Measurement of semileptonic asymmetries at LHCb

- LHCb Collaboration, "*Measurement of the flavour-specific CP-violating asymmetry a_{sl}^{s} in B_s^0 decays*", PLB 728C 607-615 (2014).
- LHCb Collaboration, "*Measurement of the semileptonic CP asymmetry in B^0 - $\overline{B}^0$ mixing*", LHCb-PAPER-2014-053 (**NEW**)

Mika Vesterinen

Physikalisches Institut Heidelberg

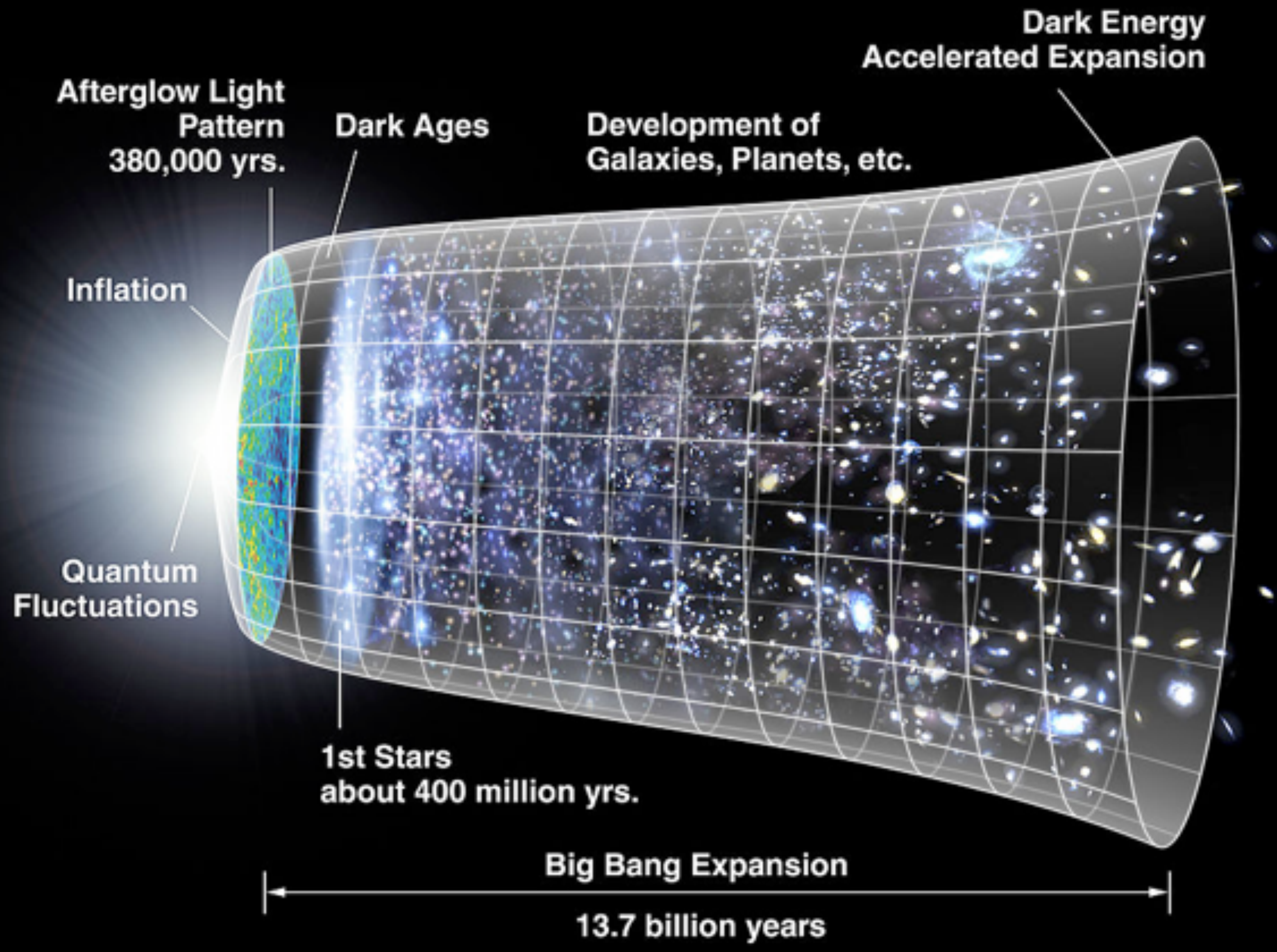
On behalf of the LHCb collaboration

CERN LHC seminar

30th September 2014

CP-violation

- Violation of symmetry under **C**harge and **P**arity
  - Discovered in the weak interaction in 1964



- Baryon asymmetry of the universe: $n_b/n_\gamma \sim 10^{-10}$
- CP-violation in the Standard Model accounts for $\sim 10^{-20}$
- Must be new new physics and new sources of CP-violation.

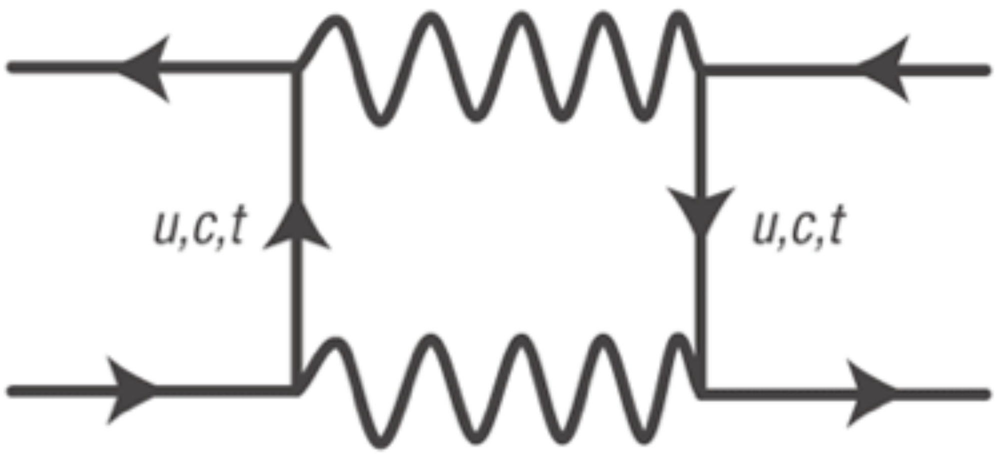
Two ways to find new physics at the LHC

Direct observation

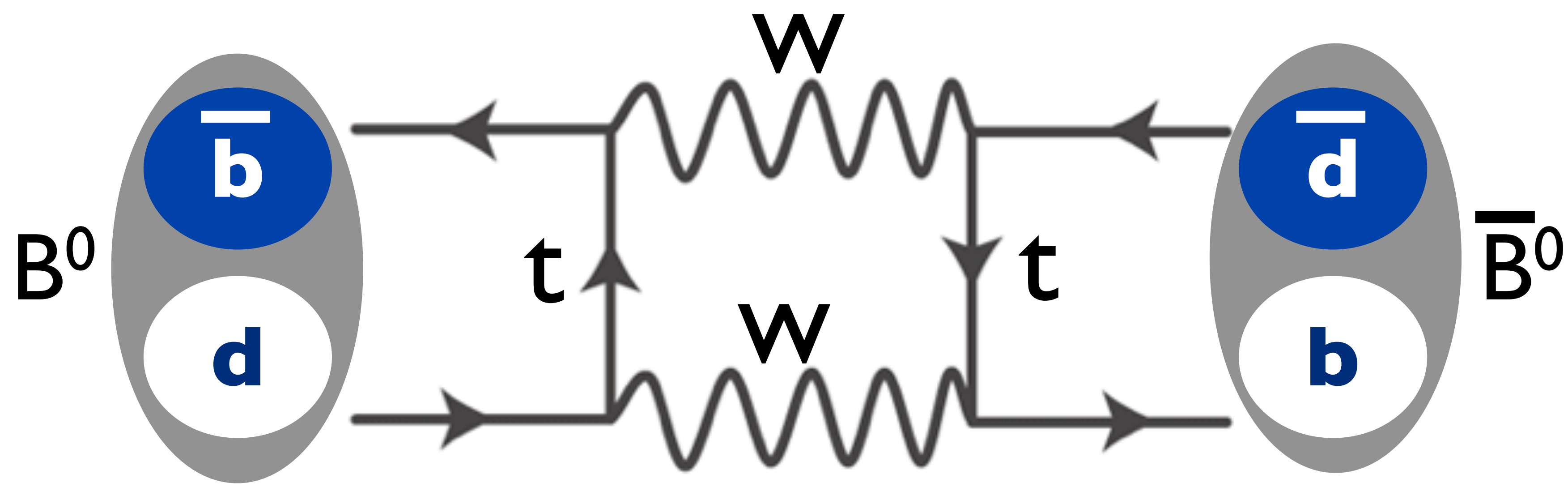
Note that particles with $MC^2 > E$ can't be produced directly...

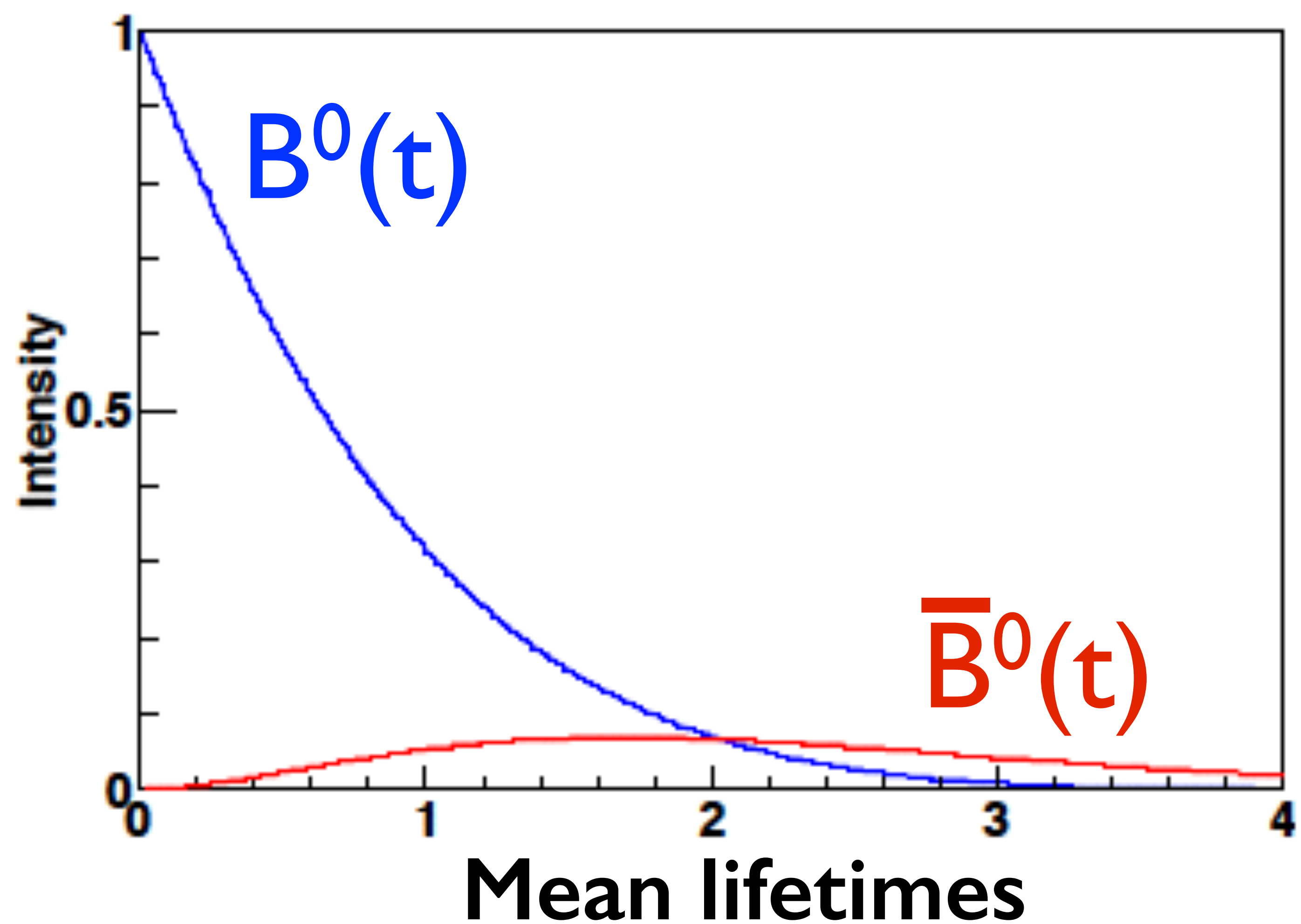
Indirect effects

… but they can have an effect through quantum corrections



Neutral meson mixing





Neutral meson mixing

- Time evolution from Schrodinger's equation:

$$i\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} |B^0(t)\rangle \\ |\overline{B}^0(t)\rangle \end{pmatrix} = \left(M - \frac{i}{2}\Gamma\right)\begin{pmatrix} |B^0(t)\rangle \\ |\overline{B}^0(t)\rangle \end{pmatrix}$$

- With "heavy" and "light" mass eigenstates:

$$|B_{H,L}\rangle = p|B^0\rangle \mp q|\overline{B}^0\rangle$$

- Which can have different masses and decay widths

$$\Delta m = m_H - m_L$$

$$\Delta\Gamma = \Gamma_L - \Gamma_H$$

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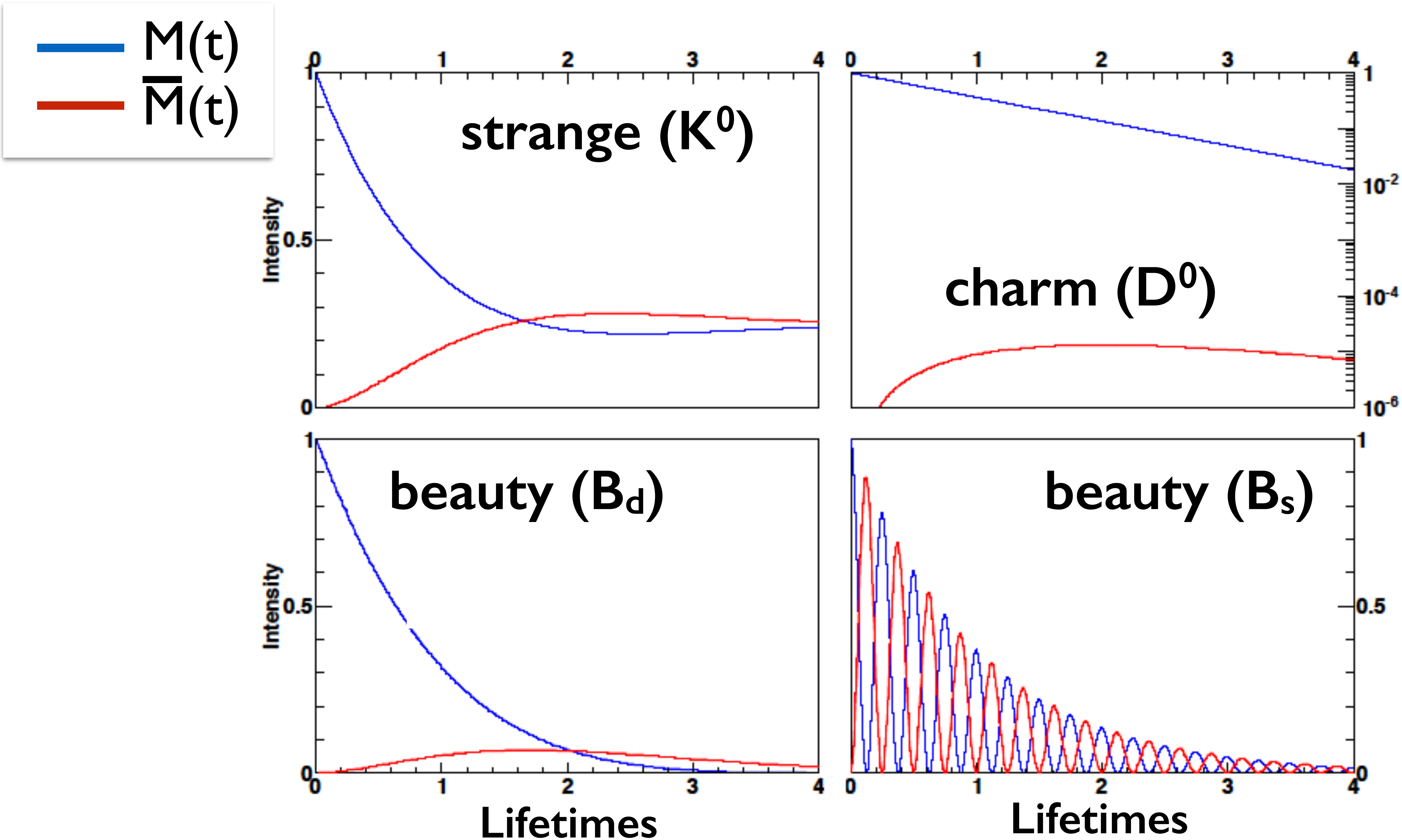
$$\Delta m = m_H - m_L$$

$$\Delta\Gamma = \Gamma_L - \Gamma_H$$

- Probability to find $\overline{\mathrm{B}}$ at time t in a B beam:

$$\propto e^{-\Gamma t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\left(\Delta m t\right)\right]$$

Mixing phenomenology



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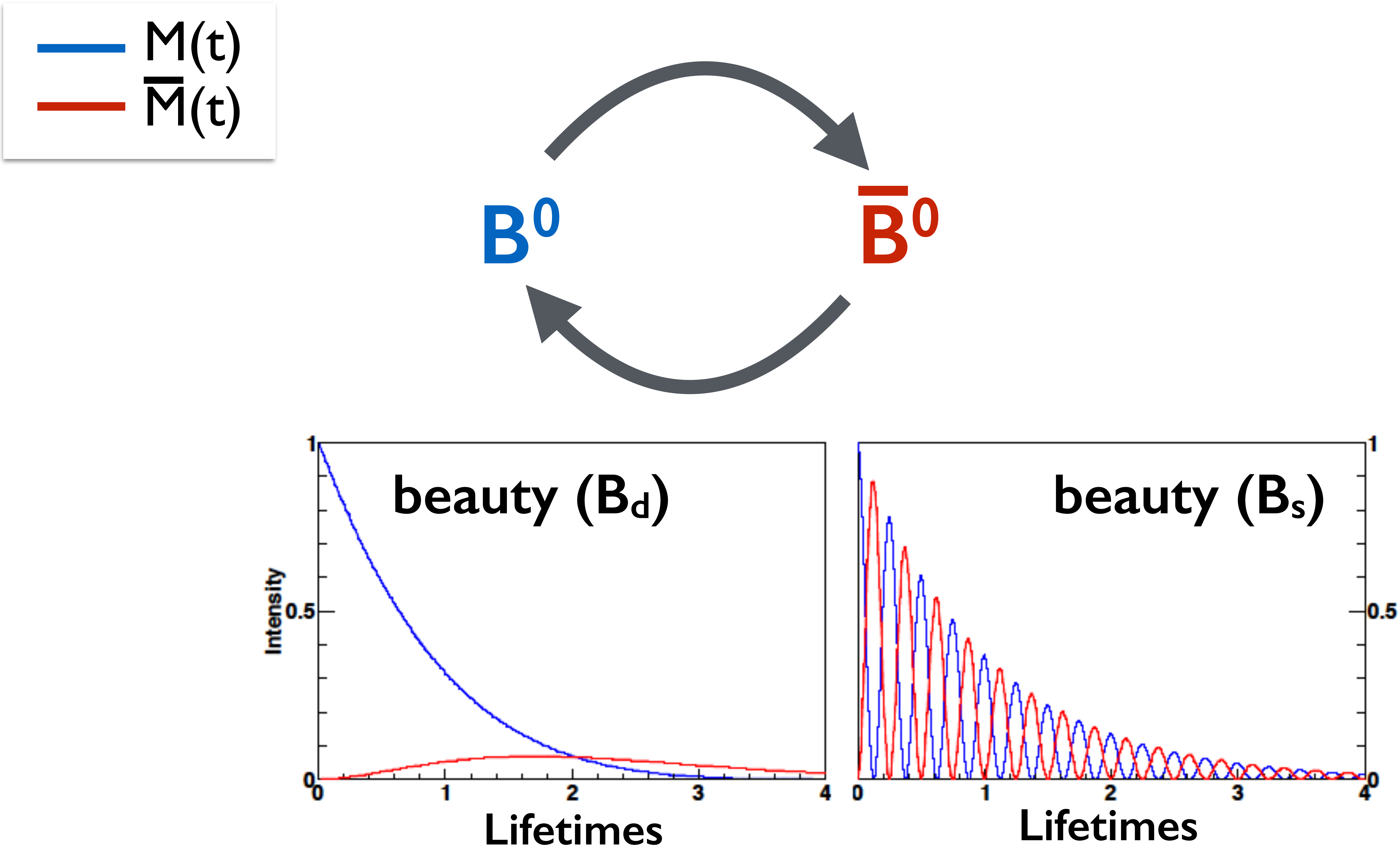

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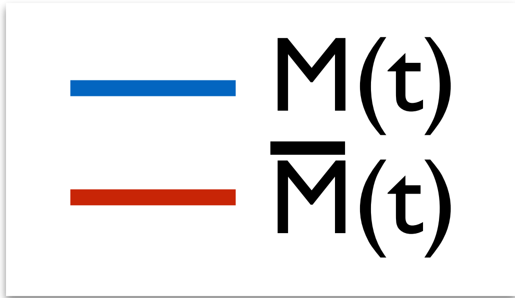
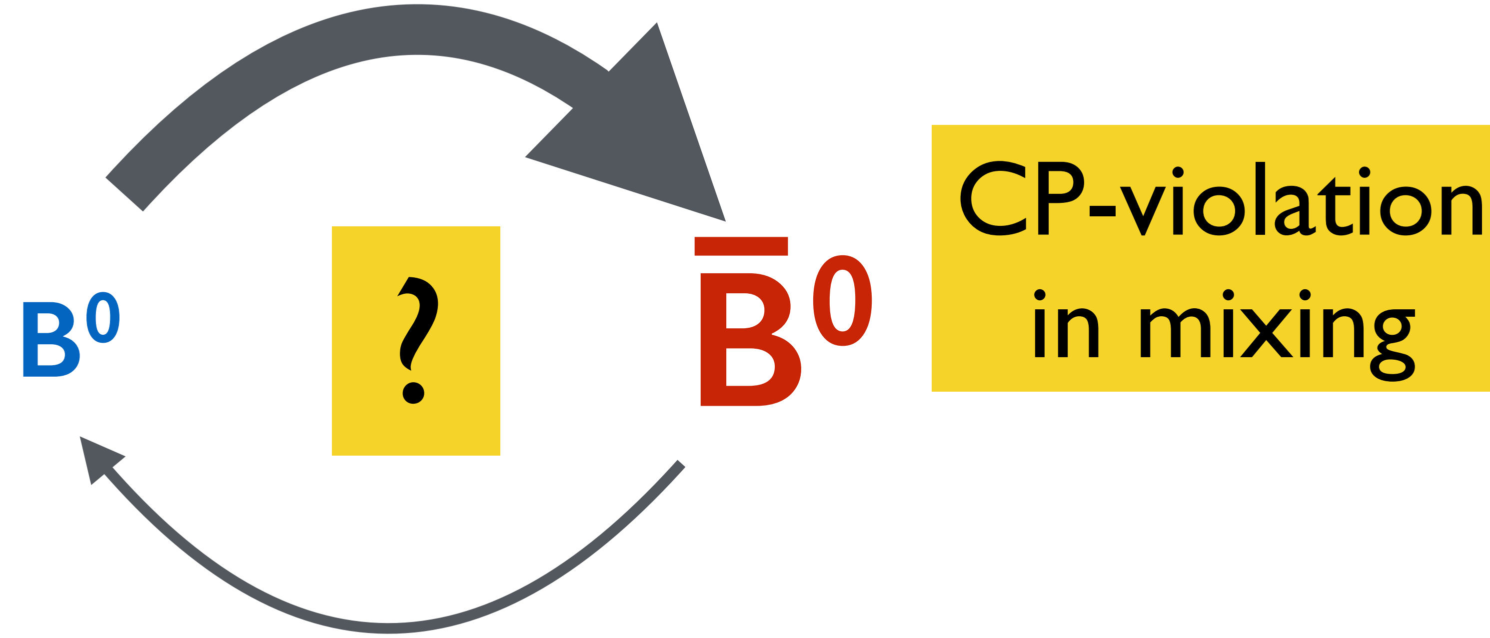
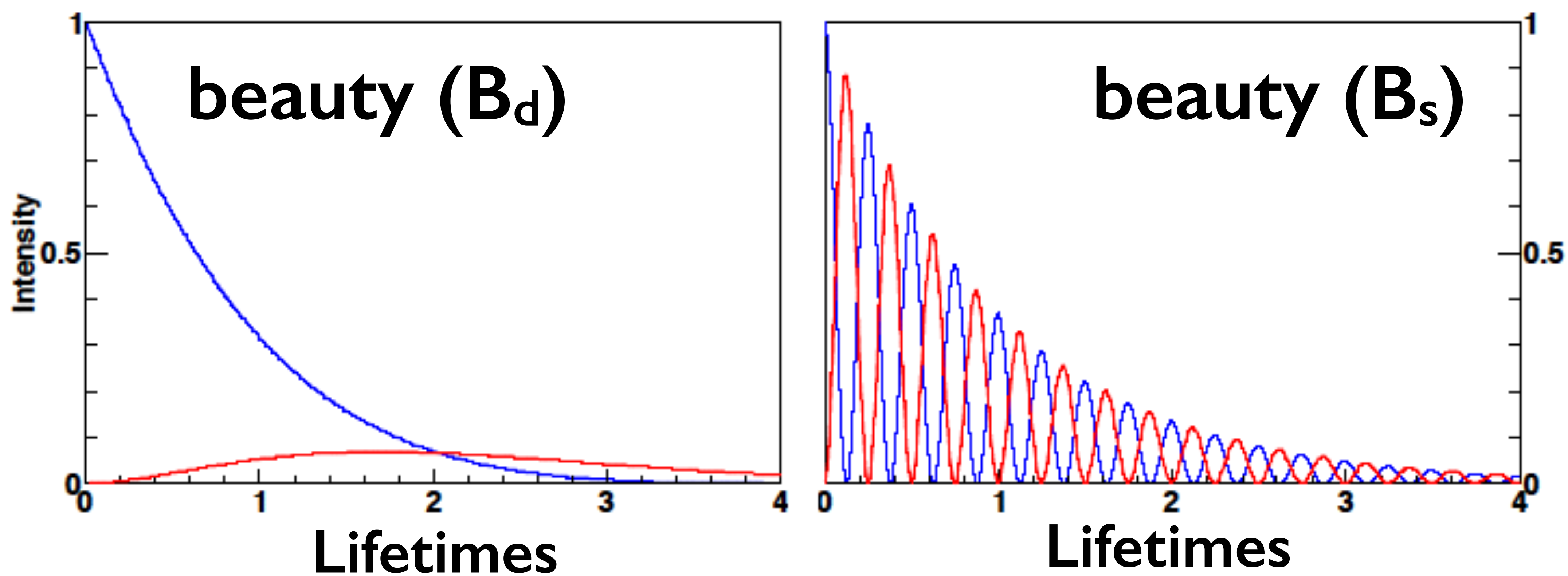




