Future of Hadron Spectroscopy at the Large Hadron Collider

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Los Alamos
NATIONAL LABORATORY

Community Summer Study
SNOWMASS
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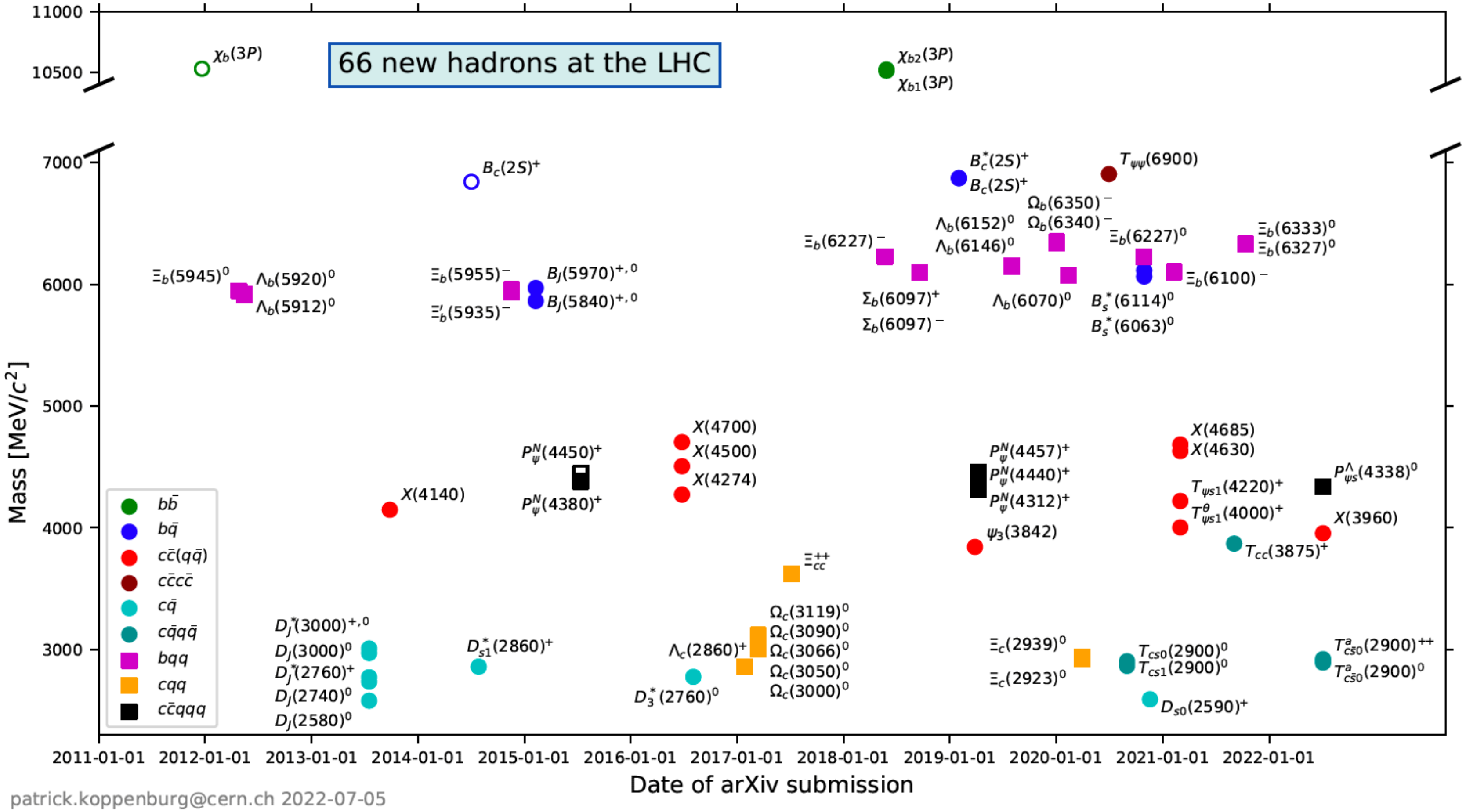
The New Particle Zoo

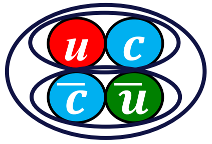


https://www.nikhef.nl/~pkoppenb/particles.html

- LHC has found dozens of new hadrons: quarkonia, mesons, baryons
- A significant fraction of these DO NOT fit into conventional framework:

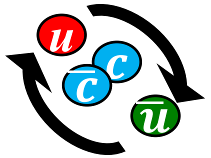
Diquark-diantiquark

PRD 71, 014028 (2005)
PLB 662 424 (2008)

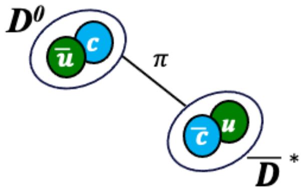


Hadrocharmonium/ adjoint charmonium

PLB 666 344 (2008)
PLB 671 82 (2009)



Hadronic Molecules



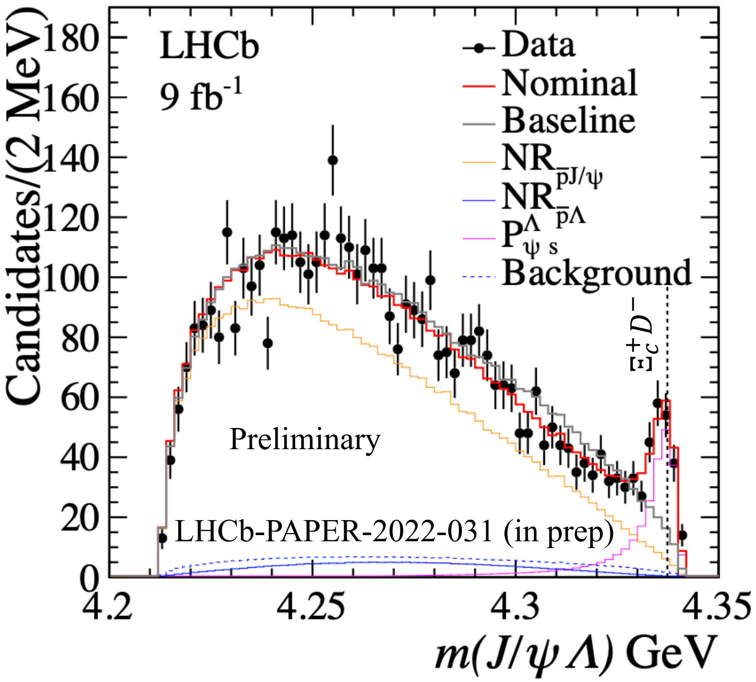
PLB 590 209 (2004)
PRD 77 014029 (2008)
PRD 100 0115029(R) (2019)

