

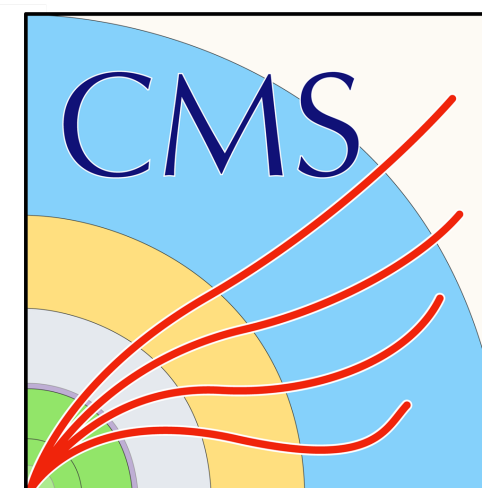
Precision CP-Violation in a General-Purpose Detector: $\sin(2\beta)$ with CMS

Based on CMS-BPH-26-005

Valeriia (Lera) Lukashenko



**Universität
Zürich**^{UZH}

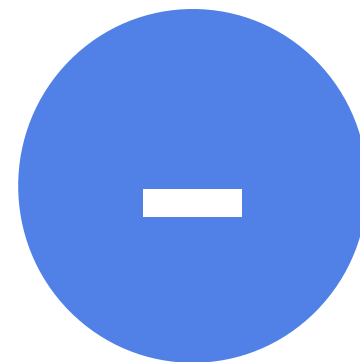
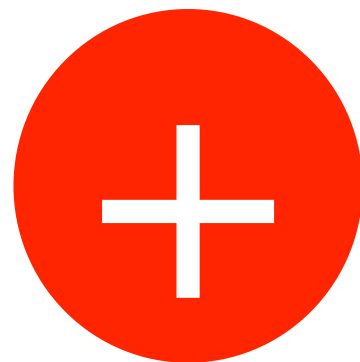


02.07.26, TU Dortmund

Physics laws are the same everywhere and always

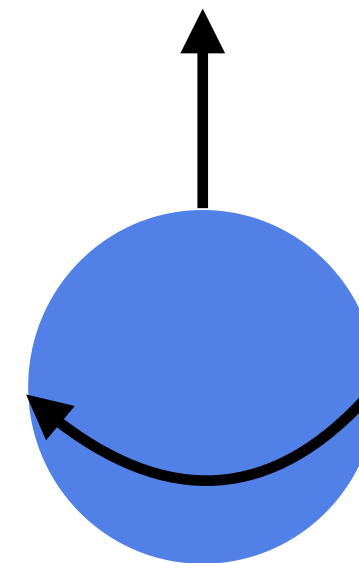
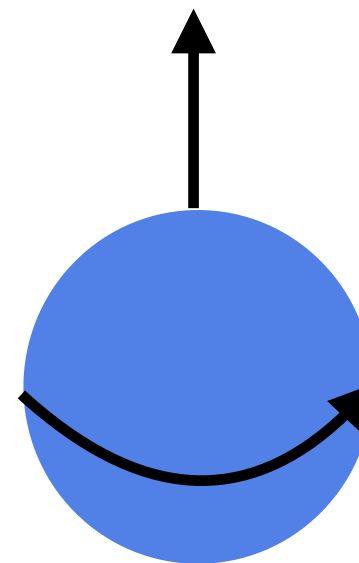
C

charge



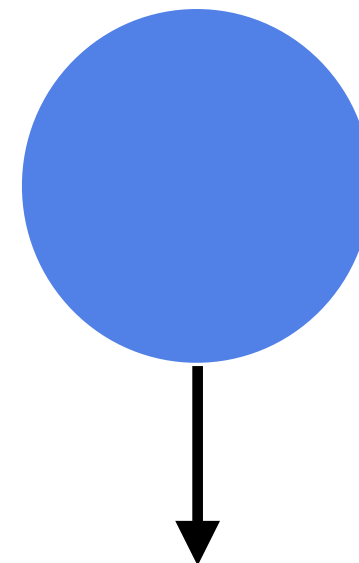
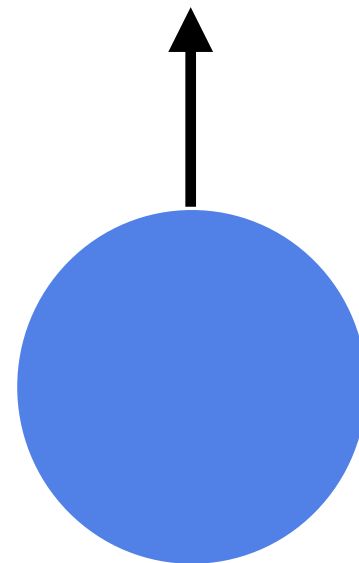
P

parity



T

time



CP-conservation

matter

$C \times$



$P \times$

anti-matter

CP-conservation

matter

$C \times$



$P \times$



anti-matter

CP-conservation

matter

$C \times$

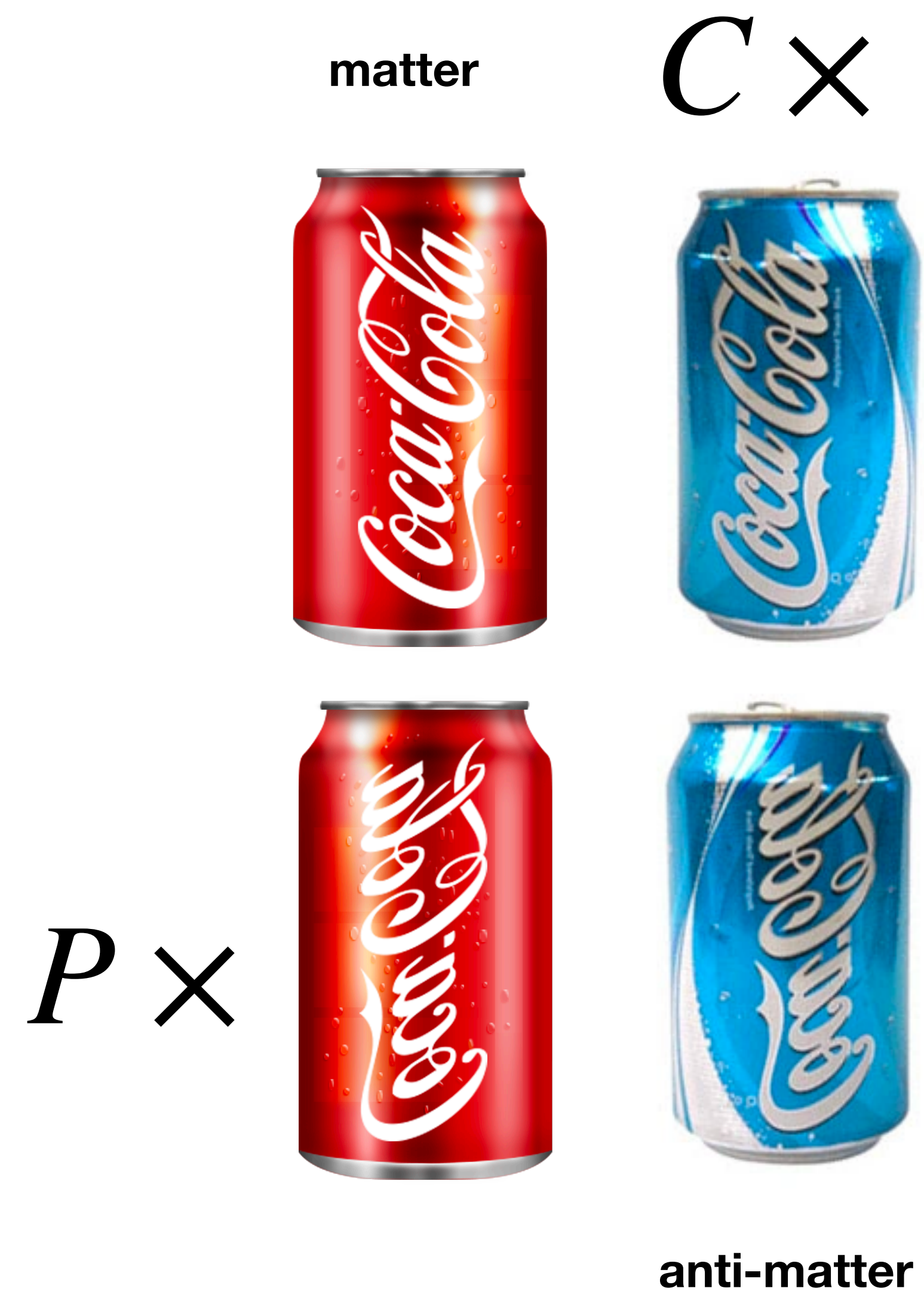


$P \times$

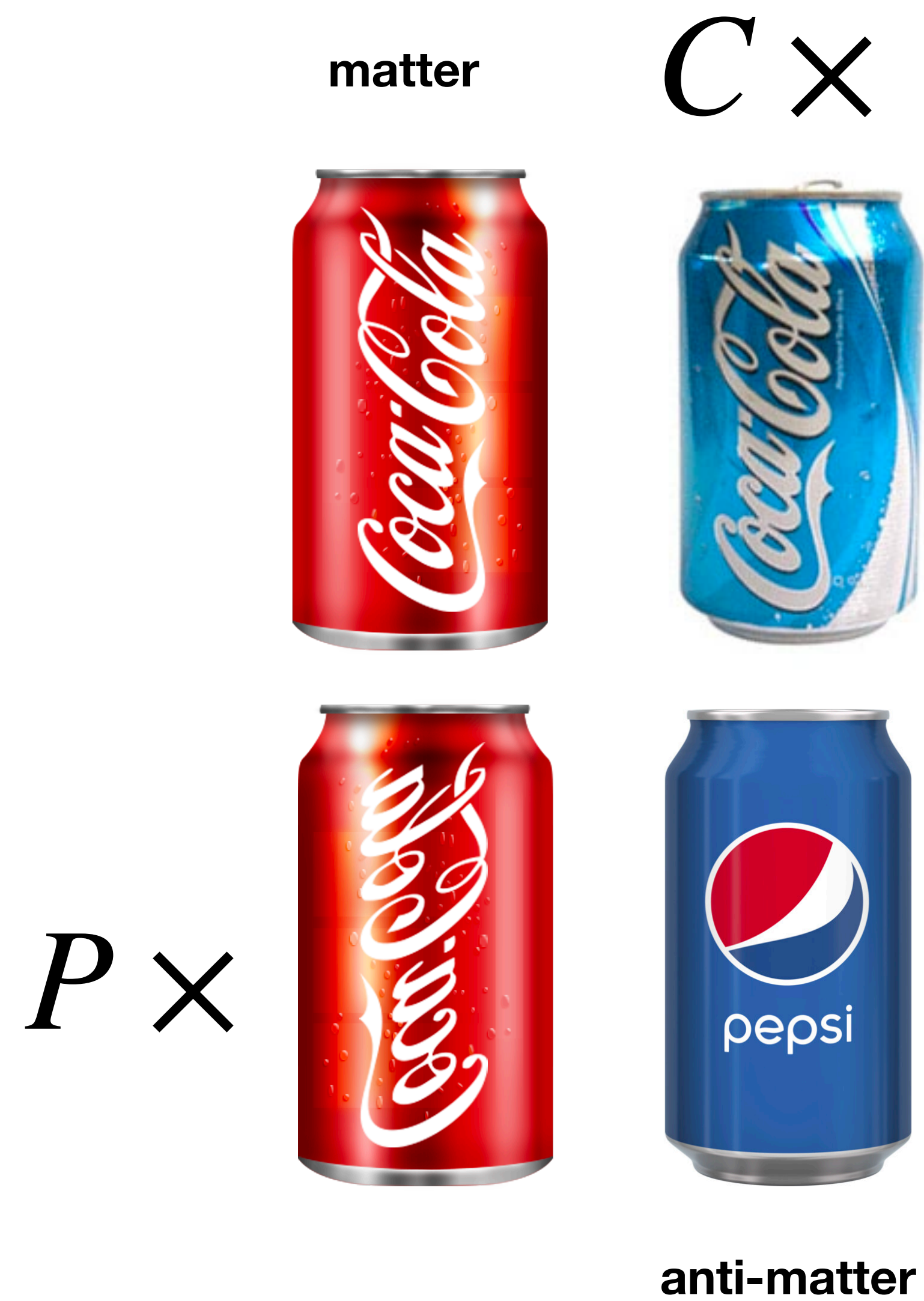


anti-matter

CP-conservation



CP-violation



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

Sakharov conditions for baryogenesis

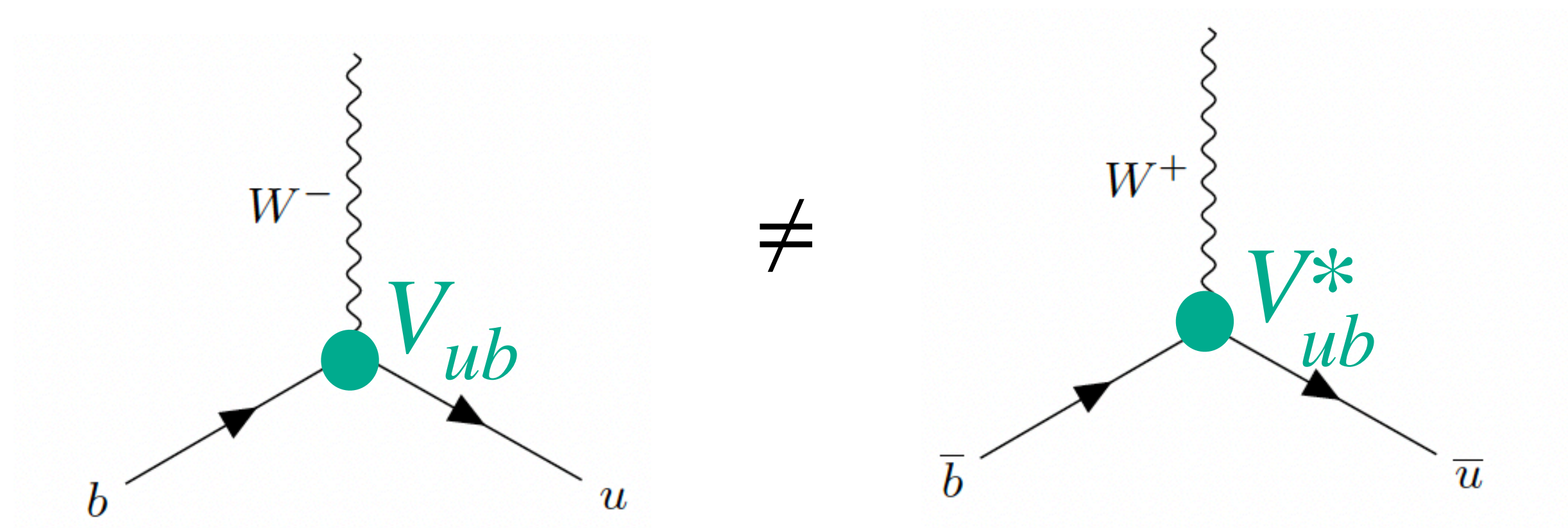
- ✓ 1. Baryon number violation
- ✓ 2. Interactions out of thermal equilibrium
- ✓ 3. C- and CP-violation

in SM

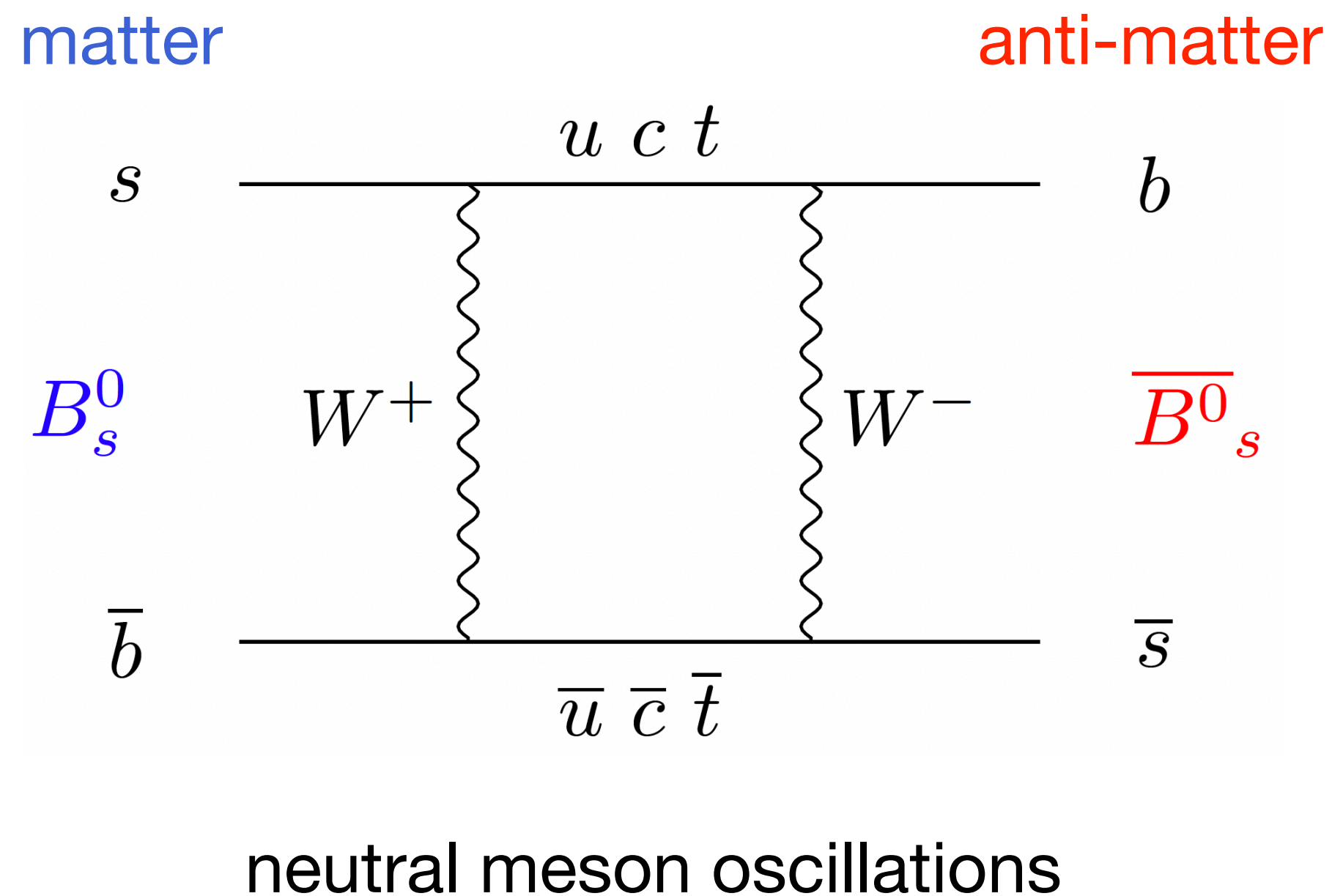
But only 10^{-20} from SM quark sector CPV

Weak interactions and CP-violation

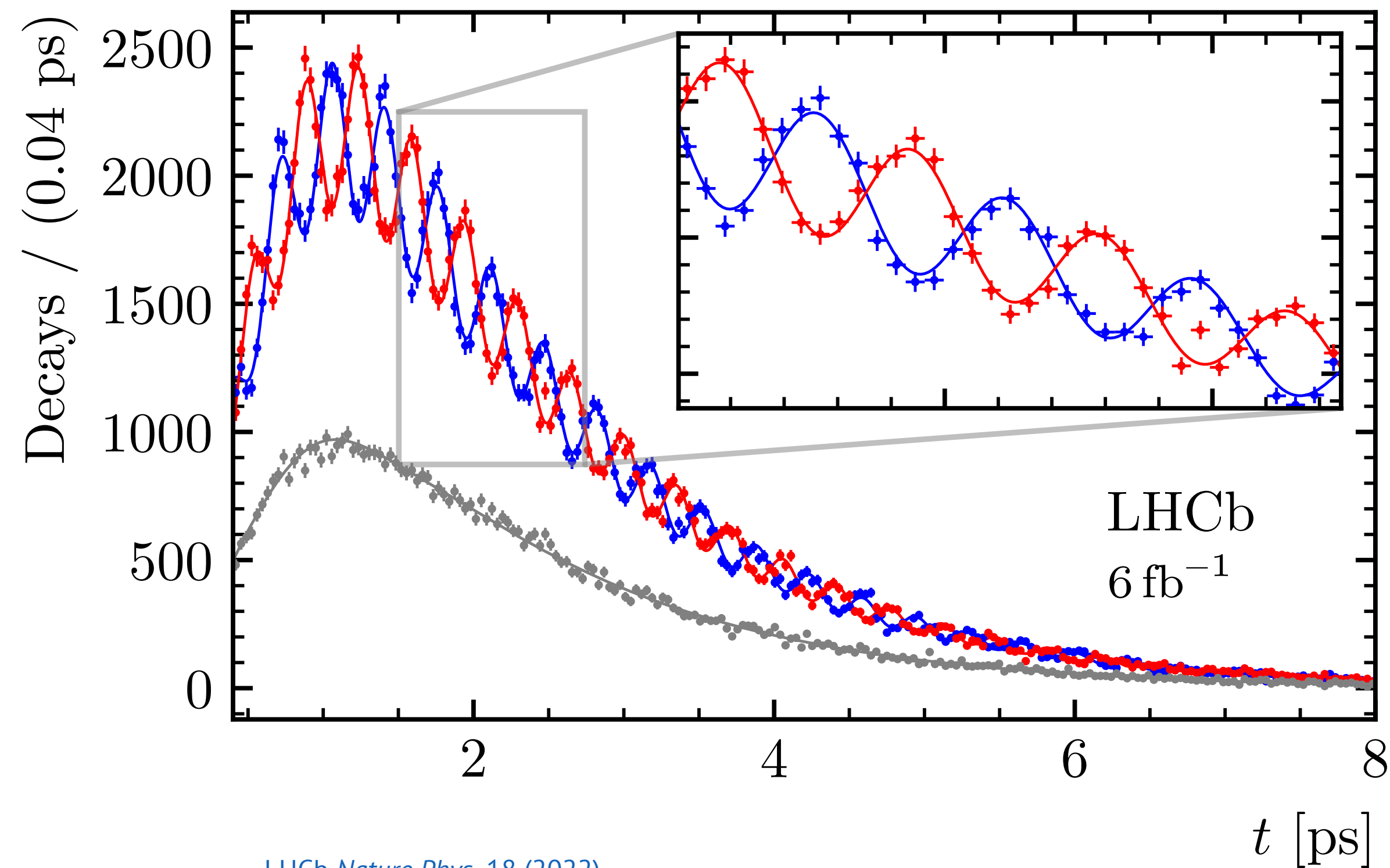
- Weak interactions govern quark transitions
- Quarks transitions enable the neutral meson oscillations!
- In Standard Model CP-violation appears in weak interactions



Neutral meson oscillations



— $B_s^0 \rightarrow D_s^- \pi^+$ — $\bar{B}_s^0 \rightarrow B_s^0 \rightarrow D_s^- \pi^+$ — Untagged



LHCb *Nature Phys.* 18 (2022)

Why do we have CP-violation in Standard Model?

1.

$$\psi_I \neq \psi_m$$

2.

3 generations of matter

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

CKM matrix

Why do we have CP-violation in Standard Model?

1.

$$\psi_I \neq \psi_m$$

2.

3 generations of matter

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

CKM matrix

Real

Complex

Why do we have CP-violation in Standard Model?

1.

$$\psi_I \neq \psi_m$$

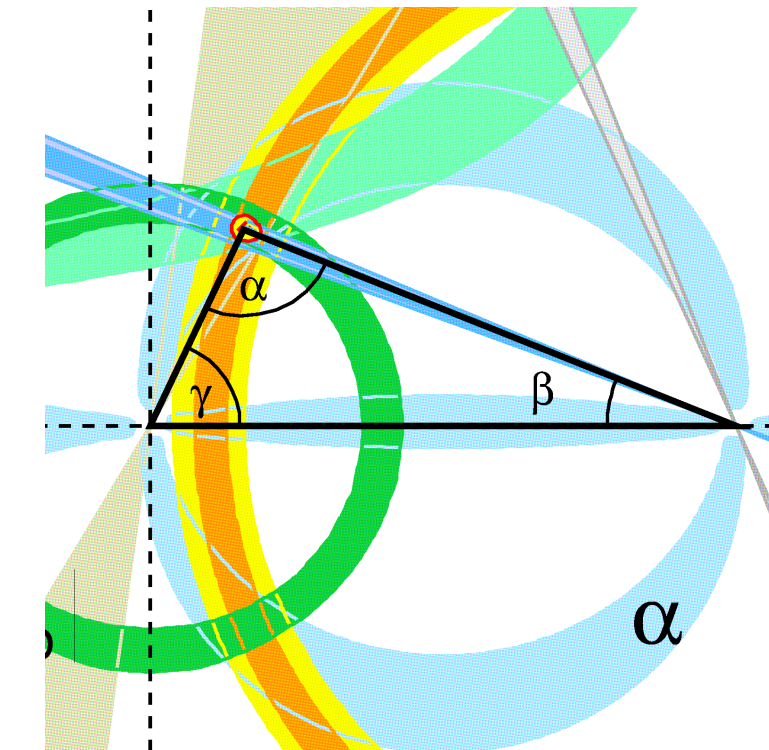
2.

