Beyond the Standard Model Physics at the LHC and HL-LHC upgrades

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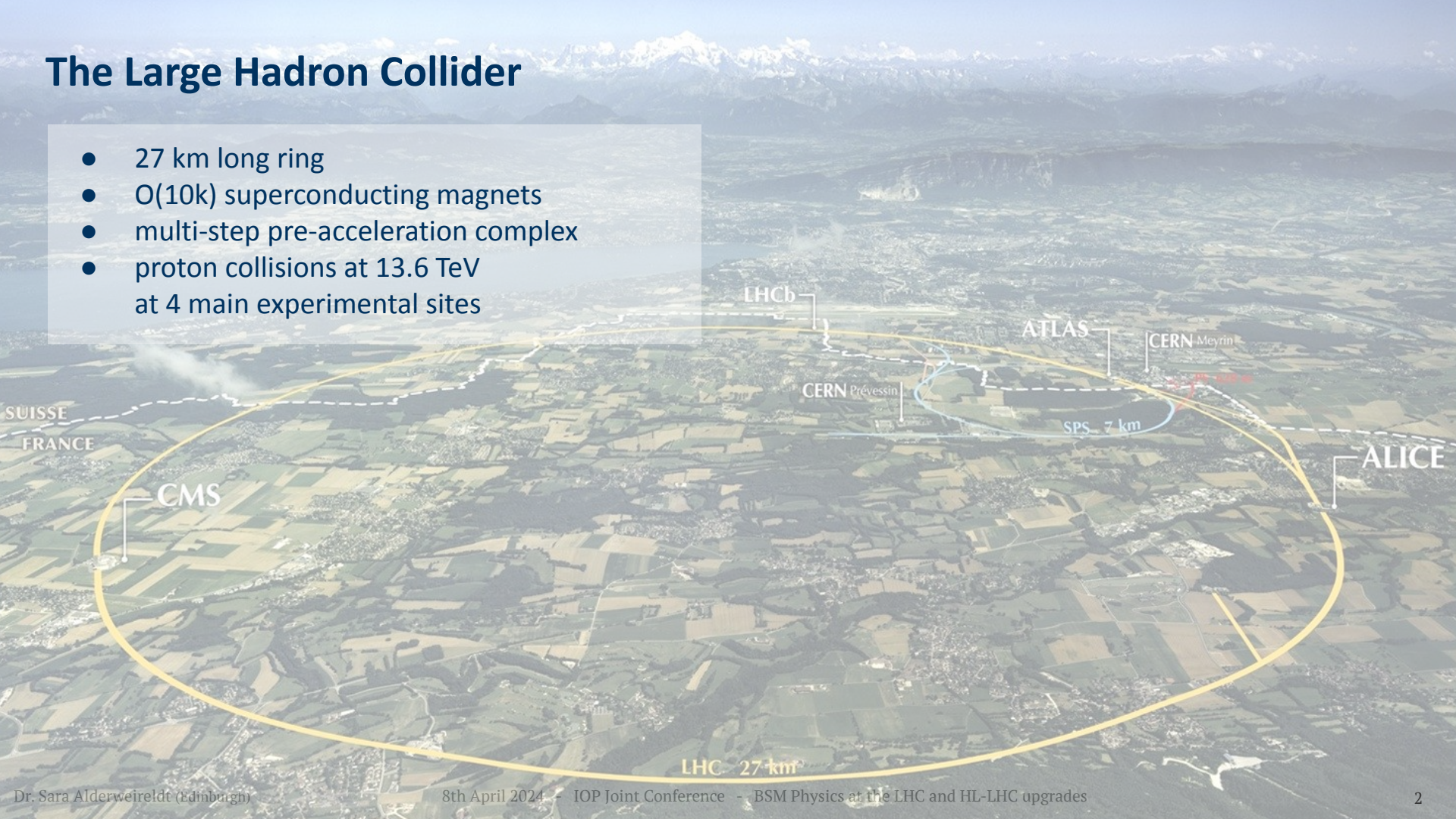
University of Edinburgh

on behalf of many

IOP Joint APP, HEPP and NP
Annual Conference 2024
Liverpool, UK
8-11 April 2024

The Large Hadron Collider

- 27 km long ring
- O(10k) superconducting magnets
- multi-step pre-acceleration complex
- proton collisions at 13.6 TeV
  at 4 main experimental sites



Experiments at the Large Hadron Collider

General purpose experiments ATLAS & CMS

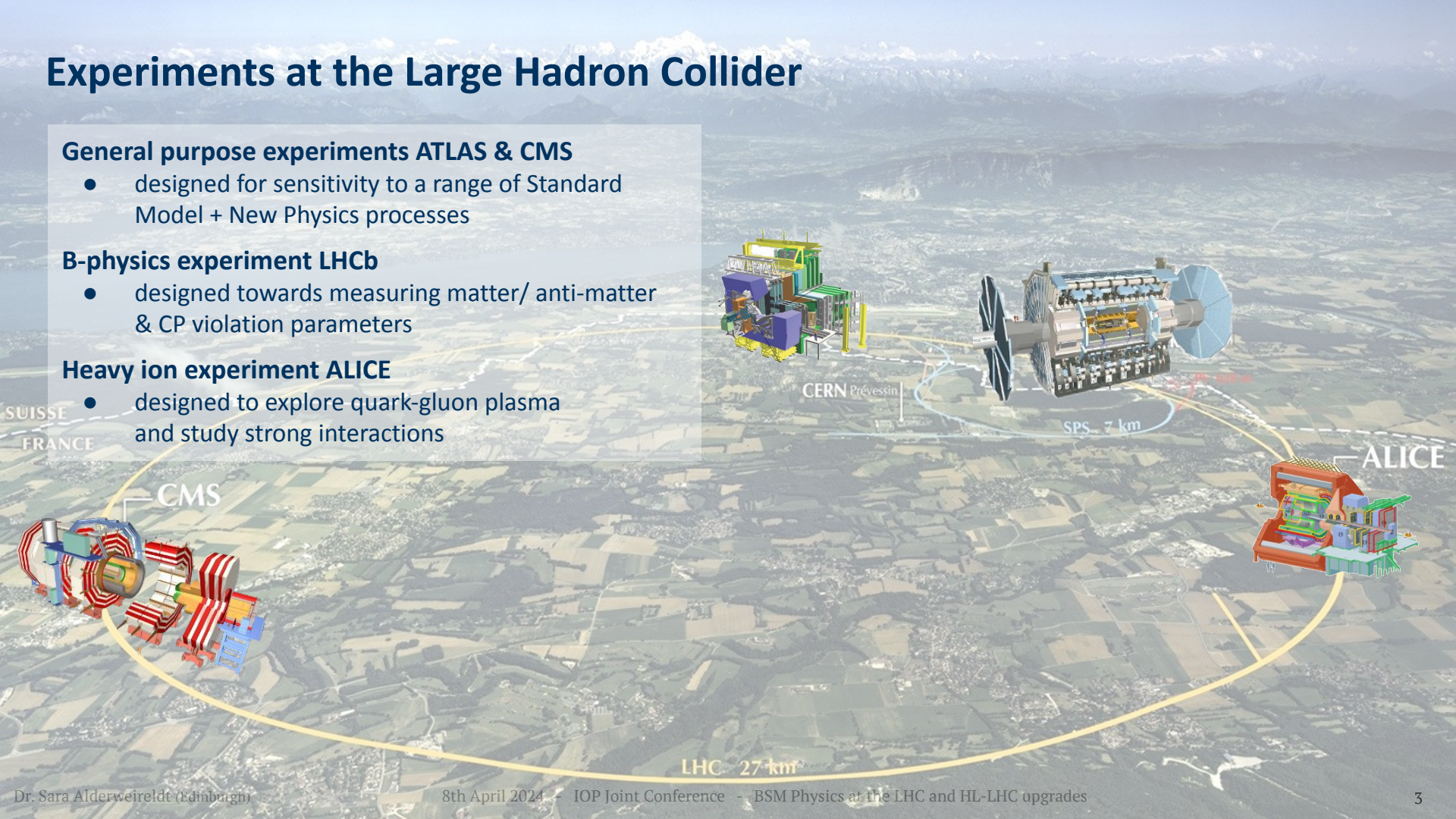
- designed for sensitivity to a range of Standard Model + New Physics processes

B-physics experiment LHCb

- designed towards measuring matter/ anti-matter & CP violation parameters

Heavy ion experiment ALICE

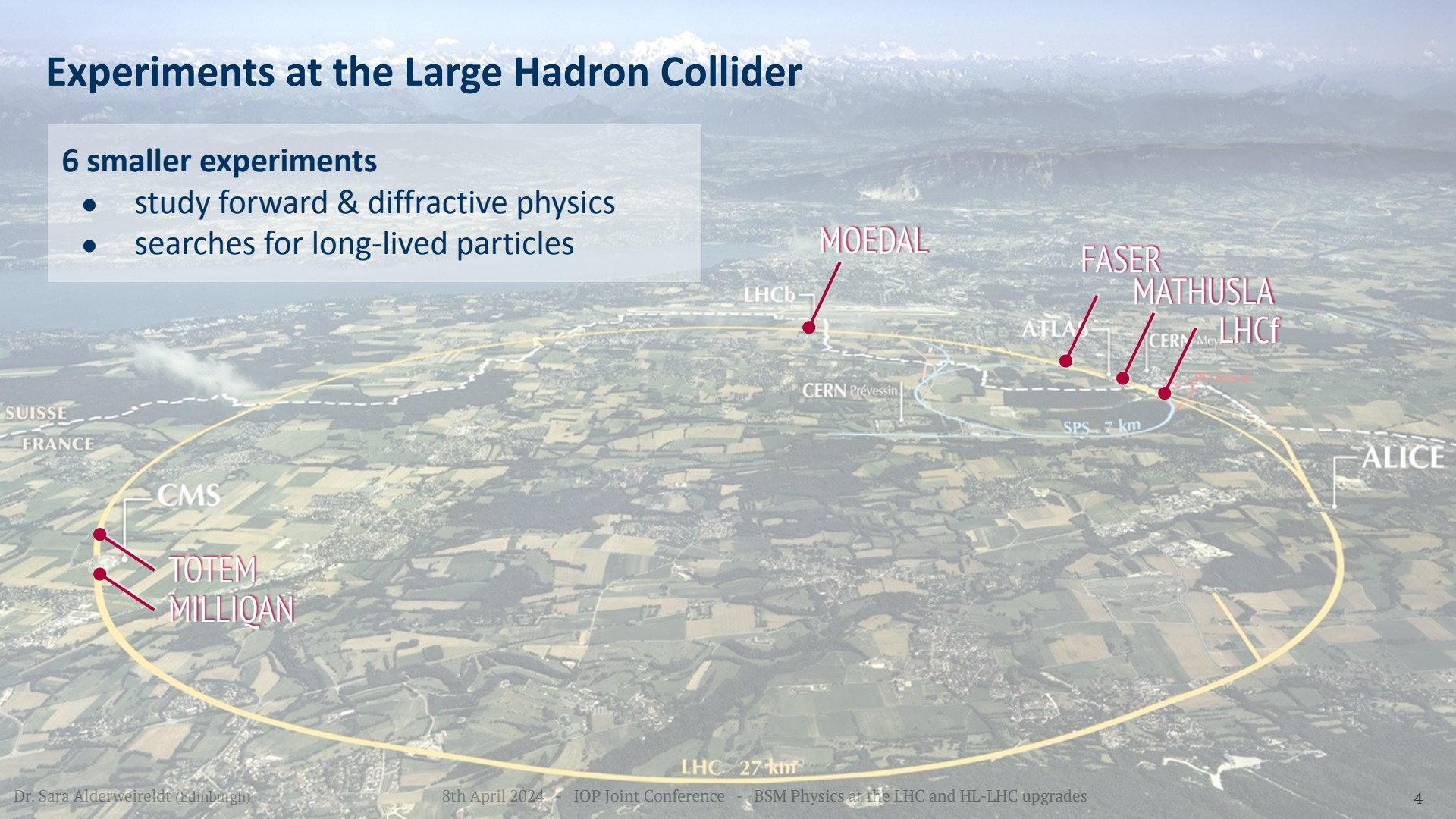
- designed to explore quark-gluon plasma and study strong interactions

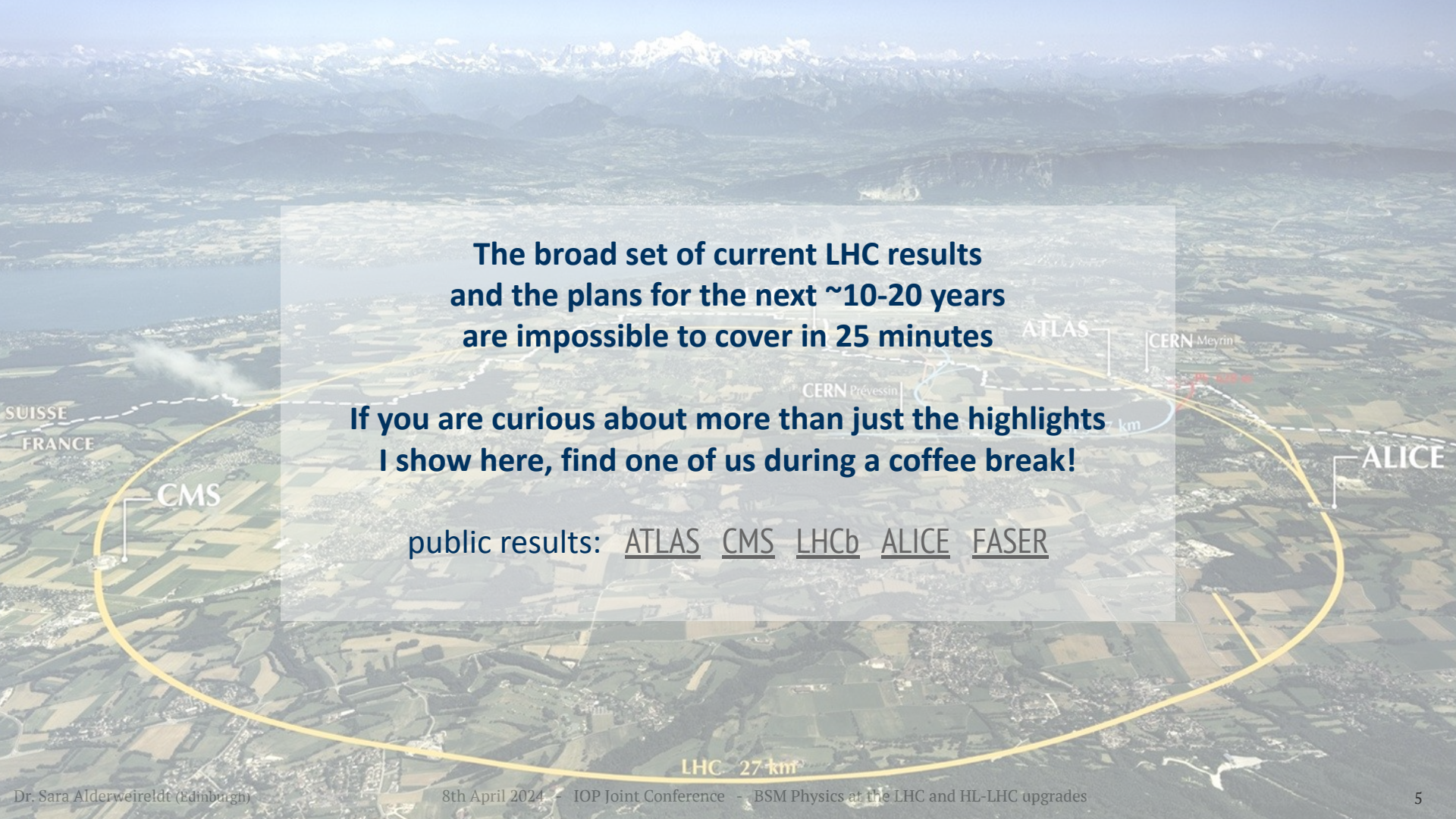


Experiments at the Large Hadron Collider

6 smaller experiments

- study forward & diffractive physics
- searches for long-lived particles



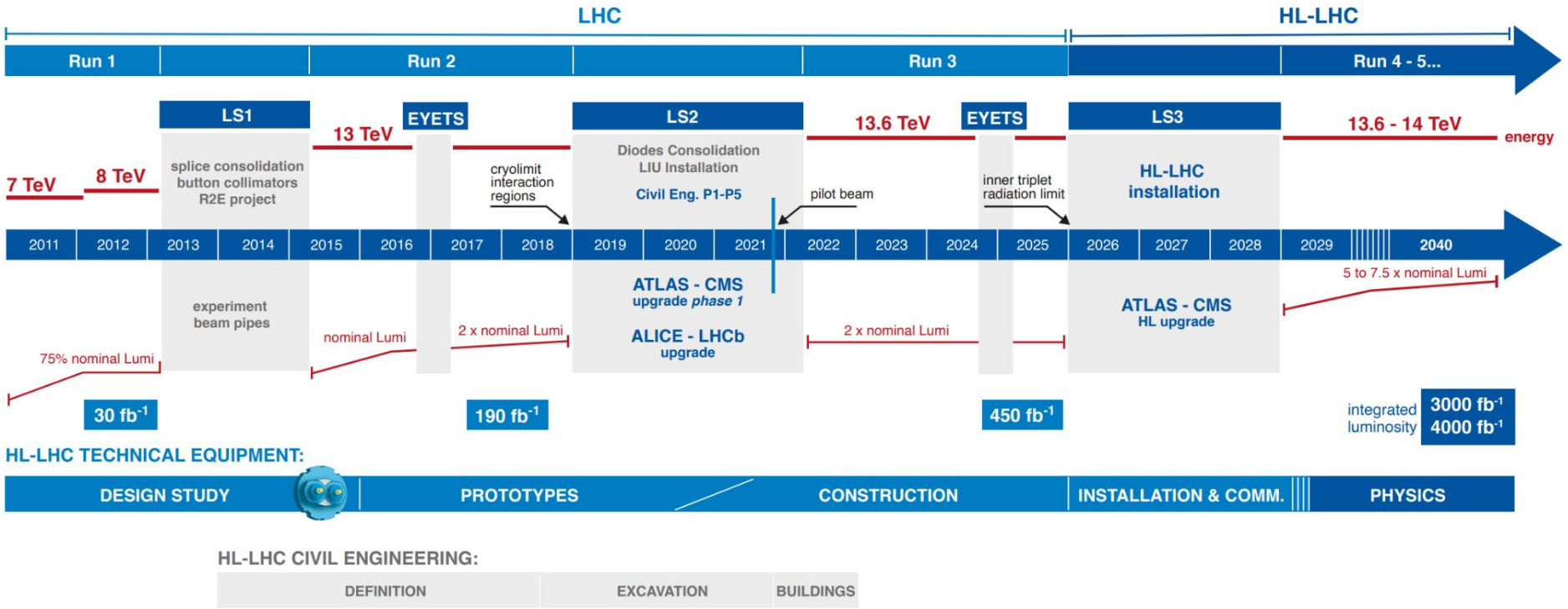


The broad set of current LHC results and the plans for the next ~10-20 years are impossible to cover in 25 minutes

If you are curious about more than just the highlights I show here, find one of us during a coffee break!

public results: ATLAS CMS LHCb ALICE FASER

LHC / HL-LHC TIMELINE



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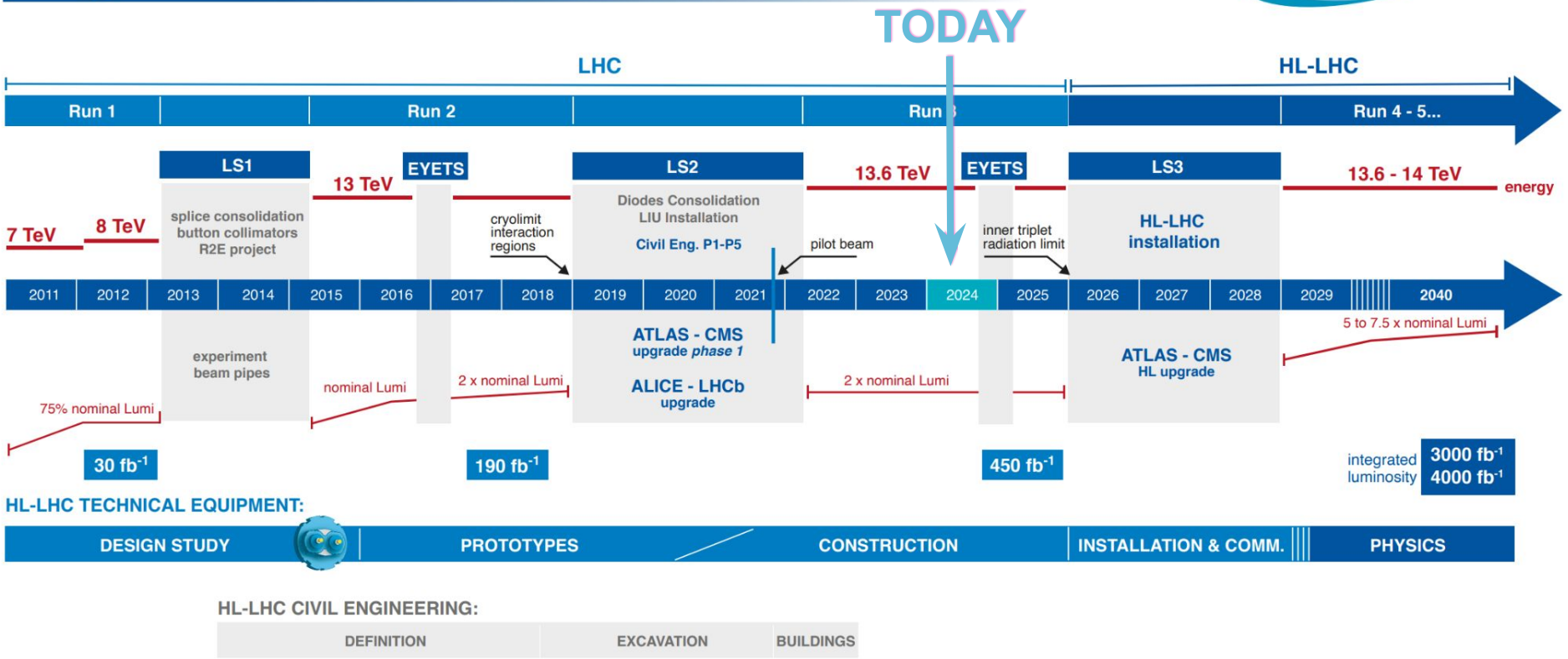