Mixtures

$$X = a\,|c\bar{c}\rangle + b\,|c\bar{c}q\bar{q}\rangle$$

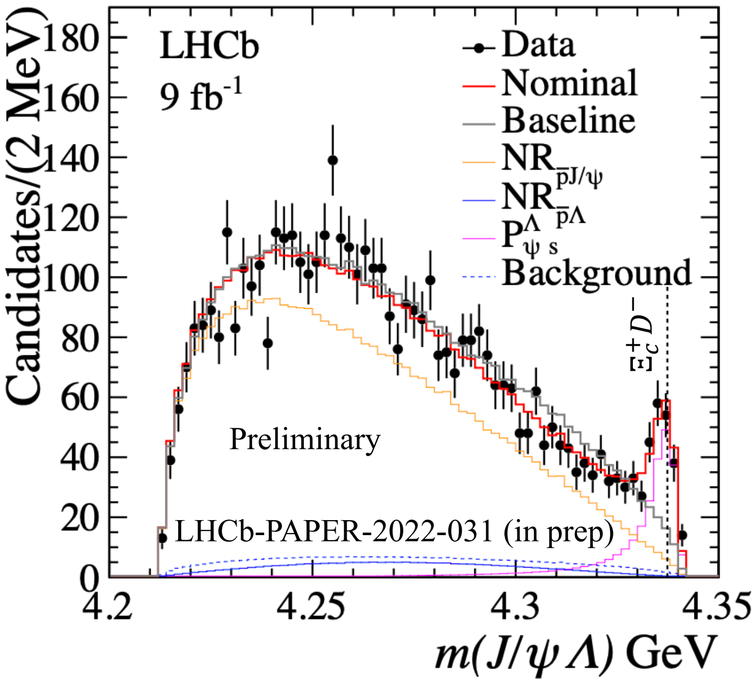
PLB 578 365 (2004)
PRD 96 074014 (2017)

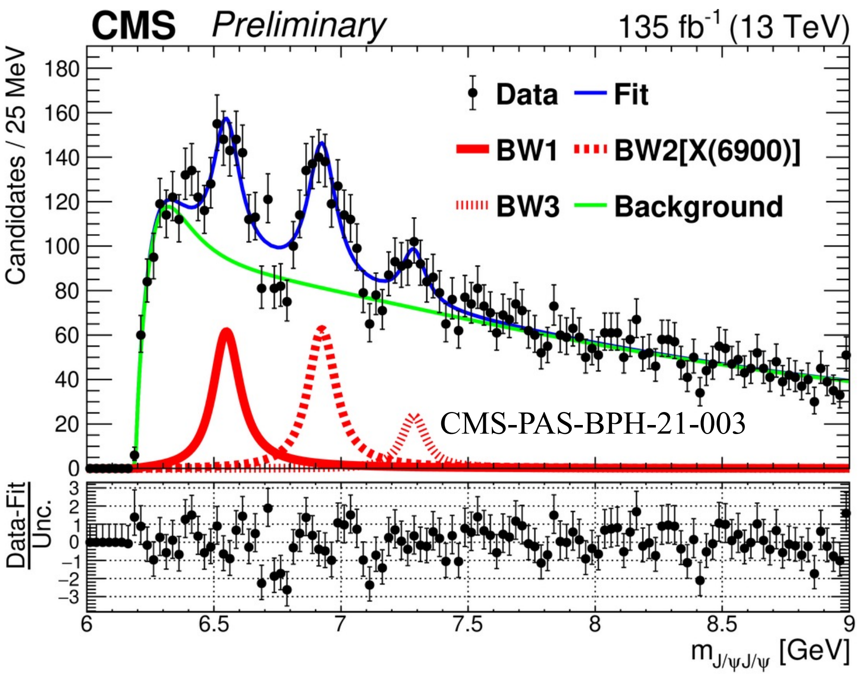
Recent examples



- LHCb observes new $P^{\Lambda}_{\psi s}(J/\psi\Lambda)$ state consistent with $c\bar{c}uds$
- Close to $\Xi_c^+ D^-$ mass threshold

Recent examples





- LHCb observes new $P_{\psi s}^{\Lambda}(J/\psi\Lambda)$ state consistent with $c\bar{c}uds$
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- CMS confirms X(6900) and finds other peaks in di-J/ψ mass spectrum

Recent examples

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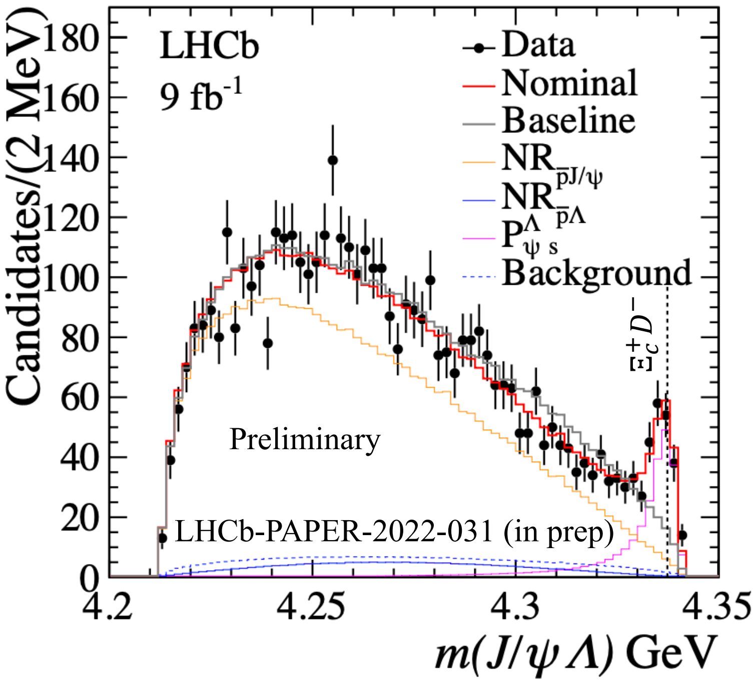

