Prospects: LHC in Run 3 and the HL-LHC

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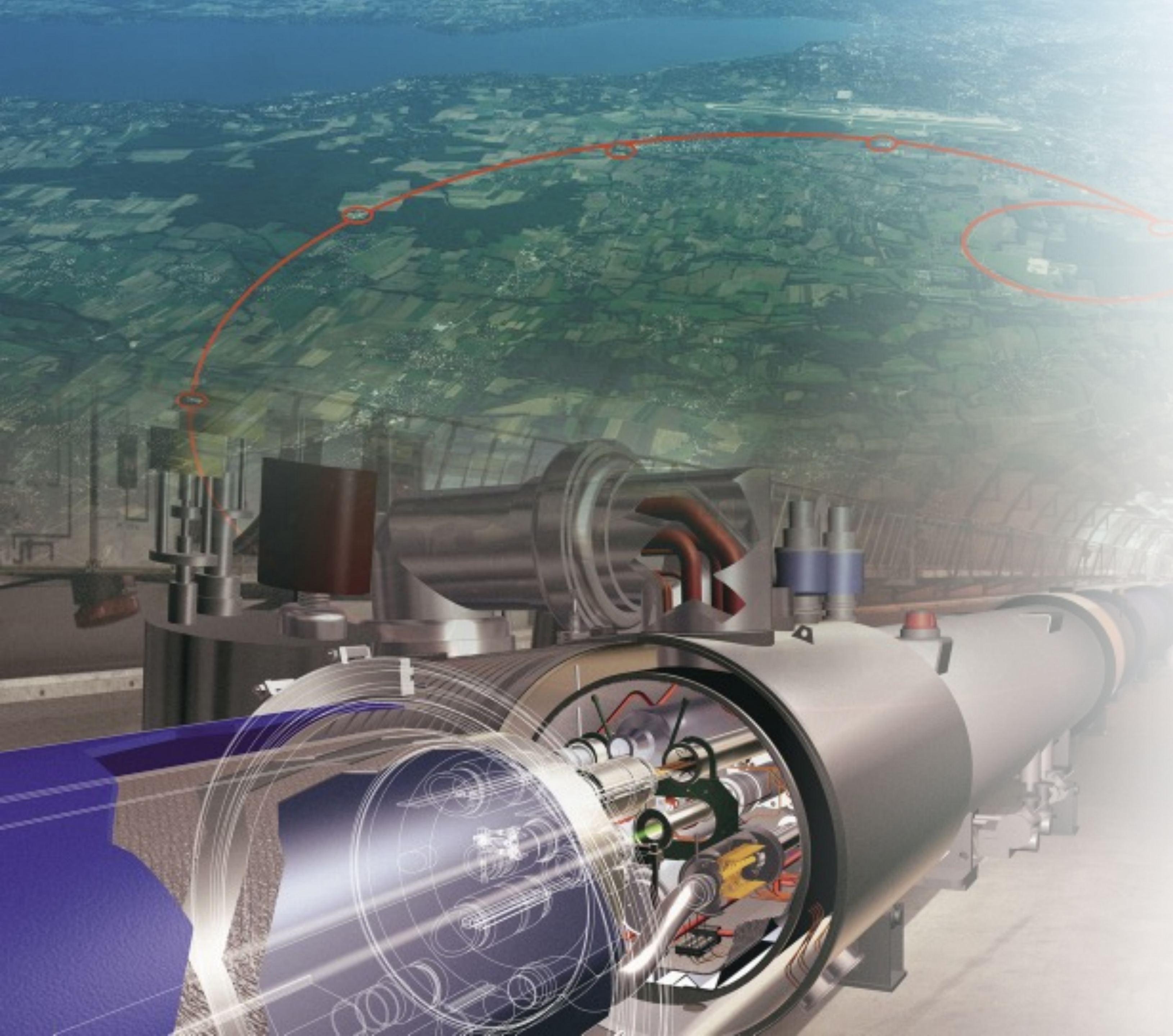
2022 ASIA EUROPE PACIFIC SCHOOL OF HIGH-ENERGY PHYSICS



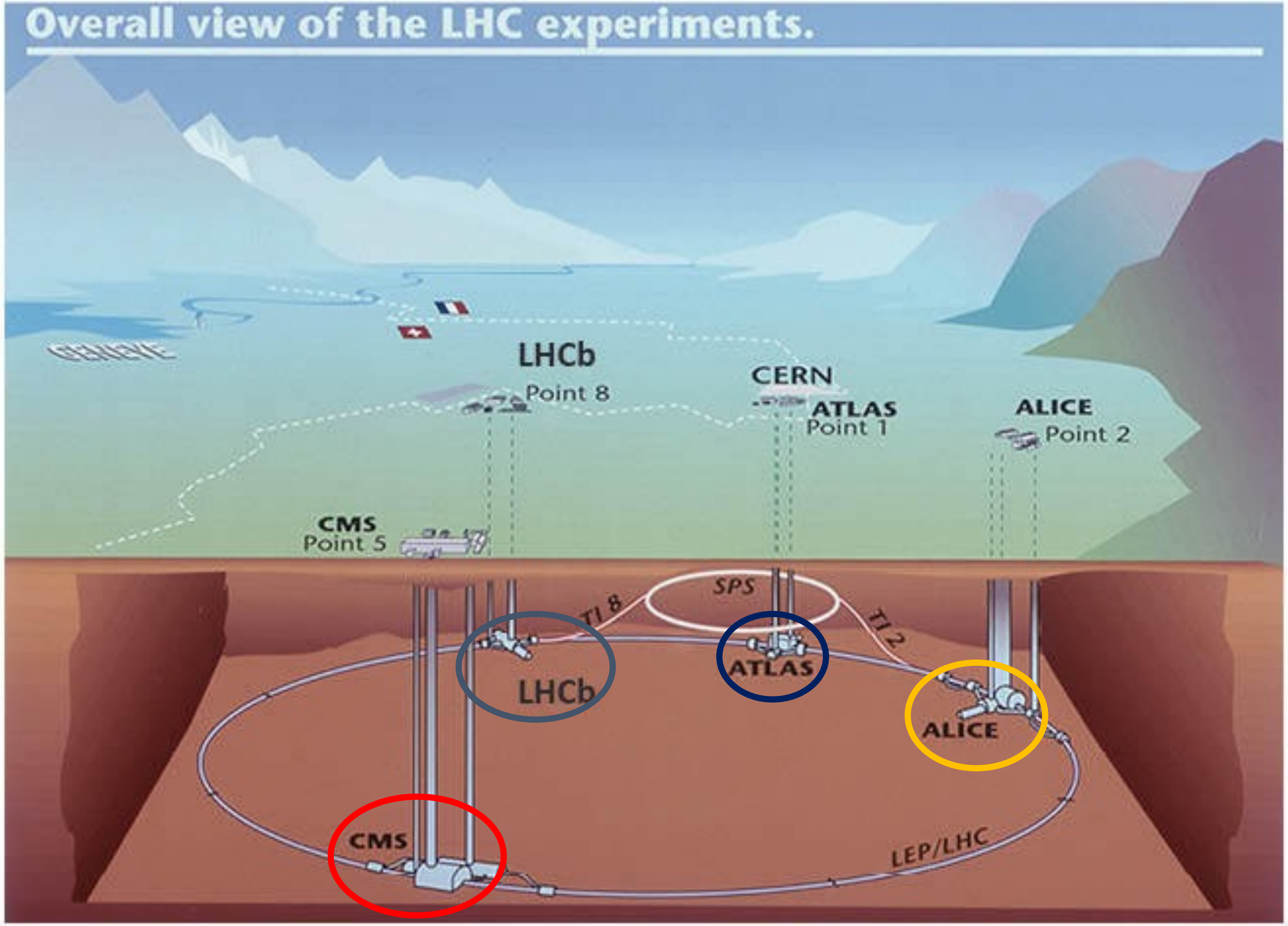
Outline

- Introduction
- Perspectives
  - Energy
  - Luminosity
  - Technology
  - Techniques
- Run 3
- High-Luminosity LHC (HL-LHC)

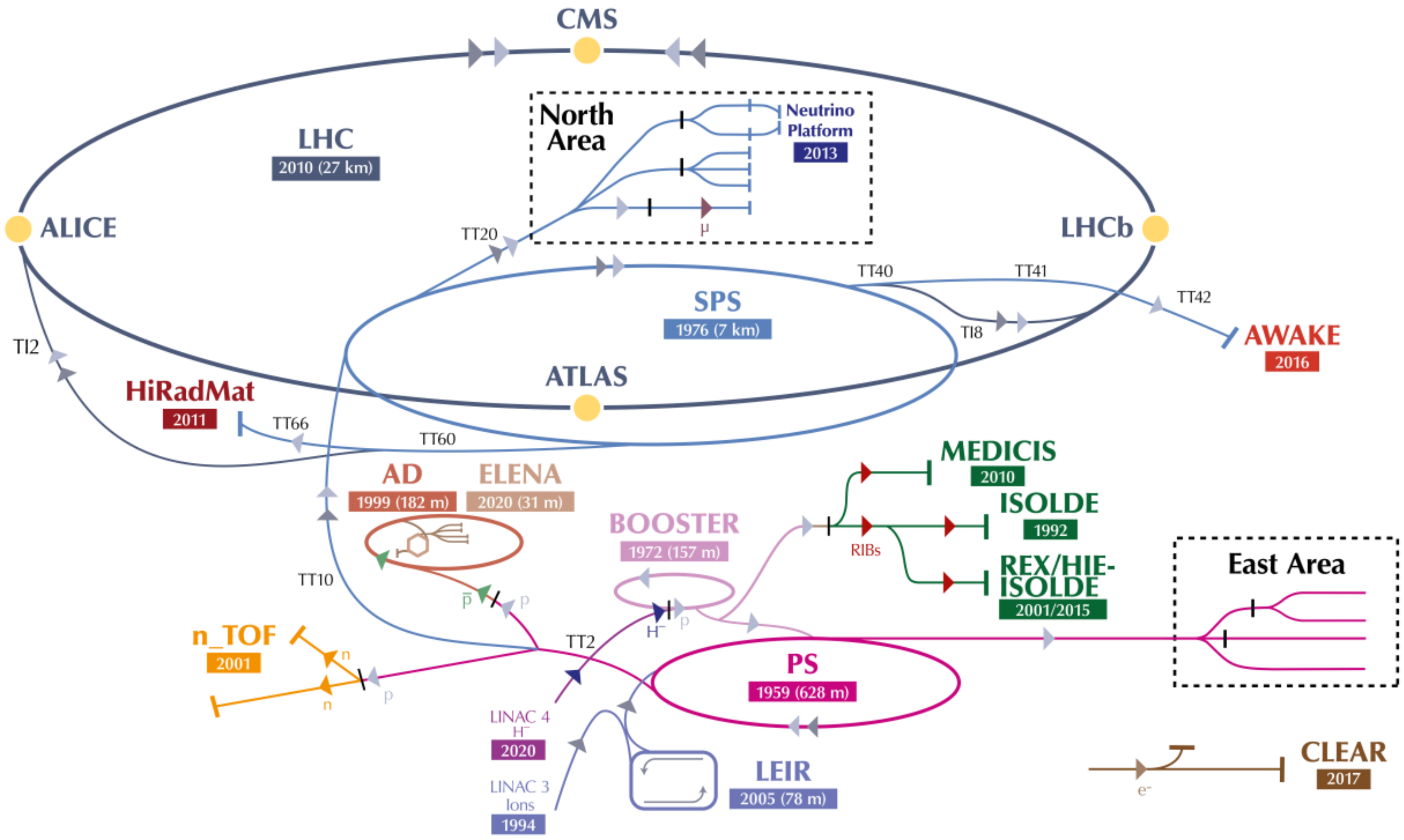
Motivation

- You’ve heard over the past week about the
  - Impressive performance of the standard model (SM), and what it lacks
  - Status of SM measurements
    - most are in line with predictions. We have a few several-sigma discrepancies that need to be chased down, particularly in flavor physics, but no ”smoking gun”
  - The need to improve the precision of our measurements of the Higgs boson
  - Motivation for extending searches for BSM to higher-mass particles and lower cross-section processes
- We need to fully exploit the Run 3 and HL-LHC datasets, and provide direction for our field’s next step

I'll focus primarily on **ATLAS** and **CMS**, but say a few words about **ALICE** and **LHCb**



The CERN accelerator complex
Complexe des accélérateurs du CERN



▶ H^- (hydrogen anions) ▶ p (protons) ▶ ions ▶ RIBs (Radioactive Ion Beams) ▶ n (neutrons) ▶ $\bar{p}$ (antiprotons) ▶ e^- (electrons) ▶ μ (muons)

LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE-ISOLDE - Radioactive EXperiment/High Intensity and Energy ISOLDE // MEDICIS // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials // Neutrino Platform

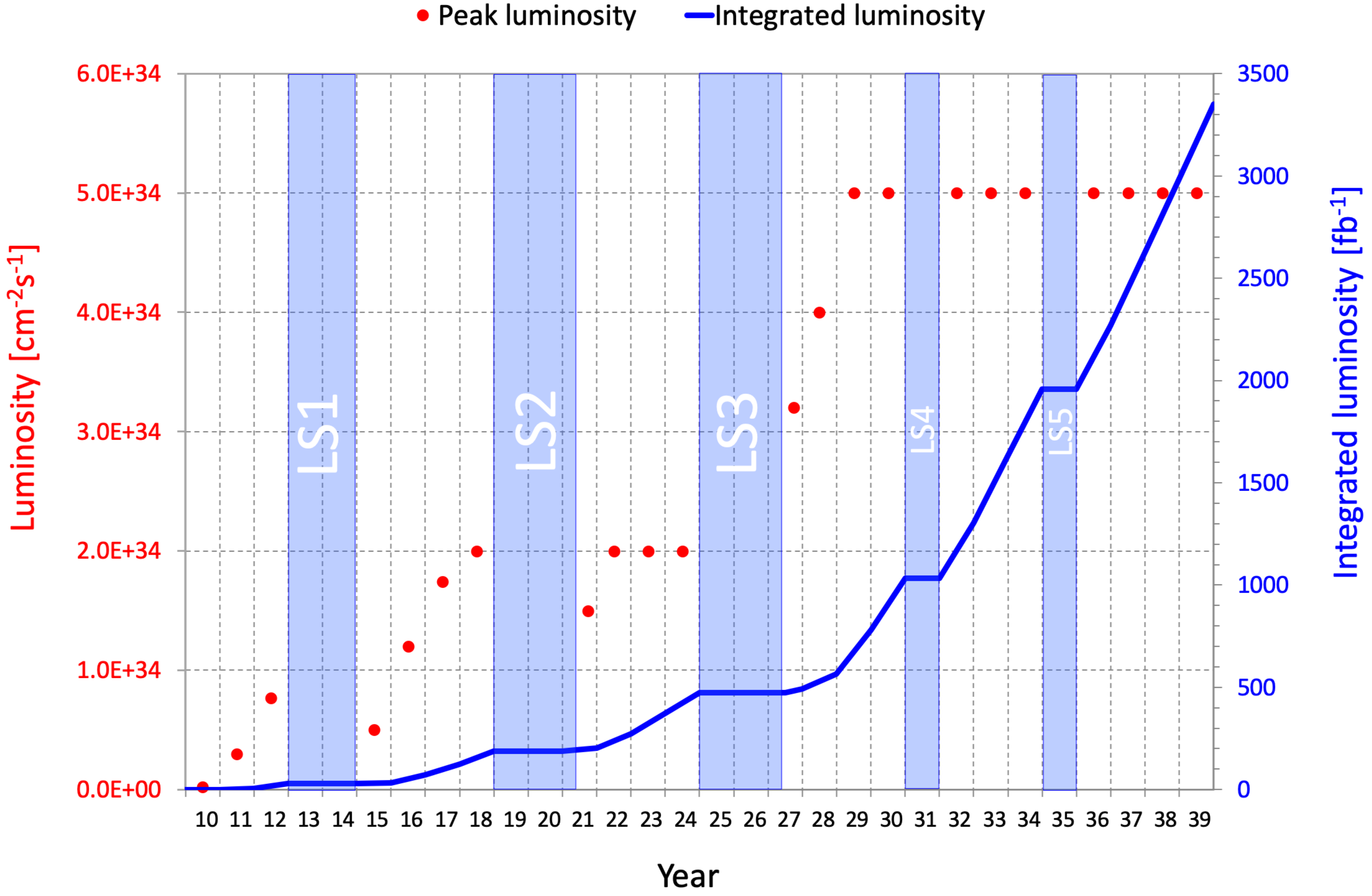
A cheat sheet for recent LHC-schedule-related terminology....

RUN 2	Long Shutdown 2 (LS2)	RUN 3	Long Shutdown 3 (LS3)	RUN 4
2015 – 2018	**Phase-I** upgrades installed in preparation for Run 3	2022 – 2025	**Phase-II** upgrades installed in preparation for Run 4	2029 – 2032
	2018 - 2022		2025 - 2029	begins HL-LHC era

LHC

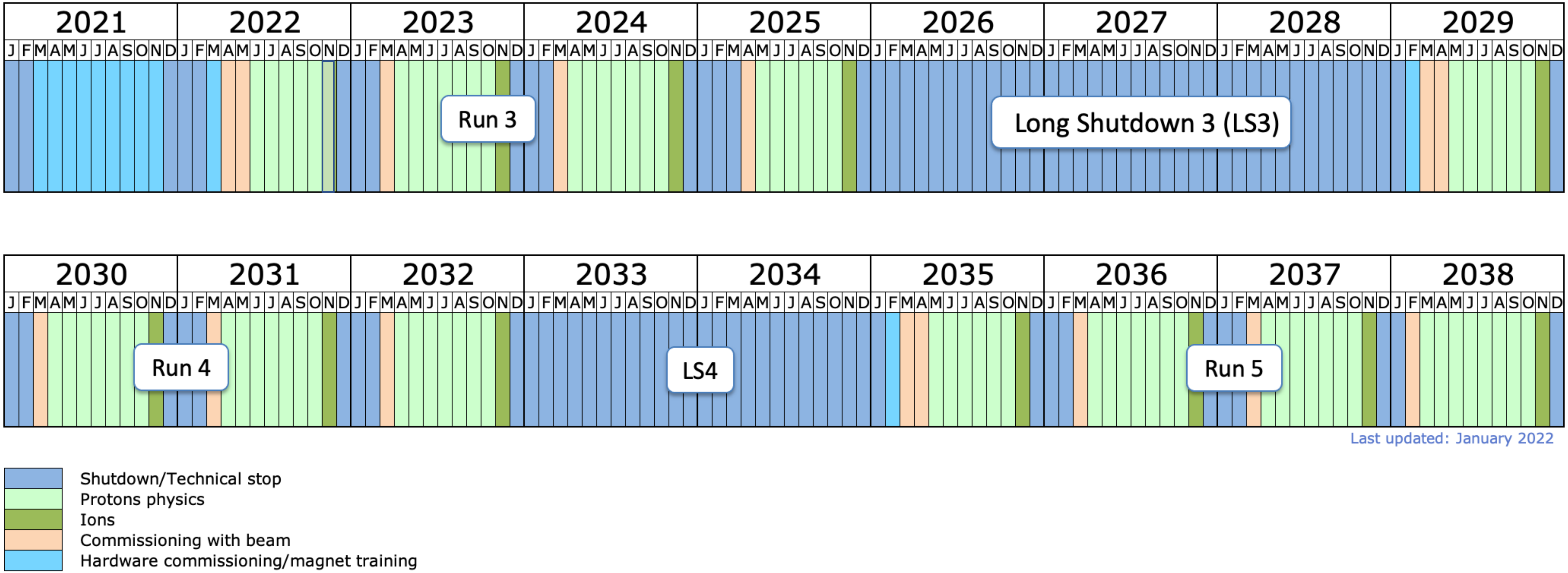
HL-LHC

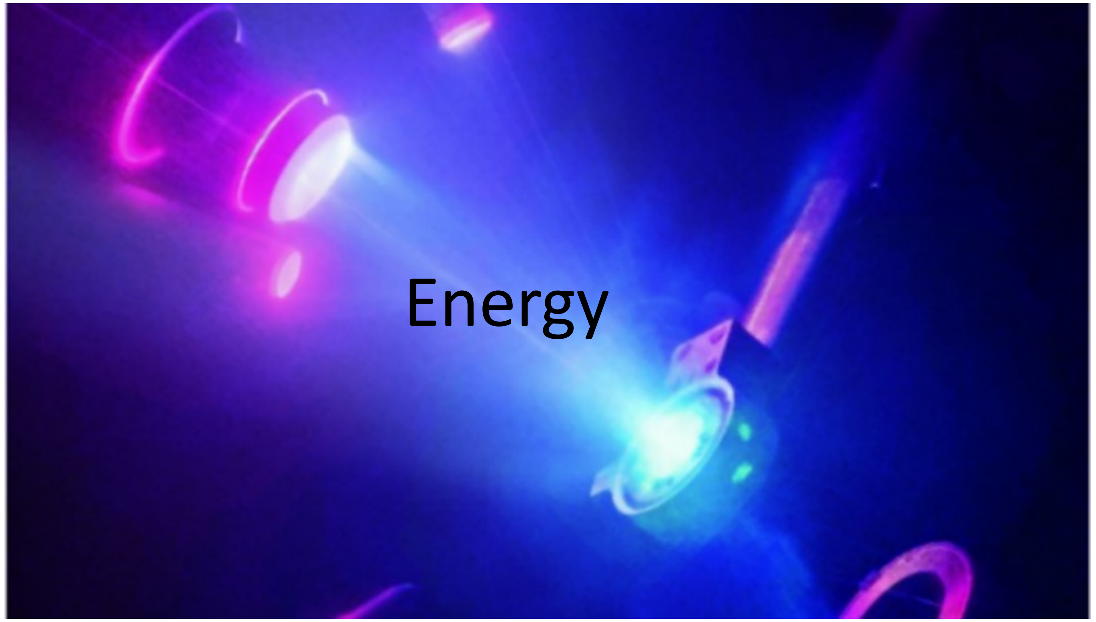
NOTE: LS3 has been shifted one year forward (see next slide)

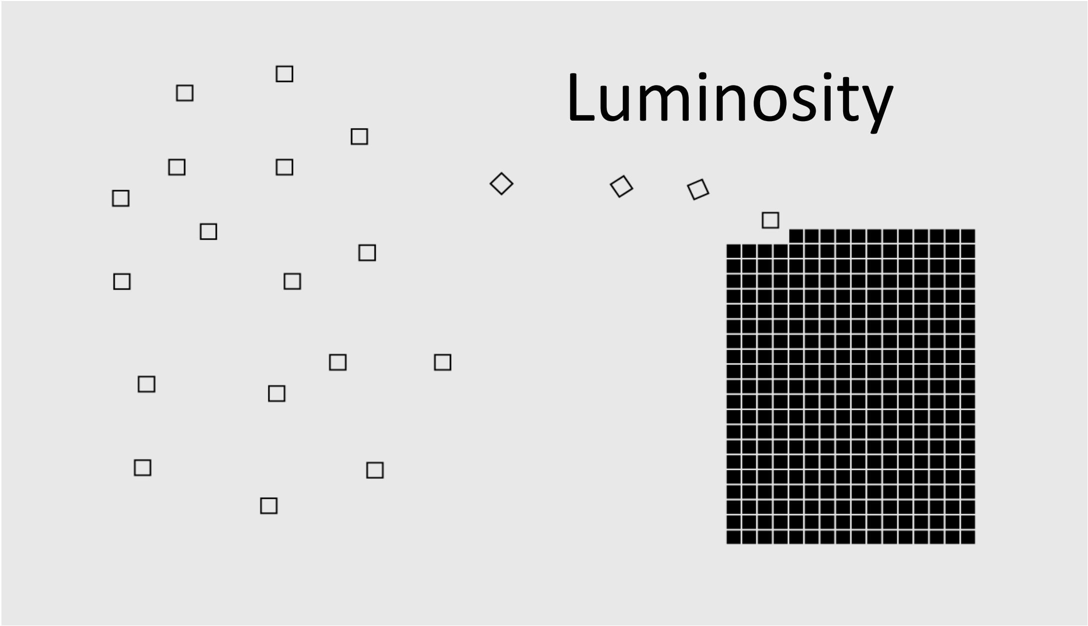


ATLAS & CMS

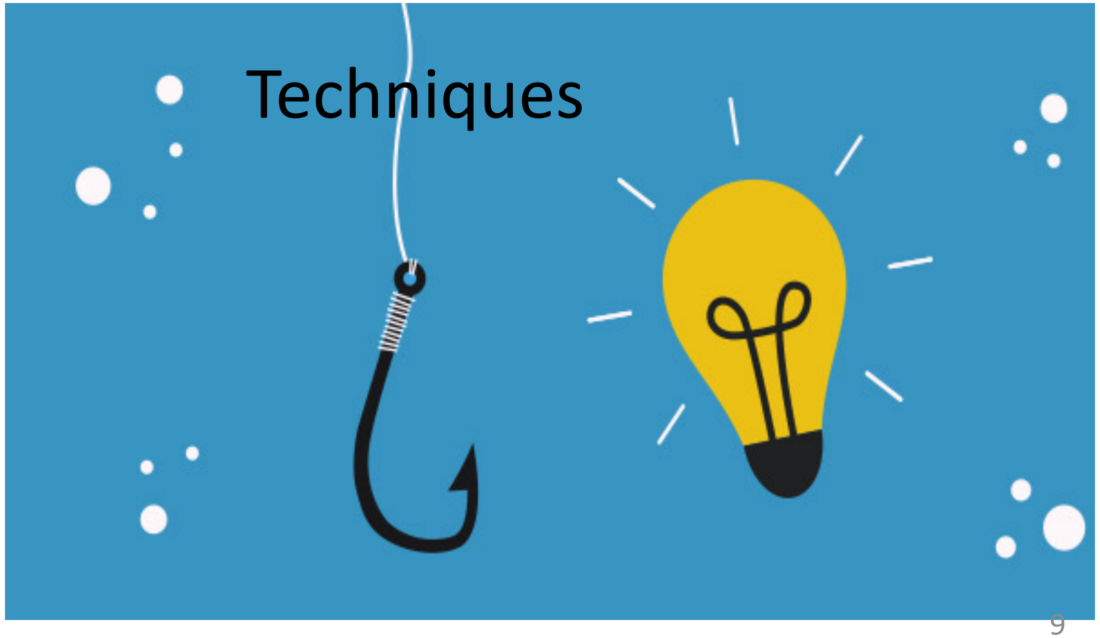
The LHC Schedule is *DYNAMIC* so take schedules as current drafts