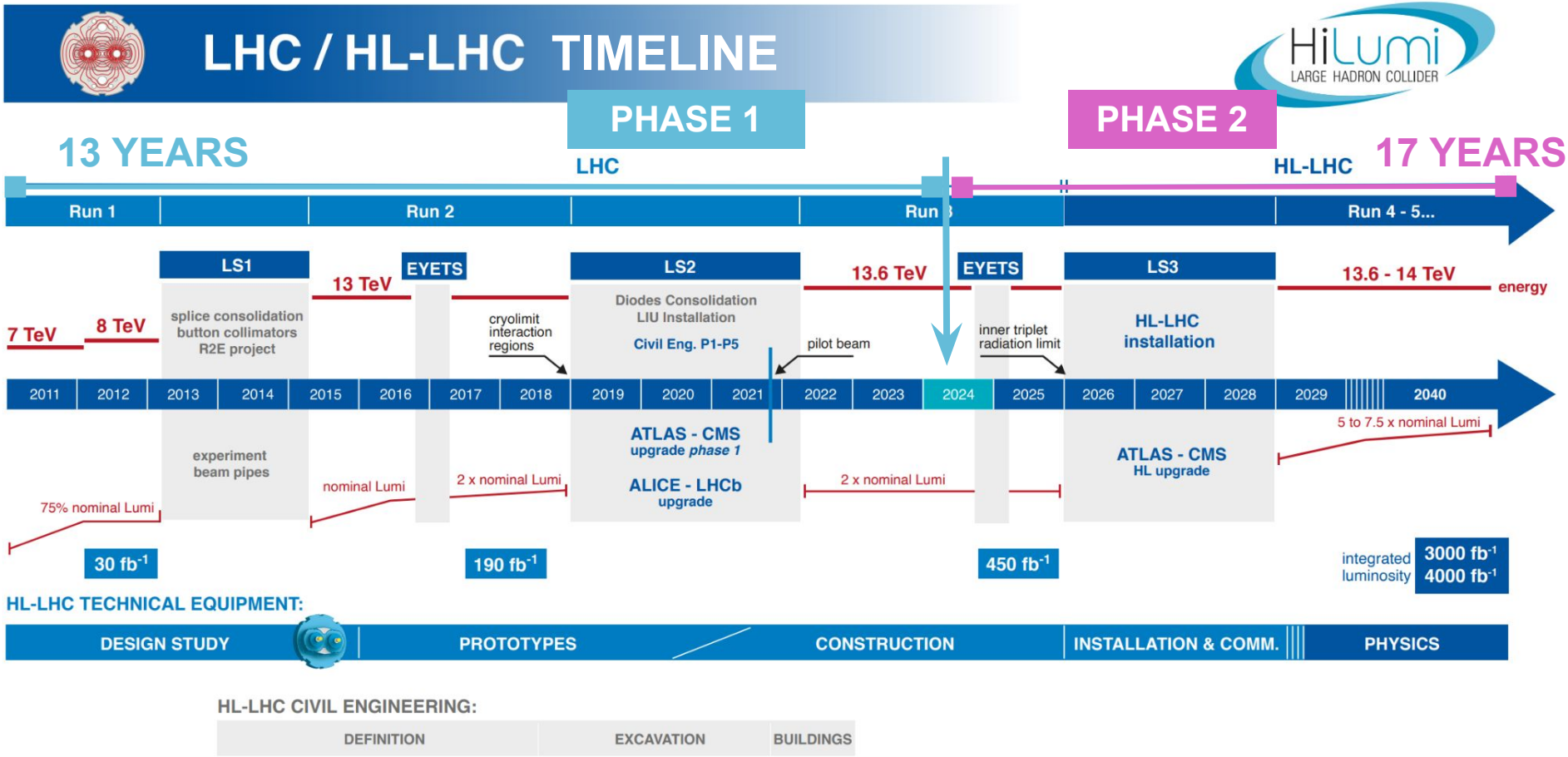
LHC / HL-LHC TIMELINE
HiLumi LARGE HADRON COLLIDER
PHASE 1
PHASE 2
13 YEARS
LHC
HL-LHC
17 YEARS
Run 1
Run 2
Run 3
Run 4 - 5...
LS1
EYETS
LS2
EYETS
LS3
7 TeV
8 TeV
13 TeV
13.6 TeV
13.6 - 14 TeV
energy
splice consolidation
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Diodes Consolidation
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pilot beam
inner triplet
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HL-LHC
installation
2011
2012
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2020
2021
2022
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2024
2025
2026
2027
2028
2029
2040
experiment
beam pipes
ATLAS - CMS
upgrade phase 1
ALICE - LHCb
upgrade
ATLAS - CMS
HL upgrade
5 to 7.5 x nominal Lumi
75% nominal Lumi
nominal Lumi
2 x nominal Lumi
2 x nominal Lumi
30 fb-1
190 fb-1
450 fb-1
integrated
luminosity
3000 fb-1
4000 fb-1
HL-LHC TECHNICAL EQUIPMENT:
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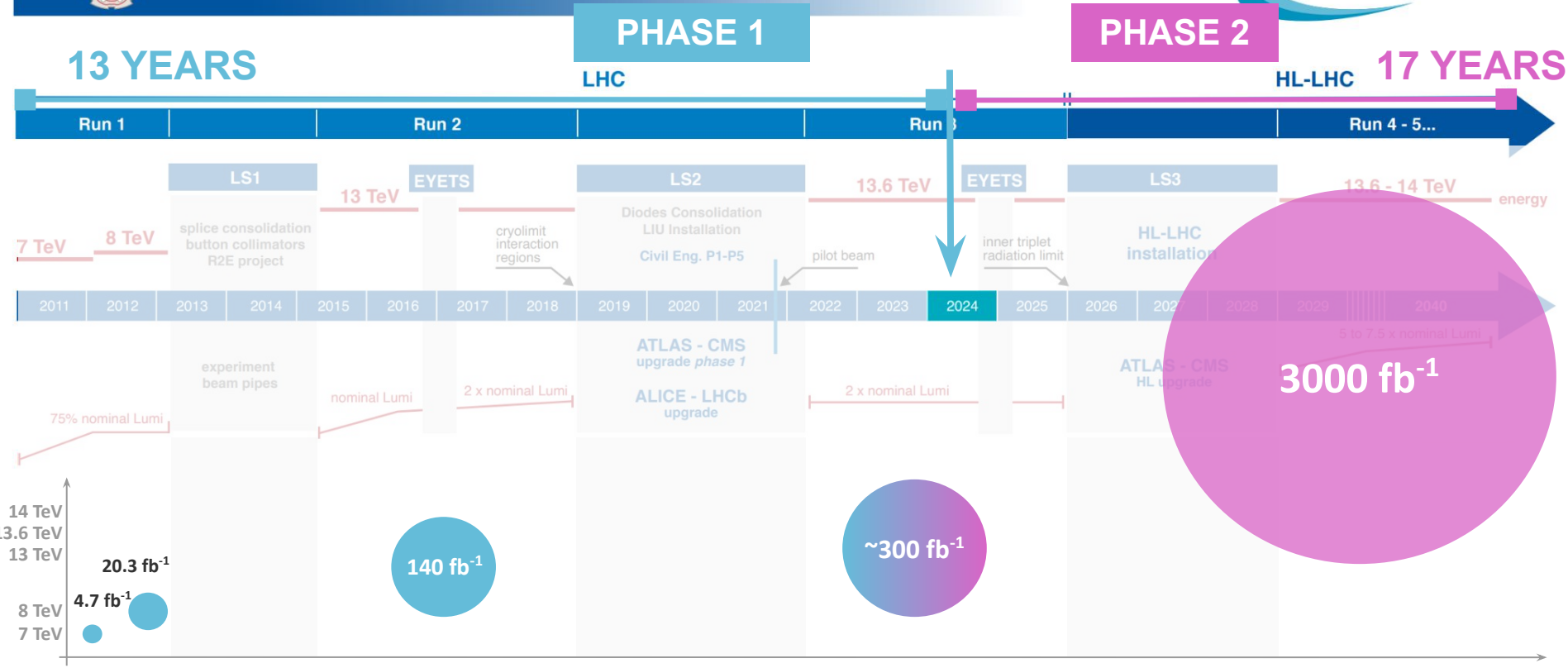
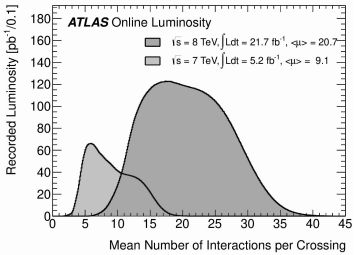
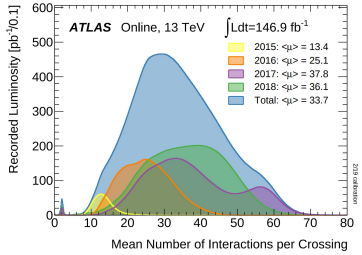
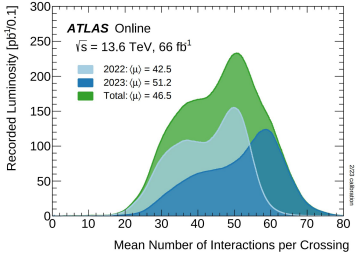






PHASE 1



PHASE 2

HiLumi LARGE HADRON COLLIDER

HL-LHC 17 YEARS

Run 1 | Run 2 | Run 3 | Run 4 - 5...

LS1 | EYETS | LS2 | EYETS | LS3

7 TeV | 8 TeV | 13 TeV | 13.6 TeV | 13.6 - 14 TeV energy

splice consolidation
button collimators
R2E project

cryolimit
interaction
regions

Diodes Consolidation
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pilot beam

inner triplet
radiation limit

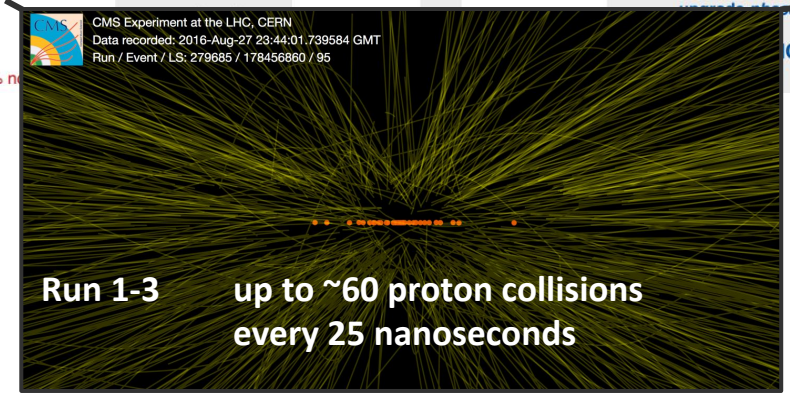
HL-LHC
installation

2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2040

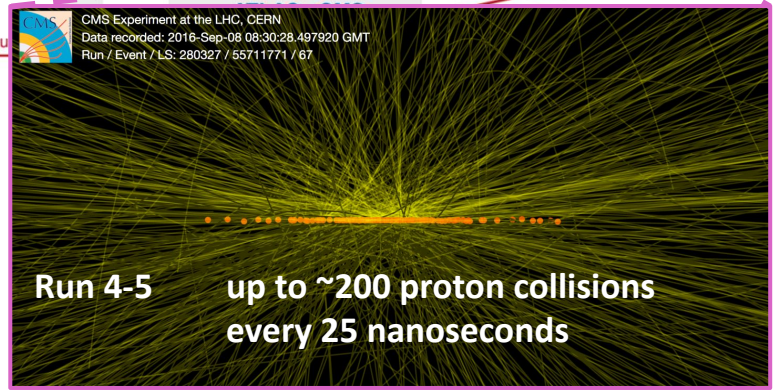
ATLAS - CMS

2 x nominal Lu

5 to 7.5 x nominal Lumi



Run 1-3 up to ~60 proton collisions every 25 nanoseconds



Run 4-5 up to ~200 proton collisions every 25 nanoseconds

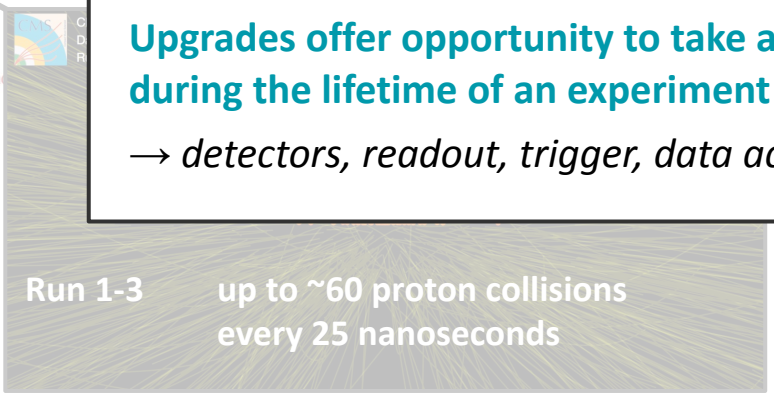
*visualisation taken from 2016 high pile-up runs

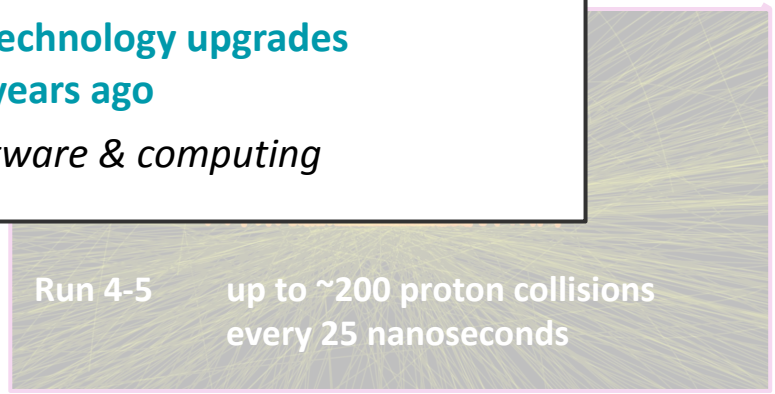
Challenges towards HL-LHC / Run 4-5

→ **high radiation environment** for detectors and front-end electronics
→ increasing **number of pp interactions** per 25ns bunch crossing
→ vertex & track **reconstruction algorithms** less discriminating
→ require tighter selections with **trigger and readout bandwitdh contraints** to achieve similar purity (at the cost of signal acceptance)
→ more data ~ exceeds **available resources**

Upgrades offer opportunity to take advantage of technology upgrades during the lifetime of an experiment designed 30 years ago

→ *detectors, readout, trigger, data acquisition, software & computing*





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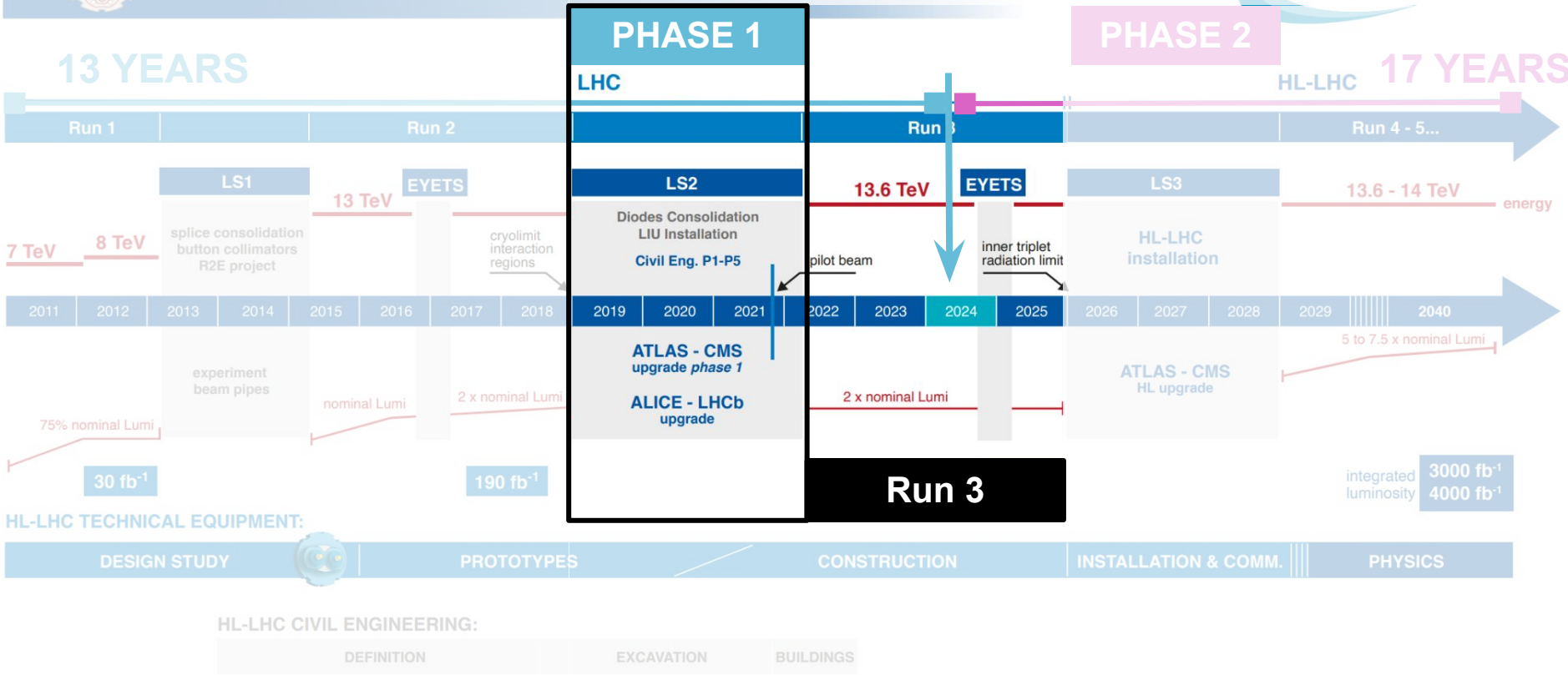
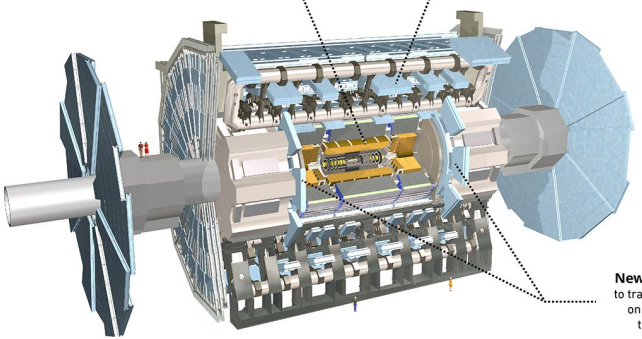


