The What, Why, and How of flavour physics

"the chronicles of experimental B physics"

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Outline

- **What** is our current state of understanding of particle physics?
  - the Standard Model of particle physics, flavour physics
- **Why** is it interesting to study flavour physics (main focus on B-meson observables)?
  - CKM matrix and unitarity triangles
  - neutral meson mixing and oscillation
  - CP violation
- **How** do we study flavour observables experimentally?
  - techniques for heavy meson production
  - hadron vs e^+e^- machines: which one is better?
  - symmetric vs asymmetric e^+e^- machines
  - flavour tagging
  - measurements of flavour observables (CKM matrix elements, CP violation)

What?

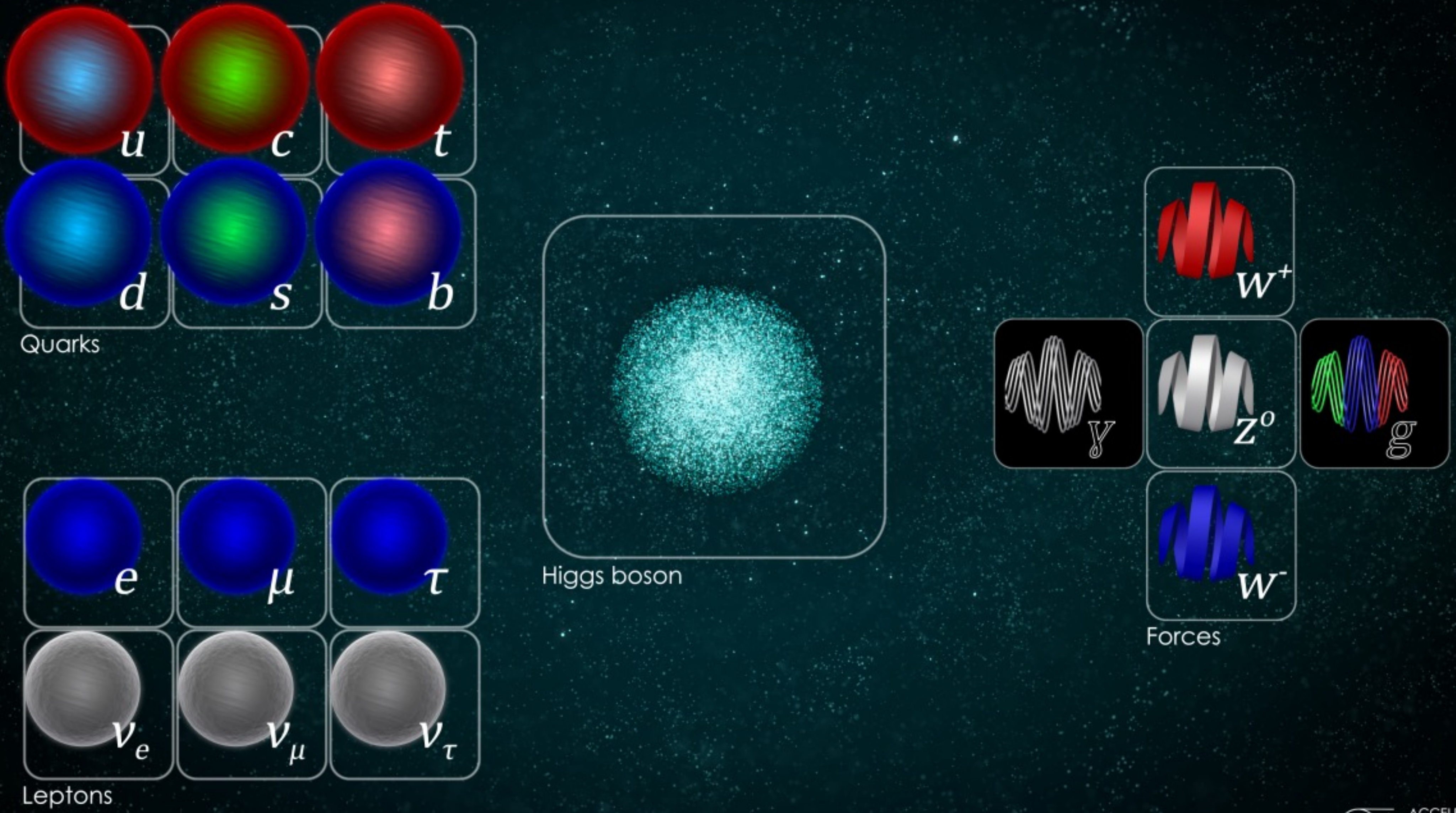
Introduction

- Main goal of particle physics (also known as high energy physics):

Understand what are the fundamental laws of Nature

- Particle physics experiments probed energy scales as high as 10 TeV ($m_p \sim 1$ GeV) ↔ distances $10^{-20} m$
- Our understanding of how Nature works at short distances has significantly improved over the past century
  - quantum mechanics → understanding of atomic spectra and the periodic system of elements
  - insight into the structure of the atomic nucleus → paved the way to our understanding of strong interaction
  - flavour-changing transition → started with the discovery of radioactivity (β decay) and had huge importance in the development of the SM
- *All of these findings culminated in the development of the Standard Model (SM) of particle physics:* amazing achievement of humanity!

The Standard Model for pedestrians



From quarks to hadrons (QCD at low energies)

- *High energy (short distances):* QCD is perturbative ($\alpha_S \ll 1$) **[asymptotic freedom]**
- *Low energy (long distances):* QCD is strongly coupled → no perturbative expansion

- **Confinement hypothesis:** quarks ($SU(3)_C$ triplets) must be confined within color-singlet bound states
- No formal proof of that hypothesis but many indications that it is true
- Experimentally we do not observe free quarks and gluons but rather bound states we call **hadrons**
  - bosonic hadrons are called mesons ($q\bar{q}$) → **today we will focus on mesons**
  - fermionic hadrons are called baryons (qqq)
- Hadrons are formed due to the confining nature of QCD → can't be treated perturbatively
- Some properties of hadrons can be determined independent of our ability to describe their internal structure

Mesons

(open) B mesons: main focus today

(open) charm (D) mesons

kaons $(\mathrm{K}$ mesons$)$

Meson	**Quark content $[q\bar{q}']$**	**$I(J^P)$**	**Mass [GeV/c^2]**	**Mean lifetime**		**$c\tau$**
$B^+(B^-)$	$\bar{b}u(\bar{u}b)$	$1/2(0^-)$	5.3	1.6 ps		491 μm
$B^0(\bar{B}^0)$	$\bar{b}d\ (b\bar{d})$	$1/2(0^-)$	5.3	1.5 ps		455 μm
$B_s^0(\bar{B}_s^0)$	$\bar{b}s\ (b\bar{s})$	$0(0^-)$	5.4	1.5 ps		455 μm
$B_c^+(B_c^-)$	$\bar{b}c\ (b\bar{c})$	$0(0^-)$	6.3	0.5 ps		150 μm
$D^0(\bar{D}^0)$	$c\bar{u}\ (\bar{c}u)$	$1/2(0^-)$	1.9	0.4 ps		129 μm
$D^+(D^-)$	$c\bar{d}\ (\bar{c}d)$	$1/2(0^-)$	1.9	1.0 ps		312 μm
$D_s^+(D_s^-)$	$c\bar{s}\ (\bar{c}s)$	$0(0^-)$	2.0	0.5 ps		151 μm
$K^+(K^-)$	$\bar{s}u\ (s\bar{u})$	$1/2(0^-)$	0.494	12 ns		3.7 m
$K^0(\bar{K}^0)$	$\bar{s}d\ (s\bar{d})$	$1/2(0^-)$	0.498	K_S	90 ps	2.7 cm
				K_L	51 ns	15.3 m

Flavour physics

- In the SM fermions interact through pure gauge interactions (related to unbroken gauge symmetries), weak and Yukawa interactions (source of flavour and CP violation)
- *Flavour physics:* interactions that distinguish between particle flavours ($W -$ mediated weak interactions and Yukawa interactions)
- *Flavour parameters:* parameters that carry flavour indices (10 in the SM, 6 quark masses + 4 CKM parameters)

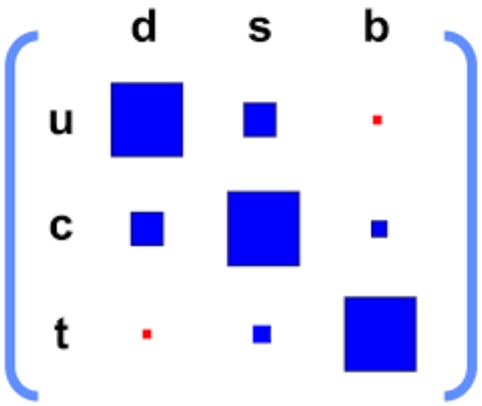
- Flavour physics can predict New Physics (NP) before it's directly observed
    - smallness of $\Gamma(K_L \to \mu^+\mu^-)/\Gamma\left(K^+ \to \mu^+\nu_\mu\right)$ allowed the prediction of the existence of the charm quark
    - size of Δm_K(kaon mixing) allowed for the charm mass prediction
    - measurement of ϵ_K (CP violation in the kaon sector) allowed for the prediction of the existence of third generation particles
    - size of Δm_B(B-meson mixing) allowed for a quite accurate top mass prediction
    - measurement of neutrino flavour transitions led to the discovery that neutrinos have a mass $\neq 0$

Why?

CKM matrix and the unitarity triangles

Wolfenstein parametrisation

$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4) \Rightarrow$$



- The CKM matrix must be unitary: $V_{\rm CKM}V_{\rm CKM}^\dagger = V_{\rm CKM}^\dagger V_{\rm CKM} = \mathbb{I}$
- The parameters of the CKM matrix in nature are **far from generic**
    - strong hierarchy is observed in the off-diagonal elements expansion ion the small parameter $\lambda = 0.225$
- Geometrical interpretation of the off-diagonal elements: 6 independent "unitarity" triangles

$$\sum_{i=u,c,t} V_{iq}V^*_{iq'} = 0, \qquad (qq' = ds, db, sb) \qquad\qquad \sum_{i=d,s,b} V_{qi}V^*_{q'i} = 0, \qquad (qq' = uc, ut, ct)$$

- ***Note:*** the area of all CKM unitarity triangles is the same $A = |J_{\rm CKM}|/2$, (Jarlskog invariant)

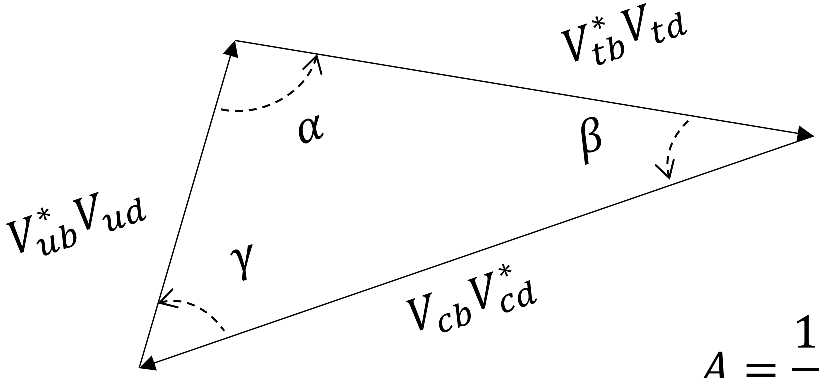
$$J_{\rm CKM} = c_{12}c_{23}c_{13}^2 s_{12}s_{23}s_{13}\sin\delta \approx \lambda^6 A^2 \eta = \left(3.115^{+0.047}_{-0.059}\right)\times 10^{-5}$$

$\delta(\eta)$ is [the only] source of CP-violation in the SM

“The” unitarity triangle

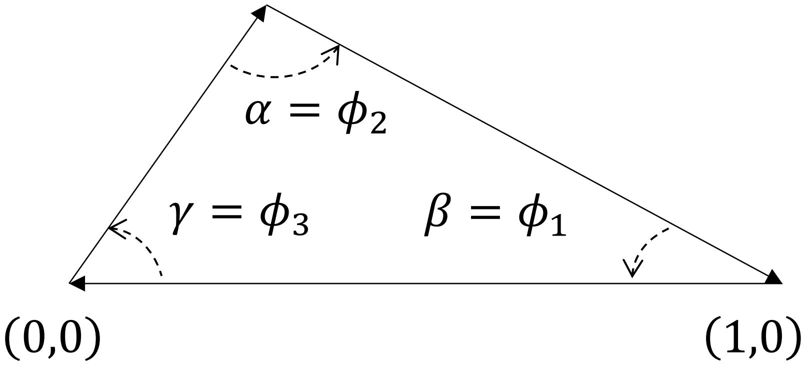
- “The” unitarity triangle: all sides are of similar length and its parameters can be studied using B^0, B^+ decays

$$\sum_{i=u} V_{iq} V^*_{iq'} = 0, \qquad (qq' = db) \qquad \Longrightarrow \qquad \underset{\mathcal{O}(\lambda^3)}{V^*_{ub} V_{ud}} + \underset{\mathcal{O}(\lambda^3)}{V^*_{tb} V_{td}} + \underset{\mathcal{O}(\lambda^3)}{V_{cb} V^*_{cd}} = 0$$



rescale by $V_{cb}V^*_{cd}$ and rotate $\longrightarrow$

(ρ, η) complex plane



$$A = \frac{1}{2}[V_{cd}V_{cb}][V_{ud}V_{ub}\sin\gamma] = \frac{1}{2}|J_{\text{CKM}}|$$

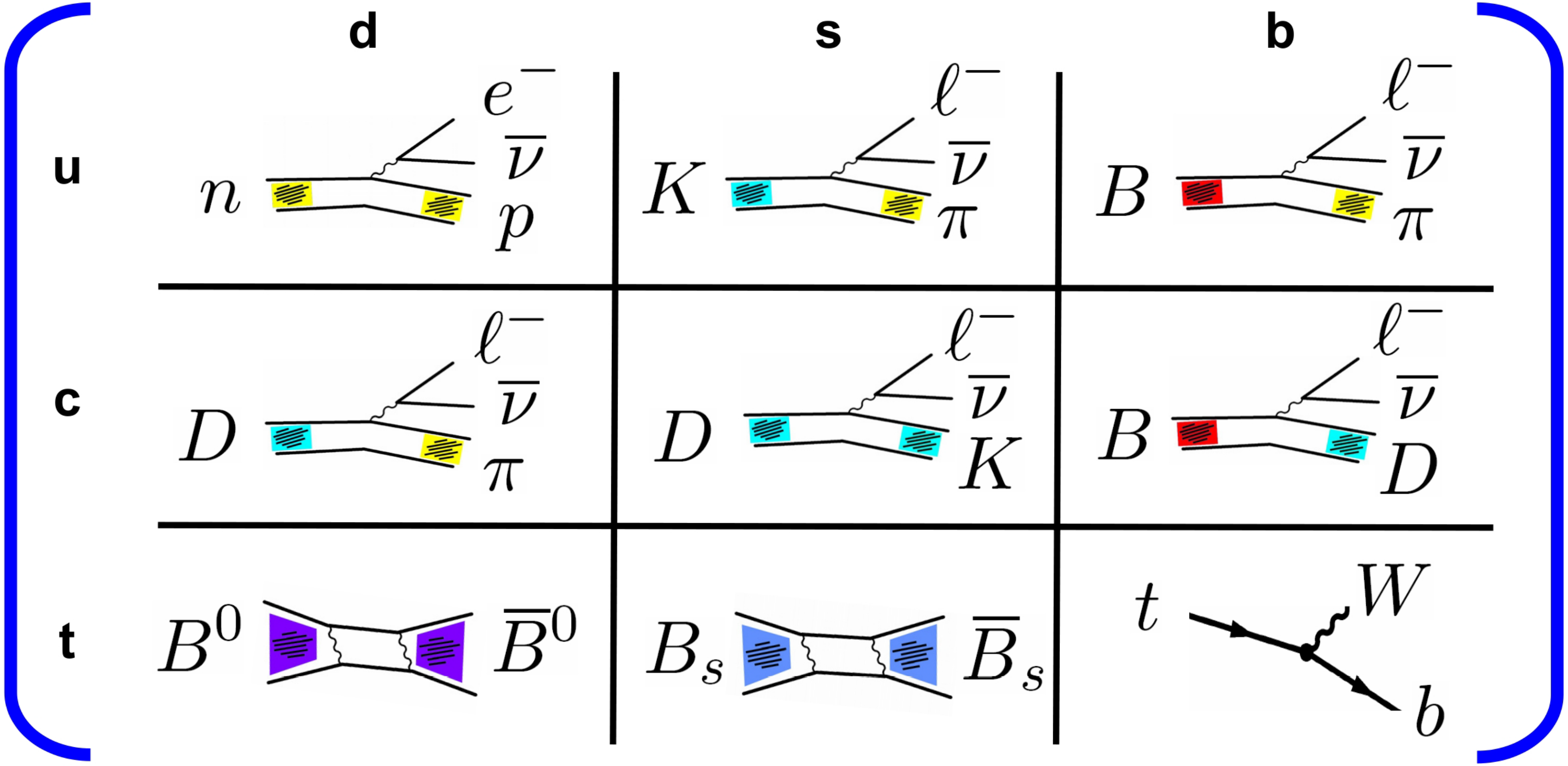
$$\left.\begin{aligned} \alpha &= \arg\left(-\frac{V_{td}V^*_{tb}}{V_{ud}V^*_{ub}}\right) \\ \beta &= \arg\left(-\frac{V_{cd}V^*_{cb}}{V_{td}V^*_{tb}}\right) \\ \gamma &= \arg\left(-\frac{V_{ud}V^*_{ub}}{V_{cd}V^*_{cb}}\right) \end{aligned}\right\} \text{observables}$$

Goal of unitarity triangle tests

- Over-constrain the triangle by making measurements of all parameters
- Comparing those in tree-level processes (pure SM) and those in loops (sensitive to New Physics)
- Inconsistencies can help us pin-point the flavour structure of New Physics

CKM matrix

V =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$\overline{B}_s$
t
W
b

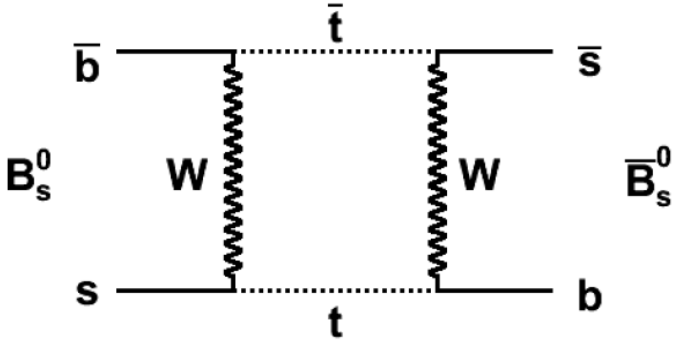
Phenomenology of neutral meson mixing and oscillation

- Pseudoscalar mesons $P^0, \bar{P}^0$ $(P = K, D, B, B_s)$ with well-defined flavour quantum numbers
- Within QCD and QED they are stable and do not mix with their antiparticle
- The weak interaction does not respect these flavour symmetries and thus P^0 and $\bar{P}^0$decay
- These states are neutral under the unbroken symmetries of the SM $\Longrightarrow$ weak interaction leads to mixing
- Mixing is generated by $P \leftrightarrow \bar{P}^0$ transition amplitudes
- The mixing lifts the degeneracy between the masses m_P and $m_{\bar{P}}$ resulting in two physical (mass) eigenstates that are superpositions of P^0 and $\bar{P}^0$
    - Different masses $\Delta m = m_P - m_{\bar{\bar{P}}} \neq 0$
    - Different widths $\Delta\Gamma \neq 0$

Flavour mixing

- Mixing occurs in all neutral meson systems and is physically caused by

off-shell
short-range
(box diagrams)



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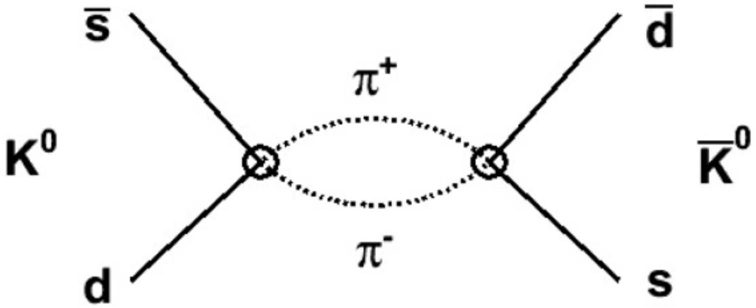


on-shell
long-range
(common intermediate
states)

