

Energy Frontier LHC & HL-LHC

Michael Begel
April 16, 2019

BROOKHAVEN
NATIONAL LABORATORY

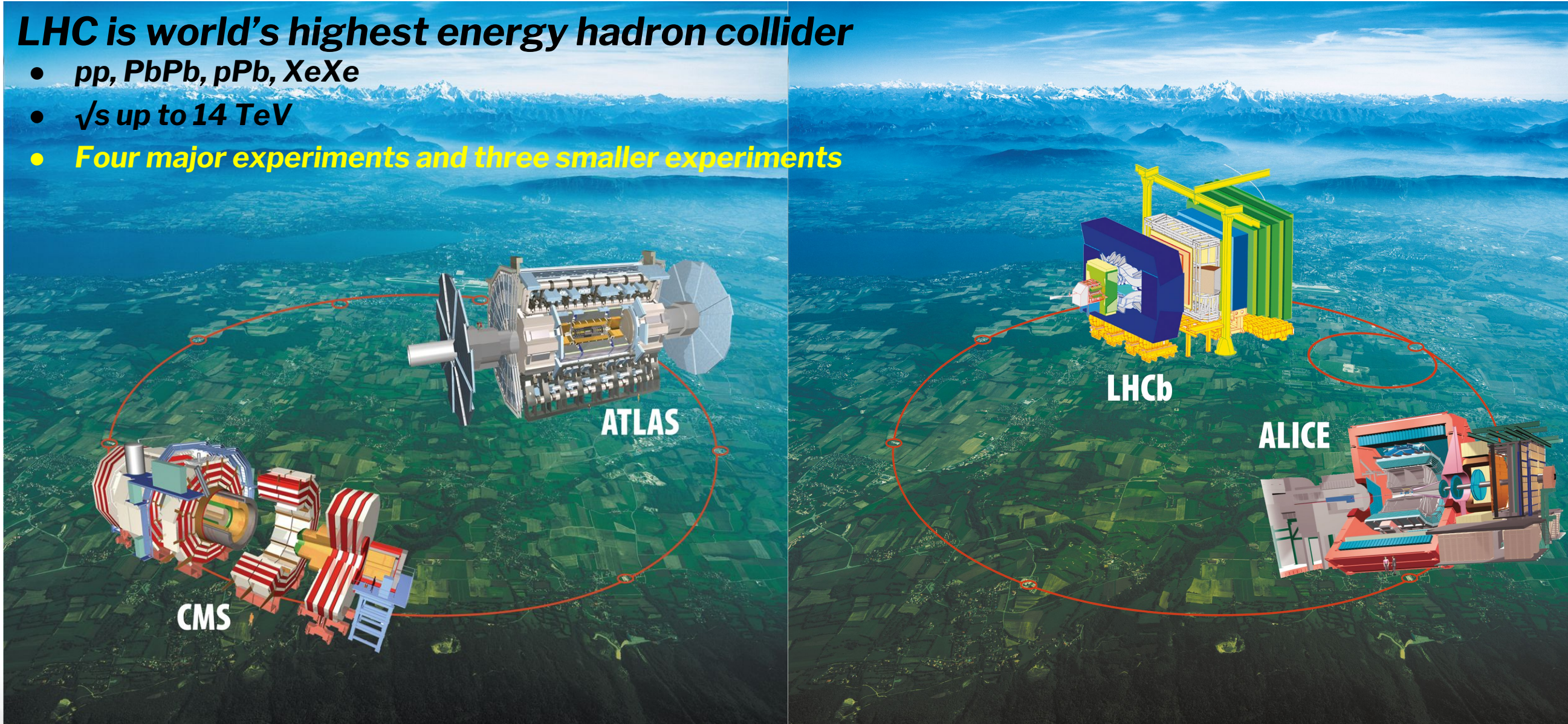


BROOKHAVEN SCIENCE ASSOCIATES

LHC at CERN

LHC is world's highest energy hadron collider

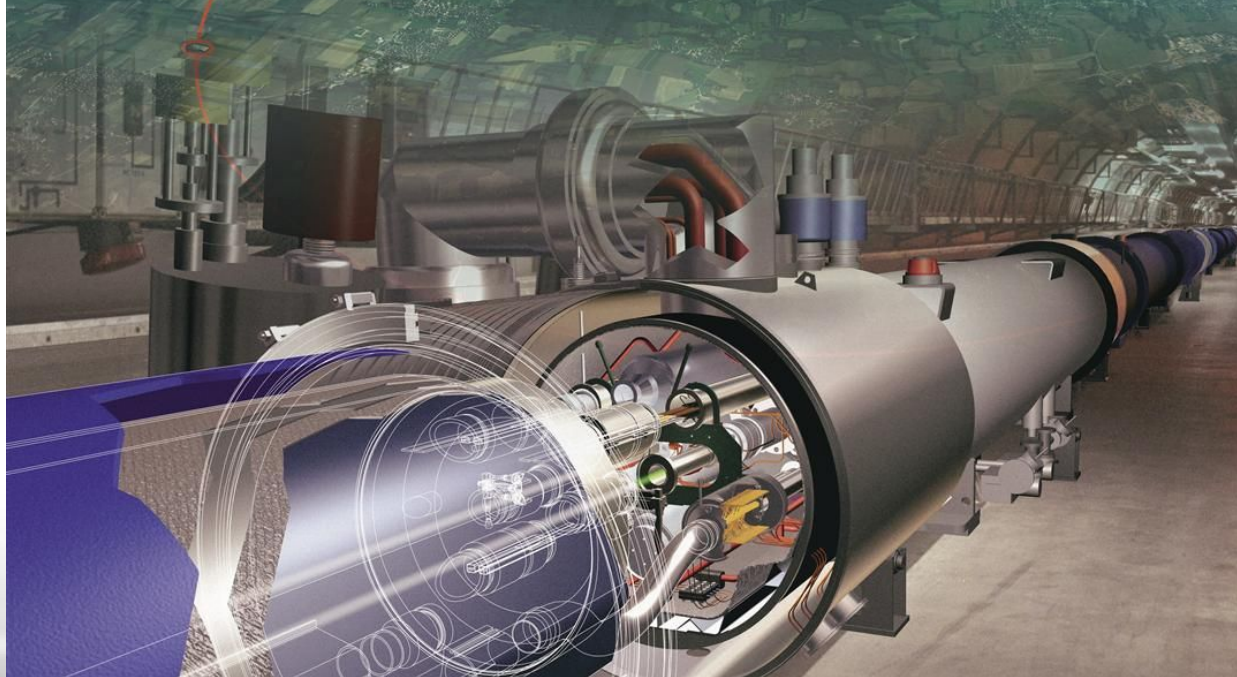
- $pp, PbPb, pPb, XeXe$
- \sqrt{s} up to 14 TeV
- **Four major experiments and three smaller experiments**



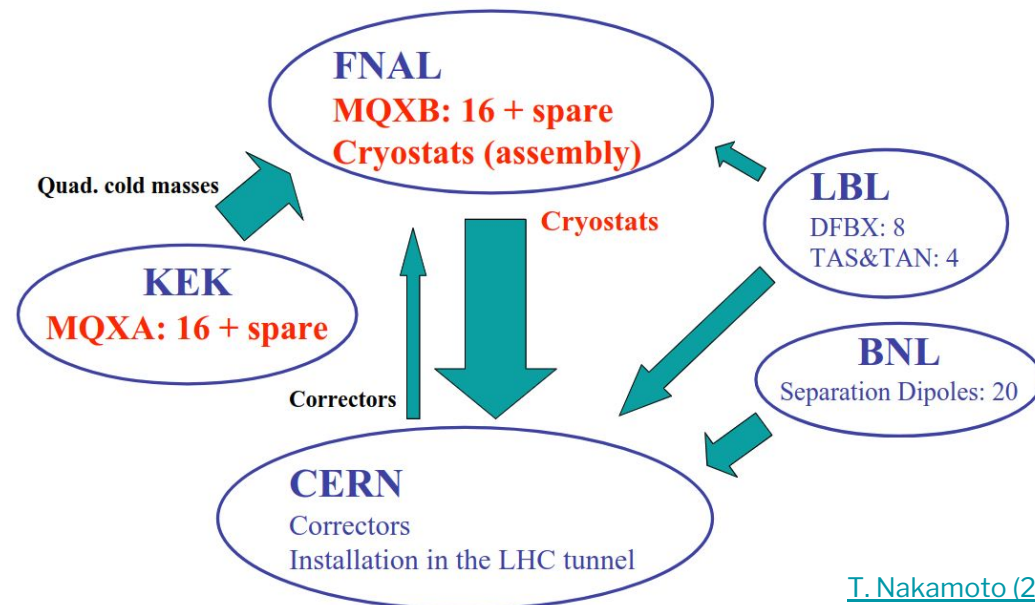
LHC at CERN

LHC is world's highest energy hadron collider

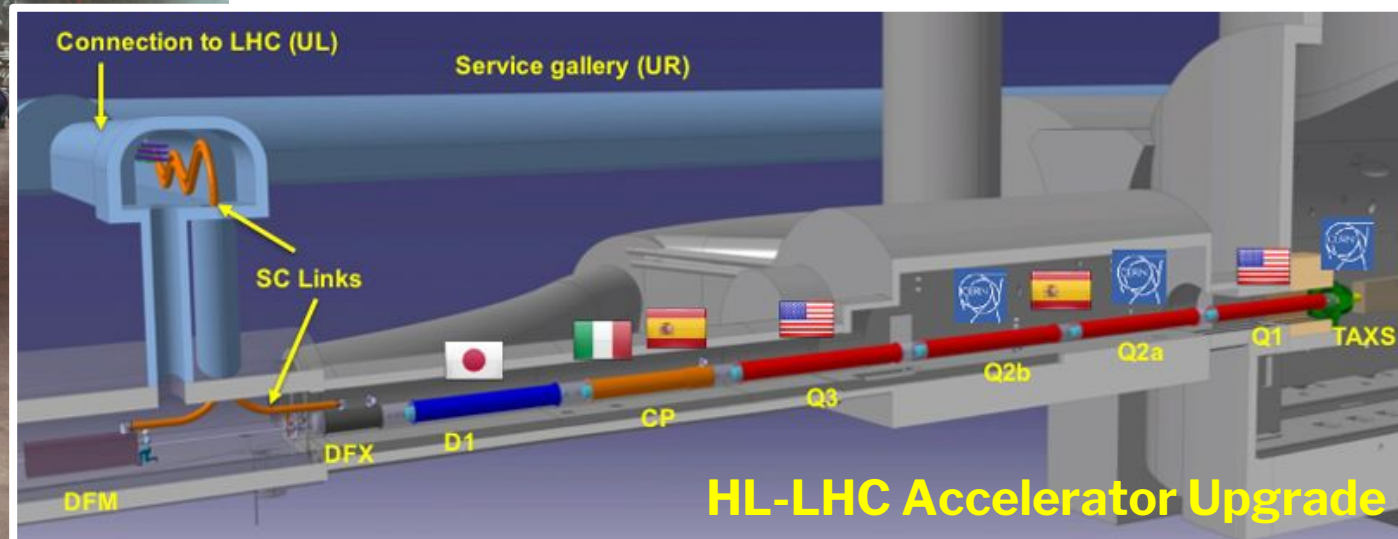
- pp, PbPb, pPb, XeXe
- \sqrt{s} up to 14 TeV
- Four major experiments and three smaller experiments
- **US & Japan built inner triplet magnets that focus beams at LHC experimental interaction regions**
 - upgrades for High Luminosity LHC (HL-LHC)
 - $\sim 1 \times 10^{34} \rightarrow \sim 5.0-7.5 \times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



LHC CERN-US-KEK Collaboration for the Low-Beta Insertions

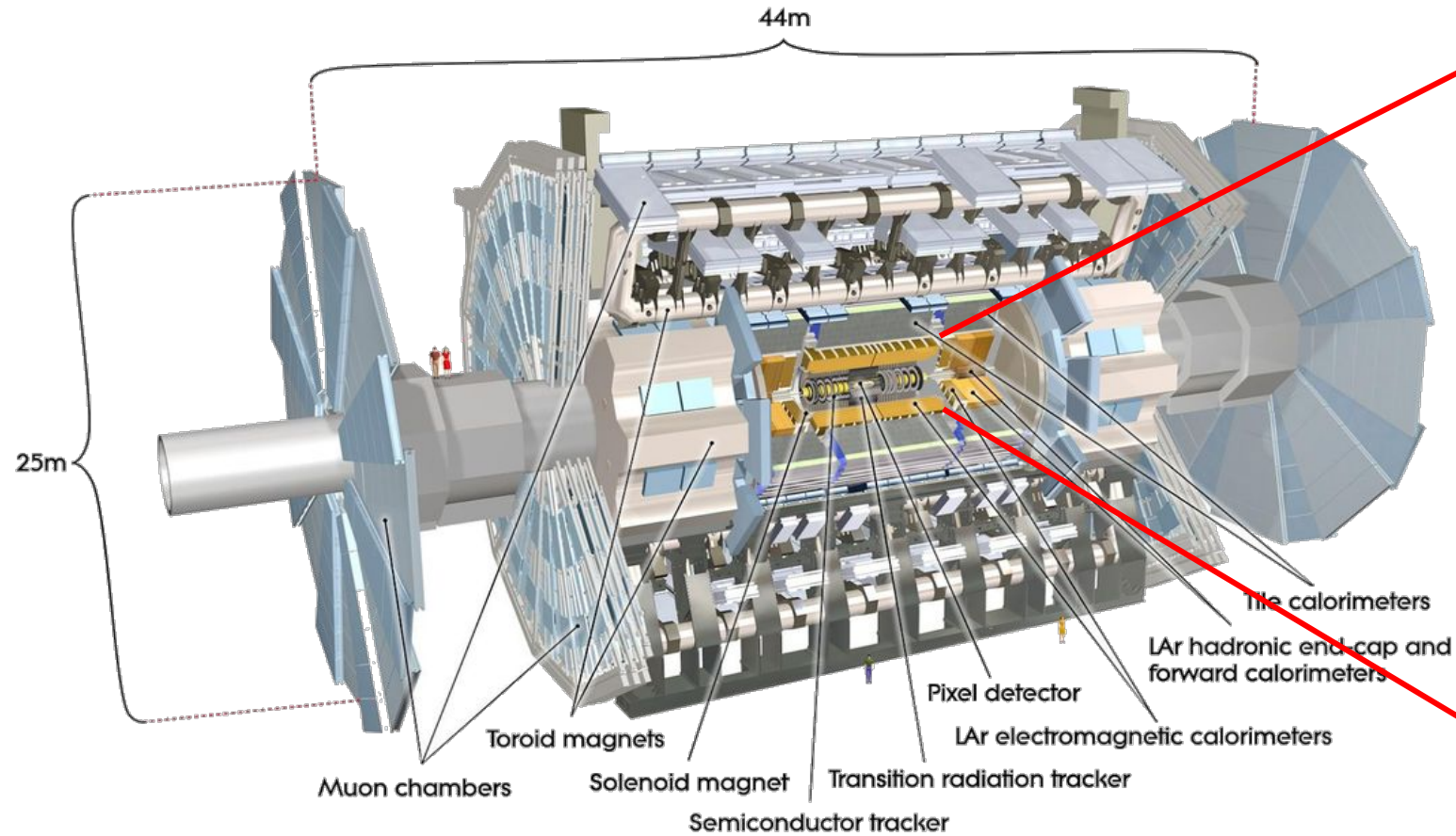


[T. Nakamoto \(2007\)](#)



HL-LHC Accelerator Upgrade

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 m² 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

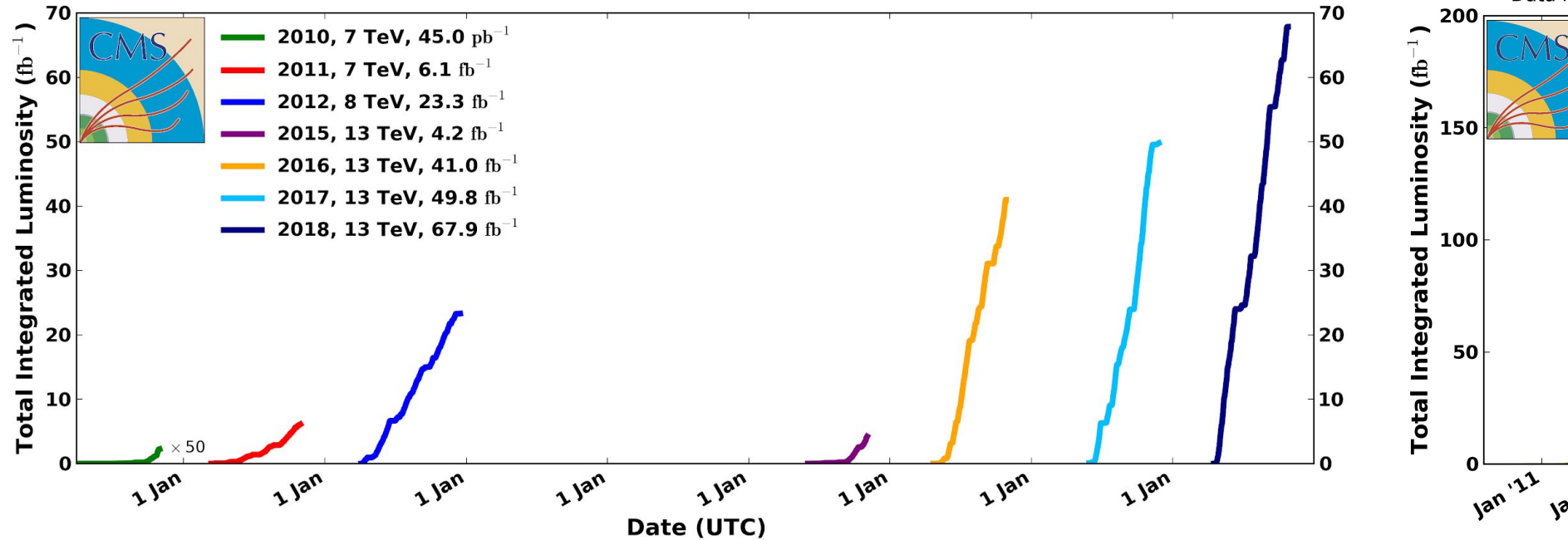
**183 institutes from
38 countries**

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

Integrated Luminosity: LHC Runs 1 & 2

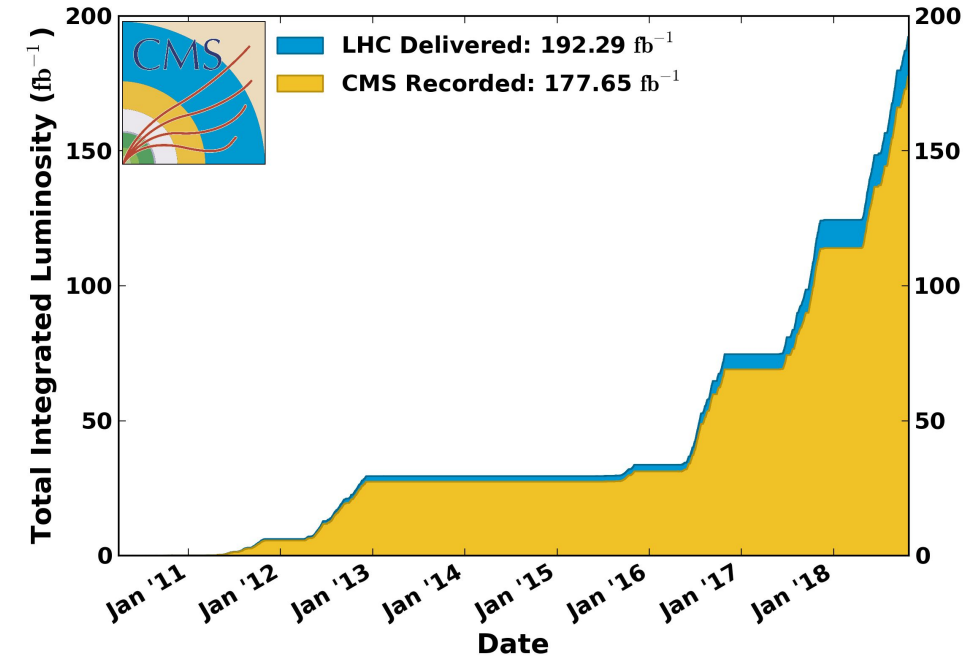
CMS Integrated Luminosity Delivered, pp

Data included from 2010-03-30 11:22 to 2018-10-26 08:23 UTC



CMS Integrated Luminosity, pp, $\sqrt{s} = 7, 8, 13$ TeV

Data included from 2010-03-30 11:22 to 2018-10-26 08:23 UTC



- **LHC delivered $\sim 190 \text{ fb}^{-1}$ of integrated luminosity to ATLAS and to CMS and $\sim 9 \text{ fb}^{-1}$ to LHCb from 2010–2018**