Energy

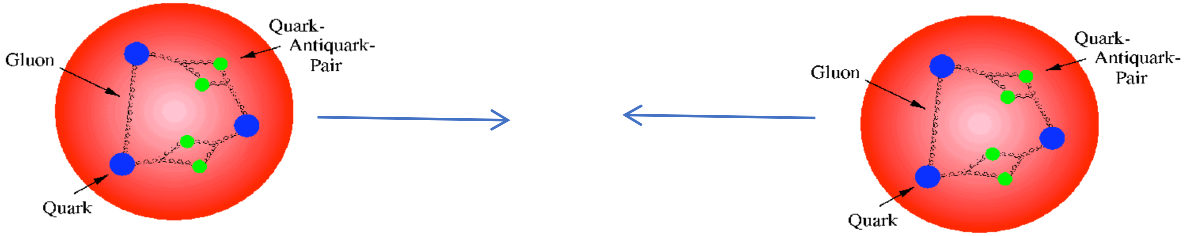

Luminosity


Technology

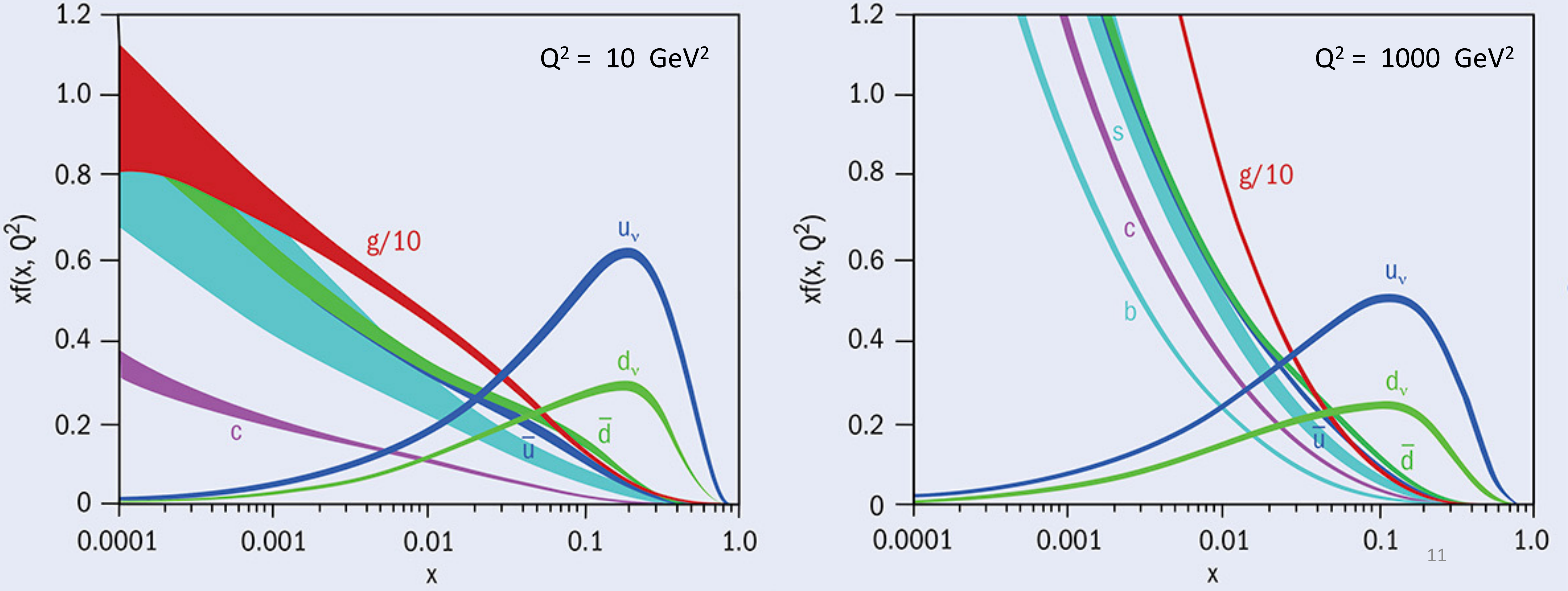

Techniques

The Energy Frontier

Available Energy

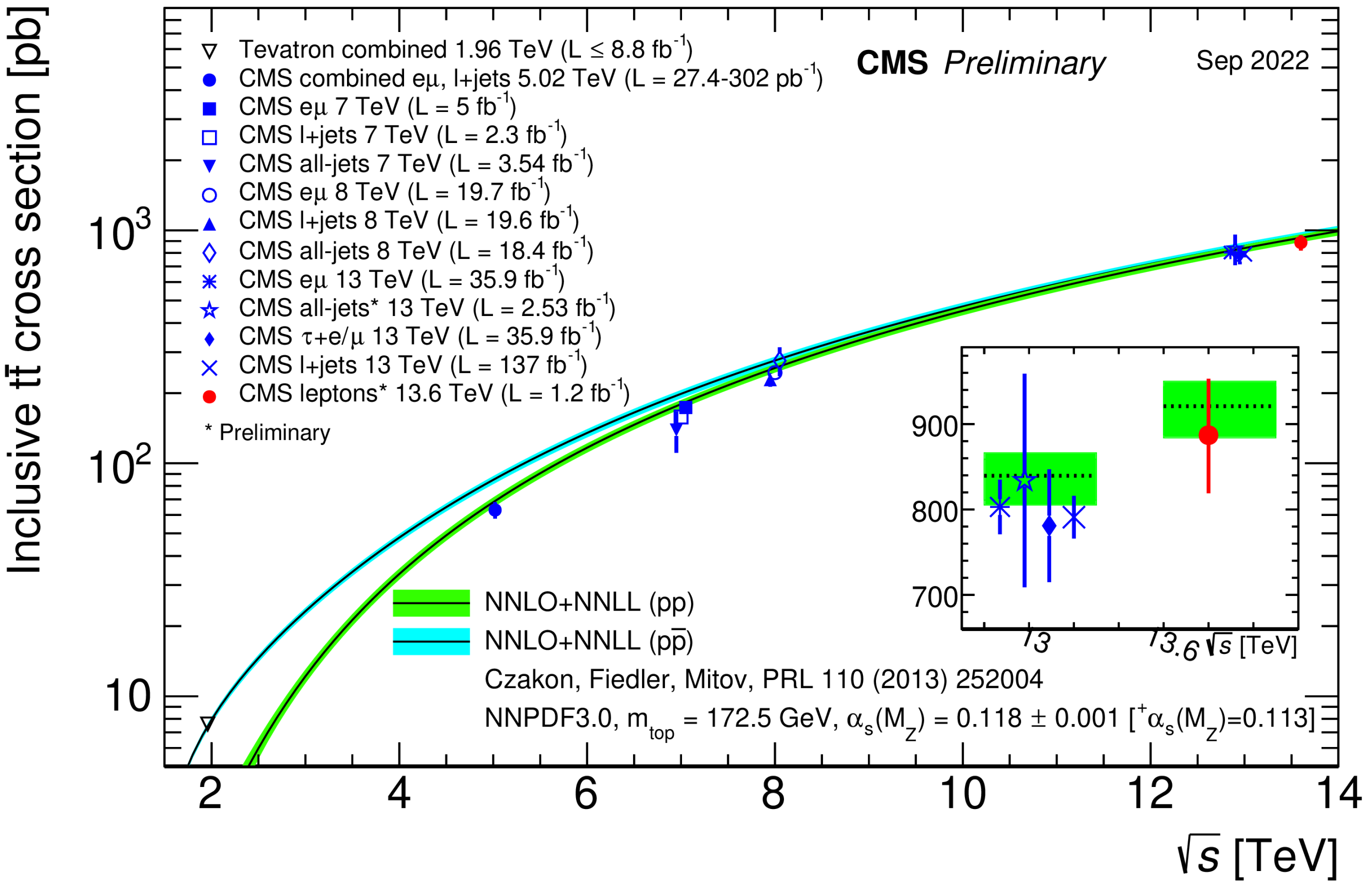


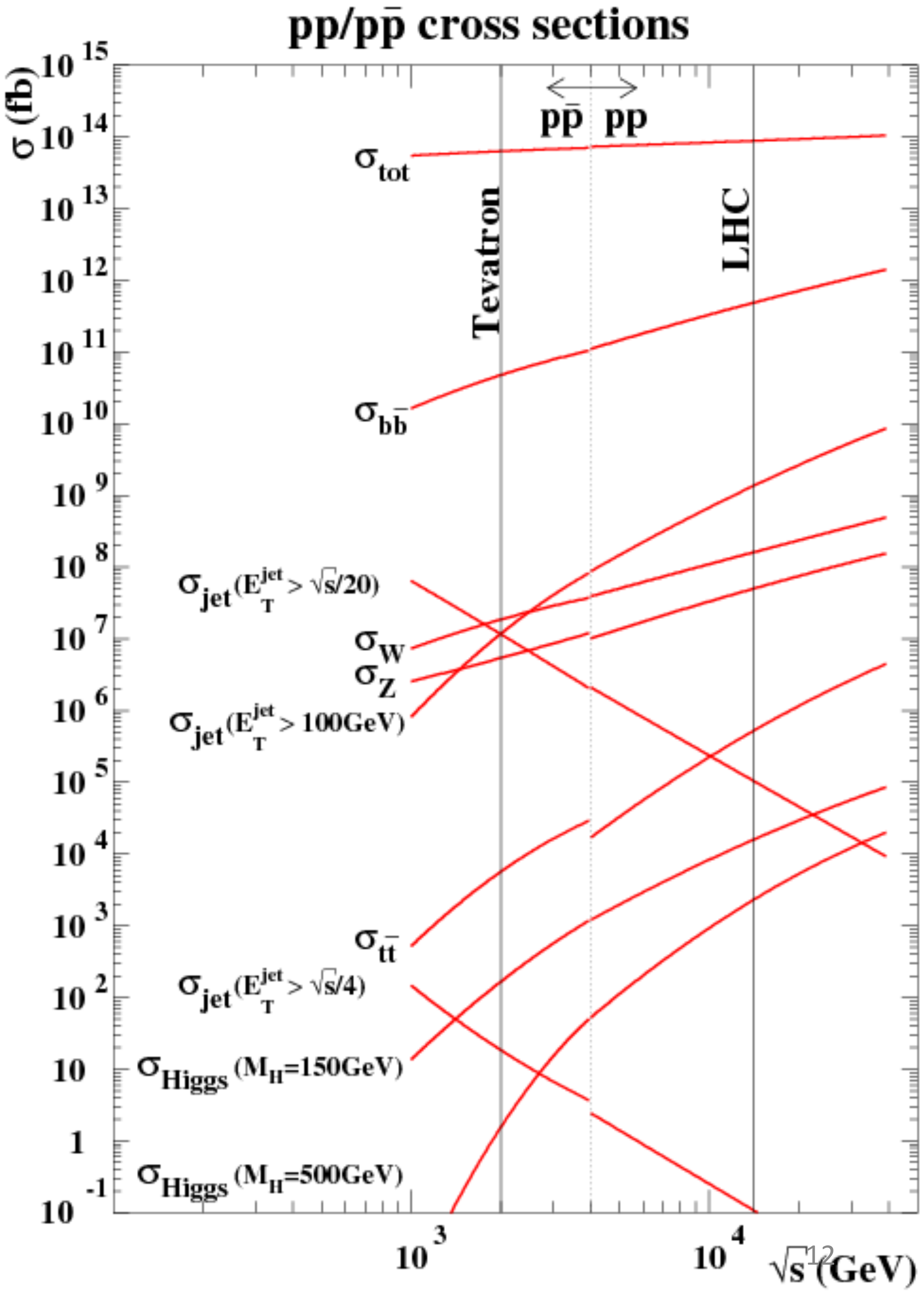
Protons are not fundamental particles. It's their constituents that collide.
This explains our need for huge datasets and need to save only a small fraction of collisions we see…



Energy and Cross Section

High-mass particle cross sections rise more quickly with center-of-mass energy.



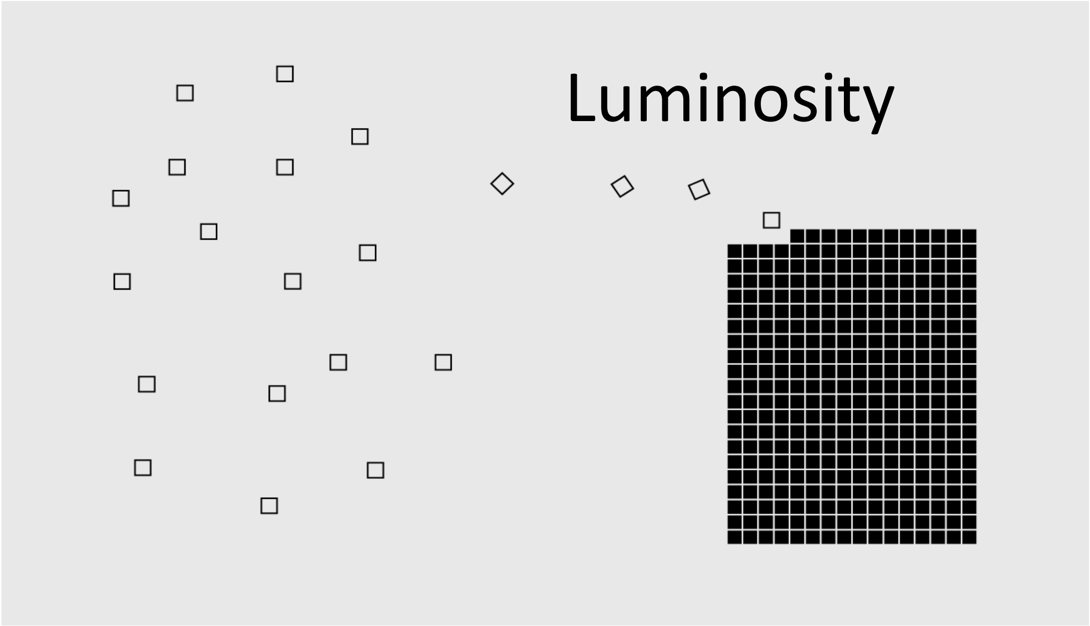


Higgs Boson Cross Sections

$\sqrt{s}$	σ	δ(theory)	δ(PDF)	$\delta(\alpha_s)$
13 TeV	48.61 pb	$^{+2.08\text{pb}}_{-3.15\text{pb}} \left(^{+4.27\%}_{-6.49\%}\right)$	± 0.89 pb ($\pm 1.85\%$)	$^{+1.24\text{pb}}_{-1.26\text{pb}} \left(^{+2.59\%}_{-2.62\%}\right)$
14 TeV	54.72 pb	$^{+2.35\text{pb}}_{-3.54\text{pb}} \left(^{+4.28\%}_{-6.46\%}\right)$	± 1.00 pb ($\pm 1.85\%$)	$^{+1.40\text{pb}}_{-1.41\text{pb}} \left(^{+2.60\%}_{-2.62\%}\right)$

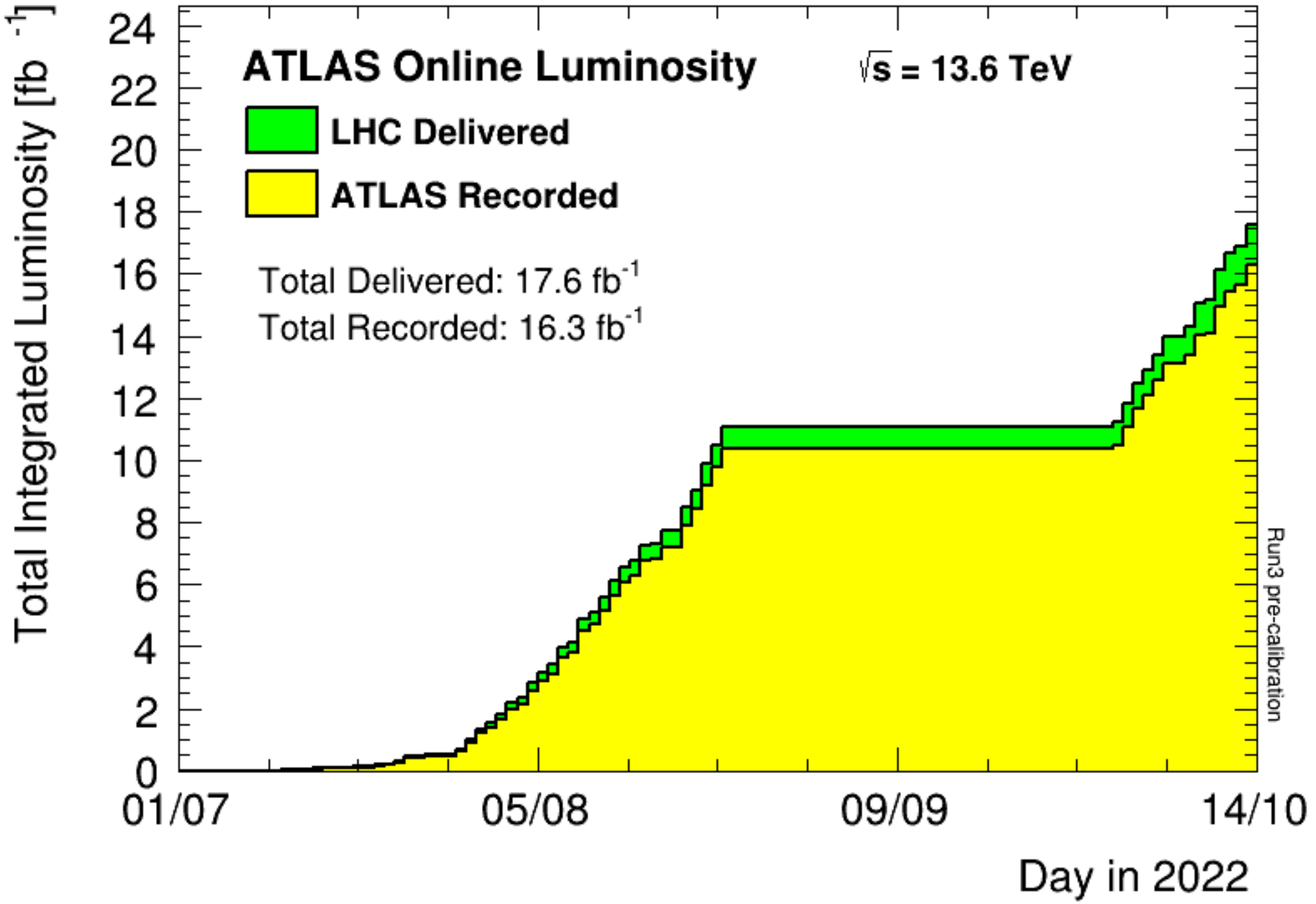
$\sqrt{s}$ [TeV]	σ^{VBF} [fb]	Δ_{scale} [%]	$\Delta_{\text{PDF}\oplus\alpha_s}$ [%]	$\sigma^{\text{DIS}}_{\text{NNLO}}$ [fb]	δ_{ELWK} [%]	σ_γ [fb]	$\sigma_{s\text{-ch}}$ [fb]
13	3766	$^{+0.43}_{-0.33}$	± 2.1	3939	-5.3	35.3	1412
14	4260	$^{+0.45}_{-0.34}$	± 2.1	4460	-5.4	40.7	1555

ggH (top) and VBF (bottom) Cross Section at 13 and 14 TeV uncertainties provided as a function of the pp collider energy (From CERN Yellow Report)


Luminosity

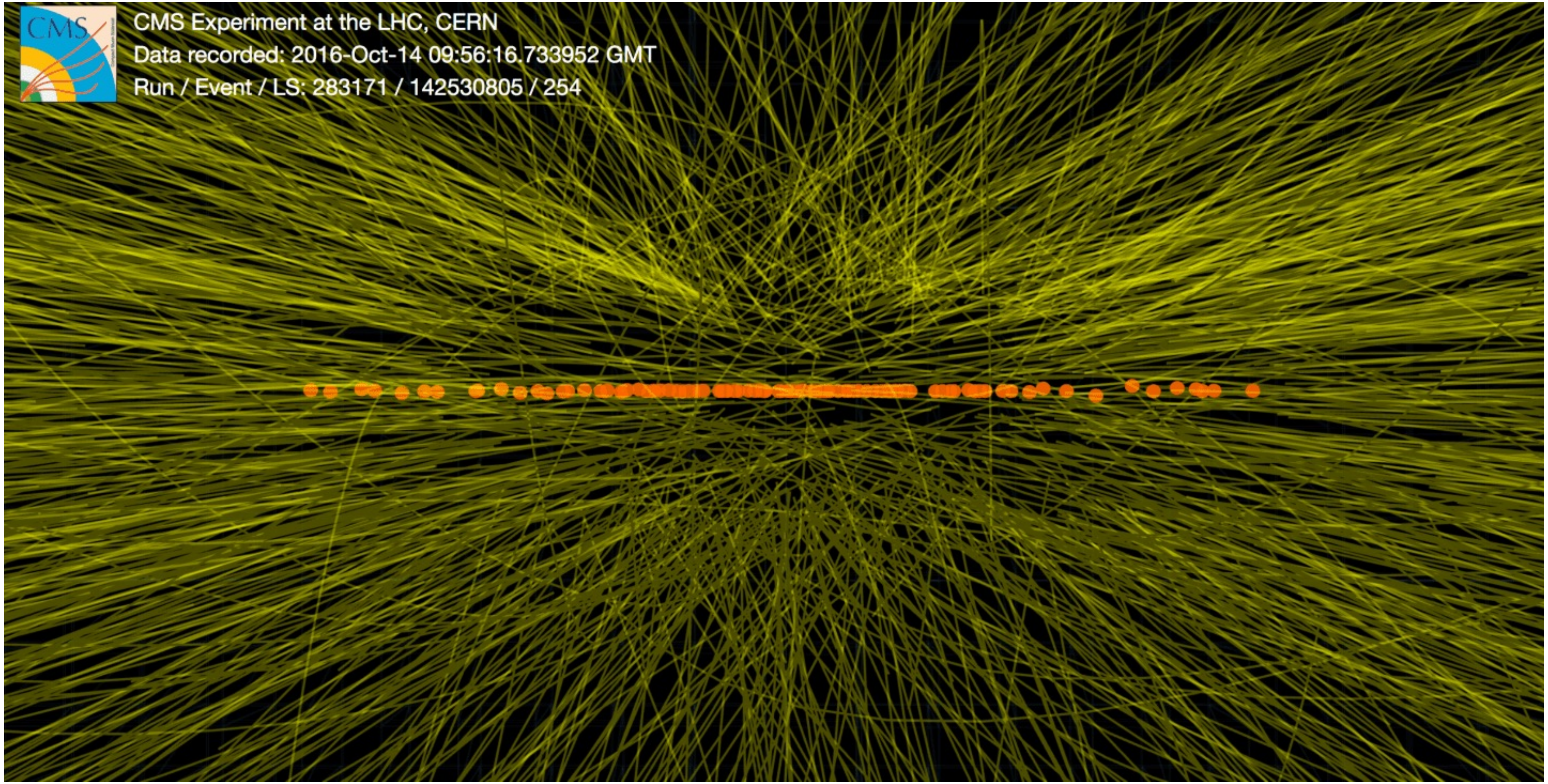
Integrated Luminosity (data accumulated) enables

- Accessing rare decay modes
- Increasing precision of measurements
- Opening up analysis options