- Physical states (mass eigenstates) are a superposition of flavour eigenstates

physical eigenstates

$$|P_{L,H}\rangle = p|P^0\rangle \pm q|\bar{P}^0\rangle,$$

complex

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

mass difference

$$\Delta m \equiv m_H - m_L$$

width difference

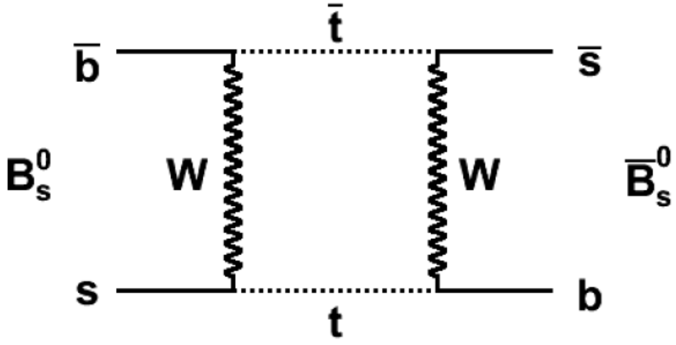
$$\Delta\Gamma \equiv \Gamma_H - \Gamma_L$$

- *If CP is conserved* ***mass eigenstates = CP eigenstates*** (*i.e.* $|p/q| = 1$)
- Known to be the case for the kaon system, where $\epsilon_K = \frac{p-q}{p+q} \approx 2\times10^{-3}$
  - SM calculations indicate small, but finite, breaking in the other systems too

Flavour oscillation

- Mixing occurs in all neutral meson systems and is physically caused by

off-shell
short-range
(box diagrams)



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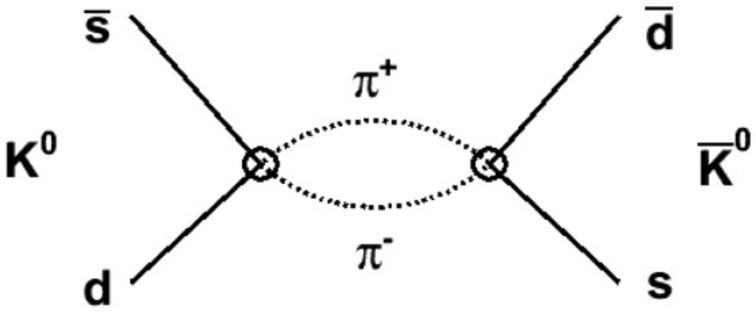

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mass difference

$$\Delta m \equiv m_H - m_L$$

width difference

$$\Delta\Gamma \equiv \Gamma_H - \Gamma_L$$

- Mixing leads to an **oscillation probability** to observe a meson in either flavour eigenstate
- *Example:* if at $t = 0$ we have B^0 then at a later time t we have

Probability to decay as $\frac{B^0}{B^0} \propto e^{-\Gamma_d t}[1 \pm \cos(\Delta m_d\, t)]$

We can measure both time-integrated and time dependent CP violation effects

Flavour oscillation parameters

$$x \equiv \frac{\Delta m}{\Gamma}, \qquad y \equiv \frac{\Delta\Gamma}{2\Gamma}, \qquad \Delta m \equiv m_H - m_L, \qquad \Delta\Gamma \equiv \Gamma_H - \Gamma_L$$

$$\mathcal{P}(t) \propto [\cosh(y\Gamma t) \pm \cos(x\Gamma t)]$$

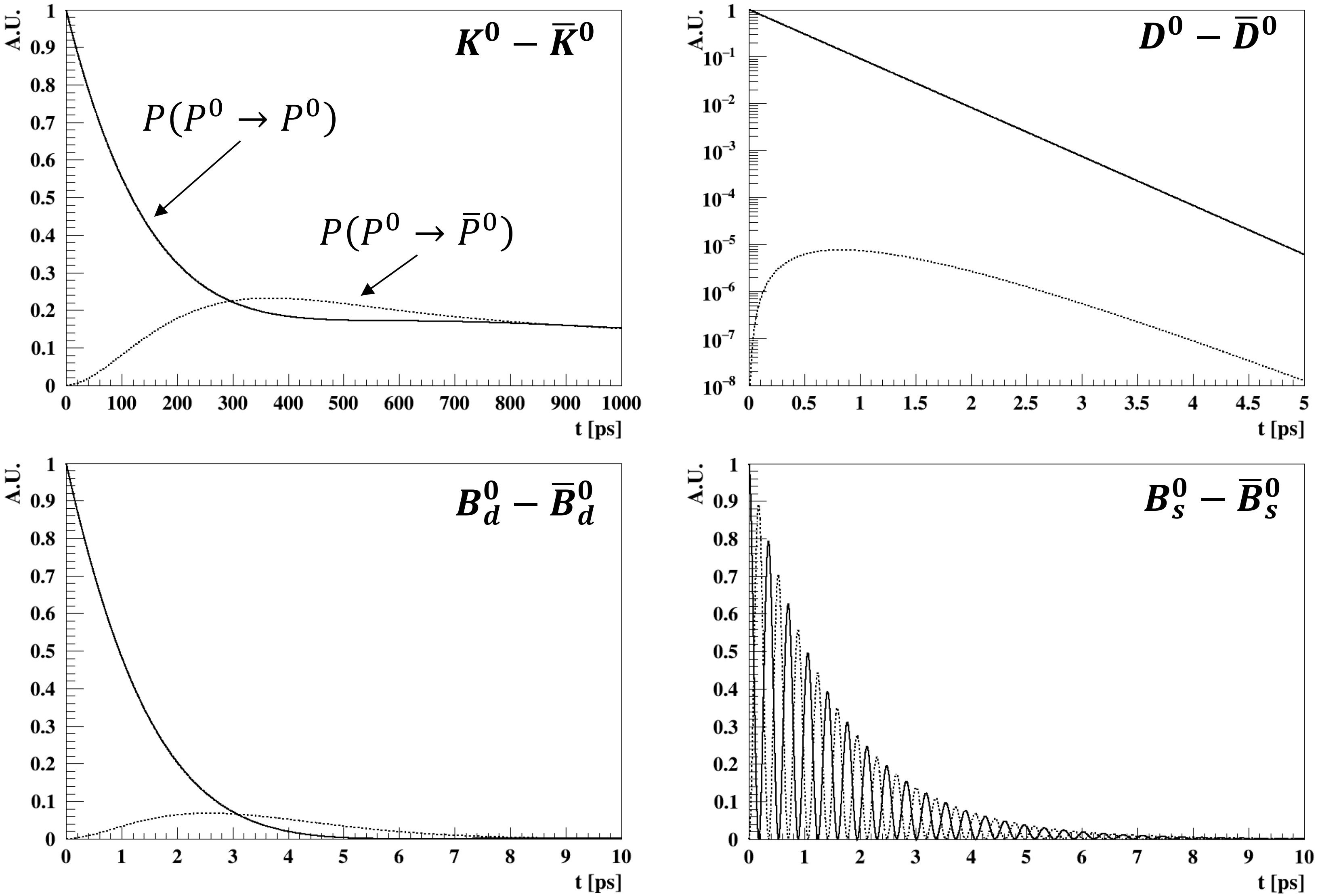
	$\Delta m\ [s^{-1}]$	$\Gamma\ [s^{-1}]$	$\Delta\Gamma\ [s^{-1}]$	x	y
$\boldsymbol{K^0 - \bar{K}^0}$	0.53×10^{10}	0.6×10^{10}	-1.1×10^{10}	~0.9	~-1
$\boldsymbol{D^0 - \bar{D}^0}$	$\sim0.01\times10^{12}$	$\sim2.4\times10^{12}$	3.4×10^{10}	~0.004	~0.007
$\boldsymbol{B_d^0 - \bar{B}_d^0}$	0.51×10^{12}	$\sim0.67\times10^{12}$	~0	~0.77	~0
$\boldsymbol{B_s^0 - \bar{B}_s^0}$	17.7×10^{12}	$\sim0.66\times10^{12}$	9.0×10^{10}	~27	~0.06

- Wide range in the sizes of the mixing parameters across the four neutral meson systems
  - significant practical consequences for measurements
- Size of mixing effects are highly sensitive to SM parameters (CKM elements, GIM mechanism, quark masses …)
- Due to its suppressed nature mixing can be used to set severe bounds ($\sim10^3$ TeV) on most general New Physics scenarios

Flavour oscillation

- Wide range of experimental sensitivities required to observe meson oscillations

- Meson time evolution depends also on CP – violation in mixing ($q/p \neq 1$)



CP violation

- *CP* asymmetries arise when two processes related by *CP* conjugation differ in their rates
- *CP* violation is related to a phase in the Lagrangian ⟹ all *CP* asymmetries must arise from interference effects

$$x \equiv \frac{\Delta m}{\Gamma}, \qquad y \equiv \frac{\Delta\Gamma}{2\Gamma}, \qquad \lambda_f \equiv \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

A_f: $P^0 \to f$ amplitude

$\bar{A}_{\bar{f}}$: $\bar{P}^0 \to \bar{f}$ amplitude of the *CP*-conjugated process

- Full time evolution formula

$$2\hat{\Gamma}[P^0(t) \to f] = \left(1 + \left|\lambda_f\right|^2\right)\cosh(y\Gamma t) \; + \left(1 - \left|\lambda_f\right|^2\right)\cos(x\Gamma t) \; + 2\mathcal{Re}\left(\lambda_f\right)\sinh(y\Gamma t) \; - 2\mathcal{Im}\left(\lambda_f\right)\sin(x\Gamma t)$$

$$2\hat{\Gamma}[\bar{P}^0(t) \to f] = \left(1 + \left|\lambda_f\right|^{-2}\right)\cosh(y\Gamma t) + \left(1 - \left|\lambda_f\right|^{-2}\right)\cos(x\Gamma t) + 2\mathcal{Re}\left(\lambda_f^{-1}\right)\sinh(y\Gamma t) - 2\mathcal{Im}\left(\lambda_f^{-1}\right)\sin(x\Gamma t)$$

CP violation: amplitudes

- It’s useful to factorise an amplitude in three parts
  - magnitude a_i
  - weak phase ϕ_i
  - strong phase δ_i
- If there are two such contributions to an amplitude we can write

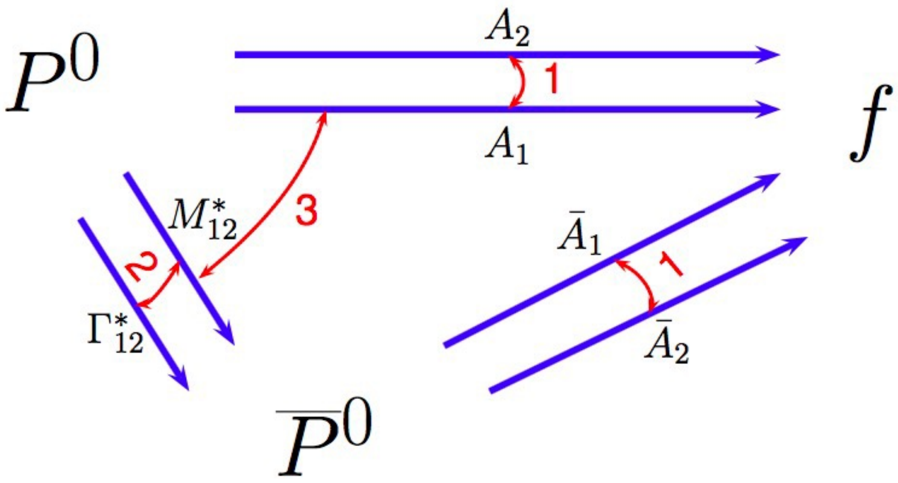
$$A_f = a_1 e^{i(\delta_1+\phi_1)} + a_2 e^{i(\delta_2+\phi_2)} \qquad \bar{A}_{\bar{f}} = a_1 e^{i(\delta_1-\phi_1)} + a_2 e^{i(\delta_2-\phi_2)}$$

- We always choose $a_1 > a_2$

$$r_f = \frac{a_2}{a_1}, \qquad \phi_f = \phi_2 - \phi_1, \qquad \delta_f = \delta_2 - \delta_1$$

Types of *CP* violation

- Each phase is convention-dependent but ϕ_f, δ_f are physical
- Phenomenology of *CP* violation is very rich in neutral meson decays: mixing can contribute to the interference
- Three types of *CP* violation mechanisms depending on which amplitudes interfere
  - *In decay:* interference between two decay amplitudes
  - *In mixing:* interference between absorbtive (on-shell intermediate states) and dispersive (off-shell intermediate state) mixing amplitudes
  - *In interference between decays with and without mixing:* interference between direct decay and first-mix-then-decay amplitude



CP violation in decay

$$\frac{|A_f|}{|\bar{A}_{\bar{f}}|} \neq 1$$

- In charged particle decays this is the only possible contribution to the *CP* asymmetry:

$$\mathcal{A}_f \equiv \frac{\Gamma(B^- \to f^-) - \Gamma(B^+ \to f^+)}{\Gamma(B^- \to f^-) + \Gamma(B^+ \to f^+)} = \frac{\left|\bar{A}_{f^-}/A_{f^+}\right|^2 - 1}{\left|\bar{A}_{f^-}/A_{f^+}\right|^2 + 1}$$

- Using the equation from slide 19 we obtain for $r_f \ll 1$

$$\mathcal{A}_f = 2r_f \sin\phi_f \sin\delta_f$$

- We need two decay amplitudes $(r_f \neq 0)$ with different weak phases $(\phi_f \neq 0, \pi)$ and strong phases $(\delta_f \neq 0, \pi)$

CP violation in decay: comments

$$\mathcal{A}_f = 2r_f \sin\phi_f \sin\delta_f$$

- To have large *CP* asymmetry we need each of the three factors not to be small
- Similar expression holds for the contribution of *CP* violation in decay in neutral mesons decays but with additional contributions from mixing
- Another complication in neutral meson decays is that it is not always possible to tell the flavour of the decaying meson (e.g. if it's a B^0 or $\bar{B}^0$) which can be a problem or an advantage
- In general, strong phase is not calculable since it is related to QCD
    - not a problem if the aim is to demonstrate *CP* violation
    - problem if we want to extract the weak phase ϕ_f
    - in some cases, the strong phase can be measured experimentally, eliminating the source of theoretical uncertainty

CP violation in mixing

$$\left|\frac{q}{p}\right| \neq 1$$

- In decays of neutral mesons into favour-specific final states ($\bar{A}_f = 0$, and consequently $\lambda_f = 0$)
- In semileptonic neutral meson decays, this is the only source of *CP* violation

$$\mathcal{A}_{\mathrm{SL}}(t) \equiv \frac{\hat{\Gamma}\left(\overline{B}^0(t) \to l^+X\right) - \hat{\Gamma}\left(B^0(t) \to l^-X\right)}{\hat{\Gamma}\left(\overline{B}^0(t) \to l^+X\right) + \hat{\Gamma}\left(B^0(t) \to l^-X\right)} = \frac{1 - |q/p|^4}{1 + |q/p|^4}$$

- The $\mathcal{A}_{\mathrm{SL}}(t)$ quantity which is an asymmetry of time-dependent decay rates, is actually time-independent
- The extraction of the value of the *CP* violating phase from a measurement of $\mathcal{A}_{\mathrm{SL}}$ involves, in general, large hadronic uncertainties
- Differences between the manifestation of CP violation in the different systems (different dependence on q/p)

CP violation in interference of decays with and without mixing

$$\mathcal{Im}(\lambda_f) \neq 0$$

- *CP* asymmetry in decays into final *CP* eigenstates
- Situation relevant in many cases is when one can neglect the effects of *CP* violation in decay and in mixing

$$\left|\bar{A}_{f_{CP}}/A_{f_{CP}}\right| \approx 1 \qquad |q/p| \approx 1 \qquad \left|\lambda_{f_{CP}}\right| = 1$$

- If we consider in addition, the case where we can neglect y ($y \ll 1$) then

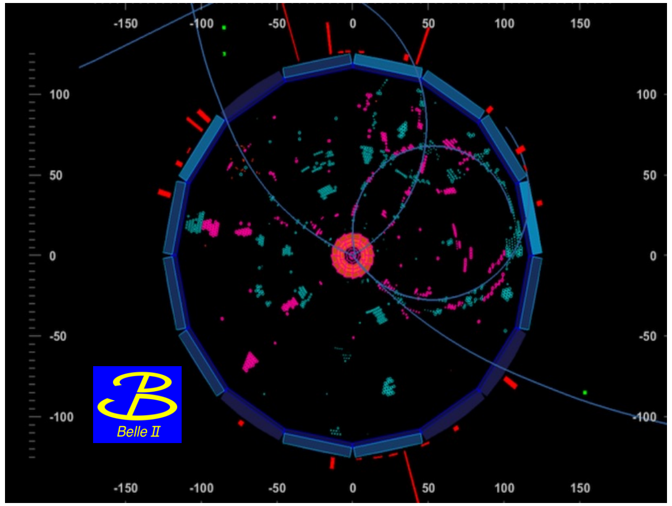
$$\mathcal{A}_{f_{CP}}(t) \equiv \frac{\Gamma\left(\overline{B}^0(t) \to f_{CP}\right) - \Gamma\left(B^0(t) \to f_{CP}\right)}{\Gamma\left(\overline{B}^0(t) \to f_{CP}\right) + \Gamma\left(B^0(t) \to f_{CP}\right)} = \mathcal{Im}\left(\lambda_{f_{CP}}\right)\sin(\Delta m_B t)$$

- Measurement of a *CP* asymmetry in a process where these approximations are valid provides a direct probe of the weak phase between the mixing amplitude and the decay amplitude (kaon physics)

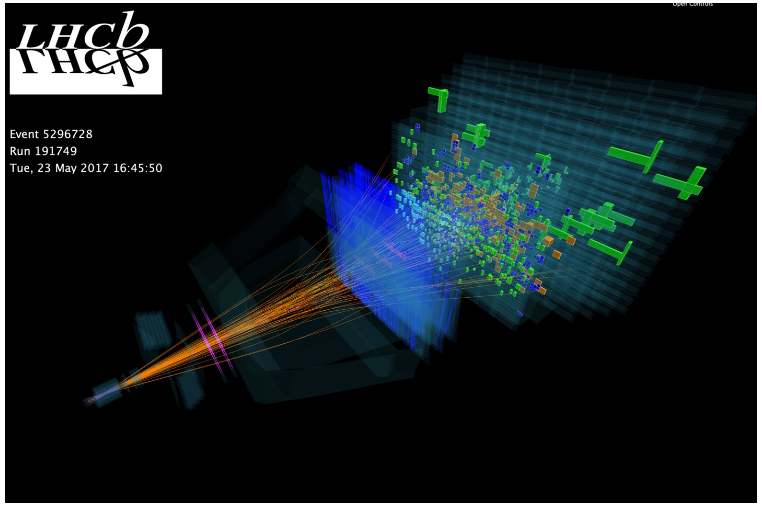
How?