- **sustained performance of LHC operations has been stellar!**
- >90% efficiency for each experiment

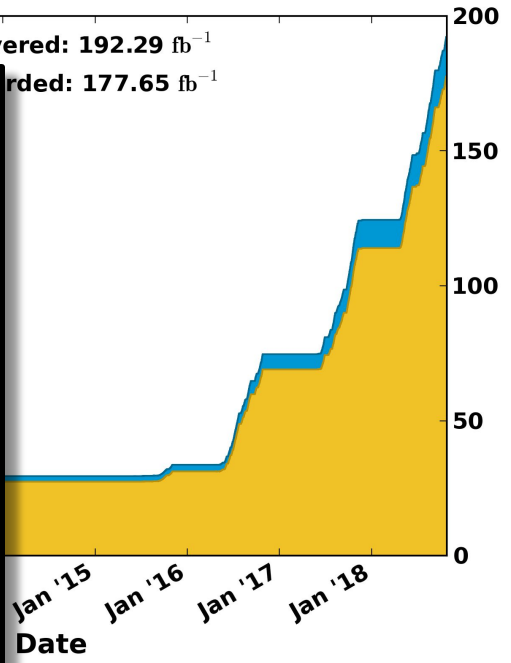
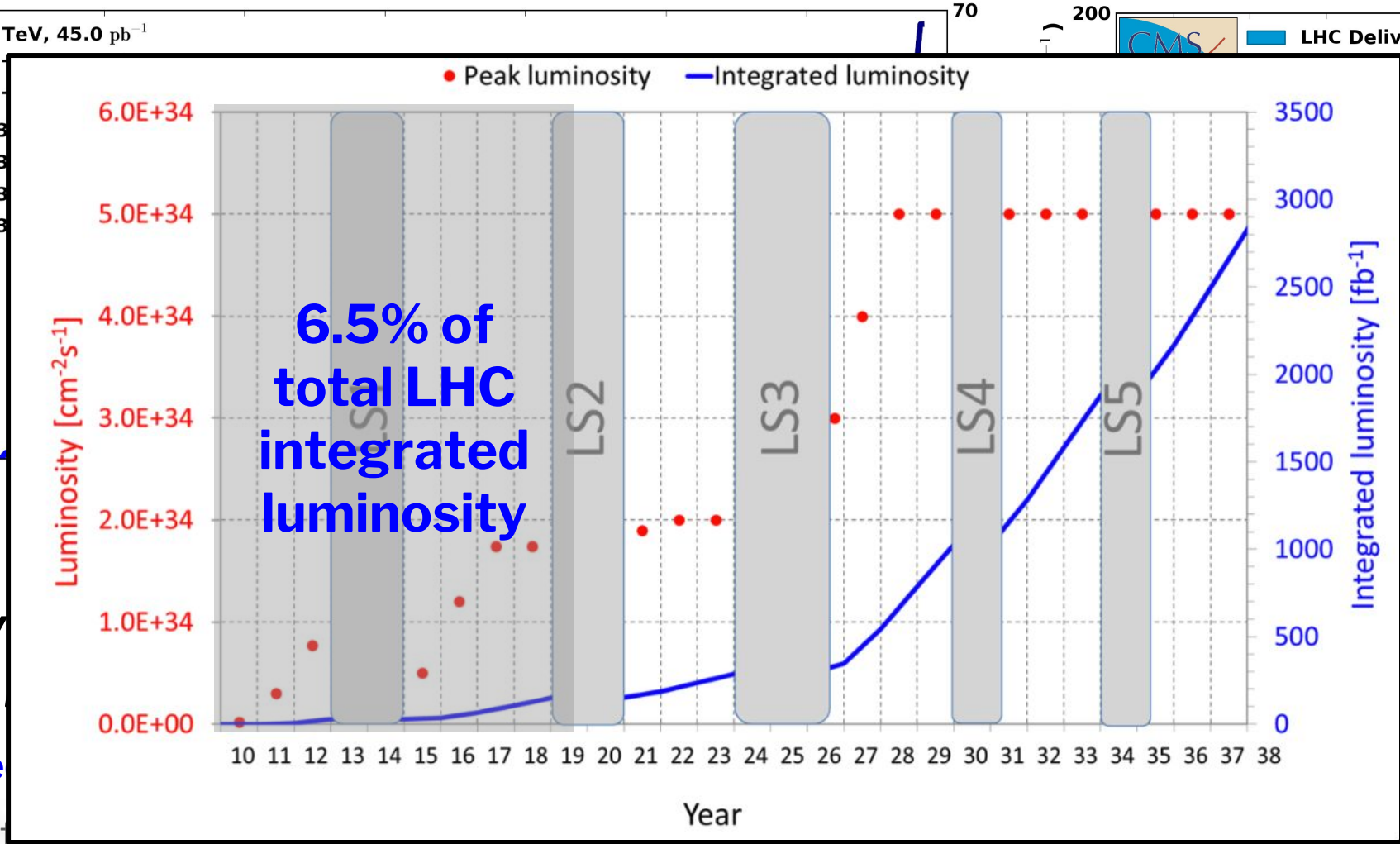
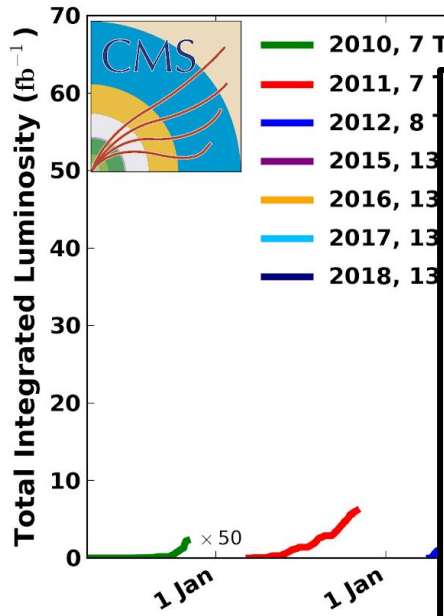
Integrated Luminosity: LHC Runs 1 & 2

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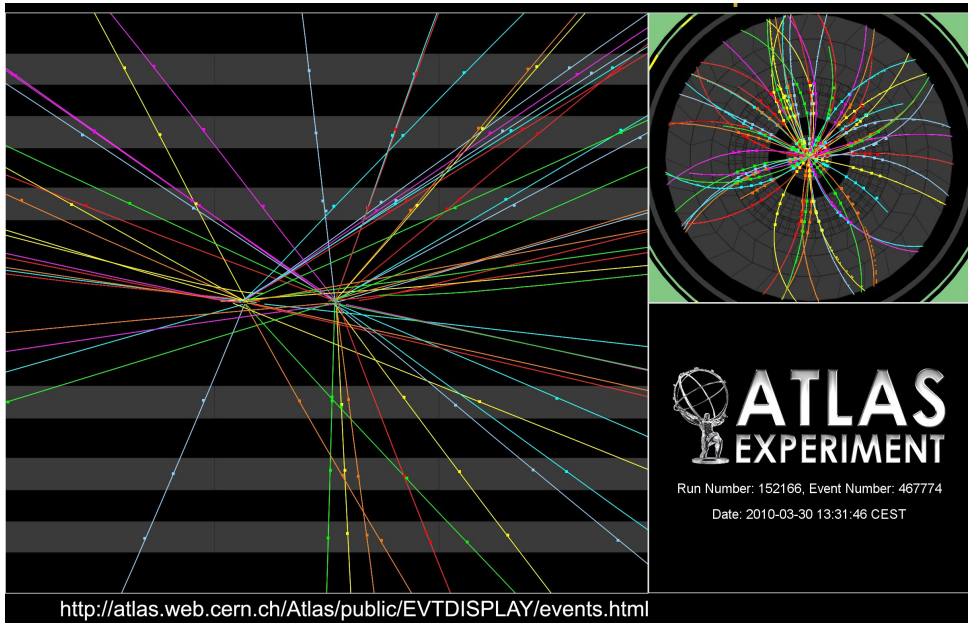
Data included from 2010-03-30 11:22 to 2018-10-26 08:23 UTC



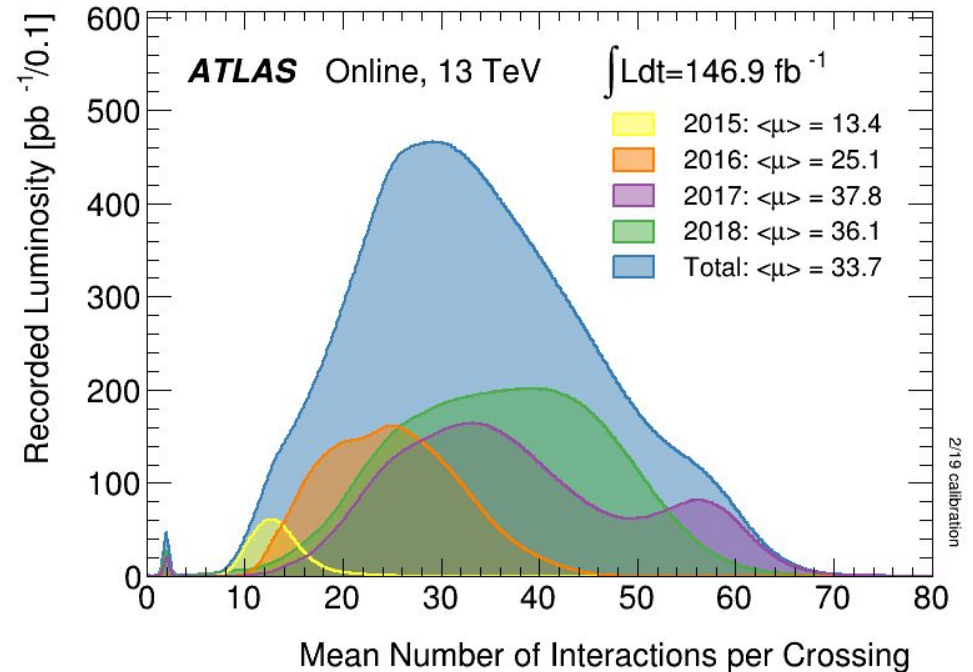
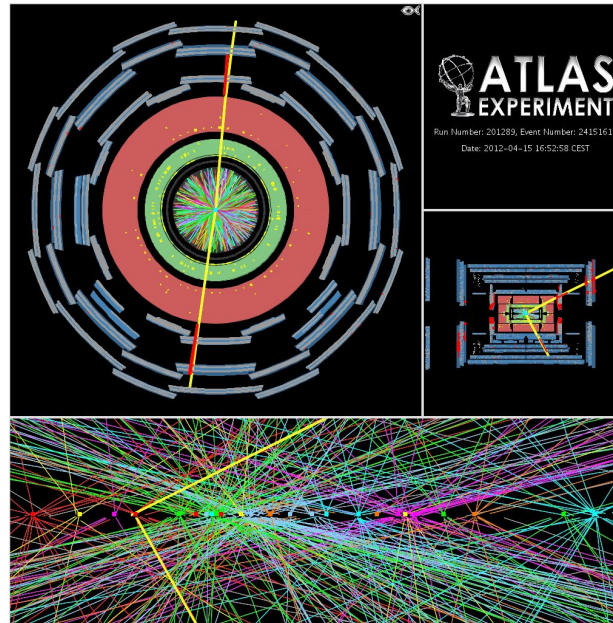
- LHC delivered ~9 fb⁻¹ to CMS and ATLAS
- sustained
- >90% efficiency for each experiment

High Luminosity @ Hadron Colliders: Pileup

2 pileup vertices



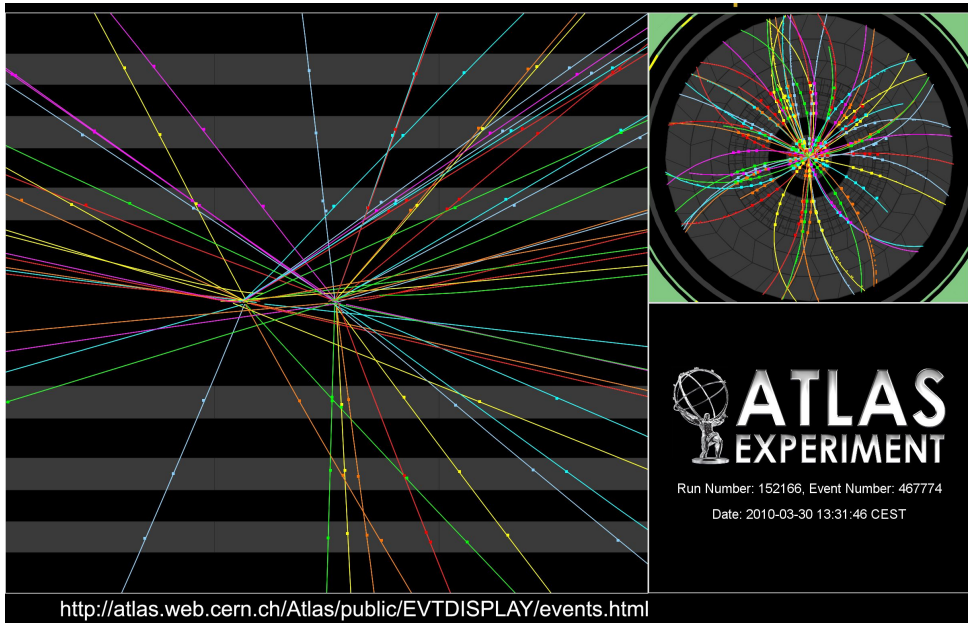
25 pileup vertices



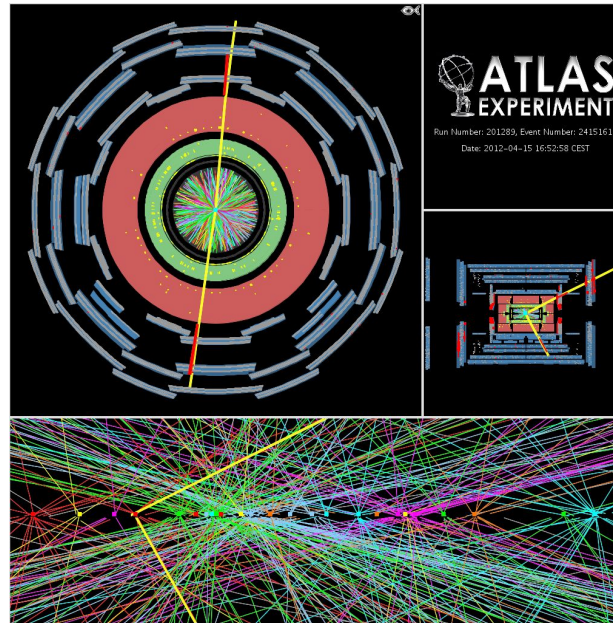
- **Considerable effort to mitigate impact of pileup on detectors, trigger, computing, software, reconstruction, performance, and physics analyses**
 - improved algorithms such as particle flow

High Luminosity @ Hadron Colliders: Pileup

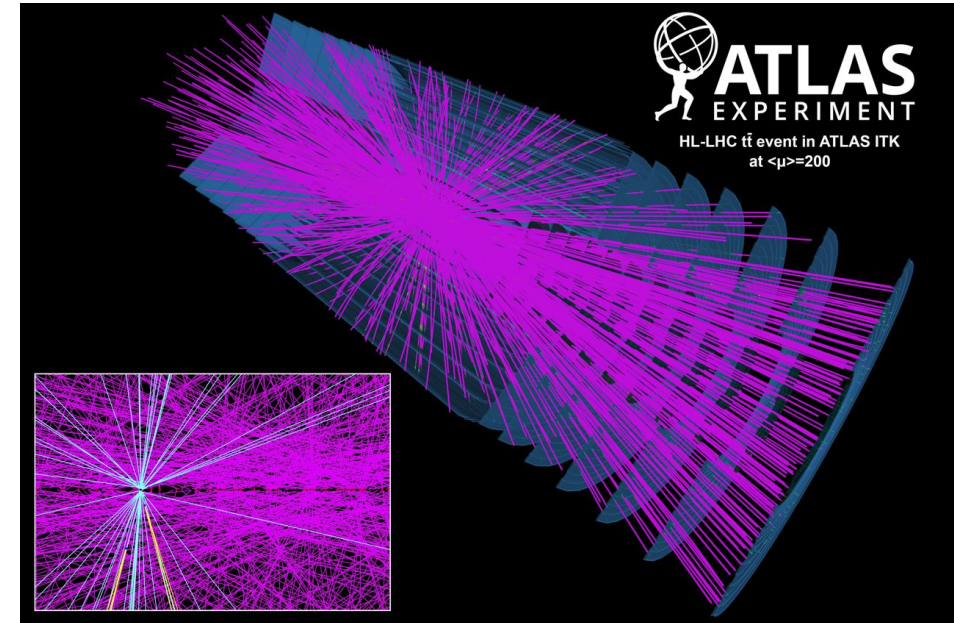
2 pileup vertices



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

Phase-I upgraded LHCb detector

- Particle ID**
Replace HPDs + electronics
- Calorimeters**
Reduce PMT gain + new electronics
- Muon**
new electronics
- New Vertex Detector**
- New Tracking stations**
- + trigger-less readout system**

