How to design heavy flavor experiment at the LHC

Andrii Usachov

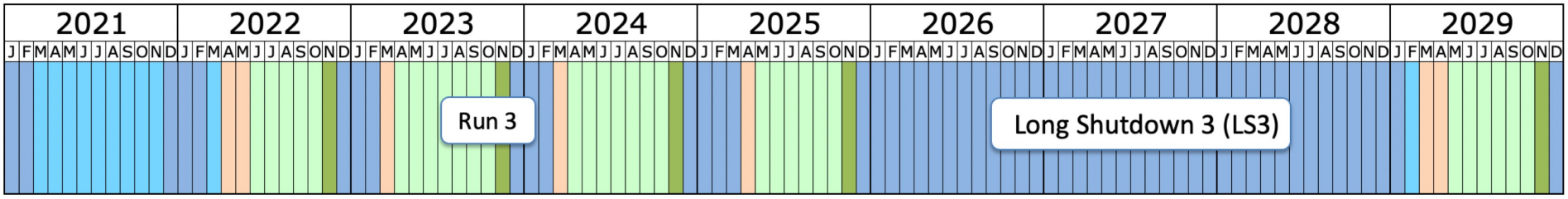
June 6, 2023
Topical lectures on LHC physics - Nikhef

Few words about myself

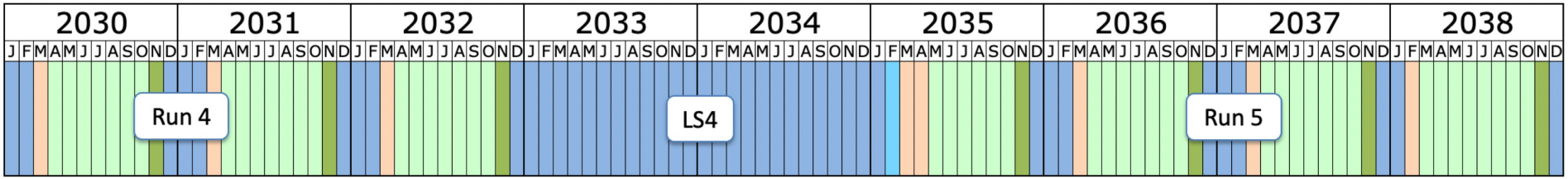
- Bachelor, particle and nuclear physics in Kyiv U.
- 2016
  Master in particle and astroparticle physics,
  University Paris-Saclay
- 2016 – 2019
  PhD at University Paris-Saclay
  - study of quarkonium at LHCb – i.e. QCD data analysis
- 2019 – 2022
  Postdoc at Nikhef with a focus on LHCb tracking for current upgrade
- since mid 2022 - Veni scholar at VU Amsterdam
  - search for long-lived particles at LHCb

LHCb week, Valencia, 2018

Keep this in mind

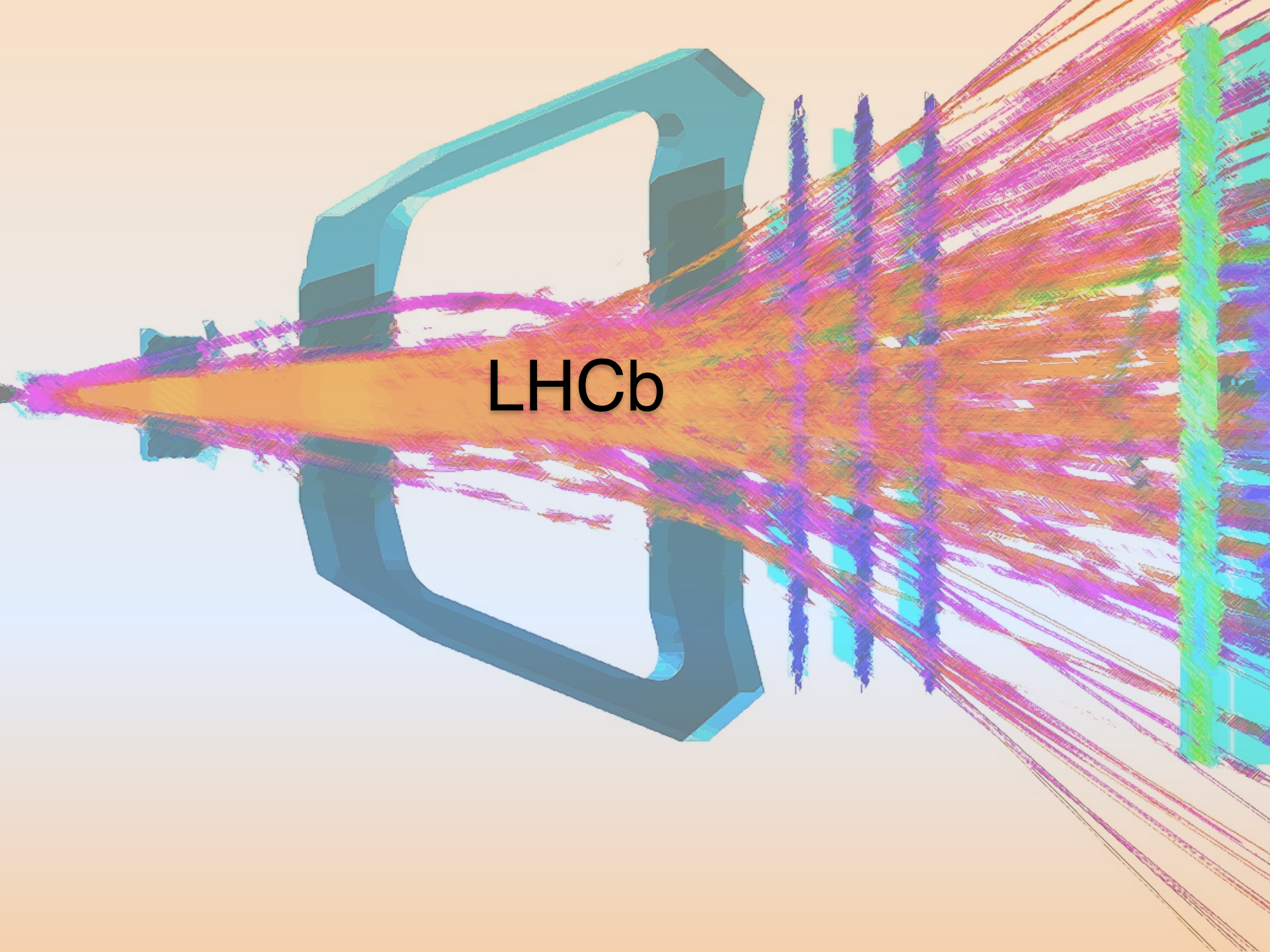


increase in lumi by x5 at LHCb



high lumi LHC

- during runs – focus on physics but also RD for next upgrade
- long shutdowns – produce hardware and software
- every upgrade is a massive challenge for hardware and software


LHCb

LHC-B back in 1995

LHC-B

LETTER OF INTENT

A Dedicated LHC Collider Beauty Experiment for Precision Measurements of CP-Violation

Abstract

The LHC-B Collaboration proposes to build a forward collider detector dedicated to the study of CP violation and other rare phenomena in the decays of Beauty particles. The forward geometry results in an average 80 GeV momentum of reconstructed B-mesons and, with multiple, efficient and redundant triggers, yields large event samples. B-hadron decay products are efficiently identified by Ring-Imaging Cerenkov Counters, rendering a wide range of multi-particle final states accessible and providing precise measurements of all angles, α, β and γ of the unitarity triangle. The LHC-B microvertex detector capabilities facilitate multi-vertex event reconstruction and proper-time measurements with an expected few-percent uncertainty, permitting measurements of B_s-mixing well beyond the largest conceivable values of x_s. LHC-B would be fully operational at the startup of LHC and requires only a modest luminosity to reveal its full performance potential.

LHC-B back in 1995

NIKHEF, Amsterdam, The Netherlands

[1]University of Amsterdam[2]University of Utrecht[3]Foundation for Fundamental Research of Matter in the Netherlands

G. v. Apeldoorn[1]Th.S. Bauer[2,3] A. Buijs[2]B. Koene[3]P.M. Kooijman[1]M. Merk[3]W. Ruckstuhl[3]J. Timmermans[3]J. Visschers[3]

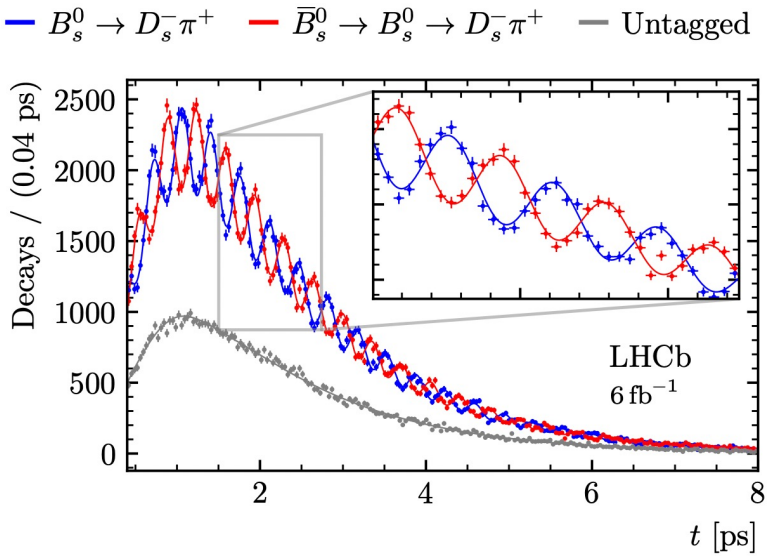
The exercise for today

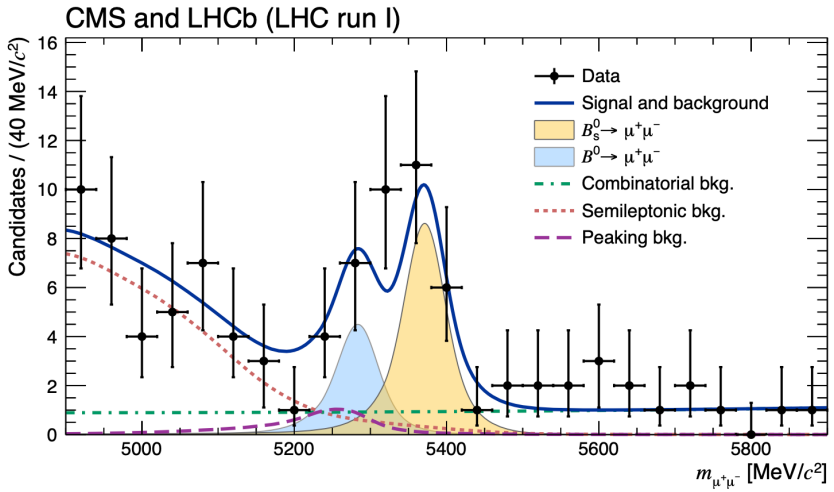
Provided:

- desire to study *b*-hadrons
- LHC machine with proton beams of 3.5 – 6.5 TeV
- cavern and space in it for ~20m long detector

⇒ **end up with the detector design**
**focus on tracking, not so much on PID*

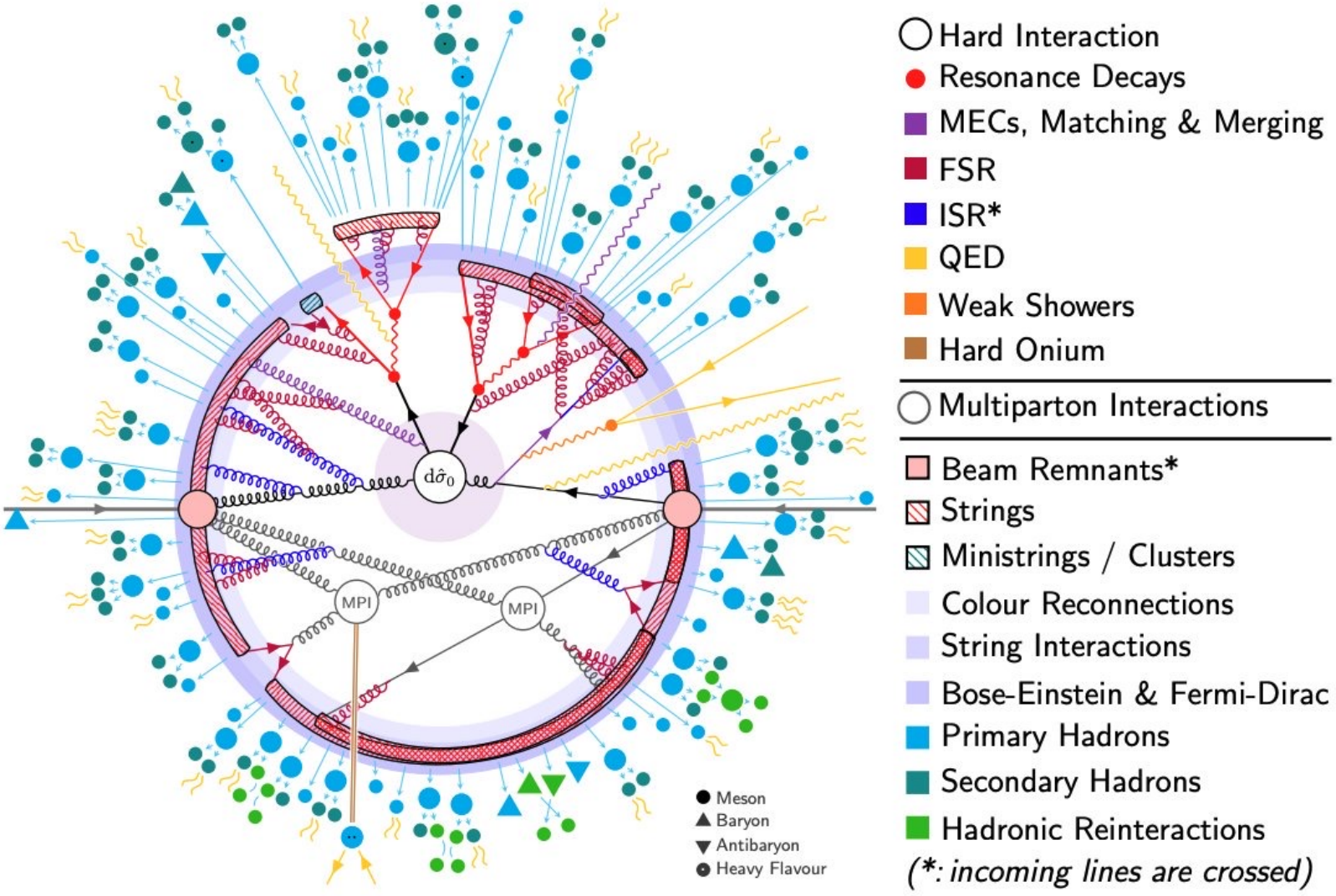
- compare current LHCb and LHC-B back in 1995
- physics reach and competitors?