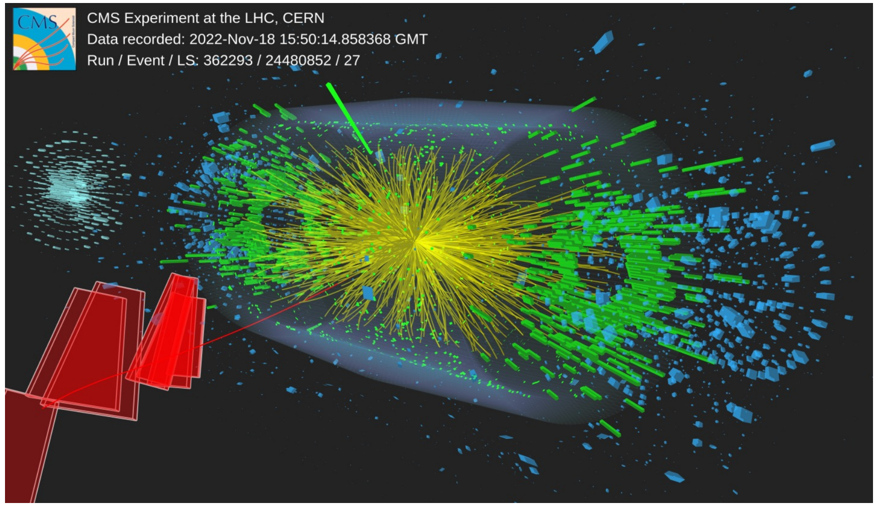
Flavour physics at different machines

B-factory



LHC





- Flavour physics requires precise measurements of delicate and rare processes: choice of environment matters!
- The event complexity has important experimental consequences
  - (Initial) background much higher at a hadron machine, particularly for studies with neutral particles
  - hadron machines pose a much more severe trigger challenge
  - Coherent production (B-factories) is valuable for flavour tagging

Heavy meson production

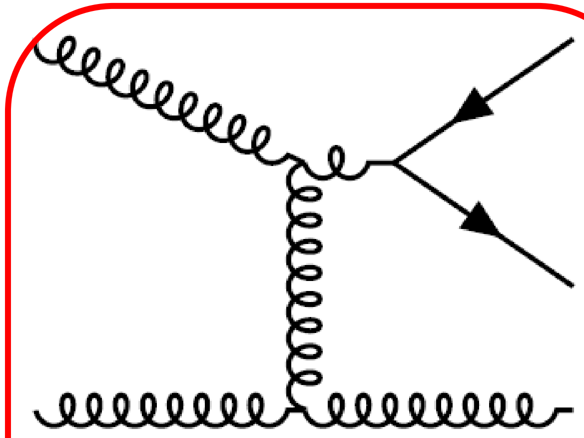
- electron – positron: $\boldsymbol{P\bar{P}}$ **pair** → strong (QCD) or EW-NC (γ/Z) processes [flavour conserving]
- proton – (anti)proton: $\boldsymbol{P\bar{P}}$ **pair** → strong (QCD) processes [flavour conserving]

  $\boldsymbol{P\bar{P}}$ **pair** or **single** $\boldsymbol{P}$ → EW processes (via $Z, W, t \to Wb$)
- heavier hadron decays $\boldsymbol{P\bar{P}}$ **pair** or **single** $\boldsymbol{P}$ → EW processes ($B \to D, K; D \to K; J/\psi \to D, K; \dots$)
- Mesons often products of "free" quark hadronization (jets)

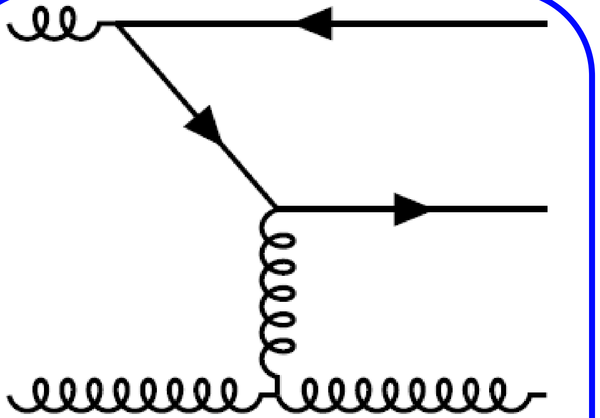
$\boldsymbol{B}$	$\boldsymbol{D}$	$\boldsymbol{K}$
$e^+e^- \to \Upsilon(4S) \to B\bar{B}$	$e^+e^- \to \psi(3770) \to D\bar{D}$	$e^+e^- \to \phi(1020) \to K\bar{K}$
$e^+e^- \to b\bar{b}$ (continuum)	$e^+e^- \to q\bar{q}(c, b)$ (continuum)	$e^+e^- \to q\bar{q}(c, b, s)$ (continuum)
$e^+e^- \to Z \to b\bar{b}$	$e^+e^- \to Z \to q\bar{q}(q = c, b)$	$e^+e^- \to Z \to q\bar{q}(q = c, b, s)$
$pp(\bar{p}) \to b\bar{b}X$	$pp(\bar{p}) \to q\bar{q}X(q = c, b)$	$pp(\bar{p}) \to q\bar{q}X(q = c, b, s)$
	Decay of B or $b\bar{b}$ resonances	Decay of B, D or $b\bar{b}, c\bar{c}$ resonances

Heavy flavour production in pp collisions

Main heavy quark production diagrams in hadronic collisions

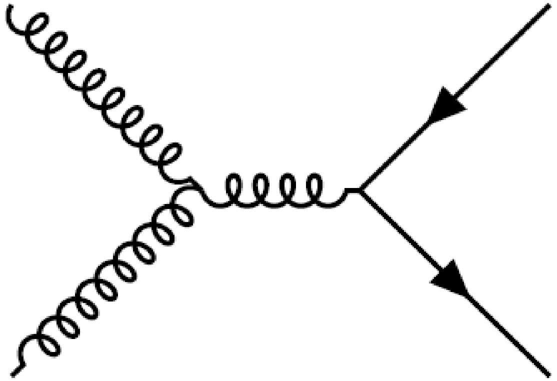


(a) Gluon Splitting

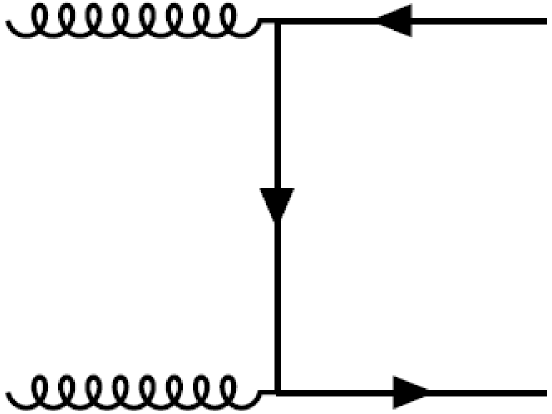


(b) Flavor Excitation

Sub-leading order heavy quark production diagram in hadronic collisions



(c) s-channel Flavor Creation

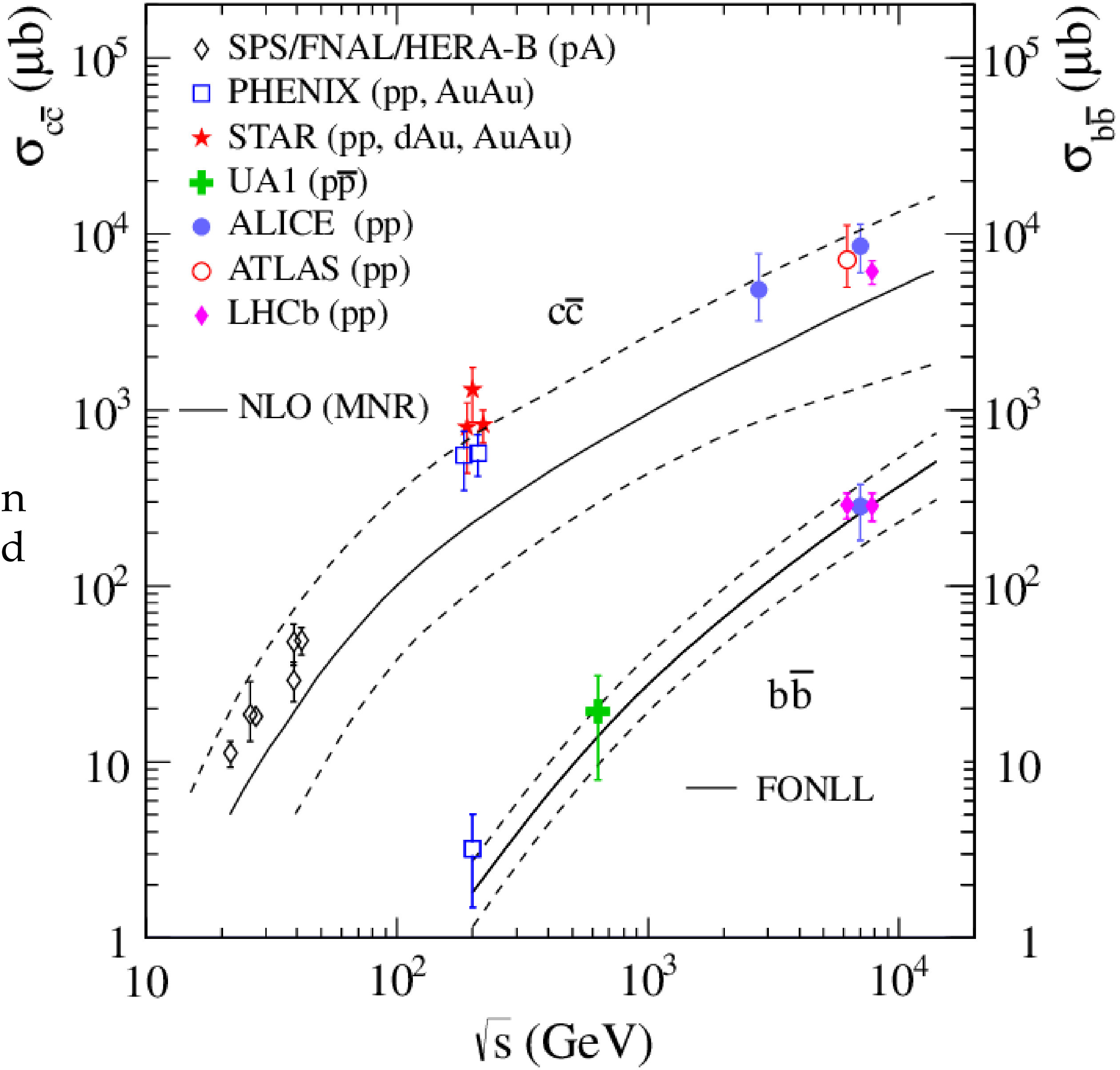


(d) t-channel Flavor Creation

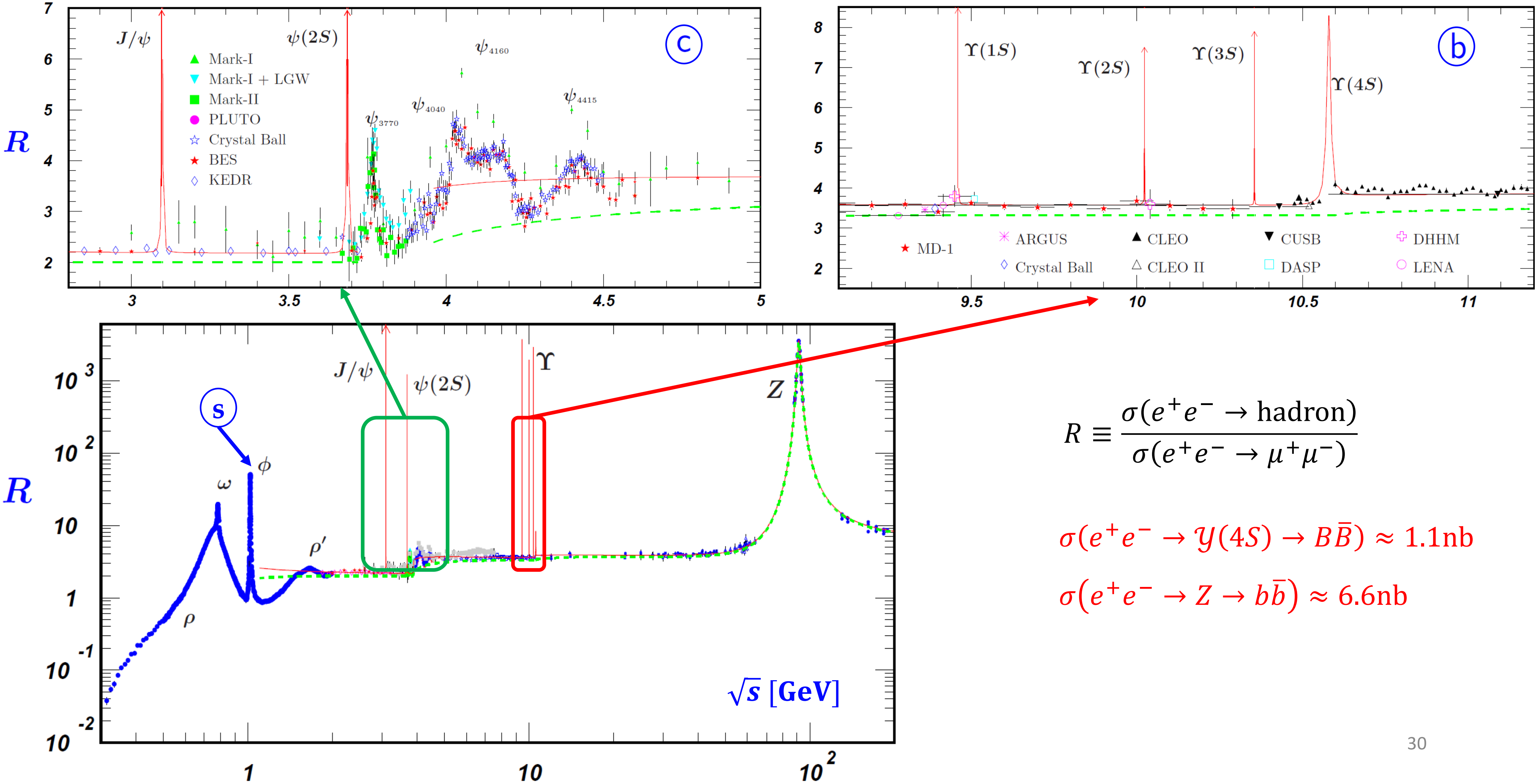
Heavy flavour production in $\boldsymbol{pp}$ collisions

$\sigma(pp \to b\bar{b}X) \sim 30 - 600\ \mu b\ @ \sqrt{s} \sim 1 - 13\ \text{TeV}$

Heavy flavour production in (anti)proton – proton collisions depends on transverse momentum and (pseudo)rapidity, according to the type of production



Meson production in e^+e^- collisions



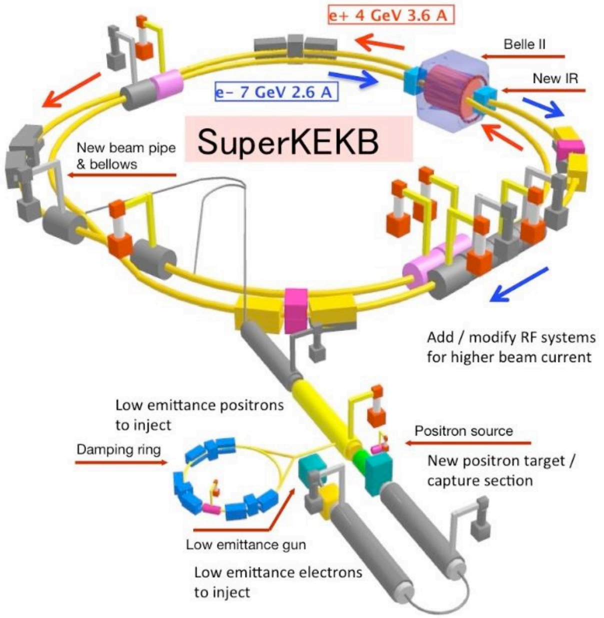
$$R \equiv \frac{\sigma(e^+e^- \to \text{hadron})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

$$\sigma(e^+e^- \to \mathcal{Y}(4S) \to B\bar{B}) \approx 1.1\text{nb}$$

$$\sigma\left(e^+e^- \to Z \to b\bar{b}\right) \approx 6.6\text{nb}$$

Flavour physics facilities

e^+e^- colliders for production at threshold



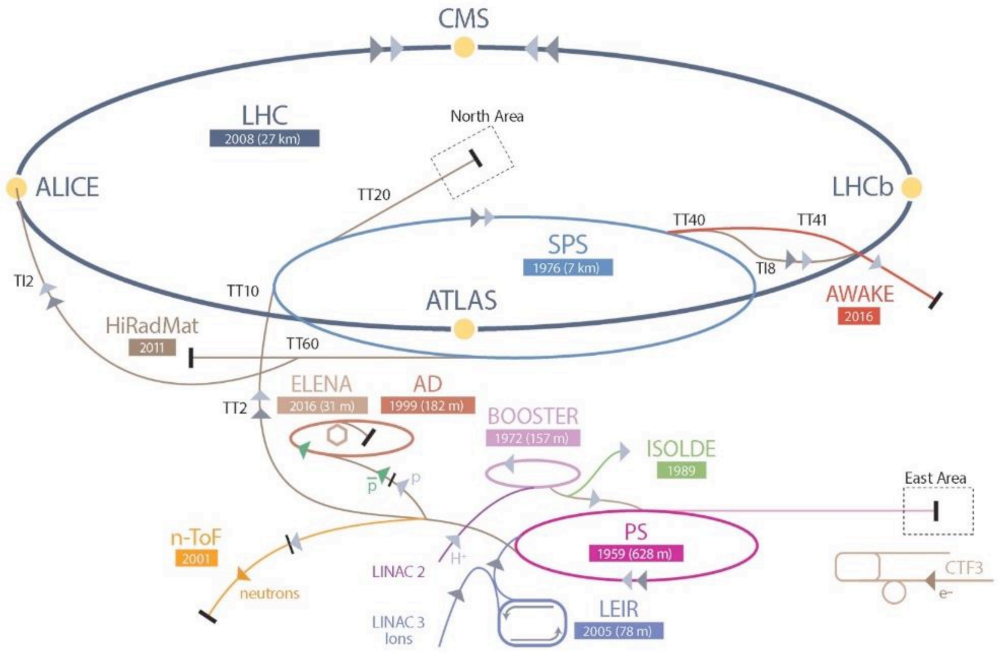
KEKB & super KEKB (Japan)

PEPII (SLAC – USA)

CESR (Cornell – USA)

…

High energy colliders



LHC (CERN)

Tevatron (Fermilab – USA)

LEP (CERN)

Flavour physics experimental principles

e^+e^- colliders for production at threshold

- Symmetric or asymmetric beams
- 4π detector configuration
- $\mathcal{O}(0.5 - 2\ \text{GeV})$ energy range of the decay products

High energy colliders

- Symmetric beams
- 4π or forward detector configuration
- $\mathcal{O}(10 - 100\ \text{GeV})$ energy range of the decay products

<u>Common features</u>

- Vertexing: reconstruct the position of the decay vertex of the flavoured mesons (when/if possible)
- Tracking: reconstruct the charged decay products of the mesons
- Particle identification (PID): identify the different types of charged decay products (e, μ, π, K, p)
- Electromagnetic calorimetry: reconstruct the neutral decay products of the mesons (photons)
- Hadronic calorimetry / “muon” detection: reconstruct the long-living penetrating particles (π, K, p, μ)

$\boldsymbol{B}$ – factories

$\mathcal{Y}(4S)$ cleanest source of $B\bar{B}$ pairs

- Only $B^0\bar{B}^0$ (50%) or $B^+\bar{B}^-$ (50%)
- B produced almost at rest and small particle multiplicity per $\mathcal{Y}(4S)$ decay
- Secondaries spread over the full solid angle: large reconstruction efficiency with barrel-like configuration
- On-resonance background from continuum: measurable from off-resonance side-bands
- Kinematic constraints: B mass resolution improves ×10 using $E^*_{beam} = \sqrt{s}/2$ instead of E^*_B

Coherent $B\bar{B}$ production (entangled state)

- Physics is sensitive to the time difference between the $B's$ when they decay

High luminosity: $\int \mathcal{L} \sim \mathcal{O}(ab^{-1})$ with peak at $\mathcal{L} = 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ [BaBar + Belle]

- Beam-induced background (synchrotron radiation, beam-beam interactions) increases detector occupancy and challenges detector technology (scales with $\mathcal{L}$)
- Cross section: $\sigma_{b\bar{b}} \sim 1.1$ nb $\Longrightarrow$ $\sim 1.1\times10^9$ $b\bar{b}$ pairs /ab^{-1}

Asymmetric $\boldsymbol{B}$ − factories

- B meson production at threshold: $e^+e^- \rightarrow \mathcal{Y}(4S) \rightarrow B\bar{B},\ m_{ee} = 10.58\ \text{GeV}$

- **Problem** with symmetric beams: $\mathcal{Y}(4S)$ at rest **not measurable**
  - B in $\mathcal{Y}(4S)$ rest frame has $p_B^* \approx 330\ \text{MeV}/c \rightarrow \Delta z^* < \beta^*\gamma^* c\tau_B \approx 30\mu\text{m}$ $\left(\beta^*\gamma^* = p_B^* c/(m_B c^2)\right)$

- **Solution:** asymmetric e^+e^- to boost $\mathcal{Y}(4S)$ in the lab frame (β, γ)

$z = \gamma(z^* + \beta c t^*) = \gamma(z^* + \beta\gamma^* c\tau_B)$

$z^* = \beta^* c \cos\theta^* \gamma^* \tau_B$ [θ^*, B emission angle in $\mathcal{Y}(4S)$ rest frame]

$z = \gamma(\beta^*\gamma^* \cos\theta^* + \beta\gamma^*)c\tau_B = \gamma\left(\alpha\cos\theta^* + \beta\sqrt{1+\alpha^2}\right)c\tau_B,\qquad \left[\alpha \equiv \beta^*\gamma^* \ll 1, \gamma^* = \sqrt{1+\alpha^2}\right]$

