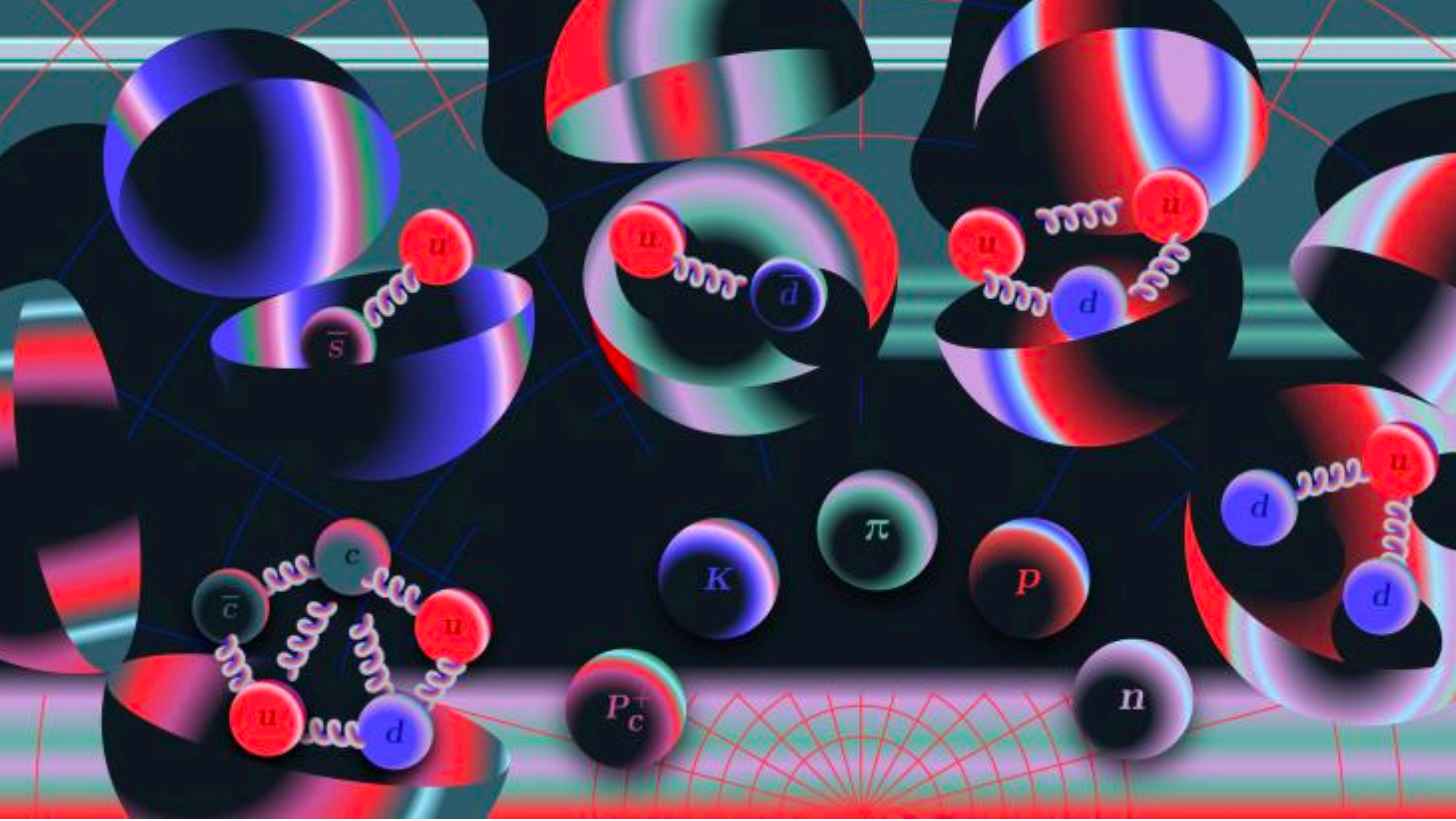


Measuring CP-violating phase ϕ_s

Lera Lukashenko

Nikhef Junior Colloquium

Nikhef

PhDs care about details. Old farts, like me, don’t.

Anonymous Nikhef Senior

PDF in details

$$E_\pm = \frac{1}{2}\left[e^{+i\omega t} \pm e^{-i\omega t}\right] \quad \text{with } \omega = \frac{\Delta m}{2} + i\frac{\Delta\Gamma}{4} \tag{1}$$

$$|E_\pm(t)|^2 = \frac{1}{2}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) \pm \cos(\Delta m t)\right] \tag{2}$$

$$E_+^*(t)E_-(t) = \frac{1}{2}\left[-\sinh\left(\frac{\Delta\Gamma}{2}t\right) + i\sin(\Delta m t)\right] \tag{3}$$

$$|\mathcal{A}_i(t)|^2 = \mathcal{A}_i^*(t)\mathcal{A}_i(t) \quad (\text{note : no summation!}) \tag{4}$$

$$\mathcal{A}_i^*(t)\mathcal{A}_j(t) = \frac{a_i^* a_j e^{-t/\tau}}{1+C}\Big[(1+C)|E_+(t)|^2 + \eta_i\eta_j(1-C)|E_-(t)|^2 - \eta_j(D+iS)E_+^*E_- - \eta_i(D-iS)E_+E_-^*\Big] \tag{5}$$

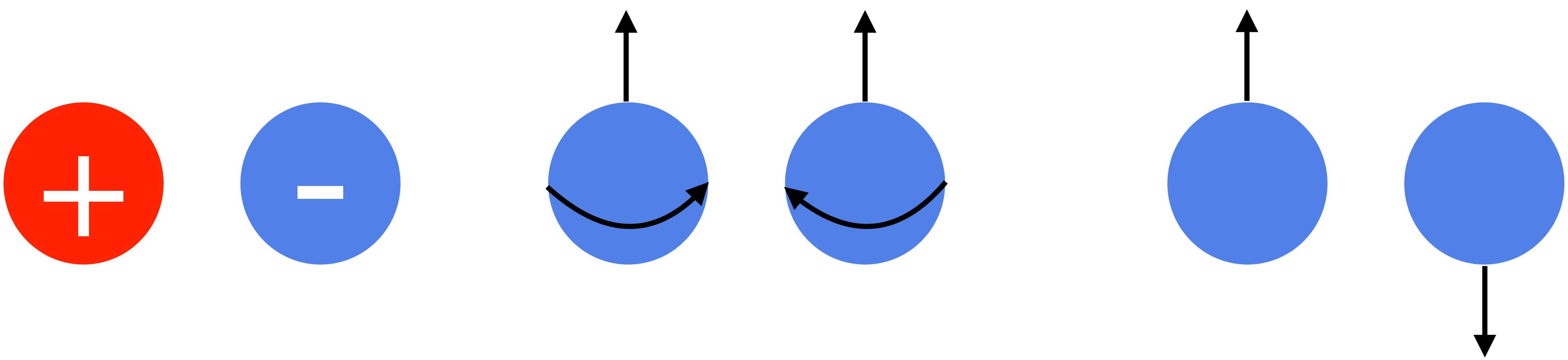
$$= \frac{a_i^* a_j e^{-t/\tau}}{1+C}\Bigg[\left(\frac{1+\eta_i\eta_j}{2} + \frac{1-\eta_i\eta_j}{2}C\right)\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \left(\frac{1-\eta_i\eta_j}{2} + \frac{1+\eta_i\eta_j}{2}C\right)\cos(\Delta m t) + \left(\frac{\eta_i+\eta_j}{2}D - \frac{\eta_i-\eta_j}{2}iS\right)\sinh\left(\frac{\Delta\Gamma}{2}t\right) + \left(\frac{\eta_i+\eta_j}{2}S + \frac{\eta_i-\eta_j}{2}iD\right)\sin(\Delta m t)\Bigg] \tag{6}$$

$q_T=+1$	$q_T=-1$		$\cosh\left(\frac{\Delta\Gamma}{2}t\right)$	$q_T\cos(\Delta m t)$	$\sinh\left(\frac{\Delta\Gamma}{2}t\right)$	$q_T\sin(\Delta m t)$
$\lvert\mathcal{A}_0(t)\rvert^2$		$\frac{\lvert a_0\rvert^2 e^{-t/\tau}}{1+q_T C}$	1	C	D	S
$\lvert\mathcal{A}_\parallel(t)\rvert^2$		$\frac{\lvert a_\parallel\rvert^2 e^{-t/\tau}}{1+q_T C}$	1	C	D	S
$\lvert\mathcal{A}_\perp(t)\rvert^2$		$\frac{\lvert a_\perp\rvert^2 e^{-t/\tau}}{1+q_T C}$	1	C	$-D$	$-S$
$\Im(\mathcal{A}_\parallel^*(t)\mathcal{A}_\perp(t))$		$\frac{\Re(a_\parallel^* a_\perp)e^{-t/\tau}}{1+q_T C}$	0	0	$-S$	D
		$\frac{\Im(a_\parallel^* a_\perp)e^{-t/\tau}}{1+q_T C}$	C	1	0	0
$\Re(\mathcal{A}_0^*(t)\mathcal{A}_\parallel(t))$		$\frac{\Re(a_0^* a_\parallel)e^{-t/\tau}}{1+q_T C}$	1	C	D	S
		$\frac{\Im(a_0^* a_\parallel)e^{-t/\tau}}{1+q_T C}$	0	0	0	0
$\Im(\mathcal{A}_0^*(t)\mathcal{A}_\perp(t))$		$\frac{\Re(a_0^* a_\perp)e^{-t/\tau}}{1+q_T C}$	0	0	$-S$	D
		$\frac{\Im(a_0^* a_\perp)e^{-t/\tau}}{1+q_T C}$	C	1	0	0
$\lvert\mathcal{A}_S(t)\rvert^2$		$\frac{\lvert a_S\rvert^2 e^{-t/\tau}}{1+q_T C}$	1	C	$-D$	$-S$
$\Re(\mathcal{A}_S^*(t)\mathcal{A}_\parallel(t))$		$\frac{\Re(a_S^* a_\parallel)e^{-t/\tau}}{1+q_T C}$	C	1	0	0
		$\frac{\Im(a_S^* a_\parallel)e^{-t/\tau}}{1+q_T C}$	0	0	$-S$	D
$\Im(\mathcal{A}_S^*(t)\mathcal{A}_\perp(t))$		$\frac{\Re(a_S^* a_\perp)e^{-t/\tau}}{1+q_T C}$	0	0	0	0
		$\frac{\Im(a_S^* a_\perp)e^{-t/\tau}}{1+q_T C}$	1	C	$-D$	$-S$
$\Re(\mathcal{A}_S^*(t)\mathcal{A}_0(t))$		$\frac{\Re(a_S^* a_0)e^{-t/\tau}}{1+q_T C}$	C	1	0	0
		$\frac{\Im(a_S^* a_0)e^{-t/\tau}}{1+q_T C}$	0	0	$-S$	D

$$\begin{aligned}
|\mathbf{A}(t)\wedge\hat{n}|^2 = {} & \frac{1}{2}|\mathcal{A}_\parallel(t)|^2\sin^2\psi\cos^2\theta + \frac{1}{2}|\mathcal{A}_\perp(t)|^2\sin^2\psi\sin^2\theta\sin^2\phi \\
& + - \Im(\mathcal{A}_\parallel^*(t)\mathcal{A}_\perp(t))\sin^2\psi\cos\theta\sin\theta\sin\phi \\
+ {} & |\mathcal{A}_0(t)|^2\cos^2\psi\cos^2\theta + \frac{1}{2}|\mathcal{A}_\perp(t)|^2\sin^2\psi\sin^2\theta\cos^2\phi \\
& + - \sqrt{2}\Im(\mathcal{A}_\perp^*(t)\mathcal{A}_0(t))\cos\psi\cos\theta\sin\psi\sin\theta\cos\phi \\
+ {} & |\mathcal{A}_0(t)|^2\cos^2\psi\sin^2\theta\sin^2\phi + \frac{1}{2}|\mathcal{A}_\parallel(t)|^2\sin^2\psi\sin^2\theta\cos^2\phi \\
& + \sqrt{2}\Re(\mathcal{A}_0^*(t)\mathcal{A}_\parallel(t))\cos\psi\sin\psi\sin^2\theta\sin\phi\cos\phi \\
= {} & |\mathcal{A}_0(t)|^2\cos^2\psi\left(\cos^2\theta + \sin^2\theta\sin^2\phi\right) \\
+ {} & \frac{1}{2}|\mathcal{A}_\parallel(t)|^2\sin^2\psi\left(\cos^2\theta + \sin^2\theta\cos^2\phi\right) \\
+ {} & \frac{1}{2}|\mathcal{A}_\perp(t)|^2\sin^2\psi\sin^2\theta \\
+ {} & -\Im(\mathcal{A}_\parallel^*(t)\mathcal{A}_\perp(t))\sin^2\psi\cos\theta\sin\theta\sin\phi \\
+ {} & -\sqrt{2}\Im(\mathcal{A}_\perp^*(t)\mathcal{A}_0(t))\cos\psi\cos\theta\sin\psi\sin\theta\cos\phi \\
+ {} & \sqrt{2}\Re(\mathcal{A}_0^*(t)\mathcal{A}_\parallel(t))\cos\psi\sin\psi\sin^2\theta\sin\phi\cos\phi \\
= {} & \frac{1}{2}|\mathcal{A}_\parallel(t)|^2\sin^2\psi\left(1 - \sin^2\theta\sin^2\phi\right) \\
+ {} & \frac{1}{2}|\mathcal{A}_\perp(t)|^2\sin^2\psi\sin^2\theta \\
+ {} & |\mathcal{A}_0(t)|^2\cos^2\psi\left(1 - \sin^2\theta\cos^2\phi\right) \\
+ {} & -\frac{1}{2}\Im(\mathcal{A}_\parallel^*(t)\mathcal{A}_\perp(t))\sin^2\psi\sin(2\theta)\sin\phi \\
+ {} & \frac{1}{2\sqrt{2}}\Im(\mathcal{A}_0^*(t)\mathcal{A}_\perp(t))\sin(2\psi)\sin(2\theta)\cos\phi \\
+ {} & \frac{1}{2\sqrt{2}}\Re(\mathcal{A}_0^*(t)\mathcal{A}_\parallel(t))\sin(2\psi)\sin^2\theta\sin(2\phi)
\end{aligned} \tag{7}$$

Physics laws are the same everywhere and always

C	P	T
charge	parity	time



*This is not a product placement

CP-conservation

matter $C\times$

$P\times$

anti-matter

*This is not a product placement

CP-violation

matter

$C\times$

$P\times$

anti-matter

matter - anti-matter asymmetry is $\sim \mathcal{O}(10^{-10})$

Sakharov conditions for baryogenesis

1. Baryon number violation
2. Interactions out of thermal equilibrium
3. C- and CP-violation

in SM

But only 10^{-20} from SM quark sector CPV

Sakharov, A. D., *JETP Letters,* 5 (1967) 32-35

ϕ_s : amount of mixing induced CP-violation in B_s^0

$$\phi_s = \phi_s^{SM} + \phi_s^{NP}$$

Hard to compute in SM

$$\phi_s^{SM} = \phi_s^{LO} + \Delta\phi_s^{HO}$$

But there is a decay where $\Delta\phi_s^{HO}$ suppressed by a factor of 0.05

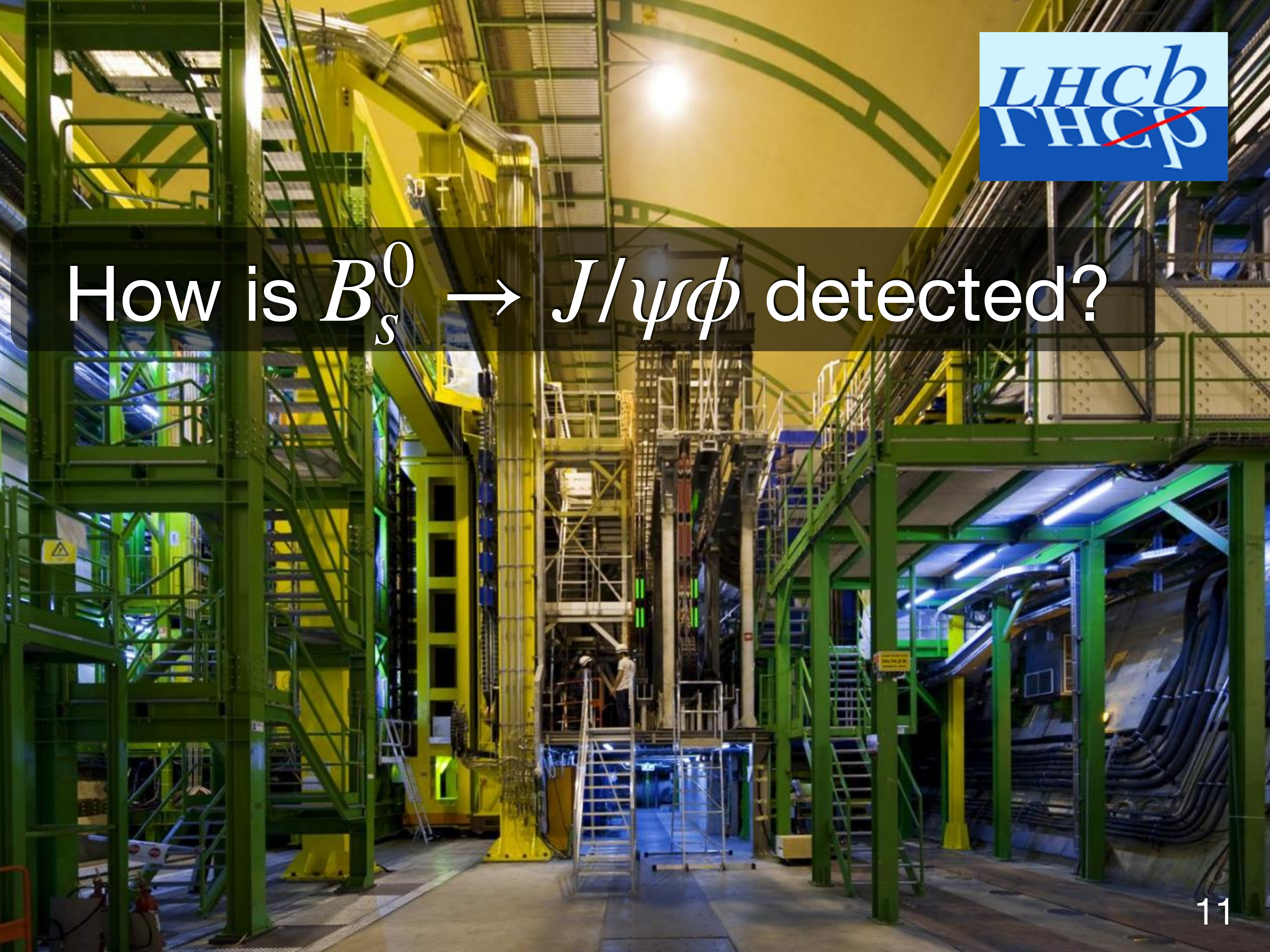
M.Z.Barel, K.DeBruyn, R.Fleischer, E.Malami, J.Phys. G (2021) 48: 6

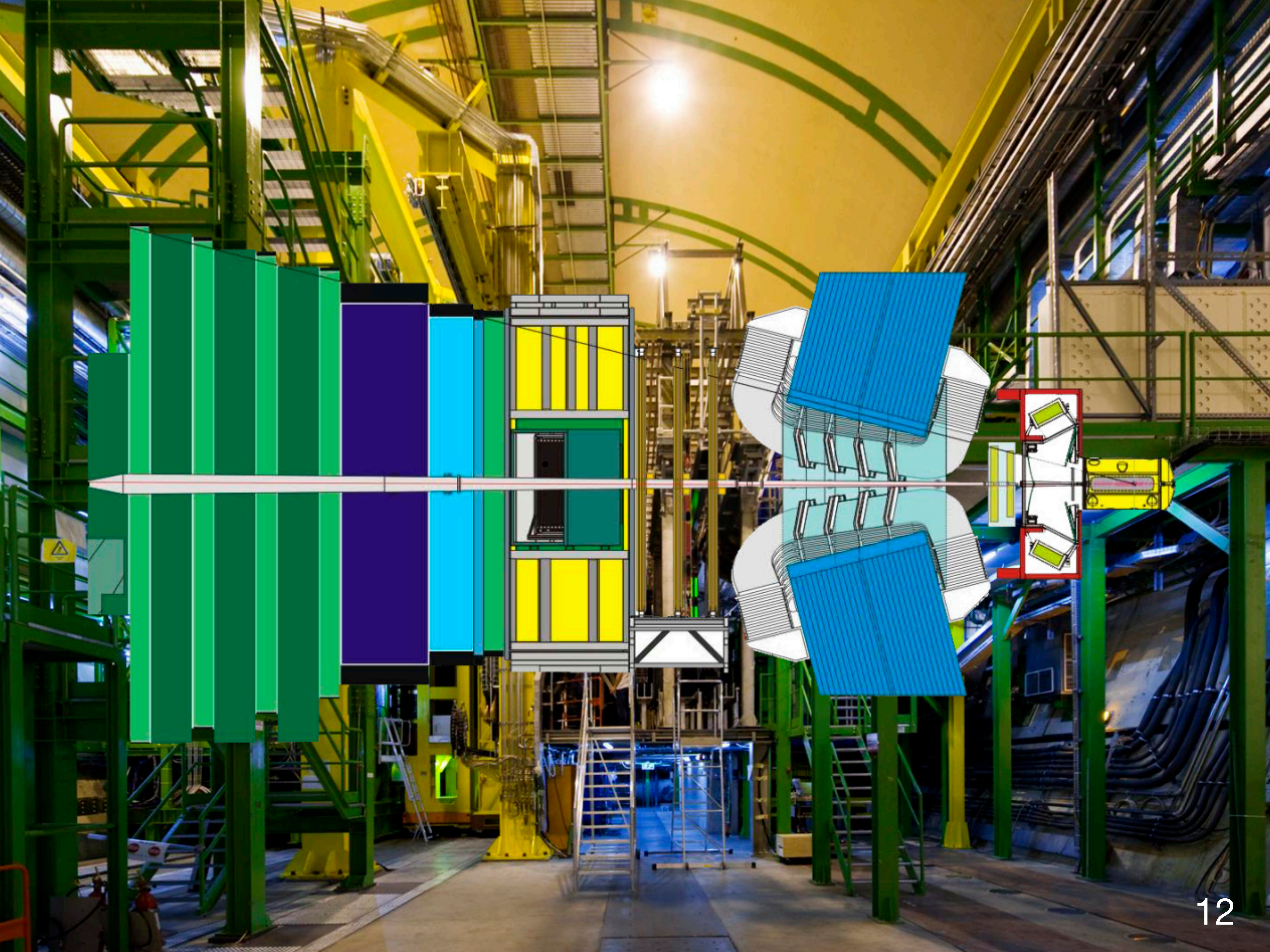
"golden mode"

