

LHC*b* a *b*eautiful journey

Consiglio di sezione – INFN Pisa, 25/06/2024
Elena Graverini

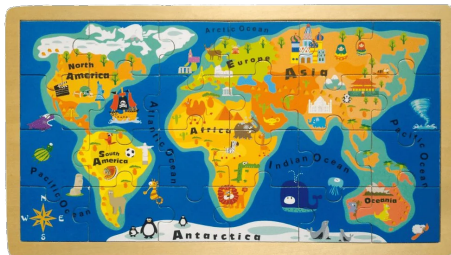


The LHCb experiment at LHC



The LHCb experiment at LHC

- 1050 authors from 99 institutes in 23 countries
- on CERN's LHC, that collides protons
 - each proton carries the energy of a mosquito buzzing around at 20 cm/s
 - (a mosquito contains $\sim 1'000'000'000'000$ billions protons)



Tu

calcola il numero di protoni in una zanzara



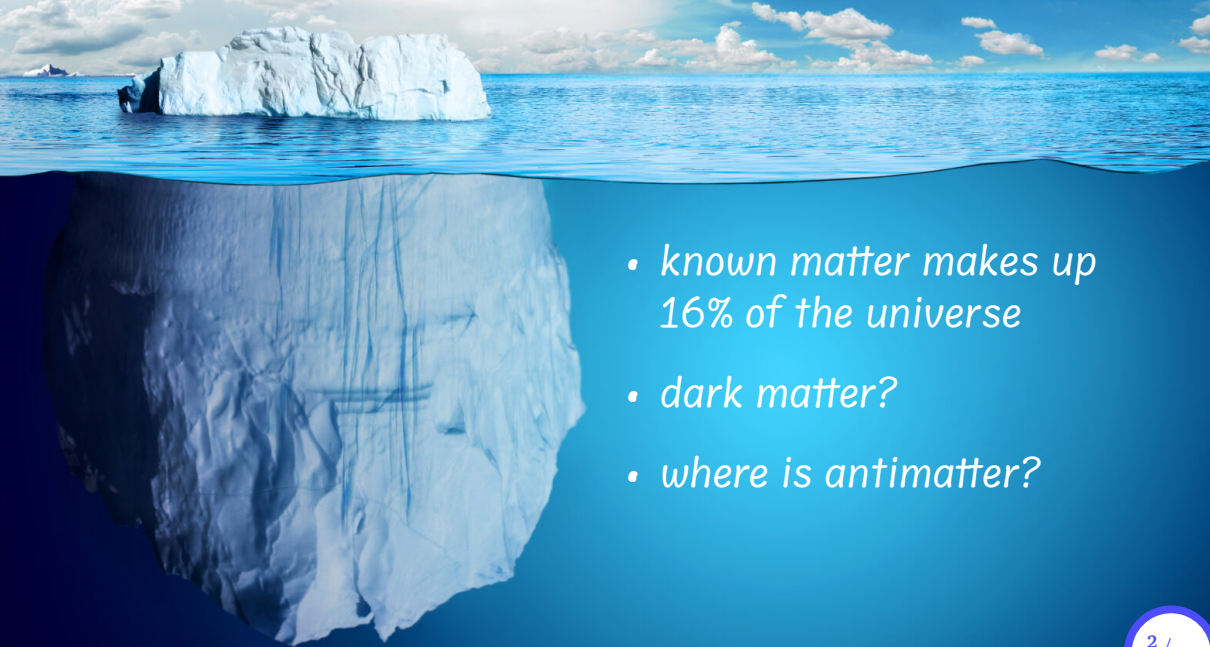
Copilot

✓ Generazione di risposte per te in corso...

Le zanzare sono piccoli insetti fastidiosi, ma la loro vita è breve e intensa. In media, una zanzara della specie più comune, la *Culex Pipiens*, vive tra i **12 e i 132 giorni** ¹. Ora, per calcolare il numero di protoni in una zanzara, dobbiamo considerare il suo numero atomico. L'elemento boro (B), ad esempio, ha un numero atomico pari a 5, il che significa che ha **5 protoni** ². Quindi, possiamo dire che una zanzara ha lo stesso numero di protoni del boro. 🐛

- from the pp collisions a heap of particles emerge, that are not normally present in nature





- *known matter makes up 16% of the universe*
- *dark matter?*
- *where is antimatter?*

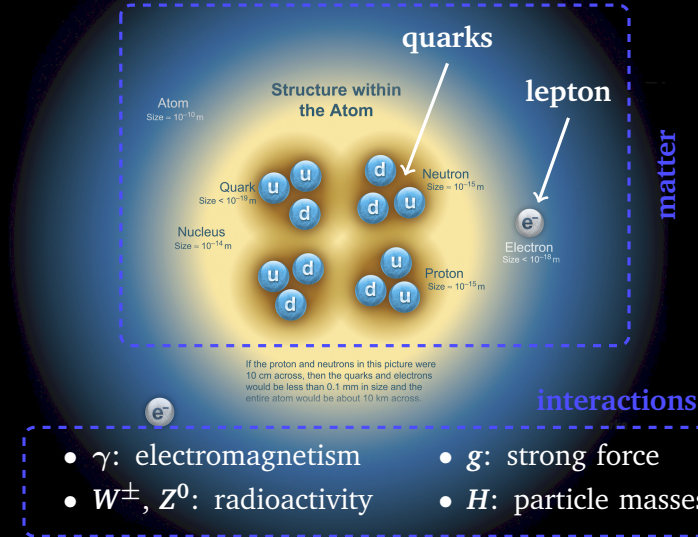
A “flavourful” take

The term *flavor* 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 color and flavor so do quarks ([Fritzsch, 2008](#)).

[RMP 81 (2009) 1887]

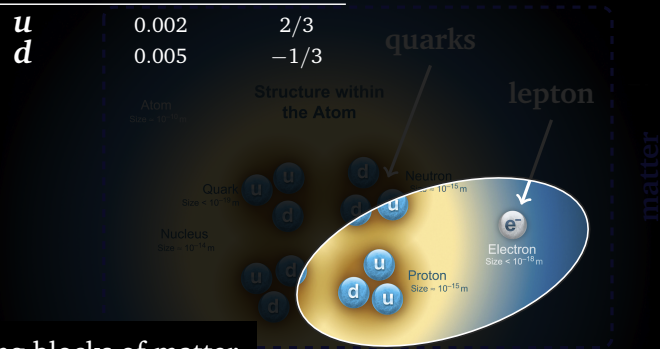
What is flavour? Why is it relevant?

Fundamental particles of the Standard Model



Fundamental particles of the Standard Model

Leptons			Quarks		
flavour	mass (GeV/c ²)	charge	flavour	mass (GeV/c ²)	charge
ν_e	$\lesssim 10^{-9}$	0	<i>u</i>	0.002	2/3
<i>e</i>	0.000511	-1	<i>d</i>	0.005	-1/3



e*, ν_e , *u*, *d: fundamental building blocks of matter

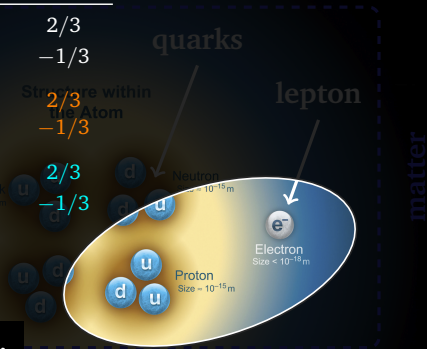
The electron and neutrons in this picture were scaled so that they were 1 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

interactions

- γ : electromagnetism
- $W^\pm, Z^0$: radioactivity
- g : strong force
- H : particle masses

