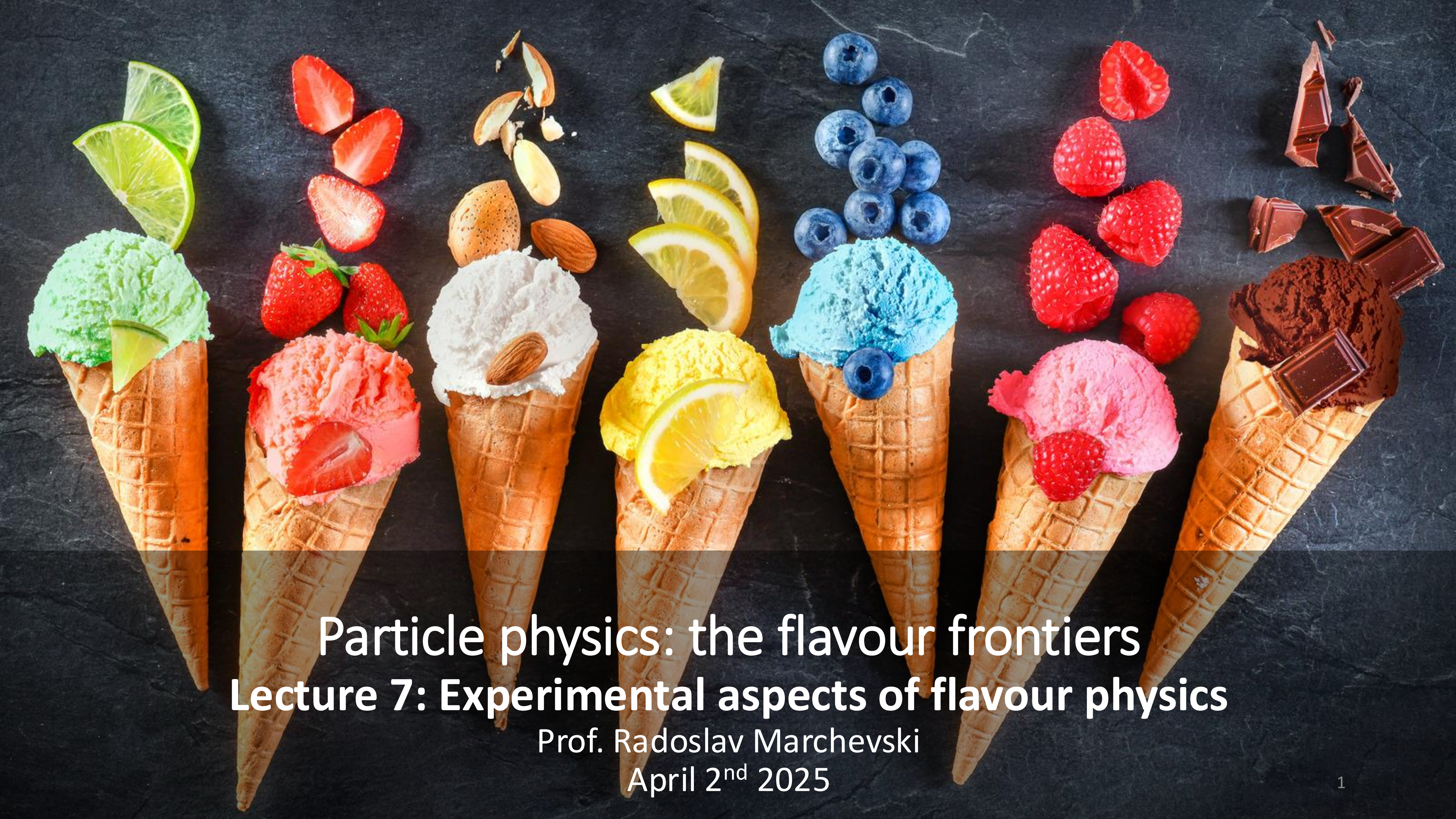

Particle physics: the flavour frontiers

Lecture 7: Experimental aspects of flavour physics

Prof. Radoslav Marchevski

April 2nd 2025

Short recap and today's learning targets

Last time we discussed

- How to do parameter counting in the Standard Model: physical parameters and broken generators
- Flavour physics and quark mixing via the CKM matrix: unitarity constraints and unitarity triangles

Today you will …

- learn how mesons are produced at different accelerators
- learn some experimental aspects of flavour physics
- get familiar with some of the main past and present facilities used to perform flavour physics experiments

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

- **<u>Confinement hypothesis</u>:** 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 ($q\bar{q}$)
  - 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

General properties of hadrons

- Experiments measure generic properties of states
- Measurable properties: *hadron mass, lifetime, spin, electric charge*
- Other properties are not exact, but they are still generic
- Three classes of hadronic quantum numbers (QN)

- **Exact quantum numbers**
  - ?
- **QN respected by QCD and QED but broken by the weak interaction**
  - ?
- **QN under approximate symmetries of QCD**
  - ?

General properties of hadrons

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- Three classes of hadronic quantum numbers (QN)

- **Exact quantum numbers**
  - electromagnetic charge, Q
  - total angular momentum, J
  - Baryon number, B
- **QN respected by QCD and QED but broken by the weak interaction**
  - charges under global $[U(1)]^6$ flavour symmetry of QED and QCD *(flavour quantum numbers)*
  - parity, P
  - for neutral mesons, charge conjugation, C
- **QN under approximate symmetries of QCD**
  - $SU(2)$ – isospin and $SU(3)$ flavour
  - heavy quark symmetry

Flavour refers only to quark flavour unless explicitly mentioned otherwise

The Quark Model

- **Basic idea:** hadrons are color-singlet combinations of quarks and antiquarks
- Quantum numbers of the hadrons are dictated by the quantum numbers of the constituent quarks and antiquarks
- *Assumption:* minimum quark content of the hadron (in reality much more complex)
  - works surprisingly well and provides many insights into the IR (infrared, low energy) properties of QCD
- In the quark model the simplest hadrons are: mesons ($q\bar{q}$), baryons (qqq), and antibaryons ($\bar{q}\bar{q}\bar{q}$)
- Lightest mesons are the pions

$$\pi^+ = u\bar{d}, \qquad \pi^0 = \frac{1}{\sqrt{2}}\left(u\bar{u} - d\bar{d}\right), \qquad \pi^- = \bar{u}d$$

- Lightest baryons are the proton and the neutron

$$p = uud, \qquad n = udd$$

- Mesons carry no baryon number, baryons carry a baryon number that we normalize to $B = +1$, and antibaryons carry a baryon number $B = -1$ (note that B can also be used to denote B-mesons)

The Quark Model

- Some properties of the hadrons can be interpreted using the quark model
- *Example:* the total spin J, of a meson
  - combination of the spins of the quark and antiquark, S (can be 0 or 1) and the orbital angular momentum L
- Let's take the charged pion π^+ and the charged rho meson ρ^+
  - π^+ is a pseudoscalar ($J^P = 0^-$) with a mass $m_{\pi^+} \approx 140$ MeV
  - ρ^+ is a vector ($J^P = 1^-$) with a mass $m_{\rho^+} \approx 770$ MeV
  - within the quark model both mesons are $u\bar{d}$ states
  - both correspond to the ground state ($n = 1, L = 0$)
  - distinguished by their spin: $S = 0$ for the pion and $S = 1$ for the rho meson
  - $J = S + L$ and $P = -(-1)^L$

More complex hadrons exist: tetraquarks ($q\bar{q}q\bar{q}$) and pentaquarks ($qqqq\bar{q}$), as well as glueballs

Mesons

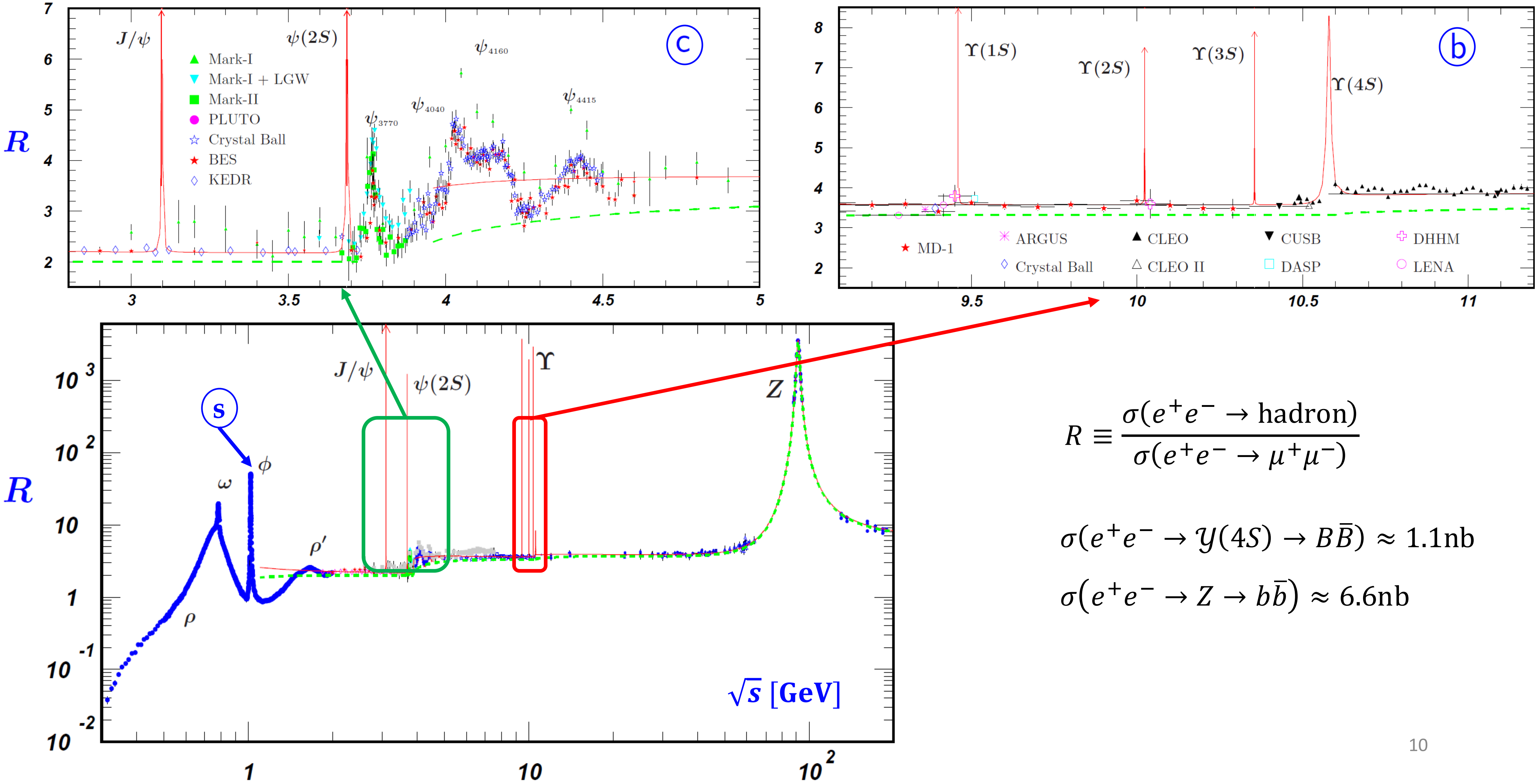
	Meson	Quark content $[q\bar{q}']$	$I(J^P)$	Mass [GeV/c^2]	Mean lifetime		$c\tau$
(open) B mesons	$B^+(B^-)$	$\bar{b}u(\bar{u}b)$	$1/2(0^-)$	5.3	1.6 ps		491 μm
	$B^0(\bar{B}^0)$	$\bar{b}d\ (b\bar{d})$	$1/2(0^-)$	5.3	1.5 ps		455 μm
	$B_s^0(\bar{B}_s^0)$	$\bar{b}s\ (b\bar{s})$	$0(0^-)$	5.4	1.5 ps		455 μm
	$B_c^+(B_c^-)$	$\bar{b}c\ (b\bar{c})$	$0(0^-)$	6.3	0.5 ps		150 μm
(open) charm (D) mesons	$D^0(\bar{D}^0)$	$c\bar{u}\ (\bar{c}u)$	$1/2(0^-)$	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
kaons (K mesons)	$K^+(K^-)$	$\bar{s}u\ (s\bar{u})$	$1/2(0^-)$	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

