Highlights from LHC Detector Upgrades

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on behalf of the ALICE, ATLAS, CMS and LHCb Collaborations

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in the City of New York

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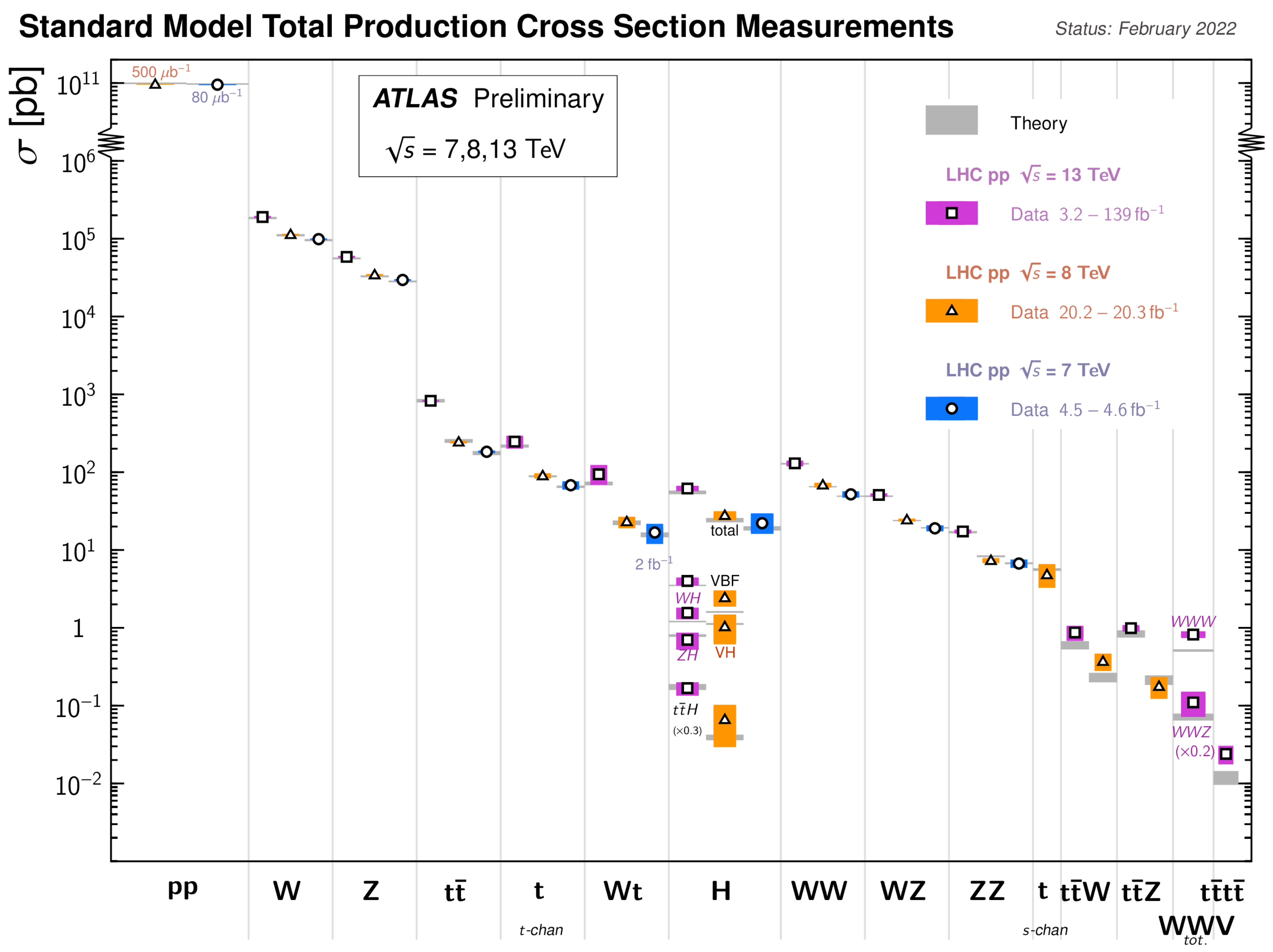
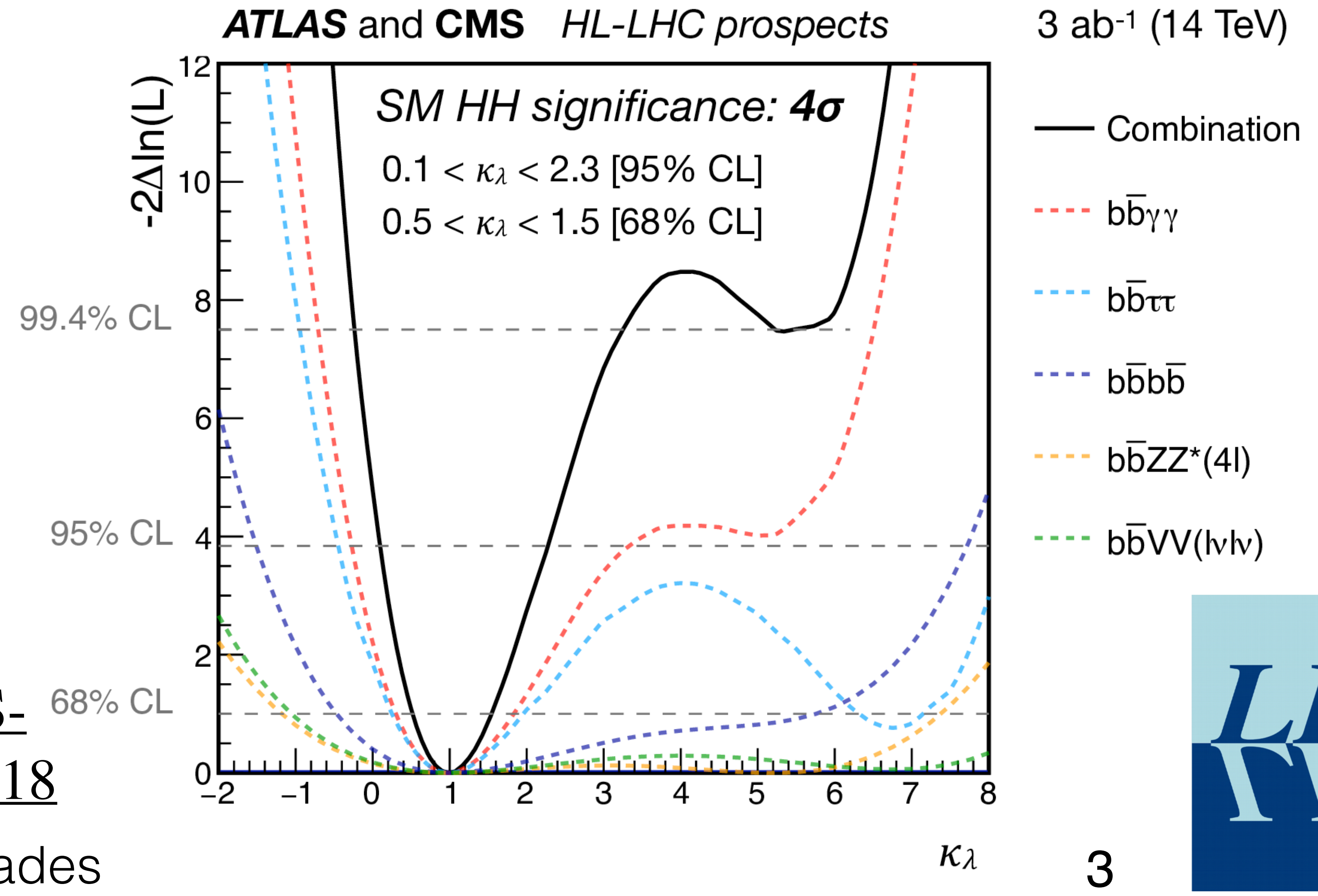
Outline

- The High Luminosity LHC
- Tracking
- Timing
- Cherenkov
- Calorimetry
- Muons
- Trigger and data acquisition
- Closing

High Luminosity-LHC

- LHC so far
  - Run 1 (2010-2012, 7-8 TeV, ~30 fb^{-1})
    - Higgs discovery
  - Run 2 (2015-2018, 13 TeV, ~150 fb^{-1})
    - Observed Higgs is within ~20% of the SM Higgs, tribosons, 4 tops, … no new physics yet
  - Run 3 (2022-2025, 13.6 TeV, underway)
    - Get to ~250 fb^{-1}
    - Reaching the edge of current detector capabilities (pile-up at ~60 interactions/bunch crossing)
- HL-LHC: 14 TeV, 3000+ fb^{-1} (ATLAS and CMS)
  - **20x** more data than analyzed so far!
  - Expect to measure di-Higgs production
    - Probe Higgs potential, "loose" Standard Model prediction (see e.g. Matt's talk Wednesday)





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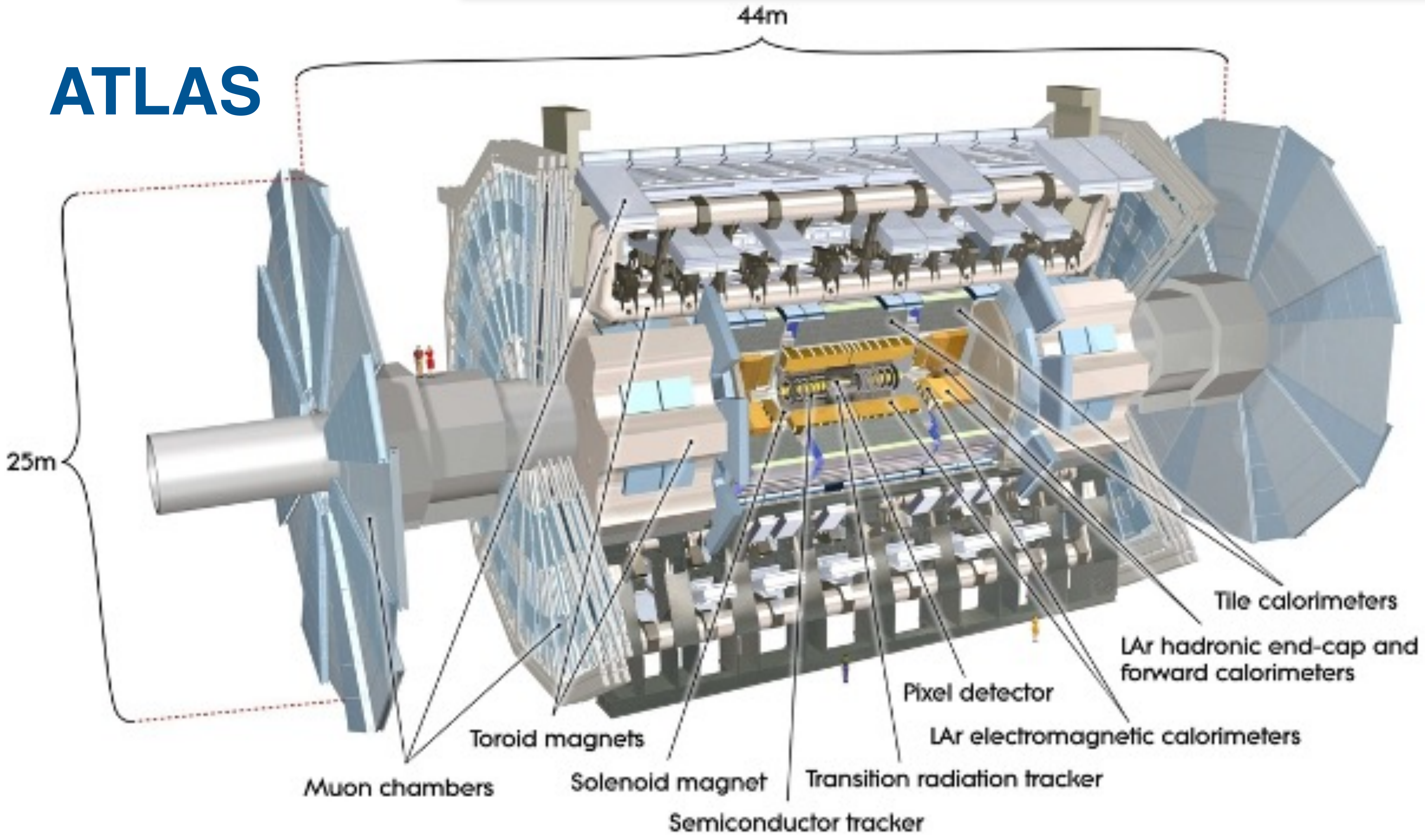
HL-LHC Environment

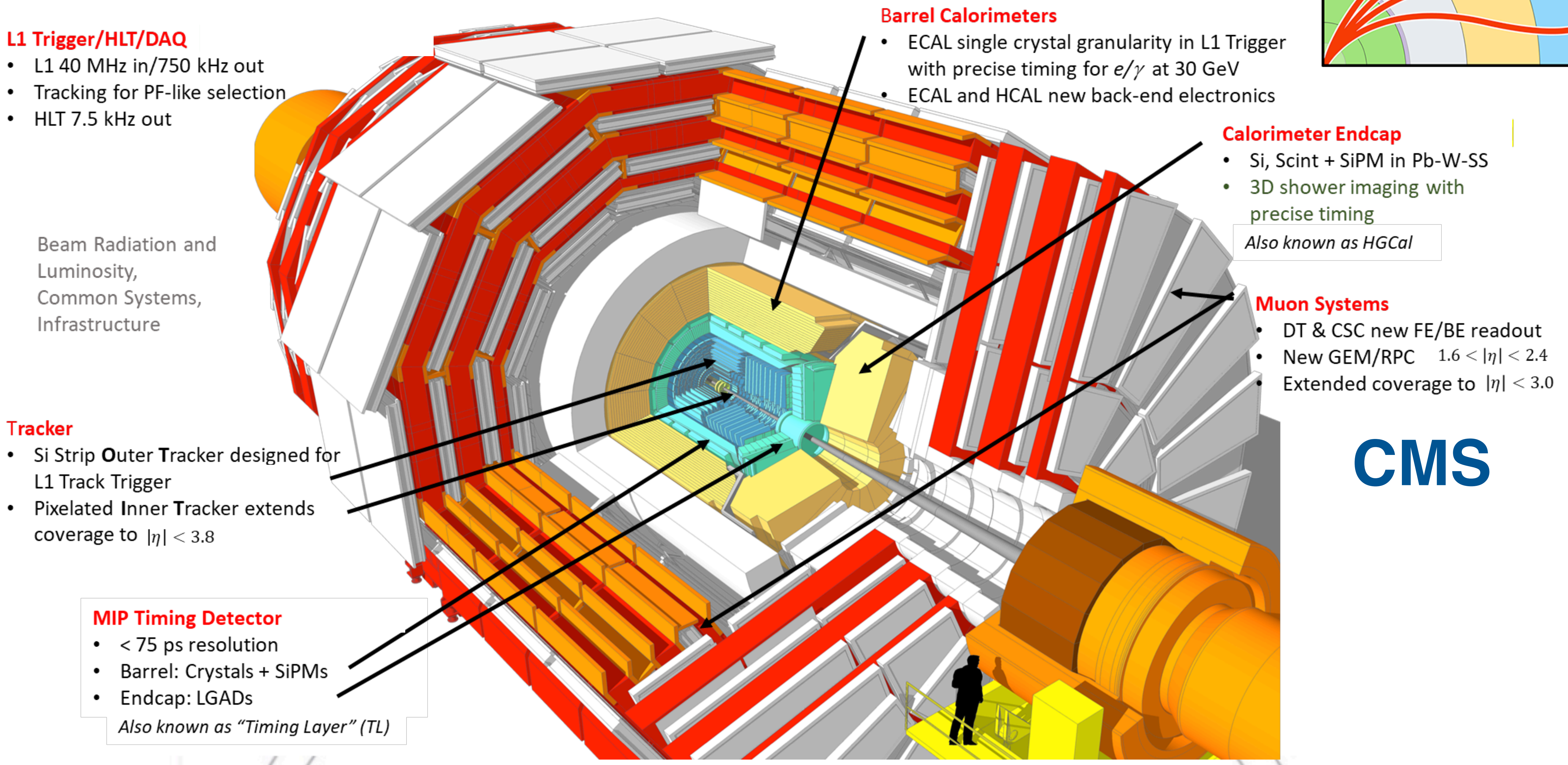
- Instantaneous luminosity target is 7.5 x LHC design luminosity
  - Expect up to 200 proton-proton collisions per bunch crossing, ie every 25 ns
- Current expectation is to operate for about ten years to collect 3000+ fb^{-1}, 3 x design
  - Multi-MRad integrated dose for inner tracking detectors, well beyond expected survival range of current detectors
  - 200 pile-up events implies complex events
    - Increase detector granularity, add handles (timing!)
  - High rate of interesting events
    - Move offline algorithms upstream into the trigger system, write more data to “tape”
    - Offline computing challenge!