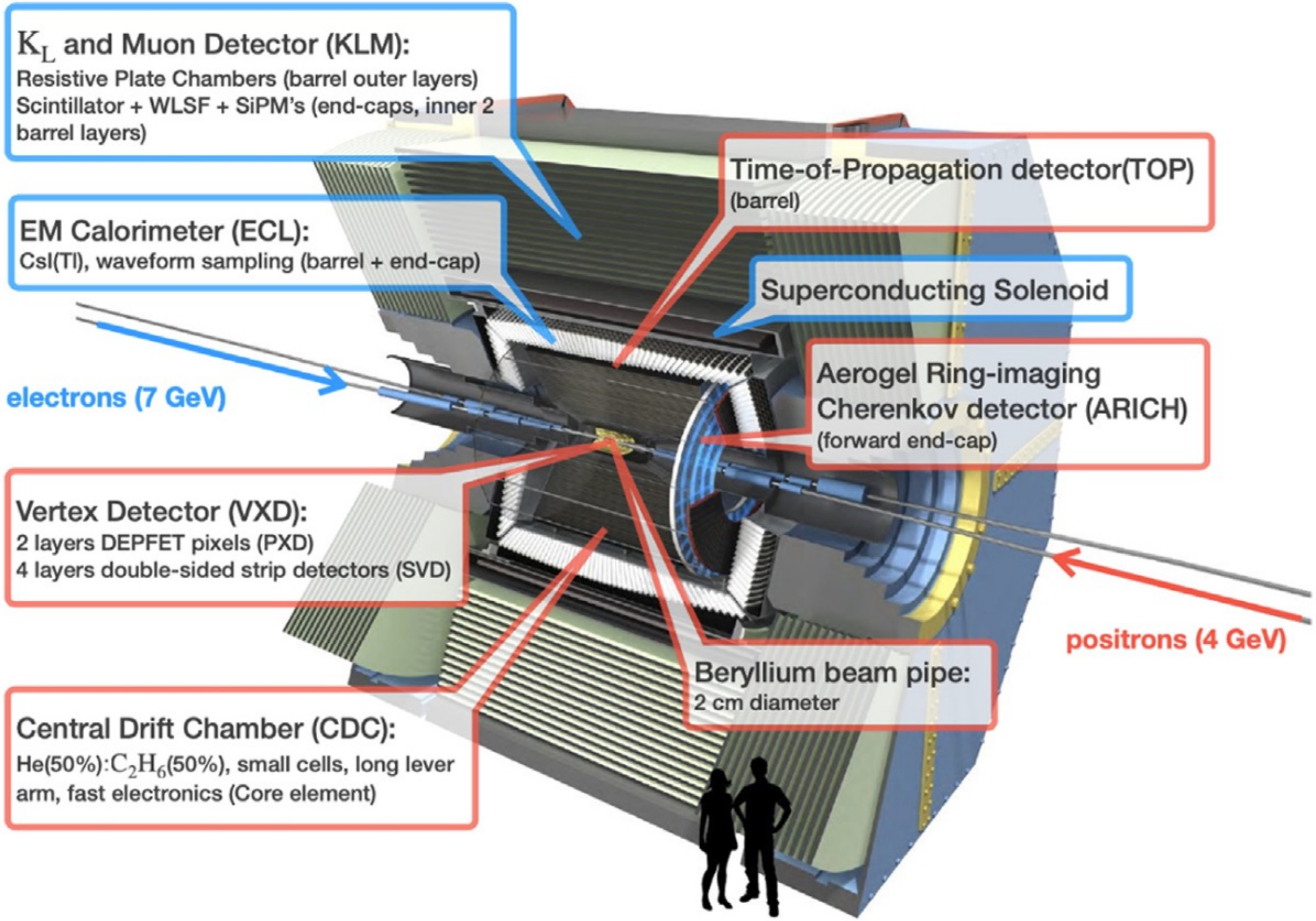
$z_1 - z_2 = \gamma\beta\sqrt{1+\alpha^2}\,c(t_1 - t_2) + \gamma\alpha\cos\theta^*\,c(t_1 + t_2)$, [1,2 denote the $B\bar{B}$ produced]

measurable

<u>**Example:**</u> $E_{e^-} = 9.1\ \text{GeV}, E_{e^+} = 3.0\ \text{GeV} \rightarrow \gamma\beta = 0.56 \Longrightarrow \boldsymbol{\Delta z \approx \gamma\beta\Delta t \approx 300\ \mu}$

Experiments at $\boldsymbol{B}$ factories: BaBar, Belle, Belle II

- BaBar (PEPII), Belle (KEKB), Belle II (superKEKB)
- *Presently running:* Belle II (goal $\int \mathcal{L} \sim \mathcal{O}(50\ ab^{-1})$ with peak at $\mathcal{L} > 10^{35}\ \text{cm}^{-2}\text{s}^{-1}$



Flavour physics at $\boldsymbol{pp}$ collider (LHC)

Large $\boldsymbol{b\bar{b}}$ and $\boldsymbol{c\bar{c}}$ cross sections

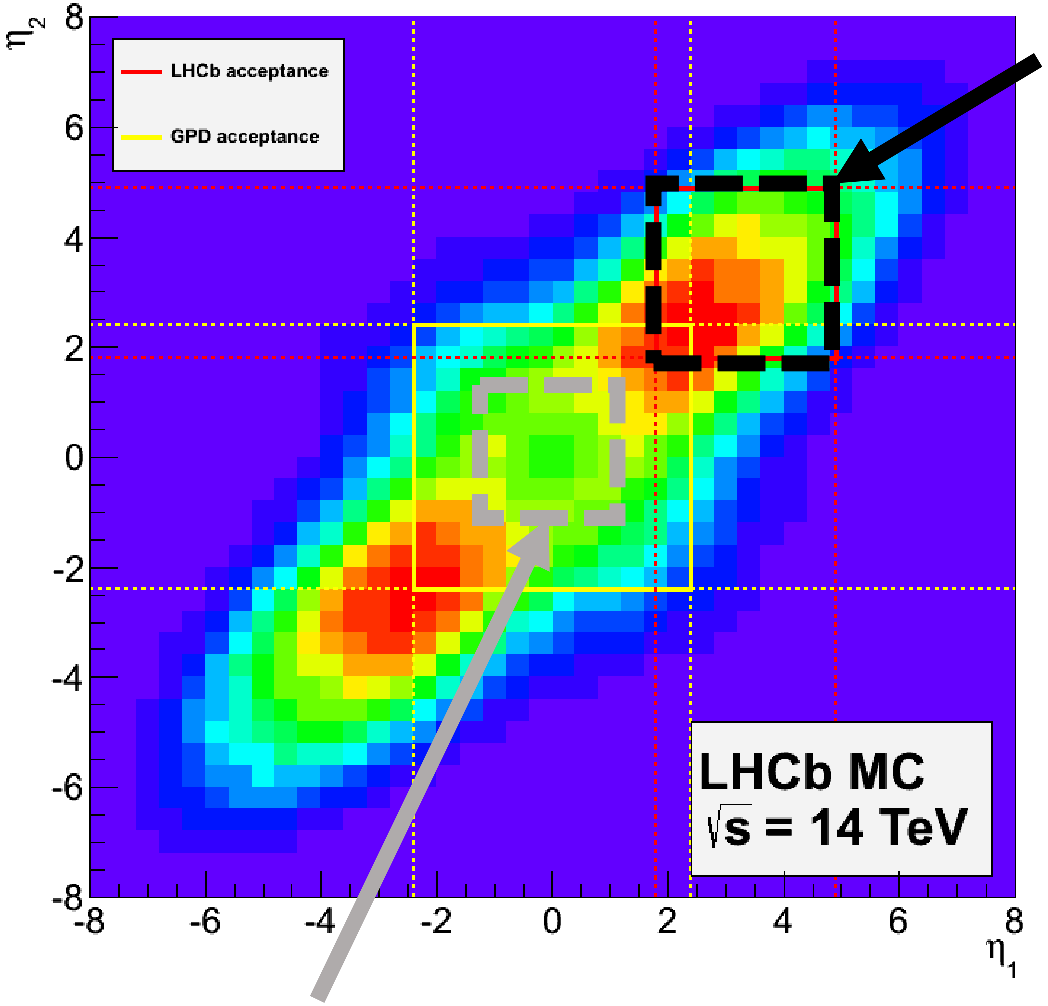
- All possible types of b, c- hadrons produced
- B, D produced with large boost in lab frame
- High energy decay products, but clean particle identification and muon reconstruction
- Relatively low detection efficiency, depending on the detector configuration
- No kinematic constraints
- $\sigma_{b\bar{b}}/\sigma_{\text{inelastic}} \sim 10^{-3}$: high particle multiplicity from QCD, requires selective triggers

Not extreme luminosity: $\int \mathcal{L} \sim \mathcal{O}(\text{fb}^{-1})$ with peak at $\mathcal{L} = 4\times10^{34}\ \text{cm}^{-2}\text{s}^{-1}$ [LHCb]

- High cross section: $\sigma_{b\bar{b}} \sim 150\ \mu\text{b}$ @ 13 TeV (LHCb detector coverage) $\Longrightarrow$ $\sim 1.5\times10^{11}\ b\bar{b}$ pairs $/\text{fb}^{-1}$
    - compare with $\sim 1.1\times10^{9}\ b\bar{b}$ pairs $/\text{ab}^{-1}$ for B factories
- Prospects for ×5 increase soon
- Radiation – resistant detector technology

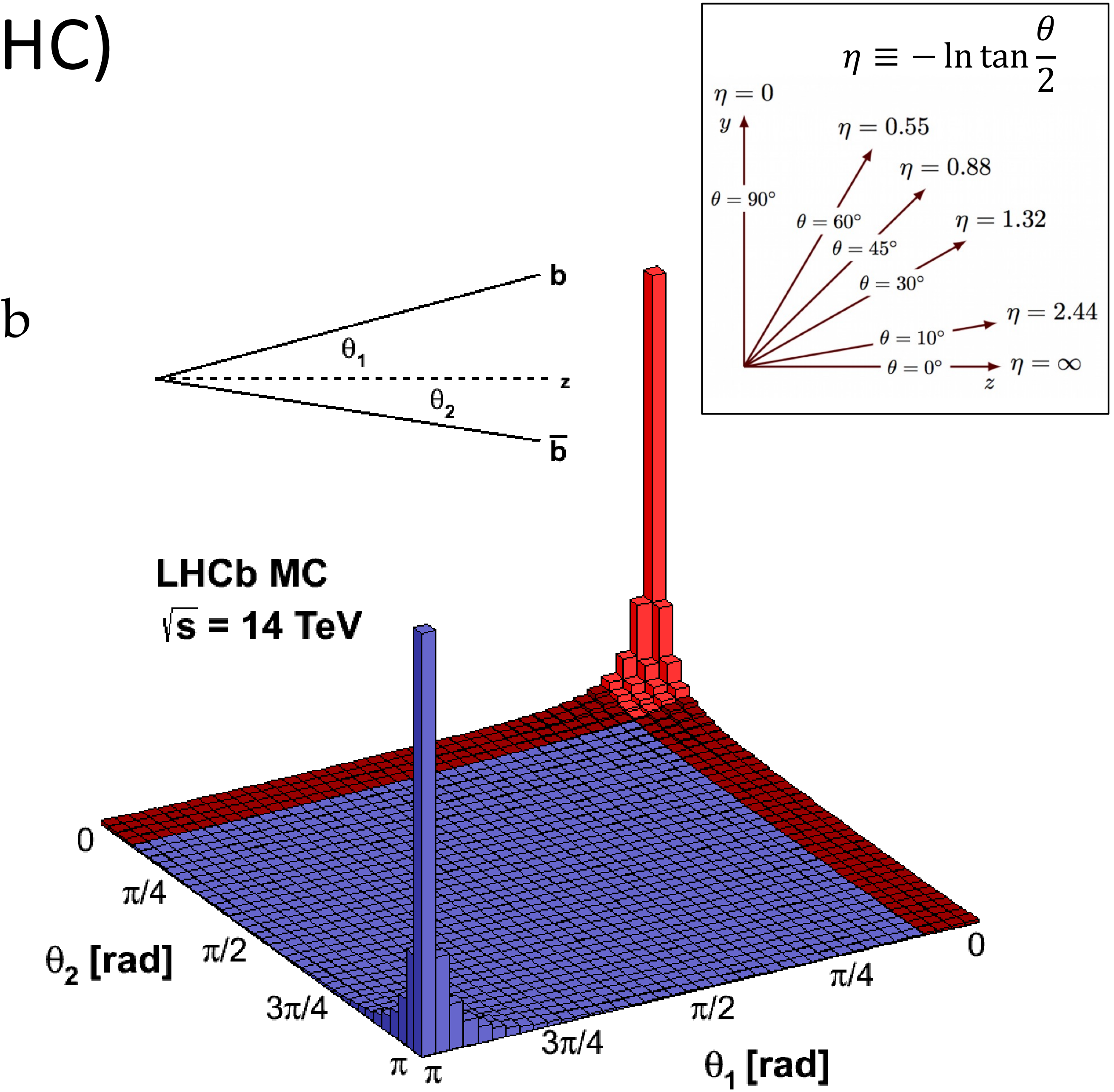
Flavour physics at pp collider (LHC)

- $\eta_{1,2}(\theta_{1,2})$ = pseudorapidity (polar angle) of the quarks



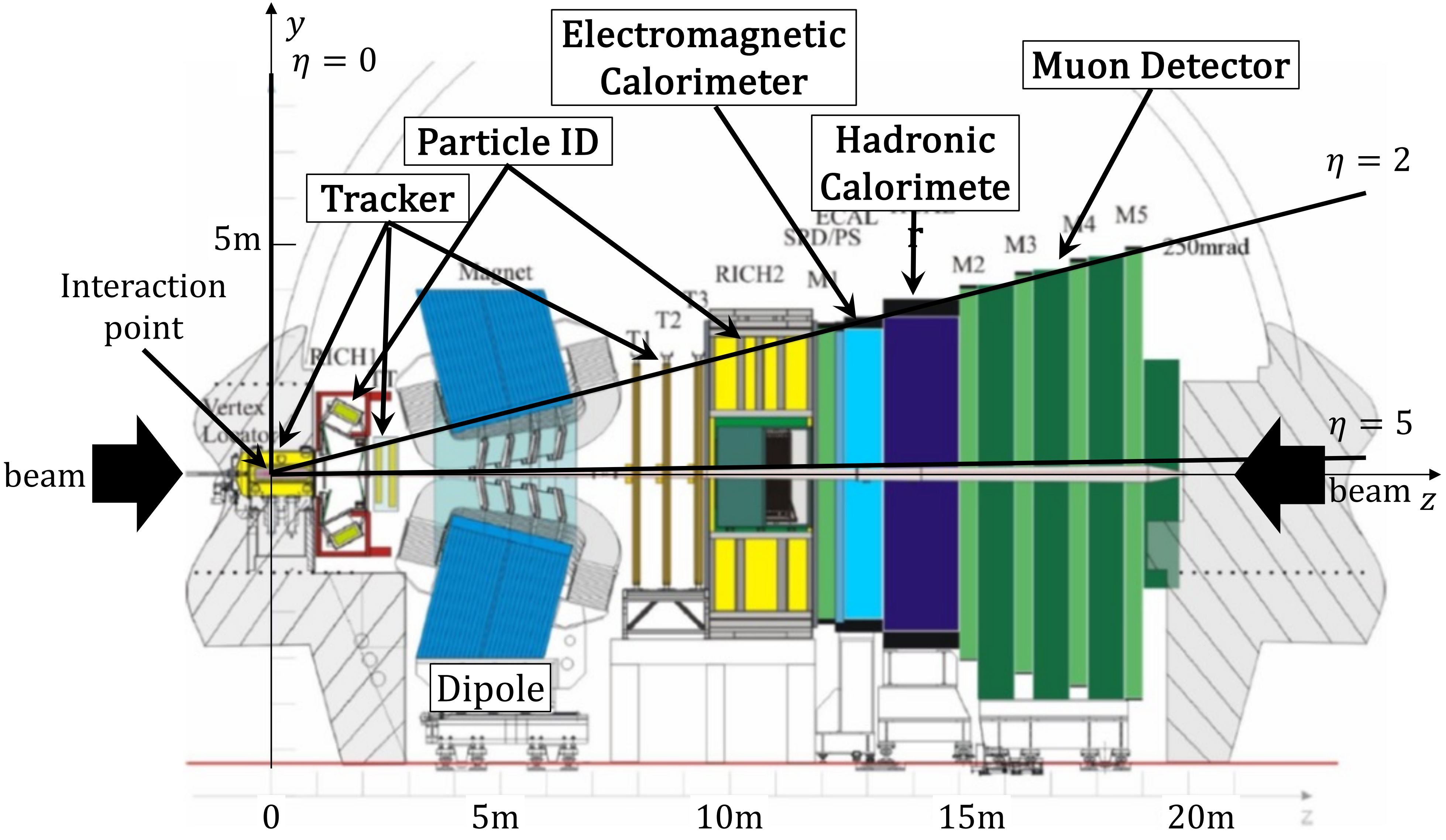
LHCb

CMS barrel



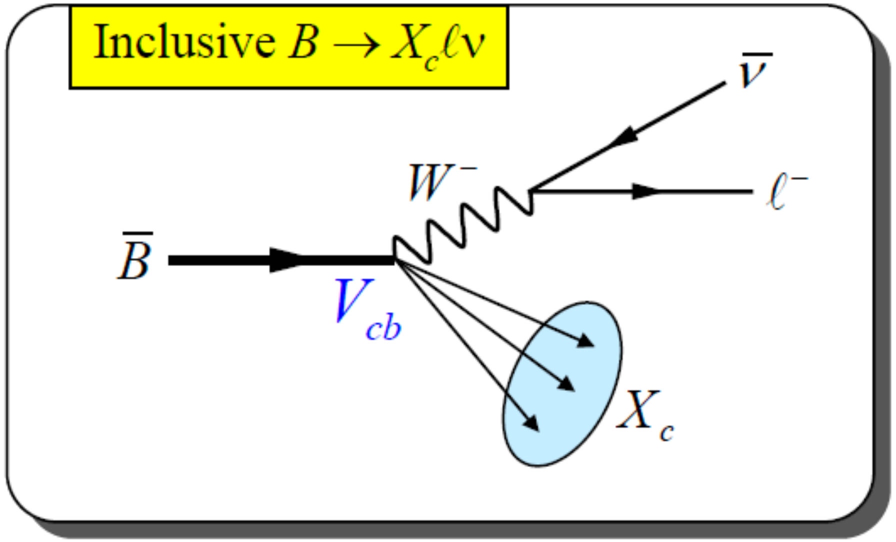
$$\eta \equiv -\ln \tan\frac{\theta}{2}$$