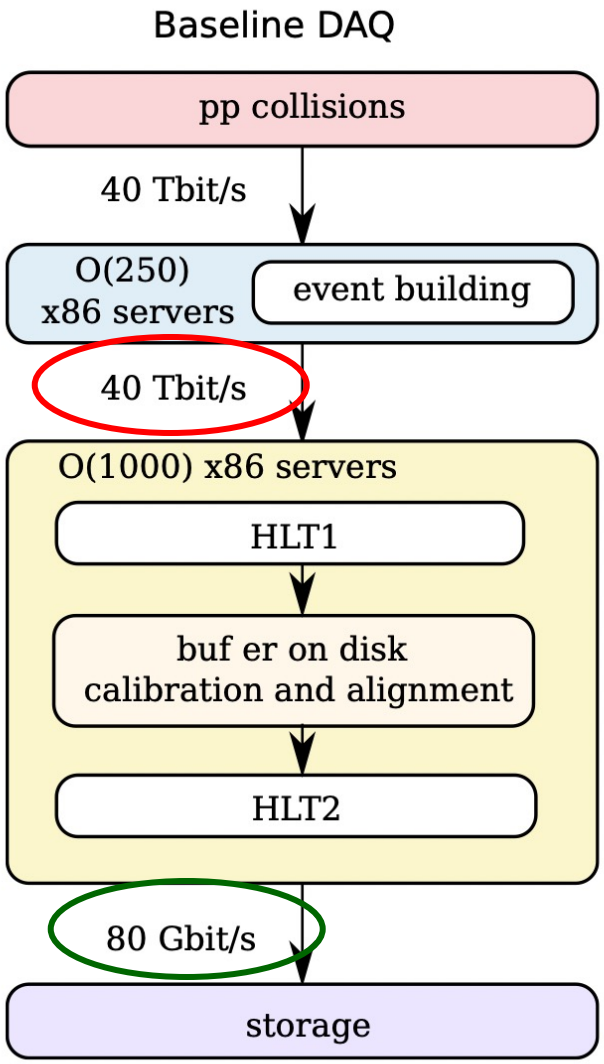
LHC collision in one picture

https://twitter.com/PlotPhysics
best physics plot of 2022



mess every 25 ns

computing challenge: trigger



impossible to store

fast online real-time analysis, partial reconstruction to identify events with b-quark

affordable data flow

computing challenge: trigger

impossible to store

fast online real-time analysis, partial reconstruction to identify events with b-quark

affordable data flow

we need to find a way to identify events with *b*-quark quickly/online

* without storing all the event information

1. what particles are produced in LHC collisions?

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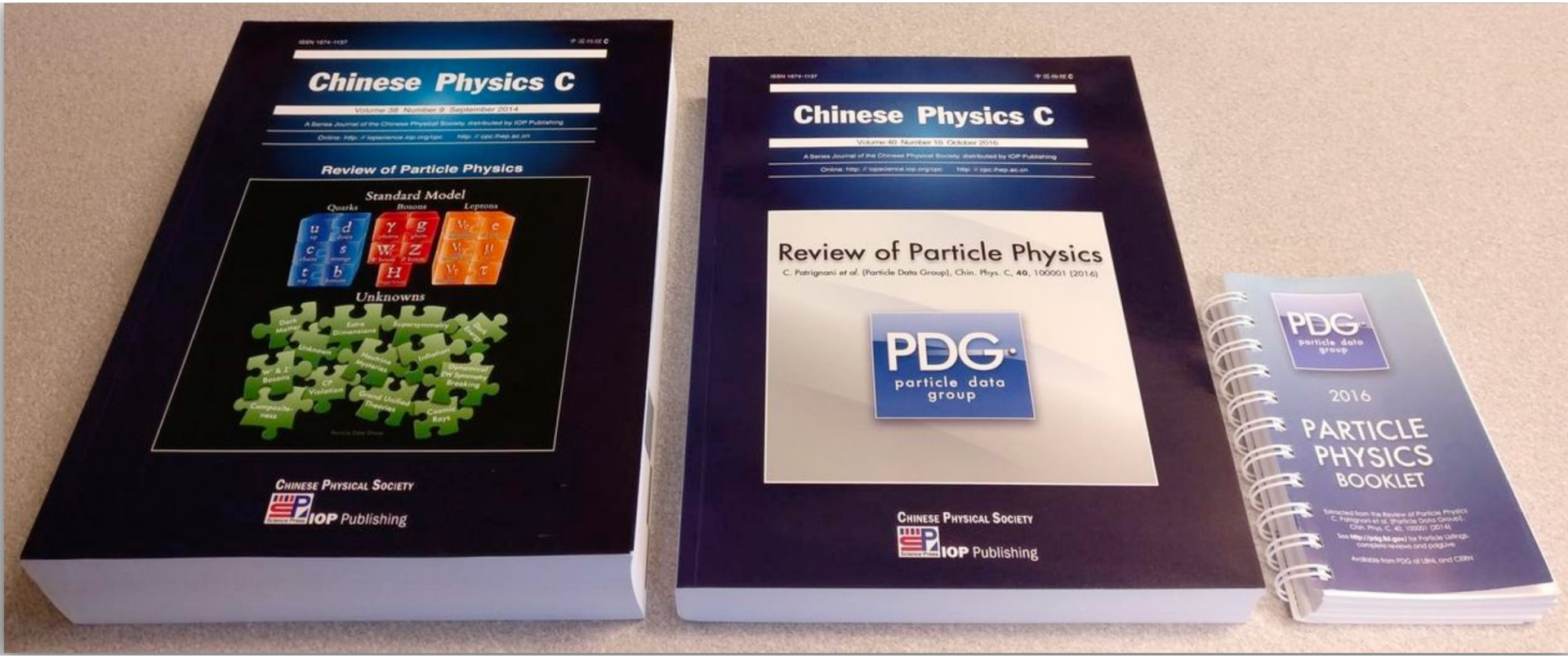
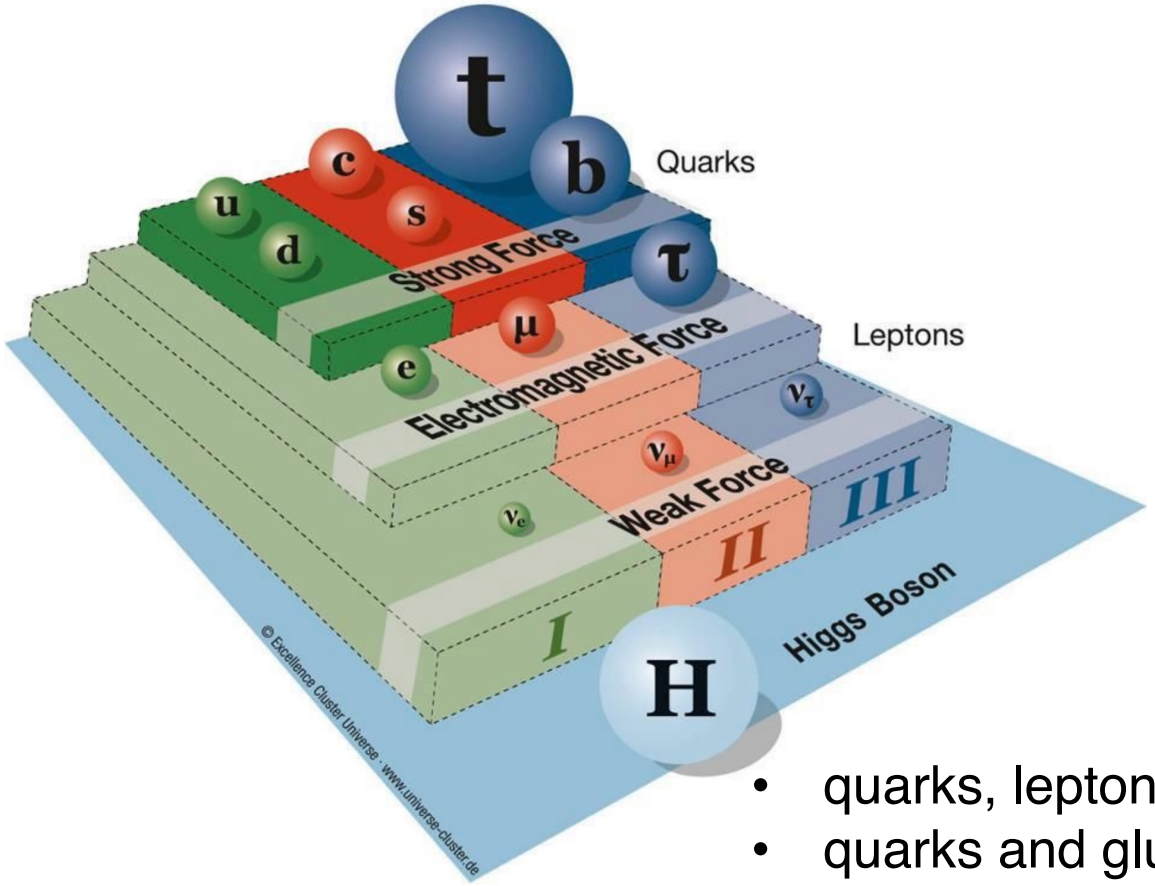
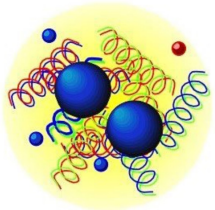


all of them

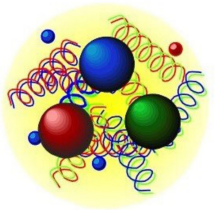
standard model



- quarks, leptons and gauge bosons
- quarks and gluons are confined in hadrons: mesons and baryons (mainly)

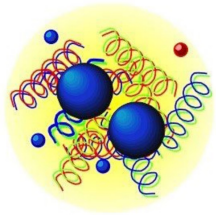


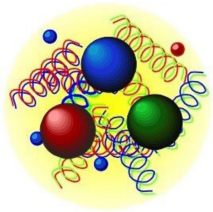
meson



baryon

zoo of particles: mesons and baryons



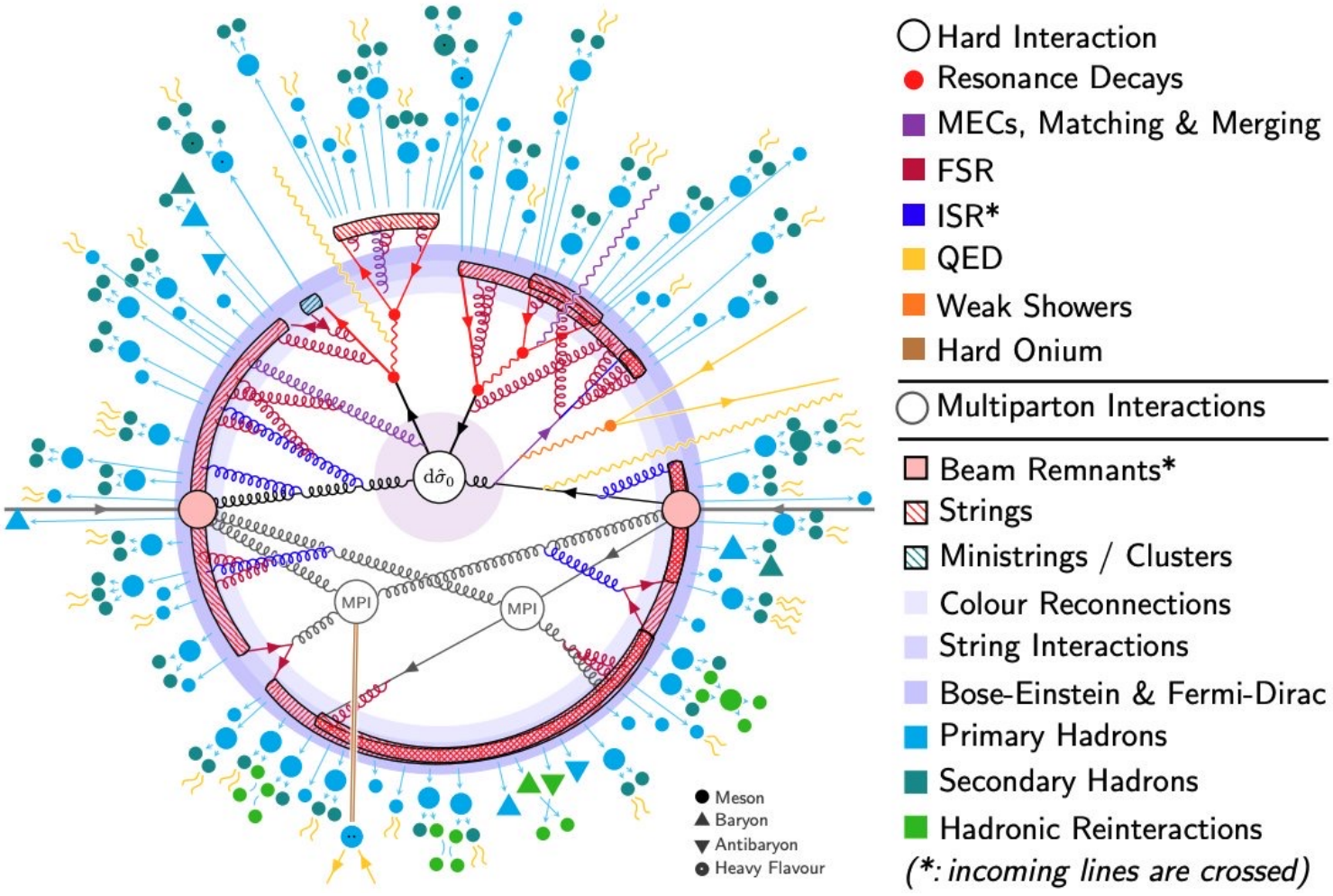


Mesons	reviews
Light Unflavored	
Strange	
Charmed	
Charmed, Strange (incl. possibly non-$q\bar{q}$ states)	
Bottom	
Bottom, Strange	
Bottom, Charmed	
$c\bar{c}$ (incl. possibly non-$q\bar{q}$ states)	
$b\bar{b}$ (incl. possibly non-$q\bar{q}$ states)	
Other Mesons	

Baryons	reviews
N Baryons	
Δ Baryons	
Λ Baryons	
Σ Baryons	
Ξ Baryons	
Ω Baryons	
Charmed Baryons	
Doubly-Charmed	
Bottom Baryons	
Exotic Baryons	