High **Instantaneous Luminosity** (*rate*) challenges

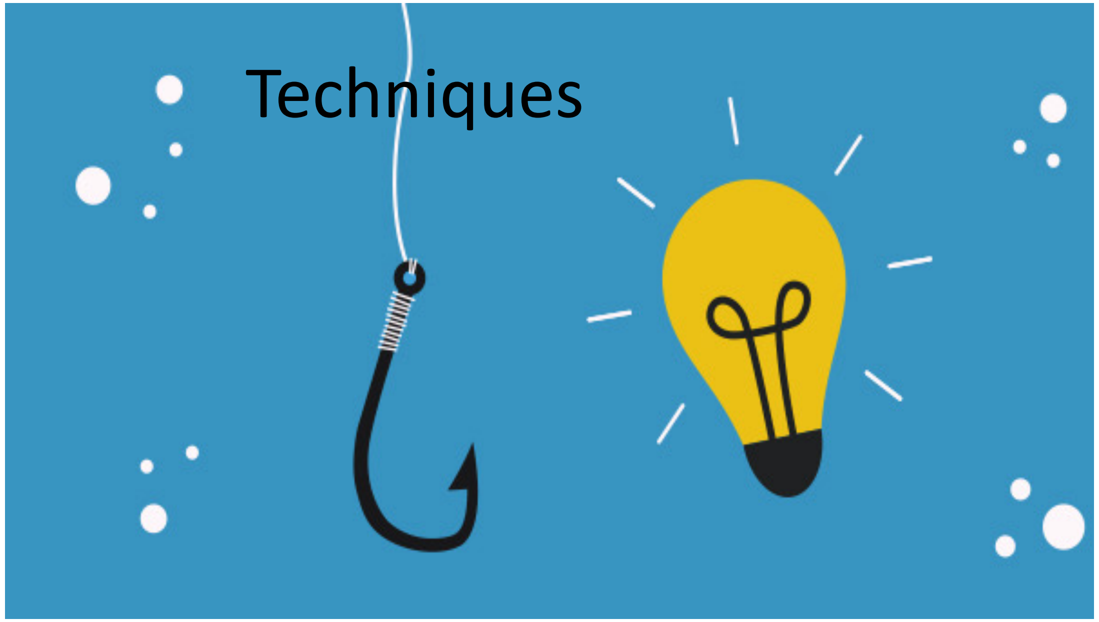
- detectors
- data acquisition systems
- analysis techniques



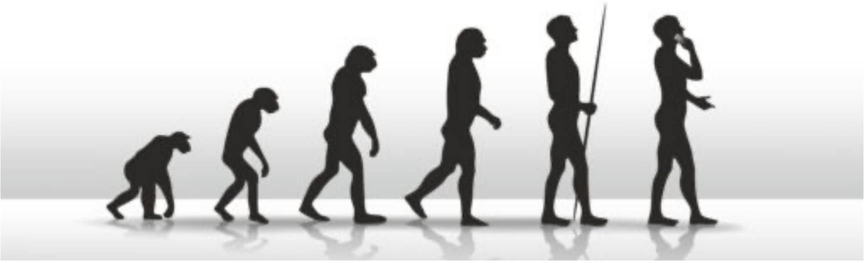
Technology

Enable or improve measurements & searches

- We need to answer the challenges of higher instantaneous luminosities and more sophisticated data analysis techniques with detector design choices.
- Improvements include
  - Higher granularity detectors to handle higher particle densities
  - Electronics that are more radiation hard
  - Lower material budgets, particularly for un-instrumented components such as support structures
  - Making additional information available, such as high-precision timing
  - Better switches and connections for detector readout
  - Making critical information, such as tracking, available earlier in trigger chain
  - Moving analysis to the trigger step


Techniques

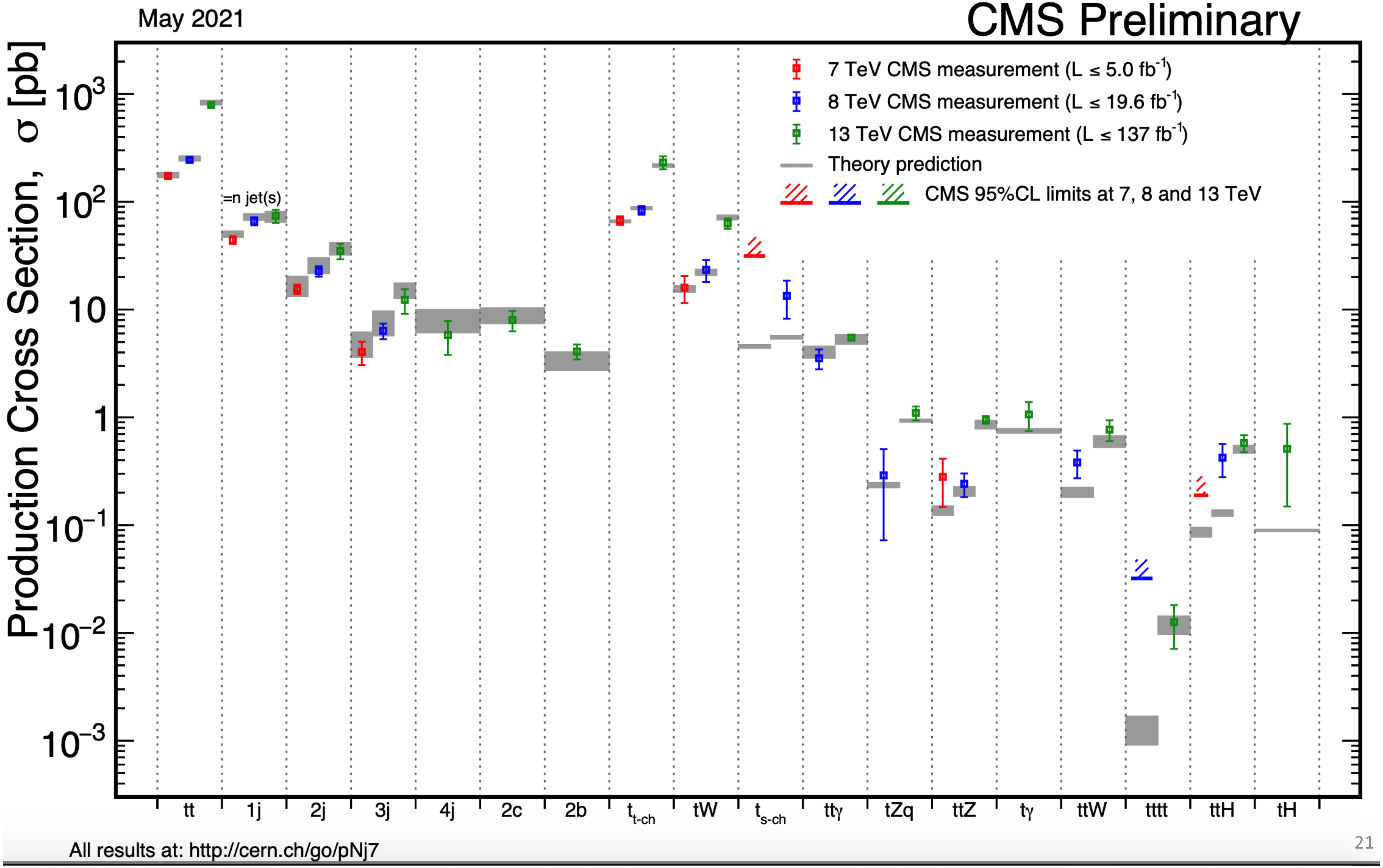
AI, AI Everywhere!



cuts -> likelihoods -> BDT -> NN -> Deep Learning

- More challenging data-taking environments require, and more sophisticated detectors enable, the use of machine-learning in many physics analyses
- Special training is required so we know how to:
  - choose an algorithm or strategy
  - optimize an algorithm
  - interpret results, including the evaluation of systematic uncertainties
- Use cases are ever increasing!
  - We've moved beyond simple object identification or classification
  - Extract sensitivity from fit to ML output rather than a kinematic variable like mass
  - Object calibration (such as energy scale determination)

It isn't just analysis techniques that are critical, but also other storage and I/O optimizations. Our datasets aren't getting any smaller



May 2021
CMS Preliminary
Production Cross Section, σ [pb]
7 TeV CMS measurement (L ≤ 5.0 fb-1)
8 TeV CMS measurement (L ≤ 19.6 fb-1)
13 TeV CMS measurement (L ≤ 137 fb-1)
Theory prediction
CMS 95%CL limits at 7, 8 and 13 TeV
=n jet(s)
tt
1j
2j
3j
4j
2c
2b
tt-ch
tW
ts-ch
ttγ
tZq
ttZ
tγ
ttW
tttt
ttH
tH
All results at: http://cern.ch/go/pNj7

ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

Status: July 2022

ATLAS Preliminary

$\int \mathcal{L}\,dt = (3.6 - 139)$ fb^{-1} $\sqrt{s}$ = 8, 13 TeV

	Model	ℓ,γ	Jets†	E_T^{miss}	$\int \mathcal{L}\,dt$[fb^{-1}]	Limit		Reference
Extra dimensions	ADD $G_{KK}+g/q$	$0\ e,\mu,\tau,\gamma$	1 – 4 j	Yes	139	M_D 11.2 TeV	$n=2$	2102.10874
	ADD non-resonant $\gamma\gamma$	$2\ \gamma$	–	–	36.7	M_S 8.6 TeV	$n=3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	139	M_{th} 9.4 TeV	$n=6$	1910.08447
	ADD BH multijet	–	≥3 j	–	3.6	M_{th} 9.55 TeV	$n=6$, $M_D=3$ TeV, rot BH	1512.02586
	RS1 $G_{KK}\to\gamma\gamma$	$2\ \gamma$	–	–	139	G_{KK} mass 4.5 TeV	$k/\overline{M}_{Pl}=0.1$	2102.13405
	Bulk RS $G_{KK}\to WW/ZZ$	multi-channel			36.1	G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl}=1.0$	1808.02380
	Bulk RS $G_{KK}\to WV\to\ell\nu qq$	$1\ e,\mu$	2 j / 1 J	Yes	139	G_{KK} mass 2.0 TeV	$k/\overline{M}_{Pl}=1.0$	2004.14636
	Bulk RS $g_{KK}\to tt$	$1\ e,\mu$	≥1 b, ≥1J/2j	Yes	36.1	g_{KK} mass 3.8 TeV	$\Gamma/m=15\%$	1804.10823
	2UED / RPP	$1\ e,\mu$	≥2 b, ≥3 j	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)}\to tt)=1$	1803.09678
Gauge bosons	SSM $Z'\to\ell\ell$	$2\ e,\mu$	–	–	139	Z' mass 5.1 TeV		1903.06248
	SSM $Z'\to\tau\tau$	$2\ \tau$	–	–	36.1	Z' mass 2.42 TeV		1709.07242
	Leptophobic $Z'\to bb$	–	2 b	–	36.1	Z' mass 2.1 TeV		1805.09299
	Leptophobic $Z'\to tt$	$0\ e,\mu$	≥1 b, ≥2 J	Yes	139	Z' mass 4.1 TeV	$\Gamma/m=1.2\%$	2005.05138
	SSM $W'\to\ell\nu$	$1\ e,\mu$	–	Yes	139	W' mass 6.0 TeV		1906.05609
	SSM $W'\to\tau\nu$	$1\ \tau$	–	Yes	139	W' mass 5.0 TeV		ATLAS-CONF-2021-025
	SSM $W'\to tb$	–	≥1 b, ≥1 J	–	139	W' mass 4.4 TeV		ATLAS-CONF-2021-043
	HVT $W'\to WZ\to\ell\nu qq$ model B	$1\ e,\mu$	2 j / 1 J	Yes	139	W' mass 4.3 TeV	$g_V=3$	2004.14636
	HVT $W'\to WZ\to\ell\nu\,\ell'\ell'$ model C	$3\ e,\mu$	2 j (VBF)	Yes	139	W' mass 340 GeV	$g_V c_H=1$, $g_f=0$	ATLAS-CONF-2022-005
	HVT $W'\to WH\to\ell\nu bb$ model B	$1\ e,\mu$	1-2 b, 1-0 j	Yes	139	W' mass 3.3 TeV	$g_V=3$	2207.00230
	HVT $Z'\to ZH\to\ell\ell/\nu\nu bb$ model B	$0,2\ e,\mu$	1-2 b, 1-0 j	Yes	139	Z' mass 3.2 TeV	$g_V=3$	2207.00230
	LRSM $W_R\to\mu N_R$	$2\ \mu$	1 J	–	80	W_R mass 5.0 TeV	$m(N_R)=0.5$ TeV, $g_L=g_R$	1904.12679
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV	η_{LL}^-	1703.09127
	CI $\ell\ell qq$	$2\ e,\mu$	–	–	139	Λ 35.8 TeV	η_{LL}^-	2006.12946
	CI $eebs$	$2\ e$	1 b	–	139	Λ 1.8 TeV	$g_*=1$	2105.13847
	CI $\mu\mu bs$	$2\ \mu$	1 b	–	139	Λ 2.0 TeV	$g_*=1$	2105.13847
	CI $tttt$	$\geq1\ e,\mu$	≥1 b, ≥1 j	Yes	36.1	Λ 2.57 TeV	$\lvert C_{4t}\rvert=4\pi$	1811.02305
DM	Axial-vector med. (Dirac DM)	$0\ e,\mu,\tau,\gamma$	1 – 4 j	Yes	139	m_{med} 2.1 TeV	g_q=0.25, g_χ=1, $m(\chi)$=1 GeV	2102.10874
	Pseudo-scalar med. (Dirac DM)	$0\ e,\mu,\tau,\gamma$	1 – 4 j	Yes	139	m_{med} 376 GeV	g_q=1, g_χ=1, $m(\chi)$=1 GeV	2102.10874
	Vector med. Z'-2HDM (Dirac DM)	$0\ e,\mu$	2 b	Yes	139	m_{med} 3.1 TeV	$\tan\beta$=1, g_Z=0.8, $m(\chi)$=100 GeV	2108.13391
	Pseudo-scalar med. 2HDM+a	multi-channel			139	m_{med} 560 GeV	$\tan\beta$=1, g_χ=1, $m(\chi)$=10 GeV	ATLAS-CONF-2021-036
LQ	Scalar LQ 1st gen	$2\ e$	≥2 j	Yes	139	LQ mass 1.8 TeV	$\beta=1$	2006.05872
	Scalar LQ 2nd gen	$2\ \mu$	≥2 j	Yes	139	LQ mass 1.7 TeV	$\beta=1$	2006.05872
	Scalar LQ 3rd gen	$1\ \tau$	2 b	Yes	139	LQ_3^u mass 1.2 TeV	$\mathcal{B}(LQ_3^u\to b\tau)=1$	2108.07665
	Scalar LQ 3rd gen	$0\ e,\mu$	≥2 j, ≥2 b	Yes	139	LQ_3^u mass 1.24 TeV	$\mathcal{B}(LQ_3^u\to t\nu)=1$	2004.14060
	Scalar LQ 3rd gen	$\geq2\ e,\mu,\geq1\ \tau$	≥1 j, ≥1 b	–	139	LQ_3^d mass 1.43 TeV	$\mathcal{B}(LQ_3^d\to t\tau)=1$	2101.11582
	Scalar LQ 3rd gen	$0\ e,\mu,\geq1\ \tau$	0 – 2 j, 2 b	Yes	139	LQ_3^d mass 1.26 TeV	$\mathcal{B}(LQ_3^d\to b\nu)=1$	2101.12527
	Vector LQ 3rd gen	$1\ \tau$	2 b	Yes	139	LQ_3^V mass 1.77 TeV	$\mathcal{B}(LQ_3^V\to b\tau)=0.5$, Y-M coupl.	2108.07665
Vector-like fermions	VLQ $TT\to Zt+X$	2e/2μ/≥3e,μ	≥1 b, ≥1 j	–	139	T mass 1.4 TeV	SU(2) doublet	ATLAS-CONF-2021-024
	VLQ $BB\to Wt/Zb+X$	multi-channel			36.1	B mass 1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3}T_{5/3}\lvert T_{5/3}\to Wt+X$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3}\to Wt)$= 1, $c(T_{5/3}Wt)$= 1	1807.11883
	VLQ $T\to Ht/Zt$	$1\ e,\mu$	≥1 b, ≥3 j	Yes	139	T mass 1.8 TeV	SU(2) singlet, κ_T= 0.5	ATLAS-CONF-2021-040
	VLQ $Y\to Wb$	$1\ e,\mu$	≥1 b, ≥1 j	Yes	36.1	Y mass 1.85 TeV	$\mathcal{B}(Y\to Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B\to Hb$	$0\ e,\mu$	≥2b, ≥1j, ≥1J	–	139	B mass 2.0 TeV	SU(2) doublet, κ_B= 0.3	ATLAS-CONF-2021-018
	VLL $\tau'\to Z\tau/H\tau$	multi-channel	≥1 j	Yes	139	τ' mass 898 GeV	SU(2) doublet	ATLAS-CONF-2022-044
Excited fermions	Excited quark $q^*\to qg$	–	2 j	–	139	q^* mass 6.7 TeV	only u^* and d^*, $\Lambda=m(q^*)$	1910.08447
	Excited quark $q^*\to q\gamma$	$1\ \gamma$	1 j	–	36.7	q^* mass 5.3 TeV	only u^* and d^*, $\Lambda=m(q^*)$	1709.10440
	Excited quark $b^*\to bg$	–	1 b, 1 j	–	139	b^* mass 3.2 TeV		1910.0447
	Excited lepton ℓ^*	$3\ e,\mu$	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda=3.0$ TeV	1411.2921
	Excited lepton ν^*	$3\ e,\mu,\tau$	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda=1.6$ TeV	1411.2921
Other	Type III Seesaw	$2,3,4\ e,\mu$	≥2 j	Yes	139	N^0 mass 910 GeV		2202.02039
	LRSM Majorana ν	$2\ \mu$	2 j	–	36.1	N_R mass 3.2 TeV	$m(W_R)=4.1$ TeV, $g_L=g_R$	1809.11105
	Higgs triplet $H^{\pm\pm}\to W^\pm W^\pm$	$2,3,4\ e,\mu$ (SS)	various	Yes	139	$H^{\pm\pm}$ mass 350 GeV	DY production	2101.11961
	Higgs triplet $H^{\pm\pm}\to\ell\ell$	$2,3,4\ e,\mu$ (SS)	–	–	139	$H^{\pm\pm}$ mass 1.08 TeV	DY production	ATLAS-CONF-2022-010
	Higgs triplet $H^{\pm\pm}\to\ell\tau$	$3\ e,\mu,\tau$	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm}\to\ell\tau)=1$	1411.2921
	Multi-charged particles	–	–	–	139	multi-charged particle mass 1.59 TeV	DY production, $\lvert q\rvert=5e$	ATLAS-CONF-2022-034
	Magnetic monopoles	–	–	–	34.4	monopole mass 2.37 TeV	DY production, $\lvert g\rvert=1g_D$, spin 1/2	1905.10130

$\sqrt{s}$ = 8 TeV | $\sqrt{s}$ = 13 TeV partial data | $\sqrt{s}$ = 13 TeV full data

