6th Summer School on INtelligent signal
processing for FrontIEr Research&Industry

LHCb, AN INNOVATIVE EXPERIMENT @CERN TO SEARCH FOR NEW PHYSICS THROUGH FLAVOUR

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INFIERI 26/08/2021

Outline of the lecture

- What is flavour physics and why it is interesting
- CP Violation and baryogenesis
- The search for New Physics through rare b decays
- The LHCb experiment and its trigger
- A brief mention of the LHCb flavour anomalies

What is flavour?

Flavour physics refers to the study of the interactions that distinguish between the fermion generations

Just as ice cream has both color and flavour, so do quarks

Quark flavour

- Six different quark types

Q: electric charge in units of the p charge	**up**	**charm**	**top**
Q=+2/3	**u**	**c**	**t**
mass (GeV)	**0.0025**	**1.3**	**173**
	down	**strange**	**beauty** or **bottom**
Q=-1/3	**d**	**s**	**b**
mass (GeV)	**0.0048**	**0.1**	**4.5**

Plus the corresponding antiquarks

$$\bar{u},\ \bar{d},\ \bar{c},\ \bar{s},\ \bar{t},\ \bar{b}$$

- Q_{proton}[uud]= 2/3+2/3-1/3 = 1 Q_{neutron}[udd] = 2/3-1/3-1/3 = 0

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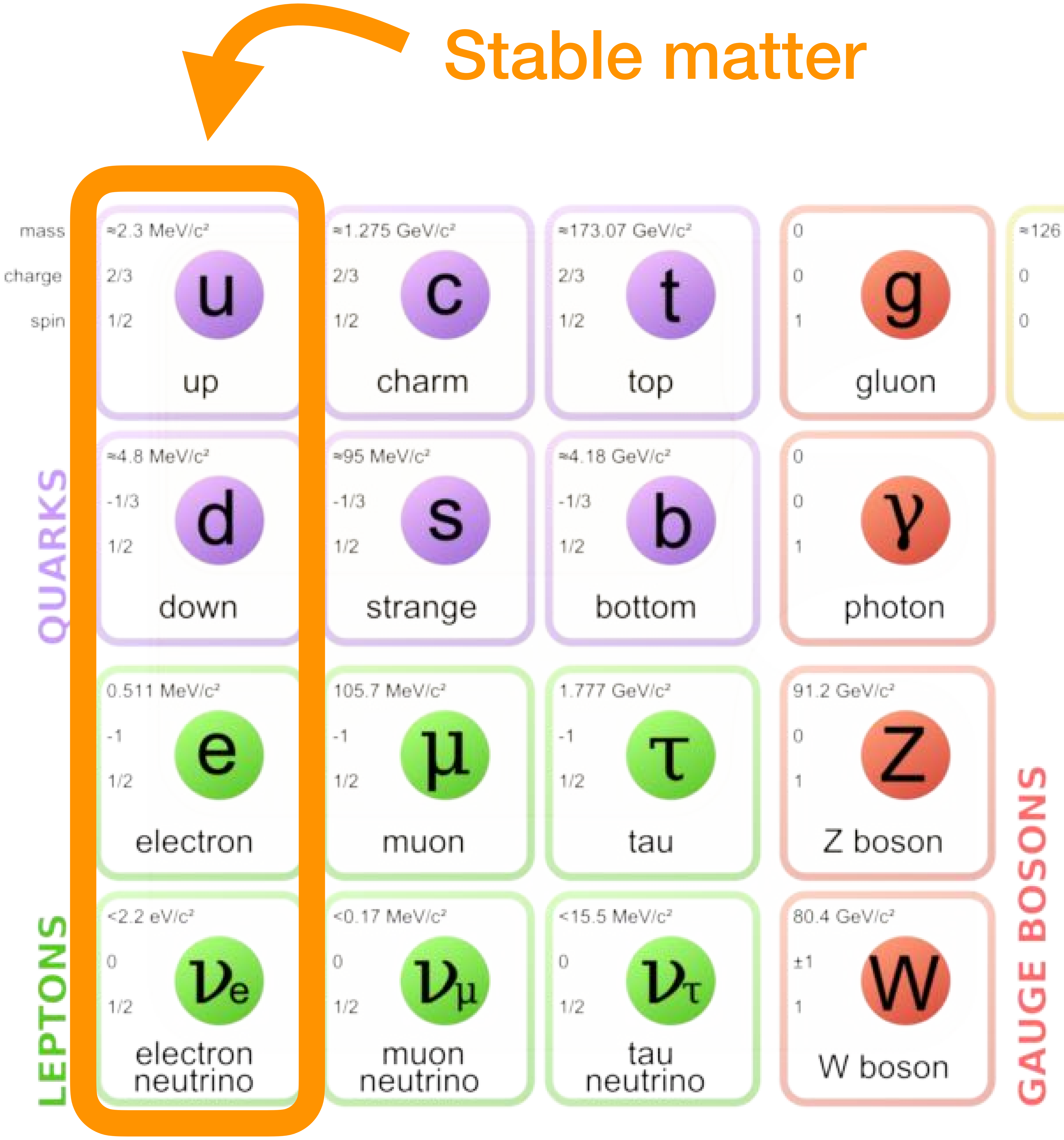
- Q_{proton}[uud]= 2/3+2/3-1/3 = 1 Q_{neutron}[udd] = 2/3-1/3-1/3 = 0

Who ordered that?



Stable matter

mass charge spin	≈2.3 MeV/c^2 2/3 1/2 u up	≈1.275 GeV/c^2 2/3 1/2 c charm	≈173.07 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	≈126 GeV/c^2 0 0 H Higgs boson	
QUARKS	≈4.8 MeV/c^2 -1/3 1/2 d down	≈95 MeV/c^2 -1/3 1/2 s strange	≈4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon		
	0.511 MeV/c^2 -1 1/2 e electron	105.7 MeV/c^2 -1 1/2 μ muon	1.777 GeV/c^2 -1 1/2 τ tau	91.2 GeV/c^2 0 1 Z Z boson		GAUGE BOSONS
LEPTONS	<2.2 eV/c^2 0 1/2 ν_e electron neutrino	<0.17 MeV/c^2 0 1/2 ν_μ muon neutrino	<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino	80.4 GeV/c^2 ±1 1 W W boson		

- $m_\mu / m_e = 207$
- $m_t / m_u \sim \mathcal{O}(10^5)$!
- ν masses many orders of magnitude lighter than any other matter field!

Three perfect replicas,
differentiated only by mass
Why???
“Who ordered that?” (I.Rabi)

Many mysteries…

- We have a theory, called the Standard Model, which, at the current level of experimental precision and at the energies reached so far, is the most successful and best tested theory of nature at a fundamental level.

  What determines the observed pattern of masses of quarks and leptons? Why are they arranged in generations? Why three?

- In the SM, the only interaction distinguishing the three flavours is the interaction of the matter fields with the Higgs boson (Yukawa interaction). The complex phases present in the Yukawa couplings are also the only source of Charge-Parity (CP) violation.

C = charge conjugation (swapping particles & antiparticles)
P = parity (spatial inversion, like reflection in a mirror)

- CP (Charge-Parity) violation is required to explain the matter-antimatter asymmetry of the Universe

  Are there other sources of flavour (and CP) symmetry breaking, beside the SM Yukawa couplings?

Why flavour is interesting

- To be able to answer these questions is likely to shed light on physics beyond the SM…

- Flavour physics might provide the first indications of new physics at energy scales that are beyond the reach of direct searches

- CP (Charge-Parity) violation is connected to the matter-antimatter asymmetry of the Universe

Where did the anti-matter go?

Where did the anti-matter go?

- What led to the disappearance of antimatter assuming an initial symmetric state (or that inflation washed out any possible prior asymmetry)?
  - There are anti-protons in cosmic rays, consistent with secondaries due to the interactions of cosmic-ray protons in the Interstellar Medium
  - We can produce and study anti-matter in accelerators
  - But apparently no anti-matter around us
  - This looks really strange, given that the properties of matter and antimatter are very similar.
  - **Where did it go? Why is the universe 100% matter-antimatter asymmetric ?**

Primordial Baryon Asymmetry

- We can define the Baryon Asymmetry of the Universe (BAU) as

$$\Delta(t) = \frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}}$$

We already know that $\Delta(10^{10}\,\text{years}) = 1$

- Another interesting point: $t_0 \sim 10^{-6} s$ (or $T \sim 1\text{GeV} \sim \mathrm{m_p}$) when the universe had cooled enough to allow the first protons and neutrons to form

- From thermodynamics: $N_B \sim N_{\bar{B}} \sim N_\gamma \;\rightarrow\; \Delta(t_0) = \dfrac{N_B - N_{\bar{B}}}{N_\gamma}$

- This ratio is in fact almost time-independent, so $\Delta(t_0)$ can be estimated by the baryon to photon ratio today: $\eta = \dfrac{N_B}{N_\gamma}$

Primordial Baryon Asymmetry

- From observations:
  - $N_\gamma \simeq 410$ photons/cm^3 (at T= 2.73^{0}K)
  - $N_B \simeq 0.25$ nucleons/m^3

$$\eta = \frac{N_B}{N_\gamma} \simeq 6 \times 10^{-10}$$

Small baryon-to-photon ratio in Universe today

- Big Bang theory tells us that the baryon asymmetry of the early universe was a very small number , **i.e., today's huge matter-antimatter asymmetry was a tiny number in the past**

$$\Delta(t_0) = \frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}} \sim 10^{-10}$$

Beginning of Universe

10,000,000,000

matter

10,000,000,000

anti-matter

~10^{-6} seconds later

10,000,000,001

matter

10,000,000,000

anti-matter

Universe now

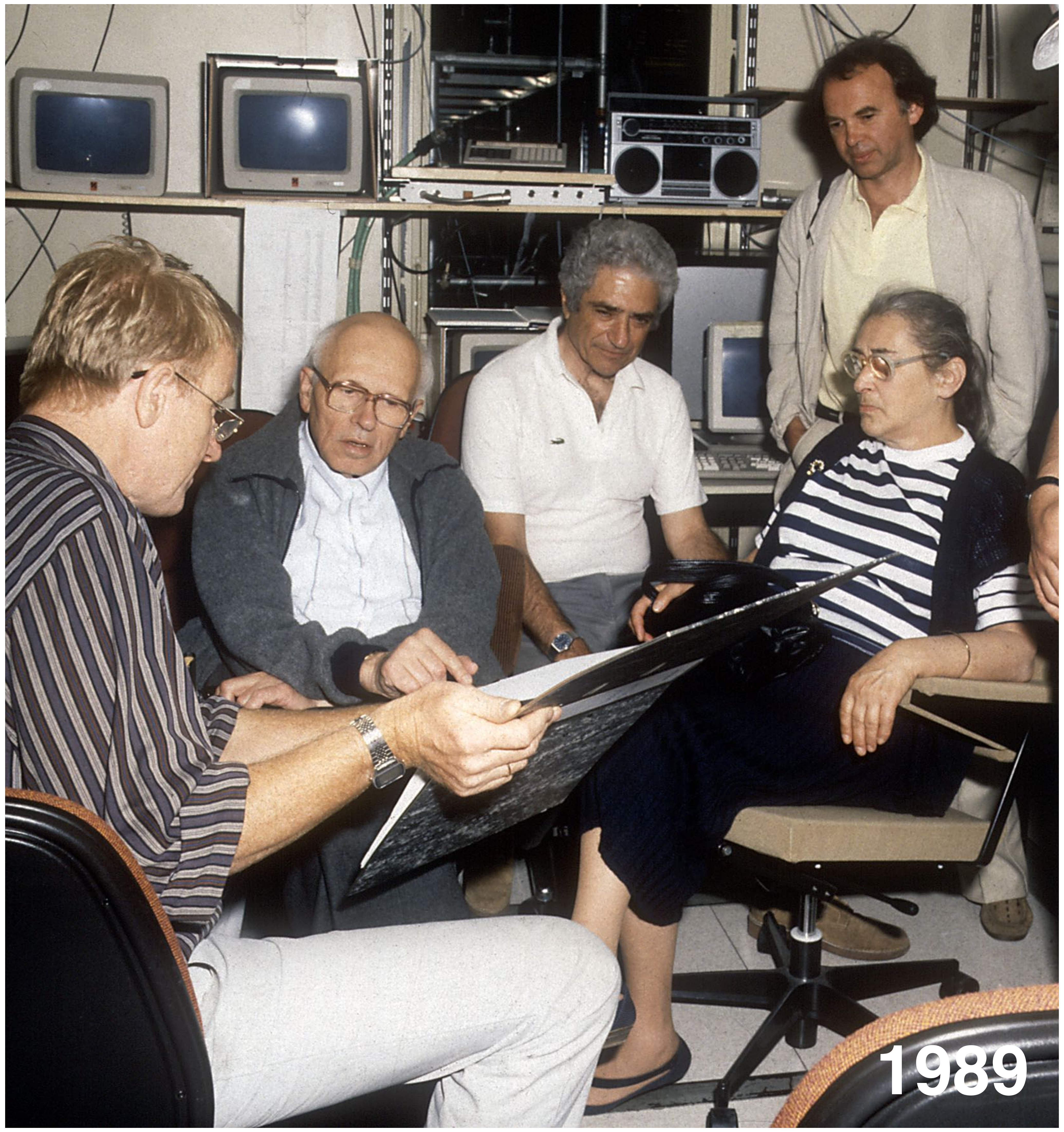
- Antimatter and matter particles annihilated massively in the early universe, but a tiny fraction of matter was left over: every 10 billion particles, a handful was not annihilated away

- We are very lucky!

Baryogenesis and Sakharov conditions

- A process called baryogenesis was hypothesized to generate this asymmetry dynamically from a matter-antimatter symmetric initial state

- In 1967 A.D. Sakharov enumerated three necessary conditions for baryogenesis (incidentally, his work went unnoticed for 11 years!)



1989

Sakharov conditions

1. Baryon number violation

- Otherwise there's no way to produce an excess of baryons

2. C and CP violation

- If C and CP are exact symmetries, the total rate for any process which produces an excess of baryons is equal to the rate of the complementary process which produces an excess of antibaryons

3. Thermodynamic non equilibrium

- Otherwise any asymmetry would be washed away by simple thermodynamics

Can the SM explain baryogenesis?

- In principle SM carries all the ingredients to satisfy the Sakharov conditions

- Relevant measure is Jarlskog determinant J (I will come back to it!), an invariant that identifies CP violation in the SM and that depends on every physical quark mixing angle $J \sim \Pi(\delta m_q^2/M_W^2)\,\Pi(\text{angles})$

- CP violation in the SM is proportional to J (a dimensionless quantity is constructed by dividing by the relevant temperature at which the BAU freezes out) **$\sim 10^{-20}$**

- Many orders of magnitude below the observation!

We need more CP violation!

- CP violation beyond the SM must exist!
- Where might we find it?
  - **quark sector**, as deviations from CKM predictions
  - **lepton sector,** e.g. as CP violation in neutrino oscillations
  - **other new physics**: almost all TEV-scale NP contains new sources of CP violation and precision measurements of flavour observables are generically sensitive to additions to the Standard Model

Cabibbo-Kobayashi-Maskawa

- CKM theory specifies rates of different quark weak decays and predicts matter-antimatter asymmetries in these decays (CP violation)

- In particular, large CP violating asymmetries are expected in b-decays!

Cabibbo-Kobayashi-Maskawa

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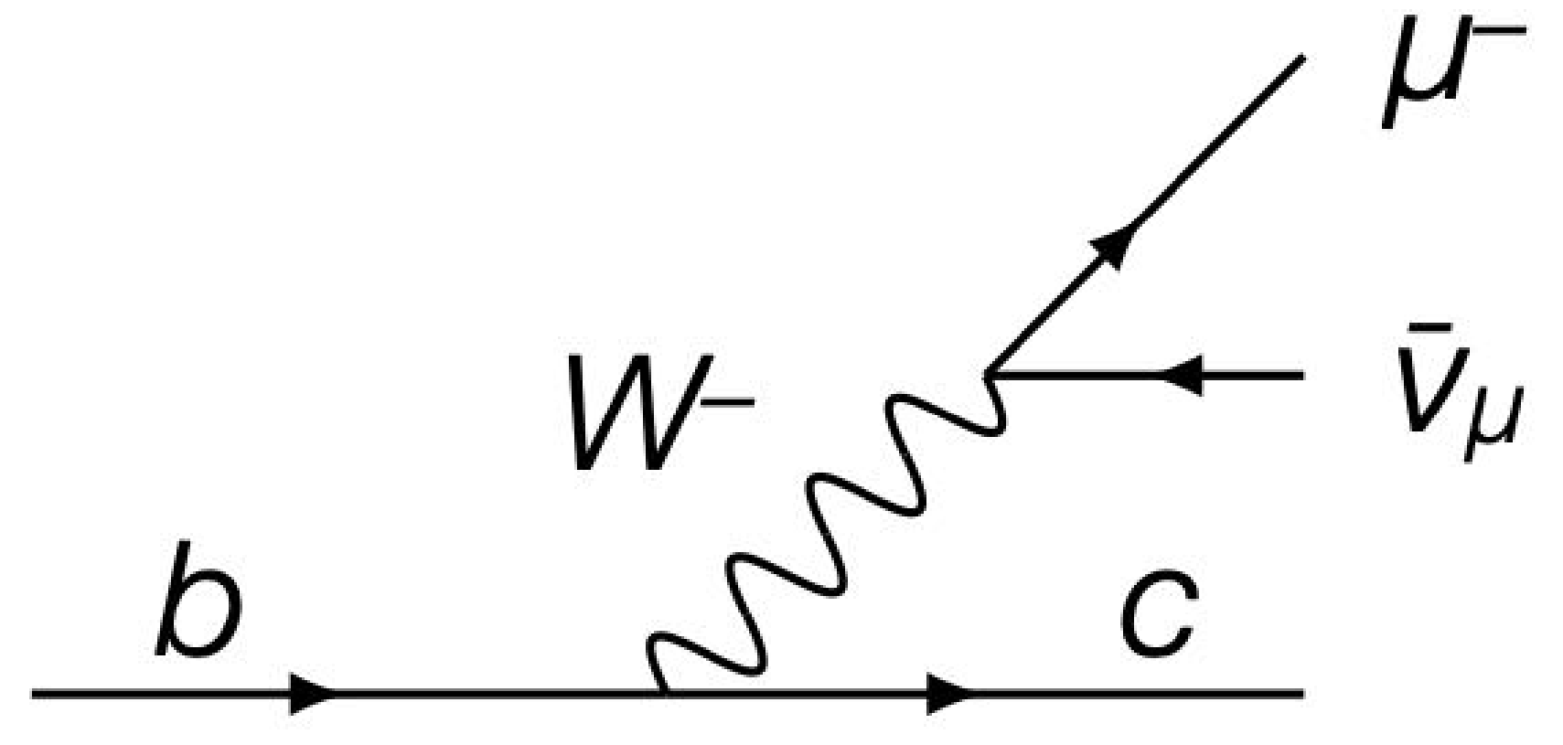
- In particular, large CP violating asymmetries are expected in b-decays!
- 2008 Nobel prize to K&M: CP violation requires the existence of at least three families of quarks in nature

The Cabibbo-Kobayashi-Maskawa matrix

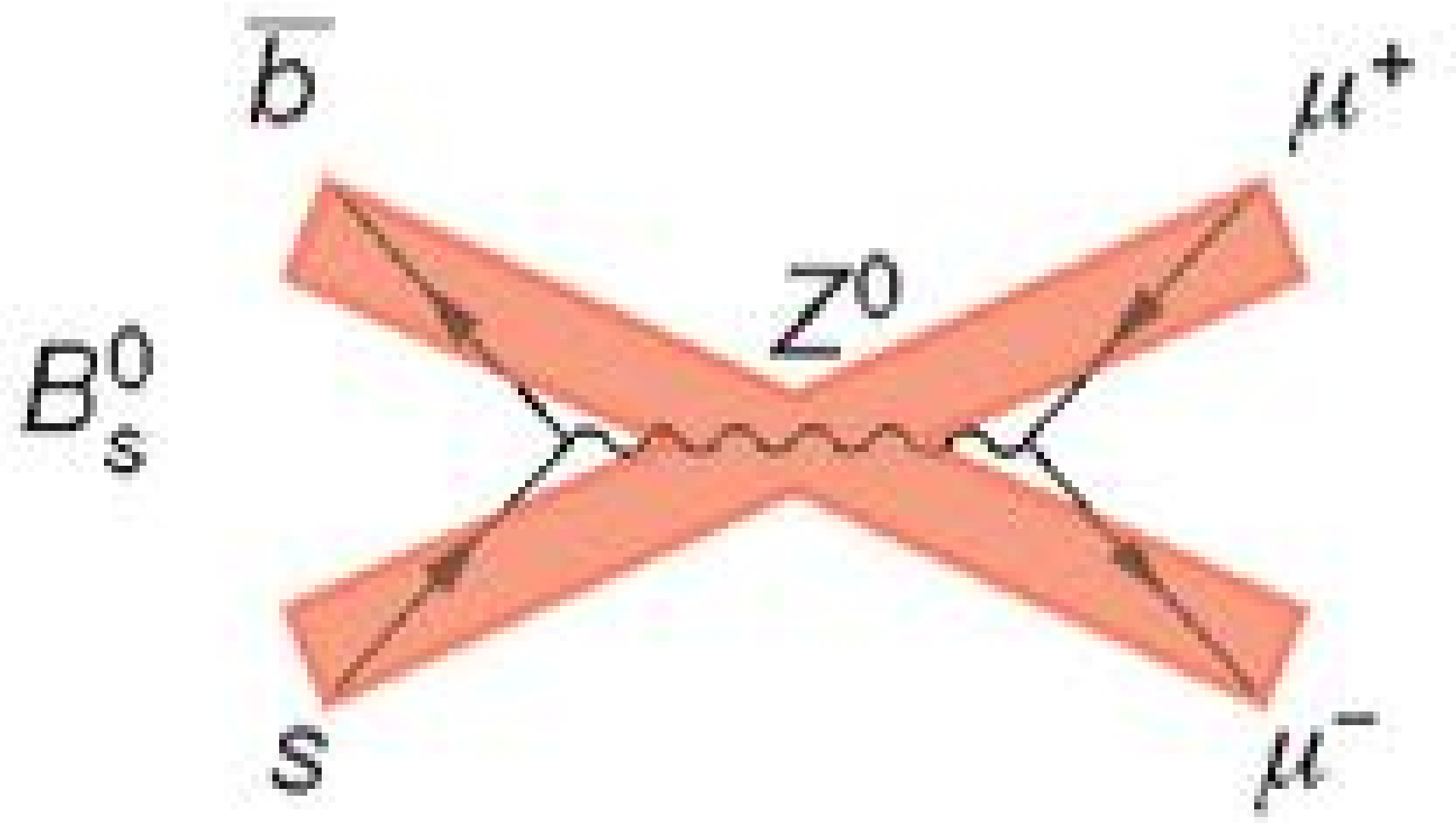
- Describes the couplings of quark-flavour changing interactions
    - Heavy quarks are unstable and decay via weak interactions to lighter quarks
    - V_{ij} proportional to transition amplitude from quark i to quark j

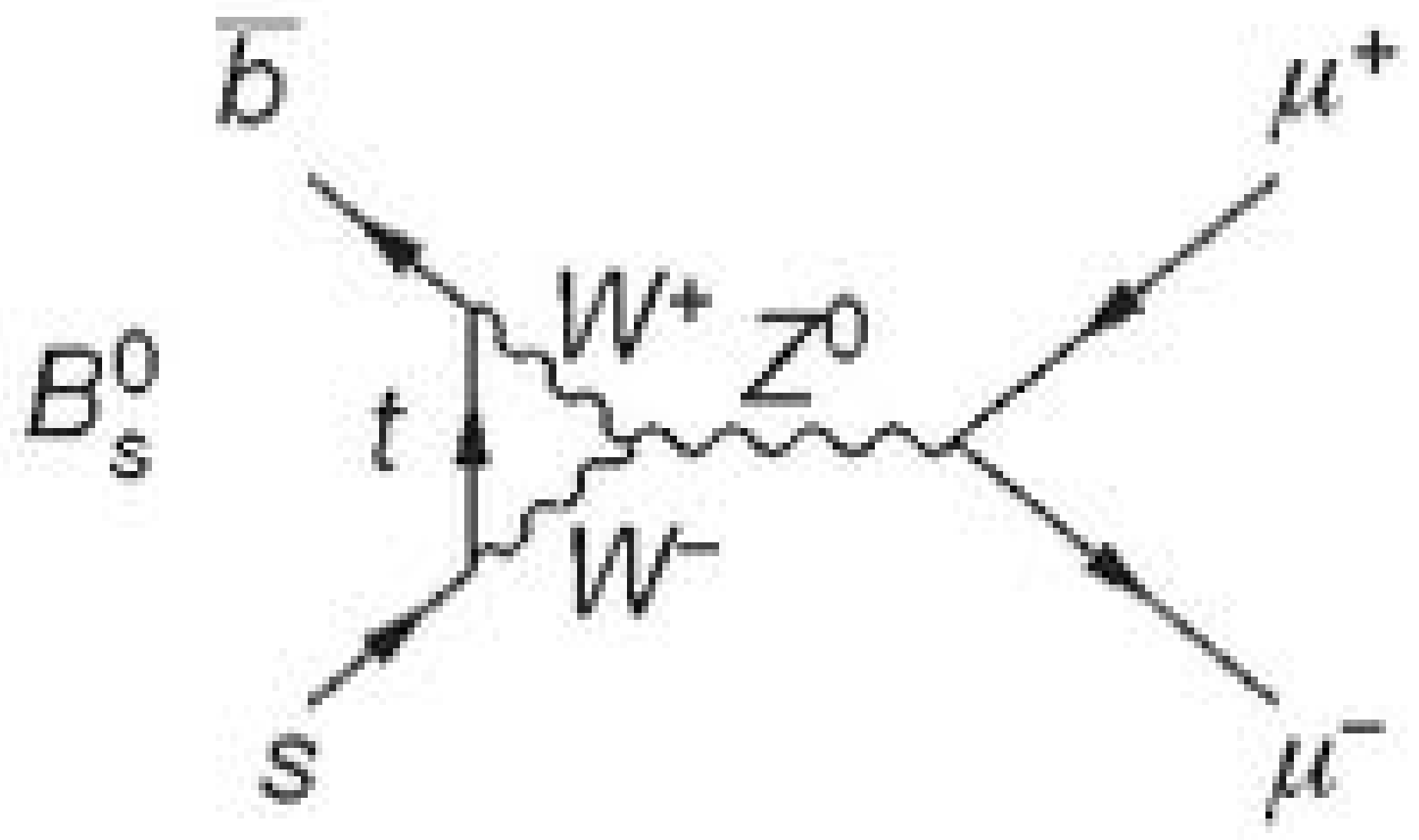


V_{cb}

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- V_{CKM} induces flavour-changing transitions inside and between generations in the charged sector at tree level ($W^{\pm}$interaction).
  [By contrast, there are no flavour-changing transitions in the neutral sector at tree level. No FCNC]





Hierarchy in quark mixing

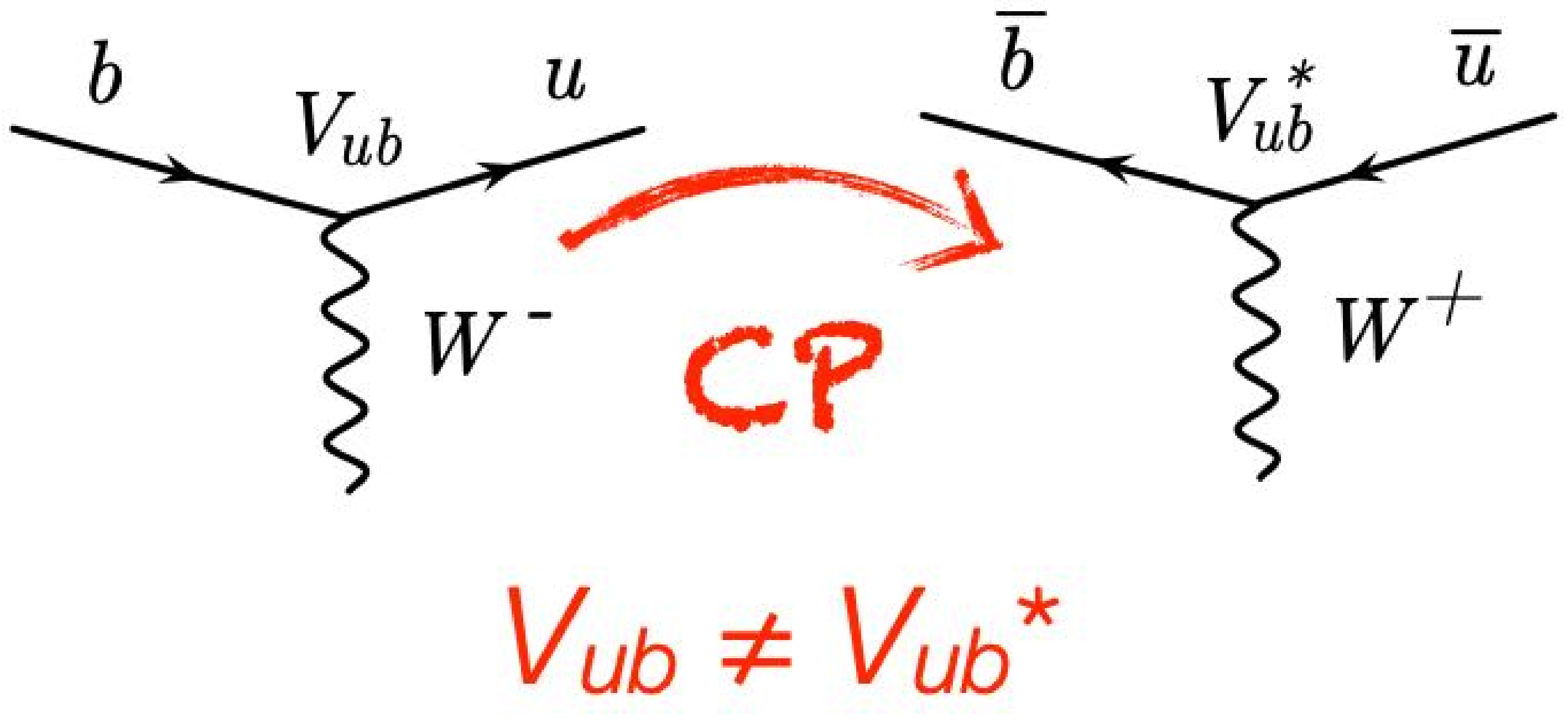
$$\lambda \sim 0.22$$

$$V \approx \begin{array}{cccc} d & s & b & \\ 1 & \lambda & \lambda^3 e^{i\varphi} & u \\ -\lambda & 1 & \lambda^2 & c \\ -\lambda^3 e^{-i\varphi} & -\lambda^2 & 1 & t \end{array}$$

