LHC Future Challenges: Physics

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Outline

- LHC experiments
- LHC upgrades
- Upgrades for the LHC experiments
- Selected topics in HL-LHC physics opportunities
- Connections with the CWP process

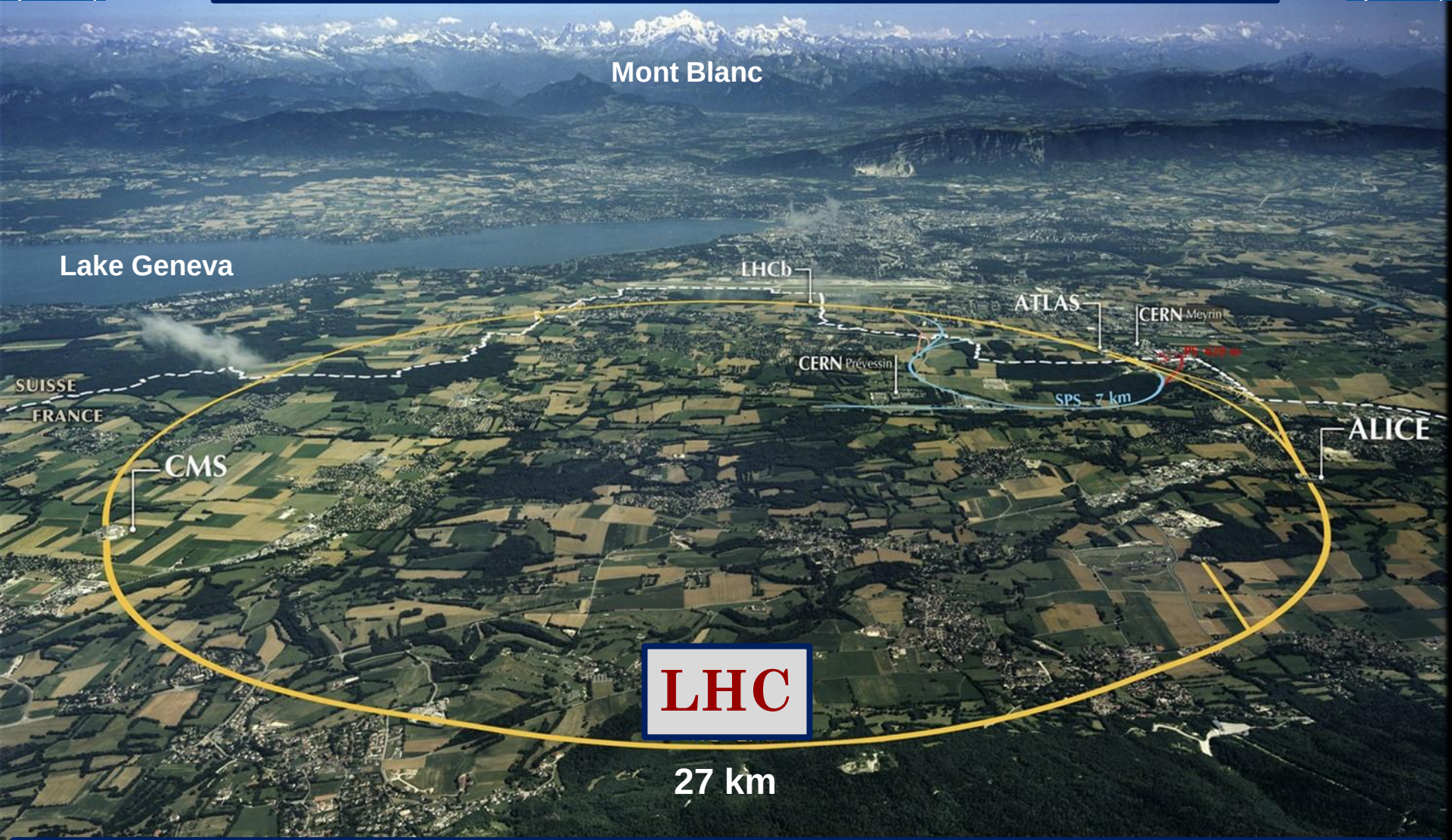
Note: These slides draw heavily from the ECFA HL-LHC Workshop held in October 2016. Please see

https://indico.cern.ch/event/524795

for the details and much more additional information

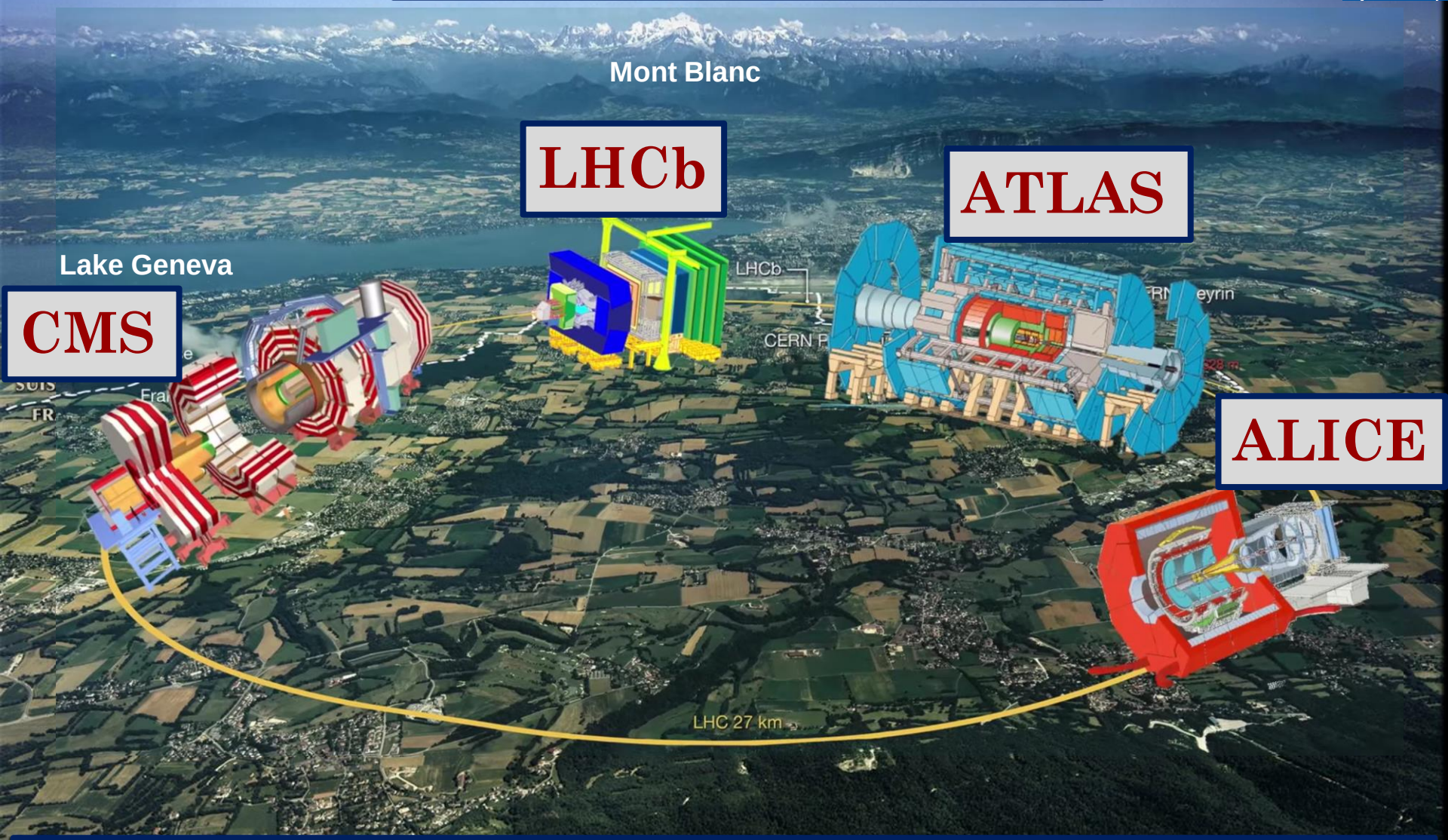
Thanks also to Andrea Dainese, Vladimir Gligorov and Dan Tovey for input on the slides preparation