10^{-1} 1 10 **Mass scale [TeV]**

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

ATLAS SUSY Searches* - 95% CL Lower Limits

March 2022

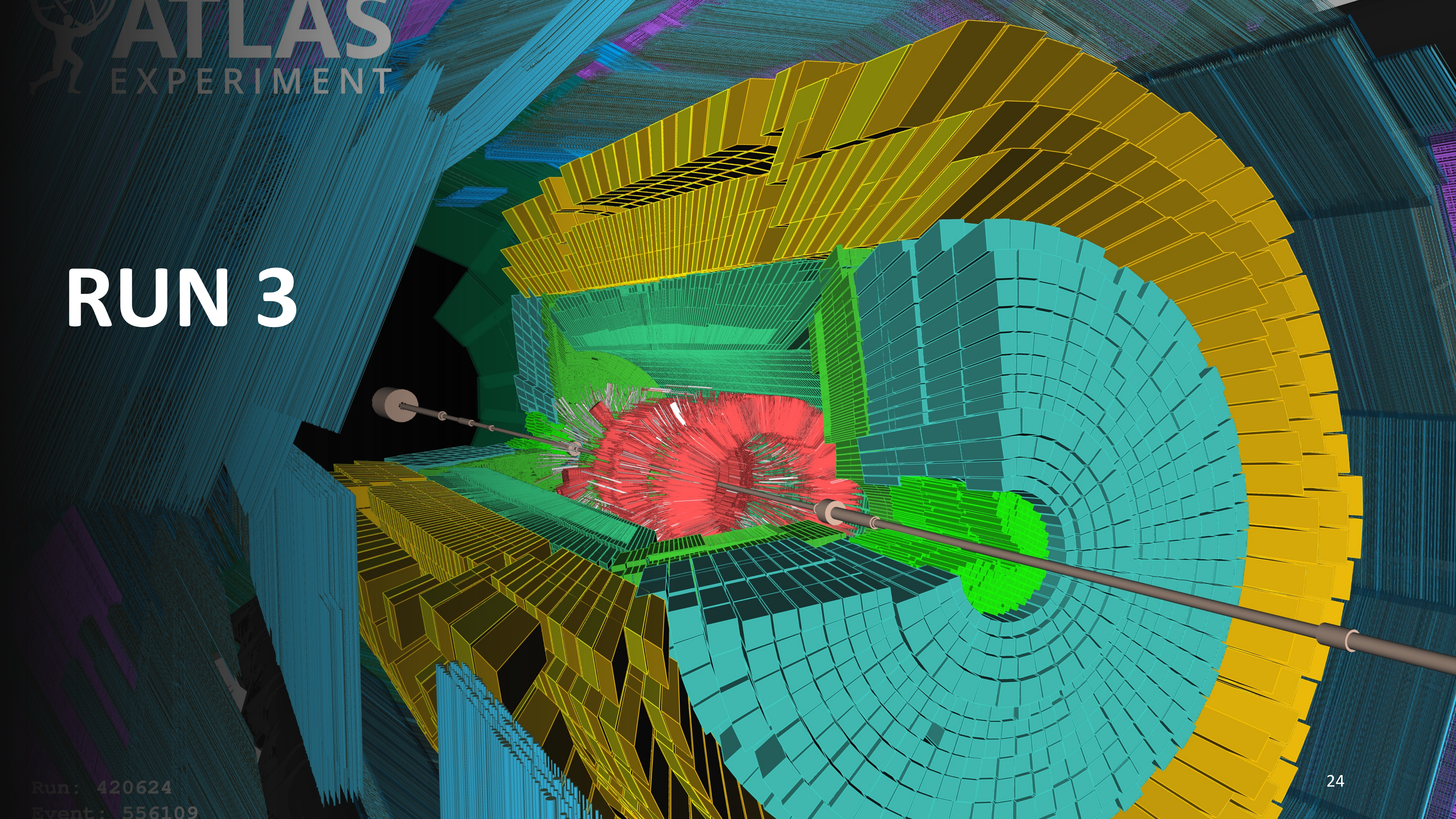
ATLAS Preliminary
$\sqrt{s}$ = 13 TeV

	Model	Signature			$\int \mathcal{L}\, dt$ [fb^{-1}]	Mass limit			Reference
Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0 e,μ	2-6 jets	E_T^{miss}	139	$\tilde{q}$ [1×, 8× Degen.]	1.0 / 1.85	m($\tilde{\chi}_1^0$)<400 GeV	2010.14293
		mono-jet	1-3 jets	E_T^{miss}	139	$\tilde{q}$ [8× Degen.]	0.9	m($\tilde{q}$)-m($\tilde{\chi}_1^0$)=5 GeV	2102.10874
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0 e,μ	2-6 jets	E_T^{miss}	139	$\tilde{g}$	2.3	m($\tilde{\chi}_1^0$)=0 GeV	2010.14293
						$\tilde{g}$	Forbidden 1.15-1.95	m($\tilde{\chi}_1^0$)=1000 GeV	2010.14293
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}W\tilde{\chi}_1^0$	1 e,μ	2-6 jets		139	$\tilde{g}$	2.2	m($\tilde{\chi}_1^0$)<600 GeV	2101.01629
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	$ee,\mu\mu$	2 jets	E_T^{miss}	139	$\tilde{g}$	2.2	m($\tilde{\chi}_1^0$)<700 GeV	CERN-EP-2022-014
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}_1^0$	0 e,μ	7-11 jets	E_T^{miss}	139	$\tilde{g}$	1.97	m($\tilde{\chi}_1^0$) <600 GeV	2008.06032
		SS e,μ	6 jets		139	$\tilde{g}$	1.15	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=200 GeV	1909.08457
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	E_T^{miss}	79.8	$\tilde{g}$	2.25	m($\tilde{\chi}_1^0$)<200 GeV	ATLAS-CONF-2018-041
		SS e,μ	6 jets		139	$\tilde{g}$	1.25	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=300 GeV	1909.08457
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$	0 e,μ	2 b	E_T^{miss}	139	$\tilde{b}_1$	1.255	m($\tilde{\chi}_1^0$)<400 GeV	2101.12527
						$\tilde{b}_1$	0.68	10 GeV<Δm($\tilde{b}_1$,$\tilde{\chi}_1^0$)<20 GeV	2101.12527
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_2^0\to bh\tilde{\chi}_1^0$	0 e,μ	6 b	E_T^{miss}	139	$\tilde{b}_1$	Forbidden 0.23-1.35	Δm($\tilde{\chi}_2^0$,$\tilde{\chi}_1^0$)=130 GeV, m($\tilde{\chi}_1^0$)=100 GeV	1908.03122
		2 τ	2 b	E_T^{miss}	139	$\tilde{b}_1$	0.13-0.85	Δm($\tilde{\chi}_2^0$,$\tilde{\chi}_1^0$)=130 GeV, m($\tilde{\chi}_1^0$)=0 GeV	2103.08189
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}_1^0$	0-1 e,μ	$\geq$ 1 jet	E_T^{miss}	139	$\tilde{t}_1$	1.25	m($\tilde{\chi}_1^0$)=1 GeV	2004.14060,2012.03799
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	1 e,μ	3 jets/1 b	E_T^{miss}	139	$\tilde{t}_1$	Forbidden 0.65	m($\tilde{\chi}_1^0$)=500 GeV	2012.03799
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to\tilde{\tau}_1 b\nu$, $\tilde{\tau}_1\to\tau\tilde{G}$	1-2 τ	2 jets/1 b	E_T^{miss}	139	$\tilde{t}_1$	Forbidden 1.4	m($\tilde{\tau}_1$)=800 GeV	2108.07665
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$ / $\tilde{c}\tilde{c}$, $\tilde{c}\to c\tilde{\chi}_1^0$	0 e,μ	2 c	E_T^{miss}	36.1	$\tilde{c}$	0.85	m($\tilde{\chi}_1^0$)=0 GeV	1805.01649
		0 e,μ	mono-jet	E_T^{miss}	139	$\tilde{t}_1$	0.55	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}_1^0$)=5 GeV	2102.10874
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}_2^0$, $\tilde{\chi}_2^0\to Z/h\tilde{\chi}_1^0$	1-2 e,μ	1-4 b	E_T^{miss}	139	$\tilde{t}_1$	0.067-1.18	m($\tilde{\chi}_2^0$)=500 GeV	2006.05880
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ	1 b	E_T^{miss}	139	$\tilde{t}_2$	Forbidden 0.86	m($\tilde{\chi}_1^0$)=360 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)= 40 GeV	2006.05880
EW direct	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via WZ	Multiple ℓ/jets		E_T^{miss}	139	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	0.96	m($\tilde{\chi}_1^0$)=0, wino-bino	2106.01676, 2108.07586
		$ee,\mu\mu$	$\geq$ 1 jet	E_T^{miss}	139	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	0.205	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV, wino-bino	1911.12606
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ via WW	2 e,μ		E_T^{miss}	139	$\tilde{\chi}_1^\pm$	0.42	m($\tilde{\chi}_1^0$)=0, wino-bino	1908.08215
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via Wh	Multiple ℓ/jets		E_T^{miss}	139	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	Forbidden 1.06	m($\tilde{\chi}_1^0$)=70 GeV, wino-bino	2004.10894, 2108.07586
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e,μ		E_T^{miss}	139	$\tilde{\chi}_1^\pm$	1.0	m($\tilde{\ell}$,$\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1908.08215
	$\tilde{\tau}\tilde{\tau}$, $\tilde{\tau}\to\tau\tilde{\chi}_1^0$	2 τ		E_T^{miss}	139	$\tilde{\tau}$ [$\tilde{\tau}_L$, $\tilde{\tau}_{R,L}$]	0.16-0.3 / 0.12-0.39	m($\tilde{\chi}_1^0$)=0	1911.06660
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0 jets	E_T^{miss}	139	$\tilde{\ell}$	0.7	m($\tilde{\chi}_1^0$)=0	1908.08215
		$ee,\mu\mu$	$\geq$ 1 jet	E_T^{miss}	139	$\tilde{\ell}$	0.256	m($\tilde{\ell}$)-m($\tilde{\chi}_1^0$)=10 GeV	1911.12606
	$\tilde{H}\tilde{H}$, $\tilde{H}\to h\tilde{G}/Z\tilde{G}$	0 e,μ	$\geq$ 3 b	E_T^{miss}	36.1	$\tilde{H}$	0.13-0.23 / 0.29-0.88	BR($\tilde{\chi}_1^0\to h\tilde{G}$)=1	1806.04030
		4 e,μ	0 jets	E_T^{miss}	139	$\tilde{H}$	0.55	BR($\tilde{\chi}_1^0\to Z\tilde{G}$)=1	2103.11684
		0 e,μ	$\geq$ 2 large jets	E_T^{miss}	139	$\tilde{H}$	0.45-0.93	BR($\tilde{\chi}_1^0\to Z\tilde{G}$)=1	2108.07586
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	E_T^{miss}	139	$\tilde{\chi}_1^\pm$	0.66	Pure Wino	2201.02472
						$\tilde{\chi}_1^\pm$	0.21	Pure higgsino	2201.02472
	Stable $\tilde{g}$ R-hadron	pixel dE/dx		E_T^{miss}	139	$\tilde{g}$	2.05		CERN-EP-2022-029
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}_1^0$	pixel dE/dx		E_T^{miss}	139	$\tilde{g}$ [$\tau(\tilde{g})$ =10 ns]	2.2	m($\tilde{\chi}_1^0$)=100 GeV	CERN-EP-2022-029
	$\tilde{\ell}\tilde{\ell}$, $\tilde{\ell}\to\ell\tilde{G}$	Displ. lep		E_T^{miss}	139	$\tilde{e},\tilde{\mu}$	0.7	$\tau(\tilde{\ell})$ = 0.1 ns	2011.07812
						$\tilde{\tau}$	0.34	$\tau(\tilde{\ell})$ = 0.1 ns	2011.07812
		pixel dE/dx		E_T^{miss}	139	$\tilde{\tau}$	0.36	$\tau(\tilde{\ell})$ = 10 ns	CERN-EP-2022-029
RPV	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_1^0$, $\tilde{\chi}_1^\pm\to Z\ell\to\ell\ell\ell$	3 e,μ			139	$\tilde{\chi}_1^\pm/\tilde{\chi}_1^0$ [BR($Z\tau$)=1, BR(Ze)=1]	0.625 / 1.05	Pure Wino	2011.10543
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets	E_T^{miss}	139	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ [$\lambda_{i33}\neq 0$, $\lambda_{12k}\neq 0$]	0.95 / 1.55	m($\tilde{\chi}_1^0$)=200 GeV	2103.11684
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$		4-5 large jets		36.1	$\tilde{g}$ [m($\tilde{\chi}_1^0$)=200 GeV, 1100 GeV]	1.3 / 1.9	Large λ''_{112}	1804.03568
	$\tilde{t}\tilde{t}$, $\tilde{t}\to t\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to tbs$		Multiple		36.1	$\tilde{t}$ [λ''_{323}=2e-4, 1e-2]	0.55 / 1.05	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}$, $\tilde{t}\to b\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^\pm\to bbs$		$\geq$ 4b		139	$\tilde{t}$	Forbidden 0.95	m($\tilde{\chi}_1^\pm$)=500 GeV	2010.01015
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$		2 jets + 2 b		36.7	$\tilde{t}_1$ [qq, bs]	0.42 / 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to q\ell$	2 e,μ	2 b		36.1	$\tilde{t}_1$	0.4-1.45	BR($\tilde{t}_1\to be/b\mu$)>20%	1710.05544
		1 μ	DV		136	$\tilde{t}_1$ [1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9]	1.0 / 1.6	BR($\tilde{t}_1\to q\mu$)=100%, cosθ_t=1	2003.11956
	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0/\tilde{\chi}_1^0$, $\tilde{\chi}_{1,2}^0\to tbs$, $\tilde{\chi}_1^+\to bbs$	1-2 e,μ	$\geq$6 jets		139	$\tilde{\chi}_1^0$	0.2-0.32	Pure higgsino	2106.09609

Mass scale [TeV] (axis: 10^{-1} – 1)

*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.

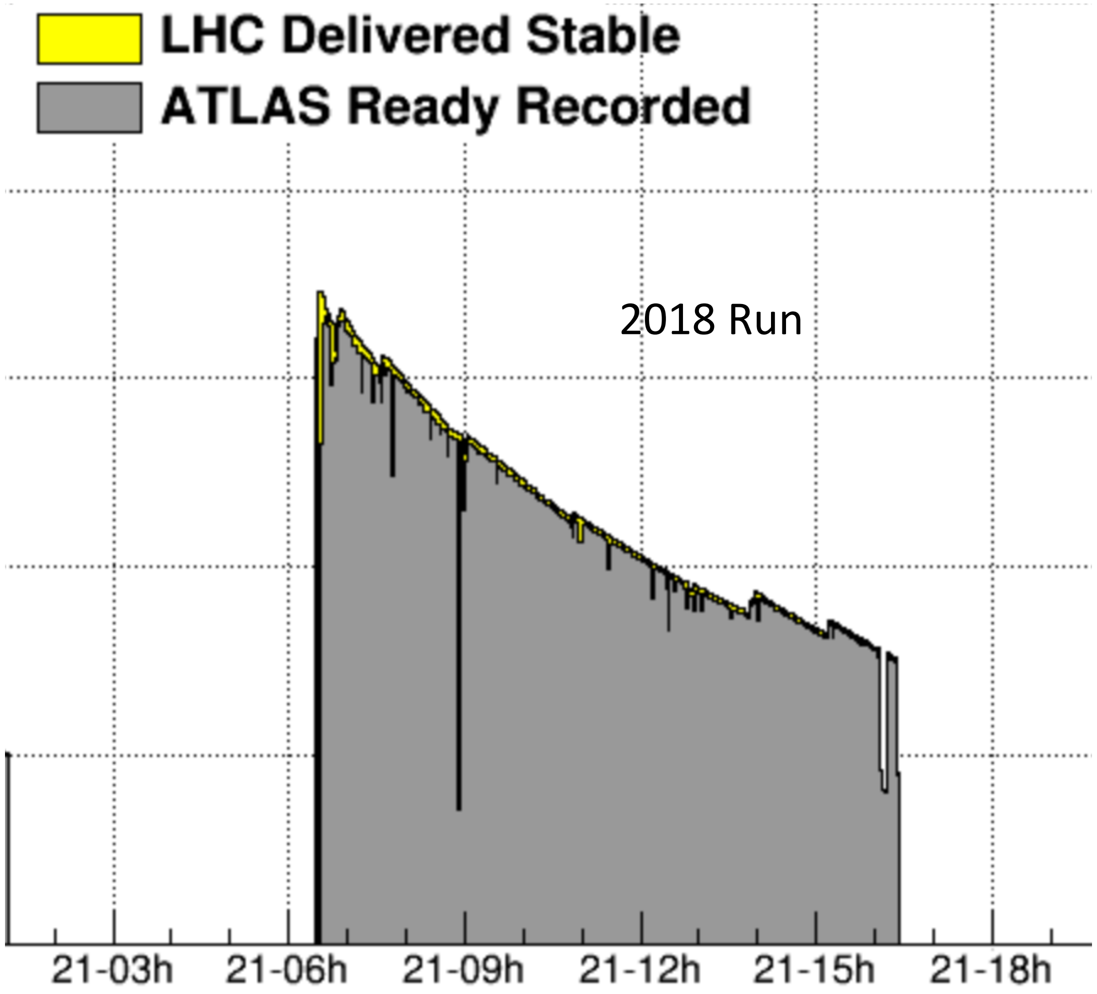
RUN 3

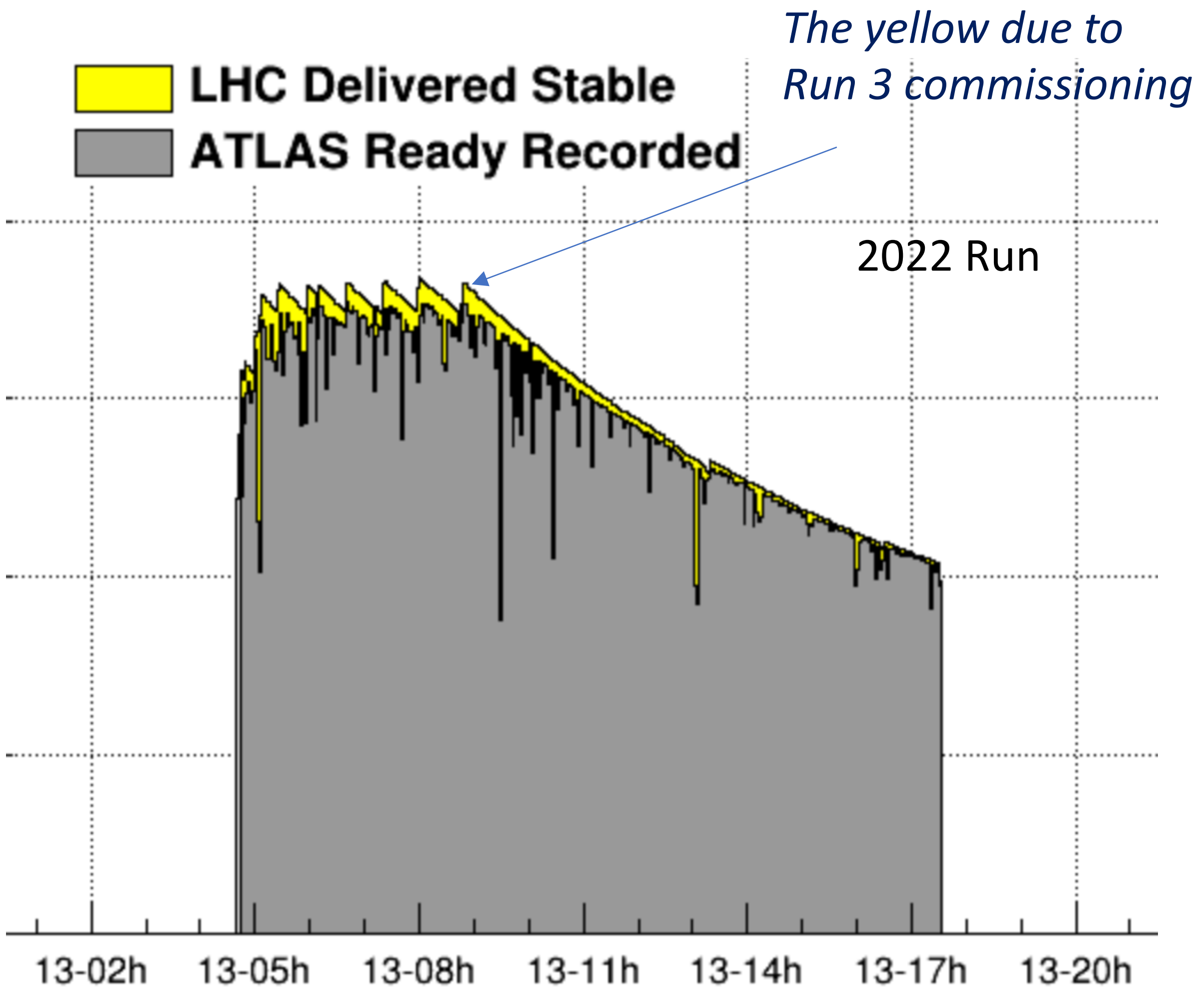


What is new in Run 3?

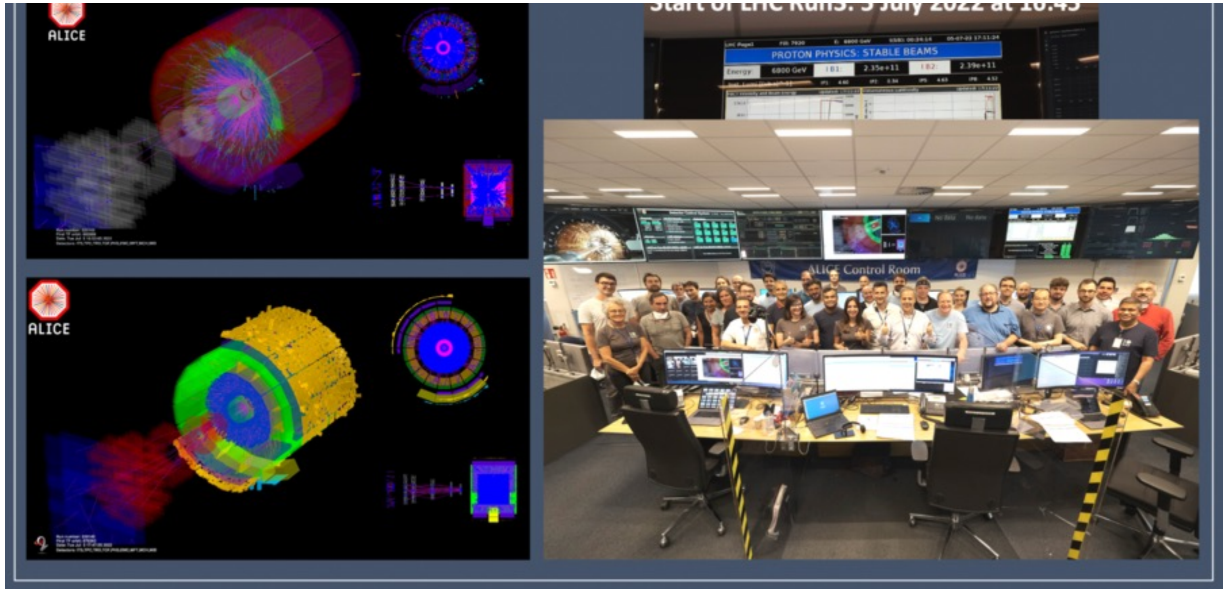
- World-breaking energy achieved on July 5, 2022: $\sqrt{s} = 13.6$ TeV
- More than double the Run 2 dataset
- LHC providing luminosity leveling

Luminosity Leveling Example: Run 2 vs. Run 3



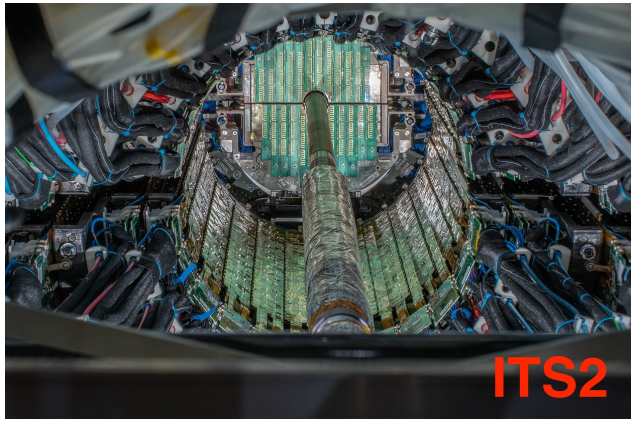


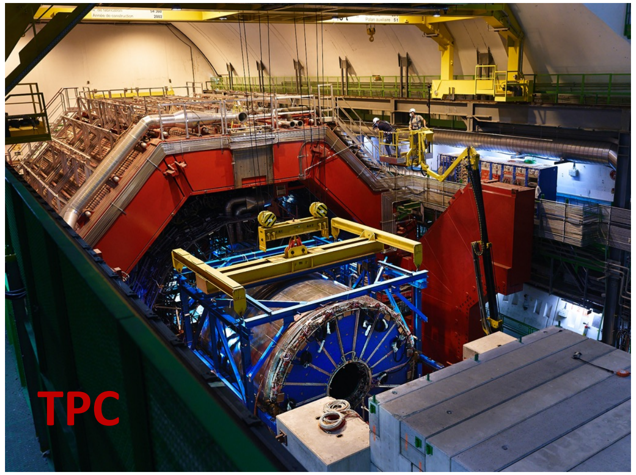

LHCb Control Room

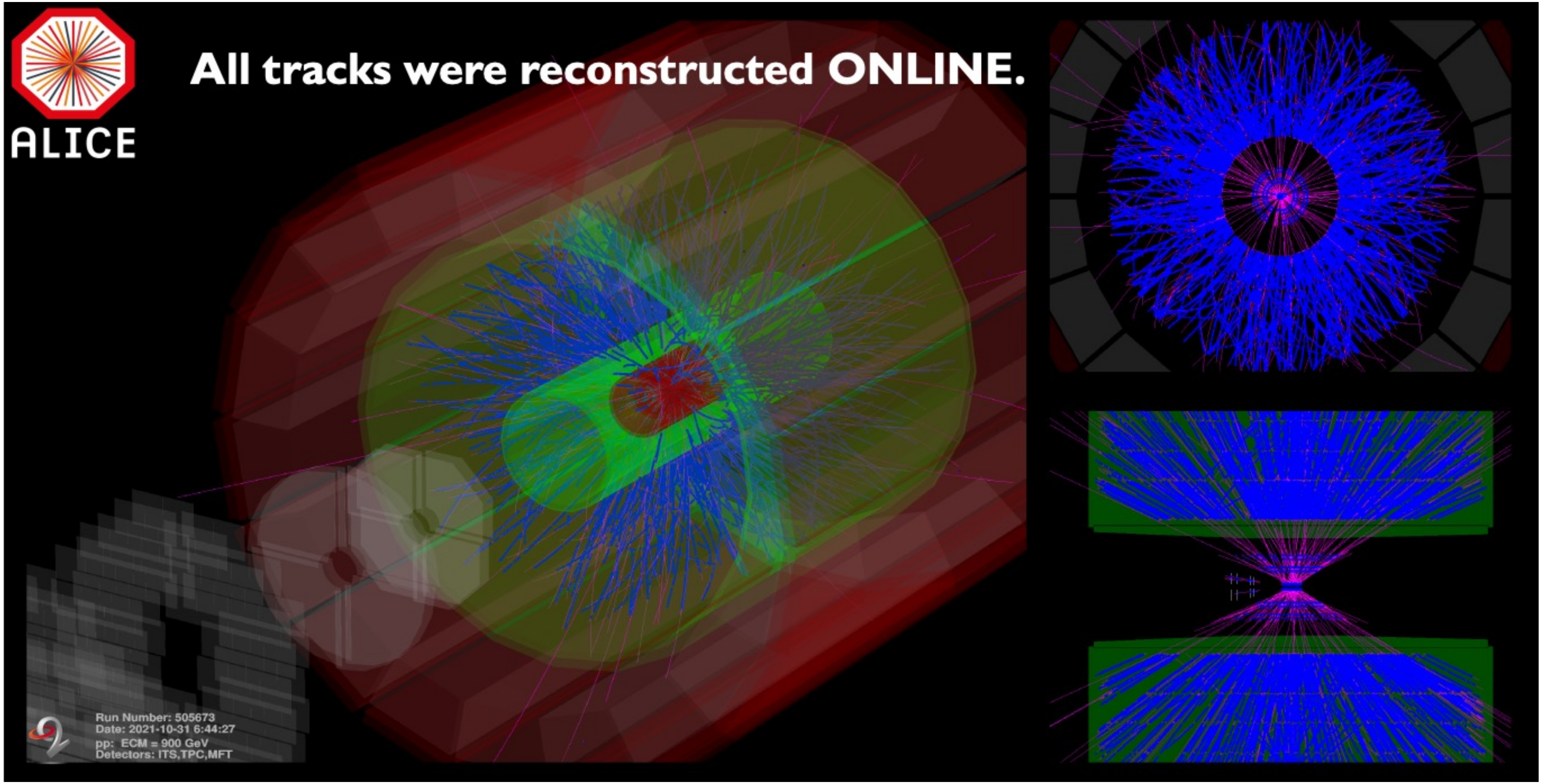

ALICE
ALICE
PROTON PHYSICS: STABLE BEAMS
ALICE Control Room

A Large Heavy Ion Experiment (ALICE)

- Significant upgrades for Run 3 to handle 50 kHz Pb-Pb collisions & high occupancies
- Many new systems
  - Inner Tracking System (ITS2)
  - Muon Forward Tracker
  - Fast Interaction Trigger
  - Time Projection Chamber (TPC) with GEMS
  - Online-offline software framework
- 3 TB/s readout with specialized hardware and GPU-based data reduction