3 generations of matter

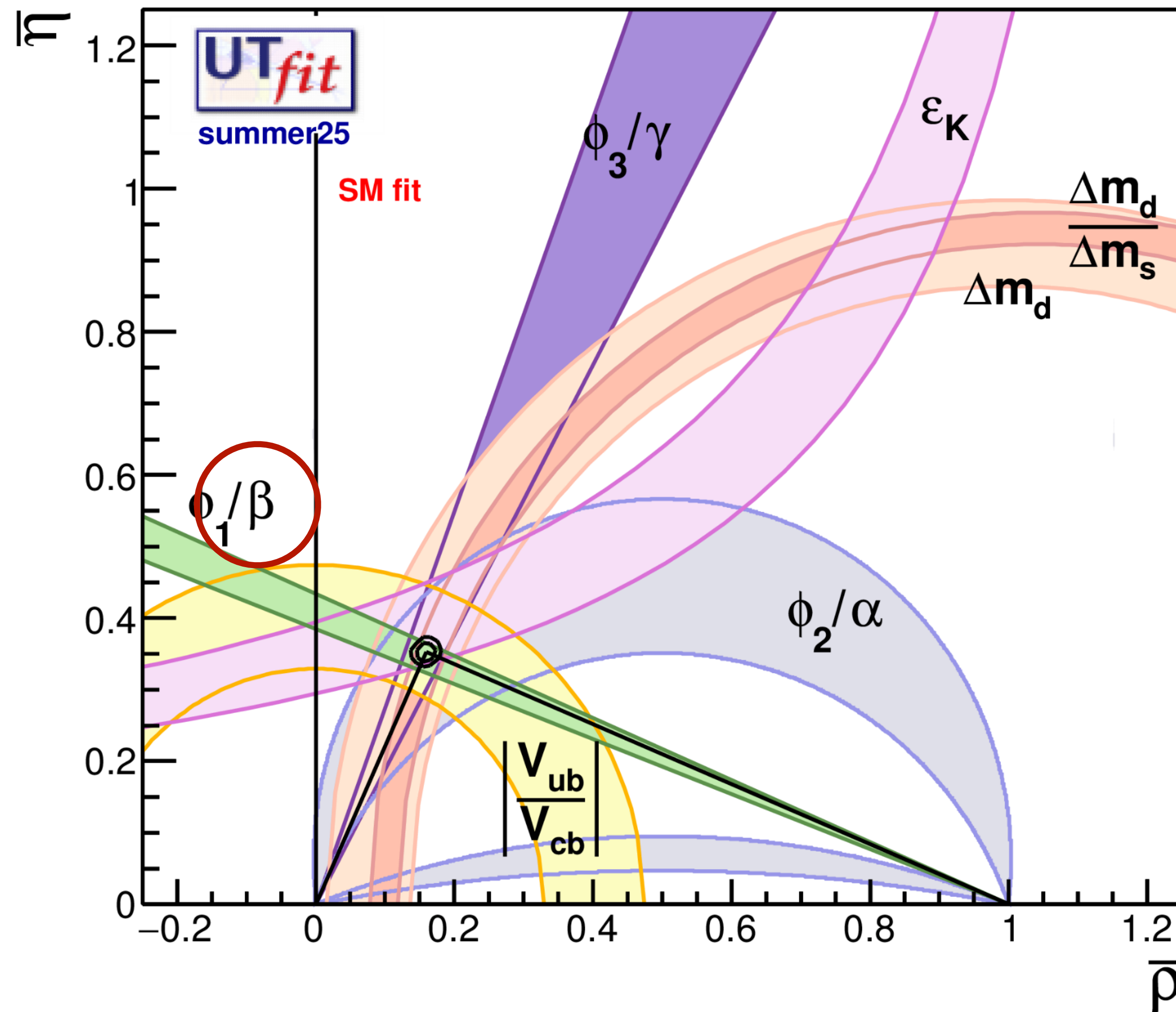
Real Complex

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

CKM matrix



The Unitarity triangle



The Unitarity triangle:

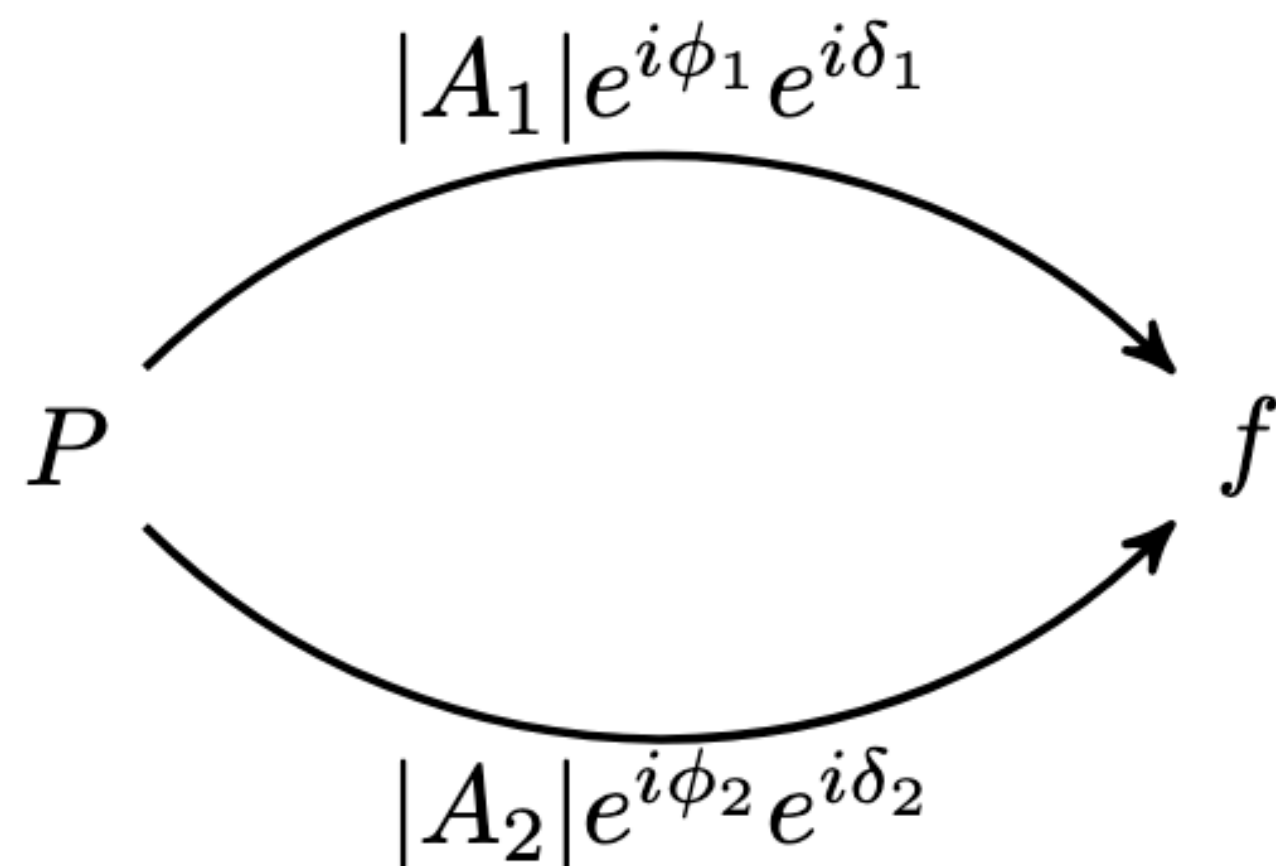
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

where

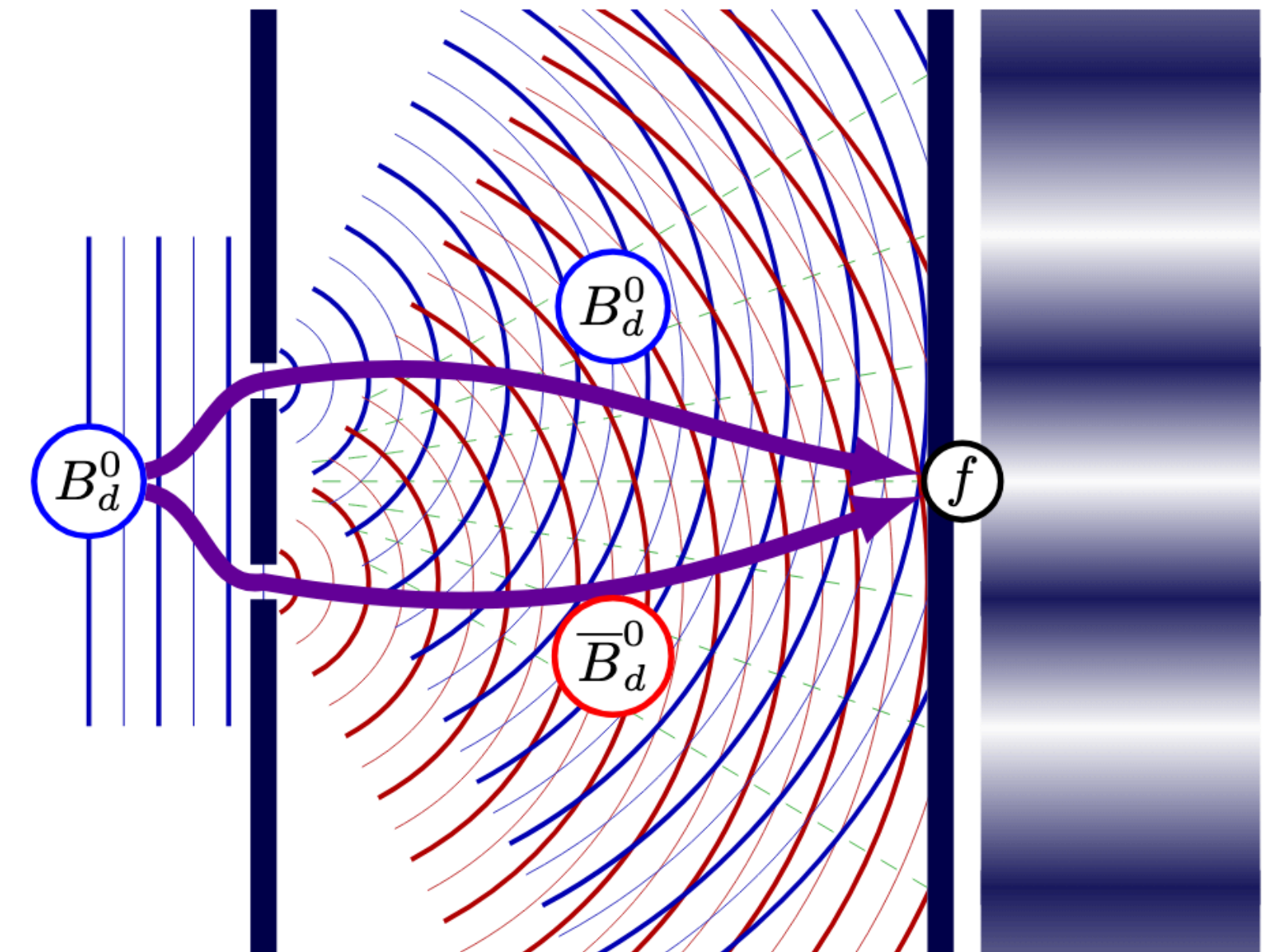
$$\bar{\rho} + i\bar{\eta} \equiv \frac{V_{ud}V_{ub}^*}{V_{cb}V_{cb}^*}$$

How to observe CP-violation?

1. Two paths to the same final state
2. Amplitudes have a weak CP-violating and a strong phase CP-conserving phase
3. Weak phases are different and strong phases are different

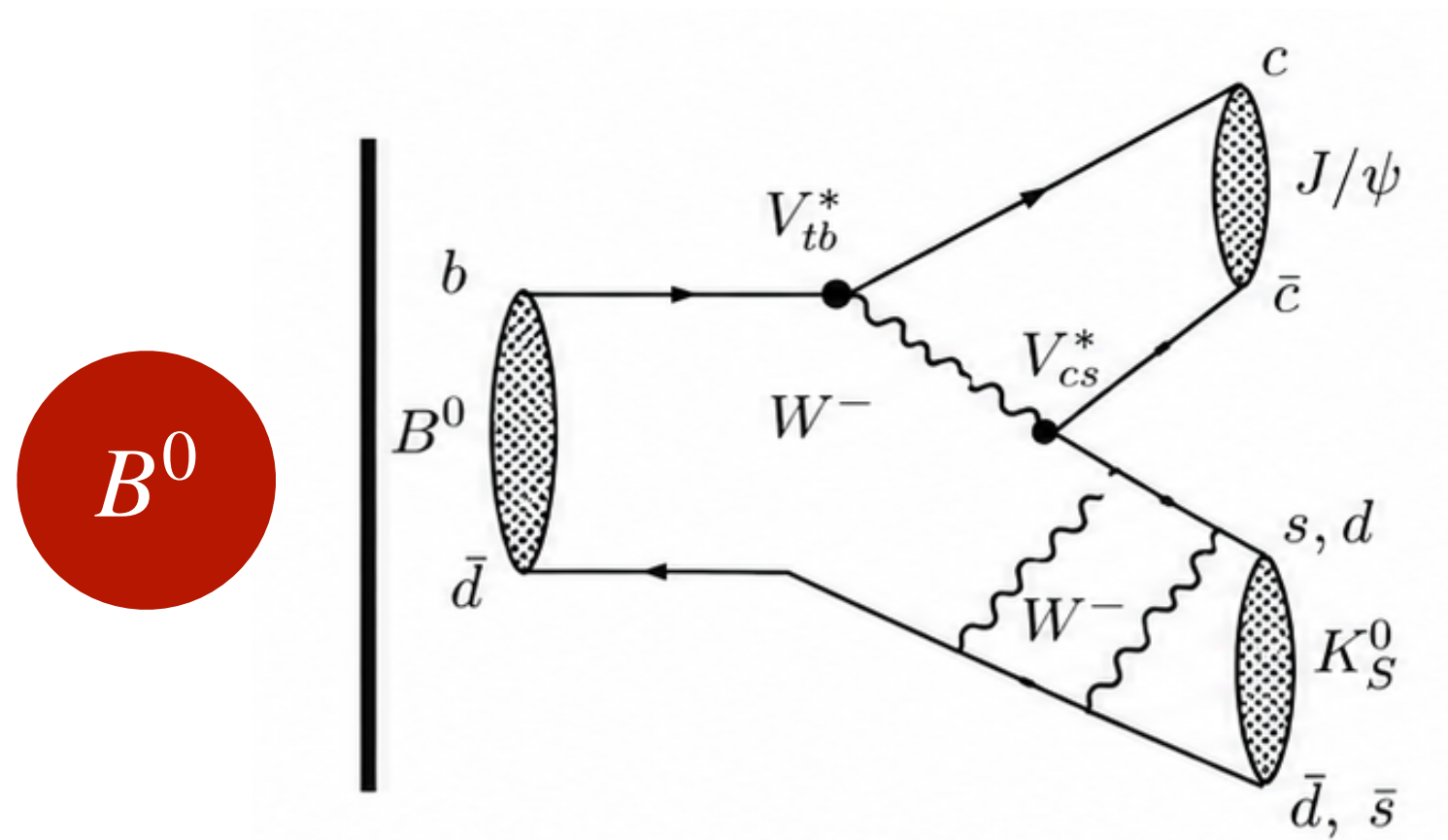


$$|A_f|^2 = |A_1|^2 + |A_2|^2 + 2|A_1||A_2|(\cos(\phi_1 - \phi_2)\cos(\delta_1 - \delta_2) - \sin(\phi_1 - \phi_2)\sin(\delta_1 - \delta_2)).$$



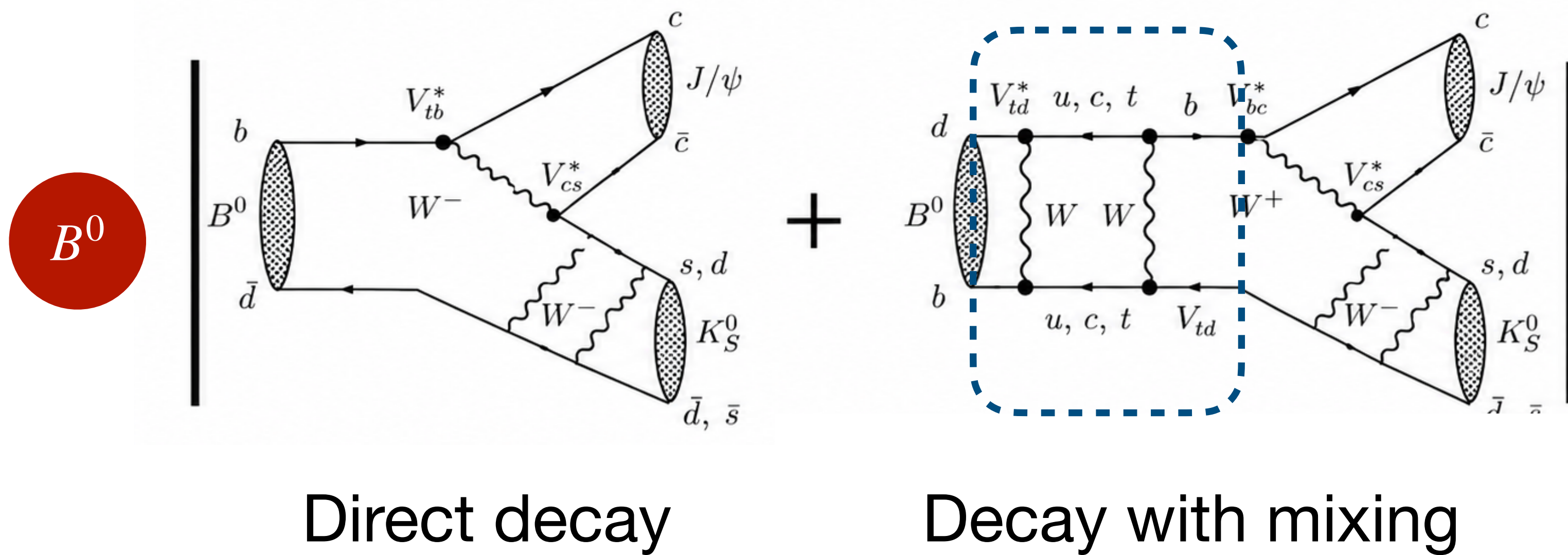
Today: CPV in interference between direct decay and decay with mixing

Golden channel for $\sin 2\beta$: $B^0 \rightarrow J/\psi K_S^0$

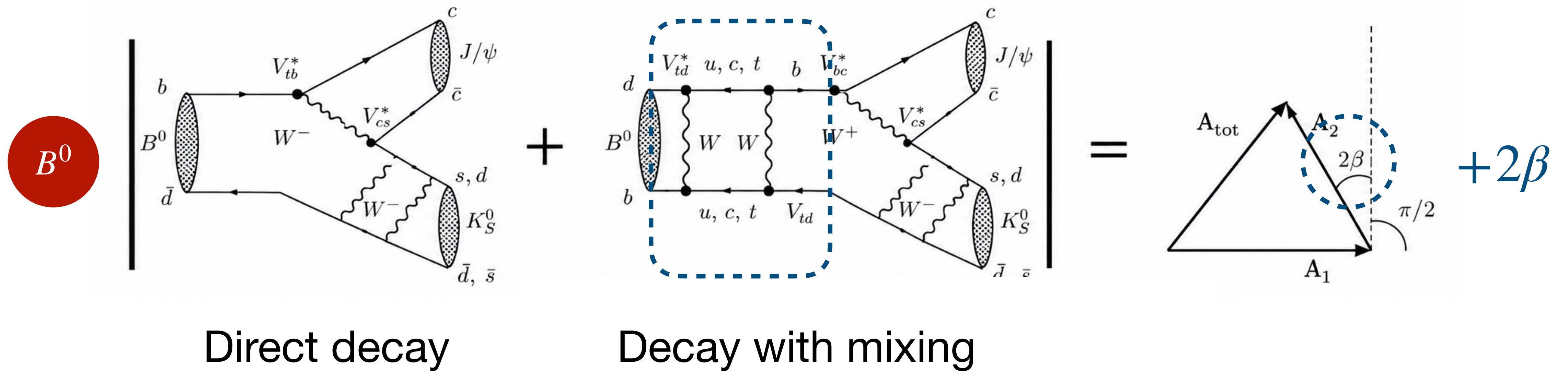


Direct decay

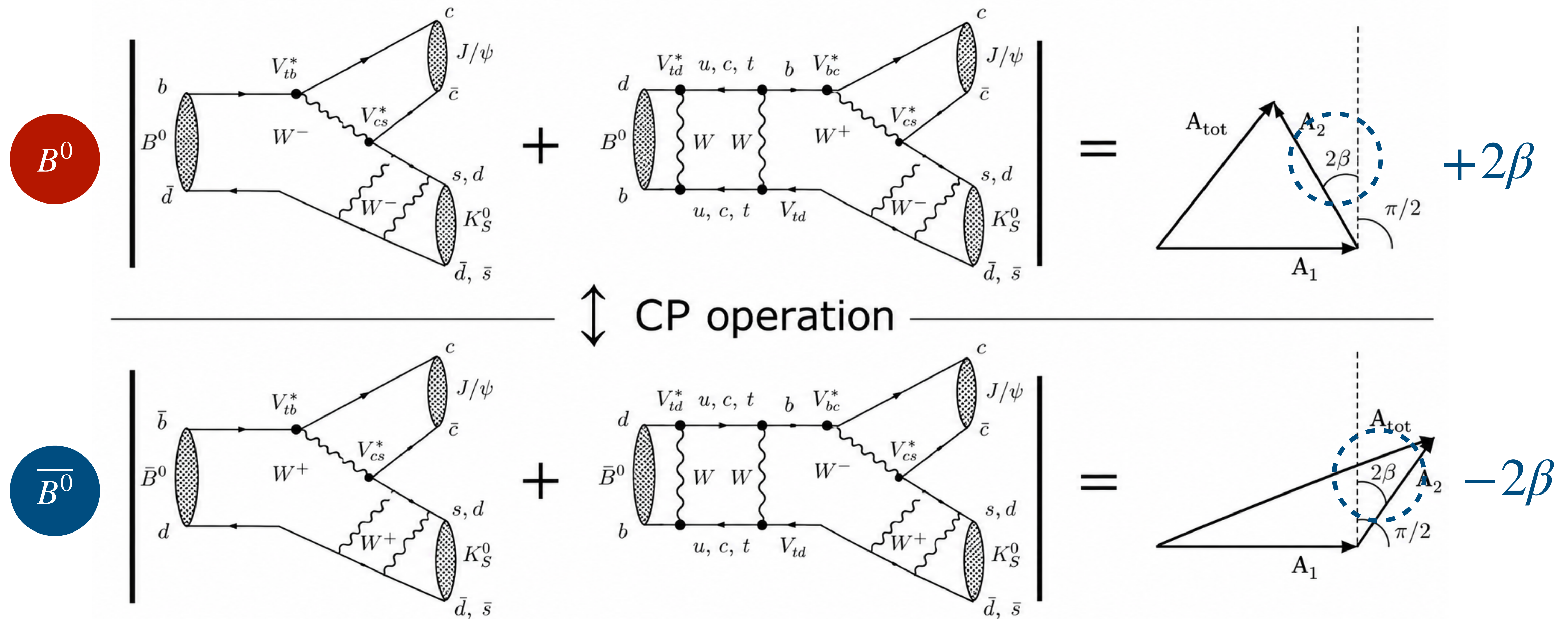
Golden channel for $\sin 2\beta$: $B^0 \rightarrow J/\psi K_S^0$



Golden channel for $\sin 2\beta$: $B^0 \rightarrow J/\psi K_S^0$



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Golden channel for $\sin 2\beta$: $B^0 \rightarrow J/\psi K_s^0$

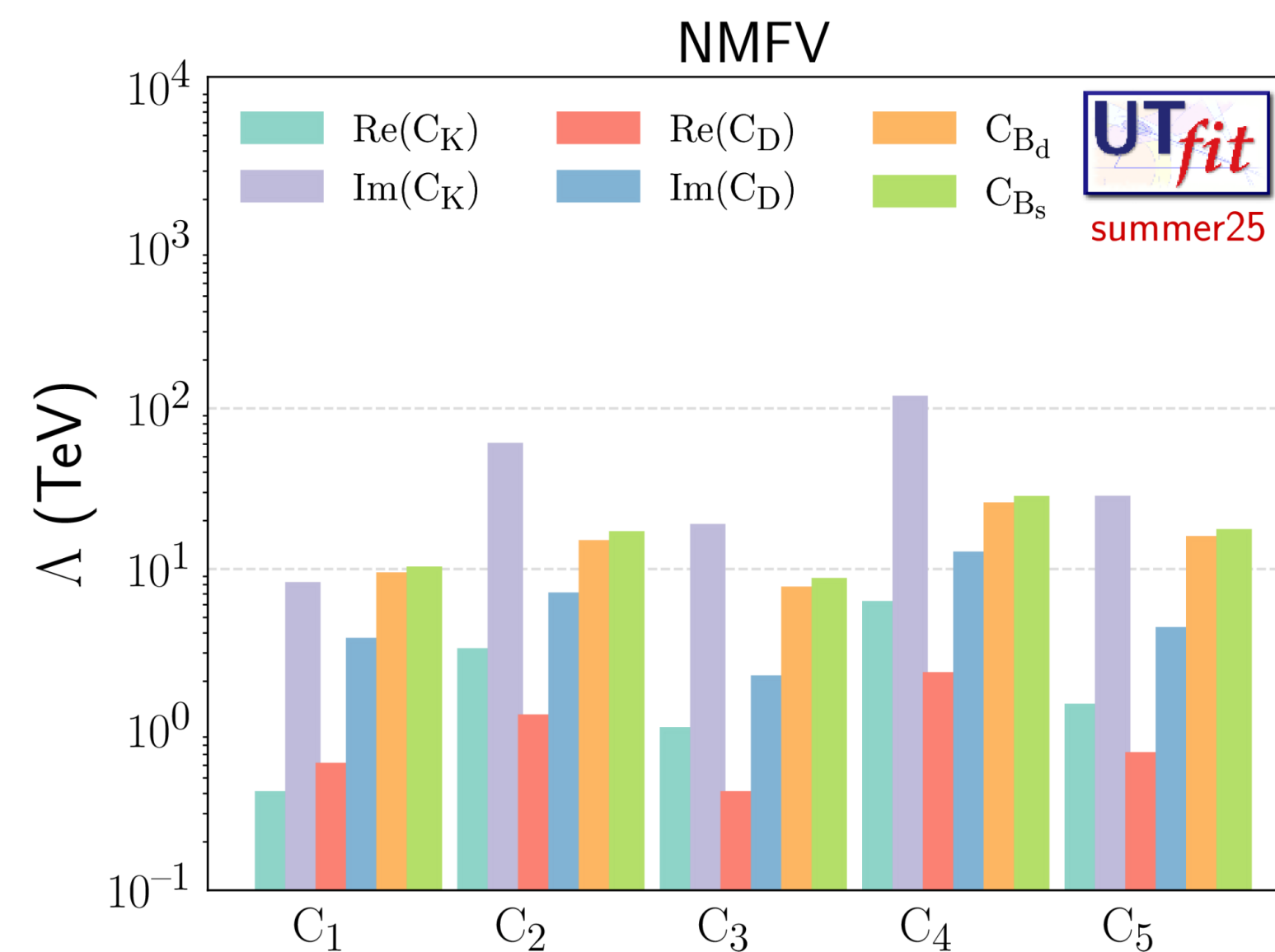
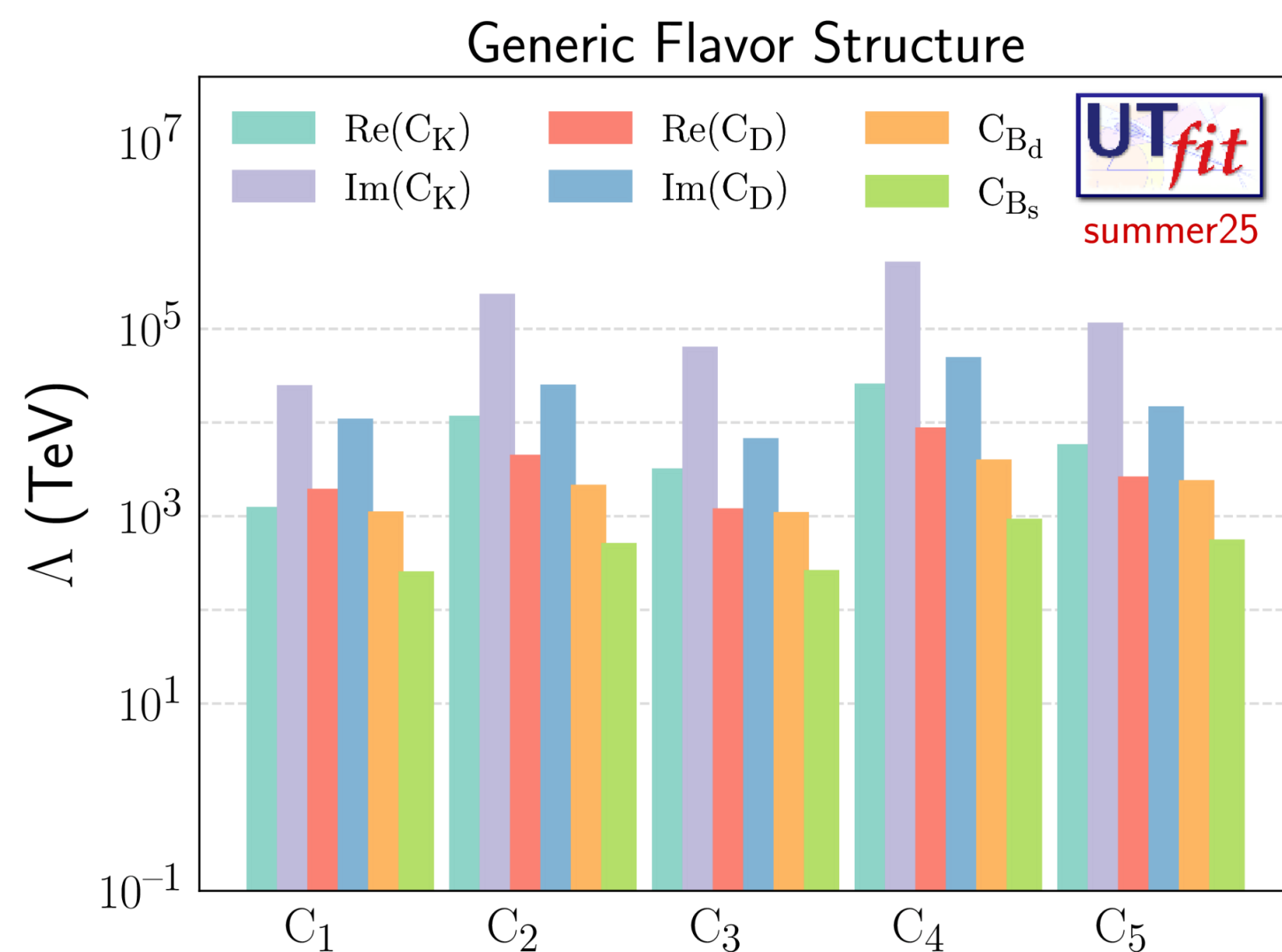
- Time-dependent asymmetry:

$$a_{CP}(t) = \frac{\Gamma_{\bar{B}^0 \rightarrow f}(t) - \Gamma_{B^0 \rightarrow f}(t)}{\Gamma_{\bar{B}^0 \rightarrow f}(t) + \Gamma_{B^0 \rightarrow f}(t)} = \frac{\overset{\text{Time-dependent CPV } \sin 2\beta}{S_f} \sin(\Delta m_d t) - \overset{\text{Direct CPV}}{C_f} \cos(\Delta m_d t)}{\cosh\left(\frac{\Delta\Gamma_d t}{2}\right) - \underset{\cos 2\beta}{D_f} \sinh\left(\frac{\Delta\Gamma_d t}{2}\right)}$$