The Experiments

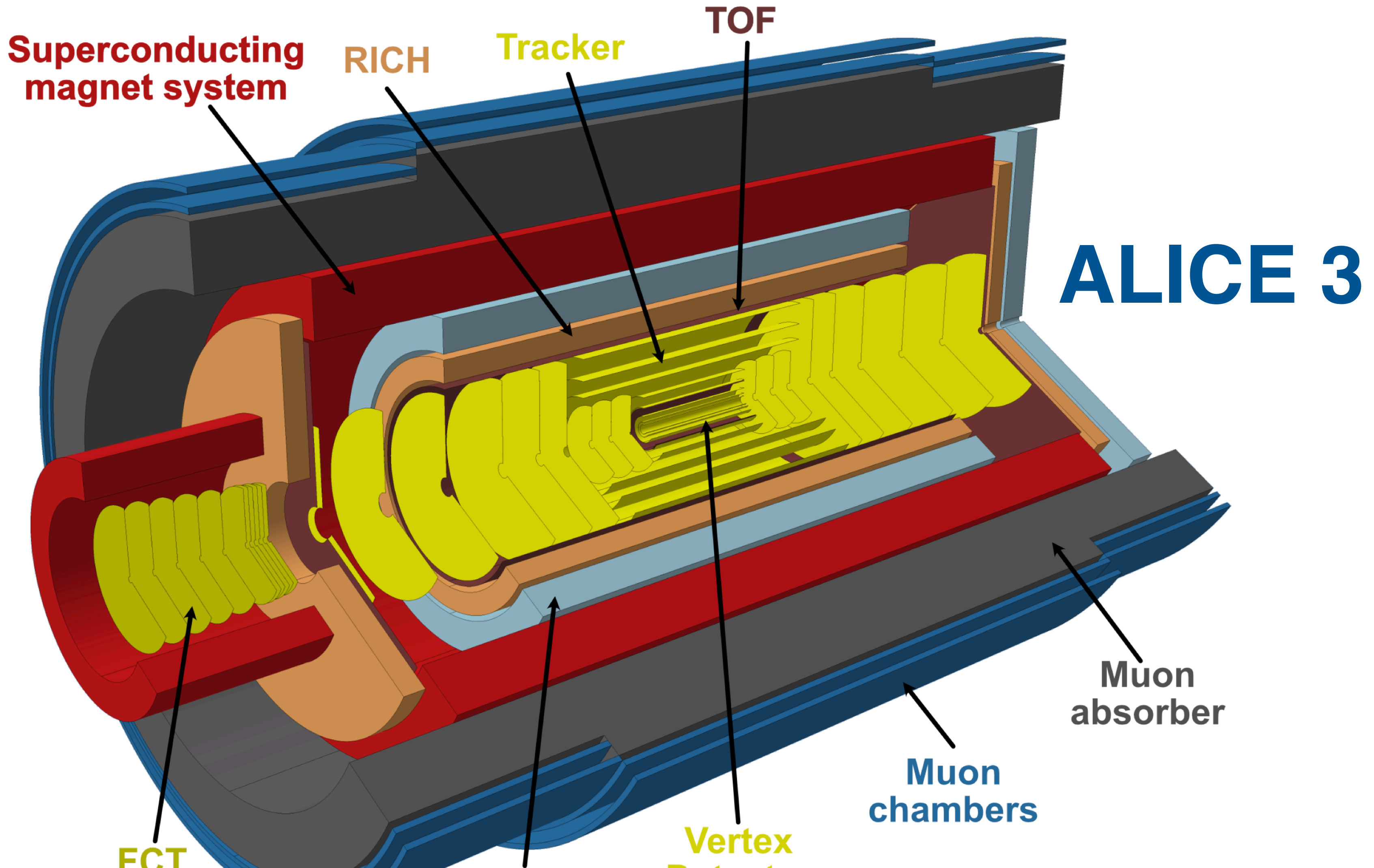
ATLAS



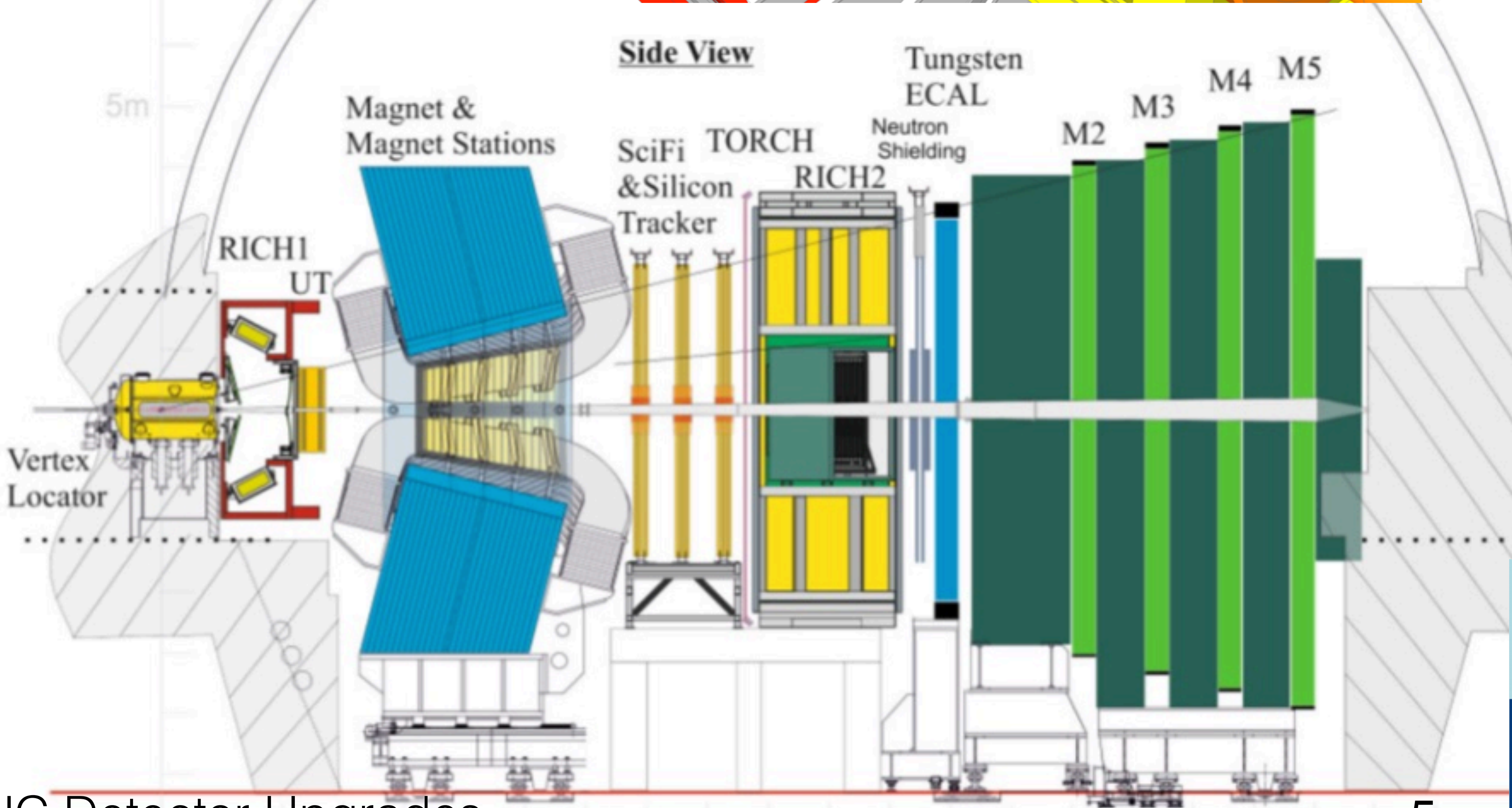
CMS



ALICE 3

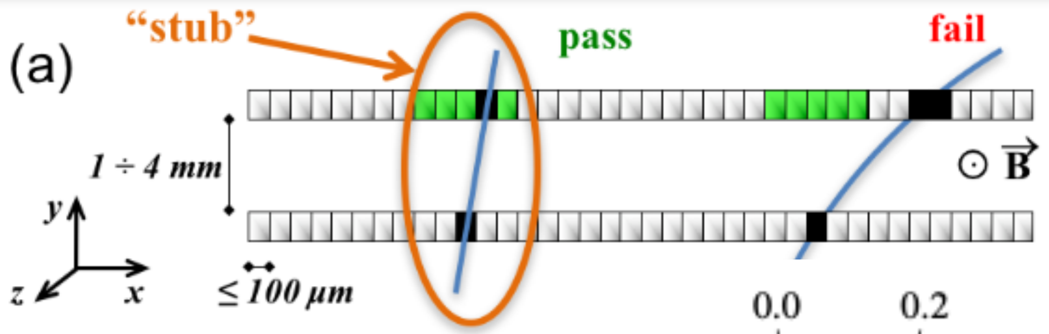


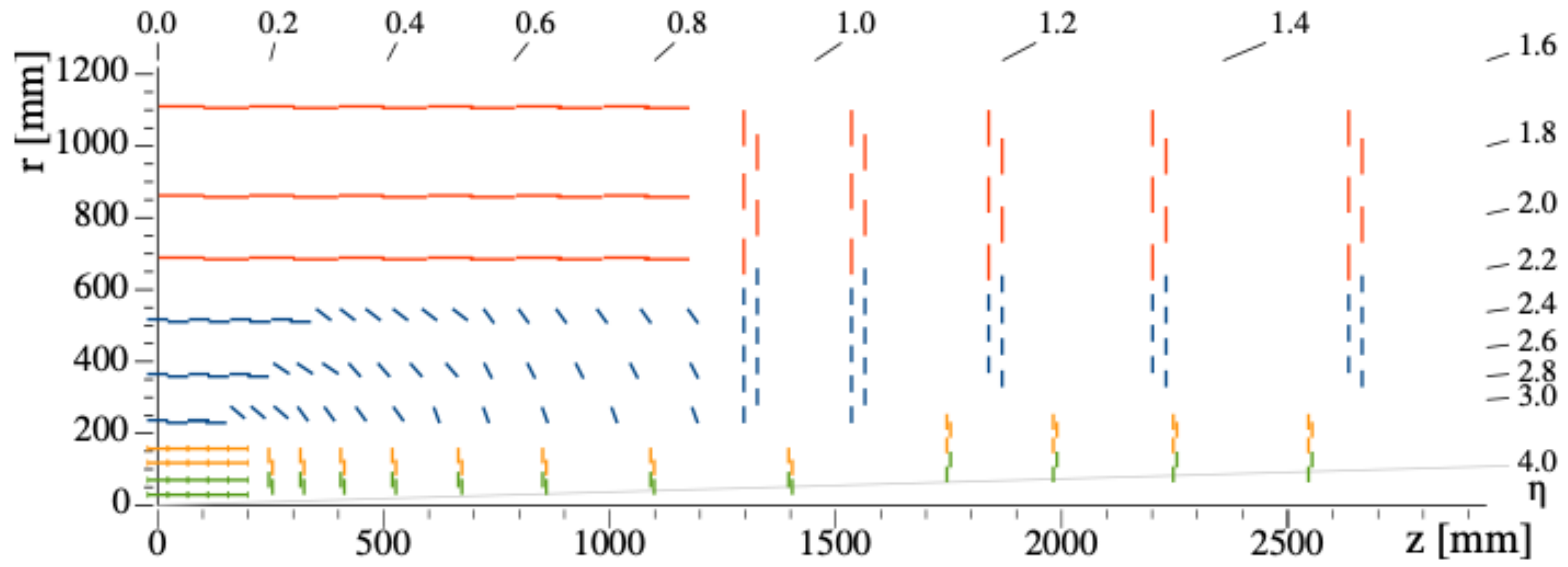
LHCb



Tracking Detectors

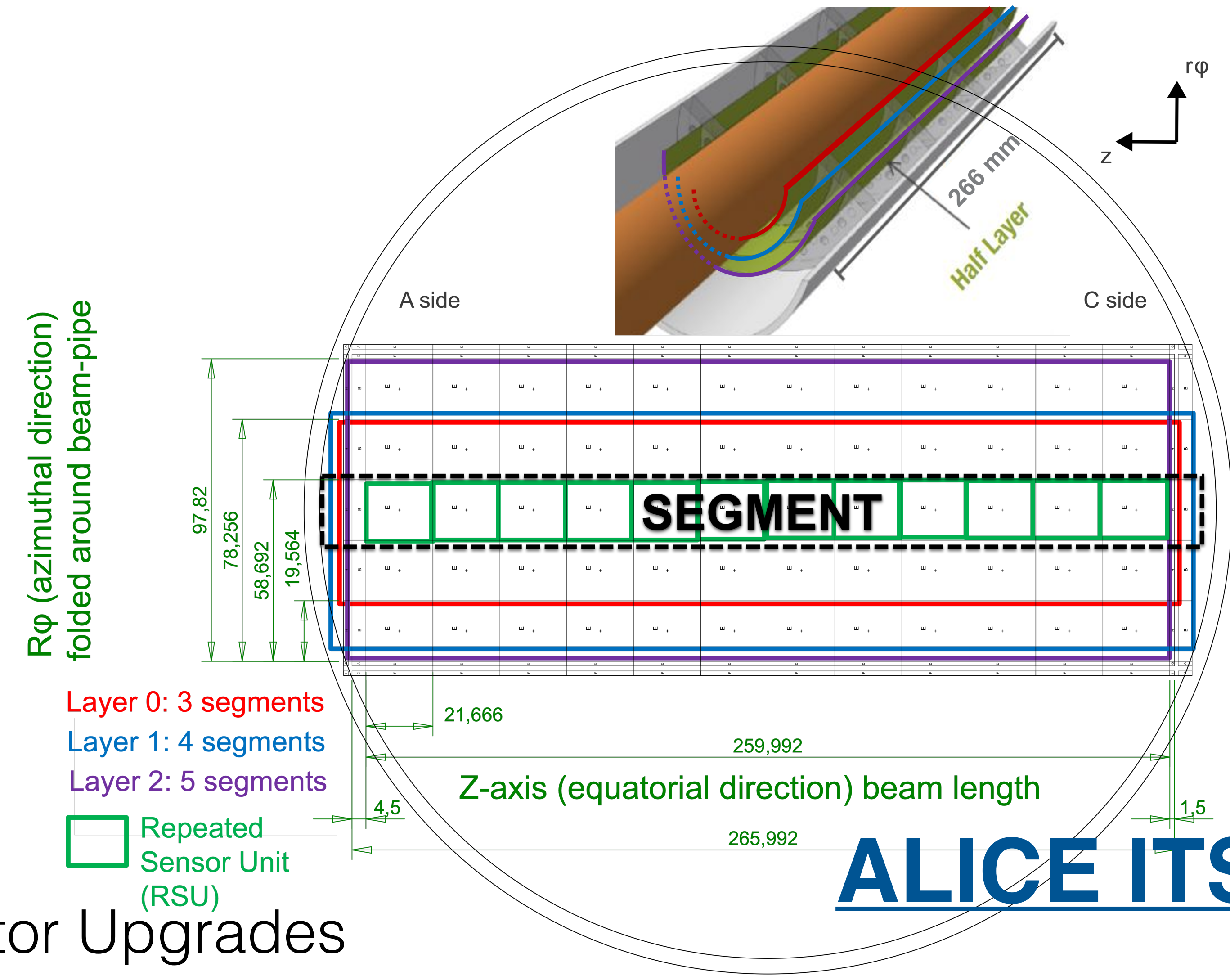
- Increased granularity, capability
  - ATLAS & CMS go from tens of millions of channels to ~5 billion (10+ m² of pixels!)
    - Industrialize production, simplify assembly
    - Extend range from η ≤ 2 to η ≤ 4
    - 3D pixels at inner radii
    - Read out at 1 MHz
    - CMS Outer Tracker provides track stubs to Level-1 trigger
    - Dual phase CO_2 cooling
  - ALICE and LHCb use Monolithic Active Pixels
    - Integrated sensors and read-out!
    - For ALICE, bent, stitched sensors!