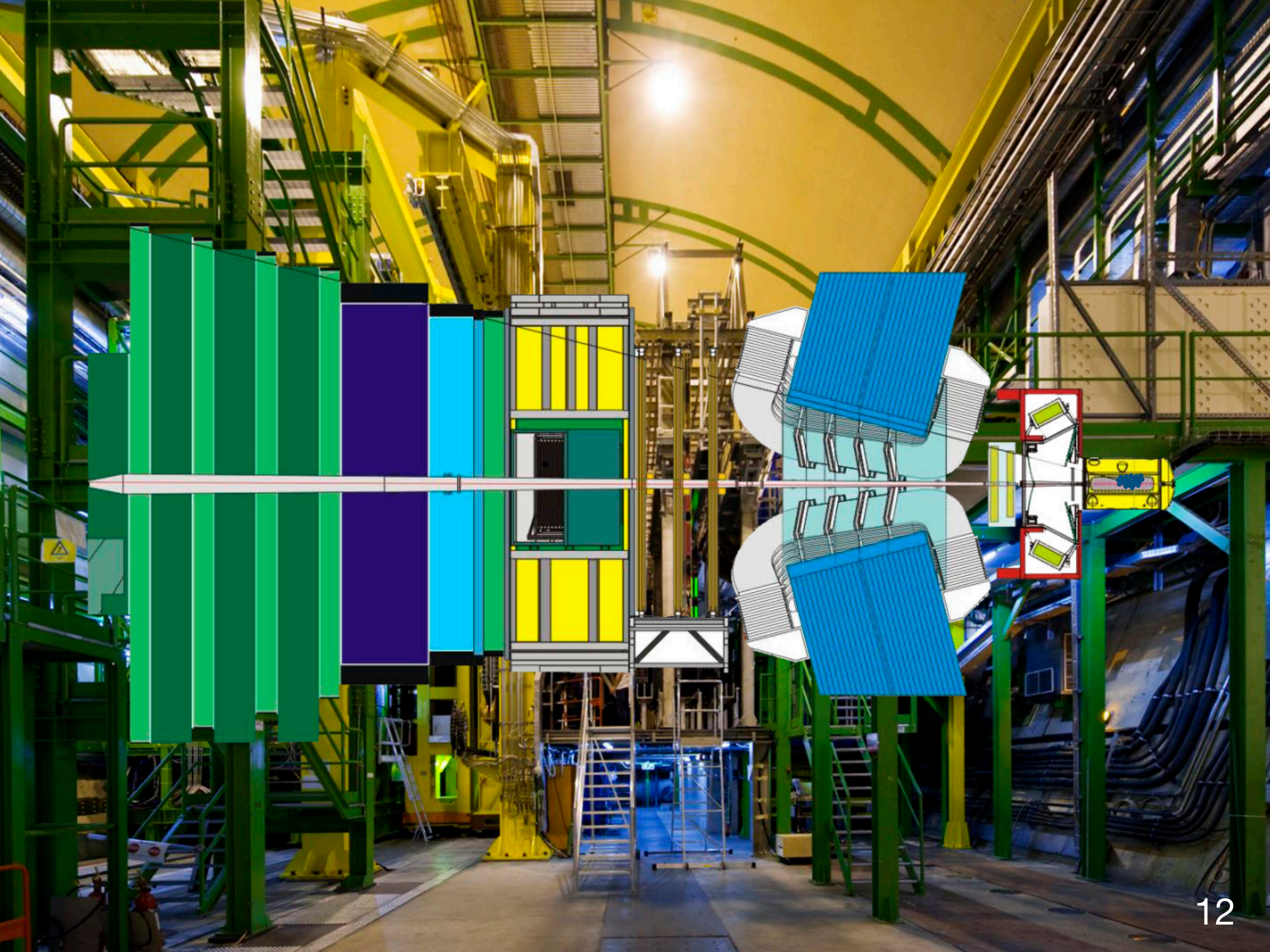
$$B_s^0 \to J/\psi\ \phi(1020)$$

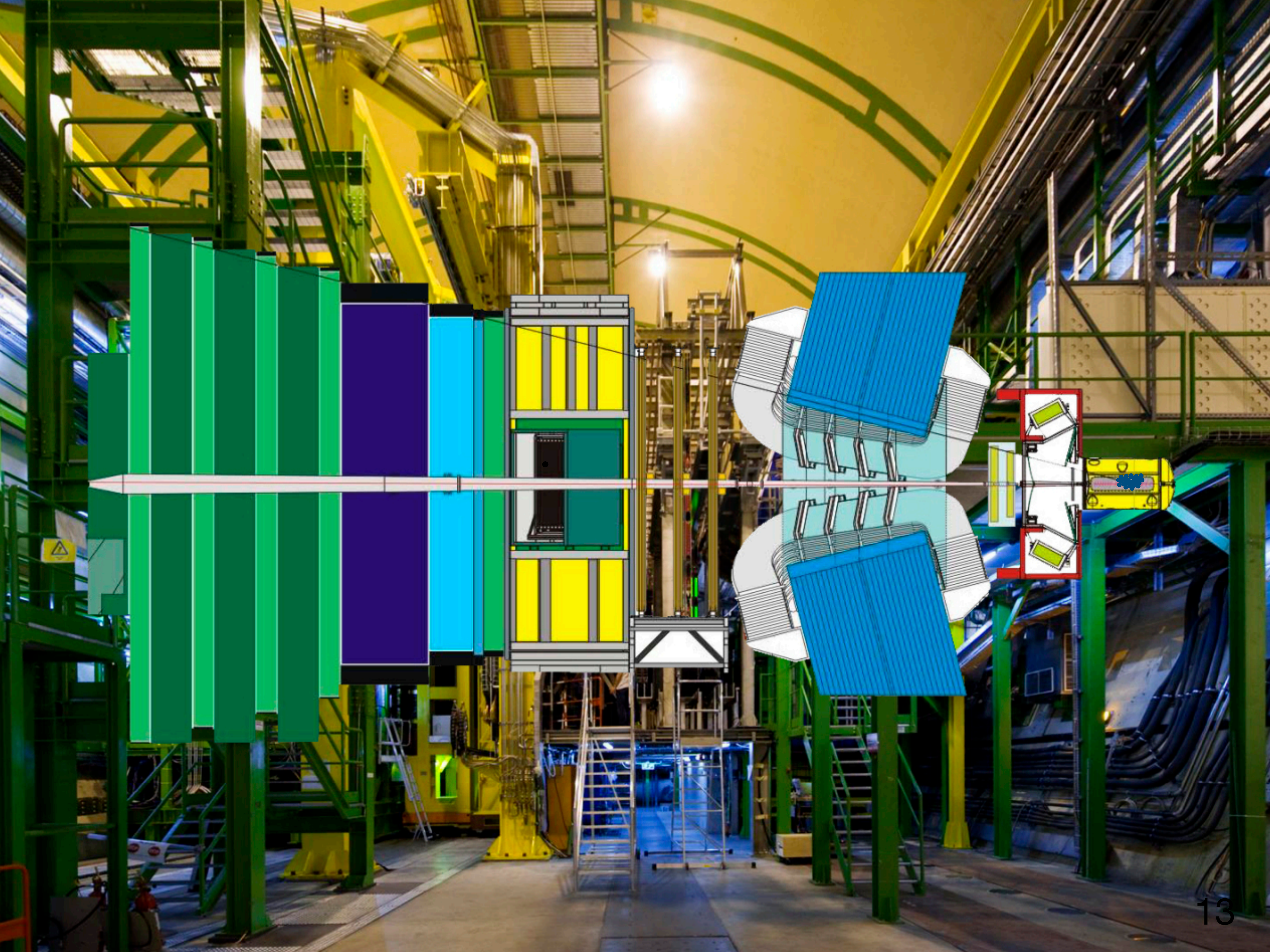
$J/\psi \to \mu^+\mu^-$, $\phi(1020) \to K^+K^-$

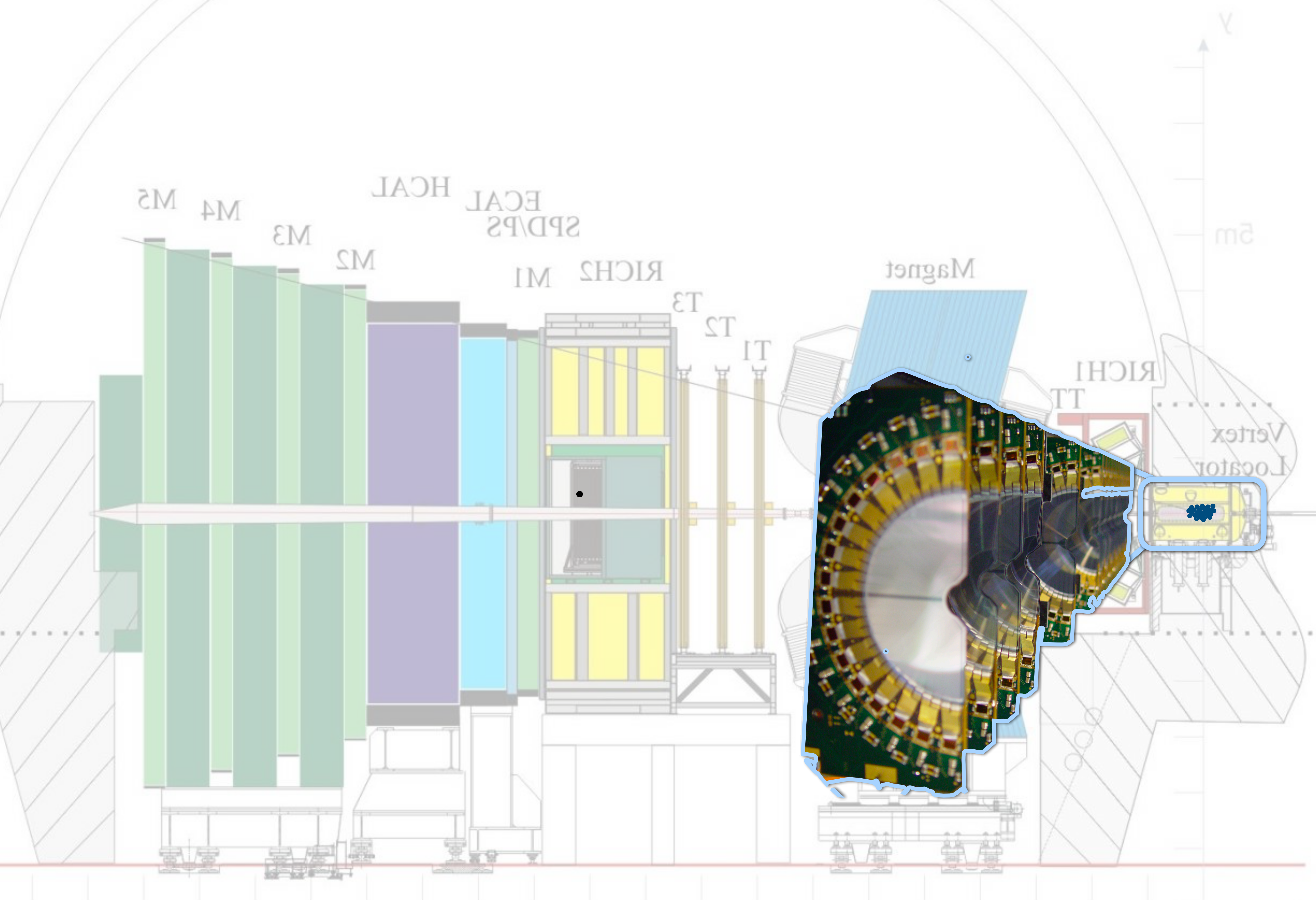
How is $B_s^0 \to J/\psi\phi$ detected?