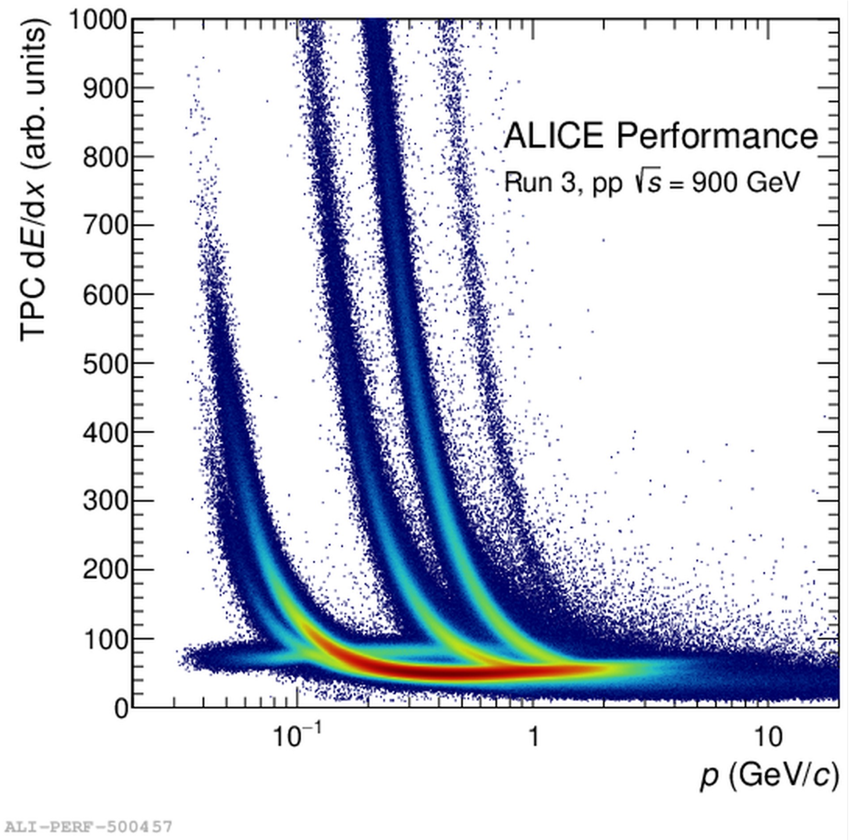


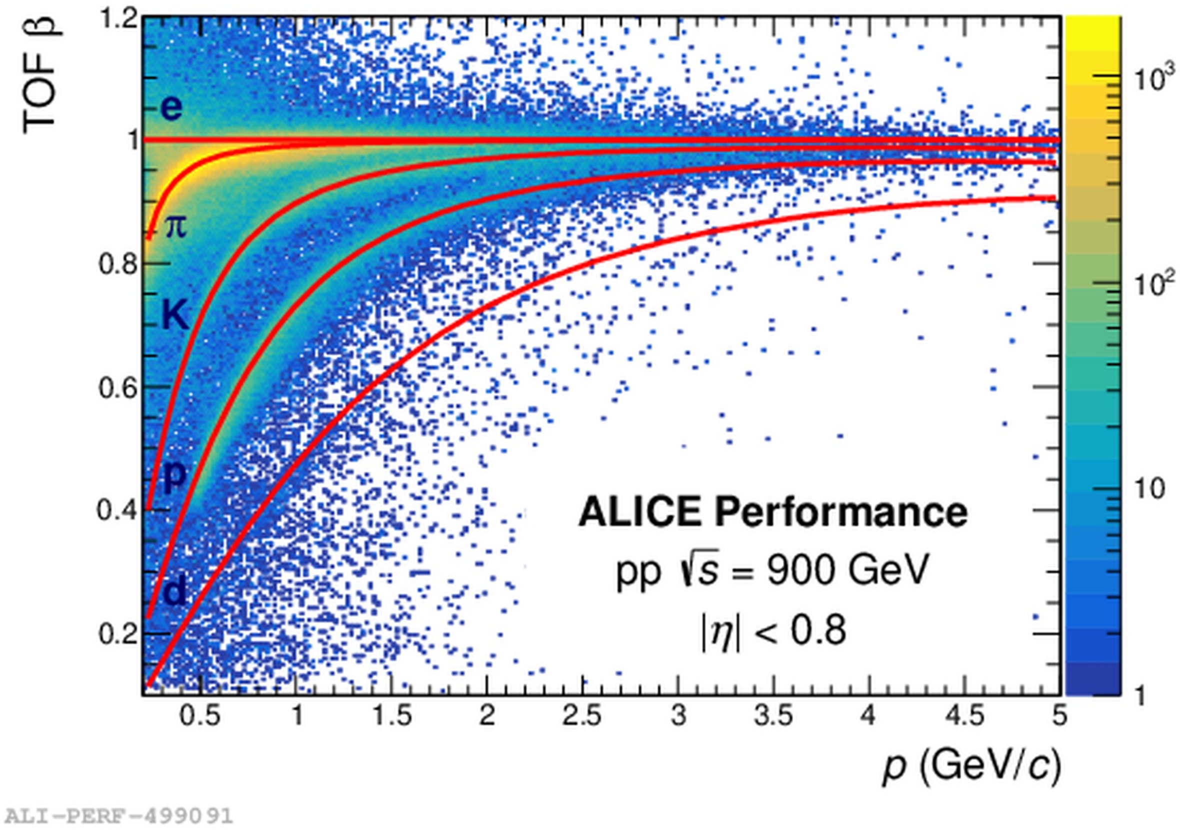


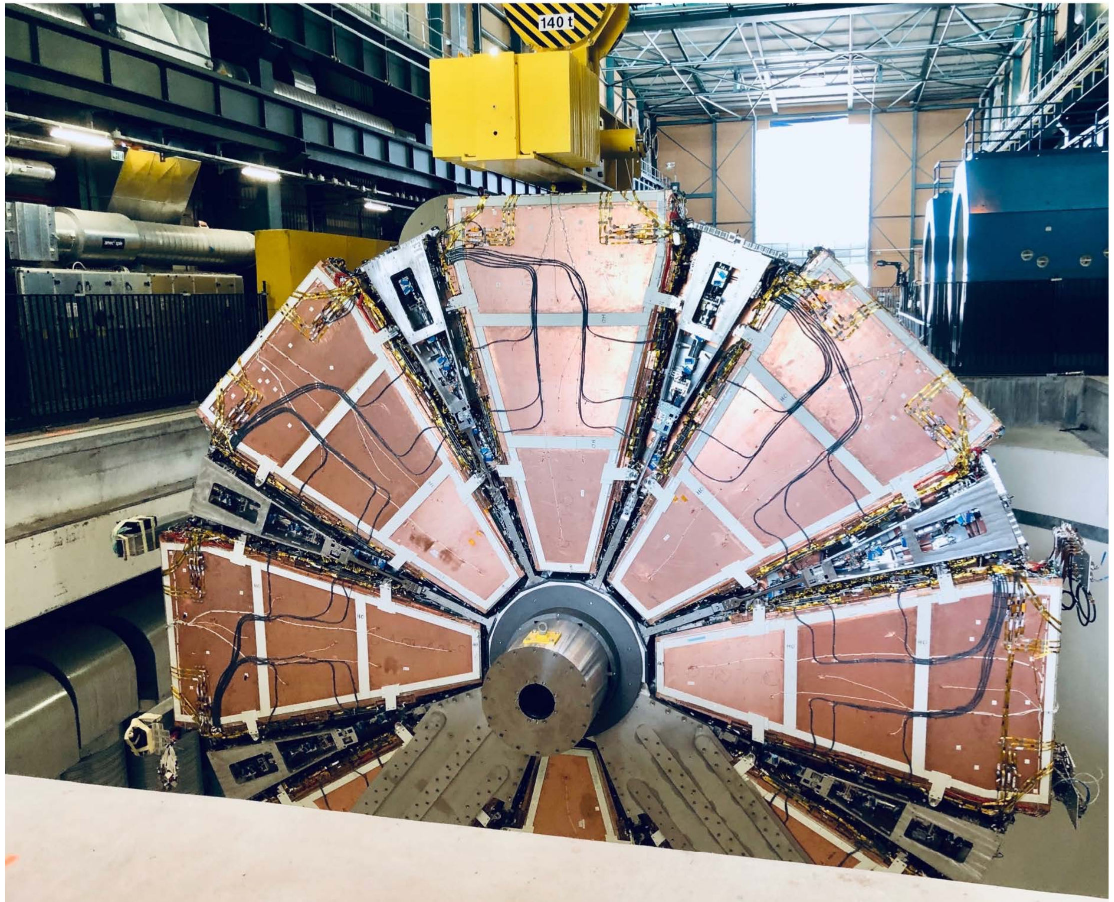

ALICE
All tracks were reconstructed ONLINE.
Run Number: 505673
Date: 2021-10-31 6:44:27
pp: ECM = 900 GeV
Detectors: ITS,TPC,MFT

ALICE Performance: from November pilot beam

Beautiful particle ID from dE/dx and time of flight measurements







THE ATLAS EXPERIMENT
est. 2022
13.6 TeV
LHC RUN 3

ATLAS Upgrades for Run 3

MUON NEW SMALL WHEELS (NSW)

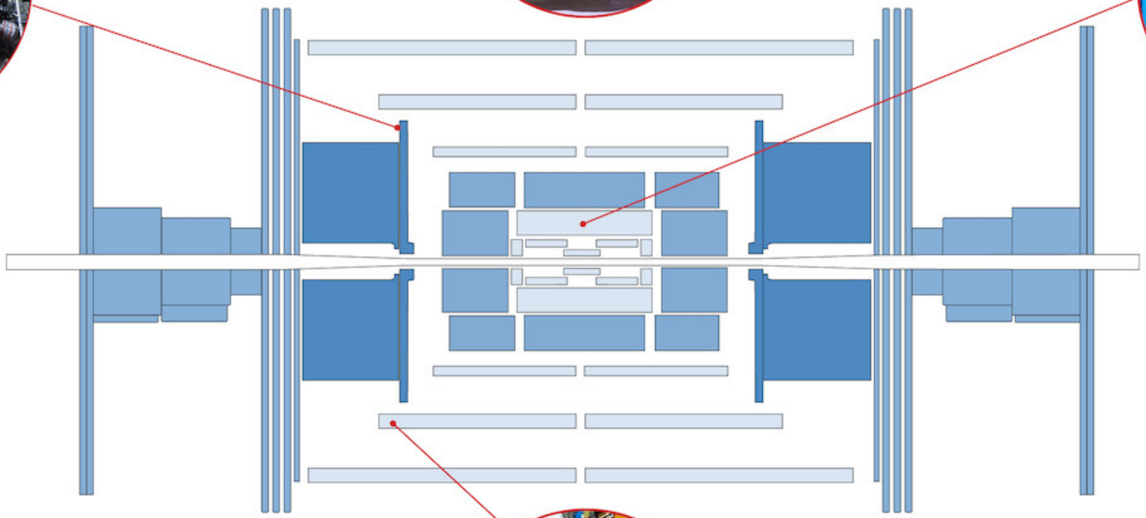
Installed new muon detectors with precision tracking and muon selection capabilities. Key preparation for the HL-LHC.

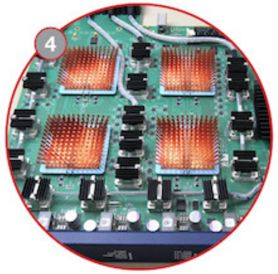
NEW READOUT SYSTEM FOR THE NSWs

The NSW system includes two million micromega readout channels and 350 000 small strip thin-gap chambers (sTGC) electronic readout channels.

LIQUID ARGON CALORIMETER

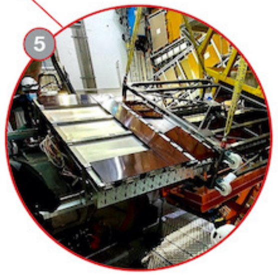
New electronics boards installed, increasing the granularity of signals used in event selection and improving trigger performance at higher luminosity.





TRIGGER AND DATA ACQUISITION SYSTEM (TDAQ)

Upgraded hardware and software allowing the trigger to spot a wider range of collision events while maintaining the same acceptance rate.



NEW MUON CHAMBERS IN THE CENTRE OF ATLAS

Installed small monitored drift tube (sMDT) detectors alongside a new generation of resistive plate chamber (RPC) detectors, extending the trigger coverage in preparation for the HL-LHC.

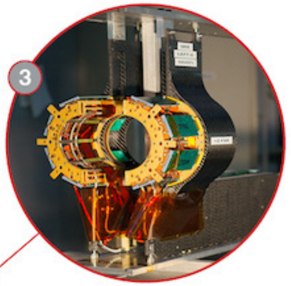
ATLAS FORWARD PROTON (AFP)

Re-designed AFP time-of-flight detector, allowing insertion into the LHC beamline with a new “out-of-vacuum” solution.

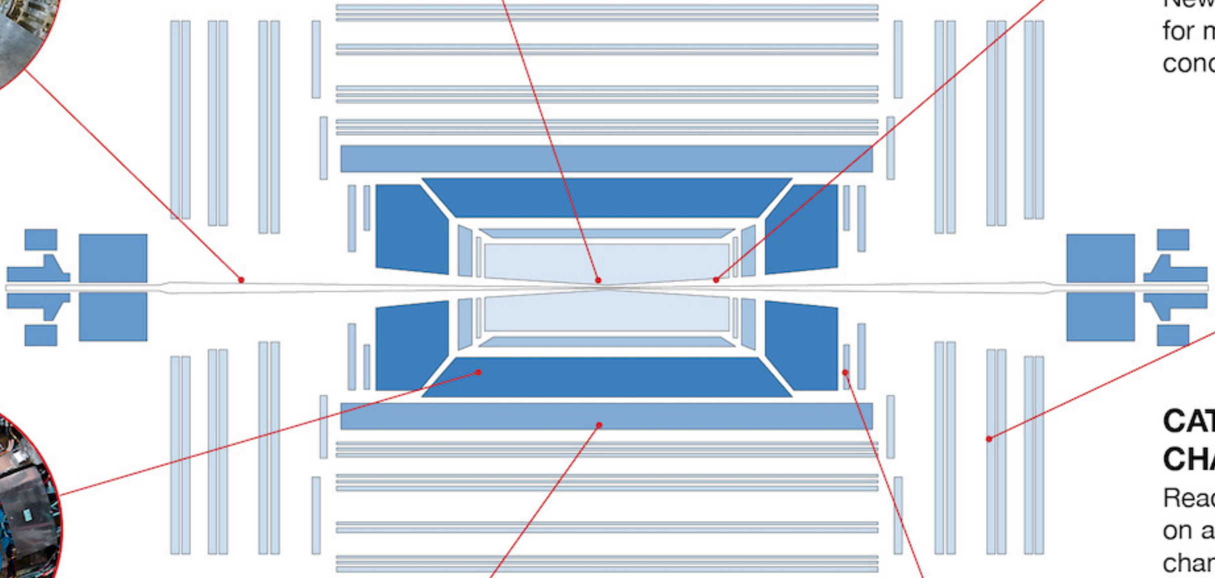
CMS Upgrades for Run 3

BEAM PIPE
Replaced with an entirely new one compatible with the future tracker upgrade for HL-LHC, improving the vacuum and reducing activation.

PIXEL TRACKER
All-new innermost barrel pixel layer, in addition to maintenance and repair work and other upgrades.

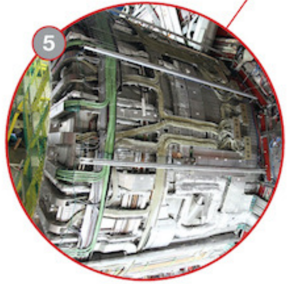


BRIL
New generation of detectors for monitoring LHC beam conditions and luminosity.



CATHODE STRIP CHAMBERS (CSC)
Read-out electronics upgraded on all the 180 CSC muon chambers allowing performance to be maintained in HL-LHC conditions.

HADRON CALORIMETER
New on-detector electronics installed to reduce noise and improve energy measurement in the calorimeter.



SOLENOID MAGNET
New powering system to prevent full power cycles in the event of powering problems, saving valuable time for physics during collisions and extending the magnet lifetime.

GAS ELECTRON MULTIPLIER (GEM) DETECTORS
An entire new station of detectors installed in the endcap-muon system to provide precise muon tracking despite higher particle rates of HL-LHC.

Run 3 ATLAS and CMS Physics Program

- Take advantage of **trigger improvements** to push on searches for unconventional signatures, such as long-lived particles.
- Make **Run 2 + Run 3 combinations** to improve precision of Higgs boson production/decay cross sections and other SM measurements
  - aim to constrain $H \to bb$ and $H \to \mu\mu$ couplings at 20% level
- Benefit from increased data push mass reach on **searches** for supersymmetric or exotic particles
  - up to a 1 TeV increase can be achieved with respect to Run 2 in some cases
- Pushing on **techniques** such as "parking" data, "scouting" or "trigger-level-analysis" to access challenging phase space for b-physics or low-momentum hadronic physics.

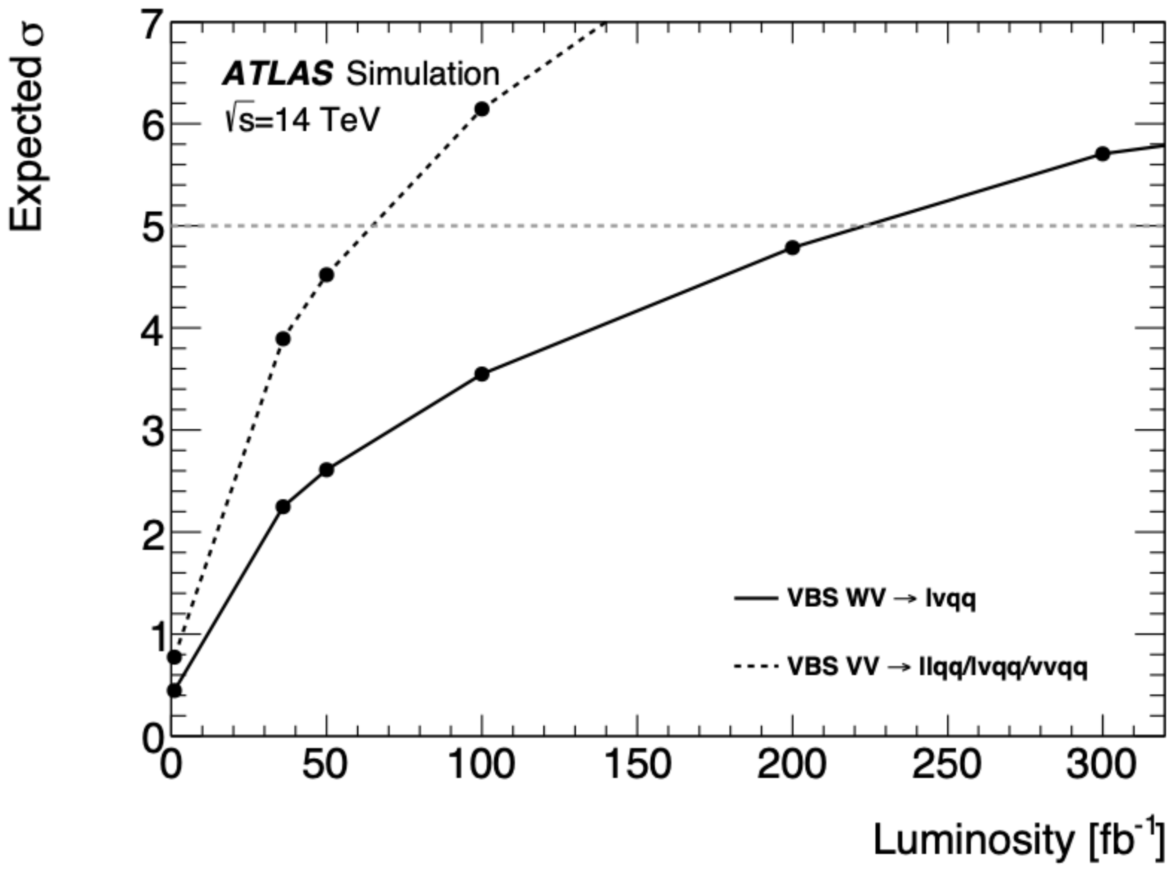
Inclusive vector boson scattering (VBS)

Important for the story of EWK symmetry breaking:

Without the SM Higgs boson, the longitudinal VV scattering cross section increases with $\sqrt{s}$ and would violate unitarity at high energies!

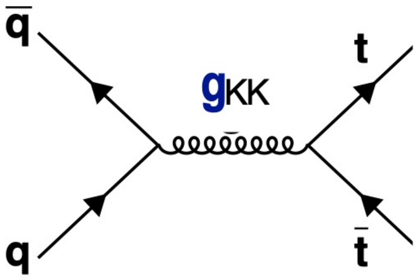
Additionally, VBS provides indirect searches for BSM by giving access to anomalous quartic gauge couplings.

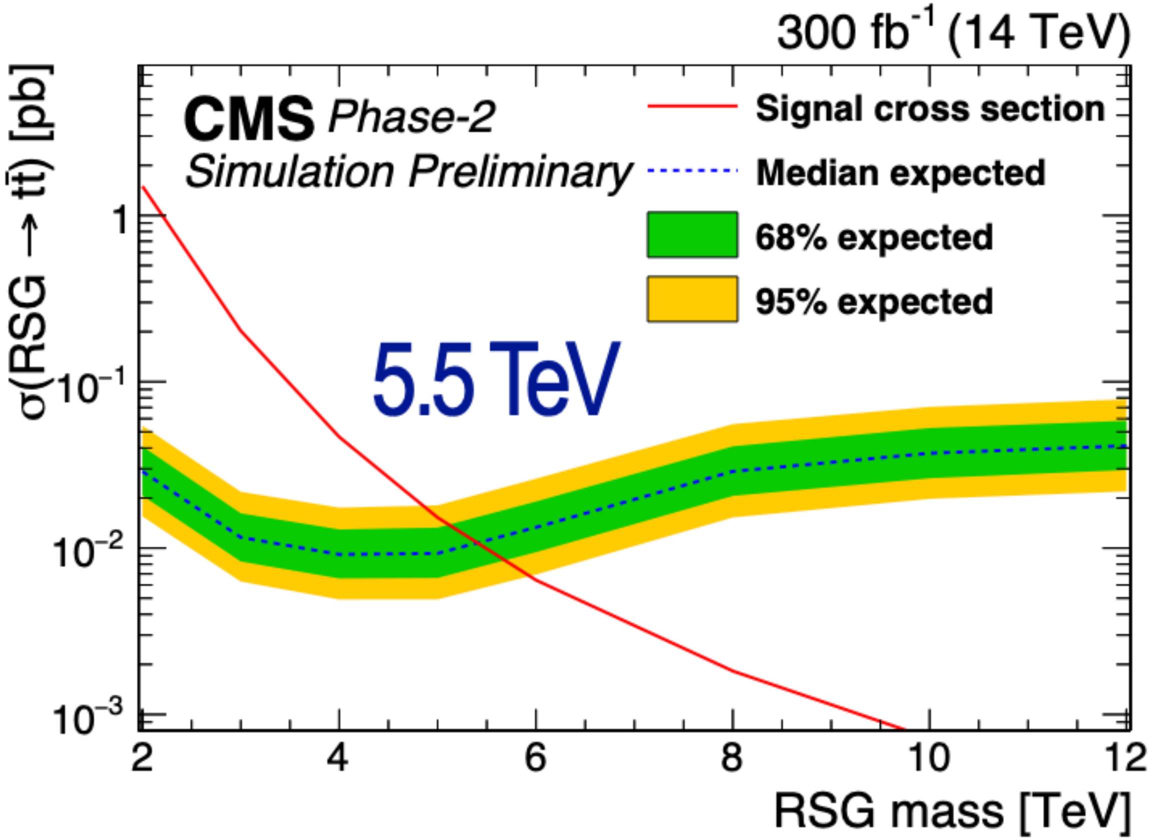
The study of **inclusive** VV scattering was done assuming $\sqrt{s} = 14\, TeV$ so is a bit optimistic for Run 3, but gives some confidence that we will have 5 sigma significance with Run 3 data. Picking out the **longitudinal component** requires the HL-LHC for sensitivity.



