Universität Zürich[UZH]

The LHCb experiment

[PHY213 Kern- und Teilchenphysik II]

Rafael Silva Coutinho

May 23rd, 2018

Outline

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This lecturer will cover some aspects involved in the “flavour sector”

- Why LHCb?

  [Physics programme, b-physics, design]

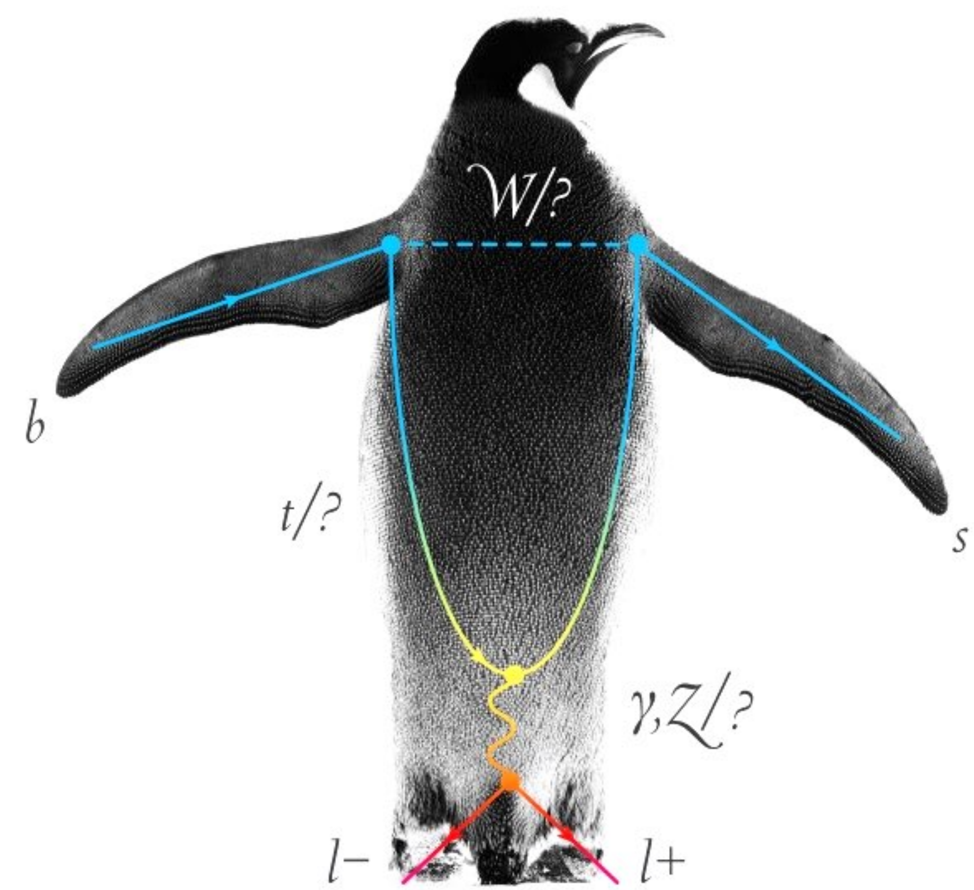
- The LHCb detector

- How to perform an analysis at LHCb?

  [e.g. CP violation and LFU measurement]

- Lots of material taken from (thanks!)

  [Roger Forty: ICFA, School]
  [Monica Pepe-Altarelli, Carfu Summer School]
  [Daniel Saunders, iCSC]



Flavour (particle physics)

From Wikipedia, the free encyclopedia

In particle physics, **flavour** or **flavor** refers to a species of an elementary particle. The Standard Model counts six flavours of quarks and six flavours of leptons. They are conventionally parameterized with *flavour quantum numbers* that are assigned to all subatomic particles, including composite ones. For hadrons, these quantum numbers depend on the numbers of constituent quarks of each particular flavour.

“The term flavour was first used in particle physics in the context of the quark model of hadrons. It was coined in 1971 by Murray Gell-Mann and his student at the time, Harald Fritzsch, at a Baskin-Robbins ice-cream store in Pasadena. Just as ice cream has both colour and flavour so do quarks.”

RMP 81 (2009) 1887

Flavour in particle physics

Flavour quantum numbers

- Isospin: **I** or I_3
- Charm: *C*
- Strangeness: *S*
- Topness: *T*
- Bottomness: *B′*

Related quantum numbers

- Baryon number: *B*
- Lepton number: *L*
- Weak isospin: **T** or T_3
- Electric charge: *Q*
- X-charge: *X*

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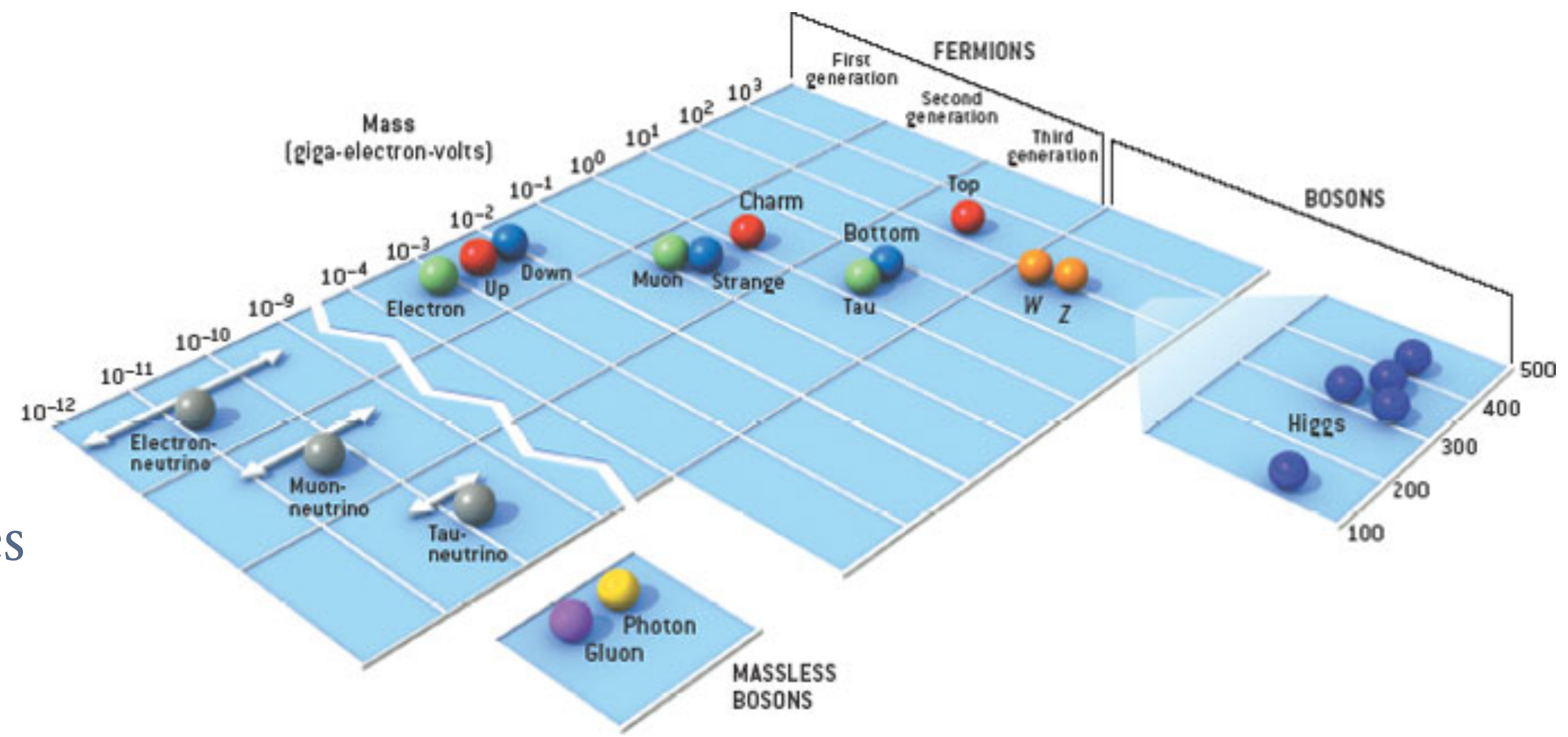
Flavour physics

Parameters of the Standard Model

- 3 gauge couplings
- 2 Higgs parameters
- 6 quark masses
- 3 quark mixing angles
  + 1 phase
- 3 + 3* lepton masses
- (3 lepton mixing angles + 1 phase)



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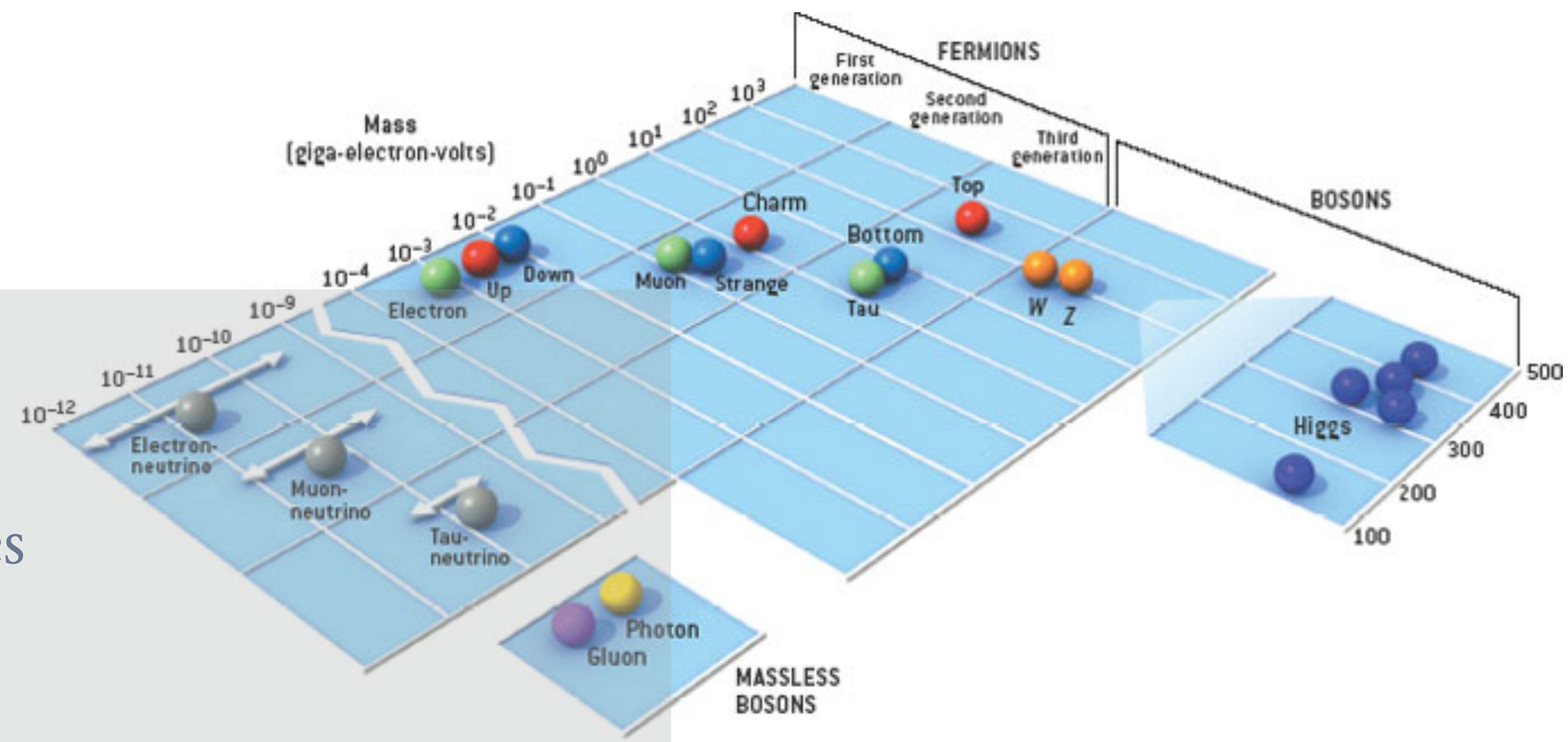
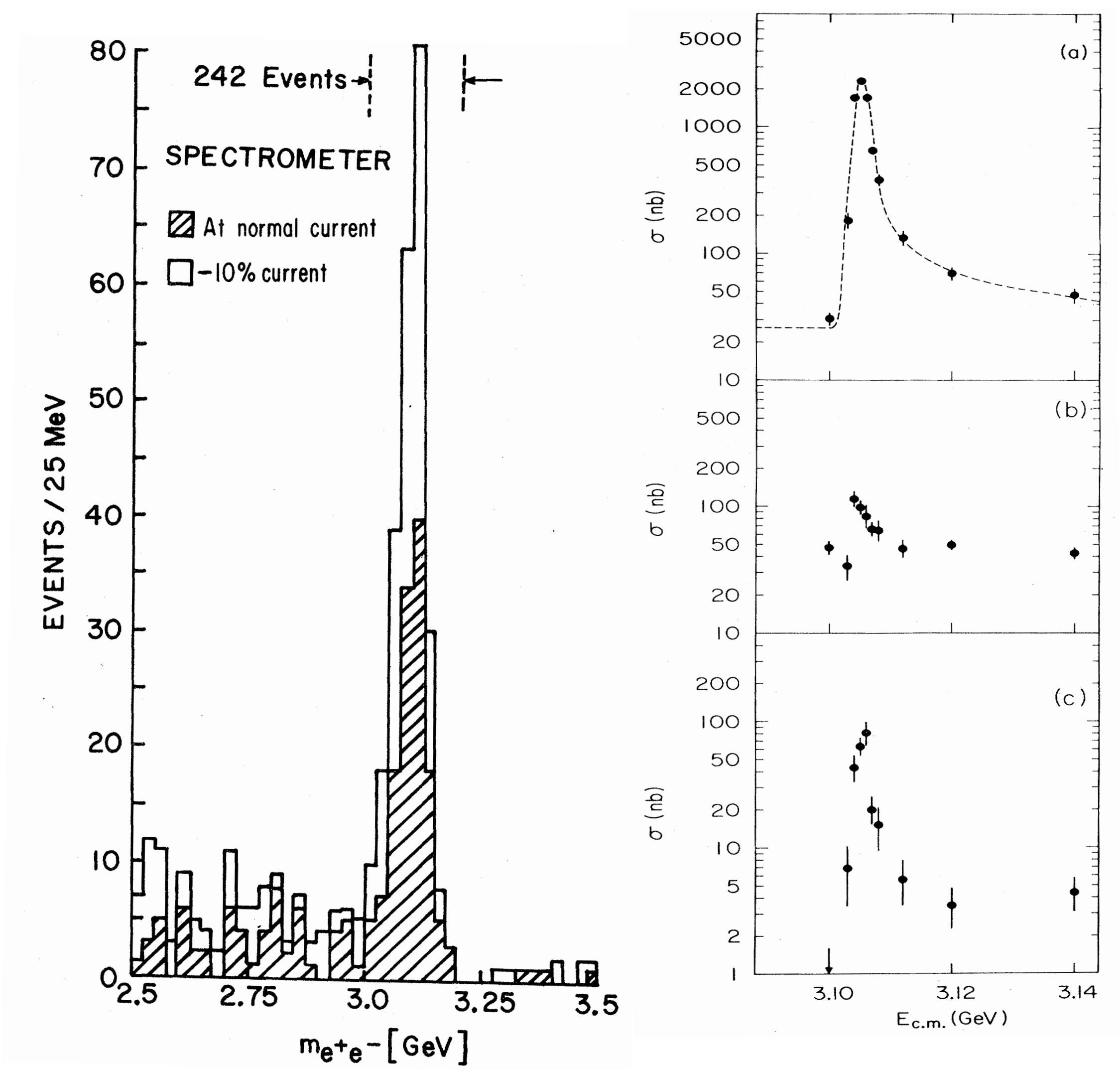


Flavour parameters

How do we search for New Physics?

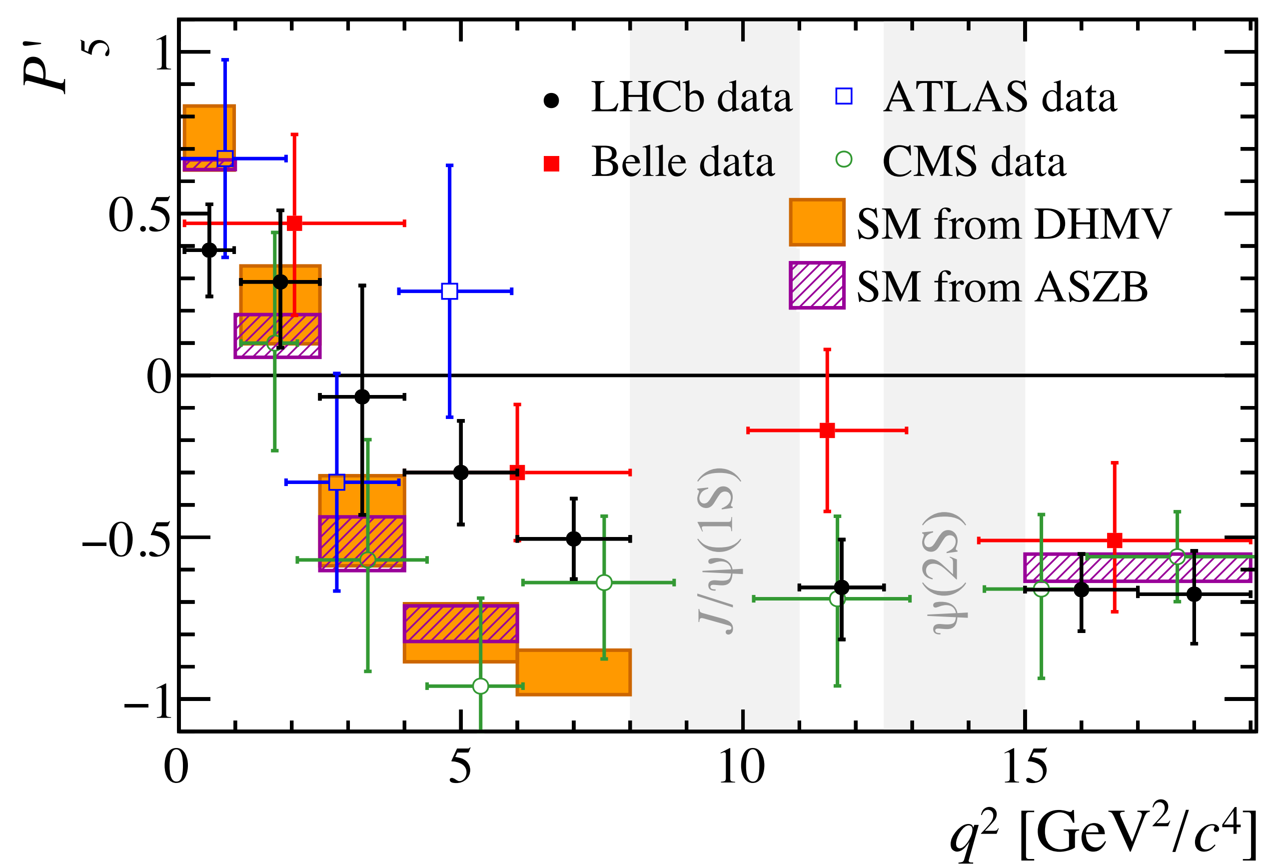
Direct production of new particles

[PRL 33 (1974) 1404, PRL 33 (1974) 1406]



Indirect effects of new particles on well-predicted observables, e.g., the flavour anomalies

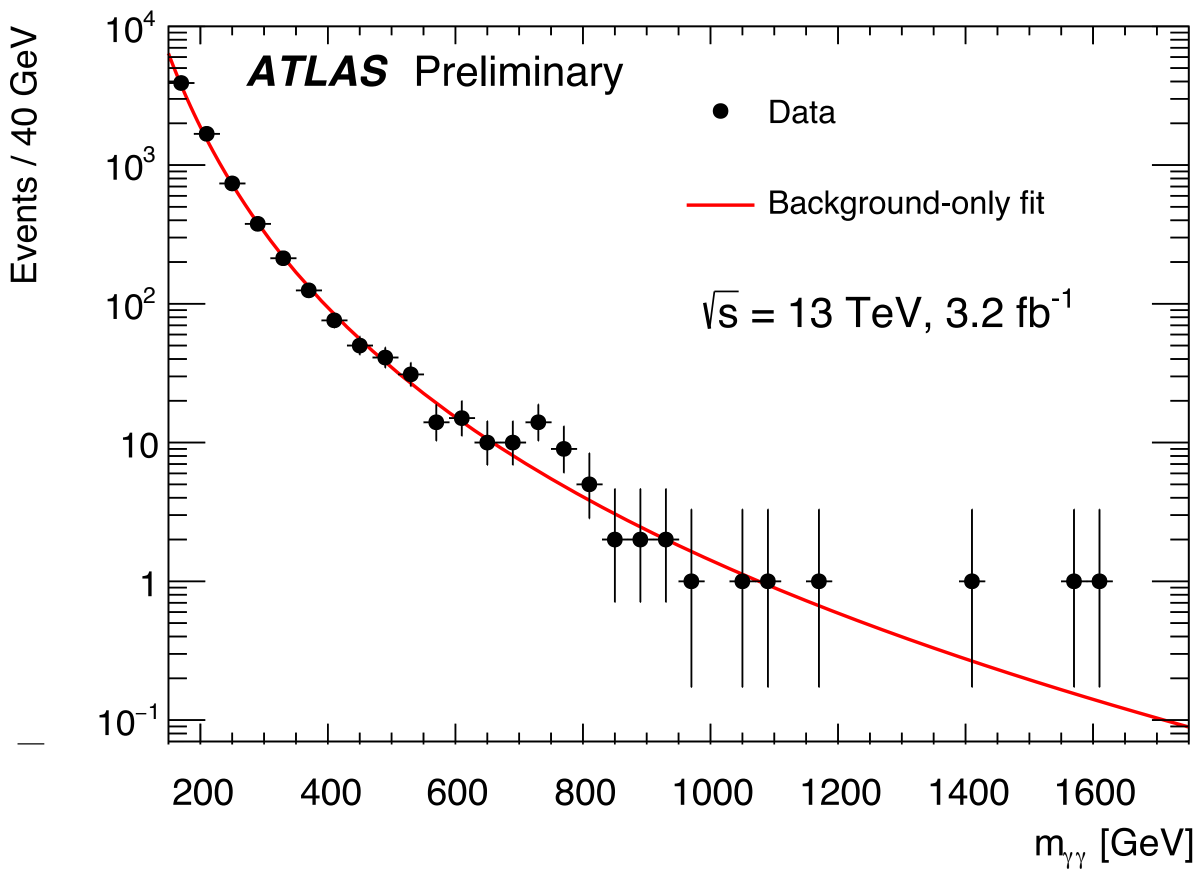
[LHCb JHEP 02 (2016) 104]



[Belle arXiv:1612.05014, ATLAS-CONF-2017-023
CMS-PAS-BPH-15-008]

How do we search for New Physics?

Direct production of new particles, such as the initial excess observed by ATLAS/CMS at 750 GeV di-photon



[ATLAS-CONF-2015-081]
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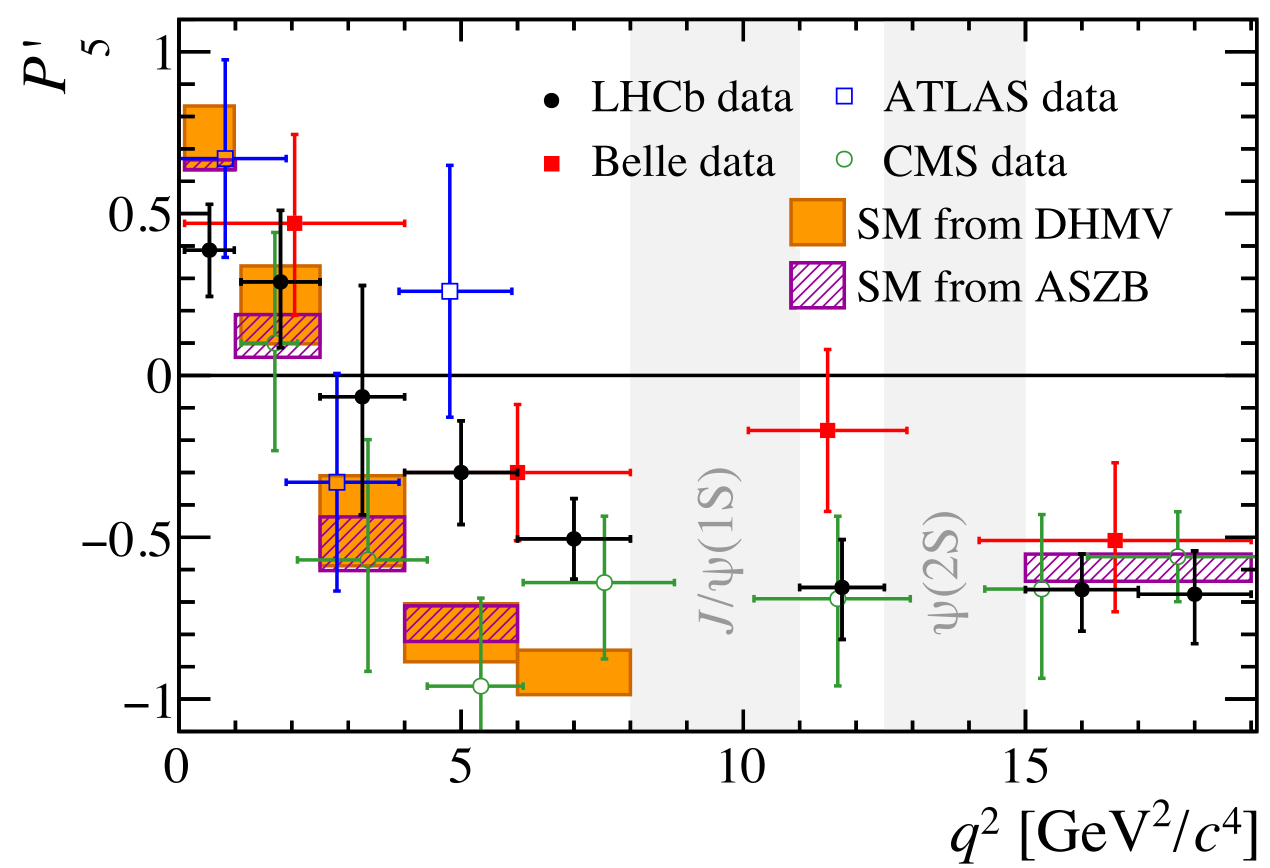

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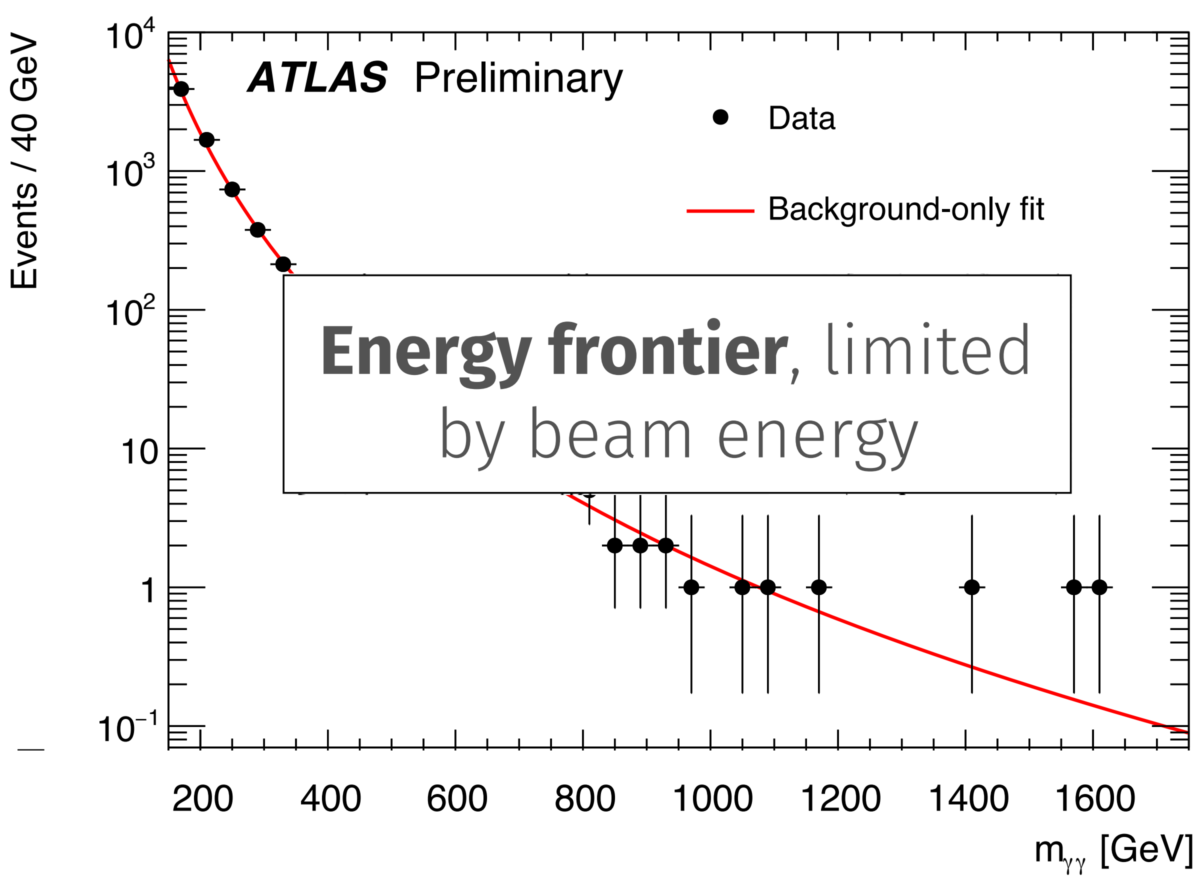

Energy frontier, limited by beam energy

[ATLAS-CONF-2015-081]
[CMS-PAS-EXO-15-004]

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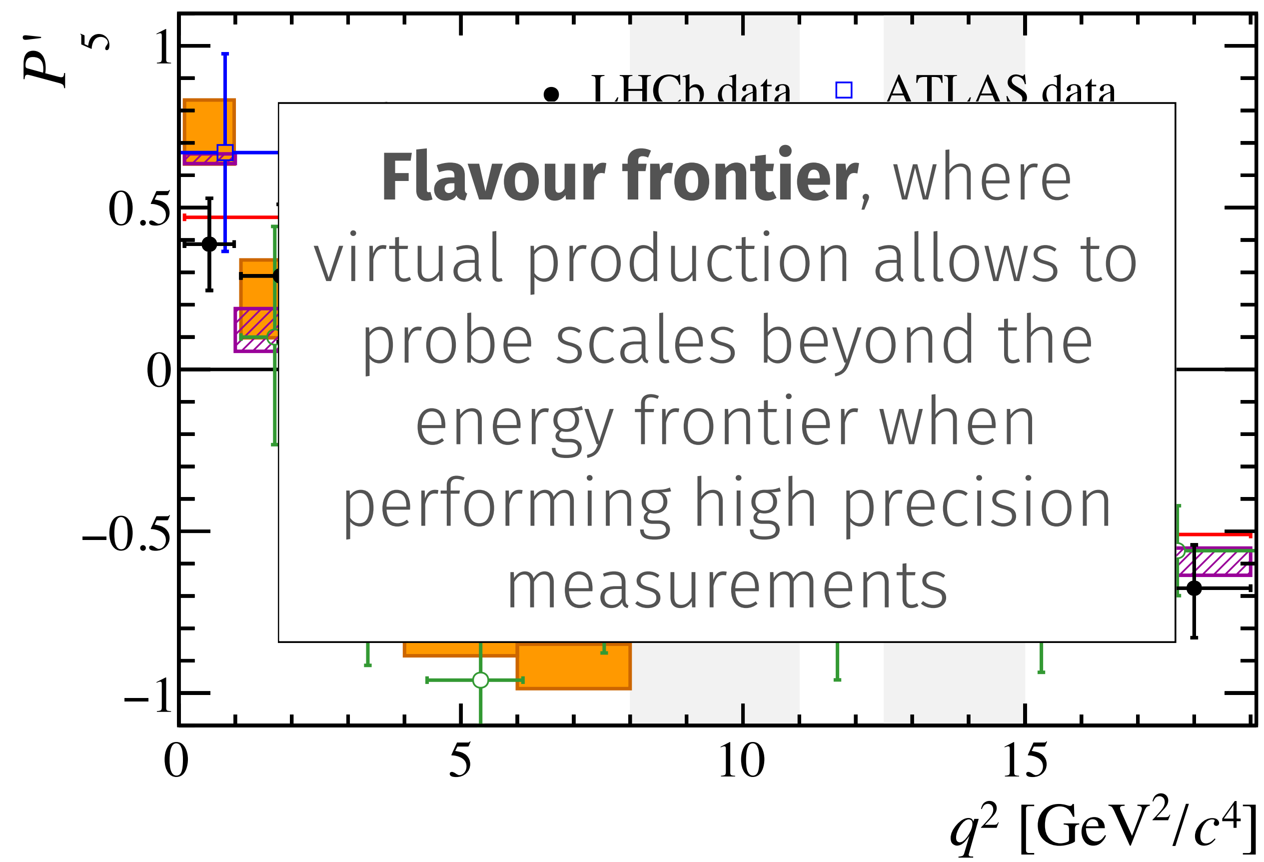

Flavour frontier, where virtual production allows to probe scales beyond the energy frontier when performing high precision measurements

[Belle arXiv:1612.05014, ATLAS-CONF-2017-023
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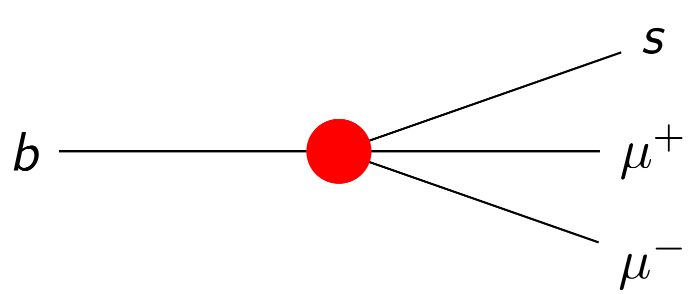
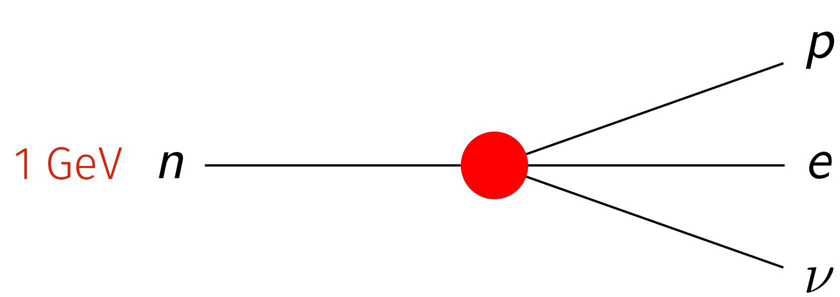
The indirect approach

Decays that are forbidden at tree level are sensitive to quantum corrections from degrees of freedom at larger scales



This indirect approach has historically been used to predict the existence of new particles before direct observation was possible



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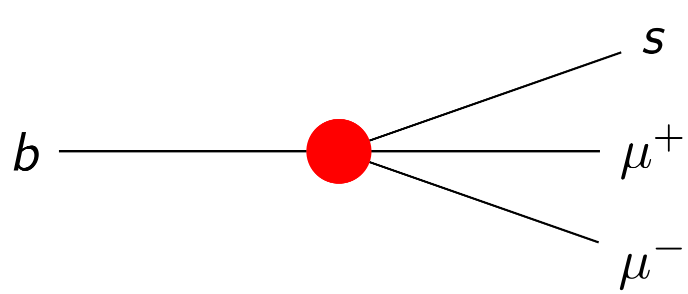

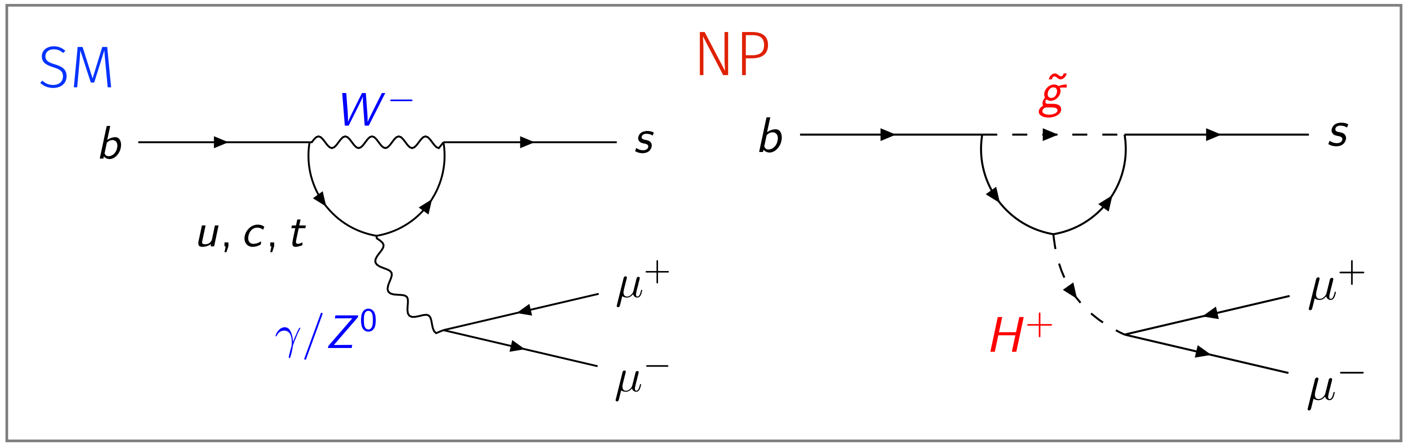

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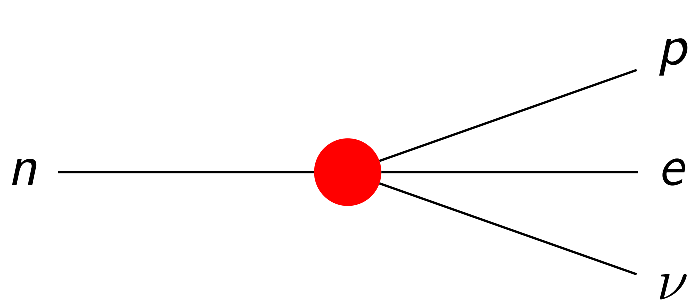
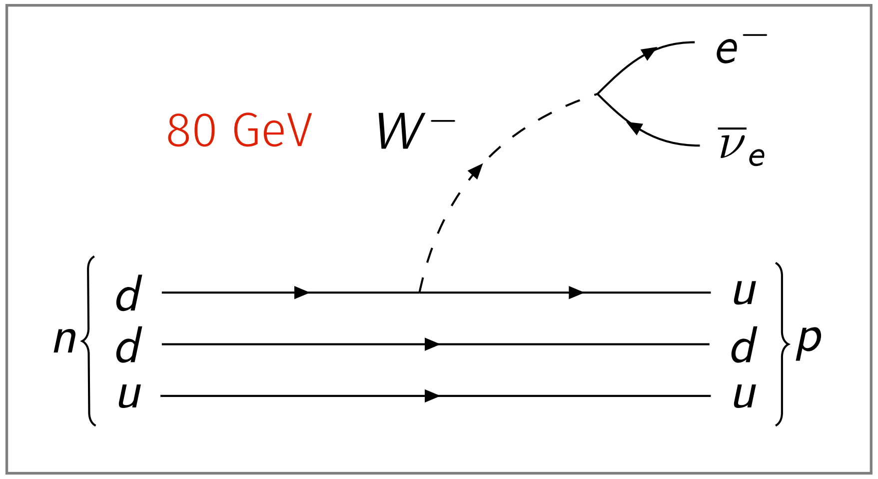




A lesson from history ...

