Measuring the CP asymmetry in B^0 meson mixing at LHCb

Lucia Grillo

Heidelberg University, Physikalisches Institut

6th. IMPRS-PTFS, 7th November 2013

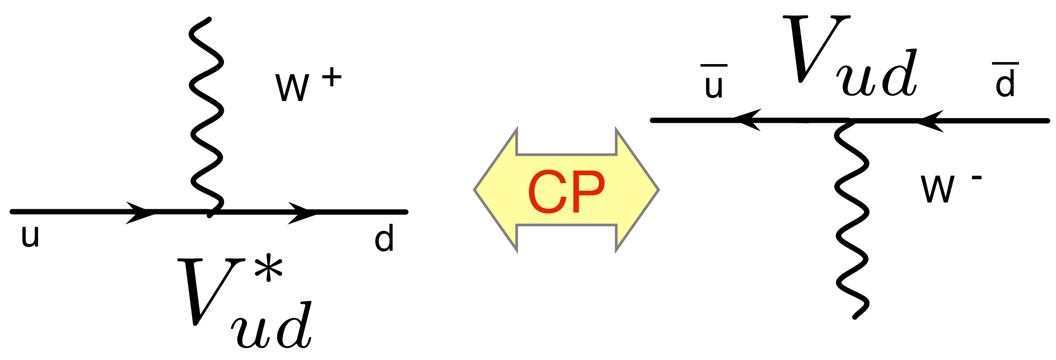
Outline

- CP violation in neutral B meson mixing
- Current experimental status
- Measurement strategy at LHCb
- Focus on the time dependence of our analysis
- Conclusions and perspectives

Short introduction to CP-violation

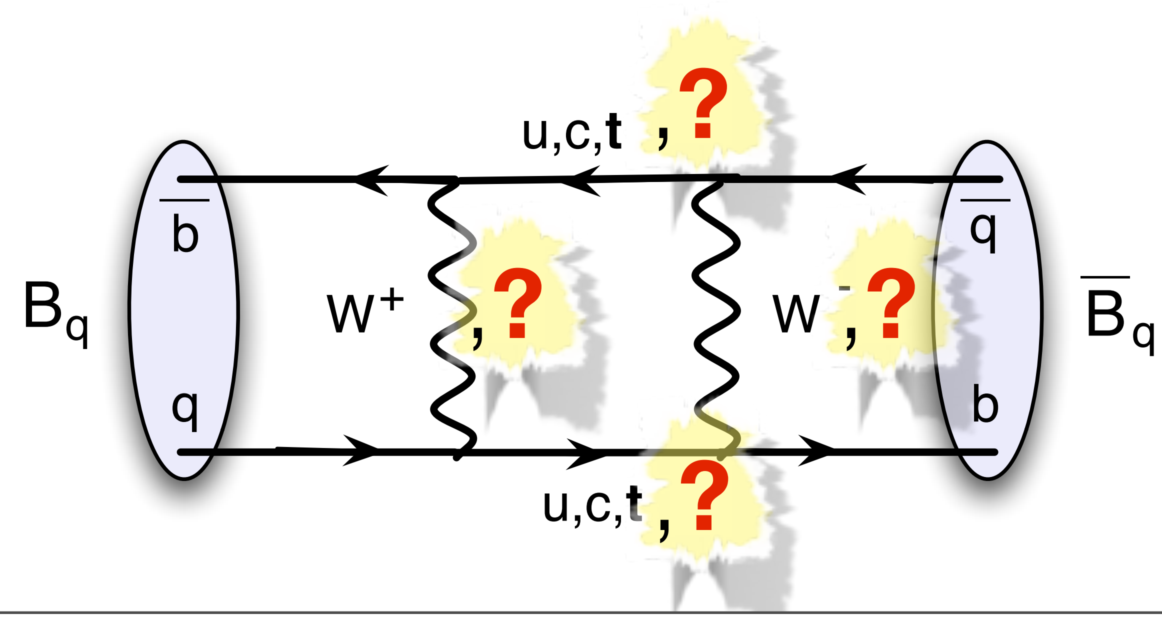
- CKM mechanism: the only way to accommodate CP violation in the Standard Model framework.

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

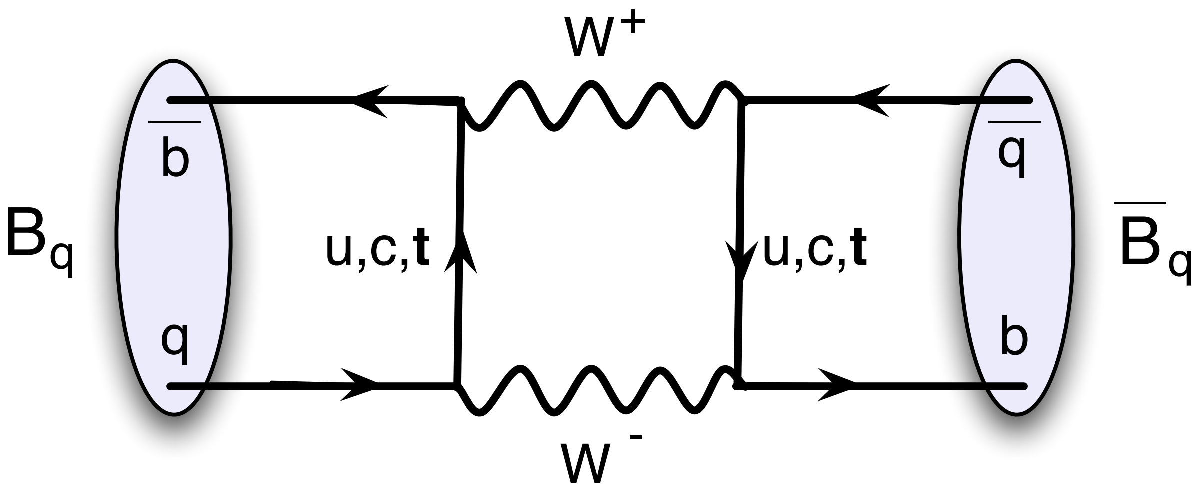


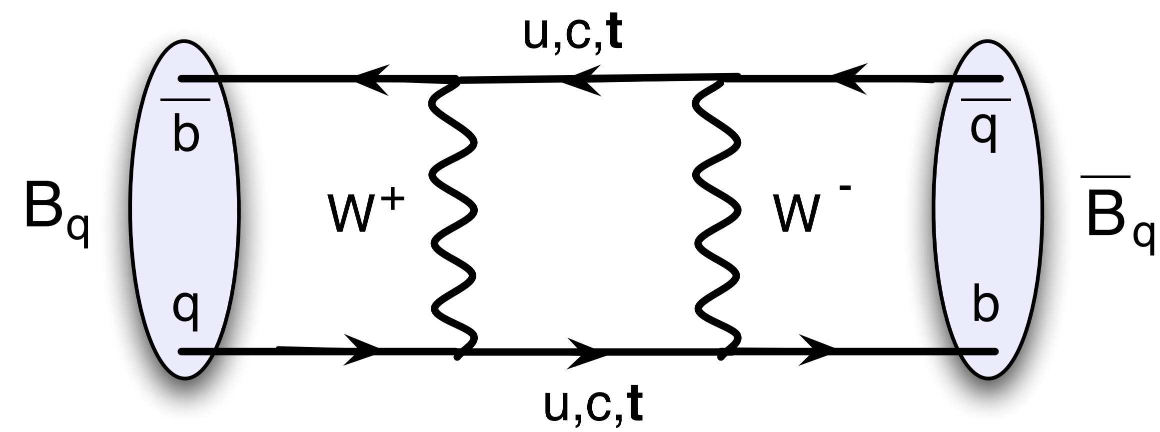
transitions between quarks

- In many extensions of the standard model, additional sources of CP violation can arise from exchange of **new particles** exchanged in virtual transitions, or couplings



B meson mixing...





- Phenomenological Schroedinger equation describing oscillation and decay

$$i\frac{t}{dt}\begin{pmatrix} |B_q(t)\rangle \\ |\bar{B}_q(t)\rangle \end{pmatrix} = \begin{pmatrix} M_{11} - i\frac{\Gamma_{11}}{2} & M_{12} - i\frac{\Gamma_{12}}{2} \\ M_{12}^* - i\frac{\Gamma_{12}^*}{2} & M_{22} - i\frac{\Gamma_{22}}{2} \end{pmatrix}\begin{pmatrix} |B_q(t)\rangle \\ |\bar{B}_q(t)\rangle \end{pmatrix}$$

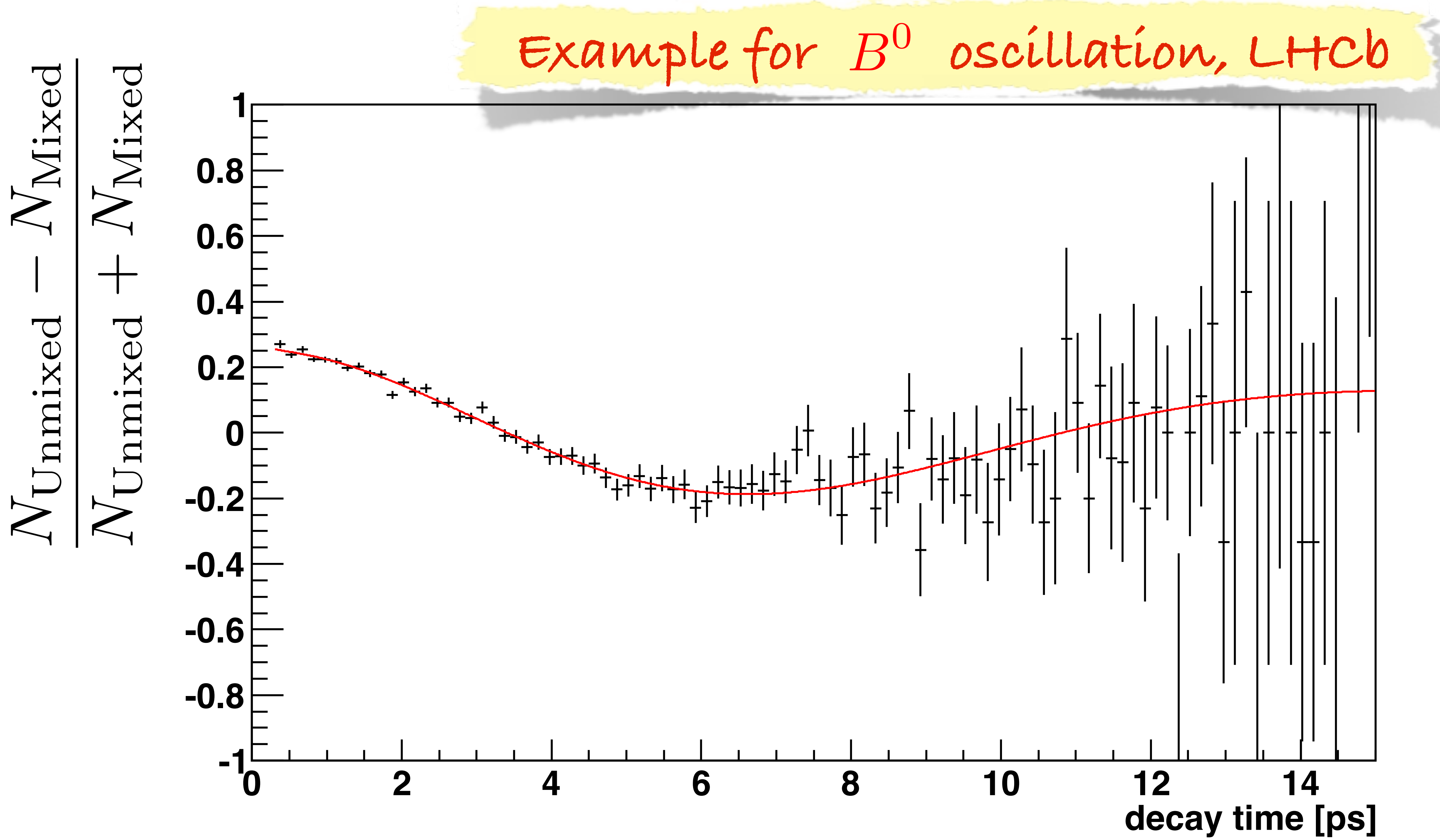
- Mass eigenstates are superpositions of flavor eigenstates

$$|B_L\rangle = p|B_q\rangle + q|\bar{B}_q\rangle$$
$$|B_H\rangle = p|B_q\rangle - q|\bar{B}_q\rangle$$

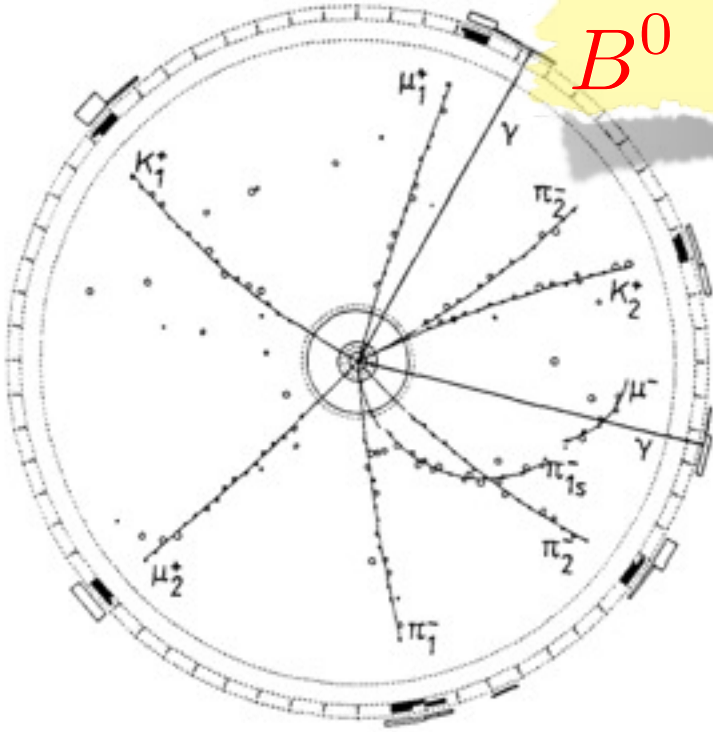
- Mixing observables related to the off diagonal matrix elements M_{12} , Γ_{12} and to the phase $\phi_{12} = \arg(-\mathrm{M}_{12}/\Gamma_{12})$

$$\Delta M = M_H - M_L \approx 2|M_{12}|$$
$$\Delta\Gamma = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|\cos\phi_{12}$$

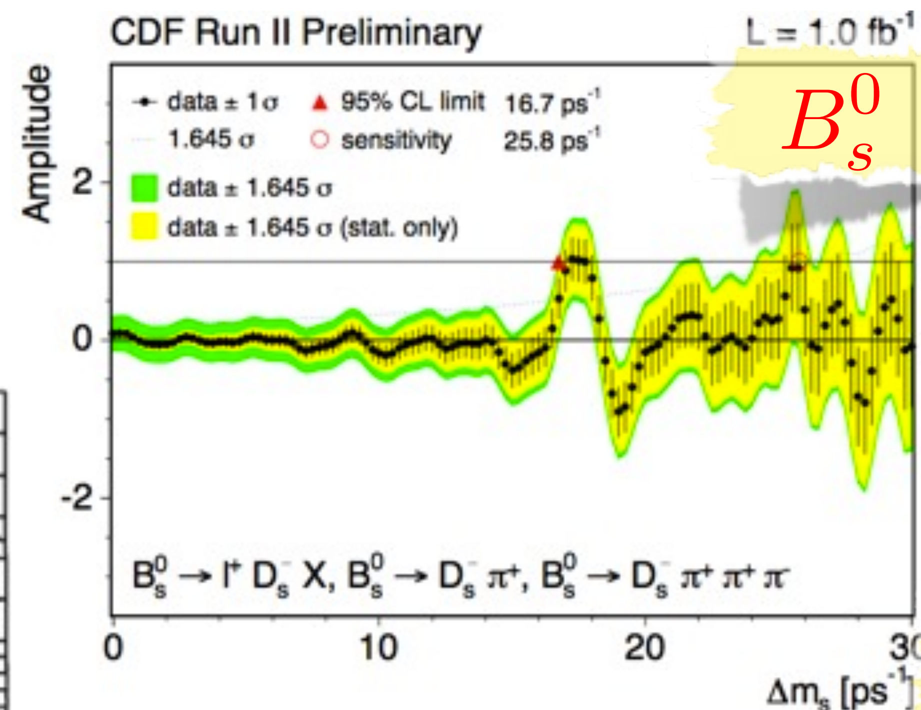
B meson mixing...