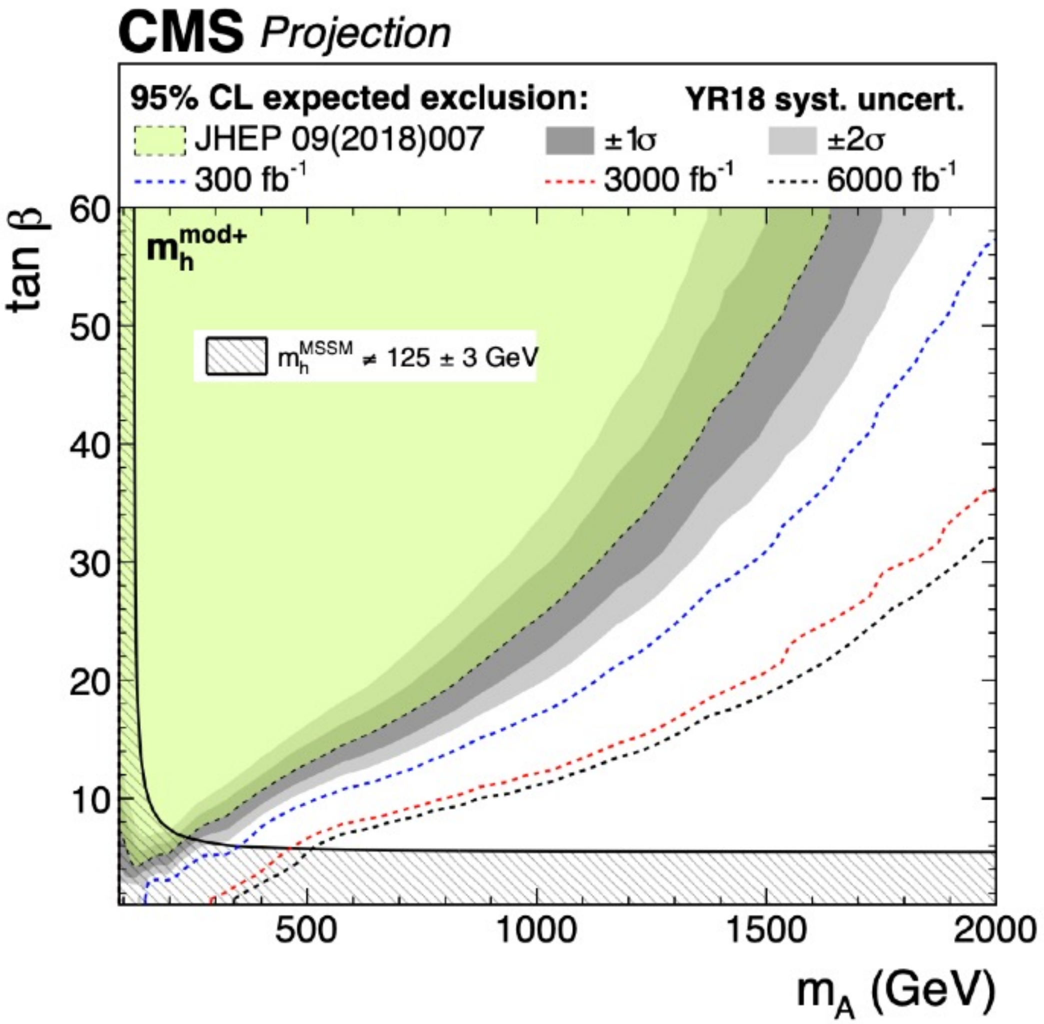
Can extend search reach with additional data

Randall-Sundrum particle reach extended by ~1 TeV over Run 2. (Note that many Run 3 projections were done assuming 14 TeV, so need slight adjustments…)



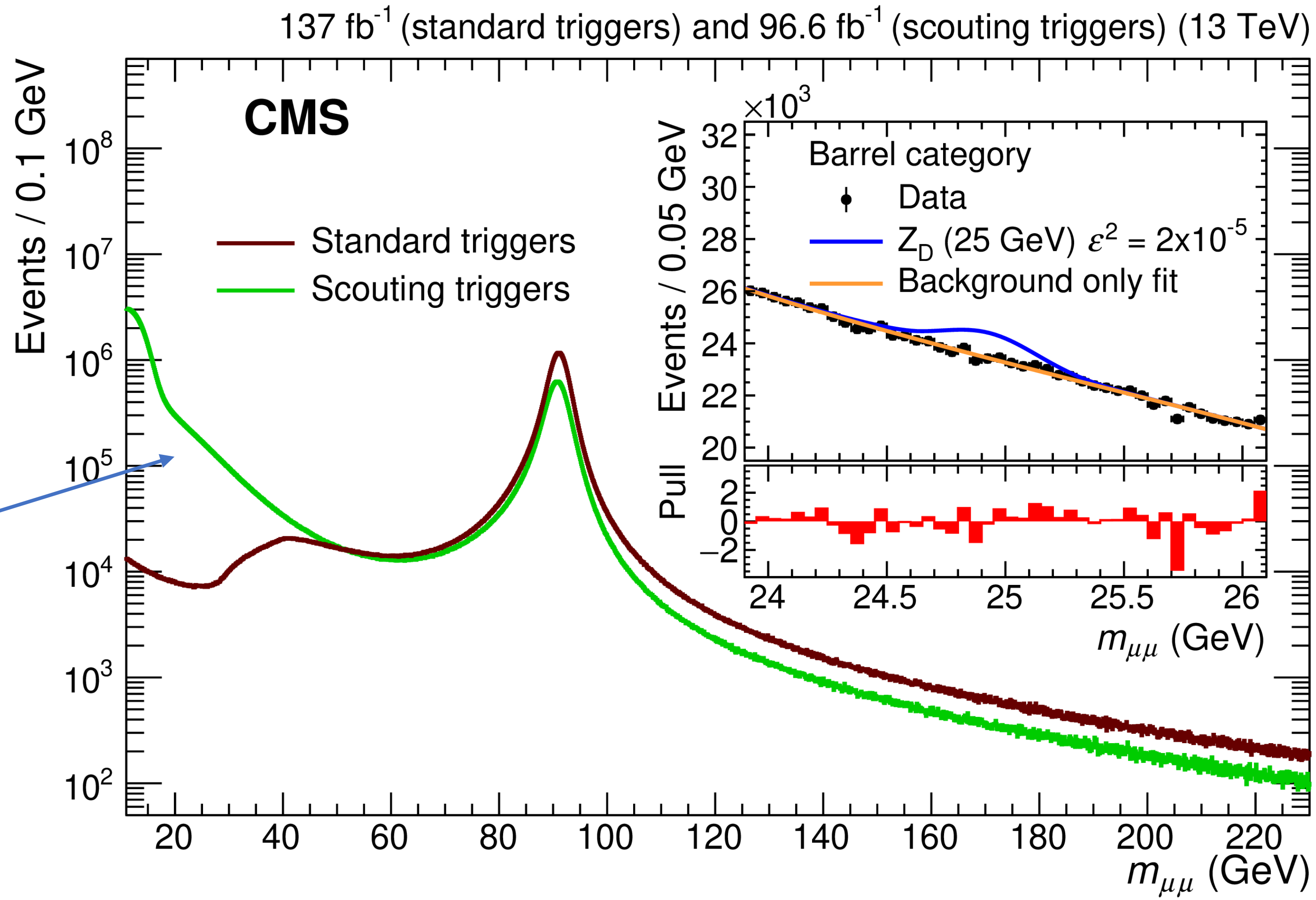


$H/A \rightarrow \tau\tau$ Search exclusions

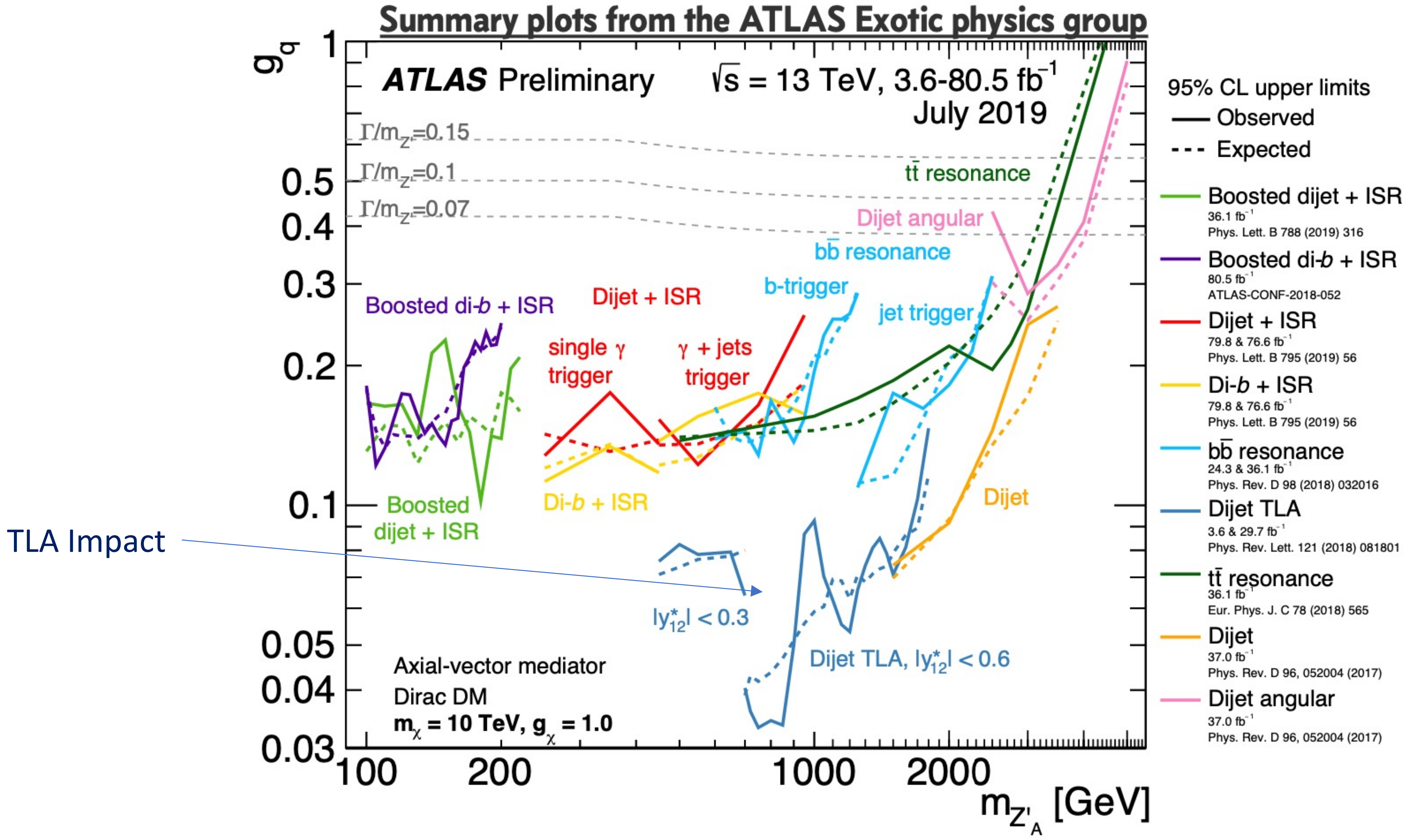


We've seen that trigger scouting (CMS) provides access to expanded phase space

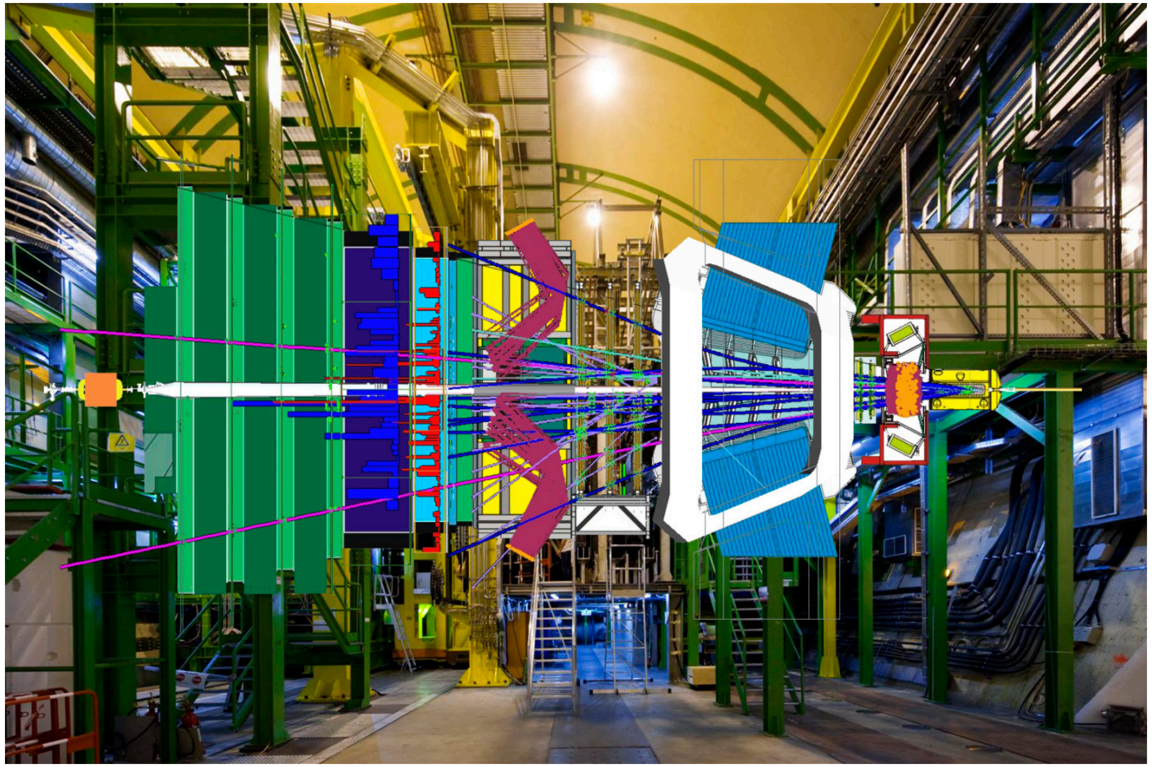
This Run 2 search for low-mass dimuon pairs provides a nice example of trigger scouting opening up phase space



Similarly, trigger-level analysis (TLA @ ATLAS) has extended the reach, shown here for Z'

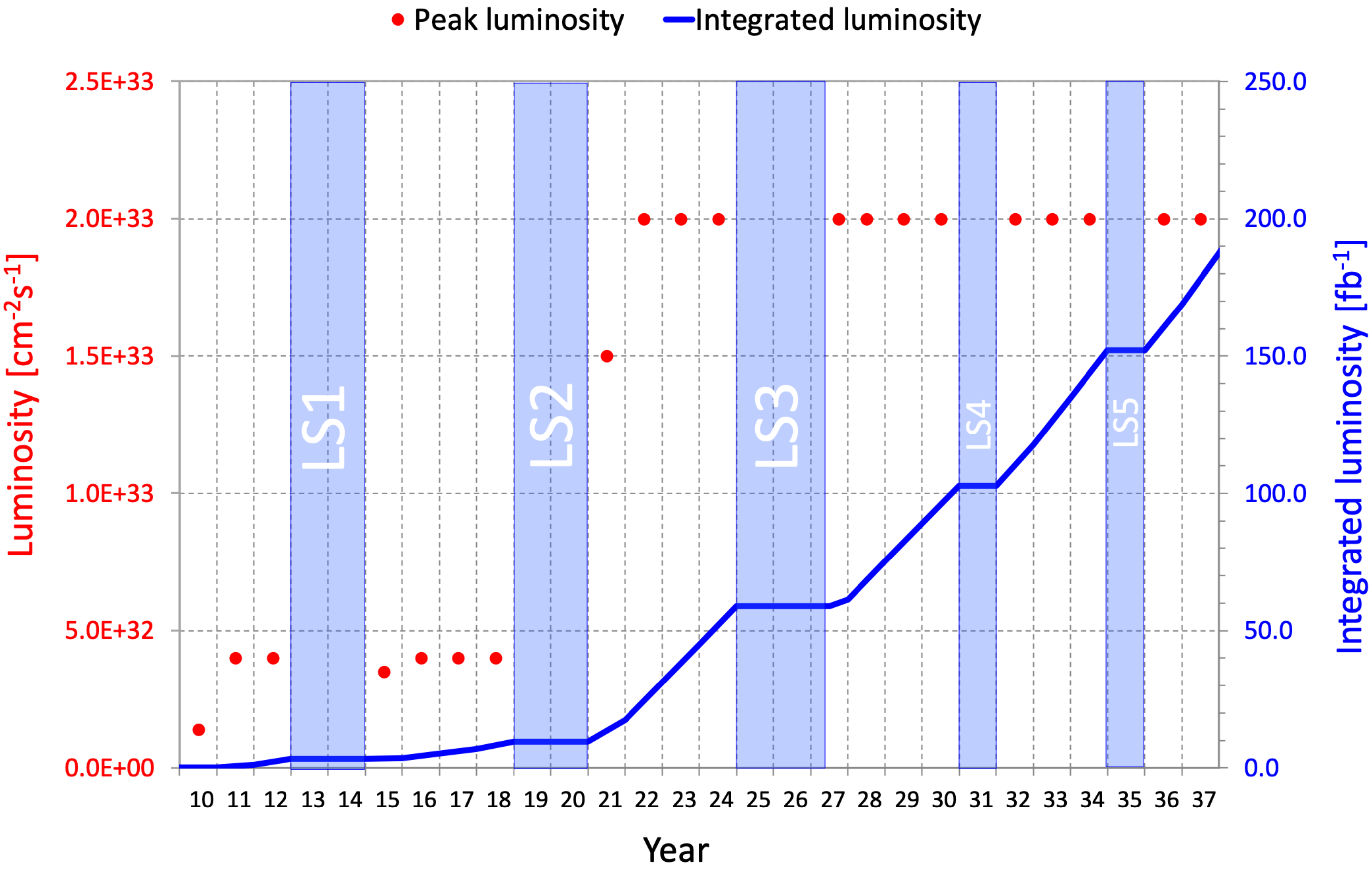


LHCb:
Run 3 and beyond



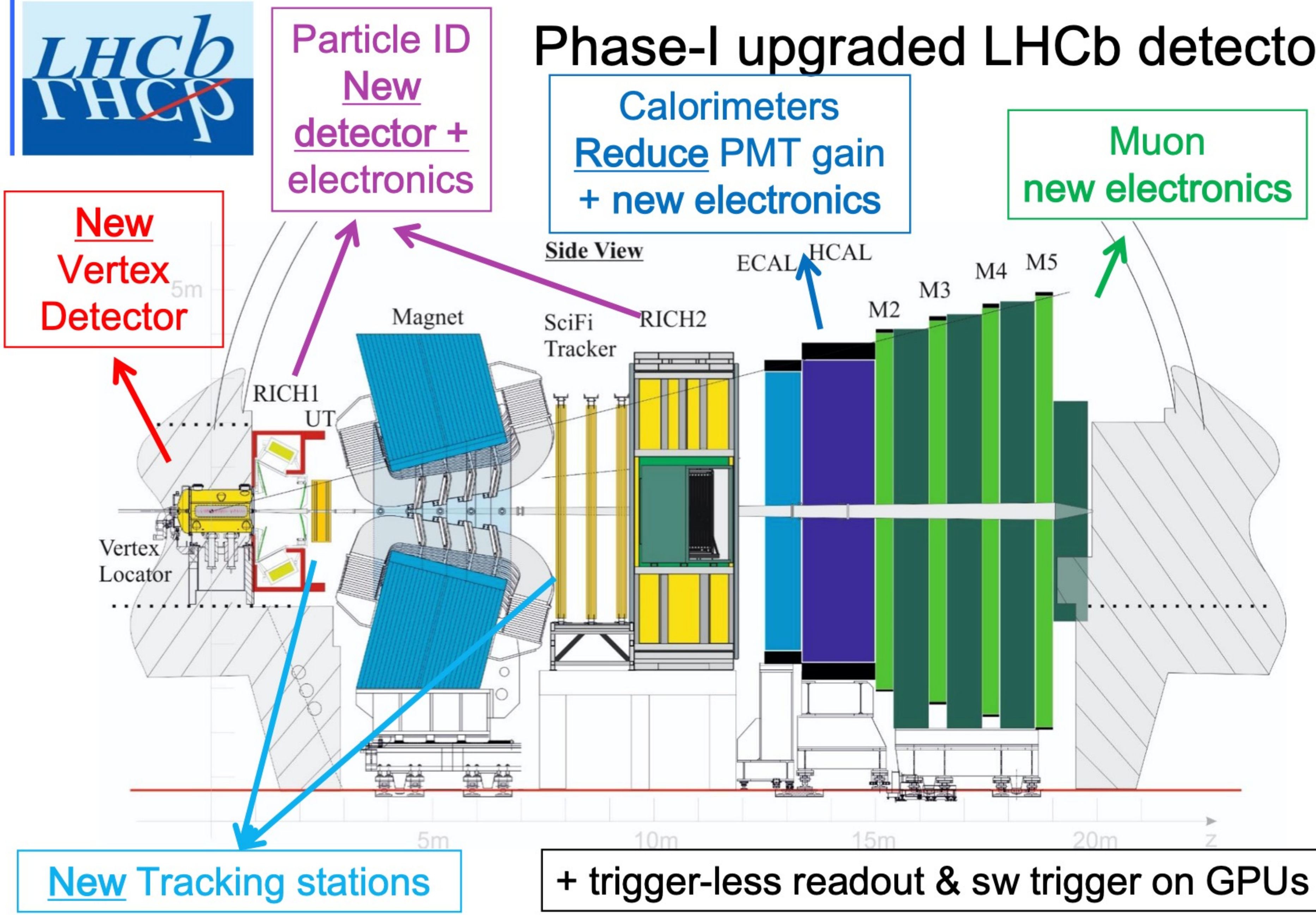
- LHCb is a forward arm spectrometer, working with particles from collisions in the forward region ($2 < \eta < 5$)
- Targets precision measurements in the b and charm quark sectors
- Has extended to access to exploring QCD and EW physics
- Participates in pp running, with lower luminosities, and heavy ion runs

NOTE: LS3 has been shifted one year forward (see next slide)



LHCb

Phase-I upgraded LHCb detector



+ trigger-less readout & sw trigger on GPUs

See talk by F. Alessio for more details

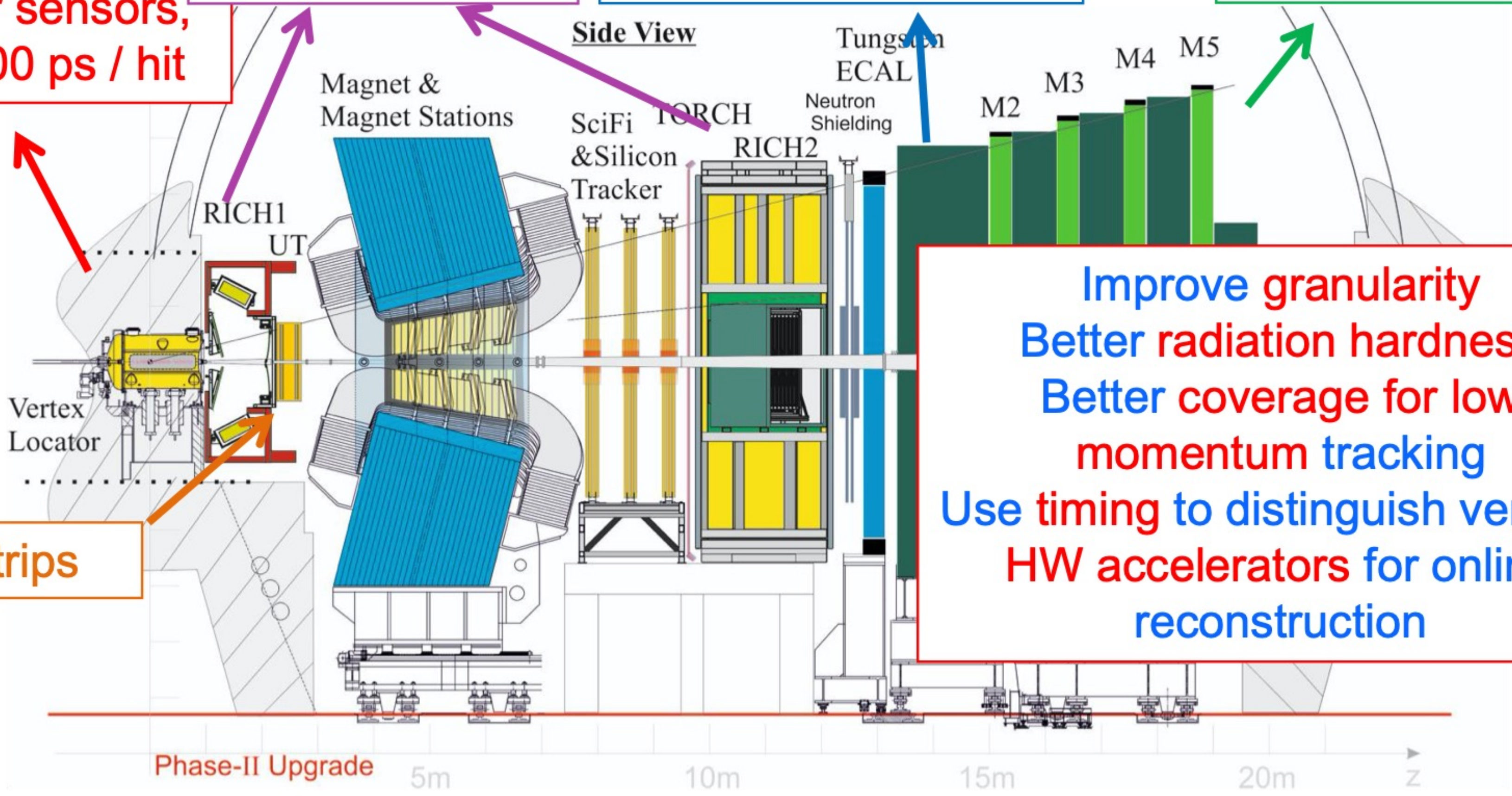
Phase-II upgraded LHCb detector

New Vertex Detector II
Smaller pixels, thinner sensors,
$\sigma_t < 200$ ps / hit

RICH with new photon detectors
$\sigma_t < 100$ ps / photon

ECAL with finer segmentation and timing with
$\sigma_t \approx 20 - 50$ ps

MUON with MPGD (μ-RWELL), modified shielding



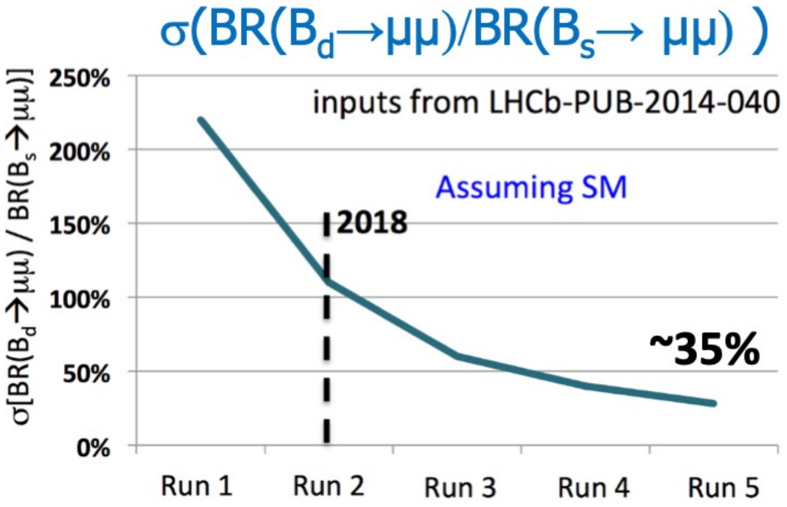
Si-strips

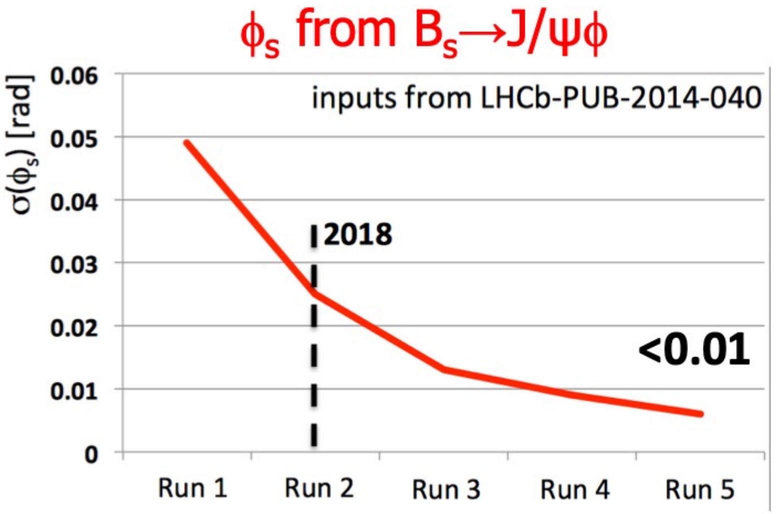
Improve granularity
Better radiation hardness
Better coverage for low momentum tracking
Use timing to distinguish vertices
HW accelerators for online reconstruction

