Flavour oscillations and CP violation in neutral mesons

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

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Part 2.a

Roma — May 31st & Jun 1st, 2016

Outline

1. Introduction
2. Mixing of neutral mesons

Part 1

3. CP violation phenomenology
4. Put everything in the SM…
5. (and maybe a look beyond)

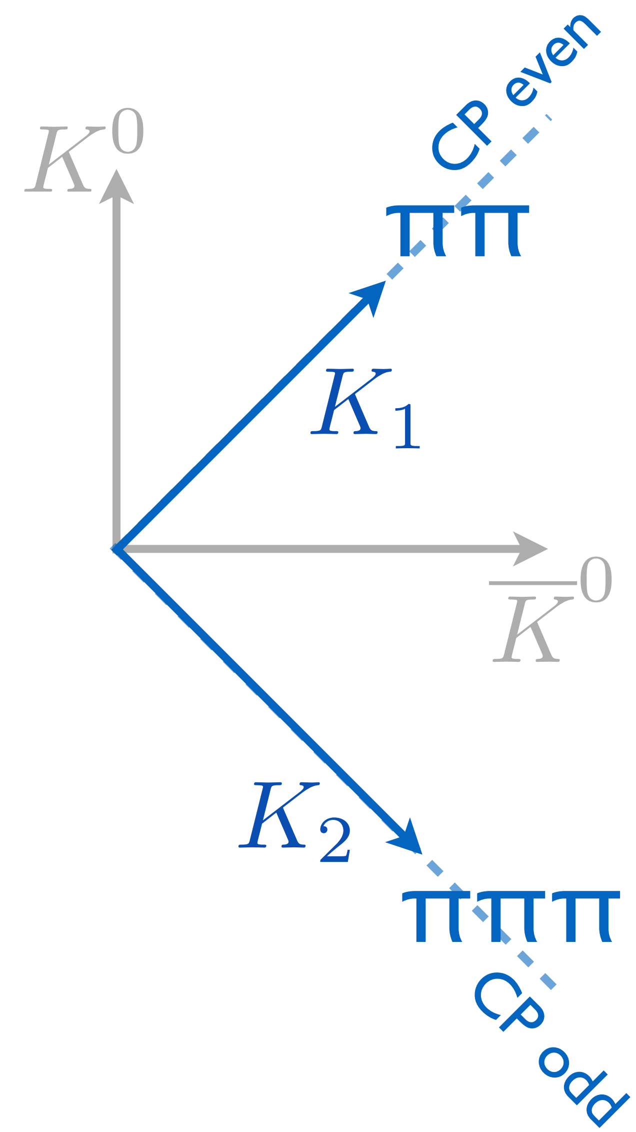
Part 2

CP violation
i.e. matter-antimatter asymmetry

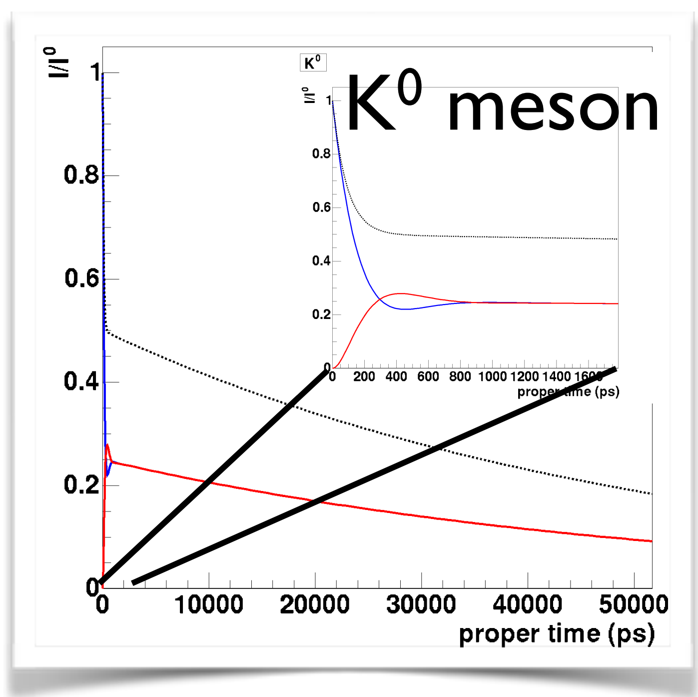
Back in the '60s

- CP still a good symmetry
- Observed neutral kaon mixing

- Neutral kaons come into two states:
  - ✦ K_1 with $\tau_1 = 0.89 \times 10^{-10}$ s (CP even)
  - ✦ K_2 with $\tau_2 = 5.2 \times 10^{-8}$ s (CP odd)

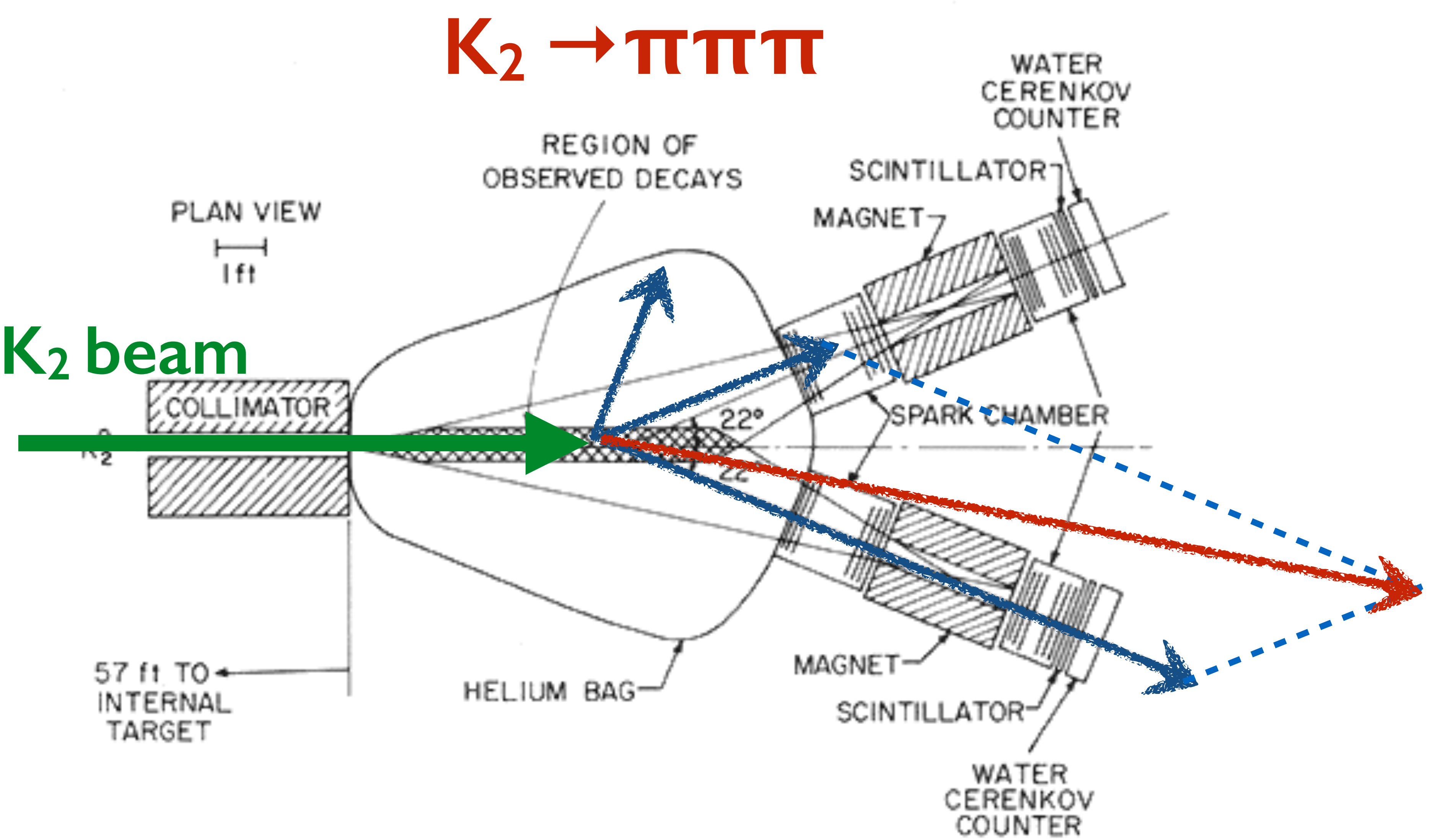


- Can have a beam of pure K_2
- If CP is conserved K_2 **never** decays into 2 pions



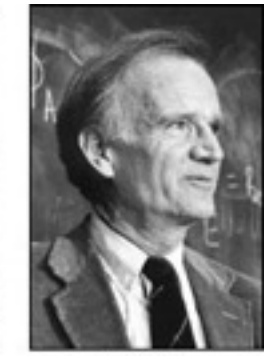
Cronin & Fitch experiment

Search for the CP violating $K_2 \to \pi\pi$ decay.

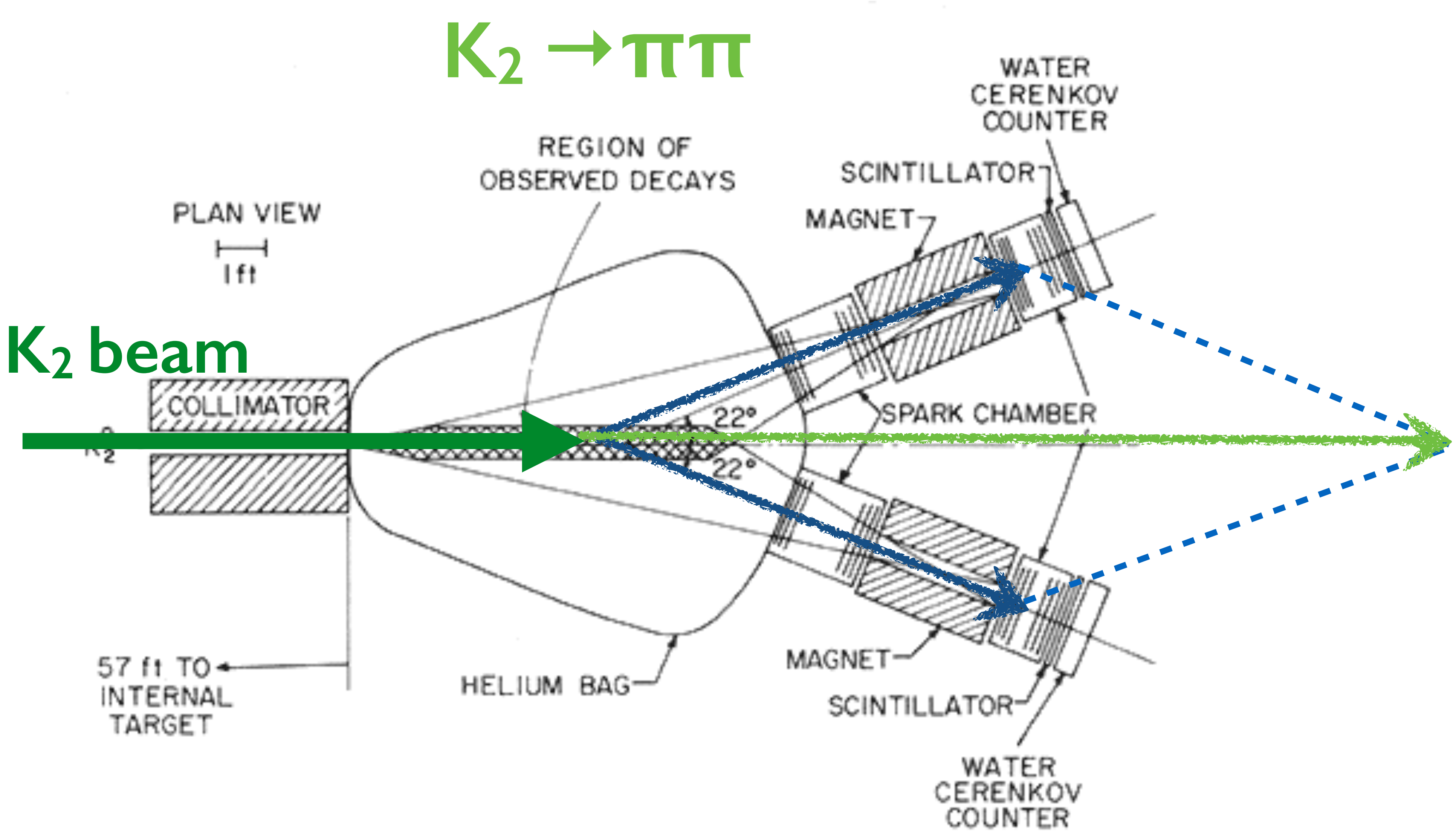


Cronin & Fitch experiment


James Cronin


Val Fitch

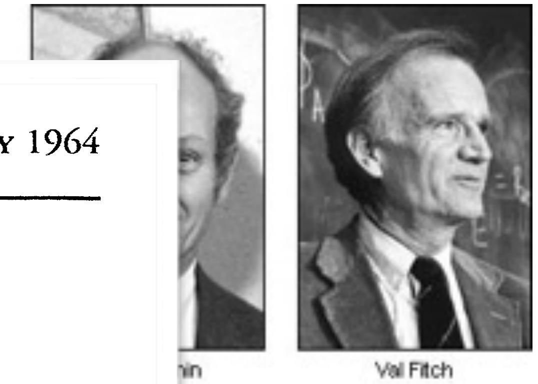
Search for the CP violating $K_2 \to \pi\pi$ decay.