Fundamental particles of the Standard Model

Leptons			Quarks		
flavour	mass (GeV/c ²)	charge	flavour	mass (GeV/c ²)	charge
ν_e	$\lesssim 10^{-9}$	0	<i>u</i>	0.002	2/3
<i>e</i>	0.000511	-1	<i>d</i>	0.005	-1/3
ν_μ	$\lesssim 10^{-9}$	0	<i>c</i>	1.3	2/3
<i>μ</i>	0.106	-1	<i>s</i>	0.1	-1/3
ν_τ	$\lesssim 10^{-9}$	0	<i>t</i>	173	2/3
<i>τ</i>	1.777	-1	<i>b</i>	4.2	-1/3



e*, ν_e , *u*, *d: fundamental building blocks of matter

...coming in **three** “identical” copies: **flavours!**

- γ : electromagnetism
- $W^\pm, Z^0$: radioactivity
- g : strong force
- H : particle masses

Fundamental particles of the Standard Model

Leptons			Quarks		
flavour	mass (GeV/c ²)	charge	flavour	mass (GeV/c ²)	charge
ν_e	$\lesssim 10^{-9}$	0	u	0.002	2/3
e	0.000511	-1	d	0.005	-1/3
ν_μ	$\lesssim 10^{-9}$	0	c	1.3	2/3
μ	0.106	-1	s	0.1	-1/3
ν_τ	$\lesssim 10^{-9}$	0	t	173	2/3
τ	1.777	-1	b	4.2	-1/3



Why are there three flavours?

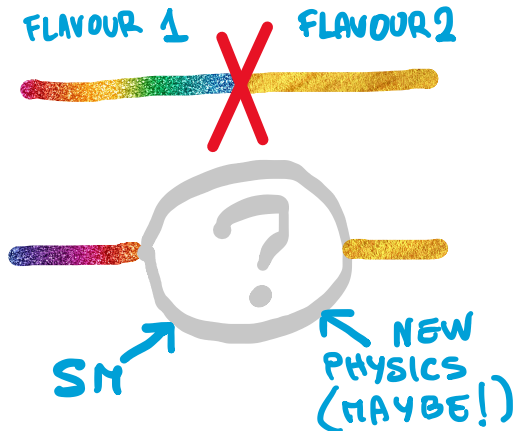
Why are the masses so different?

How do flavours transform into one another?

- $W^\pm, Z^0$: radioactivity
- H : particle masses

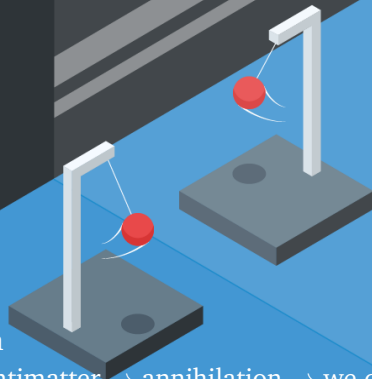
Flavour and new particles

- in the Standard Model, certain decays are prohibited: changing flavour without changing charge
- we know very well that laws can be circumvented if loopholes are found
- particles know, too, so they decay (much more rarely) via quantum loops
- new particles can hide in there
- we cannot observe them, but we can measure their effects



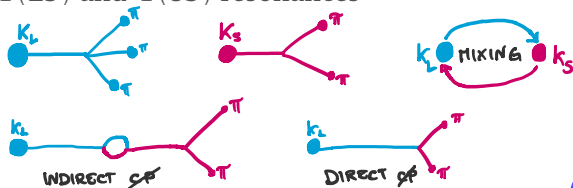
Flavour and matter/antimatter (a)symmetry

- CP symmetry transforms matter $\leftrightarrow$ antimatter
- if less than 3 families $\rightarrow$ no known source of CP violation
 - same amount of matter and antimatter $\rightarrow$ annihilation $\rightarrow$ we could not exist!
- we have 3 families! (could there be more?)
 - amount of CP violation measured in SM too small by several orders of magnitude to explain why we exist. Needs investigation.



Brief history of flavour

- 1953** discovery of “strange” particles: produced via strong force, decay by weak force
- 1956** weak interactions violate P : strange particles (K) decay to both $P = \pm 1$ states
- 1963** $\mathcal{B}(K \rightarrow \ell \nu) \ll \mathcal{B}(\pi \rightarrow \ell \nu)$: Cabibbo introduces mixing angle θ_C , weak quark couplings are not universal
- 1964** decays of neutral kaons violate CP symmetry: K mixing. Birth of the quark model.
- 1970** GIM mechanism: 4th quark “charm” (c) explains “strangeness” of weak interactions
- 1972** CKM: hey, by adding another two quarks (beauty b , top t) we get CP violation!
- 1974** discovery of charm quark. J/ψ gets two names due to scientific competition
- 1977** discovery of beauty quark in $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ resonances
- 1987** evidence of $B^0 - \bar{B}^0$ mixing
- 1999** direct CP violation in K decays
- 2001** CP violation in B mesons



Towards LHC

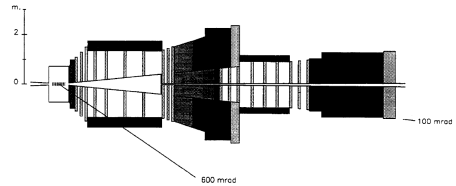
- b physics dominated by e^+e^- experiments
- some measurements at fixed-target experiments
- too few b 's, too much background
- **1993**: 3 beauty experiments proposed for LHC, main goal: measure CPV

COBEX pp collisions, forward direction

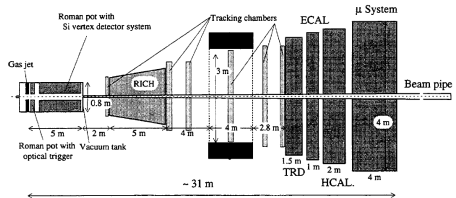
LHB extraction of p to fixed target

GAJET gas as fixed target

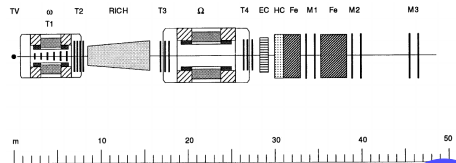
- CERN: merge the 3 collaborations and propose new collider-mode experiment → **LHCb** (1994)



Longitudinal cross section, **COBEX** proposal (CERN/LHCC 93-50)