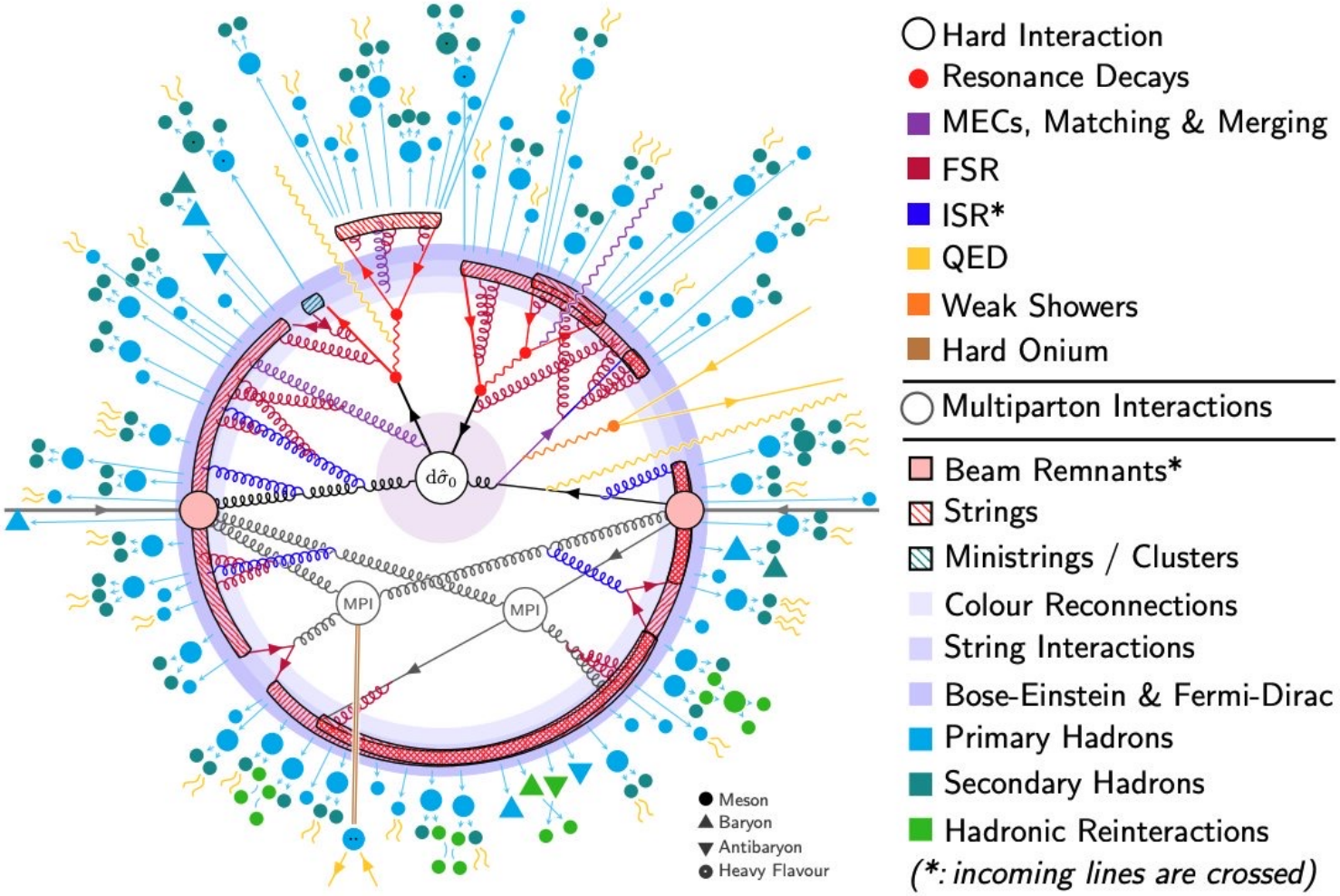
Each category is a family of particles:

- ground state and excited states
- excited states decay strongly, i.e. immediately



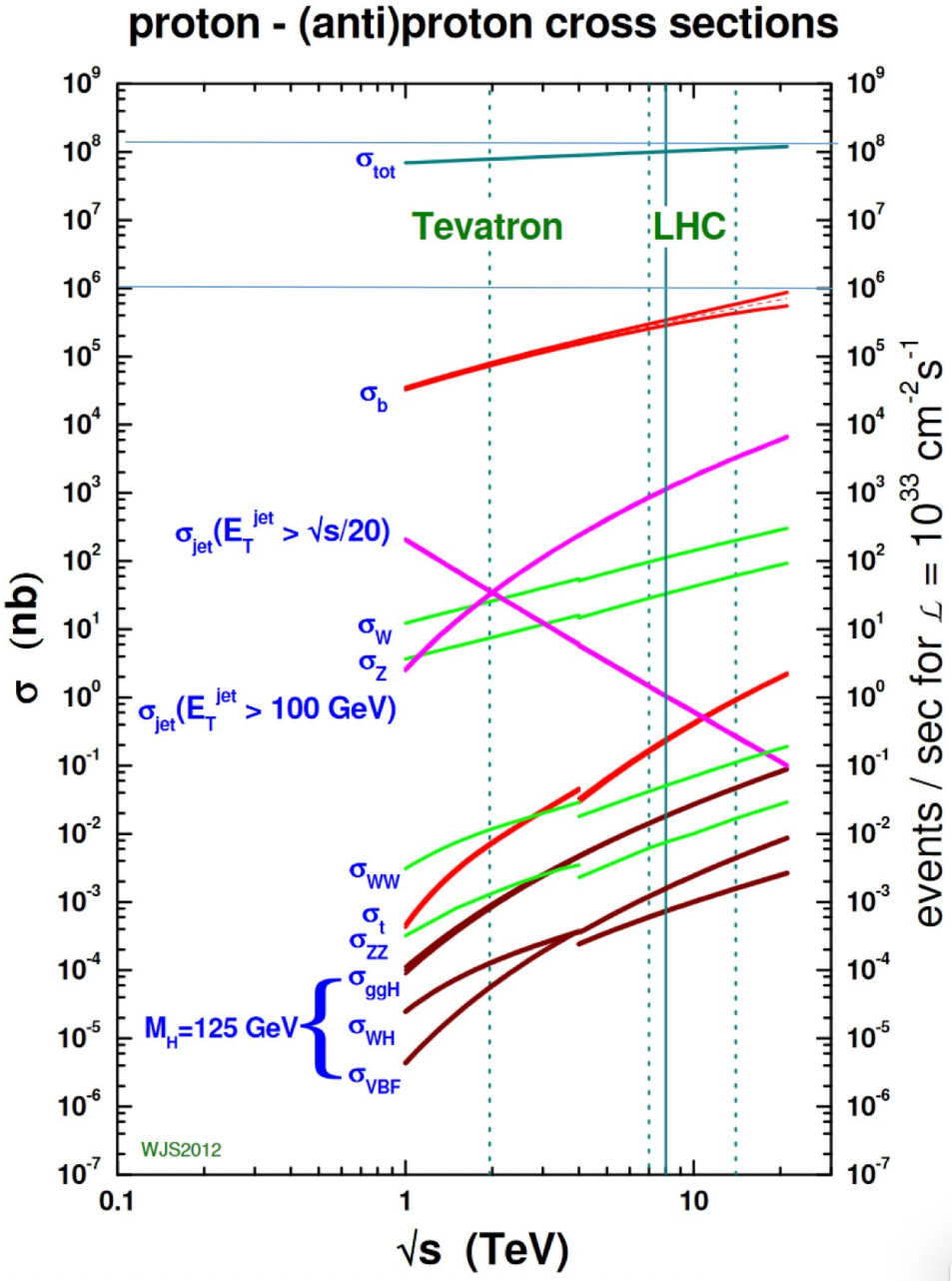
top N most abundantly produced particles in LHC collisions?

most abundant particles



- QCD is the origin of large particle multiplicity
- lighter particles are more abundant*
- hadronic resonances decay immediately to lighter hadrons

b-quark production

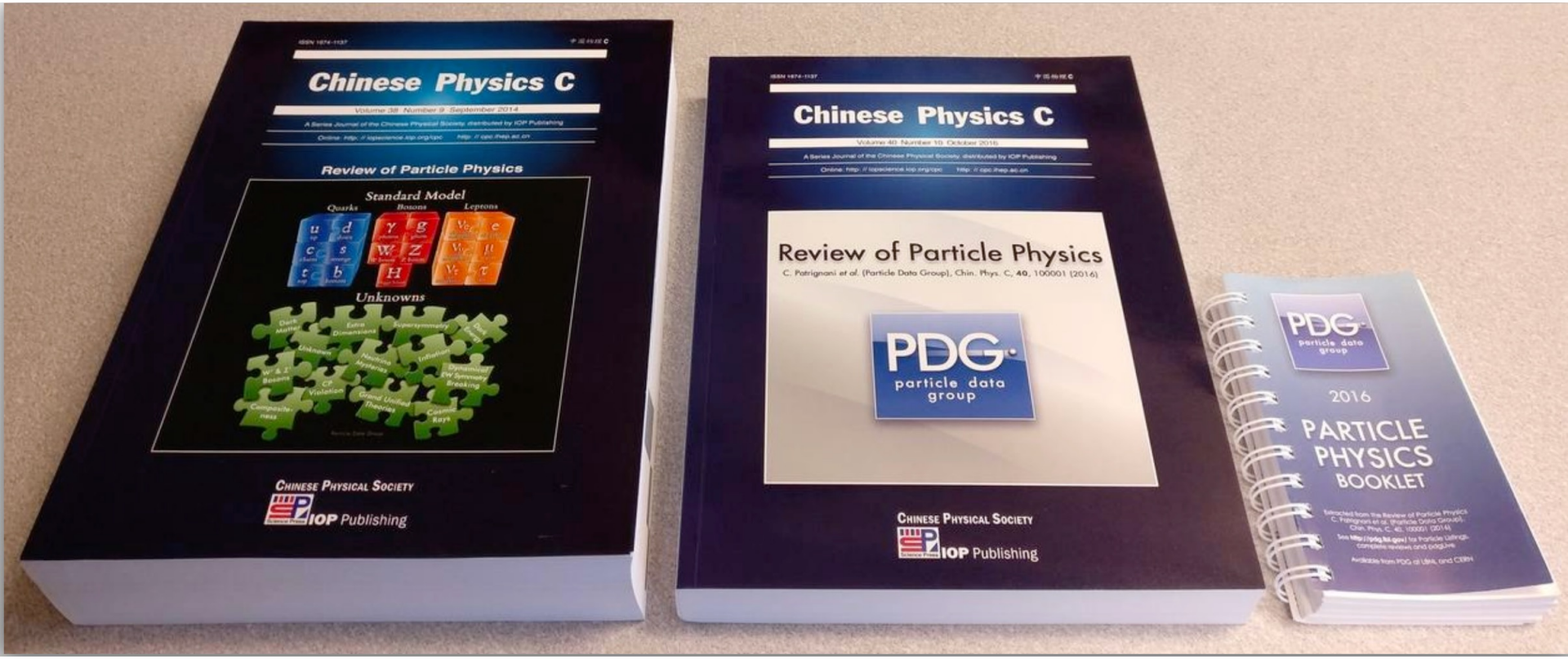


b quark is produced in <1% of collisions

particles vs lifetime

sort particles by lifetime and identify

- detector-stable : flight distance > 20m
- long-lived : significant non-zero flight distance
- prompt : all the others



particles vs lifetime

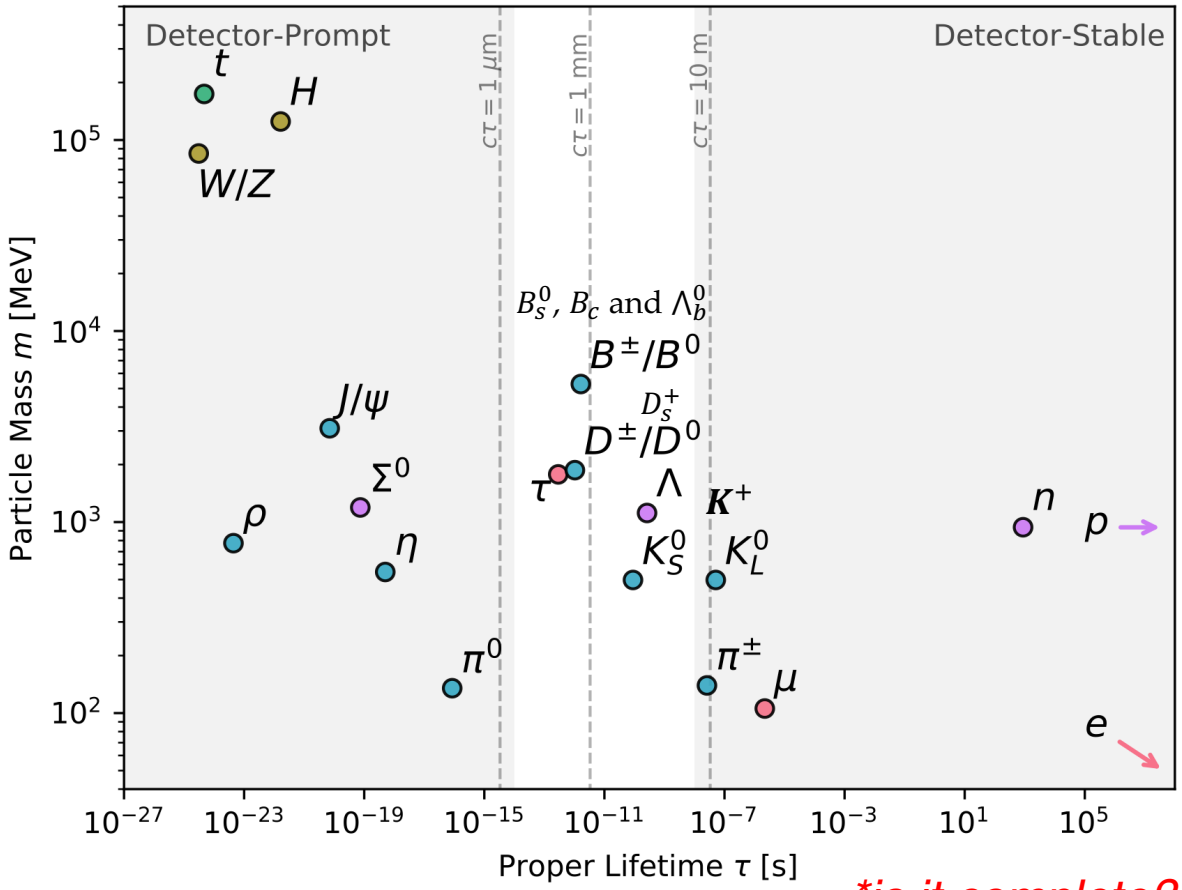
sort particles by lifetime and identify

- detector-stable : flight distance > 20m
- long-lived : significant non-zero flight distance
  (sort in 2 groups)
- prompt : all the others

