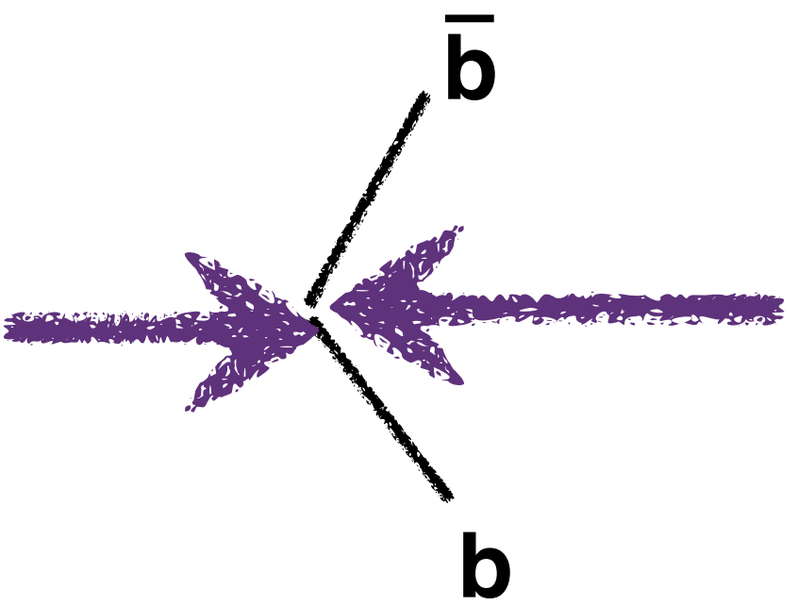




Huge samples of these decays in LHCb!

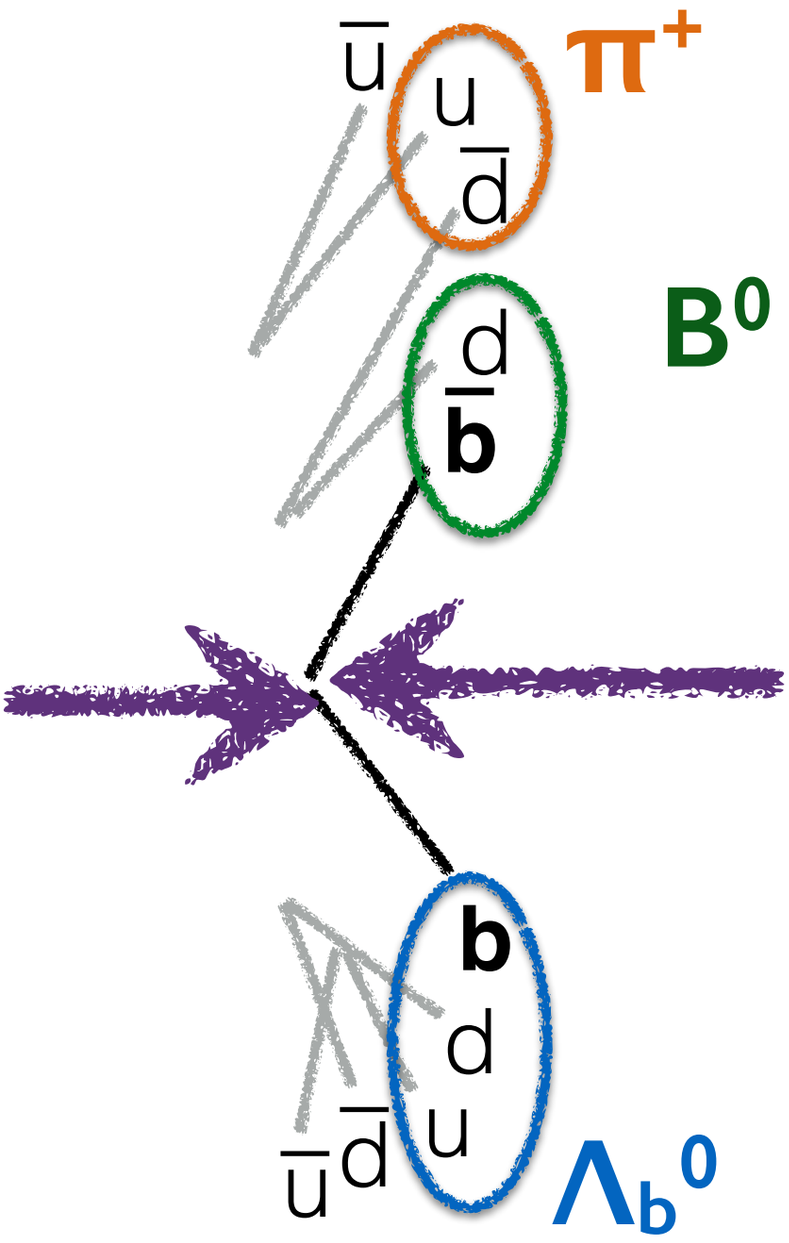
But how do we know the initial flavour of the B^0 meson?

