

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

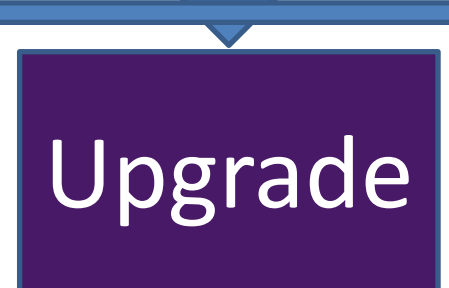
**Spokesperson of the LHCb Collaboration
Covering all LHC Collaborations**



LHC Experiment Cycle



**Completed
~2008
Take Data
Analyse Data**



- **First decade of Operations**
 - 1000 papers/expt !
- **Major Upgrades**
 - Upgrade 1, & later 2
 - Now and later in decade

Upgrade I: ATLAS & CMS



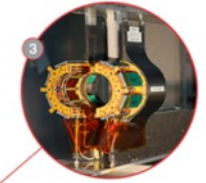
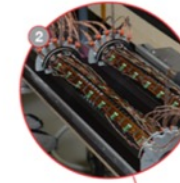
BEAM PIPE

Replaced with an entirely new one compatible with the future tracker upgrade for HL-LHC, improving the vacuum and reducing activation.



PIXEL TRACKER

All-new innermost barrel pixel layer, in addition to maintenance and repair work and other upgrades.



BRIL

New generation of detectors for monitoring LHC beam conditions and luminosity.



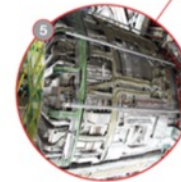
CATHODE STRIP CHAMBERS (CSC)

Read-out electronics upgraded on all the 180 CSC muon chambers allowing performance to be maintained in HL-LHC conditions.



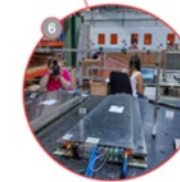
HADRON CALORIMETER

New on-detector electronics installed to reduce noise and improve energy measurement in the calorimeter.



SOLENOID MAGNET

New powering system to prevent full power cycles in the event of powering problems, saving valuable time for physics during collisions and extending the magnet lifetime.



GAS ELECTRON MULTIPLIER (GEM) DETECTORS

An entire new station of detectors installed in the endcap-muon system to provide precise muon tracking despite higher particle rates of HL-LHC.

ATLAS UK:

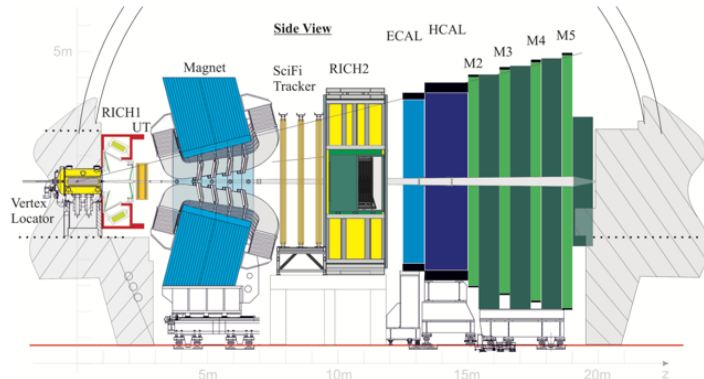
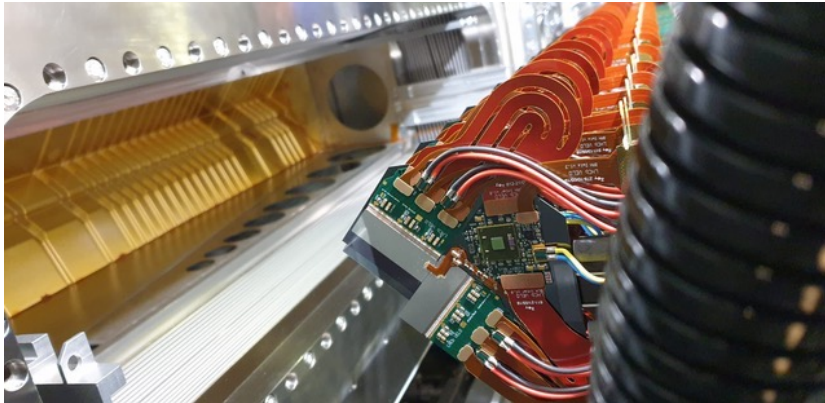
- Calorimeter Trigger upgrade
- High-Level Trigger software

CMS UK:

- Trigger & data acquisition system
- **Major Upgrades for LS3 in 2025**

Upgrade I: LHCb

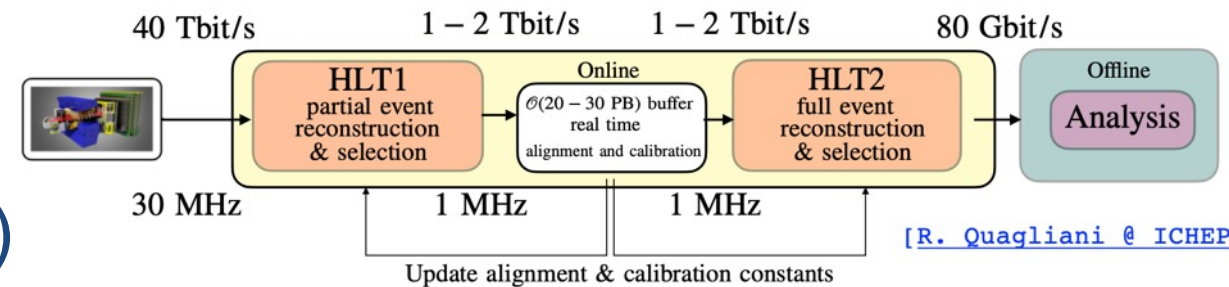
- Largest CERN particle physics detector project since completion of LHC
- Completed on budget and *near* schedule



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

LHCb UK lead contribution to:

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



ALICE Upgrade for Run 3

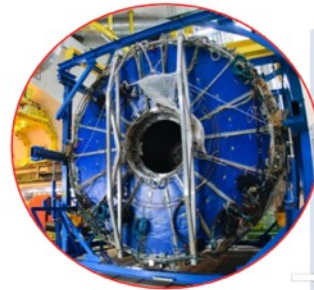
> Improve tracking resolution at low p_T

x50 statistics increase for most observables

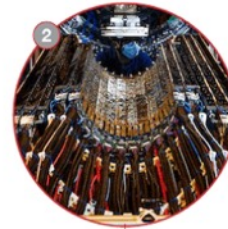


Run 3+4: **13 nb⁻¹ Pb-Pb**
50 kHz (Pb-Pb), ≈ 1 MHz (pp)
online reconstruction
all events to storage!

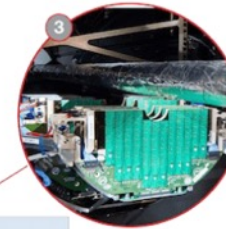
New GEM-based TPC
with continuous readout



New Inner Tracking System (ITS)
– 7 barrels, 10 m² silicon tracker based on MAPS (12.5 G pixels)



New Muon Forward Tracker (MFT) - 5 disks based on MAPS

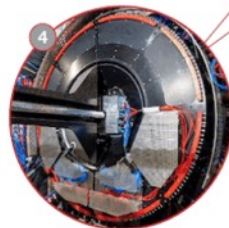


New Trigger and Readout
Upgrade of readout electronics of all detector, new Central Trigger Processor



New Online/Offline (O2)

New Fast Interaction Trigger (FIT)
– 3 detector technologies: interaction trigger, online luminometer, forward multiplicity