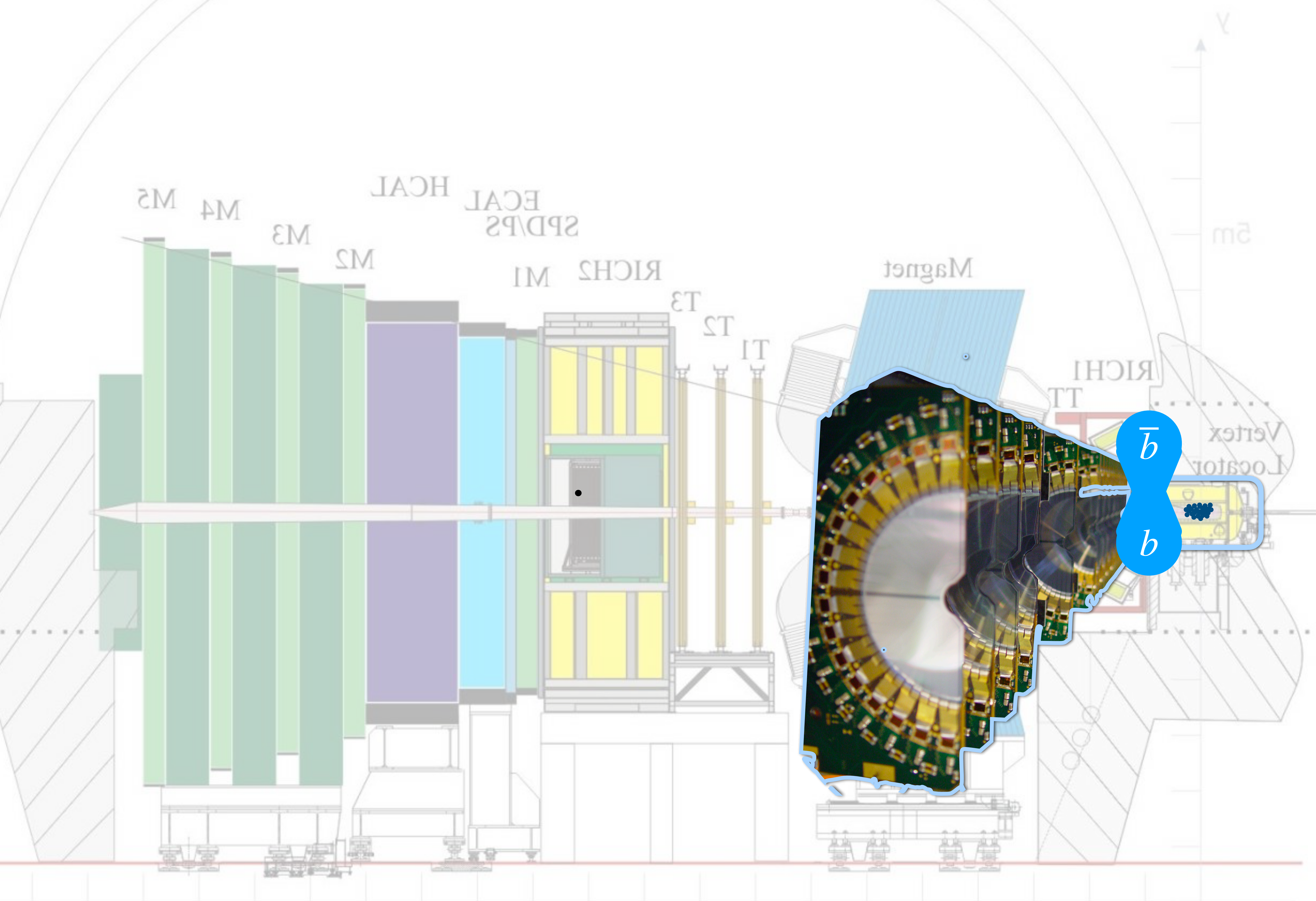


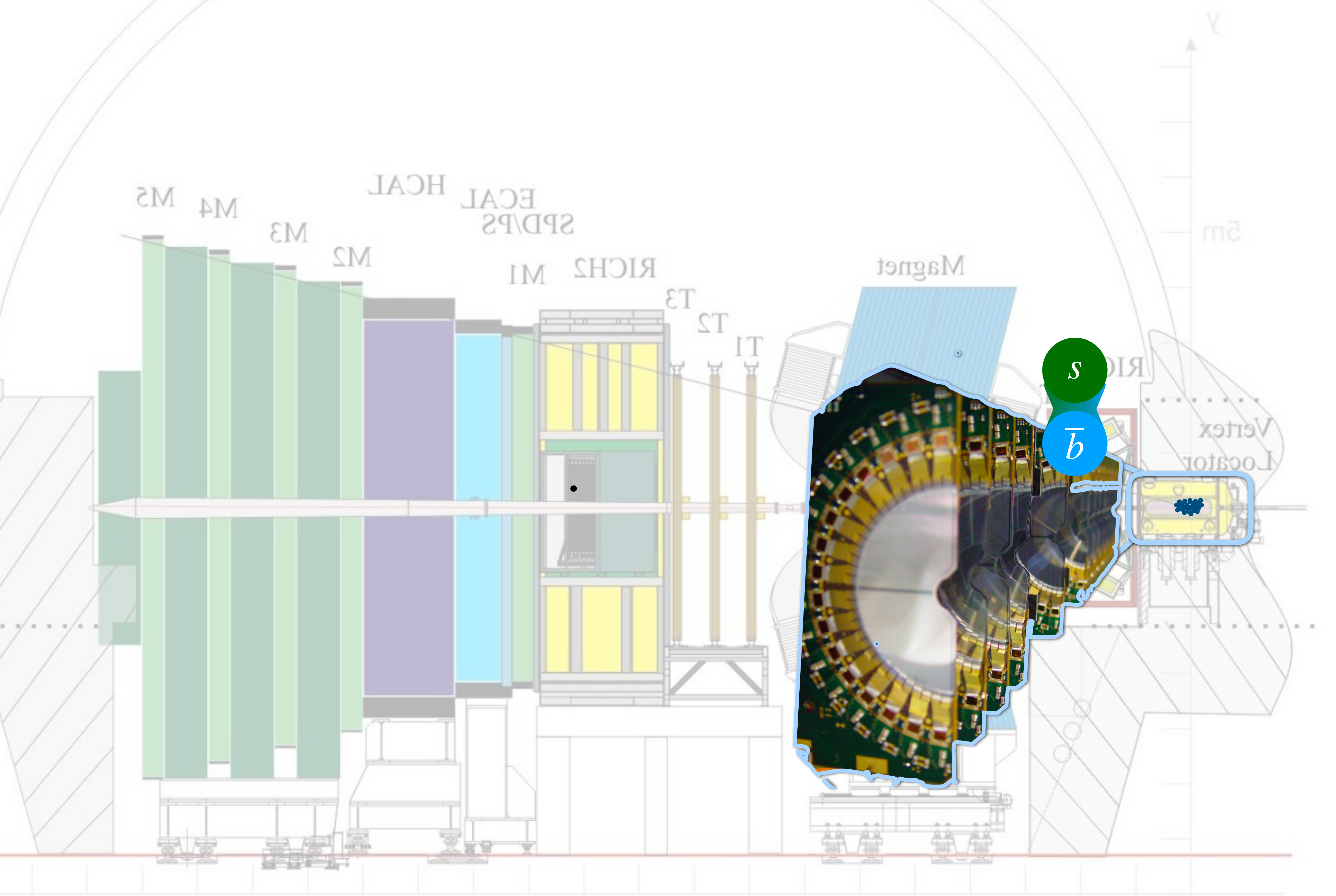


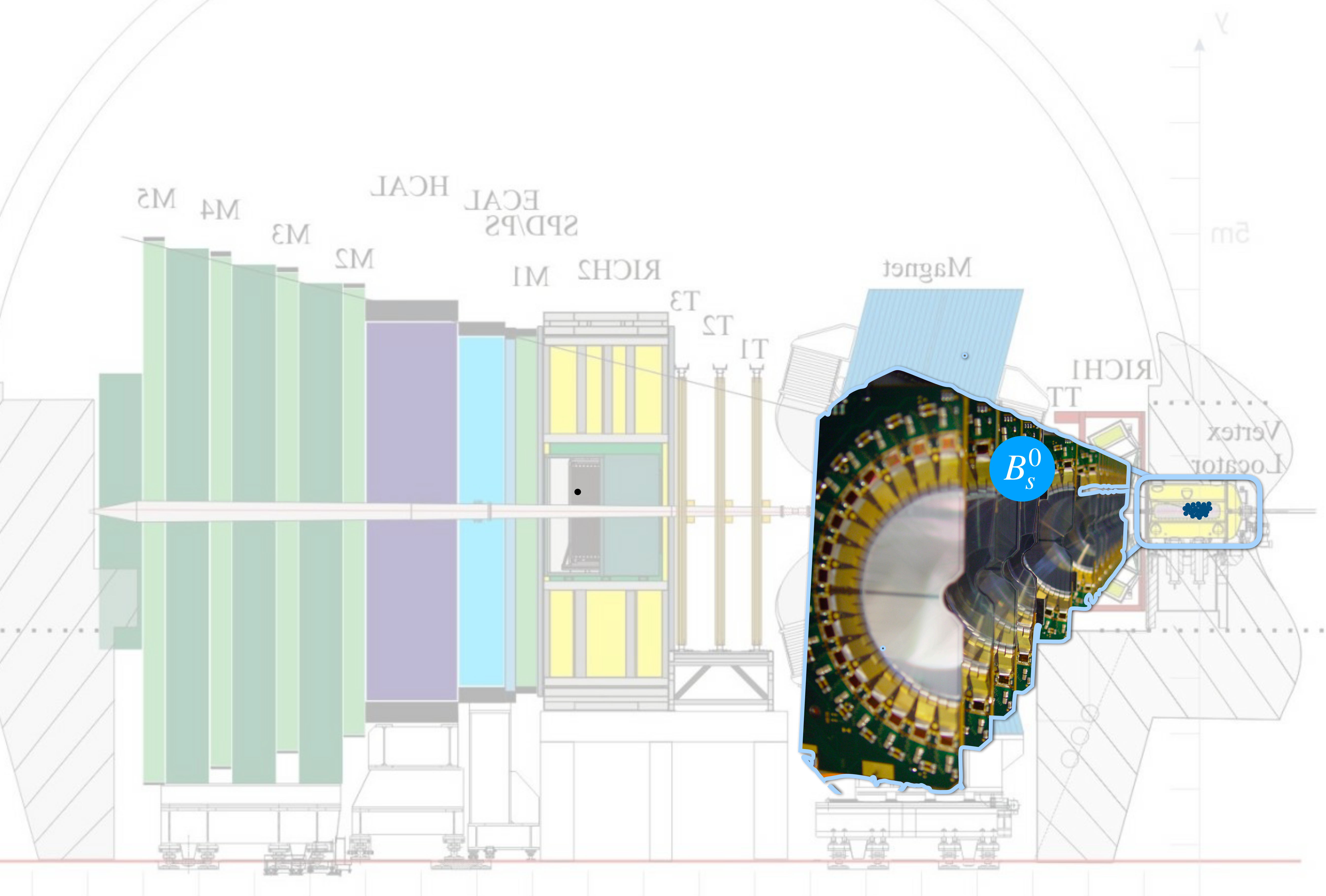


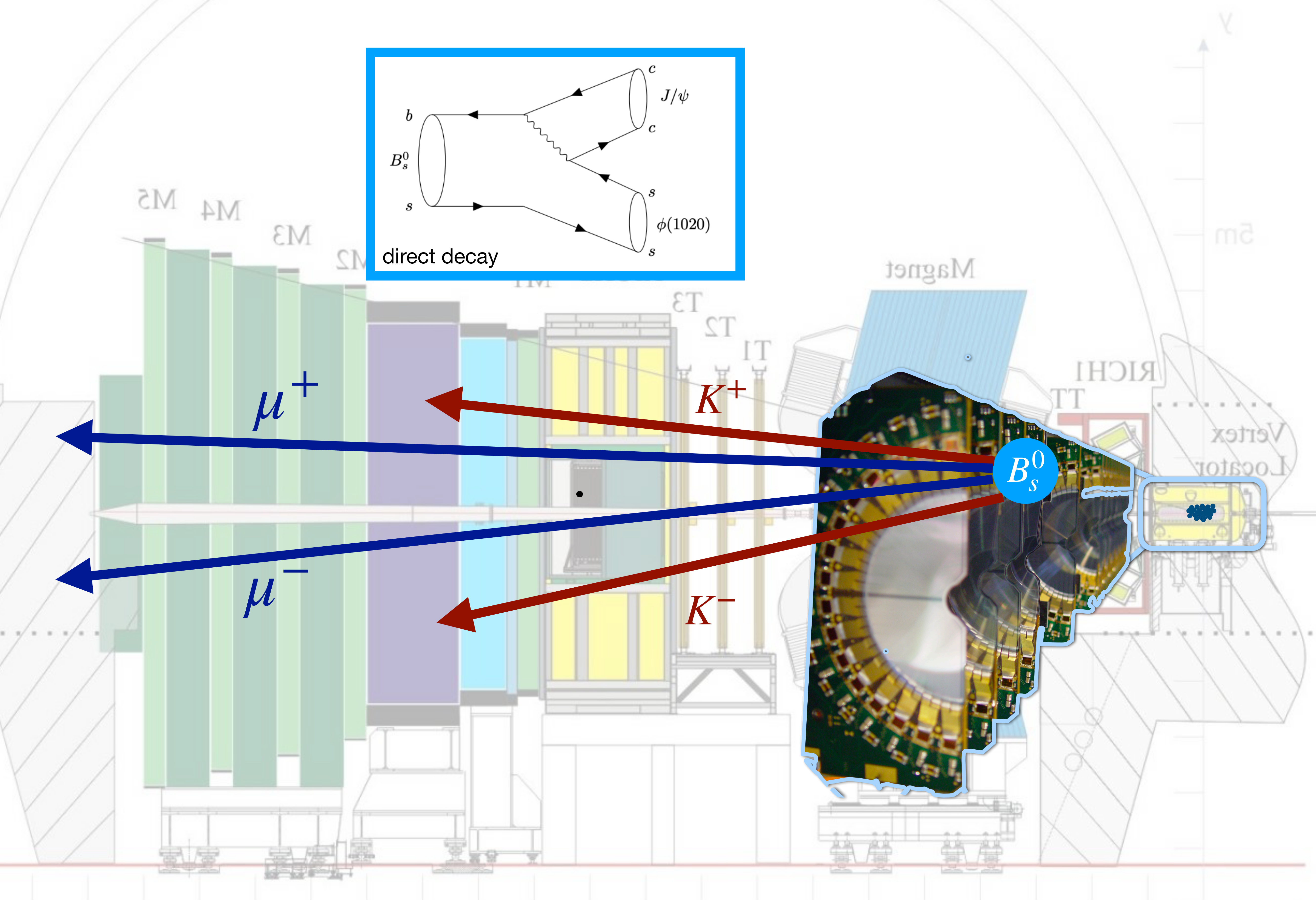


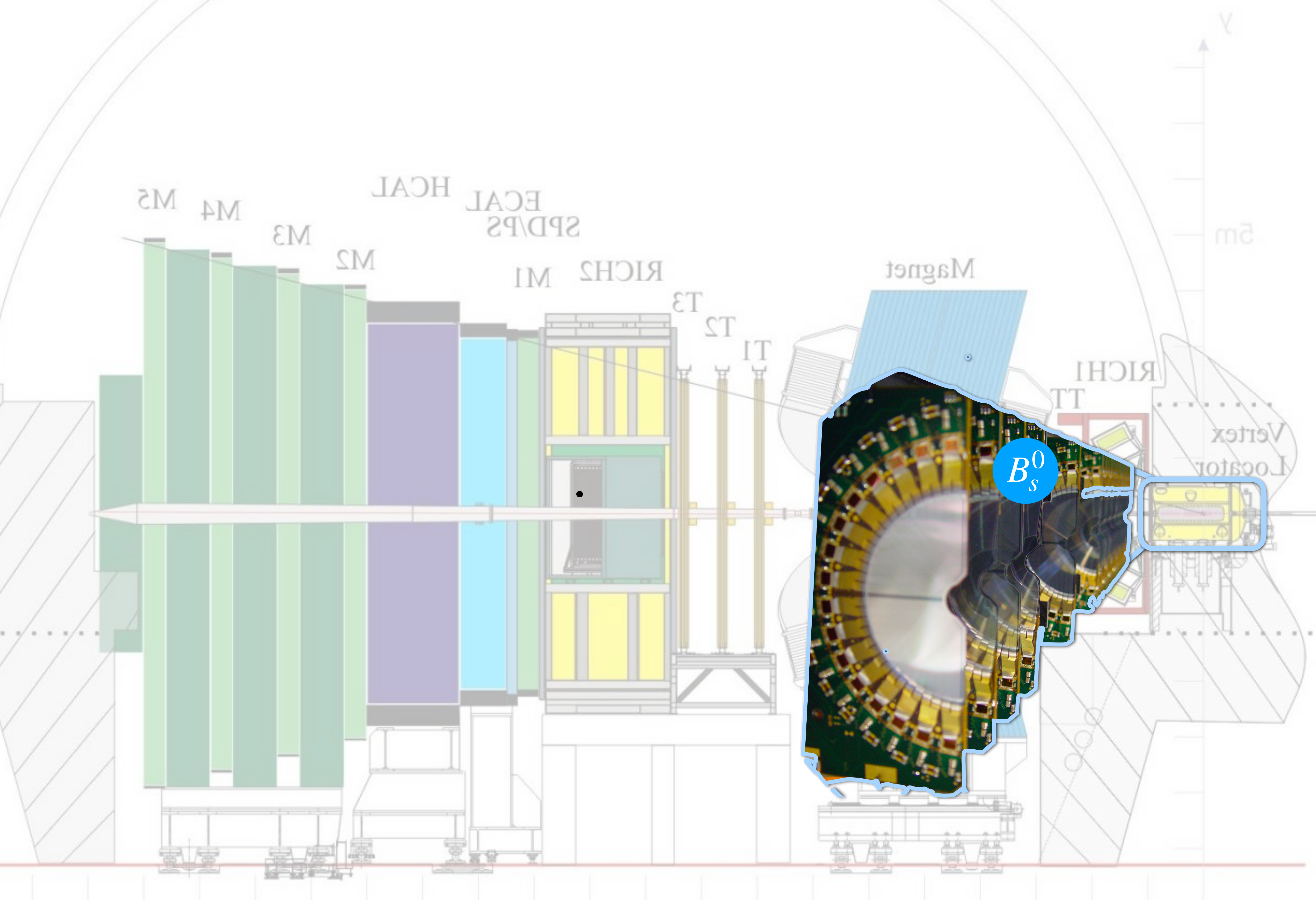

M5
M4
M3
M2
HCAL
ECAL
SPD/PS
M1
RICH2
T3
T2
T1
Magnet
RICH1
TT
Vertex
Locator
5m
y

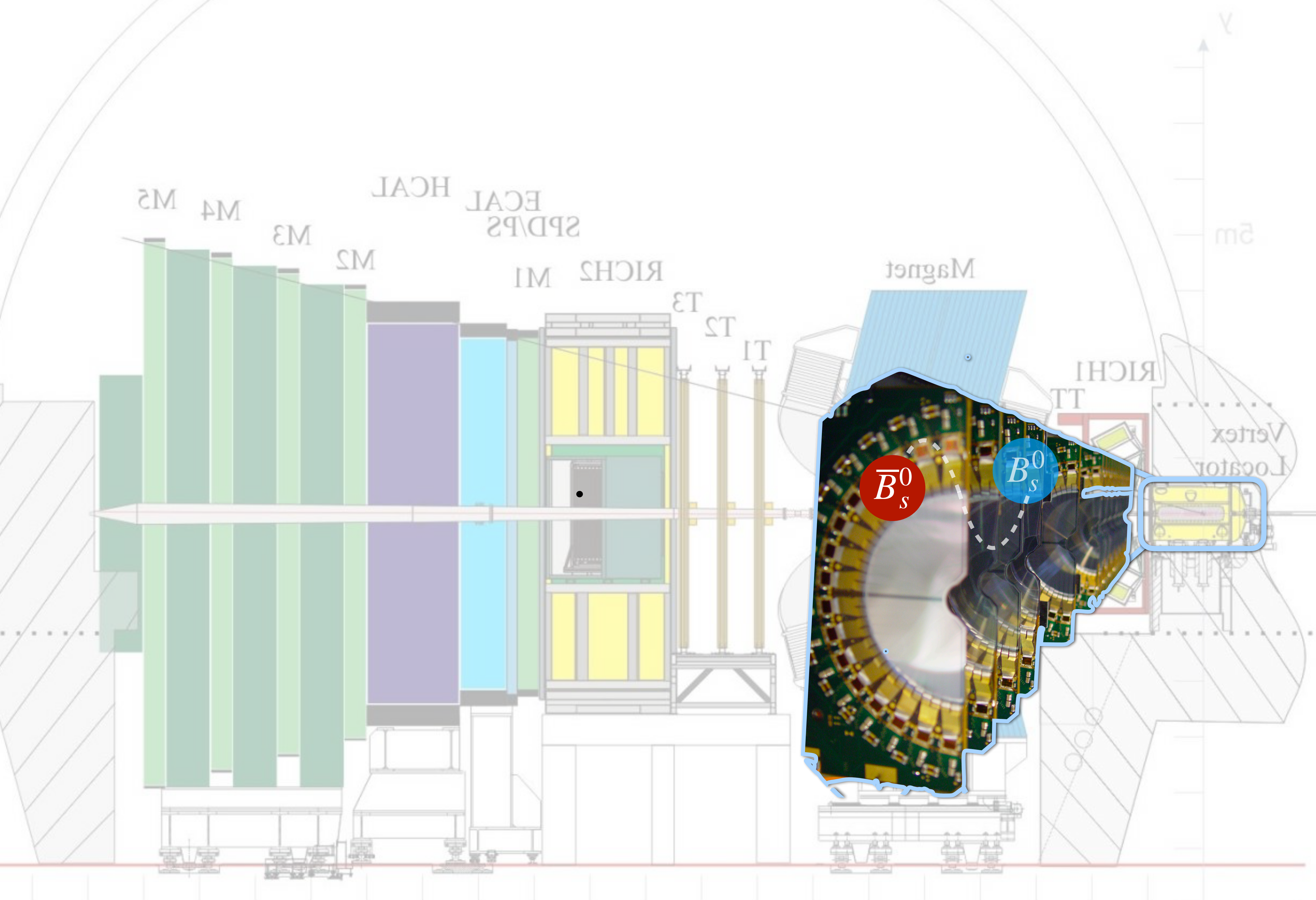

M5
M4
M3
M2
HCAL
ECAL
SPD/PS
M1
RICH2
T3
T2
T1
Magnet
RICH1
TT
Vertex
Locator
5m
y
$\bar{b}$
b


M5
M4
M3
M2
HCAL
ECAL
SPD/PS
M1
RICH2
T3
T2
T1
Magnet
Vertex
Locator
5m
s
$\overline{b}$

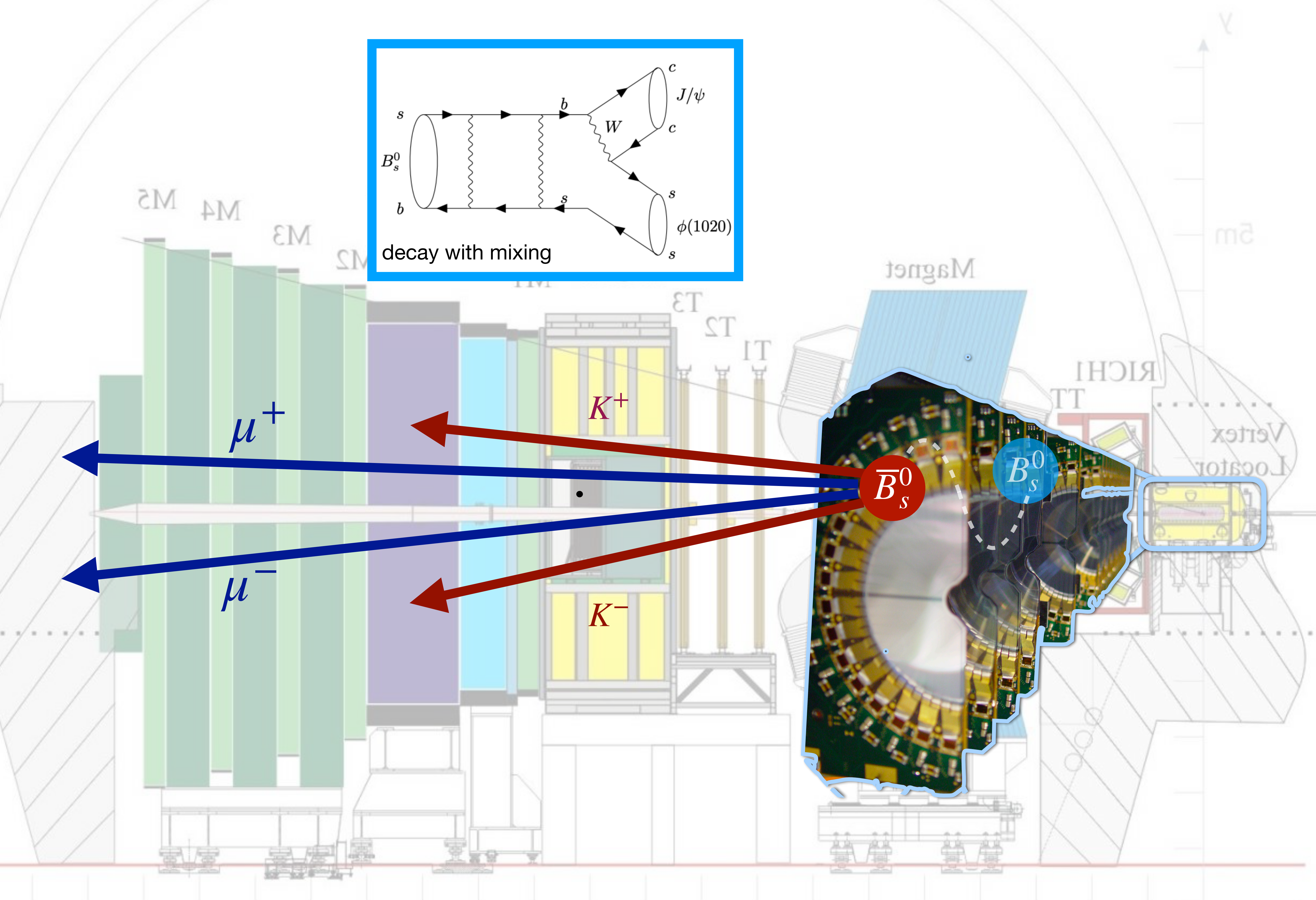

M5
M4
M3
M2
HCAL
ECAL
SPD/PS
M1
RICH2
T3
T2
T1
Magnet
RICH1
TT
Vertex
Locator
5m
y
B_s^0


b
B_s^0
s
c
J/ψ
c
s
$\phi(1020)$
s
direct decay
μ^+
K^+
μ^-
K^-
B_s^0

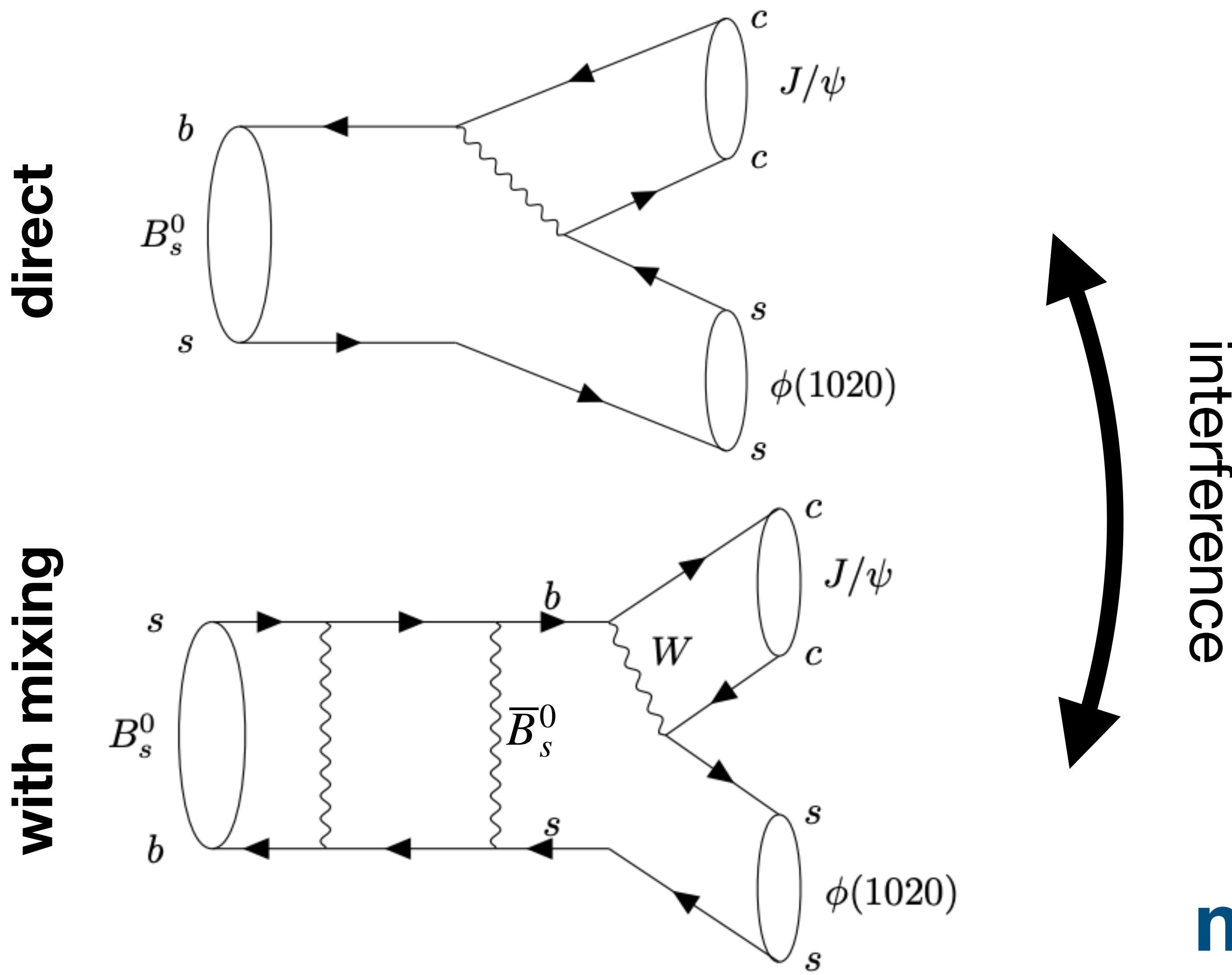

M5
M4
M3
M2
HCAL
ECAL
SPD/PS
M1
RICH2
T3
T2
T1
Magnet
RICH1
TT
Vertex Locator
B_s^0
5m
y



M5
M4
M3
M2
HCAL
ECAL
SPD/PS
M1
RICH2
T3
T2
T1
Magnet
RICH1
TT
Vertex Locator
5m
$\overline{B}_s^0$
B_s^0

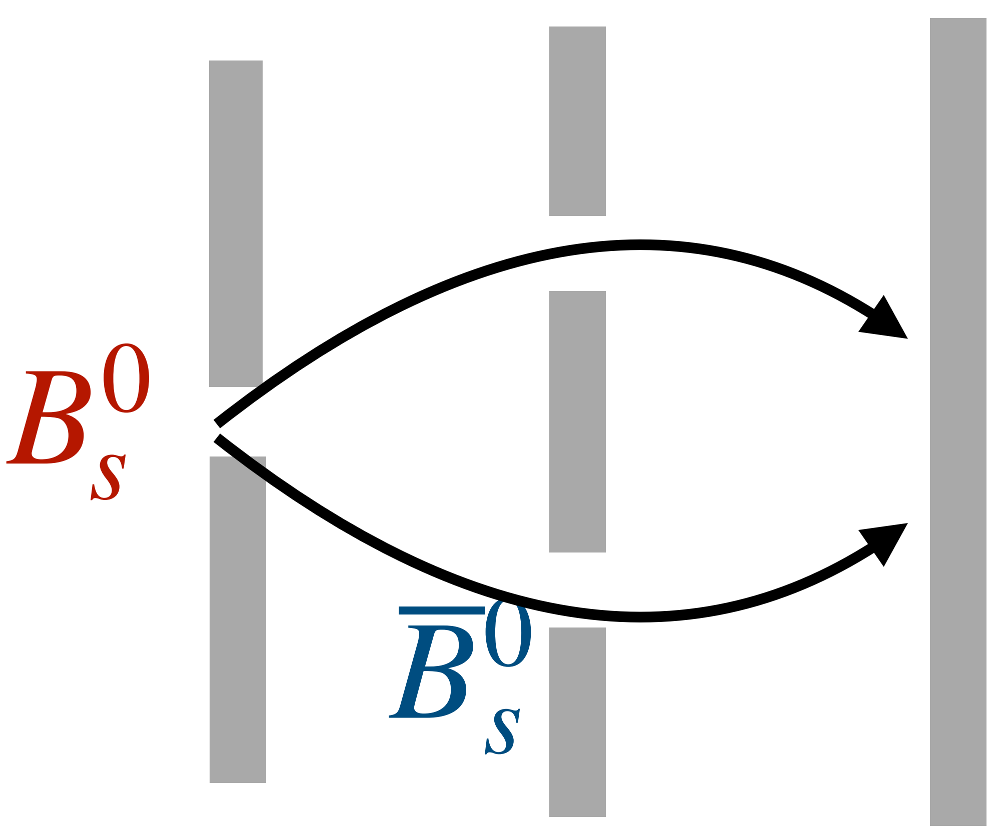


decay with mixing
B_s^0
s
b
W
J/ψ
c
$\phi(1020)$
K^+
K^-
μ^+
μ^-
$\overline{B}_s^0$
B_s^0



$$\propto \phi_s$$

mixing induced CP-violation

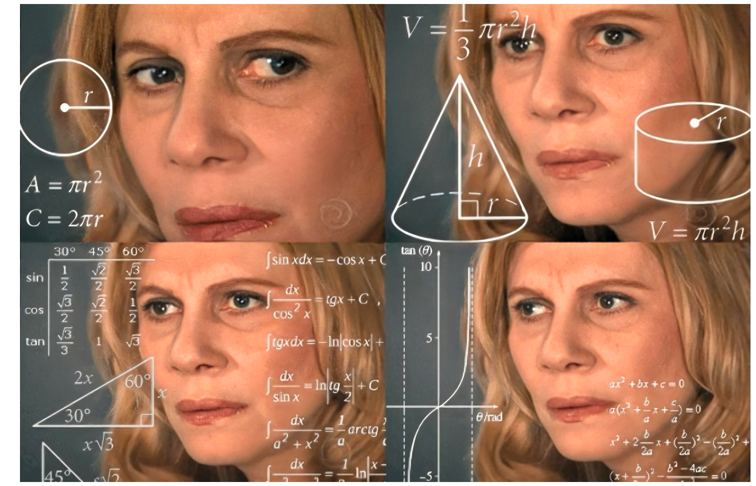


$$J/\psi\phi \quad \propto \phi_s$$

double slit experiment

Dissecting ϕ_s measurement

I only talk about my personal work here

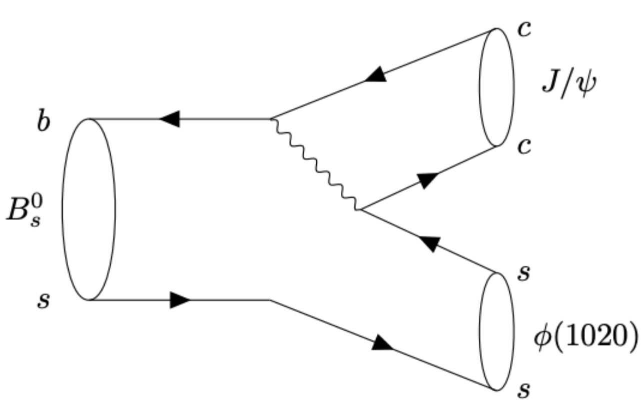


decay rate

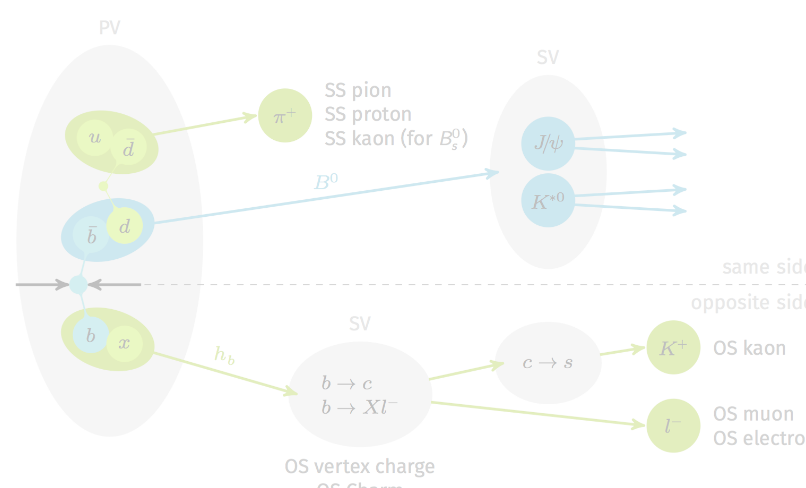
matter — anti-matter

$$\frac{d\Gamma}{dt} = \sum_{k=1}^{10} C_k f_k(\Omega)\left[p\Gamma_k(t\,|\,B_s^0) + (1-p)\Gamma_k(t\,|\,\overline{B}_s^0)\right]\varepsilon(t,\Omega)\otimes R(t\,|\,\sigma_t)$$