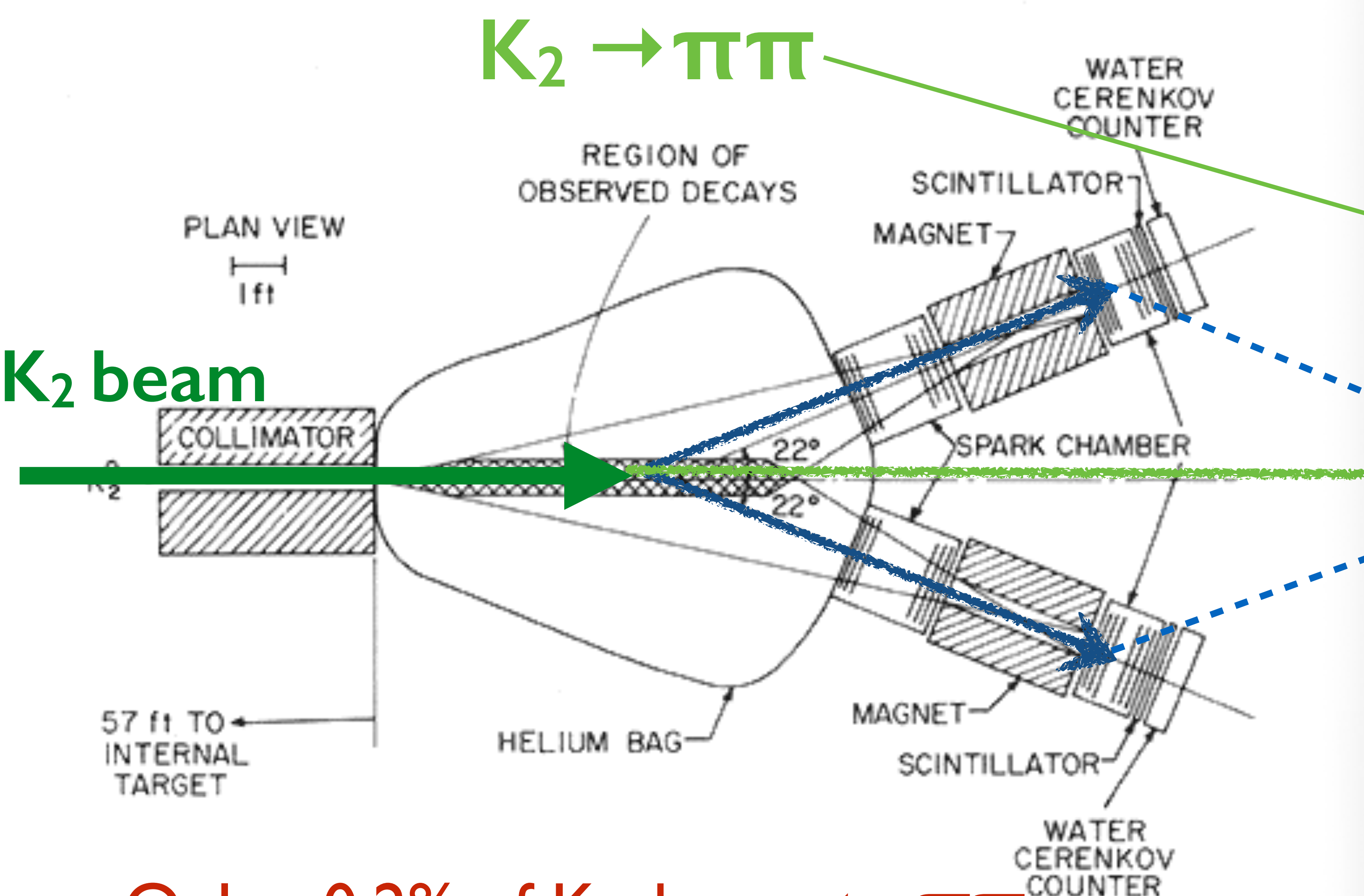


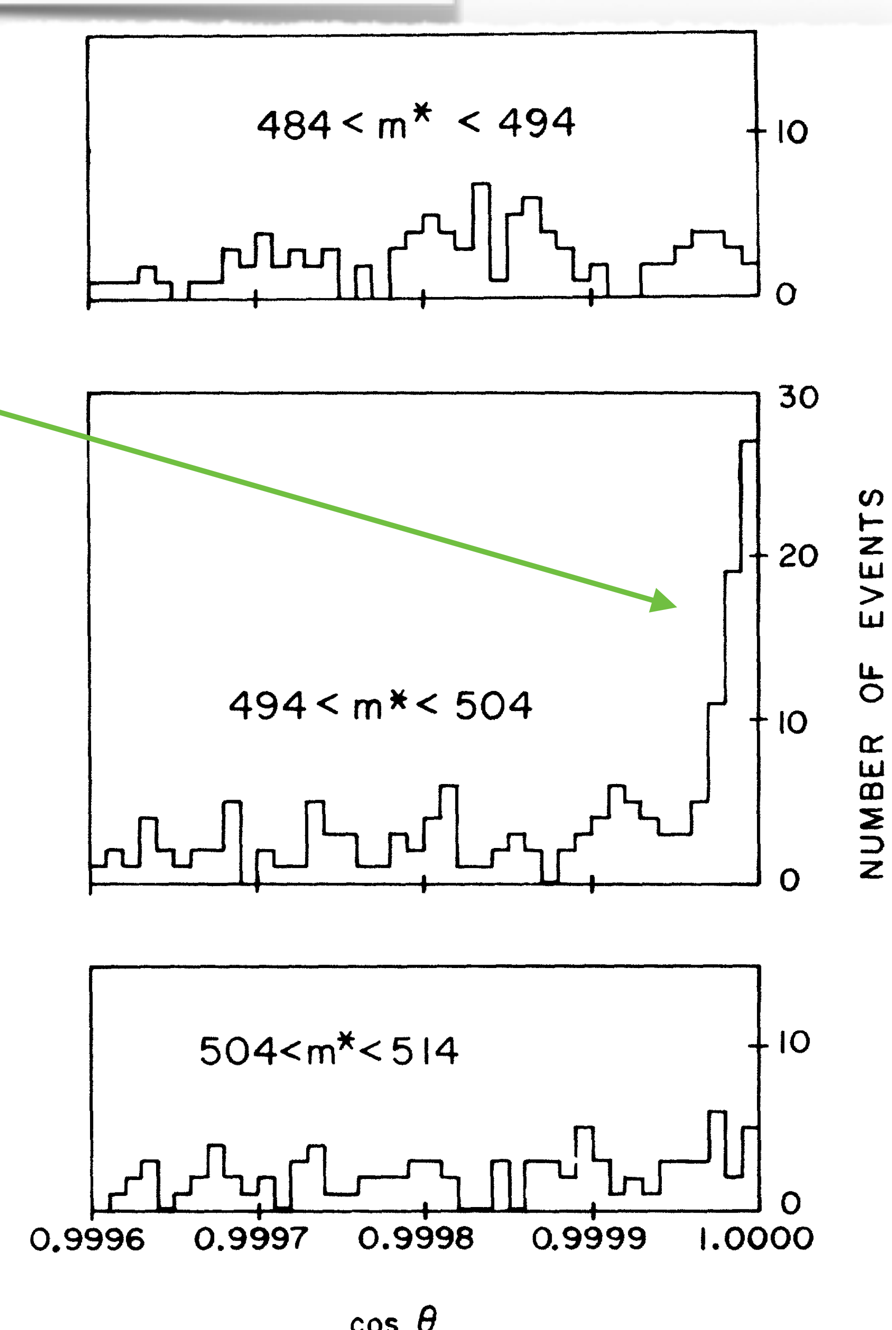
VOLUME 13, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JULY 1964

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)







Only ~0.2% of K_L decays to $\pi\pi$
but CP violation is broken!

Remember?

No assumption on CP conservation, take a more general basis

$$|K_L\rangle = p|K^0\rangle - q|\overline{K}^0\rangle$$

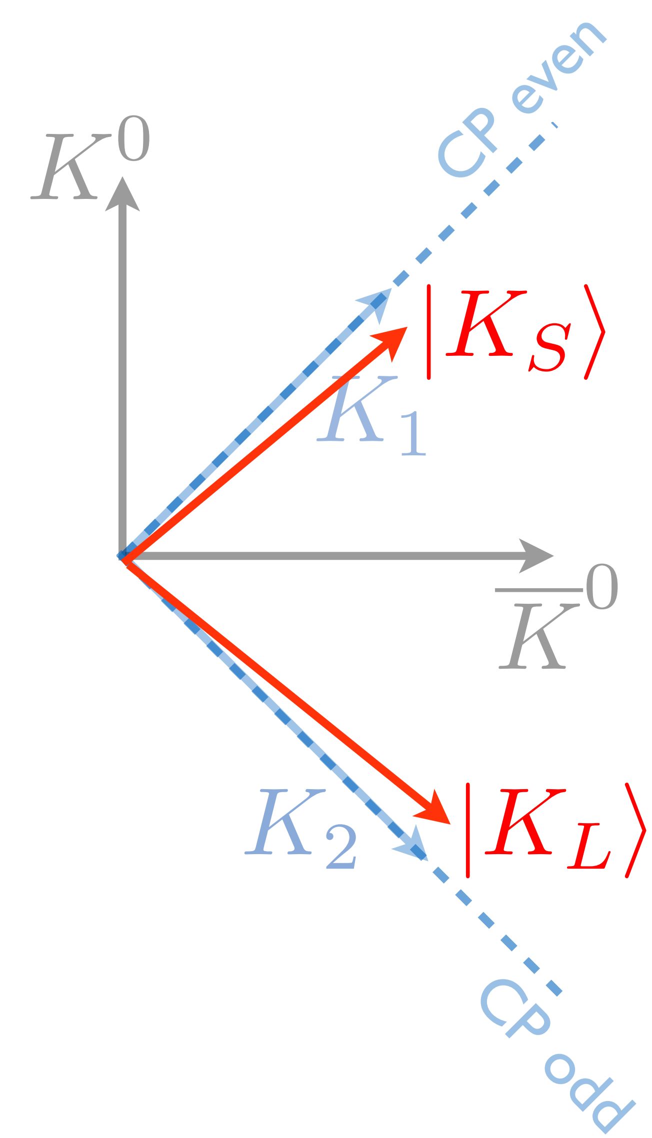
$$|K_S\rangle = p|K^0\rangle + q|\overline{K}^0\rangle$$

with the normalisation condition

$$|p|^2 + |q|^2 = 1$$

These are the physical states!

$$p = 1 + \epsilon \qquad q = 1 - \epsilon \qquad \text{with } |\epsilon| << 1$$



$$|K_L\rangle = |K_2\rangle + \epsilon\,|K_1\rangle$$

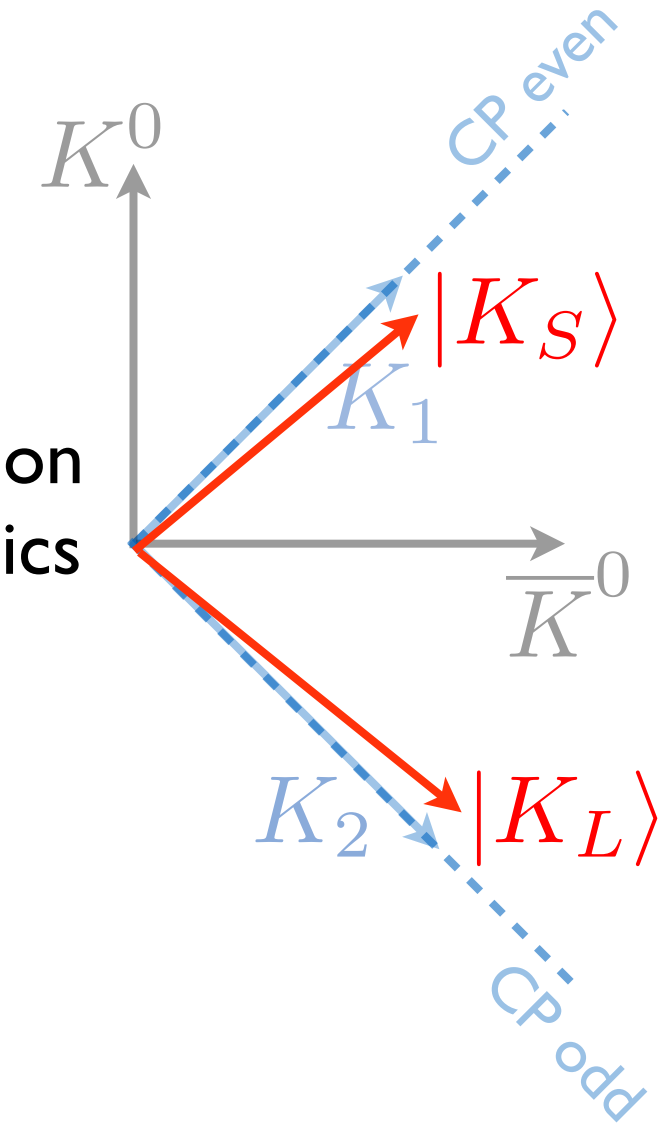
$$|K_S\rangle = |K_1\rangle + \epsilon\,|K_2\rangle$$

Confusing standards…

No assumption on CP conservation, take a more general basis

$$|K_L\rangle = p|K^0\rangle - q|\overline{K}^0\rangle$$
$$|K_S\rangle = p|K^0\rangle + q|\overline{K}^0\rangle$$

Parameterisation used in B physics



with the normalisation condition

$$|p|^2 + |q|^2 = 1$$

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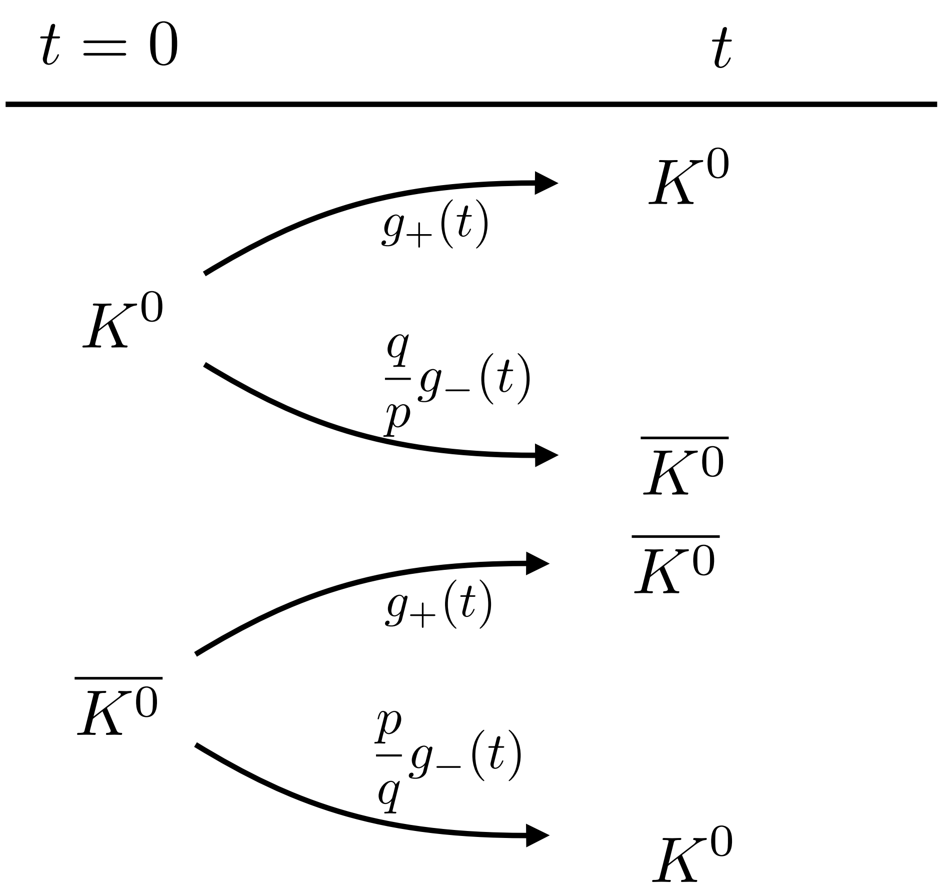
$$|K_L\rangle = |K_2\rangle + \epsilon\,|K_1\rangle$$
$$|K_S\rangle = |K_1\rangle + \epsilon\,|K_2\rangle$$

Parameterisation used in Kaon physics

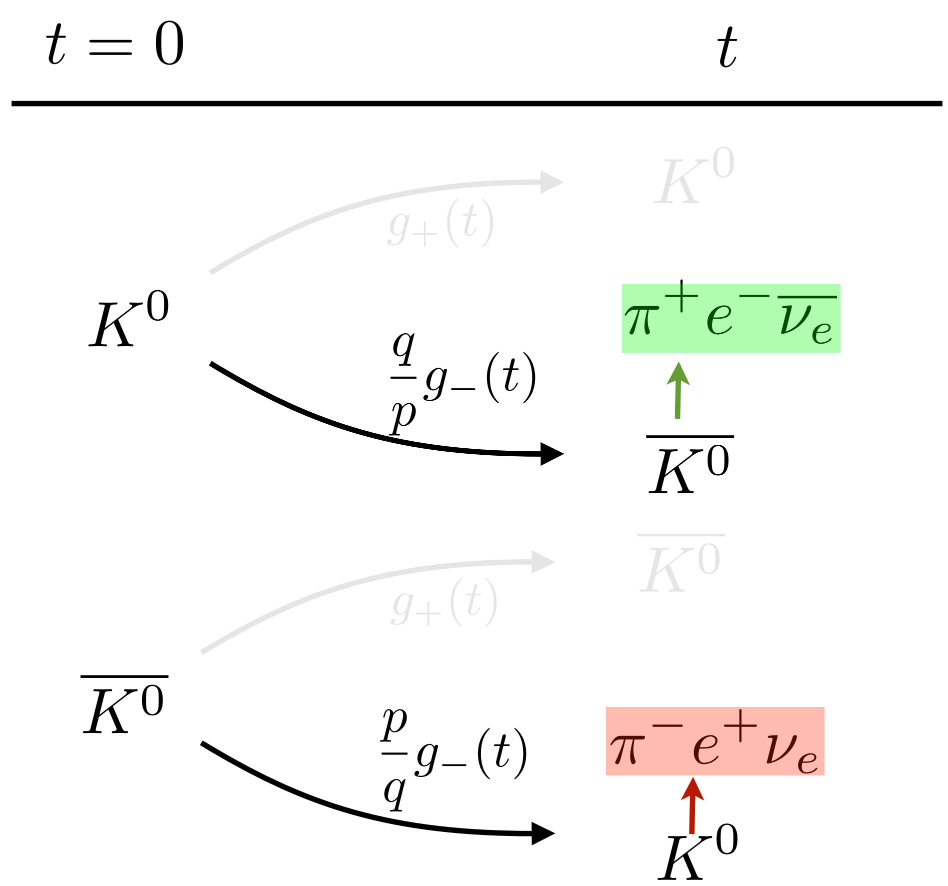
Time evolution (again…)

$$g_{\pm}(t) = \frac{e^{-i\omega_S t} \pm e^{-i\omega_L t}}{2}$$



Time evolution (again...)

$$A_T(t) = \frac{\overline{I}_{\pi^- e^+ \nu}(t) - I_{\pi^+ e^- \overline{\nu}}(t)}{\overline{I}_{\pi^- e^+ \nu}(t) + I_{\pi^+ e^- \overline{\nu}}(t)} = \frac{1 - |q/p|^4}{1 + |q/p|^4} = 4\mathcal{R}\epsilon$$



