Energy Frontier LHC & HL-LHC

Michael Begel

April 16, 2019

BROOKHAVEN NATIONAL LABORATORY

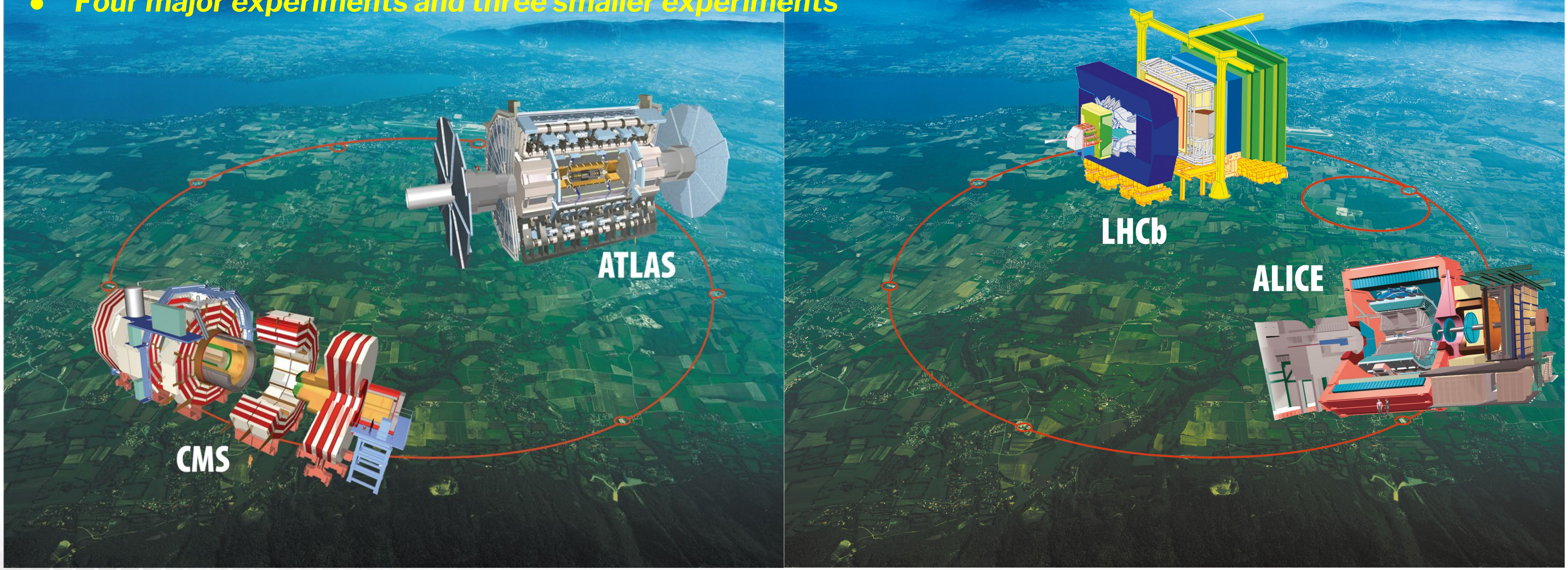
U.S. DEPARTMENT OF ENERGY

BROOKHAVEN SCIENCE ASSOCIATES

LHC at CERN

LHC is world's highest energy hadron collider

- ***pp, PbPb, pPb, XeXe***
- ***√s up to 14 TeV***
- ***Four major experiments and three smaller experiments***

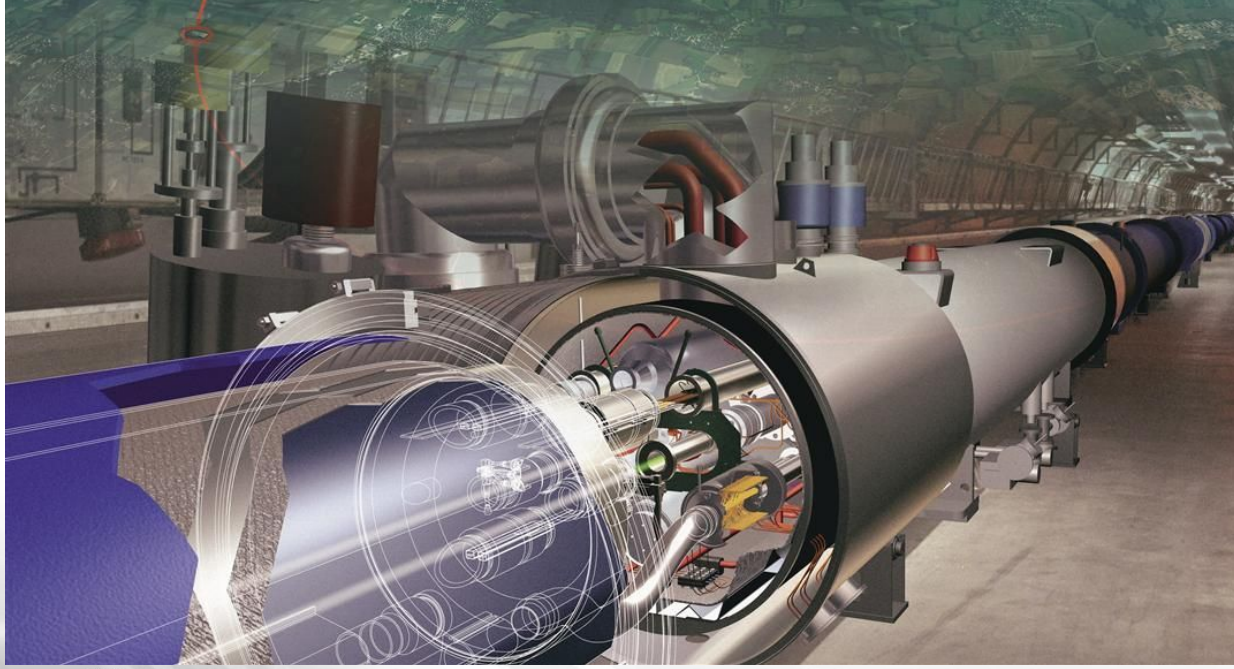


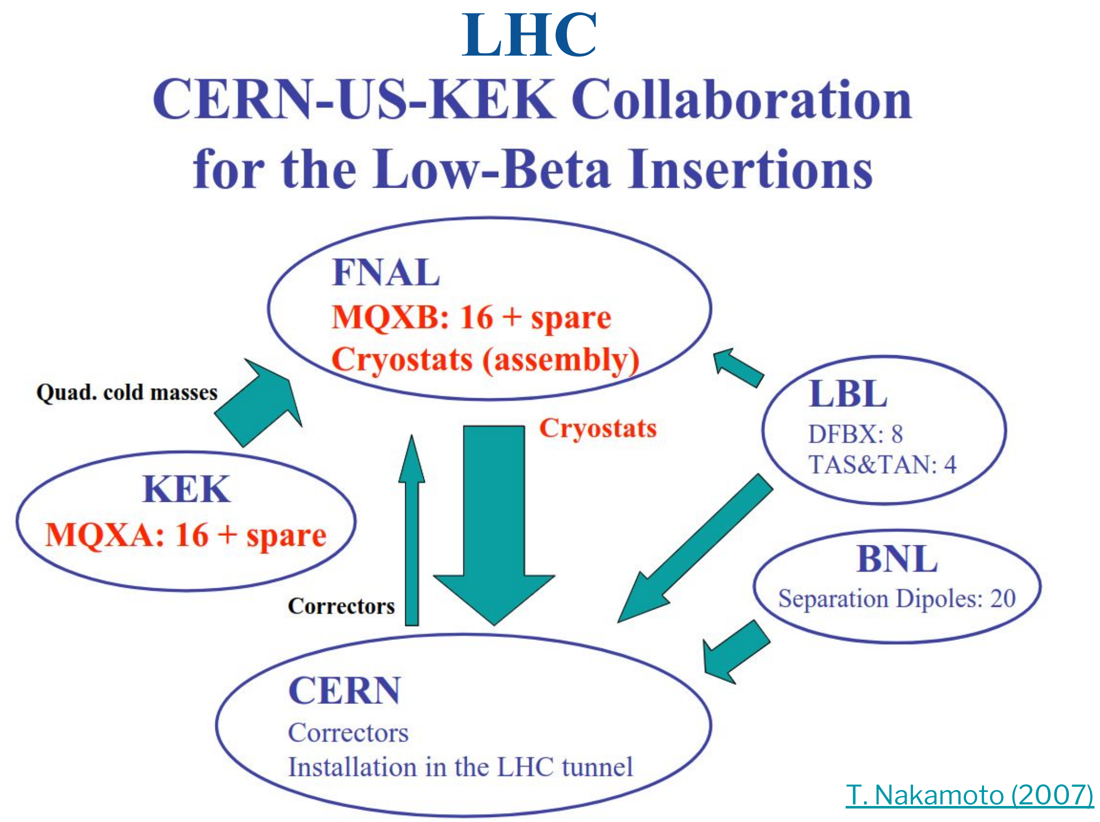
T. Nakamoto (2007)

LHC at CERN

LHC is world's highest energy hadron collider

- ***pp, PbPb, pPb, XeXe***
- ***$\sqrt{s}$ up to 14 TeV***
- ***Four major experiments and three smaller experiments***
- ***US & Japan built inner triplet magnets that focus beams at LHC experimental interaction regions***
  - upgrades for High Luminosity LHC (HL-LHC)
  - ~1 x 10^{34} → ~5.0—7.5 x 10^{34} $cm^{-2}s^{-1}$
    ~60 → ~140—200 pp interactions/crossing





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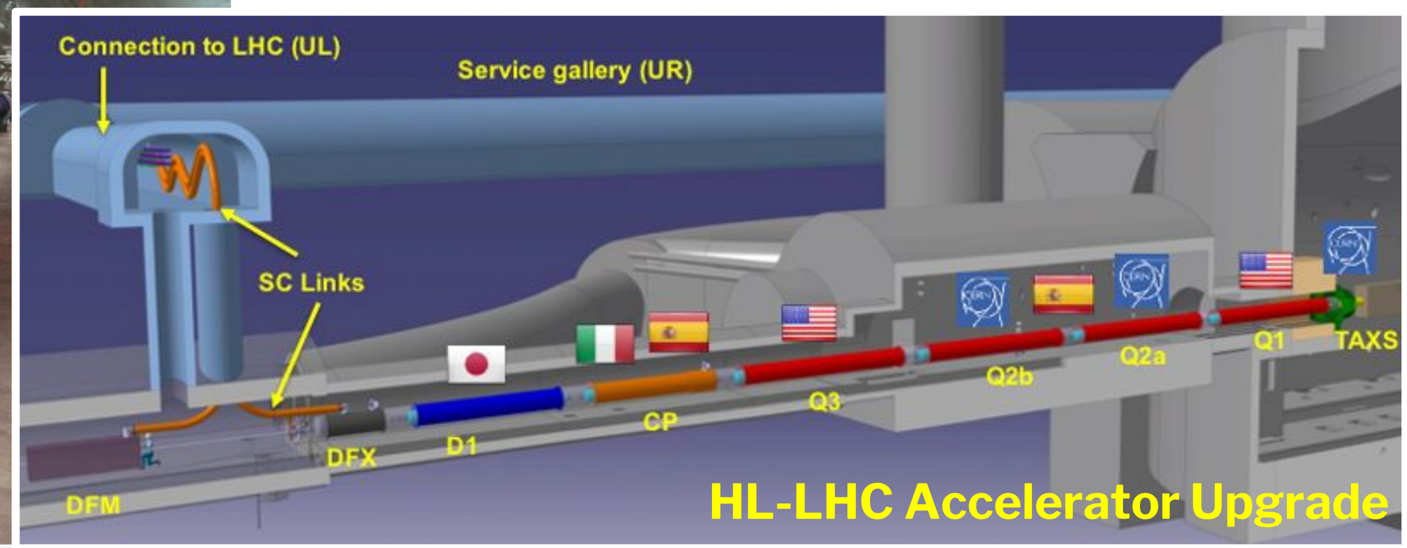
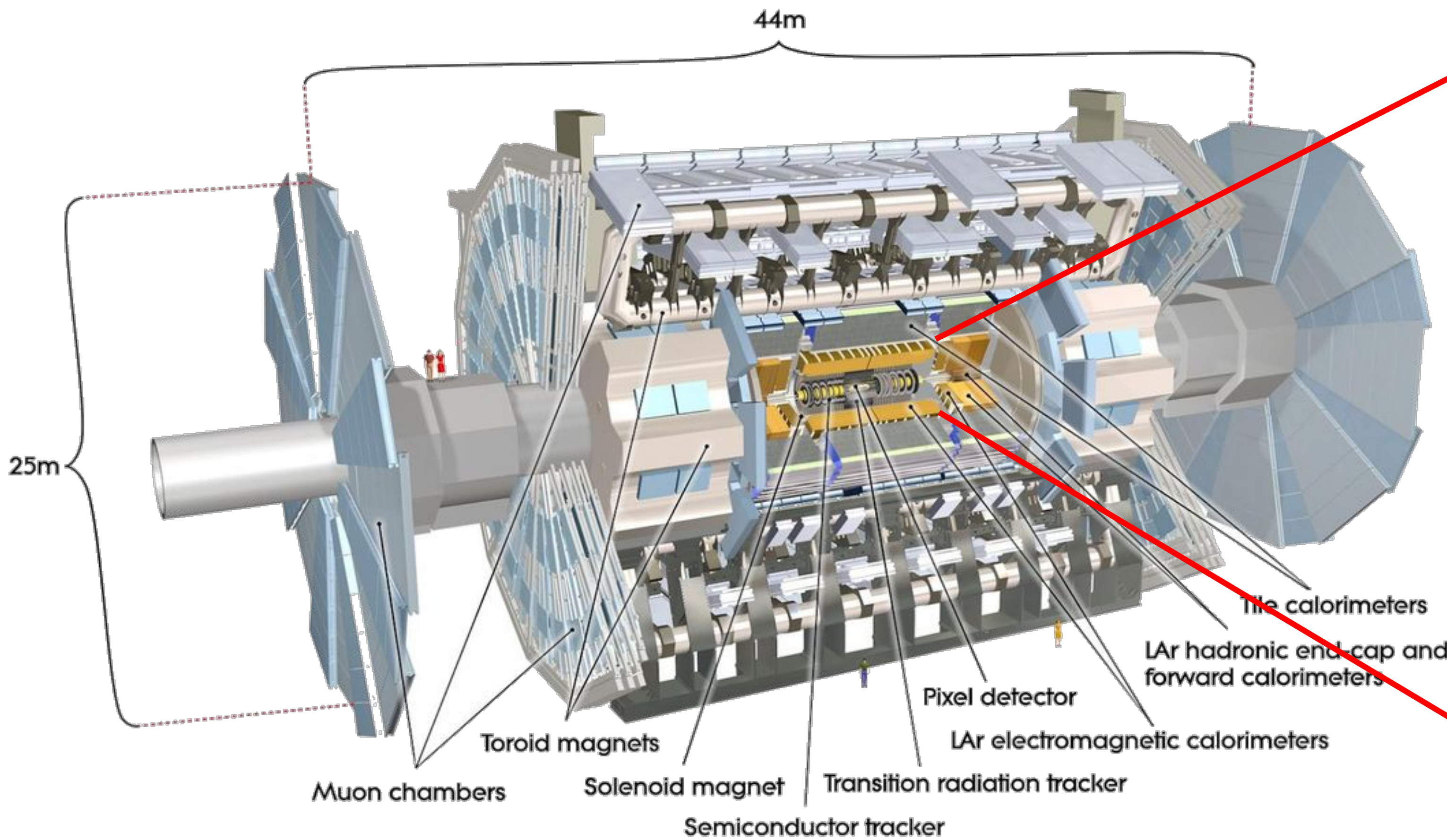


ATLAS Detector



26 February 2004
Insertion of Solenoid Magnet into Liquid Argon Barrel Cryostat

Factoids

ATLAS LOI on October 1, 1992

~7000 tons — comparable to Eiffel Tower

~62 m^2 of silicon sensors in tracking system

~100 million electronics channels and ~3000 km of cables

2 T Solenoid Magnet has ~9 km of superconducting wire

~2 billion collisions per second yielding ~200 TB/s data of which only ~1 GB/s are recorded

~1 PB transferred every day on LHC world-wide grid

ATLAS Collaboration

United States of America

41 ATLAS institutions (45 institutes)

1115 (479) ATLAS members (authors) of which 262 students

- silicon detectors
- transition radiation detector
- liquid argon calorimeter
- tile calorimeter
- muon spectrometer
- trigger & data acquisition
- technical coordination
- computing & software

Japan

16 ATLAS institutions (16 institutes)

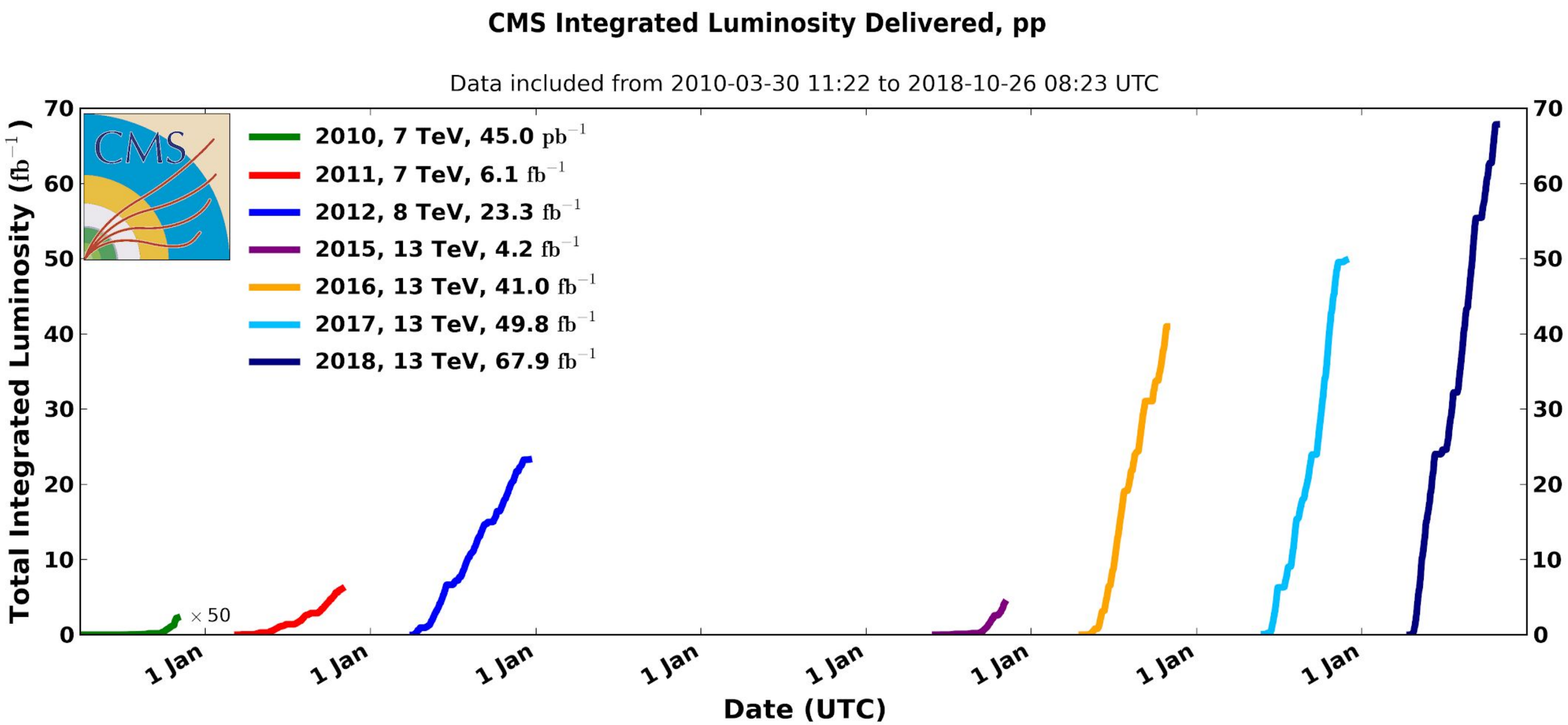
147 (86) ATLAS members (authors) of which 32 students