The Large Hadron Collider



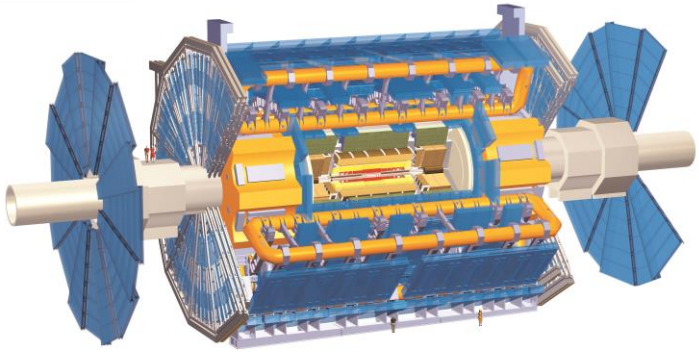
pp, pPb and PbPb collisions at highest energies

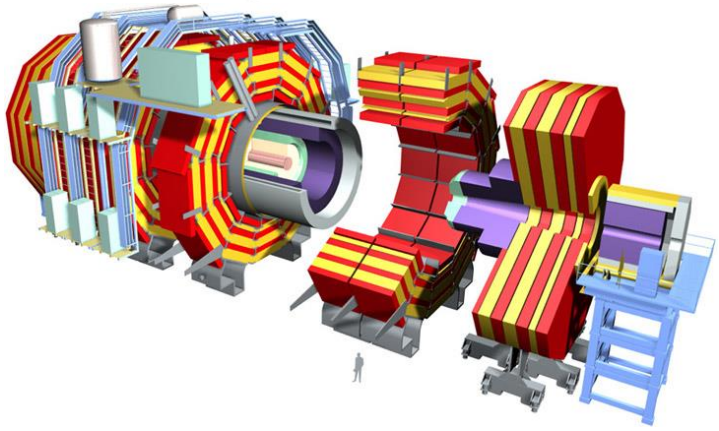
LHC Experiments



pp, pPb and PbPb collisions at highest energies

ATLAS & CMS Experiments





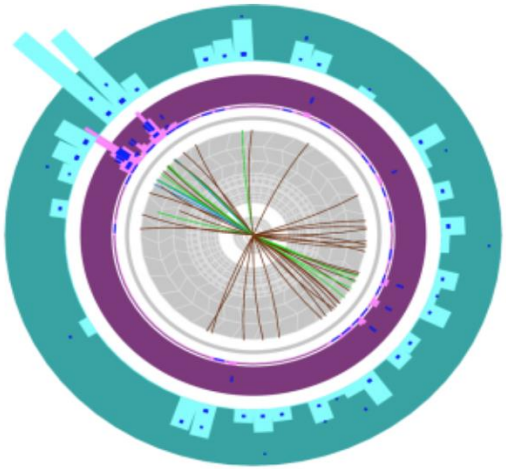
Two “general purpose” detectors that analyze pp and HI collisions at the LHC

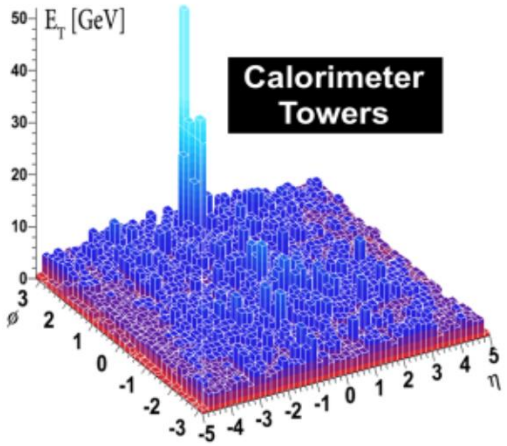
Key physics topics

- Precision SM & Higgs measurements
- Search for new particles/phenomena at TeV scale (more Higgses, SUSY, DM, W’, Z’, ED, FCNC, top partner, ...)
- Strong dynamics of quarks & gluons in hot, dense nuclear matter (QGP)

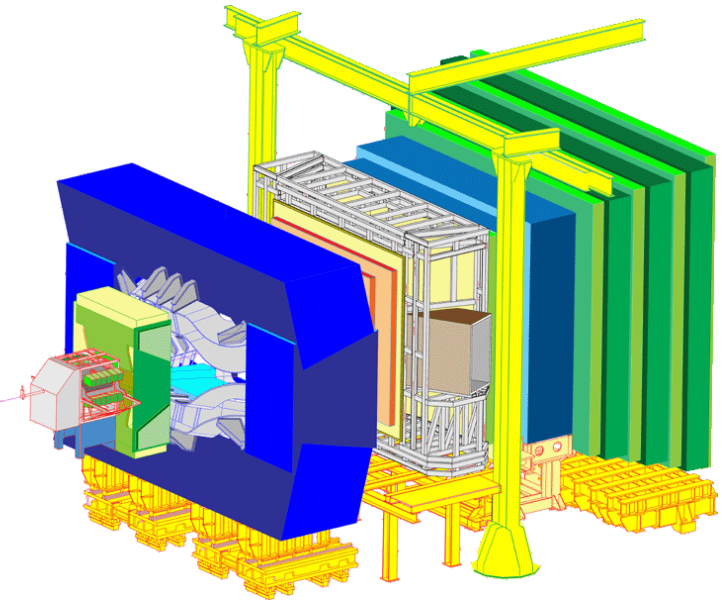
Selected highlights

- Higgs boson discovery!
- Large fraction of highly asymmetric jet pairs → First direct observation of jet quenching effect





LHCb Experiment



General purpose detector optimized to measure *b*-hadron pairs produced in the forward region from pp or HI collisions at the LHC

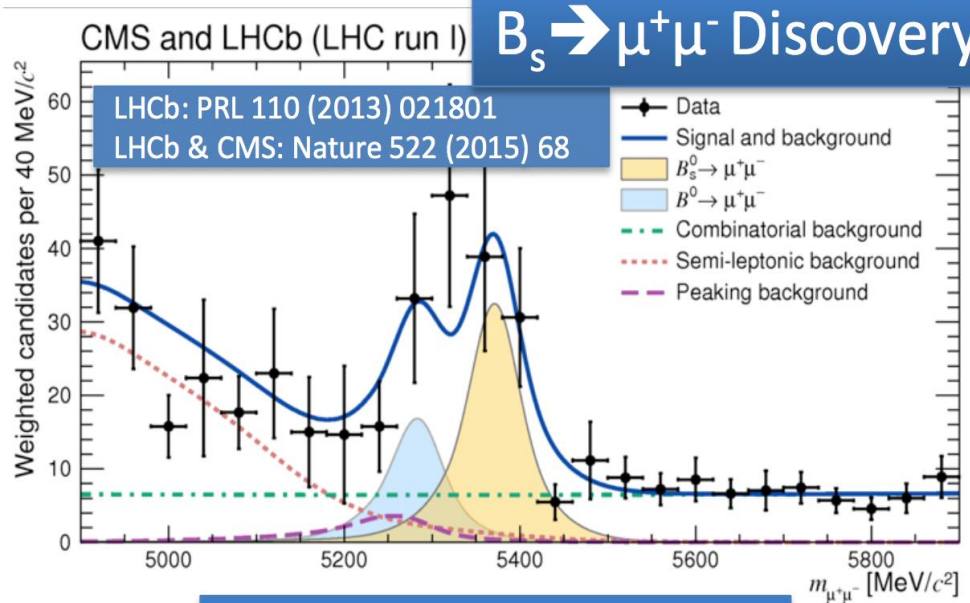
Core program is to measure parameters of CP violation in an effort to help explain the observed matter/anti-matter asymmetry of the Universe