New Beampipe
smaller diameter (36.4 mm), first detection layer at 20 mm

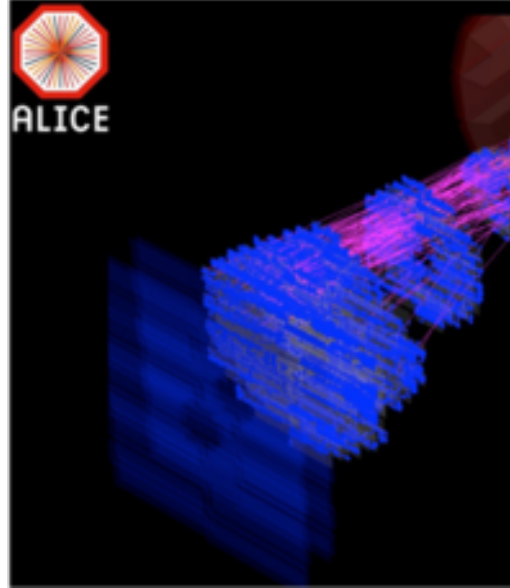
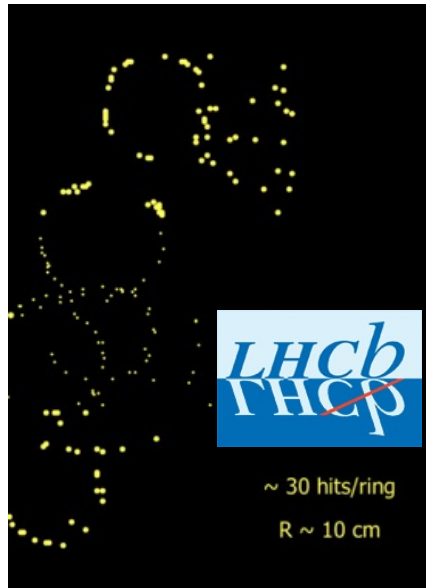
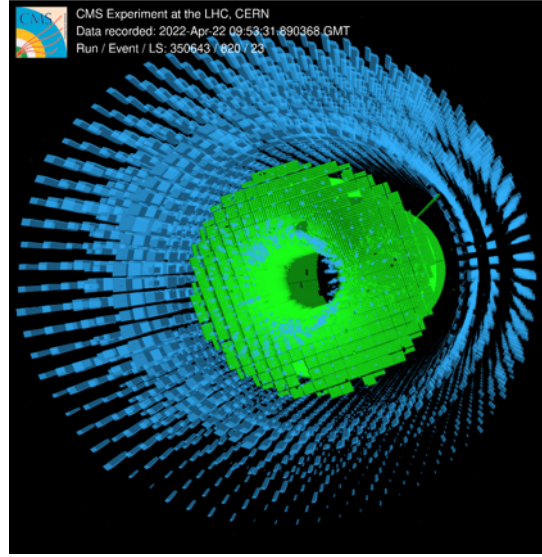
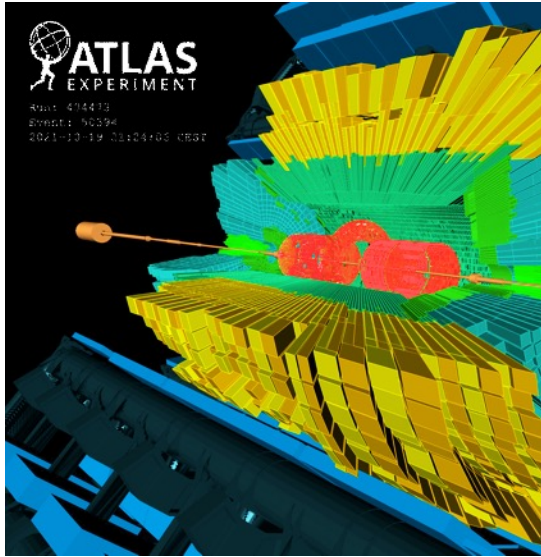


ALICE UK:

- Inner Tracking System
- Central Trigger Processor

Commissioning underway

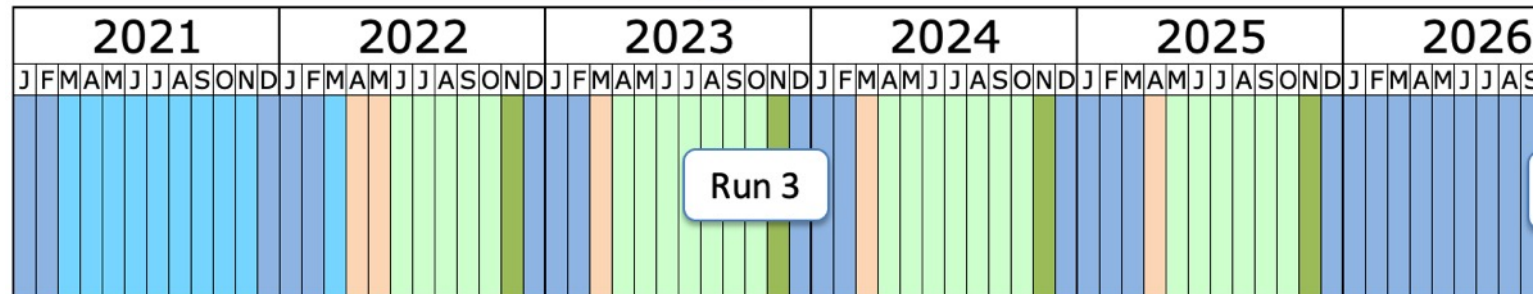
Start of LHC Run 3



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

5th July 2022

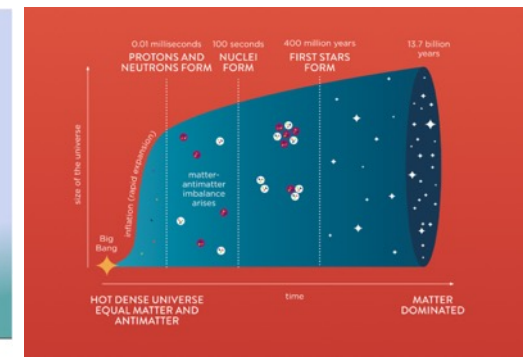
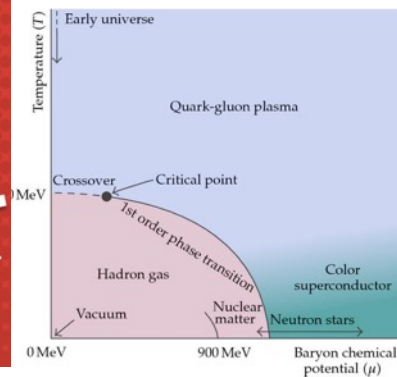
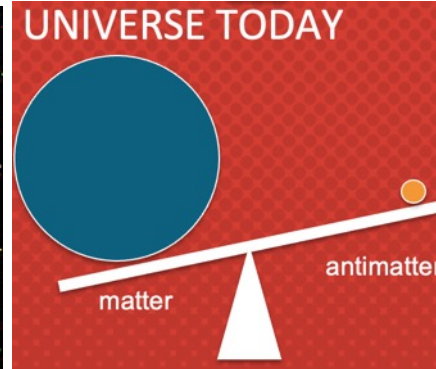
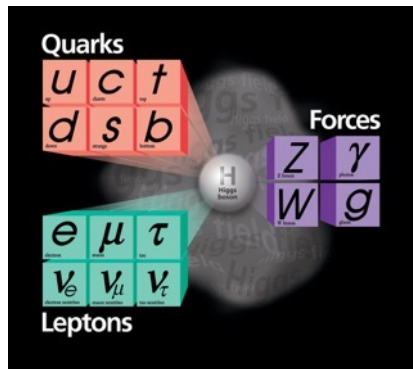
■ Shutdown/Technical stop
■ Protons physics
■ Ions
■ Commissioning with beam
■ Hardware commissioning/magnet training