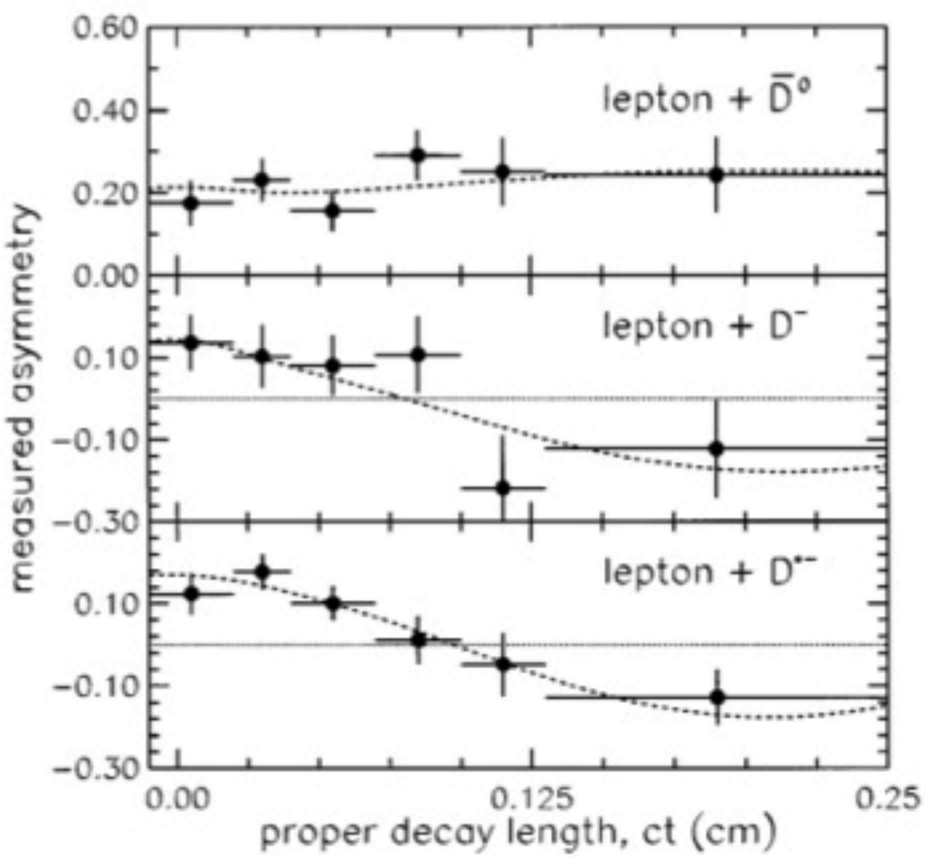
... a well established oscillation



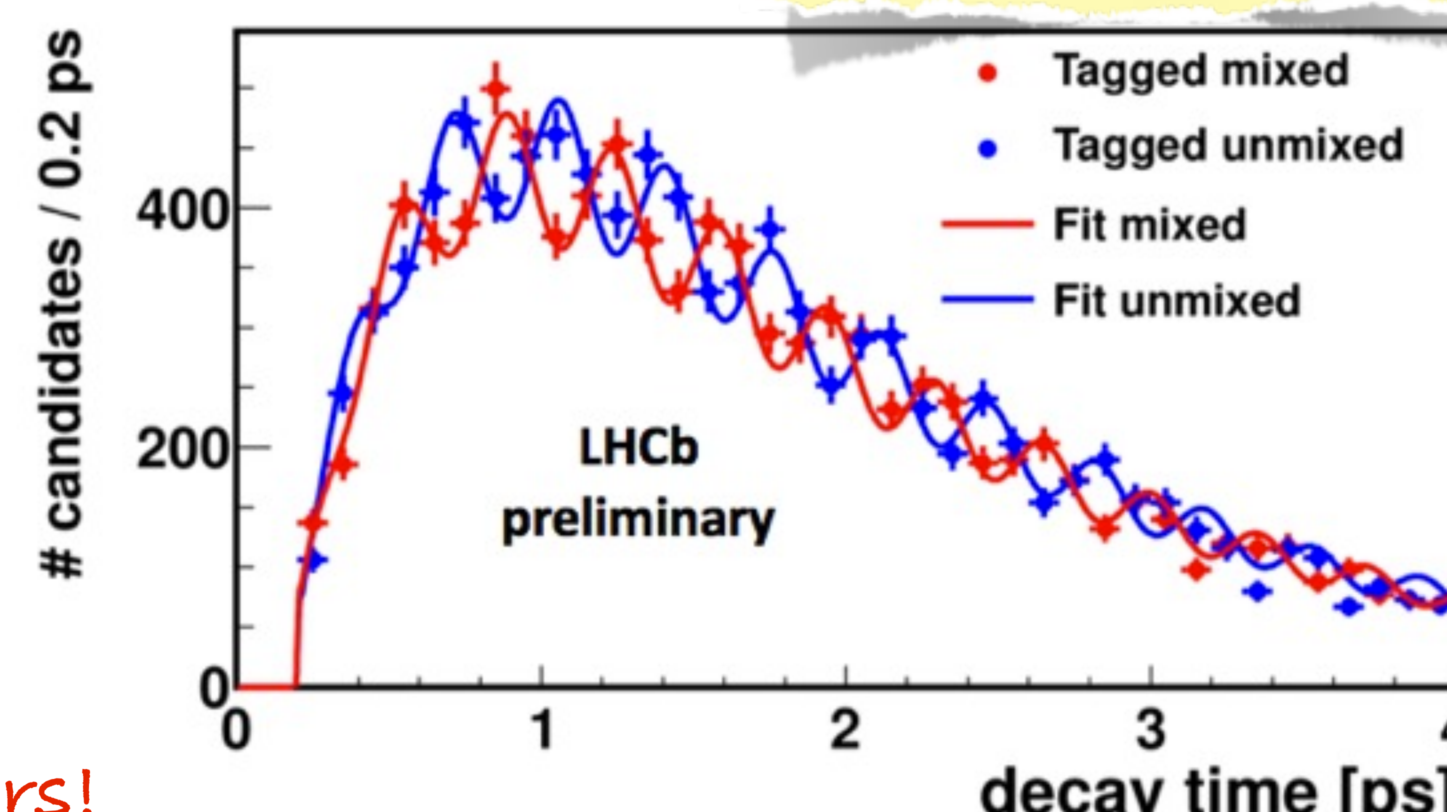
B^0 ARGUS 1987



B_s^0 CDF 2006



B_s^0 LHCb 2013

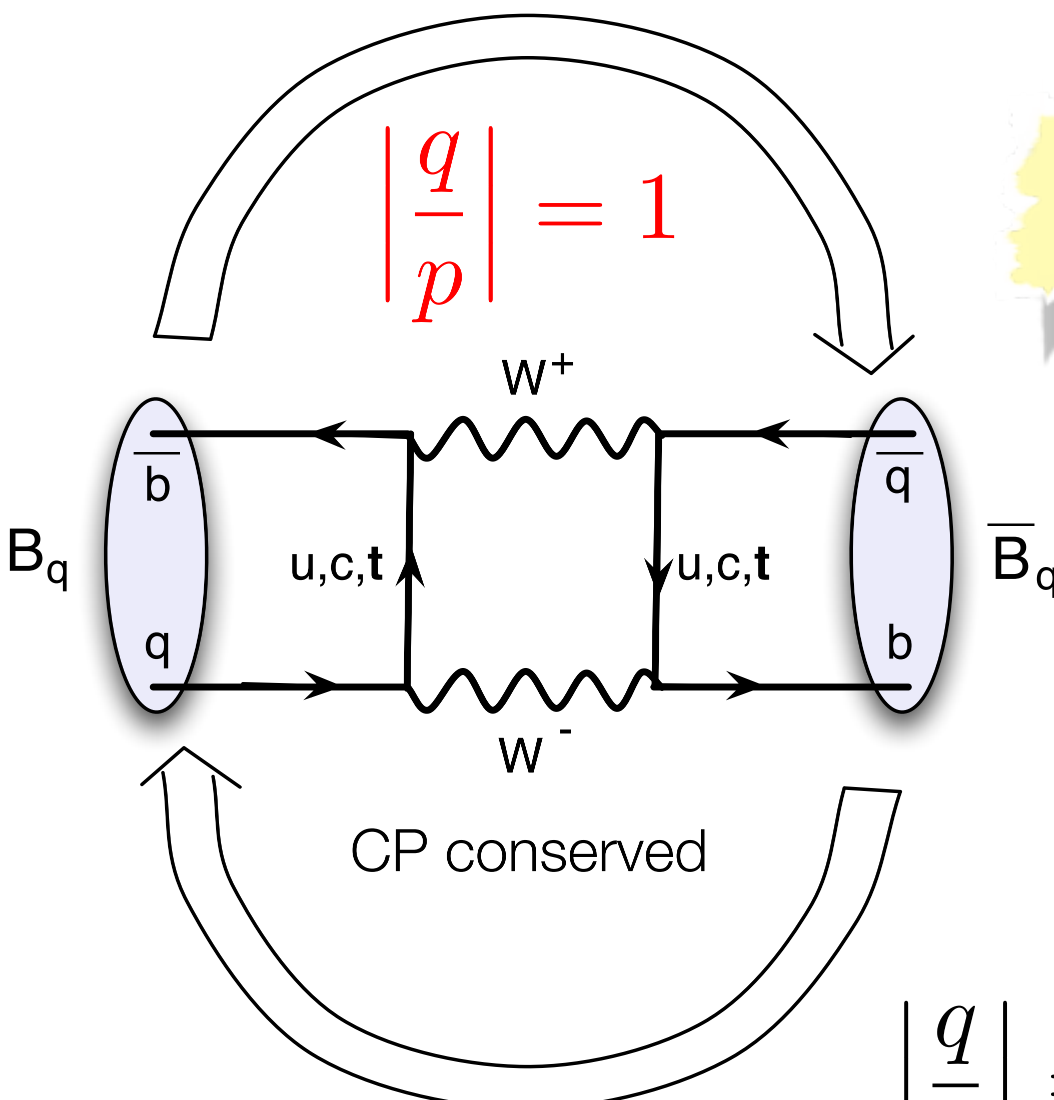


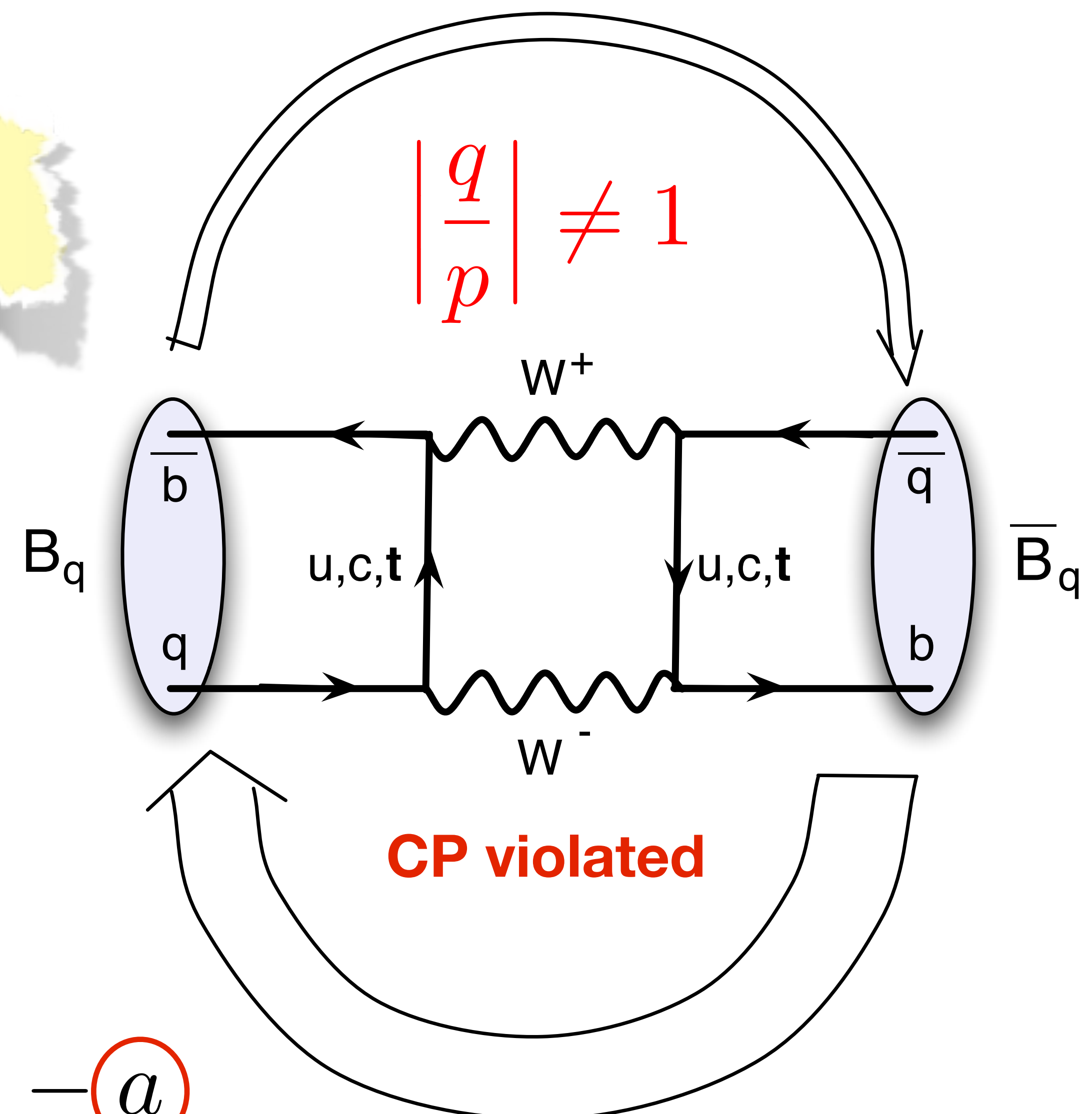
B^0 CDF 1997

... and many others!

CP violation in mixing

- Physical meaning: the probability that a B mixes into a $\bar{B}$ is different from the probability that a $\bar{B}$ mixes into a B





$$\left|\frac{q}{p}\right| = 1 - a$$

Semileptonic ...

$$\left|\frac{q}{p}\right| = 1 - a$$

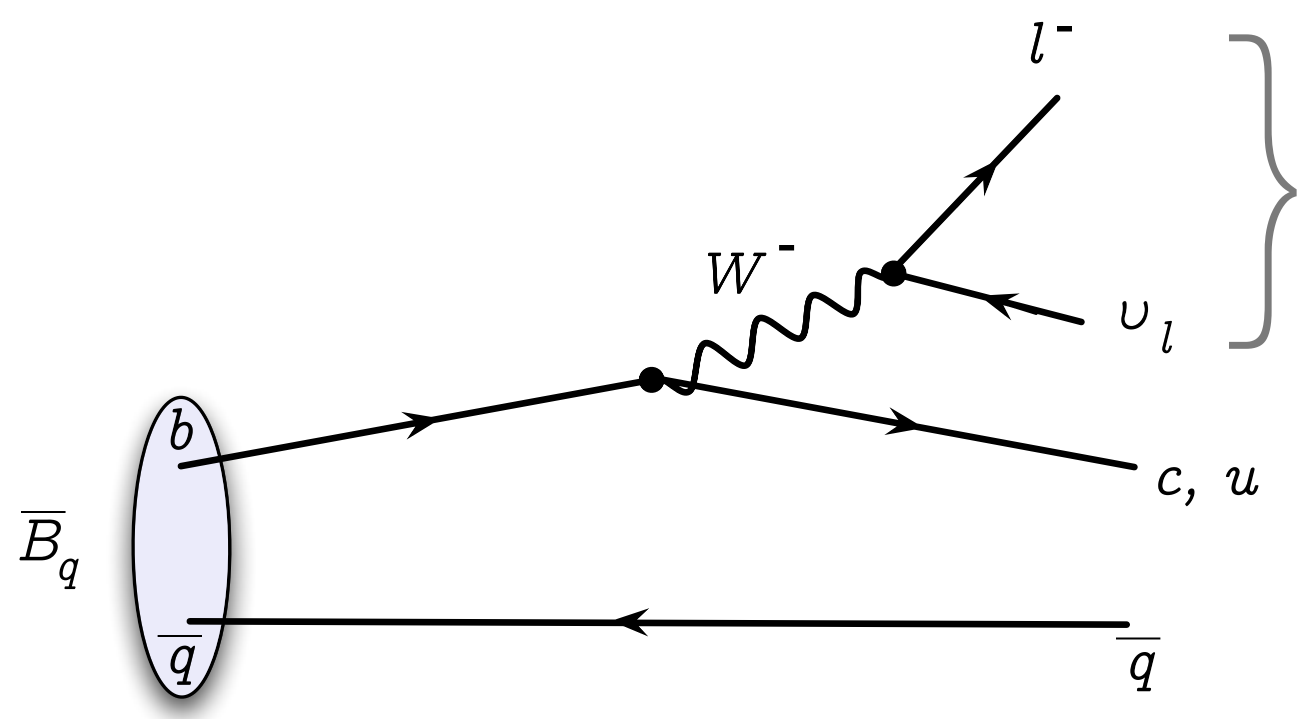
TINY!!!

SM predictions
$10^{-5} B_s^0, 10^{-4} B^0$

- The tinier the asymmetry, the larger the sample we need

SEMILEPTONIC SAMPLES have the highest possible statistics

$\sim 10^7$ events @LHCb



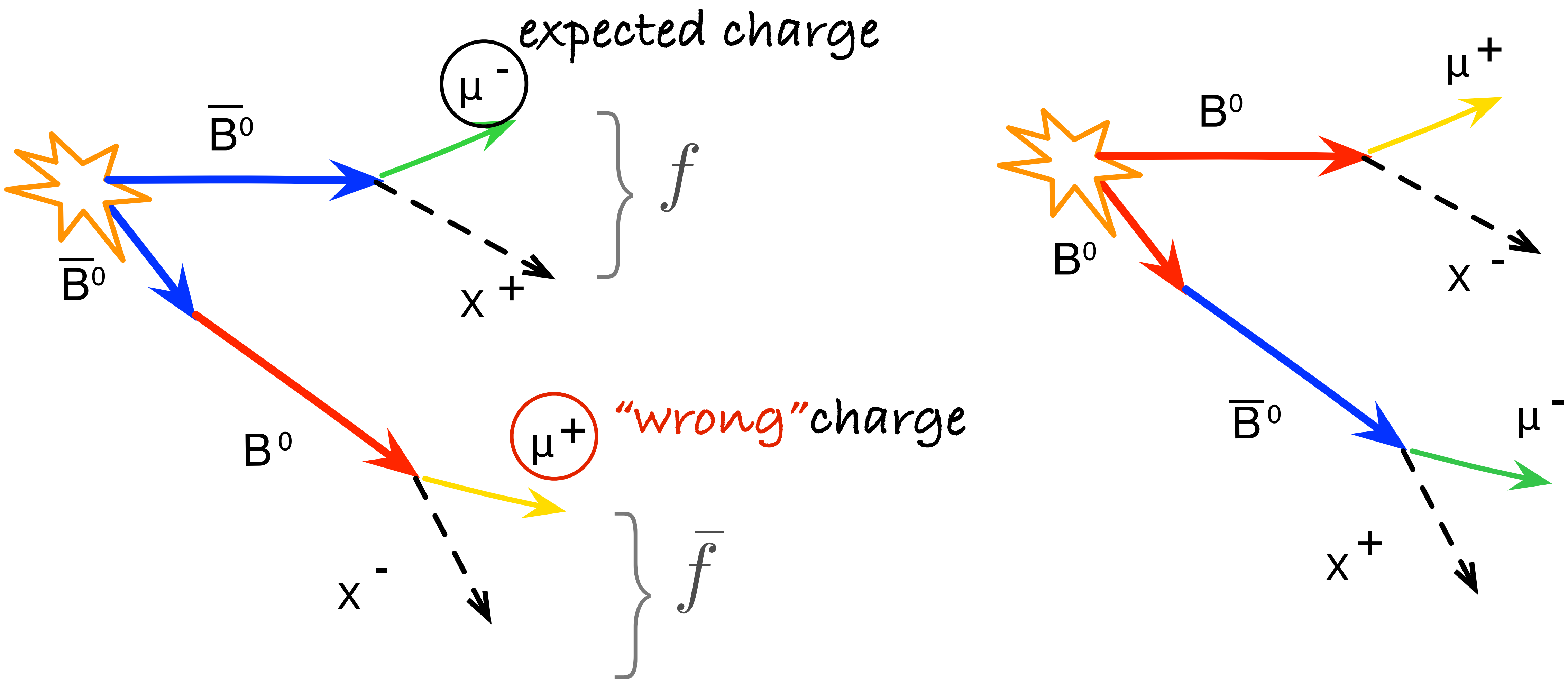
leptonic part
μ^-, ν_μ for example

hadronic part
D^+ for example

... CP violating ...

- we want to quantify how much CP parity is violated in mixing:

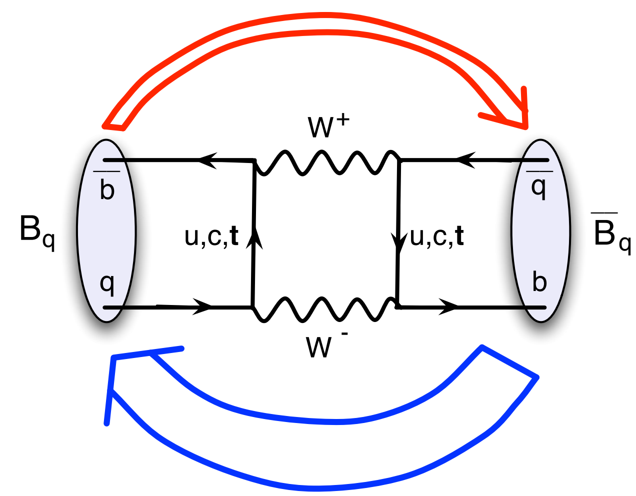
we need to know for each decay if the meson had mixed or not before decaying



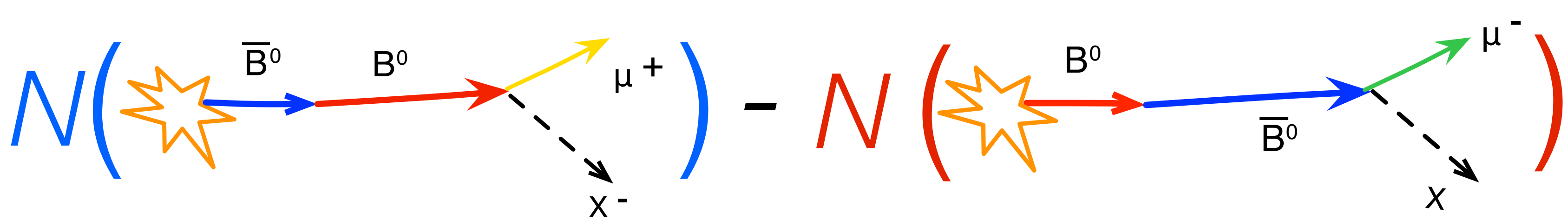
- the charge of the final states particles tells us if the meson had mixed or not

... asymmetry

need to compare the number of decays where mixing had happened



$\Longleftrightarrow$



$\neq 0$

- To measure a ,the amount of CP violation in mixing, we can use the *asymmetry*

$$a = \frac{N(\bar{B}\to f) - N(B\to \bar{f})}{N(\bar{B}\to f) + N(B\to \bar{f})}$$

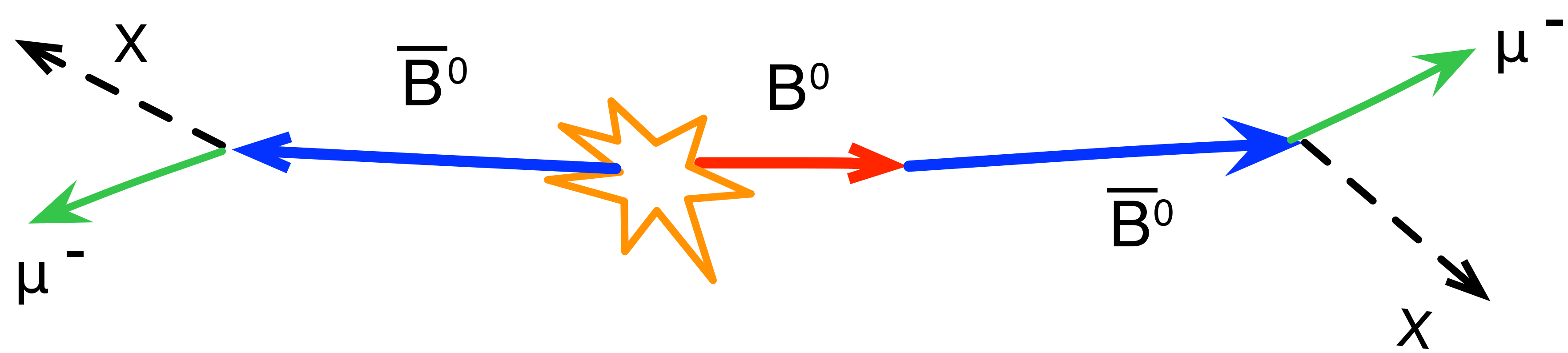
Semileptonic CP violating asymmetry

- The *semileptonic CP asymmetry*

$$a_{sl} = \quad a = \frac{N(\bar{B}\to f) - N(B\to \bar{f})}{N(\bar{B}\to f) + N(B\to \bar{f})}$$

we still need to know if at the production we had a B or $\bar{B}$

- We can just consider the asymmetry in the final state particles



$$A_{\text{meas}} = \frac{N(f) - N(\bar{f})}{N(f) + N(\bar{f})} = \frac{a_{sl}}{2}$$

ASSUMPTION NEEDED:

$$N(B^0) = N(\bar{B}^0)$$

Experimental status

LHCb result for a_{sl}^{s}

LHCb-CONF-2012-022.

MORE THAN 3 σ AWAY from STANDARD MODEL!