Phase 1 upgrade ~ Long Shutdown 2 / commissioned for Run 3

ATLAS detector

LAr Calorimeter
new electronics
& cabling

New Small Wheel
sMDT/TGC: improved
muon path resolution



New small wheel
to track more muons
on both sides of
the detector

Trigger / Data Acquisition
L1 hardware trigger, readout system, HLT

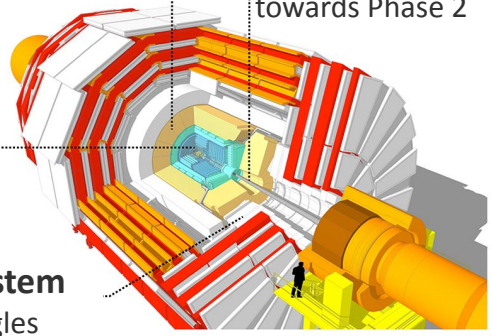
CMS detector

Pixel detector
replaced barrel layer
and connectors

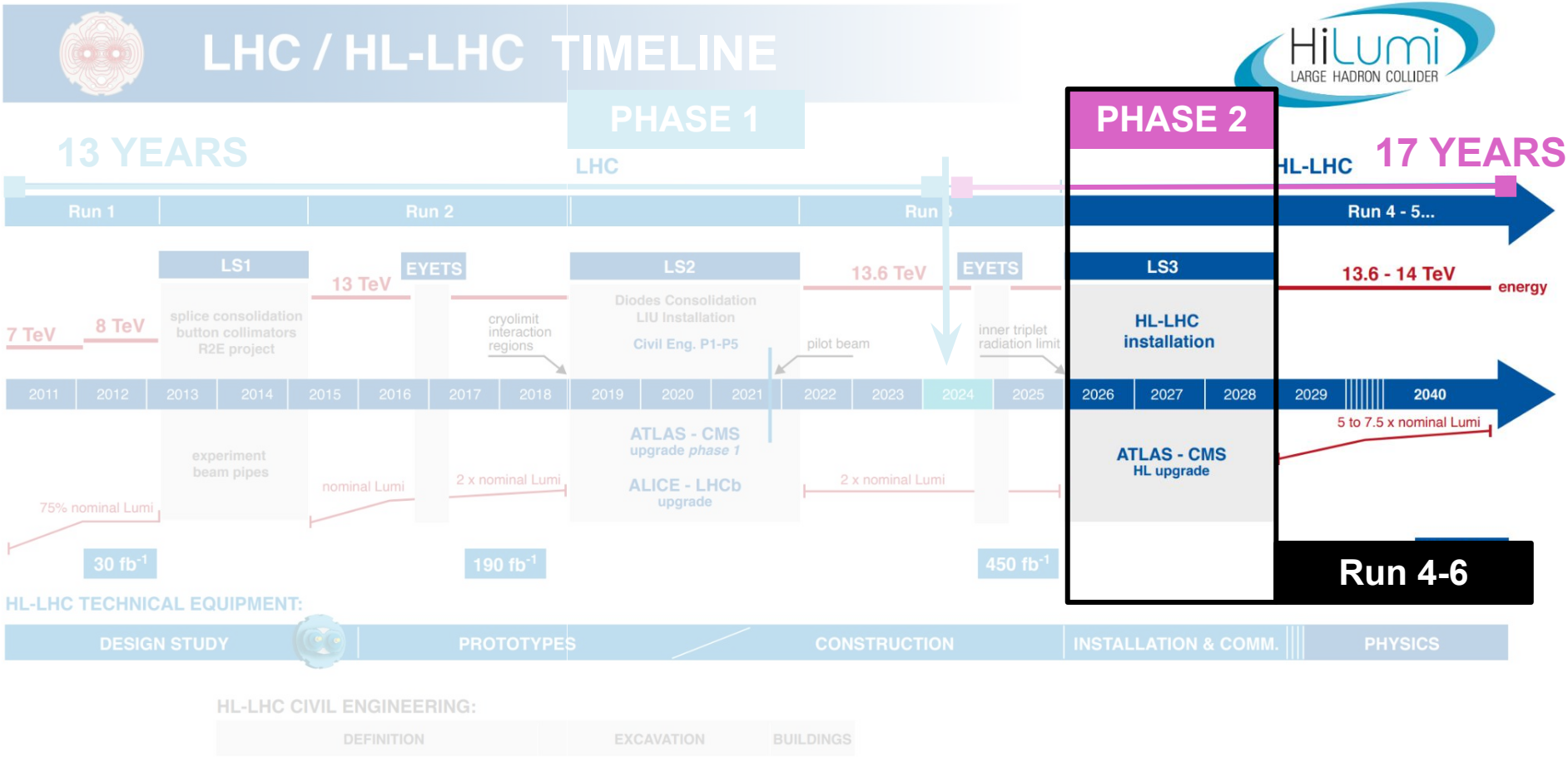
Hadron calorimeter
5 Gb/s readout

Beam pipe
new design
towards Phase 2

Open CMS detector, showing the endcap calorimeter sticking out, which will be replaced with the new **high granularity calorimeter (HGCAL)** in Phase 2.



New muon system
detect @ 10° angles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Why HL-LHC? Projections?

- a lot more data + a slight energy increase
- SM precision measurements → Jonathon's talk
- The Higgs boson as new physics probe
- Rare BSM physics

(a) extrapolate from earlier results

(b) fully
  - consider uncertainty scenarios

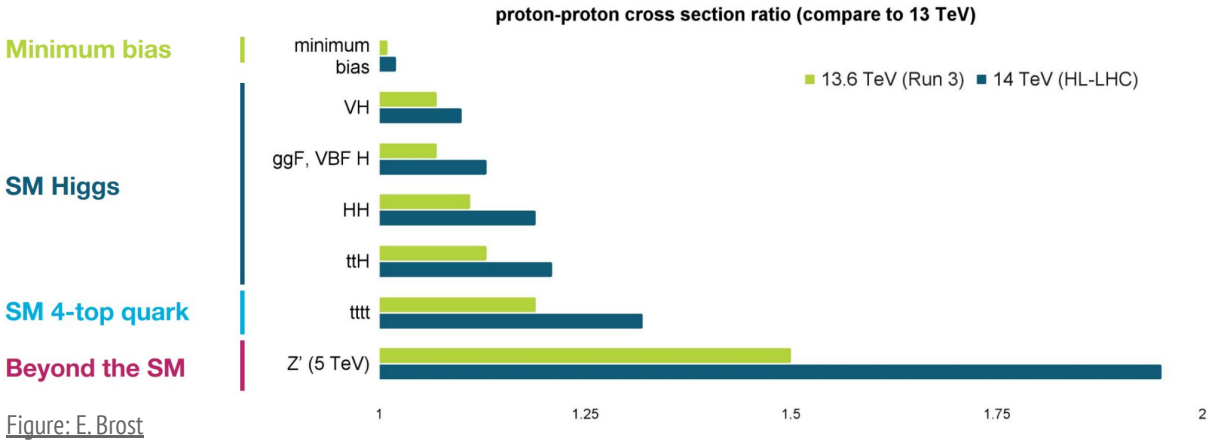
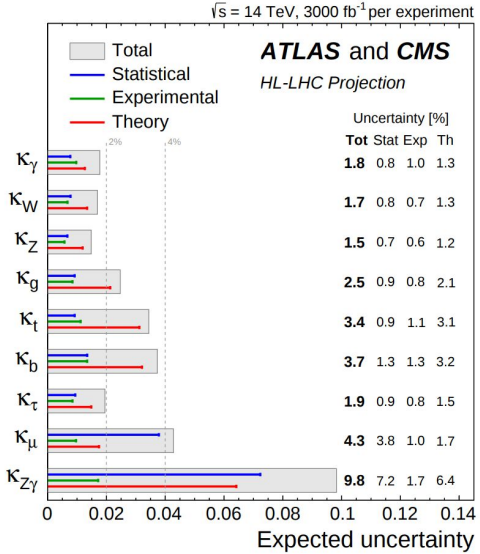


Figure: E. Brost

arXiv:1902.00134



Phase 2 upgrade for HL-LHC ~ Long Shutdown 3 → Run 4-6

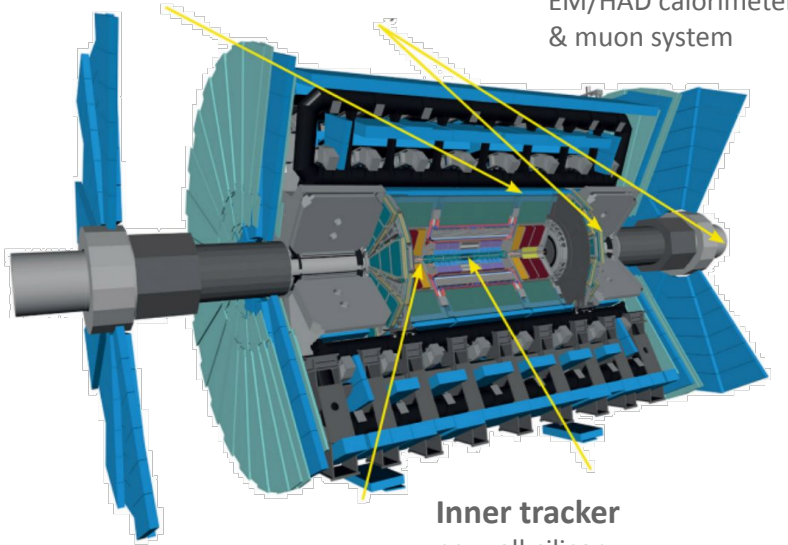
ATLAS detector

Trigger/DAQ
L1/HLT - 1Mhz / 1kHz

Muon detector
improved coverage

Luminosity & forward detectors

Upgraded electronics
EM/HAD calorimeters & muon system



Timing detector
high-granularity timing detector, pile-up mitigation

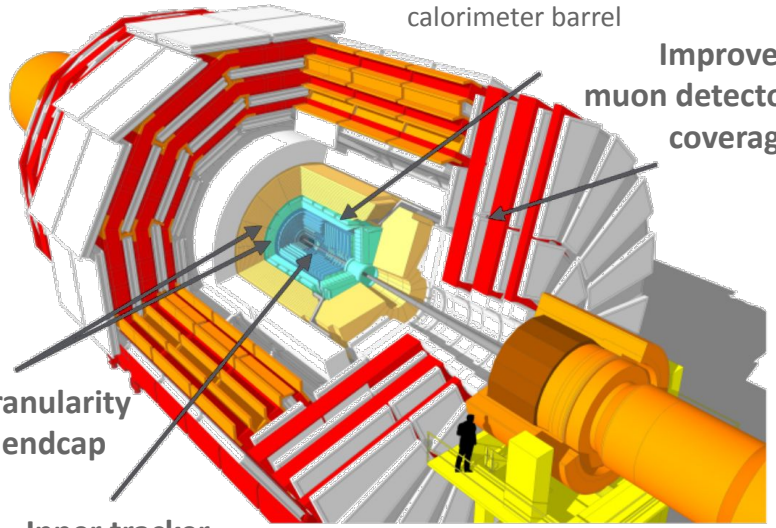
Inner tracker
new, all-silicon, coverage up to $|\eta| < 4$

CMS detector

Trigger/DAQ
L1/HLT - 750kHz / 7.5kHz
Track info at L1

Upgraded electronics
calorimeter barrel

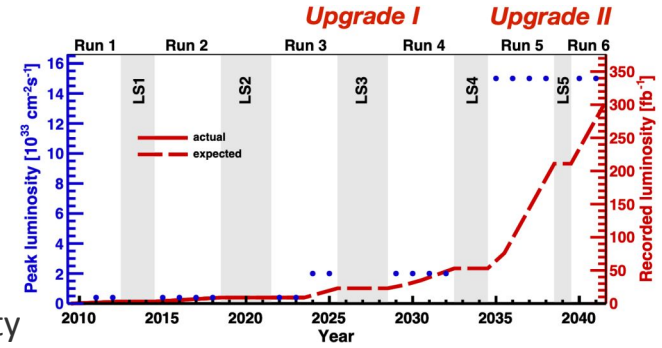
Improved muon detector coverage



New high-granularity calorimeter endcap

Inner tracker
new, coverage up to $|\eta| < 3.8$

Upgrade 1 & 2 ~ LHCb



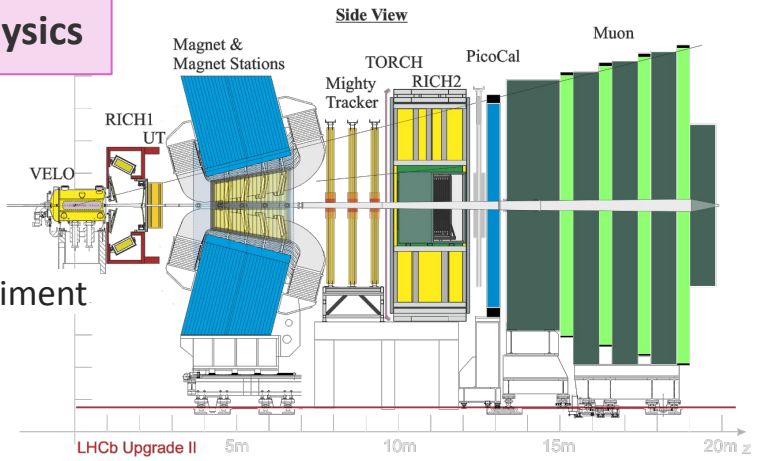
LHCb schedule shifted w.r.t. the main upgrade schedule

- Upgrade 1 was designed to collect 50 fb^{-1} by the end of Run 4
- Opportunity to run the experiment till the end of HL-LHC
- Upgrade 2 designed to accumulate maximum possible integrated luminosity
  → ~50 fb^{-1} / year → 300 fb^{-1} by the end of Run 6

LHCb Upgrade 2 is the the only way to achieve the European Strategy objective of **full exploitation of the HL-LHC, including flavour physics**

Upgrade 2 requirements

- novel technology developments with many potential applications
  → *including precision timing*
- more data will be read out from the detectors than in any other experiment
  →needs state-of-the-art online processing capability



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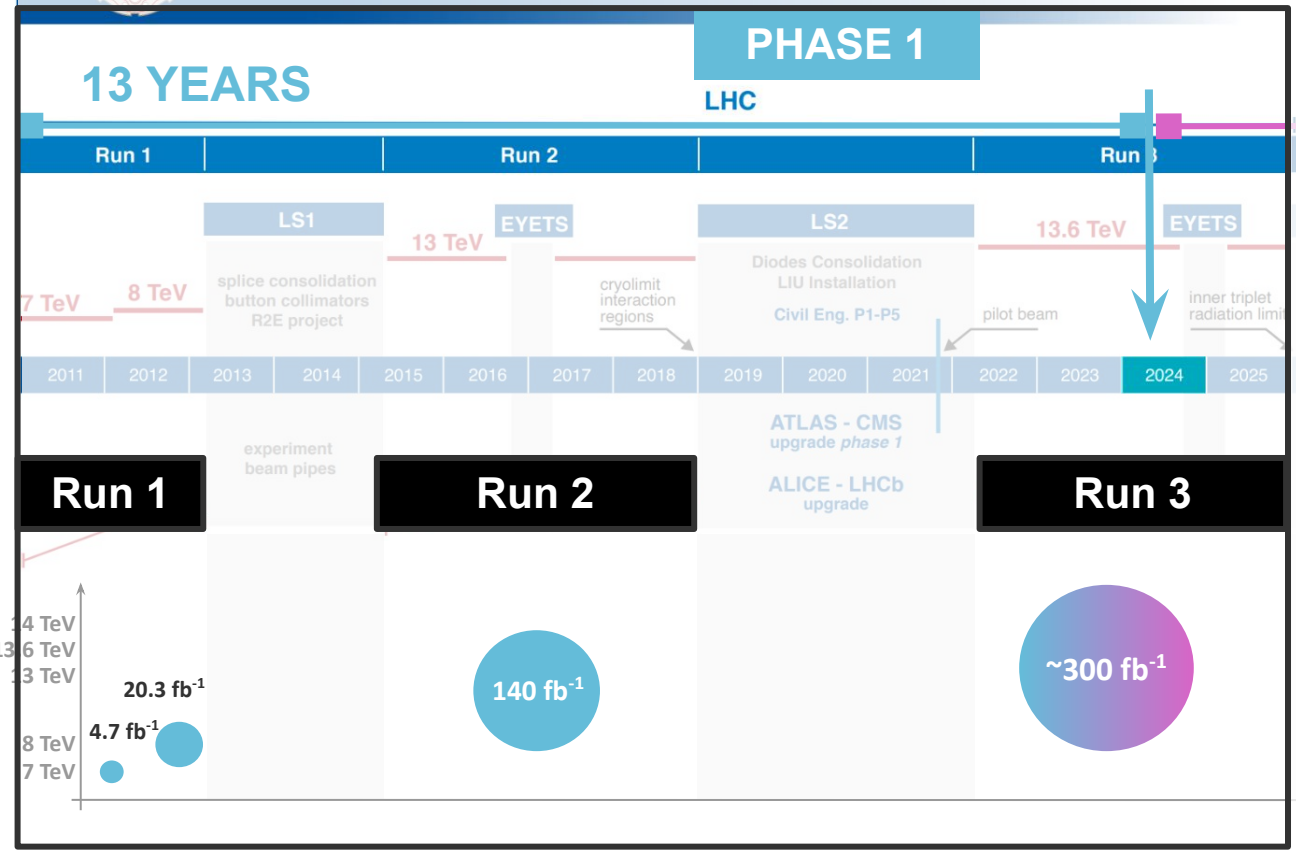

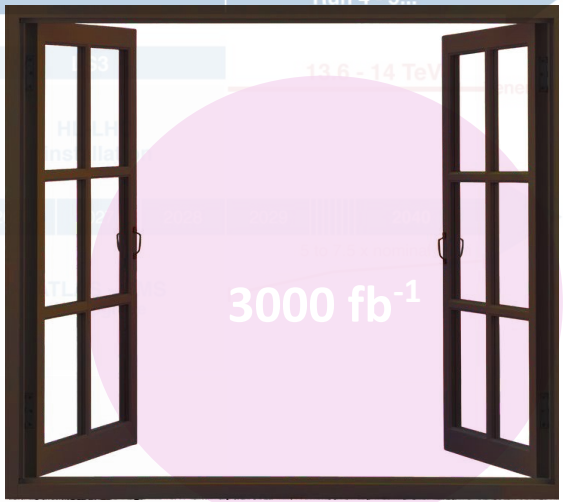

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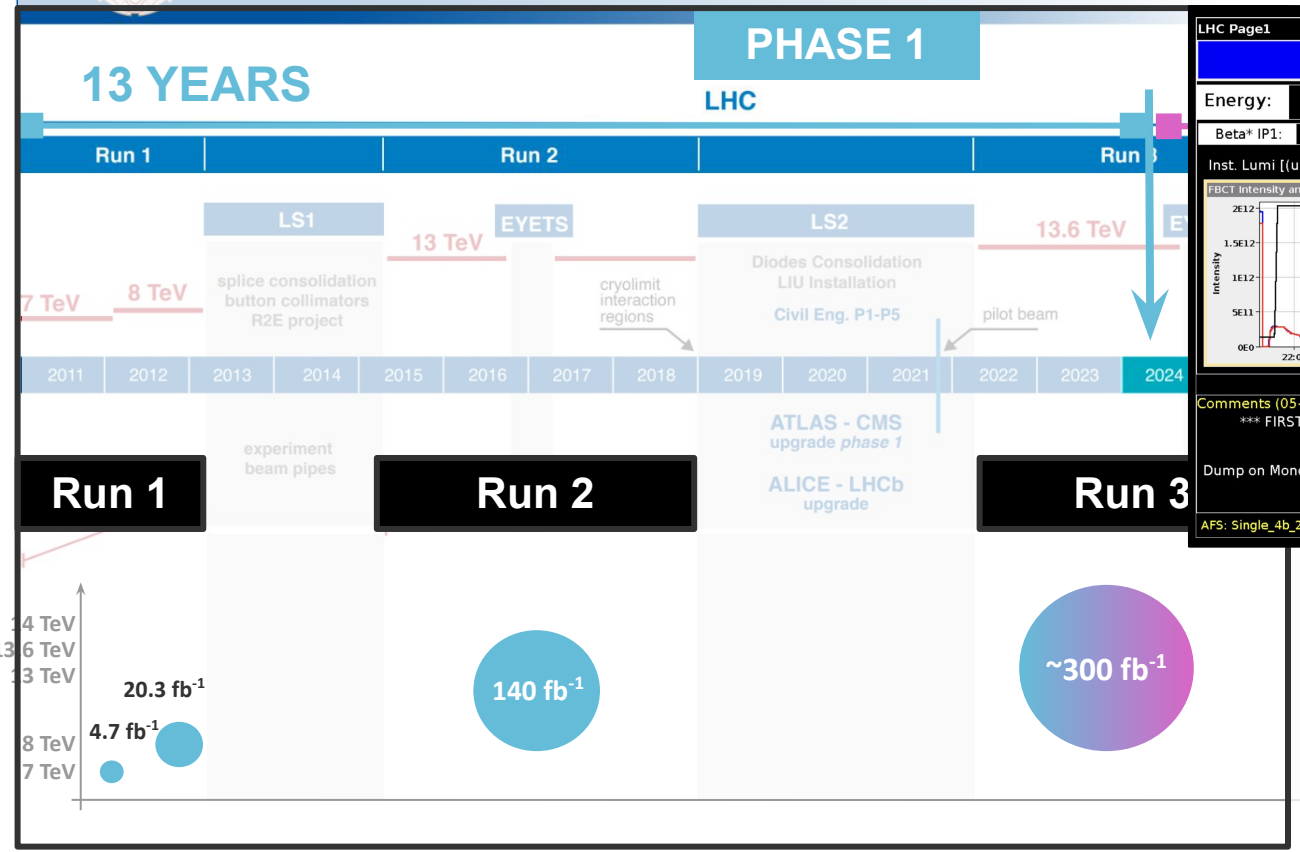
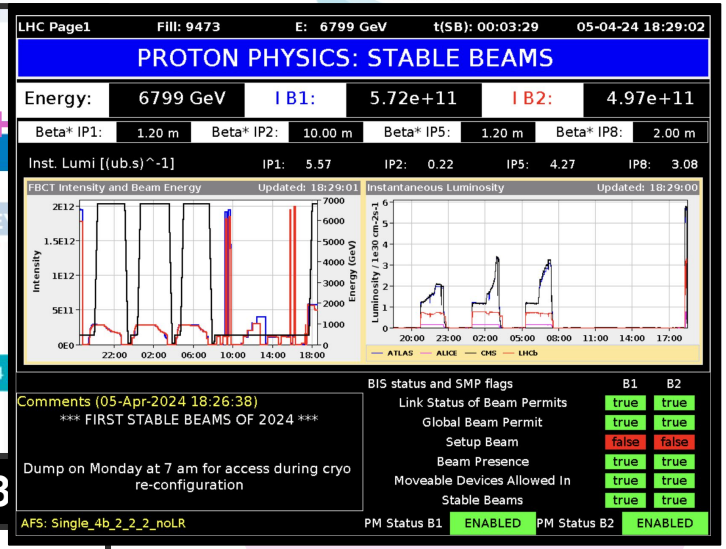


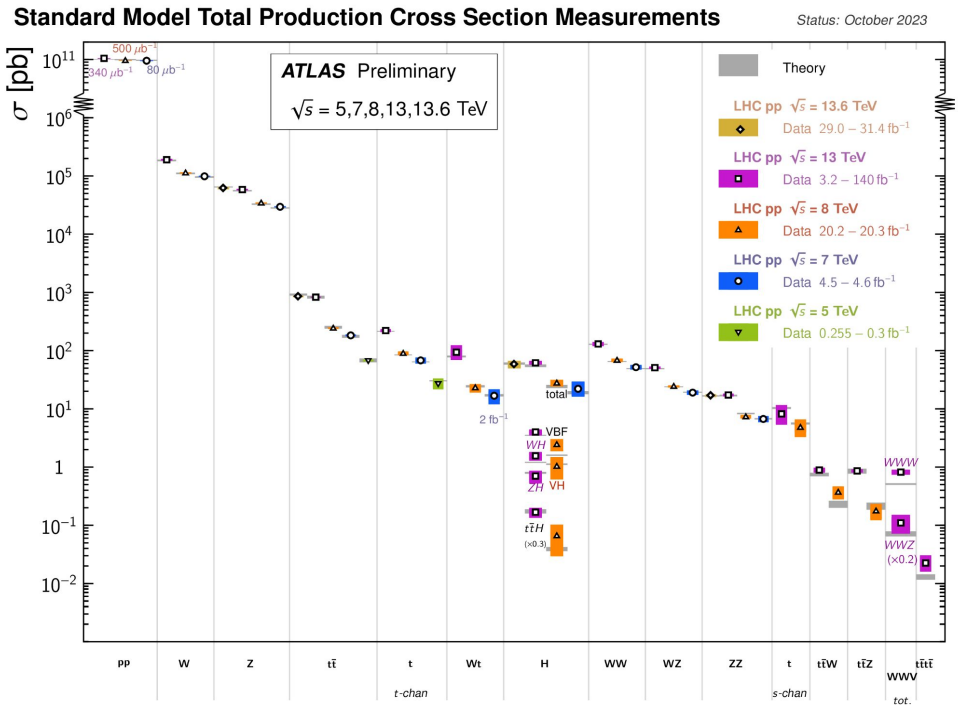


first stable beams of 2024 last Friday!