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



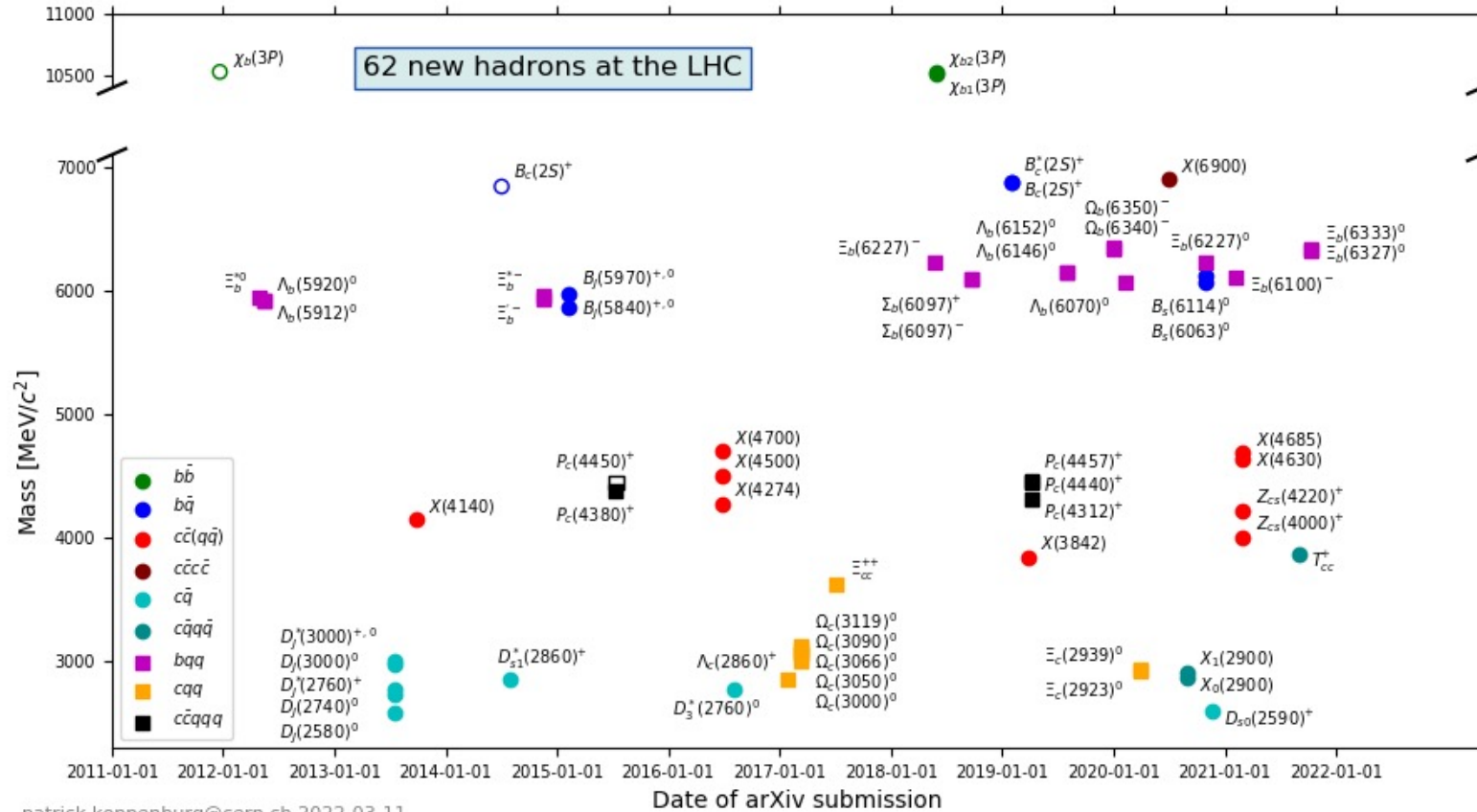
One step at a time.....



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

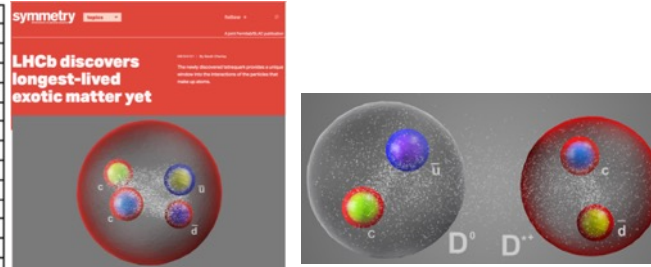
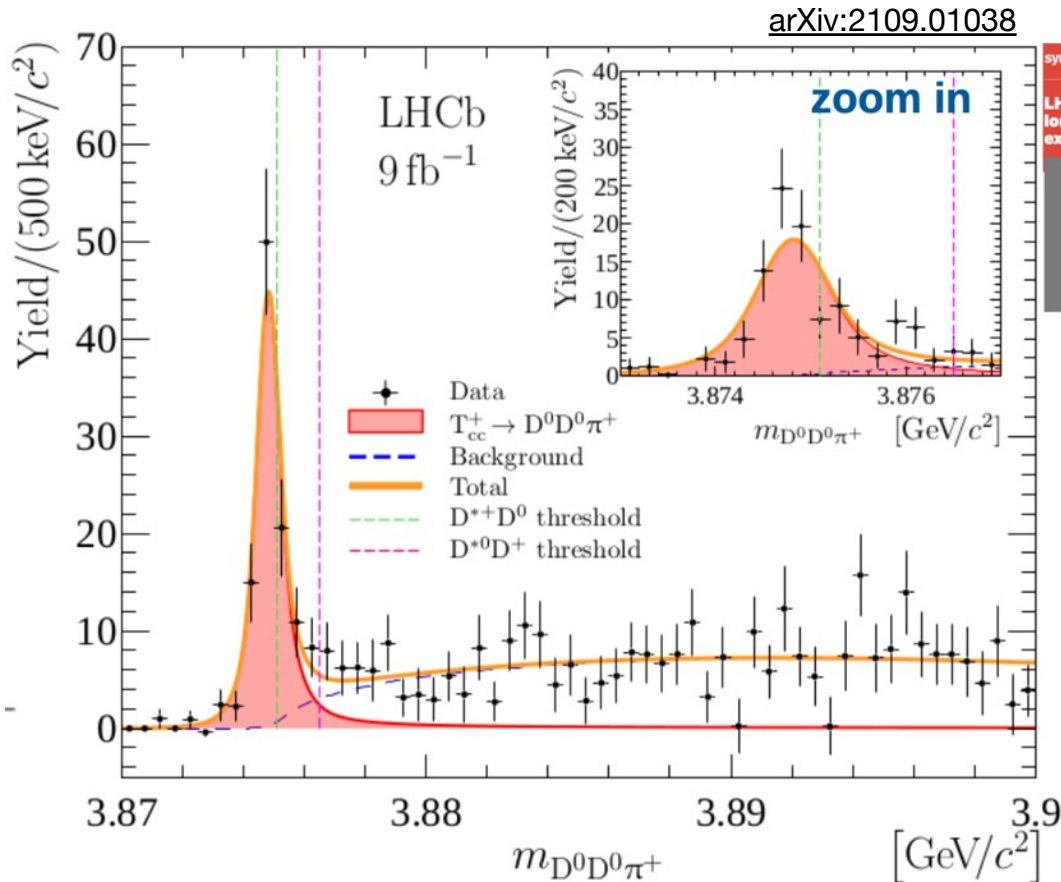
Beyond the proton : Exotic Hadrons