L1-Trigger/HLT/DAQ
<https://cds.cern.ch/record/2283192>
<https://cds.cern.ch/record/2283193>

- Tracks in L1-Trigger at 40 MHz for 750 kHz PFlow-like selection rate
- HLT output 7.5 kHz

Barrel Calorimeters
<https://cds.cern.ch/record/2283187>

- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

Muon systems
<https://cds.cern.ch/record/2283189>

- DT & CSC new FE/BE readout
- New GEM/RPC 1.6 <math>\eta < 2.4</math>
- Extended coverage to $\eta \approx 3$

Calorimeter Endcap
<https://cds.cern.ch/record/2293646>

- Si, Scint+SiPM in Pb-W-SS
- 3D shower topology with precise timing

Tracker <https://cds.cern.ch/record/2272264>

- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \approx 3.8$

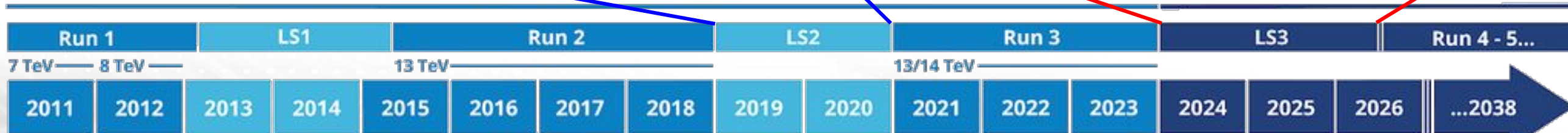
MIP Timing Detector
<https://cds.cern.ch/record/2296612>

- ≈ 30 ps resolution
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

Beam Radiation Instr. and Luminosity, and Common Systems and Infrastructure
<https://cds.cern.ch/record/2020886>

Large Hadron Collider (LHC)

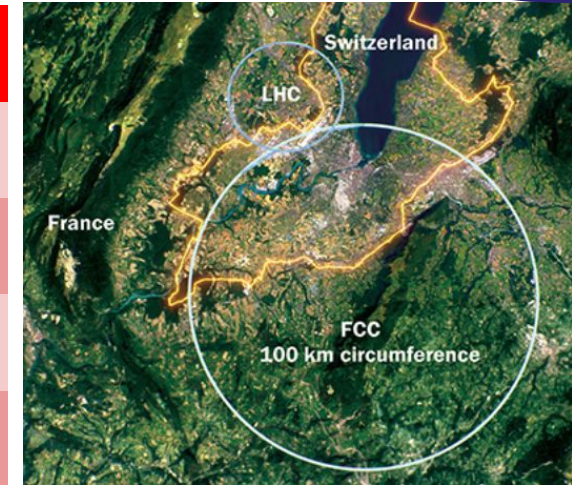
HL-LHC



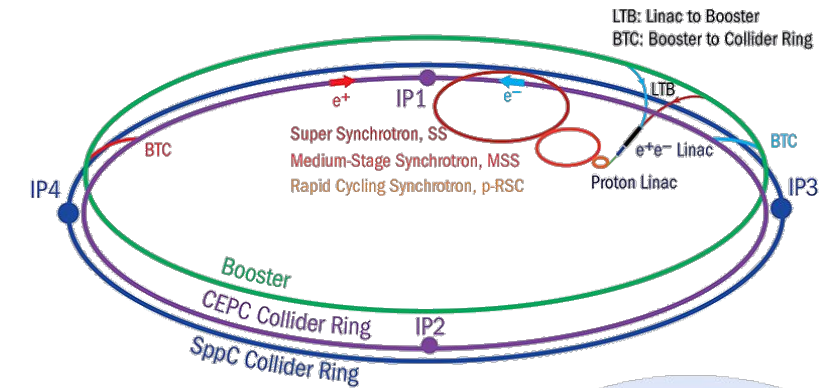
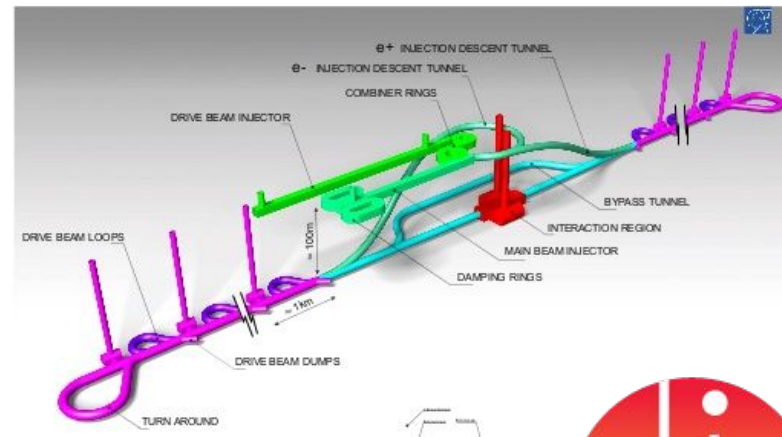
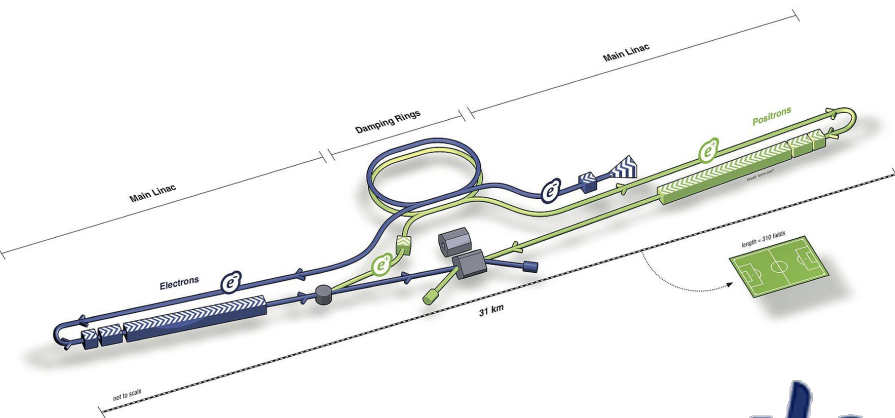
LHC and Future Landscape



	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 ($10^{34} \text{ cm}^{-2}\text{s}^{-1}$)	1	5–7	28	~10	5/30
peak events/crossing	~60	140–200	~800	~300	~1000

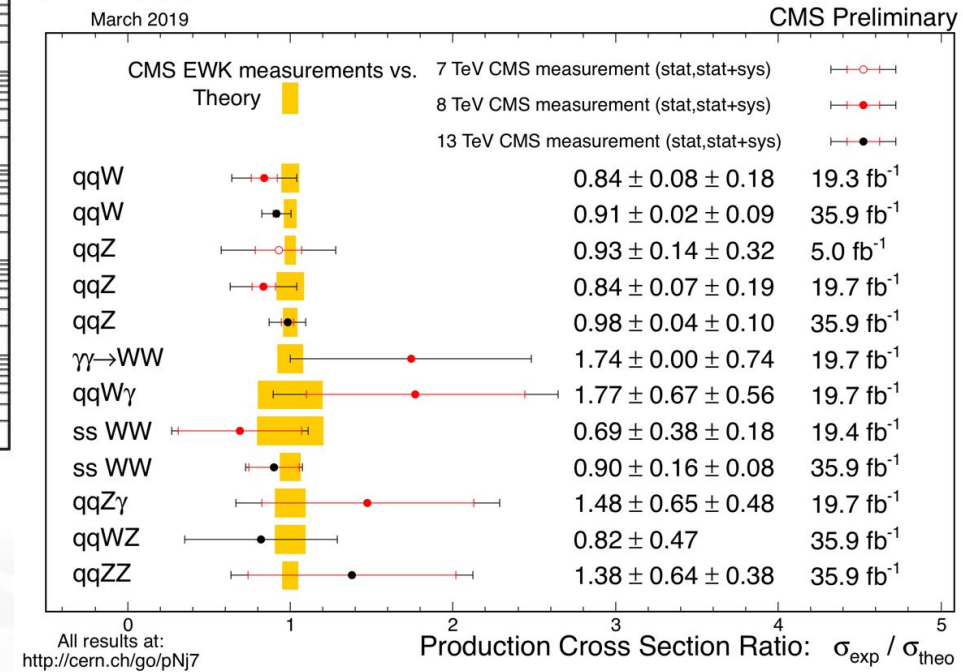
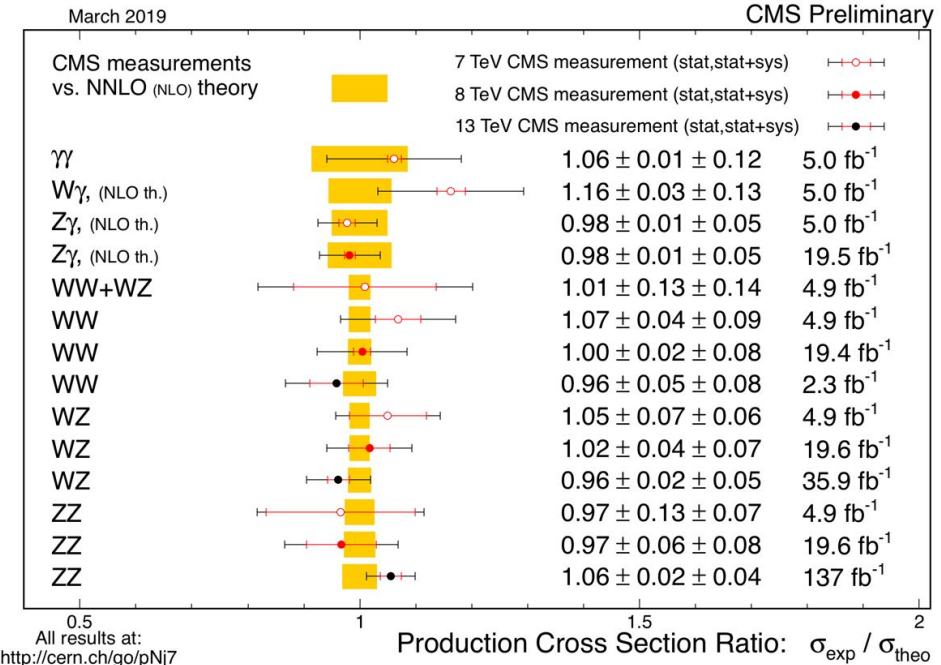
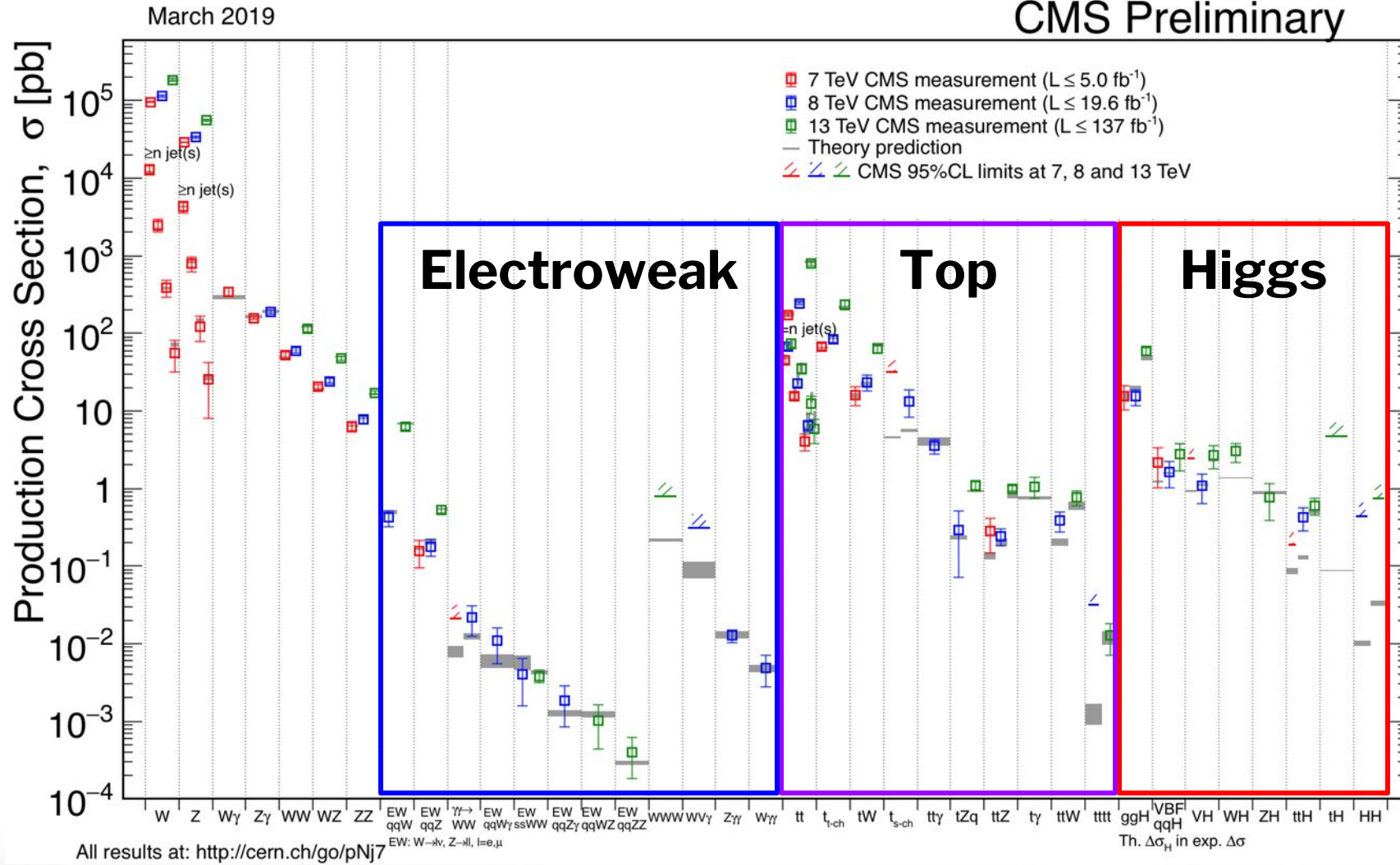


- pp & ee colliders provide complementary physics information*



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:**

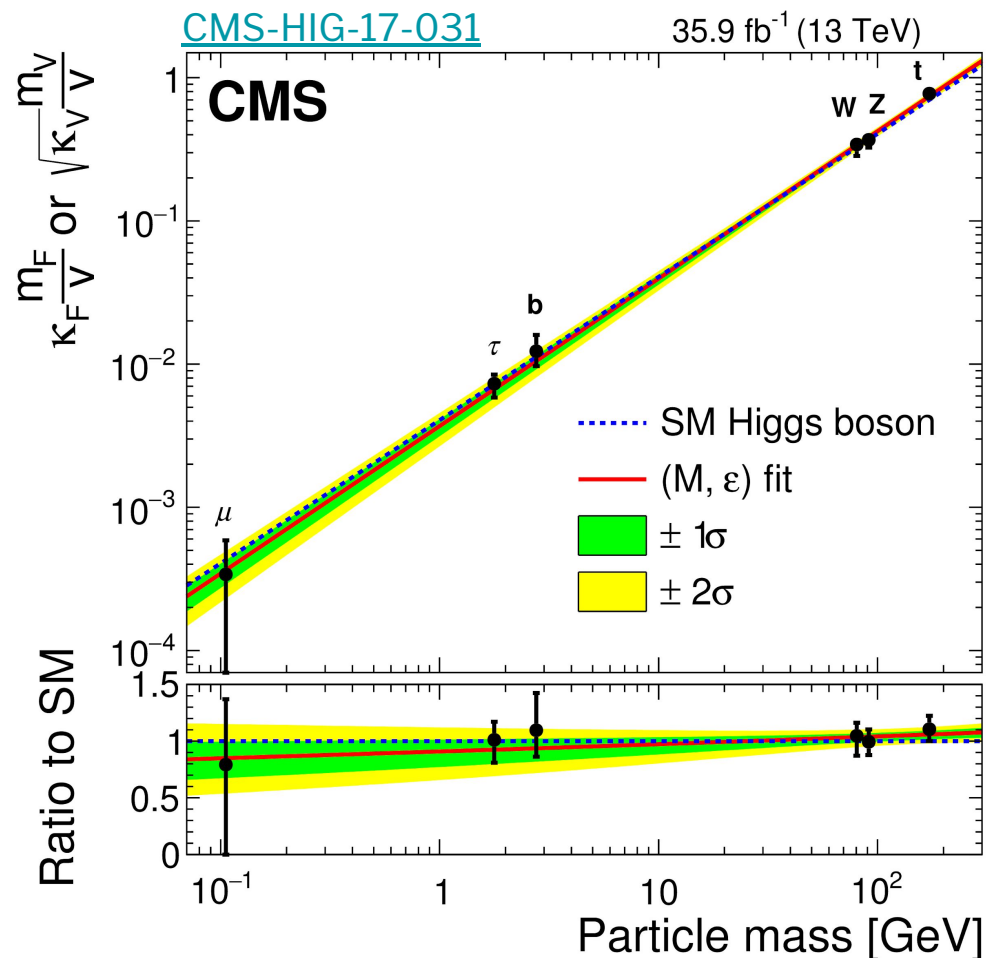
- <1 GeV (direct)
- <14 MeV (indirect)

CMS: JHEP 11 (2017) 047
ATLAS: PLB 786 (2018) 223
CMS: CMS-PAS-HIG-18-002

- **Direct couplings:**

- Weak Bosons
- Tau Leptons
- Top Quarks
- Bottom Quarks

ATLAS: PLB 716 (2012) 1-29
CMS: PLB 716 (2012) 30
ATLAS: arXiv:1811.08856
CMS: PLB 779 (2018) 283
ATLAS: PLB 784 (2018) 173
CMS: PRL 120 (2018) 231801
ATLAS: PLB 786 (2018) 59
CMS: PRL 121 (2018) 121801



All measurements consistent with SM expectations

Higgs: Standard Model?