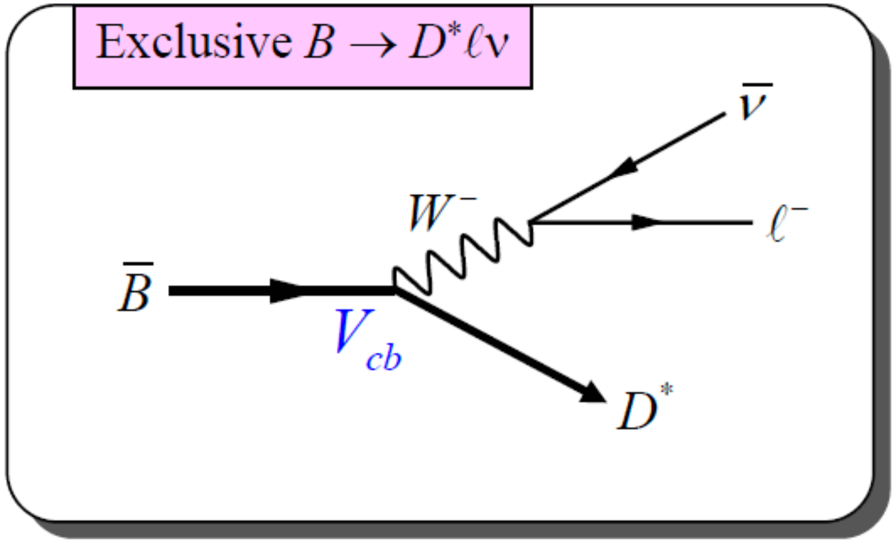
LHCb experiment

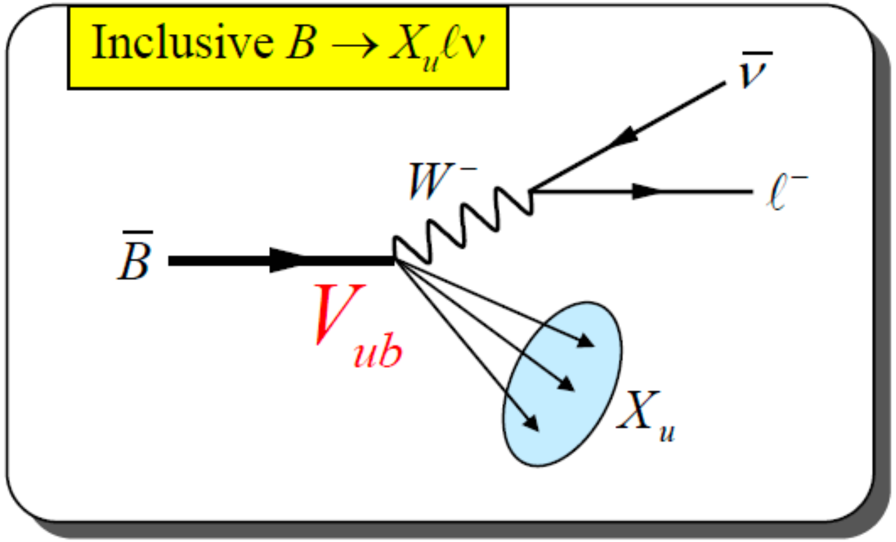


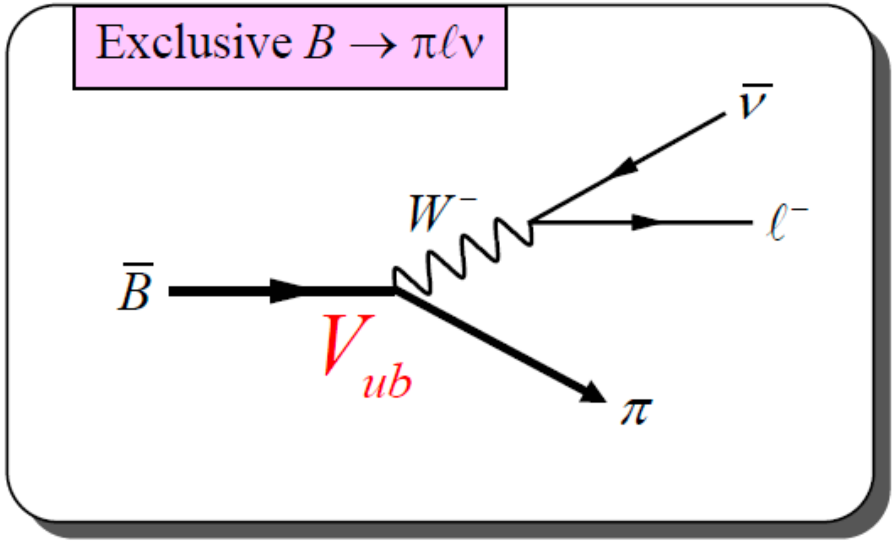
CKM measurements: semileptonic $\boldsymbol{B}$ meson decays

Inclusive vs exclusive: two different theoretical and experimental approaches


Inclusive $B \to X_c \ell \nu$

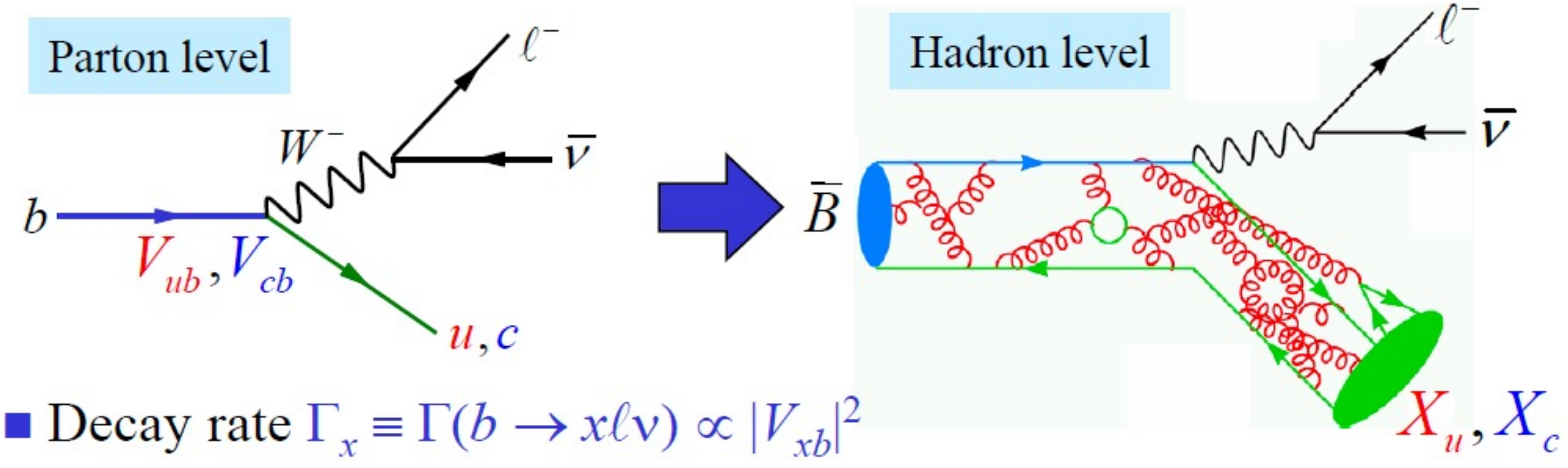

Exclusive $B \to D^* \ell \nu$


Inclusive $B \to X_u \ell \nu$


Exclusive $B \to \pi \ell \nu$

Semileptonic (tree-level) $\boldsymbol{B}$ decays

$B \to X_{u,c} l \nu$



- Decay rate $\Gamma_x \equiv \Gamma(b \to x \ell \nu) \propto |V_{xb}|^2$

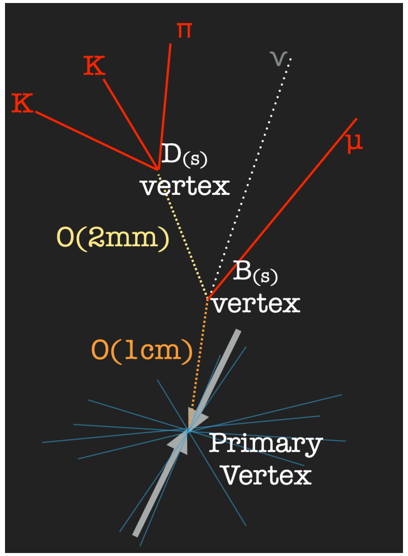
Different theoretical and experimental approaches depending on the flavour

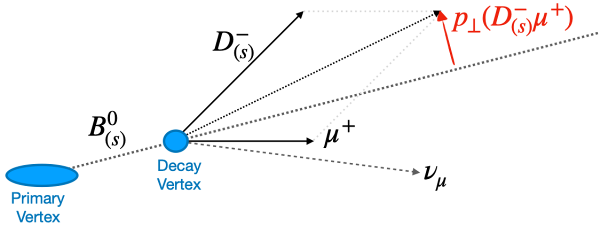
Form factors

- Encode the non-perturbative part of the hadronic matrix element (can be calculated by lattice QCD)
- We can use approximate symmetries of QCD to learn more about them and relate them to each other
- The physics intuition is that form factors arise from the overlap of the wave function of the two hadrons
  - from QM: probability of a fast transition between two states $i \to f$ depends on the overlap between their wavefunctions
- The sudden transition in semileptonic hadron decays is due to the weak interaction

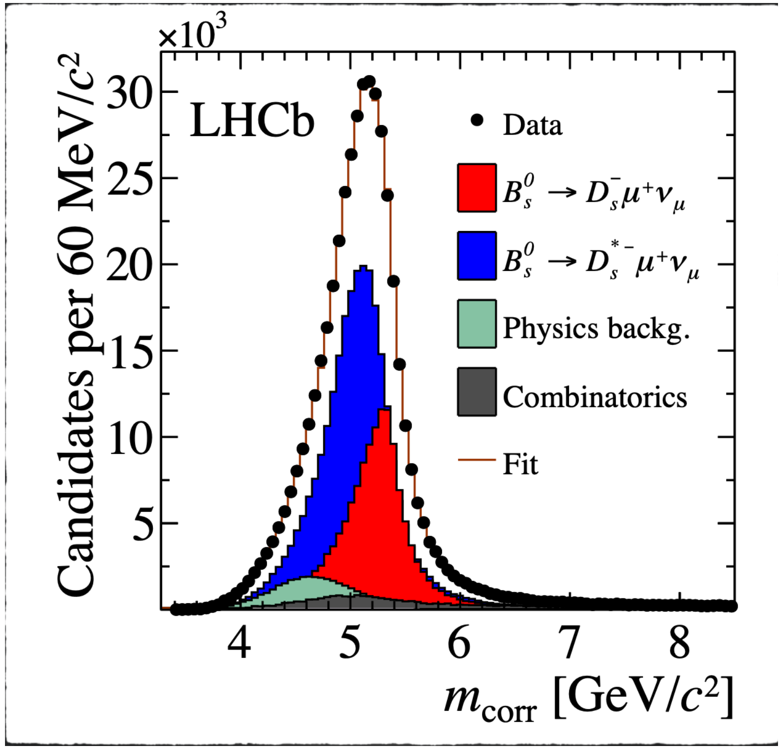
Exclusive determination of $|V_{cb}|$: $B_s \rightarrow D_s^{(*)-}\mu^+\nu_\mu$

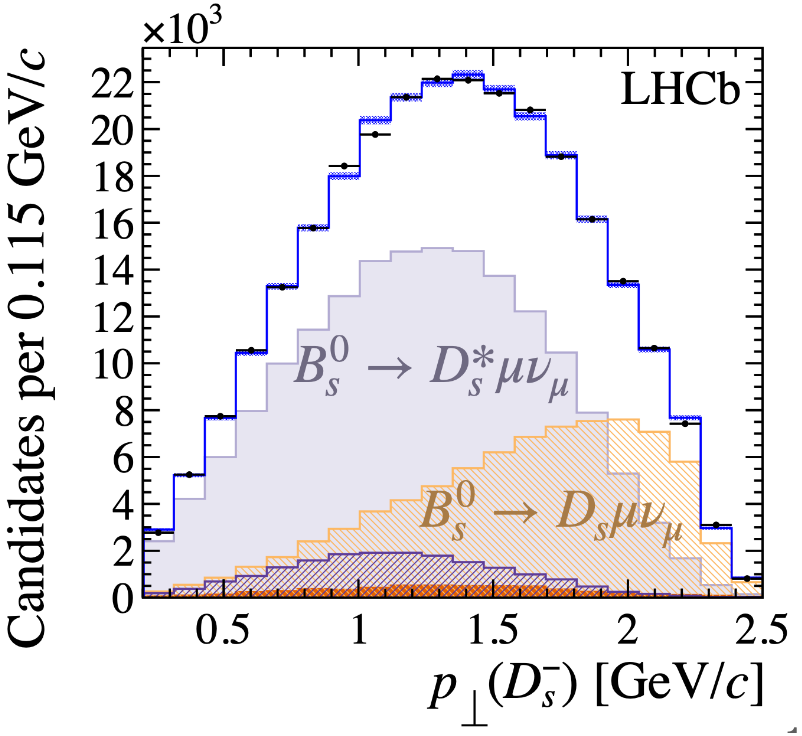
- Exclusive determination of $|V_{cb}|$ using B_s decays
  - not the most precise exclusive $|V_{cb}|$ measurement but a very nice demonstration of the techniques used at LHCb
  - $|V_{cb}|$ extraction depends on the Form Factor parametrisation (interplay with theory)





$$m_{corr} \equiv \sqrt{m^2(D_s^-\mu^+) + p_\perp^2(D_s^-\mu^+)} + p_\perp(D_s^-\mu^+)$$





$$|V_{cb}|_{\rm CLN} = (40.8 \pm 0.6({\rm stat}) \pm 0.9({\rm syst}) \pm 1.1({\rm ext})) \times 10^{-3}$$

$$|V_{cb}|_{\rm BGL} = (41.7 \pm 0.8({\rm stat}) \pm 0.9({\rm syst}) \pm 1.1({\rm ext})) \times 10^{-3}$$

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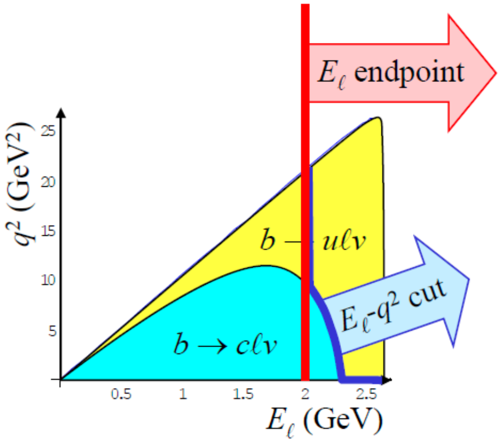
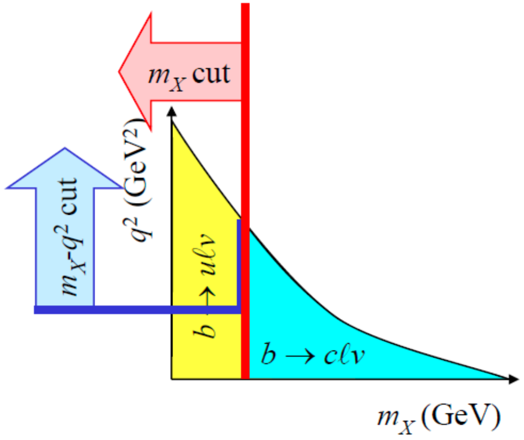
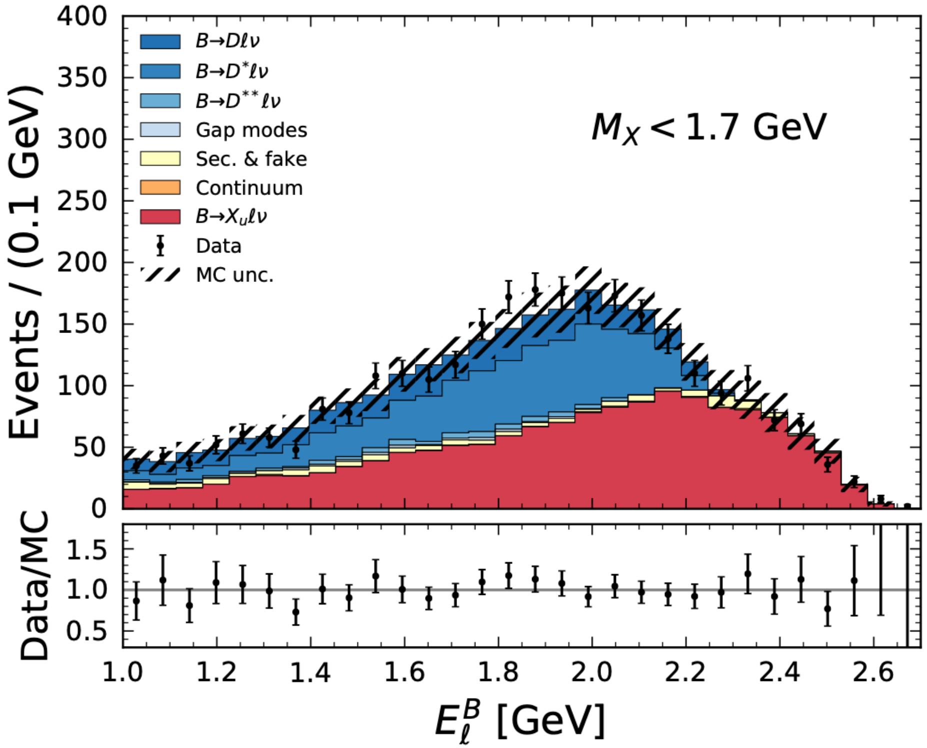
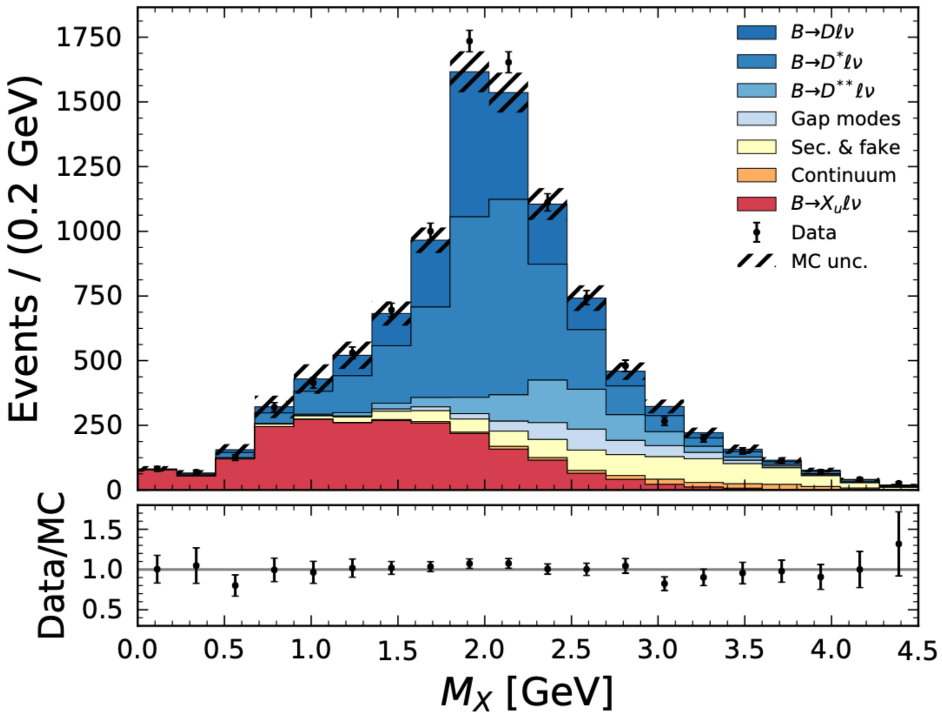
Inclusive determination of $|V_{ub}|$

- $B \to X_u l^+ \nu$: inclusive approach at Belle
- *Event selection:*
  - low statistics, large background from $B \to X_c l^+ \nu$ requires a selection of **small portions** of the phase space









$$|V_{ub}| = (4.10 \pm 0.09 \pm 0.22 \pm 0.15) \times 10^{-3}$$

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Measurement of the CKM angle $\boldsymbol{\gamma}$

- Weak phase between $b \to c$ (Cabibbo—favoured “fav”) and $b \to u$(Cabibbo – suppressed “sup”) quark transitions

$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

- **Measurement**
  - processes receiving contributions from both Cabibbo-favoured and suppressed amplitudes
  - study the interference between the two amplitudes

- **Gronau-London-Wyler method (GLW)**
  - Build observables of “fav”-”sup” amplitudes interference from the decays

    $B^+ \to \overline{D}^0 K^+ \qquad B^+ \to D^0 K^+ \qquad B^- \to \overline{D}^0 K^- \qquad B^- \to D^0 K^- \qquad B^\pm \to D_{CP} K^\pm$
  - $D^0, \overline{D}^0$ = flavour-specific D final state (e.g. (~) $D^0 \to K^-\pi^+$, $\overline{D}^0 \to K^+\pi^-$)
  - D_{CP} = CP-eigenstate D final state (e.g. $\pi^+\pi^-, K^+K^-, K_S\pi^0$, ...)

