Flavour Physics

- at the LHCb experiment -

May 22nd 2026

Master thesis topics

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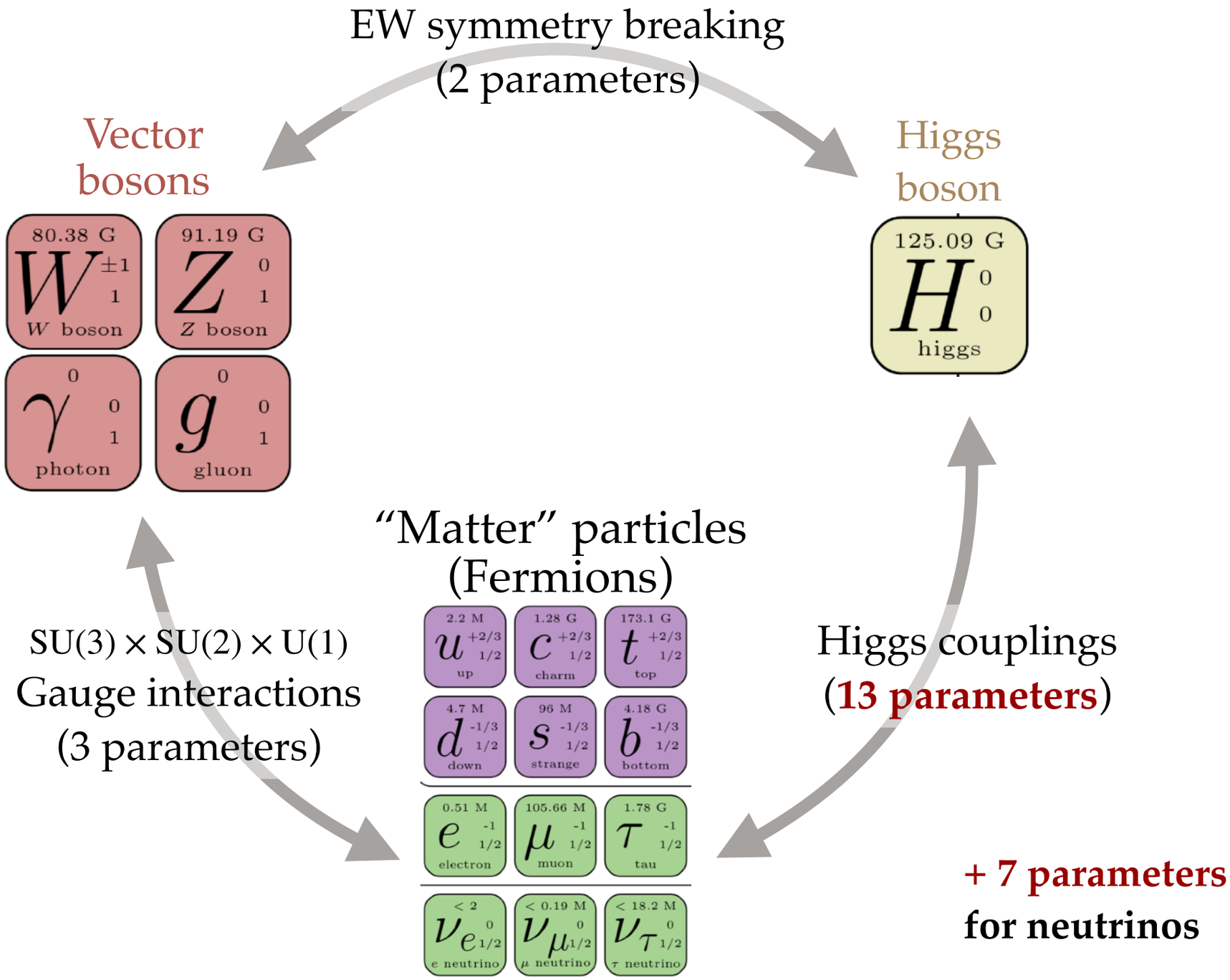
The Standard Model

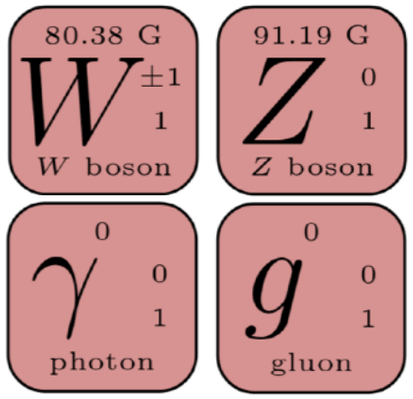


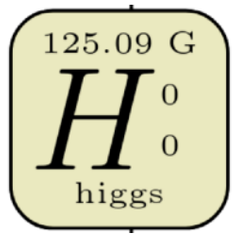
The Standard Model

EW symmetry breaking
(2 parameters)

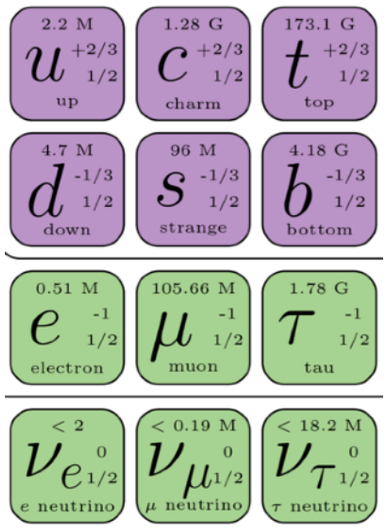
Vector bosons

Higgs boson





“Matter” particles
(Fermions)



$SU(3) \times SU(2) \times U(1)$
Gauge interactions
(3 parameters)

Higgs couplings
(**13 parameters**)

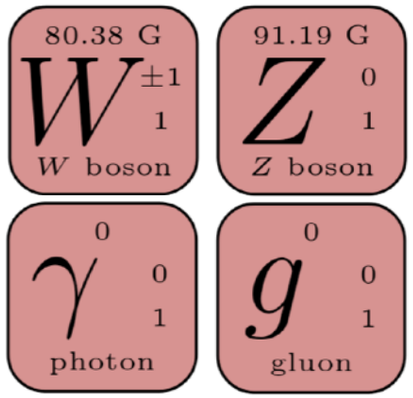
+ 7 parameters
for neutrinos

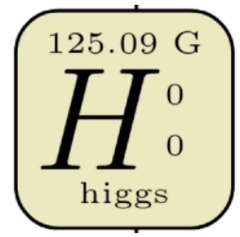
The Standard Model

EW symmetry breaking
(2 parameters)

Vector bosons

Higgs boson





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Gauge interactions
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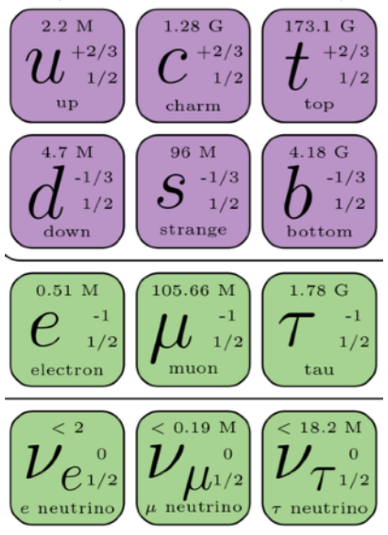


Higgs couplings
(**13 parameters**)

+ 7 parameters
for neutrinos

Flavour sector

The flavour sector

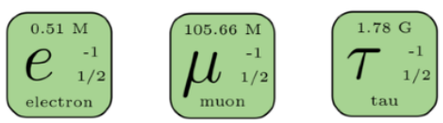
Higgs couplings (Yukawa)