Home | Video | Themen | Forum | English | DER SPIEGEL | SPIEGEL TV | Abo | Shop

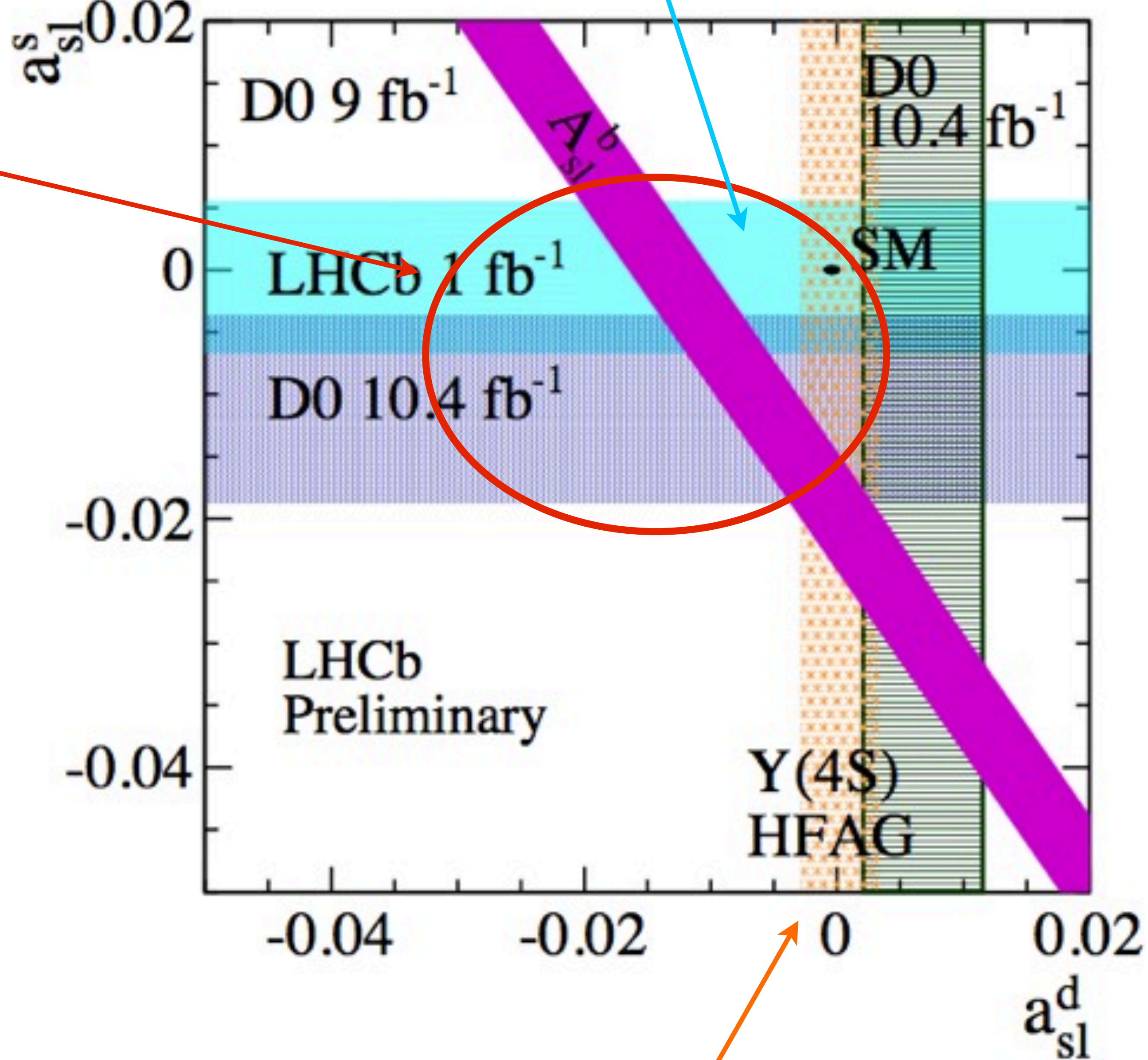
SPIEGEL ONLINE WISSENSCHAFT

Politik | Wirtschaft | Panorama | Sport | Kultur | Netzwelt | Wissenschaft | Gesundheit | einestages | Karriere | Uni | Schule | Reise | Auto

Nachrichten > Wissenschaft > Natur > Physik > Fermilab: Neue Asymmetrie zwischen Materie und Antimaterie entdeckt

Fermilab: Neue Asymmetrie zwischen Materie und Antimaterie entdeckt

Antimaterie ist eben doch nicht das perfekte Spiegelbild von Materie. Einen neuen Beweis dafür haben Physiker jetzt bei Protonen-Antiprotonen-Kollisionen entdeckt. Die Unterschiede, die sie dabei beobacht haben, sind erstaunlich: Sie widersprechen den bisherigen Theorien der Teilchenphysik.



DØ Collaboration: evidence for an asymmetry of (-0.787 ± 0.172 ± 0.093)% in a mixture of B^0 and B_s^0 semileptonic decays

DØ collaboration, V. M. Abazov et al.,Phys.Rev. D84 (2011) 052007, arXiv:1106.6308.

Still more than 3 σ away

arXiv:1310.0447v1 [hep-ex]

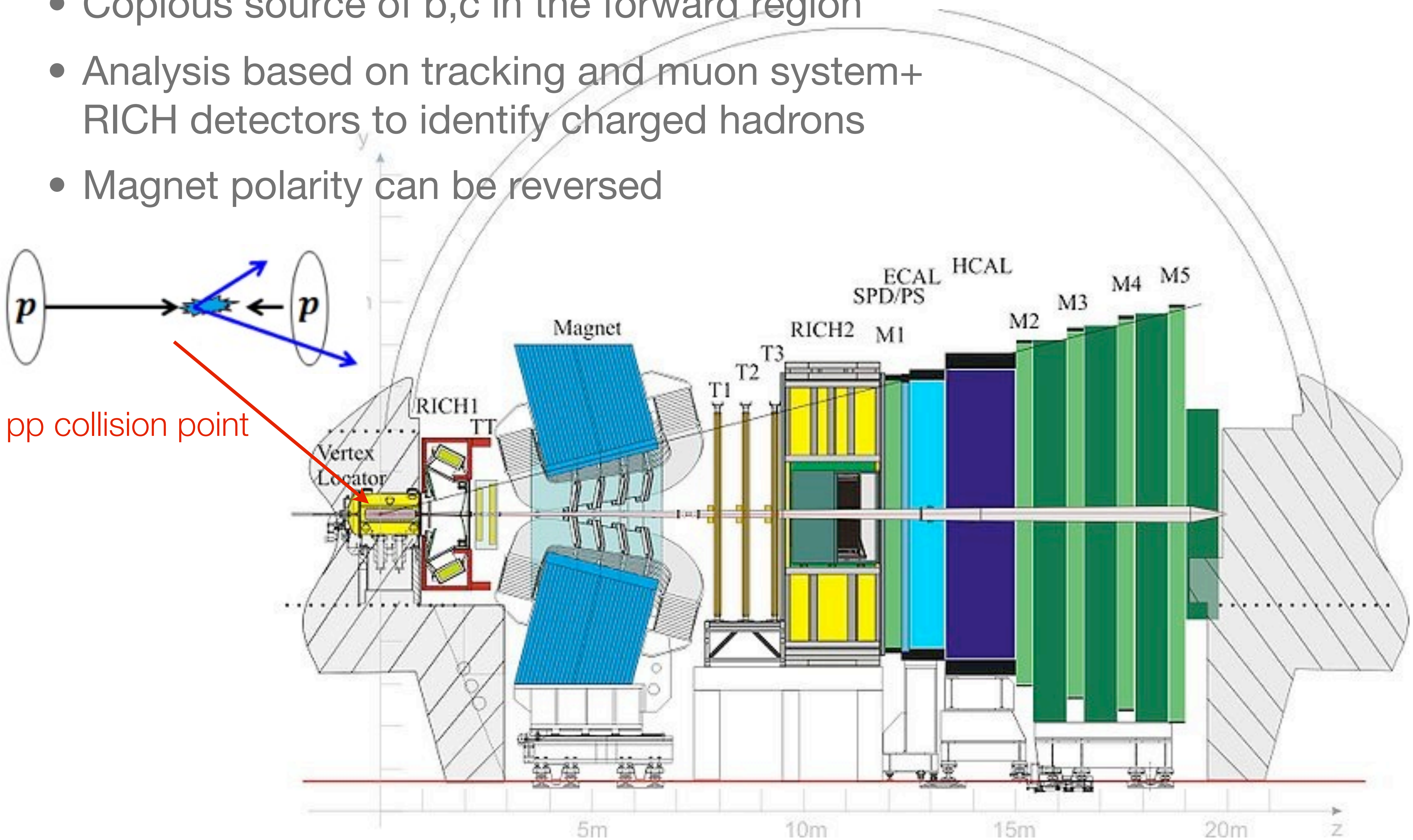
e+e− experiments operating on the Υ(4S) resonance: a_{sl}^{d} observed to be small

Heavy Flavor Averaging Group, D. Asner et al., Averages of b-hadron, c-hadron, and τ-lepton properties, arXiv:1010.1589, online updates available at http://www.slac.stanford.edu/xorg/hfag/

LHCb

Single-arm forward spectrometer at LHC collider

- Copious source of b,c in the forward region
- Analysis based on tracking and muon system+ RICH detectors to identify charged hadrons
- Magnet polarity can be reversed



Production asymmetry

- in proton-proton collisions the quarks b and $\bar{b}$ are produced in equal amount, but that is not true for the mesons

$$N(B^0) \neq N(\bar{B}^0)$$

- production asymmetry definition: $A_p = \frac{N(B) - N(\bar{B})}{N(B) + N(\bar{B})}$

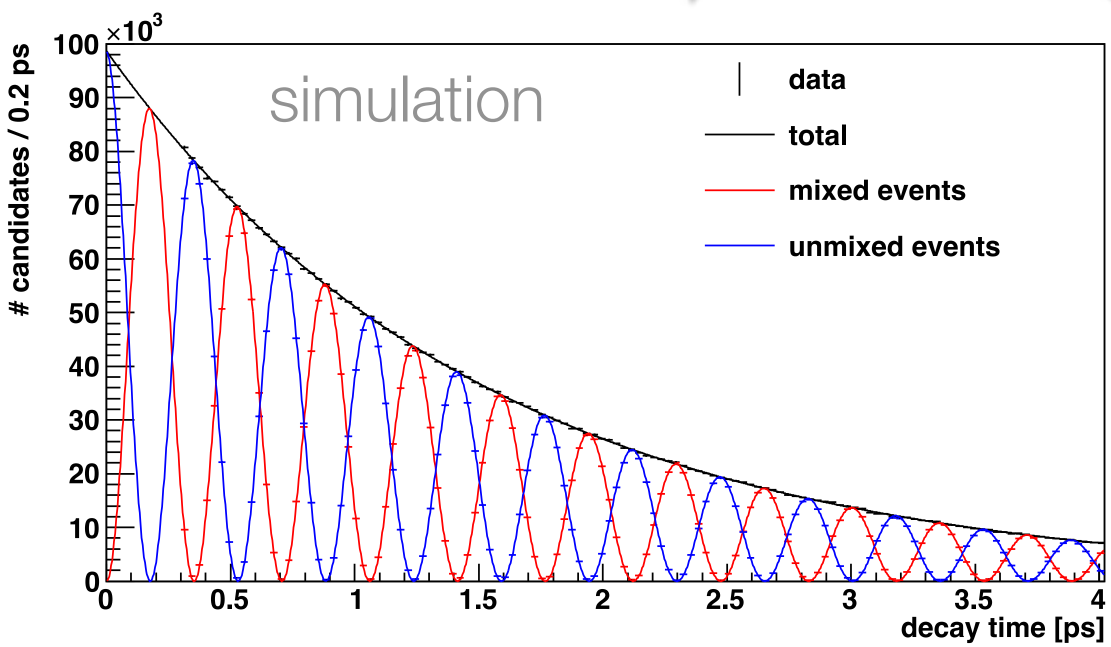
- the time integrated asymmetry cannot be used anymore, we need to count the number of decays in each interval of time:

$$A_{\text{meas}} = \frac{\Gamma[f,t] - \Gamma[\bar{f},t]}{\Gamma[f,t] + \Gamma[\bar{f},t]} = \frac{a_{sl}}{2} + \left(A_p - \frac{a_{sl}}{2}\right)\cos(\Delta\text{M}t)$$

Measurement Strategy of a_{sl} at LHCb

- When $N(B^0) \neq N(\bar{B}^0)$ makes a difference?...

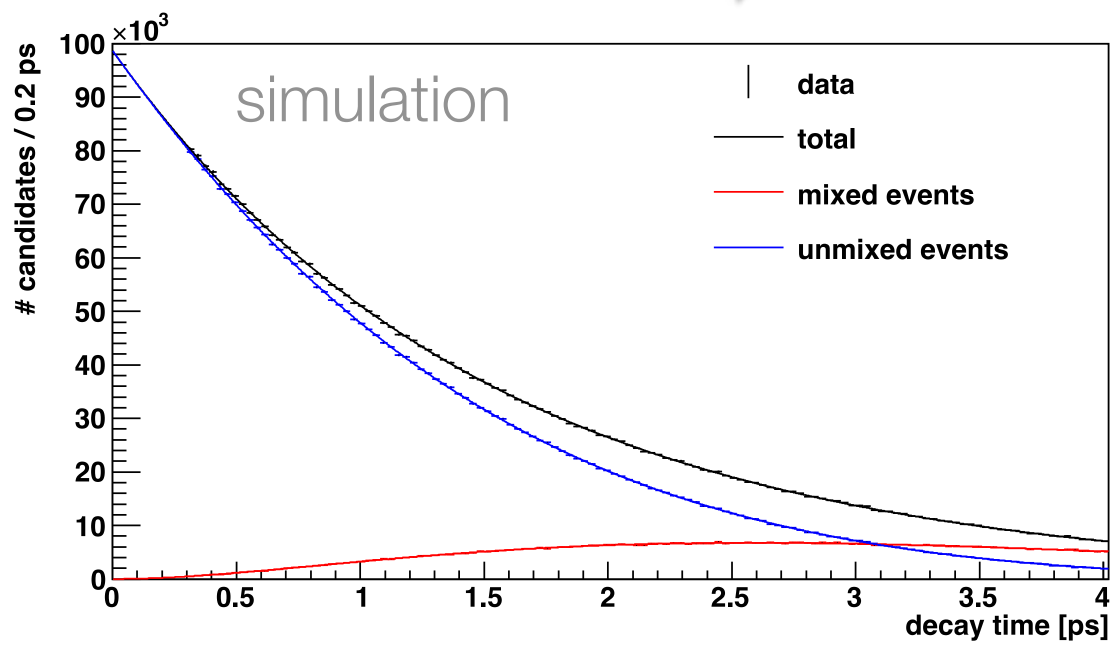
B_s^0 case



$$\Delta M_s = 17.768 \text{ps}^{-1}$$

time integrated analysis is feasible

B^0 case

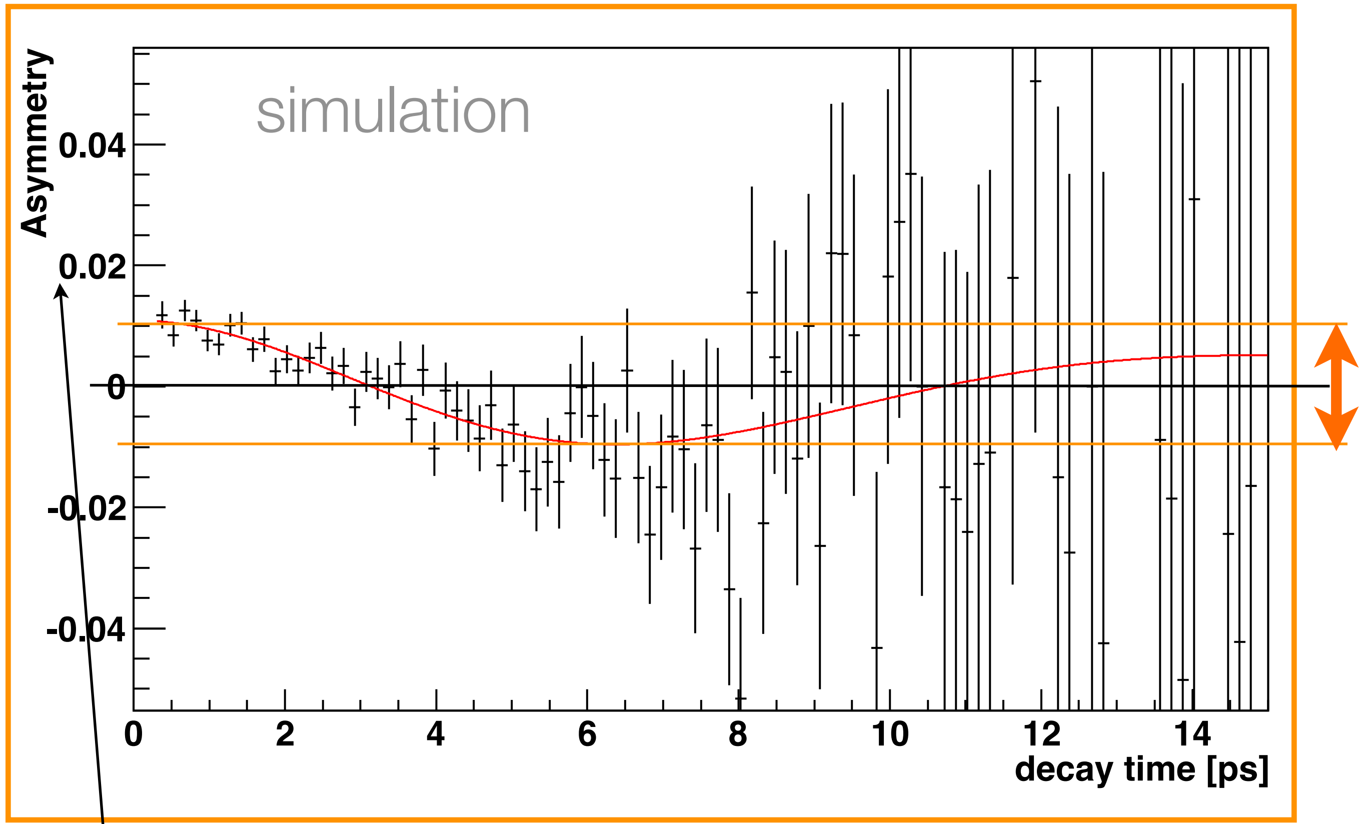


$$\Delta M_d = 0.51 \text{ps}^{-1}$$

time dependent analysis is needed

....in our case!

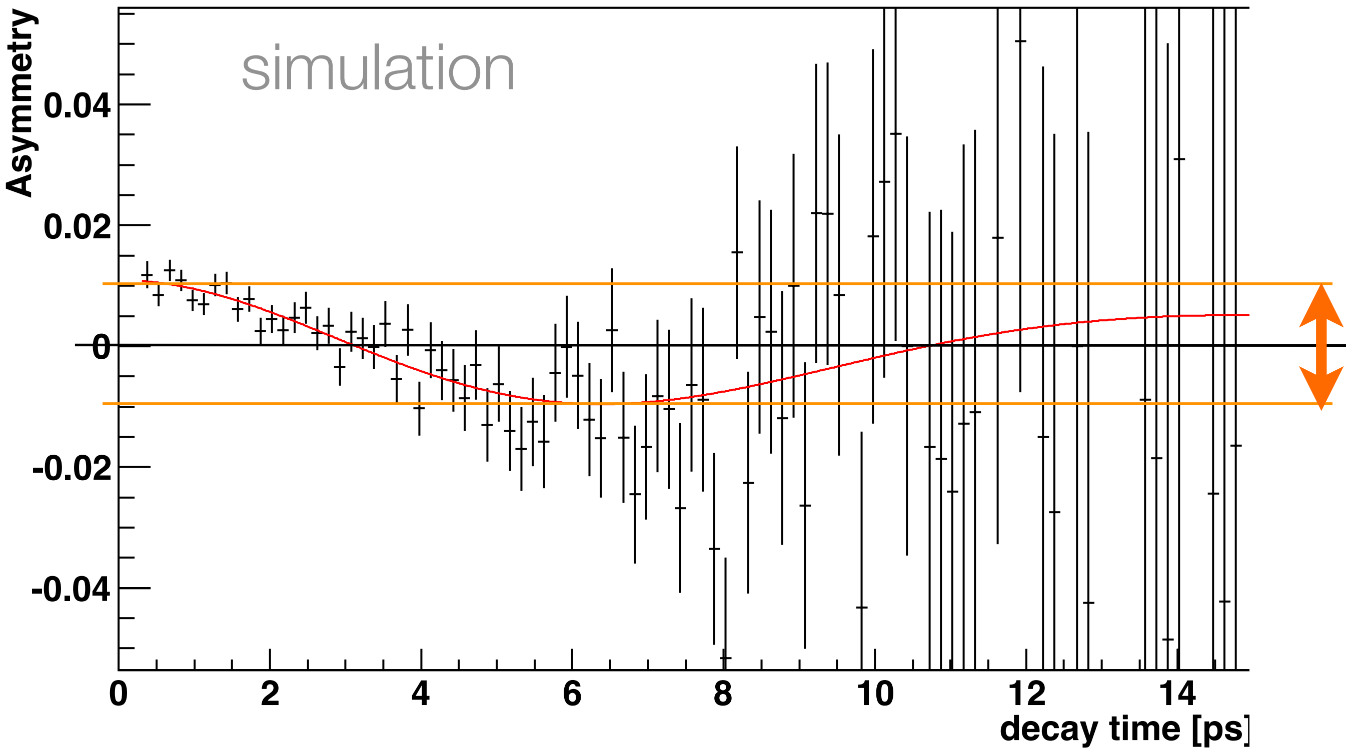
$$A_{\text{meas}} = \frac{\Gamma[f,t] - \Gamma[\bar{f},t]}{\Gamma[f,t] + \Gamma[\bar{f},t]} = \frac{a_{sl}}{2} + \left(A_p - \frac{a_{sl}}{2}\right)\cos(\Delta \text{M} t)$$