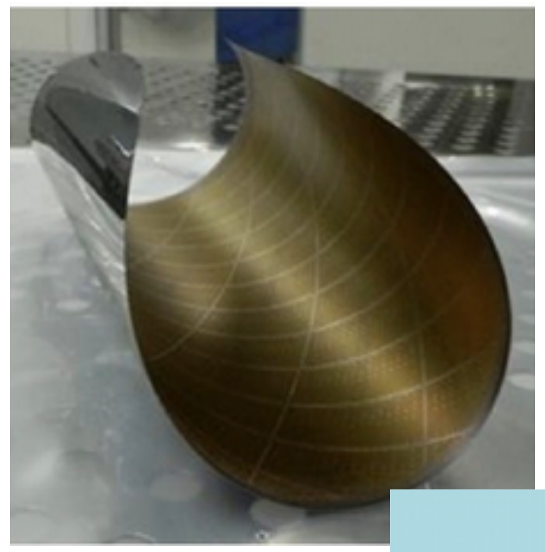




CMS Tracker TDR

ATLAS strip detector "stave" (1.4 meter long)

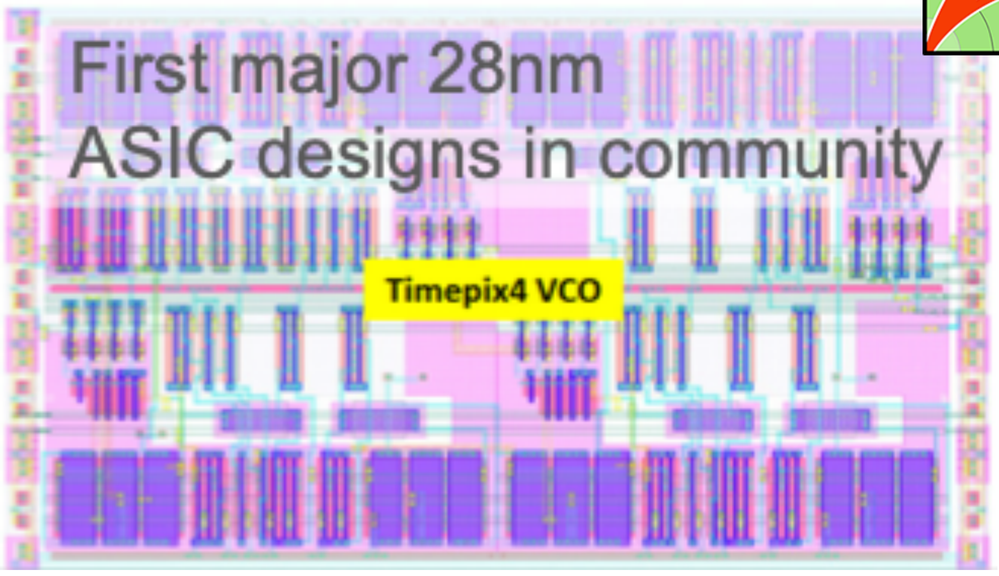




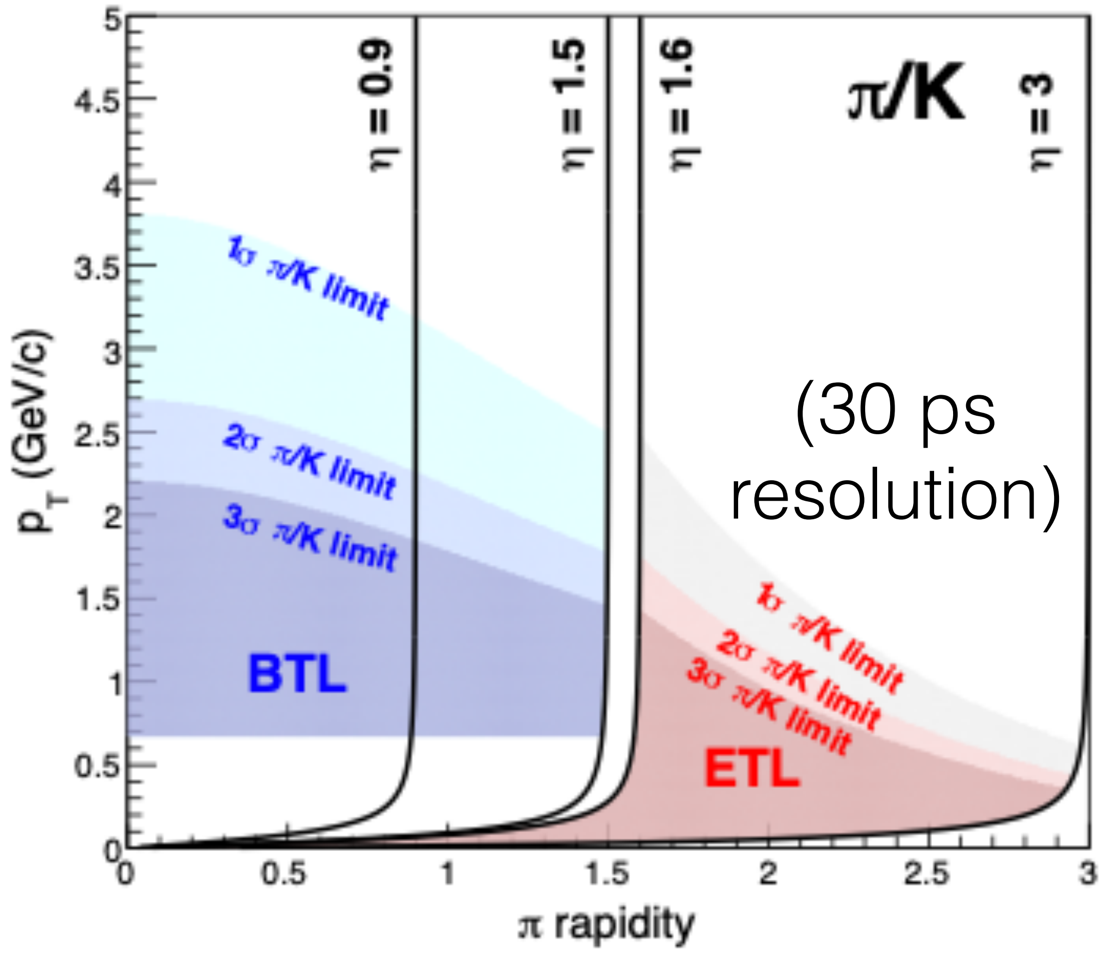
ALICE ITS3 TDR

Timing

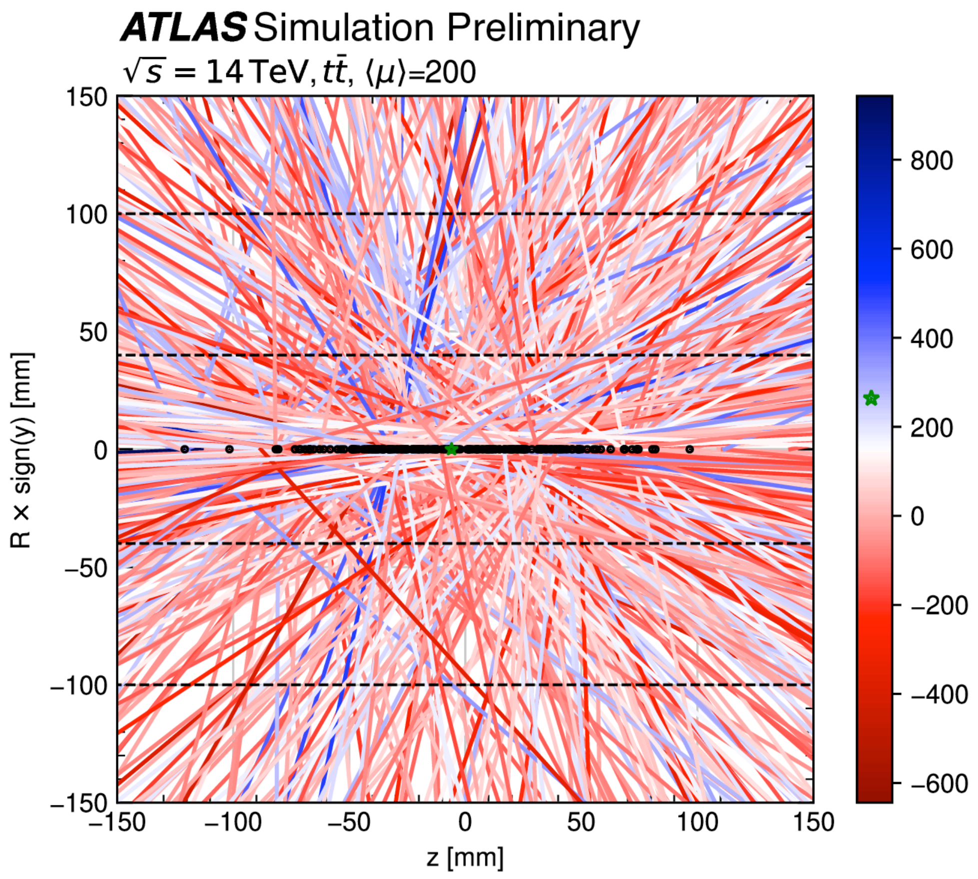
- Go to "4-D tracking" by including precise timing detectors in track reconstruction
  - LGAD-based (typically) sensors in front of calorimeters
    - ALICE barrel + endcap (PID mainly), ATLAS only endcaps, CMS LGADs in endcaps, LYSO crystals + SiPMs in barrel, LHCb in the VELO (Vertex Locator) but technology TBD
  - Reject pile-up tracks and assist in particle ID
  - Target 50 ps or better resolution (electronics included)



