# LHC Run 3: The start of a new era

26th May 2022

- Detector Upgrades
  - New technology, new possibilities
- Physics opportunities for Run3
  - Broad programme, new options


**Chris Parkes**
**Spokesperson of the LHCb Collaboration**
**Covering all LHC Collaborations**

# LHC Experiment Cycle



**Completed ~2008**
**Take Data**
**Analyse Data**

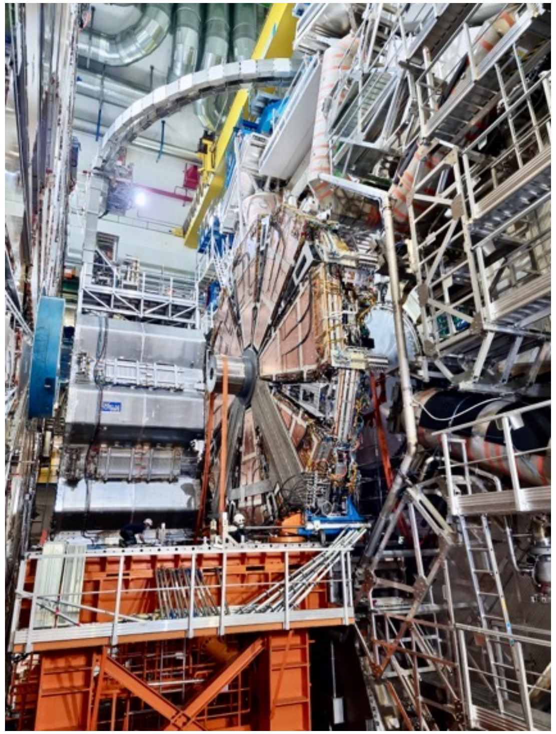
Install → Operate

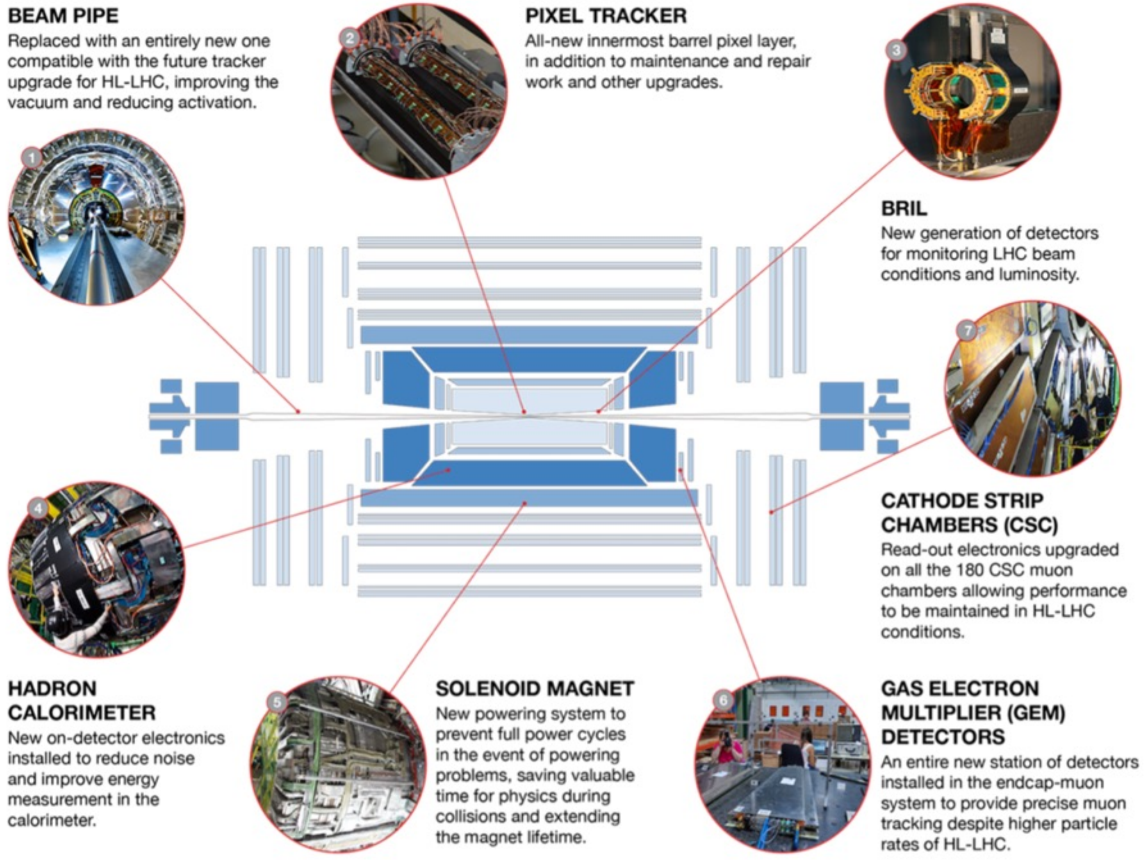
- **First decade of Operations**
  - 1000 papers/expt !
- **Major Upgrades**
  - Upgrade I, & later 2
  - Now and later in decade

**Improve**
**Technology**
**Enhance**
**Opportunities**

Upgrade → Operate

# Upgrade I: ATLAS & CMS






ATLAS UK:

- Calorimeter Trigger upgrade
- High-Level Trigger software

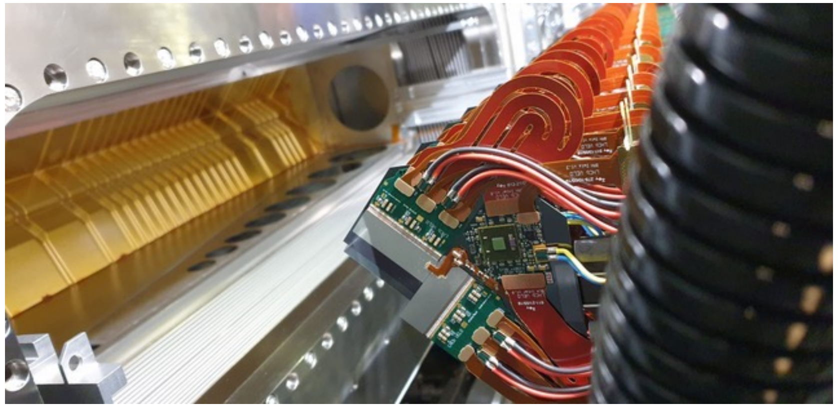
CMS UK:

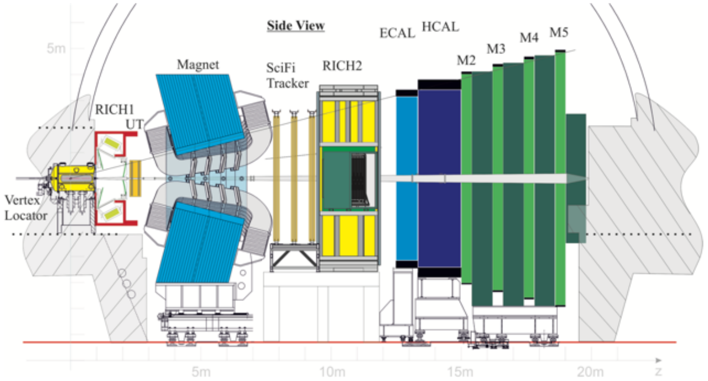
- Trigger & data acquisition system

- **Major Upgrades for LS3 in 2025**

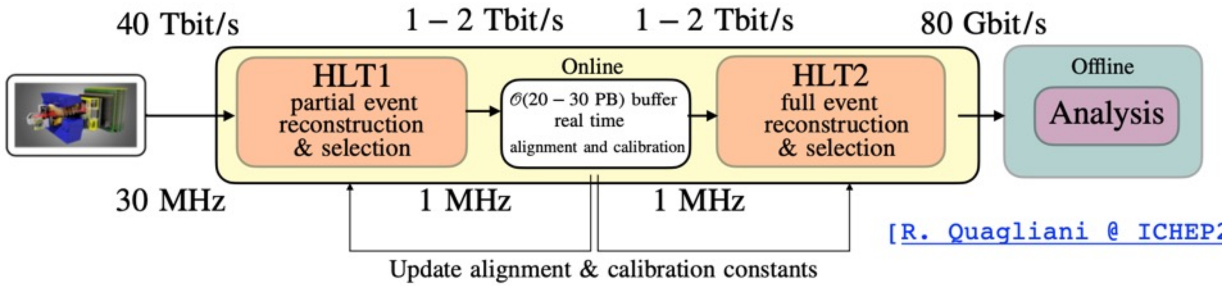
# Upgrade I: LHCb

- Largest CERN particle physics detector project since completion of LHC
- Completed on budget and *near* schedule






- Innovative Trigger & Real-Time Analysis
- Flexibility to expand physics programme




[R. Quagliani @ ICHEP2

LHCb UK lead contribution to:

- Silicon pixel vertex detector (VELO)
- Particle Identification (RICH)

