Flavour Physics

LECTURE 2

Monica Pepe Altarelli (CERN)

Moscow International School of Physics 2020

Outline of the three lectures

1 {
- What is flavour physics and why it is interesting
- CP Violation and baryogenesis
- Some historical remarks
- The CKM Matrix
- The rise of b physics

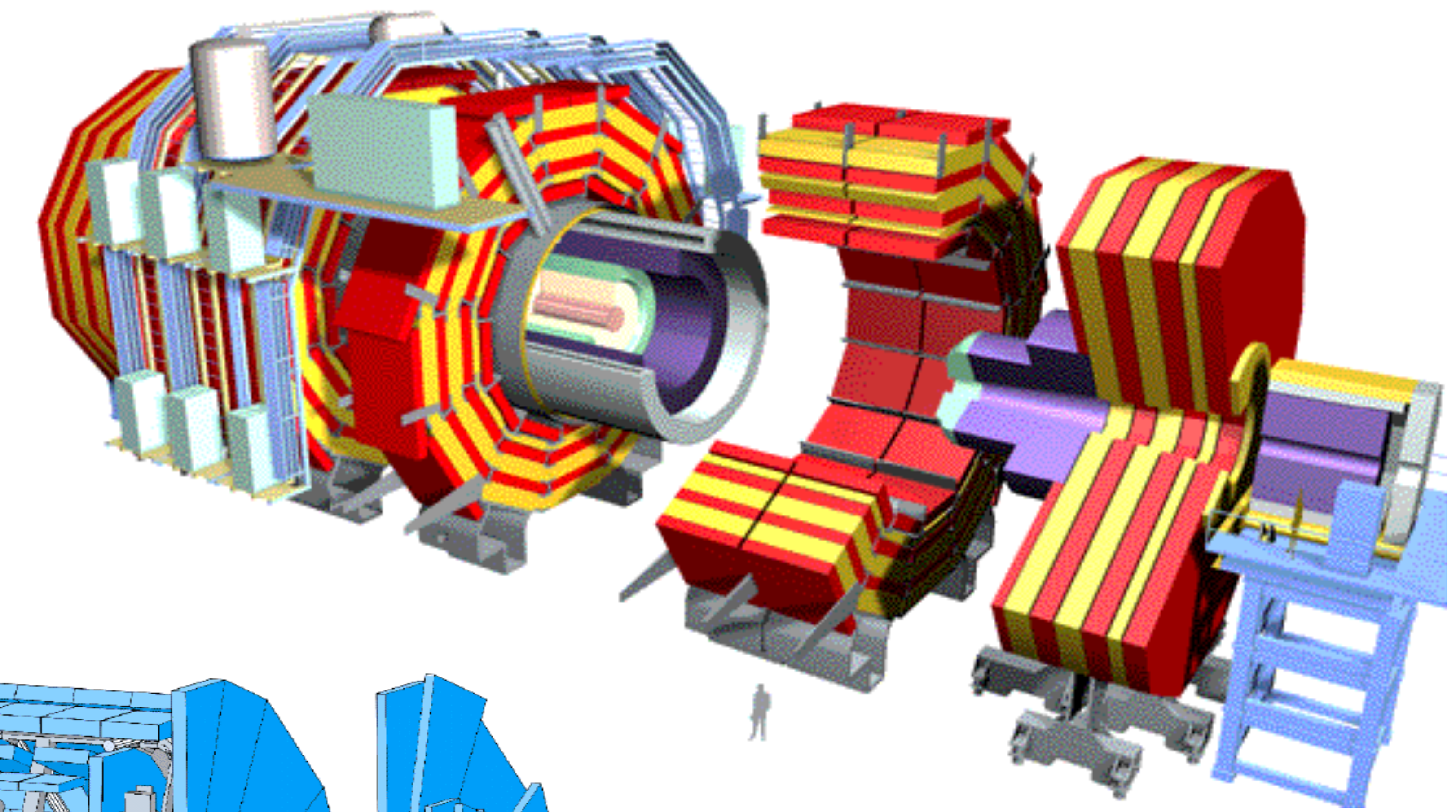
What we have learned from current experiments and the excitement of the field

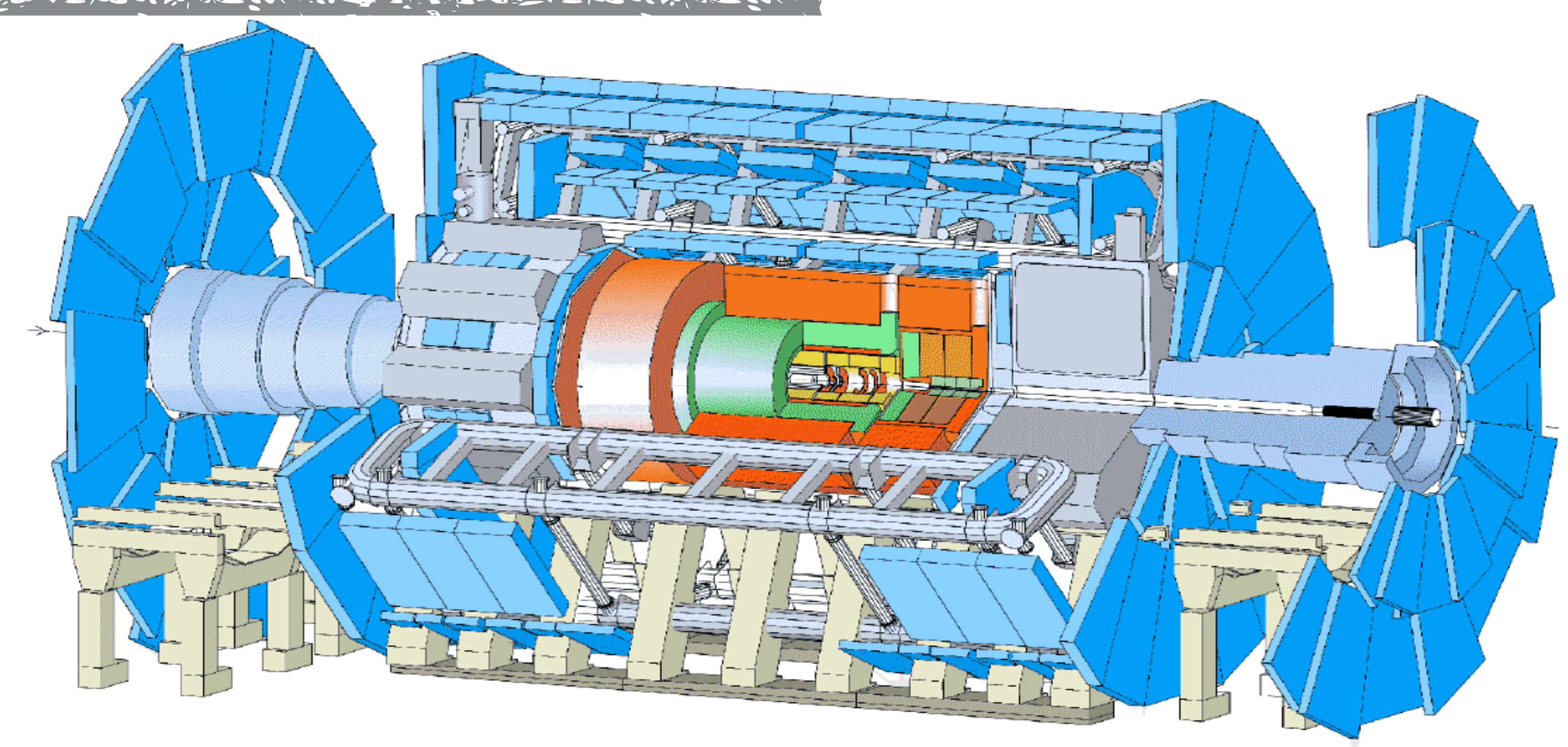
2 {
- LHCb: a heavy-flavour physics detector at the LHC - experimental aspects, the LHCb upgrade
- CKM metrology and selected CP violation measurements

3 {
- Selected results on rare decays, tests of LFU and conclusions

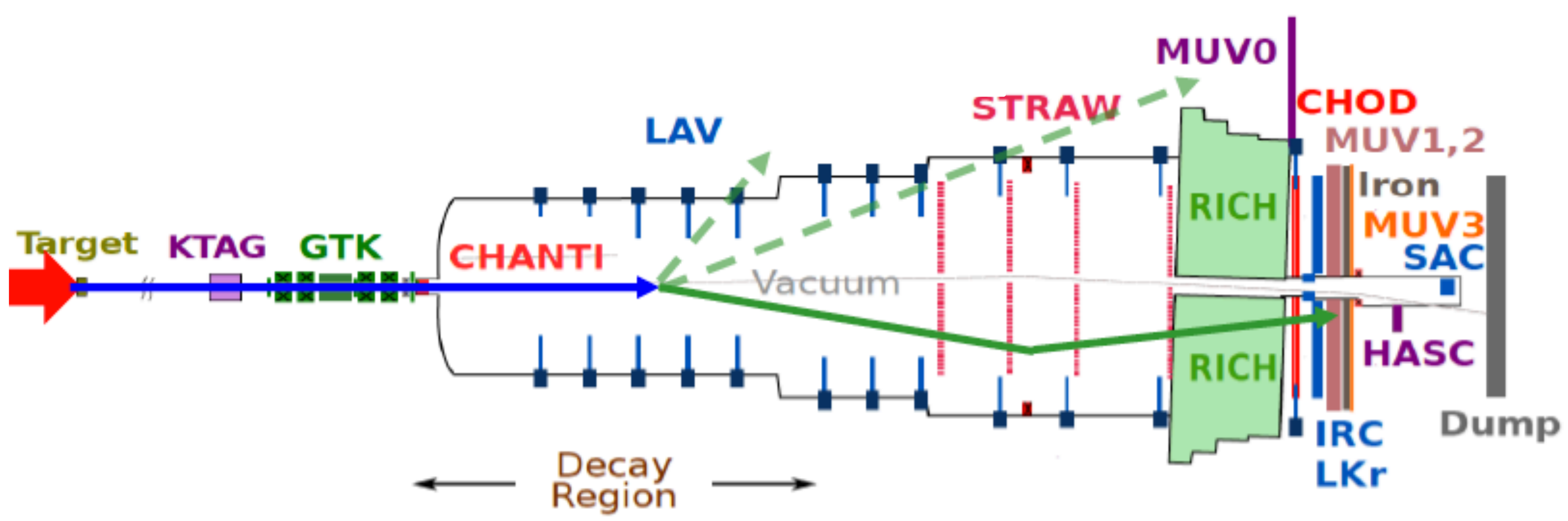
The main actors today

ATLAS and CMS @ LHC are “General Purpose Detectors”, but can measure a few flavour observables, mainly with muons in final state



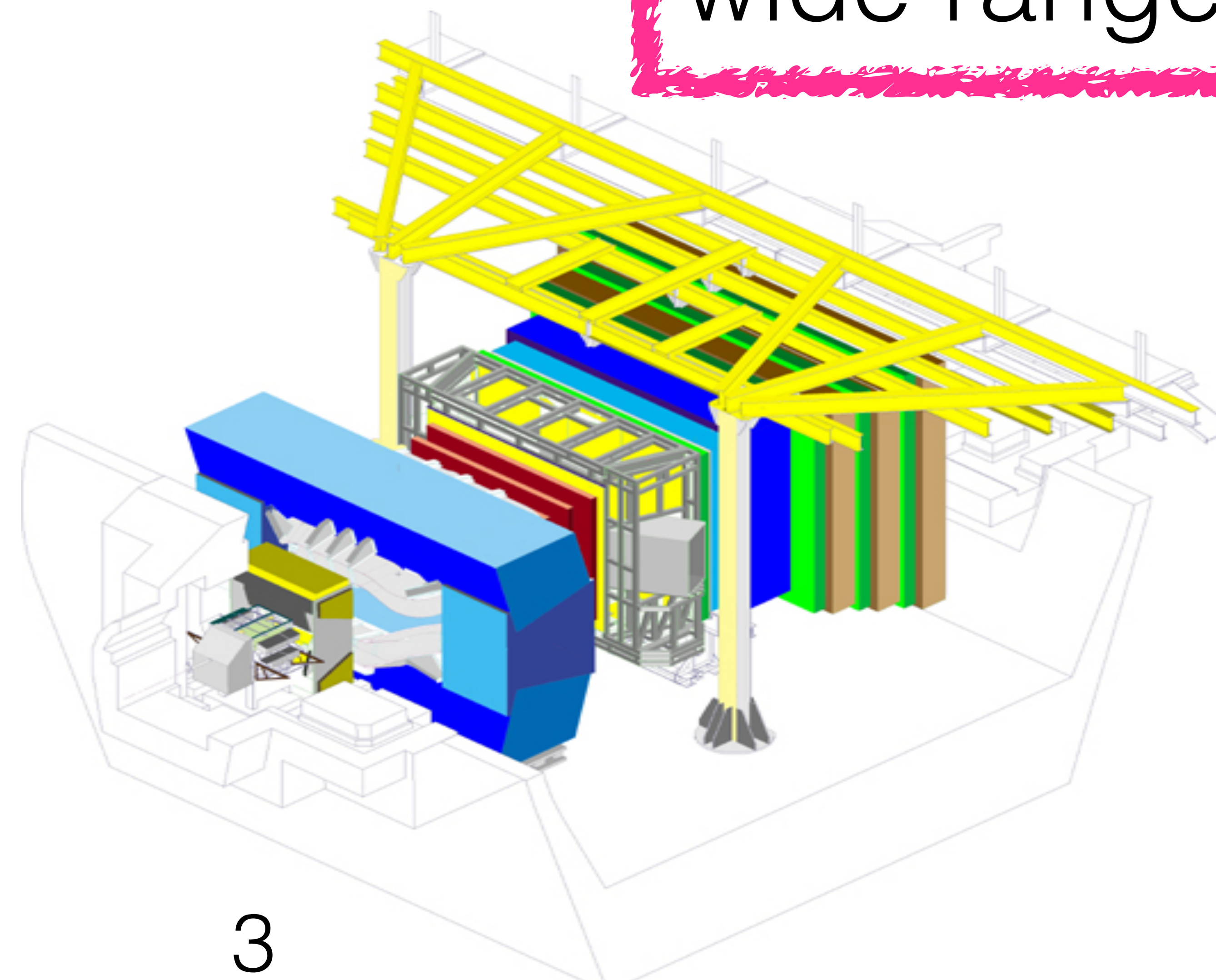


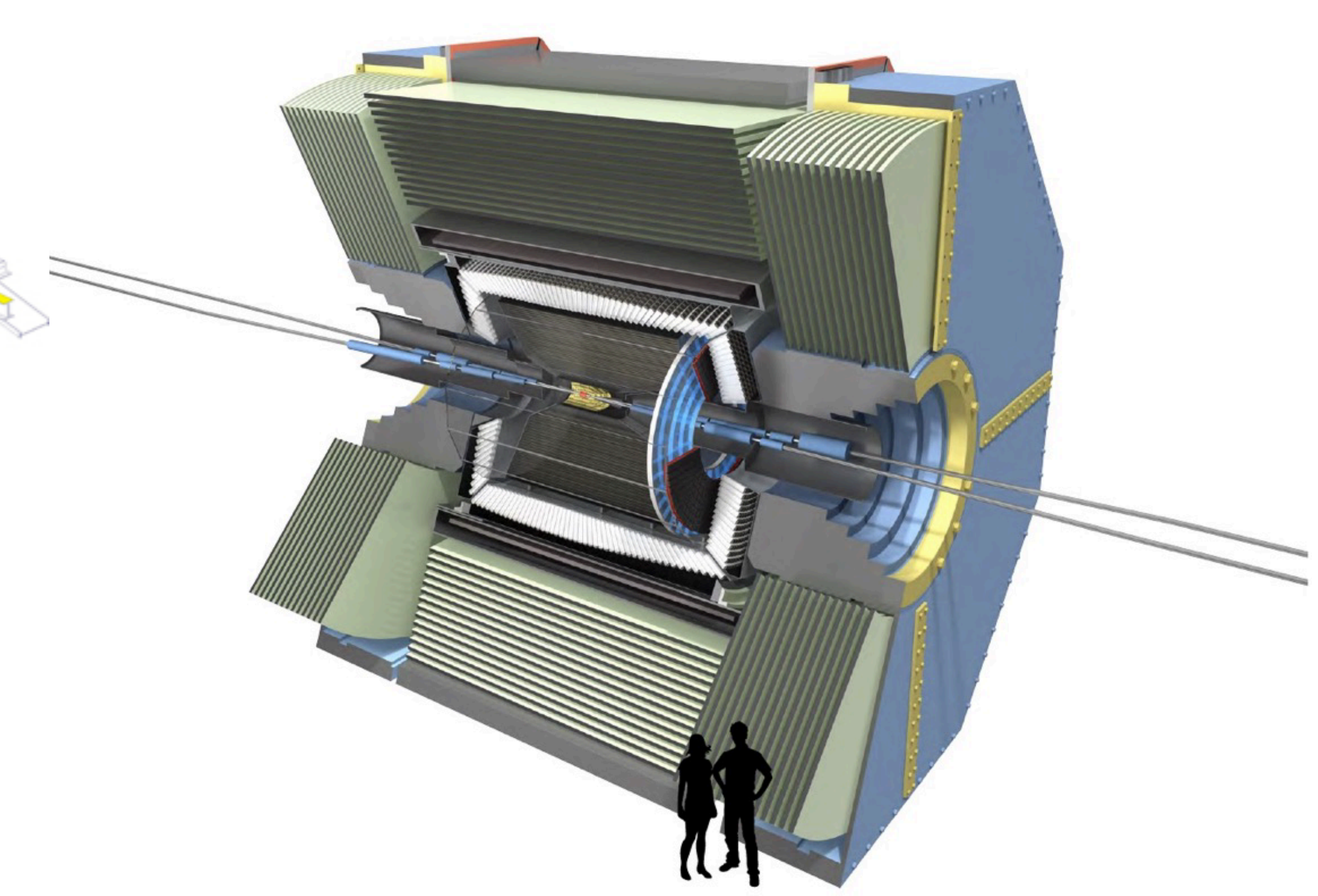
NA62 @ CERN is an experiment to measure the very rare decay $K^+ \to \pi^+ \nu \bar{\nu}$ (BF~10^{-10})



LHCb @ LHC and Belle II @KEK are dedicated detectors for flavour physics performing a wide range of measurements

..plus BESIII, KOTO, Mu2e, MEG II, ..






LHCb
The LHC

The LHCb collaboration

- ~1350 members from 83 institutes in 19 countries
- ~500 publications, some with very high impact
- Main focus on heavy quark flavour…but plenty of other physics in the forward direction

The LHCb collaboration

- ~1250 members from 79 institutes in 18 countries
- ~450 publications, some with very high impact
- Main focus on heavy quark flavour…but plenty of other physics in the forward direction

CKM & CPV

EW and QCD

Rare decays

Spectroscopy

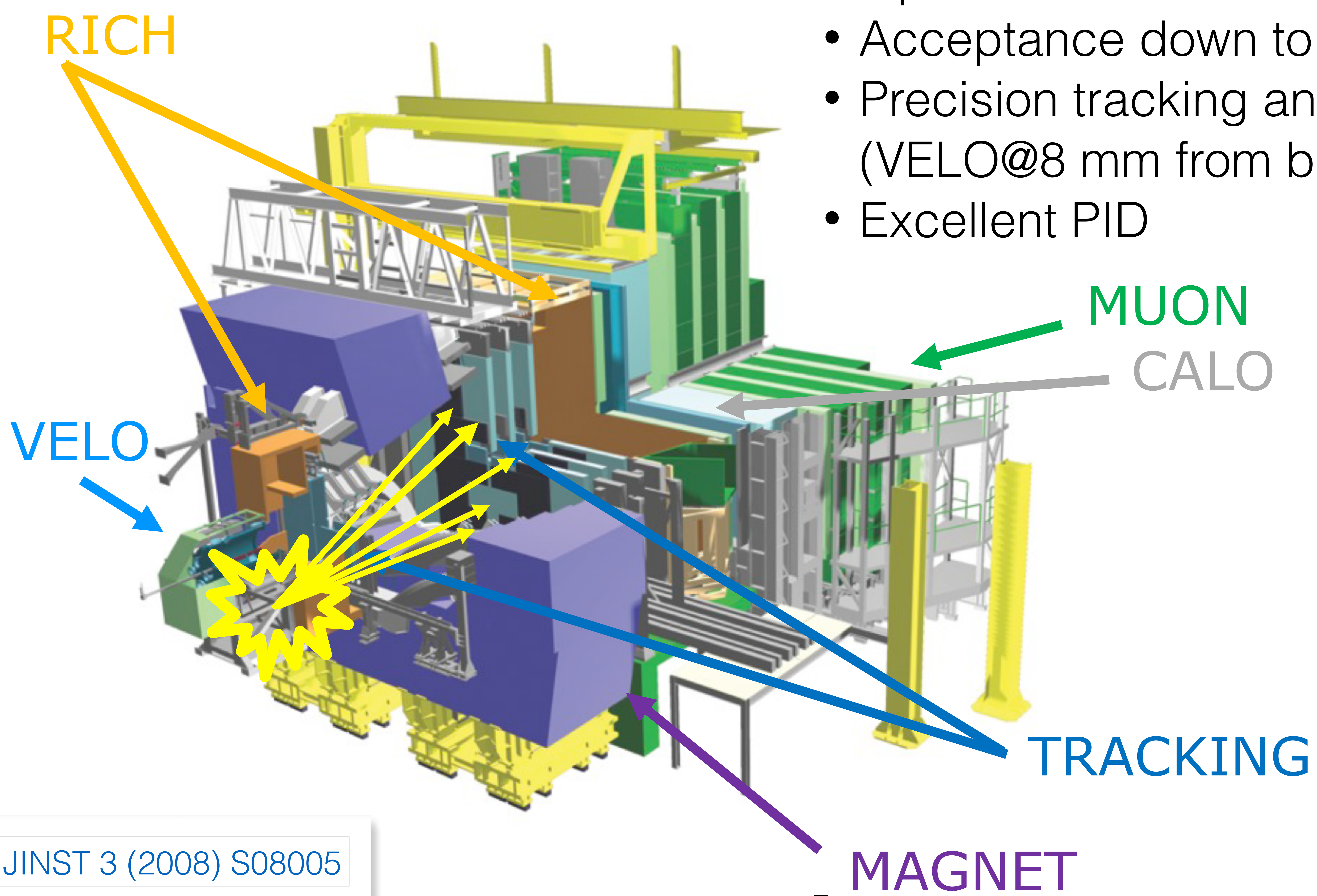
Semileptonic decays

Ions and fixed target

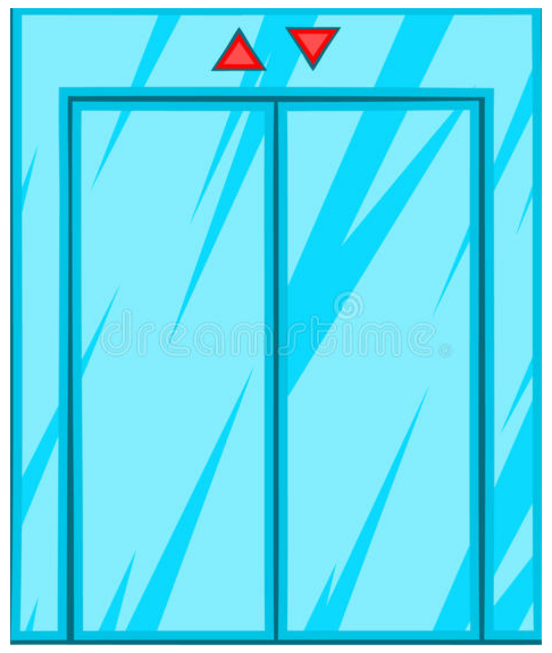
Exotica searches

LHCb detector: the essentials

- Forward acceptance
- Efficient trigger for hadronic and leptonic modes
- Acceptance down to low p_T
- Precision tracking and vertexing (VELO@8 mm from beam)
- Excellent PID



JINST 3 (2008) S08005

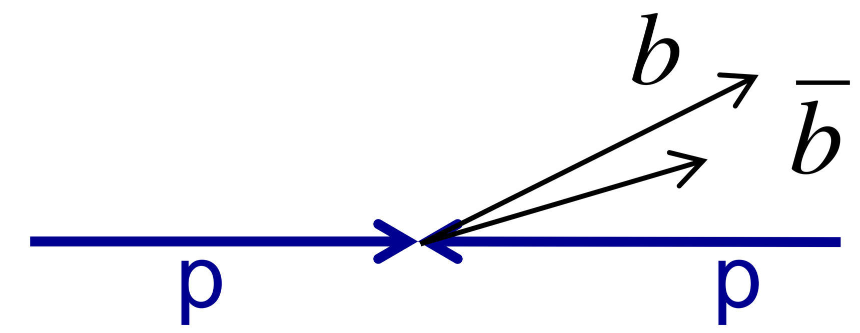


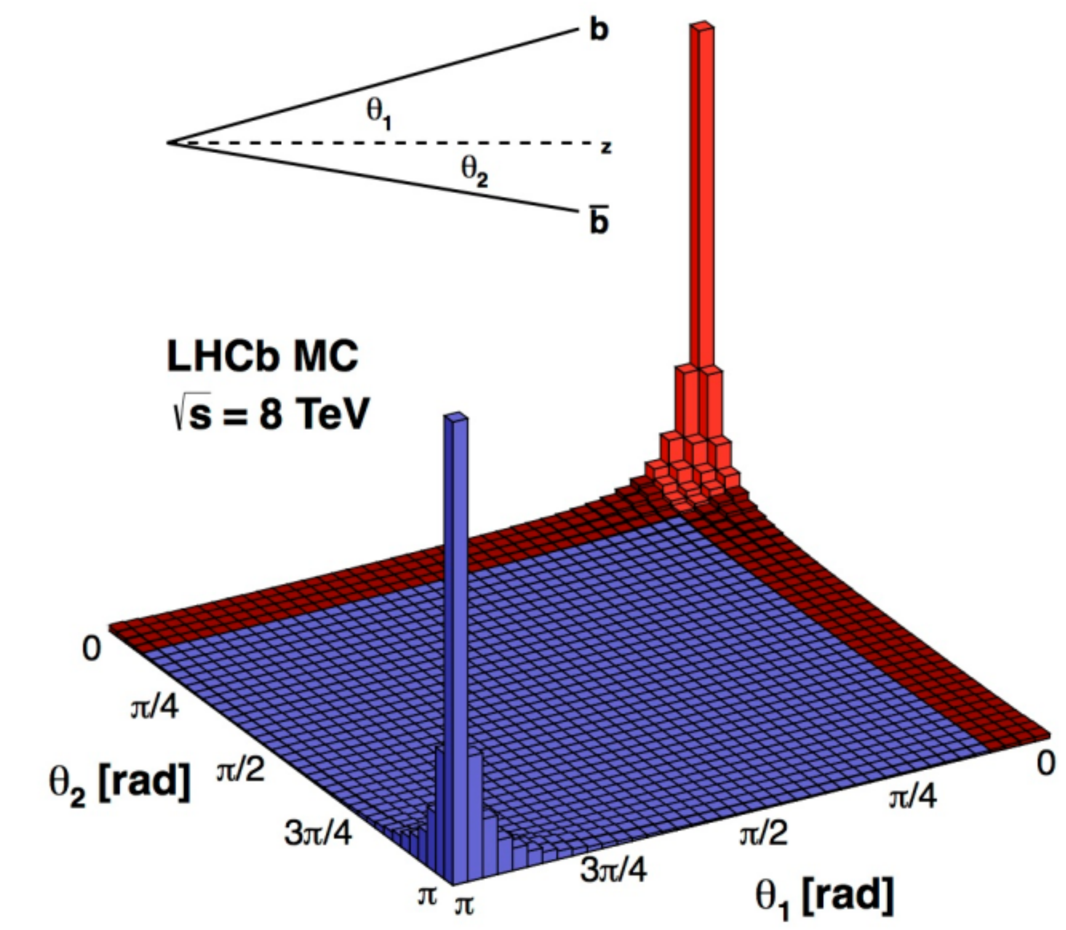
The real thing

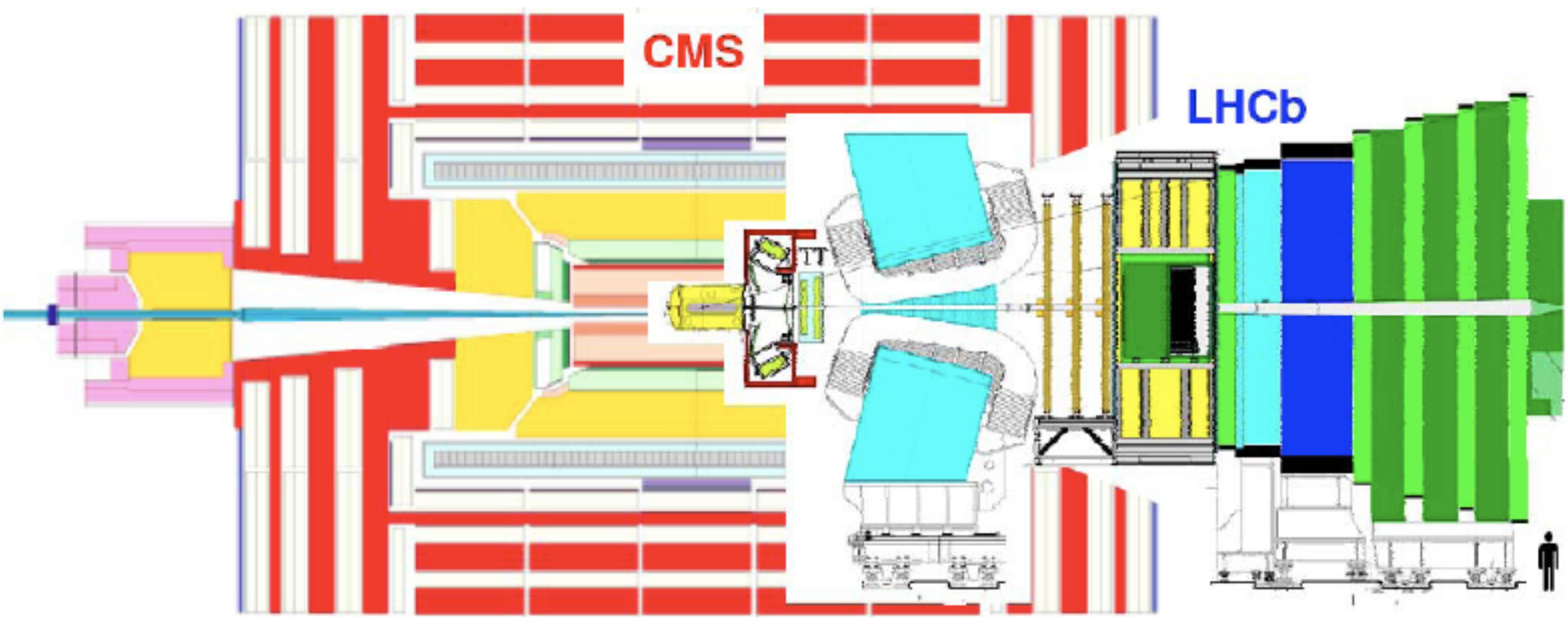
With components superimposed

Why does LHCb look so different?