Some physics topics include

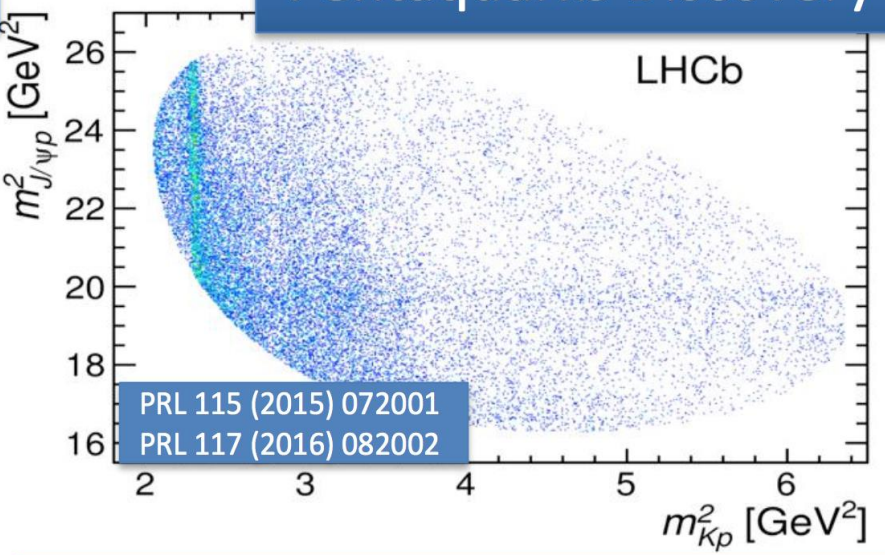
- Measuring $B_s \rightarrow \mu\mu$ decay
- Angular analysis of muons in $B_d \rightarrow K^* \mu\mu$ decay (FCNC)
- Measuring CP violating phase in $B_s \rightarrow J/\Psi \phi$ decay and angle γ
- Radiative B decays (FCNC)
- Hadron spectroscopy and search for exotic states

Some LHCb Highlights

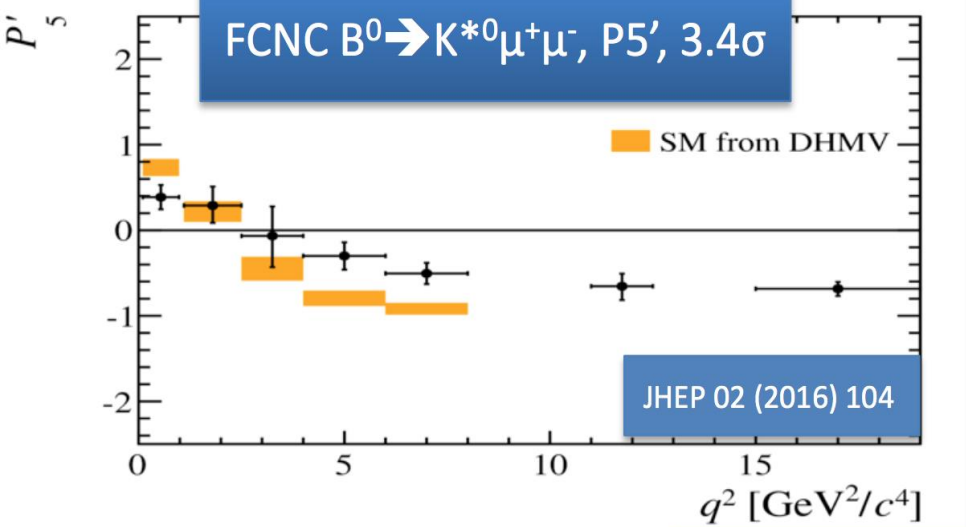
$B_s \rightarrow \mu^+\mu^-$ Discovery



Pentaquarks Discovery

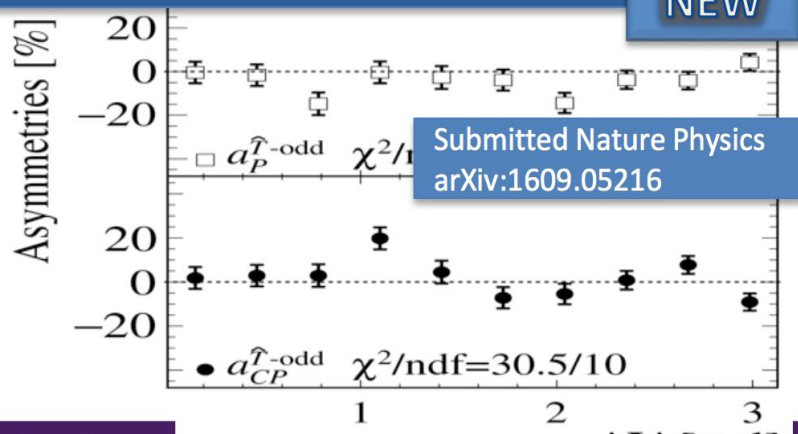


FCNC $B^0 \rightarrow K^{*0}\mu^+\mu^-$, P5', 3.4σ

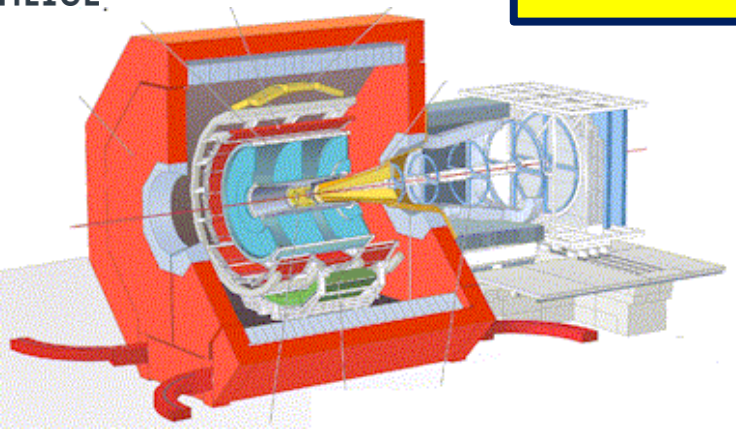


Evidence CP Violation in Baryons

NEW



ALICE Experiment



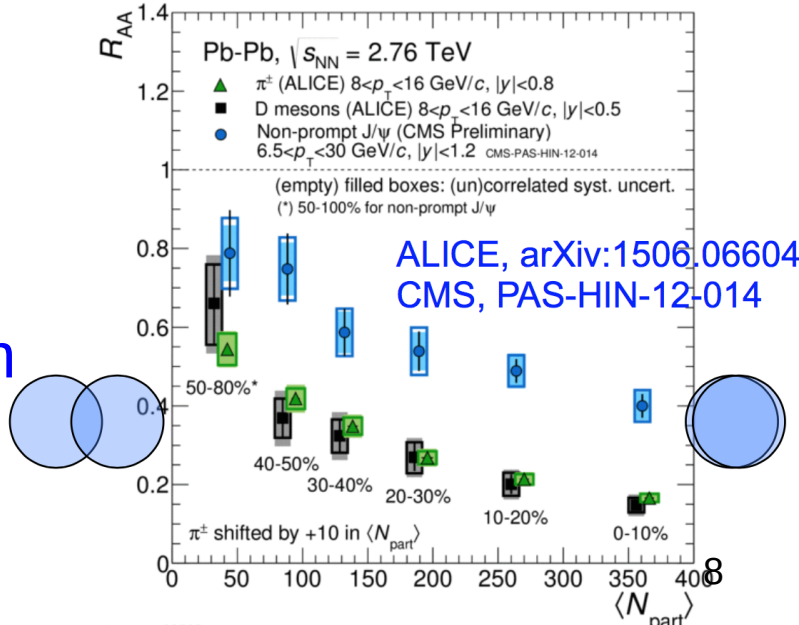
General purpose detector optimized for the high-multiplicity environment of HI collisions at the LHC. Complementary to other LHC experiments due to low-p_T threshold and excellent PID capabilities