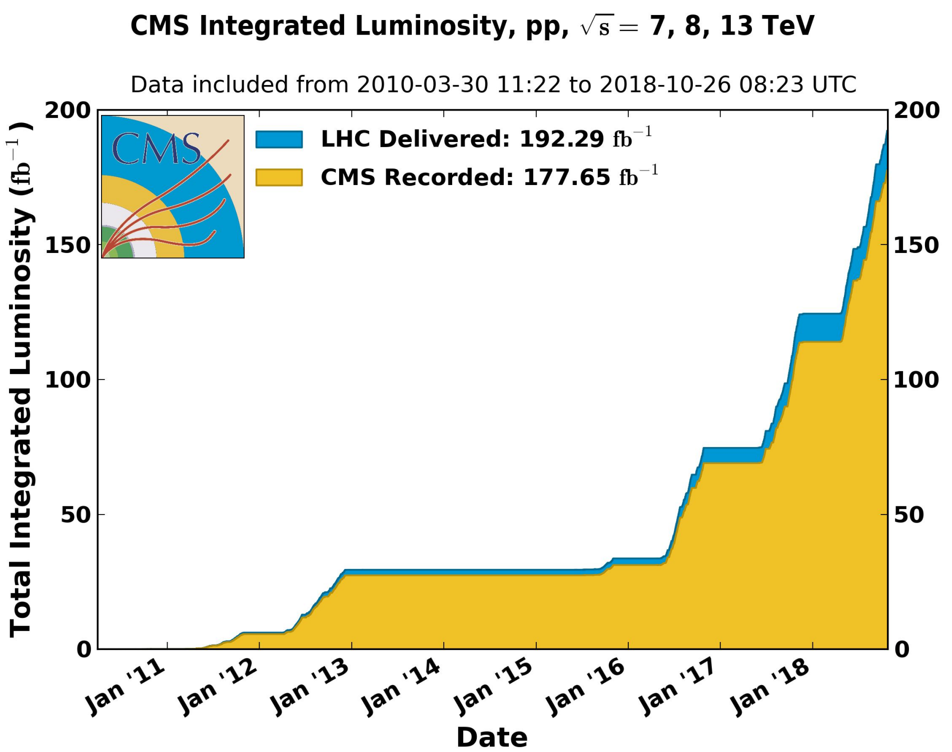
- solenoid superconducting magnet
- silicon detectors
- liquid argon calorimeter
- muon spectrometer
- trigger & data acquisition
- computing & software

183 institutes from 38 countries

Active ATLAS members	~5'500
(Physicists, students, engineers, technicians, …)	
Scientific authors	~2'900
with PhD, contributing to M&O share	~1'900
PhD students	~1'200
Master / diploma students	~500

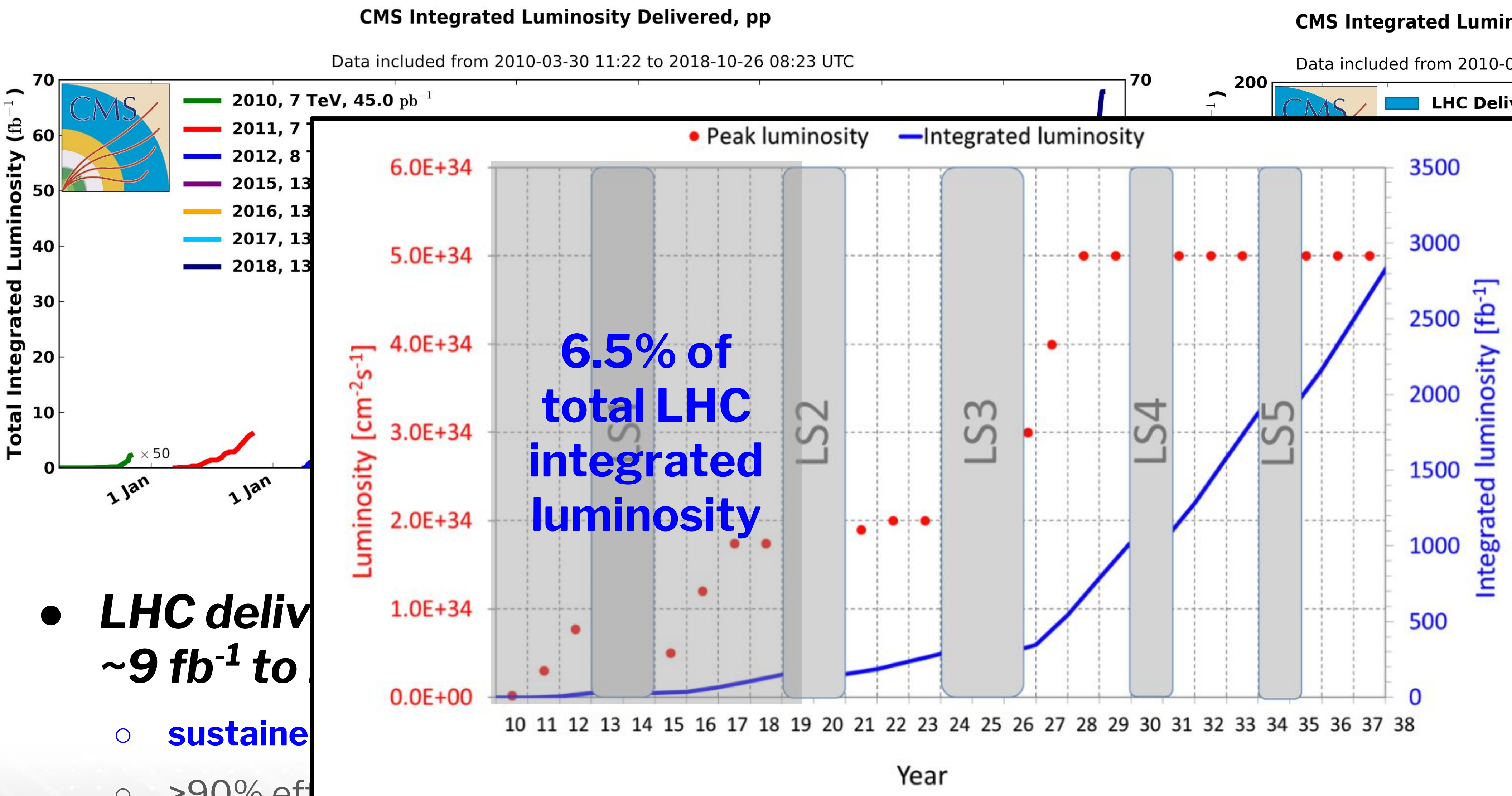
Integrated Luminosity: LHC Runs 1 & 2

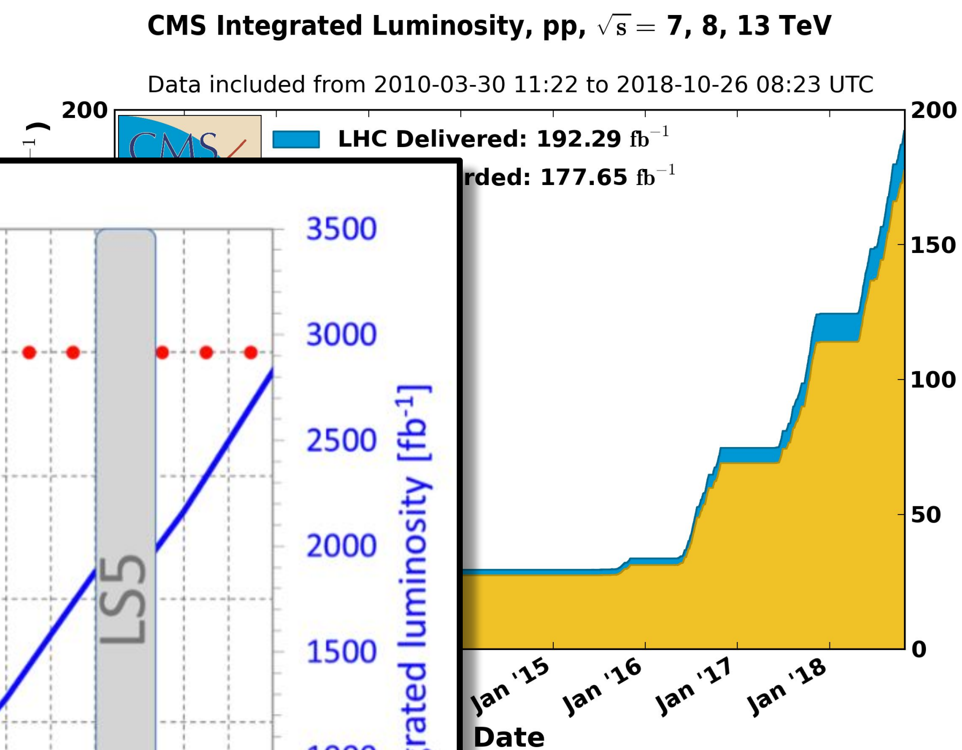




- ***LHC delivered ~190 fb^{-1} of integrated luminosity to ATLAS and to CMS and ~9 fb^{-1} to LHCb from 2010—2018***
  - **sustained performance of LHC operations has been stellar!**
  - >90% efficiency for each experiment

Integrated Luminosity: LHC Runs 1 & 2





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  - **sustaine**
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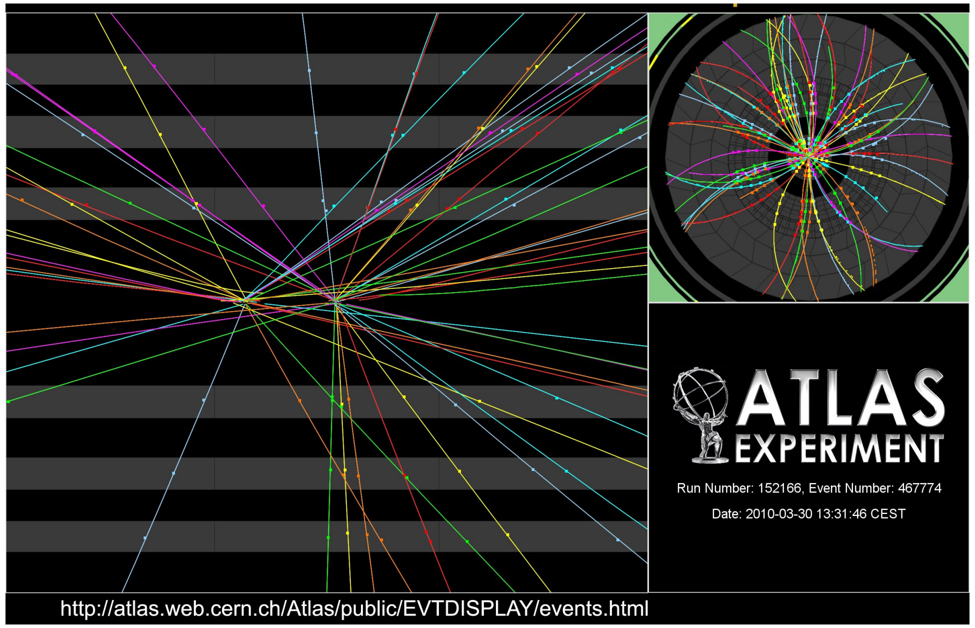
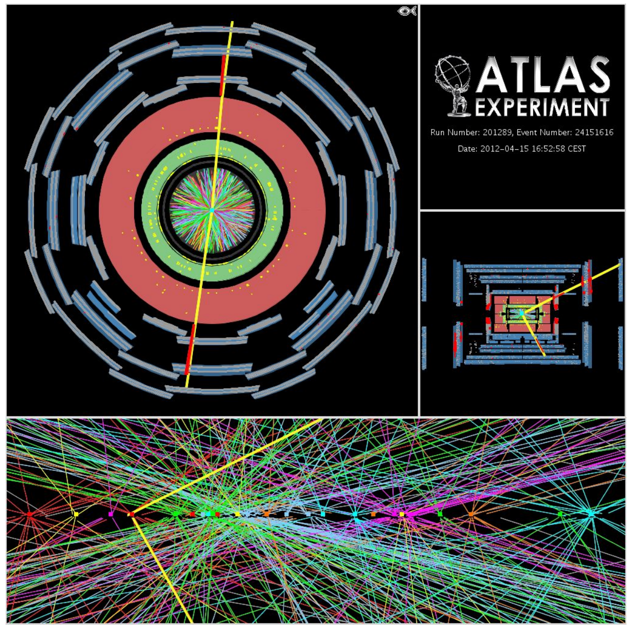
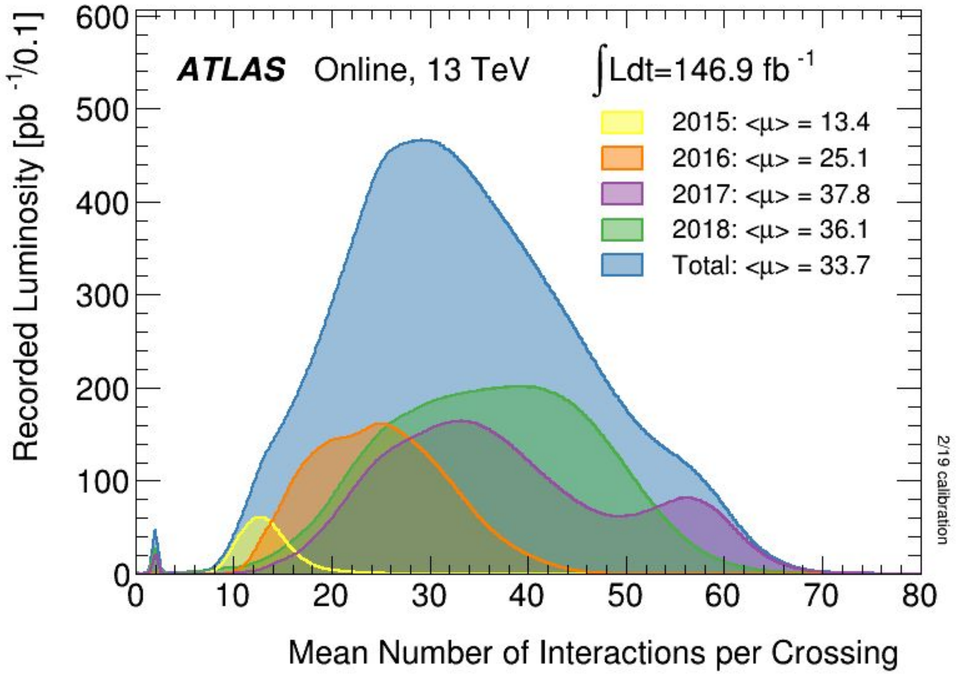
High Luminosity @ Hadron Colliders: Pileup

2 pileup vertices



25 pileup vertices

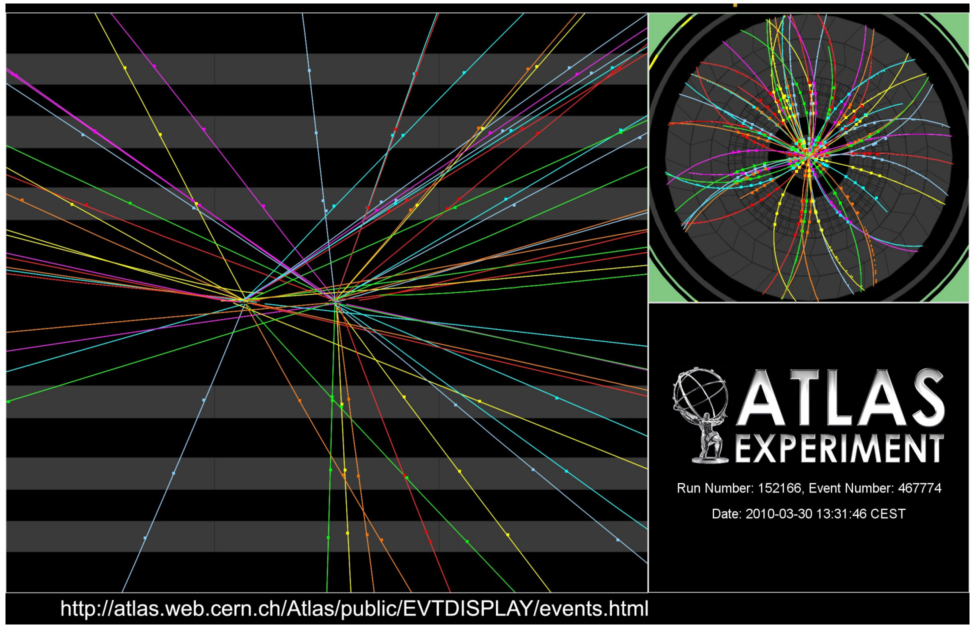




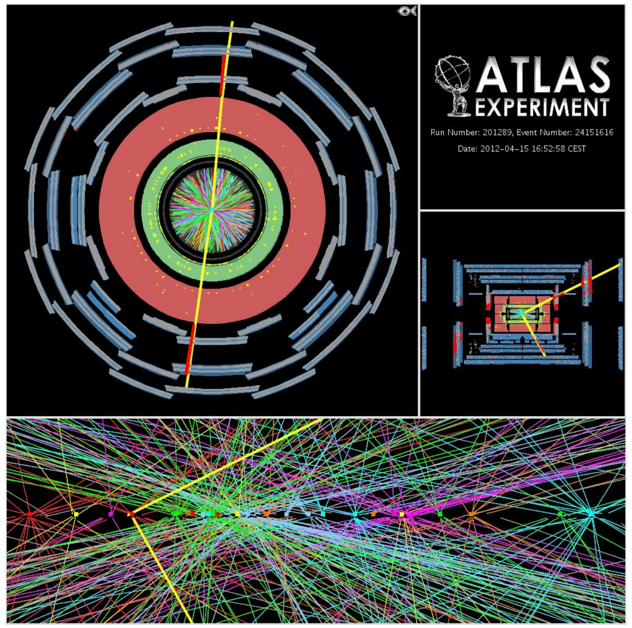
- ***Considerable effort to mitigate impact of pileup on detectors, trigger, computing, software, reconstruction, performance, and physics analyses***
    - improved algorithms such as particle flow