B^0 flavour tagging



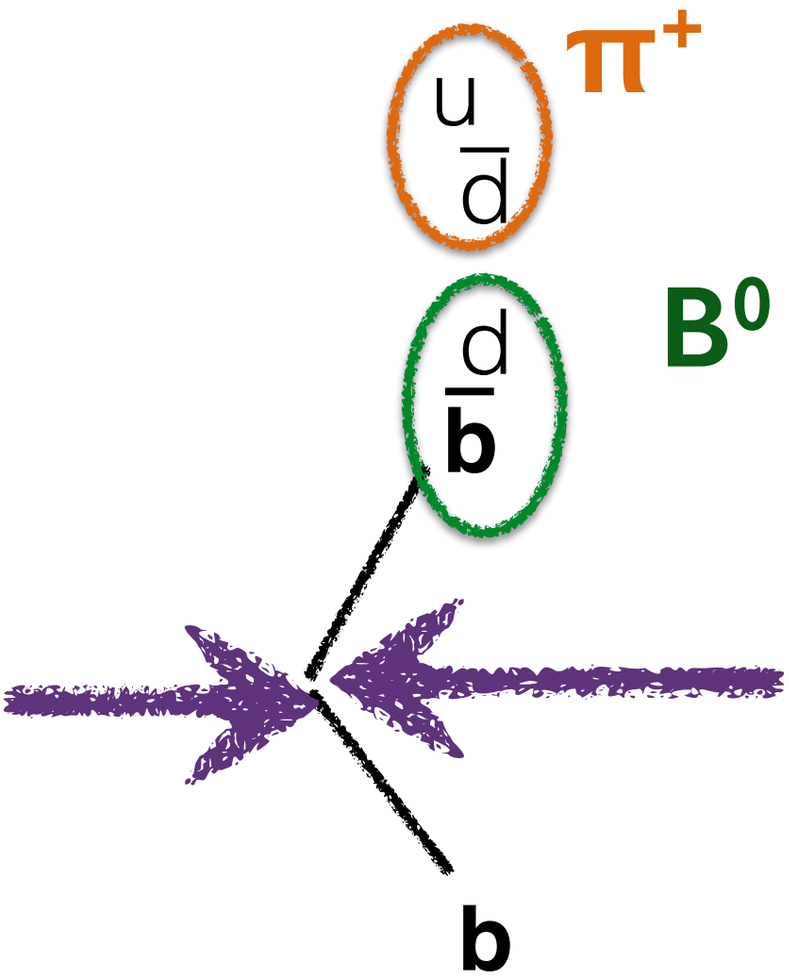
Main production mechanism of b quark
at hadron collider: b anti-b pair production

B^0 flavour tagging



The two b quarks hadronise independently into two b hadron (incoherent production)

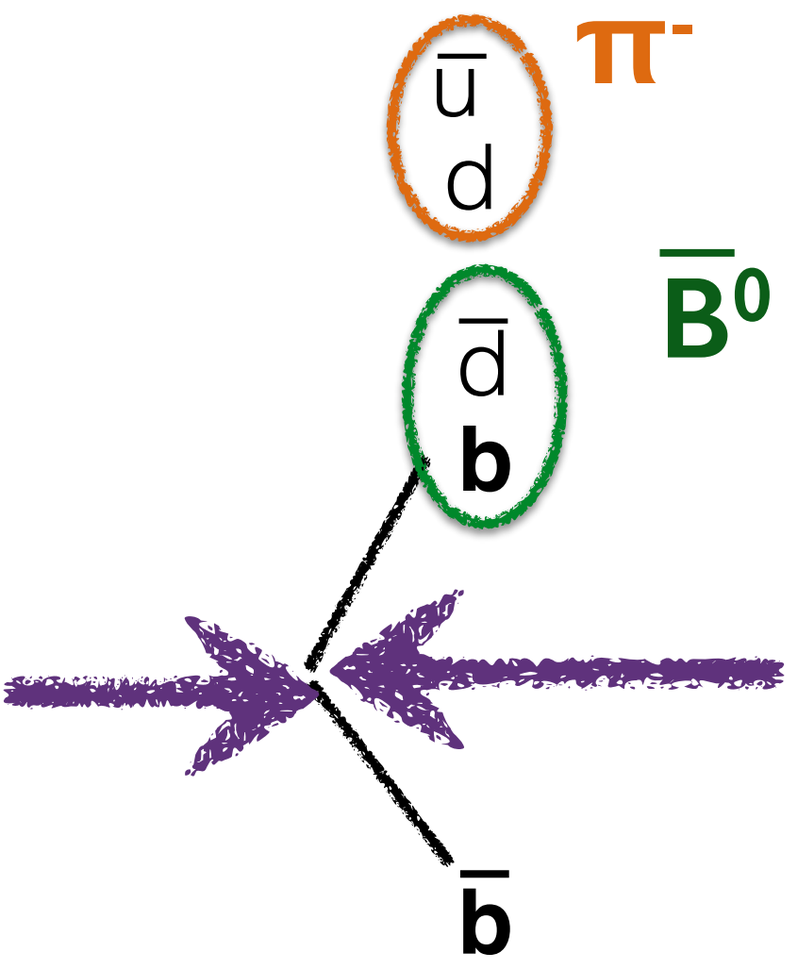
B^0 flavour tagging



The signal B^0 can be accompanied by a **charged pion** (~50% of the time): its charge gives the flavour of the B!

(Same Side tagging)