- 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

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



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

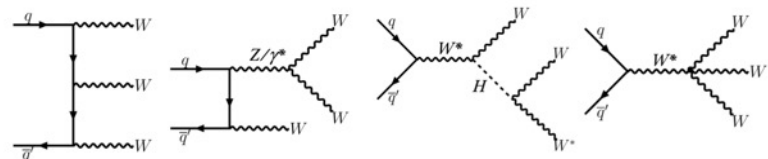
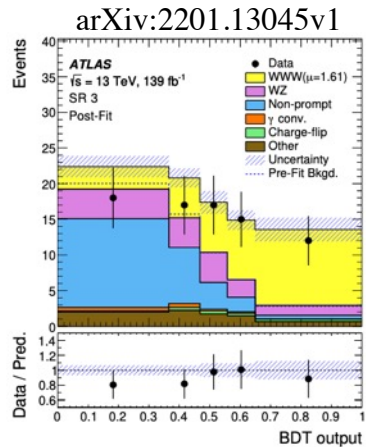
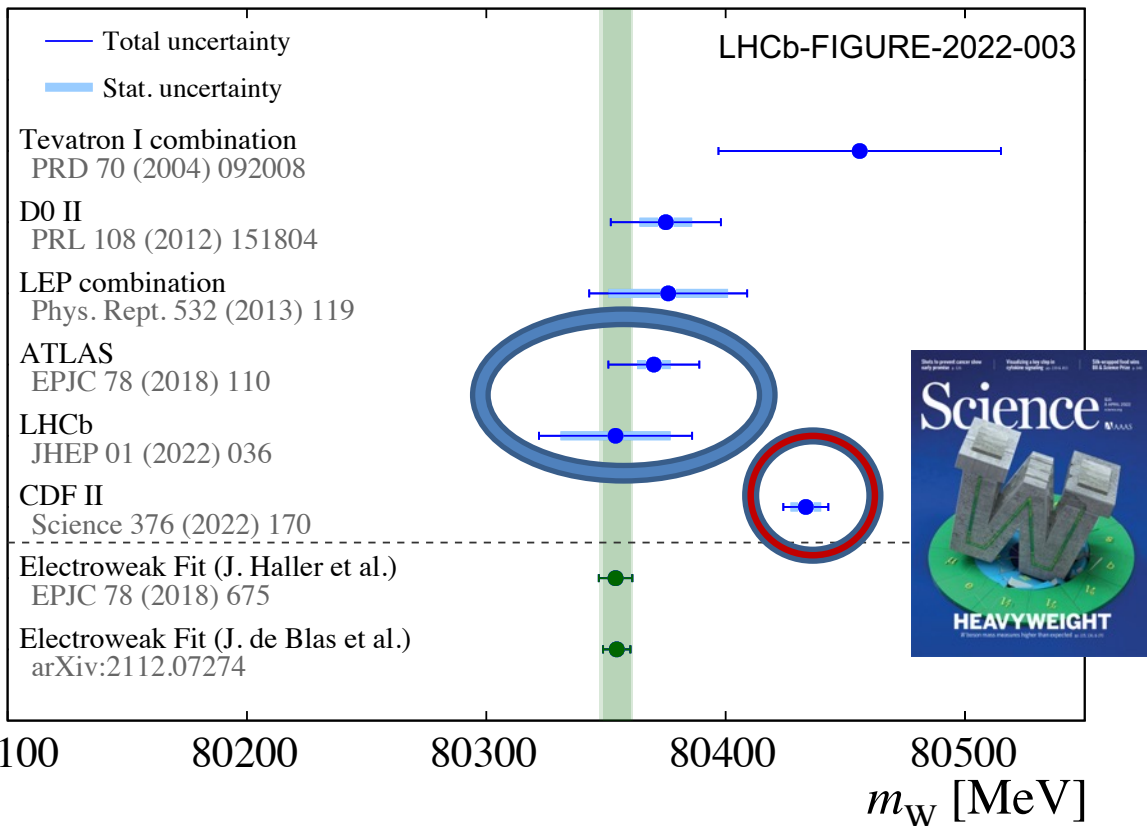
- Particles made of quarks – hadrons
 - 2 quarks (π, K...)
 - 3 quarks (p, n...)
- New states of matter
 - 4: Tetraquarks
 - 5: Pentaquarks

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

Precision measurements: W & top

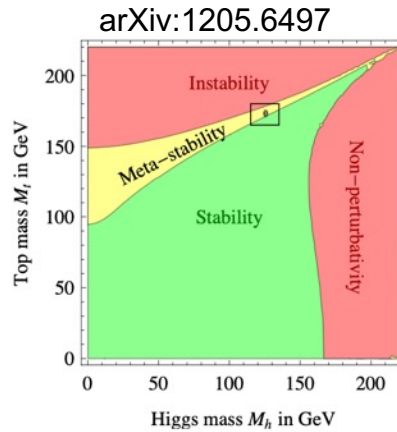


- Weak Force carriers, heaviest quark, Higgs boson related by theory



- WWW discovered (not the T. Berners-Lee variety)

Top Quark



ATLAS+CMS Preliminary
LHCtopWG

m_{top} summary, $\sqrt{s} = 7-13$ TeV March 2022

Experiment	m_{top} [GeV]	Ref.
World comb. (Mar 2014) [2]	$173.29 \pm 0.85 (0.35 \pm 0.88)$	7 TeV [1]
LHC comb. (Sep 2013) LHCtopWG	$173.34 \pm 0.76 (0.36 \pm 0.67)$	1.96-7 TeV [2]
ATLAS, l+jets	$172.33 \pm 1.27 (0.75 \pm 1.02)$	7 TeV [3]
ATLAS, dilepton	$173.79 \pm 1.41 (0.54 \pm 1.30)$	7 TeV [3]
ATLAS, all jets	$175.1 \pm 1.8 (1.4 \pm 1.2)$	7 TeV [4]
ATLAS, single top	$172.2 \pm 2.1 (0.7 \pm 2.0)$	8 TeV [5]
ATLAS, dilepton	$172.99 \pm 0.85 (0.41 \pm 0.74)$	8 TeV [6]
ATLAS, all jets	$173.72 \pm 1.15 (0.55 \pm 1.01)$	8 TeV [7]
ATLAS, l+jets	$172.08 \pm 0.91 (0.39 \pm 0.82)$	8 TeV [8]
ATLAS comb. (Oct 2018)	$172.69 \pm 0.48 (0.25 \pm 0.41)$	7-8 TeV [8]
ATLAS, leptonic invariant mass (*)	$174.48 \pm 0.78 (0.40 \pm 0.67)$	13 TeV [9]
CMS, l+jets	$173.49 \pm 1.06 (0.43 \pm 0.97)$	7 TeV [10]
CMS, dilepton	$172.50 \pm 1.52 (0.43 \pm 1.46)$	7 TeV [11]
CMS, all jets	$173.49 \pm 1.41 (0.69 \pm 1.23)$	7 TeV [12]
CMS, l+jets	$172.35 \pm 0.51 (0.16 \pm 0.48)$	8 TeV [13]
CMS, dilepton	$172.82 \pm 1.23 (0.19 \pm 1.22)$	8 TeV [13]
CMS, all jets	$172.32 \pm 0.64 (0.25 \pm 0.59)$	8 TeV [13]
CMS, single top	$172.95 \pm 1.22 (0.77 \pm 0.95)$	8 TeV [14]
CMS comb. (Sep 2015)	$172.44 \pm 0.48 (0.13 \pm 0.47)$	7-8 TeV [13]
CMS, l+jets	$172.25 \pm 0.83 (0.08 \pm 0.62)$	13 TeV [15]
CMS, dilepton	$172.33 \pm 0.70 (0.14 \pm 0.69)$	13 TeV [16]
CMS, all jets	$172.34 \pm 0.73 (0.20 \pm 0.70)$	13 TeV [17]
CMS, single top	$172.13 \pm 0.77 (0.32 \pm 0.70)$	13 TeV [18]
CMS, boosted jet mass	$172.6 \pm 2.5 (0.4 \pm 2.4)$	13 TeV [19]

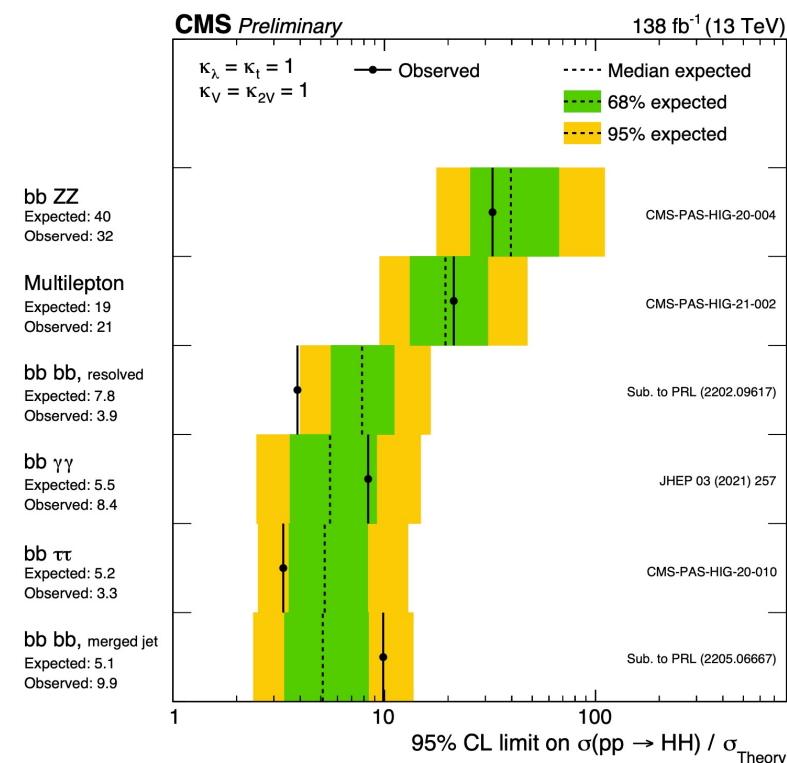
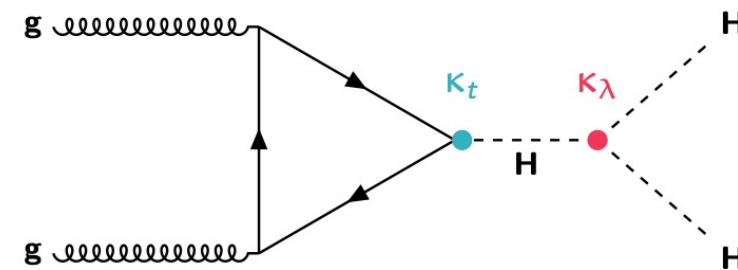
* Preliminary

