Time dependent CP violation of B^0_s mesons

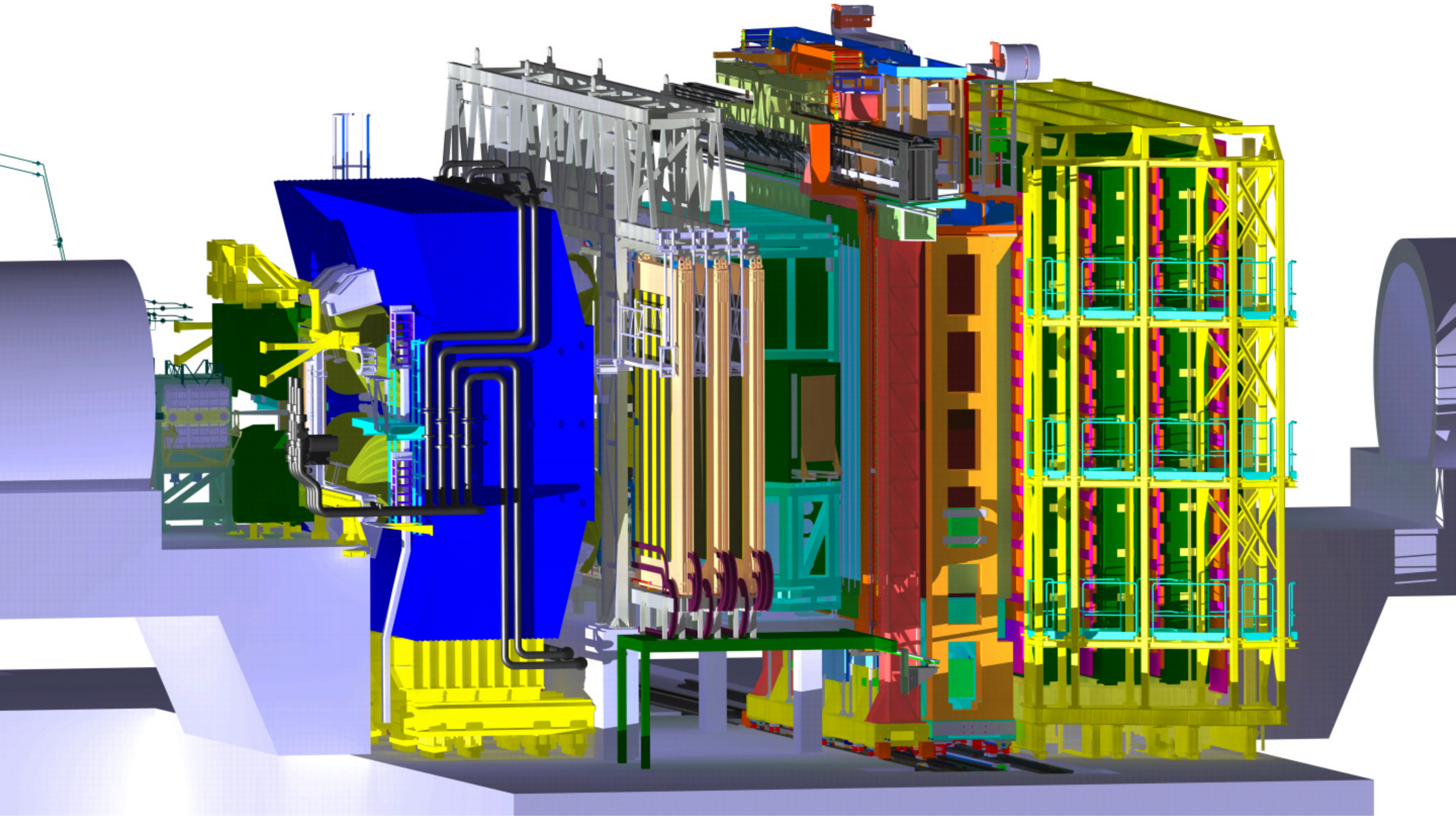
Katya Govorkova

Nikhef

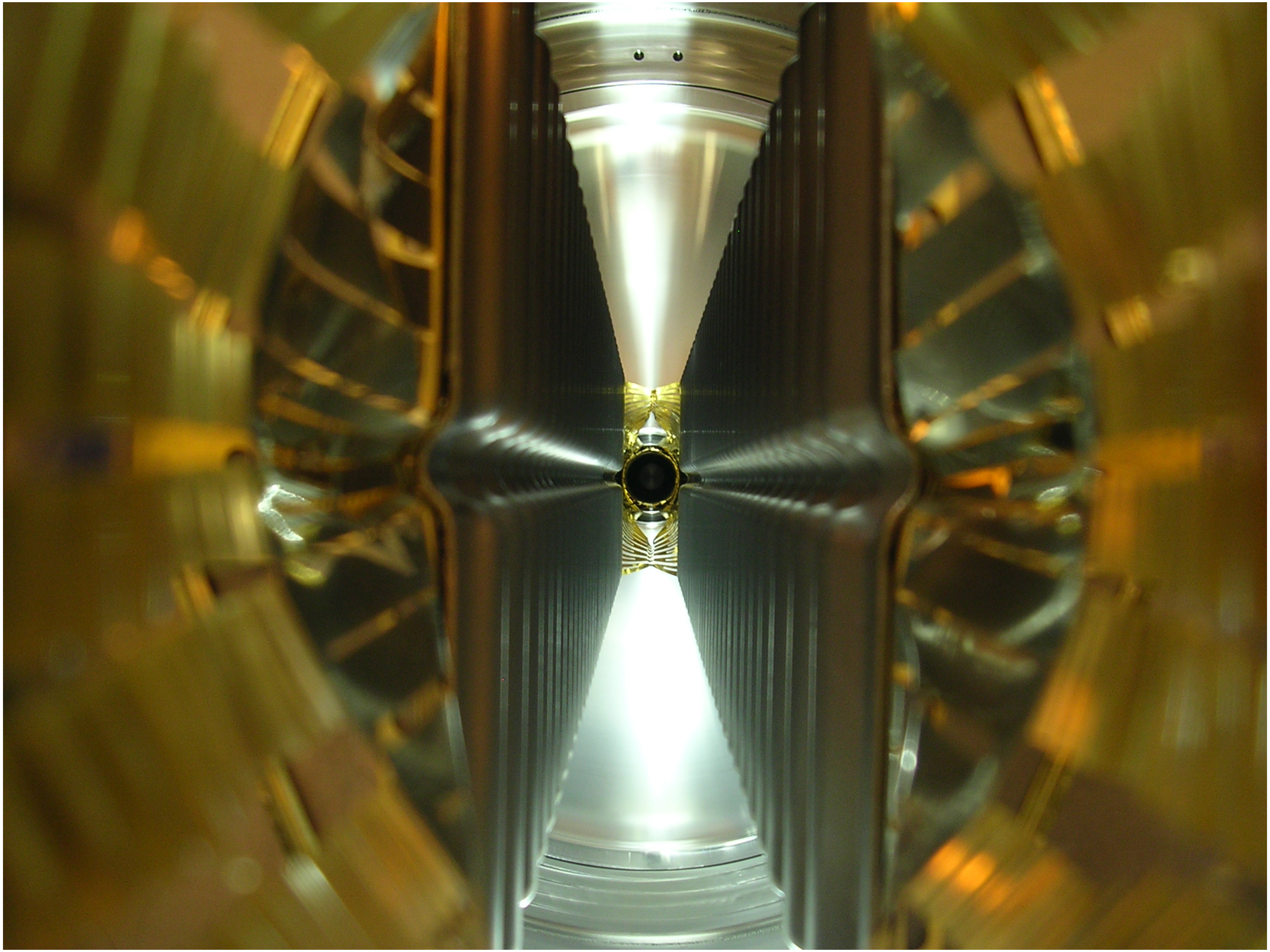
Jamboree@Utrecht

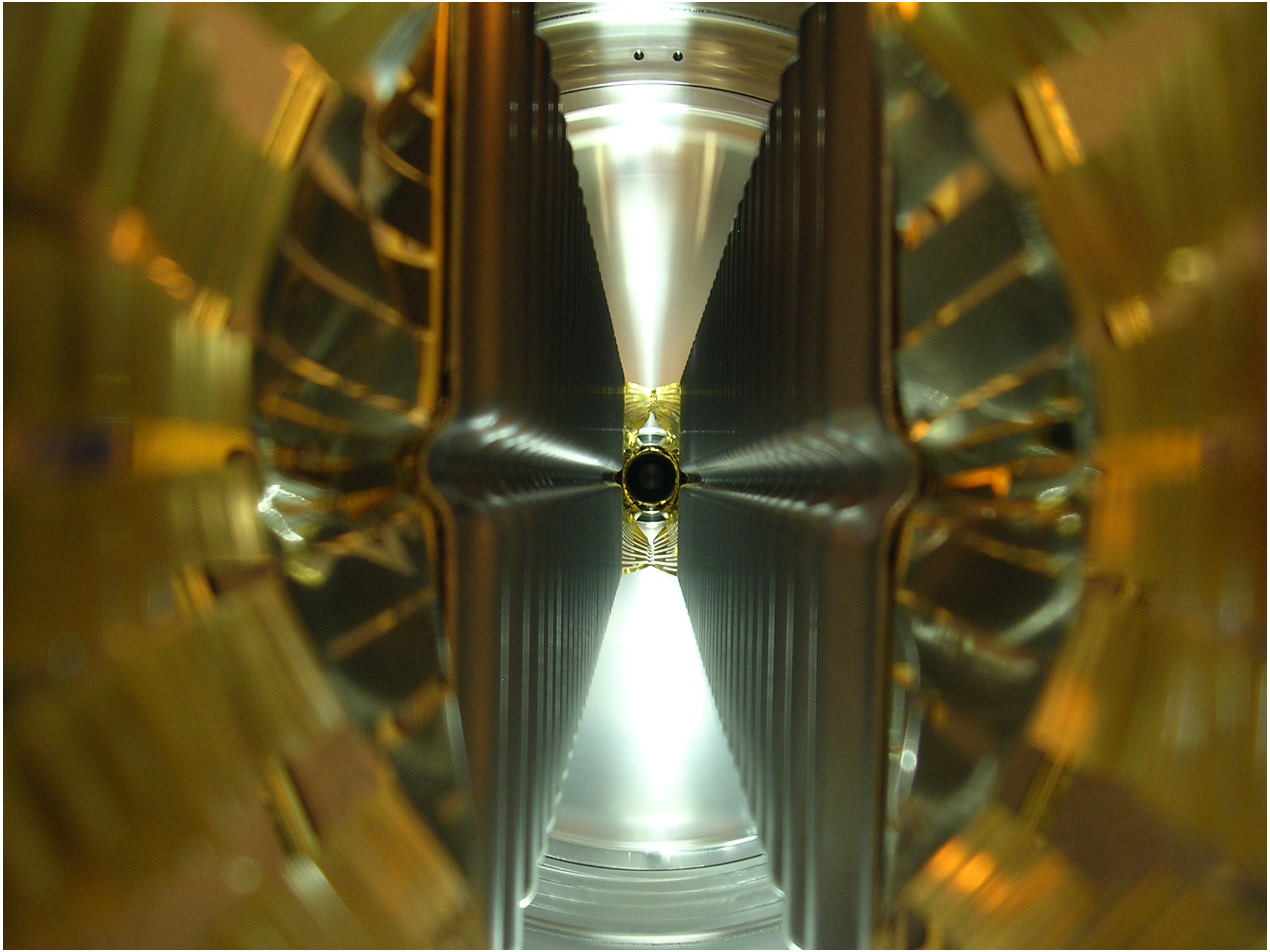
17 December 2018

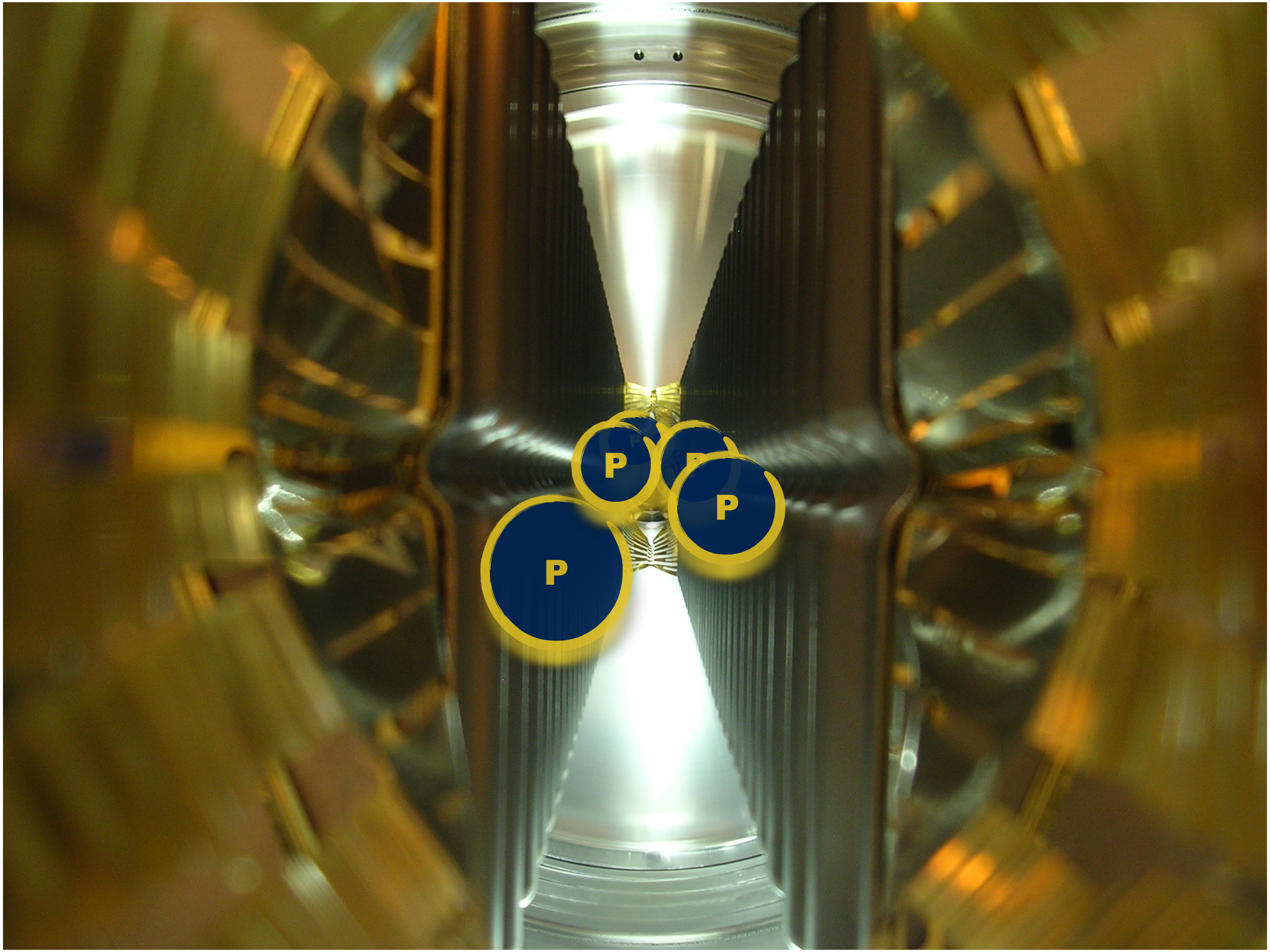
LHCb experiment



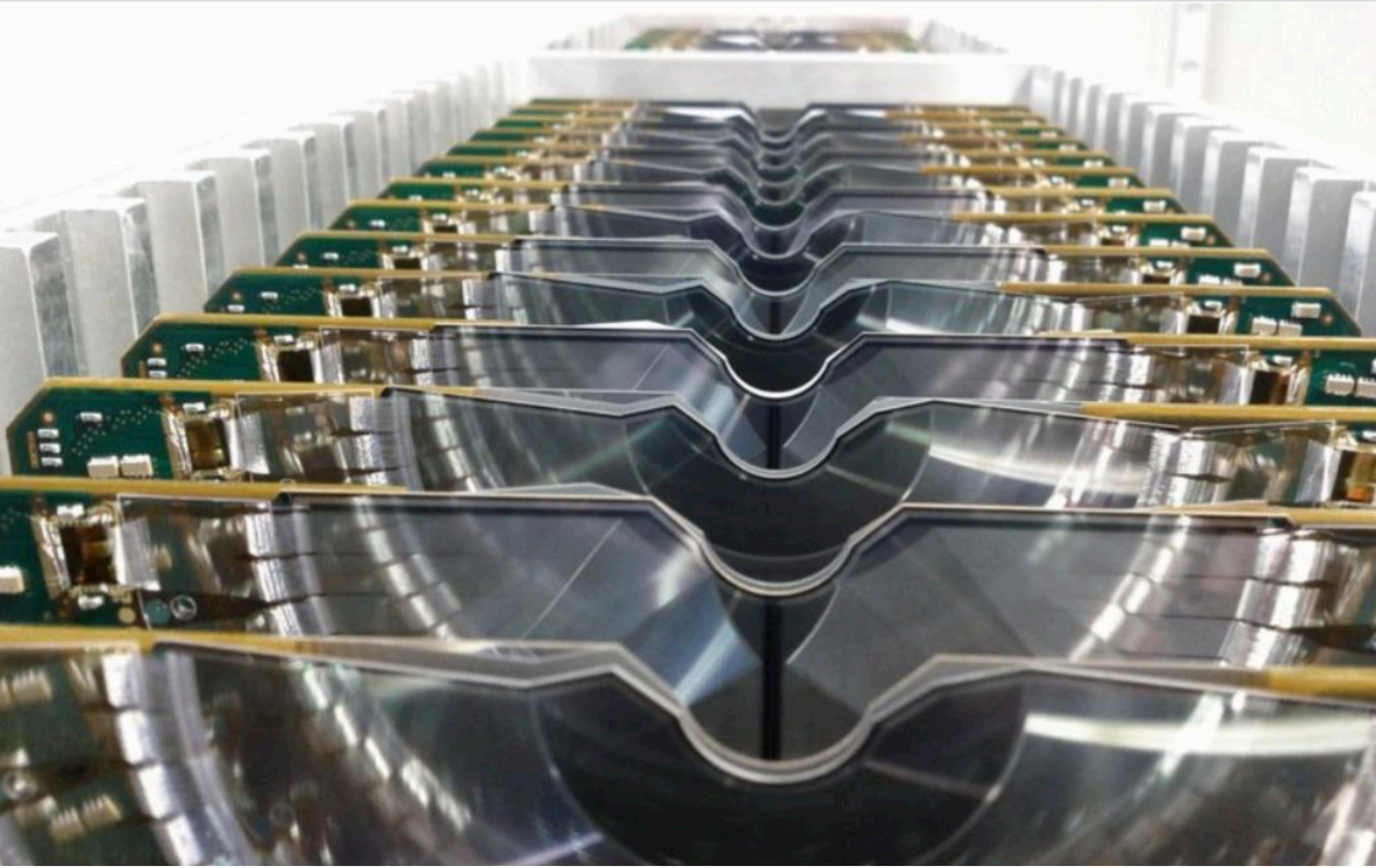
LHCb experiment



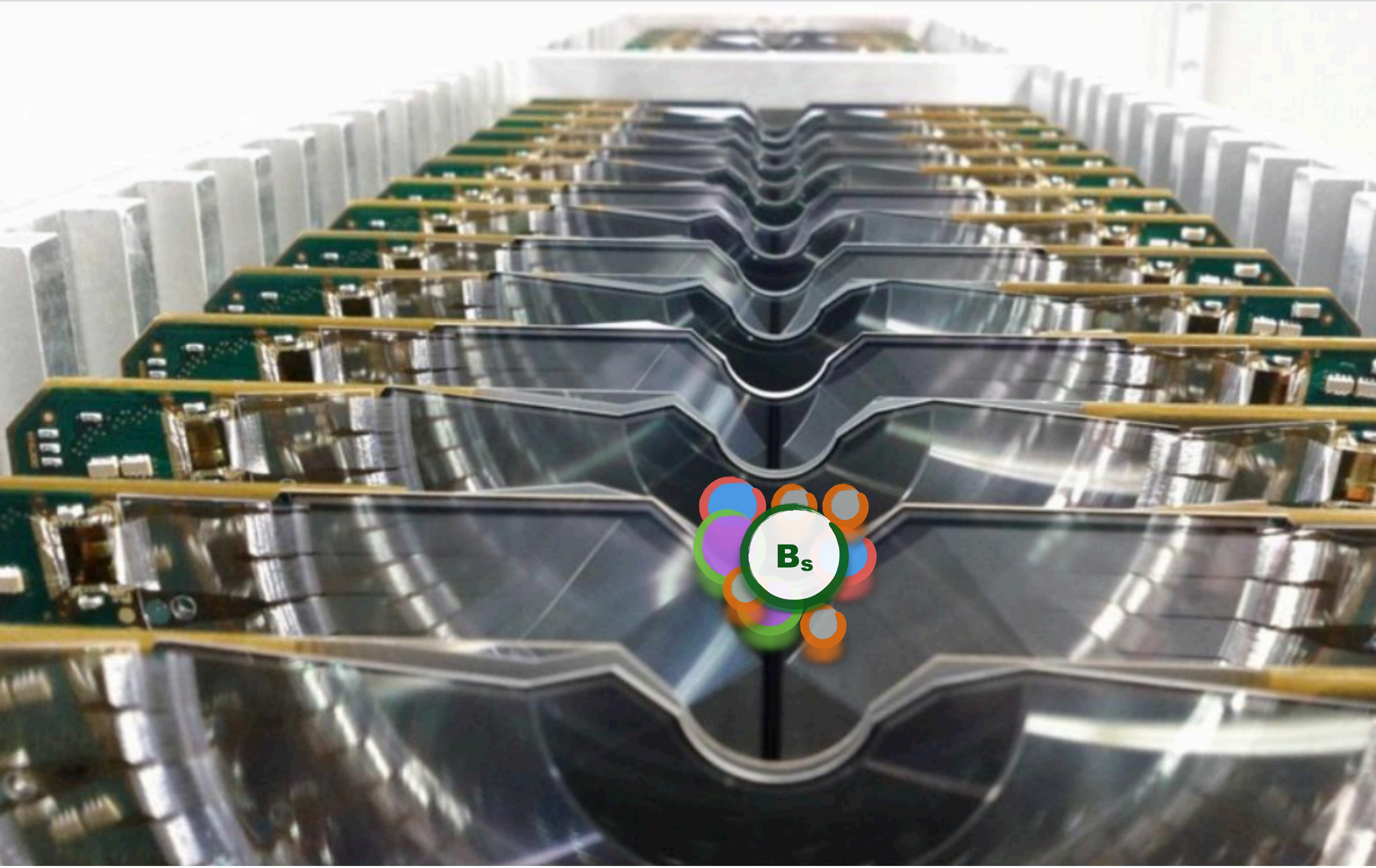



P
P
P
P

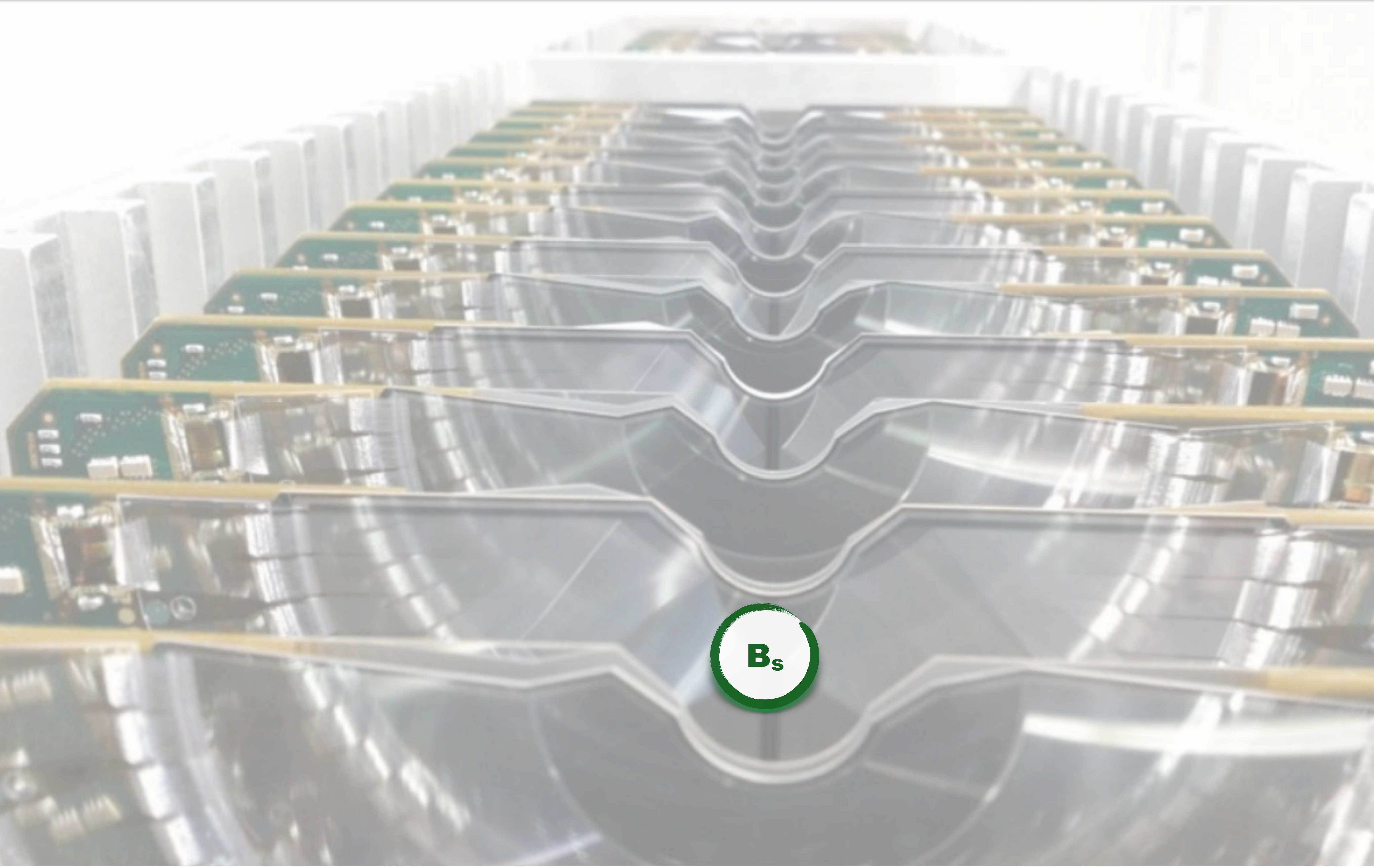
pp collision in VeLo



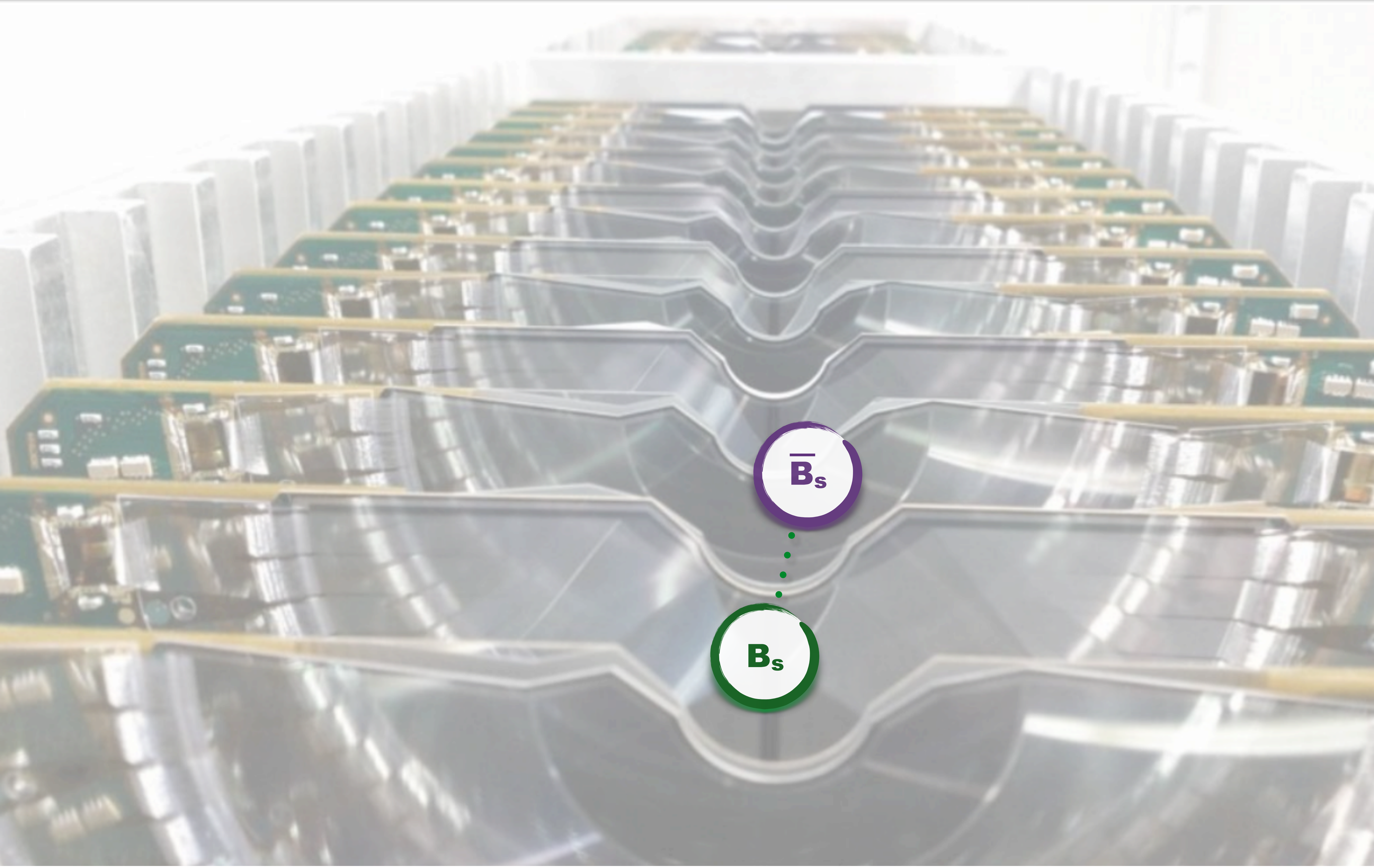
pp collision in VeLo

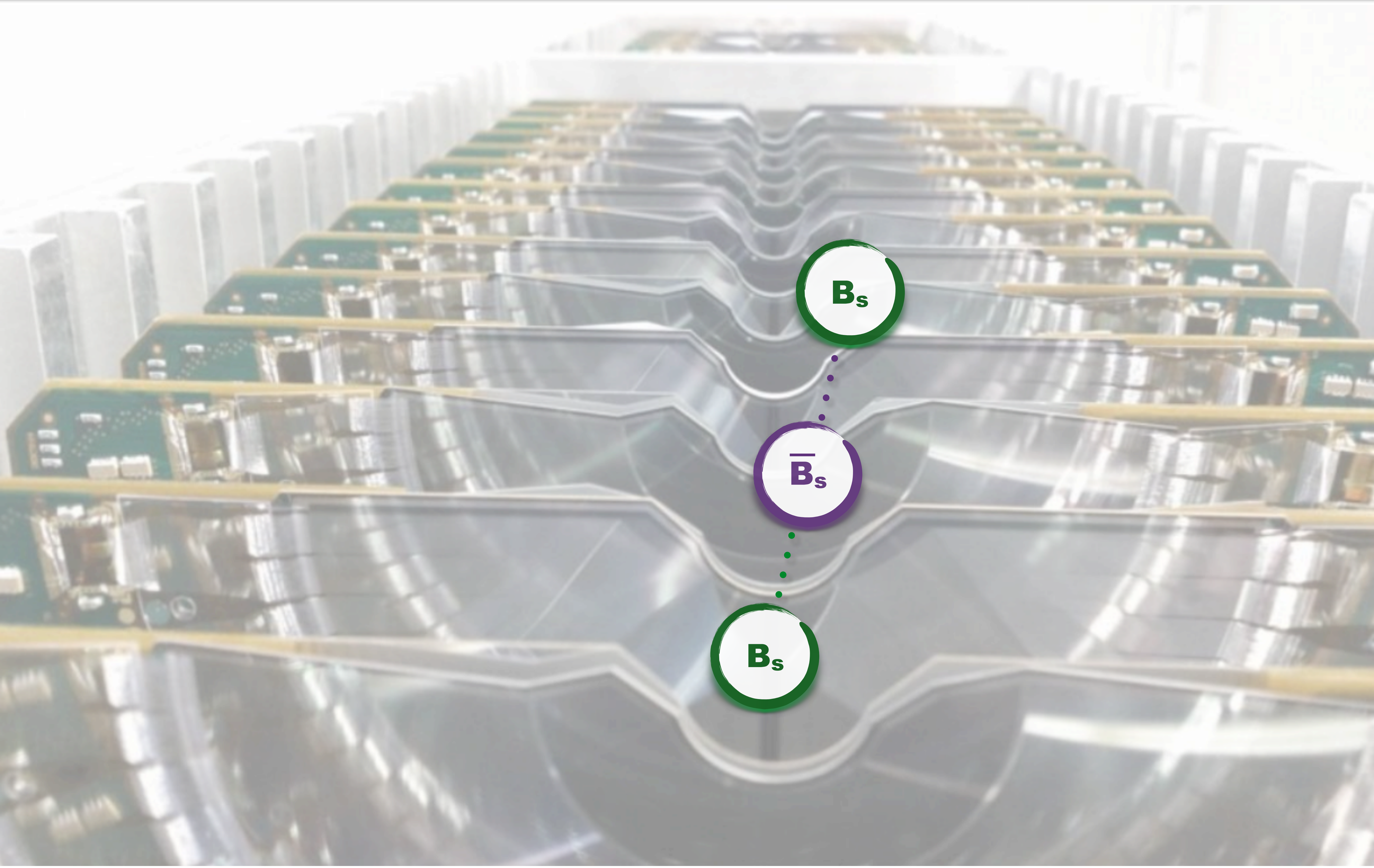


B_s-meson oscillations



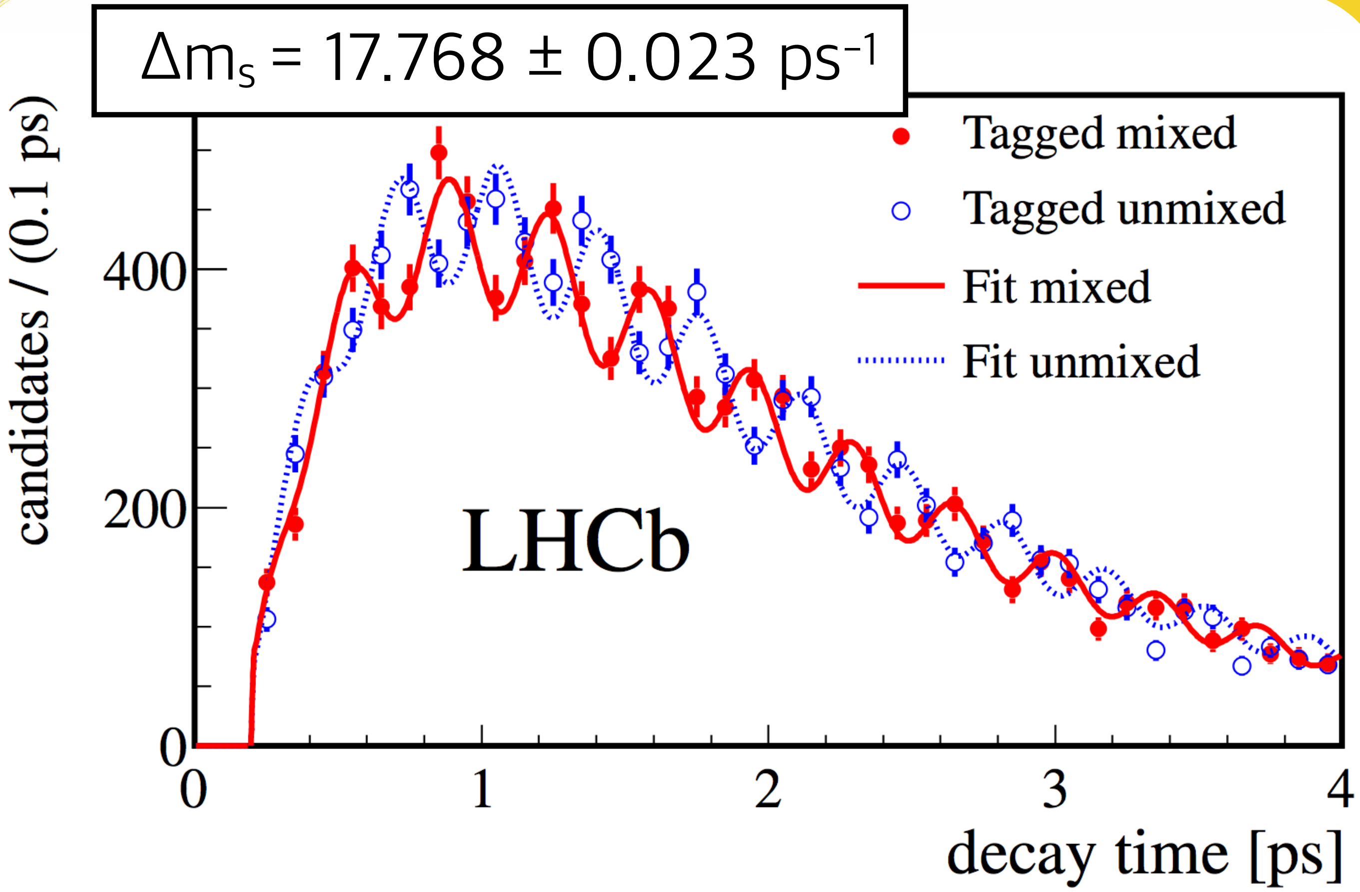
B_s-meson oscillations



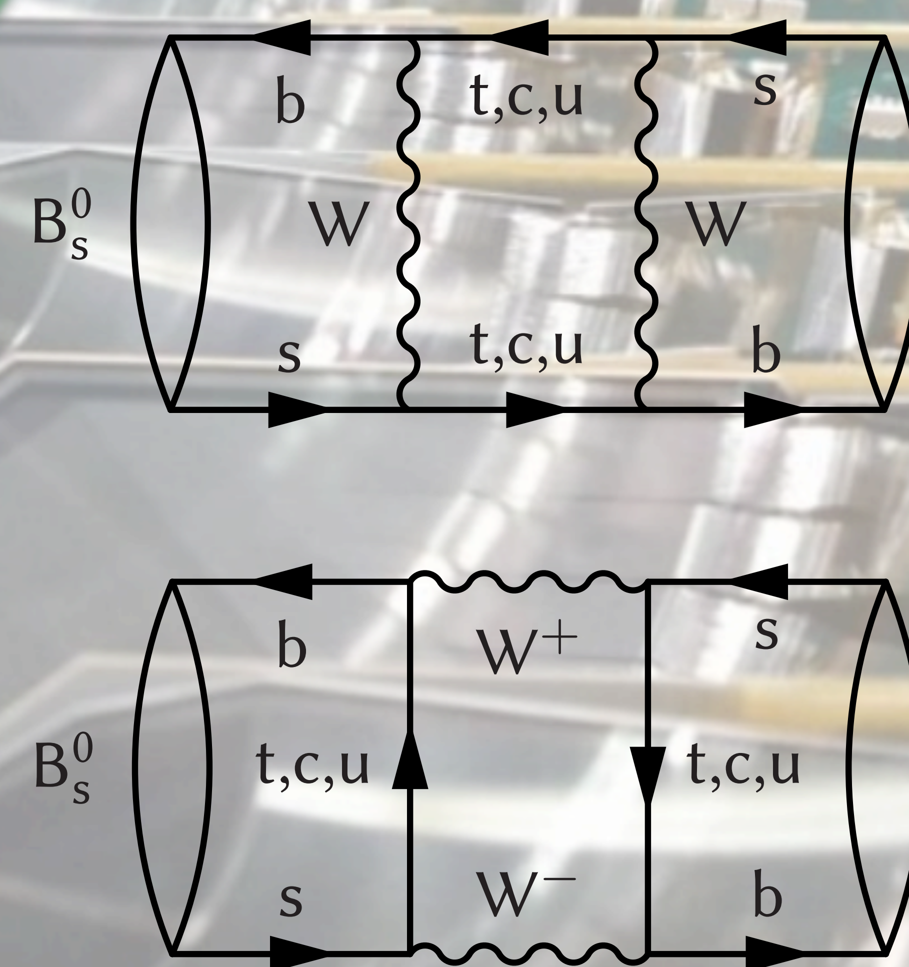


B_s
$\bar{B}_s$
B_s

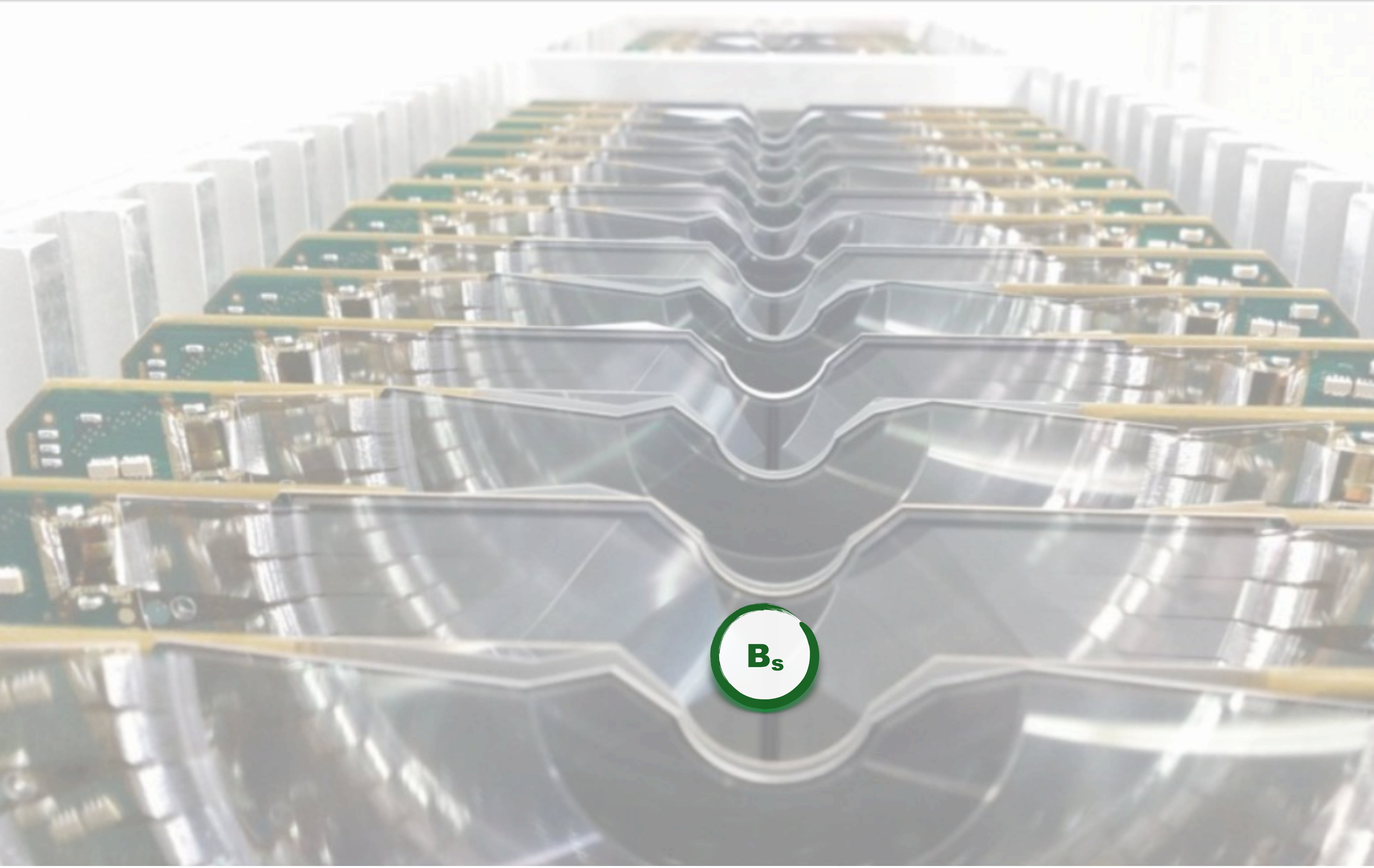
B_s-meson oscillations



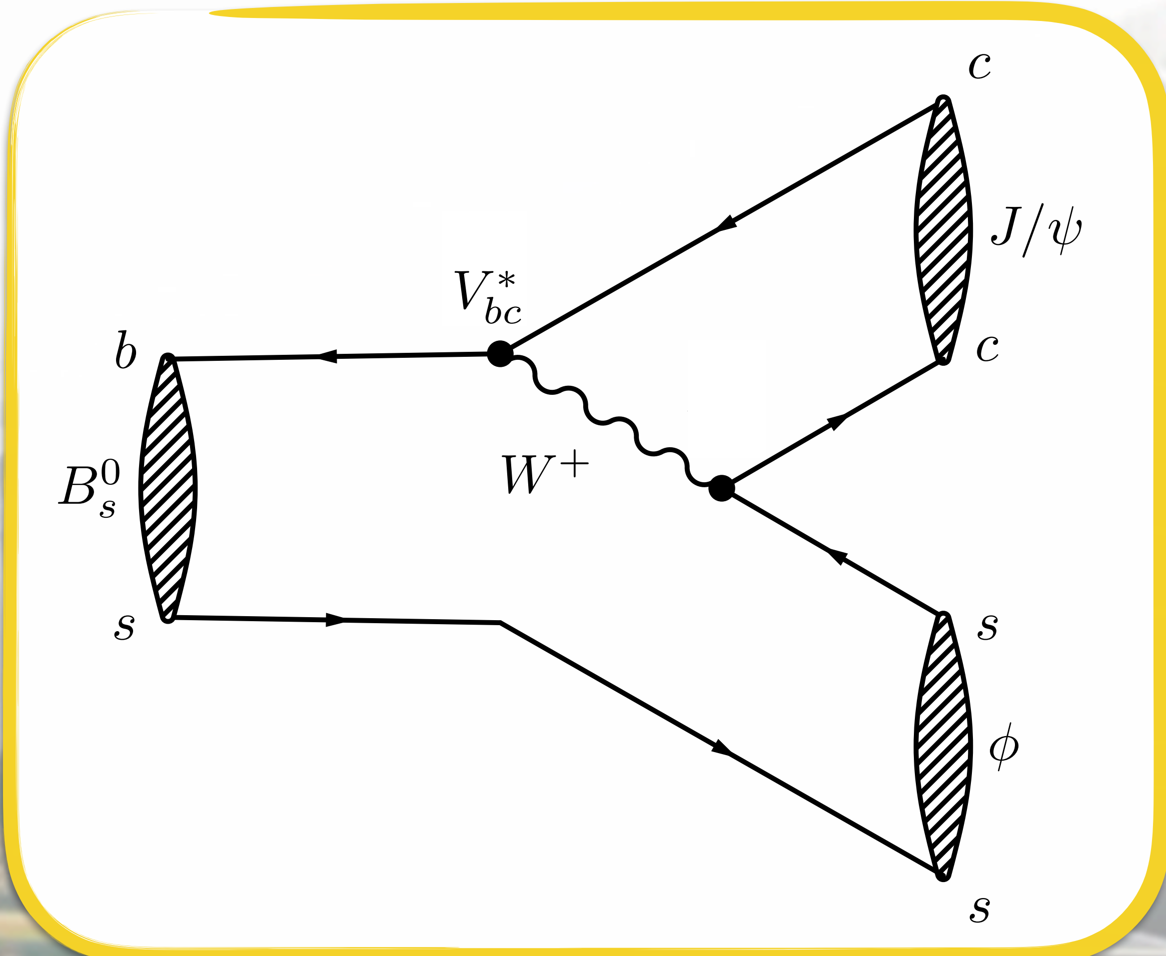
[New J. Phys. 15 (2013) 053021]