High Luminosity @ Hadron Colliders: Pileup

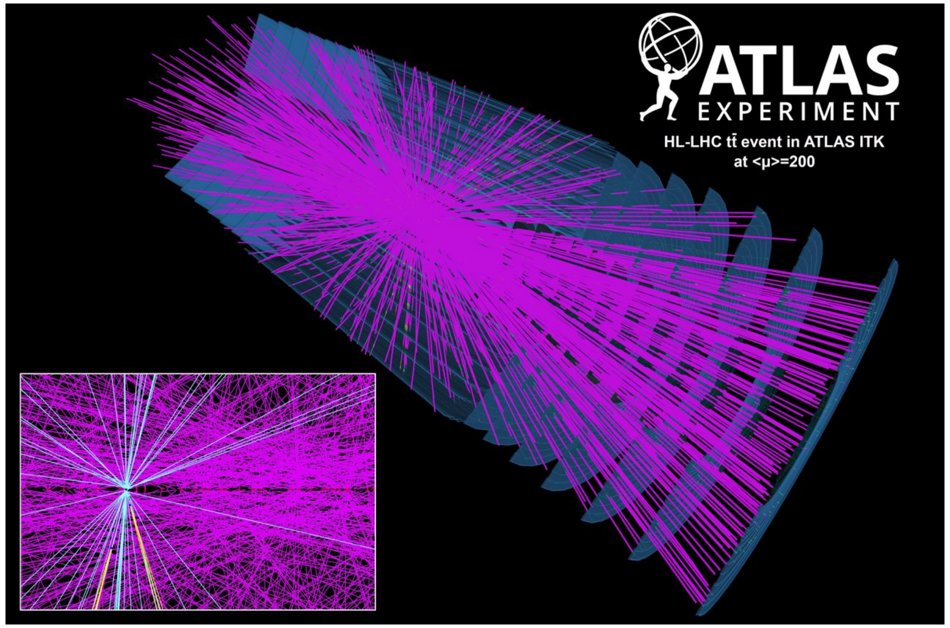
2 pileup vertices



25 pileup vertices

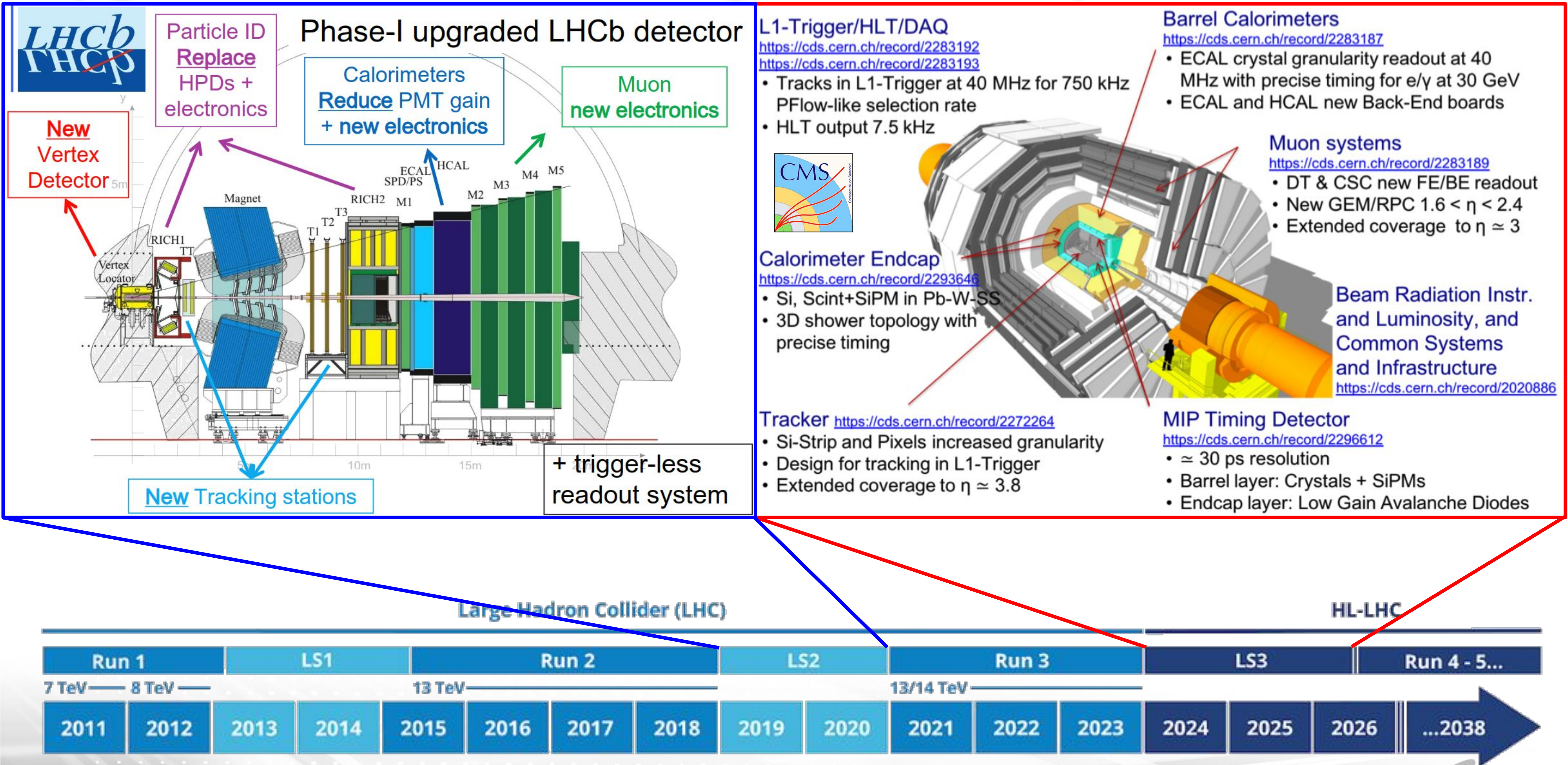


200 pileup vertices



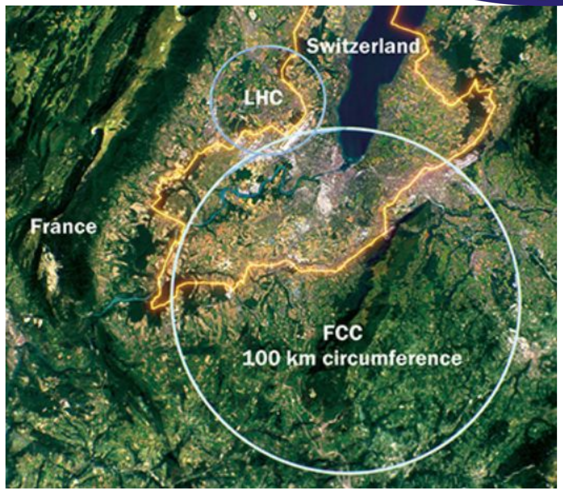
- ***Considerable effort to mitigate impact of pileup on detectors, trigger, computing, software, reconstruction, performance, and physics analyses***
  - improved algorithms such as particle flow
- ***Significant work remains given increase in average pileup for HL-LHC***
  - new detectors with all-silicon tracking systems and upgraded electronics
  - rewriting software to take better advantage of high performance computing

Upgraded Detectors at High Luminosity

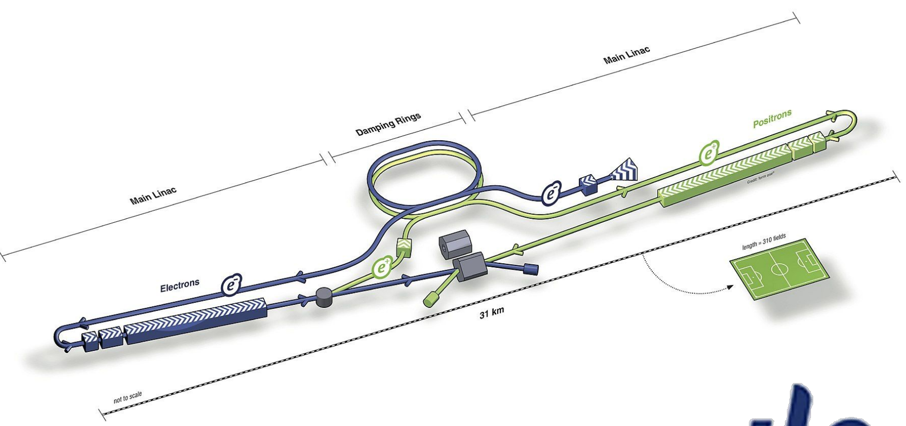


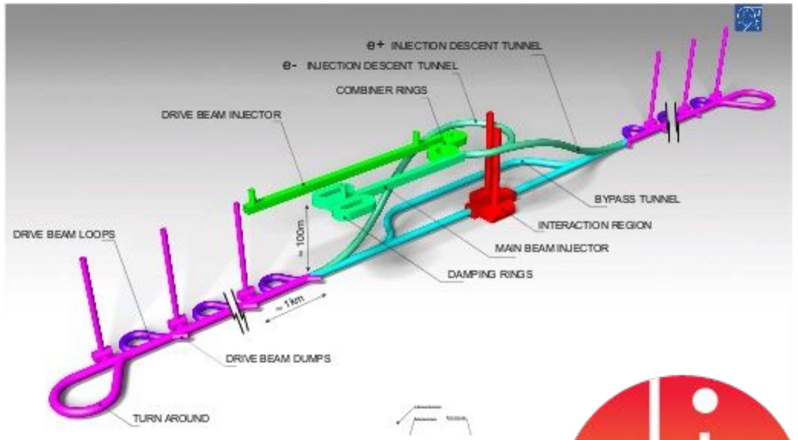
LHC and Future Landscape

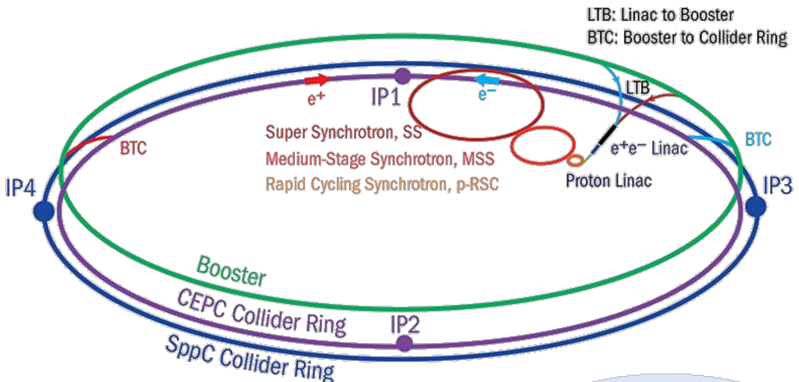
	LHC	HL-LHC	HE-LHC	SppC	FCC-hh
collision energy (TeV)	7, 8, 13	13—14	27	~75	100
dipole field (T)	8	8	16	12	16
luminosity/IP (10^{34} $cm^{-2}s^{-1}$)	1	5—7	28	~10	5/30
peak events/crossing	~60	140—200	~800	~300	~1000



- *pp & ee colliders provide complementary physics information*

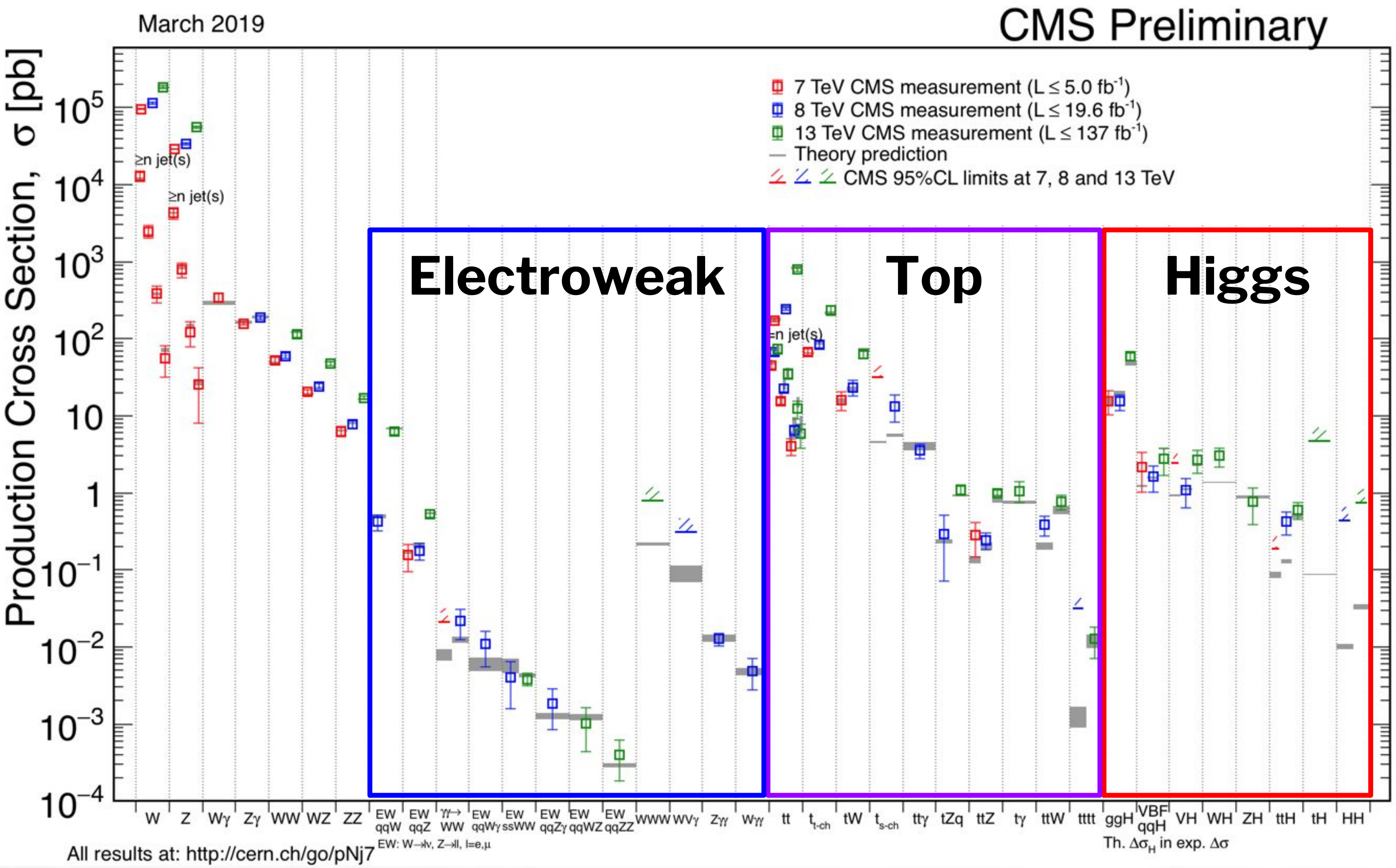


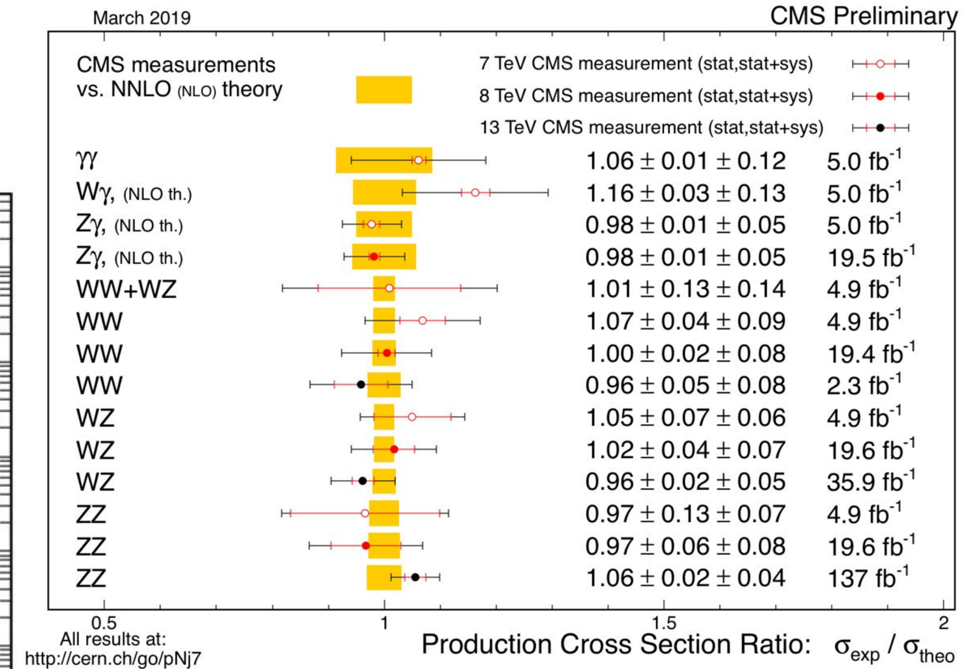


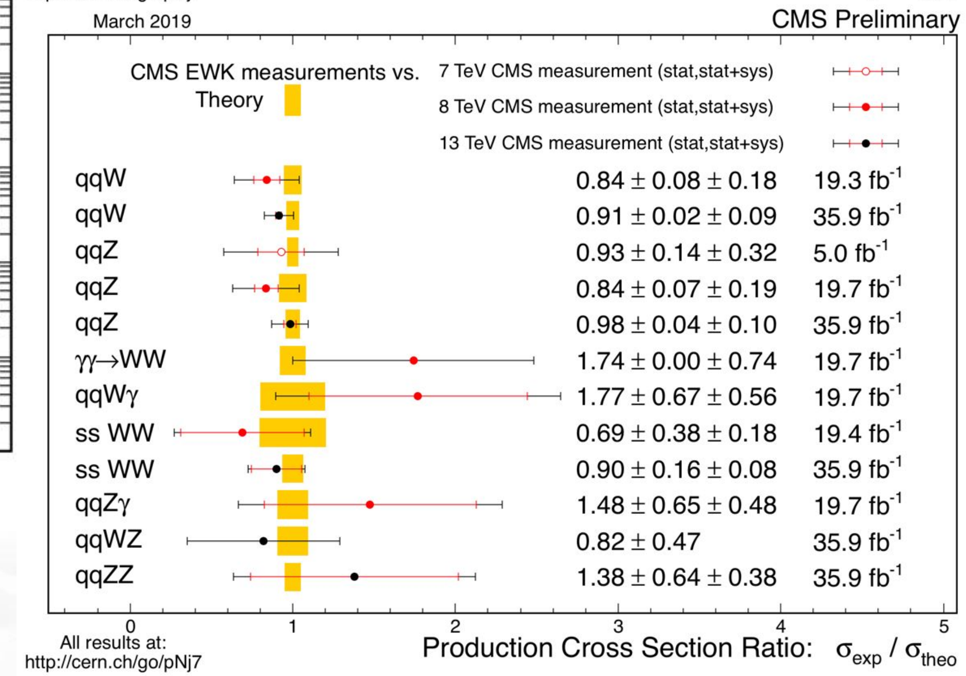


Physics Results and Prospects

Measurements





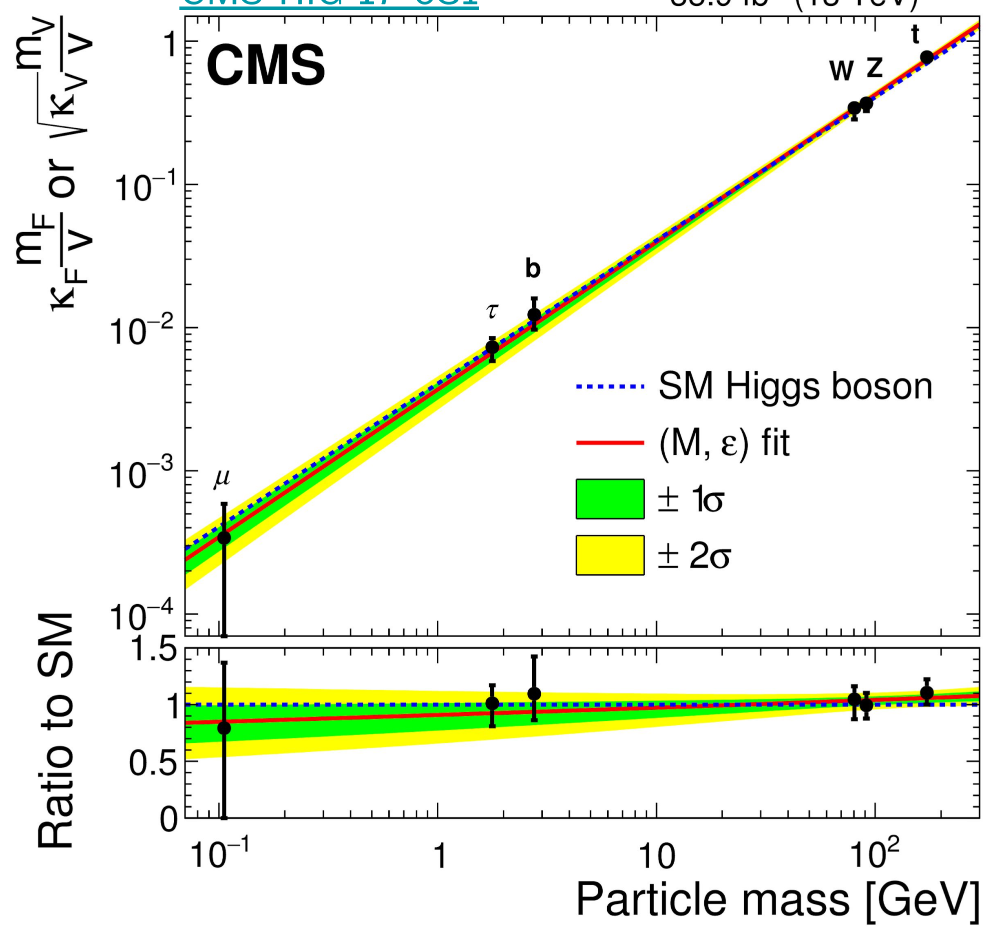


Higgs: Standard Model?