  N.B. no need to study time-dependent asymmetries (charged B mesons)

Measurement of the CKM angle γ

- Only 1 tree-level amplitude in “fav” and “sup”

  $|A_{+\bar{D}}| = |A_{-D}| \equiv |A_{fav}|$

  $|A_{+D}| = |A_{-\bar{D}}| \equiv |A_{sup}|$

- *CP* - conservation in strong/em interactions

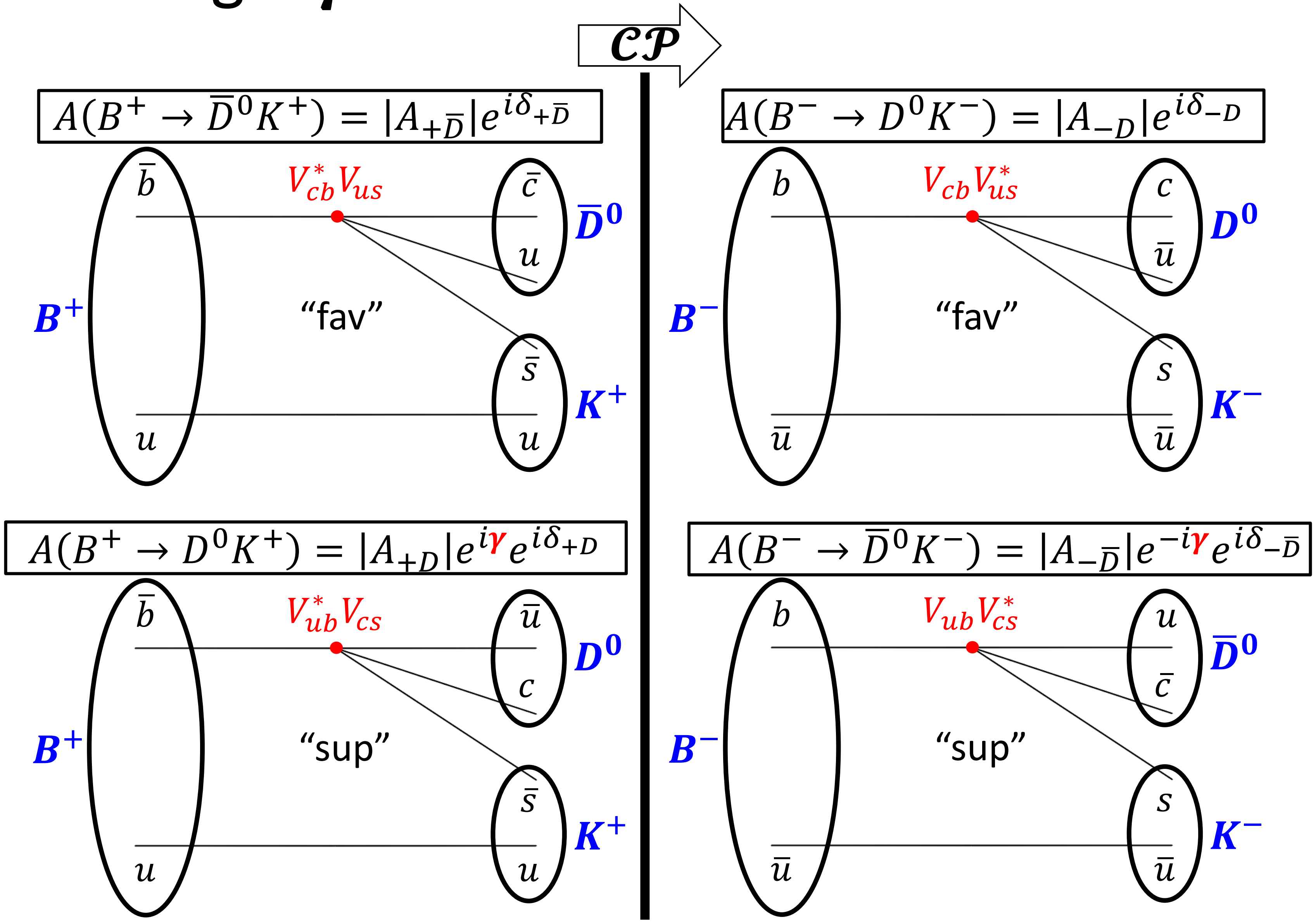
  $\delta_{+\bar{D}} = \delta_{-D} \equiv \delta_f$

  $\delta_{+D} = \delta_{-\bar{D}} \equiv \delta_s$

- Notation

  $r_B \equiv |A_{sup}|/|A_{fav}|$

  $\delta_B \equiv \delta_s - \delta_f$



$A(B^+ \to \bar{D}^0 K^+) = |A_{+\bar{D}}| e^{i\delta_{+\bar{D}}}$

$A(B^- \to D^0 K^-) = |A_{-D}| e^{i\delta_{-D}}$

$A(B^+ \to D^0 K^+) = |A_{+D}| e^{i\gamma} e^{i\delta_{+D}}$

$A(B^- \to \bar{D}^0 K^-) = |A_{-\bar{D}}| e^{-i\gamma} e^{i\delta_{-\bar{D}}}$

Measurement of the CKM angle $\boldsymbol{\gamma}$

$\boxed{\boldsymbol{B^{\pm} \to D_{CP} K^{\pm}}}$

- hyp. 1: no D^0 oscillation
- hyp. 2: no CP violation in D decay

$$A(B^+ \to D_{CP\pm} K^+) = \frac{1}{\sqrt{2}} [A(B^+ \to D^0 K^+) \pm A(B^+ \to \overline{D}^0 K^+)]$$

$$A(B^- \to D_{CP\pm} K^-) = \frac{1}{\sqrt{2}} [A(B^- \to D^0 K^-) \pm A(B^- \to \overline{D}^0 K^-)]$$

Observables

$$R_{CP\pm} \equiv 2 \frac{\Gamma(B^- \to D_{CP\pm} K^-) + \Gamma(B^+ \to D_{CP\pm} K^+)}{\Gamma(B^- \to D^0 K^-) + \Gamma(B^+ \to \overline{D}^0 K^+)} = 1 + r_B^2 \pm 2 r_B \cos \boldsymbol{\delta_B} \cos \boldsymbol{\gamma}$$

$$\mathcal{A}_{CP\pm} \equiv \frac{\Gamma(B^- \to D_{CP\pm} K^-) - \Gamma(B^+ \to D_{CP\pm} K^+)}{\Gamma(B^- \to D_{CP\pm} K^-) + \Gamma(B^+ \to D_{CP\pm} K^+)} = \frac{\pm 2 r_B \sin \boldsymbol{\delta_B} \sin \boldsymbol{\gamma}}{1 + r_B^2 \pm 2 r_B \cos \boldsymbol{\delta_B} \cos \boldsymbol{\gamma}}$$

$$r_B = \frac{\Gamma(B^- \to \overline{D}^0 K^-)}{\Gamma(B^- \to D^0 K^-)} = \frac{\Gamma(B^+ \to D^0 K^+)}{\Gamma(B^+ \to \overline{D}^0 K^+)}$$

Measurement of the CKM angle $\boldsymbol{\gamma}$

- **Gronau-London-Wyler method** (GLW)
  - Experimental difficulty due to small r_B leading to large uncertainty
  - Angular solution up to a four – fold ambiguity
  - D^0 oscillation cannot be fully neglected
- **GLW example (BaBar)**
  - Measure R_{CP+}, R_{CP-}, $\mathcal{A}_{CP+}$, $\mathcal{A}_{CP-}$
  - Extract the parameters γ,δ_B,r_B
  - Decays: $B^{\pm} \to Dh^{\pm}$ with $h = K, \pi$

D_{CP+}	$[K^+K^-]_D h^{\pm}$ $[\pi^+\pi^-]_D h^{\pm}$
D_{CP-}	$[K_S\pi^0]_D h^{\pm}$ $[K_S\phi]_D h^{\pm}$ $[K_S\omega]_D h^{\pm}$
Non - CP	$[K^-\pi^+]_{D^0} h^-$ $[K^+\pi^-]_{\bar{D}^0} h^+$

$(K_S \to \pi^+\pi^-, \phi \to K^+K^-, \omega \to \pi^+\pi^-\pi^0)$

Measurement of the CKM angle γ

Legend:
– – $B \to D\pi$
– – other backgrounds
– – combined fit (adding $B \to DK$)

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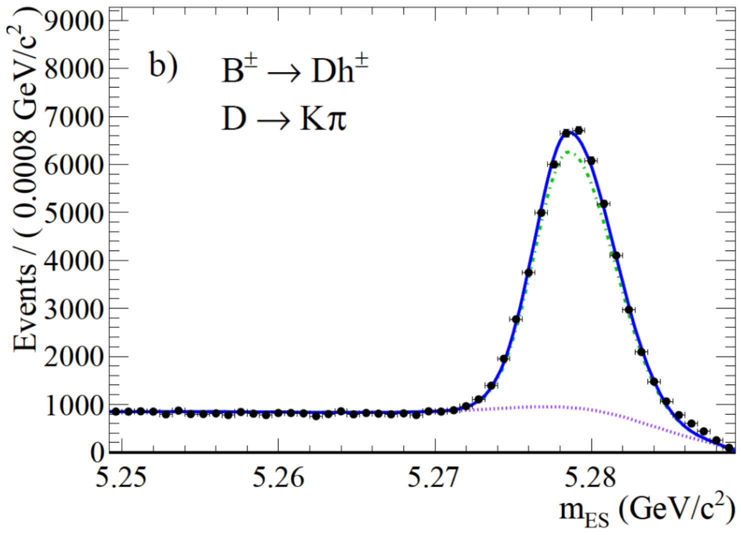
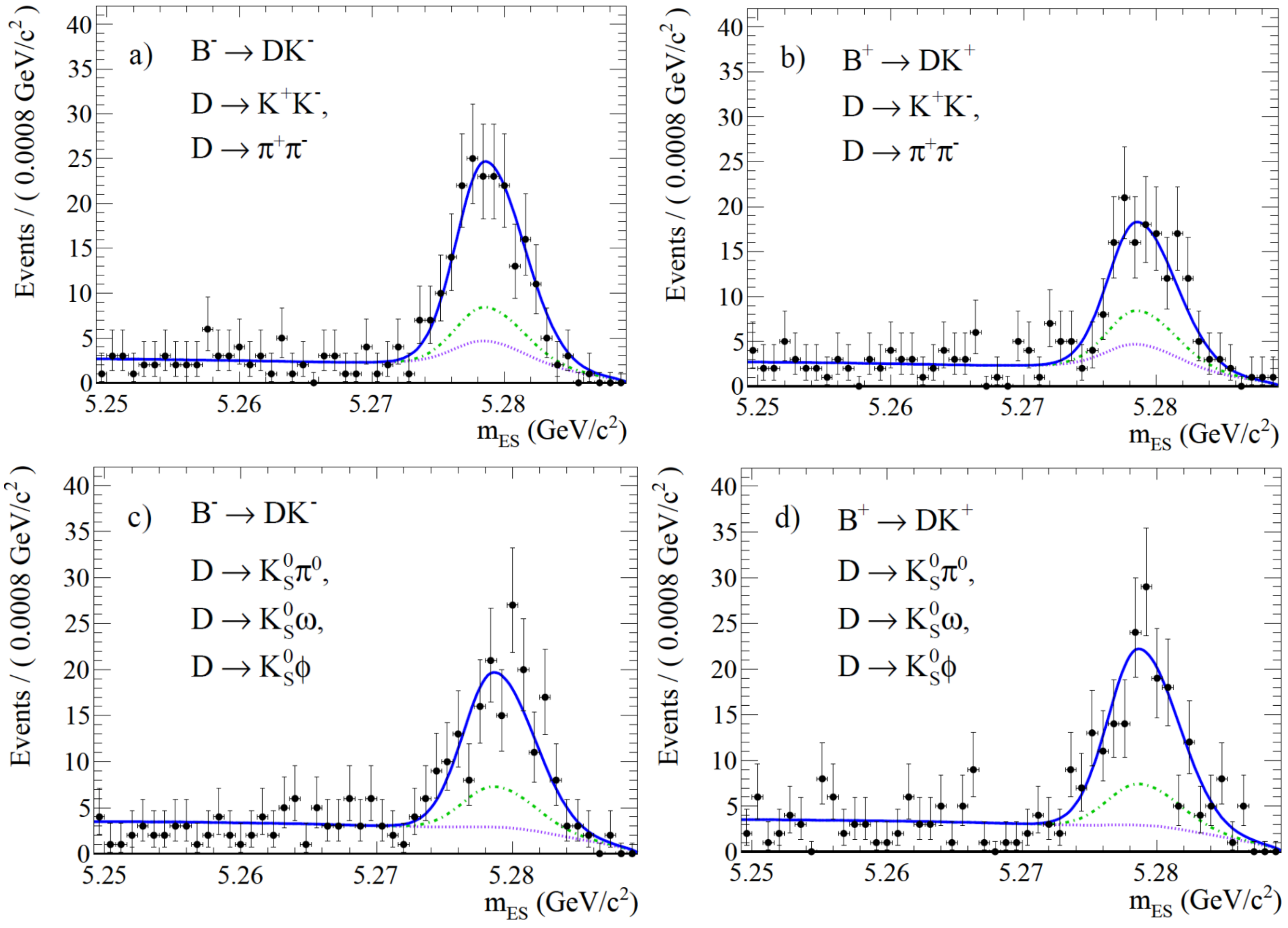
- **GLW example (BaBar)**

D^0 mode	$N(B^\pm \to DK^\pm)$	$N(B^\pm \to D\pi^\pm)$
K^+K^-	367 ± 27	4091 ± 70
$\pi^+\pi^-$	110 ± 9	1230 ± 41
$K_S^0\pi^0$	338 ± 24	4182 ± 73
$K_S^0\omega$	116 ± 9	1440 ± 45
$K_S^0\phi$	52 ± 4	648 ± 27
$K^-\pi^+$	3361 ± 82	44631 ± 232





$$m_{\mathrm{ES}} = \sqrt{(s/2 + \mathbf{p}_{ee} \cdot \mathbf{p}_B)^2 / E_{ee}^2 - p_B^2},$$

Measurement of the CKM angle γ

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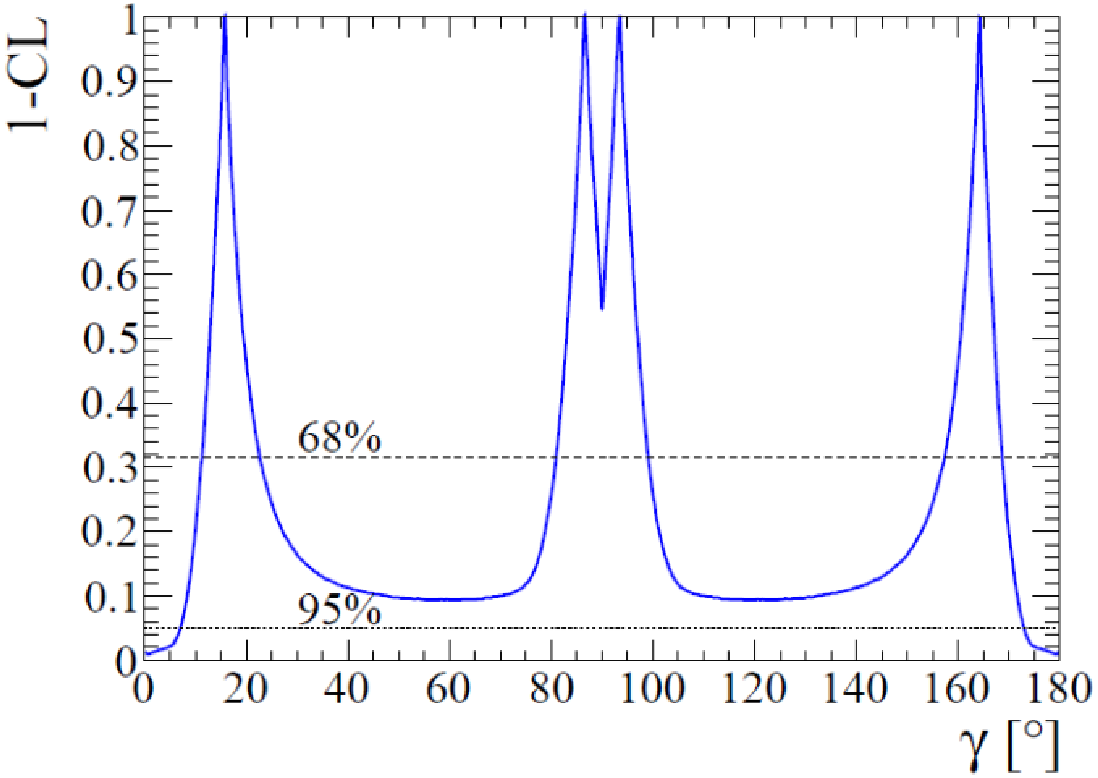
- **GLW example (BaBar)**

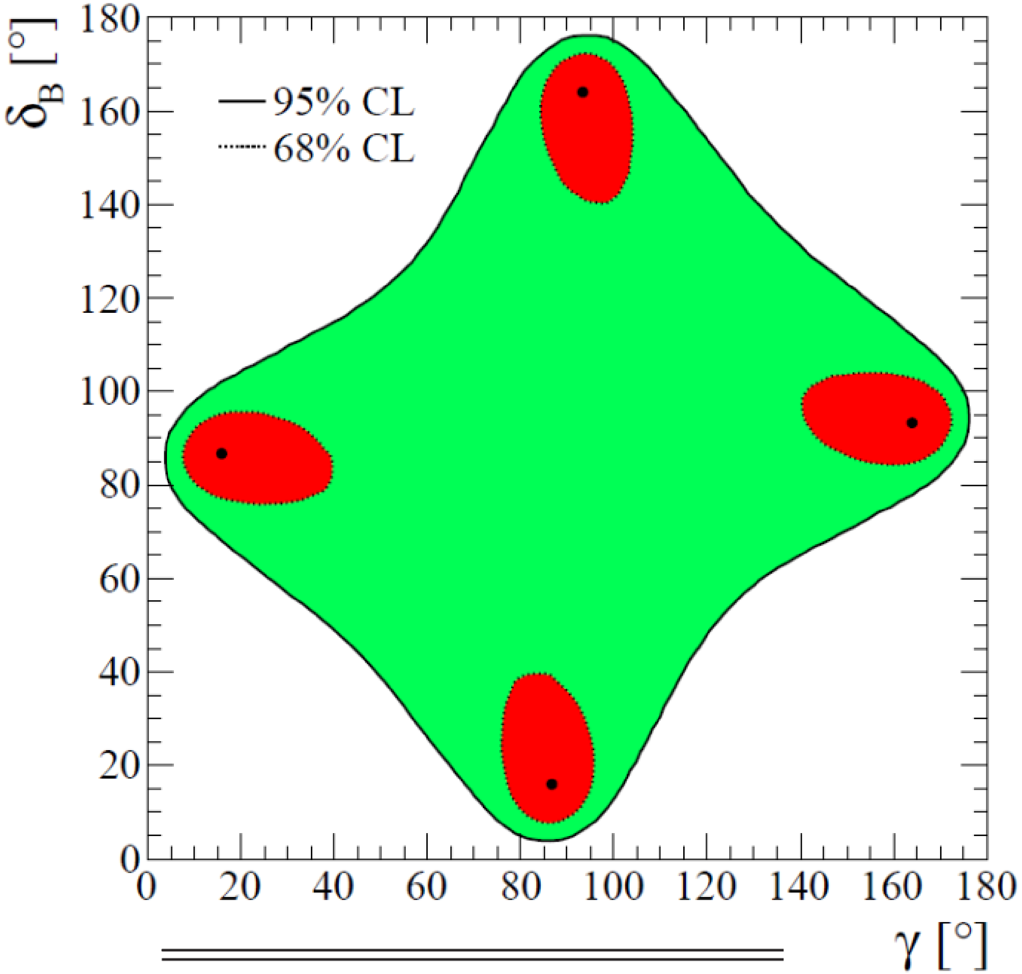
$$A_{CP+} = 0.25 \pm 0.06(\mathrm{stat}) \pm 0.02(\mathrm{syst}),$$

$$A_{CP-} = -0.09 \pm 0.07(\mathrm{stat}) \pm 0.02(\mathrm{syst}),$$

$$R_{CP+} = 1.18 \pm 0.09(\mathrm{stat}) \pm 0.05(\mathrm{syst}),$$

$$R_{CP-} = 1.07 \pm 0.08(\mathrm{stat}) \pm 0.04(\mathrm{syst}).$$



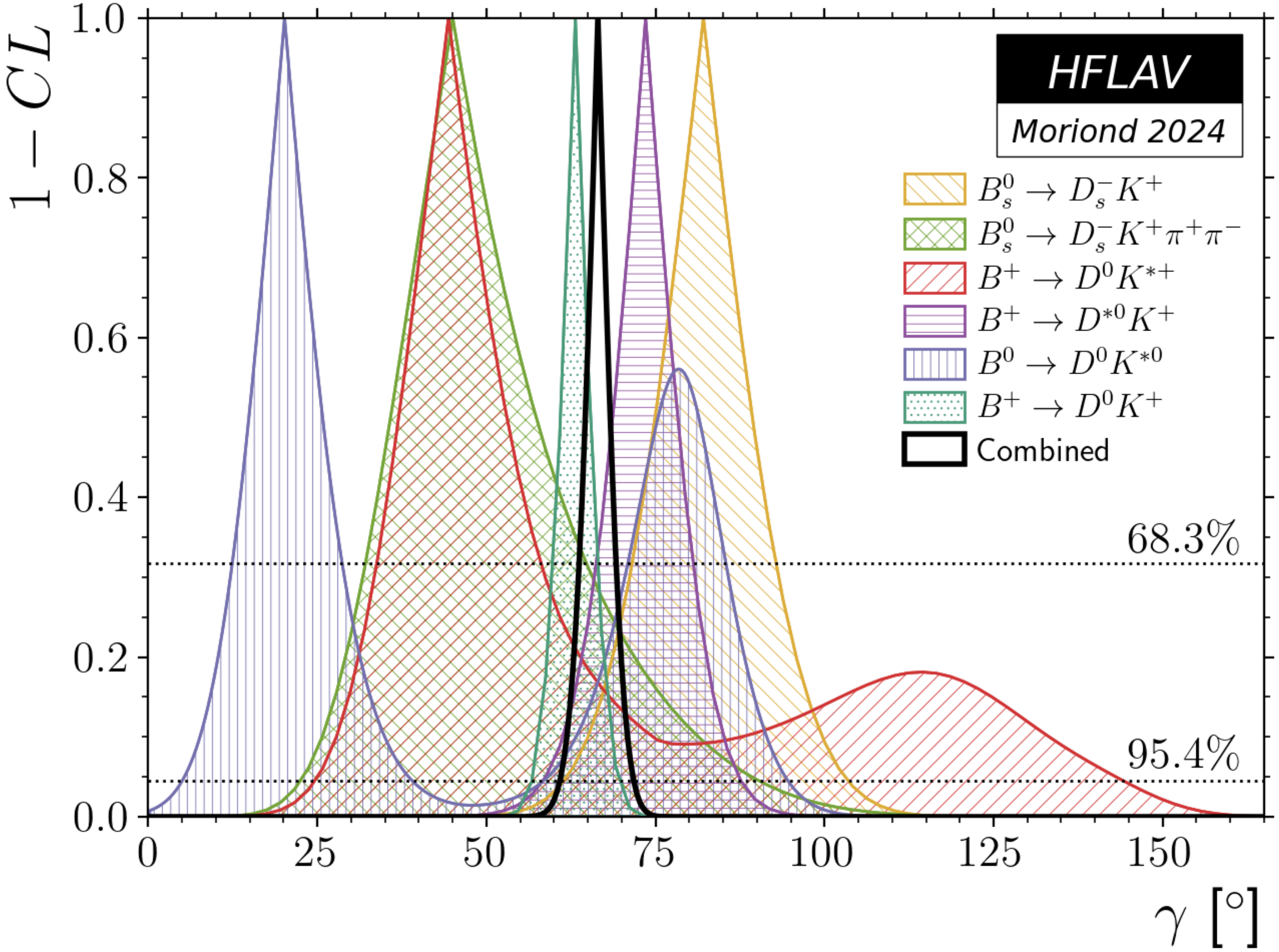


	γ mod 180 [°]
68% CL	[11.3, 22.7] [80.8, 99.2] [157.3, 168.7]
95% CL	[7.0, 173.0]