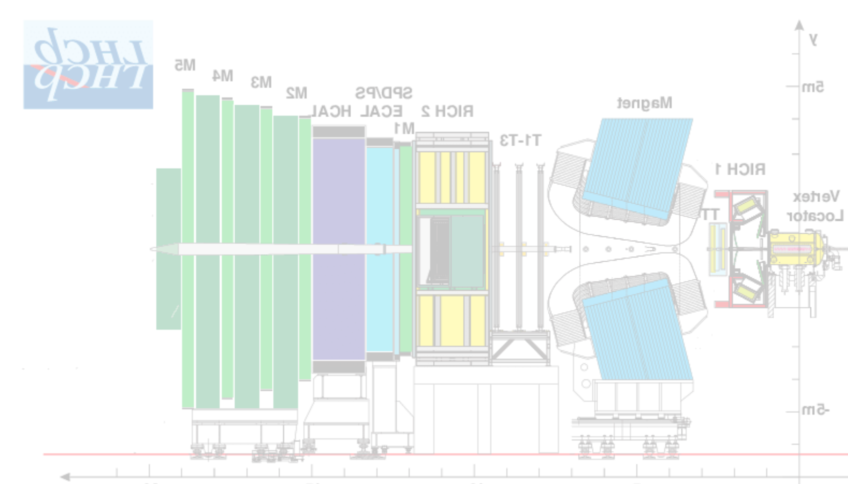
physics

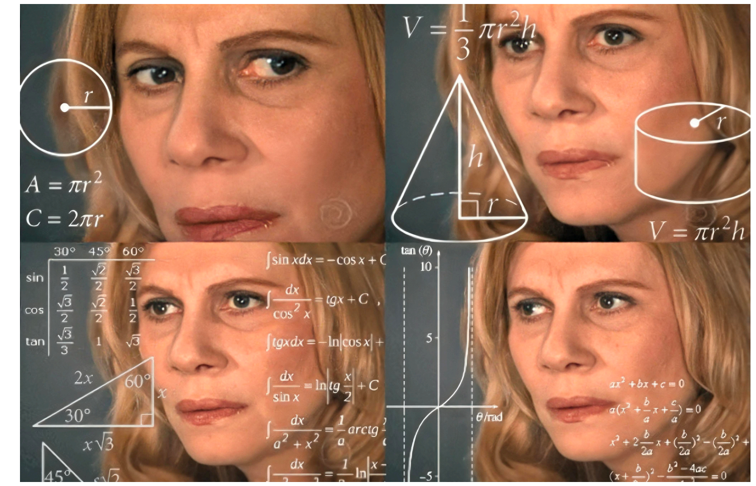


flavour tagging



detector effects



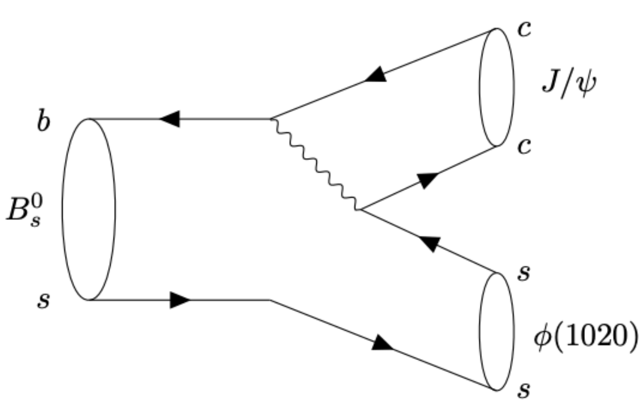


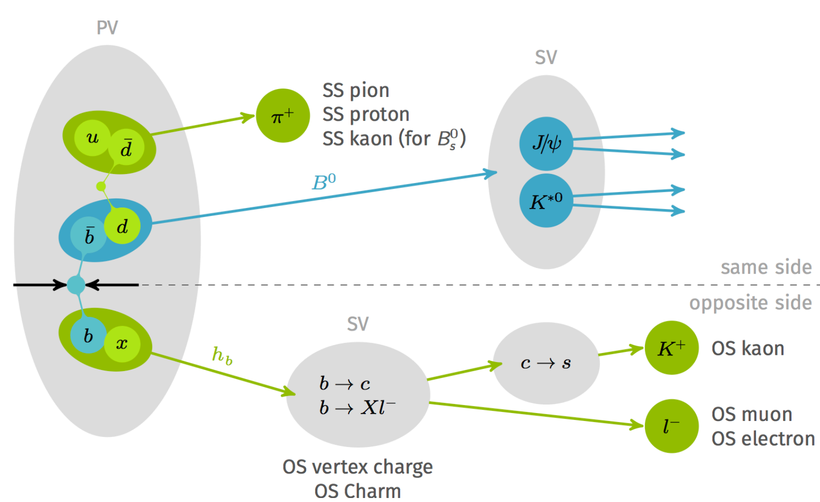
decay rate

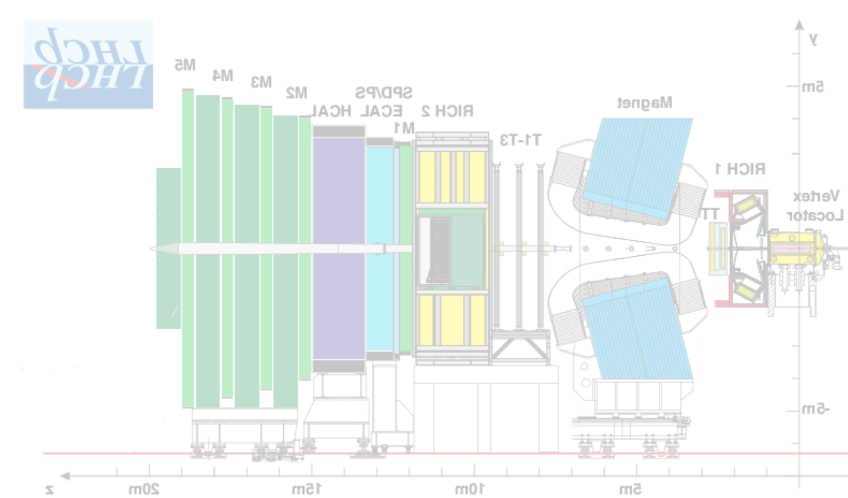
matter — anti-matter

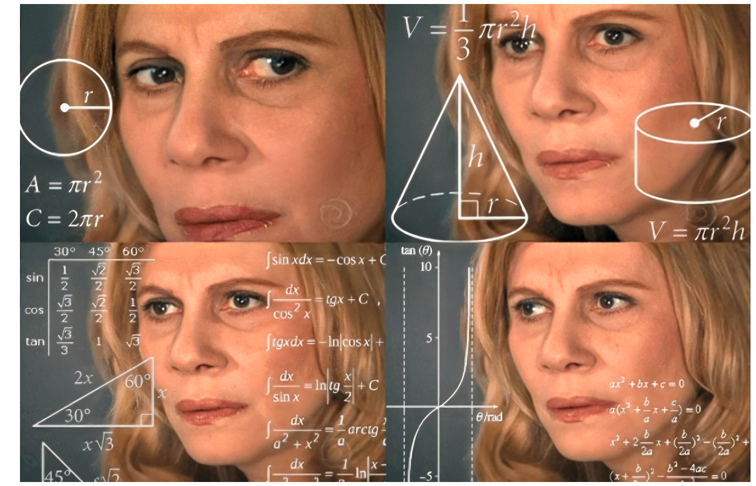
$$\frac{d\Gamma}{dt} = \sum_{k=1}^{10} C_k f_k(\Omega) \left[p\Gamma_k(t\,|\,B_s^0) + (1-p)\Gamma_k(t\,|\,\overline{B}_s^0) \right] \varepsilon(t,\Omega) \otimes R(t\,|\,\sigma_t)$$

physics | **flavour tagging** | **detector effects**









decay rate

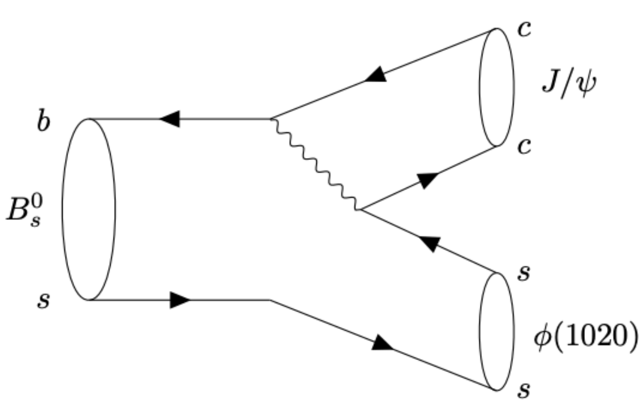
matter — anti-matter

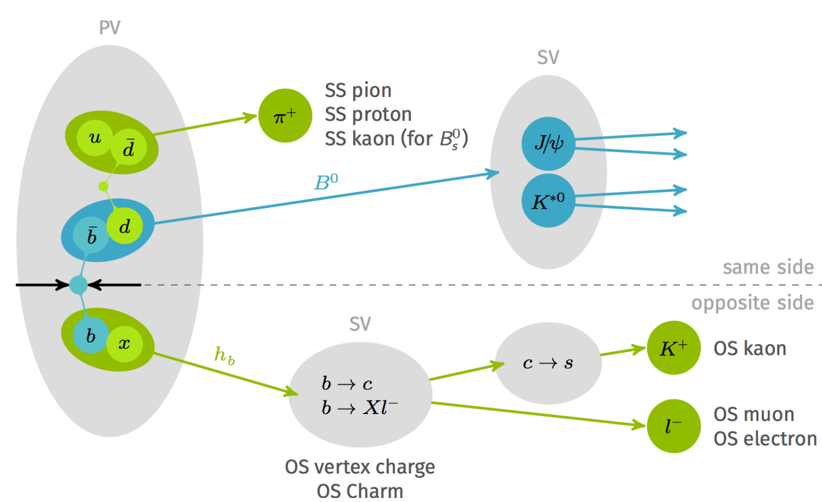
$$\frac{d^4\Gamma}{dt\,d\Omega} = \sum_{k=1}^{10} C_k f_k(\Omega)\left[p\,\Gamma_k(t\,|\,B_s^0) + (1-p)\,\Gamma_k(t\,|\,\overline{B}_s^0)\right]\varepsilon(t,\Omega)\otimes R(t\,|\,\sigma_t)$$

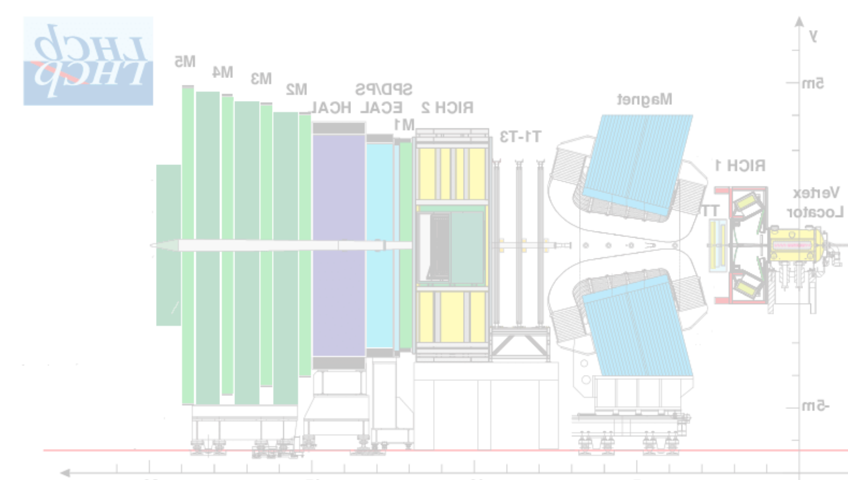
angles

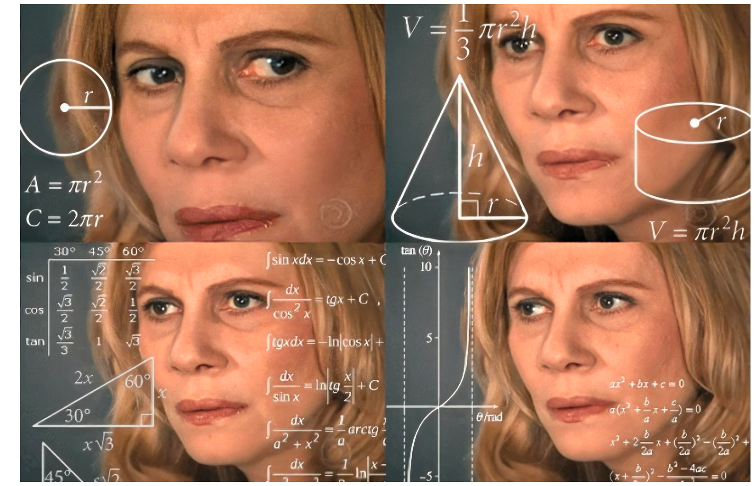
k - index for polarisation terms and their interference

physics — **flavour tagging** — **detector effects**









decay rate

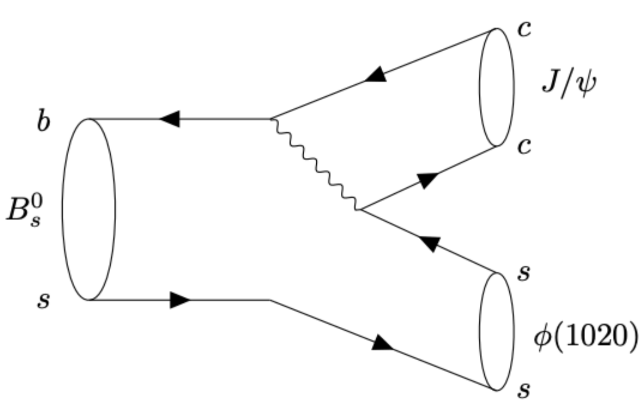
matter — anti-matter

$$\frac{d^4\Gamma}{dt\,d\Omega} = \sum_{k=1}^{10} C_k f_k(\Omega)\left[p\Gamma_k(t\,|\,B_s^0) + (1-p)\Gamma_k(t\,|\,\overline{B}_s^0)\right]\varepsilon(t,\Omega)\otimes R(t\,|\,\sigma_t)$$

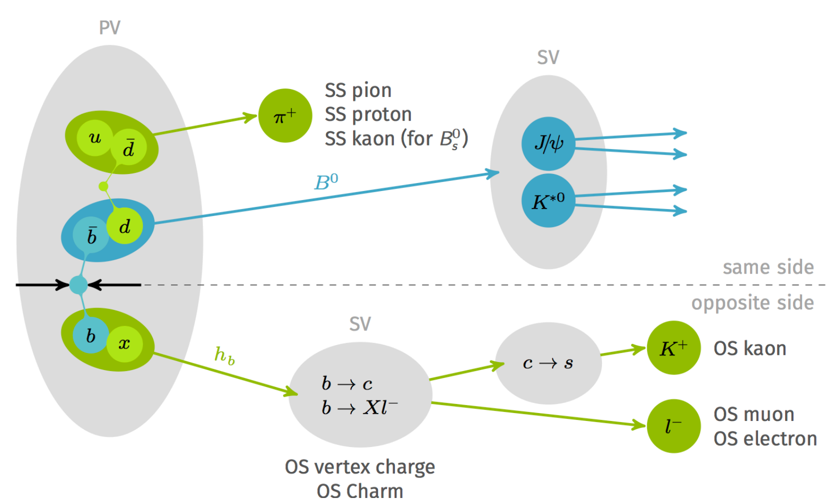
angles

k - index for polarisation terms and their interference

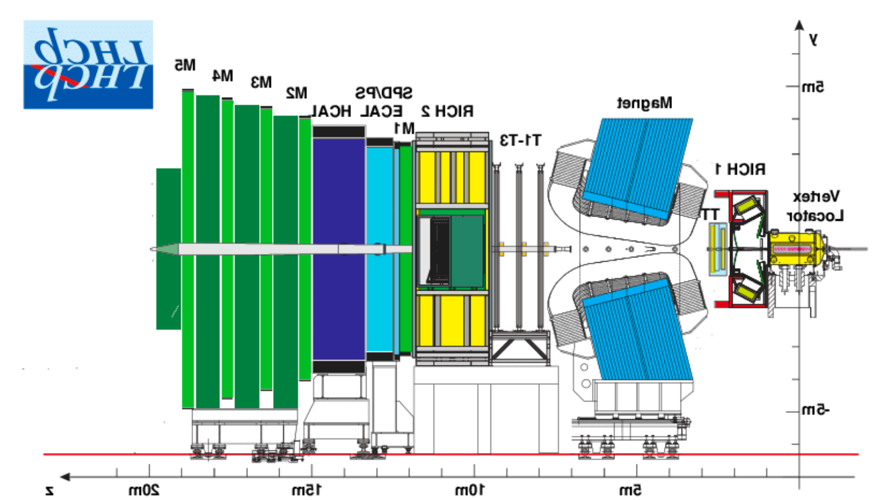
physics

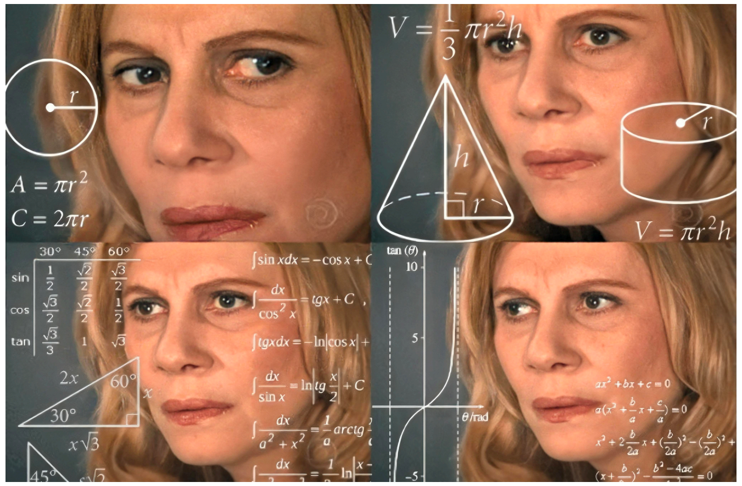


flavour tagging



detector effects





decay rate

matter — anti-matter

$$\frac{d^4\Gamma}{dt\,d\Omega} = \sum_{k=1}^{10} C_k f_k(\Omega)\left[p\Gamma_k(t\,|\,B_s^0) + (1-p)\Gamma_k(t\,|\,\overline{B}_s^0)\right]\varepsilon(t,\Omega)\otimes R(t\,|\,\sigma_t)$$

angles

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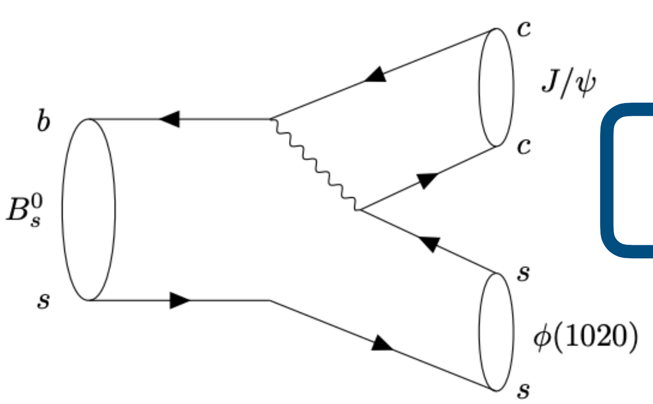
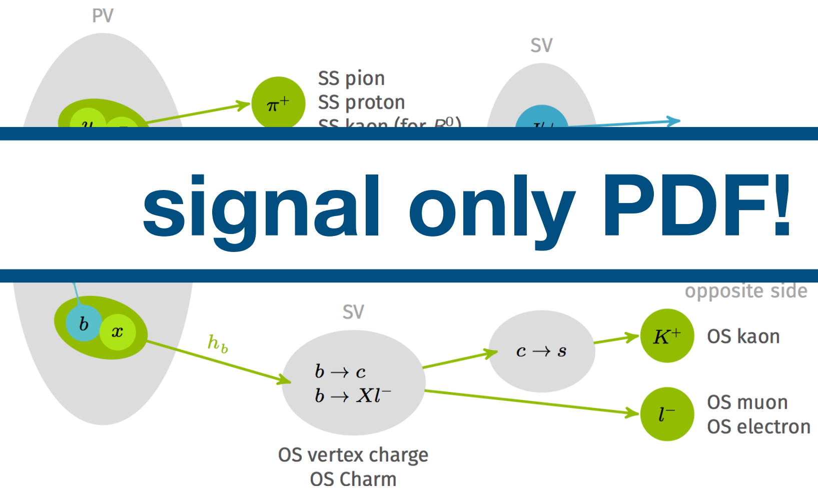
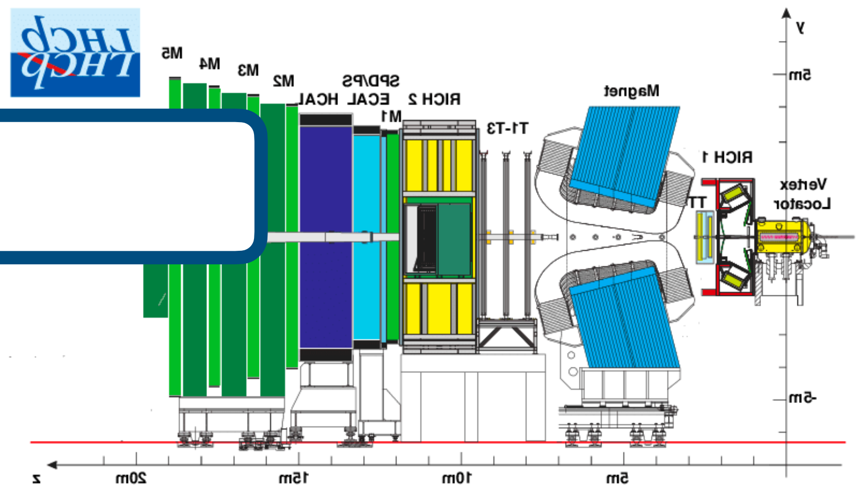
physics | **flavour tagging** | **detector effects**

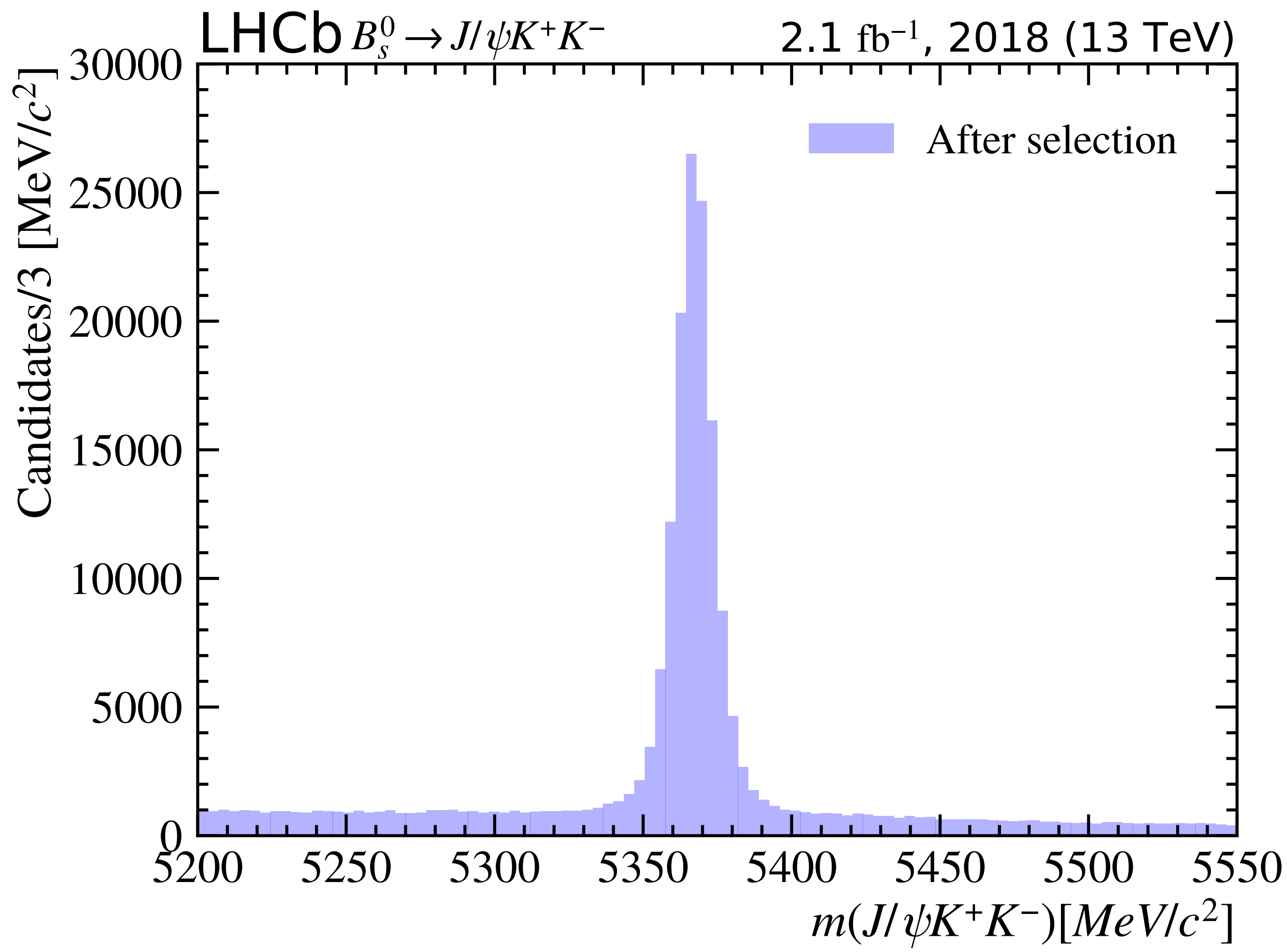




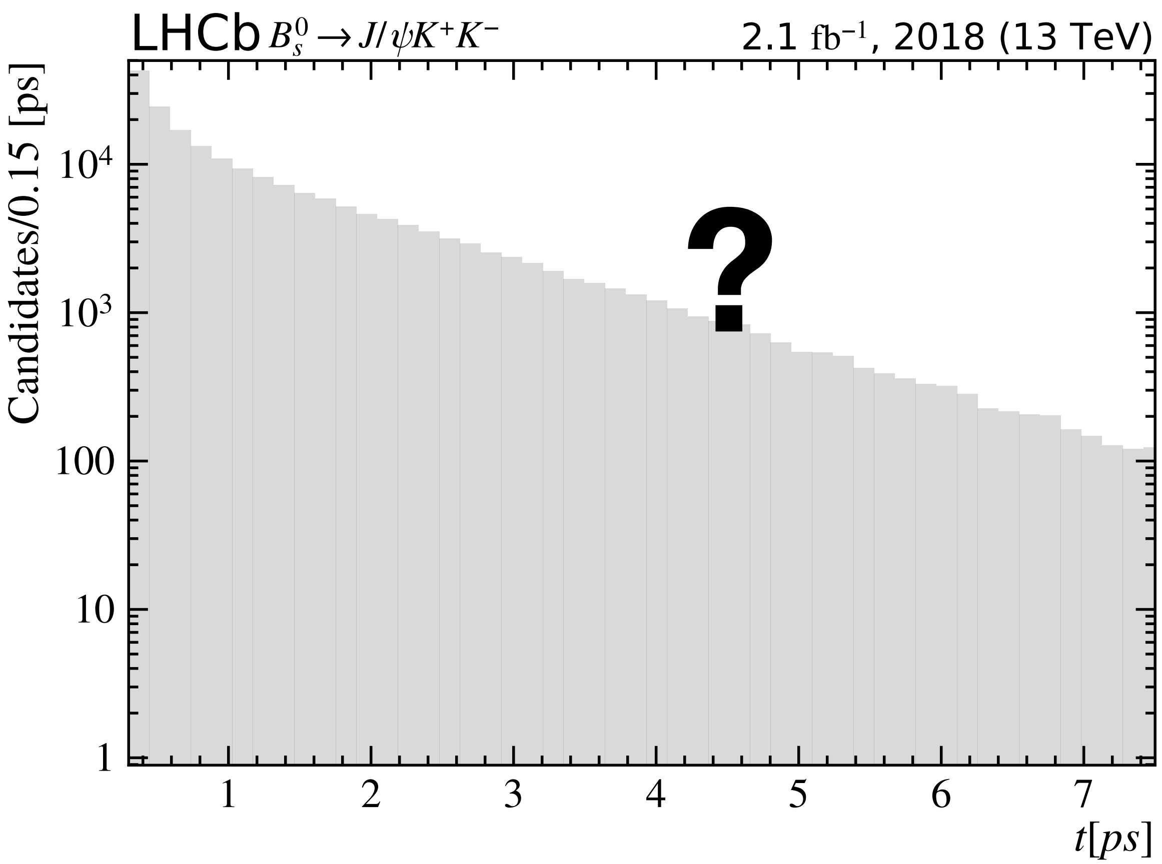


signal only PDF!