- ***Mass:* 125.09 ± 0.24 GeV** — ATLAS+CMS: PRL 114 (2015) 191803
- ***Spin/Parity:* 0^+** — ATLAS: EPJC 75 (2015) 476; CMS: PRD 92 (2015) 012004
- ***Width*:**
  - <1 GeV (direct)
  - <14 MeV (indirect)

  CMS: JHEP 11 (2017) 047; ATLAS: PLB 786 (2018) 223; CMS:CMS-PAS-HIG-18-002
- ***Direct couplings:***
  - Weak Bosons — ATLAS: PLB 716 (2012) 1-29; CMS: PLB 716 (2012) 30
  - Tau Leptons — ATLAS: arXiv:1811.08856; CMS: PLB 779 (2018) 283
  - Top Quarks — ATLAS: PLB 784 (2018) 173; CMS: PRL 120 (2018) 231801
  - Bottom Quarks — ATLAS: PLB 786 (2018) 59; CMS: PRL 121 (2018)121801

CMS-HIG-17-031



All measurements consistent with SM expectations

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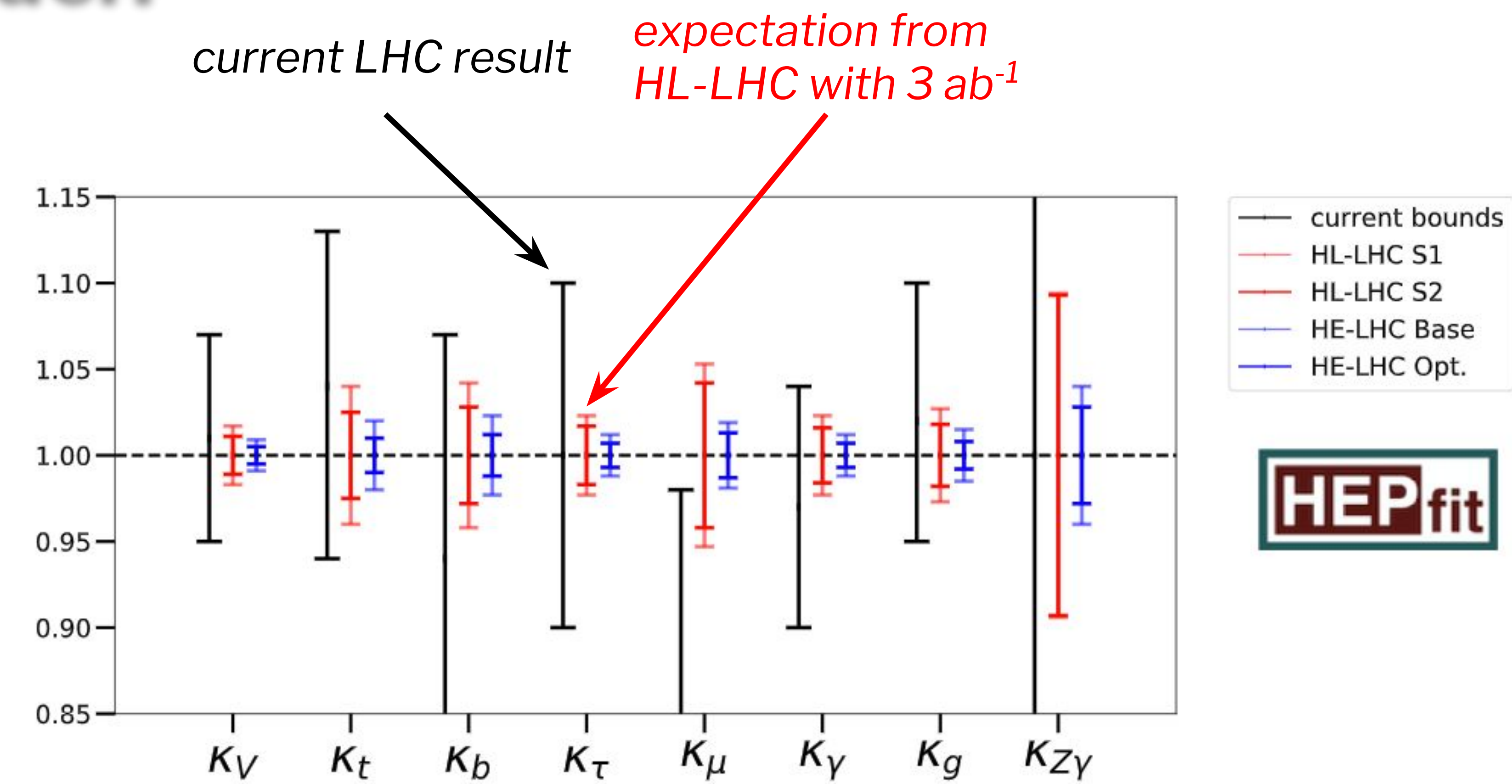
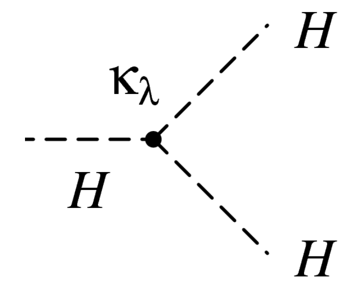
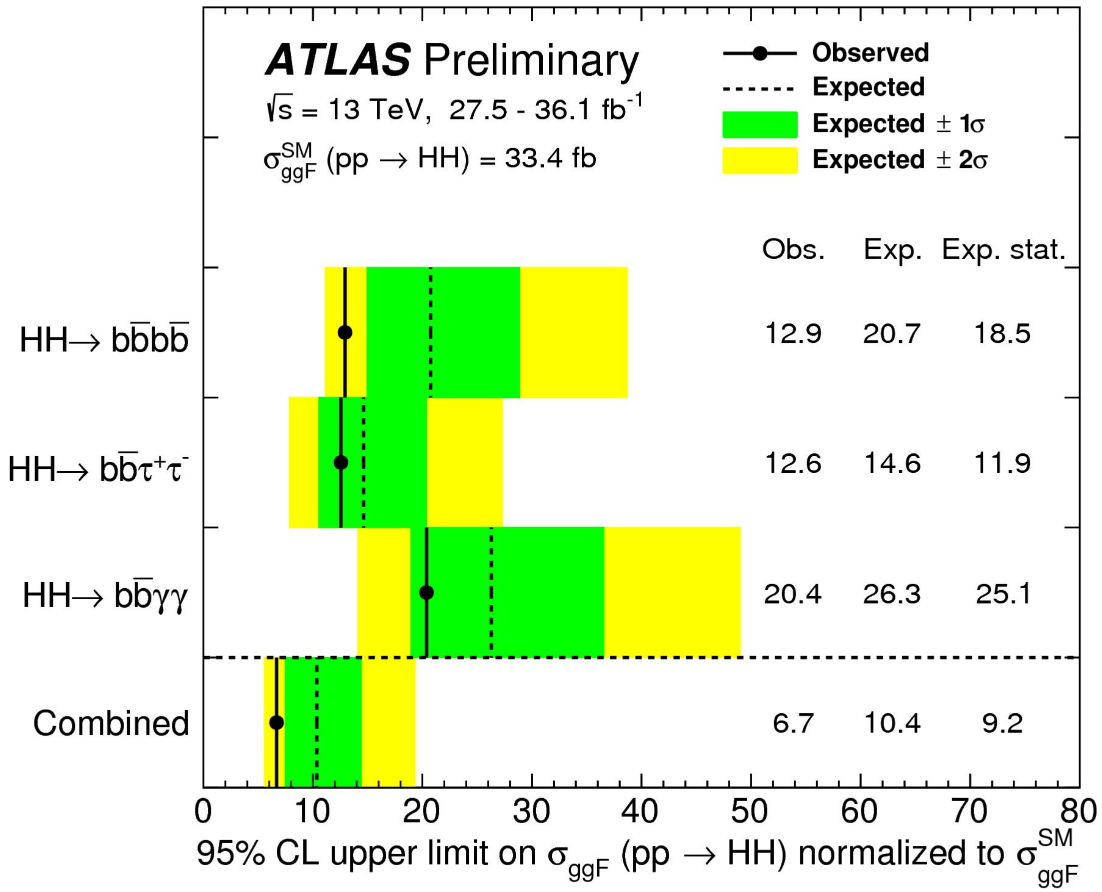


Fig. 33: Current and future constraints on κ_i. The left line of each κ is the current bound, from Ref. [185]. The central line is the projection to the HL-LHC, with the S1 scenario in light red and S2 in dark red. The right line is the projection to HE-LHC, with the base scenario in light blue and the optimistic one in dark blue.

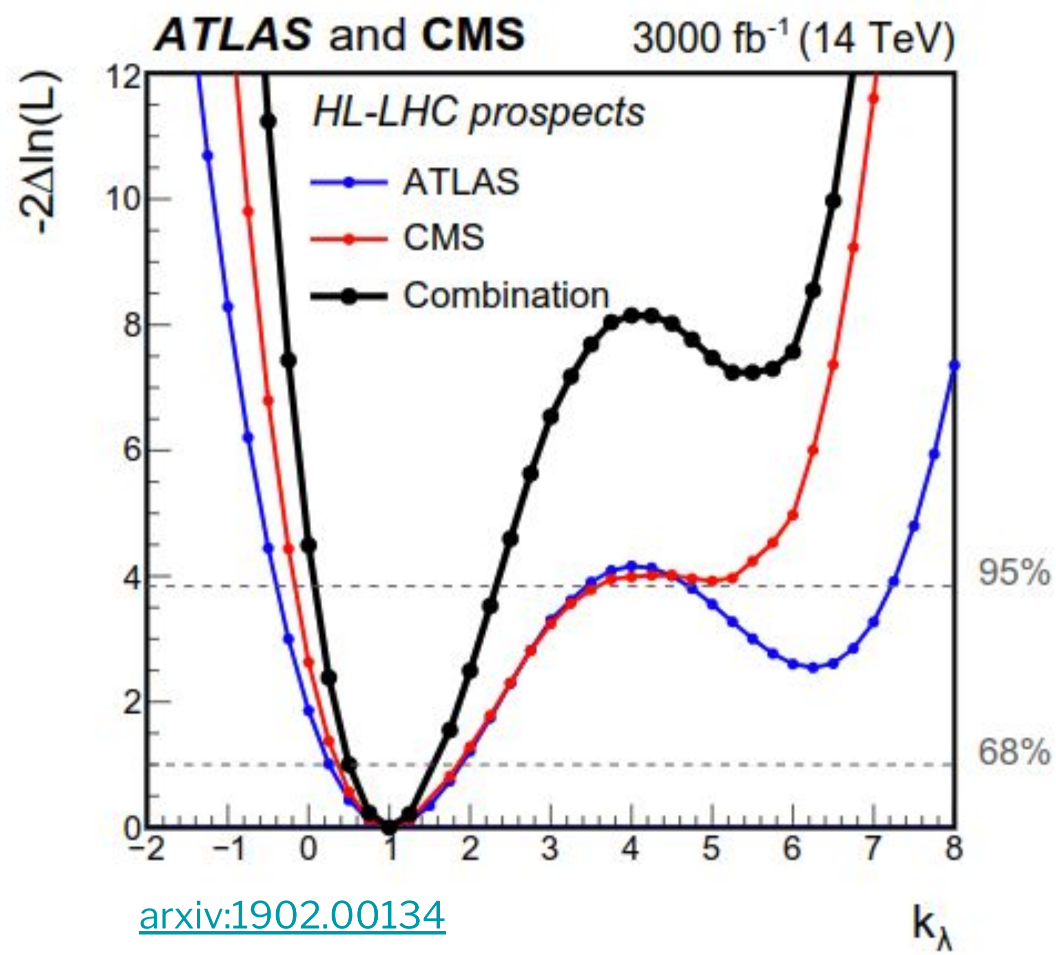
Higgs Self-Coupling



- ***Major physics driver for HL-LHC and future collider physics programs***



ATLAS-CONF-2018-043



arxiv:1902.00134

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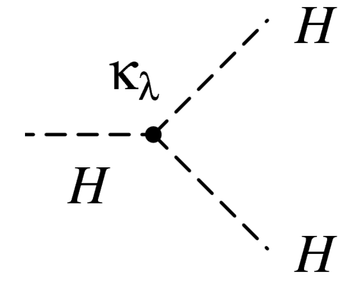

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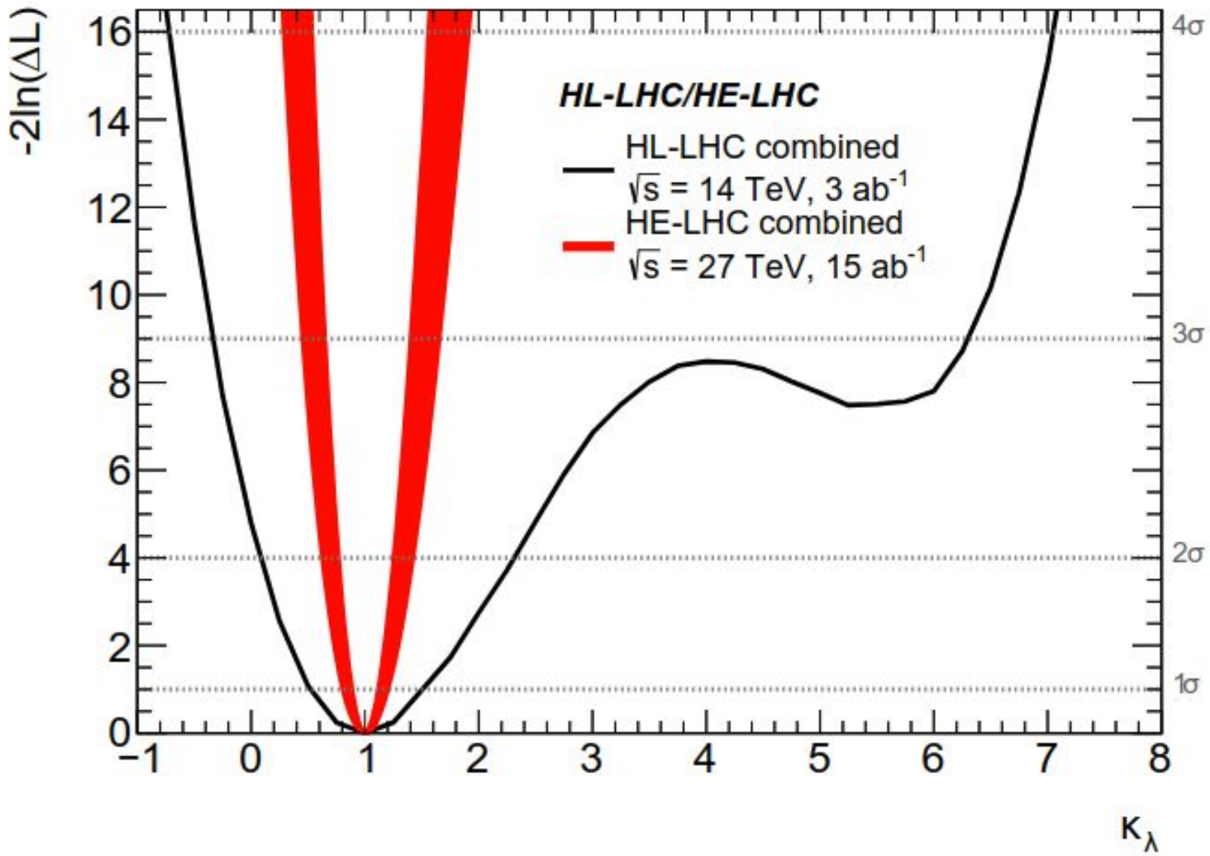
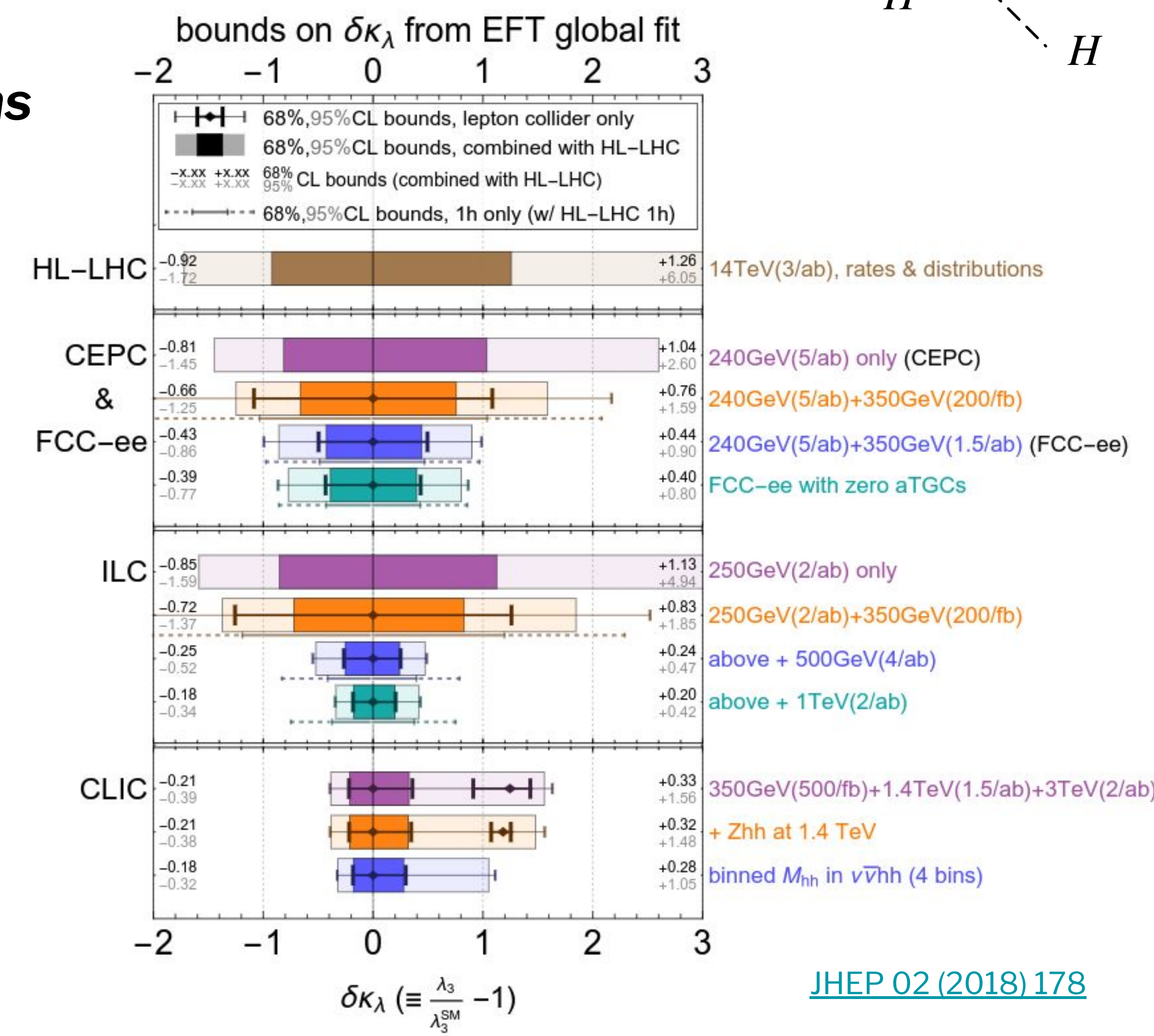