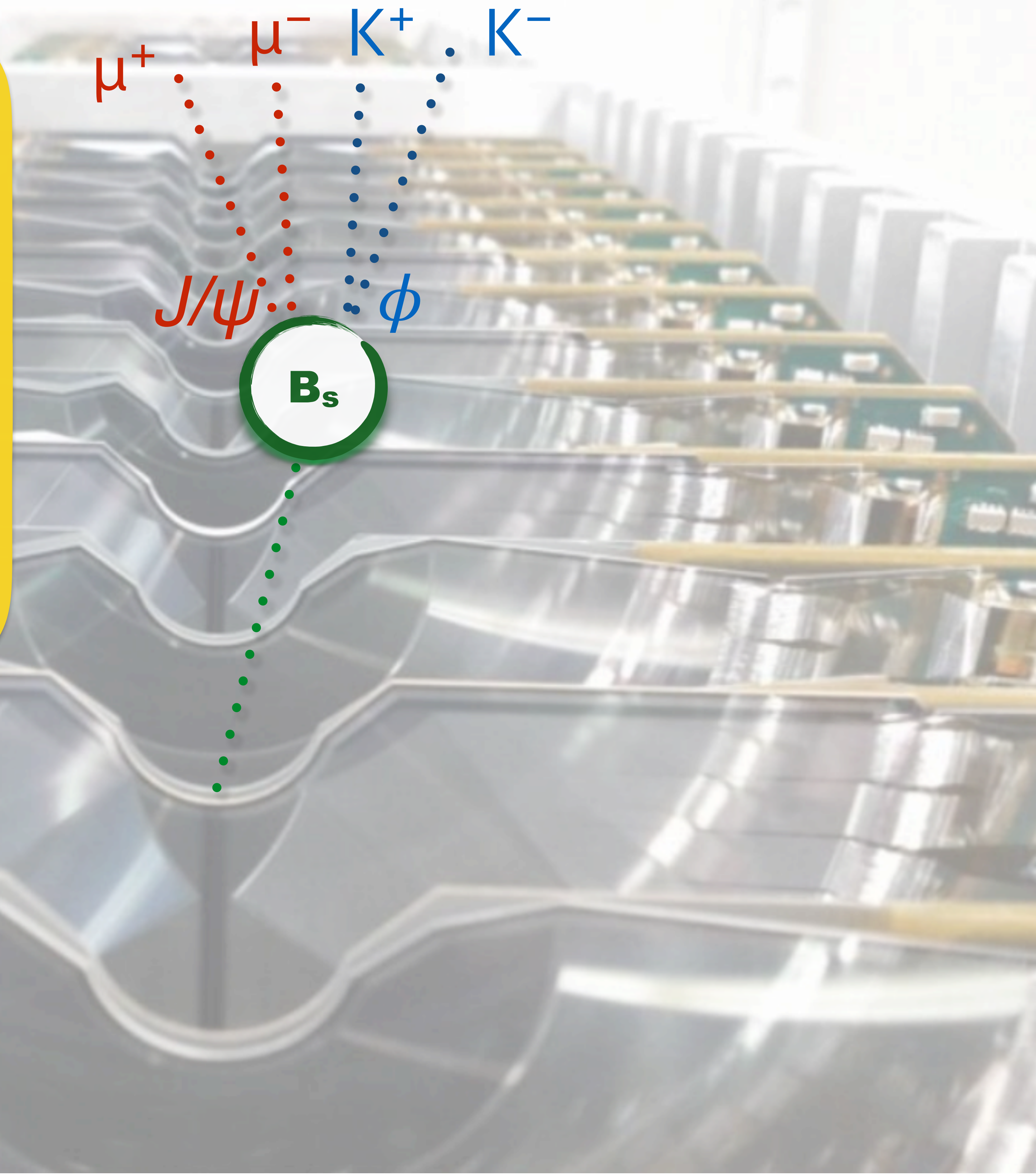


The $B_s \to J/\psi\ \phi$ decay

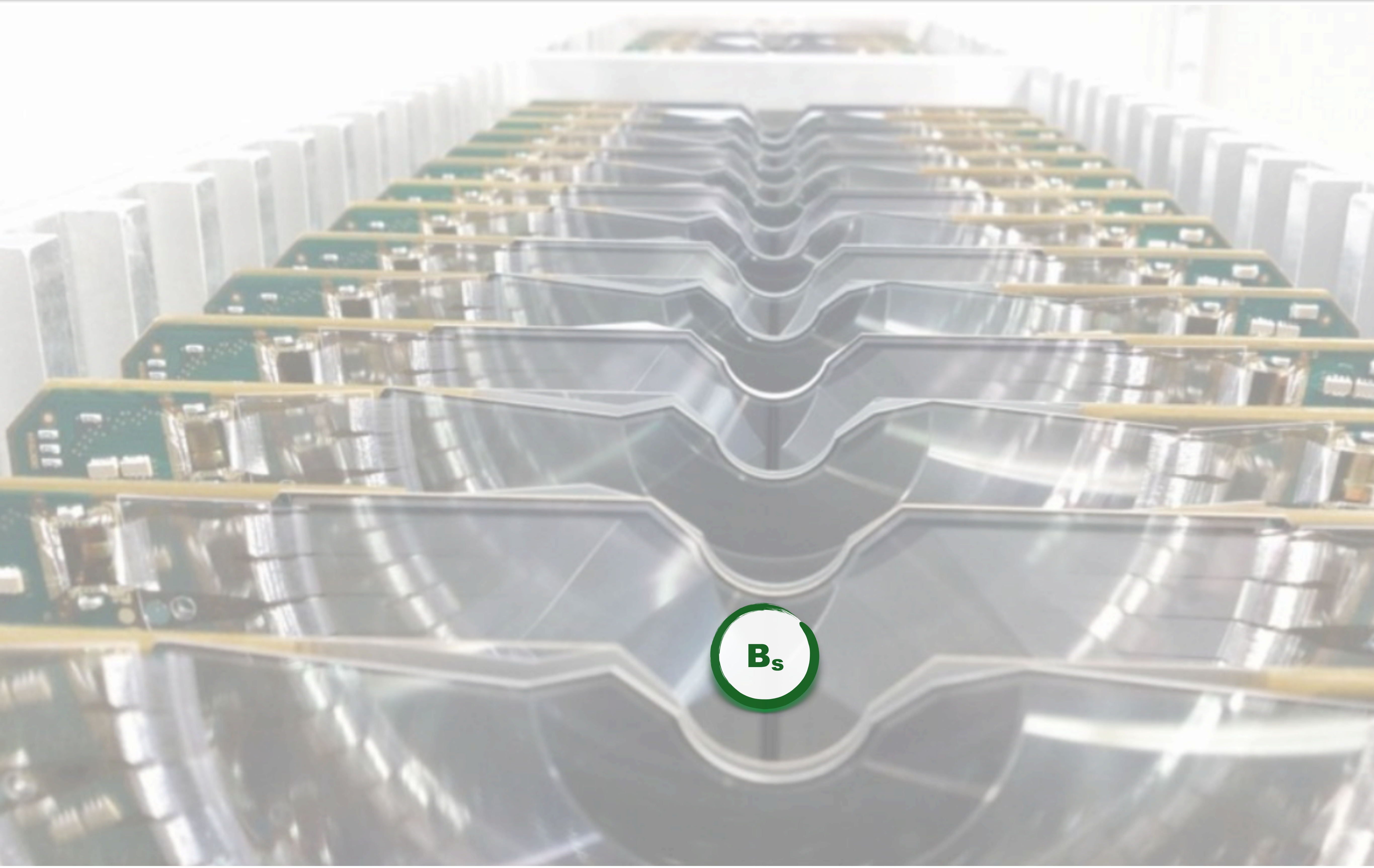


The $B_s \to J/\psi\, \phi$ decay

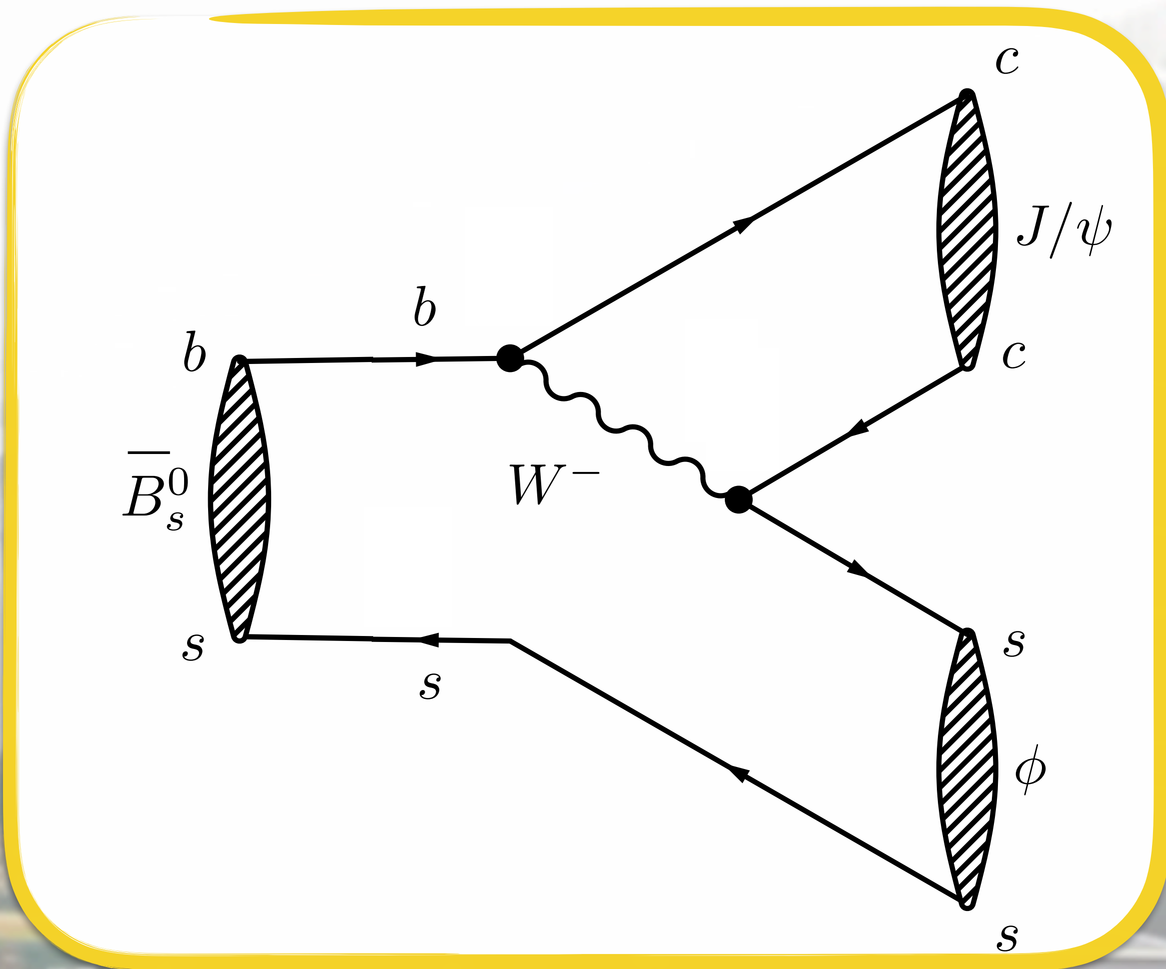


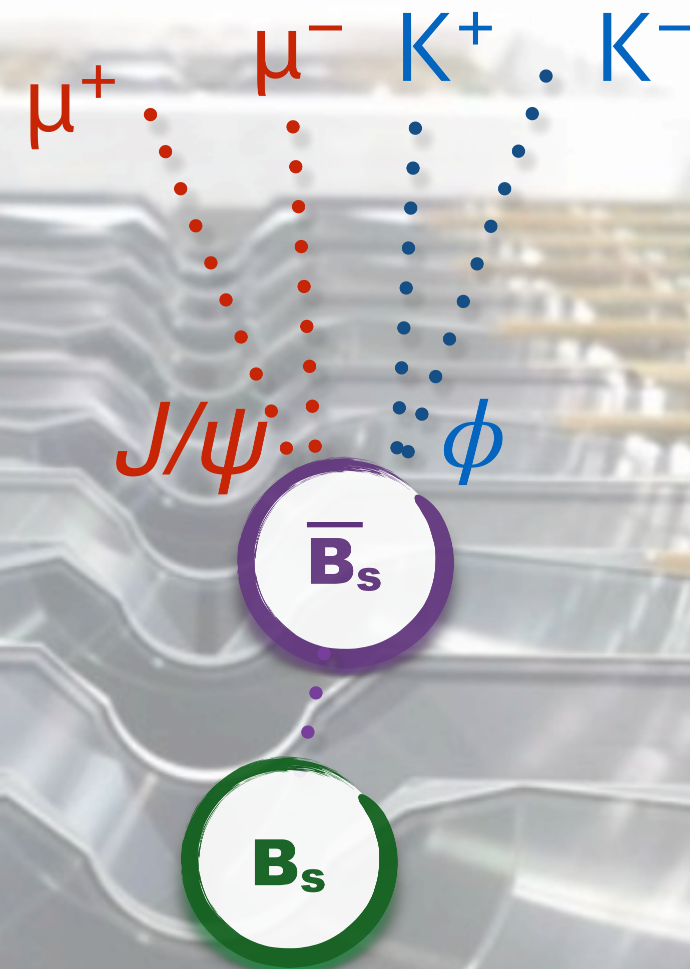


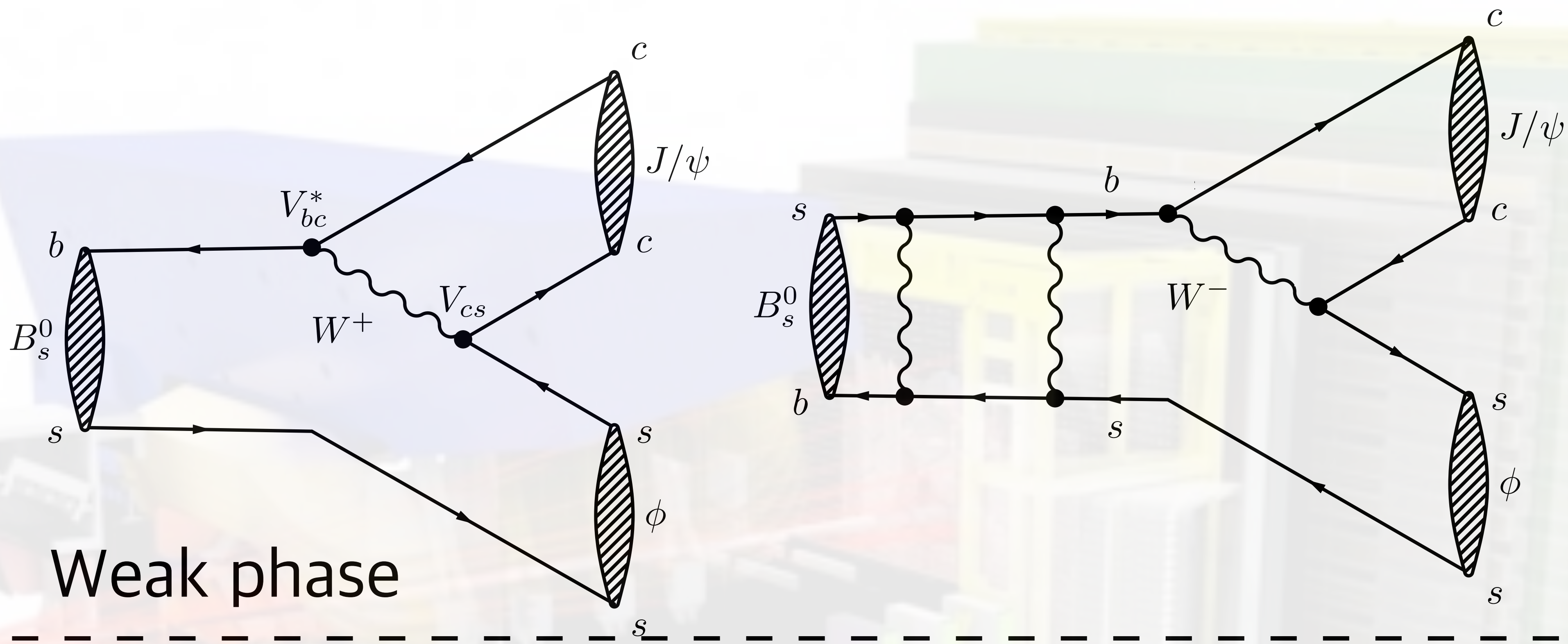
The $B_s \to J/\psi\ \phi$ decay



The $B_s \to J/\psi\ \phi$ decay







CP

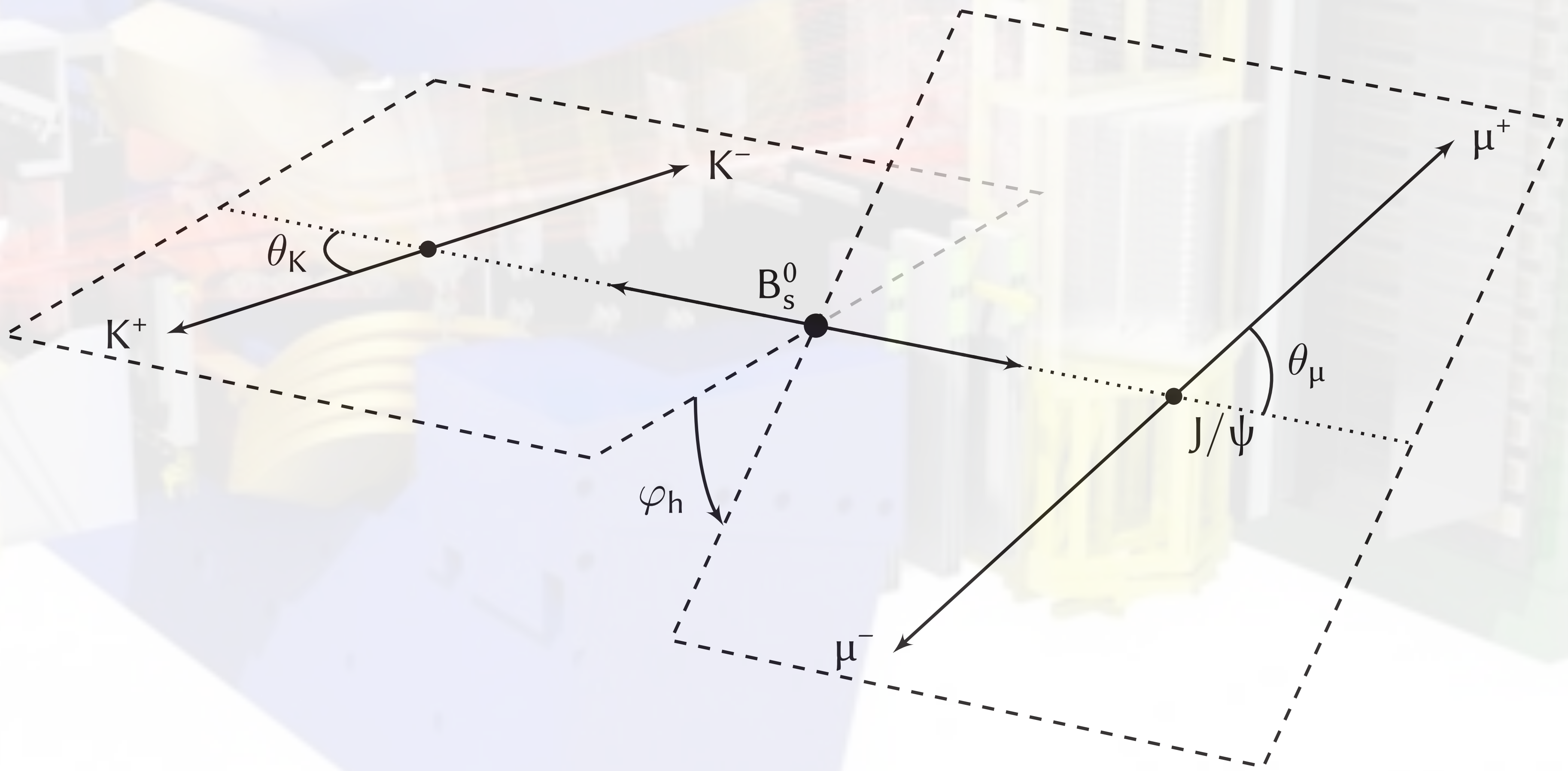
Weak phase

- Weak phase

Two components: CP-even and CP-odd

$$\mathrm{CP}|J/\psi\phi\rangle_l = (-1)^l|J/\psi\phi\rangle_l$$

Four amplitudes: $A_{||}$ $A_{\perp}$ A_0 and A_S



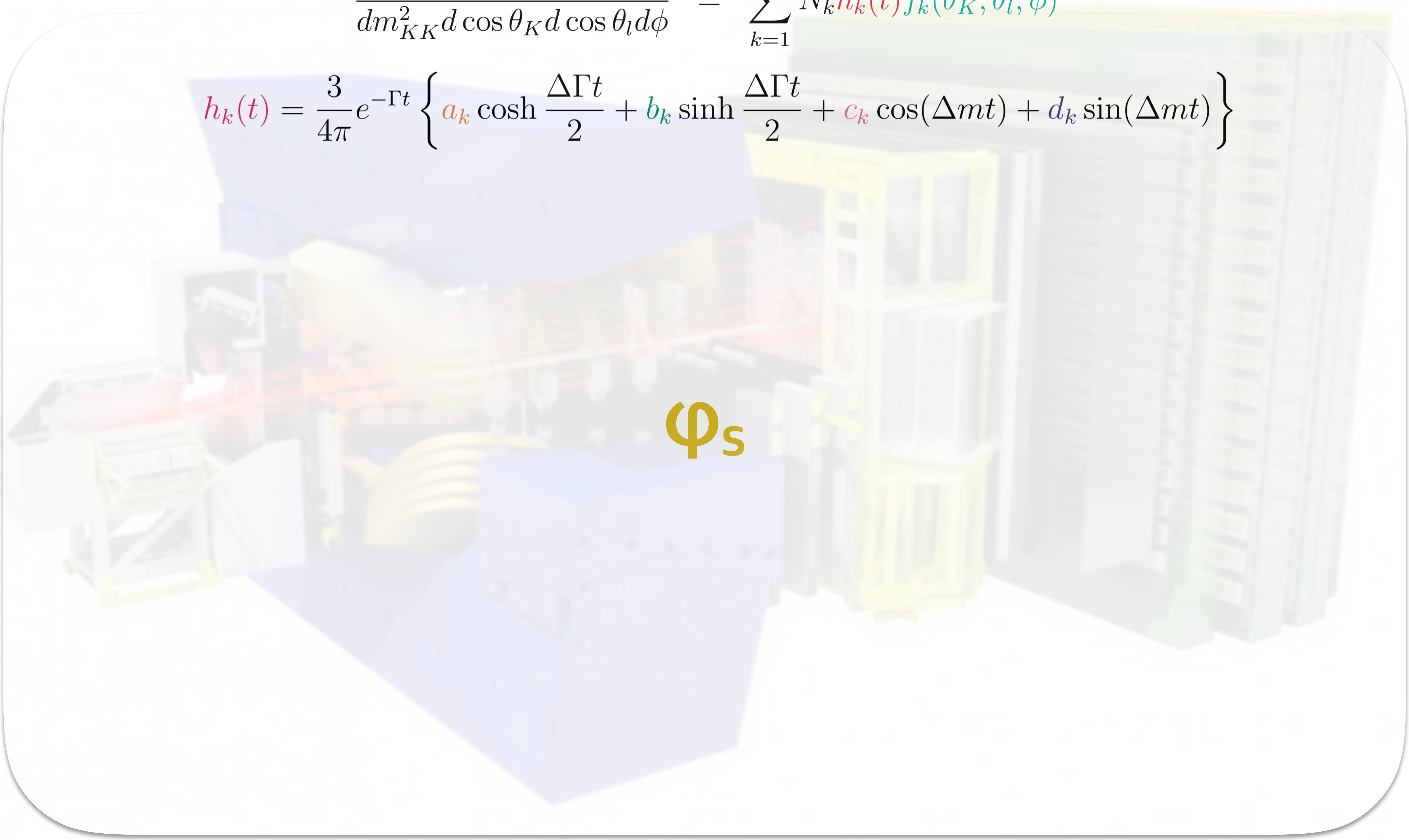
$$\frac{d^4\Gamma(t)}{dm^2_{KK}\,d\cos\theta_K\,d\cos\theta_l\,d\phi} = \sum_{k=1}^{10} N_k h_k(t) f_k(\theta_K,\theta_l,\phi)$$

$$h_k(t) = \frac{3}{4\pi}e^{-\Gamma t}\left\{a_k\cosh\frac{\Delta\Gamma t}{2} + b_k\sinh\frac{\Delta\Gamma t}{2} + c_k\cos(\Delta m t) + d_k\sin(\Delta m t)\right\}$$

	f_k	N_k	a_k	b_k	c_k	d_k
1	$c_K^2 s_l^2$	$\lvert A_0\rvert^2$	$\frac{1}{2}(1+\lvert\lambda_0\rvert^2)$	$-\lvert\lambda_0\rvert\cos(\phi_0)$	$\frac{1}{2}(1-\lvert\lambda_0\rvert^2)$	$\lvert\lambda_0\rvert\sin(\phi_0)$
2	$\frac{1}{2}s_K^2(1-c_\phi^2 s_l^2)$	$\lvert A_{\|\|}\rvert^2$	$\frac{1}{2}(1+\lvert\lambda_{\|\|}\rvert^2)$	$-\lvert\lambda_{\|\|}\rvert\cos(\phi_{\|\|})$	$\frac{1}{2}(1-\lvert\lambda_{\|\|}\rvert^2)$	$\lvert\lambda_{\|\|}\rvert\sin(\phi_{\|\|})$
3	$\frac{1}{2}s_K^2(1-s_\phi^2 s_l^2)$	$\lvert A_\perp\rvert^2$	$\frac{1}{2}(1+\lvert\lambda_\perp\rvert^2)$	$\lvert\lambda_\perp\rvert\cos(\phi_\perp)$	$\frac{1}{2}(1-\lvert\lambda_\perp\rvert^2)$	$-\lvert\lambda_\perp\rvert\sin(\phi_\perp)$
4	$s_K^2 s_l^2 s_\phi c_\phi$	$\lvert A_\perp A_{\|\|}\rvert$	$\frac{1}{2}\Big[\sin(\delta_\perp-\delta_{\|\|})-\lvert\lambda_\perp\lambda_{\|\|}\rvert\,\sin(\delta_\perp-\delta_{\|\|}-\phi_\perp+\phi_{\|\|})\Big]$	$\frac{1}{2}\Big[\lvert\lambda_\perp\rvert\sin(\delta_\perp-\delta_{\|\|}-\phi_\perp)+\lvert\lambda_{\|\|}\rvert\sin(\delta_{\|\|}-\delta_\perp-\phi_{\|\|})\Big]$	$\frac{1}{2}\Big[\sin(\delta_\perp-\delta_{\|\|})+\lvert\lambda_\perp\lambda_{\|\|}\rvert\,\sin(\delta_\perp-\delta_{\|\|}-\phi_\perp+\phi_{\|\|})\Big]$	$-\frac{1}{2}\Big[\lvert\lambda_\perp\rvert\cos(\delta_\perp-\delta_{\|\|}-\phi_\perp)+\lvert\lambda_{\|\|}\rvert\cos(\delta_{\|\|}-\delta_\perp-\phi_{\|\|})\Big]$
5	$\sqrt{2}s_K c_K s_l c_l c_\phi$	$\lvert A_0 A_{\|\|}\rvert$	$\frac{1}{2}\Big[\cos(\delta_0-\delta_{\|\|})+\lvert\lambda_0\lambda_{\|\|}\rvert\,\cos(\delta_0-\delta_{\|\|}-\phi_0+\phi_{\|\|})\Big]$	$-\frac{1}{2}\Big[\lvert\lambda_0\rvert\cos(\delta_0-\delta_{\|\|}-\phi_0)+\lvert\lambda_{\|\|}\rvert\cos(\delta_{\|\|}-\delta_0-\phi_{\|\|})\Big]$	$\frac{1}{2}\Big[\cos(\delta_0-\delta_{\|\|})-\lvert\lambda_0\lambda_{\|\|}\rvert\,\cos(\delta_0-\delta_{\|\|}-\phi_0+\phi_{\|\|})\Big]$	$-\frac{1}{2}\Big[\lvert\lambda_0\rvert\sin(\delta_0-\delta_{\|\|}-\phi_0)+\lvert\lambda_{\|\|}\rvert\sin(\delta_{\|\|}-\delta_0-\phi_{\|\|})\Big]$
6	$-\sqrt{2}s_K c_K s_l c_l s_\phi$	$\lvert A_0 A_\perp\rvert$	$-\frac{1}{2}\Big[\sin(\delta_0-\delta_\perp)-\lvert\lambda_0\lambda_\perp\rvert\,\sin(\delta_0-\delta_\perp-\phi_0+\phi_\perp)\Big]$	$\frac{1}{2}\Big[\lvert\lambda_0\rvert\sin(\delta_0-\delta_\perp-\phi_0)+\lvert\lambda_\perp\rvert\sin(\delta_\perp-\delta_0-\phi_\perp)\Big]$	$-\frac{1}{2}\Big[\sin(\delta_0-\delta_\perp)+\lvert\lambda_0\lambda_\perp\rvert\,\sin(\delta_0-\delta_\perp-\phi_0+\phi_\perp)\Big]$	$-\frac{1}{2}\Big[\lvert\lambda_0\rvert\cos(\delta_0-\delta_\perp-\phi_0)+\lvert\lambda_\perp\rvert\cos(\delta_\perp-\delta_0-\phi_\perp)\Big]$
7	$\frac{1}{3}s_l^2$	$\lvert A_S\rvert^2$	$\frac{1}{2}(1+\lvert\lambda_S\rvert^2)$	$\lvert\lambda_S\rvert\cos(\phi_S)$	$\frac{1}{2}(1-\lvert\lambda_S\rvert^2)$	$-\lvert\lambda_S\rvert\sin(\phi_S)$
8	$\frac{2}{\sqrt{6}}s_K s_l c_l c_\phi$	$\lvert A_S A_{\|\|}\rvert$	$\frac{1}{2}\Big[\cos(\delta_S-\delta_{\|\|})-\lvert\lambda_S\lambda_{\|\|}\rvert\,\cos(\delta_S-\delta_{\|\|}-\phi_S+\phi_{\|\|})\Big]$	$\frac{1}{2}\Big[\lvert\lambda_S\rvert\cos(\delta_S-\delta_{\|\|}-\phi_S)-\lvert\lambda_{\|\|}\rvert\cos(\delta_{\|\|}-\delta_S-\phi_{\|\|})\Big]$	$\frac{1}{2}\Big[\cos(\delta_S-\delta_{\|\|})+\lvert\lambda_S\lambda_{\|\|}\rvert\,\cos(\delta_S-\delta_{\|\|}-\phi_S+\phi_{\|\|})\Big]$	$\frac{1}{2}\Big[\lvert\lambda_S\rvert\sin(\delta_S-\delta_{\|\|}-\phi_S)-\lvert\lambda_{\|\|}\rvert\sin(\delta_{\|\|}-\delta_S-\phi_{\|\|})\Big]$
9	$-\frac{2}{\sqrt{6}}s_K s_l c_l s_\phi$	$\lvert A_S A_\perp\rvert$	$-\frac{1}{2}\Big[\sin(\delta_S-\delta_\perp)+\lvert\lambda_S\lambda_\perp\rvert\,\sin(\delta_S-\delta_\perp-\phi_S+\phi_\perp)\Big]$	$-\frac{1}{2}\Big[\lvert\lambda_S\rvert\sin(\delta_S-\delta_\perp-\phi_S)-\lvert\lambda_\perp\rvert\sin(\delta_\perp-\delta_S-\phi_\perp)\Big]$	$-\frac{1}{2}\Big[\sin(\delta_S-\delta_\perp)-\lvert\lambda_S\lambda_\perp\rvert\,\sin(\delta_S-\delta_\perp-\phi_S+\phi_\perp)\Big]$	$-\frac{1}{2}\Big[-\lvert\lambda_S\rvert\cos(\delta_S-\delta_\perp-\phi_S)+\lvert\lambda_\perp\rvert\cos(\delta_\perp-\delta_S-\phi_\perp)\Big]$
10	$\frac{2}{\sqrt{3}}c_K s_l^2$	$\lvert A_S A_0\rvert$	$\frac{1}{2}\Big[\cos(\delta_S-\delta_0)-\lvert\lambda_S\lambda_0\rvert\,\cos(\delta_S-\delta_0-\phi_S+\phi_0)\Big]$	$\frac{1}{2}\Big[\lvert\lambda_S\rvert\cos(\delta_S-\delta_0-\phi_S)-\lvert\lambda_0\rvert\cos(\delta_0-\delta_S-\phi_0)\Big]$	$\frac{1}{2}\Big[\cos(\delta_S-\delta_0)+\lvert\lambda_S\lambda_0\rvert\,\cos(\delta_S-\delta_0-\phi_S+\phi_0)\Big]$	$\frac{1}{2}\Big[\lvert\lambda_S\rvert\sin(\delta_S-\delta_0-\phi_S)-\lvert\lambda_0\rvert\sin(\delta_0-\delta_S-\phi_0)\Big]$

$$\frac{d^4\Gamma(t)}{dm^2_{KK}\,d\cos\theta_K\,d\cos\theta_l\,d\phi} = \sum_{k=1}^{10} N_k h_k(t) f_k(\theta_K, \theta_l, \phi)$$

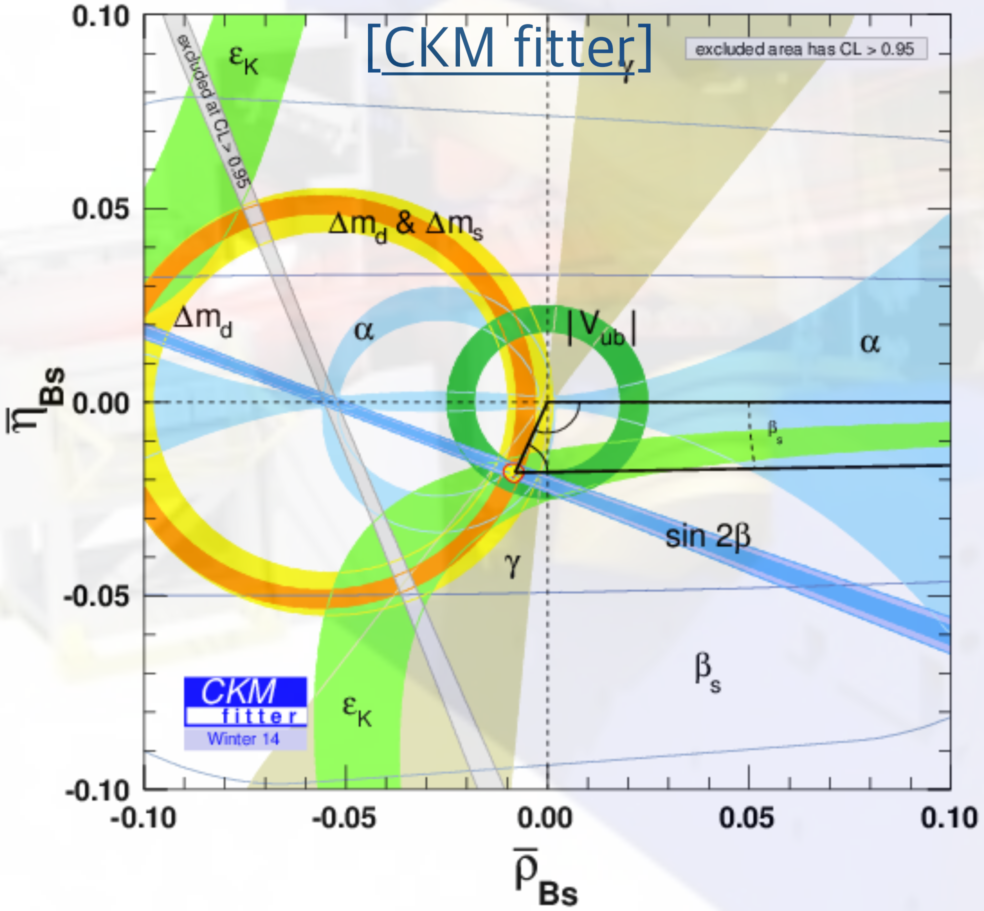
$$h_k(t) = \frac{3}{4\pi} e^{-\Gamma t} \left\{ a_k \cosh\frac{\Delta\Gamma t}{2} + b_k \sinh\frac{\Delta\Gamma t}{2} + c_k \cos(\Delta m t) + d_k \sin(\Delta m t) \right\}$$




φ_s

$$\varphi_s^{exp} \approx \varphi_s^{SM} \approx -2\beta_s$$

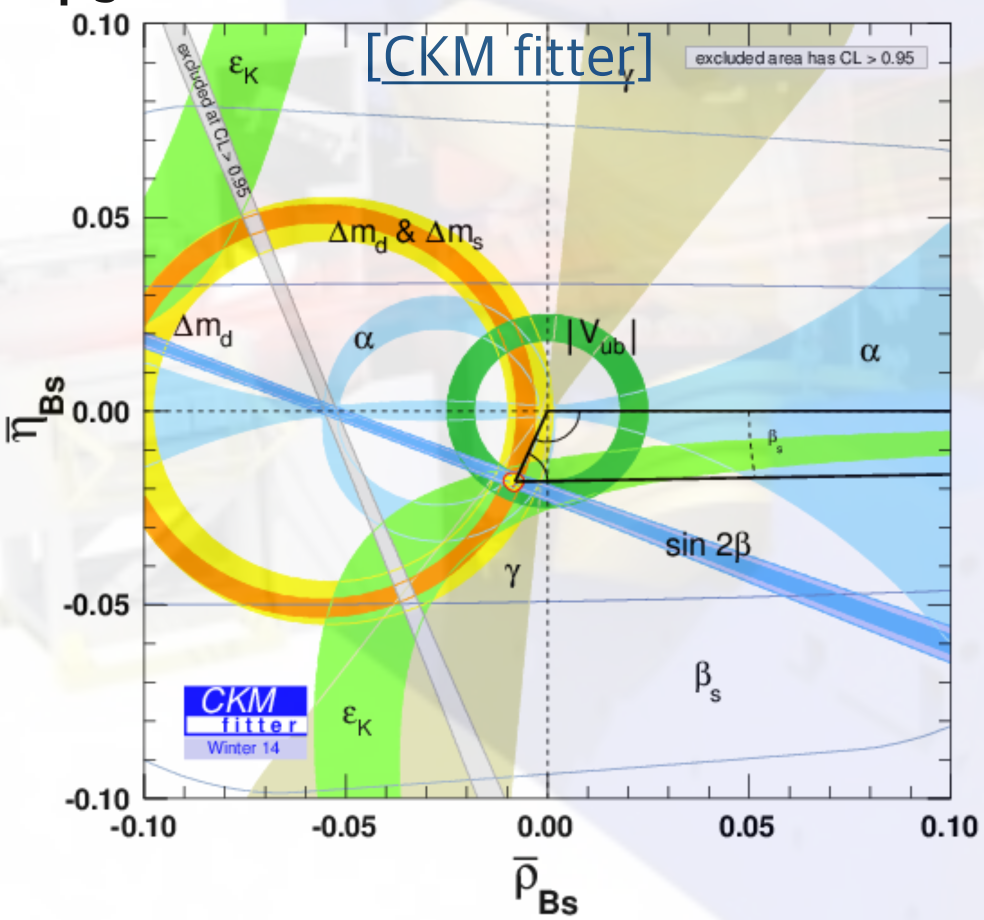
$$\varphi_s = -0.0376 \pm 0.0008 \text{ [rad]}$$



φ_s

$\varphi_s^{exp} \approx \varphi_s^{SM} \approx -2\beta_s$

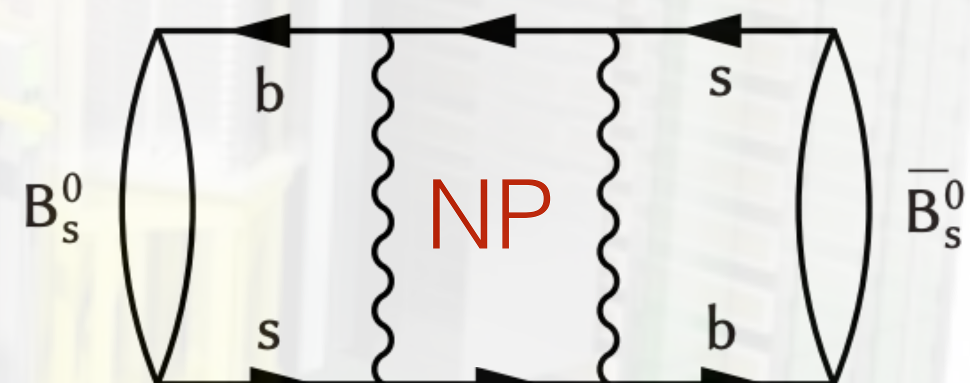
$\varphi_s = -0.0376 \pm 0.0008$ [rad]