State of the Art

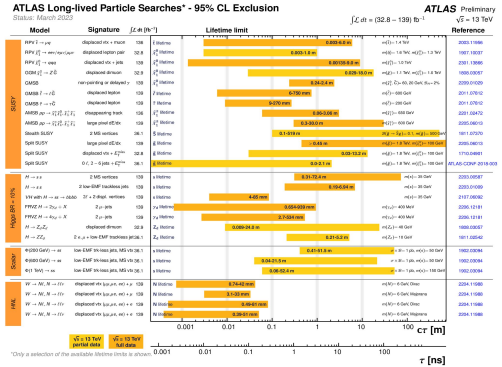
Excellent precision and agreement with theory seen from Standard Model measurements

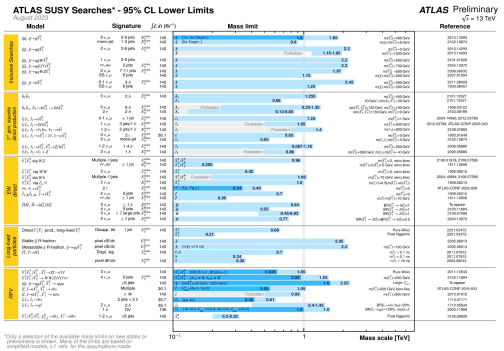
- but there are limitations



However, despite many probes

- no evidence of New Physics yet





Vast New Physics Landscape

BSM Higgs

non-resonant HH production

Rare Higgs decays

H⟶invisible

Resonances

vector bosons

(pseudo)scalars

vector like quarks

axions

heavy fermions

Long-lived particles

Leptoquarks

dark photons

R-parity

Hidden Dark Sectors

Dark Matter

Supersymmetry

Extra Dimensions

State of the Art

We are in an experimentally driven discovery era

→ large (~20x) increase in total integrated luminosity coming,
but only small increase in energy

Creativity is essential

→ target unexplored phase space
→ convert experience from Run 1-3
→ integrate new tools & methodologies
→ pave the way for future runs & experiments

Already exceeding design goals and projections in multiple places!

To-do for Run 3 and beyond

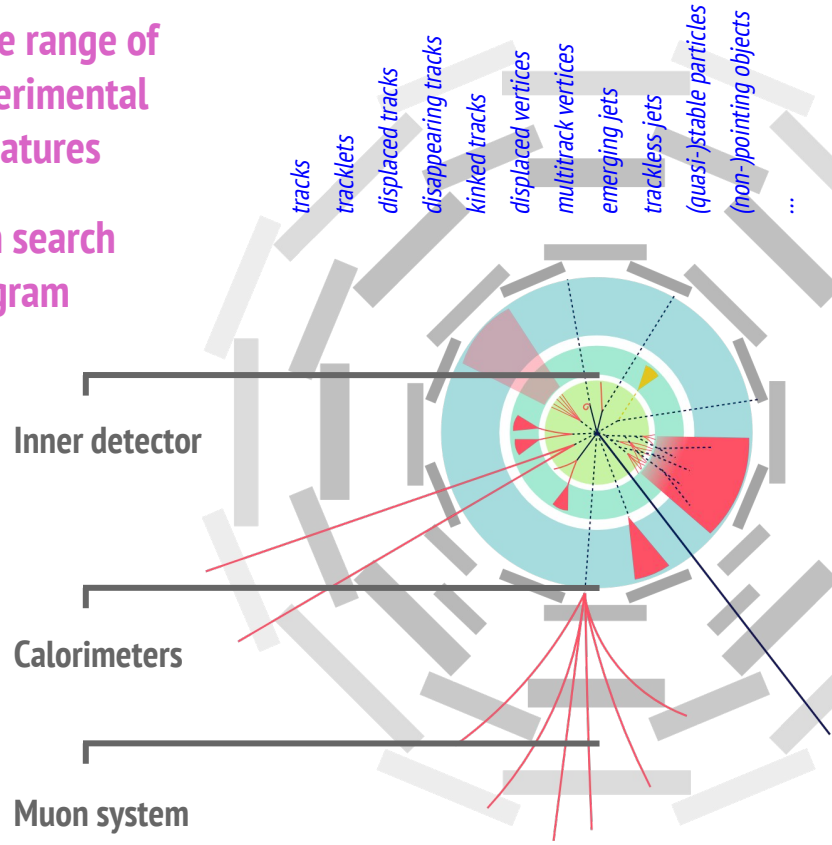
- *Things once though impossible*
- *and then some*

Cover all the bases – *searches edition*

- **Reconstruction**
  tracks, unconventional tracks, vertexing, …
- **Detector strengths & weaknesses**
  >10 years of combined expertise, upgrades
- **(Under)exploited signatures**
  long-lived particles, dark XYZ, multiplicities, …
- **New techniques**
  anomaly detection, machine learning, data-formats, computing
- **Enriched data taking**
  data scouting/TLA, event picking
- **The bigger picture**
  combinations, global interpretations
- **Think forward**
  baseline for HL-LHC, future experiments

Wide range of experimental signatures

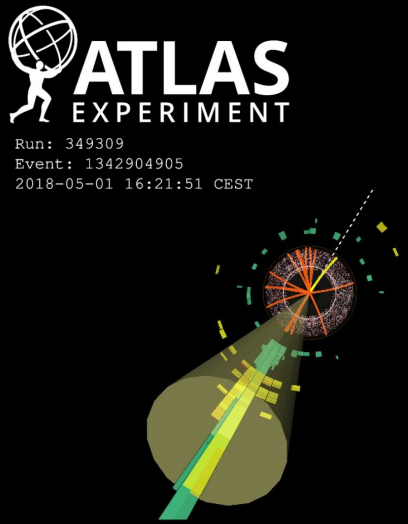
Rich search program

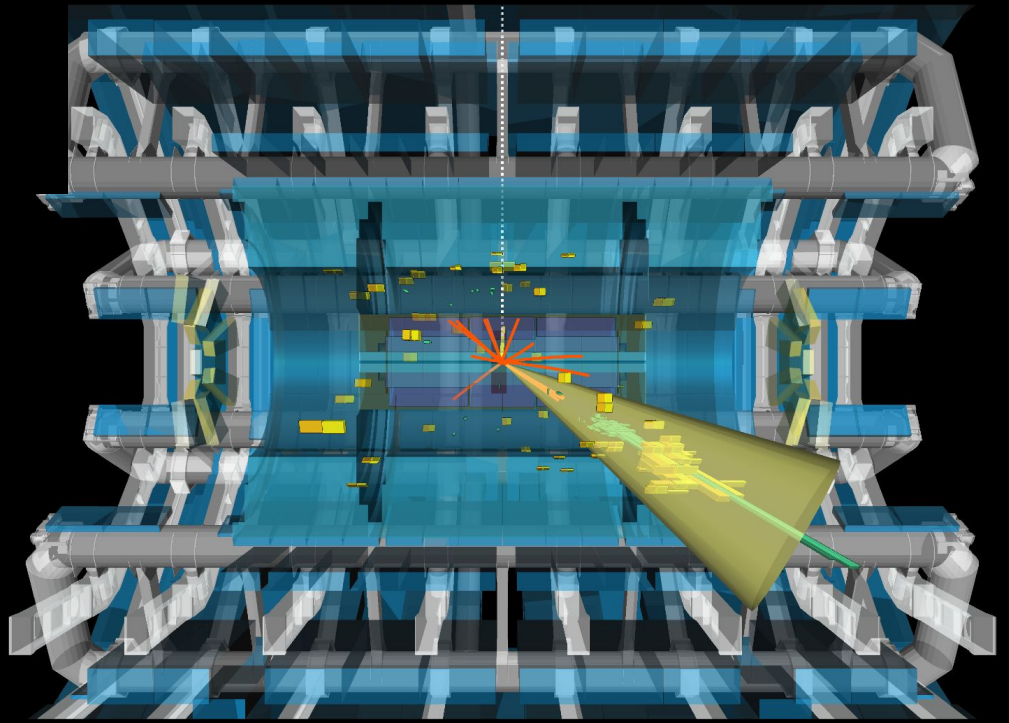


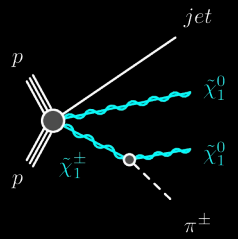
img:H. Russell

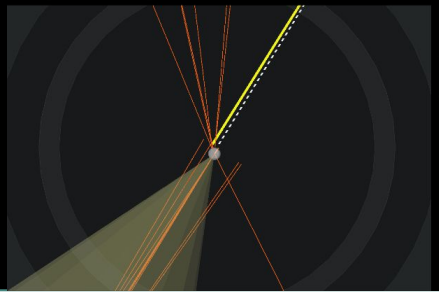
Electroweak SUSY production - *mildly Displaced Tracks*

arxiv:2401.14046









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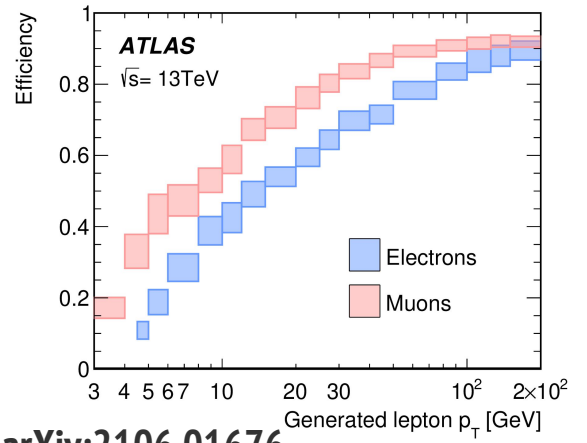
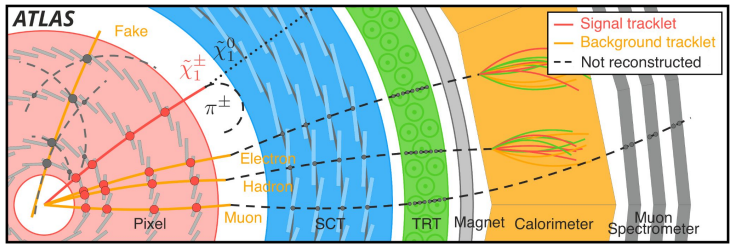


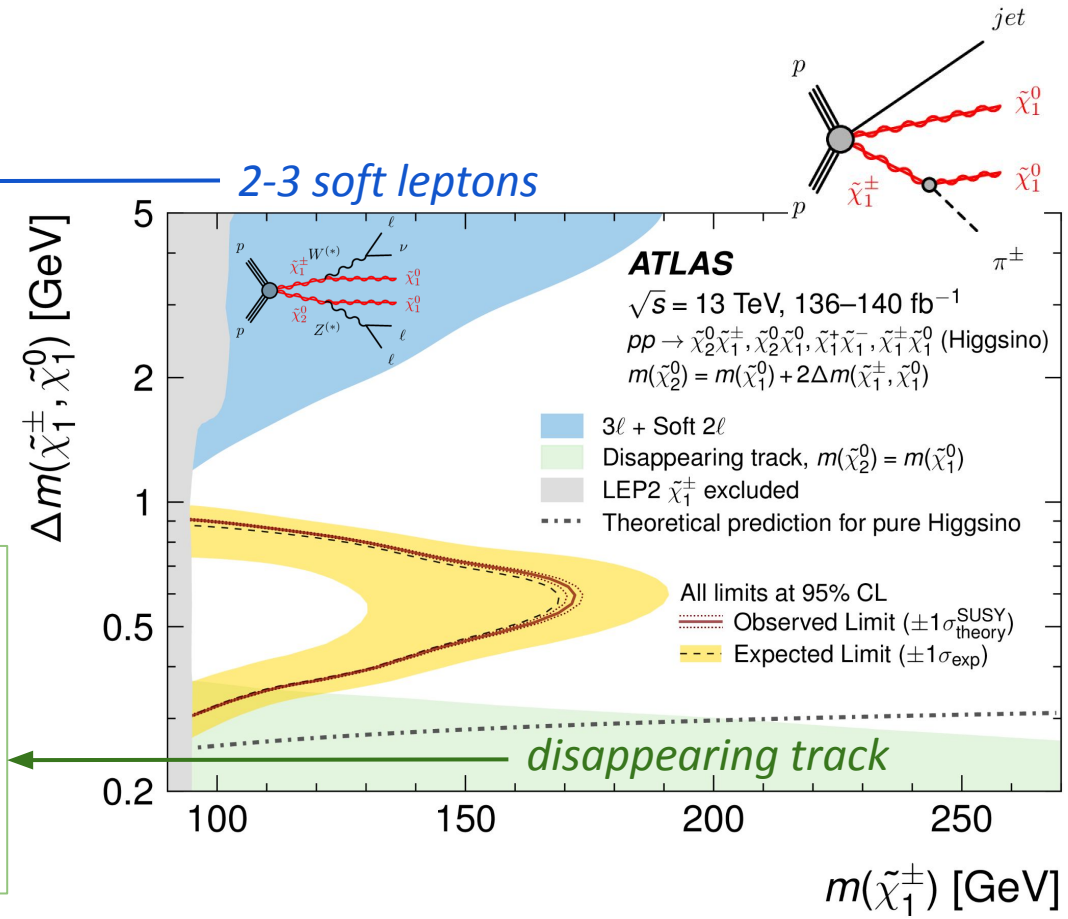
arXiv:2106.01676



arXiv:2201.02472

2-3 soft leptons

disappearing track



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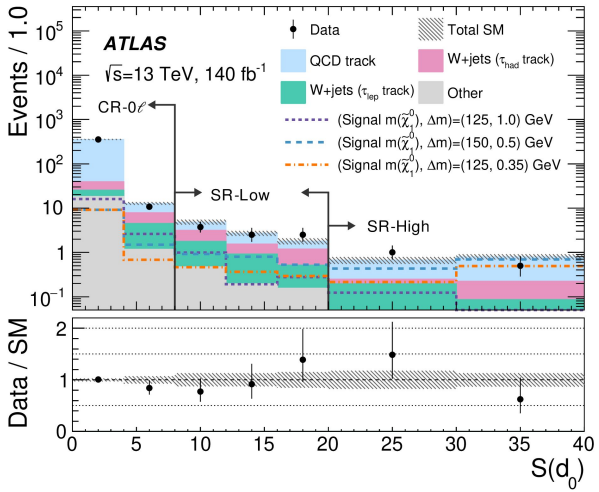
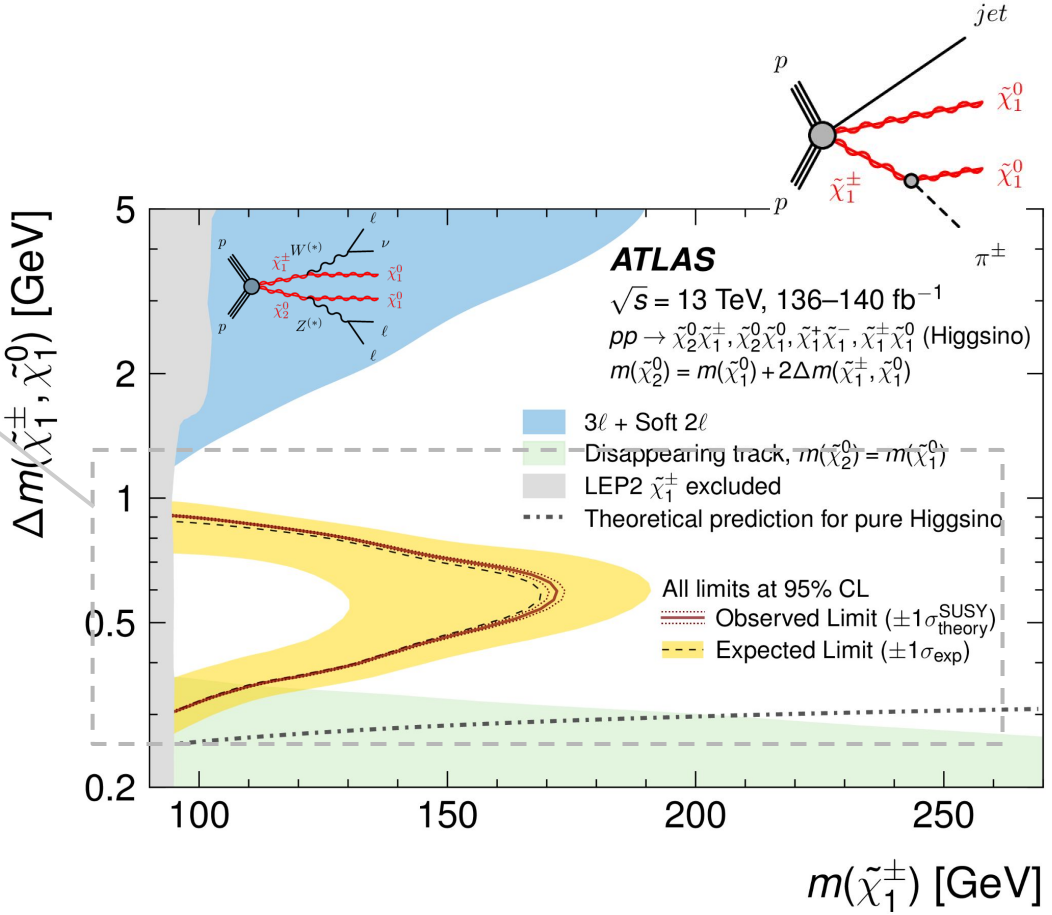
search for higgsinos

- small mass mass splittings ~ 0.3-1 GeV
  ⟶ decay flight length 0.1-1mm
  ⟶ **mildly displaced tracks**
- exploit transverse impact parameters significance $S(d_0) = |d_0|/\sigma(d_0)$