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 ($B \to D, K; D \to K; J/\psi \to D, K; \ldots$)
- 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

Meson production in e^+e^- collisions



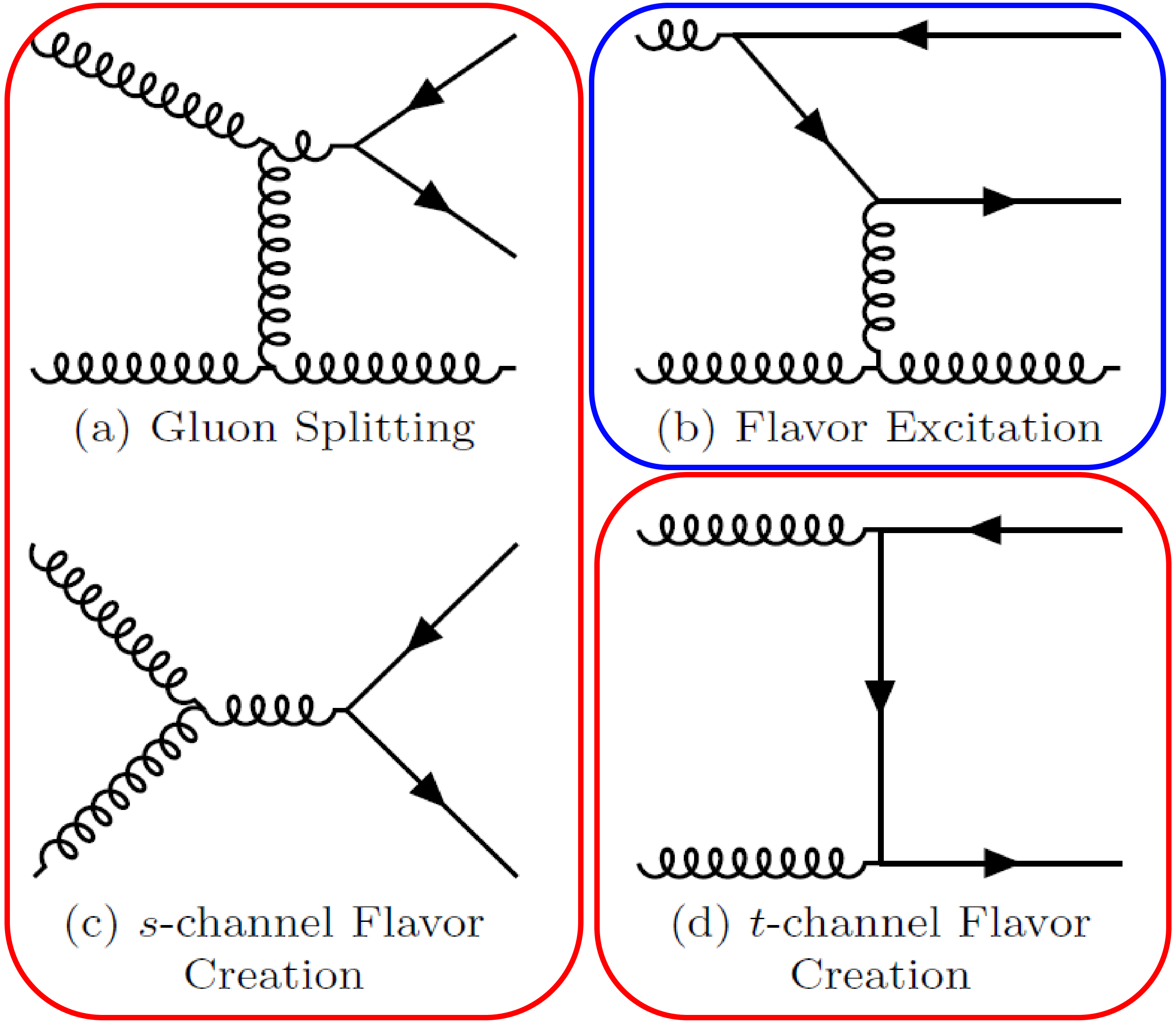
$$R \equiv \frac{\sigma(e^+e^- \to \text{hadron})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

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

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

Heavy flavour production in pp collisions

Main heavy quark production diagrams in hadronic collisions

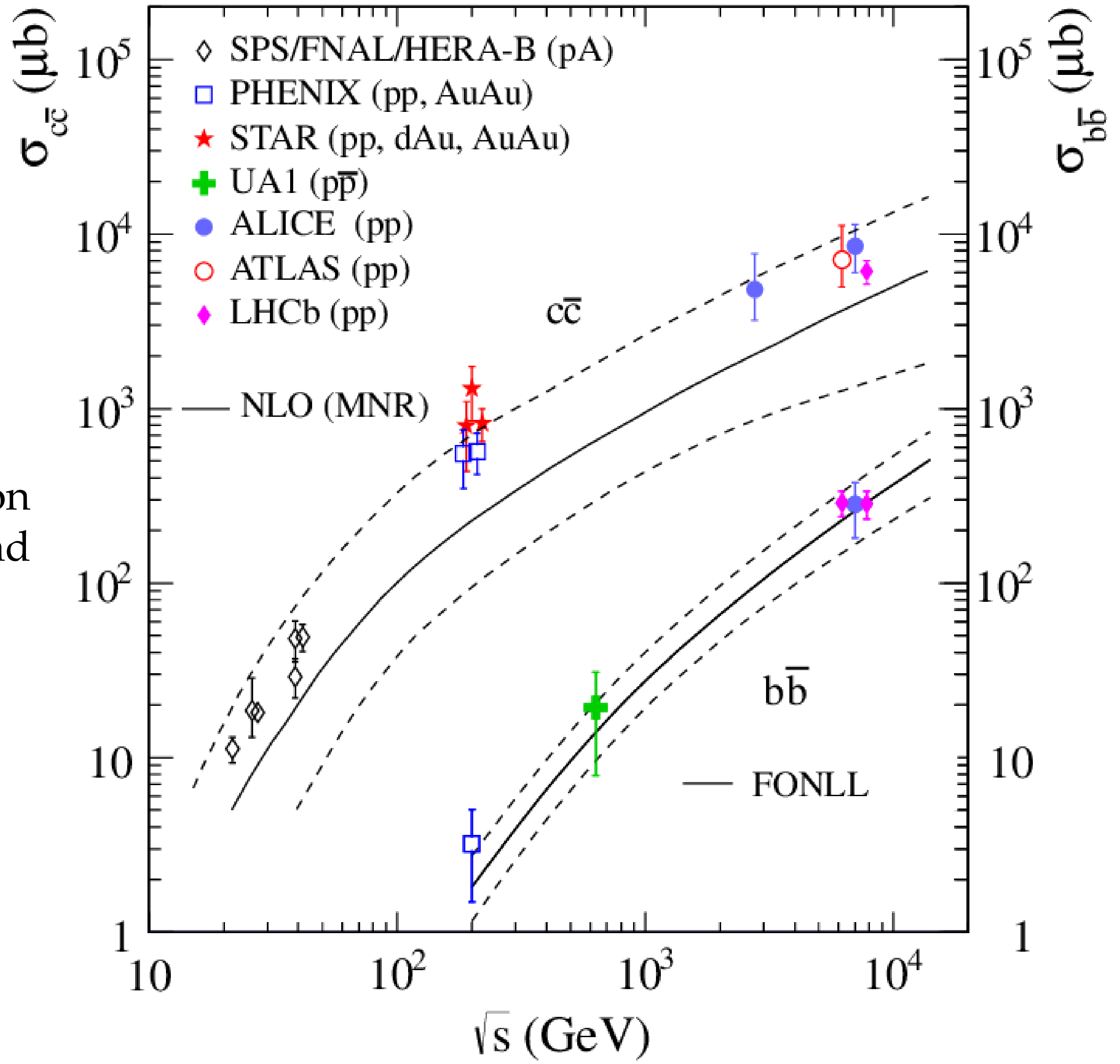


Sub-leading order heavy quark production diagram in hadronic collisions

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

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

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



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

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

$\sigma(pp \to c\bar{c}X) \sim 3000 - 10000\ \mu b\ @ \sqrt{s} \sim 1 - 13\ \text{TeV}$

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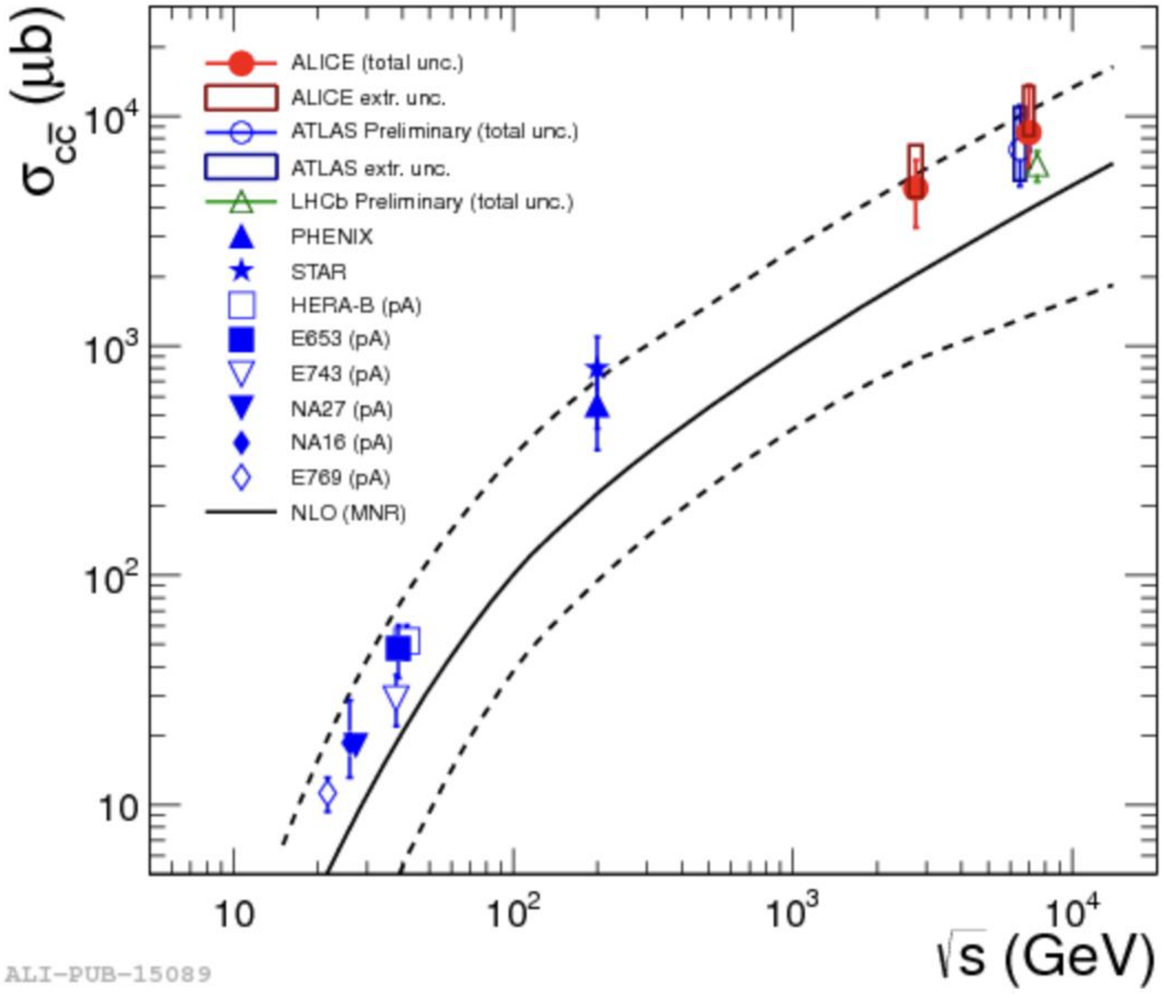