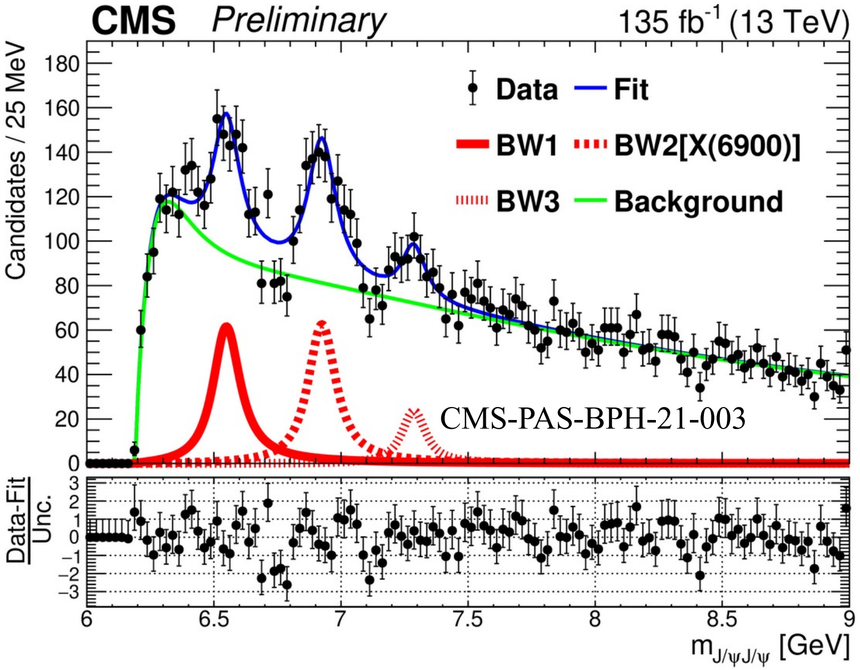

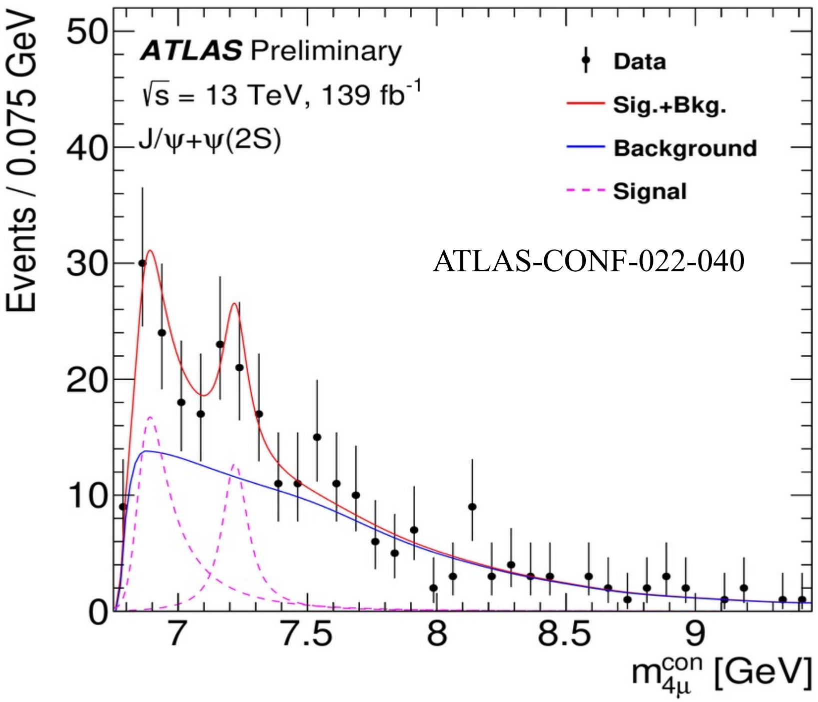

- LHCb observes new $P^{\Lambda}_{\psi s}(J/\psi\Lambda)$ state consistent with $c\bar{c}uds$
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- CMS confirms X(6900) and finds other peaks in di-J/ψ mass spectrum

- ATLAS also confirms X(6900) and finds structure in $\psi(2S) + J/\psi$ mass

- **Rich spectrum of $c\bar{c}c\bar{c}$ states accessible with dimuons.**

Goals of hadron spectroscopy

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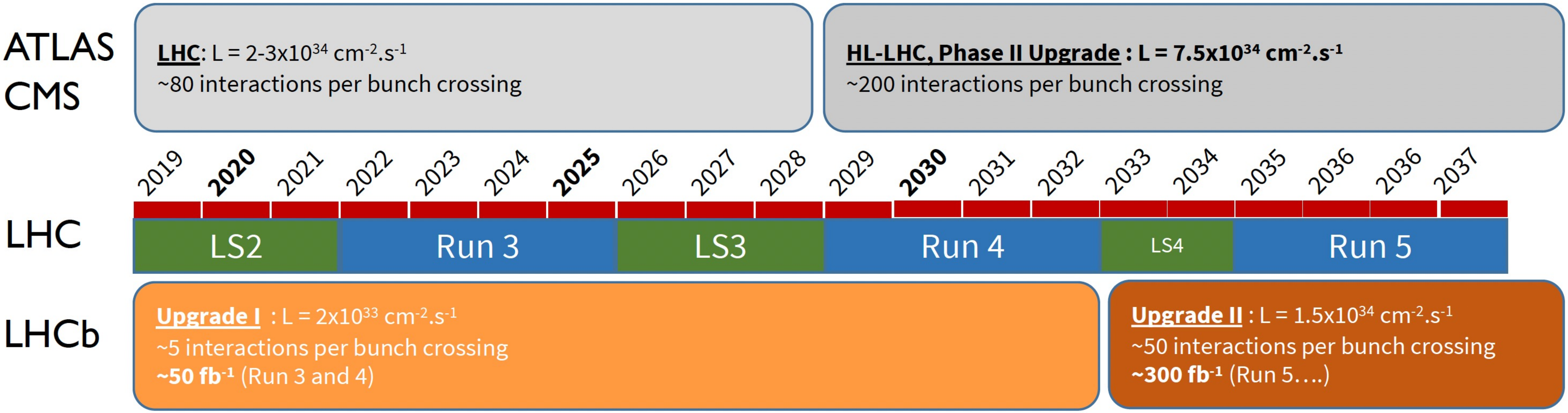
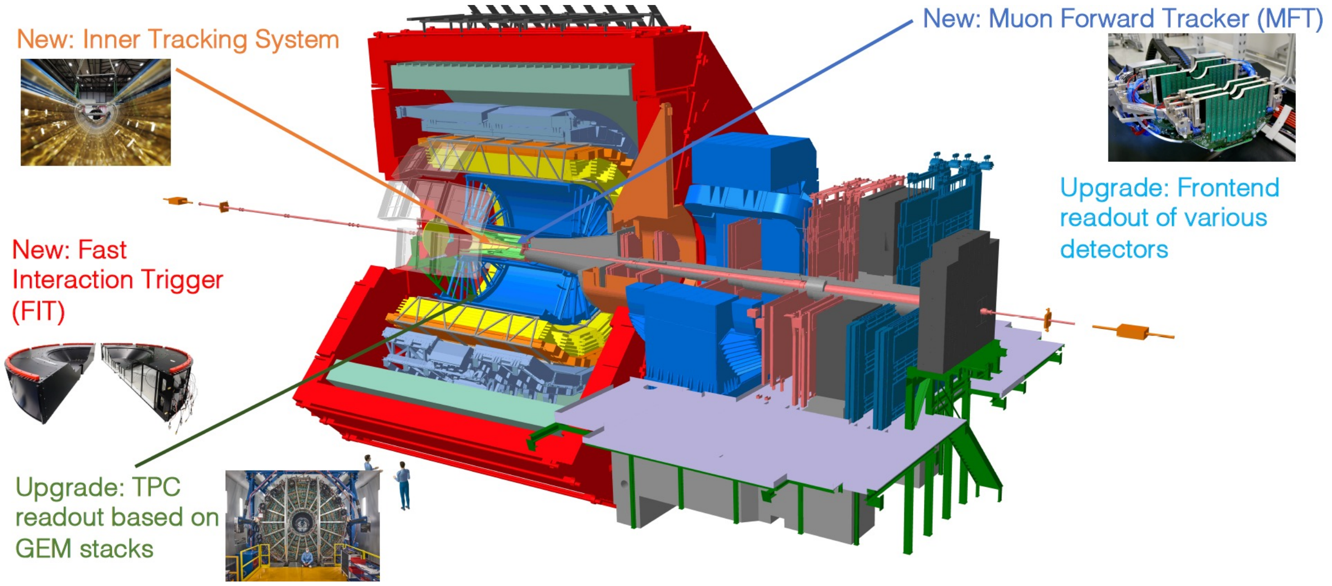
Overall goal: a complete, predictive understanding of hadrons allowed by QCD