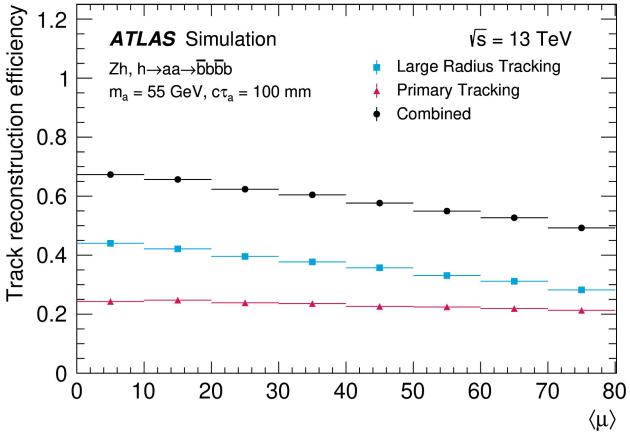


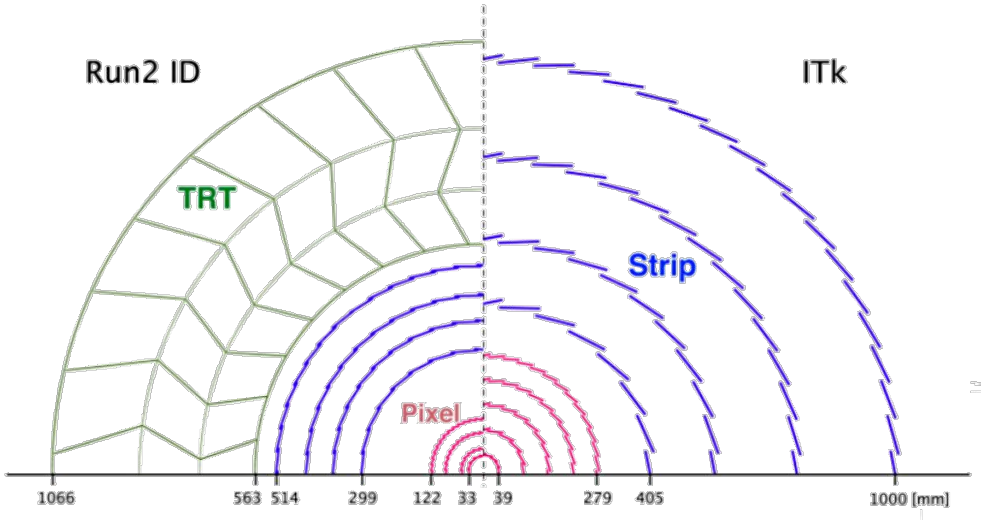
Long-lived particles - *upgrade & HL-LHC projections*

Many LLP searches will benefit from new **dedicated Large Radius Tracking algorithms**, in addition to standard tracking (both offline and at trigger level)

Significant further sensitivity improvements foreseen from **upgraded trackers for HL-LHC**

LRT performance





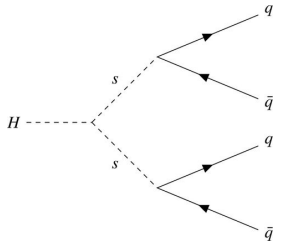
Long-lived particles - *with Displaced Vertices*

arxiv:2403.15332

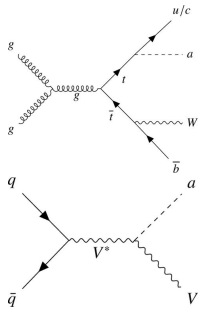
hadronically decaying LLPs → displaced jets

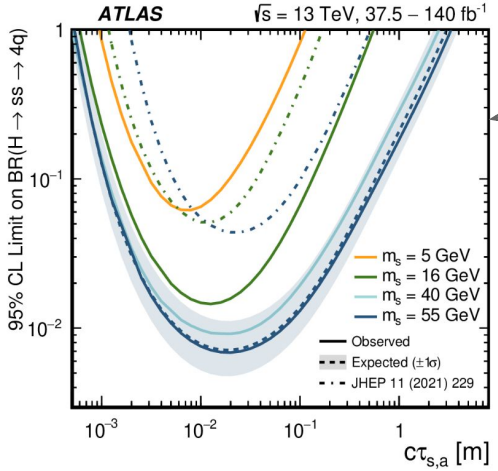
- strong gain from phase 1 upgrade in Large Radius Tracking - arxiv:2304.12867
- BDT trained on jet features to discriminate against prompt jets
- event level discrimination: $BDT_{j0} \times BDT_{j1}$

Pseudoscalar boson(s)

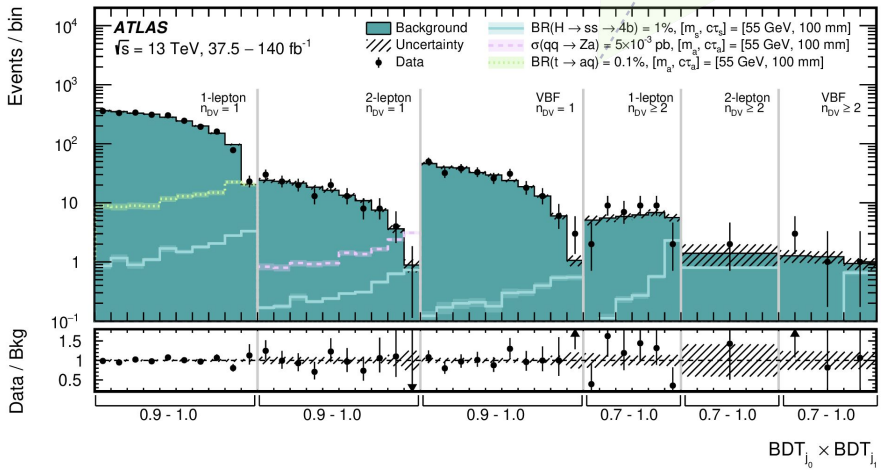


Pseudoscalar axion-like particles





- interpretation H→ss→4q/4b/4c, improvements up to x20
- new interpretations σ(Va) and B(t→aq)

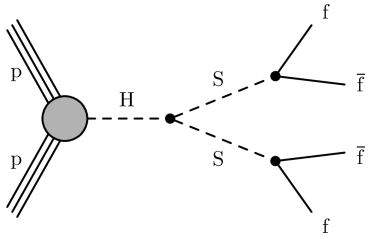


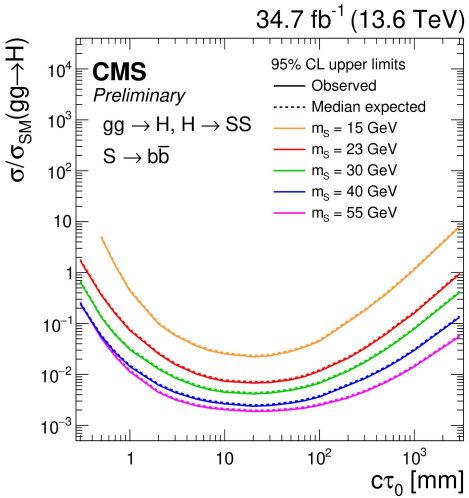
Long-lived particles - *with Displaced Vertices*

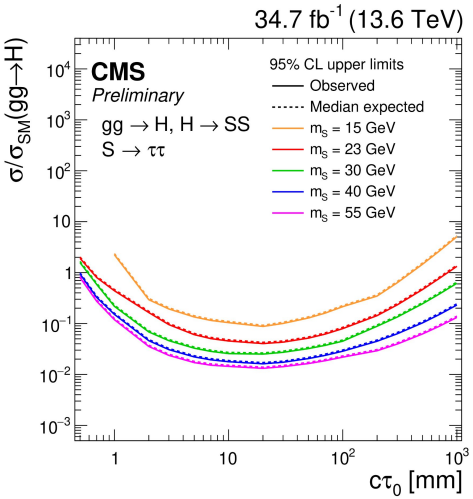
- gain from new Run 3 triggers & DV reconstruction
- using GNN-based LLP taggers
- interpretation H⟶SS

CMS-PAS-EXO-2023-013

Brand new Run 3 result from CMS as well on low-mass LLPs ⟶ displaced jets

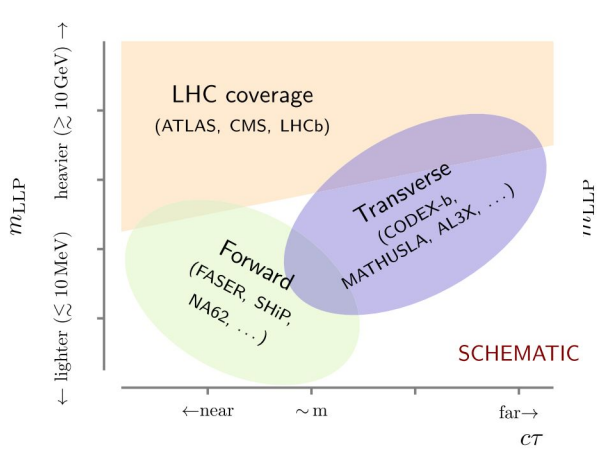


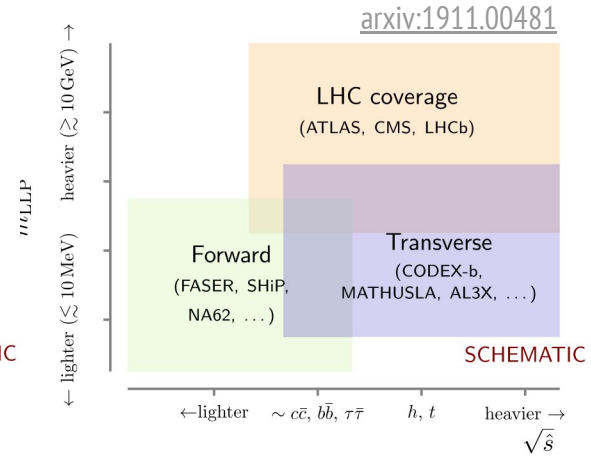


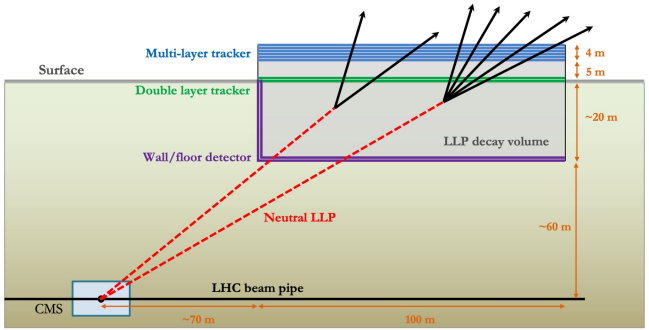


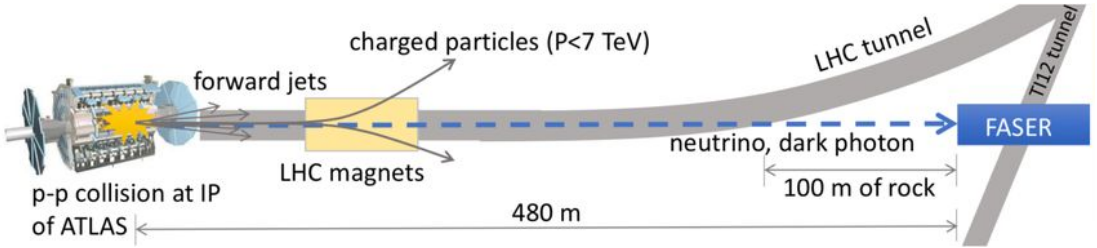
Long-lived particles - *beyond ATLAS/CMS*

- additional small(er) experiments significantly extend the coverage of the LHC for LLPs, especially towards lighter LLP masses and longer lifetimes
- e.g. FASER forward from ATLAS, or MATHUSLA transverse from CMS









Long-lived particles - *beyond ATLAS/CMS*

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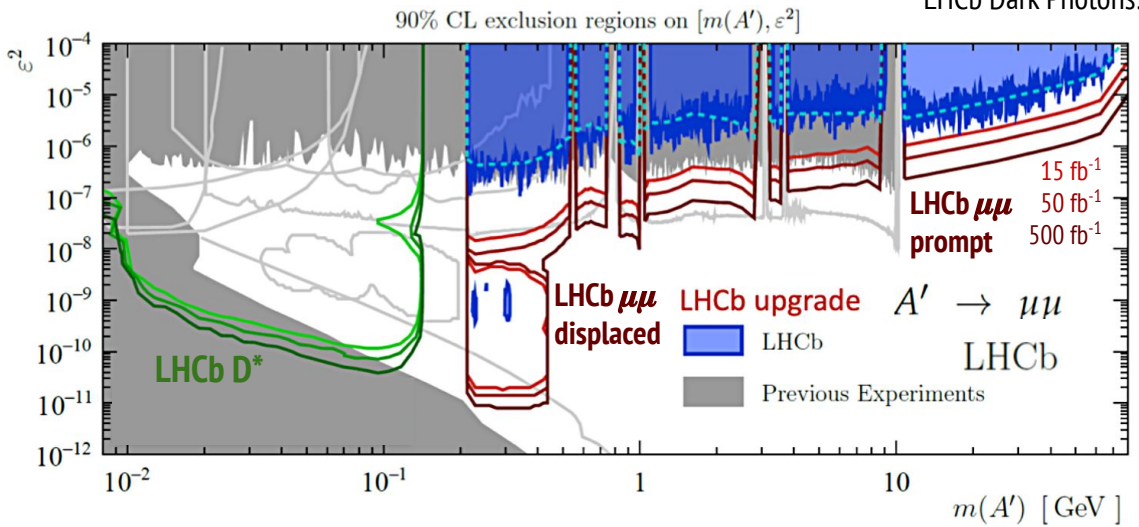
LHCb sensitivity can extend coverage in a **broad mass range**

→ displaced vertexing designed for B-meson decays

→ also performant for BSM LLP searches

→ see also LHCb **upgrade gains 15/50/500 fb^{-1}**

LHCb Dark Photons: arXiv:191006926



Long-lived particles - *beyond ATLAS/CMS*

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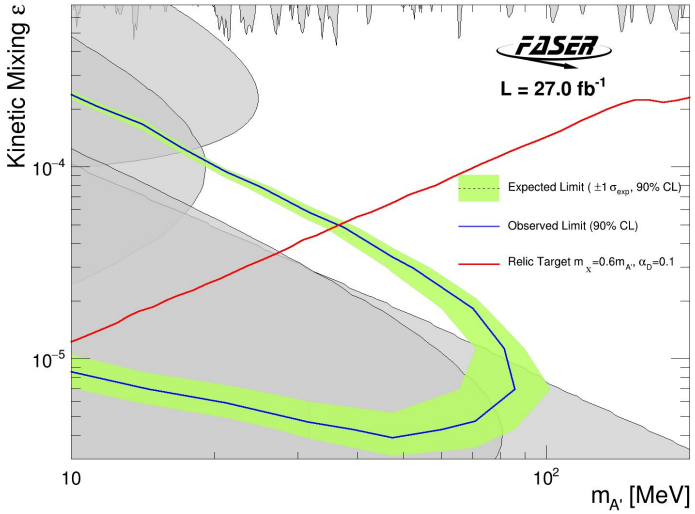
  c

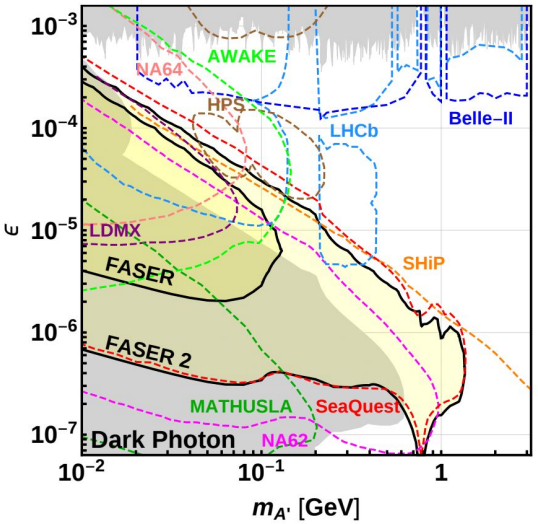
First BSM results from FASER with Long-lived Dark Photon search

FASER Dark Photons: arXiv:2308.05587



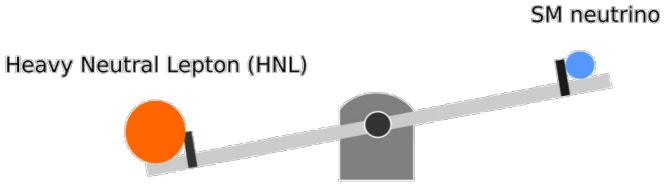
Further complementary results expected from small experiments throughout LHC+HL-LHC era

FASER reach: arxiv:1811.12522

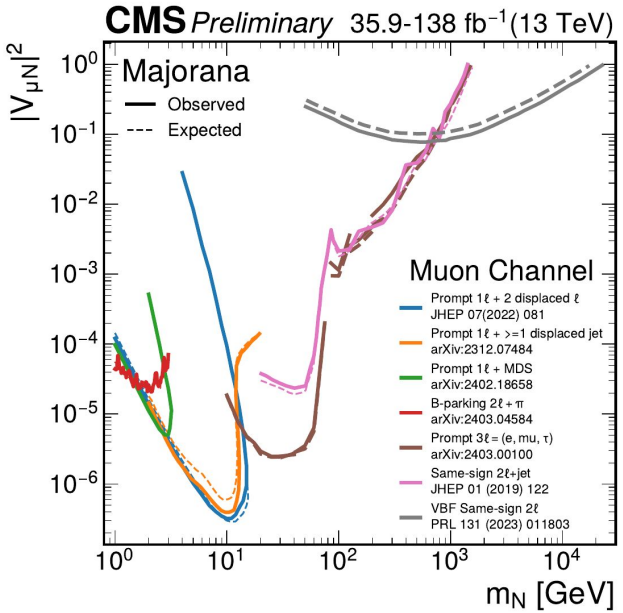


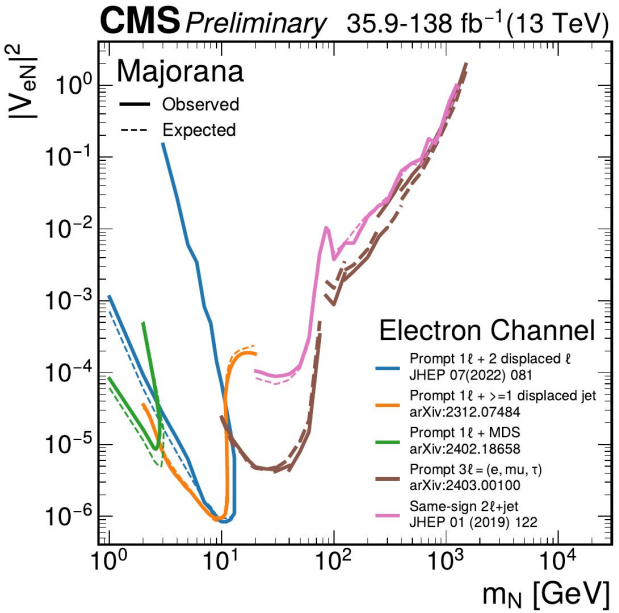
Heavy Neutral Leptons

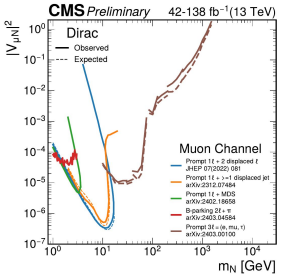
CMS summary plots 2024:HNL

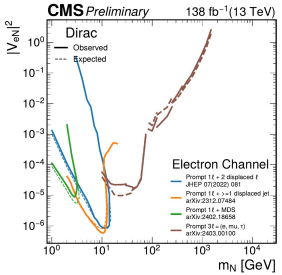


- multiple interesting final states - both prompt/displaced
- in the case of long-lived: displaced vertices
- interpretations ~ Type-I seesaw model (Majorana / Dirac)

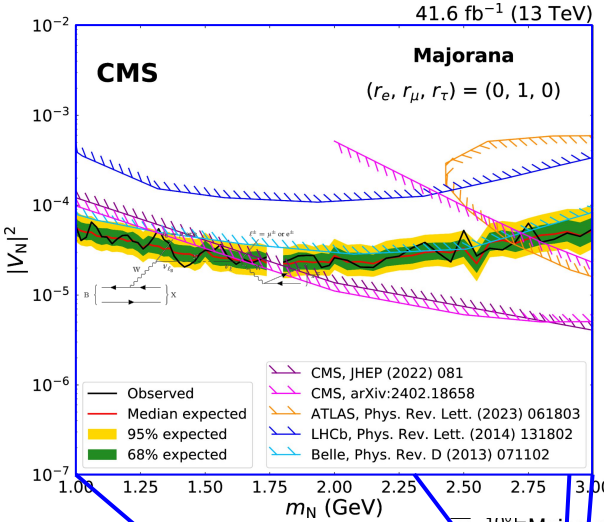


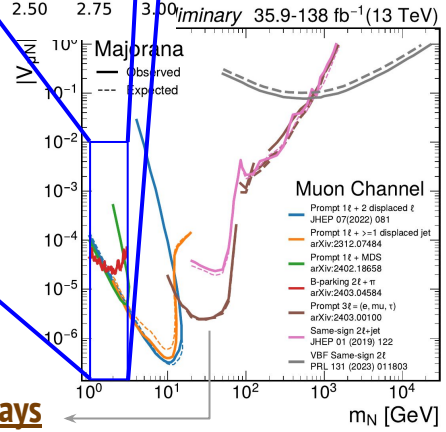


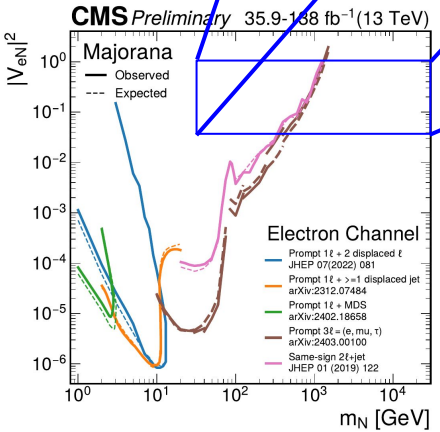


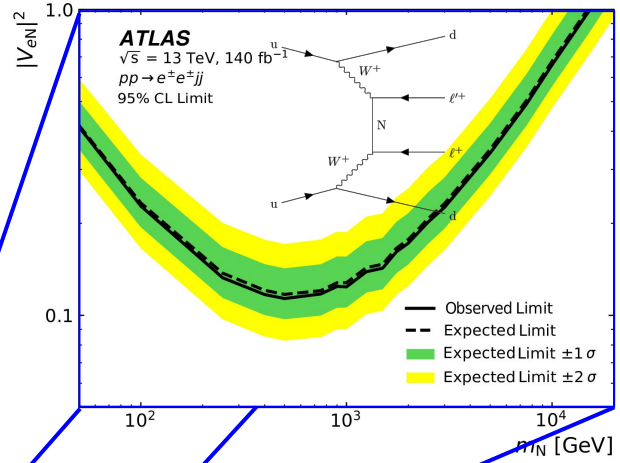


Heavy Neutral Leptons









arxiv:2403.04584
LL HNL in B-meson decays

- benefit from using data parking
- lepton from B-meson
- pNN-driven selection algorithm
- first limits for $m_N < 2$ GeV

arxiv:2403.15016
HNL via VBS scattering

- scattering of same-sign W boson pairs
- combination of ee, $e\mu$ and $\mu\mu$ channels

arxiv:2403.00100
prompt HNL in boson decays

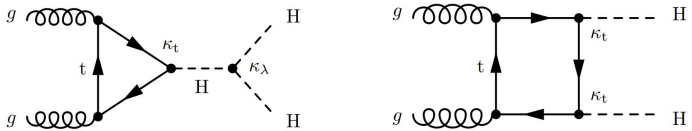
Higgs pair production - *is rare at the LHC…*

3 orders of magnitude rarer than single higgs production!