- Each quark has a preference to transform into a quark of its own generation.
- Very suggestive pattern
- No known reasons
- Completely different in neutrino sector

- For $N = 3$ (3 families) , three mixing parameters and one complex phase [For $N = 2$, one mixing angle θ_c and no phases]

- This phase is responsible for CP violation: weak-interaction couplings differ for quarks and antiquarks because CP flips the sign of imaginary numbers



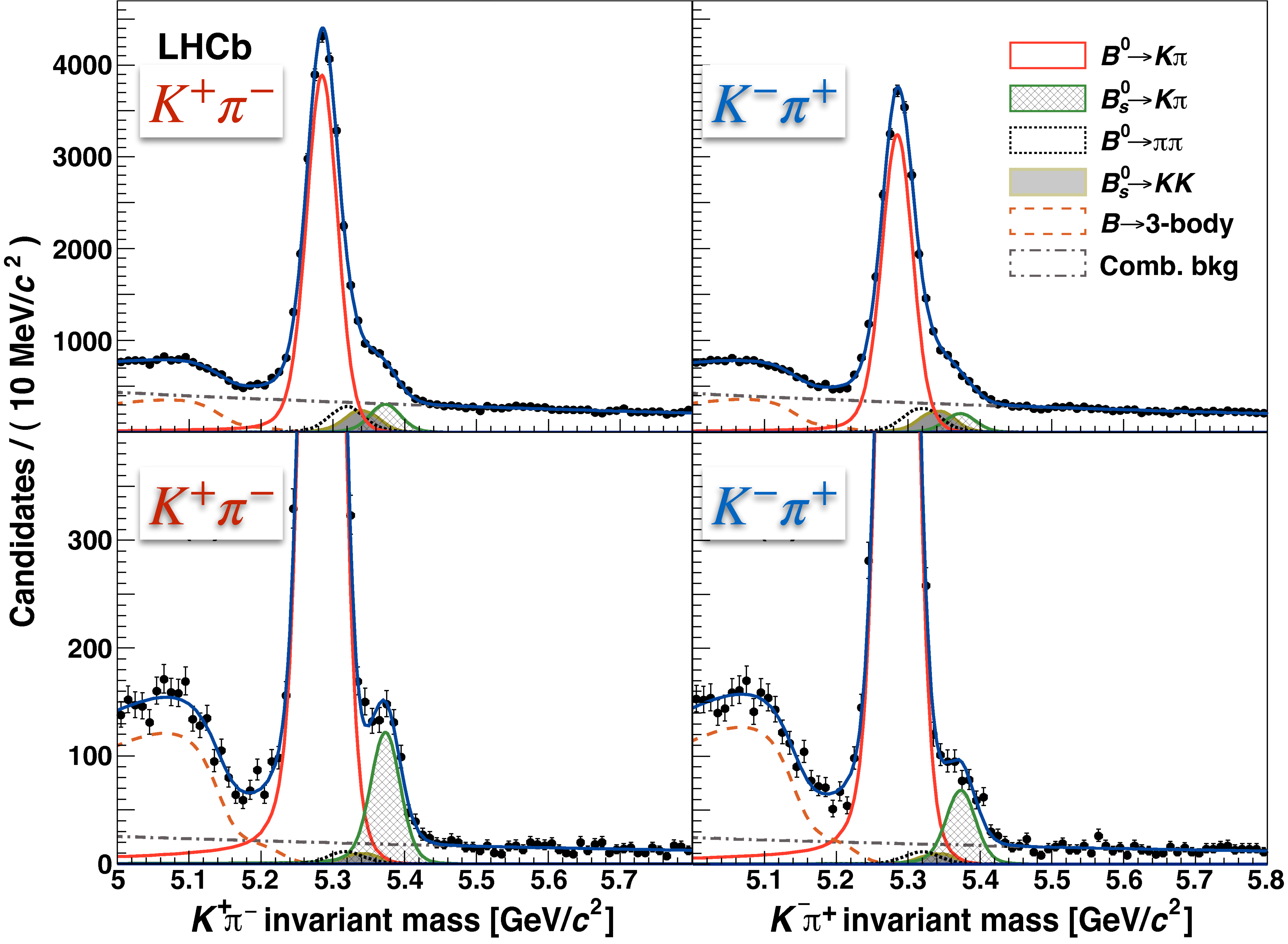
CP violation in $B^0_{(s)}$ meson decays

- Separate into B^0 and $\overline{B^0}$ from different charge combinations of K and π

$B^0 :[\bar{b}d]$

$B_s^0 :[\bar{b}s]$

B^0 $\overline{B^0}$



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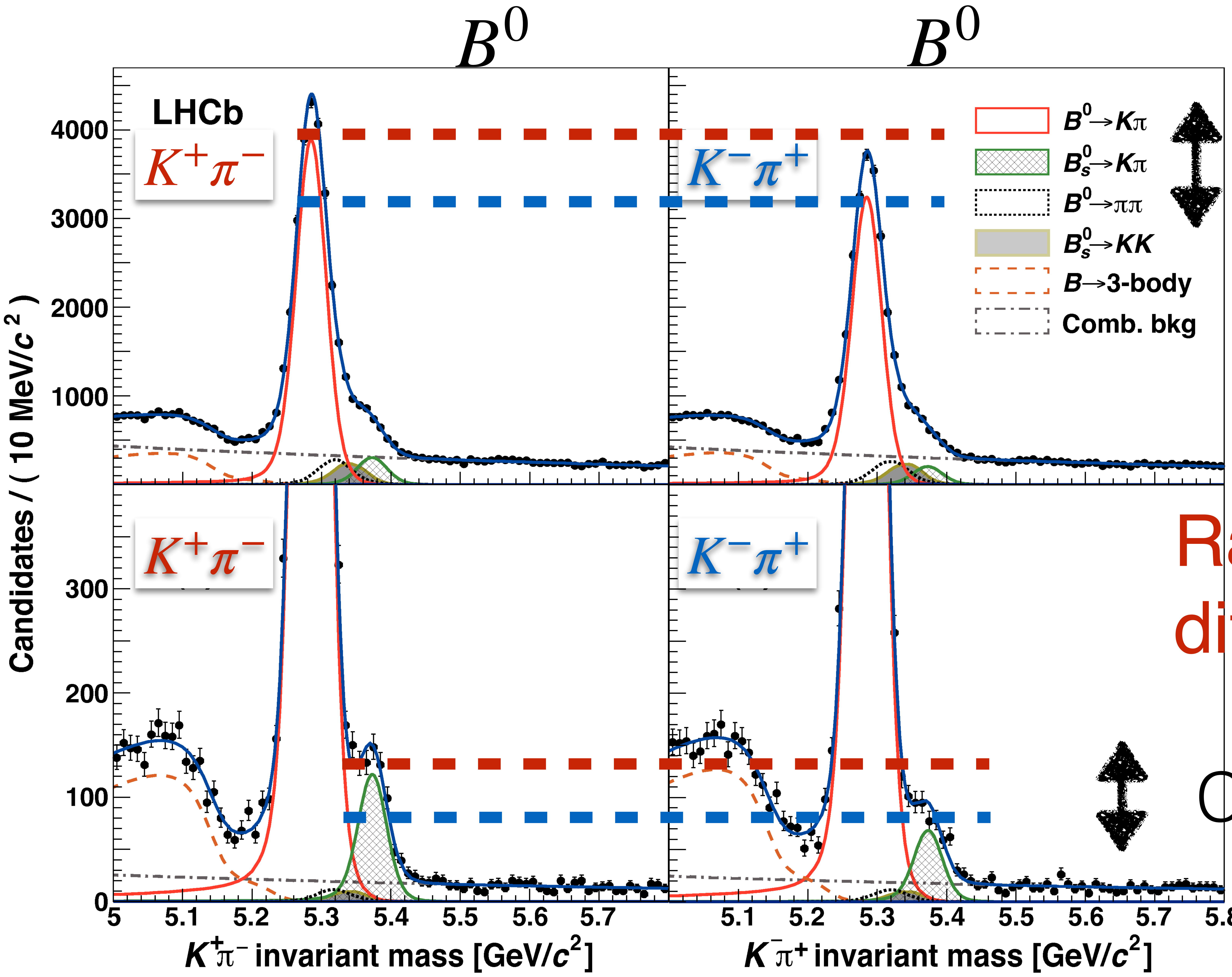
$B^0 : [\bar{b}d]$

$B^0_s : [\bar{b}s]$



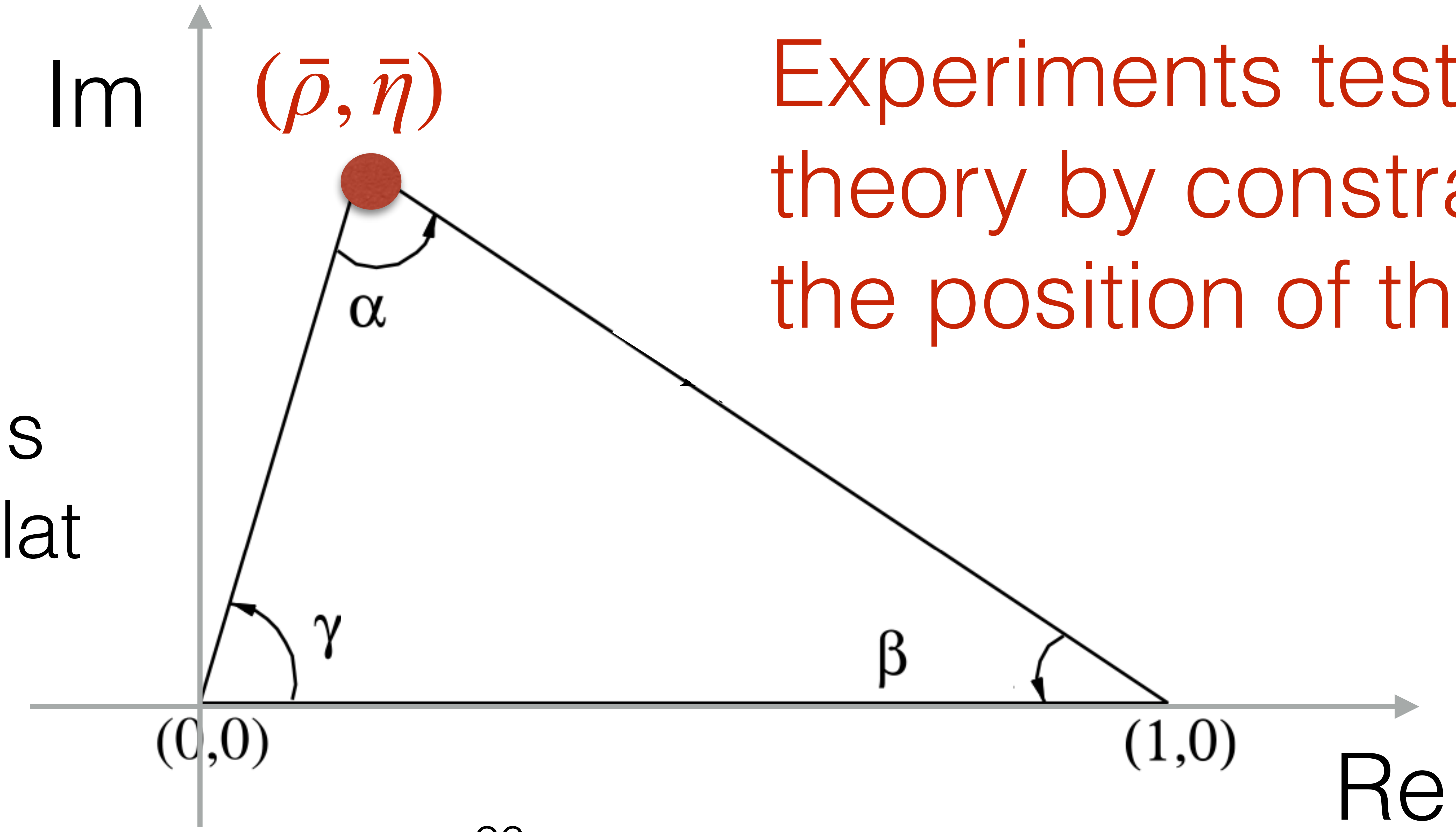
CP Violation

Rates are different!

CP Violation

Unitarity Triangle

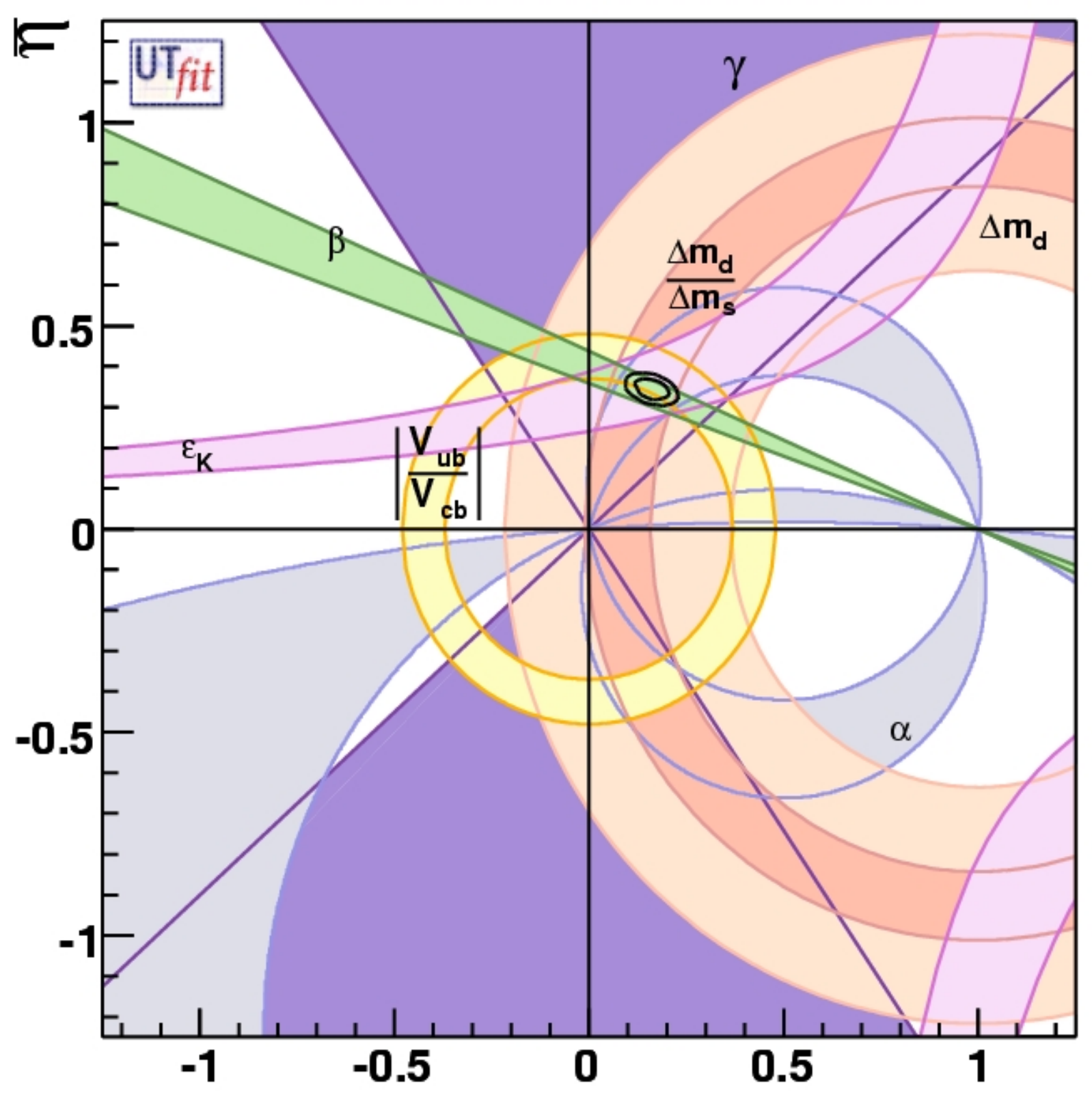
- Unitarity of CKM matrix implies relations of the form $\sum_i V_{ij}V^*_{ik} = \delta_{j,k}$, with $j \neq k$
- Each of these 6 unitarity constraints can be seen as the sum of 3 complex numbers closing a triangle in the complex plane



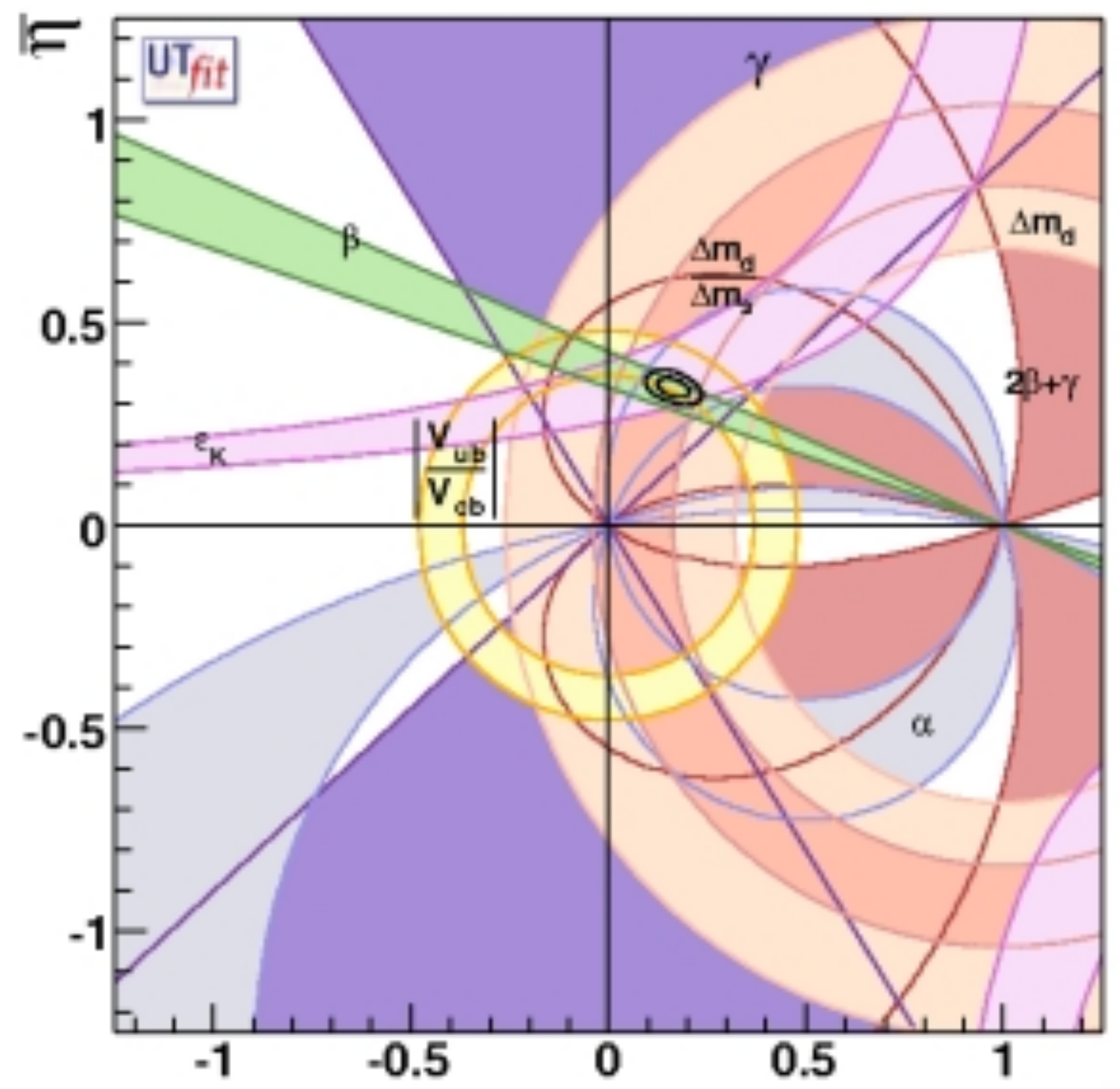
Experiments test the theory by constraining the position of the apex

CP violation in the quark sector ($\bar{\eta} \neq 0$) is translated into a non flat UT