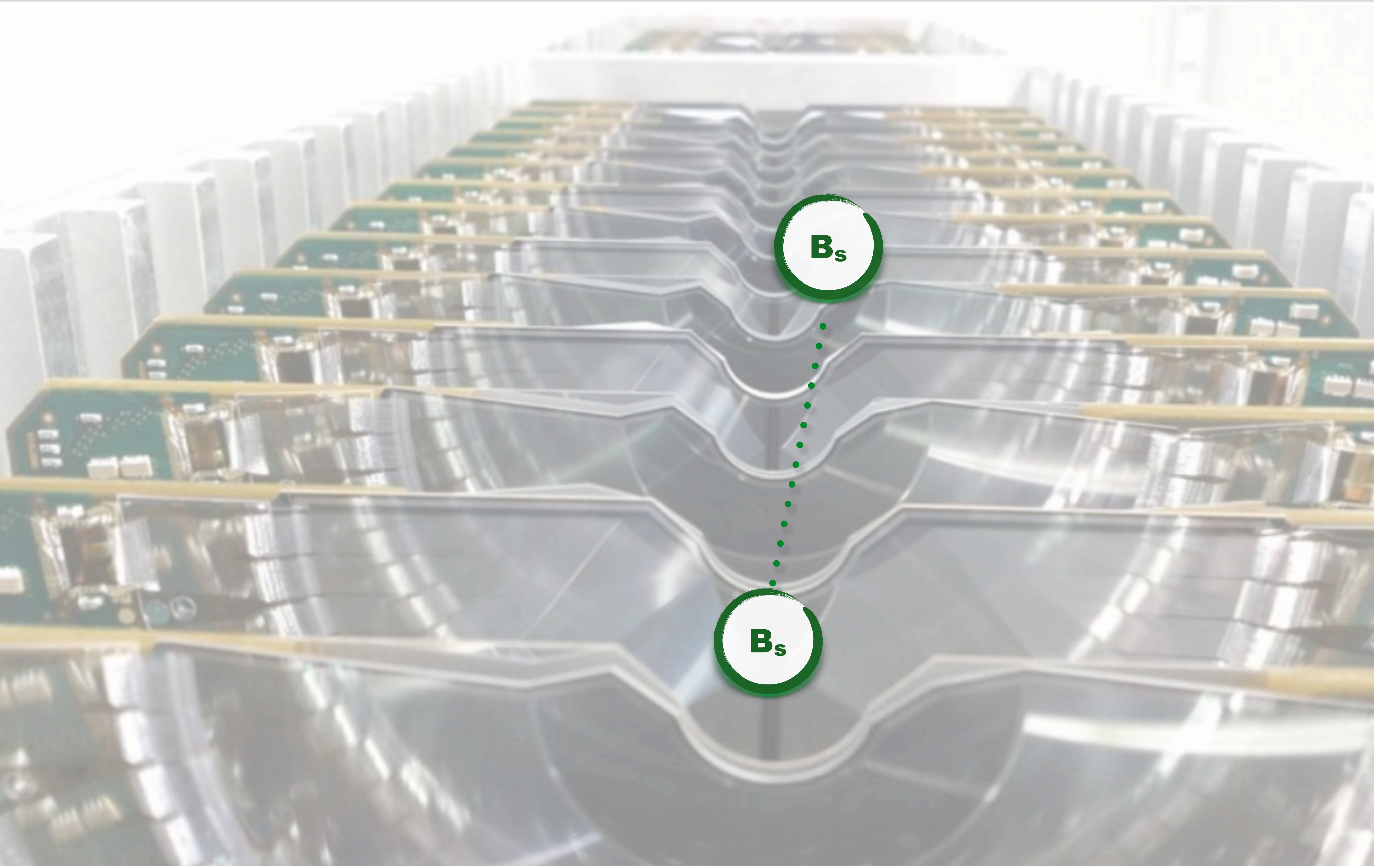
φ_s

If $\varphi_s^{exp} \not\approx \varphi_s^{SM}$

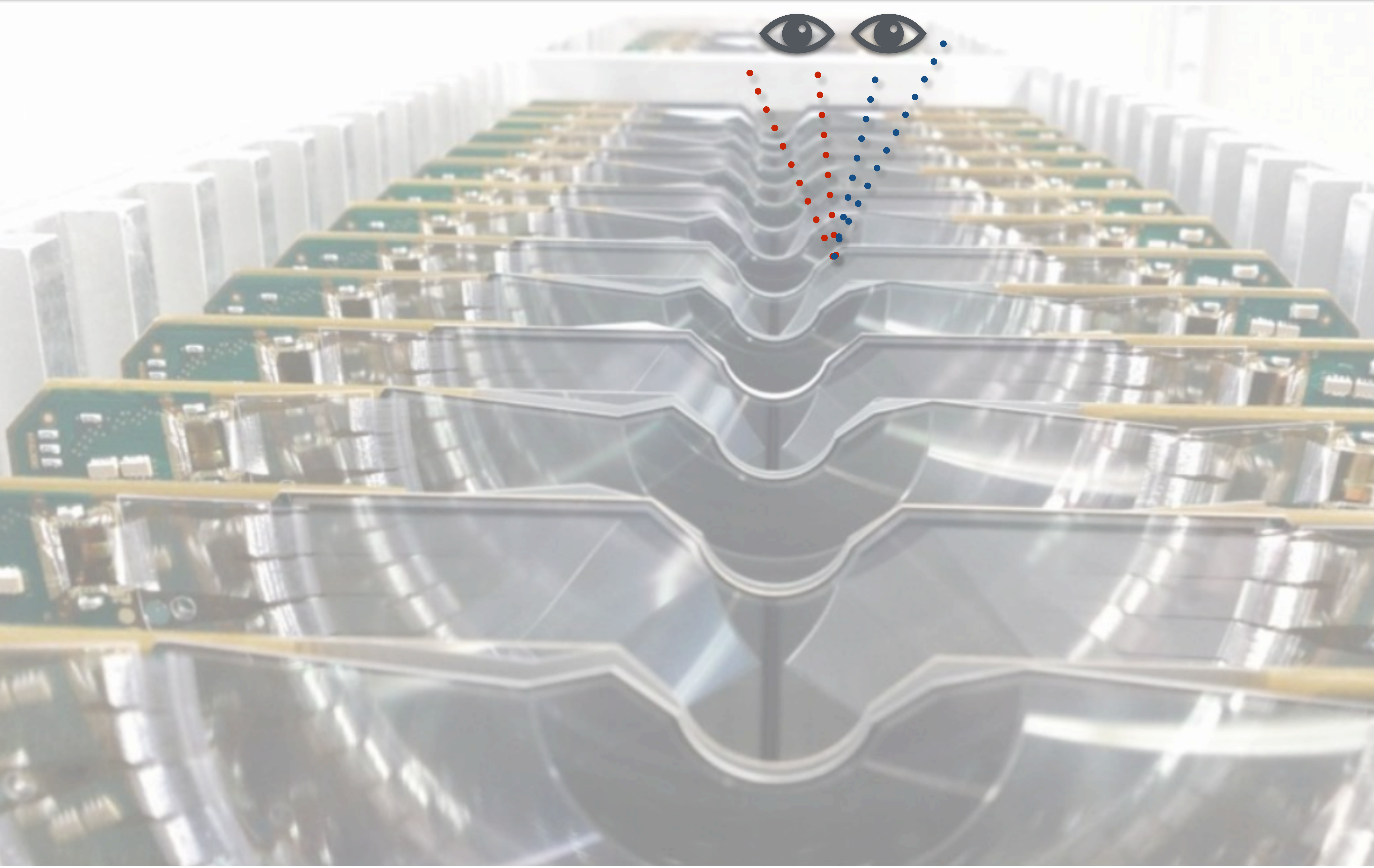
New Physics!



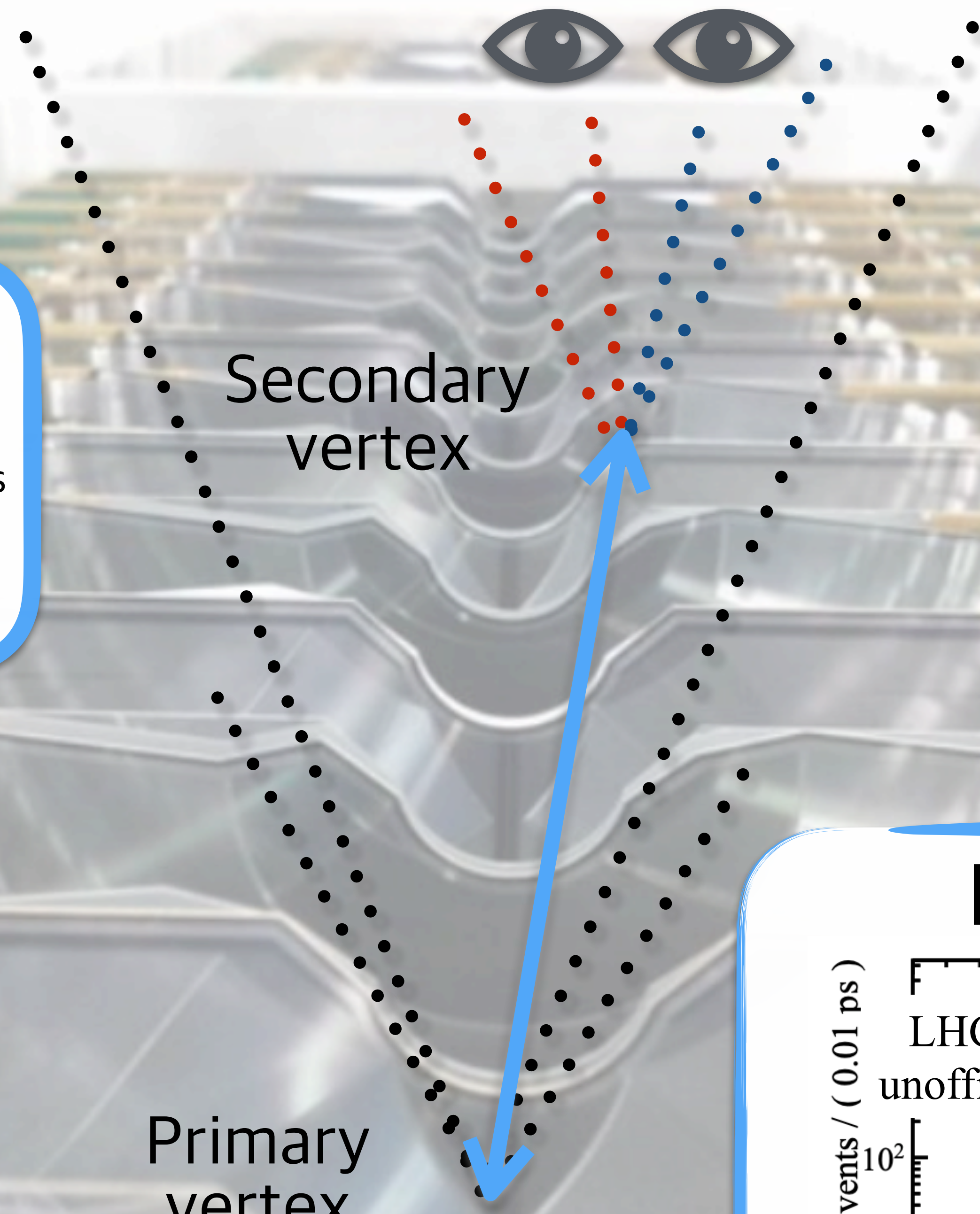
Decay time



Decay time

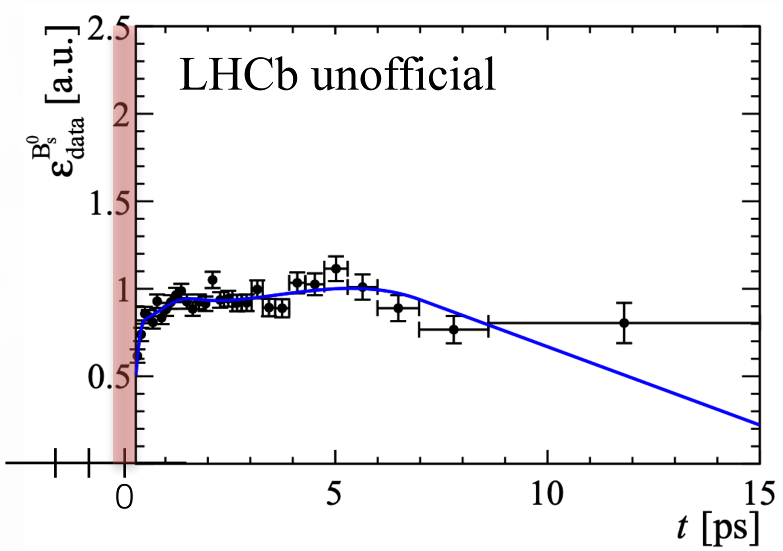


Decay time

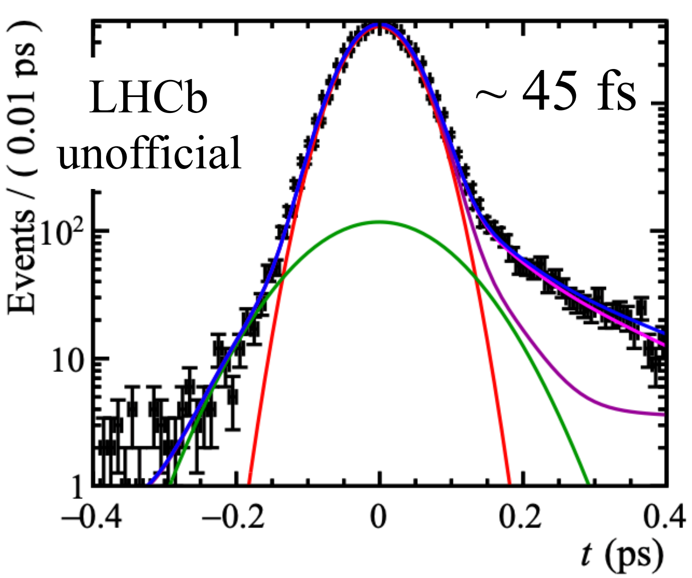


$$t = (SV-PV) \times M_{B_s} / P_{B_s}$$

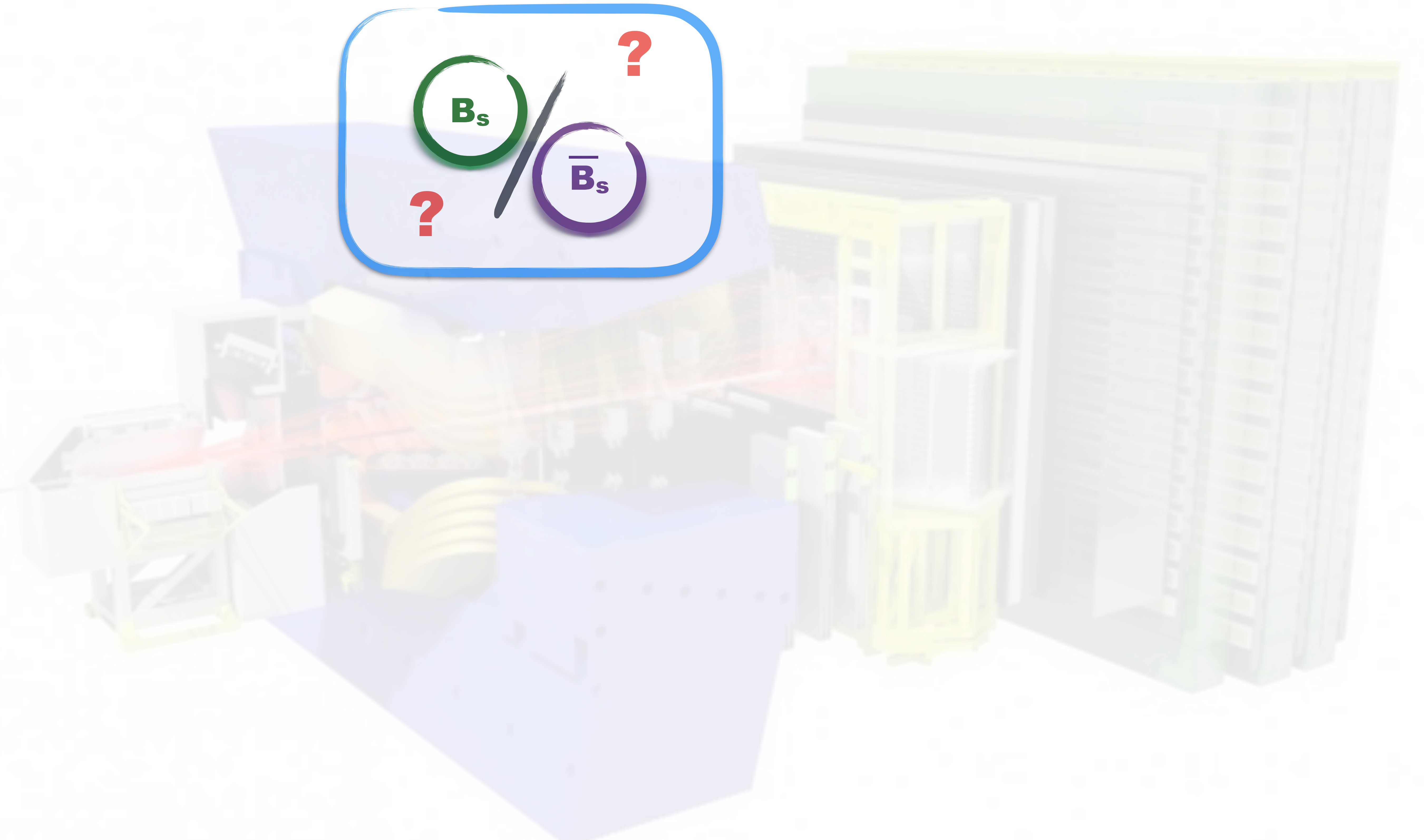
Efficiency



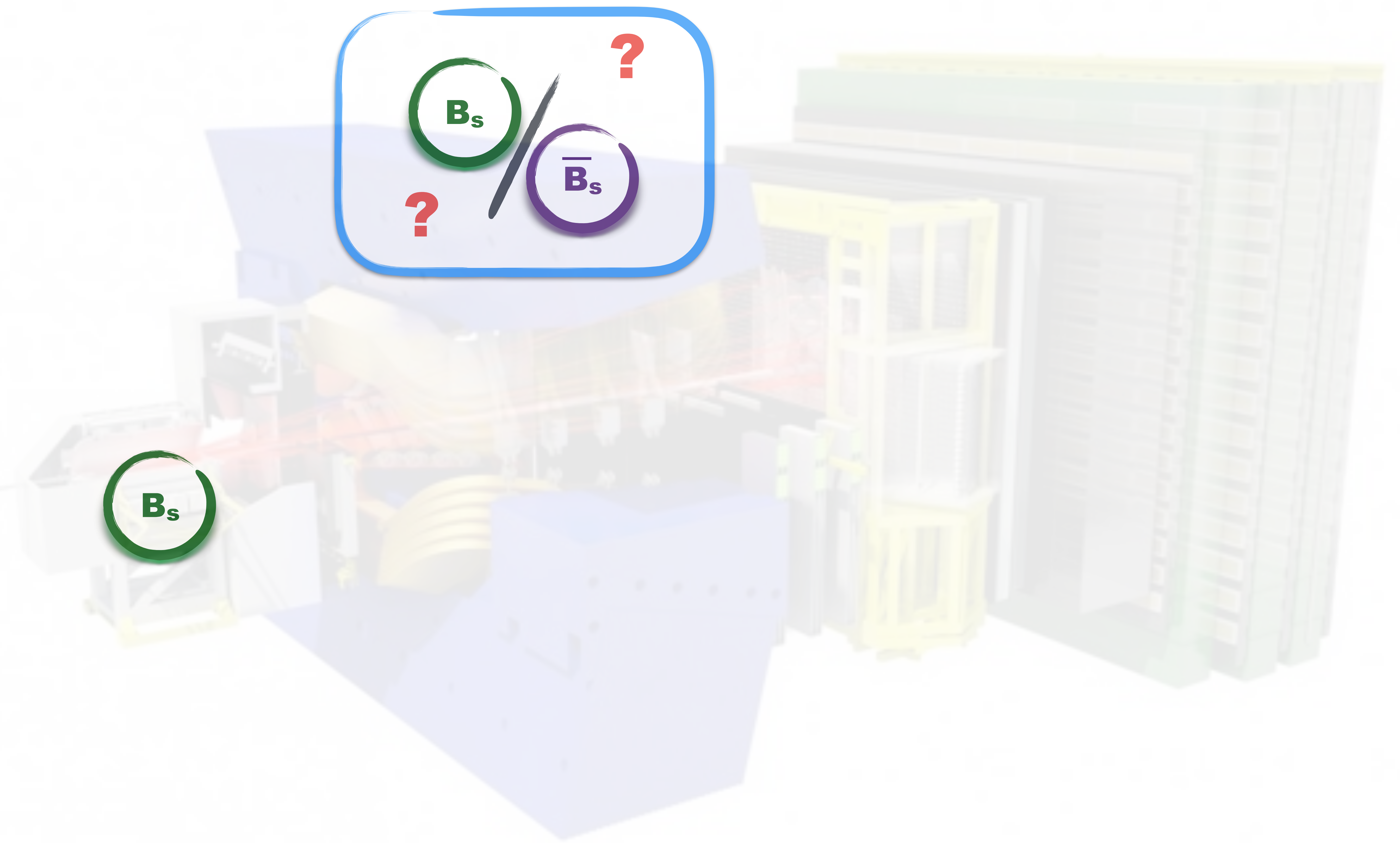
Resolution



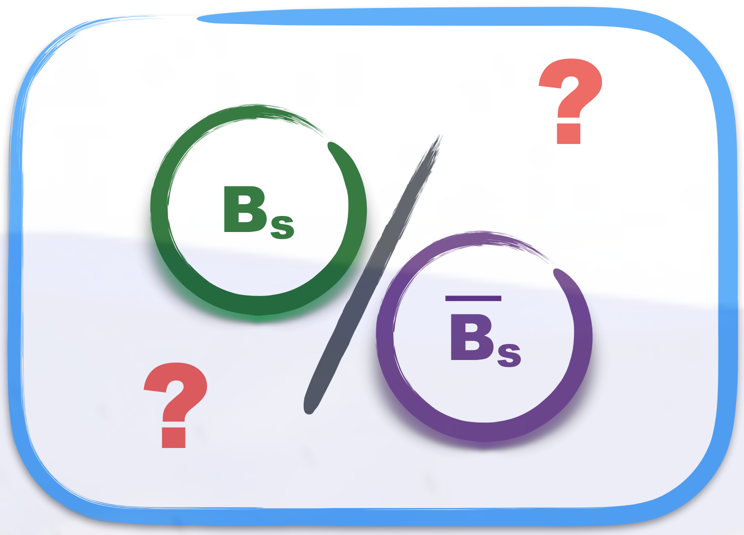
Flavour tagging

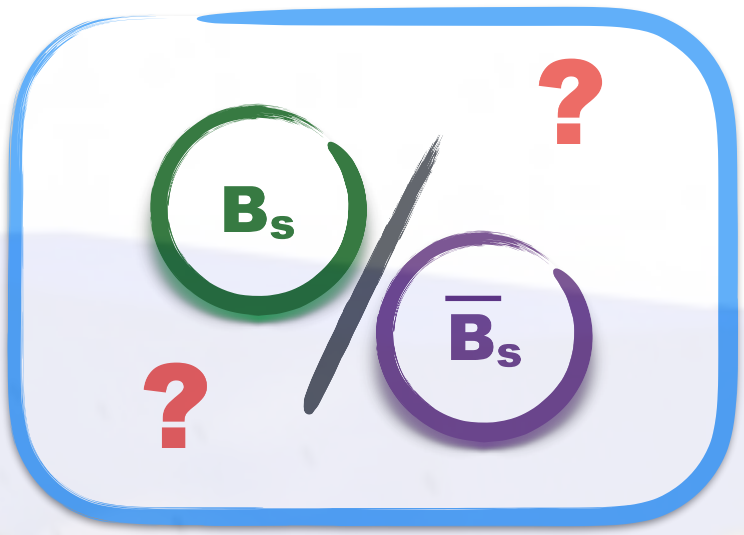


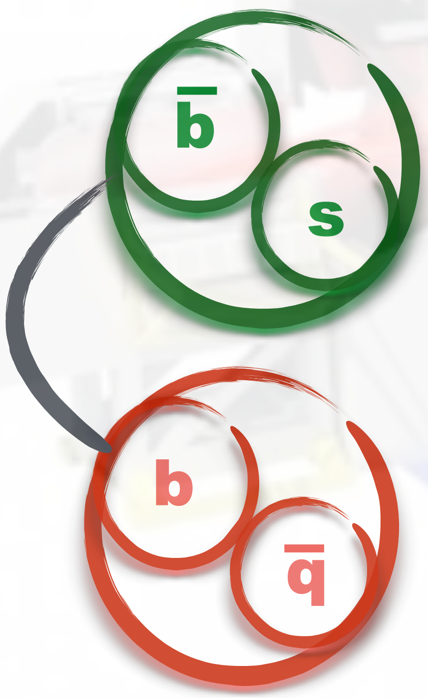
Flavour tagging



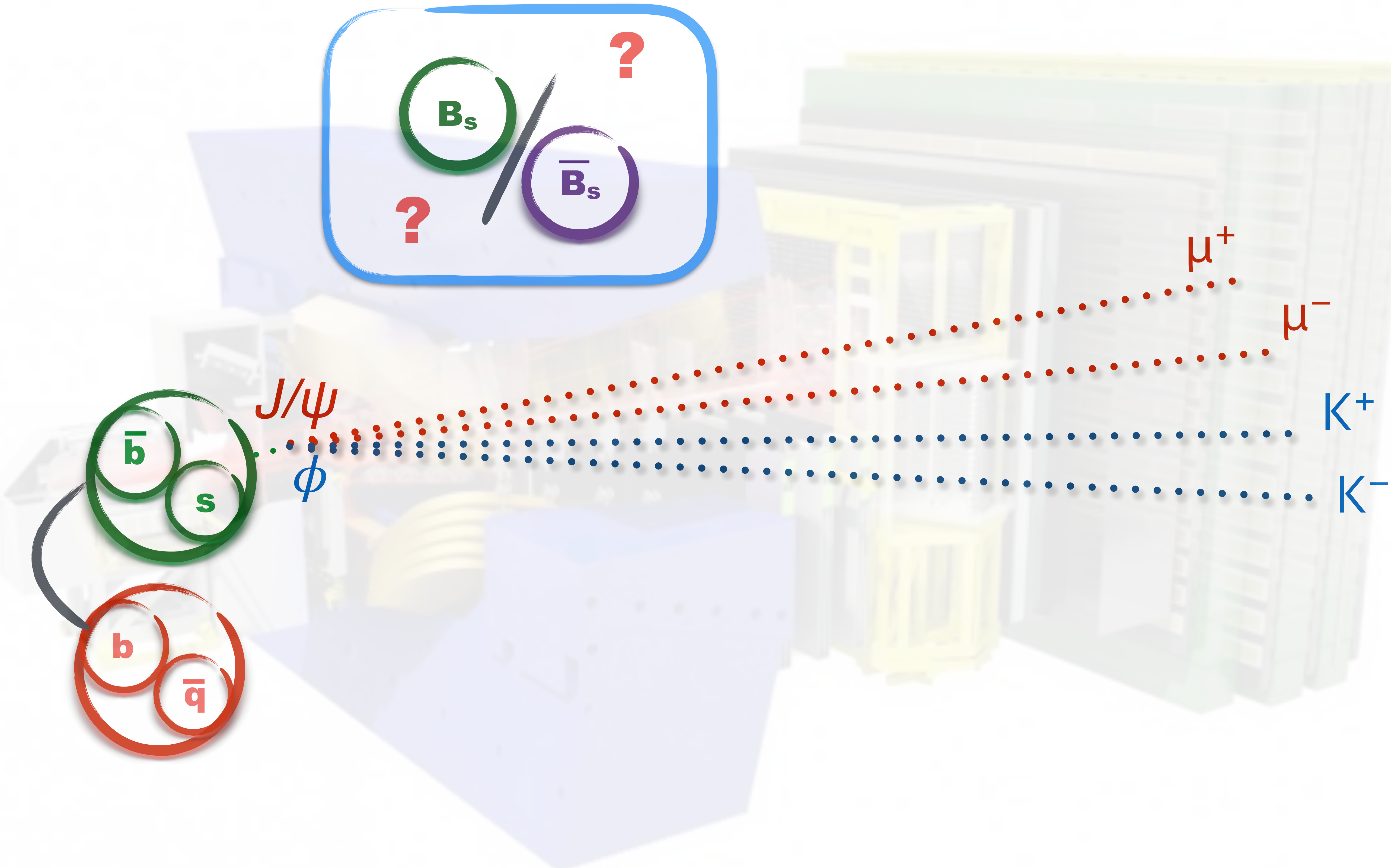
Flavour tagging

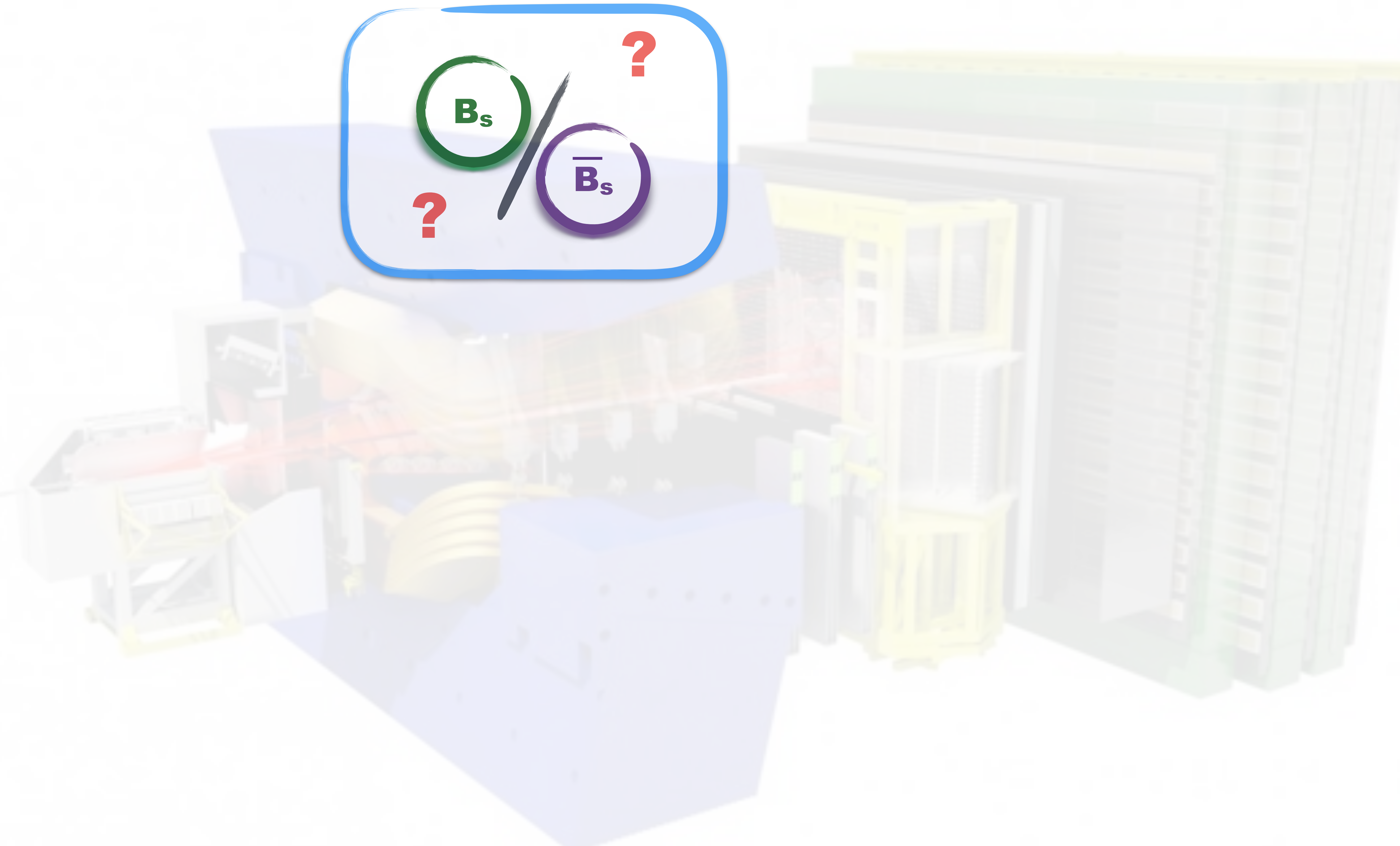



B_s
$\bar{B}_s$
?
?