13 free parameters

9 → **Fermion masses**

$m_u \ll m_c \ll m_t$

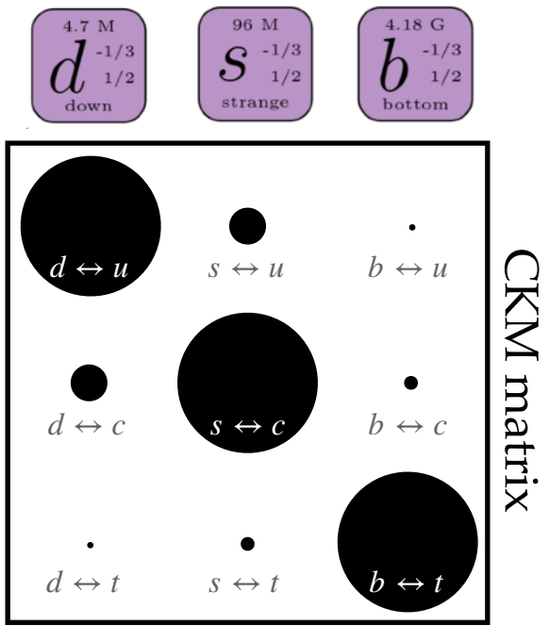
$m_d \ll m_s \ll m_b$



$m_e \ll m_\mu \ll m_\tau$

- Peculiar pattern of fermion masses

4 → **Quark mixing**



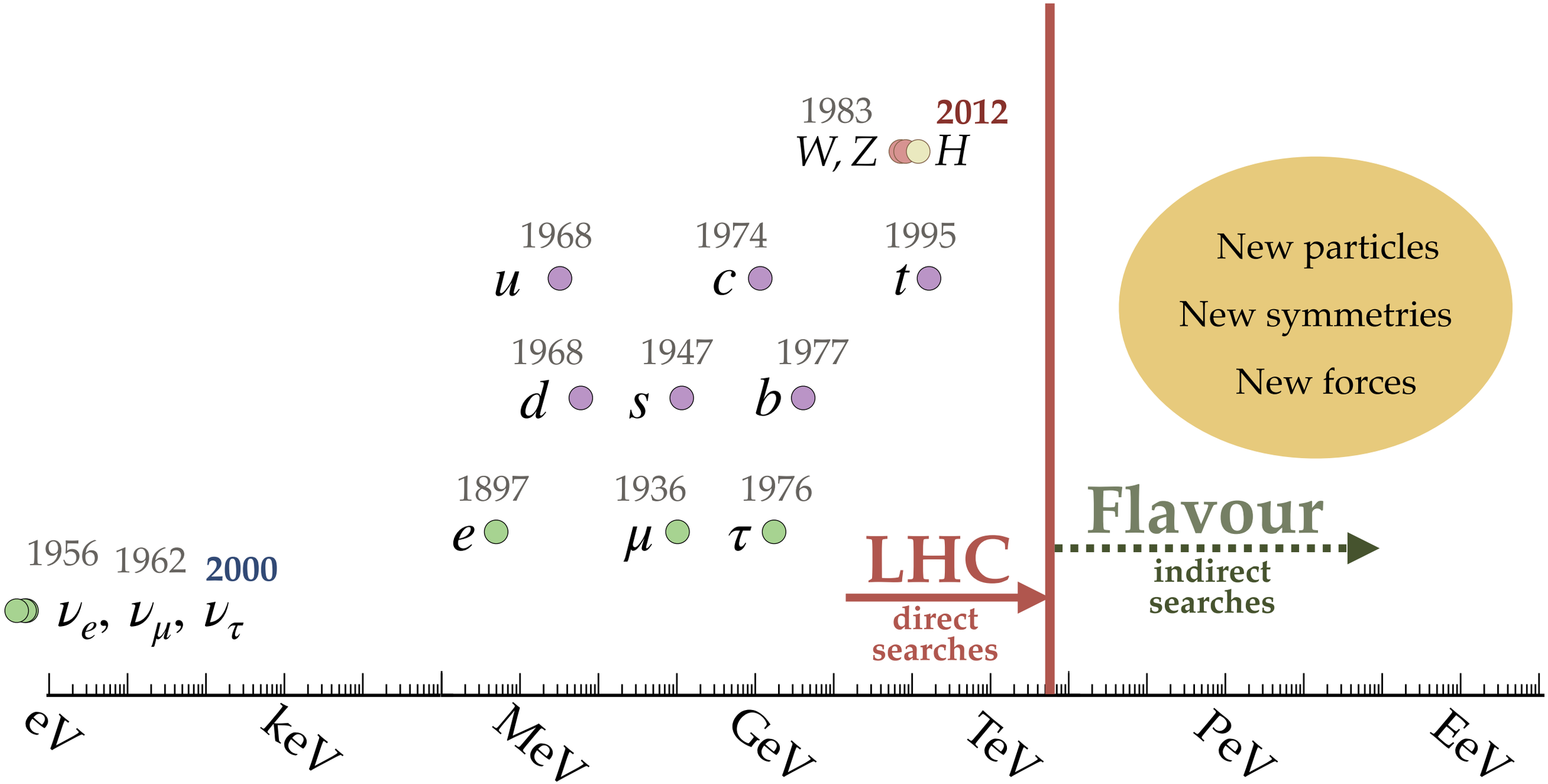
- Hierarchy in flavour transitions (CKM matrix)
- Only known source of asymmetry between matter and antimatter

"The Flavour Puzzle"

- What is the origin of the SM (Standard Model) peculiar pattern of flavors?
- The solution to this and other SM problems might lie far beyond the energy of the LHC 🫠
- Tiny quantum effects could be visible at lower energies 🤩
- **Precision studies of the SM's "flavor structure" have the potential to reveal these effects**

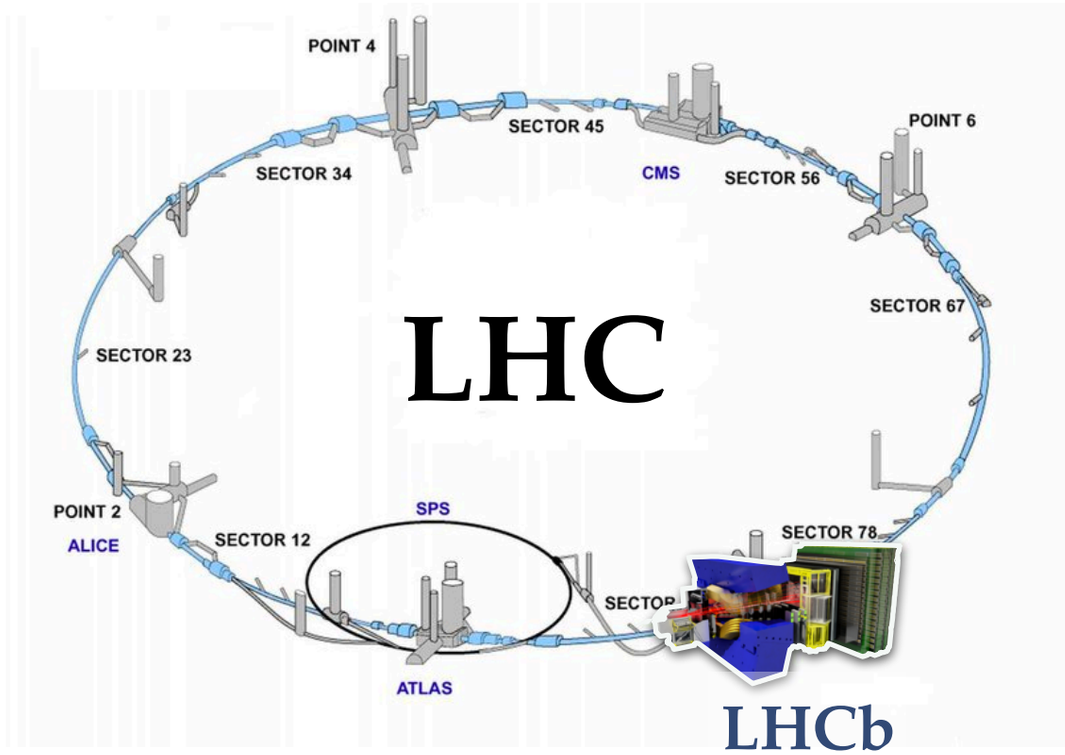
Flavour beyond the SM

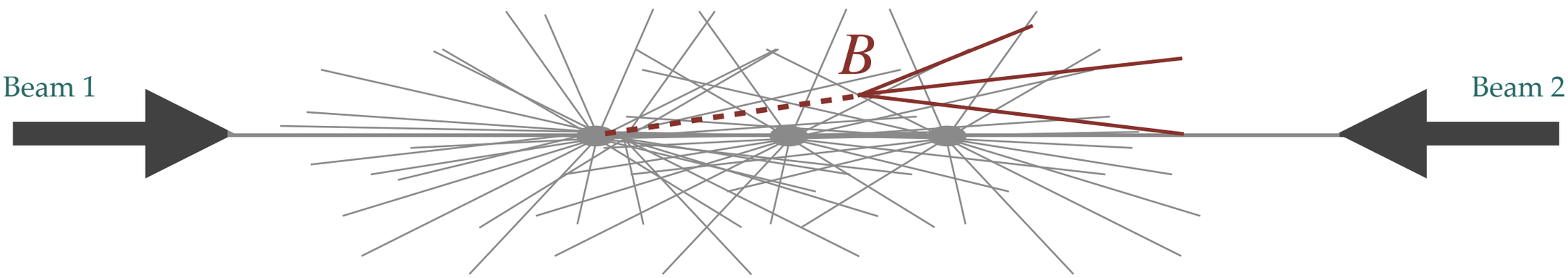
See for example UTFit and JHEP 0803:049,2008



Flavour physics at the LHC

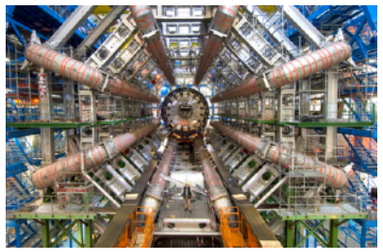
- Proton collisions at 13 TeV at 40 MHz
- The *b* quark weighs only 5 GeV → 5 million per second
- Very difficult to identify and measure precisely
- One of the 4 major LHC detectors has a dedicated design: **LHCb**





The LHCb experiment

ATLAS



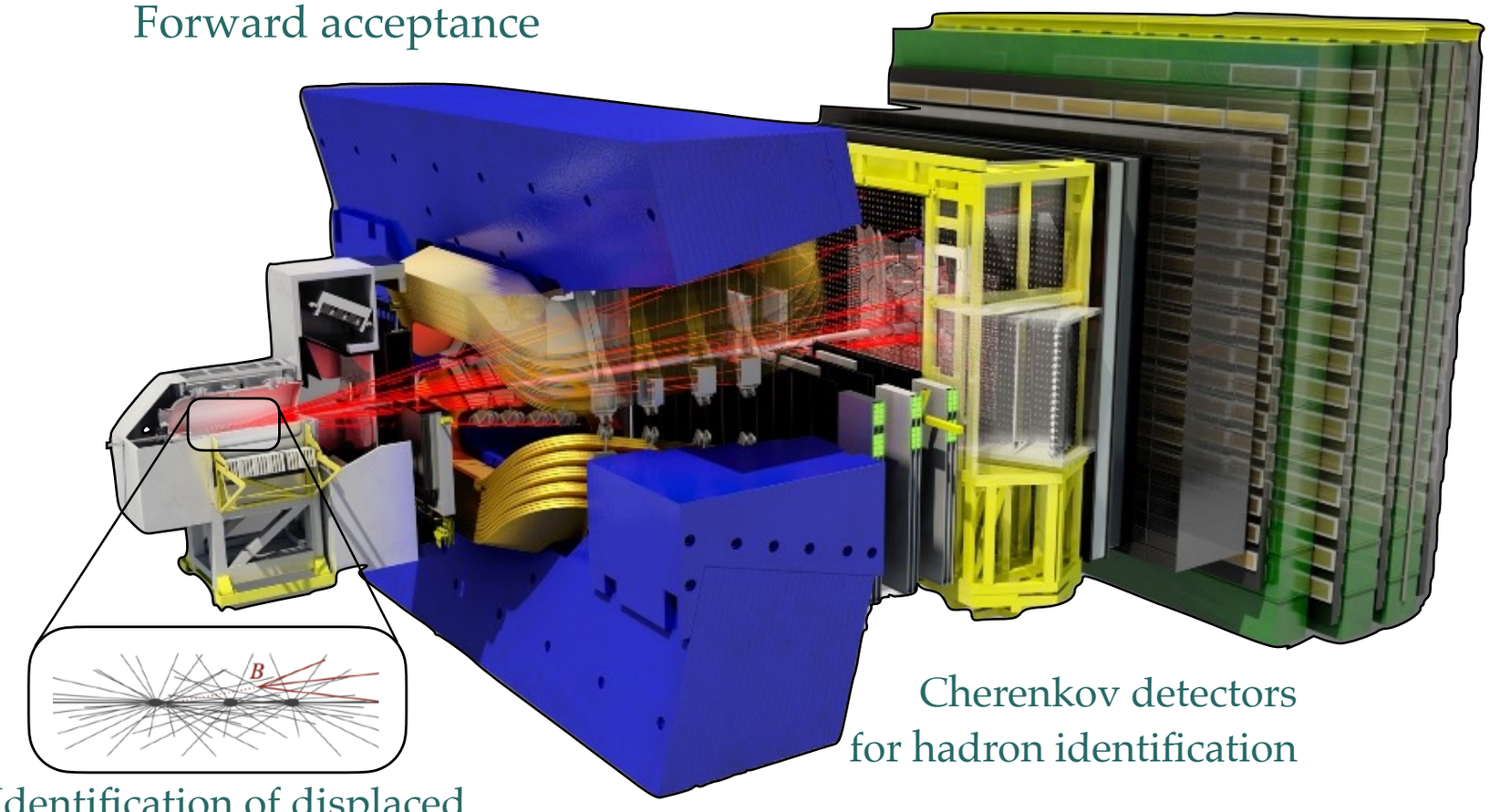
CMS

ALICE

LHCb

Designed for flavour physics

Forward acceptance



Identification of displaced decay vertices

Cherenkov detectors for hadron identification

⟶ World-largest dataset of beauty and charm hadrons

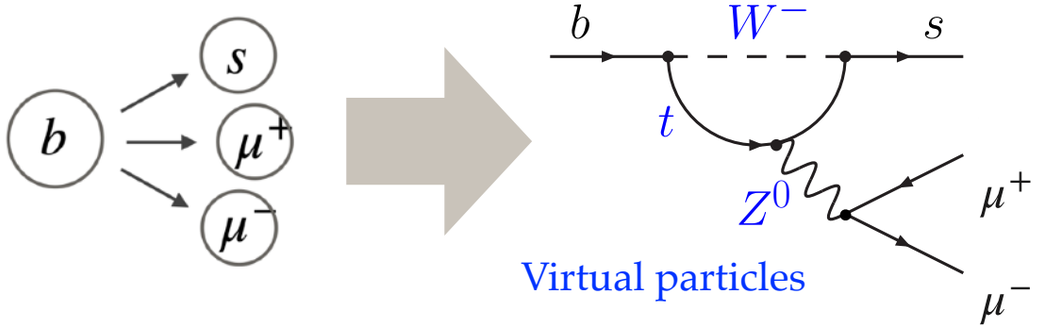
Flavour Physics analysis

Contacts: marta.calvi@unimib.it, maurizio.martinelli@unimib.it, martino.borsato@unimib.it