- HH searches are stats limited
- big improvements from reco & analysis work with Run 2 data
- **SM expectation in reach for Run 3**
  - → continue analysis improvements
  - → combine ATLAS & CMS results

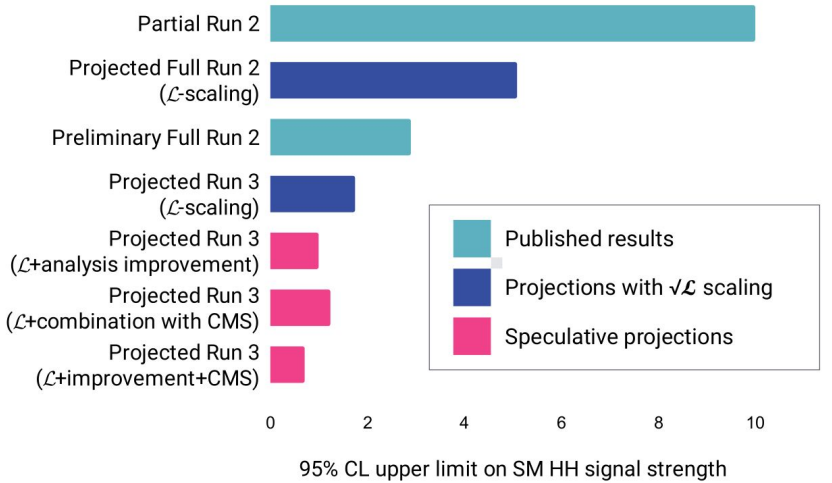
consider resonant/non-resonant production

- possible anomalous couplings
- possible new particles in loops



- wealth of channels studied in detail
- various interpretations: e.g. leptoquarks

Figure: K. Leney/E. Brost



Higgs pair production - *is rare at the LHC…*

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Projecting to HL-LHC

European Strategy (2018)

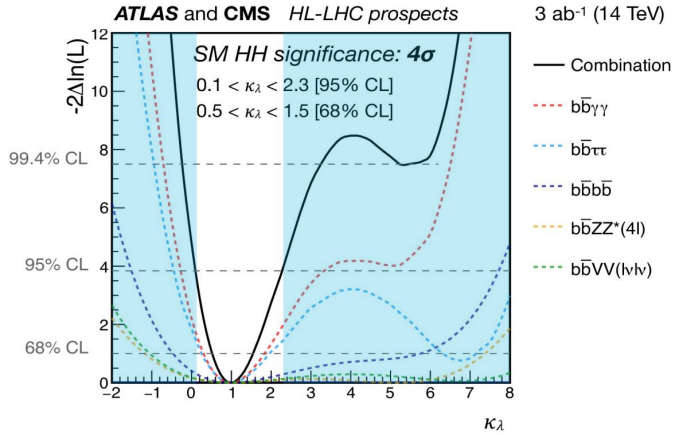
- small combination, partial dataset
- 50% precision on self-coupling
- 4σ SM HH significance (combi)

Snowmass update (2022)

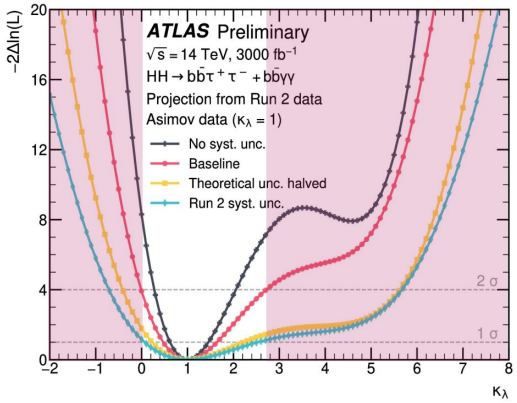
- ATLAS & CMS results updated
- new channels added
- 5σ SM HH significance back-of-the-envelope

/E. Brost

CERN-2019-007



ATL-PHYS-PUB-2022-005

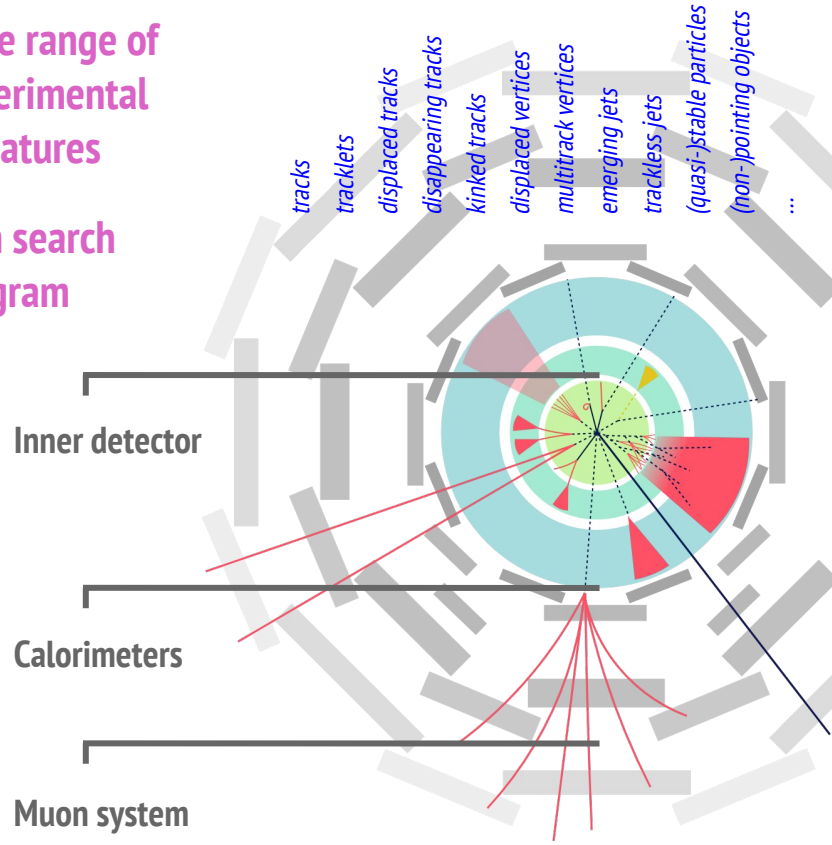


Cover all the bases – *searches edition*

- **Reconstruction**
  tracks, unconventional tracks, vertexing, …
- **Detector strengths & weaknesses**
  >10 years of combined expertise, upgrades
- **(Under)exploited signatures**
  long-lived particles, dark XYZ, multiplicities, …
- **New techniques**
  anomaly detection, machine learning, data-formats, computing
- **Enriched data taking**
  data scouting/TLA, event picking
- **The bigger picture**
  combinations, global interpretations
- **Think forward**
  baseline for HL-LHC, future experiments

Wide range of experimental signatures

Rich search program



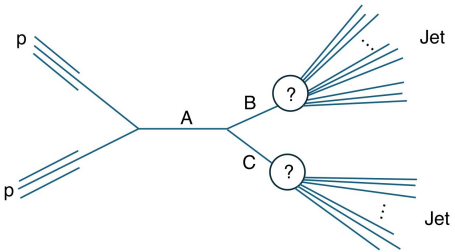
img:H. Russell

New techniques - *Anomaly Detection, Weakly/Unsupervised learning*

New ways of doing analysis

- many learning methods to be tested
- many possible targets

Example: model-agnostic search for dijet resonances



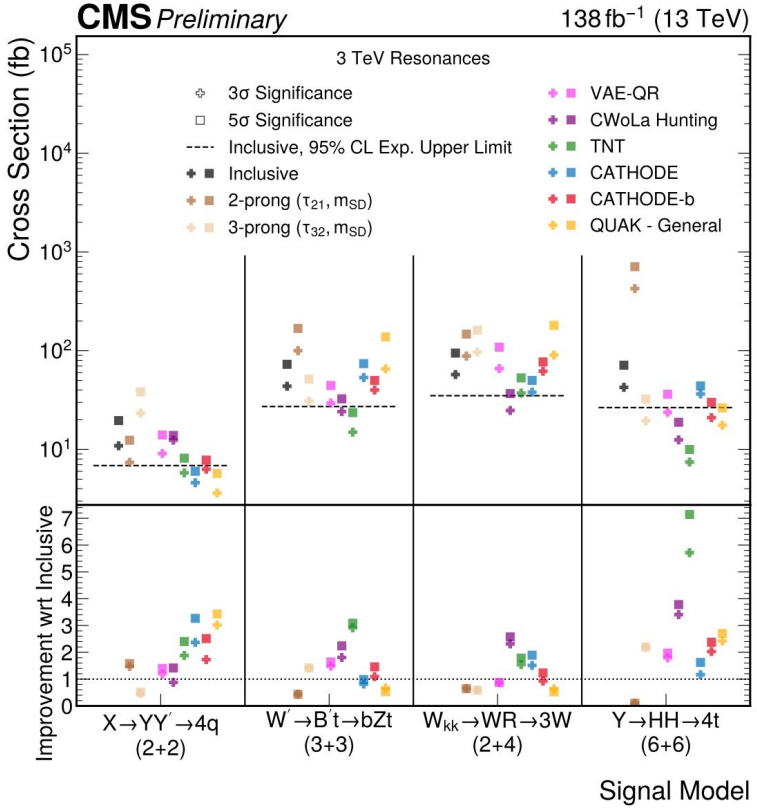
- deploying multiple multivariate ML methods
- 1.8-6 TeV mass range
- jet substructure

→ 3-7x improved sensitivity over standard incl. methods

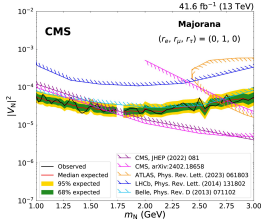
More results, and more coming

- resonances decaying to H+X - arxiv:2306.03637
- two body invariant mass distributions - arxiv:2307.01612

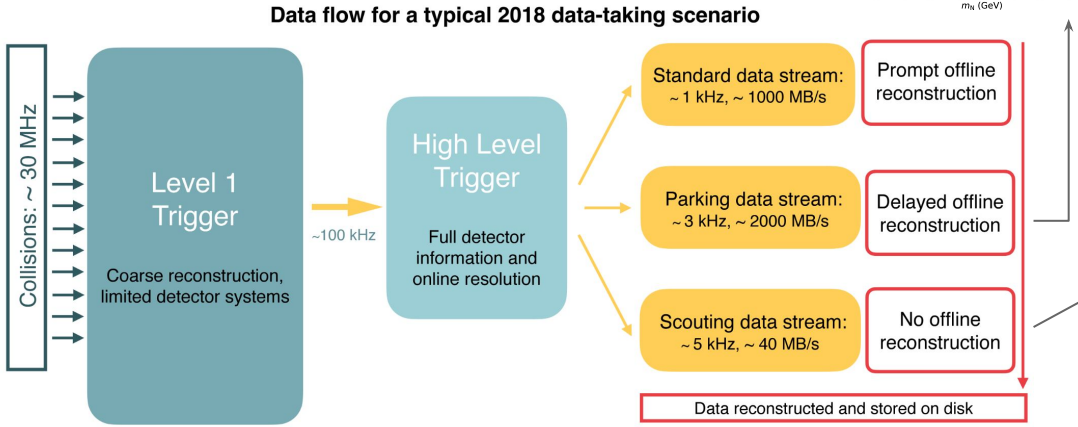
CMS-PAS-EXO-2022-026

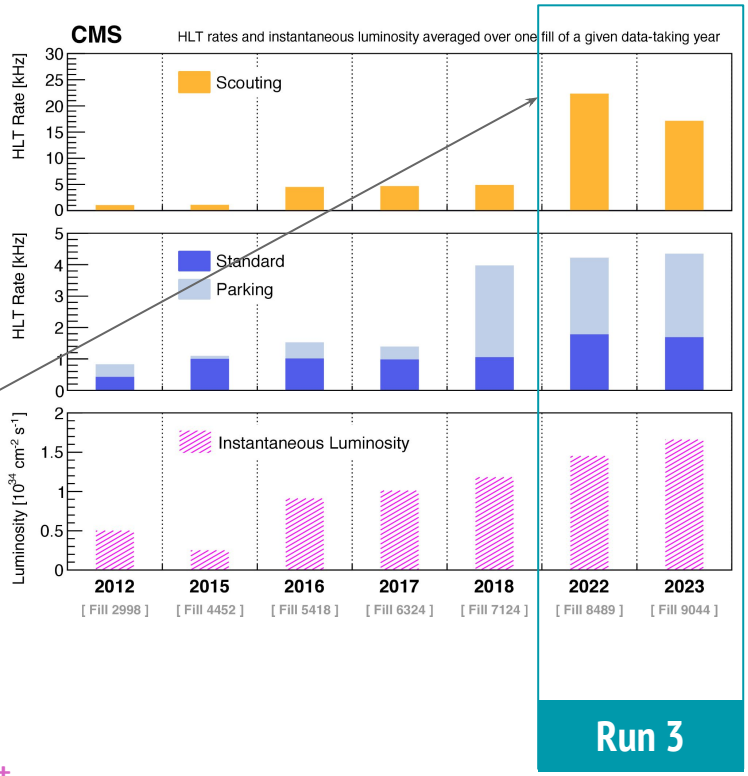


Enriched data taking



arxiv:2403.16134

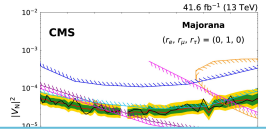




Data Scouting / Trigger Level Analysis

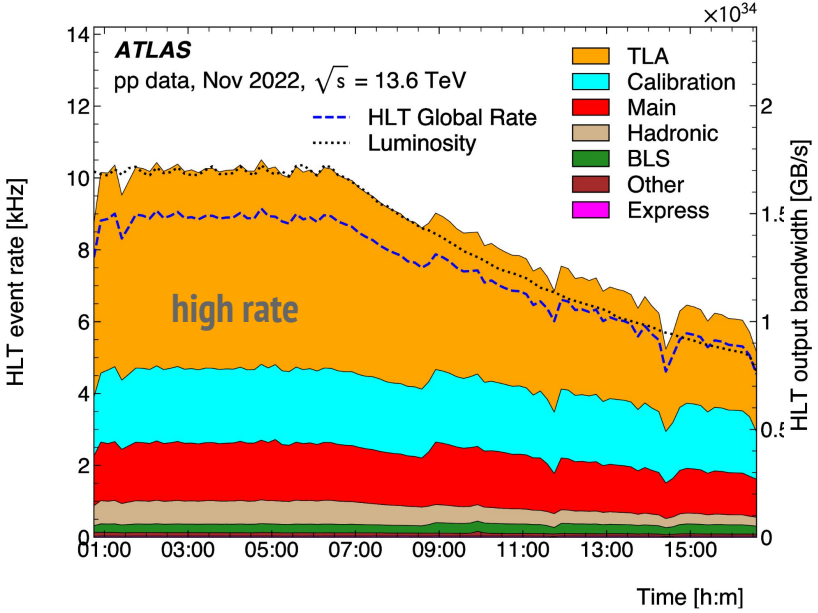
- enhance sensitivity by pushing thresholds
- respect bandwidth limits by only storing reduced event content
- analysis performed with trigger level objects

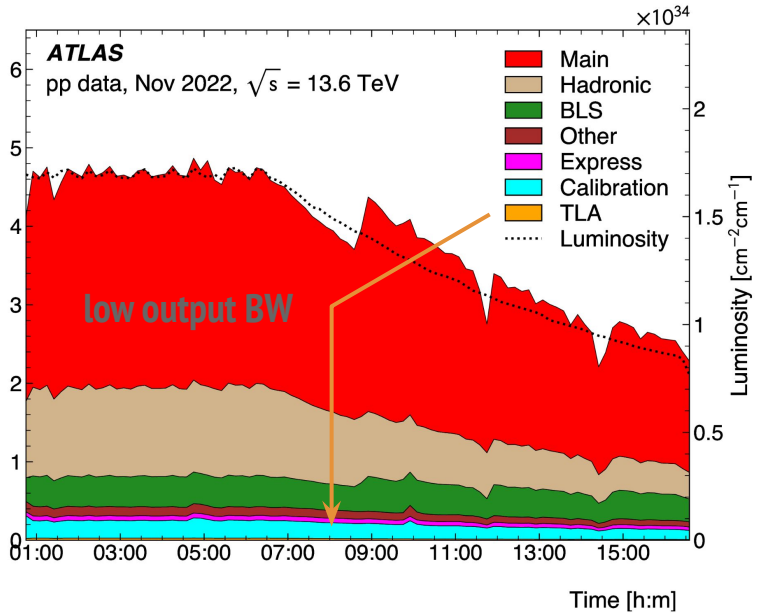
Enriched data taking



arxiv:2403.16134

Collisions: ~ 30 MHz





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arXiv:2401.06630 Trigger Level Analysis also in ATLAS

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Cover all the bases – *searches edition*