Core program is to measure observables that characterize the QCD phase diagram. Comparisons of p-Pb and Pb-Pb data can be used to disentangle cold-matter ISR/FSR effects from those that are intrinsic to the QCD medium

Selected highlight

- First indication of mass dependence to energy loss through QCD medium

$$R_{AA}^{B}\,(\text{CMS}) > R_{AA}^{D}\,(\text{ALICE})$$



LHC and Detector Upgrades

High Luminosity LHC

√s=13 TeV
Bunch spacing 25 ns

√s=14 TeV
LHC injector upgrade

New IR layout
Crab cavity

$\mathcal{L}$~1.6×10^{34} cm^{-2}s^{-1}
Pile-up ~ 40

$\mathcal{L}$~2×10^{34} cm^{-2}s^{-1}
Pile-up ~ 60

$\mathcal{L}$~7.5×10^{34} cm^{-2}s^{-1}
Pile-up ~ 200

LHC

HL-LHC

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

LS1 | EYETS | LS2 | LS3

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

splice consolidation
button collimators
R2E project

injector upgrade
cryo Point 4
Civil Eng. P1-P5

cryolimit
interaction
regions

HL-LHC installation

5 to 7 x
nominal
luminosity

2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2037

radiation
damage

75%
nominal
luminosity

experiment
beam pipes

nominal luminosity

experiment upgrade
phase 1

2 x nominal luminosity

experiment upgrade
phase 2

Luminosity
leveling

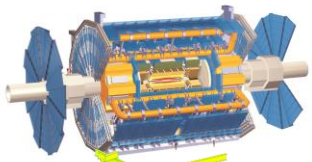
30 fb^{-1}

Now

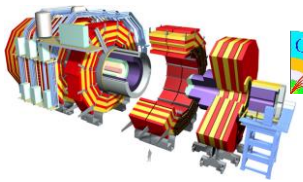
150 fb^{-1}

300 fb^{-1}

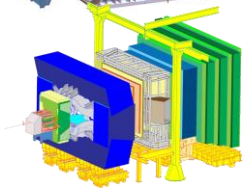
3000 fb^{-1} integrated luminosity



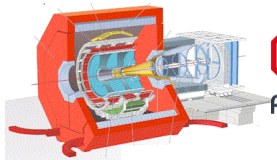
ATLAS EXPERIMENT



CMS



LHCb



ALICE

LS2

Phase 1 upgrade → Run 3 → Phase 2 upgrade → Run 4, 5, … LS4, 5, …

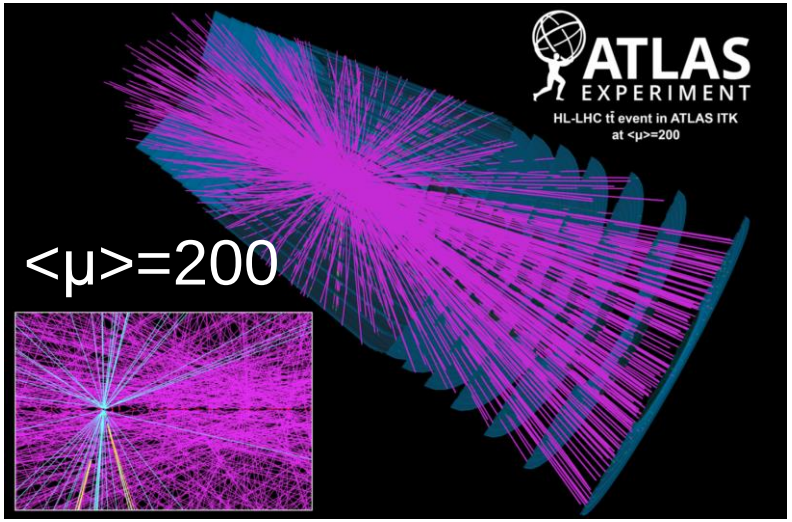
Phase 1 Upgrade → Phase 1b upgrade → Phase 2 upgrade (LS4)

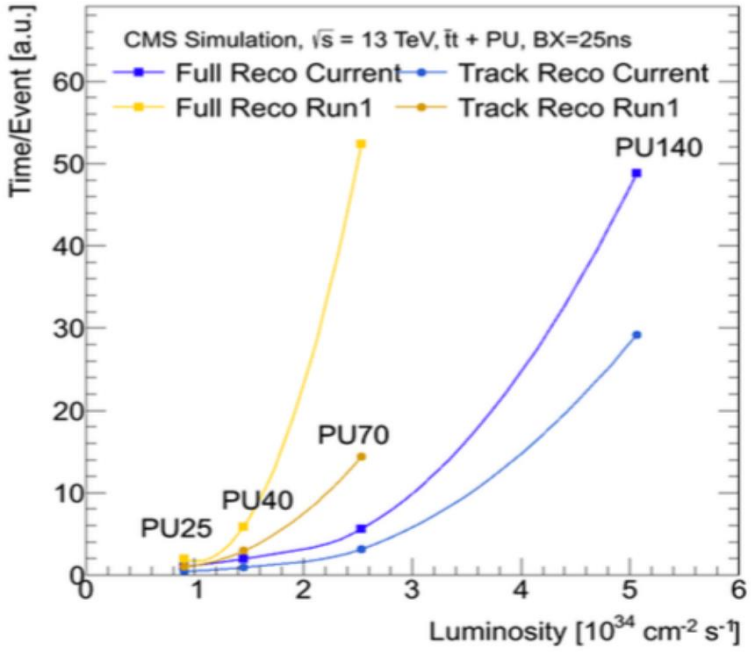
Phase 1 upgrade →

LS3

HL-LHC Challenge: Pile-up

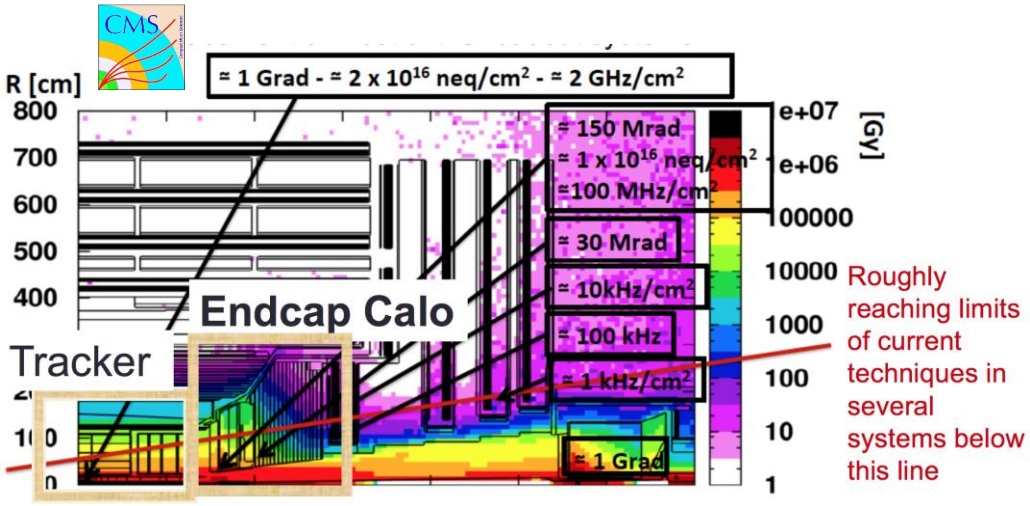
- Problem: Large number of pp interactions per bunch crossing
  - Adds extra energy to calorimeter measurements
  - Increases the amount of data to be read out in each BX
  - Increases combinatorial complexity and rate of fake tracks → computing resources
- Mitigation
  - High granularity detectors and fast electrons to identify PV
  - Precision timing for PV-to-track/cluster association
  - Better algorithms, concurrency