Flavour physics analysis

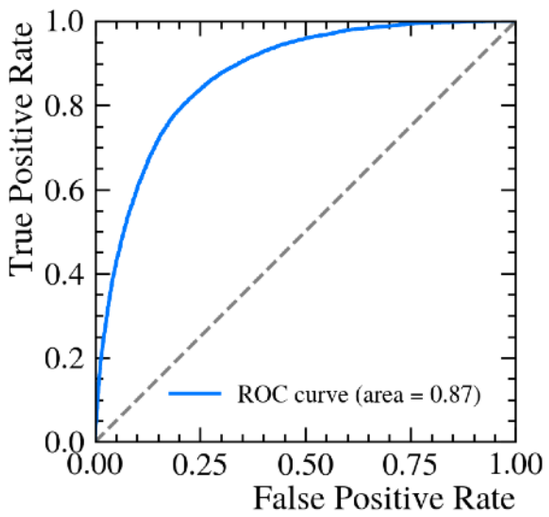
- Decays of heavy-flavour quarks and leptons
  - Measurement of fundamental SM parameters
  - Tests of SM fundamental symmetries
  - *Stress-test* of consistency of the theory
  - Anomalies → Physics beyond Standard Model?

Example of a decay



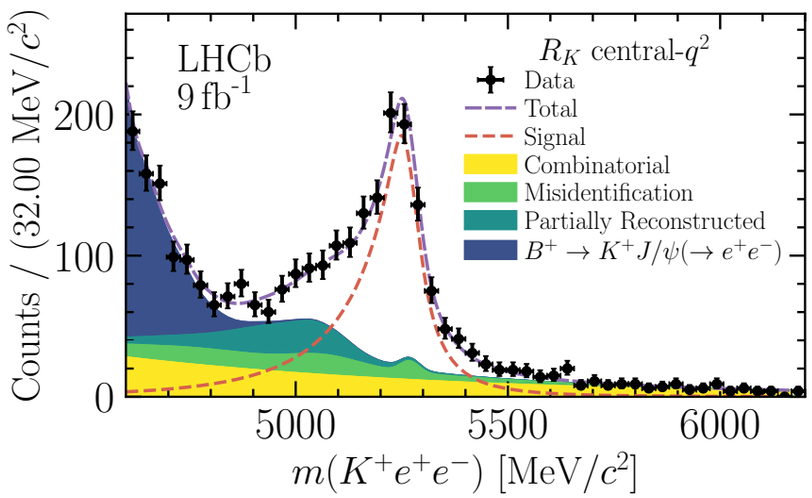
ML classification

Online and Offline

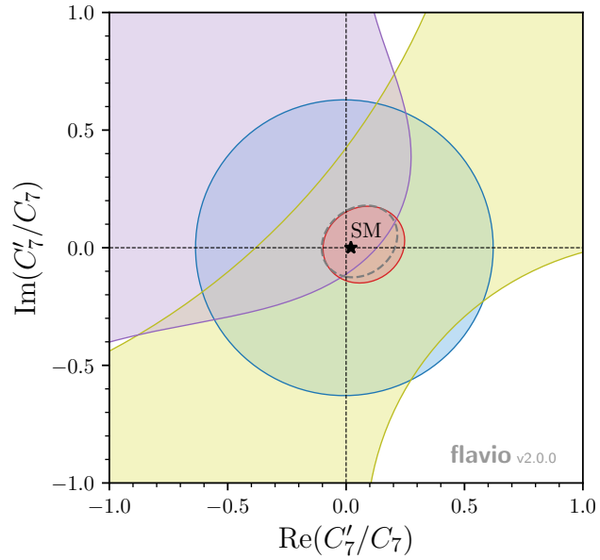


Analysis of sample composition

Subtraction of the background with a fit



Extraction of relevant parameters and comparison with theoretical predictions



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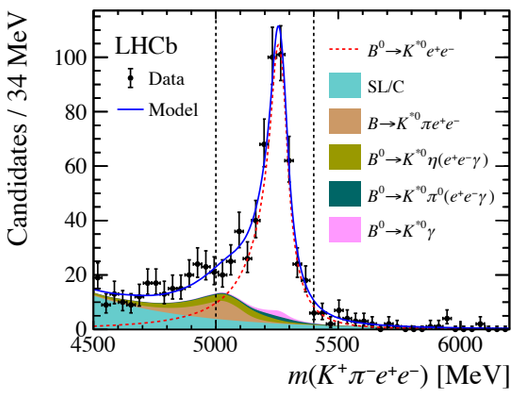
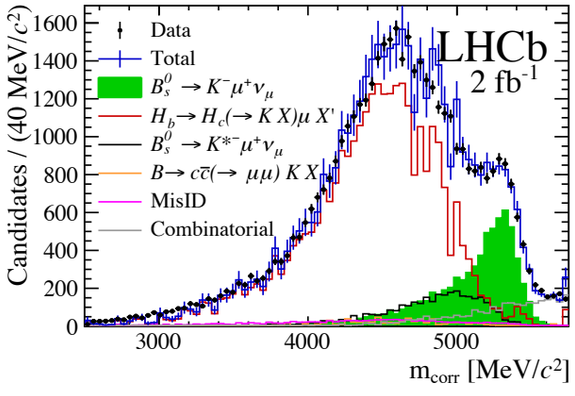
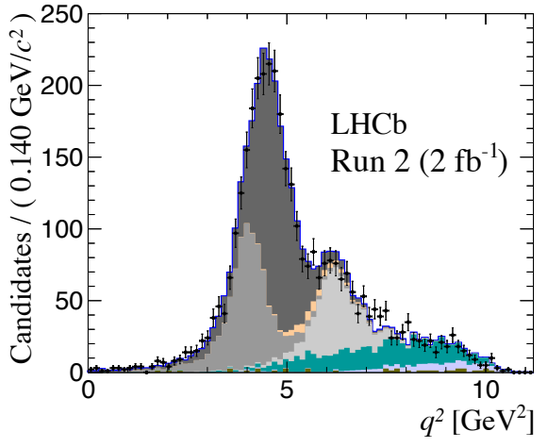
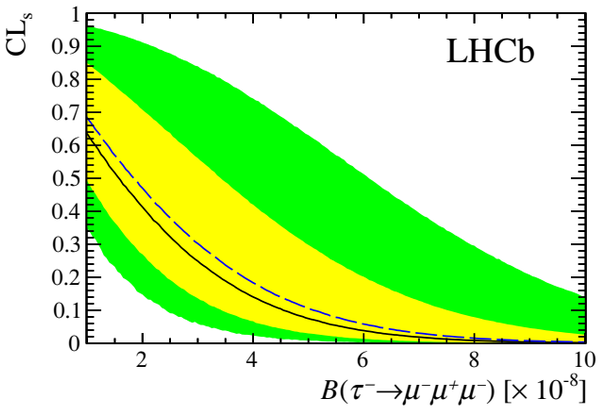
Some analyses of Bicocca@LHCb









1. Matter-antimatter asymmetry (CP violation) in charm quarks
2. Measurement of the fundamental CKM parameter V_{ub}
3. Study of the structure of the B meson ($b\bar{u}$)
4. Search for lepton-flavour violation
5. Study of rare decays of b and c quarks

- Many interesting analyses you can contribute to
- World-experts in Bicocca + international collaboration
- **Come talk to us and we can define a suitable master thesis project together**

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Hardware and software development