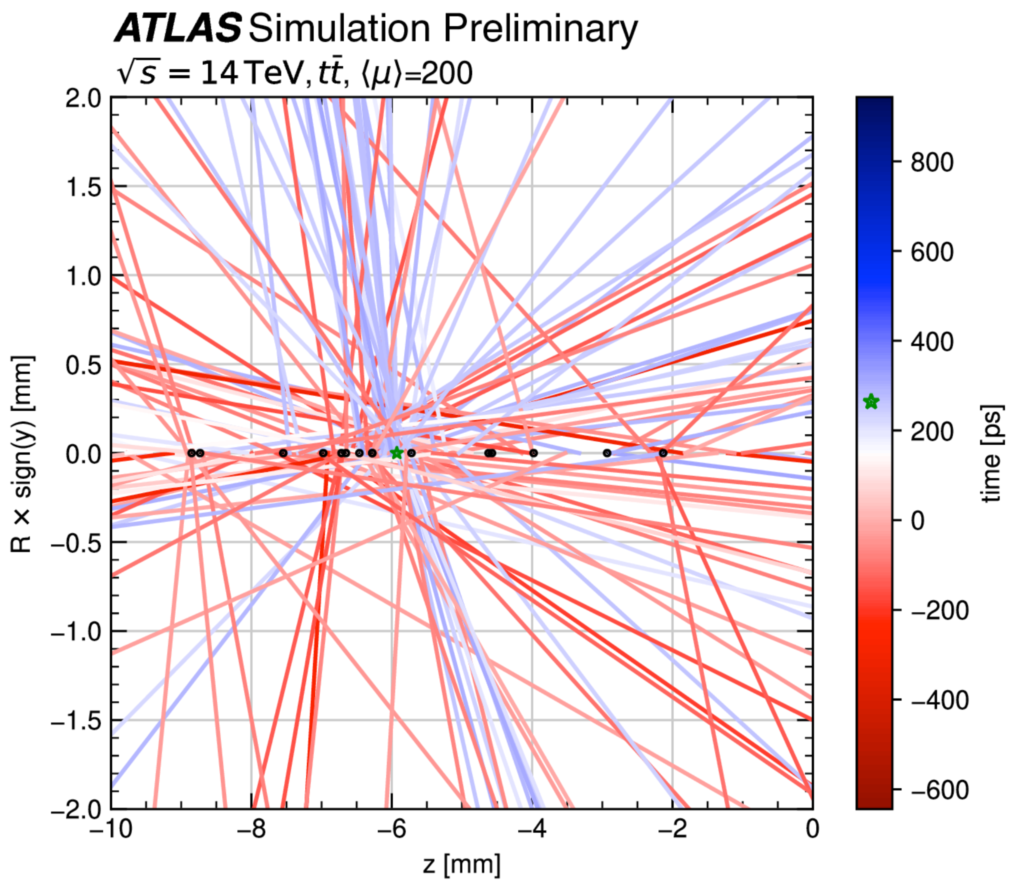
LHCb TDR



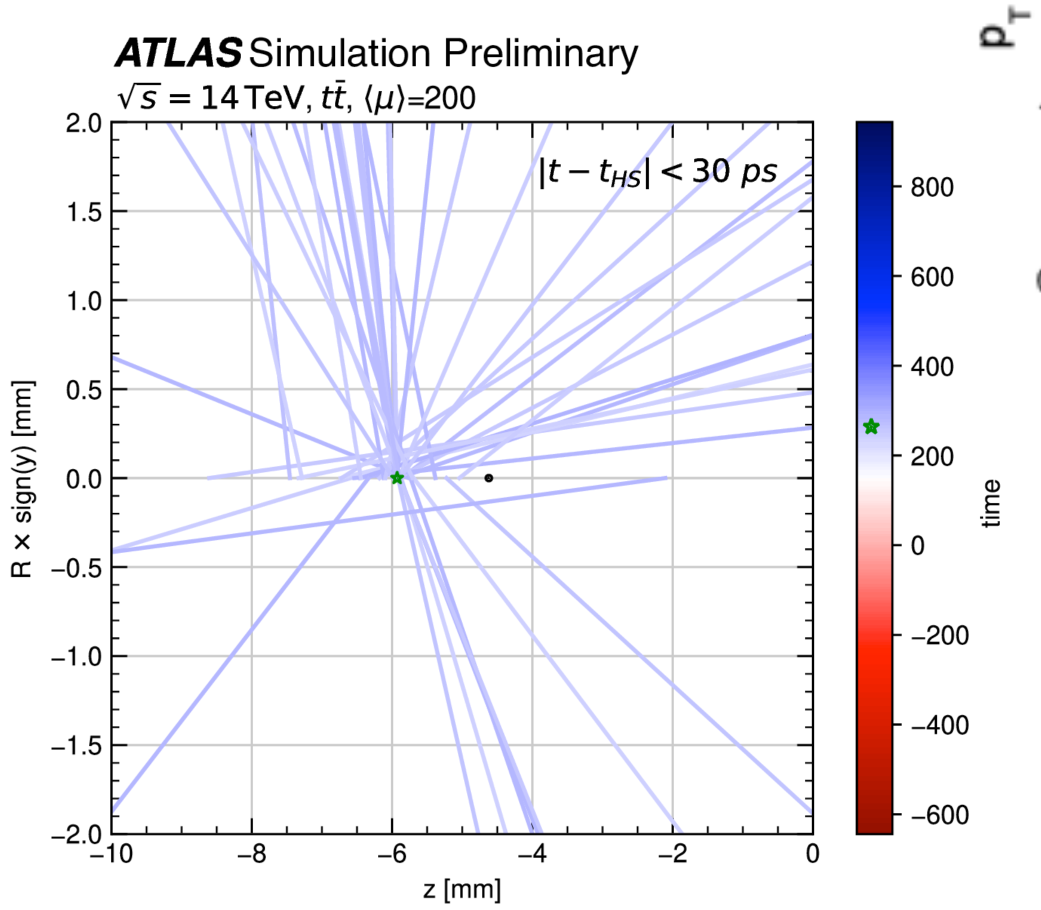
CMS MTD TDR



Zoom →



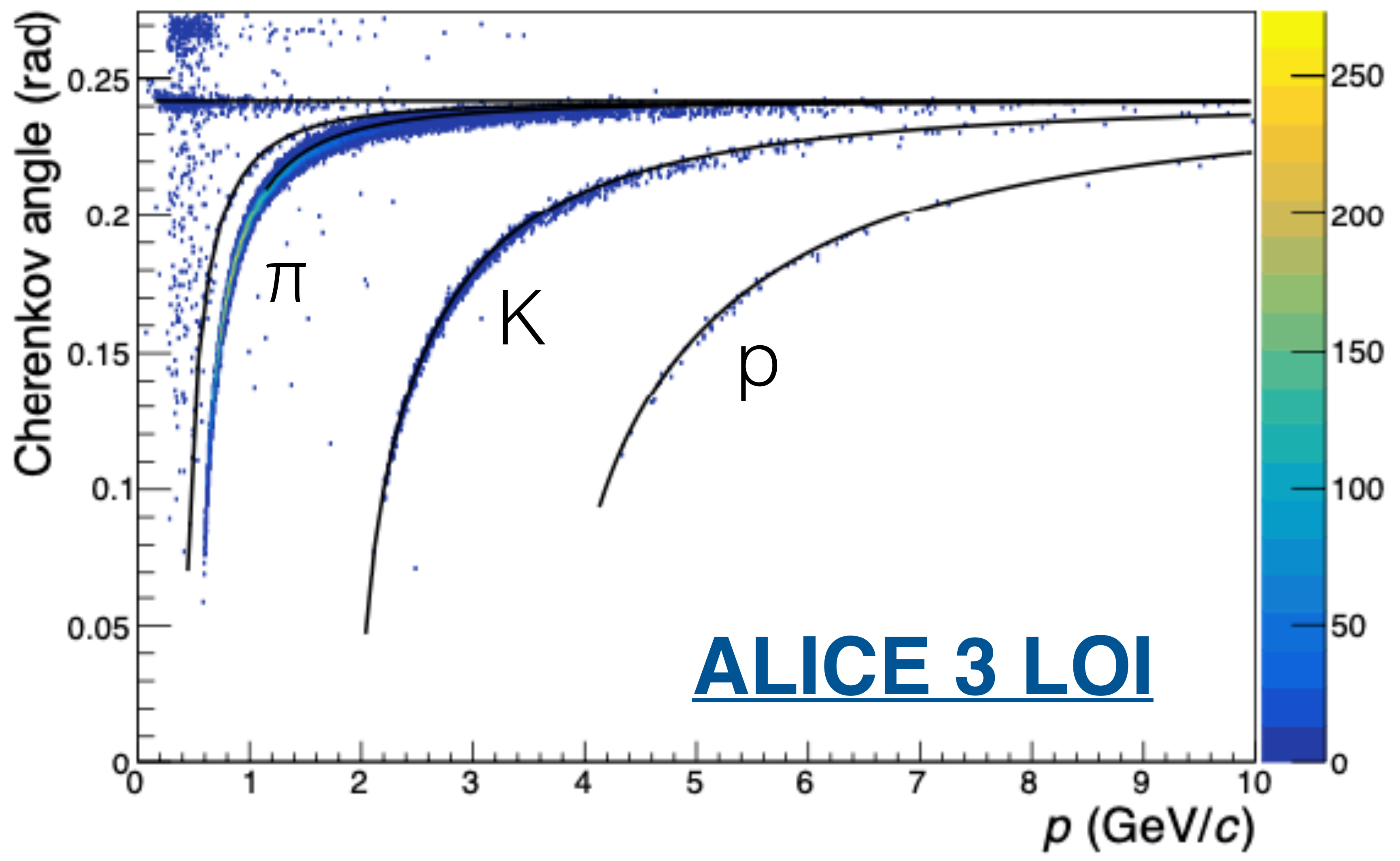
Select →

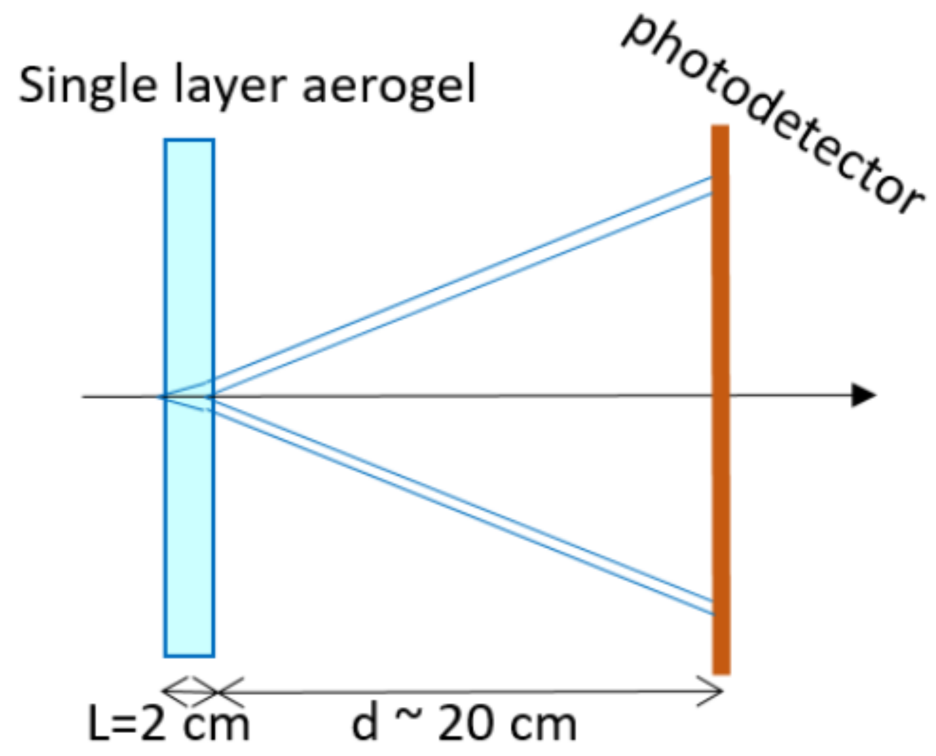


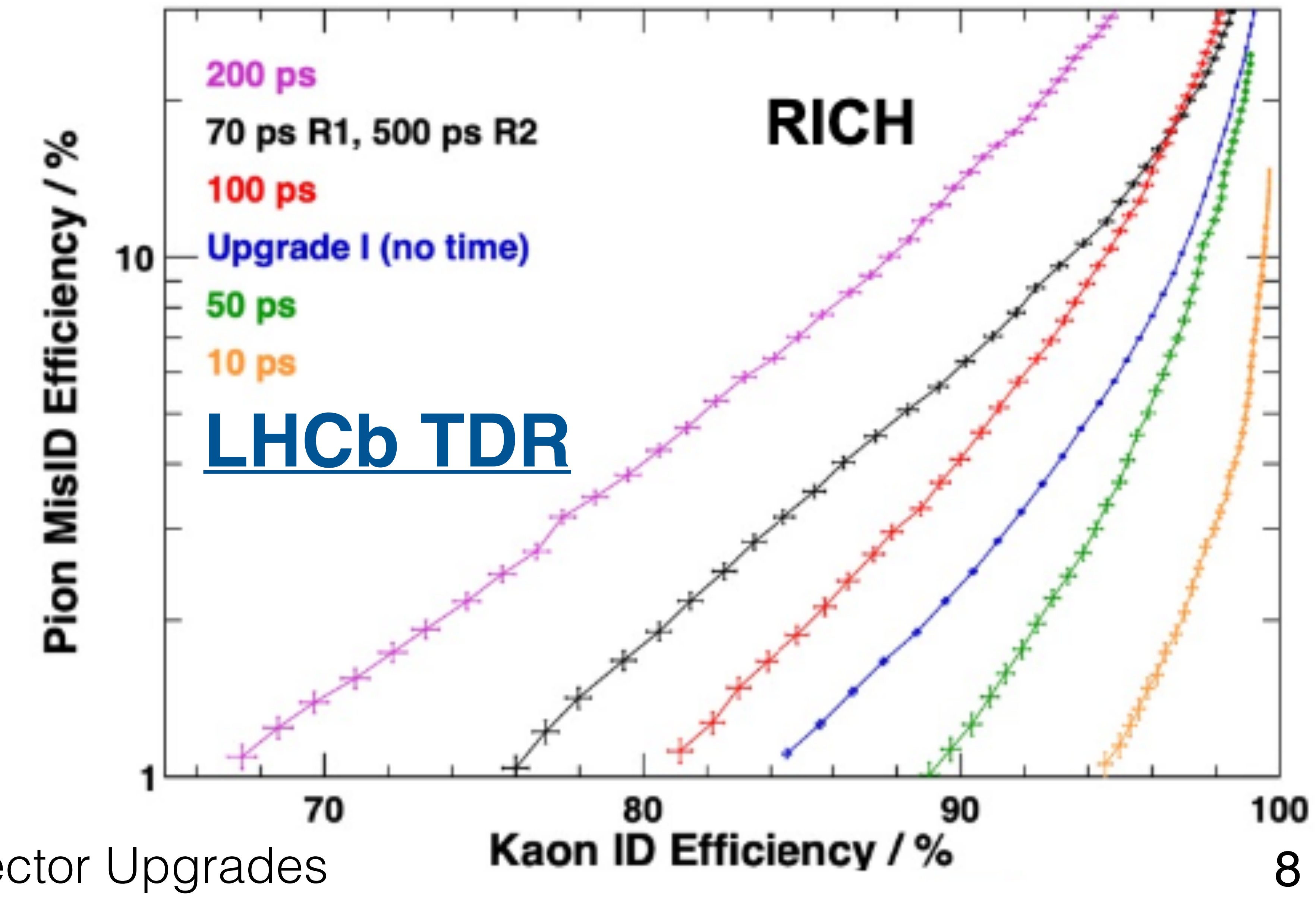
ATL-PHYS-PUB-2023-023

Cherenkov Detectors

- Timing detectors effective for particle ID at low momenta, but to extend range, rely on Cherenkov detectors
  - ALICE exploring aerogel radiator read out by SiPMs at R≈120 cm
  - LHCb: keep RICH radiator (C_4F_{10}), but
    - Reconfigure/new mirrors
    - Replace MaPMTs with SiPMs: handle higher rates, improve time resolution to reject combinatoric background