mesons

baryons

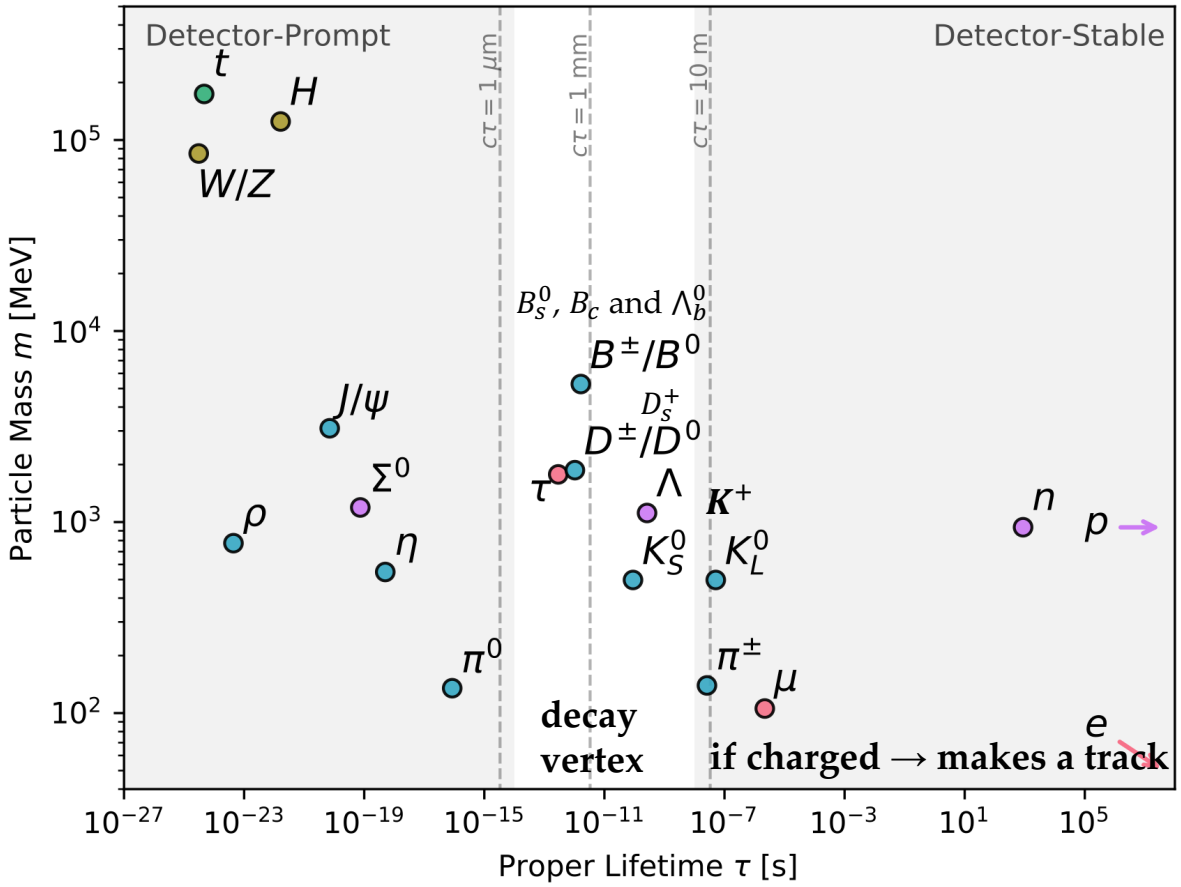
particles vs lifetime



**is it complete?*

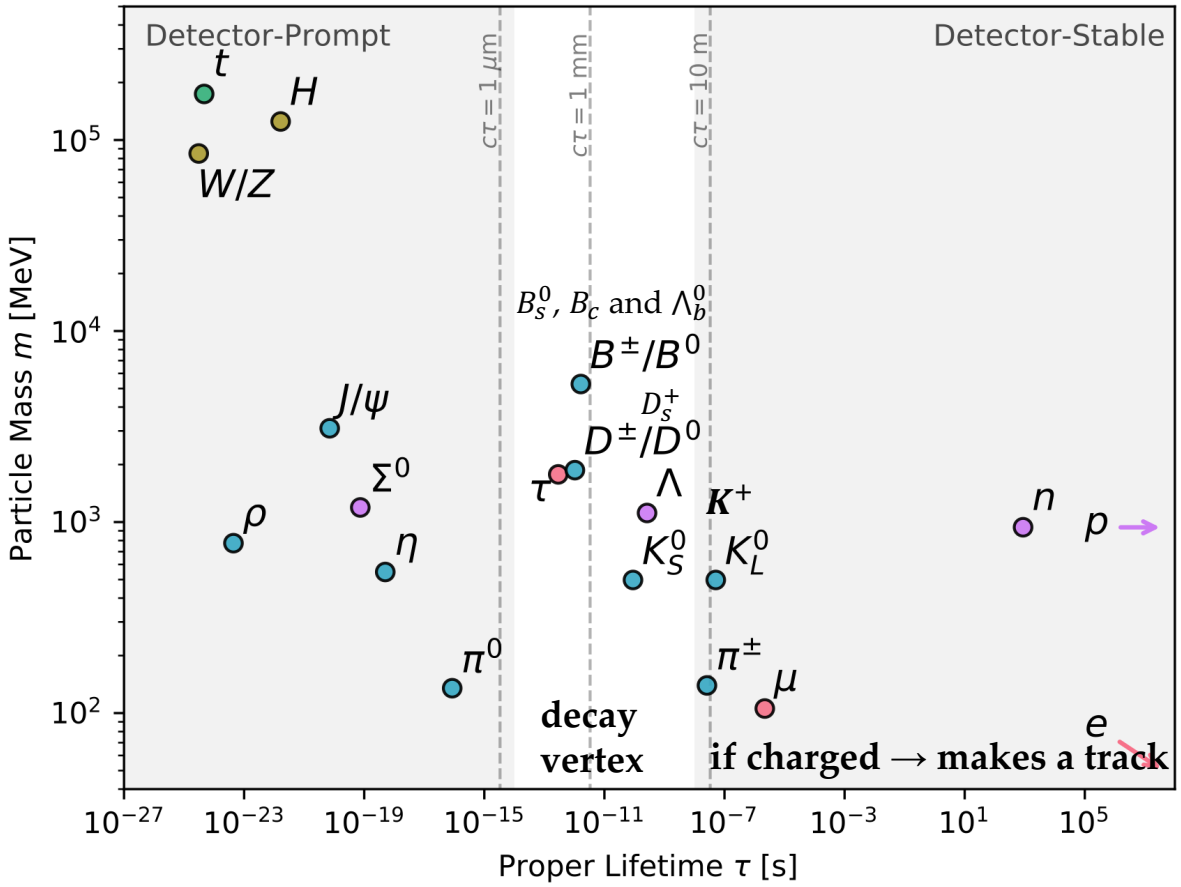
- 5 types of <u>detector-stable charged</u> particles
  => discrete problem, **distinguished by PID detectors**
- 10ish types of particles decay within detector volume
- others decay promptly

particles vs lifetime



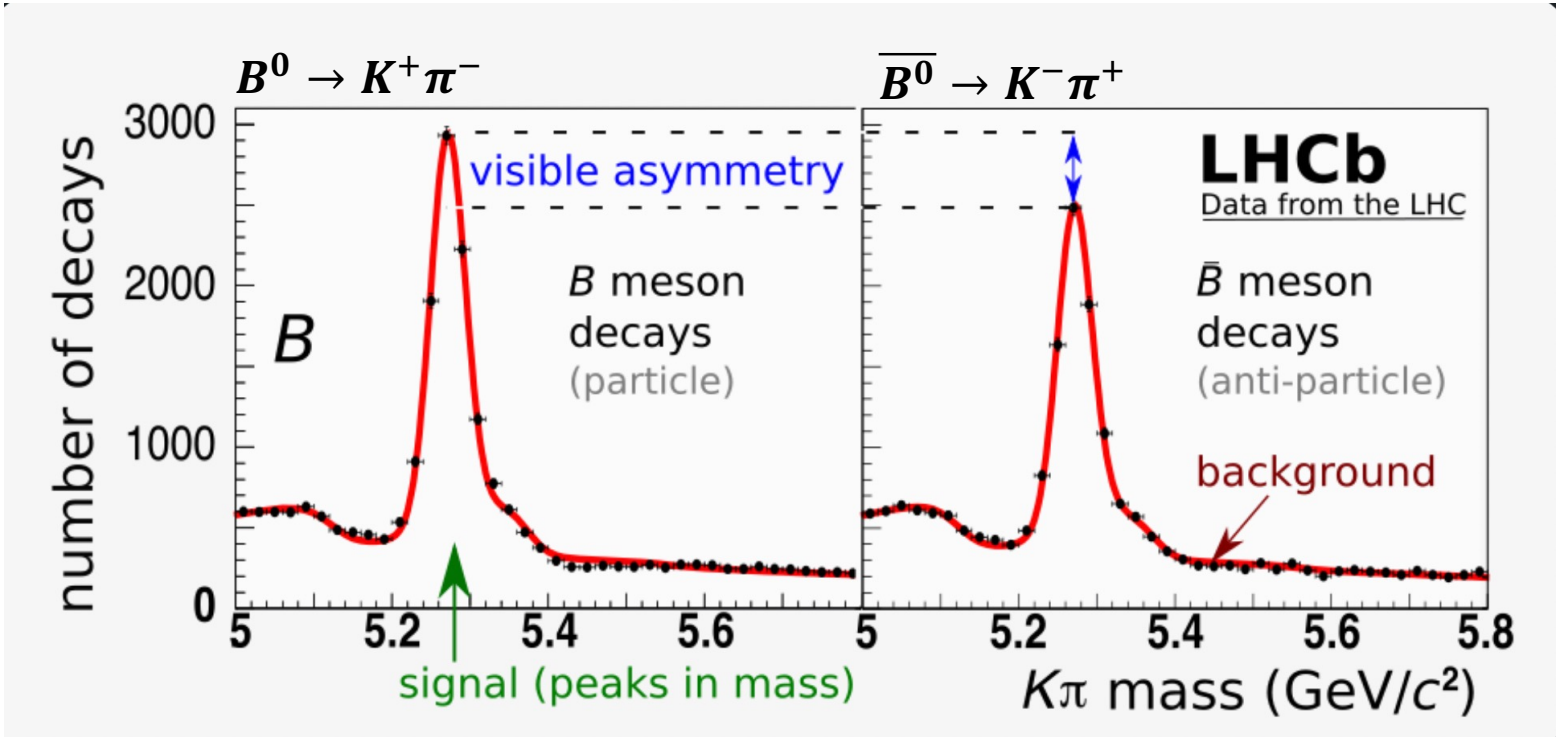
- detector-stable → direct detection
  which one is the rarest?
- long-lived → significantly displaced decay vertex
- prompt → comes from primary vertex

particles vs lifetime



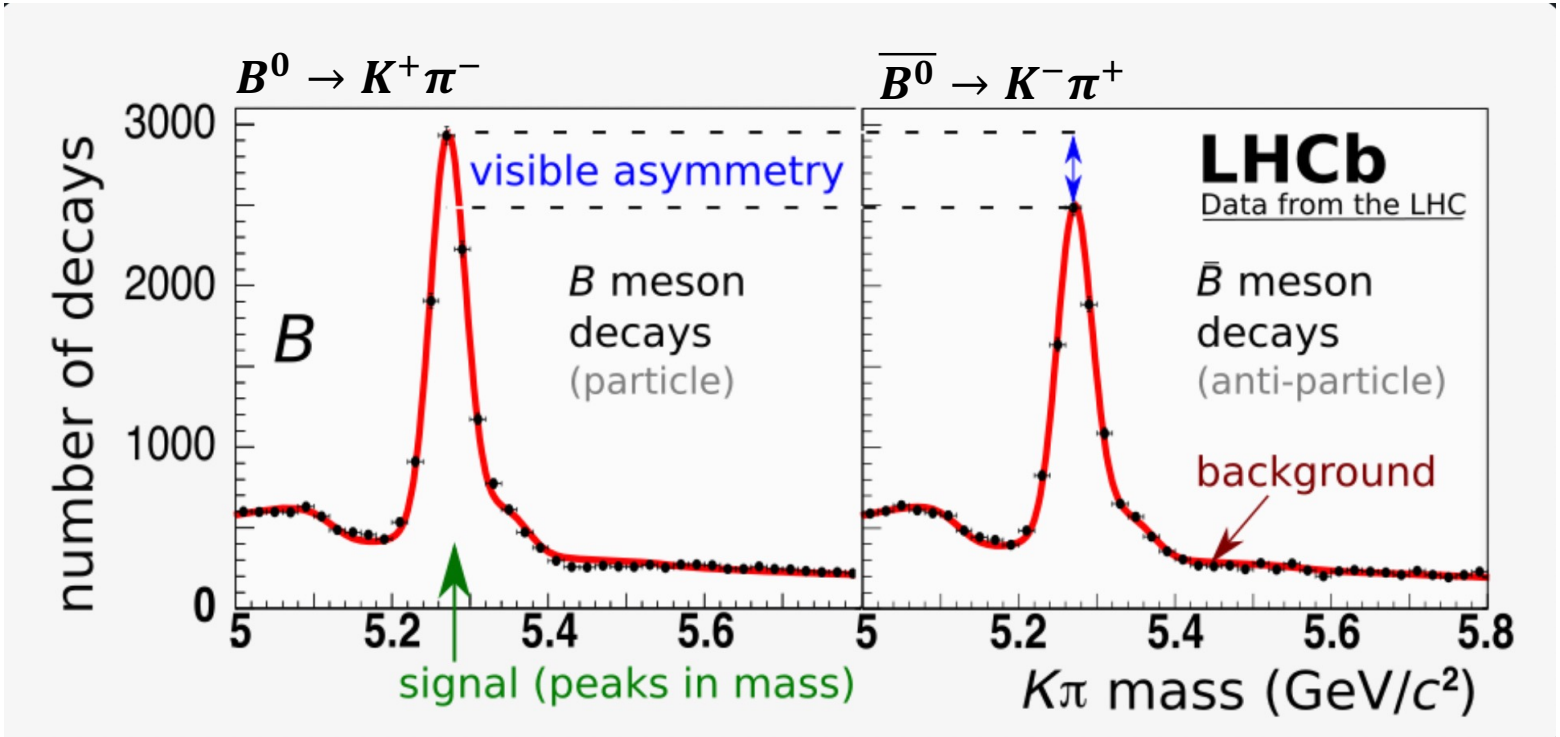
- detector-stable → direct detection
  which one is the rarest? -> muon, best for trigger
- long-lived → significantly displaced decay vertex
- prompt → comes from primary vertex (always?)