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

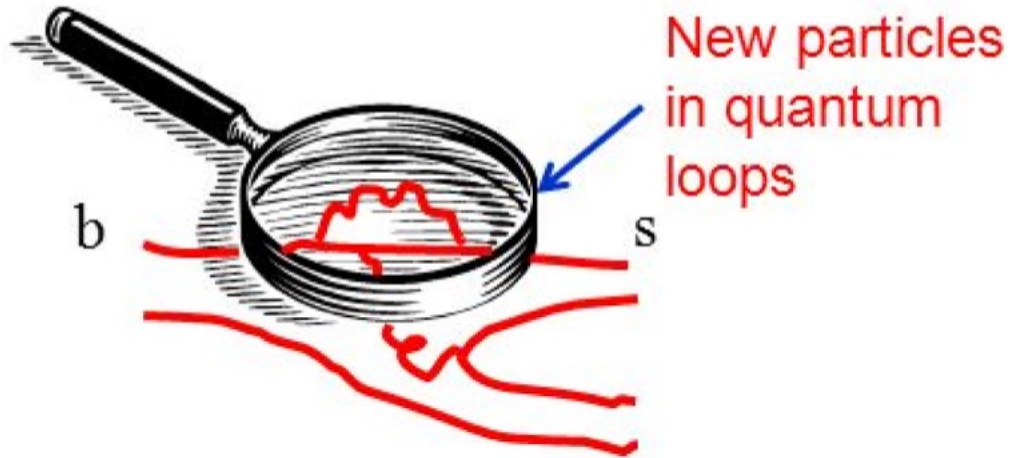
Higgs self-coupling

- 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

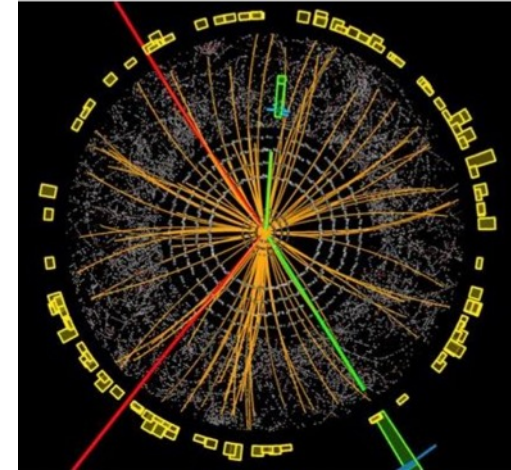
Run 3: Close to probing this new type of fundamental interaction ?



Indirect

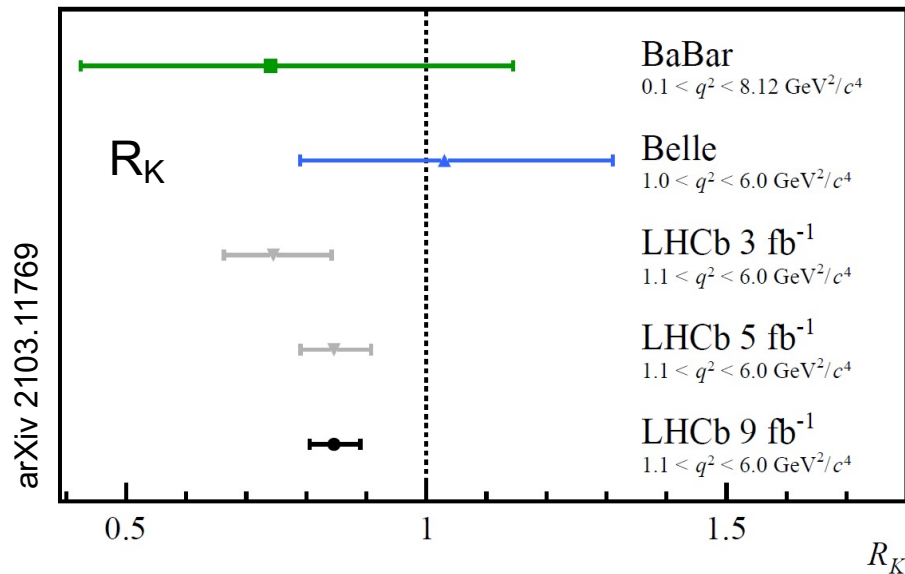


Direct



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

Indirect



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

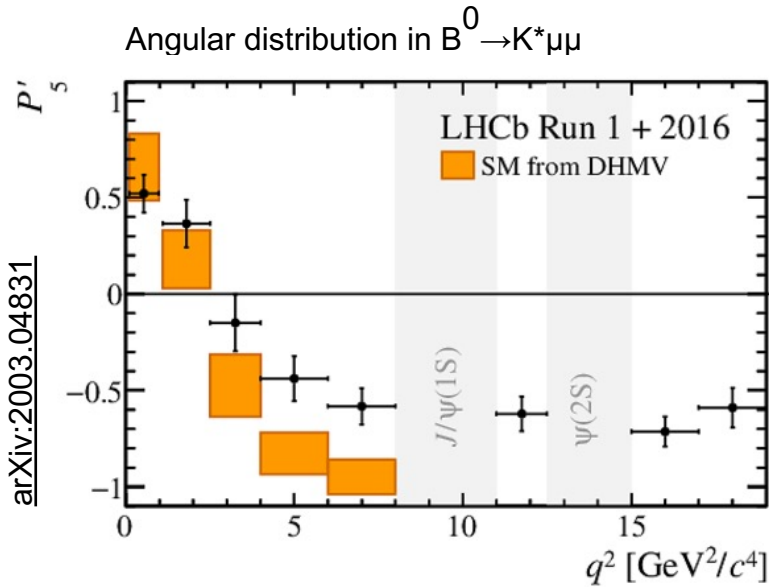
Direct

		Local(global)	m
CMS	$W' \rightarrow WZ$	3.6 (2.3) σ	2.1 & 2.9 TeV
ATLAS	$H_5' \rightarrow WZ$	2.8 (1.6) σ	350 GeV
CMS	$S \rightarrow XX \rightarrow (jj)(jj)$ $X \rightarrow (jj)$	3.9 (1.6) σ 3.6 (2.5) σ	8.5 TeV 1 TeV
CMS	$L_\nu L_\nu \rightarrow 4b2\tau$	2.8 σ	600 GeV
ATLAS	$X \rightarrow HH \rightarrow 4b$ $X \rightarrow HH \rightarrow 2b2\tau$	3.2 σ 3.1 σ	1 TeV
CMS	$\phi \rightarrow \tau\tau$	3.1 (2.7) σ 2.8 (2.4) σ	100 GeV 1.2 TeV
CMS	$H \rightarrow WW$ (VBF)	3.8 (2.6) σ	650 GeV
ATLAS	Iso track dE/dx	3.6 (3.3) σ	>1 TeV