# Upgrade I: ALICE

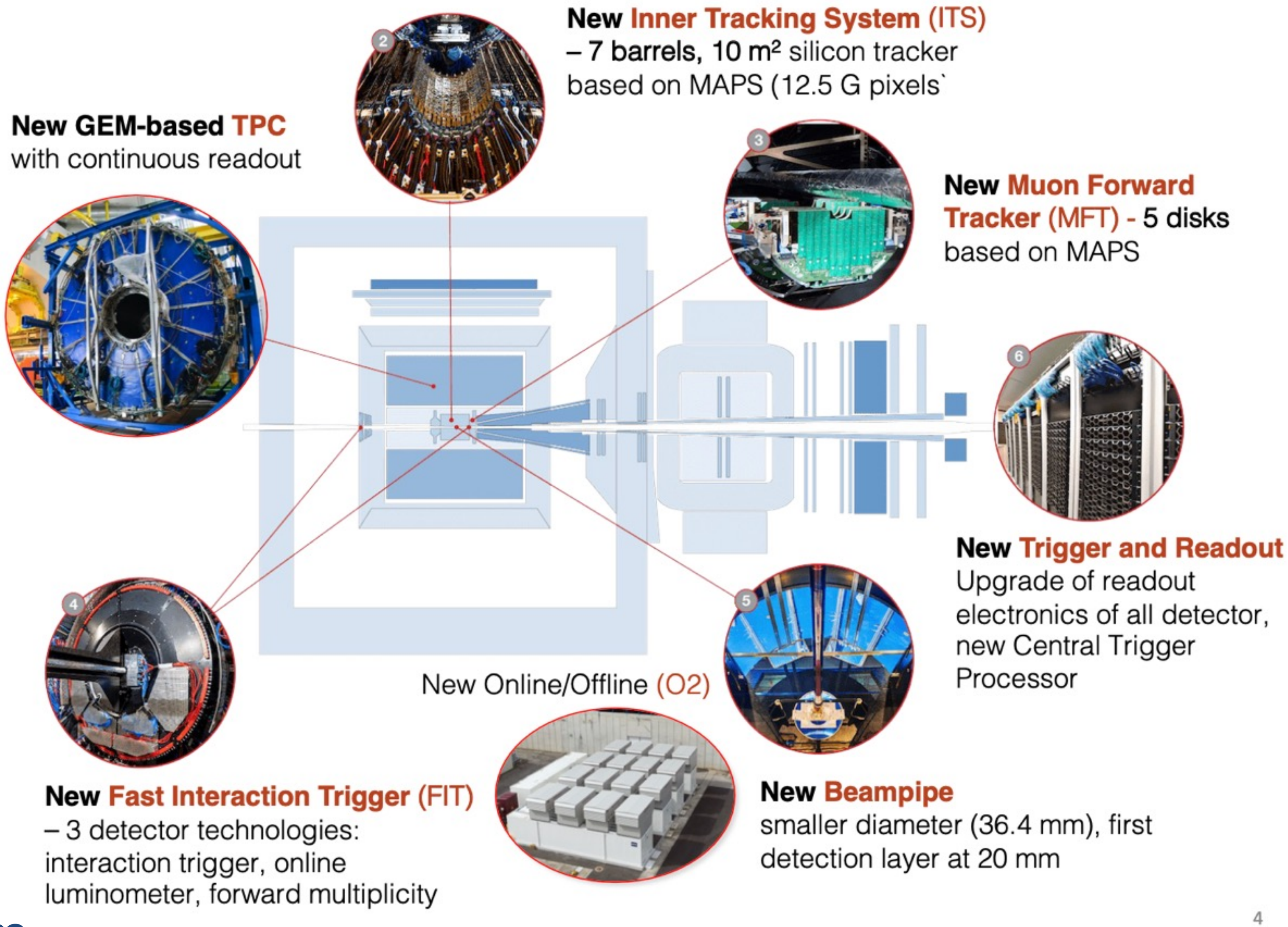
## ALICE Upgrade for Run 3

> Improve tracking resolution at low $p_T$

x50 statistics increase for most observables

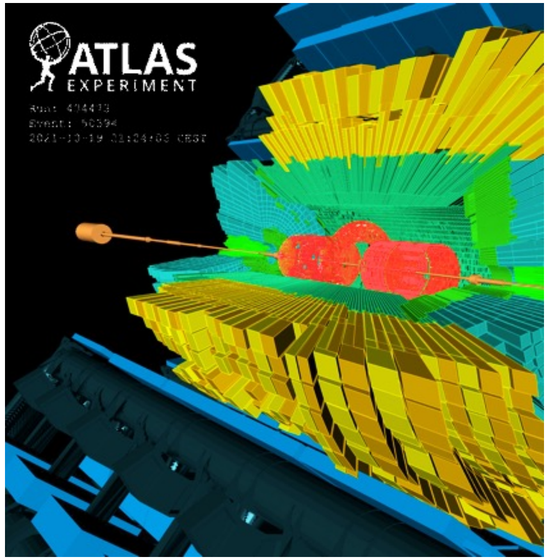
⇩

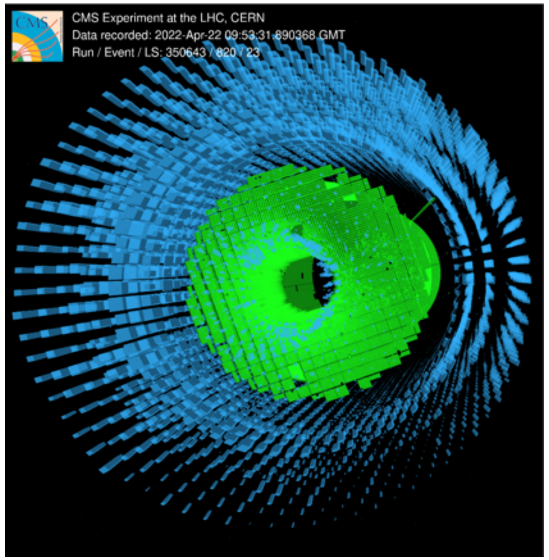
Run 3+4: **13 nb$^{-1}$ Pb-Pb**
**50 kHz (Pb-Pb), ≈ 1 MHz (pp)**
**online reconstruction**
**all events to storage!**