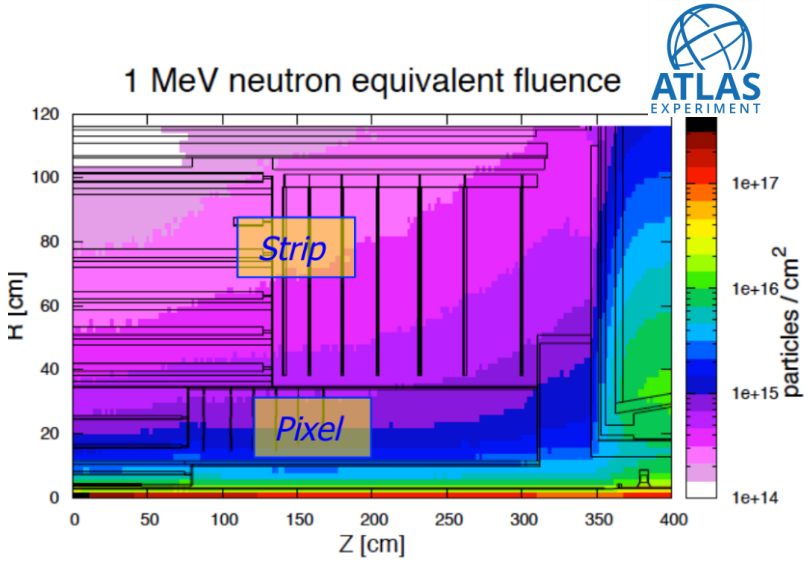




HL-LHC Challenge: Radiation

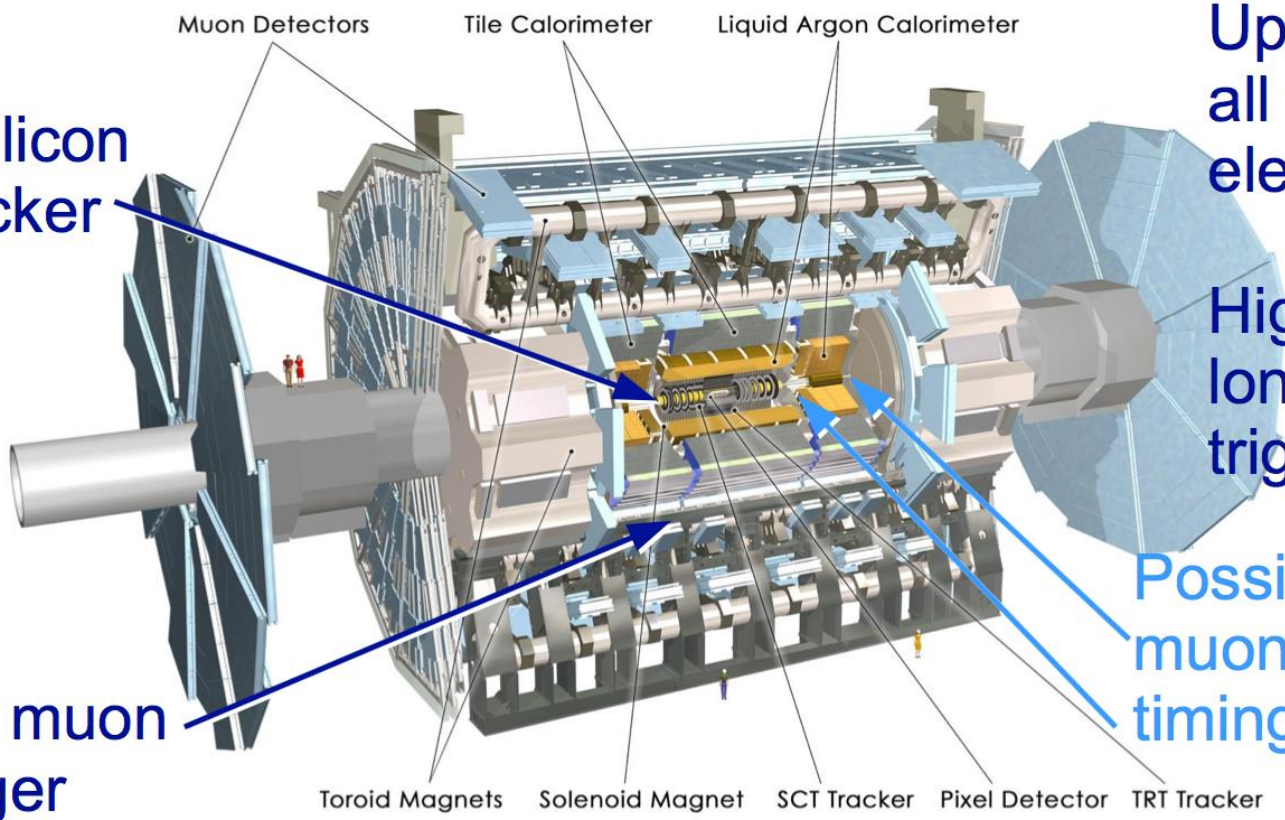
- Problem: Radiation damage to detector elements and electronics from high radiation dose during LHC operation
  - Degrades signals from systems
  - Limits lifetime of detectors





→ requires new trackers, endcap calorimeters, forward muon systems and replacement of most of the detector readout systems

HL-LHC: ATLAS Upgrade



New all-silicon Inner Tracker

New inner muon barrel trigger chambers

Upgrade all front-end electronics

Higher rate, longer latency trigger system

Possibly forward muon tagger and timing detector

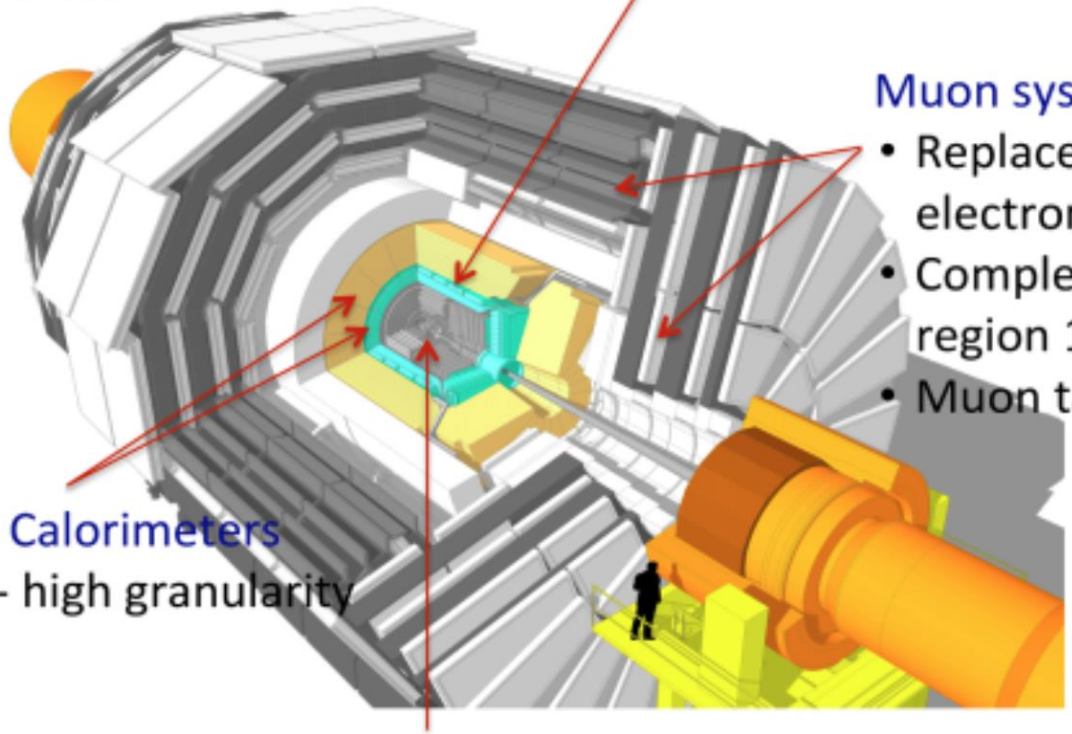
HL-LHC: CMS Upgrade

Trigger/HLT/DAQ

- Track information at L1-Trigger
- L1-Trigger: 12.5 μs latency - output 750 kHz
- HLT output ≈7.5 kHz