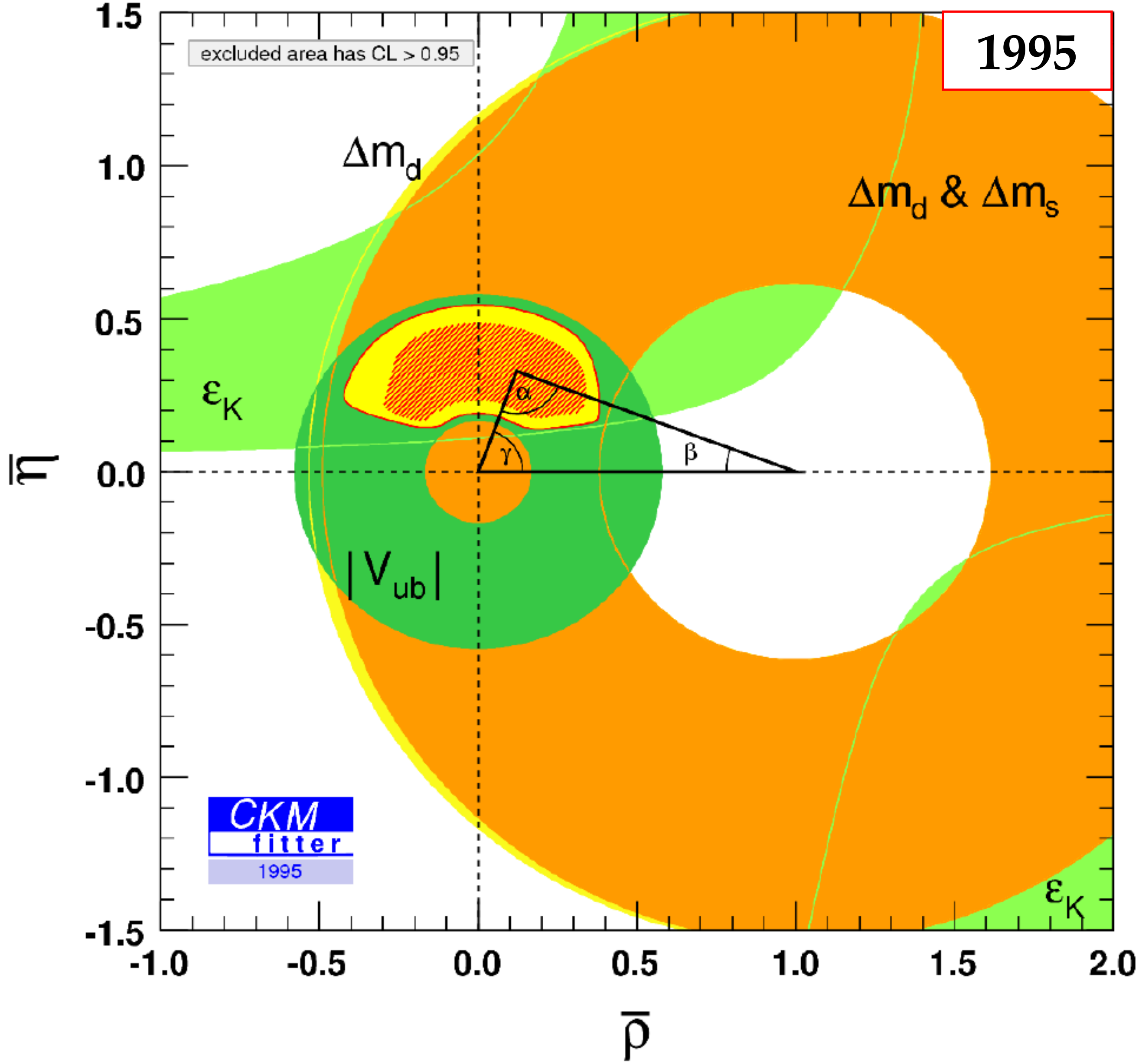
Measurement of the CKM angle γ: combination

- Other methods are analysis of multibody decays of D mesons (Dalitz analysis)
- Combinations of the results make use of all the possible ratios from various types of methods

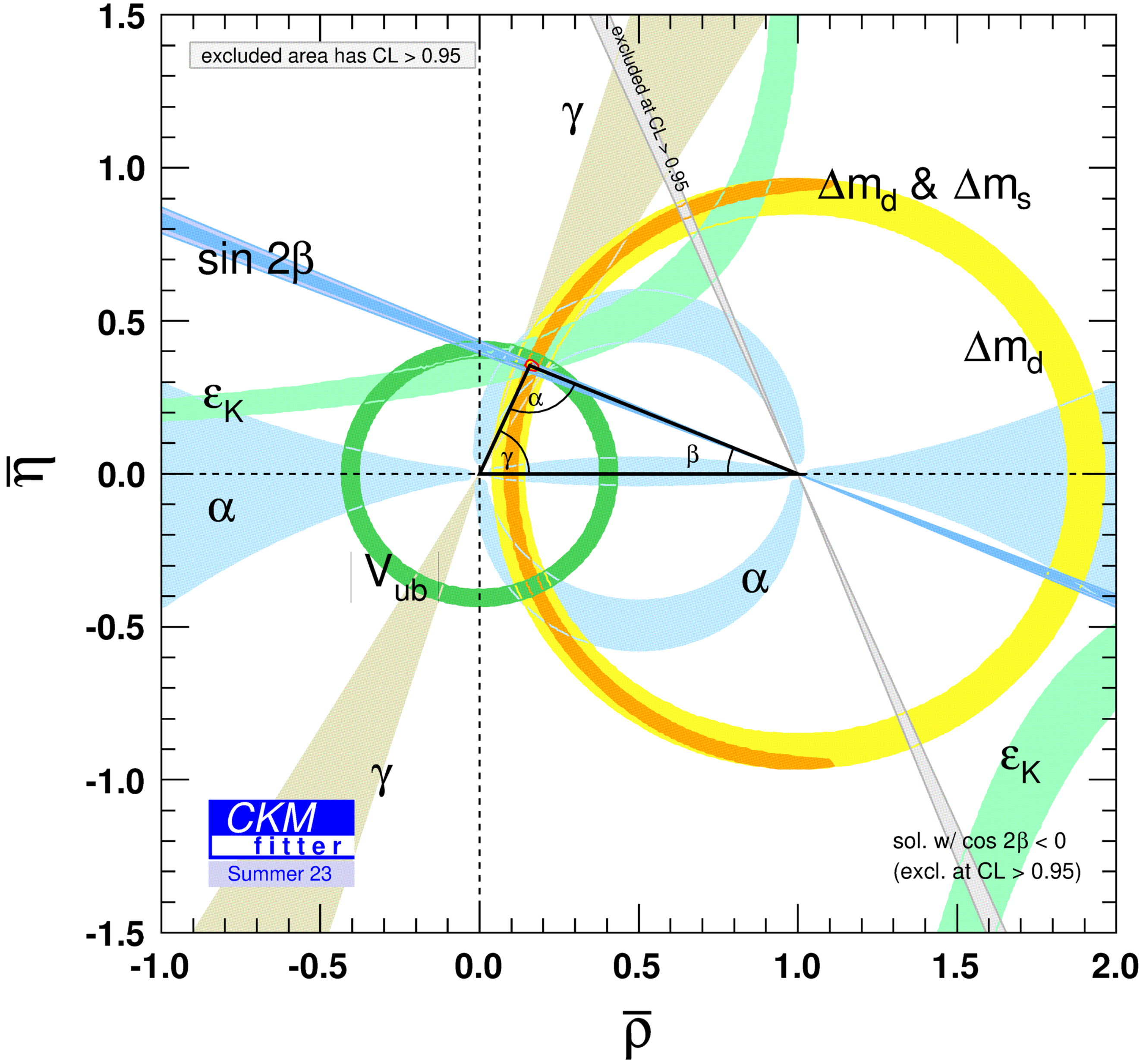
$$\gamma = \left(65.9^{+3.3}_{-3.5}\right)^{\circ}$$



Unitarity triangle: ~ 30 years of progress



Unitarity triangle: ~ 30 years of progress



2023

$$A = 0.8215^{+0.0047}_{-0.0082}$$

$$\lambda = 0.22498^{+0.00023}_{-0.00021}$$

$$\bar{\rho} = 0.1562^{+0.0112}_{-0.0040}$$

$$\bar{\eta} = 0.3551^{+0.0051}_{-0.0057}$$

Wolfenstein parameters

$$J = \left(3.115^{+0.047}_{-0.059}\right)\times 10^{-5}$$

@ 68% CL

Flavour tagging

- Flavour eigenstates P^0 and $\bar{P}^0$ have a well-defined flavour content
- *Example:* B^0 has the quantum numbers of a $\bar{b}d$ state
- In some cases, the final state of the decay informs us whether a neutral P meson is in a P^0 or a $\bar{P}^0$ state

$$\bar{B}^0 \to X_c \mu^- \bar{\nu}_\mu, \qquad B^0 \to X_{\bar{c}} \mu^+ \nu_\mu$$

hadronic system with a charm quantum number +1

hadronic system with a charm quantum number -1

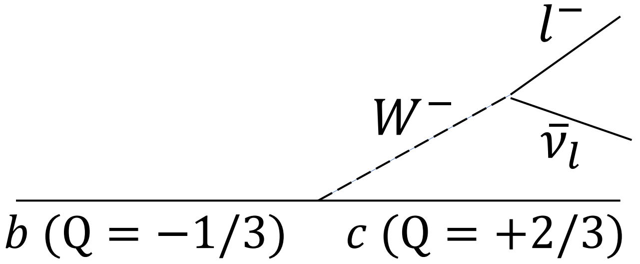
- The charge of the charged lepton tells us the flavour of the decaying meson
- Before the meson decays it can be in a superposition of B^0 and $\bar{B}^0$: **the decay is a quantum measurement**
- Tagging simplifies the oscillation formalism (taking the case of $\bar{\mathcal{A}}_f = 0 \to \lambda_f = 0$ and assuming $|q/p| = 1,\ y = 0$)

$$\hat{\Gamma}(P^0(t) \to f) = \frac{1 + \cos(\Delta m t)}{2}, \qquad \hat{\Gamma}(\bar{P}^0(t) \to f) = \frac{1 - \cos(\Delta m t)}{2}$$

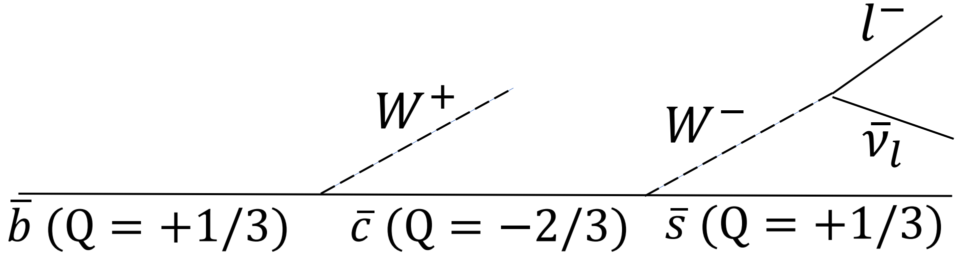
Flavour tagging at decay

- Look for flavour-specific decays

Lepton tagging

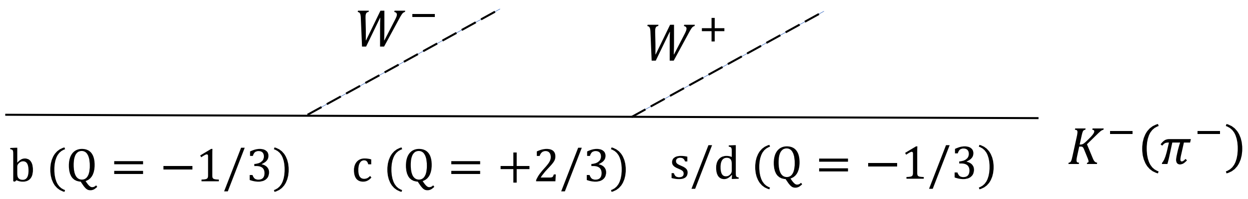


l^- tag b quark ($\bar{B}^0$),
l^+ tag $\bar{b}$ (B^0)



"cascade" events ($B \to D \to Kl\nu$) mimic opposite tag

Kaon/π tagging



K^-/π^- tag b quark ($\bar{B}^0$),

K^+/π^+ tag $\bar{b}$ (B^0)

(virtual) W can produce final states with K/π of any sign

Final cascade can produce $\phi \to K^+K^-$ or $\eta \to \pi^+\pi^-$

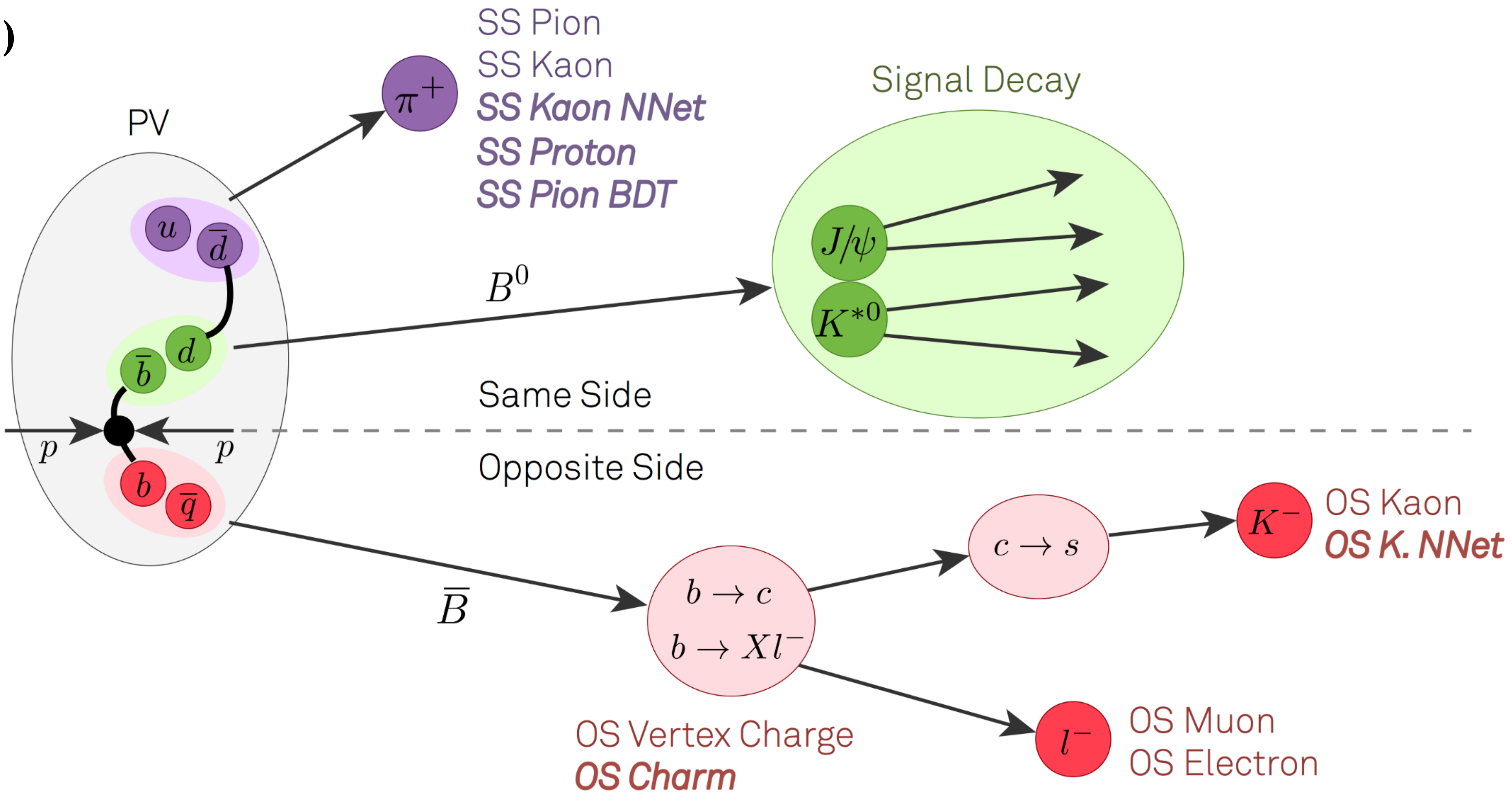
Flavour tagging at production

pp collider (e.g. LHCb)

- **Opposite-side tagging (OST):** Tag the flavour of the “other” b
  - Rationale: $b\bar{b}$ produced in pp interactions
  - Flavour tag with $l/K/\pi$ of a displaced vertex not associated to the signal B vertex
  - “Charge” of a displaced vertex not associated to the signal B vertex
- **Same-side tagging (SST):** Tag the flavour of the signal B
  - Rationale: sign of $l/K/\pi$ from primary vertex often correlated with the flavour
  - Example: zero net strangeness in pp → sign of the K associated with signal B_s gives the sign of the other s → tag the flavour of the B_s

Flavour tagging at production

pp collider (e.g. LHCb)