- **Reconstruction**
  tracks, unconventional tracks, vertexing, …
- **Detector strengths & weaknesses**
  >10 years of combined expertise, upgrades
- **(Under)exploited signatures**
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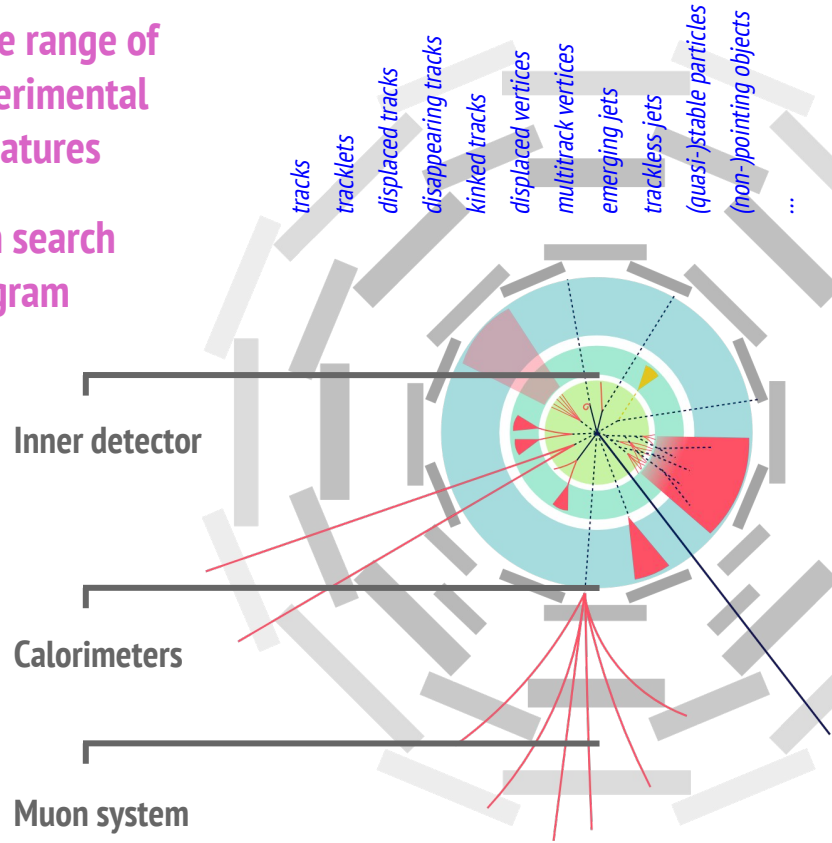


img:H. Russell

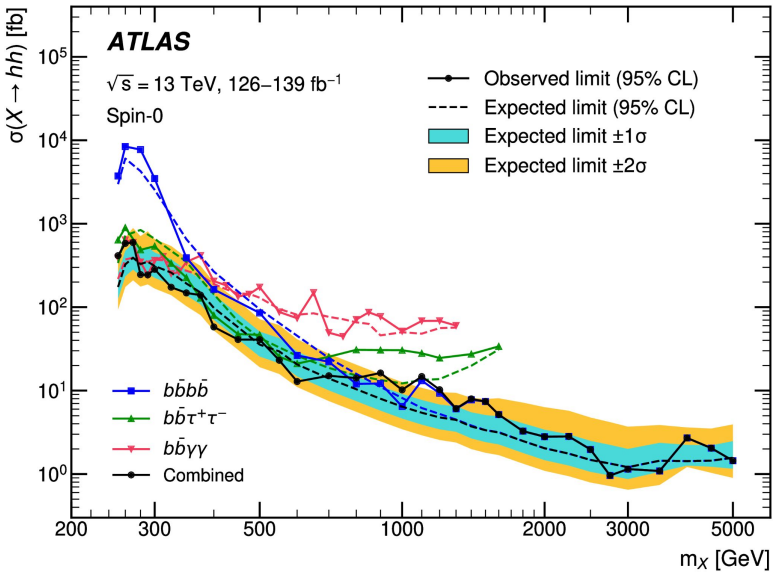
Global interpretation - *Combinations*

(some) HH combinations

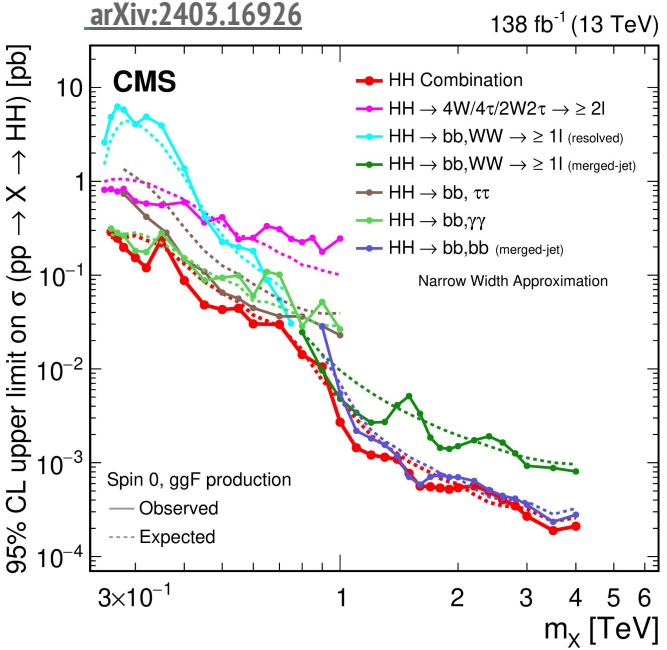
- recent resonant HH combinations from ATLAS & CMS
- many more results available

also don't have time to show any individual channel new HH results

arXiv:2311.15956



arXiv:2403.16926



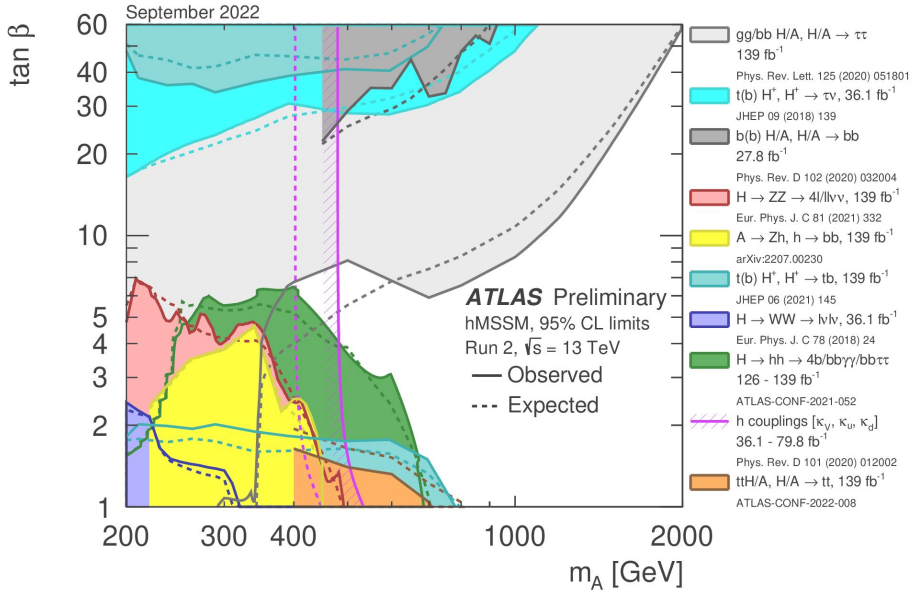
Global interpretation - *Summaries*

further BSM Higgs

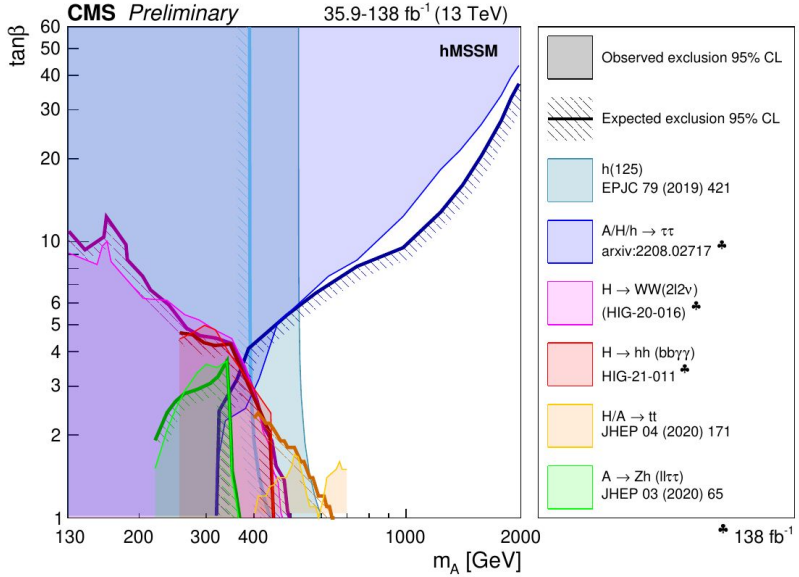
- hMSSM (type II 2HDM)
- many more results to come

Extended Higgs sector

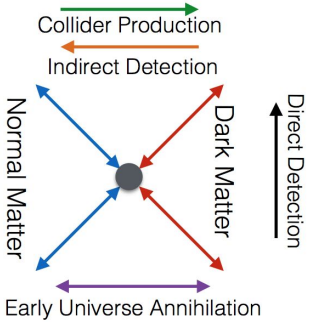
ATL-PHYS-PUB-2022-043



CMS Higgs summary plots



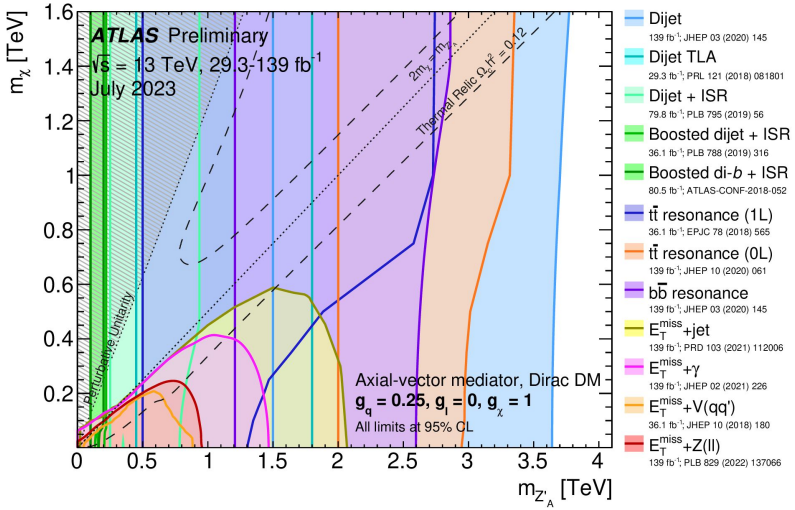
Global interpretation - *Summaries*



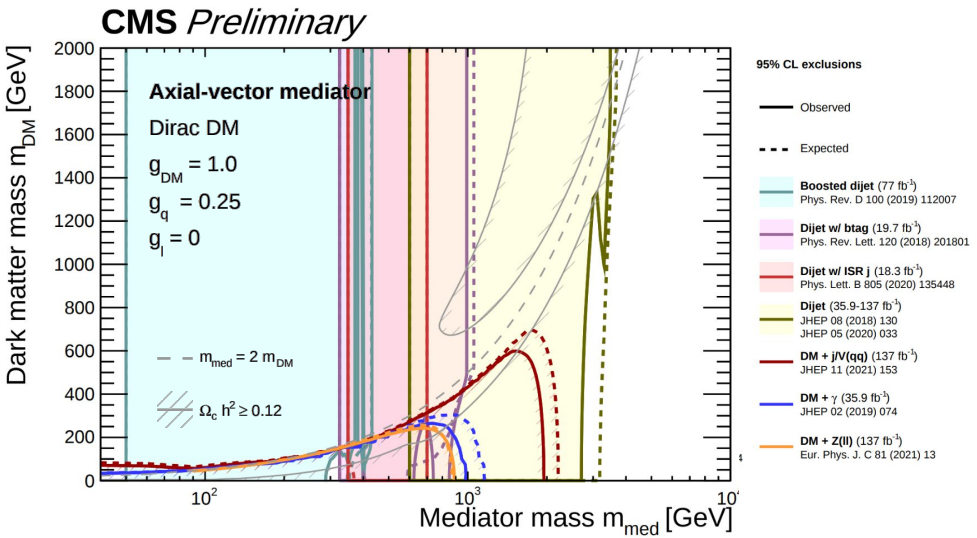
Dark matter

- showing summary for axial-vector mediator models
- many interpretations available

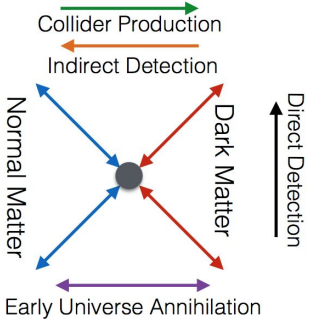
ATL-PHYS-PUB-2023-018



CMS Exotica Summary Plots



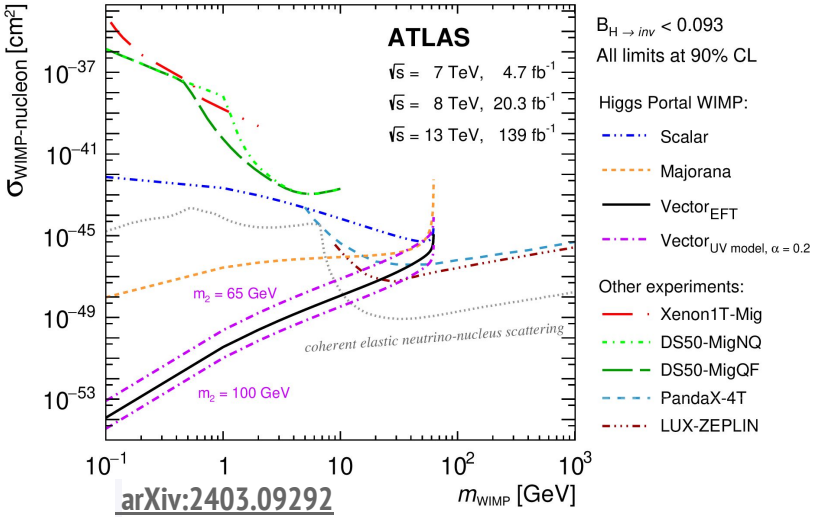
Global interpretation - *Summaries*



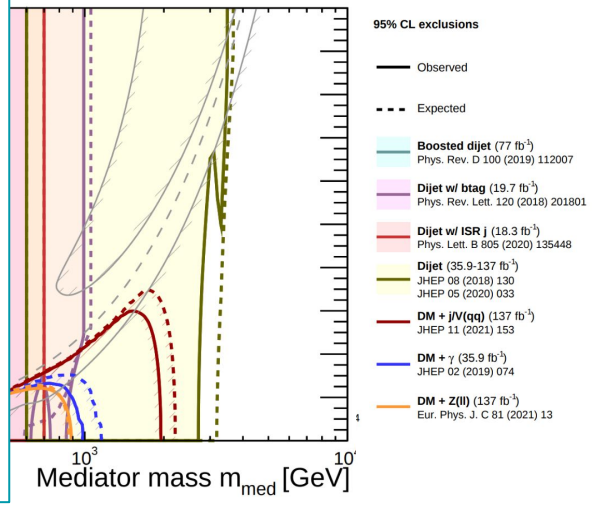
Dark matter

- showing summary for axial-vector mediator models
- many interpretations available

e.g. Higgs → invisible results & complementarity to direct detection limits



CMS Exotica Summary Plots



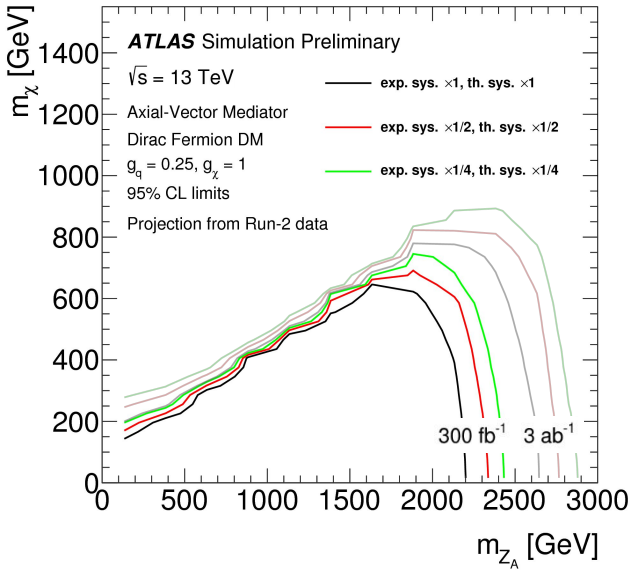
Global interpretation - *Summaries*

Collider Production
Indirect Detection

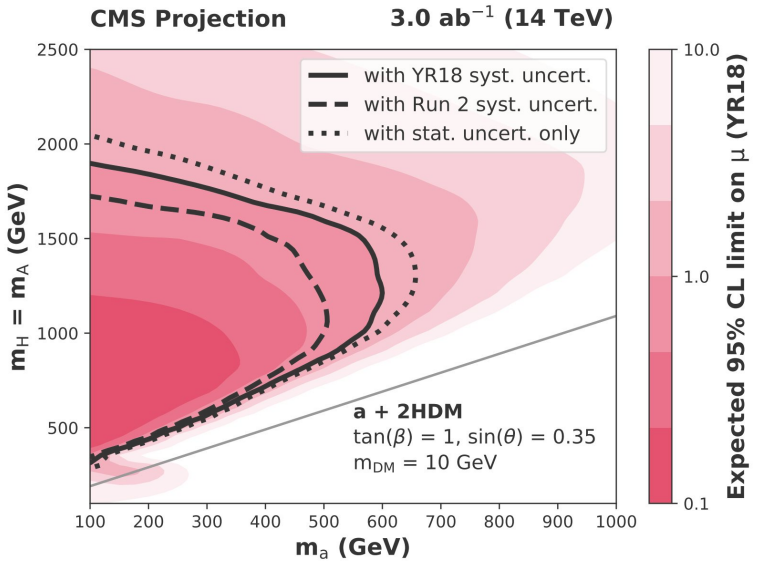
da

- **Projecting to HL-LHC**
-

ATL-PHYS-PUB-2018-043



CMS-PAS-FTR-18-007

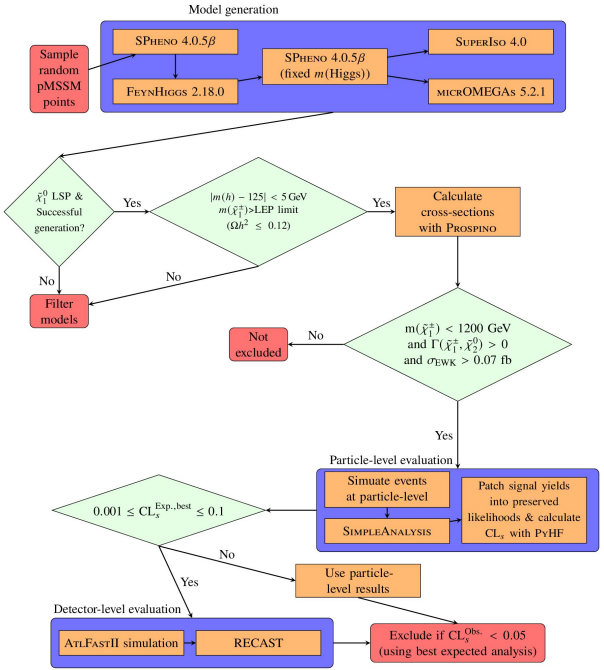


Global interpretation - *Electroweak pMSSM scan*

arXiv:2402.01392

Reinterpretation of ATLAS Run 2 EWK SUSY search results in the context of the pMSSM - 19 parameters, 5 of interest to scan

- consider LHC & external constraints
- early simple analysis filtering,
  more detailed (reinterpretation) analysis for non-excluded points
- investigate status of simplified model exclusion
  in different areas of phase space
- interpret *constraints on particle masses*,
  and test *compatibility with e.g. direct detection Dark Matter results*



Global interpretation - *Electroweak pMSSM scan*

arXiv:2402.01392

Re
in

-
-
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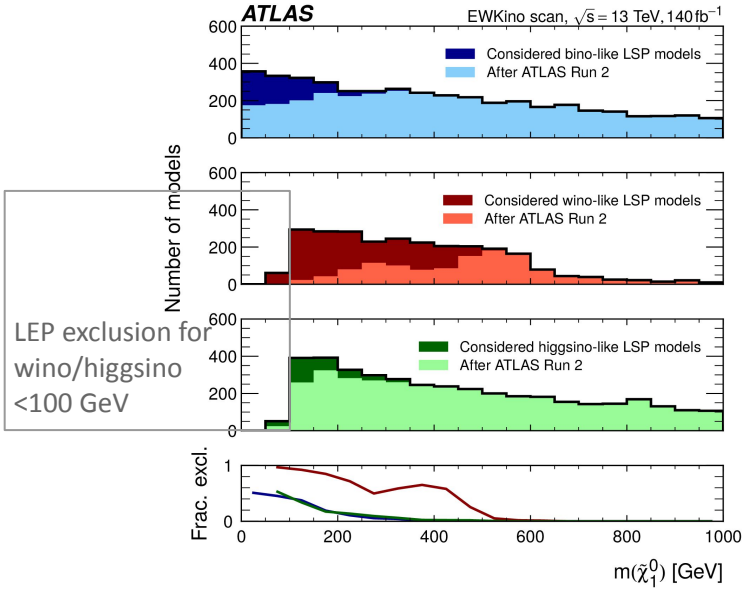
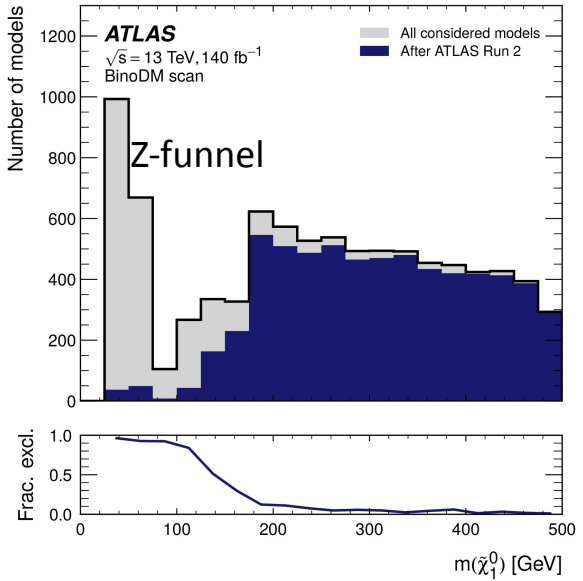
Overall improving exclusion in lower mass range