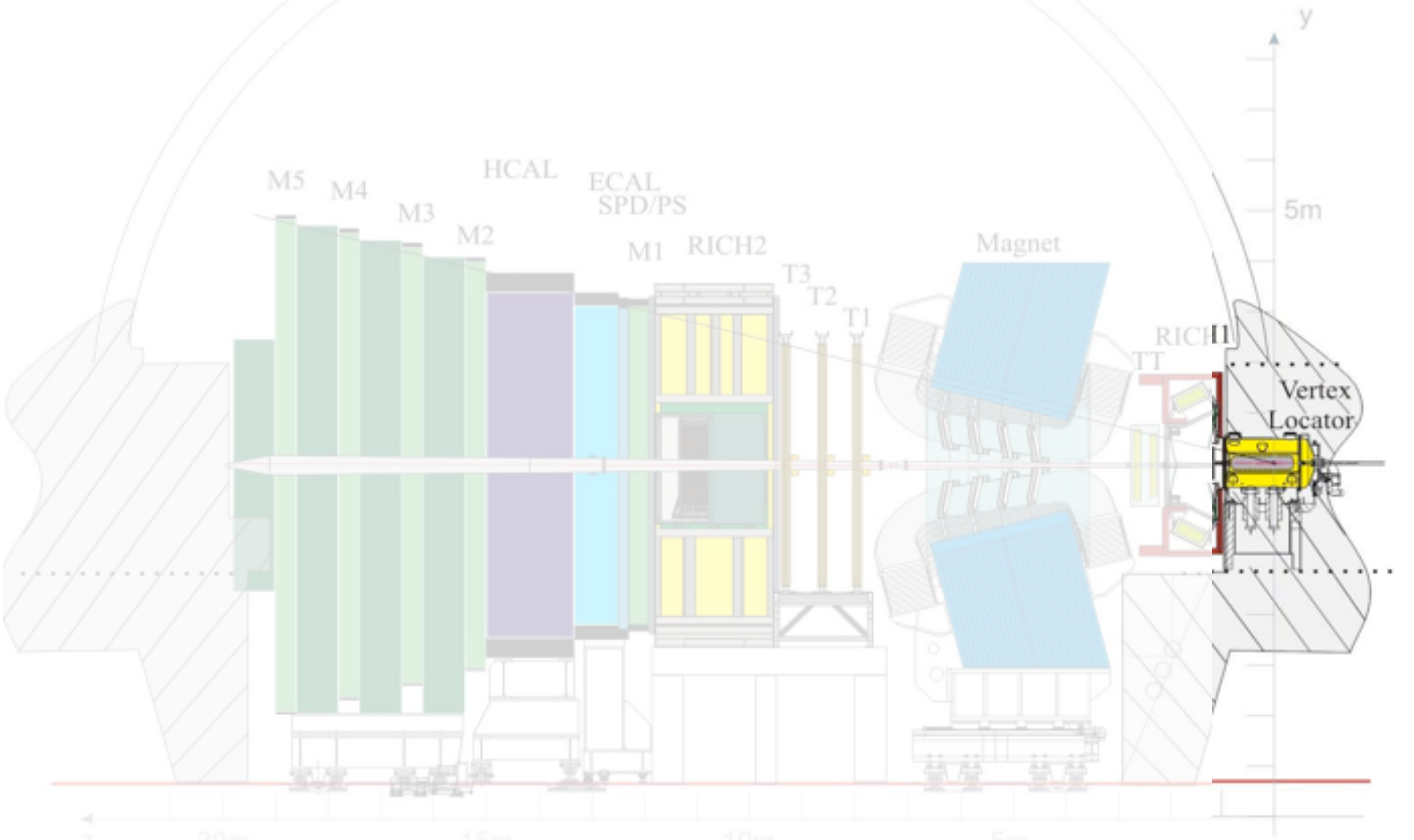
- The B mesons formed by the colliding proton beams (and the particles they decay into) stay close to the line of the beam pipe, and this is reflected in the design of the detector
- Both Bs go together forward (or backward)





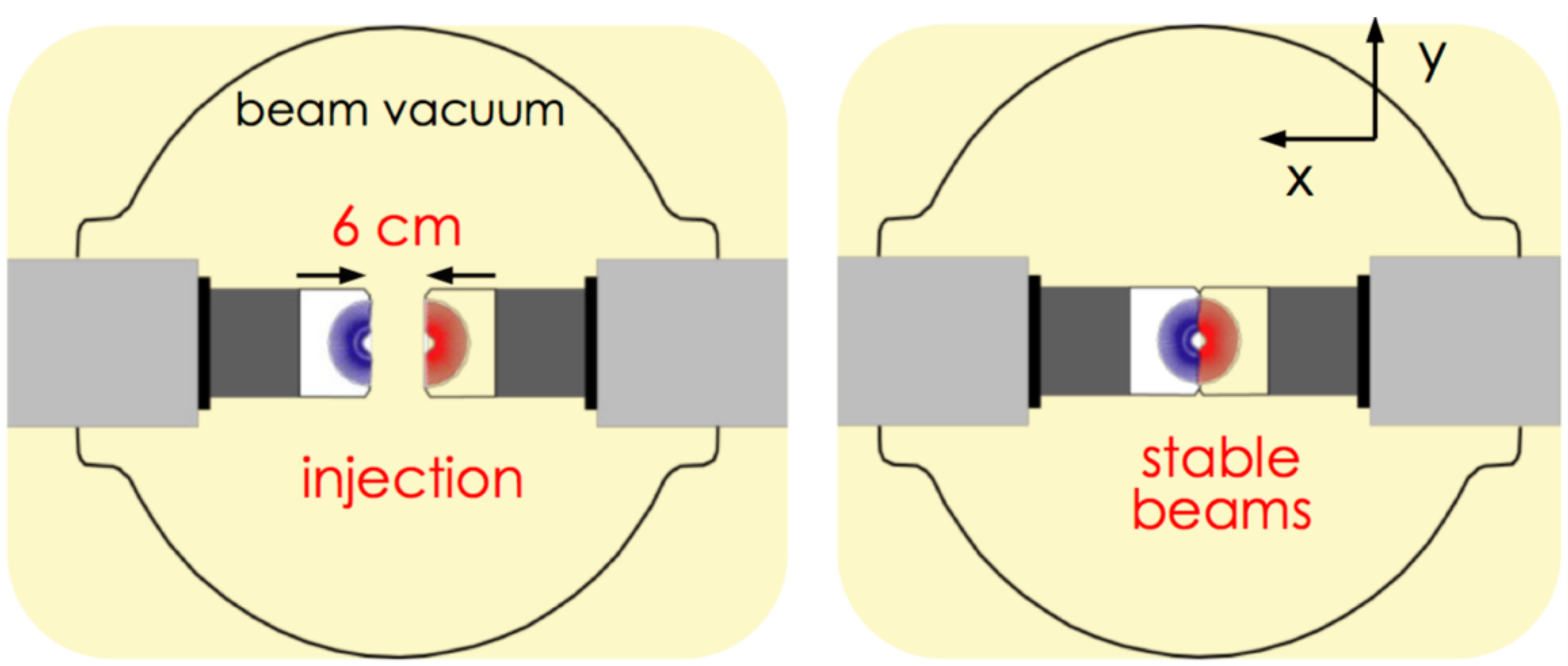


VErtex LOcator (VELO)

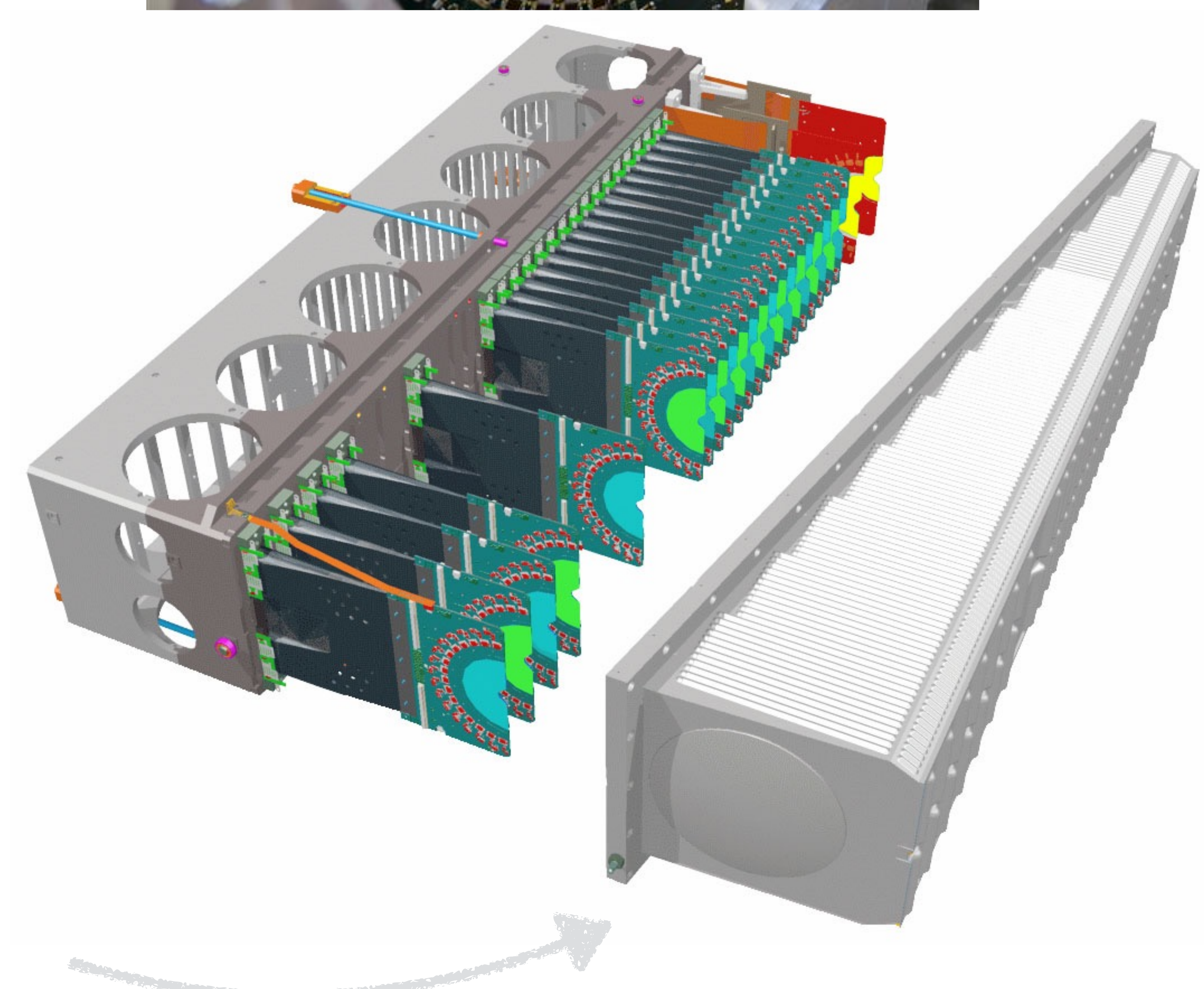


VELO

- A precise particle detector, which surrounds the pp collision point inside LHCb
- It is composed of 21 stations, each made of two silicon half disks with R-ϕ silicon strip sensors
- Retractable for safe operations outside of stable beam conditions

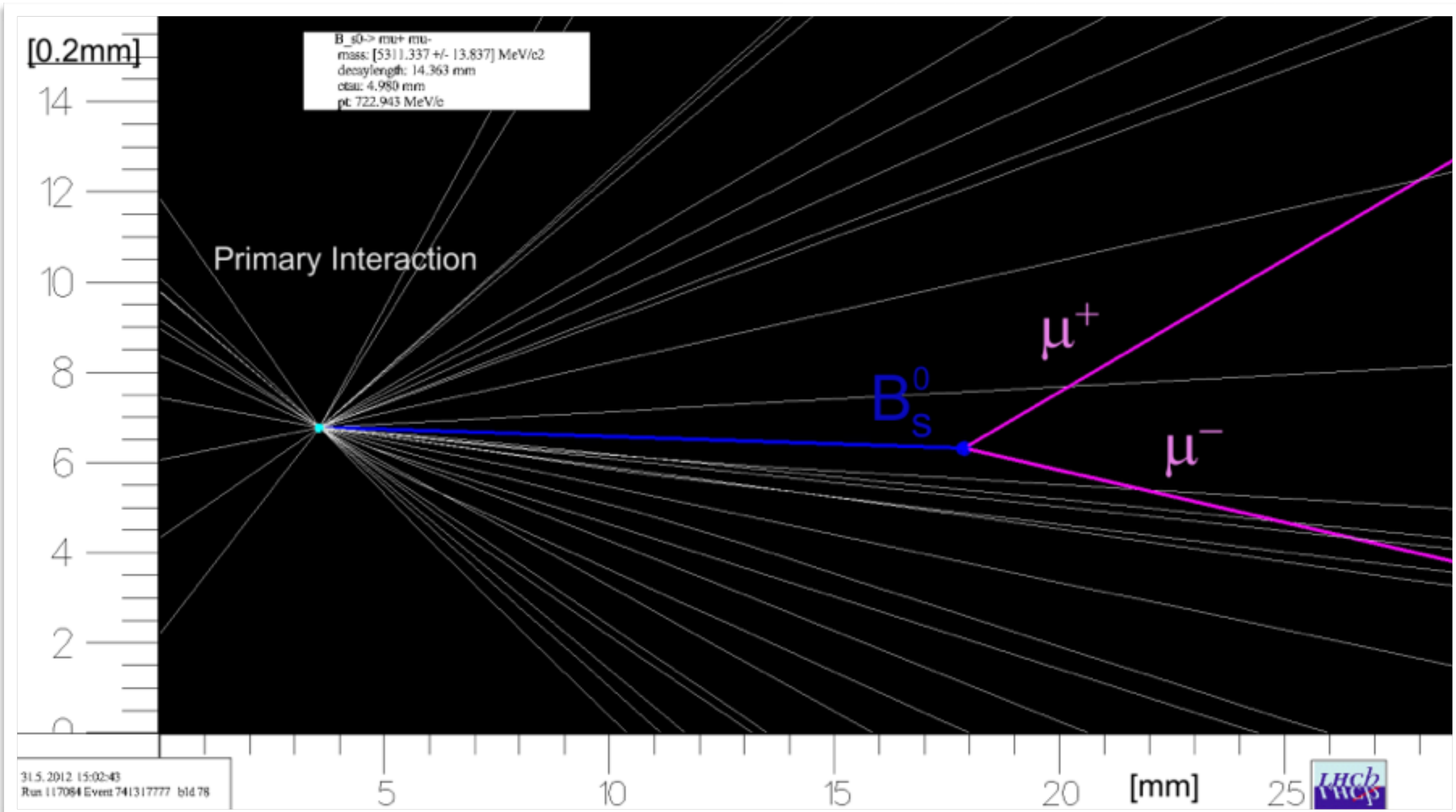


- Active area just 8.2 mm from beams
- Aluminium foil separates VELO detector vacuum from LHC vacuum and shields it from high-frequency fields of the LHC beams

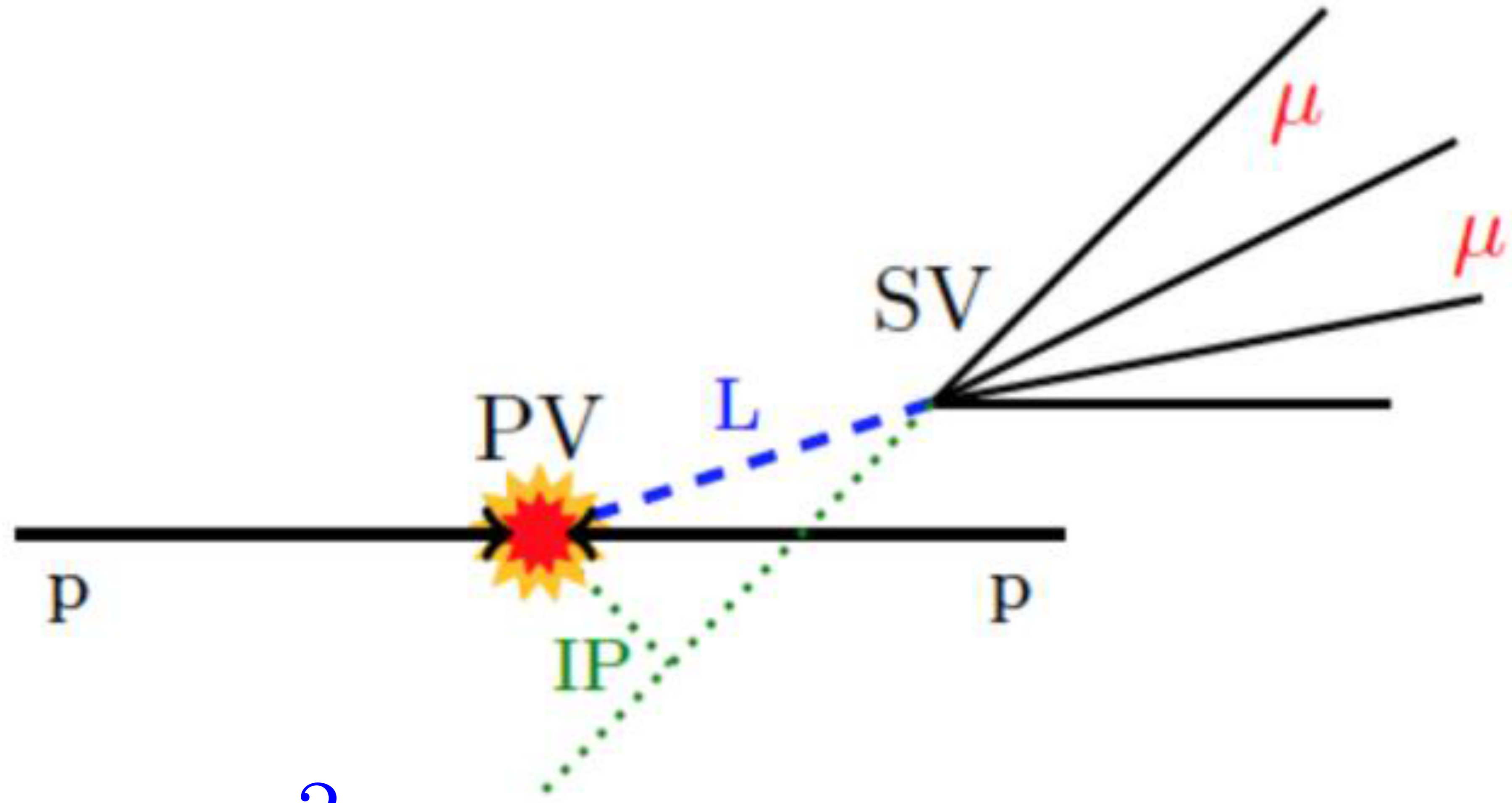


A reconstructed $B_s \to \mu^+\mu^-$ decay vertex

- $d = \beta\gamma c\tau = (p/m)c\tau$
- $\tau_{\text{beauty}} \sim 1.5\ 10^{-12}$ $\tau \sim 1/(m^5|V_{cb}|^2)$
- @LHC: $p \sim 100\,\text{GeV}$, $m \sim 5\,\text{GeV} \rightarrow d = 20 \cdot 3\ 10^{10} \cdot 15\ 10^{-12} \sim 1\,\text{cm}$



VELO performance: Impact Parameter

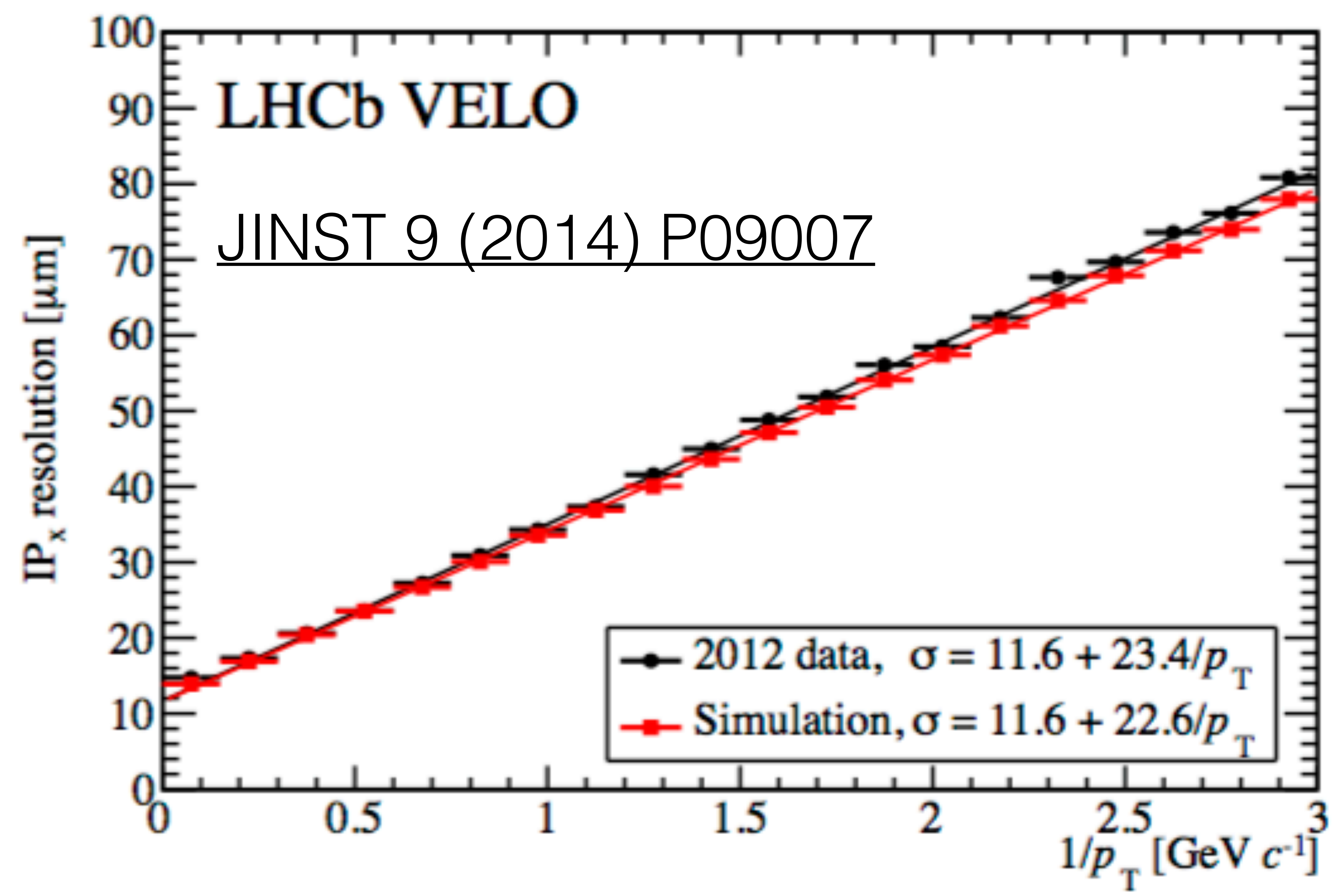


$$\sigma_{IP}^2 = \frac{{r_1}^2}{{p_T}^2} \; \sigma_{MS}^2(x/X_0) \; + \; \sigma_{extrap}^2(\sigma_1^2, \sigma_2^2)$$

- r_1 is radius of first measured point
- x/X_0 is fractional radiation length before second measured point
- σ_1 and σ_2 are measurement errors of first and second point

- IP resolution optimised by positioning sensors as close as possible to LHC beams, minimising material before first VELO hits, having small inter-strip pitch (from 40 to 100 μm)

- IP resolution <35 μm for p_T>1GeV/c

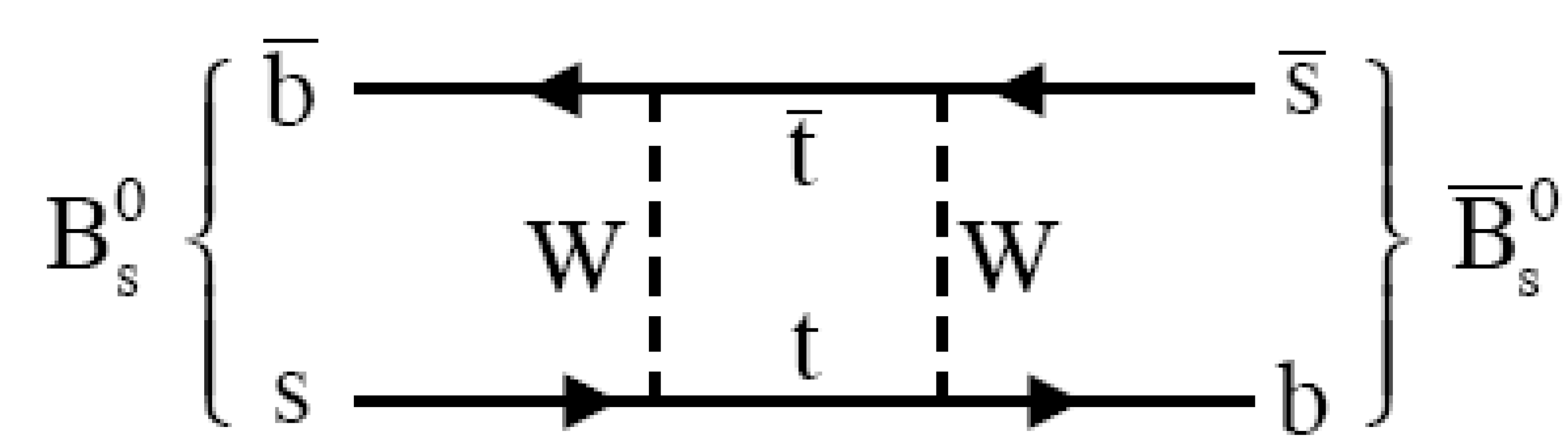


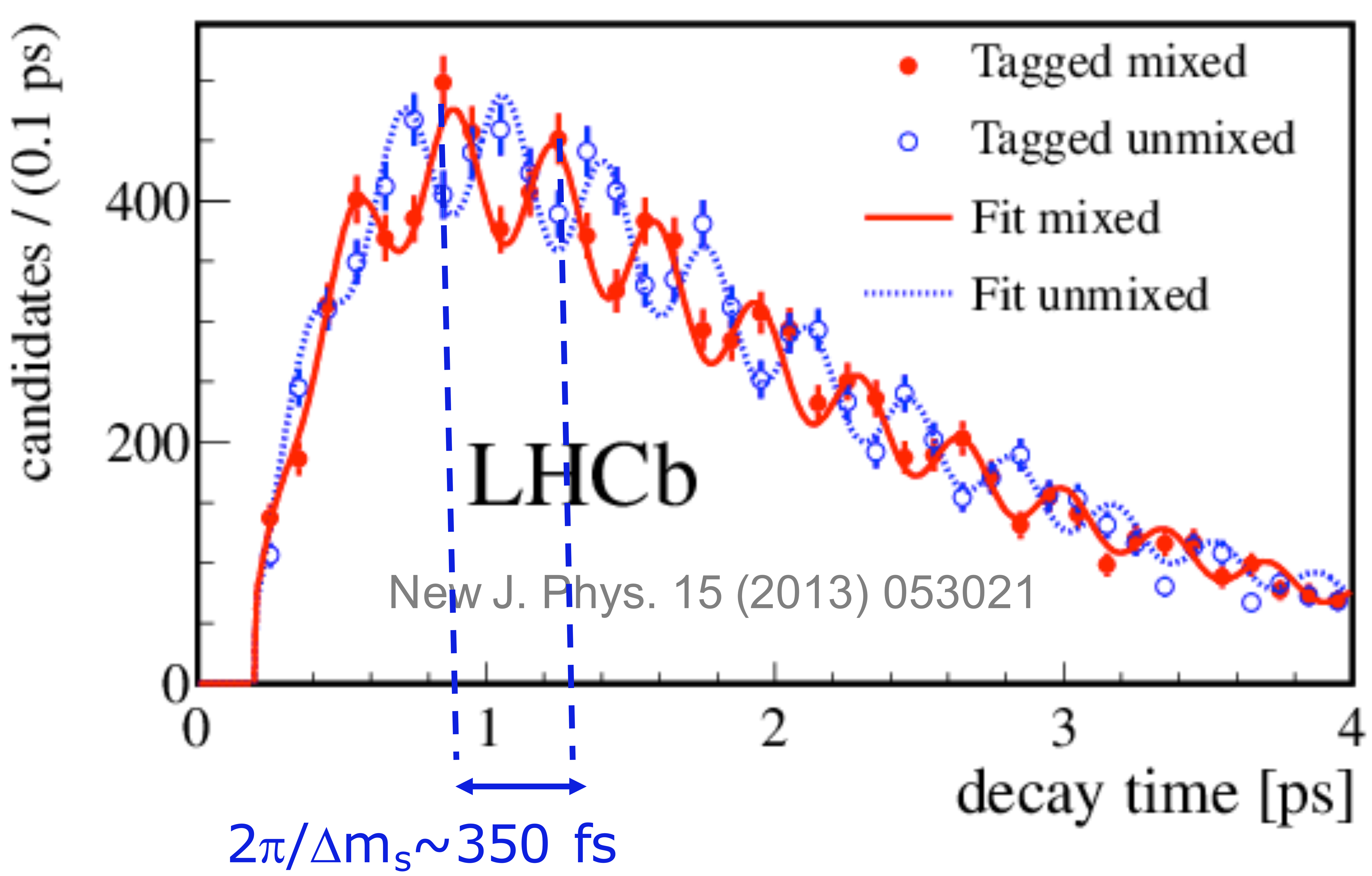
VELO performance: decay time

- Run1 decay time resolution ~50 fs
- Excellent decay time resolution essential to resolve fast $B_s^0 - \bar{B}_s^0$ oscillations : ~50 fs << 350 fs, oscillation period
- Precision measurement of $B_s^0 - \bar{B}_s^0$ oscillation frequency

$$t = ml/p$$

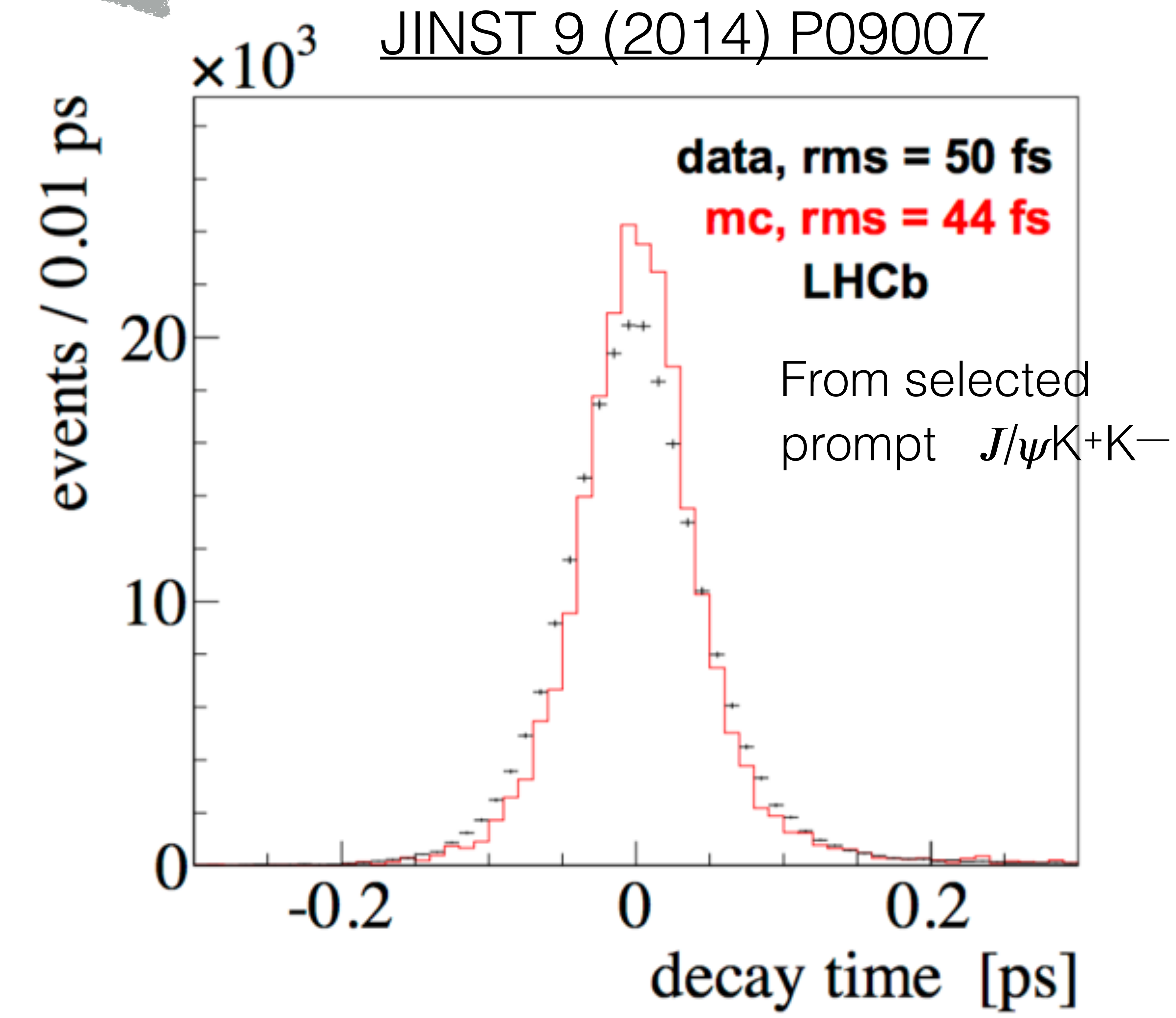
$$\sigma_t = \left(\frac{m}{p}\right)^2 \sigma_l^2 + \left(\frac{t}{p}\right)^2 \sigma_p^2$$





- Different flavour at decay and production
- Same flavour at decay and production

JINST 9 (2014) P09007

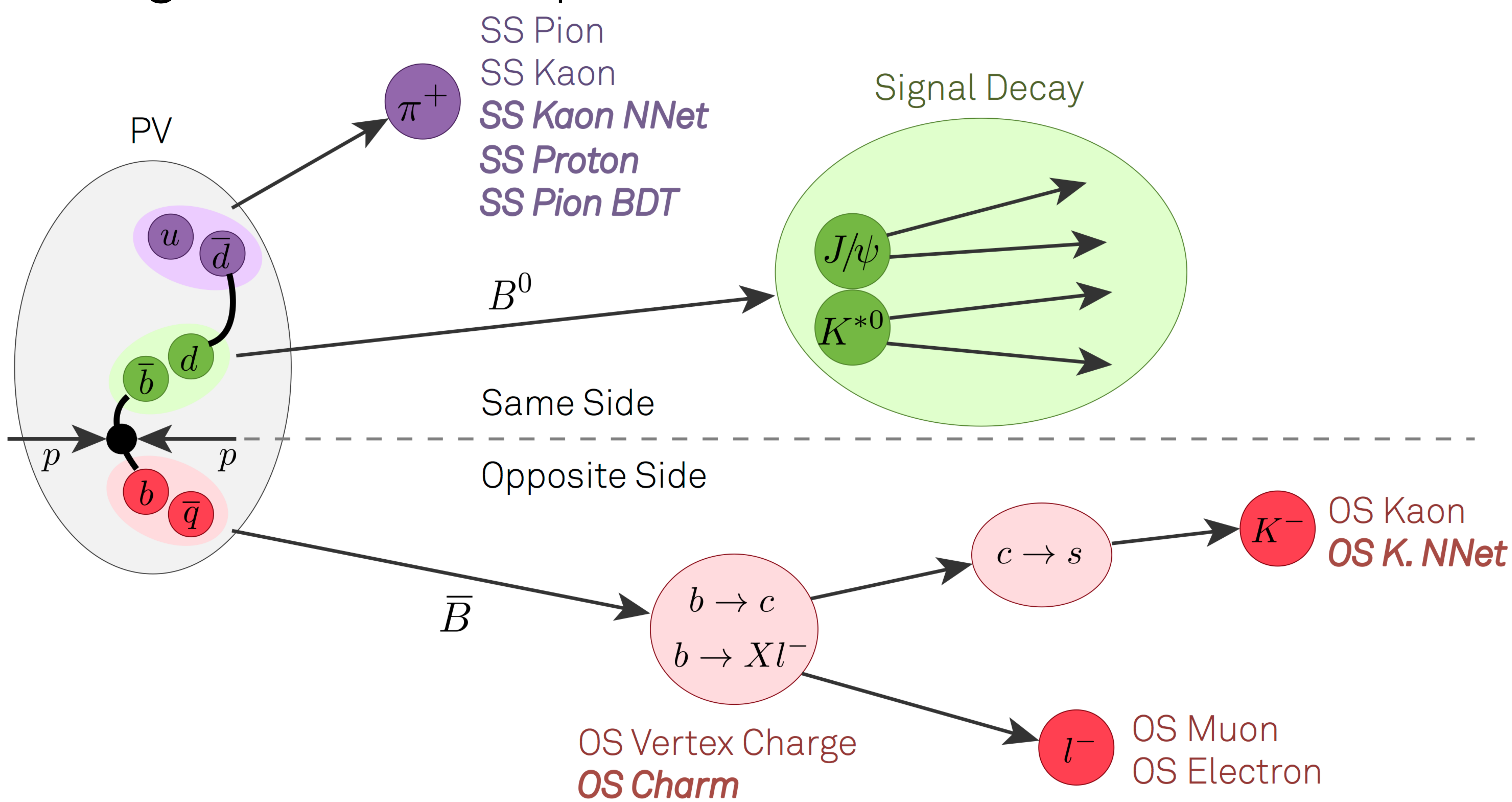


Particle Identification in flavour experiments is very important!