Barrel EM calorimeter

- Replace FE/BE electronics
- Lower operating temperature (8◦)



Muon systems

- Replace DT & CSC FE/BE electronics
- Complete RPC coverage in region $1.5 < \eta < 2.4$
- Muon tagging $2.4 < \eta < 3$

Replace Endcap Calorimeters

- Rad. tolerant - high granularity
- 3D capability

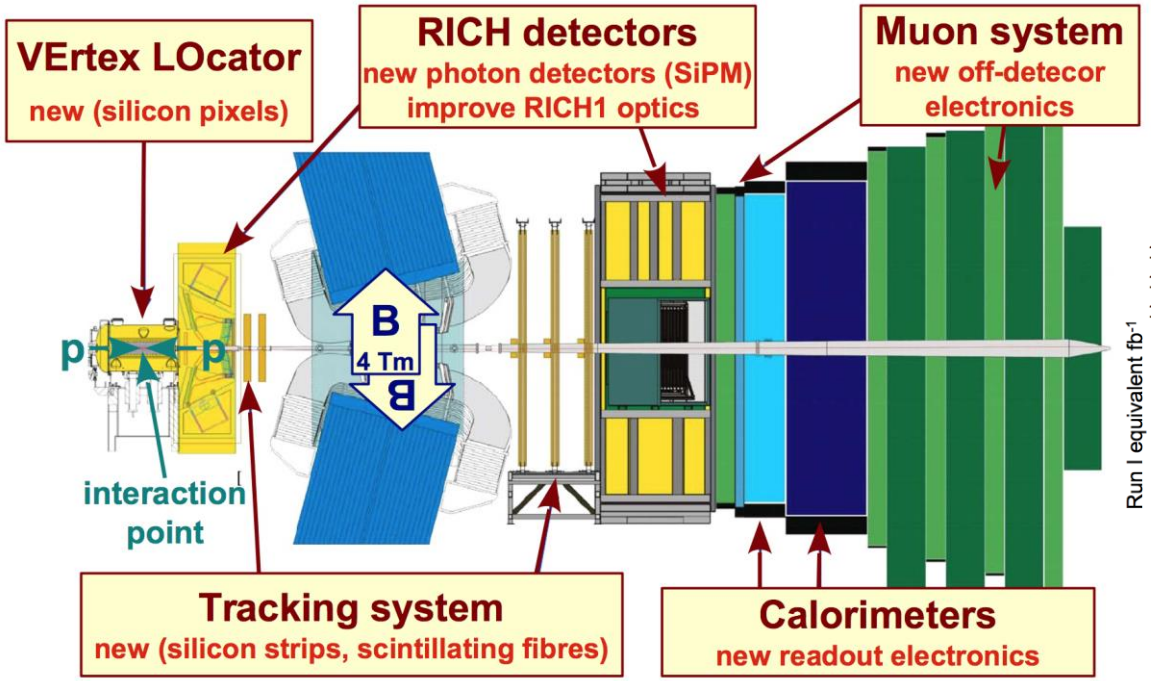
Replace Tracker

- Rad. tolerant - high granularity - significantly less material
- 40 MHz selective readout (Pt≥2 GeV) in Outer Tracker for L1-Trigger
- Extend coverage to $\eta = 3.8$

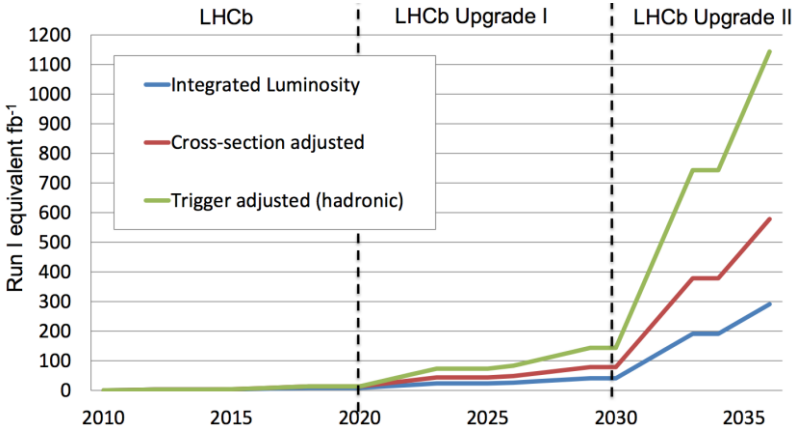
LHCb Upgrades

- Phase-1 (LS2) upgrade goal to collect 50 fb^{-1} @ $2x10^{34}$ cm^{-2} s^{-1}
  - Readout whole detector @ 40 MHz
  - Software-only trigger!
  - Real-time alignment, calibration and reconstruction

  Requires new HLT farm many-core processors (e.g. GPUs, CPU+FPGA hybrids) and new LAN system



Beyond LS2



Indicative of potential only

Phase-Ib and II still in discussion phase

Upgrades most relevant to HI

- Designed to accommodate higher luminosity after LS2
  - Pb-Pb instantaneous luminosity expected to increase x5

- ALICE (LS2)
  - New inner tracker: precision and efficiency at low p_T
  - New pixel muon tracker: precise tracking and vertexing for μ
  - New TPC readout chambers, upgraded readout for other detectors and new integrated Online-Offline: x100 faster readout (up to 50 kHz for Pb-Pb)

- ATLAS
  - Additional pixel layer (LS1), then new tracker (LS3): tracking and b-tag
  - Fast tracking trigger (LS2): high-multiplicity tracking
  - Calorimeter and muon upgrades (LS2): electron, γ, muon triggers

- CMS
  - Upgrade of trigger and DAQ, L1 calorimeter trigger (LS1): enables L1 rejection at 95%, e.g. (after LS2) from 50 kHz to <3 kHz (HLT input)
  - New pixel tracker (YETS16-17), then new tracker (LS3): tracking and b-tag
  - Extension of forward muon system (LS2): muon acceptance
  - Upgrade forward calorimeter (LS3): forward jets in HI