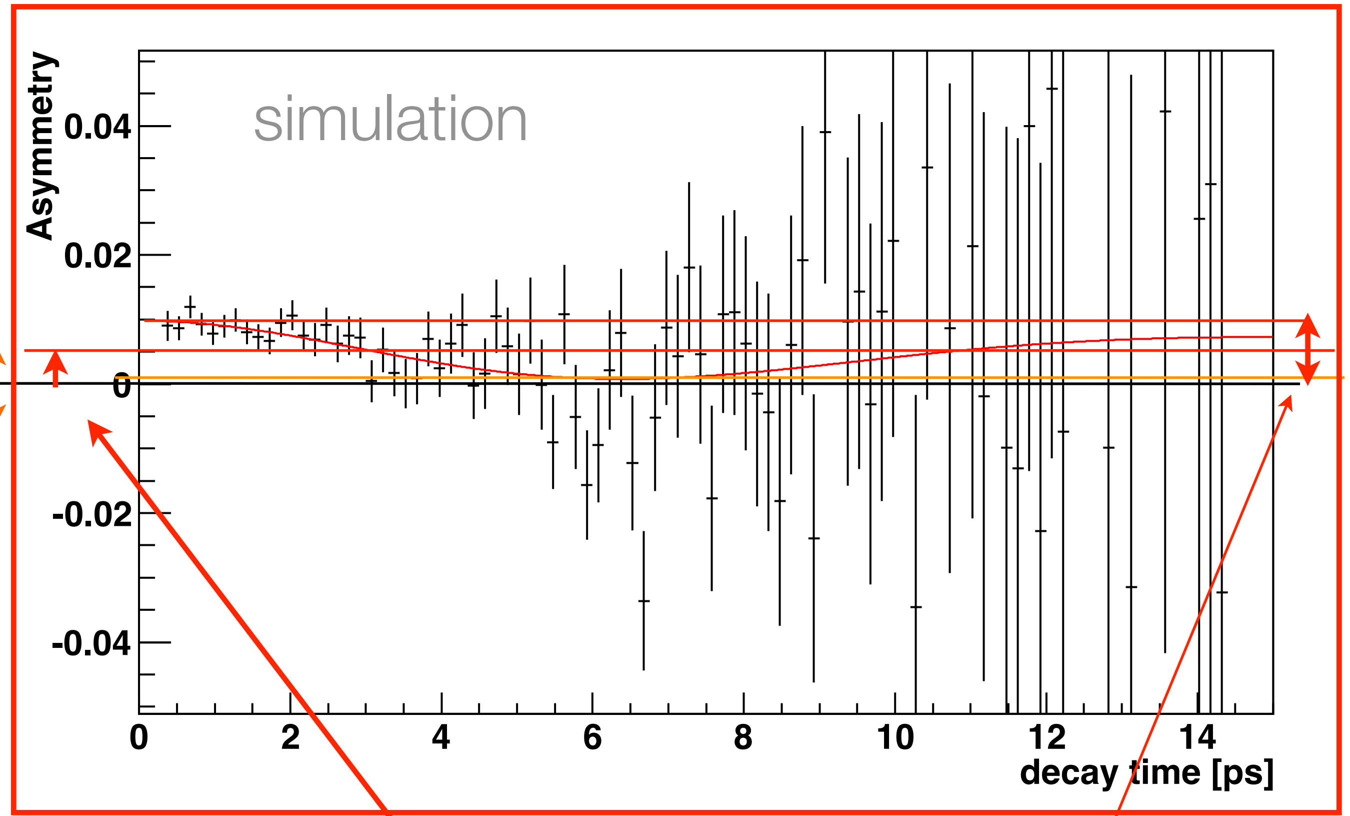


$$A_p = 1\%$$

$$\frac{N(\mu^-) - N(\mu^+)}{N(\mu^-) + N(\mu^+)}$$

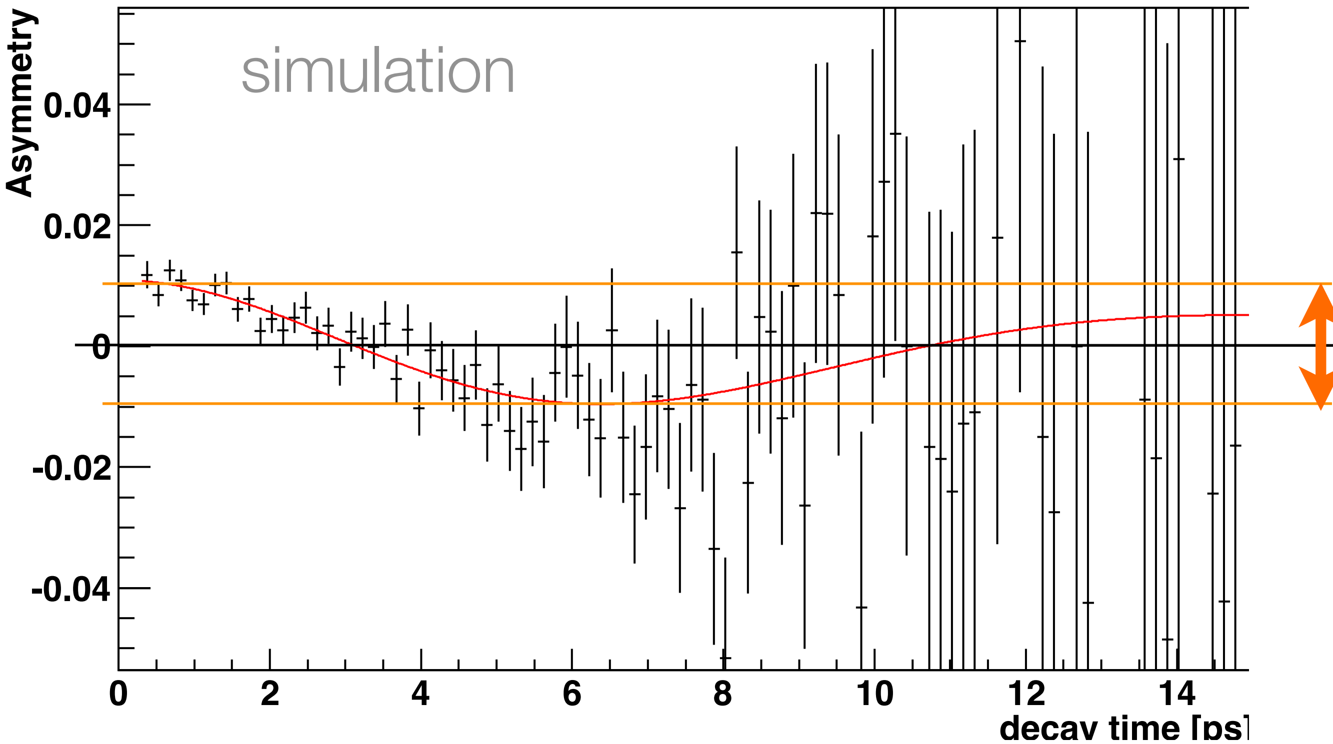
$$A_{\rm meas} = \frac{\Gamma[f,t] - \Gamma[\bar{f},t]}{\Gamma[f,t] + \Gamma[\bar{f},t]} = \frac{a_{sl}}{2} + \left(A_p - \frac{a_{sl}}{2}\right)\cos(\Delta {\rm Mt})$$

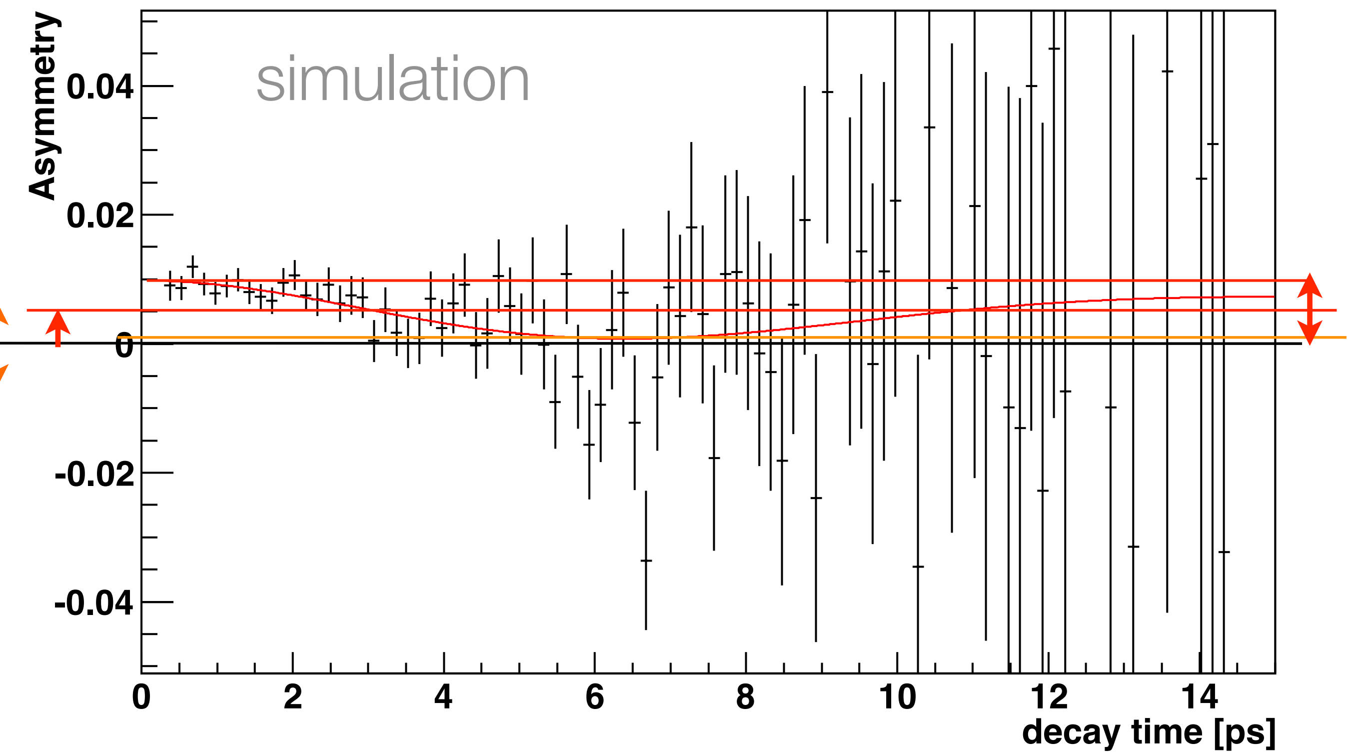




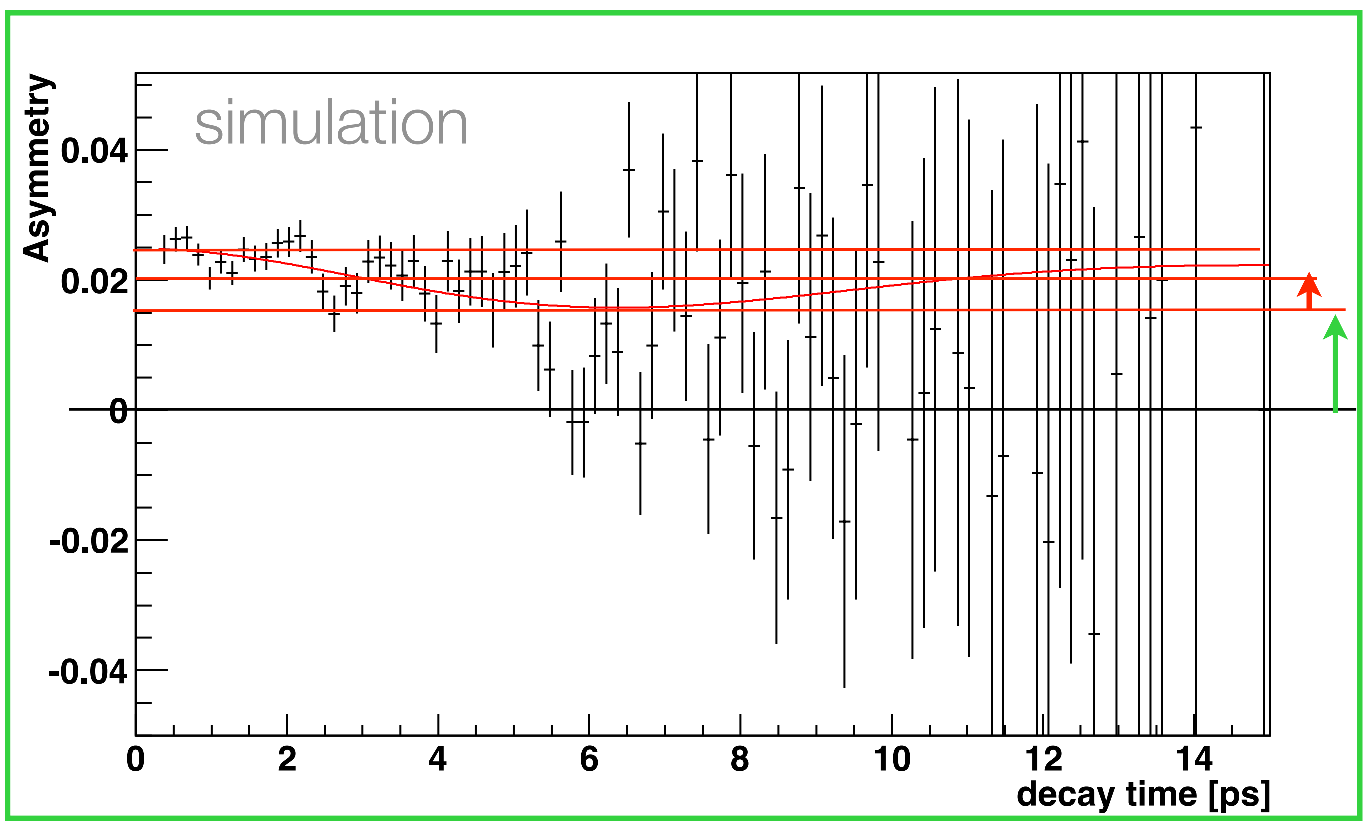
$A_p = 1\%$ + $a_{sl} = 1\%$

$$A_{\text{meas}} = \frac{\Gamma[f,t] - \Gamma[\bar{f},t]}{\Gamma[f,t] + \Gamma[\bar{f},t]} = \frac{a_{sl}}{2} + \left(A_p - \frac{a_{sl}}{2}\right)\cos(\Delta\text{Mt}) \quad + A_D$$





- it was not the end of the story!: an **additional shift** will come from the **Detection Asymmetry**



$A_p = 1\%$ +

$a_{sl} = 1\%$ +

$A_D = 1.5\%$

When the going gets tough, the tough get going

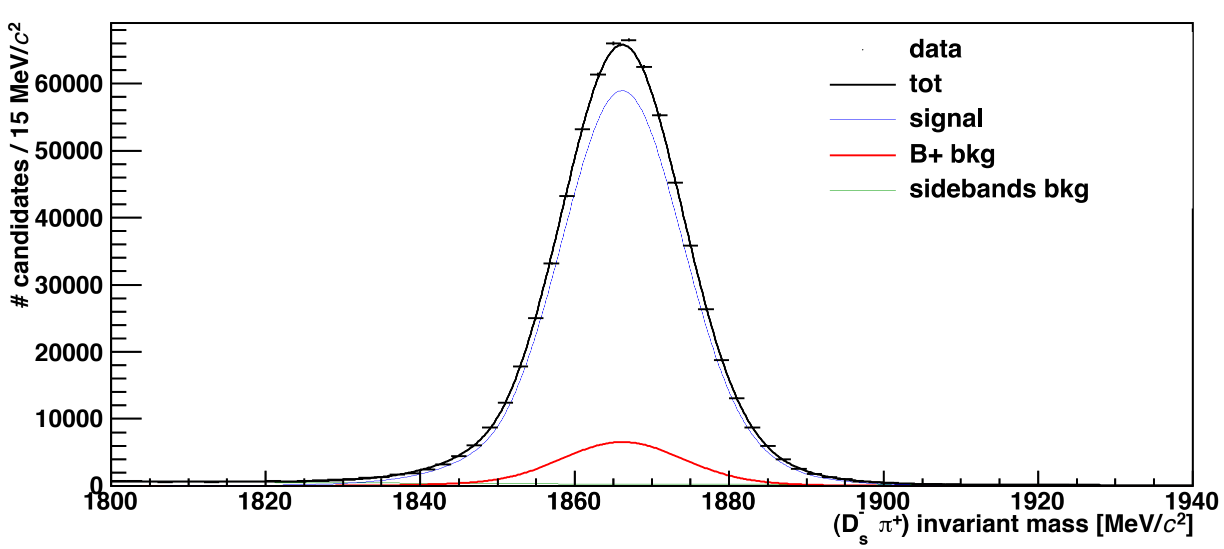
Measurement Strategy of a_{sl}^{d} at LHCb

- A binned maximum likelihood fit is used to extract a_{sl}^{d} and A_P, A_D as input
- The probability density function looks like:

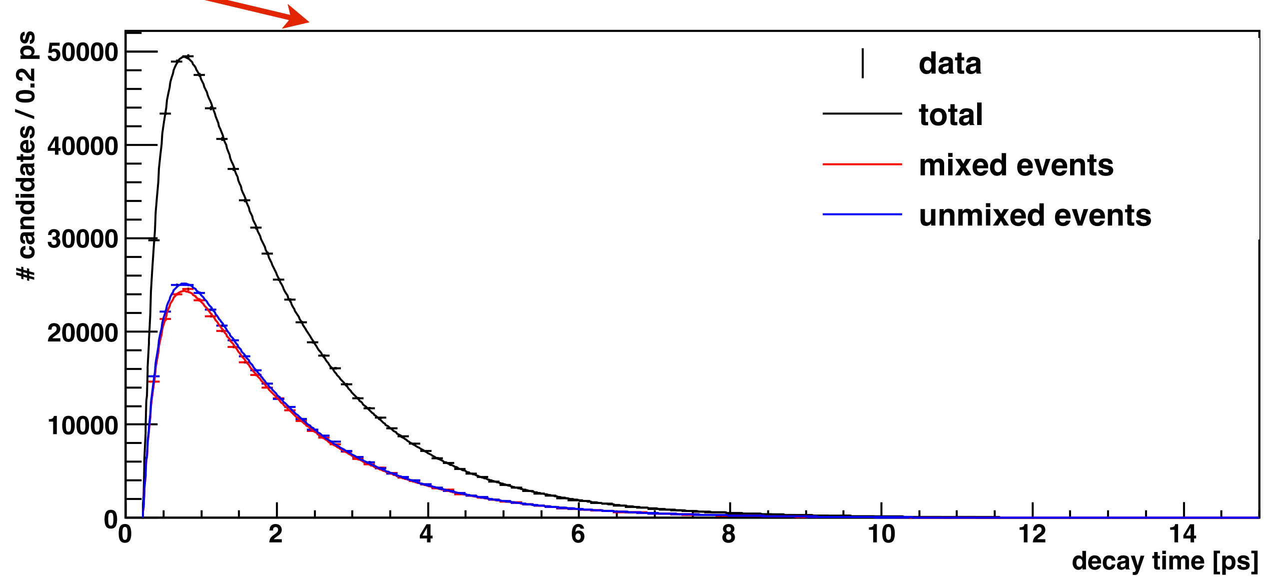
m D^0 mass (or D^+), t decay time, q final state charge

$$f_{sig}\mathcal{P}_{sig}(m) \cdot \mathcal{P}_{sig}(t,q) + (1 - f_{sig})\mathcal{P}_{bkg}(m) \cdot \mathcal{P}_{bkg}(t,q)$$

mass distribution



t distribution

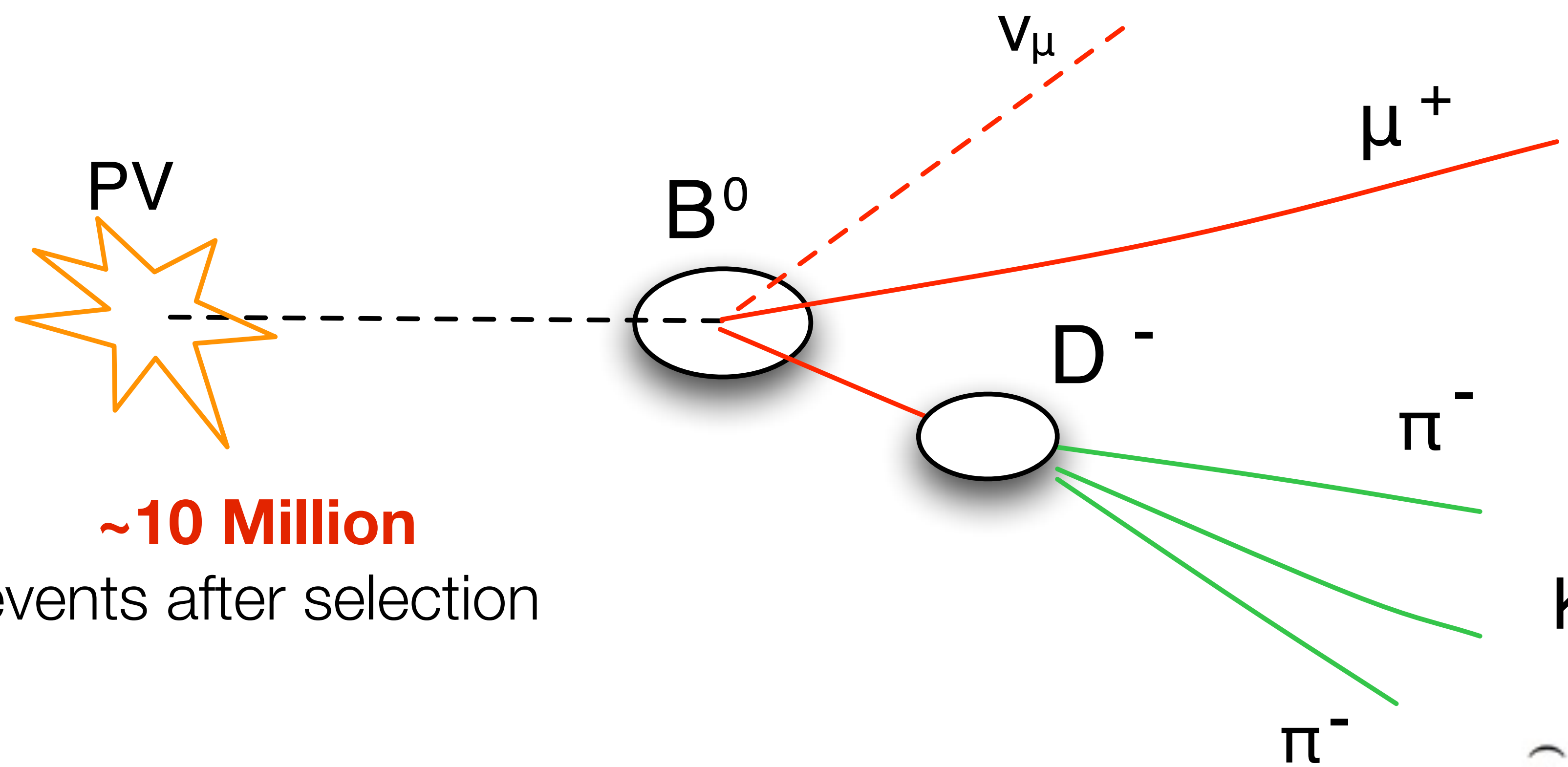


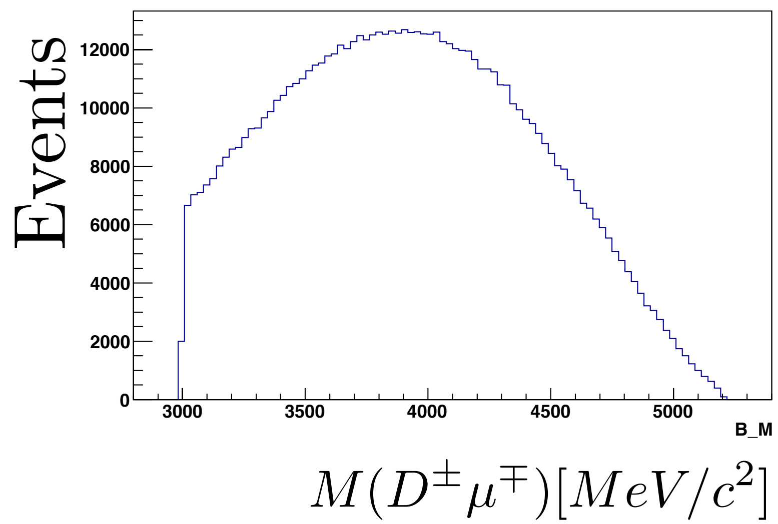
$$\mathcal{P}_{sig}(t,q) = \mathcal{N}e^{-\Gamma_d t}\left(1 \pm A_D \pm \frac{a_{sl}^{d}}{2} + \left(A_P - \frac{a_{sl}^{d}}{2}\right)\cos(\Delta \mathrm{m_d t})\right)$$