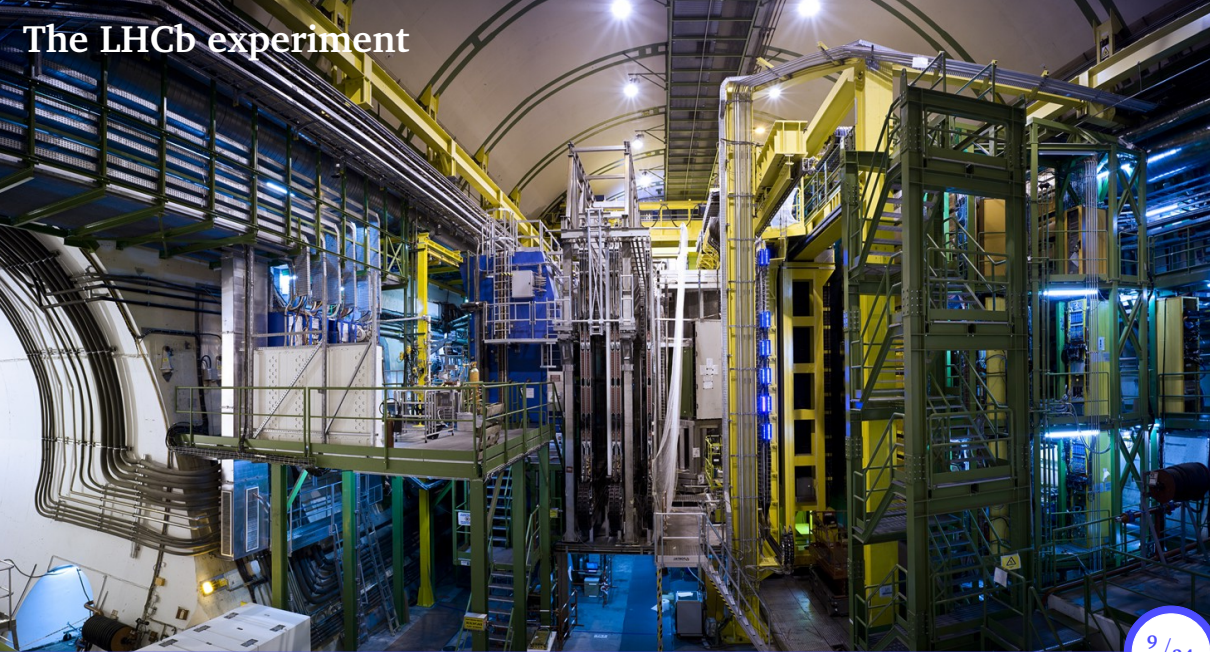


Longitudinal cross section, **GAJET** proposal (CERN/LHCC 93-54)

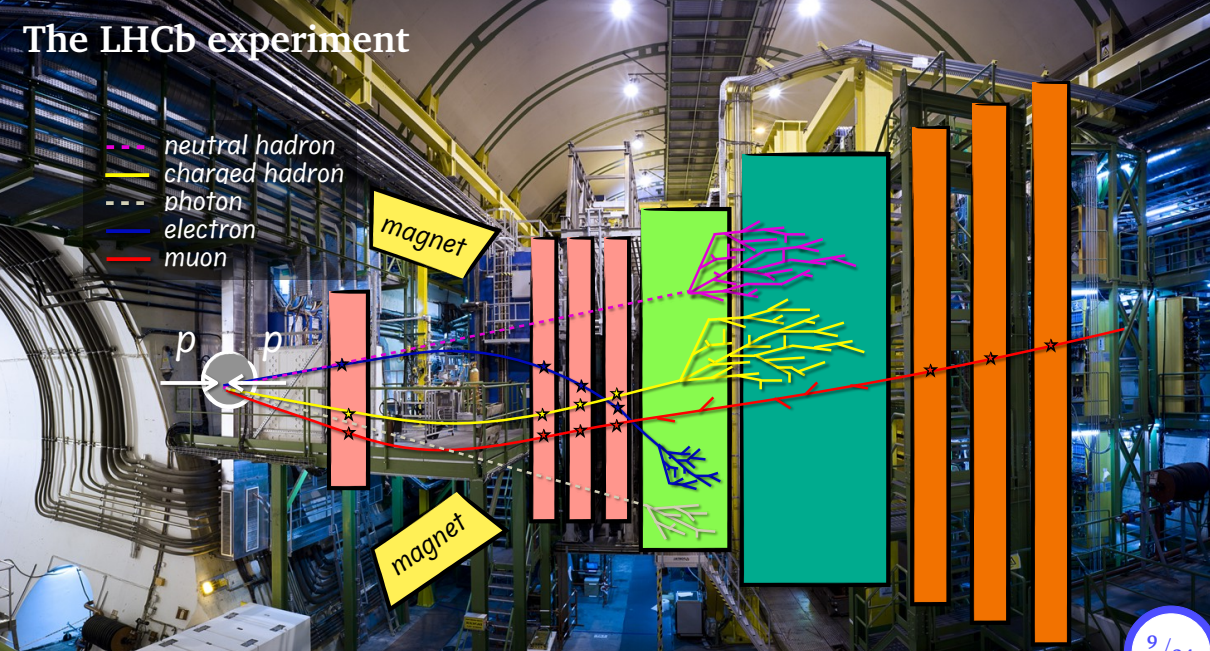


Longitudinal cross section, **LHB** proposal (CERN/LHCC 93-55)

The LHCb experiment

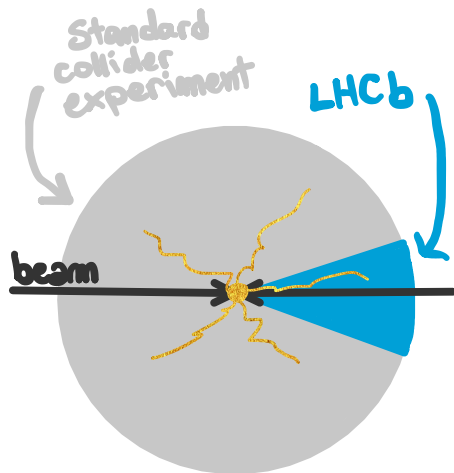


The LHCb experiment



Why that shape?

- LHCb different from other collider experiments
- the probability of producing $b\bar{b}$ pairs in pp collisions has a peak at small angles!
- detectors can be built more efficiently
 - e.g. the two RICH detectors (particle identification)
- detector organised in “planes” easier to navigate for installation / maintenance



Status of LHCb

- many changes to design introduced during construction
 - smoothly ran at higher-than-nominal pp rate 2011–2018
 - 2019 upgrade: replace all tracking detectors, replace all readout...
 - ...**drop hardware “trigger”**: this means that we analyse **5 TB/s** of data in real time, finally saving to disk 10 GB/s
- physics programme ranges wide beyond original goals
 - set new standards in beauty and charm physics
 - spectroscopy (discovered 67 new hadrons!)
 - electroweak, heavy ions, fixed target...
 - 738 papers on the arXiv, of which 720 published in peer-review journals
- here: focus on activities undertaken by Pisa group

LHCb in Pisa

Asymmetries

Trigger

Firmware

Charm

CPV

RETINA



Pisa
LHCb
LHCb

Tau

Rare decays

Real-time analysis

Simulation

Luminosity



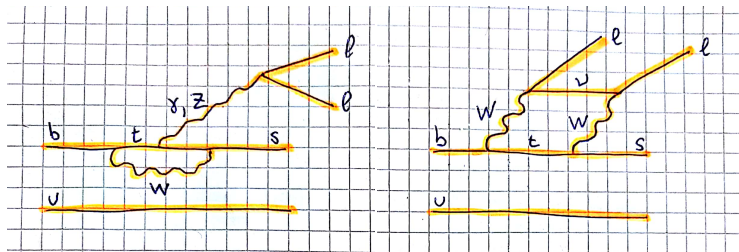
LHCb Pisa group

- largest LHCb group in Italy. Comprises people from INFN, SNS, Uni Pisa, Uni Siena
- plethora of activities (including many PhD and MSc theses)
- **Real-time Analysis (RTA)**: i.e. striving to minimize the latency between data acquisition and analysis, vital for high luminosity operation
 - here belongs the **RETINA** project
- **Simulation**: speeding up Monte Carlo simulation of complex detectors (Calo)
- **Data analysis**: leading expertise in charm physics and CP violation, and the search for new physics in rare and ultra-rare decays
- **Interaction region**: study and real-time monitoring of vital collider parameters: luminosity, relative position between detector and lumi region
- here, can only show you **small subset** of activities!