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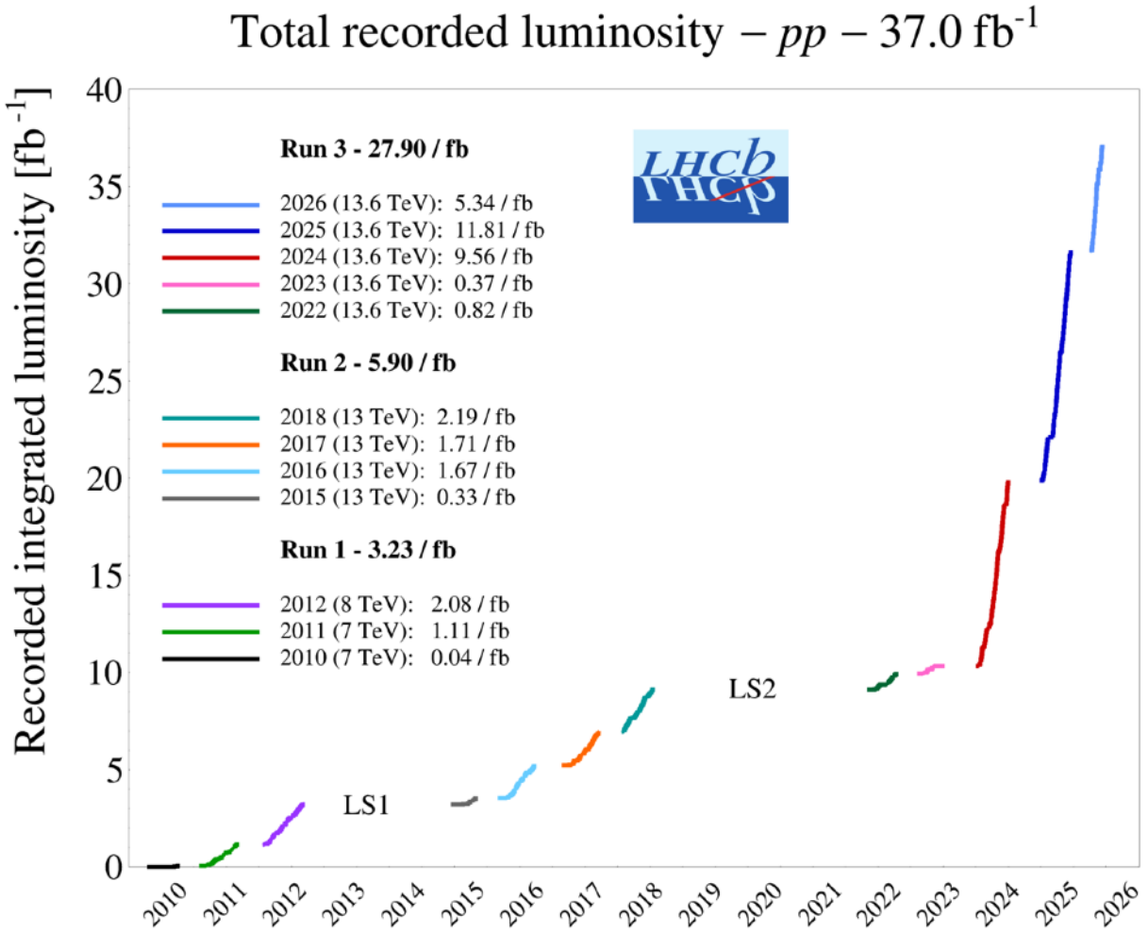
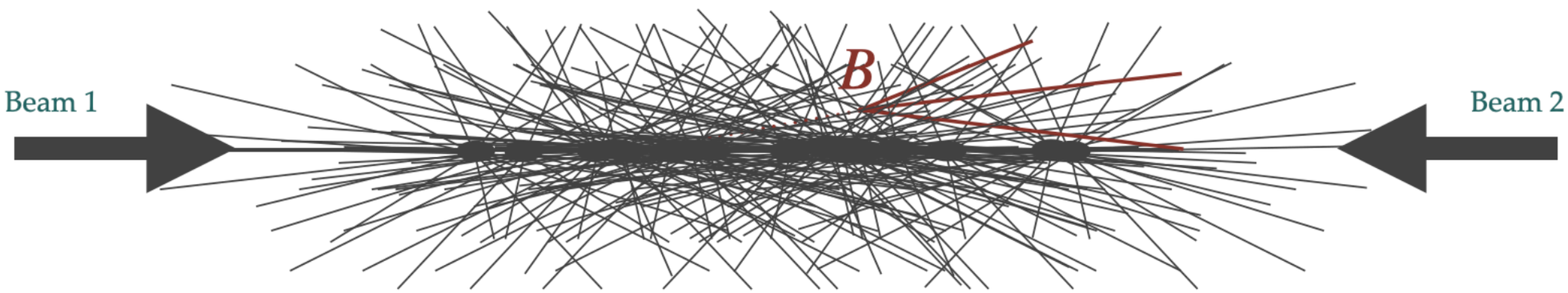
LHCb upgrade 2

- Goal: collect data faster and improve statistical sensitivity of analyses
- First upgrade was a success!
- Second upgrade planned for ~2033
  - 5 × higher luminosity
  - Higher granularity, **ps timing**, radiation resistance, high-performance computing, advanced analysis techniques

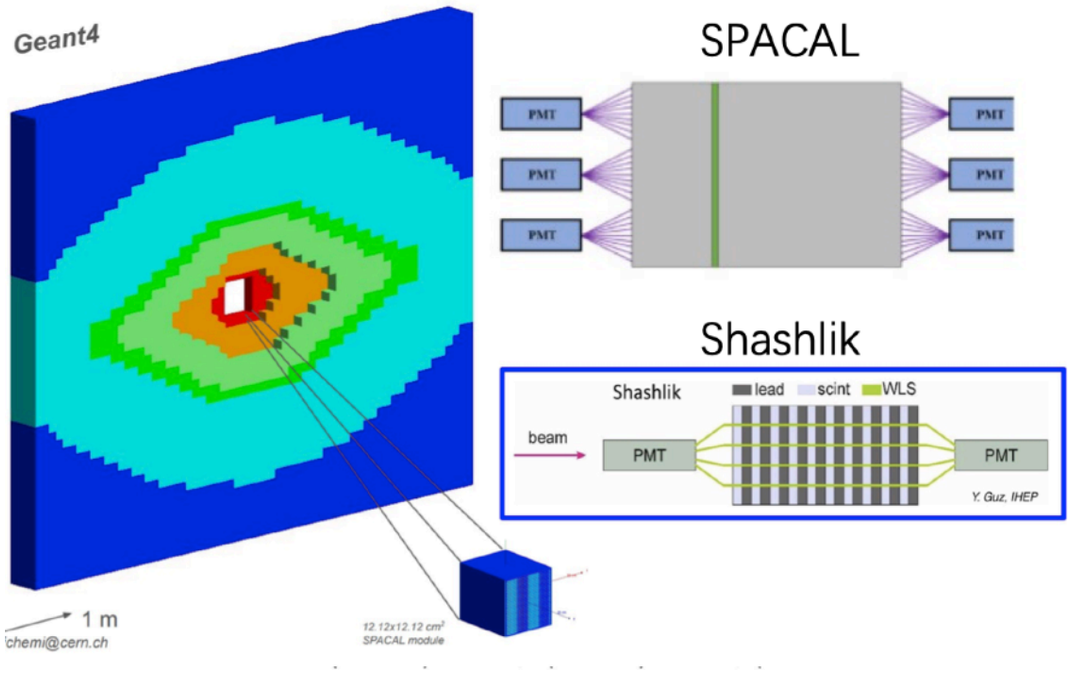




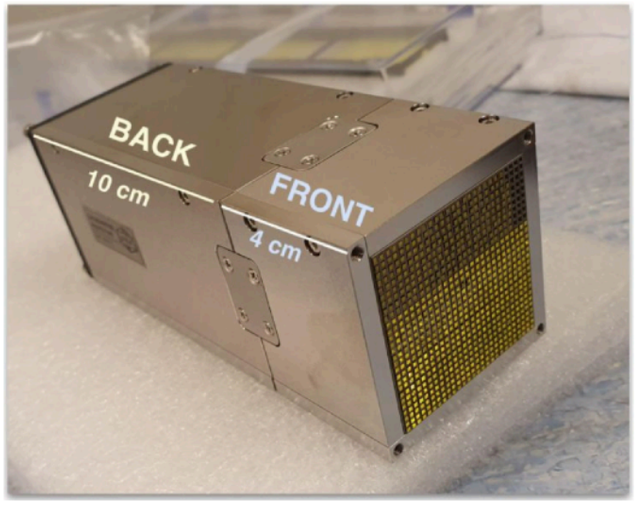
Hardware upgrade: Calorimeter

- New technology required:
  - Radiation resistance, granularity, **timing at ps level**

➡ **Spaghetti Calorimeter (SPACAL)**
  - Beam tests of prototypes
  - Design optimisation using simulation
  - Study of particle identification performance



Prototype of the SPACAL module



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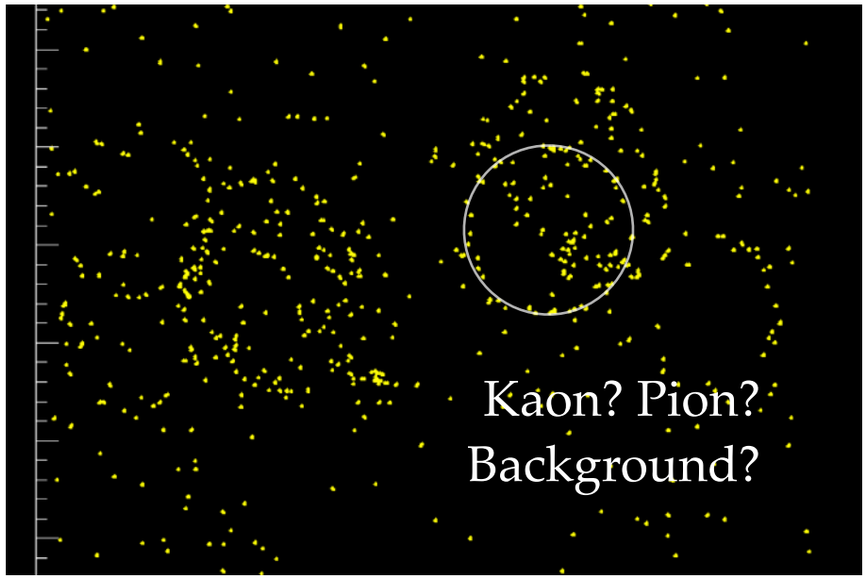
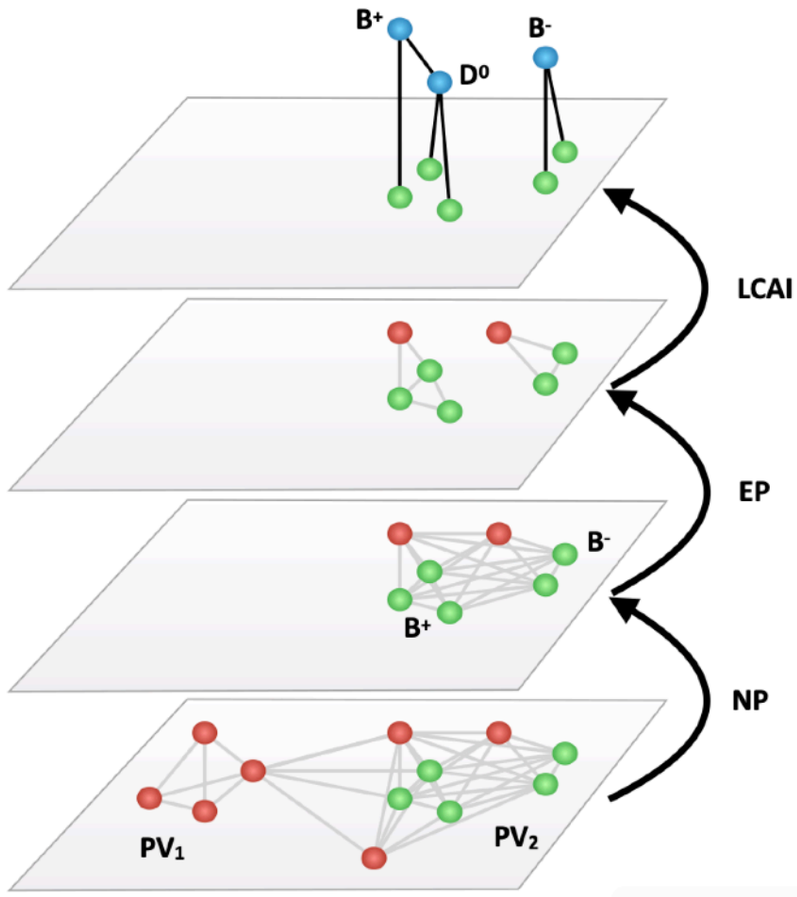
Software upgrade: Machine Learning