B^0 flavour tagging



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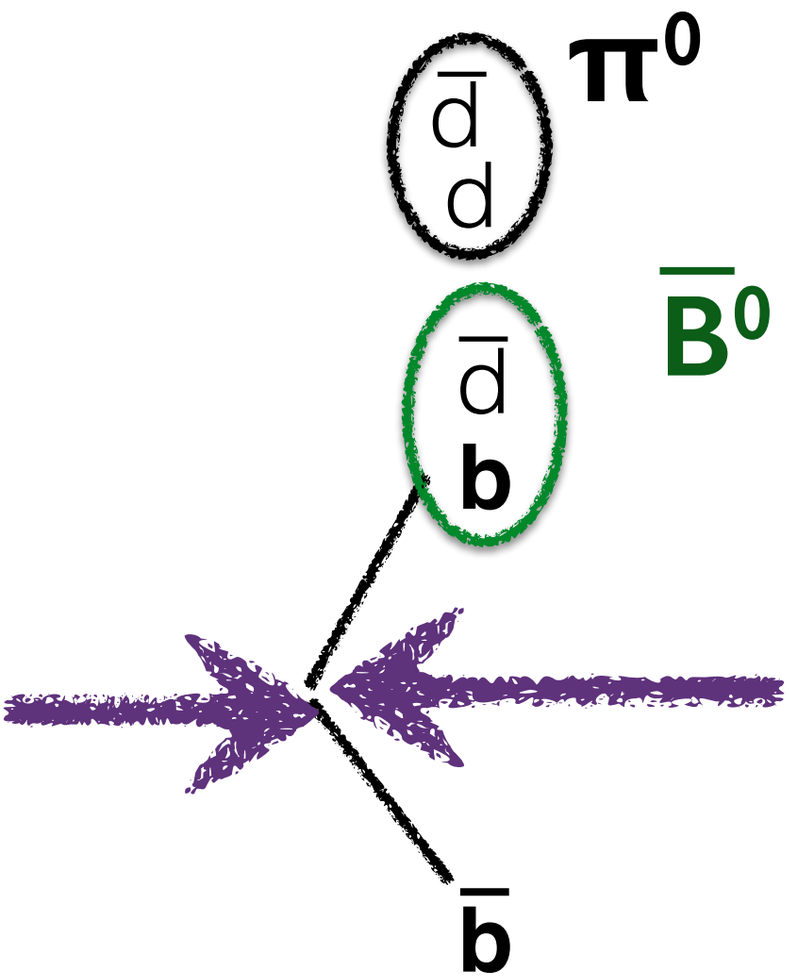
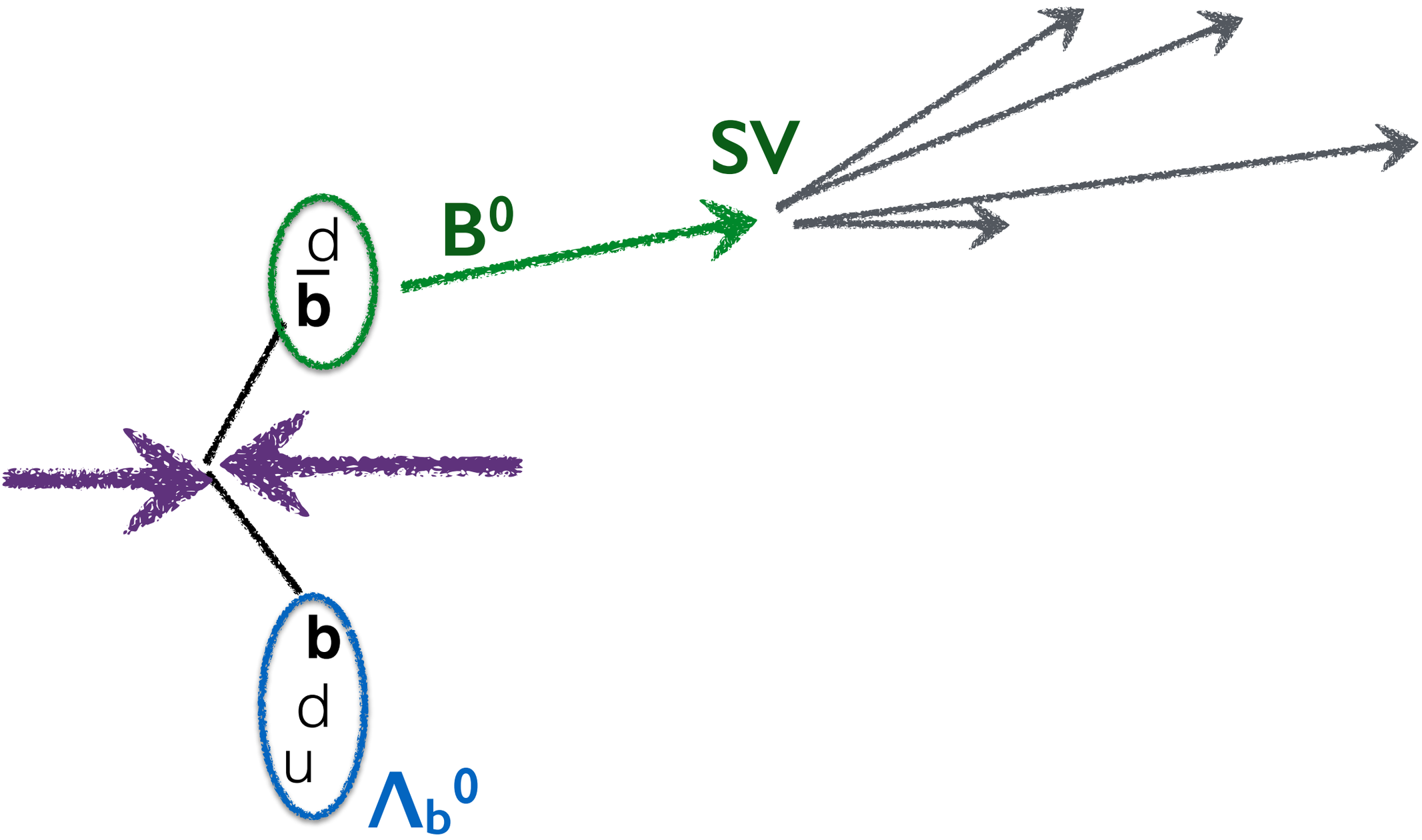
B^0 flavour tagging