- Experimental tools for reaching goal:
  - **High statistics data sets**
    - Required to access rare states, such as multi-heavy hadrons
    - Still lots to do with exotics in bottom sector, potentially $b\bar{b}b\bar{b}$ spectrum
  - **Upgraded detectors**
    - Take advantage of luminosity upgrades, separate signals from background, explore new production phase space
  - **New approaches**
    - Analysis techniques that take advantage of increased stats, heavy ion collisions, UPCs

Luminosity improvements



Detector upgrades - ALICE



ALICE for Run-3: CERN-LHCC-2013-020

- Continuous TPC readout with GEMs greatly increases event rate: ~1Mhz in pp and ~50kHz in PbPb
- Upgraded vertex detectors at mid and forward rapidity

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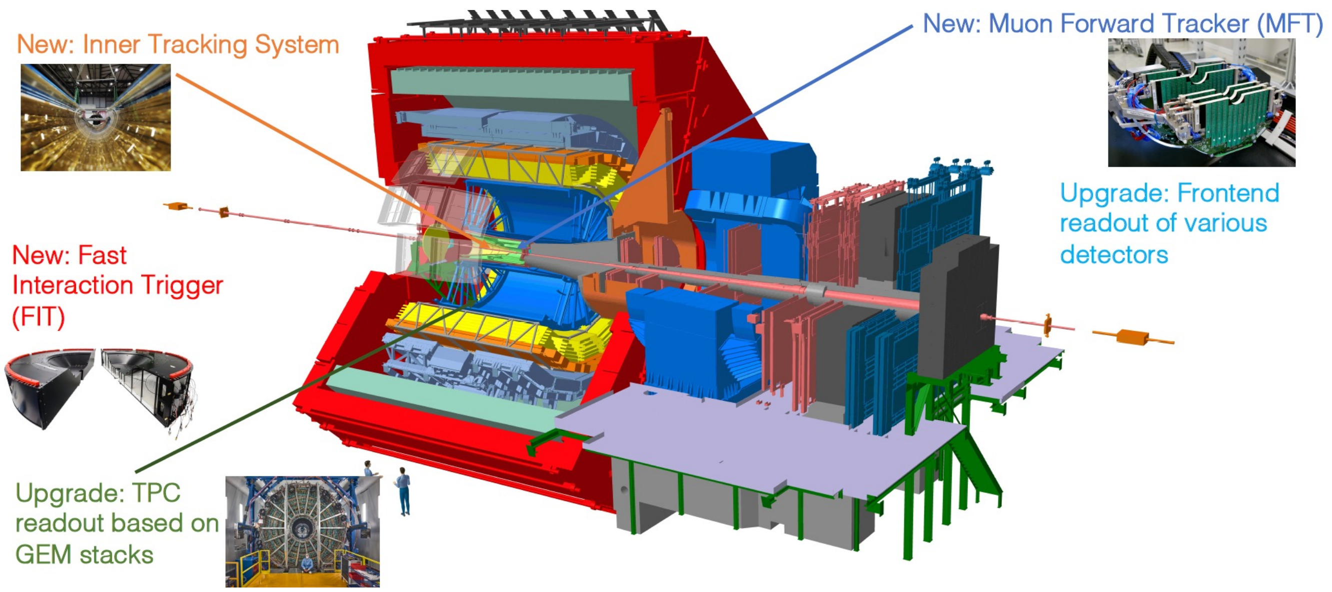

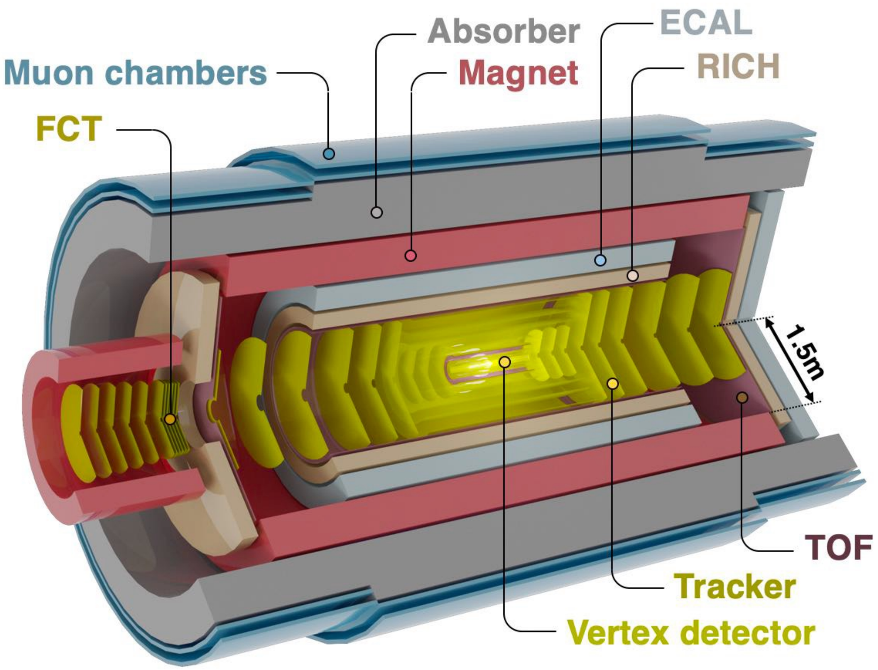

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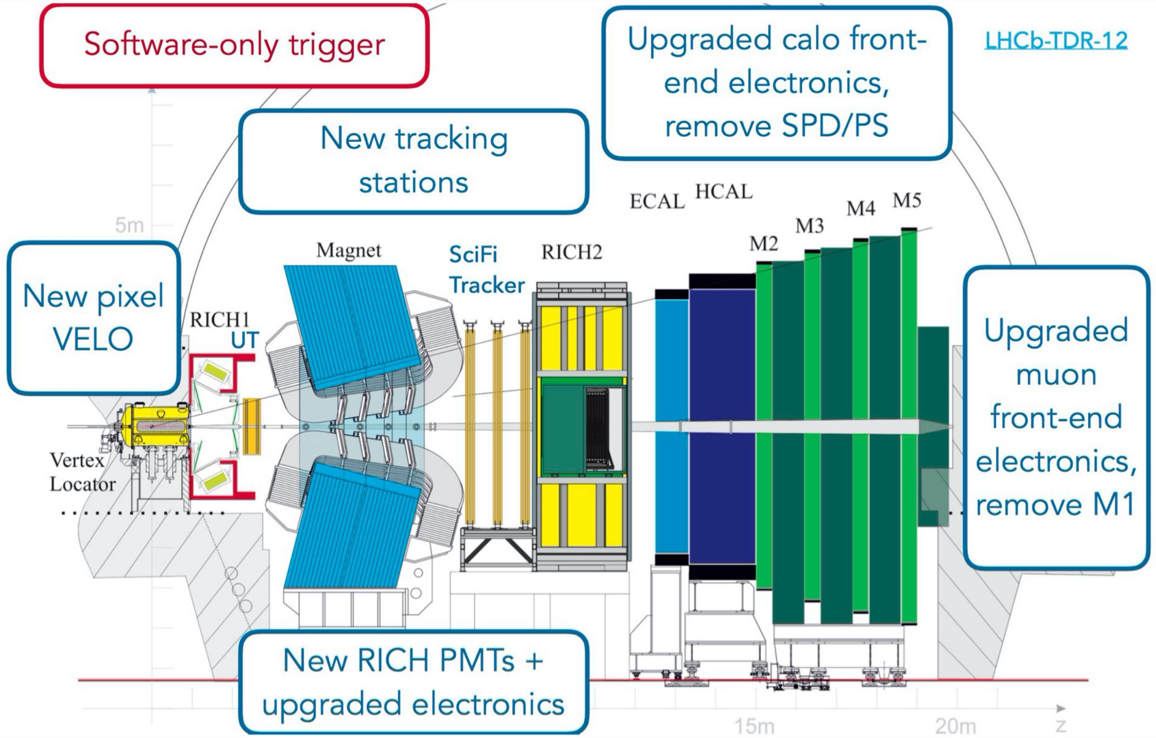
ALICE3 for Run-5: CERN-LHCC-2022-009