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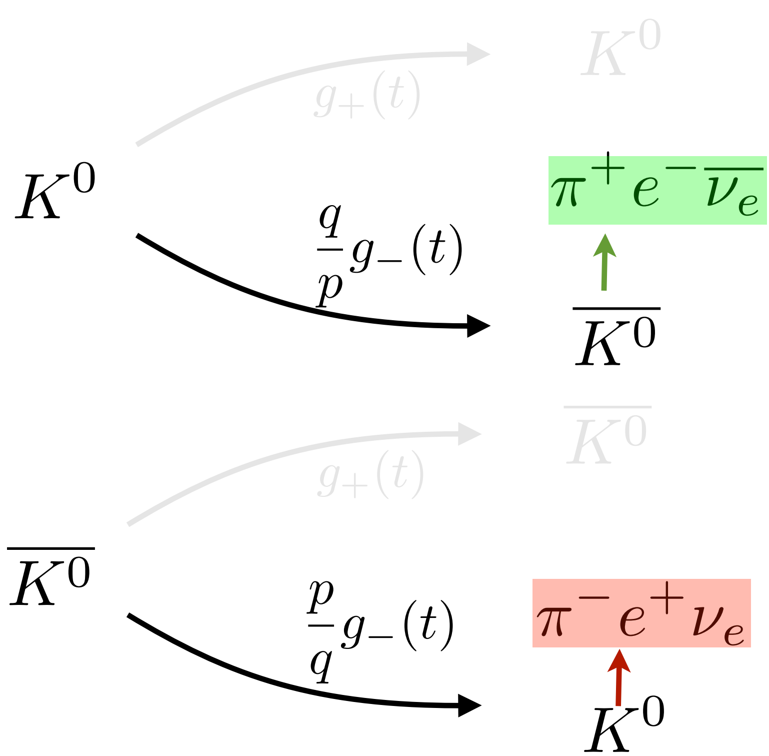
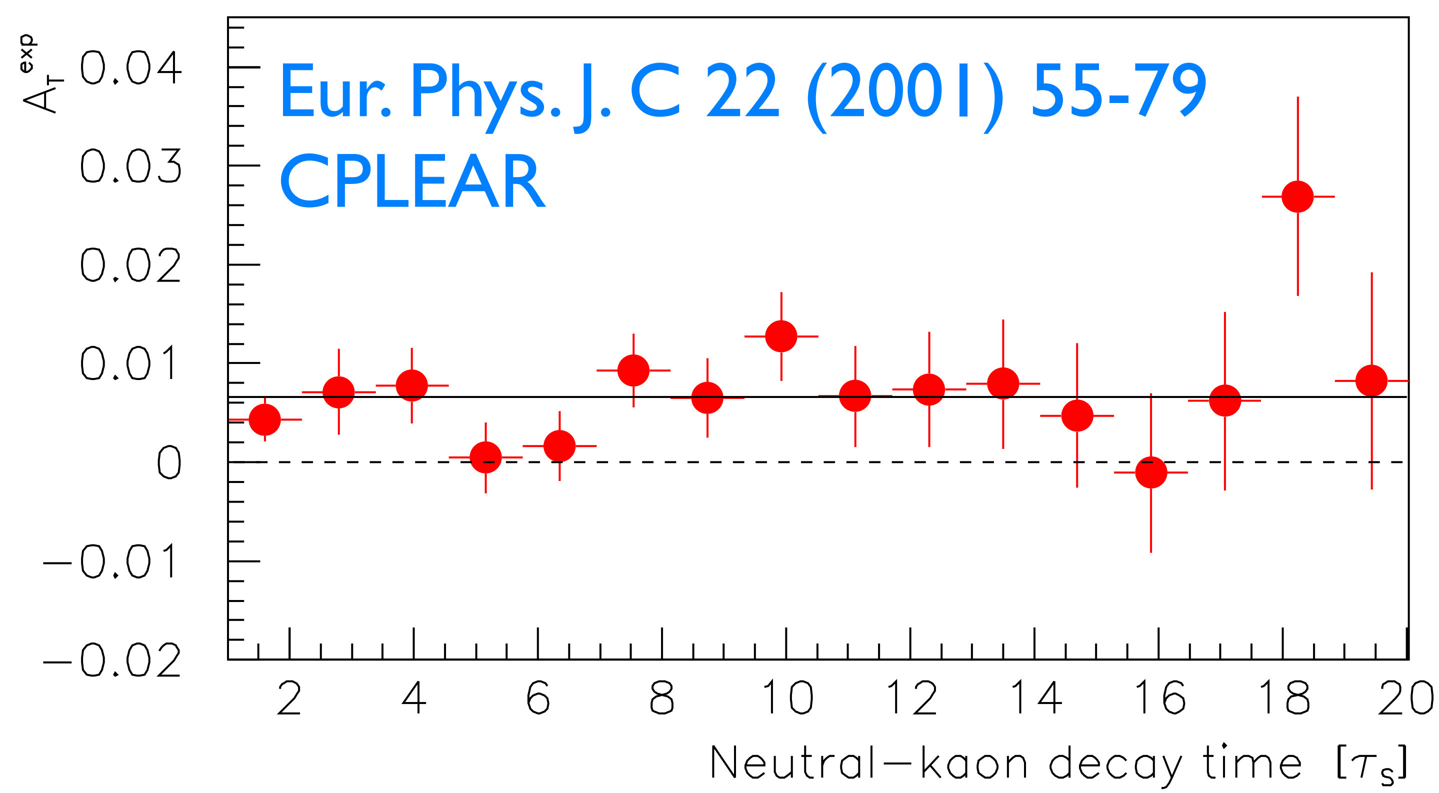
$$|q/p| = 0.9967 \pm 0.0008 \neq 1$$



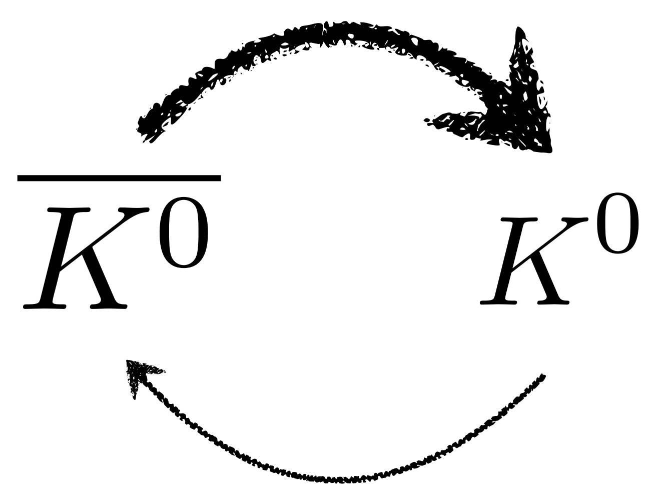


$$\langle A_T^{exp} \rangle = (6.6 \pm 1.3) \times 10^{-3}$$

$$\chi^2/\mathrm{ndf} = 0.84\,, \quad \mathrm{ndf} = 607$$

CP violation in mixing

$$|q/p| = 0.9967 \pm 0.0008 \neq 1$$



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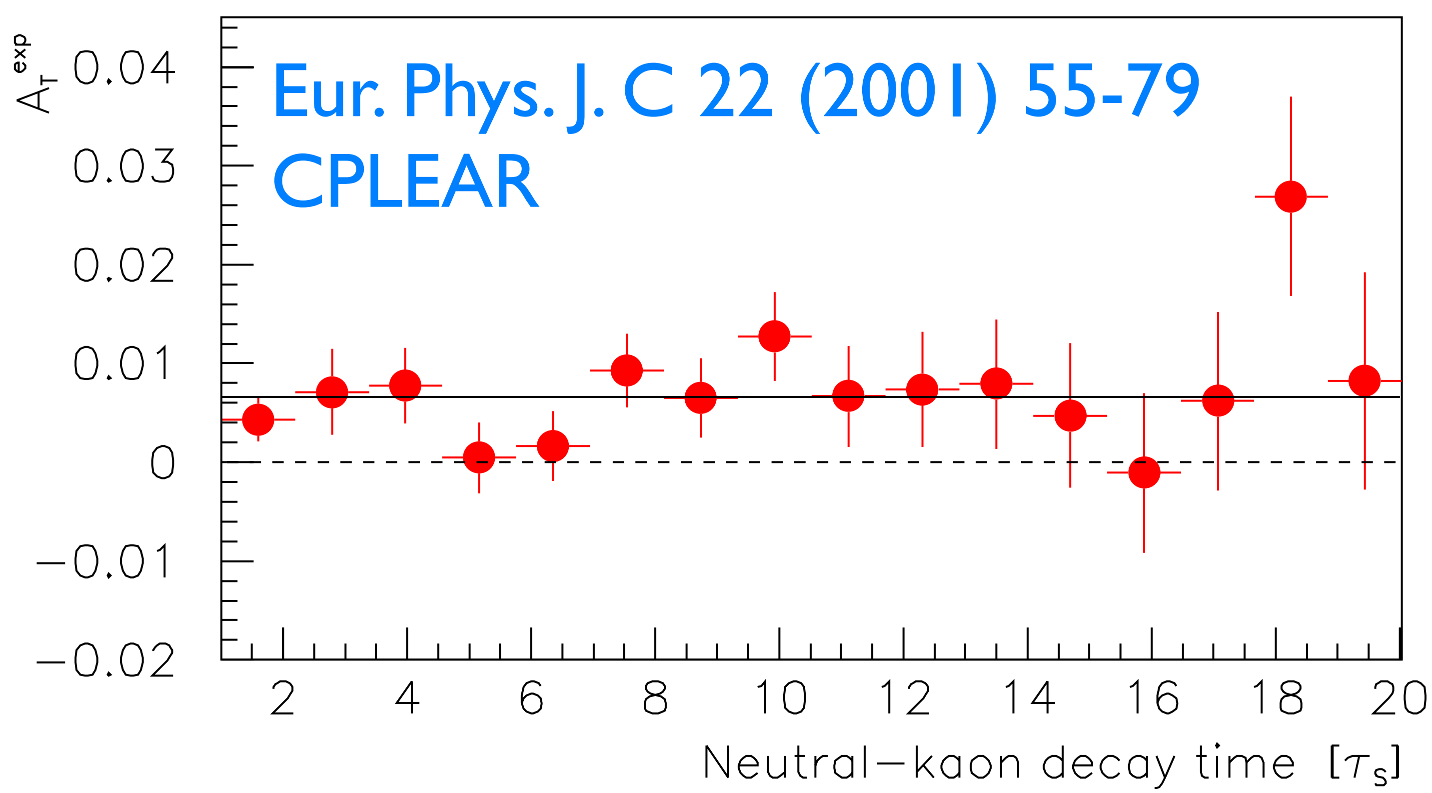

$$\langle A_{\mathrm{T}}^{\mathrm{exp}} \rangle = (6.6 \pm 1.3) \times 10^{-3}$$

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Matter and antimatter are not arbitrary

$$|q/p| = 0.9967 \pm 0.0008 \neq 1$$

$$A_T(t) = \frac{\overline{I}_{\pi^- e^+ \nu}(t) - I_{\pi^+ e^- \overline{\nu}}(t)}{\overline{I}_{\pi^- e^+ \nu}(t) + I_{\pi^+ e^- \overline{\nu}}(t)} = \frac{1 - |q/p|^4}{1 + |q/p|^4} = 4\mathcal{R}\epsilon$$

What are you made of ???

(The answer would be likely (hopefully?) straightforward… N(baryons)/N(photons) ≅ 6×10^{-10})

CP violation in mixing

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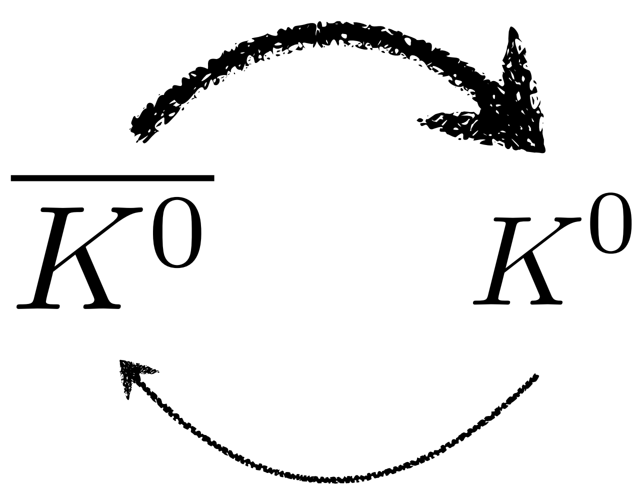
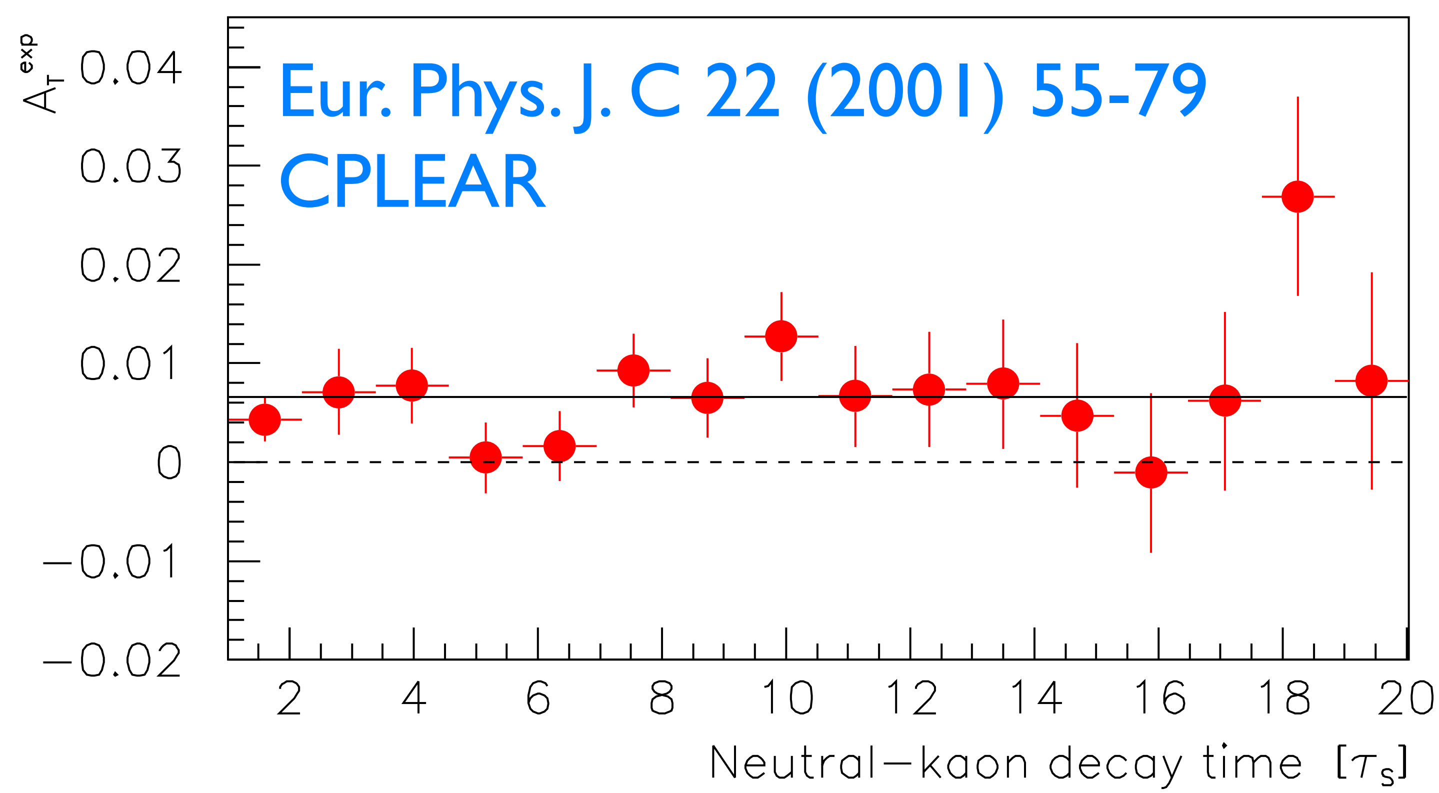


CP violation in mixing



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CP violation in B mixing?