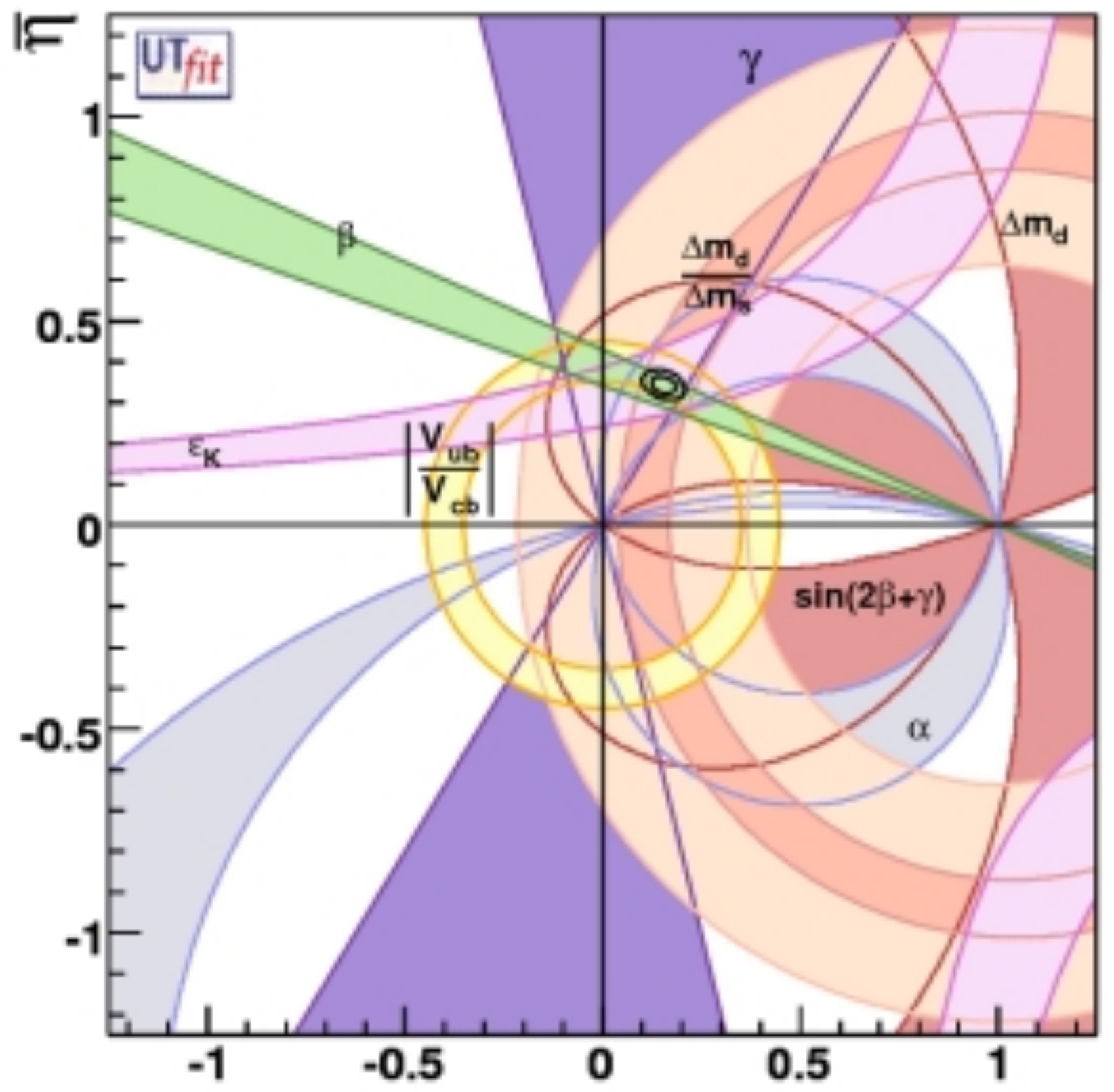
A long journey…



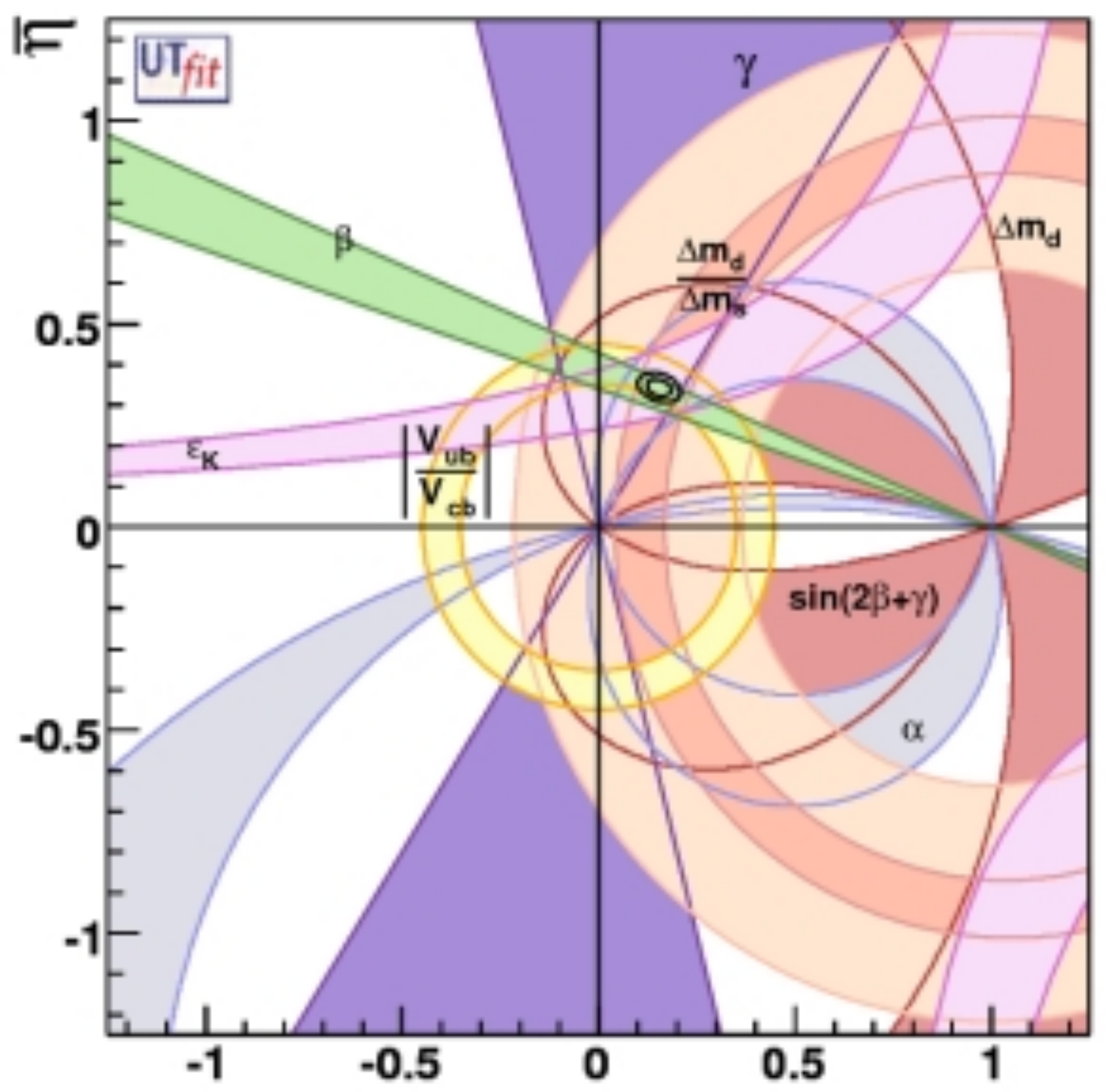
2006



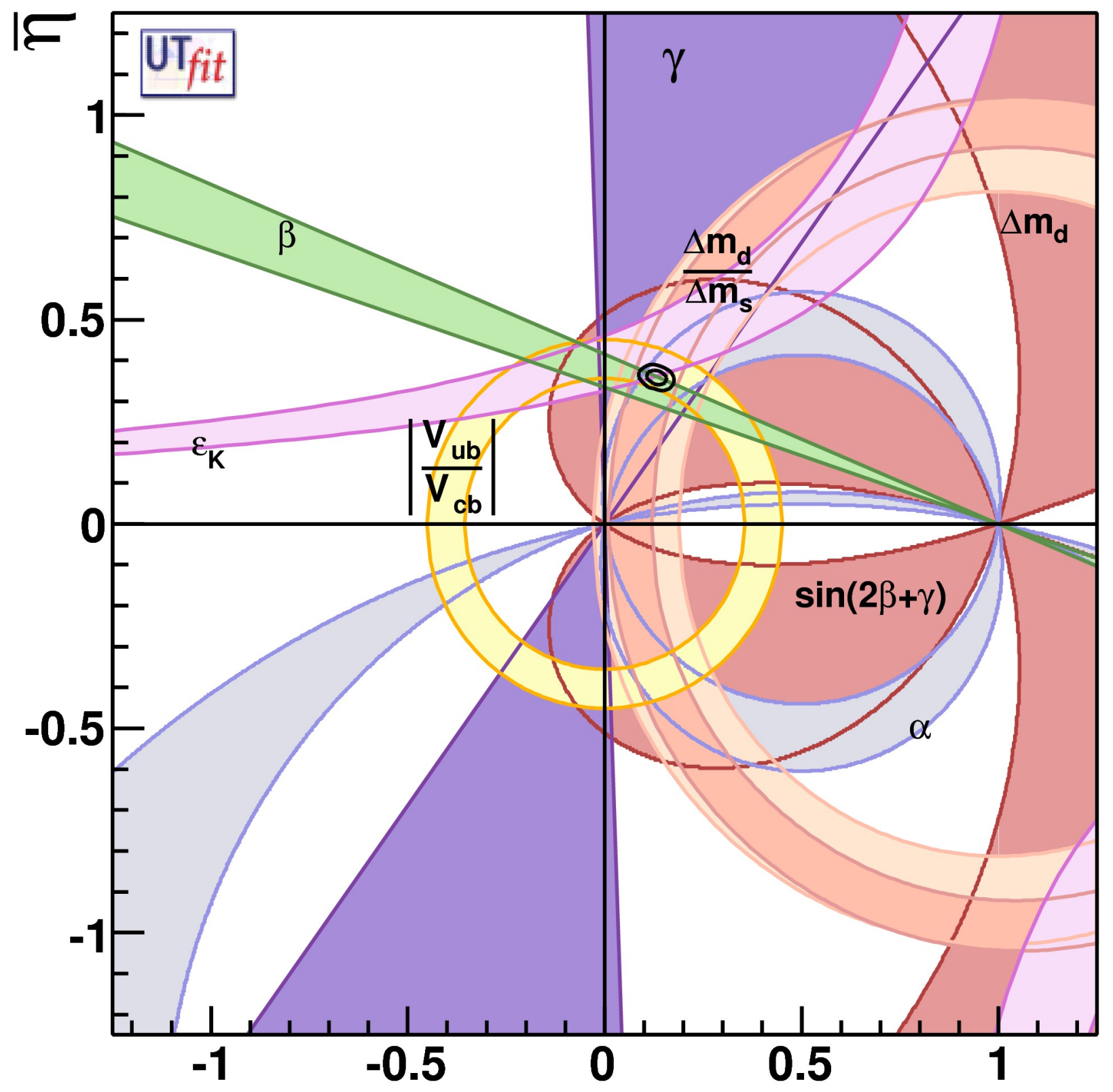
2007



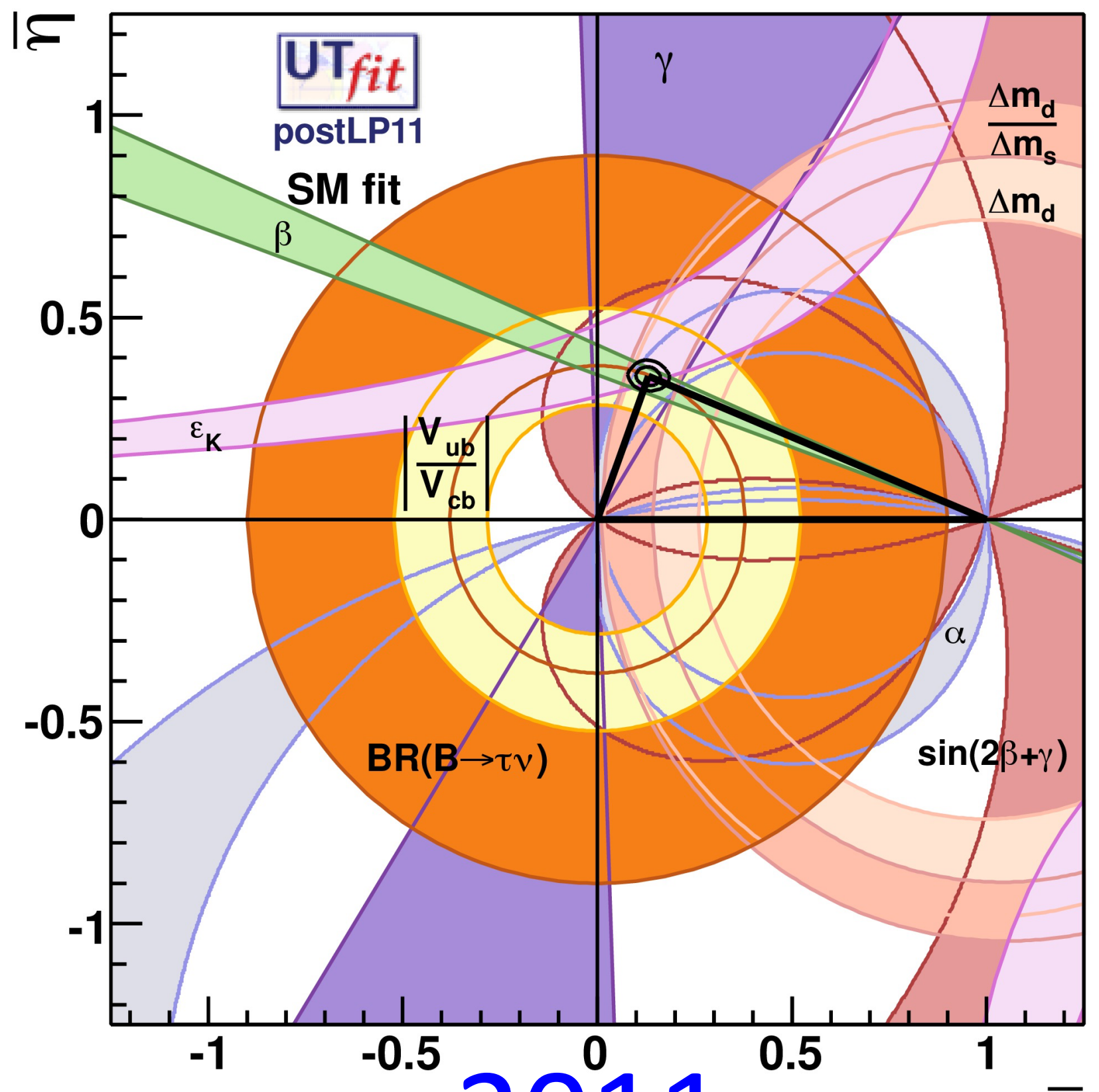
2008



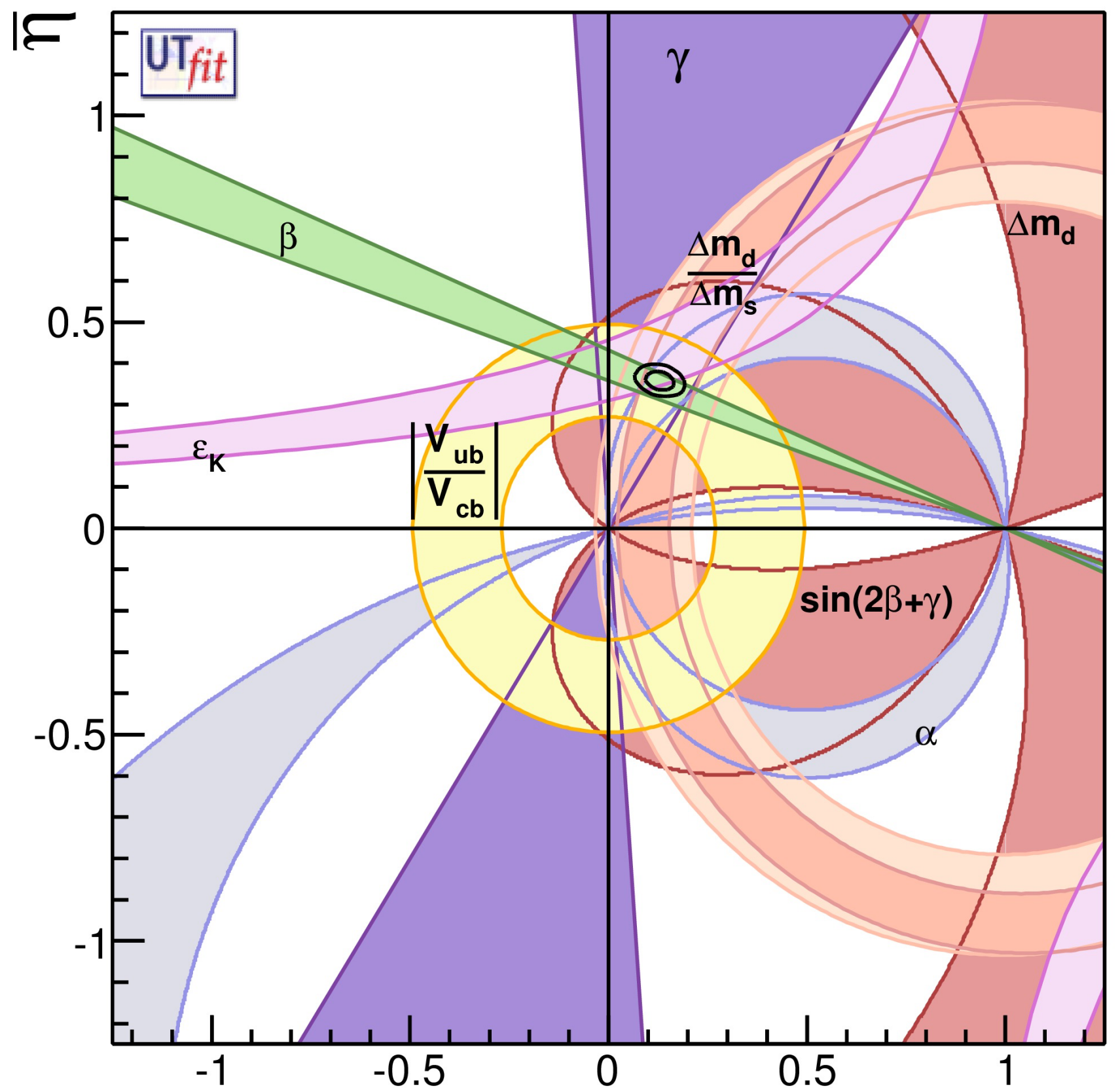
2009



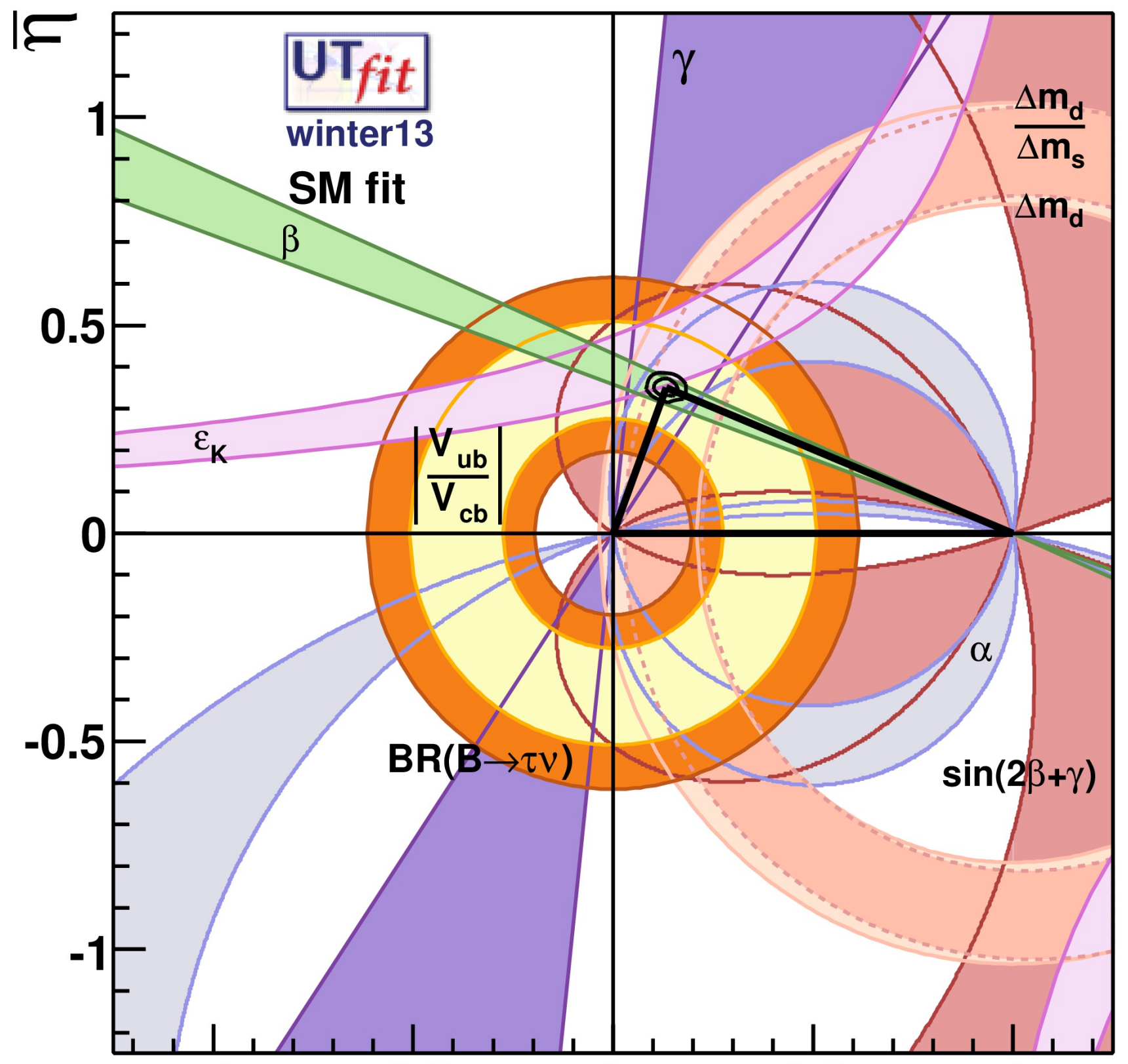
2010



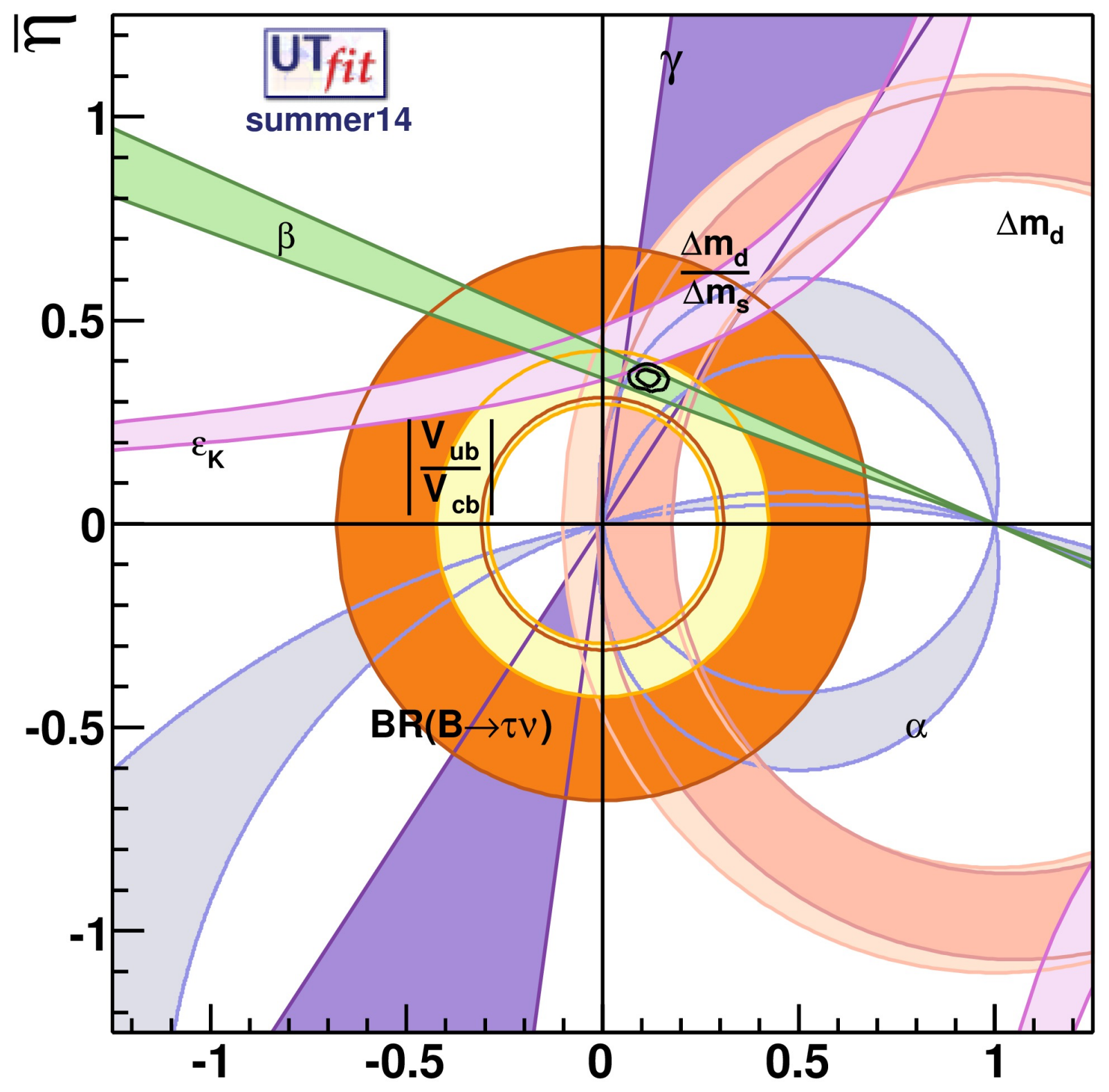
2011



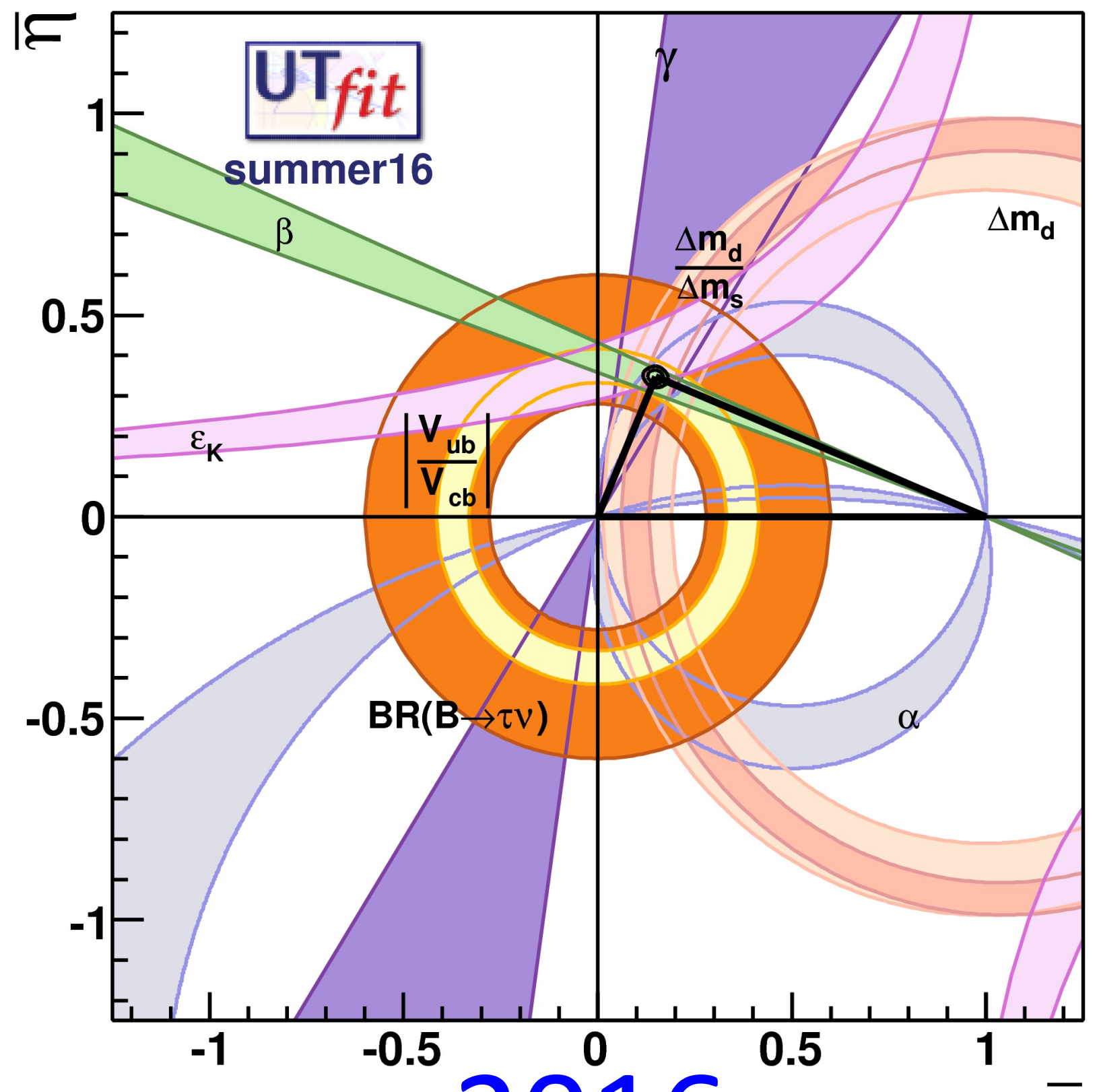
2012



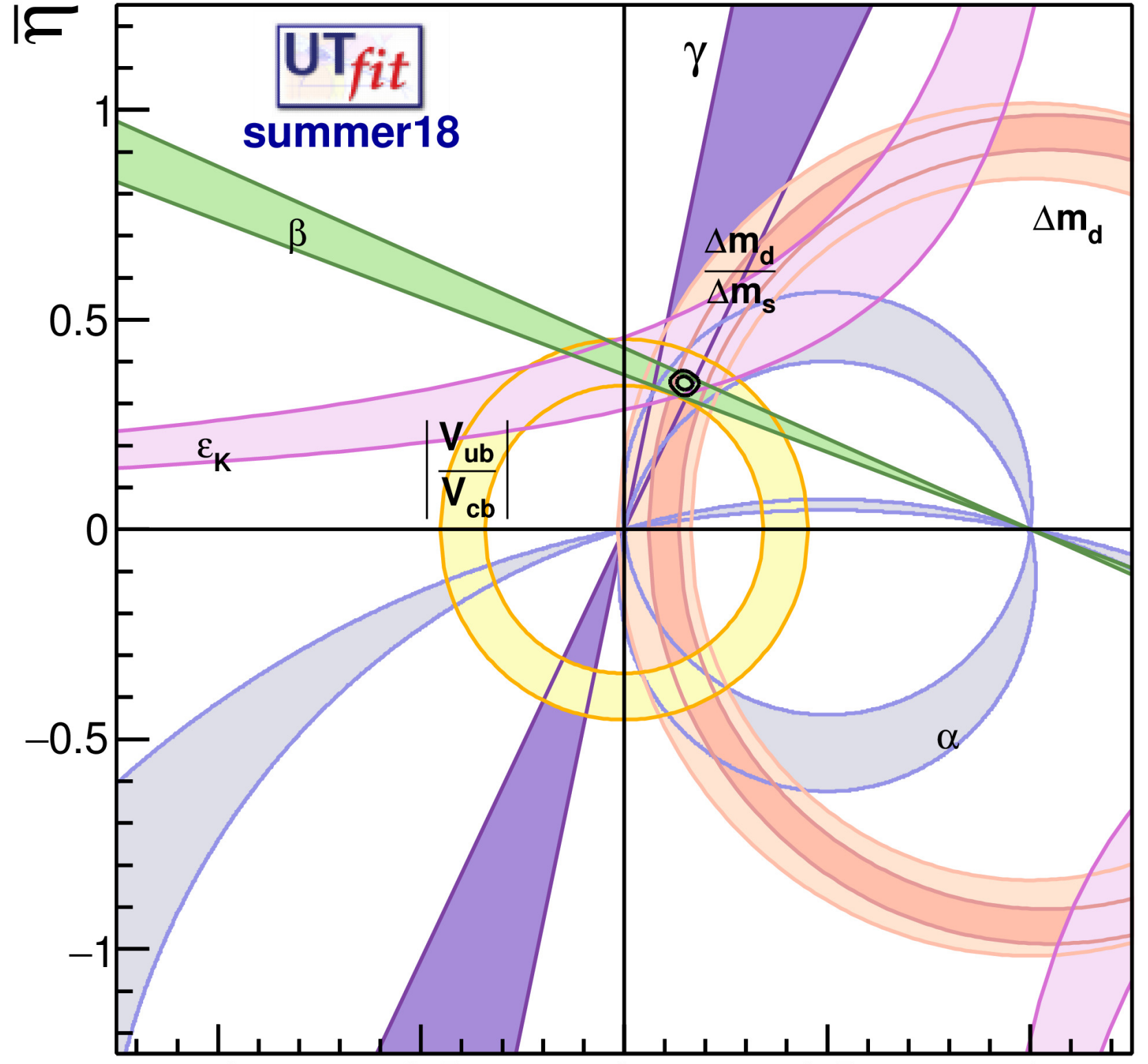
2013



2014



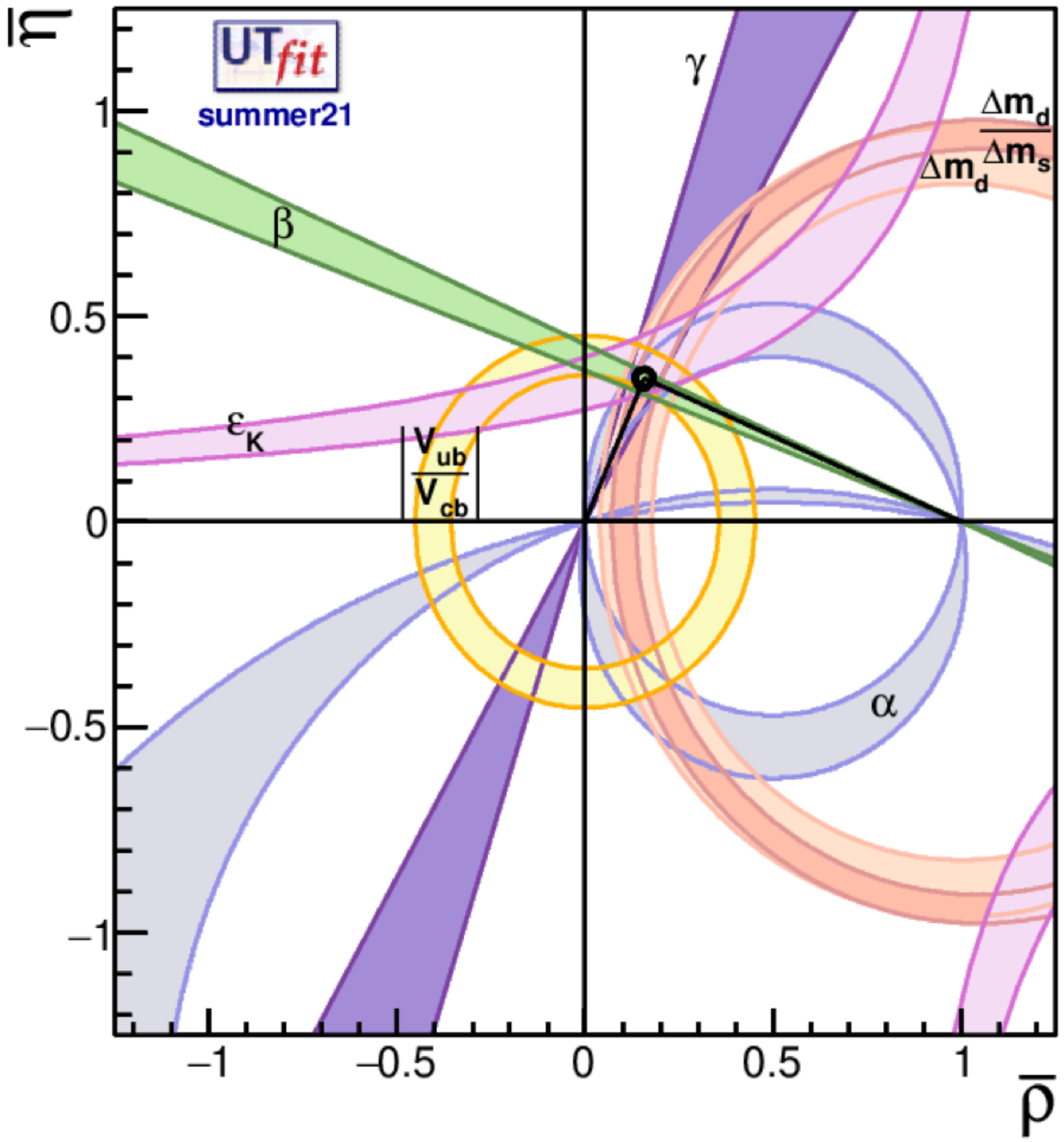
2016



2018

?