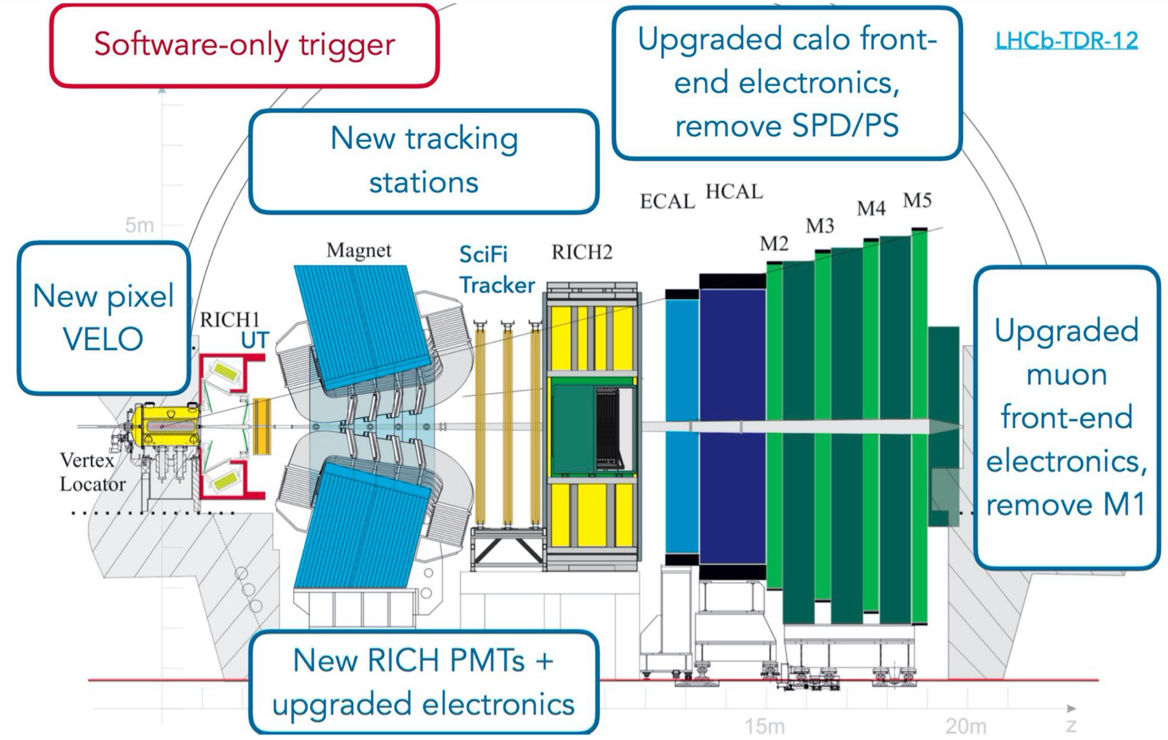
- Superconducting magnet and all silicon tracking
- Full PID with fast silicon and aerogel RICH
- EMCal coverage over full azimuth
- Charm hadronization into multi-heavy sates and exotics is a major focus → huge potential

Detector upgrades - LHCb



- **Full streaming readout**
  - Advancing the state-of-the-art for collider detector data acquisition
  - Samples full delivered luminosity at 40MHz
- **Increased granularity in tracking**
  - Improves tracking performance and enables access to central heavy ion collisions (>30% centrality)

Detector upgrades - LHCb



Plans for upgrade 2 well underway:
CERN-LHCC-2021-012

- **Full streaming readout**
  - Advancing the state-of-the-art for collider detector data acquisition
  - Samples full delivered luminosity at 40MHz
- **Increased granularity in tracking**
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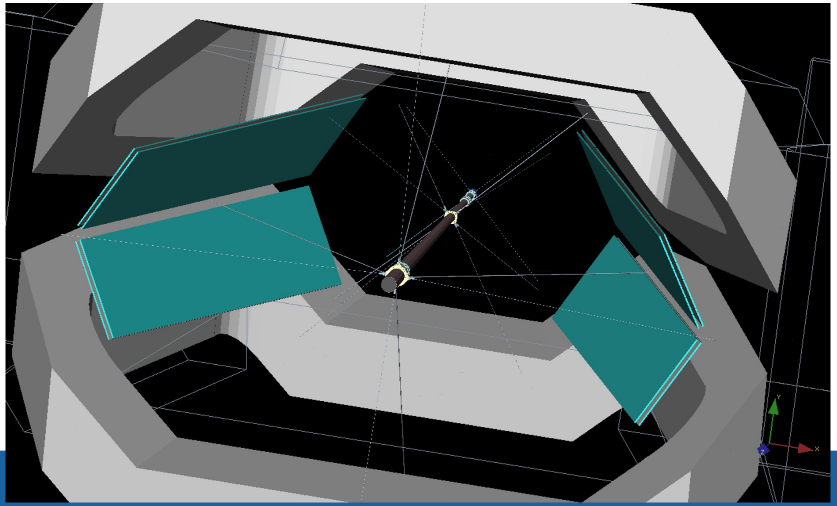
- **Magnet station tracker for coming in Run 4.**
  - Access to soft pions from e.g. $X(3872) \rightarrow J/\psi\pi\pi$ and D^* decays