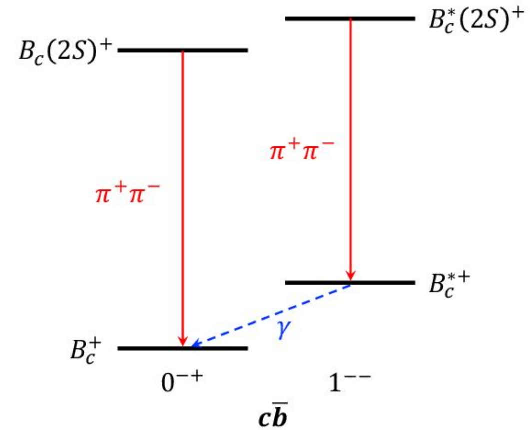


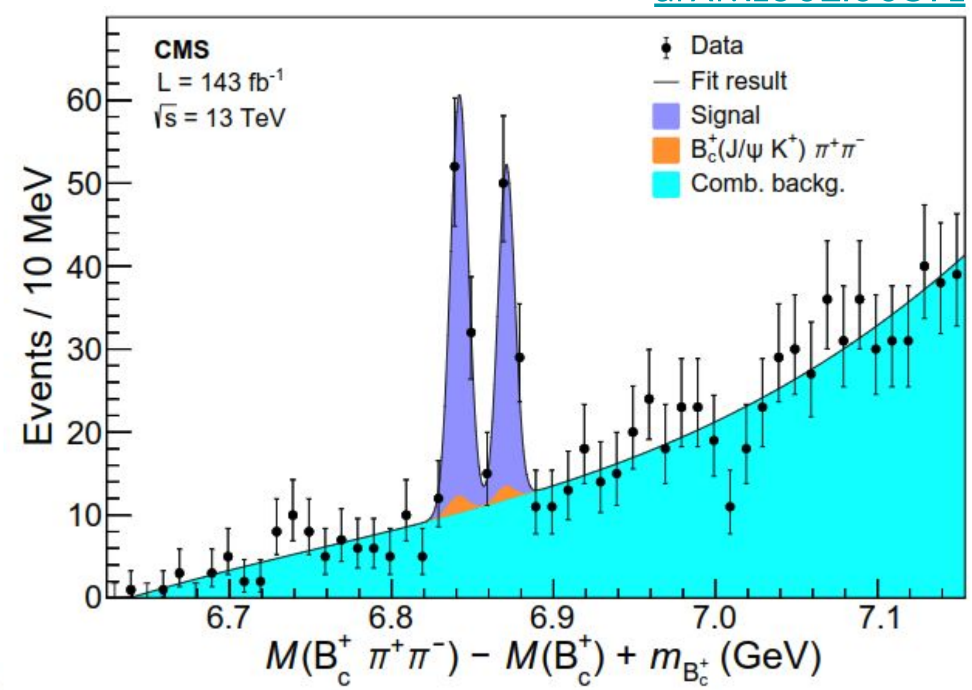
JHEP 02 (2018) 178

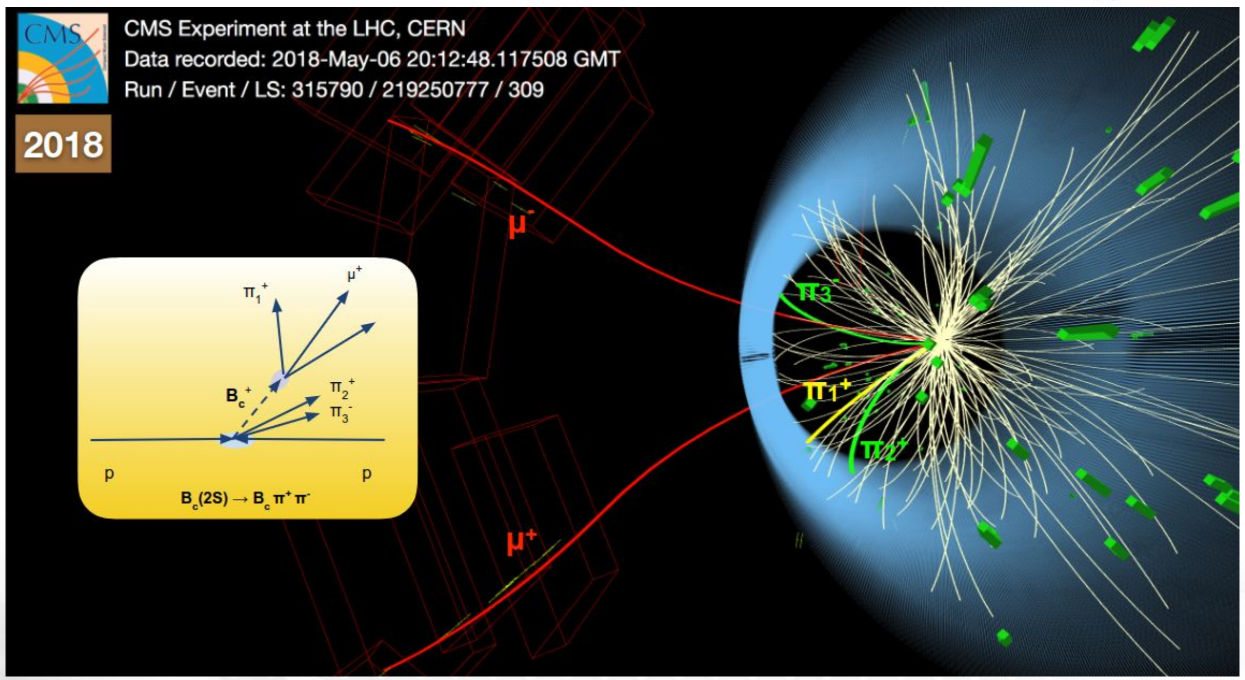
Hadronic Resonances

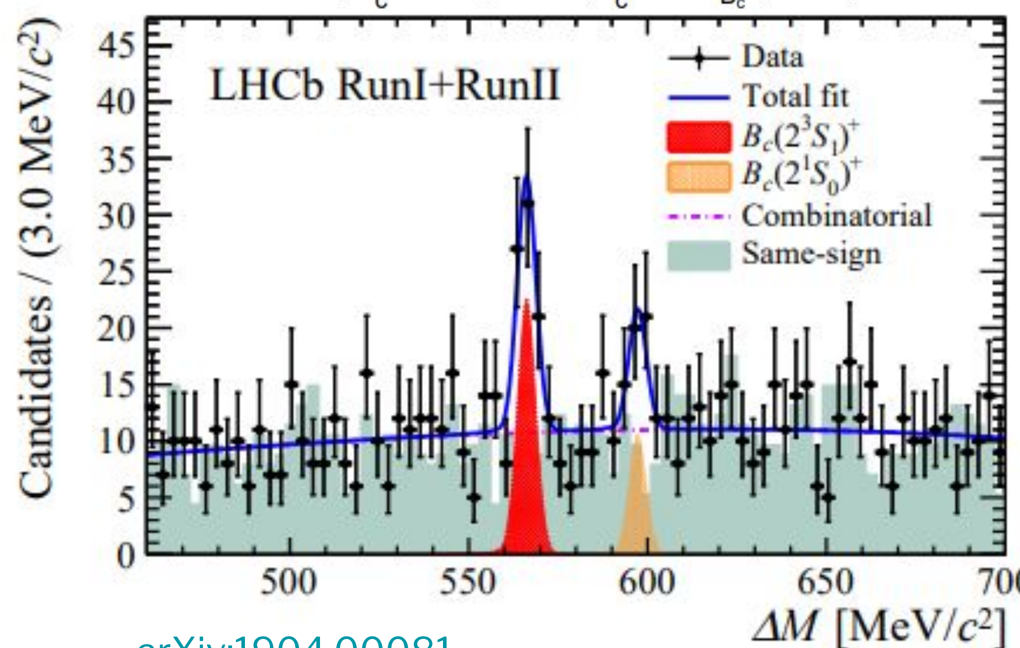
arXiv:1902.00571

- ***Observation of resolved B_c^+ (2S) by CMS & LHCb***
  - $B_c(2S) \rightarrow B_c\pi^+\pi^-$
  - $B^*_c(2S) \rightarrow B^*_c\pi^+\pi^- \rightarrow B_c\gamma\pi^+\pi^-$
  - wide peak first observed by ATLAS
    PRL 113 (2014) 212004
  - ΔM = 29.1 ± 1.5 ± 0.7 MeV (CMS)





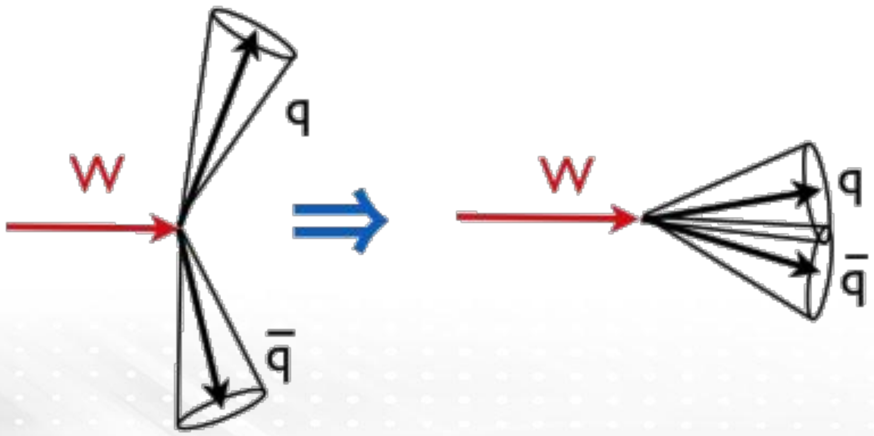


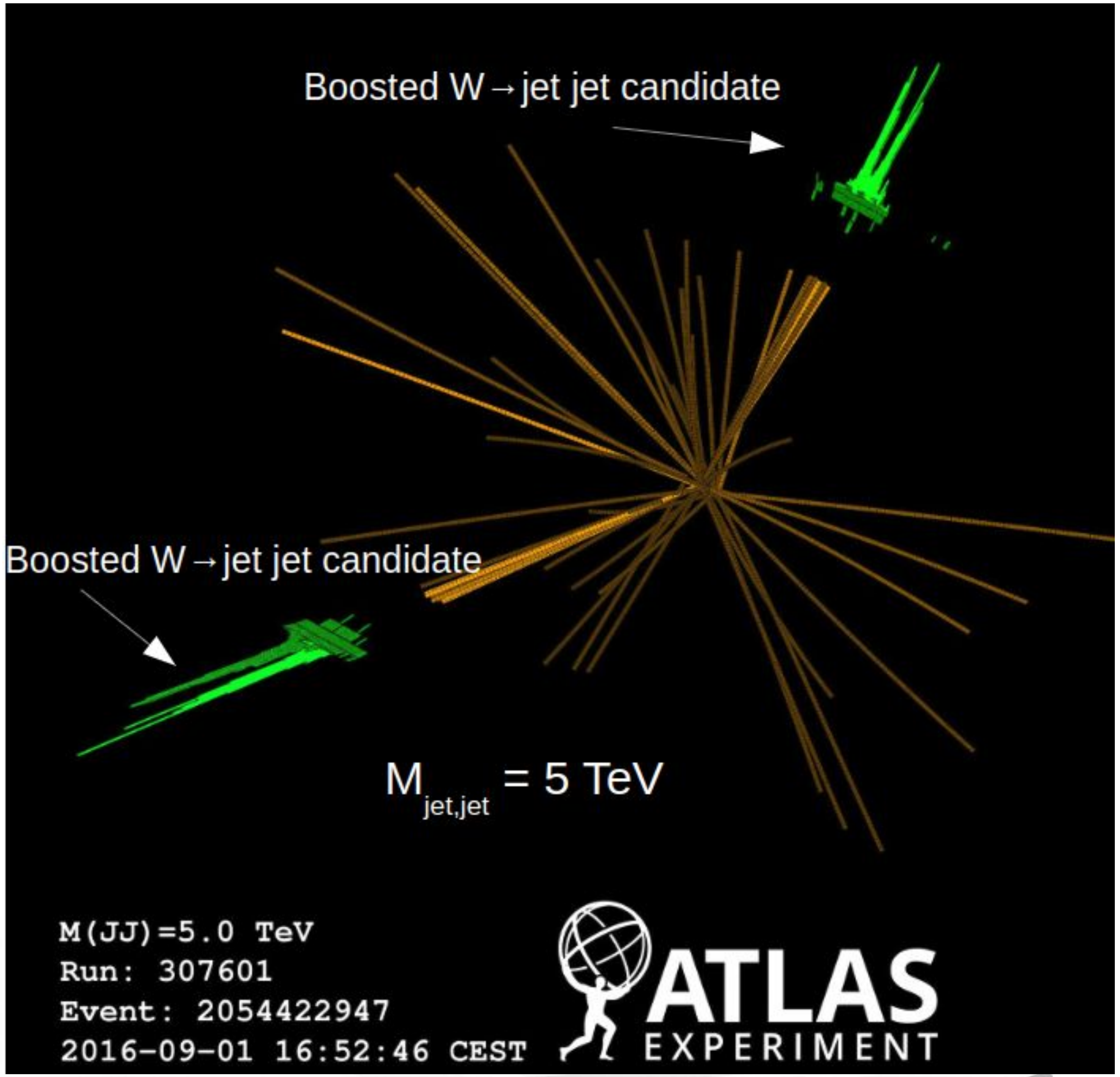


arXiv:1904.00081

Bosonic Resonances

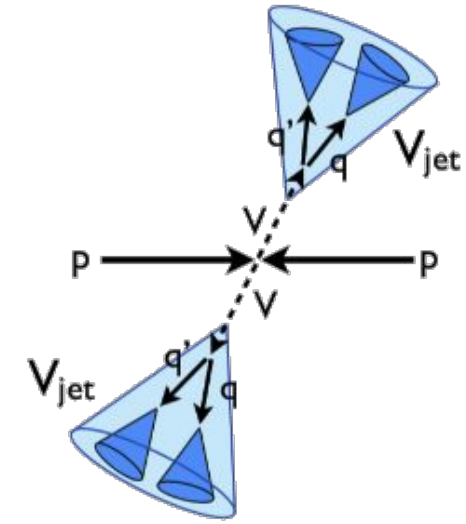
- ***Fully reconstructed resonances are a useful way to discover new particles***
  - striking signatures → bump hunt
  - small systematics → robust
- ***Search for very high-mass particles decaying into bosons***
  - **reconstruct very high-p_T W and Z bosons as large-radius jets**
  - required development of new analysis techniques → now part of standard toolkits on ATLAS & CMS

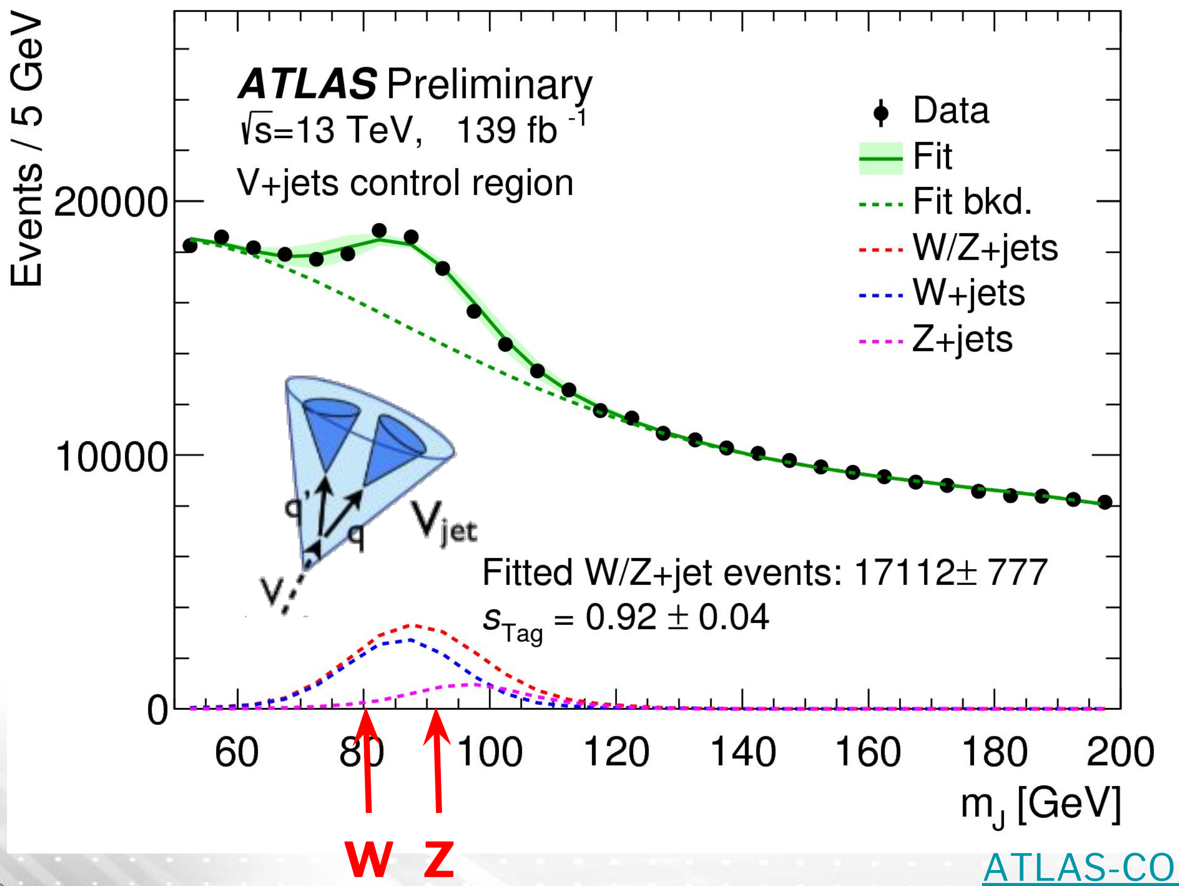


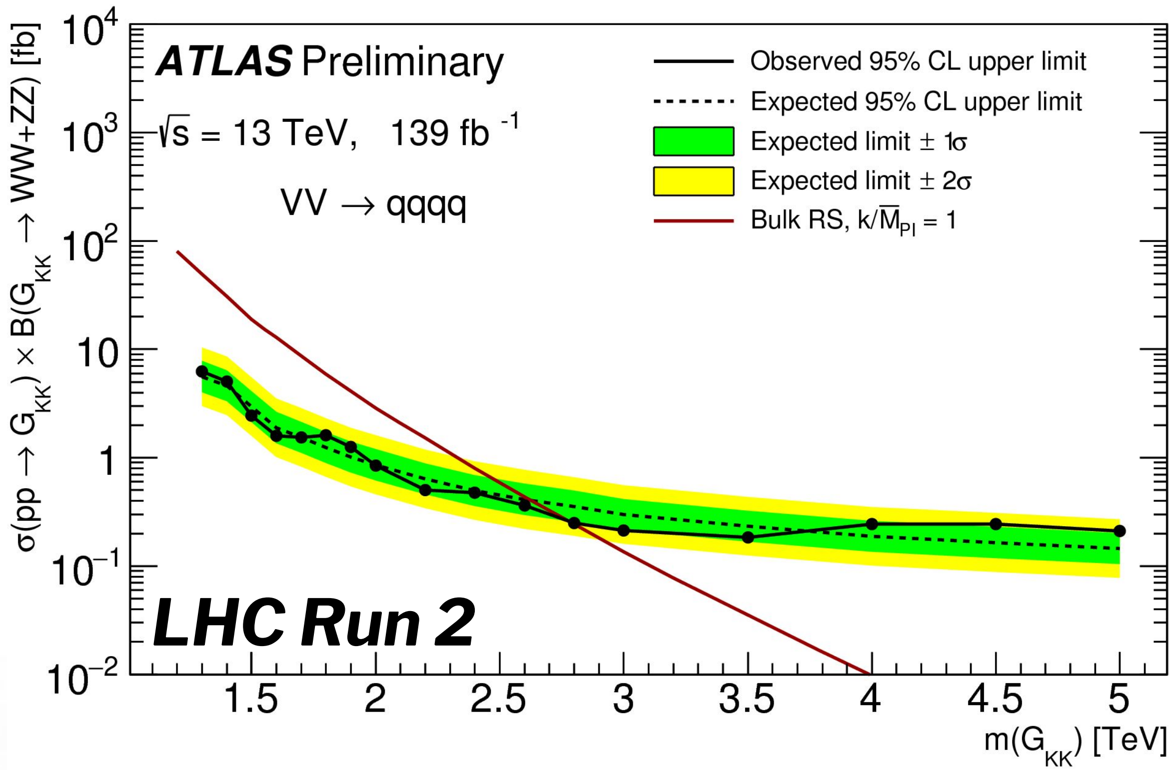


Bosonic Resonances

- ***Search for very high-mass particles decaying into bosons***
  - **initiated on ATLAS by Tokyo and BNL**
  - reconstruct very high-p_T W and Z bosons as large-radius jets