How clean is the sample?

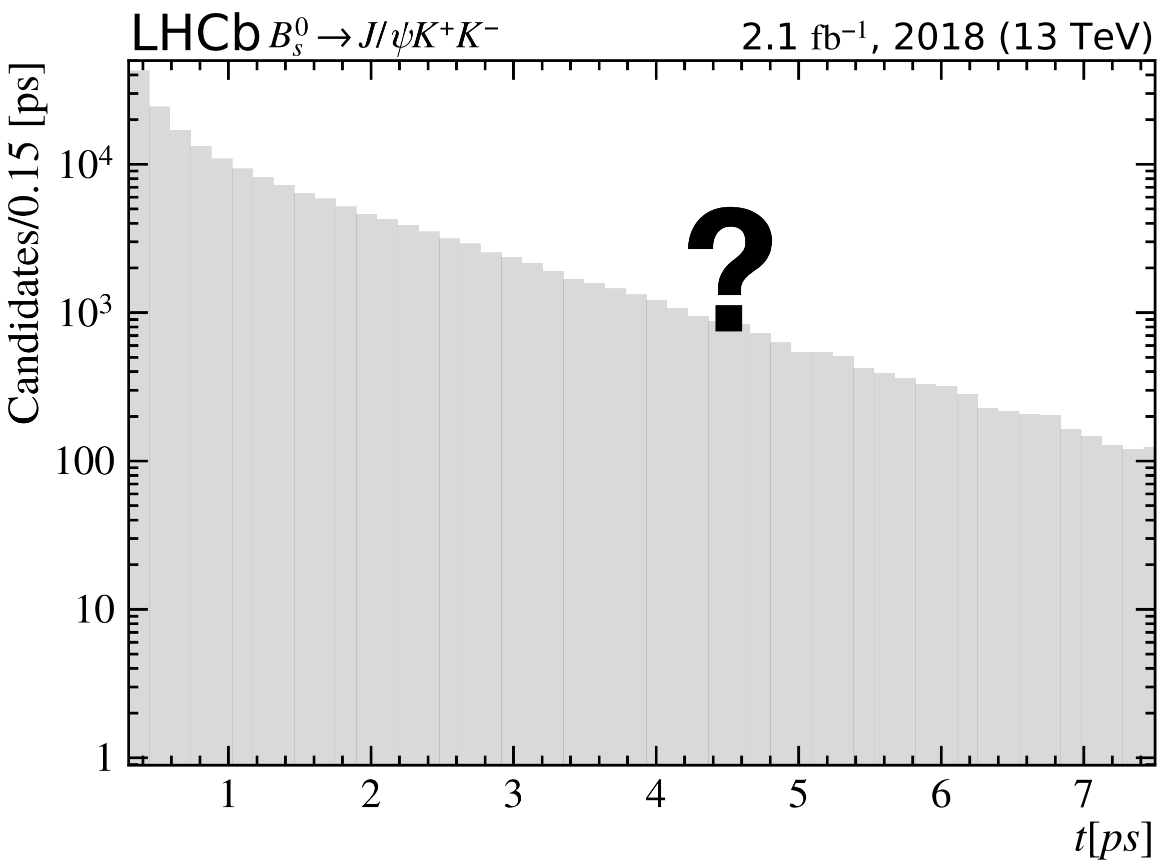


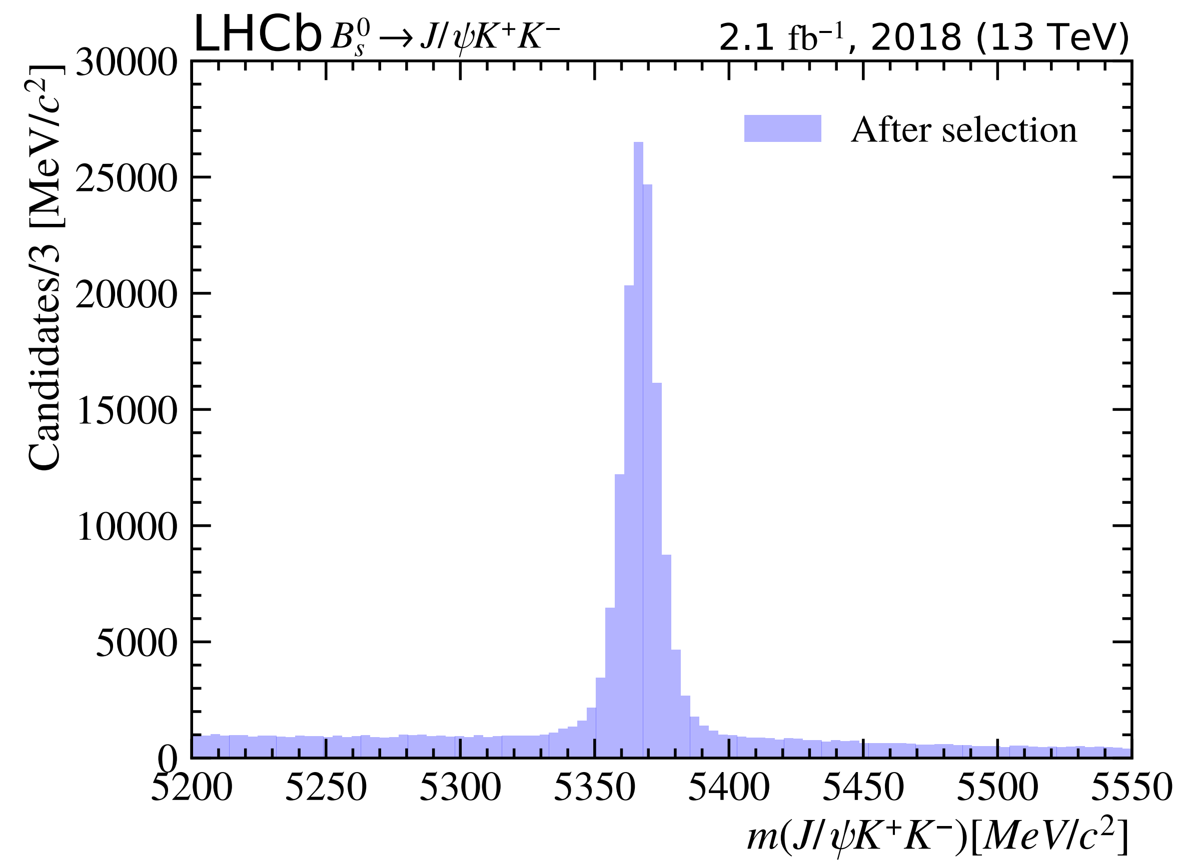
1. Background subtraction with sPlot



physics | flavour tagging | detector effects

1. Background subtraction with sPlot

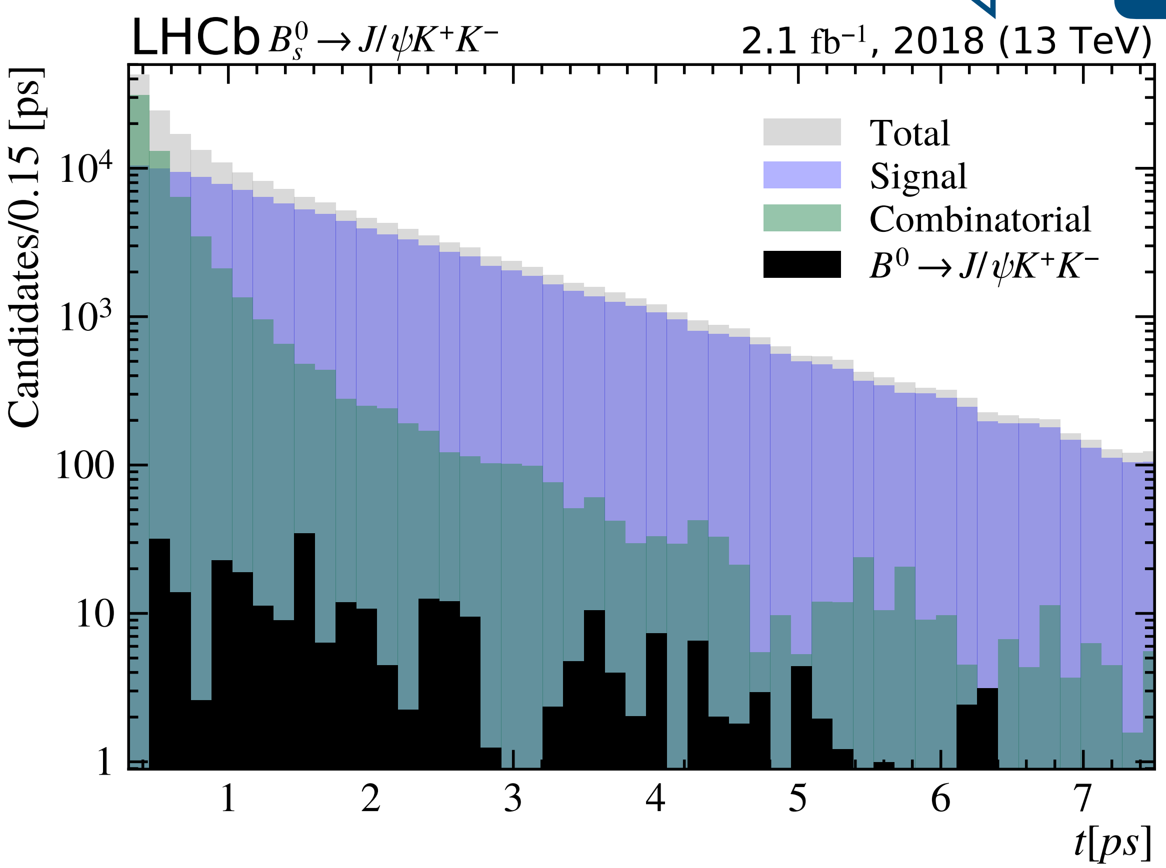


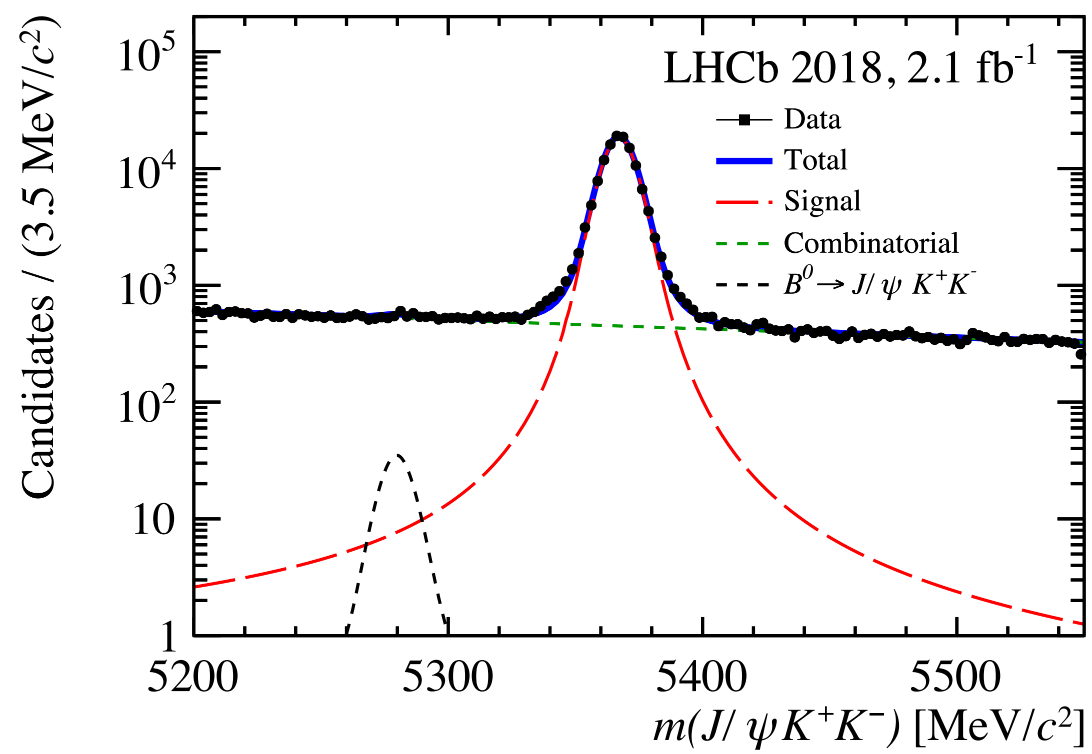


physics | flavour tagging | detector effects

1. Background subtraction with sPlot

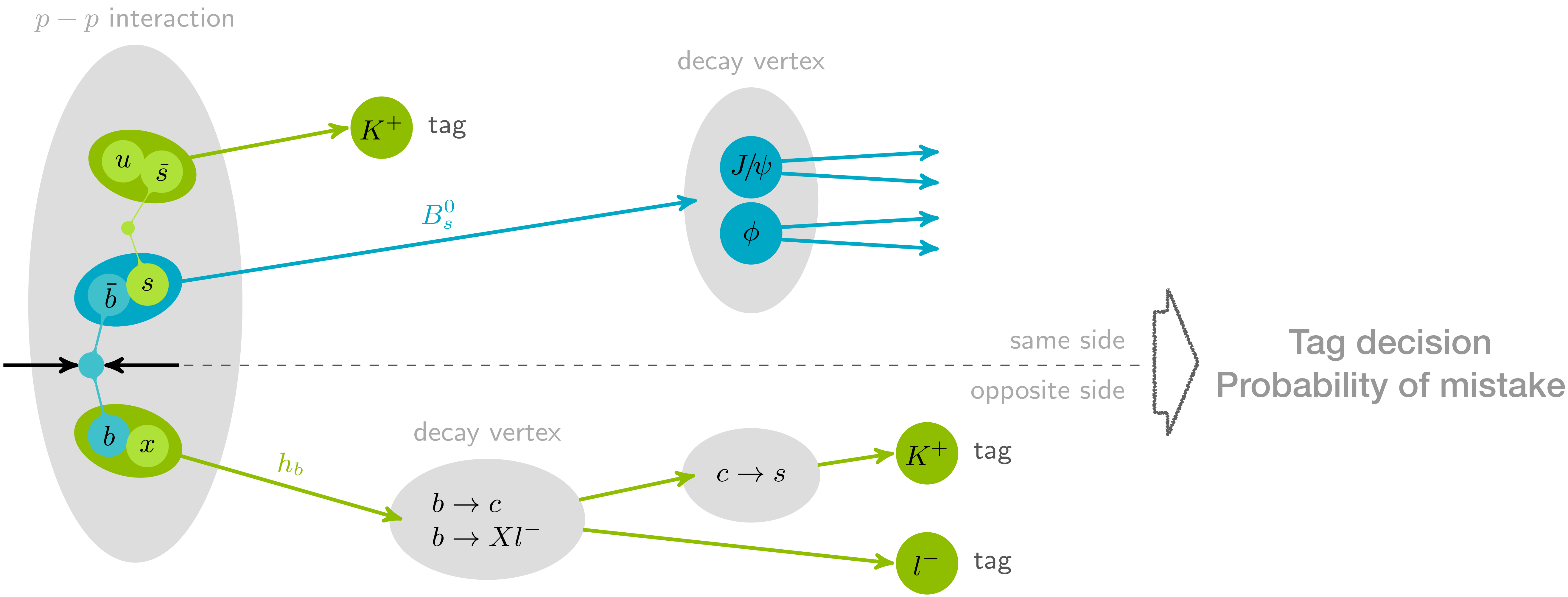
Observable ⟵ **weight** ⟵ Discriminating variable





Key assumption: discriminating variable and observable are **statistically independent!**

2. Initial flavour



Flavour tagging is the key! Defines effective statistical power of a sample

$$\sigma_{stat} = \frac{1}{\sqrt{\varepsilon_{tag}(1-2p_{mistake})N}}$$

$\approx 4\,\%$

I ignore detector effects part
for the sake of time

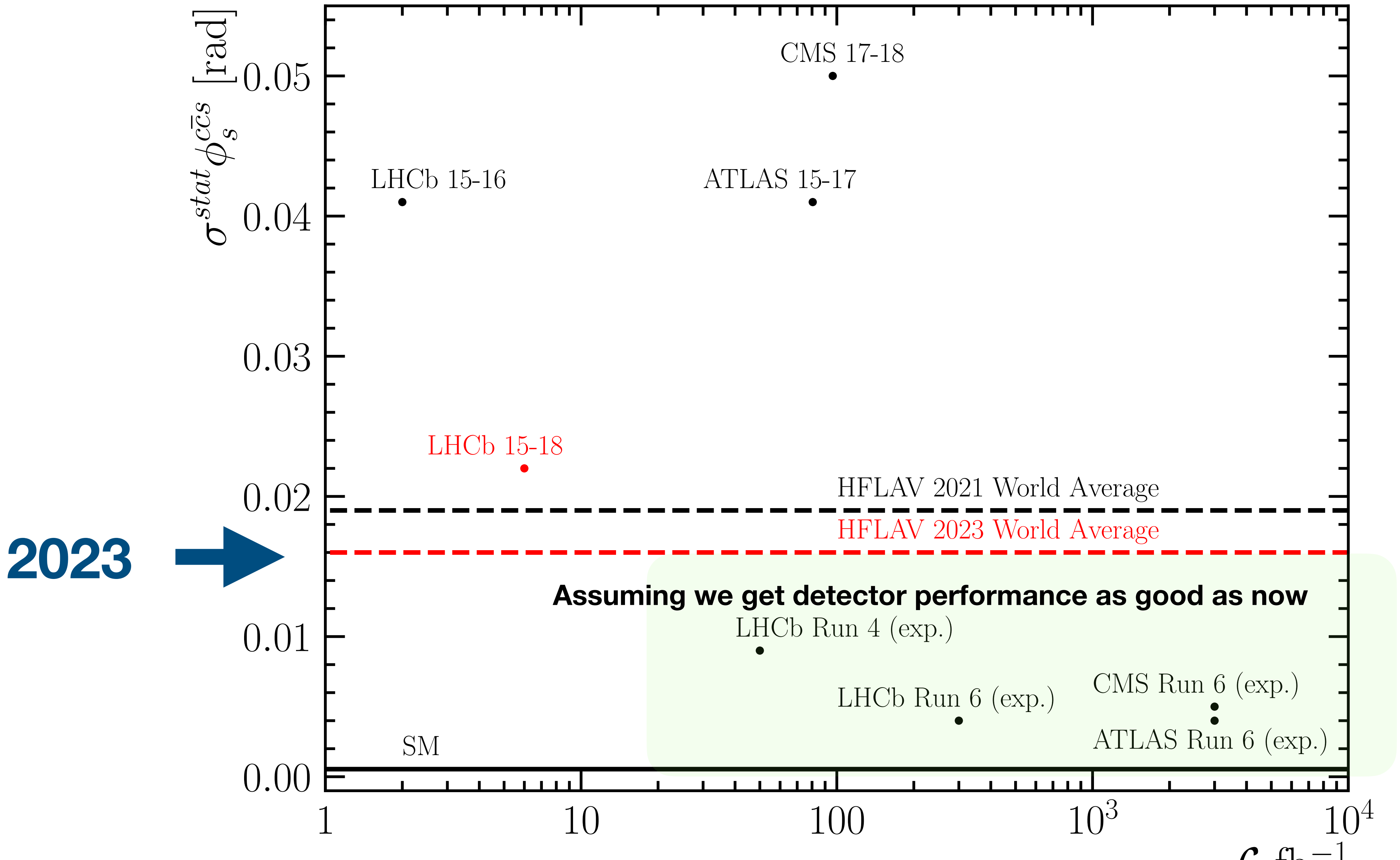
3. Results

arXiv:2308.01468

$$\phi_s = -0.039 \pm 0.022(stat.) \pm 0.006(syst.) \text{ [rad]}$$

WORLD'S BEST!

The CP-violation in $B_s^0 \to J/\psi\phi$ is not observed yet



Take home messages

- There is not enough CP-violation in quark sector in Standard Model. New Physics is necessary.
- ϕ_s is one of the probes, sensitive to the New Physics contributions, that can modify the amount of CP-violation
- The best decay to measure ϕ_s is $B_s^0 \to J/\psi\phi$
- We have not yet discovered CP-violation in $B_s^0 \to J/\psi\phi$
- Need more statistics and not just from LHCb: ATLAS and CMS have to chip in

Back up slides

Why do we have CP-violation in Standard Model?

1. $\psi_I \neq \psi_m$

2. 3 generations of matter

$$\begin{matrix} & & I & II & III & & & \\ \begin{pmatrix} d_I \\ s_I \\ b_I \end{pmatrix} & = & \Big(\blacksquare & |V_{us}| & |V_{ub}|e^{-i\gamma} \Big) & \times & \begin{pmatrix} d_m \\ s_m \\ b_m \end{pmatrix} & \begin{matrix} I \\ II \\ III \end{matrix} \\ & & -|V_{cd}| & \blacksquare & |V_{cb}| & & & \\ & & |V_{td}|e^{-i\beta} & -|V_{ts}|e^{-i\phi_s/2} & \blacksquare & & & \end{matrix}$$

CKM matrix

Why do we have CP-violation in Standard Model?