- **Mass: 125.09 ± 0.24 GeV**
- **Spin/Parity: 0^+**
- **Width:**
 - <1 GeV (direct)
 - <14 MeV (indirect)
- **Direct couplings:**
 - Weak Bosons
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 - Top Quarks
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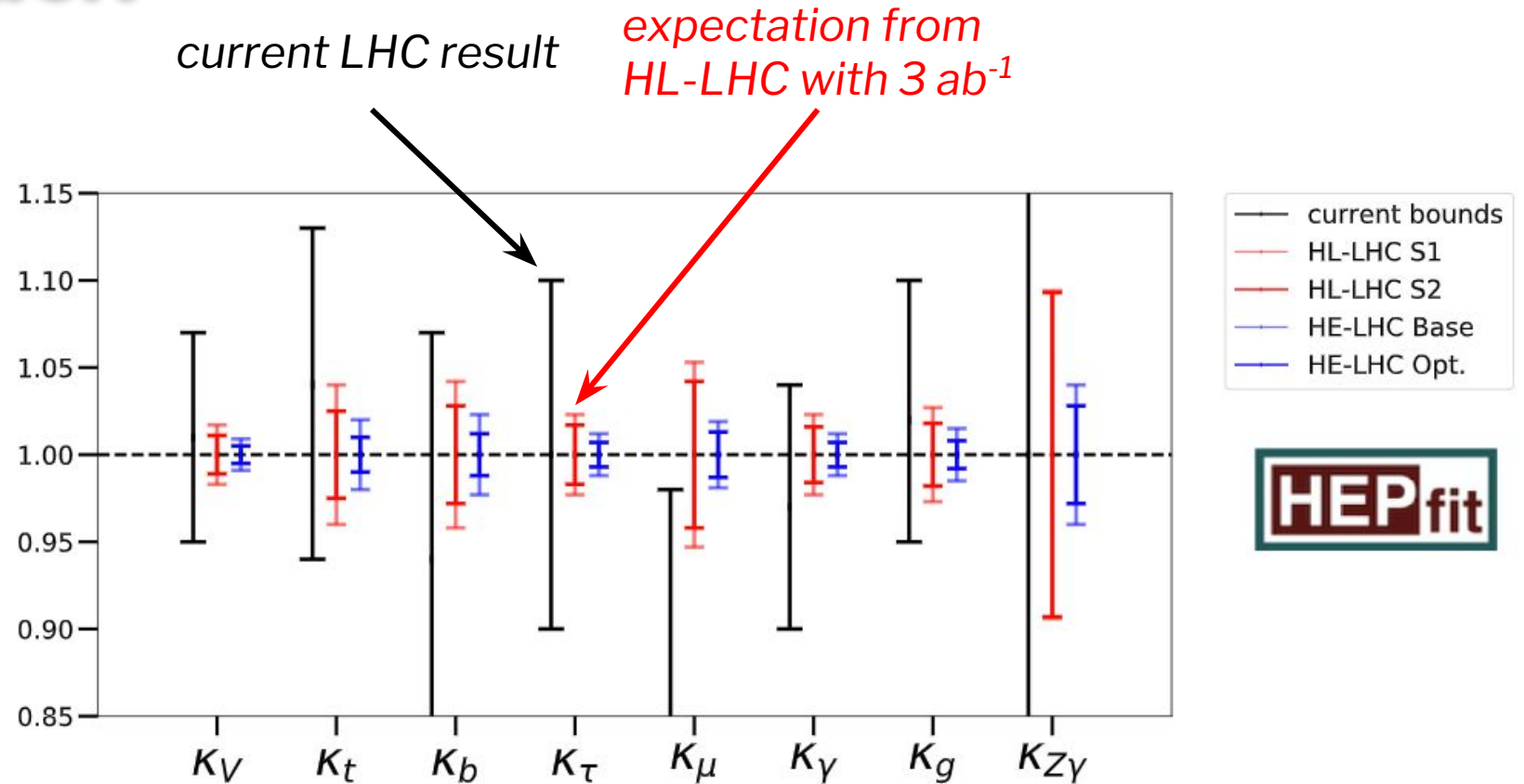
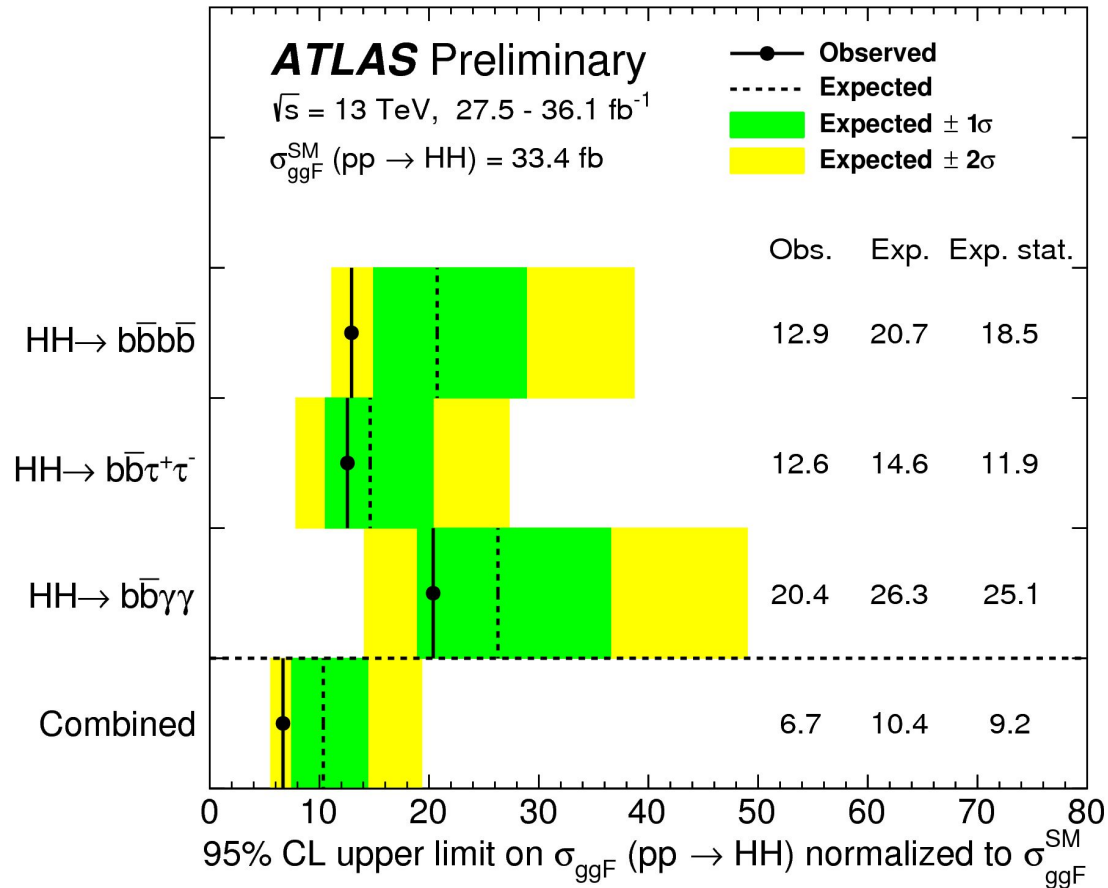
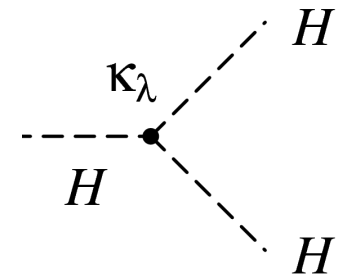


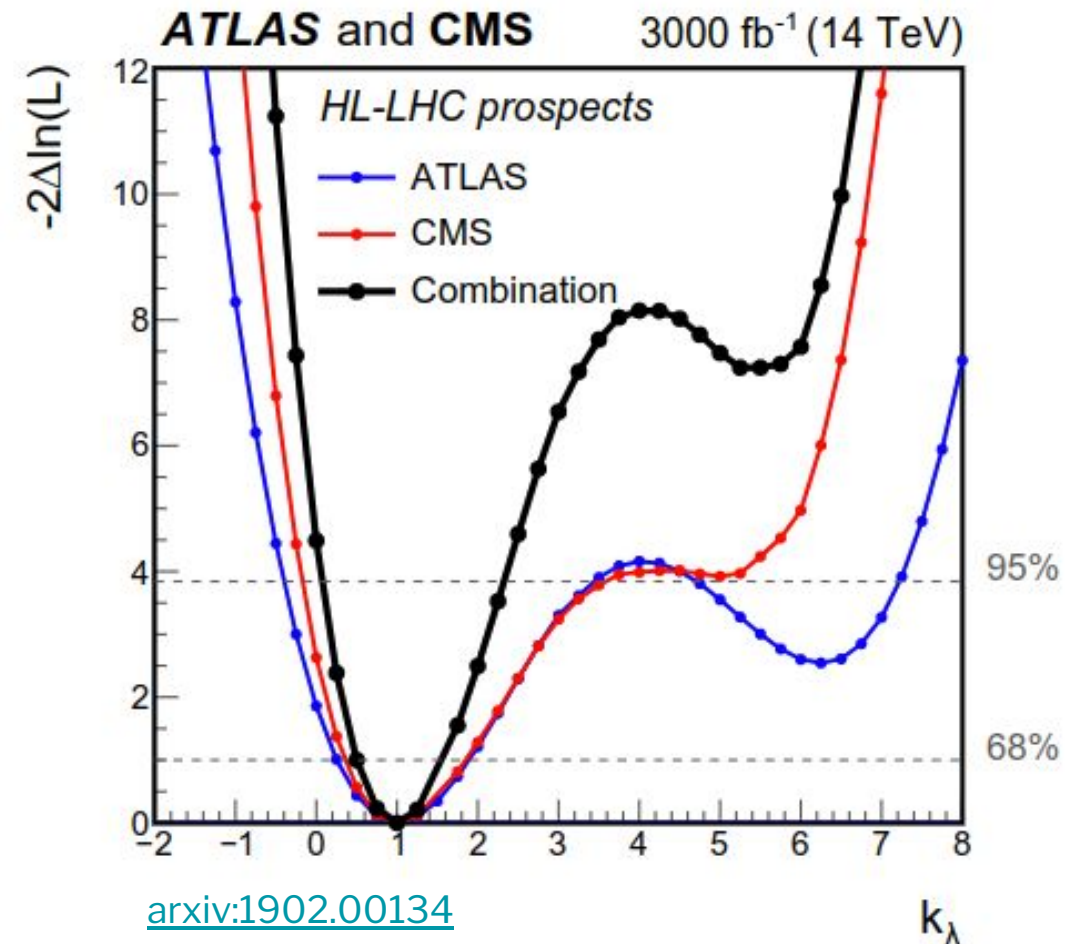
Fig. 33: Current and future constraints on κ_i . The left line of each κ is the current bound, from Ref. [185]. The central line is the projection to the HL-LHC, with the S1 scenario in light red and S2 in dark red. The right line is the projection to HE-LHC, with the base scenario in light blue and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

Higgs Self-Coupling

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

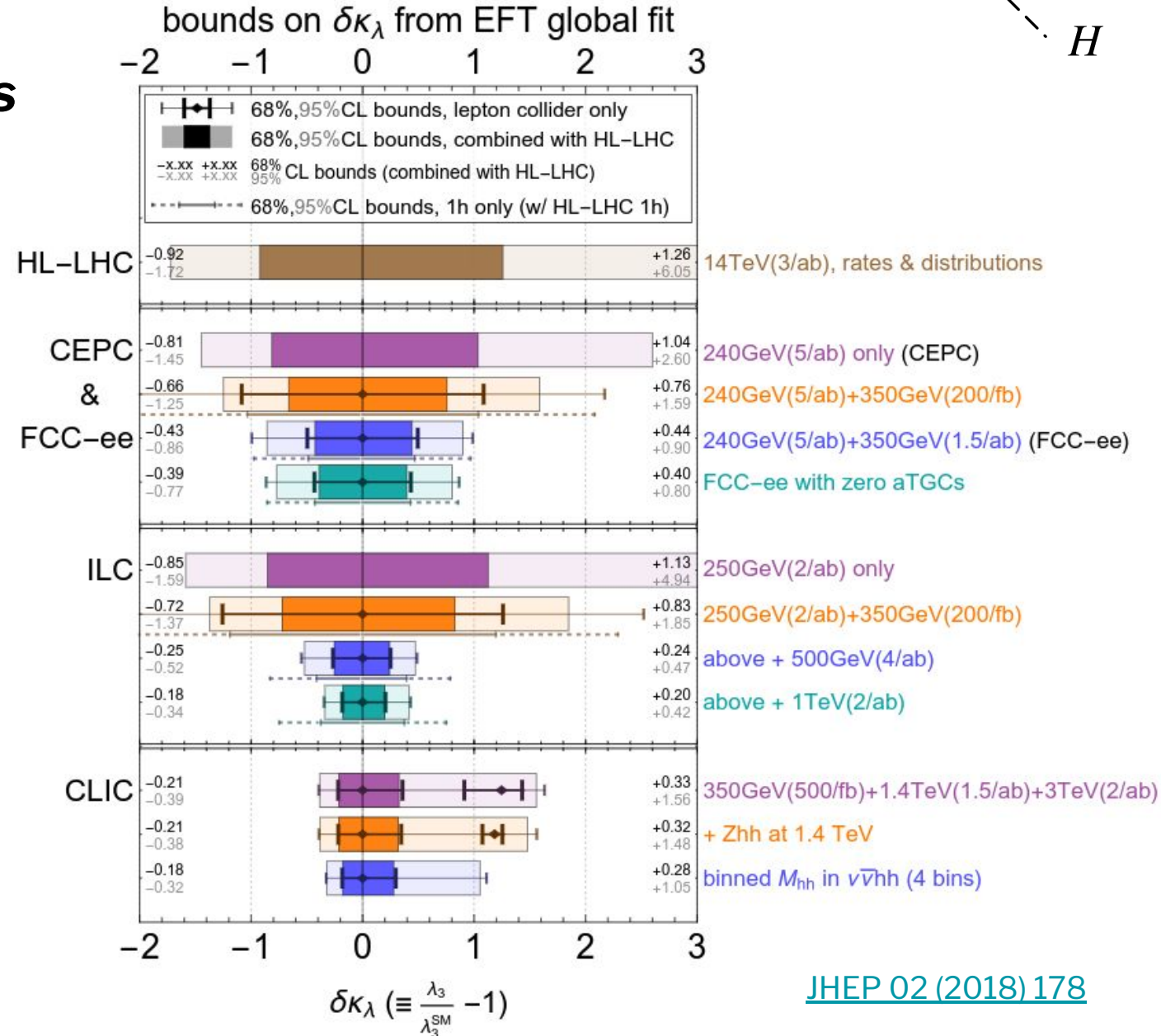
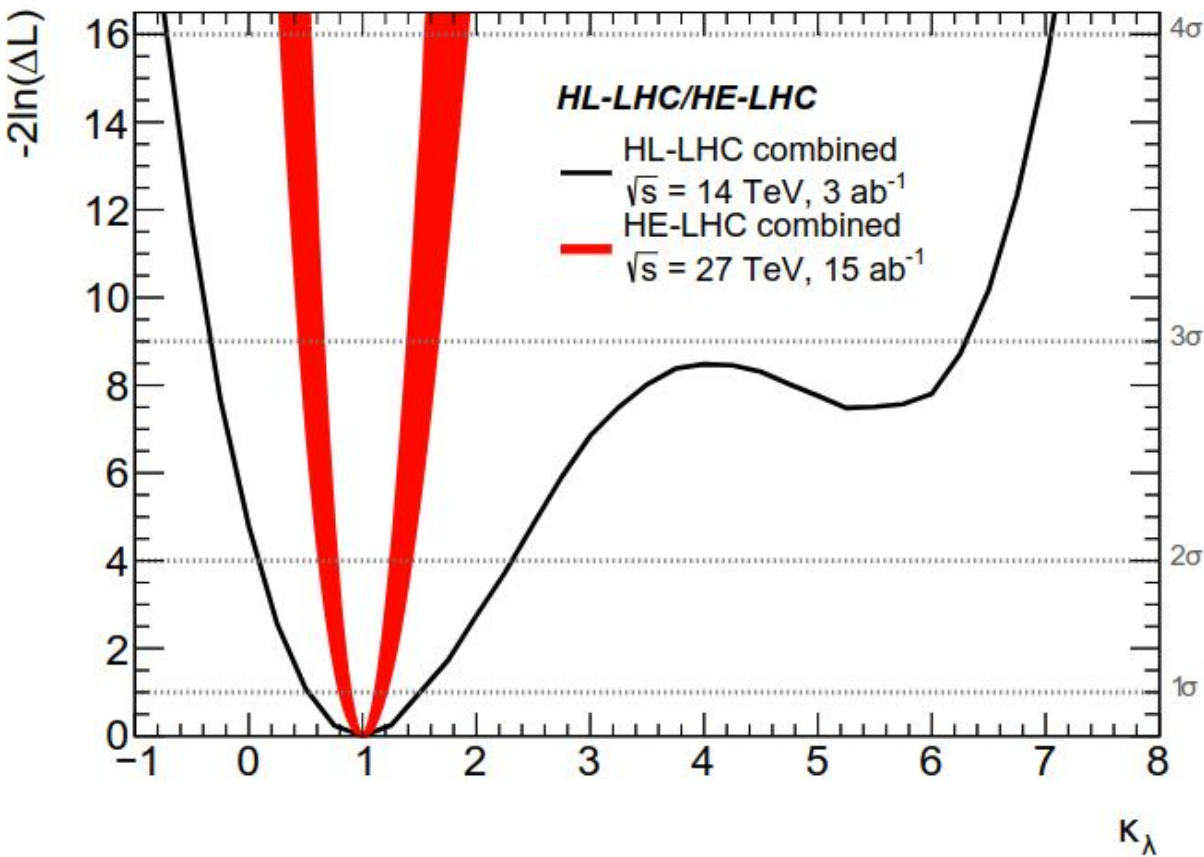
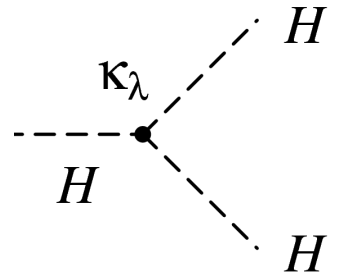