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

Credit: Niels Tuning

Indirect - Intensity



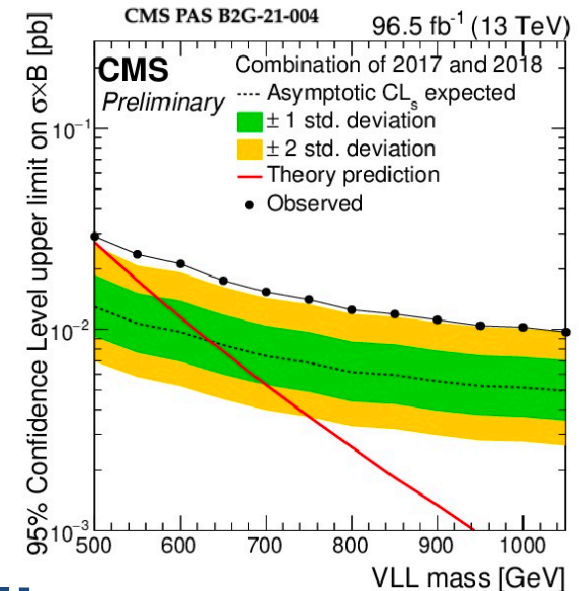
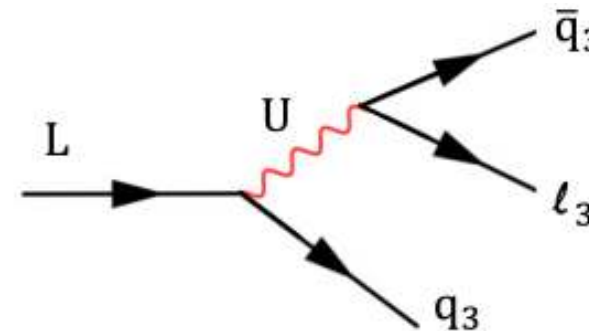
- Lepton flavour universality
- Intriguing pattern of anomalies in several b-decays

– Ratios, Rates, Angular distributions

- Run3: Statistics to understand the anomalies

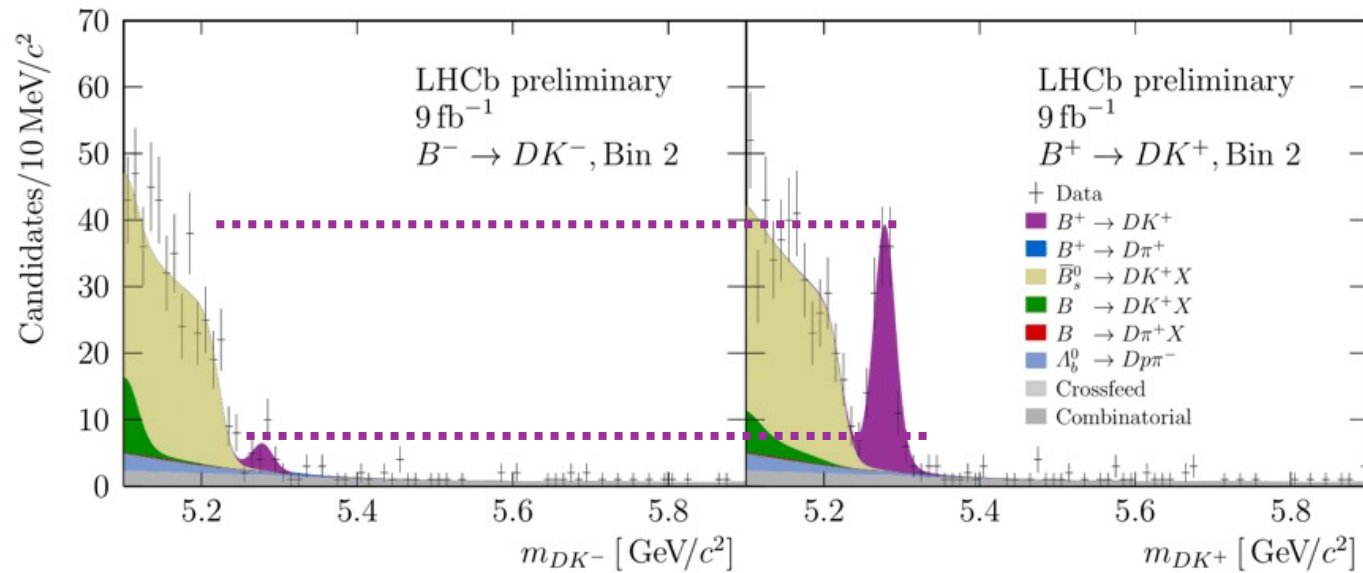
Direct - Energy

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

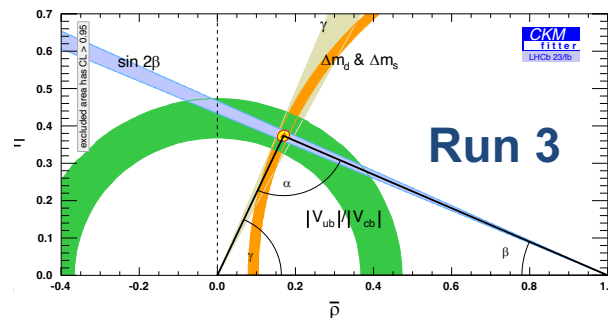
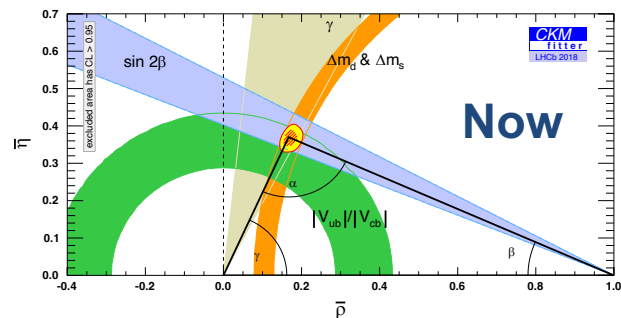


Matter Antimatter asymmetries

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

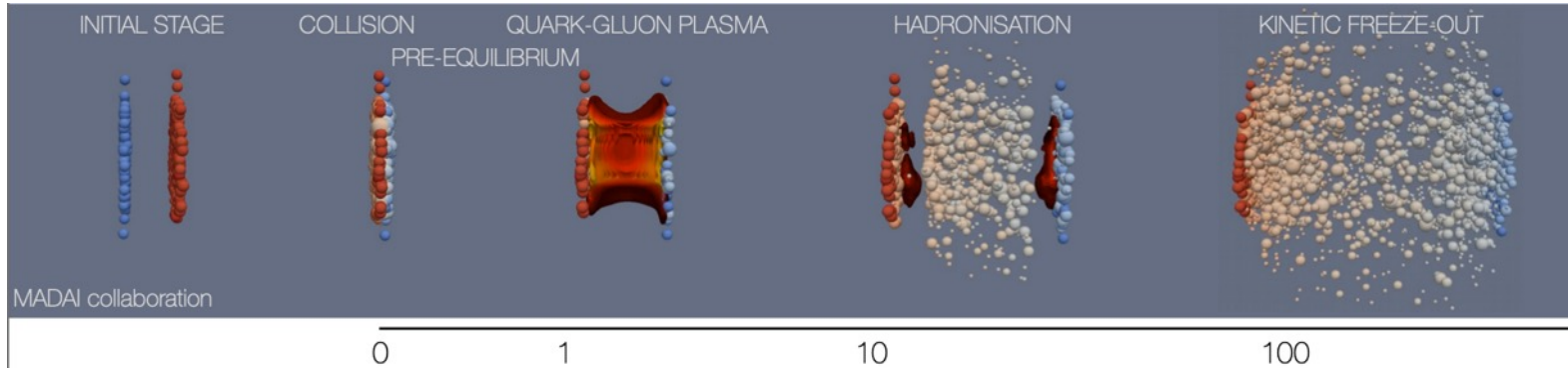


- **Largest difference ever !**
- 85% asymmetry
- 12 times more B^- than B^+ decays this way

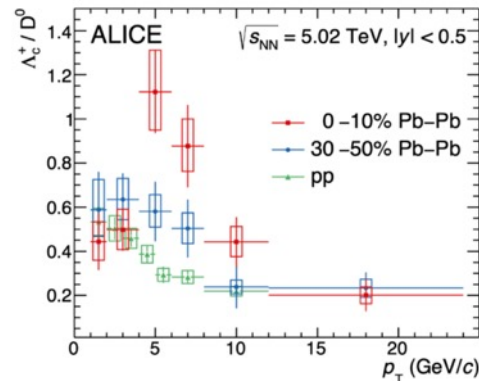
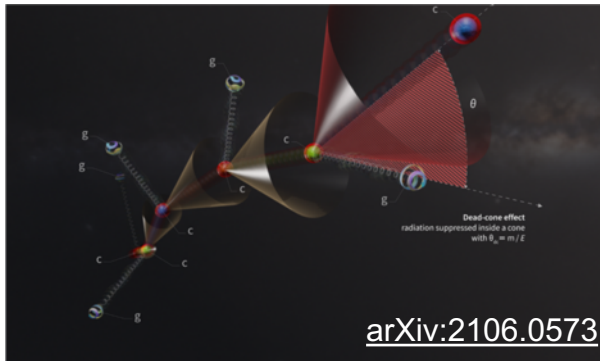