- To reduce the combinatorial background
  - Many of the interesting decay modes of b- and c-hadrons involve hadronic multi-body final states. In reconstructing the invariant mass of the decaying particle, it is important to be able to select the charged hadrons of interest to reduce combinatorics
- To discriminate final states of otherwise identical topologies, e.g. $B \to h^+h^- \ (h = \pi, K)$
- To help in flavour tagging

Flavour tagging

- Key info required for the measurement of CP violation is the knowledge of flavour at production



- Opposite side K (in addition to μ, e) and same side taggers (particle generated from the remnants of the signal *b* fragmentation (π, K, p)

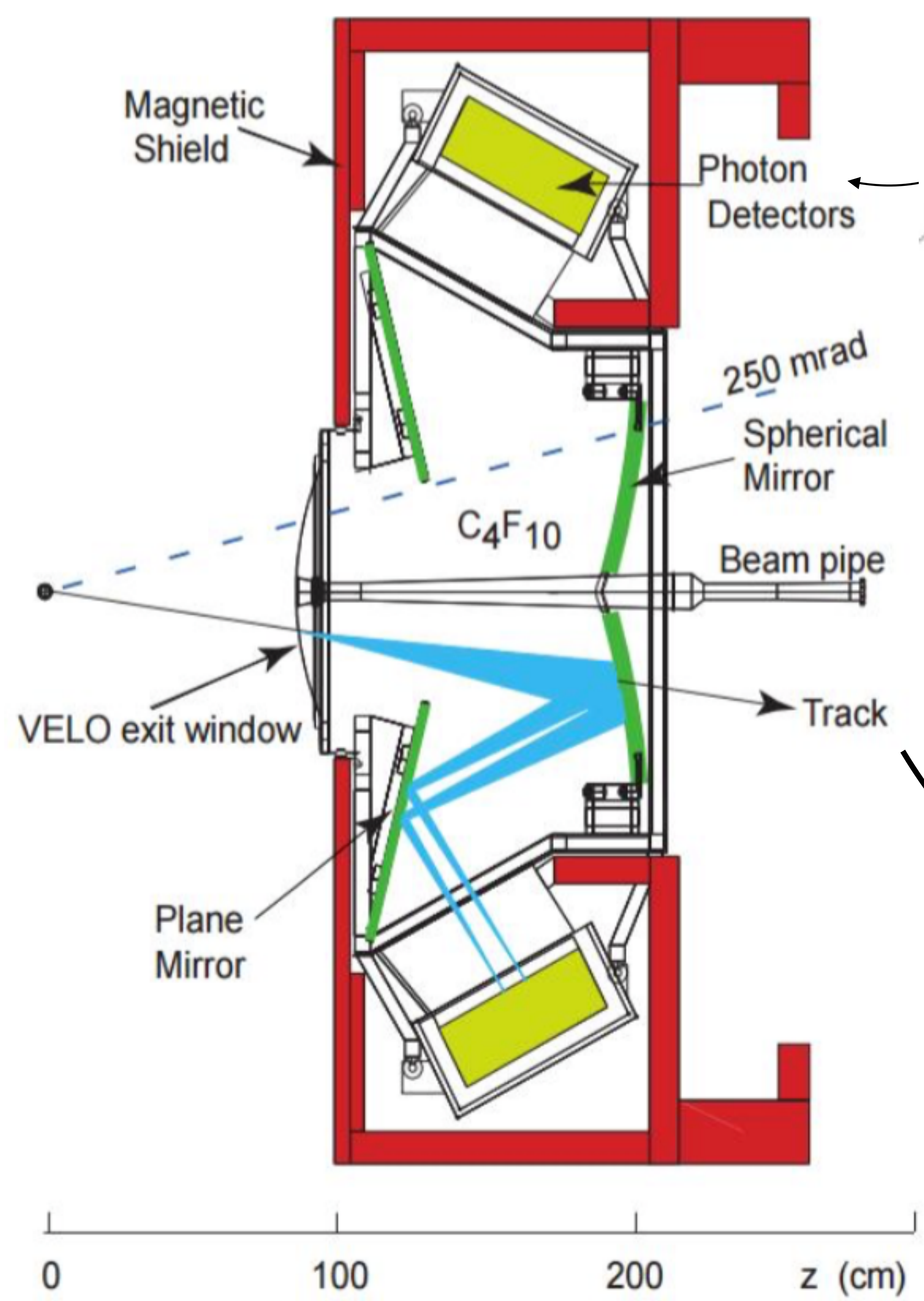
Ring-Imaging Cherenkov Detectors (RICH)

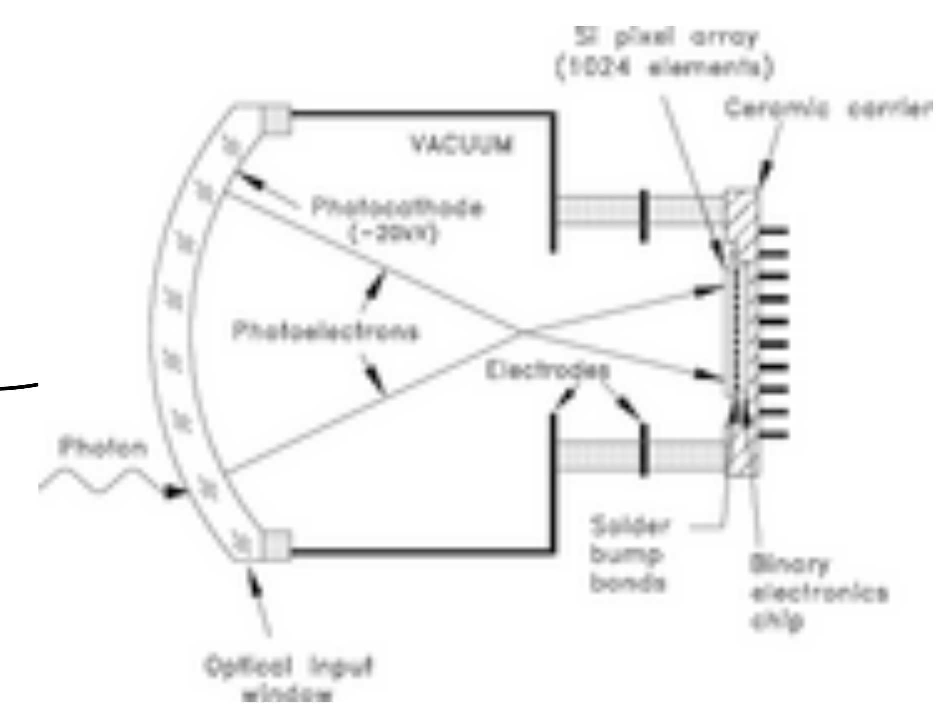
- Identification of charged hadrons (π, K, p) over a wide momentum range, from a few GeV up to100 GeV
  - 2 separate detectors and 2 separate radiators (C_4F_{10}, CF_4) to cover full acceptance range and particle momenta

RICH Detectors

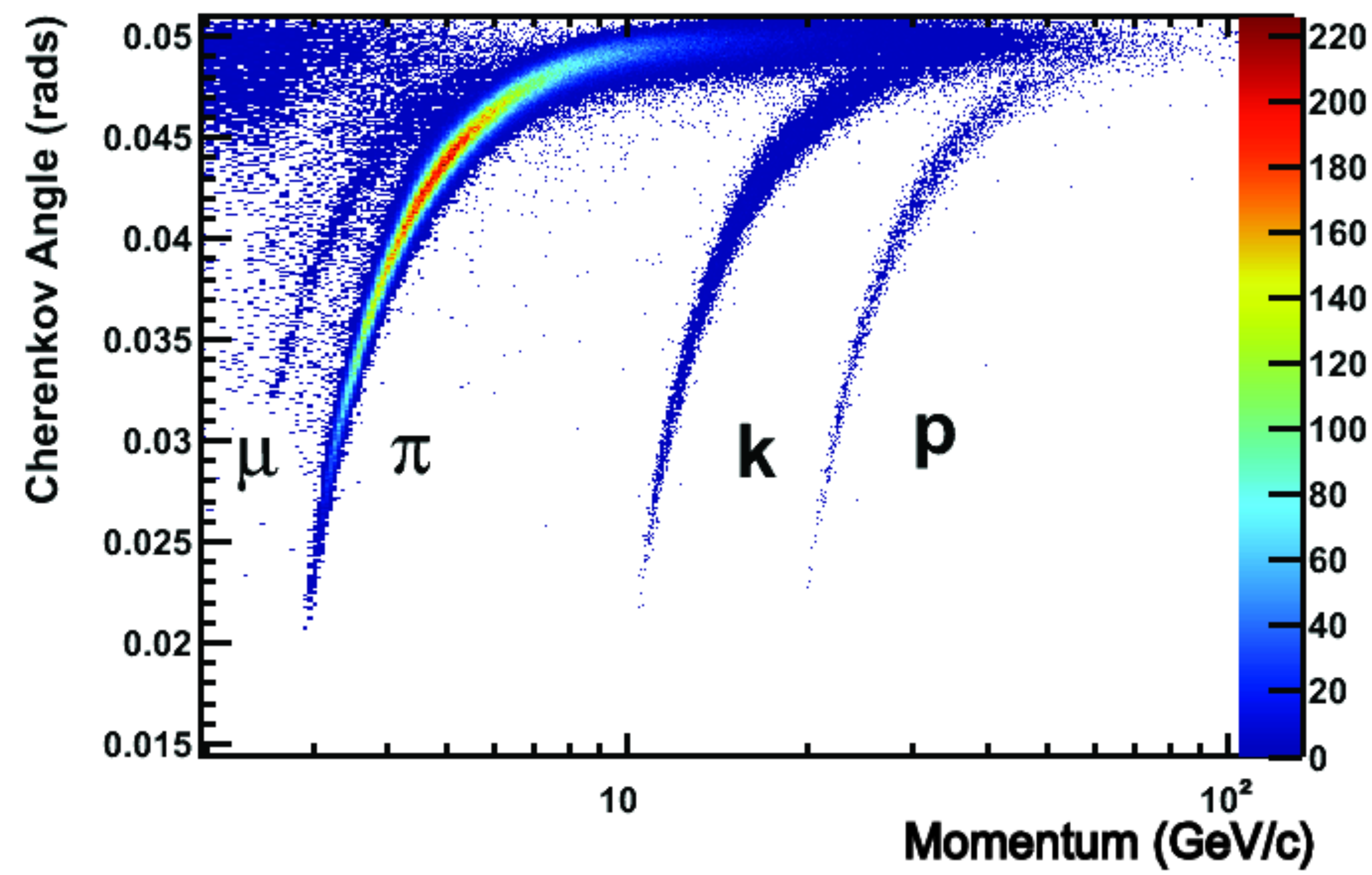
- Charged hadrons pass through a medium and when v>c/n, with n refractive index, emit a cone of Cherenkov photons ($\cos \theta_C = 1/\beta n$). These photons are focused by spherical mirrors and are then reflected by flat mirrors onto the photodetector planes positioned out of the LHCb acceptance.

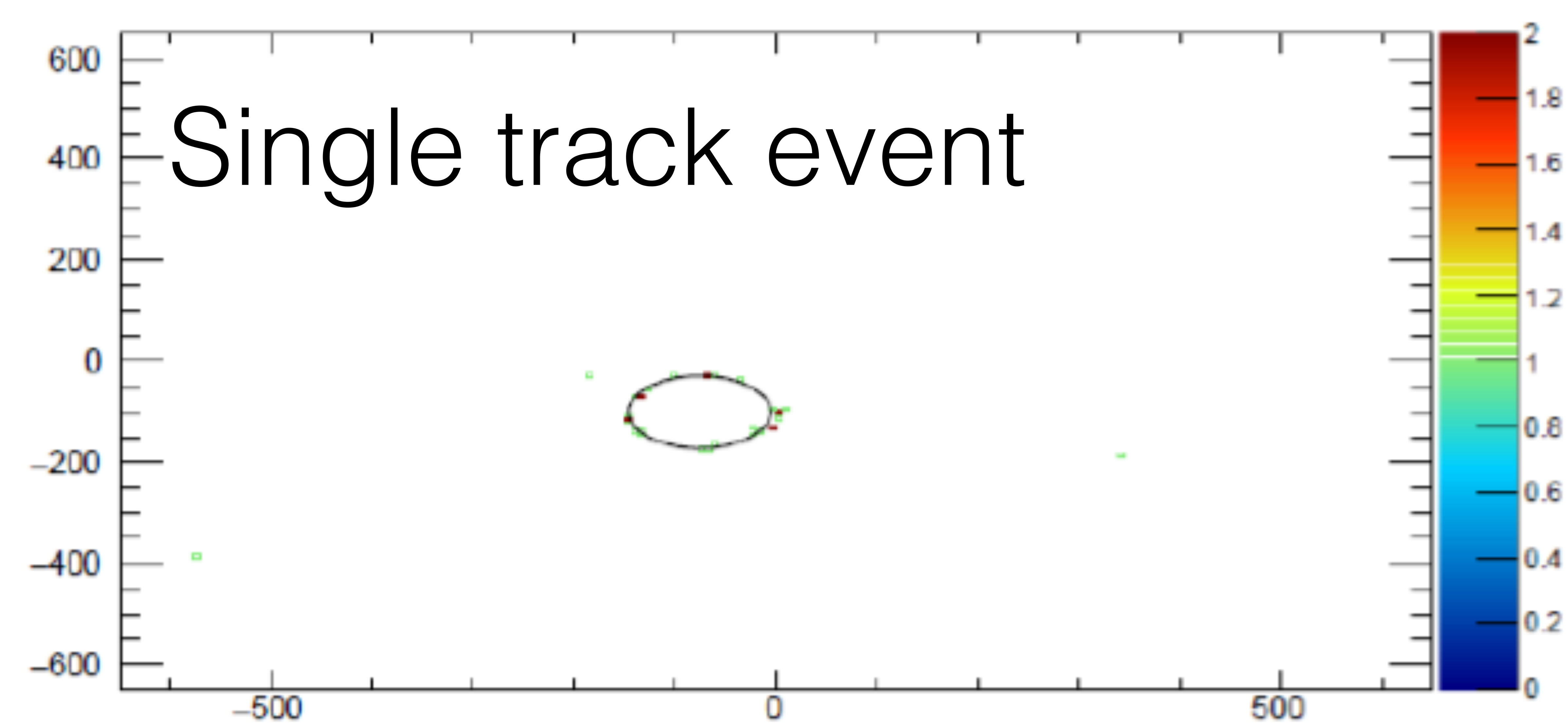
RICH1





484 Hybrid photon detectors (HPDs) covering 3.3 m²

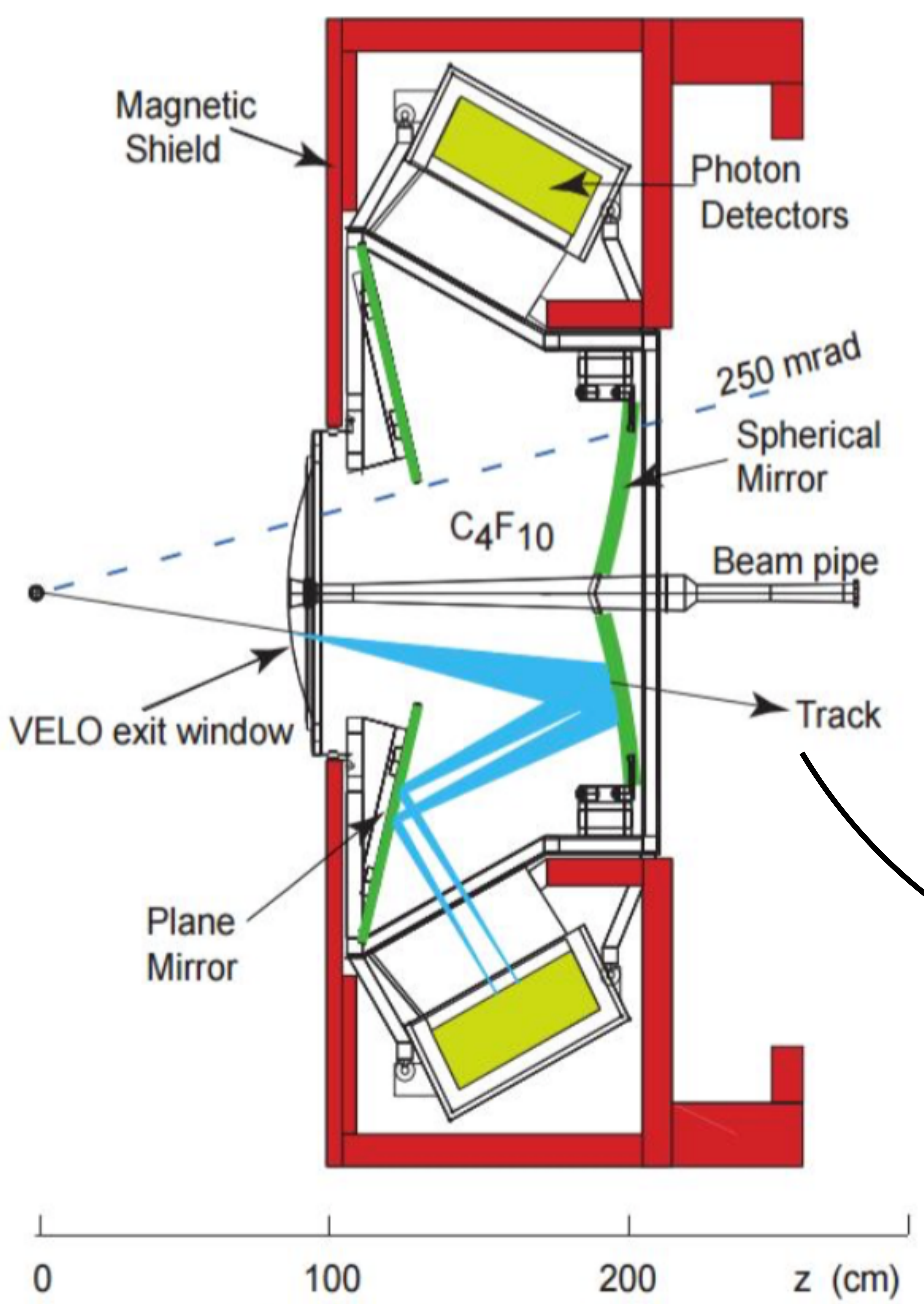


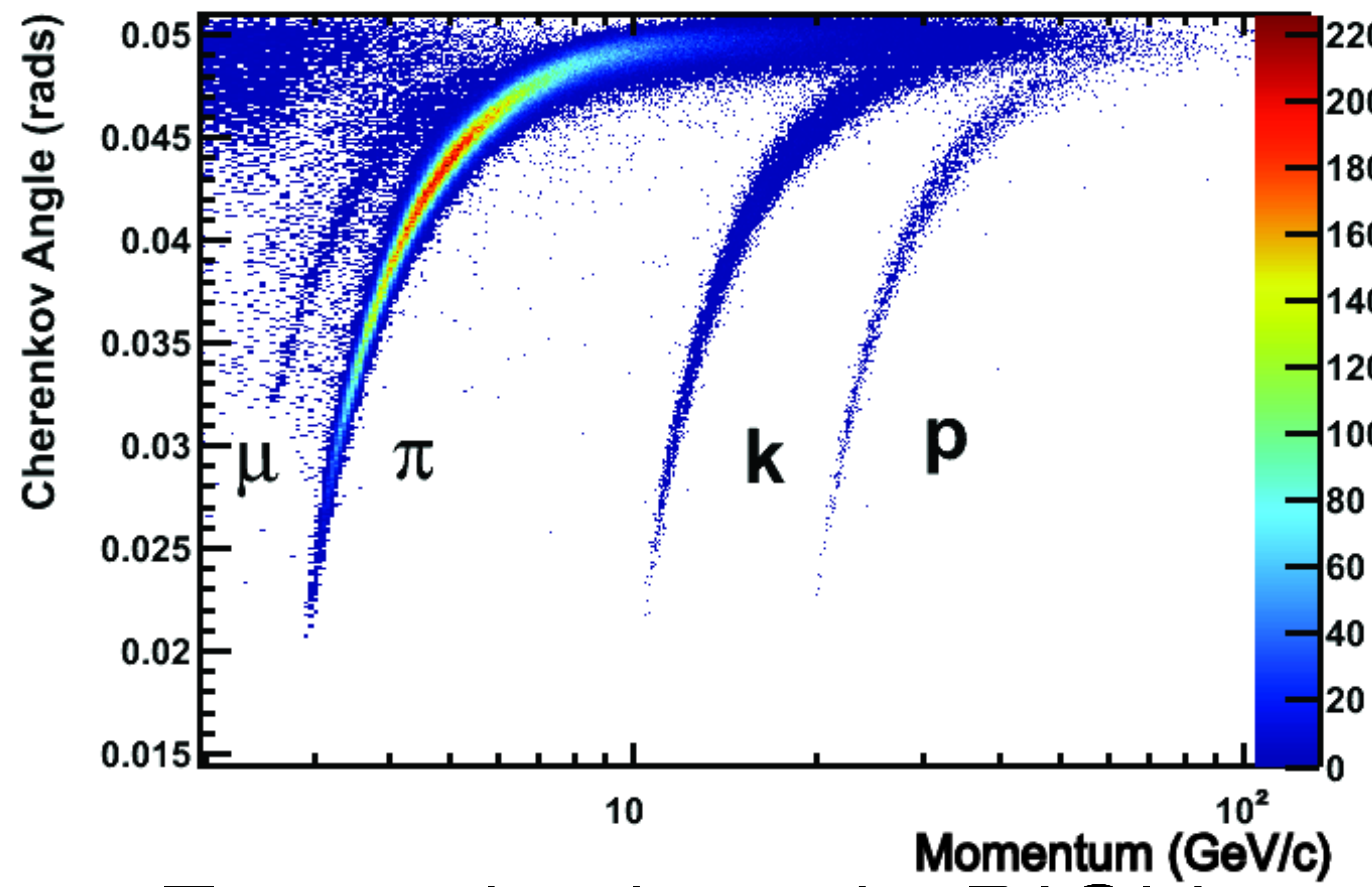


RICH Detectors

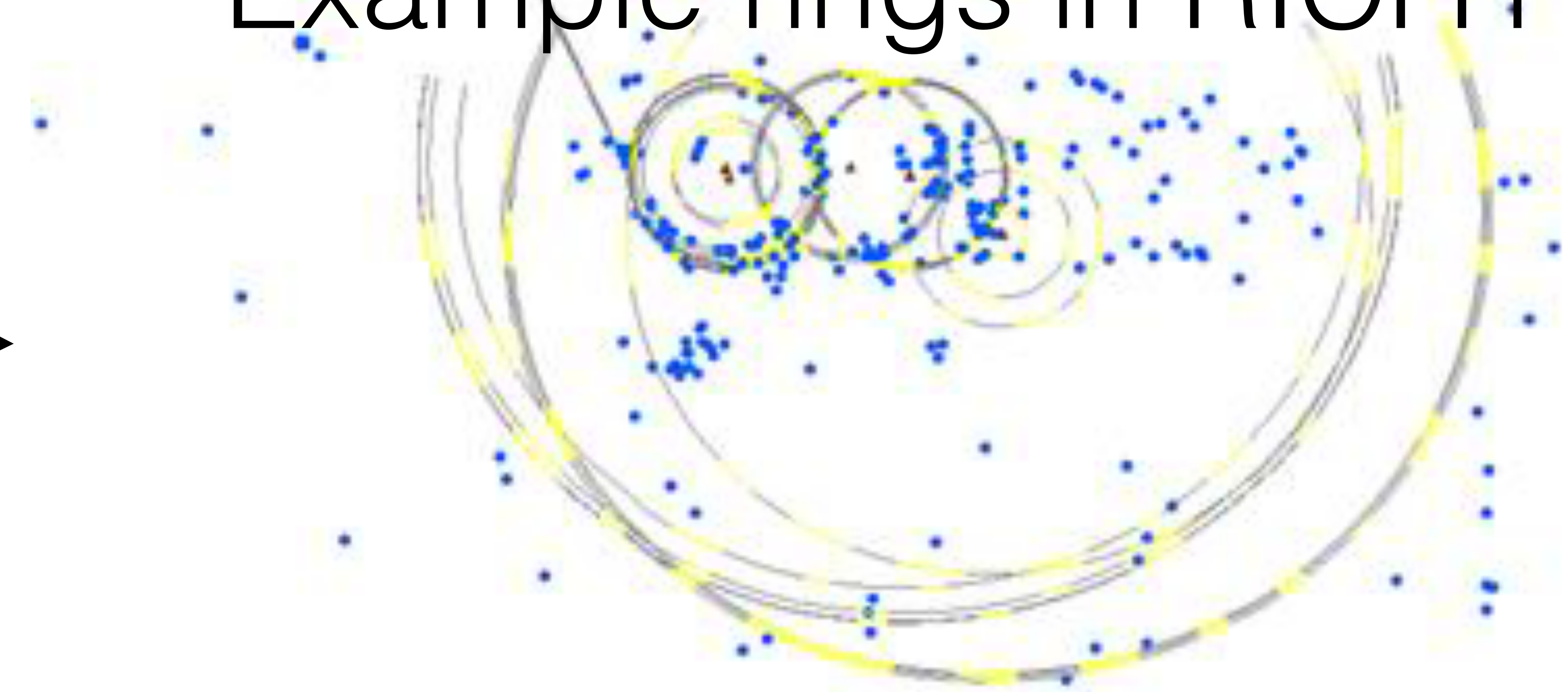
- Charged hadrons pass through a medium and when v>c/n, with n refractive index, emit a cone of Cherenkov photons ($\cos\theta_C = 1/\beta n$). These photons are focused by spherical mirrors and are then reflected by flat mirrors onto the photodetector planes positioned out of the LHCb acceptance.

RICH1



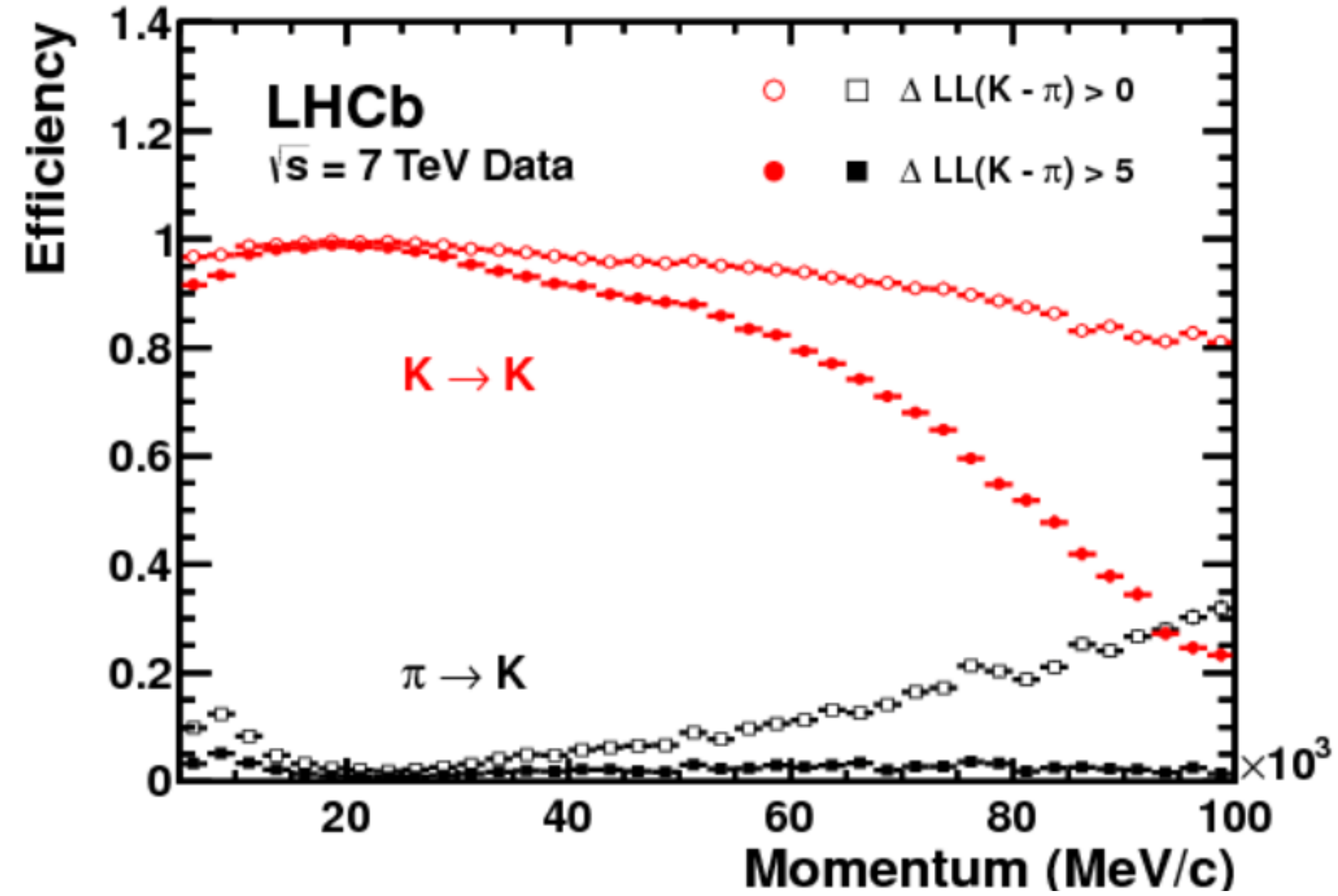


Example rings in RICH1

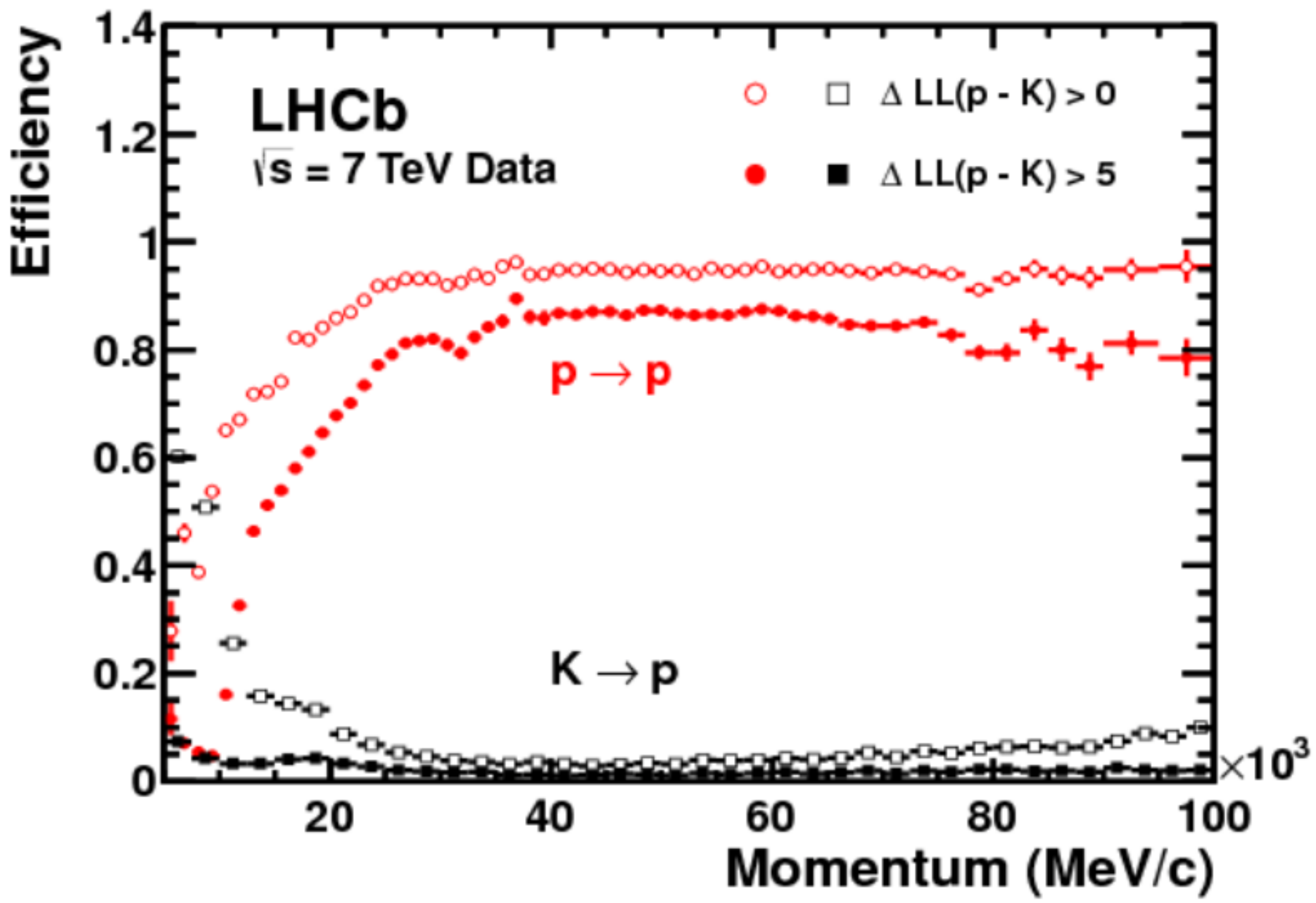


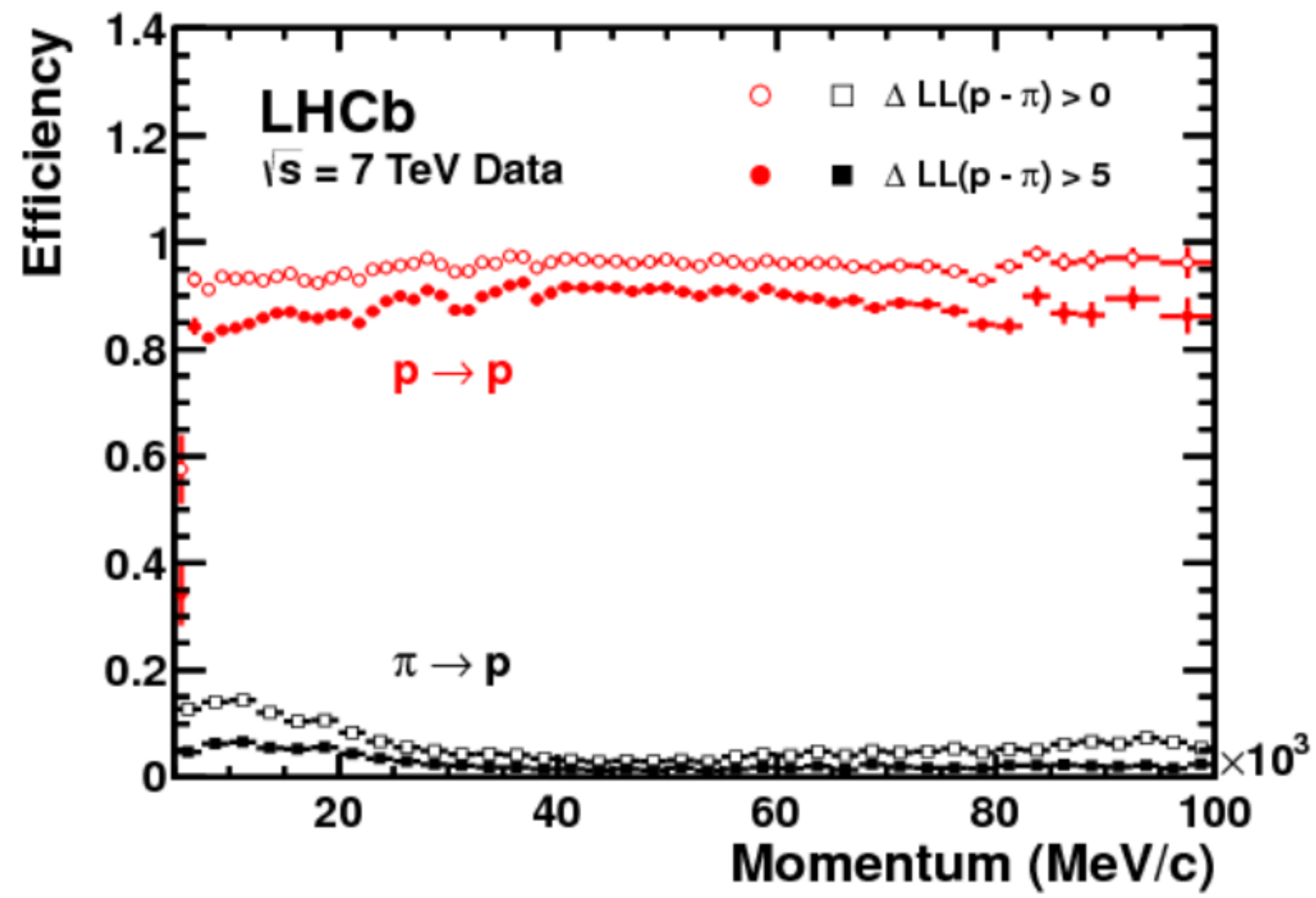
RICH performance

- K and p identification efficiency and pion (kaon) misidentification rate measured on data using control samples (Λ,K^0_S,D^0 decays)