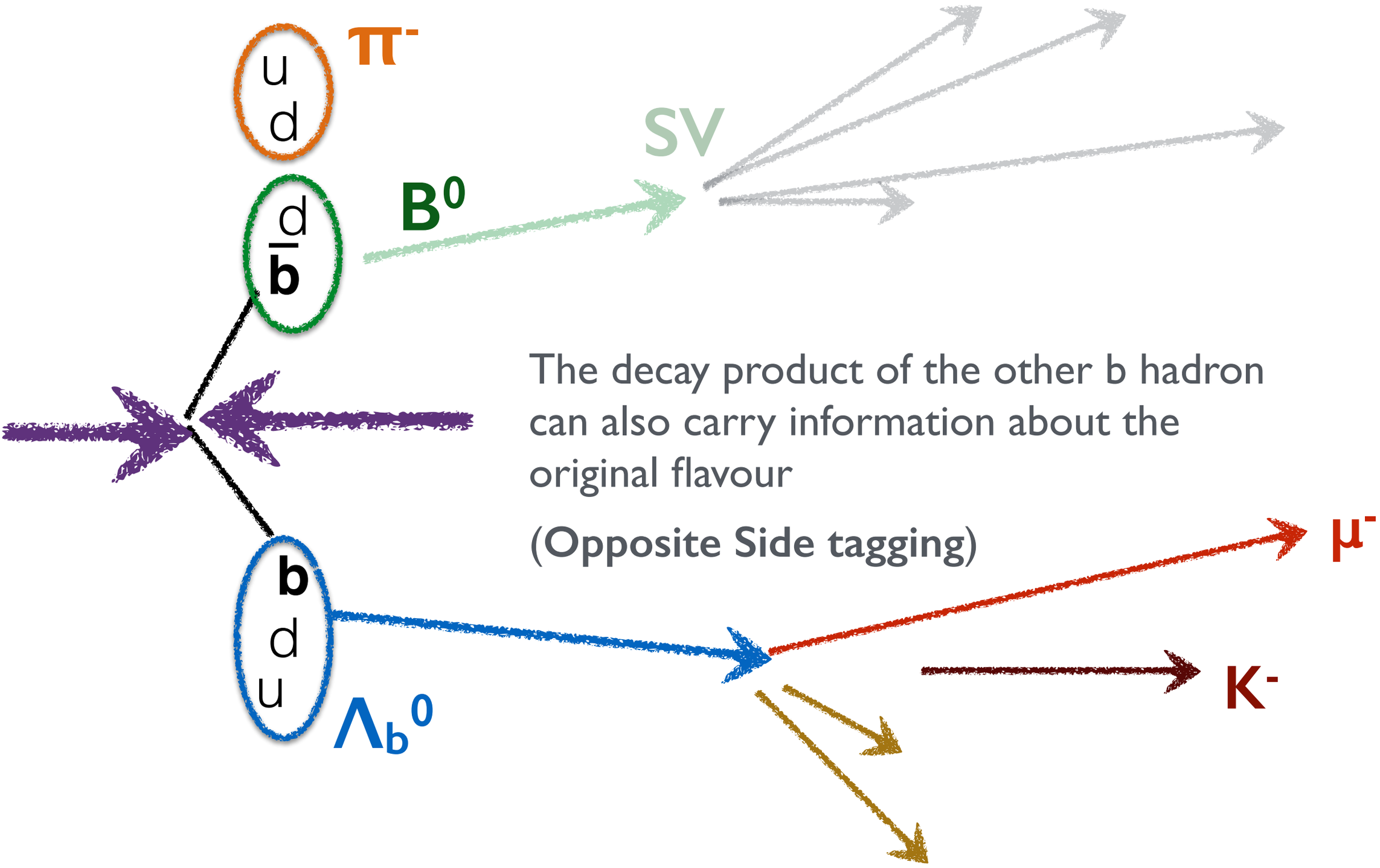


Cannot tag…

B^0 flavour tagging



B^0 flavour tagging



The decay product of the other b hadron can also carry information about the original flavour

(Opposite Side tagging)

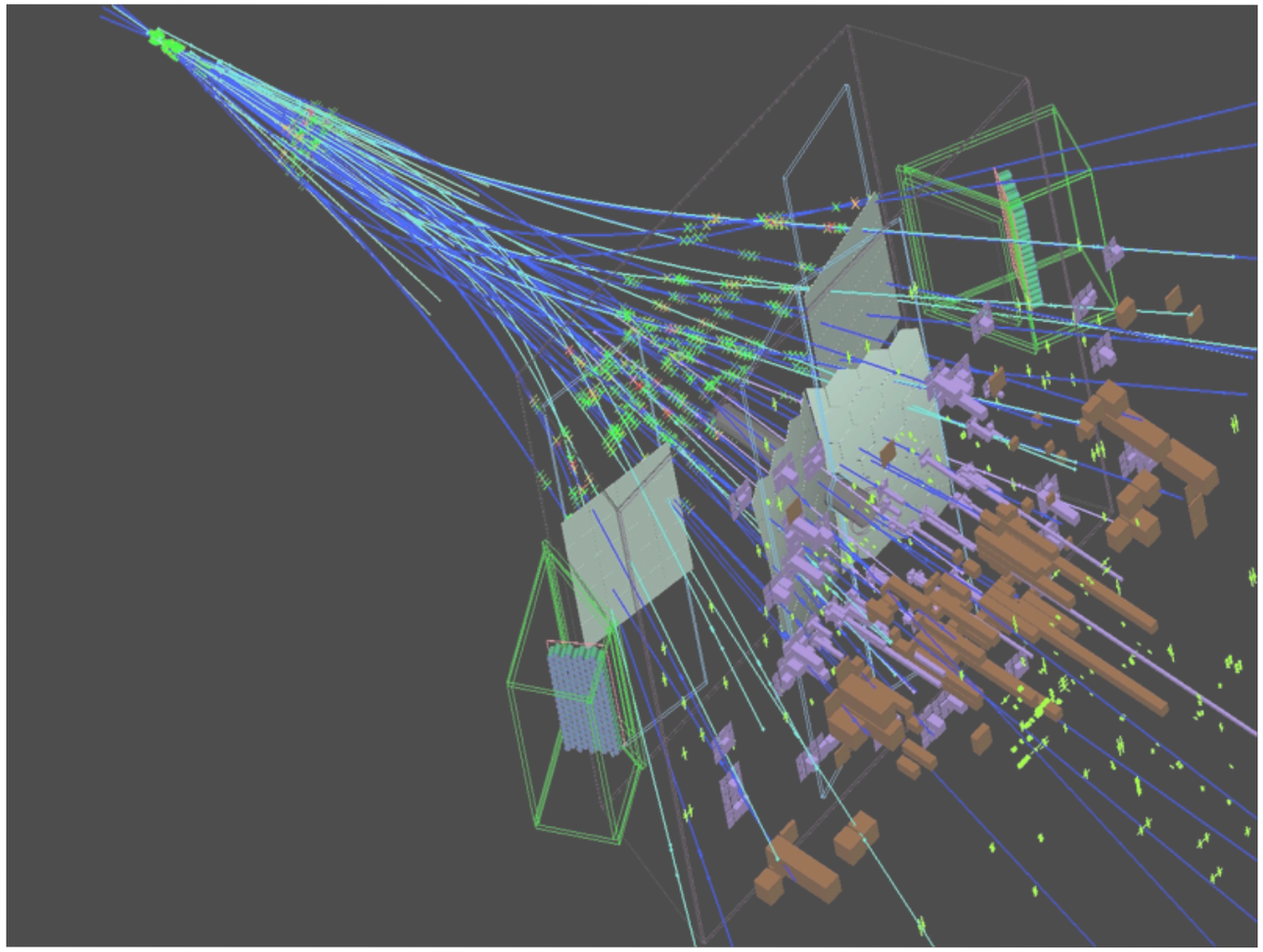
B^0 flavour tagging

"Just" need to find the right tracks in all the mess…

Mis-tag sources:

- wrong track (backgrounds, fakes)
- the OS B has oscillated!
- …

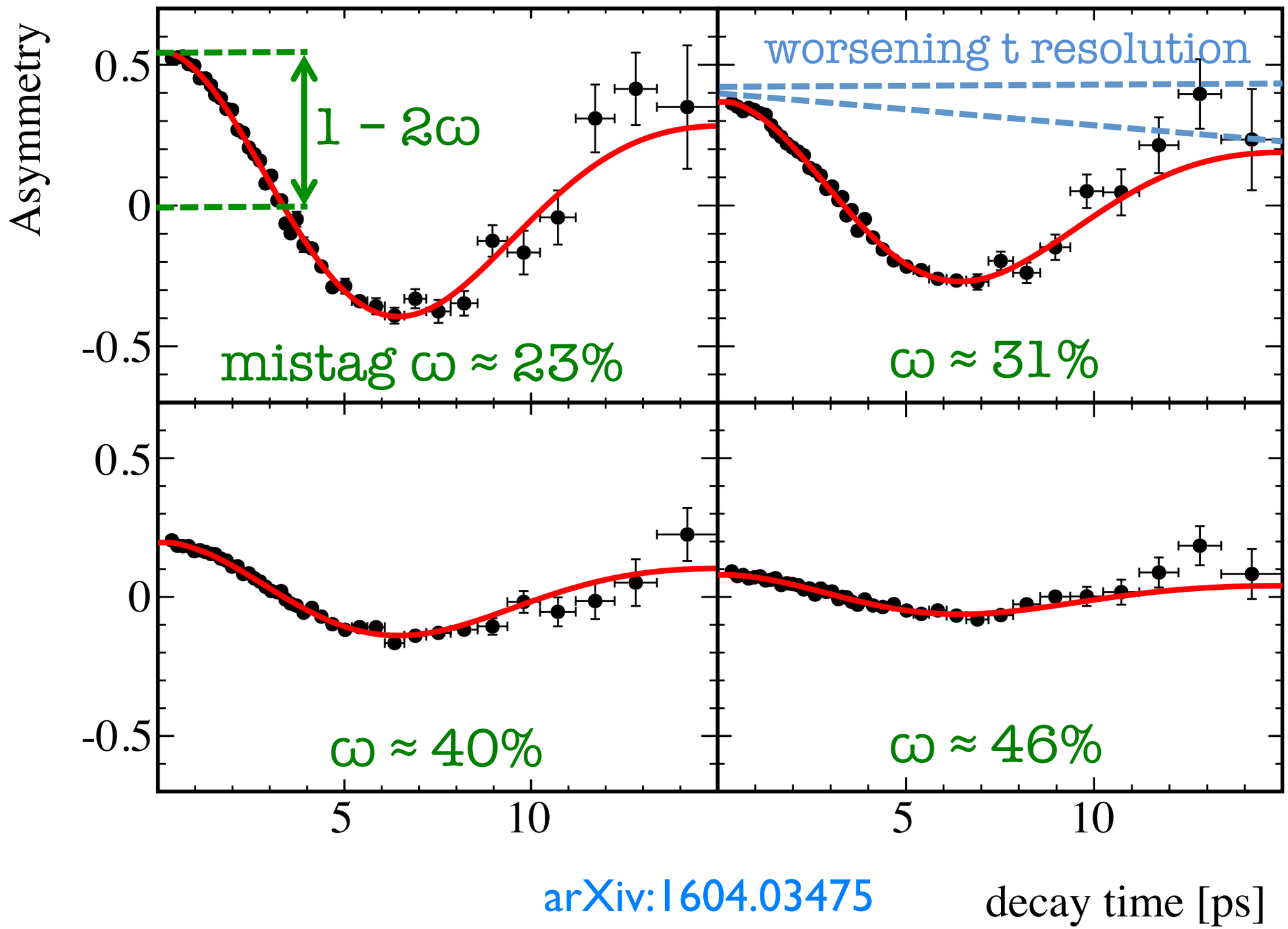
The tagging algorithm takes this into account, and compute a **mistag probability** for each tagged event.



Combining the tagging efficiency (how many events we can tag) and the mistag probability (how often wrong), the size of a **"perfectly tagged" sample (tagging power) is just O(2-5%) of the original one!**