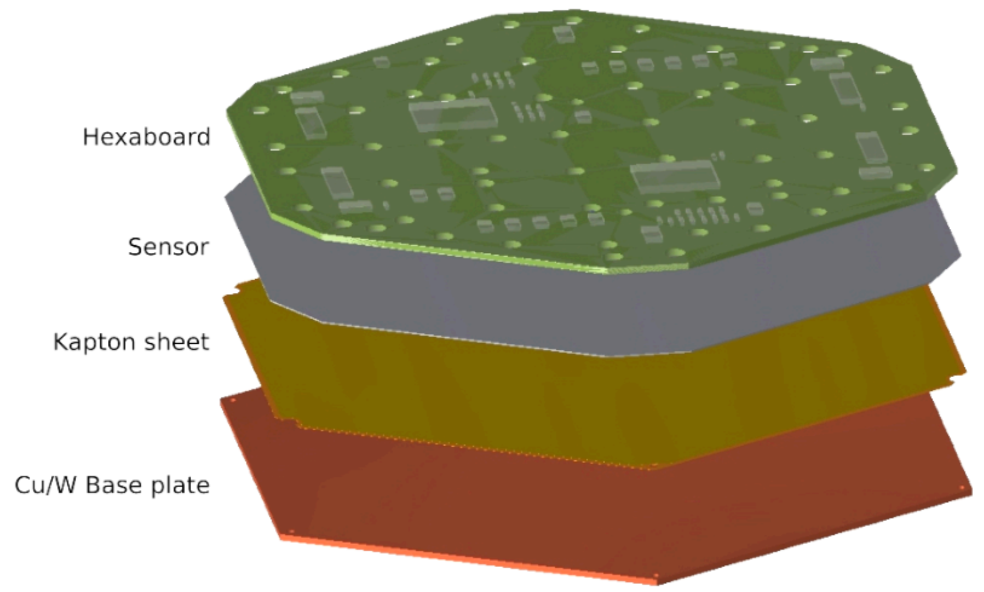


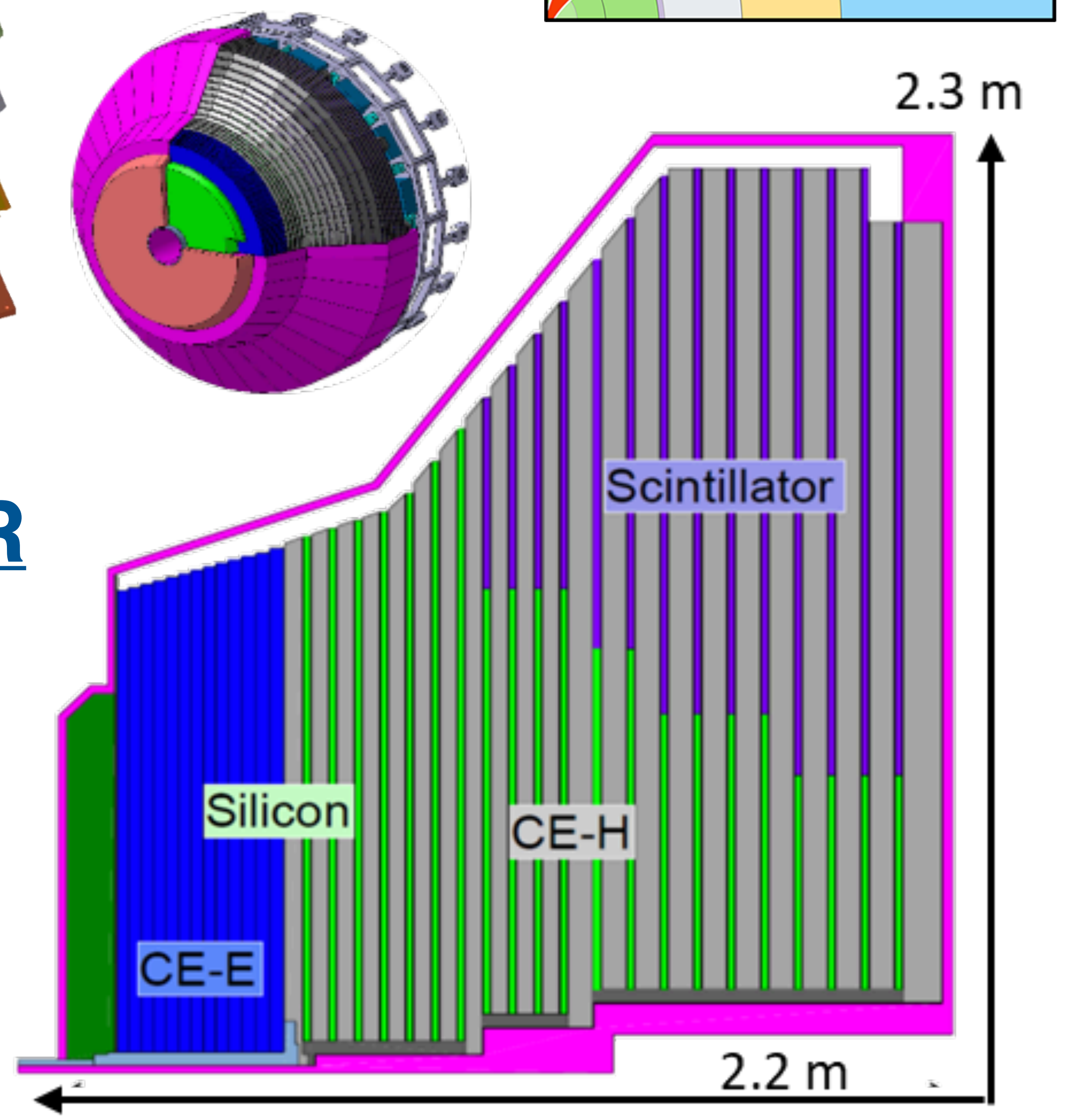




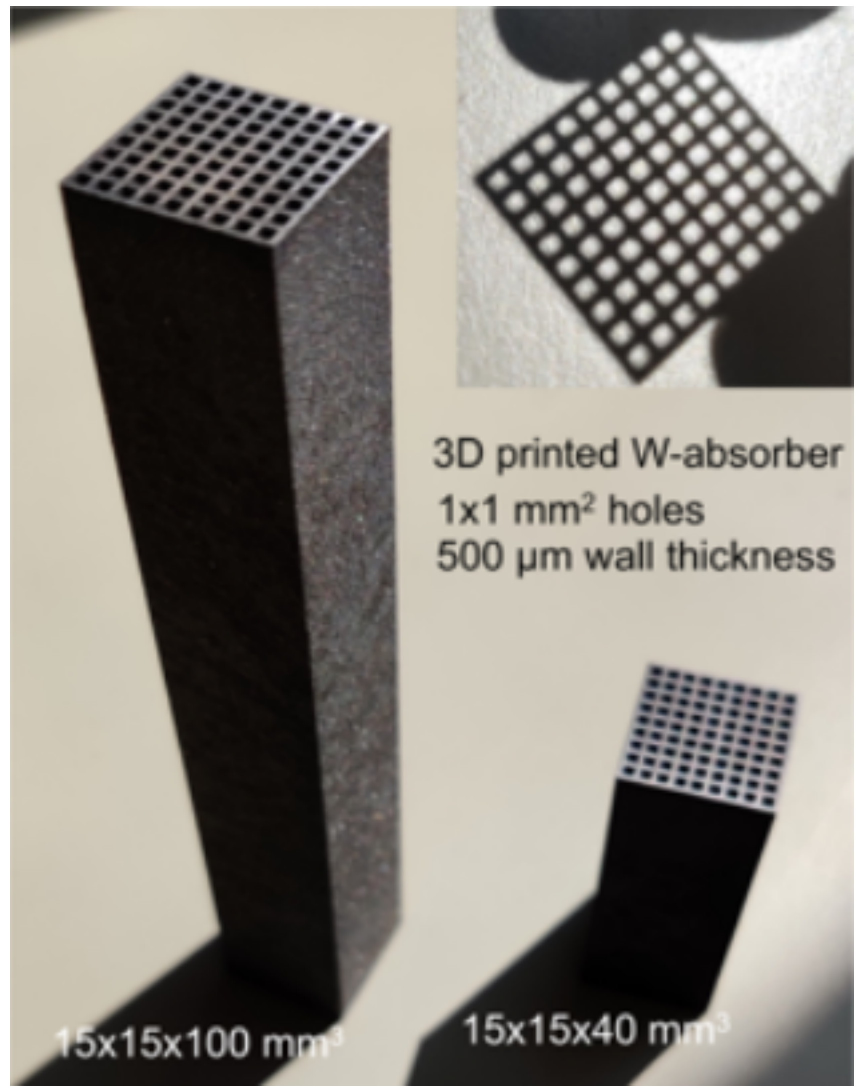
Calorimetry

- If new calorimeters needed, increase granularity and timing performance (“5D”)
  - CMS end cap crystal light yield will become insufficient: replace with Si-absorber (Si cells are ~1 cm^2) and scintillator-absorber (SiPM-on tile, 4-32 cm^2) “imaging” calorimeter
  - LHCb exploring SpaCal for inner radii
    - Crystal fibers at innermost radii
  - ATLAS will upgrade read-out only, going to free-running architecture
  - ALICE 3 likely to use combination of $PbWO_4$ and Pb/Scintillator





CMS HGCAL TDR

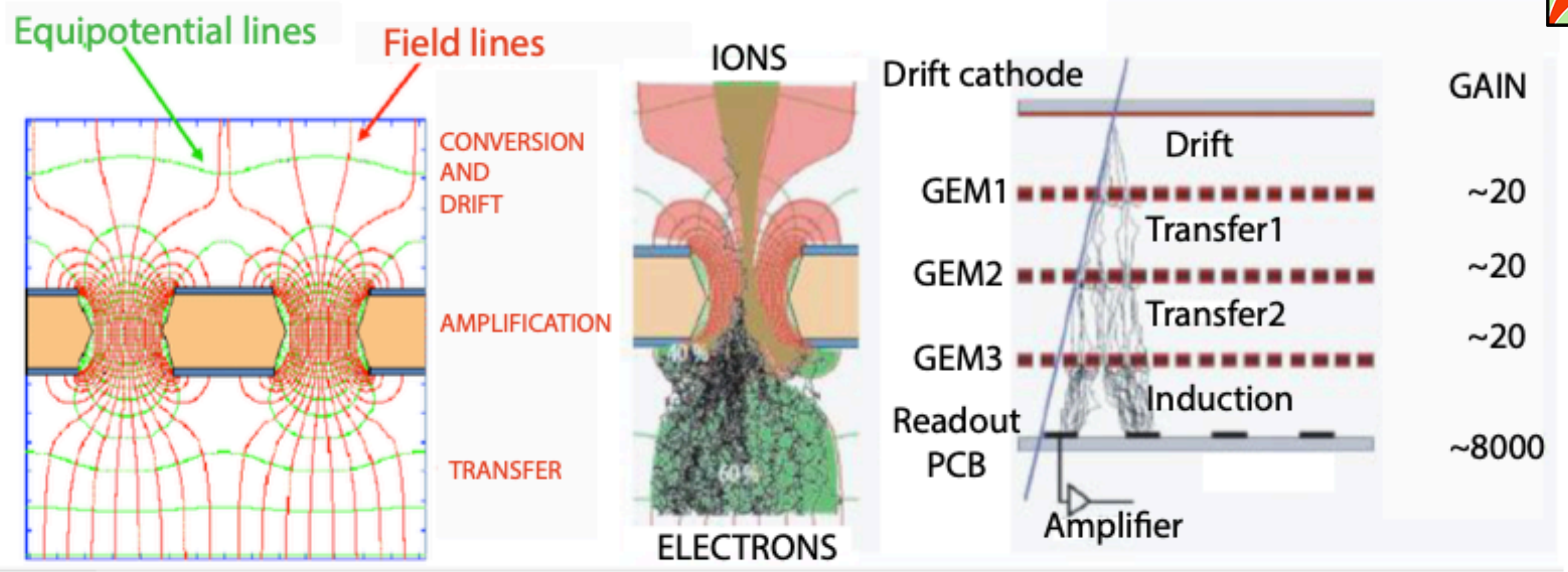


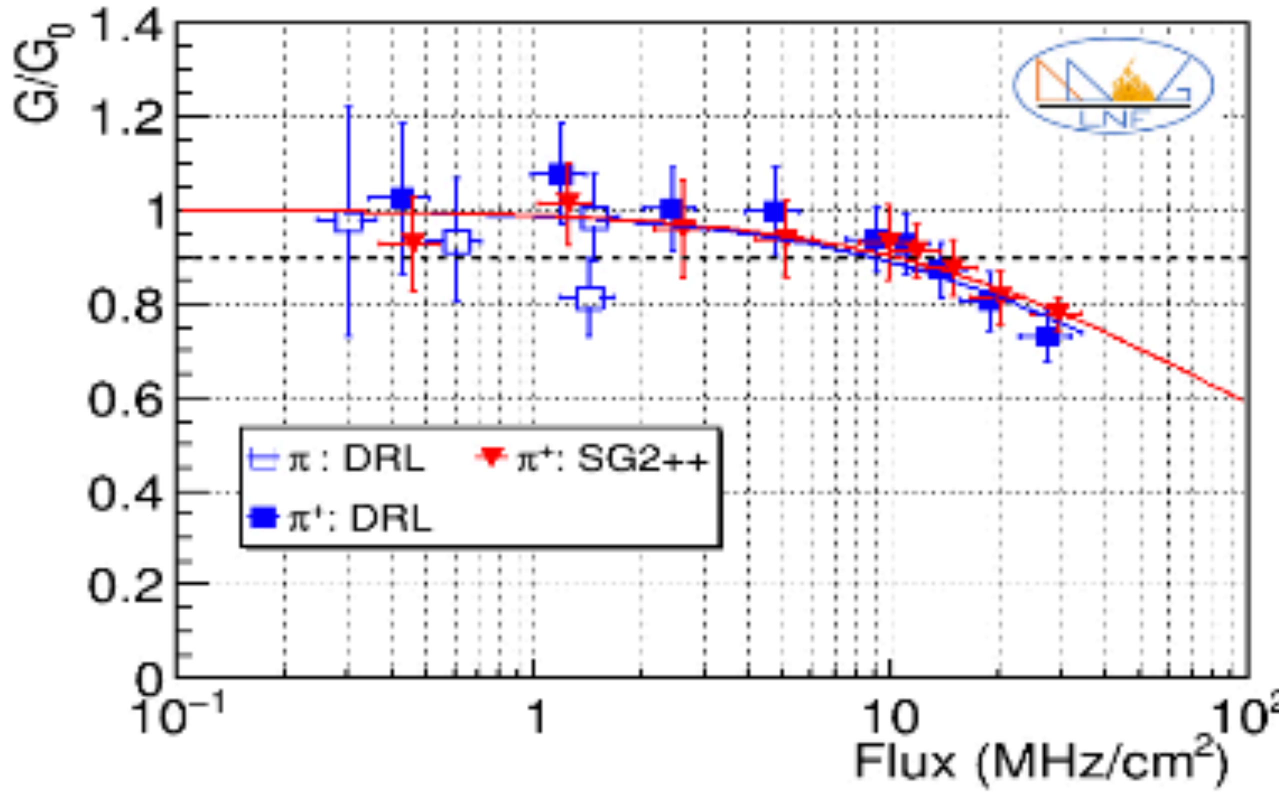
LHCb TDR

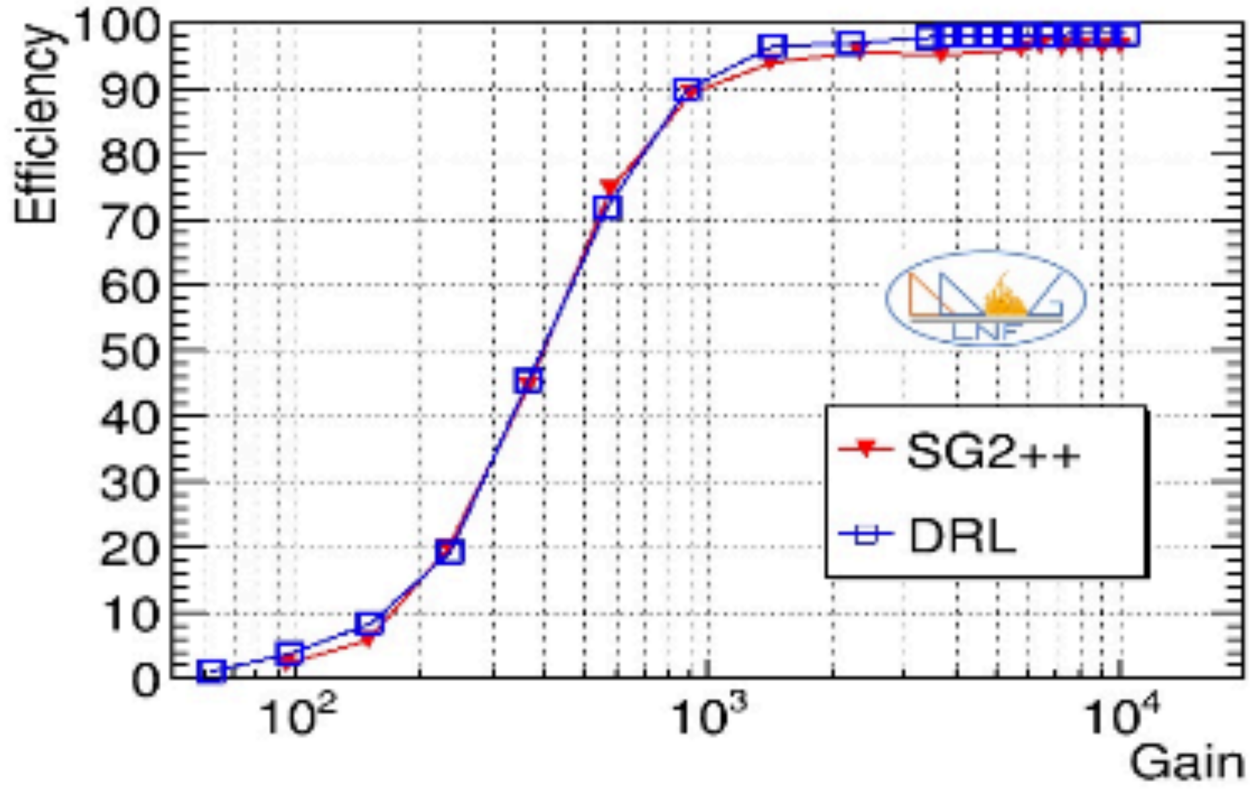
Muon Systems

CMS Muon TDR

- Main challenge is dealing with high rates in the forward regions
  - MHz/cm^2!
- Both CMS and LHCb pursuing GEM-type technologies
  - Technology already used in LHCb
  - Improved version ("µ-RWELL"), capable of sustaining ~10 MHz/cm^2 demonstrated in test beams