New physics shows up at precision frontier before energy frontier

- GIM mechanism before discovery of charm
- CP violation / CKM before discovery of bottom & top
- Neutral currents before discovery of Z

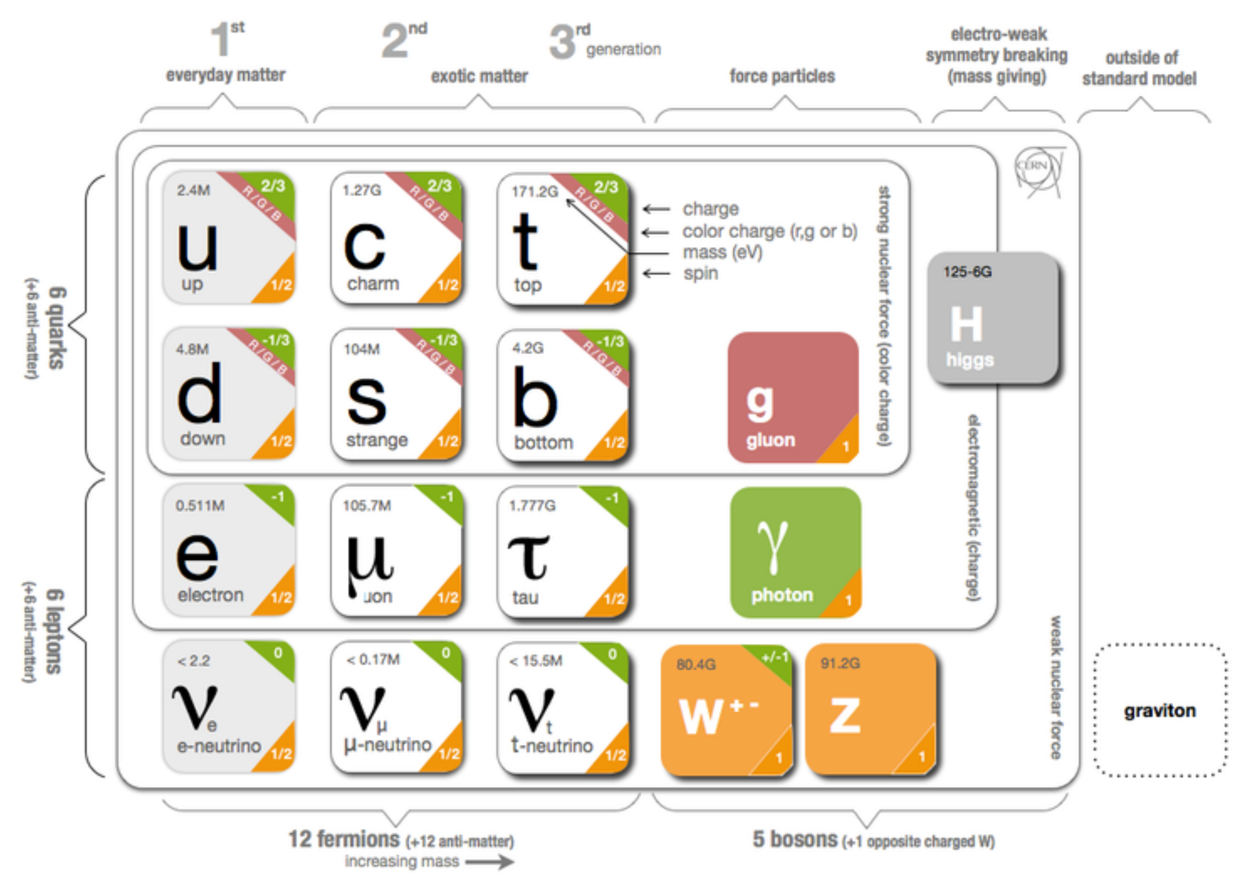
Particularly sensitive – loop processes

- Standard Model contributions suppressed / absent
- Flavour changing neutral currents (rare decays)
- CP violation
- Lepton flavour / number violation / lepton universality

LHCb roadmap: search for NP in flavour sector!

Why the b quark?

- Heaviest quark that forms hadronic bound states
- All decays are CKM suppressed
  - Long lifetime (~1.6 ps)
  - Experimentally favourable
- High mass: many accessible final states with different expected rates
  - Dominant: “tree” b→c transitions
  - Very suppressed “tree” b→u transition
  - FCNC: “penguin” b→s,d transition
  - Flavour oscillation
- CP violation – expect large CP asymmetries in some B decays



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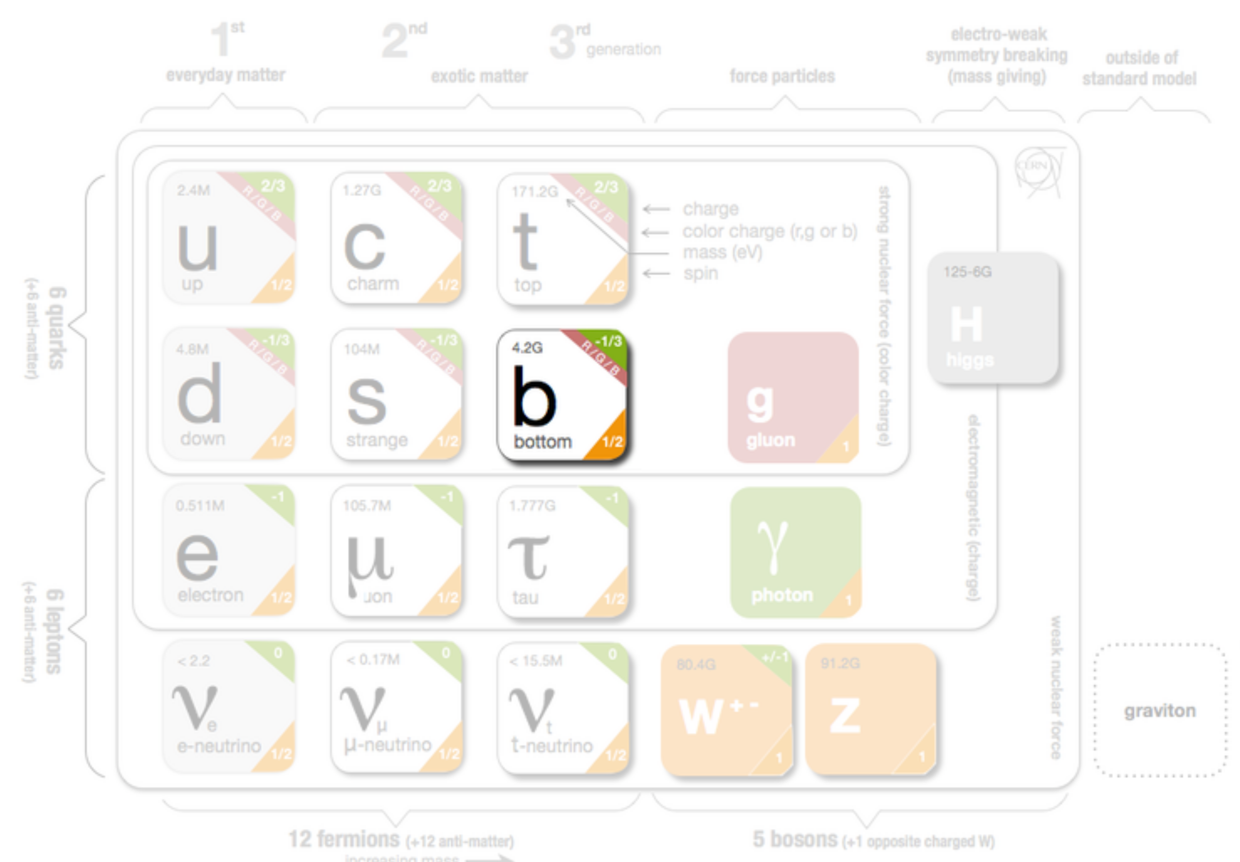

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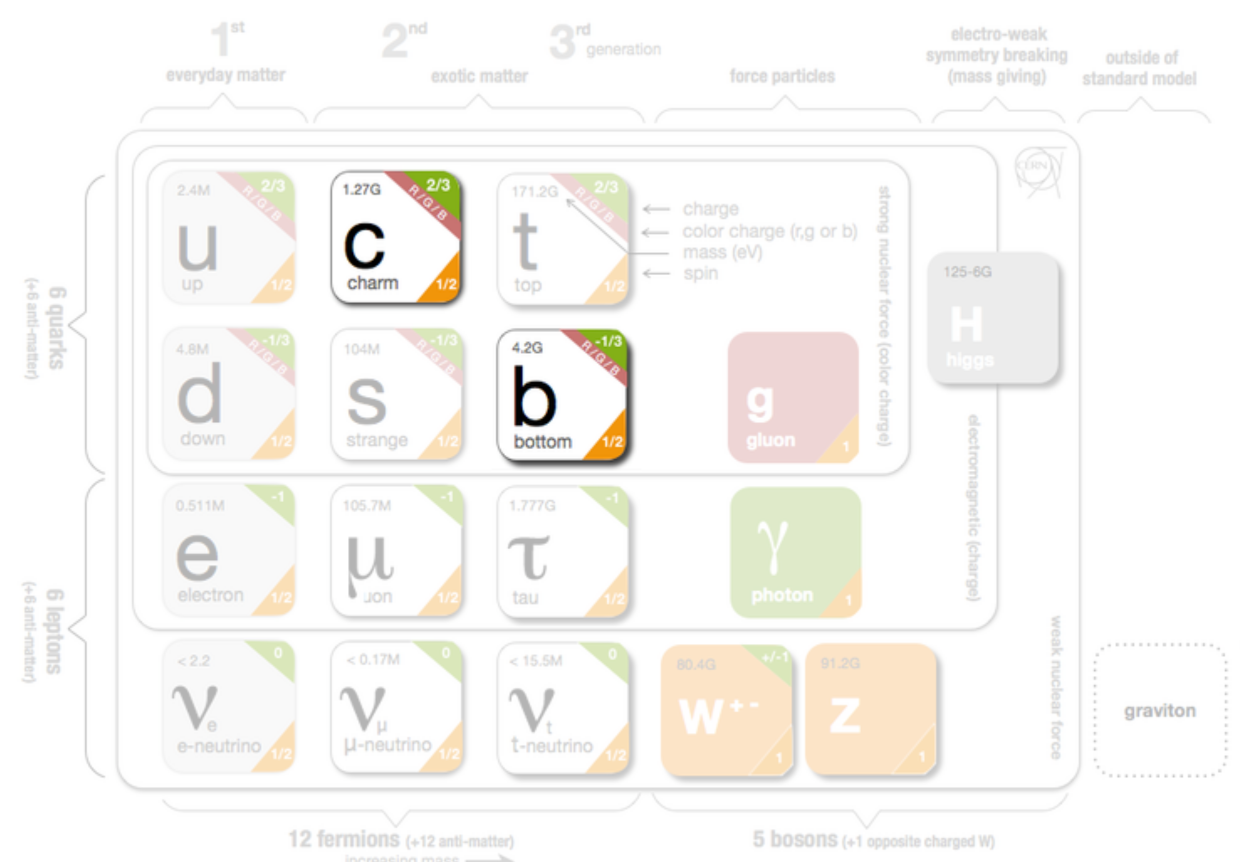

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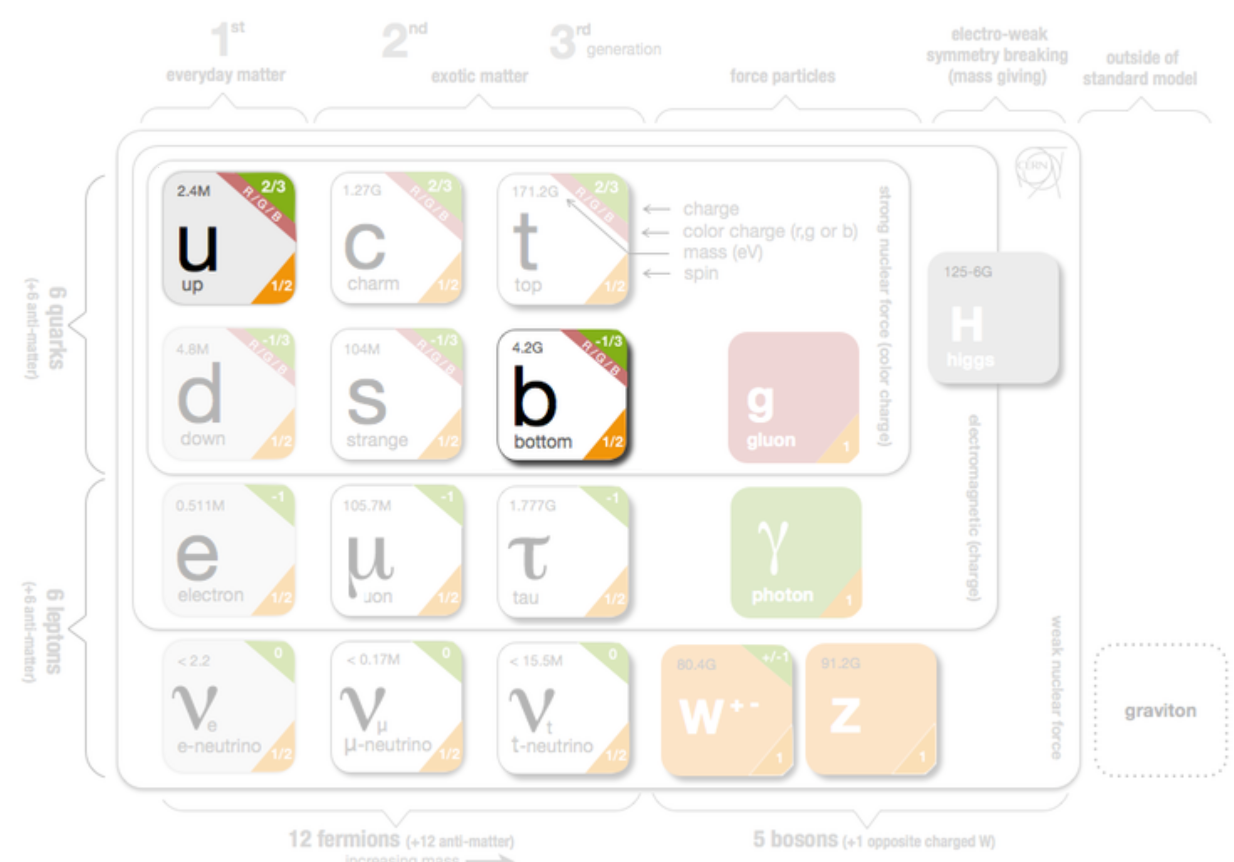

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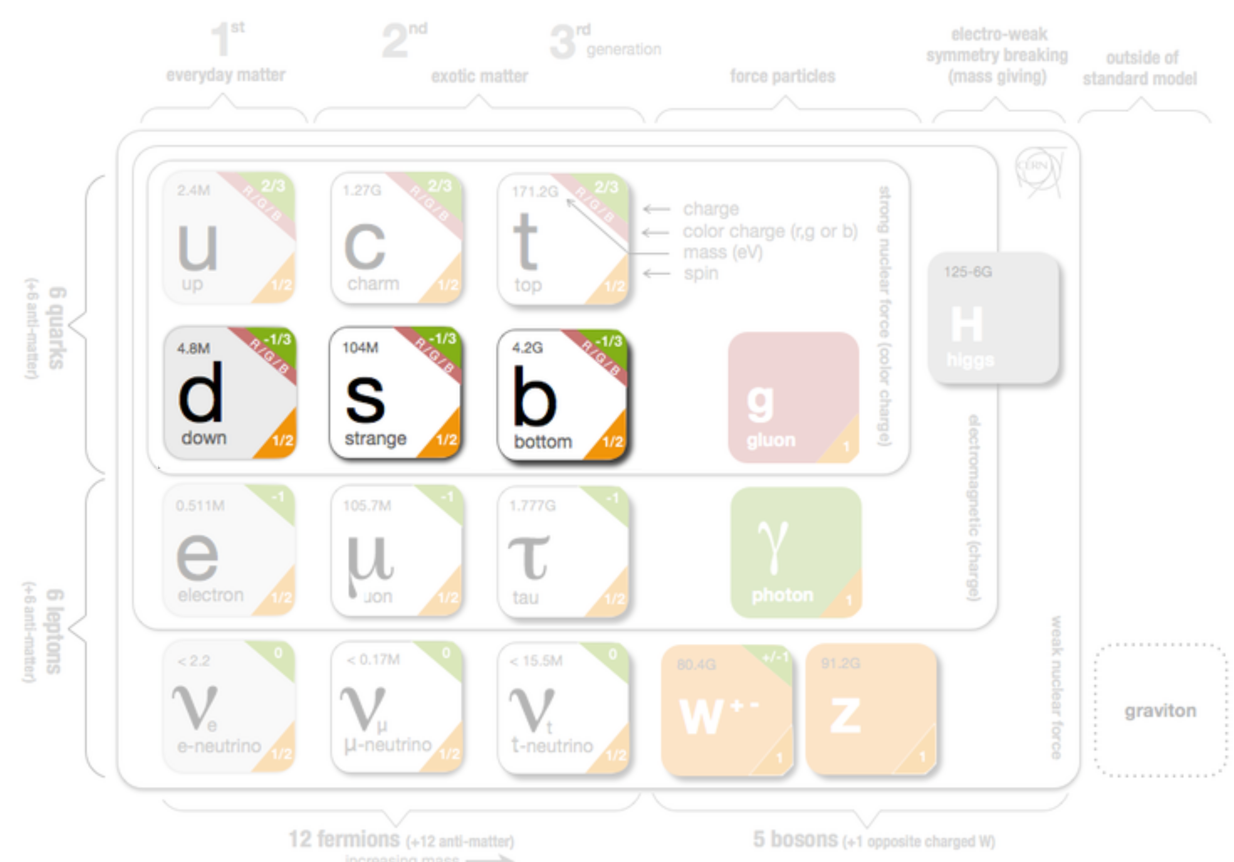

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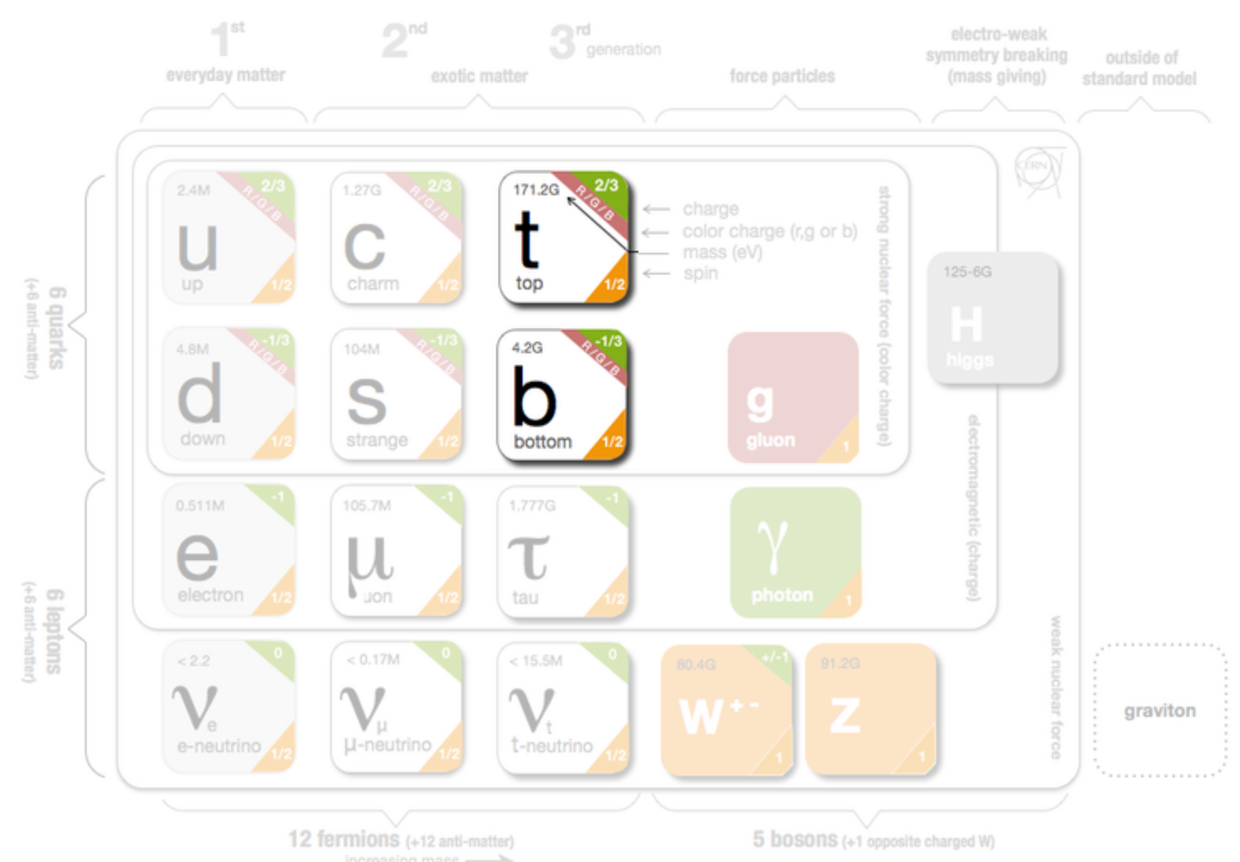
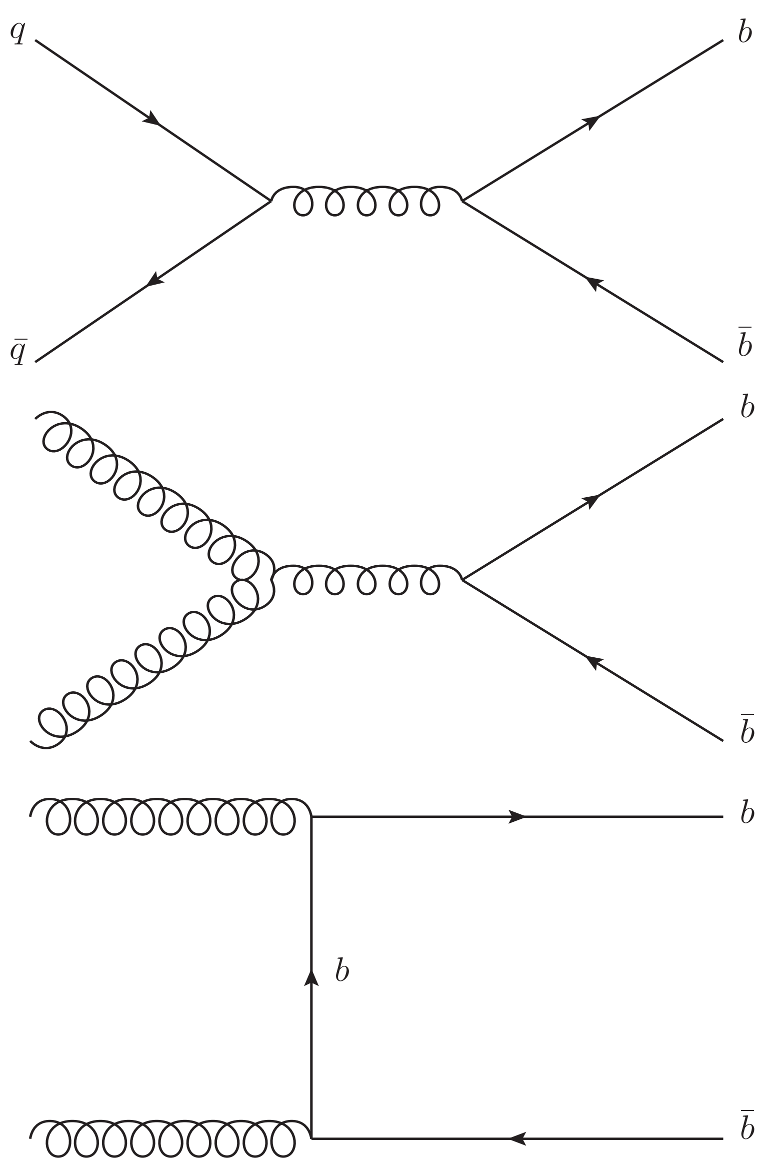
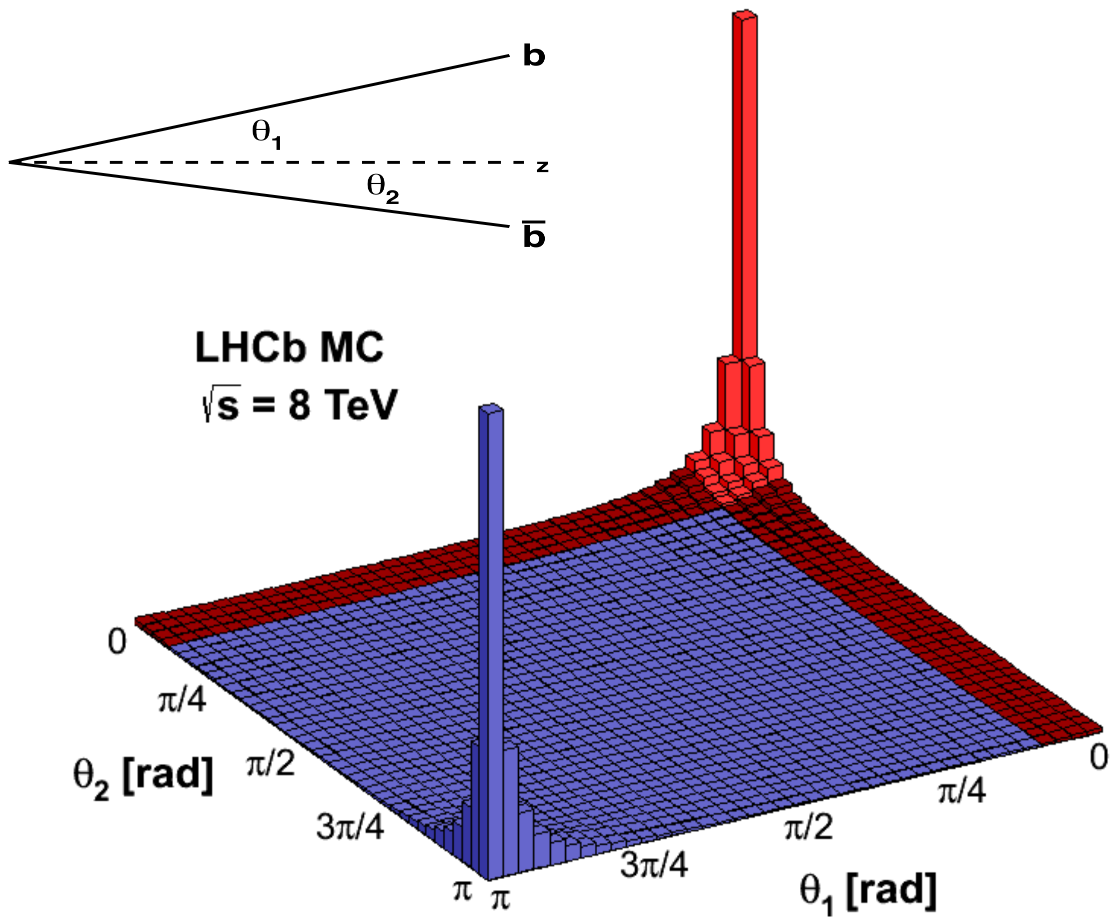


LHCb design

Detector designed to maximise the acceptance of the b-quark production



The correlation of the bb-pair produced is crucial in the design



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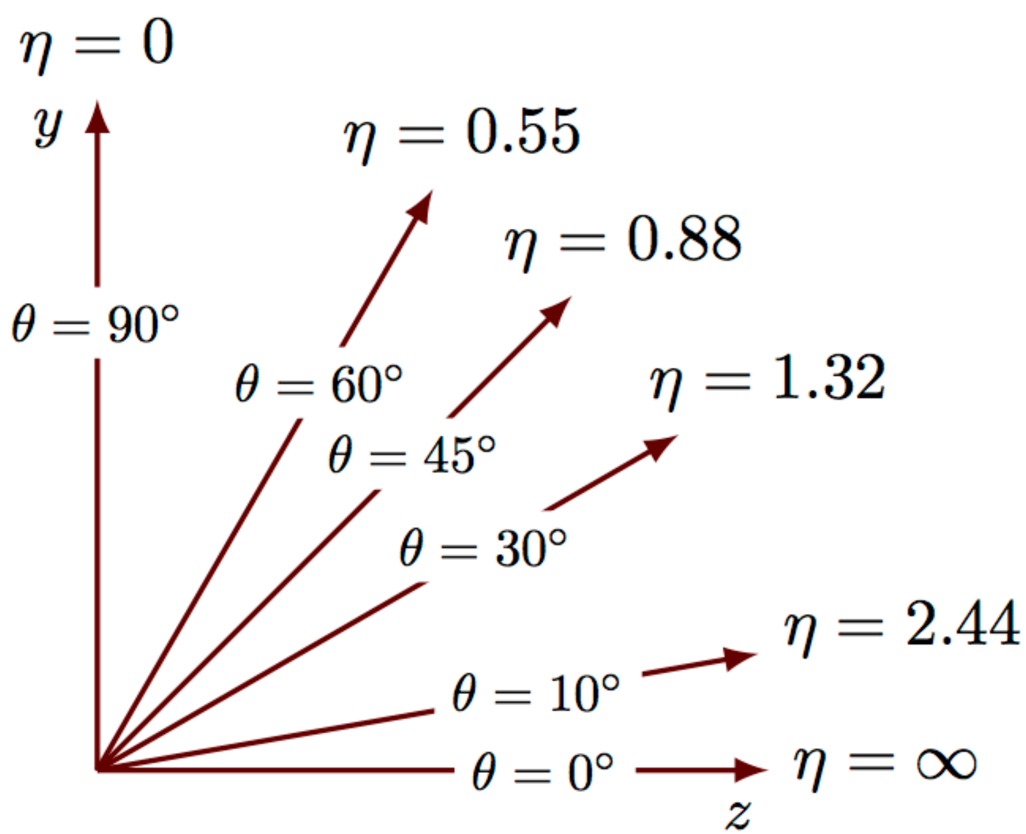
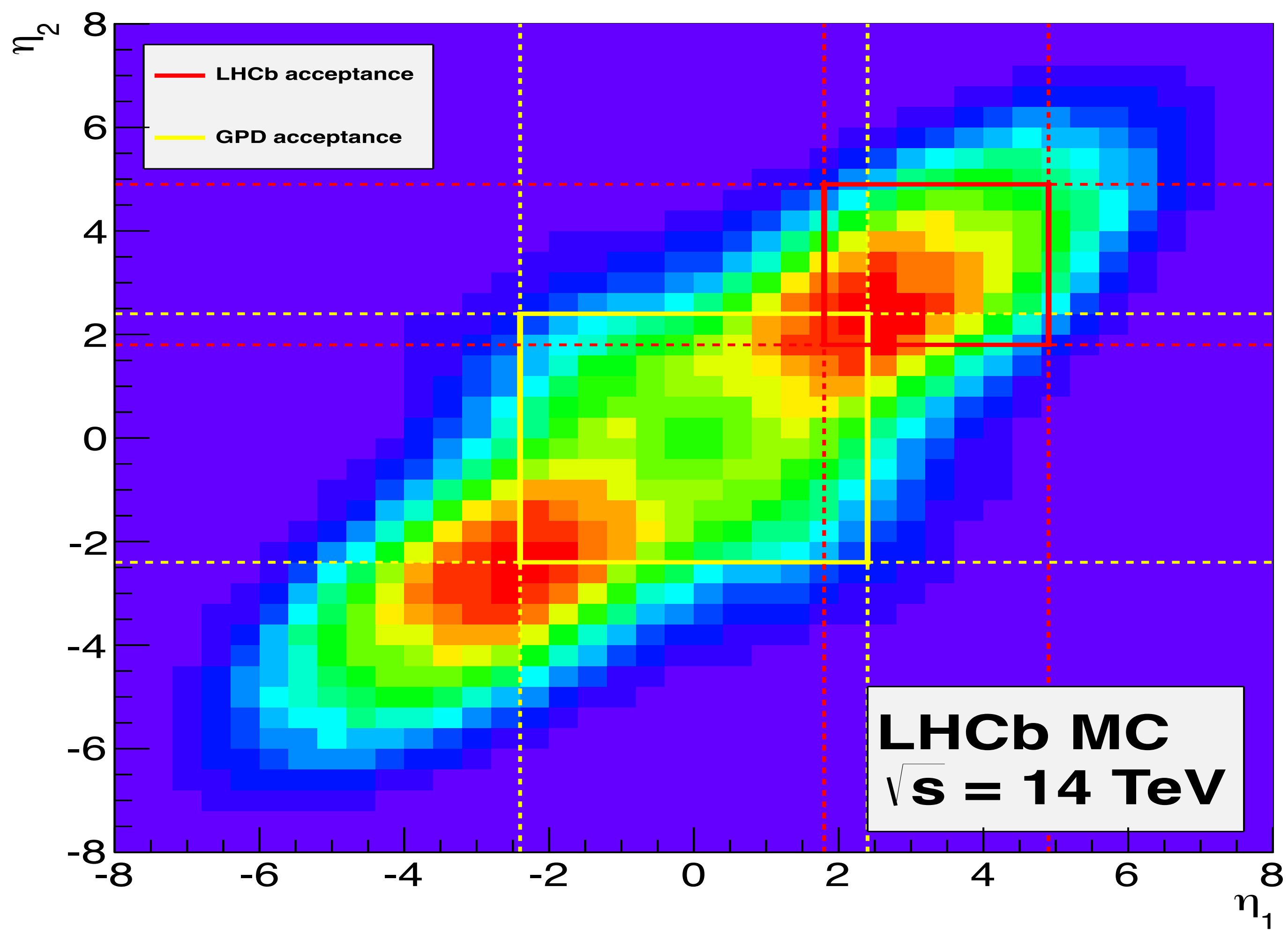
pseudo-rapidity η = -lntan(θ/2)

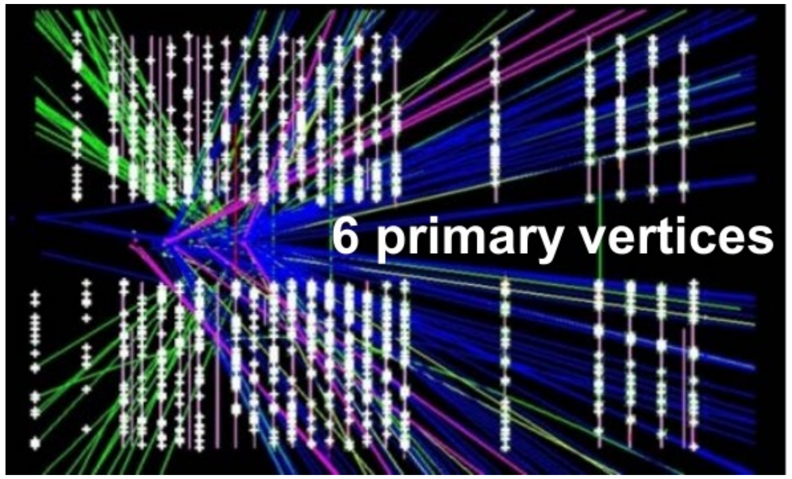




Luminosity at LHCb

At nominal LHC luminosity multiple *pp* interactions per bunch crossing

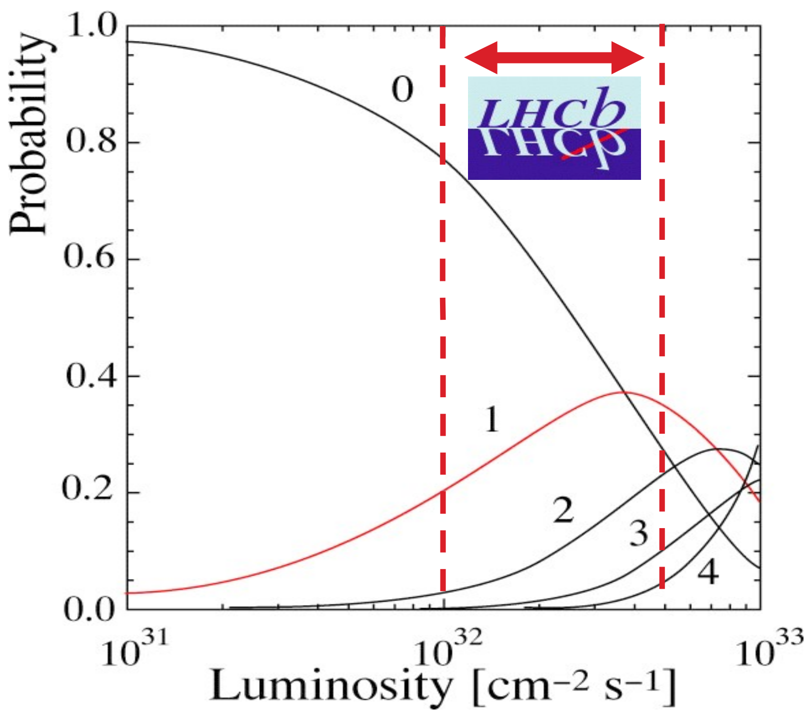
$$\langle N_{\text{int/BX}} \rangle = \frac{N_{\text{int}}/t}{N_{\text{BX}}/t} = \frac{L \times \sigma^{pp}_{\text{inelastic}}}{N_{\text{BX}}/t} = \frac{10^{34}\,\text{cm}^{-2}\text{s}^{-1} \times 80\text{ mb}}{31.6 \times 10^{6}\,\text{s}^{-1}} \approx 25$$



Particle densities are very high in the forward acceptance covered by LHCb

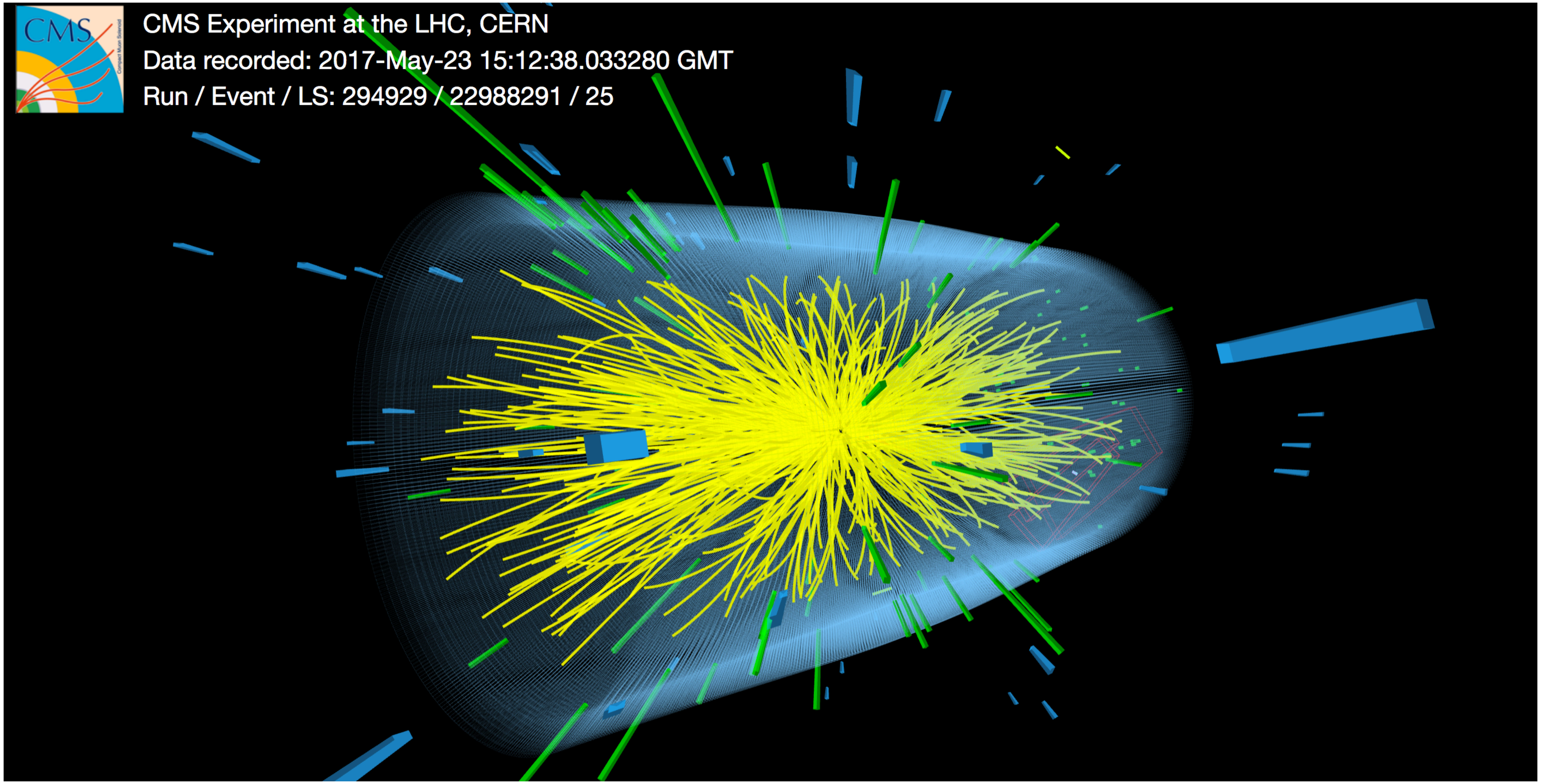
- Events with multiple *pp* interactions
  ⇒ high detector occupancy, low trigger and reconstruction efficiency, poor S/B
- Multiple primary vertices in one event
  ⇒ risk to assign wrong PV and reconstruction

Solution: slightly mis-align LHC beams in LHCb interaction point ⇒ operate at the same time as ATLAS/CMS