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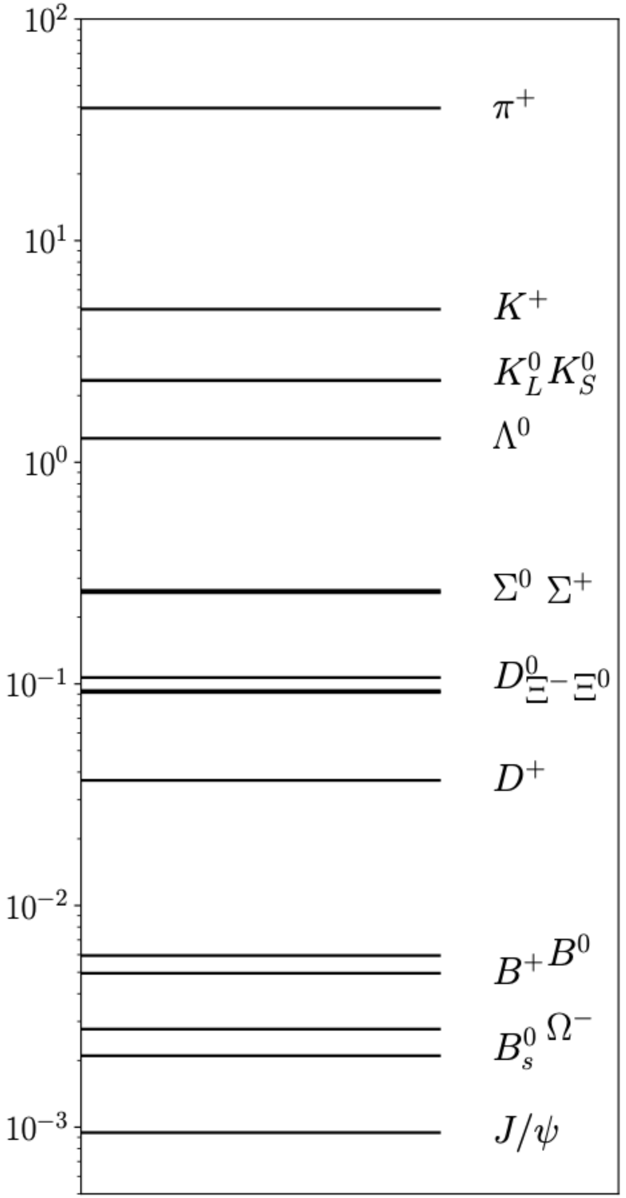
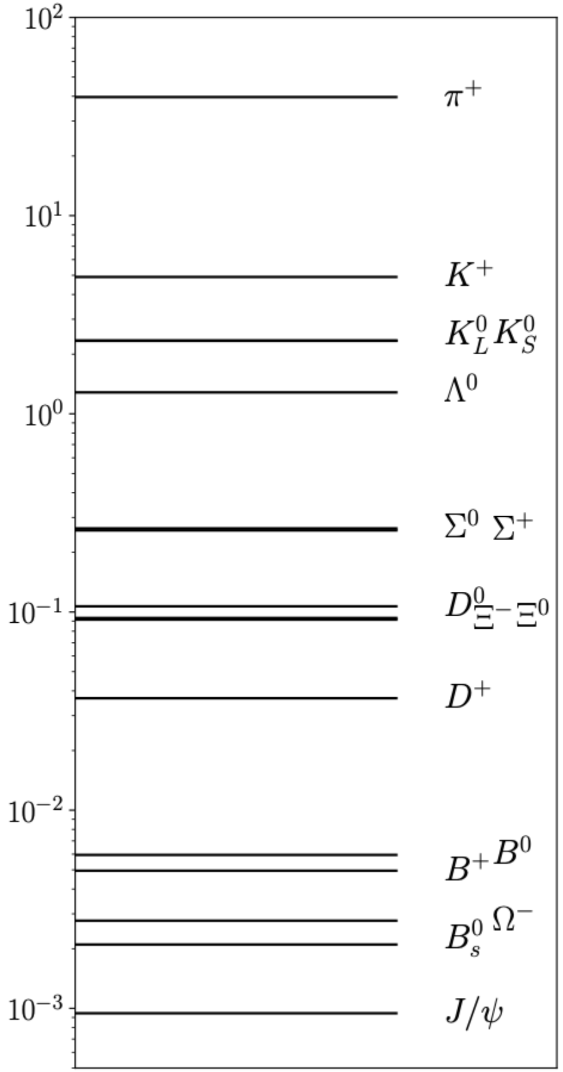
Strange hadrons and pions even more abundant by several orders of magnitude!

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



Multiplicity of particles produced in a single pp interaction at $\sqrt{s} = 13$ TeV within LHCb acceptance.

Comparison with Higgs production cross section



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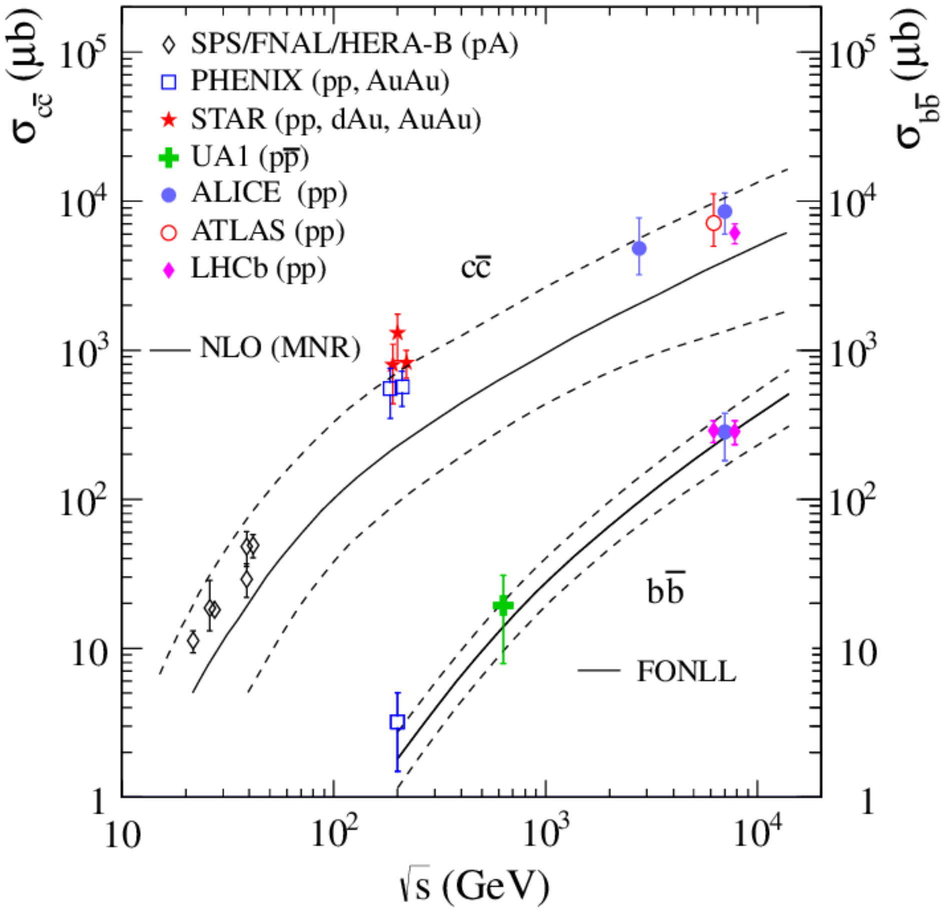
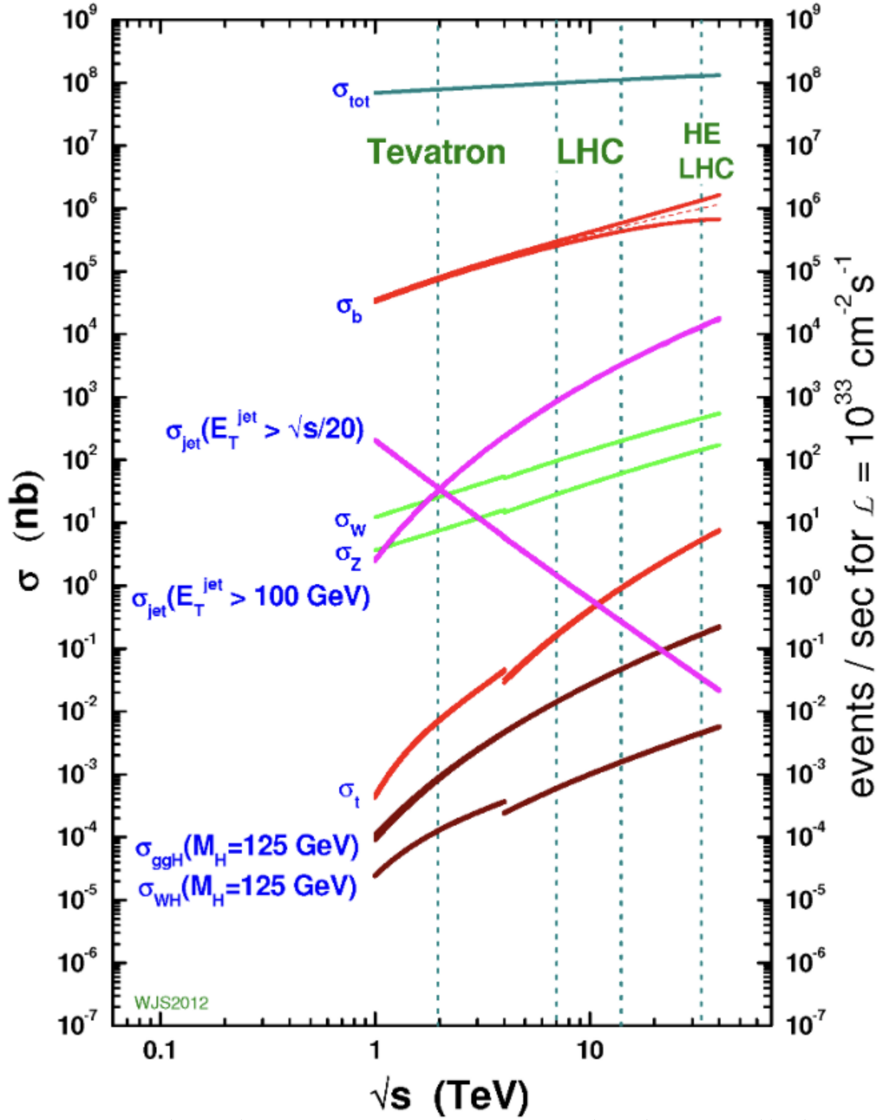