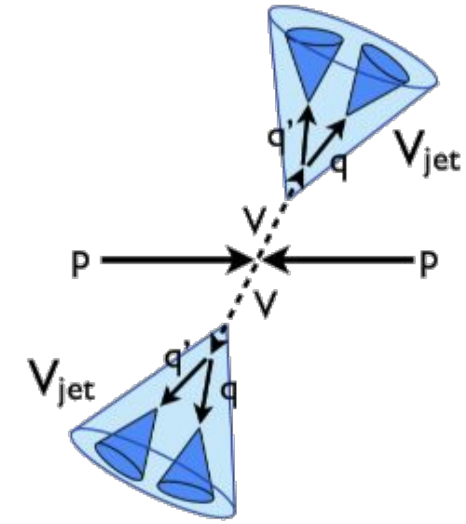


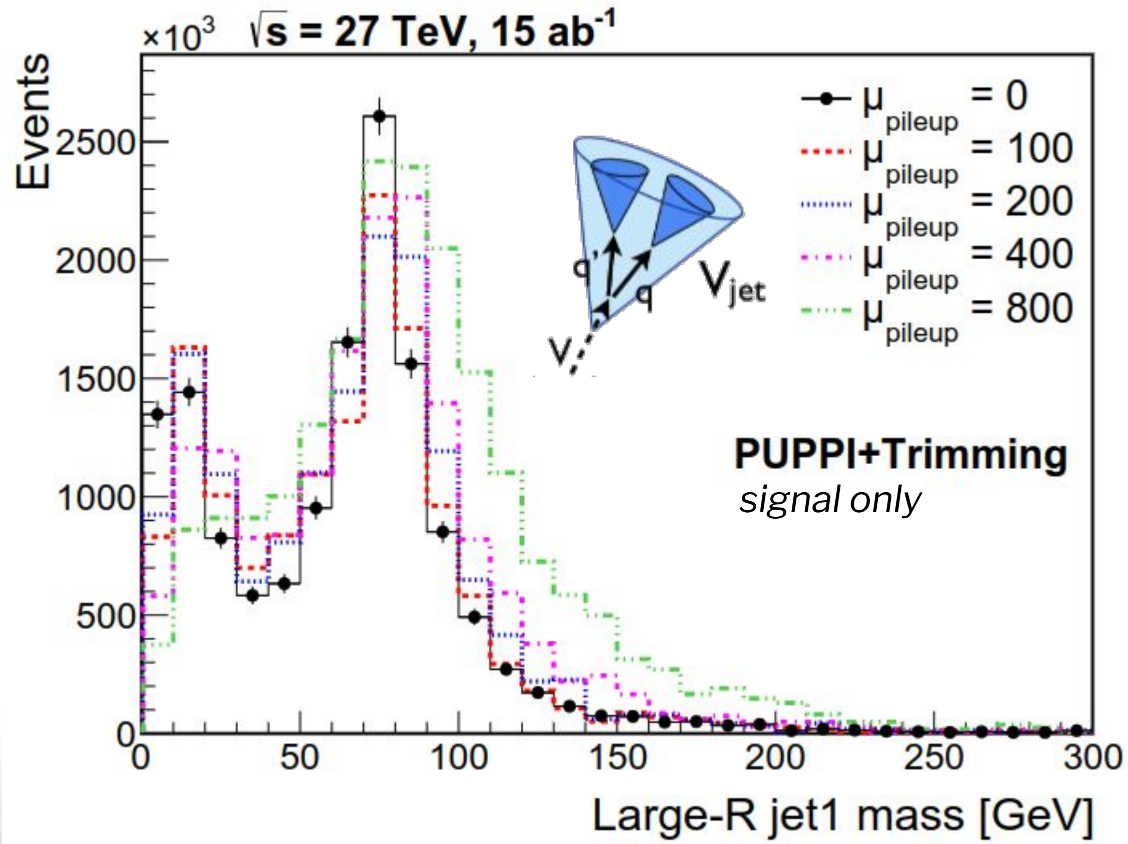


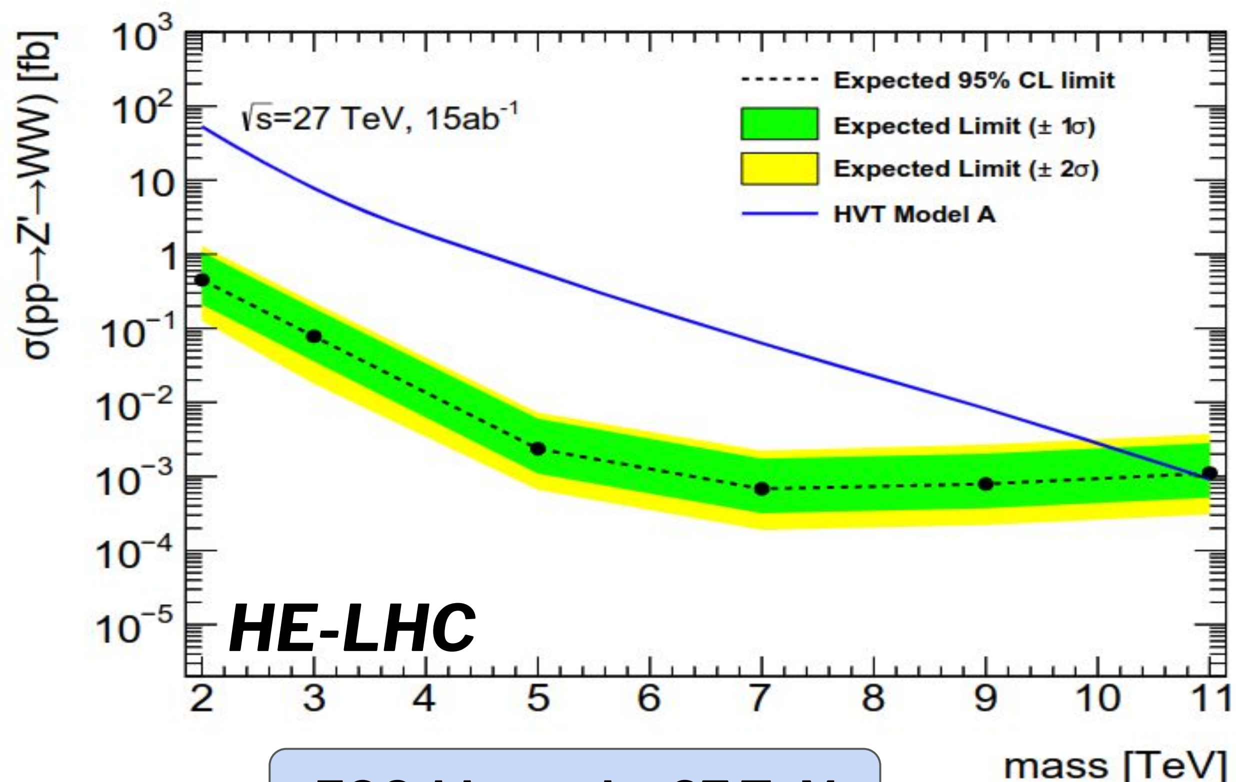
ATLAS-CONF-2019-003

Bosonic Resonances

- ***Search for very high-mass particles decaying into bosons***
  - initiated on ATLAS by Tokyo and BNL
  - **prospect at HE-LHC → European Strategy**
  - new techniques to accommodate additional factor of 30 pileup

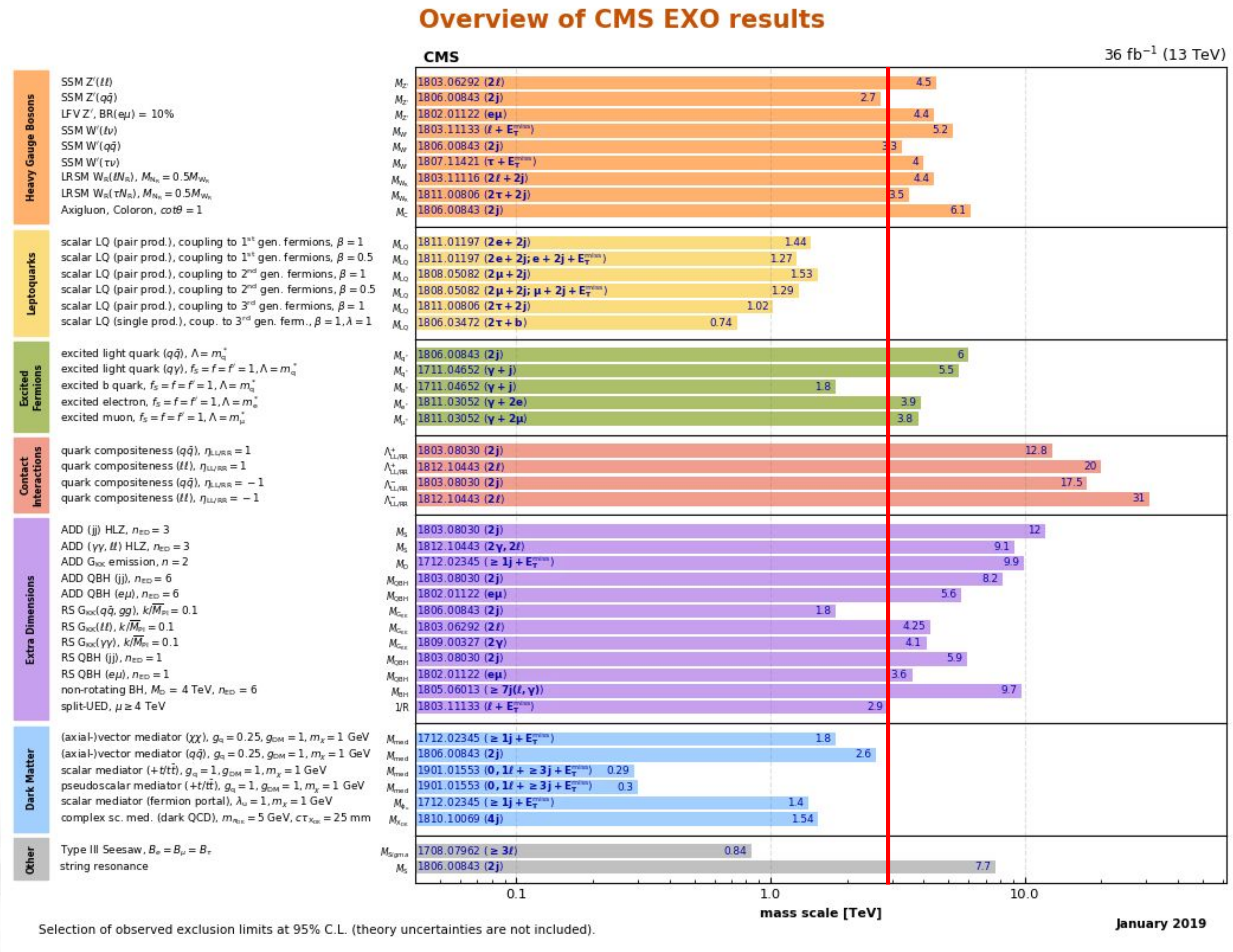






FCC-hh reach ~27 TeV

Summary of LHC Searches



Expected Reach of HL-LHC & HE-LHC

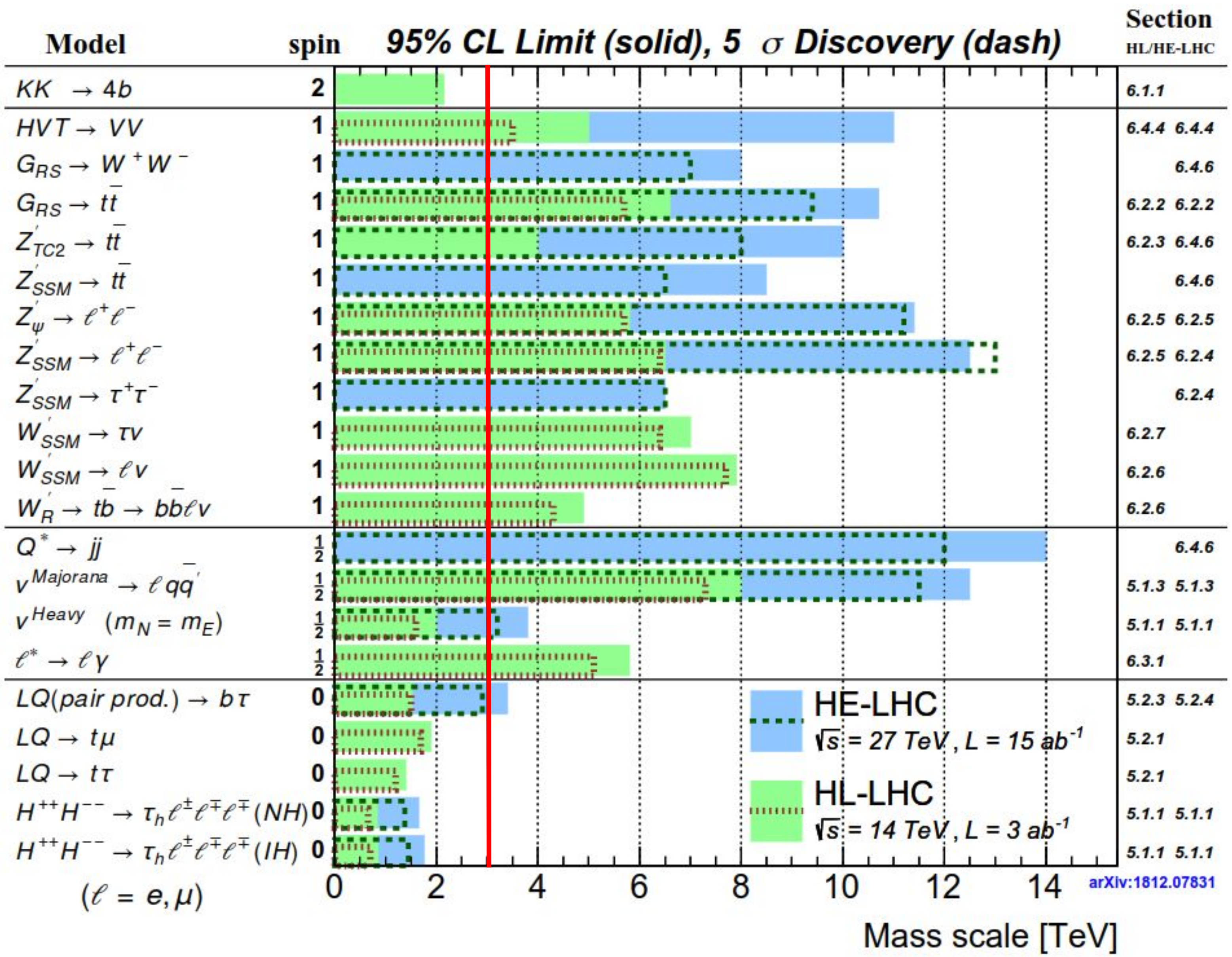


Fig. 7.2: A summary of the expected mass reach for 5σ discovery and 95% C.L. exclusion at the HL/HE-LHC, as presented in Sections 5 and 6.

arxiv:1812.07831

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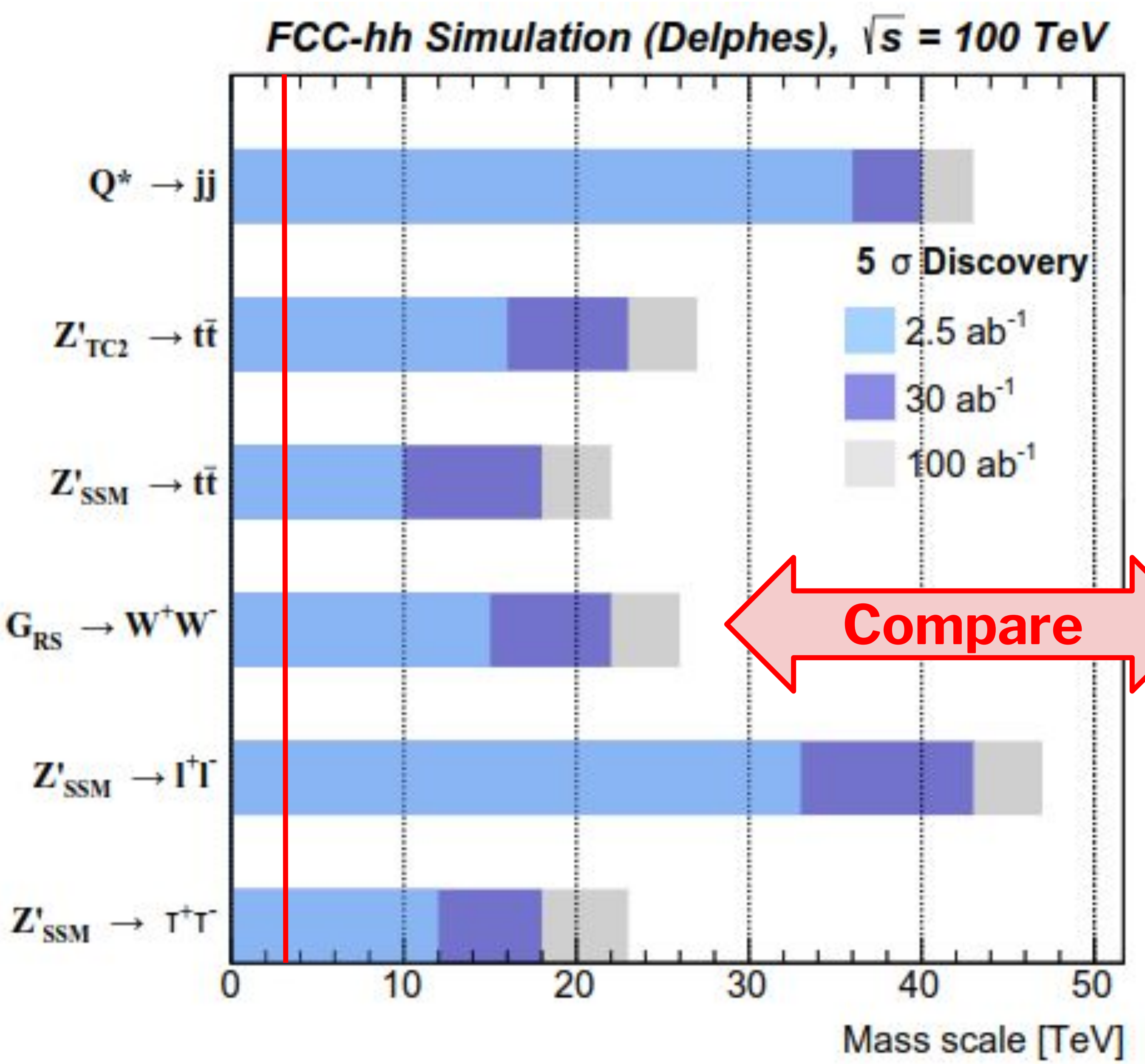
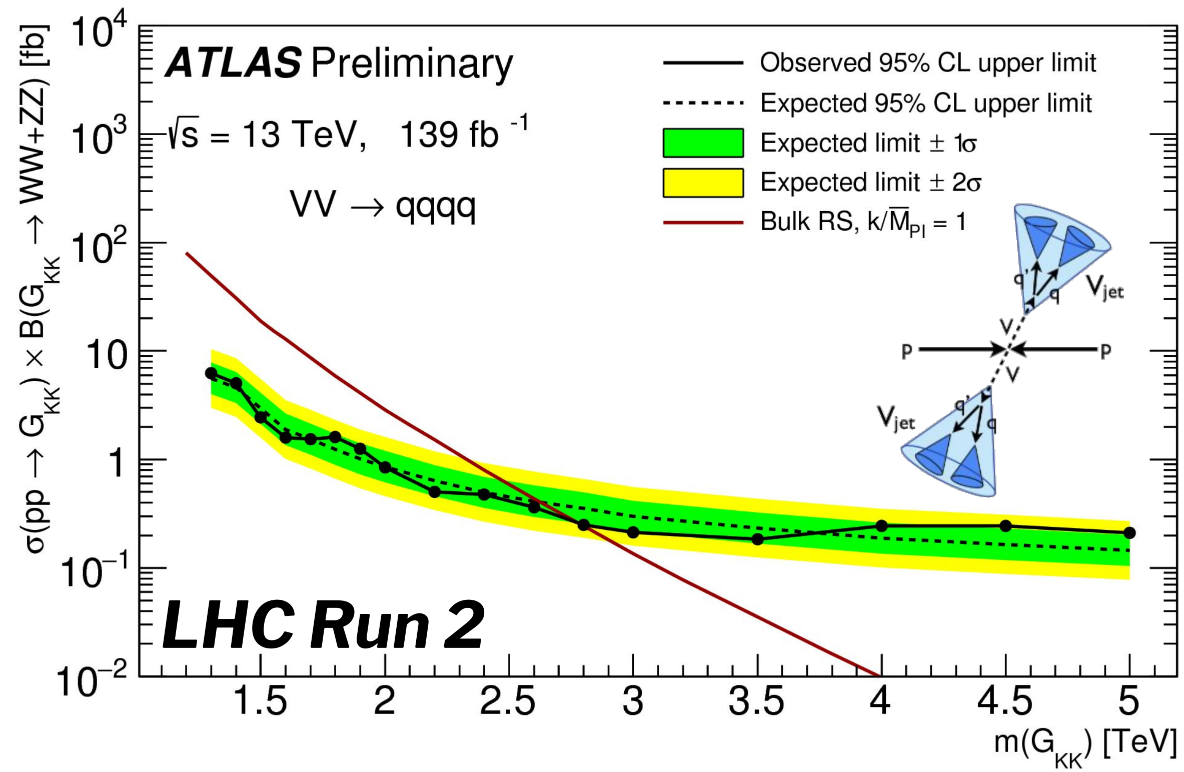
Expected Reach of FCC-hh