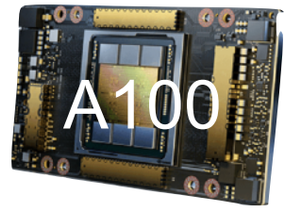
- Exploring various modern ML solutions
  - Convolutional Neural Networks
  - Graph Neural Networks
  - Tecniche di ML in real time (EdgeML)
- Advanced ML projects by Bicocca@LHCb:
  - Global event reconstruction (DFEI)
  - Identification of charged particles using Cherenkov light rings (YOLO)



GNN for full event interpretation



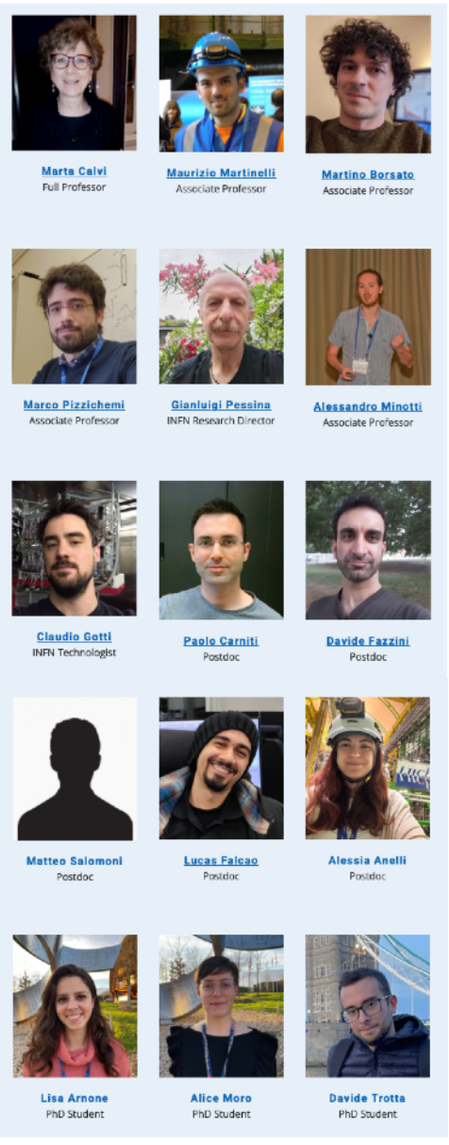
TensorFlow



NVIDIA

LHCb@Bicocca

- Collider physics, flavour physics
- Standard Model symmetries and theories beyond the Standard Model
- Statistical analysis and machine learning
- Programming in Python and/or C++
- Development of state-of-the-art detectors
- An international and growing team



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BACKUP

Hadron decays

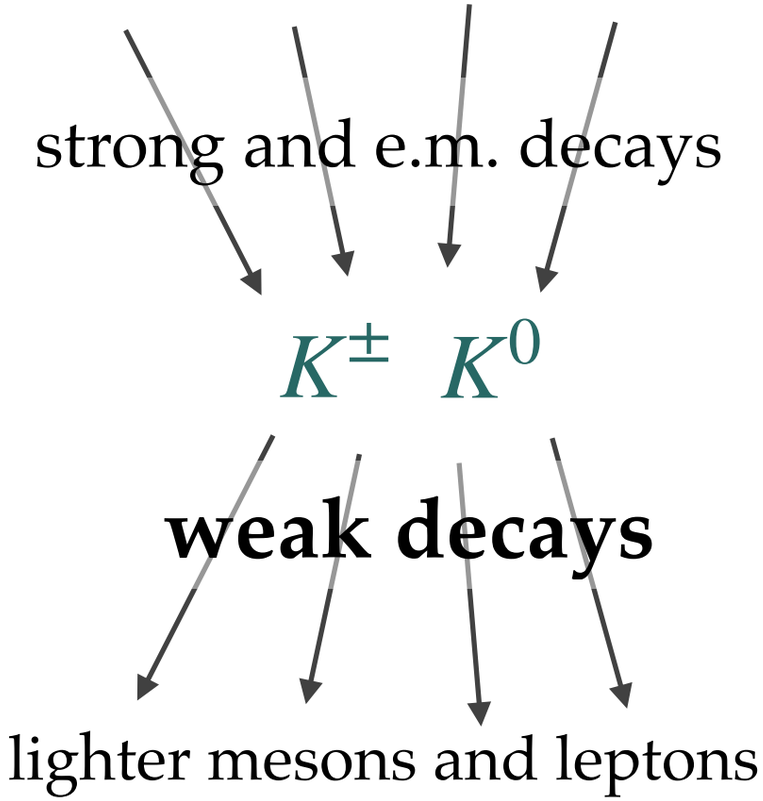
- Quarks hadronise into bound states (hadrons):
  - Unflavoured $u\bar{u}$, $d\bar{d}$, $u\bar{d}$
  - Strange mesons: $s\bar{u}$, $s\bar{d}$
  - Charm mesons: $c\bar{u}$, $c\bar{d}$, $c\bar{s}$
  - Beauty mesons: $b\bar{u}$, $b\bar{d}$, $b\bar{s}$, $b\bar{c}$
  - Baryons $q_i q_j q_k \ldots$
  - Tetraquarks, Pentaquarks
  - A huge zoo 🐆🐉🦕🐋🦩

K mesons: $s\bar{u}$, $s\bar{d}$

$K^*(892)$ $K^*(1410)$ $K(1460)$

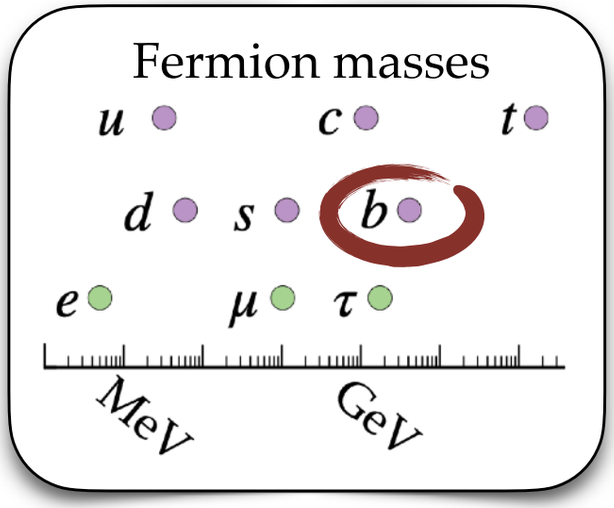
$K_0^*(700)$ $K_1(1400)$ $K_0^*(1430)$ …

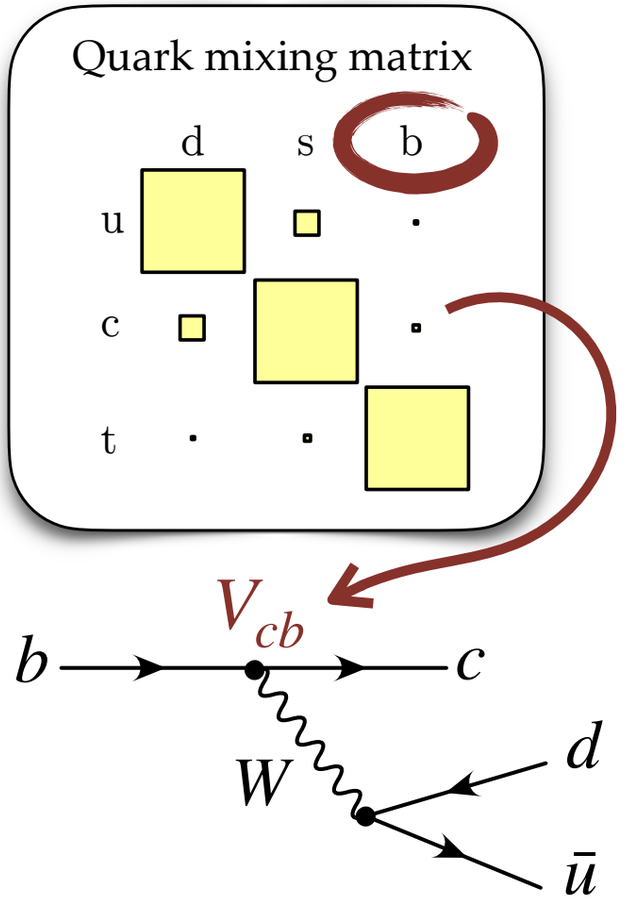
$K_1(1270)$ $K_2^*(1430)$ $K_2(1580)$



The beauty of the beauty quark

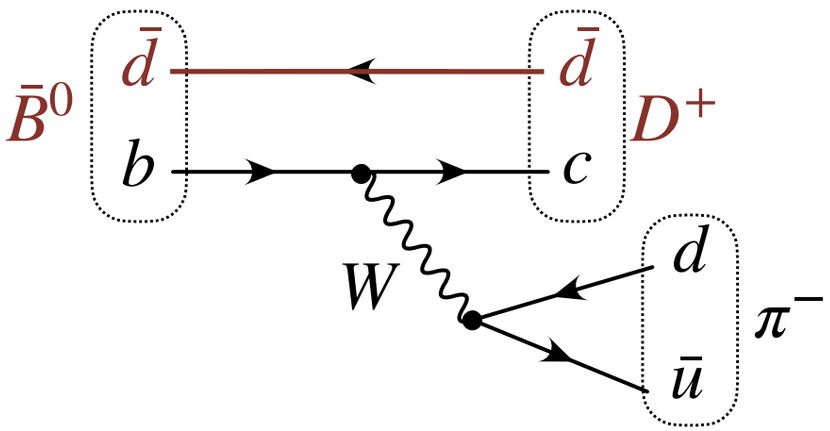
- Good **theoretical** properties:
  - Decays only via weak interaction
  - Can decay to 4 quarks and all leptons
  - Small SM decay width
    - Flavour suppressed $|V_{cb}|, |V_{ub}| \ll 1$
    - Weak suppressed $m_b/m_W \ll 1$
    - Sensitive to small new contributions
- Large mass $m_b \gg \Lambda_{\rm QCD}$
  $\Rightarrow$ precise calculations
- Hadronises before decaying