LHCb running conditions

ATLAS/CMS harsh environment would significantly affect the physics programme



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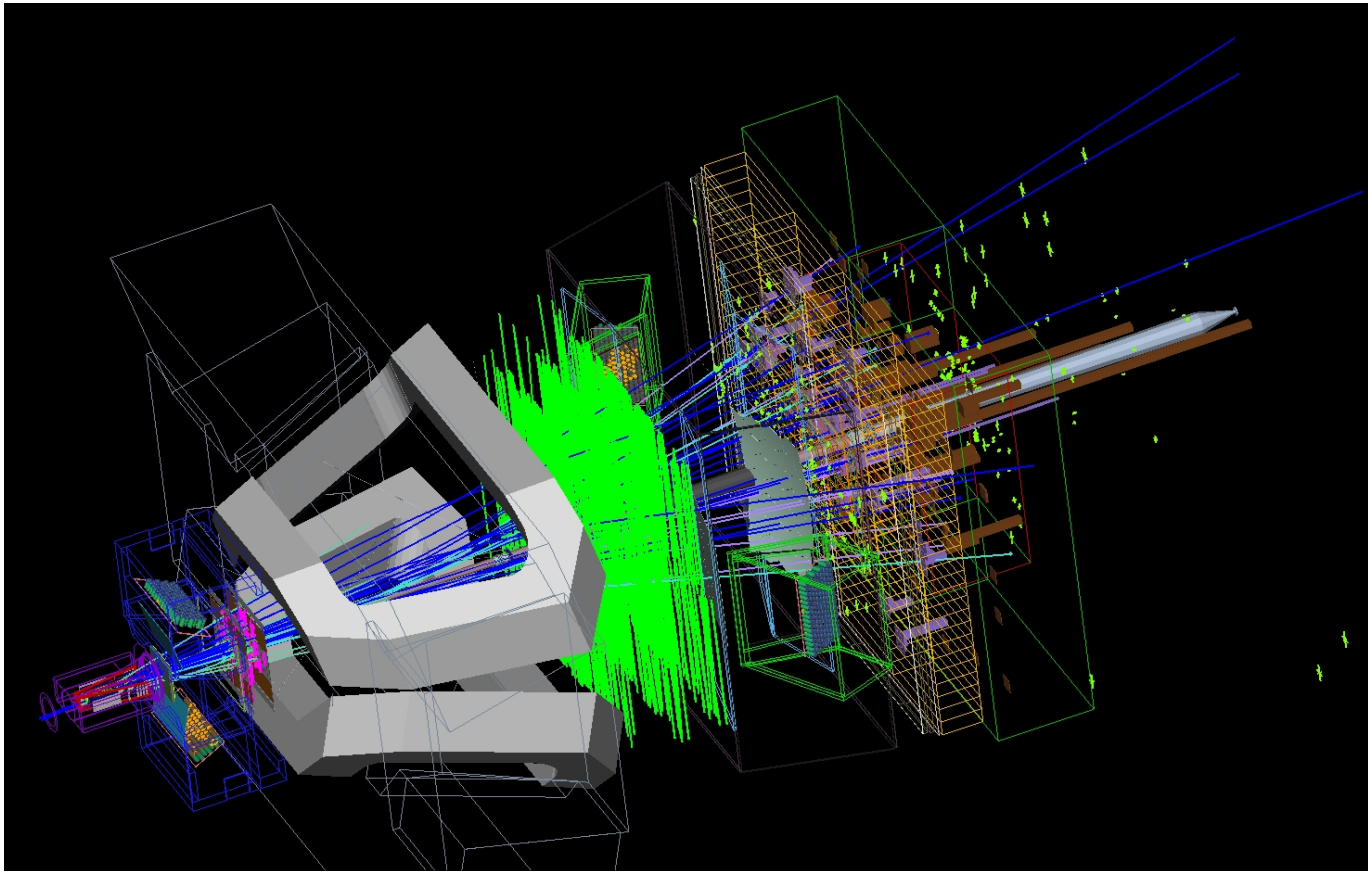
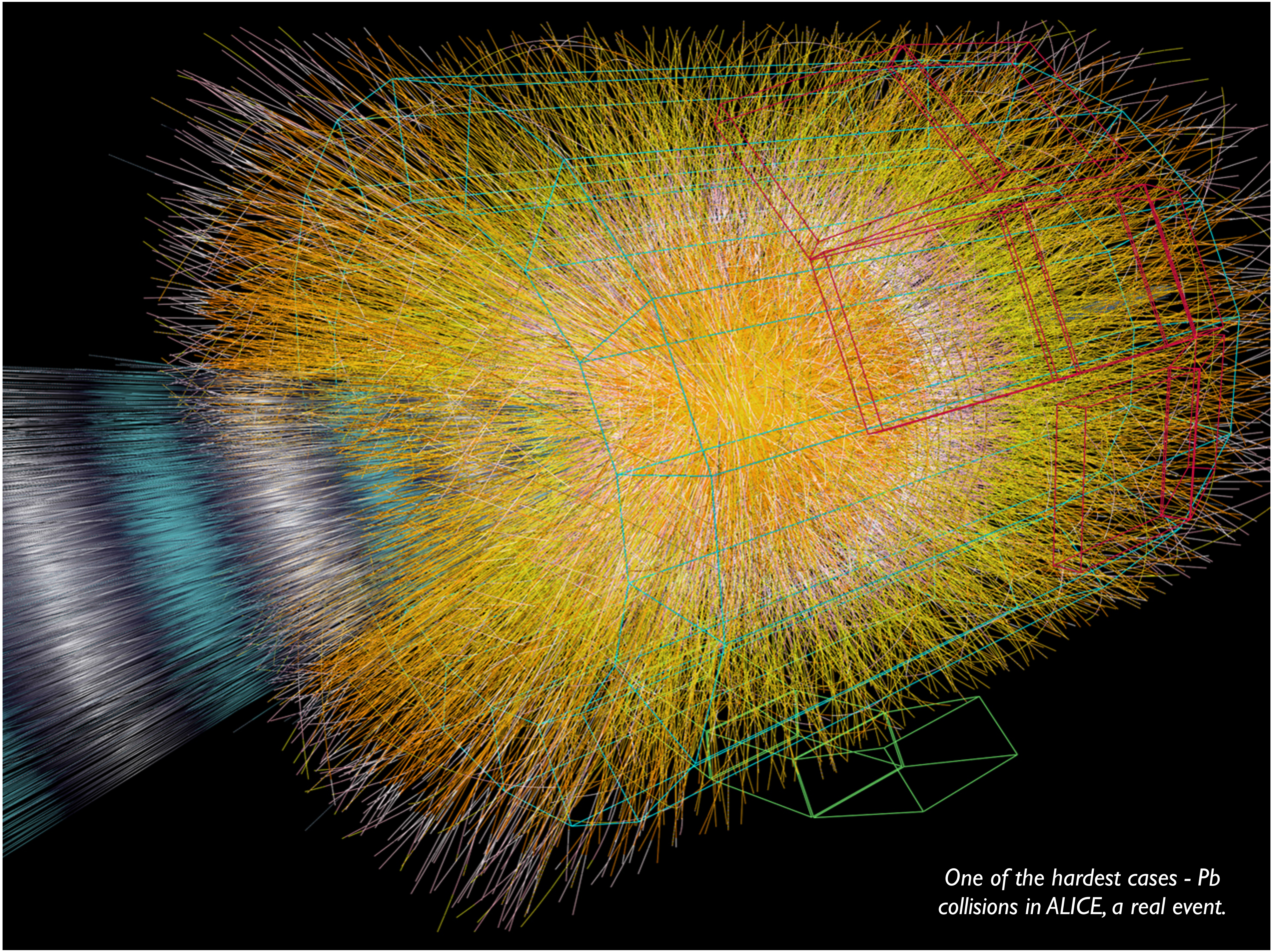
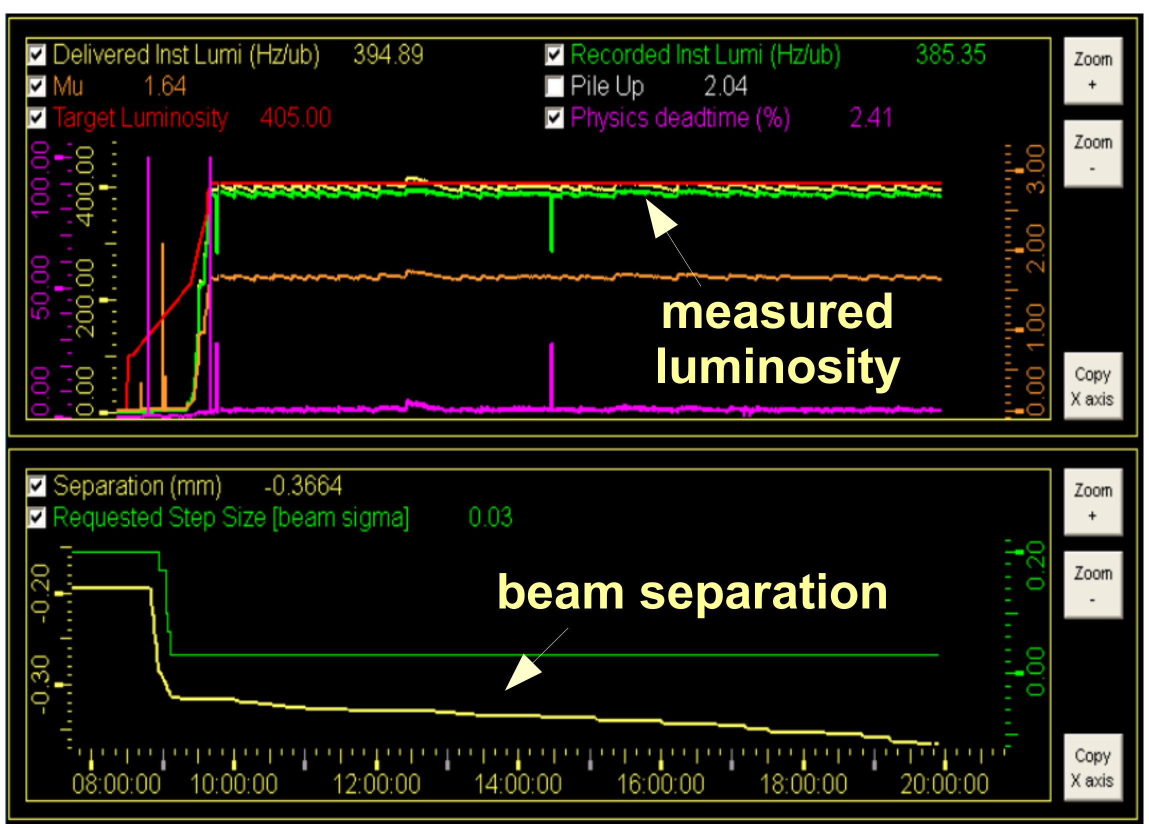


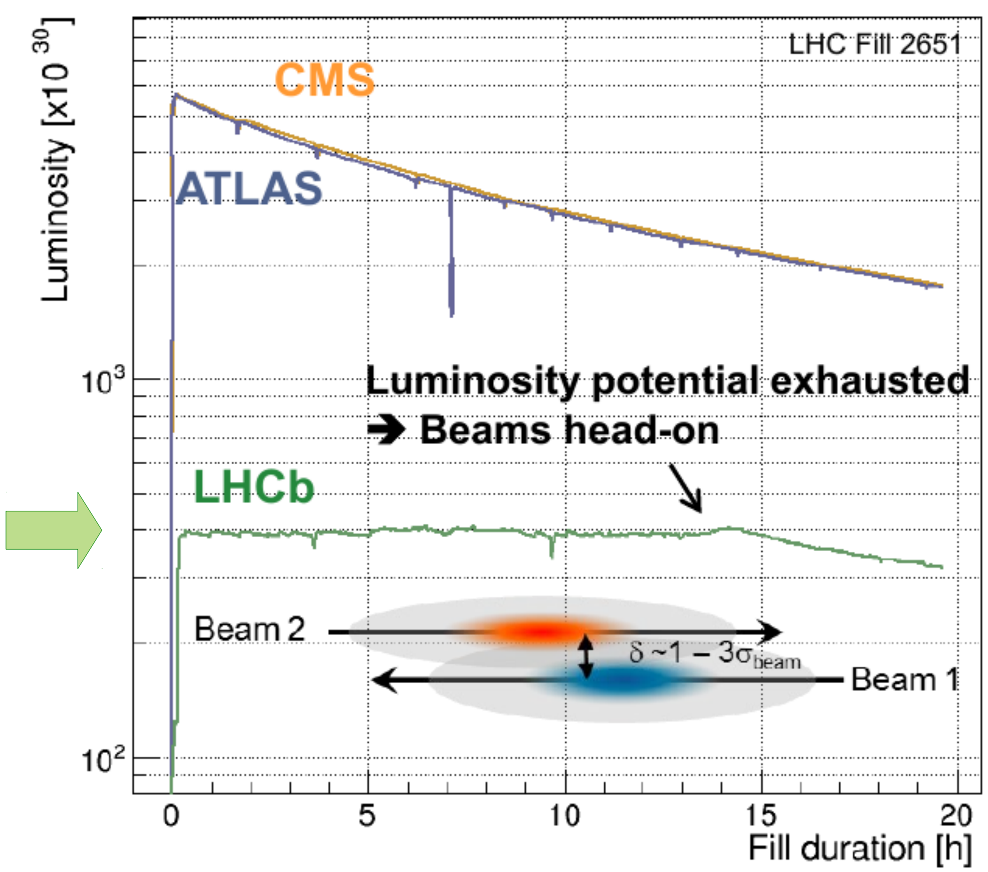


One of the hardest cases - Pb collisions in ALICE, a real event.

Keep luminosity in LHCb constant throughout LHC fills

- Continuously monitor instantaneous luminosity in LHCb at the interaction point, reduce beam separation when lumi drops below a pre-defined limit
- Larger integrated luminosity (= area underneath the curve)
- **Constant data taking conditions (**detector occupancies, trigger thresholds, etc**)**





The LHCb detector

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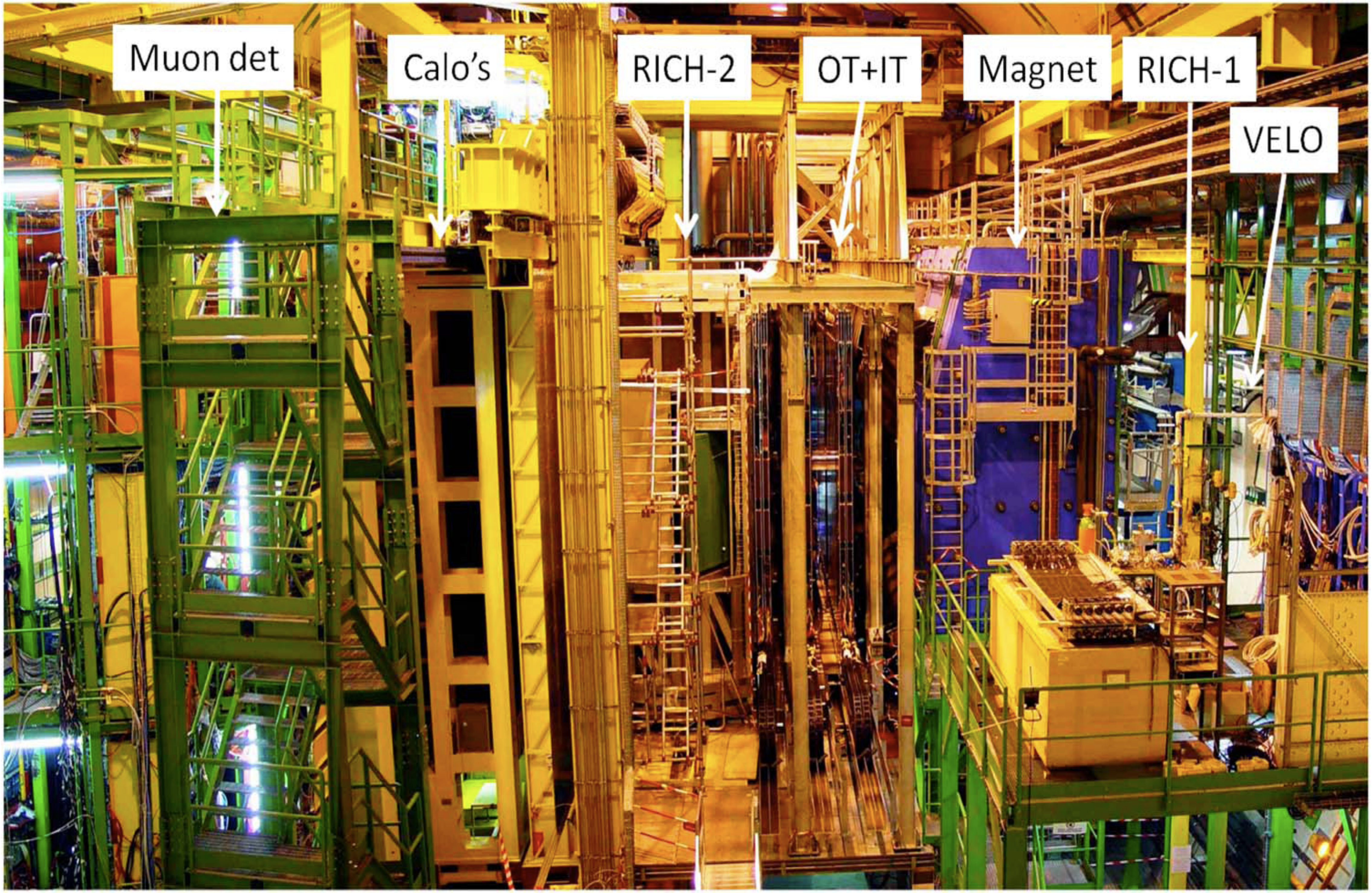

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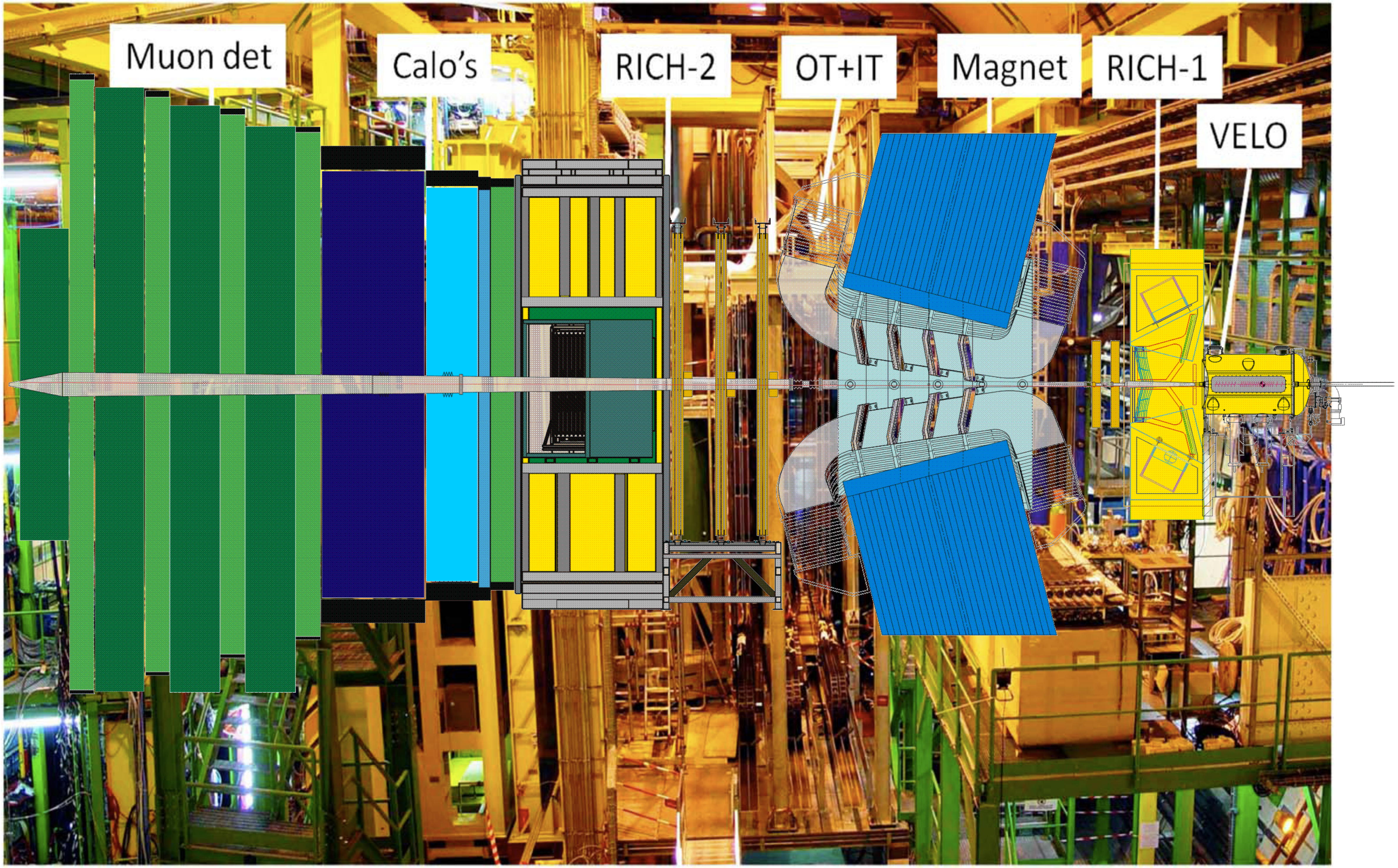

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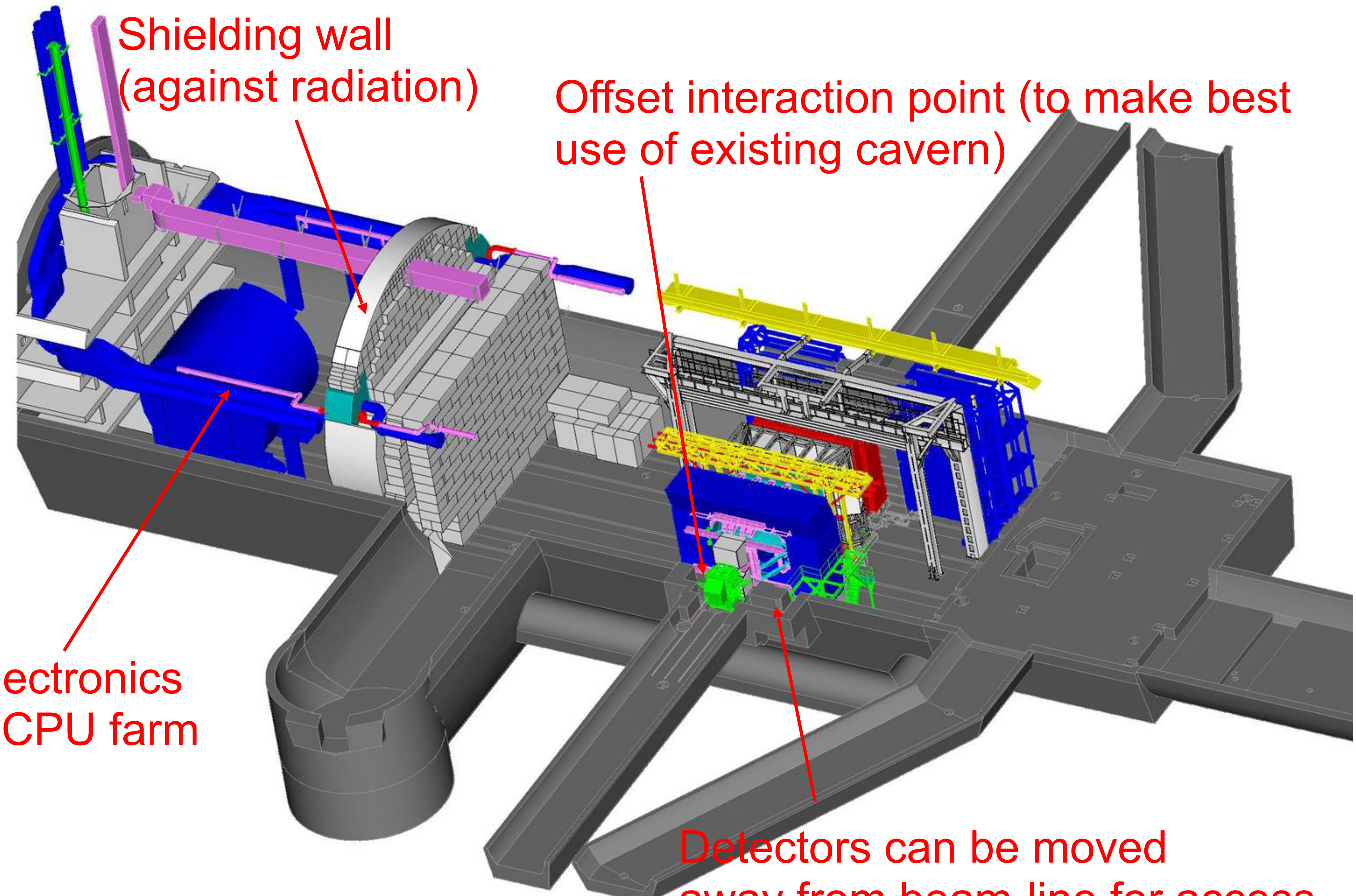

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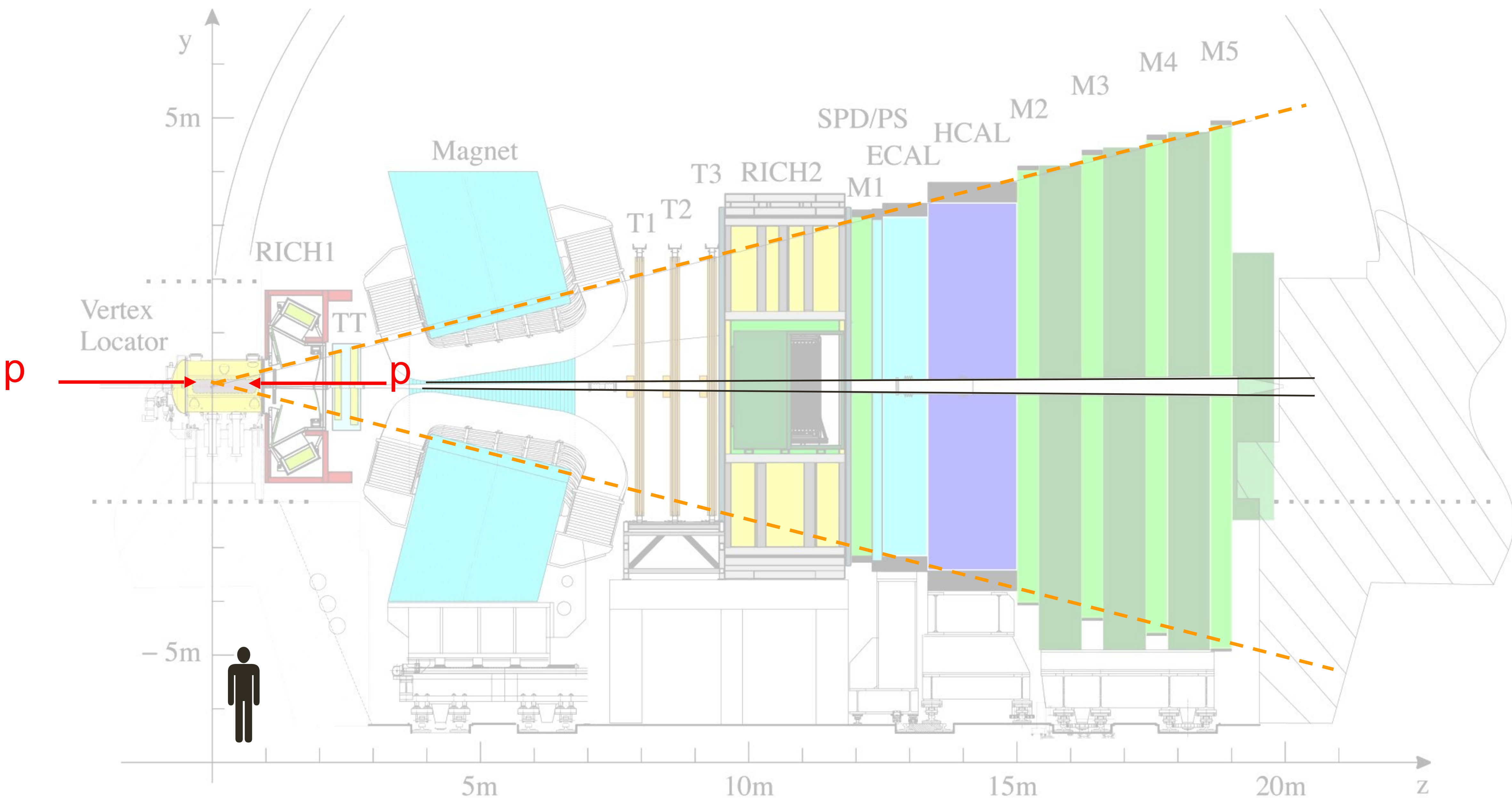

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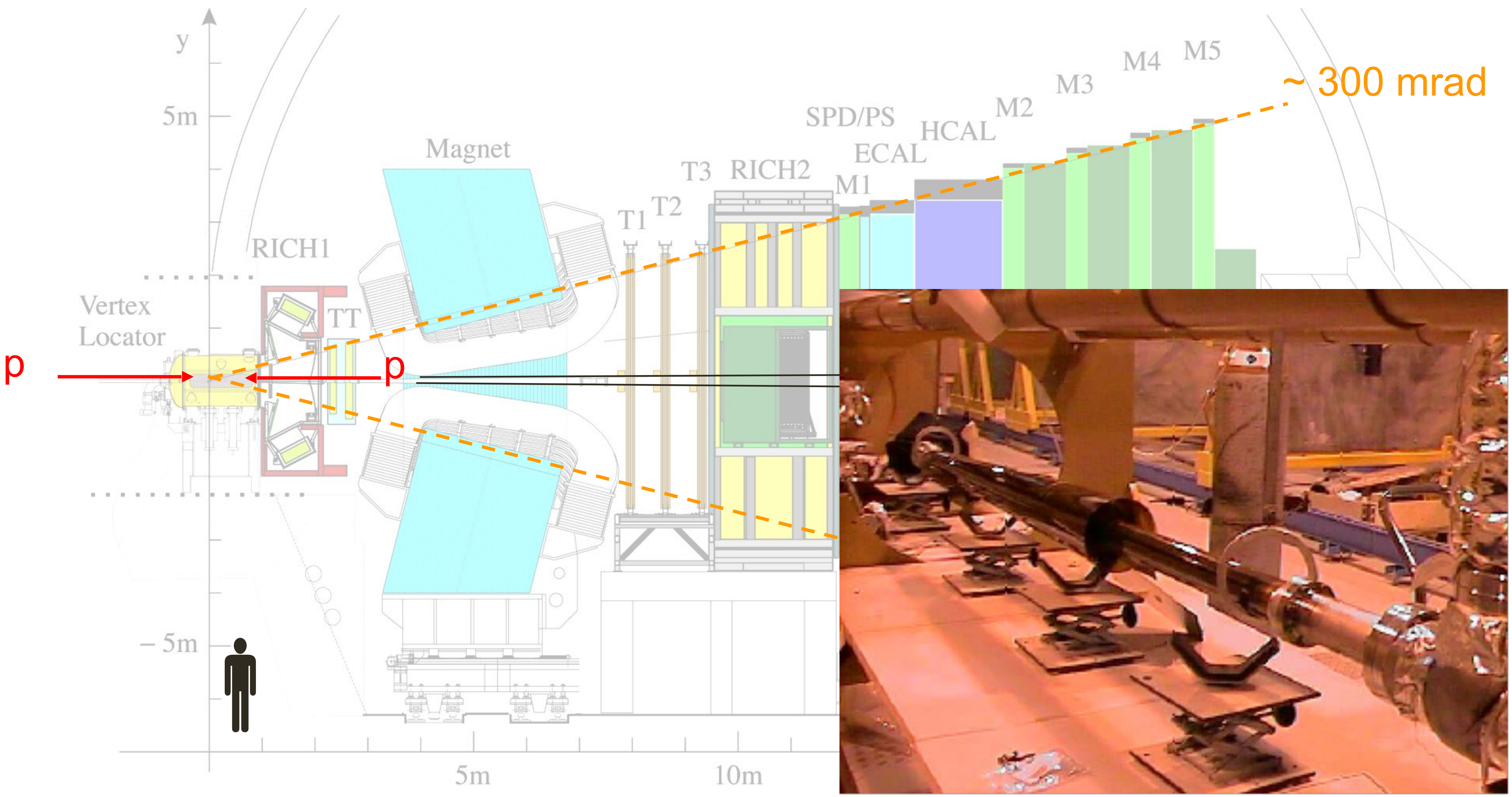

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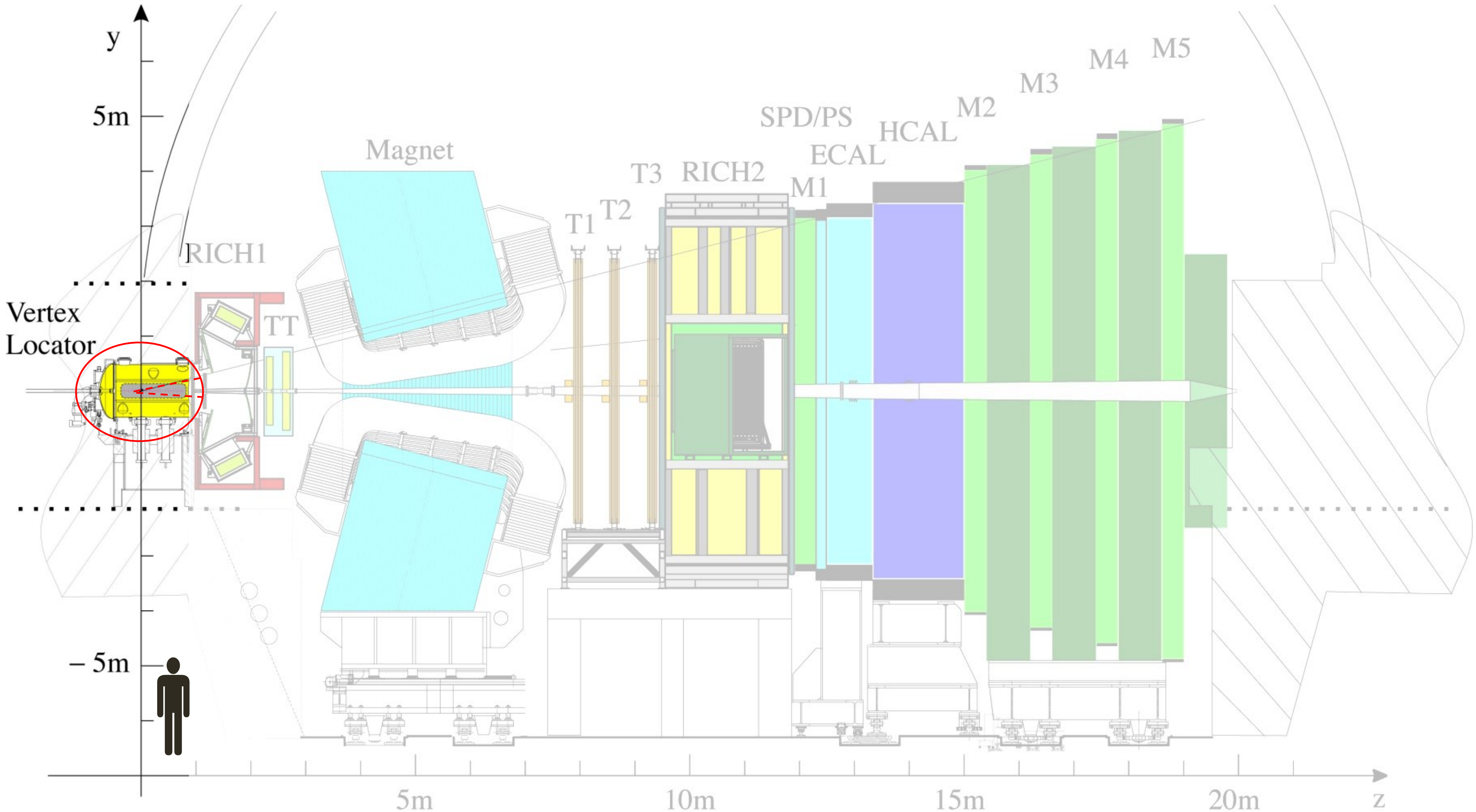


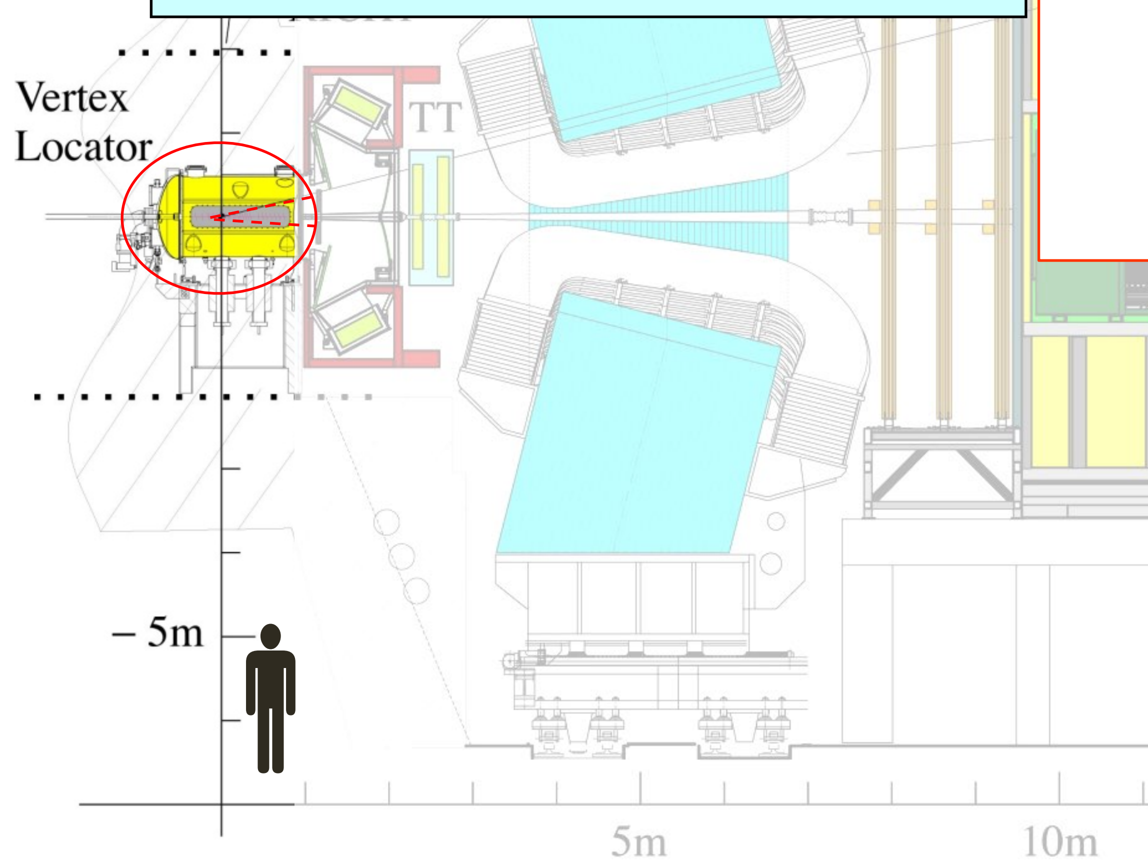
The LHCb detector

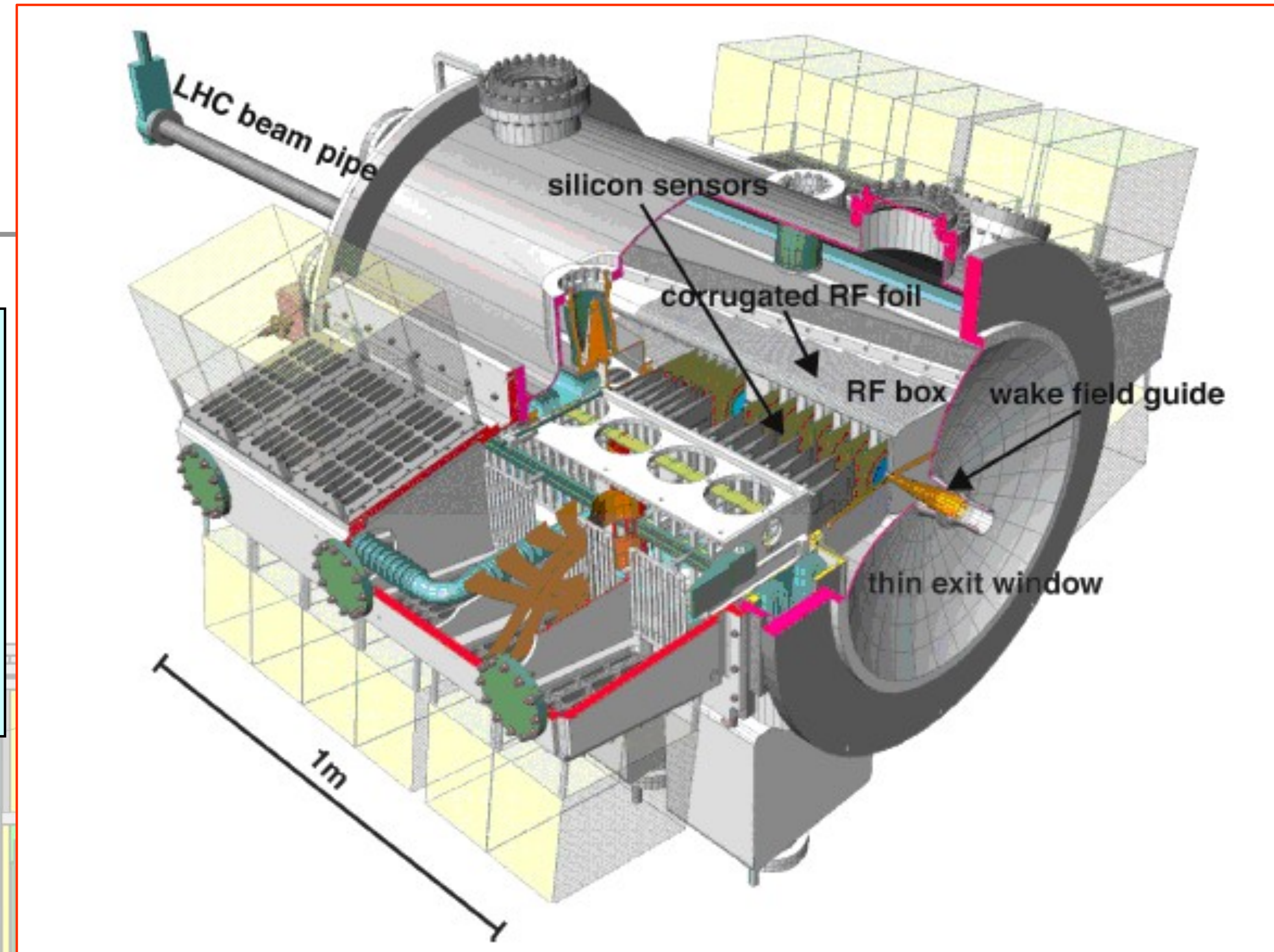
Vertex Locator (Velo)