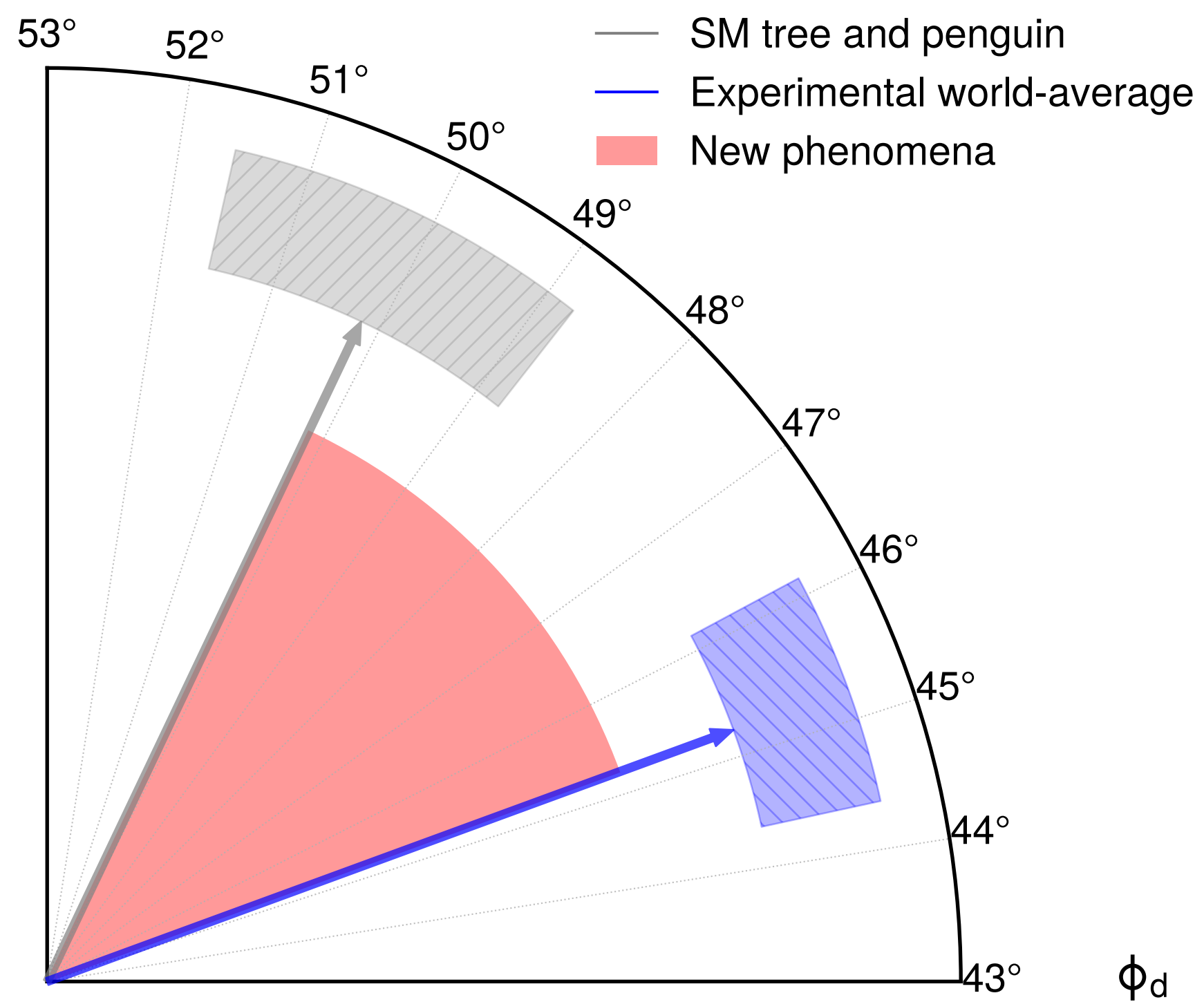
Effective phase

- Effectively measure:

$$\sin 2\beta^{eff} = \sin(2\beta + \overset{\text{penguin}}{\Delta\phi_d} + \overset{\text{NP}}{\Delta\phi_d^{NP}})$$



Space for New Physics



New Physics waking up

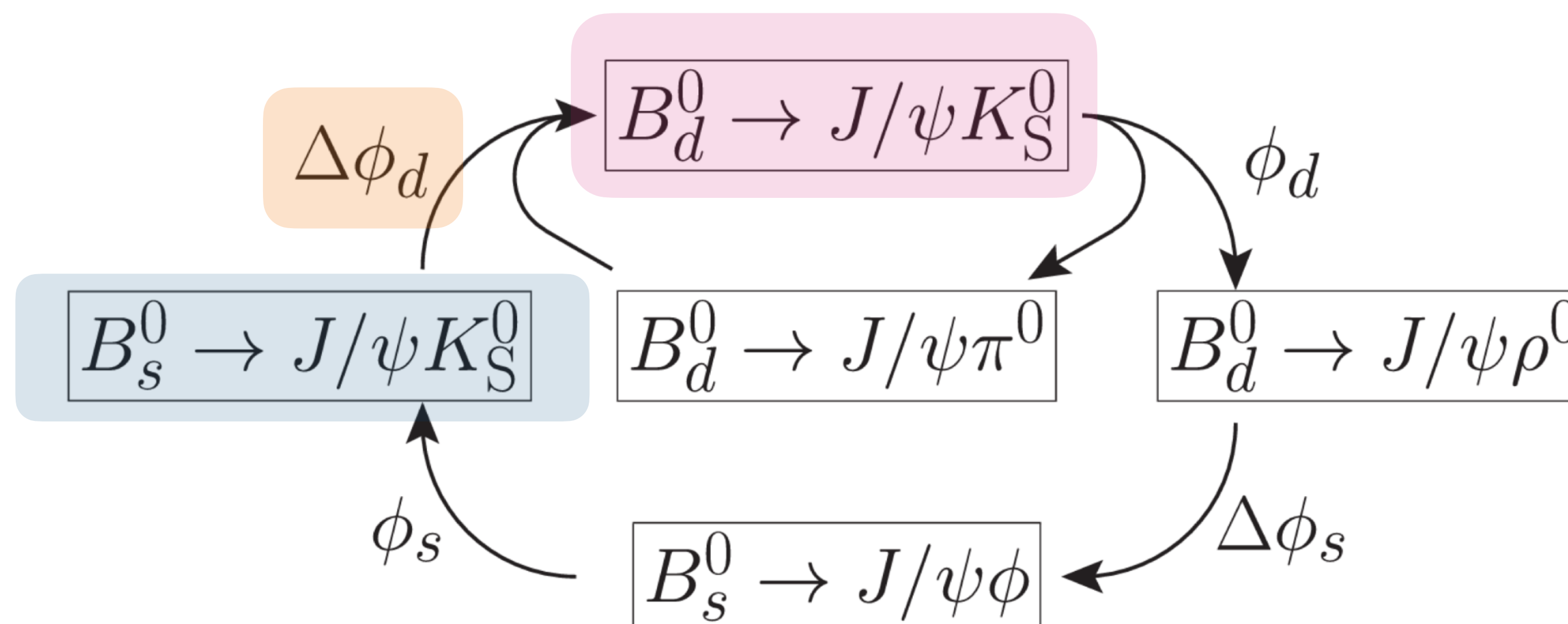


Penguin control

[Robert Fleischer, Krystof de Bruyn '15]

[Marten Barel, Robert Fleischer,
Krystof de Bruyn, Eleftheria
Malami'21]

[Robert Fleischer, Krystof de
Bruyn, Eleftheria Malami'26]

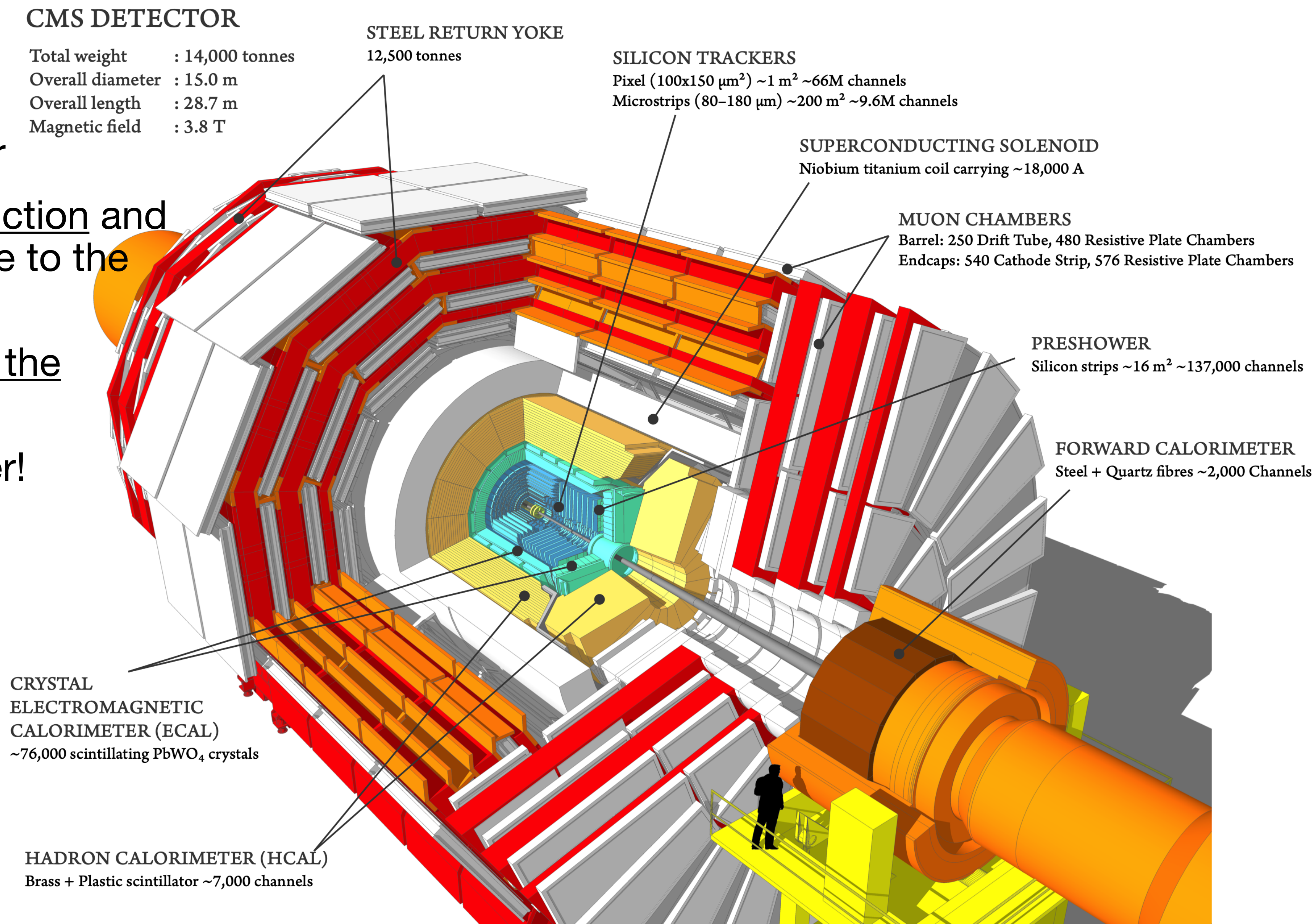


- $B_s^0 \rightarrow J/\psi K_s^0$ is the same final state! So if I reconstruct the $B^0 \rightarrow J/\psi K_s^0$, penguins control mode comes for free!

Reconstruction with CMS

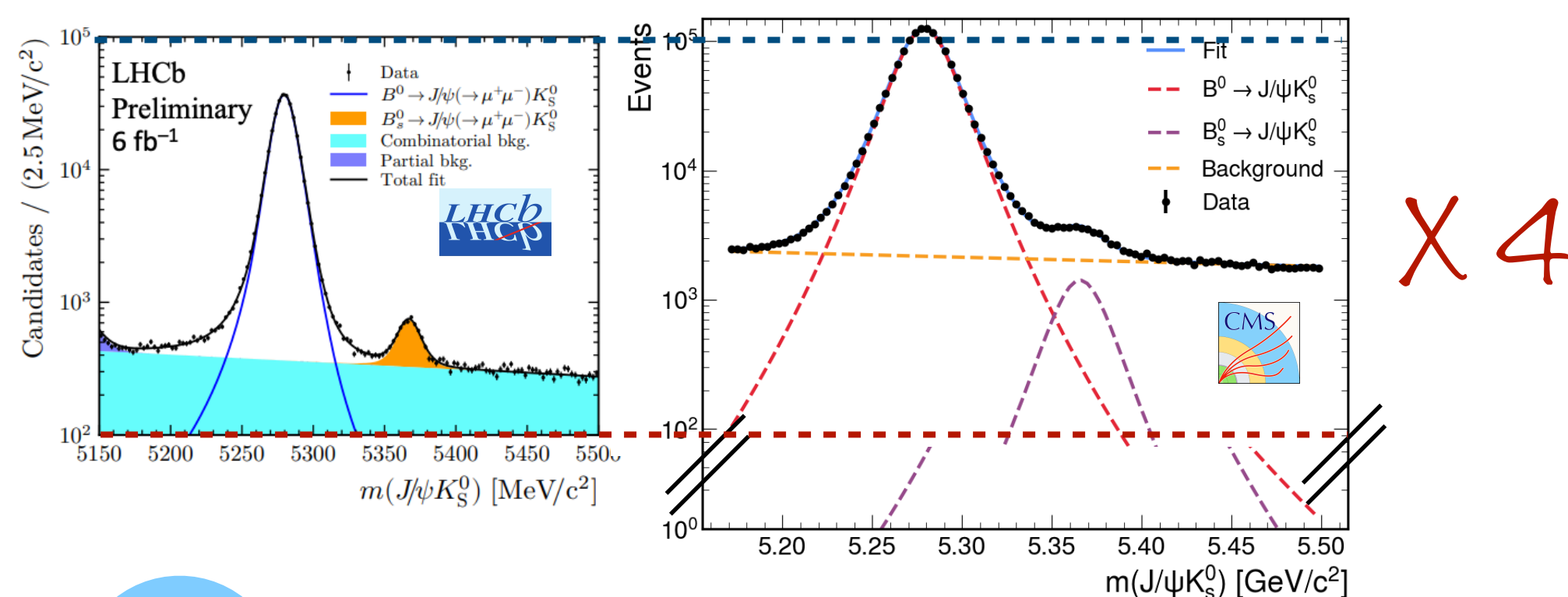
CMS detector

- General purpose detector
- Excellent muon reconstruction and momentum resolution due to the strong magnetic field
- Excellent performance of the compact silicon tracker
- But no PID or track trigger!



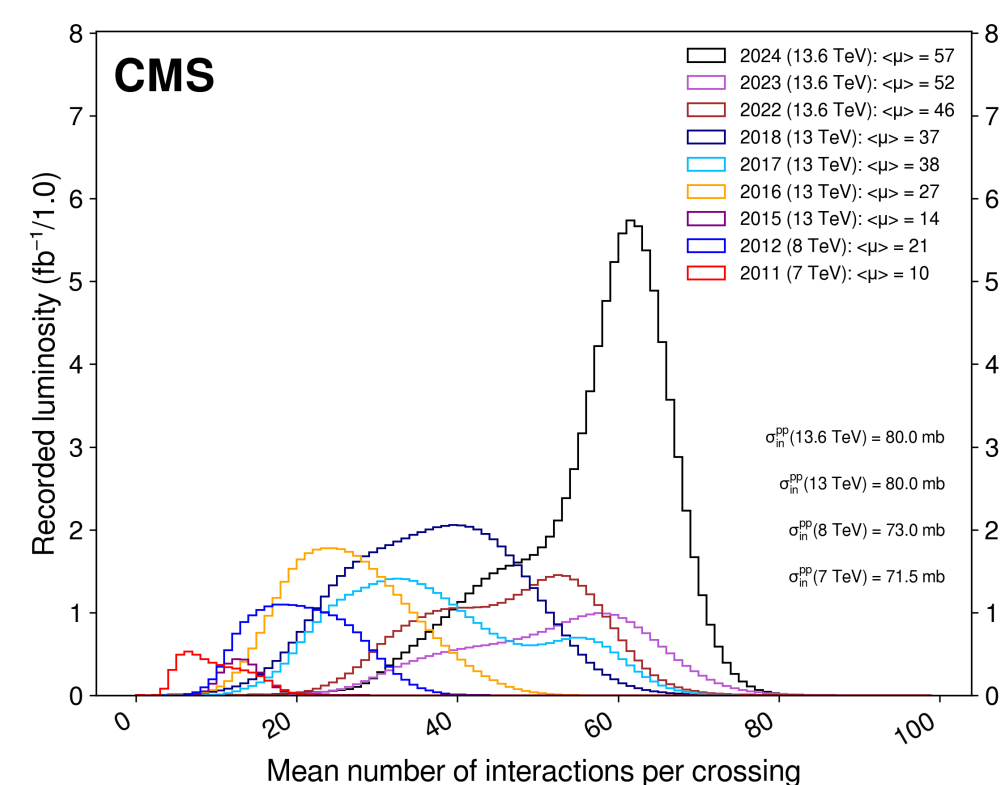
Differences with LHCb

1 Difference in S/B

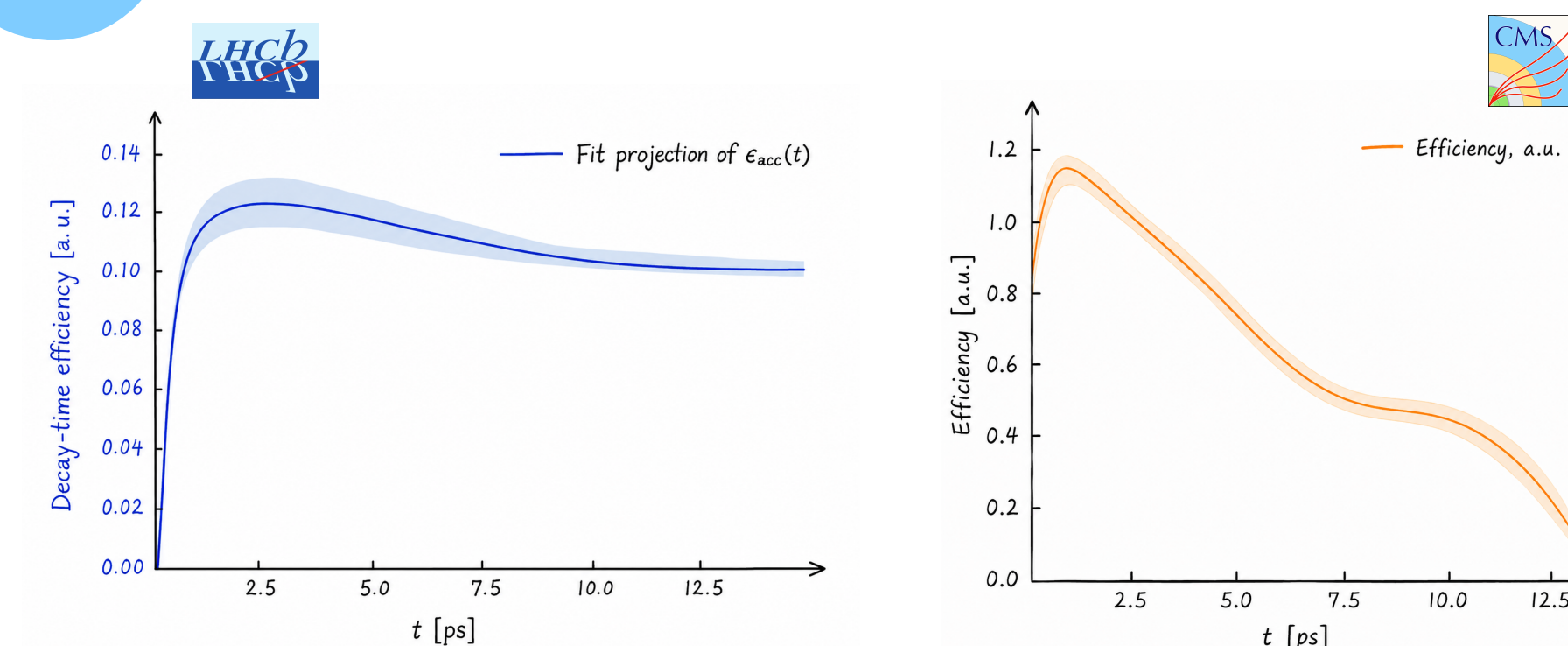


2 Higher pile-up

$$\langle \mu \rangle \approx 5$$



3 Decay time efficiency

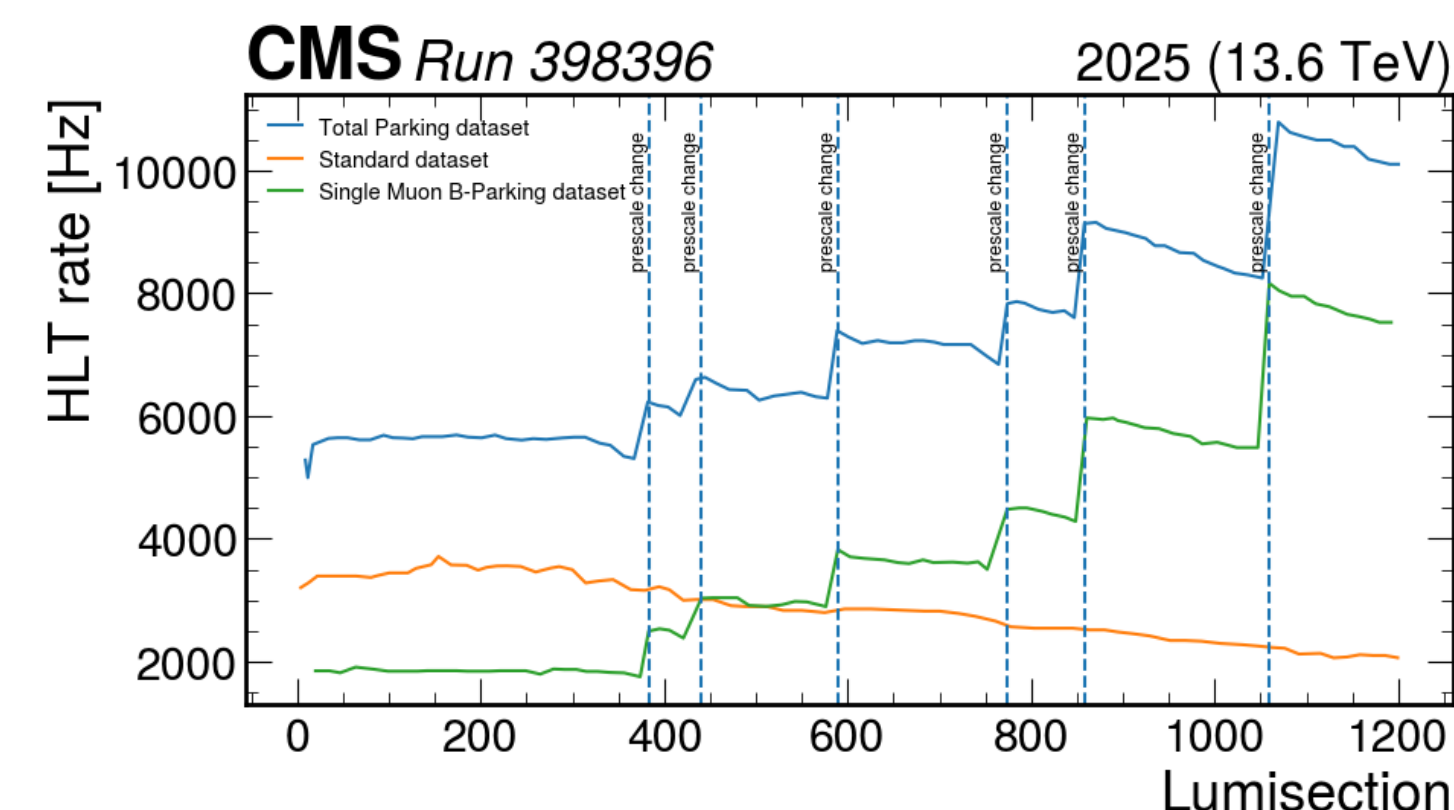
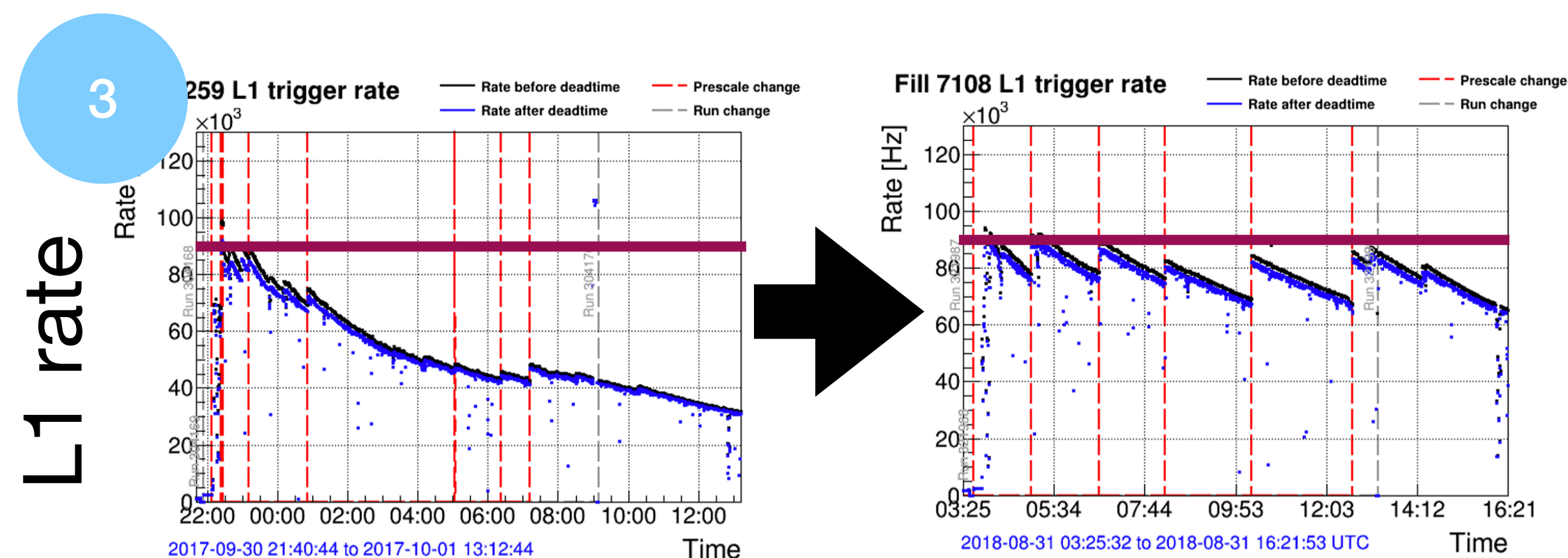
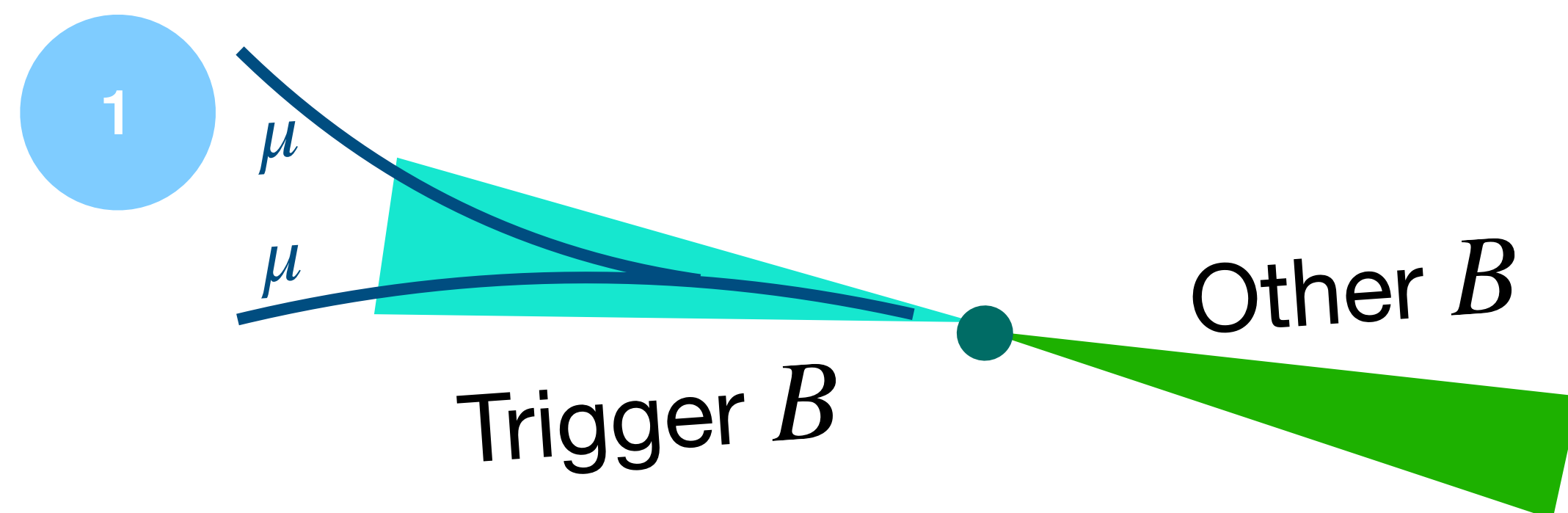