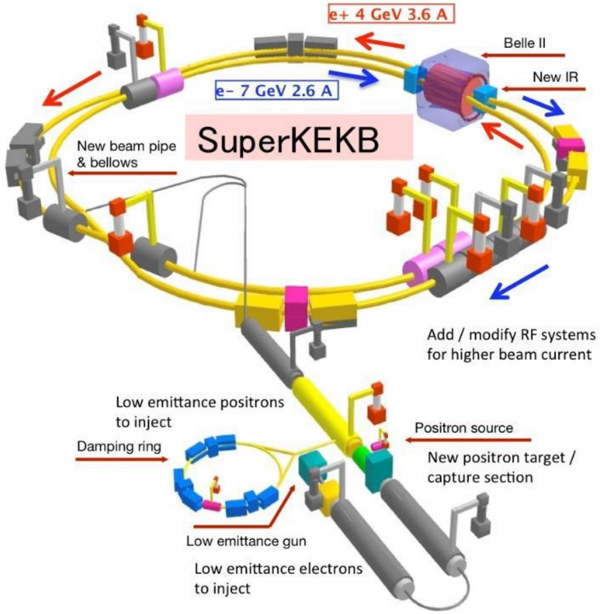
proton - (anti)proton cross sections



Total inelastic cross section at hadron colliders dominated by pion and kaon production

Flavour physics facilities

e^+e^- colliders for production at threshold



KEKB & super KEKB (Japan)

PEPII (SLAC – USA)

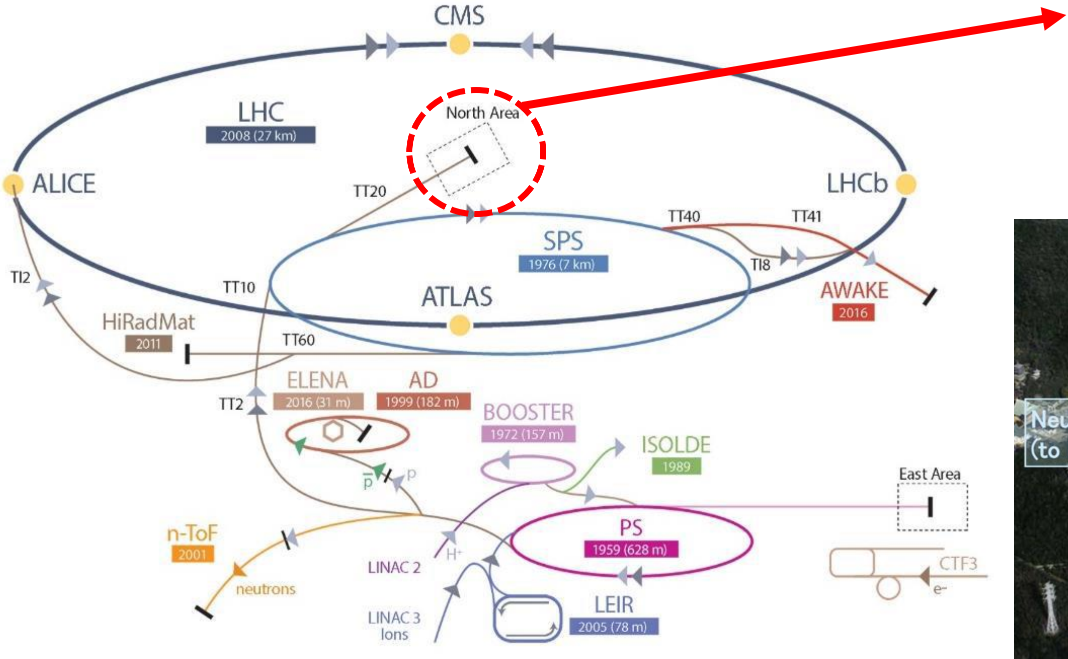
BEPCII (China)

DAPHNE (Frascati)

CESR (Cornell – USA)

…

High energy colliders

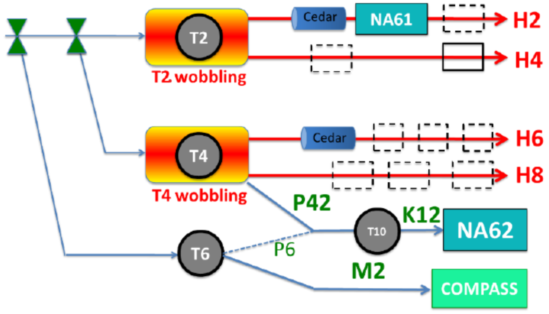


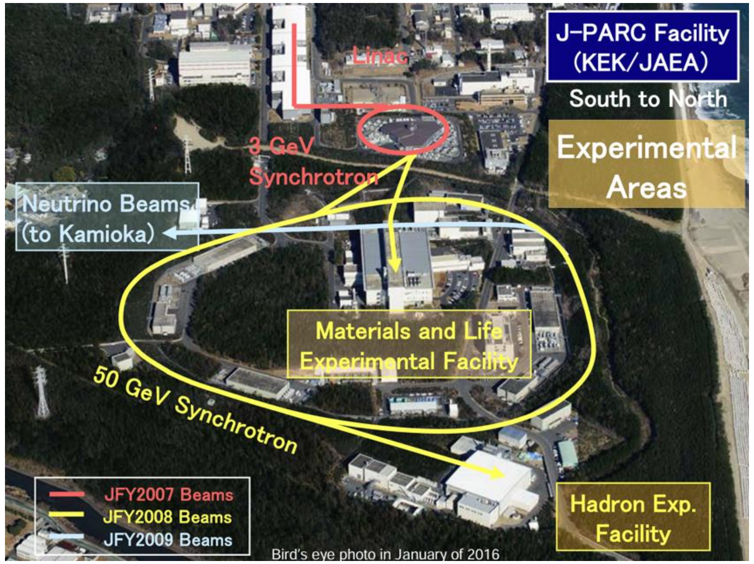
LHC (CERN)

Tevatron (Fermilab – USA)

LEP (CERN)

Fixed target





SPS – north area (CERN)

JPARC (Japan)

Fermilab Fixed Target (USA)

Separated beam line at AGS (BNL – USA)

…

Flavour physics experimental principles

e^+e^- colliders for production at threshold

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

High energy colliders

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

Fixed target

- Various beam energies
- forward detector configuration
- $\mathcal{O}(0.1-100\ \mathrm{GeV})$ energy range of the decay products

Common features

- 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)

Flavour physics experiments

e^+e^- colliders for production at threshold

KEKB & super KEKB (Japan)

Belle, Belle II

PEPII (SLAC – USA)

BaBar

BEPCII (China)

BES III

DAPHNE (Frascati)

KLOE

CESR (Cornell – USA)

CLEO

High energy colliders

LHC (CERN)

LHCb, (CMS, ATLAS)

Tevatron (Fermilab – USA)

CDF, D0

LEP (CERN)

(ALEPH, DELPHI, L3, OPAL)

$\boldsymbol{B, D, K, (\tau)}$

Fixed target

SPS – north area (CERN)

NA31, NA48, NA62

JPARC (Japan)

KOTO

Fermilab Fixed Target (USA)

KTeV

Separated beam line at AGS (BNL – USA)

E787, E949, …

$\boldsymbol{K}$

$\boldsymbol{B}$ – factories

$\boldsymbol{\Upsilon(4S)}$ cleanest source of $\boldsymbol{B\bar{B}}$ pairs

- Only $B^0\bar{B}^0$ (50%) or $B^+\bar{B}^-$ (50%)
- B produced almost at rest and small particle multiplicity per $\Upsilon(4S)$ 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 $\times$ 10 using $E^*_{beam} = \sqrt{s}/2$ instead of E^*_B

Coherent $\boldsymbol{B\bar{B}}$ 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 $\mathcal{L} = 10^{34}\ \mathrm{cm^{-2}s^{-1}}$ [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 $\Longrightarrow$ $\sim 1.1 \times 10^9$ $b\bar{b}$ pairs /ab^{-1}

Asymmetric $\boldsymbol{B}$ – factories

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

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

- **Solution:** asymmetric e^+e^- to boost $\Upsilon(4S)$ 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 $\Upsilon(4S)$ rest frame]

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

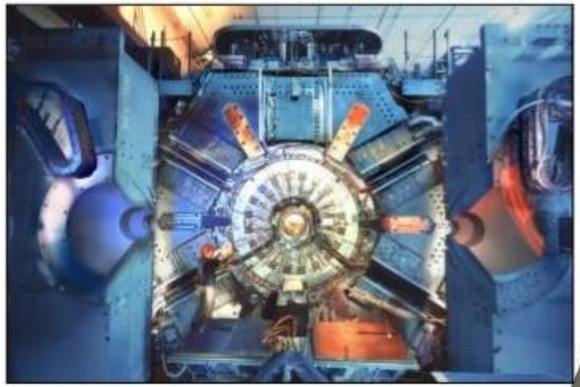
$z_1 - z_2 = \gamma\beta\sqrt{1+\alpha^2}\, c(t_1 - t_2) + \gamma\alpha\cos\theta^*\, c(t_1 + t_2),$ [1,2 denote the $B\bar{B}$ produced]