ATLAS and CMS upgrades

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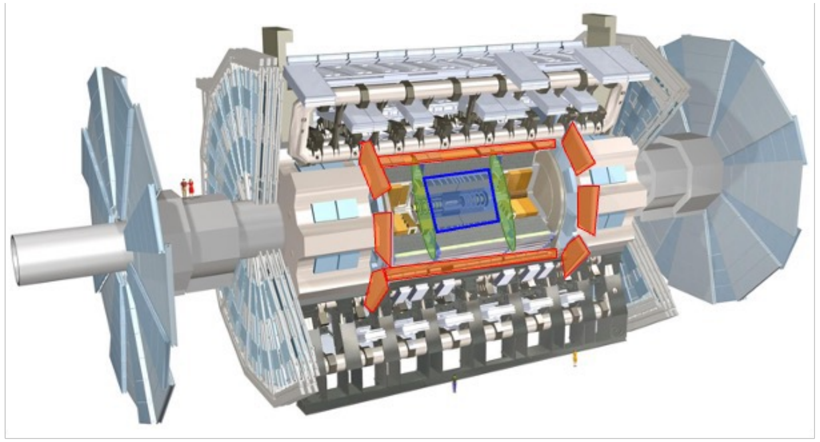
ATLAS Phase 2: CERN-LHCC-2015-020



Upgraded Trigger and Data Acquisition System
- Single Level Trigger with 1 MHz output
- Improved 10 kHZ Event Farm

Electronics Upgrades
- On-detector/off-detector electronics upgrades of LAr Calorimeter, Tile Calorimeter & Muon Detectors
- 40 MHz continuous readout with finer segmentation to trigger

High Granularity Timing Detector (HGTD)
- Precision time reconstruction (30 ps) with Low-Gain Avalanche Detectors (LGAD)
- Improved pile-up separation and bunch-by-bunch luminosity

New Muon Chambers
- Inner barrel region with new RPCs, sMDTs, and TGCs
- Improved trigger efficiency/momentum resolution, reduced fake rate

New Inner Tracking Detector (ITk)
- All silicon with at least 9 layers up to $|\eta| = 4$
- Less material, finer segmentation

Additional small upgrades
- Luminosity detectors (1% precision)
- HL-ZDC (Heavy Ion physics)

- Upgraded detector to handle high pileup in pp collisions
- Improved tracking enhances mass resolution
- Upgraded electronics samples larger fraction of delivered luminosity

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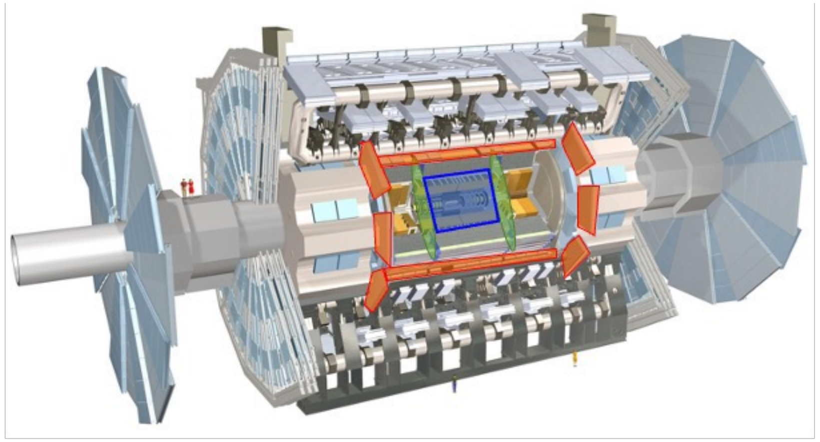

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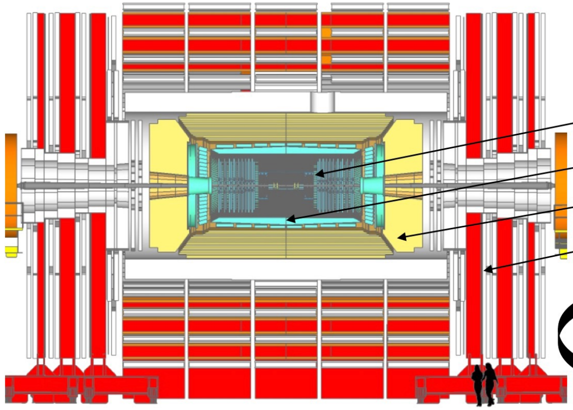
CMS Phase 2: CERN-LHCC-2015-010



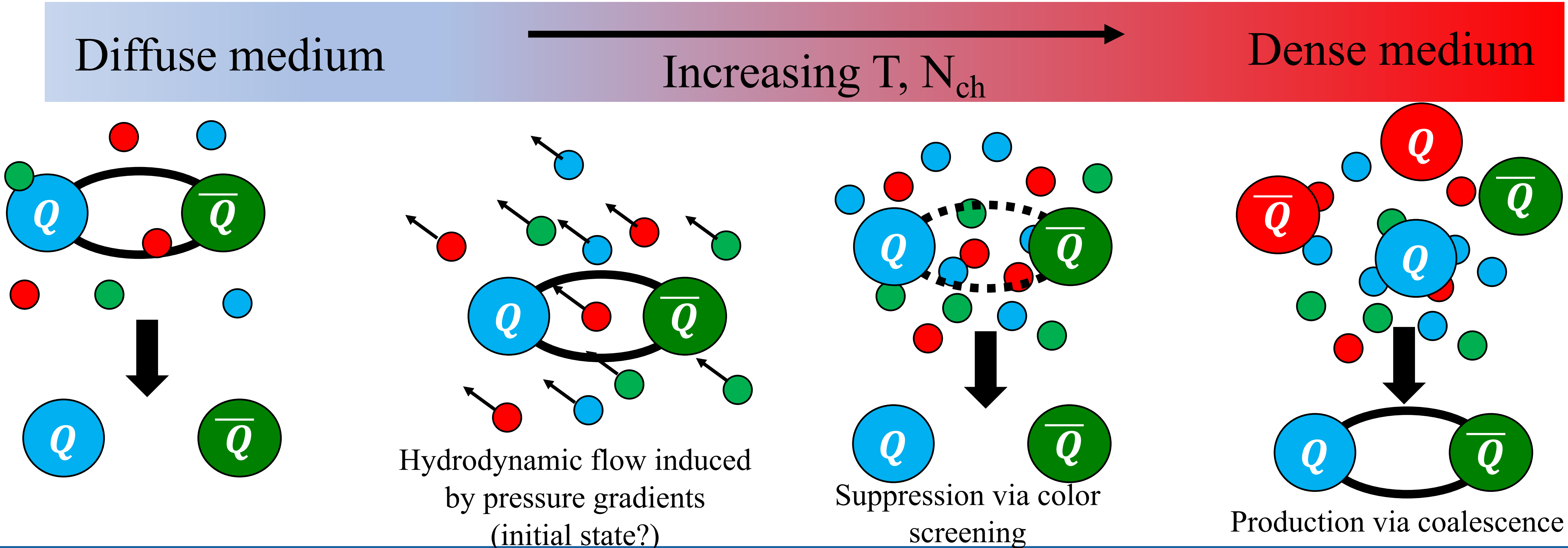
System	Present	Phase 2
Tracker	$|\eta| < 2.4$	$|\eta| < 4$
TOF	None	$|\eta| < 3$
Calorimeters	Standard	High granularity
Muon	$|\eta| < 2.4$	$|\eta| < 2.8$
Trigger	100 kHz	750 kHz
DAQ	6 GB/s	60 GB/s

Record **all** PbPb events (≈50% in Run 3)