21 stations of silicon strip detectors (r-ϕ)

~ 8 μm hit resolution

~25 μm IP resolution





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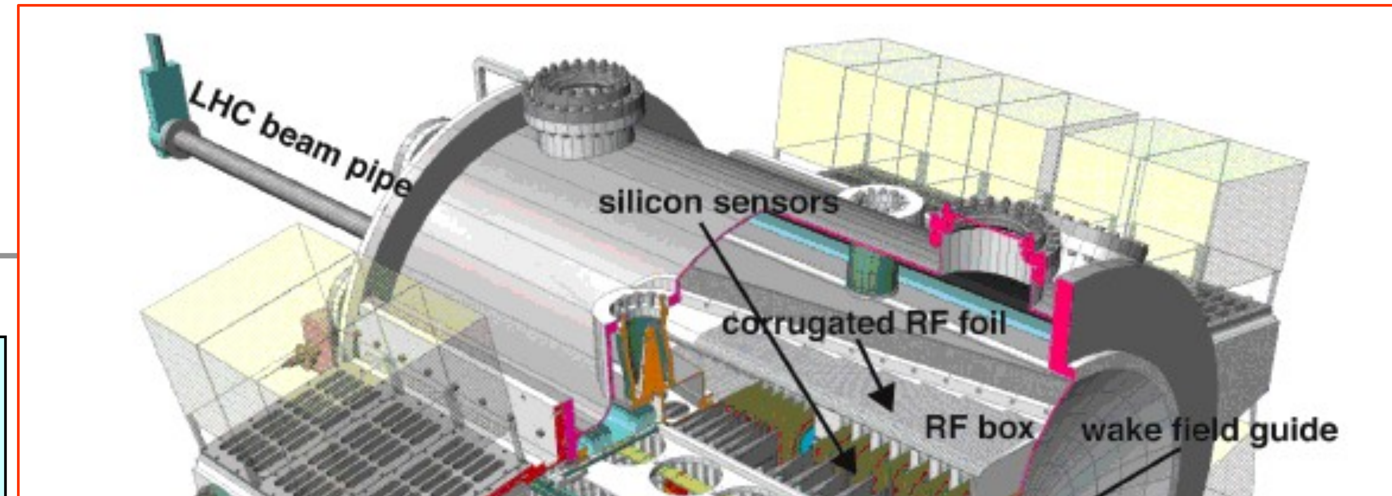
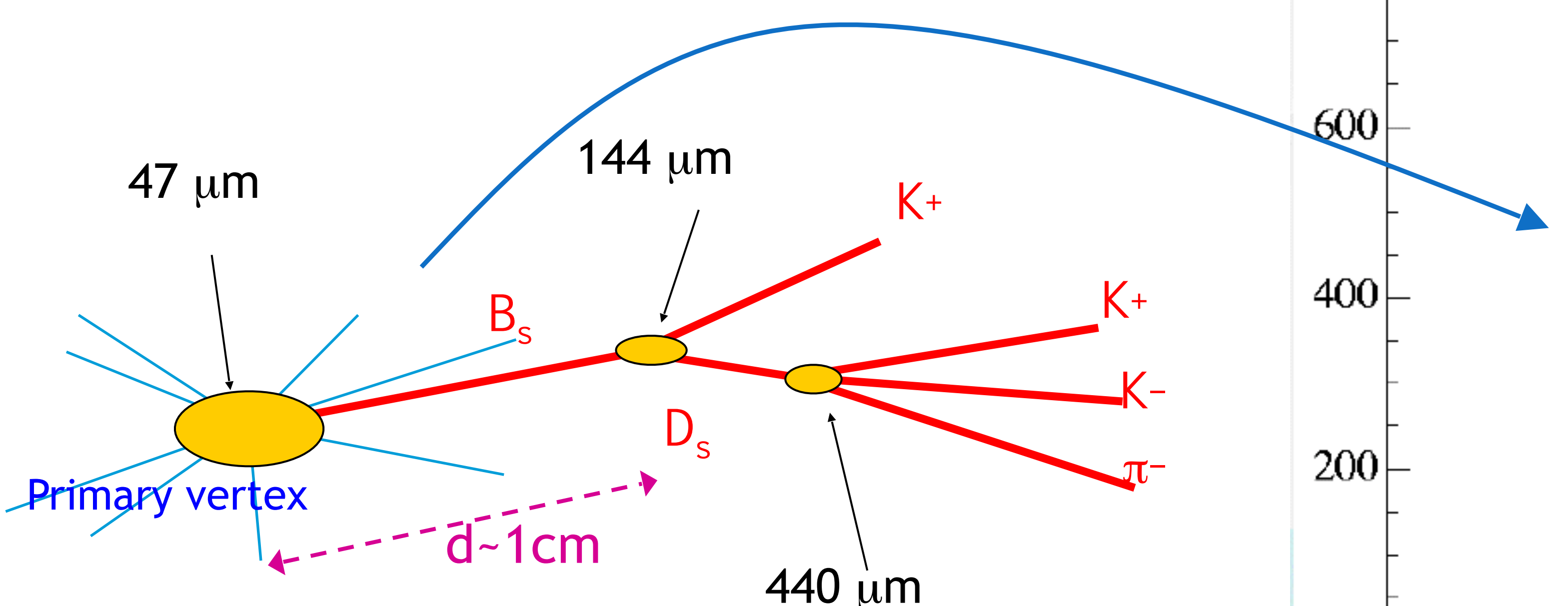
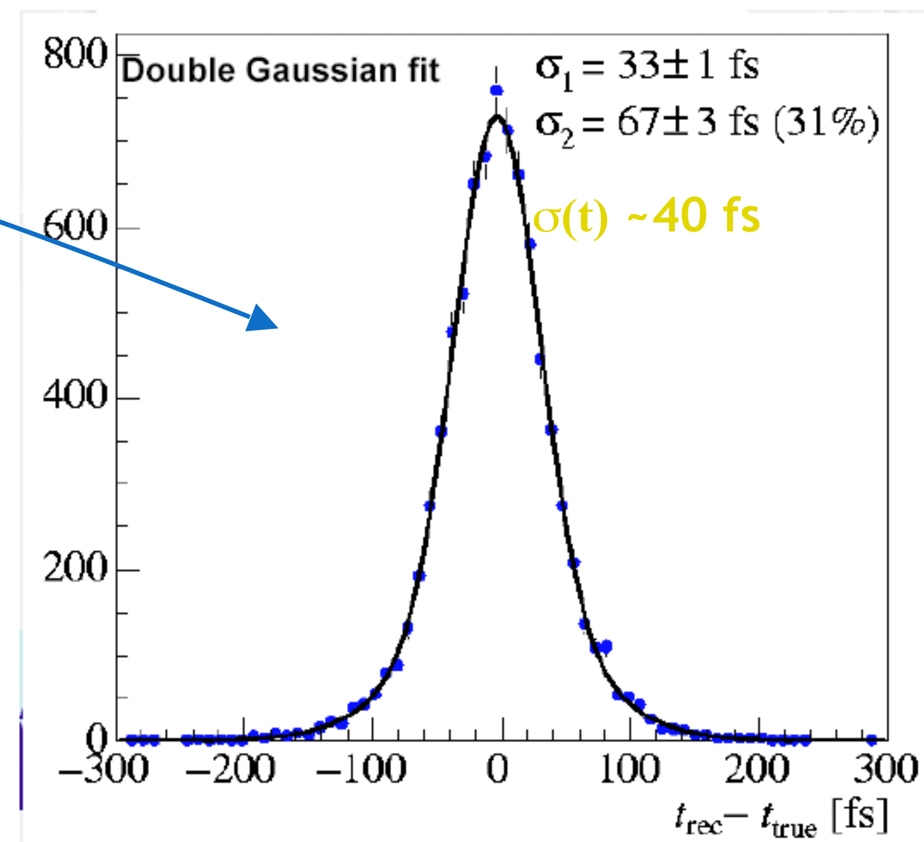
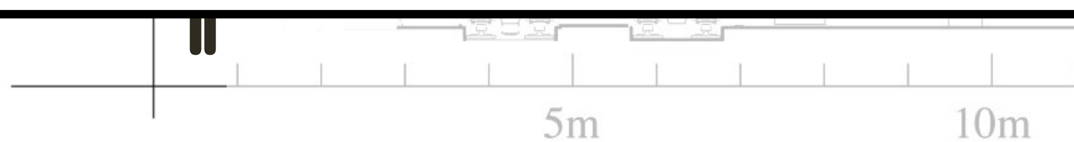


Example: $B_s \rightarrow D_s K$







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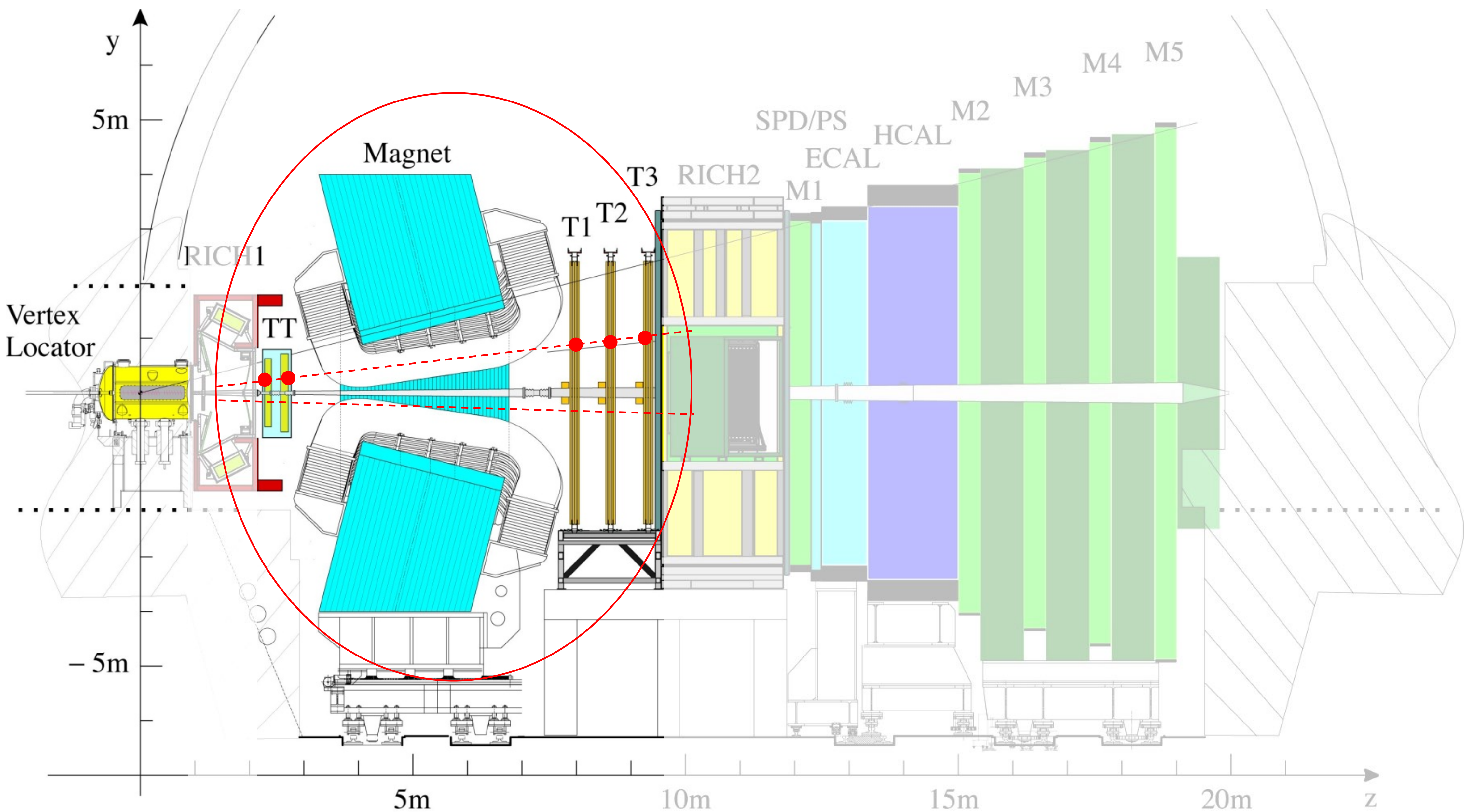

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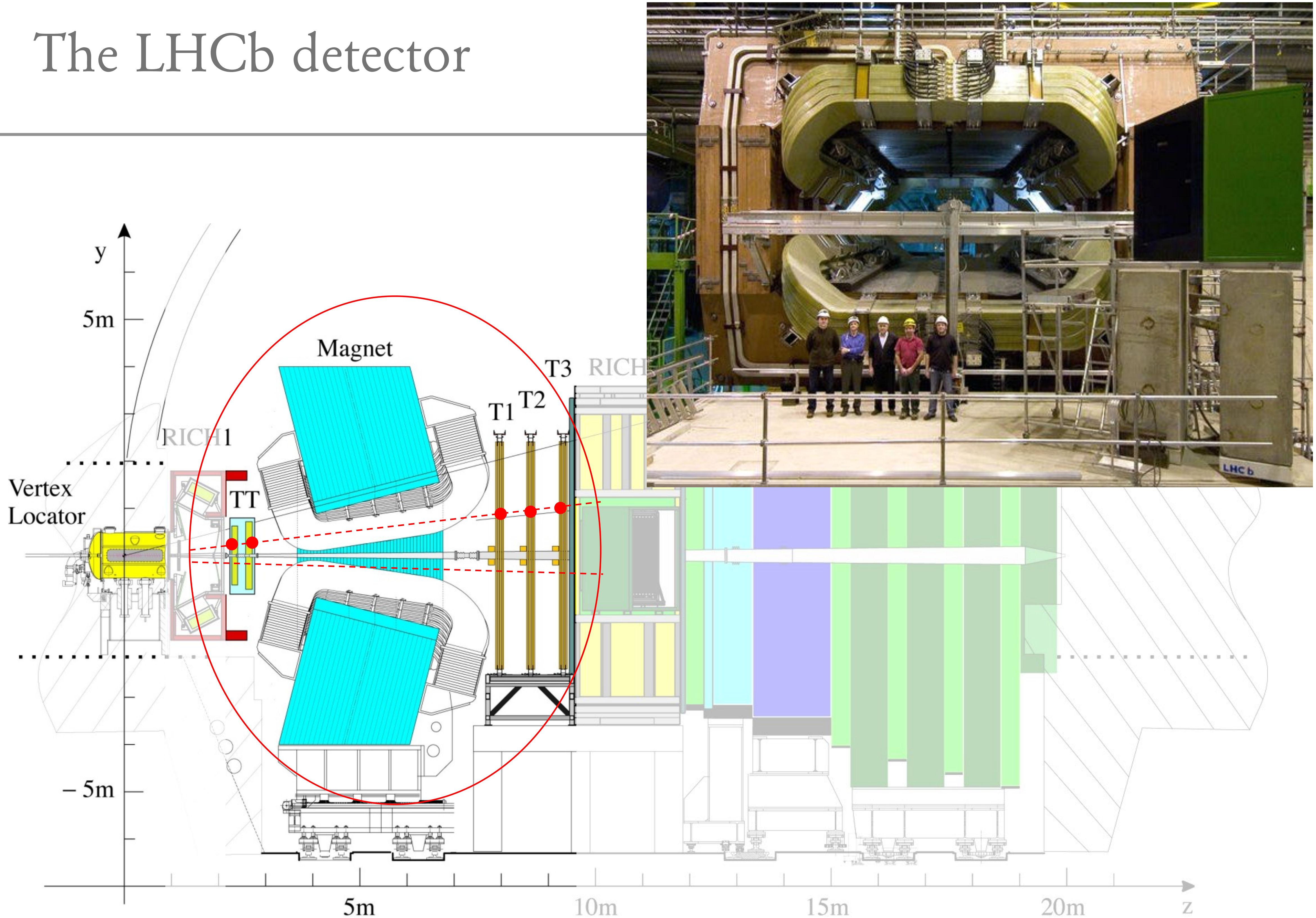
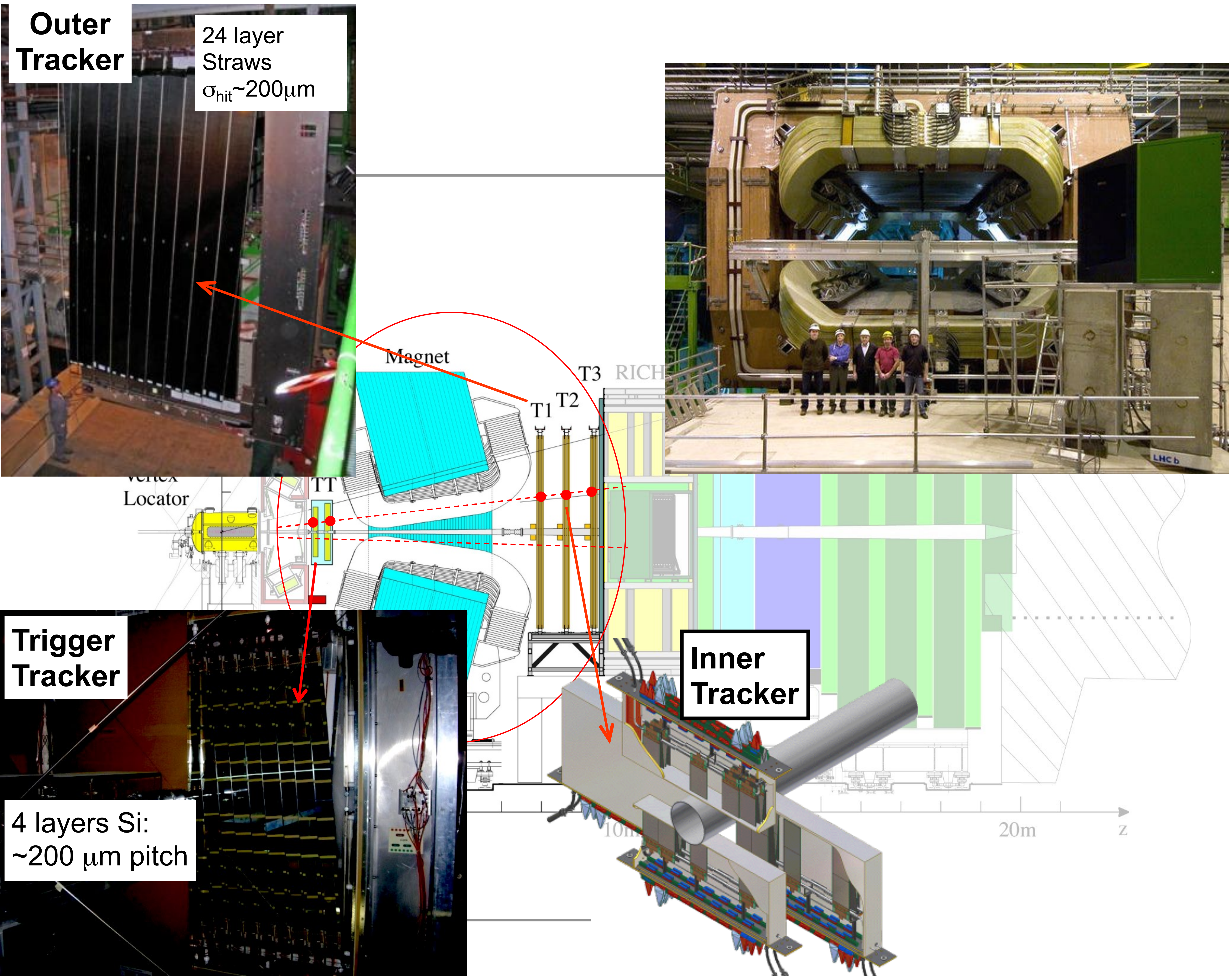
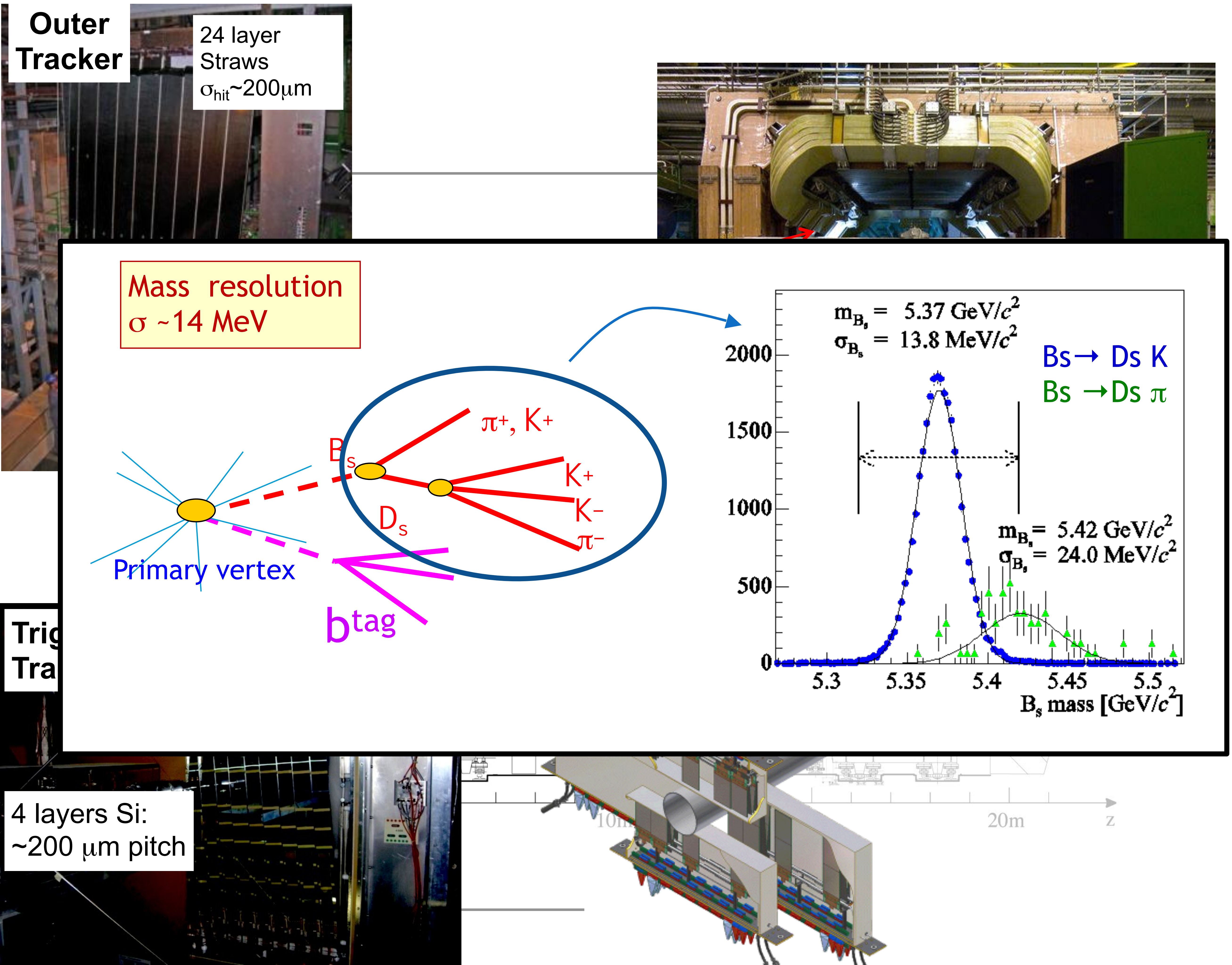
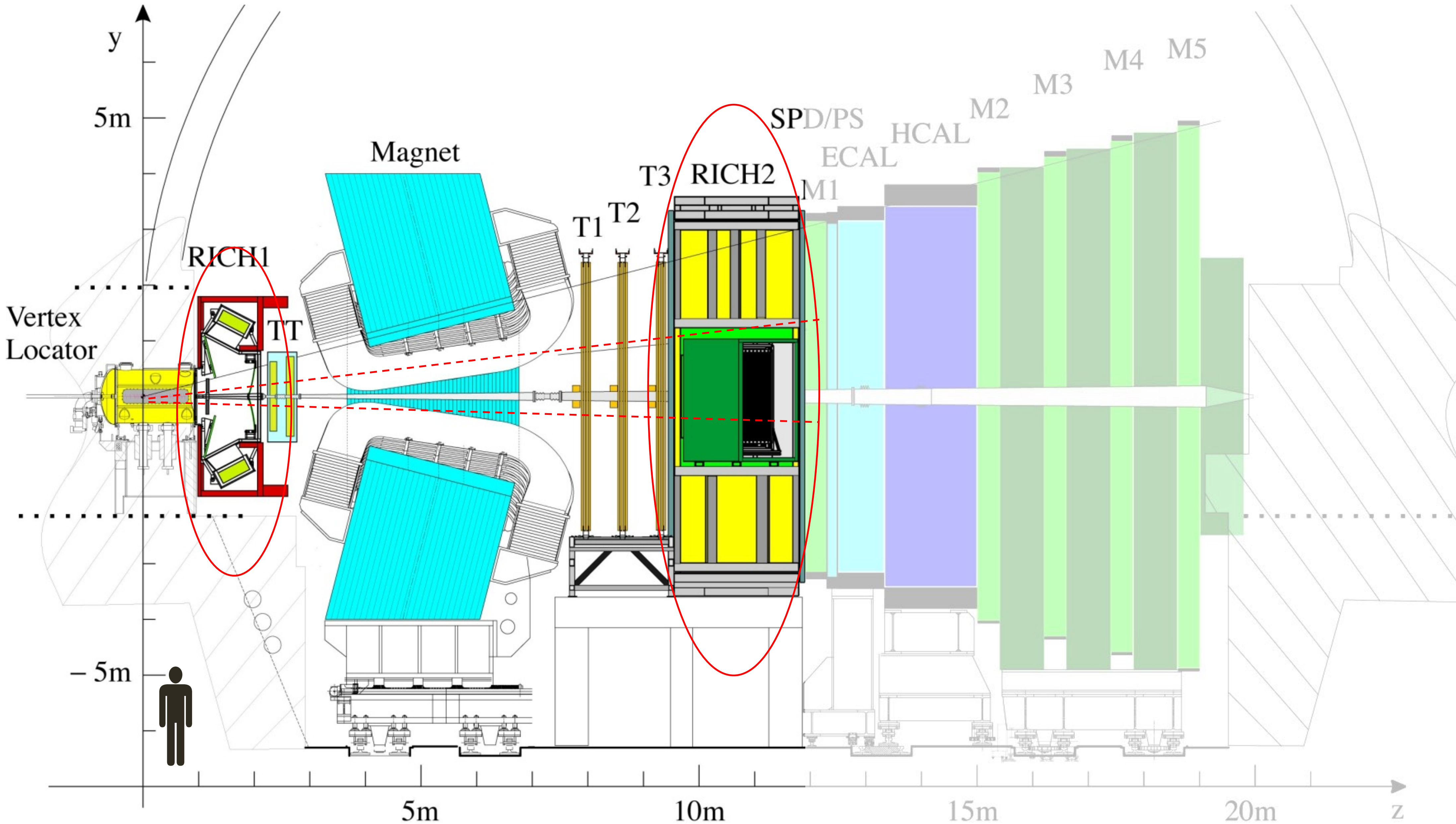


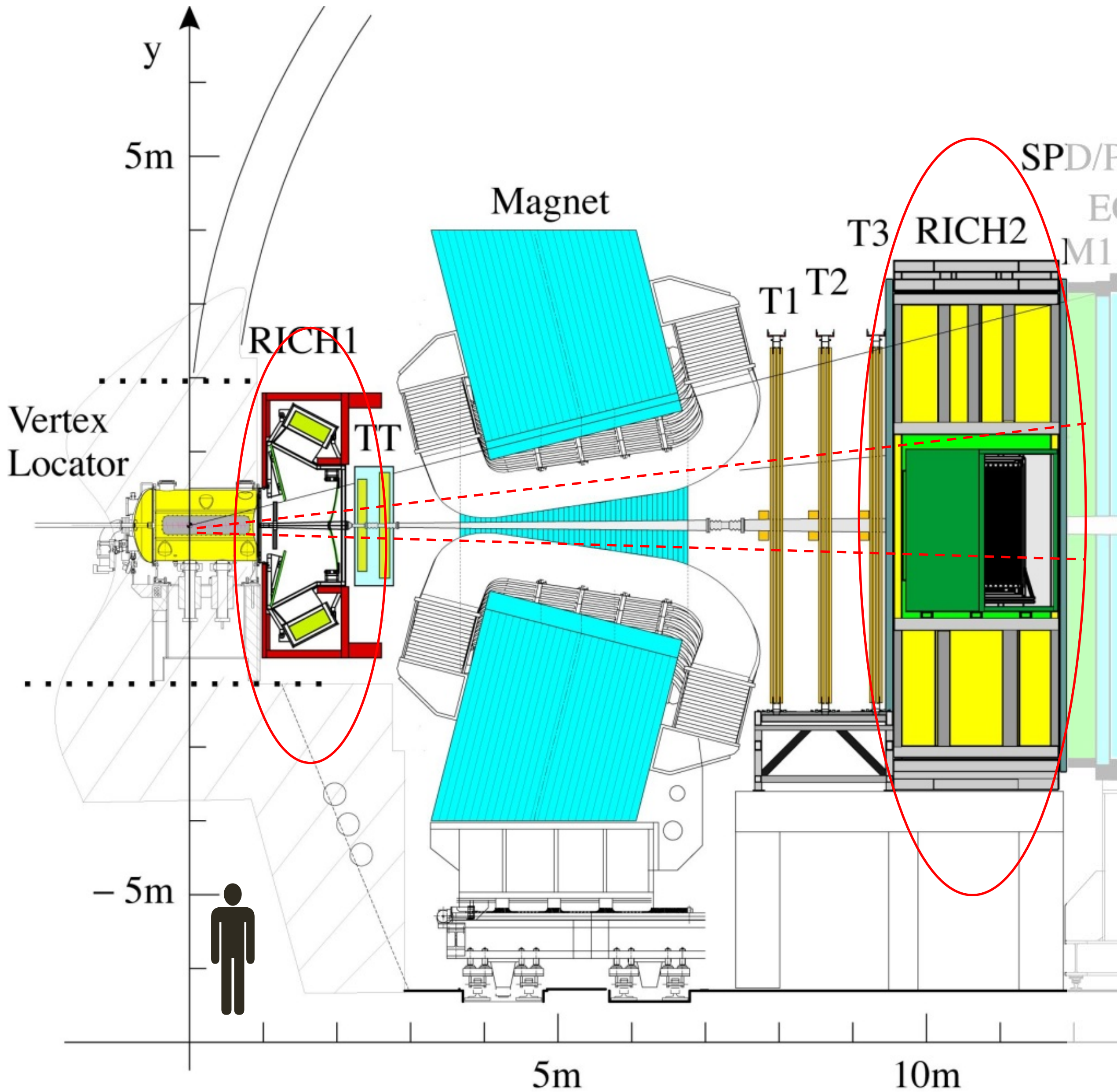

Outer Tracker
24 layer
Straws
σ_{hit}~200μm
Magnet
T1
T2
T3
RICH
TT
Locator
Trigger Tracker
4 layers Si:
~200 μm pitch
Inner Tracker
20m
z


Outer Tracker
24 layer Straws
σhit~200μm
Mass resolution σ ~14 MeV
Bs
Ds
π+, K+
K+
K−
π−
Primary vertex
btag
mBs = 5.37 GeV/c2
σBs = 13.8 MeV/c2
Bs→ Ds K
Bs →Ds π
mBs= 5.42 GeV/c2
σBs = 24.0 MeV/c2
2000
1500
1000
500
0
5.3
5.35
5.4
5.45
5.5
Bs mass [GeV/c2]
Trig
Tra
4 layers Si:
~200 μm pitch
10m
20m
z

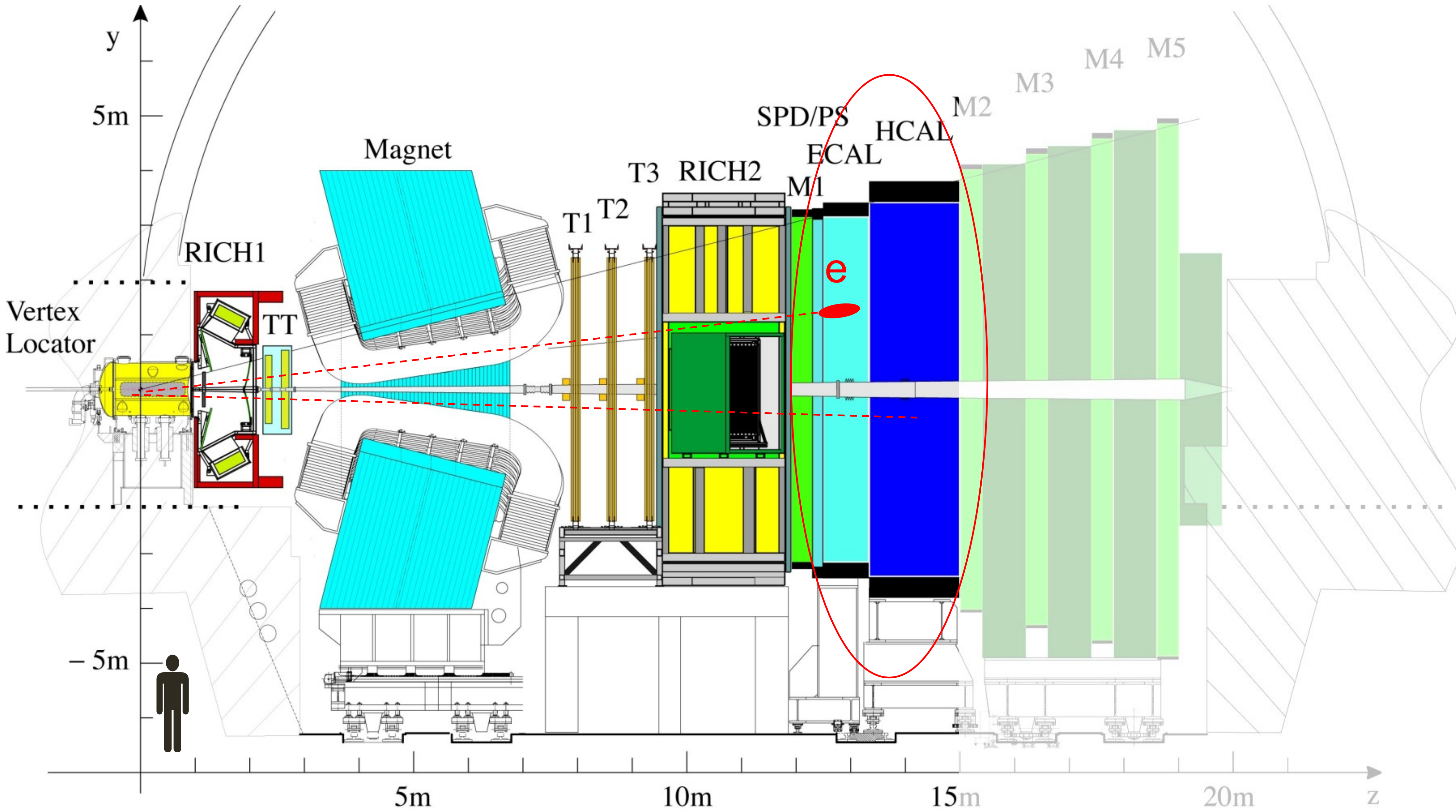
The LHCb detector



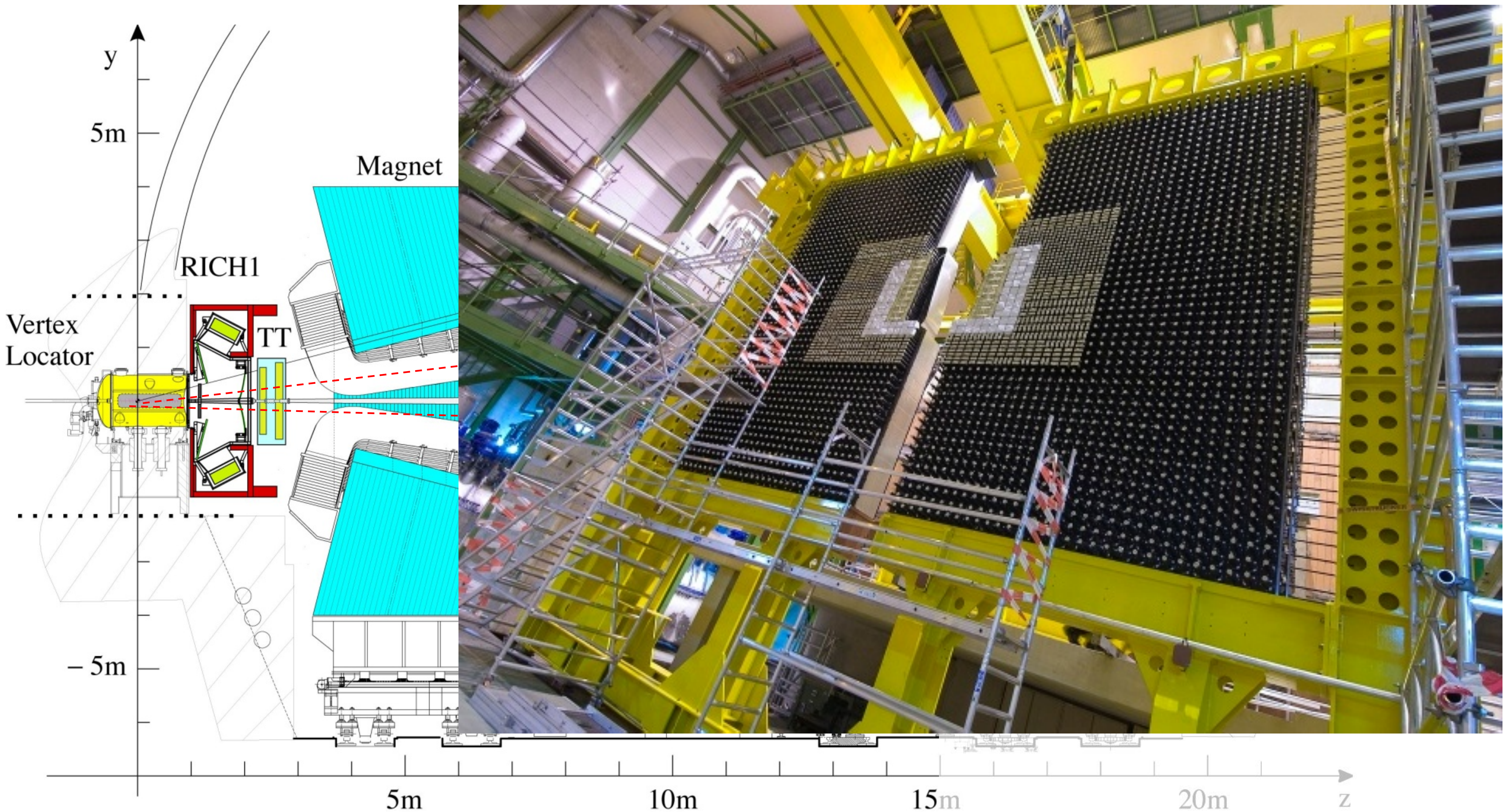
The LHCb detector



The LHCb detector



The LHCb detector



The LHCb detector

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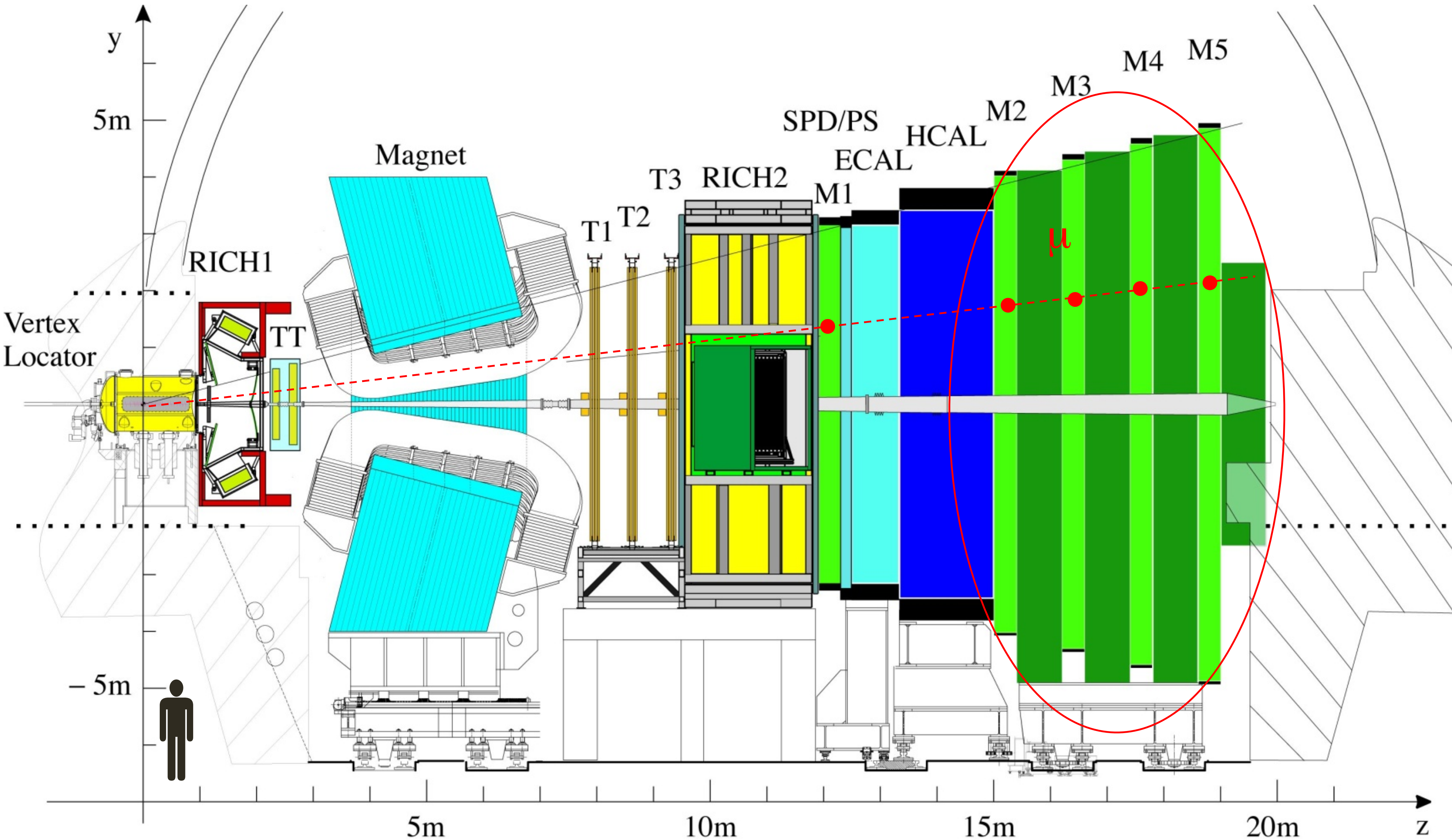
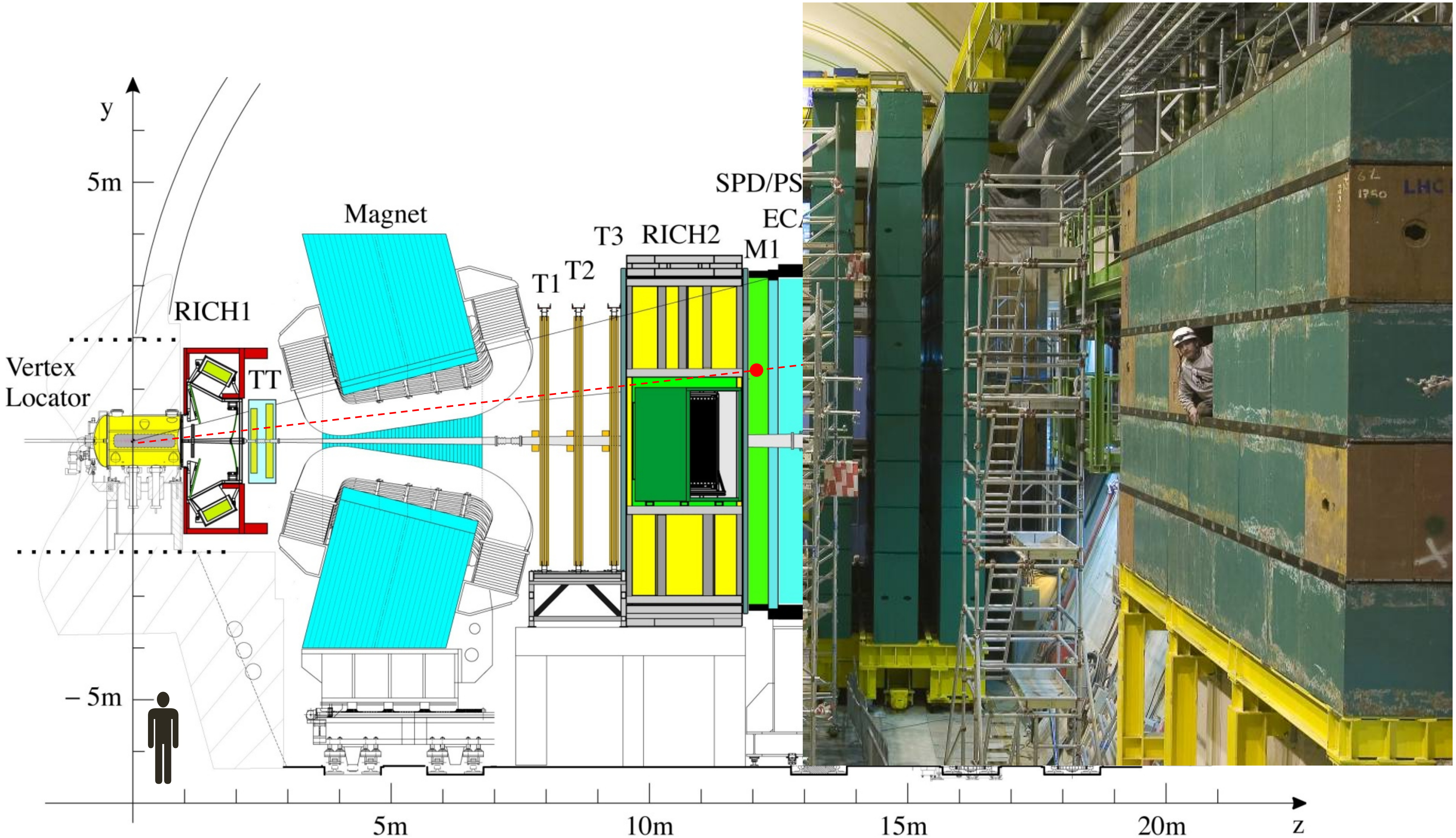