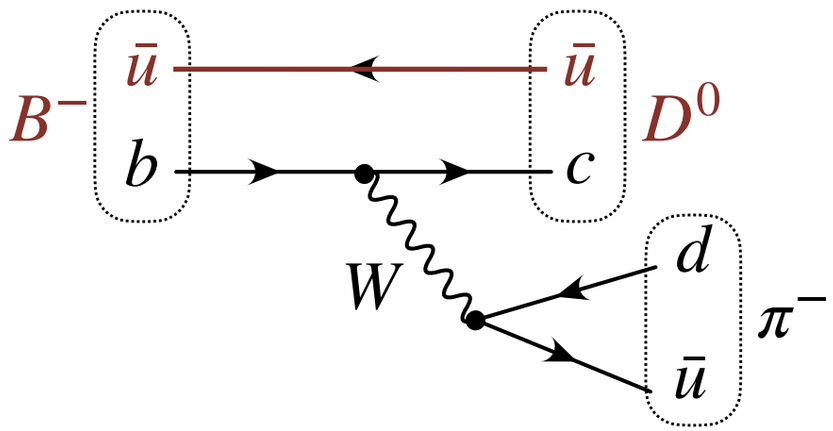


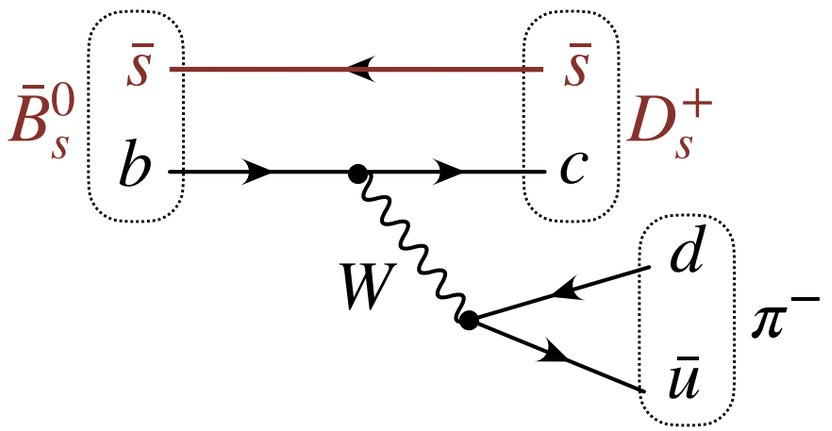


The beauty of the beauty quark

- Good **experimental** properties:
  - $\tau_B \simeq 1.5$ ps $\rightarrow$ displaced decay vertex
  - $m_b \simeq 5$ GeV $\rightarrow$ cheap to produce
  - Huge phenomenology
    - Hadronises in many ways
    - Decays to hundreds of channels

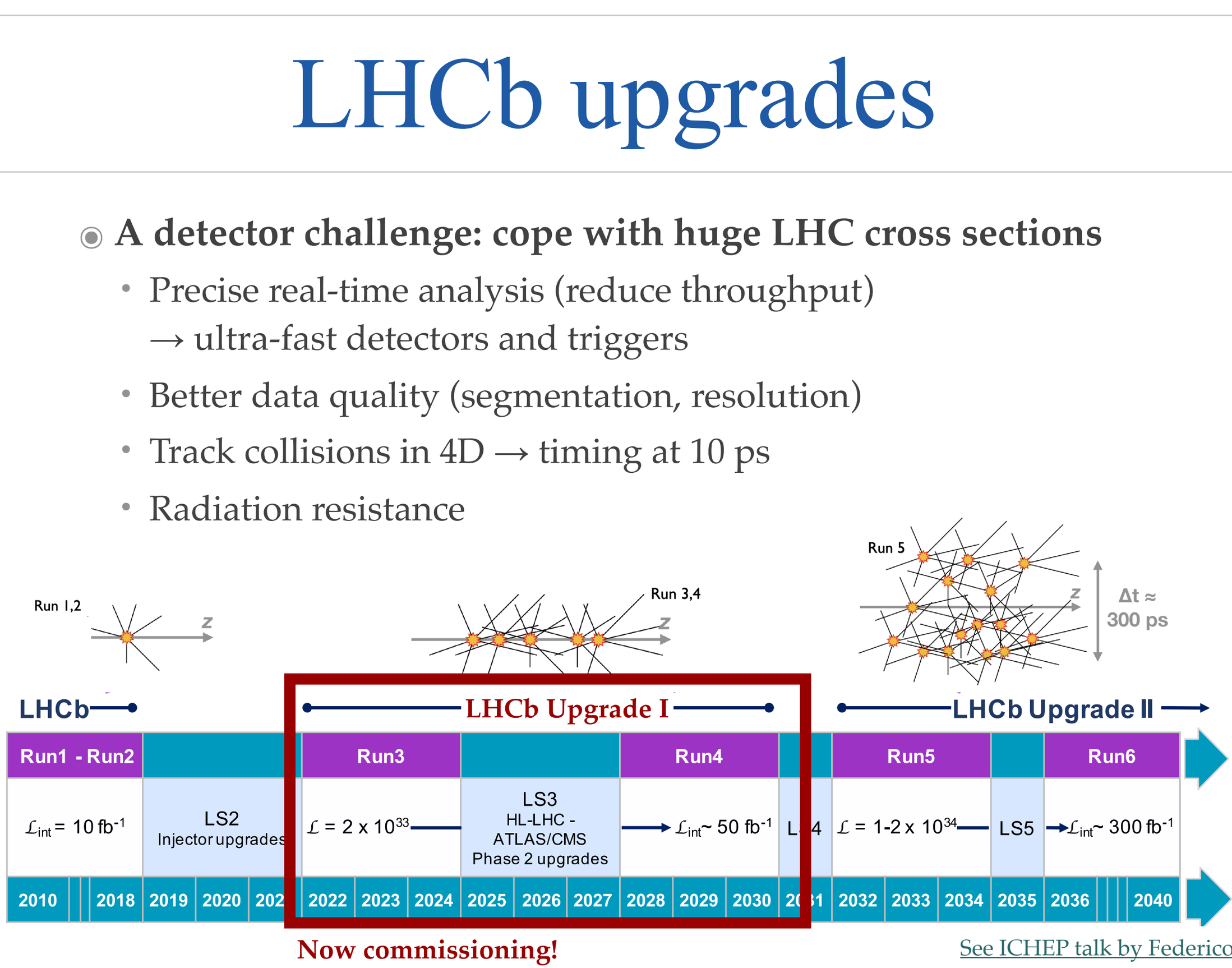






LHCb upgrades

- **A detector challenge: cope with huge LHC cross sections**
  - Precise real-time analysis (reduce throughput)
    → ultra-fast detectors and triggers
  - Better data quality (segmentation, resolution)
  - Track collisions in 4D → timing at 10 ps
  - Radiation resistance

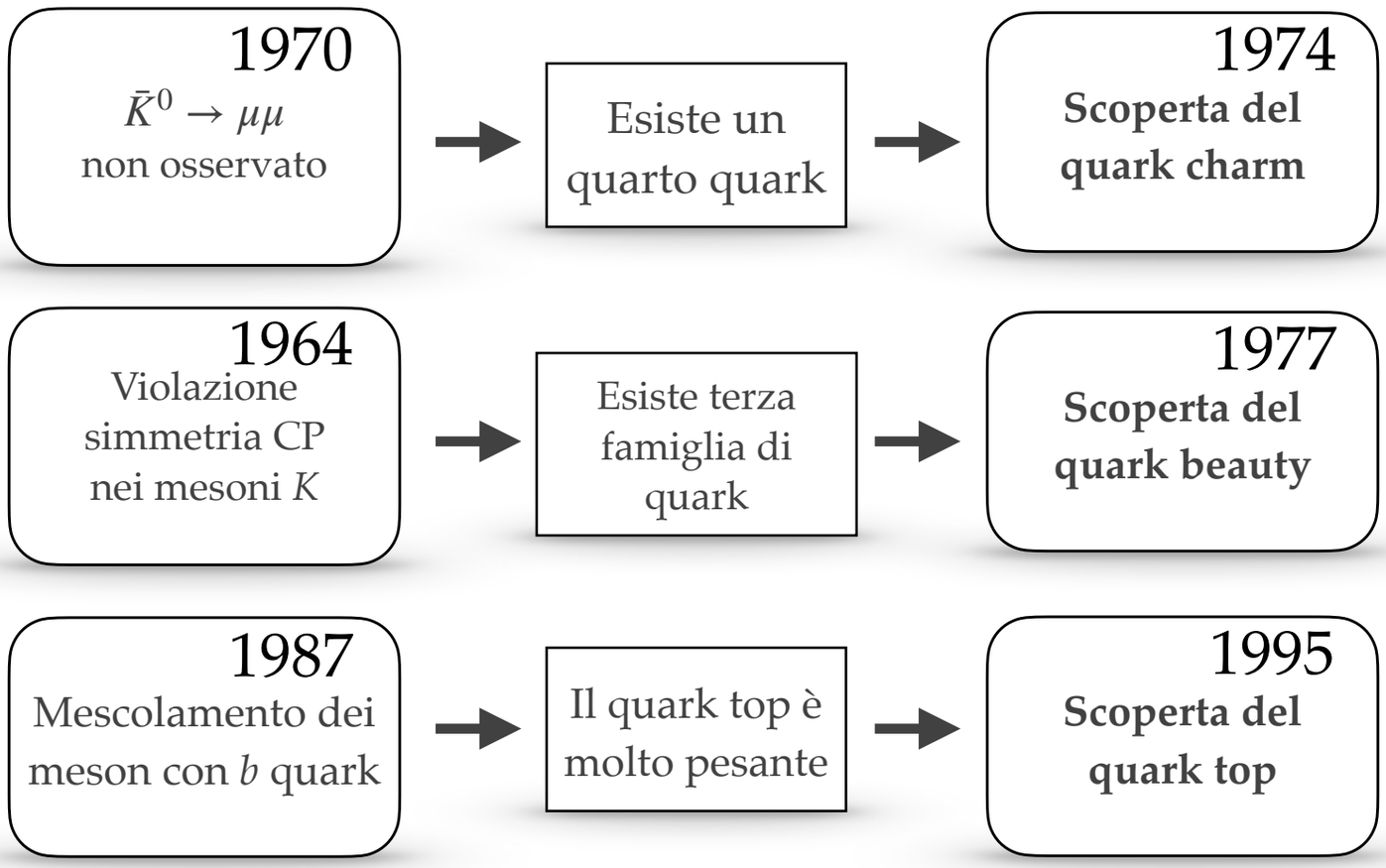


Now commissioning!