The signal (example)



- **what do we have to measure to obtain these histograms?**

The signal (example)



- $M^2 = E^2 - \boldsymbol{P}^2$
- $\boldsymbol{P} = \boldsymbol{P1} + \boldsymbol{P2}$, $E = E1 + E1$

We need to measure:

- decay vertex position – crossing point of two tracks ($\boldsymbol{K}^+$ and $\boldsymbol{\pi}^-$)
  - identify that it is displaced wrt collision point
- *P1*, *P2* and charges – by measuring tracks curvature in magnetic field
- *E1*, *E2* obtained by classifying PID of particles

Rapidity plateau

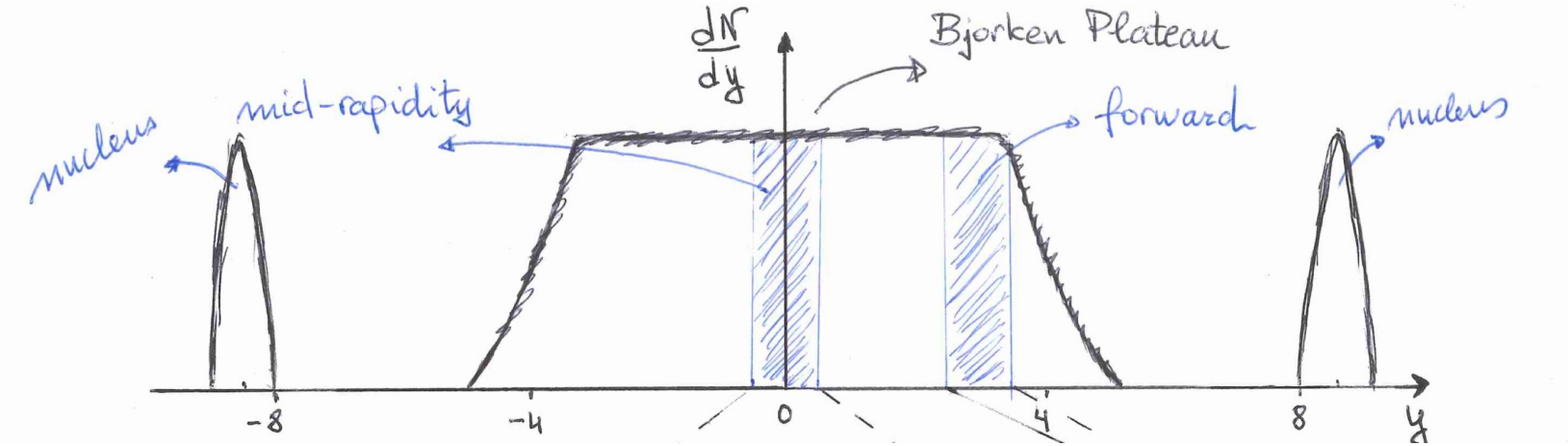
- *b*-quarks are produced with large boost, mostly in forward direction

- rapidity – kinematic variable

$$y \equiv \frac{1}{2} \ln\left(\frac{E + p_{\mathrm{L}}}{E - p_{\mathrm{L}}}\right)$$

- linked to angle theta

$$y \cong -\ln \tan(\theta/2)$$



it's beneficial to build forward detector, LHCb uses $2 < y < 5$

What do we need?

- **Make a list of *b*-hadron decay signatures (cuts)**

  - how to distinguish them from other long-lived particles?

  - mind that lighter particles are more abundant

- **Which types of subdetectors are needed?**

b-hadron signatures

- displaced (wrt primary vertex) decay vertices
- larger P_T for *b*-hadrons than for lighter particles
- PID of final state particles
- reconstructed invariant mass
- *more options to decay compared to lighter long-lived particles*

best sensitivity for fully reconstructed decay if all final state particles are charged

What do we need

Tracking:

- Forward detector
- Reconstruct tracks of charged particles and measure their momenta
  - needs strong magnetic field

    **length of the magnet is ~5m*
  - tracking detectors – measure curvature
- Reconstruct decay vertices
- Measure displacements wrt proton-proton collision point with high precision
  - needs detector very close to the collision point

PID

- Identify type of particle for each track

  * i.e. distinguish those 5 types of detector-stable charged particles

suggest and motivate your geometry, e.g. locate tracking detectors

Unique measurements and competitors

- Main competitors: B-factory experiments, e.g. Belle 2
  - production via $e^+e^- \to \Upsilon(5S) \to B^+B^-$ (or $B^0\overline{B^0}$)
  - (almost) no access to other *b*-hadrons

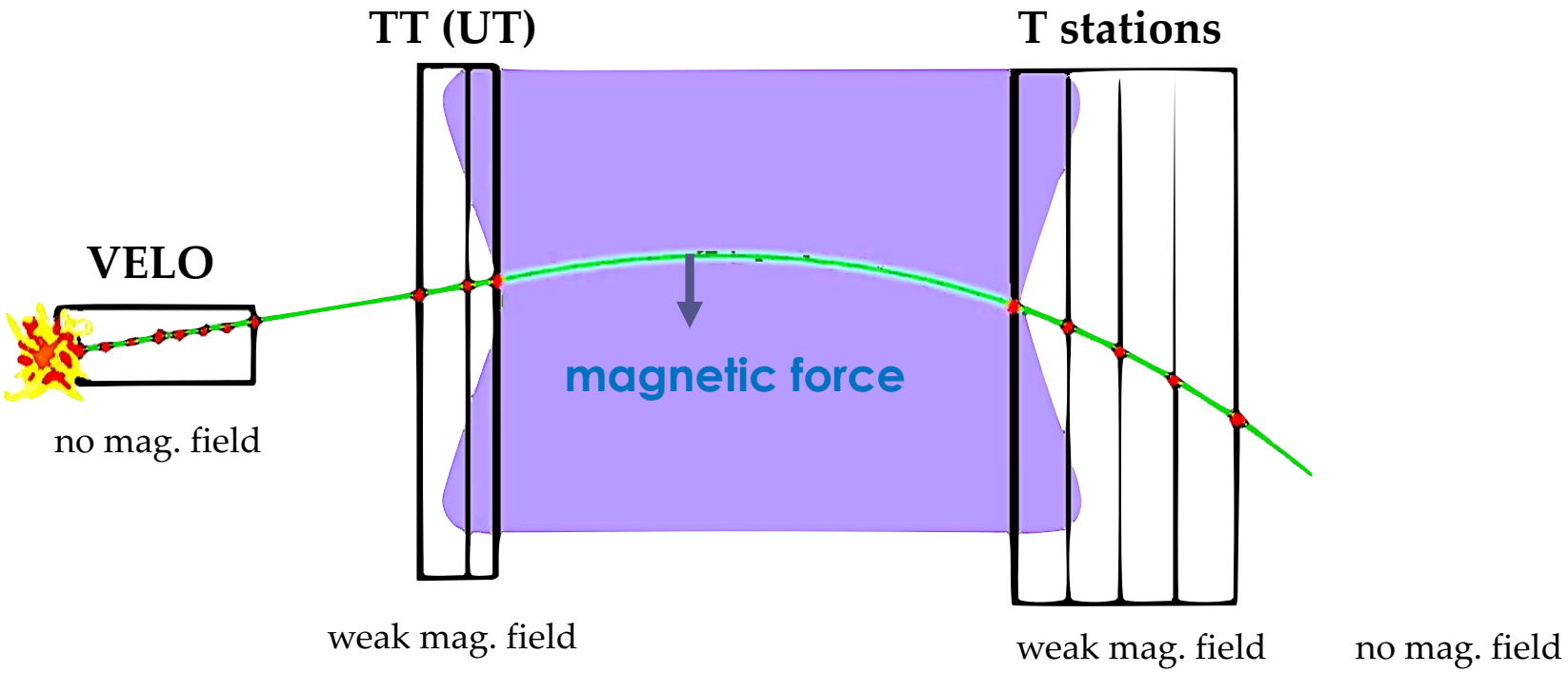
$\Rightarrow$ (almost) unique measurements of B_s^0, B_c^+, Λ_b, etc. at LHCb

what is the most promising decay mode(s) for each *b*-hadron at LHCb?

(take it into account in the detector design)

What do we need

- strong magnetic field
- tracking detectors upstream and downstream the magnet
- detector very close to the collision point



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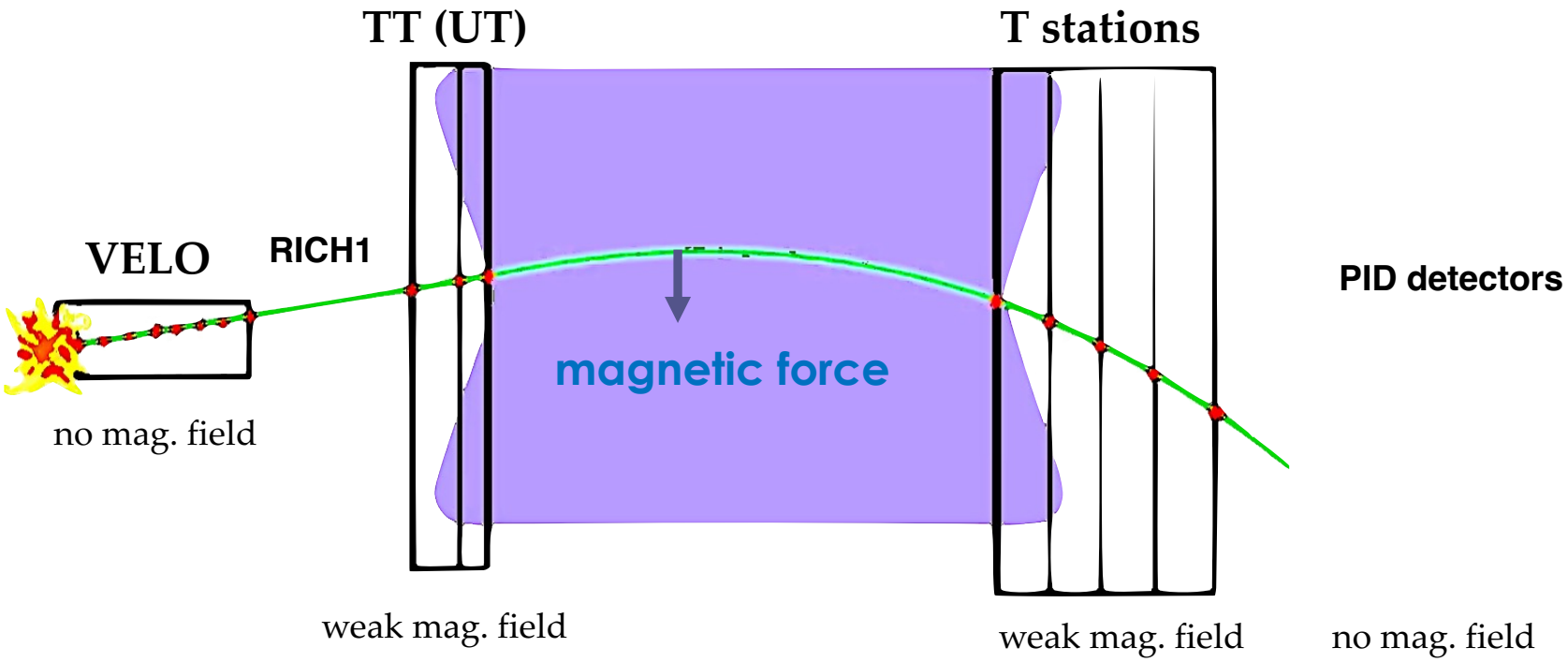
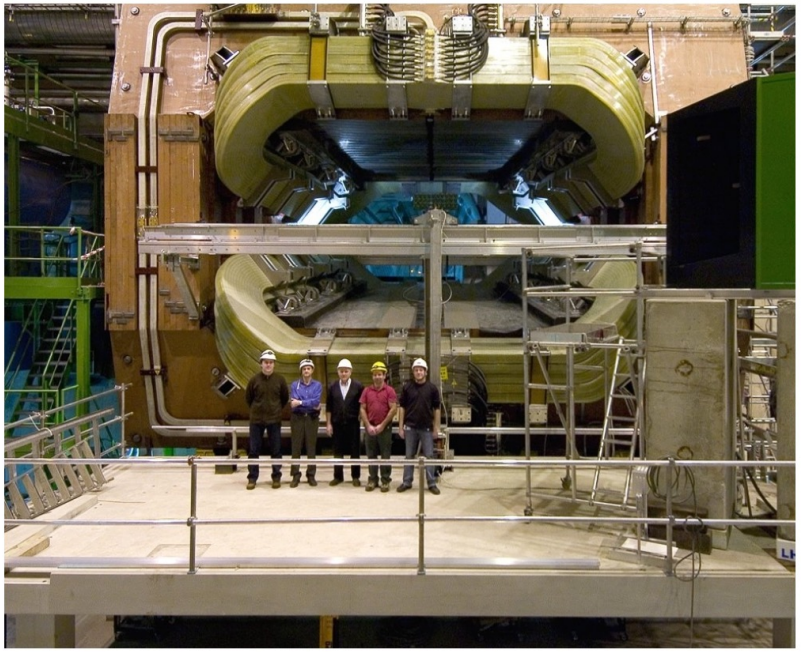


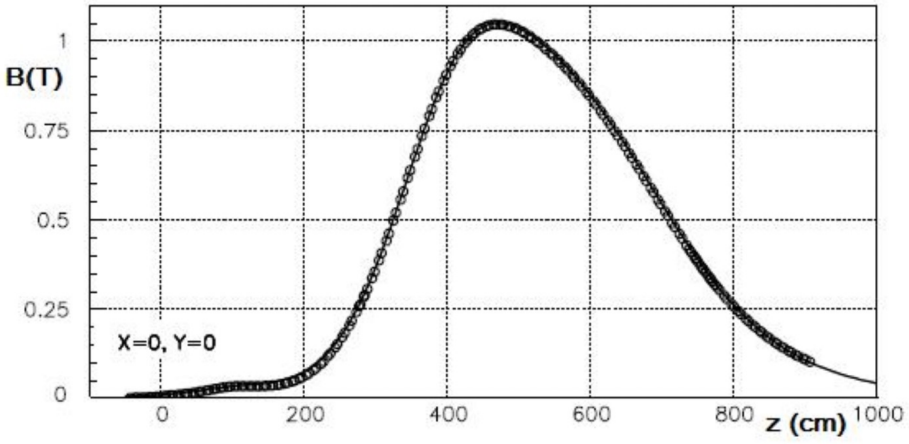
The magnet



Sigmaphi coils for the CERN LHCb experiment (The LHCb magnet consists of two huge 27 tonne coils mounted inside a 1450 tonne iron yoke)