The LHCb detector

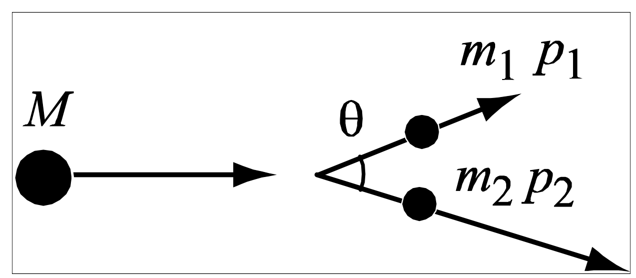


Mass reconstruction

From relativistic kinematics, the relation between energy E, momentum p, and (rest) mass m is: $E^2 = p^2 + m^2$

[The full expression: $E^2 = p^2c^2 + m^2c^4$ but factors of c are often dropped]

Consider a particle that decays to give two daughter particles:



The *invariant mass* of the two particles from the decay:

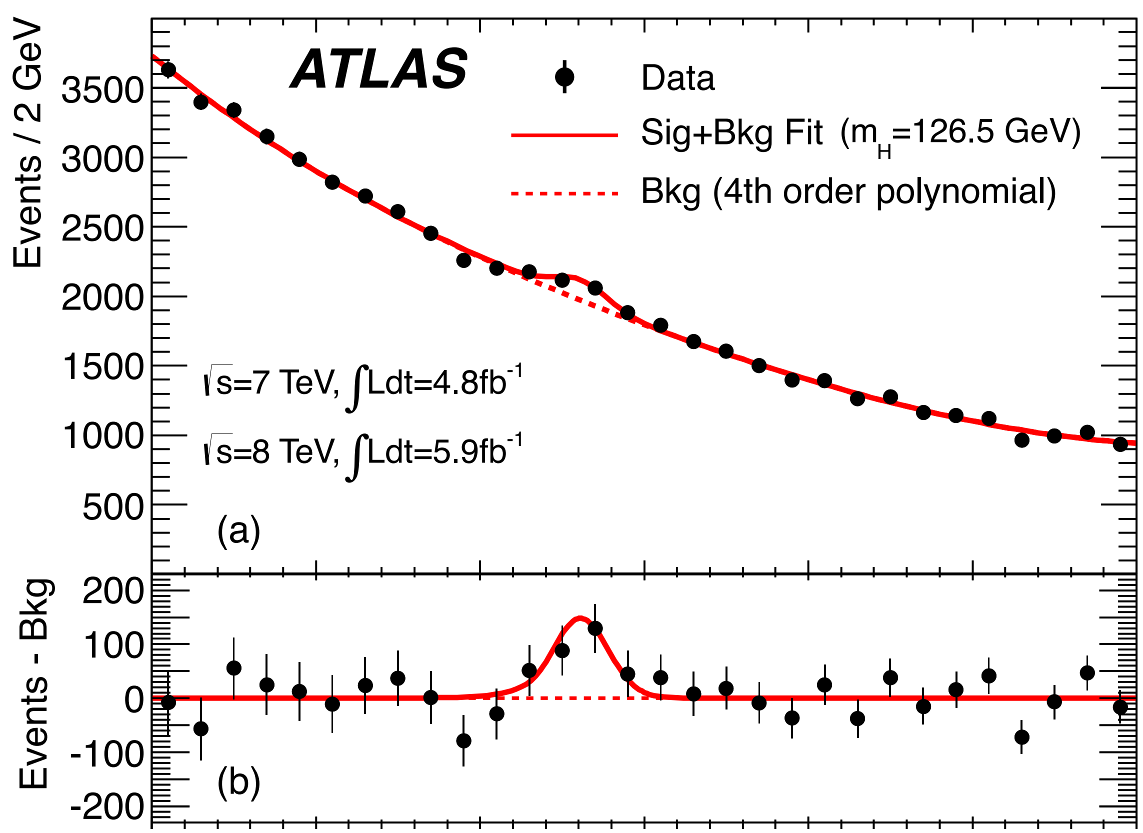
$$M^2 = m_1^2 + m_2^2 + 2(E_1E_2 \quad p_1p_2\cos\theta)$$

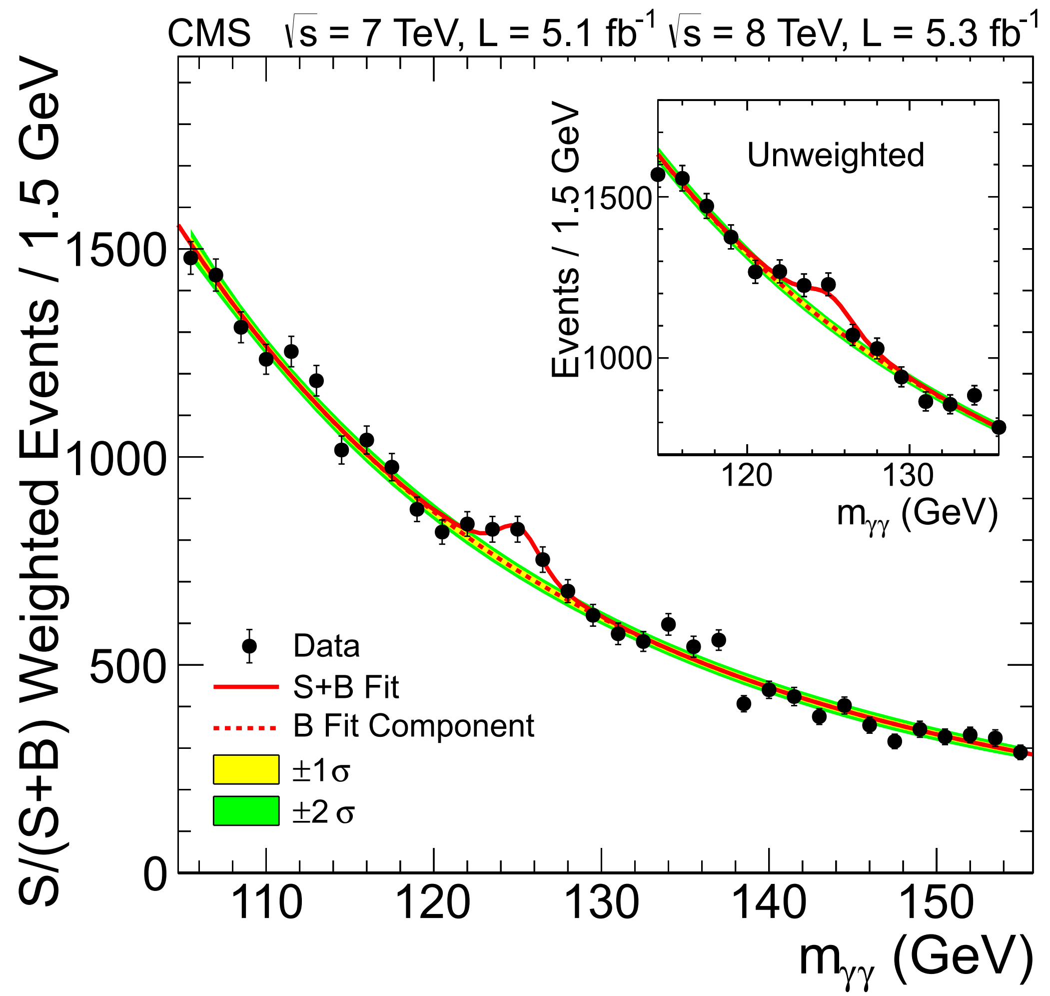
to reconstruct the parent mass a precise knowledge of the momentum and the angle θ of decay products is needed, from the tracking system, as well as their particle type, which determines their masses m_1 and m_2

Mass reconstruction

Typical example of reconstruction of a particle decay: $\pi^0 \rightarrow \gamma\gamma$
one of the first composite particles reconstructed in the LHC experiments

This technique an also be used to search for more exciting signals:





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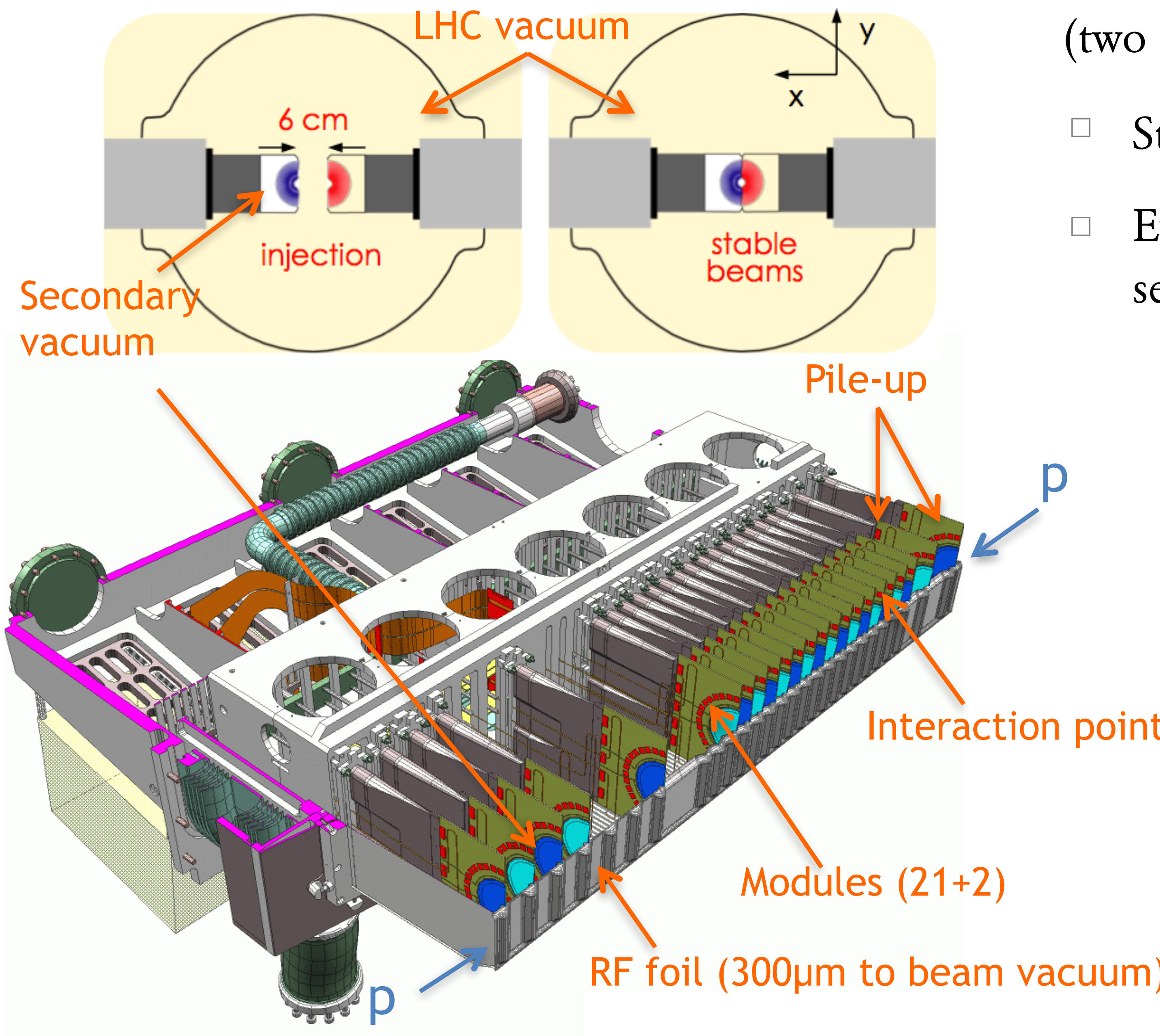
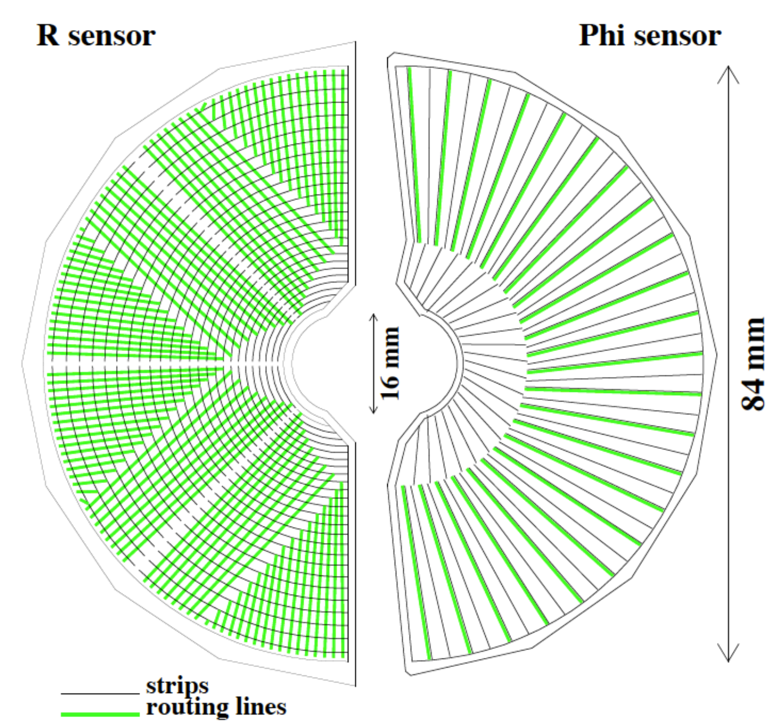
LHCb VErtex LOcator example



- 2-side semi-circular (R and ϕ sensors) microstrip silicon 300µm n^+-on-n sensors (two sensors are n^+-on-p);
- Strip pitches from 40 to 120 µm;
- Evaporative CO_2 cooling system to keep sensors at -7°C.



Tracking - Pattern recognition

Looking side on:

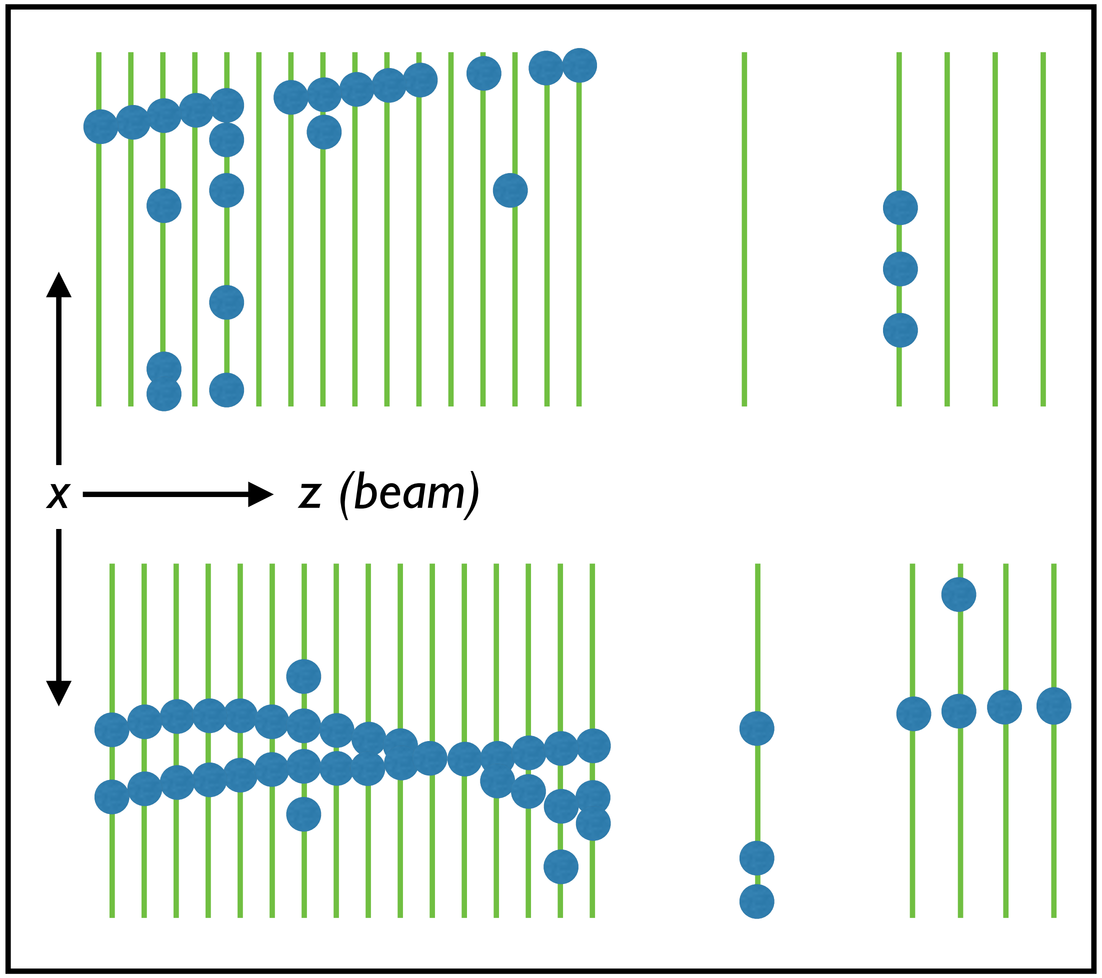
- Particle tracks clearly visible to eye
- Extra hits: typically electrical noise and/or secondary show tracks

"Transform" data points into

(x, y, z time)

Target: find an algorithm to track using this information:

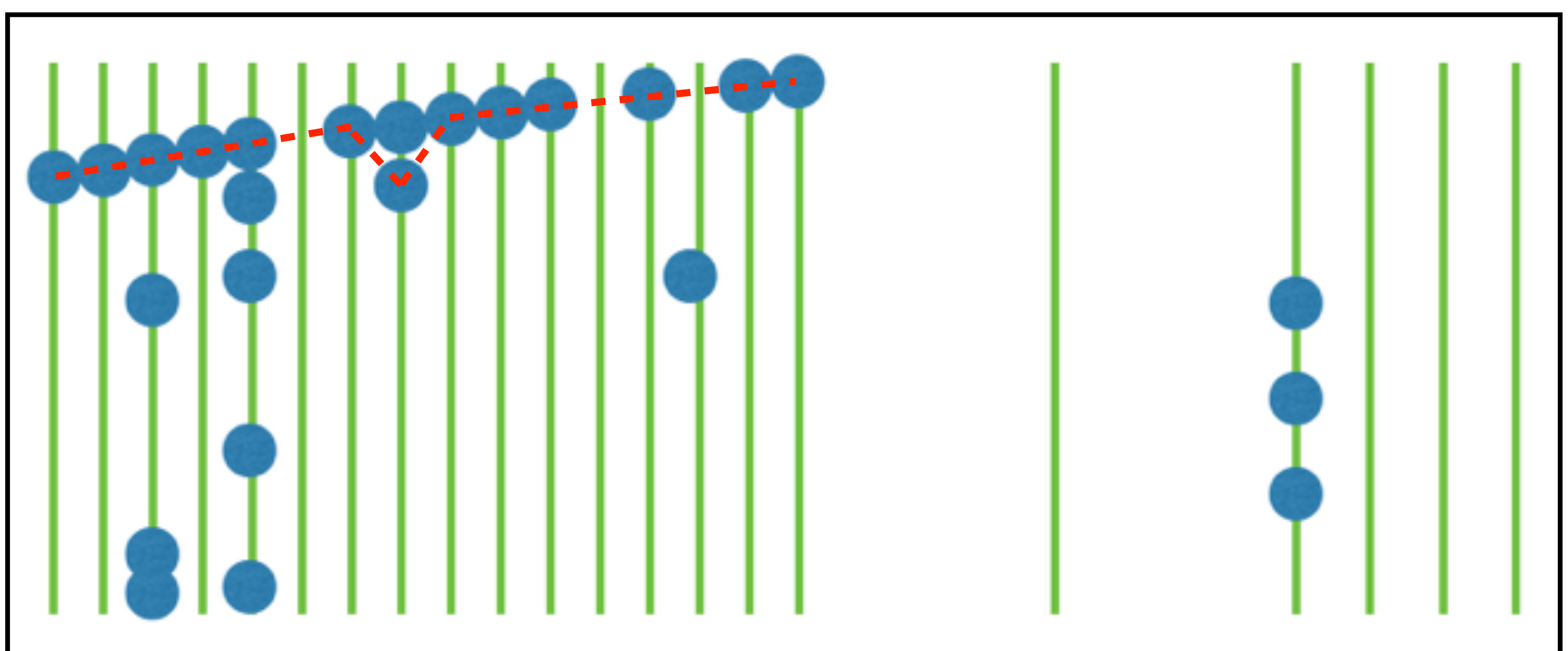
- Many possible choices, combinatorial, "seeding" ...



LHCb VELO data event (2d projection)

Tracking - Pattern recognition

Name	Description	Scalability
Combinatorial	• Form every track from each possible combination of hits. • Access each track by quality (e.g. χ^2) and tag.	$n_{Tracks}!$



LHCb VELO data event (2d projection, top half)

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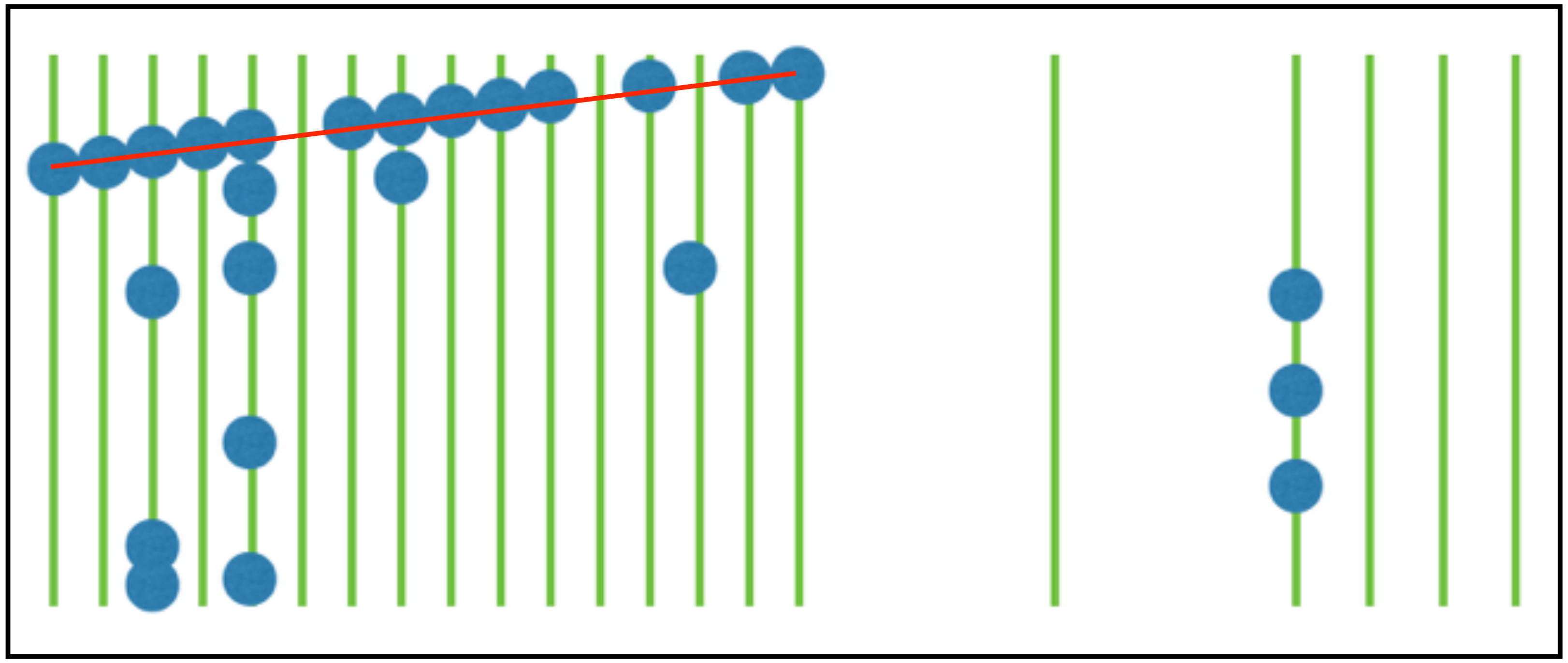
Combinatorial	• Form every track from each possible combination of hits. • Access each track by quality (e.g. χ^2) and tag.	$n_{Tracks}!$



LHCb VELO data event (2d projection, top half)

Tracking - Pattern recognition

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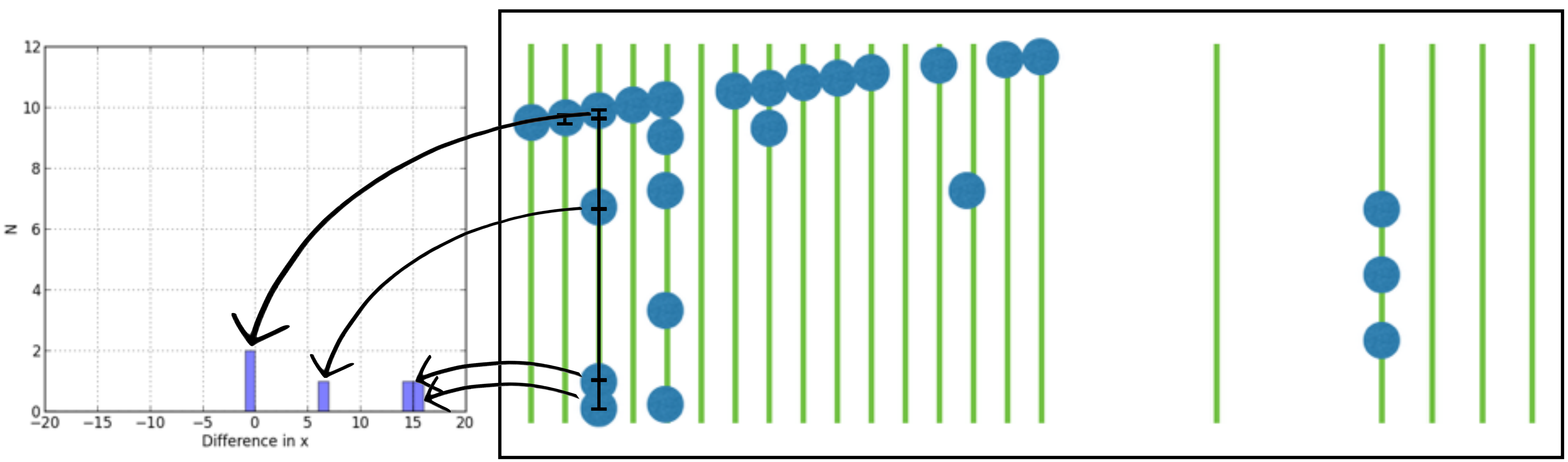
Name	Description	Scalability
Combinatorial	• Form every track from each possible combination of hits. • Access each track by quality (e.g. χ^2) and tag.	$n_{Tracks}!$
Hough Transform	• Transform points into a system where clusters form. • If straight tracks, take the difference between consecutive hits. • Group (e.g. in a histogram) and tag peaks.	n^2

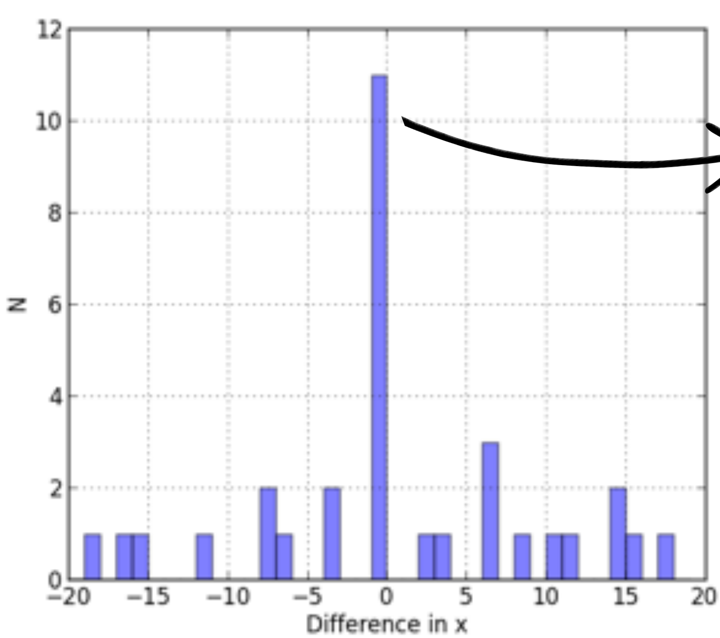


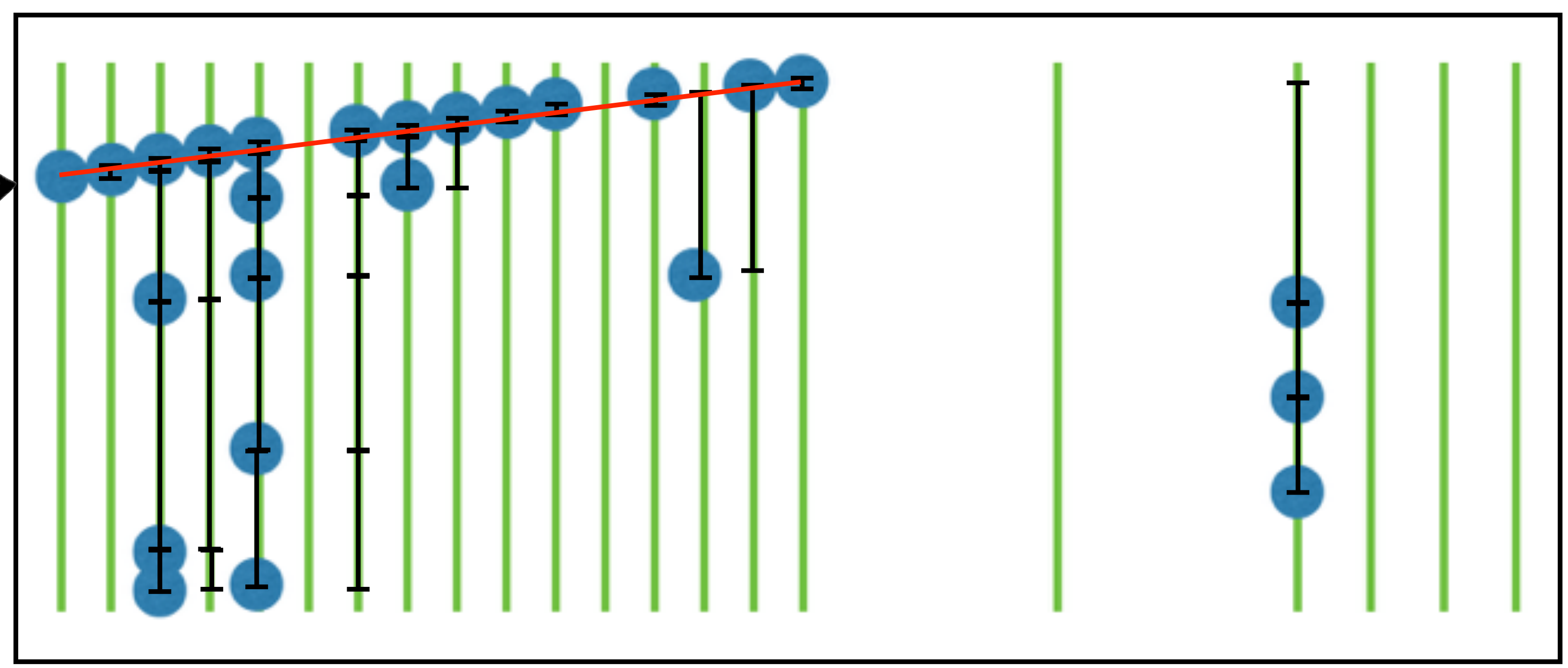
LHCb VELO data event (2d projection, top half)

39

Tracking - Pattern recognition

Name	Description	Scalability
Combinatorial	• Form every track from each possible combination of hits. • Access each track by quality (e.g. χ^2) and tag.	$n_{Tracks}!$
Hough Transform	• Transform points into a system where clusters form. • If straight tracks, take the difference between consecutive hits. • Group (e.g. in a histogram) and tag peaks.	n^2

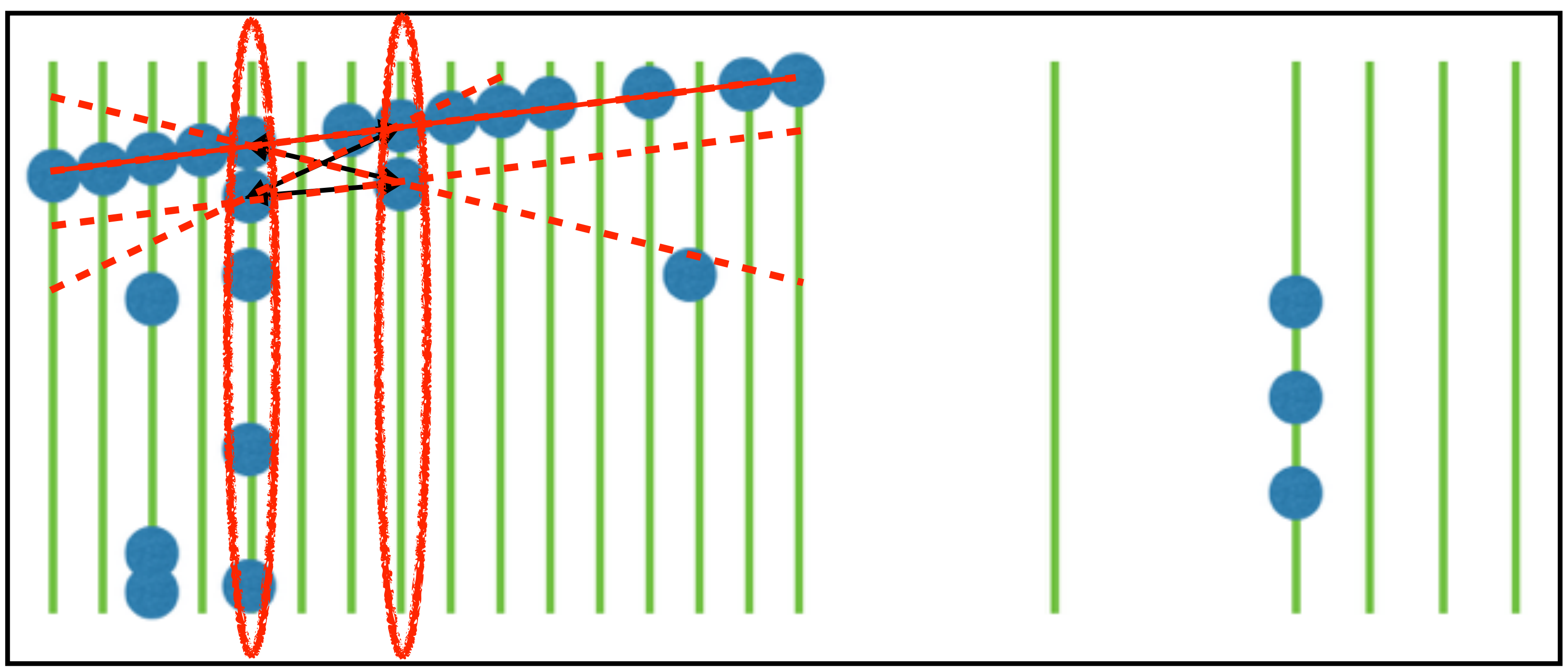




LHCb VELO data event (2d projection, top half)

Tracking - Pattern recognition

Name	Description	Scalability
Combinatorial	• Form every track from each possible combination. • Access each track by quality (e.g. χ^2) and tag.	$n_{Tracks}!$
Hough Transform	• Transform points into a system where clusters form. • E.g. for straight tracks, take the difference between consecutive hits. • Group (e.g. in a histogram) and tag peaks.	n^2
Seeding	• Form seeds from pairs of hits on a sub set of the detector. • Extrapolate the seed and count hits intercepted. • Tag if sufficient number of hits.	nlog(n)