Consistency of CKM fits



www.utfit.org

$$\bar{\rho} = 0.157 \pm 0.012$$ ~8%

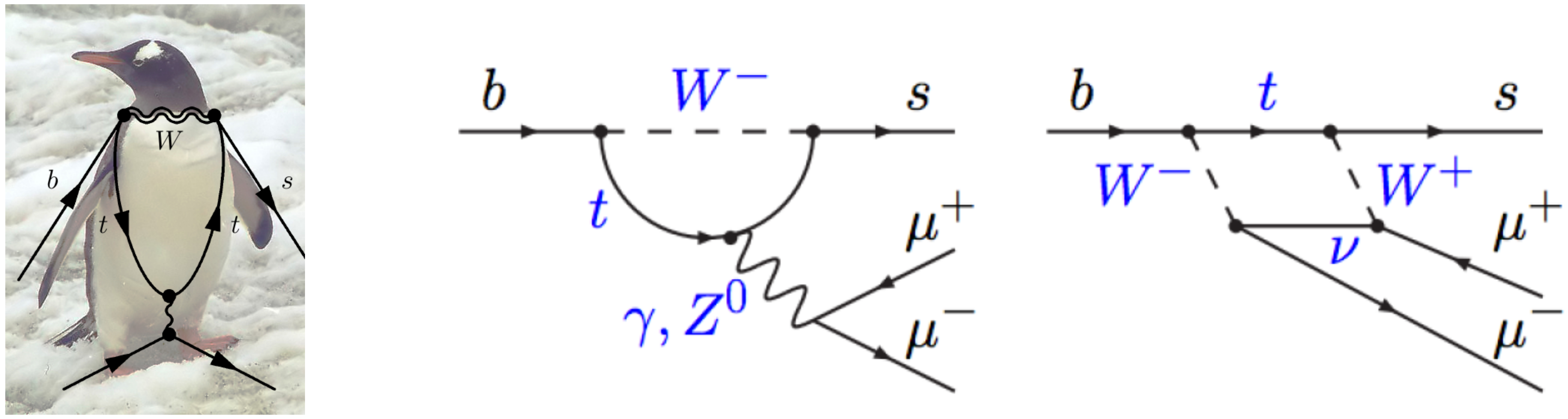
$$\bar{\eta} = 0.350 \pm 0.010$$ ~3%

- Impressive effort from community and tremendous success of CKM paradigm!
- Constraints from many different quark transitions. Extensive measurements on K, D and B mesons performed at different experiments. These constraints depend also on theory input.
- At the current level of precision, all measurements are consistent and intersect in the apex of the UT
- New Physics effects (if there) are small!

Rare b decays

Rare b decays, in a nutshell

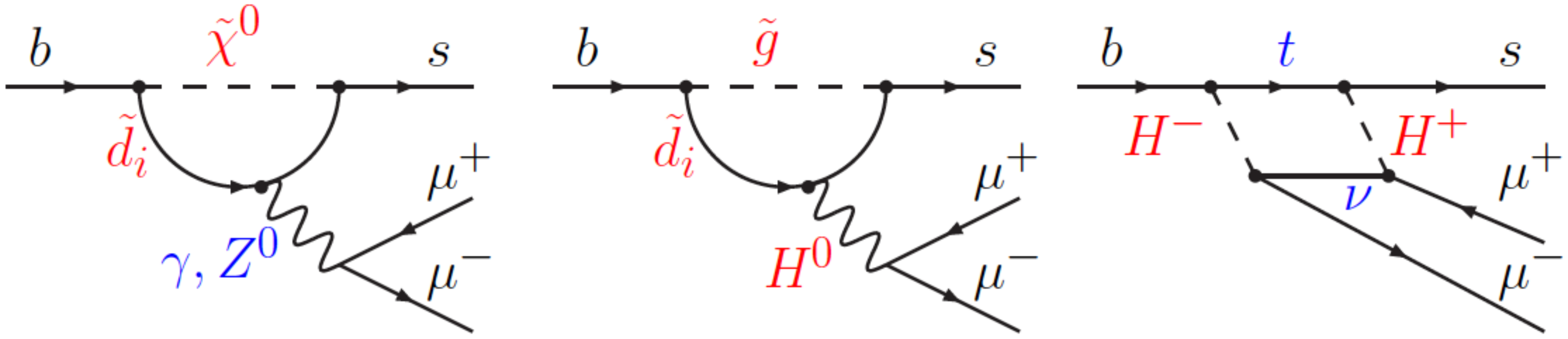
- In the SM, processes involving flavour changes between two up-type quarks (u,c,t) or between two down-type quarks (d,s,b) are forbidden at tree level and can only occur at loop level (penguin and box) → Rare FCNCs



$b \to s\ell^+\ell^-$ transitions

(BF 10^{-6} to 10^{-10})

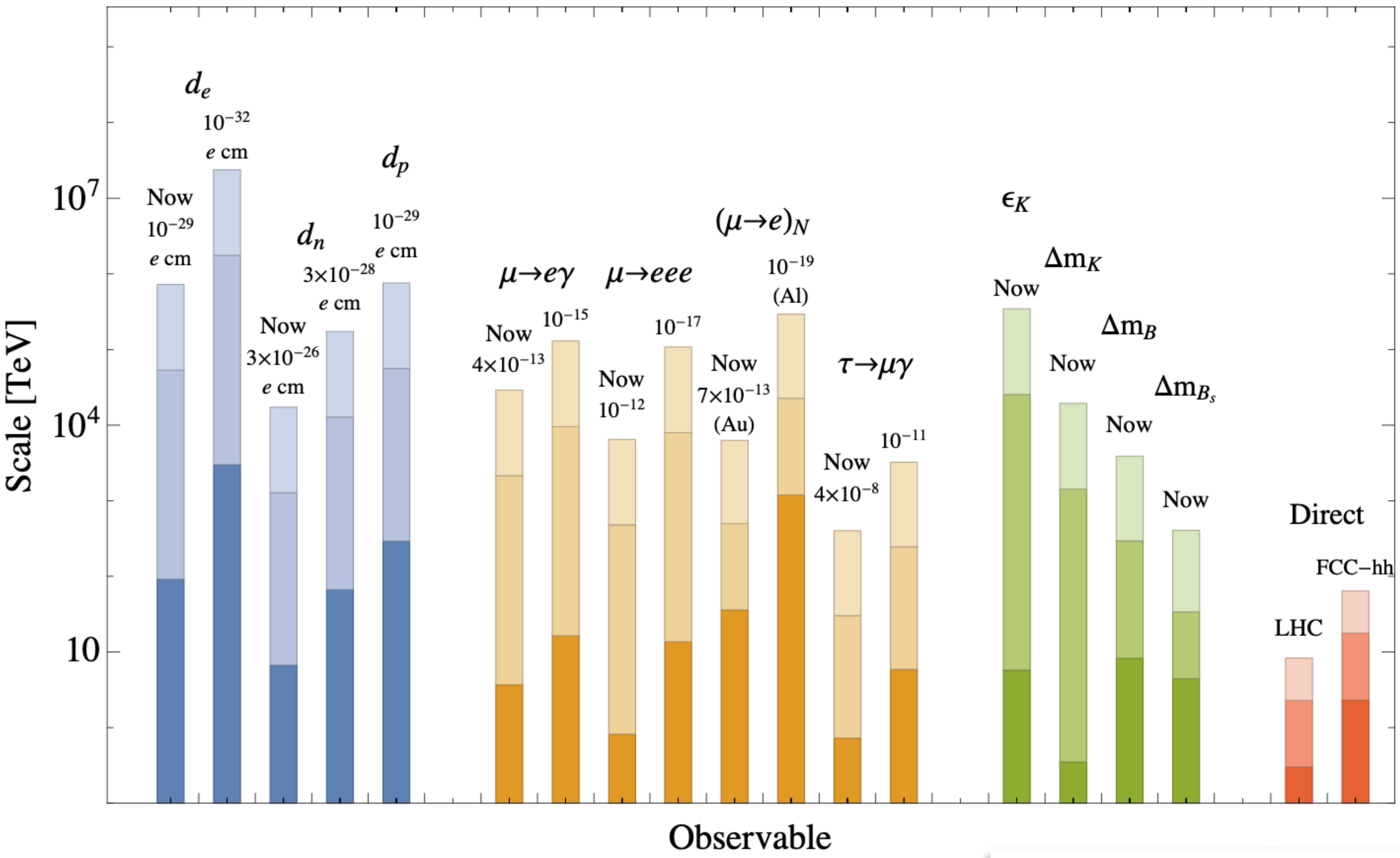
- A new particle, too heavy to be produced at the LHC, can give sizeable effects when exchanged in a loop



- Strategy: use well-predicted observables to look for deviations
- Indirect approach to New Physics searches, complementary to that of ATLAS/ CMS

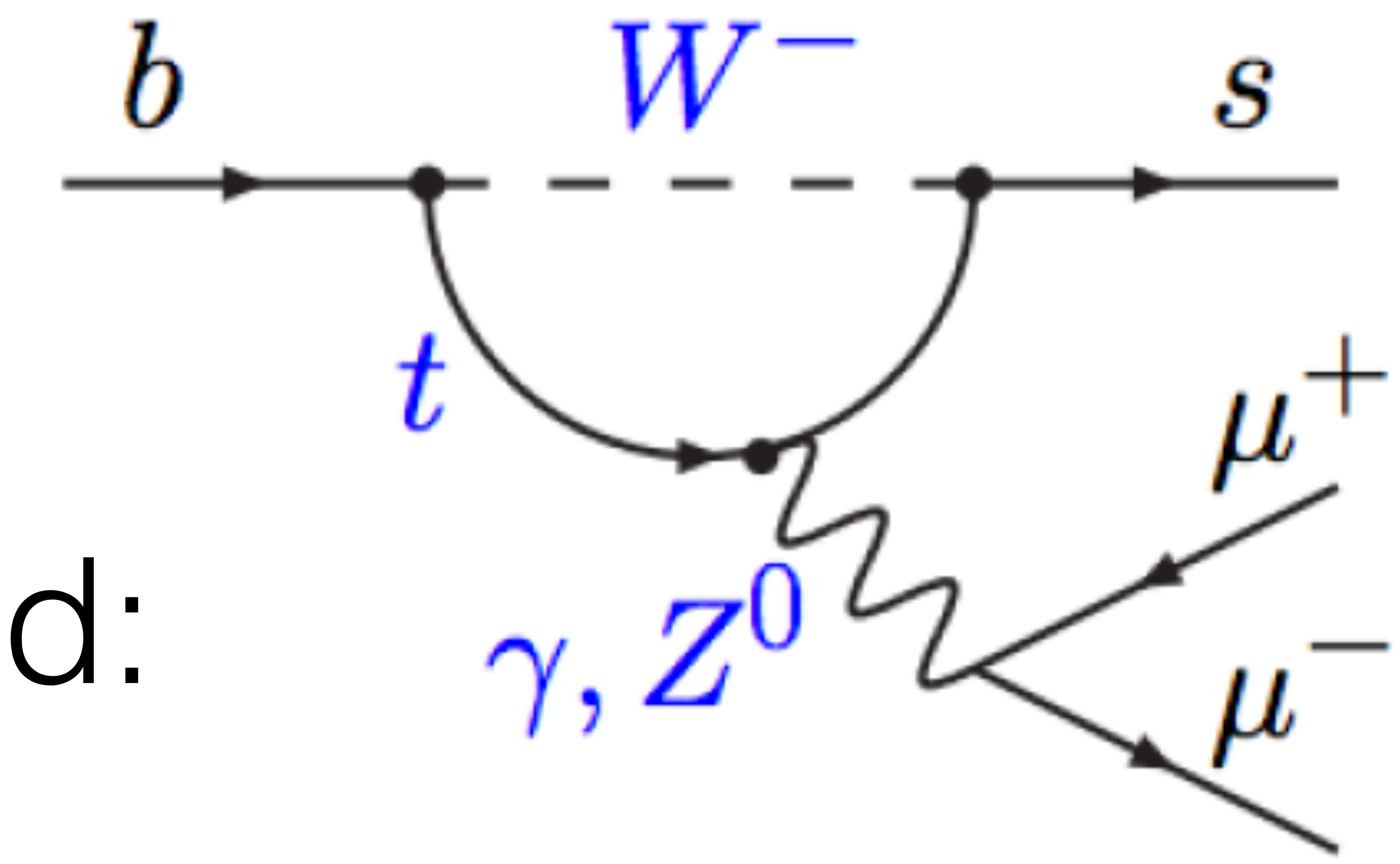
A window on NP at high scales

Energy reach of various indirect precision tests of physics beyond the SM compared to direct searches



Matt Reece, DOE Basic Research Needs Study on HEP Detector R&D

One of the milestones of flavour programme
$B_{(s)} \to \mu^+\mu^-$



- Very suppressed in the SM
  - Theoretically "clean" → precisely predicted:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\mathrm{SM}} = (3.66 \pm 0.14) \times 10^{-9}$$

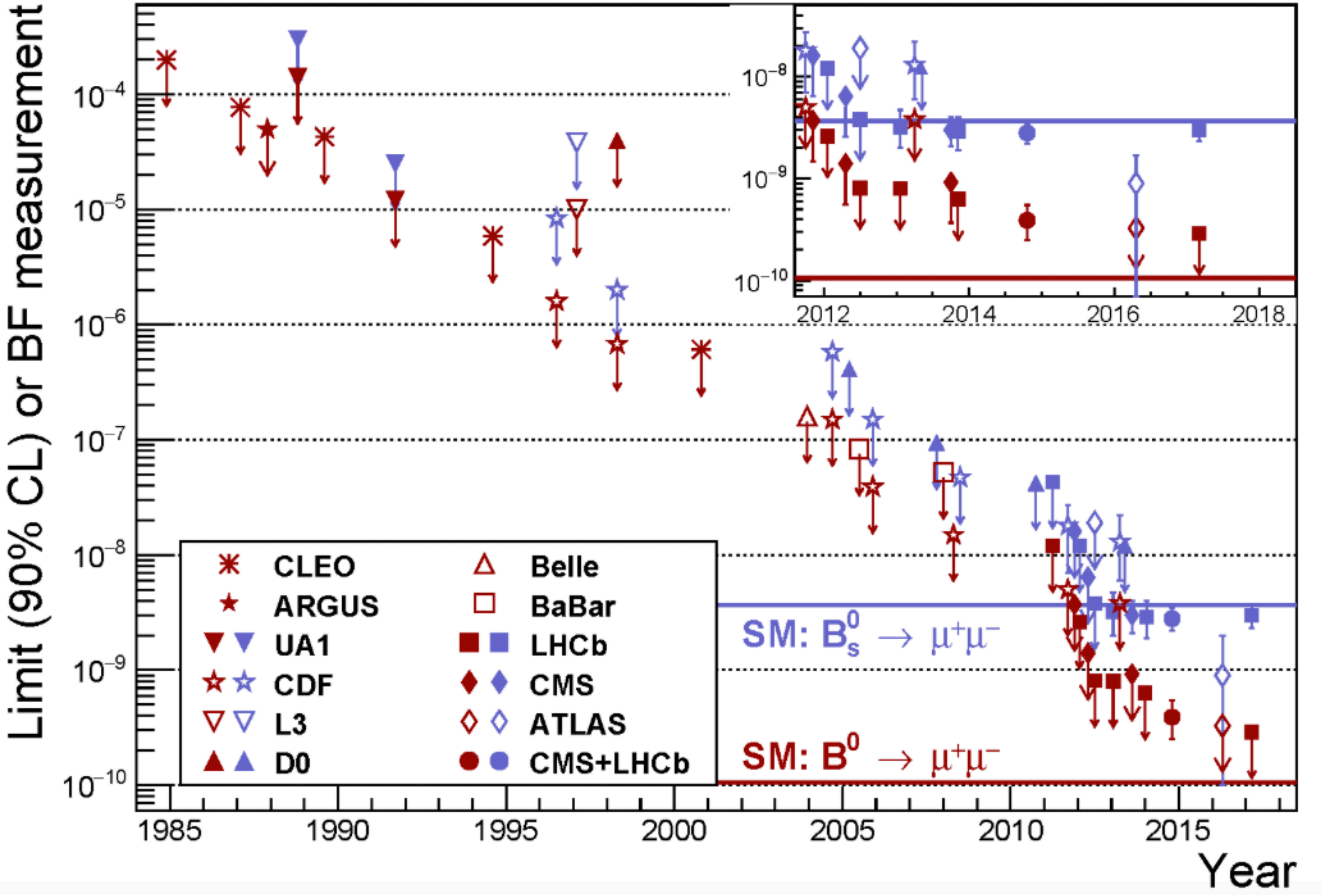
$$\mathcal{B}(B^0 \to \mu^+\mu^-)_{\mathrm{SM}} = (1.03 \pm 0.05) \times 10^{-10}$$

(~4%)

Bobeth et al.
PRL 112 (2014) 101801
Beneke et al.
JHEP 10 (2019) 232

- Sensitive to NP
  - A large class of NP theories, such as SUSY, predict significantly higher values for the $B_{(s)}$ decay probability
- Very clean experimental signature
  - Studied by all high-energy hadron collider experiments

30 years of effort!



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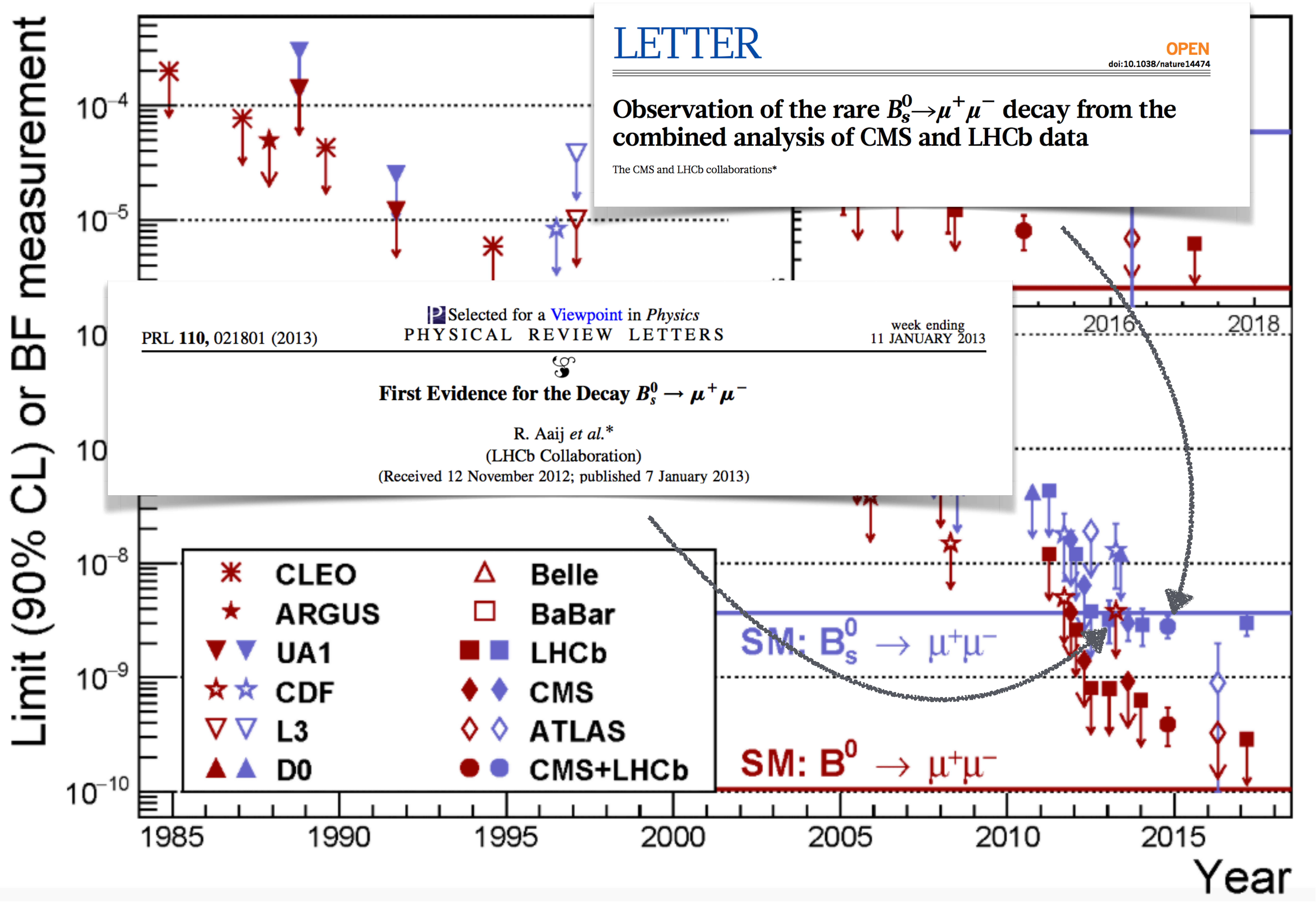


LETTER

OPEN

doi:10.1038/nature14474

Observation of the rare $B_s^0 \rightarrow \mu^+\mu^-$ decay from the combined analysis of CMS and LHCb data

The CMS and LHCb collaborations*

Selected for a Viewpoint in *Physics*

PRL **110,** 021801 (2013) PHYSICAL REVIEW LETTERS week ending 11 JANUARY 2013

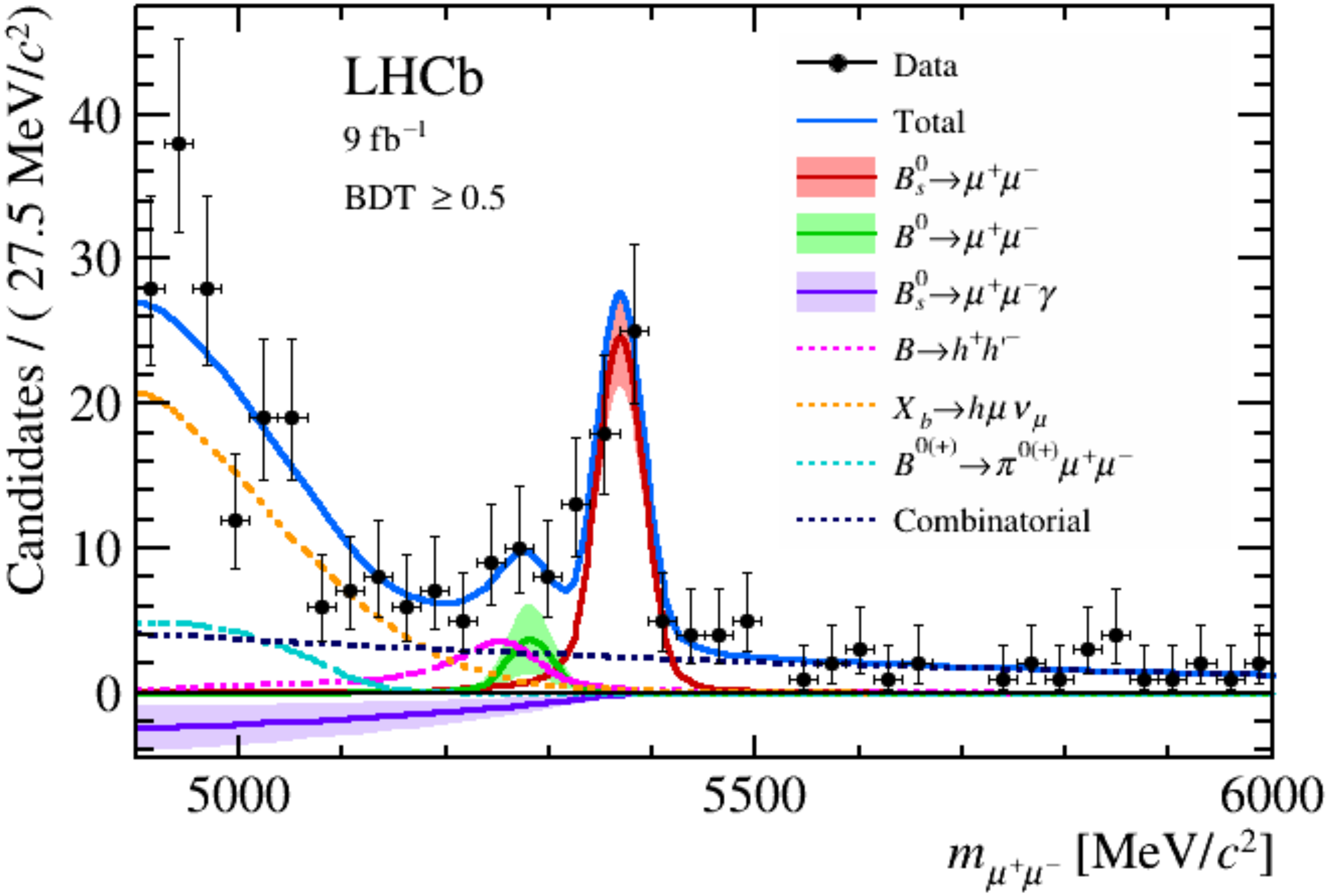
First Evidence for the Decay $B_s^0 \rightarrow \mu^+\mu^-$

R. Aaij *et al.**

(LHCb Collaboration)

(Received 12 November 2012; published 7 January 2013)

$B_{(s)} \to \mu^+\mu^-$: Latest LHCb result



Full statistics

[LHCb-PAPER-2021-007]
[LHCb-PAPER-2021-008]
in preparation

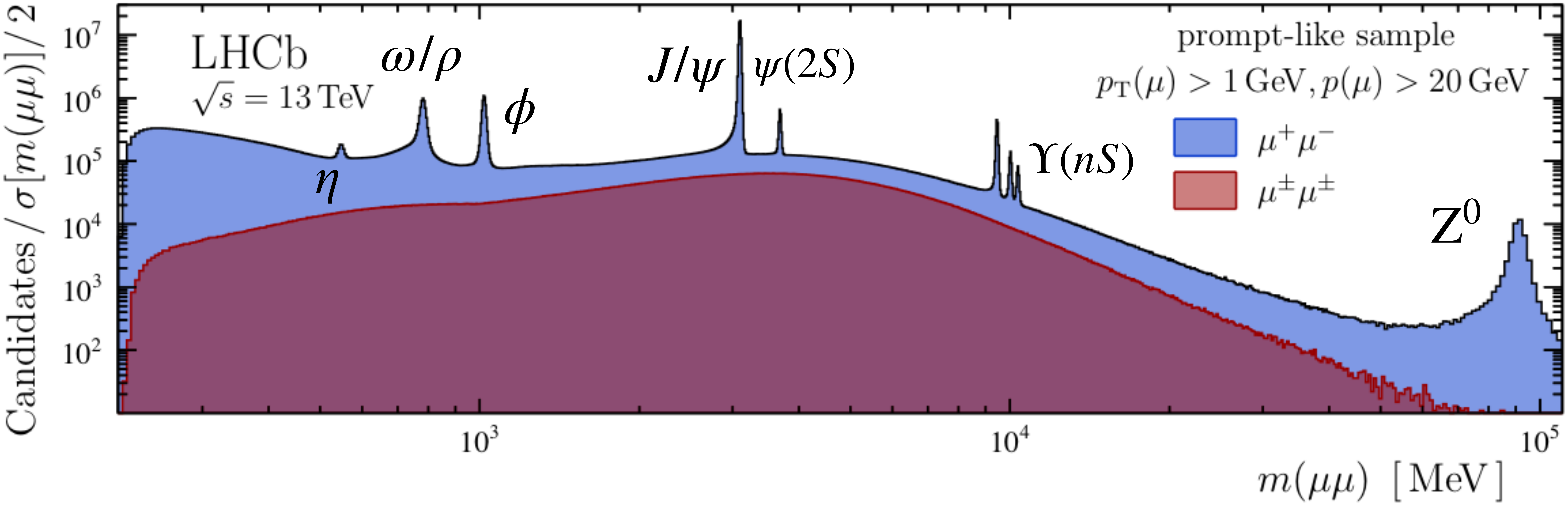
$$\mathscr{B}(B_s^0 \to \mu^+\mu^-) = (3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9}$$

$$\mathscr{B}(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10} \,@\, 95\,\%\,\mathrm{CL}$$

$B_s \to \mu^+\mu^-$ found with significance >10σ, but no evidence yet for $B^0 \to \mu^+\mu^-$ (1.7σ)

Finding a needle in a haystack!