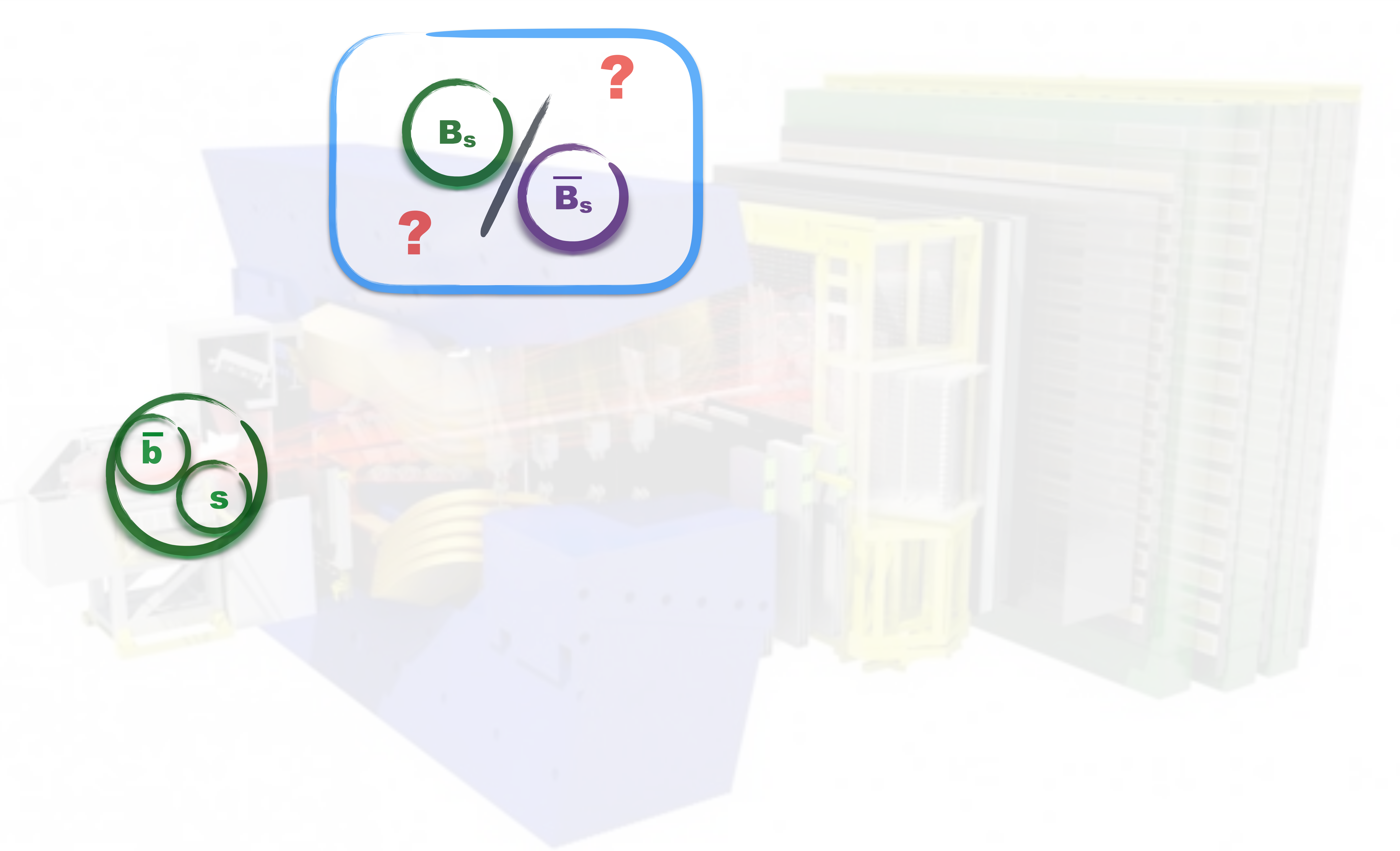

$\bar{b}$
s
b
$\bar{q}$

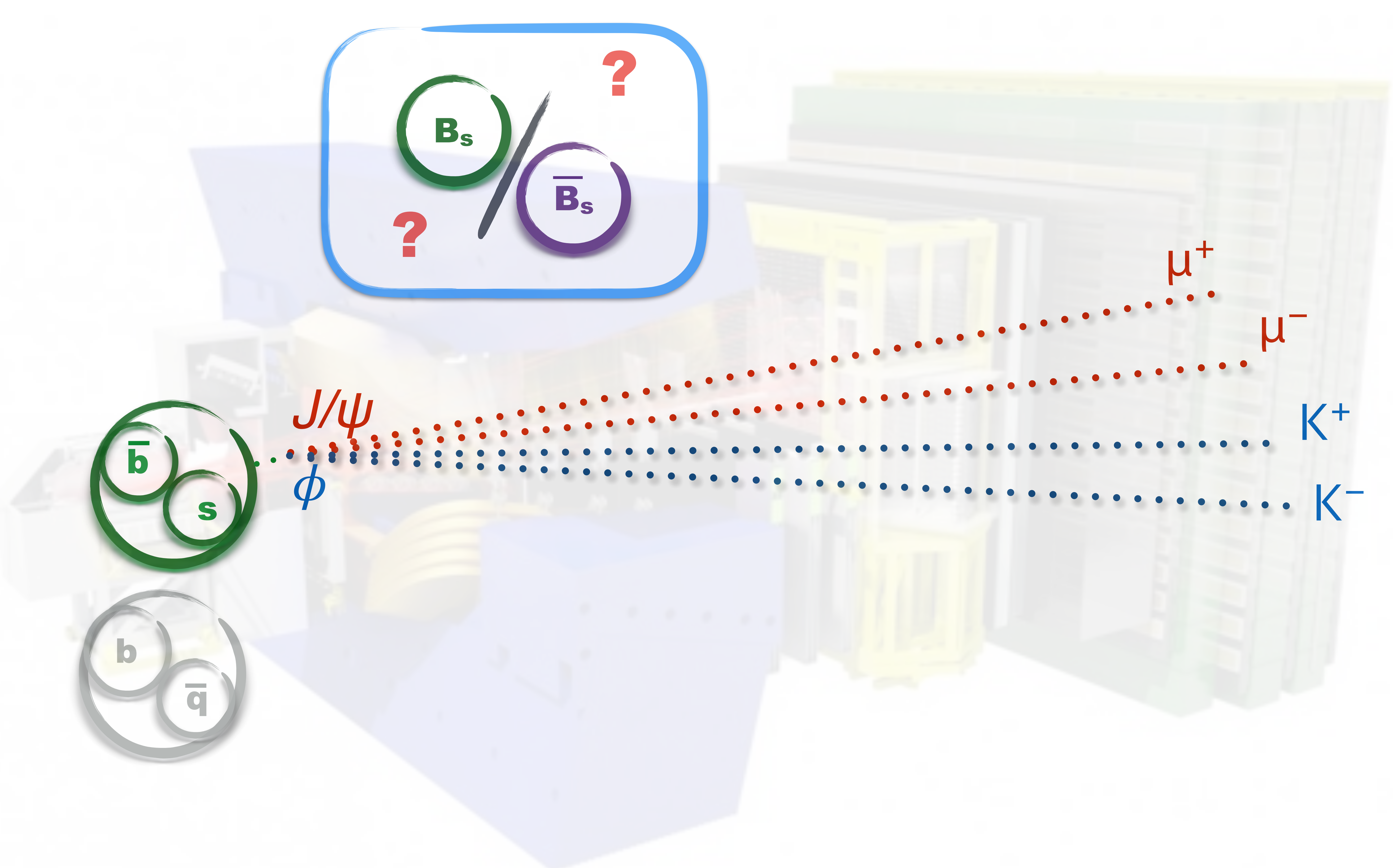
Flavour tagging

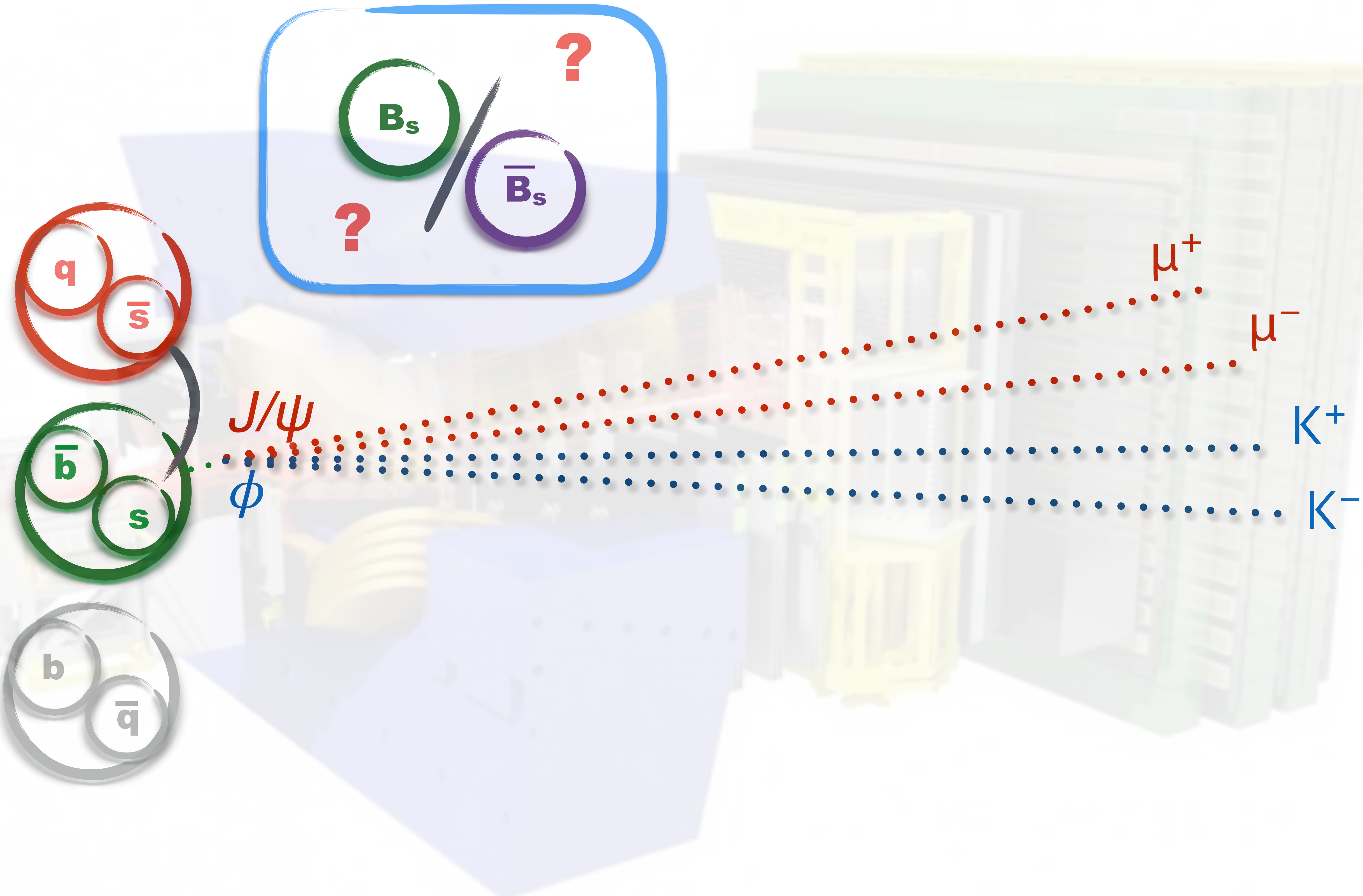


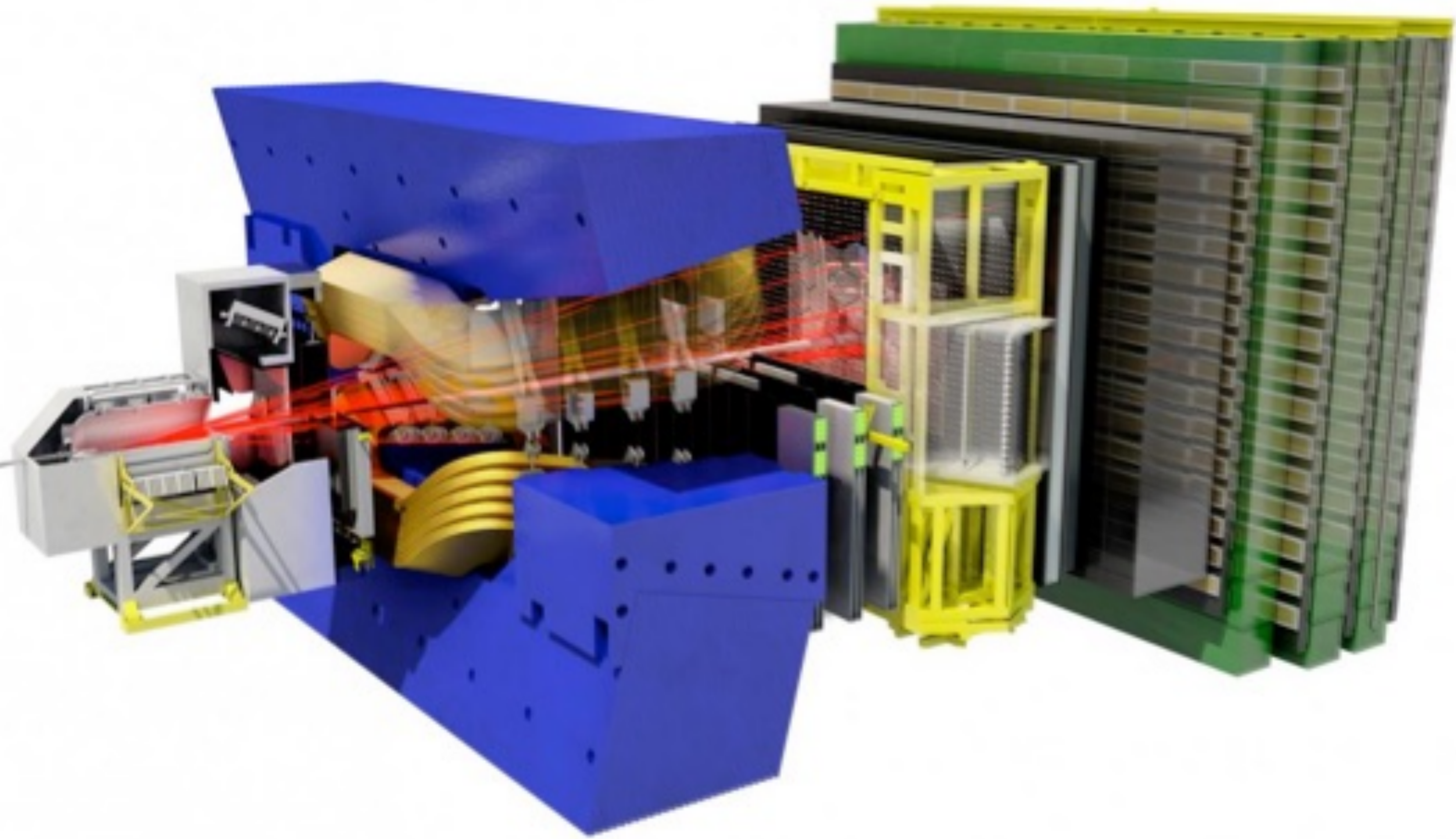

?
Bs
Bs
?