4 Dilution due to decay time resolution

40 fs vs 60 fs

Double Muon B-parking

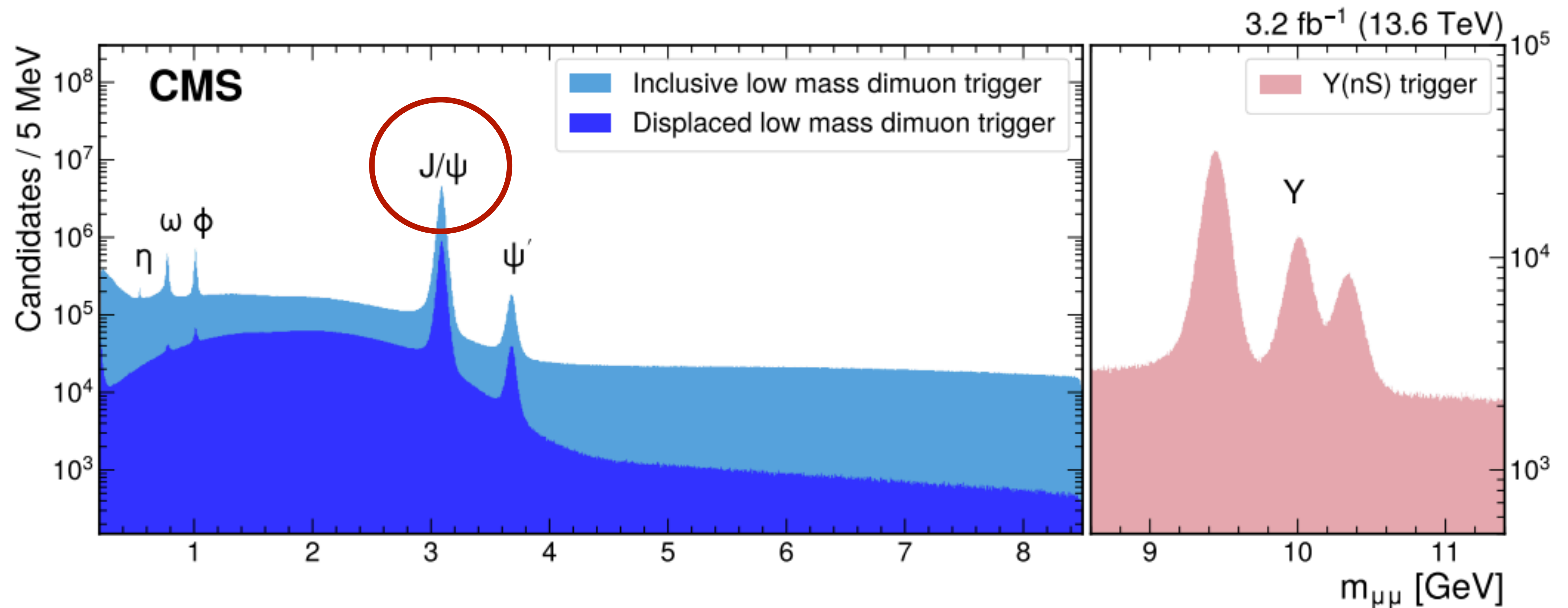
- Collect b hadron decays triggered by low-pT dimuon pairs
- Collected in 2022-2026, 299 fb^{-1}



HLT rate

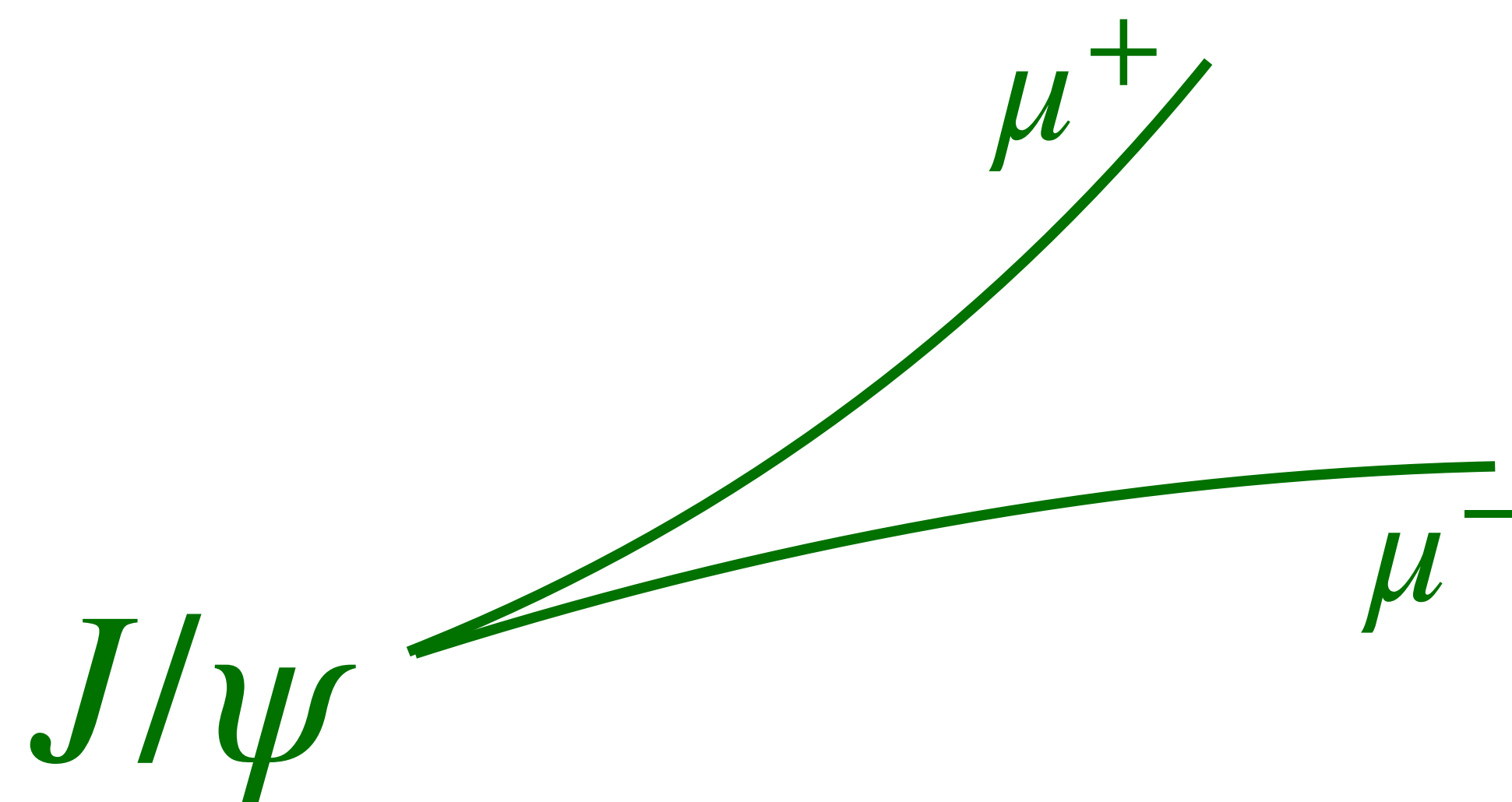
Double Muon B-parking

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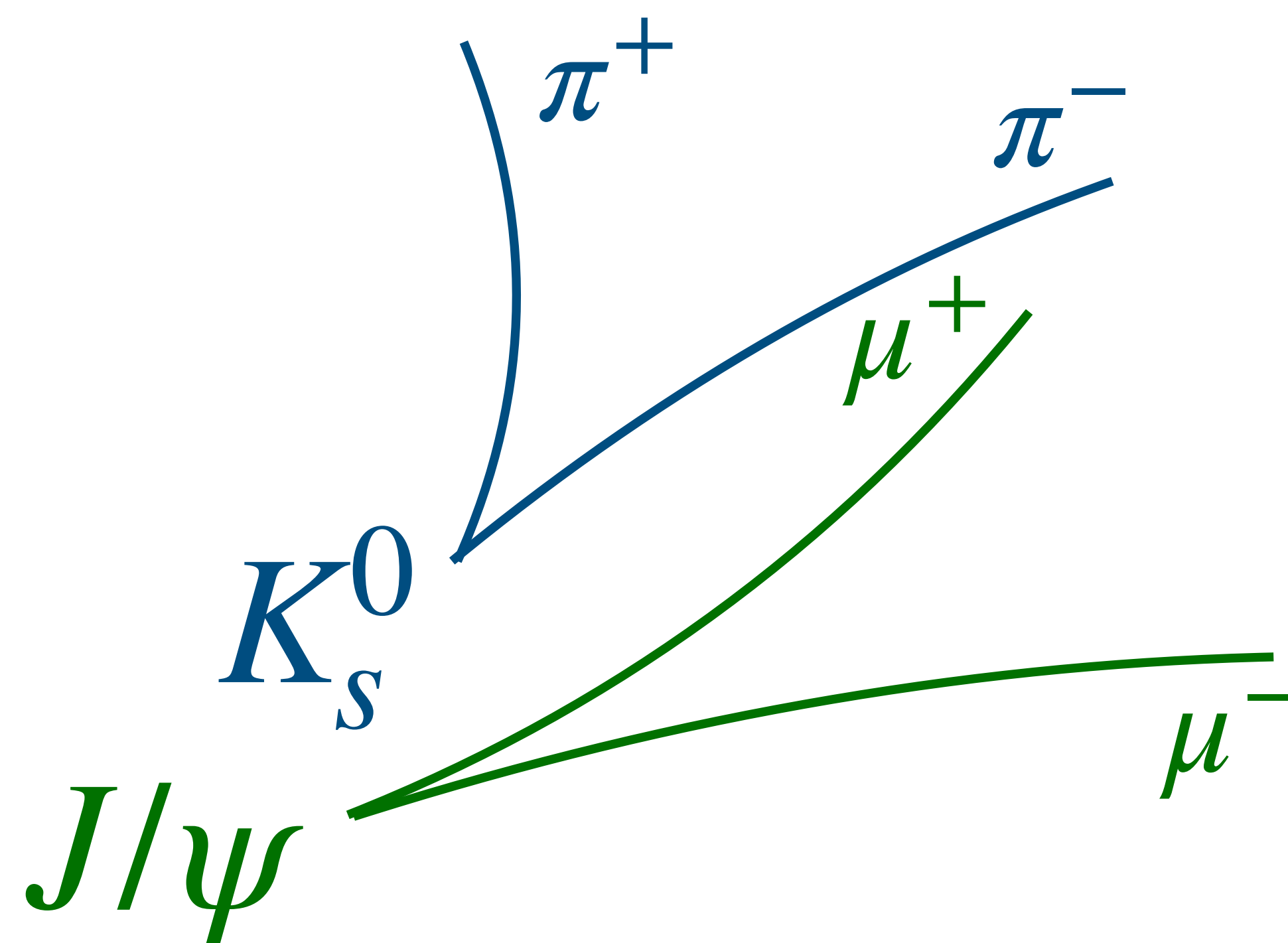
Reconstruction

- 1 Search for the two trigger opposite charged muons close to J/ψ ; constrain to the J/ψ mass



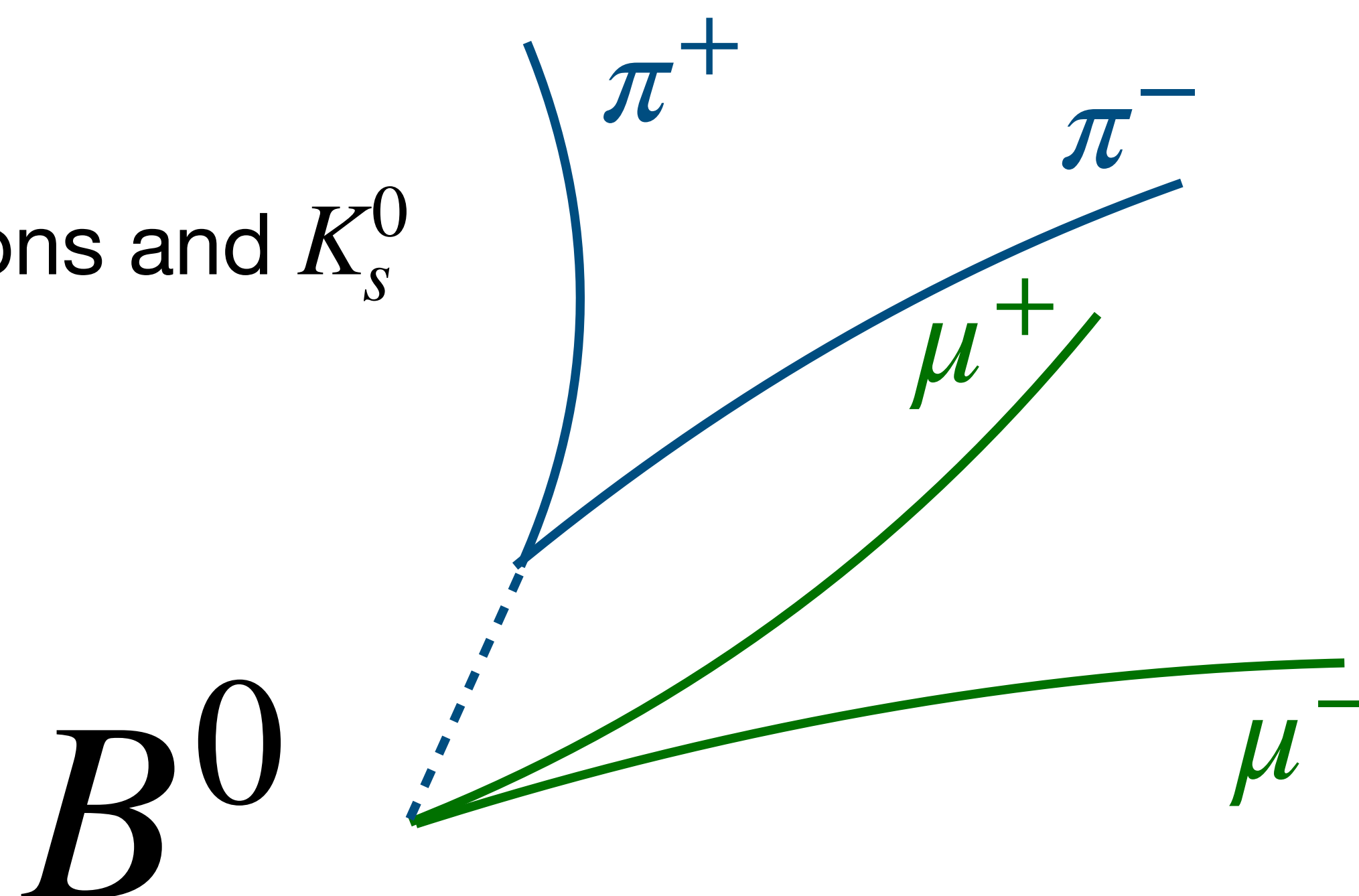
Reconstruction

- 1 Search for the two trigger opposite charged muons close to J/ψ ; constrain to the J/ψ mass
- 2 Search for the two track close to the J/ψ ; assign pion mass; constrain to the K_s^0 mass



Reconstruction

- 1 Search for the two trigger opposite charged muons close to J/ψ ; constrain to the J/ψ mass
- 2 Search for the two track close to the J/ψ ; assign pion mass; constrain to the K_s^0 mass
- 3 Fit the B^0 vertex with two muons and K_s^0



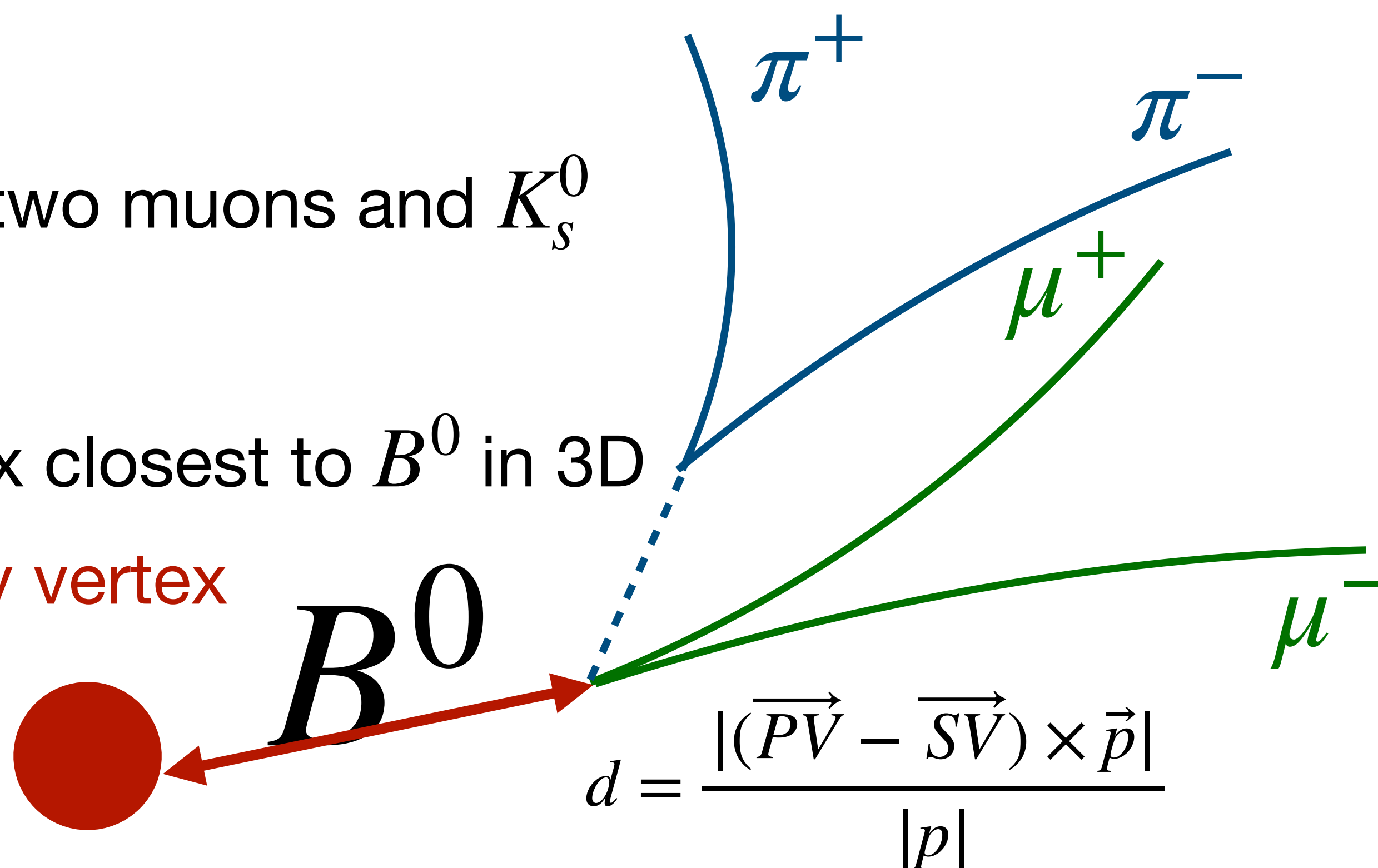
Reconstruction

- 1 Search for the two trigger opposite charged muons close to J/ψ ; constrain to the J/ψ mass
- 2 Search for the two track close to the J/ψ ; assign pion mass; constrain to the K_s^0 mass
- 3 Fit the B^0 vertex with two muons and K_s^0
- 4 Find the primary vertex closest to B^0 in 3D