See ICHEP talk by Federico

Il sapore nella storia del MS

Alcune scoperte indirette nel sapore



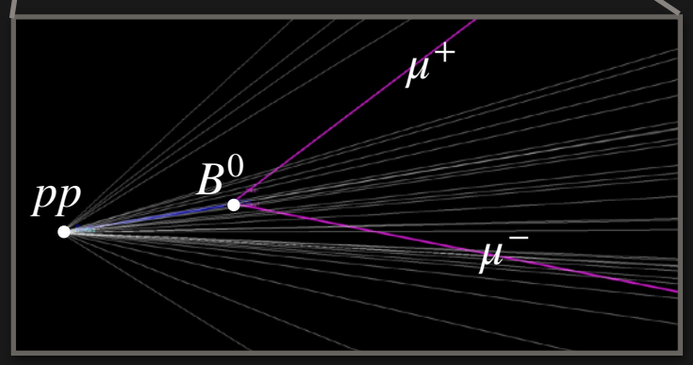
Magnete

Rivelatore
luce Cherenkov

Tracking in
tempo reale

Alta densità
di particelle

Collisioni
a 40 MHz



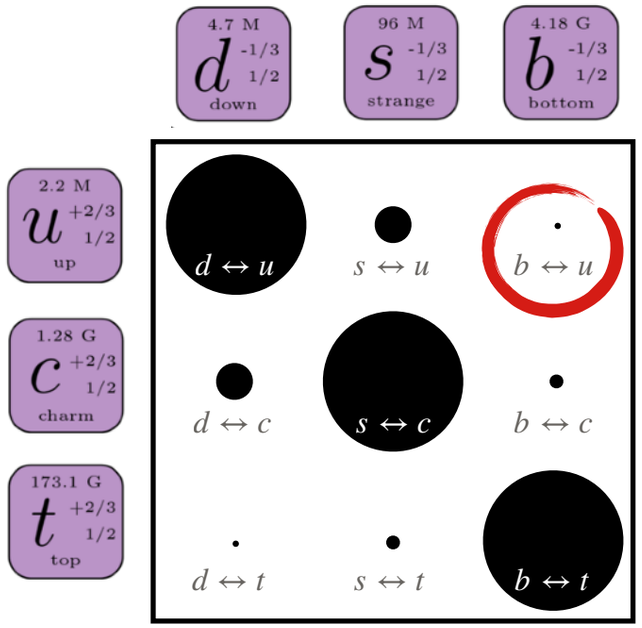
Identificazione vertici secondari

La sfida sperimentale

- Isolare i decadimenti di interesse e misurarli con alta precisione
- Operare il detector a luminosità ancora più alta in futuro

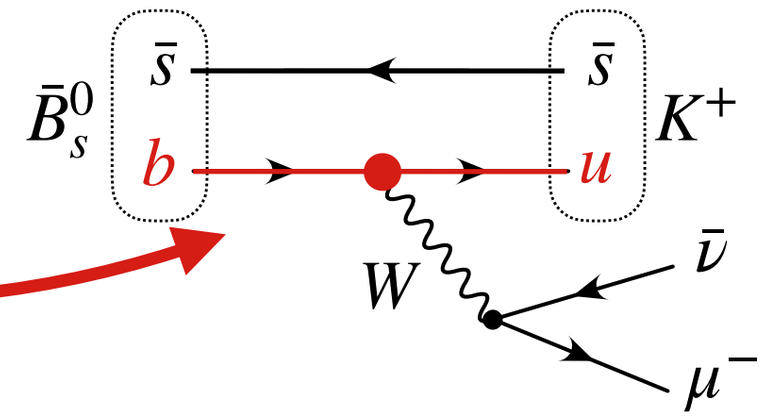
fattore $\times 5$ *nel 2024 e* $\times 50$ *nel 2033*

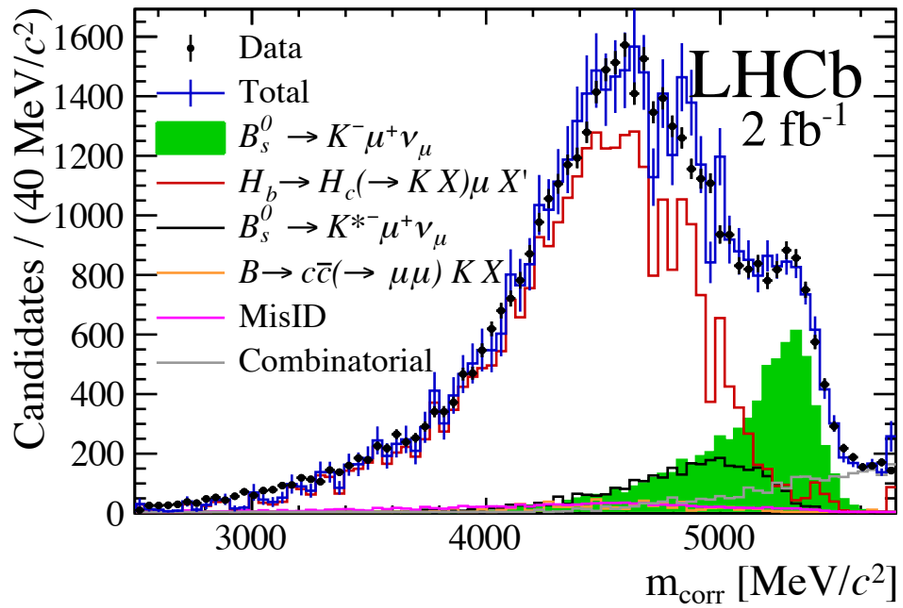
Transizioni $b \to u$



- Transizione quark $b \to u$ soppressa nel MS
- Precisione di misura dell'elemento di matrice V_{ub} ancora limitata
- **Tensioni** tra determinazioni "esclusive" e "inclusive"
- Cosa c'è dietro?

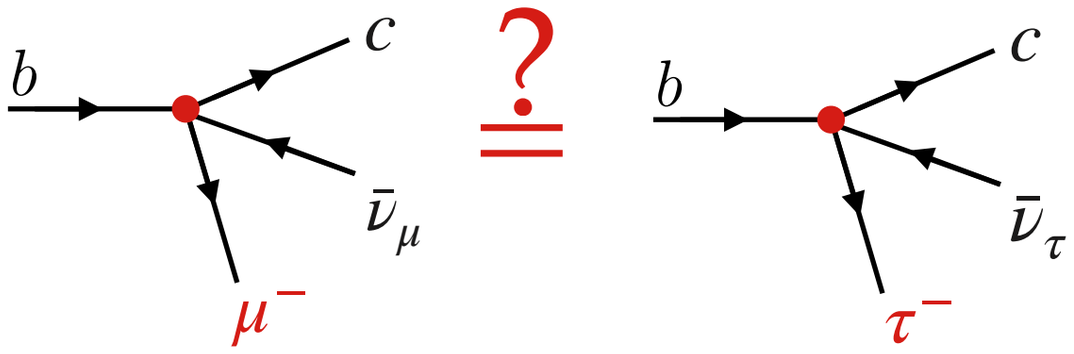
$b \to u$ adronizzata in $\bar{B}_s^0 \to K^+ \mu^- \bar{\nu}$





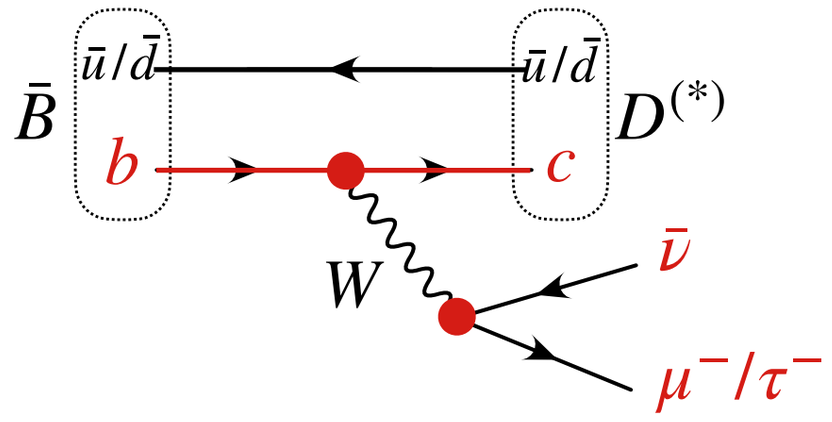
Proposta di tesi: Misura V_{ub} con il decadimento $B_s \to K\mu\nu$. Classificazione del segnale con ML, modellizzazione e sottrazione statistica del fondo, determinazione dell'elemento di matrice CKM V_{ub} con fit multidimensionale

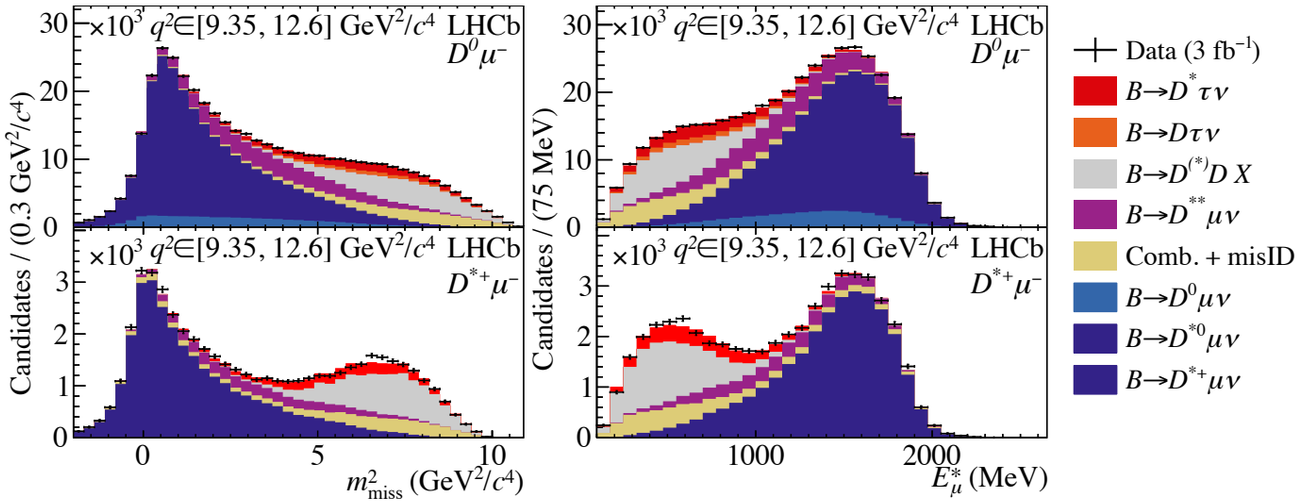
Universalità leptonica



- **“Universalità leptonica”**
  Il MS prevede che le interazioni di gauge siano indipendenti dal sapore dei leptoni (μ, τ)
- Nuove interazioni potrebbero violare questa simmetria → sarebbe un segno chiarissimo di fisica oltre il MS
- I dati indicano una possibile (~3σ) violazione dell’universalità leptonica → necessarie altre misure

$b \to c\ell\nu$ adronizzata in $\bar{B} \to D^{(*)}\ell^-\bar{\nu}$





Proposta di tesi: Test dell’universalità leptonica in $b \to c\ell\nu$. Prima analisi del grande dataset di Run2 e possibilità di partecipare all’analisi dei nuovi dati 2024. Test con nuovi osservabili. Studio della sensibilità di una analisi angolare ai coefficienti della teoria effettiva di campo.