- Expanded tracking over larger rapidity interval
- PID with combinational of pixel DE/dx and TOF – allows π/K/p separation down to p_T~300 MeV

New collision systems

- Interactions of exotic states with other particles produced in the collision provide new probes of their binding energy/structure: comover breakup and coalescence dominate in different multiplicity regimes
- Models predict drastically different production rates for compact tetraquarks vs hadronic molecules (see backup)



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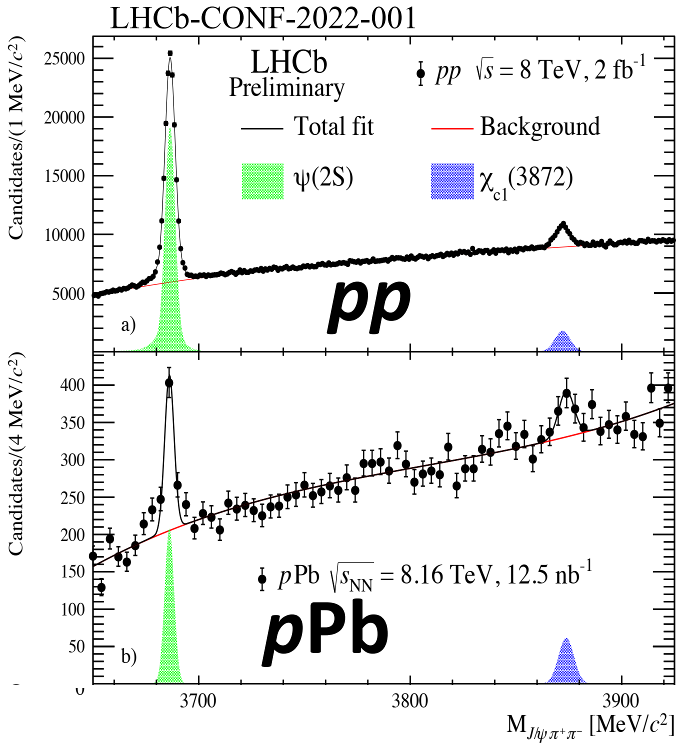

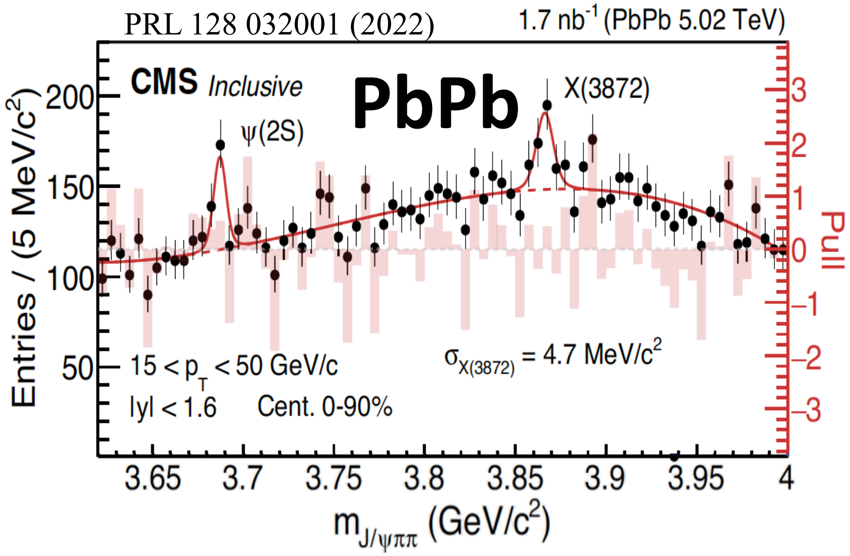

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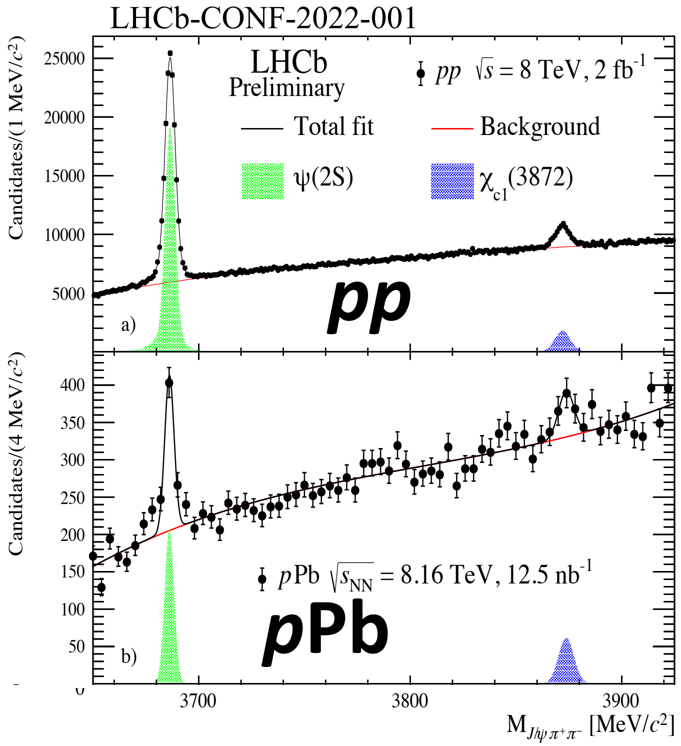