Chosen primary vertex

PV 1

PV 2

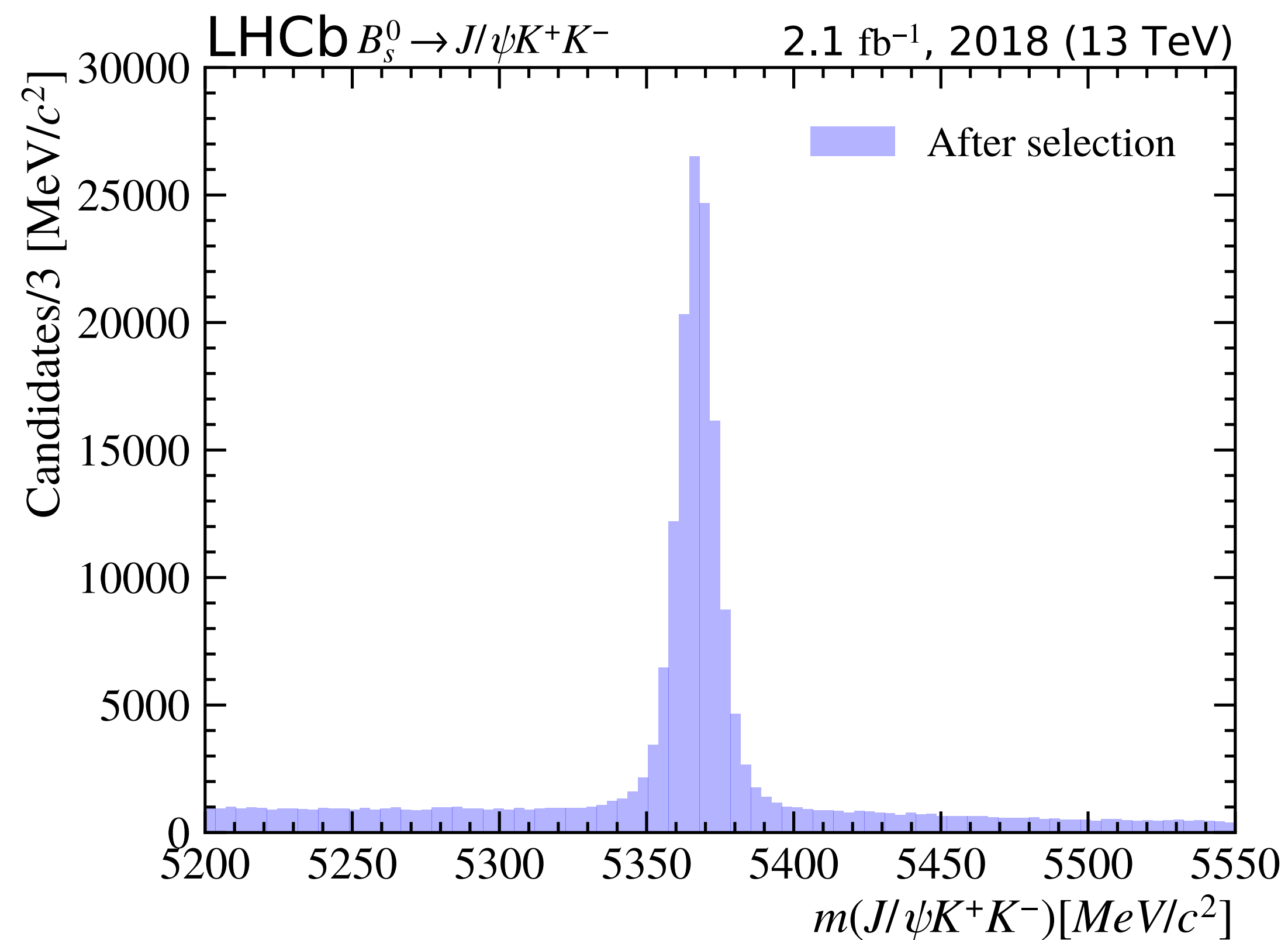


Statistics in 2022-2025

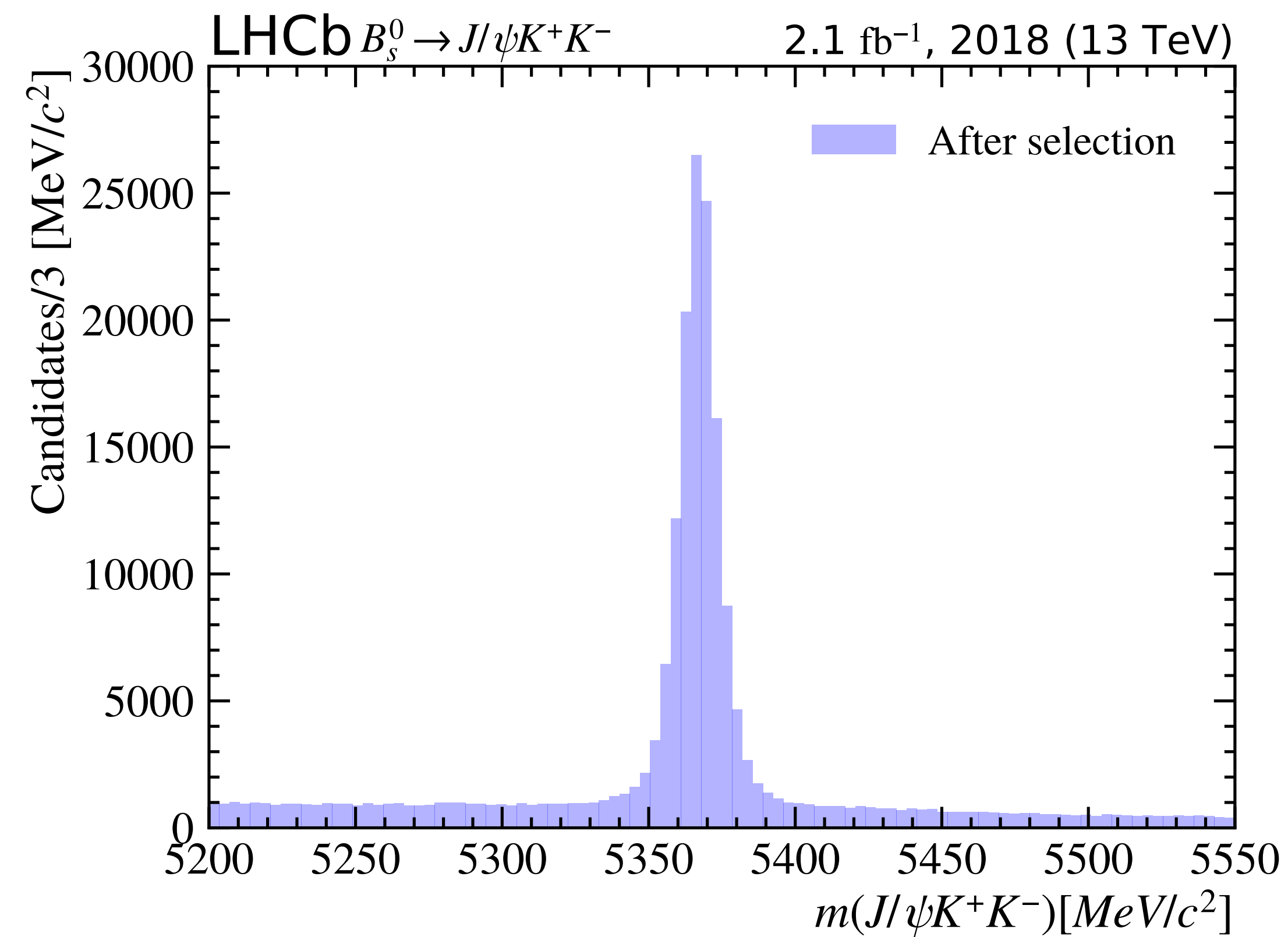
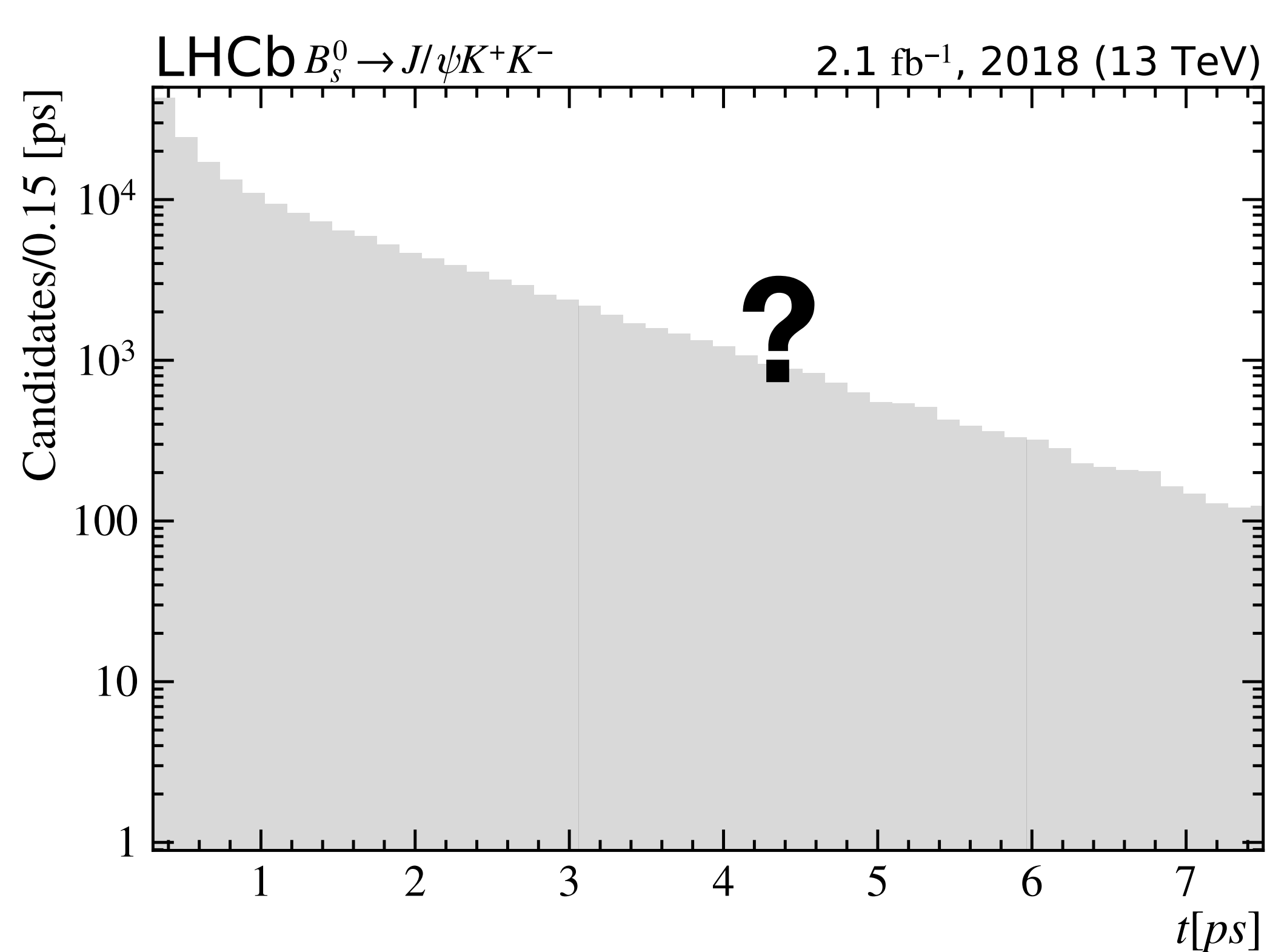
~ 1.4 millions of $B^0 \rightarrow J/\psi K_s^0$ decays

~ 16 thousands of $B_s^0 \rightarrow J/\psi K_s^0$ decays

Background subtraction



Background subtraction

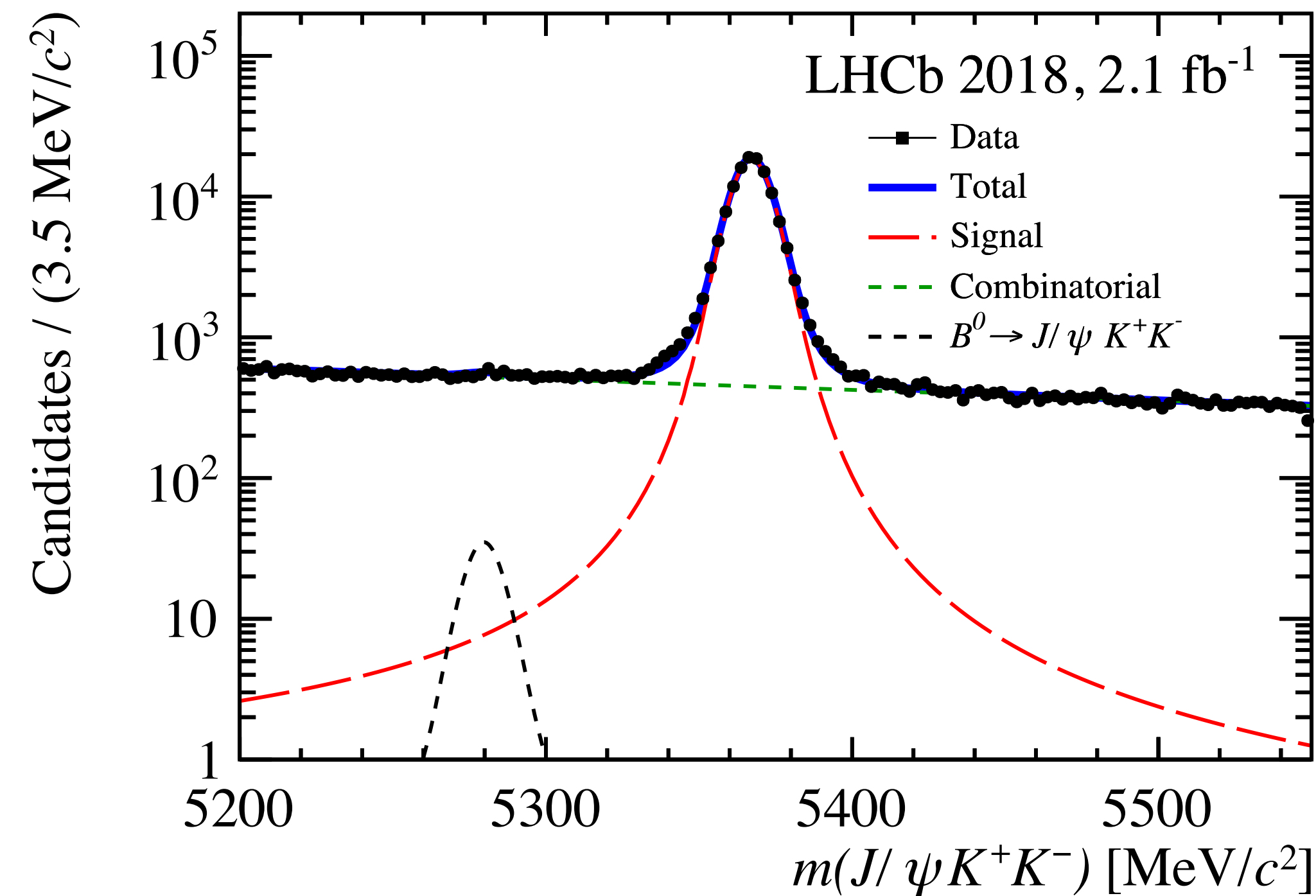
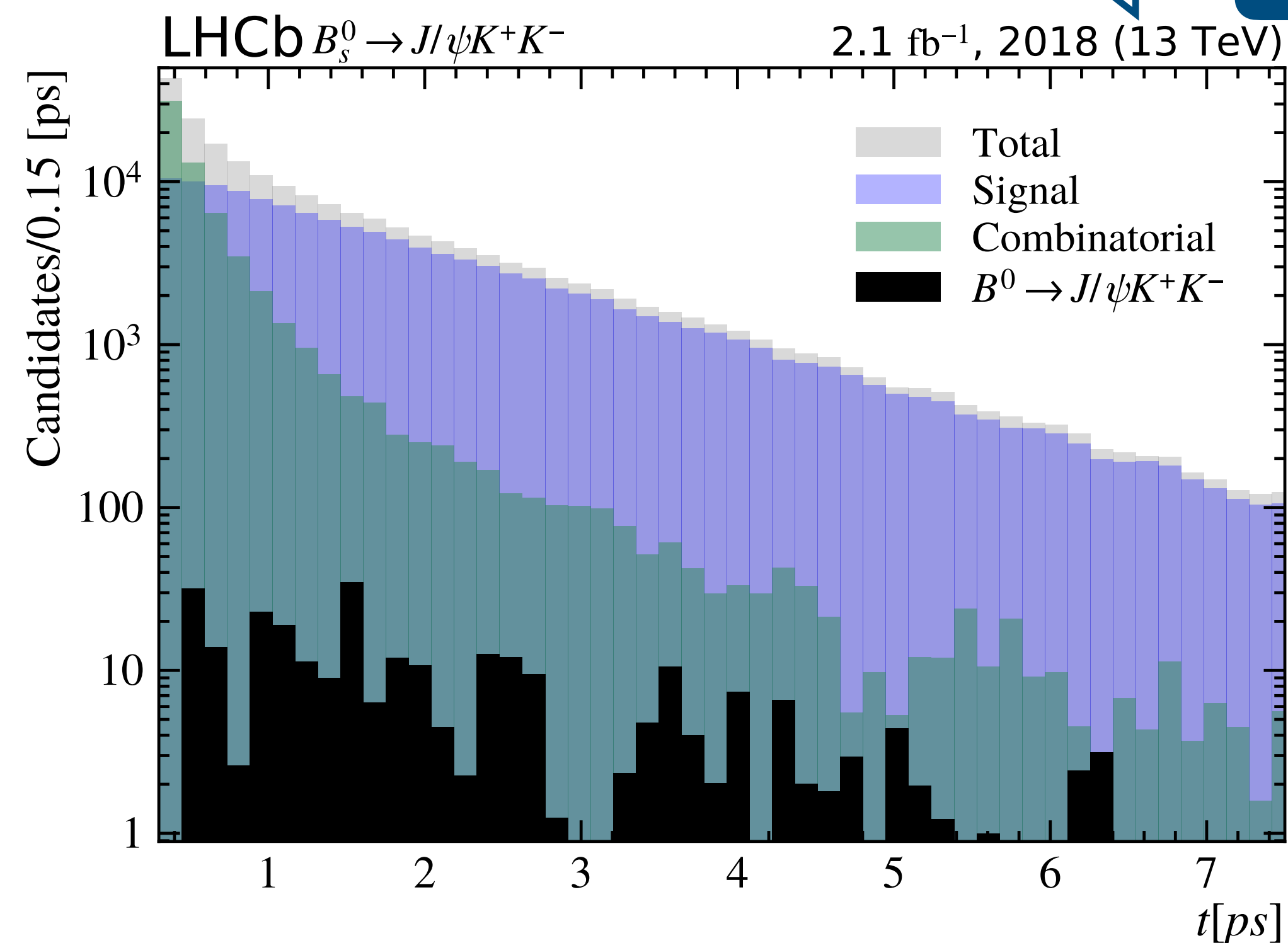


Background subtraction

Observable

sWeight

Discriminating variable



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

Background subtraction

[NIMT A, 1040, 167270.](#)

- Custom Orthogonal Weights (COW) allow to include non-factorizable effects in the signal efficiency
- Generalisation of sPlot method

$$A_{kl}^{-1} = W_{kl} = \int dm \frac{g_k(m) g_l(m)}{I(m)}$$

$$w_k(m) = \sum_{l=0}^n \frac{A_{kl} g_l(m)}{I(m)}$$

Discriminant variable

Distribution for component l

Variance function

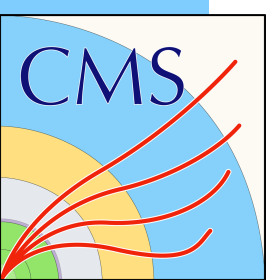
- Difference:

$$I(m) = g(m) \quad \text{vs} \quad I(m) \neq g(m)$$

Fit model

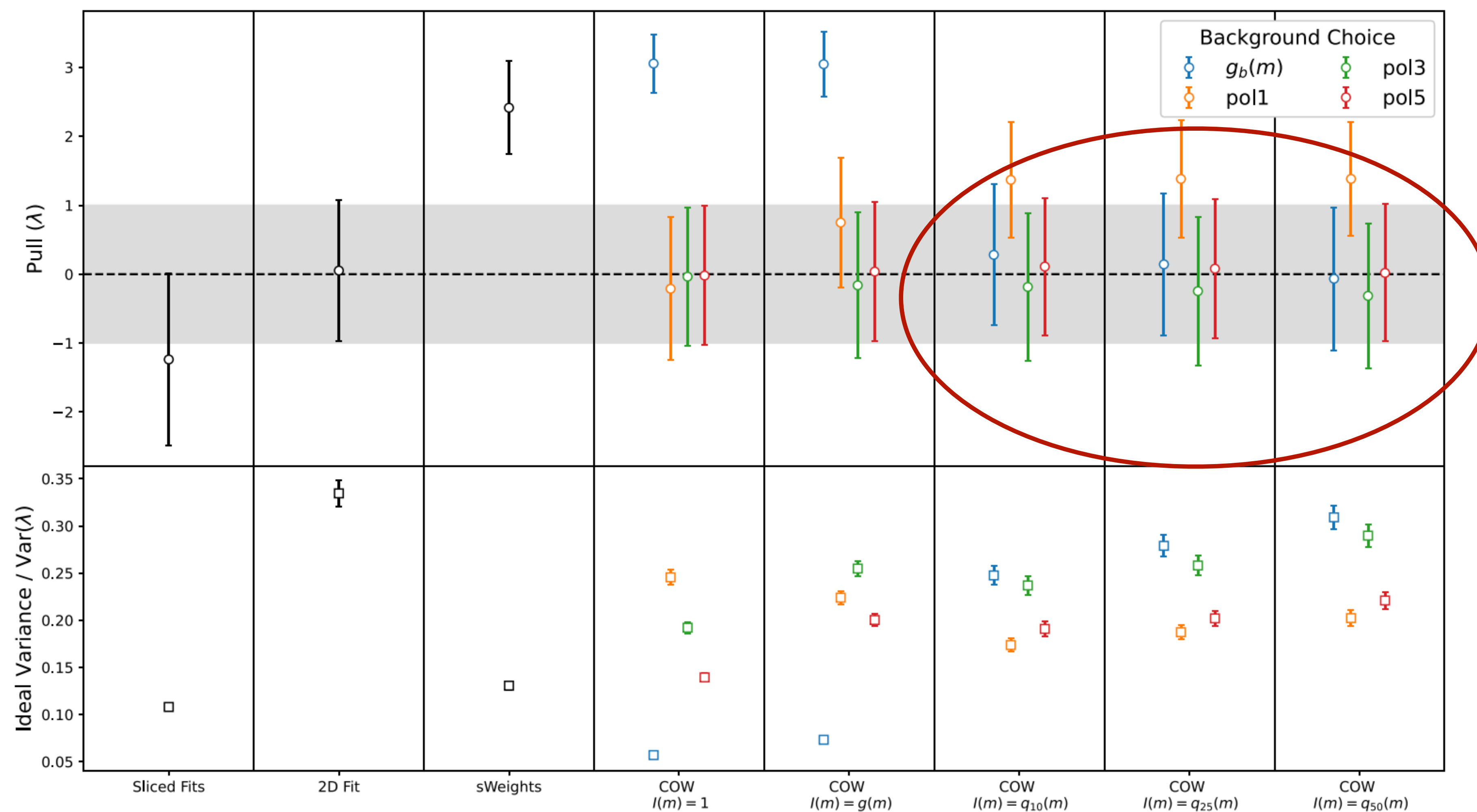
sPlot

COW



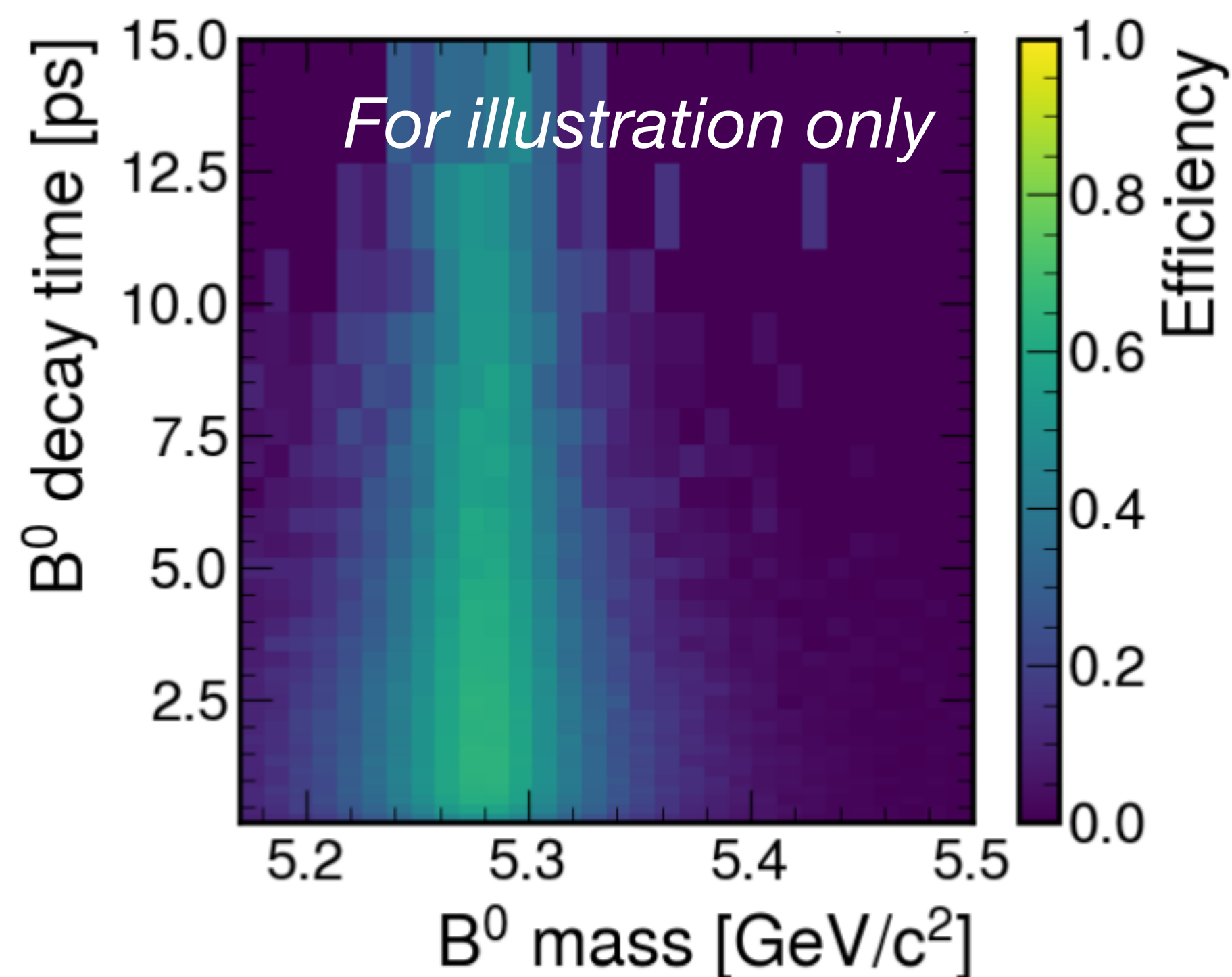
Background subtraction

[NIMT A, 1040, 167270.](#)



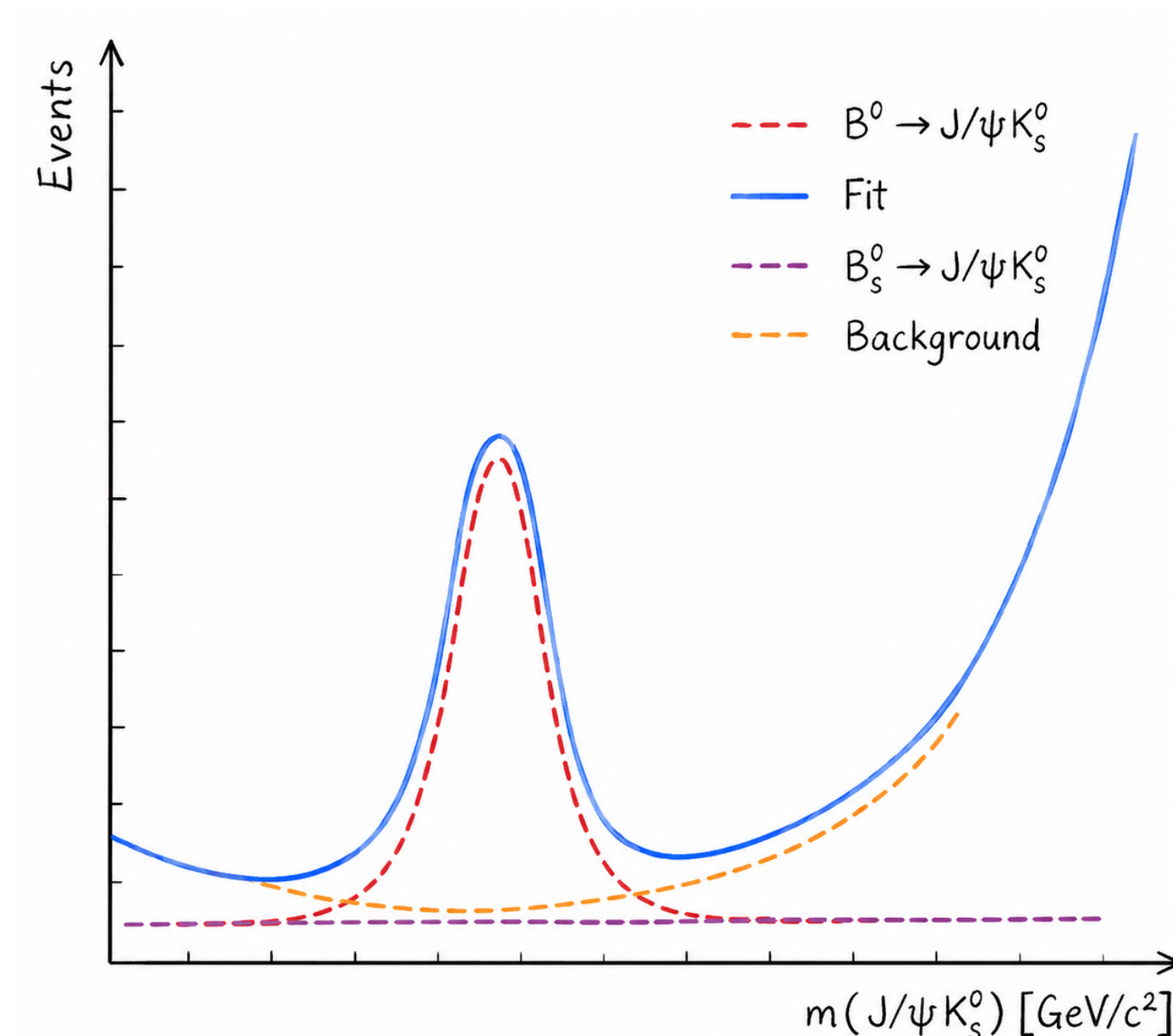
COWs and Variance Function

[NIMT A, 1040, 167270.](#)