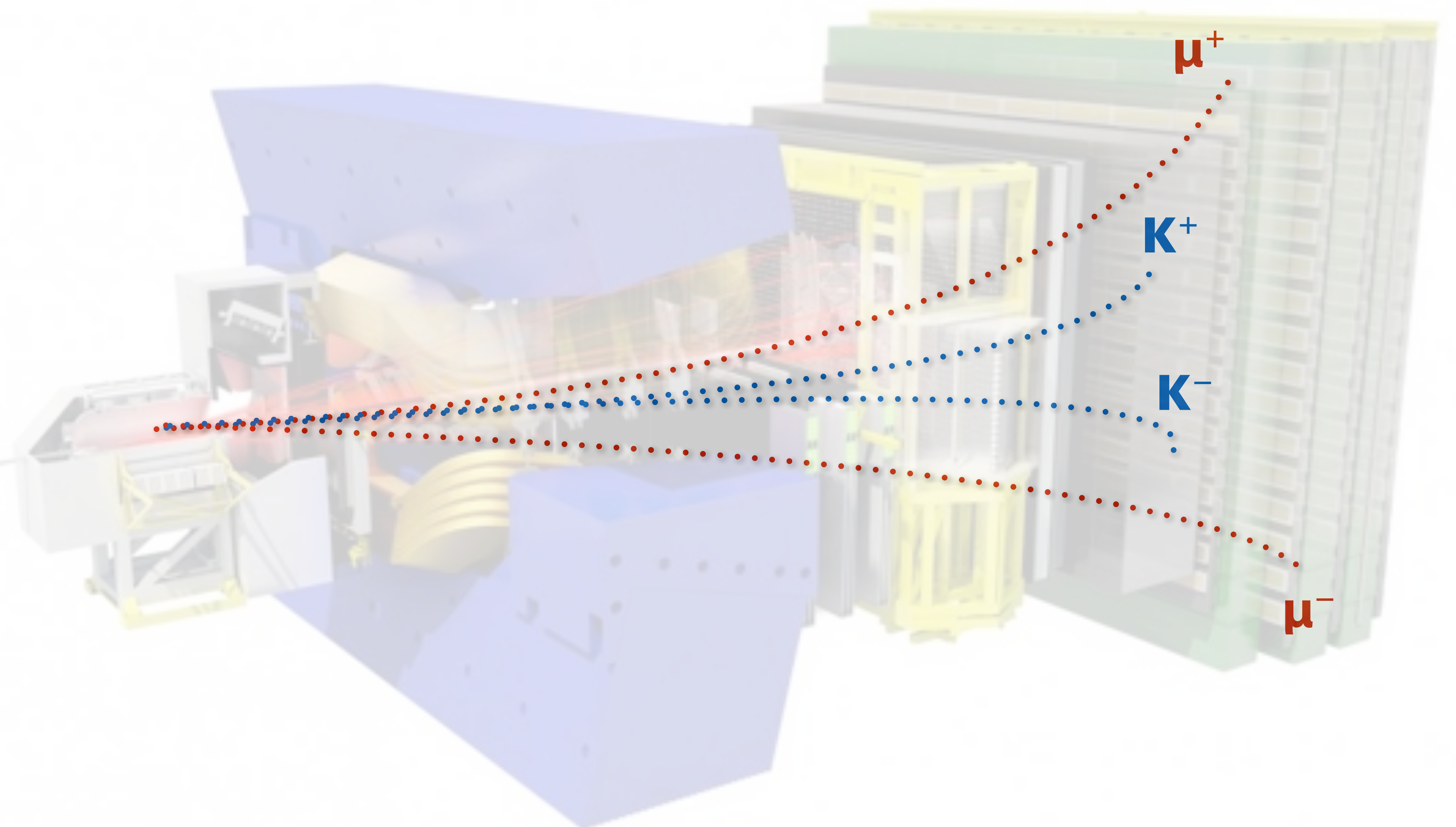
B_s / $\bar{B}_s$
?
?
B_s

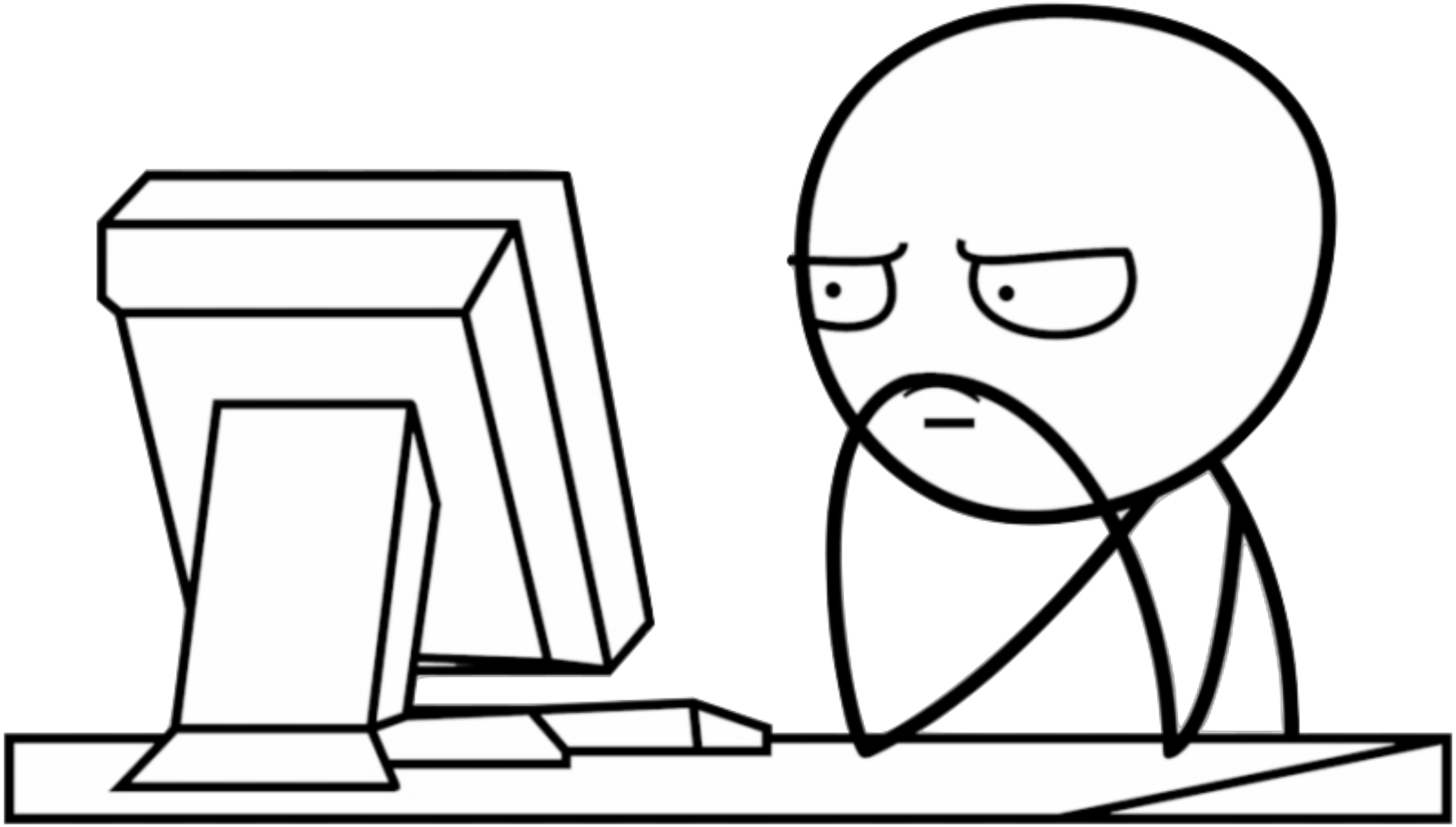

B_s
$\overline{B}_s$
?
?
$\overline{b}$
s

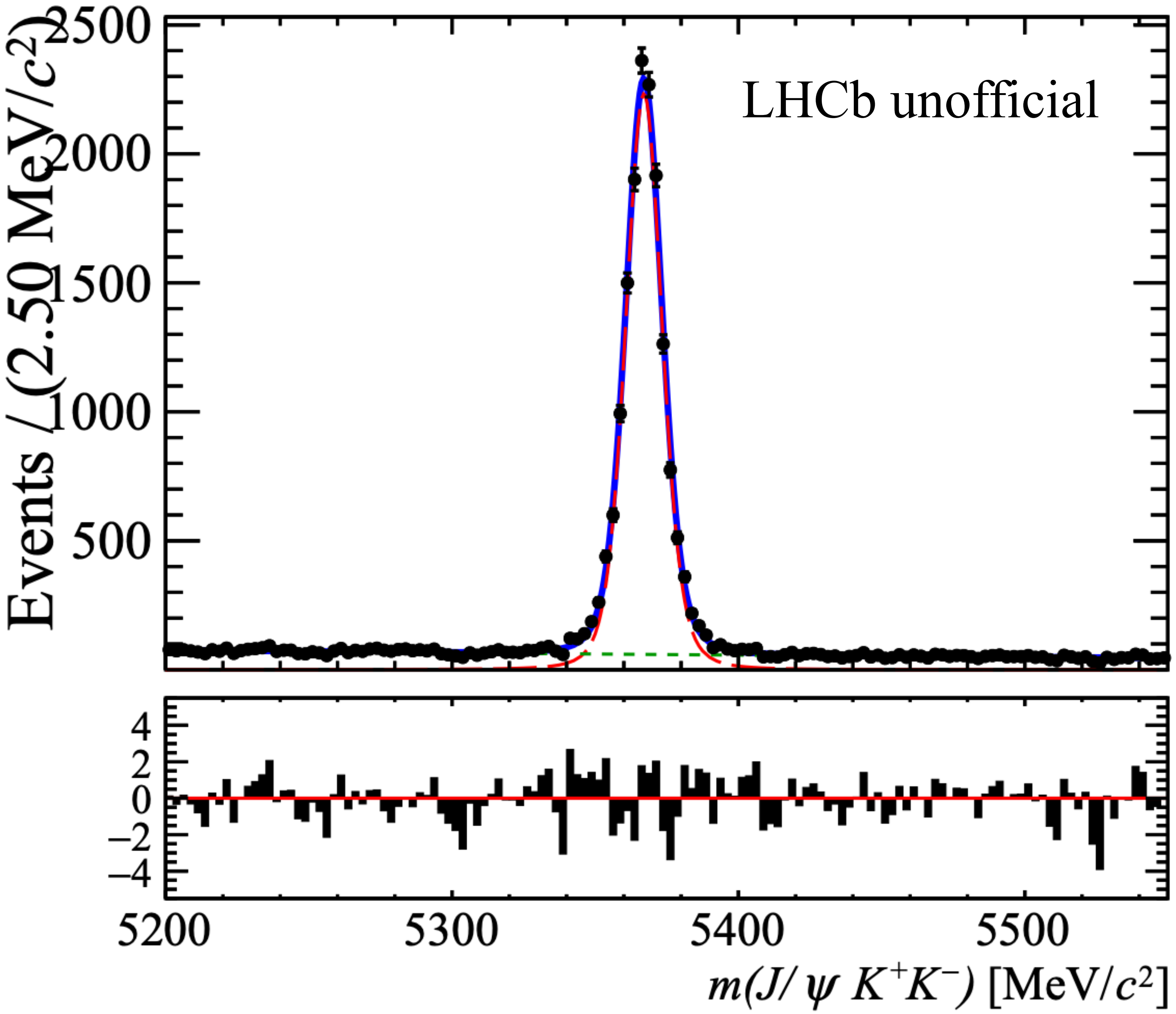

B_s
B̄_s
?
?
μ+
μ−
J/ψ
K+
K−
φ
b̄
s
b
q̄

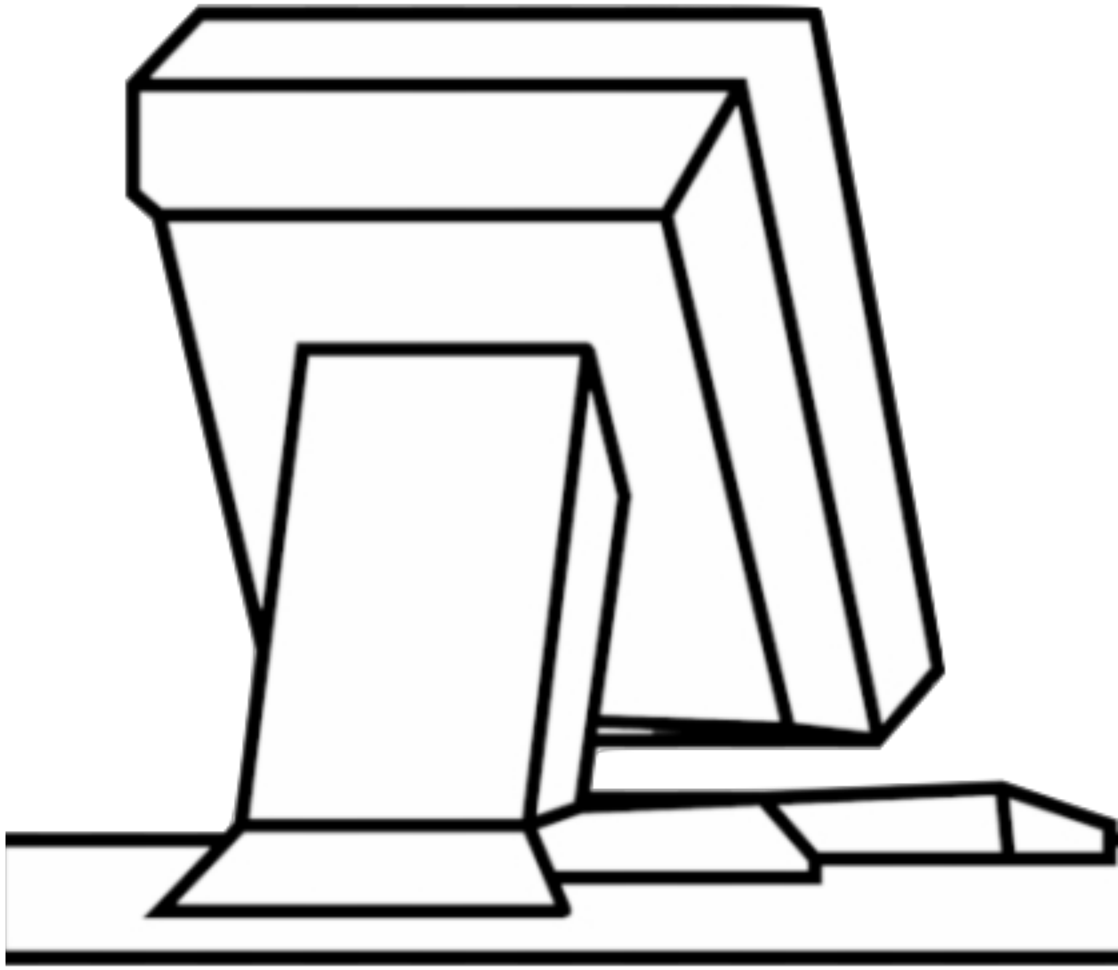

B_s
B̄_s
?
?
q
s̄
b̄
s
b
q̄
J/ψ
φ
μ+
μ−
K+
K−



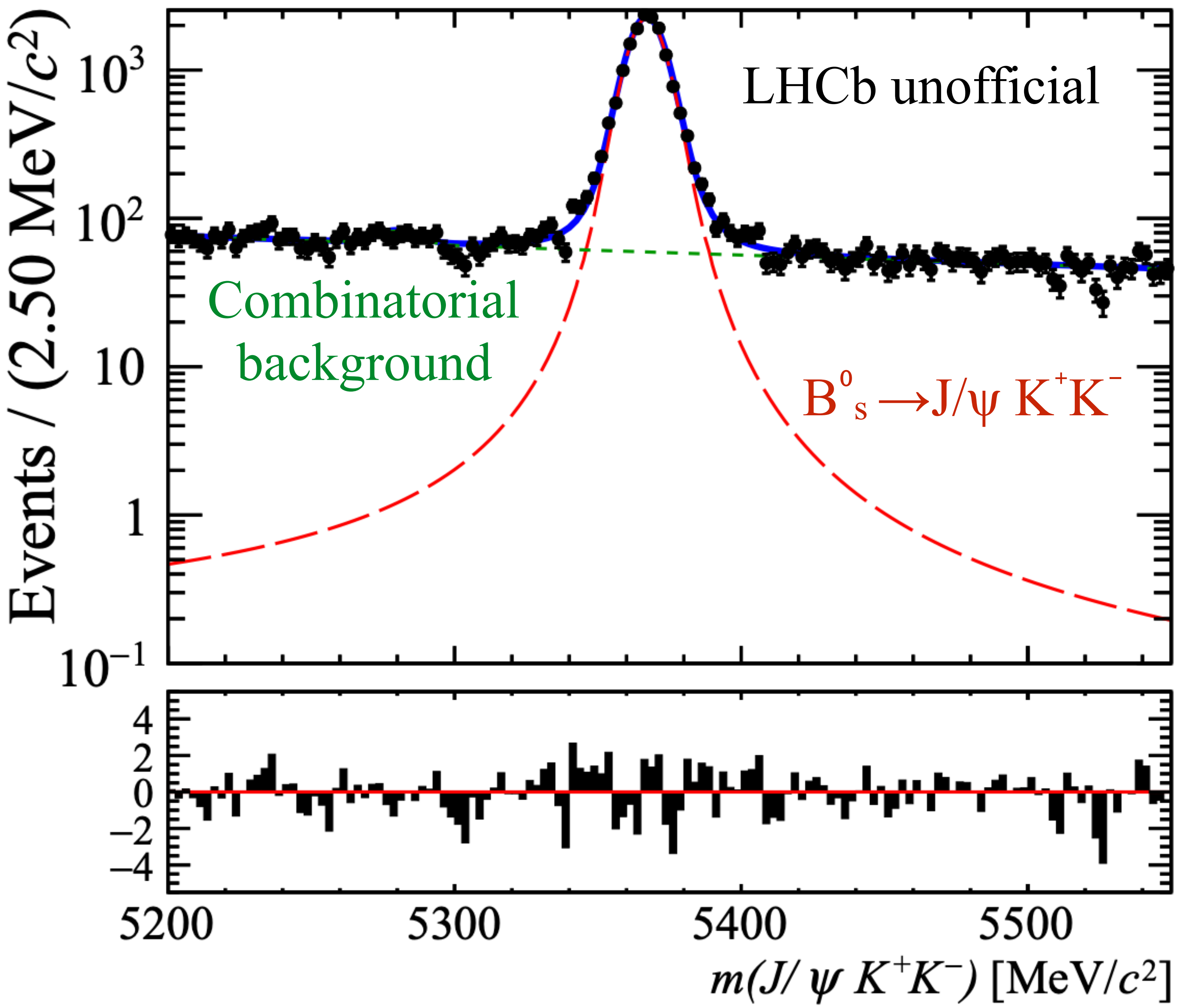

μ^+
K^+
K^-
μ^-

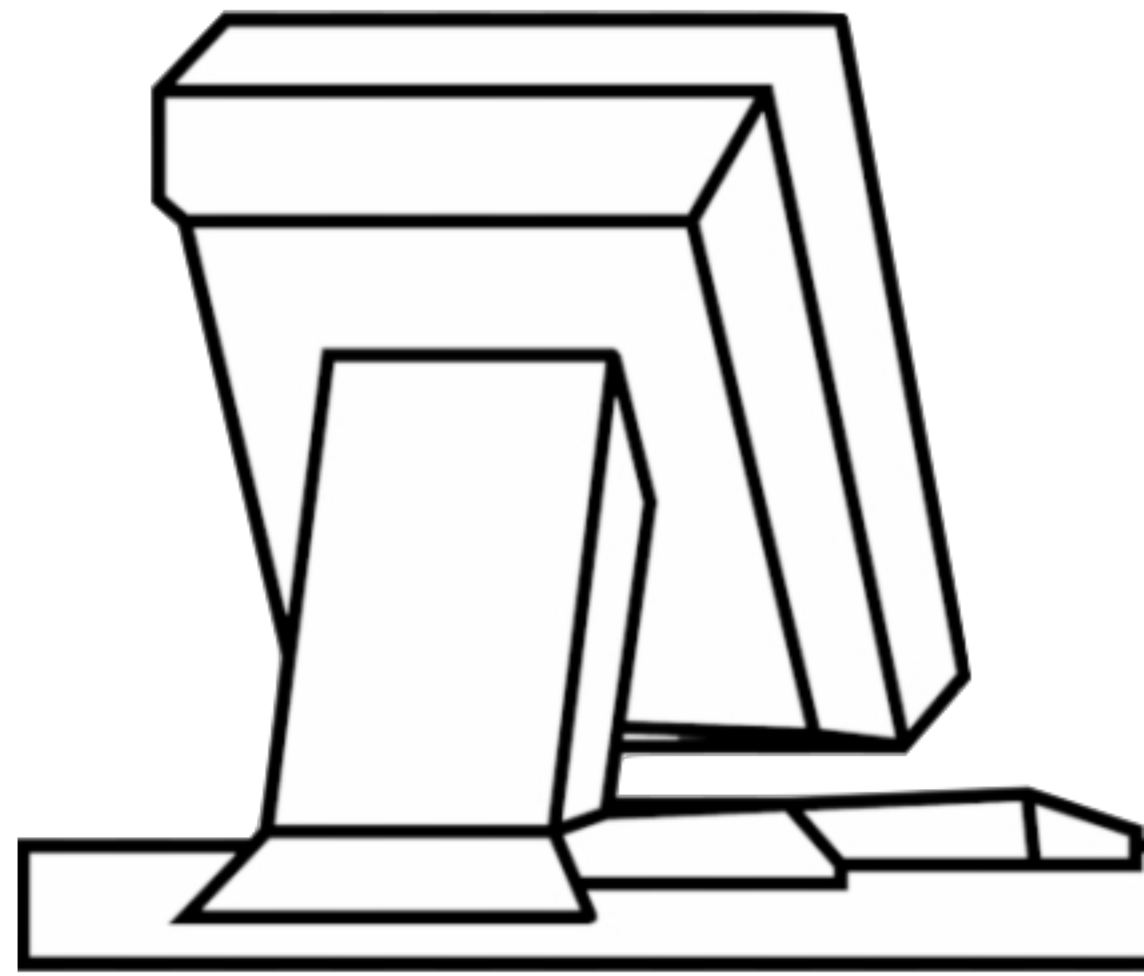



Events / (2.50 MeV/c^2)
2500
2000
1500
1000
500
LHCb unofficial
4
2
0
−2
−4
5200
5300
5400
5500
$m(J/\psi\ K^+K^-)$ [MeV/c^2]