[ATLAS-CONF-2018-043](#)



Higgs Self-Coupling

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



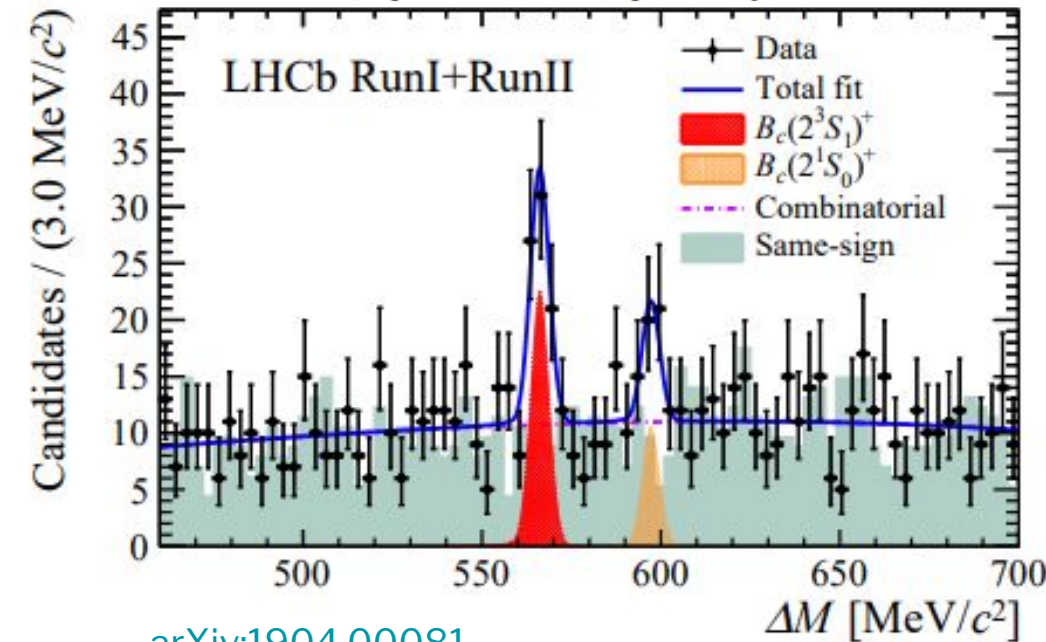
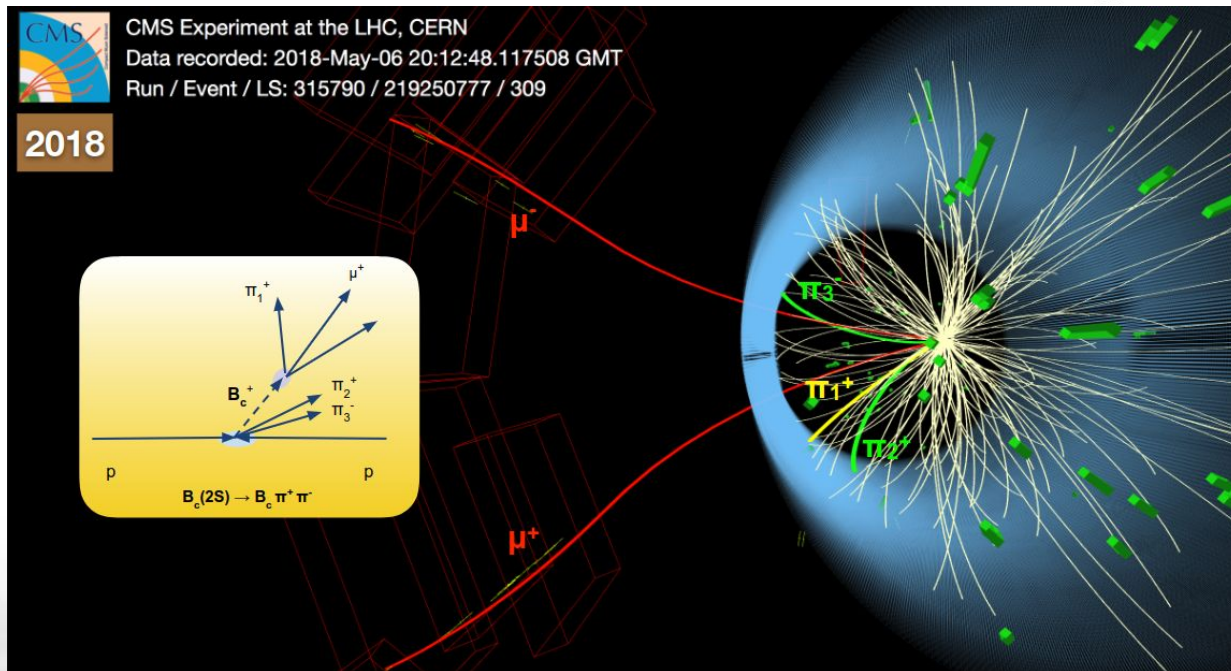
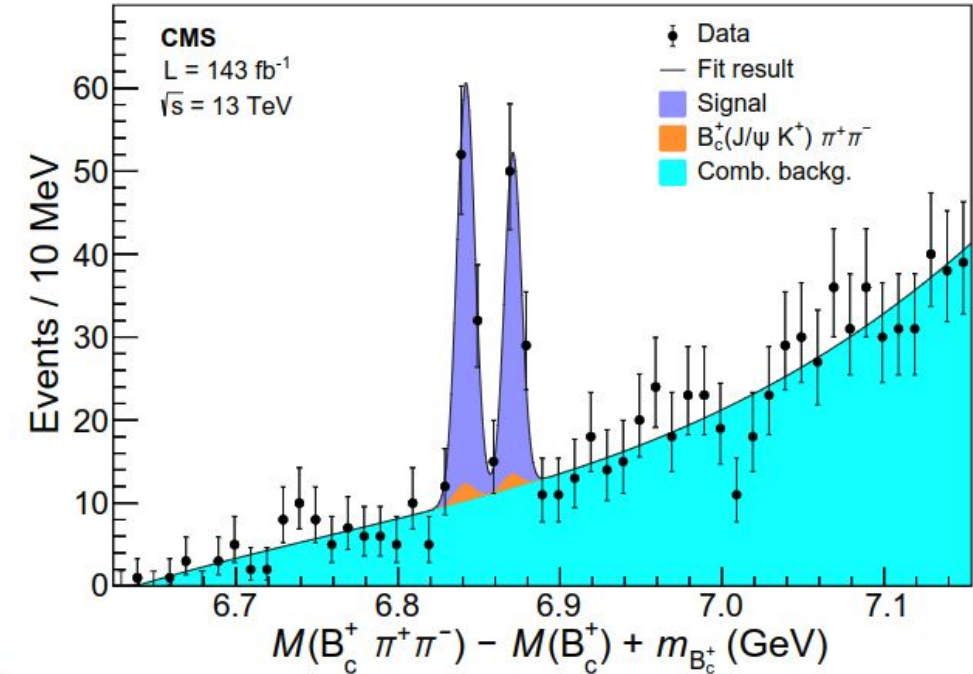
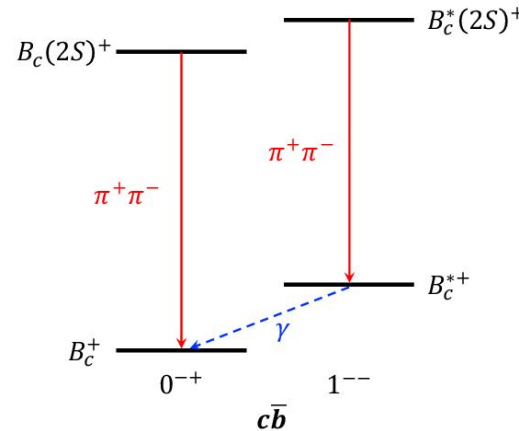
[JHEP 02 \(2018\) 178](#)

Hadronic Resonances

[arXiv:1902.00571](https://arxiv.org/abs/1902.00571)

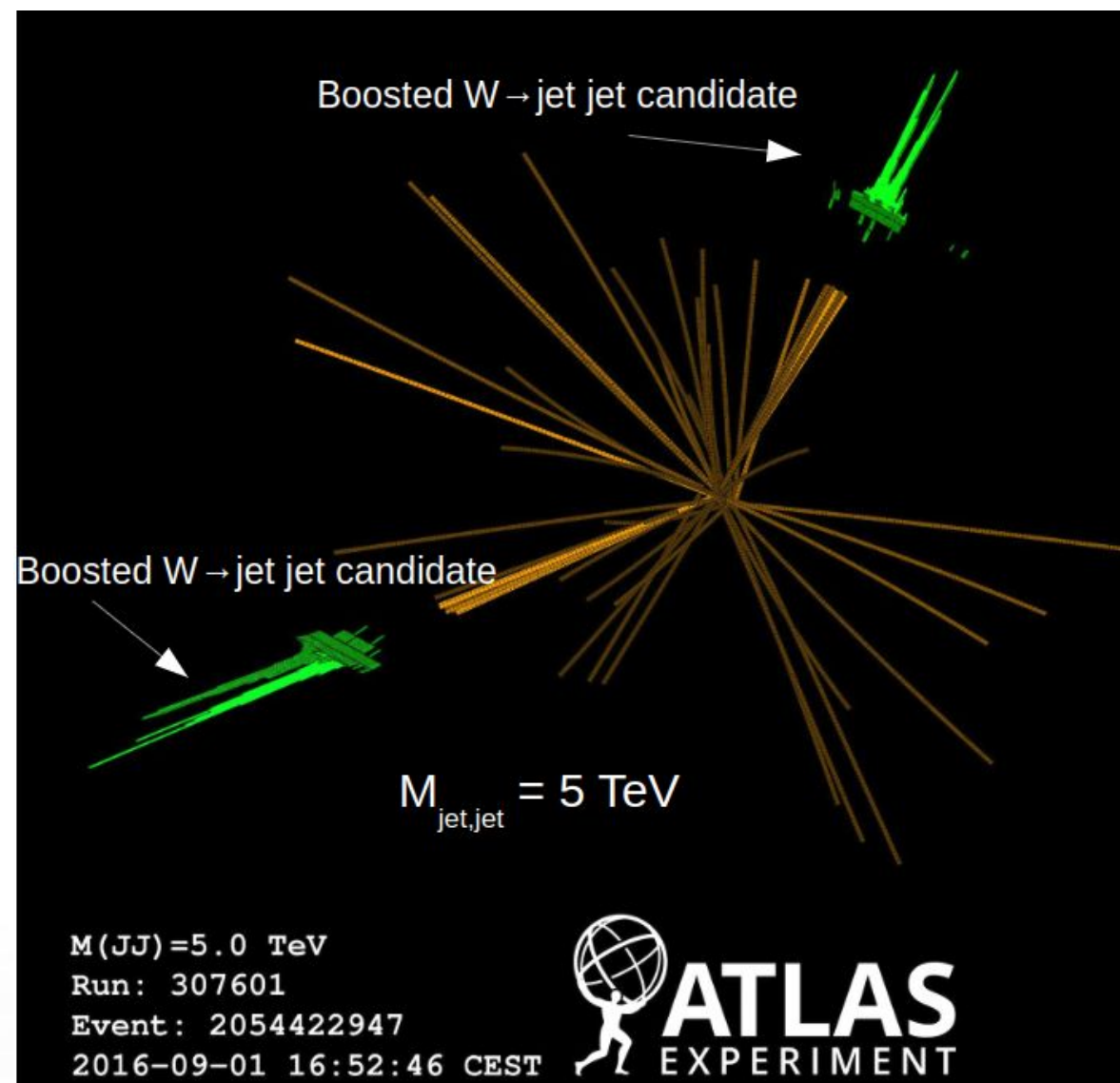
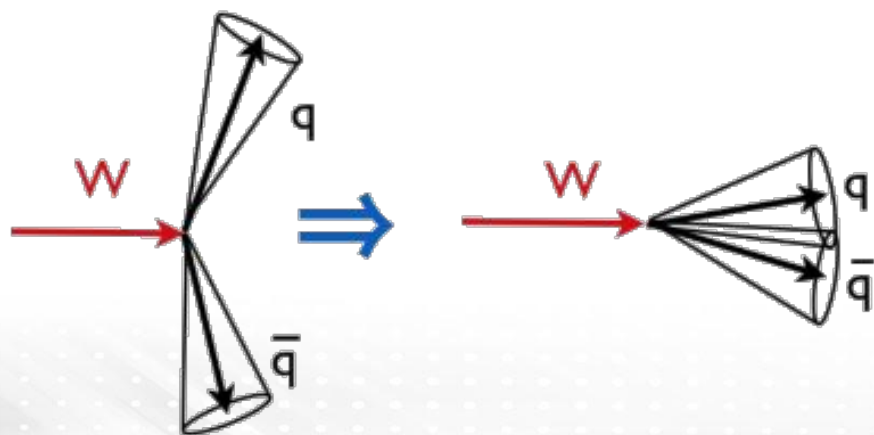
● Observation of resolved $B_c^+(2S)$ by CMS & LHCb

- $B_c(2S) \rightarrow B_c \pi^+ \pi^-$
- $B_c^*(2S) \rightarrow B_c^* \pi^+ \pi^- \rightarrow B_c \gamma \pi^+ \pi^-$
- wide peak first observed by ATLAS
[PRL 113 \(2014\) 212004](https://arxiv.org/abs/1404.2120)
- $\Delta M = 29.1 \pm 1.5 \pm 0.7$ MeV (CMS)



Bosonic Resonances

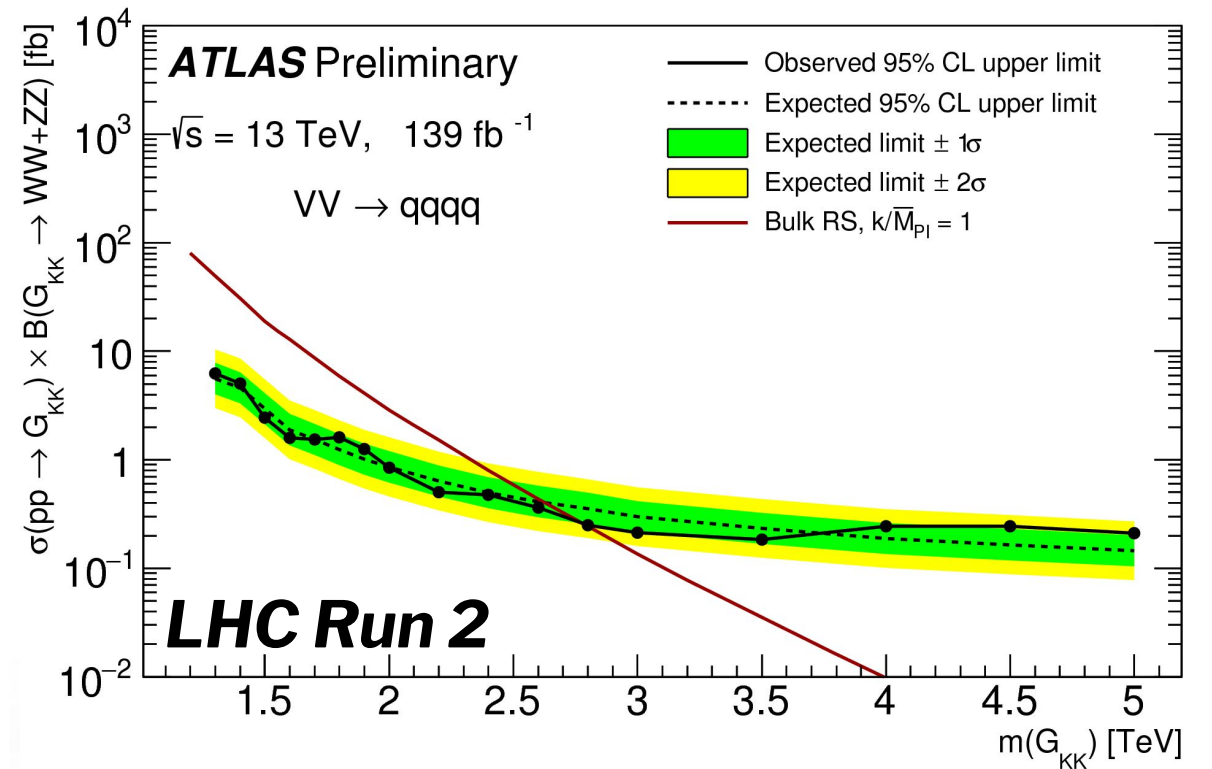
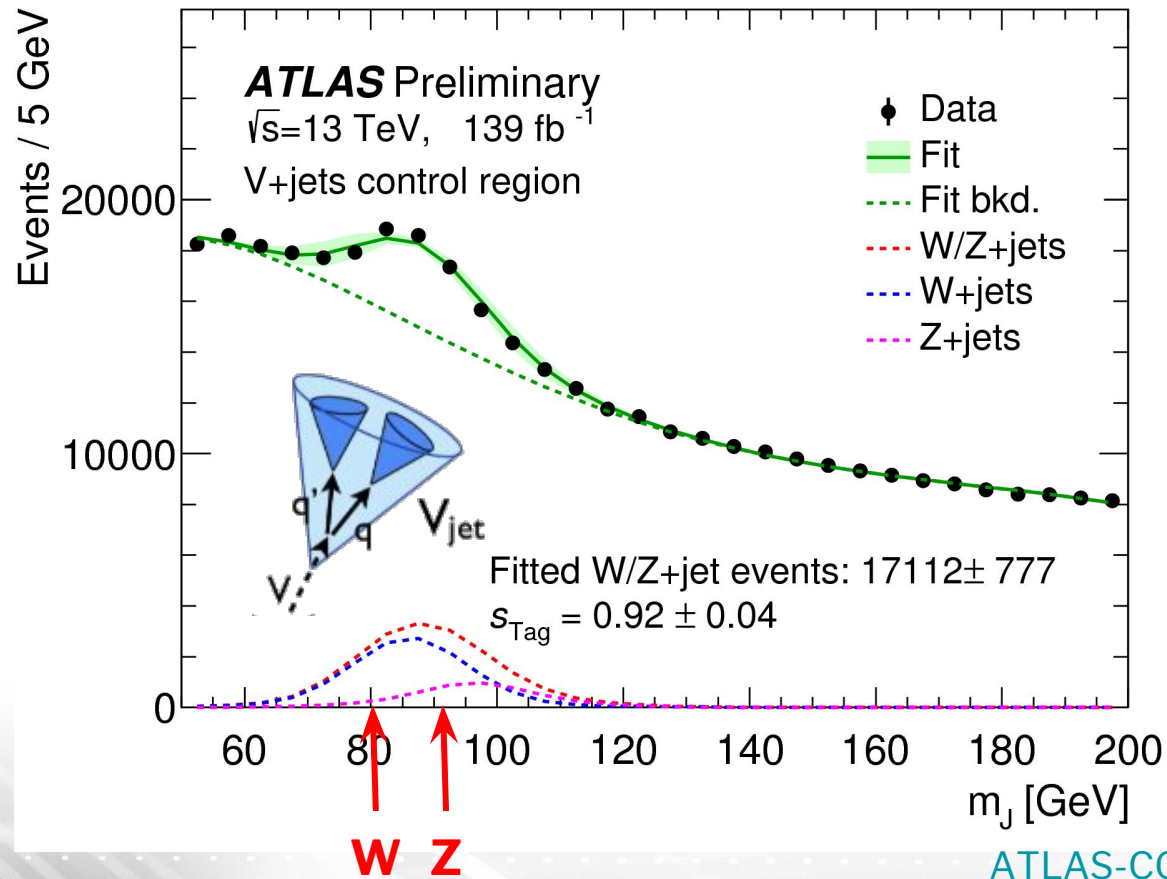
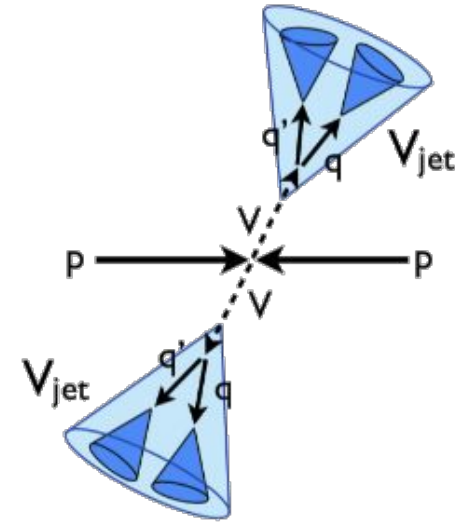
- **Fully reconstructed resonances are a useful way to discover new particles**
 - striking signatures → bump hunt
 - small systematics → robust
- **Search for very high-mass particles decaying into bosons**
 - **reconstruct very high- p_T W and Z bosons as large-radius jets**
 - required development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