2D signal efficiency

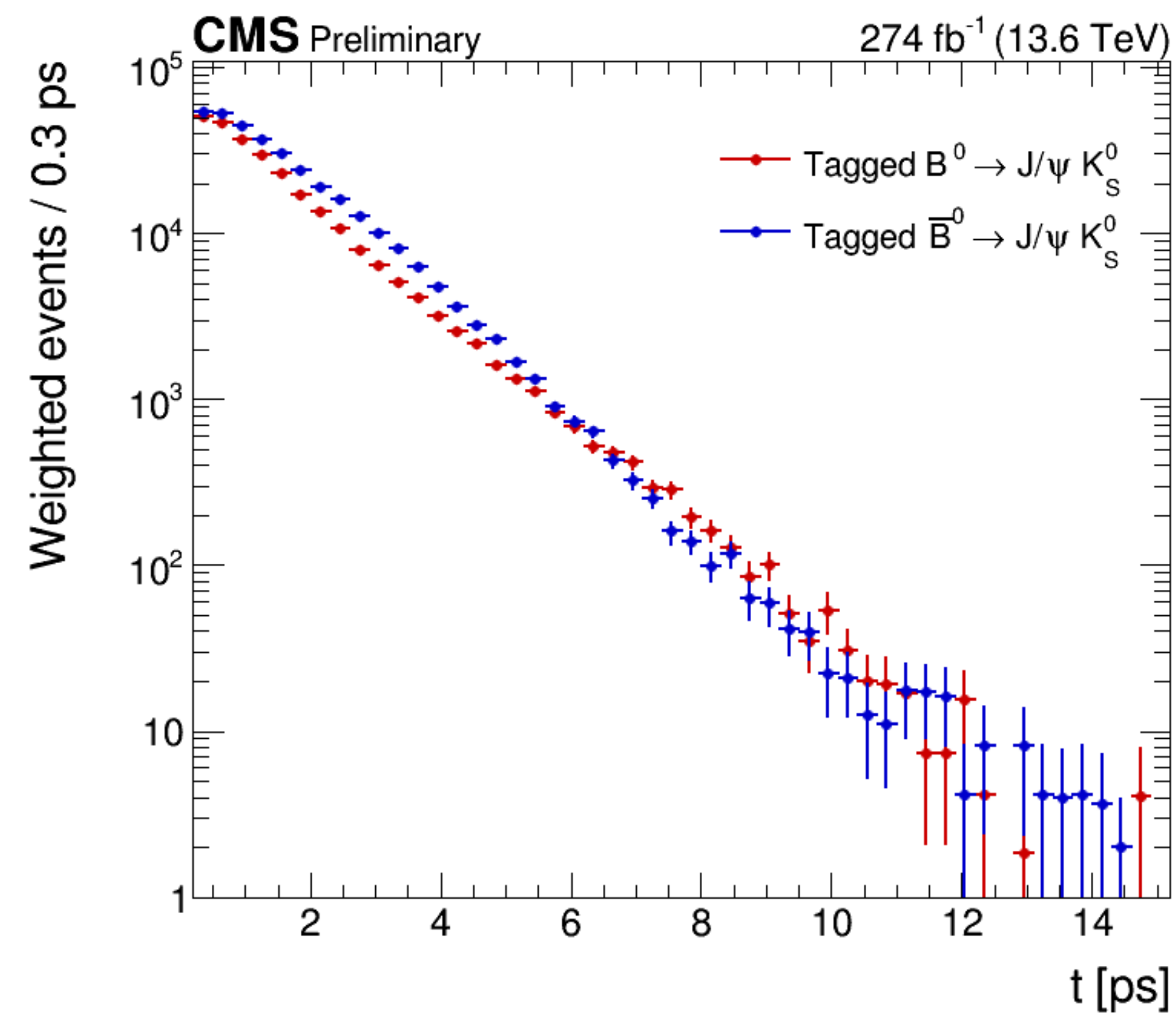
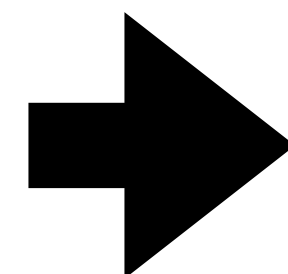
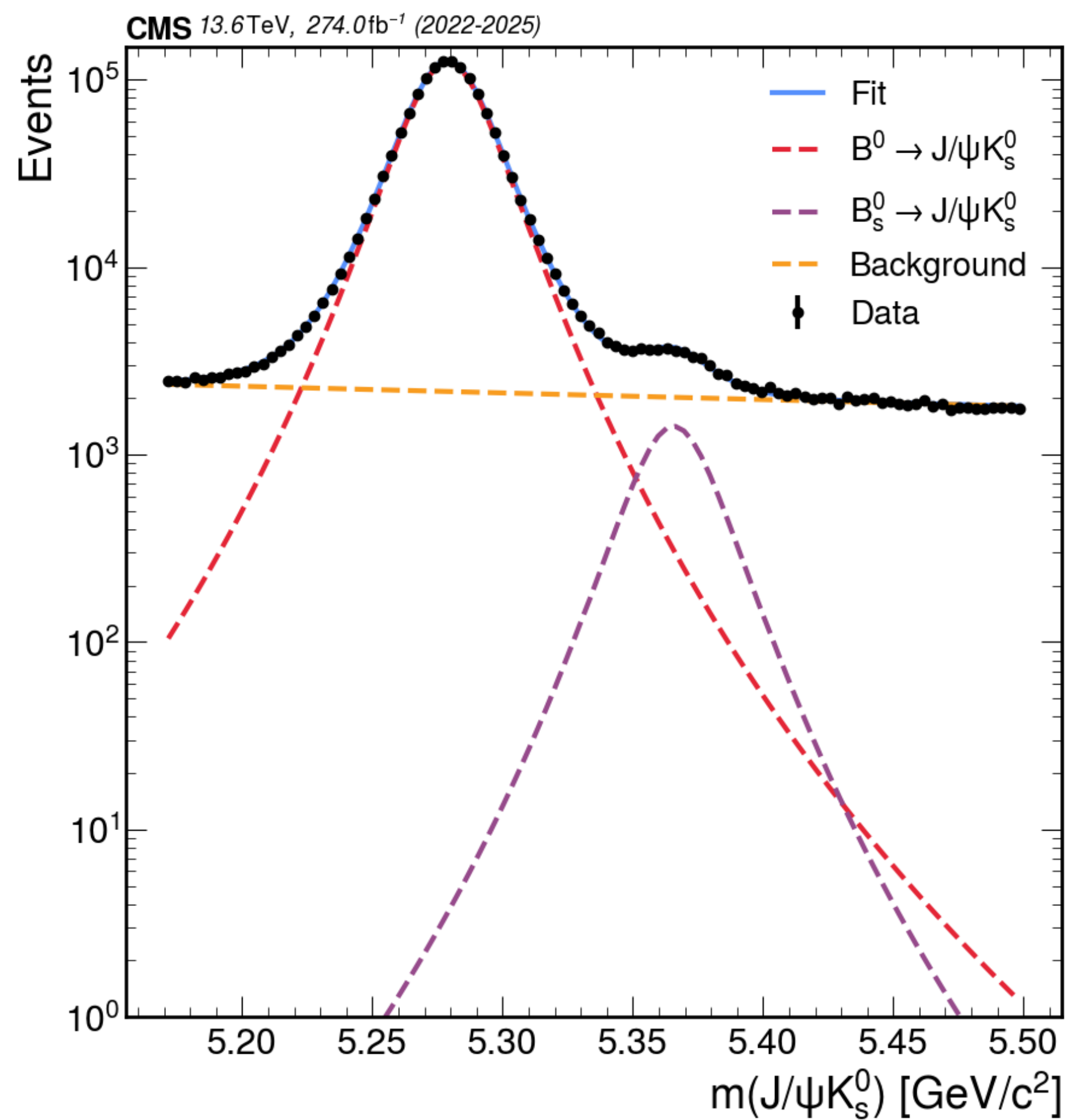
Variance function $I(m)$



2D signal efficiency weighted mass distribution

Background subtraction

[NIMT A, 1040, 167270.](#)



COW-weighted decay time distributions

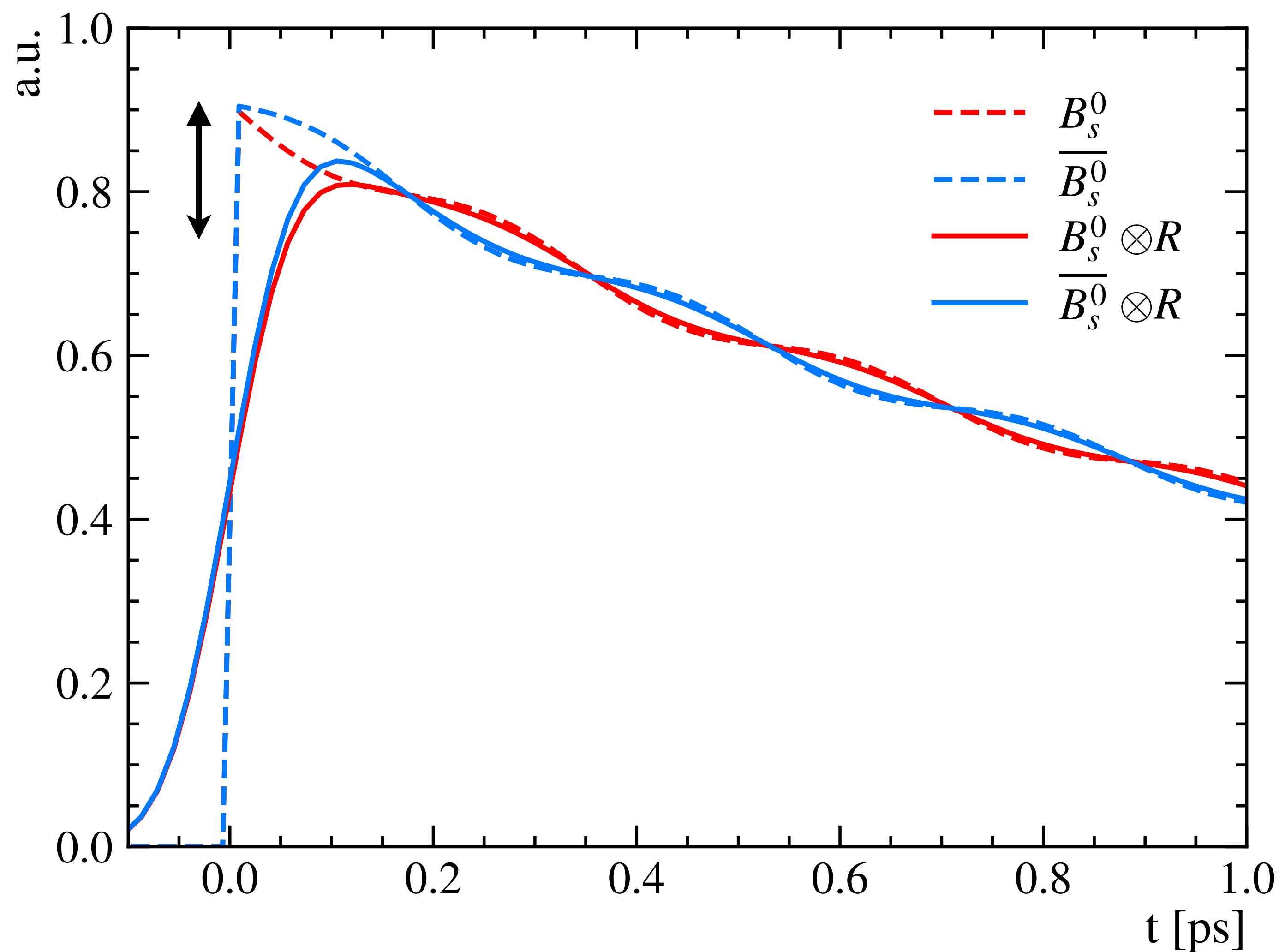
Asymmetry fit

- Adoption of COWs allows to explicitly fit the matter-antimatter asymmetry :

Asymmetry in data :

$$a_{CP}^{\text{bin}} = \frac{\sum_i^{i \in \text{bin}} \left(\overset{\text{tag decision}}{-q_{\text{tag},i}} \overset{\text{cow-weight}}{w_i} D_i \right)}{\sum_i^{i \in \text{bin}} (w_i D_i^2)} \quad D_i = D_i^{\text{tag}} \times D_i^{\text{time.res}}$$

Decay time resolution



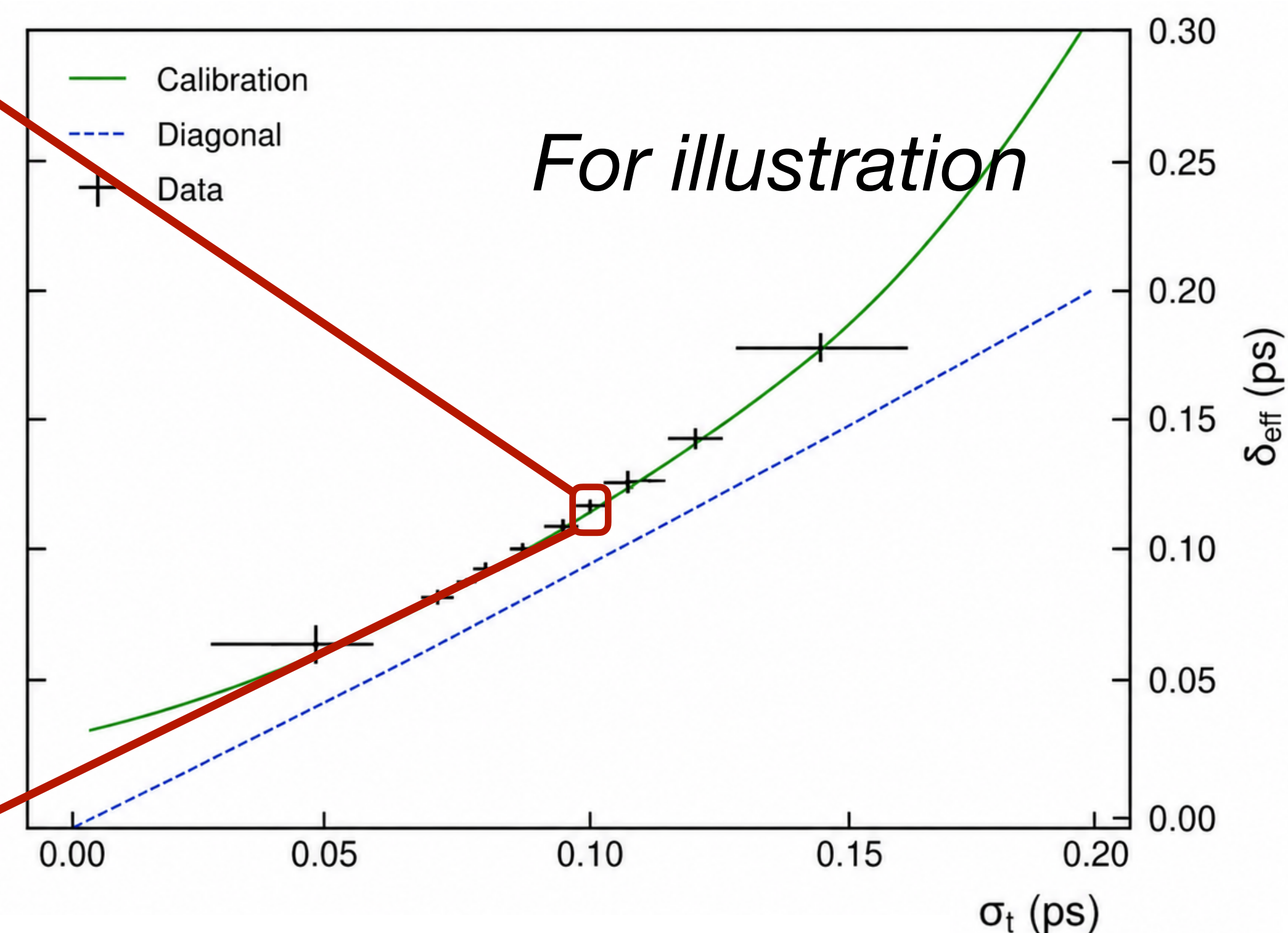
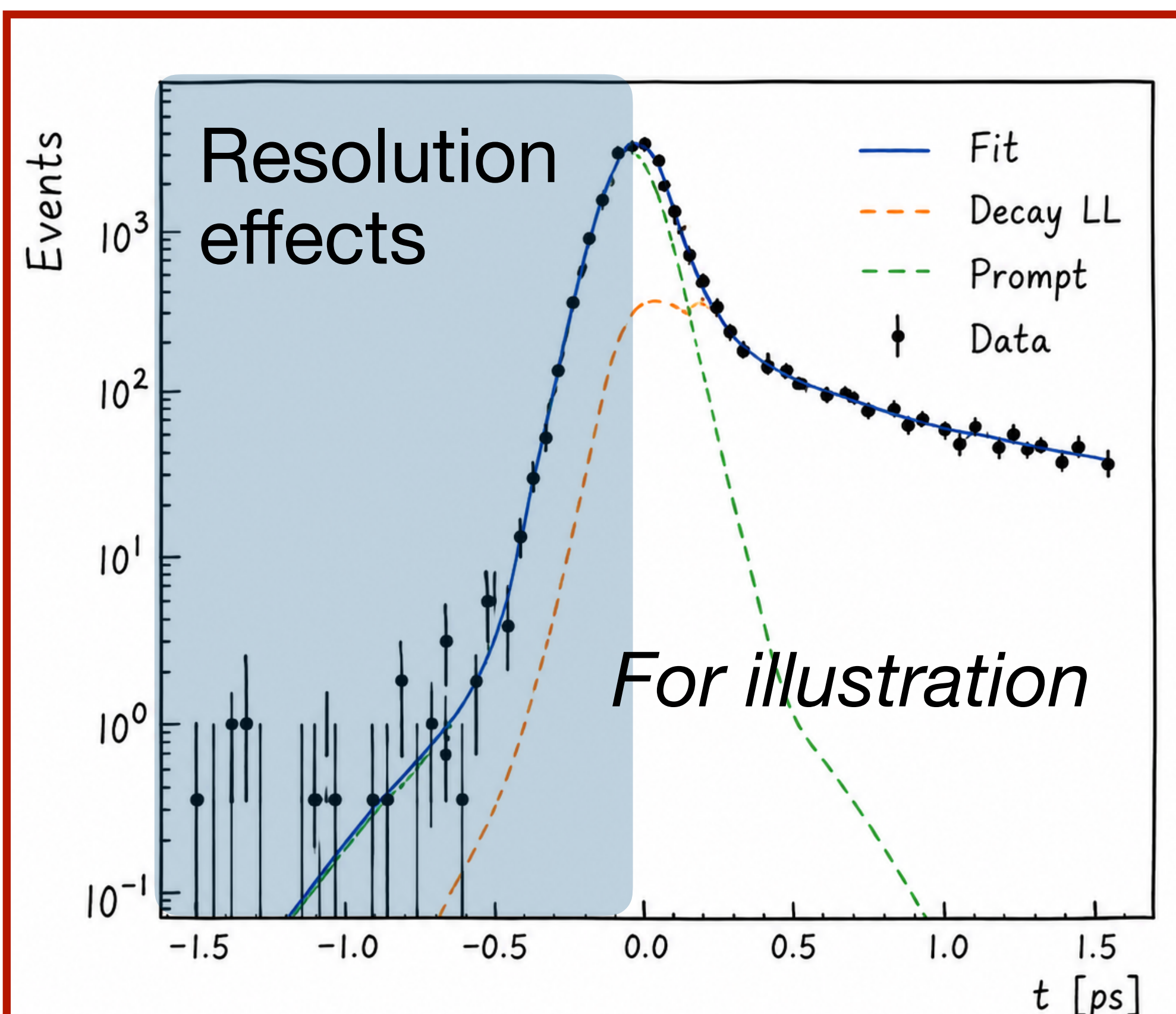
$D_{res}?$

$$D_{res} = \exp\left(-\frac{\sigma^2 \Delta m_{s,d}^2}{2}\right)$$

- B^0 oscillates 35 times slower than B_s^0
- ~ 1 for B^0 and ~ 0.6 for B_s^0

Decay time resolution

- Look at the candidates with reconstructed decay times close to 0.
- Calibrate measured decay time error to the true decay time resolution



Measured decay time error

Effective width of resolution model

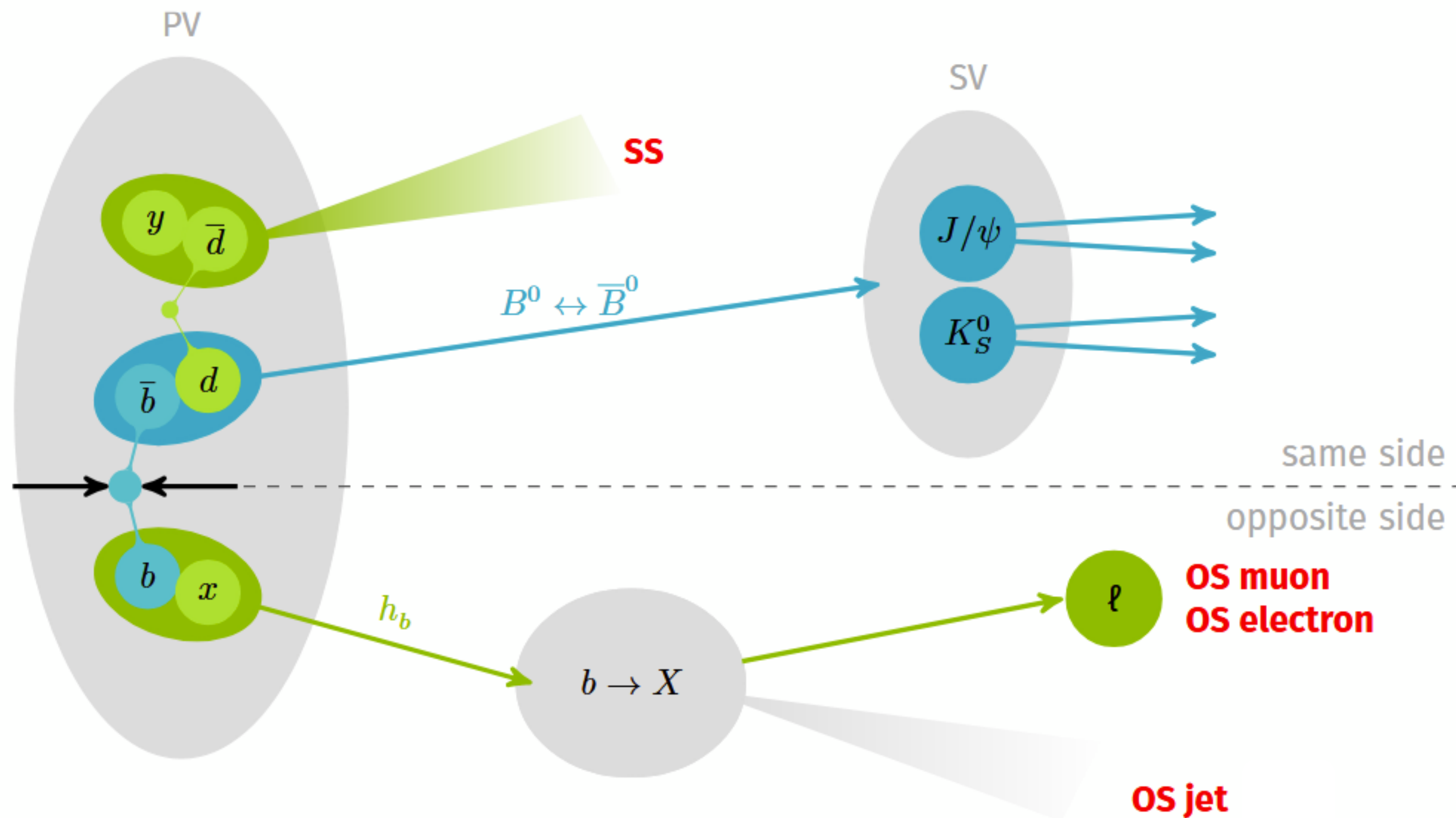
Flavour tagging = neutral meson tagging

Tagging algorithms distinguish $\overline{B}^0$ from B^0

Defines effective size of statistics available for the asymmetry measurement:

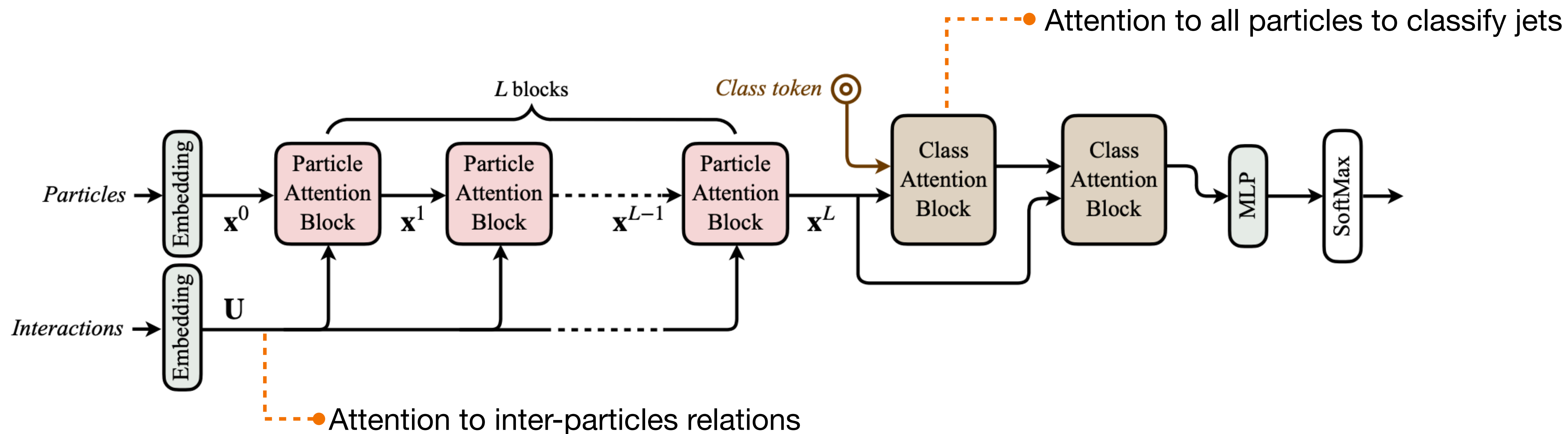
$$\sigma_{stat} \propto \frac{1}{\sqrt{\underbrace{\epsilon_{tag}(1-2\omega)^2 N}_{P_{tag} = \epsilon D_{tag}^2}}}}$$

Flavour tagging = neutral meson tagging



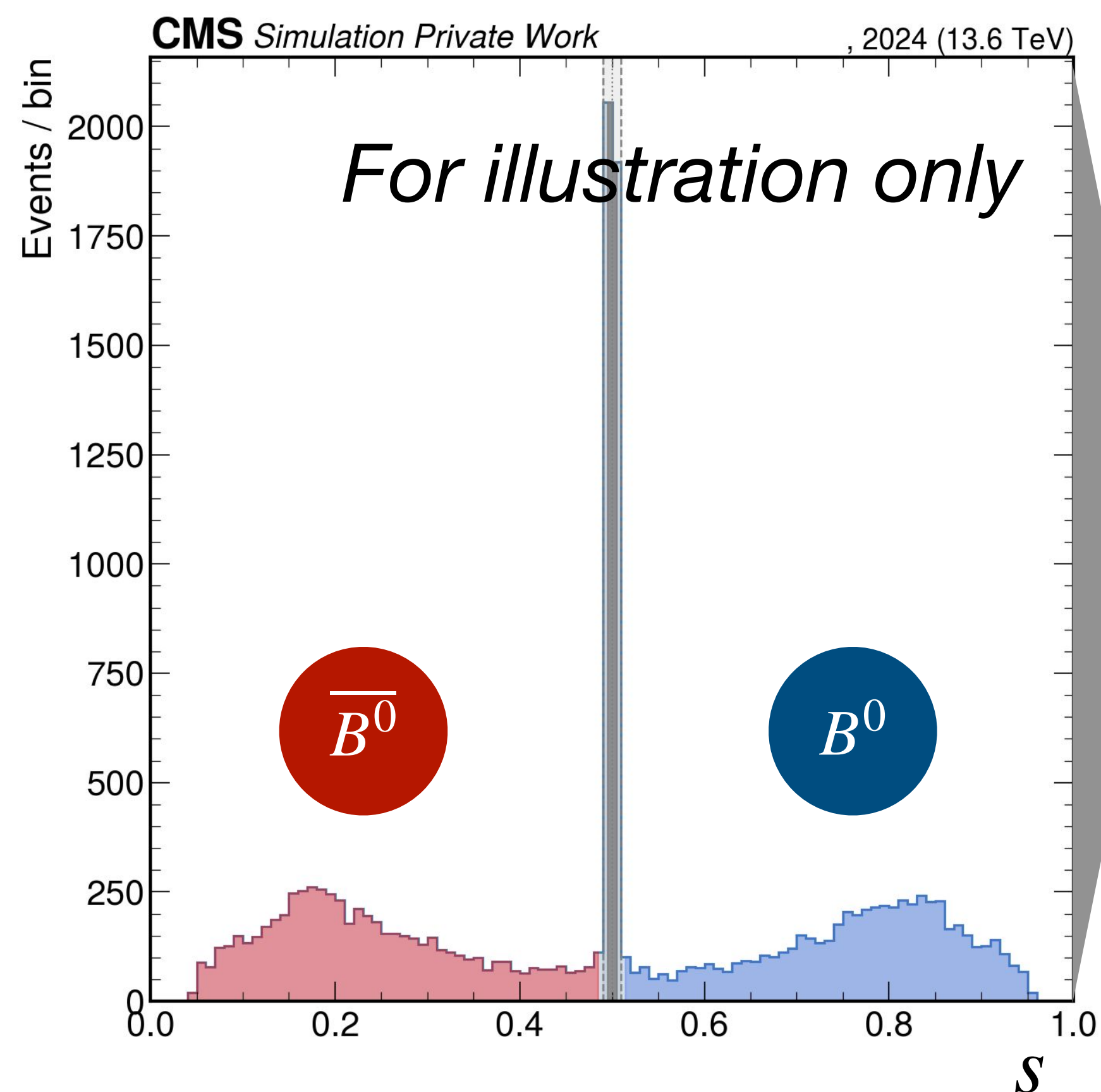
Flavour tagging = neutral meson tagging

- New taggers based on [ParticleTransformer](#) jet tagger developed for Run 3
- Key idea : add variables describing relations between jet-components into the attention mechanism