+ detector resolution, trigger, selection effects

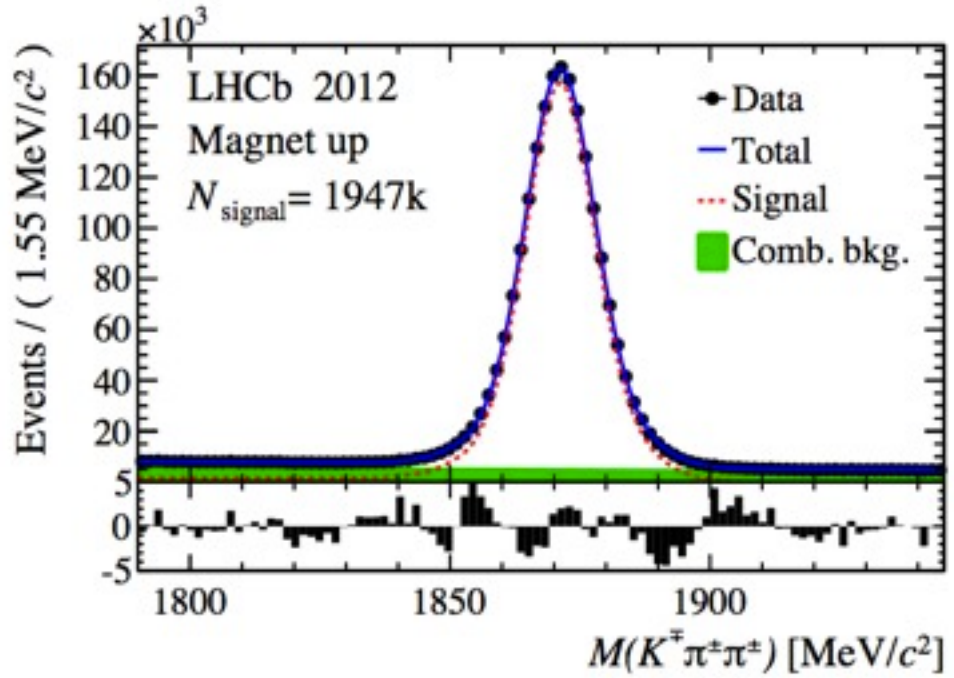
Signal decays

$$B^0 \to D^- \mu^+ \nu_\mu, D^- \to K^+ \pi^- \pi^-$$

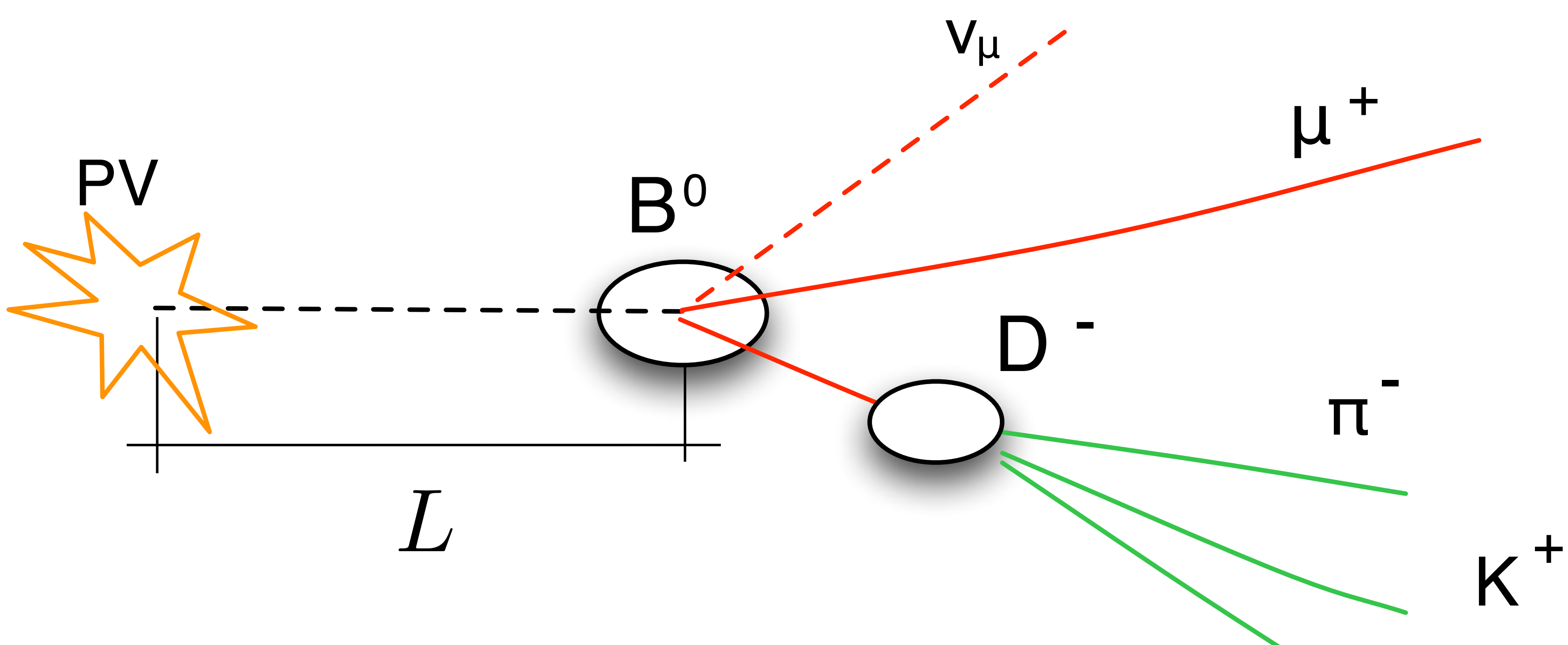




~10 Million
events after selection



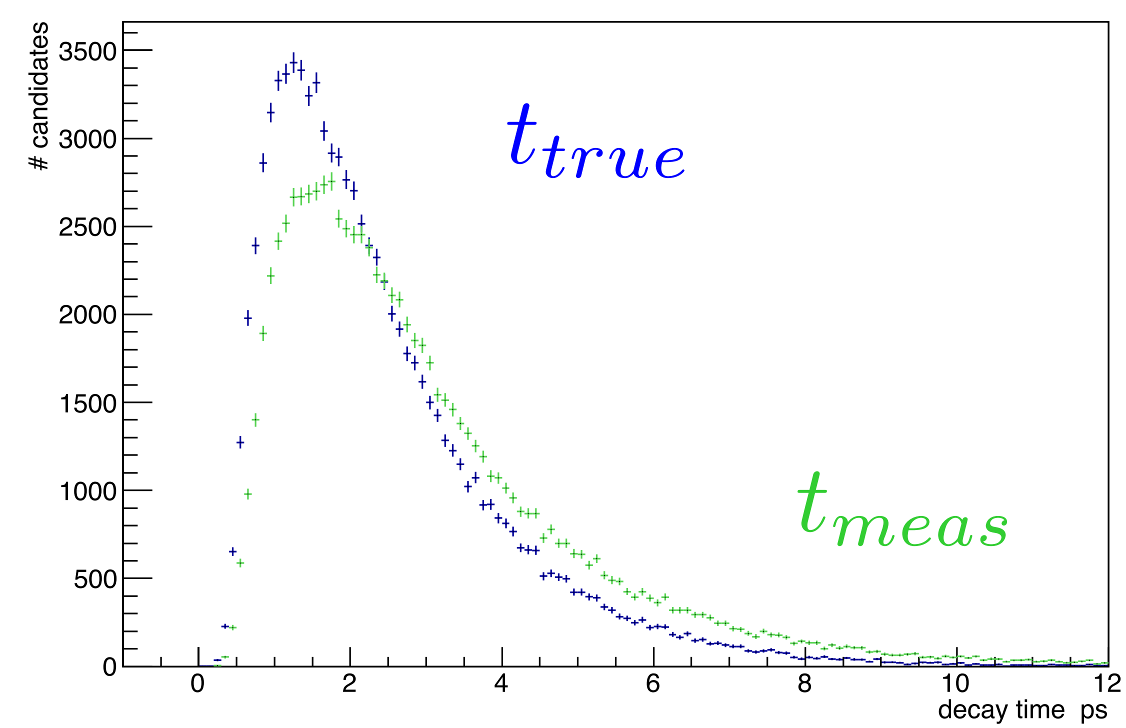
Missing a neutrino...



$$t = \frac{L}{\beta}\gamma = \frac{L \cdot M}{|\vec{p}|}$$

leads to a different time distribution

studies form MC:



Missing neutrino: k-factor method

- measured proper time:

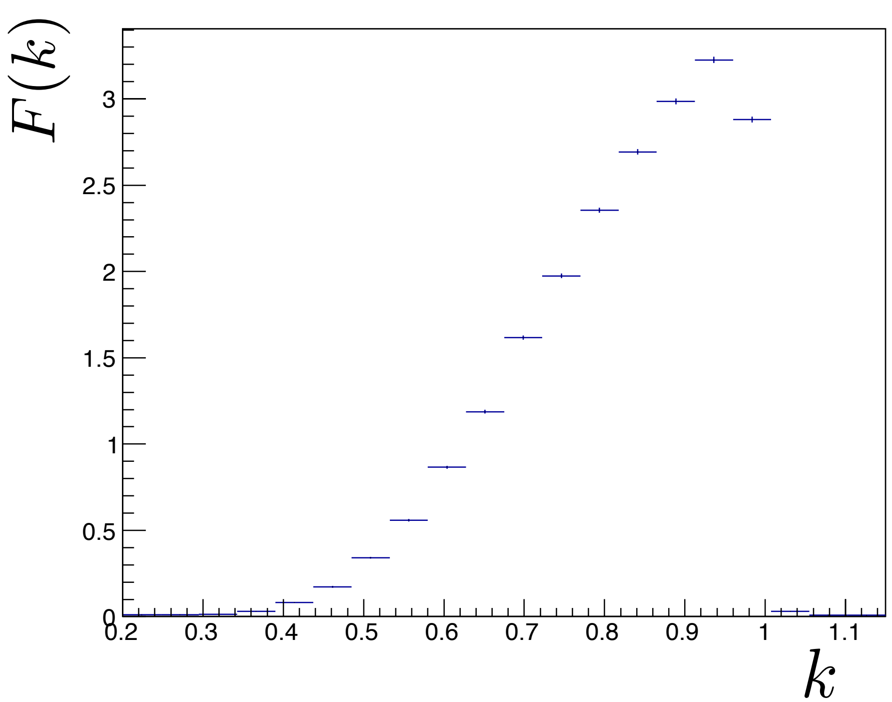
$$t = \frac{L_{reco} \cdot M_{PDG}}{|\vec{p_{reco}}|}$$

"mass problem" solved

"momentum problem":

- to correct for this, one can use the MC and define k factors:

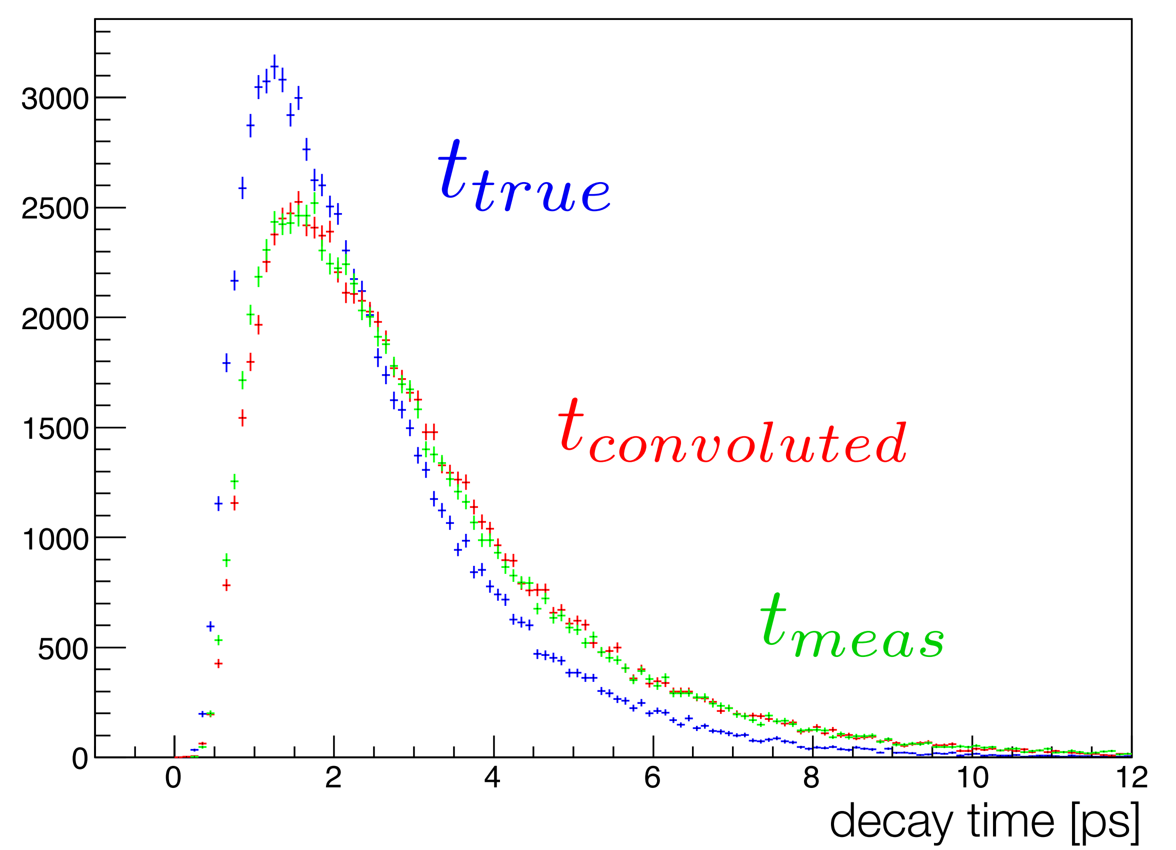
$$k = \frac{|\vec{p_{reco}}|}{|\vec{p_{true}}|}$$



- idea: use the k-factor distribution **as a resolution**:

  * The convolution of t_{meas} with the k distribution should give t_{true}

  * ... and the convolution of t_{true} with the $1/k$ distribution should give t_{meas}