Bosonic Resonances

- **Search for very high-mass particles decaying into bosons**

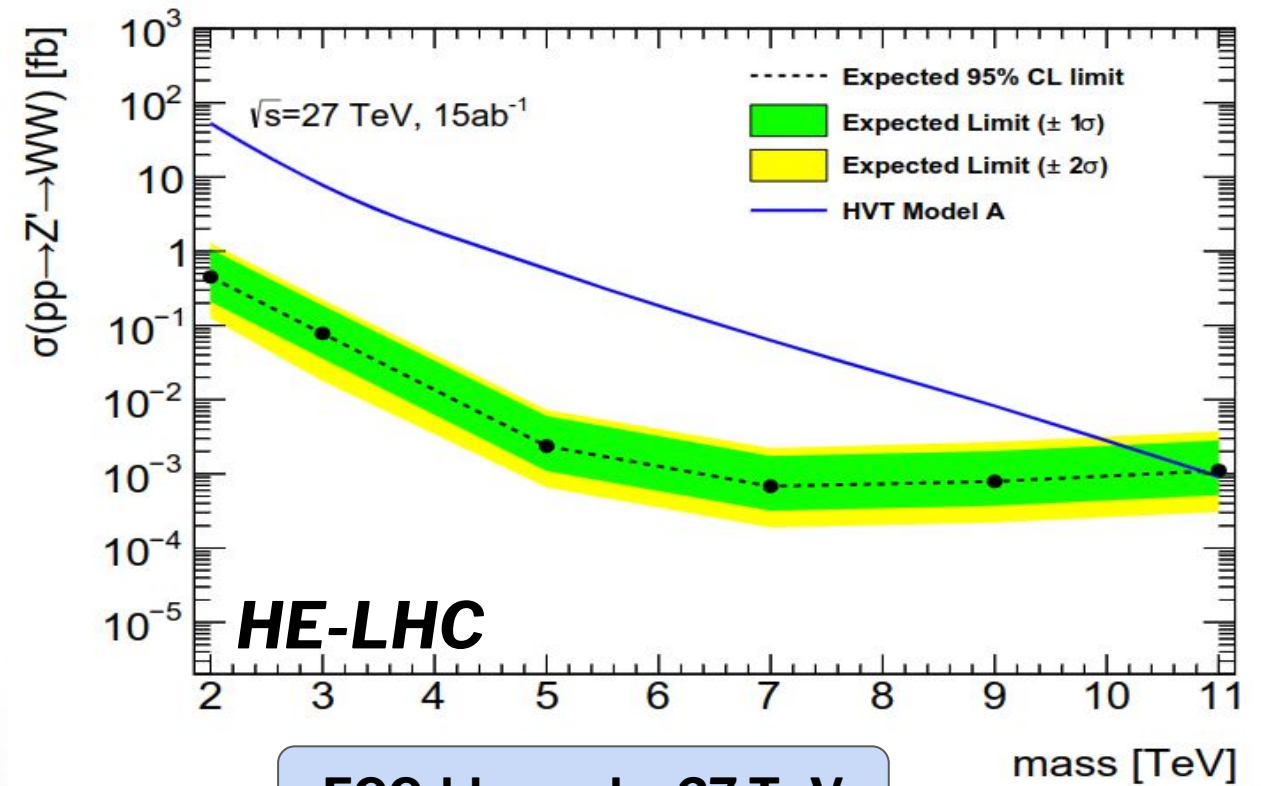
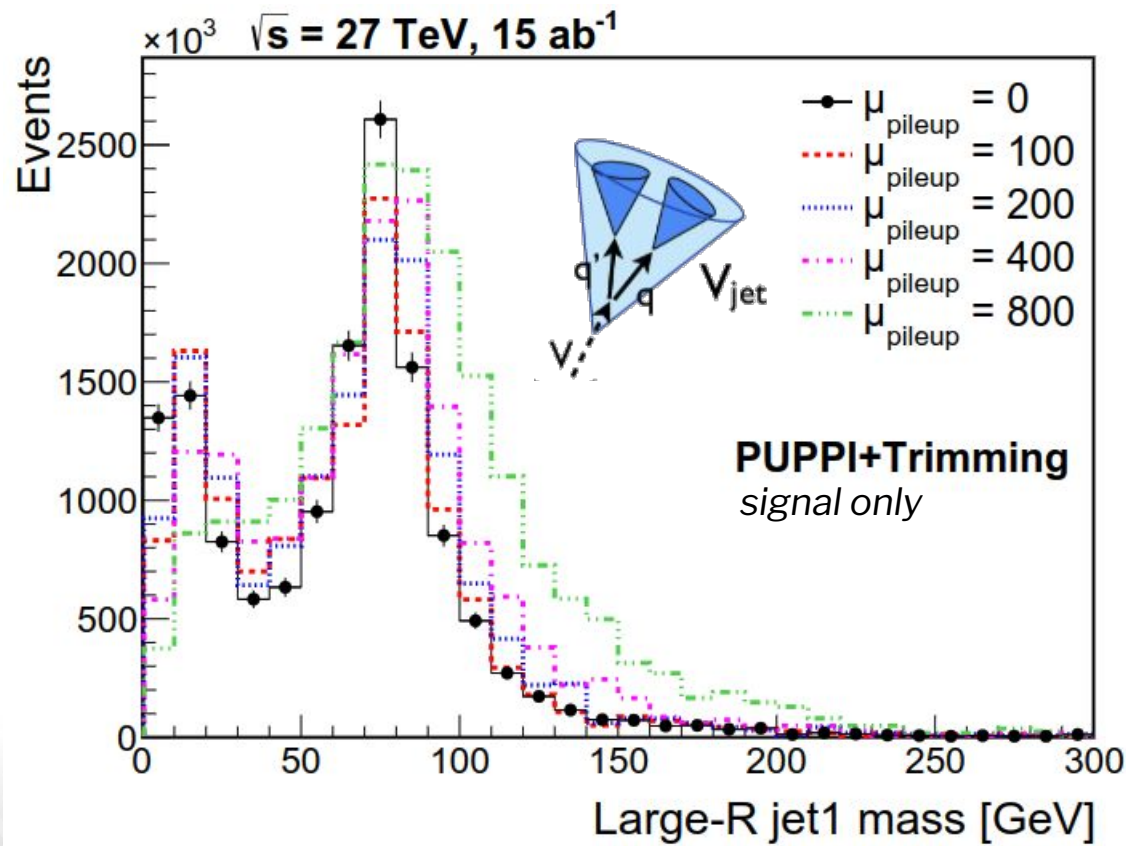
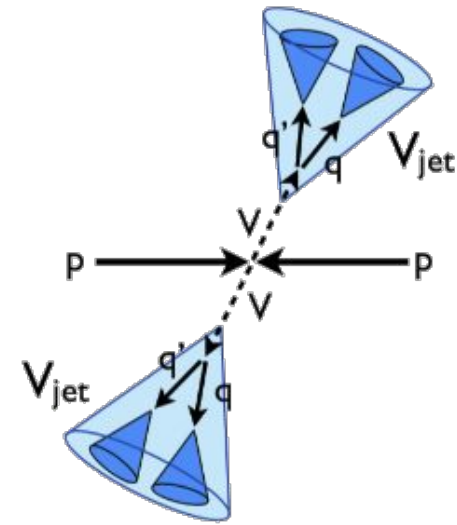
- initiated on ATLAS by Tokyo and BNL
- reconstruct very high- p_T W and Z bosons as large-radius jets



Bosonic Resonances

- **Search for very high-mass particles decaying into bosons**

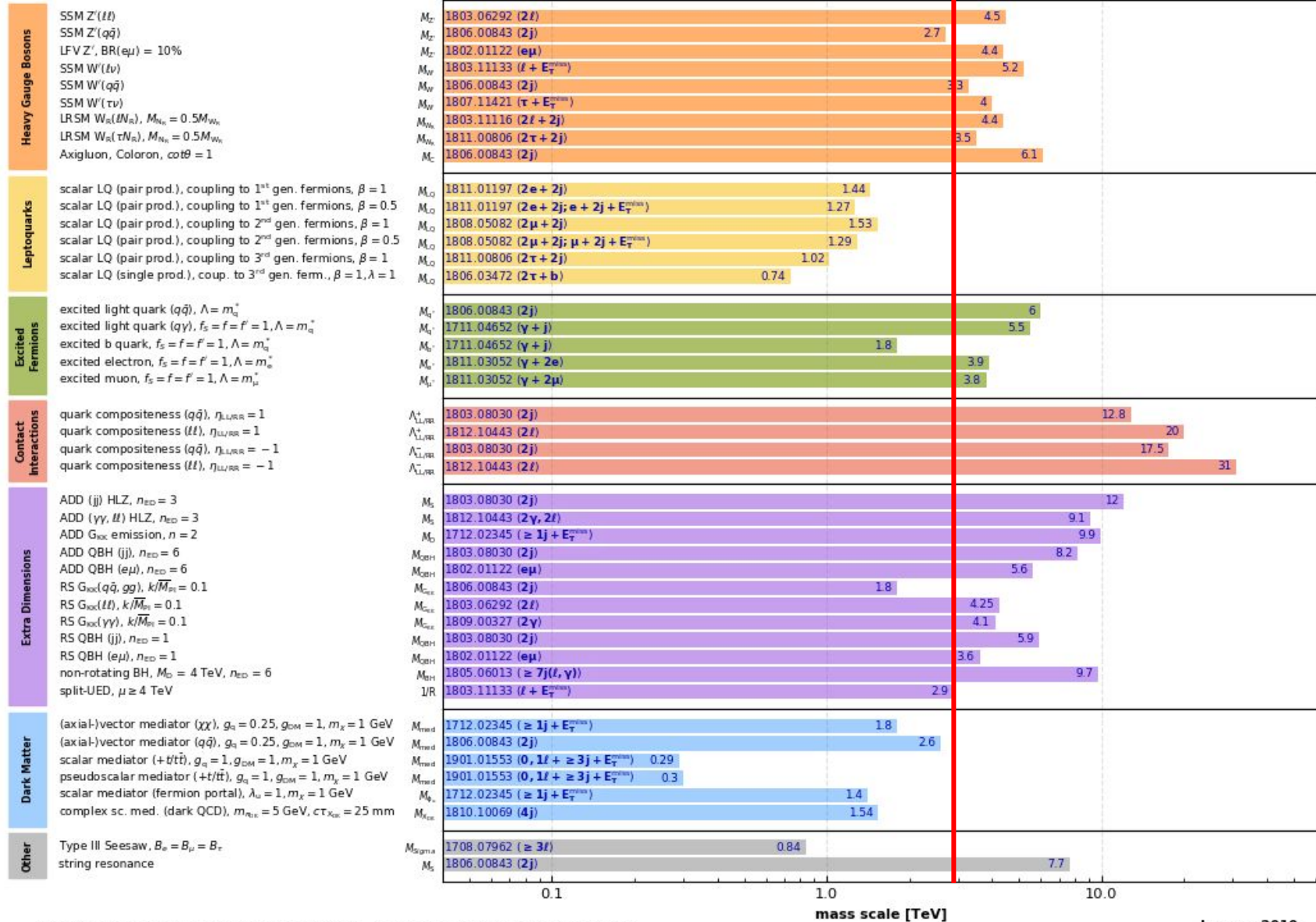
- initiated on ATLAS by Tokyo and BNL
- **prospect at HE-LHC → European Strategy**
- new techniques to accommodate additional factor of 30 pileup



Summary of LHC Searches

Overview of CMS EXO results

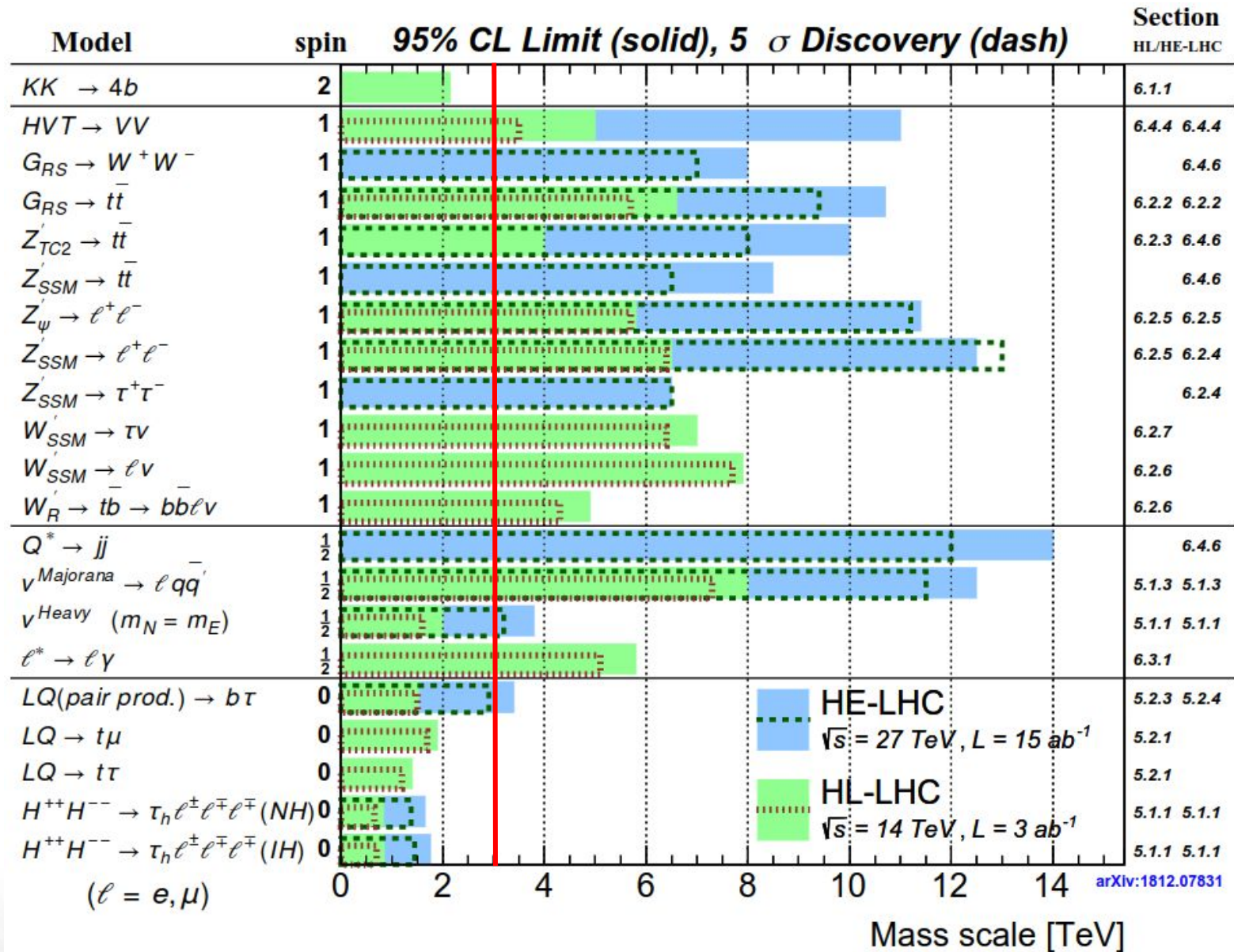
36 fb⁻¹ (13 TeV)