New physics in rare decays

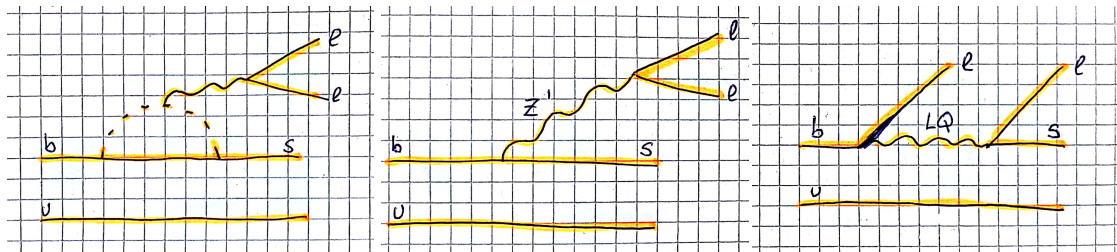


Vedo-non-vedo



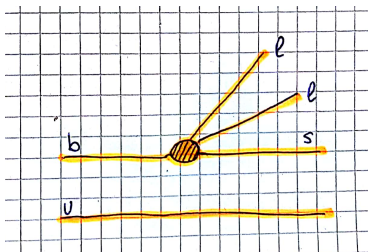
- look for new physics where it is easier to hide it: **rare stuff**
 - Flavour Changing Neutral Currents suppressed in SM $\Rightarrow$ NP contrib. can be sizeable
 - effective indirect search for new particles
 - not limited by collision energy
- we only **see** the final-state particles
- but we can **infer** about decay mediators
 - language: Effective Field Theory $\rightarrow$ measurable coefficients

Vedo-non-vedo



- look for new physics where it is easier to hide it: **rare stuff**
 - Flavour Changing Neutral Currents suppressed in SM $\Rightarrow$ NP contrib. can be sizeable
 - effective indirect search for new particles
 - not limited by collision energy
- we only **see** the final-state particles
- but we can **infer** about decay mediators
 - language: Effective Field Theory $\rightarrow$ measurable coefficients

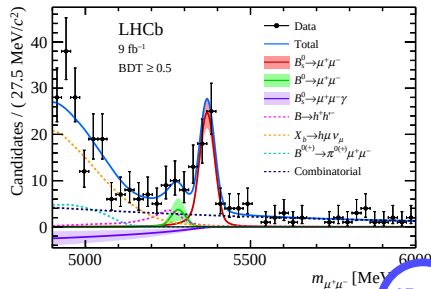
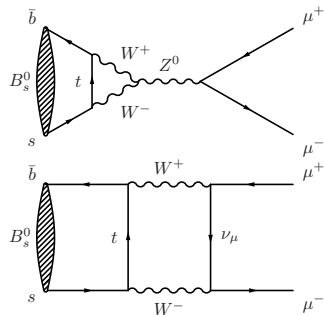
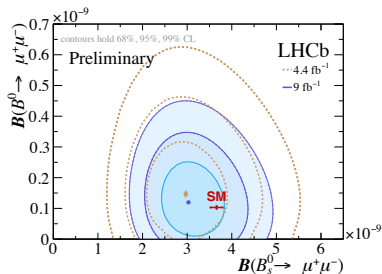
Vedo-non-vedo



- look for new physics where it is easier to hide it: **rare stuff**
 - Flavour Changing Neutral Currents suppressed in SM $\Rightarrow$ NP contrib. can be sizeable
 - effective indirect search for new particles
 - not limited by collision energy
- we only **see** the final-state particles
- but we can **infer** about decay mediators
 - language: Effective Field Theory $\rightarrow$ measurable coefficients

$$B_s \rightarrow \mu^+ \mu^-$$

- $b \rightarrow s \ell \ell$ at the quark level (FCNC $\rightarrow$ rare)
- $B_{(s)} \rightarrow \mu^+ \mu^-$ even rarer, due to helicity
- SM calculations very precise, indicating B_s decays to $\mu^+ \mu^- \sim 3.66$ times every billion decays
 - any deviation would signal new physics!
- first seen in 2015 in LHCb+CMS data
- measured with whole dataset, compatible with SM!



Why have we all gone nuts over $b \rightarrow s\ell\ell$

$b \rightarrow s\ell\ell$ can also have a hadron in the final state. Over the past decade, *tensions* with respect to the SM predictions accumulated in *different* observables:

1. Branching Fractions

$$B \rightarrow K^{(*)}\mu^+\mu^-, B_s \rightarrow \phi\mu^+\mu^-, \Lambda_b \rightarrow \Lambda\mu^+\mu^-, \dots$$

suffer from uncertainties related to the hadronic matrix element

2. Angular observables

$$B \rightarrow K^{(*)}\mu^+\mu^-, \Lambda_b \rightarrow \Lambda\mu^+\mu^-, \dots$$

profit from cancellation of most form factors

3. Ratios of branching fractions involving μ/e

$$B^0 \rightarrow K^{*0}\ell^+\ell^-, B^+ \rightarrow K^+\ell^+\ell^-, \dots$$

all theoretical uncertainties cancel



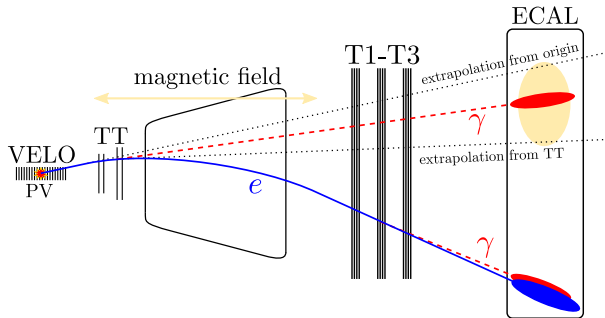
Electron vs. muons

- in the SM, decays to all lepton generations are equally probable

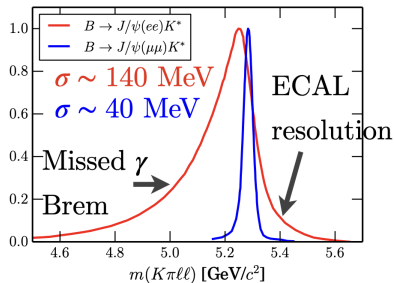
- $$m_\ell \ll m_B \implies R_K^{\text{SM}} = \frac{\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)} \bigg|_{[q_{\min}^2, q_{\max}^2]} = \mathbf{1} \pm \mathcal{O}(10^{-2})_{(\text{QED})} \pm \mathcal{O}(10^{-4})_{(\text{QCD})}$$

[JHEP 12 (2007) 040] [EPJC 76 (2016) 440]

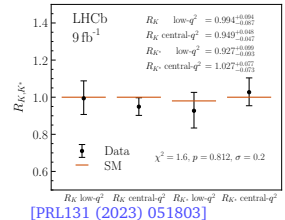
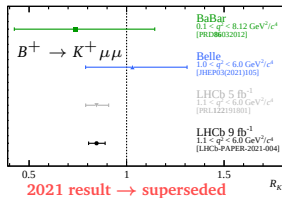
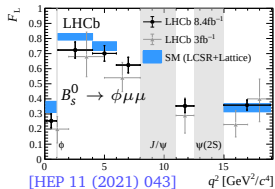
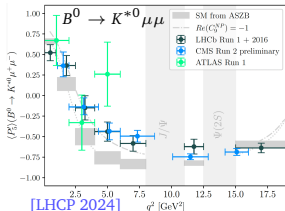
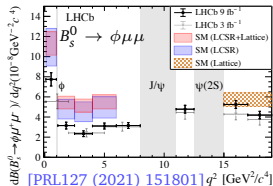
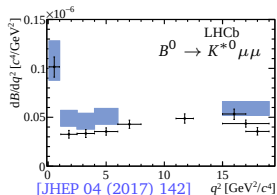
- electrons are the experimental limiting factor: ECAL trigger thresholds, resolution



Mass resolution: **muons** vs **electrons**

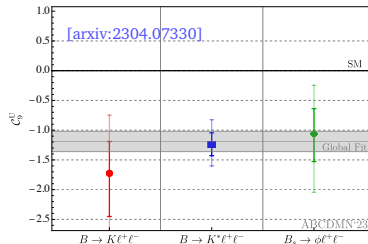


“Flavour anomalies”



What now?