Compare

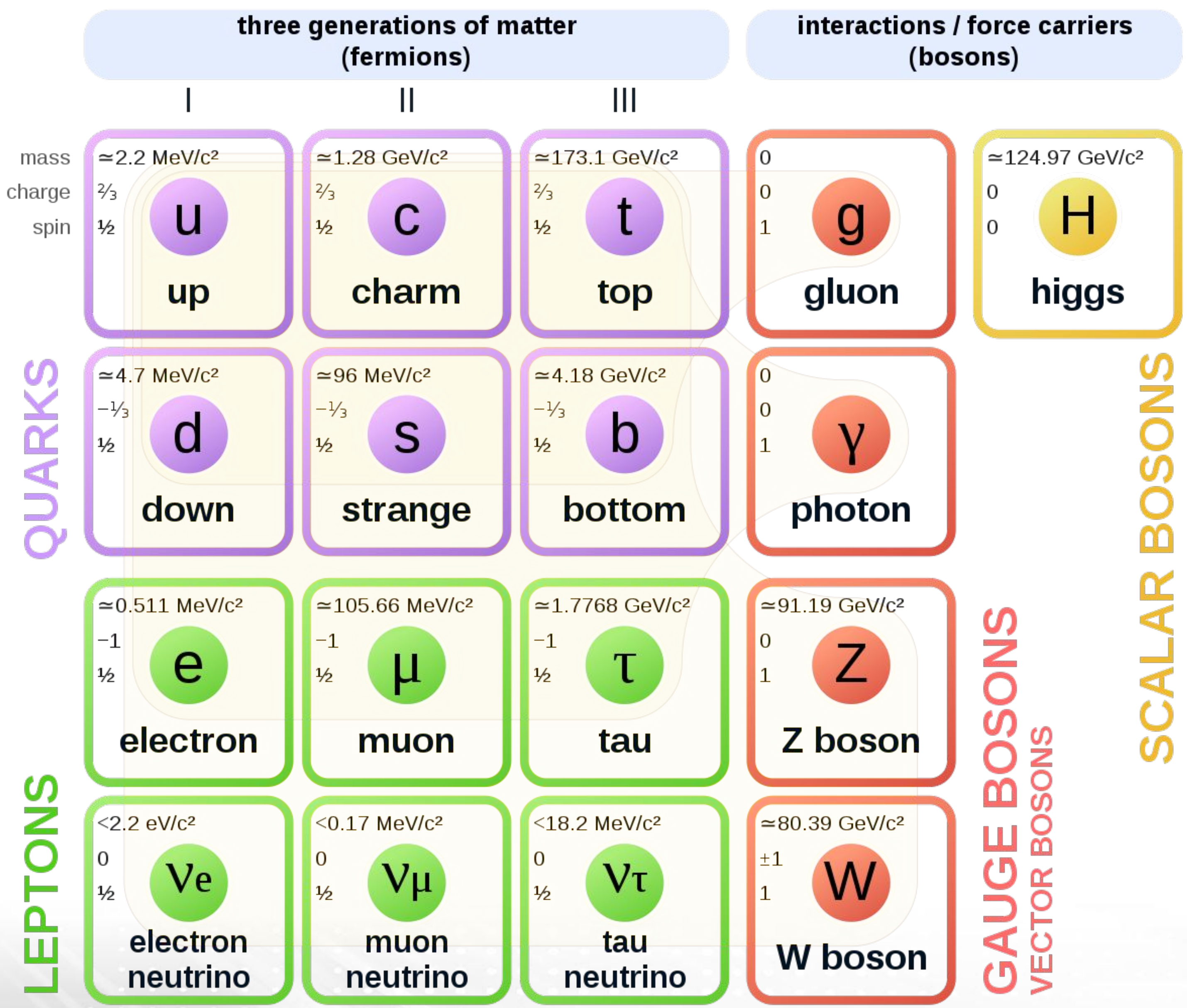


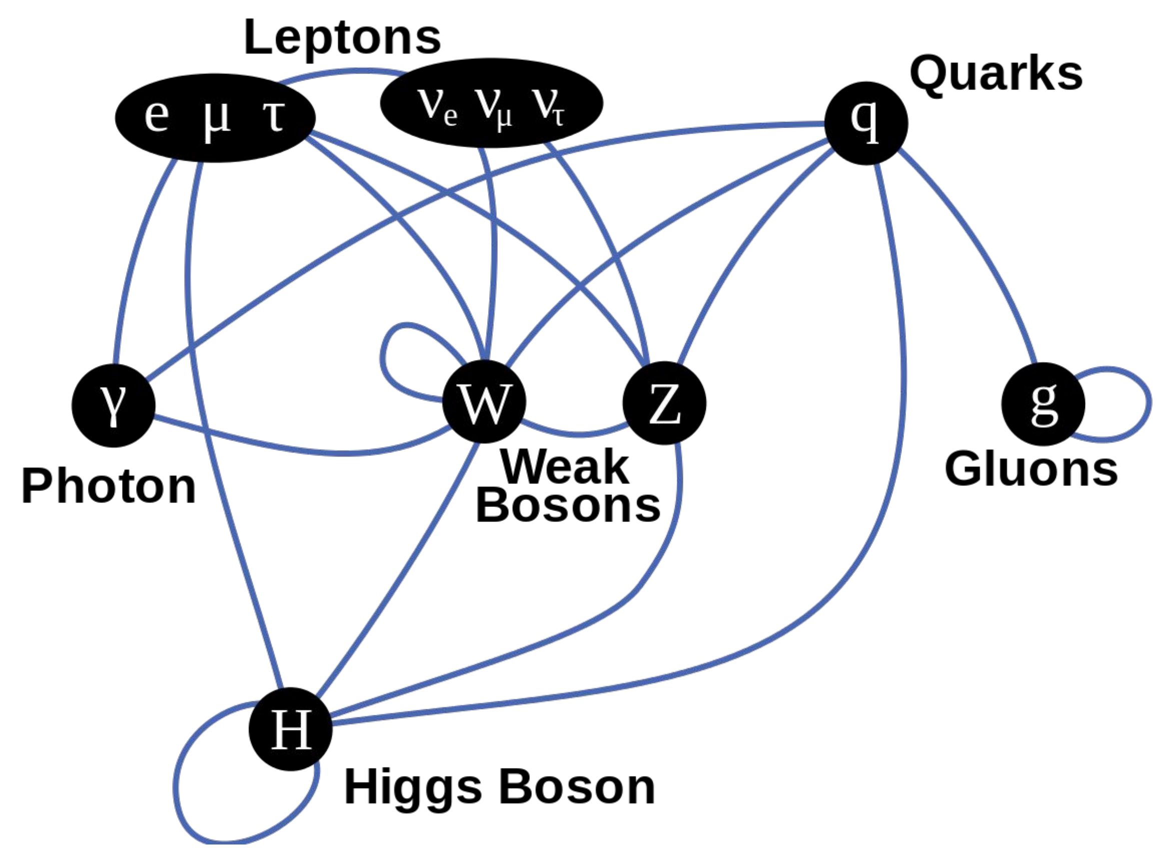
Summary

- ***Large LHC data sets collected in Run 2 by ATLAS, CMS, & LHCb allow for precise probes of Standard Model and exploration for New Physical Phenomena***
    - **only ~10% of the way through the (HL-)LHC program by 2026**
    - **just started tapping full LHC potential — many more new results still to come!**
- ***Upgraded detectors key for a successful physics program at high luminosity***
    - **significant increase in detector capabilities**
    - **major ongoing efforts to mitigate impact of pileup on detectors, trigger, computing, software, reconstruction, performance, and physics analyses**
- ***pp and ee colliders provide complementary physics information***
    - **important to have both to further explore mechanisms behind Electroweak Symmetry Breaking!**
- ***US and Japan are crucial to success at the Energy Frontier***
    - **strong collaborations on LHC & ATLAS and towards the next generation of colliders**

Backup

Standard Model





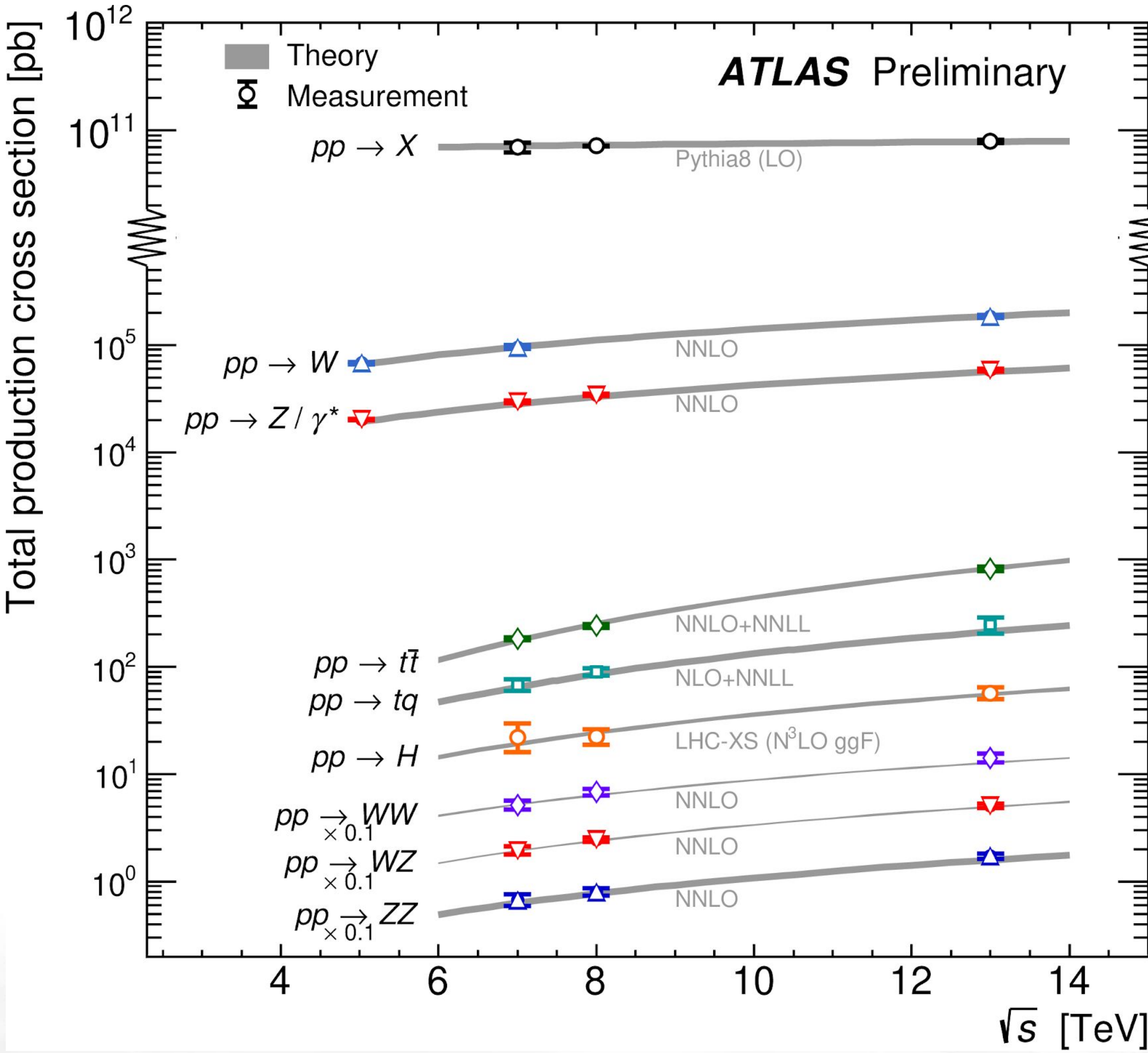
- ***over a century in the making***
- ***very successful but incomplete***
  - neutrino mass
  - dark matter
  - gravity & dark energy

Standard Model

pp cross section

W & Z bosons

rare processes (very interesting!)



$pp \to X$
7 TeV, 20 μb^{-1}, Nat. Commun. 2, 463 (2011)
8 TeV, 500 μb^{-1}, Phys.Lett. B761 158 (2016)
13 TeV, 60 μb^{-1}, Phys. Rev. Lett. 117 182002 (2016)

$pp \to W$ $pp \to Z/\gamma^*$
5 TeV, 25 pb^{-1}, Eur. Phys. J. C79 (2019) 128 (for Z/W)
7 TeV, 4.6 fb^{-1}, Eur. Phys. J. C77 (2017) 367 (for Z/W)
8 TeV, 20.2 fb^{-1}, JHEP 02, 117 (2017) (for Z)
13 TeV, 81 pb^{-1}, PLB 759 (2016) 601 (for W)
13 TeV, 3.2 fb^{-1}, JHEP 02, 117 (2017) (for Z)

$pp \to t\bar{t}$
7 TeV, 4.6 fb^{-1}, Eur. Phys. J. C 74:3109 (2014)
8 TeV, 20.3 fb^{-1}, Eur. Phys. J. C 74:3109 (2014)
13 TeV, 3.2 fb^{-1}, Phys. Lett. B 761 (2016)

$pp \to tq$
7 TeV, 4.6 fb^{-1}, PRD 90, 112006 (2014)
8 TeV, 20.3 fb^{-1}, Eur. Phys. J. C 77 (2017) 531
13 TeV, 3.2 fb^{-1}, JHEP 1704 (2017) 086

$pp \to H$
7 TeV, 4.5 fb^{-1}, Eur. Phys. J. C76 (2016) 6
8 TeV, 20.3 fb^{-1}, Eur. Phys. J. C76 (2016) 6
13 TeV, 36.1 fb^{-1}, Phys. Lett. B 786 (2018) 114

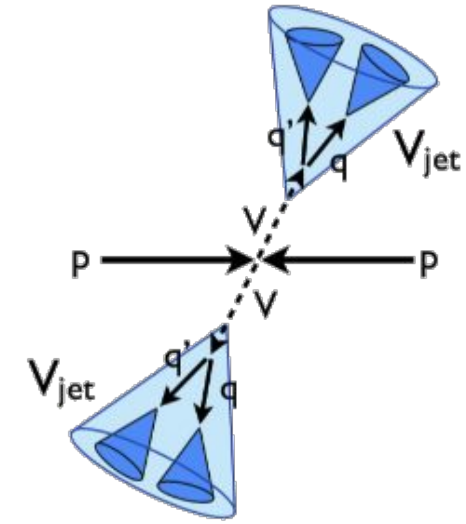
$pp \to WW$
7 TeV, 4.6 fb^{-1}, PRD 87, 112001 (2013)
8 TeV, 20.3 fb^{-1}, JHEP 09 029 (2016)
13 TeV, 3.2 fb^{-1}, Phys. Lett. B 773 (2017) 354

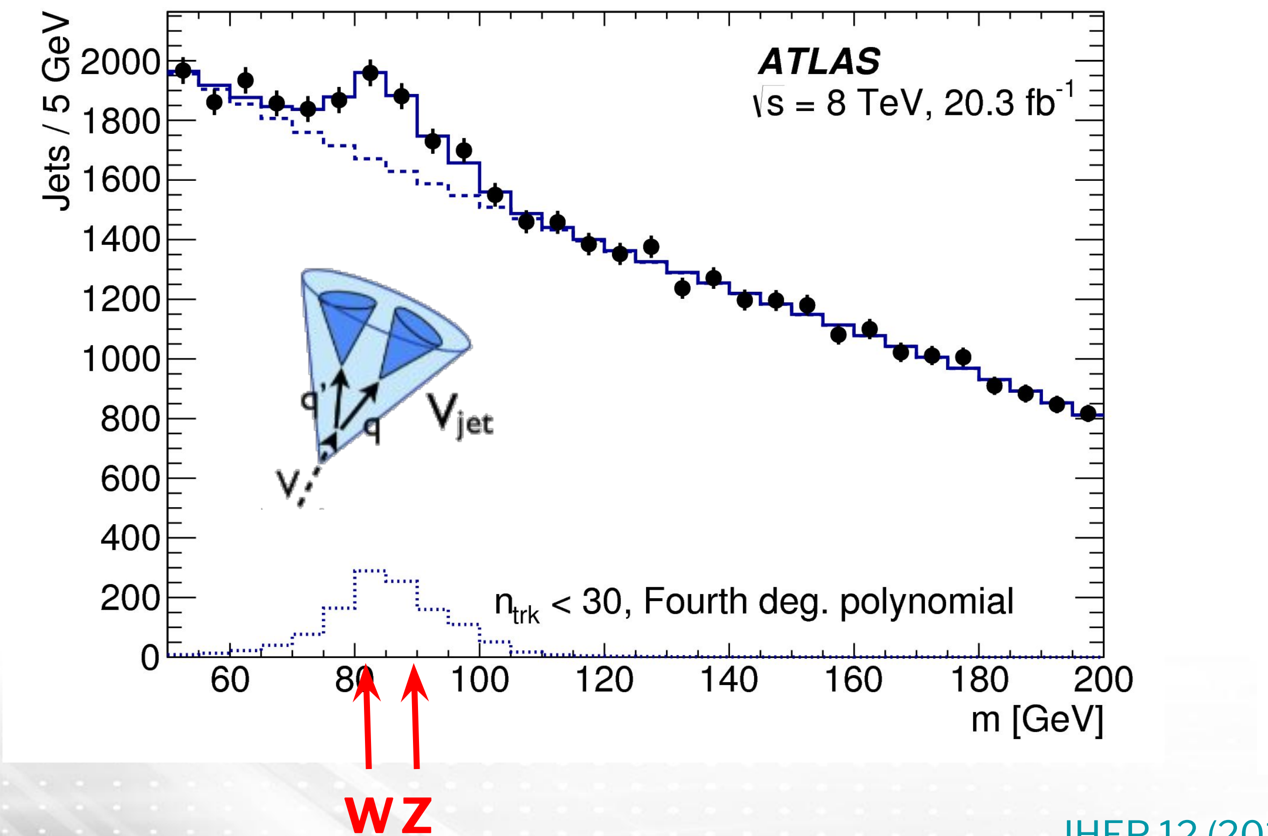
$pp \to WZ$
7 TeV, 4.6 fb^{-1}, Eur. Phys. J. C (2012) 72:2173
8 TeV, 20.3 fb^{-1}, PRD 93, 092004 (2016)
13 TeV, 36.1 fb^{-1}, arXiv:1902.05759