Eur.Phys.J.C 73 (2013) 2431

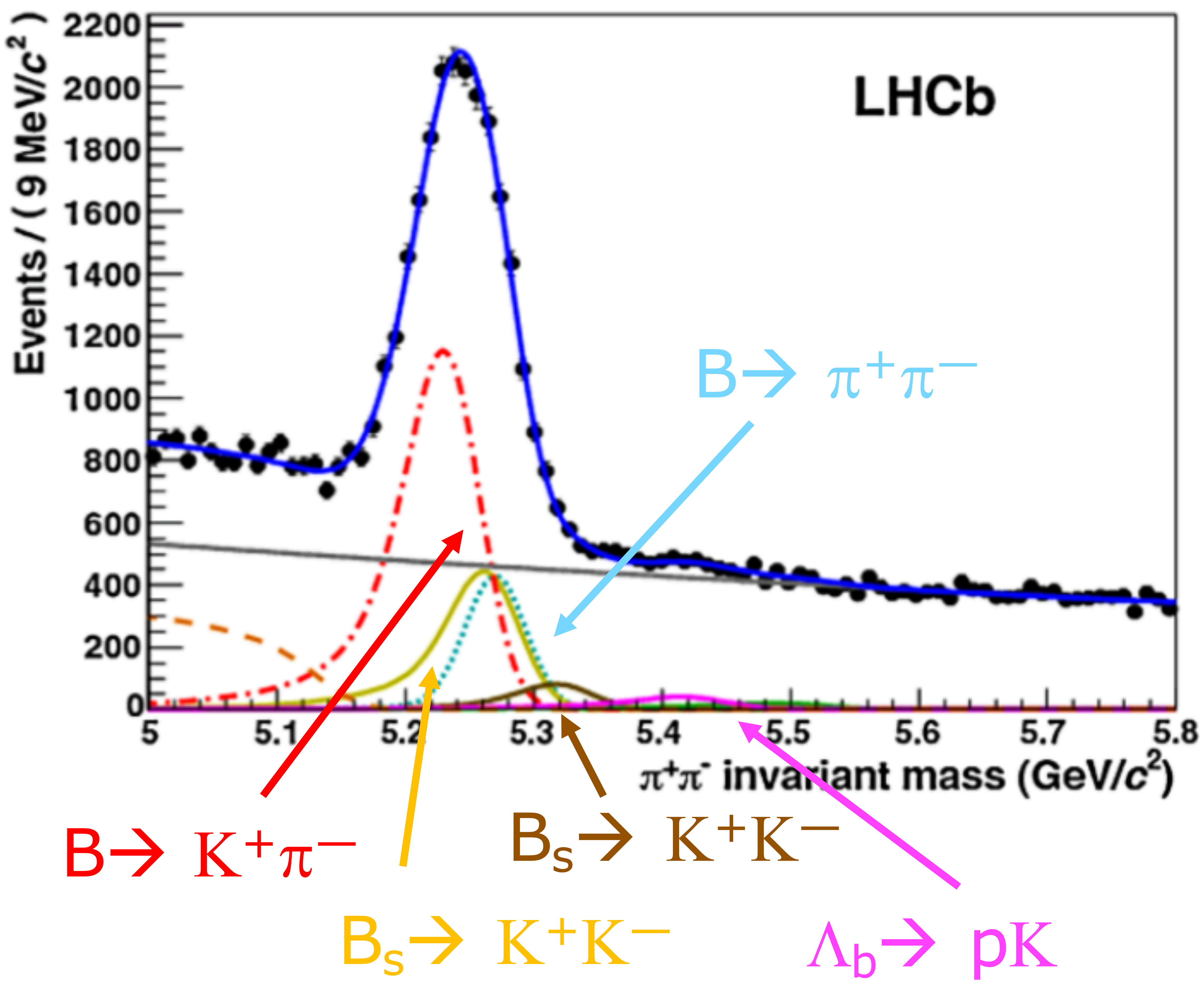




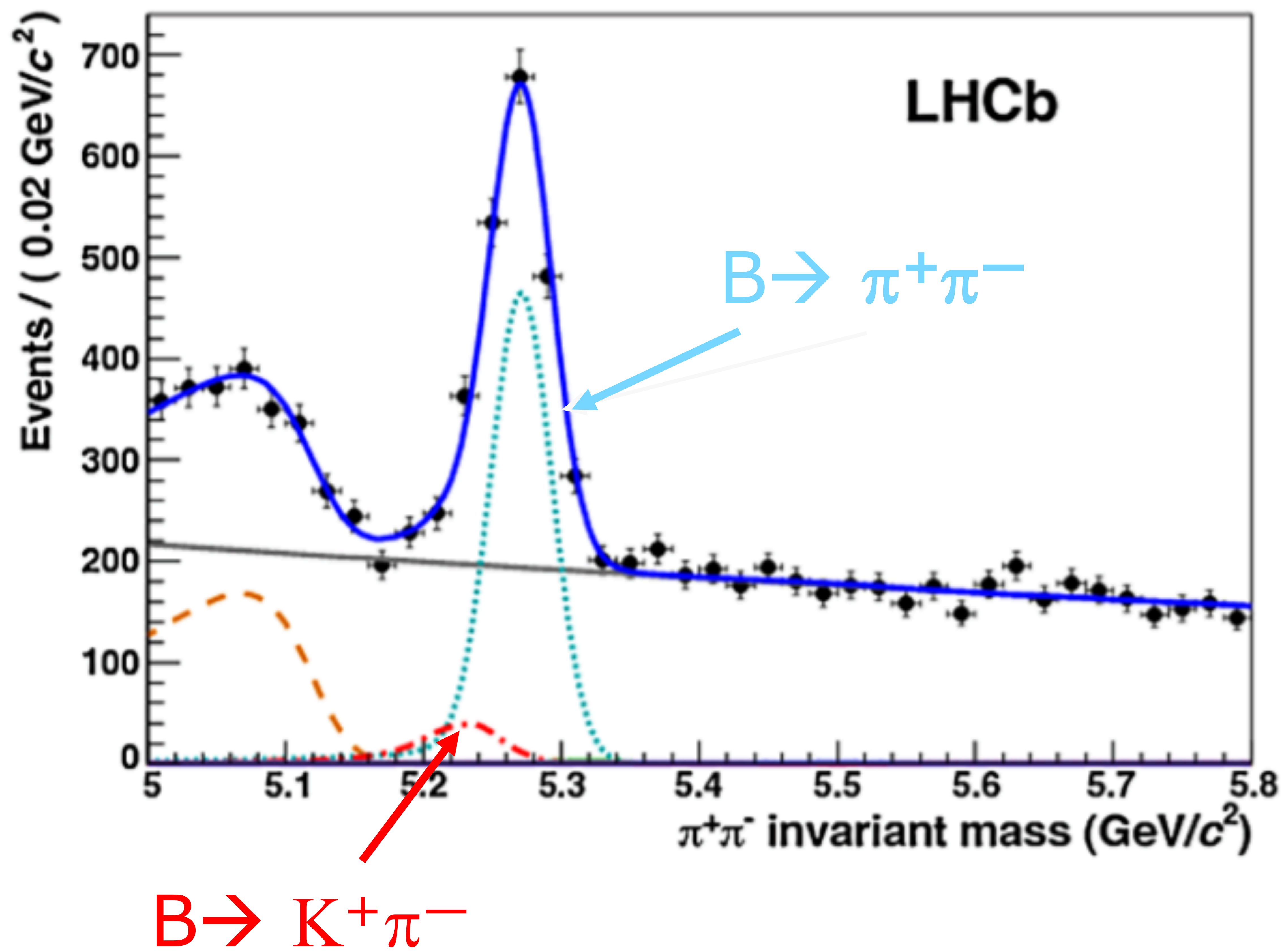
RICH performance (II)

- Invariant mass distribution for $B \to h^+h^- \, (h = \pi, K)$ before and after use of the RICH information
- Signal under study is $B \to h^+h^-$

before



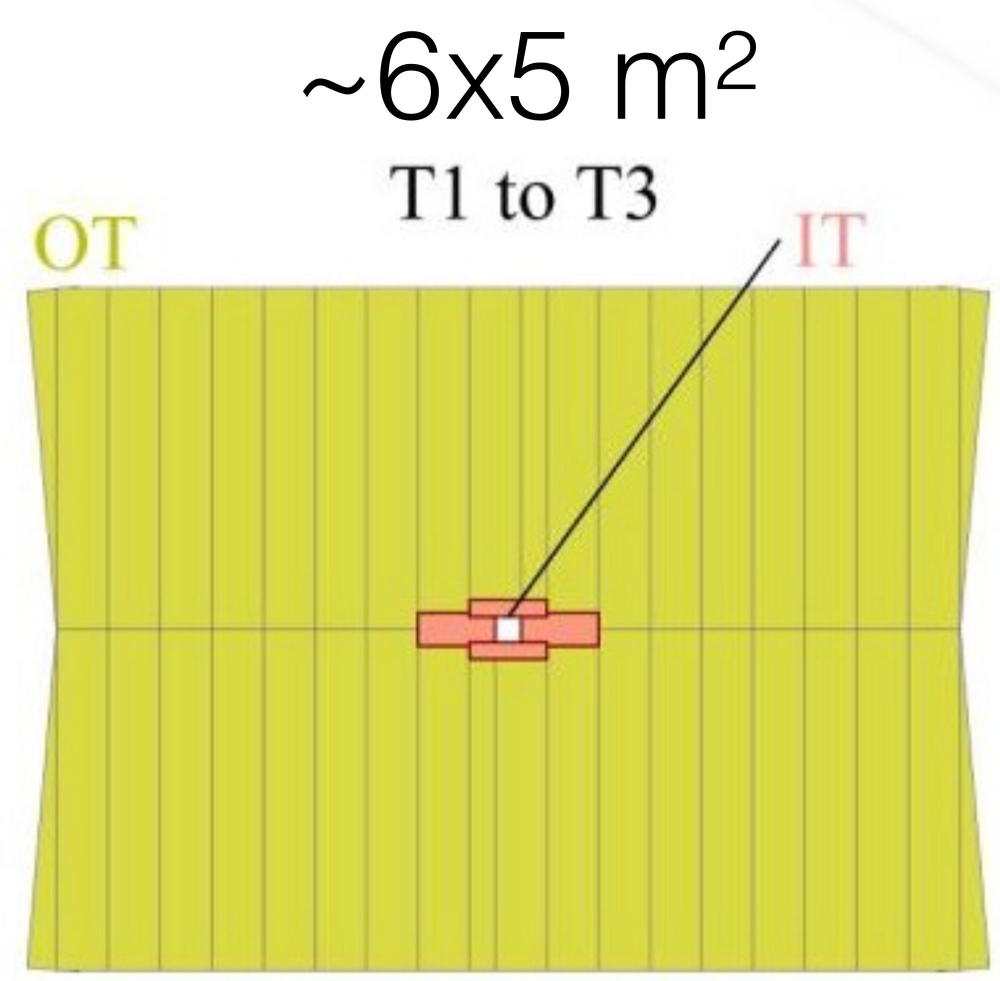
after

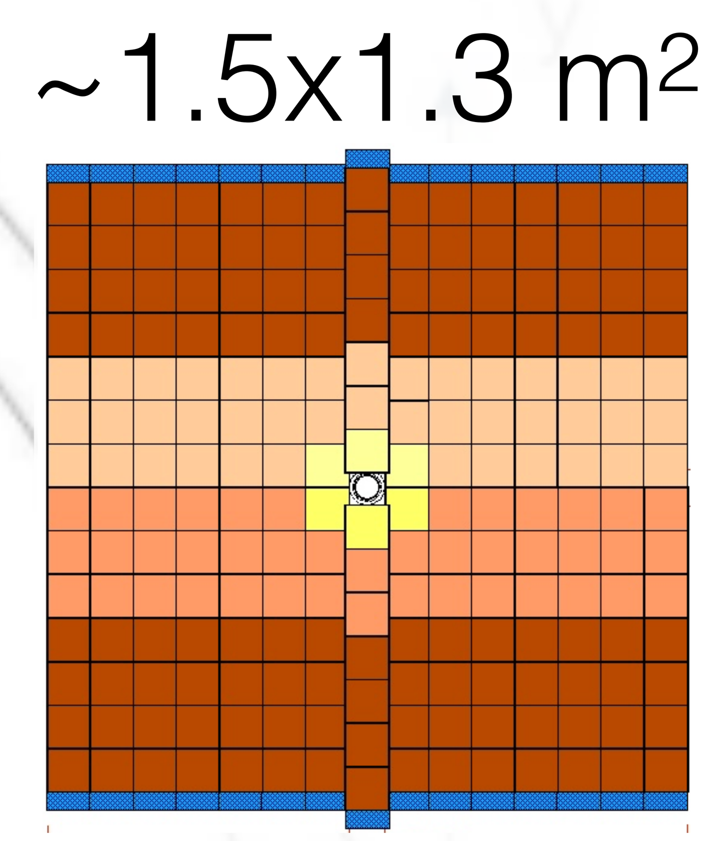


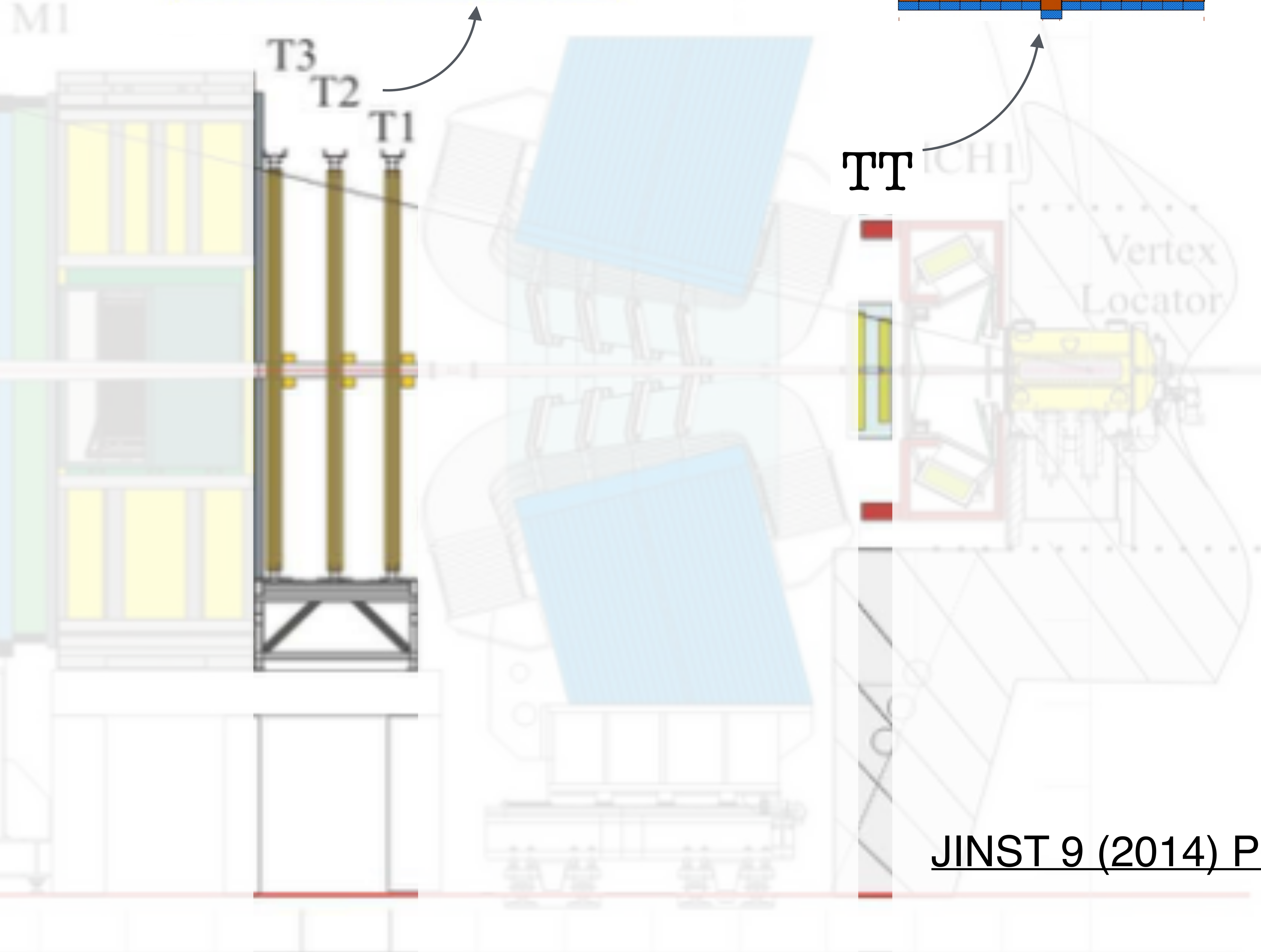
Eur.Phys.J.C 73 (2013) 2431

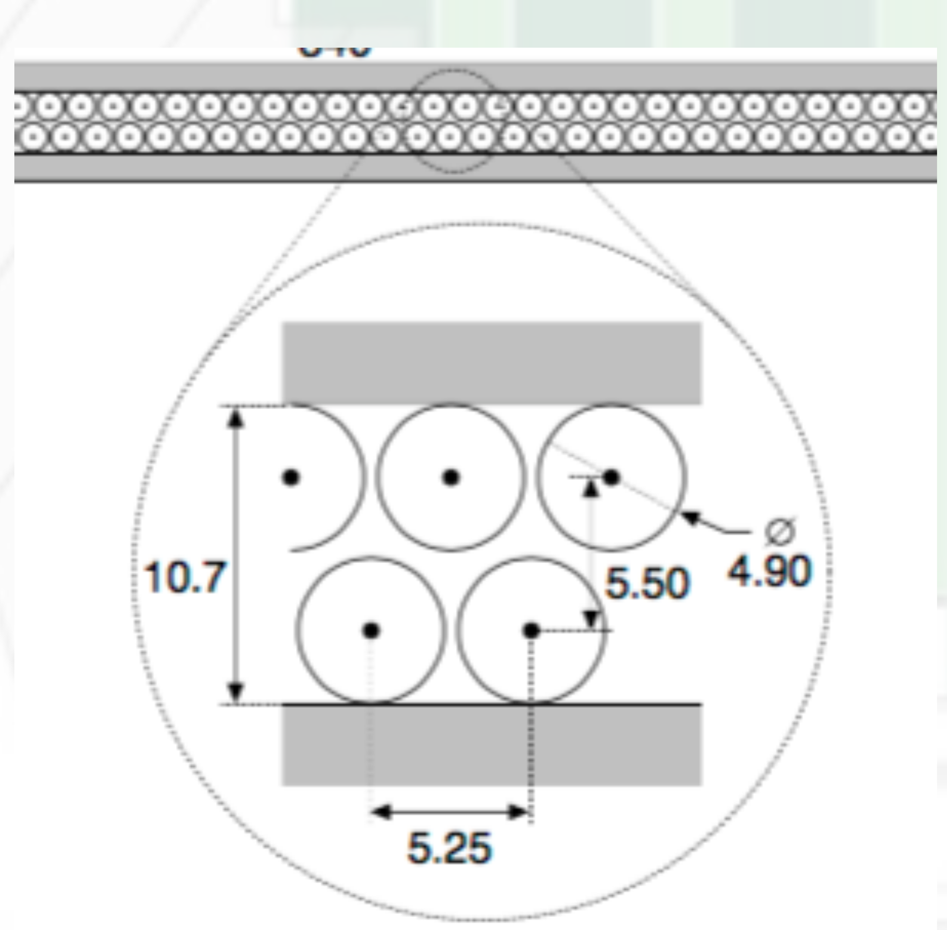
Tracking detectors (TT,IT,OT)

- TT station before the magnet: 4 planes of silicon strip detectors (vertical, -5^0,+5^0, vertical), ~8m^2 of silicon, already sensitive to magnetic field, which bends tracks horizontally
- T1,T2,T3 stations after the magnet, each with 4 planes (vertical, -5^0,+5^0, vertical), silicon strip detectors in the inner region (IT, 4.2 m^2) as for TT, straw tubes if the outer region (OT) → 24 straw layers in z



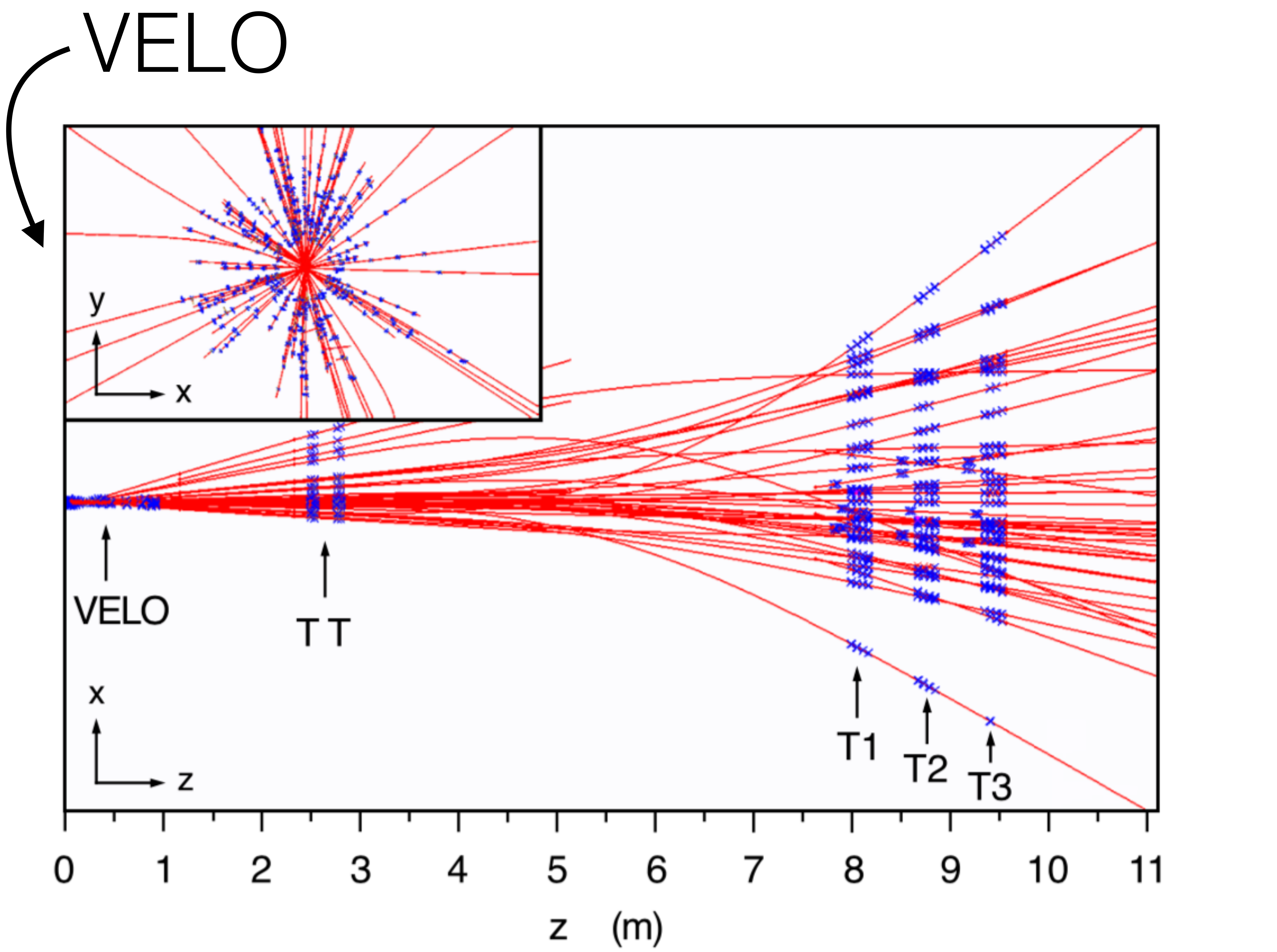


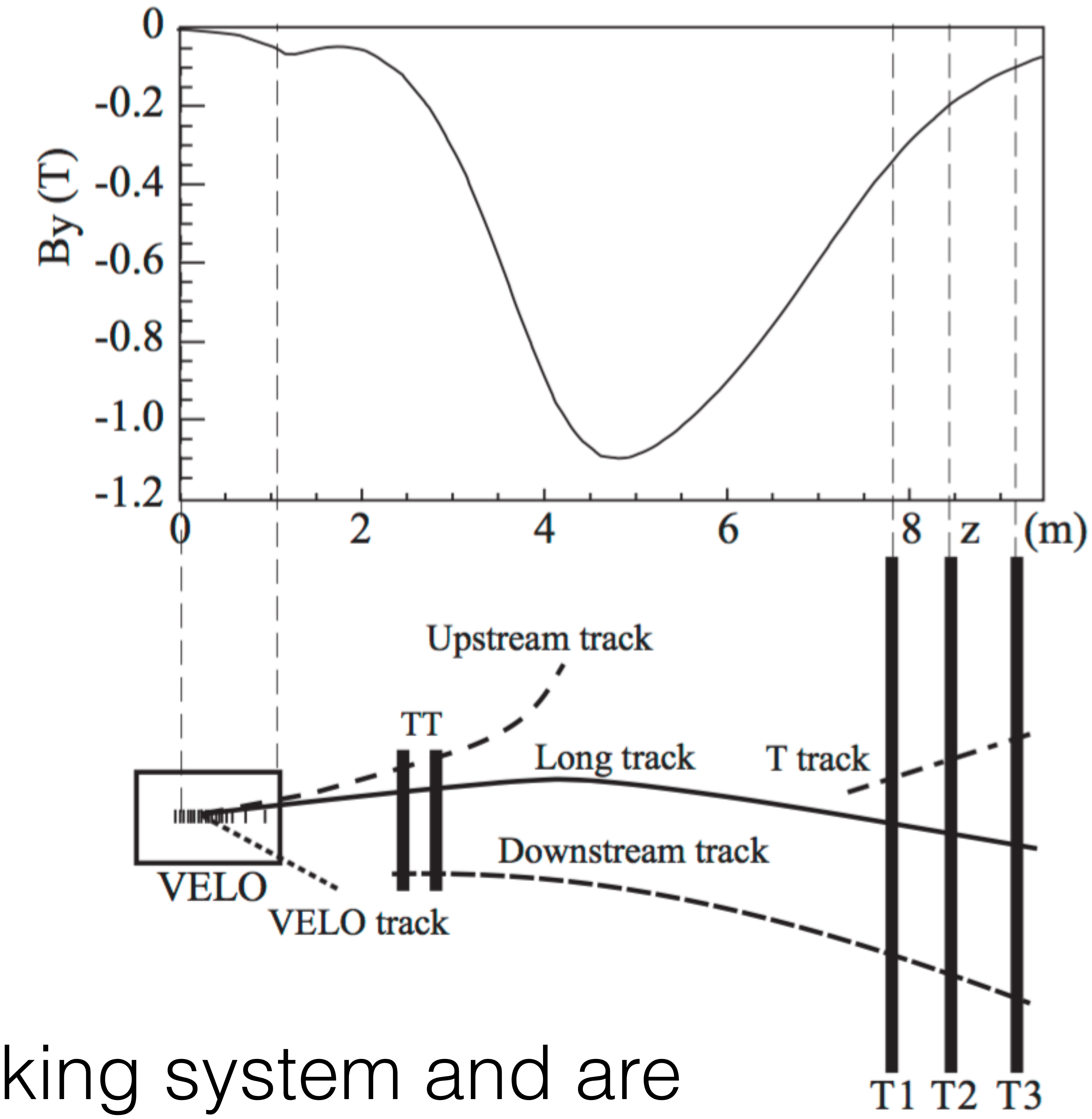




JINST 9 (2014) P01002

Tracking in LHCb





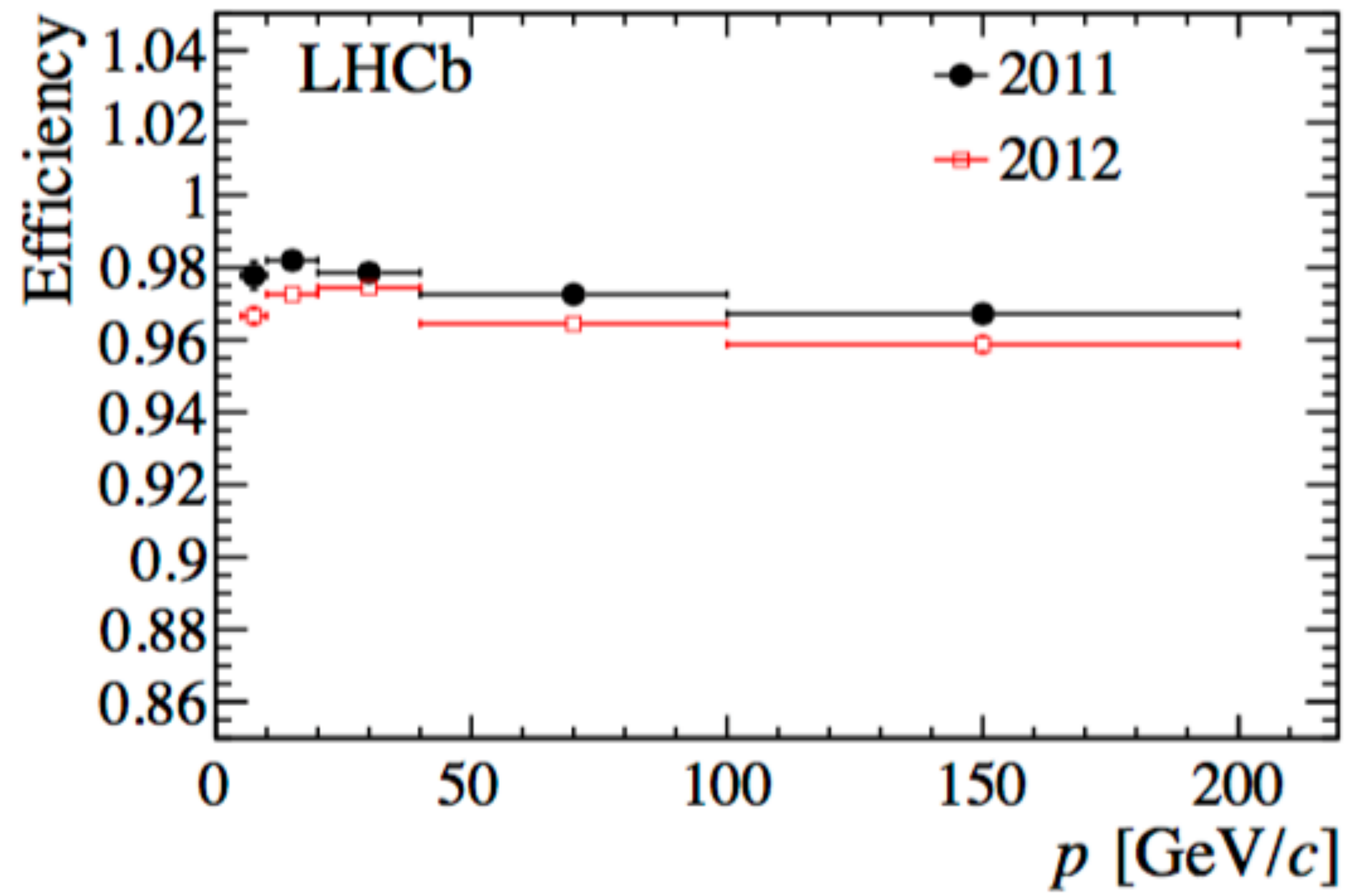
- Long tracks traverse the full tracking system and are the most important tracks for physics analysis
- Downstream tracks are important for the reconstruction of long-lived particles (e.g. K^0_S and Λ)

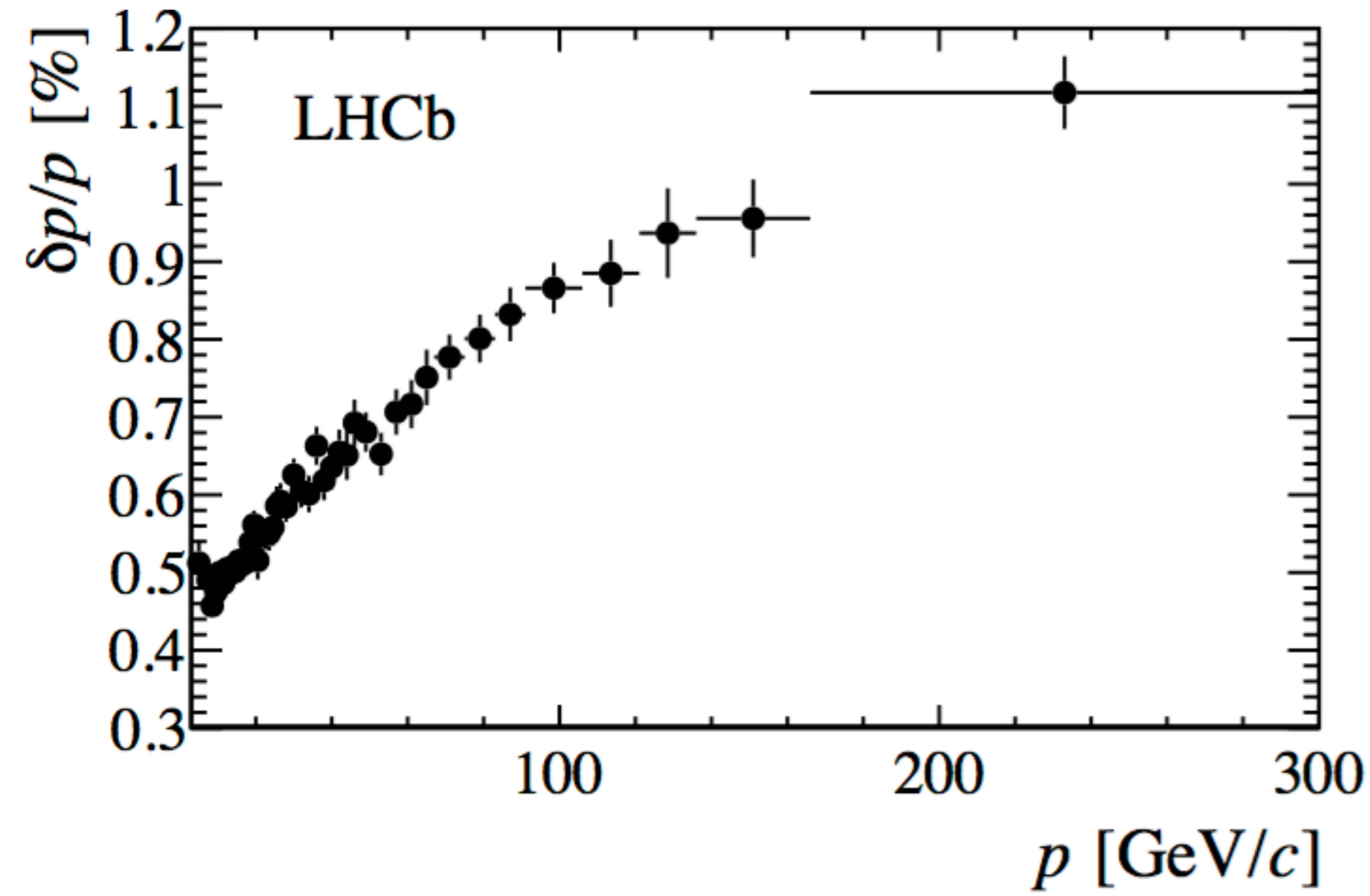
Tracking performance

- Tracking efficiency > 96% (measured with tag-and-probe technique with $J/\psi \rightarrow \mu^{+}\mu^{-}$)