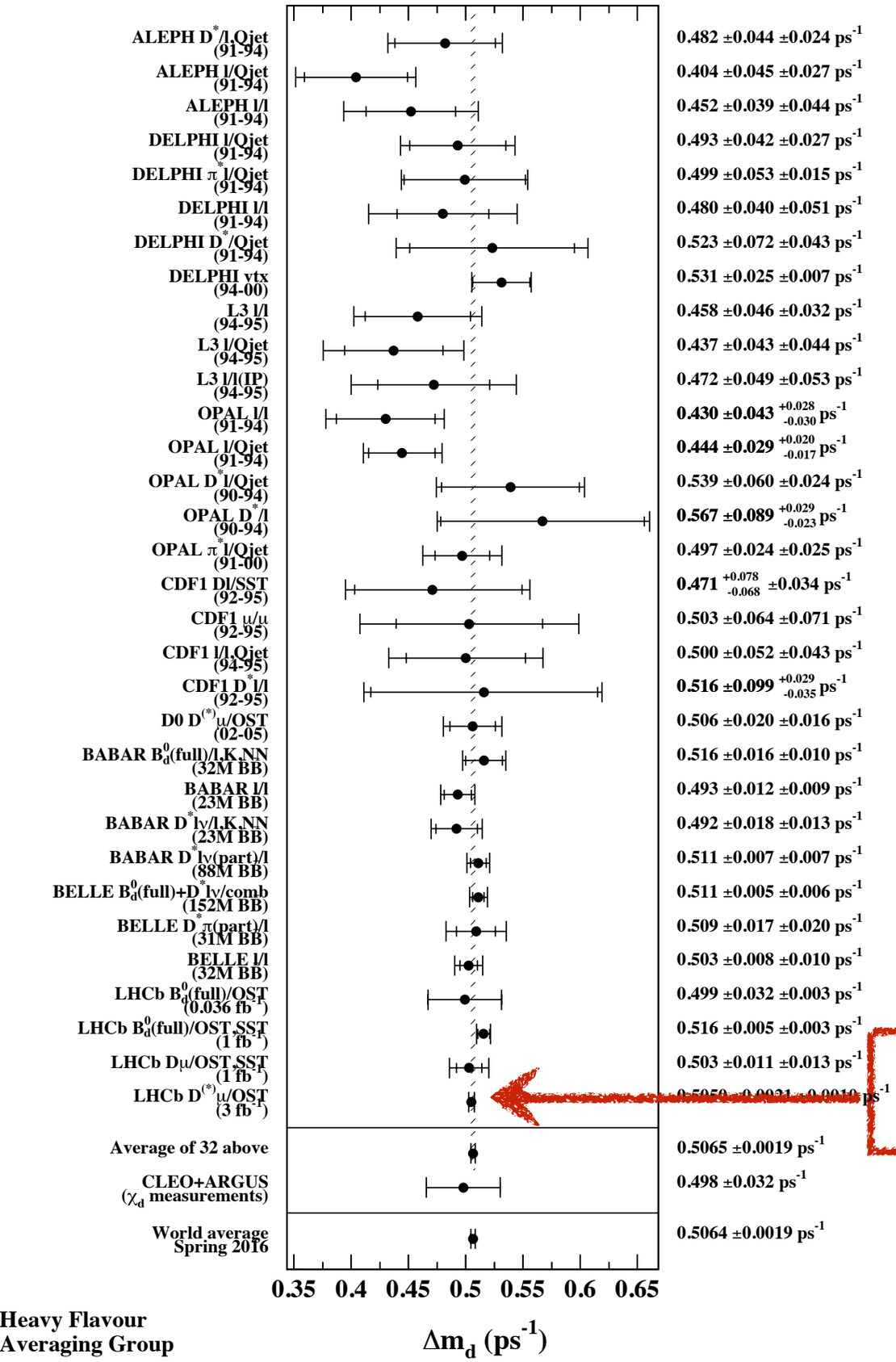
But still…

B^0 mixing asymmetry



arXiv:1604.03475

Δm_d at high precision



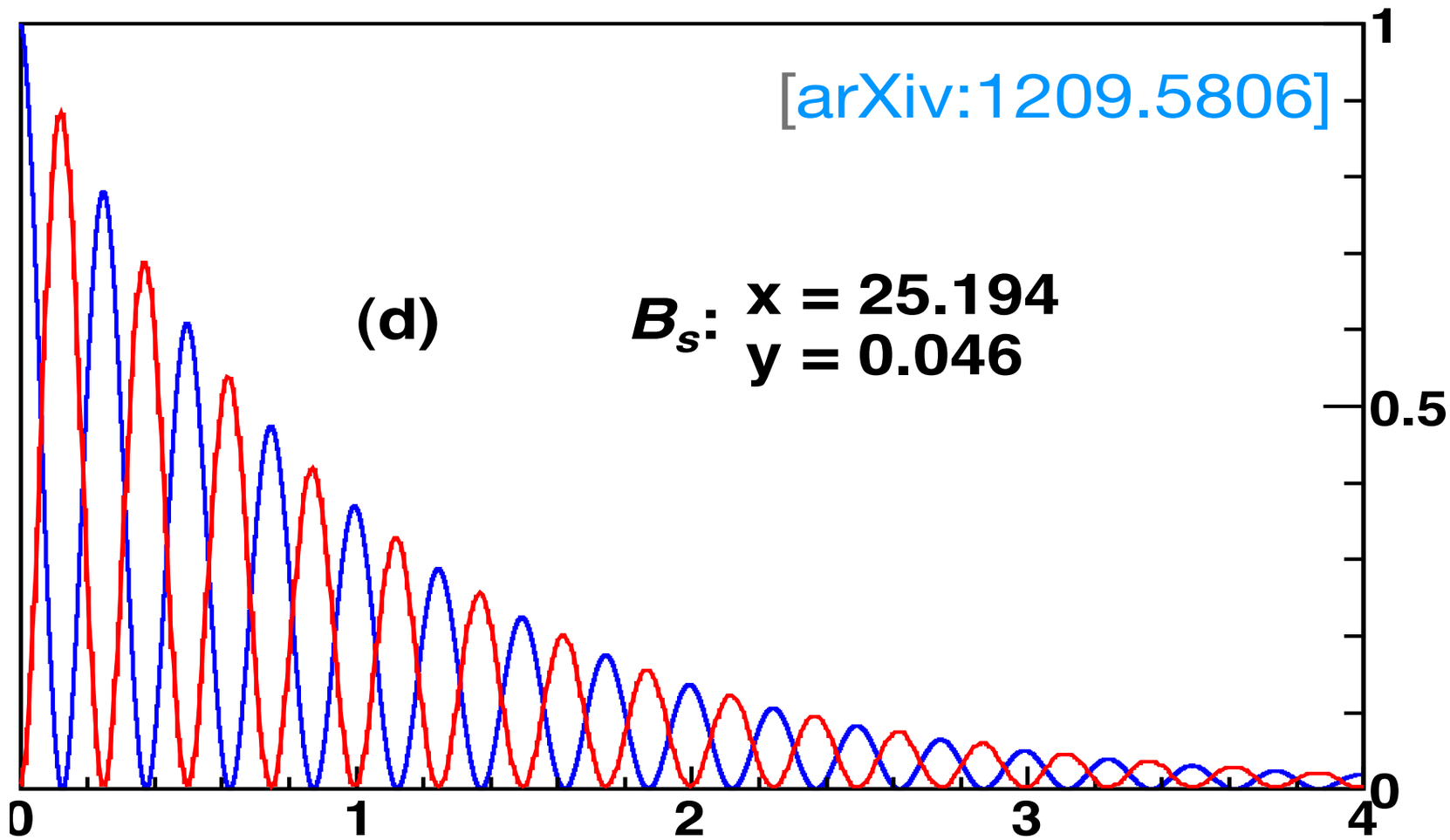
arXiv:1604.03475

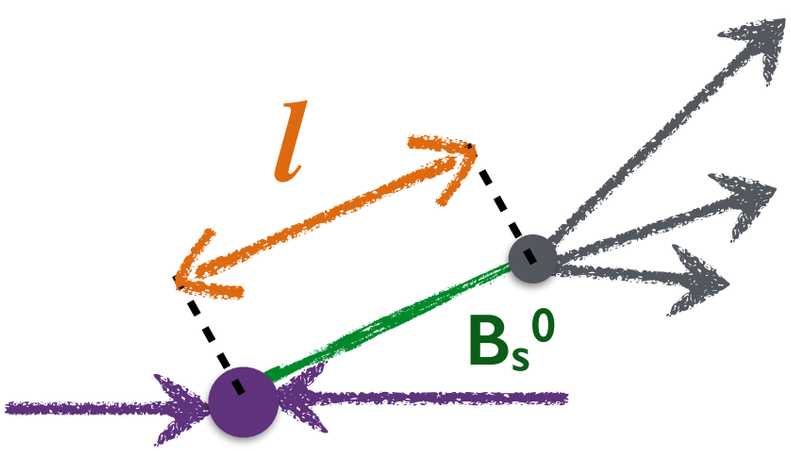
$$\Delta m_d = (505.0 \pm 2.1\,(\text{stat}) \pm 1.0\,(\text{syst}))\,\text{ns}^{-1}$$