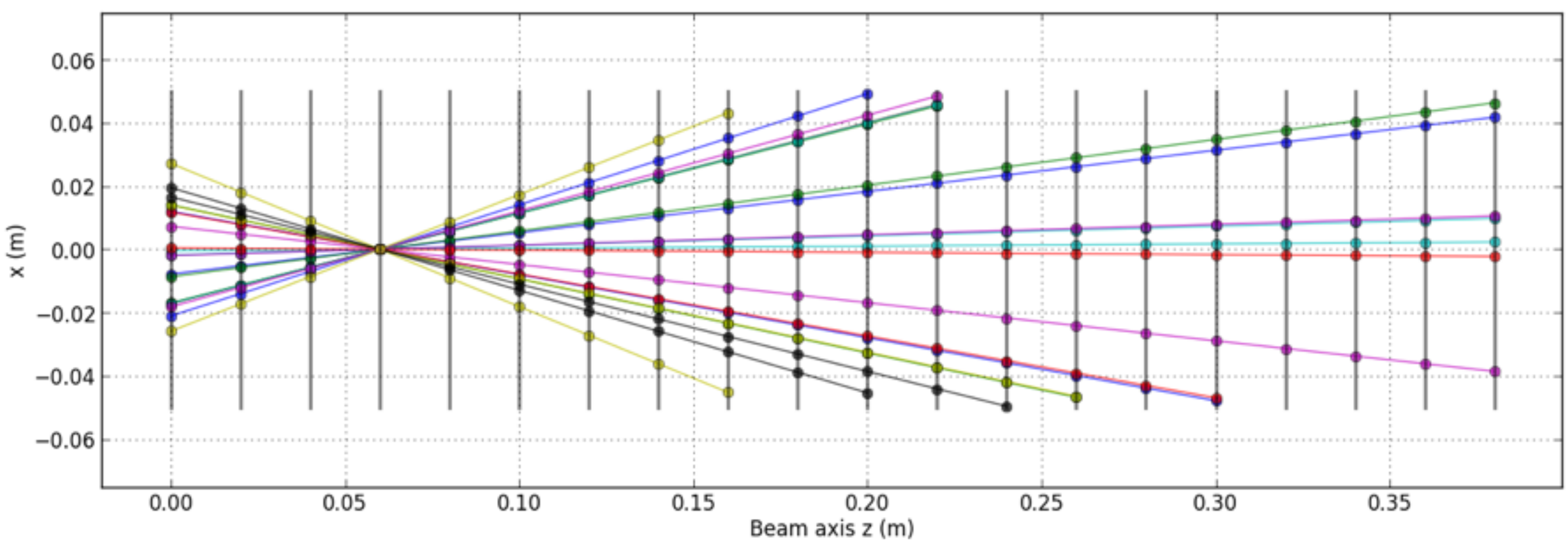
LHCb VELO data event (2d projection, top half)

Tracking - Pattern recognition

Three main features used to decide most appropriate algorithm

- Efficiency: fraction of real tracks found
- Purity: fraction of tracks that are real
- Computational speed

Simplified simulation using LHCb VELO design



LHCb VELO toy event (2d projection)

Tracking - Pattern recognition

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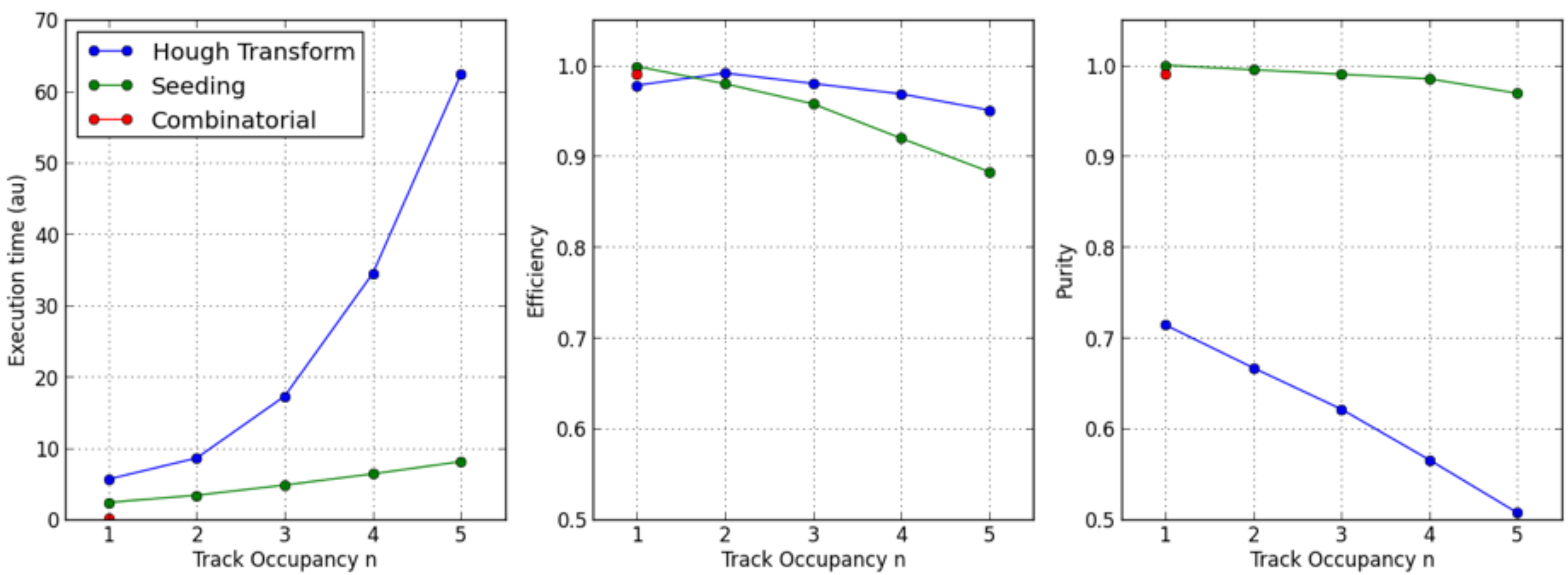
Three main features used to decide most appropriate algorithm

- Efficiency: fraction of real tracks found
- Purity: fraction of tracks that are real
- Computational speed

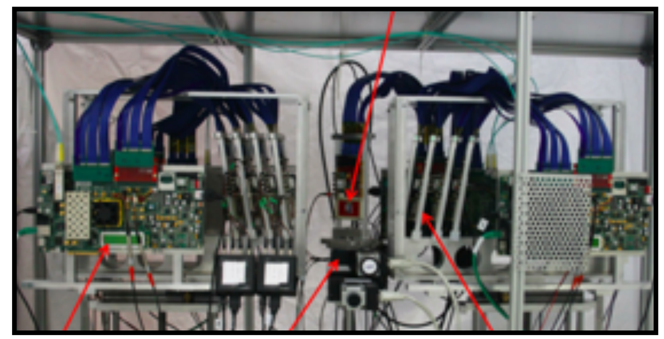
Simplified simulation using LHCb VELO design



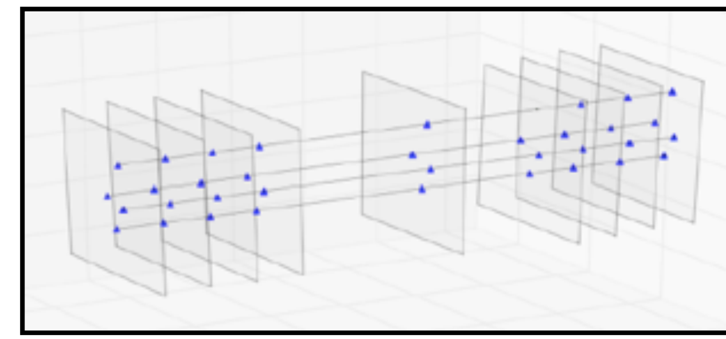
Tracking - Pattern recognition

In general experiments use a combination of these approaches

- Combinatorial often used at testbeams:
  - Low occupancy, so fast.
  - Efficient and pure.



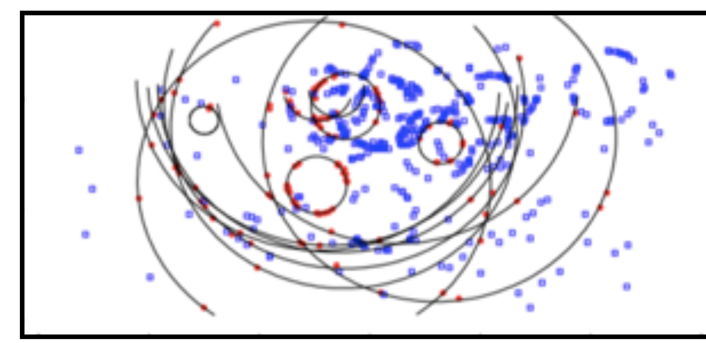
Timepix3 Tracking Telescope



Testbeam Data

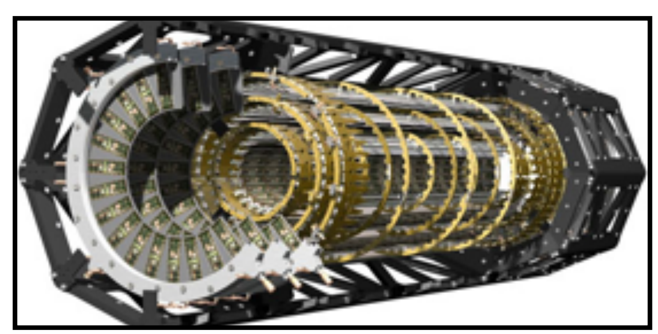
- Hough transforms used for more complicated shapes (e.g. rings in LHCb RICH*).

LHCb RICH Subdetector

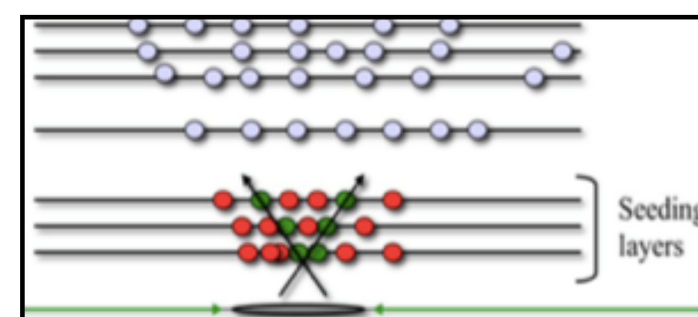


RICH Data

- All LHC experiments use seeding extensively (highest occupancy).



ATLAS Tracker



ATLAS Inner Layers

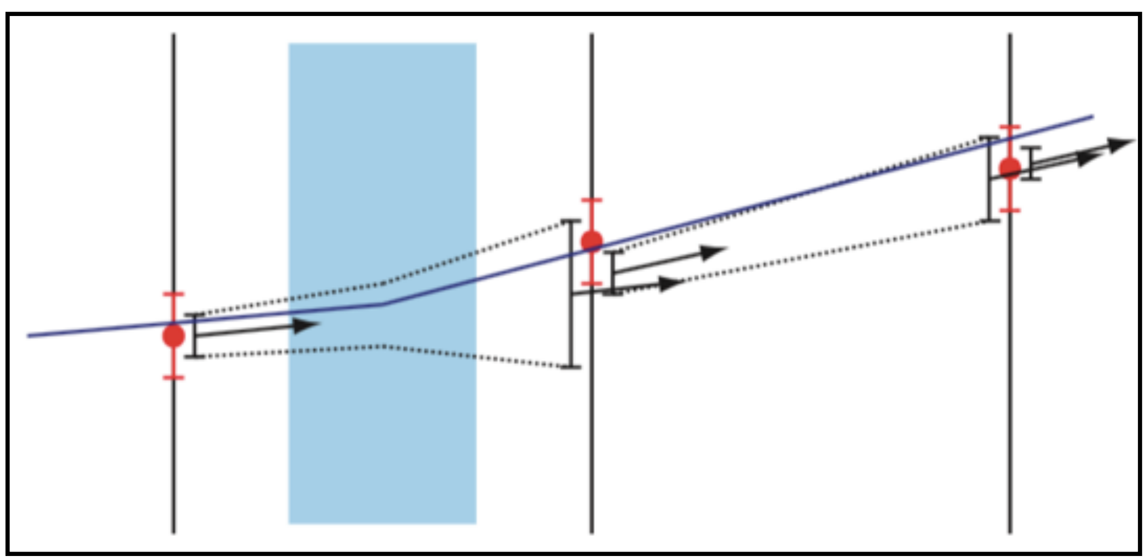
Tracking Fitting

Tracking particles through the detectors involve two steps

- Pattern recognition: identify detector hits in order to build a track
- Track fit: approximate the path of the particle with an equation

Mostly approximated using a “Kalman-Fitter”:

- Track is approximated as a “zig-zag”
- Start with a seed to estimate of track parameters
- propagate to the next plane
- Predict position of next particle, weighting by closest hits



Kalman Filter Example

Tracking refinement

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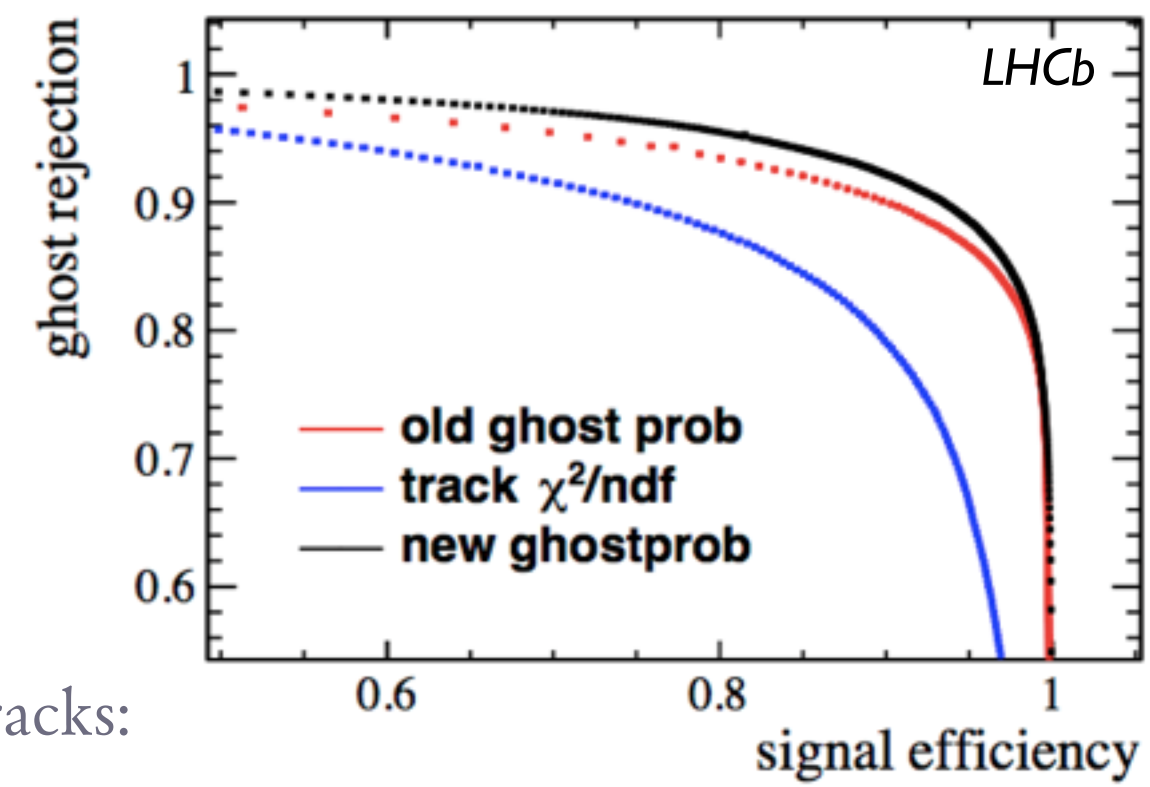
Common to tune pattern recognition to be efficient and impure: refine selection later using addition information

- Can use χ^2 to find well fitted tracks
- Typically combine with information from different detectors and number of hits

- For optimal approach a MVA is often used in experiments



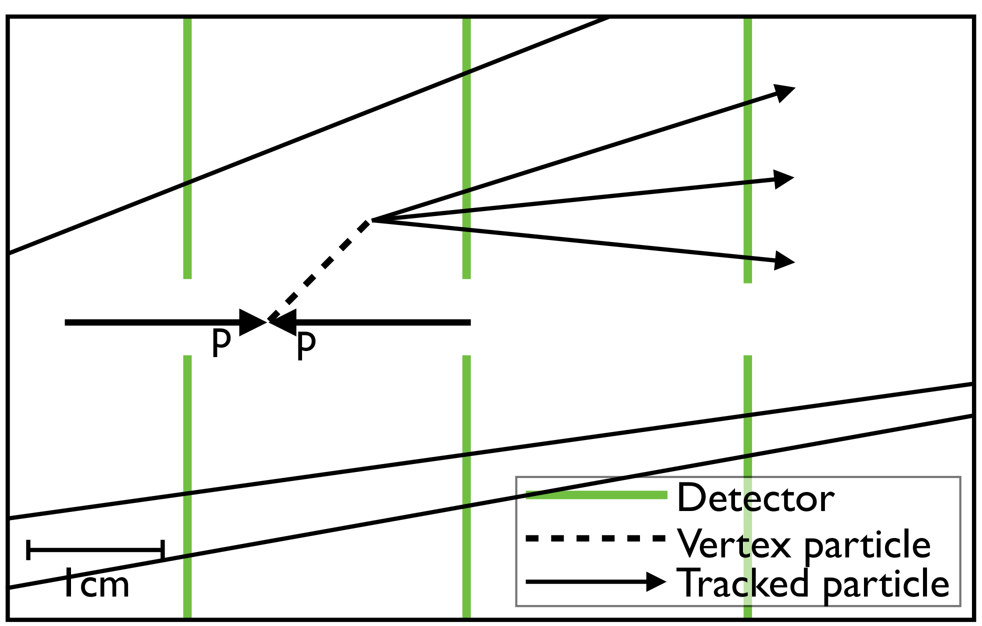
Detector hits can also be part of multiple tracks:

- Detector spatial resolution too low to separate tracks
- Secondary tracks produced with the interaction with material

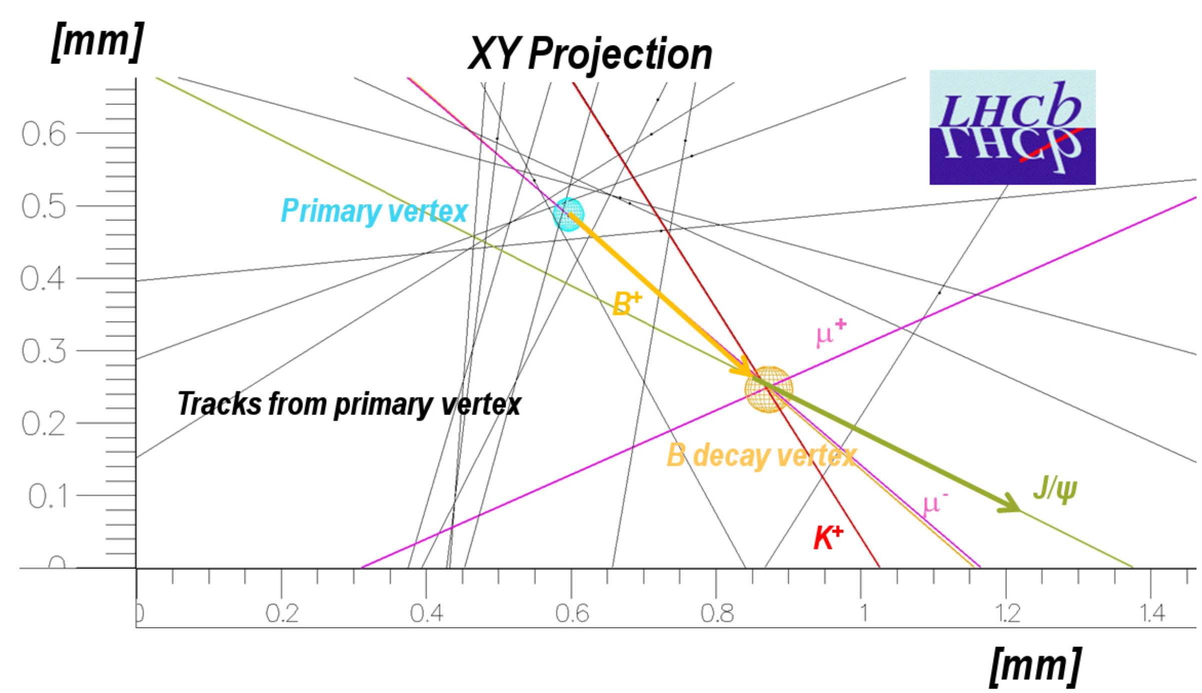
Vertexing

Vertexing involves clustering tracks that originated from the same point

- Easy in cases that the vertex location is known - extrapolate all tracks and apply some selection
- Physics inputs can narrow search region significantly
- Some analytical methods can also be used to seed search
- Common approach to seed by projecting in 2D plane and searching for a point with high track density



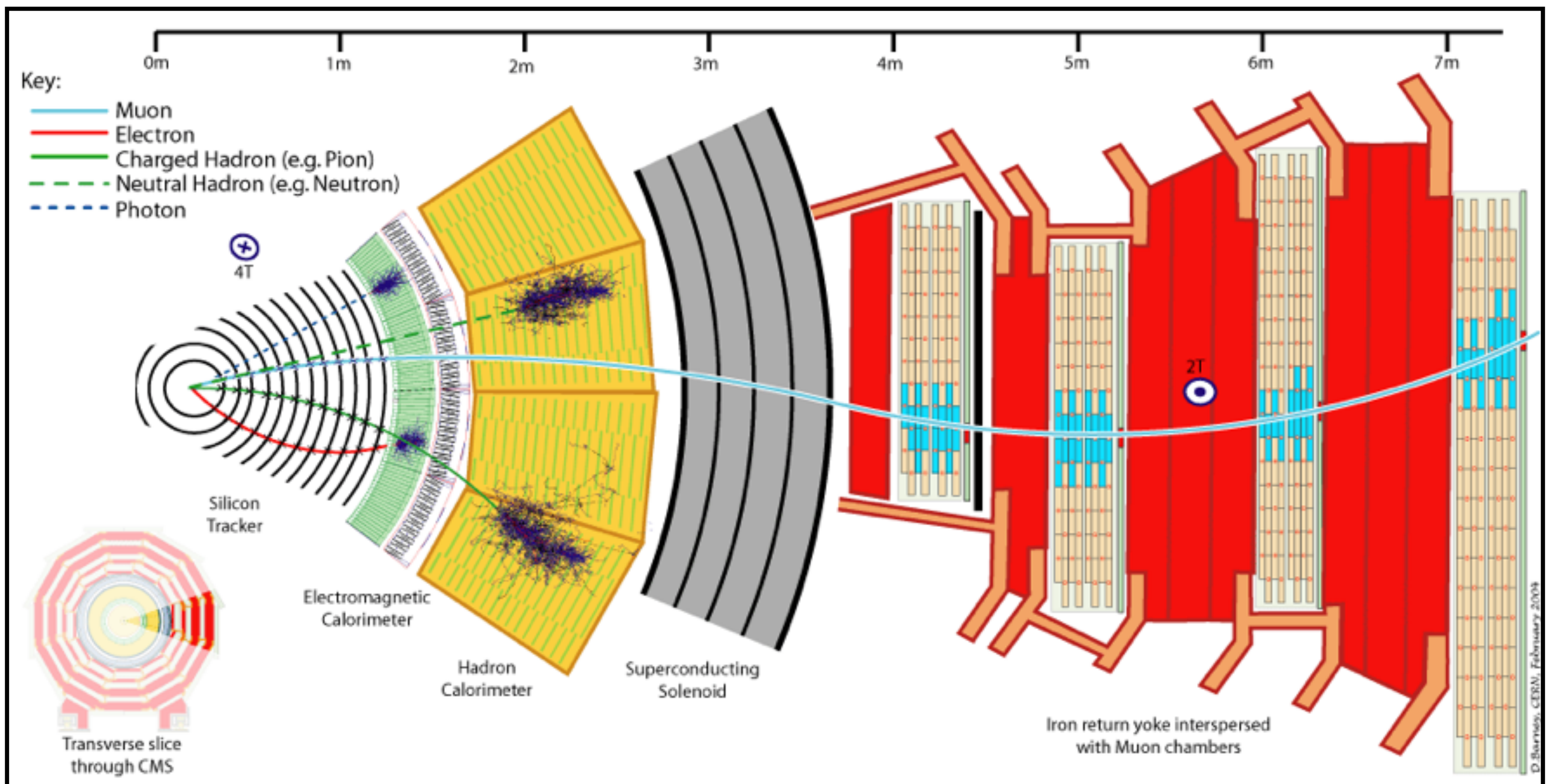
Vertex example in LHCb Velo.



Particle identification

- Classify each track as a type of particle event by event
- Many kinds of particle, not just fundamental particles, also composite hadrons (e.g. Pion, Kaon)

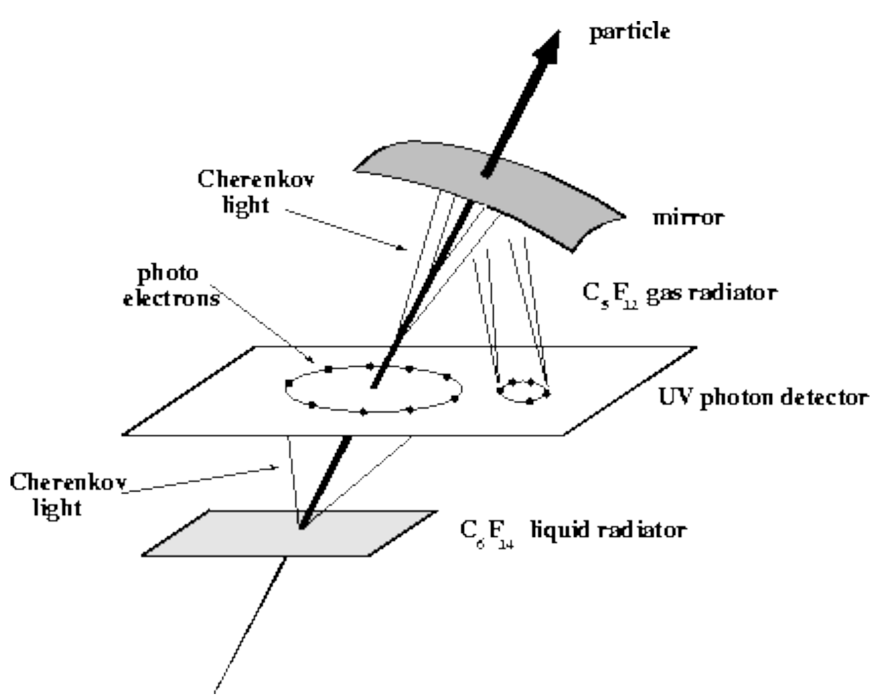
"Simple" example in CMS:

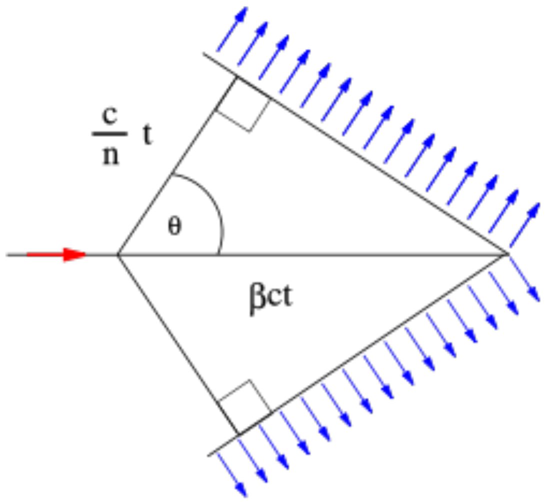


Particle identification

- RICH detector at LHCb uses Cherenkov radiation:
  - Light emitted when a particle slows passing through a material
  - Emission is isotropic, and forms rings on detectors
  - Not required to reconstruct the ring itself - instead, test different hypotheses

Light produced in a cone with $\cos\theta_c = 1/\beta n$
can be detected as a ring image





By measuring θ_c ($\propto$ radius of ring)
the velocity β of the particle is found
Then with knowledge of its momentum
the mass of the particle can be found

Particle identification

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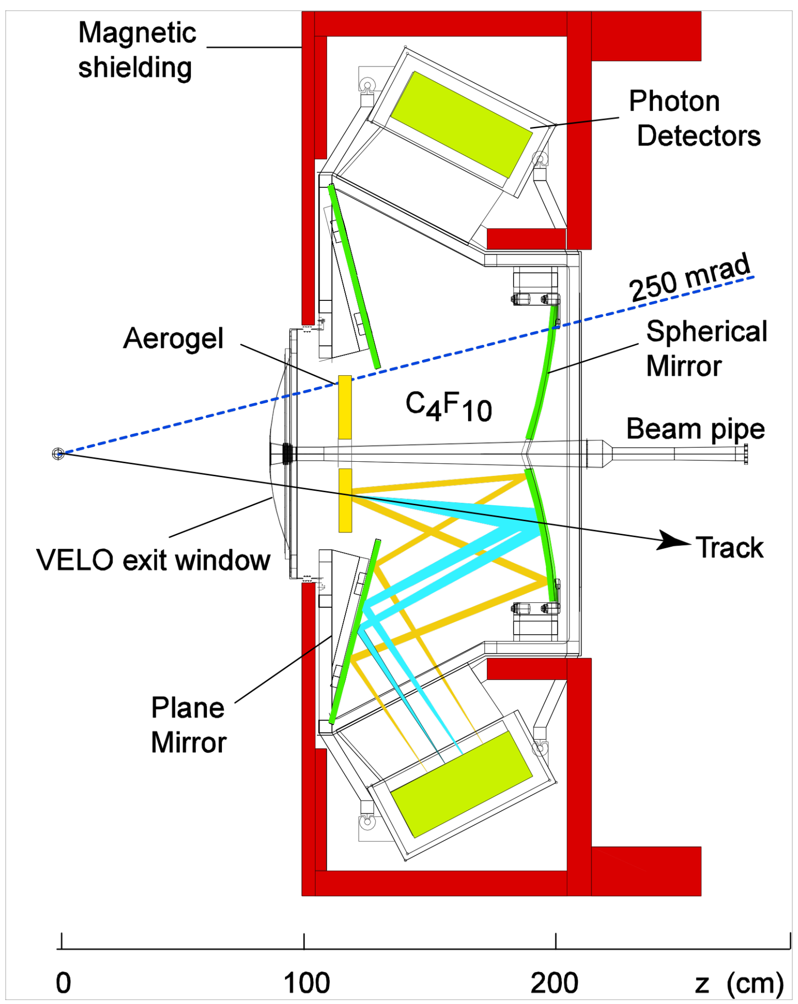
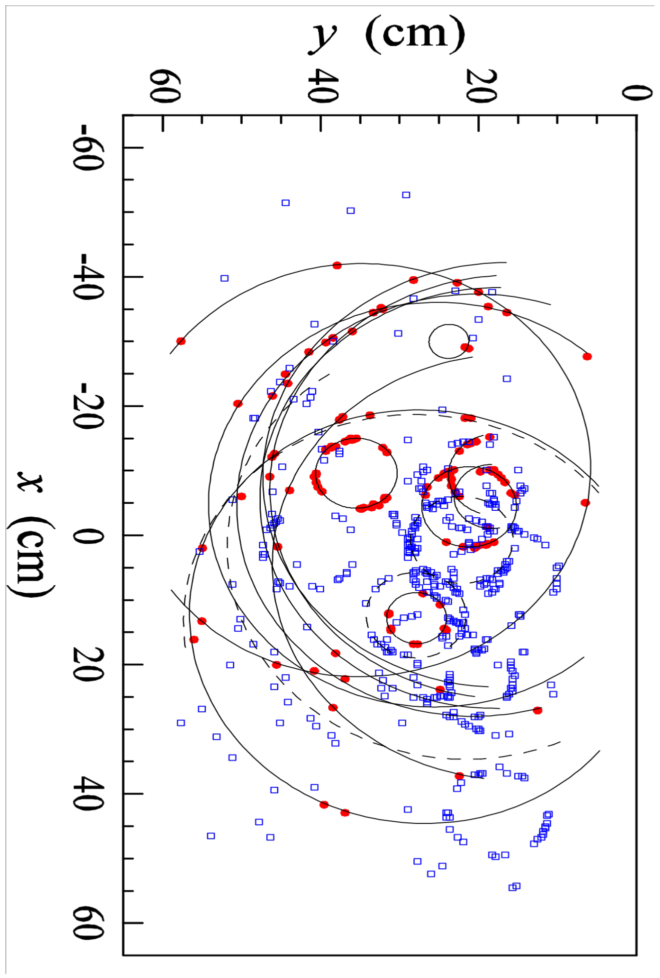
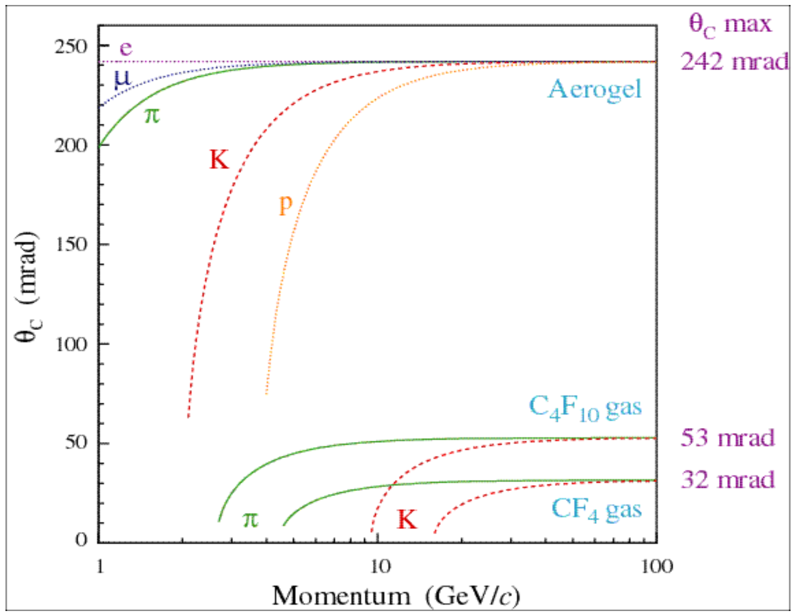
  - Light emitted when a particle slows passing through a material
  - Emission is isotropic, and forms rings on detectors
  - Not required to reconstruct the ring itself - instead, test different hypotheses



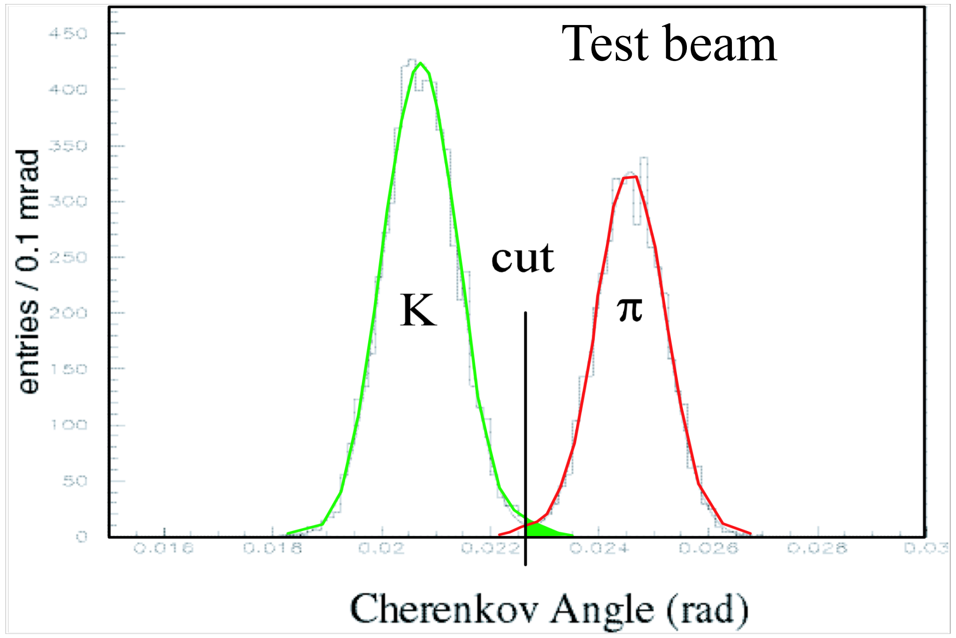


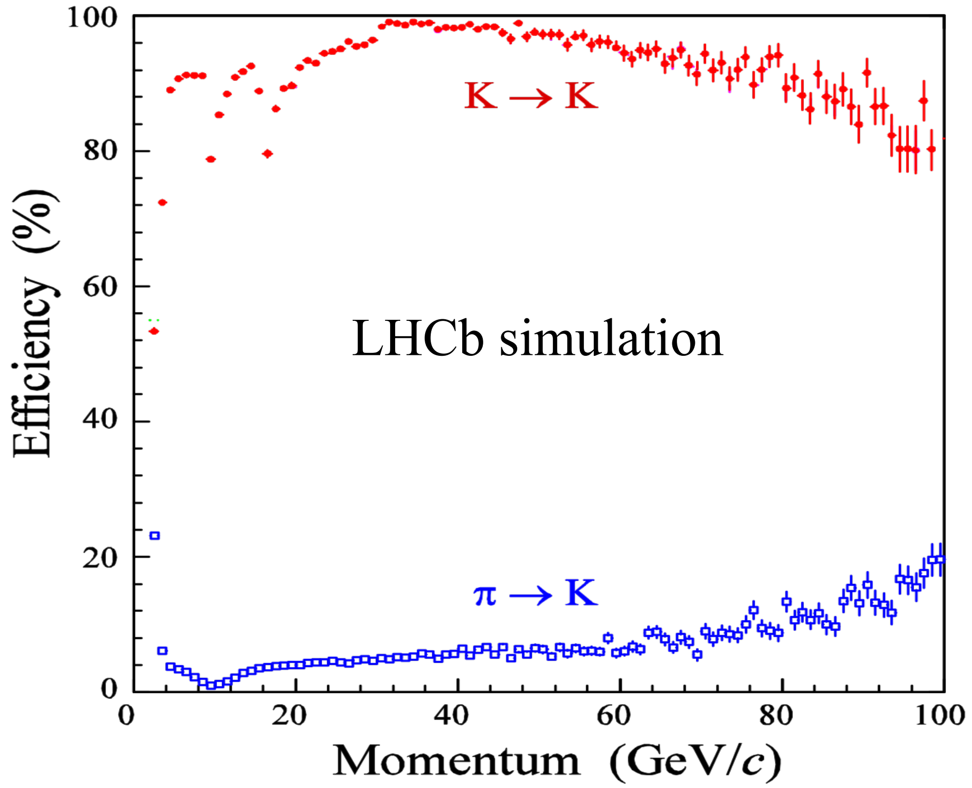
Simulated event in RICH-1
Large rings: aerogel, small: C_4F_{10}



Particle identification

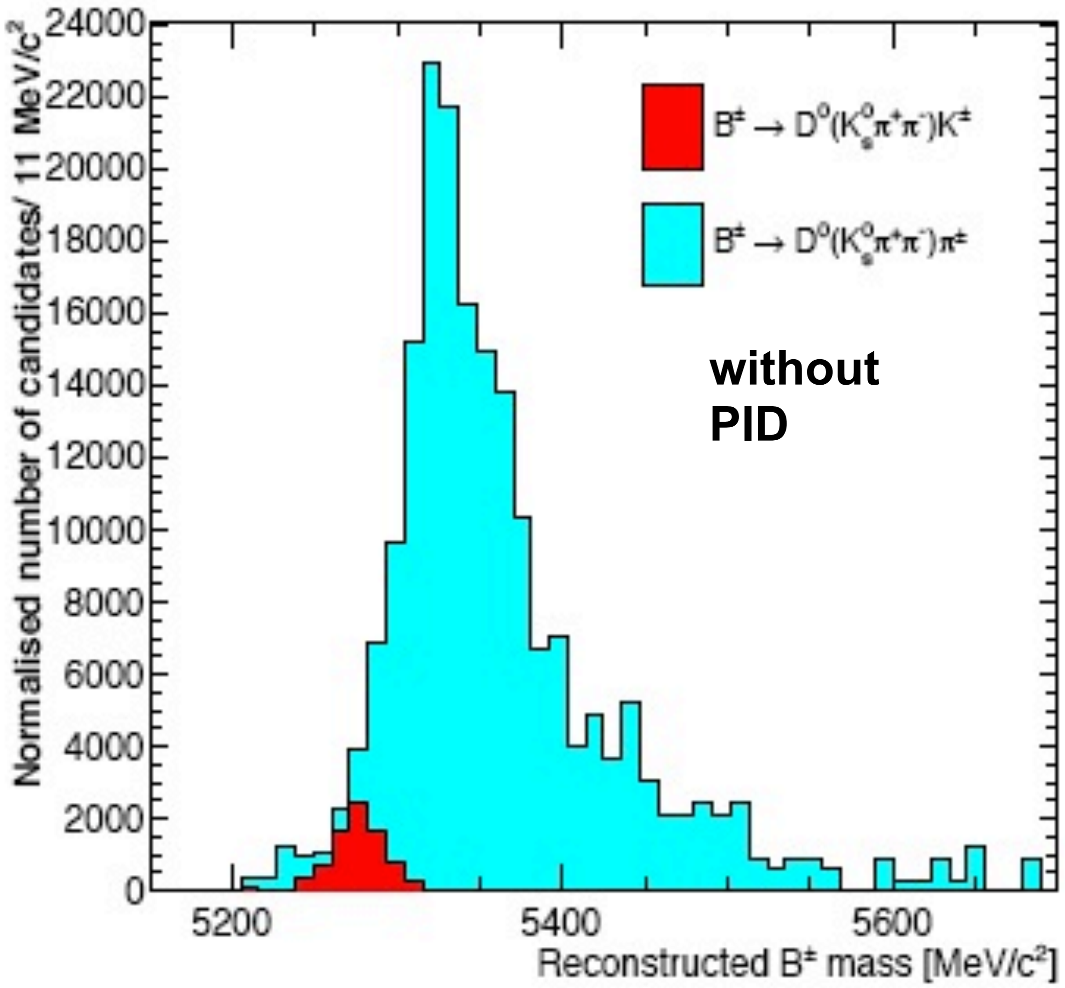
- Separating two particle types using the signal from a RICH detector is illustrated for K and π from a test beam
- Adjusting the position of the cut placed between the two peaks to identify a ring as belonging to a K or π gives a trade-off between *efficiency* and *misidentification*
- LHCb particle identification is actually built by combining not only information from the RICH, but also from other sub-detector in a multivariate analysis

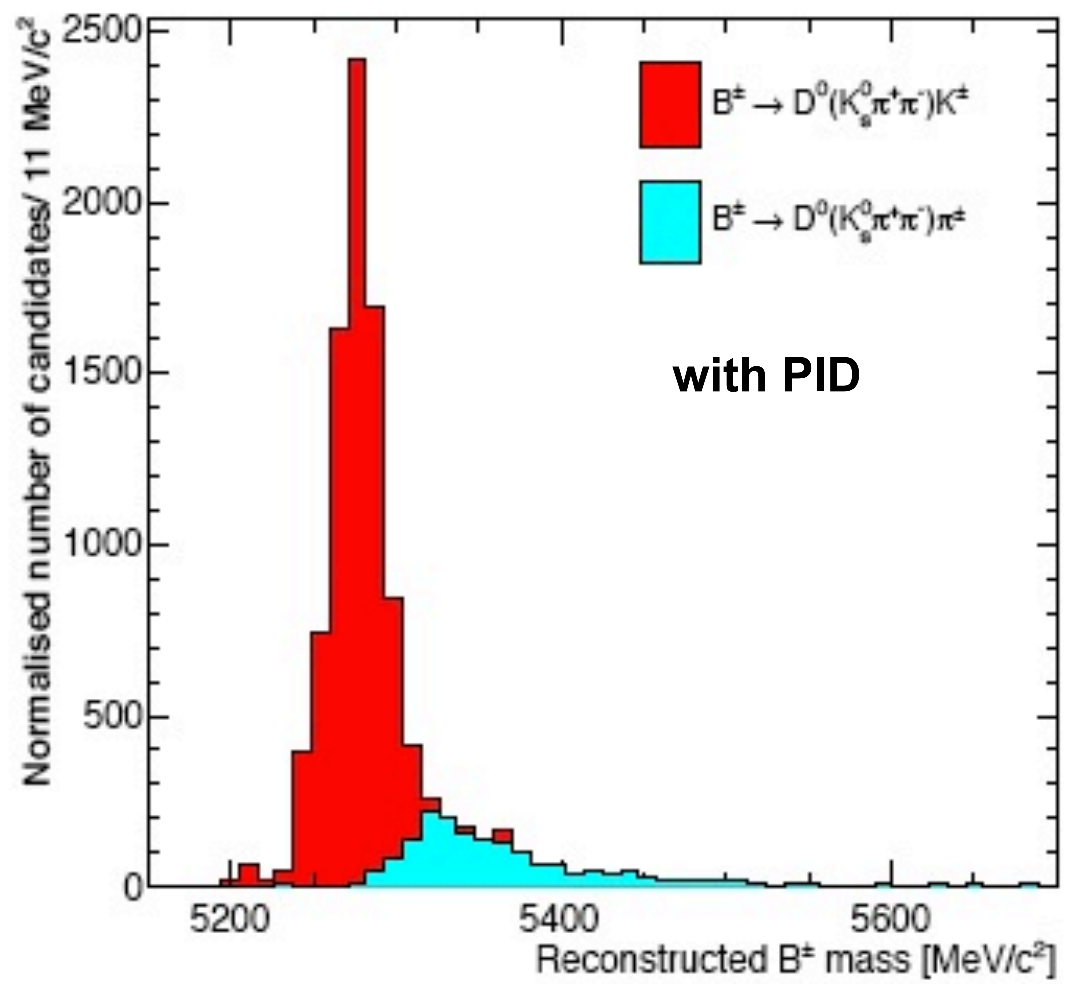




Particle identification performance

- Example: clean separation of $B_{d,s} \rightarrow hh$ modes





Criteria inly applied in the bachelor Kaon

Physics case - Previous lecture by Nico

CP Violation in the Early Universe

- Very early in the universe might expect equal numbers of baryons and anti-baryons
- However, today the universe is matter dominated (no evidence for anti-galaxies, etc.)
- From "Big Bang Nucleosynthesis" obtain the matter/anti-matter asymmetry

$$\xi = \frac{n_B - n_{\overline{B}}}{n_\gamma} \approx \frac{n_B}{n_\gamma} \approx 10^{-9}$$

i.e. for every baryon in the universe today there are 10^9 photons

- How did this happen?