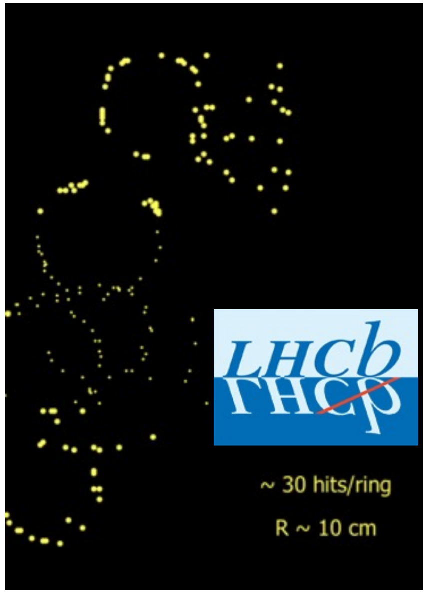


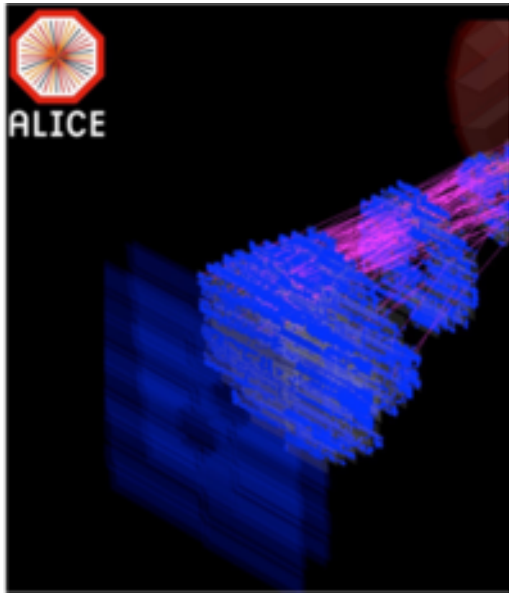

ALICE UK:
- Inner Tracking System
- Central Trigger Processor

# Commissioning underway



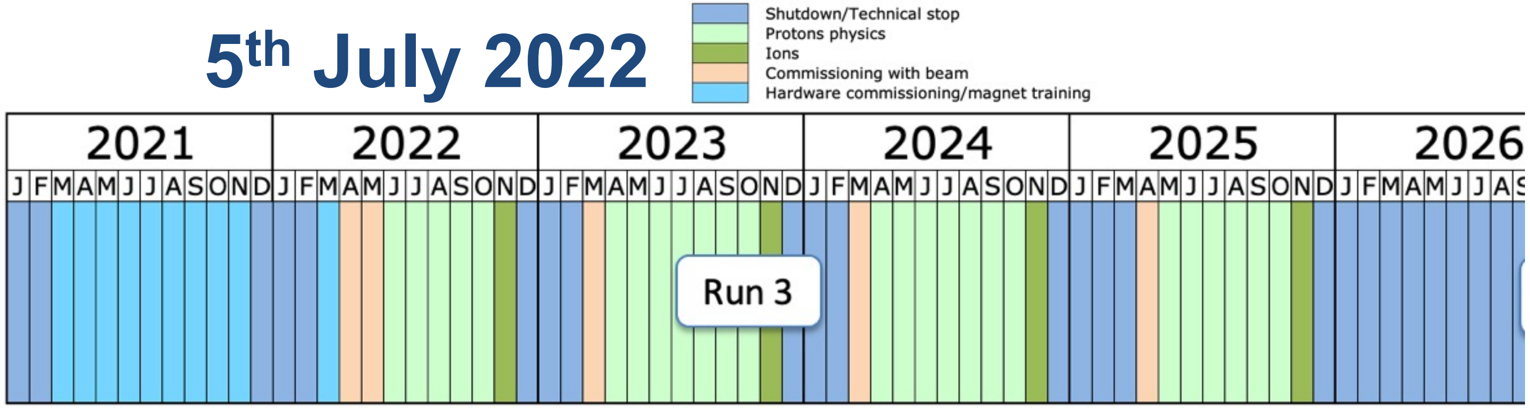




# Start of LHC Run 3

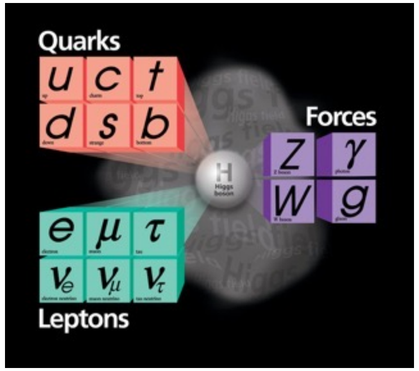
- Excitement and energy in control rooms
- First high-energy collisions expected

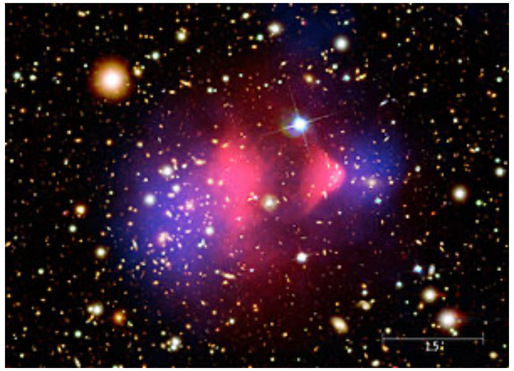
**5th July 2022**

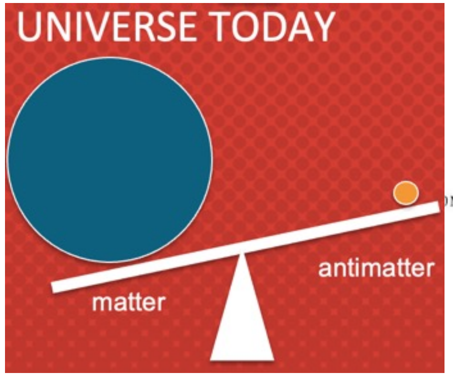


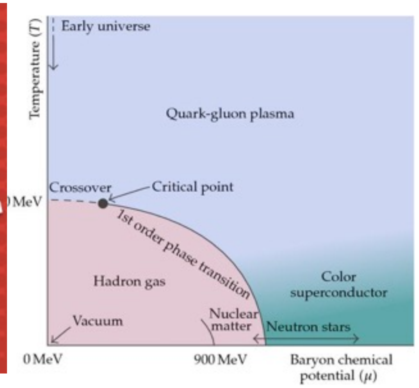
# Big Physics Questions

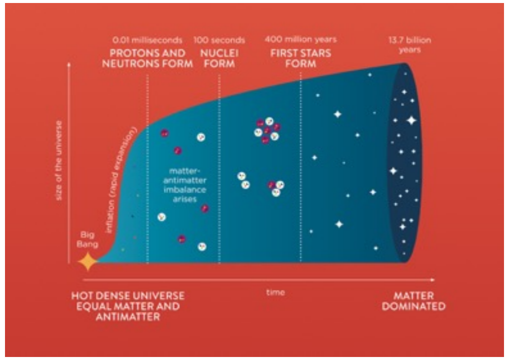
- **Understanding the Standard Model.** Precision measurements
- **What is the nature of dark-matter ?** New-physics searches
- **Where did the Antimatter go ?** Comparing particles & anti-particles
- **How are quarks and gluons confined ?** Recreating the primordial state of matter





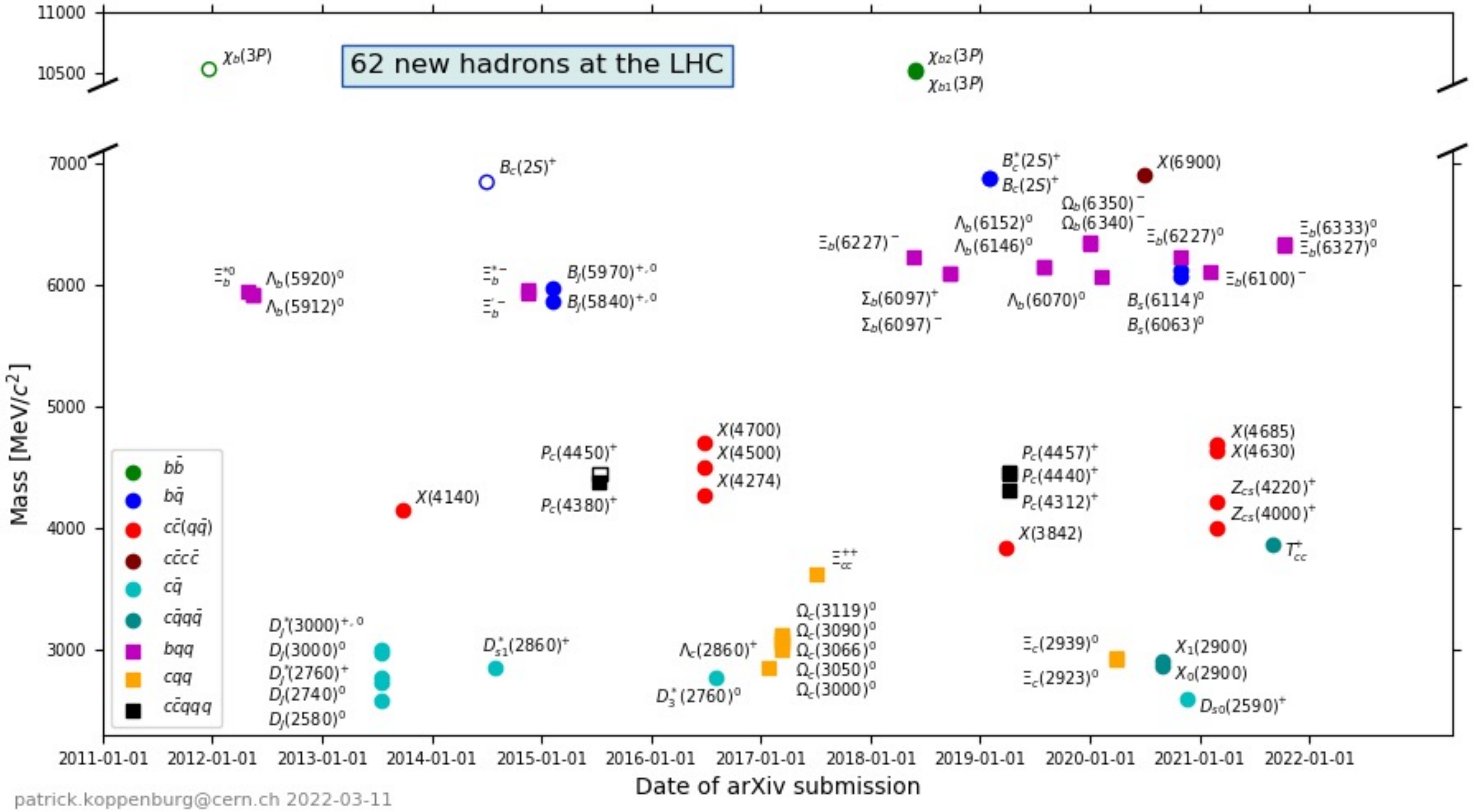




# One step at a time…..

- Recent examples (outside Higgs) setting the direction of travel….