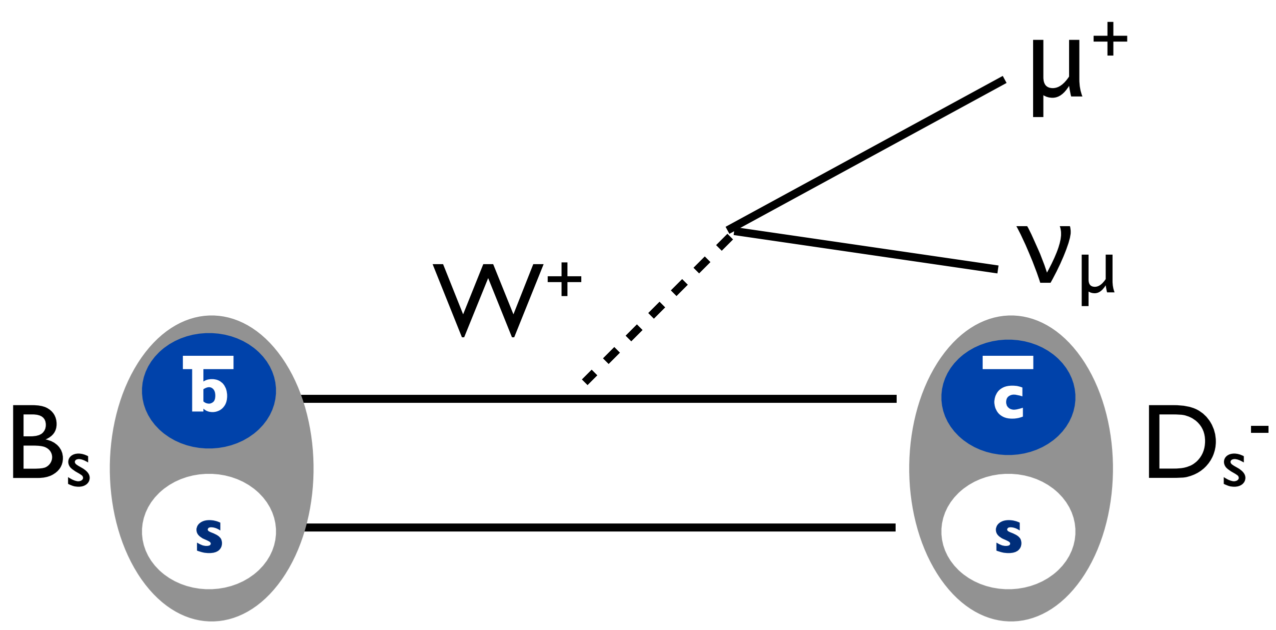


CP violation in mixing

- The CP-violating "semileptonic" asymmetry:

$$a_{\mathrm{sl}} = \frac{\Gamma(\overline{B} \to B \to f) - \Gamma(B \to \overline{B} \to \bar{f})}{\Gamma(\overline{B} \to B \to f) + \Gamma(B \to \overline{B} \to \bar{f})}$$

- Semileptonic decays tag the flavour



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In the Standard Model*:

$$a_{sl}^{d} = (-4.1 \pm 0.6) \times 10^{-4}$$
$$a_{sl}^{s} = (1.9 \pm 0.3) \times 10^{-5}$$

* A. Lenz, 2012, 1205.1444 [hep-ph]

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$a_{sl}^{d} = (-4.1 \pm 0.6) \times 10^{-4}$
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≈ ZERO

(Experimental precision: few x 10^{-3})

* A. Lenz, 2012, 1205.1444 [hep-ph]

A little theory

- Time dependent Schrodinger equation

$$i\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} |B^0(t)\rangle \\ |\overline{B}^0(t)\rangle \end{pmatrix} = \left[\begin{pmatrix} M_{11} & M_{12} \\ M_{12}^* & M_{22} \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{22} \end{pmatrix}\right]\begin{pmatrix} |B^0(t)\rangle \\ |\overline{B}^0(t)\rangle \end{pmatrix}$$

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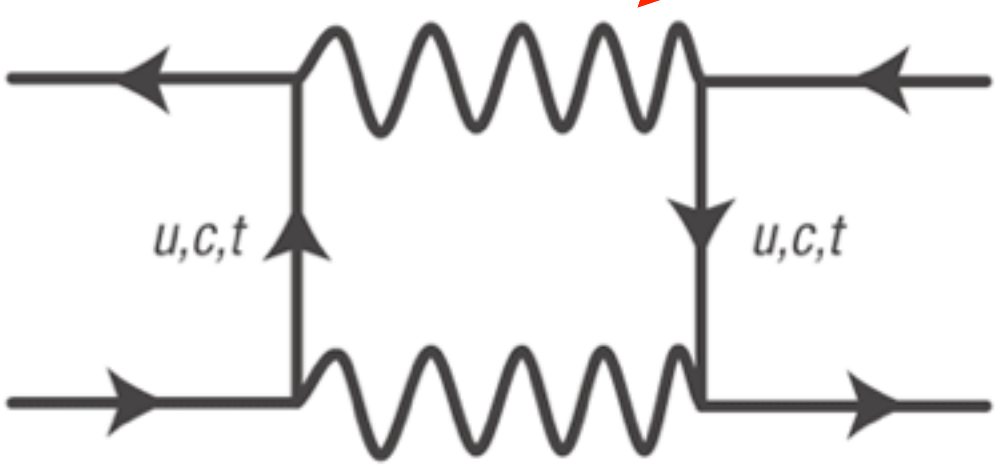
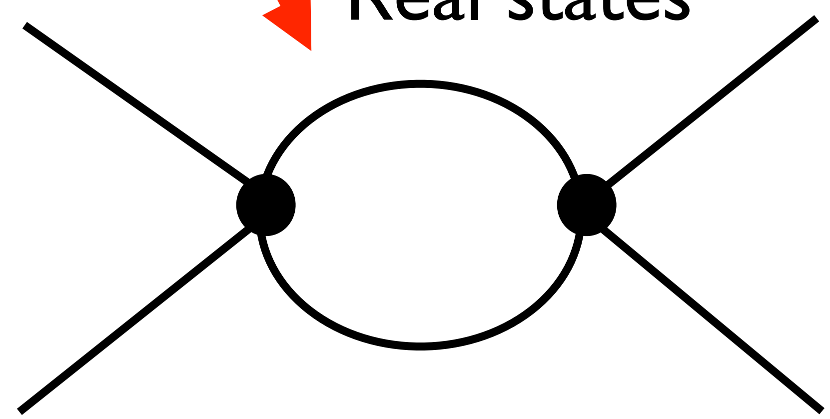
Virtual states



Real states



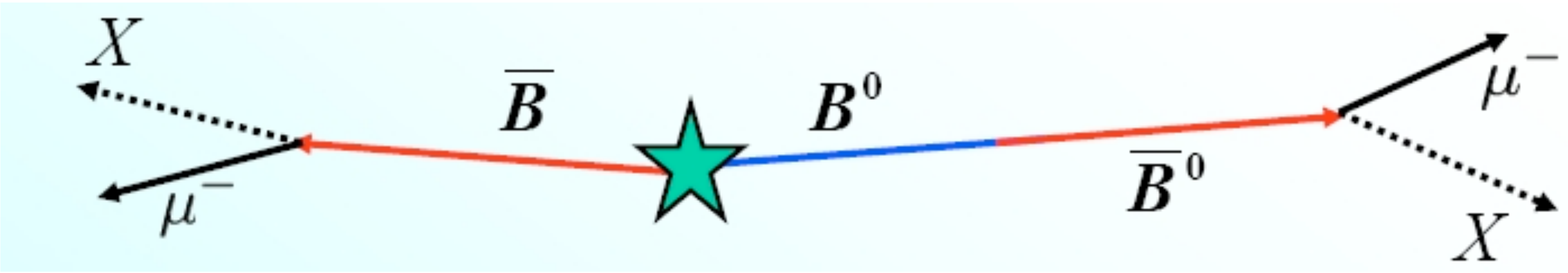
- CP-violation in mixing

$$a_{sl}=\mathrm{Im}(M_{12}/\Gamma_{12})$$

How to measure?

$$a_{\rm sl} = \frac{\Gamma(\overline{B} \to B \to f) - \Gamma(B \to \overline{B} \to \bar{f})}{\Gamma(\overline{B} \to B \to f) + \Gamma(B \to \overline{B} \to \bar{f})}$$

Method A: Inclusive like-sign dilepton asymmetry



$$A_{\ell\ell} \equiv \frac{\Gamma(\ell^+\ell^+) - \Gamma(\ell^-\ell^-)}{\Gamma(\ell^+\ell^+) + \Gamma(\ell^-\ell^-)} = a_{\rm sl}$$

How to measure?

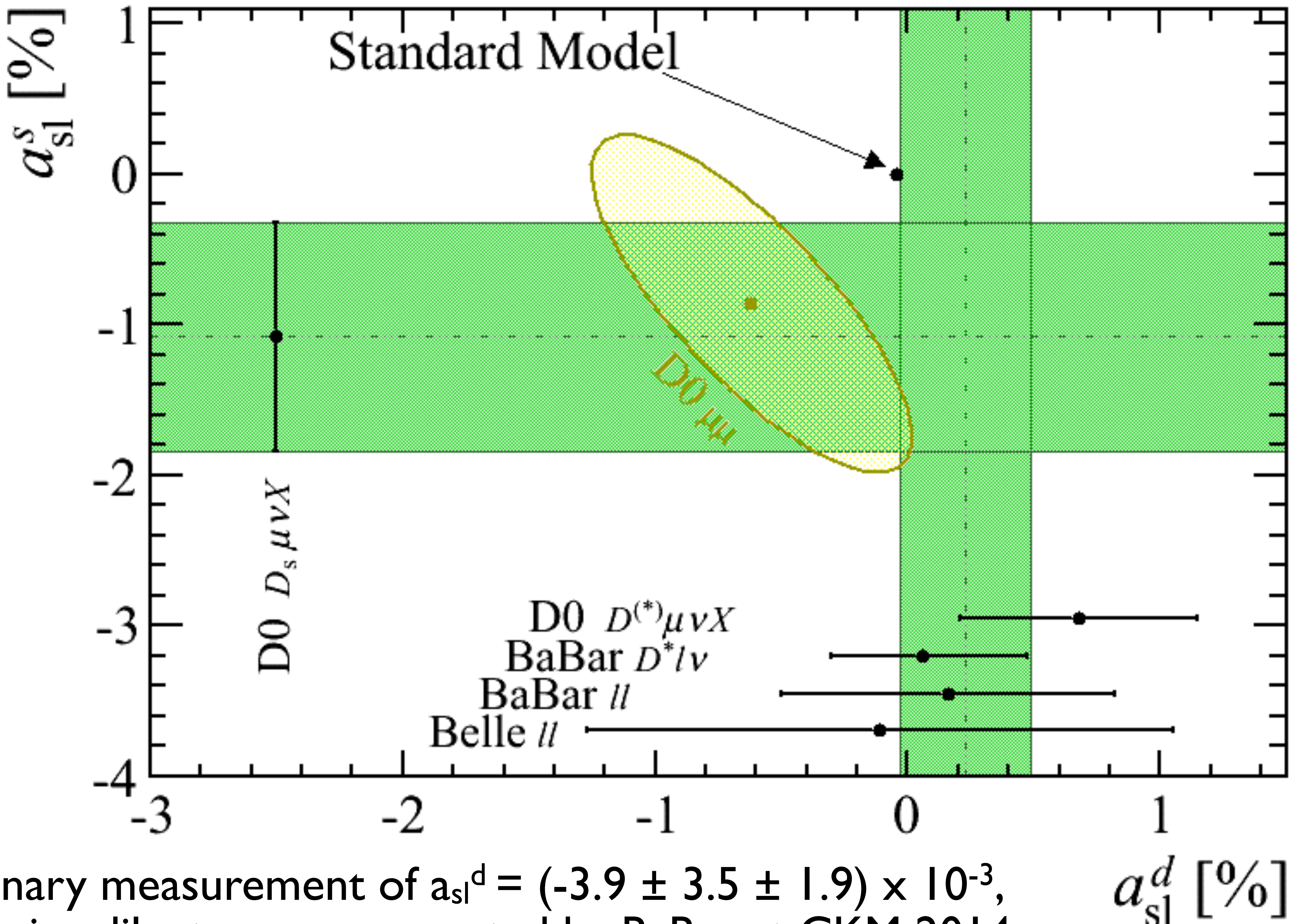
$$a_{\rm sl} = \frac{\Gamma(\overline{B} \to B \to f) - \Gamma(B \to \overline{B} \to \bar{f})}{\Gamma(\overline{B} \to B \to f) + \Gamma(B \to \overline{B} \to \bar{f})}$$

Method B: Untagged asymmetry (used by LHCb)

$$\frac{N(B,t) - N(\bar{B},t)}{N(B,t) + N(\bar{B},t)} = \frac{a_{\rm sl}}{2} \cdot \left[1 - \frac{\cos \Delta M t}{\cosh \frac{\Delta\Gamma t}{2}}\right]$$

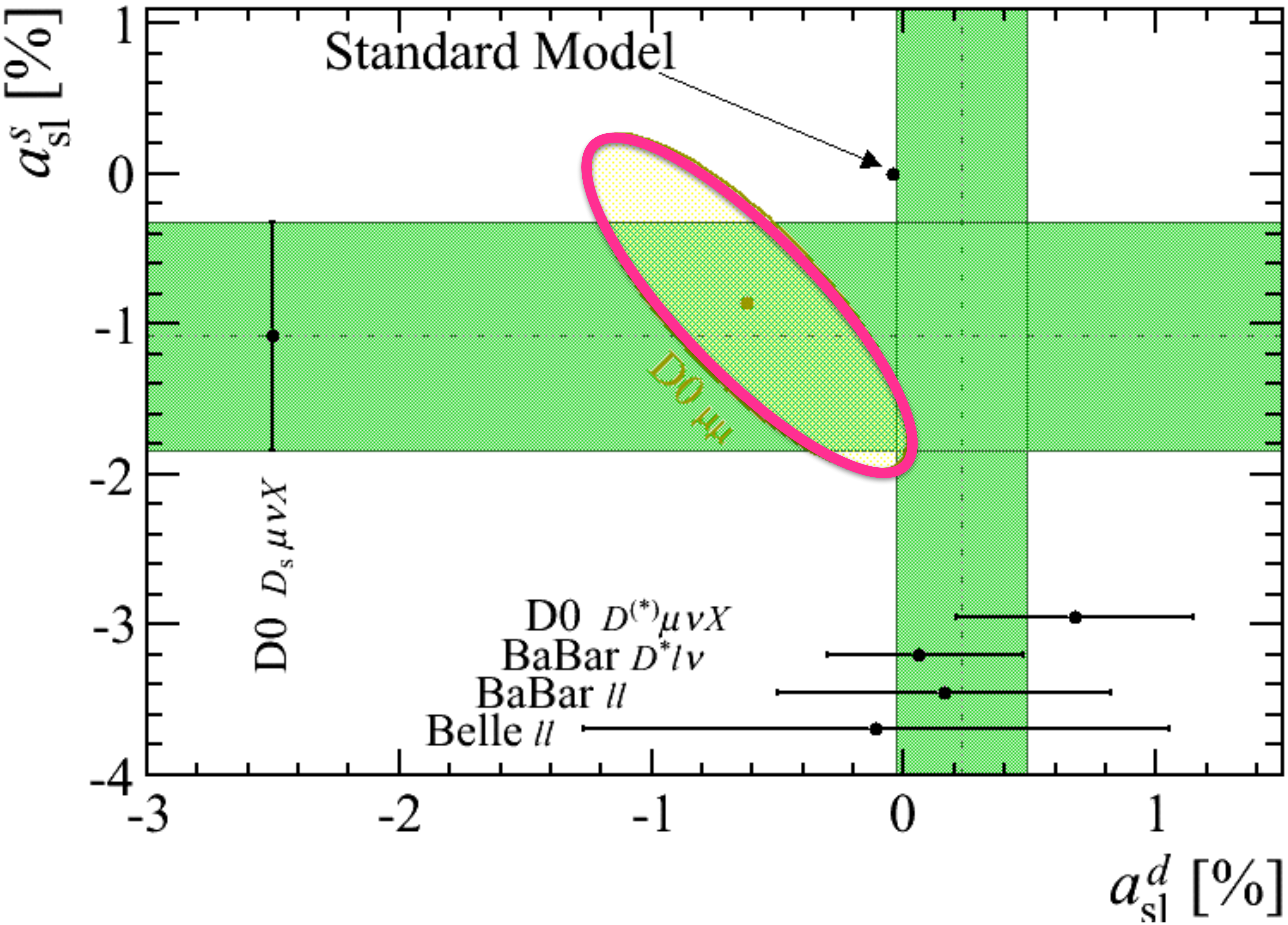
Look for an oscillating asymmetry as a function of decay time

Experimental landscape before LHCb



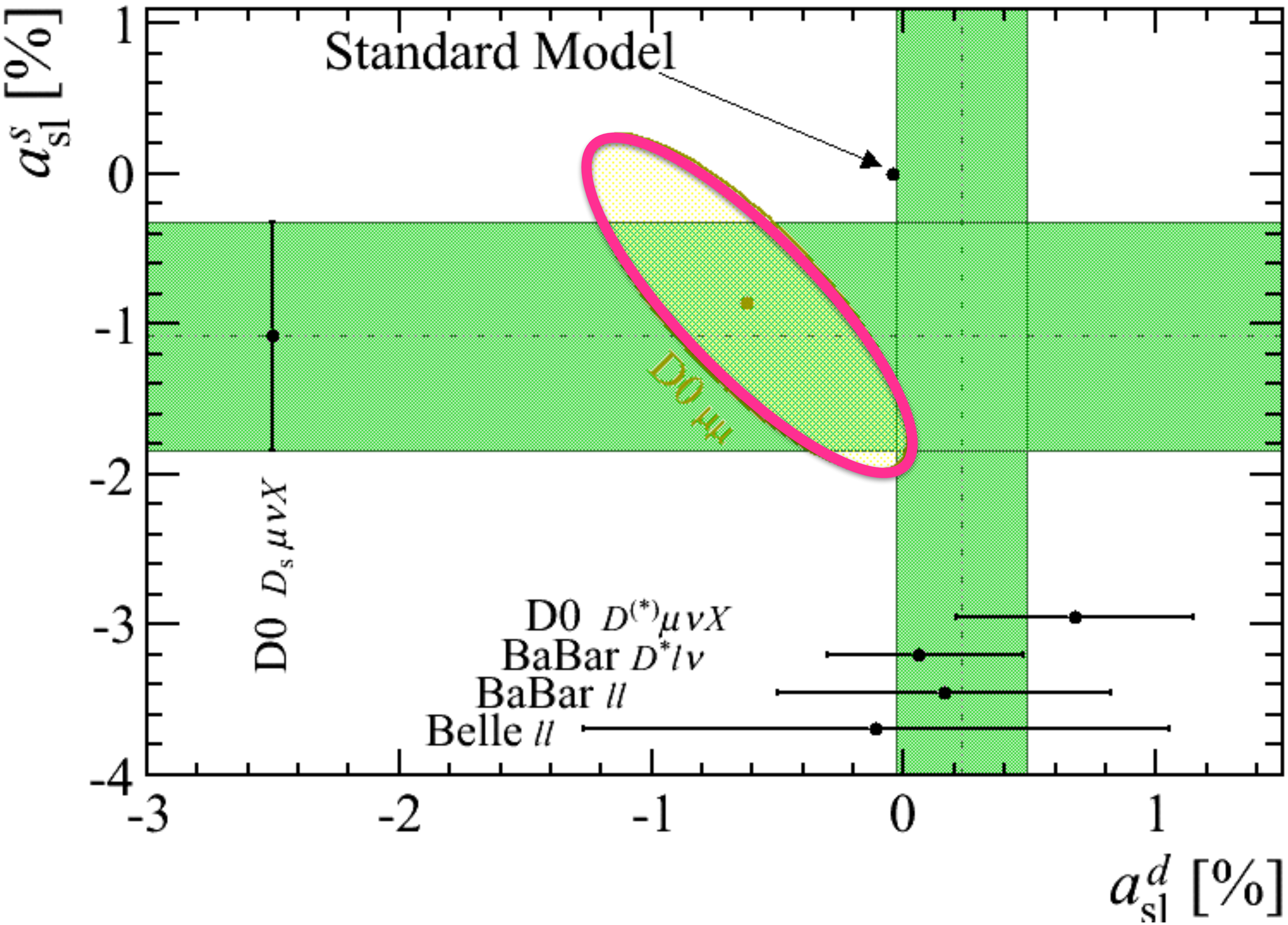
A preliminary measurement of $a_{sl}^d = (-3.9 \pm 3.5 \pm 1.9) \times 10^{-3}$, with inclusive dileptons was reported by BaBar at CKM 2014 (see slides of Chih-hsiang Cheng)

Experimental landscape before LHCb



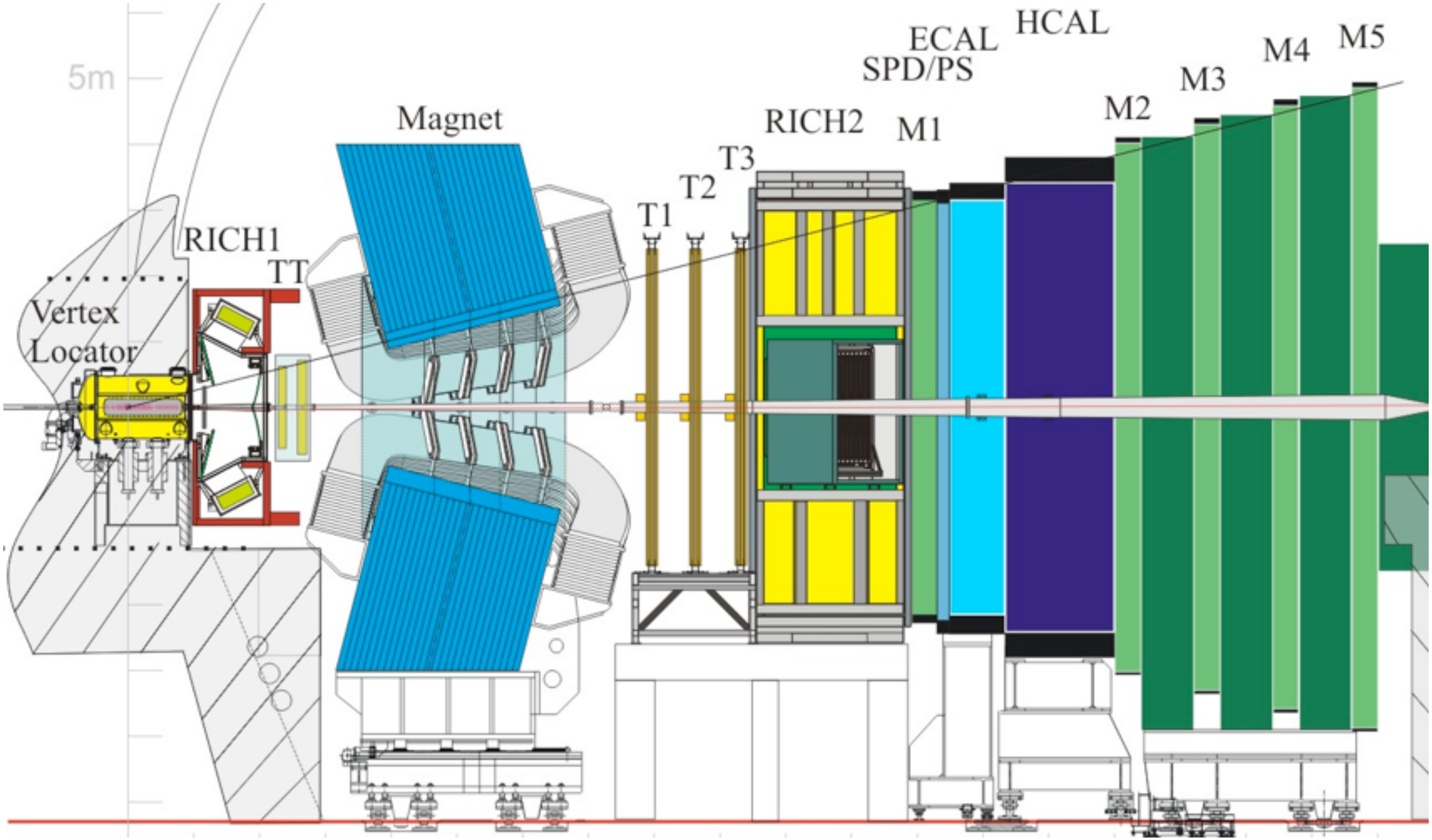
Dimuon asymmetry from D0 is 3.6σ from the SM

Experimental landscape before LHCb



New measurements urgently needed

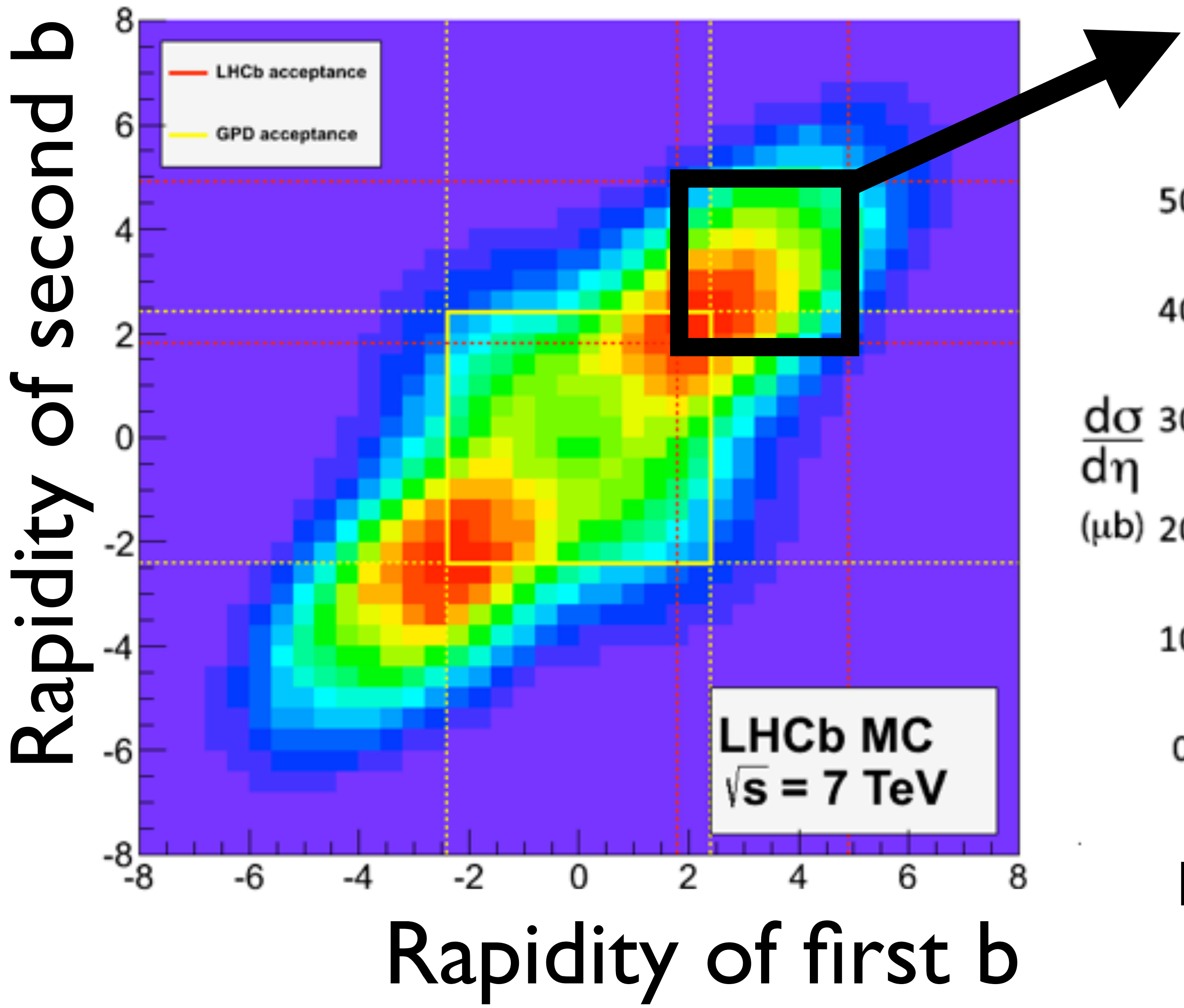
The LHC beauty experiment



LHCb reoptimized detector design and performance :Technical Design Report,
CERN-LHCC-2003-030