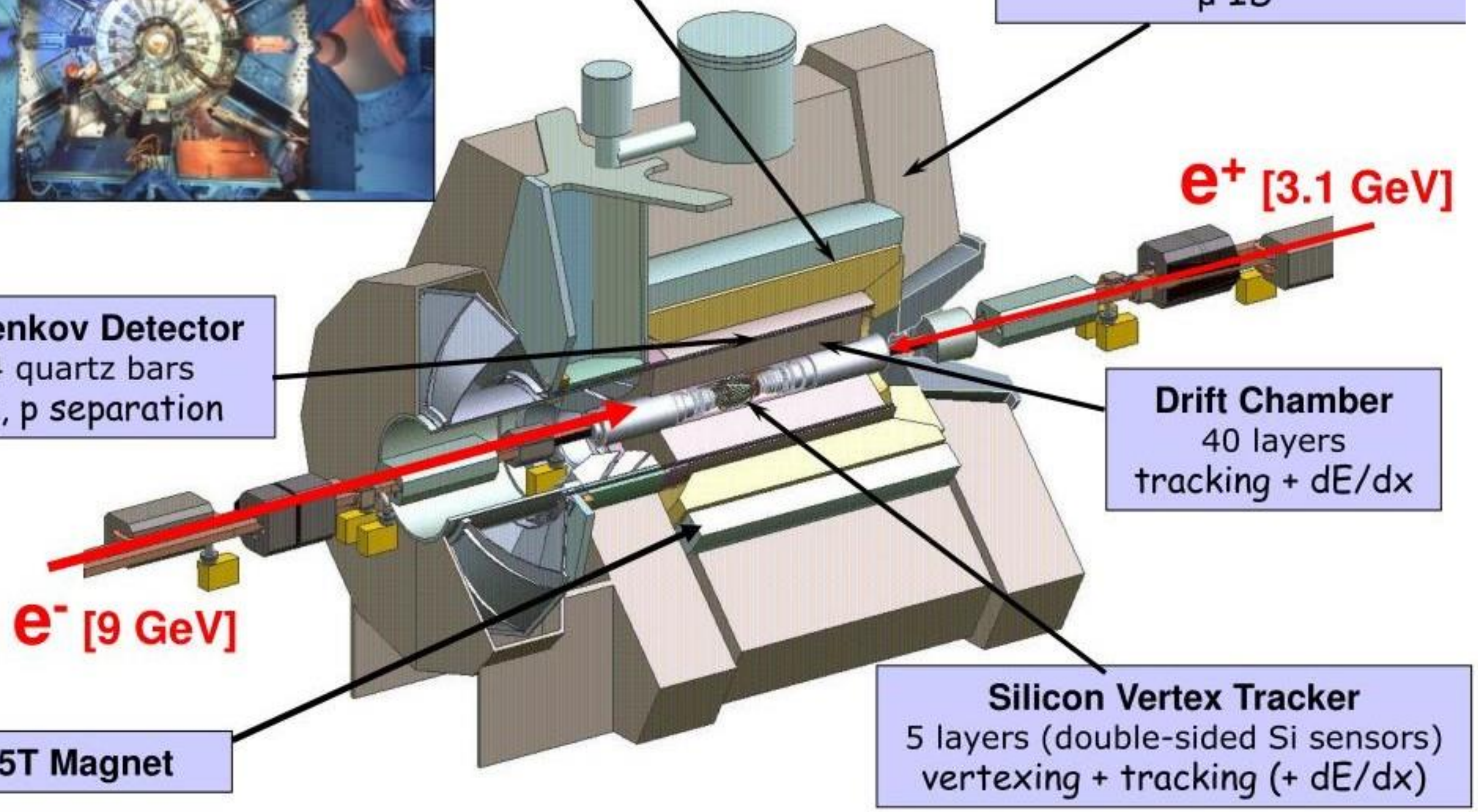
measurable

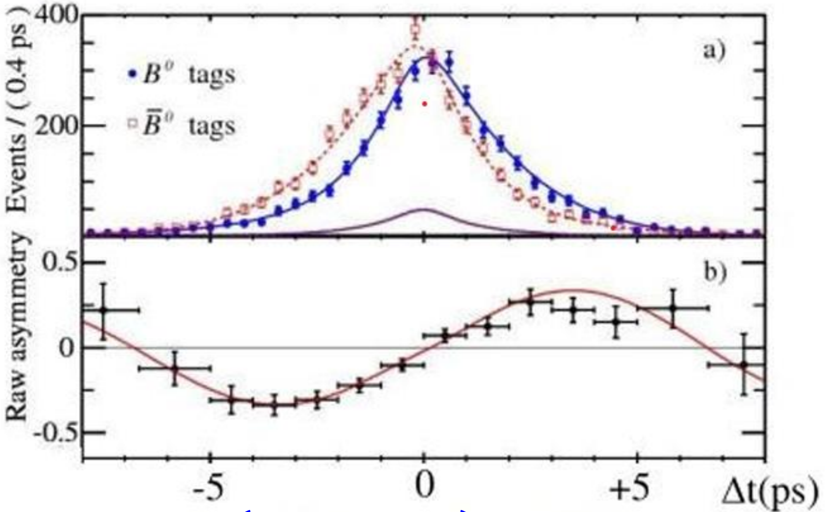
<u>**Example:**</u> $E_{e^-} = 9.1$ GeV, $E_{e^+} = 3.0$ GeV $\to \gamma\beta = 0.56 \Longrightarrow \boldsymbol{\Delta z \approx \gamma\beta\Delta t \approx 300\ \mu}$

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

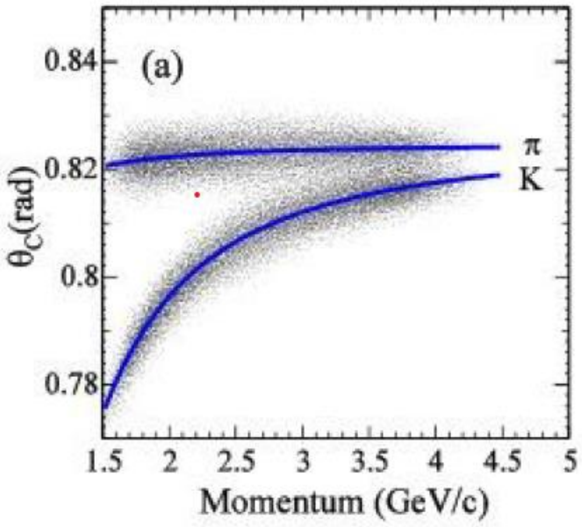
- BaBar (PEPII), Belle (KEKB), Belle II (superKEKB)







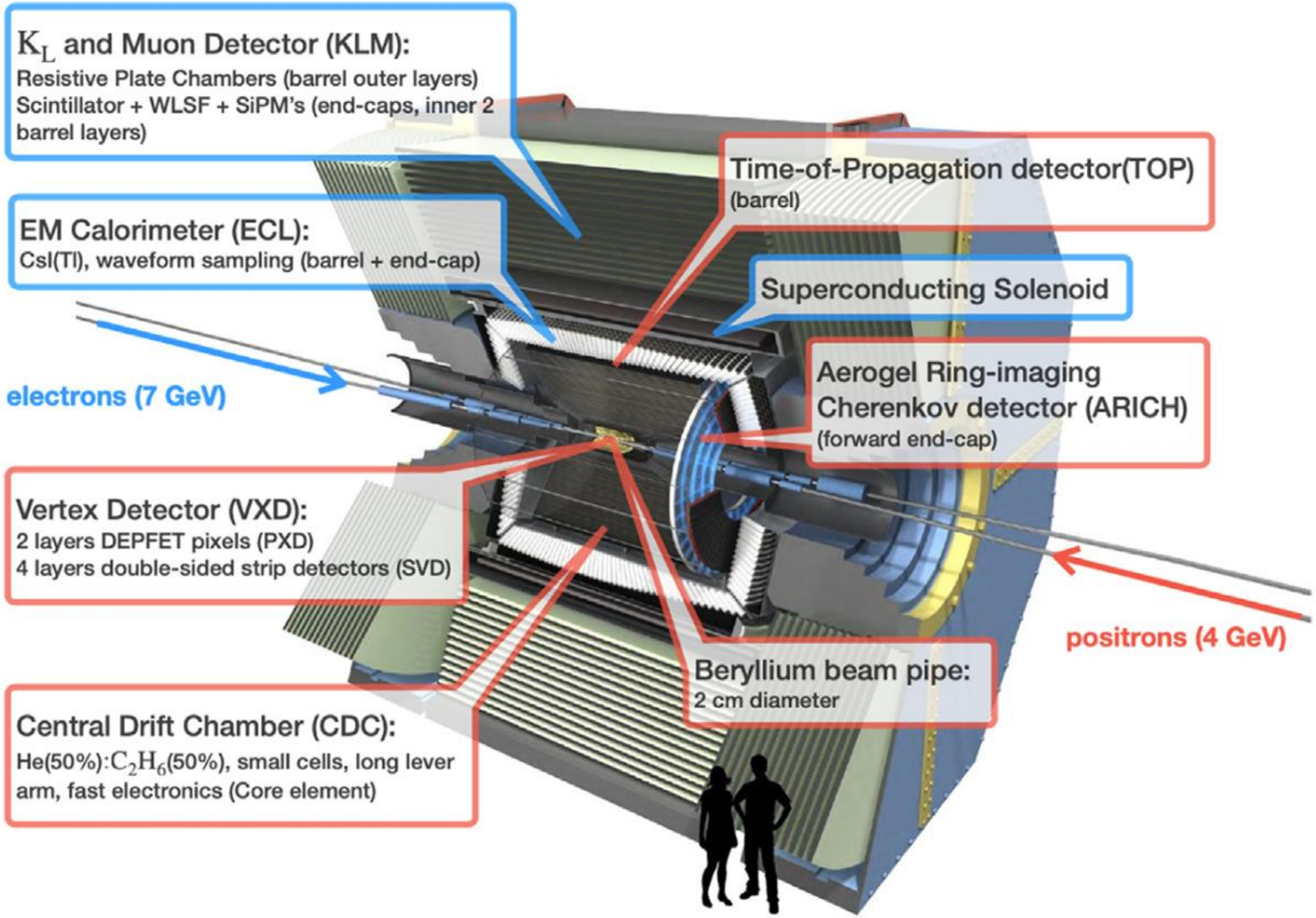
$\sigma_z(\text{vtx } B \text{ reco}) \sim 80\mu m$



Cherenkov angle vs momentum for pions and kaons

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 $\mathcal{L} > 10^{35}\ \mathrm{cm^{-2}s^{-1}}$



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

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

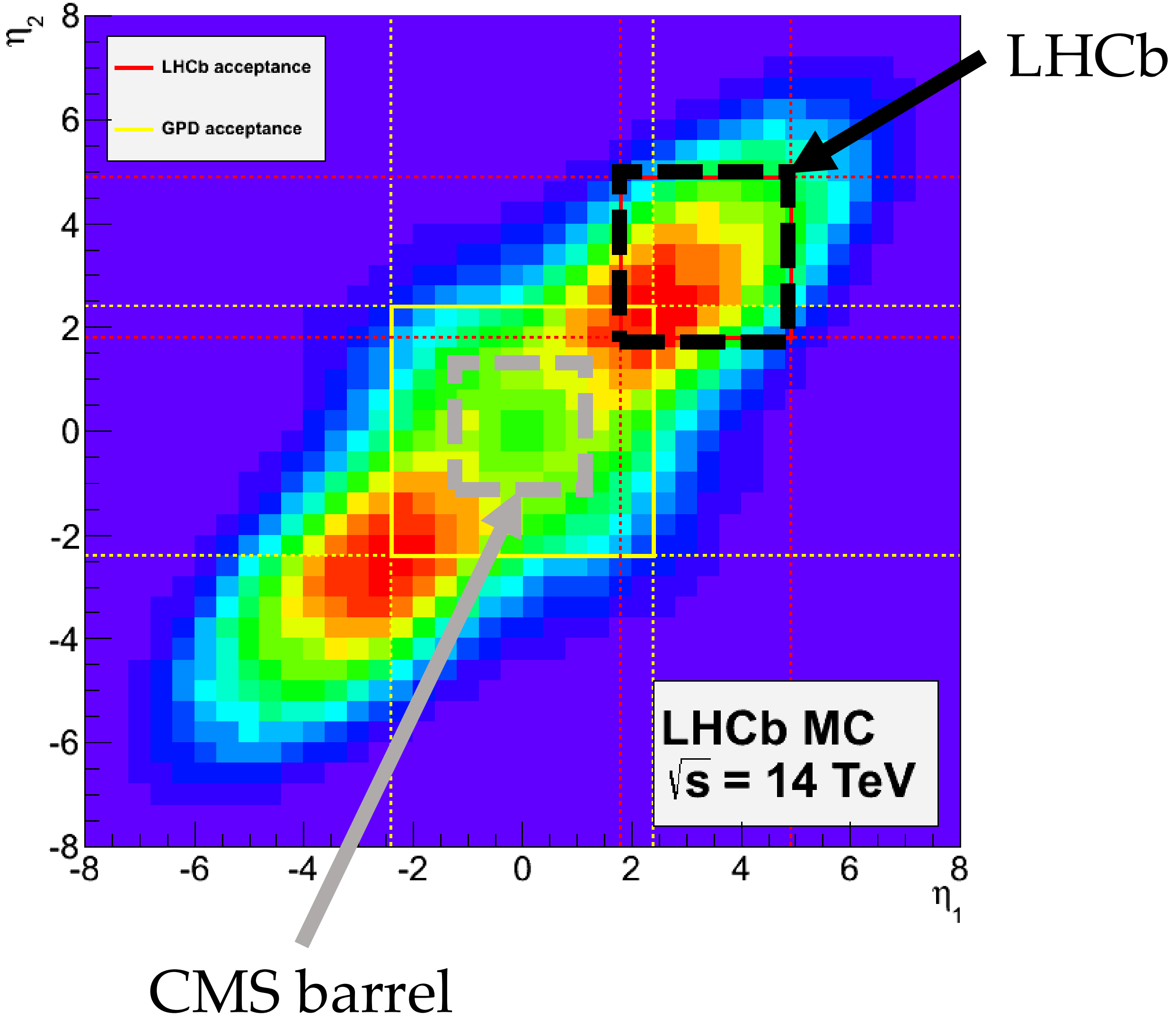
- All possible types of b, c- hadrons produced
- B, D produced with large boost in lab frame
- High energy decay products, but clean particle identification and muon reconstruction
- Relatively low detection efficiency, depending on the detector configuration
- No kinematic constraints
- $\sigma_{b\bar{b}}/\sigma_{\text{inelastic}}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