Use large samples of semileptonic $B^0 \to D\mu\nu$ and $B_s^0 \to D_s\mu\nu$ decays at LHCb to measure CP violation in mixing

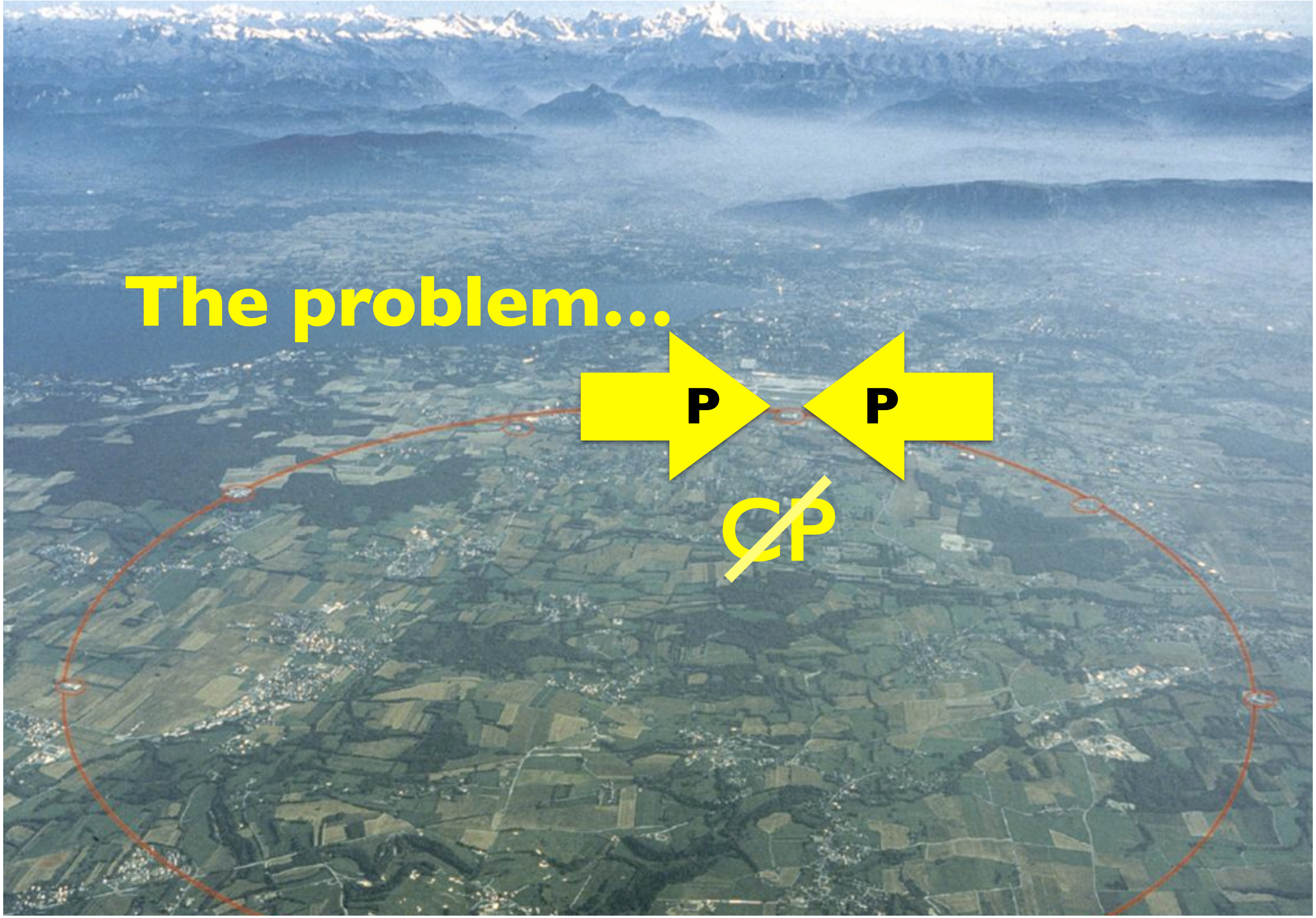
$$a_{\rm sl} = \frac{\Gamma(\bar{B}^0_{(s)} \to \ell^+ X) - \Gamma(B^0_{(s)} \to \ell^- X)}{\Gamma(\bar{B}^0_{(s)} \to \ell^+ X) + \Gamma(B^0_{(s)} \to \ell^- X)} = \frac{1 - |q/p|^4}{1 + |q/p|^4} = \mathrm{Im}(M_{12}/\Gamma_{12})$$

The "untagged" asymmetry:

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

but there are other asymmetries to consider…

Production asymmetry



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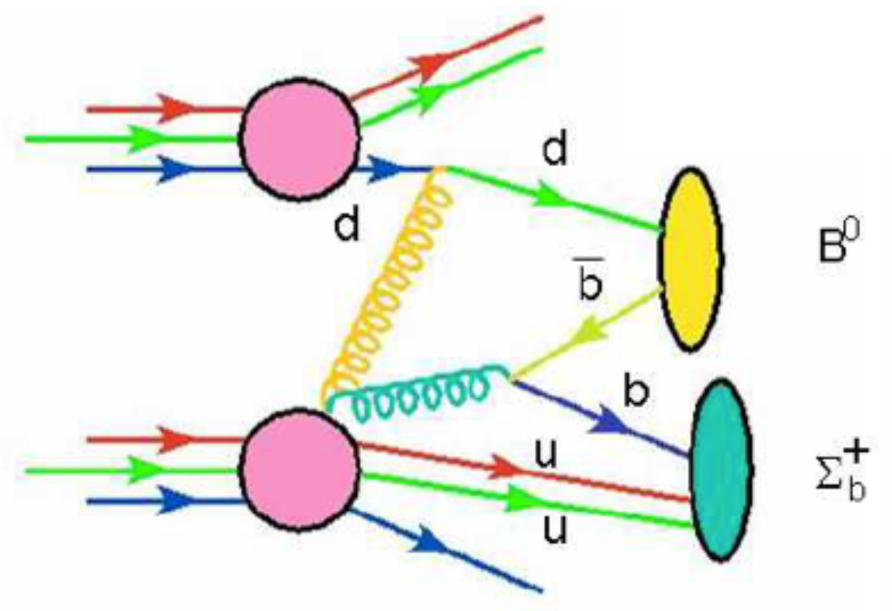

An examples of the mechanism.

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

These are expected to be O(1%) to be compared with a_{sl} ~ O(0.01-0.001%)

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

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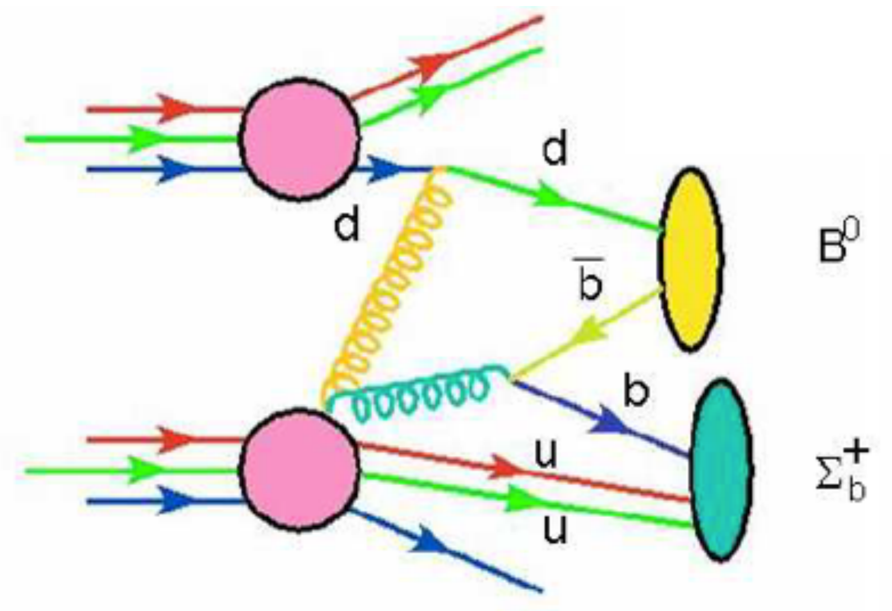

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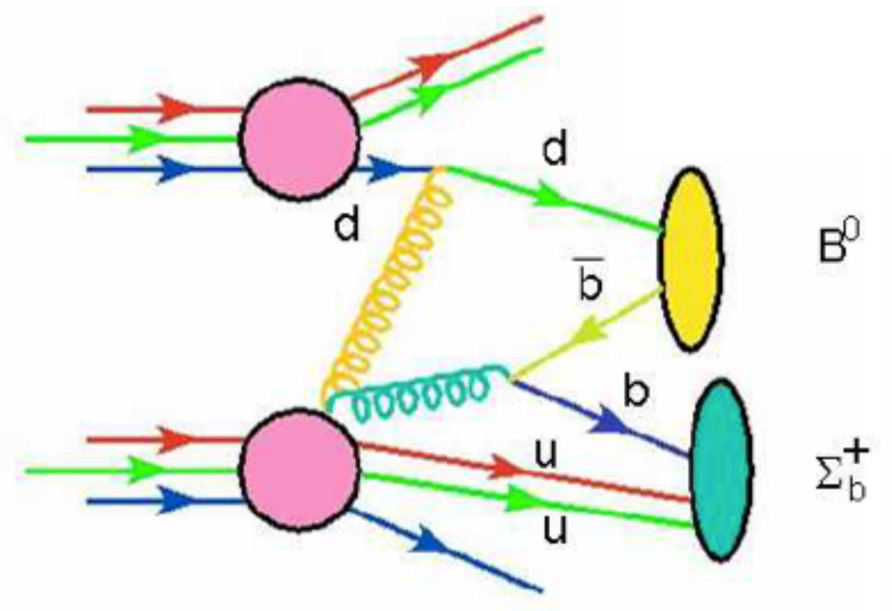
Production asymmetry



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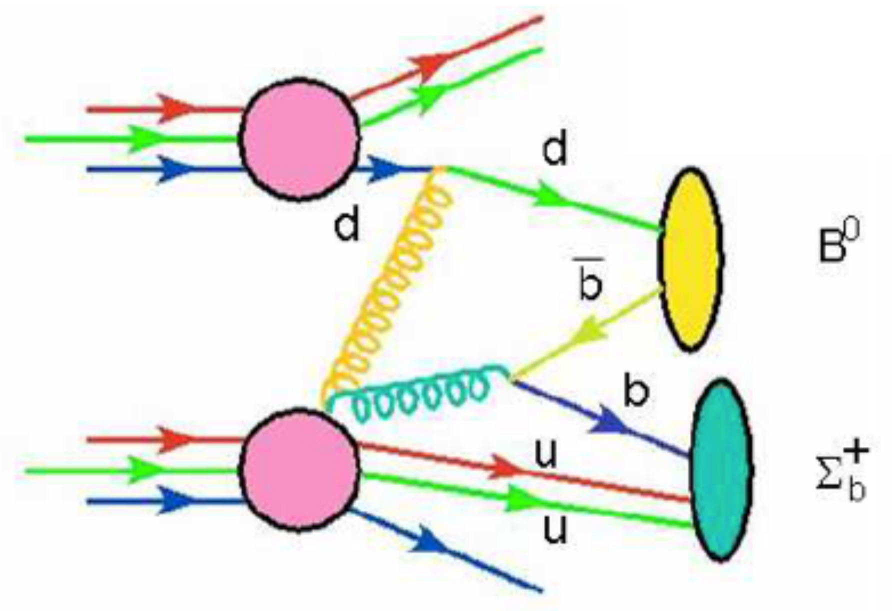
Integrate in time:

$$A_{\rm meas} \equiv \frac{\Gamma[D^-\mu^+] - \Gamma[D^+\mu^-]}{\Gamma[D^-\mu^+] + \Gamma[D^+\mu^-]} = \frac{a_{\rm sl}}{2} + \left[a_{\rm P} - \frac{a_{\rm sl}}{2}\right] \frac{\int_{t=0}^{\infty} e^{-\Gamma\ t} \cos(\Delta M\ \ t)\epsilon(t)dt}{\int_{t=0}^{\infty} e^{-\Gamma\ t} \cosh(\frac{\Delta\Gamma\ \ t}{2})\epsilon(t)dt}$$

Production asymmetry



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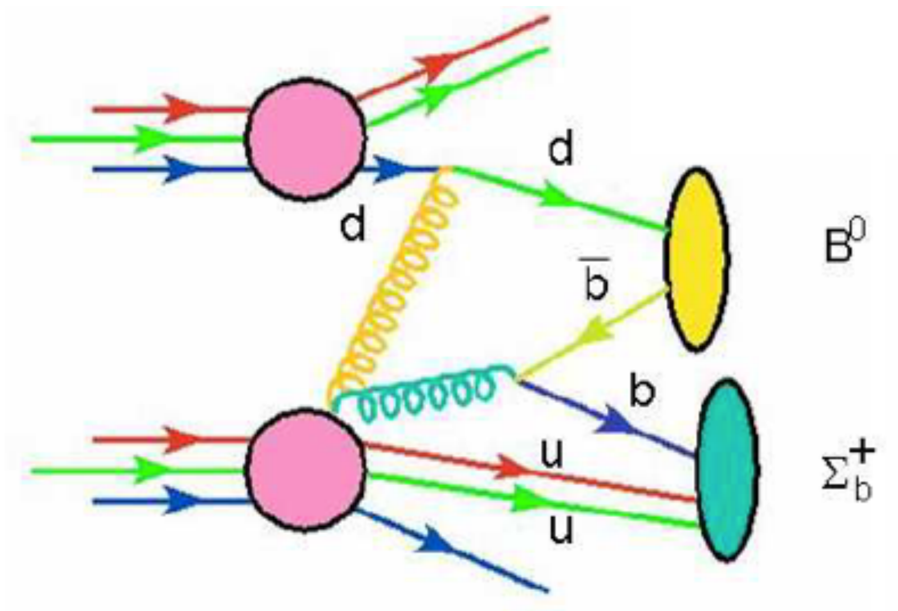
$<10^{-4}$ for $\Delta m_s = 18\ ps^{-1}$

Production asymmetry



An examples of the mechanism.

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Integrate in time:

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Expected sensitivity on a_{sl}: 10^{-3}

<10^{-4} for Δm_s=18 ps^{-1}

Signal Yields

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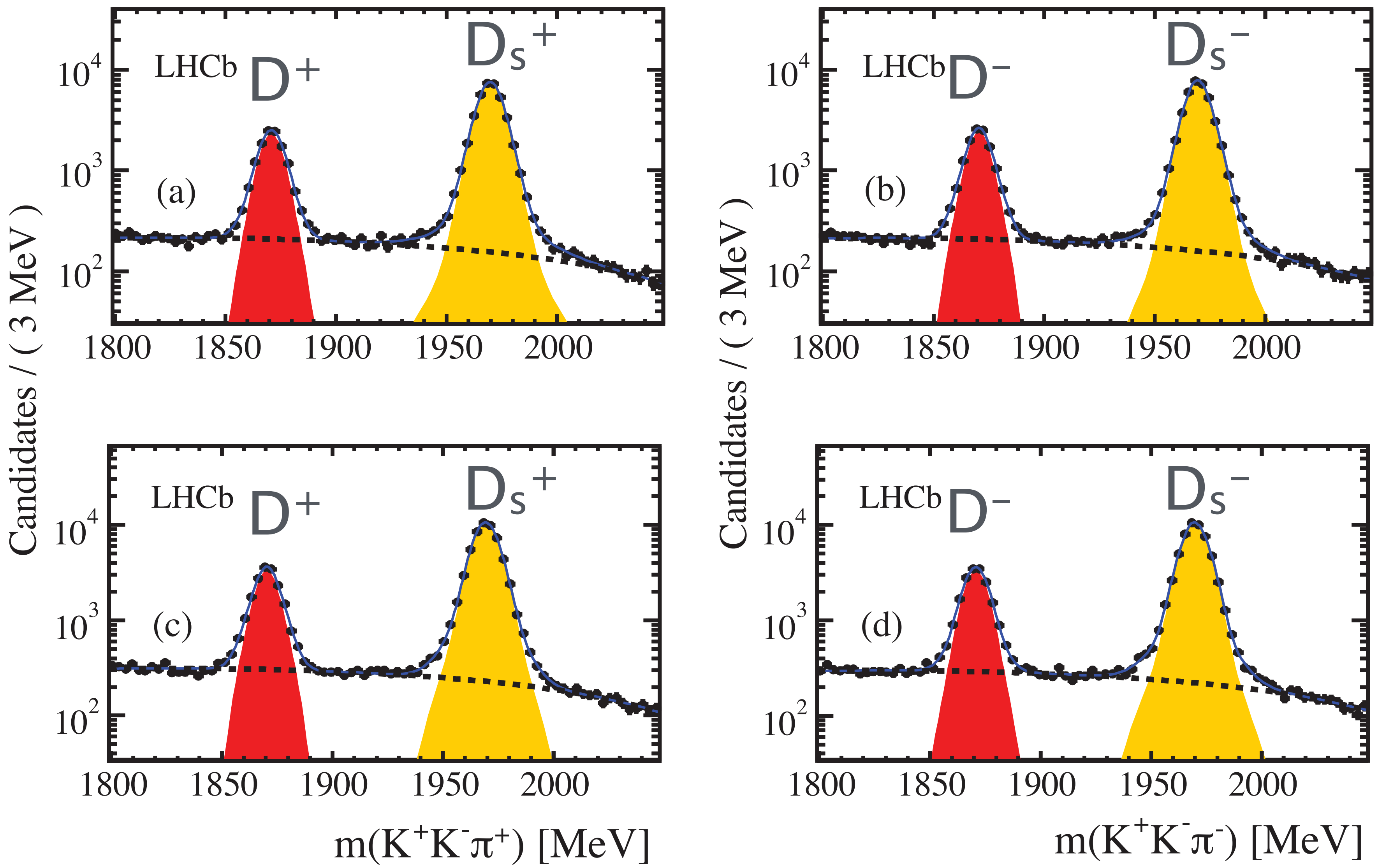
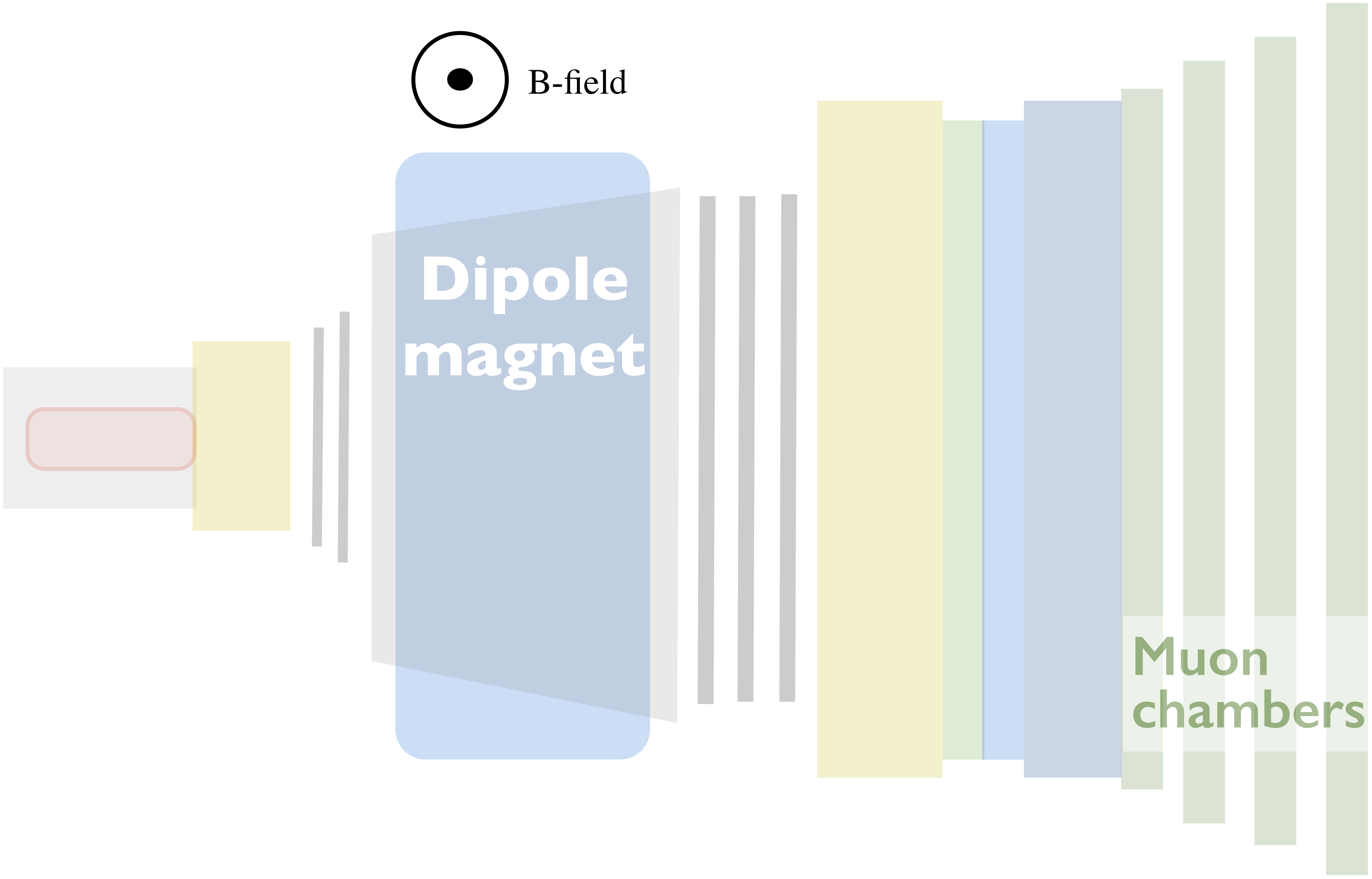
Magnet Up