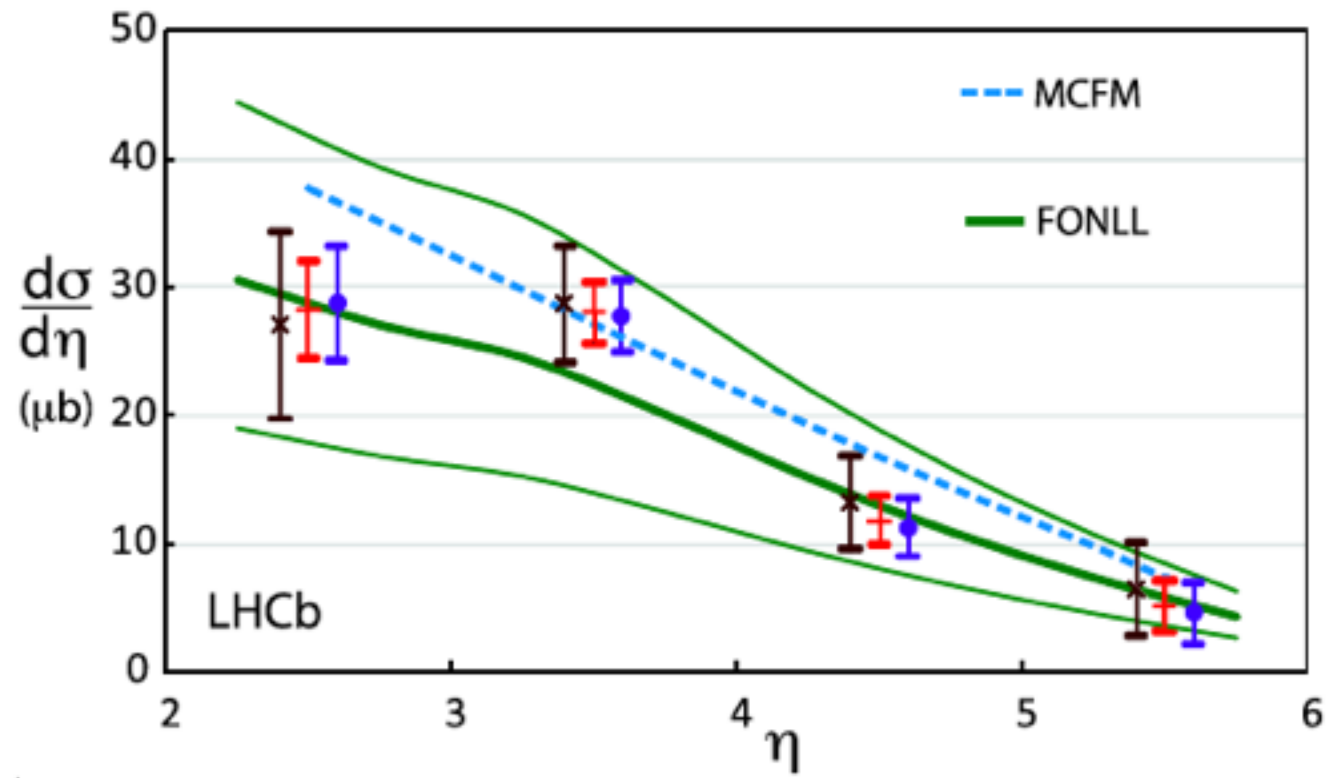
The LHC beauty experiment

b production at the LHC is mostly in the forward direction



b cross section in LHCb:

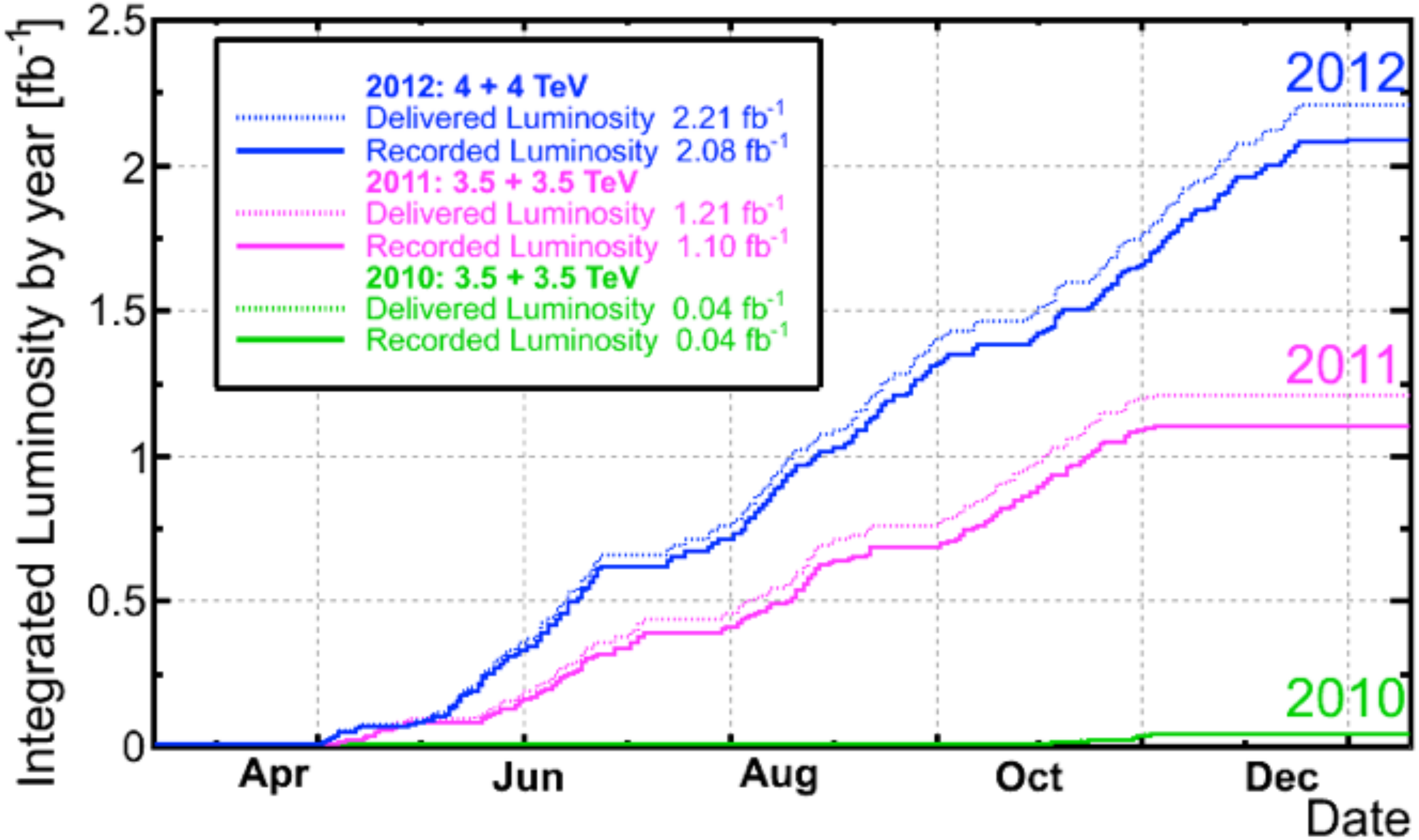
(75 ± 14) μb @ 7 TeV



LHCb, Phys Lett. B694 209-2016 (2010)

The LHC beauty experiment

3 fb^{-1} recorded in Run-I
Around 10^{12} b hadrons!

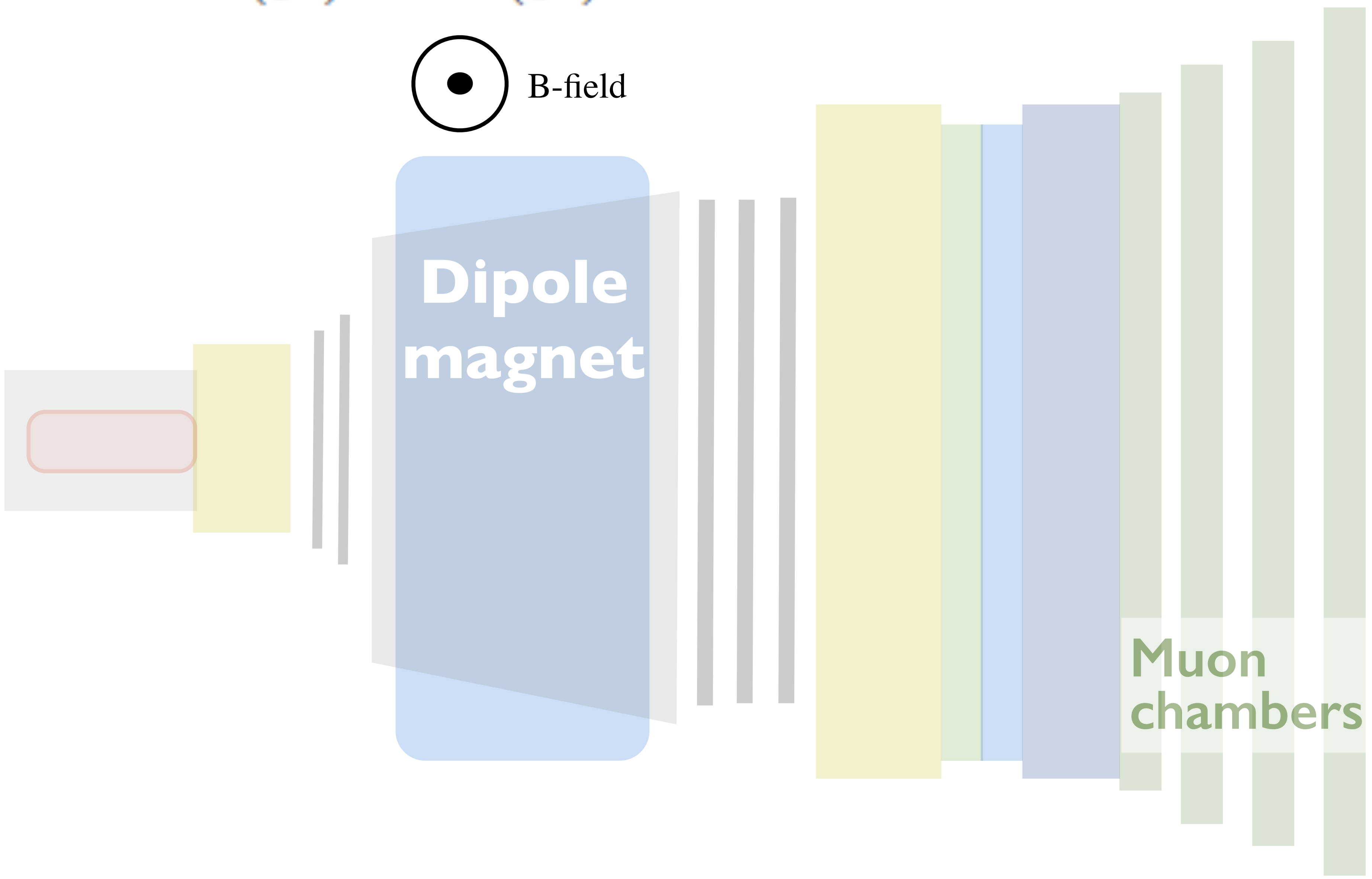


Thanks to the machine people!
Also for delivering our two polarity scheme…

MV, "*Considerations on the LHCb dipole magnet polarity reversal*", LHCb-PUB-2014-006.

Detection asymmetries

$$A_D = \frac{\varepsilon(f) - \varepsilon(\overline{f})}{\varepsilon(f) + \varepsilon(\overline{f})}$$



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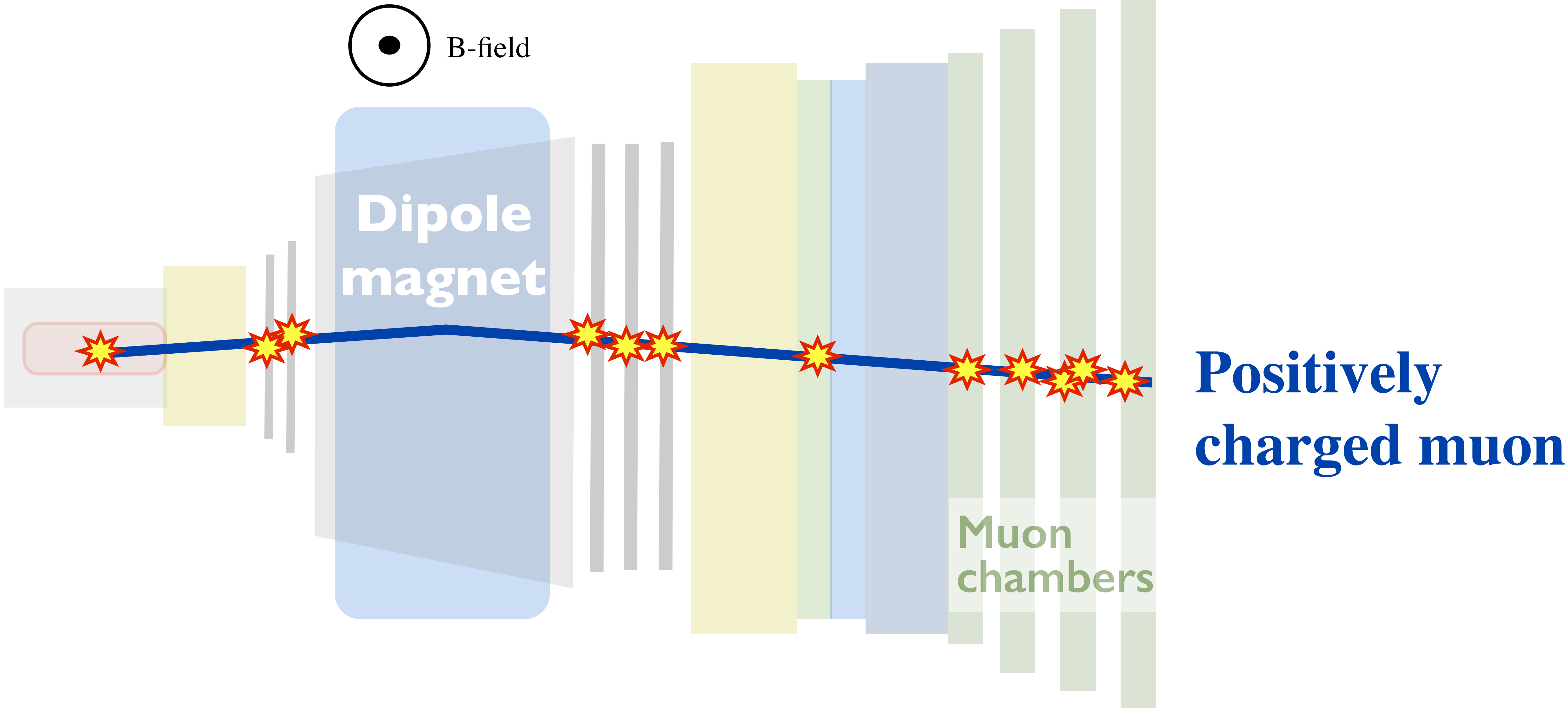

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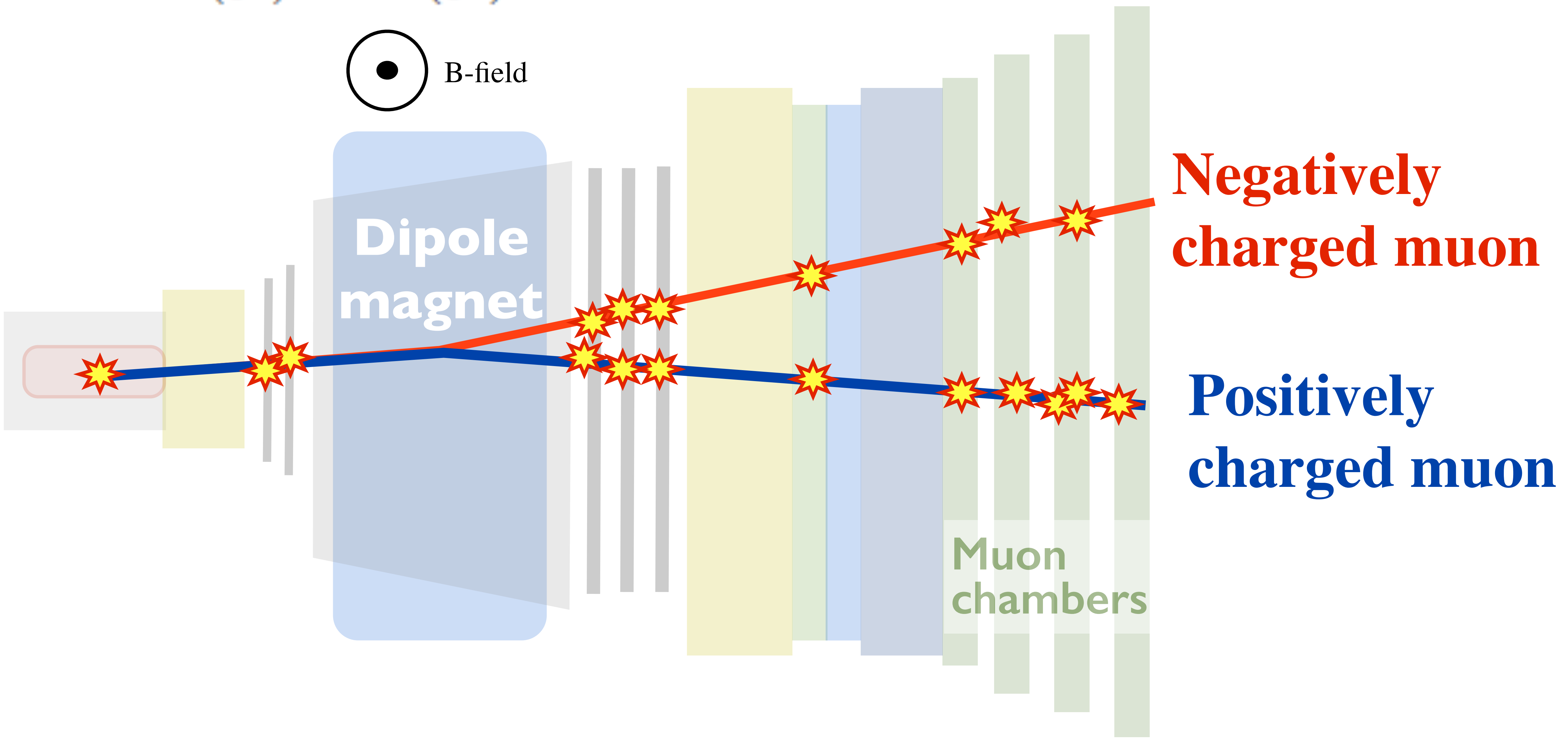

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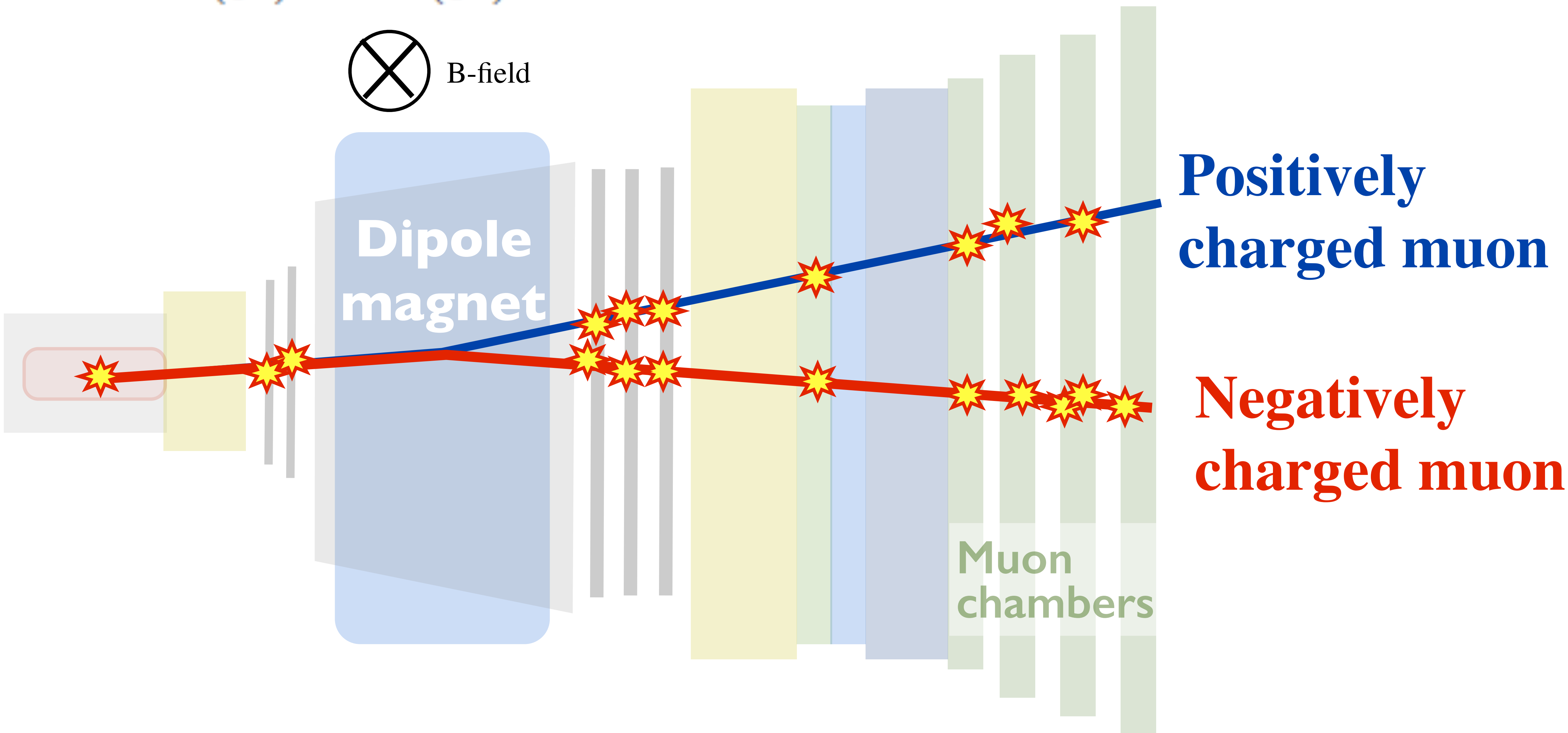
Reversed magnet polarity



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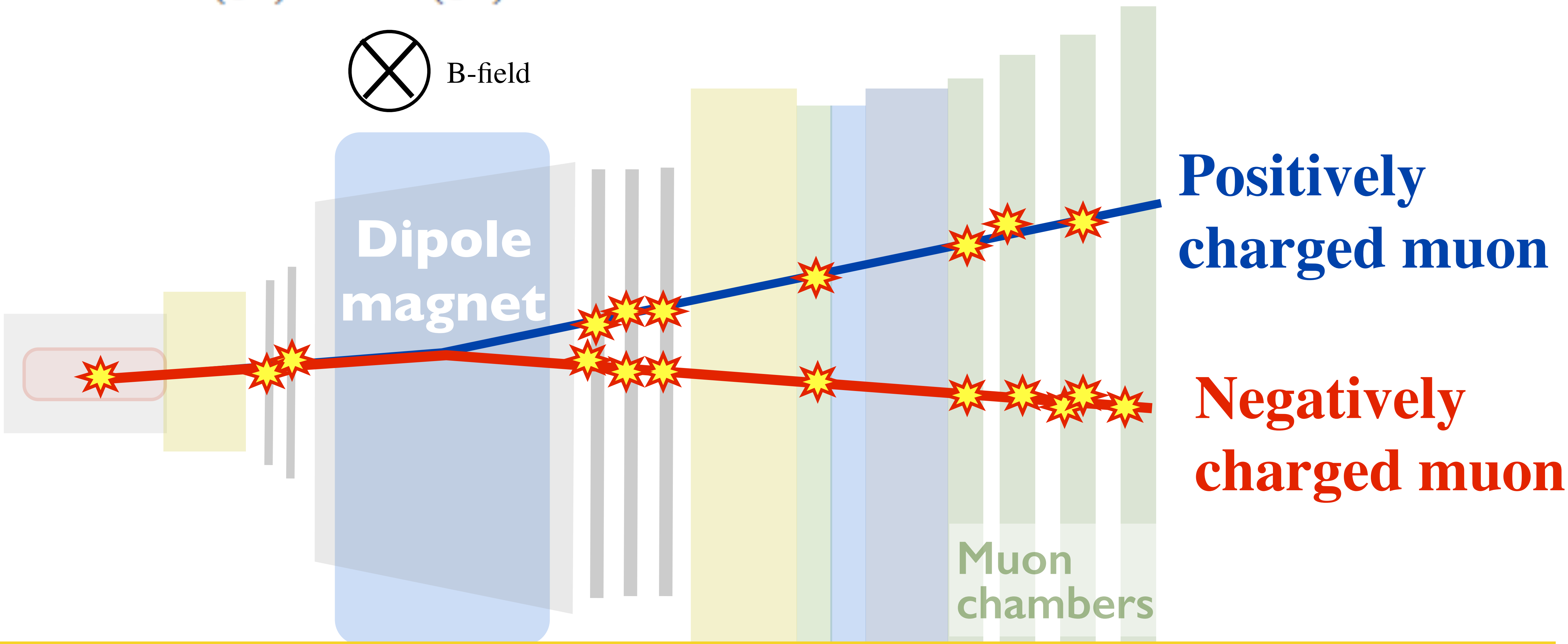
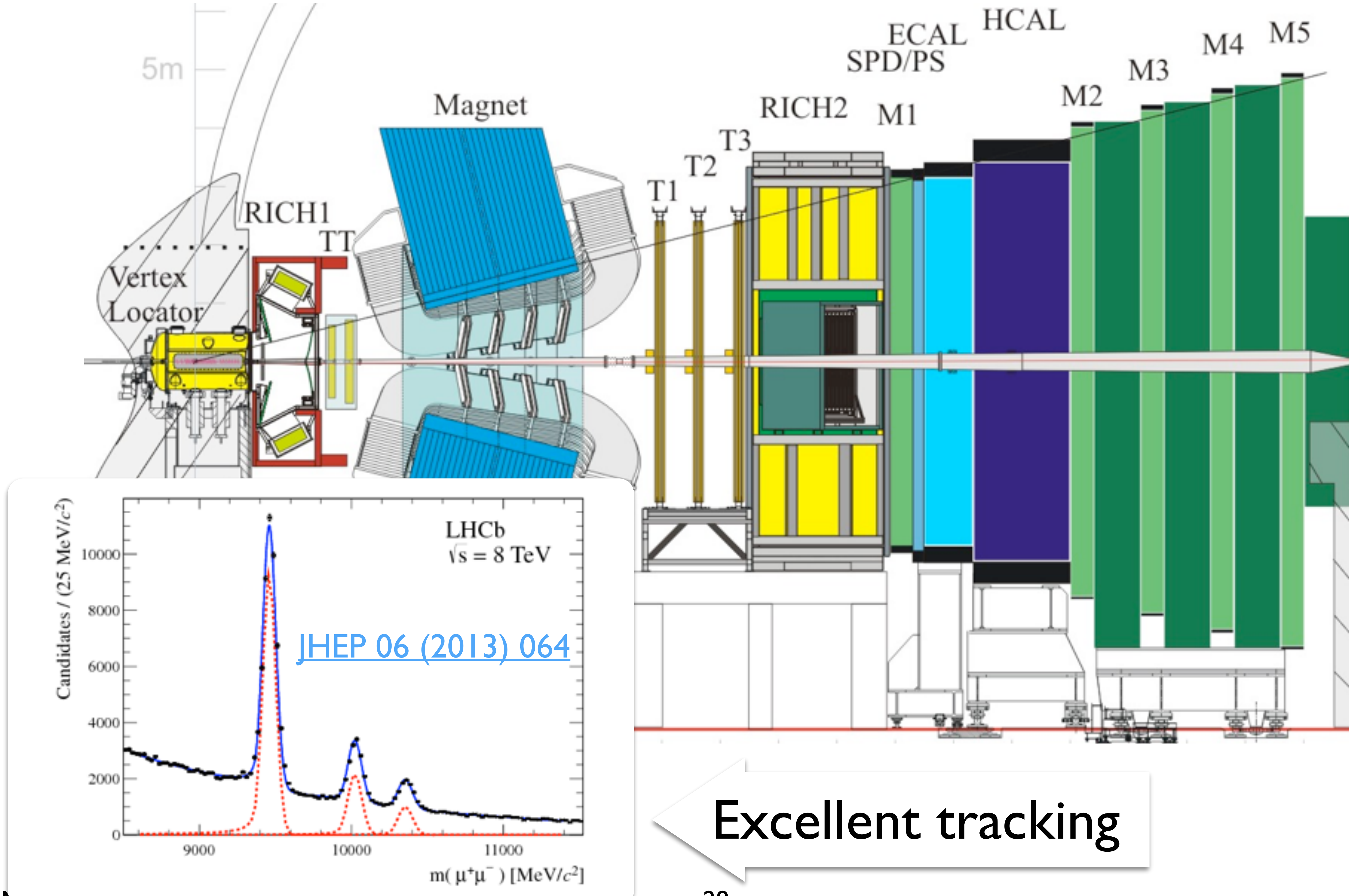


- Effectiveness depends on high frequency (2 week) of changes.
- Does not cancel asymmetries to 10^{-3} level, but crucial systematic check of result.