# Beyond the proton : Exotic Hadrons

- **More than 60 particles discovered at LHC**

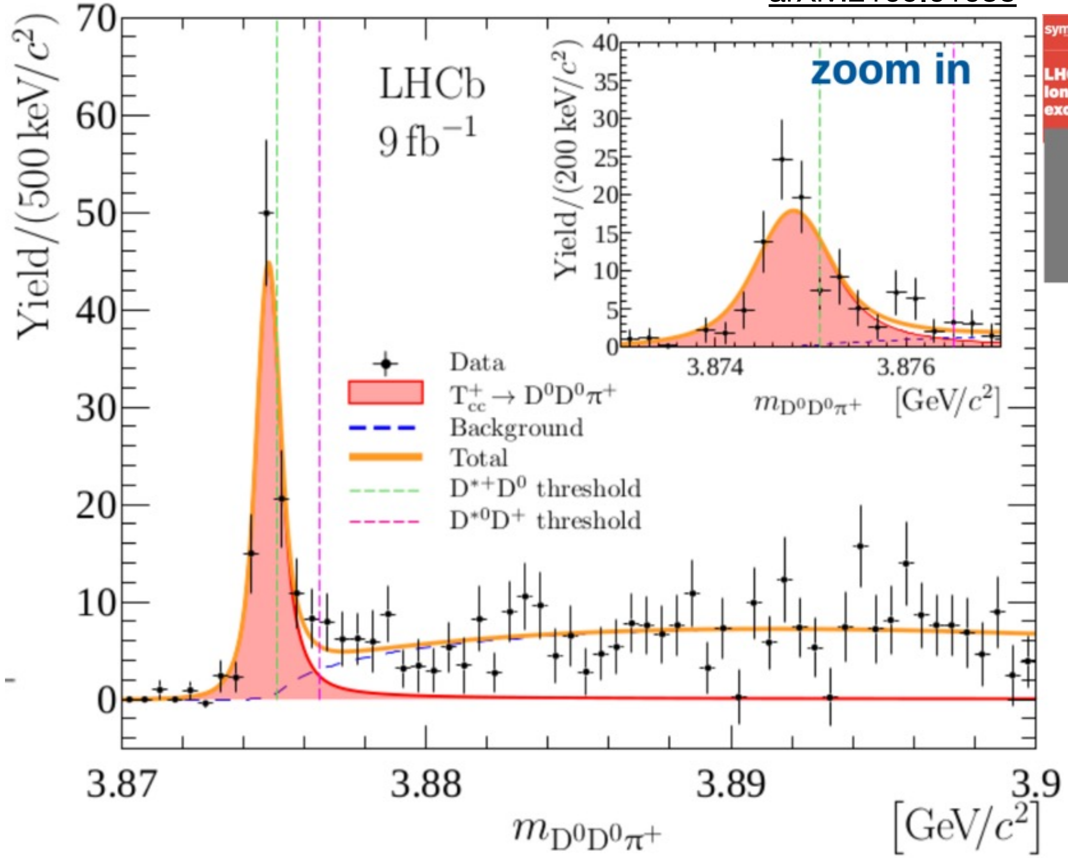



- Particles made of quarks – hadrons
  - 2 quarks (π, K…)
  - 3 quarks (p, n…)
- New states of matter
  - 4: Tetraquarks
  - 5: Pentaquarks

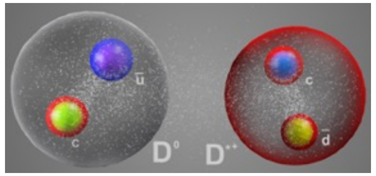
# Beyond the proton: Exotic Hadrons

- *Charming* Tetraquark Discovery: $T_{cc}^{+}$

arXiv:2109.01038







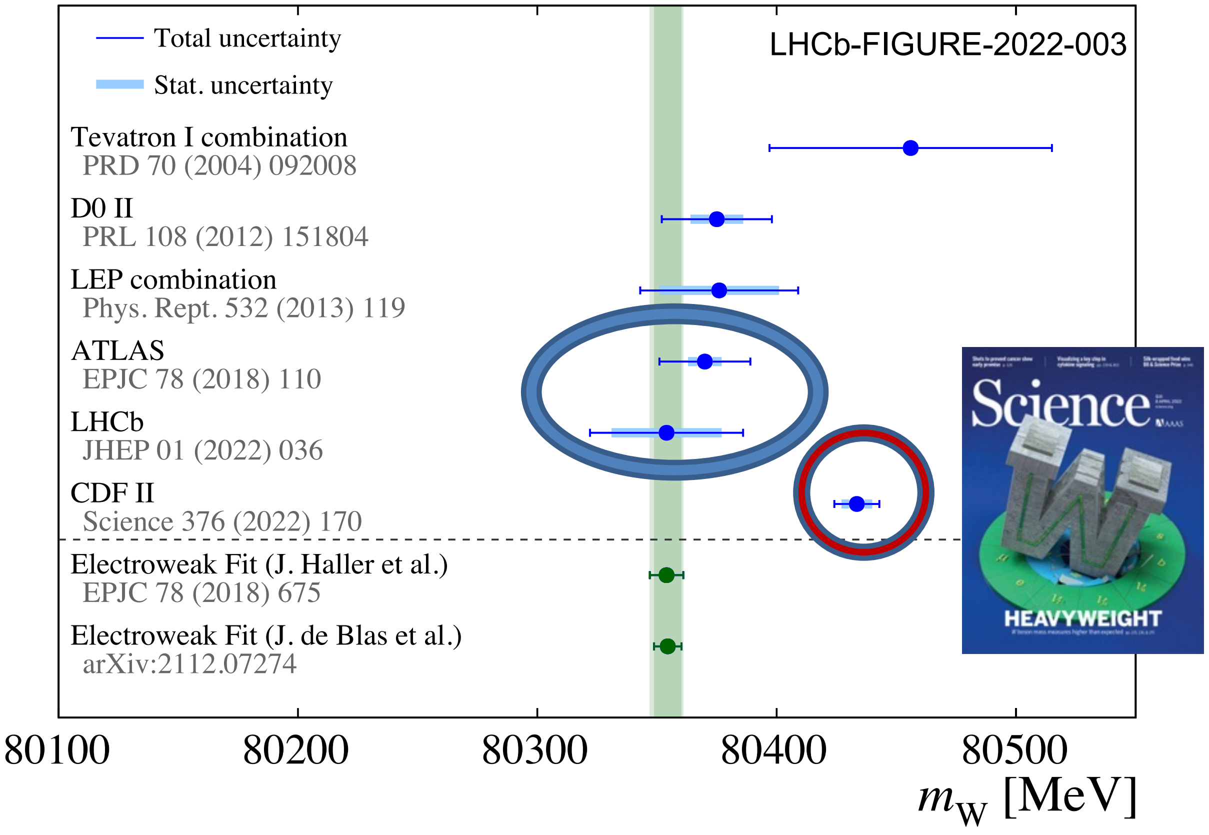

Prediction: the equivalent state with beauty quarks might fly for ~ cm before decaying !

- Particles made of quarks – hadrons
  - 2 quarks (π, K…)
  - 3 quarks (p, n…)
- New states of matter
  - 4: Tetraquarks
  - 5: Pentaquarks

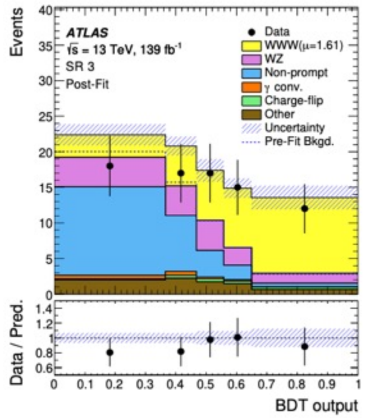
- **Run 3: Discover more states ? Relatively long-lived states ?**
- **Run 3: Exotics- Tightly bound ? molecule-like ?**