Bino LSP excluded below 100 GeV by ATLAS + other constraints



Global interpretation - *Electroweak pMSSM scan*

arXiv:2402.01392

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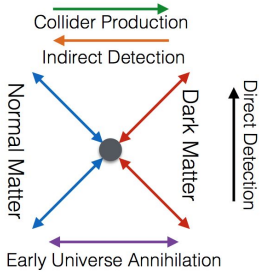
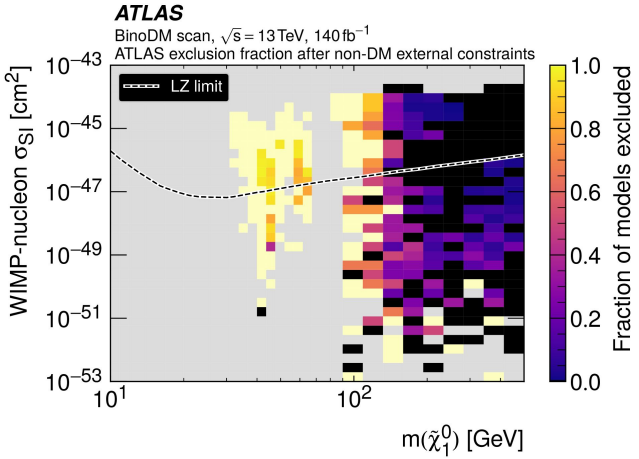


Complementarity between collider and direct searches

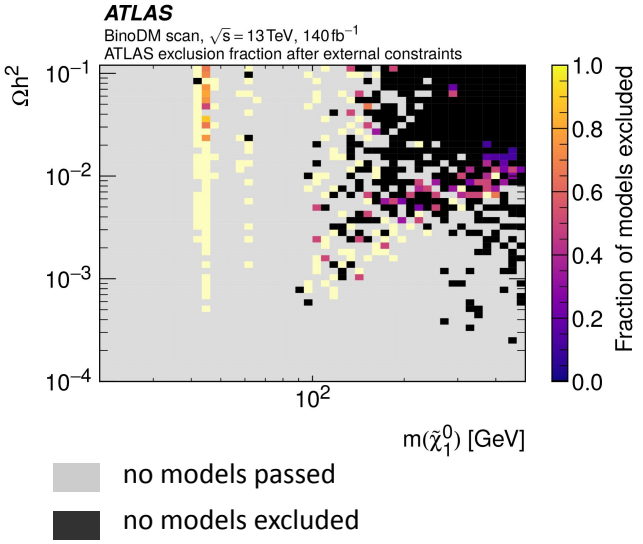
WIMP-nucleon cross section

(applying all non-DM external contraints)



relic density Ωh^2

(all external constraints applied)

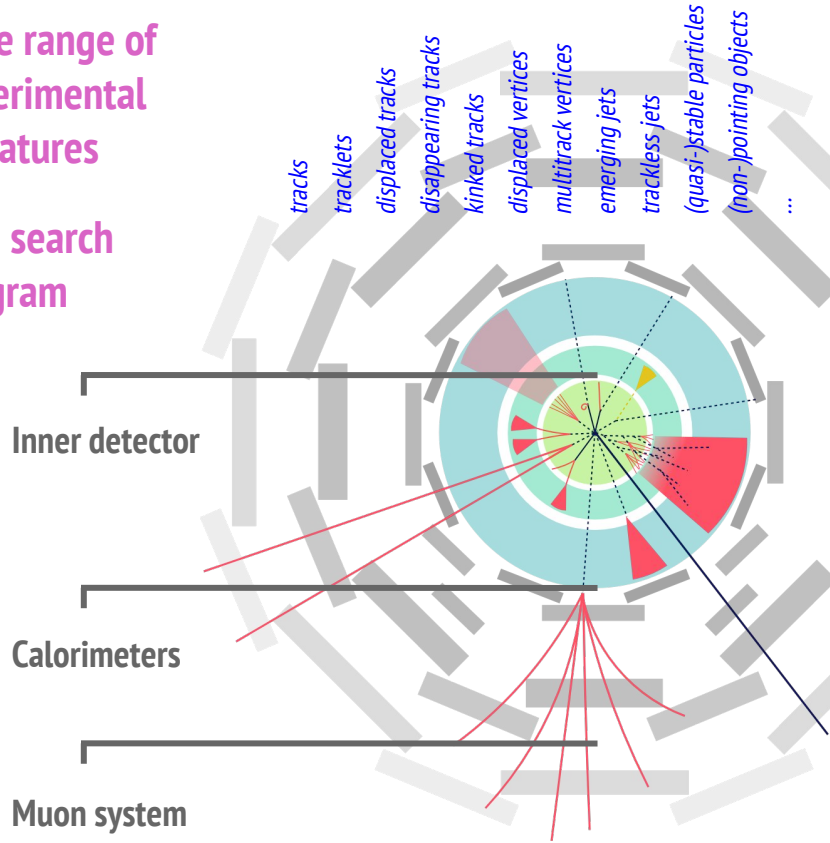


Cover all the bases – *searches edition*

- ✔ **Reconstruction**
  tracks, unconventional tracks, vertexing, …
- ✔ **Detector strengths & weaknesses**
  >10 years of combined expertise, upgrades
- ✔ **(Under)exploited signatures**
  long-lived particles, dark XYZ, multiplicities, …
- ✔ **New techniques**
  machine learning, data-formats, computing
- ✔ **Enriched data taking**
  data scouting/TLA, event picking
- ✔ **The bigger picture**
  anomaly searches, combinations, global interpretations
- ✔ **Think forward**
  baseline for HL-LHC, future experiments

Wide range of experimental signatures

Rich search program



img:H. Russell

Summary & Outlook

This talk could only cover a tiny fraction of the extremely **rich and varied LHC searches and HL-LHC upgrade programme**

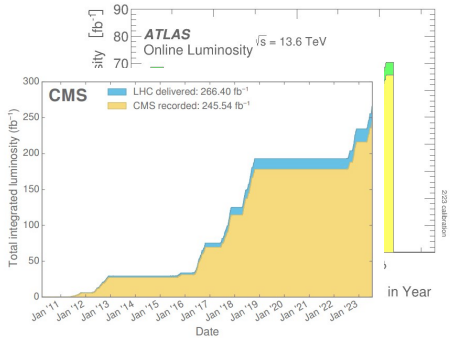
Many results are still forthcoming from the Run 2 dataset, and we're starting to see the first impact of the Run 3 one

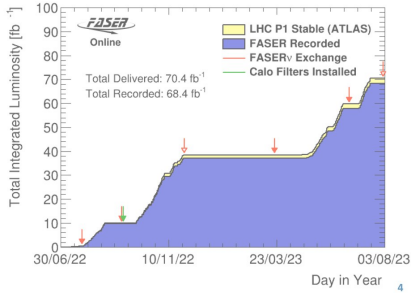
The **HL-LHC upgrades** will bring many **new possibilities** … and **many challenges**

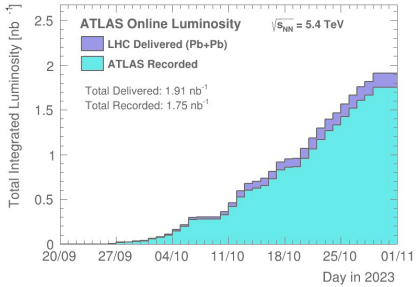
Promising plans and projections are in place, and experience from past runs has taught us that by being **meticulous** and staying **creative**, we can do even more

Technologies being developed today will allow us to **keep pushing boundaries and expanding frontiers**

Thank you - and stay tuned!





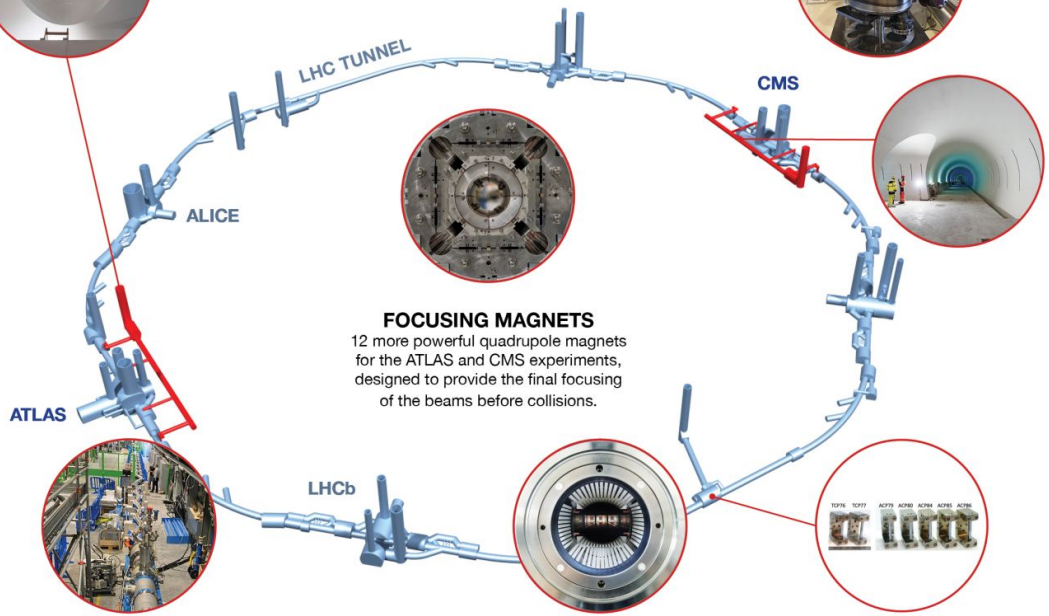


Backup Material

NEW TECHNOLOGIES FOR THE HIGH-LUMINOSITY LHC

CIVIL ENGINEERING
2 new 300-metre service tunnels and 2 shafts near ATLAS and CMS.

"CRAB" CAVITIES
16 superconducting "crab" cavities for the ATLAS and CMS experiments to tilt the beams before collisions.



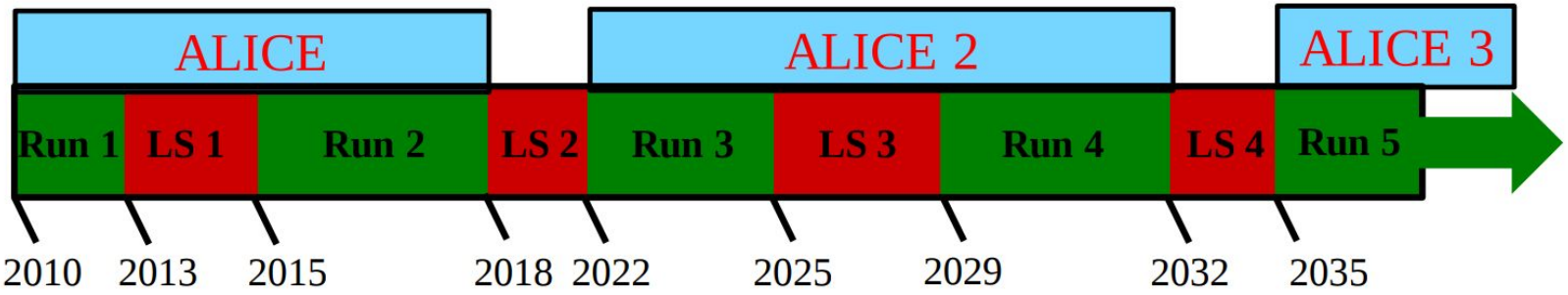
FOCUSING MAGNETS
12 more powerful quadrupole magnets for the ATLAS and CMS experiments, designed to provide the final focusing of the beams before collisions.

SUPERCONDUCTING LINKS
Electrical transmission lines based on a high-temperature superconductor to carry the very high DC currents to the magnets from the powering systems installed in the new service tunnels near ATLAS and CMS.

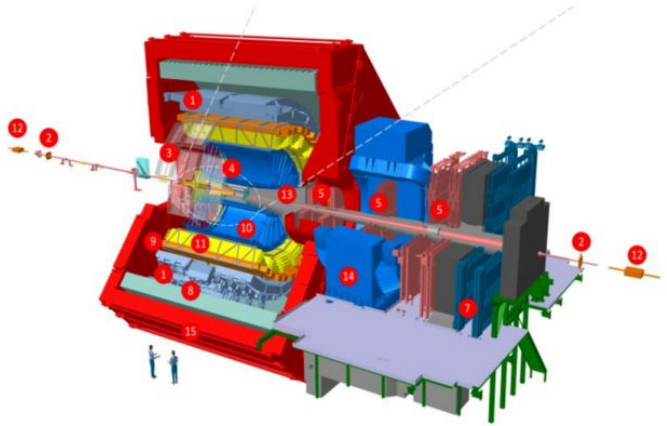
COLLIMATORS
15 to 20 additional collimators and replacement of 60 collimators with improved performance to reinforce machine protection.

CRYSTAL COLLIMATORS
New crystal collimators in the IR7 cleaning insertion to improve cleaning efficiency during operation with ion beams.

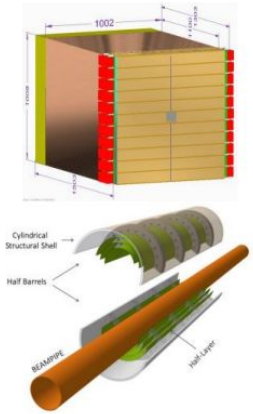
CERN February 2024



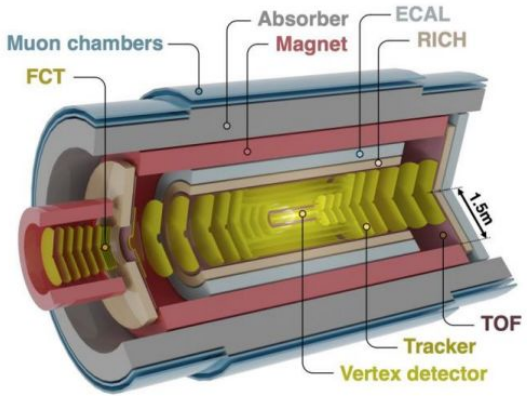
Run 3 ALICE 2

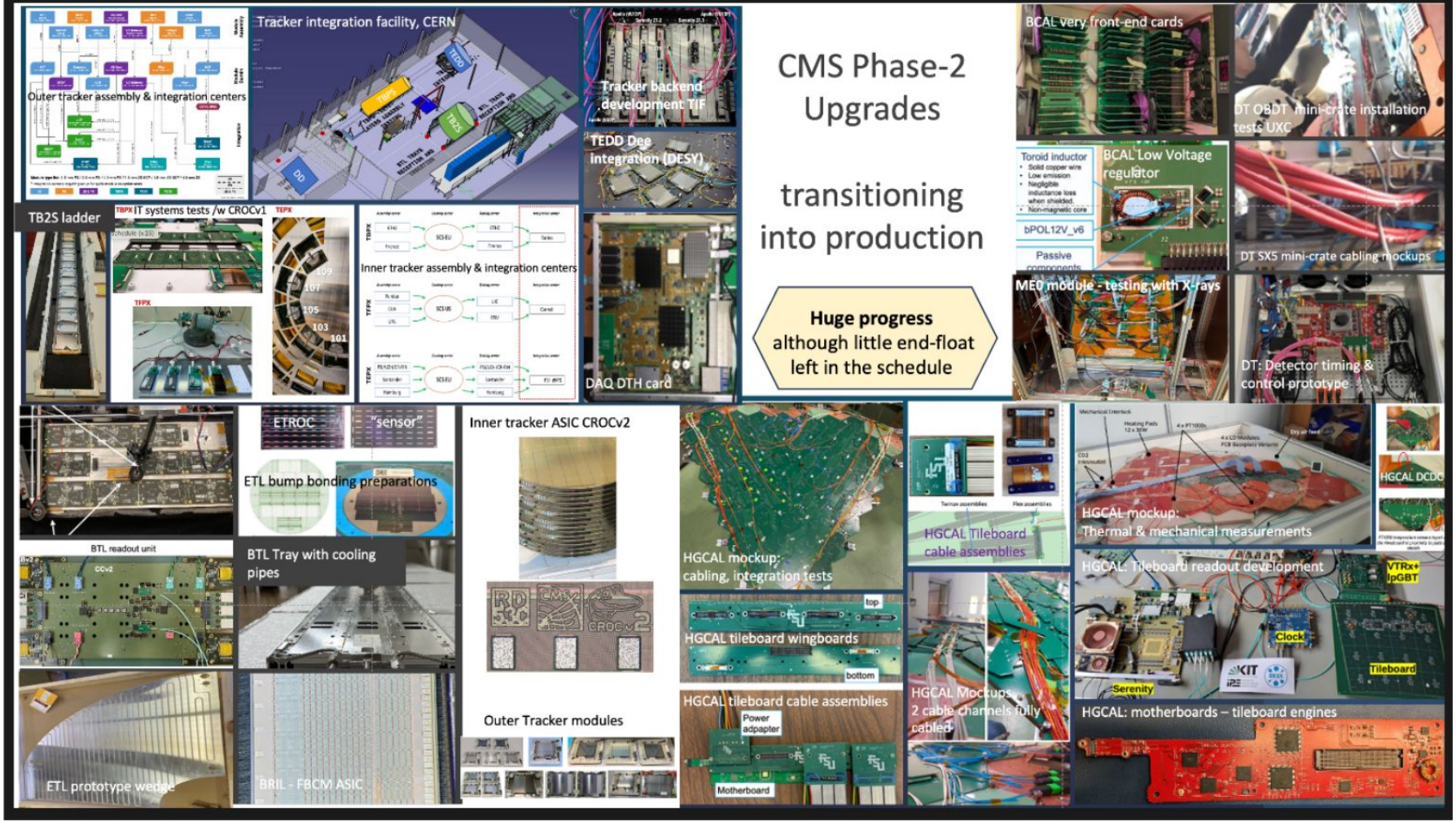


Run 4 FoCal and ITS 3

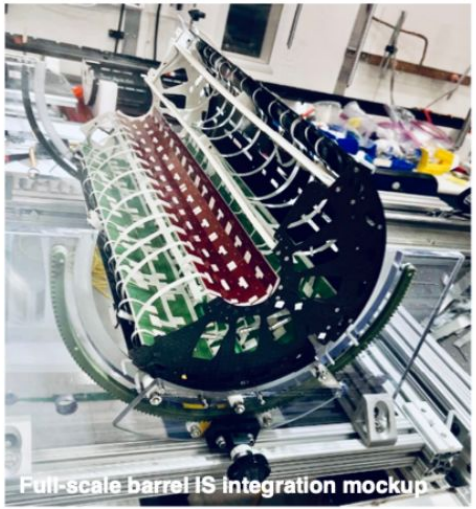


Run 5 ALICE 3




Outer tracker assembly & integration centers
Tracker integration facility, CERN
Tracker backend development TIF
TEDD Dee integration (DESY)
CMS Phase-2 Upgrades
transitioning into production
Huge progress
although little end-float left in the schedule
BCAL very front-end cards
DT OBDT mini-crate installation tests UXC
Toroid inductor
Solid copper wire
Low emission
Negligible inductance loss when shielded
Non-magnetic core
bPOL12V_v6
Passive components
BCAL Low Voltage regulator
DT SX5 mini-crate cabling mockups
TB2S ladder
IT systems tests /w CROCv1
Inner tracker assembly & integration centers
DAQ DTH card
ME0 module - testing with X-rays
DT: Detector timing & control prototype
ETROC
"sensor"
ETL bump bonding preparations
Inner tracker ASIC CROCv2
HGCAL mockup: cabling, integration tests
HGCAL Tileboard cable assemblies
HGCAL mockup: Thermal & mechanical measurements
HGCAL DCDC
BTL readout unit
BTL Tray with cooling pipes
HGCAL tileboard wingboards
top
bottom
HGCAL: Tileboard readout development
VTRx+ lpGBT
Clock
Tileboard
Serenity
HGCAL Mockups 2 cable channels fully cabled
HGCAL tileboard cable assemblies
Power adapter
Motherboard
HGCAL: motherboards – tileboard engines
Outer Tracker modules
ETL prototype wedge
BRIL - FBCM ASIC

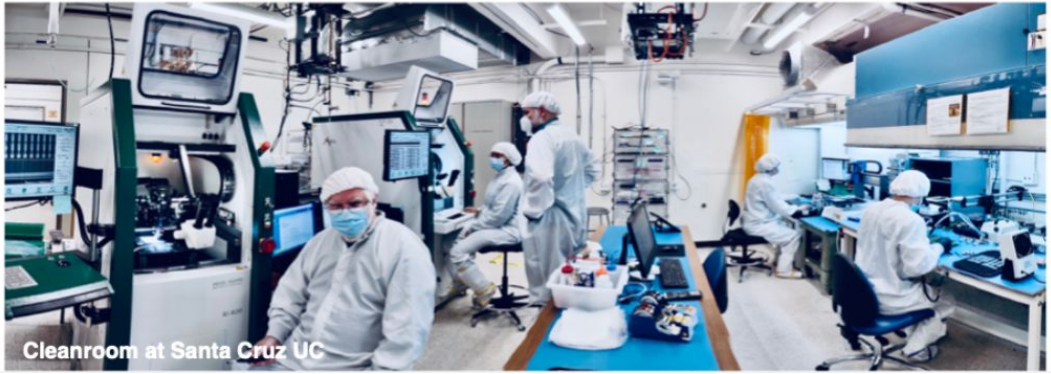

sR1 ITk surface assembly cleanroom at CERN


Full-scale barrel IS integration mockup

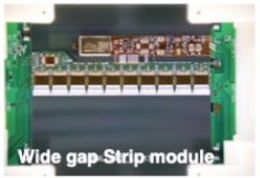

sMDT chambers at CERN (BB5)


GCM prototype v2b


LAr ALFEv2 ASIC


Cleanroom at Santa Cruz UC

ALTIROC-3 beamtest at DESY


Wide gap Strip module


Tile Main Board burn-in test at Chicago