- **Run3: Push toward % level determination (CKM angle γ)**

Understanding the strong force: Lead ions and p



- Understanding particle formation from quarks

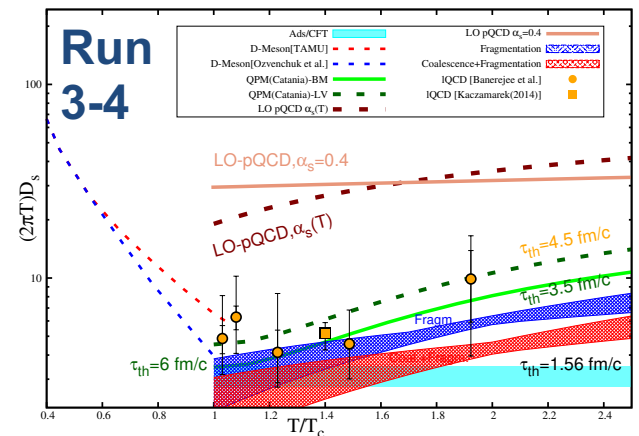
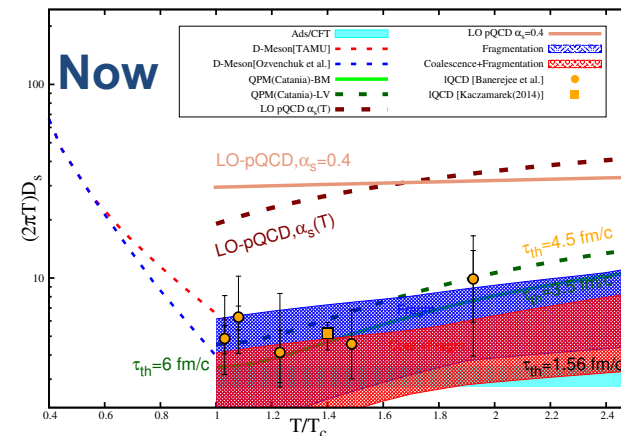


- Radiation from quarks (QCD dead cone)
- 3-quark & 2-quark state formation

- Run 3: Upgraded ALICE will explore quark gluon plasma

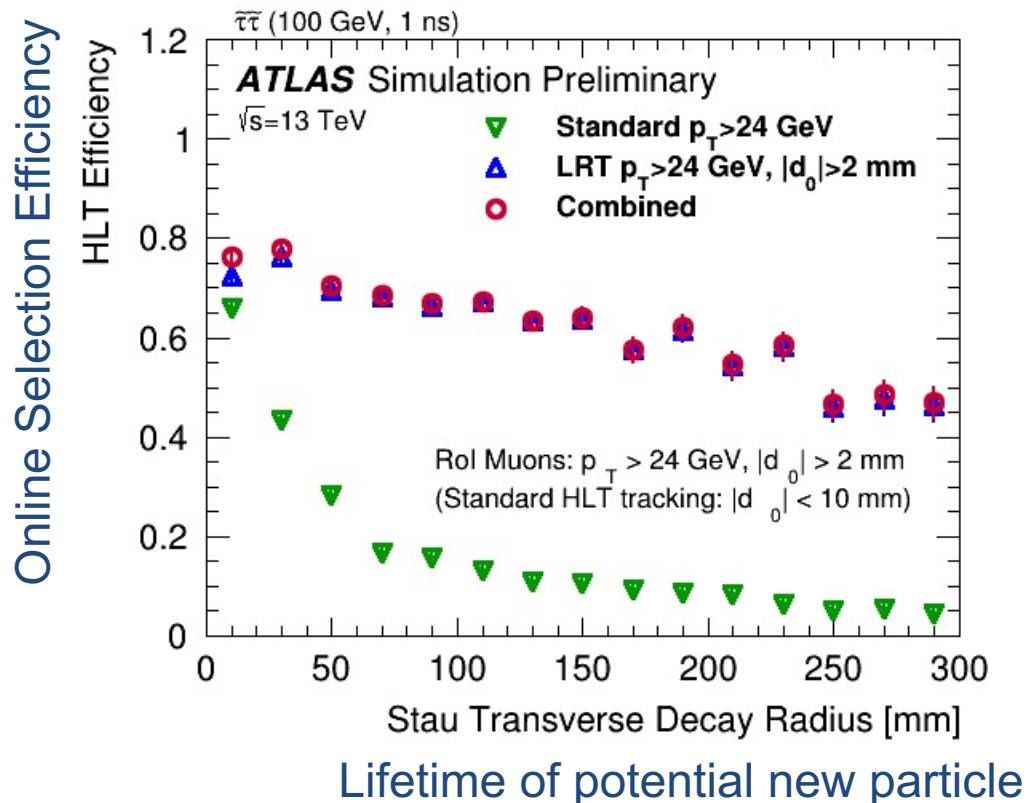
Interaction charm quarks with QGP

arXiv:1812.06772

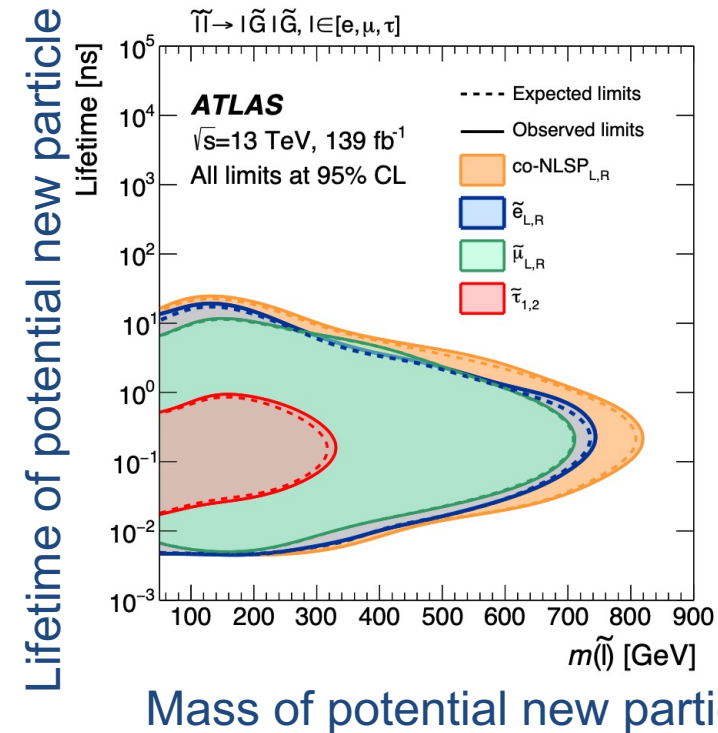


Long-lived Particles: dark sector ?

- 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



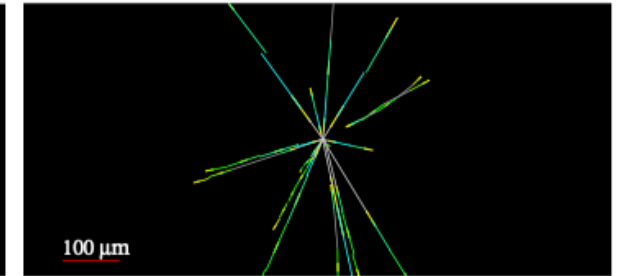
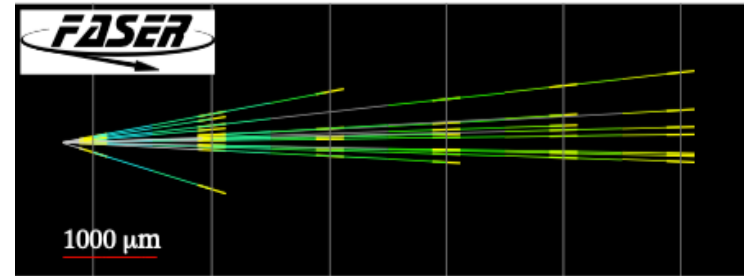
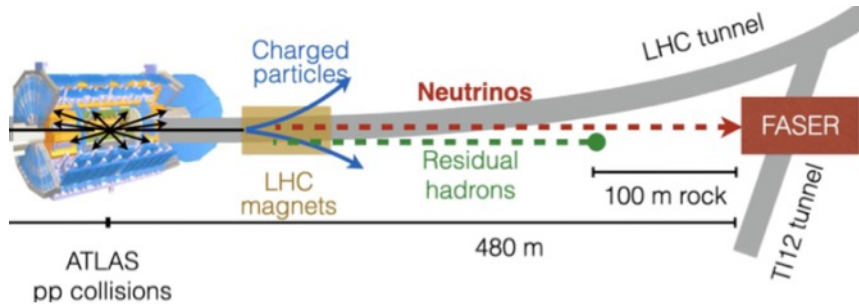
Physical Review Letters 127, 051802 (2021)