1. $\psi_I \neq \psi_m$

2. 3 generations of matter

$$\begin{matrix} & & I & II & III & & & \\ \begin{pmatrix} d_I \\ s_I \\ b_I \end{pmatrix} & = & \Bigg(|V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \Bigg) & \times & \begin{pmatrix} d_m \\ s_m \\ b_m \end{pmatrix} & \begin{matrix} I \\ II \\ III \end{matrix} \end{matrix}$$

$$\begin{pmatrix} d_I \\ s_I \\ b_I \end{pmatrix} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{-i\phi_s/2} & |V_{tb}| \end{pmatrix} \times \begin{pmatrix} d_m \\ s_m \\ b_m \end{pmatrix}$$

CKM matrix

Real | Complex

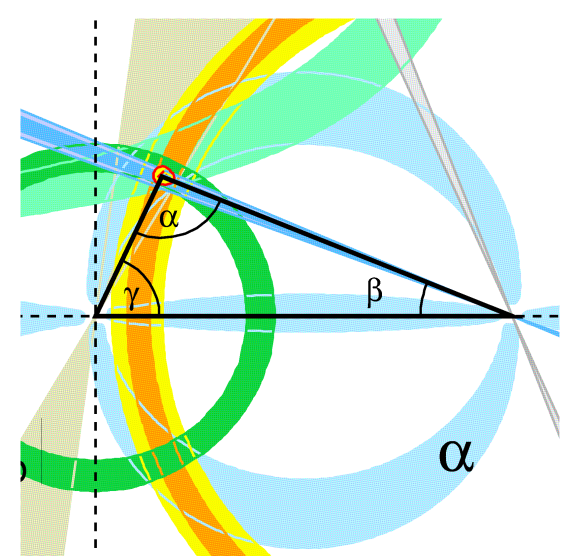
Why do we have CP-violation in Standard Model?

1. $\psi_I \neq \psi_m$

2. 3 generations of matter

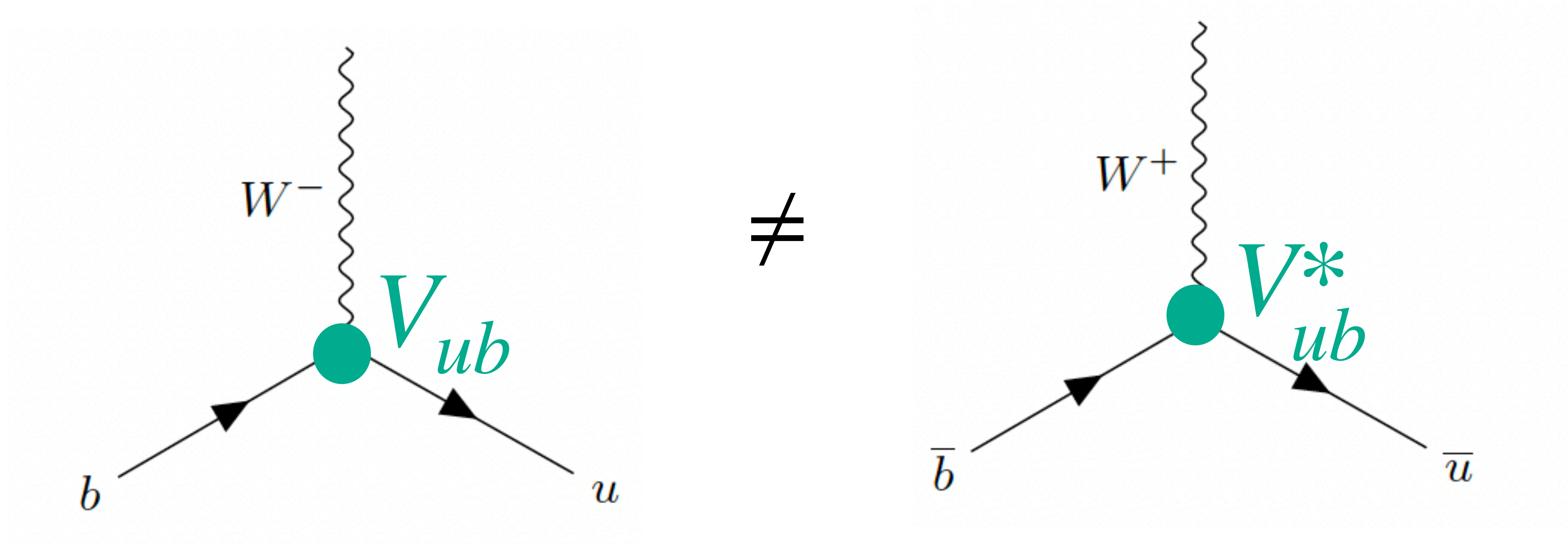
Real | Complex

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{-i\phi_s/2} & |V_{tb}| \end{pmatrix} =$$



CKM matrix

Why do we have CP-violation in Standard Model?



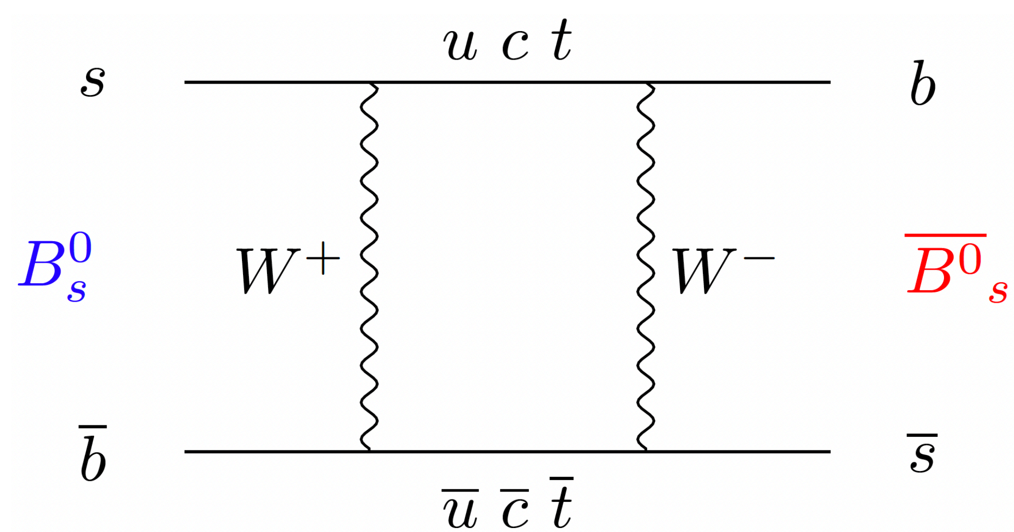
1. $P(X \to f) \neq P(\overline{X} \to \bar{f})$

2. matter-antimatter oscillations

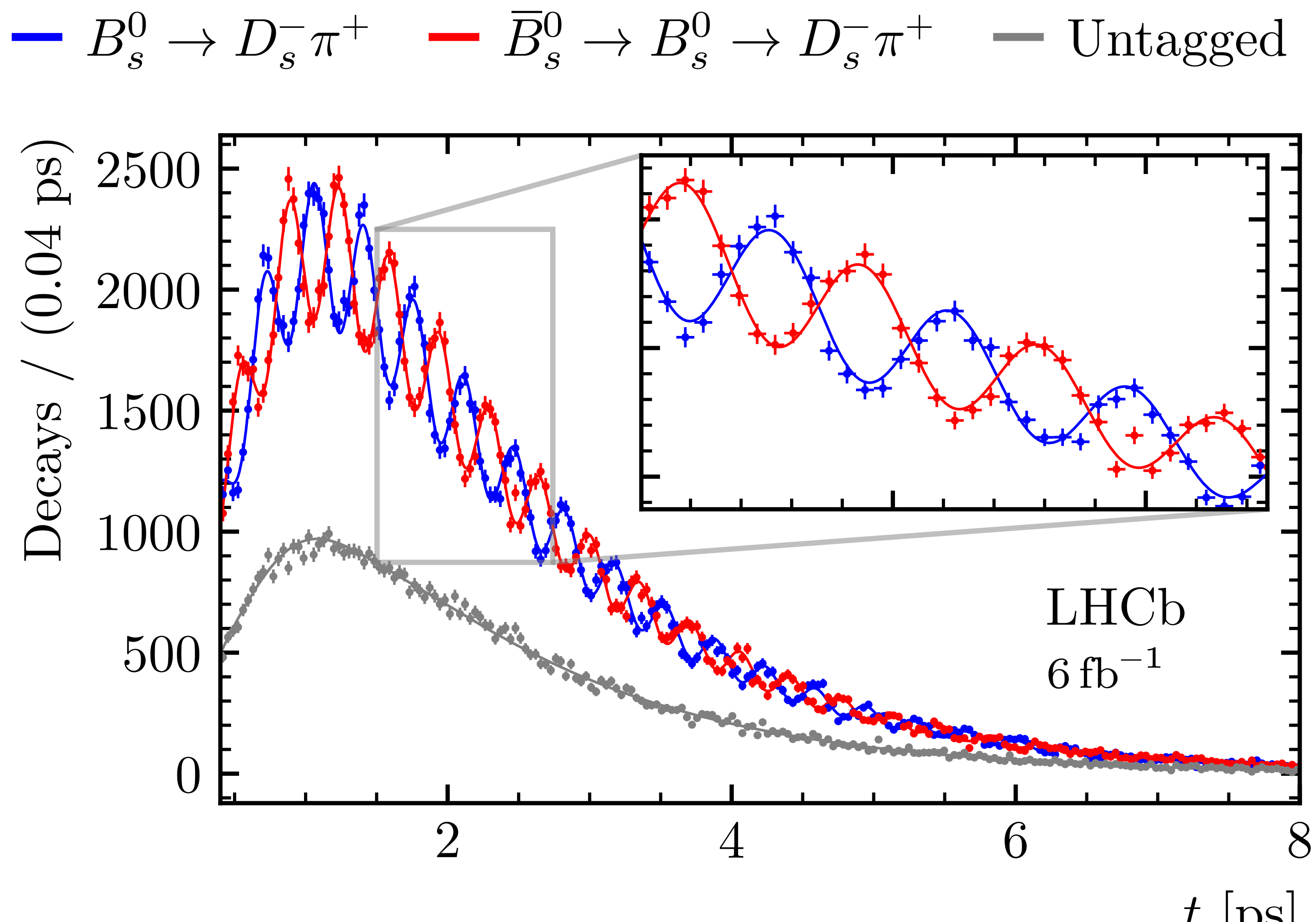
B_s^0 meson oscillation

matter

anti-matter



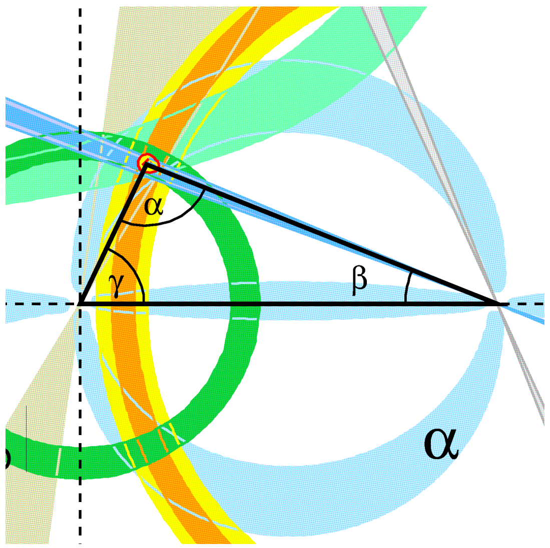
neutral meson oscillations



LHCb *Nature Phys.* 18

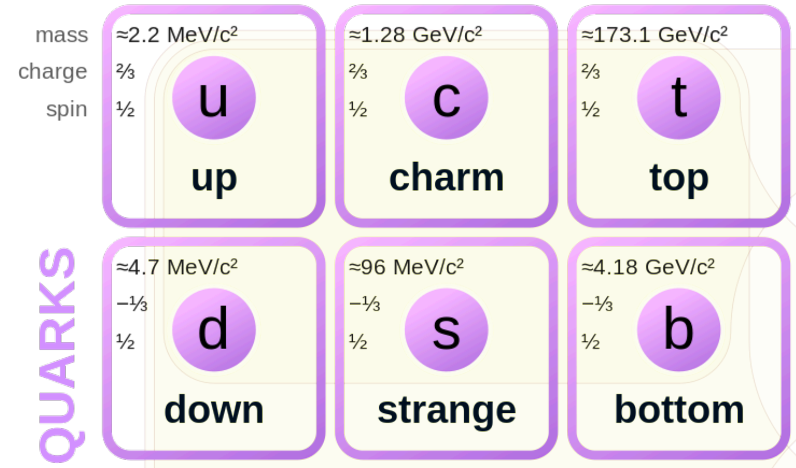
Amount of CP-violation in Standard Model quark sector

$4 \times$



$\approx 10^{-5}$

$\times$

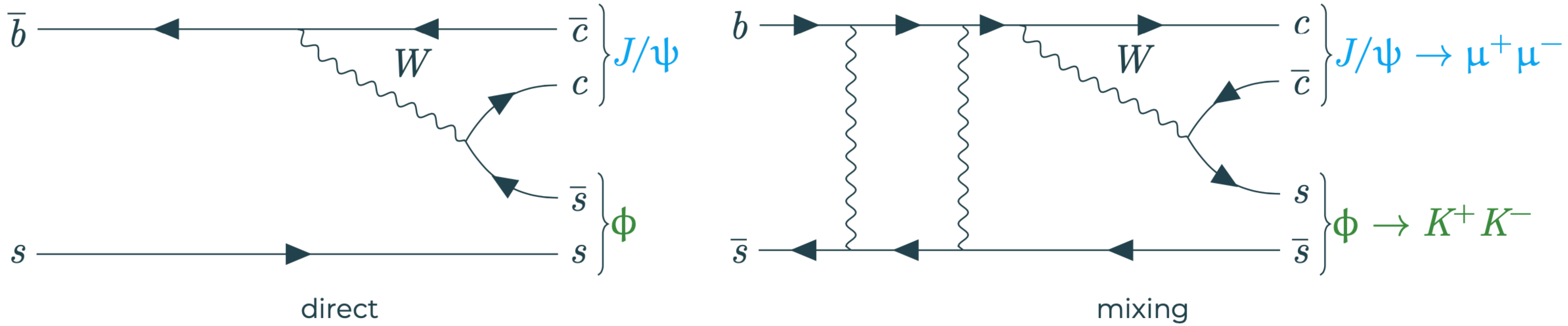


$$(m_t^2 - m_c^2)(m_u^2 - m_t^2)(m_c^2 - m_u^2)$$
$$(m_b^2 - m_s^2)(m_s^2 - m_d^2)(m_d^2 - m_b^2)$$
$$\approx 10^{45}\text{MeV}^{12}$$

$$T^{12}_{freeze-out} \qquad \approx 10^{60}\ \text{MeV}^{12}$$

$$= 10^{-20}$$

There is not enough CP-violation in quark sector alone

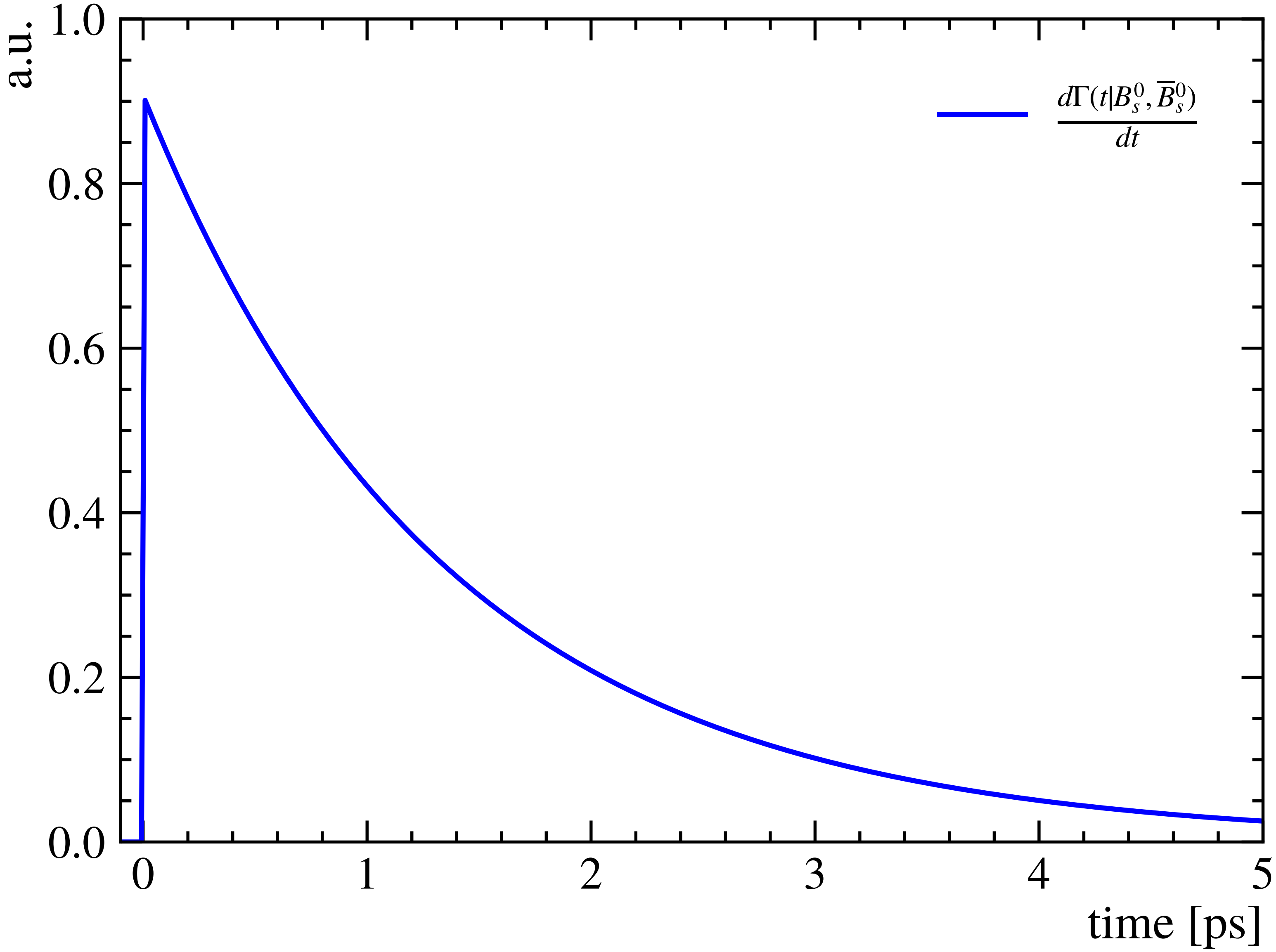


$$A_{CP}(t) = \frac{\Gamma(\overline{B}^0_{(s)} \to f) - \Gamma(B^0_{(s)} \to f)}{\Gamma(\overline{B}^0_{(s)} \to f) + \Gamma(B^0_{(s)} \to f)} = \frac{S_f^{d(s)} \sin(\Delta m_{d(s)} t) - C_f^{d(s)} \cos(\Delta m_{d(s)} t)}{\cosh(\Delta\Gamma_{d(s)} t/2) + D_f^{d(s)} \sinh(\Delta\Gamma_{d(s)} t/2)}$$

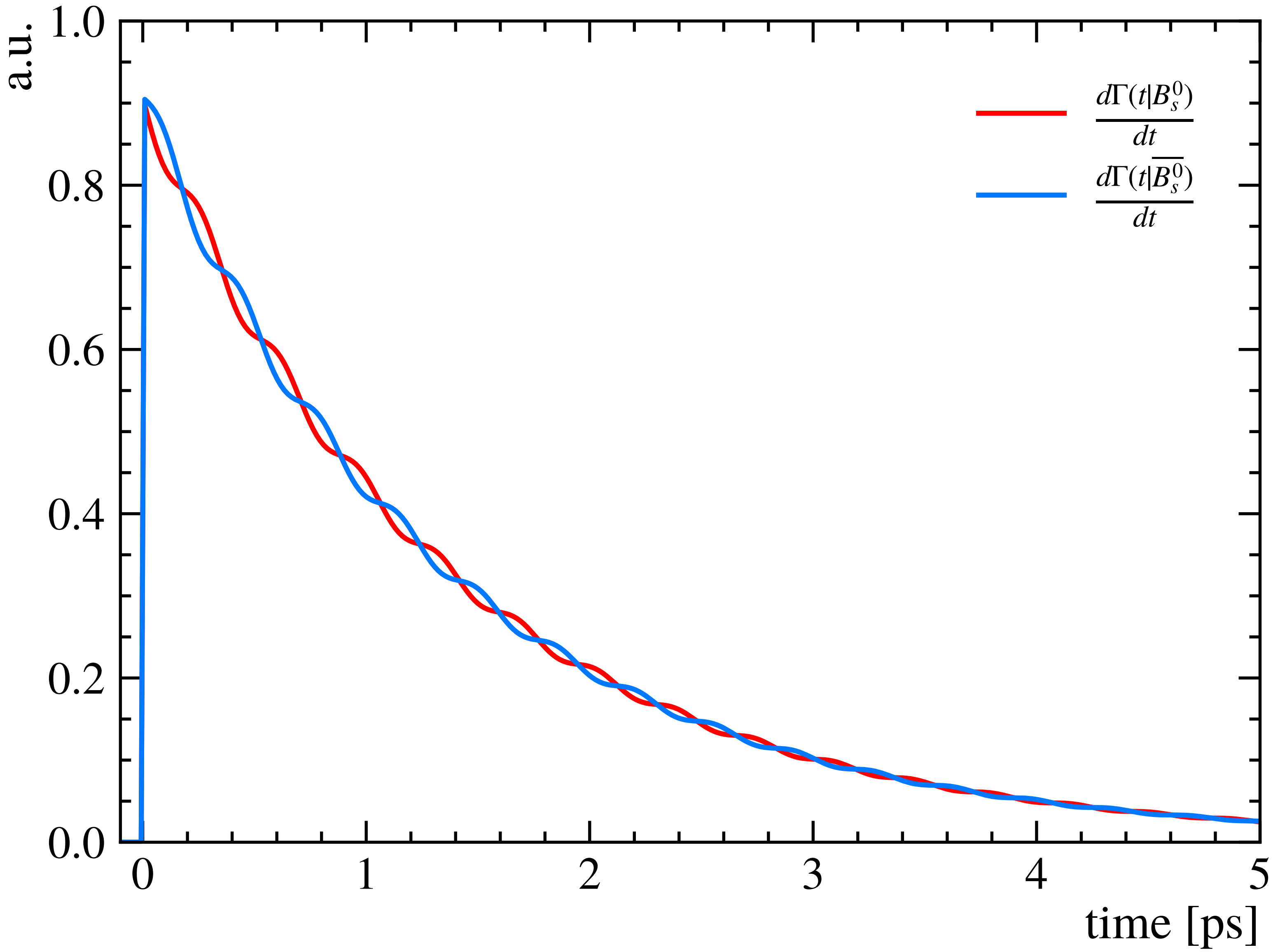
mixing induced CPV direct CPV

Dissecting ϕ_s measurement

1. measure decay rate $B_s^0, \overline{B_s^0}$



Dissecting ϕ_s measurement



1. measure decay rate $B_s^0, \overline{B_s^0}$

2. know initial flavour $B_s^0 \,||\, \overline{B_s^0}$

B_s^0

simplified pdf*

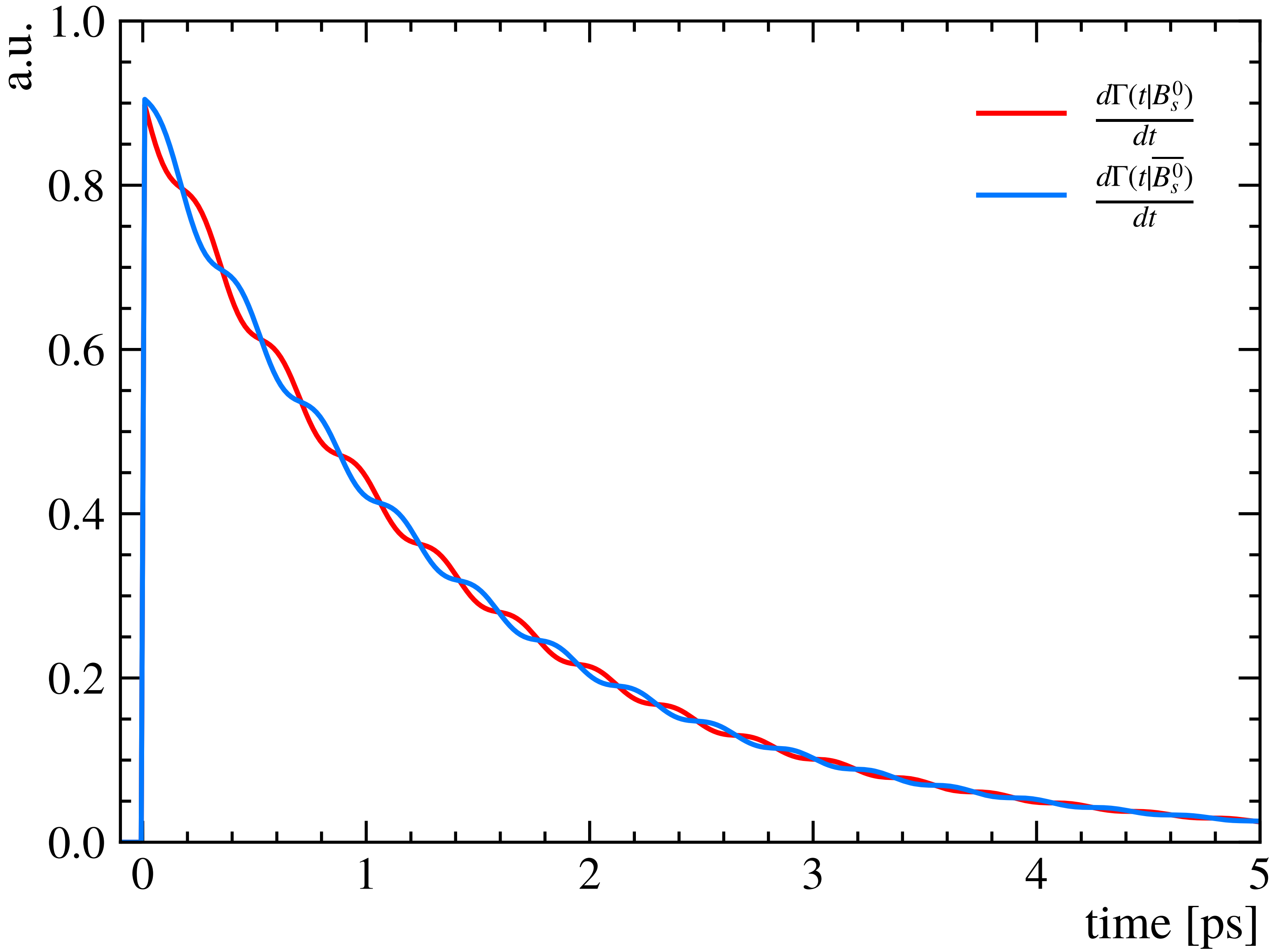
$$\propto [1 \pm \sin(\phi_s)\sin(\Delta m_s t)]e^{-t\Gamma}$$