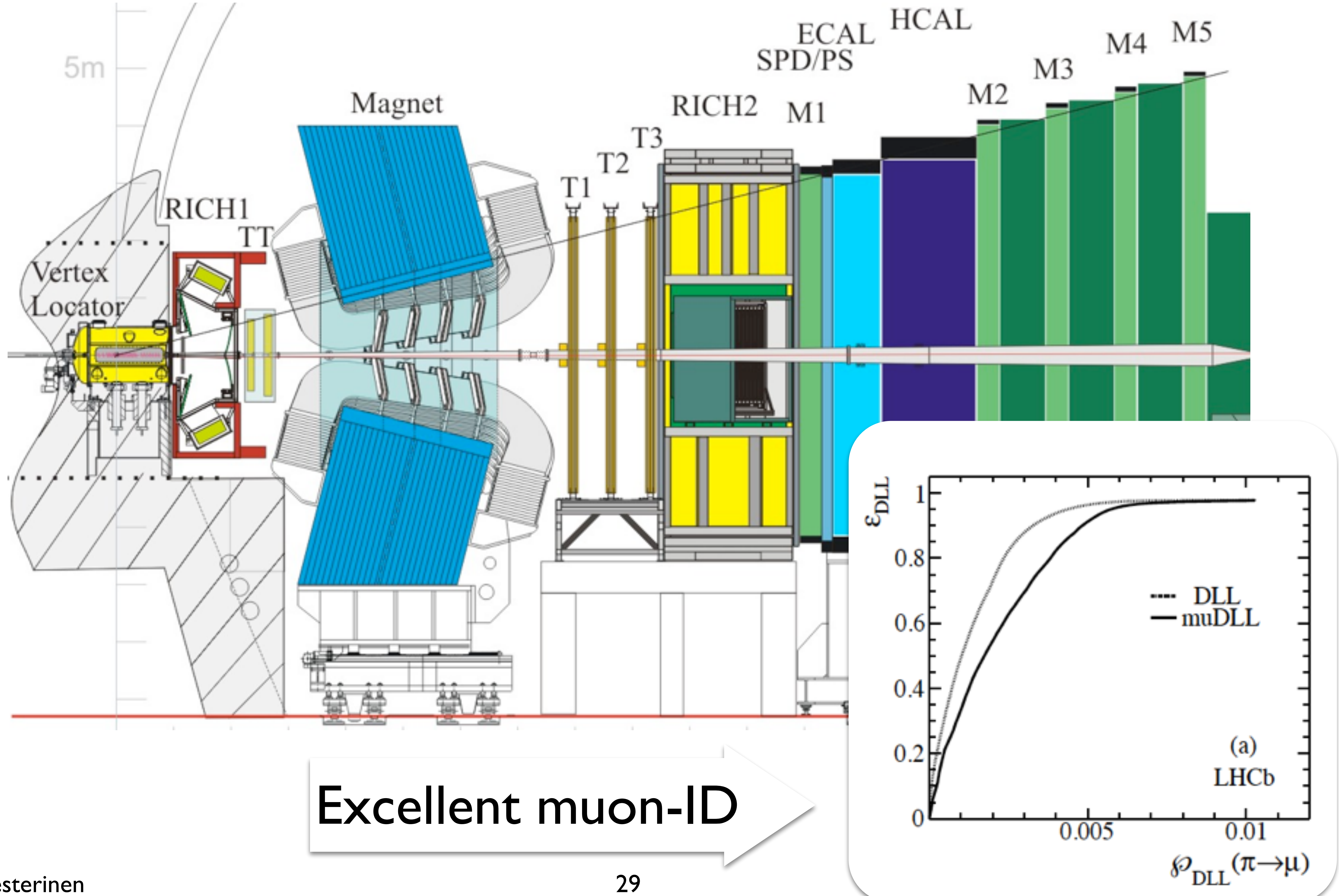
The LHC beauty experiment



[JHEP 06 (2013) 064]

Excellent tracking

The LHC beauty experiment

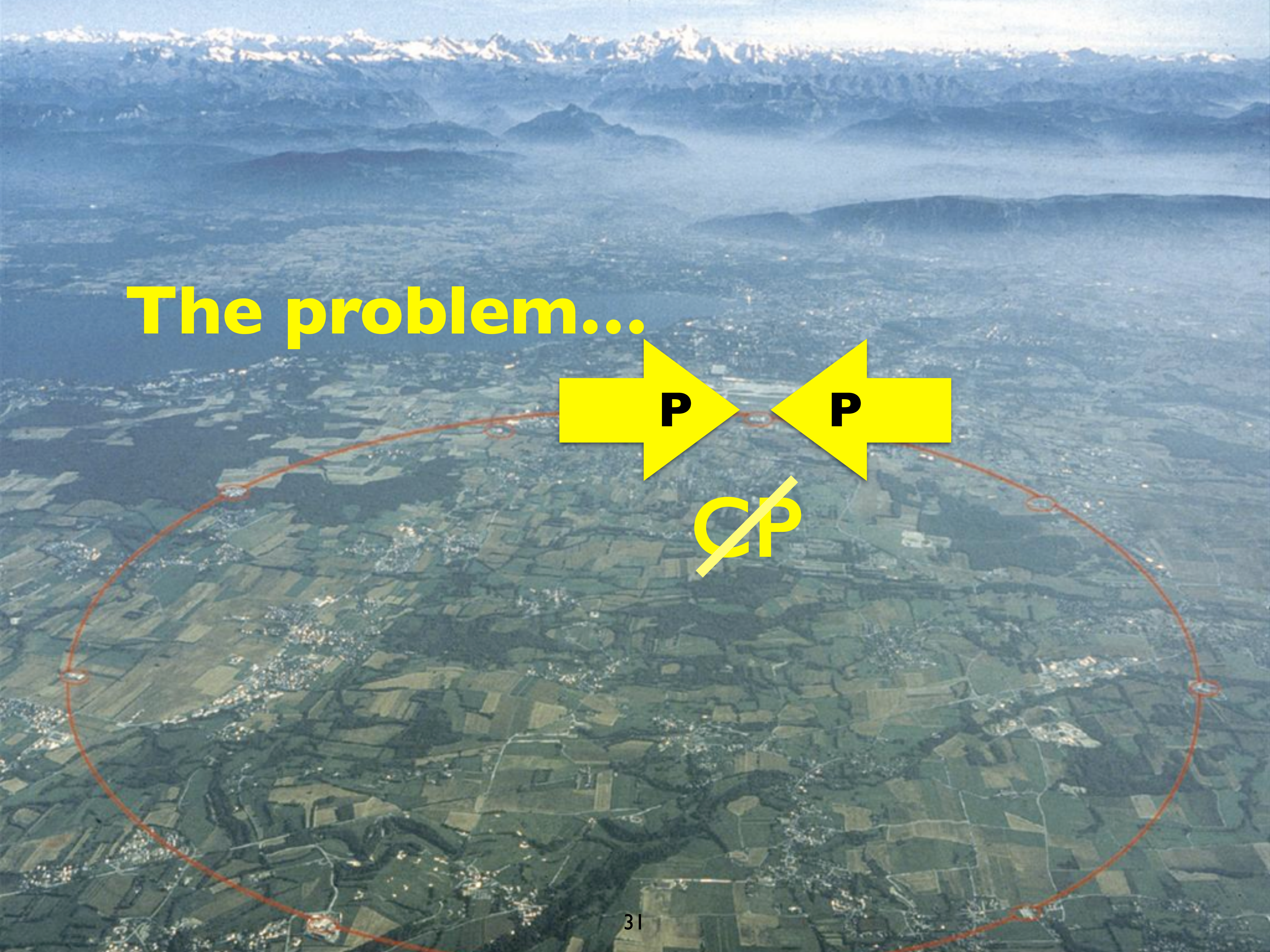


Measuring a_{sl} at LHCb

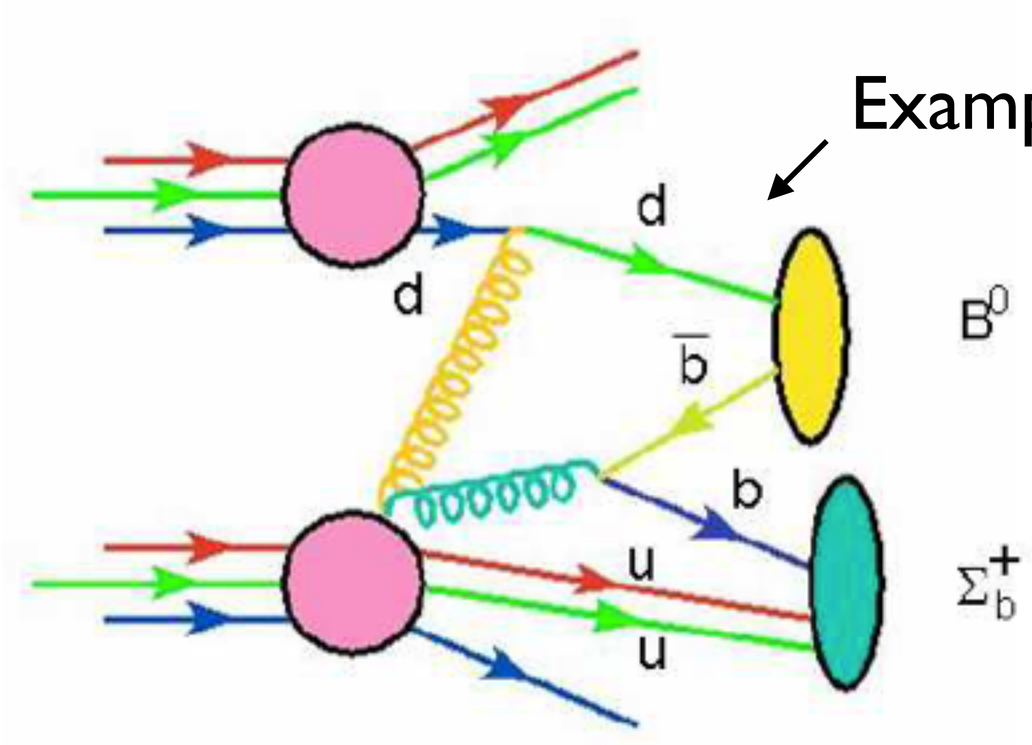
- This is what we need to measure

$$\frac{N(B,t) - N(\bar{B},t)}{N(B,t) + N(\bar{B},t)} = \frac{a_{\mathrm{sl}}}{2} \cdot \left[1 - \frac{\cos \Delta M t}{\cosh \frac{\Delta\Gamma t}{2}}\right]$$

The problem...



Production asymmetries



Example mechanism

Expected to be around 1%

$$a_P = \frac{\sigma(pp \to \bar{B}) - \sigma(pp \to B)}{\sigma(pp \to \bar{B}) + \sigma(pp \to B)}$$

Now need to measure:

$$\frac{N(B,t) - N(\bar{B},t)}{N(B,t) + N(\bar{B},t)} = \frac{a_{\rm sl}}{2} - \left[a_P + \frac{a_{\rm sl}}{2}\right] \cdot \frac{\cos \Delta M t}{\cosh \frac{\Delta\Gamma t}{2}}$$

Simpler for a_{sl}^{s}

Decay time integrated asymmetry

$$\frac{N(B_s^0) - N(\overline{B}_s^0)}{N(B_s^0) + N(\overline{B}_s^0)} = \frac{a_{\rm sl}^s}{2} + \left[a_{\rm P} - \frac{a_{\rm sl}^s}{2}\right] \frac{\int_{t=0}^{\infty} e^{-\Gamma_s t} \cos(\Delta M_s\, t)\epsilon(t)dt}{\int_{t=0}^{\infty} e^{-\Gamma_s t} \cosh(\frac{\Delta\Gamma_s\, t}{2})\epsilon(t)dt}$$

Simpler for a_{sl}^s

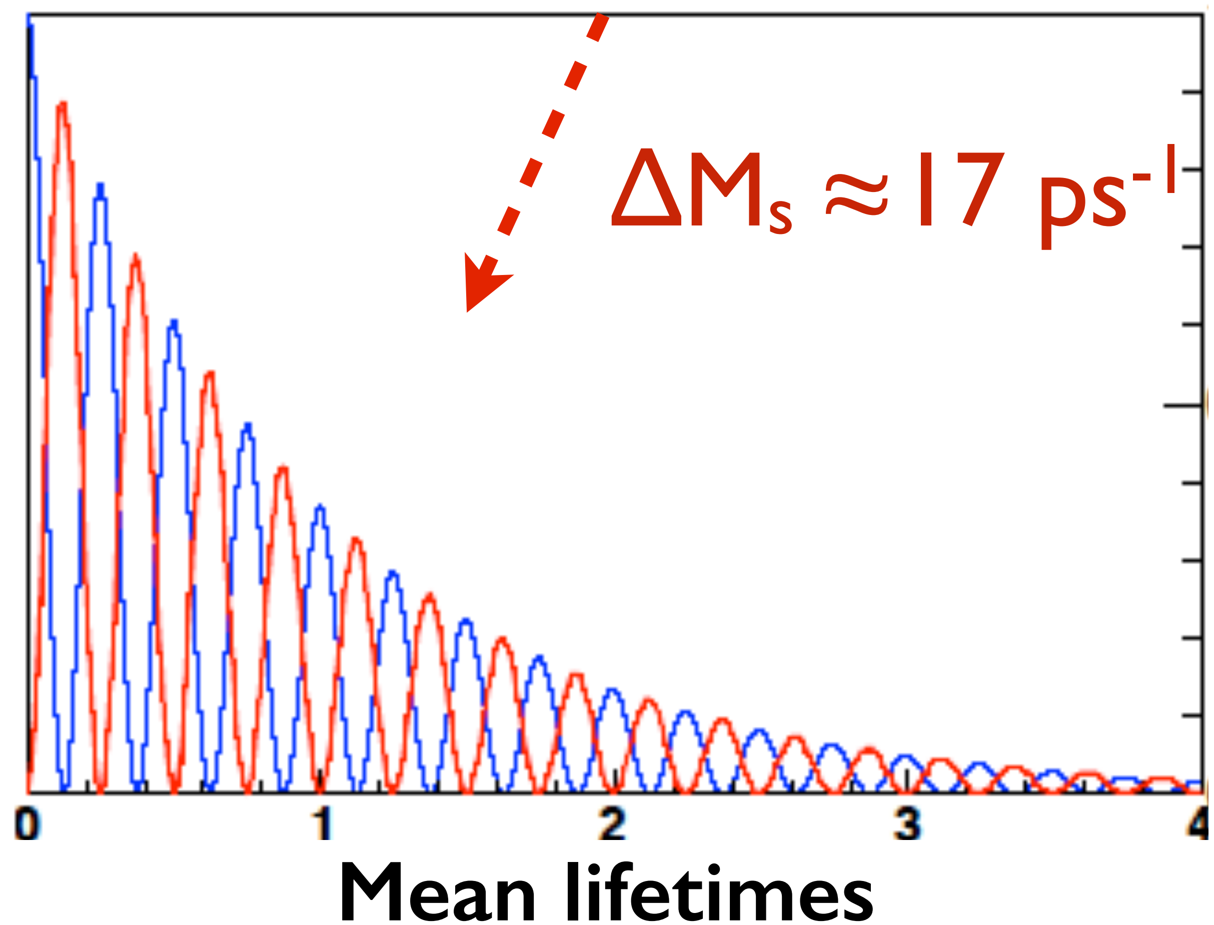
Decay time integrated asymmetry

< 10^{-4}

$$\frac{N(B_s^0) - N(\overline{B}_s^0)}{N(B_s^0) + N(\overline{B}_s^0)} = \frac{a_{\rm sl}^s}{2} + \left[a_{\rm P} - \frac{a_{\rm sl}^s}{2}\right] \frac{\int_{t=0}^{\infty} e^{-\Gamma_s t}\cos(\Delta M_s t)\epsilon(t)dt}{\int_{t=0}^{\infty} e^{-\Gamma_s t}\cosh(\frac{\Delta\Gamma_s t}{2})\epsilon(t)dt}$$

Effect of a_P is washed out by the fast oscillations!

$\Delta M_s \approx 17\ \mathrm{ps}^{-1}$



Simpler for a_{sl}^s

"Simply" need to measure:

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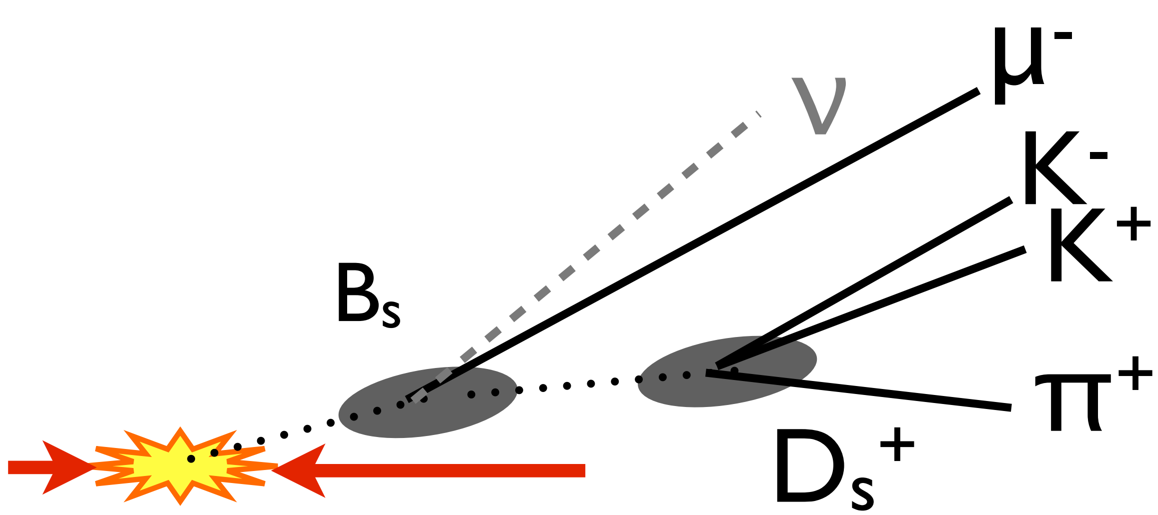

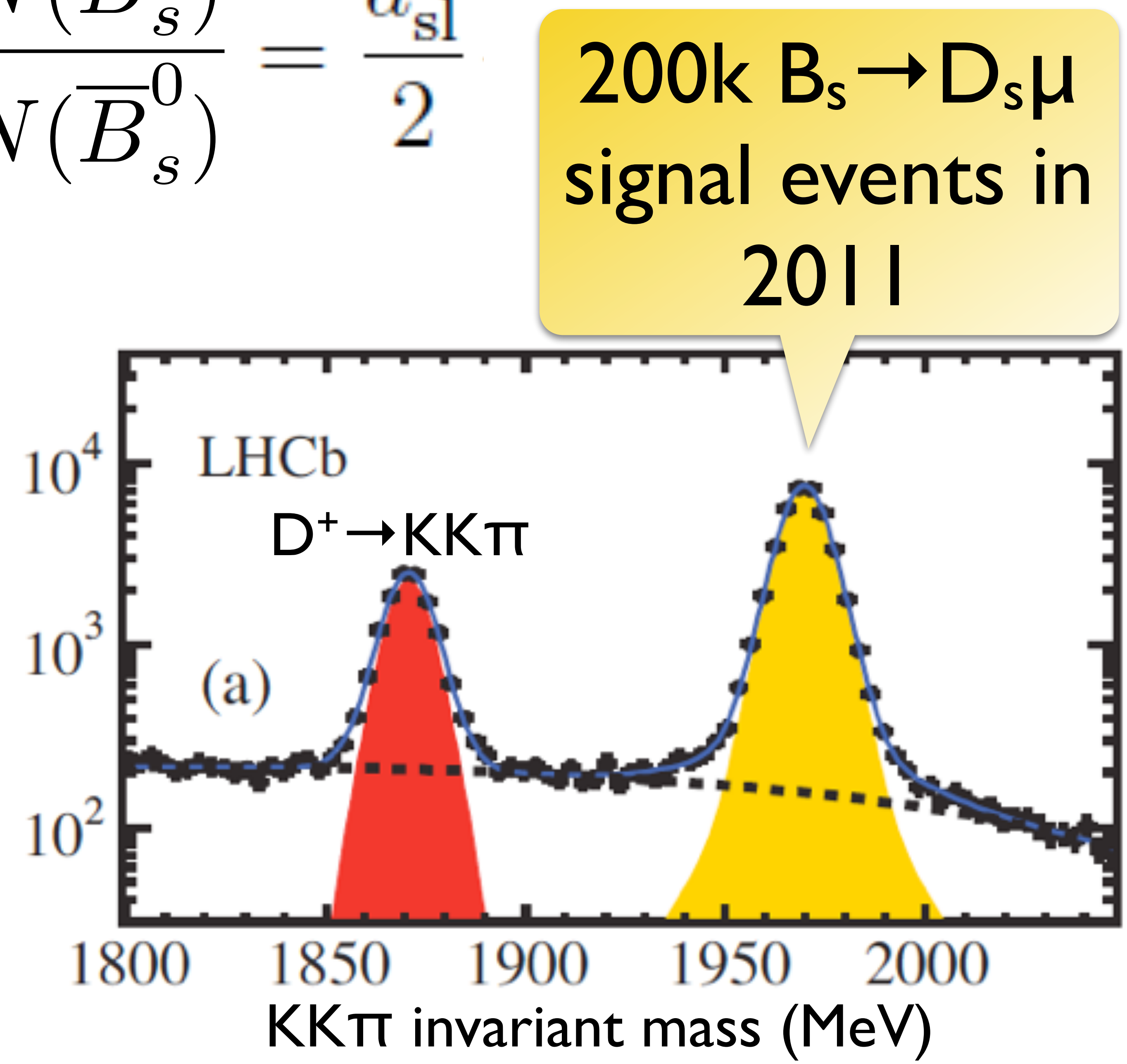

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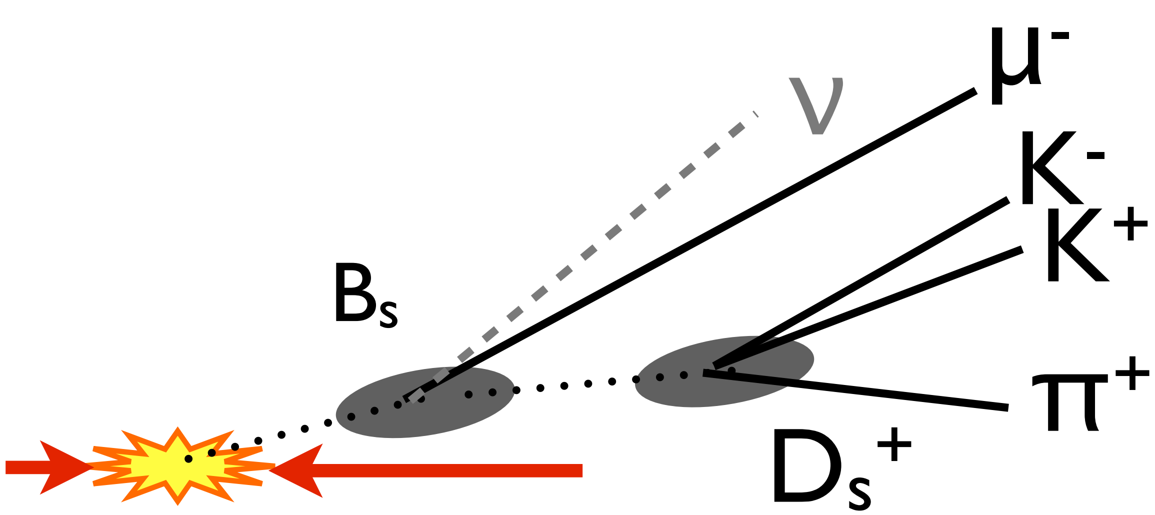


- The main problem is the detection asymmetry.
- Restricting to the $\phi \rightarrow KK$ resonance so only have a $\mu^{\pm}\pi^{\mp}$ asymmetry.