PRL 120 (2018) 061801



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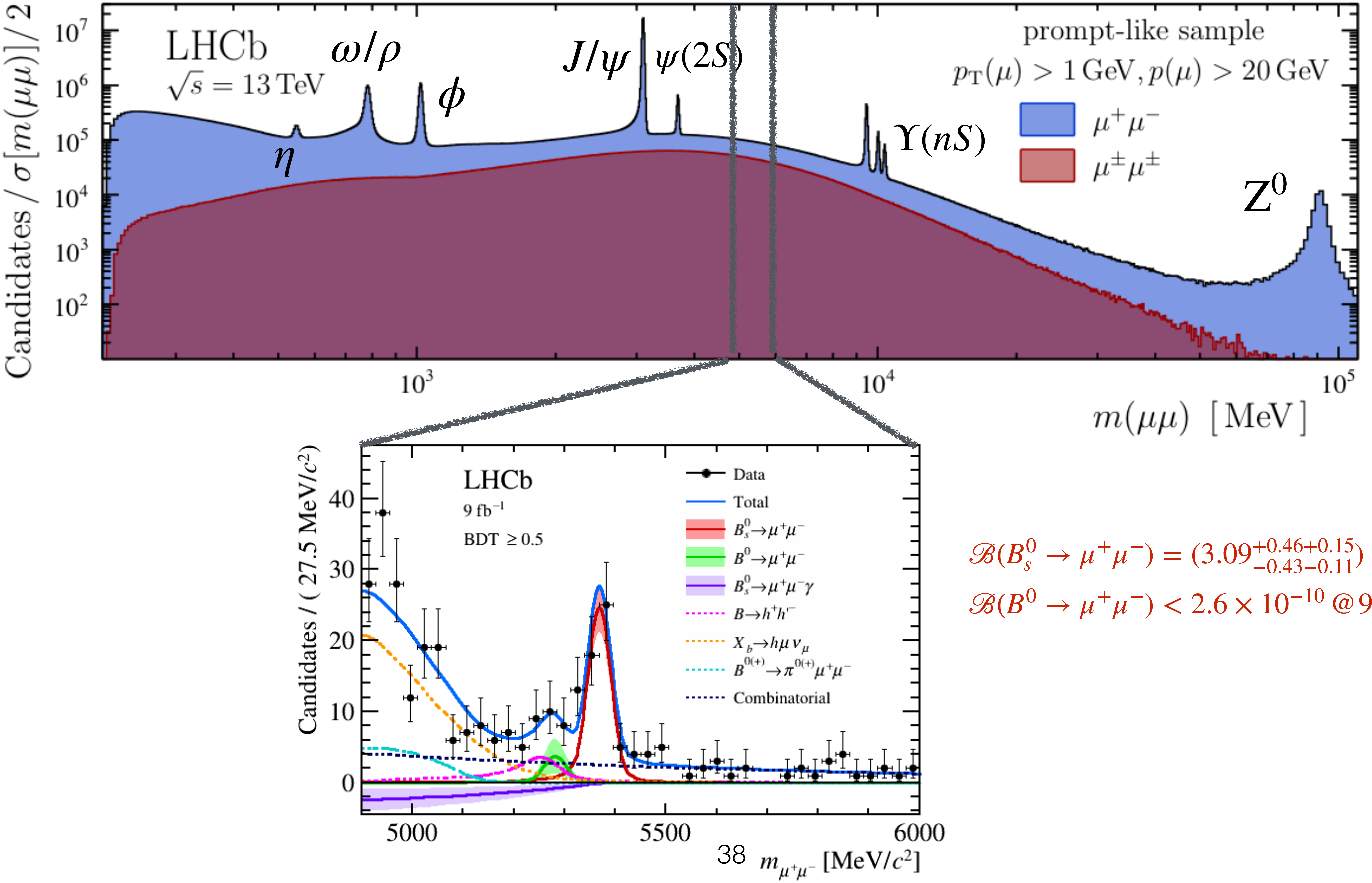
PRL 120 (2018) 061801



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Finding a needle in a haystack!

Latest LHC combination

- **LHCb**, PRL 118 (2017) 191801

$B(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$ 7.8σ

$B(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10}$ @ 95 % CL

- **CMS**, JHEP 04 (2020) 188

$B(B_s^0 \to \mu^+\mu^-) = (2.9 \pm 0.7\,(\text{exp}) \pm 0.2\,(\text{frag})) \times 10^{-9}$ 5.6σ

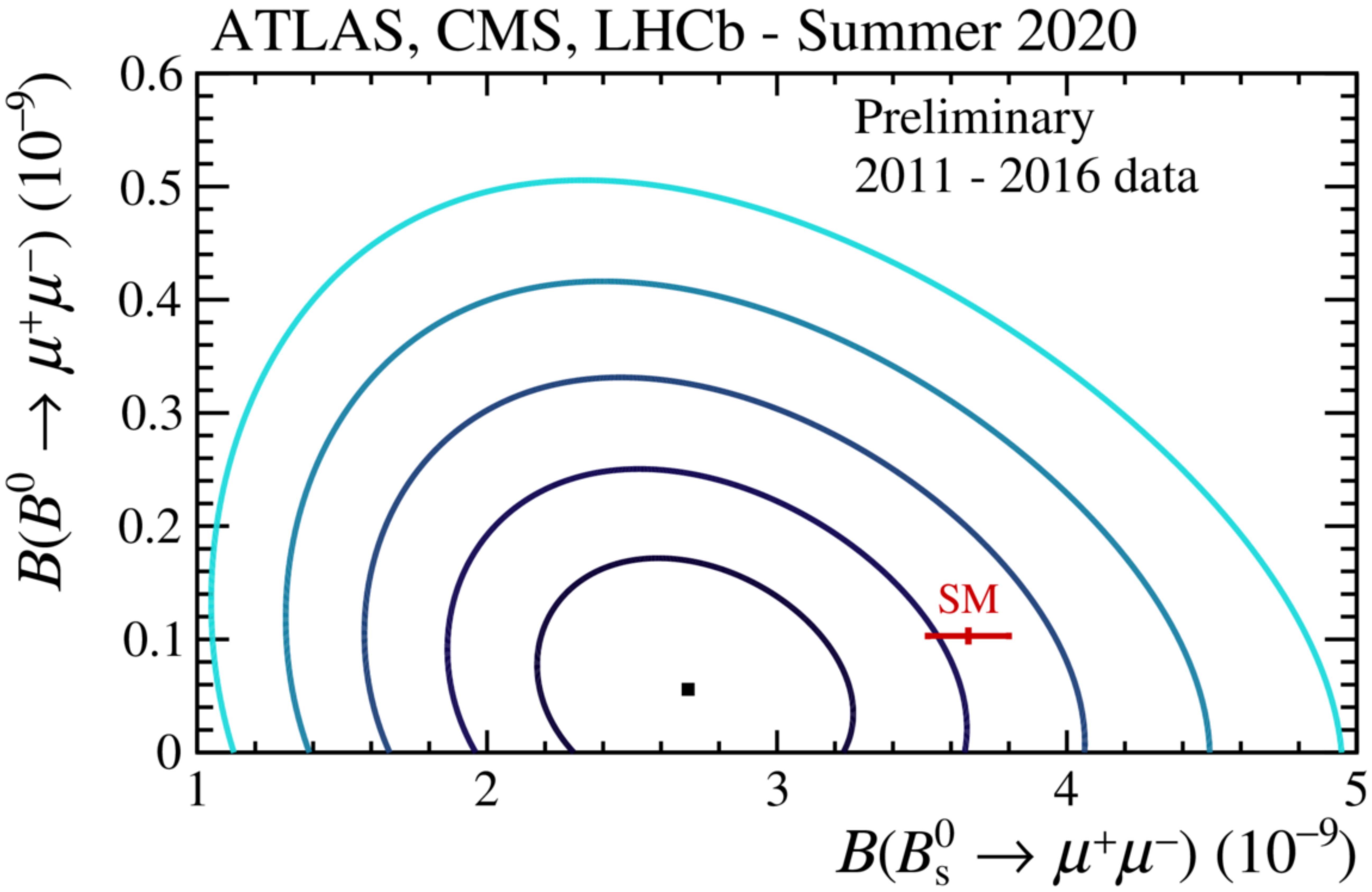
$B(B^0 \to \mu^+\mu^-) < 3.6 \times 10^{-10}$ @ 95 % CL

- **ATLAS**, JHEP 04 (2019) 098

$B(B_s^0 \to \mu^+\mu^-) = (2.8^{+0.8}_{-0.7}) \times 10^{-9}$ 4.6σ

$B(B^0 \to \mu^+\mu^-) < 2.1 \times 10^{-10}$ @ 95 % CL

LHCb-CONF-2020-002
CMS PAS BPH-20-003
ATLAS-CONF-2020-049



Era of precision measurements of $B_{(s)} \to \mu^+\mu^-$ has started

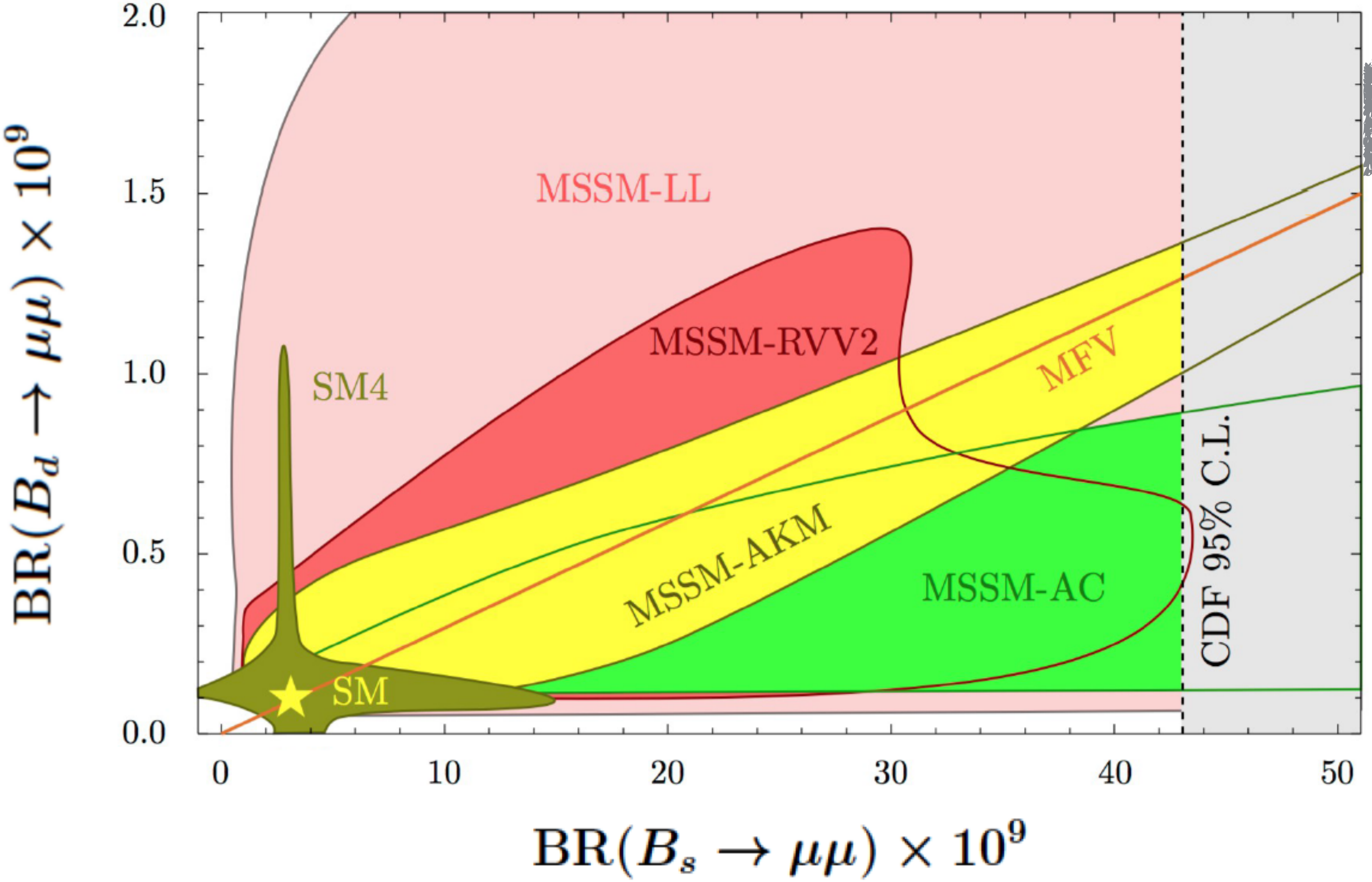
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.69^{+0.37}_{-0.35}) \times 10^{-9}$$

2.1σ below SM prediction

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.9 \times 10^{-10} \text{ @ } 95\,\%\ \text{CL}$$

Sizeable effects expected in many MSSM models

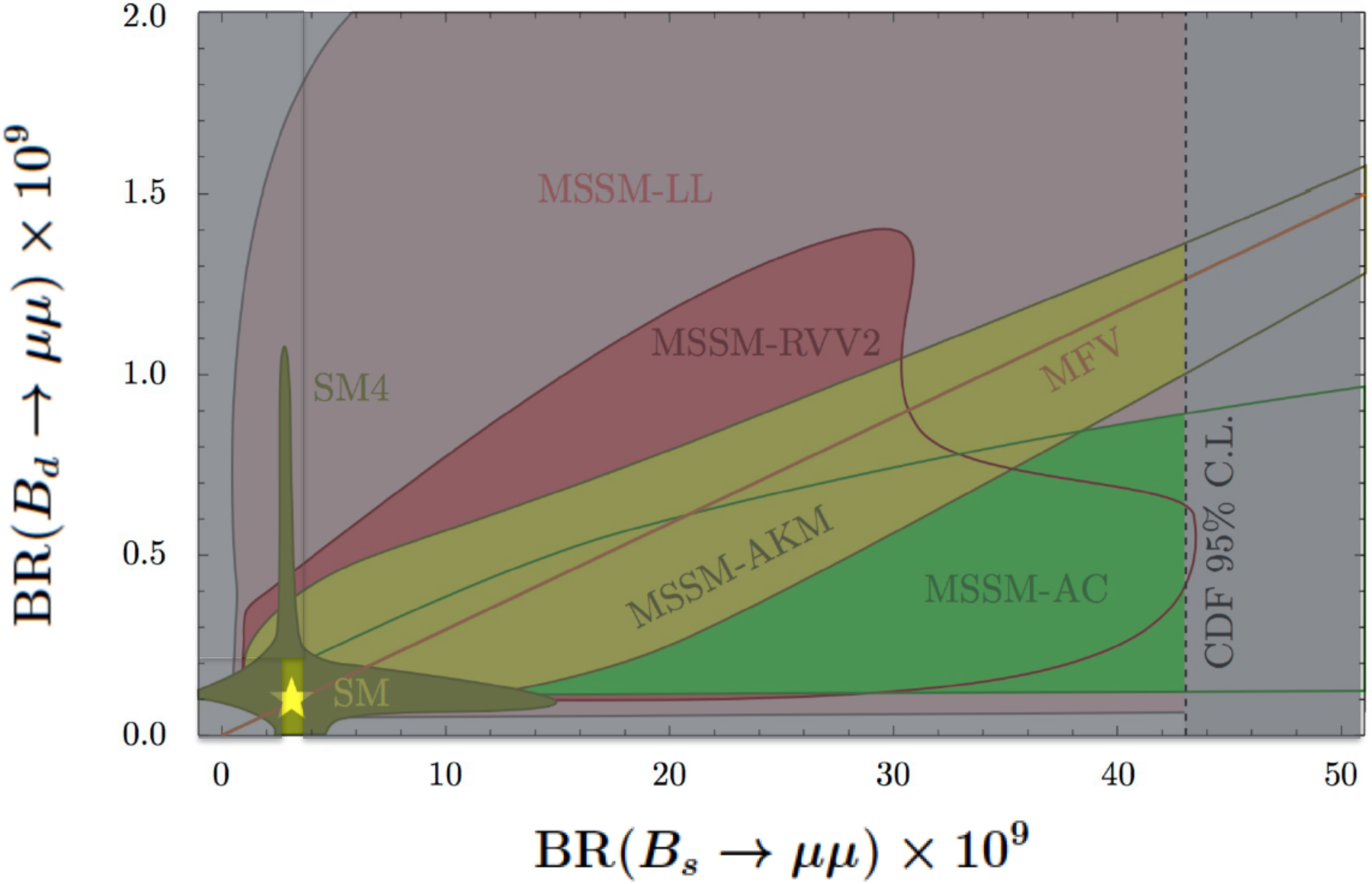
Straub, arXiv:1107.0266



Pre-LHC

The SM stands its ground

Straub, arXiv:1107.0266



Now


LHCb
The LHC

The LHCb collaboration

- **~1000 authors from 109 institutes in 19 countries**
- **~570 publications, some with very high impact**
- **Main focus on heavy quark flavour (beauty and charm)**
  …but plenty of other physics in the forward direction

The detector with components superimposed

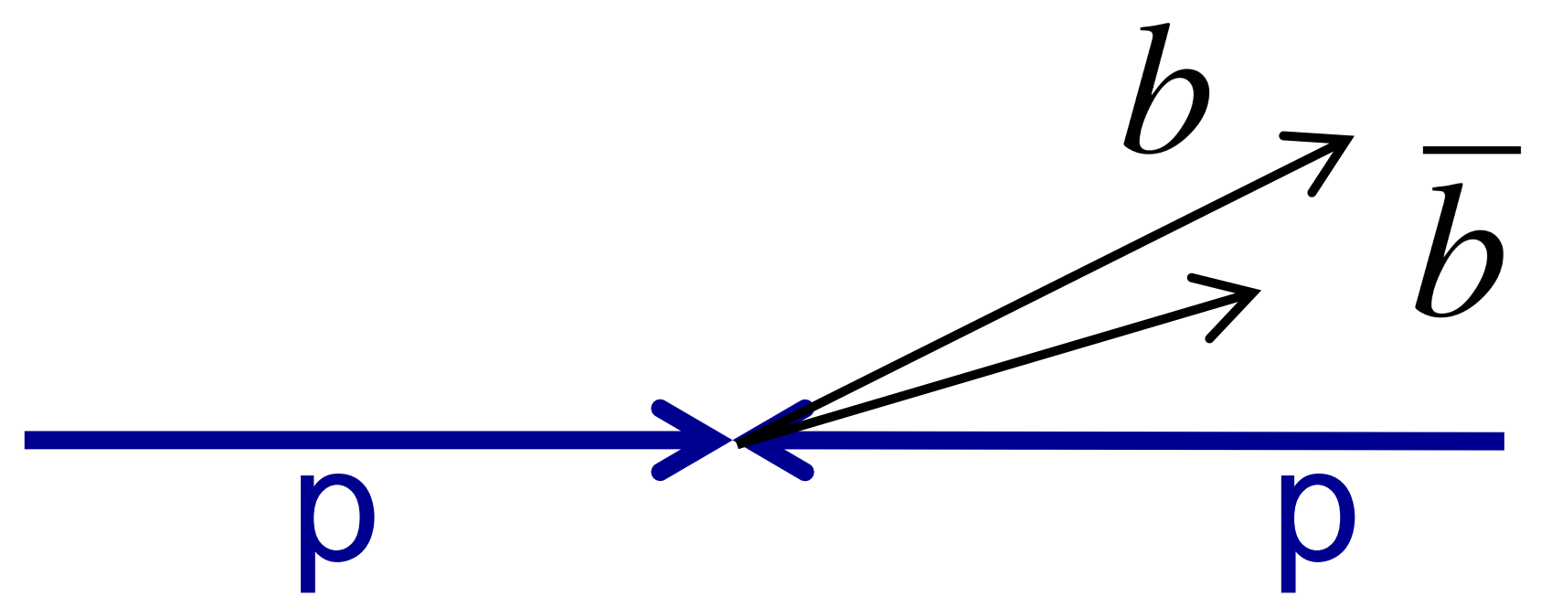
The LHCb detector

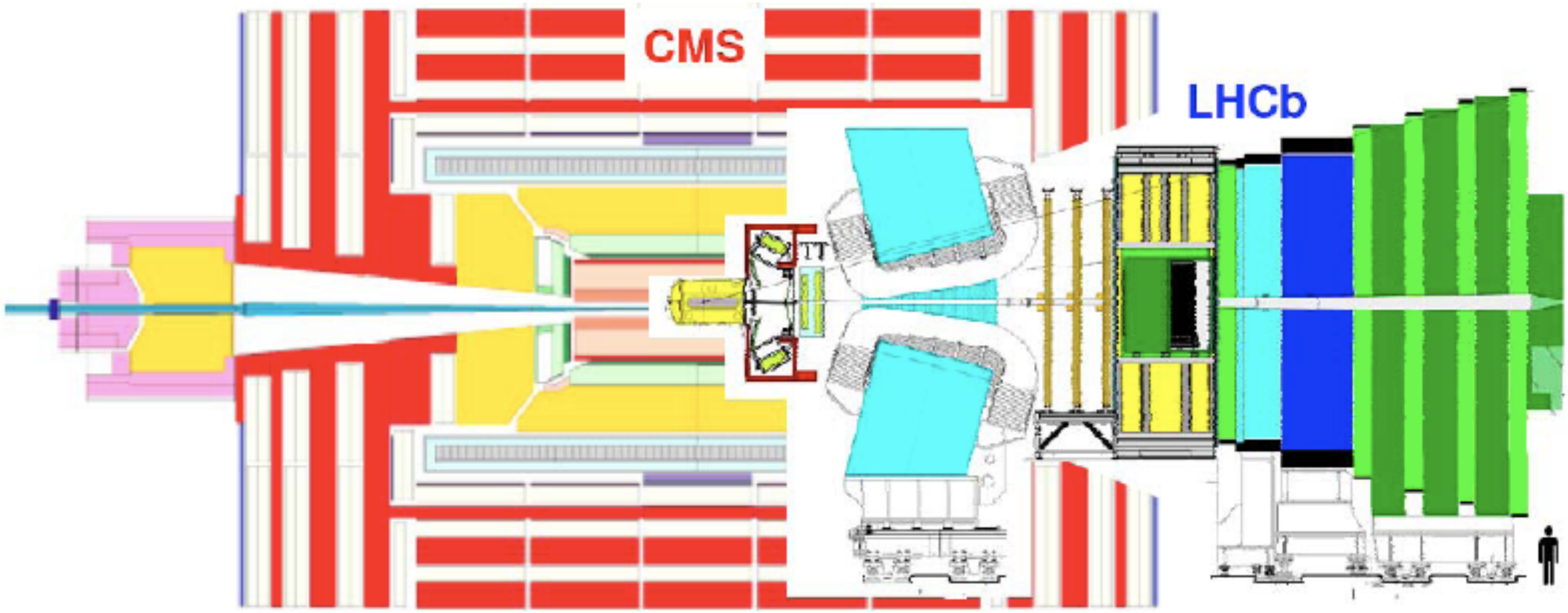
- **Forwards acceptance**
- **Efficient trigger for leptonic and hadronic modes**
- **Precision tracking & vertexing (Vertex Locator @ 8 mm from beam)**
- **Excellent PID**

JINST 3 (2008) S08005

Why does LHCb look so different?

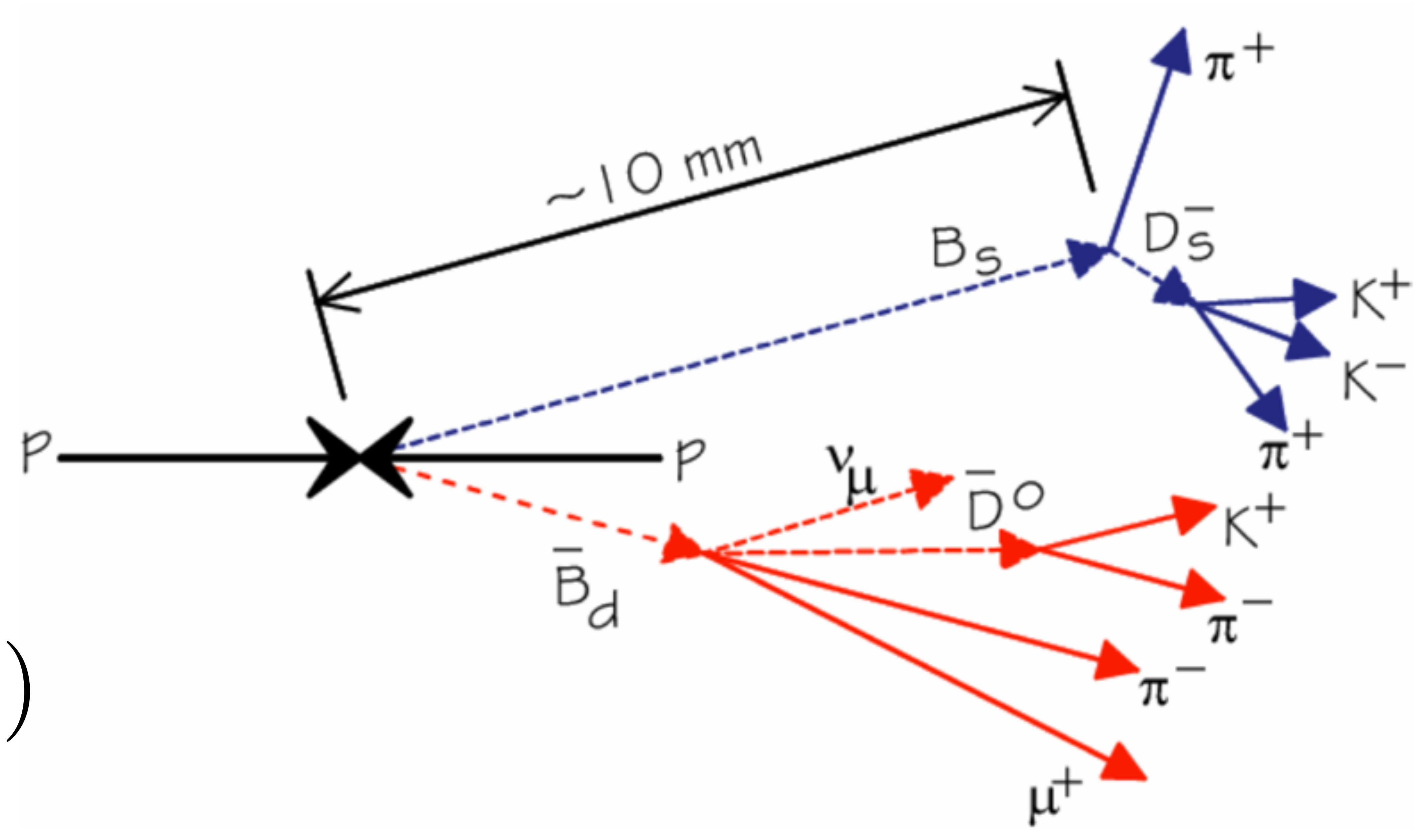
- The $\boldsymbol{B}$ mesons formed by the colliding proton beams (and the particles they decay into) stay close to the line of the beam pipe, and this is reflected in the design of the detector





b lifetime long enough for experimental detection

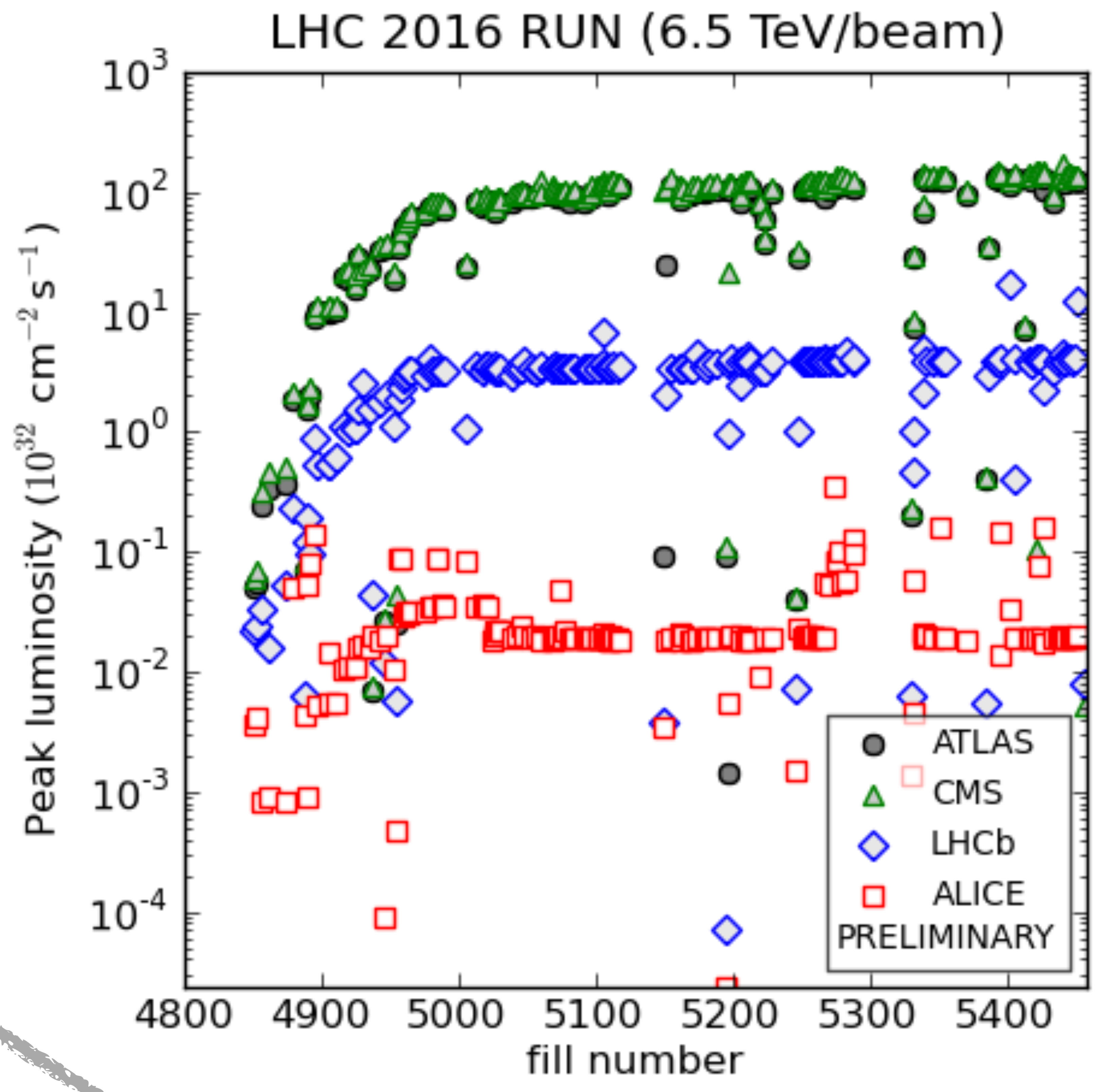
- $\tau_{\text{beauty}} \sim 1.5 \cdot 10^{-12}\,\text{s}$ $\tau \sim 1/(m^5|V_{\text{cb}}|^2)$
- $D = \beta\gamma c\tau$
- @ LHC :
    - $\star\ \beta = v/c \sim 1$
    - $\star\ \gamma = E/mc^2 \sim 20 \quad (E : b \text{ energy})$
- D$= 20 \cdot 3 \cdot 10^{10} \cdot 1.5 \cdot 10^{-12} \sim 1\,\text{cm}$