- Relative momentum resolution for long tracks in J/ψ decays, $\Delta p/p$=0.5-1%

- $\Delta m/m$, is about 5 per mille up to the Υ masses





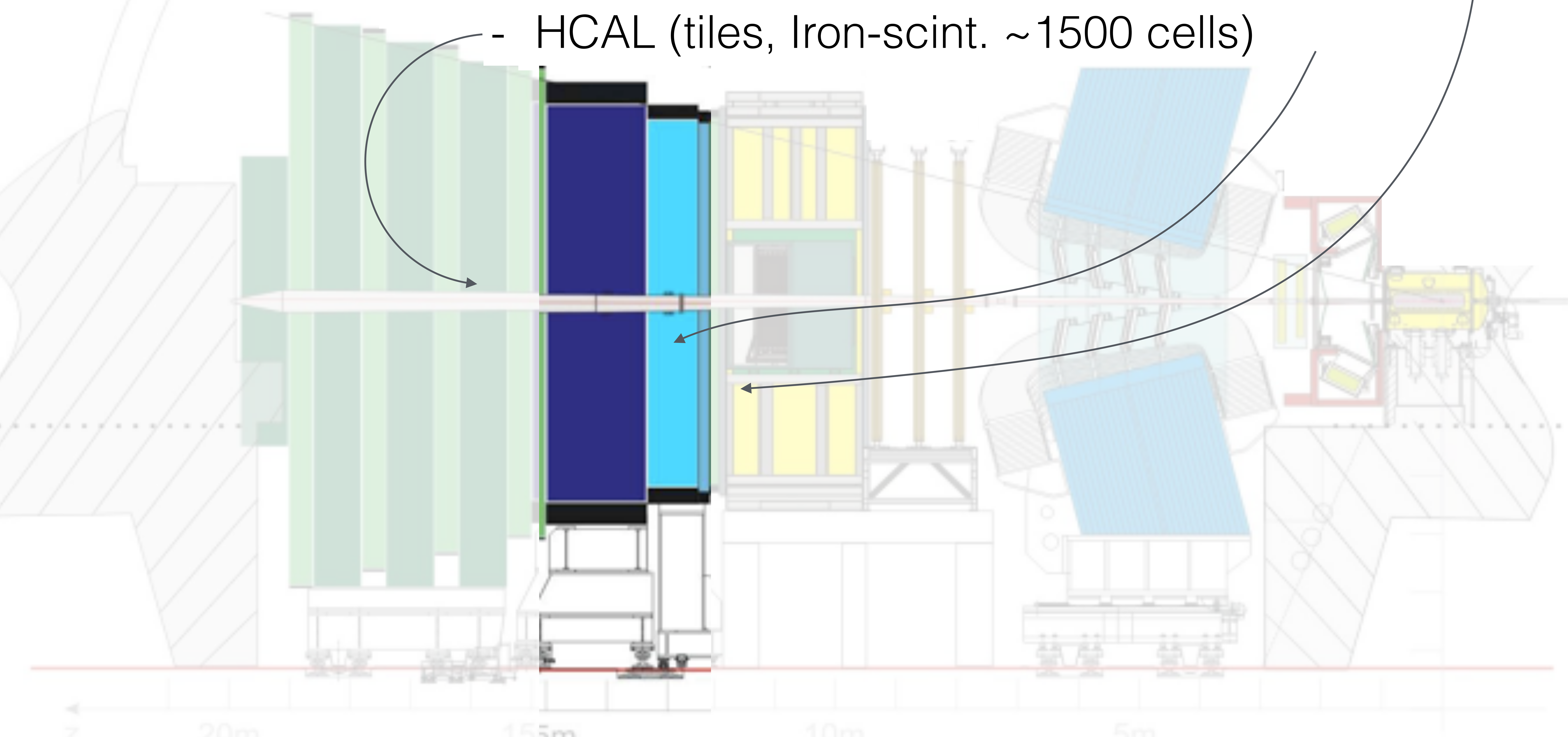
Int. J. Mod. Pays. A30 (2015) 1530022

Calorimeters

- Id of hadrons, electrons and photons, and measurement of their energies and positions, with sufficient selectivity and in a very short time (hardware trigger, L0)

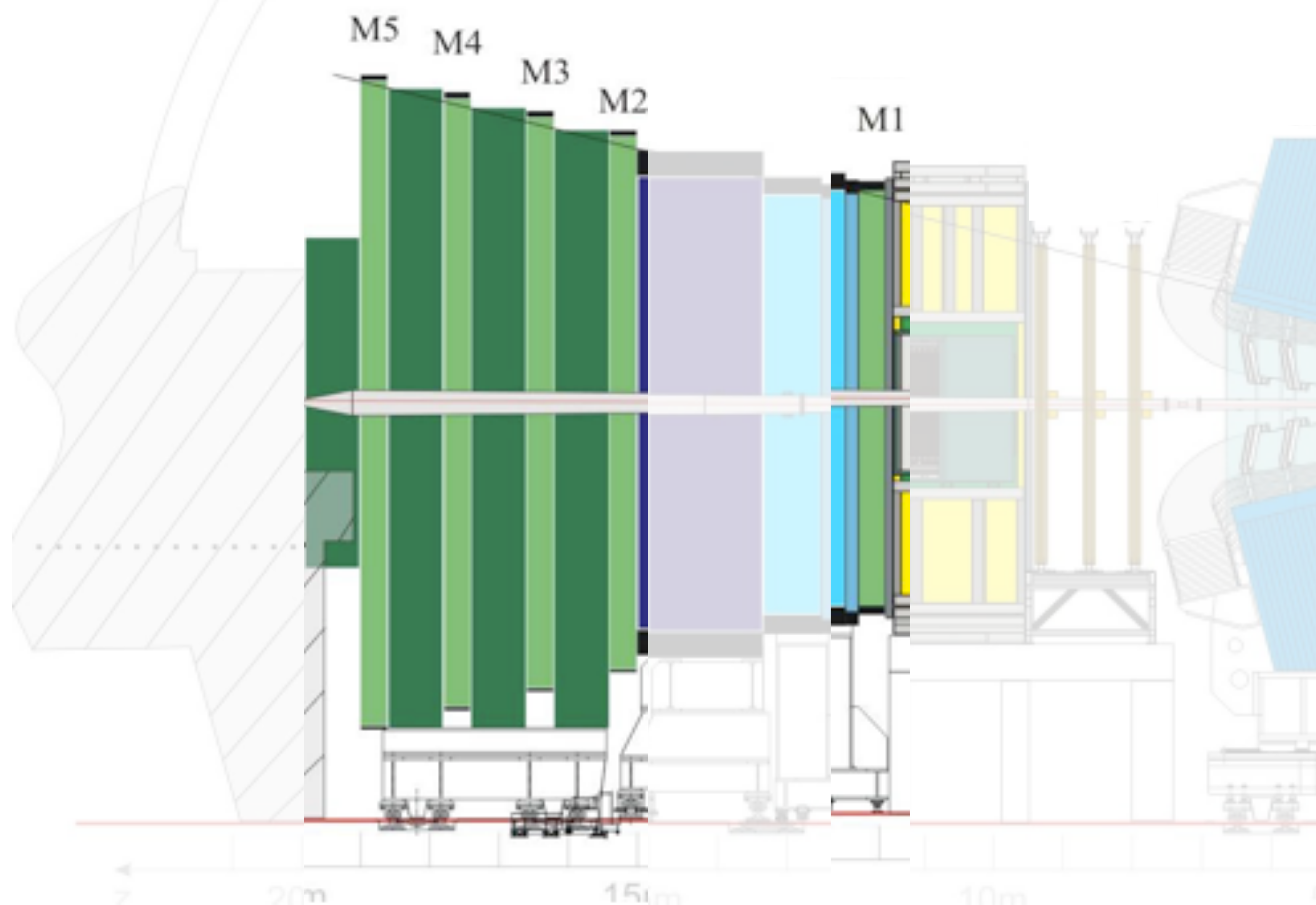
  - Scintillator hodoscopes separated by converter
  - ECAL (shashlik, Pb-scintillator ~6000 cells)
  - HCAL (tiles, Iron-scint. ~1500 cells)

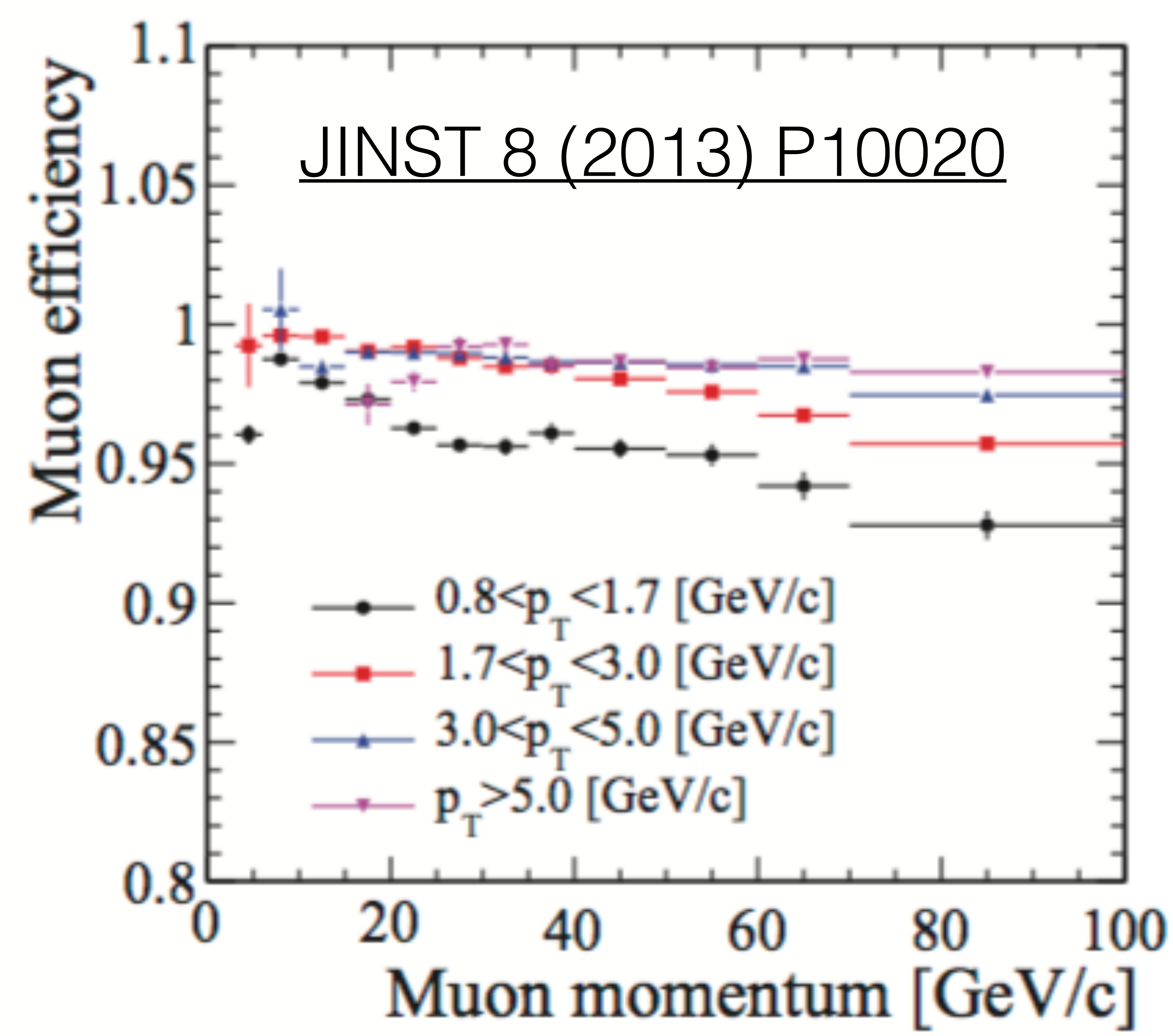
$$\frac{\delta E}{E} = \frac{10\%}{\sqrt{E}} \oplus 0.8\%$$



Muon Detectors

- Selection of high P_T muons at trigger level and offline muon identification
  - 5 stations M1-M5 each equipped with 276 multi-wire proportional chambers
  - Inner part of M1 equipped with GEM detectors





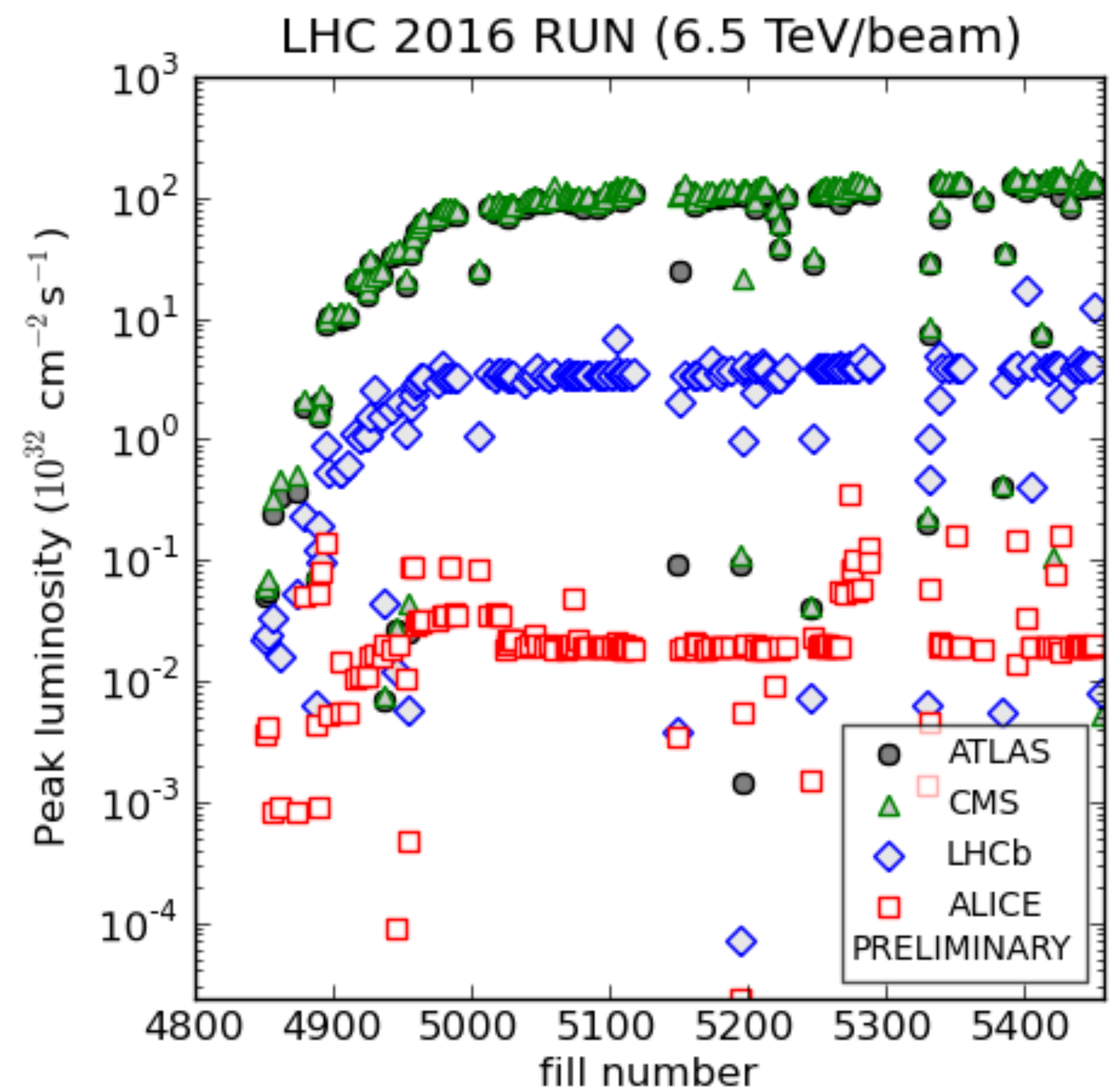
Running conditions

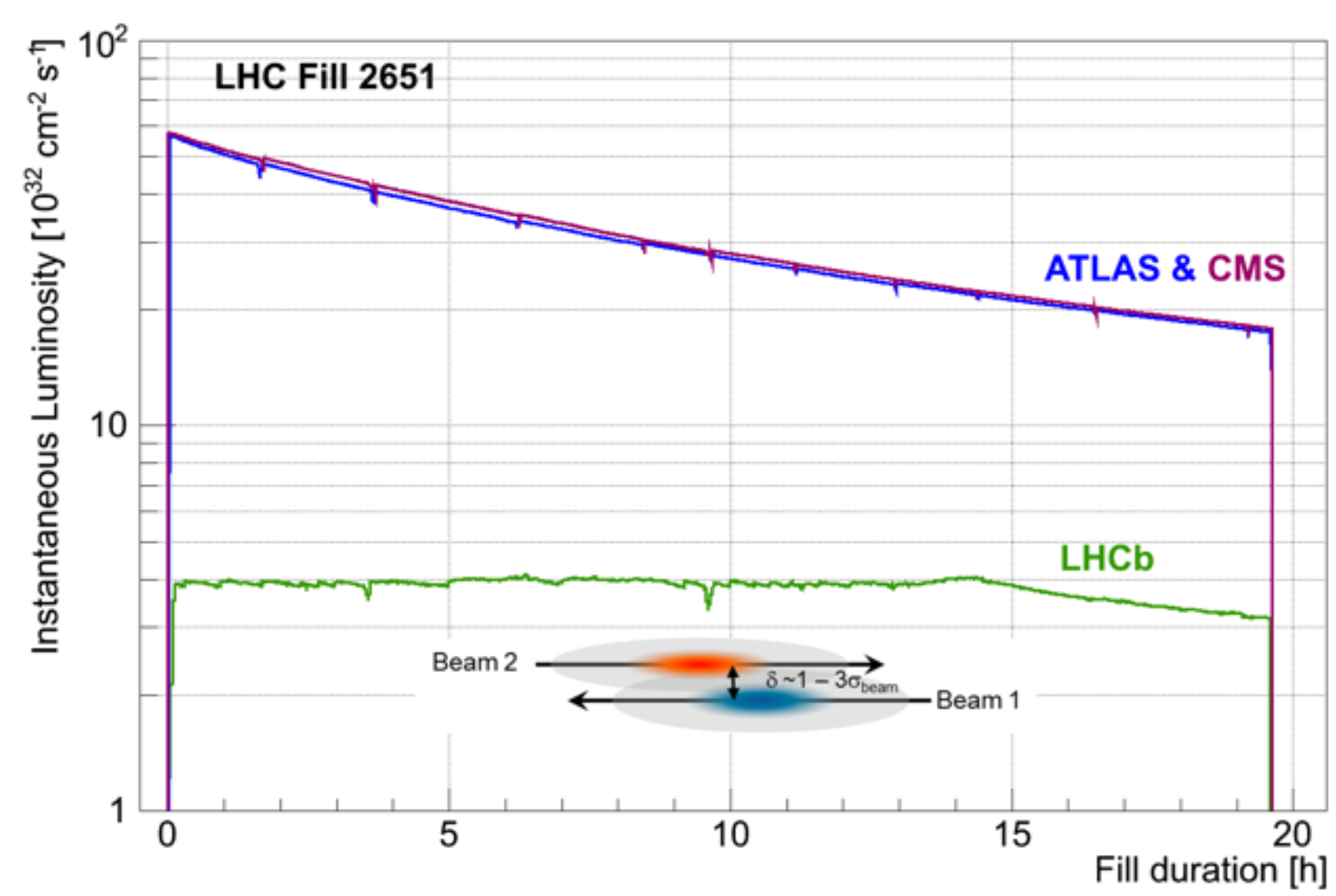
- LHCb designed to run at lower $\mathscr{L}$ than ATLAS/CMS
  - Mean number of interactions/bunch crossing ~1
  - Tracking, Particle Identification sensitive to pileup

- pp beams displaced to reduce instantaneous $\mathscr{L}$

- Experiment designed to run at constant luminosity throughout fills
  - $\mathscr{L}$ ~ 4.0 10^{32} $cm^{-2}s^{-1}$
  - For ATLAS/CMS $\mathscr{L}$ ~ 10^{34} $cm^{-2}s^{-1}$

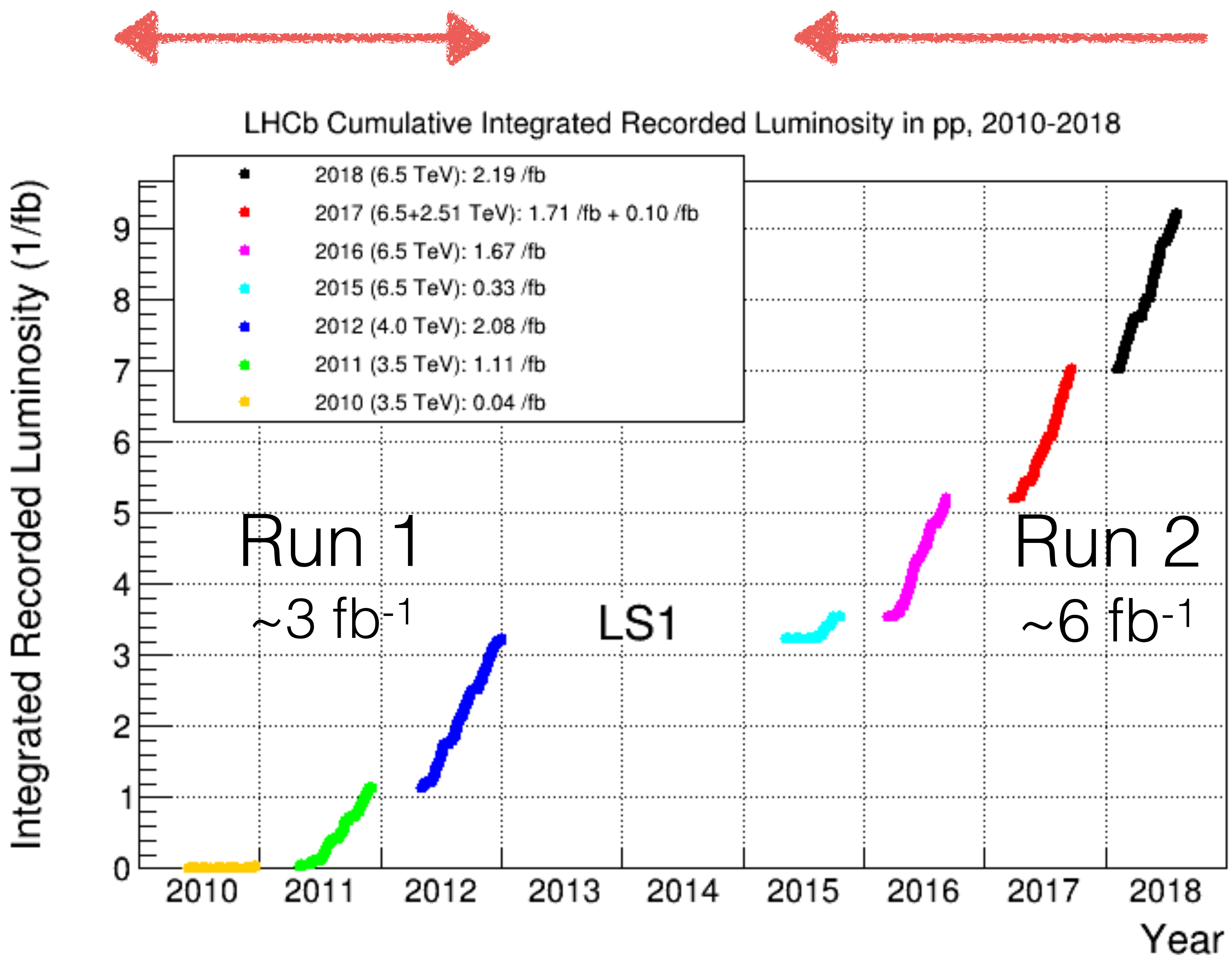
- Huge heavy quark production cross-sections !
  - σ_{bb} ~ 600 μb @ $\sqrt{s}$=13 TeV (~1nb in e+e- @Y(4s))
    - ~10^{11} b decays/fb in acceptance
  - σ_{cc} is ~ 20 times larger!
    - ~10^{12} c decays/fb in acceptance





Luminosity @ LHCb

$\int \mathcal{L}\, \mathrm{d}t \sim 9\, \mathrm{fb}^{-1}$



~10^{11} $b\bar{b}$ decays/fb in acceptance
~10^{12} $c\bar{c}$ decays/fb

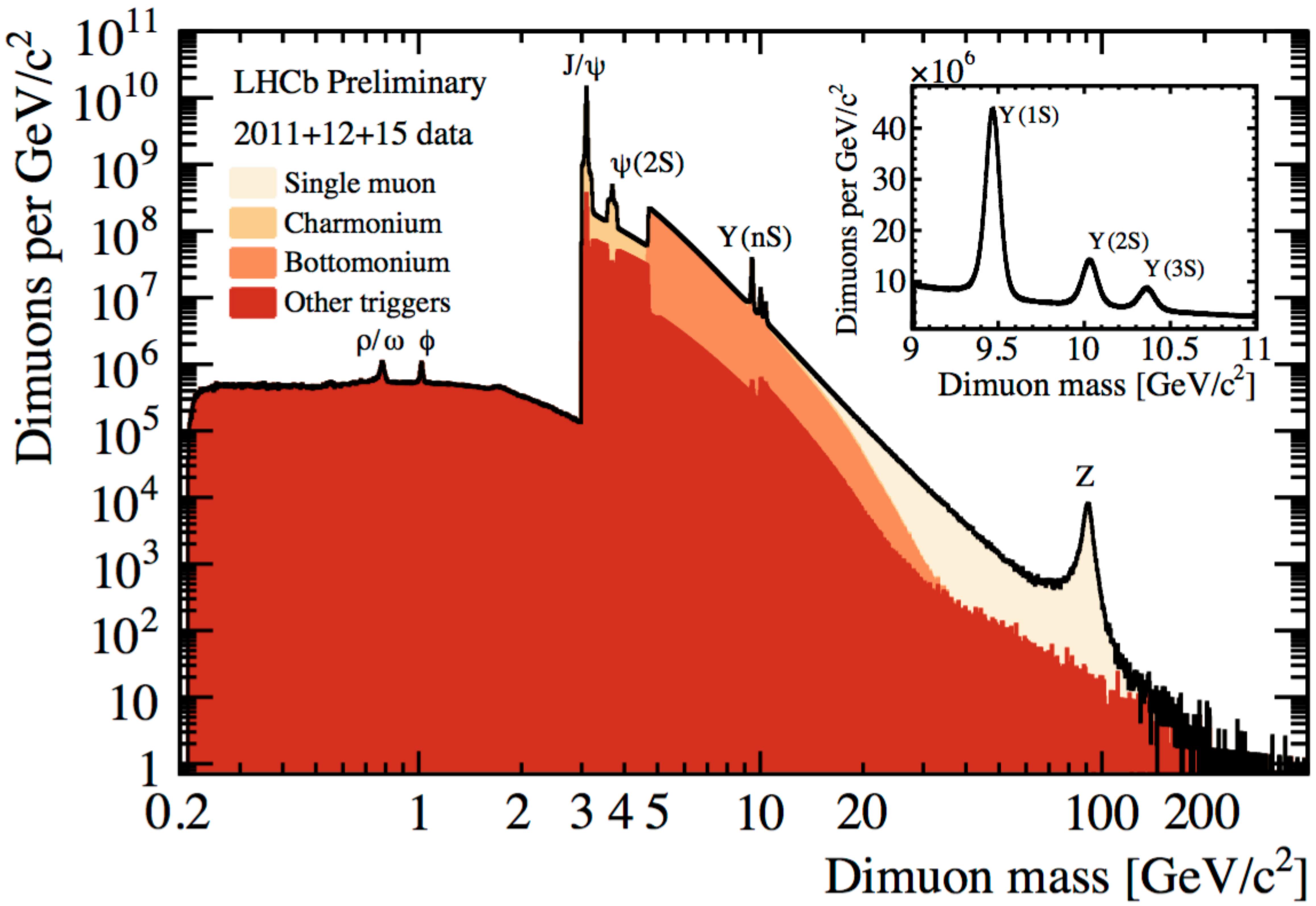
- $\mathscr{L}$ = 4 x10^{32} cm^{-2} sec^{-1} (to be raised to 2 x10^{33} cm^{-2} sec^{-1} in Run 3)

The trigger

- For LHCb, more data more important than higher energy
  - Direct searches @ATLAS/CMS: more energy → new particles could appear above threshold
  - Indirect searches: precision measurements → gain from increased production rates

- However, digesting more data is a true challenge!
  - At 13 TeV and $\mathscr{L}$=4x10^{32}/cm^2/sec, ~45 kHz $b\overline{b}$ and ~1MHz $c\overline{c}$ pairs in detector acceptance
  - Most interesting b-hadron decays occur at 10^{-5} probability or lower
  - Big challenge → requires powerful trigger

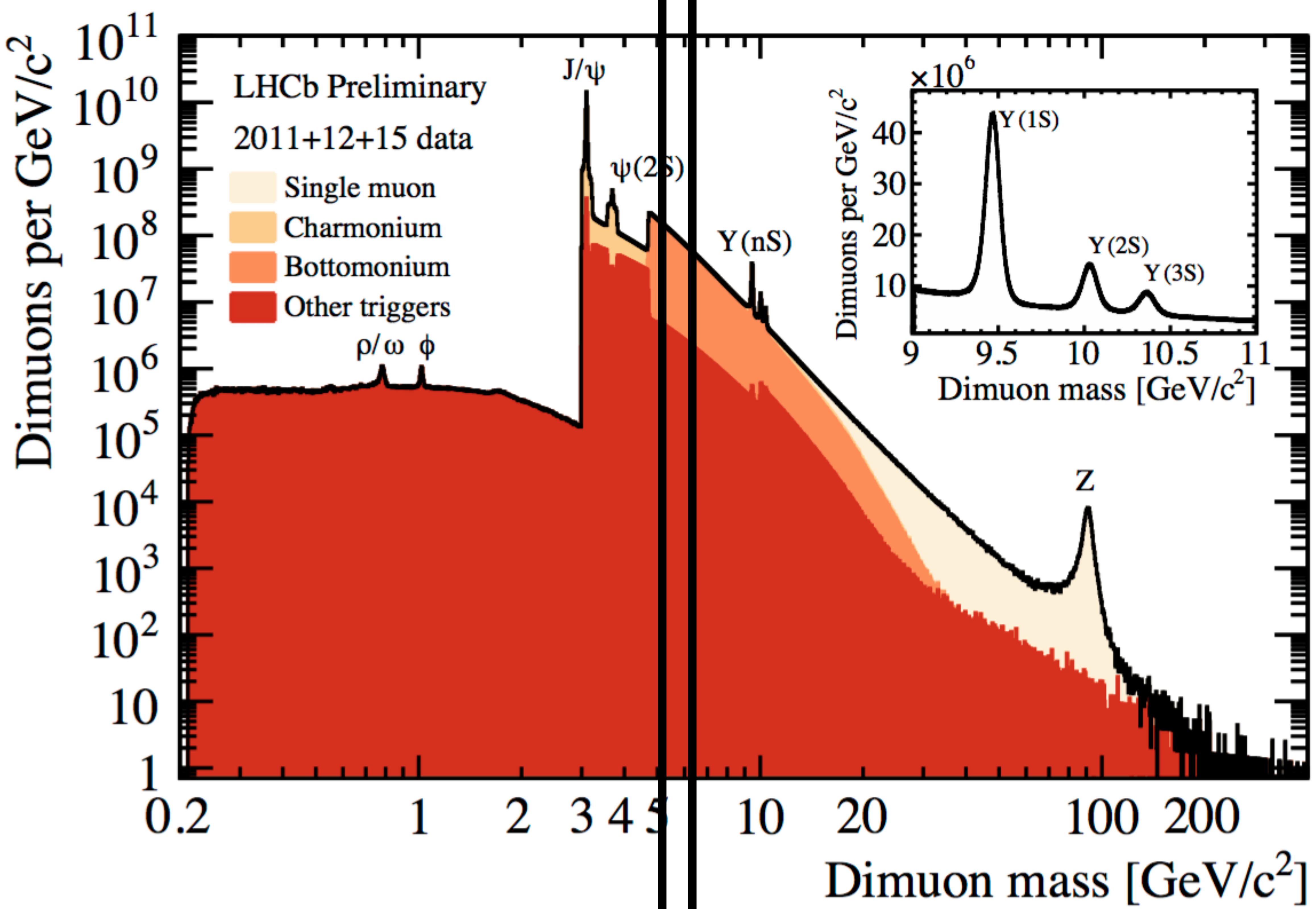
Selectivity example



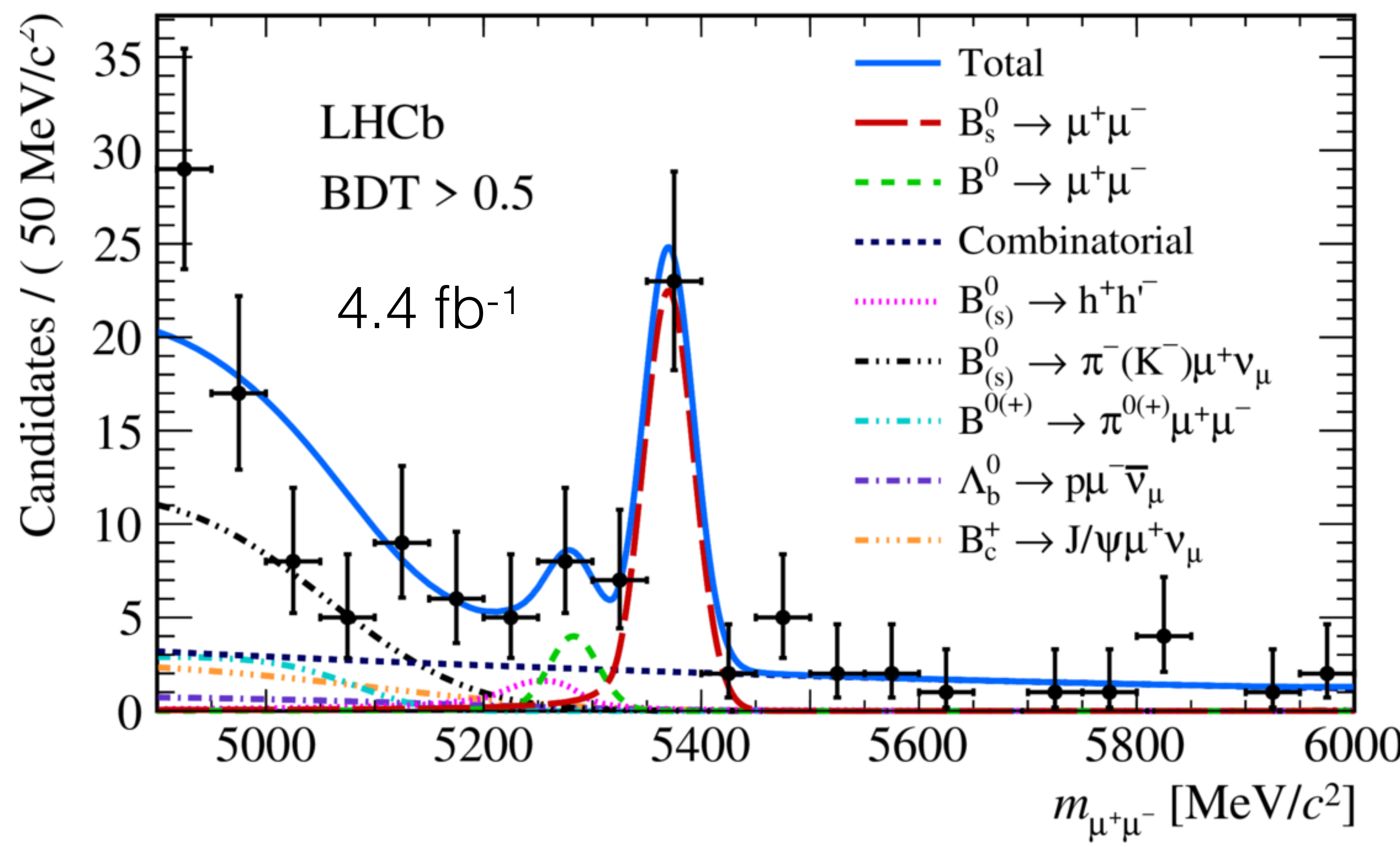
Di-muon distribution split by trigger group (LHCb-CONF-2016-05)

Selectivity example

PRL 118 (2017) 191801



Di-muon distribution split by trigger group (LHCb-CONF-2016-05)



$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.8 \pm 0.6) \times 10^{-9}$

$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10}$

A significance of 7.8 σ!