B_s^0 mixing

Need good
B flavour tagging
(what does change in
B_s^0 w.r.t B^0?).

Very fast oscillations,
(period of 350 fs),
require demanding
time resolution…

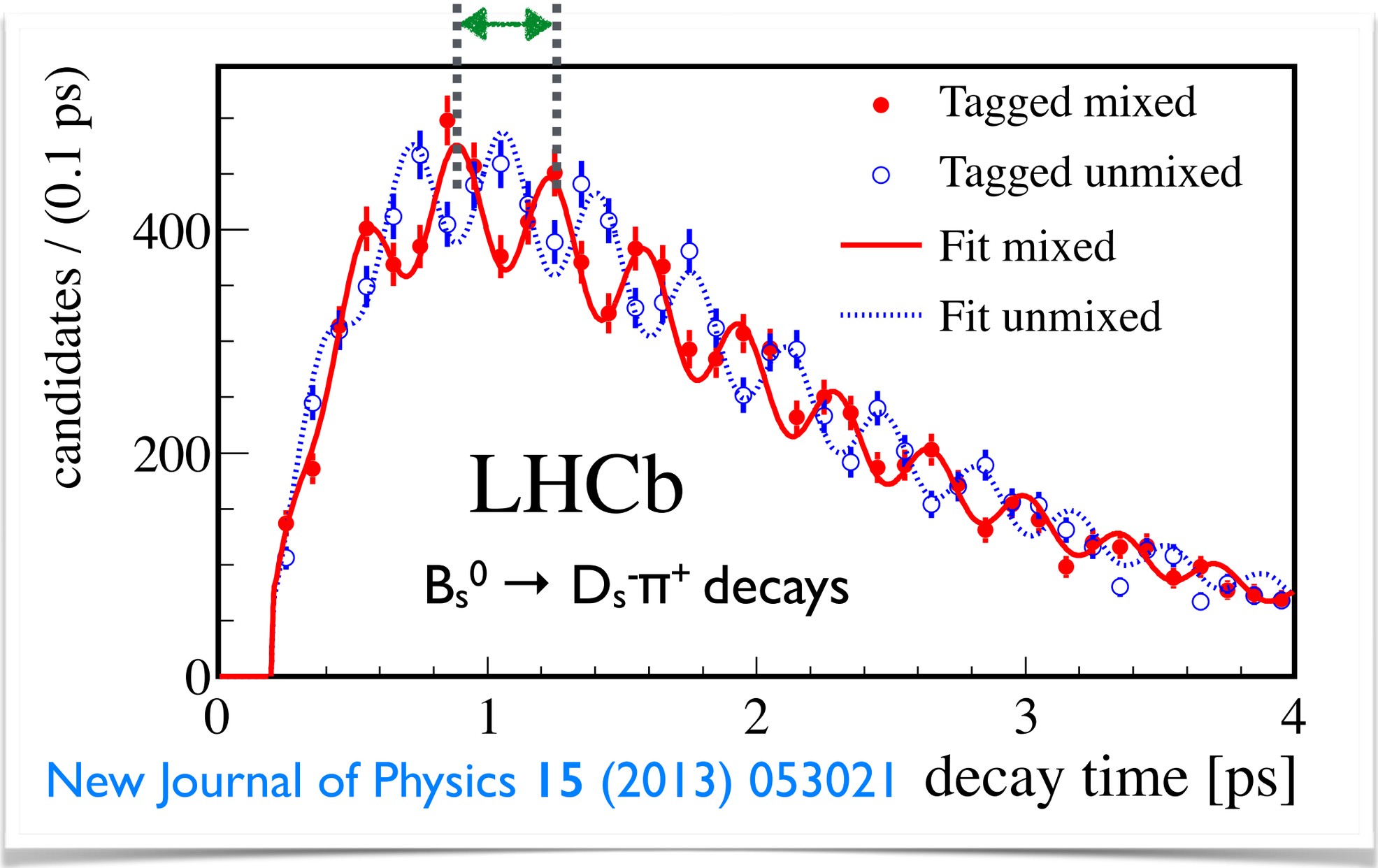




$$t = ml/p \qquad \sigma_t^2 = \left(\frac{m}{p}\right)^2 \sigma_l^2 + \left(\frac{t}{p}\right)^2 \sigma_p^2$$