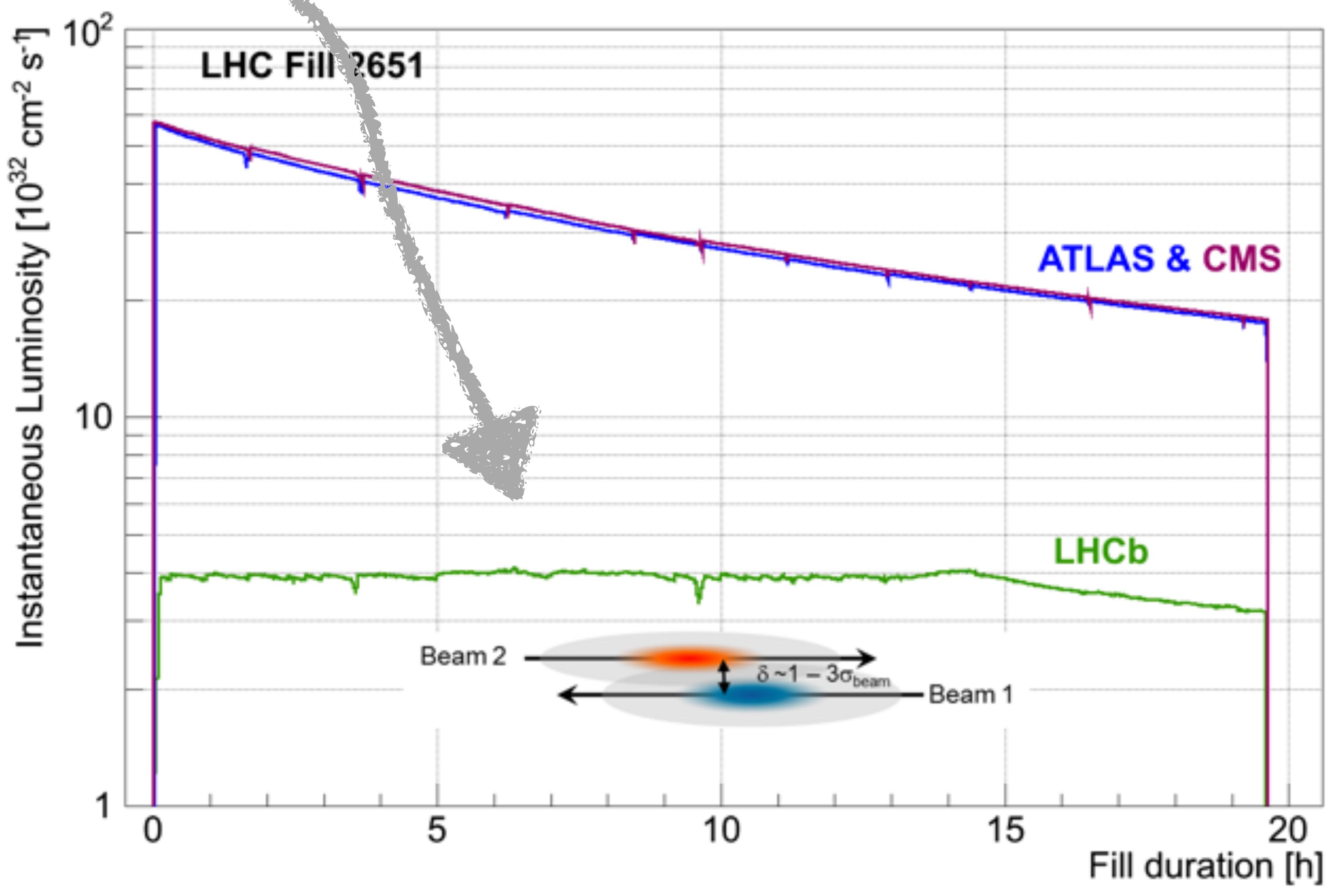
Look for displaced vertices

Running conditions

- LHCb designed to run at lower $\mathscr{L}$ than ATLAS/CMS
  - Mean number of interactions/bunch crossing ~1 (Runs 1&2)
  - Tracking, Particle Identification sensitive to pileup
  - $\mathscr{L}_{\text{int}} = 9\,\text{fb}^{-1}$ (LHCb), $\mathscr{L}_{\text{int}} = \sim 140\,\text{fb}^{-1}$ (ATLAS/CMS)



- pp beams displaced to reduce instantaneous $\mathscr{L}$
  - $\mathscr{L} \sim 4.0\ 10^{32}\ \text{cm}^{-2}\text{s}^{-1}$ (LHCb) to be increased to $2.0\ 10^{33}\ \text{cm}^{-2}\text{s}^{-1}$ in Run 3
  - $\mathscr{L} \sim 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$ (ATLAS/CMS)



- Huge heavy quark production cross-sections !
  - $\sigma_b \sim 150\mu\text{b}$ @ $\sqrt{s}$=13 TeV (~1nb in e^+e^- @Y(4s))
    - ~10^{11} b decays/fb in acceptance
  - σ_c is ~ 20 times larger!
    - ~10^{12} c decays/fb in acceptance

The trigger

- For LHCb, more data is 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 $\mathscr{L}$=2x10^{33}/cm^2/sec, ~100 kHz $b\bar{b}$ and ~1MHz $c\bar{c}$ pairs in detector acceptance
  - Most interesting b-hadron decays occur at 10^{-5} probability or lower
  - Big challenge → requires powerful trigger

The LHCb schedule

~1 visible interaction

~5 visible interaction

~50 visible interaction

LHCb

LHCb Upgrade

LHCb Upgrade II

Run1 - Run2

$\mathcal{L}_{int} = 9\ \text{fb}^{-1}$

LS2
Injector upgrades

Run3

$\mathcal{L} = 2 \times 10^{33}$

LS3
HL-LHC -
ATLAS/CMS
Phase 2 upgrades

Run4

$\mathcal{L}_{int} \sim 50\ \text{fb}^{-1}$

LS4

Run5

$\mathcal{L} = 1\text{-}2 \times 10^{34}$

LS5

Run6

$\mathcal{L}_{int} \sim 300\ \text{fb}^{-1}$

2010 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 | 2033 | 2034 | 2035 | 2036 | 2040

LHCb Upgrade I
Installation starts

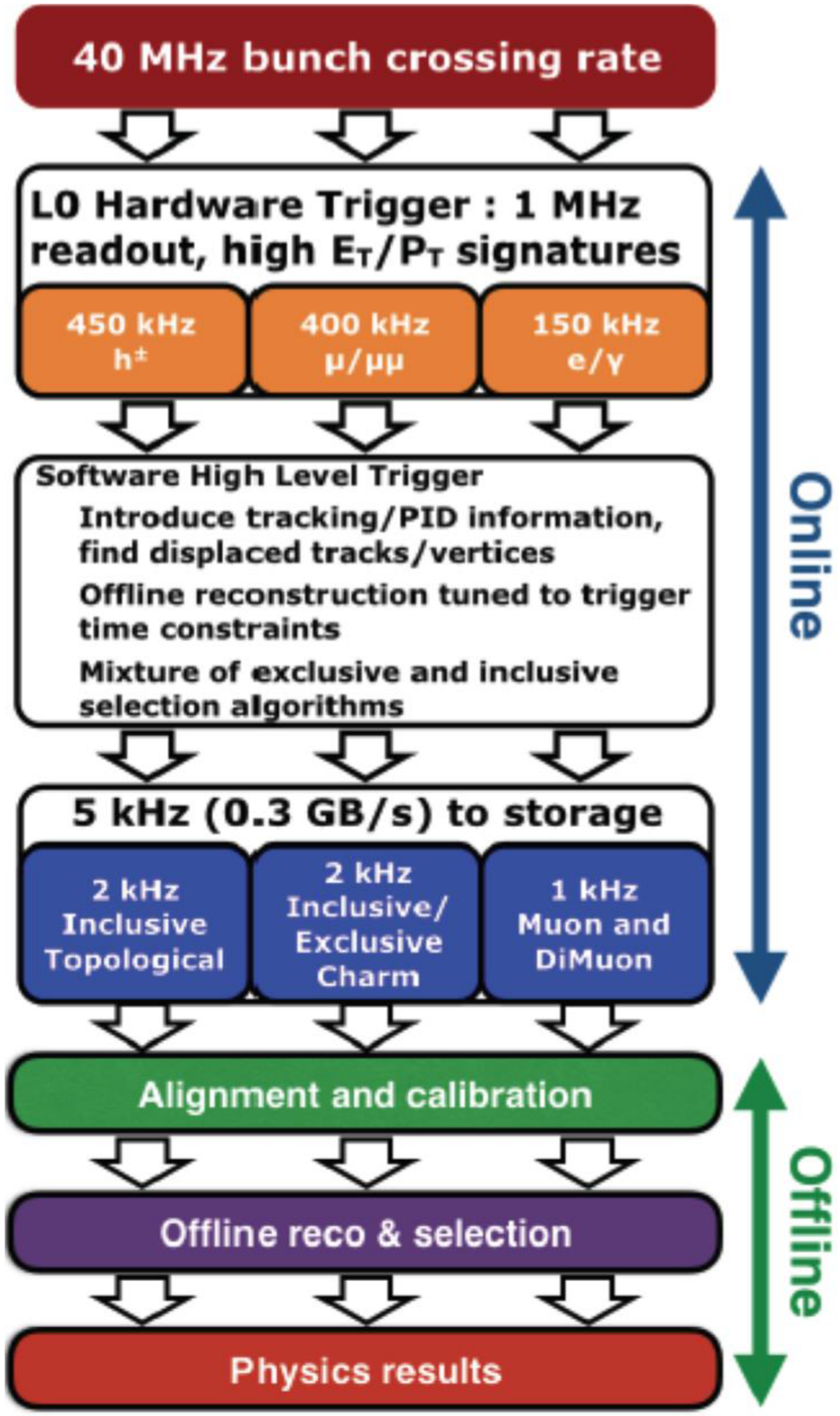
LHCb Upgrade I: incremental
improvements/prototype detectors

The trigger in Run 1&2

- Three-level trigger system of increasing complexity
- First trigger level (L0) implemented in hardware with 4μs latency
  - Half of this time is needed for the particles to travel to the detector and their signals to travel through the cables in the readout system, the other half is the time to make a decision
  - L0 is based on calorimeter and muon systems with typical thresholds: Muon p_T> 2 GeV, Hadron E_T>4 GeV, ….
  - L0 reduces rate from 40 MHz to 1 MHz, mandated by the fact that the FE-electronics can only be read out at 1 MHz
- Two-stage software High Level Triggers (HLT): software application executed on a large computing cluster, designed to reduce the event rate from 1 MHz to ~12 kHz - Running 40 k jobs simultaneously in Run 2!

Evolving strategy for the HLT

Run 1 trigger diagram



“Traditional model”

- Online reconstruction as good as possible within CPU budget, based on preliminary alignment &calibration. Fast, but less performing than full offline reconstruction.

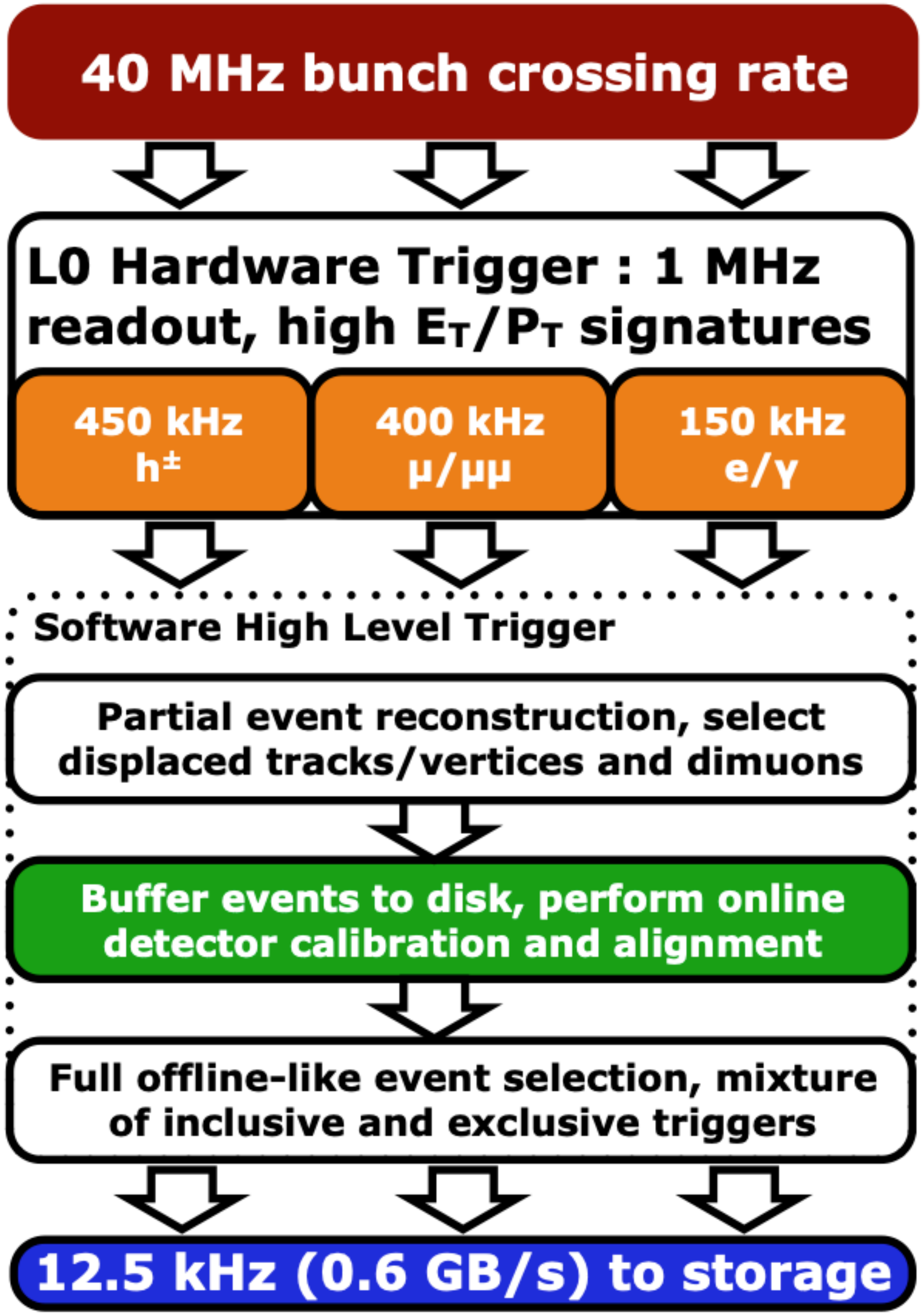
- Offline reconstruction based on full detector alignment& calibration

- Obvious disadvantages of this model:
  - time (e.g. reconstruction done twice)
  - money: costs a lot in terms of computing resources
  - physics: some data lost by an imperfect reconstruction at trigger level

Evolving strategy for the HLT

- Split the HLT!
- At the 1st stage of the HLT (HLT1) reconstruct charged particle trajectories using information from the VELO and tracking stations
- Buffers all HLT1 output to disk (10 pb available in 2016)
- Enough time to perform calibration and alignment before the 2nd trigger stage (HLT2) where offline offline-quality reconstruction is performed
- **Same constants** used by trigger and offline reconstruction
- No need to reprocess and more discriminant trigger!
- Trigger = Offline → best performance !

Run 2 trigger diagram



40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

450 kHz $h^{\pm}$

400 kHz $\mu/\mu\mu$

150 kHz e/γ

Software High Level Trigger

Partial event reconstruction, select displaced tracks/vertices and dimuons

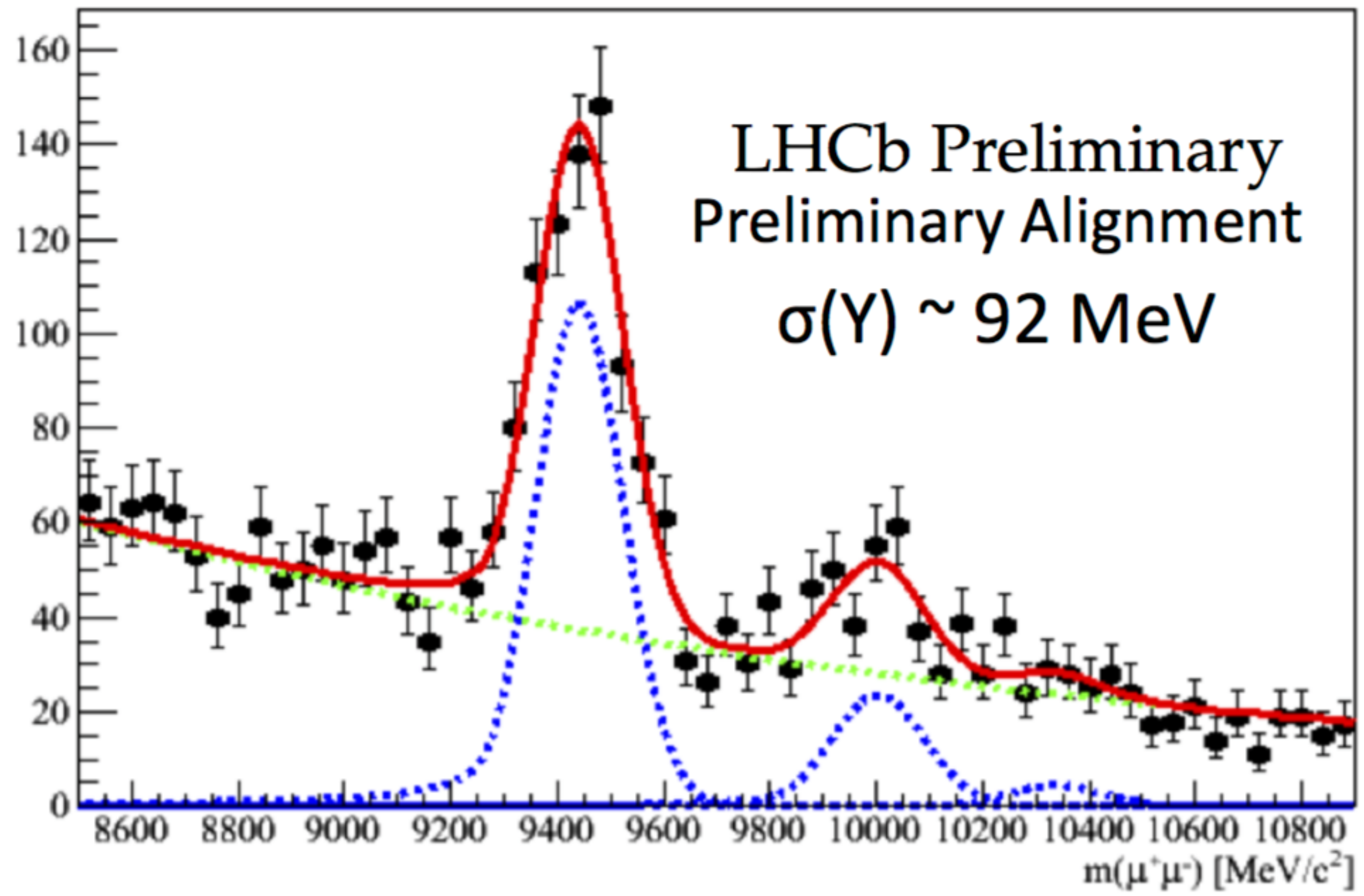
Buffer events to disk, perform online detector calibration and alignment

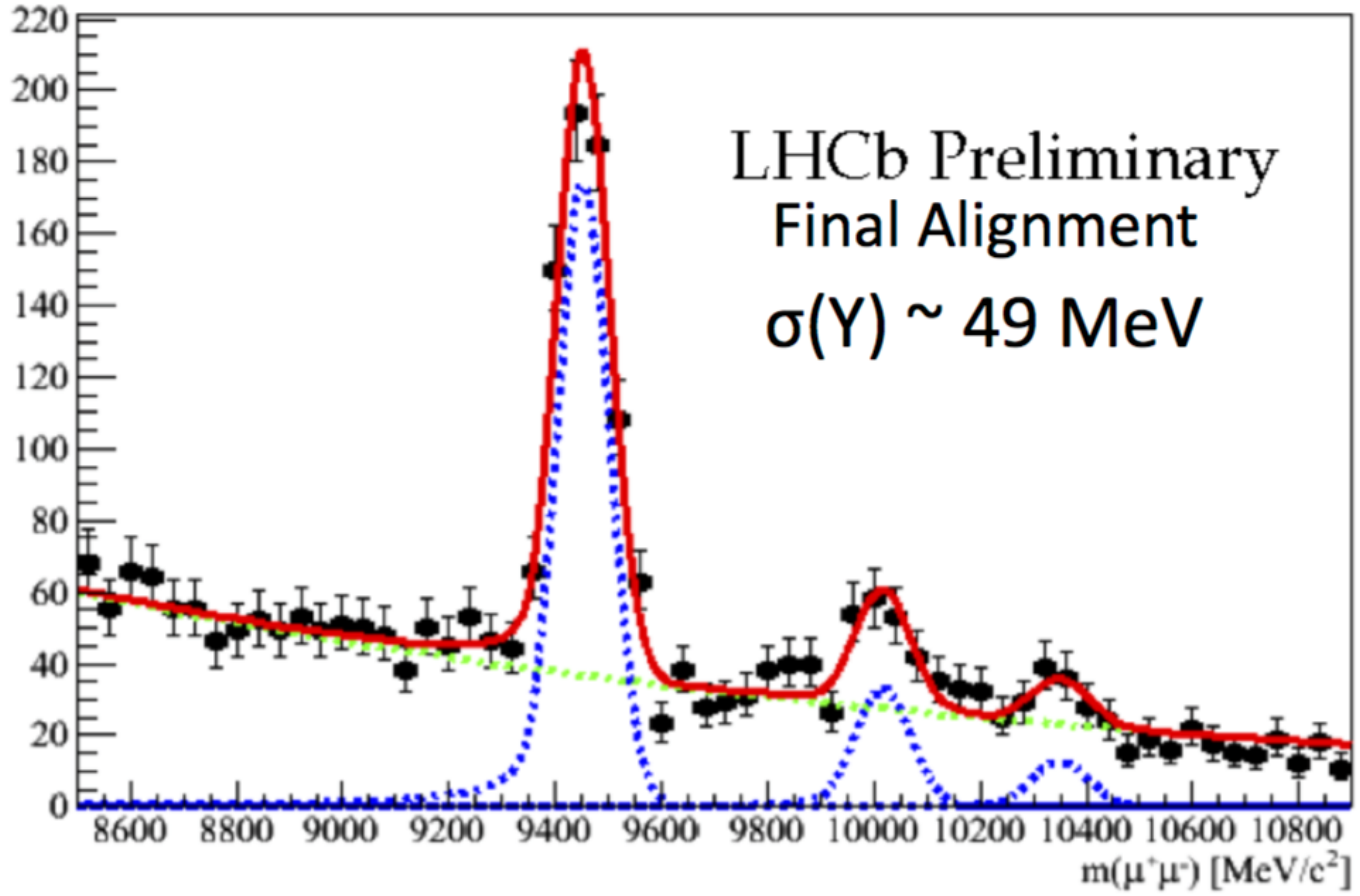
Full offline-like event selection, mixture of inclusive and exclusive triggers

12.5 kHz (0.6 GB/s) to storage

Importance of real-time alignment&calibration

- Store less background
- Alignment improves the mass resolution of the peaks
- PID allows separating the interesting channels → obvious benefit in having it available at trigger level





The Turbo stream

- With offline-quality reconstruction up-front, no need to reconstruct offline
- Can perform physics analysis directly @HLT level (“Turbo” stream)
  - Store full information of trigger candidates
  - Remove most of detector raw data
  - Smaller events (from ~100kB down to ~15 kB to ~70 kB, customisable depending on the physics) → analyse much higher rates

The Turbo stream

The Turbo stream

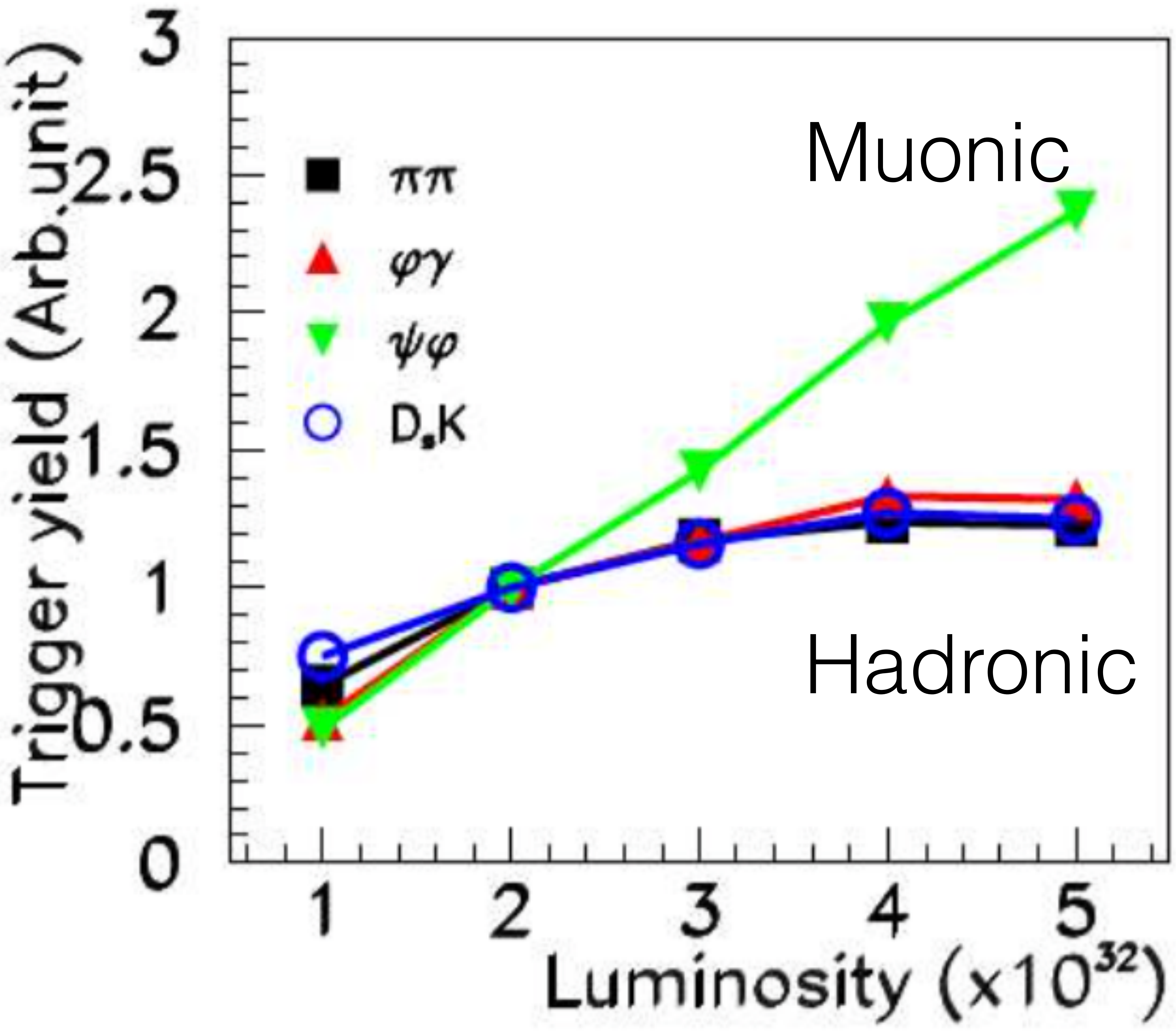
The Turbo stream

Run 2 to Upgrade

- Run 2 served as a demonstrator for the upgrade
- Two key components of upgrade selection deployed in Run 2:
  - Alignment & calibration in real time
  - Analysis with Turbo stream (reduced data format)
- The performance of a final analysis quality event reconstruction in real time crucial for processing large quantities of data
- In addition, the L0 hardware trigger will be removed for the upgrade