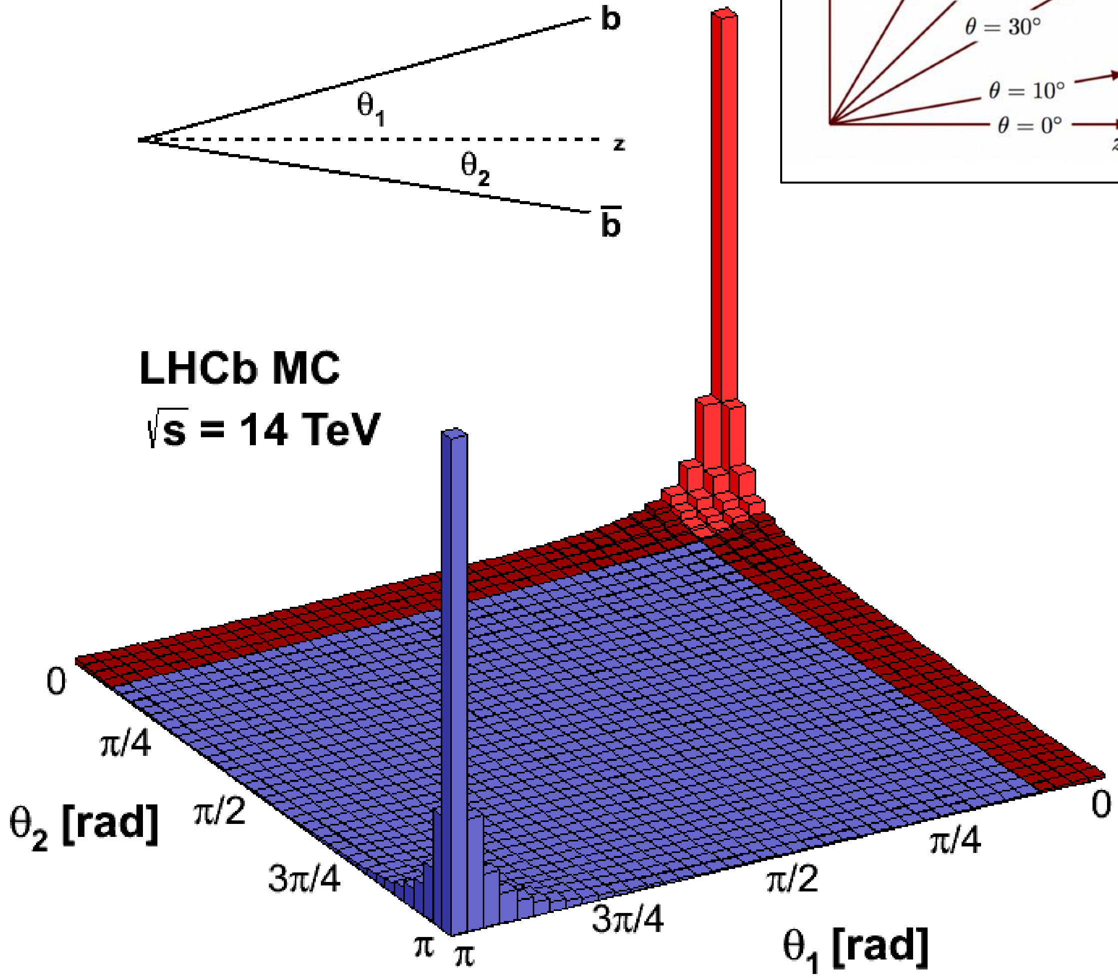
Not extreme luminosity: $\int \mathcal{L} \sim \mathcal{O}(\text{fb}^{-1})$ with peak at $\mathcal{L} = 4 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$ [LHCb]

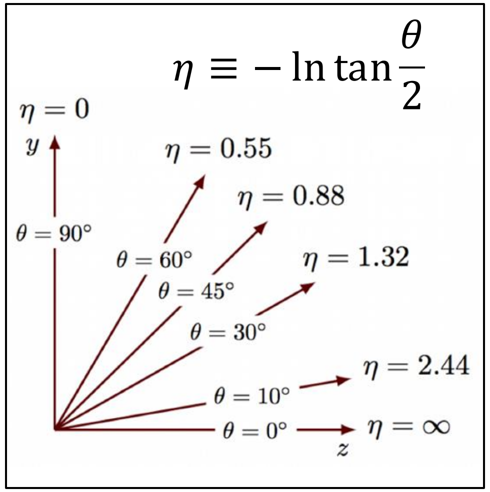
- High cross section: $\sigma_{b\bar{b}} \sim 150\ \mu\text{b}$ @ 13 TeV (LHCb detector coverage) $\Longrightarrow$ $\sim 1.5 \times 10^{11}\ b\bar{b}$ pairs $/\text{fb}^{-1}$
- Prospects for $\times\ 5$ increase soon
- Radiation – resistant detector technology

Flavour physics at pp collider (LHC)

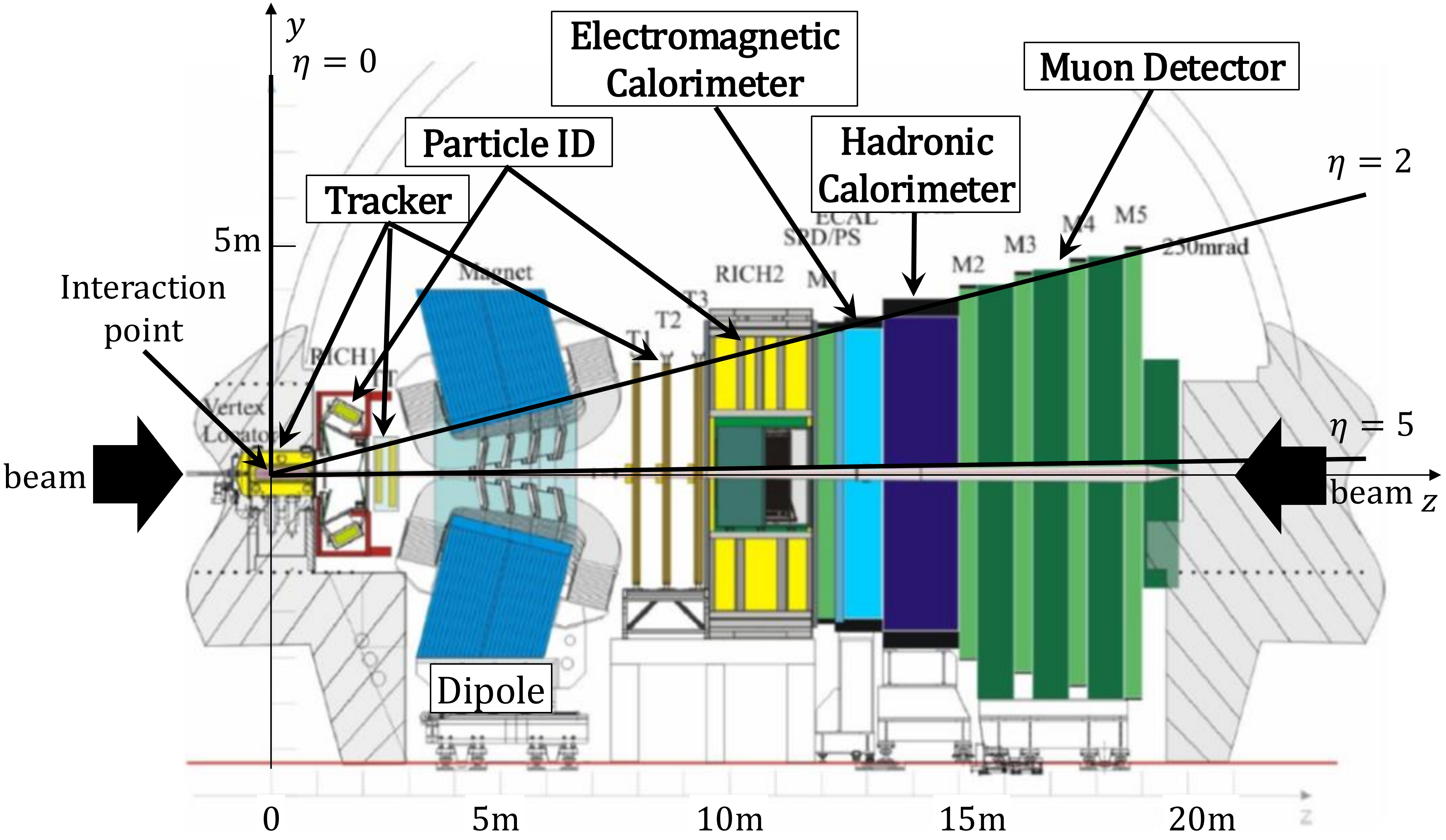
- $\eta_{1,2}(\theta_{1,2})$ = pseudorapidity (polar angle) of the quarks