Flavour tagging = neutral meson tagging

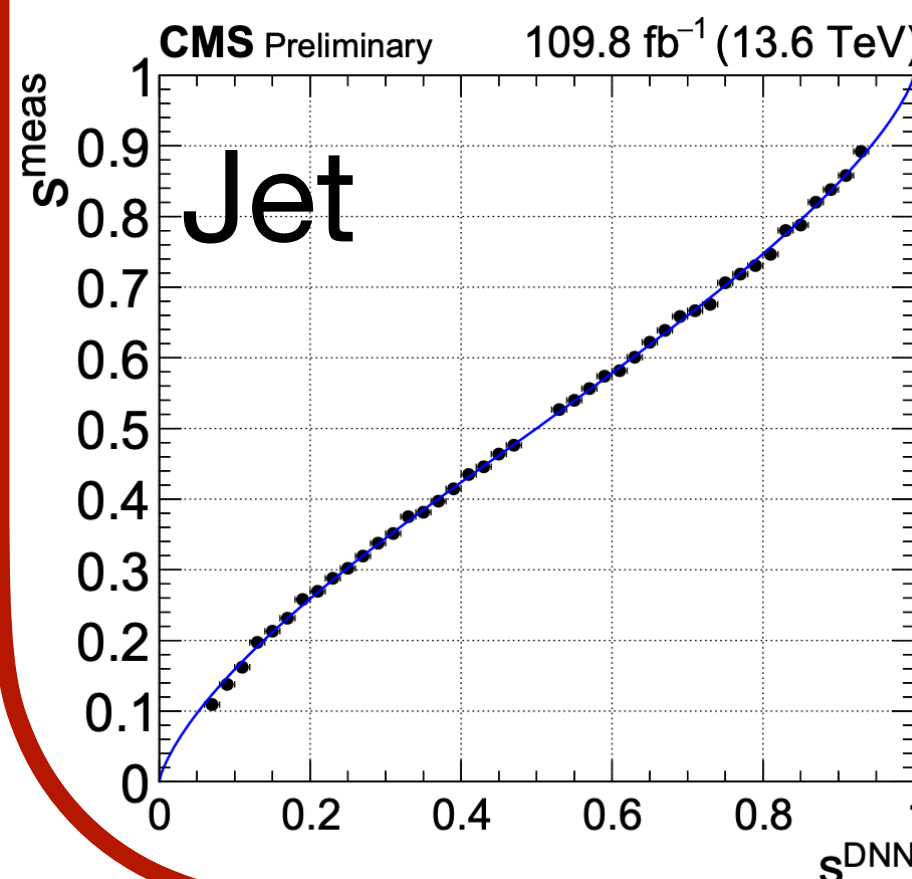
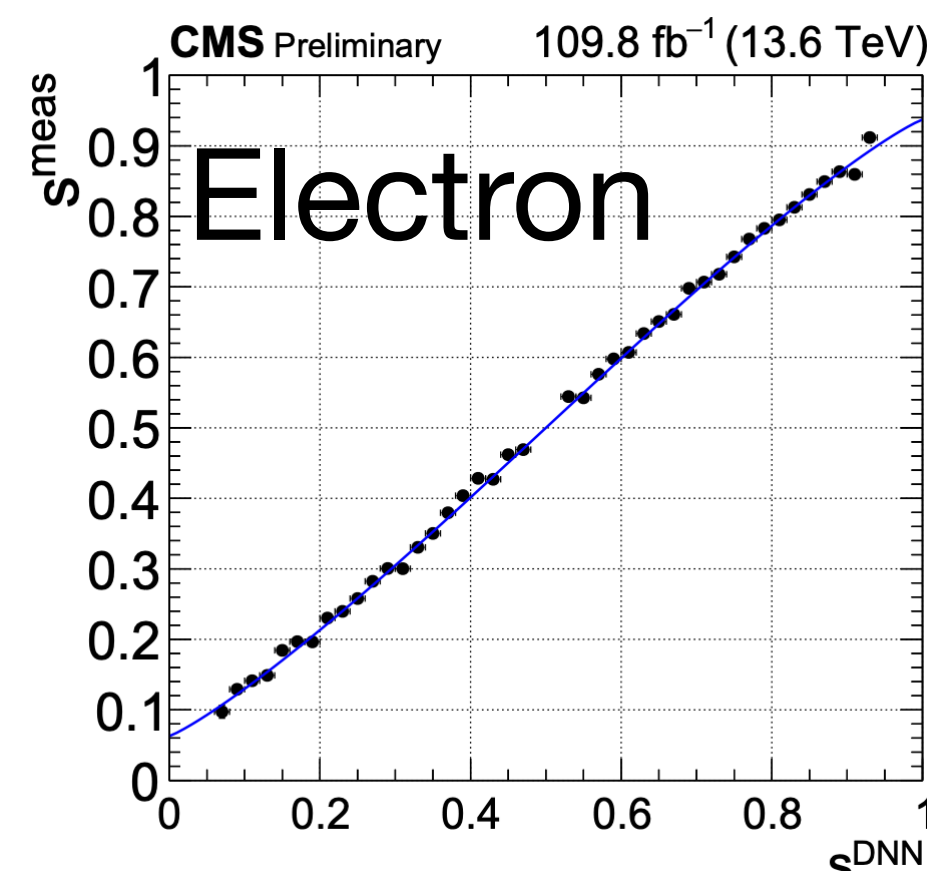
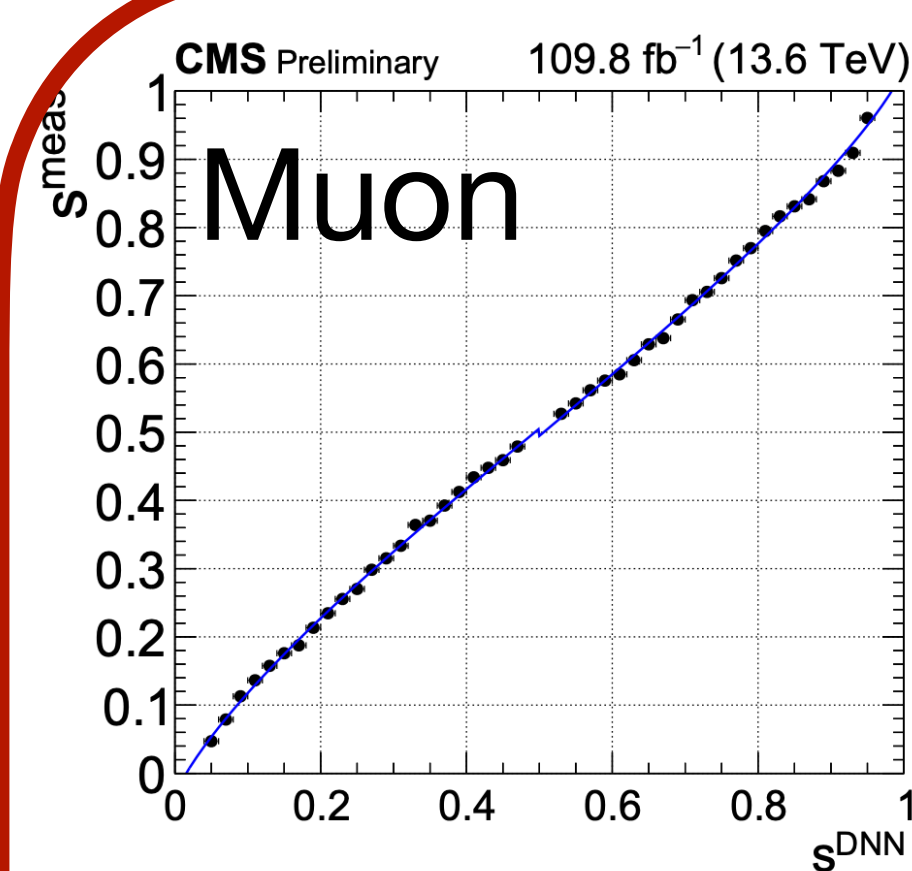
- Softmax gives a probability score for meson flavour



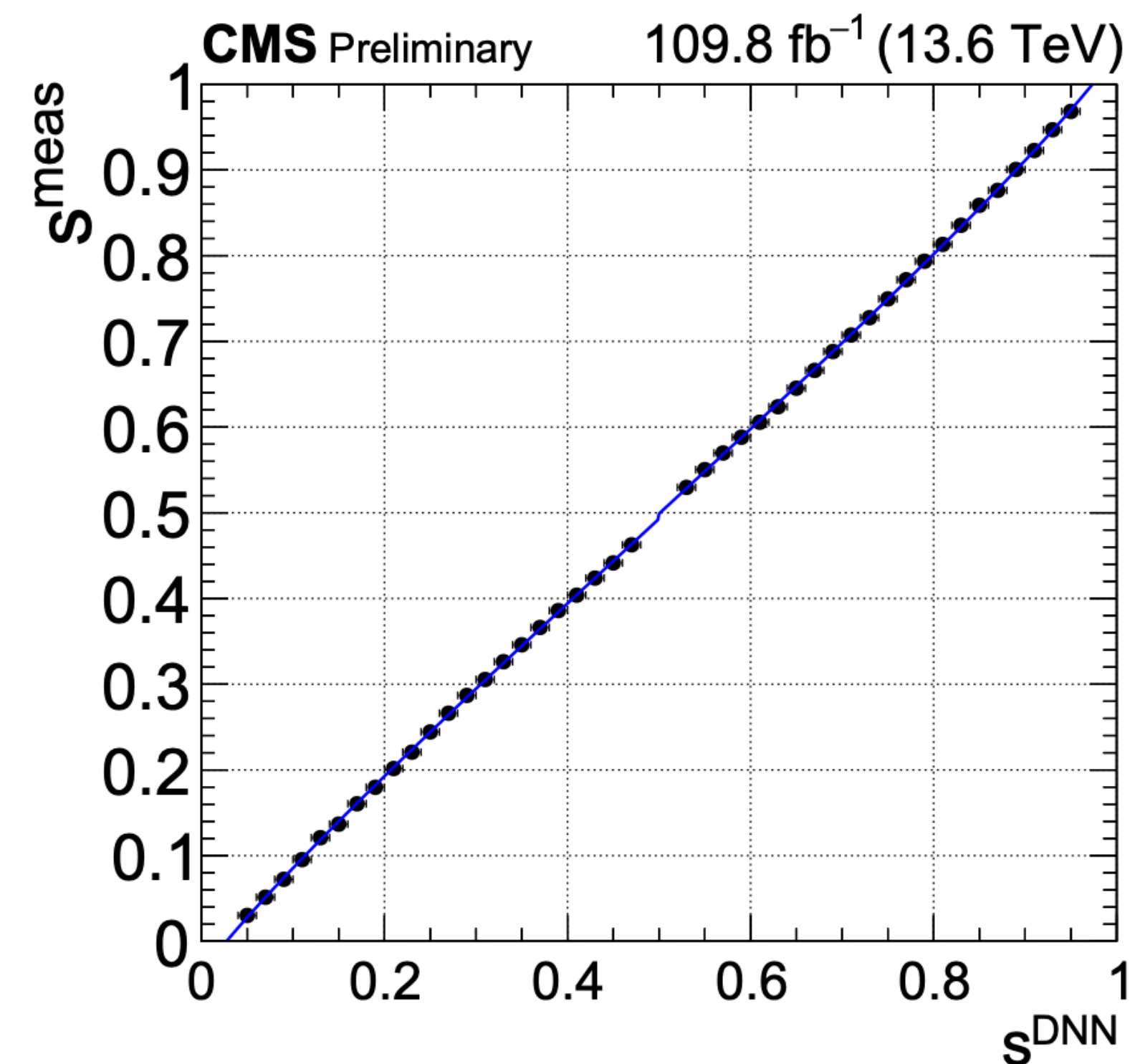
- $s > 0.5 + \delta s$: $q = +1$; $\omega = 1 - s$ B^0
- $s < 0.5 - \delta s$: $q = -1$; $\omega = s$ $\overline{B^0}$
- $0.5 - \delta s < s < 0.5 + \delta s$: $q = 0$ *Untagged*

Flavour tagging = neutral meson tagging

- Calibration done with $B^+ \rightarrow J/\psi K^+$
- Not ideal for the SS tagger, but okay for OS



Opposite Side



Same side

Flavour tagging = neutral meson tagging

Process	Period	$\epsilon_{\text{tag}} [\%]$	$\mathcal{D}_{\text{tag}}^2$	$P_{\text{tag}} [\%]$
$B^0 \rightarrow J/\psi K_S^0$	2022	18	0.11	1.9
	2023	13	0.14	1.9
	2024	13	0.13	1.6
	2025	11	0.13	1.5
$B_s^0 \rightarrow J/\psi K_S^0$	2022	74	0.11	8.2
	2023	76	0.10	7.9
	2024	73	0.10	8.0
	2025	77	0.09	7.1

Caveat: SS is not calibrated precisely enough with $B^+ \rightarrow J/\psi K^+$ for $\sin 2\beta$ so removed from B^0

Combined Performance of Run 3 taggers

Asymmetry fits

Model :

$$a_{CP}(t) = A_{\text{prod}} + A_{\text{tag}} + \frac{S \sin(\Delta m_d t) - C \cos(\Delta m_d t)}{\cosh(\Delta \Gamma_d t/2) - D \sinh(\Delta \Gamma_d t/2)}$$

$A_{\text{prod}} = (0.00 \pm 0.54) \%$ measured on control mode $B^+ \rightarrow J/\psi K^+$

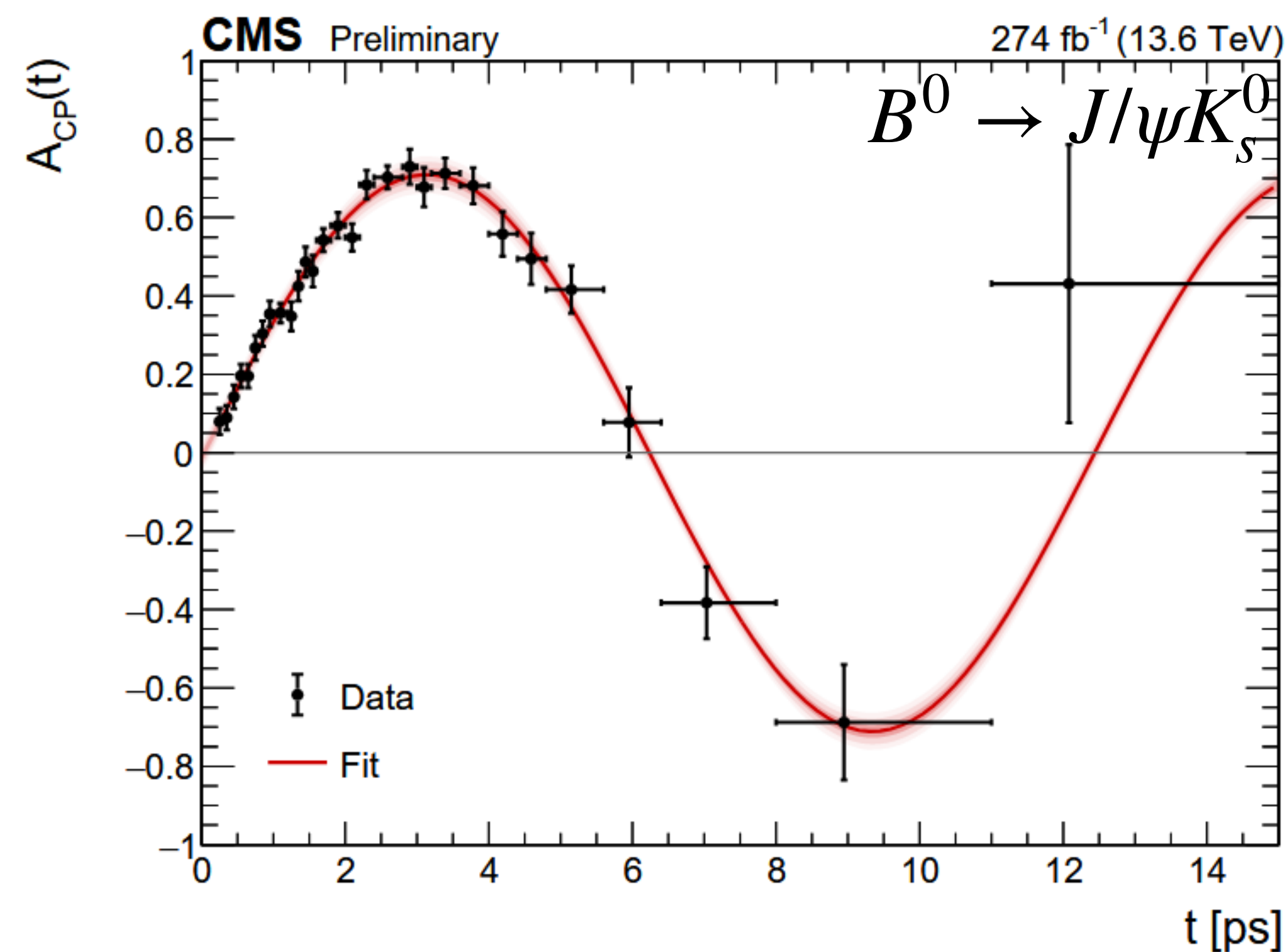
Systematical uncertainty

	S_{B^0}	C_{B^0}	$S_{B_s^0}$	$C_{B_s^0}$
Stat. uncertainty	0.013	0.011	0.19	0.23
Fit bias	0.001	$< 10^{-3}$	$< 10^{-2}$	0.01
$\Delta\Gamma_{(s)}$	0.005	0.002	$< 10^{-2}$	$< 10^{-2}$
$\Delta m_{(s)}$	$< 10^{-3}$	0.002	$< 10^{-2}$	$< 10^{-2}$
A_{prod}	0.005	0.003	—	—
Signal extraction	0.001	0.003	$< 10^{-2}$	$< 10^{-2}$
Time resolution	$< 10^{-3}$	$< 10^{-3}$	$< 10^{-2}$	$< 10^{-2}$
Flavour tagging	0.006	0.004	$< 10^{-2}$	$< 10^{-2}$
Kaon regeneration	$< 10^{-3}$	$< 10^{-3}$	$< 10^{-2}$	$< 10^{-2}$
Tot. syst. uncertainty	0.009	0.006	0.00	0.01

- External and reducible with updated measurements
- Flavour tagging calibration

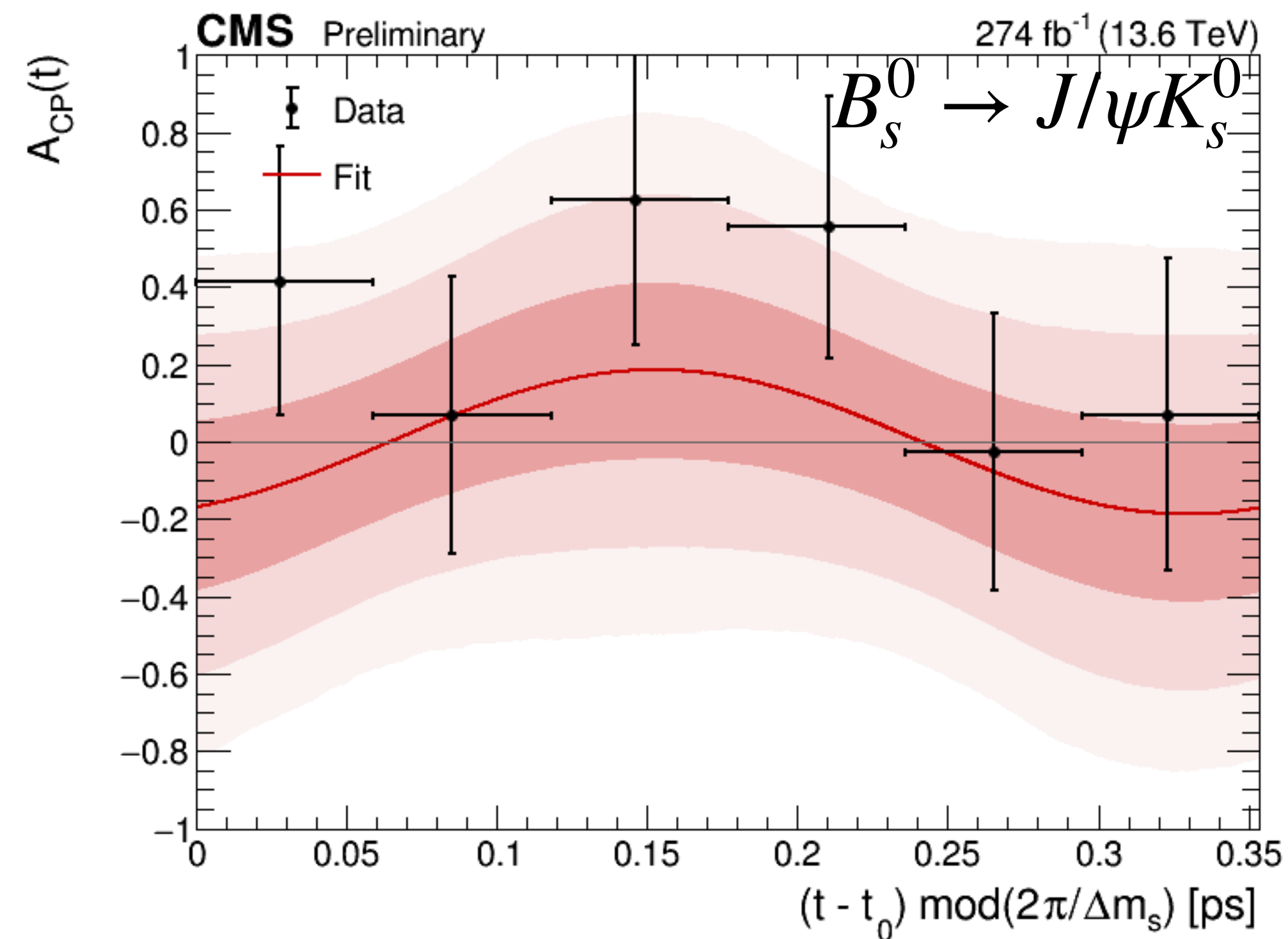
(Thanks, Vukan for helping us)