Mixing e violazione CP nel charm

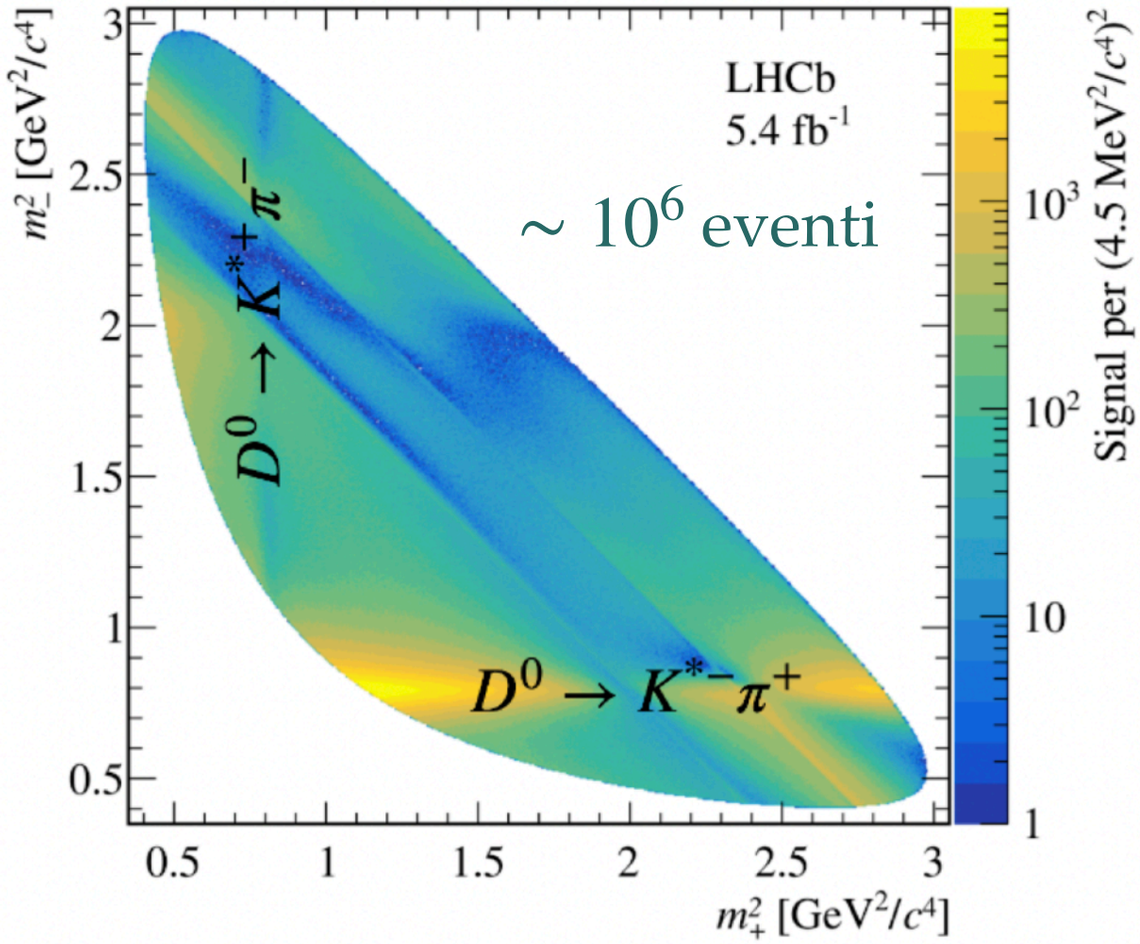
- Breve storia della violazione CP:
  - **1964**: CPV in $s \to d$ (Cronin & Fitch)
  - **2001**: CPV in $b \to d$ (BaBar & Belle)
  - **2013**: CPV in $b \to s$ (LHCb)
  - **2019: CPV in $c \to u$ (LHCb)**

Prossimo step:

Misura CPV nelle interferenze quantistiche nel mixing $D^0 - \bar{D}^0$

$$D^0 \; \bar{u}\,c \;\Longleftrightarrow\; \bar{c}\,u \; \bar{D}^0$$

Dataset di $D^0 \to K^0_S \pi^+ \pi^-$

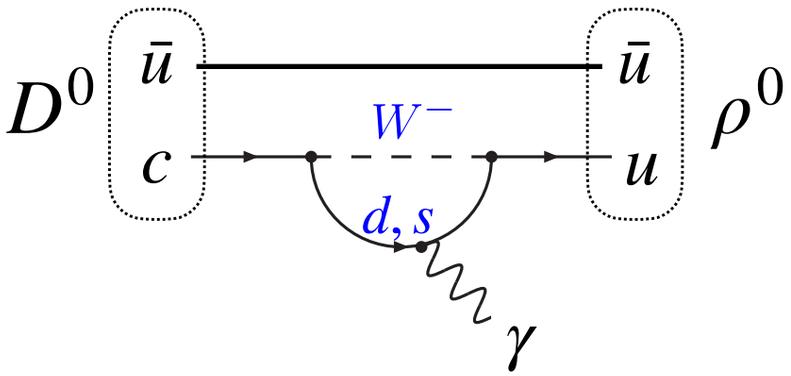


2 **Proposte di tesi**:
1) Mixing e CPV in decadimenti multibody del D^0
2) Mixing e CPV in decadimenti semileptonici del D^0

Misure di precisione con dataset molto grandi. Fit complessi di effetti quantistici di interferenza e CPV.

Identificazione di $c \to u\gamma$

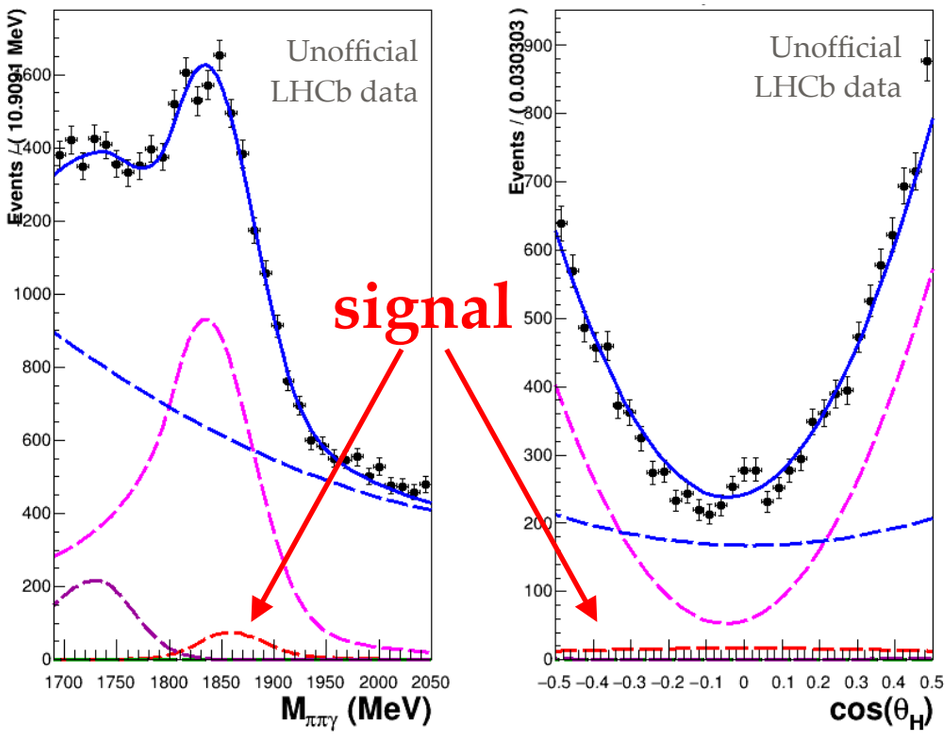
- **Transizioni $c \to u$ molto rare nel MS**
  - Cancellazione delle ampiezze (GIM)
    $A(c \to d \to u) + A(c \to s \to u) \simeq 0$
  - Sensibile a contributi di nuova fisica!



$$\mathrm{BR}(D^0 \to \rho^0\gamma) = (1.77 \pm 0.30) \times 10^{-5}$$

- **Sfida sperimentale**
  - ✅ Miliardi di charm prodotti
  - ⛔ Grande fondo da $\pi^0 \to \gamma\gamma$

Analisi LHCb con tecnica "standard"

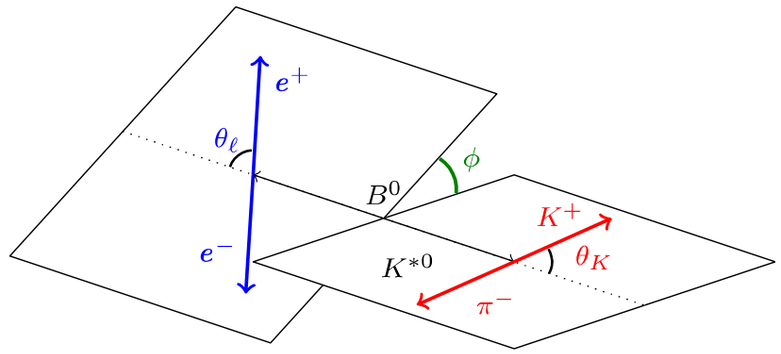


➡ Sviluppo nuova tecnica basata su conversioni $\gamma \to e^+e^-$

Proposta di tesi
Sviluppo di un classificatore basato su ML per ridurre il fondo. Fit delle distribuzioni cinematiche per la quantificazione del fondo residuo. Calcolo delle efficienze e ottimizzazione della selezione. Stima della sensibilità della misura e confronto con metodo standard.

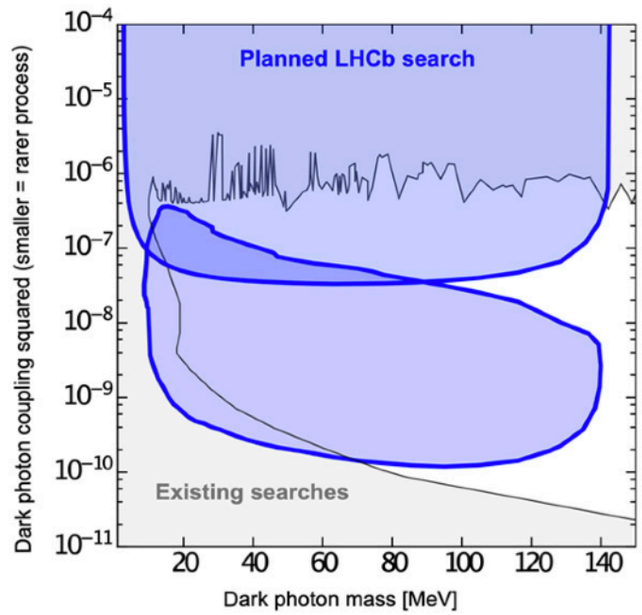
Altre analisi

- Studio della struttura del meson B con il decadimento $B^+ \to \mu\nu\gamma$
- Studio delle transizione rare $b \to s\ell^+\ell^-$ con analisi angolare di $B^0 \to K^*e^+e^-$
- Ricerca di transizioni $\tau \to \mu\mu\mu$ che violano il sapore leptonico
- Ricerca di *fotoni oscuri* molto leggeri con nuove tecniche di analisi in real time



Analisi angolari multidimensionali

Ricerca di fotoni oscuri



Venite a parlarne con noi!

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