2018 was last year of LHCb as we know it!

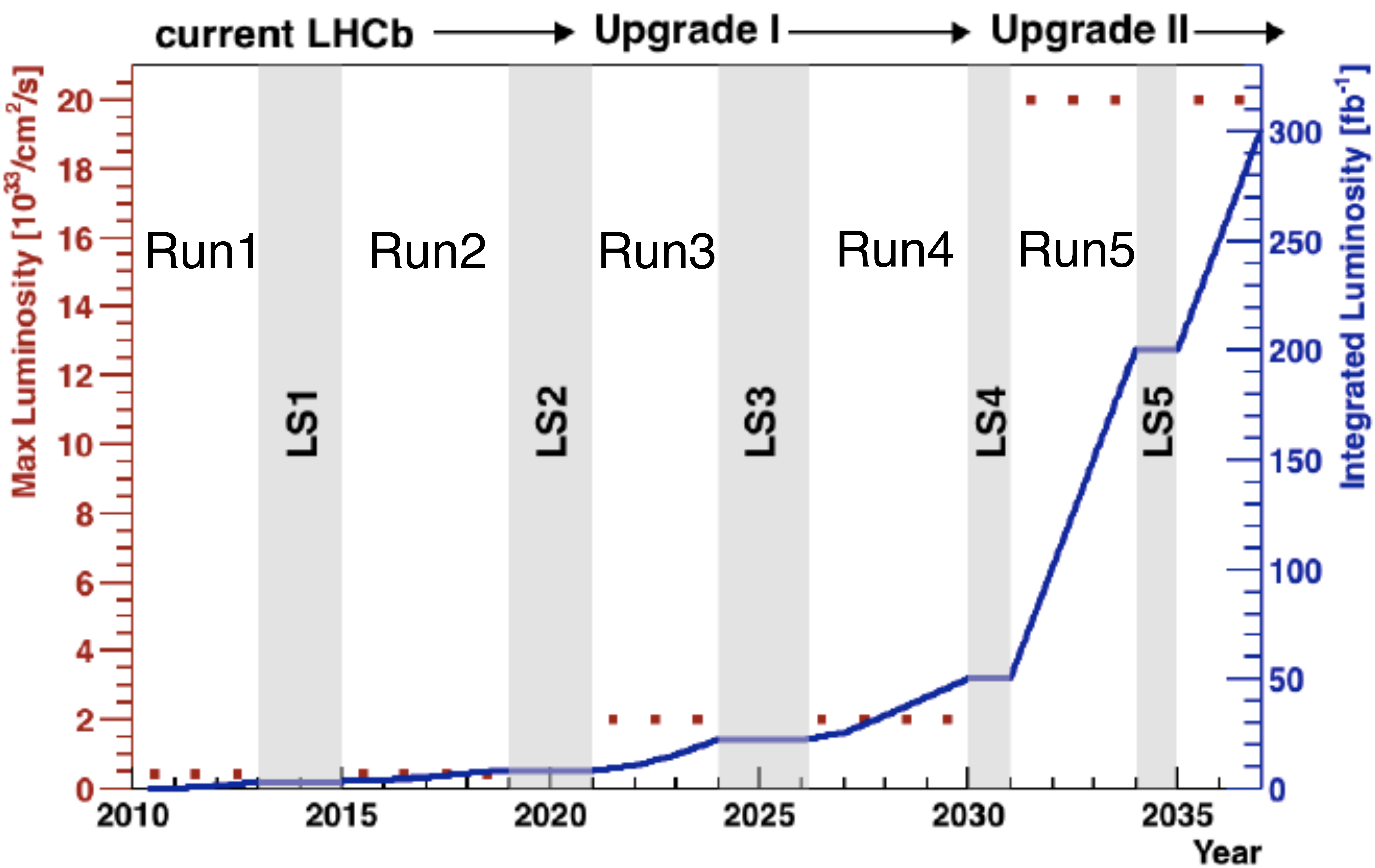
- LHCb is currently building and installing its upgrade
- Aim: to collect 50 fb^{-1} at

  $\mathscr{L} = 2 \times 10^{33}\ cm^{-2}\ s^{-1}$

Integrated Luminosity (fb^{-1})

	LHCb	ATLAS/CMS
Run 1	3	30
Run 2	9	100
Run 3	25	300
Run 4	50	…3000

Luminosity evolution



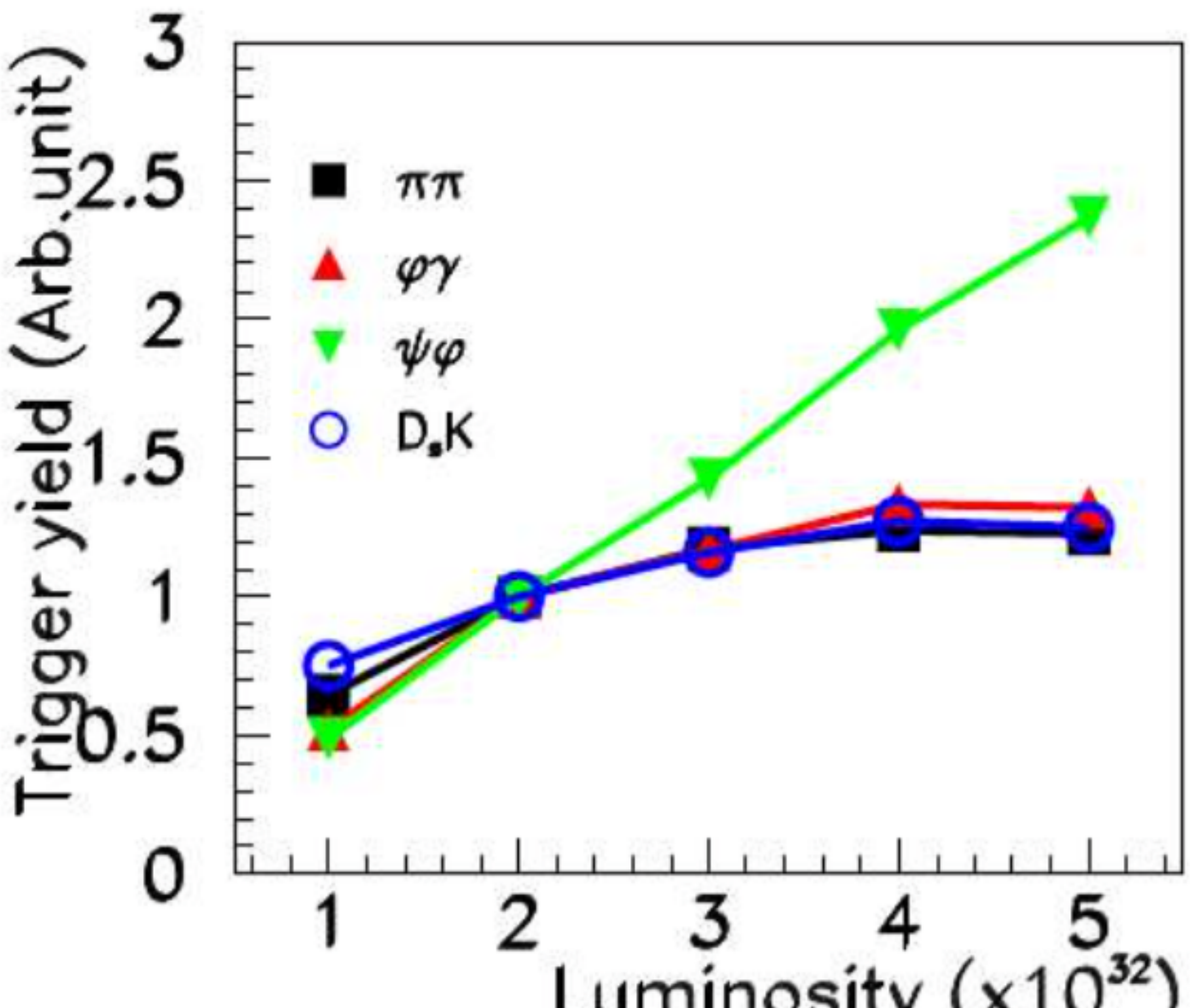
- Expression of Interest for LHCb Upgrade II (CERN-LHCC-2017-003) and physics case (CERN/LHCC 2018-027, arXiv:1808.08865) submitted to LHCC

Luminosity evolution

- Expression of Interest for LHCb Upgrade II (CERN-LHCC-2017-003) and physics case (CERN/LHCC 2018-027, arXiv:1808.08865) submitted to LHCC

Why upgrade?

- First level hardware trigger (L0) bottleneck
  - 1.1 MHz maximum detector readout
  - L0 implements selections at 40 MHz using either the Calorimeters or the Muon System
- Highly efficient for dimuon events
- For hadronic channels, any further increase in the rate requires an increase of E_T threshold → trigger yield saturates with increasing luminosity leading to ~constant signal yield



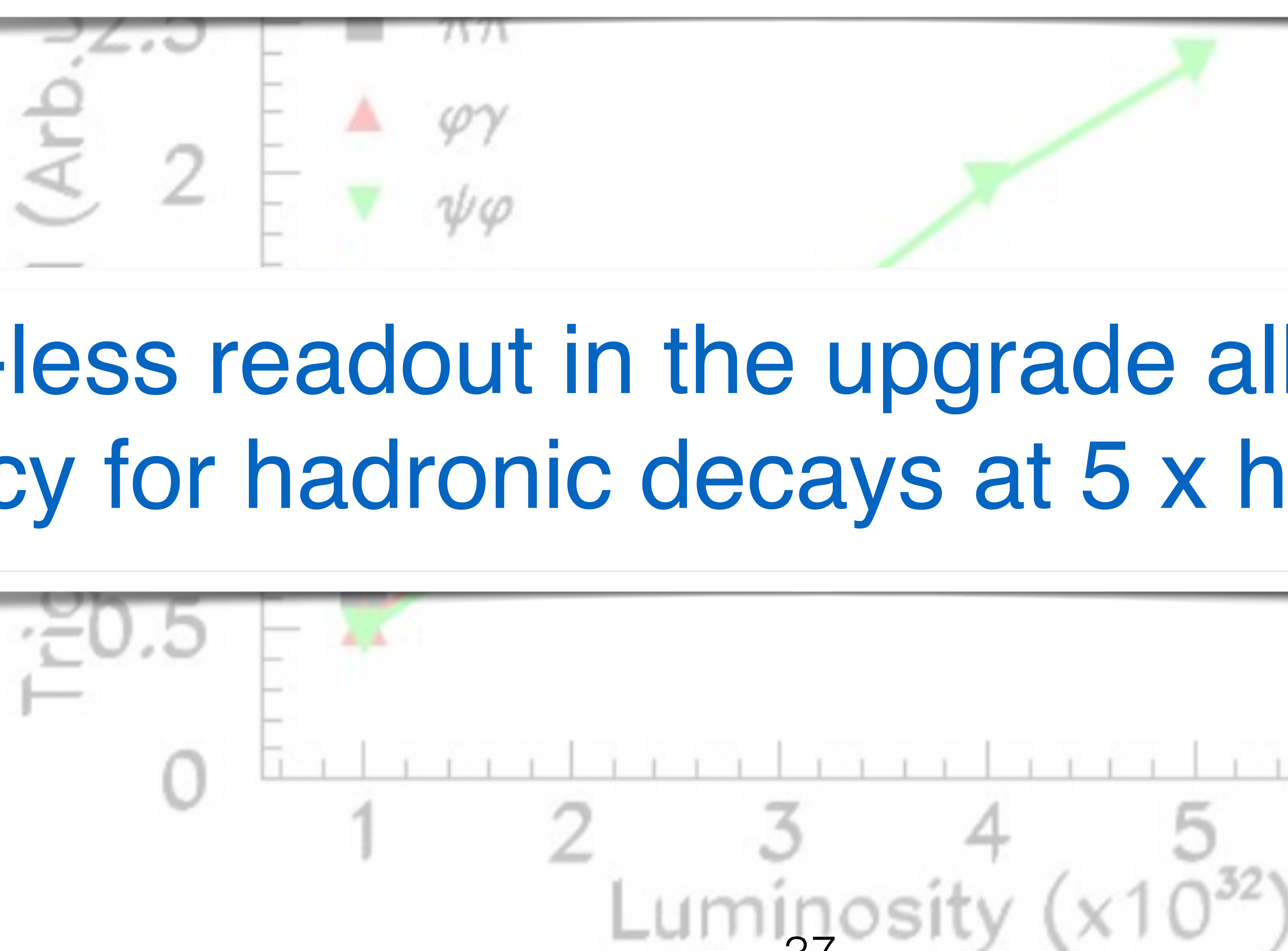
Muonic

Hadronic

Why upgrade?

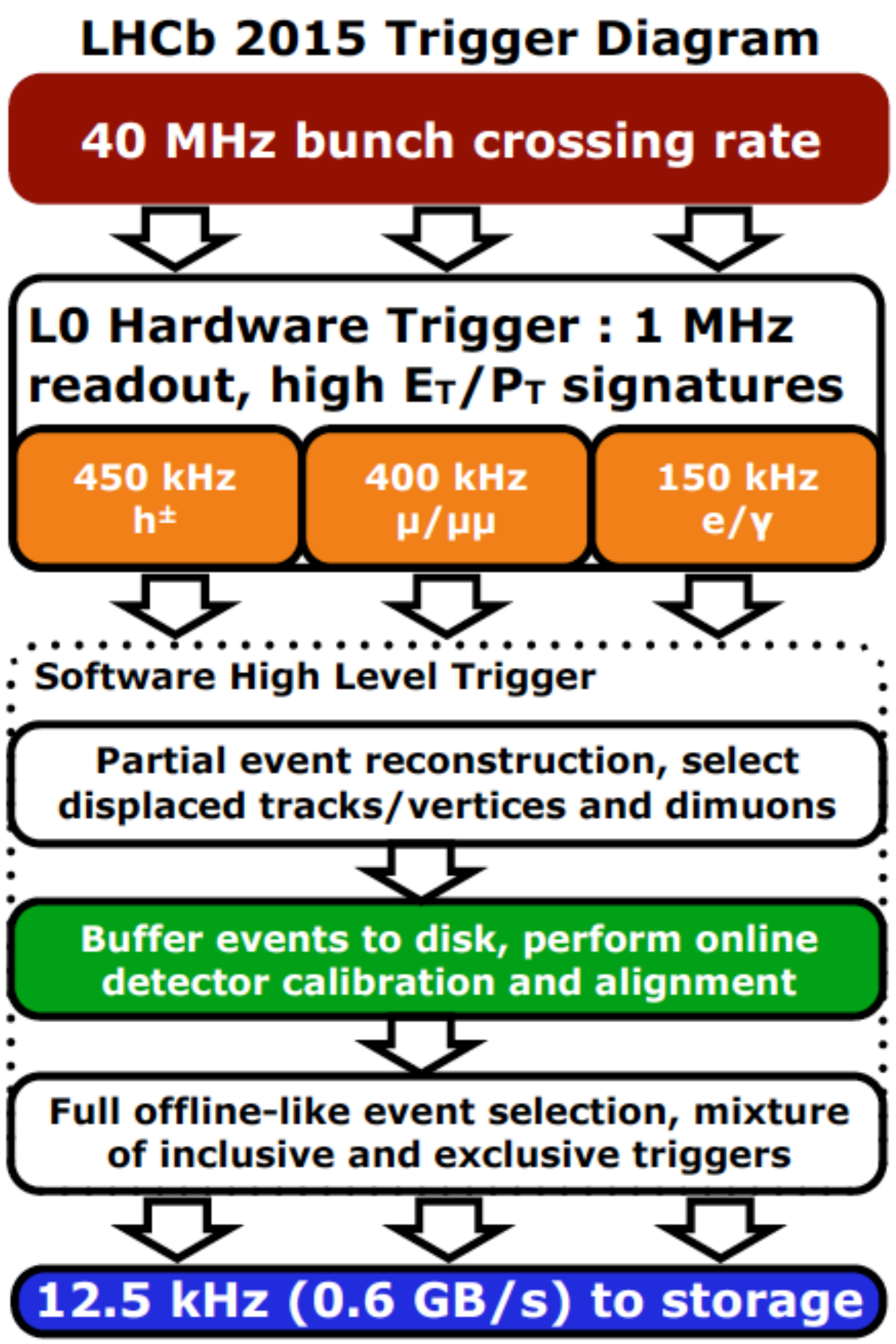
- First level hardware trigger (L0) bottleneck

Remove the 1MHz L0 bottleneck and supply the whole event information at each level of the trigger → Read the full event at 40 MHz and implement trigger in software in a custom data processing centre

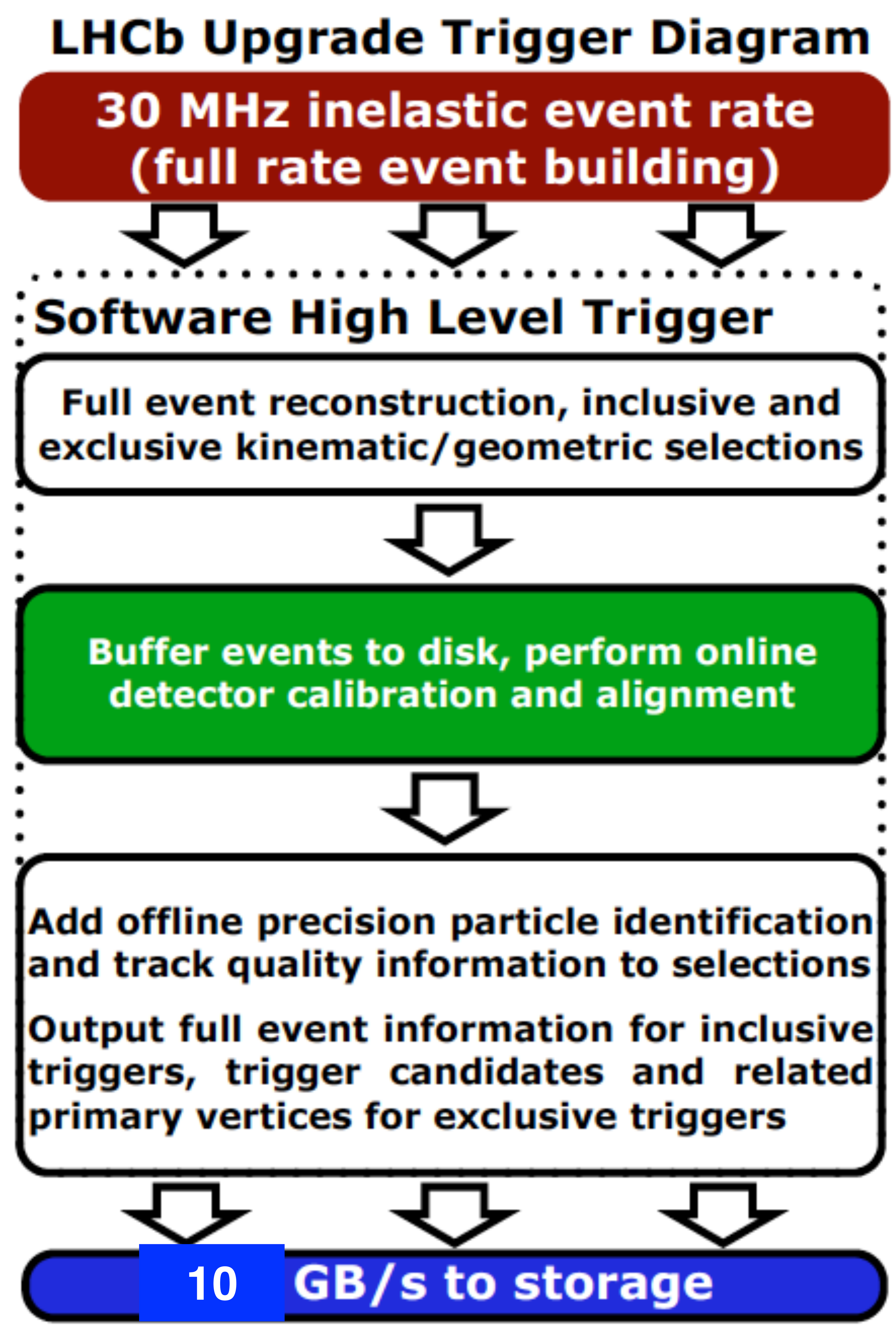


Trigger-less readout in the upgrade allows ~2 x higher efficiency for hadronic decays at 5 x higher luminosity

Run 2 to Upgrade

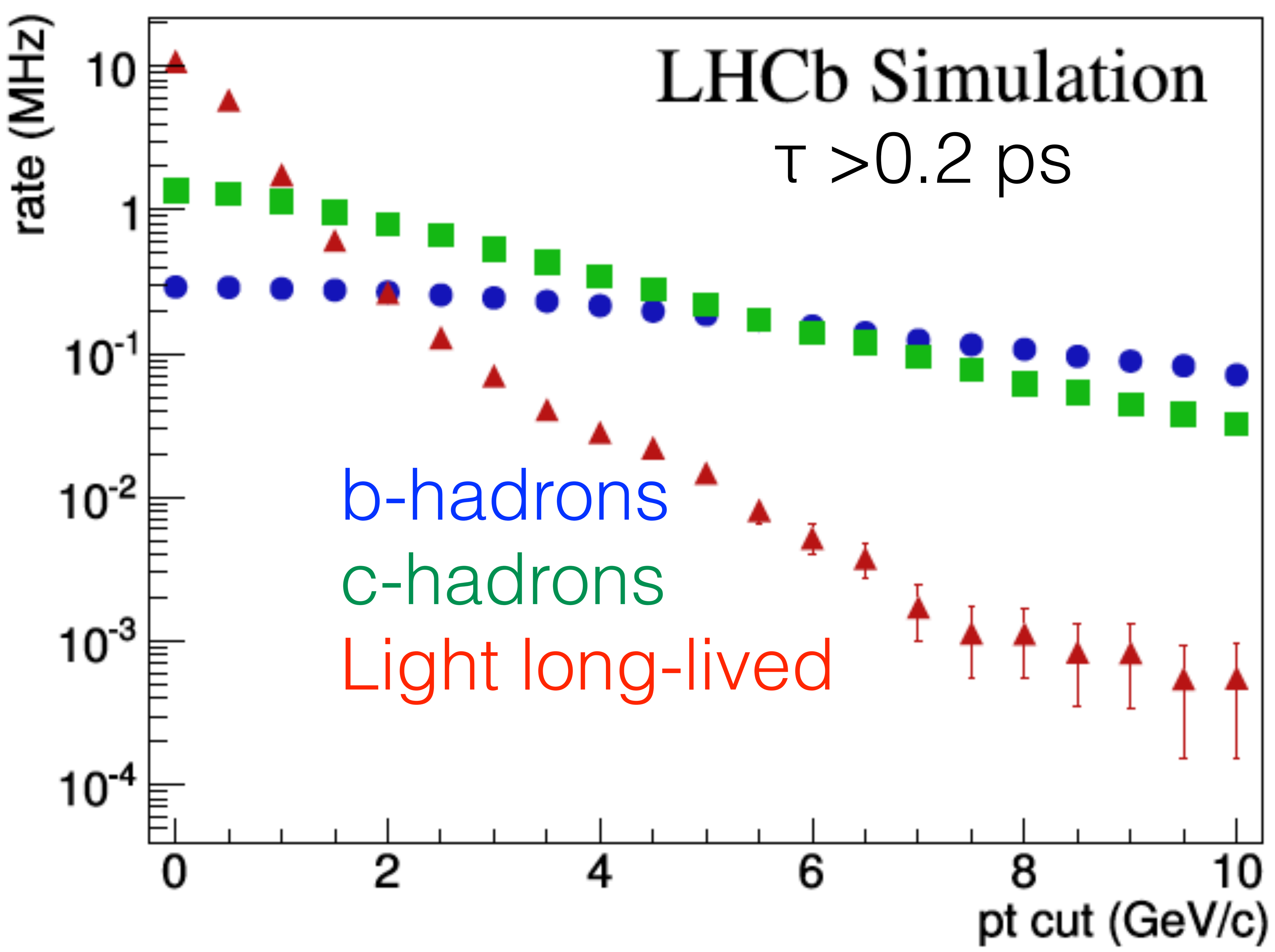


Real time analysis



Upgrade conditions and implications for the trigger

- At 2×10^{33} cm^{-2} s^{-1} every event will contains relevant signal:
  - 2% of the events will contain a reconstructible b-hadron (x 6 wrt Run 1)
  - 24% of the events will contain a reconstructible c-hadron (x 5)
  - 100% of the events will contain at least two displaced vertices from light long-lived hadrons (K^0, Λ^0, …)



Particle type	Run I (kHz)	Upgrade (kHz)
b-hadrons	17.3	270
c-hadrons	66.9	800
Light long-lived hadrons	22.8	264

- Use of specific selection triggers will become increasingly necessary
- Use of “Compact event records”, will only relevant info, e.g., a subsample of all tracks, will be increasingly utilised

- Trigger should no longer separate signal from background but rather categorise different signals

Comput.Phys.Commun. 208 (2016)

To summarise..

•Upgrade requirements:

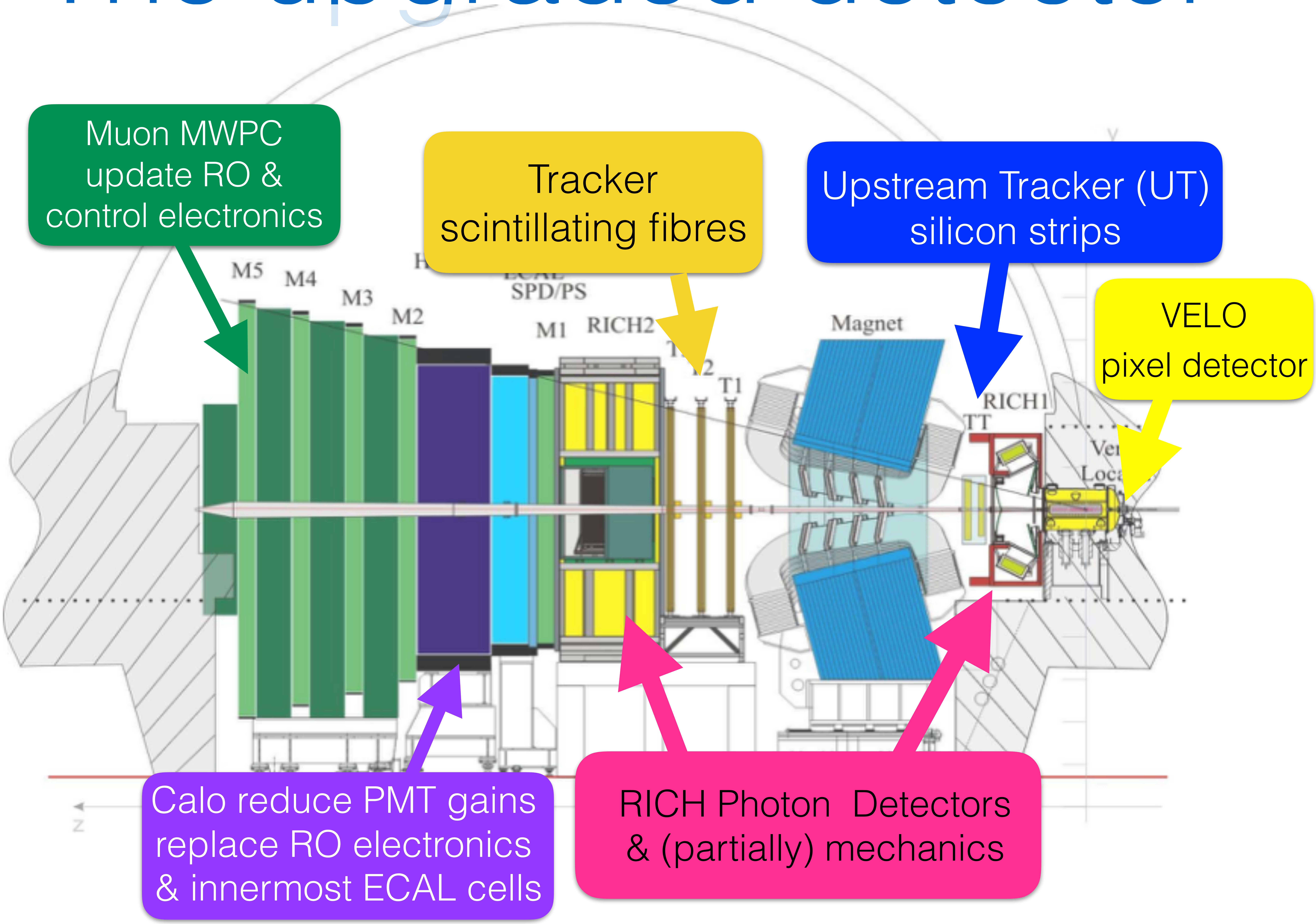
- 40 MHz readout
- Event selection performed by HLT software only
- $\mathscr{L} = 2 \times 10^{33}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ (x 5)
  - ➔ 5.5 visible interactions/crossing
  - ➔ Higher track multiplicity (from ~ <70> to <180>)

•Implications:

- New detector front-end electronics because of new readout requirement
- New HLT farm and network
- New trackers with finer granularity to reduce occupancy
- What is not changed needs to be consolidated to sustain higher Luminosity

When Run 3 begins in 2021, LHCb will have what is effectively a new detector, new readout systems, new reconstruction, a new trigger, and new running conditions.