Magnet Down



Yet, other spurious asymmetry to cancel…

Detection asymmetries



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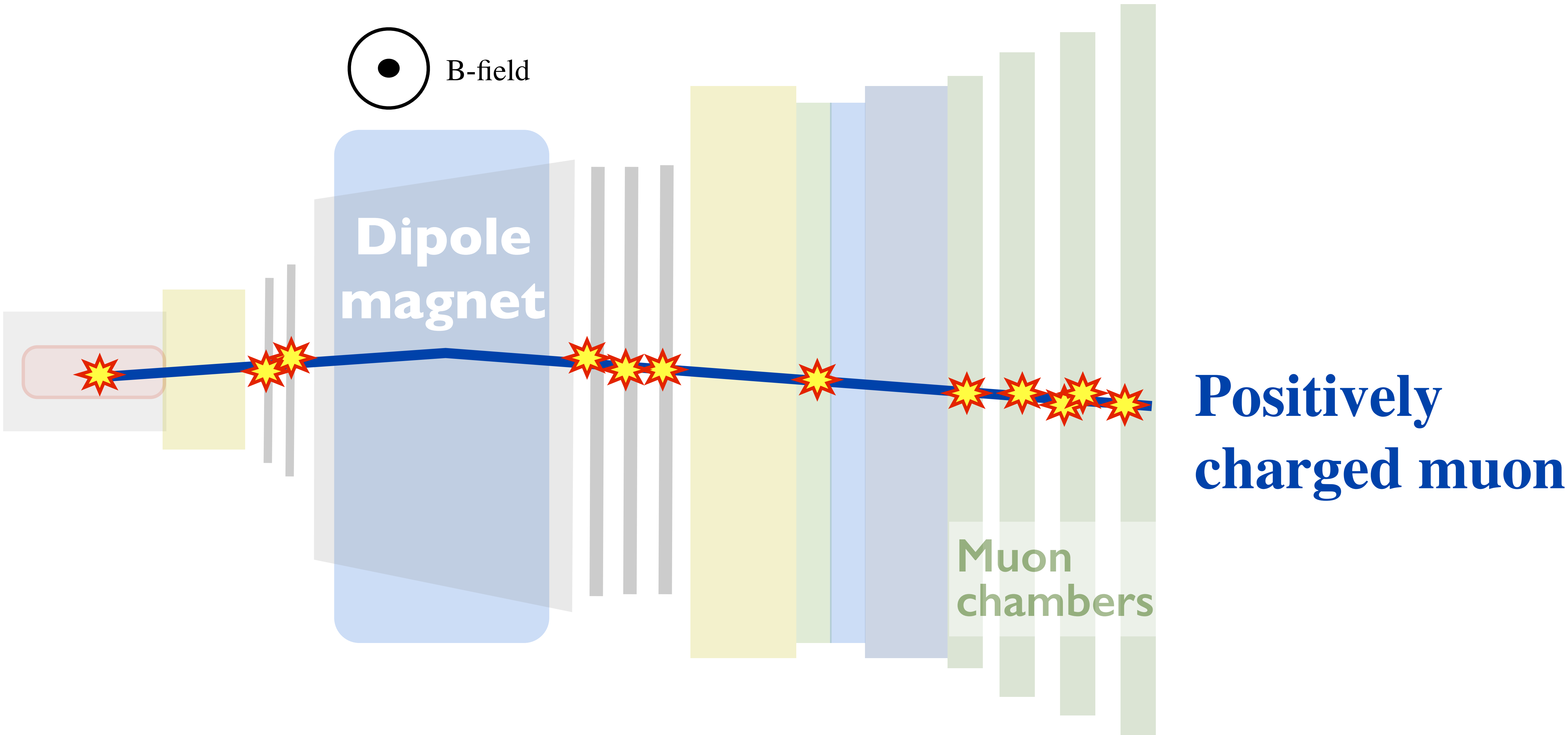
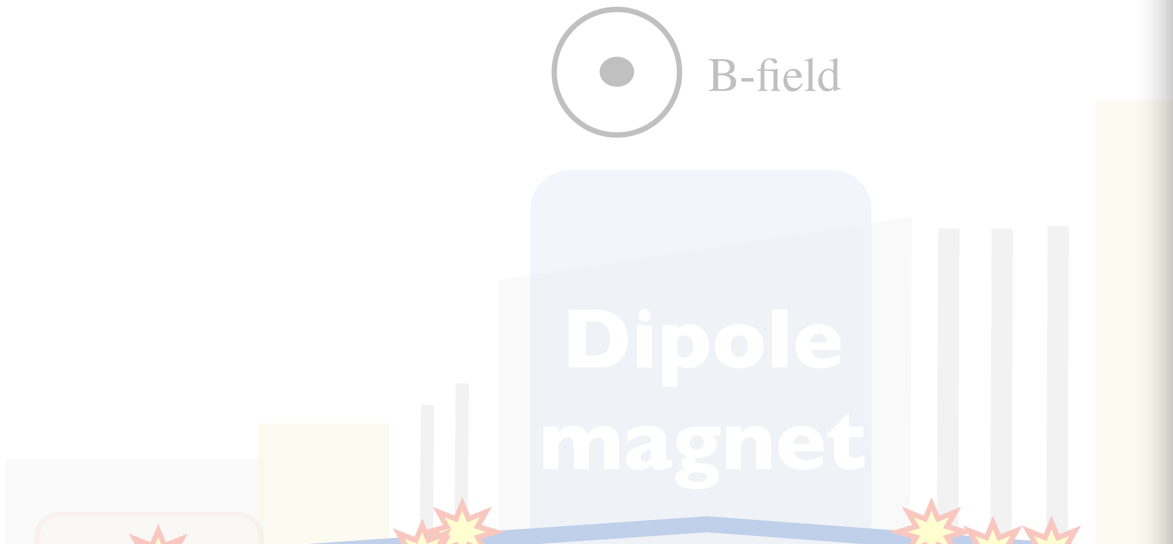
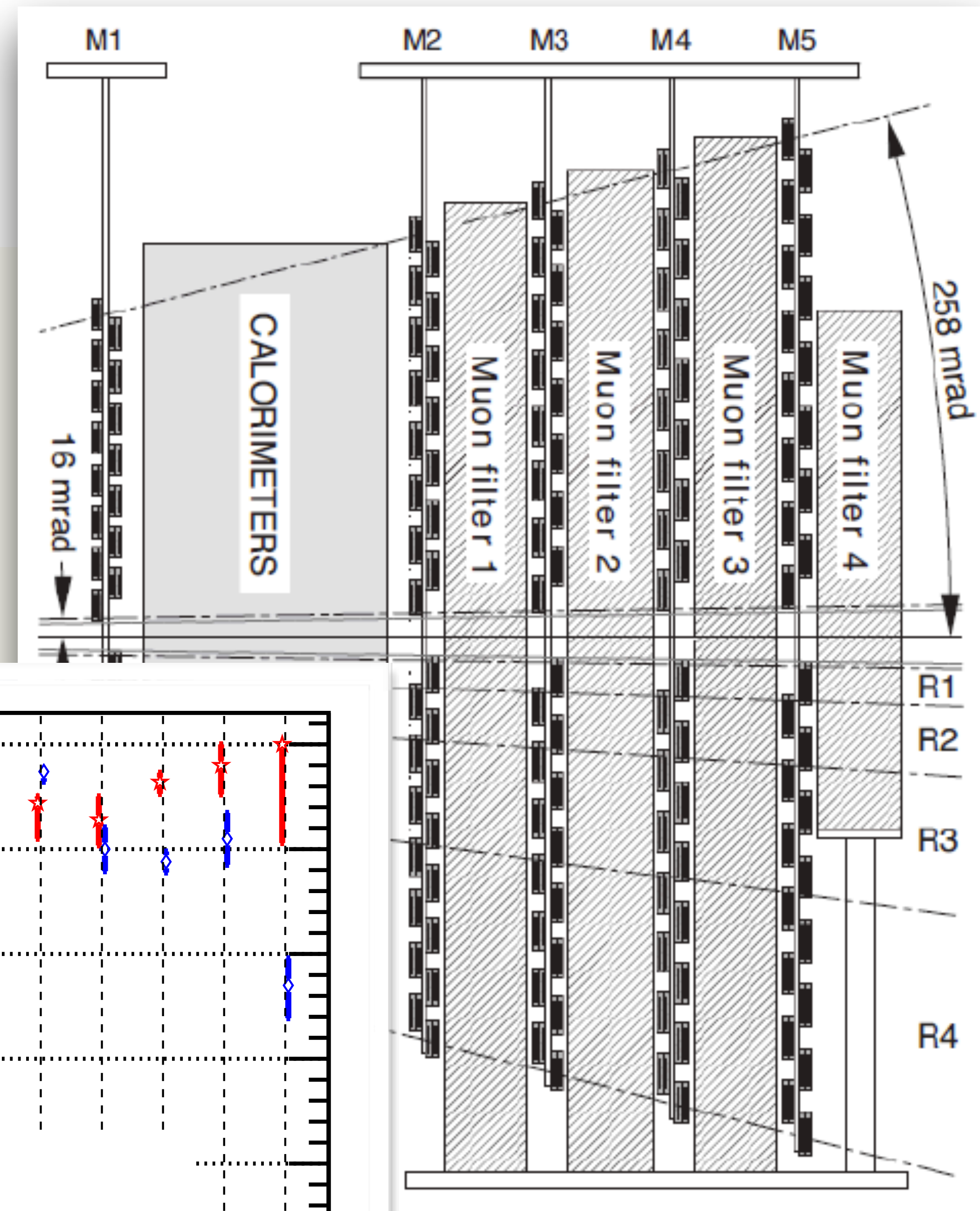