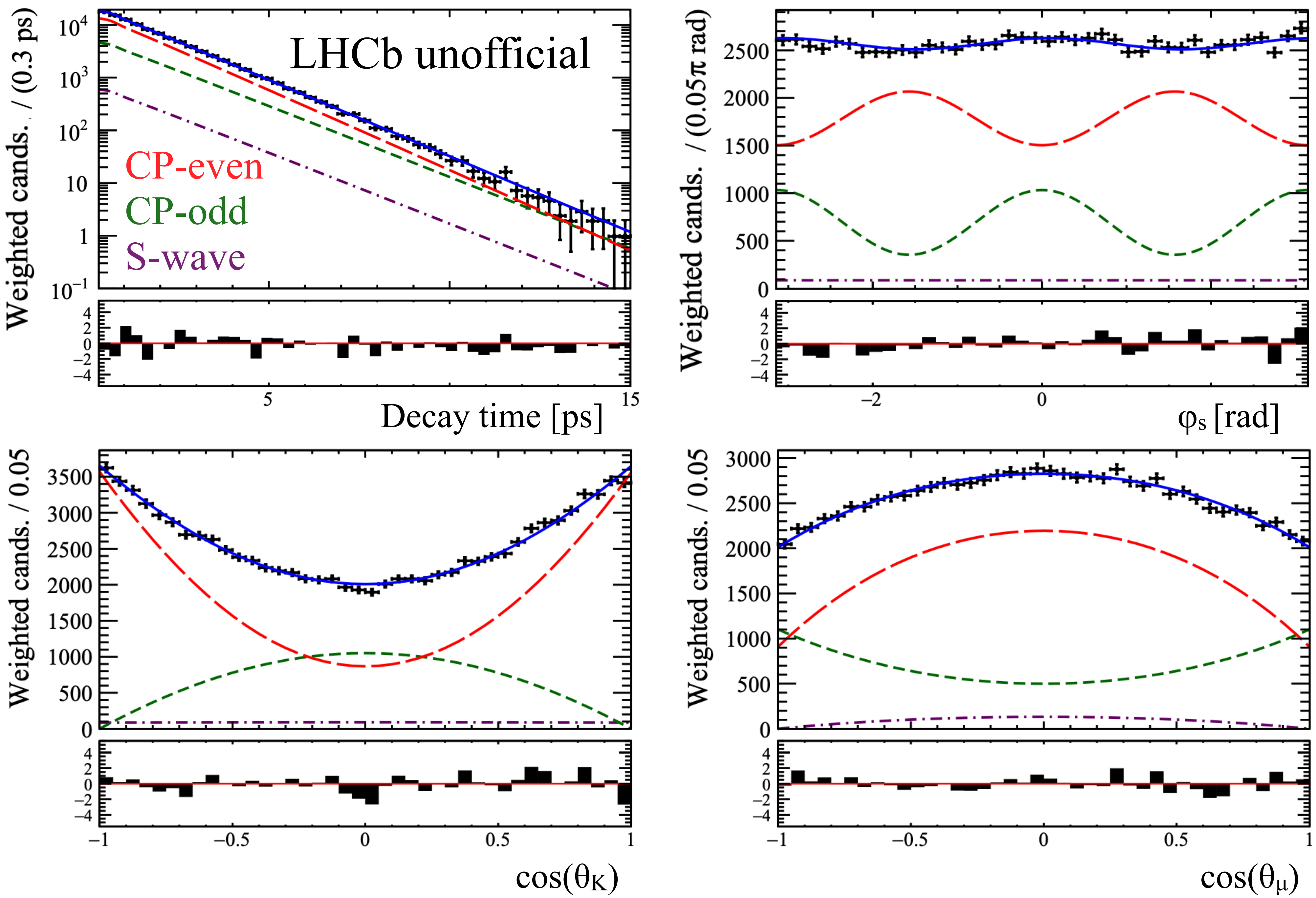


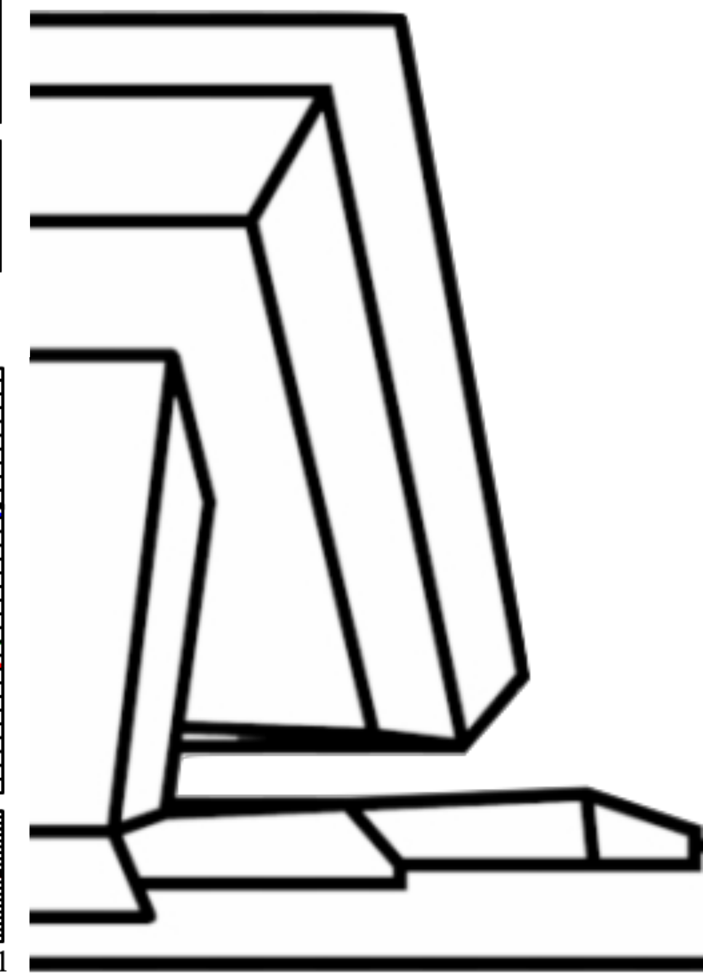
The life of analyst

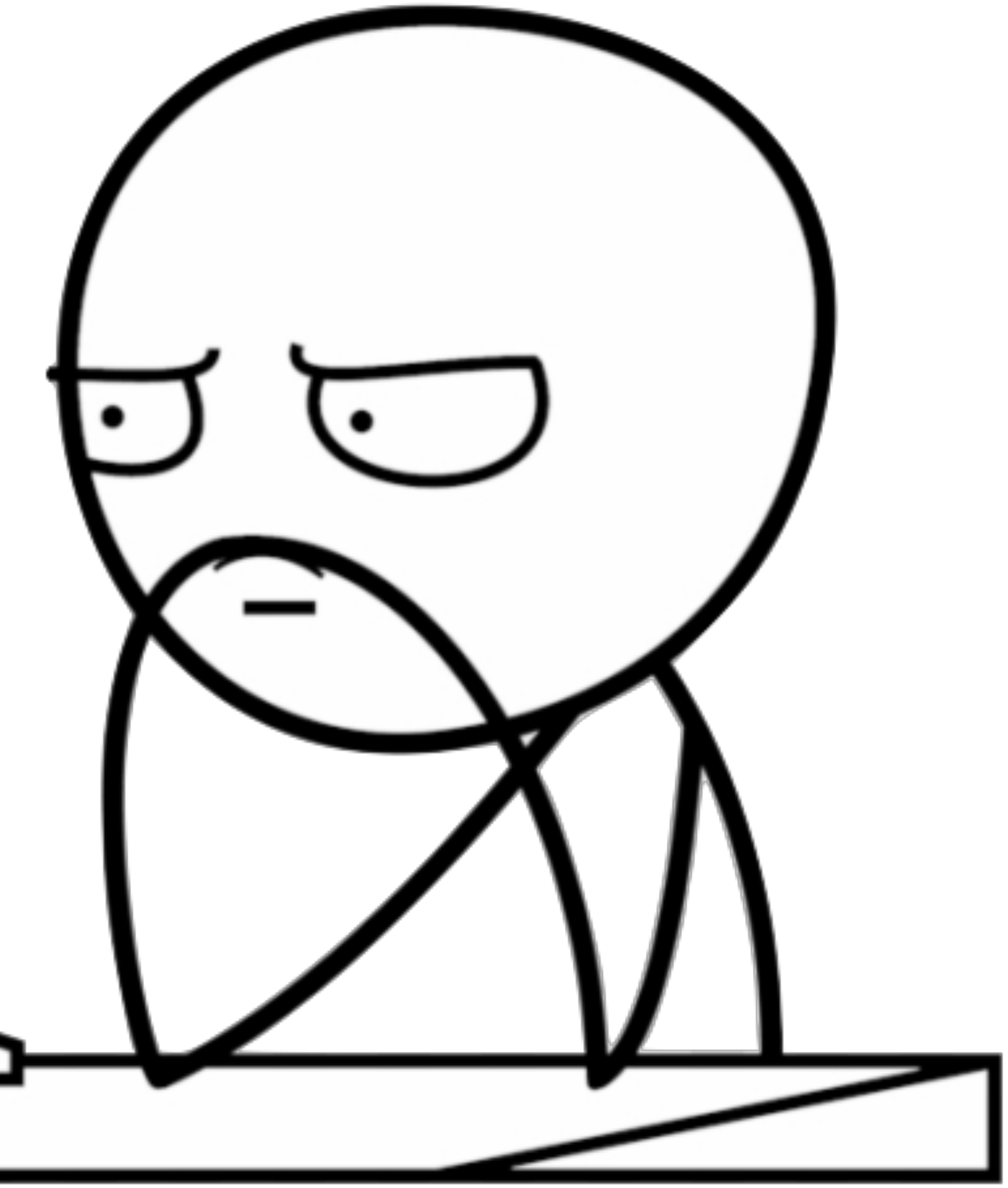


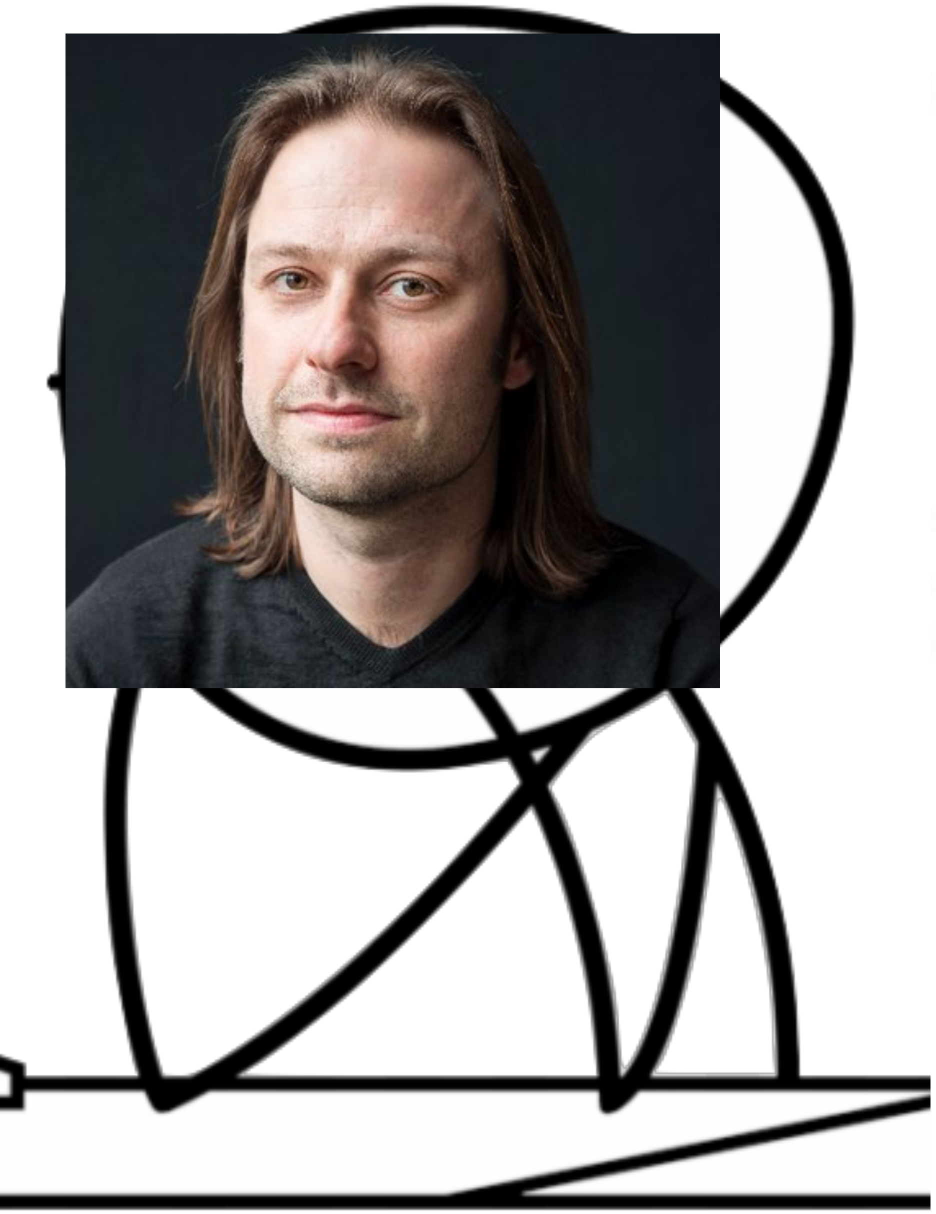


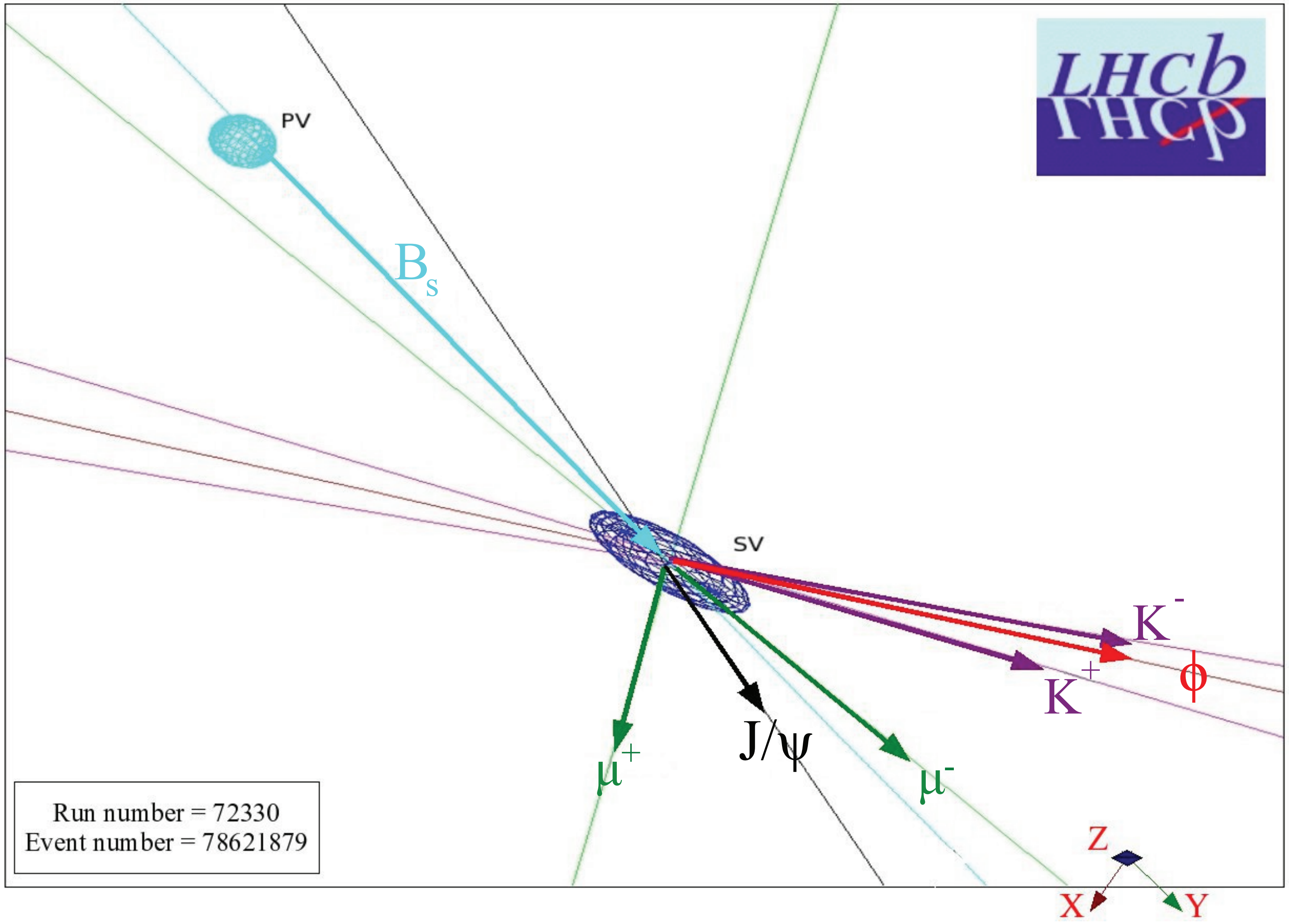
The life of analyst

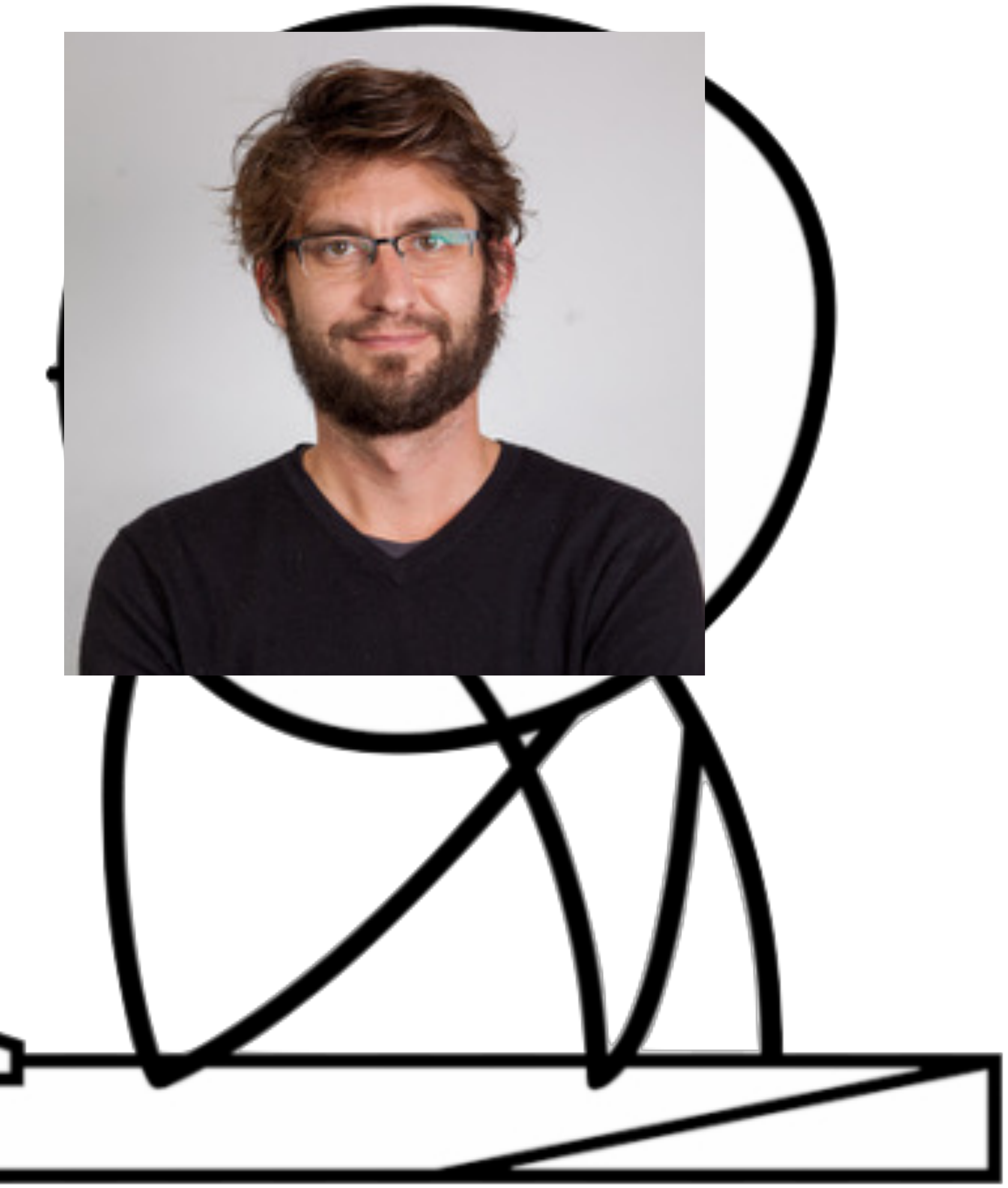






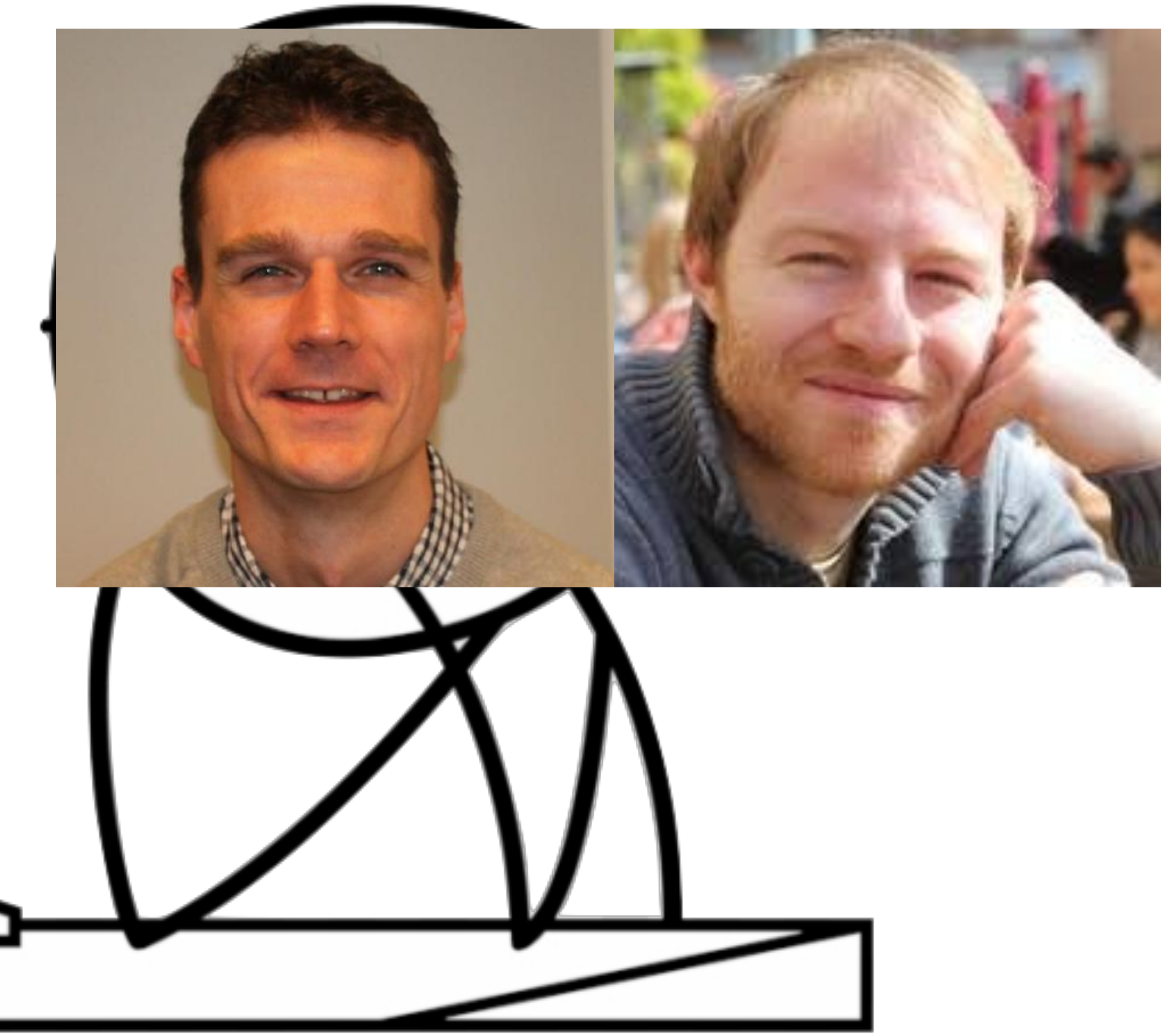



PV
B_s
SV
K^-
K^+
ϕ
J/ψ
μ^+
μ^-
Run number = 72330
Event number = 78621879
Z
X
Y



LHCb result based on 1 fb^{-1}

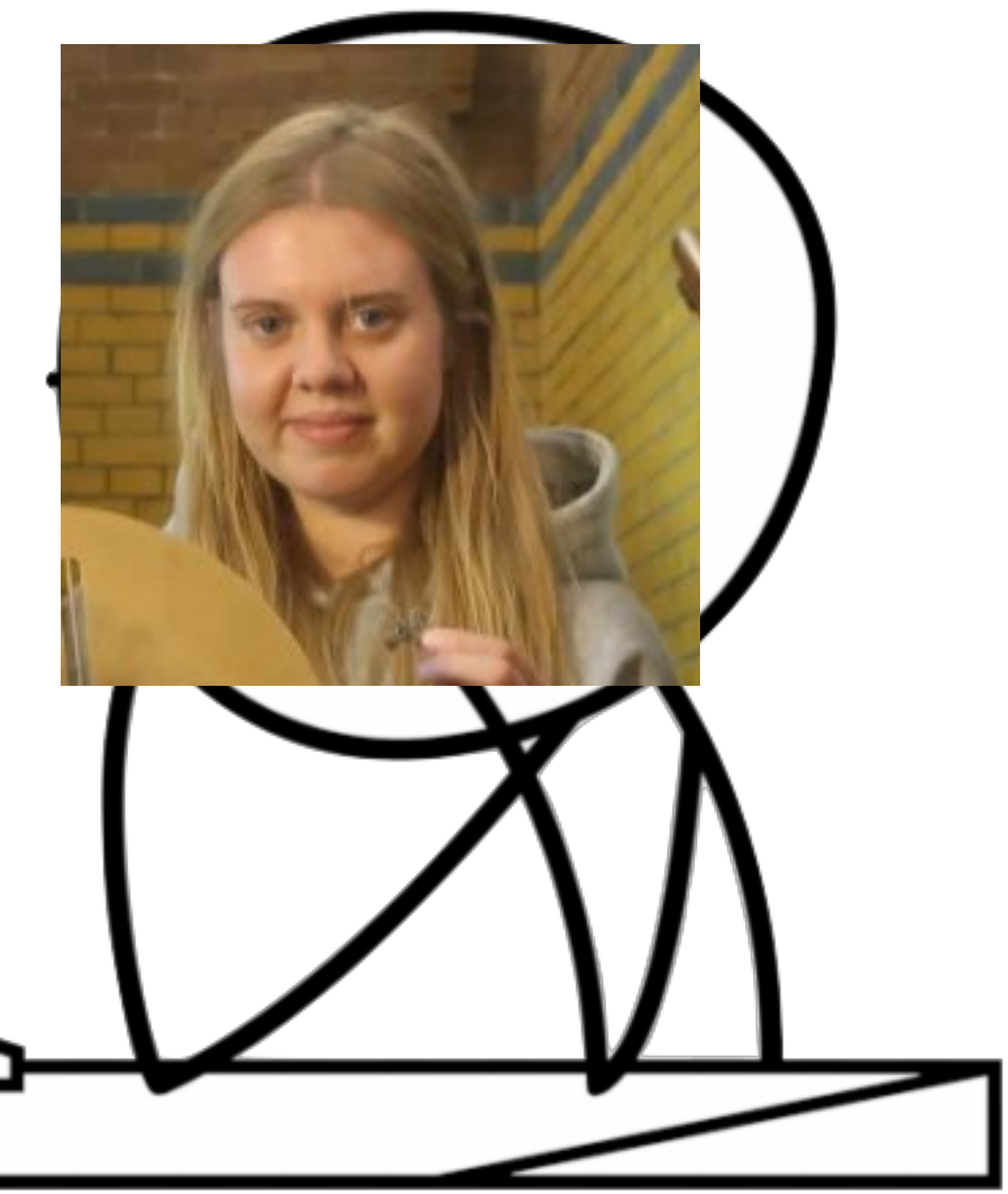
$$\phi_s = 0.00 \pm 0.10\,(\text{stat.}) \pm 0.02\,(\text{syst.})$$



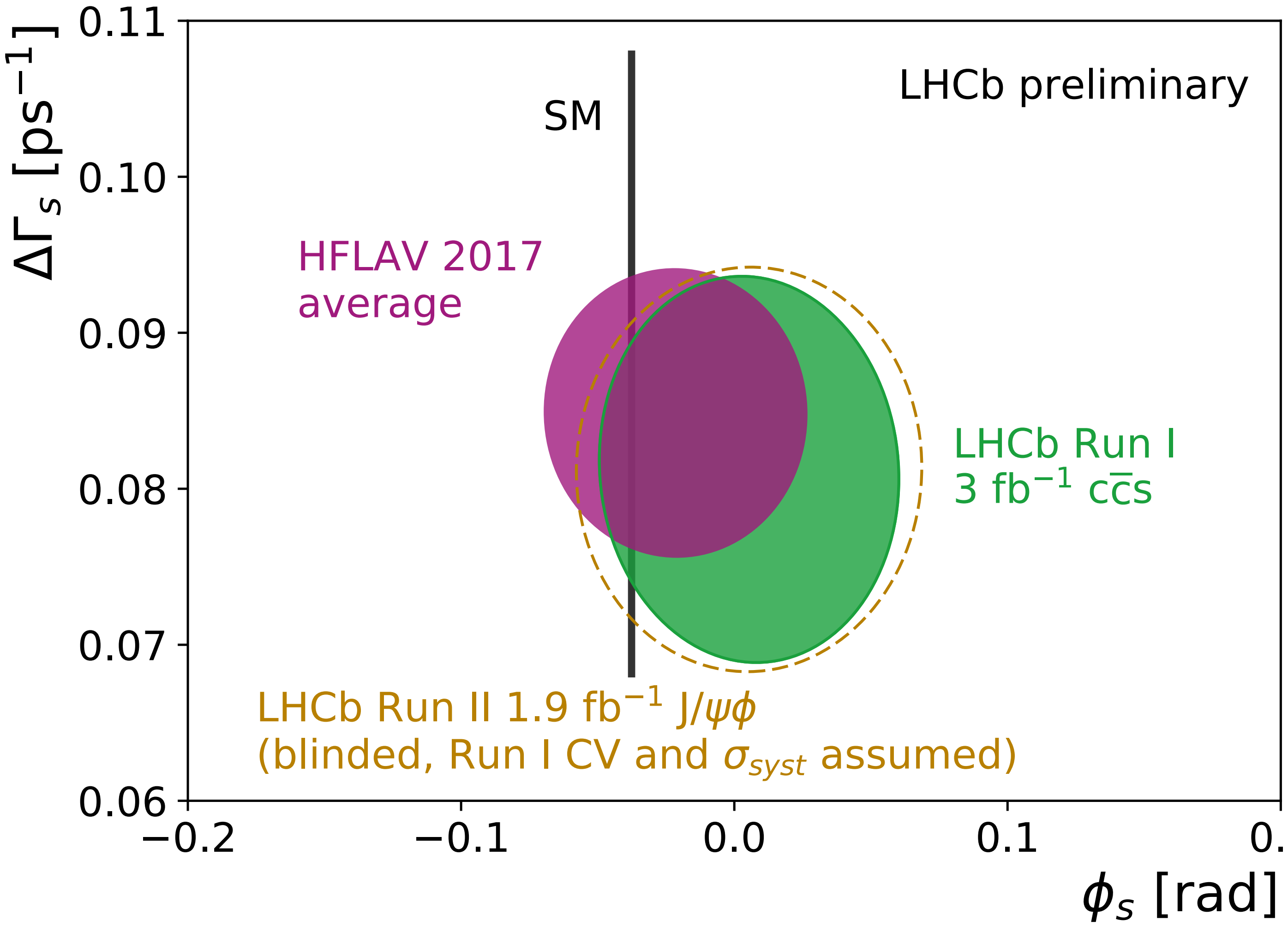
Latest result by LHCb based on 3fb^{-1}

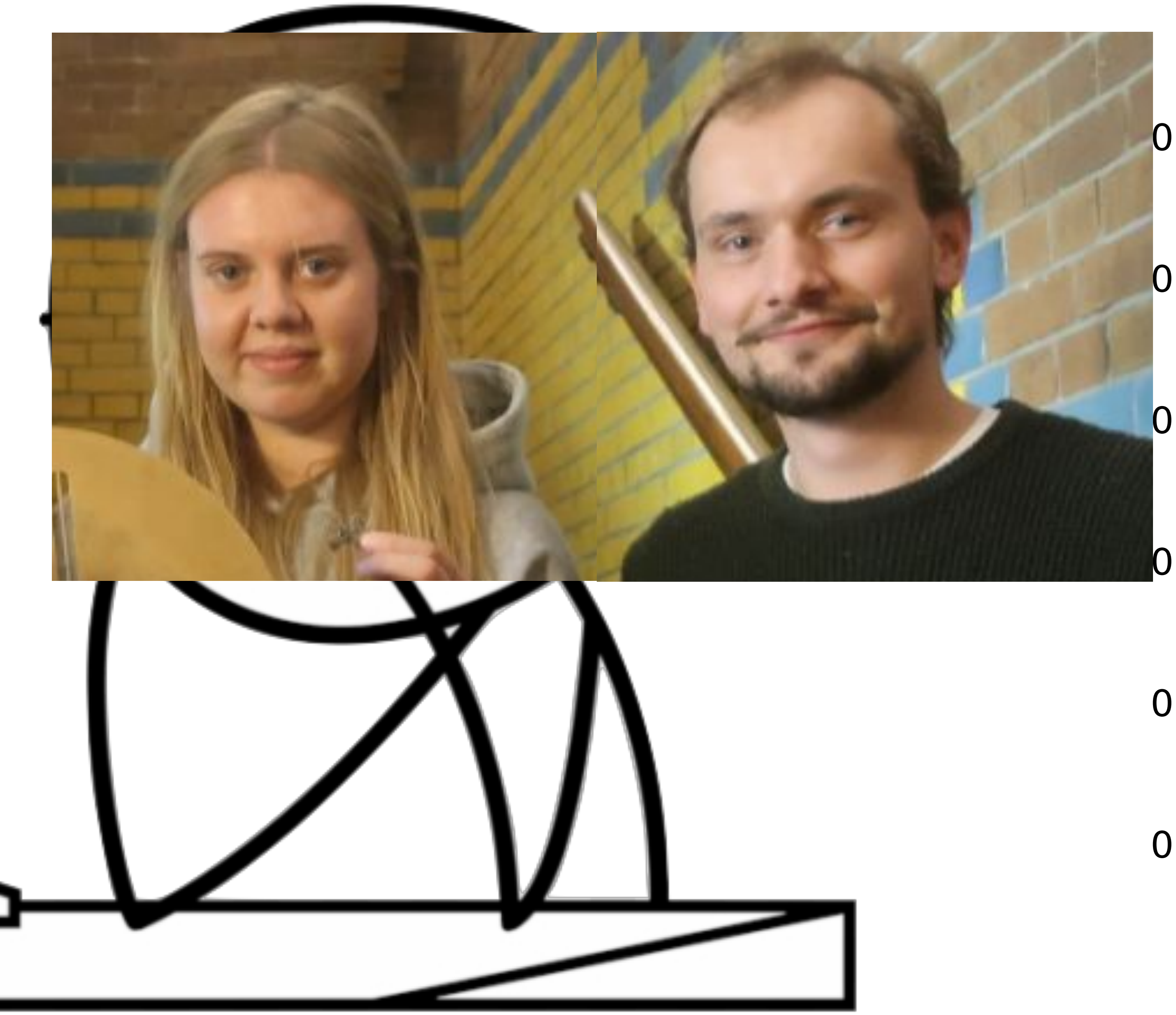
[PRL 114, 041801]

$$\phi_s = -0.058 \pm 0.049 \pm 0.006 \text{ rad}$$

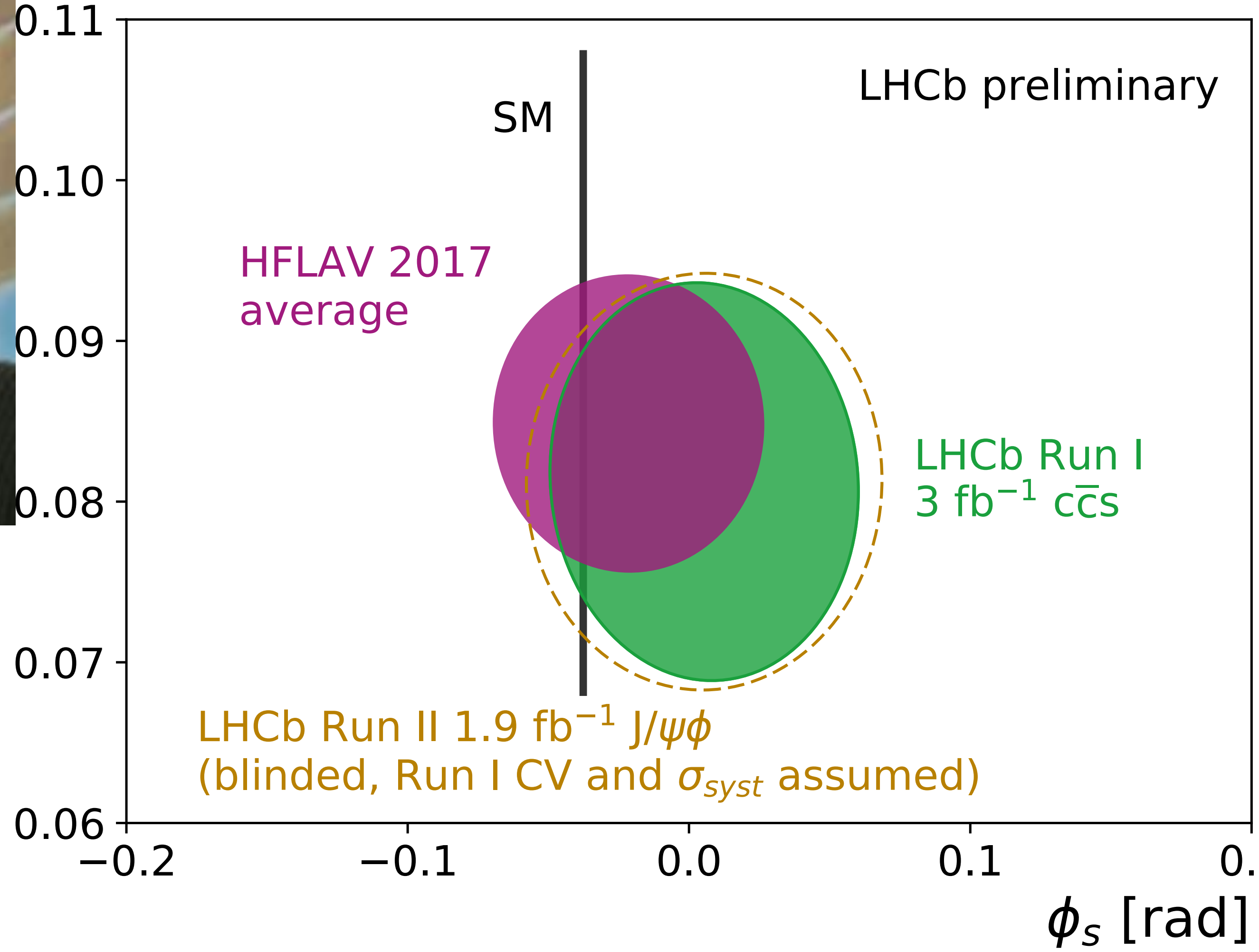


What's next?


LHCb preliminary
SM
HFLAV 2017
average
LHCb Run I
3 fb^{-1} $c\bar{c}s$
LHCb Run II 1.9 fb^{-1} $J/\psi\phi$
(blinded, Run I CV and σ_{syst} assumed)
$\Delta\Gamma_s$ [ps^{-1}]
ϕ_s [rad]
0.11
0.10
0.09
0.08
0.07
0.06
−0.2
−0.1
0.0
0.1
0.2

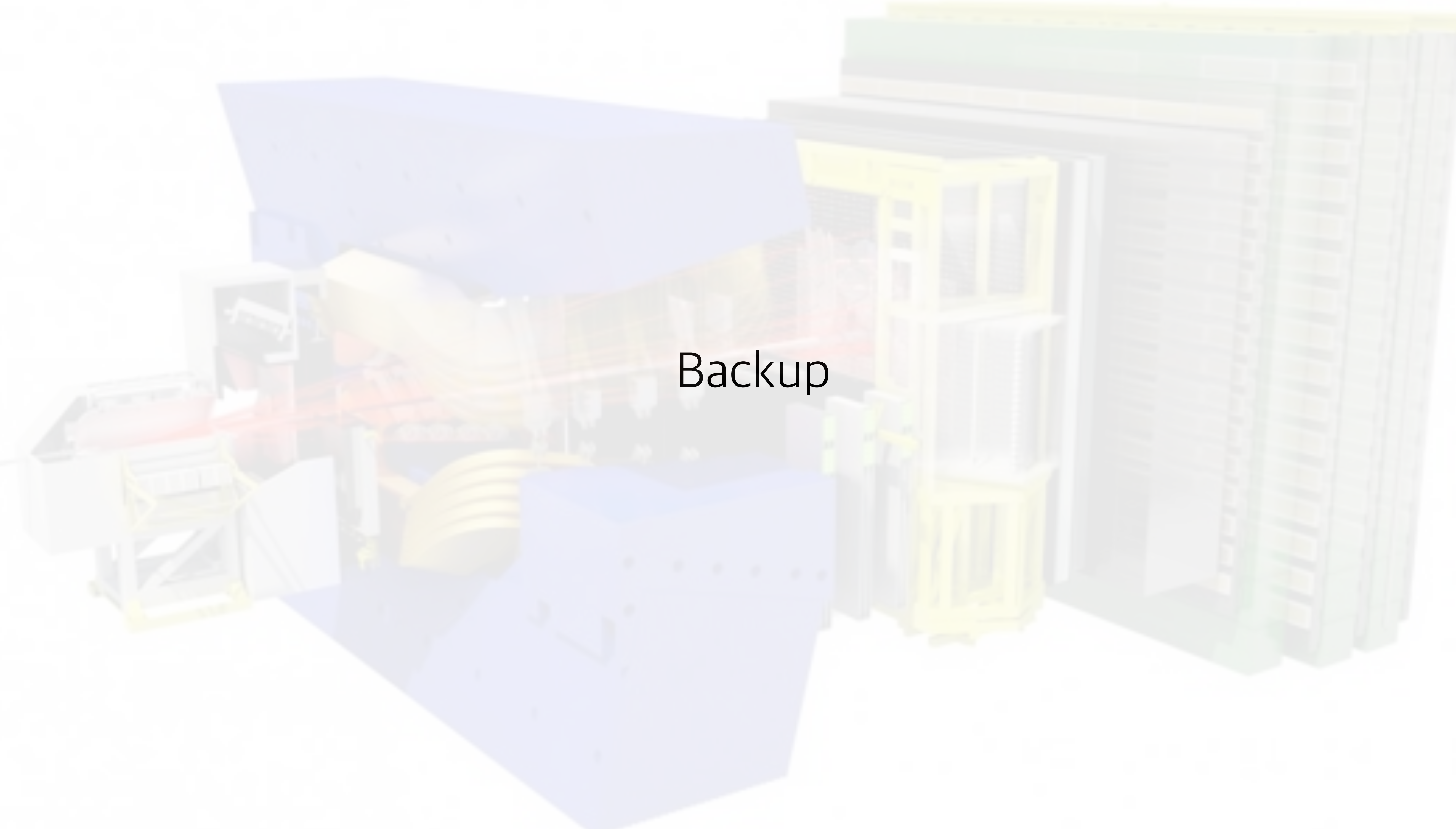