- LHCb (LS2)
  - Upgrade includes new vertexing and tracking detectors

HI Programme at HL-LHC

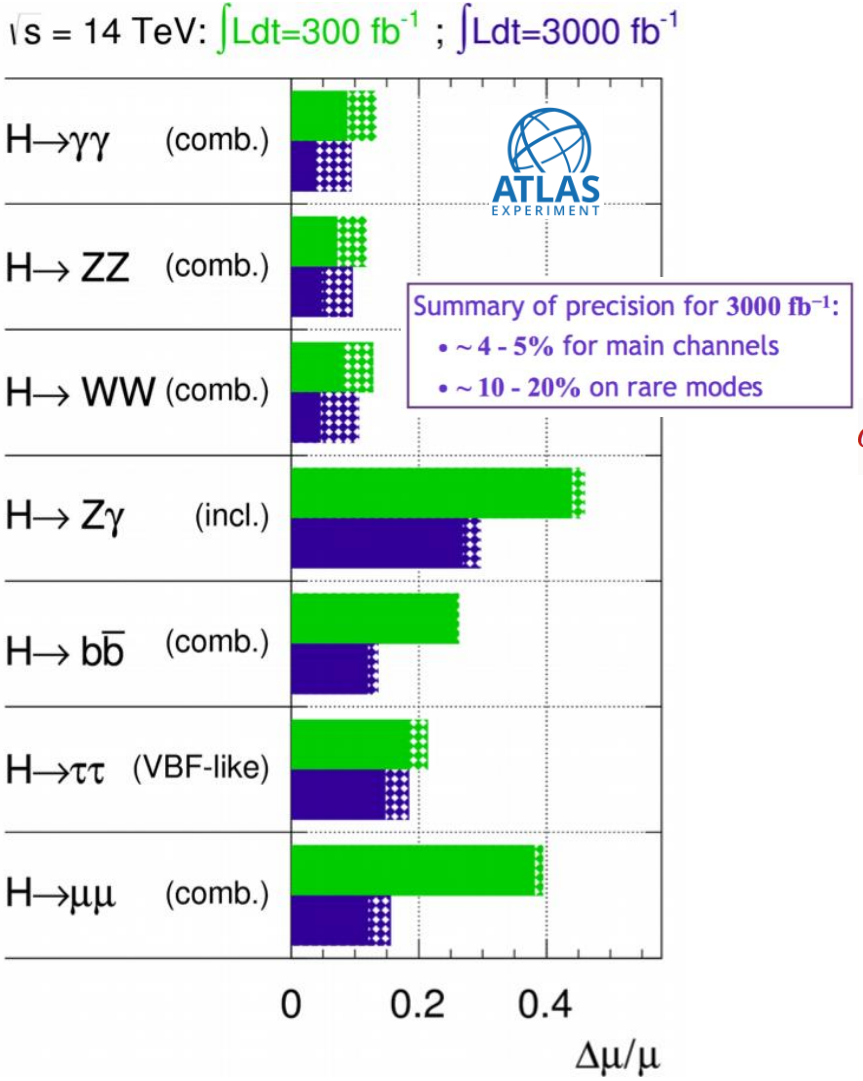
(Not exhaustive!)

- **Jets:** characterization of energy loss mechanism both as a testing ground for the multi-particle aspects of QCD and as a probe of the medium density
  - Differential studies of jets, b-jets, di-jets, γ/Z-jet at very high p_T (focus of **ATLAS** and **CMS**)
  - Flavour-dependent in-medium fragmentation functions (focus of **ALICE**)
- **Heavy flavour:** characterization of mass dependence of energy loss, HQ in-medium thermalization and hadronization, as a probe of the medium transport properties
  - Production and elliptic flow of several HF hadron species from 0 to high p_T (**ALL EXPs**)
- **Quarkonium:** precision study of quarkonium dissociation pattern and regeneration, as probes of deconfinement and of the medium temperature
  - Low-p_T charmonia and elliptic flow (focus of **ALICE**, **LHCb**)
  - Multi-differential studies of Υ states (focus of **ATLAS** and **CMS**)
- **Low-mass di-leptons:** thermal radiation γ ($\rightarrow l^+l^-$) to map temperature during system evolution; modification of ρ meson spectral function as a probe of the chiral symmetry restoration
  - (Very) low-p_T and low-mass di-electrons and di-muons (**ALICE**)

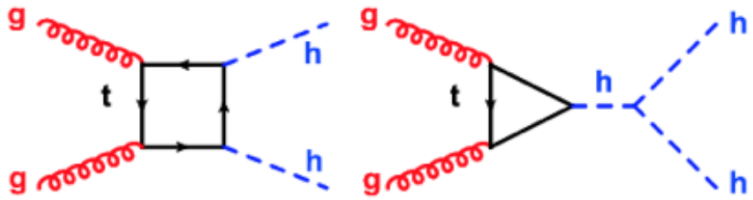
HL-LHC Higgs Prospects: Couplings

(Not exhaustive!)

- Signal strength measurements (sensitive to Higgs couplings)

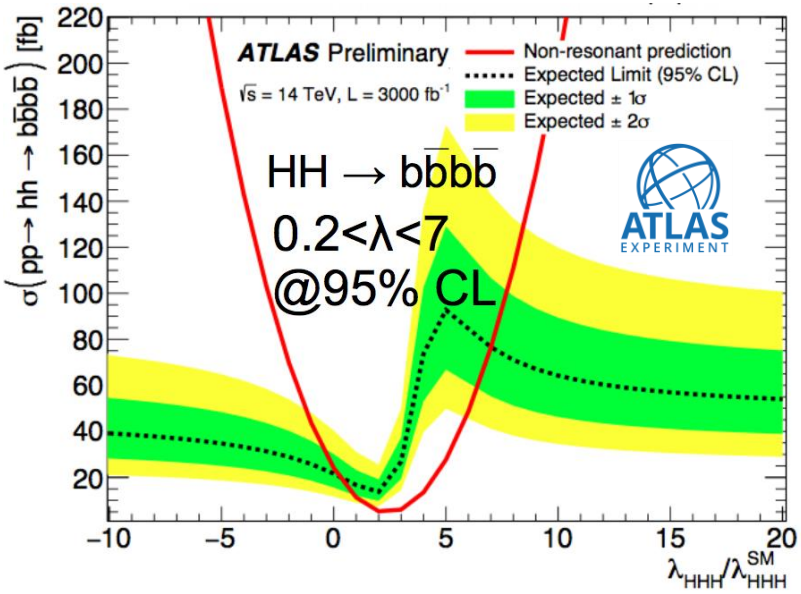


- Higgs pair production (access to H self-coupling)



- Very low cross section
  - Destructive interference

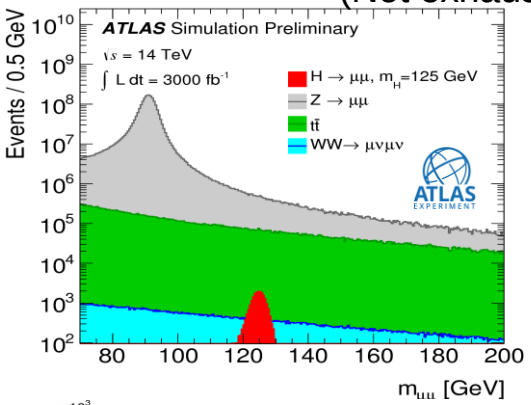
$\sigma(pp \to HH)^{SM}_{NNLO+NNLL} = 33.45$ fb (@ 13TeV)



HL-LHC Higgs Prospects: Rare Decays

(Not exhaustive!)