LHCb TDR: test beam results

Trigger and Data Acquisition

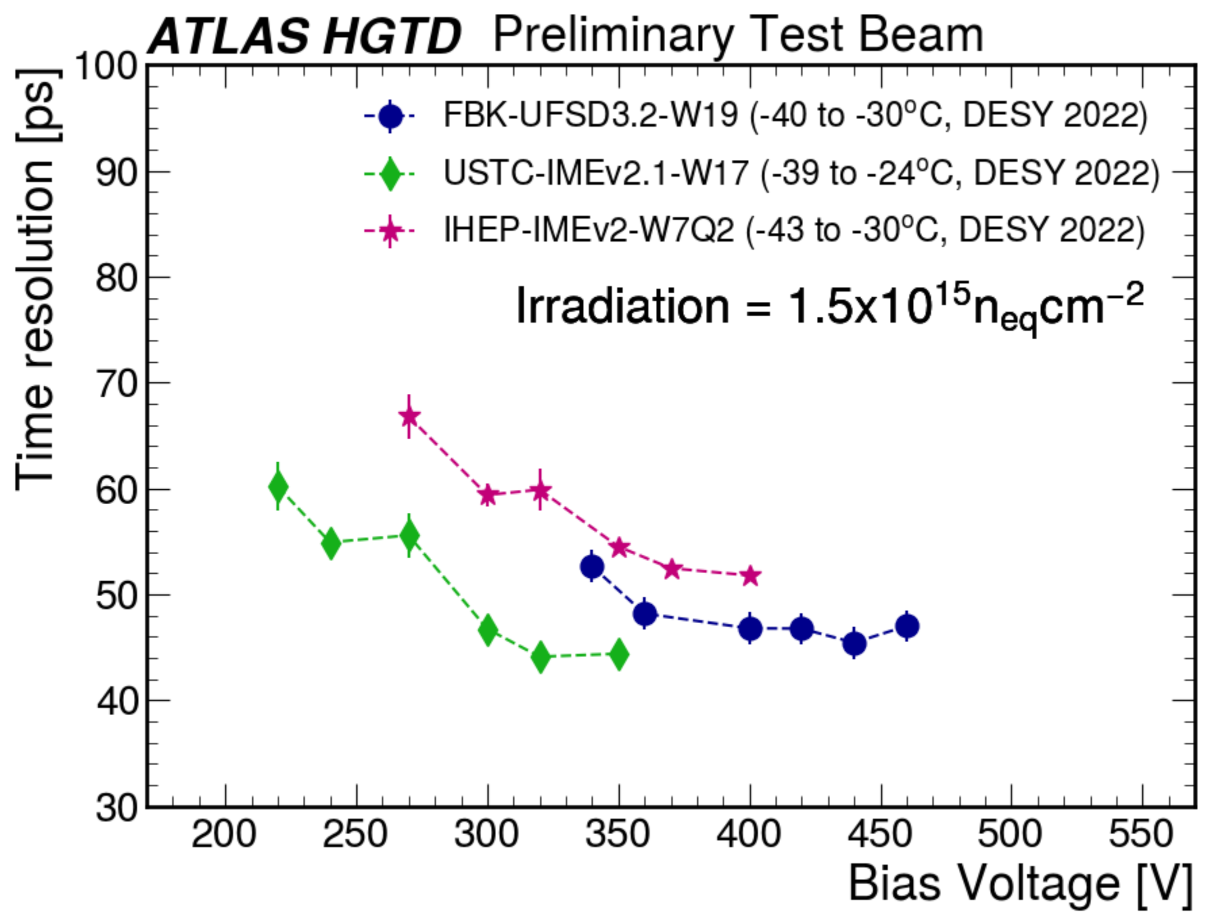
- Increase bandwidth, exploit new technologies, move algorithms upstream in the trigger architecture
  - ATLAS and CMS will increase rate to tape from 1 kHz to 10 kHz (~4 Tbps!)
    - Bandwidth from hardware to software trigger expected to be close to 1 MHz
      - HH → bbbb will remain hard to trigger on, maybe even harder if non-SM
  - Hardware trigger systems (ATLAS and CMS) based on ATCA blades hosting large FPGAs and many 25 Gbps links
    - Increased granularity (eg full calorimeter info), tracking (CMS), anticipate to run Machine Learned algorithms, O(10 μs) latency
  - Software trigger systems will implement algorithms very close to offline, implemented on heterogeneous computing farms
    - Mix of FPGA, GPU and CPU

Closing

- High Luminosity LHC construction is well underway
  - Much deeper probe of the TeV scale and beyond
- Significant rebuild of the detectors
  - New trackers, new readout electronics and trigger and data acquisition systems
- Advent of new technologies
  - MAPS pixel detectors
  - < 50 ps resolution silicon timing systems
  - High granularity silicon calorimetry
- There will be important lessons for the next generation of e^+e^- (as well as pp and $\mu^+\mu^-$) collider detectors

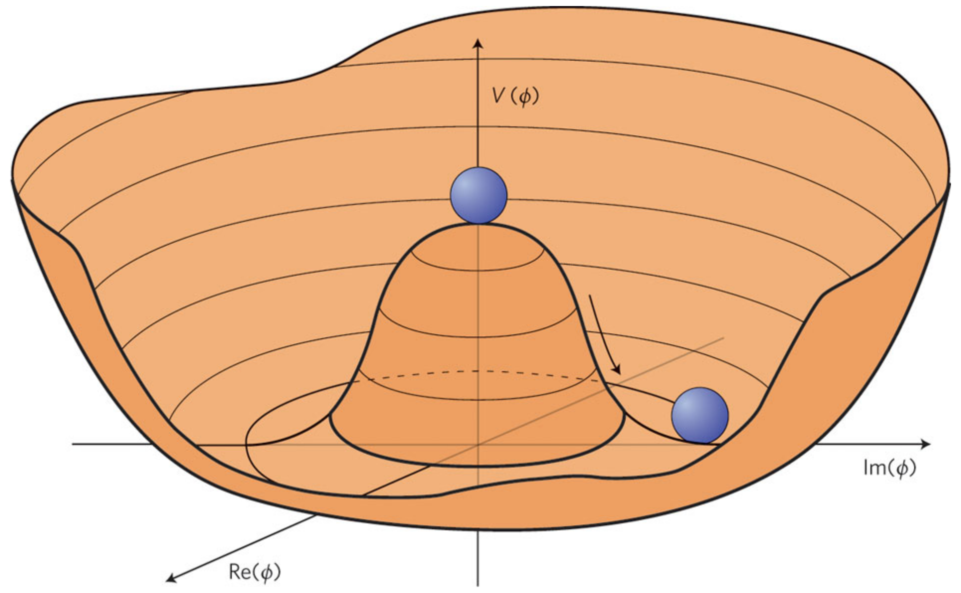
Timing

- Slide for testbeam and similar results



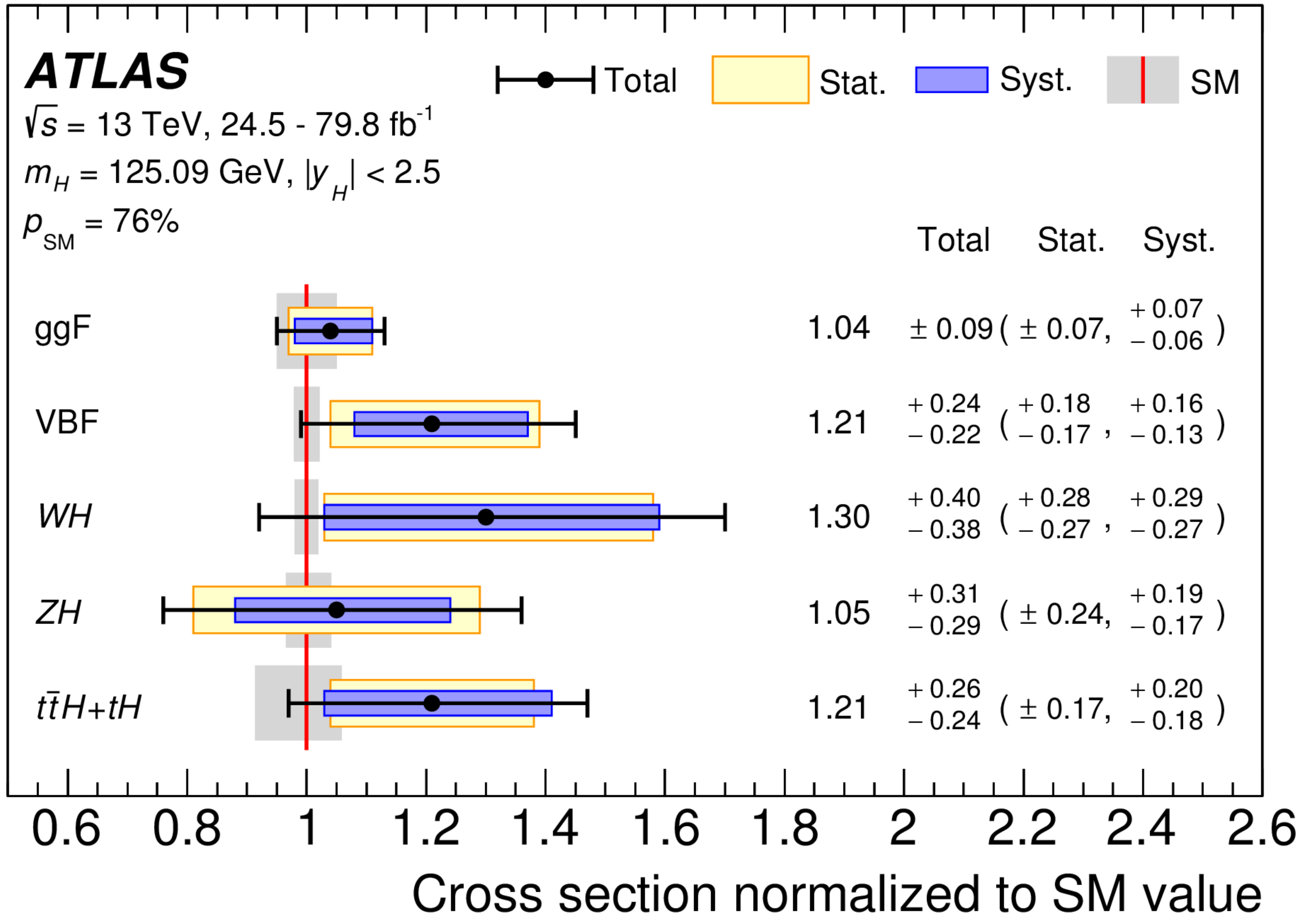
The Higgs Sector

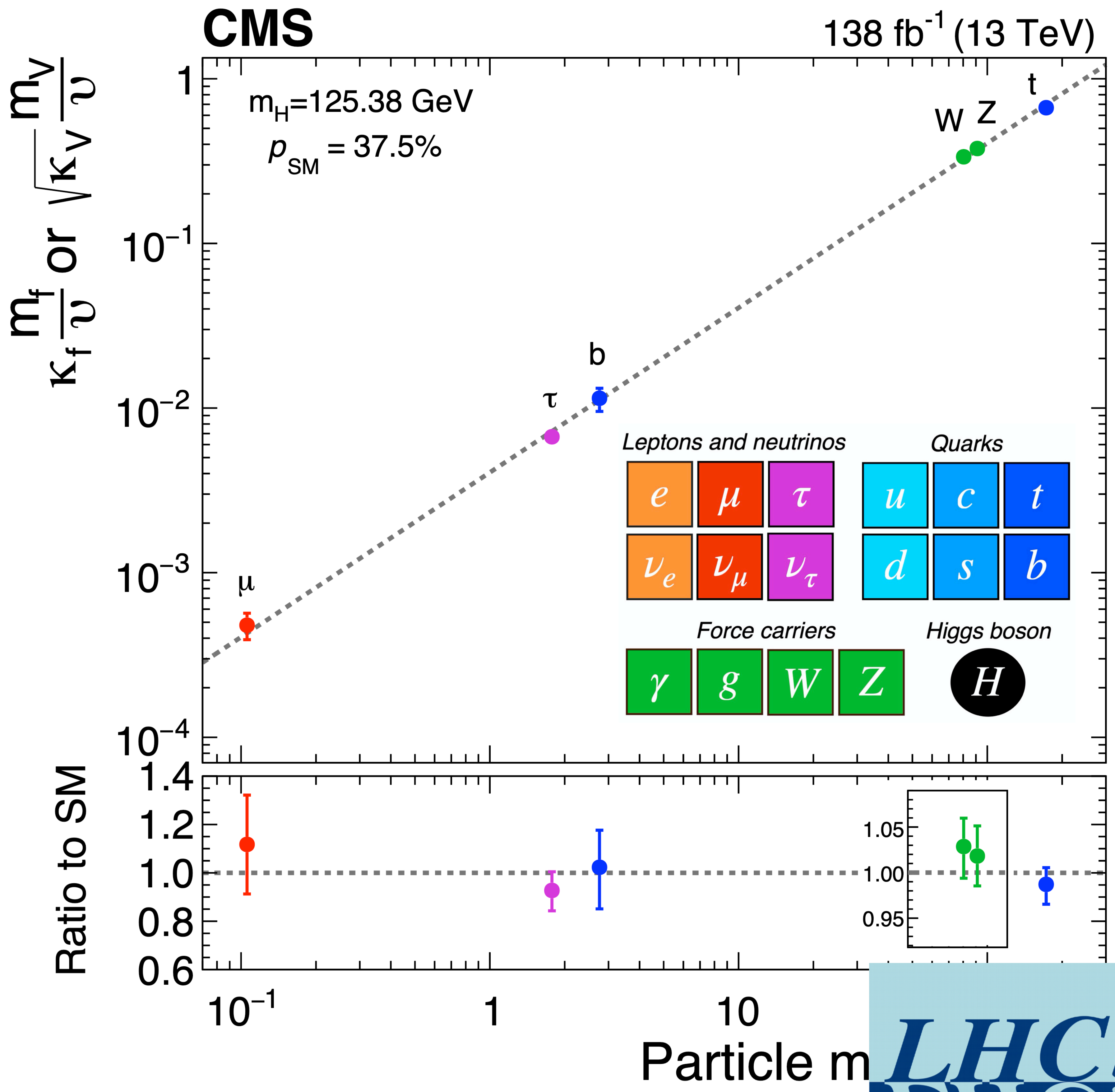
- Left-handed nature of weak interactions forbids "direct" fermion mass
  - Mechanism by which fermions acquire mass has to "connect" to parity violation
  - Mass terms $y_f(\overline{\psi}_L \phi \psi_R)$ rather than $m(\overline{\psi}_L \psi_R)$, with ϕ a weak $SU(2)_L$ (at least) doublet
- Of ϕ's 4 degrees of freedom
  - 3 are the longitudinal W and Z polarizations (which thus acquire mass)
  - 1 physical Higgs boson state
- For everything to work, $V(\phi)$ is (lightly) constrained:
  - Higgs vacuum expectation value cannot be 0 (or $-\infty$)
    - In polynomial form, at least order 4
    - SM ***assumes*** minimal form: $V = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$ with $\mu^2 < 0$ and $\lambda > 0$



Higgs Observation at the LHC

- The existence of *a* Higgs boson is firmly established
  - Couplings match SM prediction fairly well, but 20-100% level deviations allowed