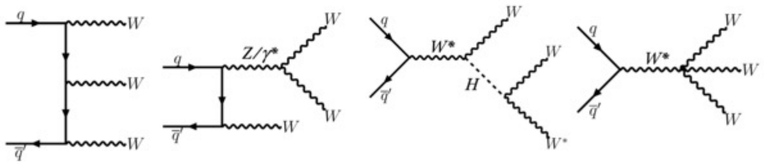
# Precision measurements: W & top

- **Weak Force carriers, heaviest quark, Higgs boson related by theory**




arXiv:2201.13045v1

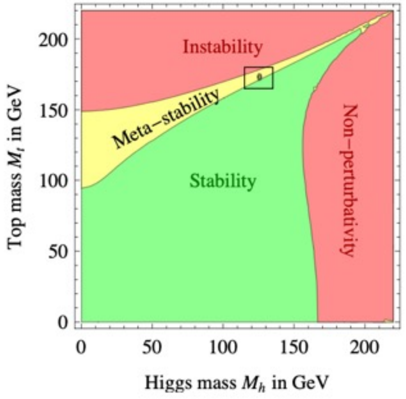


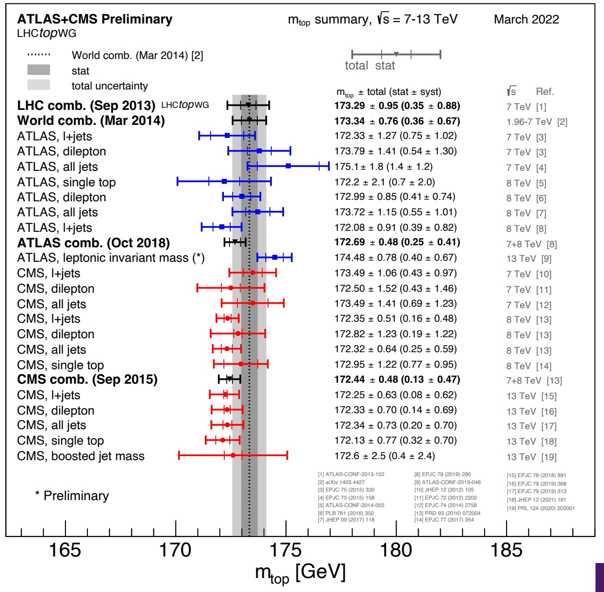
- **WWW discovered**

**(not the T. Berners-Lee variety)**

arXiv:1205.6497




- **Top Quark**

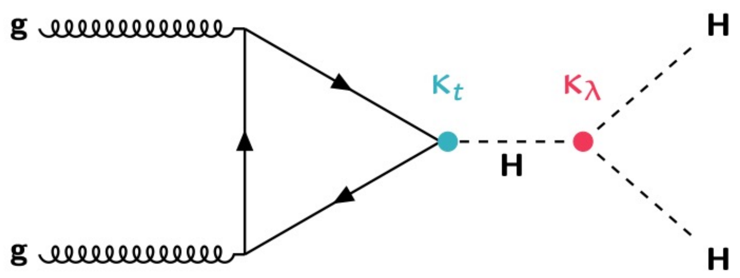


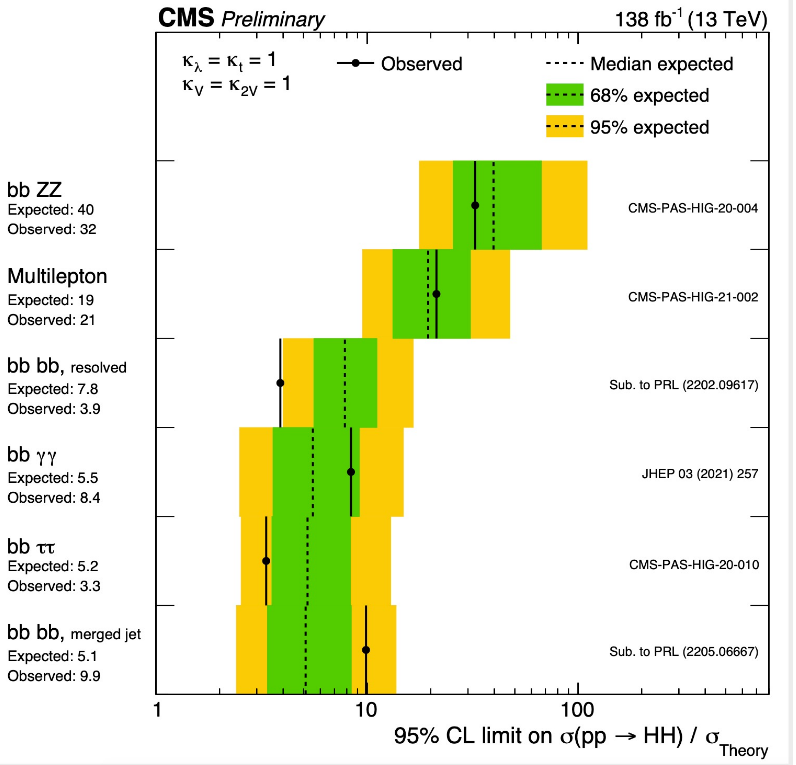

- **Run3: Resolve Discrepancy LHC & Fermilab ?**
- **End of the universe nigh ?** **Electroweak vaccuum stable ?**

# Higgs self-coupling

- Discovery of the Higgs marked the opening up of a new sector to explore
- Higgs boson is the only fundamental scalar particle we know
  - Ability to self-couple
  - Value of the self-coupling tells us about vacuum stability
  - Recent result: now sensitive to signal strength only 3x higher than prediction
  - Double the statistics, improve the methods

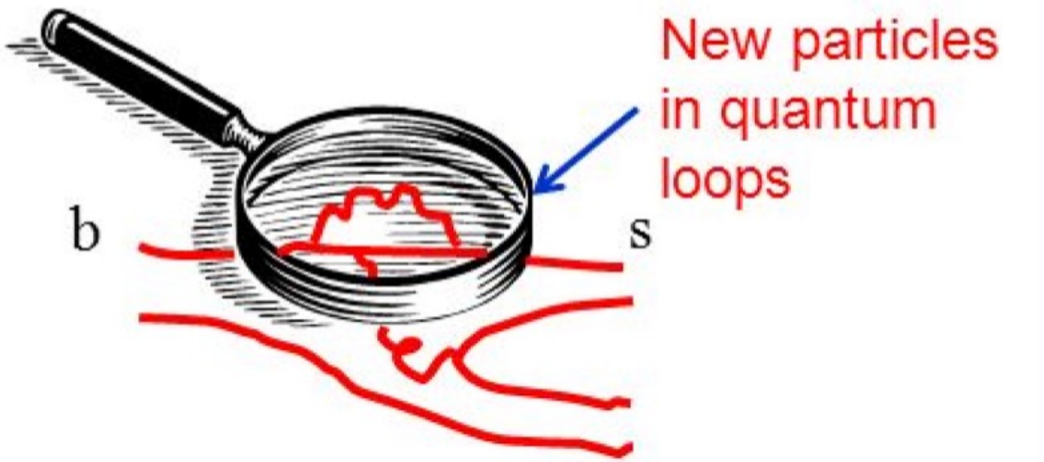
**Run 3: Close to probing this new type of fundamental interaction ?**



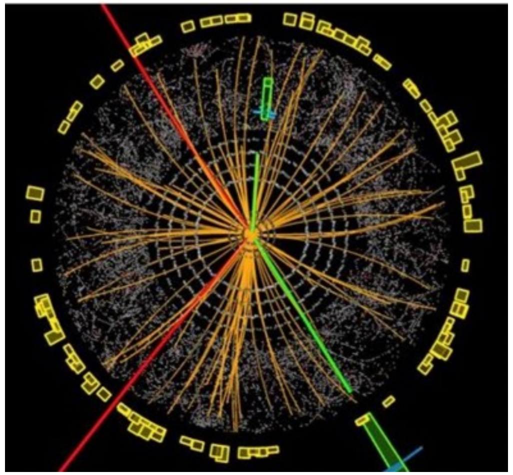



# New Physics Searches: Under watch for Run 3!

## Indirect




## Direct

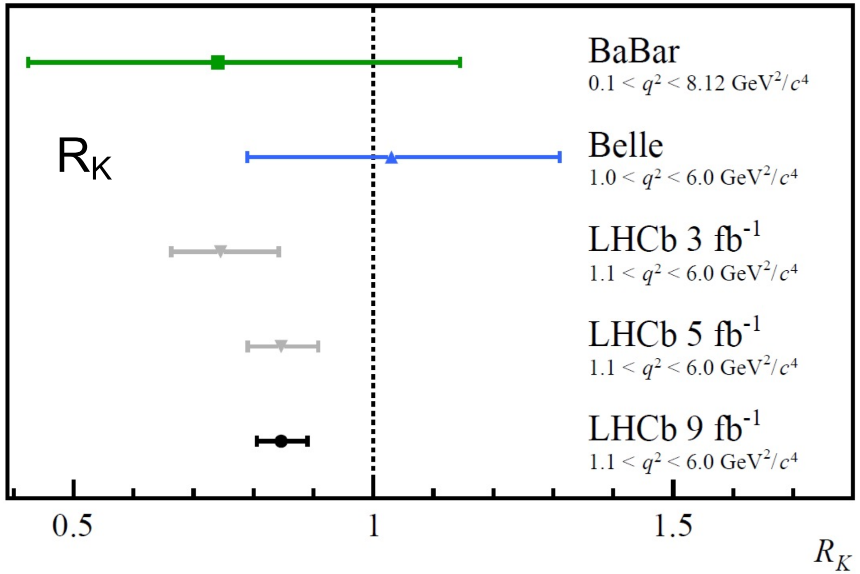


- Two complementary approaches
  – Produce unknown particles & observe their decays
    - Direct discovery
  – Compare precision measurements with theory predictions
    - Probes masses above direct discovery reach

# New Physics Searches: Under watch for Run 3!

## Indirect

arXiv 2103.11769




- Lepton flavour universality
- Intriguing pattern of anomalies in several beauty quark particle-decays
  - Ratios, Rates, Angular distributions