L0 bottleneck

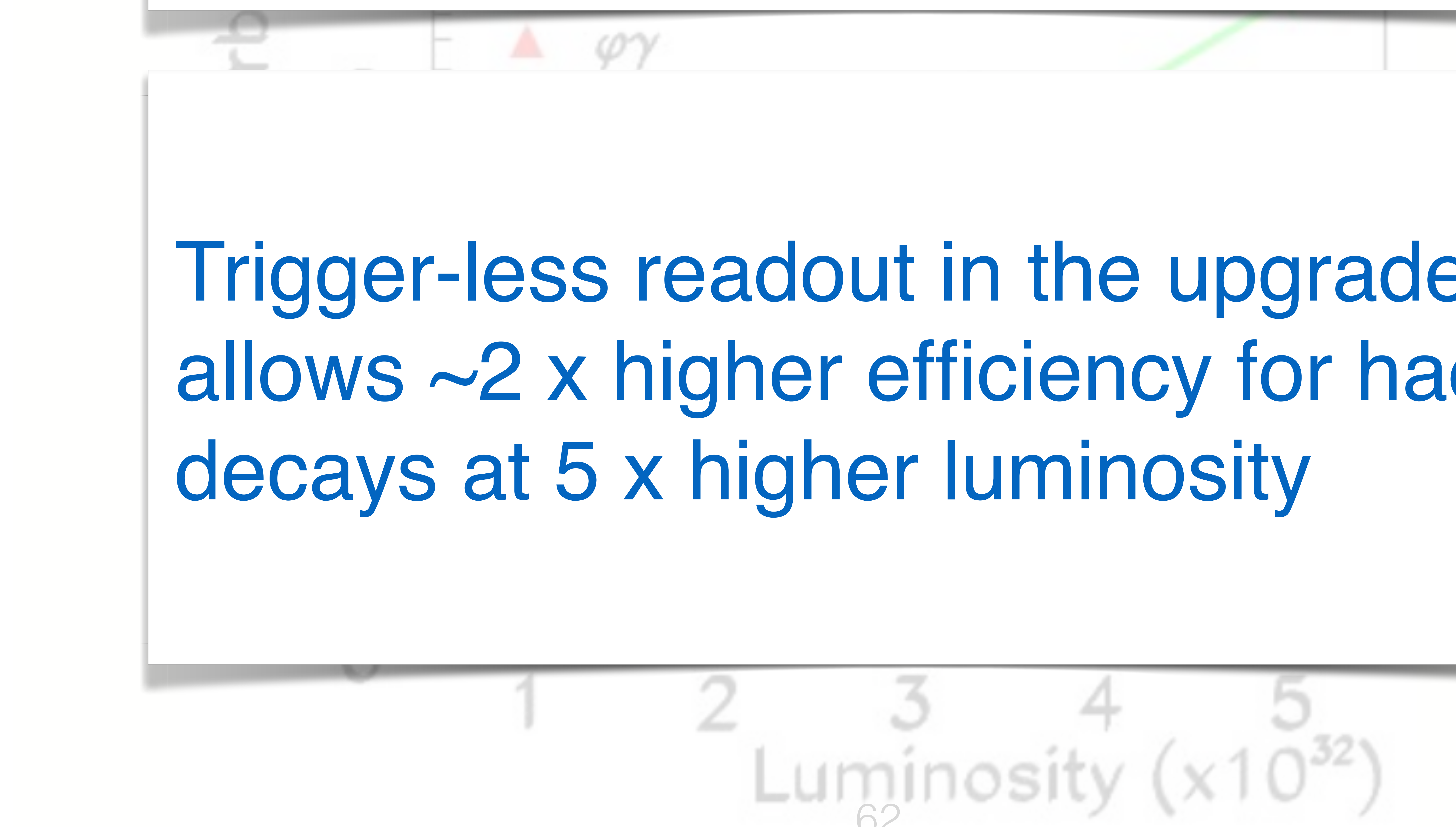
- Highly efficient for dimuons
- For hadronic channels, at constant output, any further increase in the rate requires an increase of E_T threshold
- Hadronic trigger yield saturates with increasing luminosity leading to ~constant signal yield
- Need to introduce more discriminating info than E_T earlier in the trigger



L0 bottleneck

- Highly e
- For hadr … quires an incre … h increasi

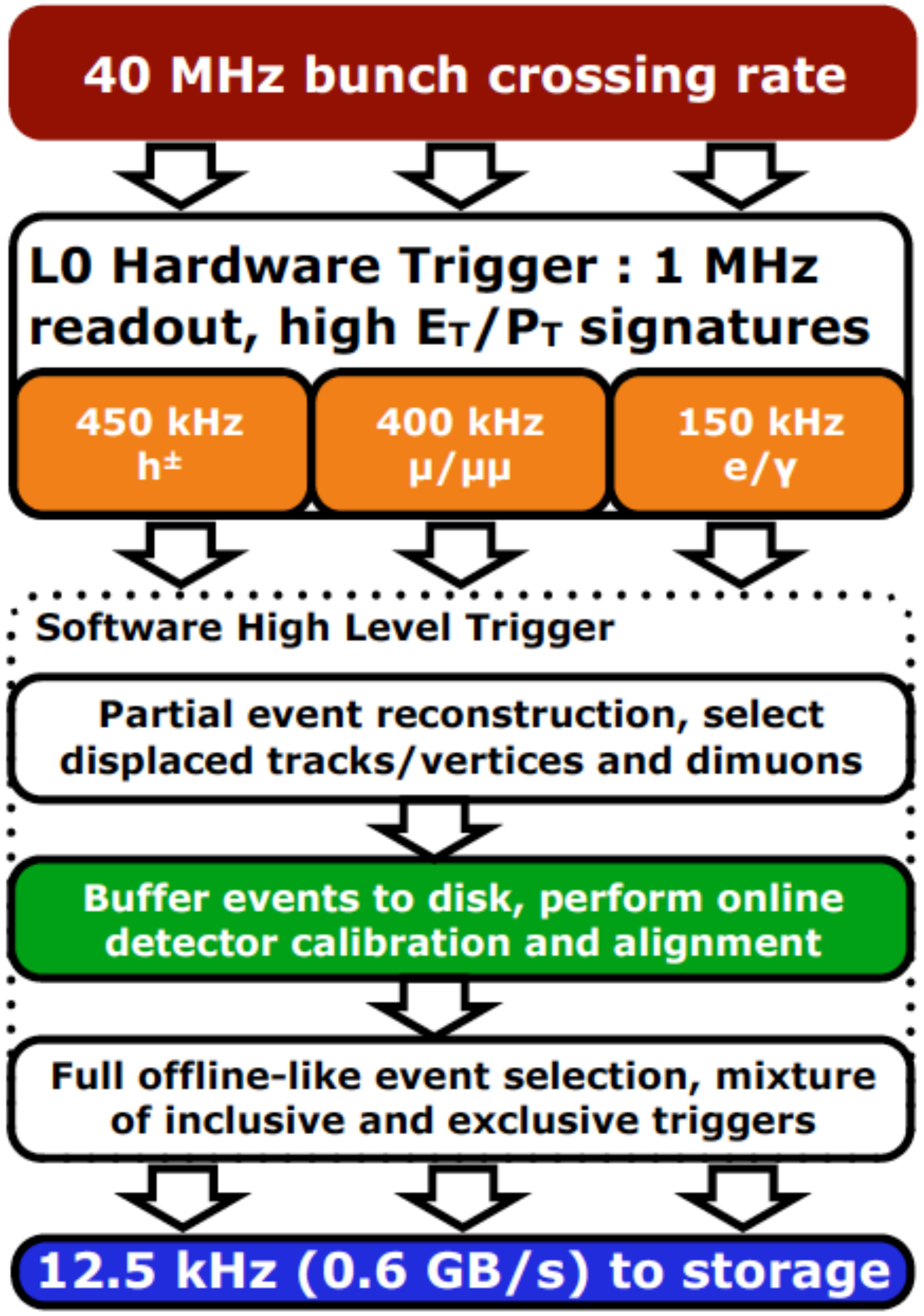
Remove the 1MHz L0 bottleneck and supply the whole event information at each level of the trigger → Read the full event at 40 MHz and implement trigger in software



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

Run 2 to Upgrade

Run 2 trigger diagram



40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

450 kHz	400 kHz	150 kHz
$h^\pm$	$\mu/\mu\mu$	e/γ

Software High Level Trigger

Partial event reconstruction, select displaced tracks/vertices and dimuons

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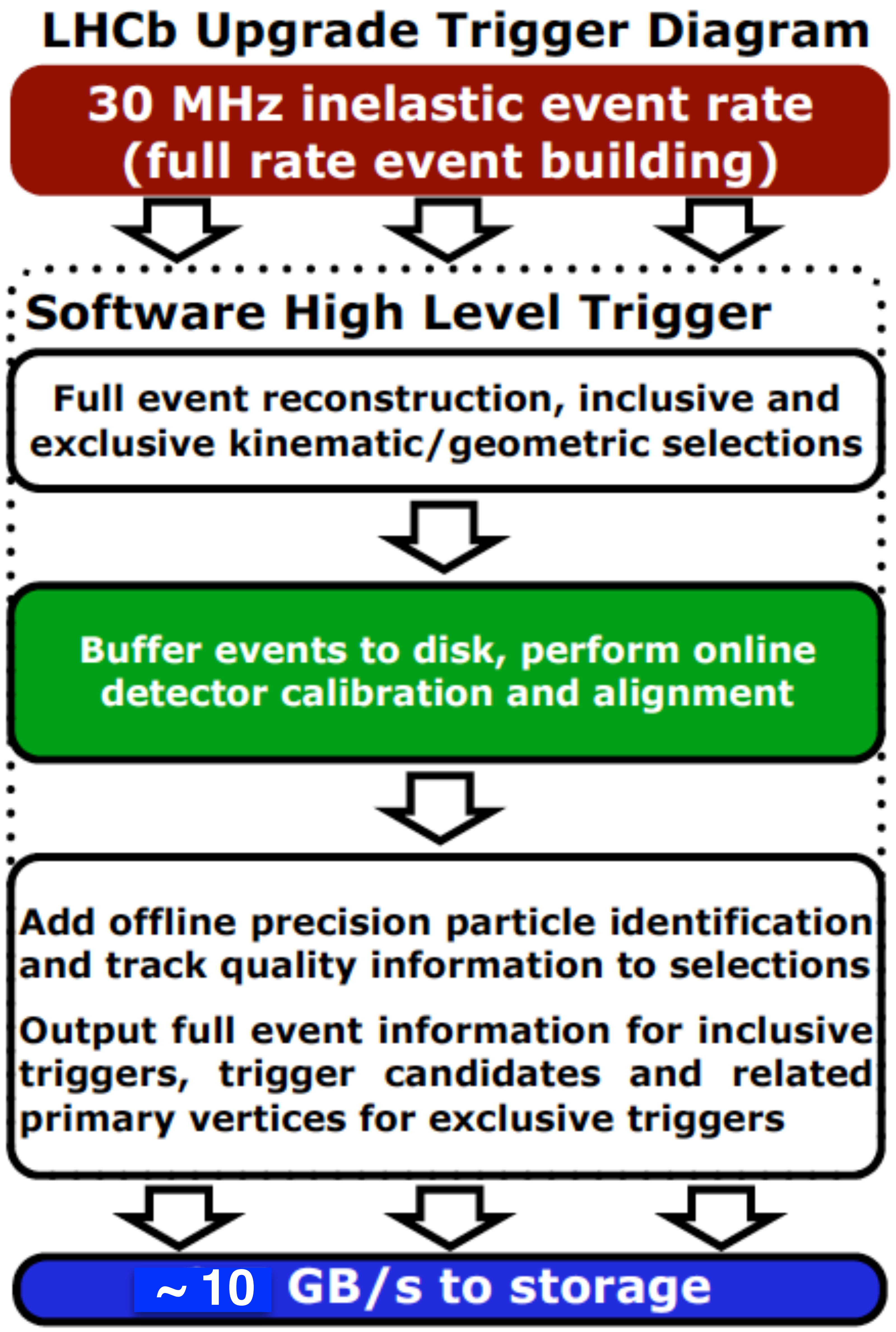


LHCb Upgrade Trigger Diagram

30 MHz inelastic event rate (full rate event building)

Software High Level Trigger

Full event reconstruction, inclusive and exclusive kinematic/geometric selections

Buffer events to disk, perform online detector calibration and alignment

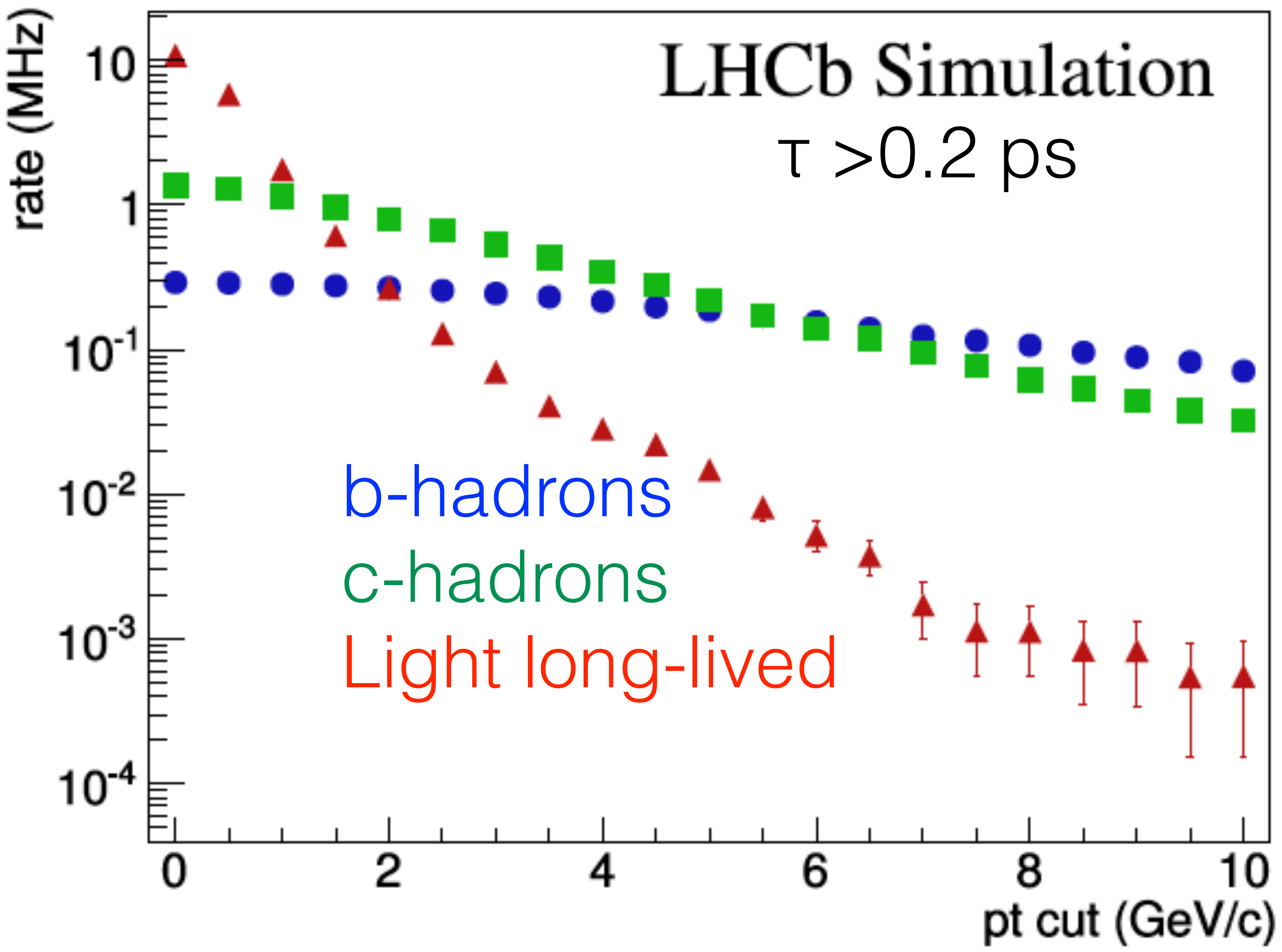
Add offline precision particle identification and track quality information to selections

Output full event information for inclusive triggers, trigger candidates and related primary vertices for exclusive triggers

~ 10 GB/s to storage

Too much of a good thing!

- At 2 x 10^{33} cm^{-2} s^{-1} every event will contains relevant signal:
  - ~2% of the events will contain a reconstructible b-hadron
  - ~20% of the events will contain a reconstructible c-hadron
  - ~100% of the events will contain at least two displaced vertices from light long-lived hadrons (K^0, Λ^0, …)



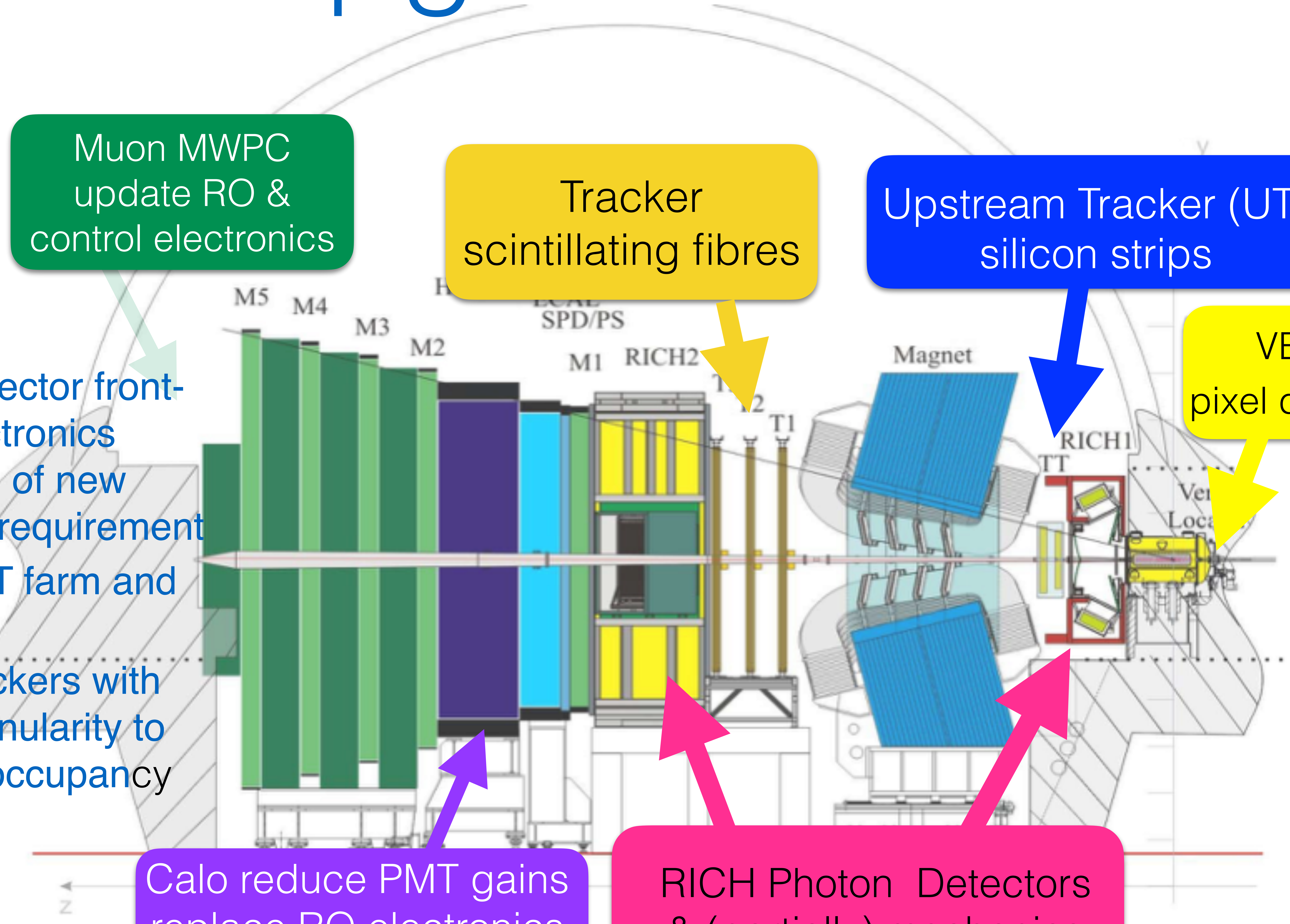
Particle type	Run I (kHz)	Upgrade (kHz)
b-hadrons	17.3	270
c-hadrons	66.9	800
Light long-lived hadrons	22.8	264

- Use of specific selection triggers will become increasingly necessary
- Turbo model will become increasingly utilised

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

LHCb-PUB-2014-027

The upgraded detector



Muon MWPC update RO & control electronics

Tracker scintillating fibres

Upstream Tracker (UT) silicon strips

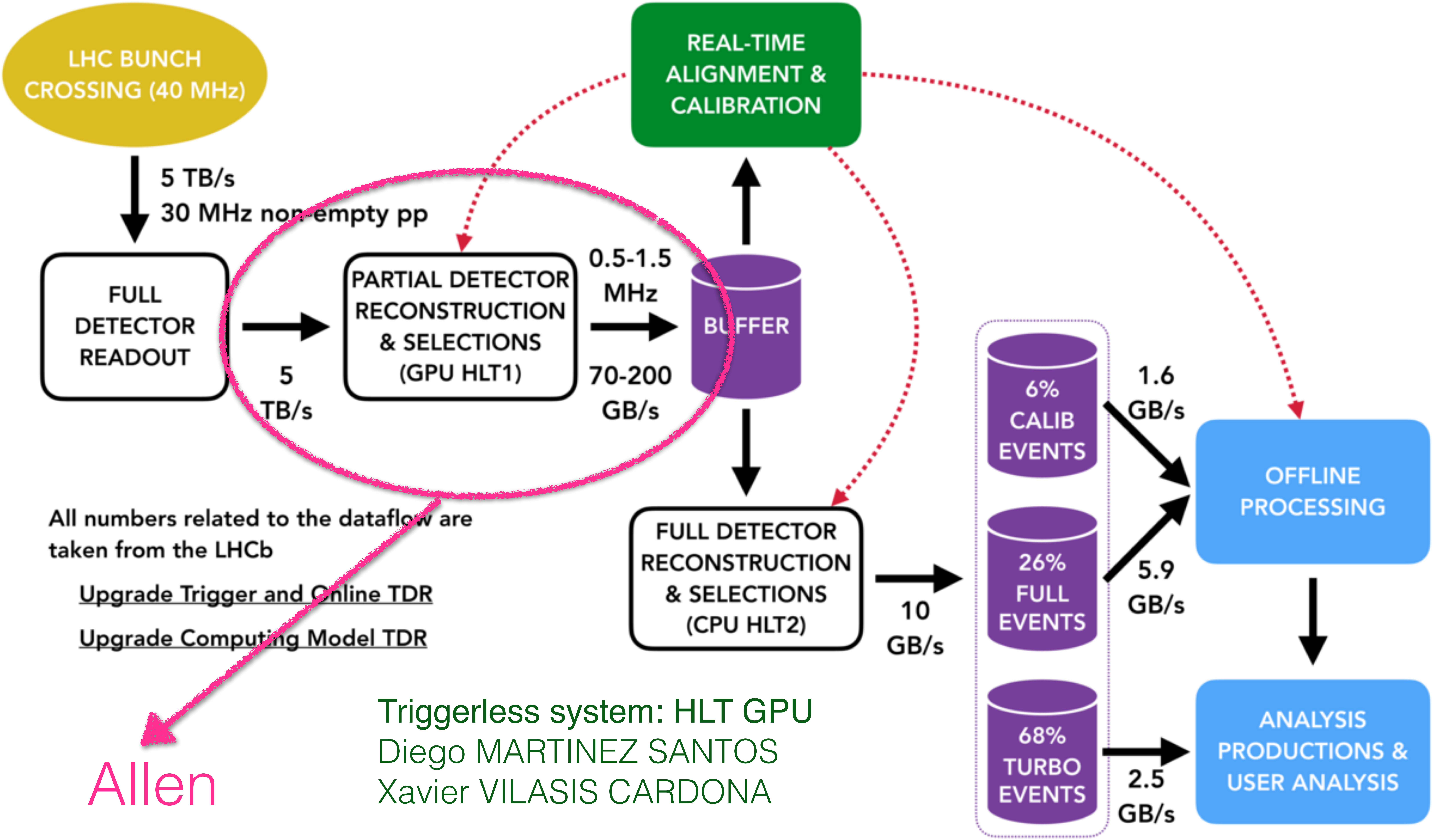
VELO pixel detector

- New detector front-end electronics because of new readout requirement
- New HLT farm and network
- New trackers with finer granularity to reduce occupancy

Calo reduce PMT gains replace RO electronics & innermost ECAL cells

RICH Photon Detectors & (partially) mechanics

Data flow



All numbers related to the dataflow are taken from the LHCb

Upgrade Trigger and Online TDR

Upgrade Computing Model TDR

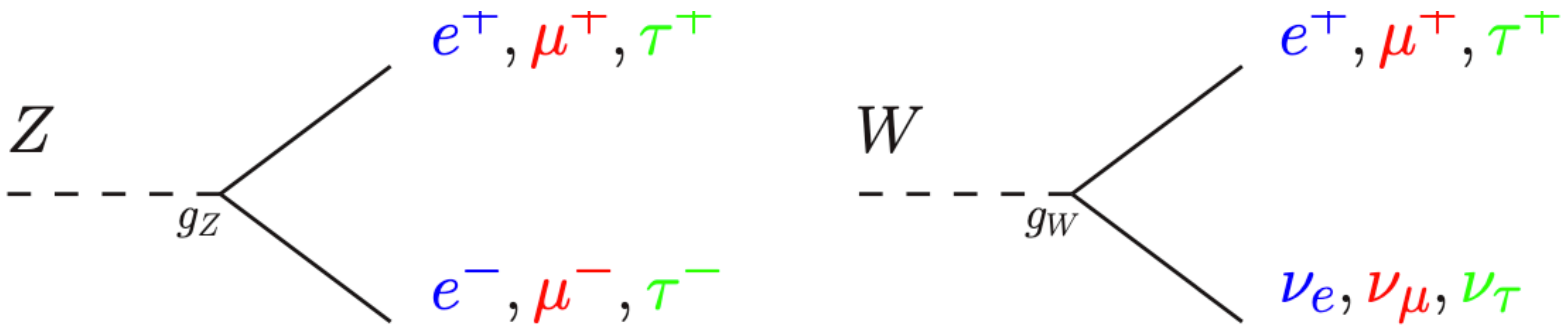
Allen

Triggerless system: HLT GPU
Diego MARTINEZ SANTOS
Xavier VILASIS CARDONA

Tests of Lepton Flavour Universality

Lepton Flavour Universality

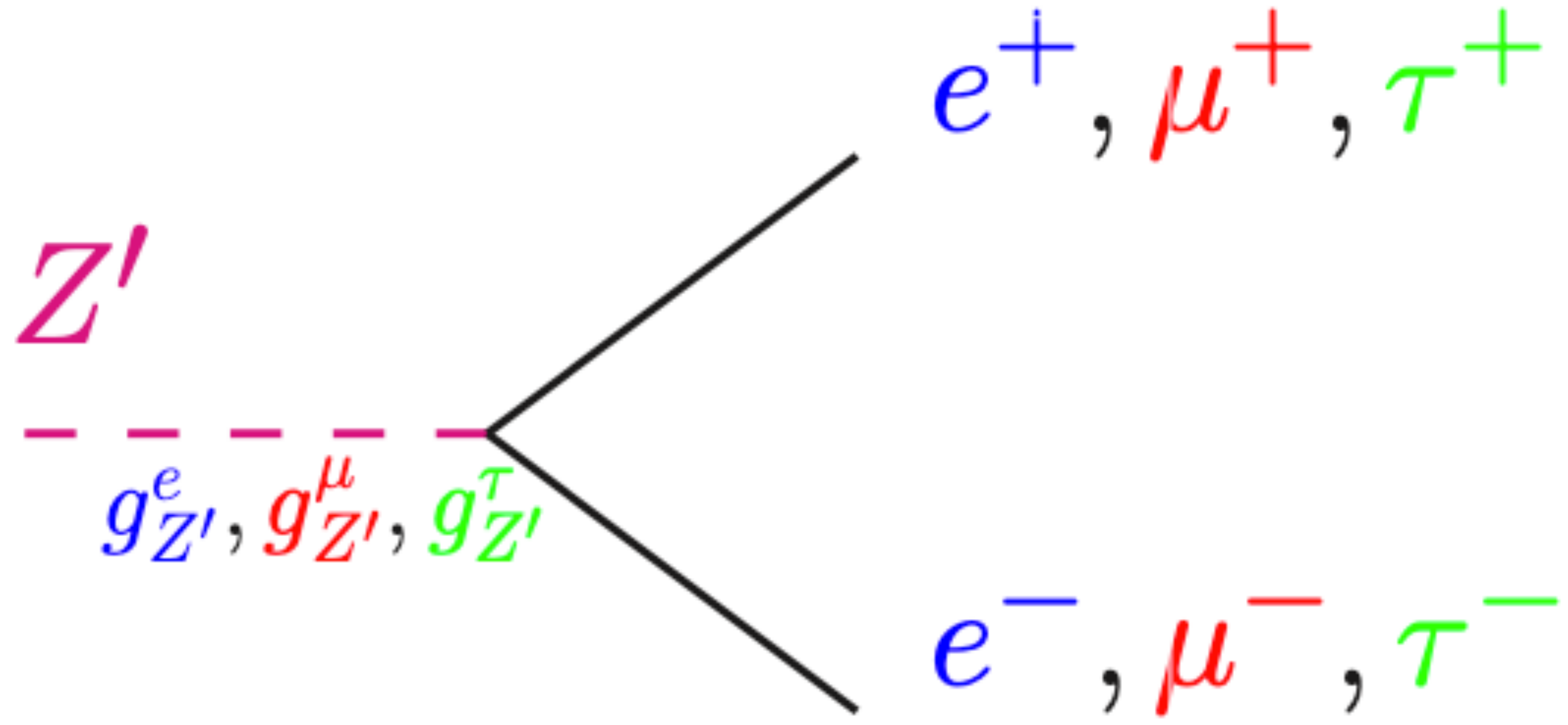
- The property that the three charged leptons (**e**, μ , τ) couple in a universal way to the SM gauge bosons