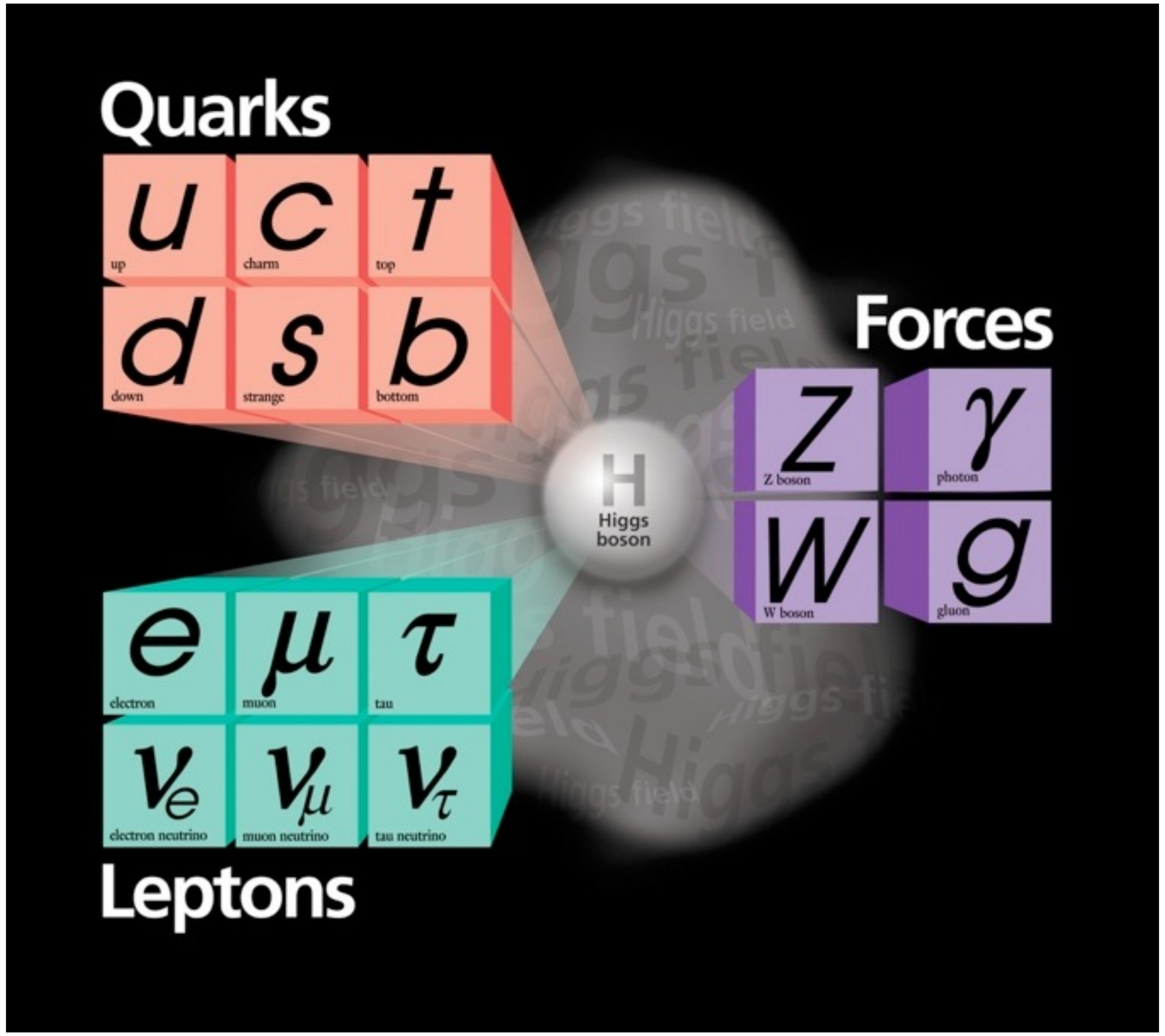


Measuring the Higgs Potential

- The Standard Model predictions for Higgs production and decay are robust, as the couplings to bosons and fermions are set by their masses
  - But this is not so true for the Higgs potential, which could be more complex
    - Around minimum, expand $V = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2 \supset \lambda v^2 H^2 + \lambda v H^3 + (\lambda/4)H^4$
    - First term is just Higgs mass, next are trilinear and quartic couplings
    - So Higgs mass sets λ, then probe if indeed get the same λ for the others
      – Requires measuring multi-Higgs production
- Multi-Higgs production cross-sections are small
  - In particular in the Standard Model, where there is large destructive interference
    - It's (mostly) easier to see new physics than the Standard Model!
- Quartic term will need higher energy (VBF di-Higgs production…)

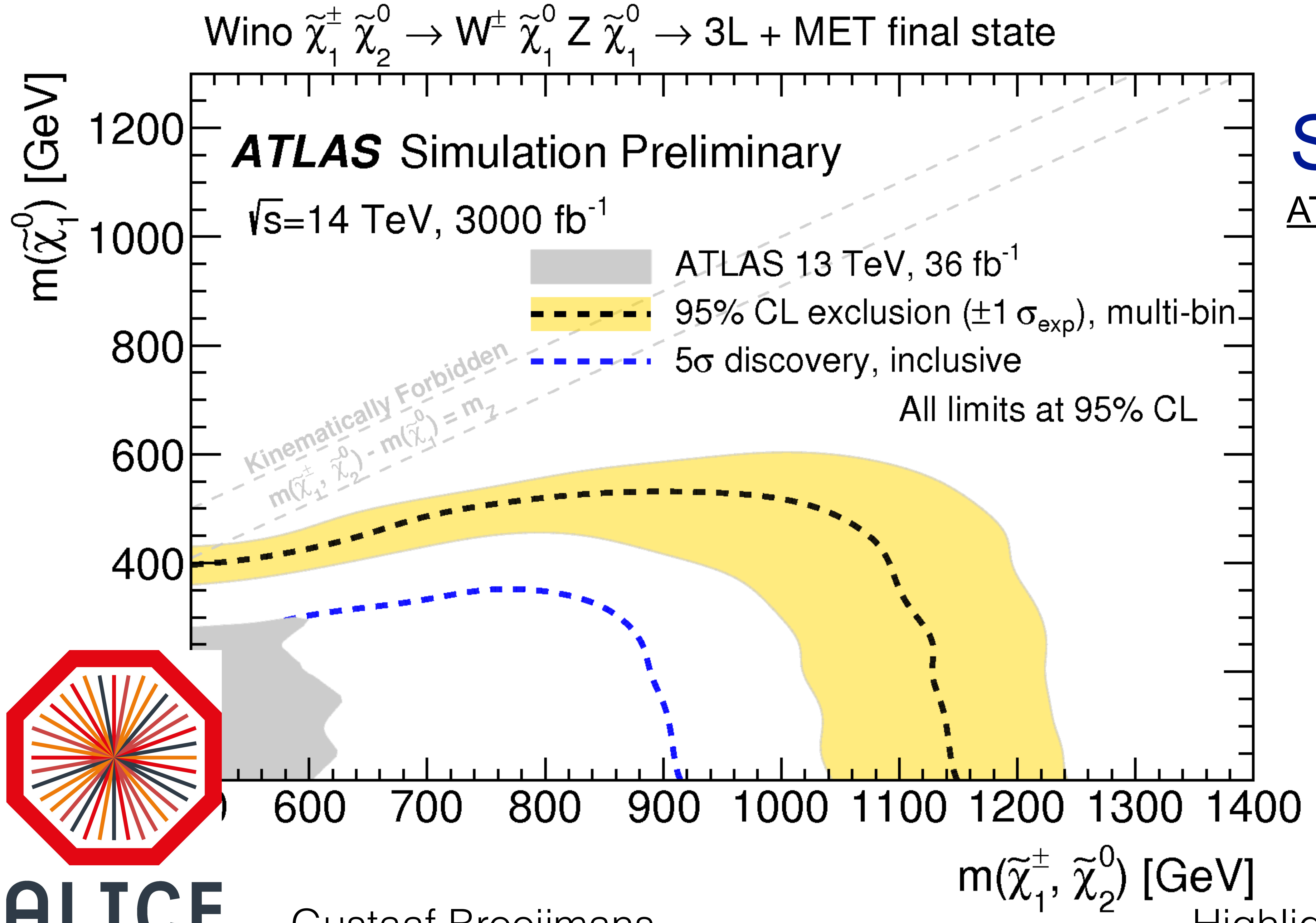
Standard Model Today

- Higgs discovery completes the Standard Model
  - Fully consistent, complete, precise description of strong, electromagnetic and weak ***interactions***
- Even generate fermion masses
  - But that is the ***only*** property of fermions we "understand"



New Physics at the HL-LHC

- HL-LHC will run at same energy as LHC (same dipole magnets)
  - But 20x more luminosity (or more)
    - For background-free searches, sensitivity is linear (in signal cross-section) with data increase
    - For searches with background, sensitivity goes with square root

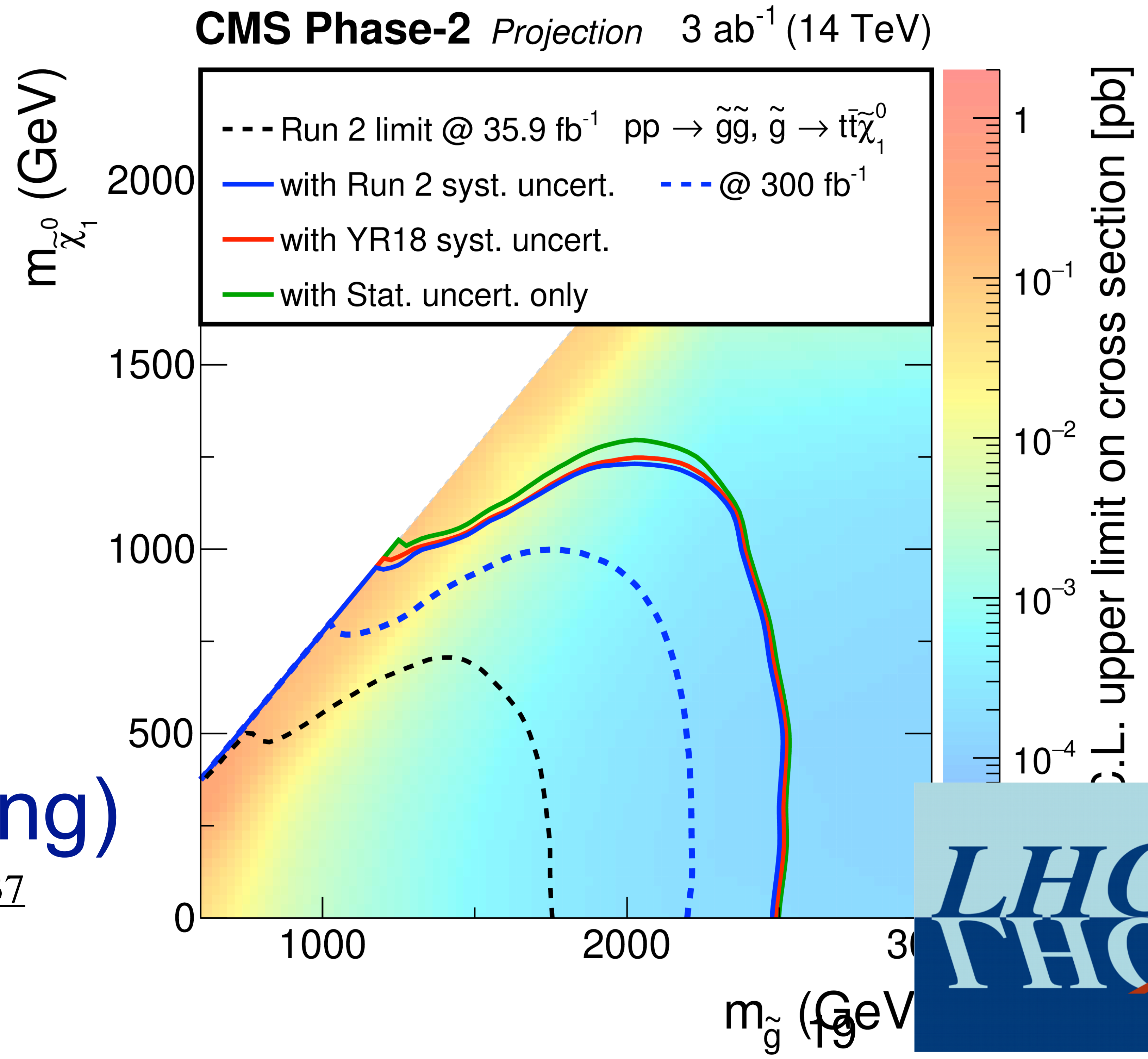


SUSY (Weak)

ATLAS-PHYS-PUB-2018-048

SUSY (Strong)

CMS-PAS-FTR-18-037

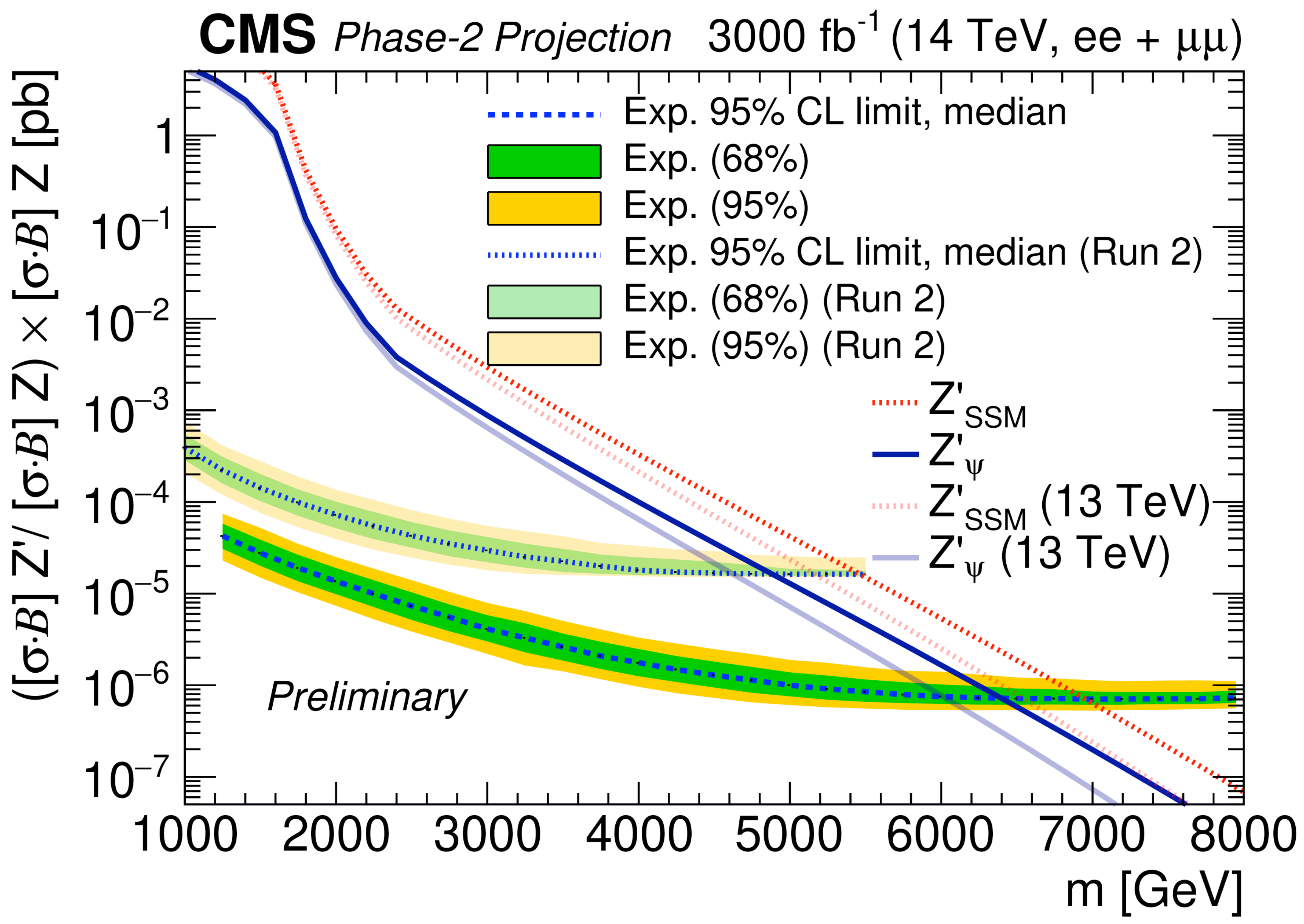


New Physics at the HL-LHC

- HL-LHC will run at same energy as LHC (same dipole magnets)
  - But 20x more luminosity (or more)
  - And new tools, more complex analyses, etc.
    - Machine learning increasingly part of our arsenal

Dilepton Resonances

CMS-PAS-FTR-21-005



New Tools

ATLAS-CONF-2022-045

Anomaly detection search for new resonances decaying into a Higgs boson and a generic new particle X in hadronic final states using $\sqrt{s}$ = 13 TeV pp collisions with the ATLAS detector