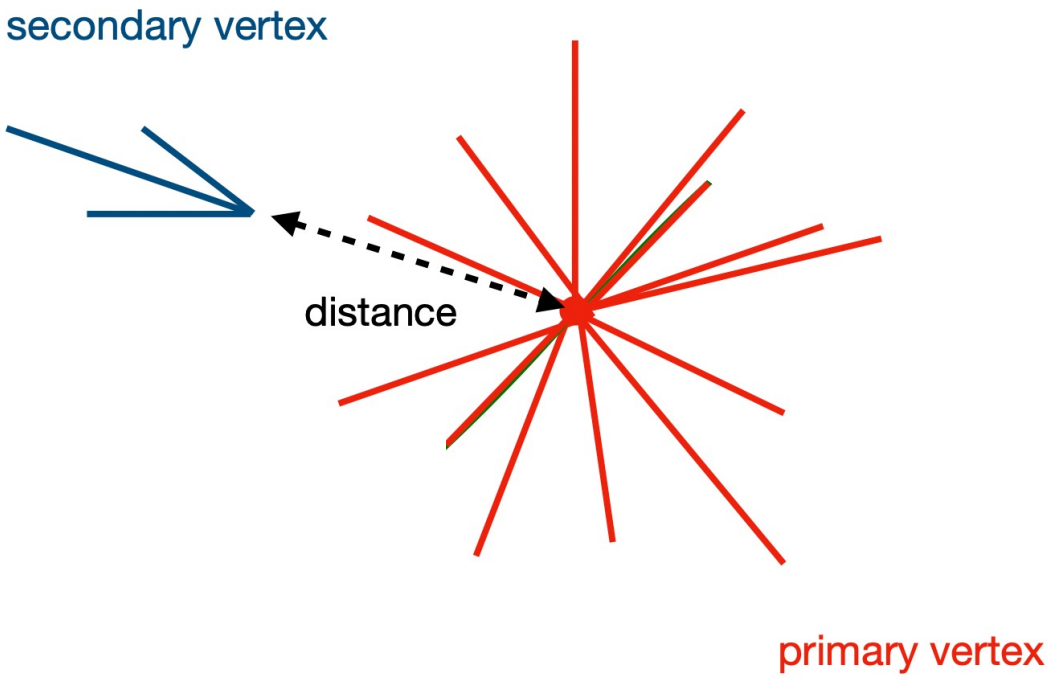
- first difficult decision to make
- warm magnet
- vertical field (mainly)
- max magnetic field of ~ 1 T
- integrated mag. field of 4 Tm
- can change polarity

- alternative: superconducting magnet



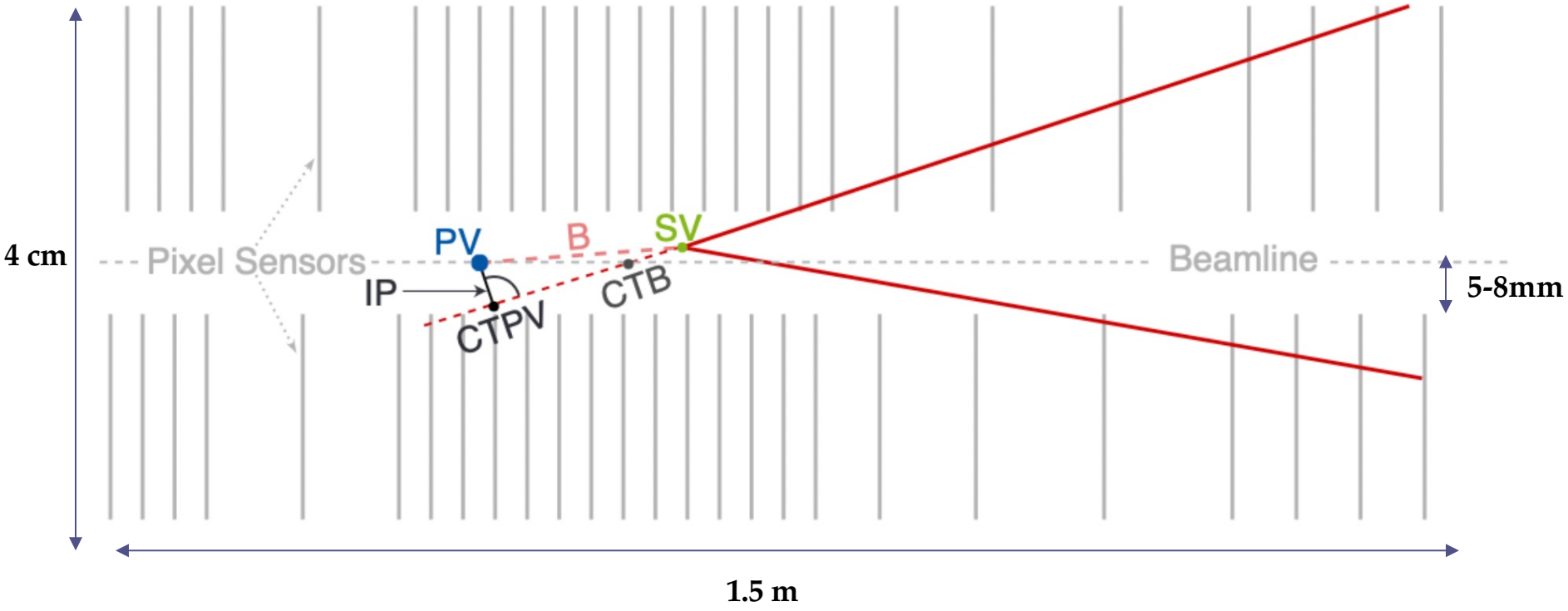
- magnetic field is not uniform

Vertex detector: typical topology



credit: V. Lukashenko

Vertex detector VELO

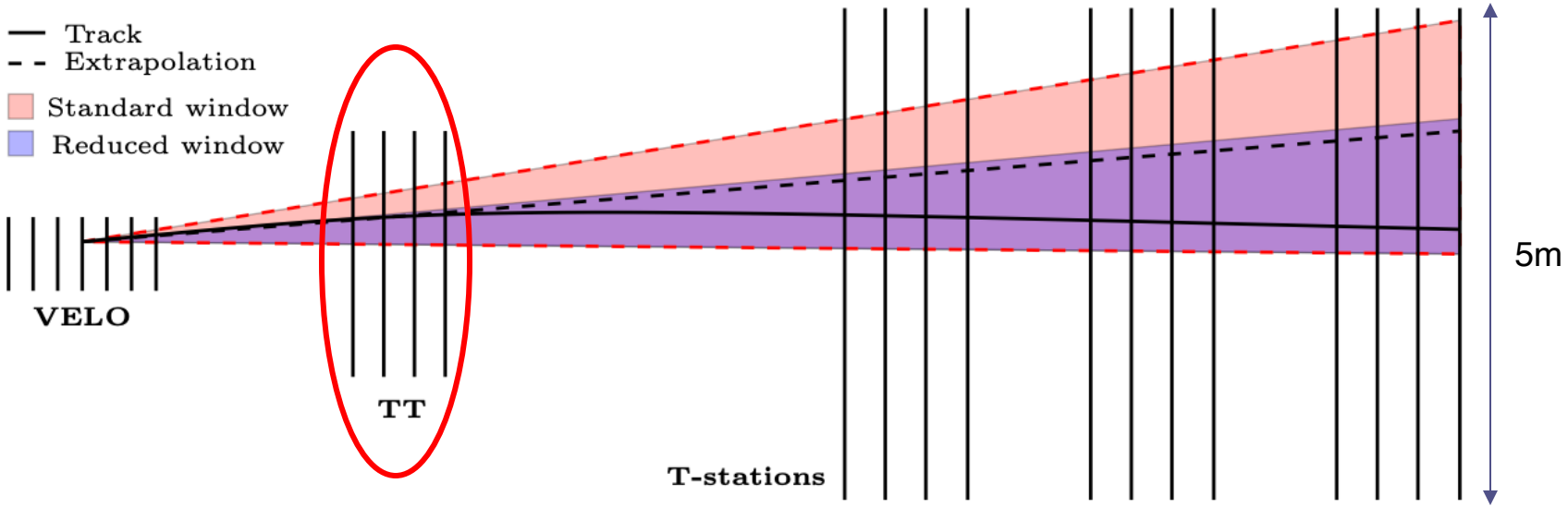


*not to scale

- the most challenging part of the detector
- surrounds the collision point very close to beamline
- can open and close
- no magnetic field

- goal: measure primary and secondary vertices and separate them

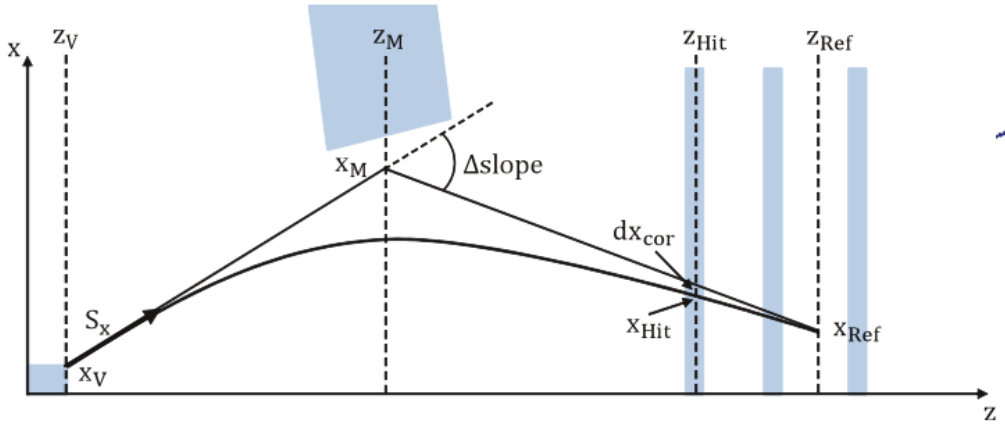
Make tracks out of parts in VELO, TT and T

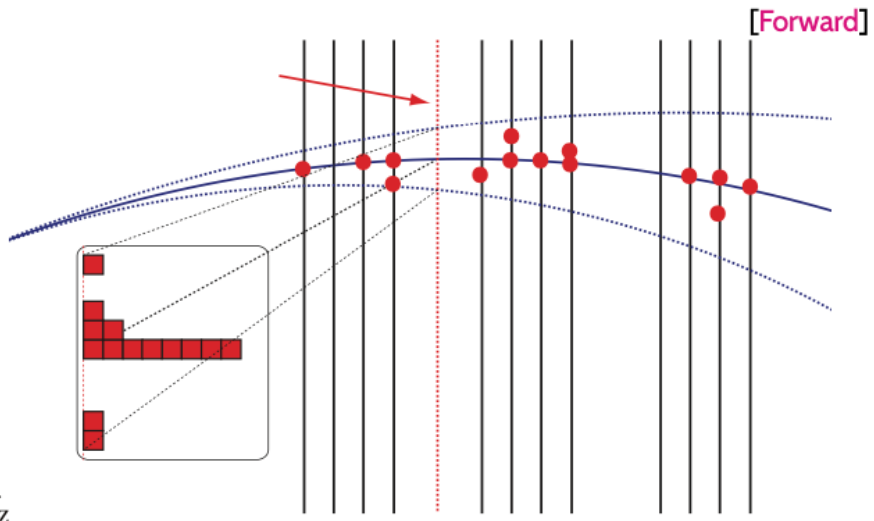


- Match tracks in VELO, TT and T
- Small bending in *y* direction – useful for search

- Reduced search window thanks to TT
- Smart algorithm using Hough transform
- Perform the search in both forward and backward directions

Match in *x* direction





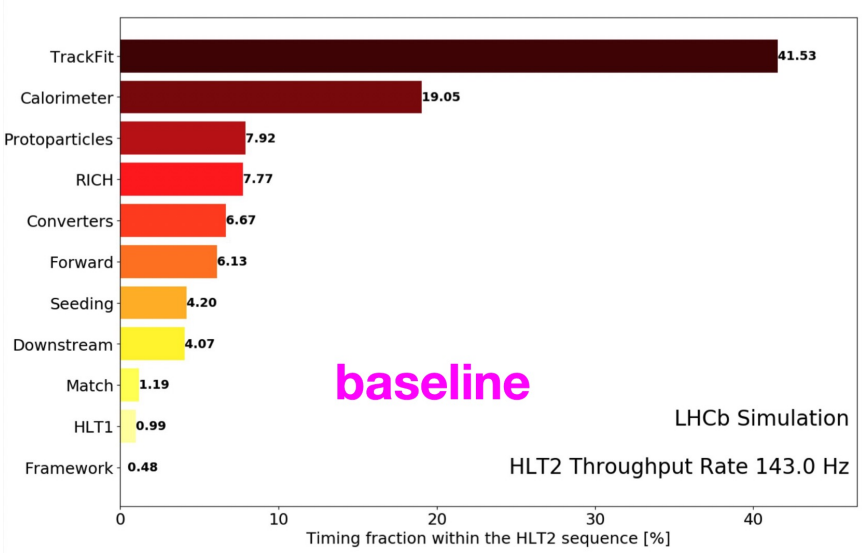
- Very simple model for magnetic field
- 0 approximation: instant momentum kick at the middle of the magnet
- 1 approximation: correct the Z_M by integrating field along the “kinked track”

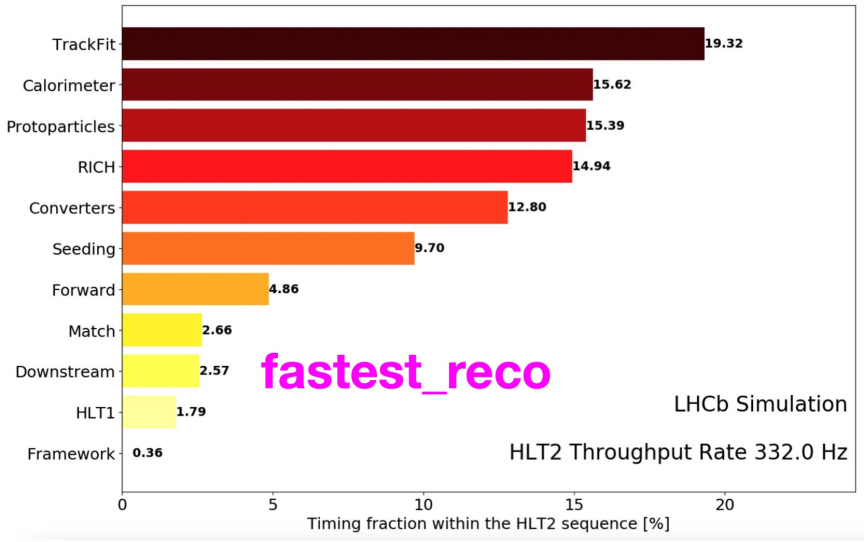
already gives momentum estimate with precision of 1%

Track fit

- once tracks are found – fit them with good accuracy
- take into account:
  - multiple scattering on material
  - precise propagation in magnetic field
    - measure magnetic field map
    - numerical methods, e.g. Runge-Kutta
  - remove outlier hits
- use Kalman Filter algorithm