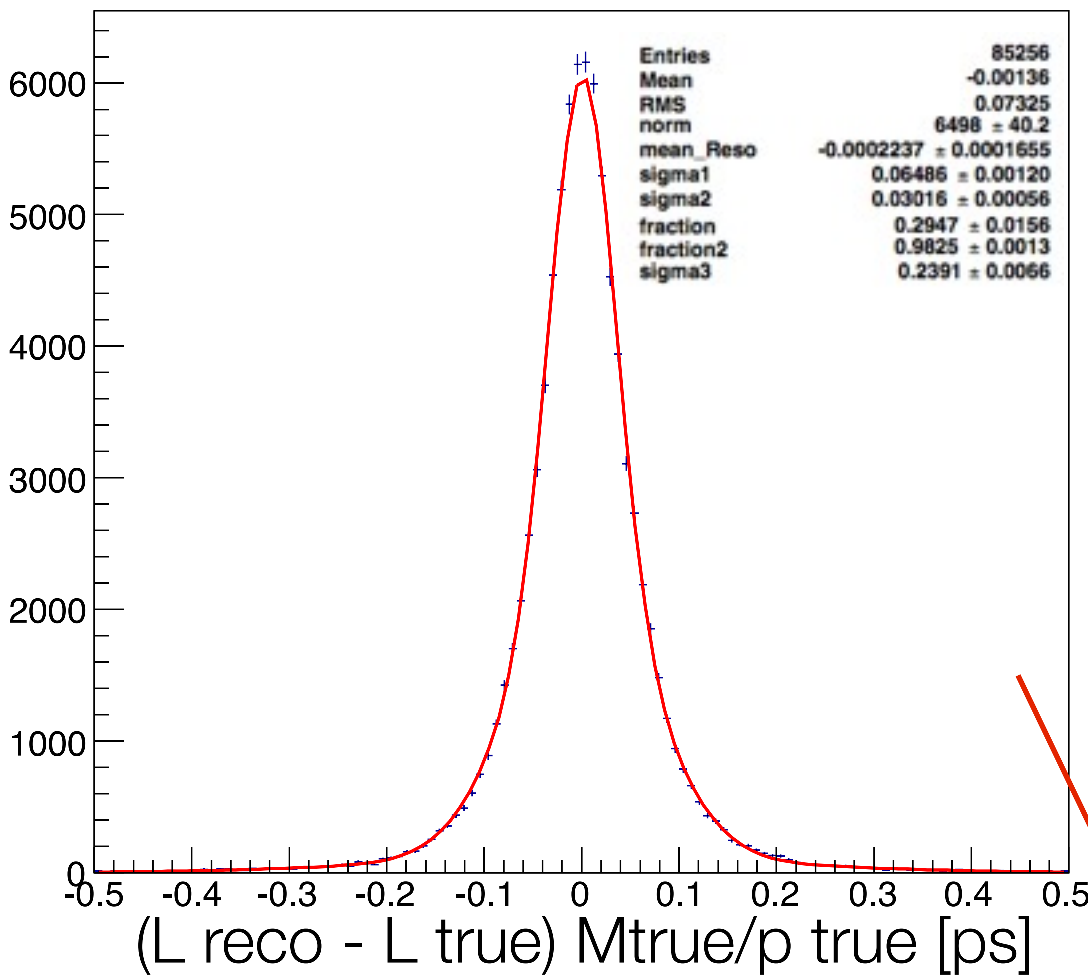


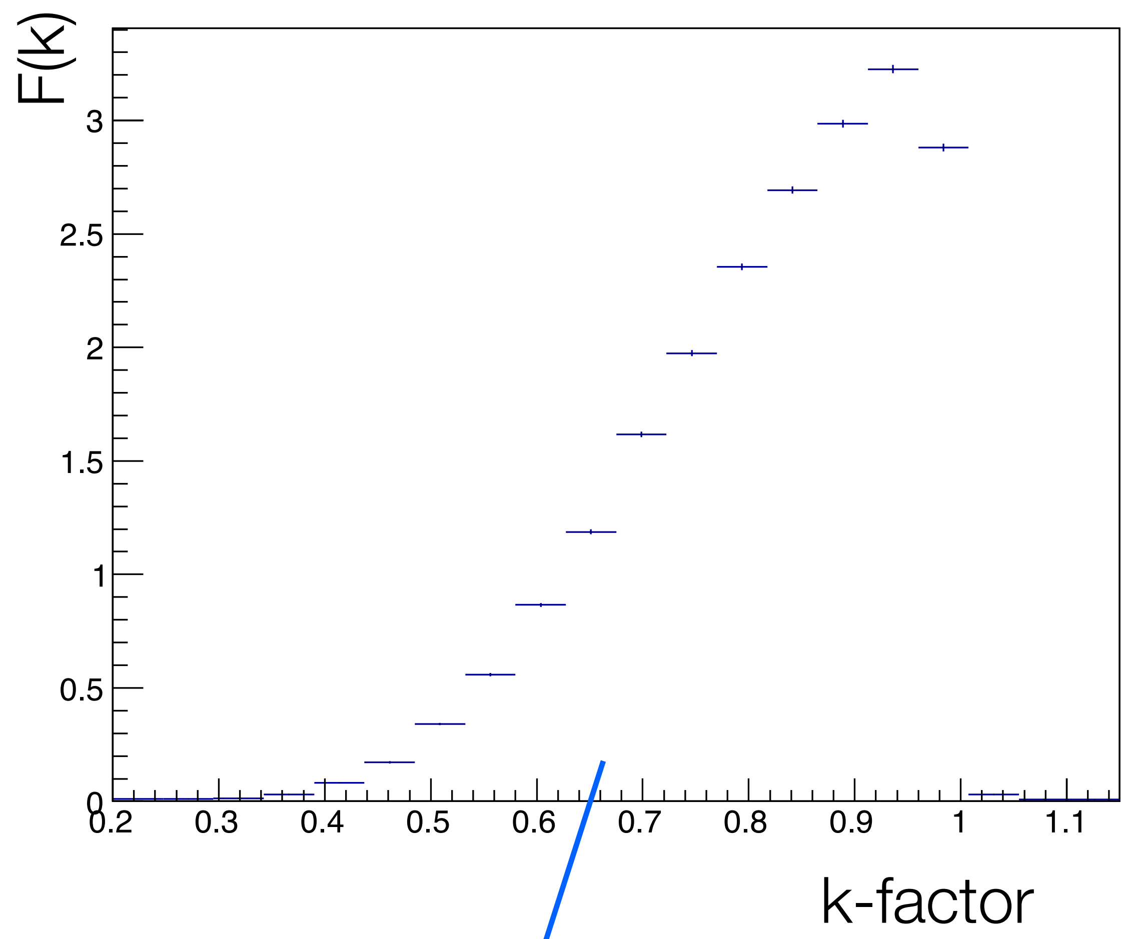
Time dependent fit: Resolution

- Trying to avoid any “effective approach”
- Similar as done by CDF

http://www-cdf.fnal.gov/physics/new/bottom/060406.blessed-semi_B0mix/

$$ct = \frac{L \cdot M_{PDG}}{|\vec{p}|}$$



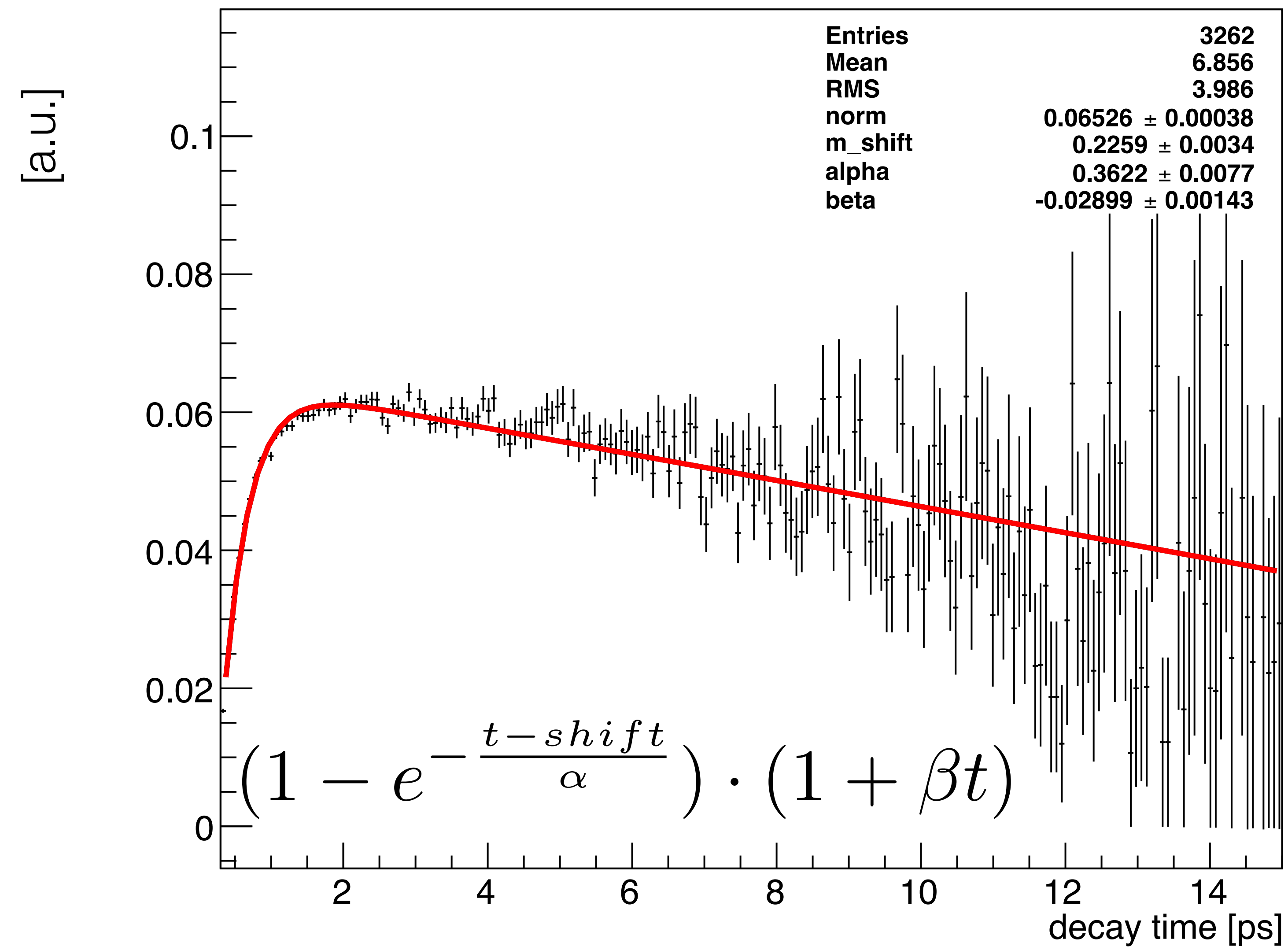


$$\mathcal{P}_{sig} = \boxed{(T(t) \otimes_t R(t) \otimes_k F(k))}$$

Acceptance

- Acceptance derived from MC

$$\mathcal{P}_{sig} = \boxed{(T(t) \otimes_t R(t) \otimes_k F(k))} \cdot A(t)$$



- **how** the time distribution is modified by reconstruction, trigger, selection requirements

Crosscheck with a known observable

- Started with the simplest time-dependent fit: the lifetime, just for validation

$$T(t) \propto e^{-\Gamma t}$$

- Moved to a more interesting benchmark, and interest measurement by itself: $B^0 - \bar{B}^0$ mixing frequency Δm_d

$$T(t,q) \propto e^{-\Gamma t}\left(1 \pm D\cos(\Delta \mathrm{m_d t})\right)$$

the B had mixed or not?

dilution from the *flavor tagging algorithms*
how likely is that my mixing decision was right?

- The meaning of the asymmetry is different (q) but the probability density function is almost the same

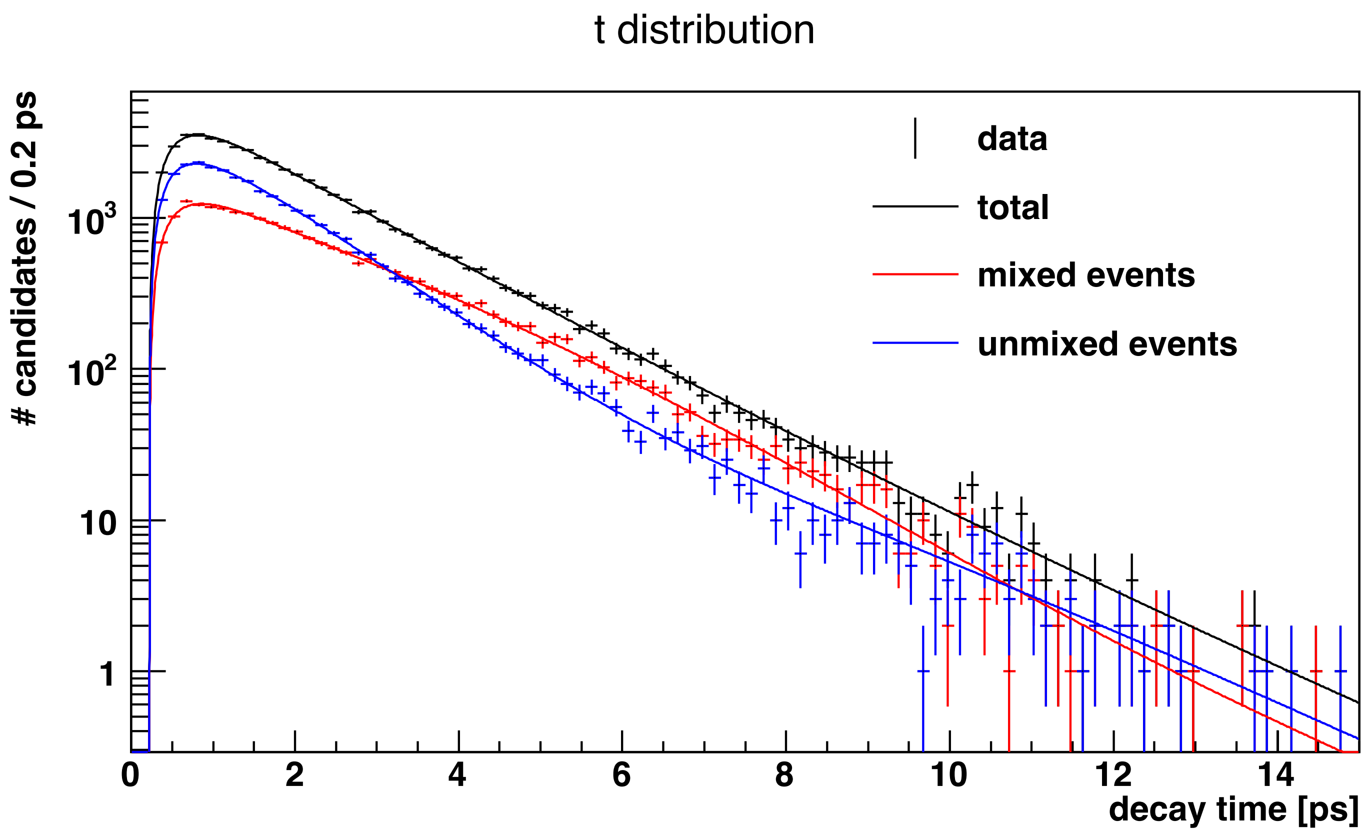
$$T(t,q) \propto e^{-\Gamma t}\left(1 \pm A_D \pm \frac{a_{sl}^d}{2} + \left(A_P - \frac{a_{sl}^d}{2}\right)\cos(\Delta \mathrm{m_d t})\right)$$

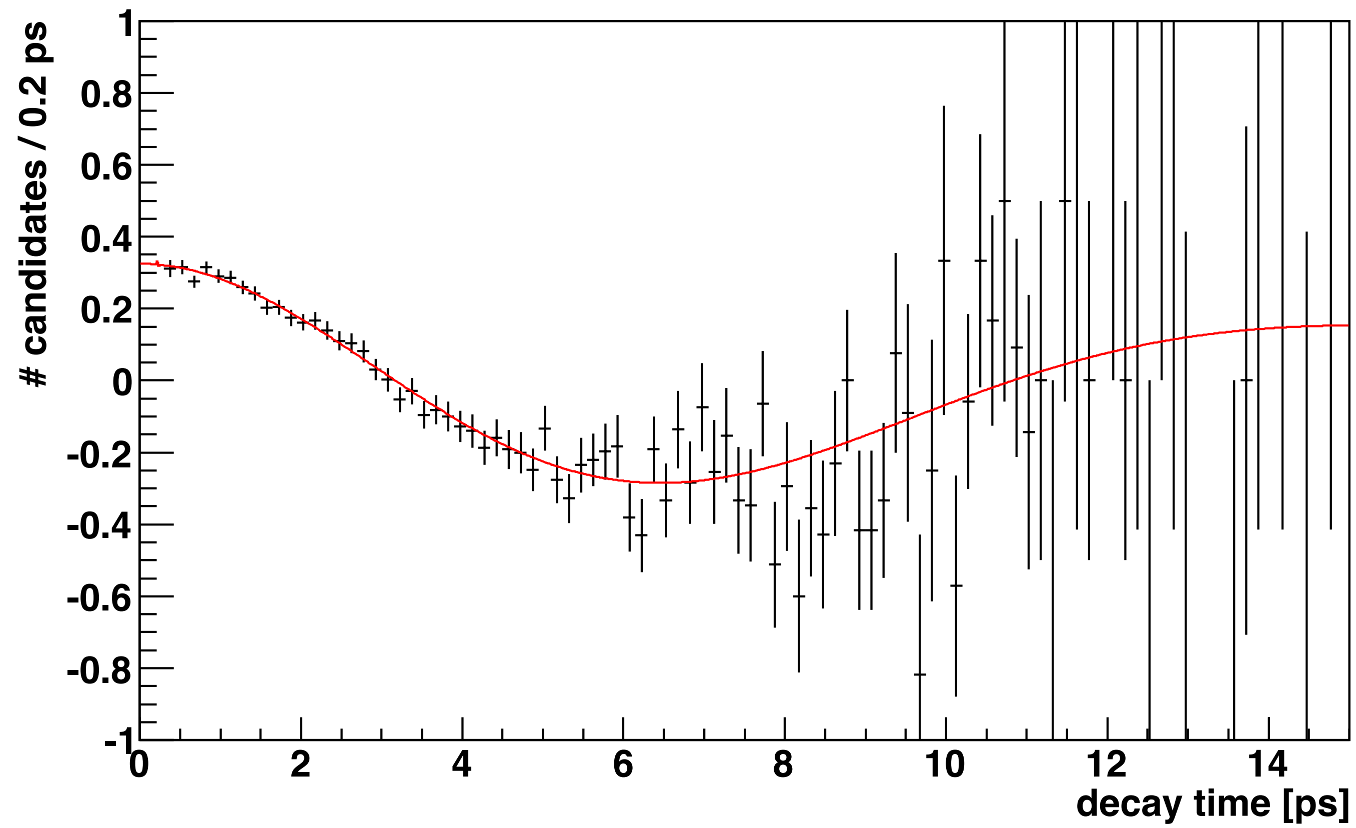
Validation of the method: realistic MC

- Test on the realistic MC sample

$$\Delta m_d^{\text{generation}} = 0.51\ \text{ps}^{-1}$$

$$\Delta m_d^{\text{fitted}} = 0.50502 \pm 0.00768$$

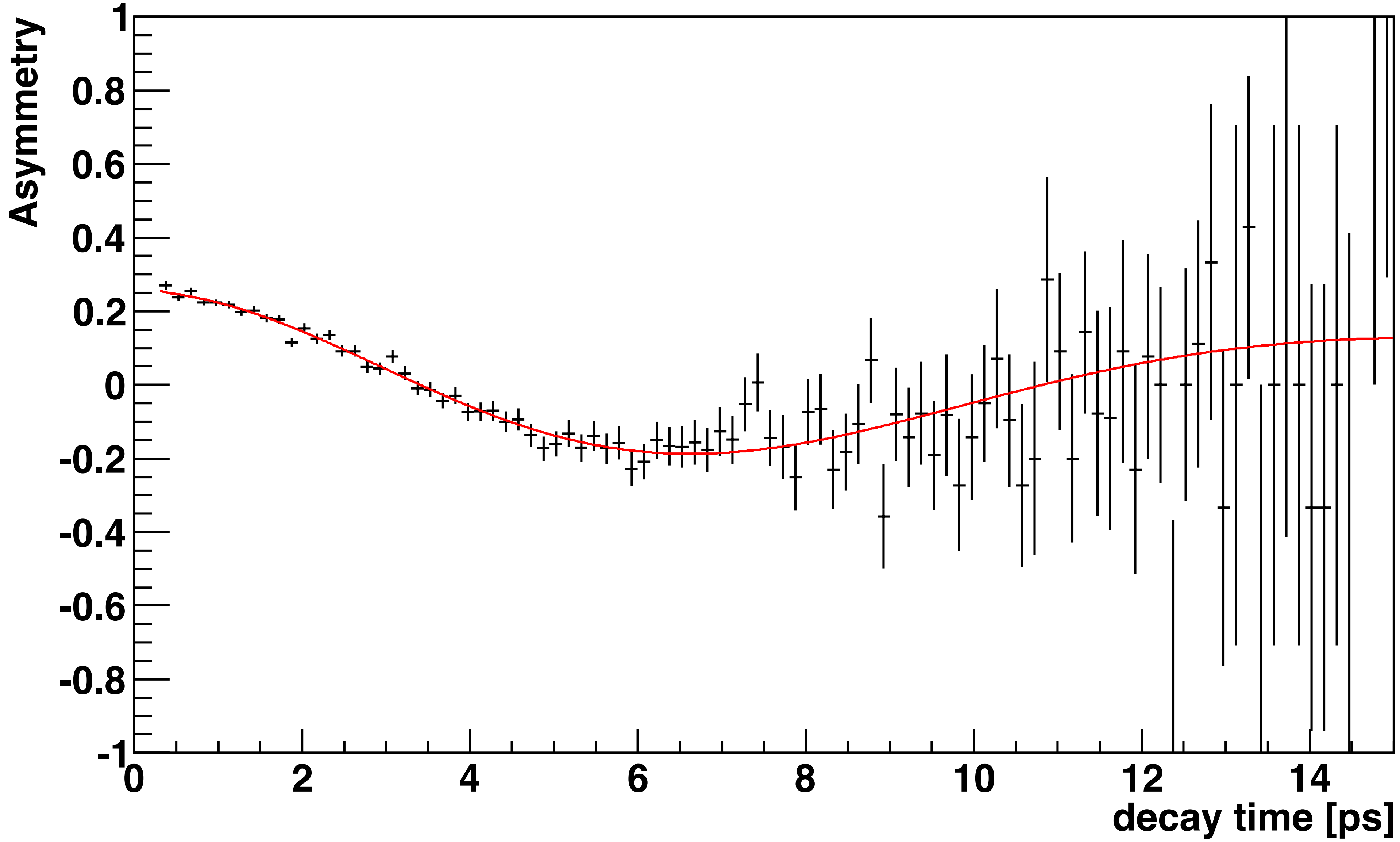




Mixing fit on data

- Only one sample, still many possible improvements...

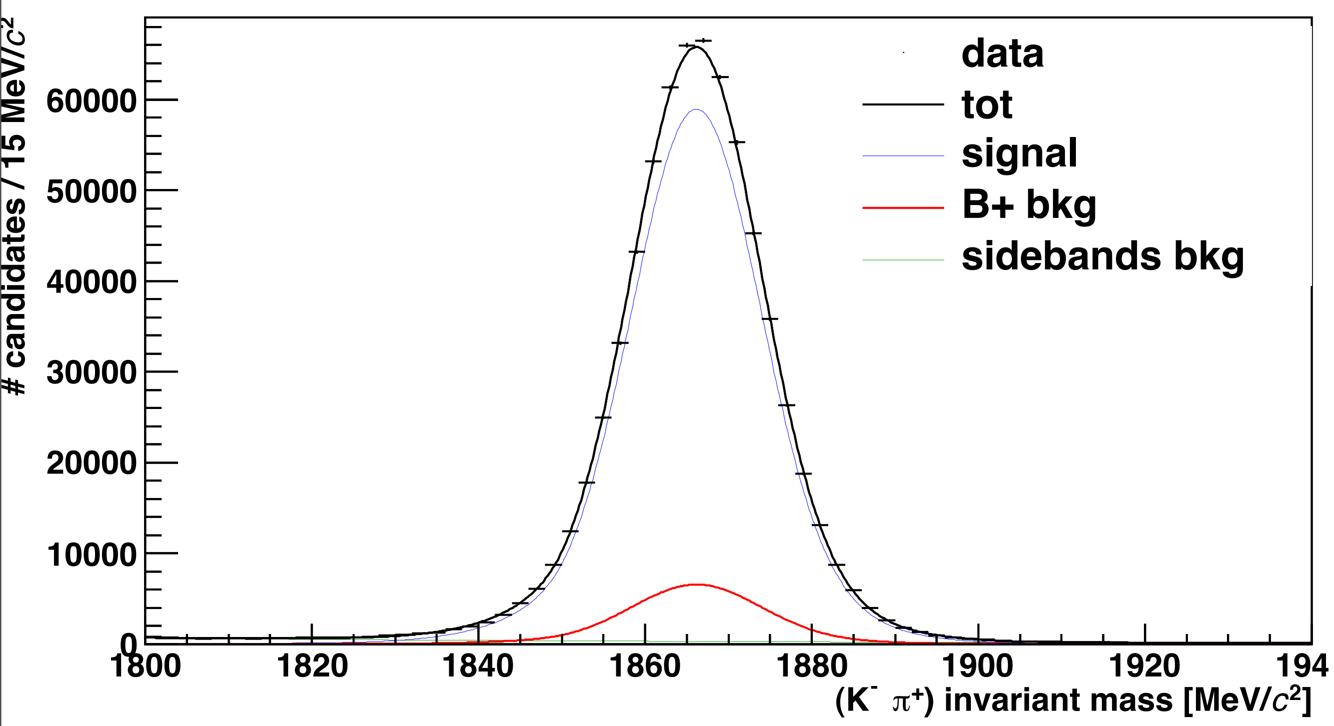
Mixing asymmetry



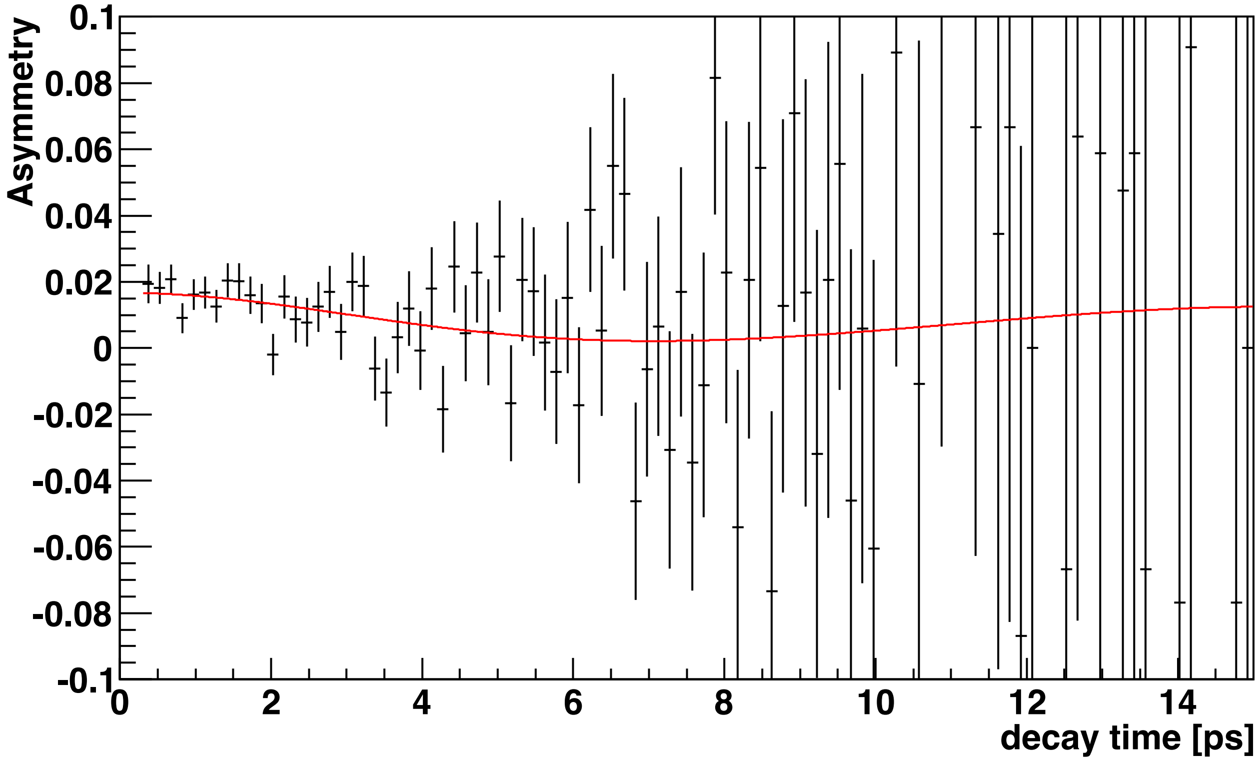
but now you know where the plot on slide 5 is coming from