The ATLAS Collaboration

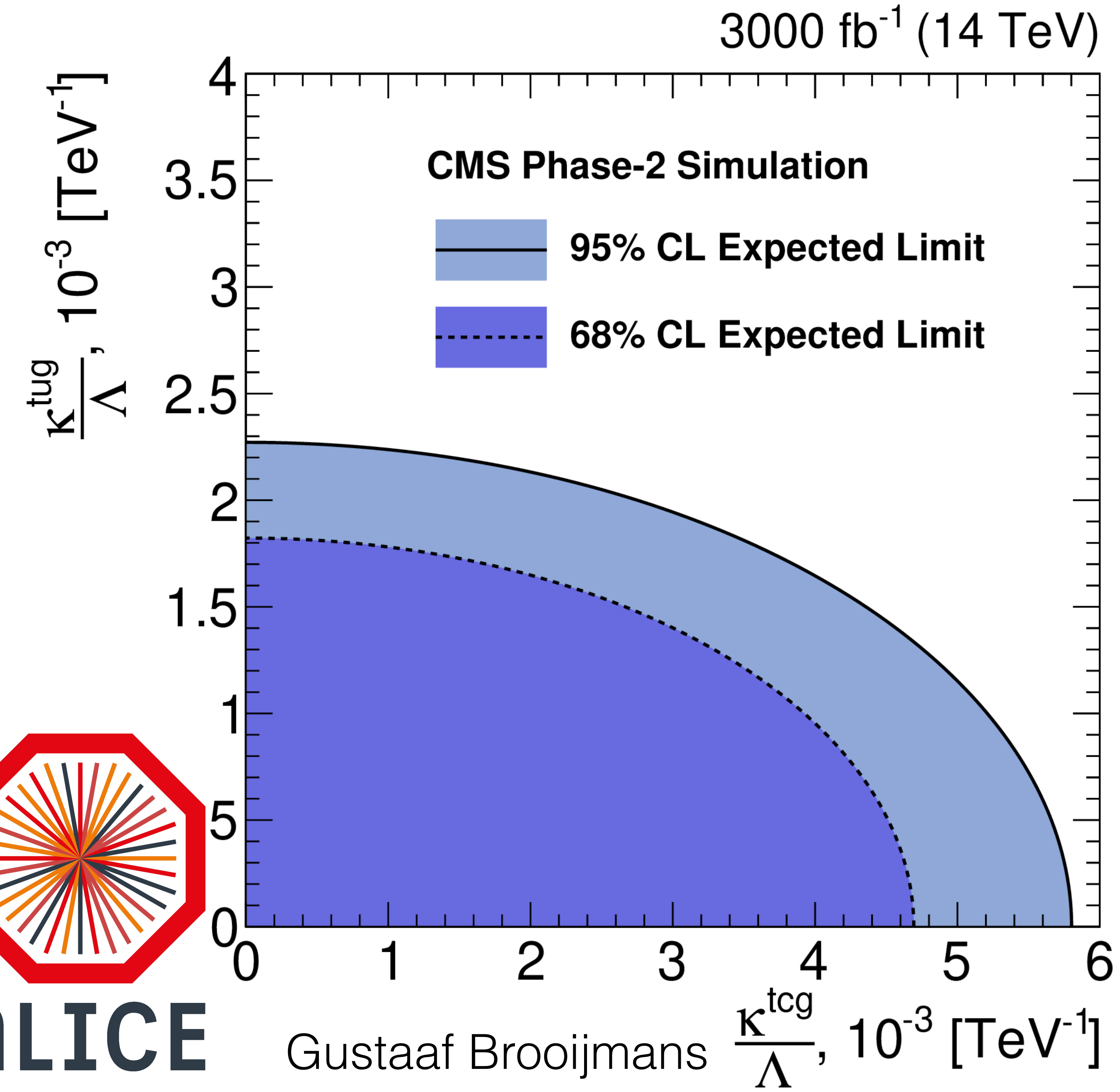
Y mass regime, where the H and X have a significant Lorentz boost. A novel anomaly detection signal region is implemented based on a jet-level score for signal model-independent tagging of the boosted X, representing the first application of fully unsupervised machine learning to an ATLAS analysis. Two additional signal regions are implemented to target a

(Indirect) New Physics at HL-

- Precision measurements to probe higher energy scales
  - Probe PeV scale in up-type quark sector
  - Pin down CP violation in B_s system (π/K separation from timing detectors?)
  - Observe $B_d \to \mu\mu$, measure $B_s \to \mu\mu$ at better than 10% level

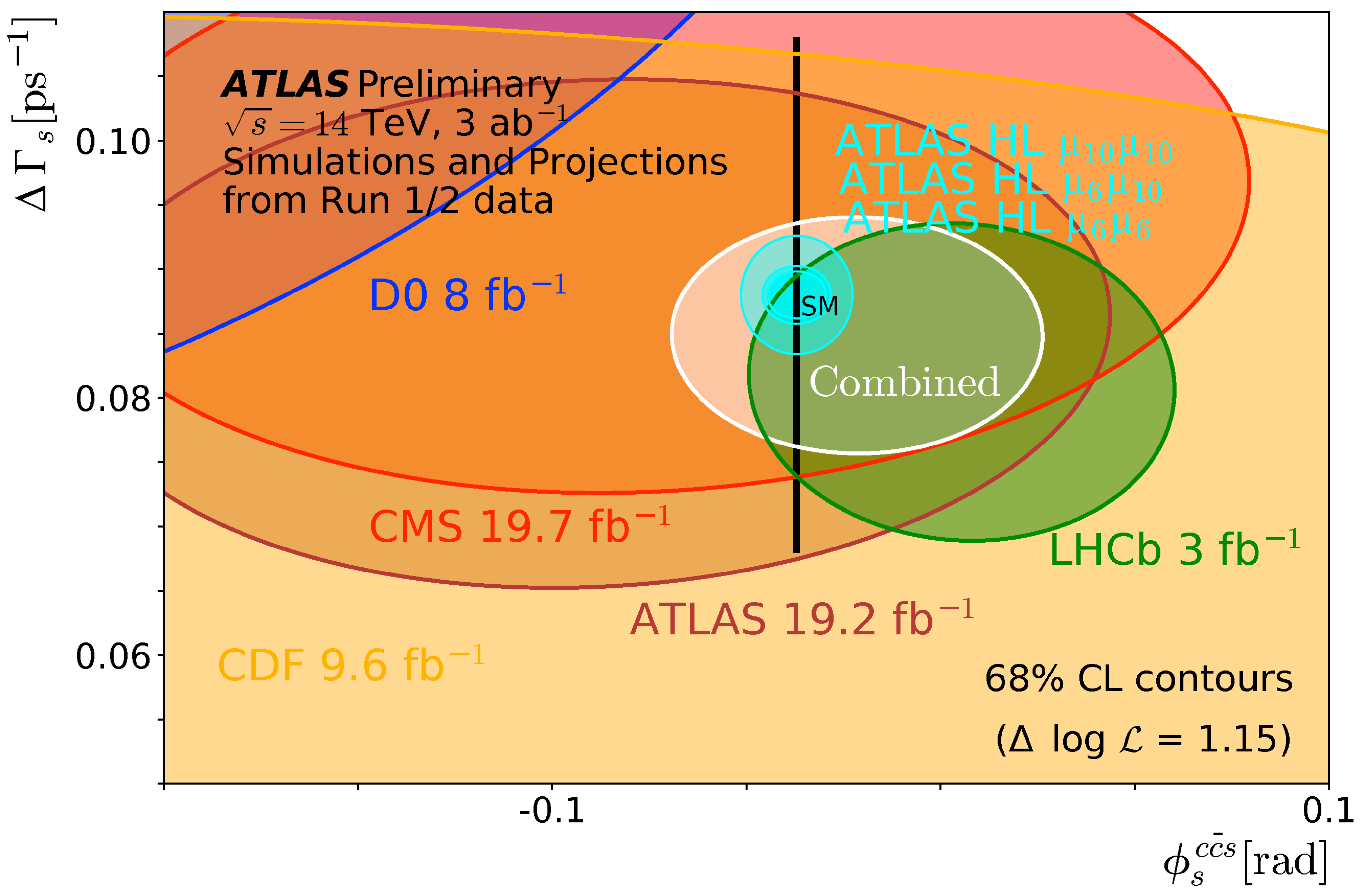
Top FCNC

CMS-PAS-FTR-2018-004



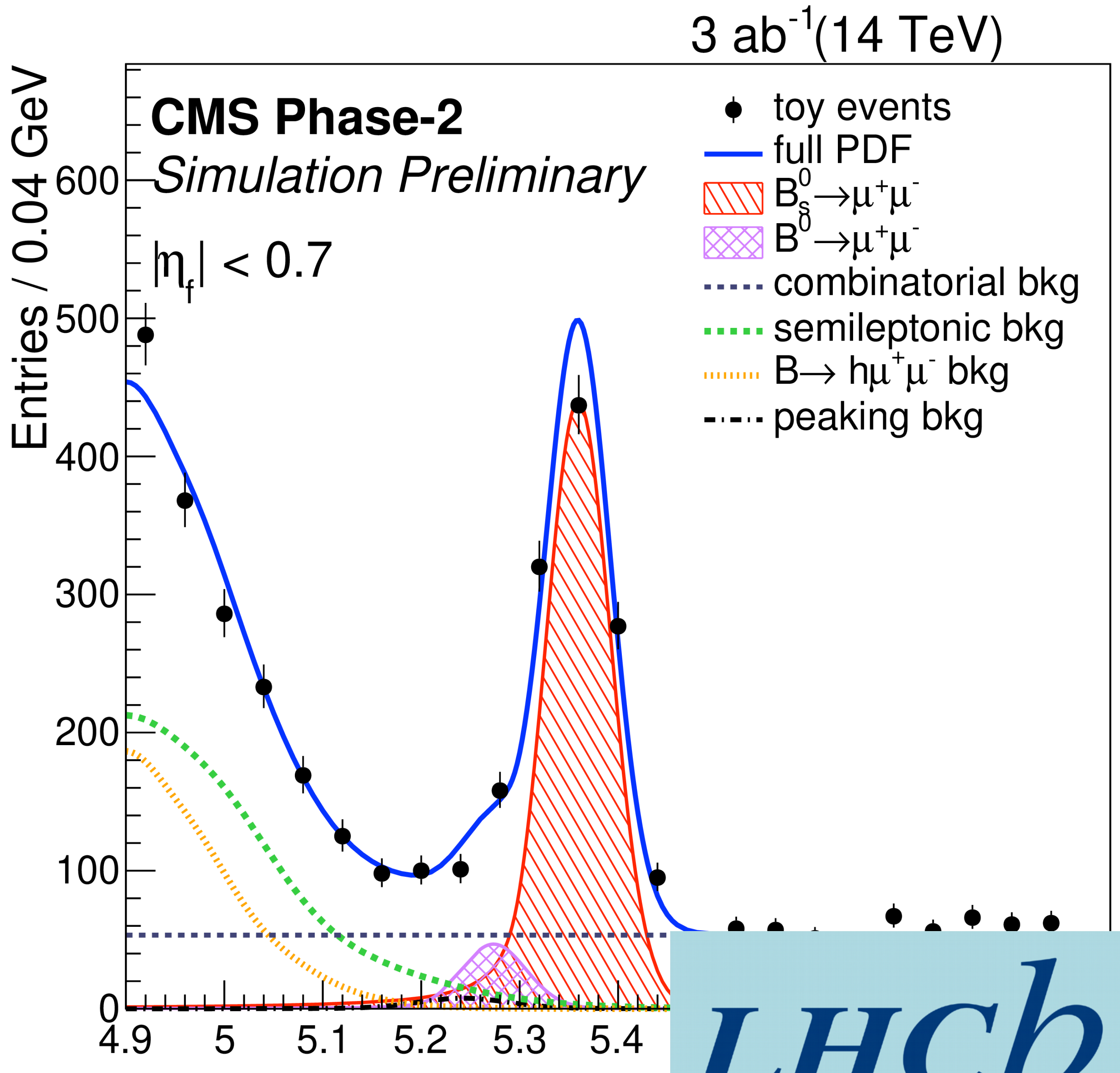
CPV in B_s

ATLAS-PHYS-PUB-2018-041



$B_{d/s} \to \mu\mu$

CMS-PAS-FTR-2018-013

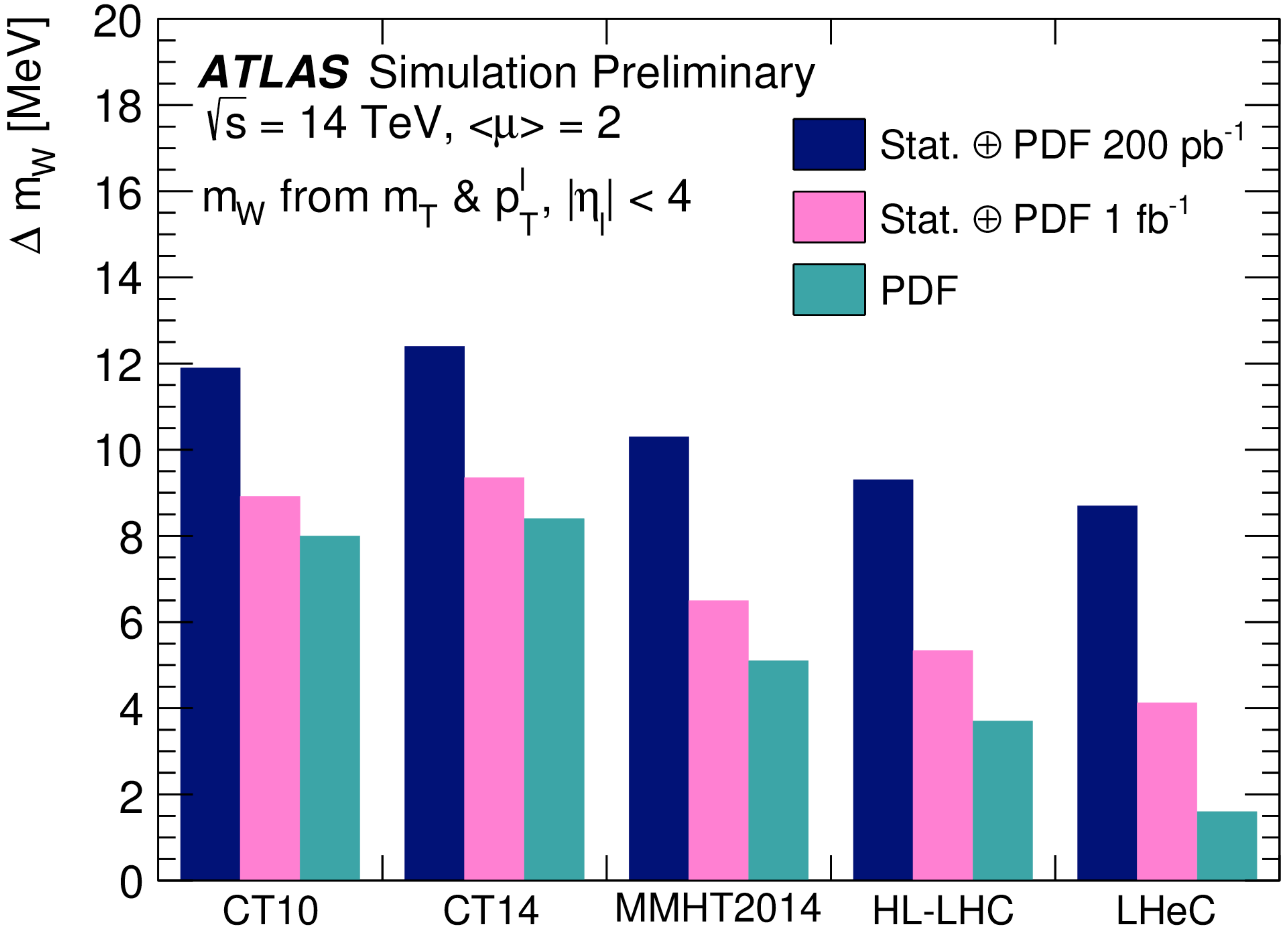


Precision SM Measurements

- (HL-)LHC is a top, Z, W factory; only place to study vector boson scattering, …
- Will also want to include special runs
  - “Low" luminosity for W mass measurement
  - Heavy ions: quark-gluon plasma studies, light-by-light scattering, …

W Mass

ATLAS-PHYS-PUB-2018-026



Current uncertainty is 16 MeV, from 7 TeV run, ATLAS-CONF-2023-004

Tau g-2

Beresford & Liu, PRD 106 039902