What's next?


LHCb preliminary
SM
HFLAV 2017
average
LHCb Run I
3 fb^{-1} $c\bar{c}s$
LHCb Run II 1.9 fb^{-1} $J/\psi\phi$
(blinded, Run I CV and σ_{syst} assumed)
0.11
0.10
0.09
0.08
0.07
0.06
−0.2
−0.1
0.0
0.1
0.2
ϕ_s [rad]


Nikhef LHCb group 2018
26/06/2018 - patrick@koppenburg


Nikhef LHCb group 2018



Backup

Mass fit

Run 1

- $m(J/\psi\, K^+K^-)$ w/o PV constraint
- Fit with Ipatia function

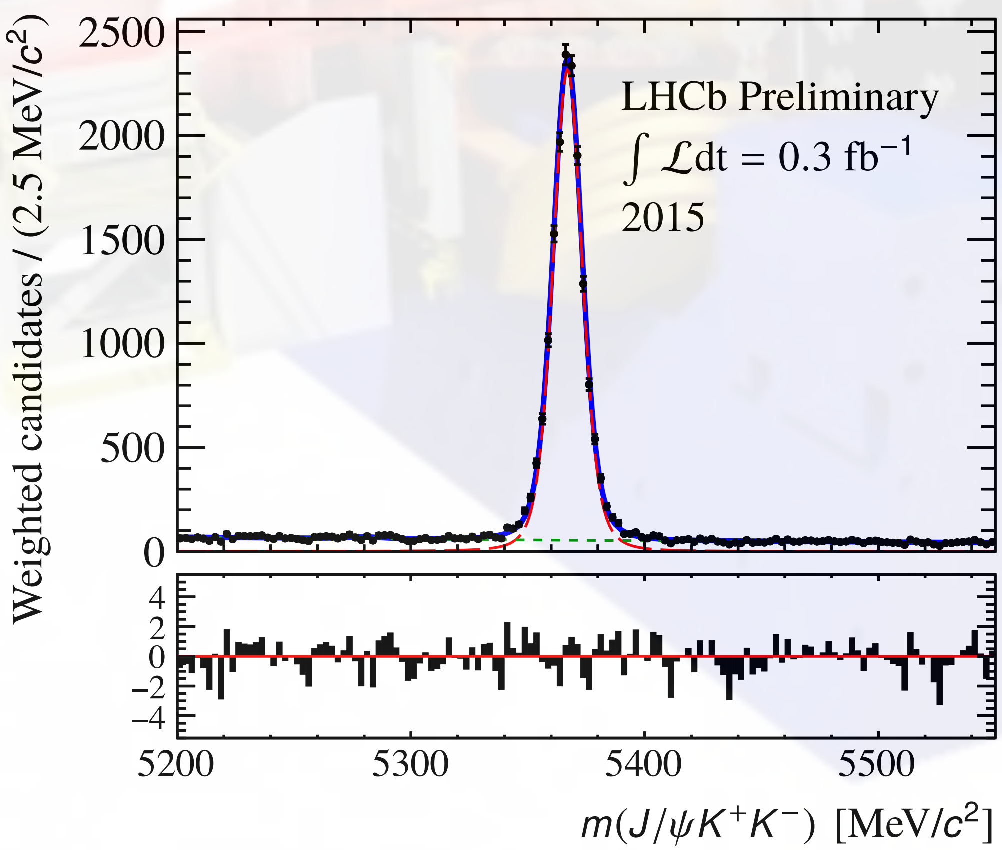
Run 2

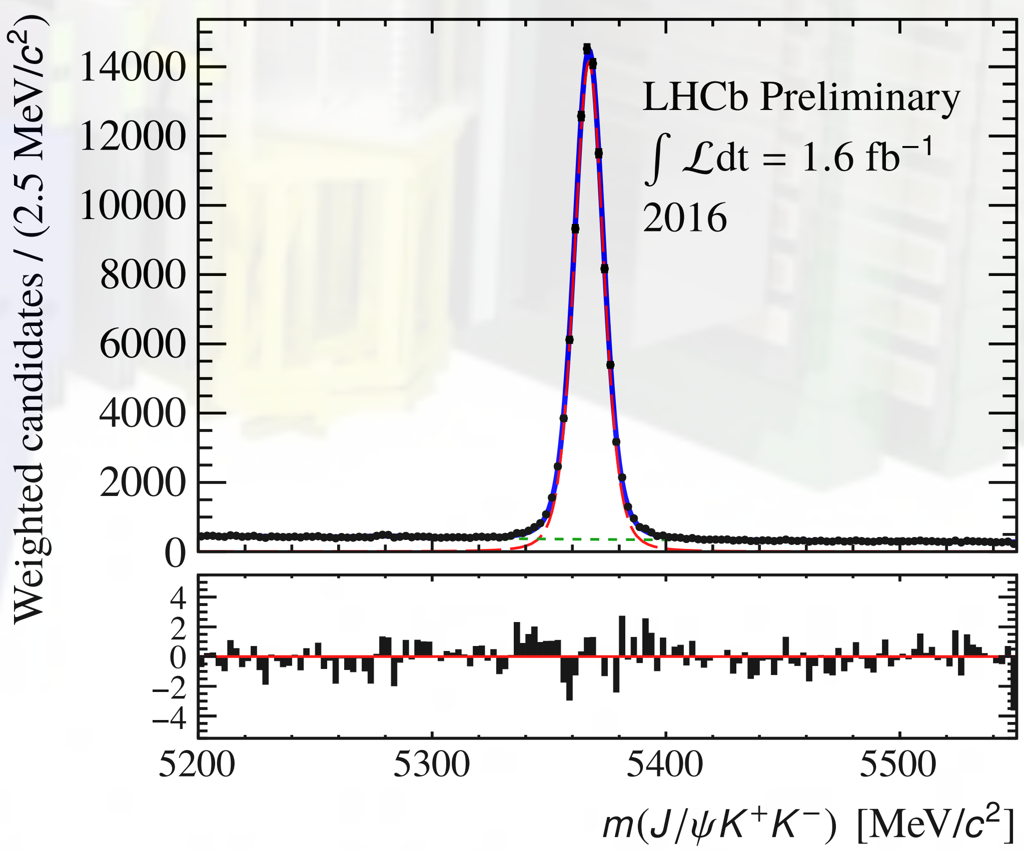
- $m(J/\psi\, K^+K^-)$ w/ PV constraint
- Per-event mass error as conditional observable
- Additional fit component for $B^0 \to J/\psi\, K^+K^-$

Signal model: Double-sided Crystal Ball function (CB2) with per-event mass error as a conditional observable
Quadratic dependence on the per-event mass error: $\sigma = s_1\sigma_i + s_2\sigma_i^2$ (s_1~0.8; s_2~0.05)

- Tails of the CB2 and scale factors are fixed from the fit to MC
- Fit in 6 $m(K^+K^-)$ bins [990, 1008, 1016, 1020, 1024, 1032, 1050] MeV/c^2

Background: Exponential for the combinatorial and gaussian for the $B^0 \to J/\psi\, K^+K^-$ contribution