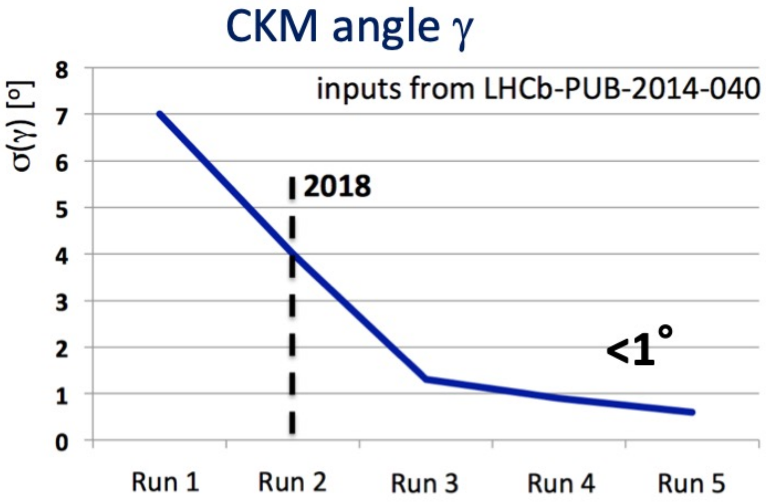
+ trigger-less readout (PCIe Gen4++) & accelerators for online reconstruction

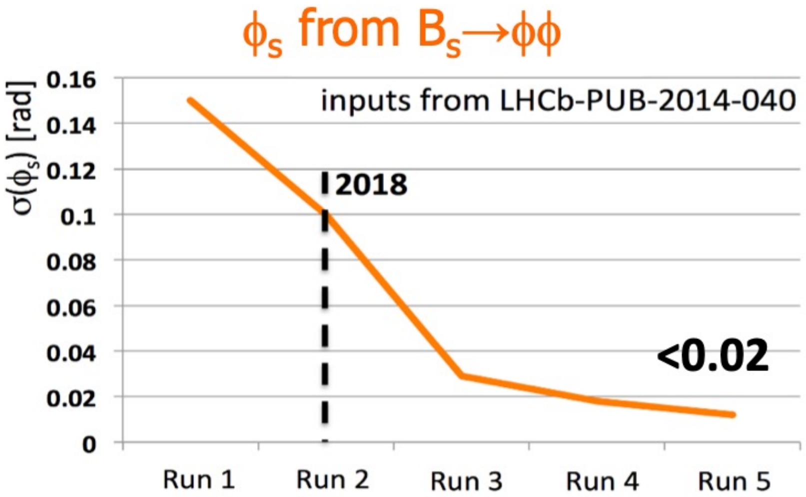
See talk by F. Alessio for more details

Sensitivity of several high-priority LHCb measurements



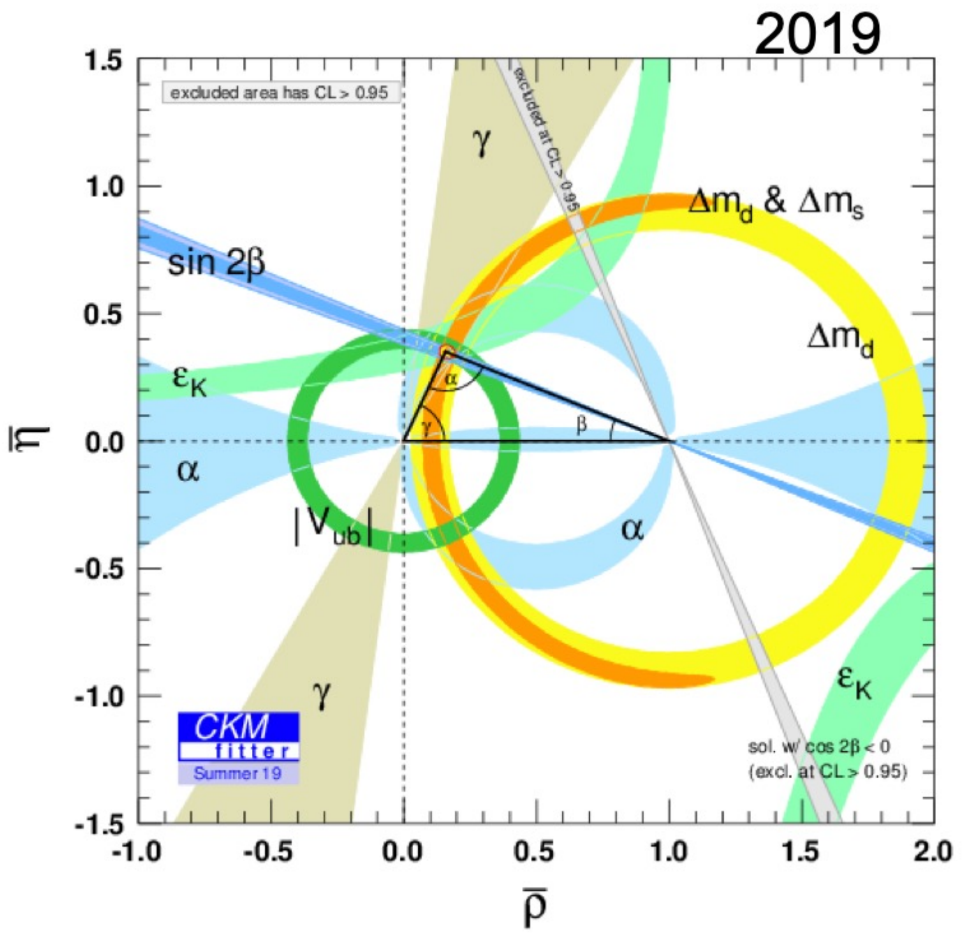


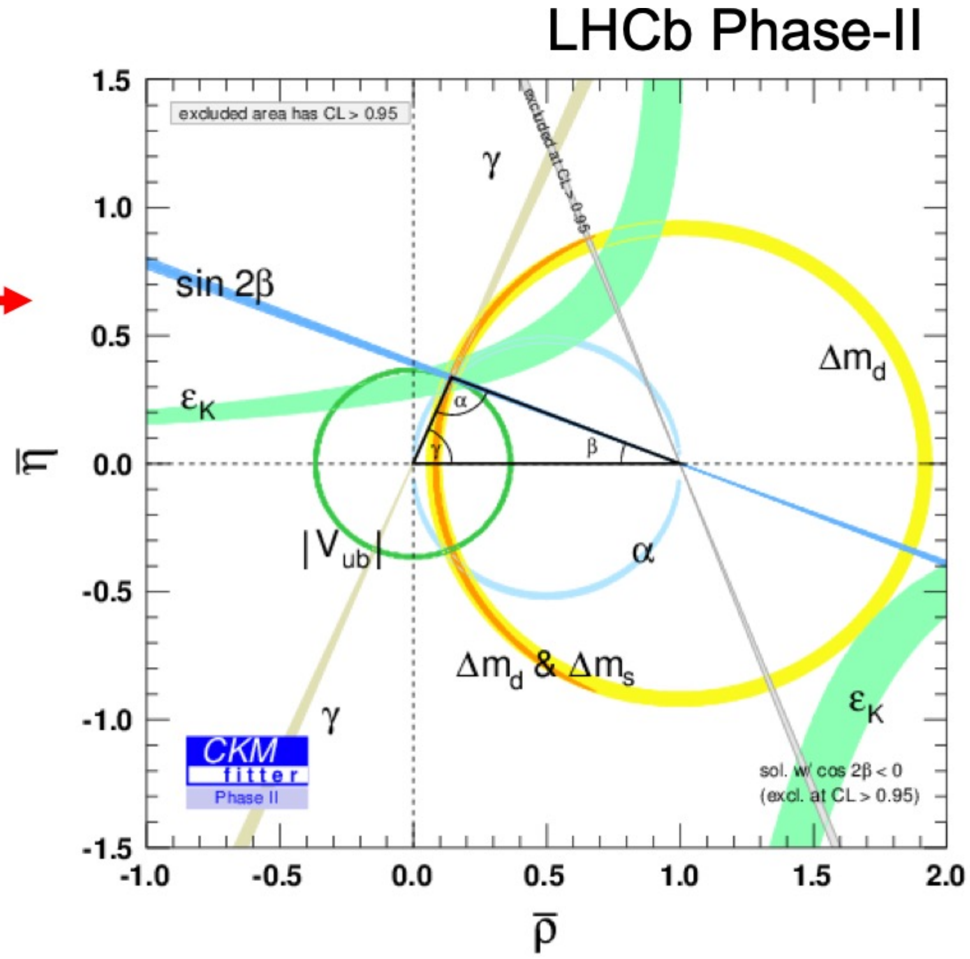




See talk by F. Alessio for more details

LHCb improvements in CKM measurements (Phase-II)





LHCb (300 fb^{-1}), Belle-II (50 ab^{-1})
ATLAS & CMS (3000 fb^{-1})

See talk by F. Alessio for more details

$\sigma_\gamma \approx 5°$ (2019) → 1° (Phase 1) → 0.35° (Phase 2)

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II
EW Penguins				
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1	0.025	0.036	0.007
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1	0.031	0.032	0.008
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05
CKM tests				
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$	4°	–	1°
γ, all modes	$(^{+5.0}_{-5.8})^\circ$	1.5°	1.5°	0.35°
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04	0.011	0.005	0.003
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad	14 mrad	–	4 mrad
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad	35 mrad	–	9 mrad
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad	39 mrad	–	11 mrad
a_{sl}^s	33×10^{-4}	10×10^{-4}	–	3×10^{-4}
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6%	3%	1%	1%
$\boldsymbol{B_s^0, B^0 \to \mu^+\mu^-}$				
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90%	34%	–	10%
$\tau_{B_s^0 \to \mu^+\mu^-}$	22%	8%	–	2%
$S_{\mu\mu}$	–	–	–	0.2
$\boldsymbol{b \to c\ell^-\bar{\nu}_l}$ **LUV studies**				
$R(D^*)$	0.026	0.0072	0.005	0.002
$R(J/\psi)$	0.24	0.071	–	0.02
Charm				
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4}	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4}	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4}	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}

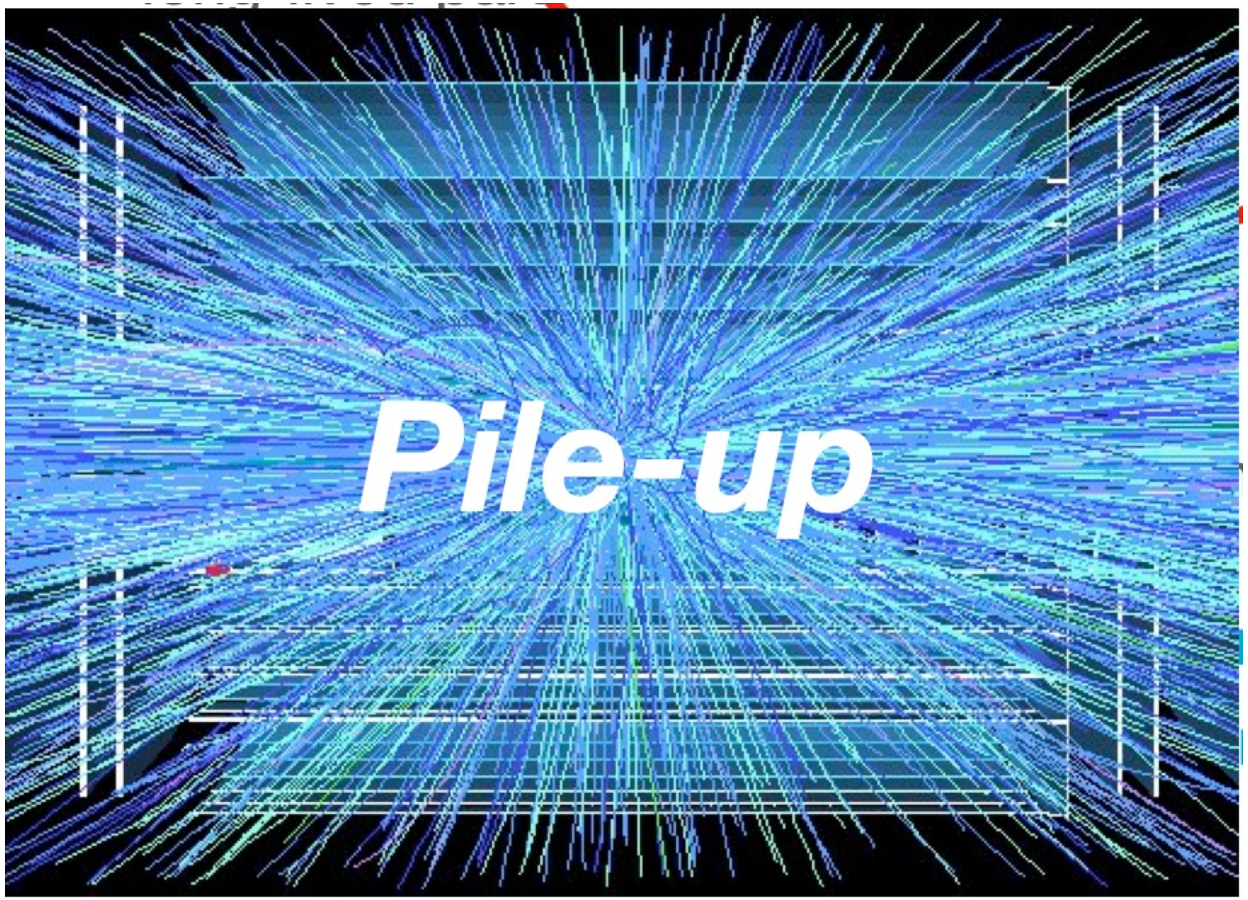
LHCb

Run 3 goal

Run 4 goal

http://arxiv.org/abs/arXiv:1808.08865

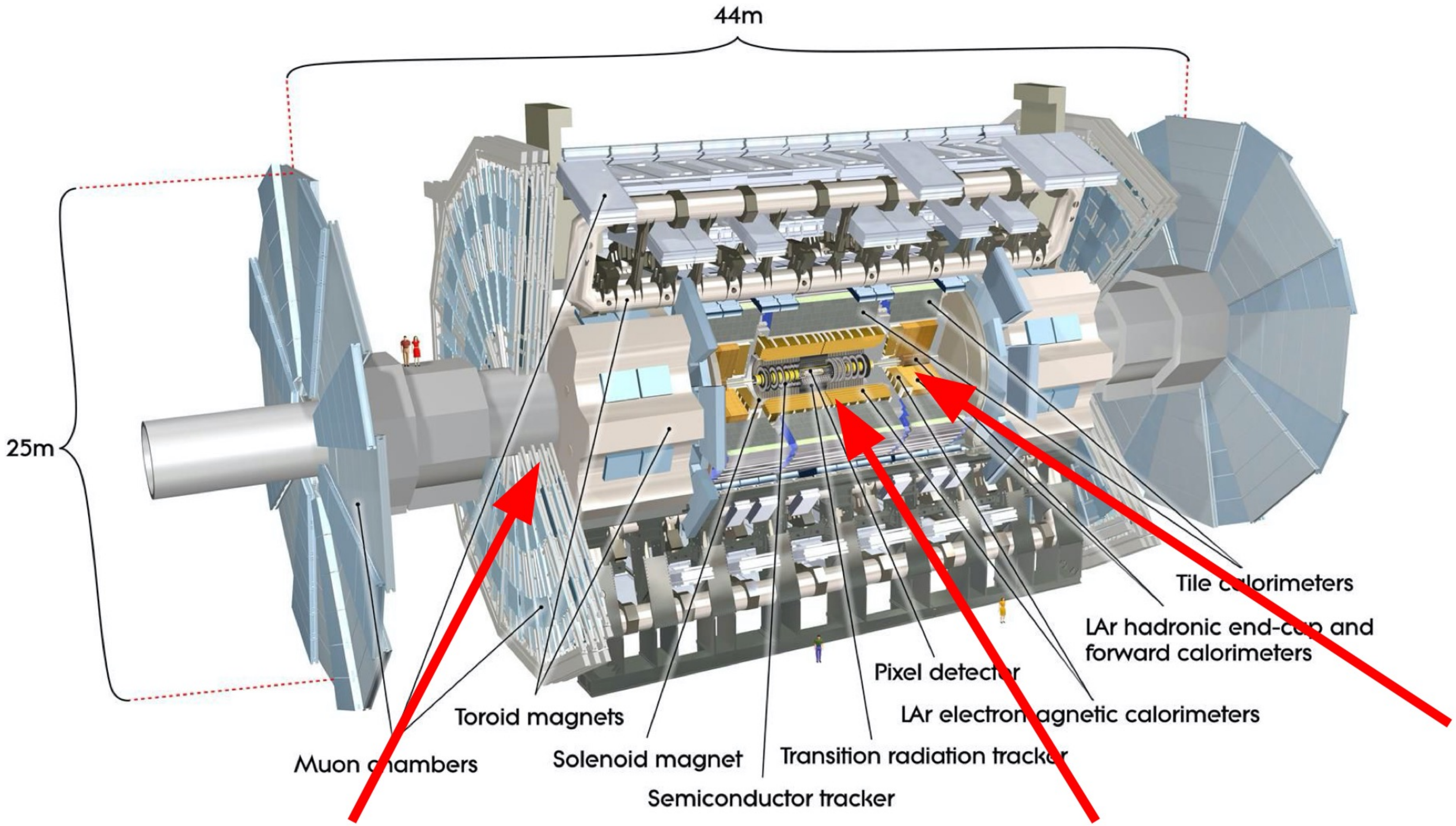
HL-LHC



What is new in the HL-LHC era?

- Higher energy, with $\sqrt{s} = 14$ TeV
- Significant increase in instantaneous luminosity (up to 140 – 200 overlapping interactions)
- Increasing dataset by factor of ten
- Many upgraded or new detector components, including timing detectors

Overview of ATLAS Phase-II Upgrades



Upgraded Trigger and Data Acquisition system

- Level-0 Trigger at 1 MHz
- Improved High-Level Trigger
- (150 kHz full-scan tracking)

Electronics Upgrades

- On-detector and off-detector electronics upgrades of:
- LAr Calorimeter
- Tile Calorimeter
- Muon Detectors

High Granularity Timing Detector (HGTD)

- Forward region
- Precision time recon. (30 ps) with Low-Gain Avalanche Detectors (LGAD)

New Muon Chambers

- Inner barrel region with new Resistive Plate Chambers and new Monitored Drift Tubes (sMDT) detectors

New Inner Tracking Detector (ITk)

- All silicon (9 layers), up to $|\eta| = 4$

Additional small upgrades

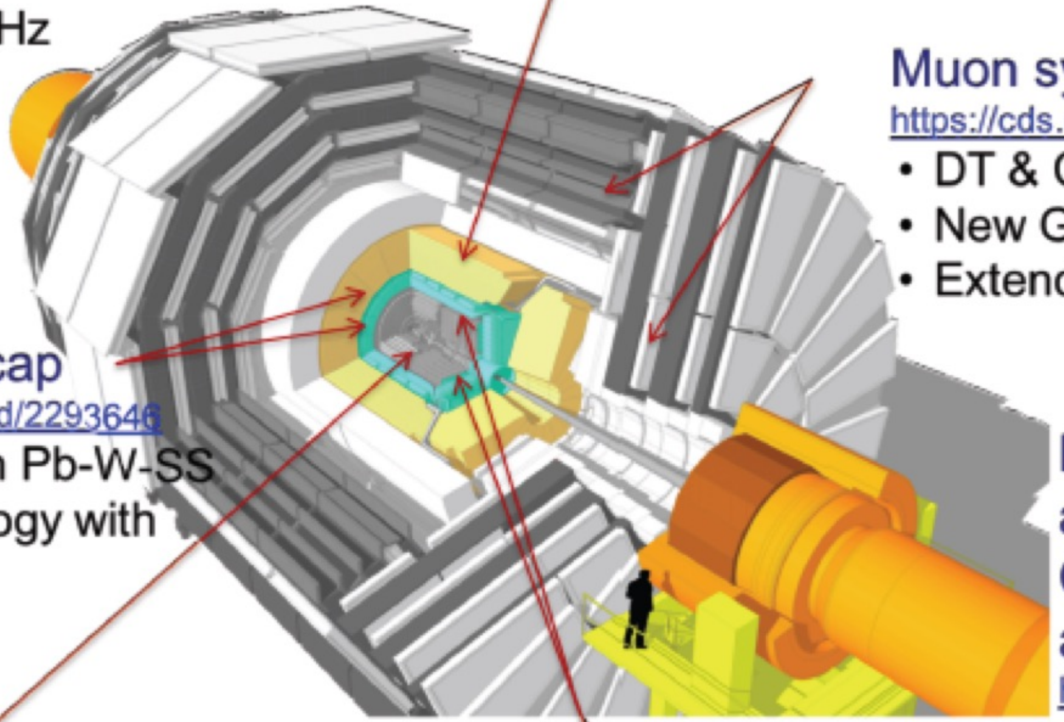
- Luminosity detectors (1% precision)
- HL-ZDC (Heavy Ion physics)

Overview of CMS Phase-II Upgrades

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 $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$



Calorimeter Endcap
https://cds.cern.ch/record/2293646
- Si, Scint+SiPM in Pb-W-SS
- 3D shower topology with precise timing

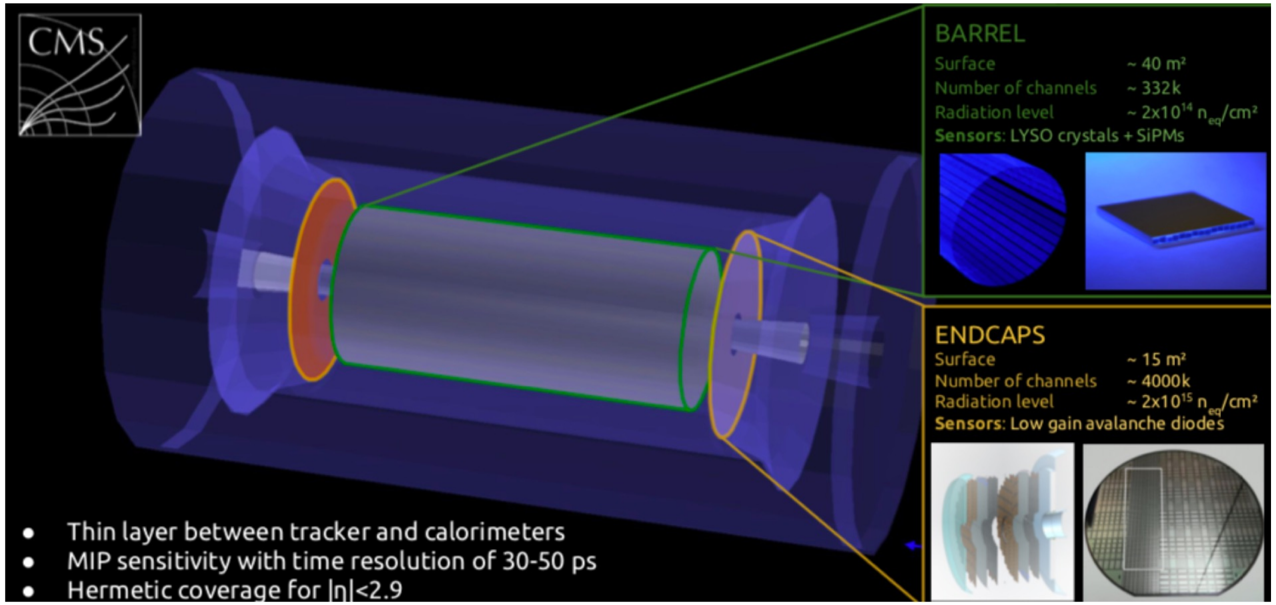
Beam Radiation Instr. and Luminosity, and Common Systems and Infrastructure
https://cds.cern.ch/record/2020886

Tracker https://cds.cern.ch/record/2272264
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$

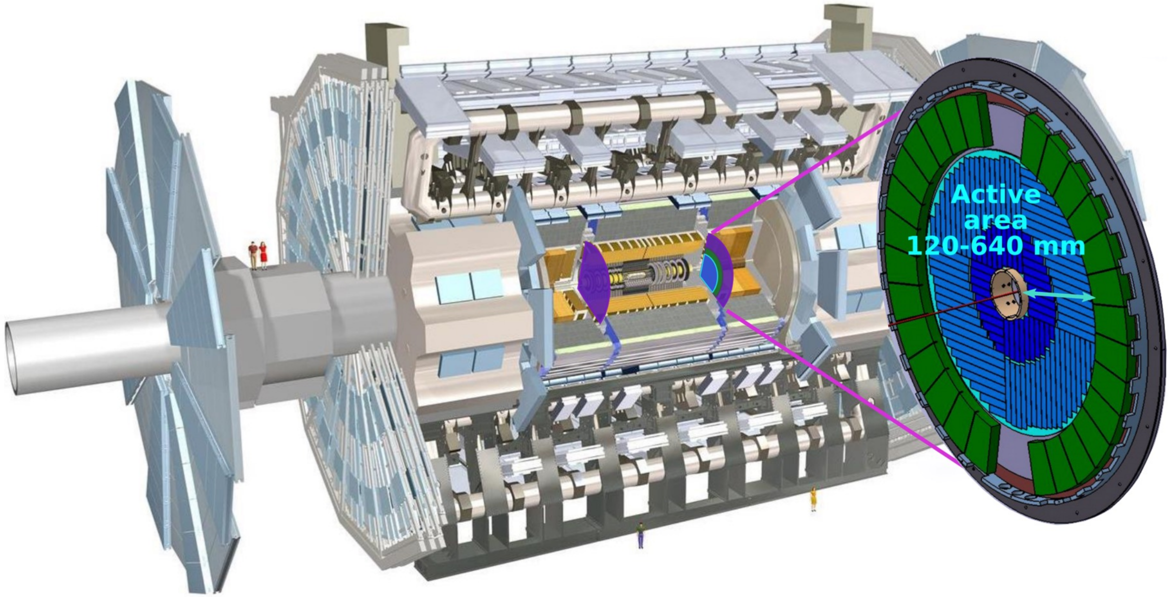
MIP Timing Detector
https://cds.cern.ch/record/2296612
- $\simeq$ 30 ps resolution
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