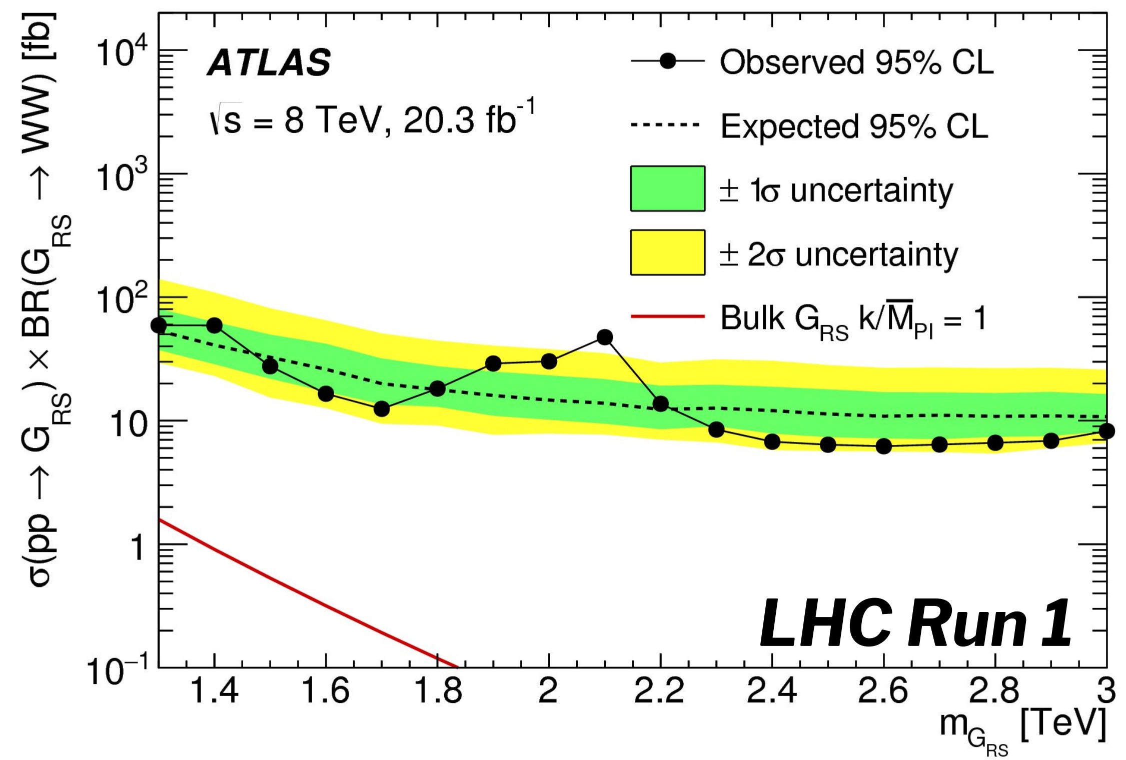
$pp \to ZZ$
7 TeV, 4.6 fb^{-1}, JHEP 03, 128 (2013)
8 TeV, 20.3 fb^{-1}, JHEP 01, 099 (2017)
13 TeV, 36.1 fb^{-1}, Phys. Rev. D 97 (2018) 032005

Diboson Resonance Search

- ***Search for very high-mass particles decaying into bosons***
  - **initiated on ATLAS by Koji Terashi (Tokyo) and David Adams (BNL)**
  - reconstruct very high-p_T W and Z bosons as large-radius jets
  - first analysis had insufficient sensitivity to typical new physics models with Run 1 data







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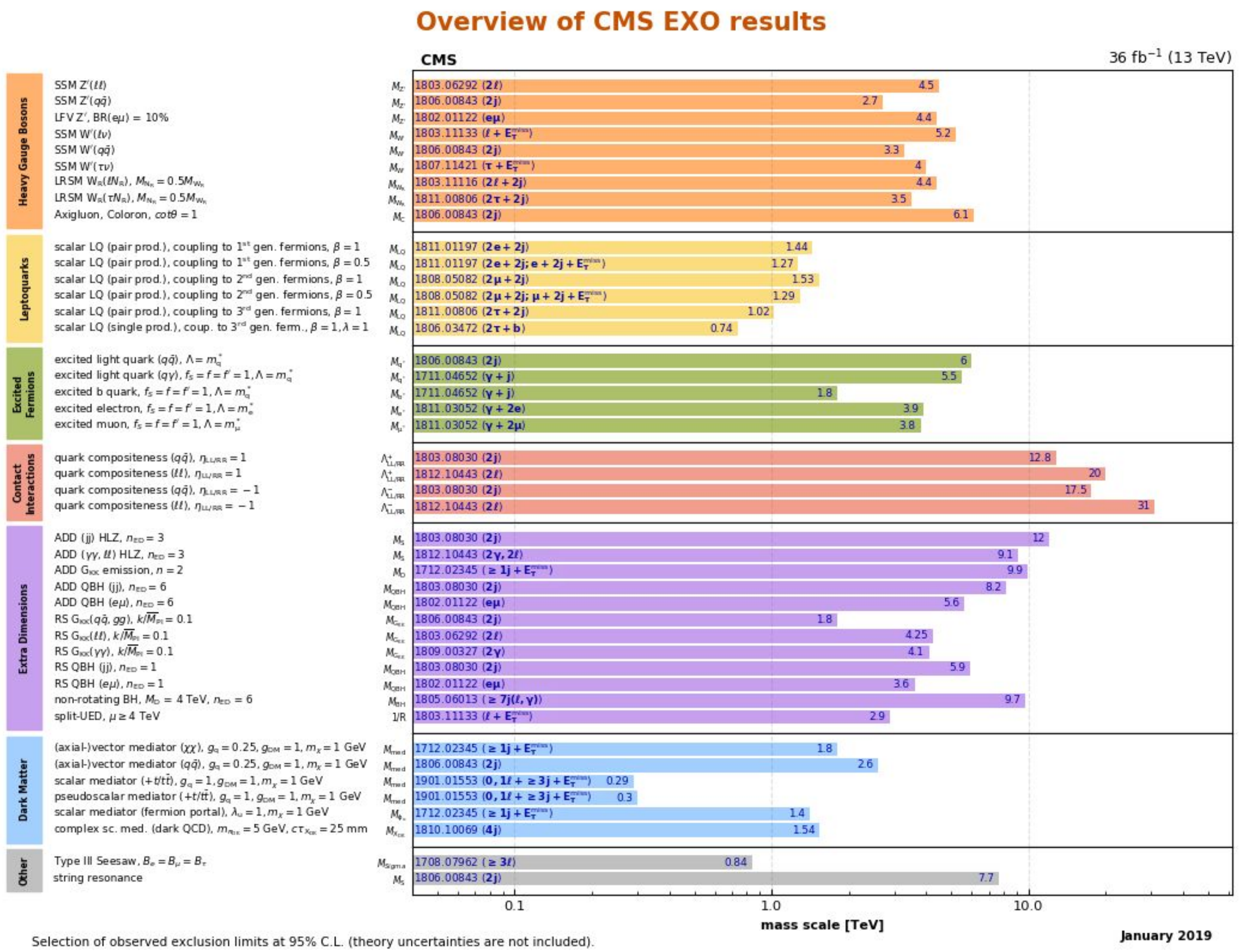
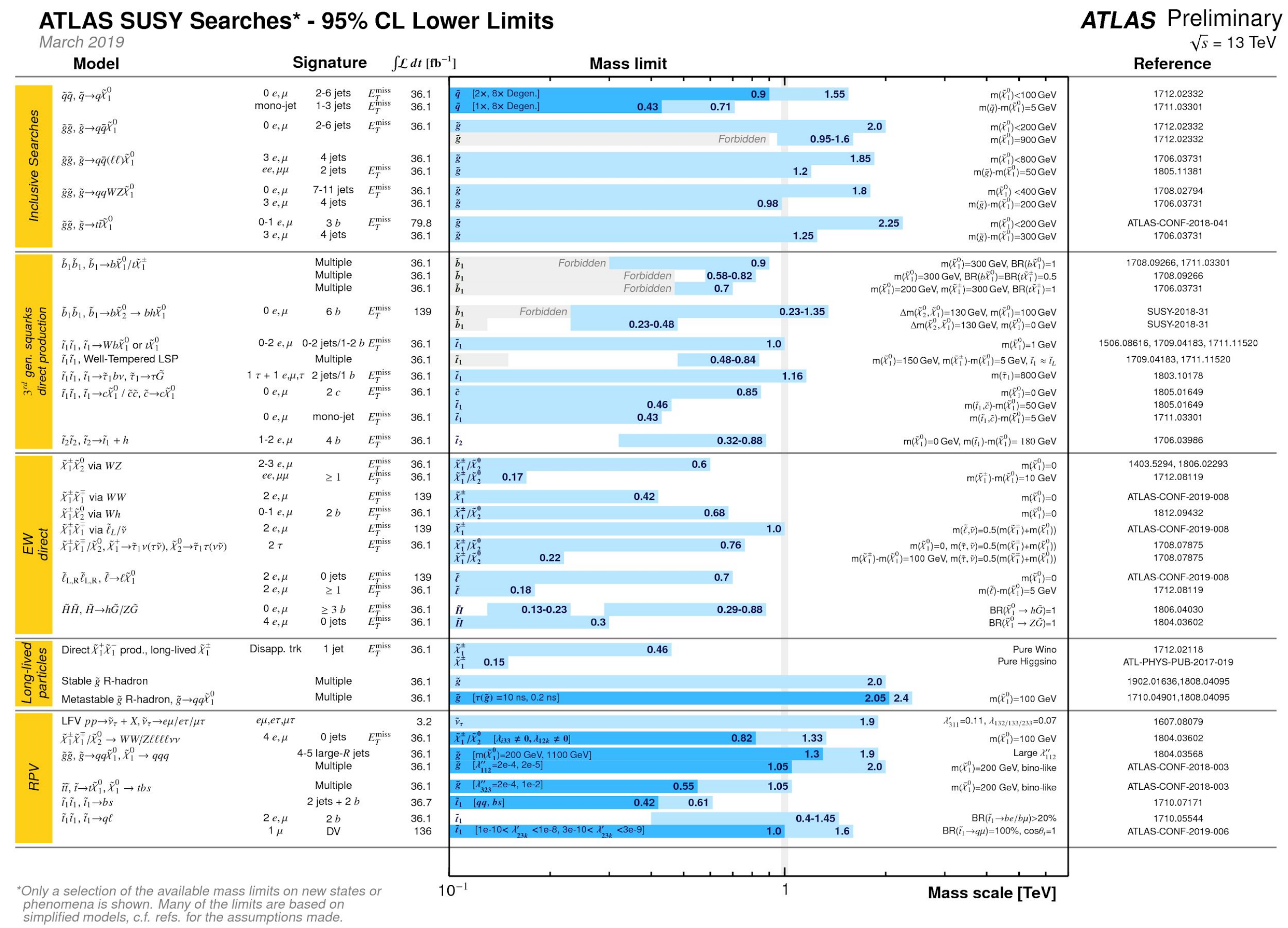
Today's New Physics Reach





Future New Physics Reach

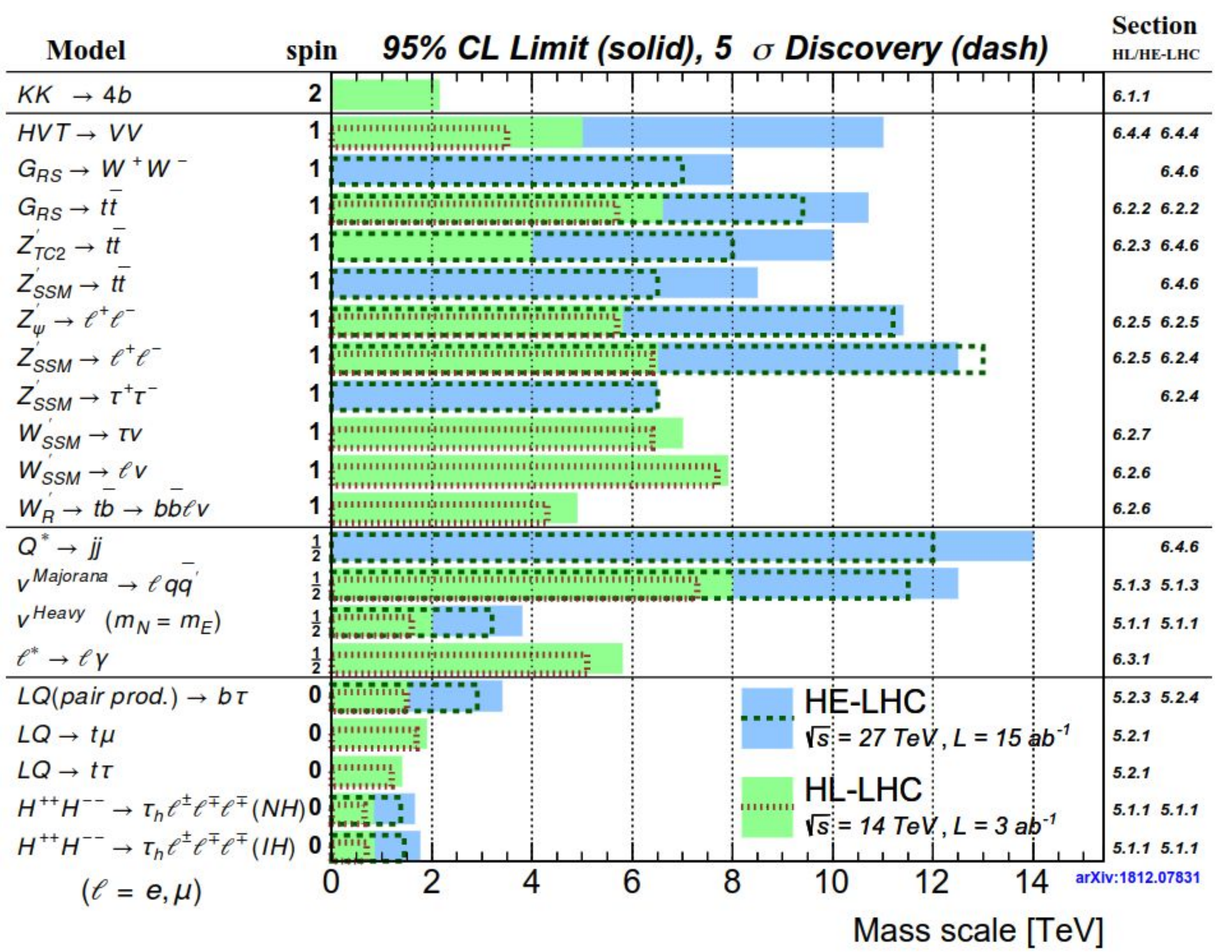


Fig. 7.2: A summary of the expected mass reach for 5σ discovery and 95% C.L. exclusion at the HL/HE-LHC, as presented in Sections 5 and 6.

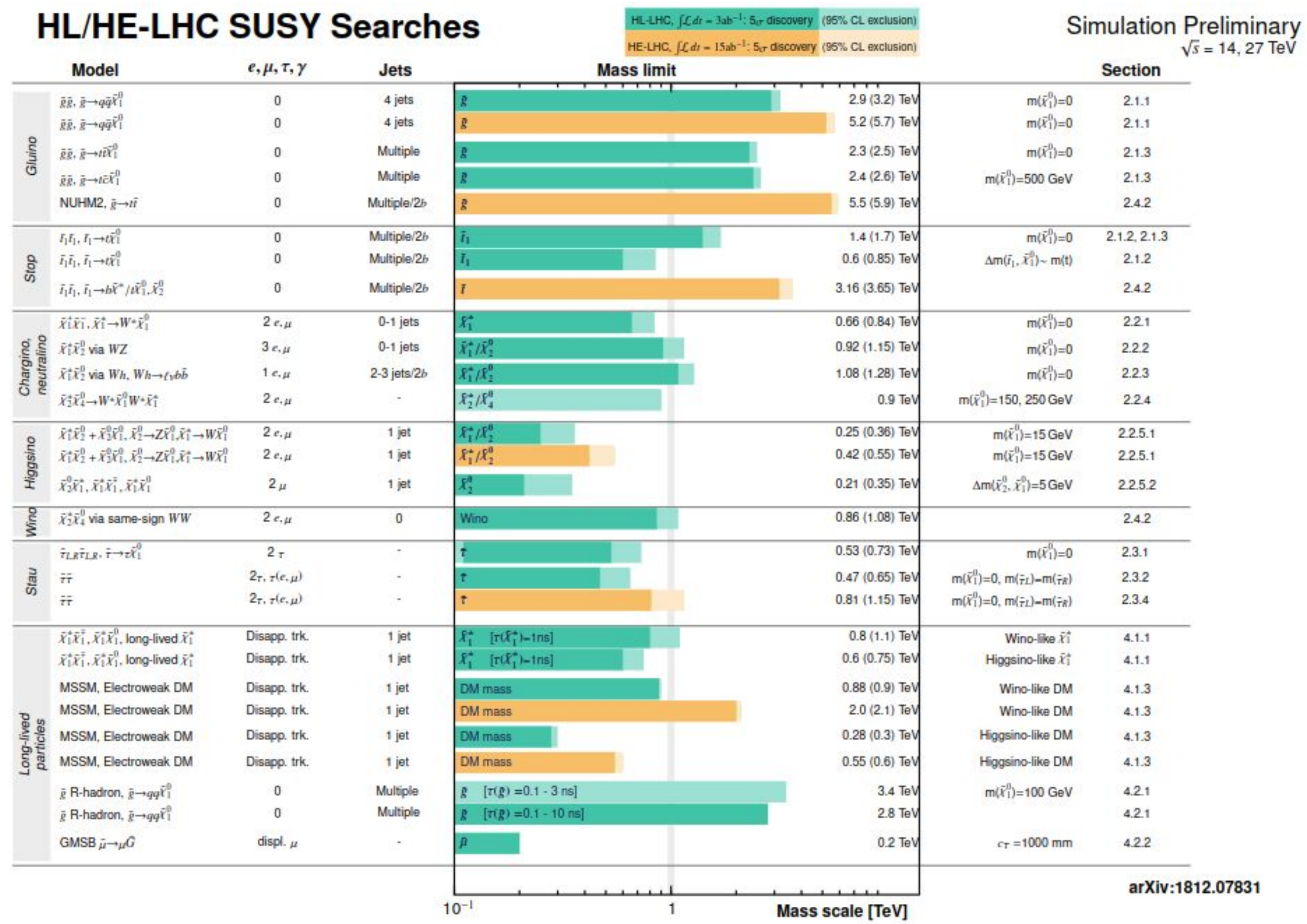


Fig. 7.1: A summary of the expected mass reach for 5σ discovery and 95% C.L. exclusion at the HL/HE-LHC, as presented in Section 2.

arxiv:1812.07831