Charge asymmetry fit on data

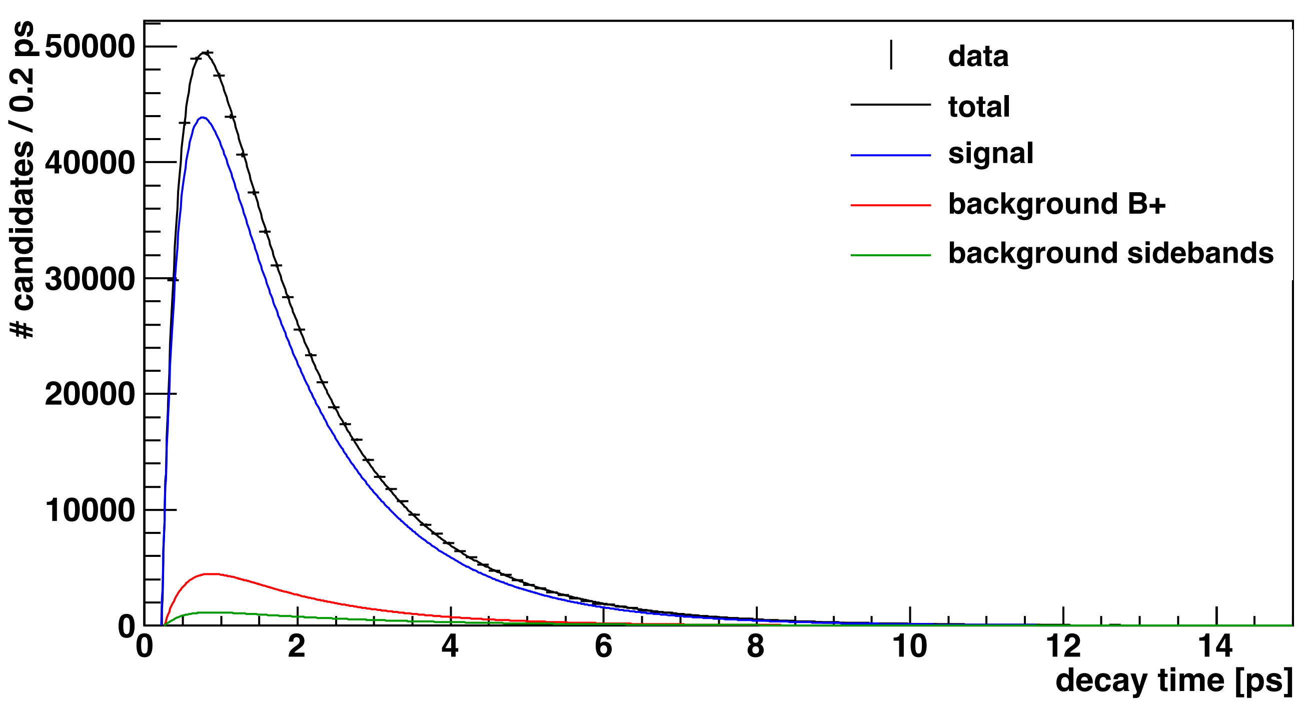
mass distribution



Charge asymmetry



t distribution



- Detection asymmetry assumed to be 0.012 (not yet the final value)

$$a_{sl}^{d} = \mathrm{XXXXX} \pm 0.00392$$

$$\text{production asymmetry} = 0.00485 \pm 0.00173$$

Systematics studies (*on going*)

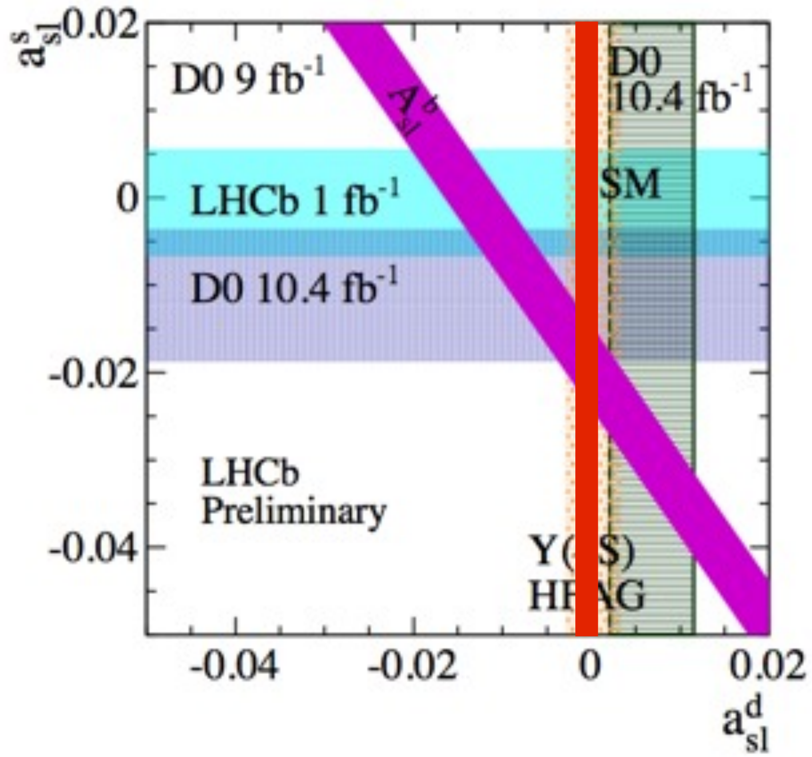
$A_D(K\pi)$	0.16%	dominated by the statistics of the control samples
B^+ Background	0.1%	entering in both B+ fraction and production asymmetry
fit model	**?**	**k-factor distribution**, flight distance resolution, decay time acceptance ....
kinematic reweighting	**?**	same kinematics on signal and control samples for detection asymetries
$A_D(\mu)$	0.06%	large control samples available
total	we want to be **< 0.2%**	best measurement to date by BaBar $a_{sl}^d = (0.06 \pm 0.17^{+0.38}_{-0.32})\%$
statistical uncertainty with all decay modes	**0.08%**	can we be a factor 2 more precise?

Summary and perspectives

- large interest in semileptonic CP asymmetry in B0 mixing

- Measurement strategy and challenges:
  production asymmetry (proton-proton collisions)
  time dependent analysis with a missing neutrino (production asymmetry + B0 slowly oscillating)
  detection asymmetries (expected)

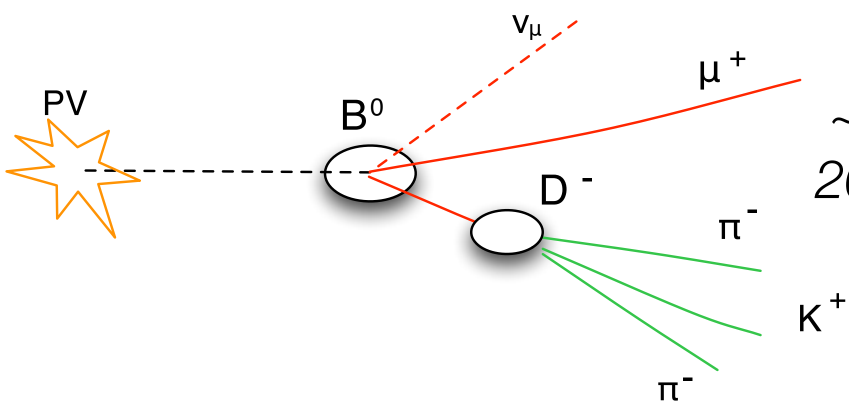
- Our purpose: the red band for winter conferences 2014



Thanks

Samples and backgrounds

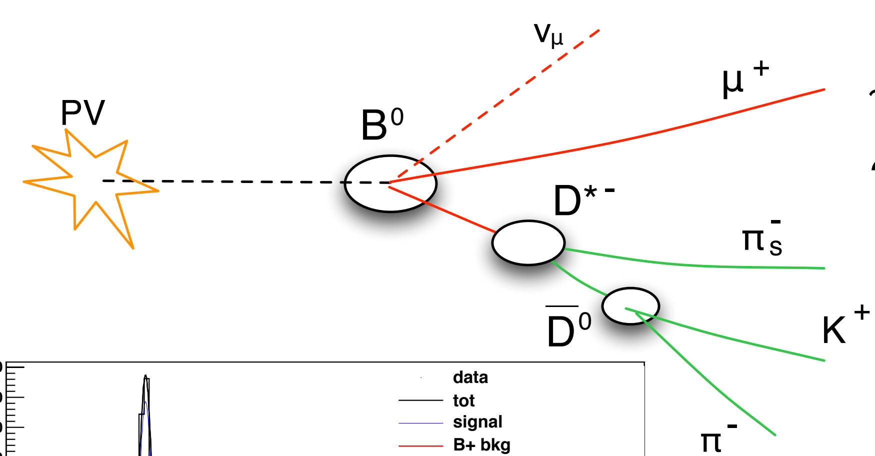
$$B^0 \to D^- \mu^+ \nu_\mu, D^- \to K^+ \pi^- \pi^-$$



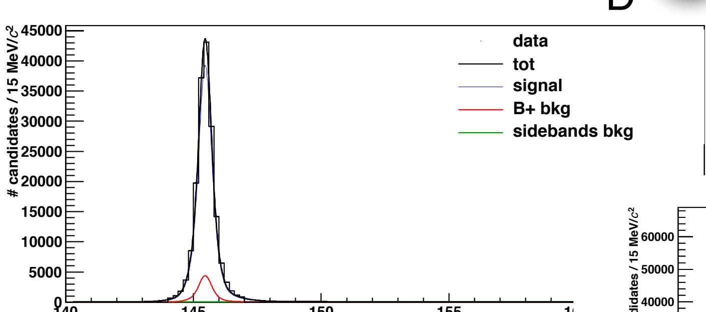
~5M events in 2012 data after selection

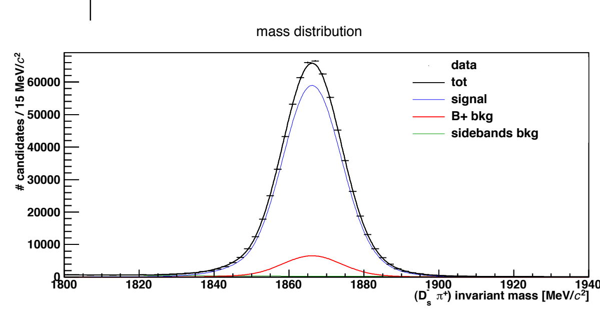
- **NON peaking background**: the B mass is useless, but the D- and the D0 (in the second sample we can also use the D*-D0 mass difference)

$$B^0 \to D^{*-} \mu^+ \nu_\mu, D^{*-} \to \bar{D}^0 \pi^-, \bar{D}^0 \to K^+ \pi^-$$



~700k events in 2012 data after selection





this talk will show results using this sample

- **Peaking background:**
  - B+ decays:

    due to a missing pion, they are different from the signal only for the non-oscillating behavior

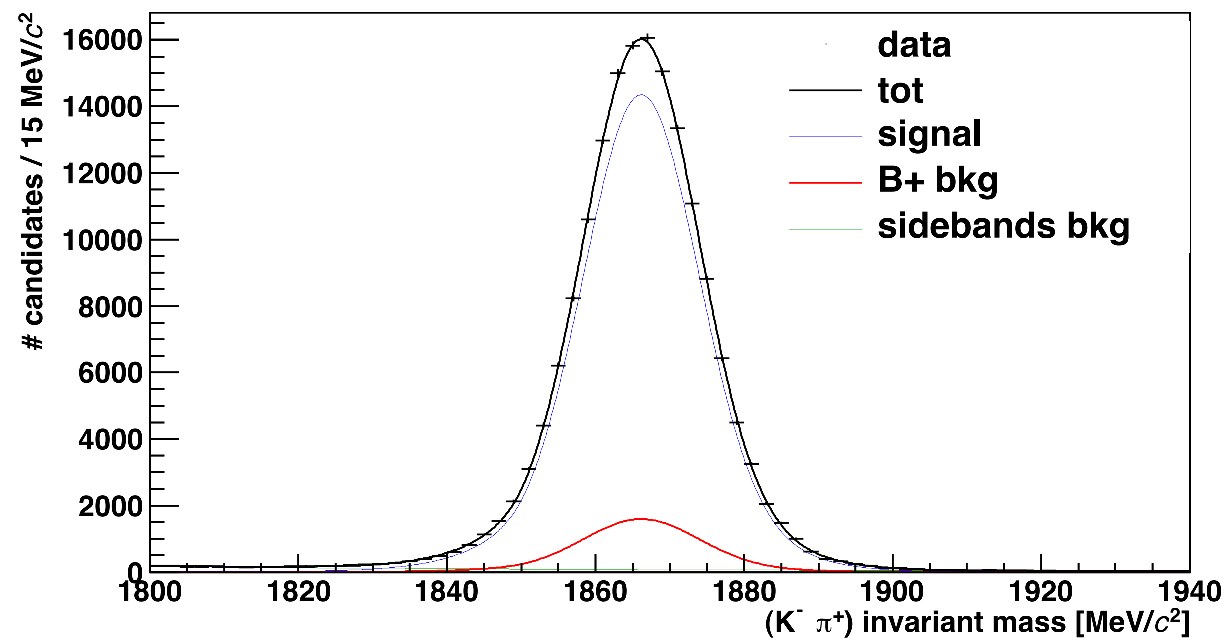
  - prompt D->Kpipi or D*->D0(->Kpi)pi

    a cut on $\log\chi^2_{\mathrm{IP}}$ could be a possibility to suppress this already small bkg, on going study

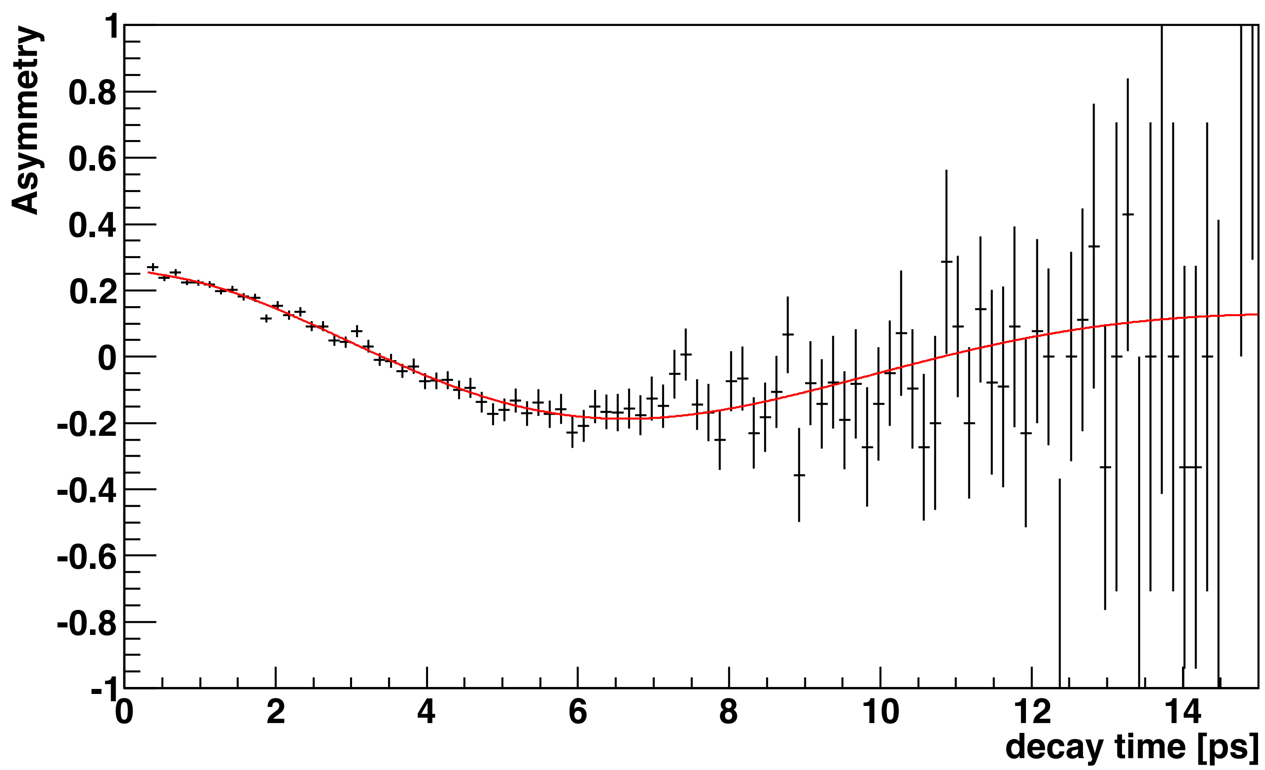
- "**Signal**" includes the "main" decay chain + decays having the same final state, but proceeding through other intermediate resonances (D**, D1', ...instead of the D*, or instead of the D)