B_s^0 mixing in real life

Period of 350 fs. LHCb time resolution LHCb O(50 fs)



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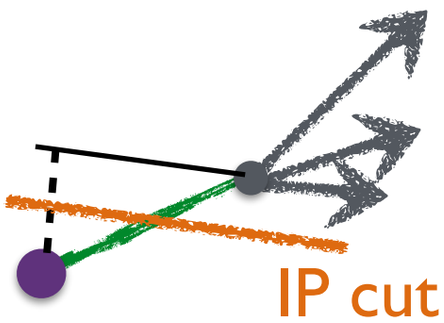
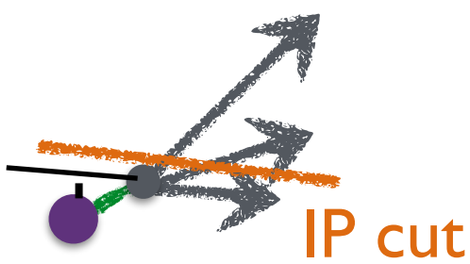
$$\Delta m_s = 17.768 \pm 0.023\,(\text{stat}) \pm 0.006\,(\text{syst})\ \text{ps}^{-1}$$

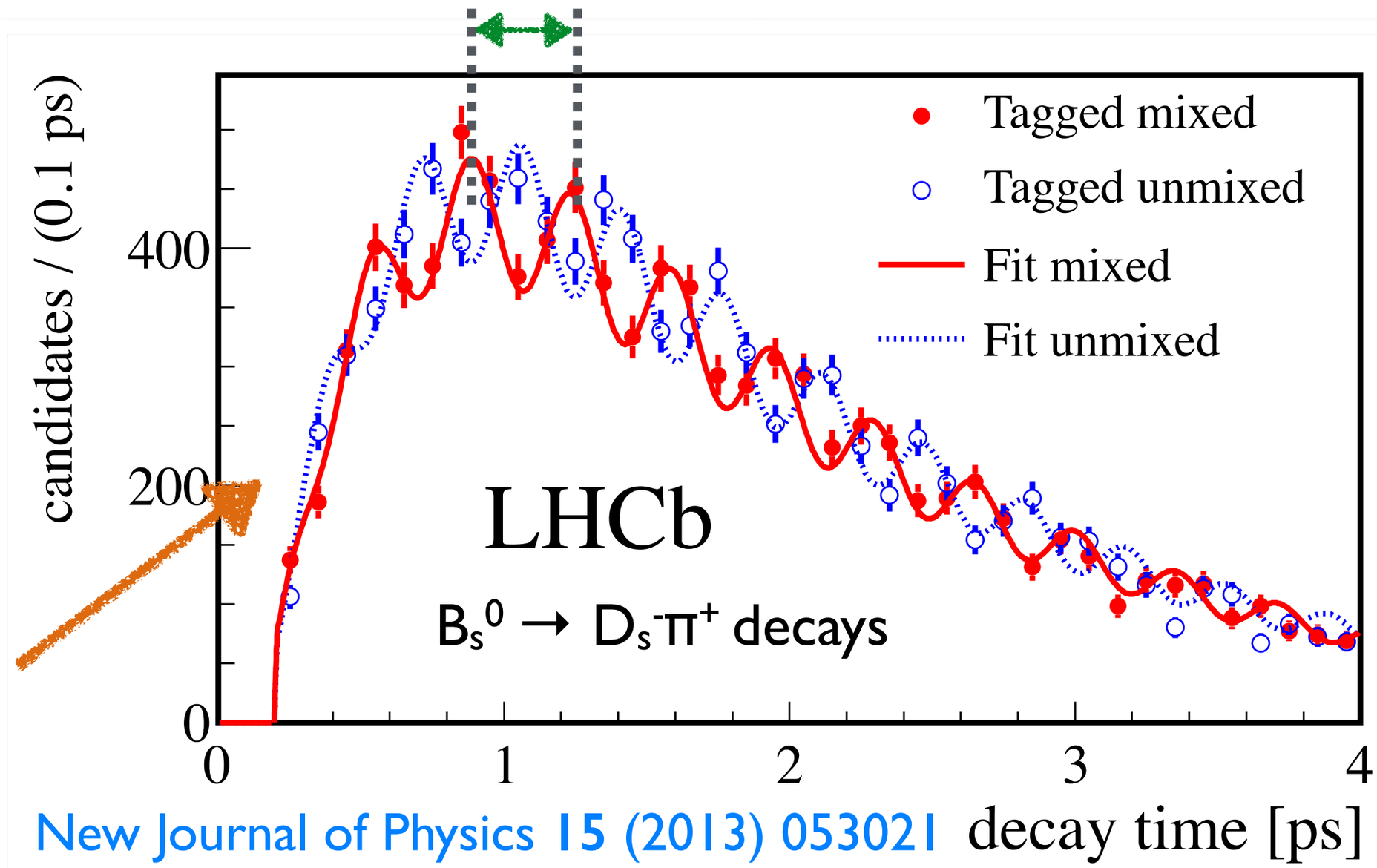
B_s^0 mixing in real life

Period of 350 fs. LHCb time resolution LHCb O(50 fs)





Efficiency varies with decay time. Selecting "large" IP(B) disfavours short decay times.



New Journal of Physics **15** (2013) 053021

$$\Delta m_s = 17.768 \pm 0.023\,(\text{stat}) \pm 0.006\,(\text{syst})\ \text{ps}^{-1}$$

So far (so good?)

- ★ No primordial antimatter observed, universe matter dominated
- ★ Need breaking of CP symmetry to explain this
- ★ C and P are violated by weak interactions (CP looks still healthy…)
- ★ Matter-antimatter oscillations: K^0 can turn into anti-K^0;
  the physical states are not the flavour eigenstates.
- ★ Using flavour-specific decays we can observe the flavour oscillations
- ★ A very rich phenomenology of mixing of K, D, and B mesons