oscillation — decay

$\overline{B_s^0}$

*assuming lifetimes of B-meson mass eigenstates are the same

Dissecting ϕ_s measurement



1. measure decay rate $B_s^0, \overline{B_s^0}$

2. know initial flavour $B_s^0 \,||\, \overline{B_s^0}$

3. good decay time resolution

~ 35 [fs] for $10\,\%$ precision on frequency

B_s^0

simplified pdf*

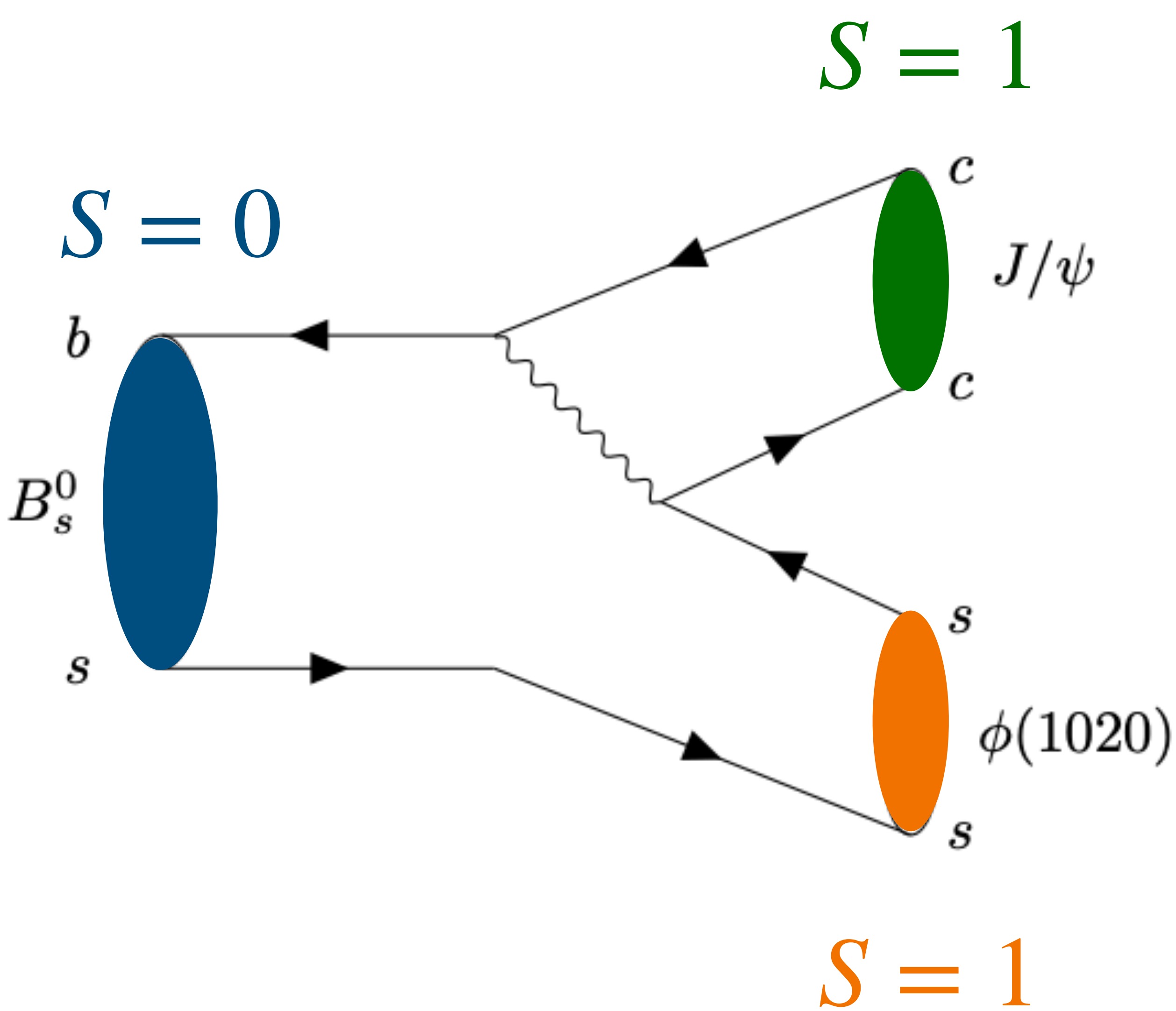
$$\propto [1 \pm \sin(\phi_s)\sin(\Delta m_s t)]e^{-t\Gamma}$$

oscillation — decay

$\overline{B_s^0}$

*assuming lifetimes of B-meson mass eigenstates are the same

Dissecting ϕ_s measurement



1. measure decay rate $B_s^0, \overline{B_s^0}$
2. know initial flavour $B_s^0 \,||\, \overline{B_s^0}$
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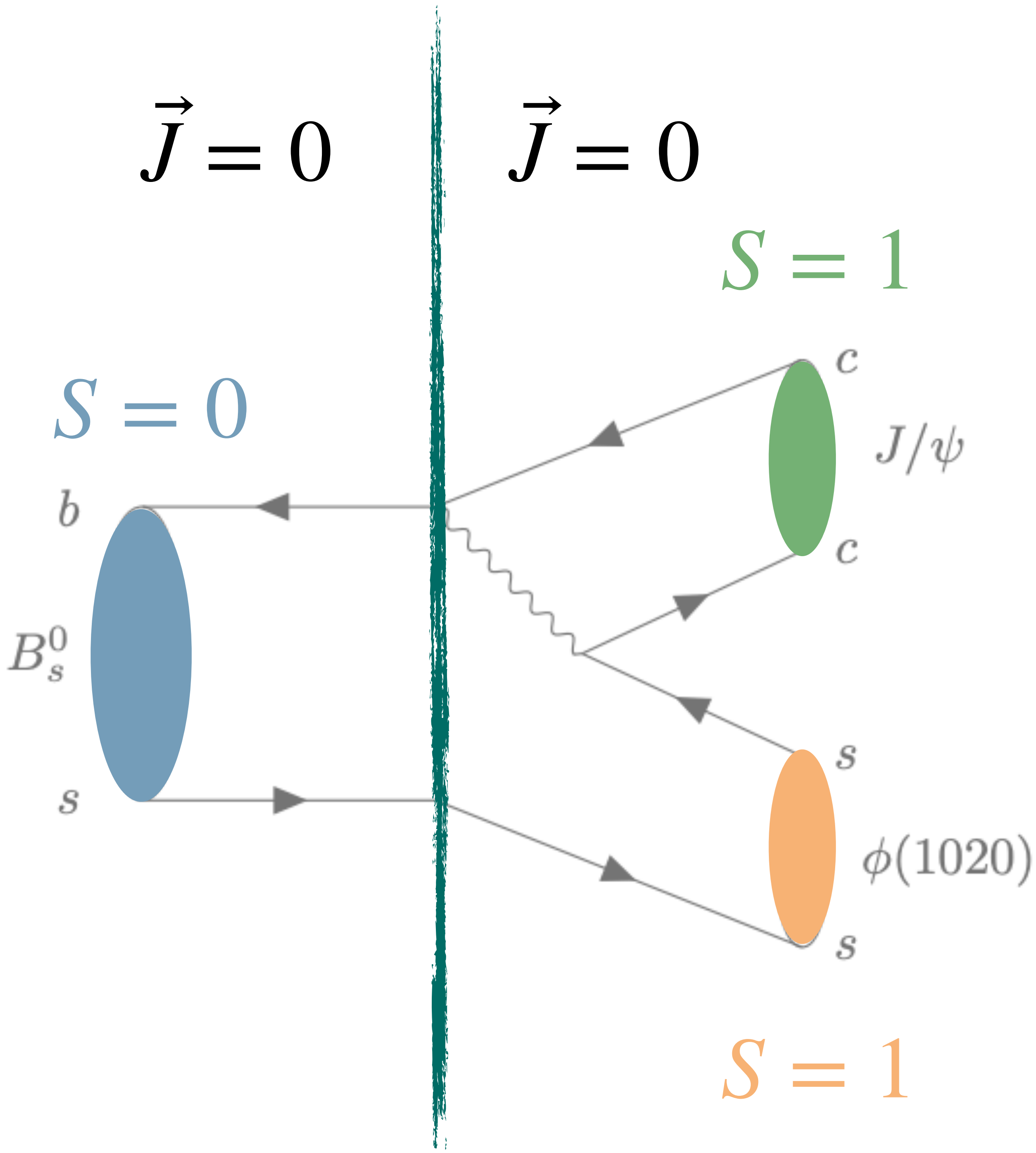
Dissecting ϕ_s measurement



1. measure decay rate $B_s^0, \overline{B_s^0}$
2. know initial flavour $B_s^0 \,||\, \overline{B_s^0}$
3. good decay time resolution

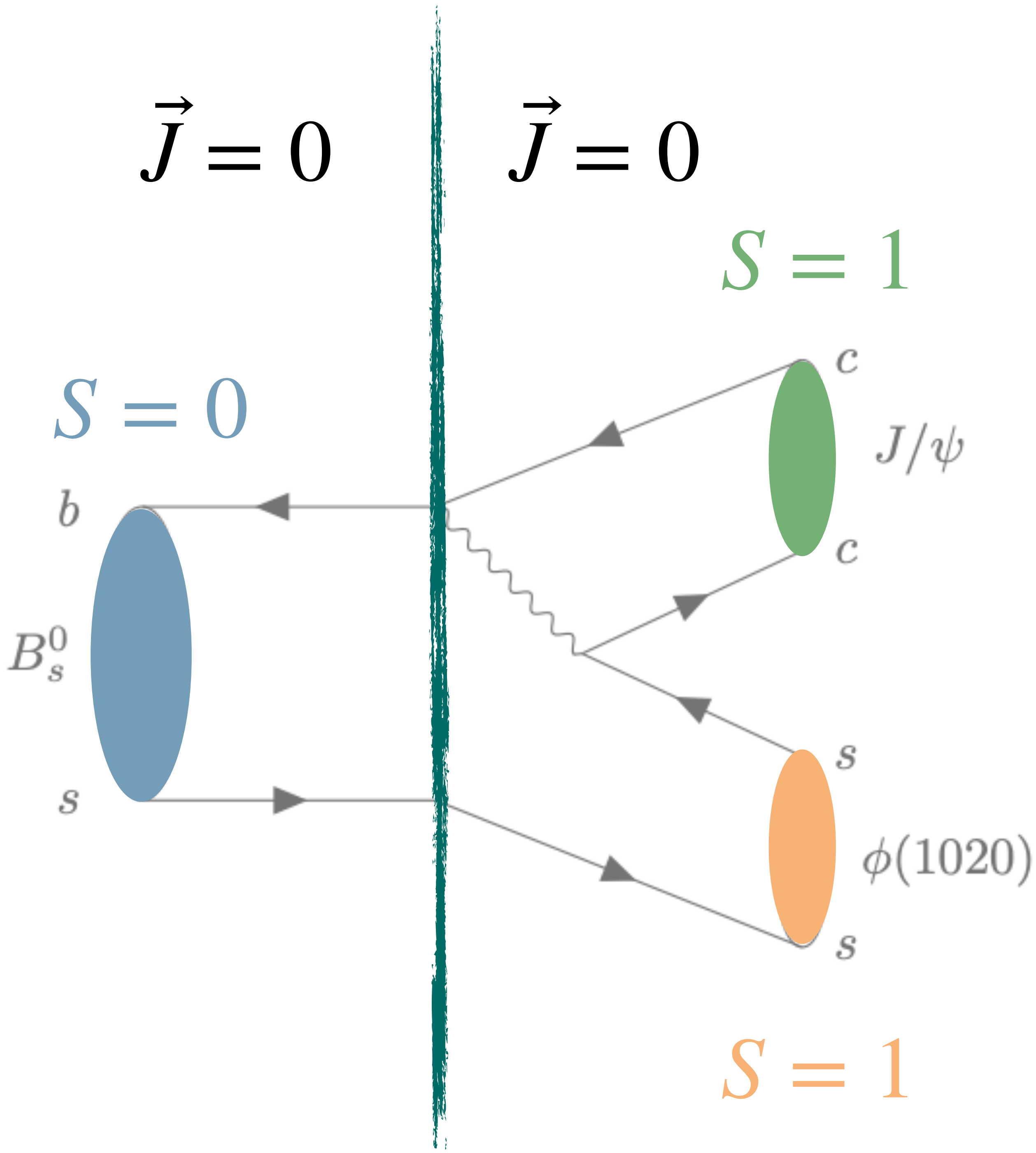
total angular momentum

$$\vec{J} = \vec{S} + \vec{L}$$

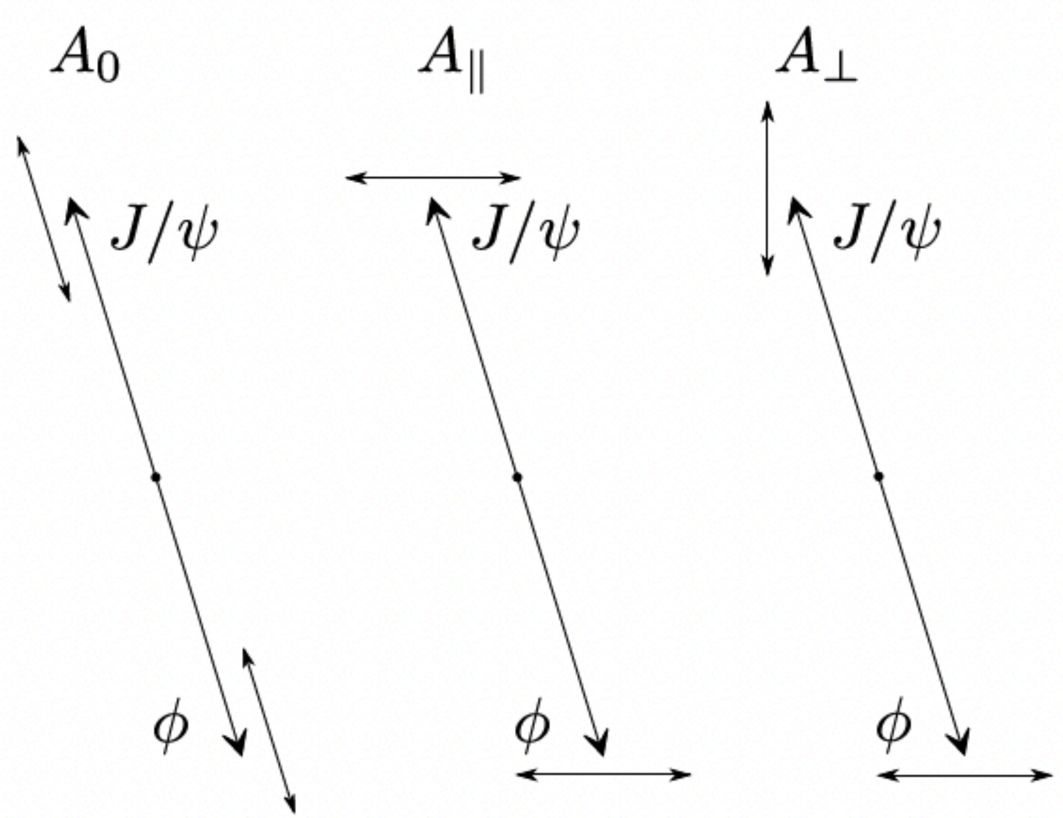
spin — orbital angular momentum

is conserved

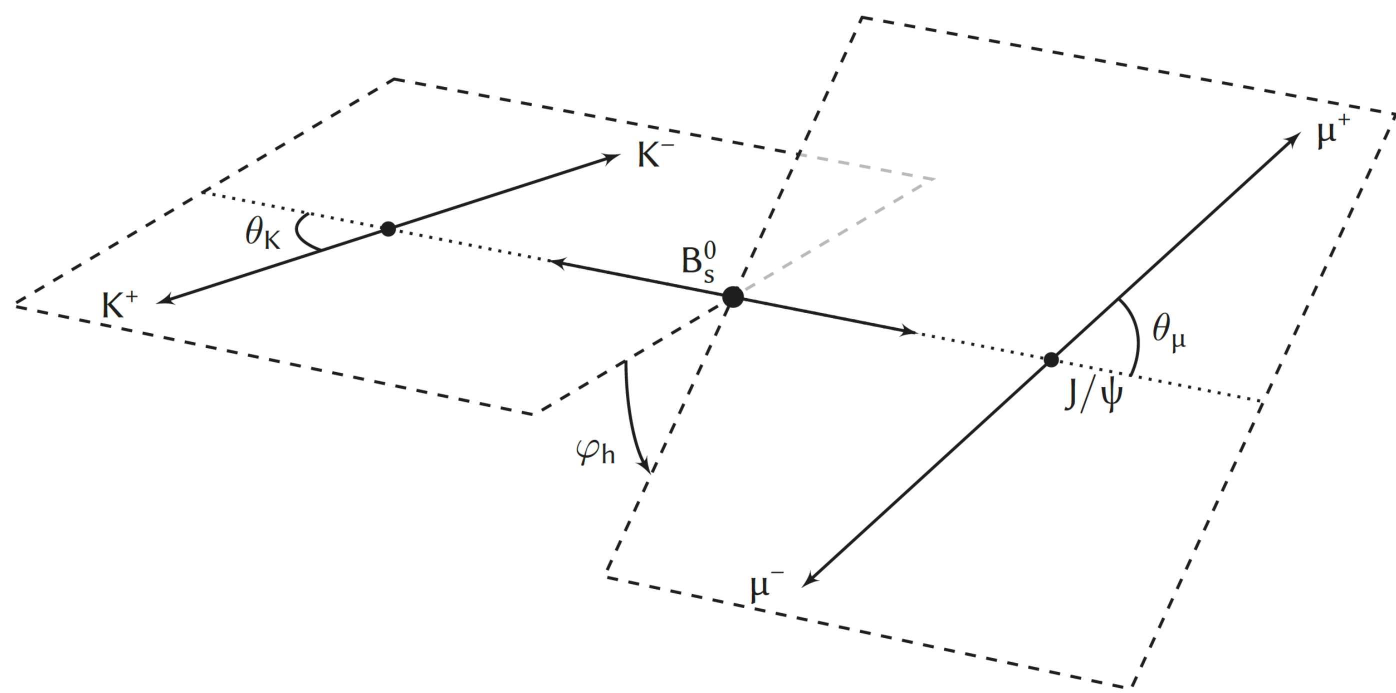
Dissecting ϕ_s measurement



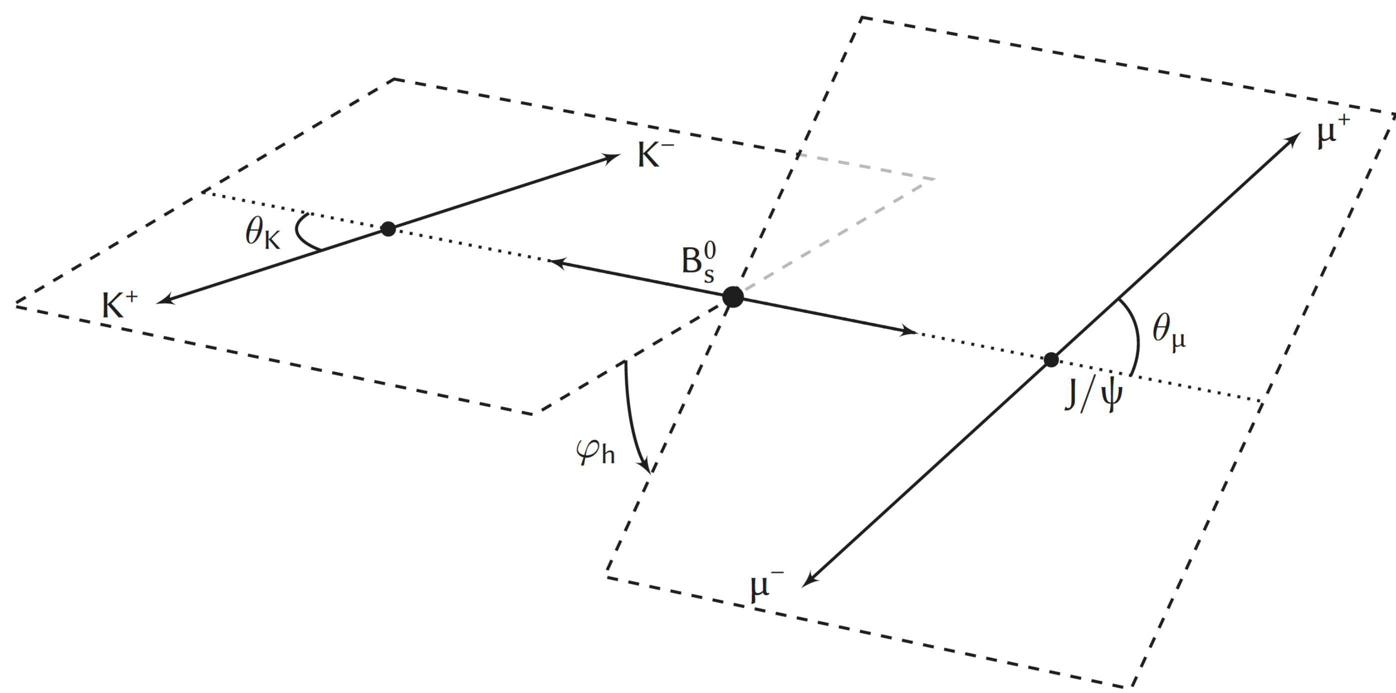
1. measure decay rate $B_s^0, \overline{B_s^0}$
2. know initial flavour $B_s^0 \,||\, \overline{B_s^0}$
3. good decay time resolution
4. angular dependence