★ Early in the universe need to create a very small asymmetry between baryons and anti-baryons

e.g. for every 10^9 anti-baryons there were 10^9+1 baryons

baryons/anti-baryons annihilate ⇨

1 baryon + ~10^9 photons + no anti-baryons

★ To generate this initial asymmetry three conditions must be met (Sakharov, 1967):

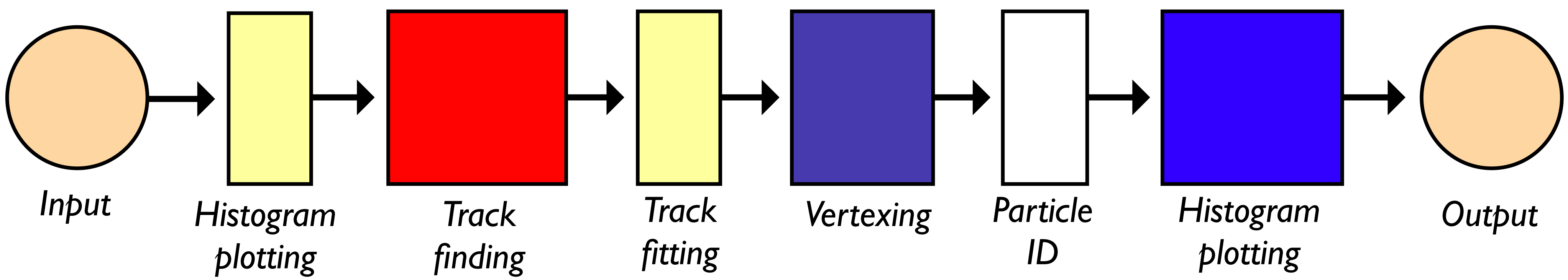
❶ "Baryon number violation", i.e. $n_B - n_{\overline{B}}$ is not constant

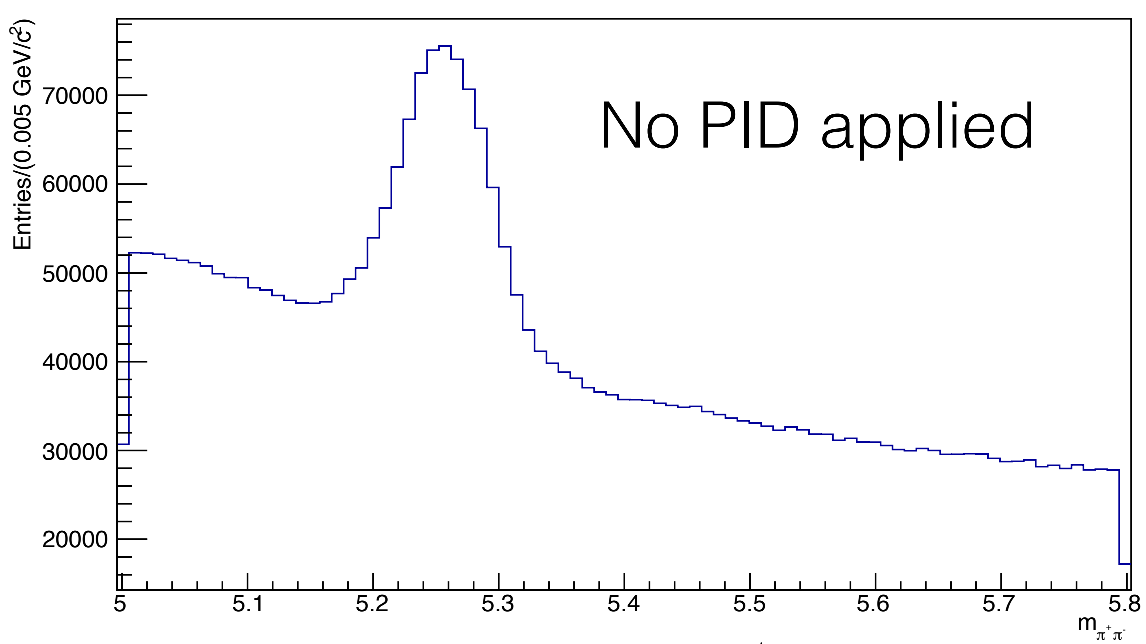
❷ "C and CP violation", if CP is conserved for a reaction which generates a net number of baryons over anti-baryons there would be a CP conjugate reaction generating a net number of anti-baryons

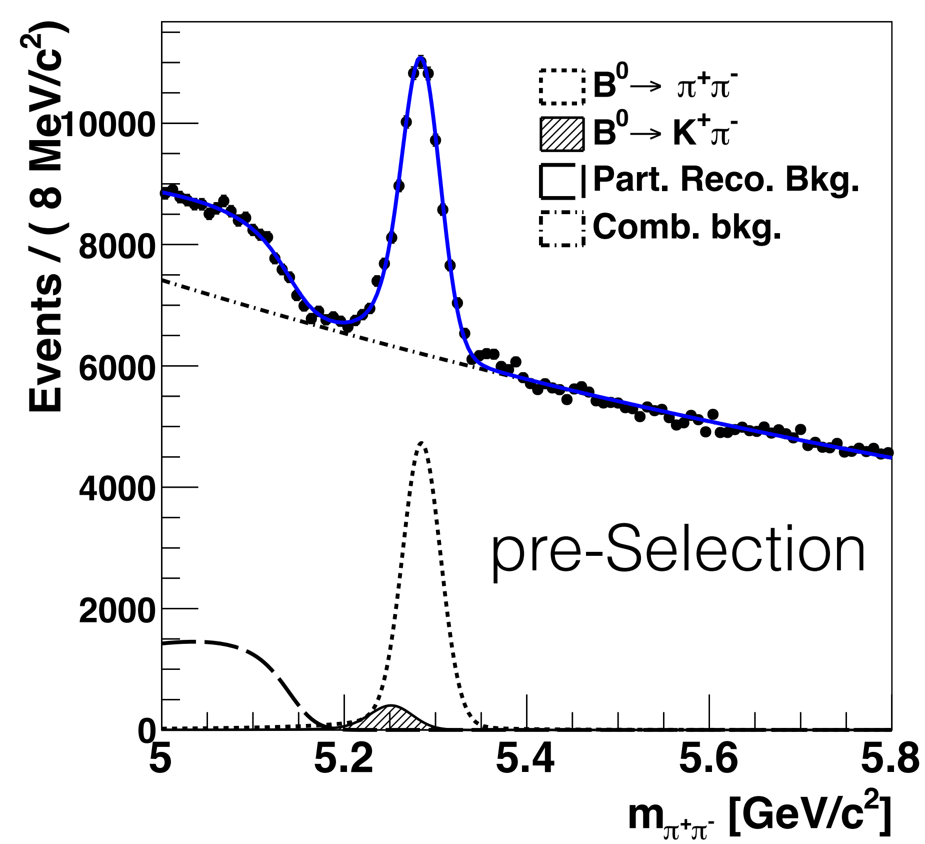
❸ "Departure from thermal equilibrium", in thermal equilibrium any baryon number violating process will be balanced by the inverse reaction

How to perform an analysis?

Analysis framework: e.g. $B \rightarrow \pi\pi$ decays

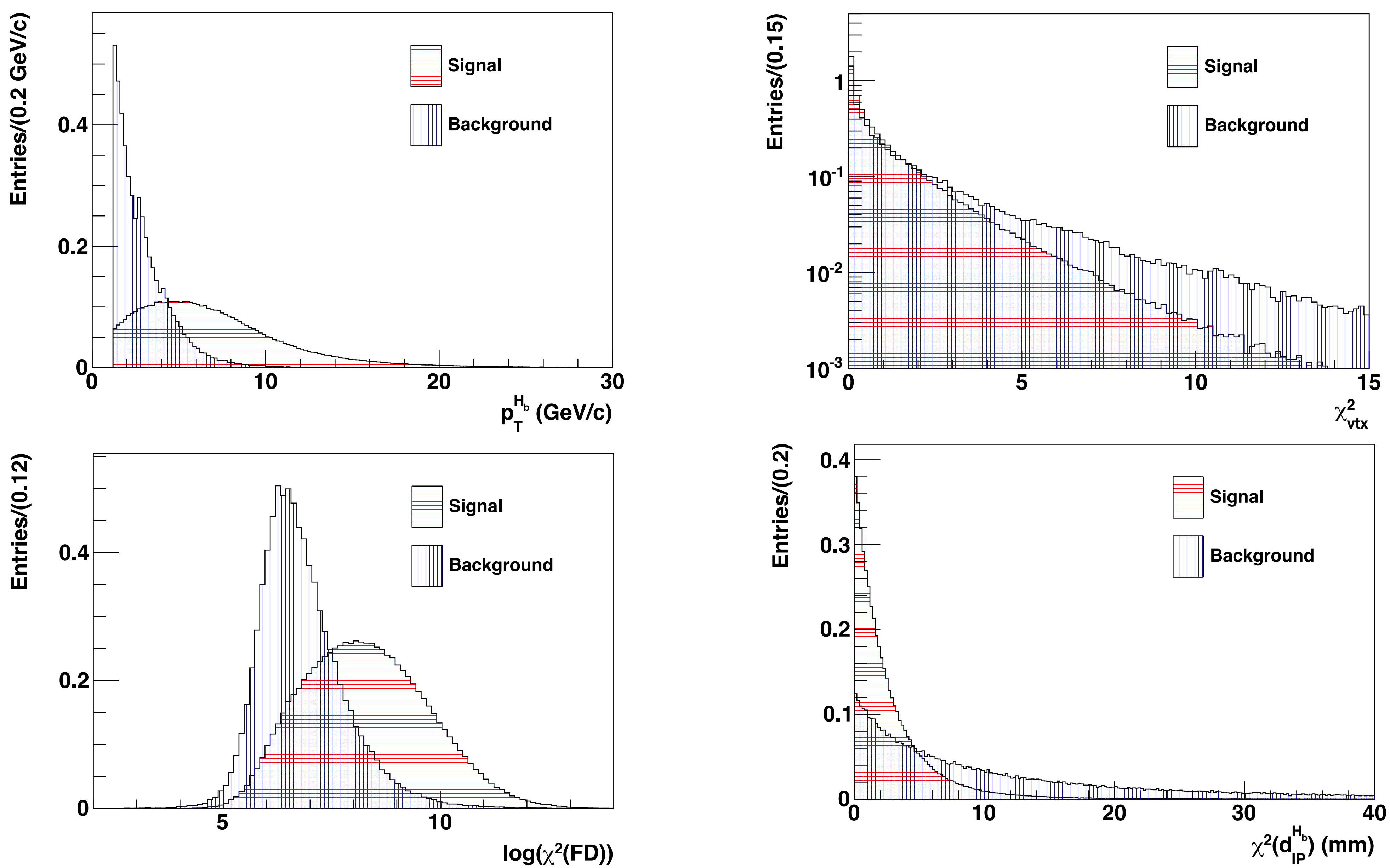






How to perform an analysis?

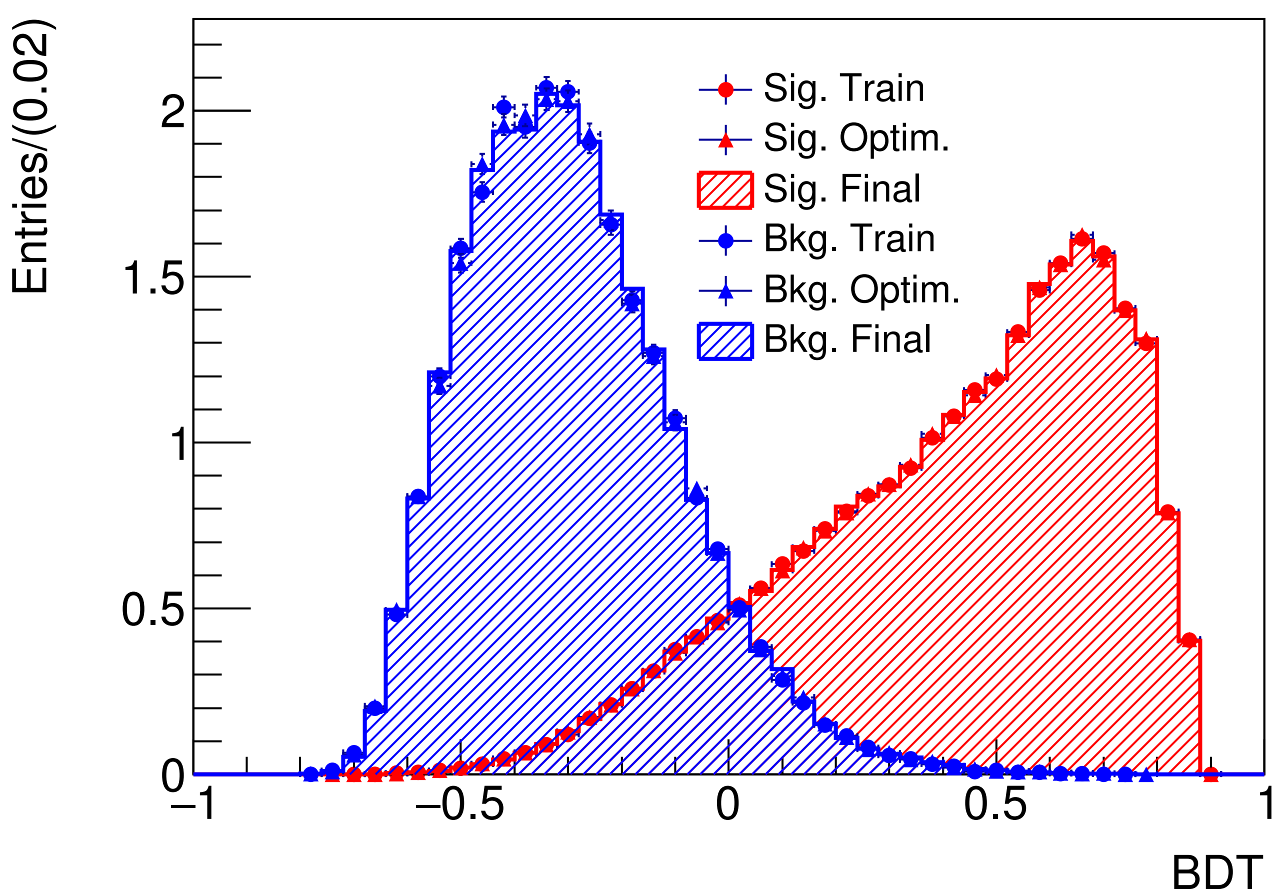
"Offline" selection: apply a set of criteria to have a "clean" signal distribution



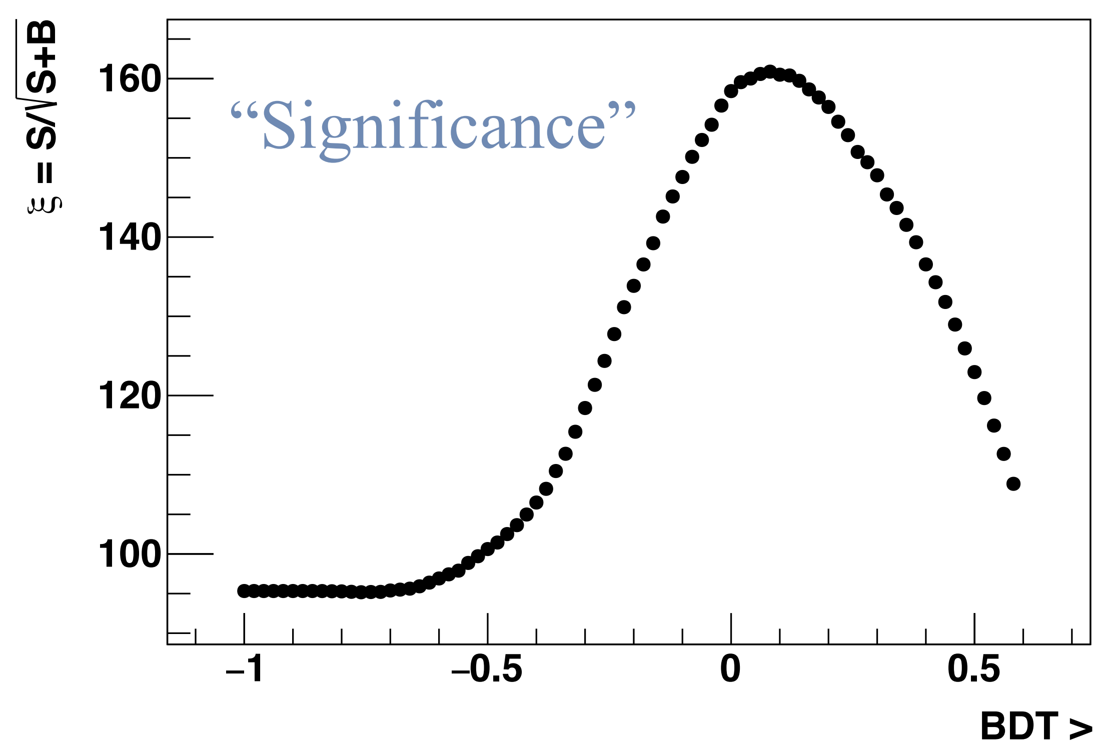
How to perform an analysis?

“Offline” selection: apply a set of criteria to have a “clean” signal distribution

- Typically experiments use a “multivariate” approach, which can then classify the events as “signal-backgrounds”



Where to apply a “cut”?



How to perform an analysis?

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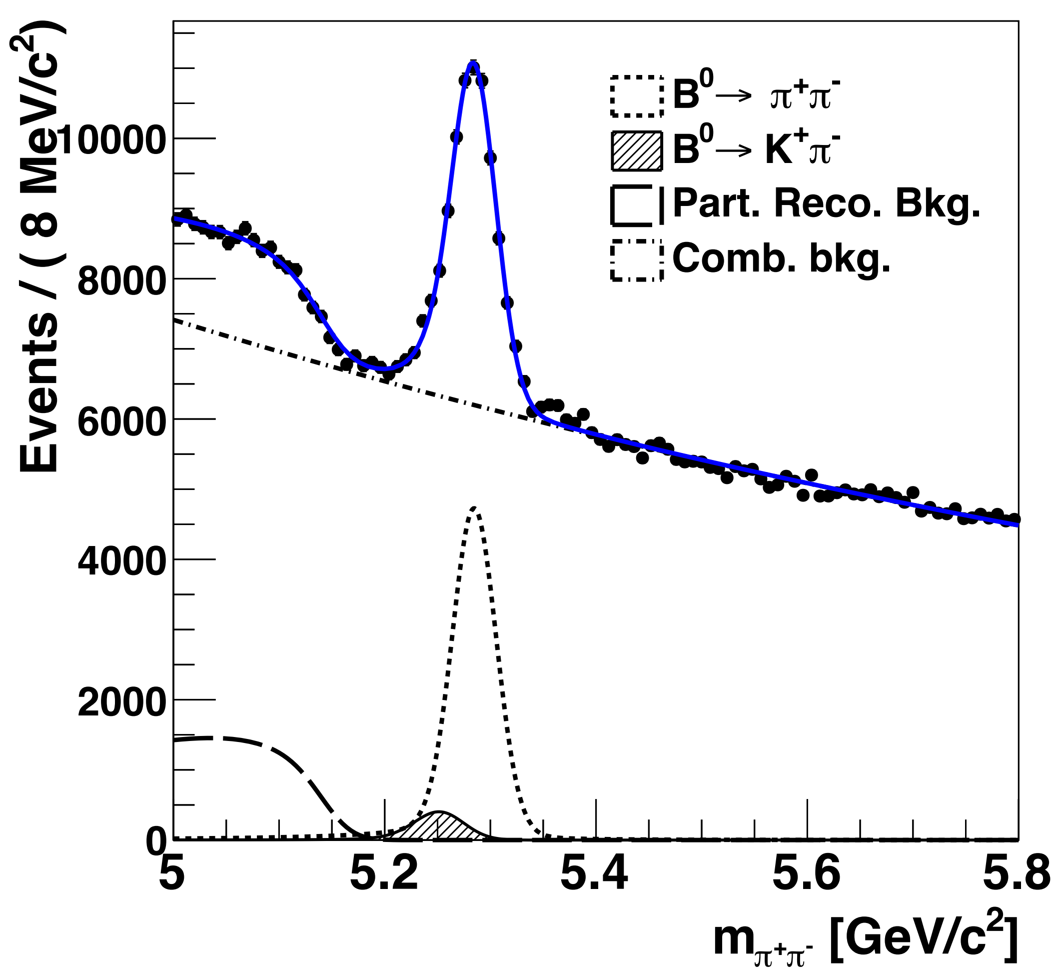
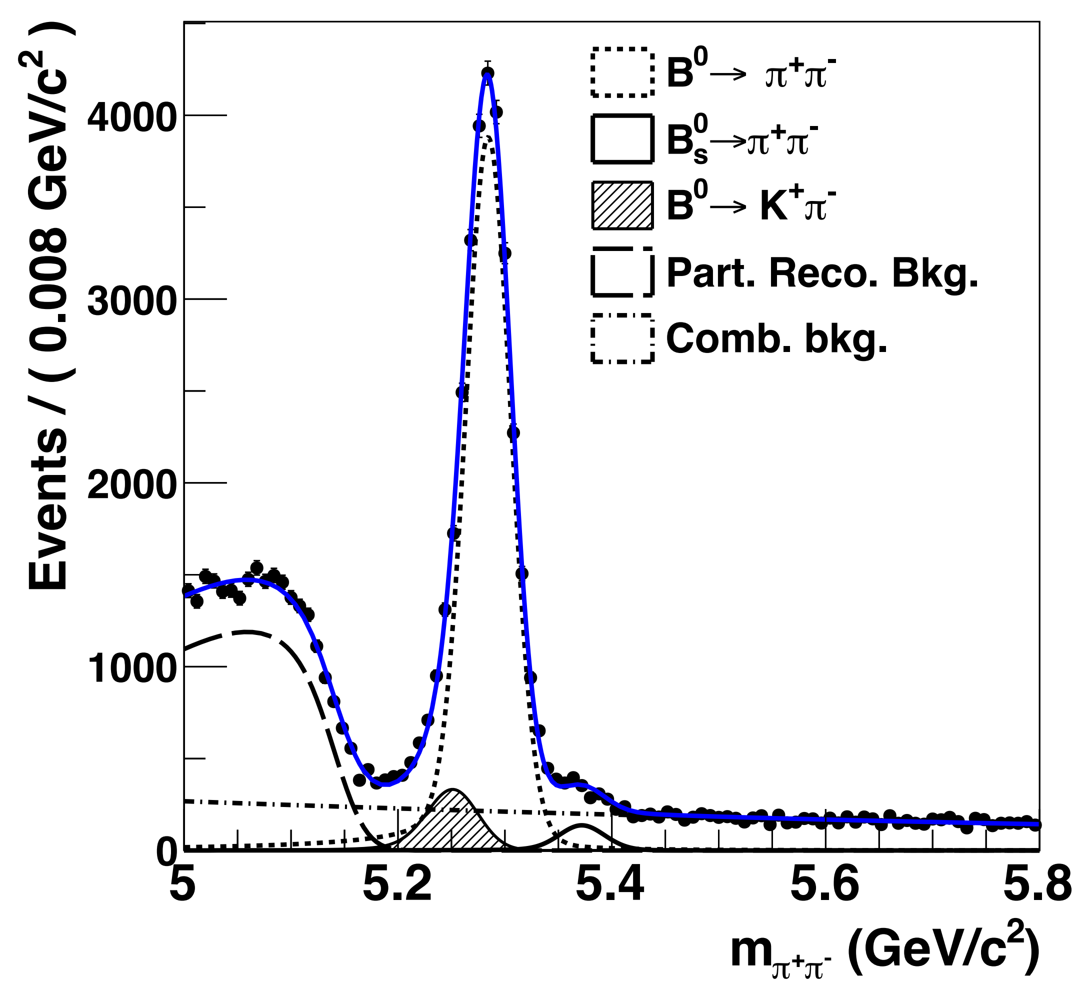
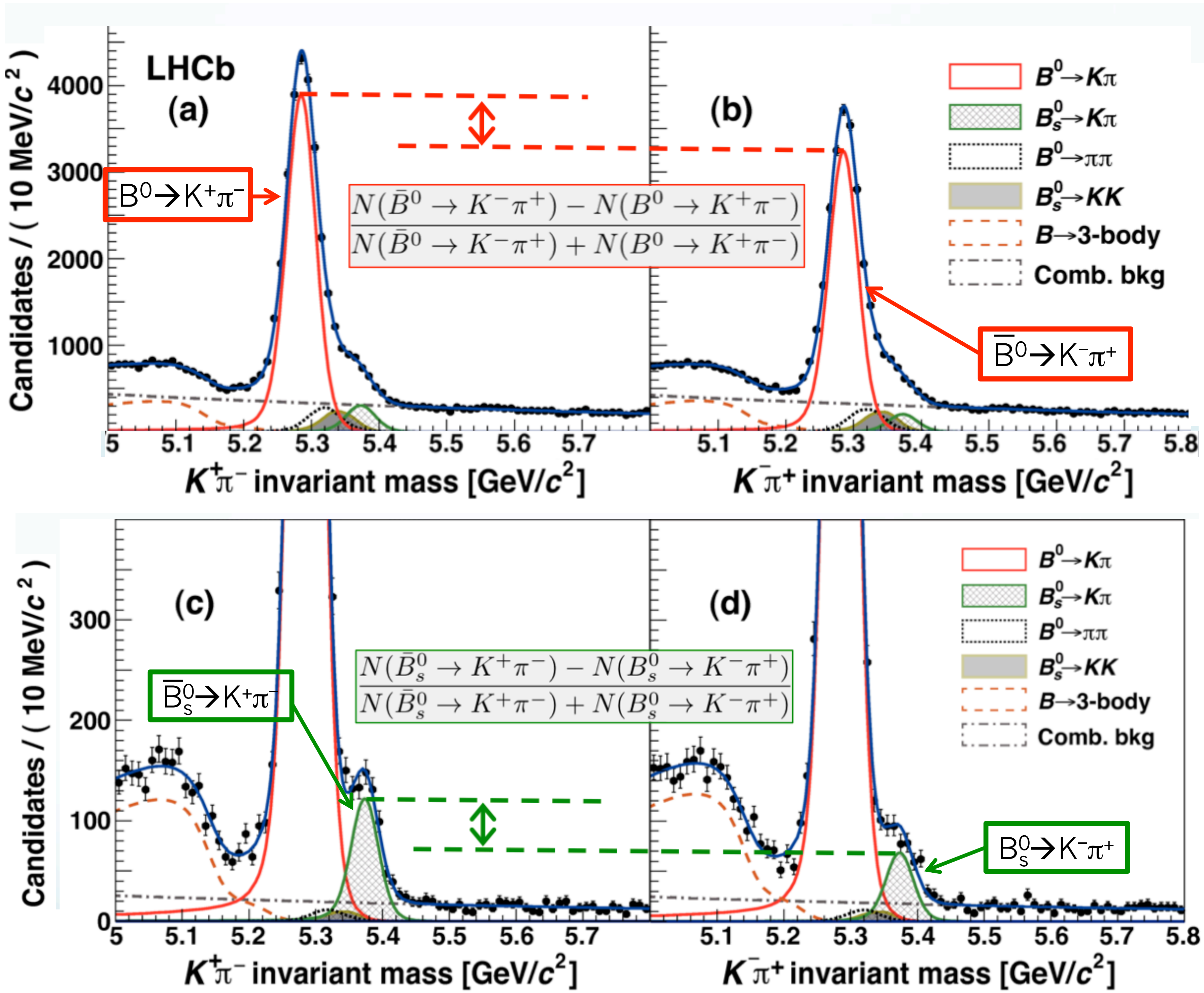
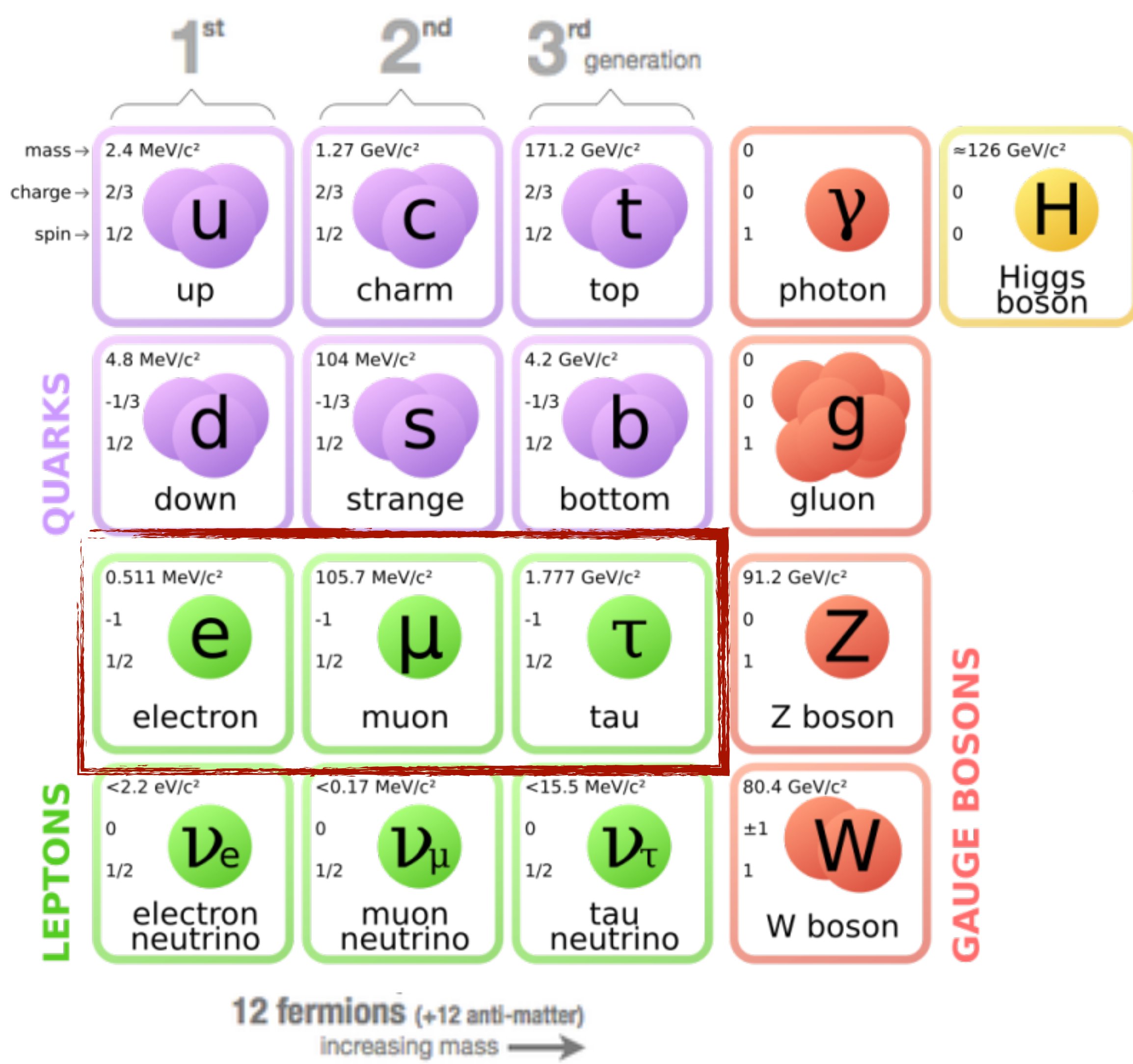




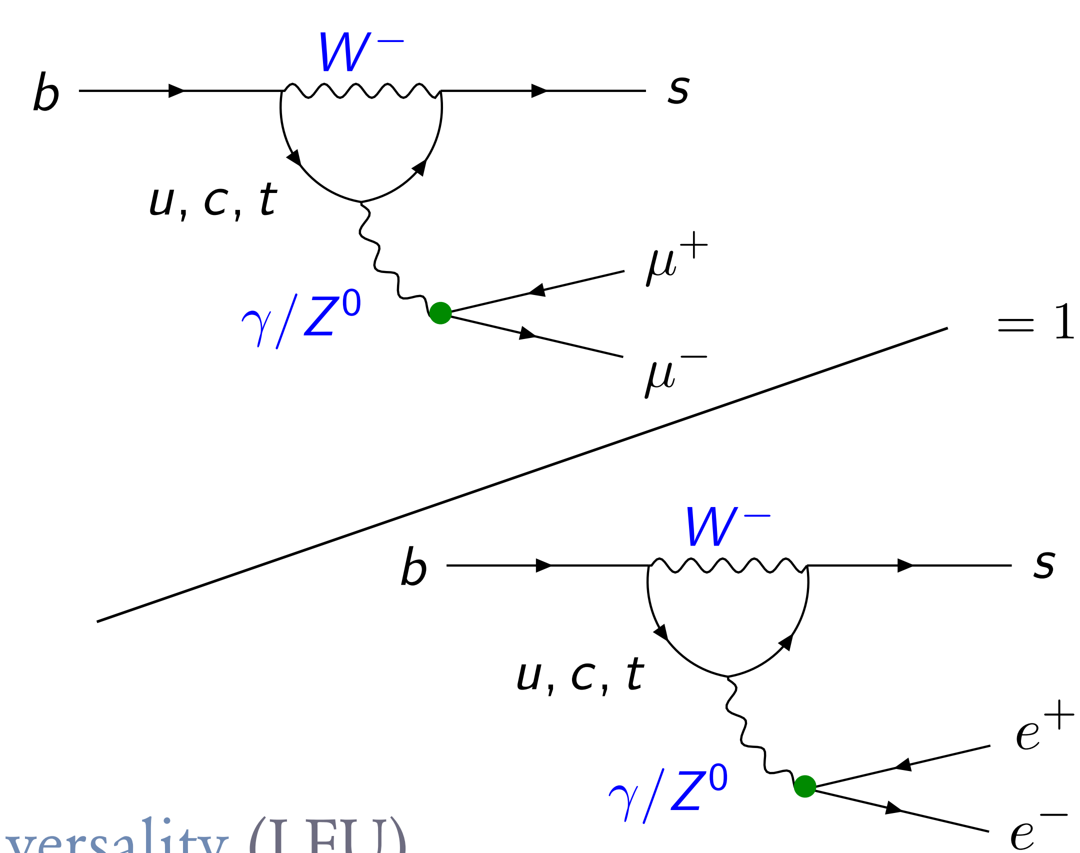
CP violation in B decays



Physics case (II) - flavour anomalies



The SM predicts that particles couple universally to leptons of different flavours