SS Pion
SS Kaon
SS Kaon NNet
SS Proton
SS Pion BDT

OS Kaon
OS K. NNet

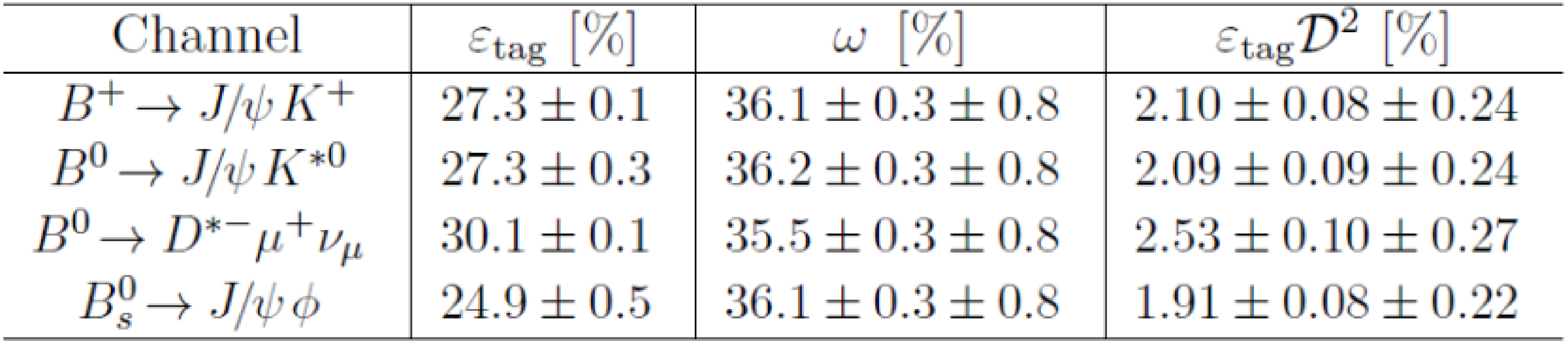
OS Vertex Charge
OS Charm

OS Muon
OS Electron

Flavour tagging performance

- Flavour tagging efficiency: ε_{tag}
- Mistag probability (initial and final): $\omega_{i,f}$ [usually $\omega_f \ll \omega_i$]
- Dilution factor: $D \equiv (1-2\omega) \equiv (1-2\omega_i)(1-2\omega_f)$
- Effective tagging efficiency: $Q \equiv \varepsilon_{tag} D^2$ ["figure of merit"]

LHCb (example OST per different B signal channels summed up on many tagging categories)



Channel	ε_{tag} [%]	ω [%]	$\varepsilon_{\text{tag}}\mathcal{D}^2$ [%]
$B^+ \to J/\psi K^+$	27.3 ± 0.1	$36.1 \pm 0.3 \pm 0.8$	$2.10 \pm 0.08 \pm 0.24$
$B^0 \to J/\psi K^{*0}$	27.3 ± 0.3	$36.2 \pm 0.3 \pm 0.8$	$2.09 \pm 0.09 \pm 0.24$
$B^0 \to D^{*-}\mu^+\nu_\mu$	30.1 ± 0.1	$35.5 \pm 0.3 \pm 0.8$	$2.53 \pm 0.10 \pm 0.27$
$B^0_s \to J/\psi \phi$	24.9 ± 0.5	$36.1 \pm 0.3 \pm 0.8$	$1.91 \pm 0.08 \pm 0.22$

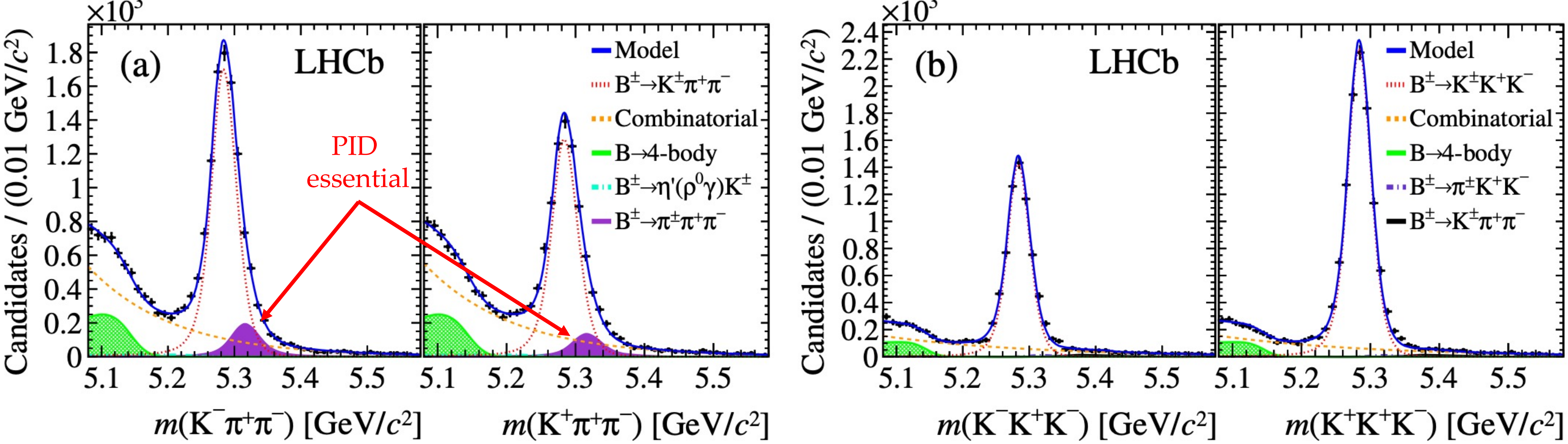
CP violation in decay: measurement

- *CP* asymmetries in charged *B* mesons has been observed in several decay modes
- *Example*: charmless three-body decay modes $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}, B^{\pm} \to K^{\pm}K^{+}K^{-}, B^{\pm} \to \pi^{\pm}K^{+}K^{-}, B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$

  measured by LHCb

$$\mathcal{A}_f \equiv \frac{\Gamma(B^- \to f^-) - \Gamma(B^+ \to f^+)}{\Gamma(B^- \to f^-) + \Gamma(B^+ \to f^+)}$$

LHCb: Phys. Rev. D 90 112004 (2014)



PID essential

Measument of $\boldsymbol{B_s^0}$ mixing parameters

- Time dependent analysis to measure Δm_s

- Steps:
    - **Reconstruct** B_s^0
    - **Measure** the decay (proper) **time** for each B_s^0
    - **Tag** the **flavour** of the B_s^0 (either B_s^0 or $\bar{B}_s^0$) at **production** and **decay**
    - **Identify** the B_s^0 candidate: **unmixed** (same flavour at production & decay), **mixed** (different flavour)
    - **Fit** to the **time distribution** separately for mixed and unmixed B decays

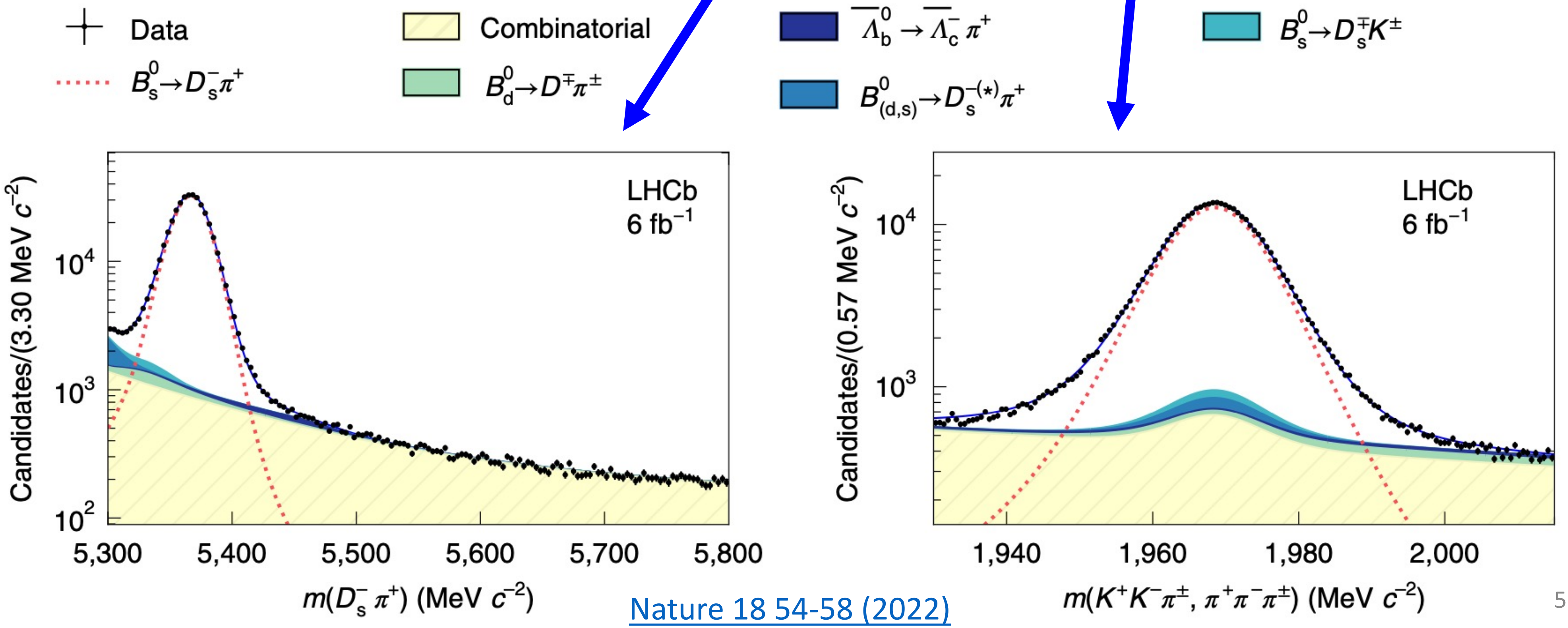
$$\Longrightarrow \text{bin entries} \propto \mathcal{P}(t) \approx e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) \pm \cos(\Delta m_s\, t)\right]$$

B_s^0 reconstruction

- Full reconstruction of both B_s^0 and D_s^- decays
- Selection based on displaced vertex and track kinematic quantities
- Flavour tagging at both production and decay

$B_s^0 \to D_s^- \pi^+$

↳ $K^+K^-\pi^-$ or $\pi^+\pi^-\pi^-$

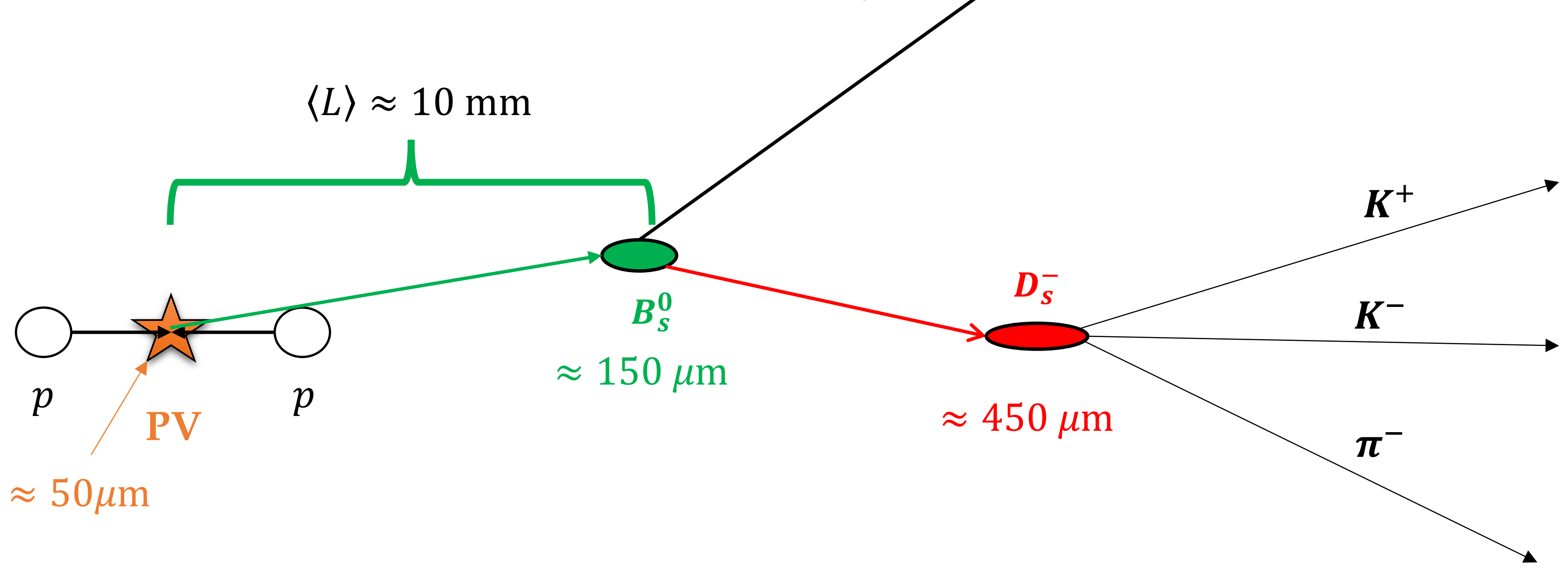


[Nature 18 54-58 (2022)]

$B_s^0 \to D_s^- \pi^+$ decay time reconstruction

LHCb

- *pp* collider (e.g. LHCb) $t = \frac{L m_B}{p_B}$



π^+

$\langle L \rangle \approx 10$ mm

B_s^0

$\approx 150\ \mu$m

D_s^-

$\approx 450\ \mu$m

K^+

K^-

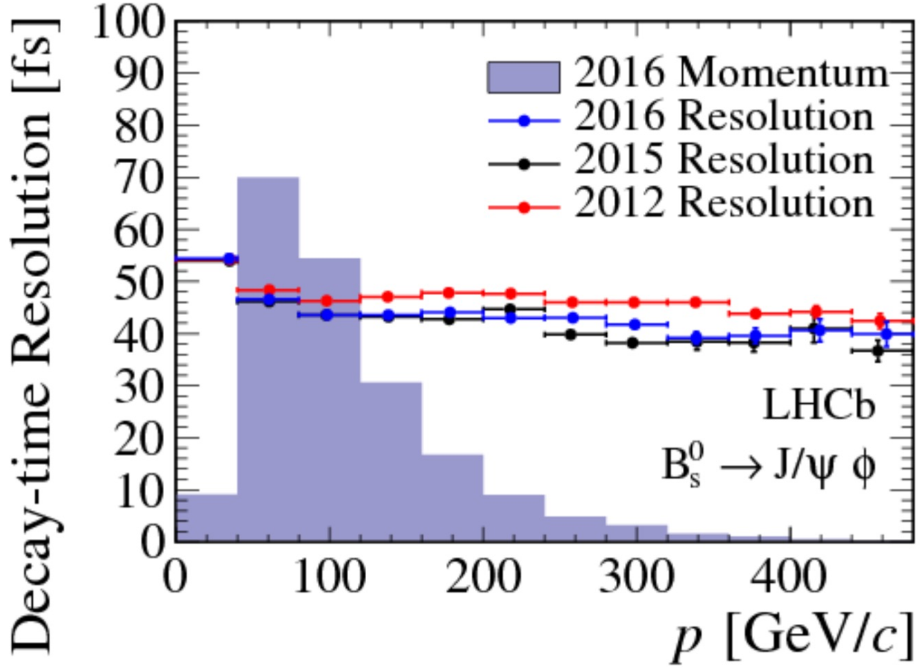
π^-

p

PV

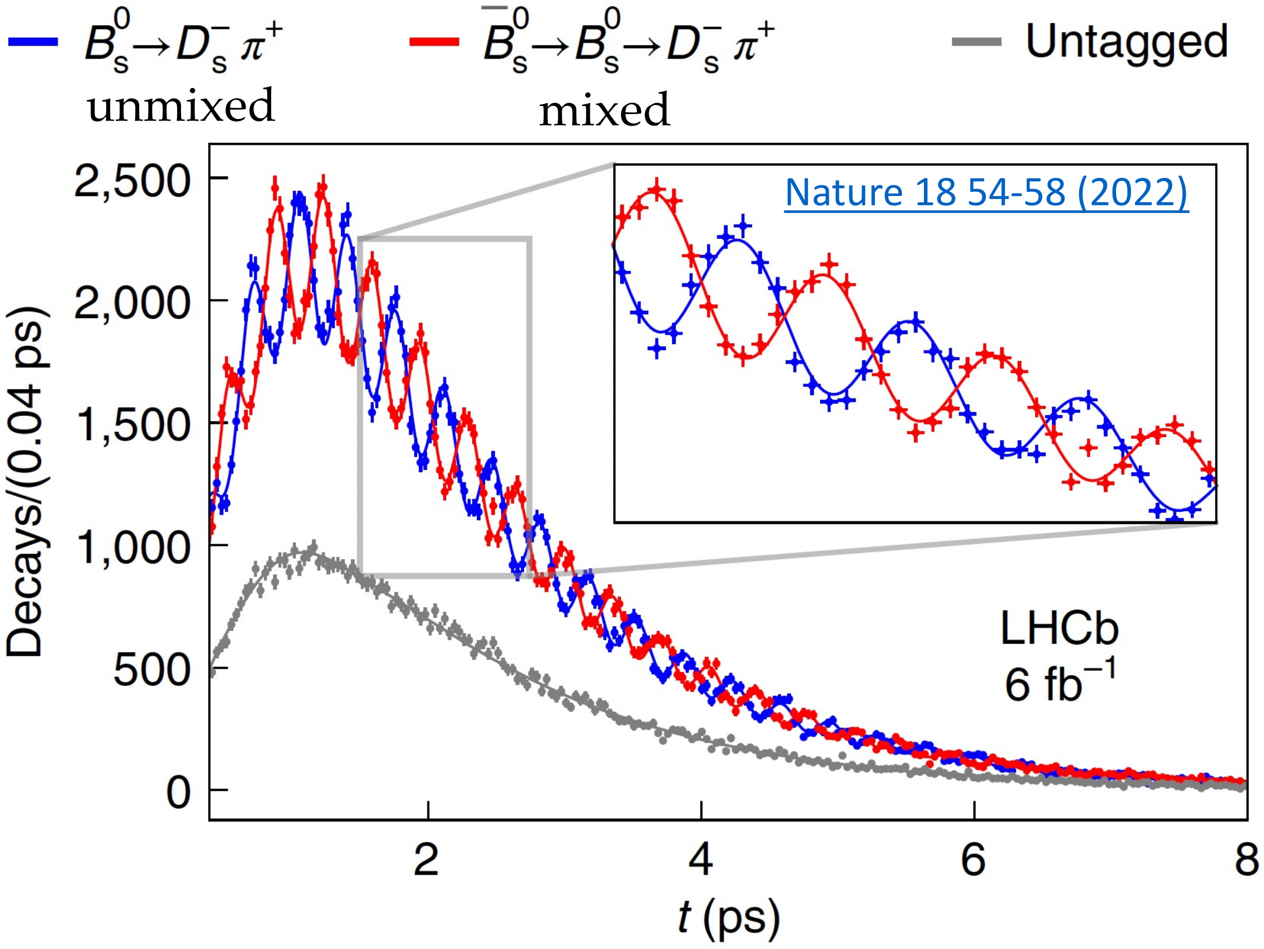
p

$\approx 50\mu$m



Δm_s measurement

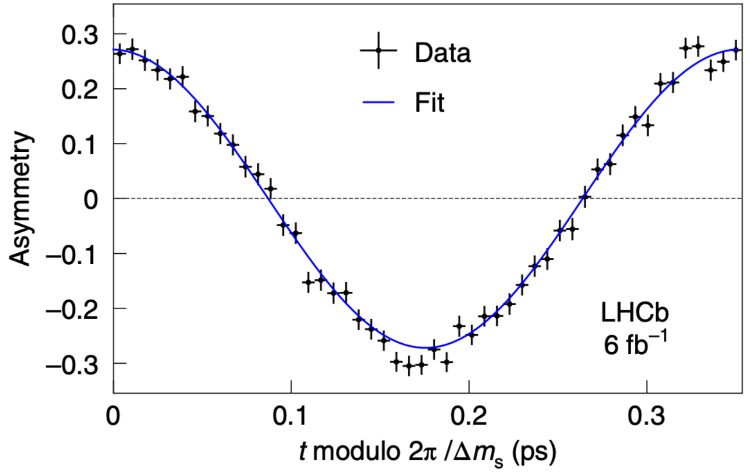
- LHCb B_s^0 mixing measurement using $B_s^0 \to D_s^- \pi^+$ decays
- Experimental proper time distribution after selection and flavour tagging:



unmixed

mixed

Nature 18 54-58 (2022)



time asymmetry between mixed and unmixed signal decays

$$\Delta m_s = 17.7683 \pm 0.0051 \pm 0.0032 \text{ ps}^{-1}$$

- Simultaneous fit to the invariant masses and decay time distributions separated per flavour
- Description of decay time resolution essential because time resolution smaller, but not negligible with respect to the oscillation period (~0.35 ps)

Take home message

- Flavour physics is a very important branch of particle physics research
  - offers unique insights into the flavour structure of the SM and has unprecedented indirect sensitivity to NP at high energies
  - CKM tests, meson mixing and oscillations, CP violation provide precision tests of the SM
- B physics offers unique experimental challenges
  - main features and difficulties associated with using hadron and lepton machines for B physics measurements
  - important complementarity between the different experimental approaches
  - flavour tagging at production and decay, proper decay time reconstruction
- Due to the limited time, I could only cover a limited number of interesting observables and experimental techniques
- **Plenty of amazing results from LHCb and *B* factories so far and many more to come in the coming decades!**