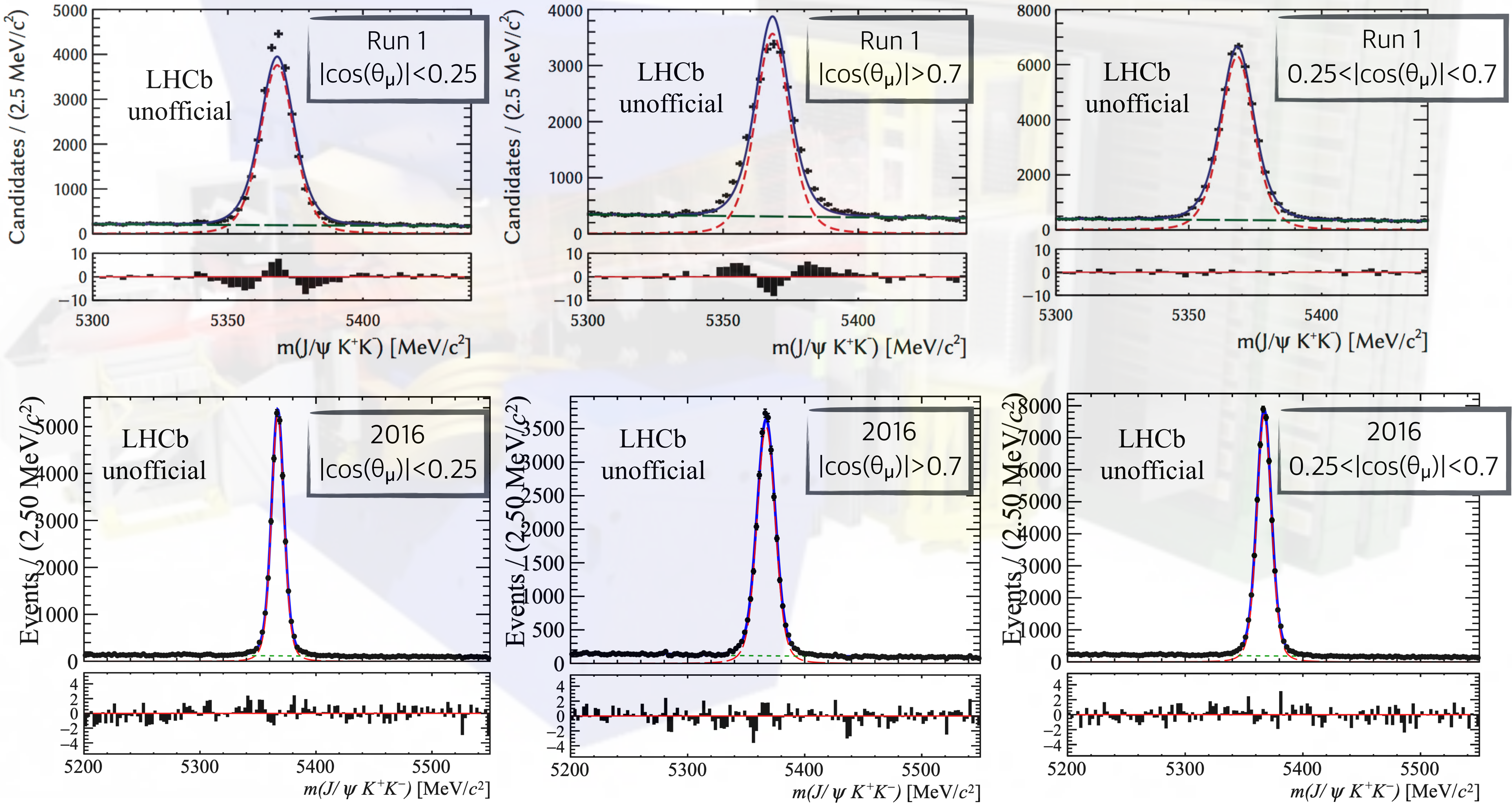




Mass fit

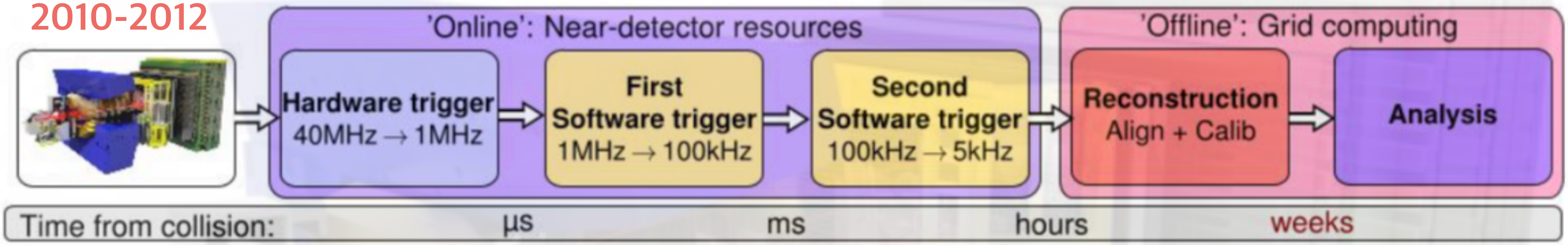
Projections of the total fit in 3 bins of cos(θ_μ)

Using the per-event mass error as a conditional observable accounts for the observed correlation between the mass shape and one of the helicity angles



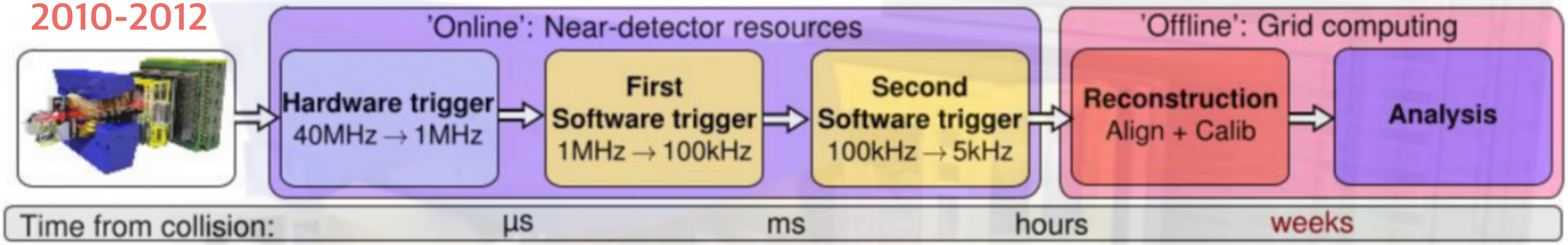
Run1:

2010-2012

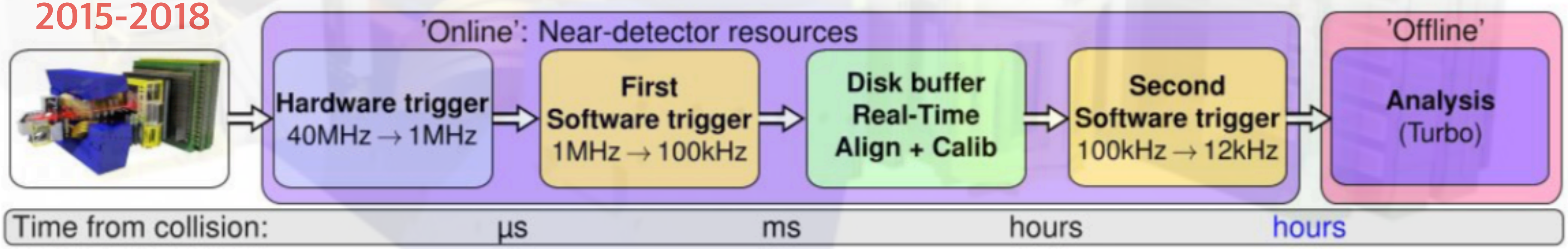


Trigger flow evolution

Run1: 2010-2012

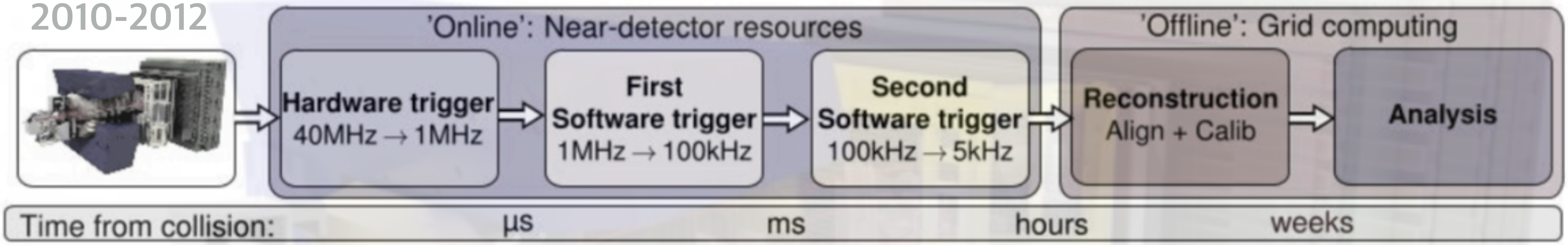


Run2: 2015-2018

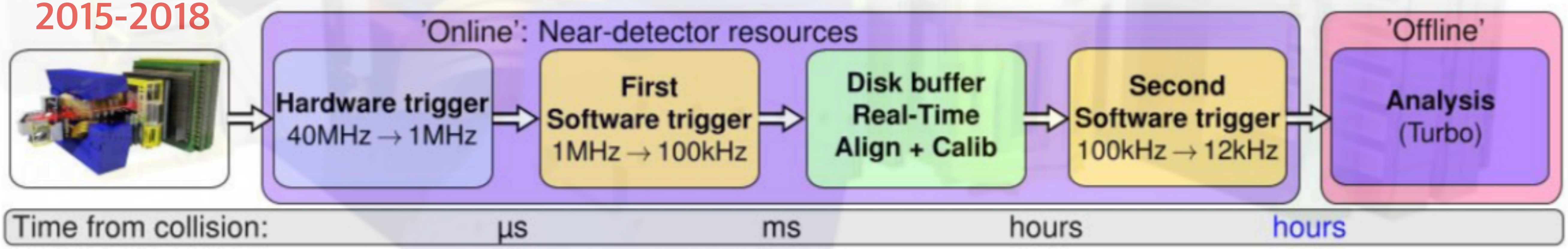


Trigger flow evolution

Run1: 2010-2012

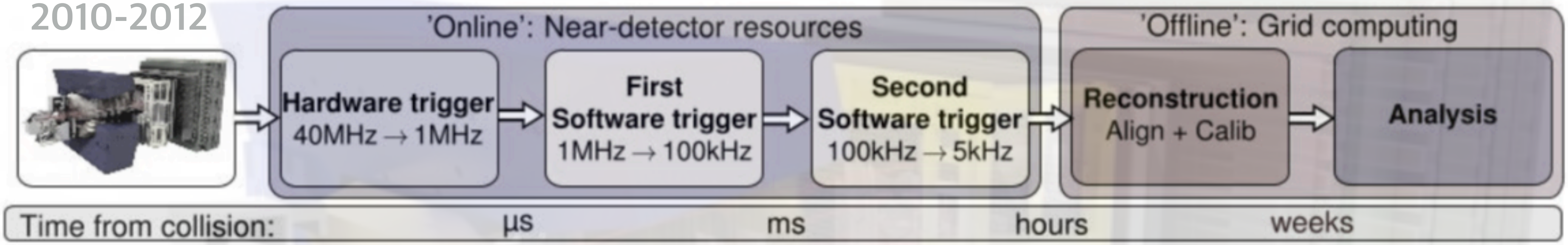


Run2: 2015-2018



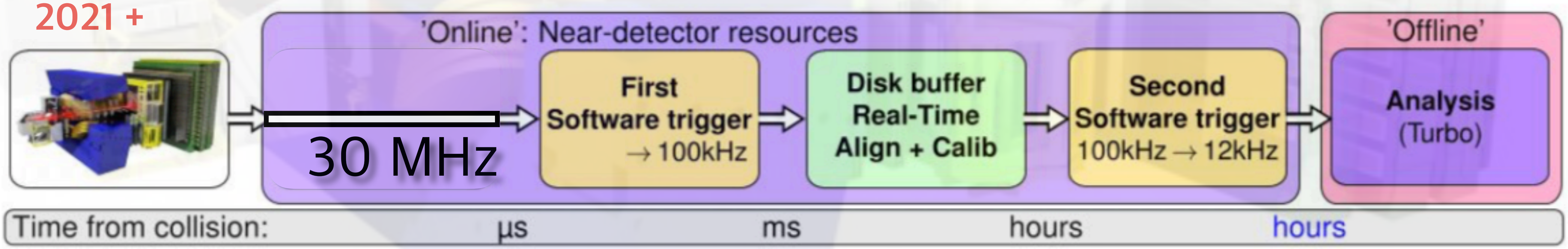
Run1:

2010-2012



Run3:

2021 +



Raw data

Persist all the raw banks in the event

Typical event size ~ 60 kB

Turbo and Turbo++

available from 2015

Persist triggered candidate

Typical event size ~ 15 kB

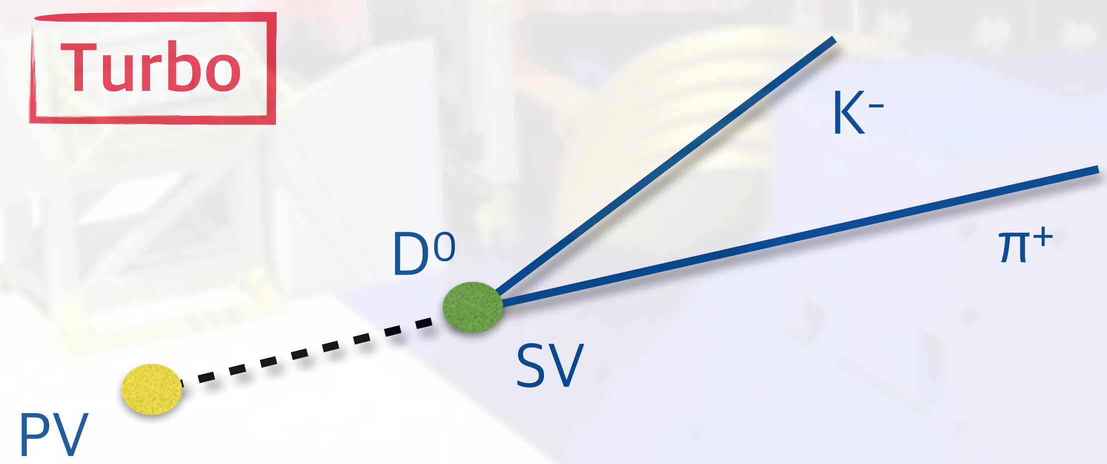
(not enough information for many analyses)

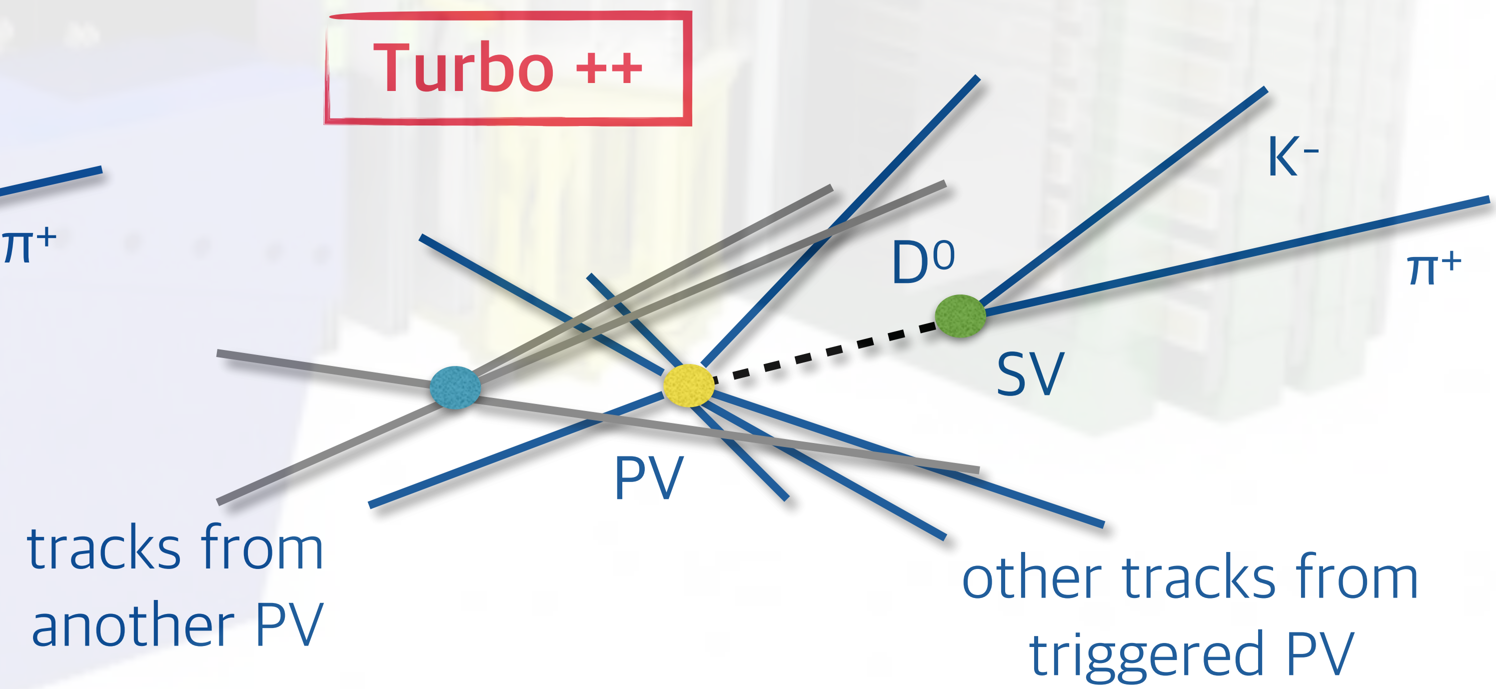
Persist triggered candidate

+

all reconstructed objects in the event

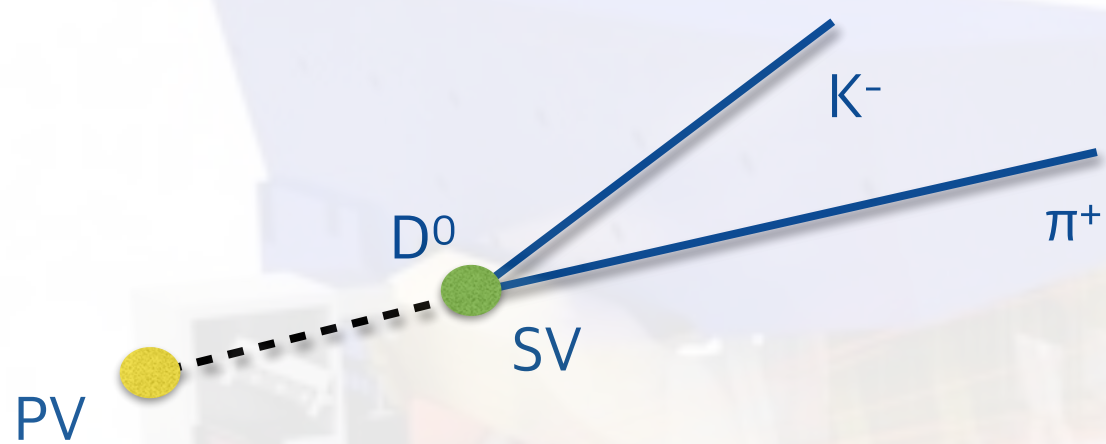
Typical event size ~ 70 kB

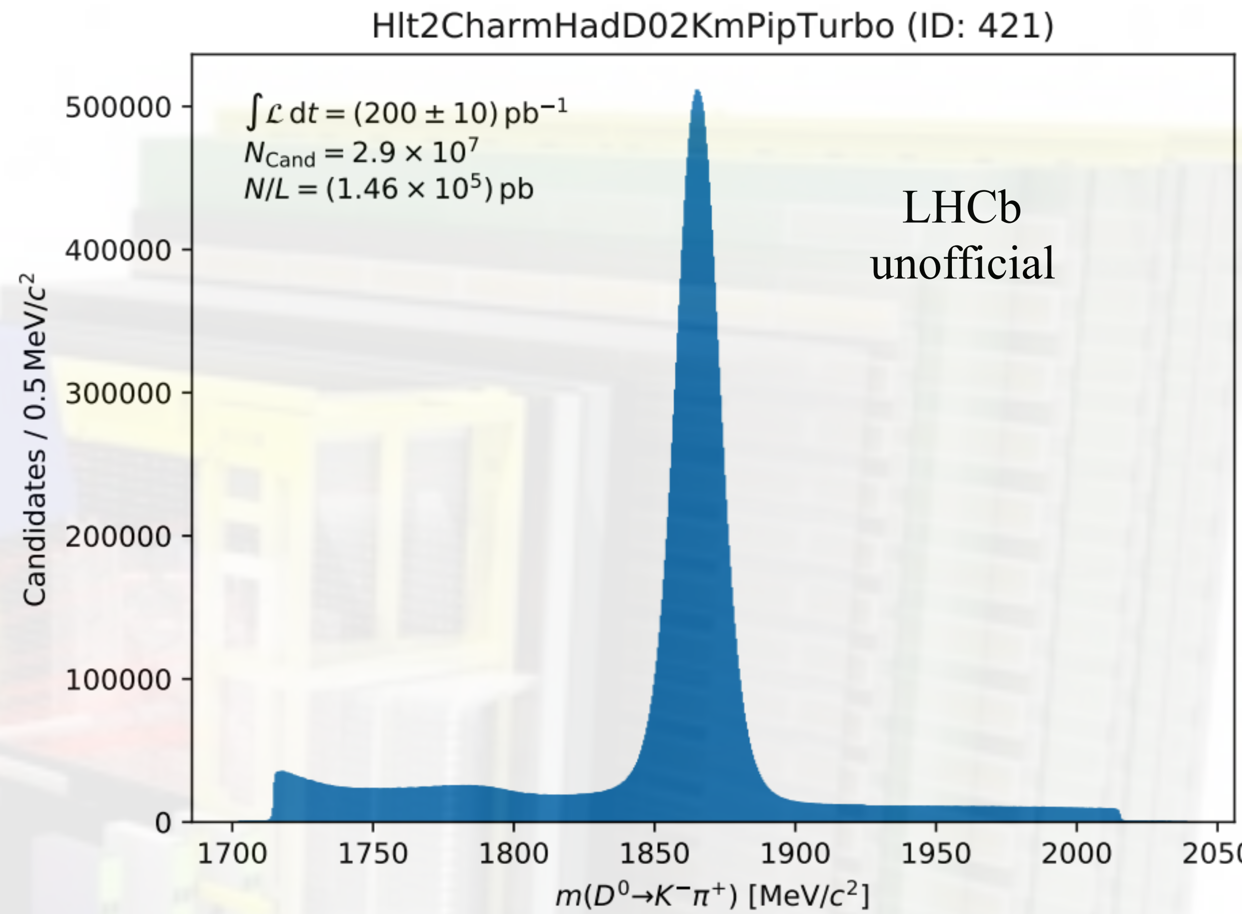




Turbo performance

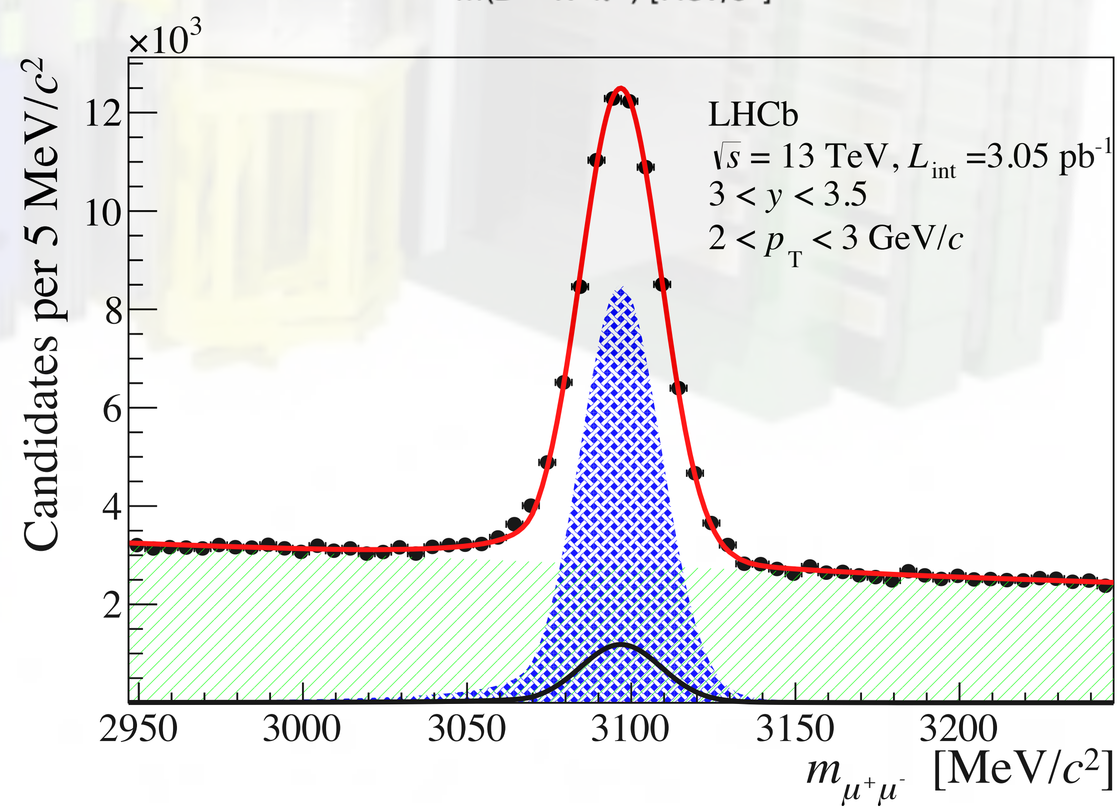
Direct output of one of the trigger lines in Turbo stream



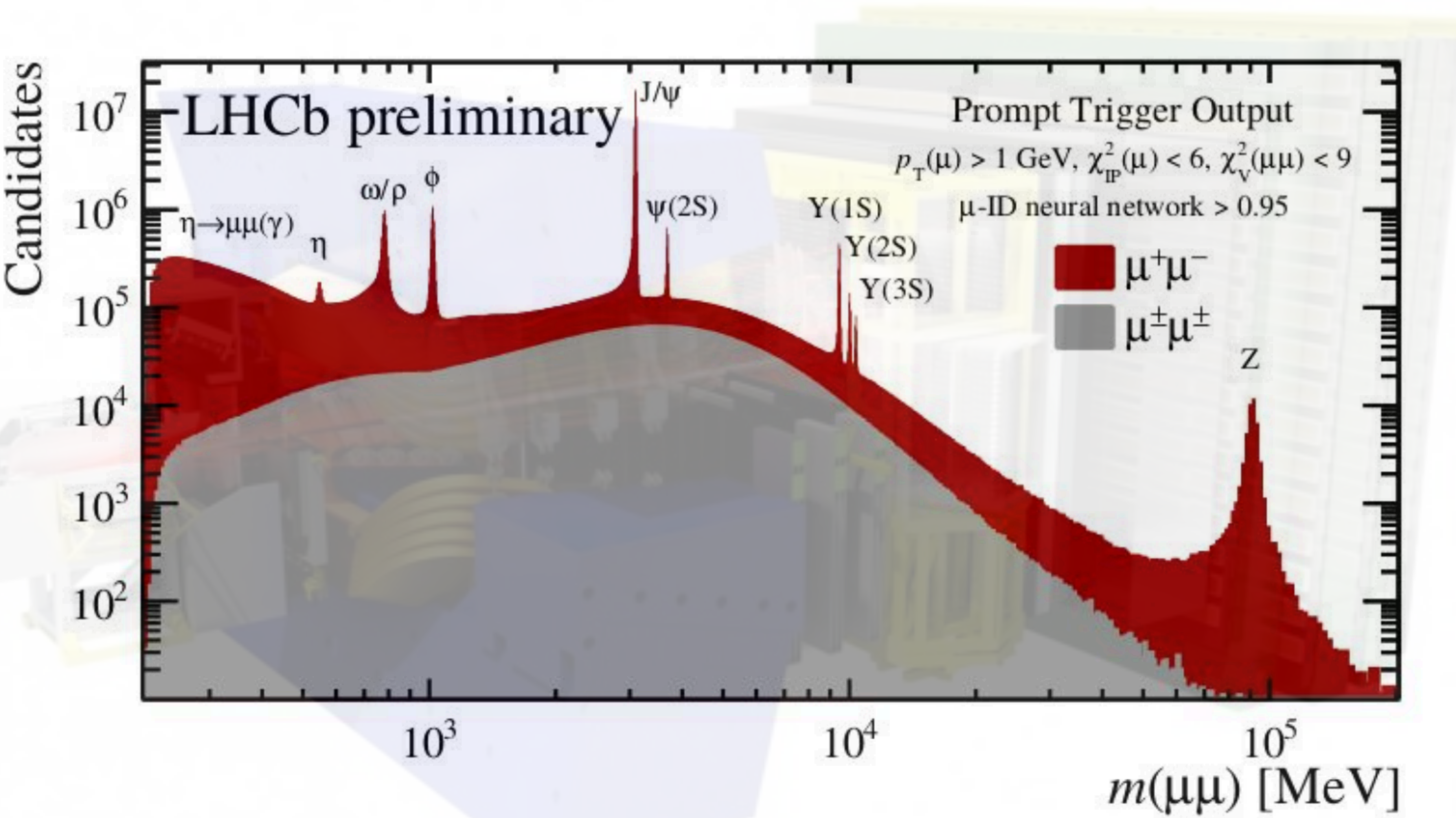


Measurement of J/ψ production cross-section at 13 TeV [JHEP 10 (2015) 172]

- Analysis finds ~ 10^6 candidates directly from the trigger
- Mass resolution 12 MeV/c^2 consistent with best previously achieved resolution
- Presented at EPS conference 18 days after data were taken



Turbo performance



TurboSP

Choose what to persist:

selectively persist raw information and/or reconstructed objects

Typical event size depends on the requirements ~ 15-70 kB

Already successfully operates in the trigger!

TurboSP is considered as the primary data flow model for the planned LHCb upgrade in Run 3

Current work: Adapting selection of $B^0_s \to J/\psi\, K^+K^-$ for TurboSP