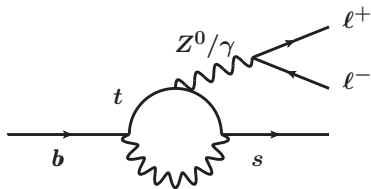
- culprit: misunderstanding of doubly-misidentified backgrounds
 - e.g. $B \rightarrow KKK$ posing as $B \rightarrow Kee$
- removes the “cleanest” anomaly from the pool, but the remaining ones have a 4-5 σ tension with the SM



- why are we not claiming new physics?
- $b \rightarrow s c \bar{c}$, $c \bar{c} \rightarrow \mu \mu$ background difficult to calculate, needs help from measurements

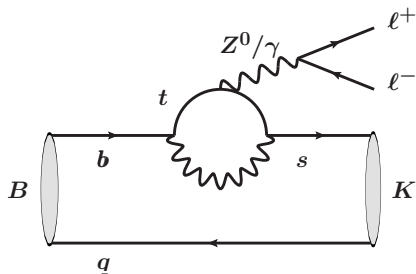


Fully exploit the available data

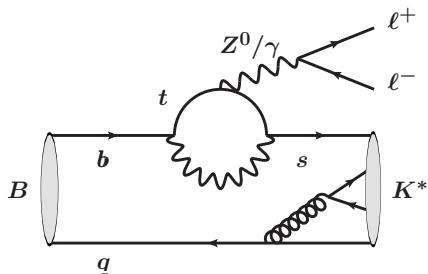


Fully exploit the available data

- quarks do not exist unbound
 - study various *hadron* decays

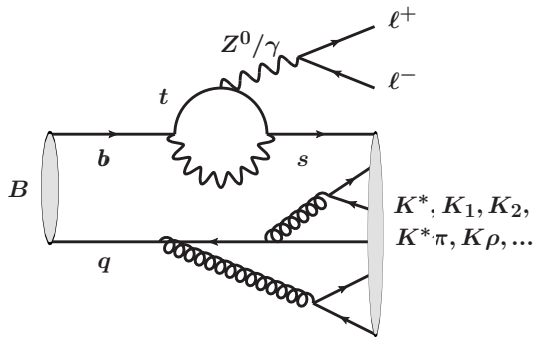


Fully exploit the available data



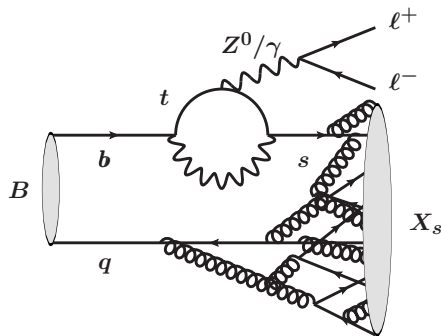
- quarks do not exist unbound
 - study various *hadron* decays
- theoretical descriptions grow complex

Fully exploit the available data



- quarks do not exist unbound
 - study various *hadron* decays
- theoretical descriptions grow complex

Fully exploit the available data



- quarks do not exist unbound
 - study various *hadron* decays
- theoretical descriptions grow complex
- **sum all decays together**: easier theoretical treatment
- extract maximum of information from **largest** data sample available

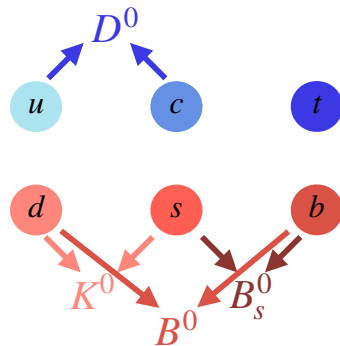
algorithm for inclusive selection of
 $B \rightarrow X_s \ell^+ \ell^-$ under development

Charm and CPV

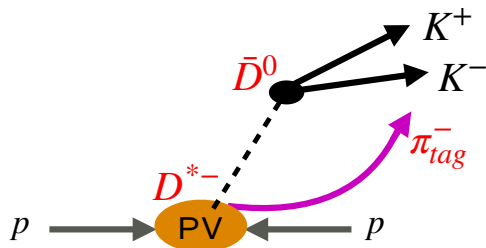
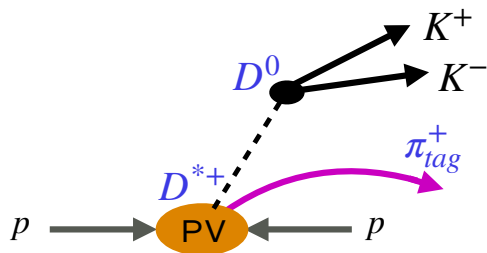


CP violation in charm

- CPV is observed in strange and beauty systems, but...
- $D^0 - \bar{D}^0$ is the only neutral system with up-type quarks!
- there could be **new** sources of CPV which only act on up-type quarks
- SM prediction $\mathcal{O}(10^{-4} - 10^{-3})$.
LHCb: $\Delta a_{CP}^d = (-15.7 \pm 2.9) \times 10^{-4}$ [PRD75, 036008][JHEP 12(2019)104]
- how to measure it?

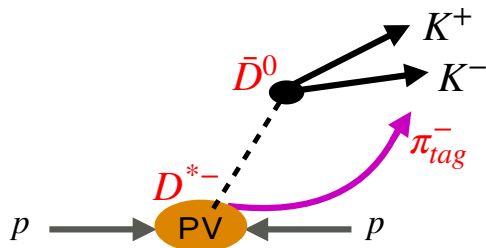
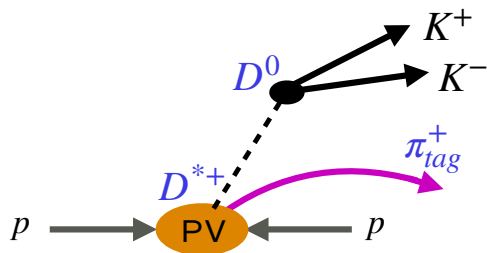


Measuring CPV: $D^0 \rightarrow K^+ K^-$



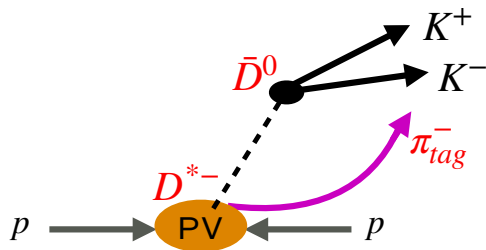
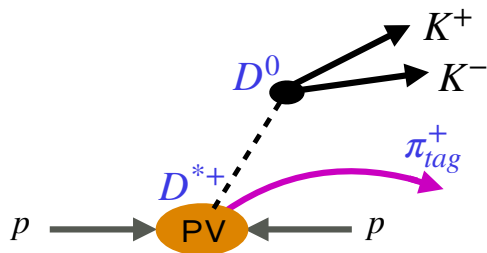
- measure relative difference between yields of $D^0 \rightarrow K^+ K^-$ and $\bar{D}^0 \rightarrow K^+ K^-$
- how to I know if it was a D^0 or $\bar{D}^0$? $\rightarrow$ take it from $D^{*+} \rightarrow D^0 \pi^+$
- are D^{*+} and π^+ sufficiently symmetric (production, detection)? $\rightarrow$ **no**