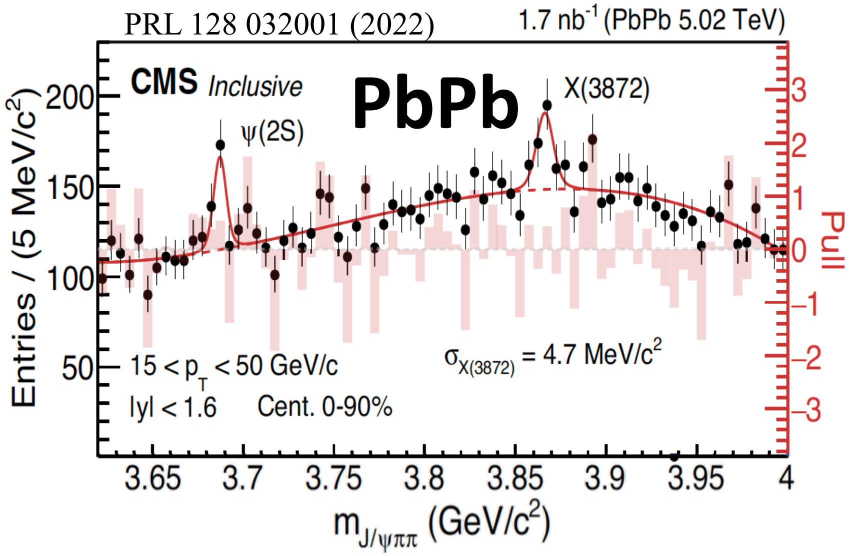

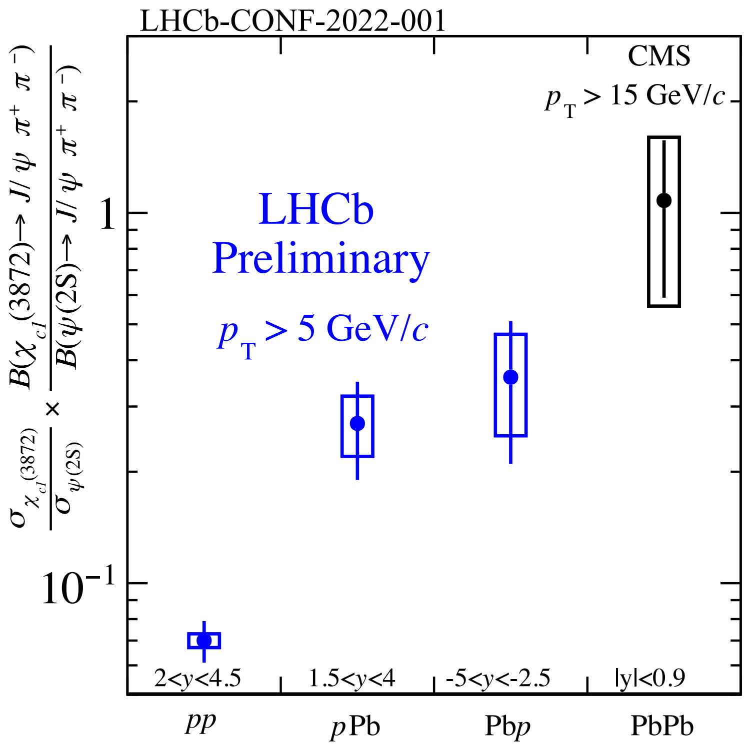

- **First studies in heavy ion collisions show differences between exotic X(3872) and conventional charmonium $\psi(2S)$**

Summary

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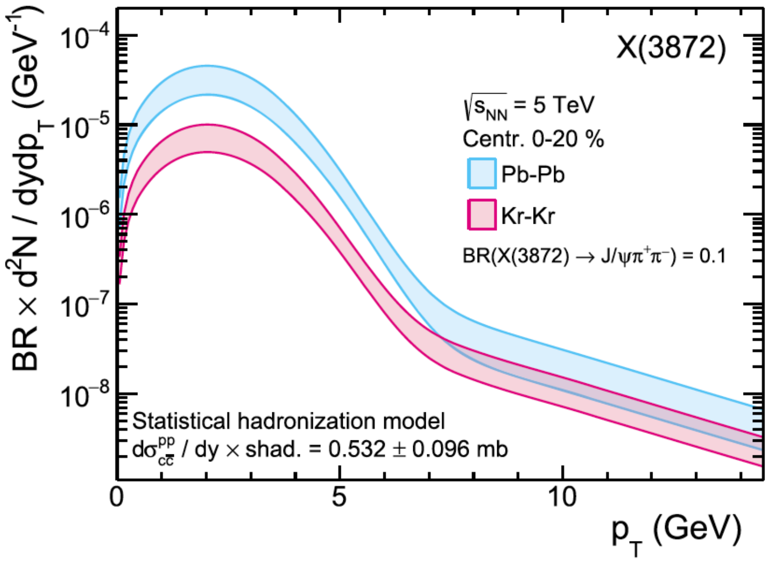
- Hadron spectroscopy is a highly active of QCD research at the LHC.
  - Pace of discoveries is *accelerating.* No reason to believe it will slow.
- *All four* major experimental collaborations at the LHC are actively pursuing upgrades that will directly improve spectroscopy capabilities.
- Upgraded detectors, more data, different collisions systems, new techniques: all contribute to a full understanding of bound states allowed by QCD.

Los Alamos National Laboratory is supported by the US Dept. of Energy/Office of Science/Nuclear Physics and DOE Early Career Awards

BACKUPS

X(3872) in PbPb

PLB 797 (2019) 134836

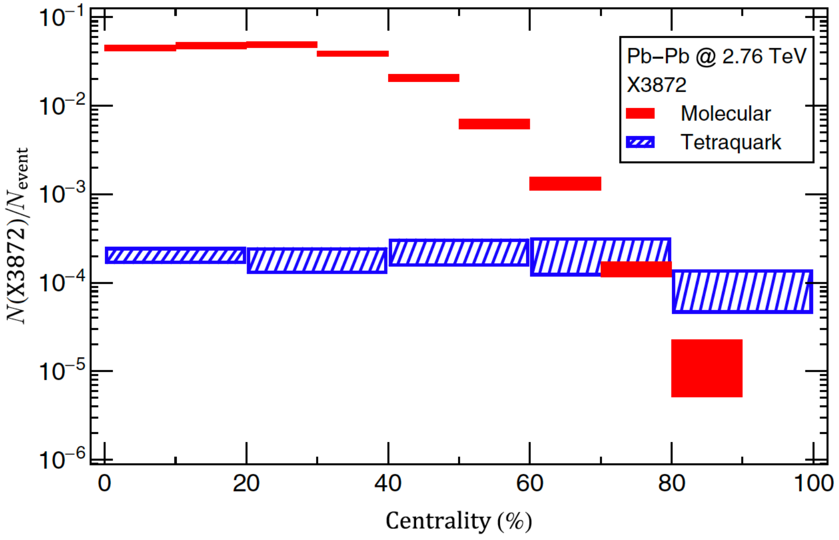


SHMC model:

Significant increase in X(3872) predicted for central AA collisions

Yield reaches up to ~1% of J/ψ yield

PRL 126 012301 (2021)

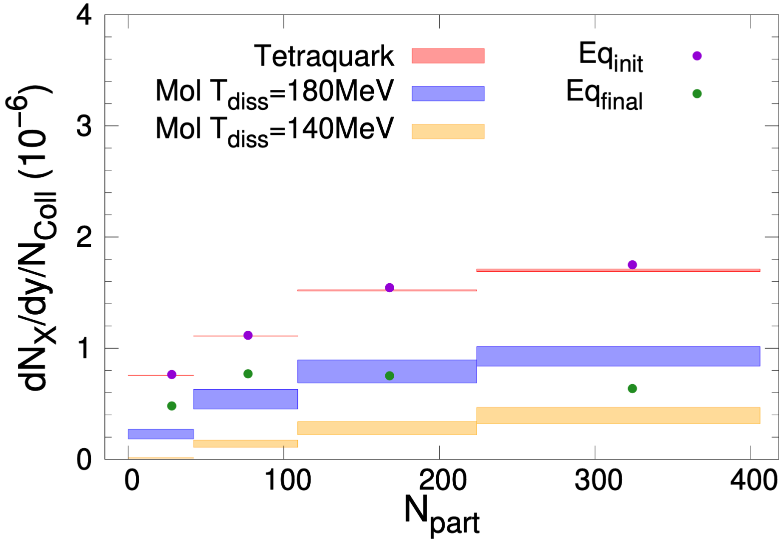


AMPT model:

difference in molecule vs diquark-diquark coalescence gives dramatically different yields and centrality dependence:

$N_{molecule} > N_{tetraquark}$

EPJA 57 122 (2021)



Transport calculation:

molecules have larger reaction rate, formed later in fireball evolution

$N_{tetraquark} > N_{molecule}$