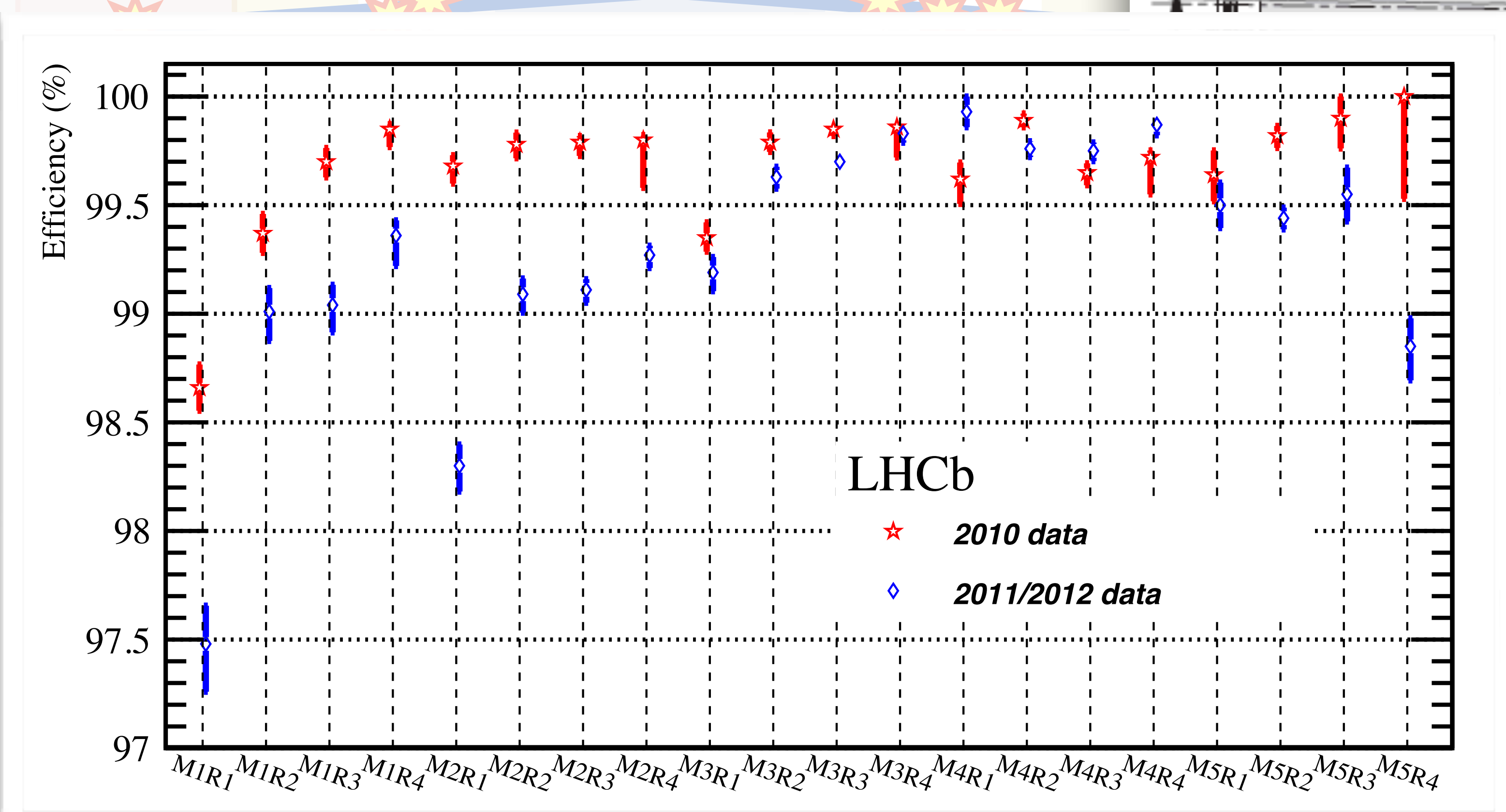
Muons



B-field
Dipole magnet

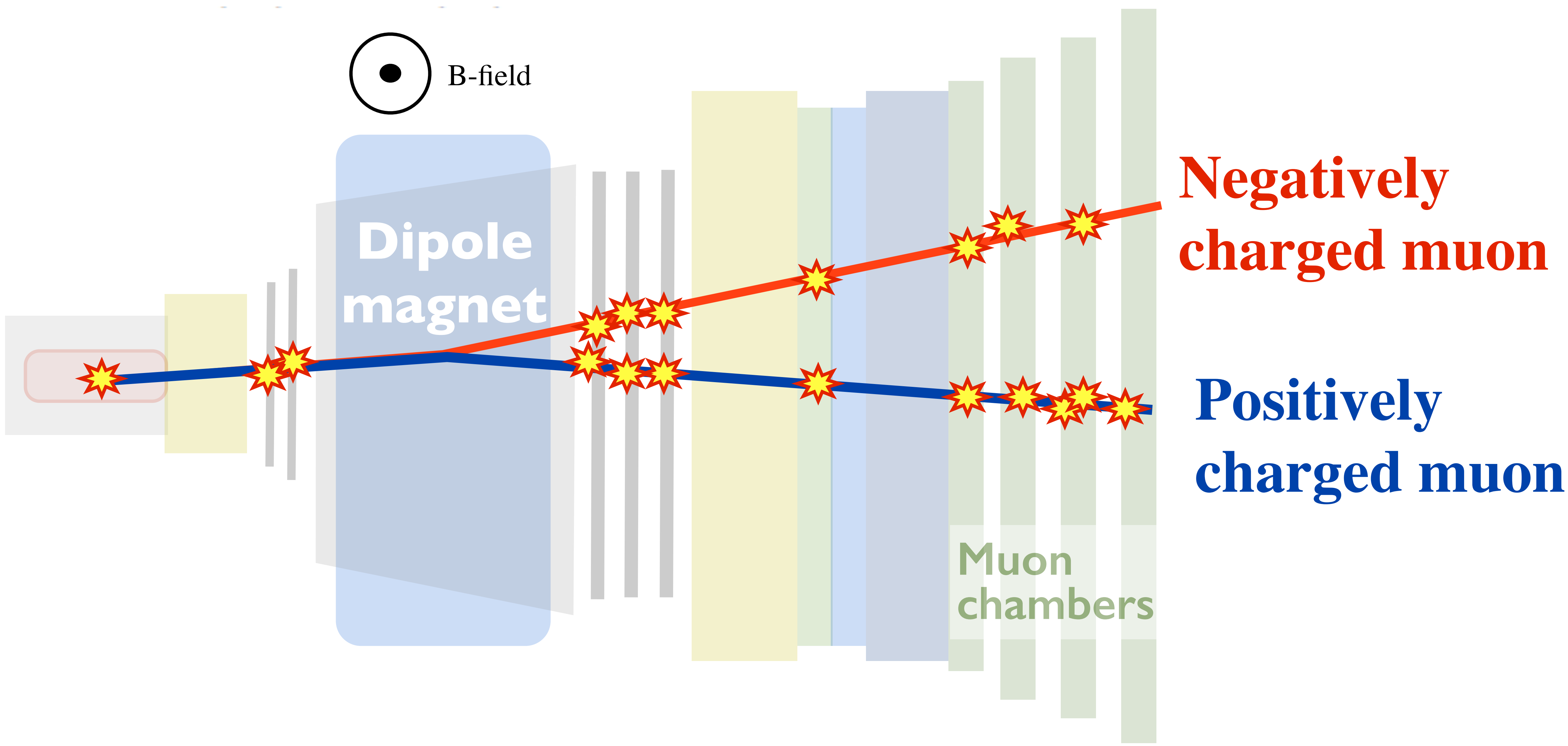


M1
M2
M3
M4
M5
CALORIMETERS
Muon filter 1
Muon filter 2
Muon filter 3
Muon filter 4
258 mrad
16 mrad
R1
R2
R3
R4



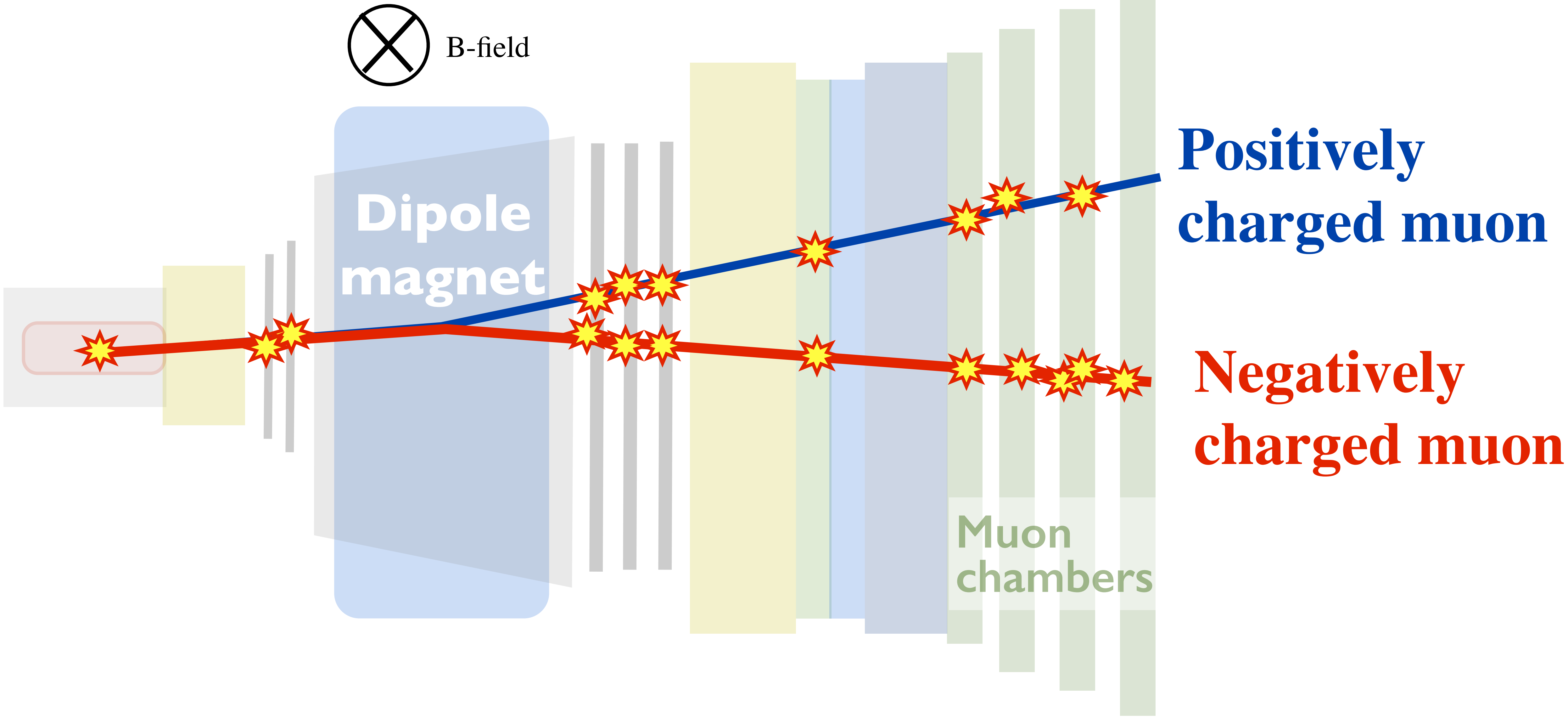
Efficiency (%)
100
99.5
99
98.5
98
97.5
97
LHCb
2010 data
2011/2012 data
M1R1
M1R2
M1R3
M1R4
M2R1
M2R2
M2R3
M2R4
M3R1
M3R2
M3R3
M3R4
M4R1
M4R2
M4R3
M4R4
M5R1
M5R2
M5R3
M5R4

Detection asymmetries



Detection asymmetries

Reversed magnet polarity



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

Result

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

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Results

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

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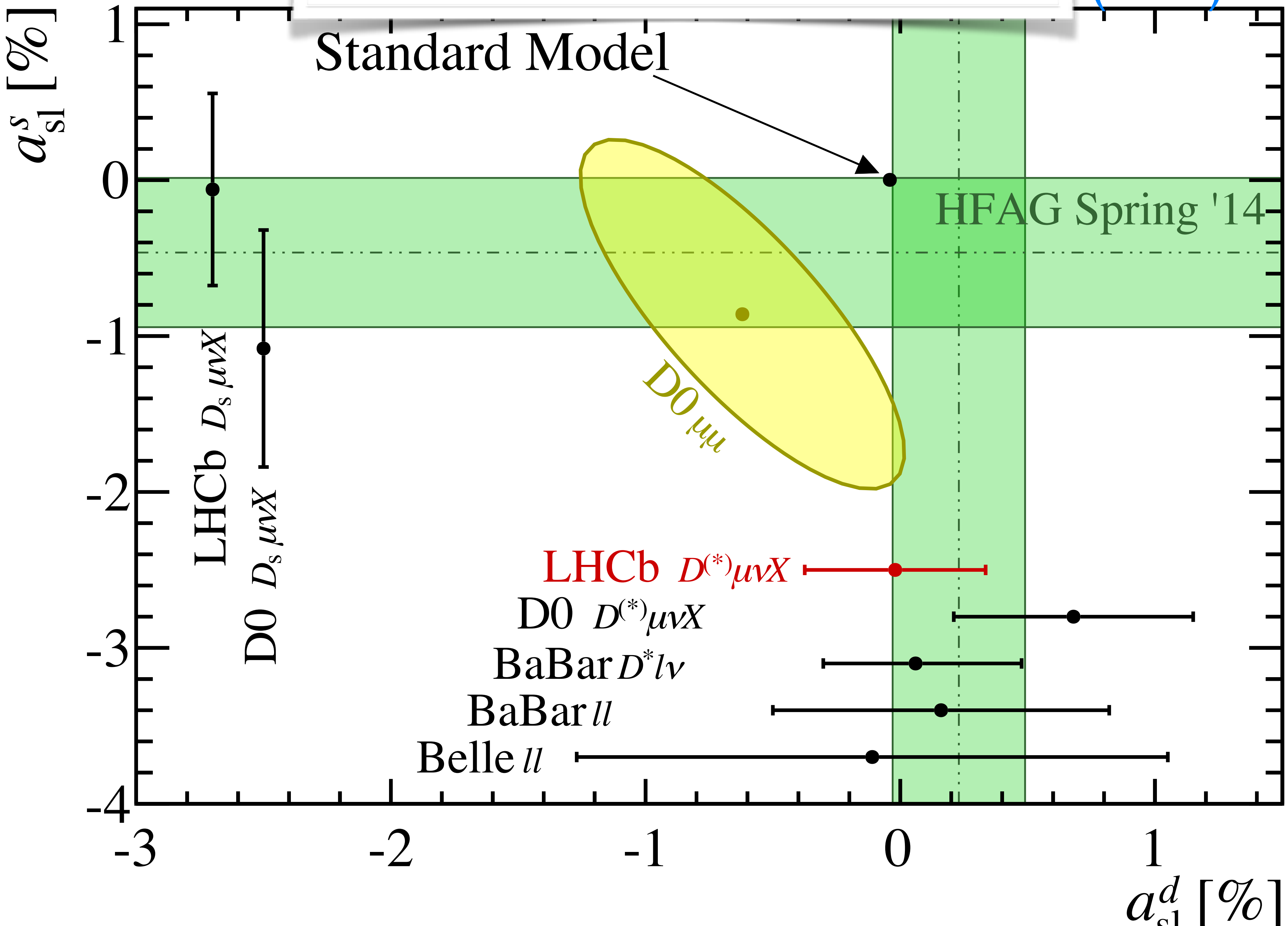
$$a_{\rm sl}^{d} = (-0.02 \pm 0.19 \pm 0.30)\%$$

Phys. Rev. Lett. 114 (2015) 041601



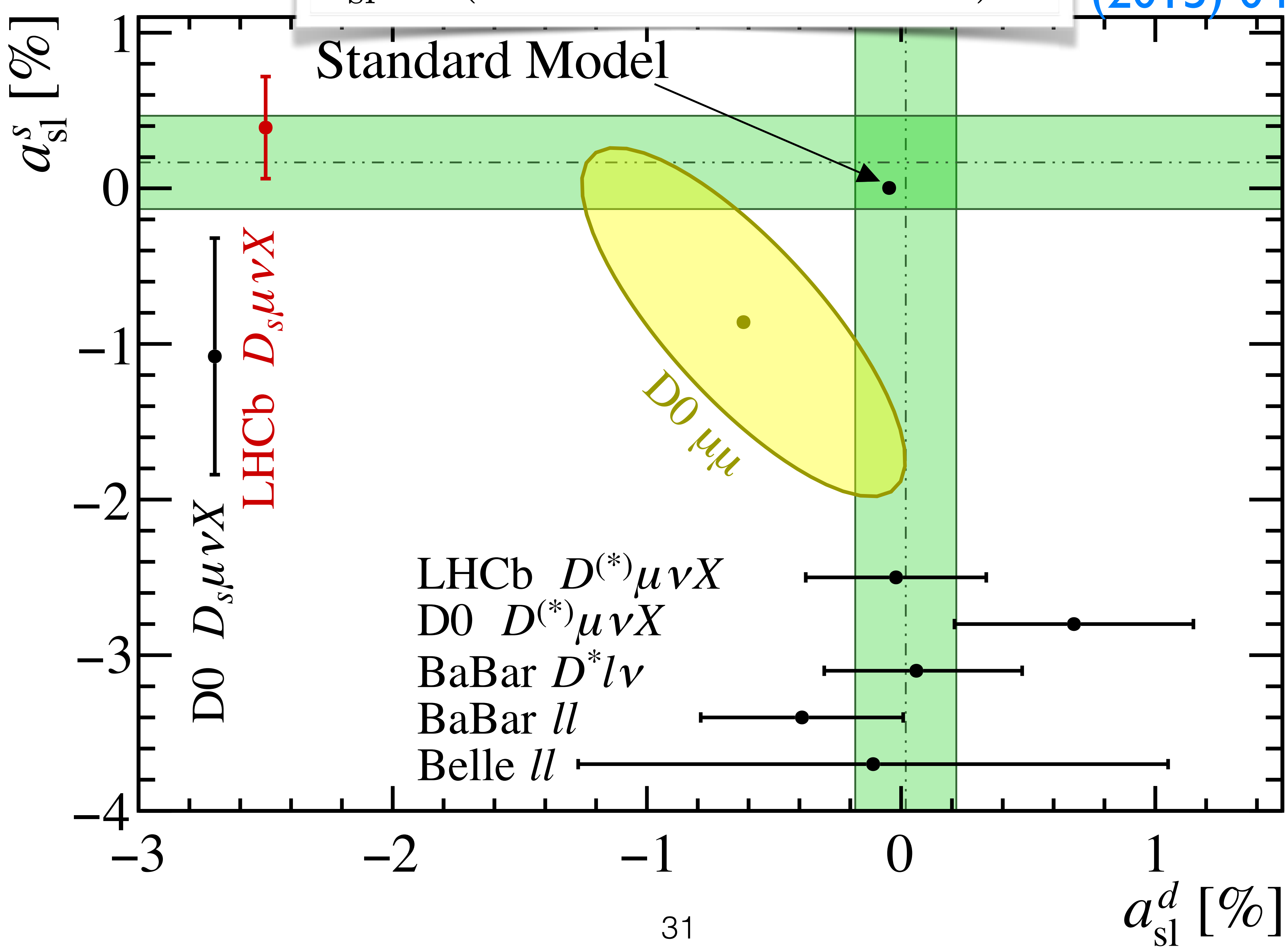
Results

$$a_{\rm sl}^{s} = (0.39 \pm 0.26 \pm 0.20)\%$$

Hot off the press!
arXiv:1605.09768

$$a_{\rm sl}^{d} = (-0.02 \pm 0.19 \pm 0.30)\%$$

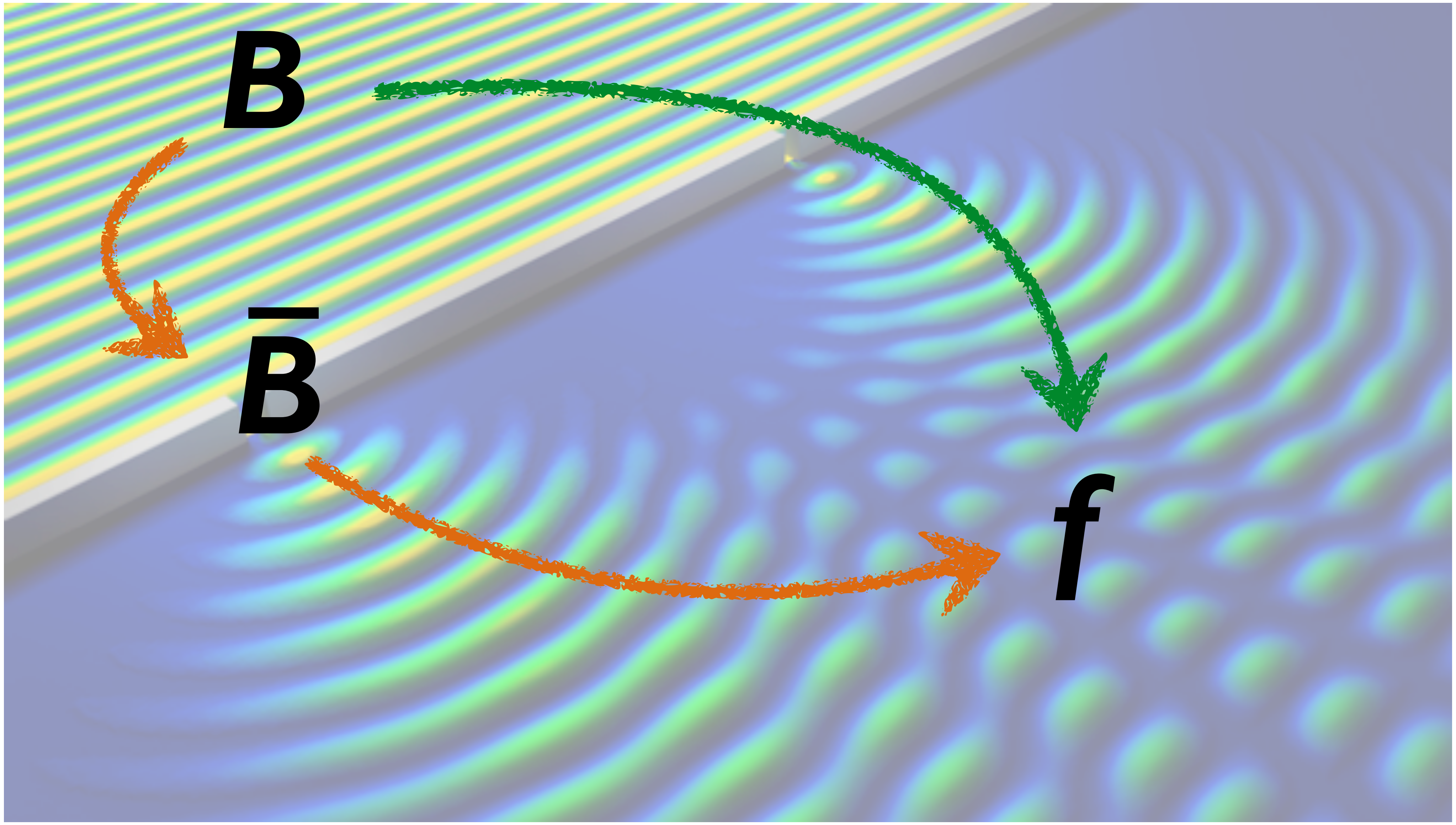
Phys. Rev. Lett. 114 (2015) 041601



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
- ★ CP is broken!
- ★ Observed CP violation in K mixing; no evidence so far for B mesons (neither for D mesons).