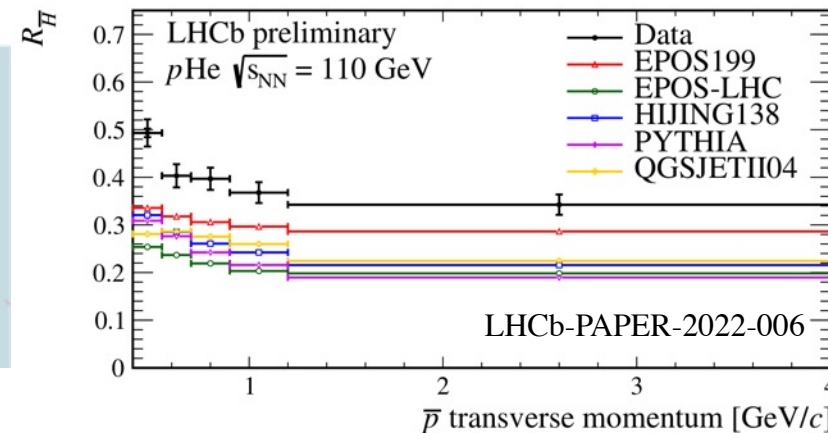
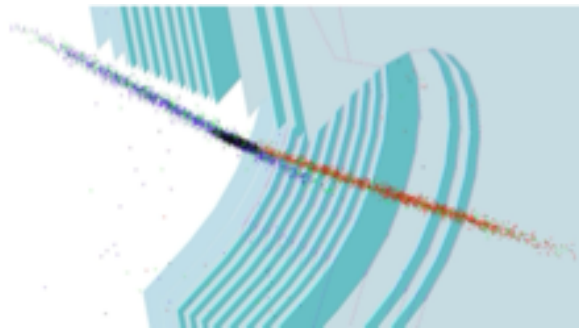
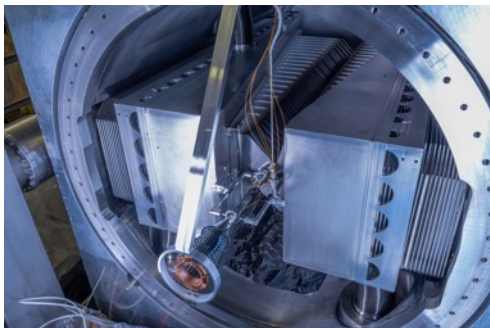
Lots of unexplored space outside these bands!

- 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



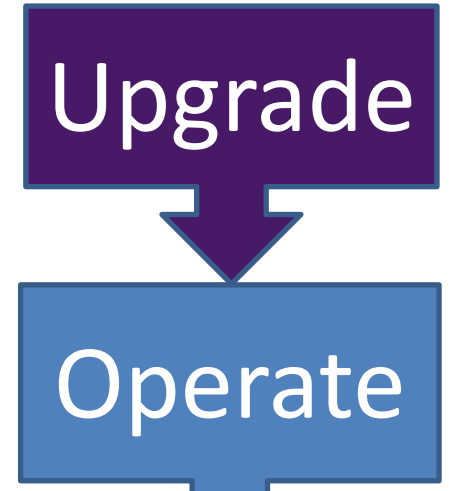
- SMOG @ LHCb – collide protons & gas (He, Ne, Kr, Ar, Xe..)
- **Run 3: Understand cosmic ray interactions, dark matter searches**

Summary: LHC Run 3 Opportunities

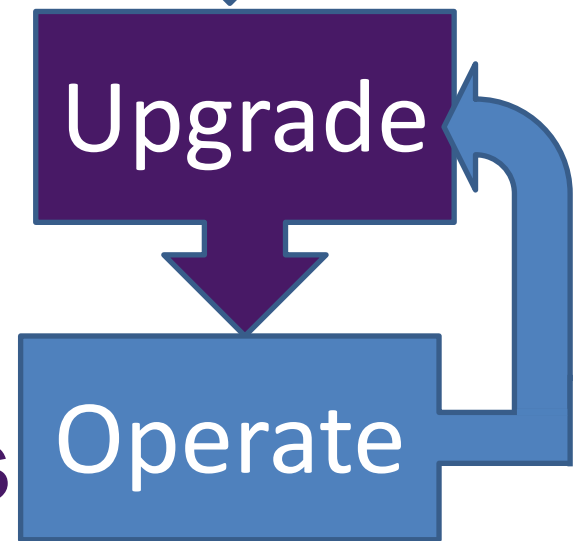


- Run 3 *same* but *different*
- Technology enhancements
- Very **broad** physics programme
- LHC makes discoveries weekly
 - Many of examples here from last months
- **Looking forward to 2000 papers/expt !**

**Completed
2022
Take Data
Analyse Data**



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



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

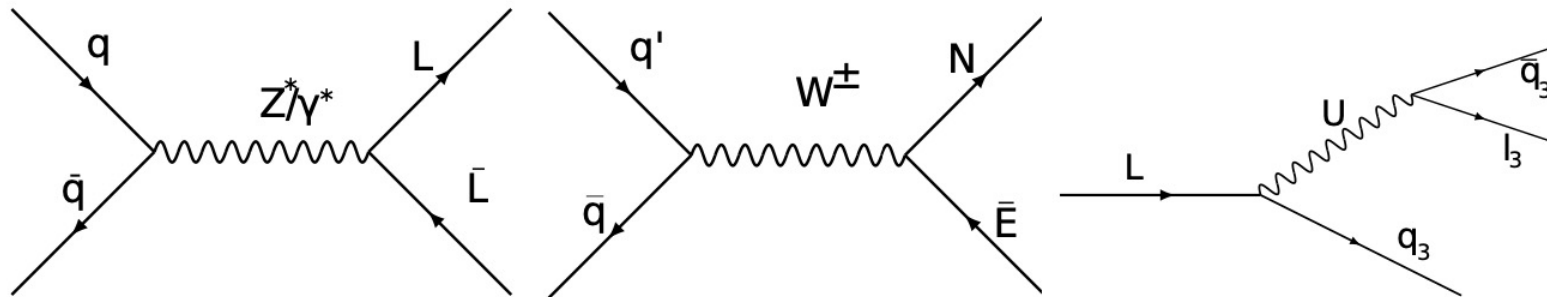
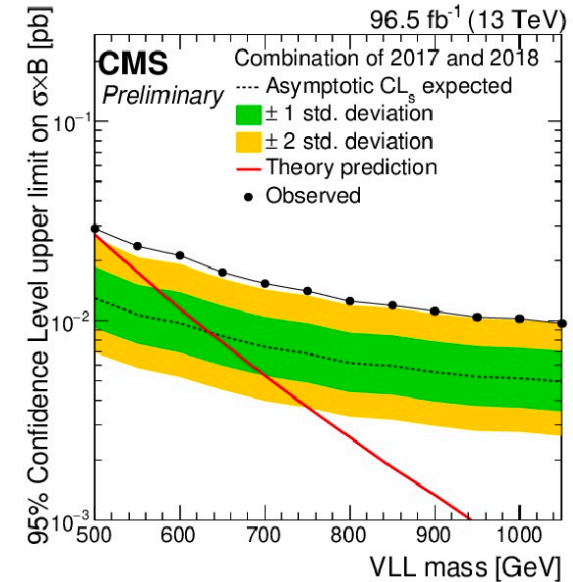


Figure 1: Left and centre: example Feynman diagrams showing production of VLL pairs through s-channel bosons, as expected at the LHC. In these diagrams, L represents either the neutral VLL, N, or the charged VLL, E. Right: vector-like lepton decays proceed through their interactions with the vector leptoquark, 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 2.8σ .