=> precise momentum and position of track, correct uncertainties

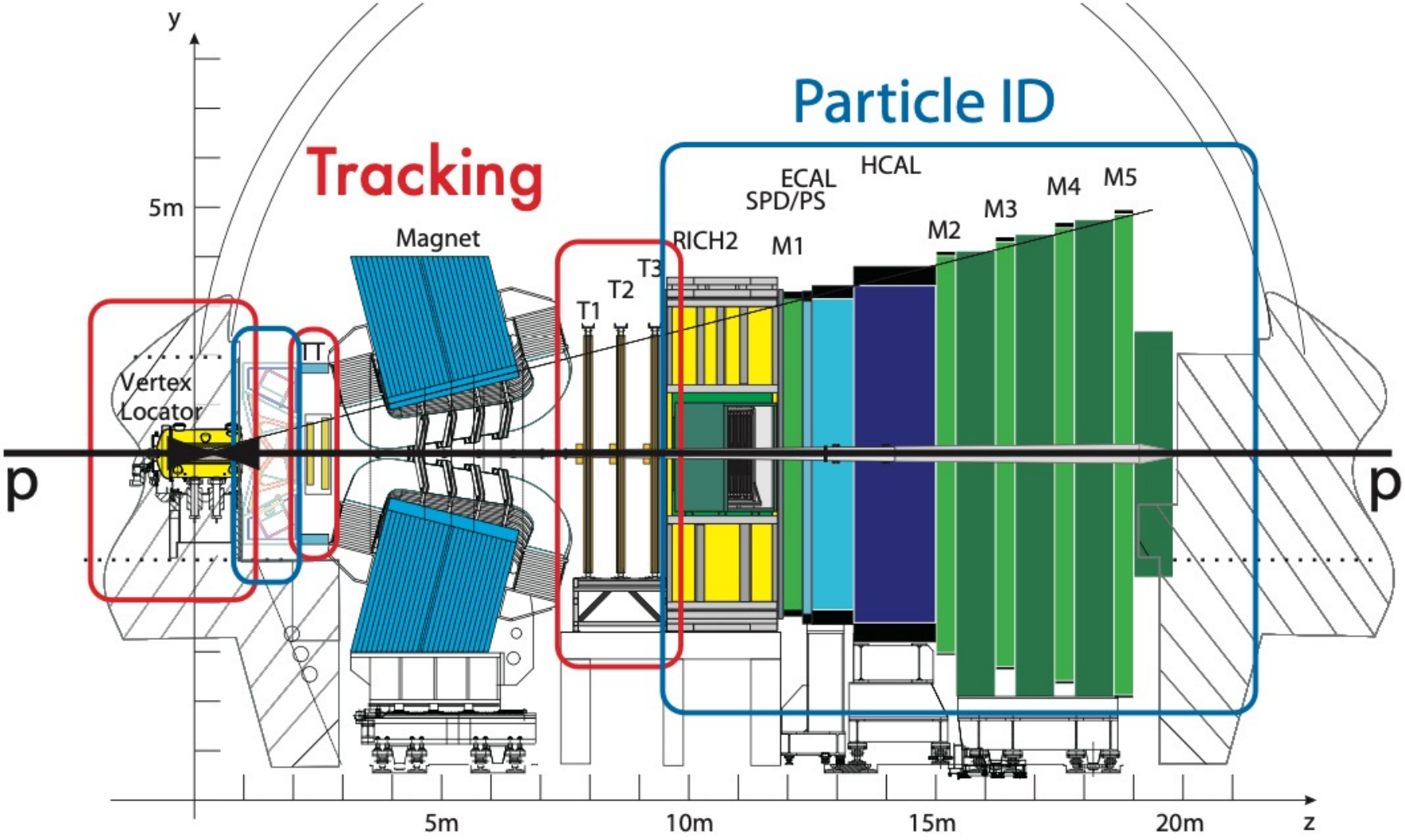




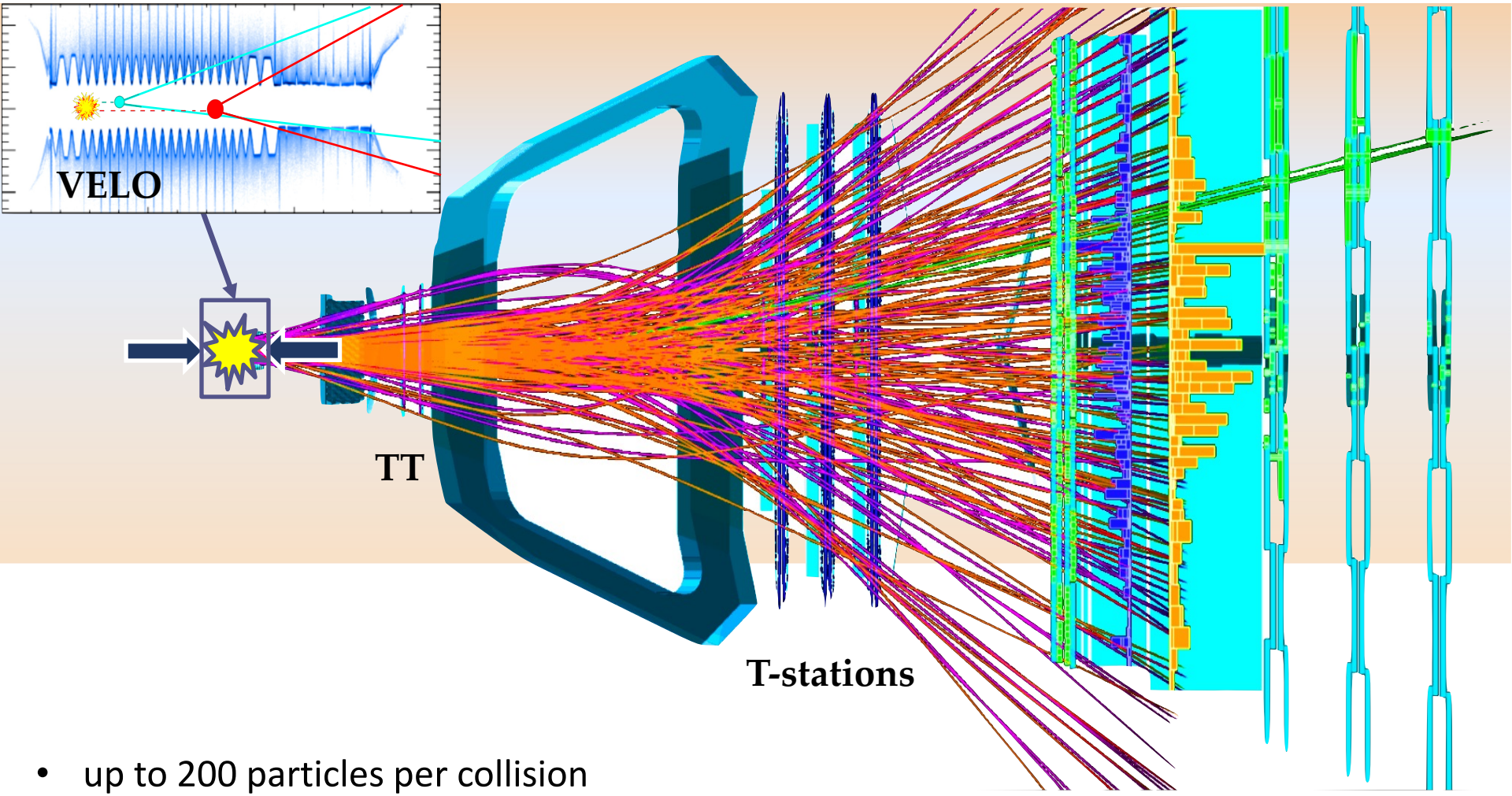
143 Hz ==> 332 Hz

quite some progress over last years

Bringing all together



Reconstructed event

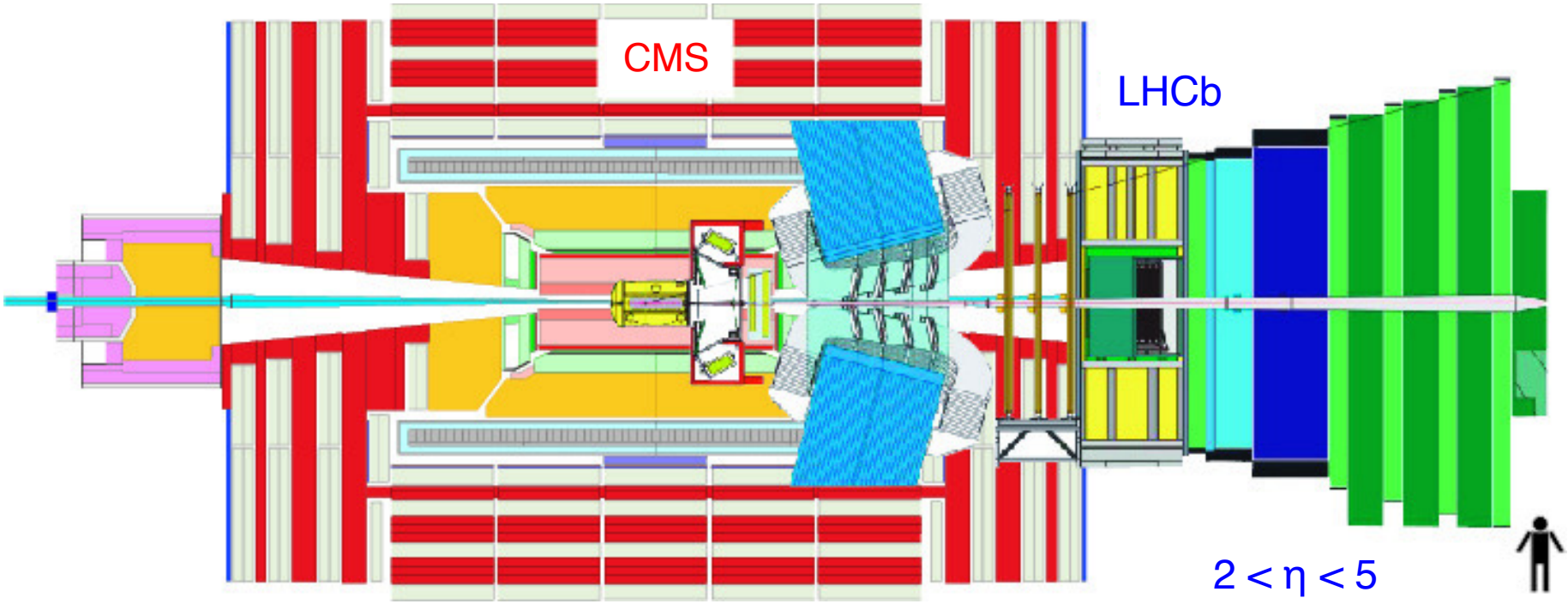


- up to 200 particles per collision
- 10 millions collisions per second

→ **fast real time analysis**: online selection of interesting collisions

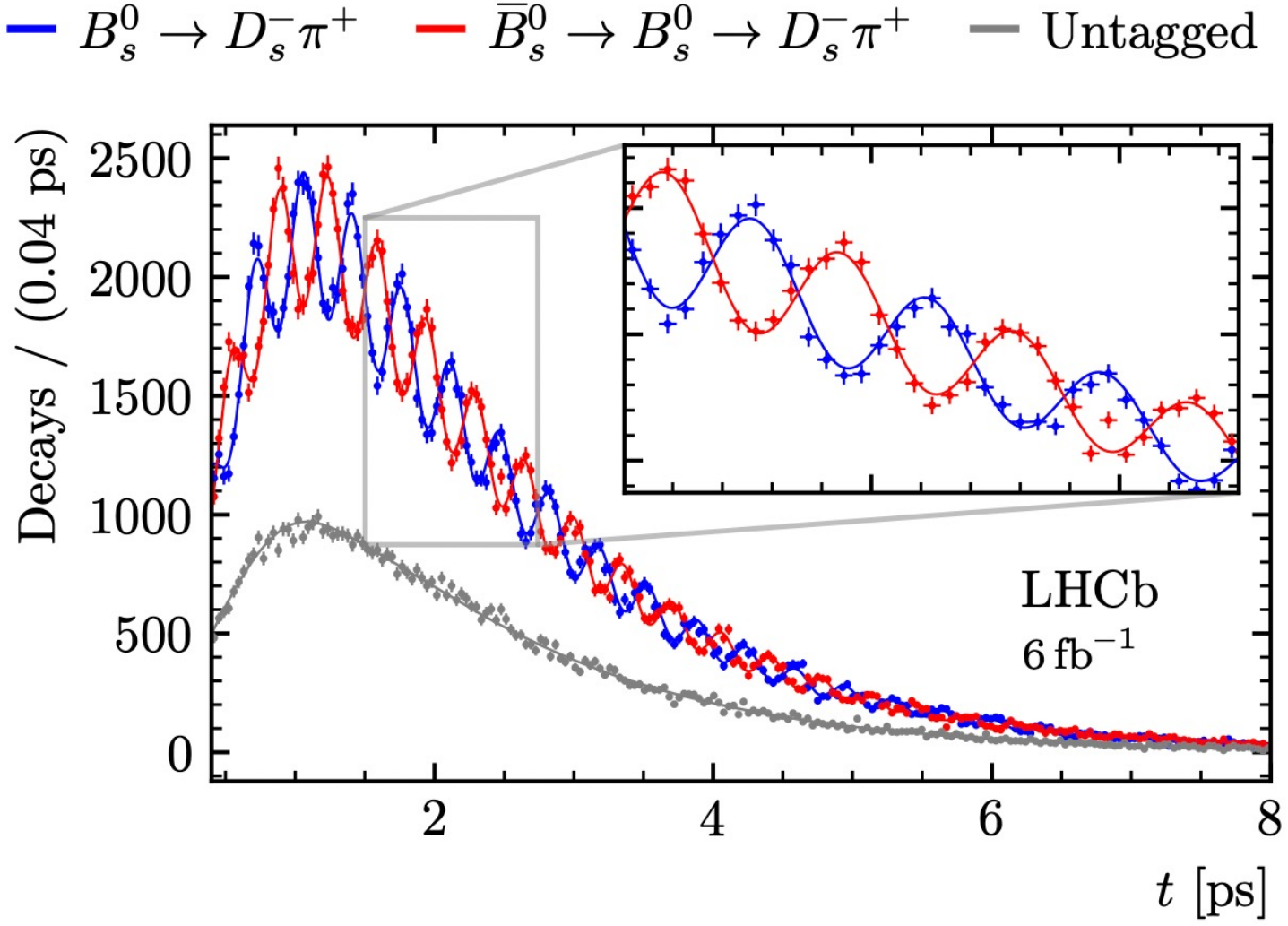
LHCb vs central detectors

IJMPA 30, 1530022
JINST 3, S08005



- Coverage complementary to ATLAS and CMS in p_{T} and η
- Limited instantaneous luminosity
- Flexible software trigger allowing **soft selections**