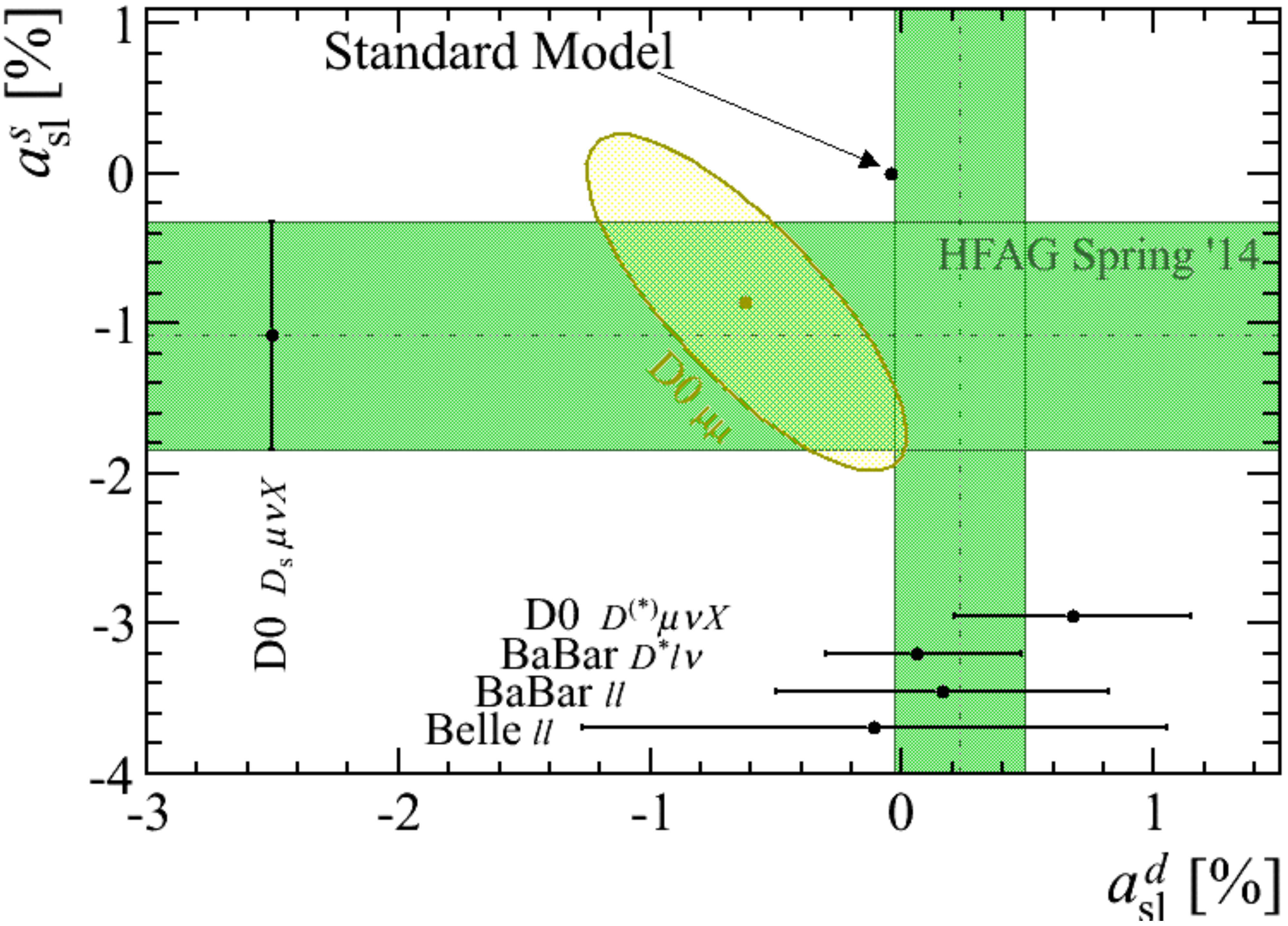
Result with 2011 dataset (1 fb^{-1})

$$a_{sl}^{s} = (-0.06 \pm 0.50_{stat} \pm 0.36_{syst})\%$$

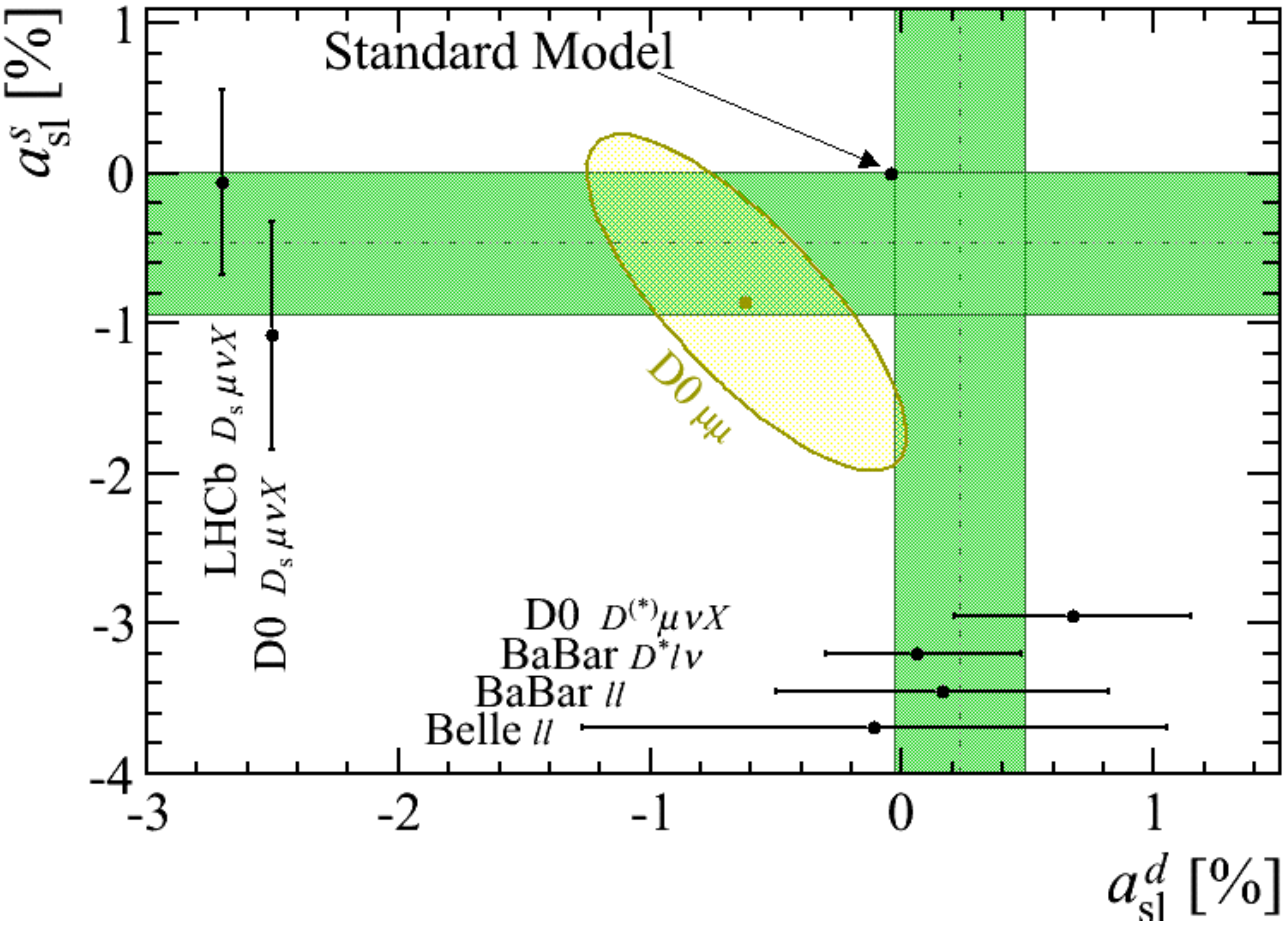
Source	δ (%)
Tracking asymmetries	0.26
Muon asymmetries	0.16
Fitting	0.15
Backgrounds	0.10
Quadratic sum	0.36

LHCb Collaboration, "*Measurement of the flavour-specific CP-violating asymmetry a_{sl}^{s} in B0s decays*", PLB 728C 607-615 (2014).

Landscape before



Landscape after



LHCb measurement of asld

- B_d mesons oscillate too slowly
- Fit the asymmetry as a function of decay time, to disentangle a_P and a_{sl}.

$$\frac{N(B,t)-N(\bar{B},t)}{N(B,t)+N(\bar{B},t)} = \frac{a_{\mathrm{sl}}}{2} - \left[a_P + \frac{a_{\mathrm{sl}}}{2}\right] \cdot \frac{\cos \Delta M t}{\cosh \frac{\Delta \Gamma t}{2}}$$

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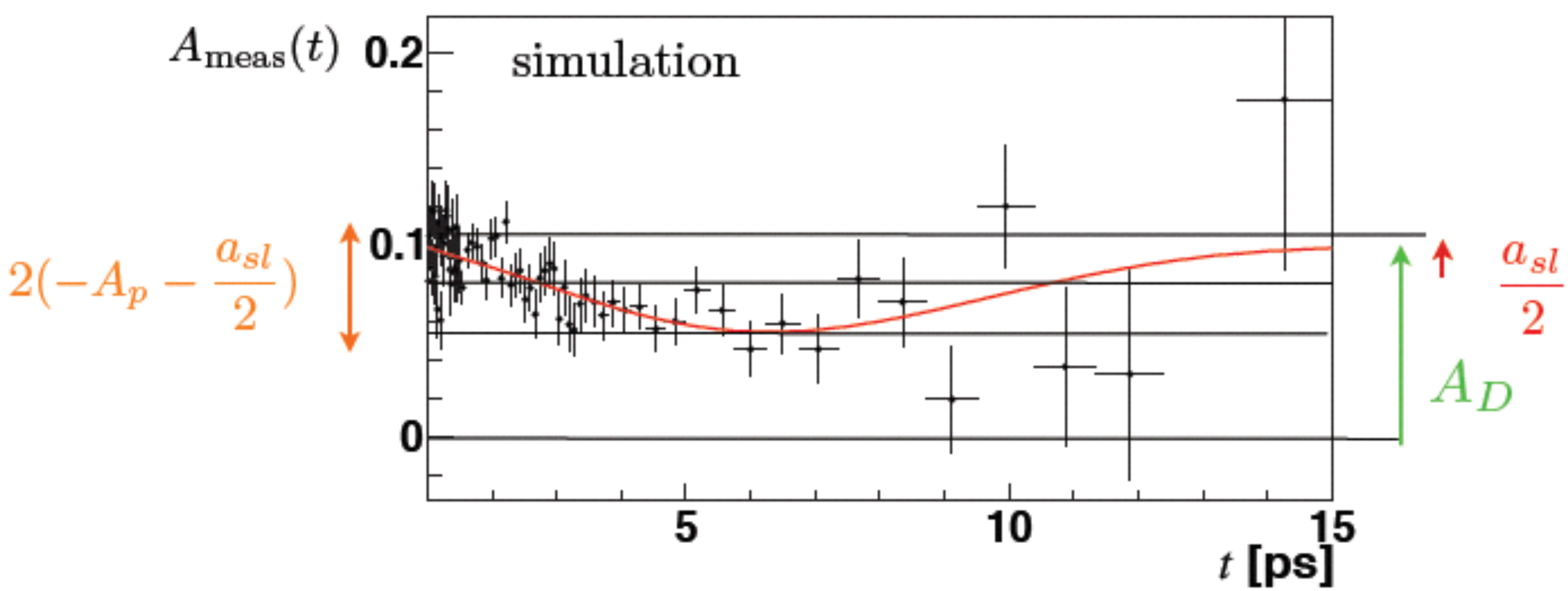
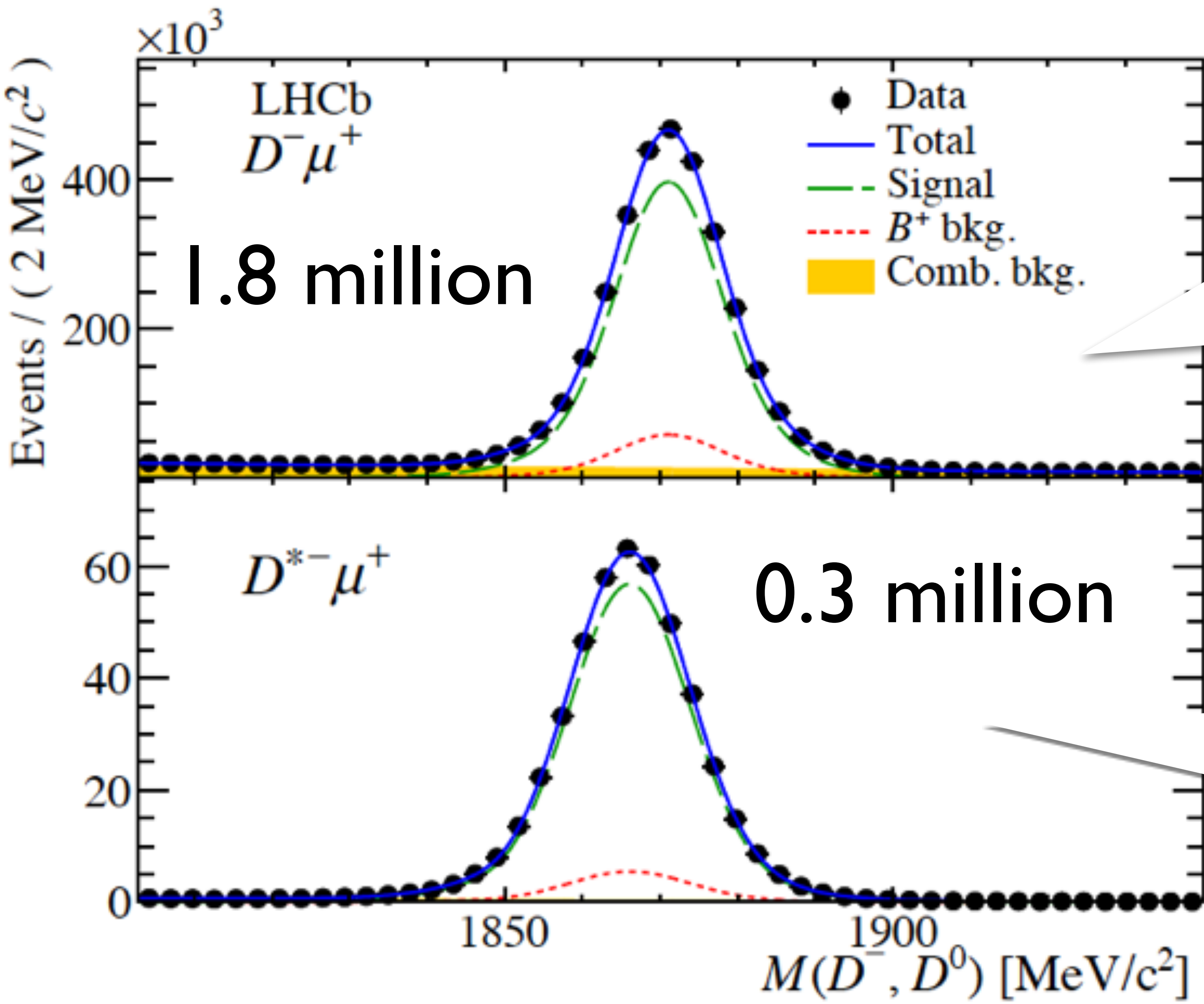
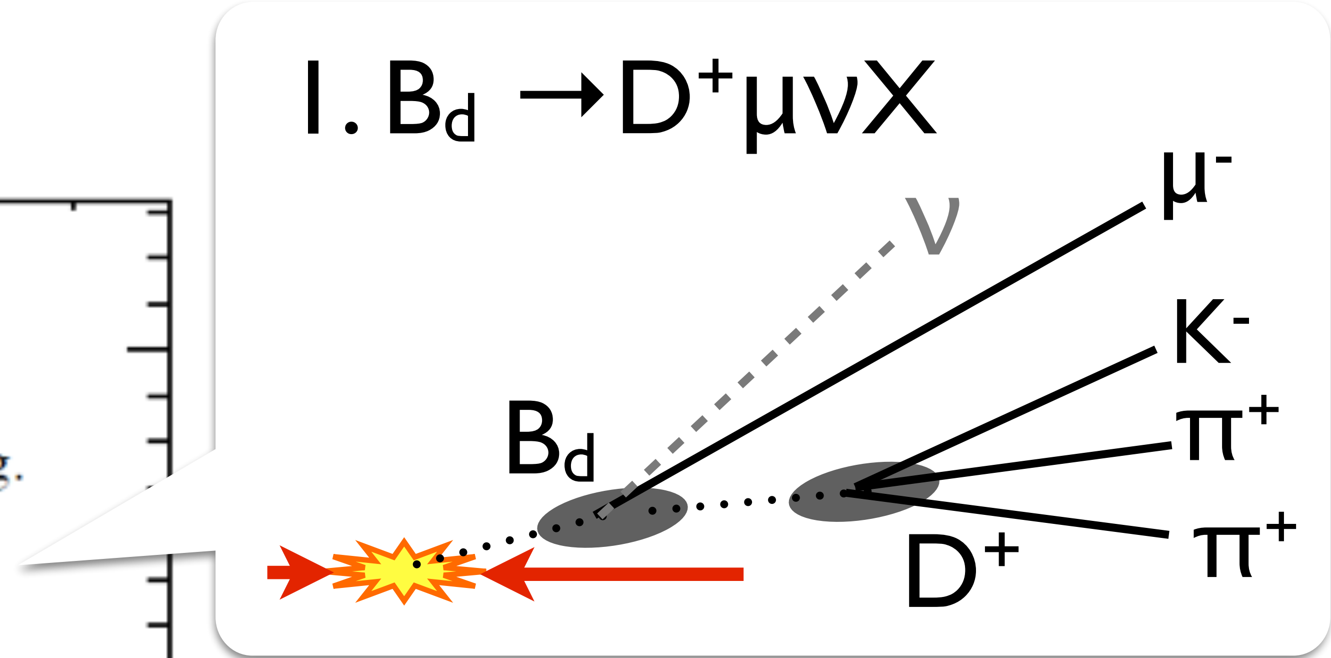


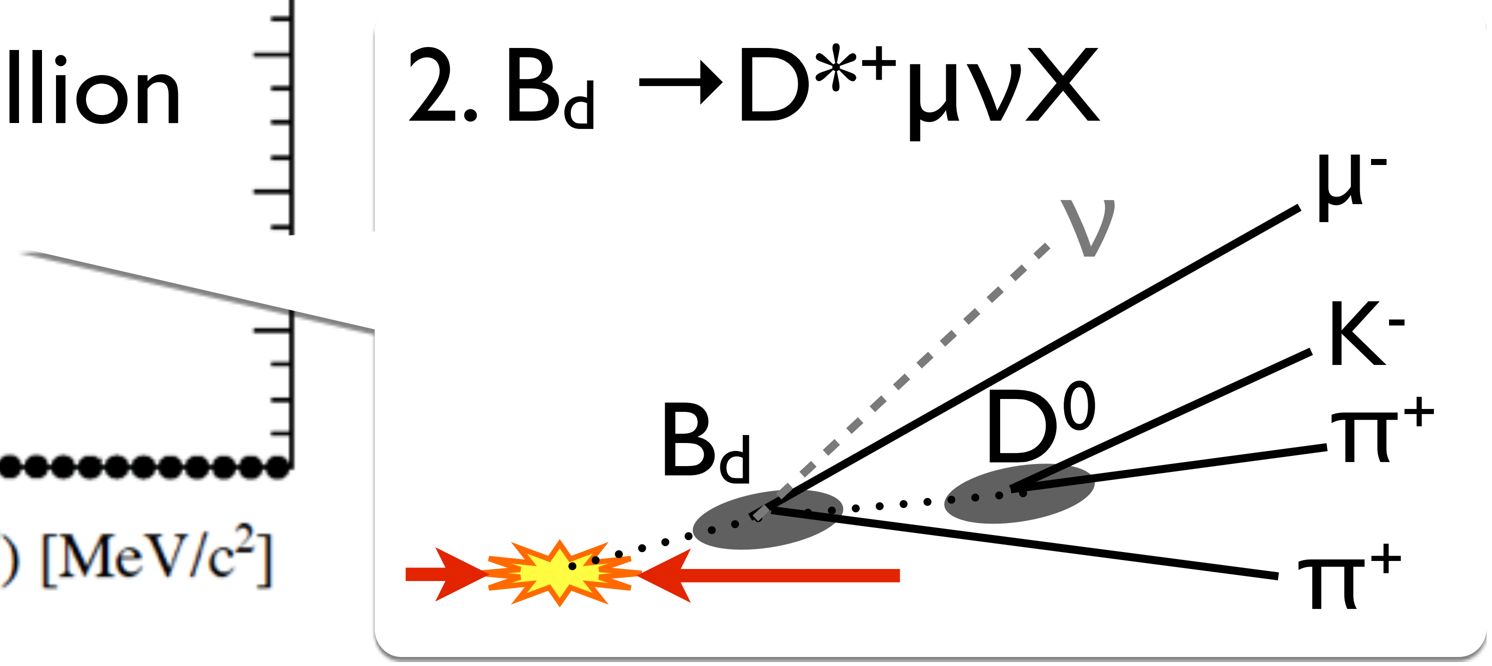
Our signals



×10^3
LHCb
$D^- \mu^+$
Data
Total
Signal
B^+ bkg.
Comb. bkg.
1.8 million
$D^{*-} \mu^+$
0.3 million
Events / (2 MeV/c^2)
400
200
60
40
20
0
1850
1900
$M(D^-, D^0)$ [MeV/c²]