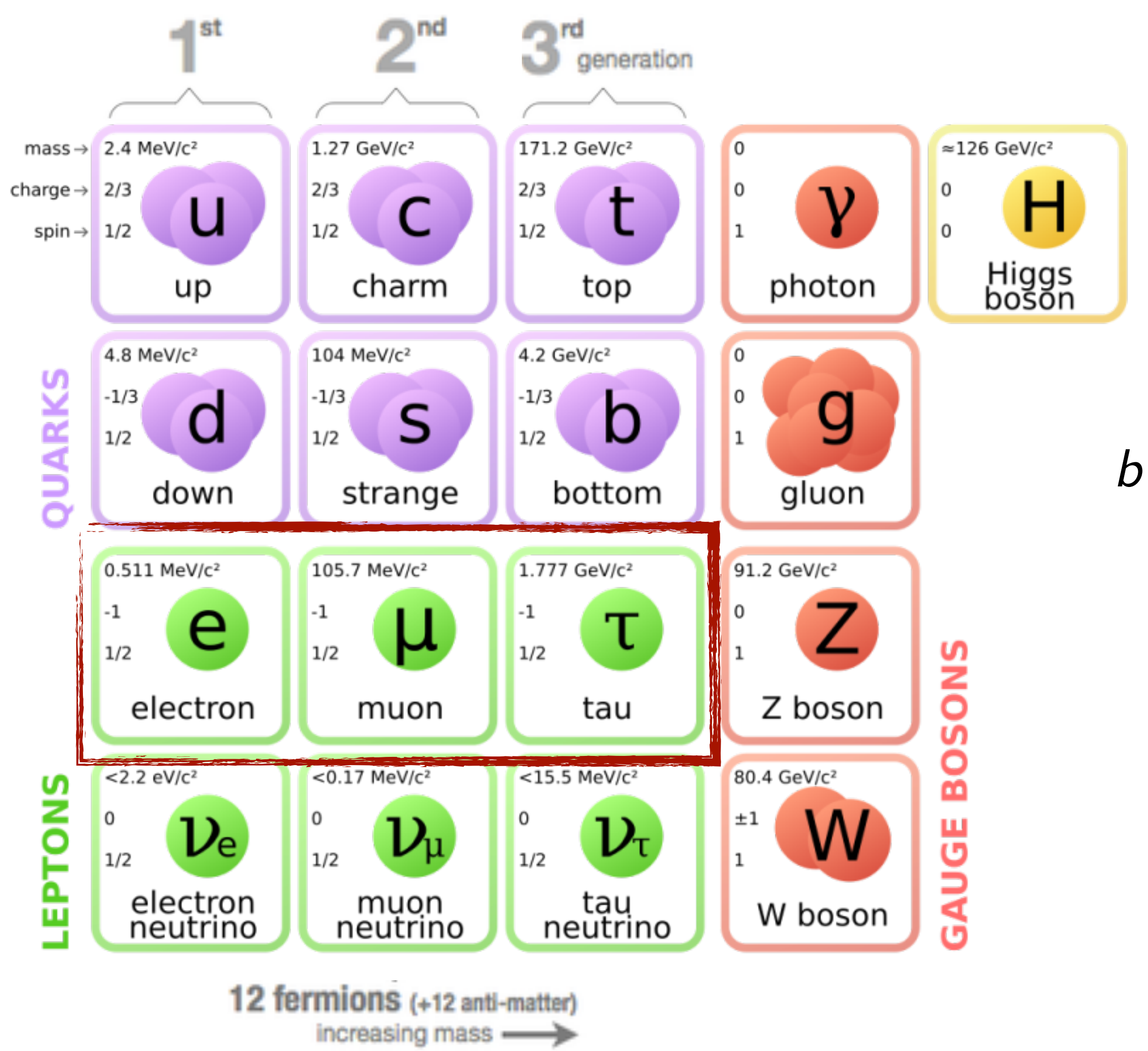


$$= 1 + \mathcal{O}(10^{-3})$$

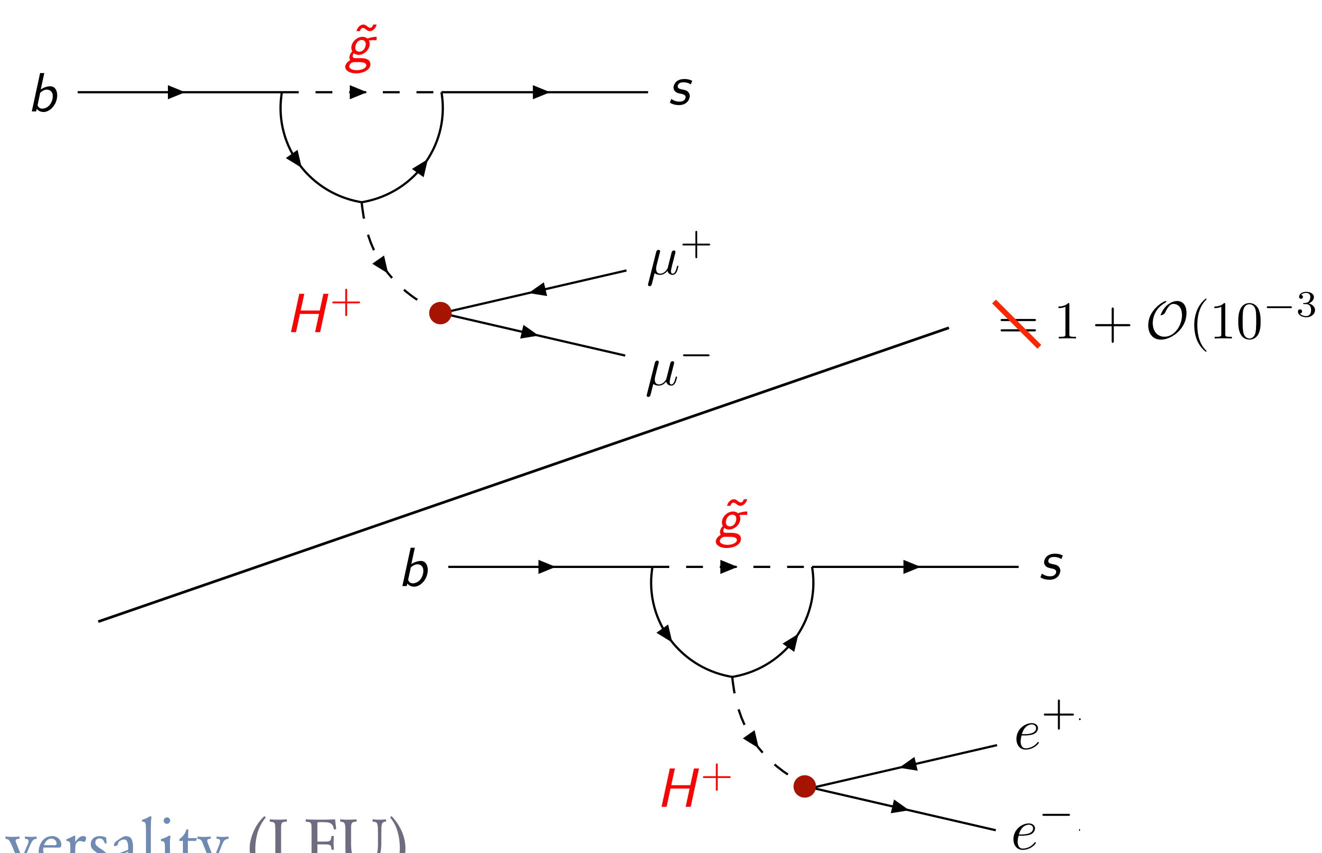
[PRD 69 074020 (2004)]

Measurements of lepton flavour universality (LFU) constitute theoretically very clean probes of this hypothesis

Physics case (II) - flavour anomalies



Beyond the SM, theories can feature non-universal couplings



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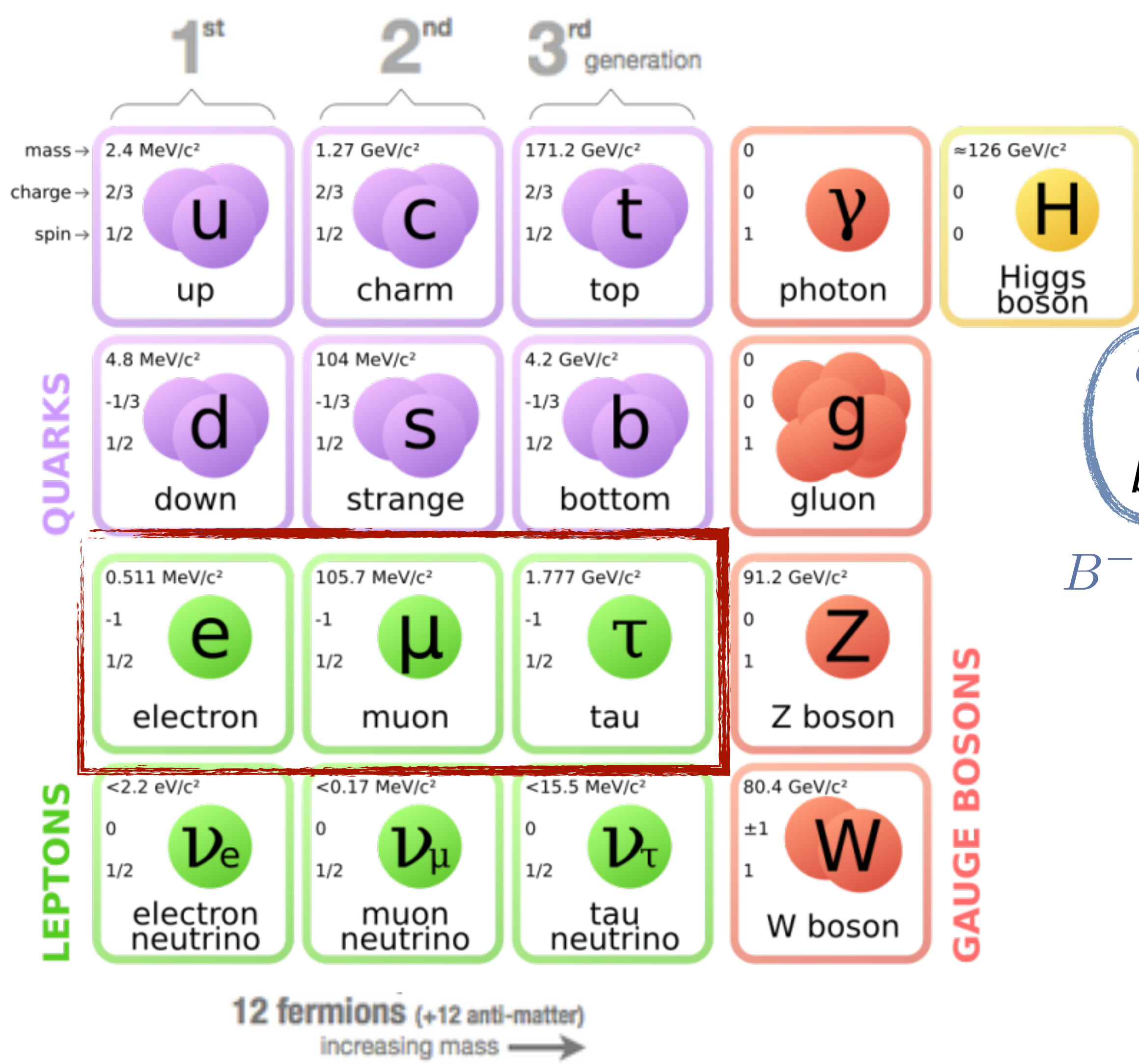
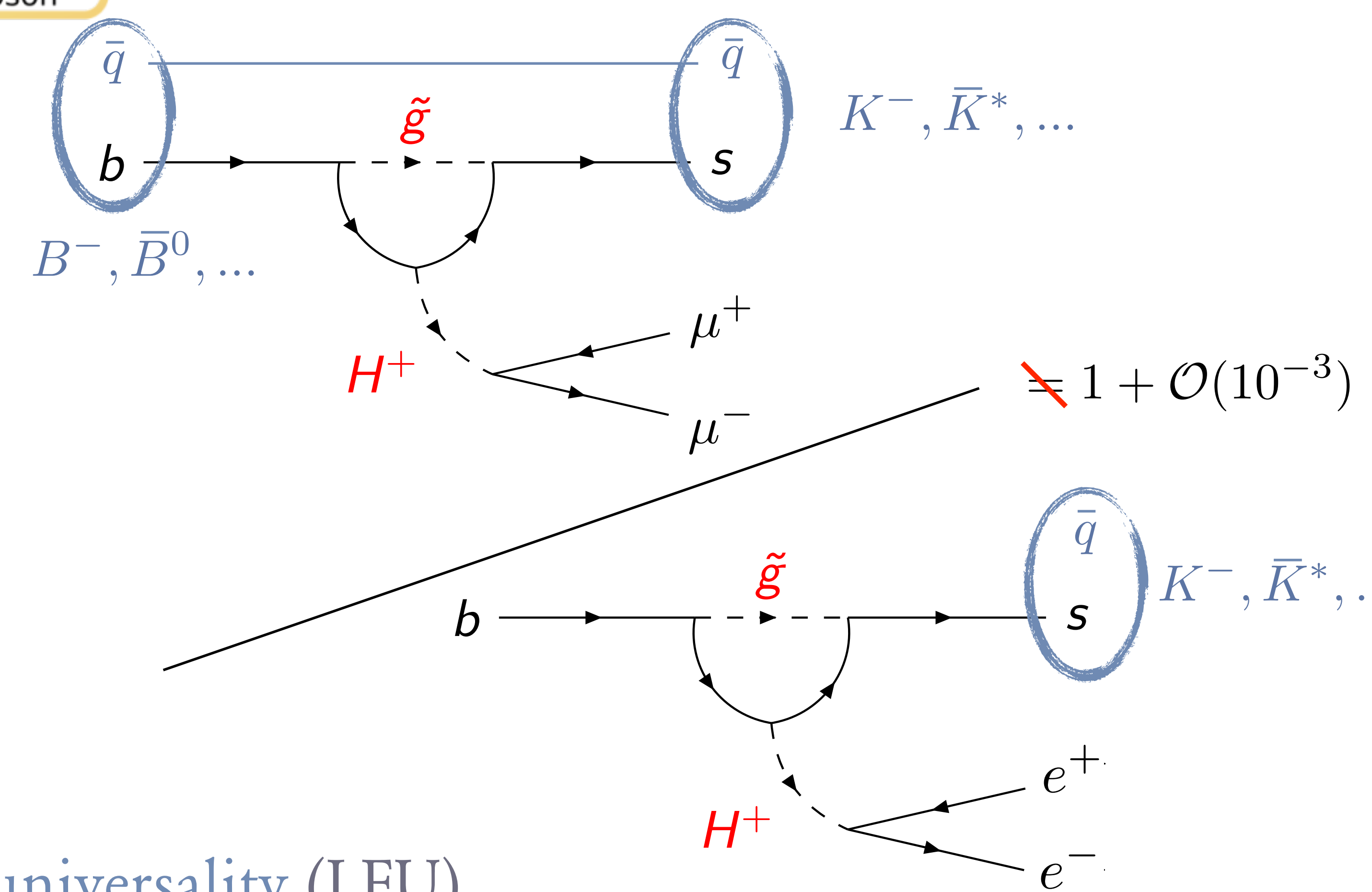
[PRD 69 074020 (2004)]

Physics case (II) - flavour anomalies



These flavour transitions can be measured through ratios of decay rates

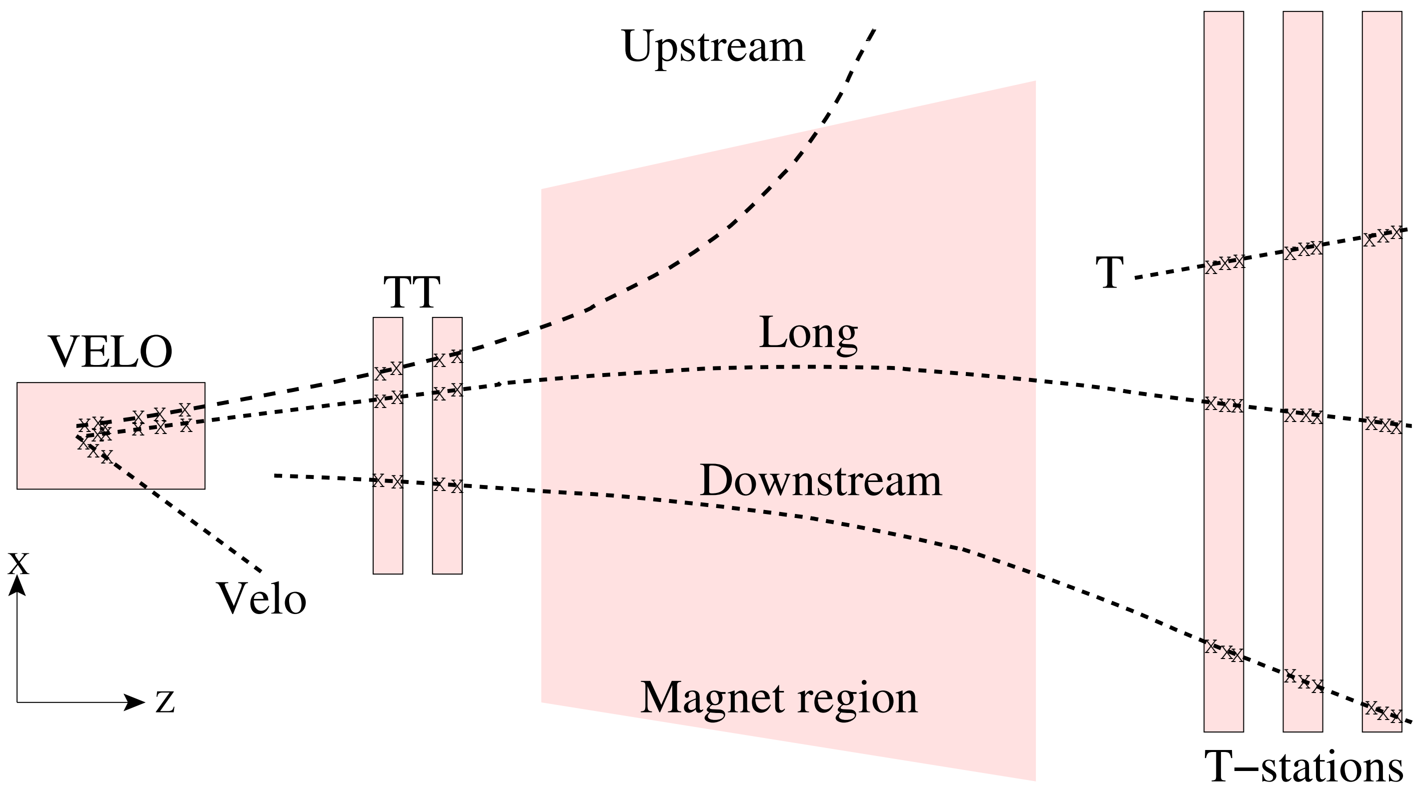


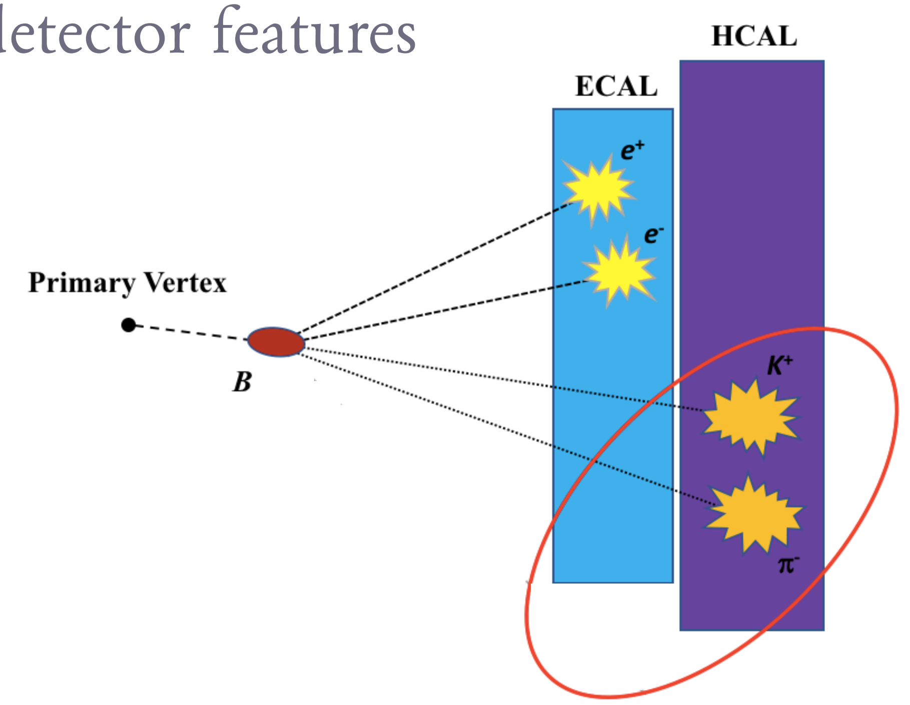
[PRD 69 074020 (2004)]

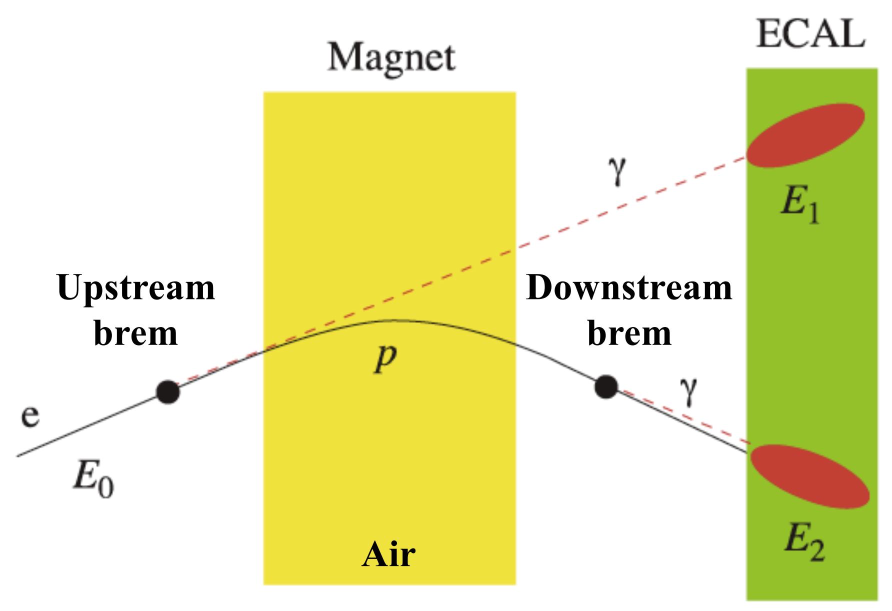
Measurements of lepton flavour universality (LFU) constitute theoretically very clean probes of this hypothesis

How to select $B \to K^{(+,*0)}e^+e^-$ events?

The electron identification at LHCb relies on a few detector features

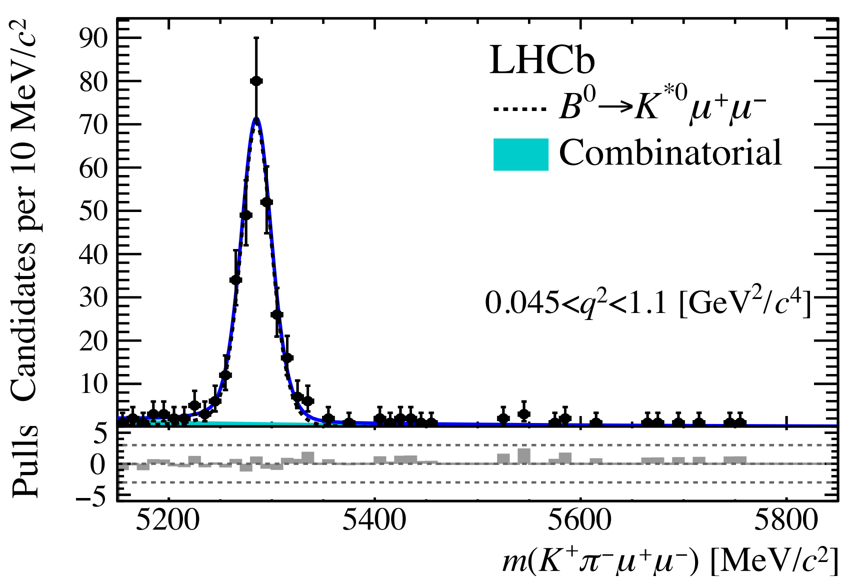




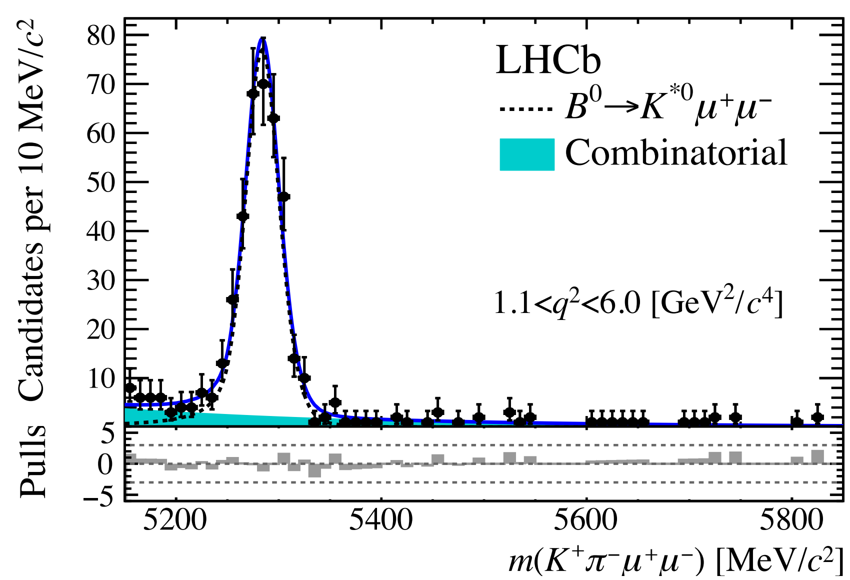


How to obtain the number of events?

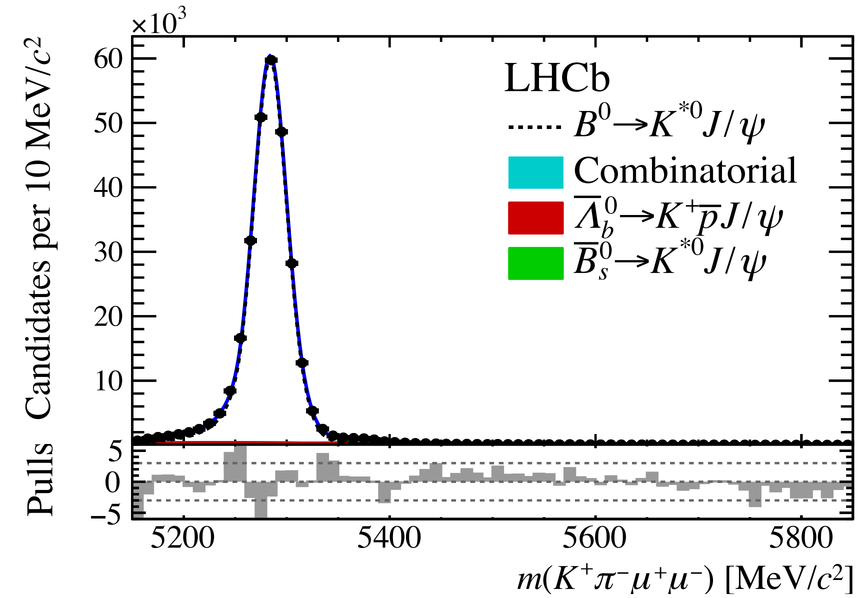
[LHCb, LHCB-PAPER-2017-013]



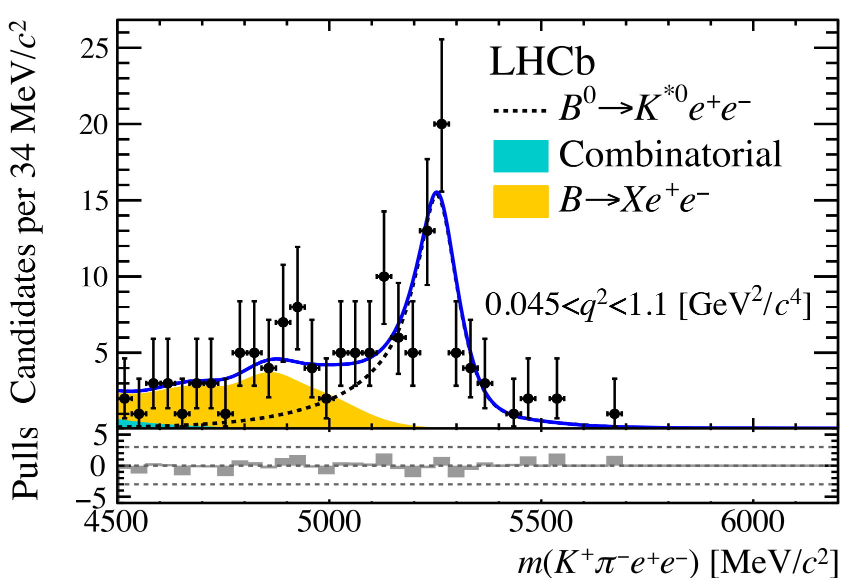
Low q^2 : 285 ± 18



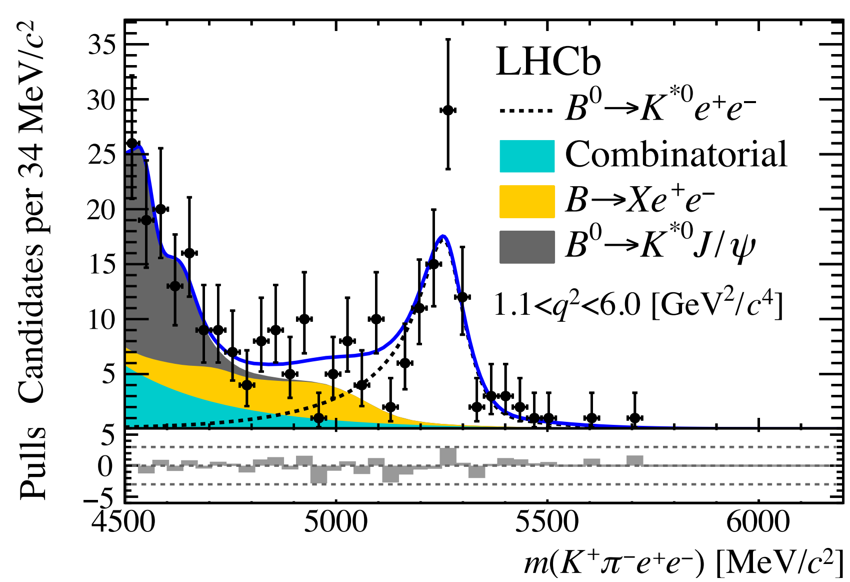
Central q^2 : 353 ± 21



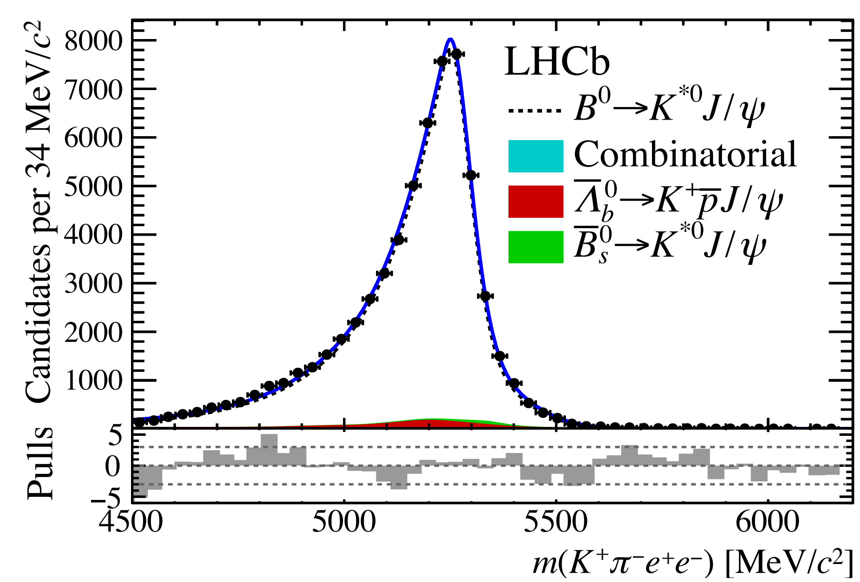
J/ψ region : 274K



Low q^2 : 89 ± 11



Central q^2 : 111 ± 14

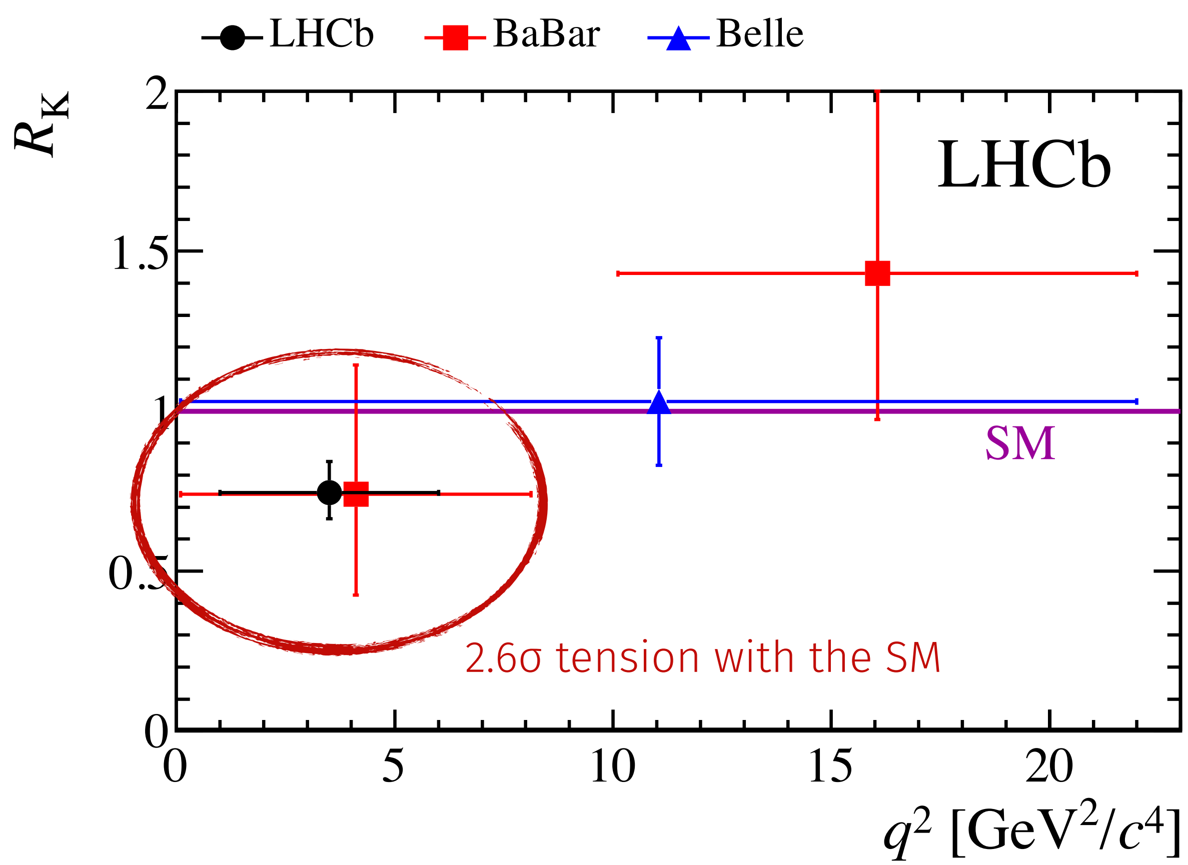


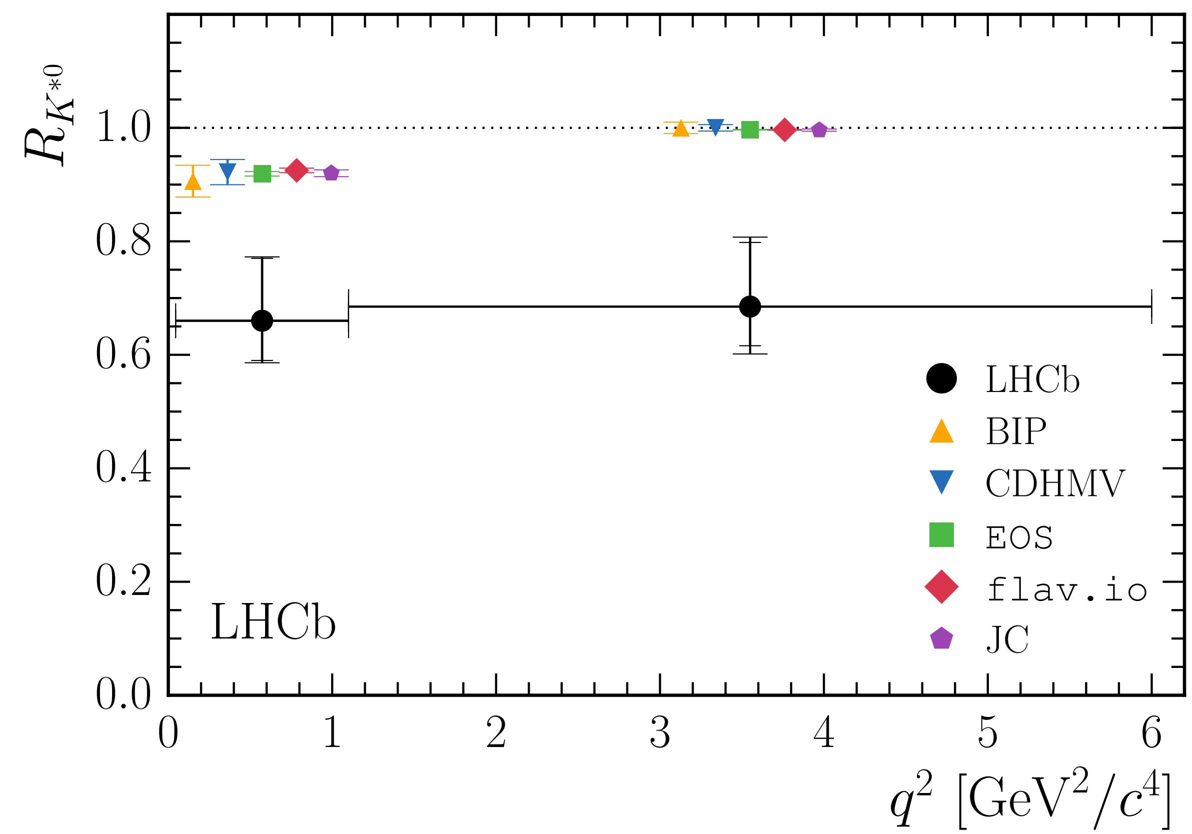
J/ψ region : 58K

Analyses results

[LHCb, LHCB-PAPER-2017-013]

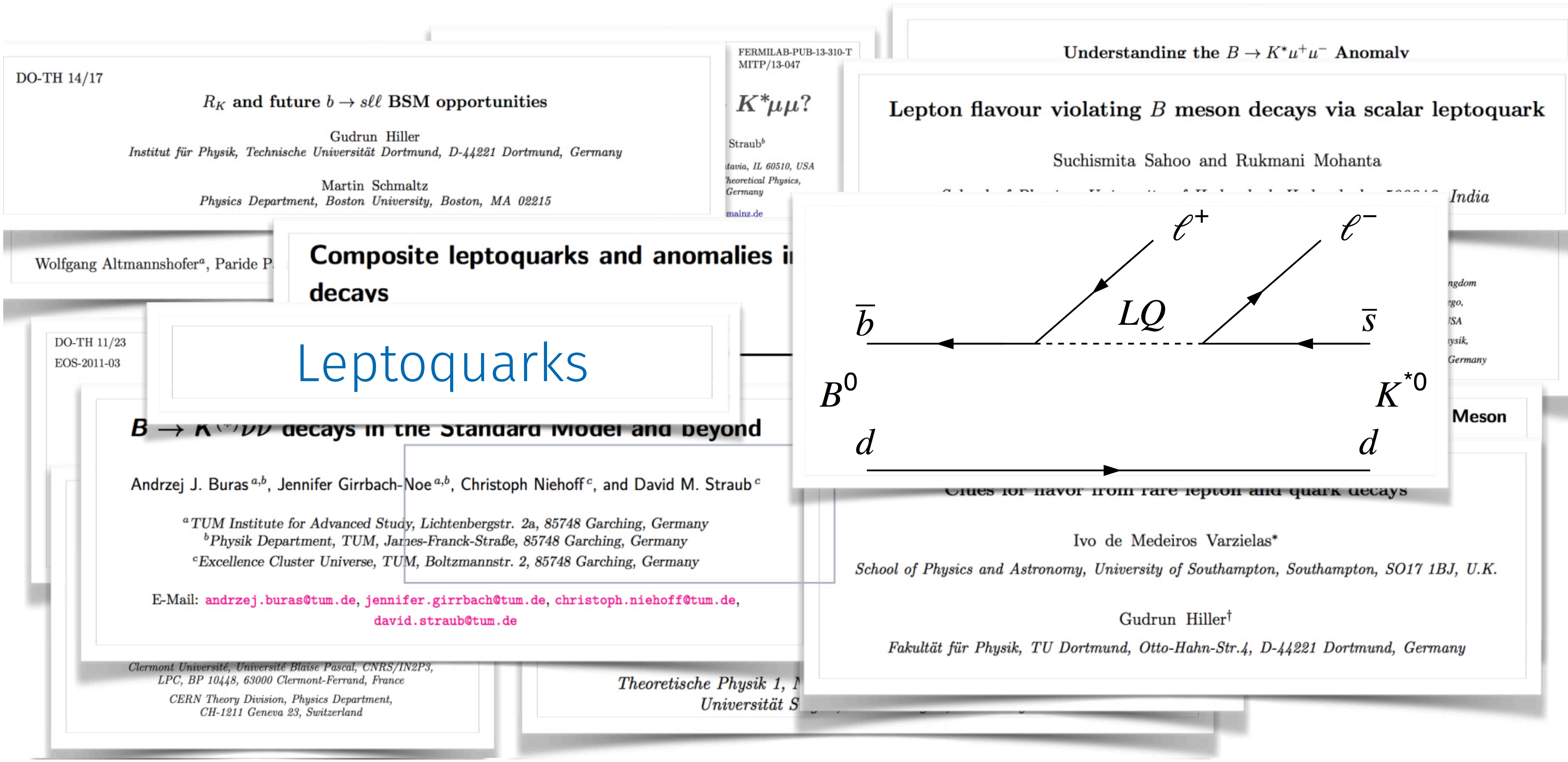
Ratios of "branching fractions" - lepton flavour universality





Intriguing! What happens next? Measure, measure, measure ...

New Physics?


DO-TH 14/17
R_K and future $b \to s\ell\ell$ BSM opportunities
Gudrun Hiller
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FERMILAB-PUB-13-310-T
MITP/13-047
$K^*\mu\mu$?
Understanding the $B \to K^*\mu^+\mu^-$ Anomaly
Lepton flavour violating B meson decays via scalar leptoquark
Suchismita Sahoo and Rukmani Mohanta
India
Wolfgang Altmannshofer[a], Paride P
Composite leptoquarks and anomalies i
decays
Leptoquarks
DO-TH 11/23
EOS-2011-03
$B \to K^{(*)}\nu\bar{\nu}$ decays in the Standard Model and beyond
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ℓ^+
ℓ^-
$\bar{b}$
LQ
$\bar{s}$
B^0
K^{*0}
d
d

New Physics?

Universität Zürich[UZH]