If the final state is a CP eigenstate



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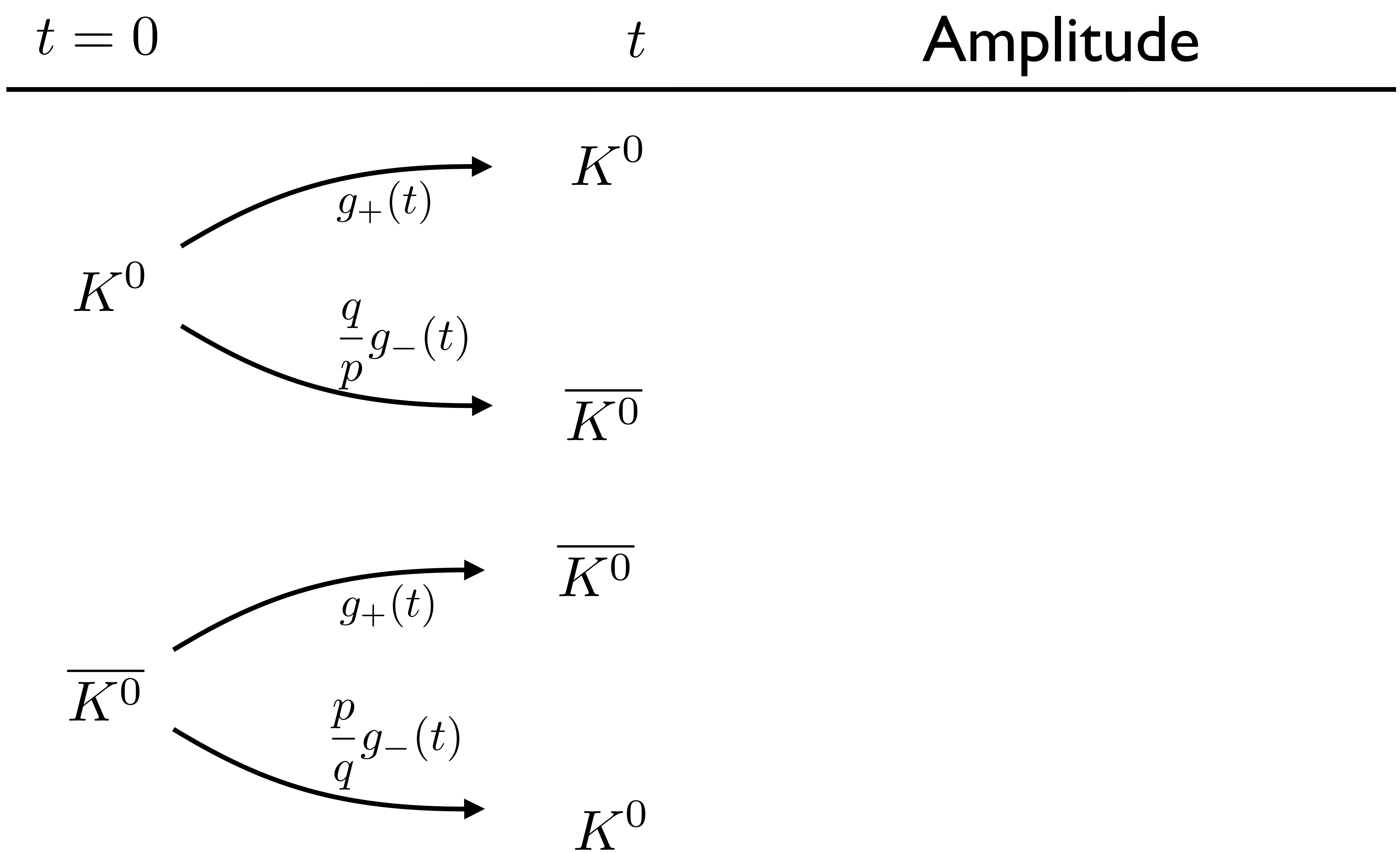
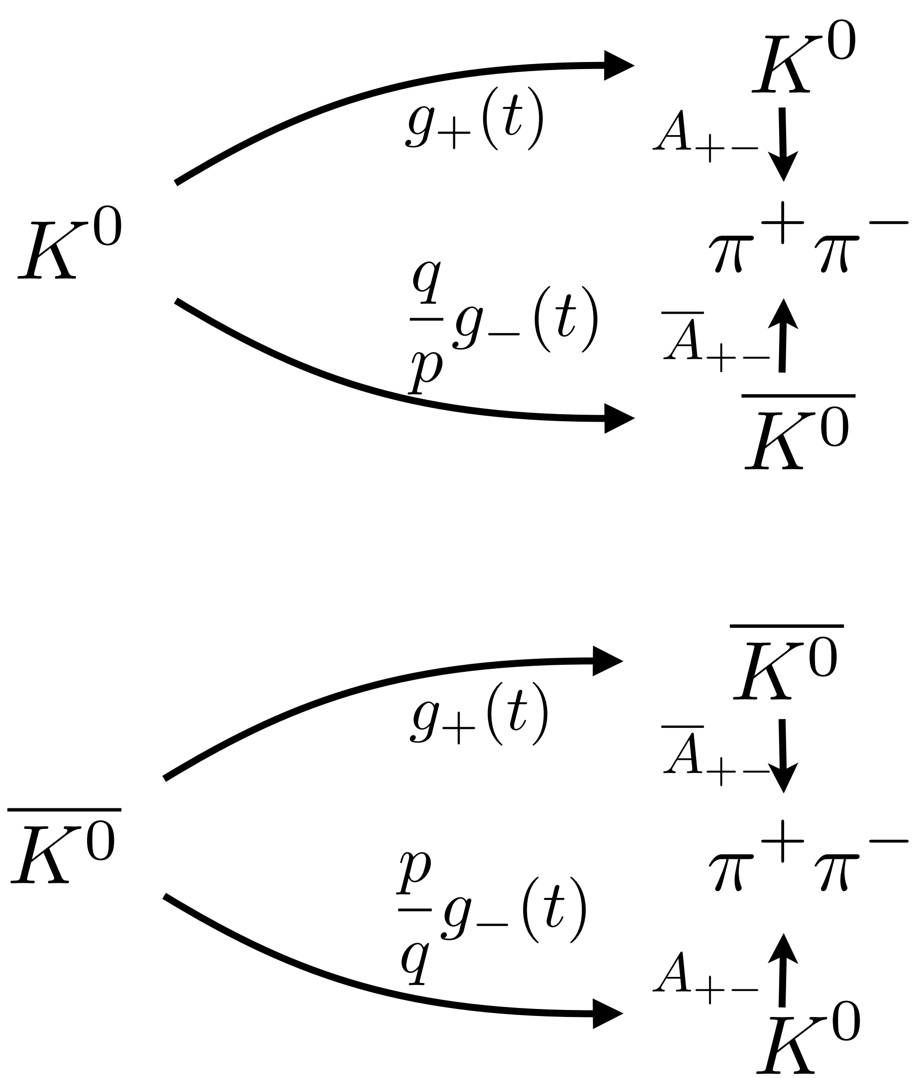


Time evolution (yes, again…)

$$g_\pm(t) = \frac{e^{-i\omega_S t} \pm e^{-i\omega_L t}}{2}$$

$$A_{+-} \equiv \langle \pi^+\pi^- | K^0 \rangle$$
$$\overline{A}_{+-} \equiv \langle \pi^+\pi^- | \overline{K^0} \rangle$$

$t = 0$	t	Amplitude

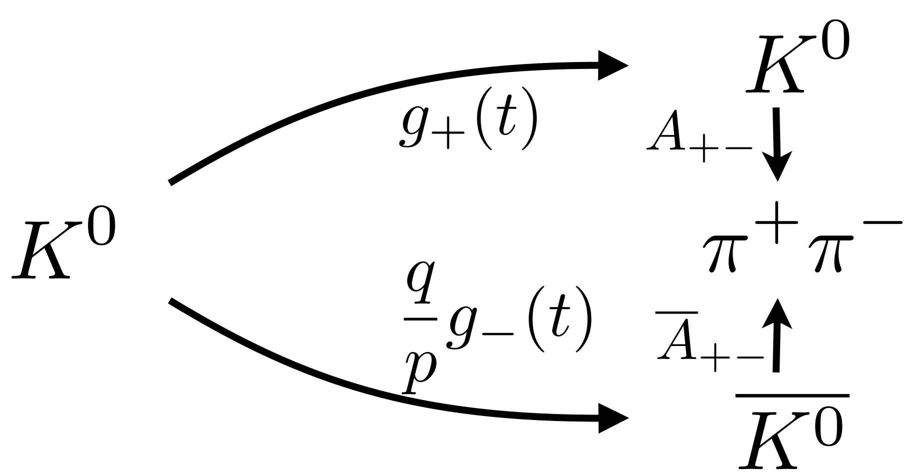


Time evolution (yes, again…)

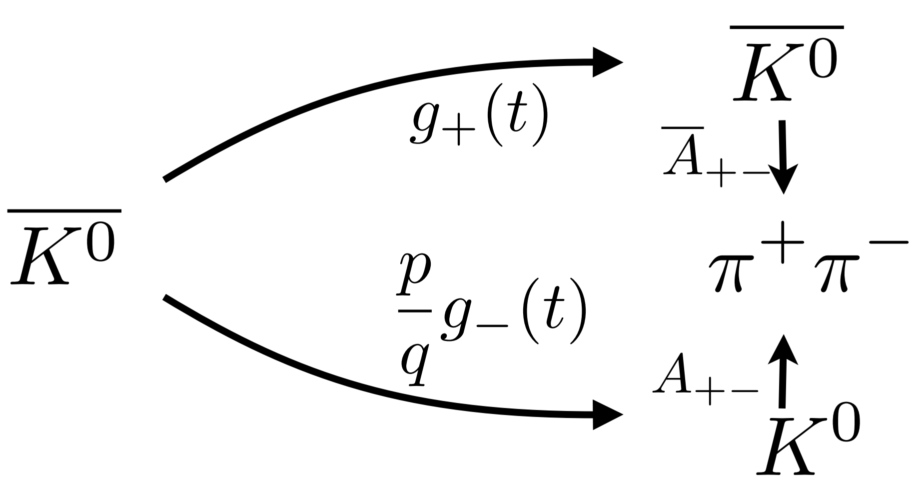
$$g_\pm(t) = \frac{e^{-i\omega_S t} \pm e^{-i\omega_L t}}{2}$$

$$A_{+-} \equiv \langle \pi^+\pi^- | K^0 \rangle$$
$$\overline{A}_{+-} \equiv \langle \pi^+\pi^- | \overline{K^0} \rangle$$

$t=0$	t	Amplitude



$$g_+(t)A_{+-} + \frac{q}{p}g_-(t)\overline{A}_{+-}$$

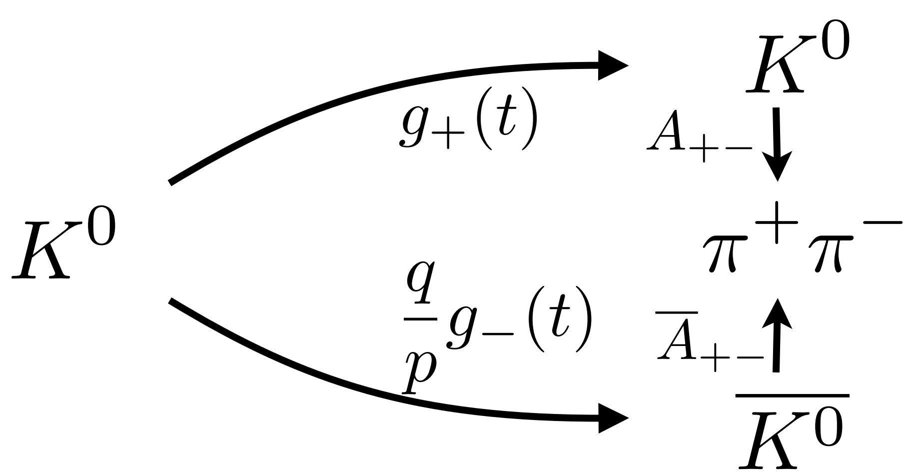


$$g_+(t)\overline{A}_{+-} + \frac{p}{q}g_-(t)A_{+-}$$

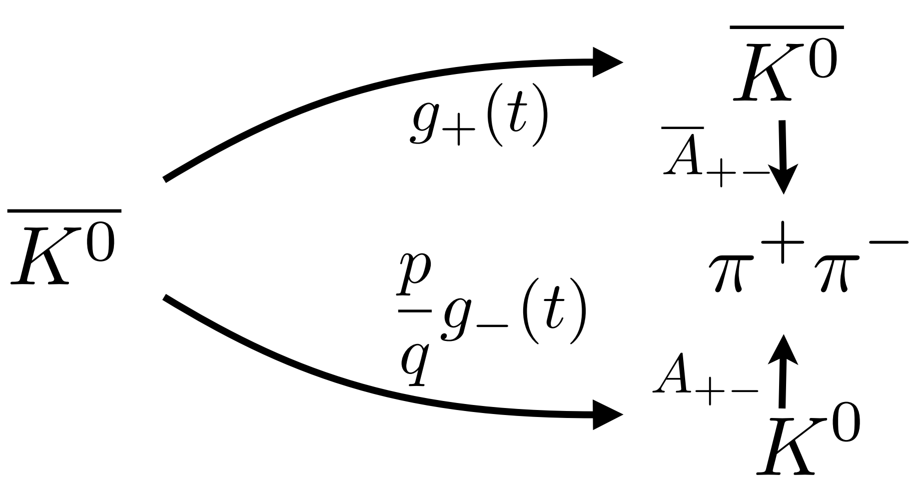
Time evolution (yes, again…)

$$g_\pm(t) = \frac{e^{-i\omega_S t} \pm e^{-i\omega_L t}}{2} \qquad \begin{aligned} A_{+-} &\equiv \langle \pi^+\pi^- | K^0 \rangle \\ \overline{A}_{+-} &\equiv \langle \pi^+\pi^- | \overline{K^0} \rangle \end{aligned} \qquad \lambda_{+-} \equiv \frac{q}{p}\frac{\overline{A}_{+-}}{A_{+-}}$$