## Direct

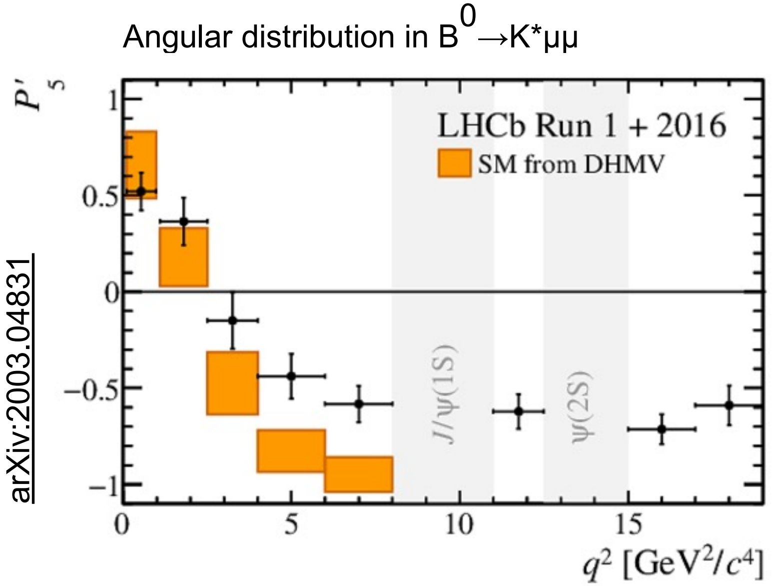
| | | Local(global) | m |
|---|---|---|---|
| CMS | W′ →WZ | 3.6 (2.3) σ | 2.1 & 2.9 TeV |
| ATLAS | $H_5$′ →WZ | 2.8 (1.6) σ | 350 GeV |
| CMS | S→XX→(jj)(jj)<br>X→(jj) | 3.9 (1.6) σ<br>3.6 (2.5) σ | 8.5 TeV<br>1 TeV |
| CMS | $L_V L_V$→4b2τ | 2.8 σ | 600 GeV |
| ATLAS | X→HH→4b<br>X→HH→2b2τ | 3.2 σ<br>3.1 σ | 1 TeV |
| CMS | φ→ττ | 3.1 (2.7) σ<br>2.8 (2.4) σ | 100 GeV<br>1.2 TeV |
| CMS | H→WW (VBF) | 3.8 (2.6) σ | 650 GeV |
| ATLAS | Iso track dE/dx | 3.6 (3.3) σ | >1 TeV |

Credit: Niels Tuning

- Bump hunting !
- **Many** searches performed
- Will always be excesses
  - See what nature gives us !

# New Physics Searches: Under watch for Run 3!

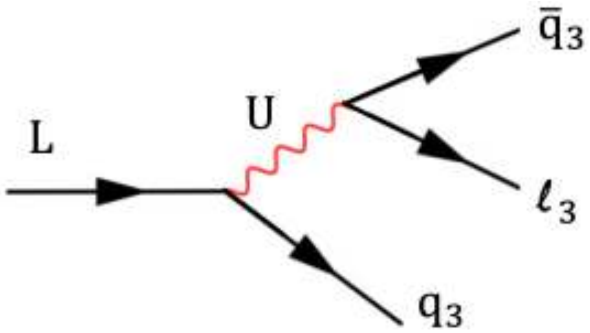
## Indirect - Intensity

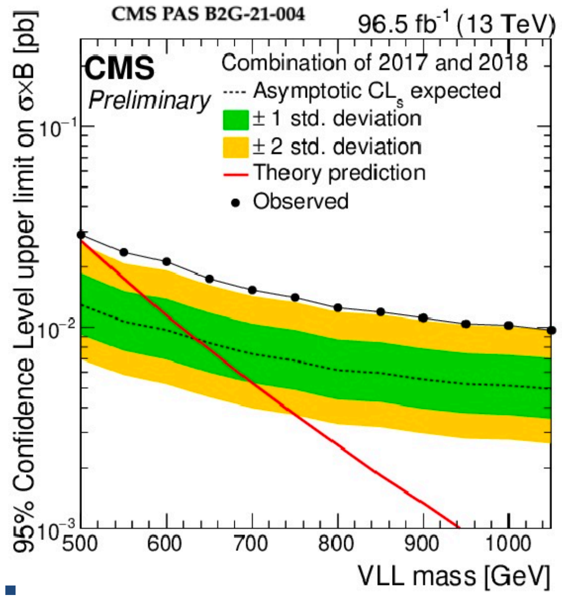



- Lepton flavour universality
- Intriguing pattern of anomalies in several b-decays
  - Ratios, Rates, Angular distributions

## Direct - Energy

- Search for new particles that could explain b anomalies
  - Vector like leptons decaying to leptoquarks

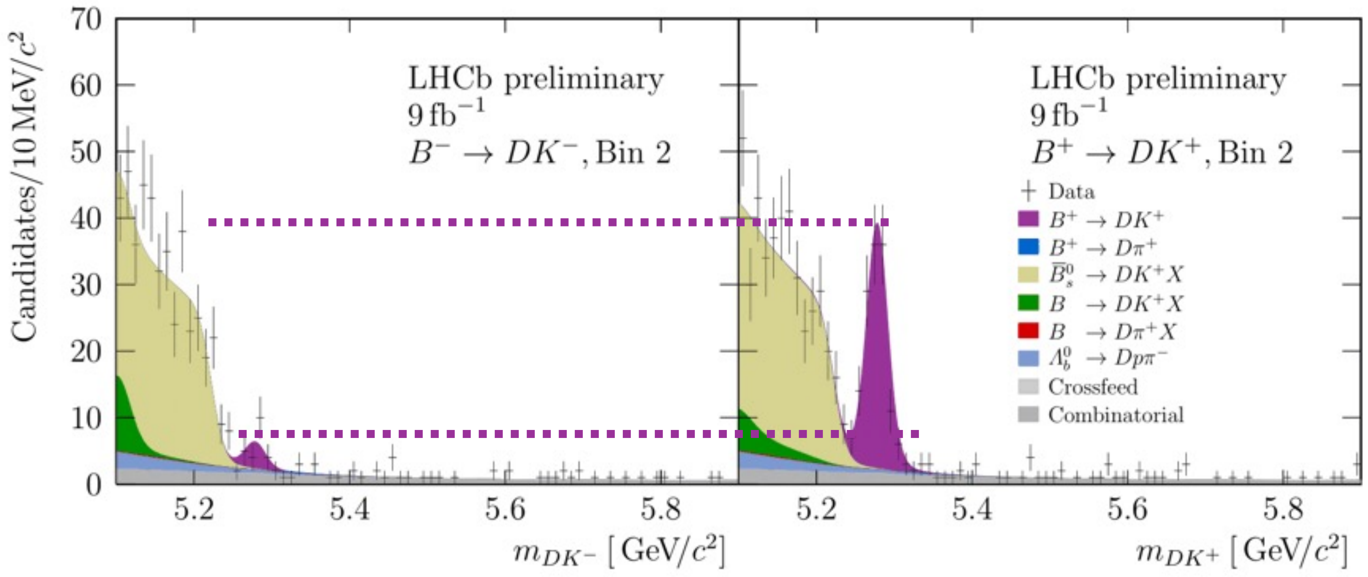


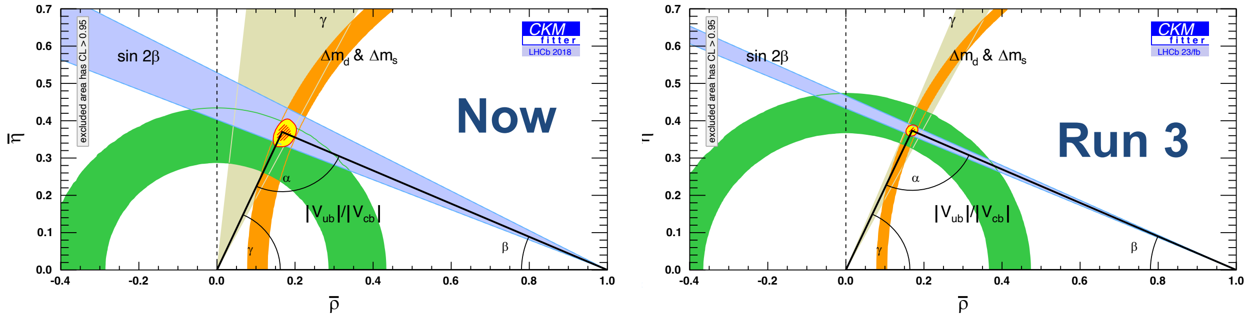

- **Run3: Statistics to understand the anomalies**

# Matter Antimatter asymmetries

- Discovered in two beauty quark system ($B+$, $B_s$) and charm at LHC
- Matter & antimatter like mirror images ?