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

January 2019

Expected Reach of HL-LHC & HE-LHC



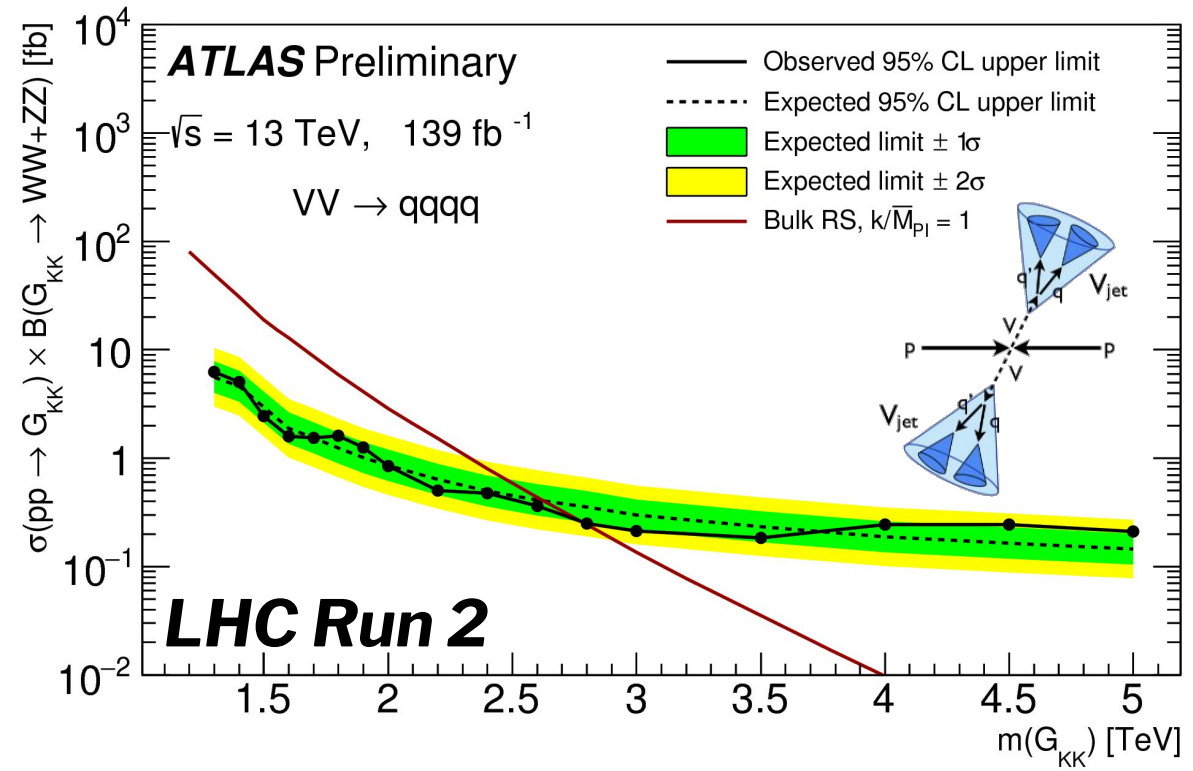
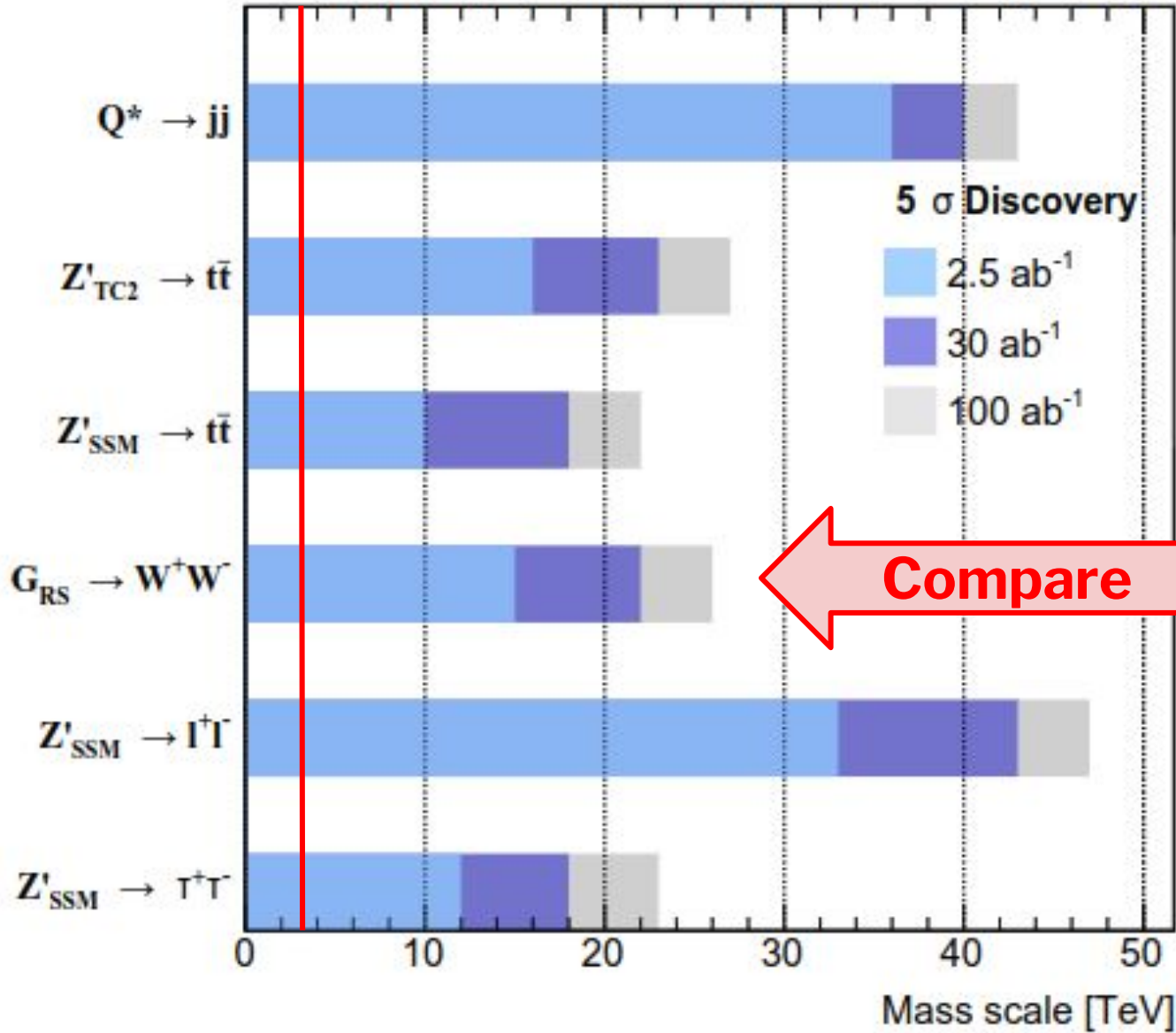
[arxiv:1812.07831](https://arxiv.org/abs/1812.07831)

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

Michael Biegel April 16, 2019

Expected Reach of FCC-hh

FCC-hh Simulation (Delphes), $\sqrt{s} = 100$ TeV



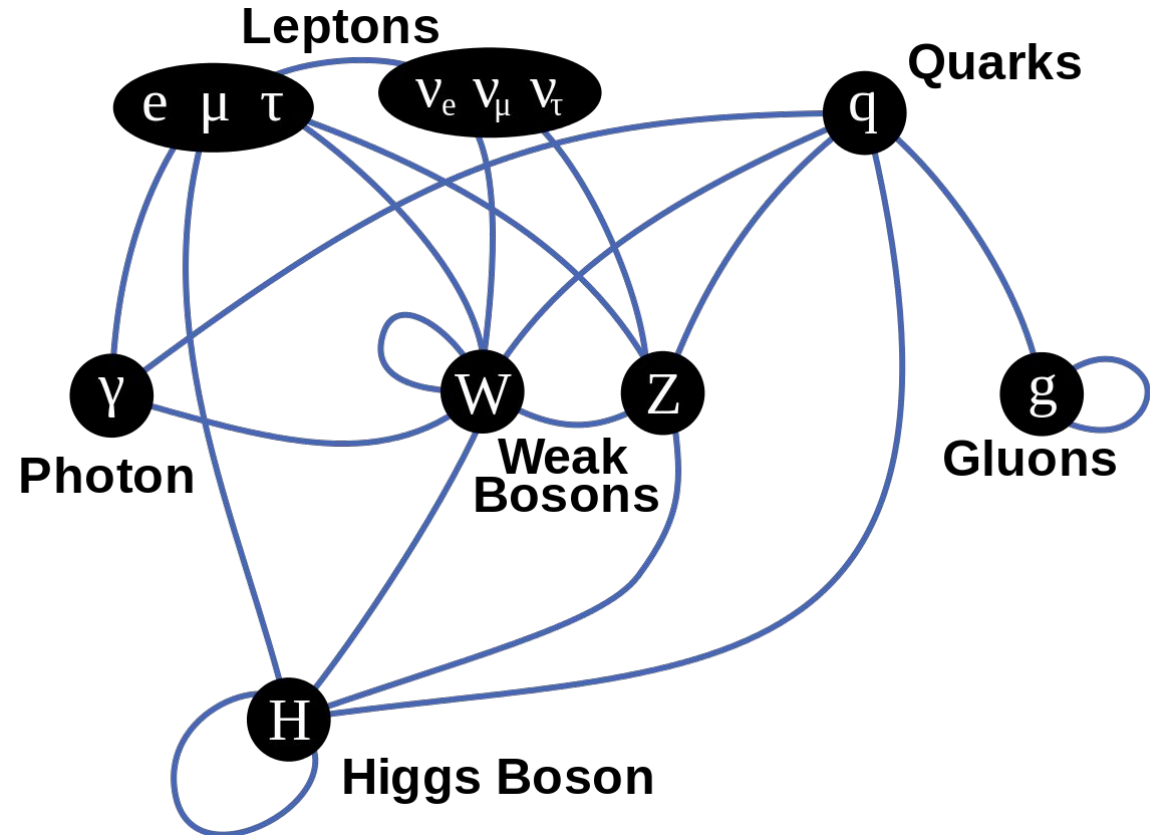
Summary

- **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

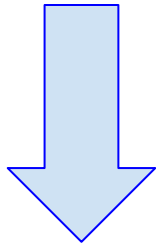
	three generations of matter (fermions)			interactions / force carriers (bosons)	
	I	II	III		
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0	$\approx 124.97 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
QUARKS	u up	c charm	t top	g gluon	H higgs
	$\approx 4.7 \text{ MeV}/c^2$	$\approx 96 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	d down	s strange	b bottom	γ photon	
	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$	$\approx 91.19 \text{ GeV}/c^2$	
	-1	-1	-1	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
LEPTONS	e electron	μ muon	τ tau	Z Z boson	
	$< 2.2 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$	$\approx 80.39 \text{ GeV}/c^2$	
	0	0	0	± 1	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	



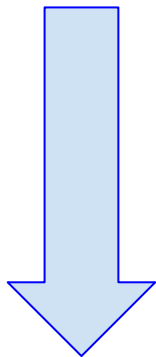
- **over a century in the making**
- **very successful but incomplete**
 - neutrino mass
 - dark matter
 - gravity & dark energy

Standard Model

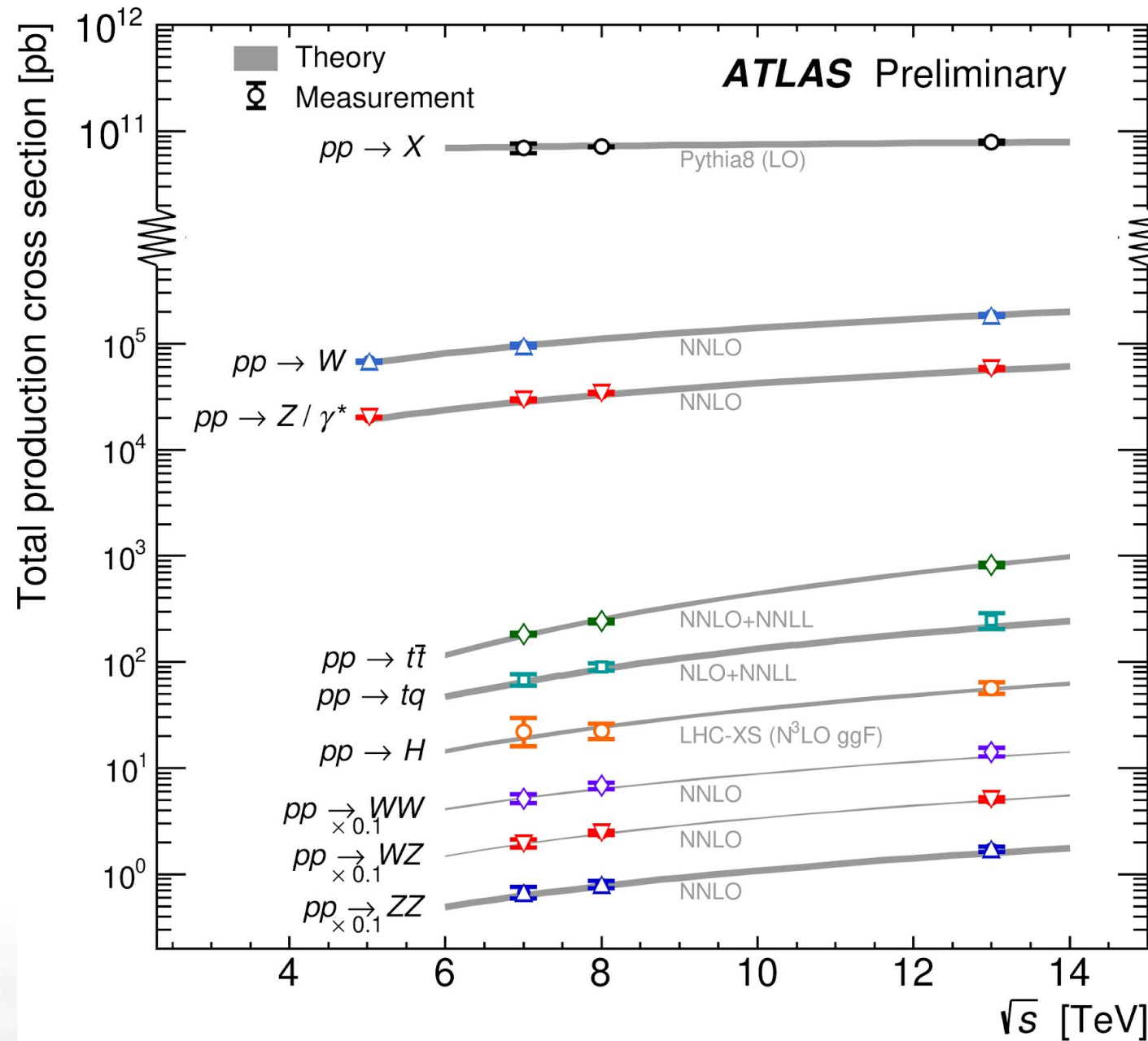
pp cross section



W & Z bosons



rare processes
(very interesting!)

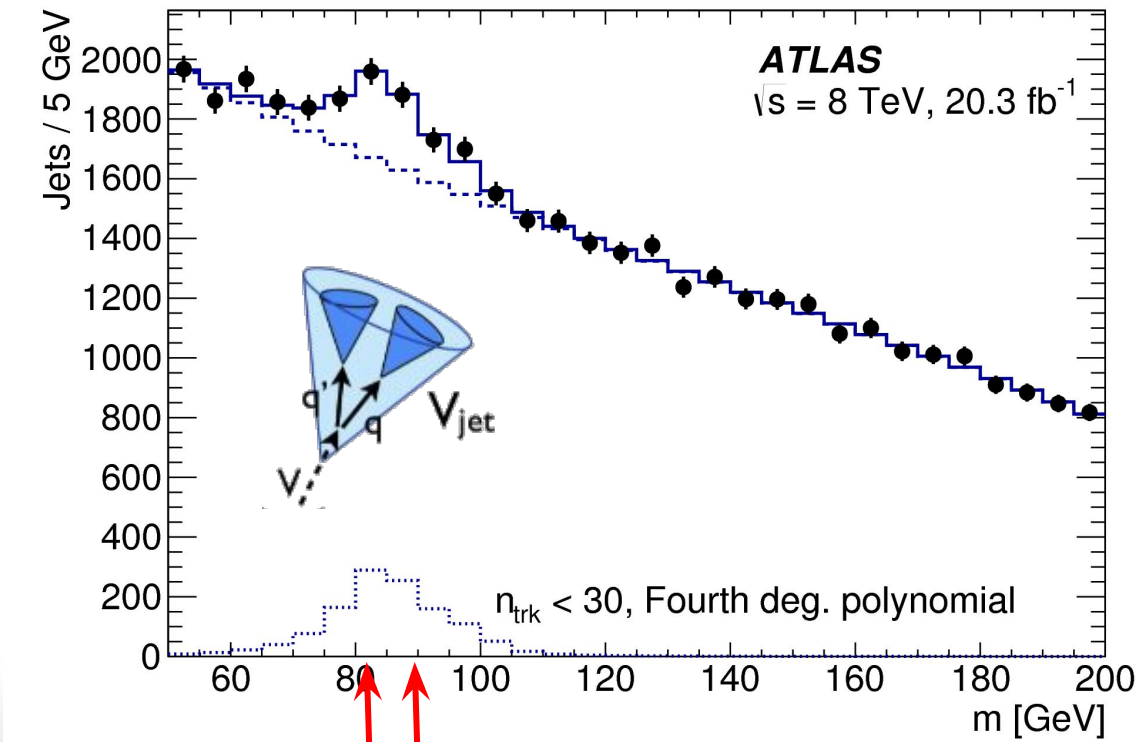
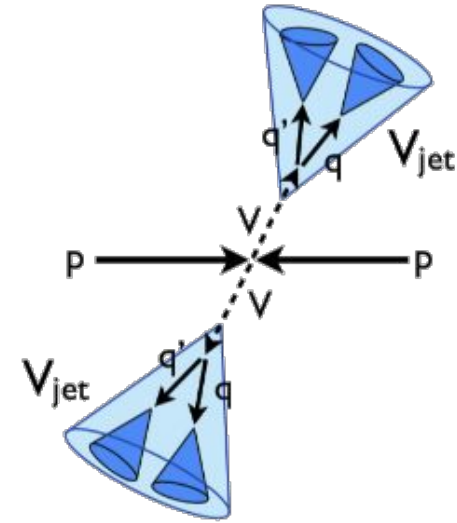


- \square $pp \rightarrow X$
 7 TeV, 20 μb^{-1} , Nat. Commun. 2, 463 (2011)
 8 TeV, 500 μb^{-1} , Phys.Lett. B761 158 (2016)
 13 TeV, 60 μb^{-1} , Phys. Rev. Lett. 117 182002 (2016)
- \triangle $pp \rightarrow W$ ∇ $pp \rightarrow Z / \gamma^*$
 5 TeV, 25 pb^{-1} , Eur. Phys. J. C79 (2019) 128 (for 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)
- \diamond $pp \rightarrow t\bar{t}$
 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)
- \square $pp \rightarrow tq$
 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
- \square $pp \rightarrow H$
 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
- \square $pp \rightarrow WW$
 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
- ∇ $pp \rightarrow WZ$
 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
- \triangle $pp \rightarrow ZZ$
 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