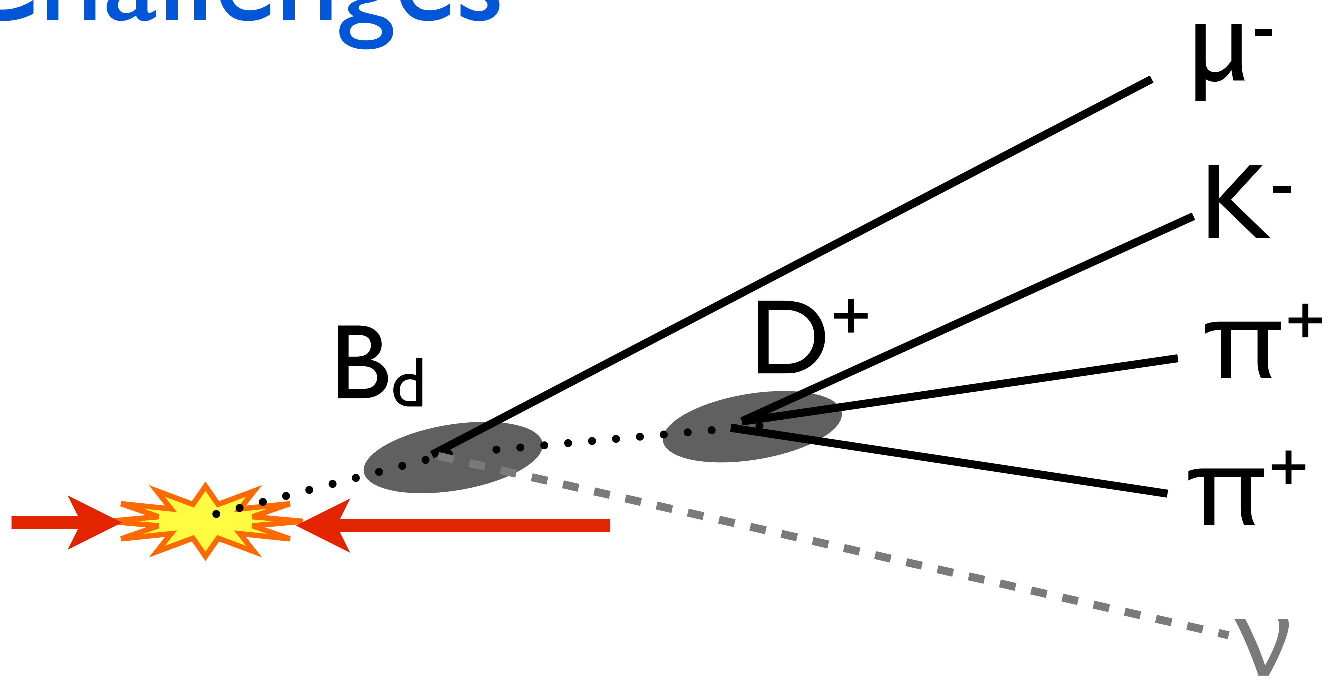


1. $B_d \rightarrow D^+ \mu \nu X$
ν
μ^-
K^-
B_d
π^+
D^+
π^+



2. $B_d \rightarrow D^{*+} \mu \nu X$
ν
μ^-
K^-
B_d
D^0
π^+
π^+

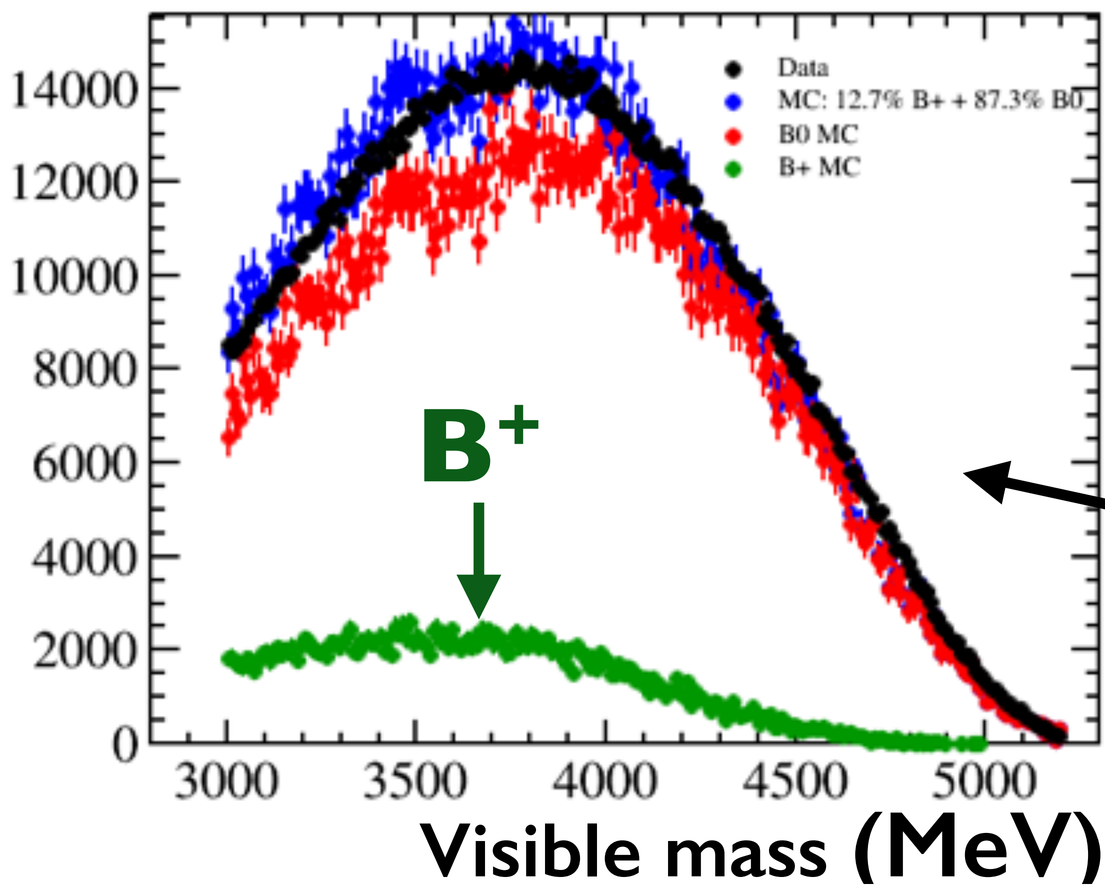
Challenges



1. The detection asymmetry for the $\mu^{\pm}\pi^{\mp}K^{\pm}\pi^{\mp}$ final state

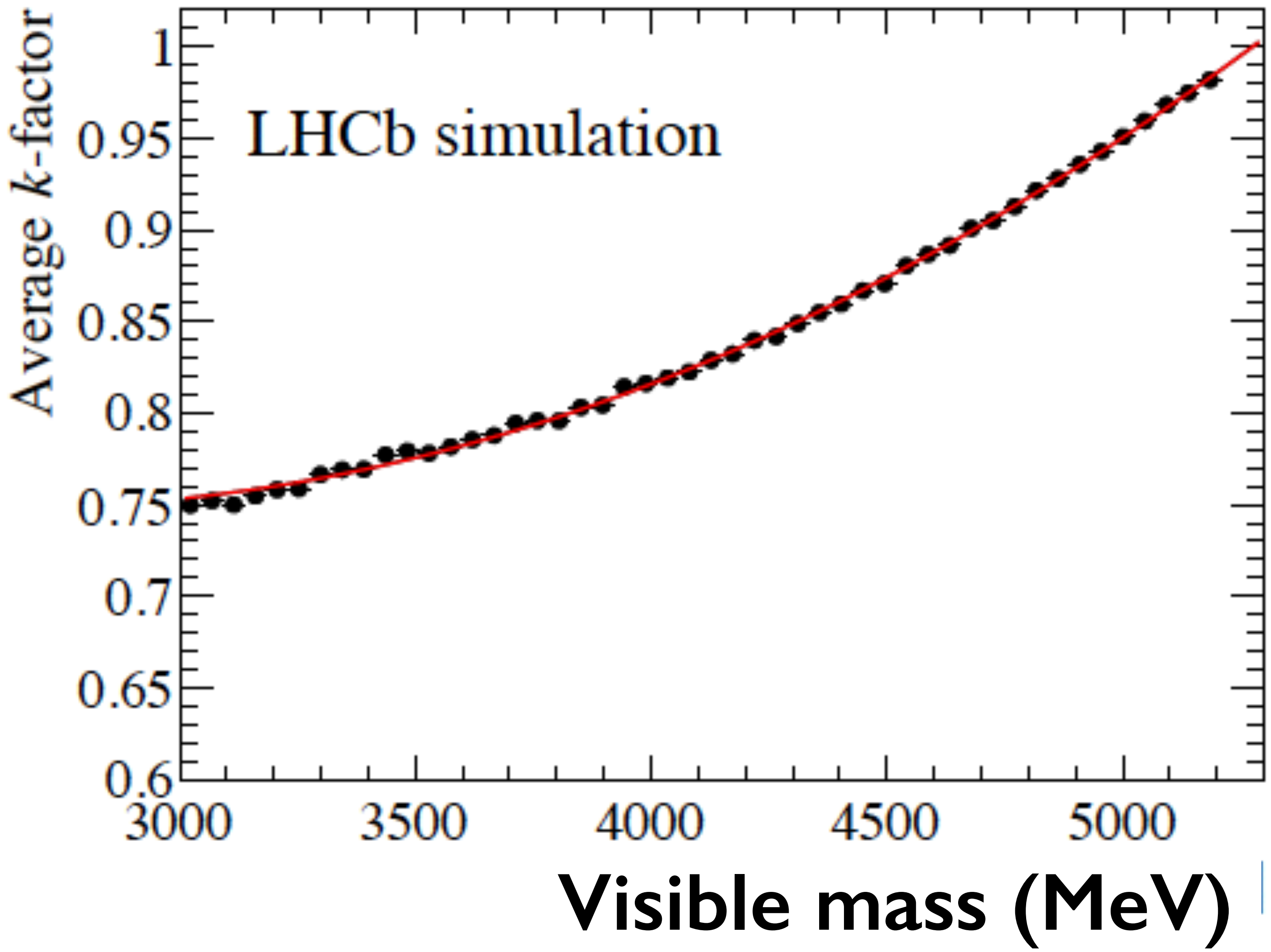
2. Don't know the B momentum

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



3. No mass peak. Backgrounds!

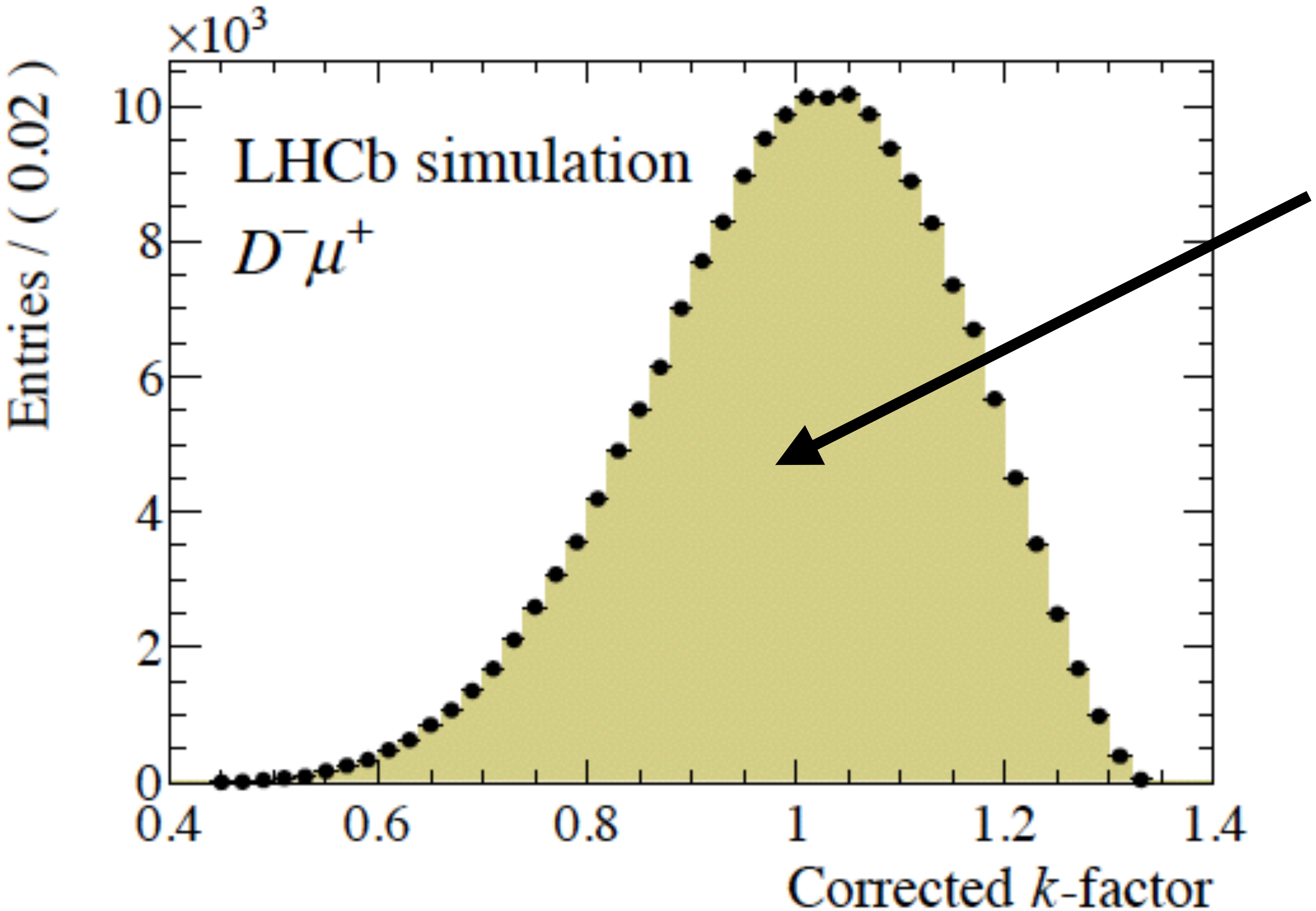
The K-factor method



Use to correct the decay time

$$t = \frac{L \cdot M_{\mathrm{PDG}}}{|p_{\mathrm{vis}}|} \cdot K(M_{\mathrm{vis}})$$

The K-factor method



Resolution to be used in time dependent fit

- Simulate a "cocktail" of sub-decays.
- Systematic uncertainty on a_{sl} is 5×10^{-4}.

Backgrounds

- The $D^{+(*)}\mu\nu X$ final state is also fed by B^+ decays
  - Also smaller backgrounds from Λ_b and B_s
- B^+ fractions estimated from simulation:

$D^+\mu\nu X$: $(12.7 \pm 2.2)\%$
$D^{*+}\mu\nu X$: $(8.8 \pm 2.2)\%$

- Also need the B^+ production asymmetry…

$$a_P(B^+) = \frac{\sigma(\bar{B}^+) - \sigma(B^-)}{\sigma(\bar{B}^+) + \sigma(B^-)}$$

Backgrounds

- Determine the B^+ production asymmetry with

$$A_P(B^+) = A_{\rm raw}(B^+ \to J/\psi K^+)$$
$$-A_{\rm CP}(B^+ \to J/\psi K^+)$$
$$-A_{\rm det}(K^+)$$

From LHCb data [1]

Other exp'ts [2]

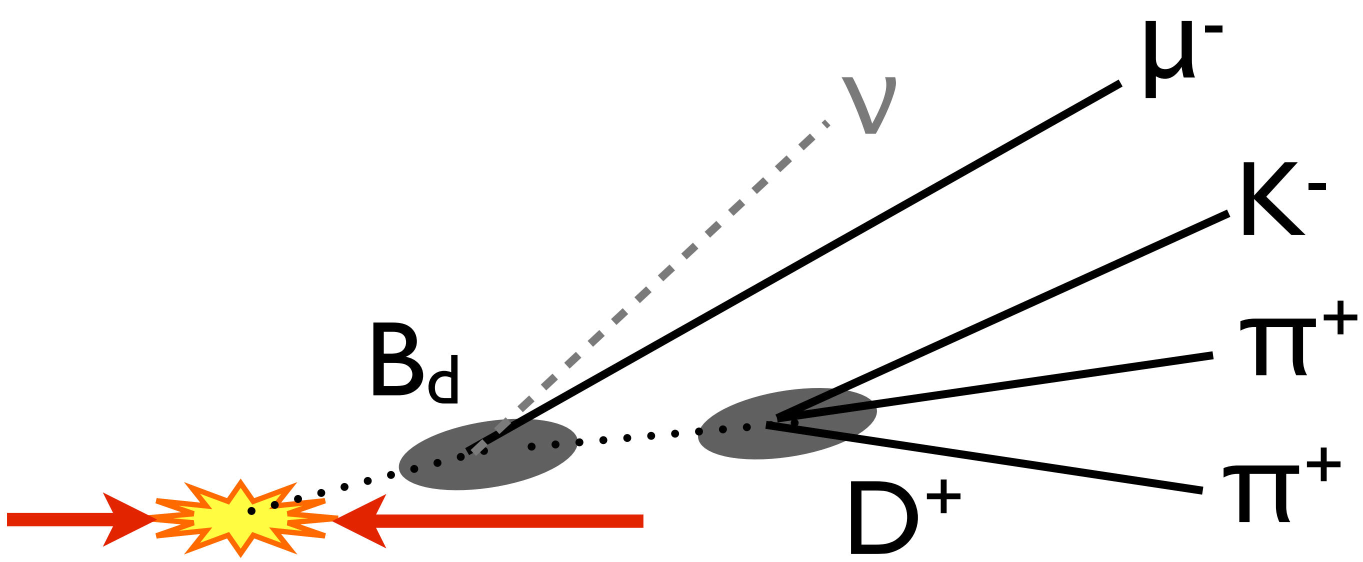
Measured

$$A_P(B^+) = (-0.6 \pm 0.6)\%$$

2nd largest systematic on a_{sl}^d

[1] http://arxiv.org/abs/1408.0978
[2] K.A. Olive et al. (Particle Data Group), Chin. Phys. C, 38, 090001 (2014).

The detection asymmetry



$$A_D = \frac{\varepsilon(f) - \varepsilon(\overline{f})}{\varepsilon(f) + \varepsilon(\overline{f})}$$

$f = \mu^+ K^+ \pi^- \pi^-$

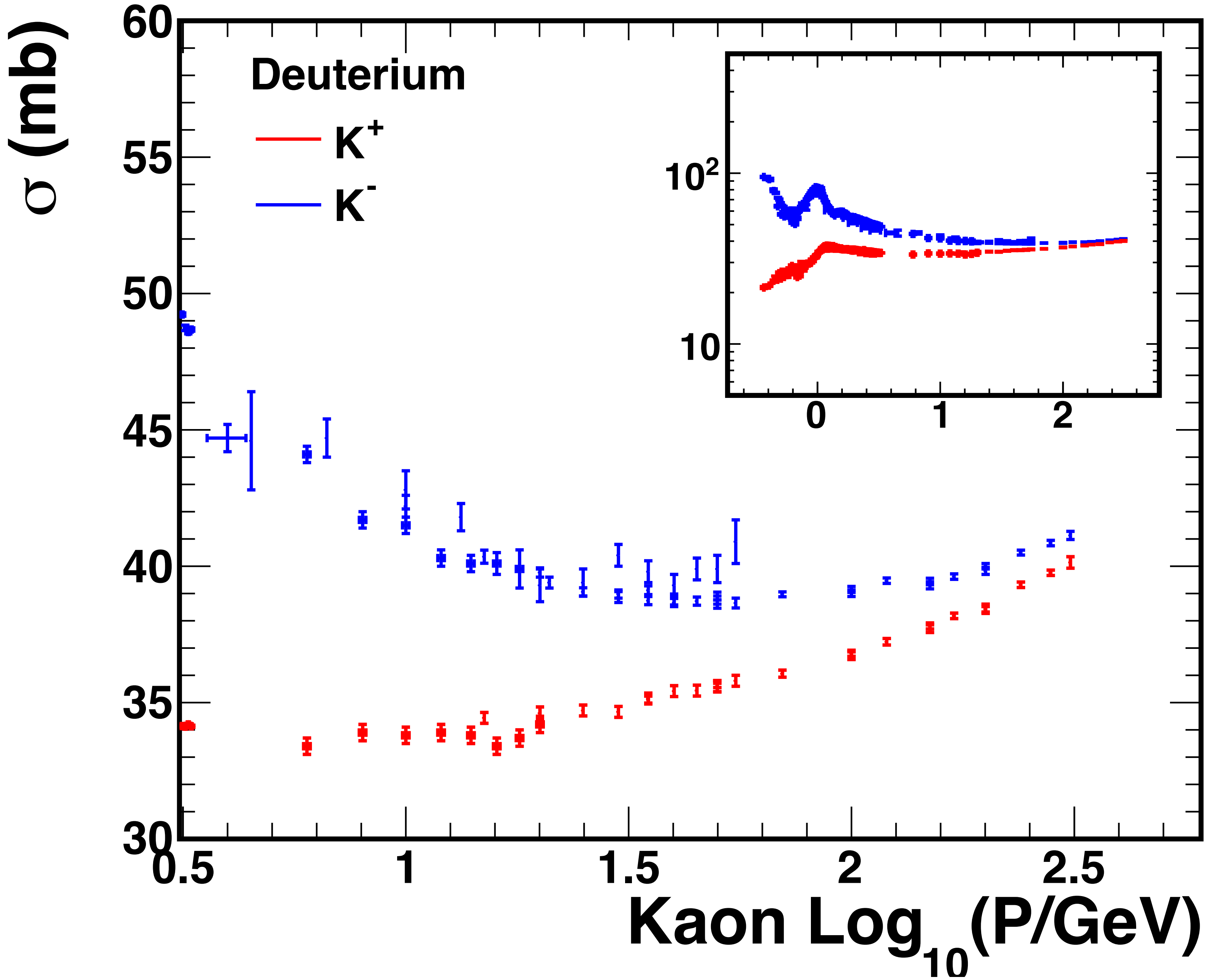
Split into

$A_D(\mu^+\pi^-)$, $A_D(K^+\pi^-)$

- Sources of asymmetry:
  - Detector mis-alignments, and inhomogeneities
  - nuclear interactions…

The kaon asymmetry

K.A. Olive et al. (Particle Data Group), Chin. Phys. C, 38, 090001 (2014).



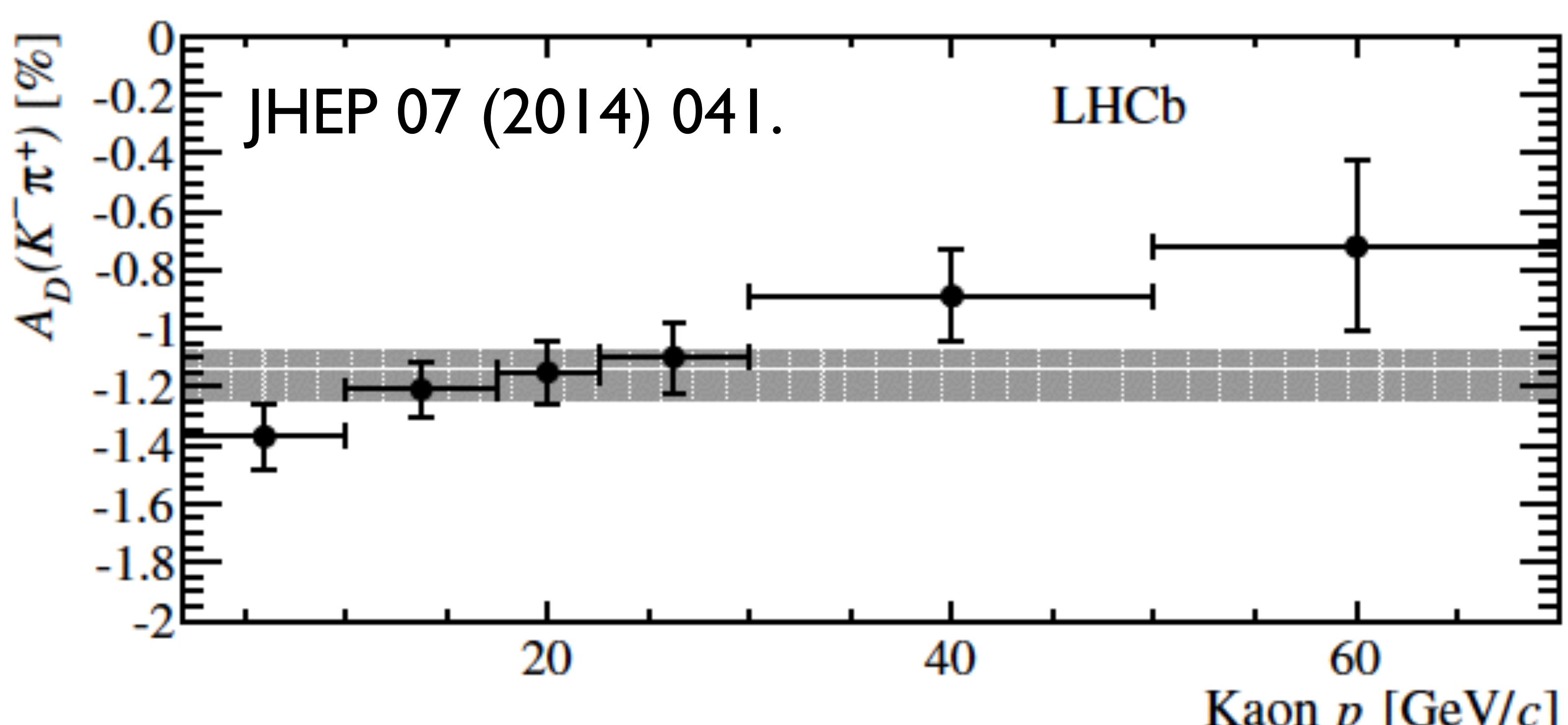
Kaon detection asymmetry of ~ 10^{-2}

Measuring the Kπ asymmetry

- Exploit the LHCb's huge charm signals

$$A_{K\pi} \equiv \frac{\epsilon(K^+\pi^-) - \epsilon(K^-\pi^+)}{\epsilon(K^+\pi^-) + \epsilon(K^-\pi^+)}$$
$$= A(D \to K\pi\pi)$$
$$- A(D \to K_S\pi)$$
$$- A(K_S)$$

Need two decay modes of the same D species to cancel the production asymmetry



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$$= A(D \to K\pi\pi)$$
$$- A(D \to K_S\pi)$$
$$- A(K_S)$$

Need two decay modes of the same D species to cancel the production asymmetry

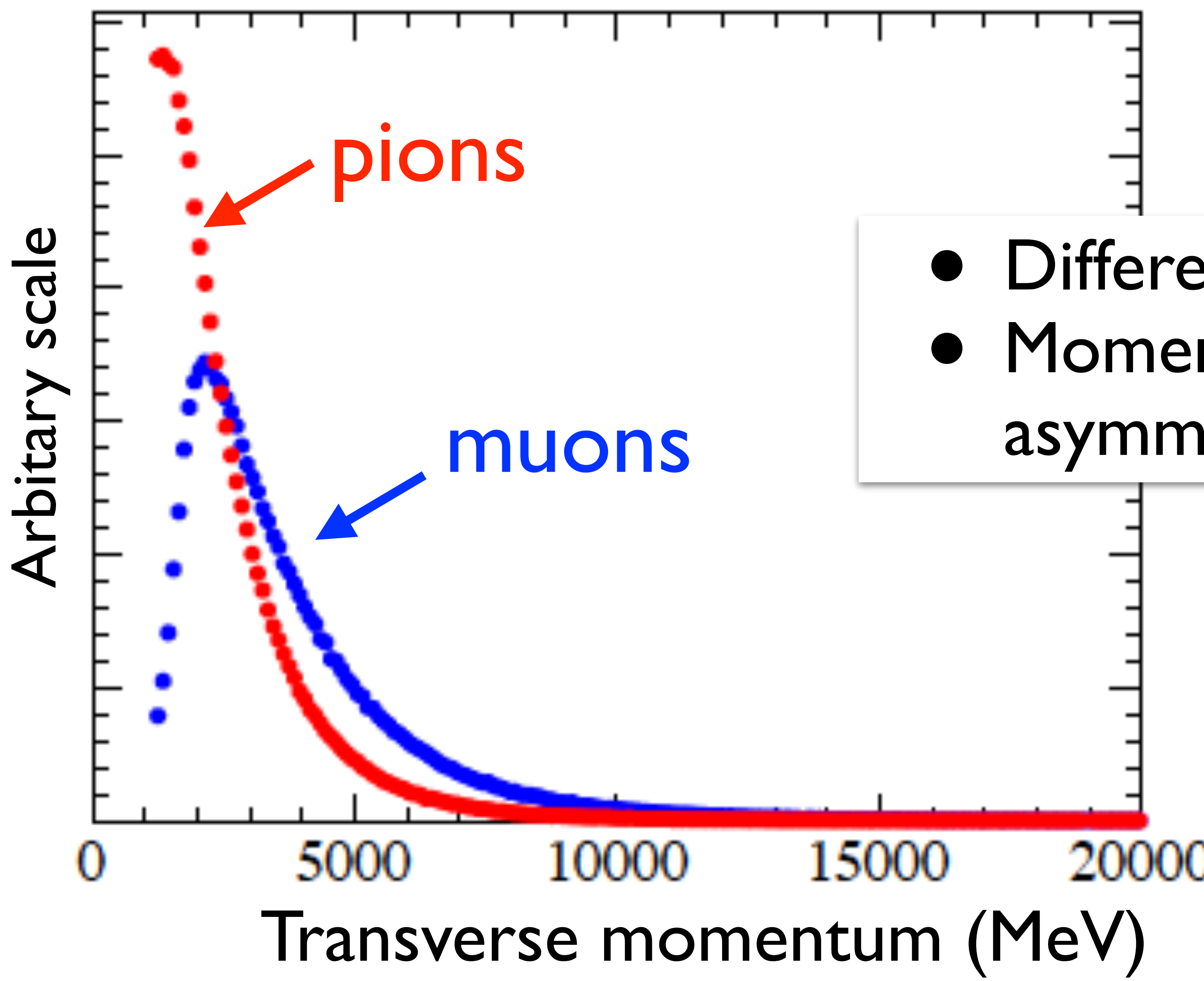
- After a weighting of the charm modes:

e.g., for $D^+\mu\nu$ mode:

$$A_{K\pi} = (1.15 \pm 0.08_{\mathrm{stat}} \pm 0.07_{\mathrm{syst}})\%$$

largest systematic uncertainty on a_{sl}^d

Measuring the μπ asymmetry

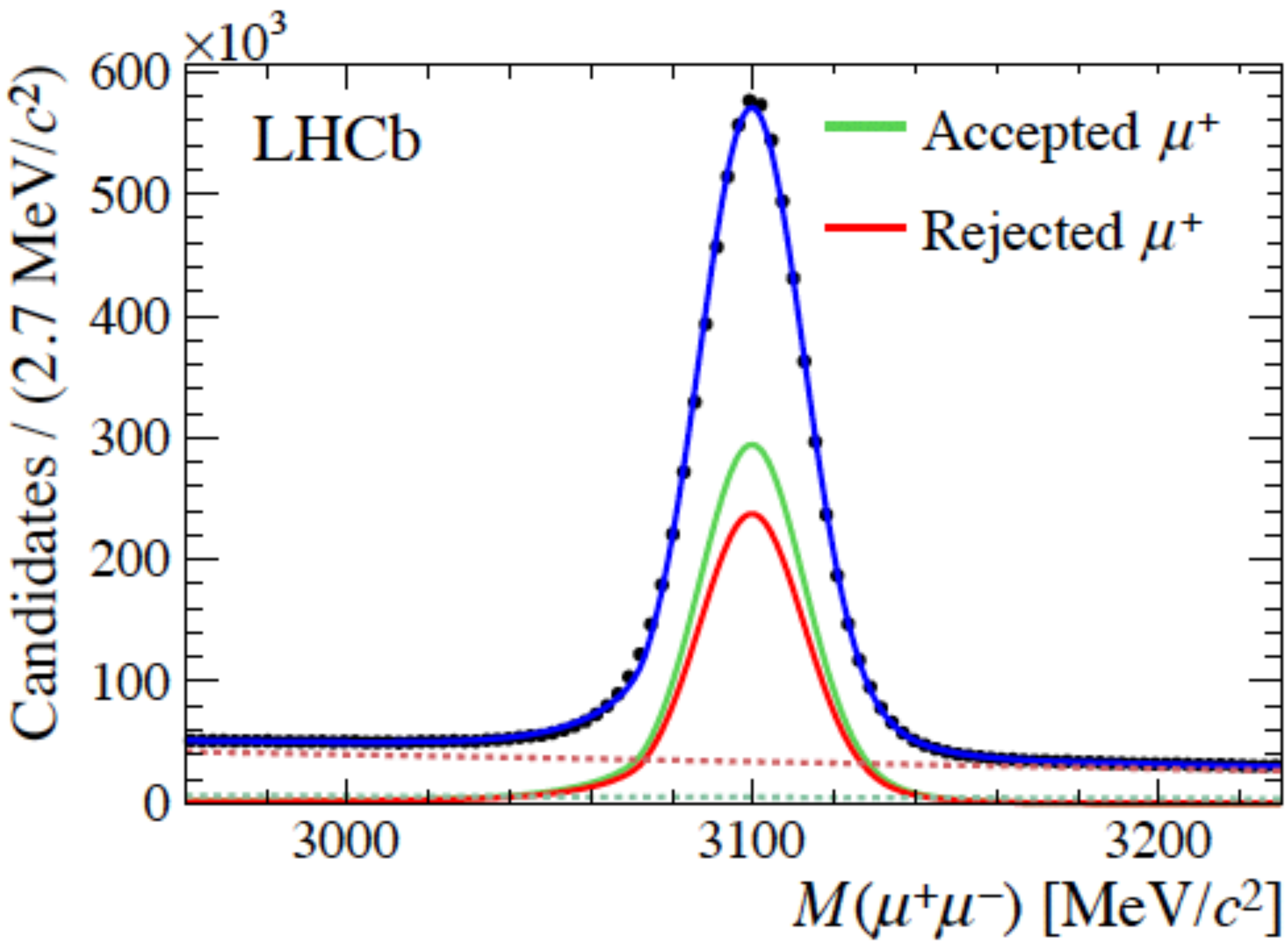


- Different kinematic spectra.
- Momentum dependent tracking asymmetries will not cancel.

- Momentum dependent weighting to equalise their spectra.
- Effective sample size reduced by factor of ≈0.8

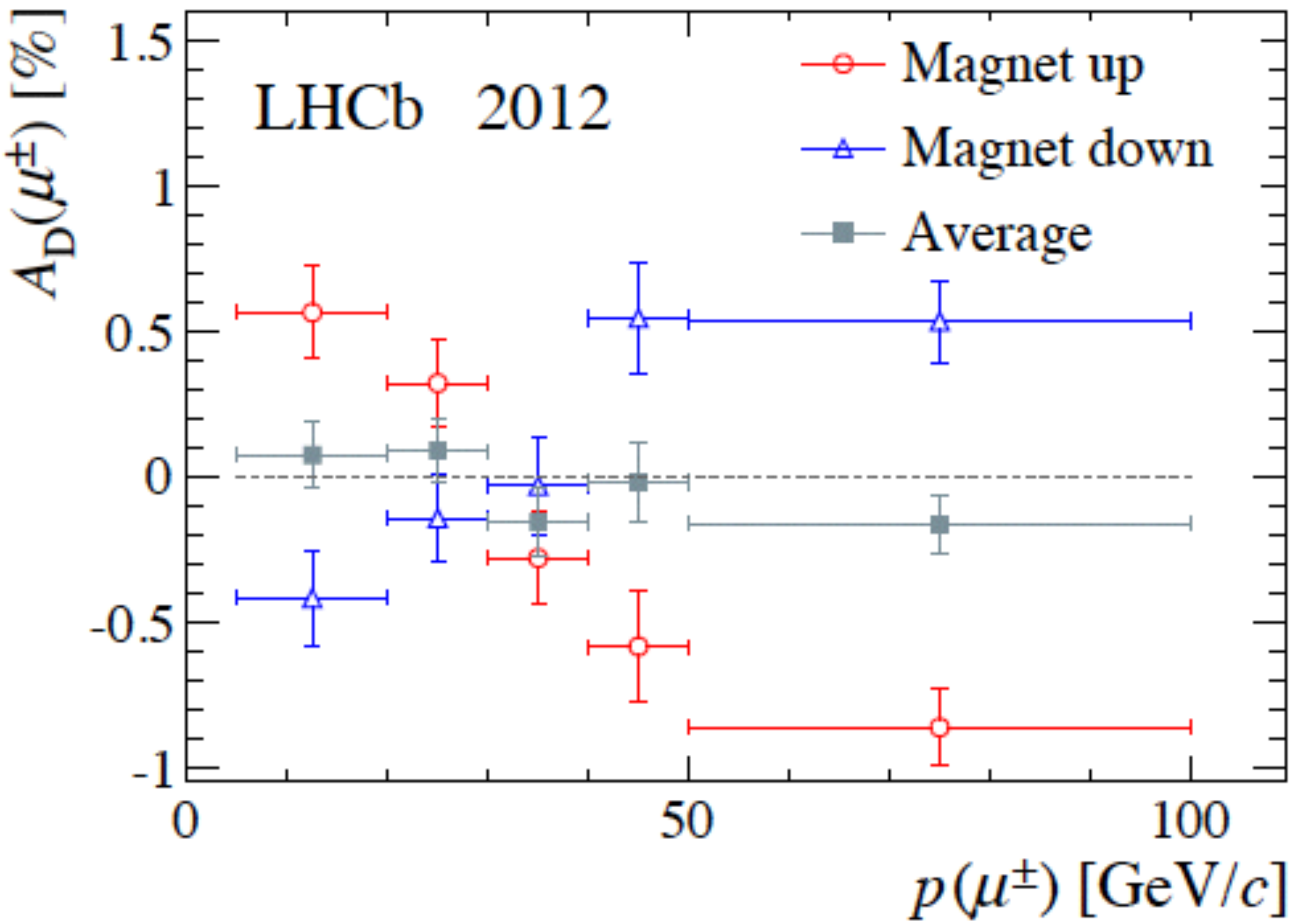
Measuring the μπ asymmetry

- Combine muon identification and trigger asymmetry measured with $J/\Psi \rightarrow \mu^{+}\mu^{-}$ decays.