Measuring CPV: $D^0 \rightarrow K^+ K^-$



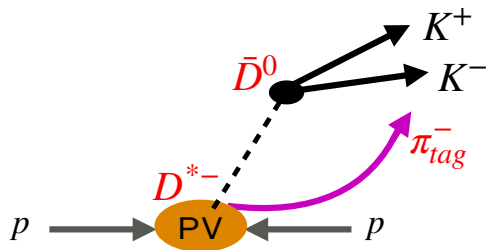
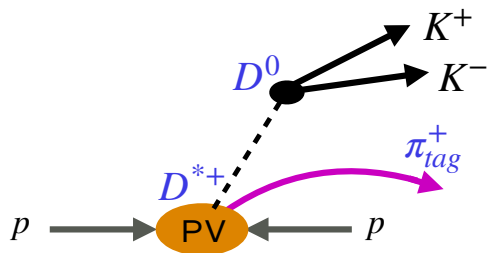
- measure relative difference between yields of $D^0 \rightarrow K^+ K^-$ and $\bar{D}^0 \rightarrow K^+ K^-$
- how to I know if it was a D^0 or $\bar{D}^0$? $\rightarrow$ take it from $D^{*+} \rightarrow D^0 \pi^+$
- are D^{*+} and π^+ sufficiently symmetric (production, detection)? $\rightarrow$ **no**
- **subtract** asymmetries measured in **control channels** such as $D^{*+} \rightarrow D^0 (\rightarrow \bar{K}^0 \pi^+ \pi^-) \pi^+$

Measuring CPV: $D^0 \rightarrow K^+ K^-$



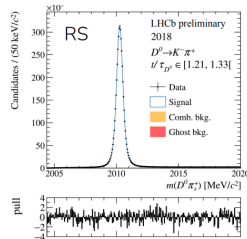
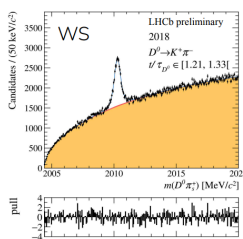
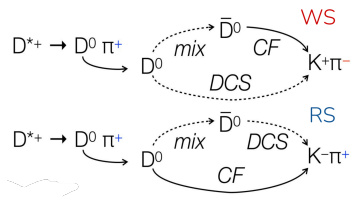
- measure relative difference between yields of $D^0 \rightarrow K^+ K^-$ and $\bar{D}^0 \rightarrow K^+ K^-$
- how to I know if it was a D^0 or $\bar{D}^0$? $\rightarrow$ take it from $D^{*+} \rightarrow D^0 \pi^+$
- are D^{*+} and π^+ sufficiently symmetric (production, detection)? $\rightarrow$ **no**
- **subtract** asymmetries measured in **control channels** such as $D^{*+} \rightarrow D^0 (\rightarrow \bar{K}^0 \pi^+ \pi^-) \pi^+$
- are $\bar{K}^0$ and $\pi^+ \pi^-$ sufficiently symmetric?

Measuring CPV: $D^0 \rightarrow K^+ K^-$



- measure relative difference between yields of $D^0 \rightarrow K^+ K^-$ and $\bar{D}^0 \rightarrow K^+ K^-$
- how to I know if it was a D^0 or $\bar{D}^0$? $\rightarrow$ take it from $D^{*+} \rightarrow D^0 \pi^+$
- are D^{*+} and π^+ sufficiently symmetric (production, detection)? $\rightarrow$ **no**
- **subtract** asymmetries measured in **control channels** such as $D^{*+} \rightarrow D^0 (\rightarrow \bar{K}^0 \pi^+ \pi^-) \pi^+$
- are $\bar{K}^0$ and $\pi^+ \pi^-$ sufficiently symmetric? **no** but **can be modeled/controlled** :)

Measuring mixing and CPV: $D^0 \rightarrow K\pi$



- measure time-dependent “wrong sign” to “right sign” decay yield $R(t)$

6 parameters of interest: $R_{K\pi}$, mixing & CPV parameters.

$$R_{ty}^{\pm} \equiv [R_{K\pi}(1 \pm A_{K\pi}) + \sqrt{R_{K\pi}(1 \pm A_{K\pi})} (c_{K\pi} \pm \Delta c_{K\pi})] \langle T \rangle_{ty}^{\pm} + (c'_{K\pi} \pm \Delta c'_{K\pi}) \langle T^2 \rangle_{ty}^{\pm} \times (1 \pm 2A_{ty} - C) + D$$

removed common WS

doubly mis-ID

$$\langle T \rangle_{ty}^{\pm} \equiv (\langle t \rangle_{ty}^{\pm} - \langle \delta T \rangle_{ty}) \cdot S$$

decay-time bias

$m(D^0)/\tau(D^0)$ ext. input

$$A_{ty} \equiv A_{ty}^{\text{raw}}(KK) - a_{KK}^d - \Delta Y \cdot \langle T \rangle_{ty}$$

raw KK asymmetry

direct KK CP asymmetry input

time dep. KK CP asymmetry input

Measuring mixing and CPV: $D^0 \rightarrow K\pi$

Mixing observables

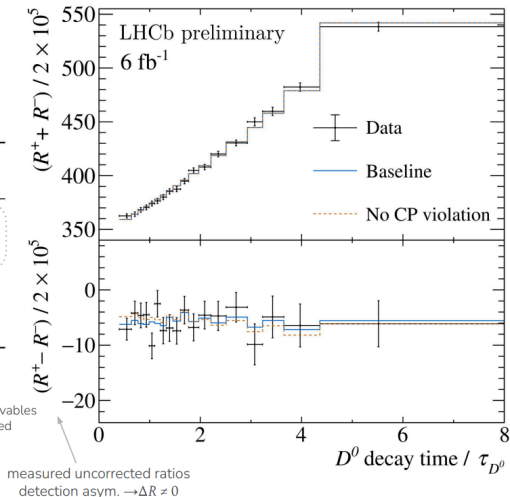
$c'_{K\pi} \neq 0$ (3.5σ) evidence for a significant quadratic term

Parameters	Correlations (%)					
	$R_{K\pi}$	$c_{K\pi}$	$c'_{K\pi}$	$A_{K\pi}$	$\Delta c_{K\pi}$	$\Delta c'_{K\pi}$
$R_{K\pi}$	$(343.1 \pm 2.0) \times 10^{-5}$	100.0	-92.4	80.0	0.9	-0.8
$c_{K\pi}$	$(51.4 \pm 3.5) \times 10^{-4}$		100.0	-94.1	-1.4	1.4
$c'_{K\pi}$	$(13.1 \pm 3.7) \times 10^{-6}$			100.0	0.7	-0.7
$A_{K\pi}$	$(-7.1 \pm 6.0) \times 10^{-3}$				100.0	-91.5
$\Delta c_{K\pi}$	$(3.0 \pm 3.6) \times 10^{-4}$					100.0
$\Delta c'_{K\pi}$	$(-1.9 \pm 3.8) \times 10^{-6}$					

CPV observables

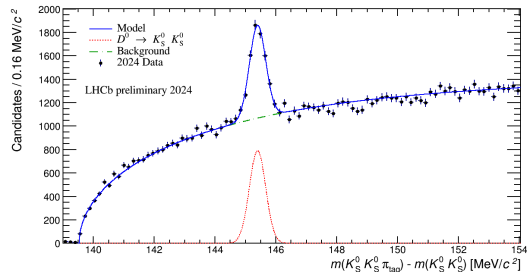
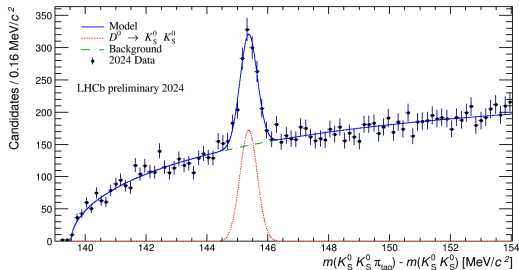
No evidence of CPV neither in decay, mixing nor interference

mixing and CPV observables largely uncorrelated

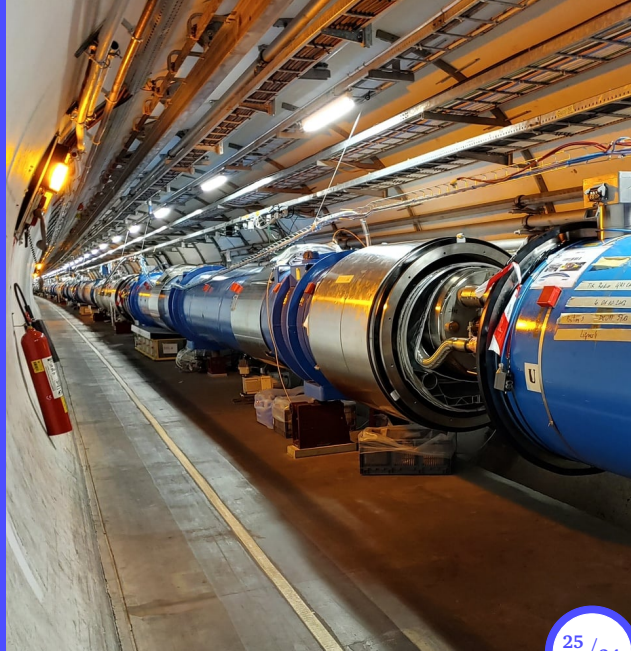


What about neutral kaons?