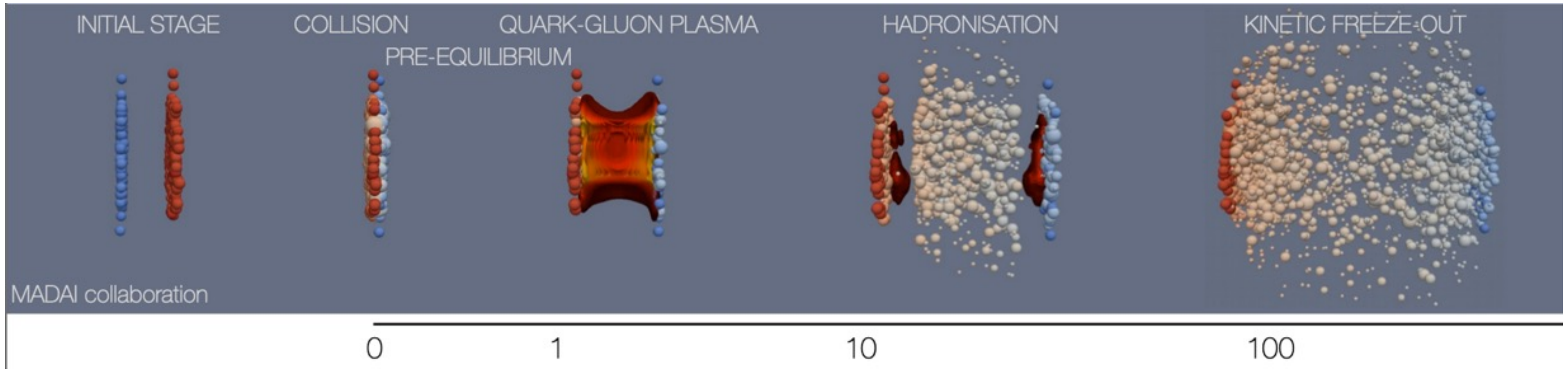



- Largest difference ever !
- 85% asymmetry
- 12 times more $B^-$ than $B^+$ decays this way

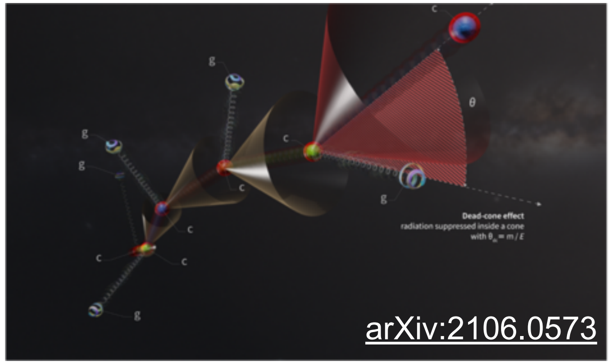


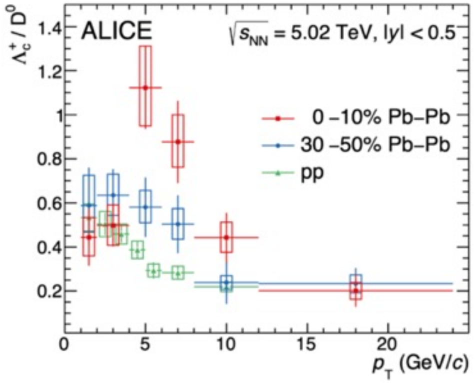

- **Run3: Push toward % level determination (CKM angle γ)**

# Understanding the strong force: Lead ions and p




- Understanding particle formation from quarks

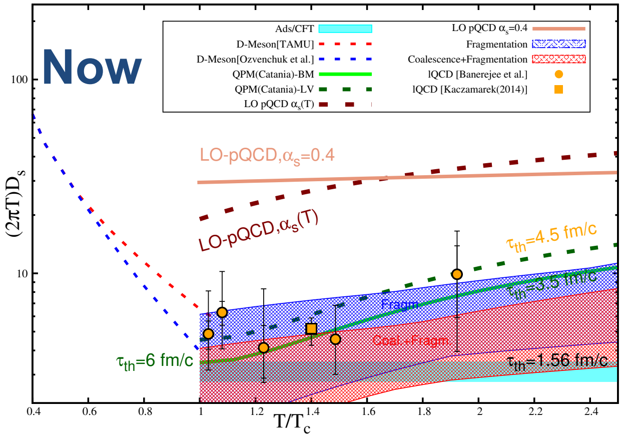


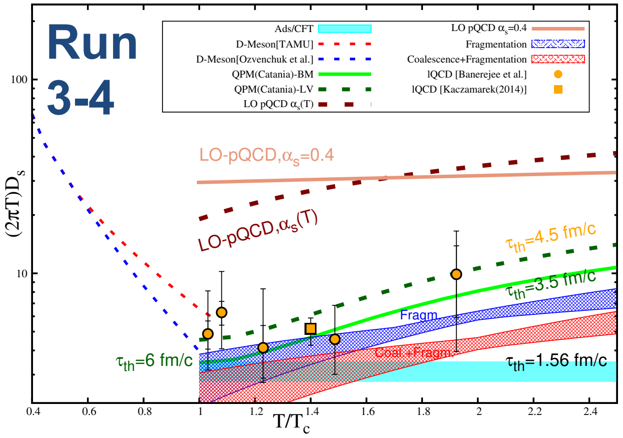




- Radiation from quarks (QCD dead cone)
- 3-quark & 2-quark state formation

- **Run 3: Upgraded ALICE will explore quark gluon plasma**

Interaction charm quarks with QGP arXiv:1812.06772

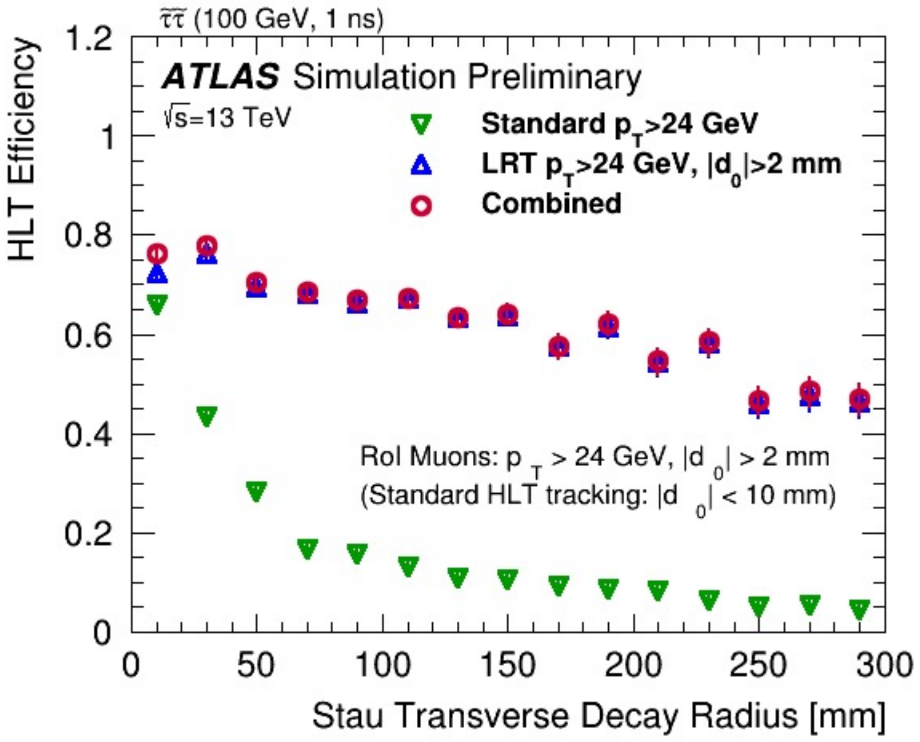


# Long-lived Particles: dark sector ?

- Addition of new online selection (triggers) in Run 3
  - ~7 times the the efficiency for  decays that happen far out from production point
  - Opens searches – in a fully generic way – into much higher lifetime objects

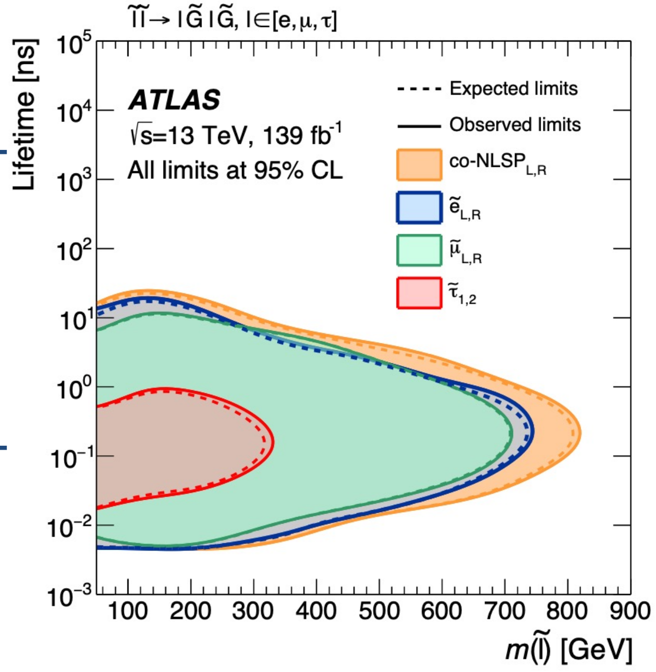
Online Selection Efficiency




Lifetime of potential new particle

Physical Review Letters 127, 051802 (2021)