Measuring the μπ asymmetry

- Combine muon identification and trigger asymmetry measured with $J/\Psi \rightarrow \mu^+\mu^-$ decays.

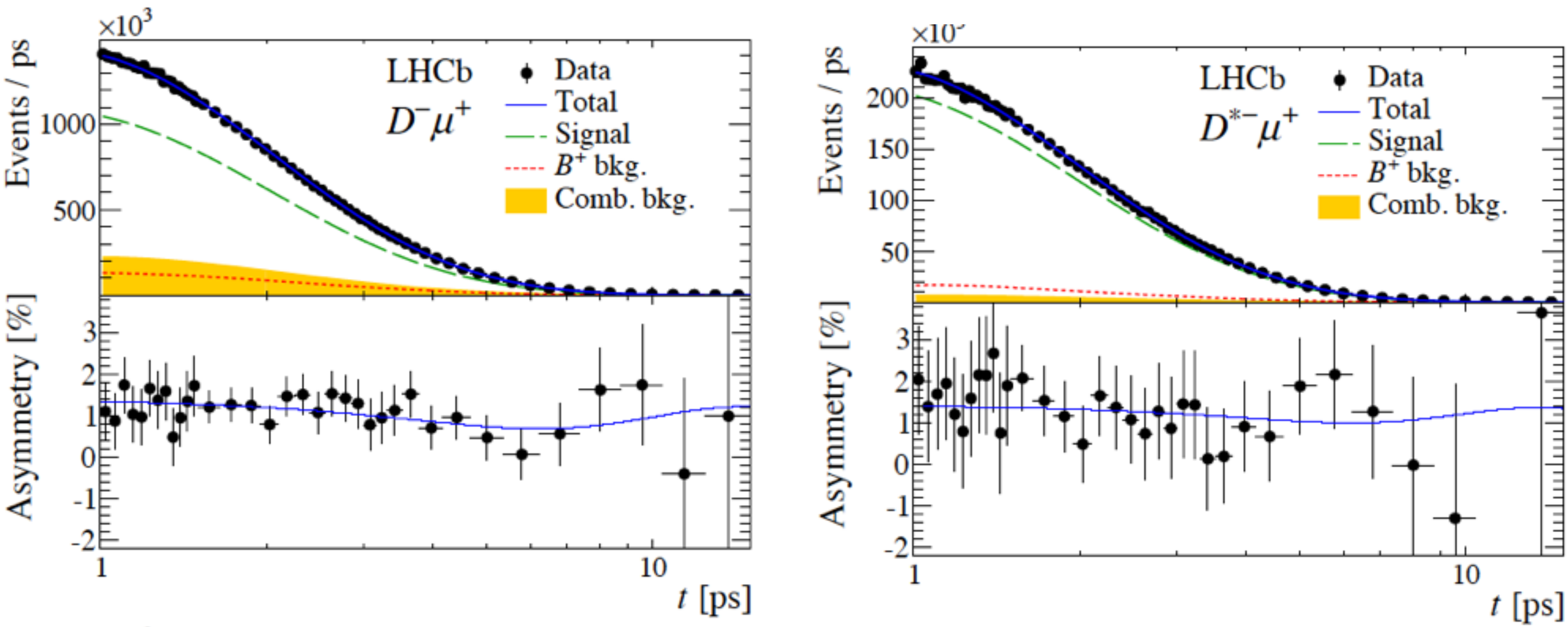


± 0.5% polarity dependent asymmetries caused by chamber mis-alignment and inefficiencies.

Only for illustrative purposes. Actually extract a single, kinematic weighted muon asymmetry.

Fit results

$$N(f,t) \propto e^{-\Gamma_d t}\left[1 \pm A_D \pm \frac{a_{\rm sl}^d}{2} \mp (A_p + \frac{a_{\rm sl}^d}{2})\cos\Delta m_d t\right]$$



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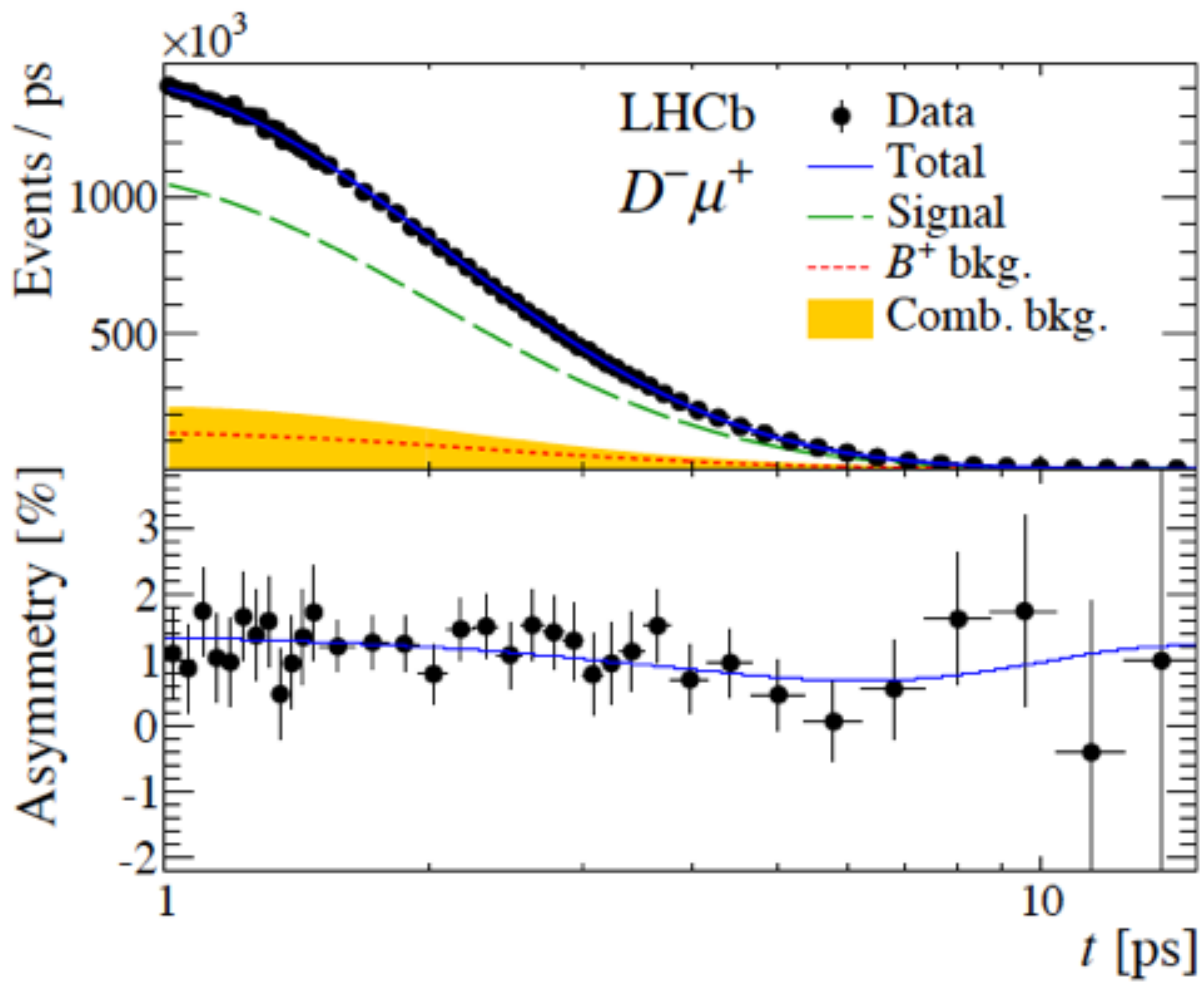
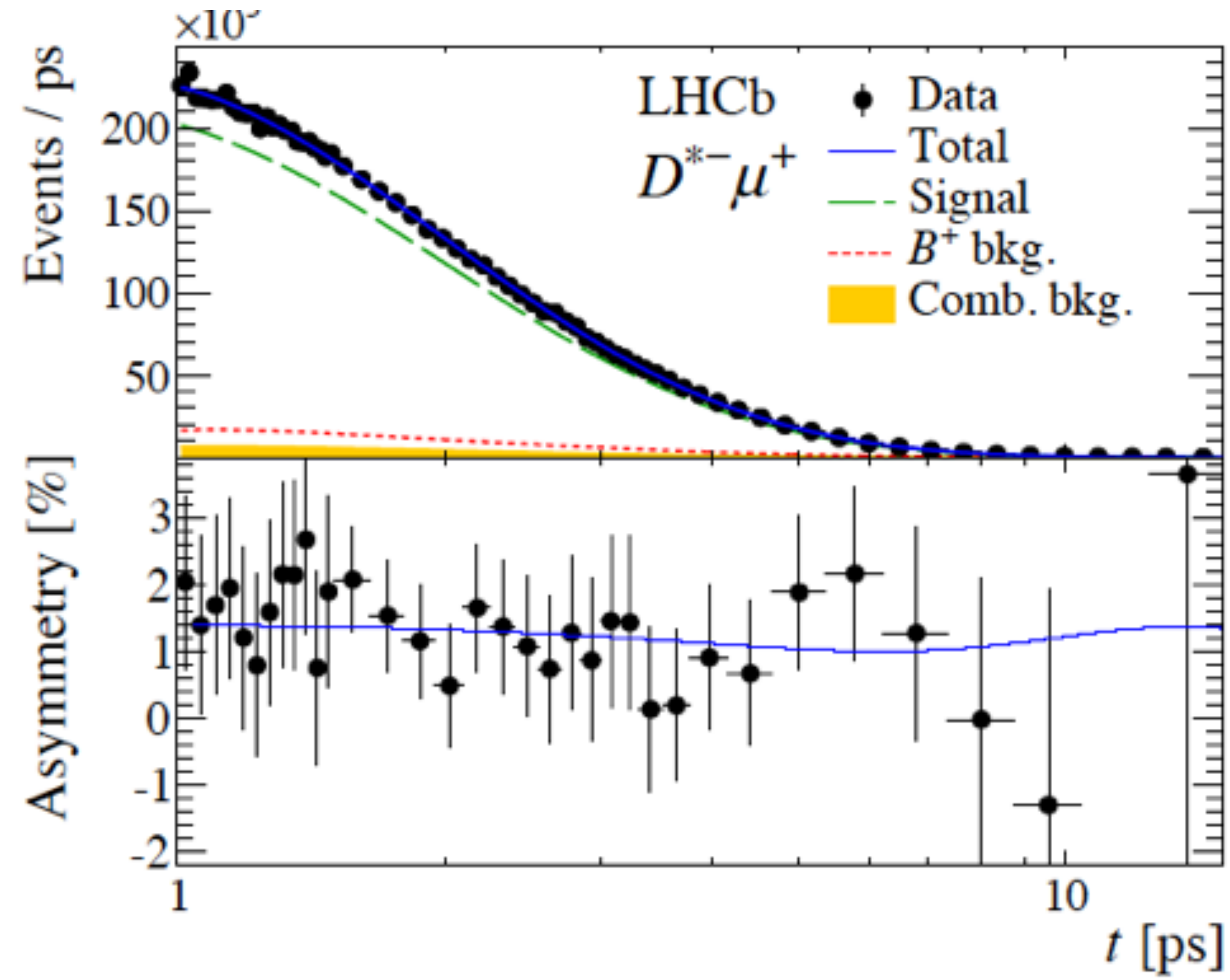




Also measure the B_d production asymmetry

$a_p(B_d, 7 \text{ TeV}) = (-0.66 \pm 0.26 \pm 0.22)\%$

$a_p(B_d, 8 \text{ TeV}) = (-0.48 \pm 0.15 \pm 0.17)\%$

Systematic uncertainties on a_{sl}

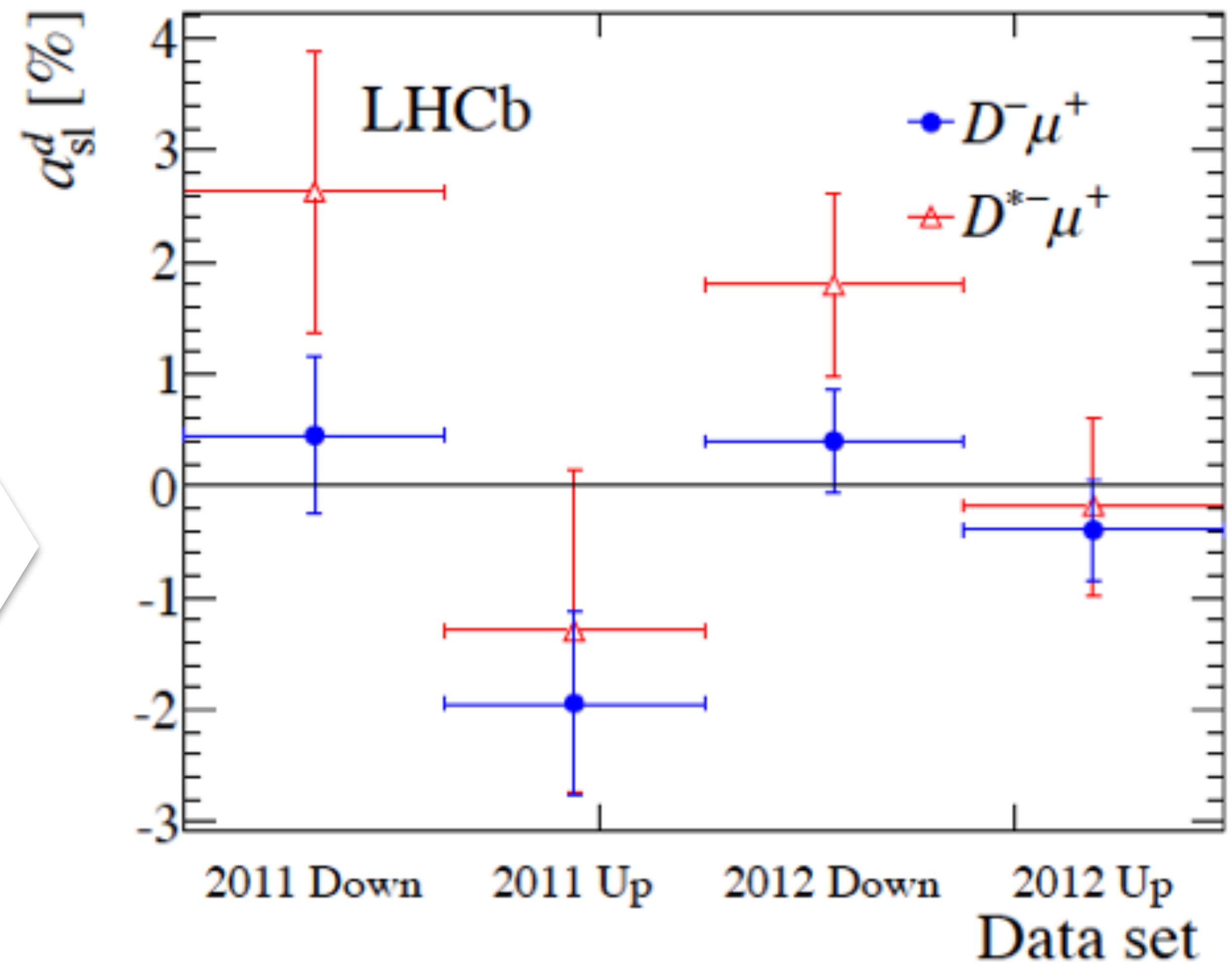
Source	δ (%)
Detection asymmetry	0.26
B plus	0.13
Baryonic background	0.07
Bs background	0.03
Fake D background	0.03
K-factor model	0.03
Decay time acceptance	0.03
Mixing frequency	0.02
Quadratic sum	0.30

Many of these are limited by control mode statistics

Results and checks

- Don't rely on the polarity reversal to cancel

Can make independent with up/down and 2011/2012.



Results and checks

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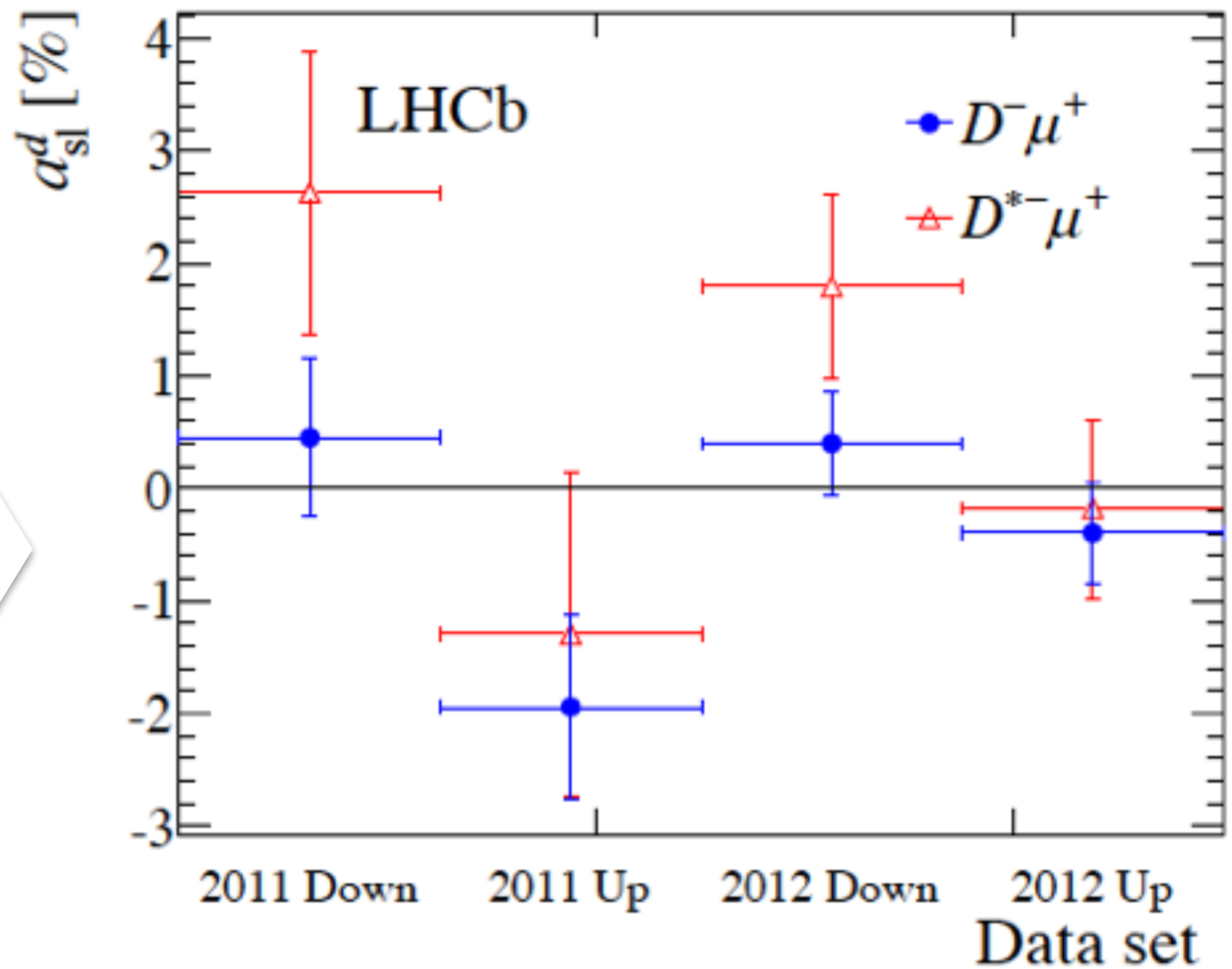


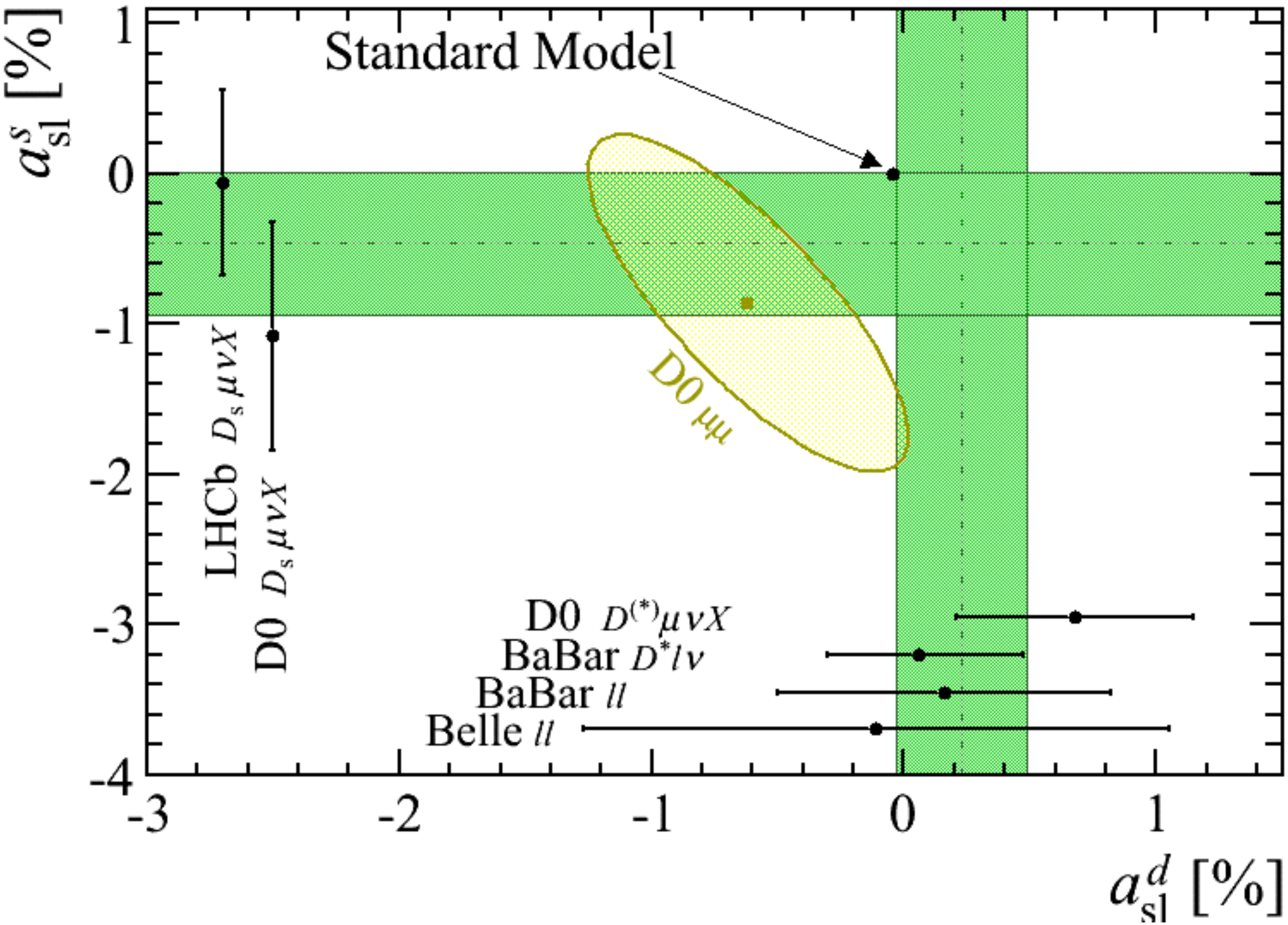
Final average:

1. **Linear** average of polarities: [u+d]/2
2. Weighted average of 2011 and 2012
3. Weighted average of D^{+} and D^{*+}

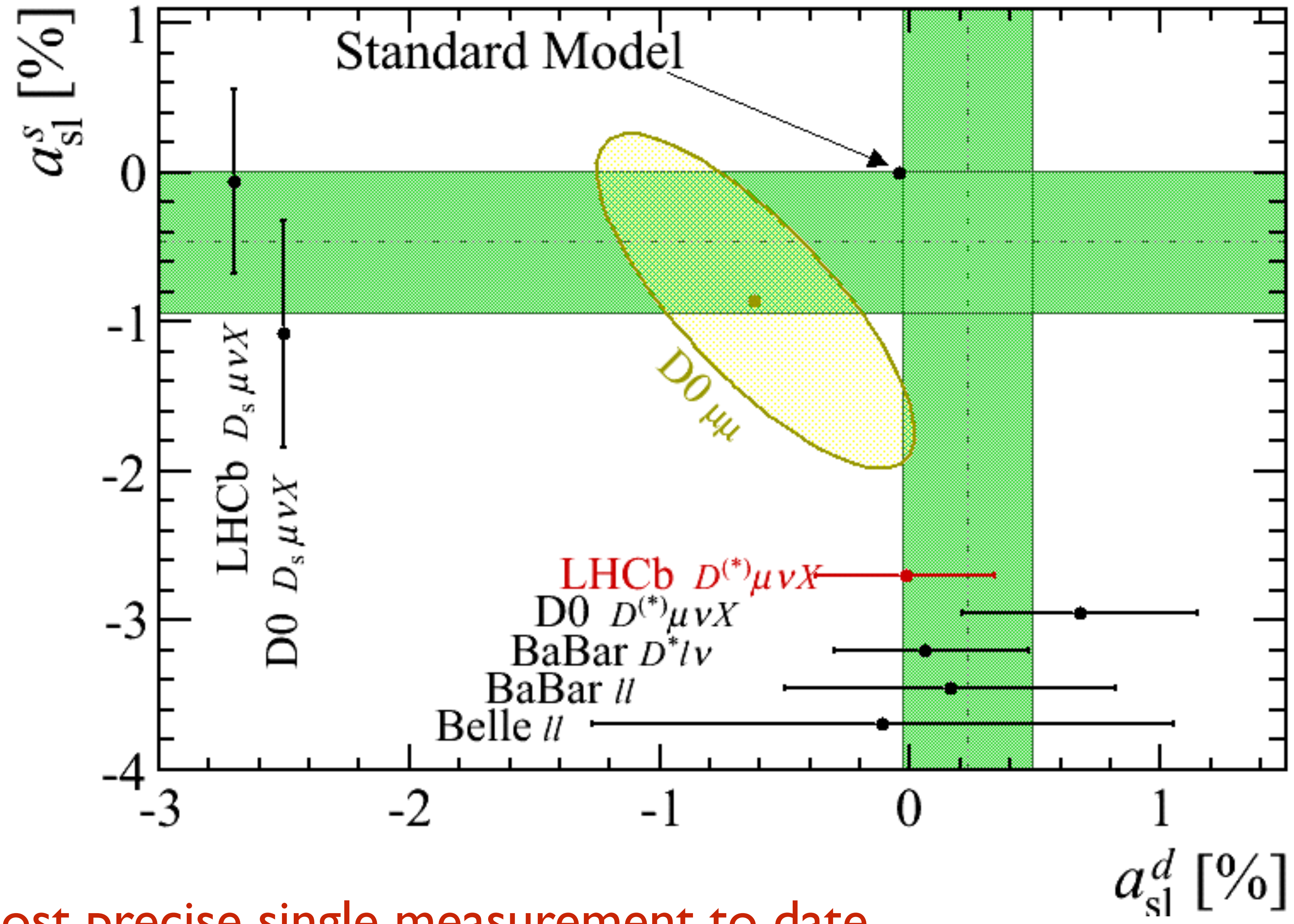
(taking into account correlations in the systematic uncertainties)