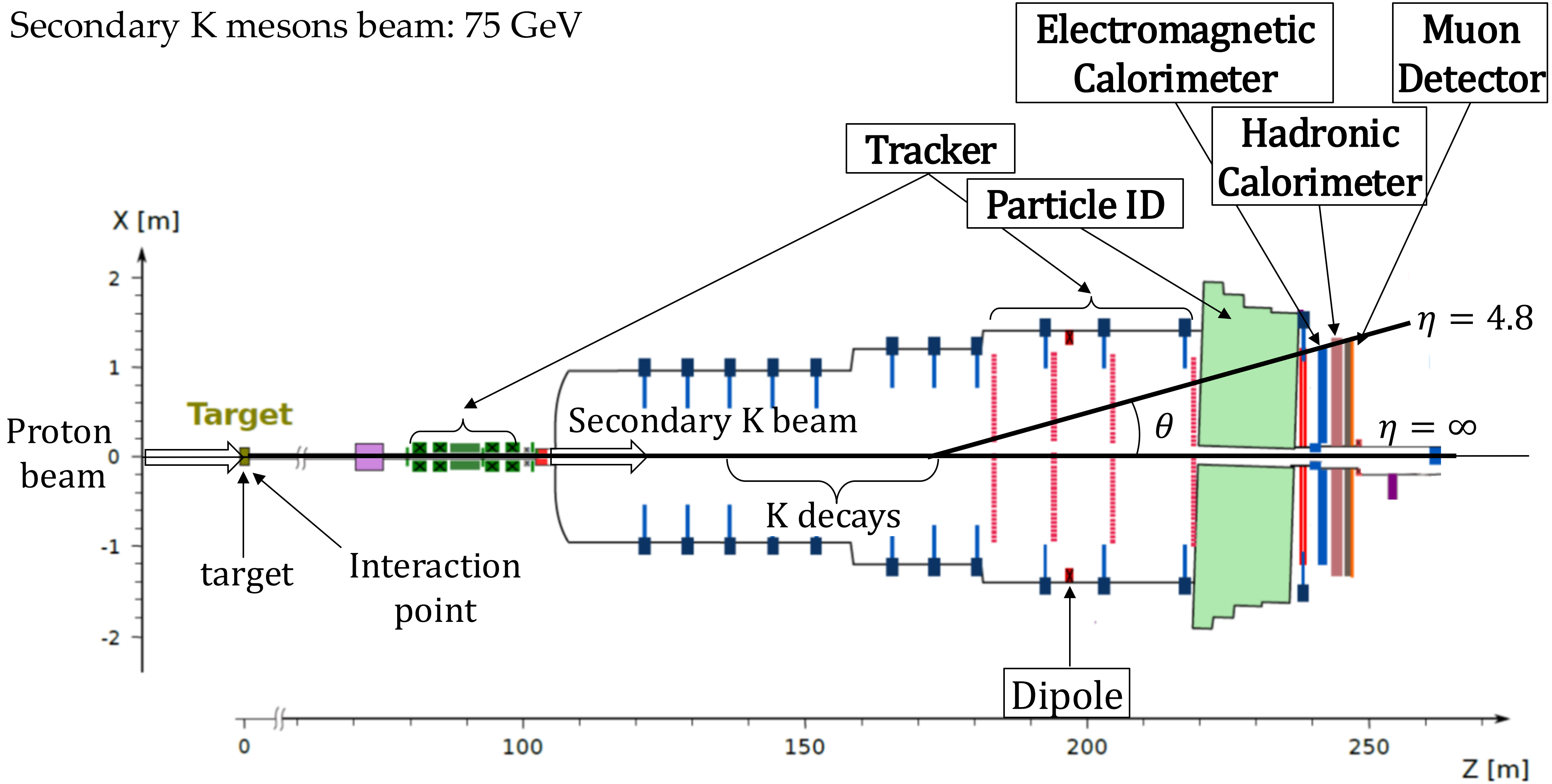


LHCb experiment

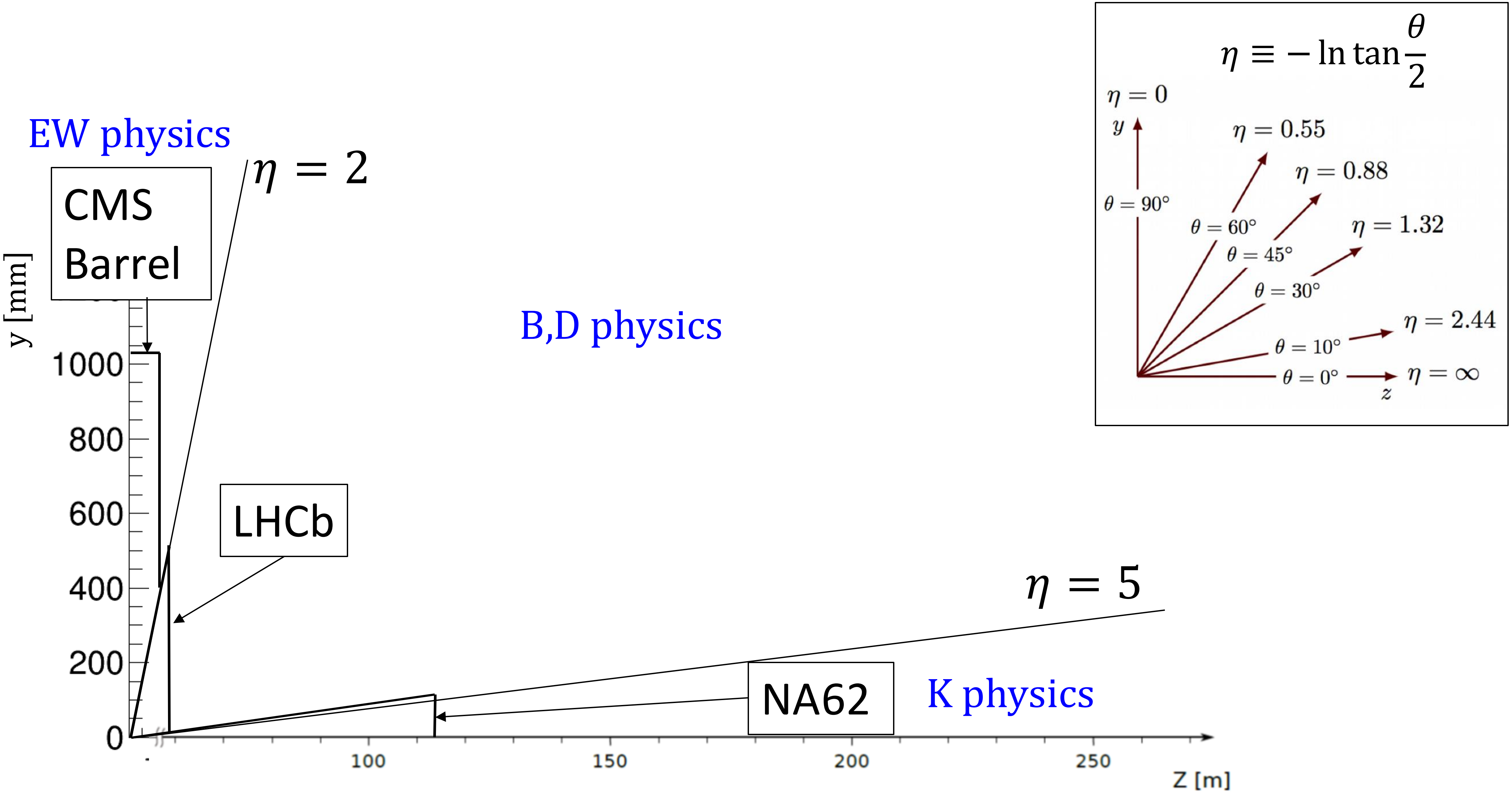


NA62 experiment (fixed target)

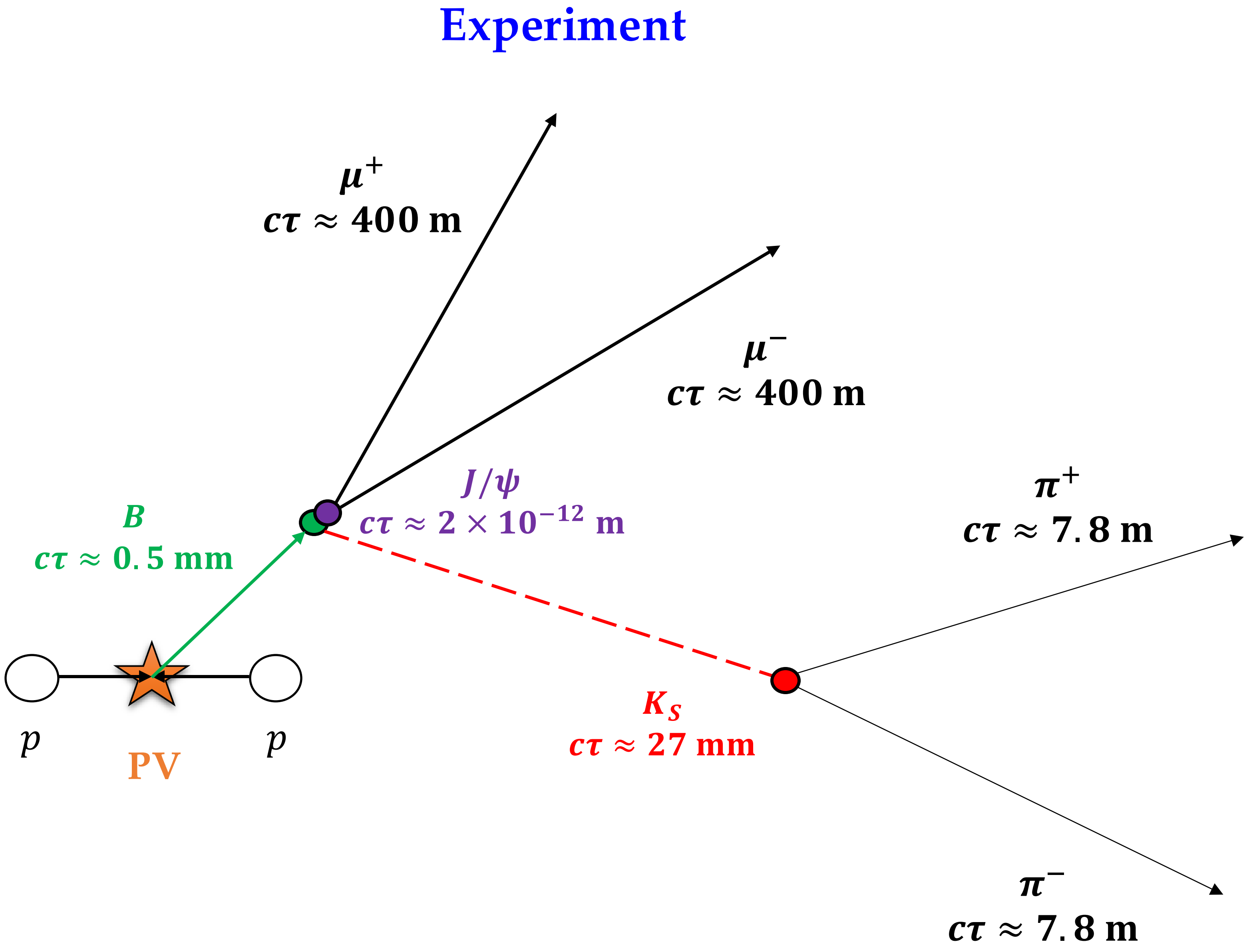
- Designed to study $K^{\pm}$ decays
- Primary protons beam: 400 GeV
- Secondary K mesons beam: 75 GeV