Mixing fit on data - projections

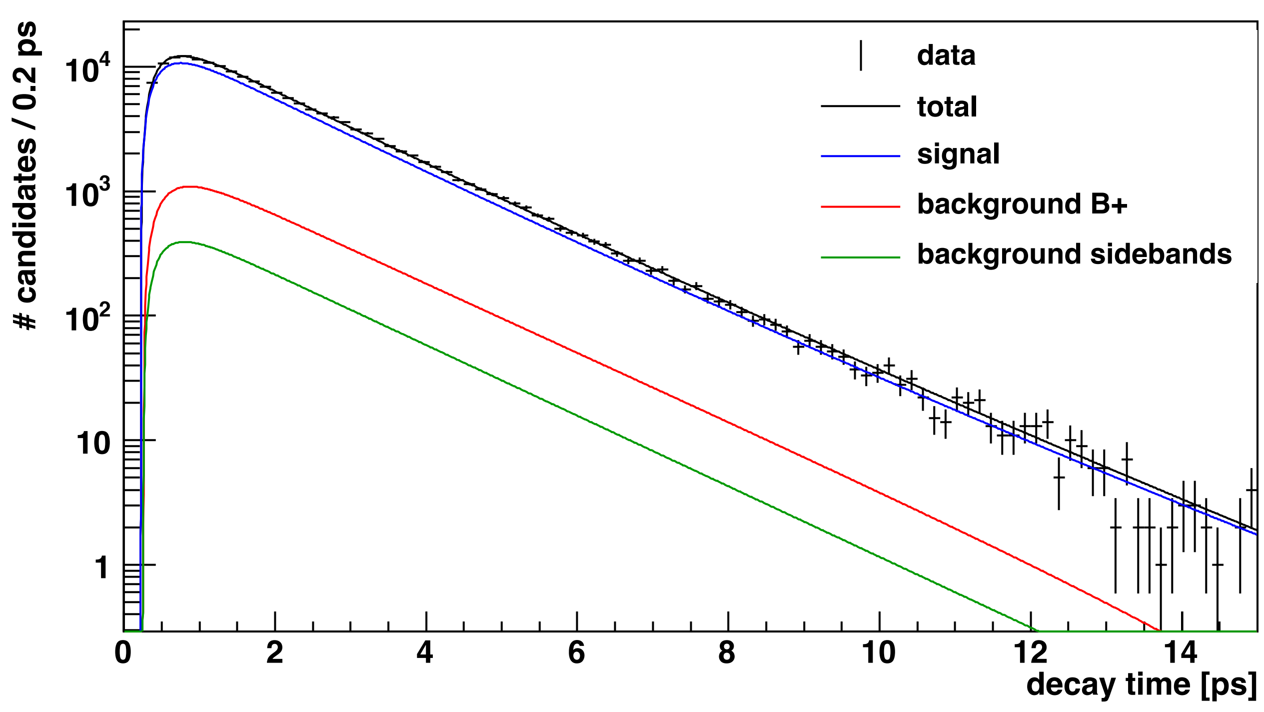
mass distribution



Mixing asymmetry

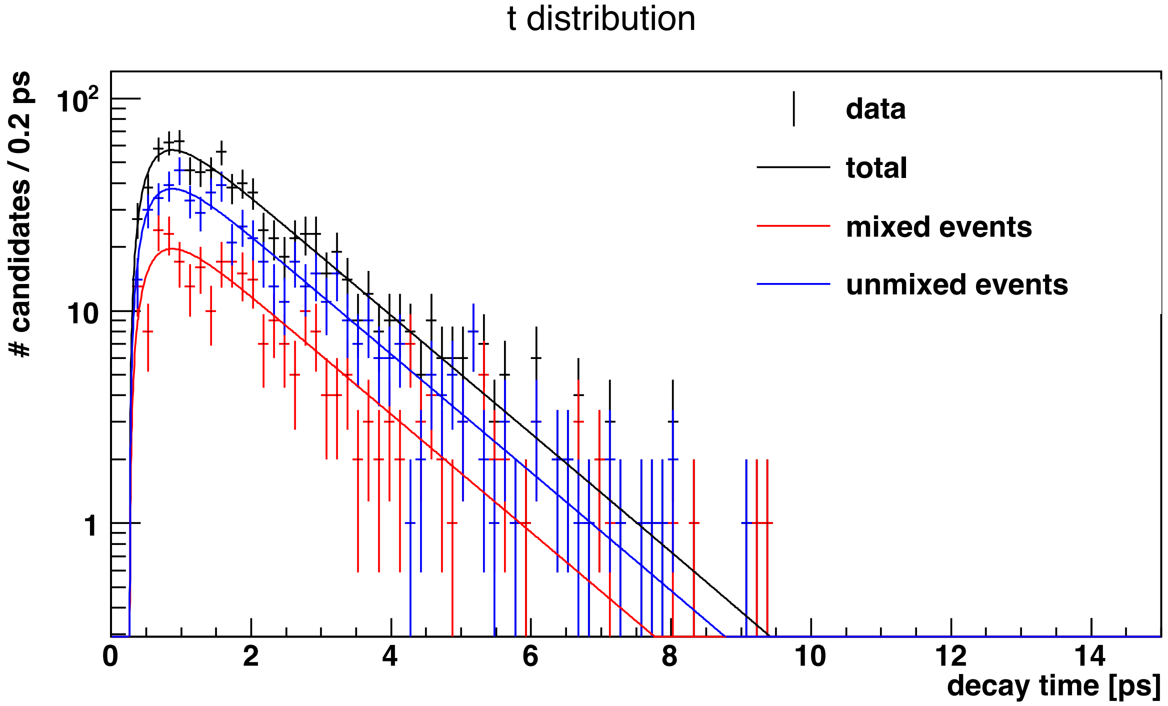


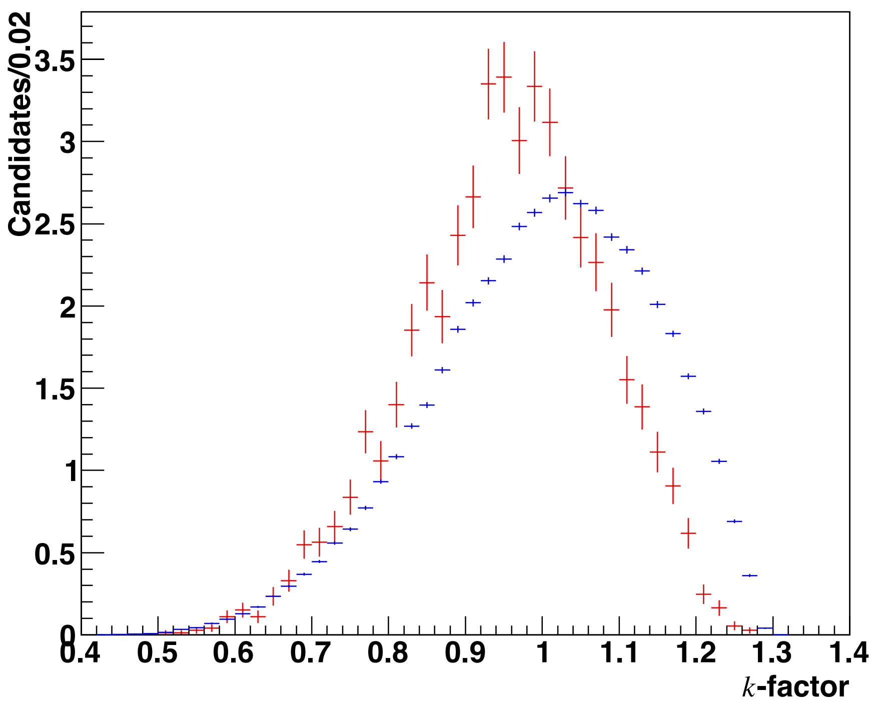
t distribution



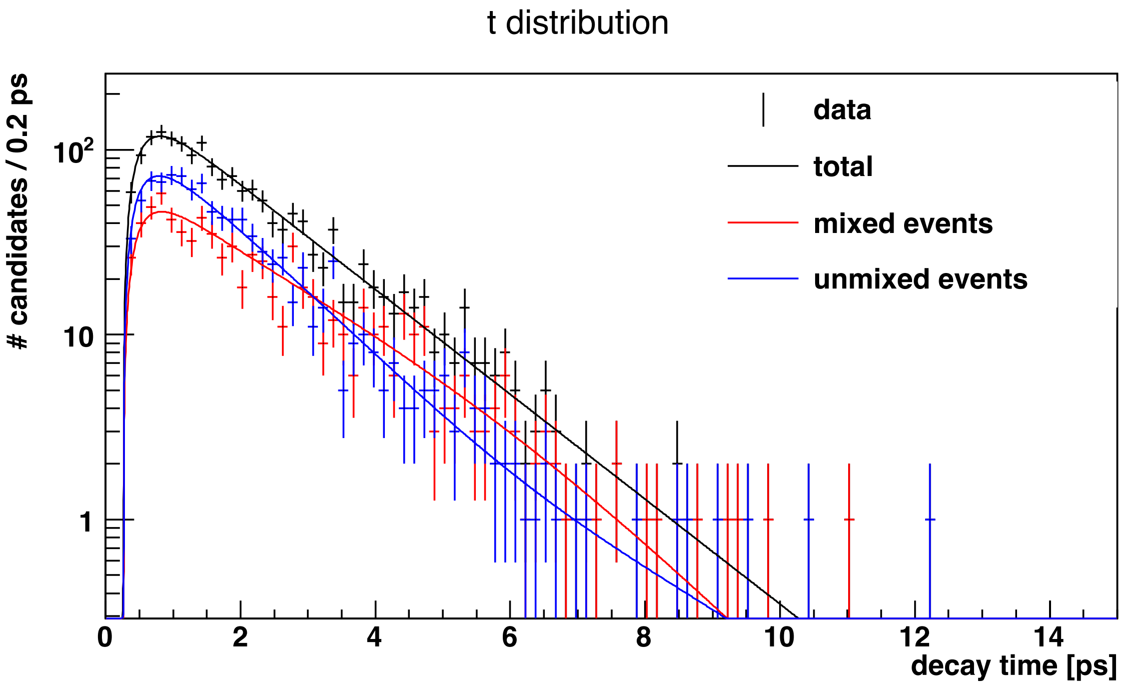
Mixing fit on data - more about backgrounds

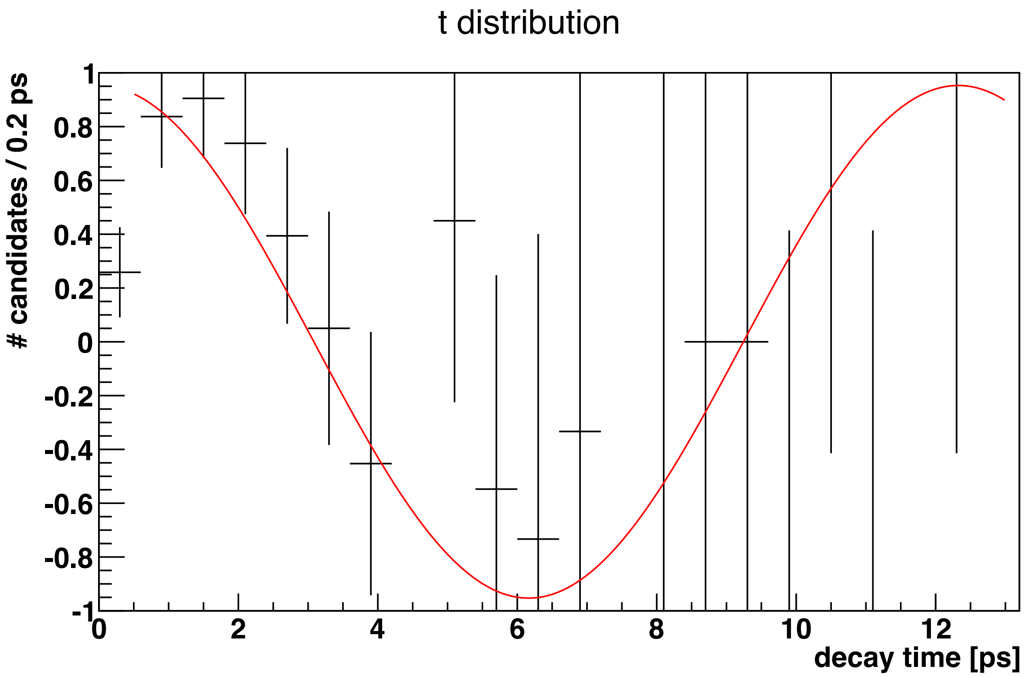
B+ bkg model similar to the signal, but with a different k-factor and not oscillating





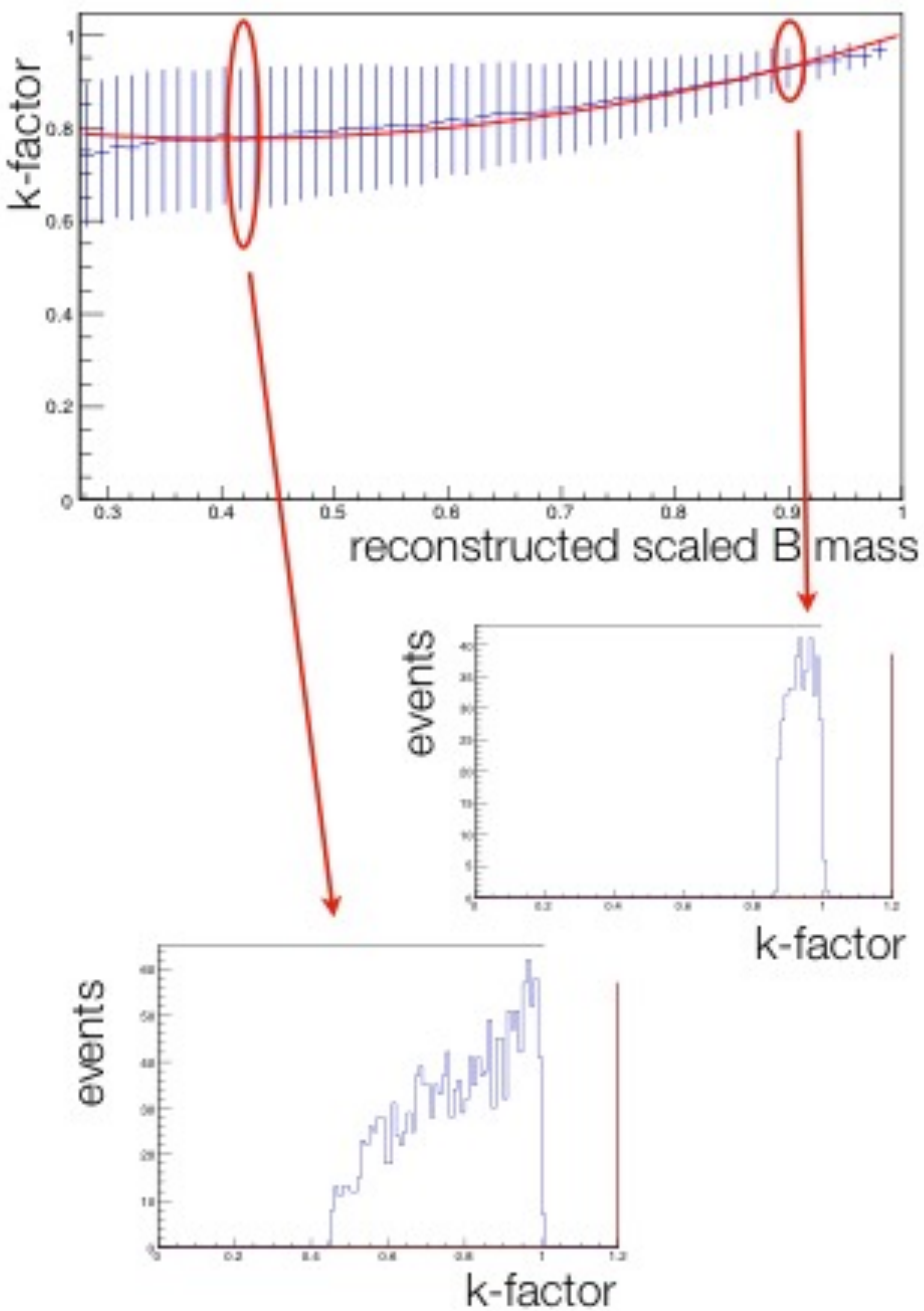
sidebands bkg Effective model, without k-factor BUT shows an oscillating behavior!





More about the k-factor method

- mass dependence of the k factor:

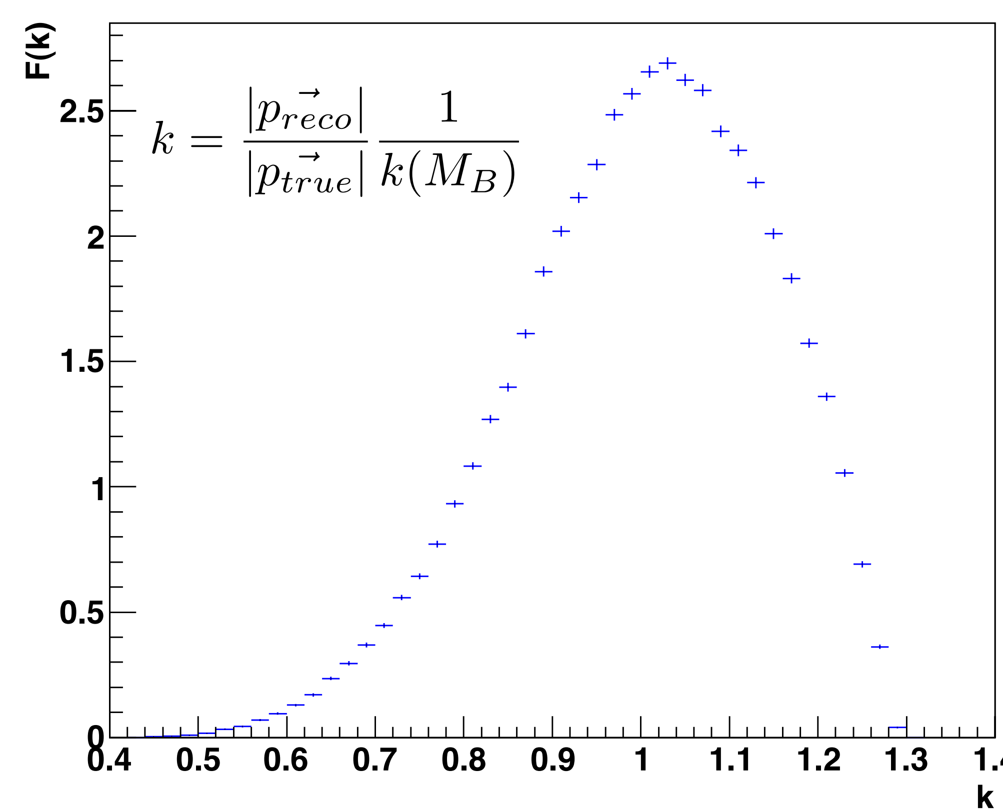


width dependence on the B mass

- the decay time can be corrected:

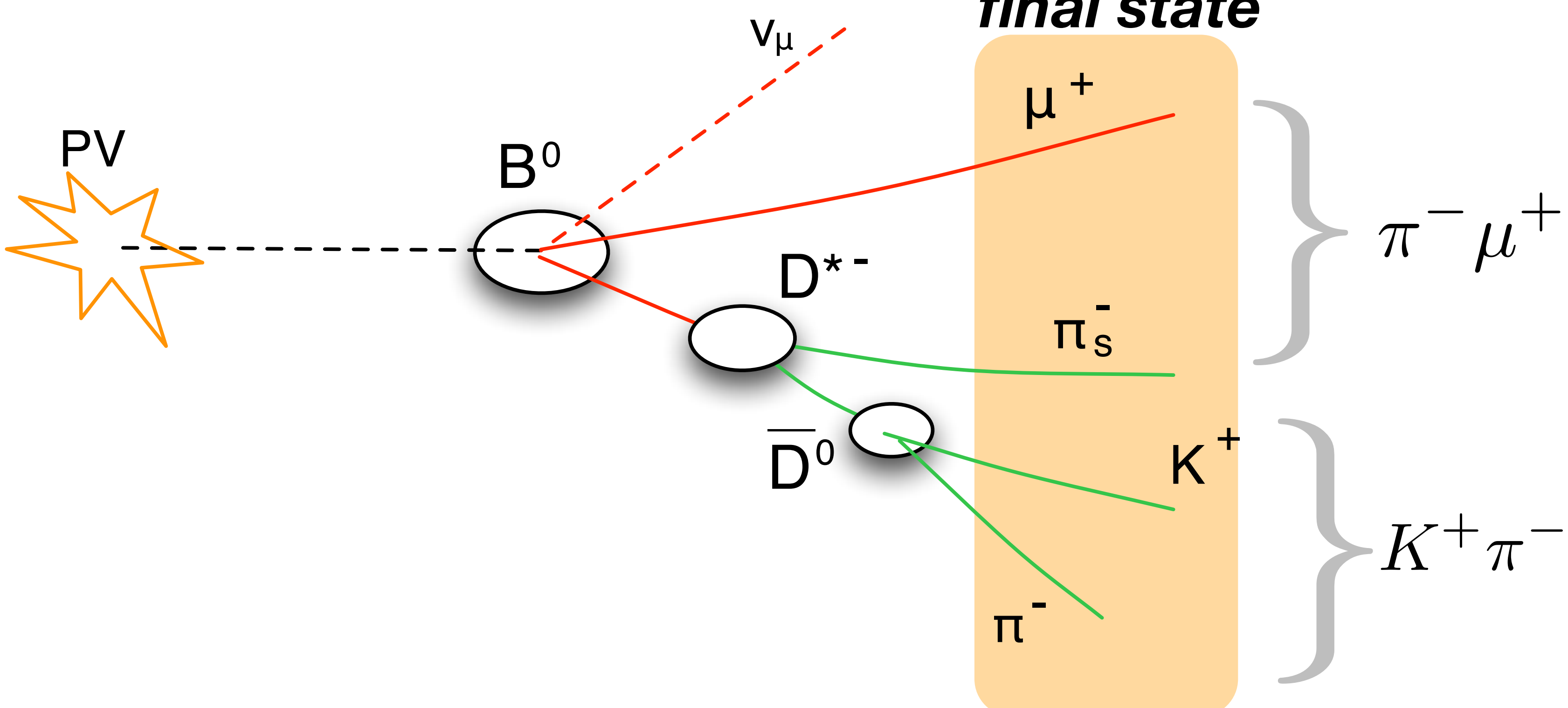
$$ct_{corr} = \frac{L_{reco} \cdot M_{PDG}}{|\vec{p_{reco}}|} \cdot k(M_B)$$

- the proper “normalized” k-factor distribution has to be used as a resolution



The "real world": 2) detection asymmetries

All the asymmetries related to the ***reconstructed final state***



$$A_D = \frac{\epsilon(f) - \epsilon(\bar{f})}{\epsilon(f) + \epsilon(\bar{f})}$$

In this case for example

pion asymmetry from nuclear reaction with the detector material + muon detection asymmetry in the muon system (investigated with J/ψ decays)

from ratio of promplty produced:
$D^+ \to K^-\pi^+\pi^+$
$D^+ \to K_S\pi^+$

good feature of LHCb:

Magnet polarity can be reversed

Detection asymmetries cancel at first order

$$A_{\rm meas} = \frac{\Gamma[f,t] - \Gamma[\bar{f},t]}{\Gamma[f,t] + \Gamma[\bar{f},t]} = A_D + \frac{a_{sl}}{2} + \left(A_p - \frac{a_{sl}}{2}\right)\frac{\cos(\Delta {\rm M t}) {\rm e}^{-\Gamma {\rm t}} {\rm A(t)}}{\cosh(\Delta\Gamma {\rm t}/2) {\rm e}^{-\Gamma {\rm t}} {\rm A(t)}}$$

Detections asymmetries

$\pi^-\mu^+$

pion asymmetry from nuclear reaction with the detector material + muon detection asymmetry in the muon system (investigated with J/ψ decays

$K^+\pi^-$

from ratio of promplty produced:

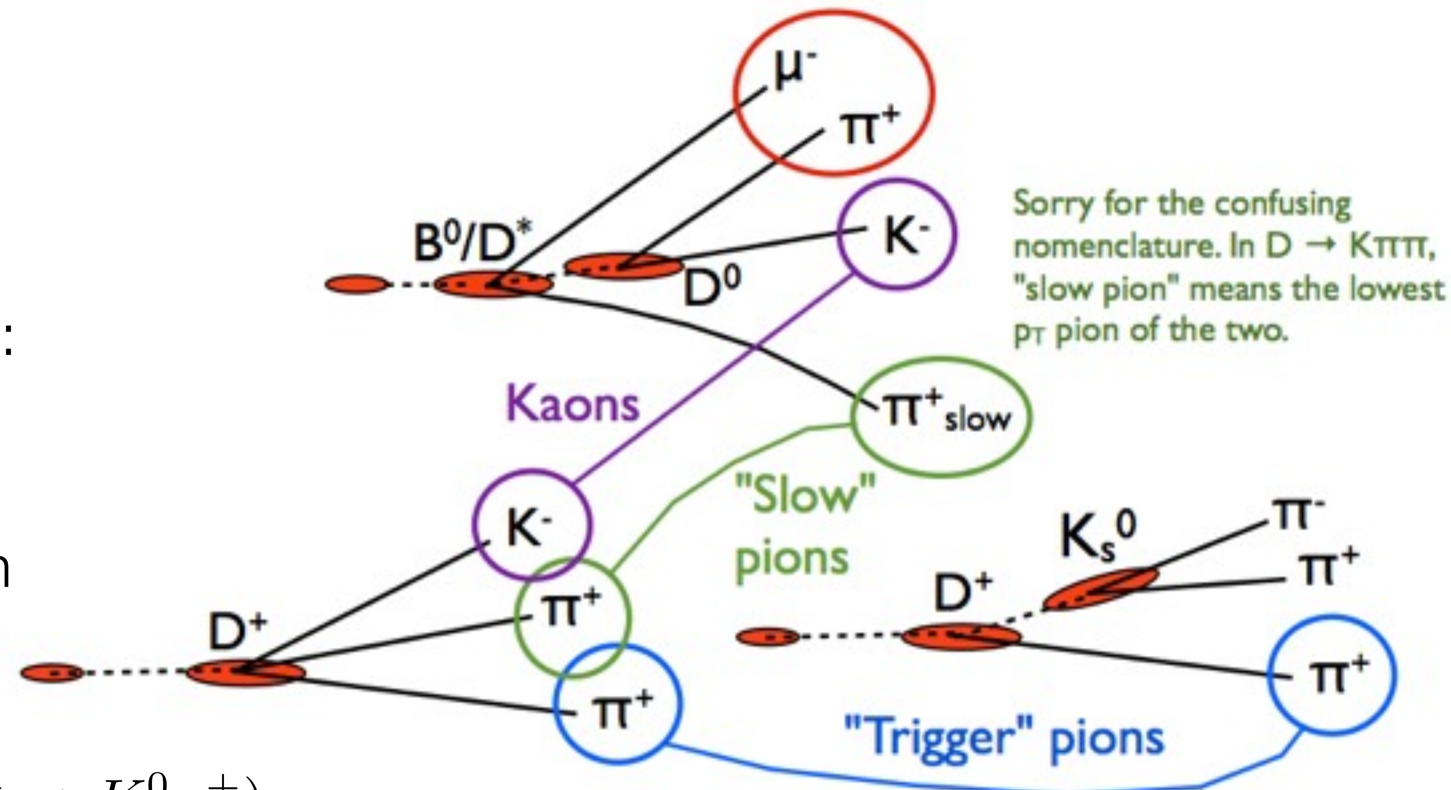
$D^+ \to K^-\pi^+\pi^+$

$D^+ \to K_S\pi^+$

strategy to correct the detection asymmetry in the D* sample:

$$\frac{\epsilon(K^+\pi^-)}{\epsilon(K^-\pi^+)} = \frac{N(D^- \to K^+\pi^-\pi^-)}{N(D^+ \to K^-\pi^+\pi^+)} \times \frac{N(D^+ \to K^0_s\pi^+)}{N(D^- \to K^0_s\pi^-)}$$

Dominant source of asymmetry is the kaon nuclear interactions.



need to take into account the different kinematics of the daughter particles in the calibration channels compared to the signal channels