Result: $a_{sl}^{d} = (-0.02 \pm 0.19_{stat} \pm 0.30)\%$

Before

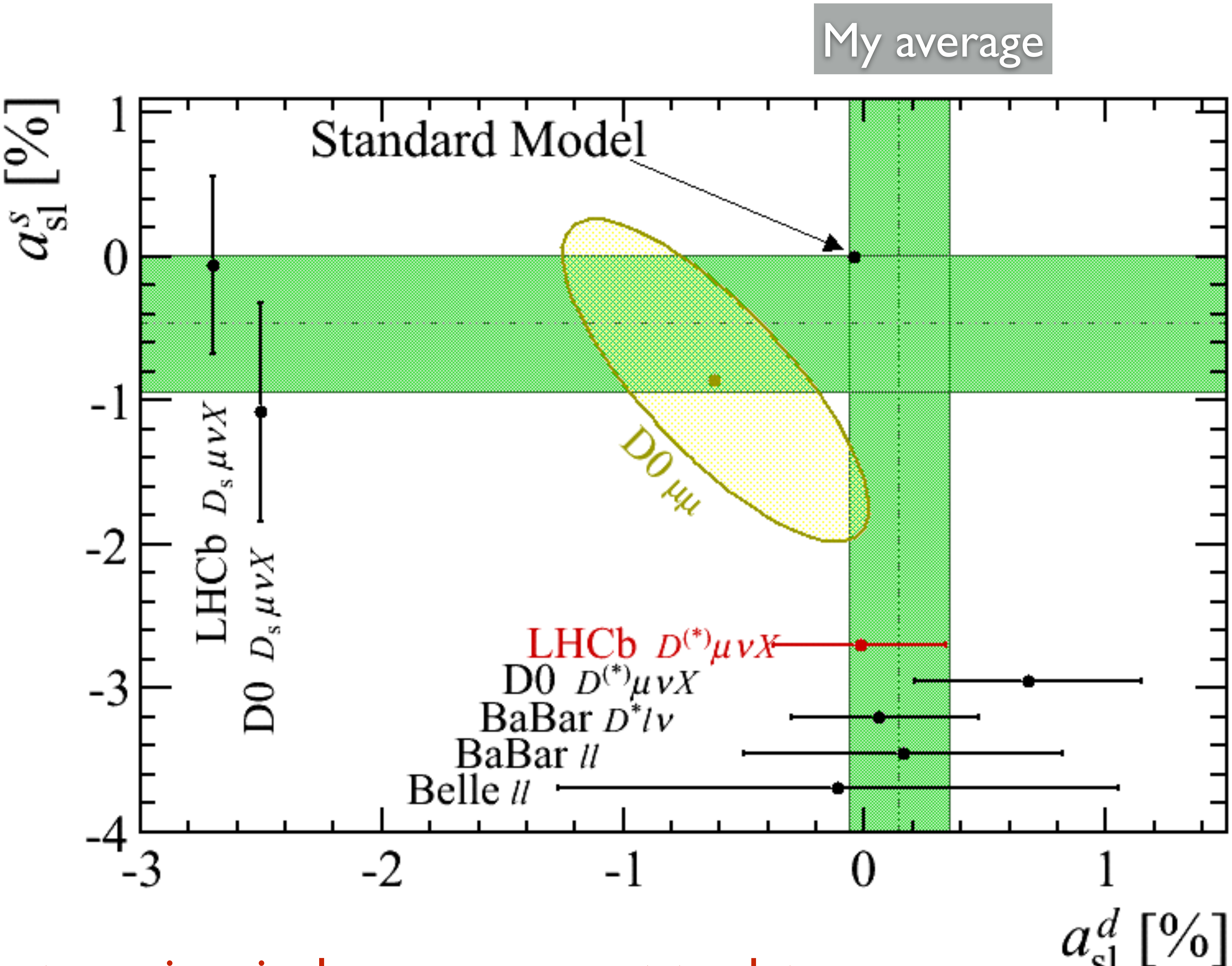

Standard Model
D0 μμ
LHCb $D_s \mu\nu X$
D0 $D_s \mu\nu X$
D0 $D^{(*)}\mu\nu X$
BaBar $D^* l\nu$
BaBar ll
Belle ll
a_{sl}^s [%]
a_{sl}^d [%]
1
0
-1
-2
-3
-4
-3
-2
-1
0
1

After



- Most precise single measurement to date.
- Do not see an anomalous asymmetry.

After



- Most precise single measurement to date.
- Do not see an anomalous asymmetry.

Conclusions

- First LHCb measurements of CP-violation in B_s and B_d mixing.

$a_{sl}^d = (-0.02 \pm 0.19_{stat} \pm 0.30_{syst})\%$ PLB 728C 607-615 (2014)

$a_{sl}^s = (-0.06 \pm 0.50_{stat} \pm 0.36_{syst})\%$ LHCb-PAPER-2014-053

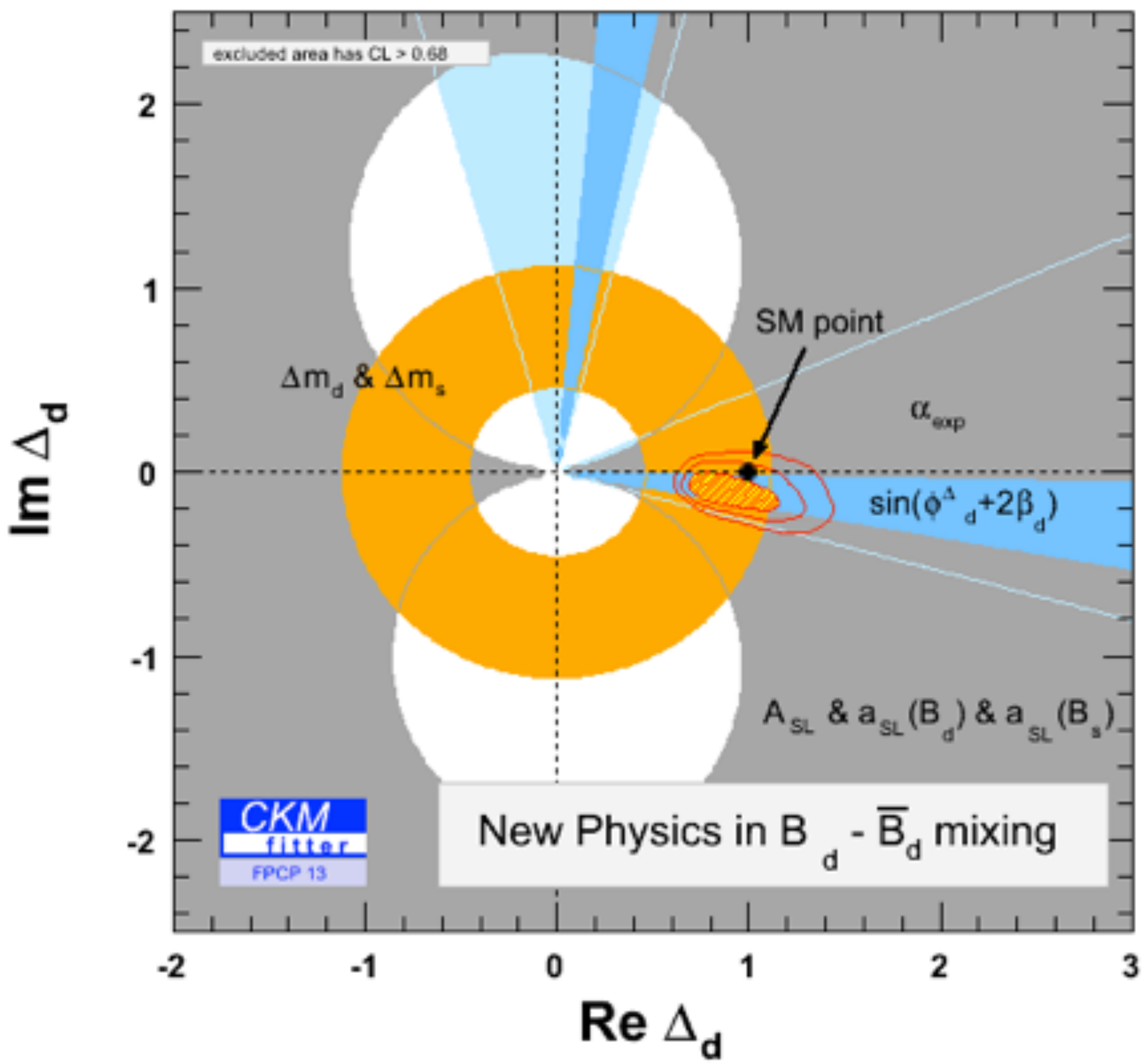
- 3 fb^{-1} update of a_{sl}^s is coming soon.
- Both are still statistically limited so exciting prospects for Run-II.

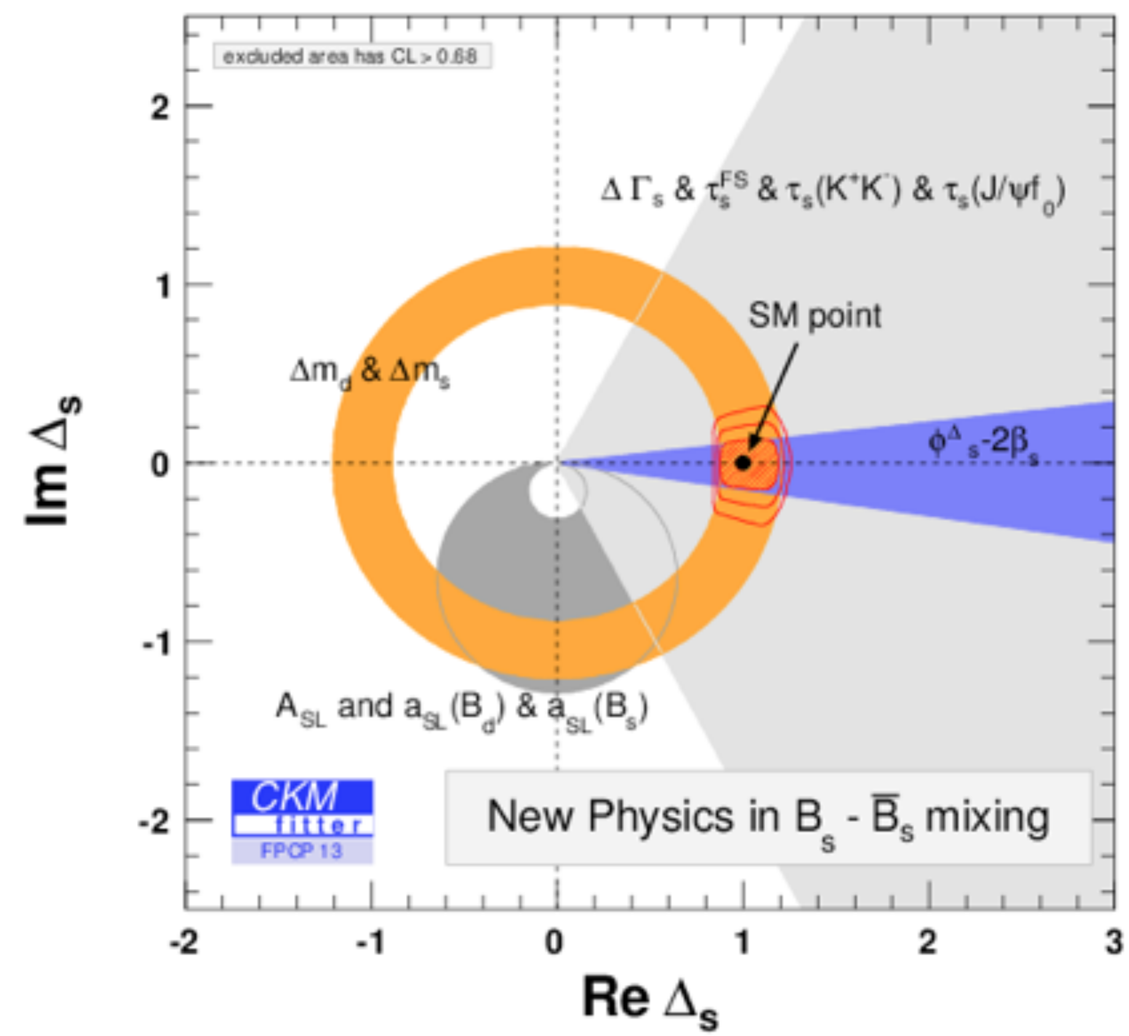
Backup slides

Model independent NP analysis

$$i\frac{\partial}{\partial t}\begin{pmatrix}|P^0(t)\rangle\\|\overline{P}^0(t)\rangle\end{pmatrix}=\left[\begin{pmatrix}M_{11} & M_{12}\\M_{12}^* & M_{22}\end{pmatrix}-\frac{i}{2}\begin{pmatrix}\Gamma_{11} & \Gamma_{12}\\\Gamma_{12}^* & \Gamma_{22}\end{pmatrix}\right]\begin{pmatrix}|P^0(t)\rangle\\|\overline{P}^0(t)\rangle\end{pmatrix}$$

$$M_{12} \rightarrow M_{12}\Delta$$





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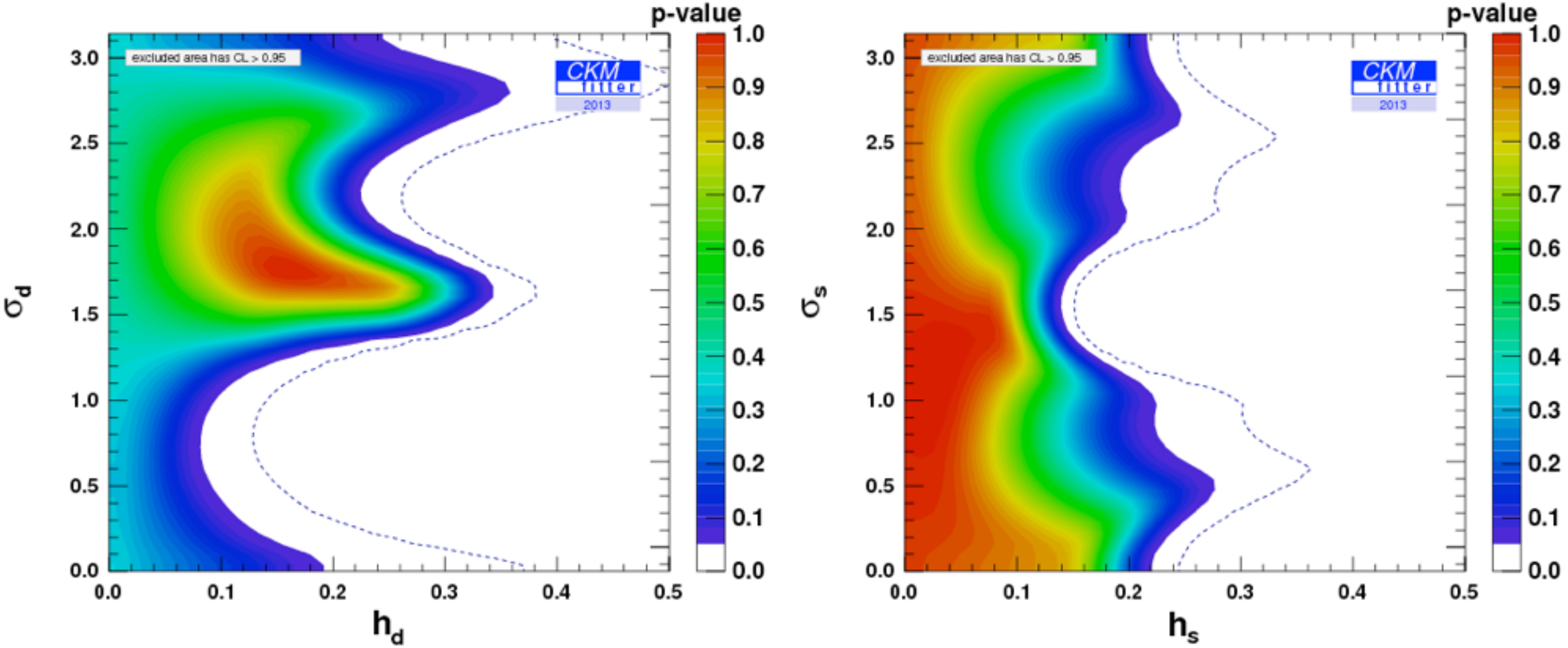
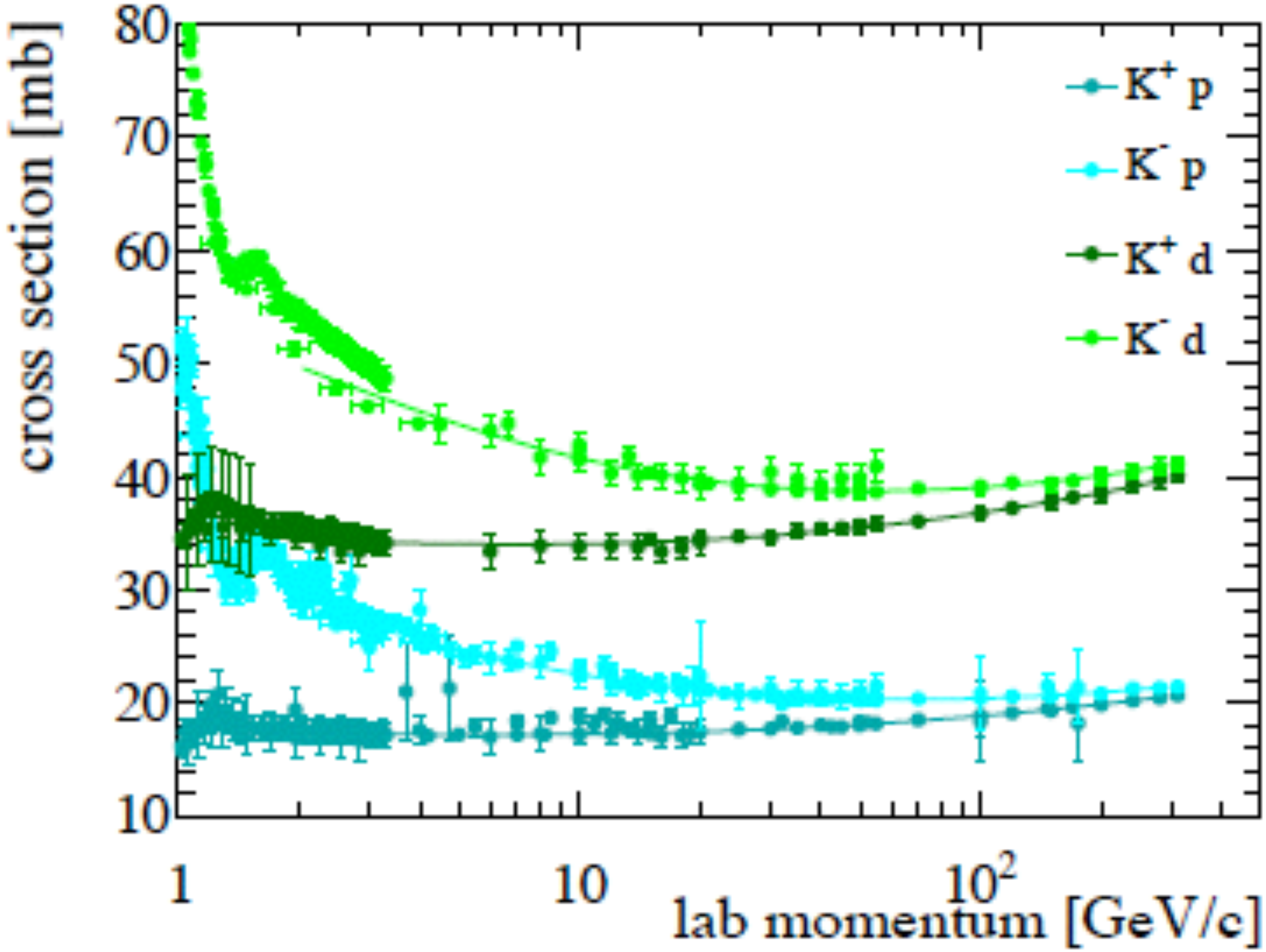
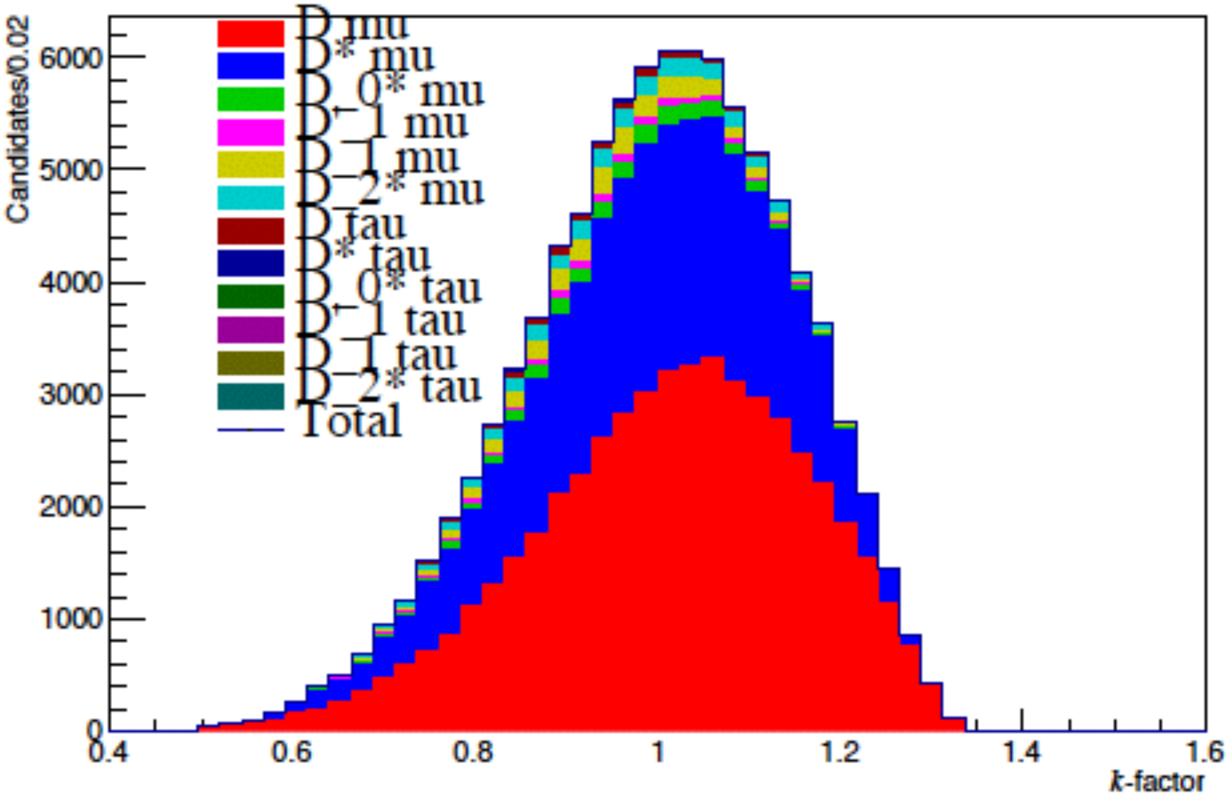
$$M_{12} \rightarrow M_{12}(1 + he^{i\phi})$$

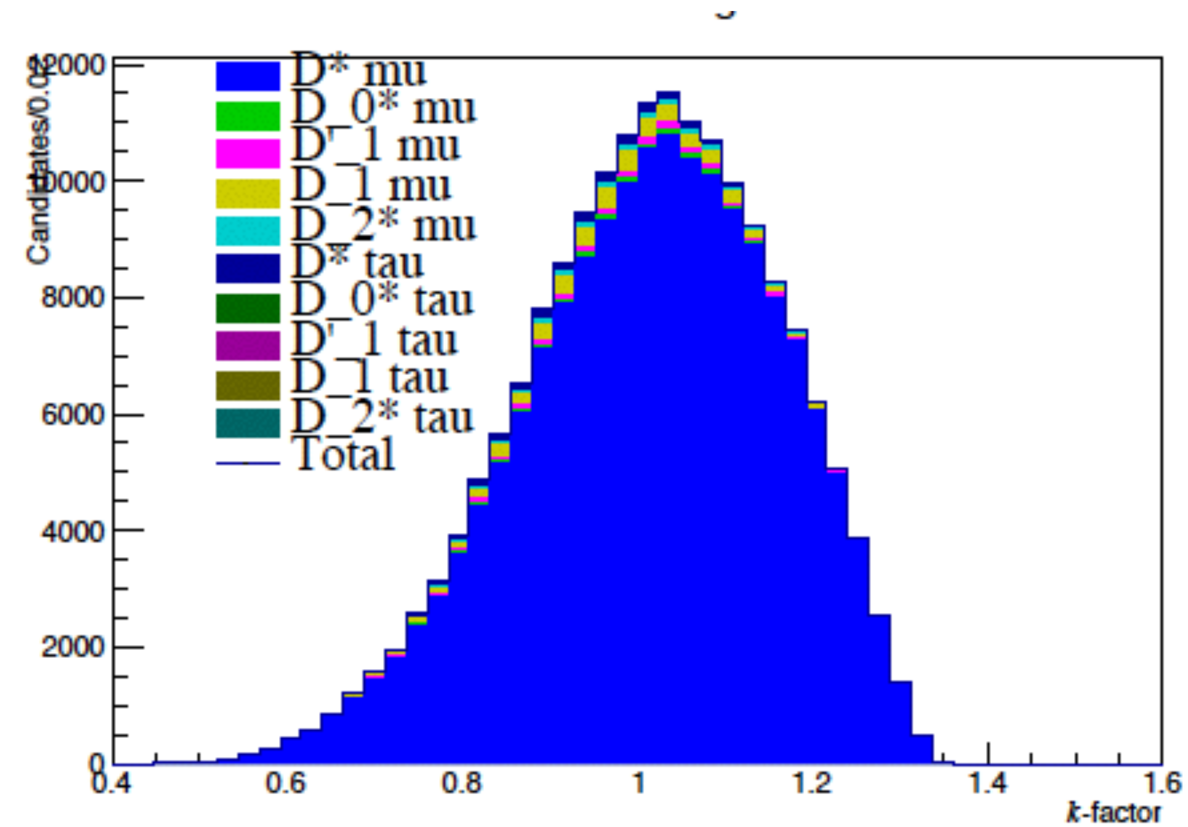


Kaon asymmetry



K-factors


D mu
D* mu
D_0* mu
D'_1 mu
D_1 mu
D_2* mu
D tau
D* tau
D_0* tau
D'_1 tau
D_1 tau
D_2* tau
Total
Candidates/0.02
0
1000
2000
3000
4000
5000
6000
0.4
0.6
0.8
1
1.2
1.4
1.6
k-factor


D* mu
D_0* mu
D'_1 mu
D_1 mu
D_2* mu
D* tau
D_0* tau
D'_1 tau
D_1 tau
D_2* tau
Total
Candidates/0.02
0
2000
4000
6000
8000
10000
12000
0.4
0.6
0.8
1
1.2
1.4
1.6
k-factor