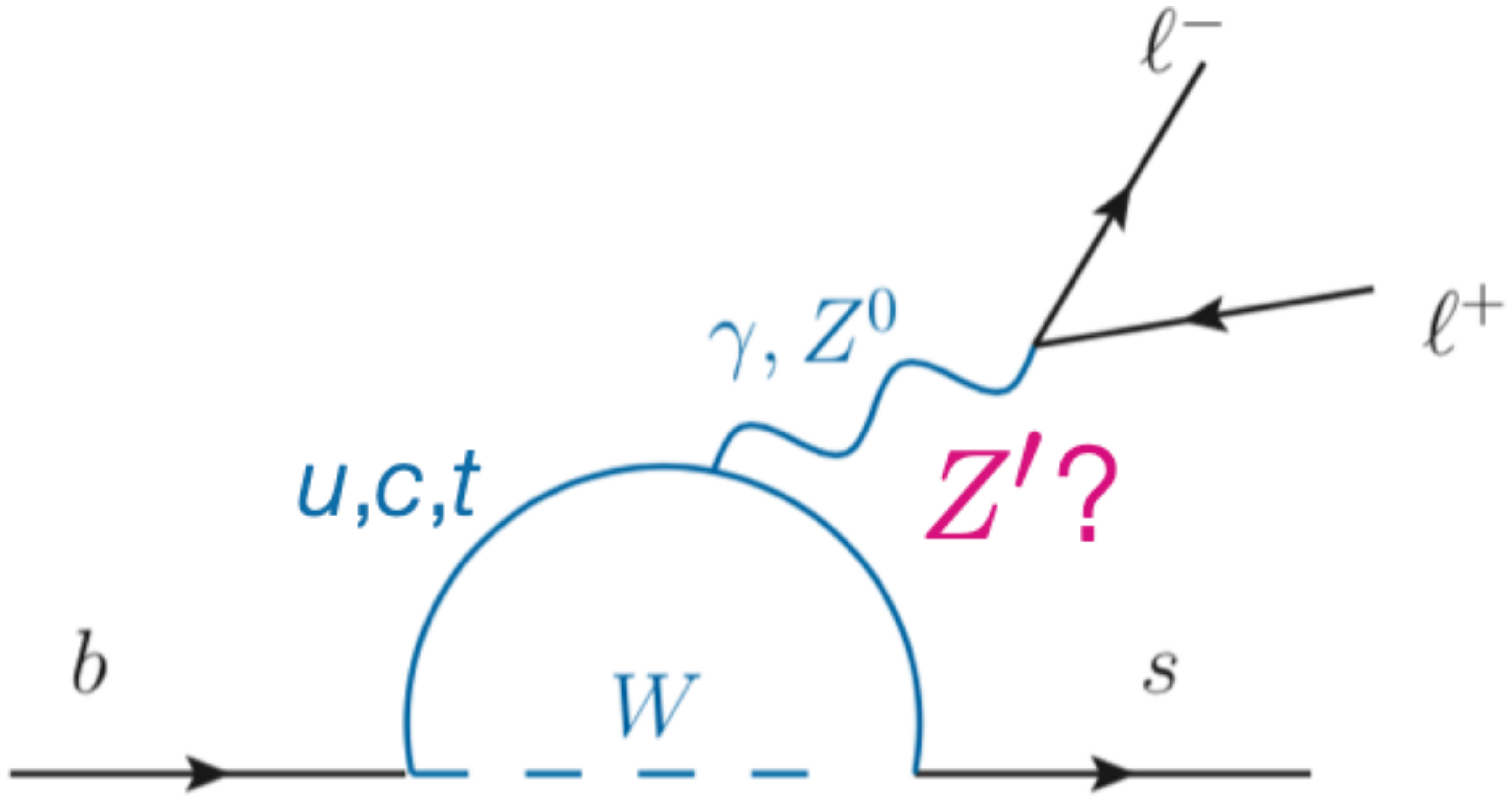
- In the SM the only flavour non-universal terms are the three lepton masses: $m_\tau, m_\mu, m_e \leftrightarrow$ 3477 / 207/ 1

Lepton Flavour Universality II

- The SM quantum numbers of the three families could be an “accidental” low-energy property: the different families may well have a very different behaviour at high energies, as signalled by their different mass



- If NP couples in a non-universal way to the three lepton families, then we can discover it by comparing classes of rare decays involving different lepton pairs (e.g. **e**/μ or μ/τ)



- Test LFU in $b \to s\ell^+\ell^-$ transitions, i.e. flavour-changing neutral currents with amplitudes involving loop diagrams

The family of R ratios

- Comparing the rates of $B \to He^+e^-$ and $B \to H\mu^+\mu^-$ allows precise testing of lepton flavour universality

$$R_{\rm H}\left[q^2_{\rm min}, q^2_{\rm max}\right] = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} {\rm d}q^2 \frac{{\rm d}\Gamma(B\to H\mu^+\mu^-)}{{\rm d}q^2}}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} {\rm d}q^2 \frac{{\rm d}\Gamma(B\to He^+e^-)}{{\rm d}q^2}} \,, \quad q^2 = m^2(\ell\ell)$$

$$H = K, K^*, \phi, ...$$

- These ratios are clean probes of NP :
  - Sensitive to possible new interactions that couple in a non-universal way to electrons and muons
  - Small theoretical uncertainties because hadronic uncertainties cancel : $R_{\rm H} = 1$ in SM, neglecting lepton masses, with QED corrections at ~% level

Very challenging measurements

- Lepton identification is anything but universal!
- Electrons emit a large amount of bremsstrahlung, degrading momentum and mass resolution

- Two situations
    - Downstream of the magnet
      Photon energy in the same calorimeter cell as the electron and momentum correctly measured
    - Upstream of the magnet
      Photon energy in different calorimeter cells than electron and momentum evaluated after bremsstrahlung

      → bremsstrahlung recovery can partially fix this

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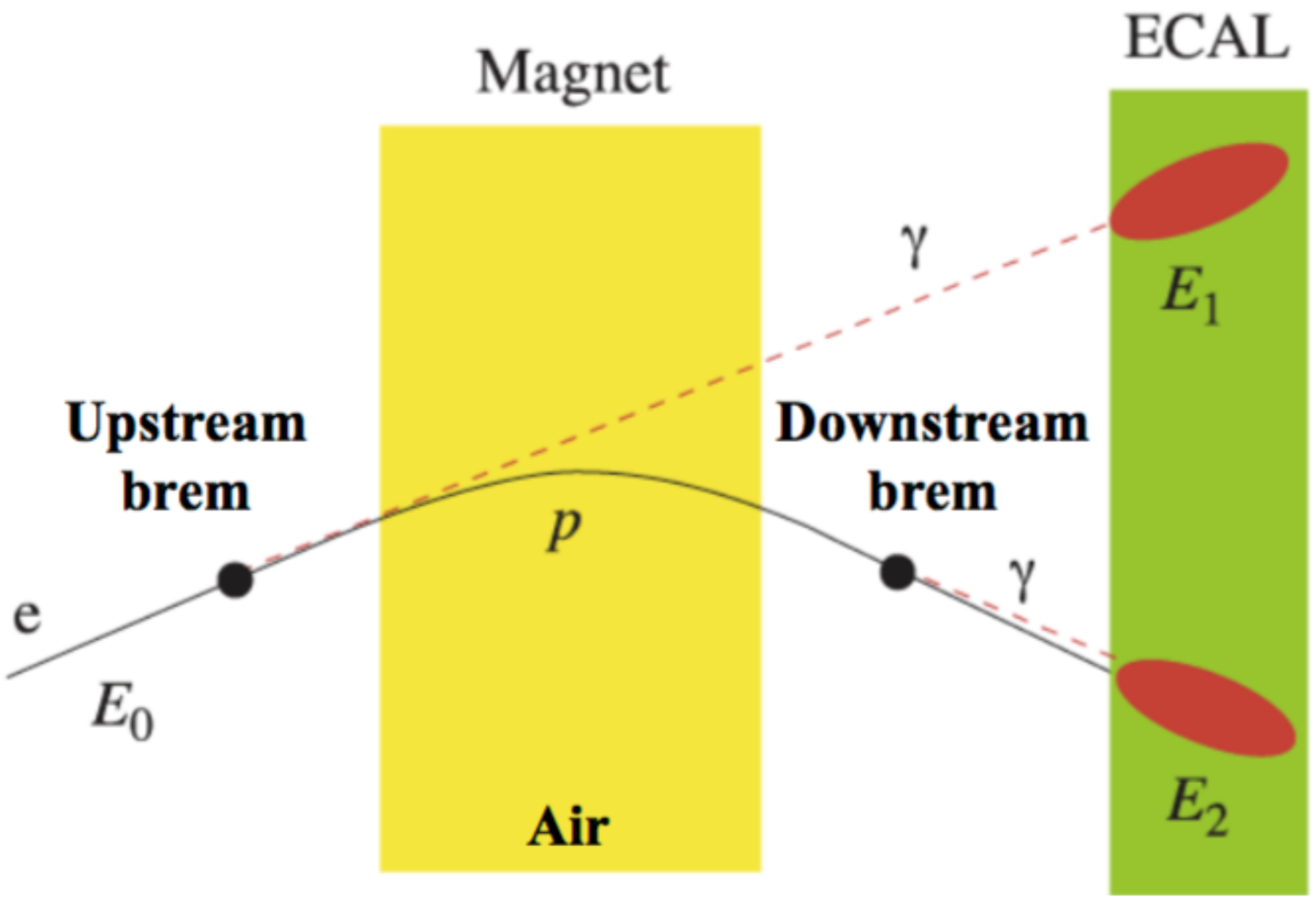


Measure as a double ratio

- To mitigate muon and electron differences due to bremsstrahlung and trigger, measurement performed as a double ratio with “resonant” control modes $B^0 \to J/\psi H$, which are not expected to be affected by NP:

$$R_{\mathrm{H}} = \frac{\mathcal{B}(B^0 \to H\mu^+\mu^-)}{\mathcal{B}(B^0 \to HJ/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to He^+e^-)}{\mathcal{B}(B^0 \to HJ/\psi(\to e^+e^-))}$$

→ Relevant experimental quantities: yields & (trigger, reconstruction and selection) efficiencies for the four decay modes

→ $r_{J/\psi} = \dfrac{B(B \to HJ/\psi(\mu^+\mu^-))}{B(B \to HJ/\psi(e^+e^-))}$ known to be compatible with unity within 0.4%

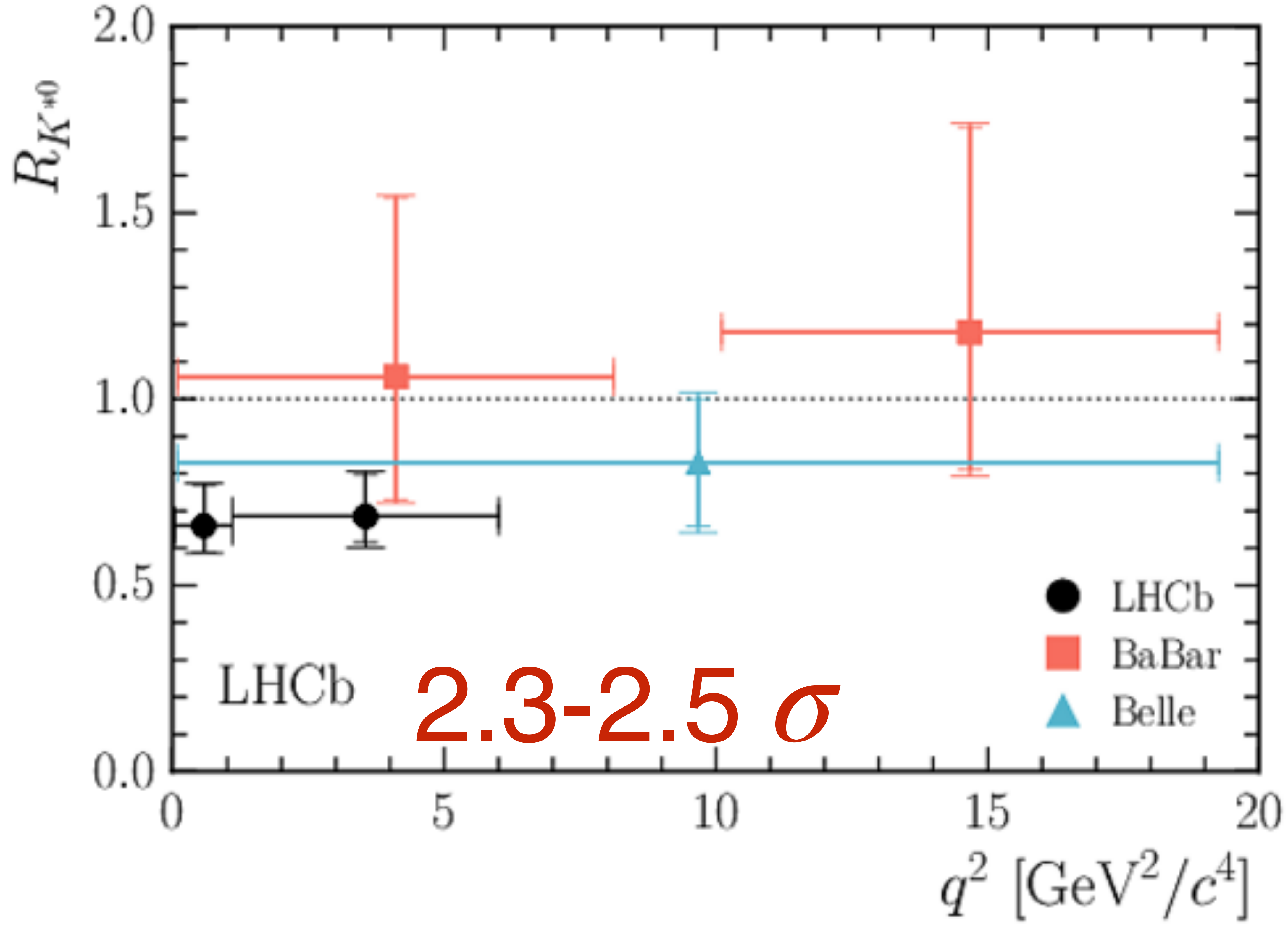
- Similarities between the experimental efficiencies of the non resonant and resonant modes ensure a substantial reduction of systematic uncertainties in the double ratio

- Analyses performed blind

Violation of lepton-flavour universality?

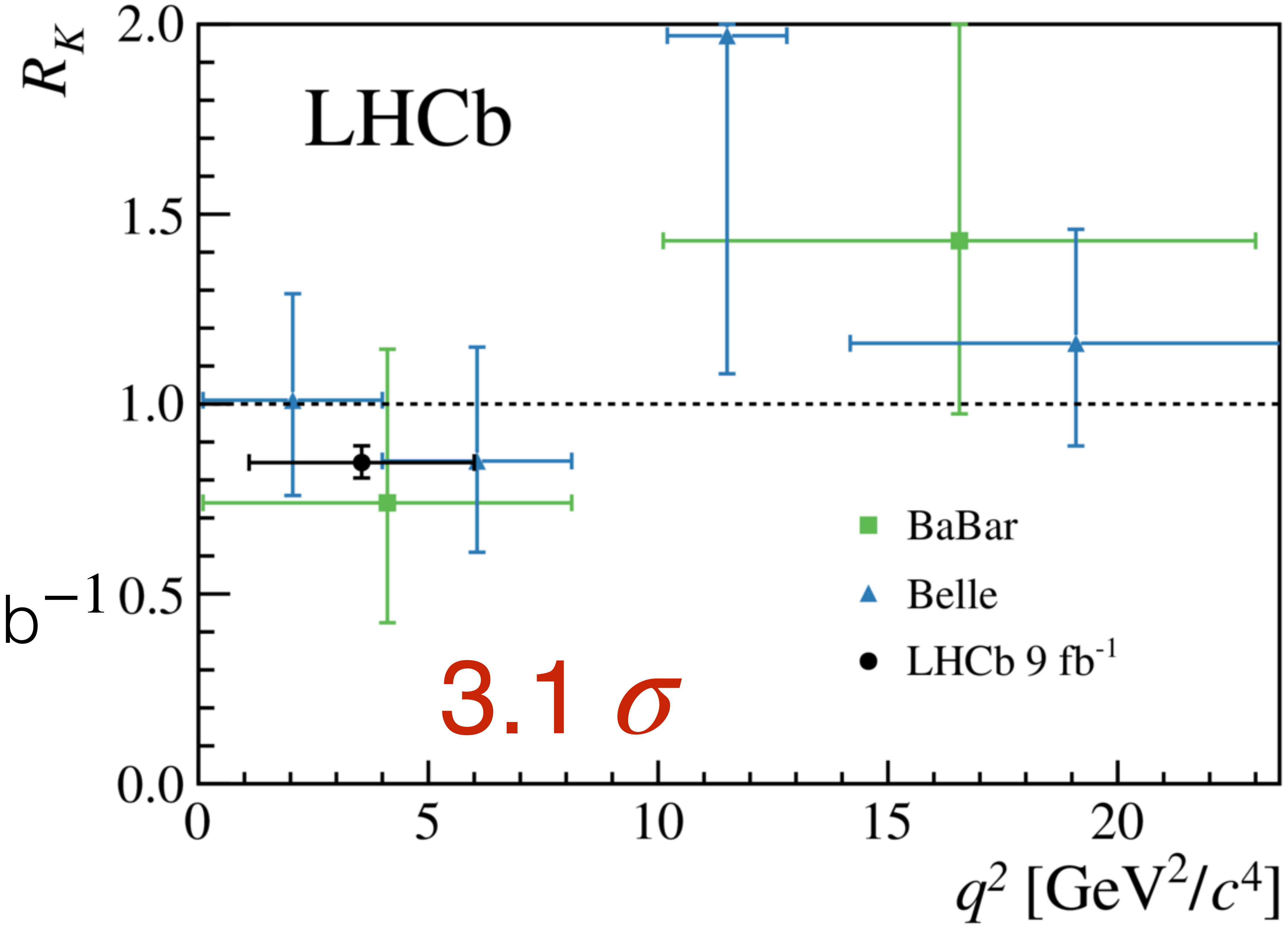
$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$

$$B^0 \to K^{*0}\mu^+\mu^-$$



2.3-2.5 σ

$$B^+ \to K^+\mu^+\mu^-$$



3 fb^{-1}

3.1 σ

- Any significant deviation from unity is a smoking gun for NP
- Aligns well with tensions seen in other $b \to s\mu^+\mu^-$ observables (differential BFs, angular observables)
- Many NP models proposed (eg. leptoquarks)

Violation of lepton-flavour universality?

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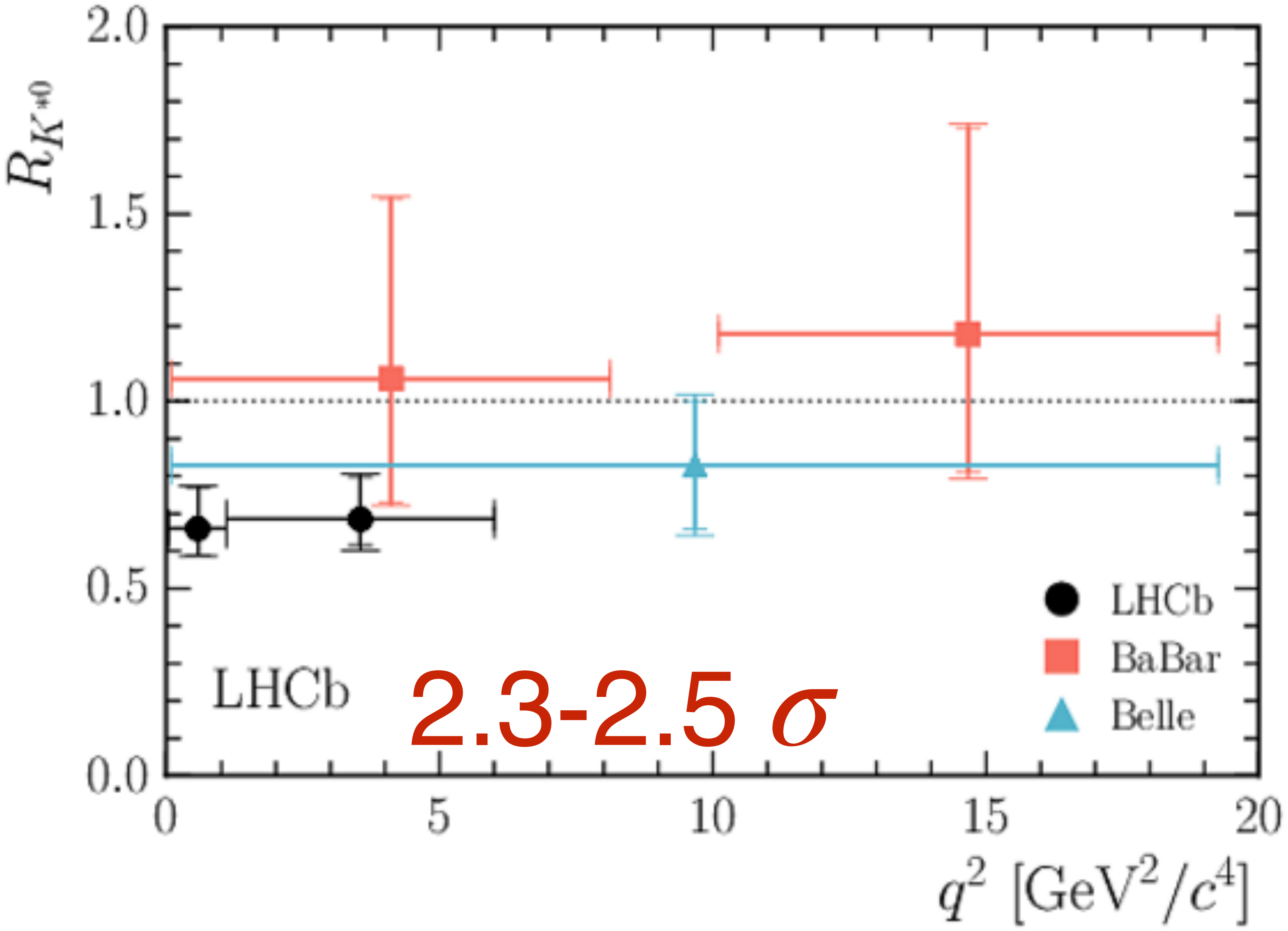
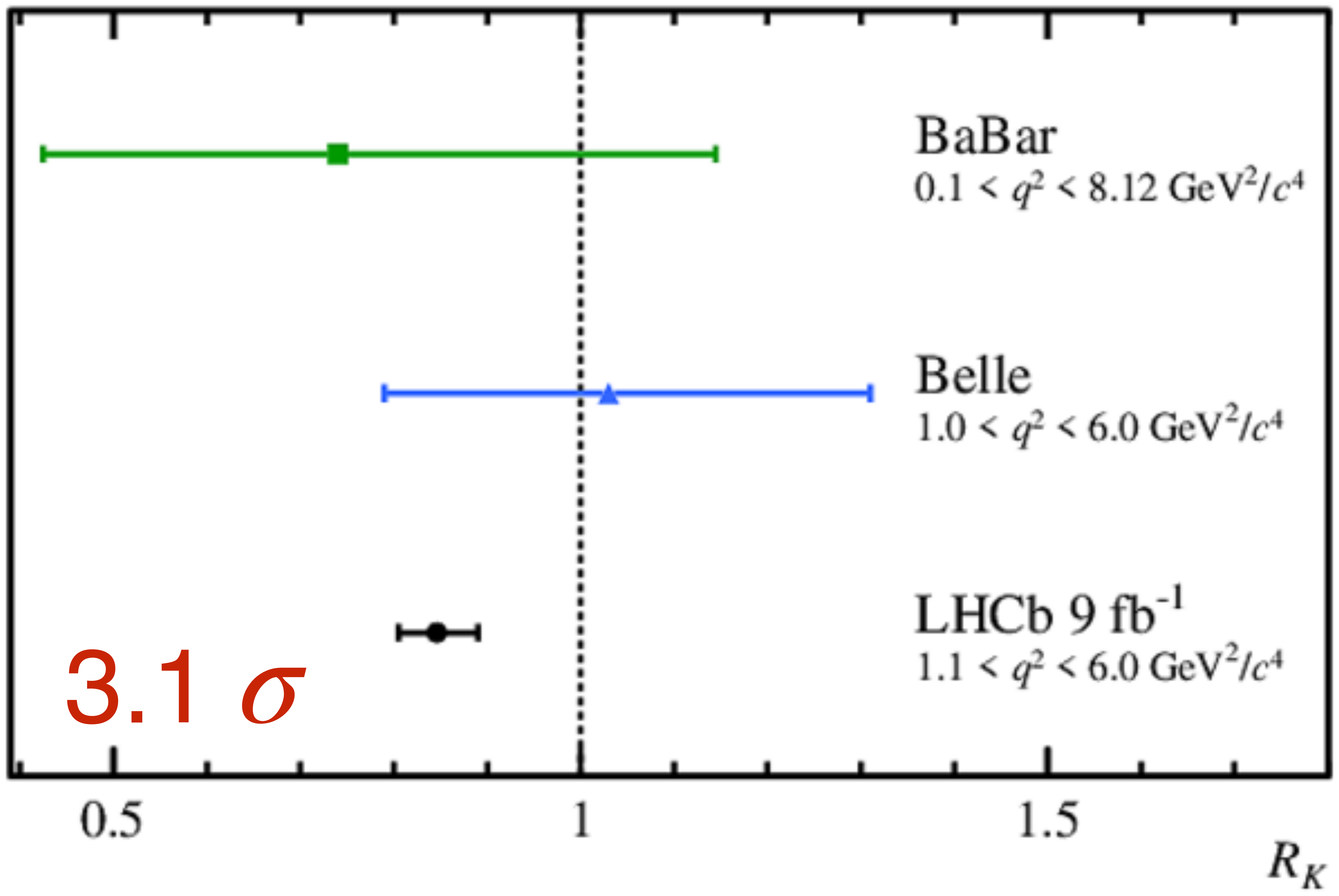

$B^0 \to K^{*0}\mu^+\mu^-$

2.3-2.5 σ

3 f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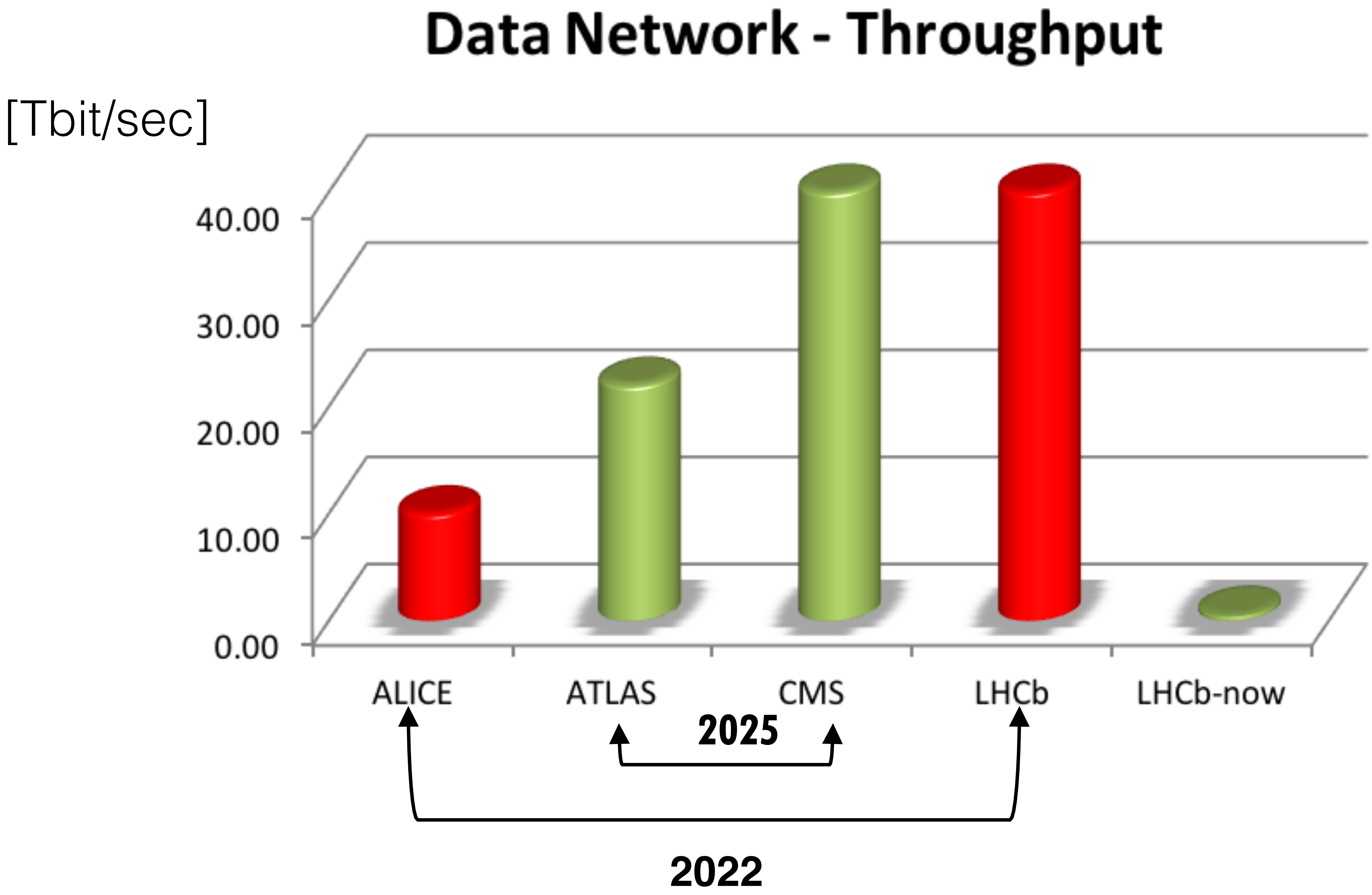
Take home message

- Flavour physics is very rich and is connected to many fundamental questions
  - What determines the observed pattern of masses and mixing angles of quarks and leptons?
  - Explaining the observed imbalance between matter and antimatter in the Universe requires CP violation. CP violation beyond the SM must exist! Keep on looking for deviations to the CKM theory
- Precise measurements of flavour observables provide a powerful way to probe for NP effects beyond the SM, complementing direct searches for NP. This is particularly relevant in the absence of direct collider production of new particles.
- LHCb is getting ready for the MHz signal era, with a trigger fully implemented in software, and Real Time event processing
- Keep an eye on LFU tests!

Supplementary material

Network throughput



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