- $H \to \mu\mu$ - measures coupling to second fermion generation
  - ATLAS and CMS expect >7σ significance with **3000 fb^{-1}**
  - coupling measured to **5-10%**



- $H \to Z\gamma$
  - Tests loop structure of decay, compare with $H \to ZZ$ $H \to \gamma\gamma$
  - ~4σ significance possible with **3000 fb^{-1}** despite the challenging background

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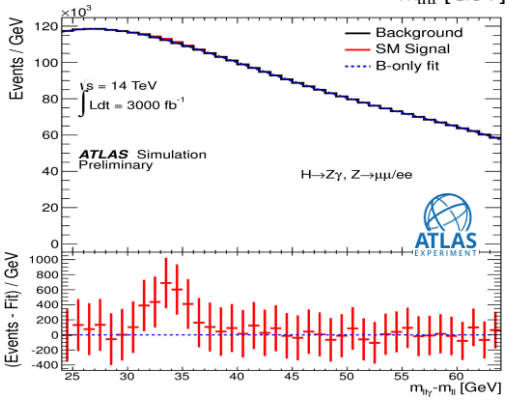

- $H \to J/\psi\,\gamma$
  - SM expectation: **BR($H \to J/\psi\,\gamma$) = (2.9 ± 0.2) × 10^{-6}**
    ATLAS Run 1 limit: **BR($H \to J/\psi\,\gamma$) = 1.5 × 10^{-3}**

Expected limits at 95% CL (using multivariate analysis):

- **BR($H \to J/\psi\,\gamma$): $(44^{+19}_{-12}) \times 10^{-6}$**
- **$\sigma(gg \to H) \times$ BR($H \to J/\psi\,\gamma$): $(3.1^{+0.9}_{-1.3})$ fb**

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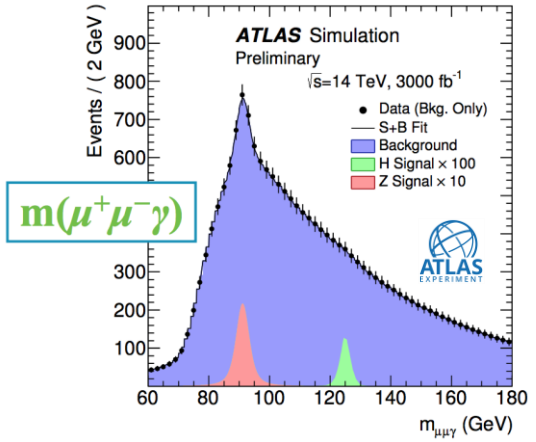
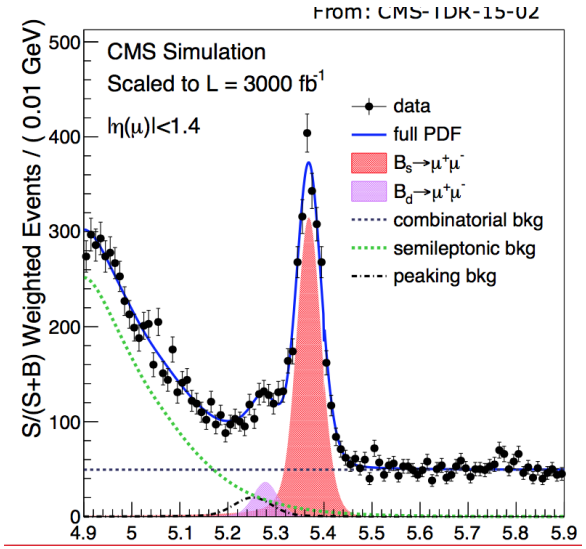
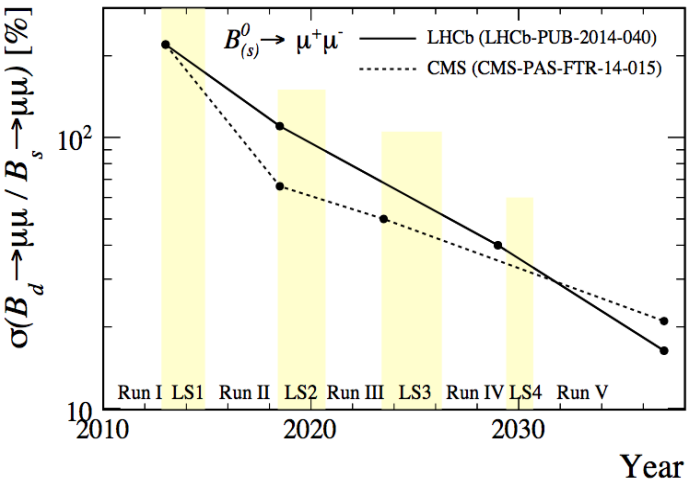


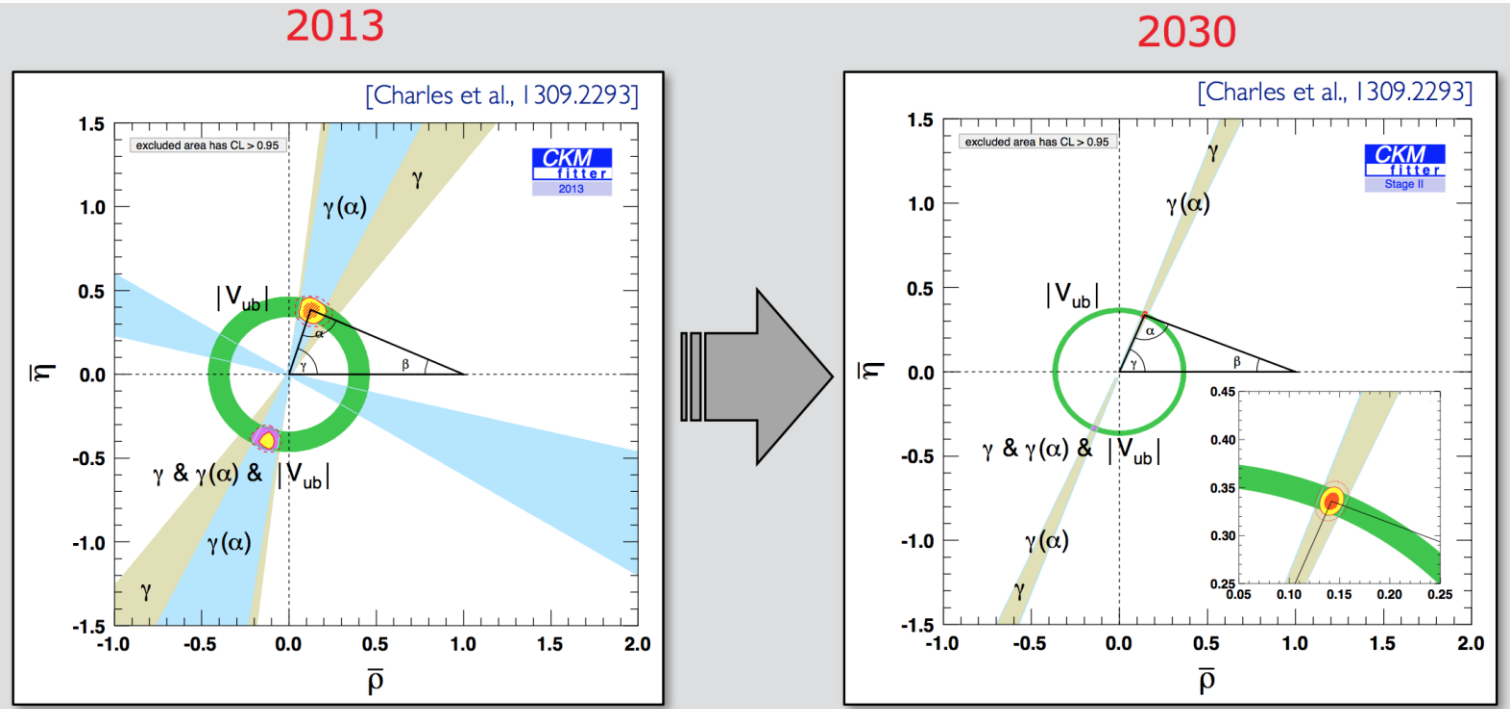
HL-LHC Prospects: Flavor Physics

(Not exhaustive!)

- Measuring $B_s \rightarrow \mu\mu$ decay has already had a large impact on constraining models of NP







- Further constraints on the CKM parameters

Connections to CWP / Closing Remarks

- Each of the LHC experiments have a series of ambitious upgrades to match the LHC upgrades
  - The primary motivation for each of the upgrades is to maximize physics performance
  - Design choices are driven mainly by physics considerations

- Some things to consider for the CWP process
  - Develop synergies between LHC experiments as much as possible
  - Each detector is a big camera – exploit developments in the ML arena
  - Include the mix of physics activities in the planning (e.g. luminosity increase vs. energy increse)
  - Visualization is an underdeveloped tool in our field for research, outreach, education and professional training