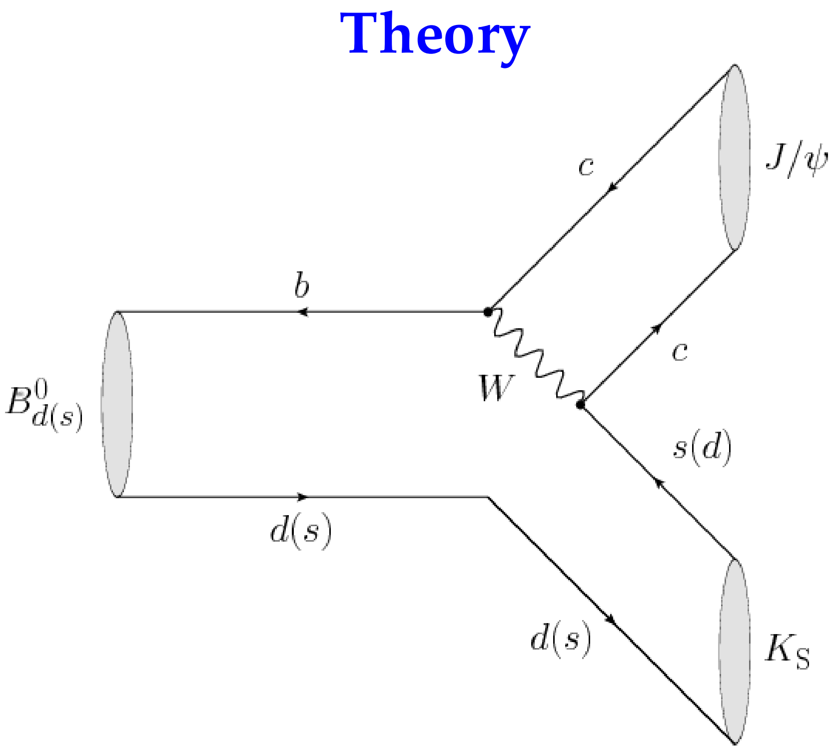


Flavour physics at high energy: summary



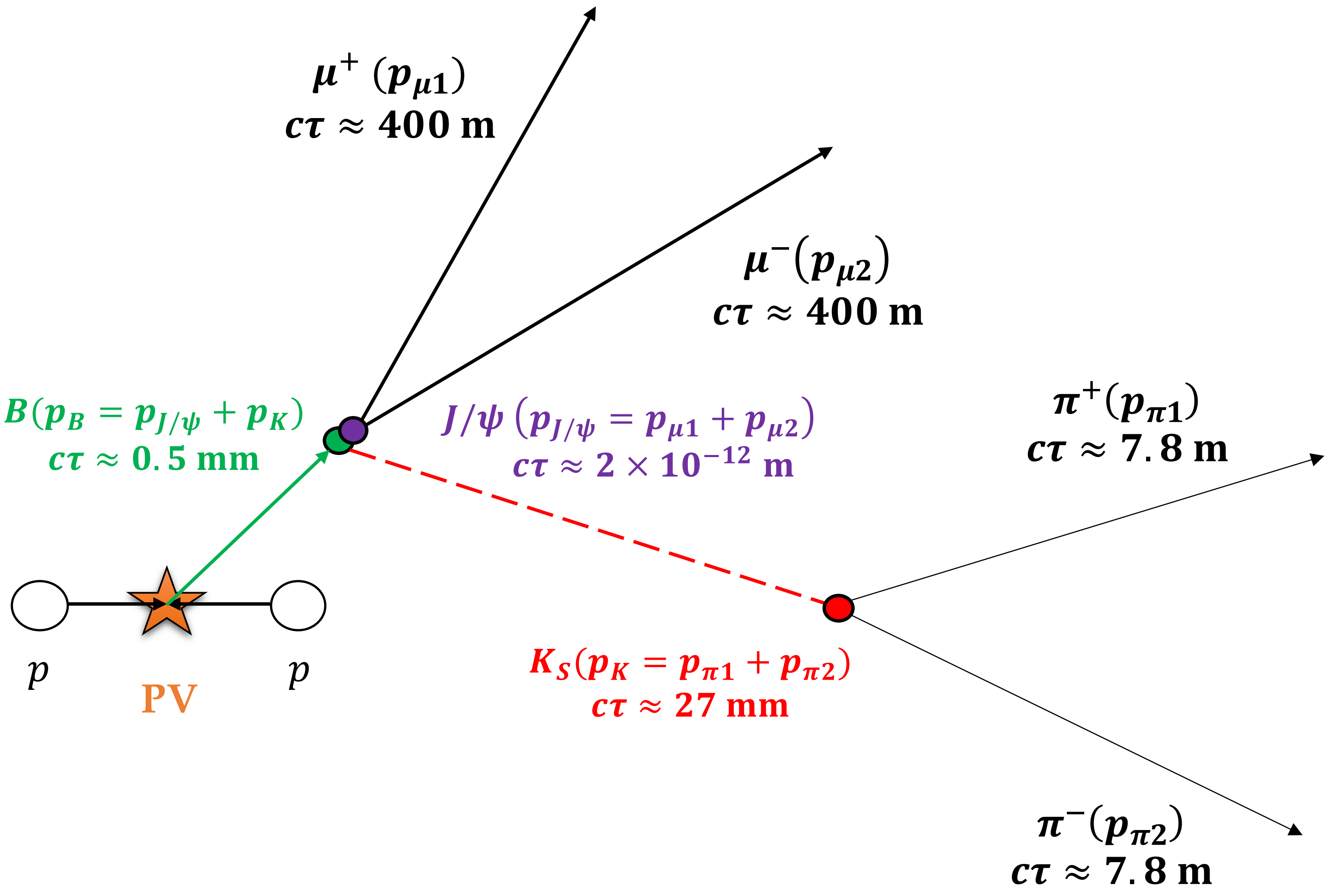
Example: $B^0_{d(s)} \rightarrow J/\psi K_S$



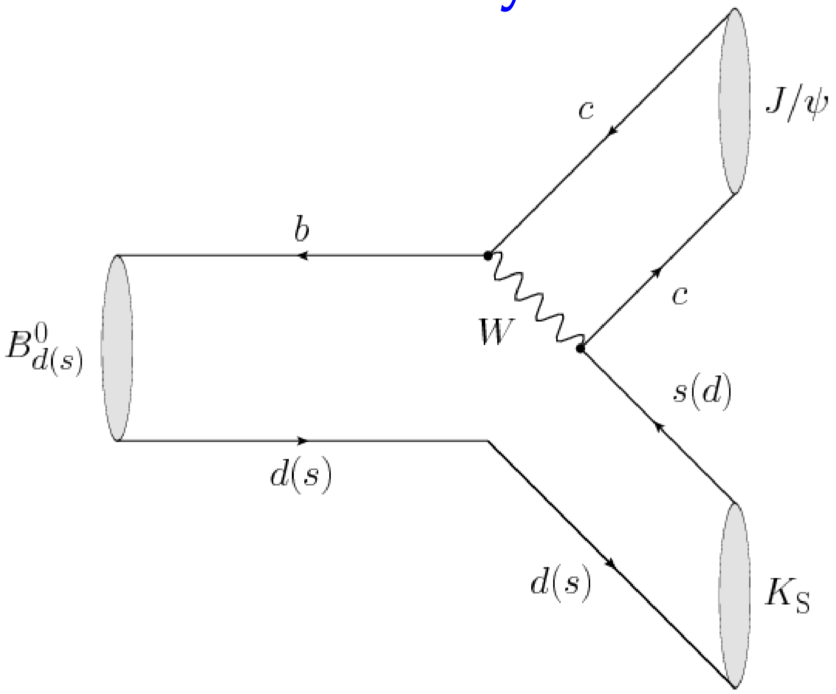


Example: $B^0_{d(s)} \to J/\psi K_S$

Experiment

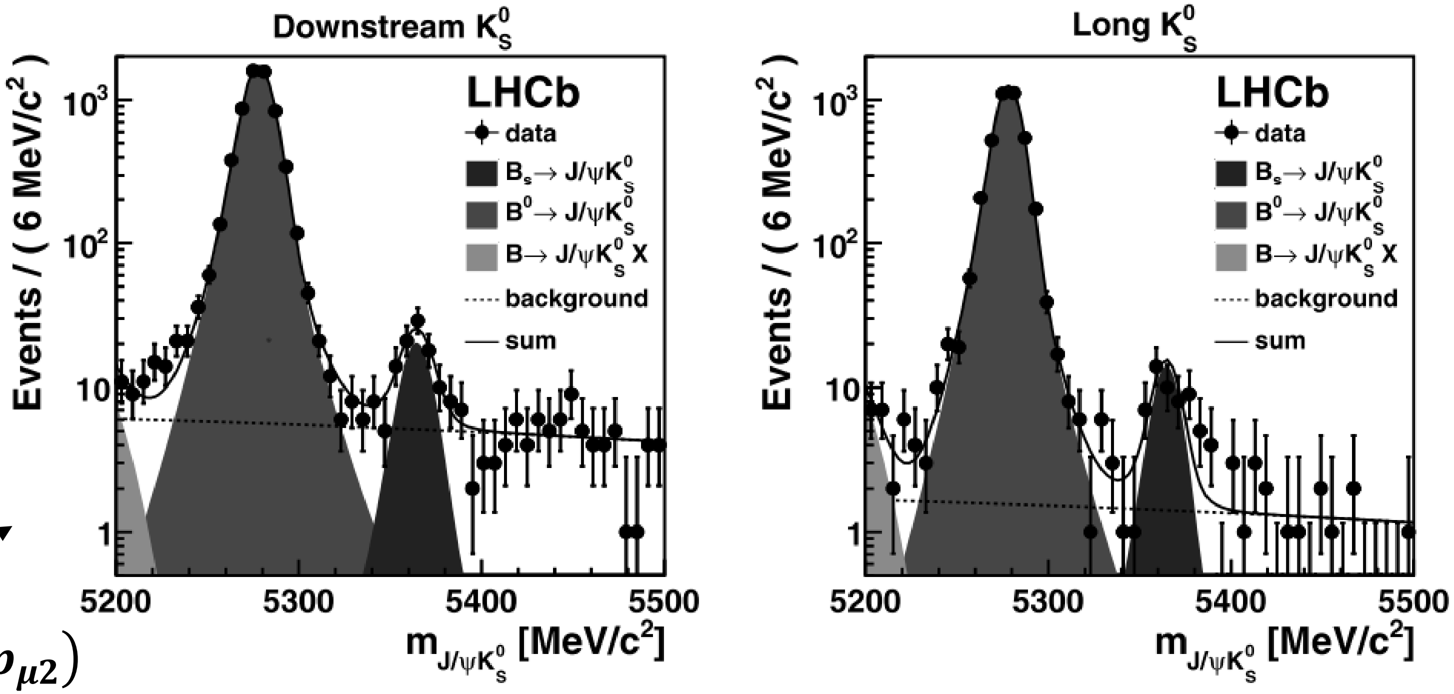


Theory

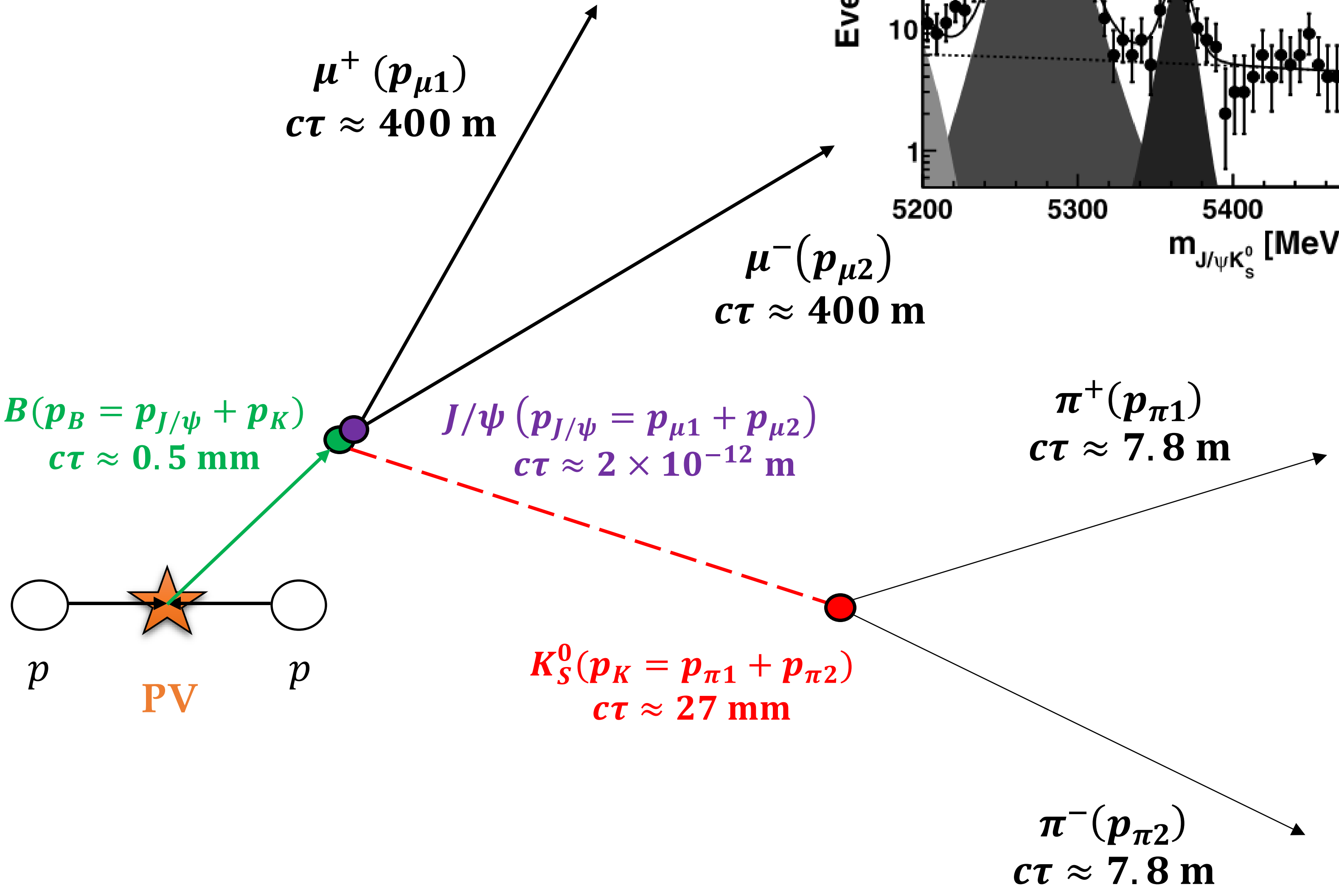


Example: $B^0_{d(s)} \to J/\psi K_S$

Experiment



$$p_B^2 = m^2_{J/\psi K^0_S}$$



Summary of Lecture 7

Main learning outcomes

- What types of mesons we study in flavour physics experiments and how they are produced
- What are the most important experimental aspects of experimental flavour physics
- What are the main past and present facilities used to perform flavour physics experiments