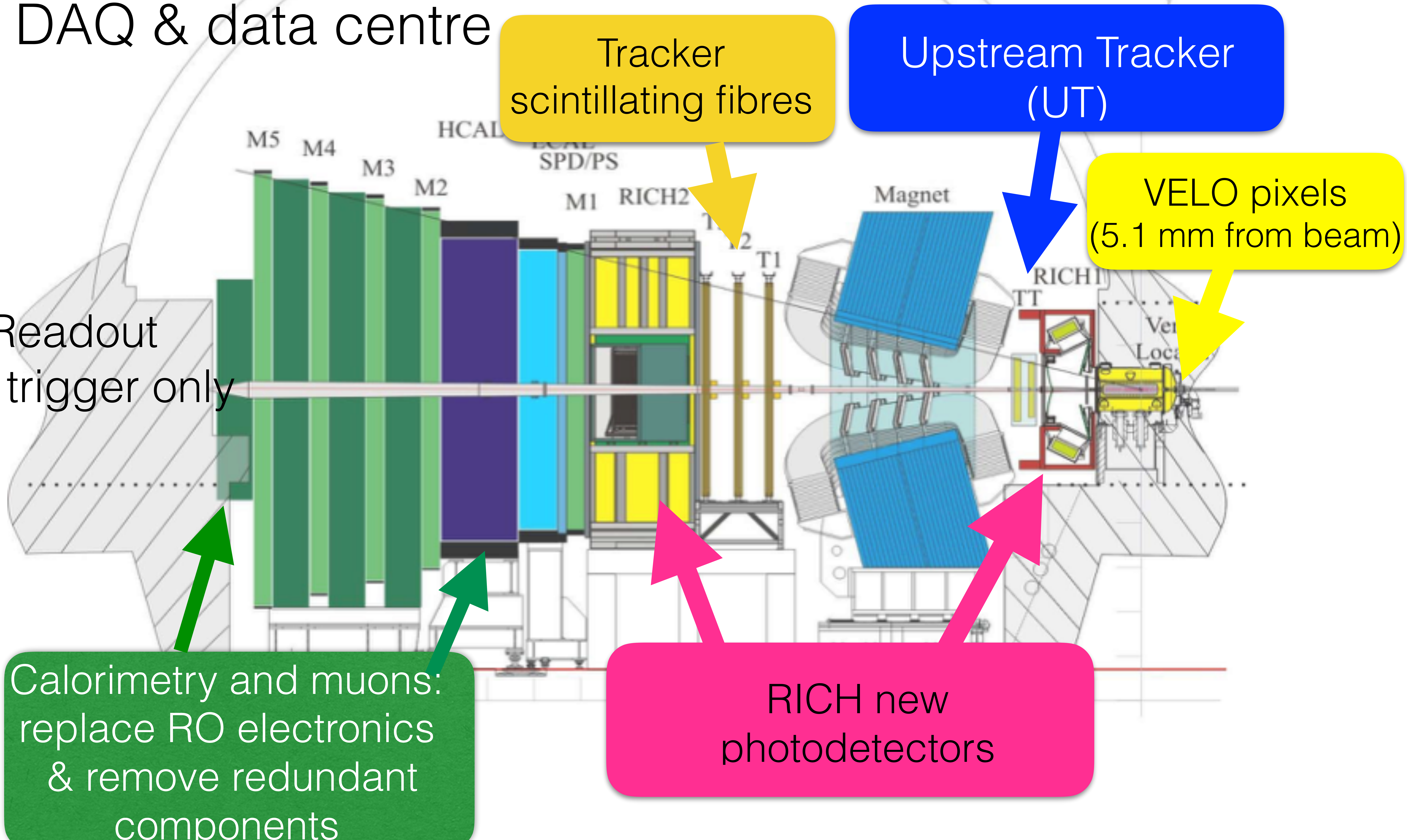
The upgraded detector



The NEW detector

- Less than 10% of all channels will be kept!
- NEW RO electronics
- NEW DAQ & data centre

40 MHz Readout
Software trigger only

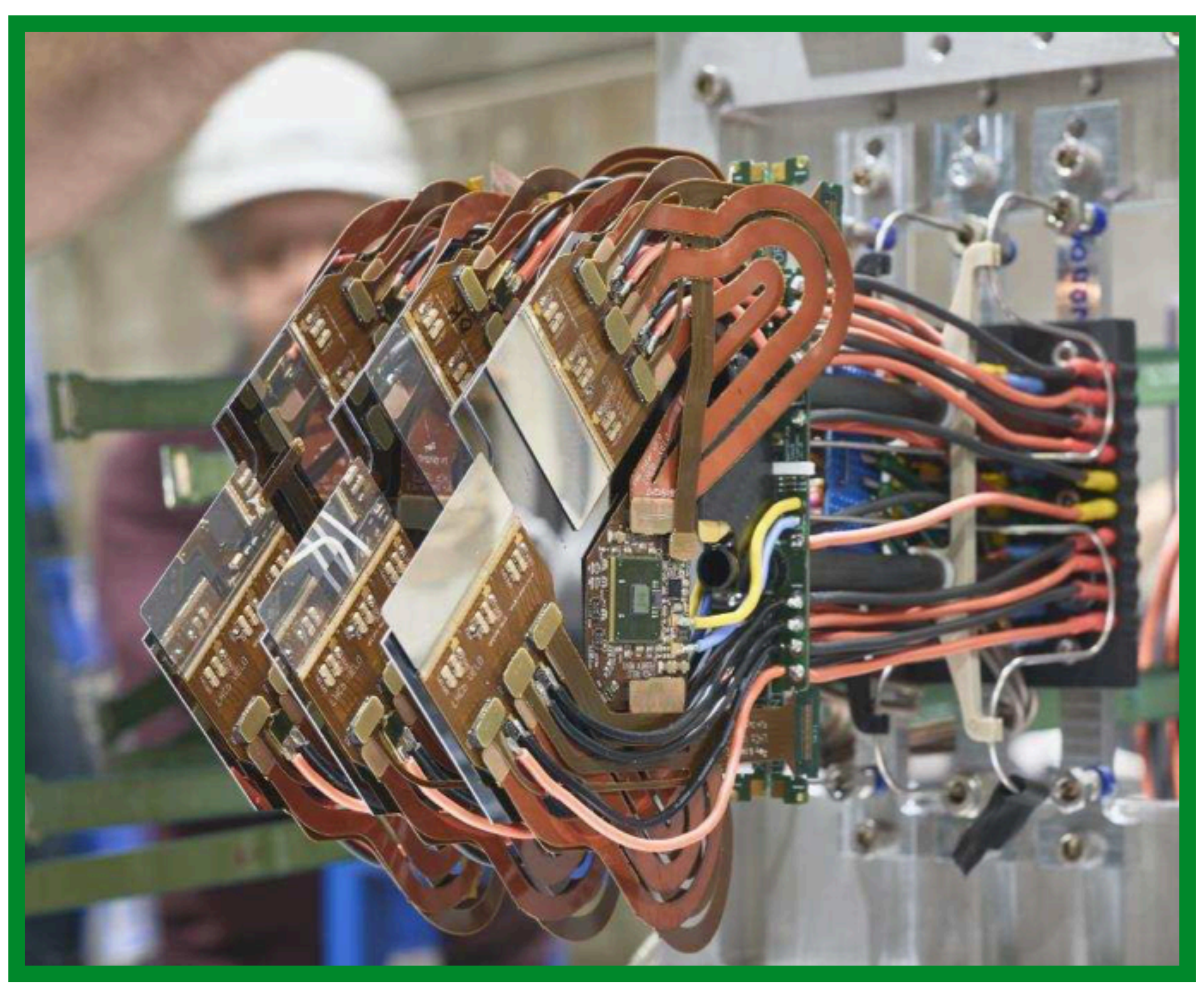


Construction and installation ongoing! Very tight timescale!

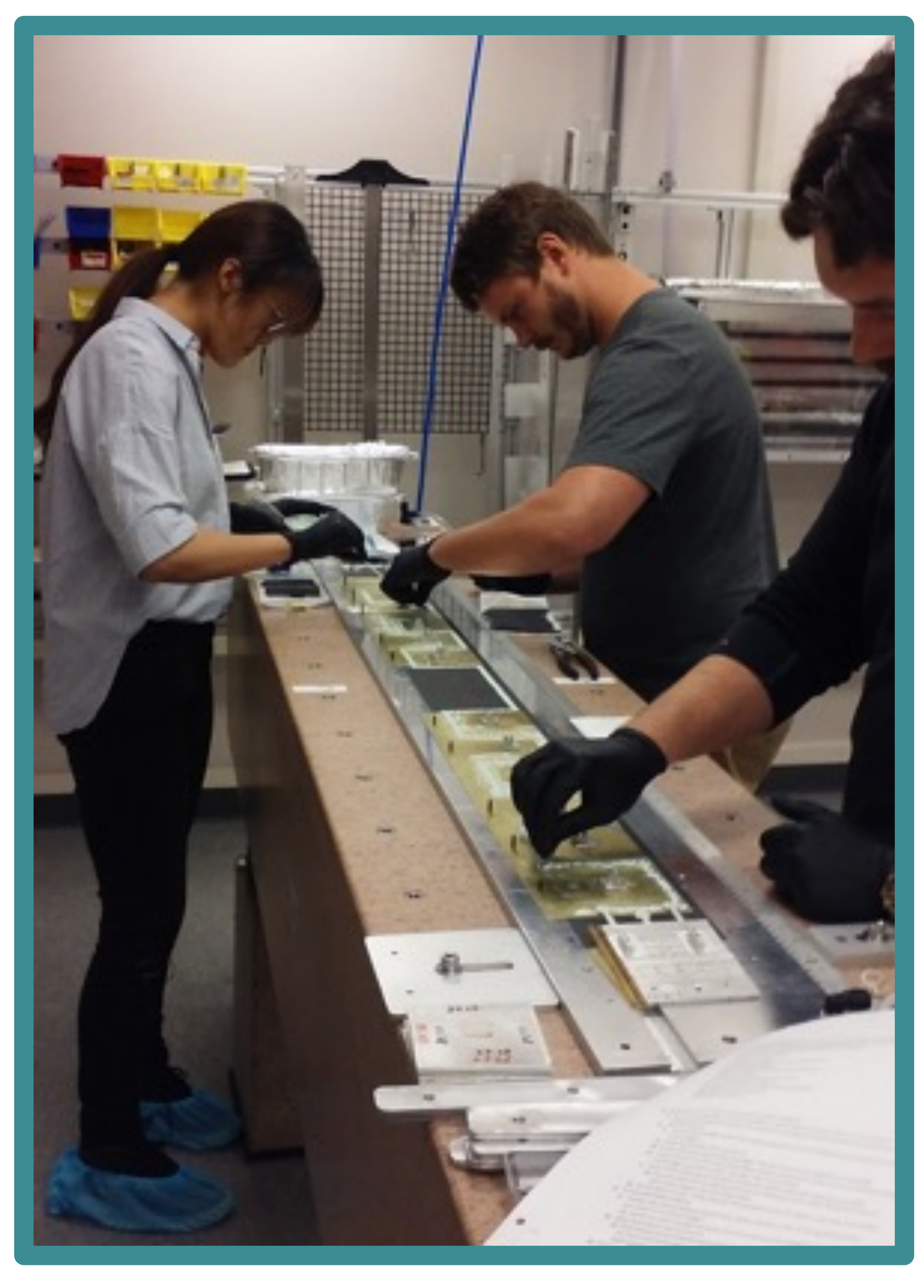
Cooling plant installation

RF foil etching

New data centre

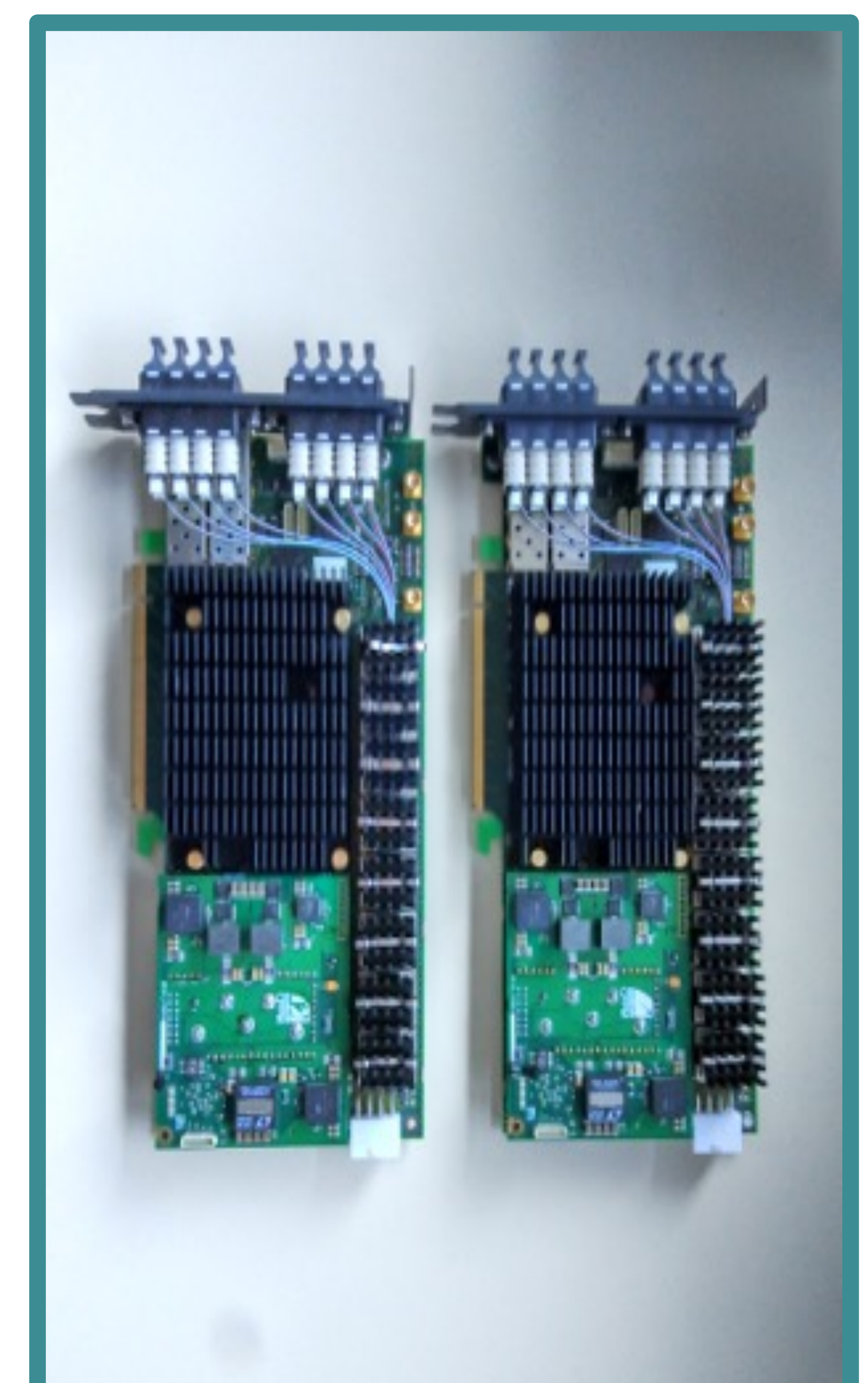


New VELO module



UT staves construction

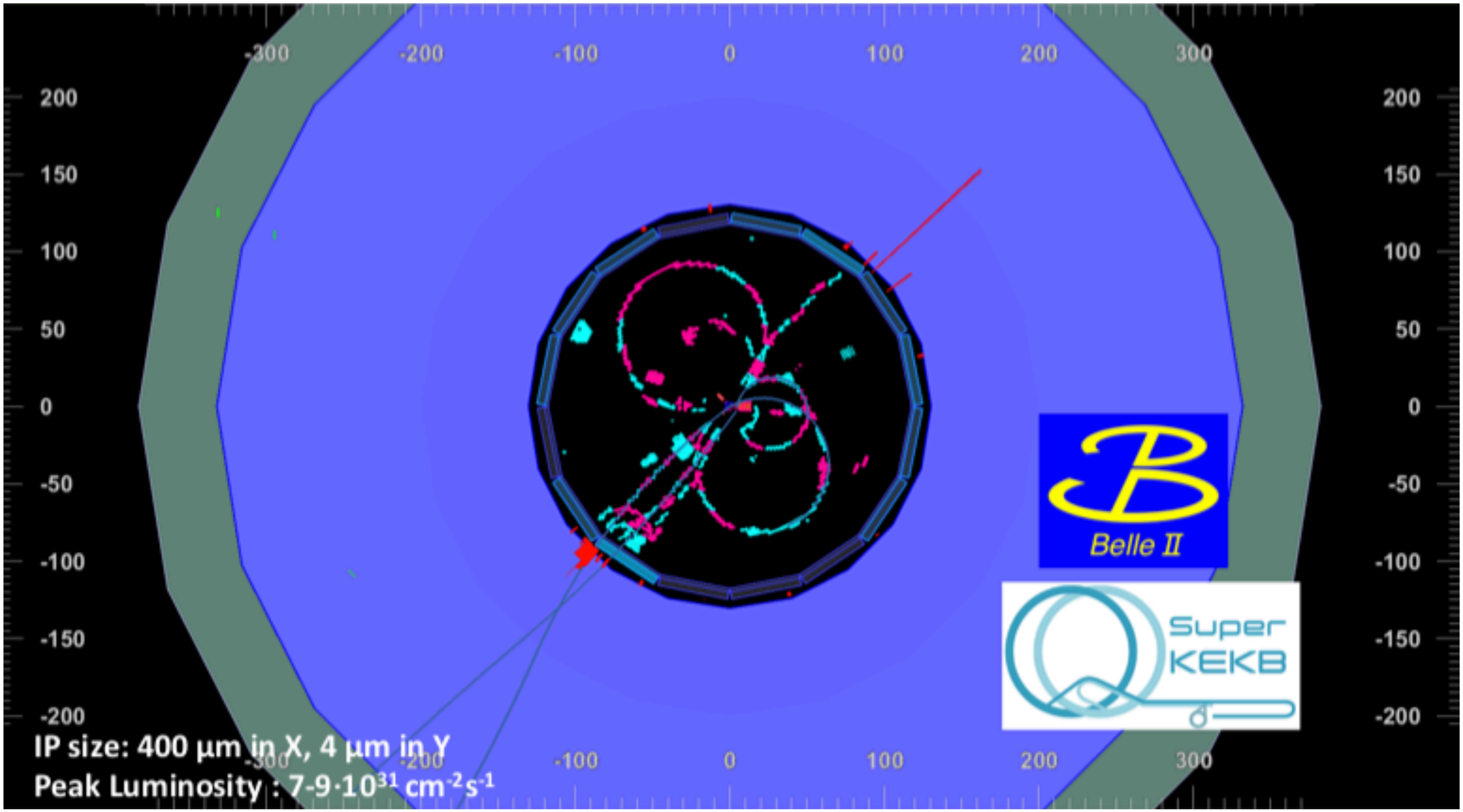
RICH MaPMTs under test



PCIe40 boards

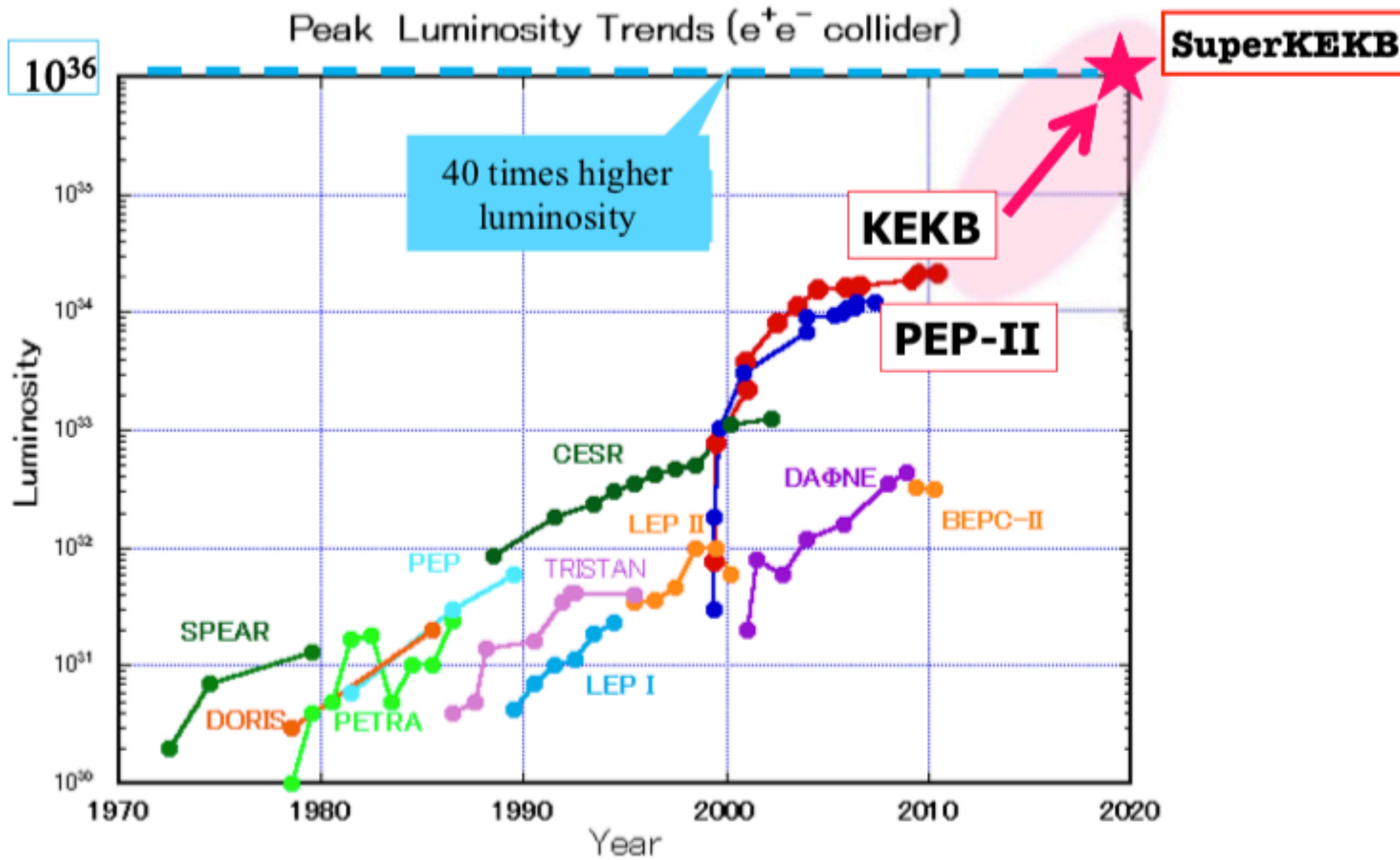
Belle II taking off

- First collisions on April 2018

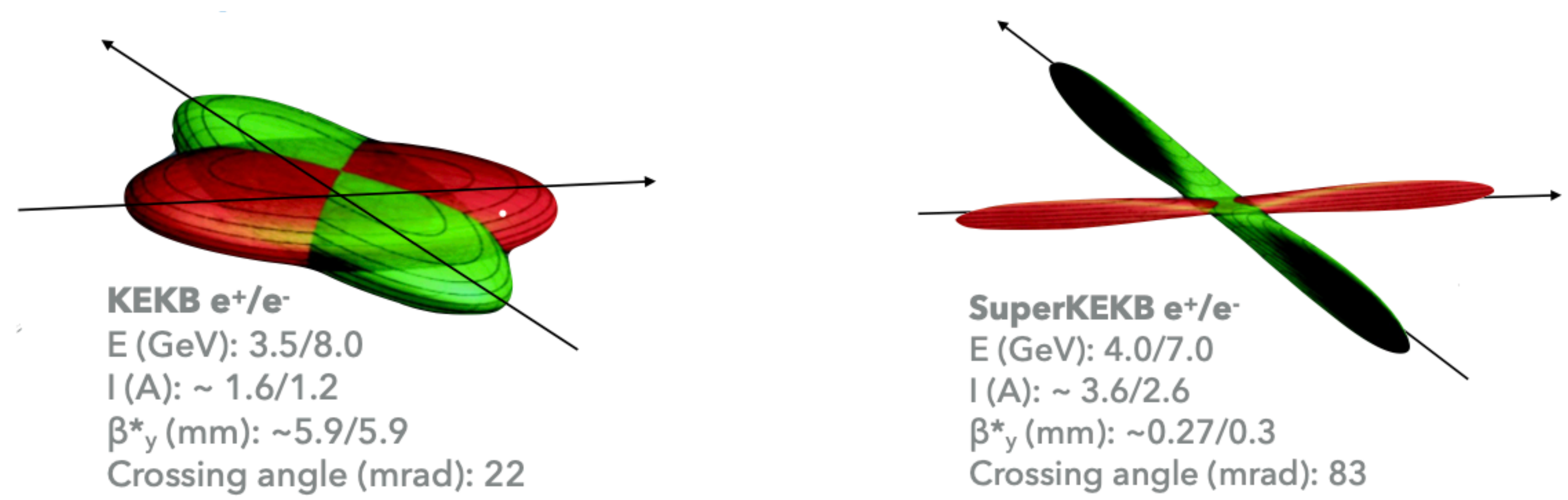


Very ambitious $\mathscr{L}$ objectives

- Completed major upgrade to the accelerator to reach 40xKEKB ($\mathscr{L} = 8\,10^{35}\,\mathrm{cm^{-2}s^{-1}}$)
  - 2x higher beam currents
  - 20 x smaller beam spot (σ_y=60 nm)



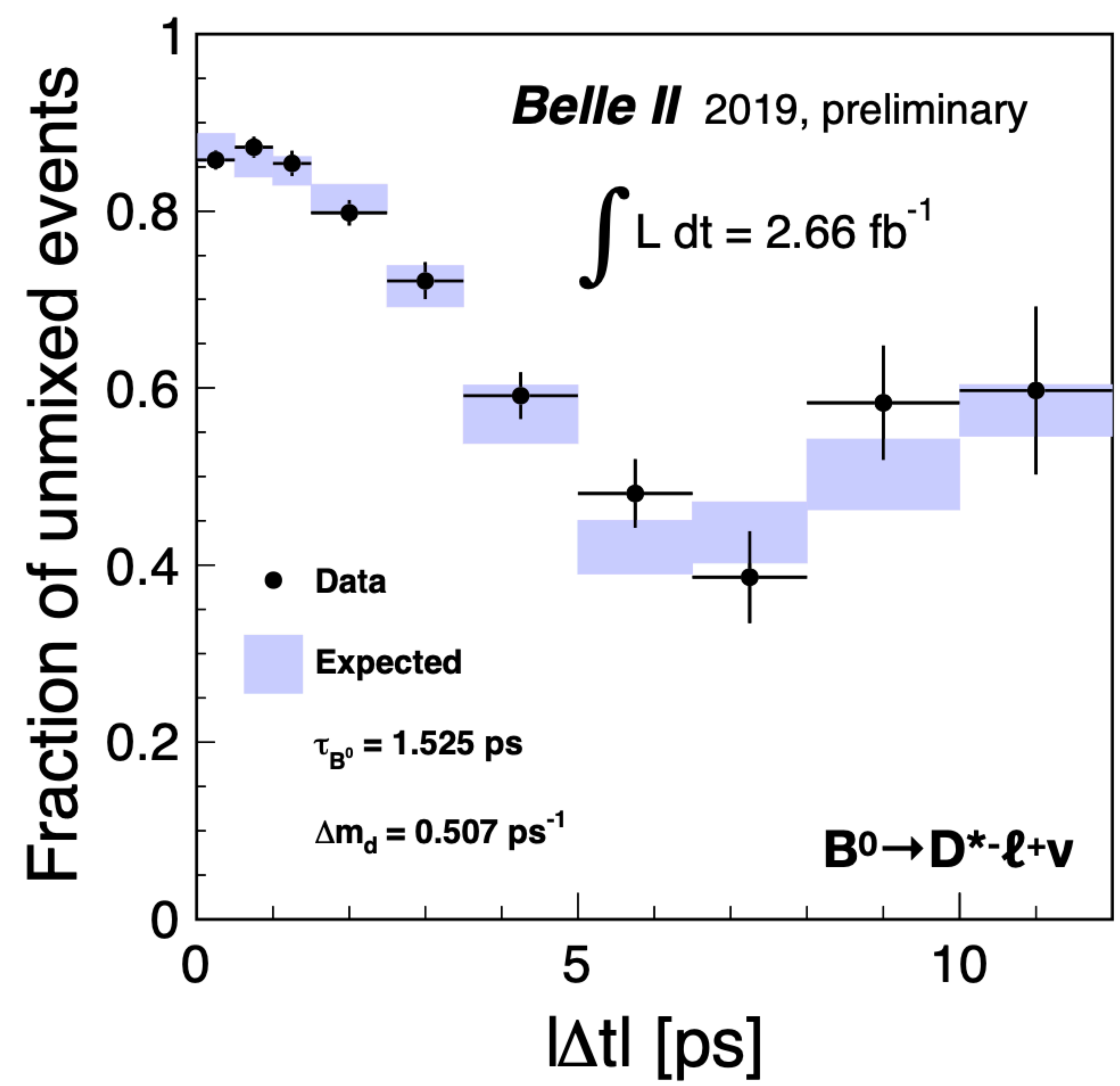
- Nano-beam scheme
  - idea is to have a very strong vertical focusing at the interaction point by making the crossing angle even larger than the previous machine, together with smaller beam emittances.



Status now

- Moving towards nano-beams gradually increasing beam-currents and reducing beam size
- Detector performance generally as expected, but challenging levels of beam-induced backgrounds in the interaction region
- Running at $\mathscr{L} \gtrsim 1 \times 10^{34}\,\mathrm{cm^{-2}s^{-1}}$ and collected ~10 fb^{-1}

Rediscovering time-dependent CP asymmetry in $B \to J/\Psi K_S^0$



e^+e^- B-Factory vs pp LHCb

- a very rough comparison

Experiment	Luminosity [cm^{-2}s^{-1}]	$b\bar{b}$ cross-section	$b\bar{b}$ pairs produced /year	Pros	Cons
BaBar/Belle	2 x10^{34}	0.001	2x10^{8}	Y(4S) is clean source of B mesons, coherent production, simpler trigger	Smaller production rate, mostly B^+/B^0
LHCb	4 x10^{32}	600	2x10^{12}	Larger production rate, all b-hadrons species	Harsher environment, difficult trigger
Belle II	8x10^{35}	0.001	8x10^{9}	Much higher background & rates, reduced boost wrt KEKB, but still Y(4S) is clean source of B mesons, better than LHCb in inclusive modes and in modes with neutrals	Less small, but still smaller production rate, mostly B^+/B^0
LHCb Upgrade	2x10^{33}	600	1x10^{13}	Even larger production rate, all b-hadrons	Even harsher environment and complex trigger

Back to CP Violation…

- Complex phases in CKM matrix lead to physical consequences only through interferences between amplitudes. **It is through interferences that the CKM phases produce CP violation**

- Let us suppose that a weak decay $B \to f$ receives contributions from two Feynman diagrams with amplitudes a, a' :

$$a = Me^{i\delta^f_{CKM}}e^{i\alpha_s},\ a' = Me^{i\delta'^f_{CKM}}e^{i\alpha'_s}$$

δ^f_{CKM} is phase of product of CKM elements

α_s is phase arising from strong interaction effects such as final-state rescattering

$$A(B \to f) = |M|e^{i\delta^f_{CKM}}e^{i\alpha_s} + |M'|e^{i\delta'^f_{CKM}}e^{i\alpha'_s}$$

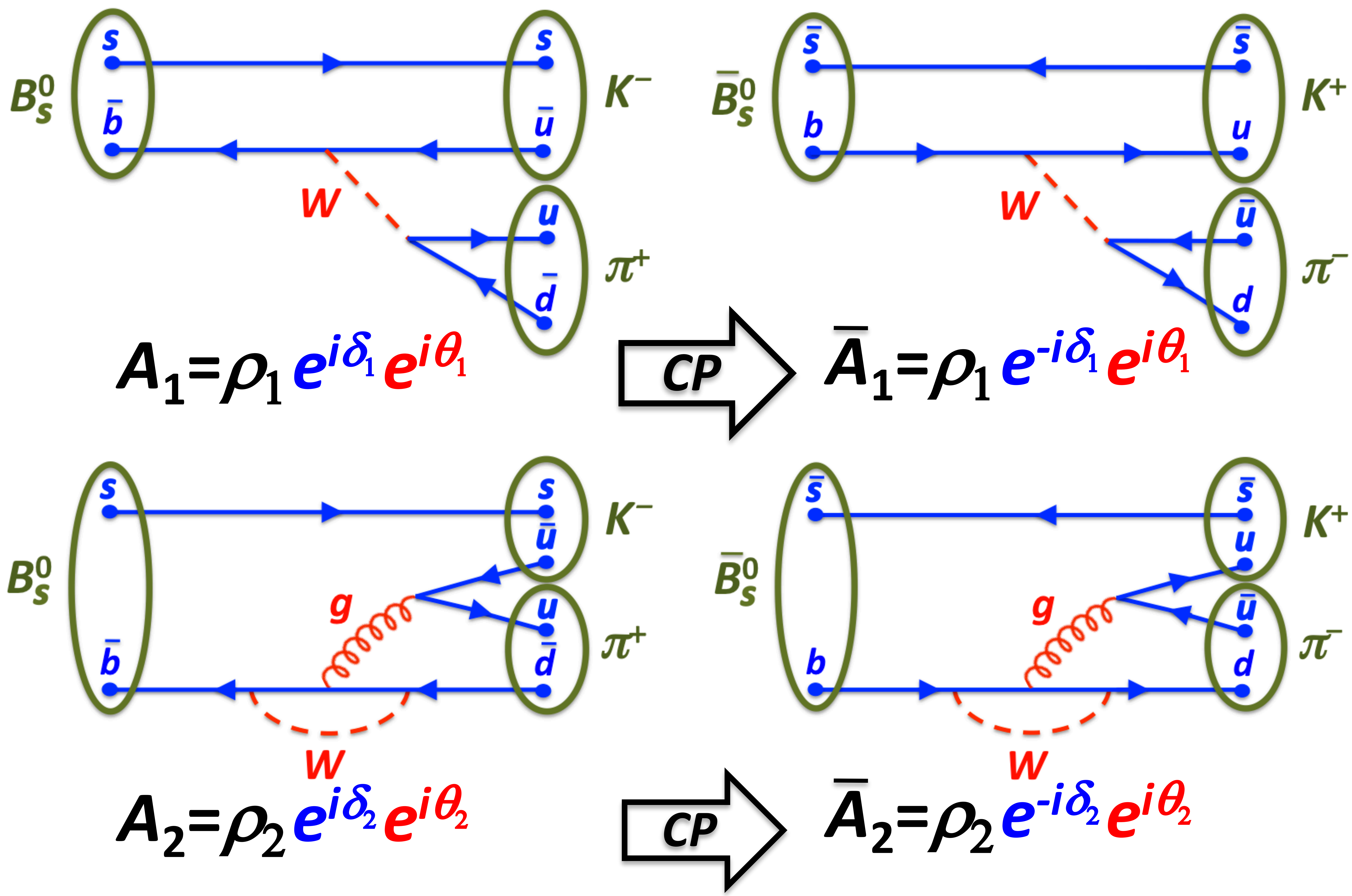
- For the CP-mirror image decay $\overline{B} \to \bar{f}$, every CKM element is replaced by complex conjugate, so CKM phases change sign while the strong phases don't (strong interactions are CP invariant)

$$A(\overline{B} \to \bar{f}) = |M|e^{-i\delta^f_{CKM}}e^{i\alpha_s} + |M'|e^{-i\delta'^f_{CKM}}e^{i\alpha'_s}$$

- So the difference in rate is proportional to

$$|A(B \to f)|^2 - |A(\overline{B} \to \bar{f})|^2 = 2|M||M'|\sin(\delta^f_{CKM} - \delta'^f_{CKM})\sin(\alpha_s - \alpha'_s)$$

Pictorially…



$$A_1 = \rho_1 e^{i\delta_1} e^{i\theta_1} \quad \xrightarrow{CP} \quad \bar{A}_1 = \rho_1 e^{-i\delta_1} e^{i\theta_1}$$

$$A_2 = \rho_2 e^{i\delta_2} e^{i\theta_2} \quad \xrightarrow{CP} \quad \bar{A}_2 = \rho_2 e^{-i\delta_2} e^{i\theta_2}$$

$$|A_1+A_2|^2 - |A_1+A_2|^2 = 4\rho_1\rho_2 \sin(\delta_1 - \delta_2)\sin(\theta_1 - \theta_2)$$

- The asymmetry becomes observable!