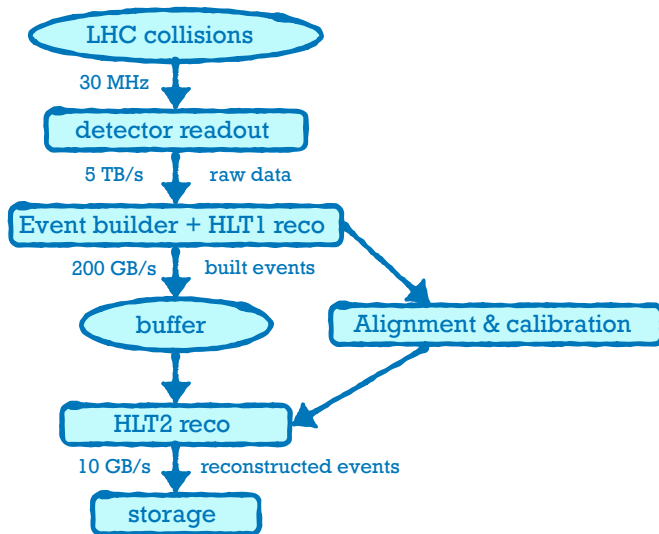
- Run 1-2: no efficient selections!
- add new “trigger” line for Run 3 for K_S : first look at $D^0 \rightarrow K_S K_S$
 - $\times$ **4.4 rate**
 - resolution on CP parameters: $\sigma(a_{CP}) = 1.2\% \rightarrow$ **0.6%!**



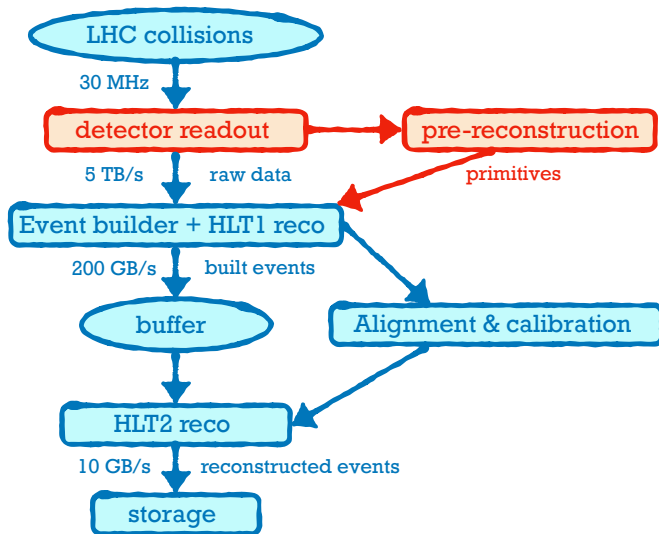
Real time analysis and luminosity



LHCb data processing model



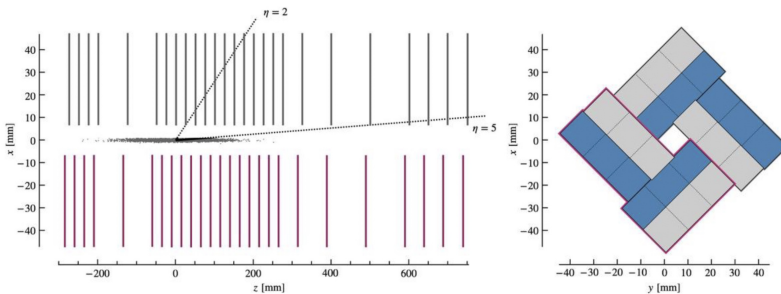
LHCb data processing model



Primitives

- raw data $\longrightarrow$ primitives $\longrightarrow$ higher level objects
 - push data processing before event building: pre-reconstruct **primitives** with local info
 - replace raw data with primitives: save HLT1 resources
 - reduce input data flow + accelerate HLT1 and HLT2 reconstruction
 - **however**: building primitives must happen at 30 MHz (pp rate)
 - embed calculation in detector readout or (if complex) external boards (FPGA)
- $\longrightarrow$ LHCb-Pisa: leading development of **Artificial RETINA** since 10 years
- fast and scalable pattern-matching method inspired by vision processing in human brain

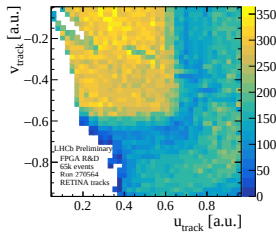
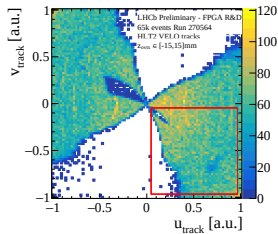
Embedded clustering



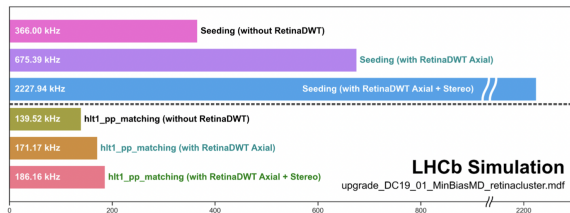
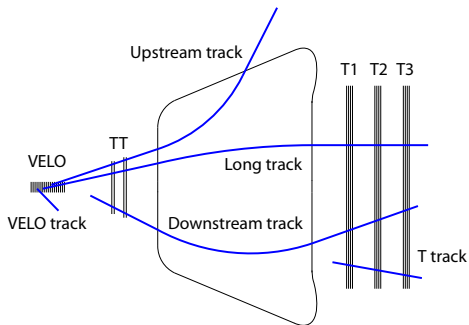
- the LHCb Vertex LOcator is our detector closest to the pp collision (~ 2 mm)
- first successful application of RETINA idea: raw hits $\longrightarrow$ positions of clusters
- after careful testing, now implemented and **fully adopted** in LHCb Run 3
- reduce input bandwidth by 15%, saving 12% HLT1 resources and using only $1/50^{\text{th}}$ of electrical power

RETINA demonstrator

- pattern recognition embedded in detector readout:
Velo pixels $\rightarrow$ array of aligned hits $\rightarrow$ tracks
- enhancement developed for high-luminosity LHC
 - can already use in Run 4!
- demonstrator installed and tested with live data at LHCb
- smooth reconstruction of tracks in one VELO quadrant