Lifetime of potential new particle

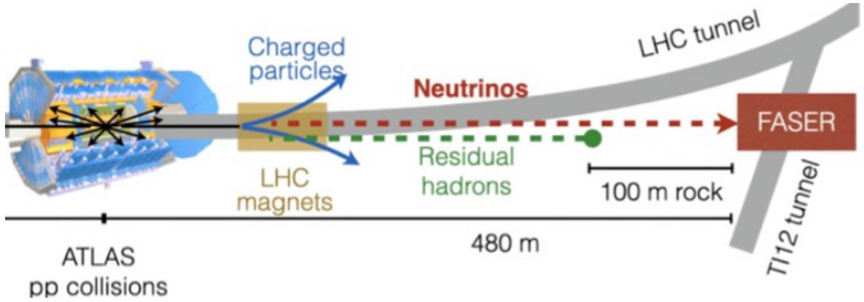


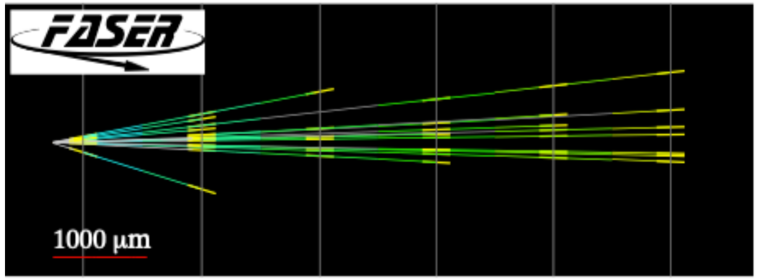

Mass of potential new particle

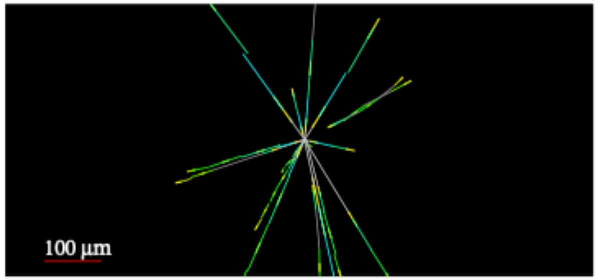
Lots of unexplored space outside these bands!

- **Run 3: New territory is being opened up**

# Extending opportunities

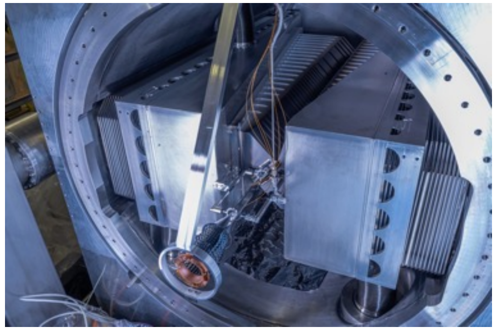


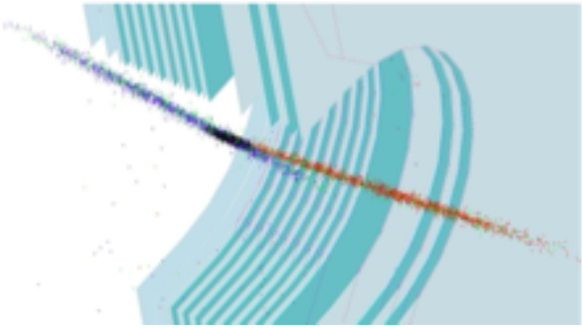



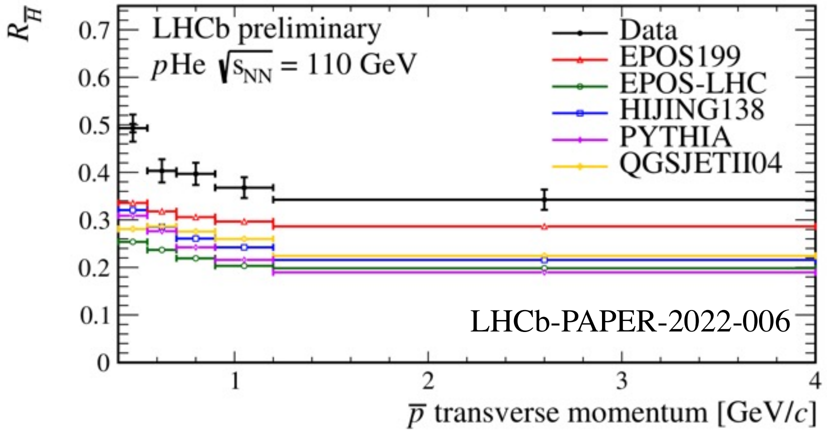




- FASER – Neutrinos observed  at LHC!
- **Run 3: New light particles produced but not yet detected at LHC ?**

- Probe anti-proton production, facilitates dark matter searches in space

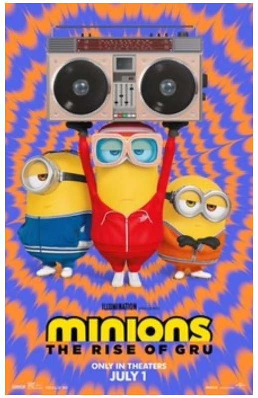







- SMOG @ LHCb – collide protons & gas (He, Ne, Kr, Ar, Xe..)
- **Run 3: Understand cosmic ray interactions, dark matter searches**

# Summary: LHC Run 3 Opportunities


- Run 3 *same* but *different*
- Technology enhancements
- Very **broad** physics programme
- LHC makes discoveries weekly
  - Many of examples here from last months
- **Looking forward to 2000 papers/expt !**

**Completed 2022**
**Take Data**
**Analyse Data**

Upgrade → Operate

**Run 4, 5, 6**
**Improve**
**Technology**
**Enhance**
**Opportunities**

Upgrade → Operate

CMS PAS B2G-21-004

# Search for pair-produced vector-like leptons in $\geq 3b + N\tau$ final states

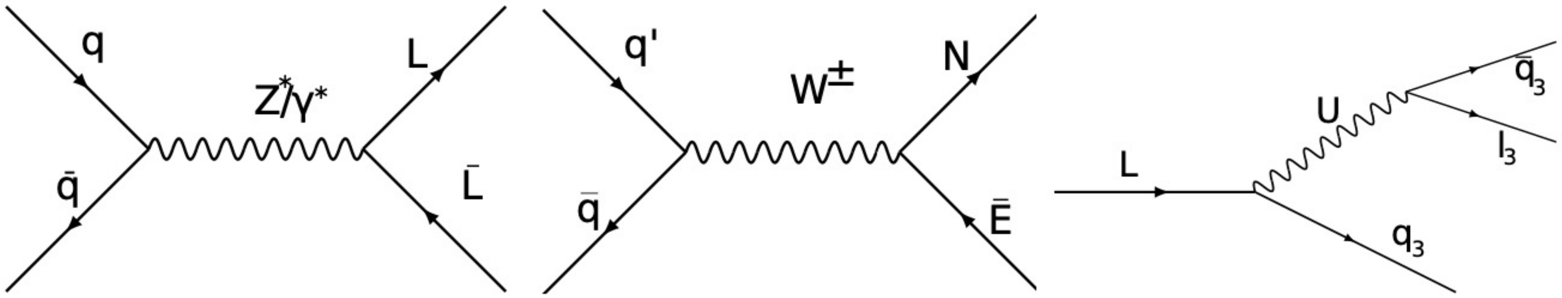
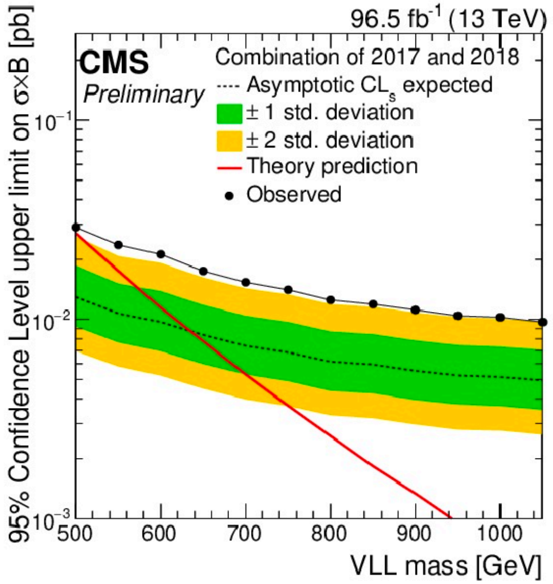



Figure 1: Left and centre: example Feynman diagrams showing production of VLL pairs through s-channel bosons, as expected at the LHC. In these diagrams, L represents either the neutral VLL, N, or the charged VLL, E. Right: vector-like lepton decays proceed through their interactions with the vector leptoquark, U. These decays are primarily to third-generation leptons and quarks.




The VLLs decay, via an intermediate leptoquark, U, to two quarks and one lepton. Because of the flavour nonuniversal couplings of the leptoquark, which make it a good candidate to explain the B anomalies, the decays are expected to be almost entirely to third-generation fermions. For each second-generation fermion, approximately an order of magnitude suppression in the branching fraction is expected, and even larger suppressions are expected for any first-generation fermion.

Vector-like lepton masses up to 640 GeV were expected to be excluded at the 95% confidence level. Mild excesses in the data, compared with the expectation, are observed in the signal-sensitive bins of the 1-$\tau_h$ and 2-$\tau_h$ regions for both 2017 and 2018 data. As a result, no VLL masses are excluded at the 95% confidence level and limits are set between 10 and 30 fb, depending on the VLL mass hypothesis. The observed excess is consistent with the presence of VLLs in the context of the 4321 model, and the excess of events over the background-only hypothesis corresponds to a significance of 2.8$\sigma$.