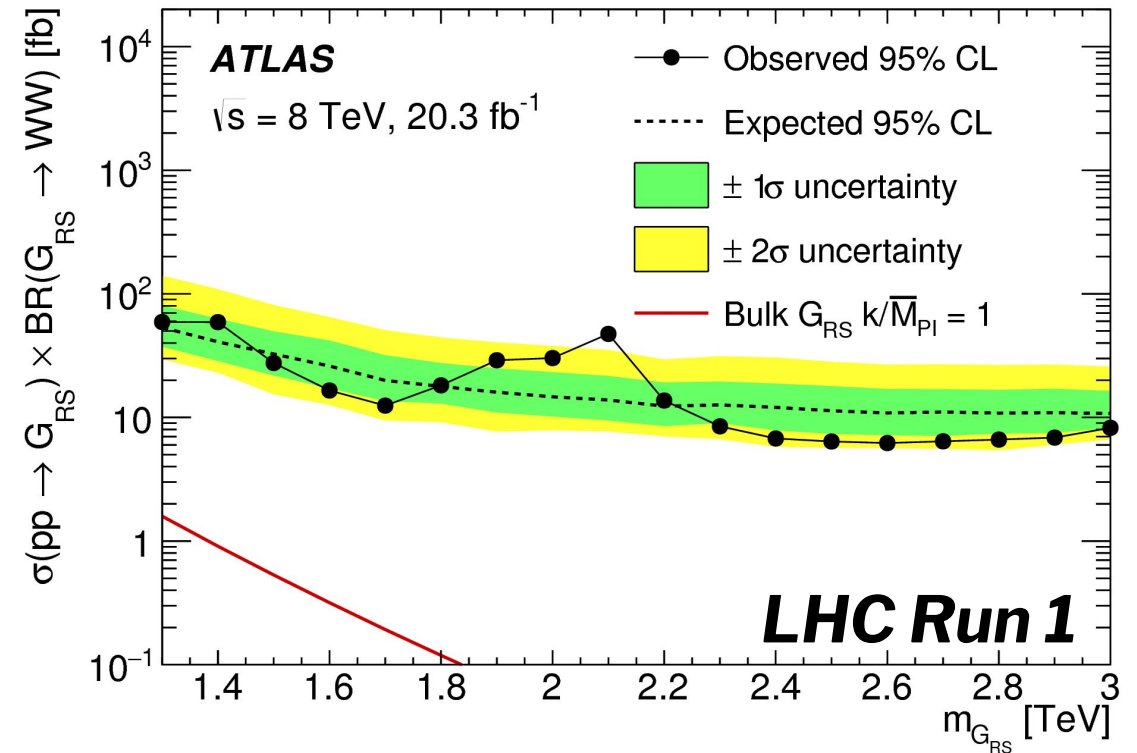
Diboson Resonance Search

- **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

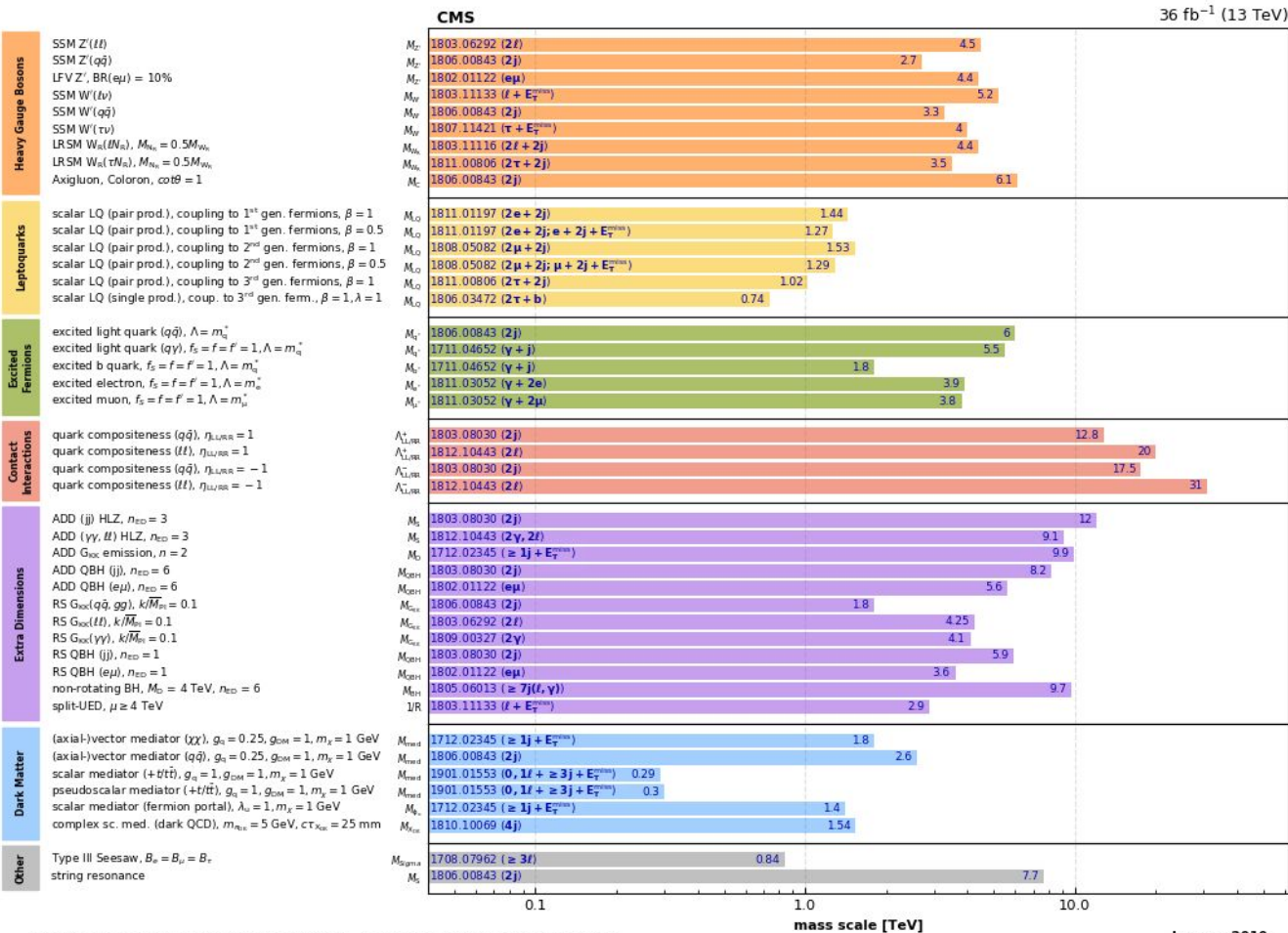


WZ



Today's New Physics Reach

Overview of CMS EXO results



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

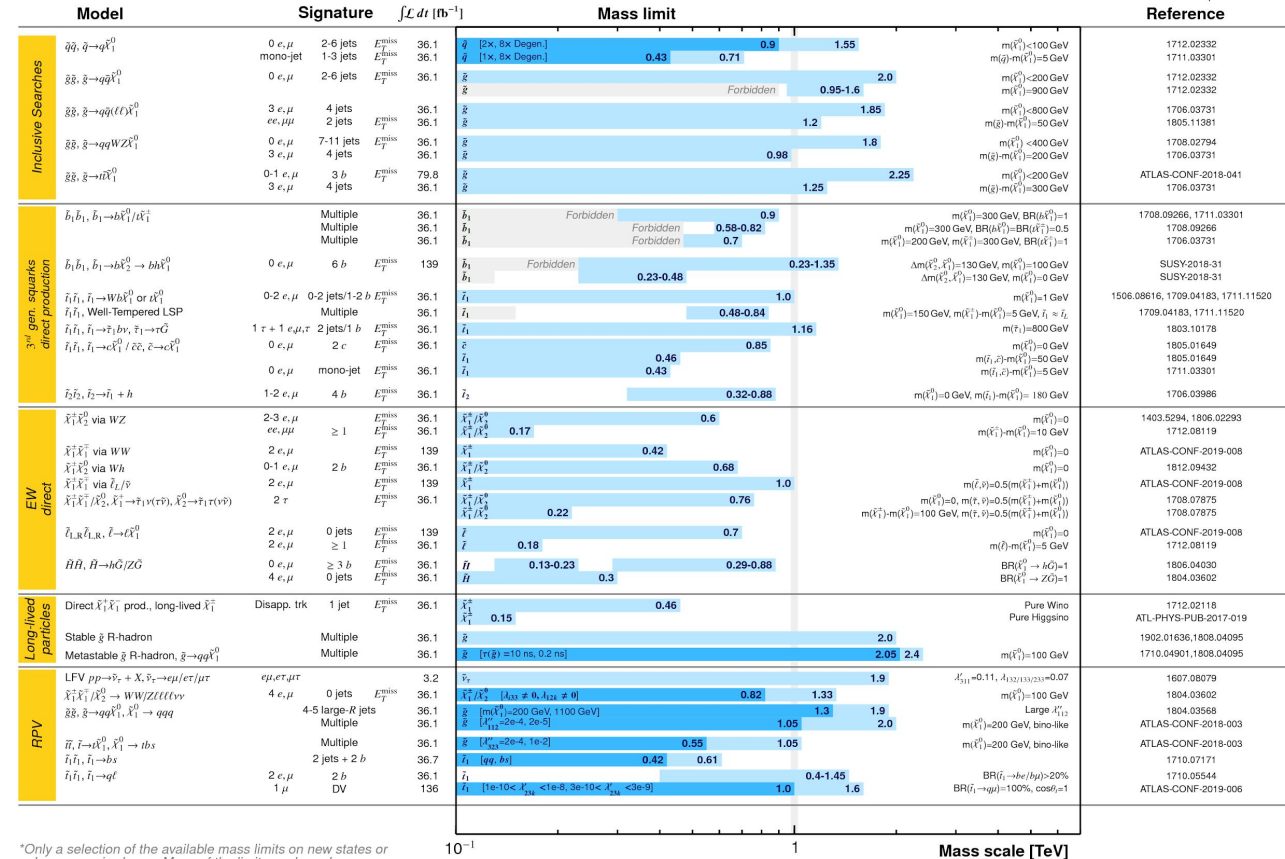
January 2019

ATLAS SUSY Searches* - 95% CL Lower Limits

March 2019

ATLAS Preliminary

√s = 13 TeV



*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Future New Physics Reach

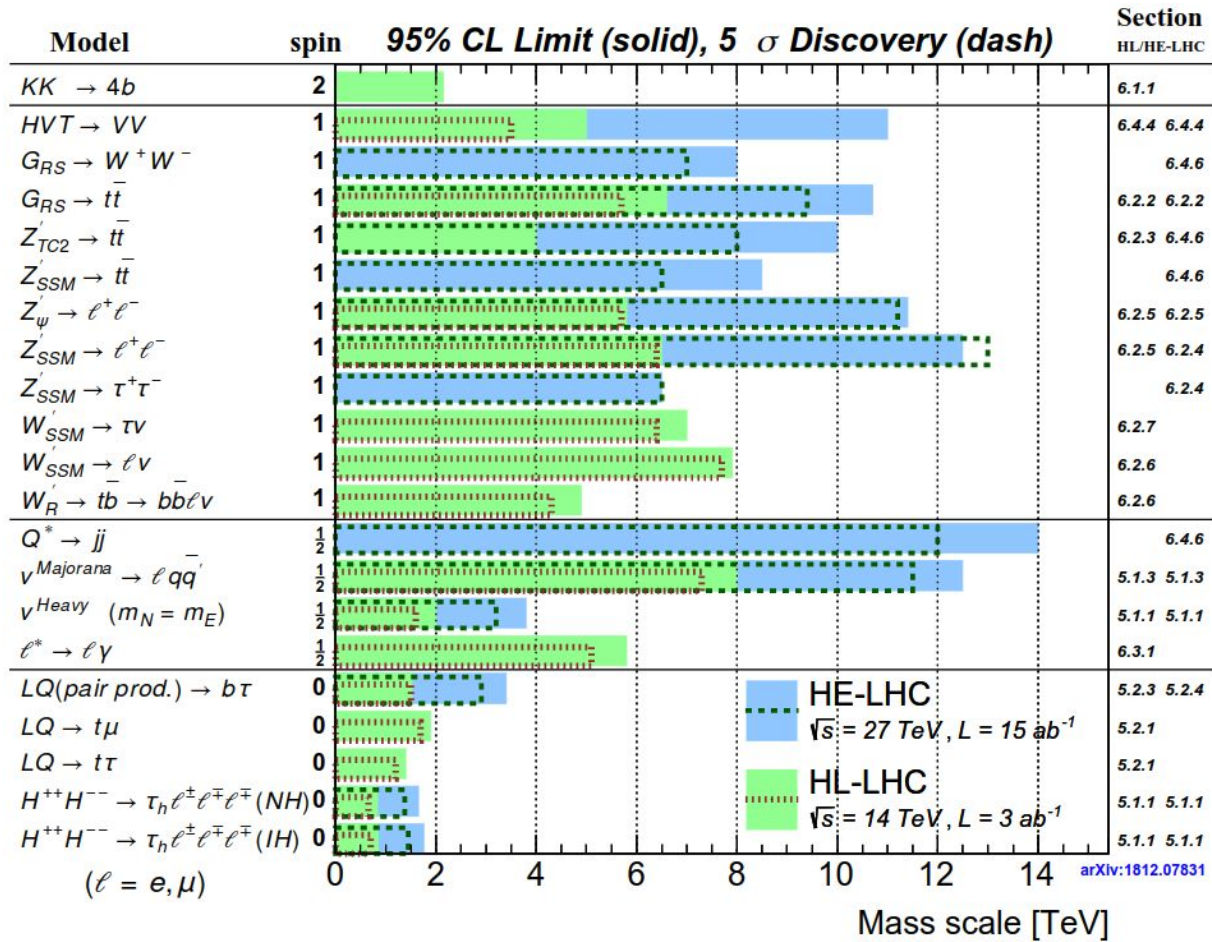


Fig. 7.2: A summary of the expected mass reach for 5 σ discovery and 95% C.L. exclusion at the HL/HE-LHC, as presented in Sections 5 and 6.

HL/HE-LHC SUSY Searches

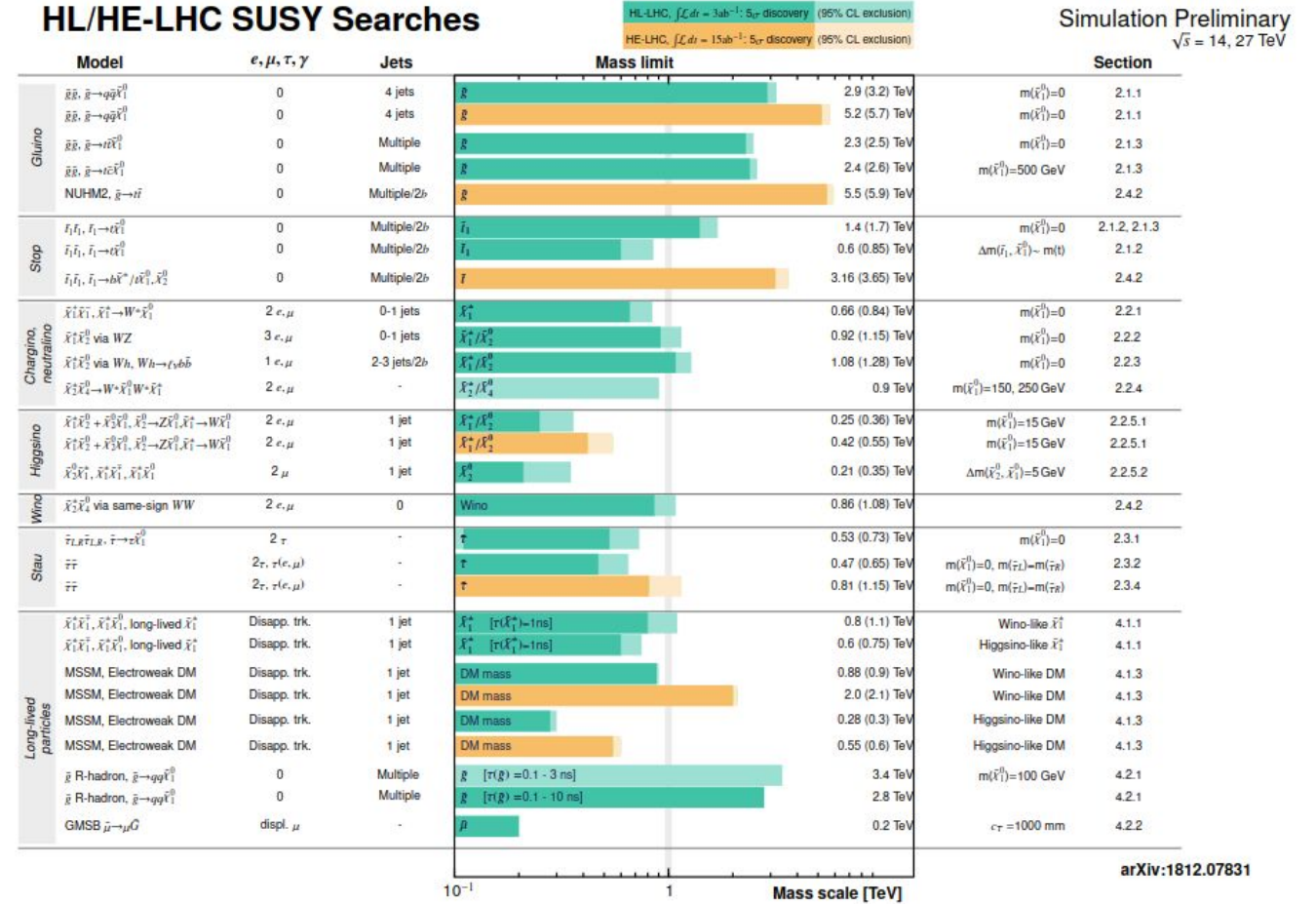


Fig. 7.1: A summary of the expected mass reach for 5 σ discovery and 95% C.L. exclusion at the HL/HE-LHC, as presented in Section 2.

arxiv:1812.07831