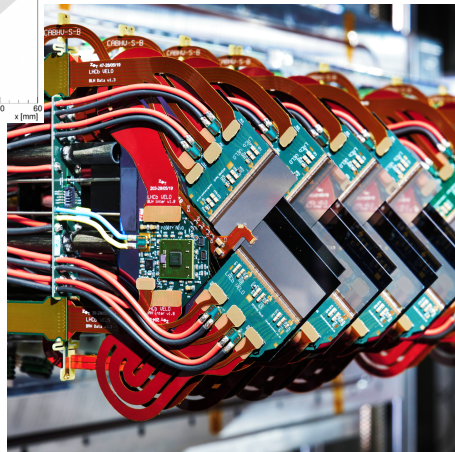
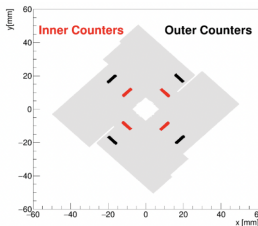
Downstream tracking



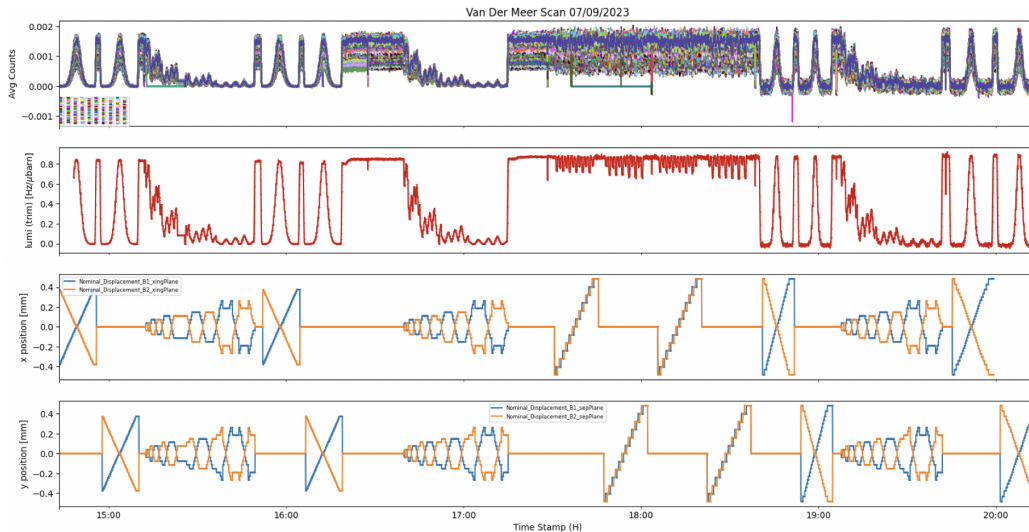
- track segments from T1,2,3 currently used as seed for HLT1 track reconstruction
- **replace** with two-step RETINA: xy then uv layers
- seeding ($1.5 \mu s$) $\rightarrow$ primitive refitting ($0.06 \mu s$). HLT1 throughput increased by **33%**!
- Run 4: install in external servers. Run 5: 100 new readout boards
- physics: neutral kaons ($D^0 \rightarrow K_s K_s$, $K_s \rightarrow \mu\mu$), search for long lived particles

More complex quantities!

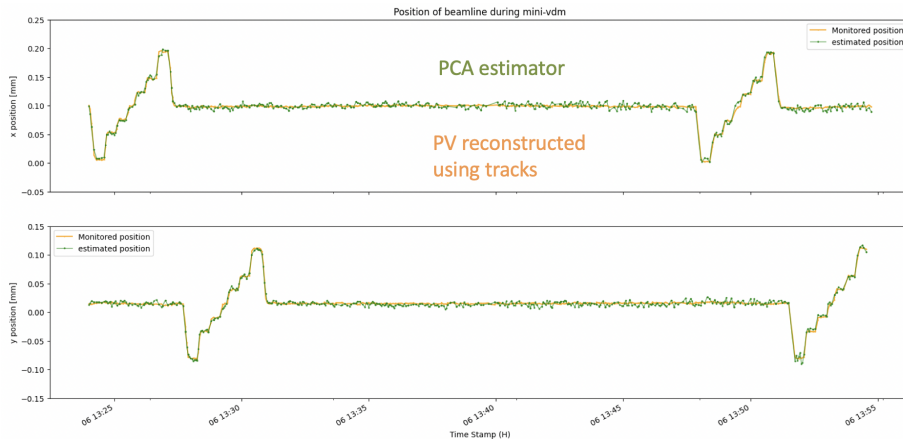
- embedded cluster finding made 10^{11} hits/s available
- can surely do something useful with these?
- *precision monitoring of interaction region parameters, in real time*
- **luminosity** measures how many pp collisions LHC delivers
- can also monitor the position where the beams overlap, and that of the **VELO modules**



Instantaneous luminosity during vdM scan

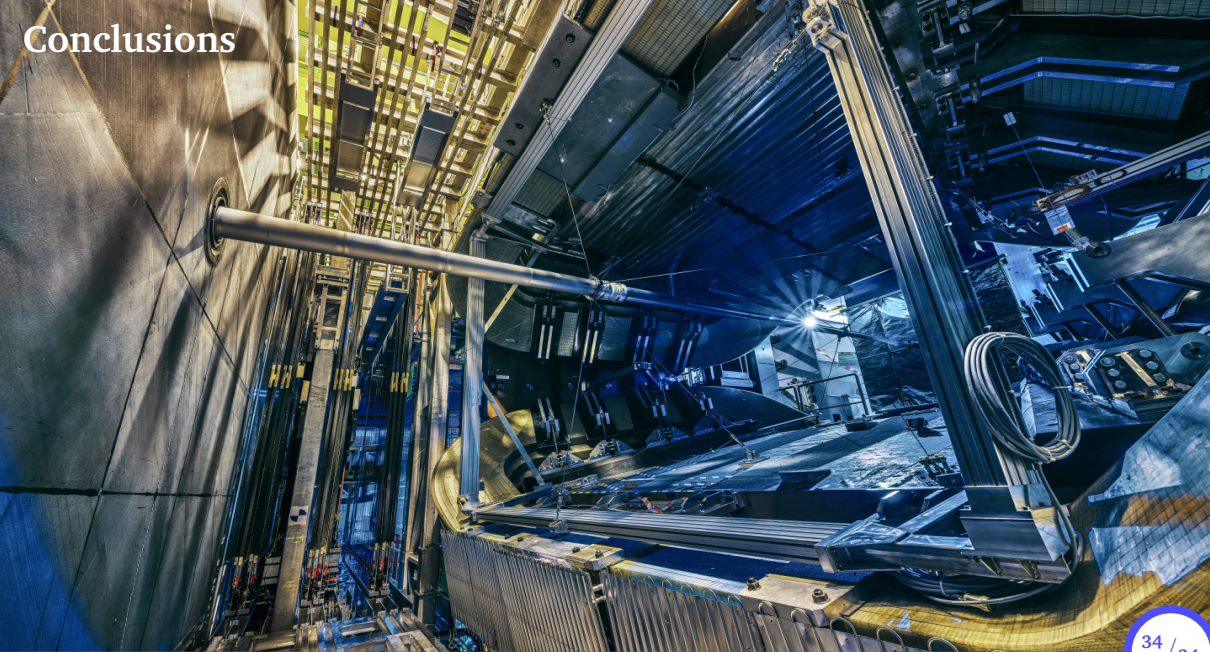


Where are my collisions?



Measurements agree very well with expectations!

Conclusions



Conclusions

- pictures in previous slides explain why I chose this title...
- LHCb is a peculiar experiment at LHC. It looks forward, and it looks at decays of heavy hadrons
- flavour physics, studied at LHCb, can shed light on mysteries still unexplained
 - why is there so little antimatter?
 - what is dark matter made of?
 - why are flavour parameters so varied?
- **is there a more fundamental theory?**
- to try and answer these questions, we look for ultra-rare decays ($< 10^{-9}$), strive to perform super-precise measurements, and face extreme computing challenges
- LHCb updated in 2019–2021. Finally, new detector commissioned and taking data!