Asymmetry fits



$$S = 0.710 \pm 0.013 \text{ (stat.)} \pm 0.009 \text{ (syst.)}$$

$$C = 0.013 \pm 0.011 \text{ (stat.)} \pm 0.006 \text{ (syst.)}$$

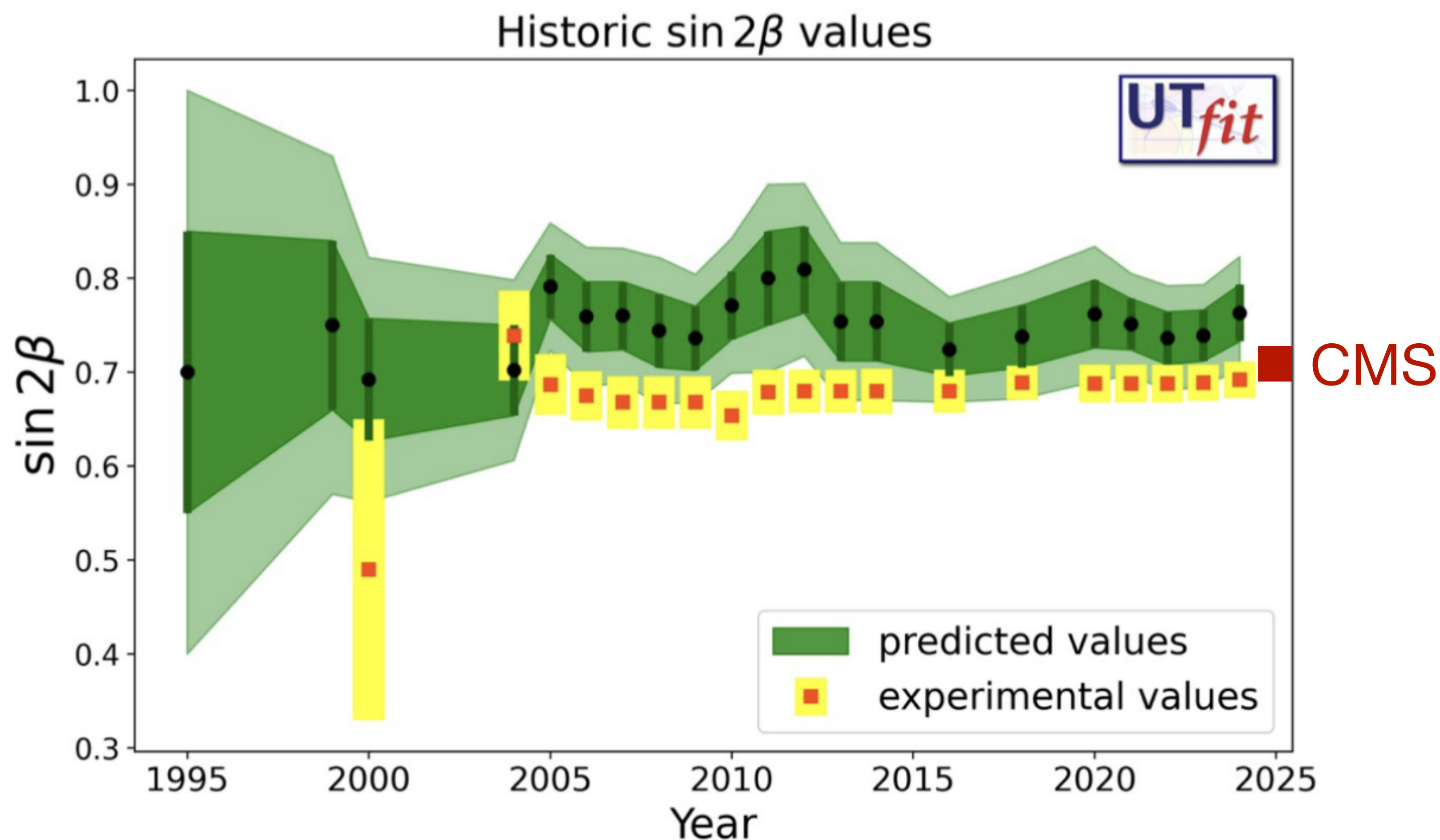


$$S = 0.00 \pm 0.19 \text{ (stat.)} \pm 0.00 \text{ (syst.)}$$

$$C = -0.18 \pm 0.23 \text{ (stat.)} \pm 0.01 \text{ (syst.)}$$

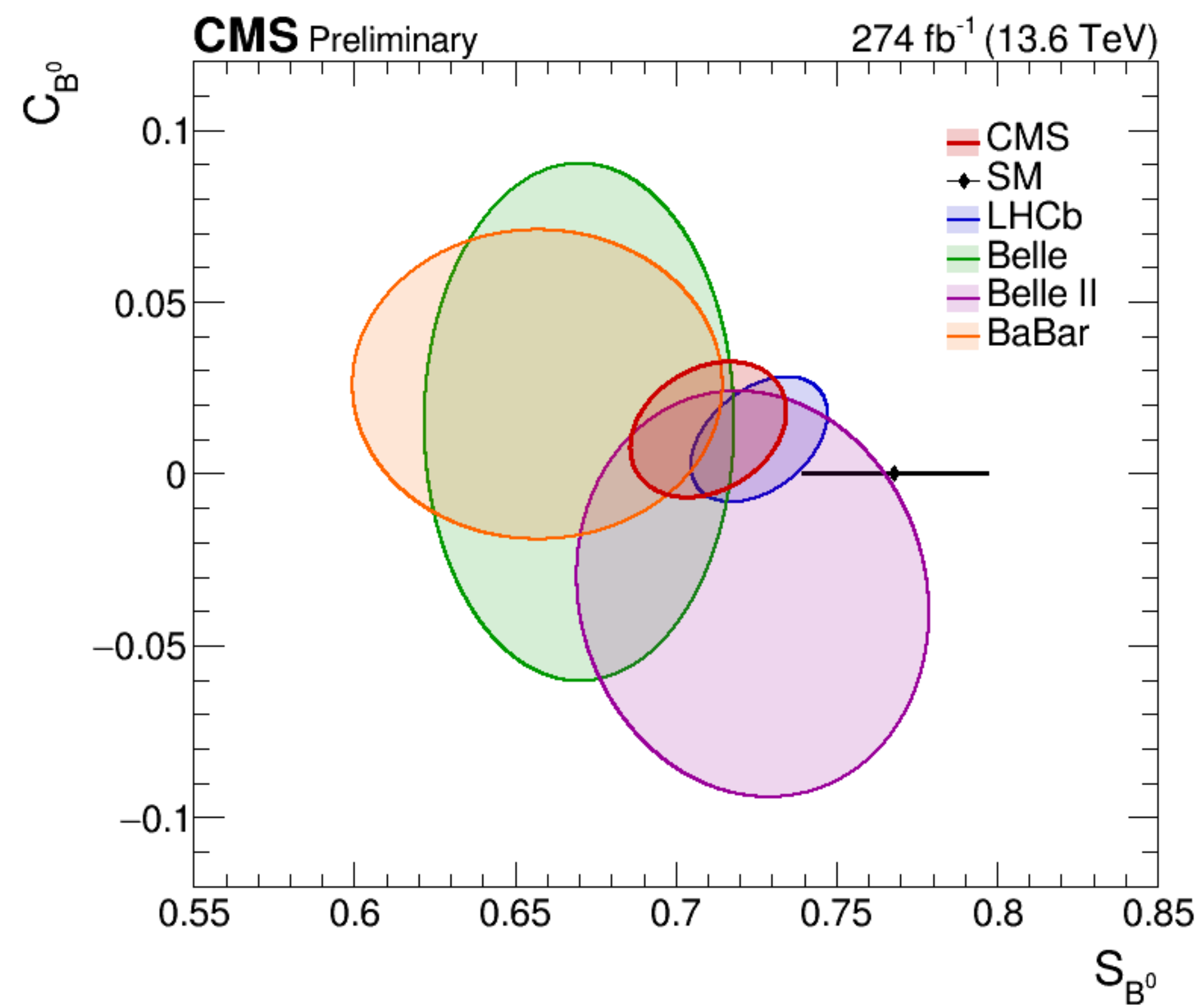
Results

- First high precision measurement of observable time-dependent CPV from CMS

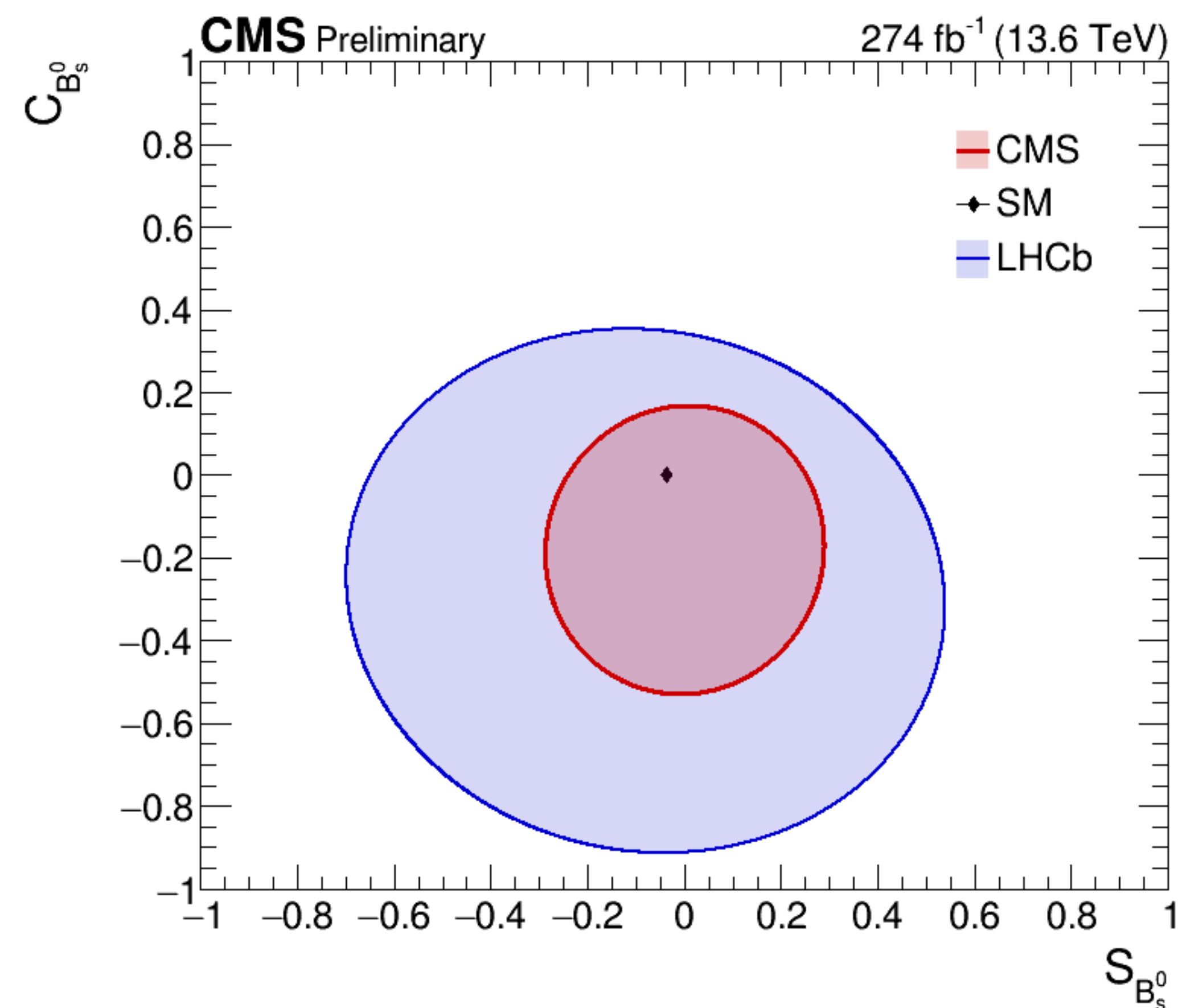


Results

$$B^0 \rightarrow J/\psi K_s^0$$

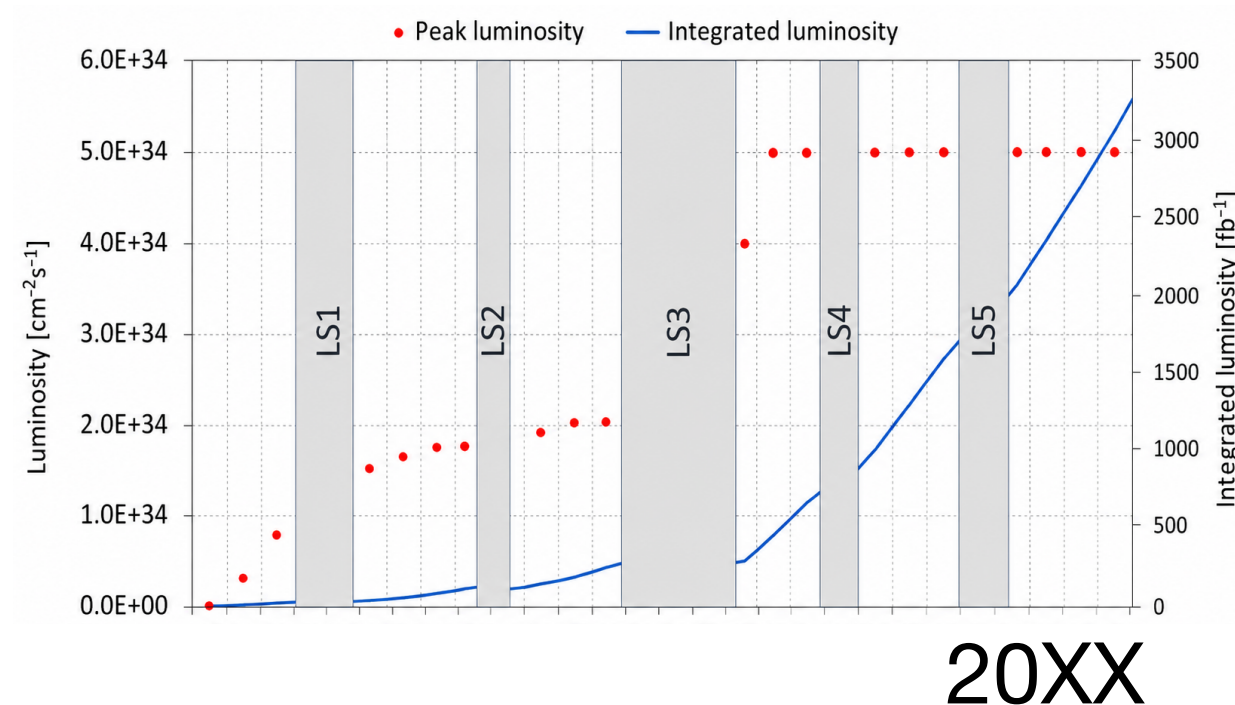


$$B_s^0 \rightarrow J/\psi K_s^0$$



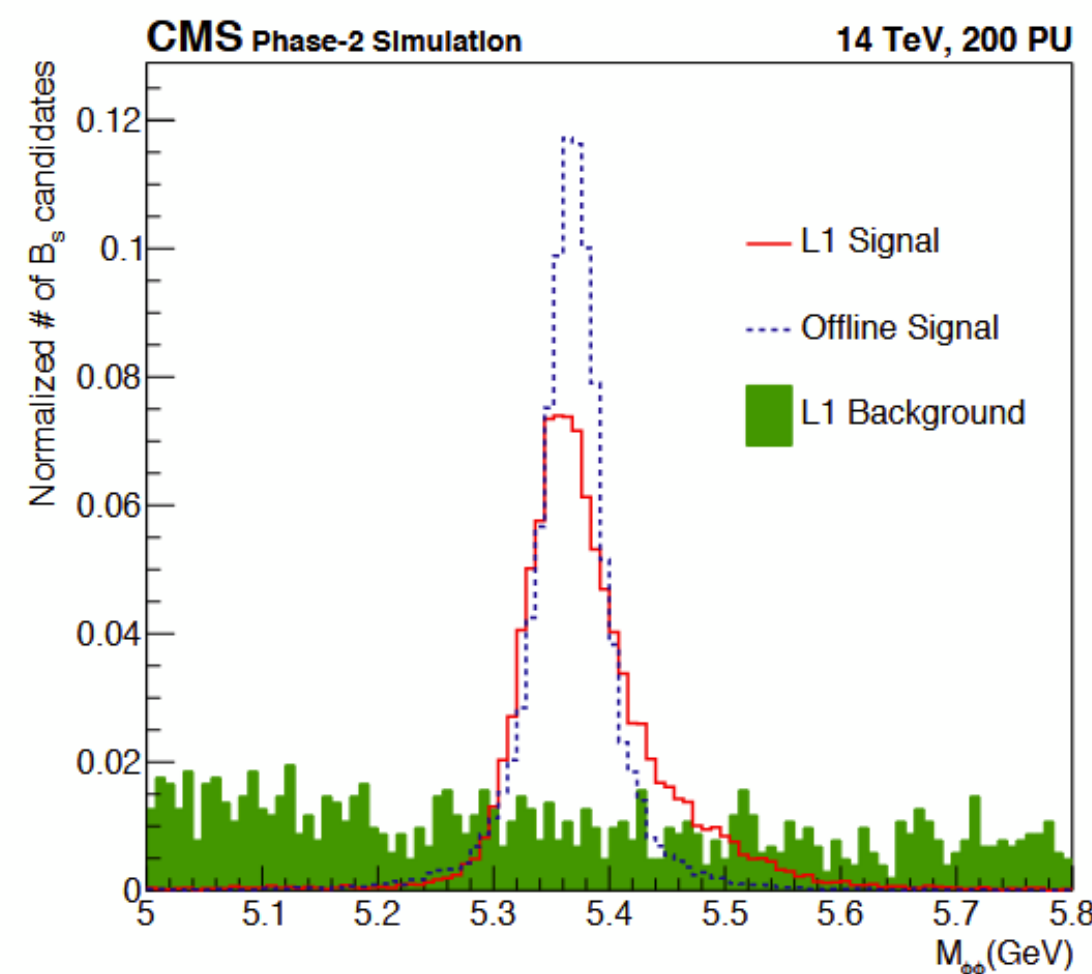
Outlook

1 Much more data $\times 6$

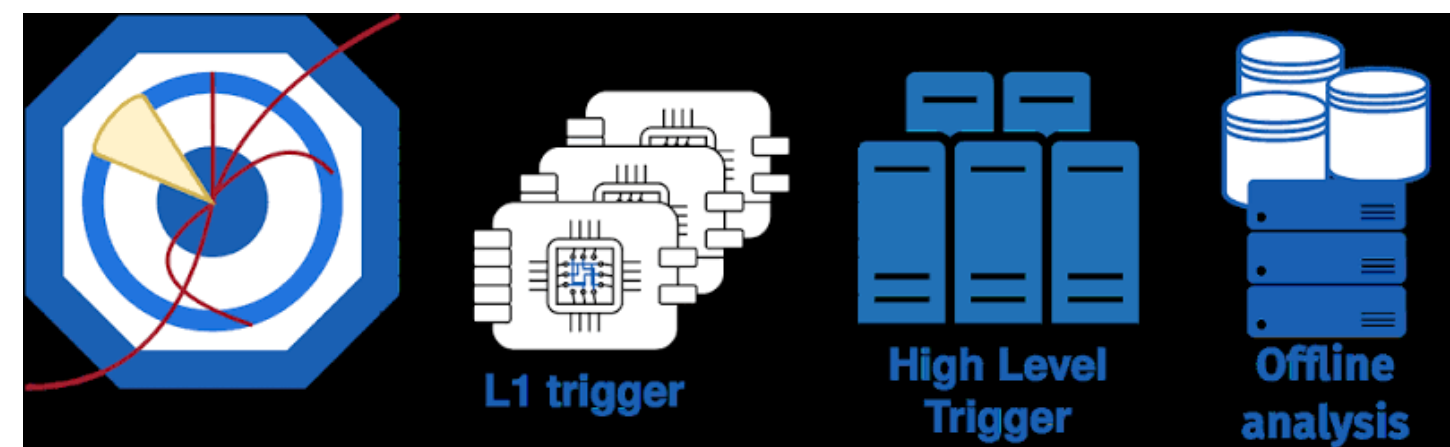


3 Trigger on tracks at L1!

$\times X$
for trigger
efficiency



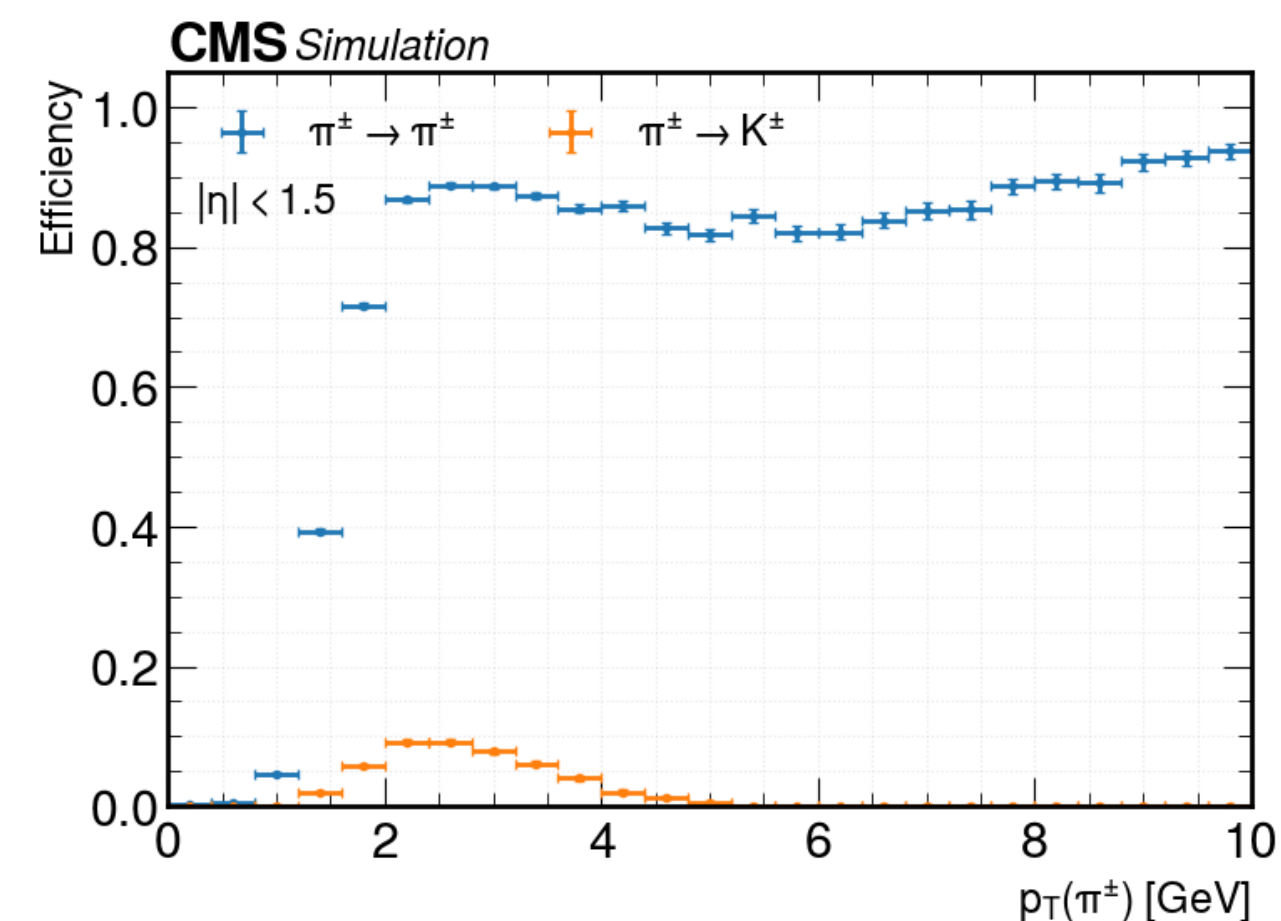
2 Much more actually collected data



$\times 7.5 \times 7.5$

4 Particle identification!

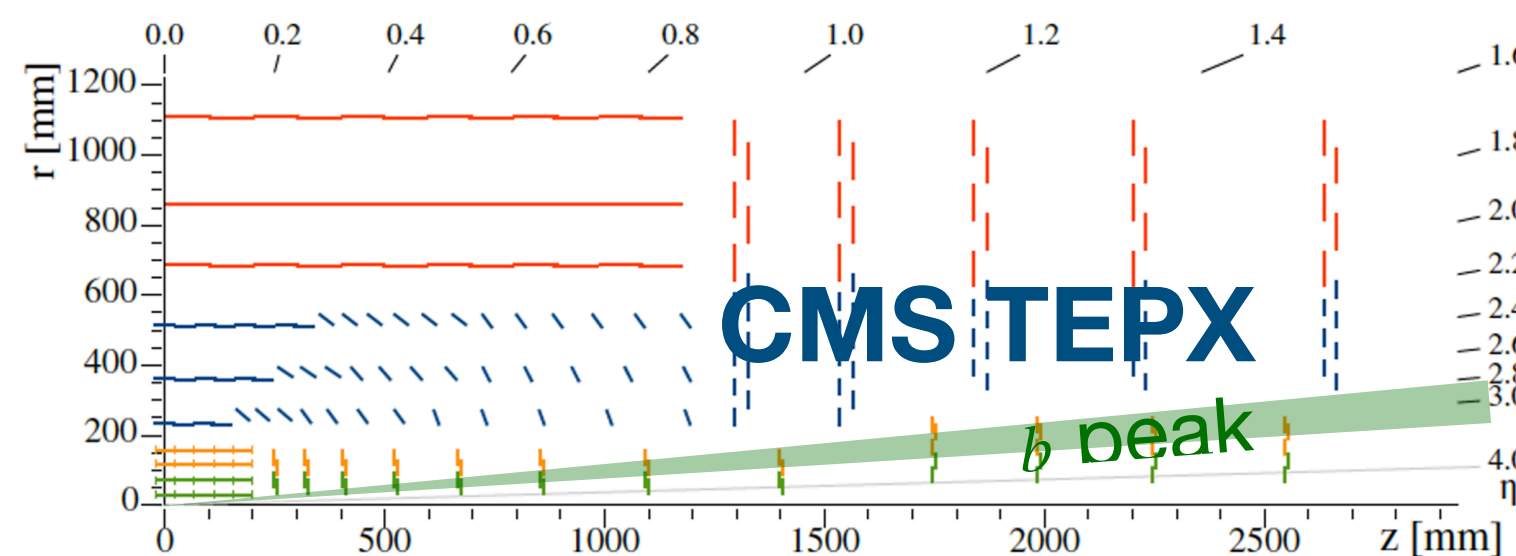
$\times X$
for S/B
 $\times 1.35$
for tagging



Minimum ionising particle timing detector - MTD

5 Larger acceptance to $|\eta| < 4$ $\times 1.5$

for b-quarks in the CMS
acceptance



Summary

- First high precision CP-violation measurement in CMS
- Update on the penguins contributions to $\sin 2\beta$
- Much more to come: interpretation of the phase, casting with respect to external inputs



Backup

Selection

Object	Variable	Requirement
Event	PV found	
	Good data-taking conditions	
	HLT fired	
	Trigger objects matched	
	No observable ill-defined (<i>NaN</i> etc.)	
$B^0 \rightarrow J/\psi K_S^0$	$m(J/\psi K_S^0)$	$\in [5.17, 5.50] \text{ GeV}$
	$p_T(B^0)$	$> 8.5 \text{ GeV}$
	B^0 vertex prob.	$> 2\%$
	$t(B^0)$	$> 0.2 \text{ ps}$
	$\cos \theta(B^0)_{2D}$	> 0.997
	$\min \Delta R(\mu_1, \mu_2, K_S^0)$	> 0.03
$J/\psi \rightarrow \mu^+ \mu^-$	Muon reconstruction	Global
	Muon identification	Loose
	$p_T(\mu_{\text{lead}})$	$> 4 \text{ GeV}$
	$p_T(\mu_{\text{sub}})$	$> 3 \text{ GeV}$
	$ \eta(\mu) $	< 2.4
	$ z(\mu_1) - z(\mu_2) $	$< 1 \text{ cm}$
	$\Delta R(\mu_1, \mu_2)$	> 0.03
	$ m(\mu^+ \mu^-) - m_{J/\psi}^{\text{w.a.}} $	$< 150 \text{ MeV}$
$K_S^0 \rightarrow \pi^+ \pi^-$	J/ψ vertex prob.	$> 0.1\%$
	Track quality	High Purity
	$p_T(\pi)$	$> 0.35 \text{ GeV}$
	$ \eta(\pi) $	< 2.5
	$p_T(K_S^0)$	$> 1.35 \text{ GeV}$
	$ m(\pi^+ \pi^-) - m_{K_S^0}^{\text{w.a.}} $	$< 25 \text{ MeV}$
	$\cos \theta_{2D}(K_S^0)$	> 0.998
	K_S^0 vertex prob.	$> 0.1\%$

Tagging variables

OSMuon

Variable	Type	Definition
Muon Charge	float	Muon electric charge
Muon ID	float	SoftMuonRun3 discriminator
Muon Iso	float	PF relative isolation ($\Delta R = 0.4$)
Muon dz	float	Muon longitudinal IP w.r.t. PV
Muon dxy	float	Muon transverse IP w.r.t. PV
Muon N_{trk}	float	Tracks near muon
Track Charge	array	Track charge
Track dxy	array	Track transverse IP w.r.t. PV
Track dz	array	Track longitudinal IP w.r.t. PV
Track χ^2	array	Normalized track χ^2
Track $N_{validhits}$	array	Valid track hits
Track $N_{validpixelhits}$	array	Valid pixel hits

Variable	Type	Description
B p_T	float	B meson p_T
B η	float	B meson η
Jet p^μ	4×float	Jet four-momentum
Jet mass	float	Jet mass
Jet b -tag score	float	b -tag probability (PNET)
Jet chHEF	float	Jet charged Hadron Energy Fraction
Jet neHEF	float	Jet neutral Hadron Energy Fraction
Jet chEmEF	float	Jet charged Electromagnetic Energy Fraction
Jet neEmEF	float	Jet neutral Electromagnetic Energy Fraction
Jet hfHEF	float	Jet hadronic Energy Fraction in HF
Jet hfEmEF	float	Jet electromagnetic Energy Fraction in HF
Jet chFPV0EF	float	Jet charged fromPV==0 Energy Fraction
Jet chMultiplicity	float	Number of charged particles in the jet before selections
Jet qgl	float	Quark vs Gluon likelihood discriminator
Track charge	array	Track charge
Track p^μ	4×array	Track four-momentum
Track mass	array	Track estimated mass
Track dxy	array	Track transverse IP w.r.t. PV
Track dz	array	Track longitudinal IP w.r.t. PV
Track sxy	array	Track transverse IP uncertainty
Track sz	array	Track longitudinal IP uncertainty
Track pterr	array	Track p_T uncertainty
Track nValidPixelHits	array	Number of valid pixel hits in track
Track nValidHits	array	Number of valid hits in track
Track normChi2	array	Track fit normalized χ^2
Track dr2Jet	array	Track squared ΔR w.r.t. jet axis
Track detaJet	array	Track η diff w.r.t. jet axis
Track dphiJet	array	Track ϕ diff. w.r.t. jet axis
Track puppiw	array	Track PU score (PUPPI)
Track VTX ass	array	Track-PV association type

OSElectron

Variable	Type	Definition
Electron Charge	float	Electron electric charge
Electron Soft MVA ID	float	Electron MVA discriminator trained on $J/\psi \rightarrow ee$ data
Electron Iso	float	PF relative isolation ($\Delta R = 0.4$)
Electron dz	float	Electron longitudinal IP w.r.t. PV
Electron dxy	float	Electron transverse IP w.r.t. PV
Electron dz uncertainty	float	Uncertainty on the longitudinal IP w.r.t. PV
Electron dxy uncertainty	float	Uncertainty on the transverse IP w.r.t. PV
Electron $\Delta R(e, B)$	float	ΔR distance between electron and the signal B meson
Electron N_{trk}	float	Tracks near electron
Track Charge	array	Track charge
Track dxy	array	Track transverse IP w.r.t. PV
Track dz	array	Track longitudinal IP w.r.t. PV
Track χ^2	array	Normalized track χ^2
Track $N_{validhits}$	array	Valid track hits
Track $N_{validpixelhits}$	array	Valid pixel hits

Variable	Requirement
B decay	$\not\in$
$\Delta R_{\eta,\phi}(B, \text{trk})$	< 0.8
$ d_z $ w.r.t. PV	$< 0.3 \text{ cm}$

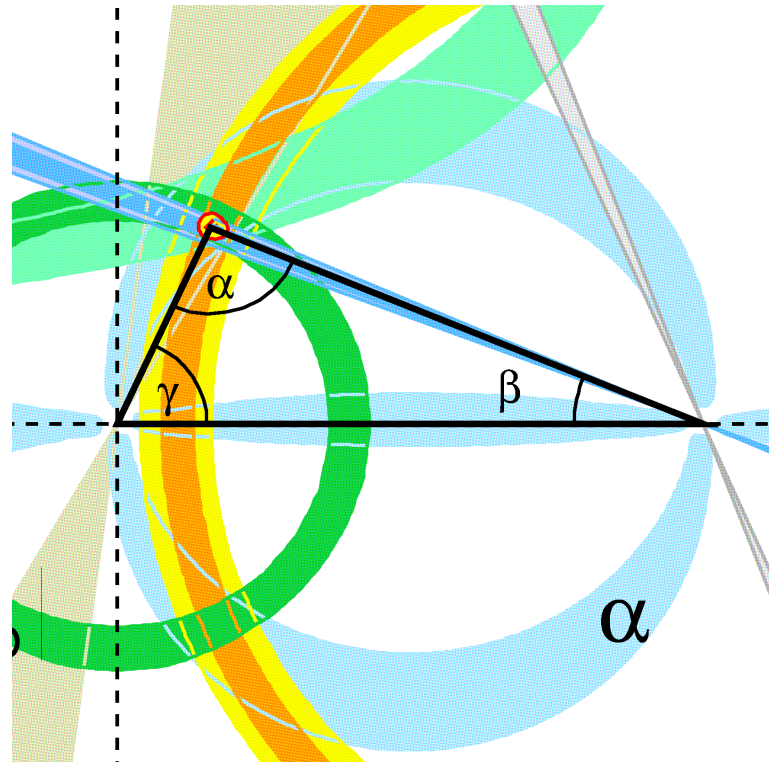
SS-Jet

Variable	Requirement
$ \eta $	≤ 2.4
ΔR w.r.t. B candidate	> 1.0
chHEF	> 0.01
PNetB score	> 0.2

OS-Jet

Jet taggers

Amount of CP-violation in Standard Model quark sector

$4 \times$

 $\approx 10^{-5}$

$\times$

QUARKS	mass charge spin	$\approx 2.2 \text{ MeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ u up	$\approx 1.28 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ c charm	$\approx 173.1 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ t top
	$\approx 4.7 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ d down	$\approx 96 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ s strange	$\approx 4.18 \text{ GeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ b bottom	

$$\frac{
 \begin{aligned}
 &(m_t^2 - m_c^2)(m_u^2 - m_t^2)(m_c^2 - m_u^2) \\
 &(m_b^2 - m_s^2)(m_s^2 - m_d^2)(m_d^2 - m_b^2)
 \end{aligned}
 }{
 T_{freeze-out}^{12} \approx 10^{60} \text{ MeV}^{12}
 }
 \approx 10^{45} \text{ MeV}^{12}$$

$$= 10^{-20}$$

There is not enough CP-violation in quark sector alone

Kaon regenerations

- The interaction of the K^0 with the detector before decay, introduce mixing between K^S and K^L which modifies the measured CPV
- **Estimated an effective CPV shift of $O(10^{-4})$, negligible within the precision of the measurement ($\sigma^{S,C} \sim 10^{-2}$)**