Example: time-integrated CP asymmetry in $B^0_{(s)} \to K^{\pm}\pi^{\mp}$ decays

- Count the number of $B \to f$ decays and compare with $\bar{B} \to \bar{f}$

- Measure time-integrated CP asymmetry

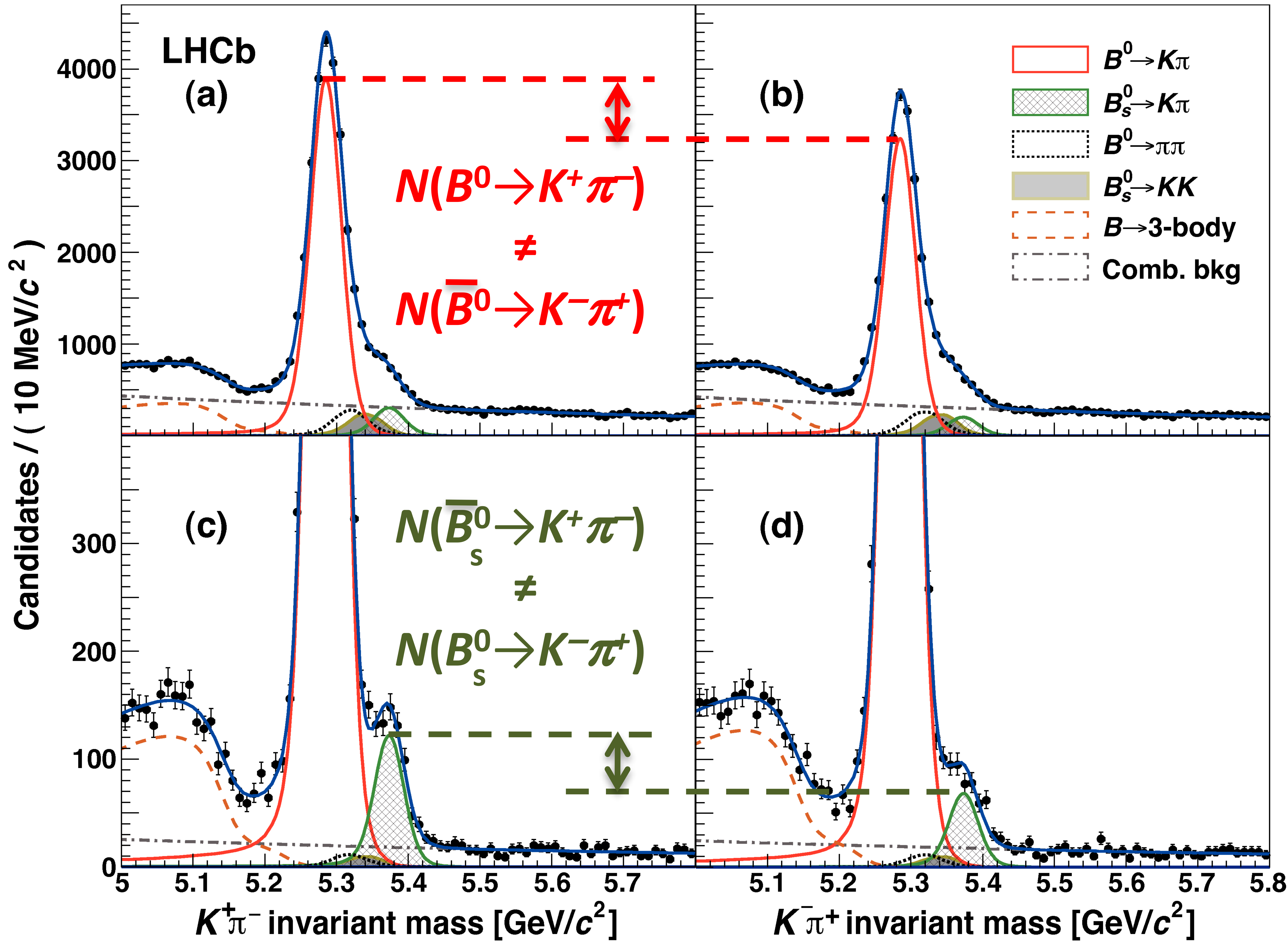
$$A_{CP} = \frac{\Gamma(\bar{B}^0_{(s)} \to \bar{f}) - \Gamma(B^0_{(s)} \to f)}{\Gamma(\bar{B}^0_{(s)} \to \bar{f}) + \Gamma(B^0_{(s)} \to f)}$$

- If $A_{CP} \neq 0$ → CP violation

Direct CP Violation

$$\Gamma(B \to f) \neq \Gamma(\bar{B} \to \bar{f})$$

First observation of CP violation in B_s mesons!



Phys. Rev. Lett. 110 (2013) 221601

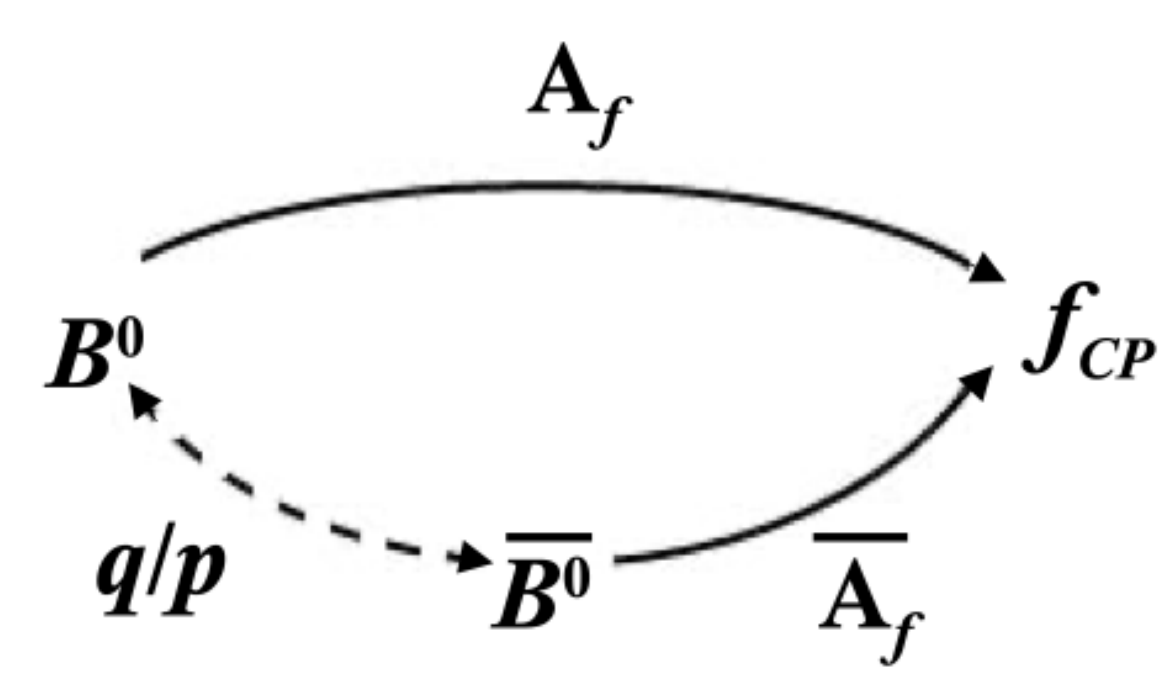
Classification of CP violating effects

- Direct CP violation:
  - $\Gamma(B \to f) \neq \Gamma(\overline{B} \to \bar{f})$
- CP violation in mixing:
  - $\Gamma(B^0 \to \overline{B}^0) \neq \Gamma(\overline{B}^0 \to B^0)$

Semileptonic decays of B^0 and $\overline{B}^0$ at the $Y(4S)$

$$A_{CP} = \frac{N_{++} - N_{--}}{N_{++} + N_{--}}$$

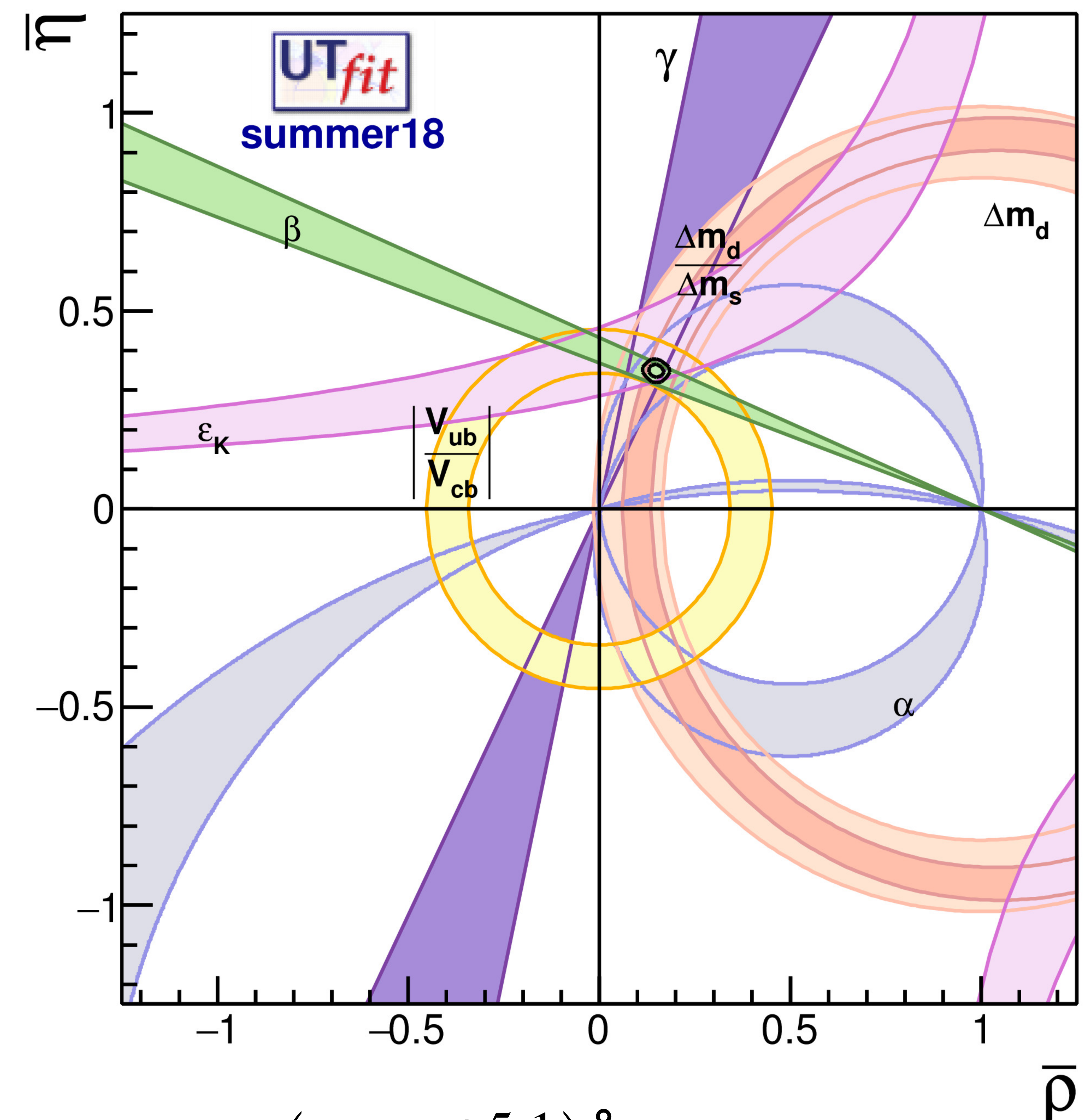
- CP violation in interference between oscillation and decay
  - $\Gamma(B^0_{(\to \overline{B}^0)} \to f)(t) \neq \Gamma(\overline{B}^0_{(\to B^0)} \to \bar{f})(t)$



Concluding on CKM metrology

- Among the most sensitive observables used to over constrain the unitarity triangle

  - Rates of charmless B decays, which depend on $|V_{ub}|$
  - Phase of $B^0 - \overline{B}^0$ mixing amplitude, which depend on $\sin 2\beta$
  - Rates of various $B \to DK$ decays , which constrain γ
  - Rate of various $B \to \pi\pi, \rho\pi, \rho\rho$ decays, which constrain α
  - The CP violating parameter in K mixing ϵ_K



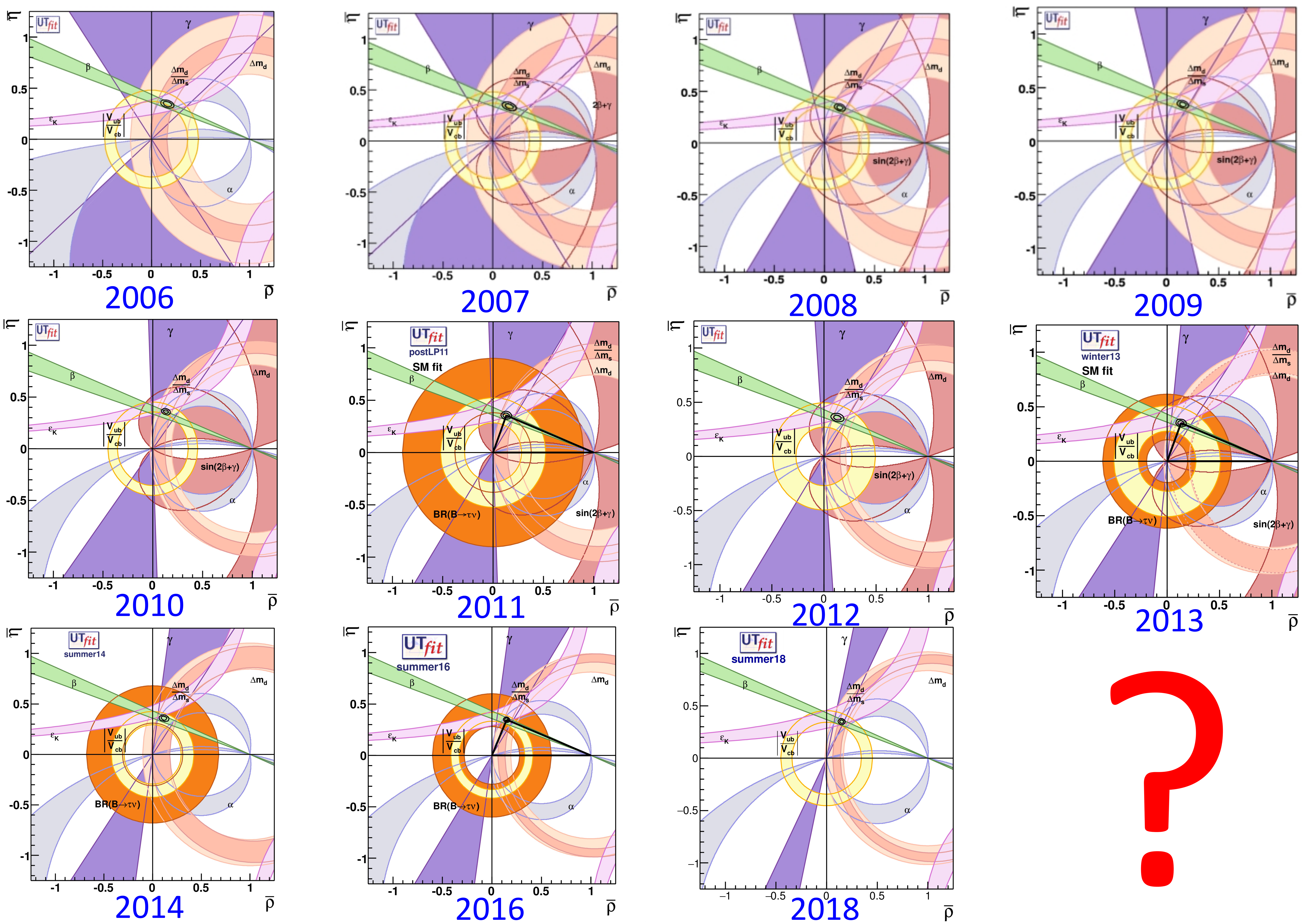
$$\alpha = \left(84.9^{+5.1}_{-4.6}\right)^\circ \quad (6\%)$$

$$\beta = (22.2 \pm 0.7)^\circ \quad (3\%)$$

$$\gamma = \left(71.1^{+4.6}_{-5.3}\right)^\circ \quad (7\%)$$

HFLAV 2018

A long journey…



What about CP Violation in charm?

- Extremely small level of CPV expected in charm with asymmetries typically of the order of 10^{-4}-10^{-3} in the SM

- This offers the opportunity for very sensitive null tests of the CKM picture

- Charm hadrons provide a unique opportunity to measure CP violation with particles containing only up-type quarks

- Caveat: theoretical predictions are difficult to compute reliably due to the presence of low-energy strong-interaction effects

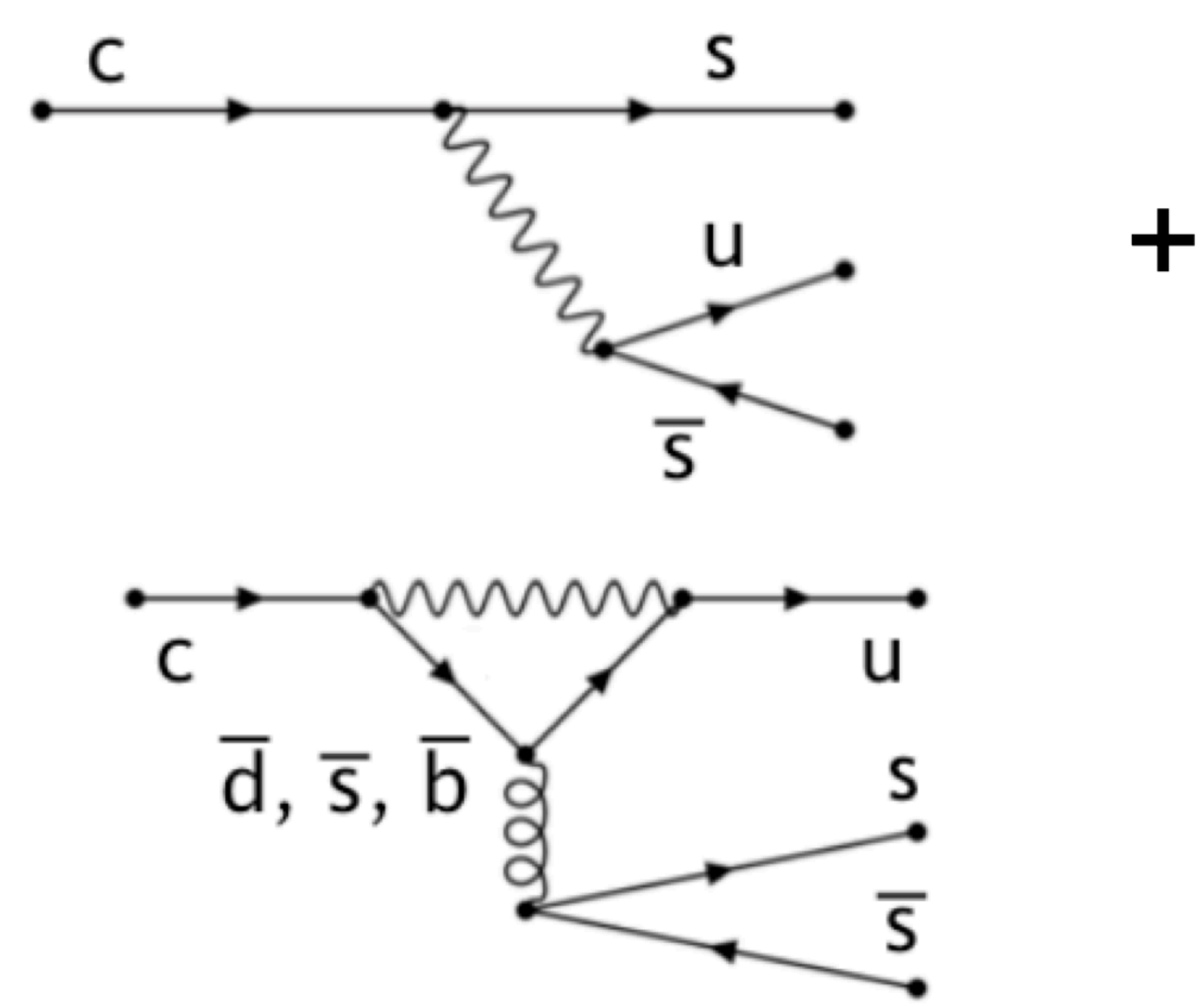
- LHCb studied he time-integrated CP-asymmetries in $D^0 \to K^+K^-, \pi^+\pi^-$ decays

Time-dependent CP asymmetry

- $$A_{CP}(f;t) = \frac{\Gamma(D^0(t) \to f) - \Gamma(\overline{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\overline{D}^0(t) \to f)}$$

$$f = K^+K^- \text{ or } \pi^+\pi^-$$

- These are channels where where CPV may arise from the interference between tree and penguin amplitudes

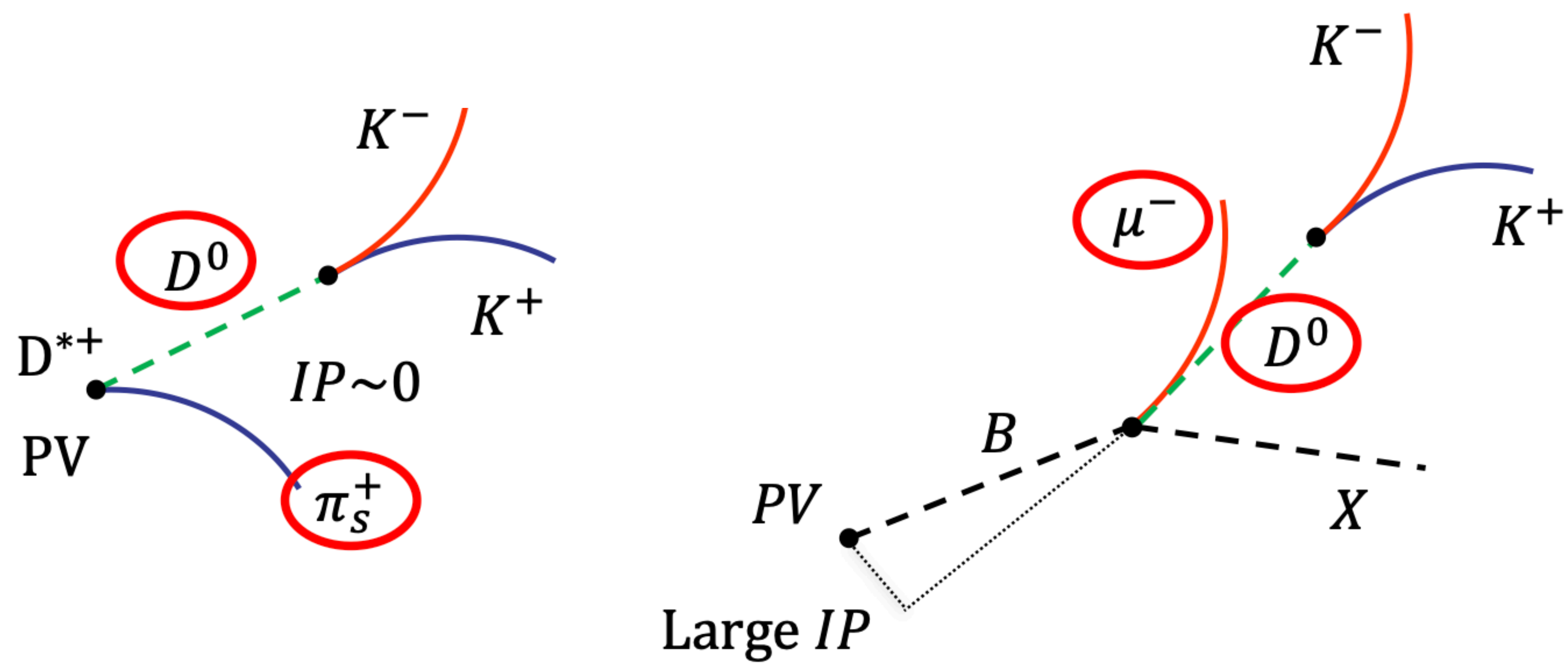


- $$A_{CP} \simeq a_{CP}^{\text{dir}}(f) - \frac{\langle t(f) \rangle}{\tau(D^0)} A_\Gamma(f)$$

where $a_{CP}^{\text{dir}}(f)$ is the direct CP asymmetry, $\langle t(f) \rangle$ is the mean decay time of $D \to f$ decays incorporating the effects of time-dependent experimental efficiency , $A_\Gamma(f)$ the asymmetry between the $D^0 \to f$ and $\overline{D}^0 \to f$ effective decay widths

The measurement

- D^0 mesons produced either promptly at collision point in the strong decay $D^{*+}(2010) \to D^0\pi^+$ or at a displaced vertex in semileptonic $\overline{B} \to D^0\mu^-\overline{\nu}_\mu X$



- Tag D^0 flavour either from π charge (π-tagged) or from μ charge (μ-tagged)

The measurement II

- The raw asymmetries are defined as:

$$A_{\text{raw}}^{\pi\text{-tagged}}(f) \equiv \frac{N\left(D^{*+} \to D^0(f)\pi^+\right) - N\left(D^{*-} \to \overline{D}^0(f)\pi^-\right)}{N\left(D^{*+} \to D^0(f)\pi^+\right) + N\left(D^{*-} \to \overline{D}^0(f)\pi^-\right)},$$

$$A_{\text{raw}}^{\mu\text{-tagged}}(f) \equiv \frac{N(\overline{B} \to D^0(f)\,\mu^-\bar{\nu}_\mu X) - N(B \to \overline{D}^0(f)\,\mu^+\nu_\mu X)}{N(\overline{B} \to D^0(f)\,\mu^-\bar{\nu}_\mu X) + N(B \to \overline{D}^0(f)\,\mu^+\nu_\mu X)}$$

- They can be approximated as:

$$A_{\text{raw}}^{\pi\text{-tagged}}(f) \approx A_{CP}(f) + A_{\text{D}}(\pi) + A_{\text{P}}(D^*)$$
$$A_{\text{raw}}^{\mu\text{-tagged}}(f) \approx A_{CP}(f) + A_{\text{D}}(\mu) + A_{\text{P}}(B),$$

- A_D are detection asymmetries due to different reconstruction efficiencies between positive and negative tagging π, μ
- A_P are production asymmetries of D^* and Bs due to hadronization of charm and beauty quarks

- …. and the trick is.. to take the difference:

$$\Delta A_{CP} = A_{\text{raw}}(K^+K^-) - A_{\text{raw}}(\pi^+\pi^-)$$

- A_D, A_P are independent of the final state and cancel in the difference!

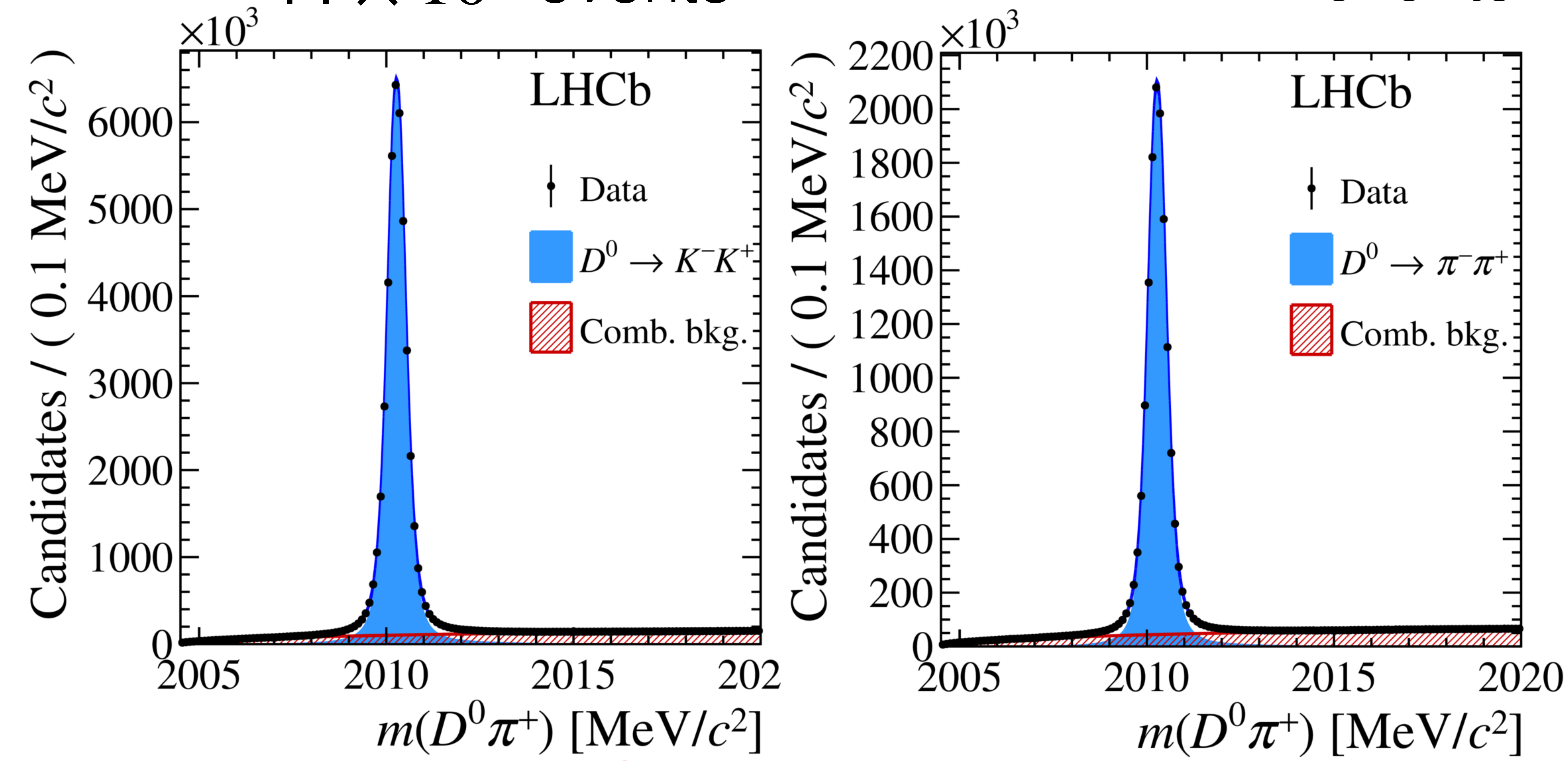
The yields

- Measurement performed with almost full Run-2 data- set (5.9/fb)
- Get the raw asymmetries from fits to the $m(D^0\pi^+)$ or $m(D^0)$ distributions

Phys. Rev. Lett. 122, 211803

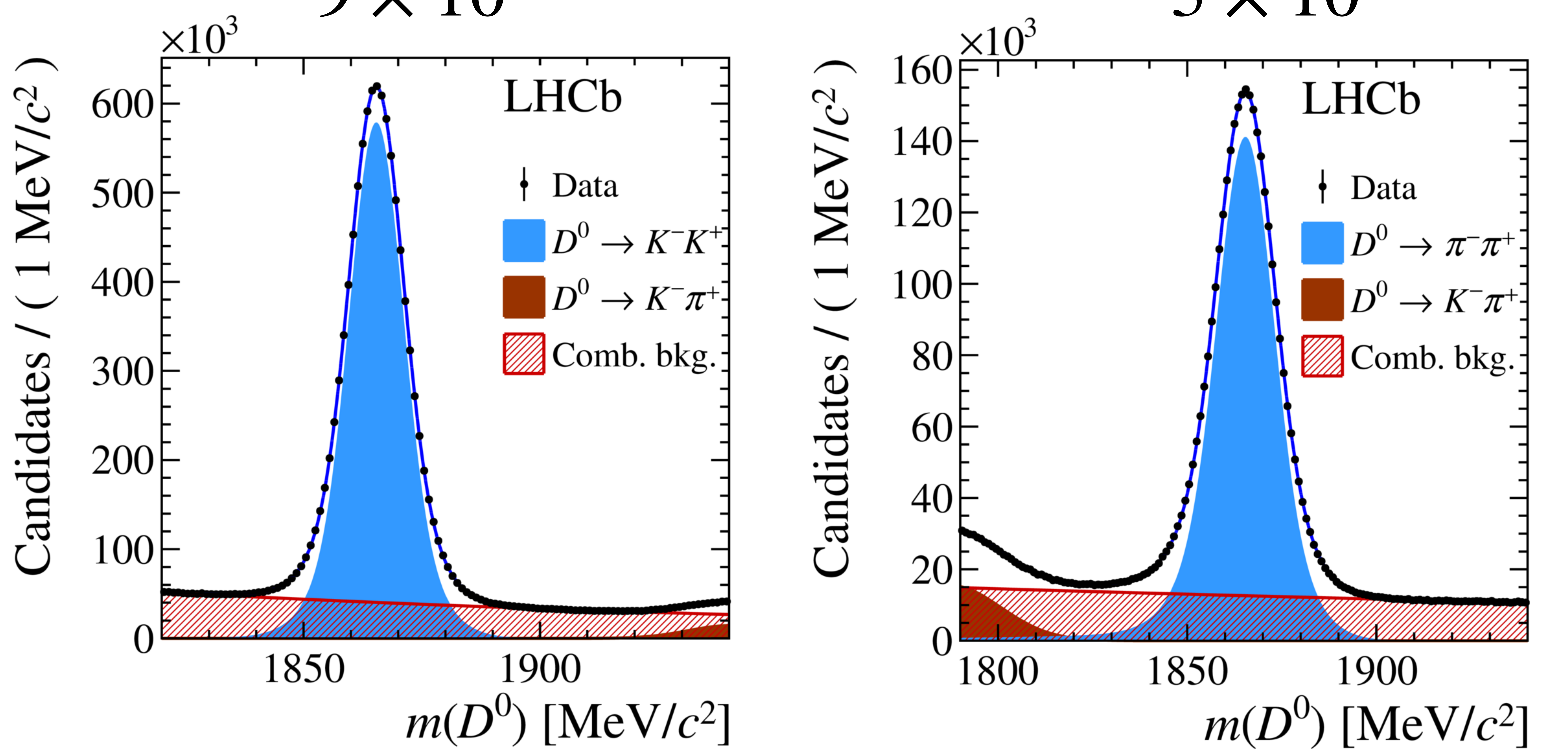
Prompt

44×10^6 events $\quad$ 14×10^6 events



Semileptonic

9×10^6 $\quad$ 3×10^6



Observation of CPV in charm decays

- Run 2 results alone

$$\Delta A_{CP}^{\pi\text{-tagged}} = [-18.2 \pm 3.2\,(\text{stat.}) \pm 0.9\,(\text{syst.})] \times 10^{-4}$$
$$\Delta A_{CP}^{\mu\text{-tagged}} = [-9 \pm 8\,(\text{stat.}) \pm 5\,(\text{syst.})] \times 10^{-4}$$

- Combing with Run 1

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

- A 5.3 σ measurement of CPV in the charm system !

- From $\Delta A_{CP} \simeq \Delta a_{CP}^{\text{dir}} - \frac{\Delta\langle t\rangle}{\tau(D^0)} A_\Gamma \rightarrow \Delta a_{CP}^{\text{dir}} = (-15.7 \pm 2.9) \times 10^{-4}$, which shows that ΔA_{CP} is primarily sensitive to direct CP violation

First presented at Moriond EW ‘19


Incidentally, Misha Danilov was also at
Moriond and this is where he lost his ski


And this is where
we found it!