$t=0$	t	Amplitude



$$A_{+-}\left[\, g_+(t) + \lambda_{+-} g_-(t) \,\right]$$

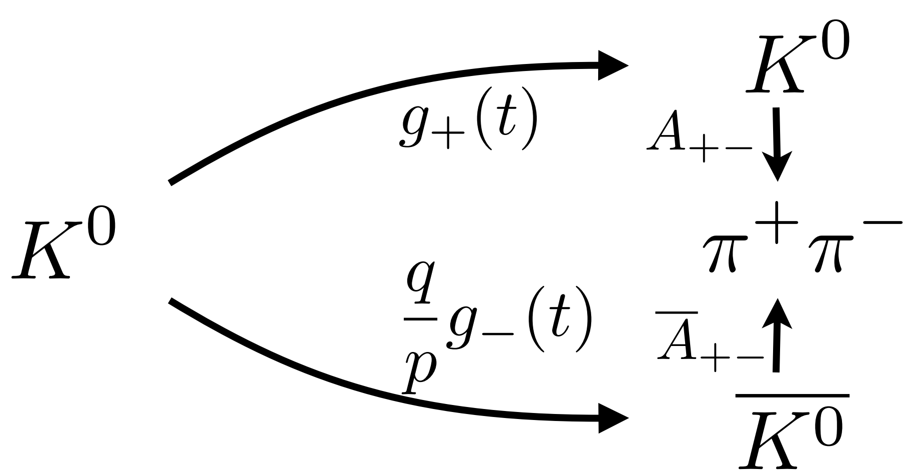


$$\overline{A}_{+-}\left[\, g_+(t) + \frac{1}{\lambda_{+-}} g_-(t) \,\right]$$

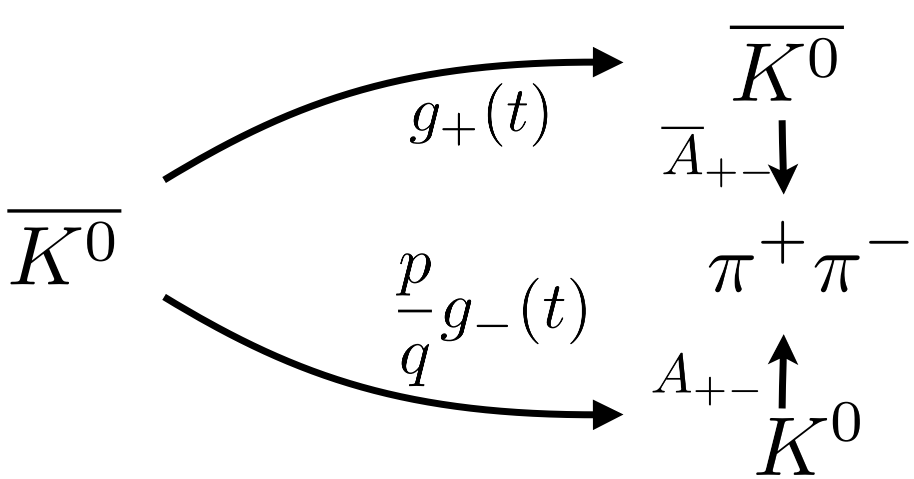
Time evolution (yes, again…)

$$g_{\pm}(t) = \frac{e^{-i\omega_S t} \pm e^{-i\omega_L t}}{2} \qquad \begin{aligned} A_{+-} &\equiv \langle \pi^+\pi^- | K^0 \rangle \\ \overline{A}_{+-} &\equiv \langle \pi^+\pi^- | \overline{K^0} \rangle \end{aligned} \qquad \lambda_{+-} \equiv \frac{q}{p}\frac{\overline{A}_{+-}}{A_{+-}}$$

$t=0$	t	**Rate**



$$\propto |A_{+-}\,[\, g_+(t) + \lambda_{+-} g_-(t) \,]\,|^2$$



$$\propto \left| \overline{A}_{+-} \left[g_+(t) + \frac{1}{\lambda_{+-}} g_-(t) \right] \right|^2$$

Interference!

$$g_\pm(t) = \frac{e^{-i\omega_S t} \pm e^{-i\omega_L t}}{2} \qquad A_{+-} \equiv \langle \pi^+\pi^- | K^0 \rangle \qquad \overline{A}_{+-} \equiv \left\langle \pi^+\pi^- | \overline{K^0} \right\rangle \qquad \lambda_{+-} \equiv \frac{q}{p}\frac{\overline{A}_{+-}}{A_{+-}}$$

$$\Gamma\left(K^0 \to \pi^+\pi^-\right) \propto |A_{+-}|^2 \left[|g_+(t)|^2 + |\lambda_{+-}|^2 |g_-(t)|^2 + 2\mathcal{R}\left(\lambda_{+-} g_+^*(t) g_-(t)\right) \right]$$

$$\Gamma\left(\overline{K^0} \to \pi^+\pi^-\right) \propto \left|\overline{A}_{+-}\right|^2 \left[|g_+(t)|^2 + \frac{1}{|\lambda_{+-}|^2} |g_-(t)|^2 + \frac{2}{|\lambda_{+-}|^2}\mathcal{R}\left(\lambda_{+-}^* g_+^*(t) g_-(t)\right) \right]$$

CP violation: 3 ways

$$g_\pm(t) = \frac{e^{-i\omega_S t} \pm e^{-i\omega_L t}}{2} \qquad \begin{array}{l} A_{+-} \equiv \langle \pi^+\pi^- | K^0 \rangle \\ \overline{A}_{+-} \equiv \left\langle \pi^+\pi^- | \overline{K^0} \right\rangle \end{array} \qquad \lambda_{+-} \equiv \frac{q}{p}\frac{\overline{A}_{+-}}{A_{+-}}$$

$$\Gamma\left(K^0 \to \pi^+\pi^-\right) \propto |A_{+-}|^2 \left[|g_+(t)|^2 + |\lambda_{+-}|^2 |g_-(t)|^2 + 2\mathcal{R}\left(\lambda_{+-} g_+^*(t) g_-(t)\right)\right]$$

$$\Gamma\left(\overline{K^0} \to \pi^+\pi^-\right) \propto \left|\overline{A}_{+-}\right|^2 \left[|g_+(t)|^2 + \frac{1}{|\lambda_{+-}|^2} |g_-(t)|^2 + \frac{2}{|\lambda_{+-}|^2}\mathcal{R}\left(\lambda_{+-}^* g_+^*(t) g_-(t)\right)\right]$$

1. CP violation in **decay**: $\left|\frac{\overline{A}_{\overline{f}}}{A_f}\right| \neq 1$

both neutral and charged mesons

CP violation: 3 ways

$$g_\pm(t) = \frac{e^{-i\omega_S t} \pm e^{-i\omega_L t}}{2} \qquad A_{+-} \equiv \langle \pi^+\pi^- | K^0 \rangle \quad \overline{A}_{+-} \equiv \left\langle \pi^+\pi^- | \overline{K^0} \right\rangle \qquad \lambda_{+-} \equiv \frac{q}{p}\frac{\overline{A}_{+-}}{A_{+-}}$$

$$\Gamma\left(K^0 \to \pi^+\pi^-\right) \propto |A_{+-}|^2 \left[|g_+(t)|^2 + |\lambda_{+-}|^2 |g_-(t)|^2 + 2\mathcal{R}\left(\lambda_{+-} g_+^*(t) g_-(t)\right) \right]$$

$$\Gamma\left(\overline{K^0} \to \pi^+\pi^-\right) \propto \left|\overline{A}_{+-}\right|^2 \left[|g_+(t)|^2 + \frac{1}{|\lambda_{+-}|^2} |g_-(t)|^2 + \frac{2}{|\lambda_{+-}|^2}\mathcal{R}\left(\lambda_{+-}^* g_+^*(t) g_-(t)\right) \right]$$

1. CP violation in **decay**: $\left|\frac{\overline{A}_{\overline{f}}}{A_f}\right| \neq 1$

both neutral and charged mesons

2. CP violation in **mixing**: $\left|\frac{q}{p}\right| \neq 1$

only neutral mesons

CP violation: 3 ways

$$g_\pm(t) = \frac{e^{-i\omega_S t} \pm e^{-i\omega_L t}}{2} \qquad A_{+-} \equiv \langle \pi^+\pi^- | K^0 \rangle \quad \overline{A}_{+-} \equiv \langle \pi^+\pi^- | \overline{K^0} \rangle \qquad \lambda_{+-} \equiv \frac{q}{p}\frac{\overline{A}_{+-}}{A_{+-}}$$

$$\Gamma\left(K^0 \to \pi^+\pi^-\right) \propto |A_{+-}|^2 \left[|g_+(t)|^2 + |\lambda_{+-}|^2 |g_-(t)|^2 + 2\mathcal{R}\left(\lambda_{+-} g_+^*(t) g_-(t)\right) \right]$$

$$\Gamma\left(\overline{K^0} \to \pi^+\pi^-\right) \propto |\overline{A}_{+-}|^2 \left[|g_+(t)|^2 + \frac{1}{|\lambda_{+-}|^2} |g_-(t)|^2 + \frac{2}{|\lambda_{+-}|^2}\mathcal{R}\left(\lambda_{+-}^* g_+^*(t) g_-(t)\right) \right]$$

1. CP violation in **decay**: $\left|\frac{\overline{A}_{\overline{f}}}{A_f}\right| \neq 1$

both neutral and charged mesons

2. CP violation in **mixing**: $\left|\frac{q}{p}\right| \neq 1$

only neutral mesons

3. CP violation in **interference**: $\mathcal{I}(\lambda_f) = \mathcal{I}\left(\frac{q}{p}\frac{\overline{A}_f}{A_f}\right) \neq 0$

only neutral mesons decaying to CP eigenstates

Interference!

$$\eta_{+-} = \frac{1-\lambda}{1+\lambda} = \frac{pA - q\bar{A}}{pA + q\bar{A}} = \frac{\langle \pi^+\pi^- | K_L \rangle}{\langle \pi^+\pi^- | K_S \rangle} \qquad \eta_{+-} = |\eta_{+-}| e^{i\phi_{+-}} \qquad \lambda_{+-} \equiv \frac{q}{p}\frac{\overline{A}_{+-}}{A_{+-}}$$

$$\Gamma\left(K^0 \to \pi^+\pi^-\right) = N\left[e^{-\Gamma_S t} + |\eta_{+-}|^2 e^{-\Gamma_L t} + 2e^{-\Gamma t}|\eta_{+-}|\cos\left(\Delta m t - \phi_{+-}\right)\right]$$

$$\Gamma\left(\overline{K^0} \to \pi^+\pi^-\right) = \overline{N}\left[e^{-\Gamma_S t} + |\eta_{+-}|^2 e^{-\Gamma_L t} - 2e^{-\Gamma t}|\eta_{+-}|\cos\left(\Delta m t - \phi_{+-}\right)\right]$$

K_S $\qquad$ K_L $\qquad$ K_S-K_L interference

$$\mathcal{A} = \frac{\Gamma\left(K^0 \to \pi + \pi-\right) - \Gamma\left(\overline{K^0} \to \pi + \pi-\right)}{\Gamma\left(K^0 \to \pi + \pi-\right) + \Gamma\left(\overline{K^0} \to \pi + \pi-\right)}$$

$$\mathcal{A} \propto \left[\cos(\Delta m t)\cos\phi_{+-} + \sin(\Delta m t)\sin\phi_{+-}\right]$$

Time-dependent CP asymmetry

Interference!

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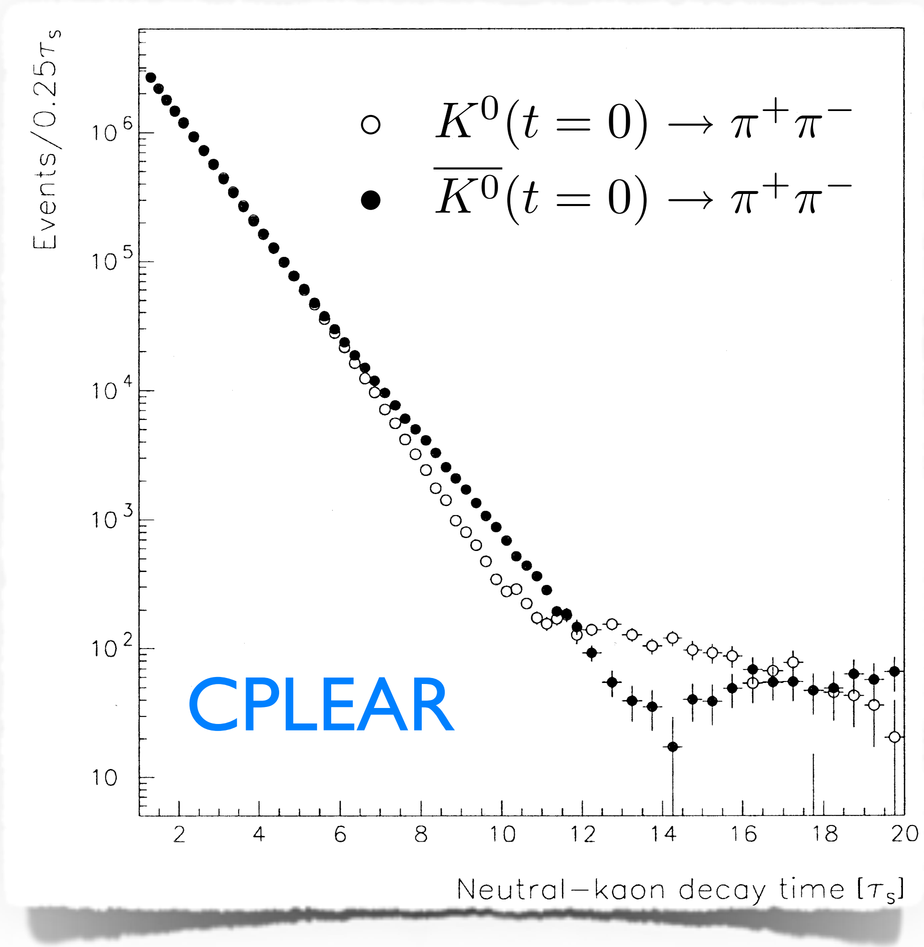

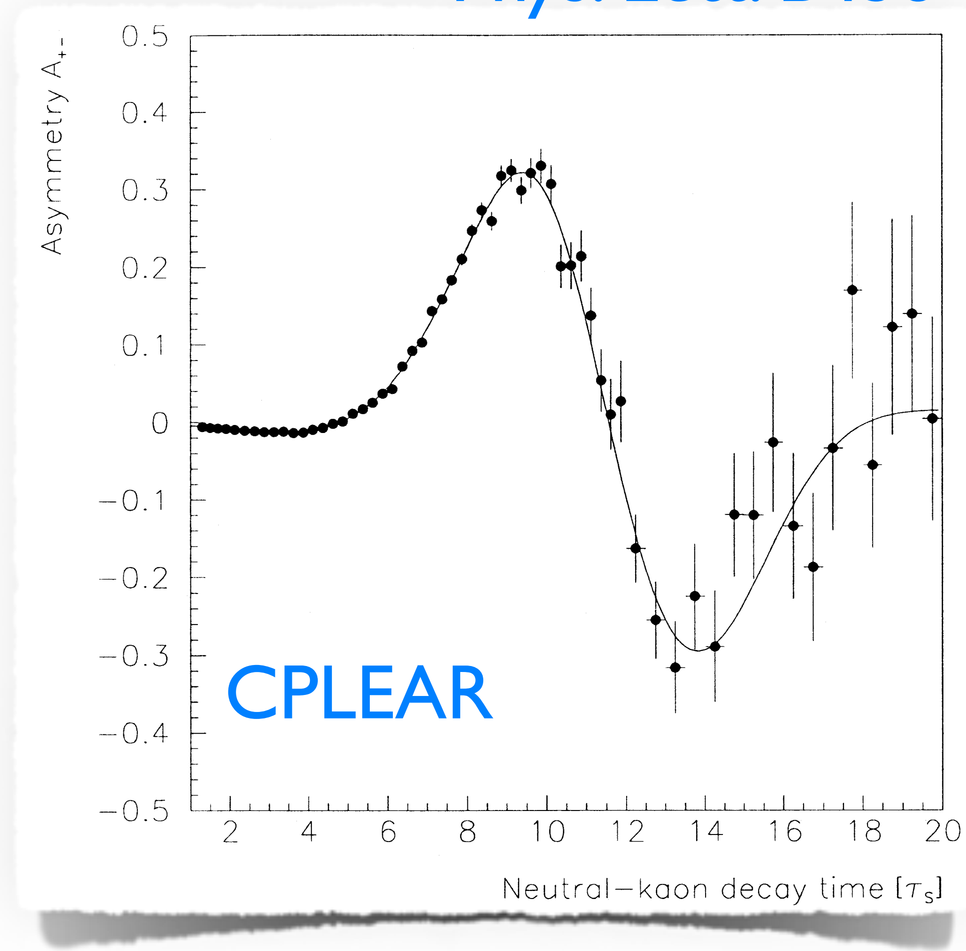

$$\mathcal{A} = \frac{\Gamma\left(K^0 \to \pi + \pi -\right) - \Gamma\left(\overline{K^0} \to \pi + \pi -\right)}{\Gamma\left(K^0 \to \pi + \pi -\right) + \Gamma\left(\overline{K^0} \to \pi + \pi -\right)}$$

$$\mathcal{A} \propto [\cos(\Delta m t)\cos\phi_{+-} + \sin(\Delta m t)\sin\phi_{+-}]$$

Time-dependent CP asymmetry

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
- ★ CP is broken!
- ★ Observed CP violation in K mixing; no evidence so far for B mesons (neither for D mesons).
- ★ We can measure CP violation in 3 ways: decays, mixing, interference
- ★ (time-dependent) CP in interference allows to measure phases (difference)