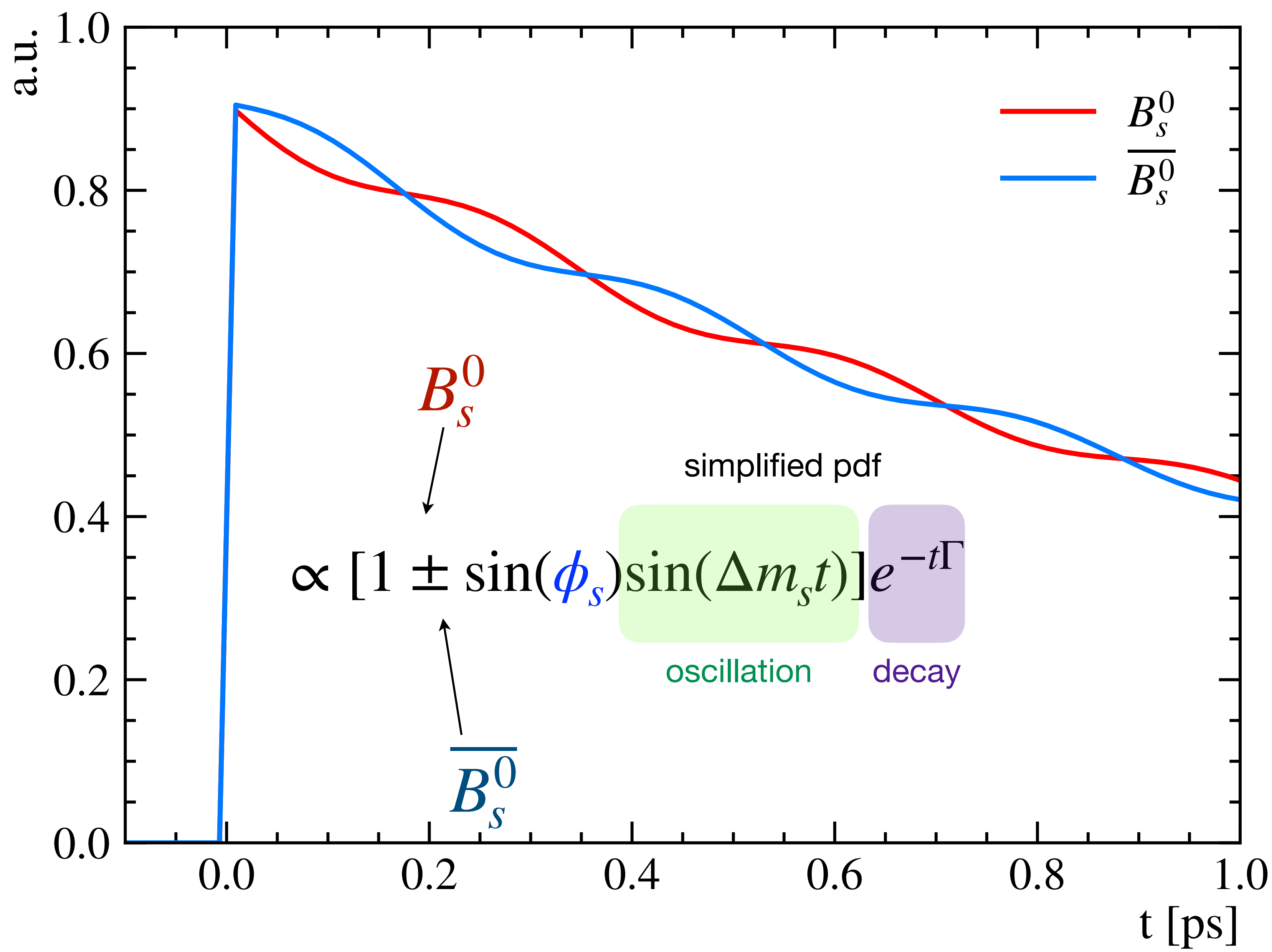
Helicity angles



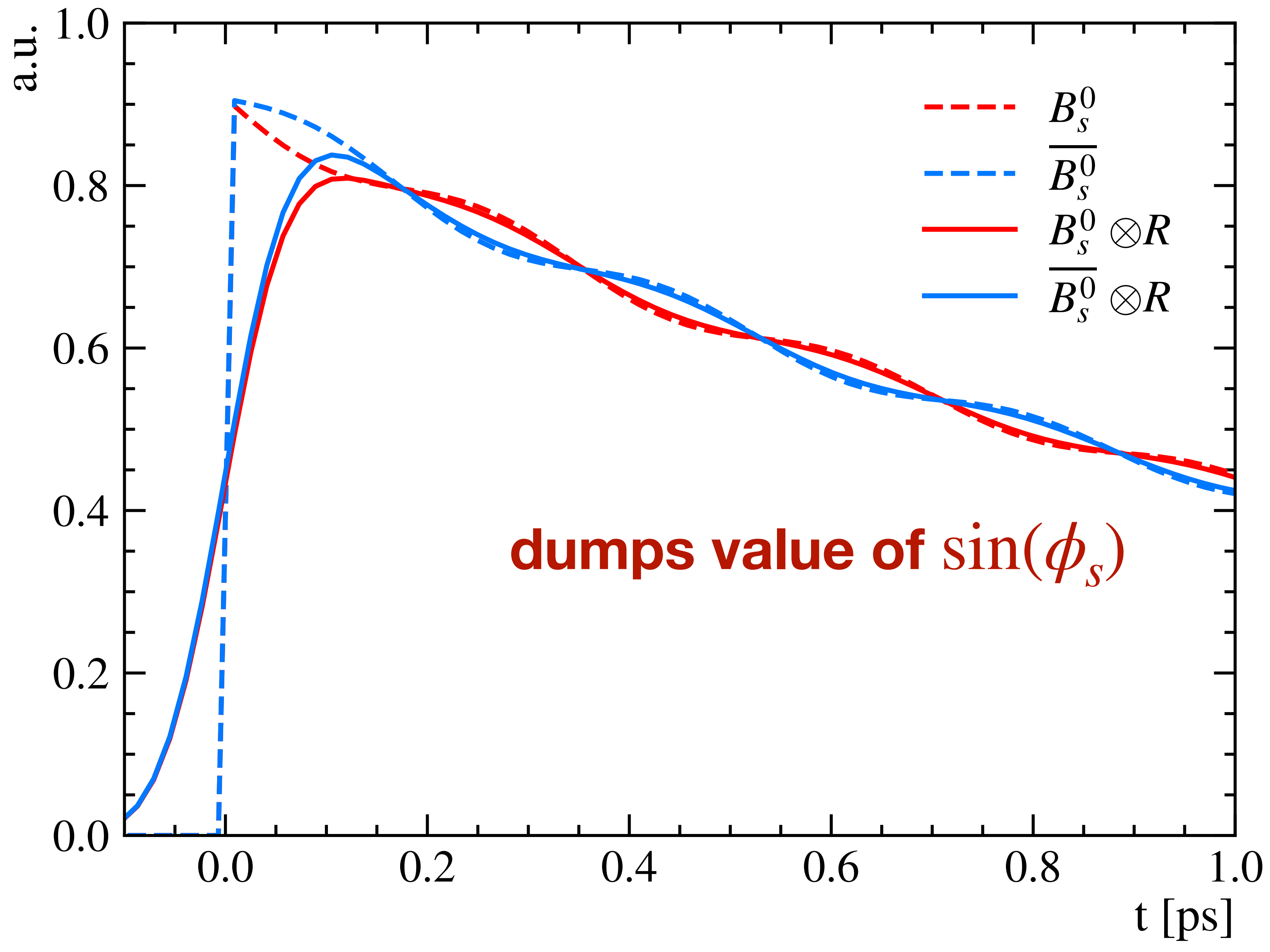
Helicity angles



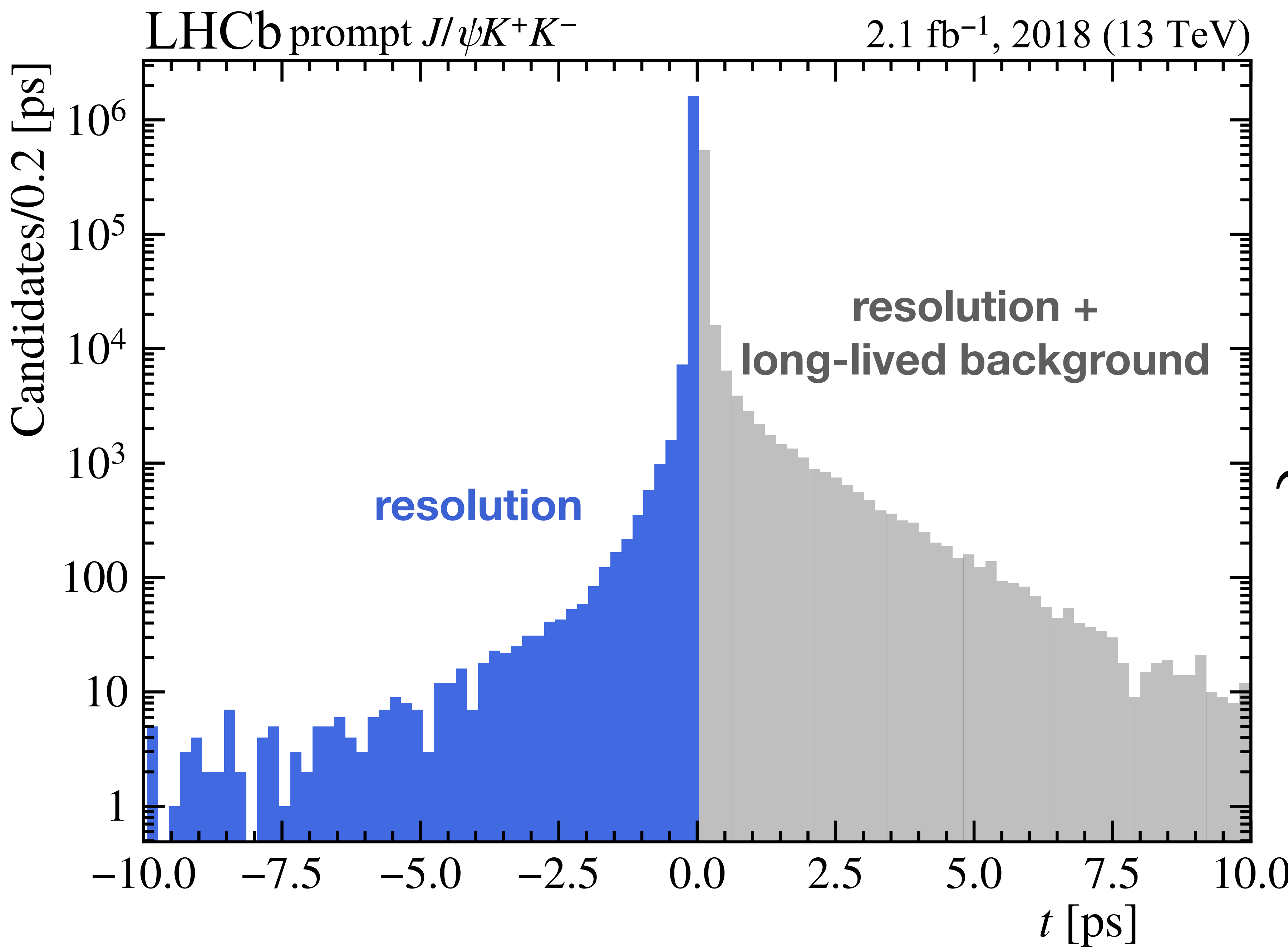
2. Decay time resolution OFF



2. Decay time resolution ON



2. Decay time resolution

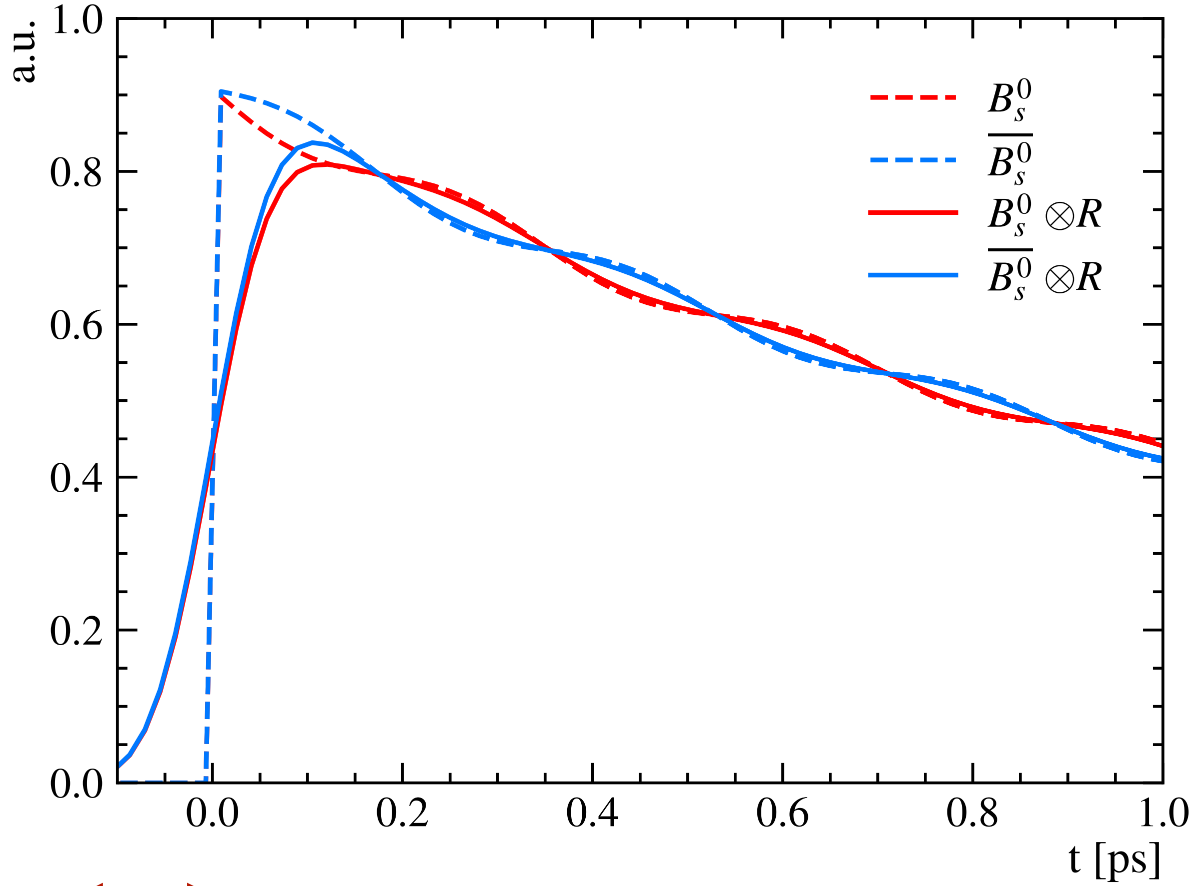


~ 42 [fs]

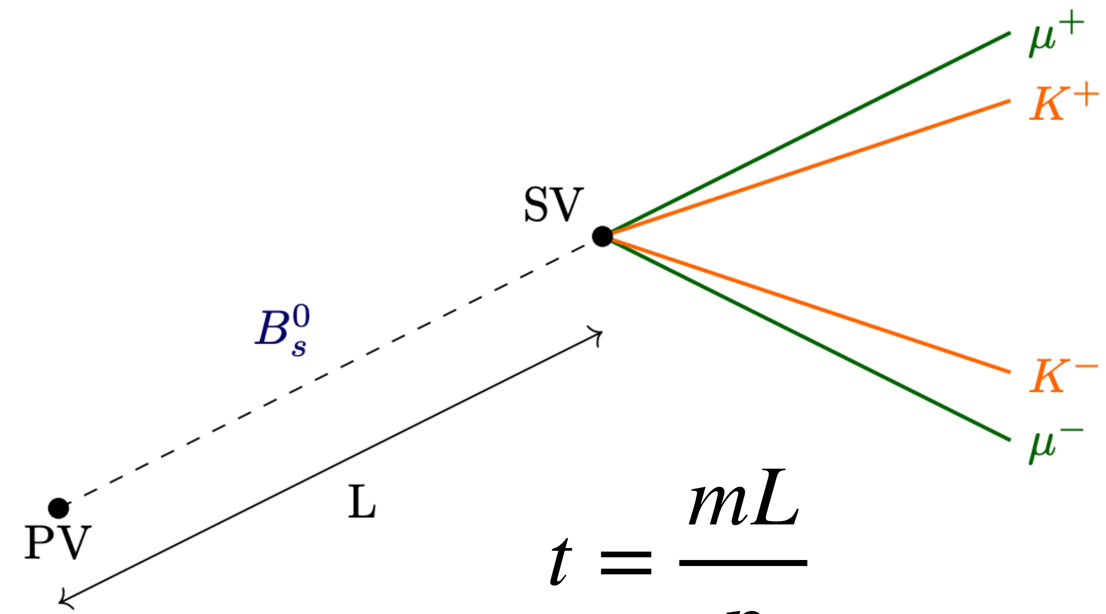
Key assumption:

resolution matters for oscillations, but not for lifetimes!

Negative times from time resolution



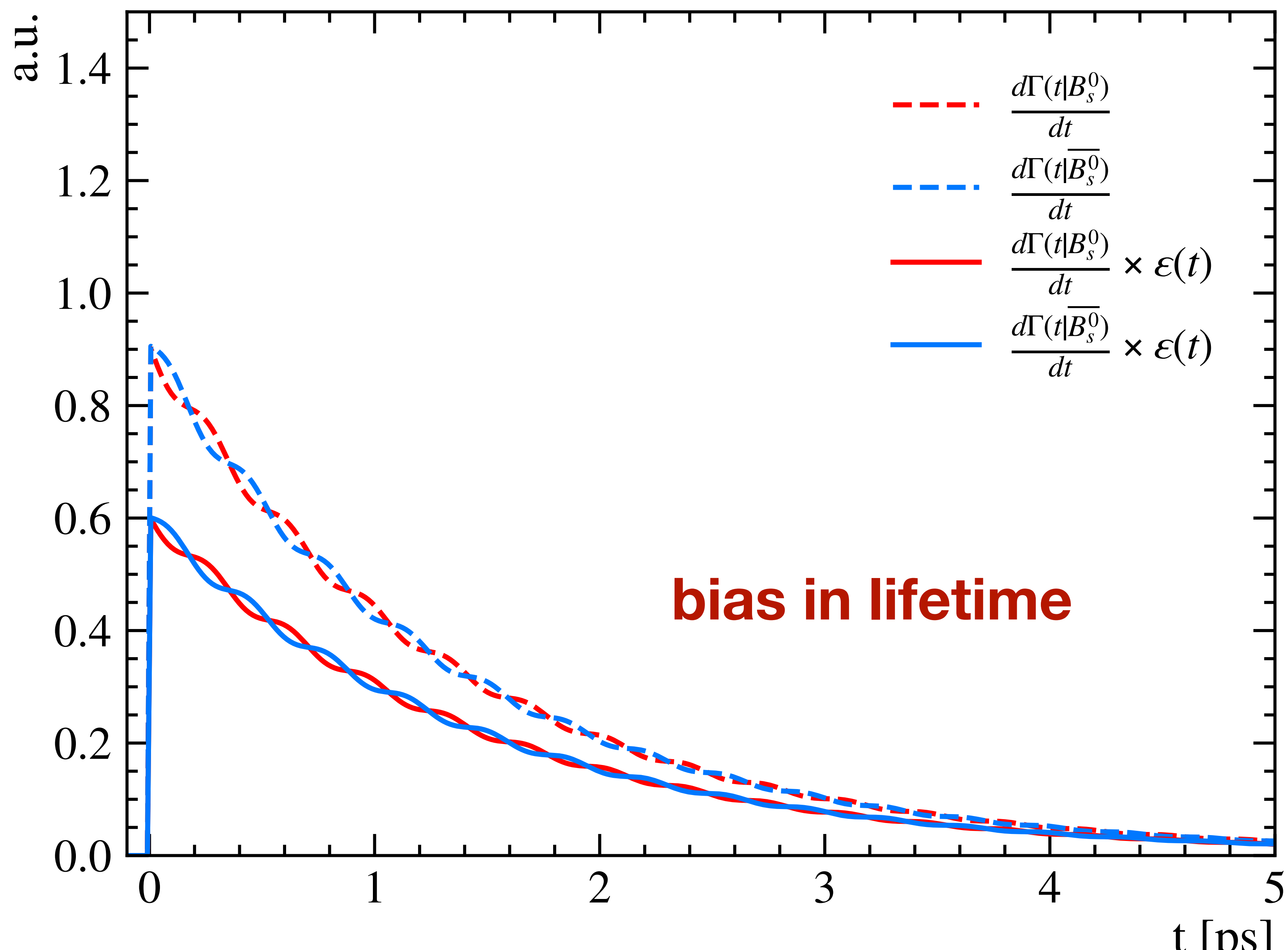
negative times



$$t = \frac{mL}{p}$$

3. Detector effects: resolutions and acceptances

2. Decay time acceptance

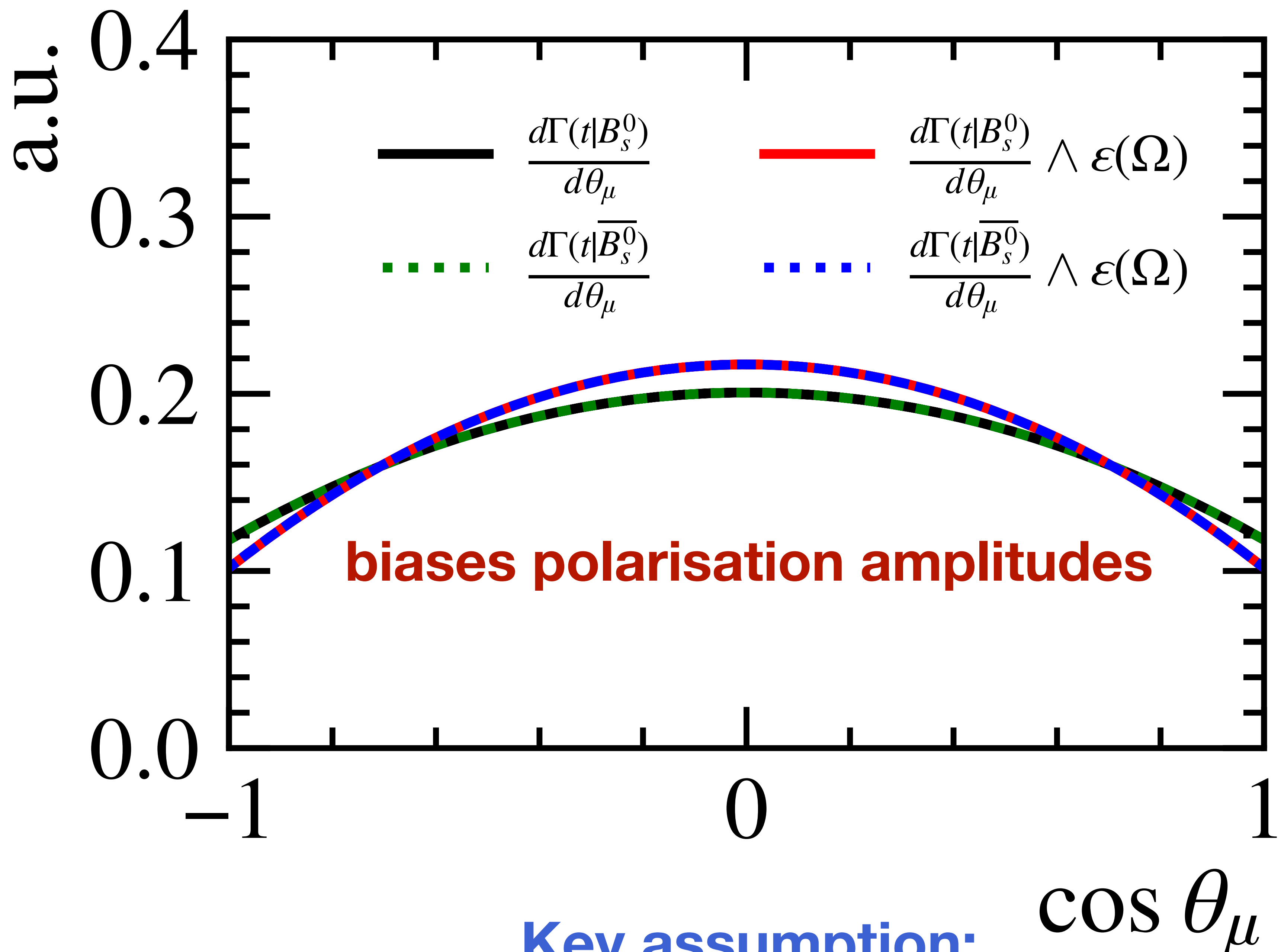


Key assumption:

angular and decay time acceptances are independent

3. Detector effects: resolutions and acceptances

3. Angular acceptance



Key assumption:

angular and decay time acceptances are independent

Assuming no NP is in the higher order contributions

$\phi_s = -0.039 \pm 0.022(stat.) \pm 0.006(syst.)$ [rad]
arXiv:2308.01468

?

$$\phi_s^{eff} = \phi_s^{SM} + \Delta\phi_s^{SM,HO} + \phi_s^{NP}$$

$\phi_s^{SM} = -0.036^{+0.0006}_{-0.0009}$
CKM Fitter 2021, Eur. Phys. J. C (2005) 41: 131

$\Delta\phi_s^{SM,HO} = -0.003^{+0.0010}_{-0.0012}$ [rad]
M.Z.Barel, K.DeBruyn, R.Fleischer, E.Malami, J.Phys. G (2021) 48: 6

No polarisation dependence is observed
arXiv:2308.01468

Meta analysis