Full power of LHCb in one plot

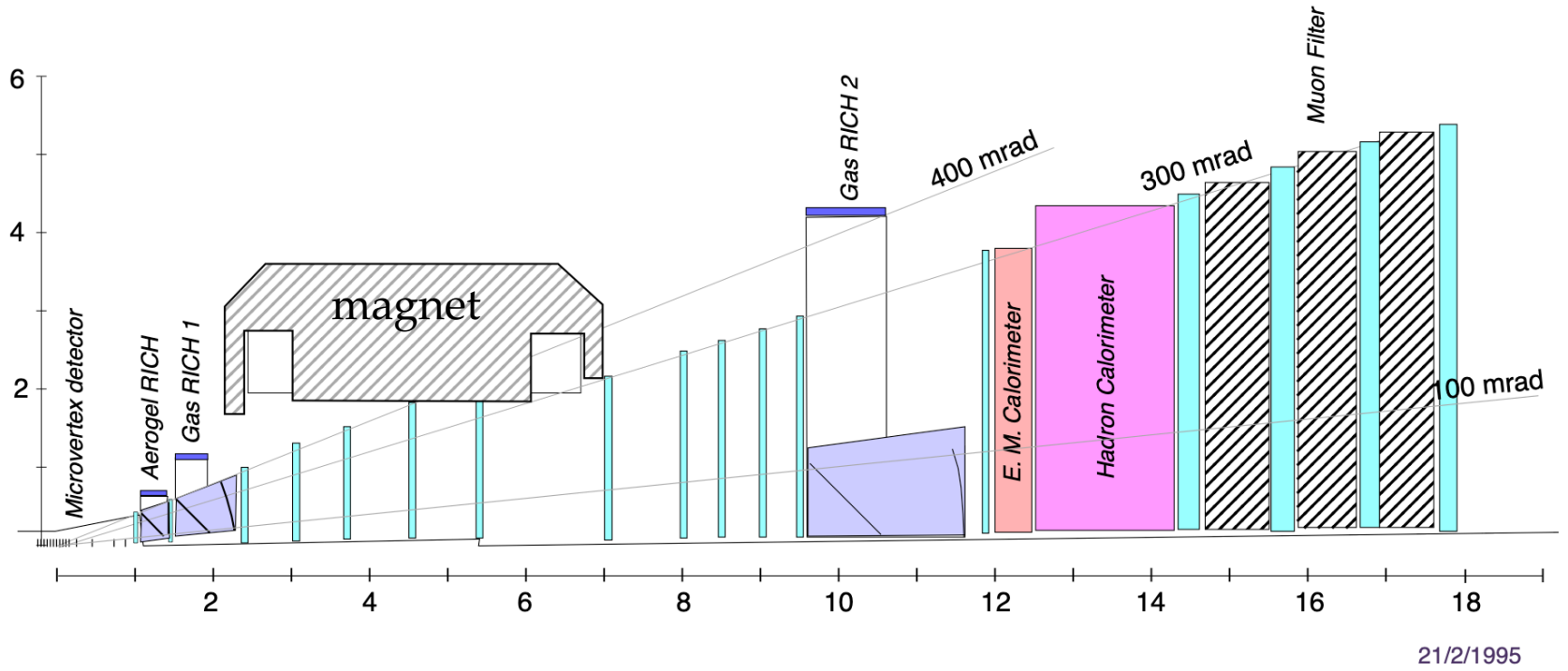


- measured very fast oscillations of B_s^0 - see next lecture
- published in Nature Physics
- PhD thesis of M. Veronesi

How was it in 1995?

How was it in 1995?

LHC-B

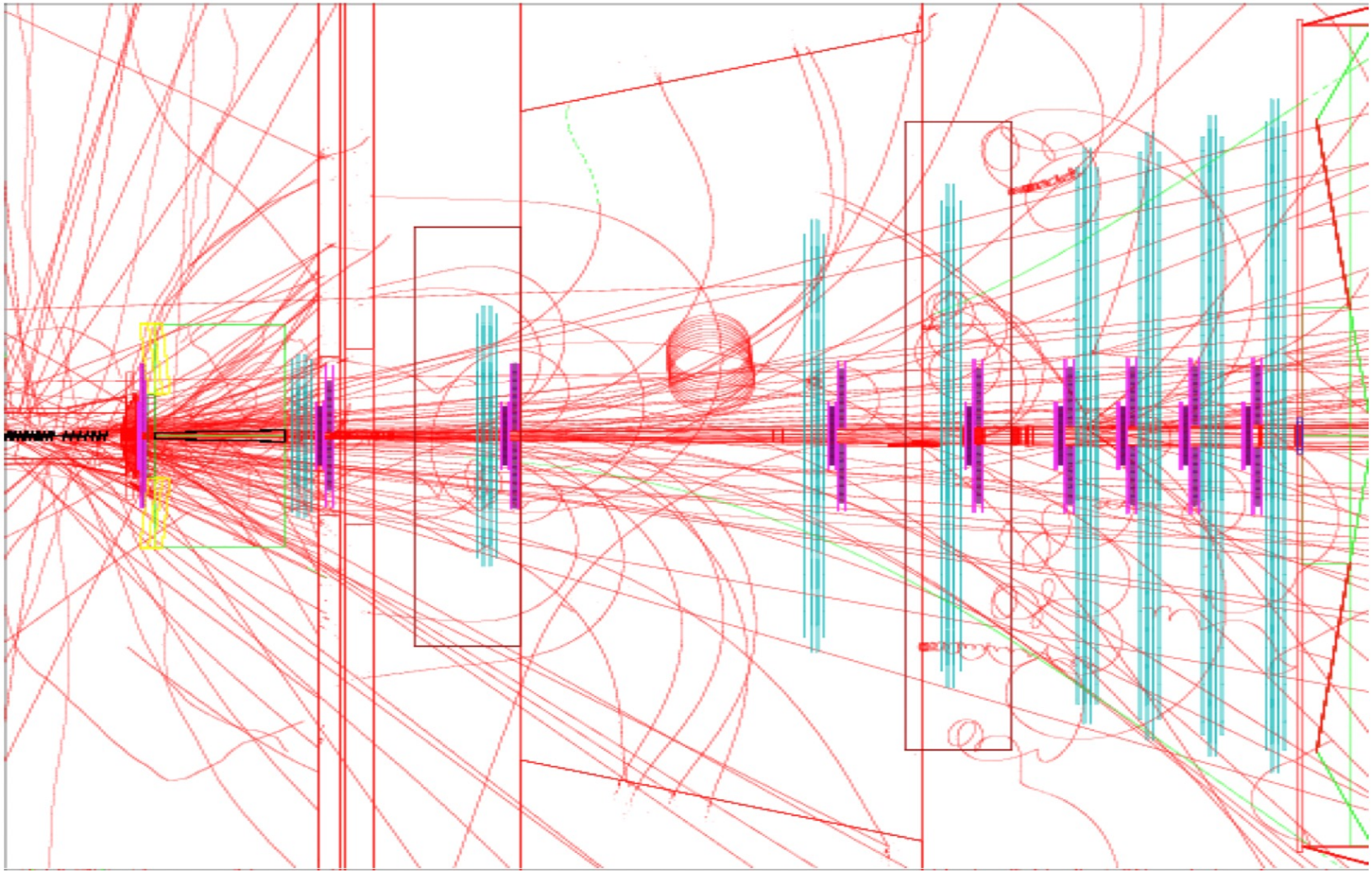


so-called ”LHCb classic”

13 tracking stations in total – track following

What was wrong

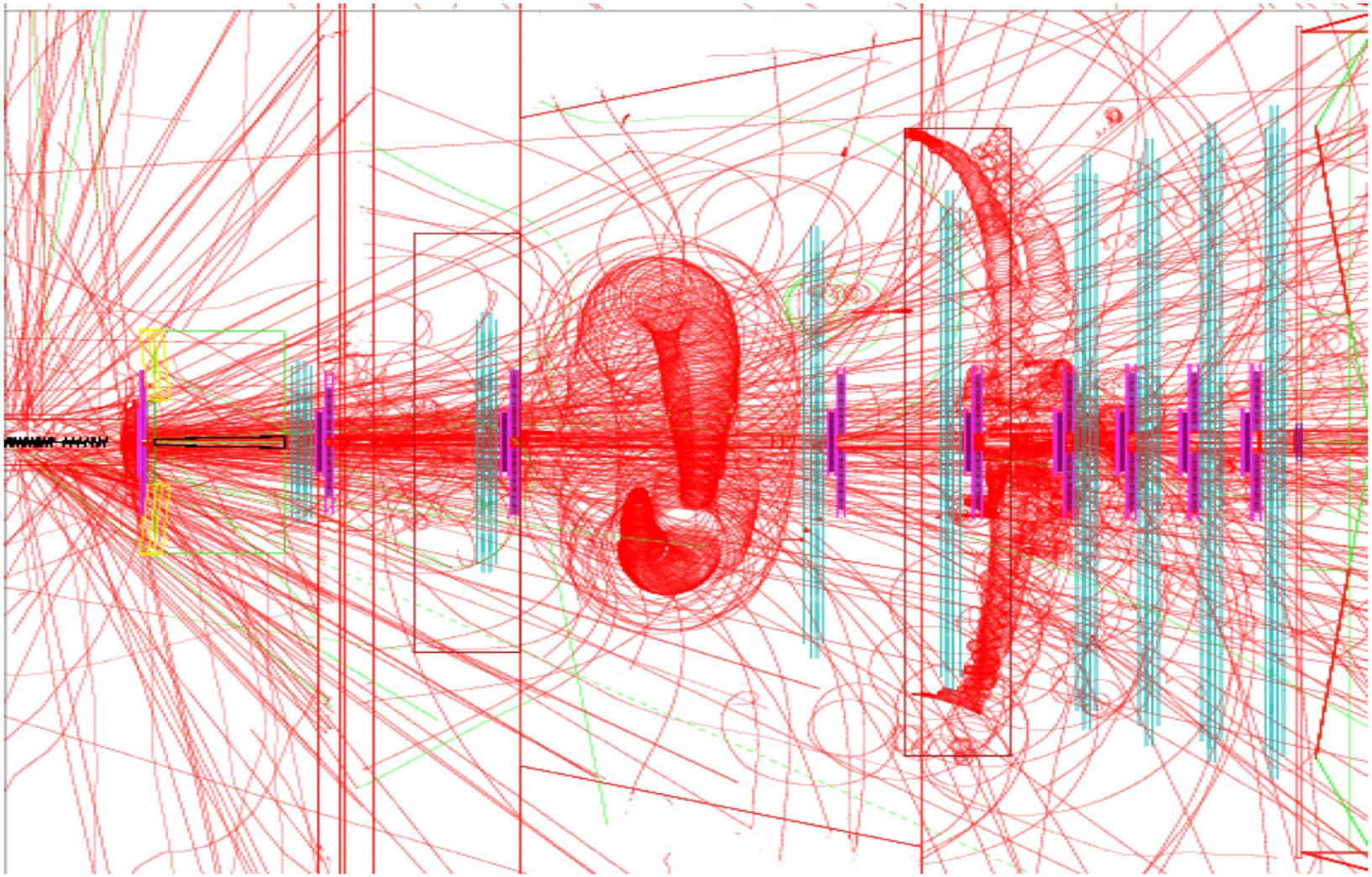
thesis of R. Hierck, 2003



Light event

What was wrong

thesis of R. Hierck, 2003



Busy event with many secondary particles
- high detector occupancy + ghost tracks

Bringing all together

IJMPA 30, 1530022
JINST 3, S08005

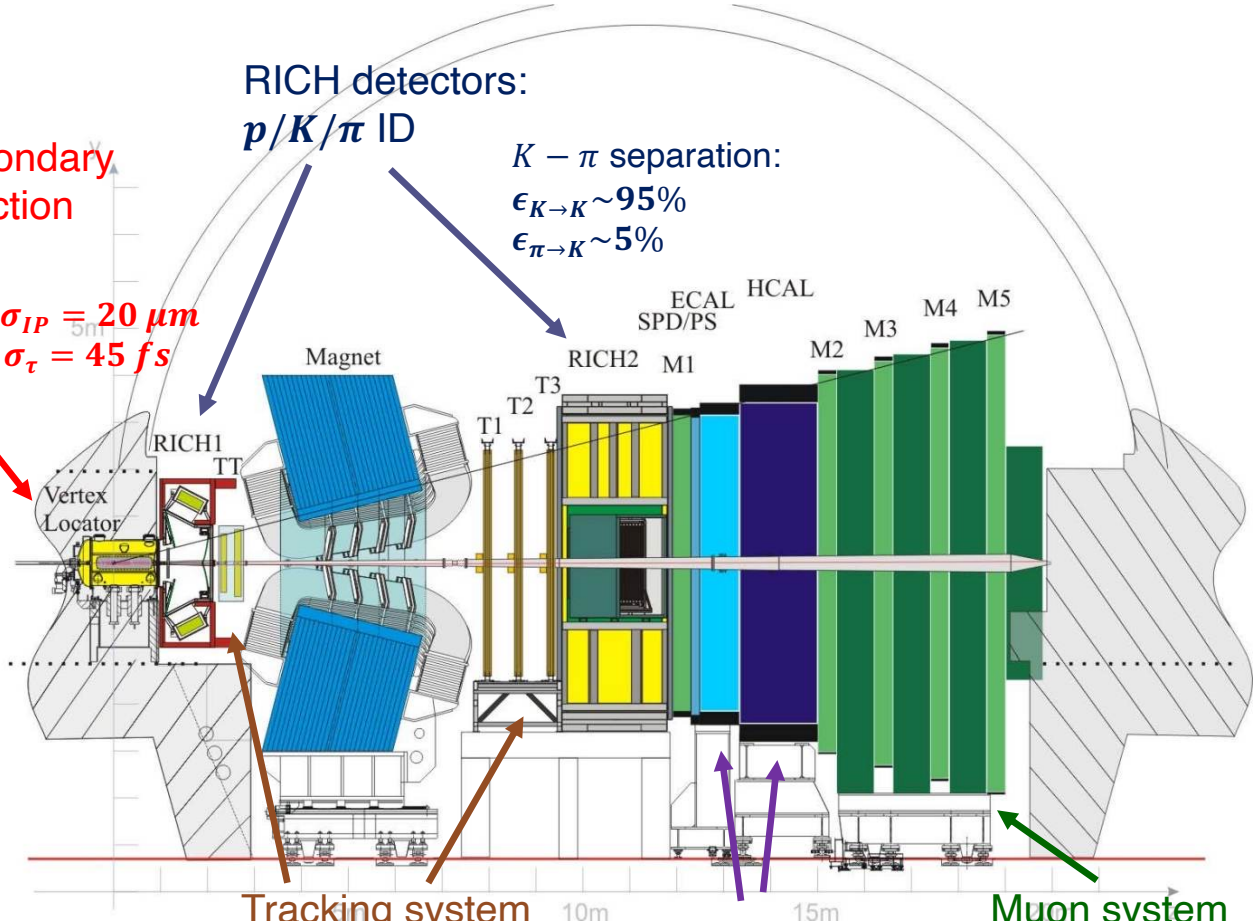
- Single-arm spectrometer designed for beauty and charm physics in forward region

VErtex LOcator:
Primary and secondary vertex reconstruction

Resolution:
Impact parameter : $\sigma_{IP} = 20\ \mu m$
Lifetime : $\sigma_\tau = 45\ fs$

RICH detectors:
$p/K/\pi$ ID

$K-\pi$ separation:
$\epsilon_{K\to K}$~95%
$\epsilon_{\pi\to K}$~5%



$\epsilon_{\mu\to\mu}$~97%
$\epsilon_{\pi\to\mu}$~1 − 3%

- Precise vertex reconstruction with VELO
- Powerful charged hadrons ID by RICH detectors