A quick aside regarding timing…

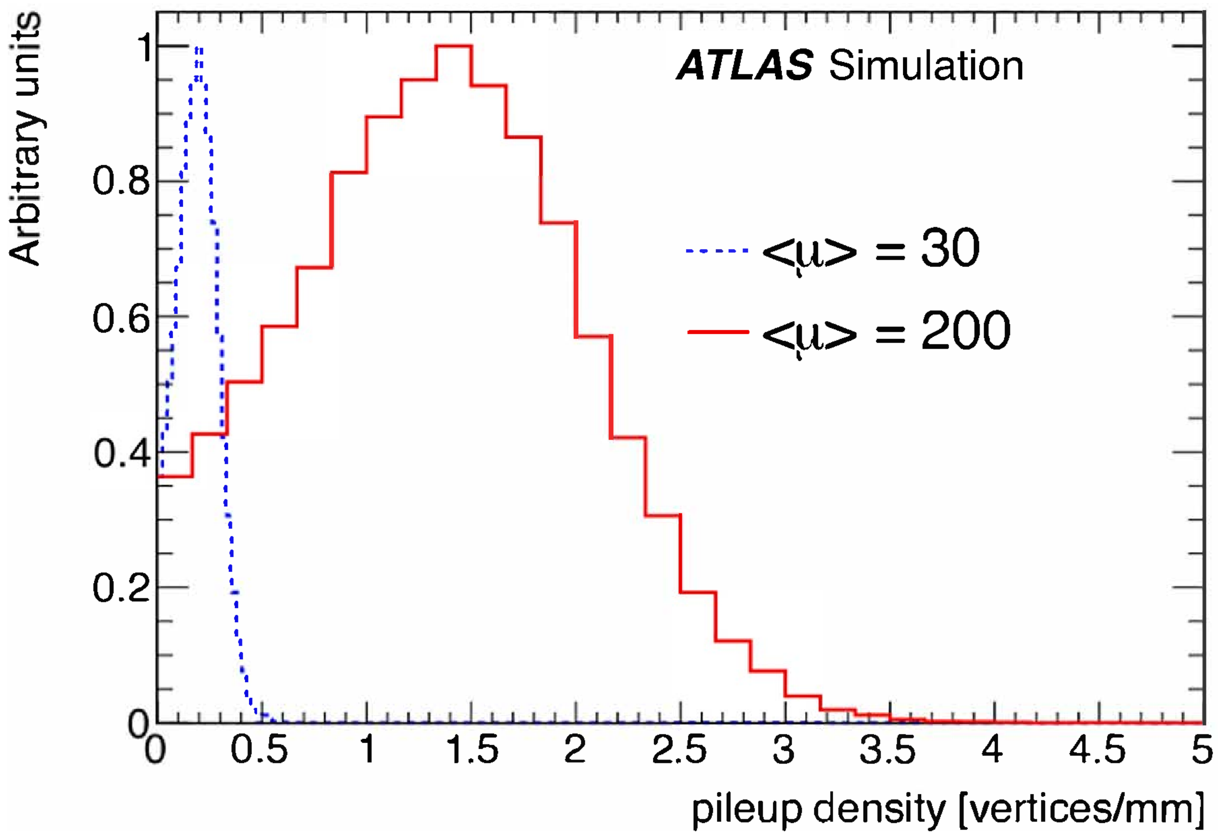
CMS MIP Timing Detector (MTD)

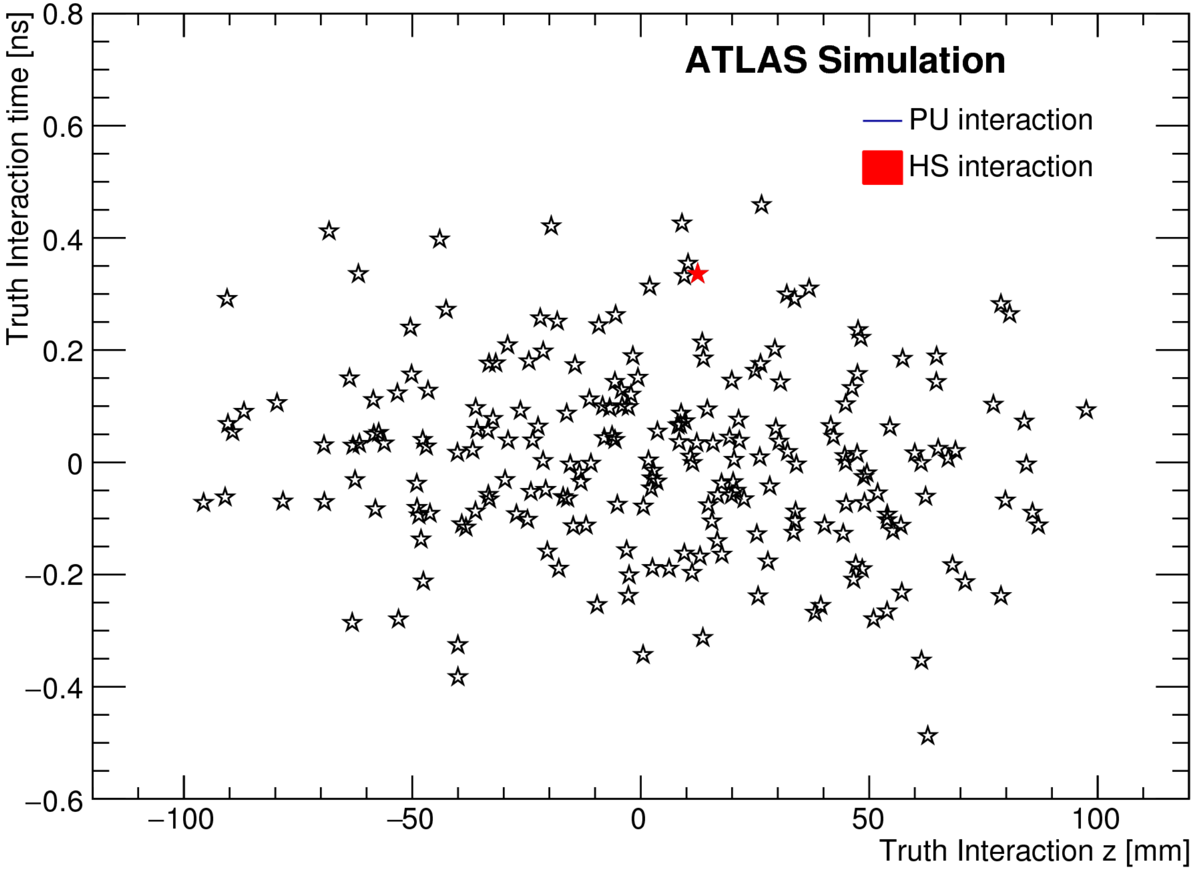


ATLAS High-Granularity Timing Detector (HGTD)

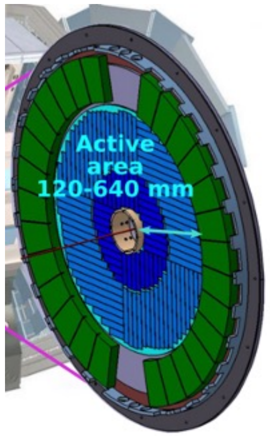


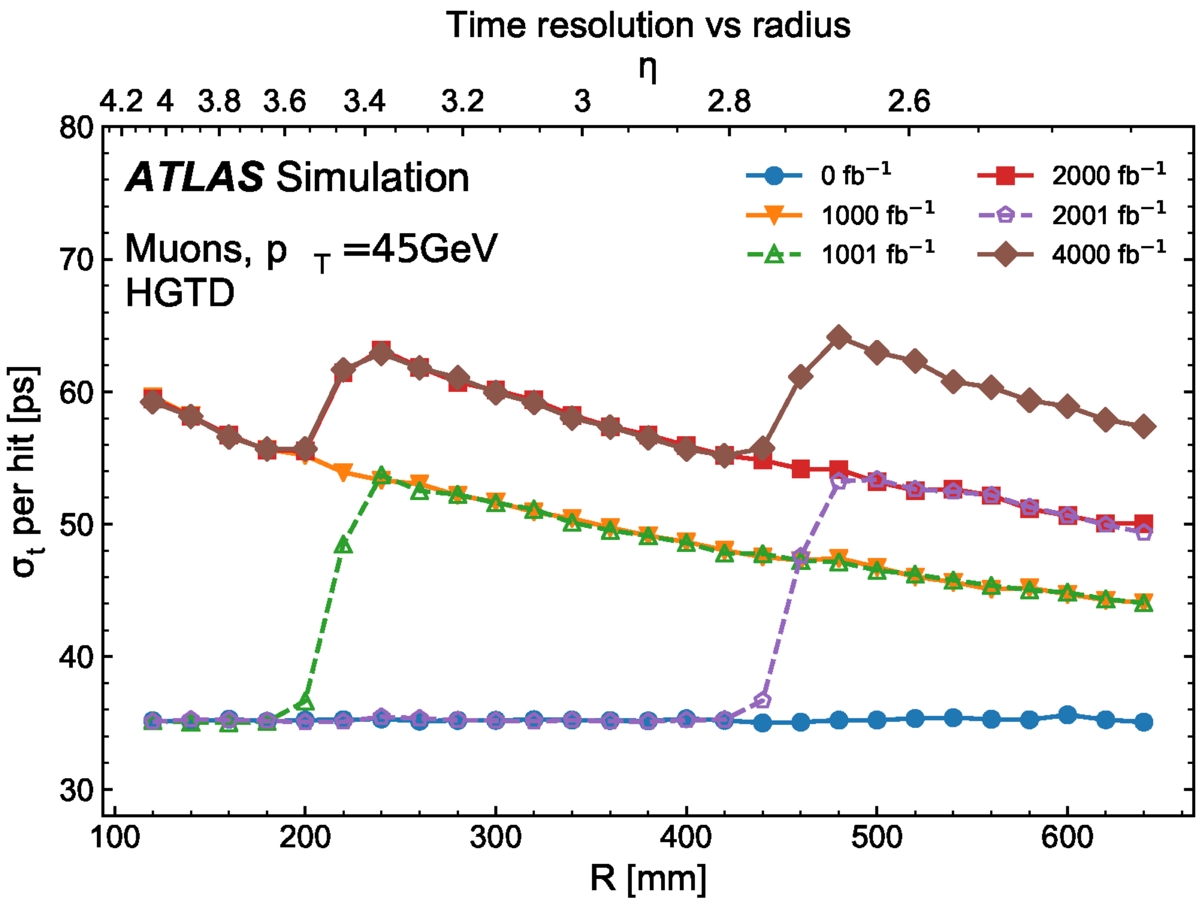
The potential of timing information…

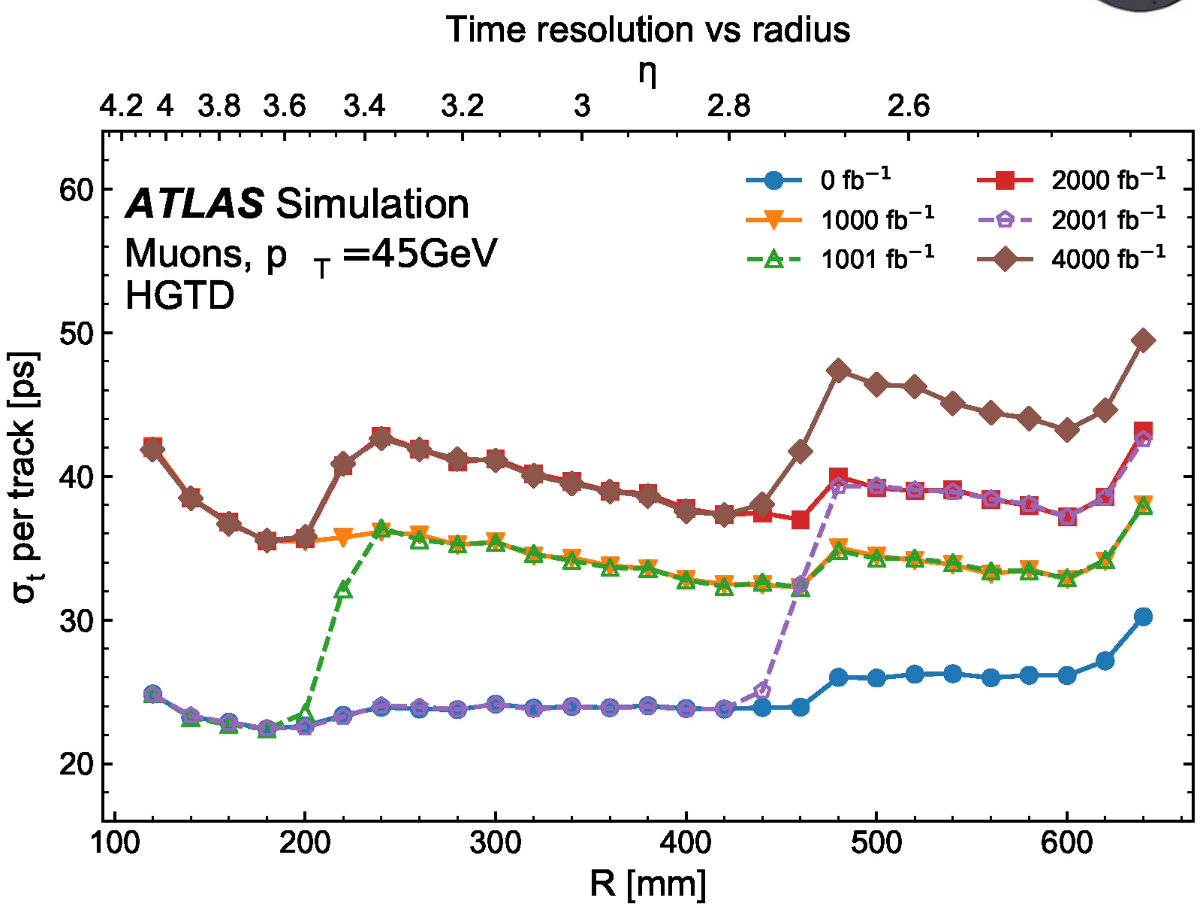




How well can we measure time?



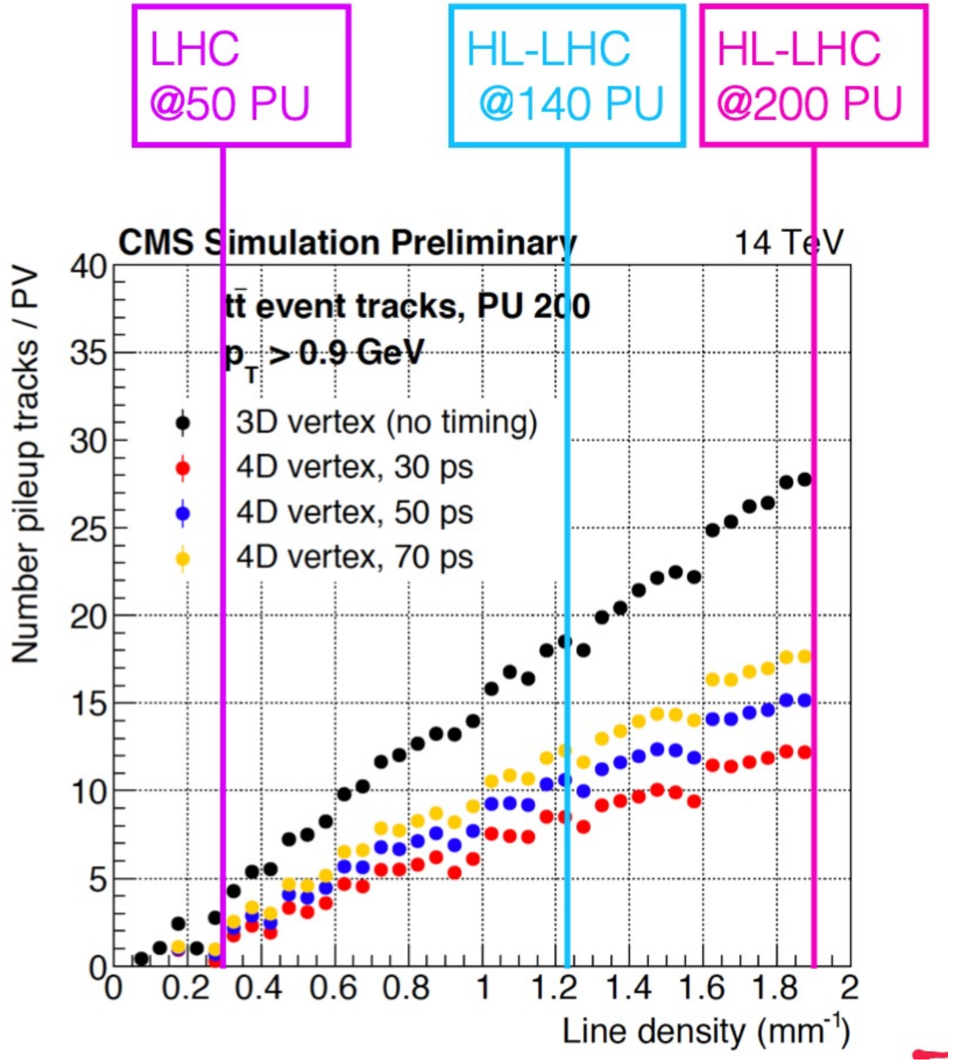




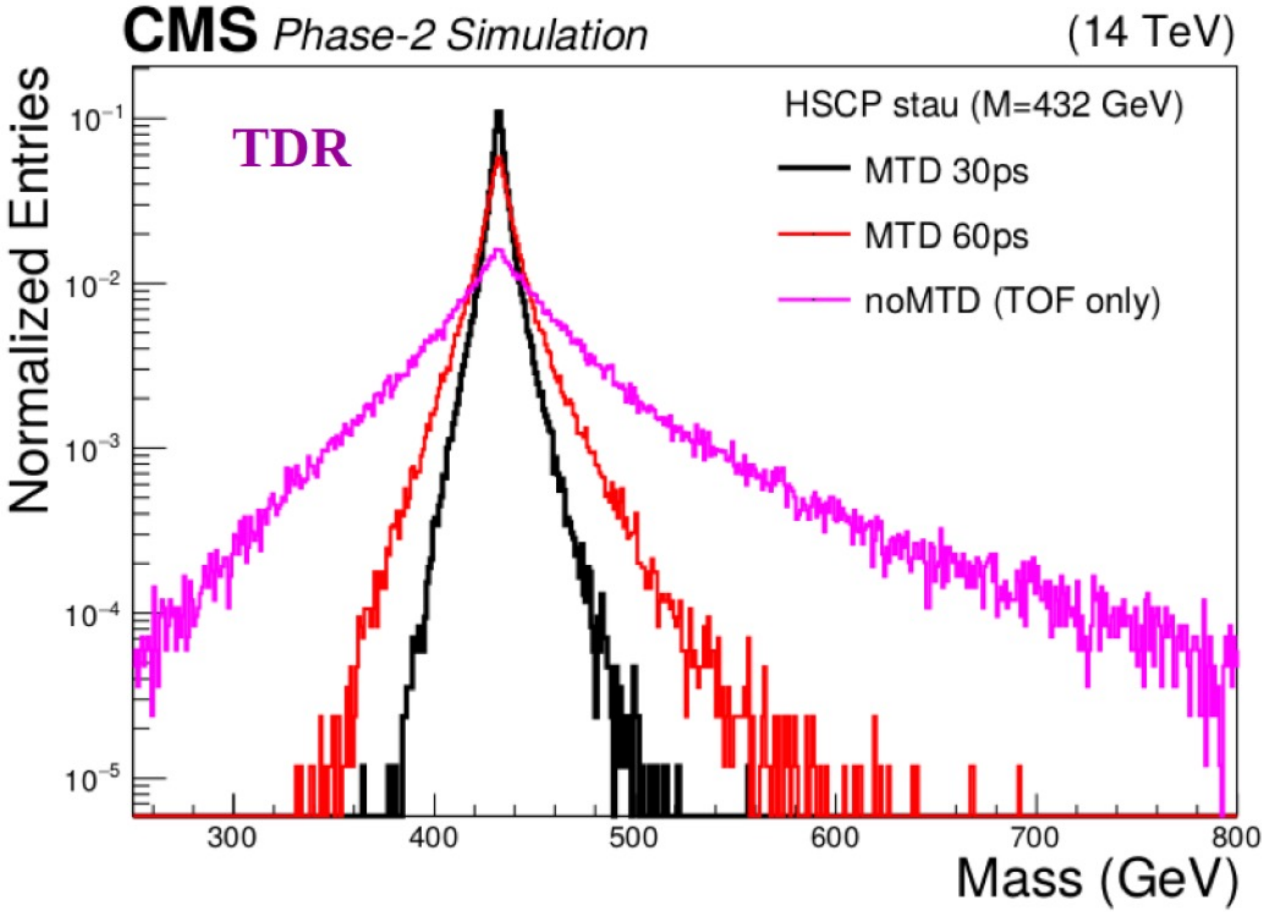
How well can we use it?

- If each hit in your timing detector has a time associated with it, you could
  - use the times to improve your tracking, reducing fakes from combinatorics
  - assign a time to each track.
- The track times could be used to assign times with reconstructed vertices so that pile-up vertices can be separated from the hard-scatter vertex of interest.
- It isn’t trivial to use the timing information an maintain high efficiency, particularly for ATLAS where we only have access to timing from forward objects which primarily helps with VBF-like signatures.
- The HL-LHC will provide a tremendous opportunity to learn how to exploit this additional dimension, on the route to 5D!

CMS MTD performance



long-lived staus moving slowly through detector (GMSB model) – for the same background they can achieve a factor of four in signal gain



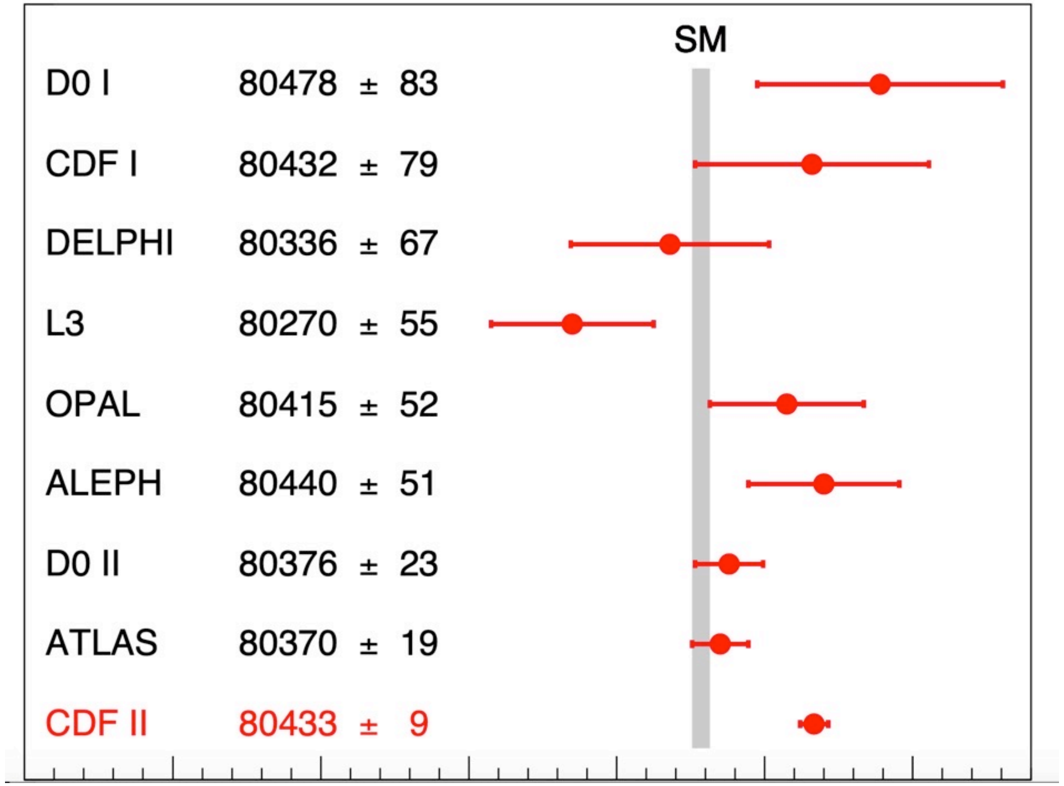
More results in a beautiful talk by Livia Soffi [here]

HL-LHC Physics Program

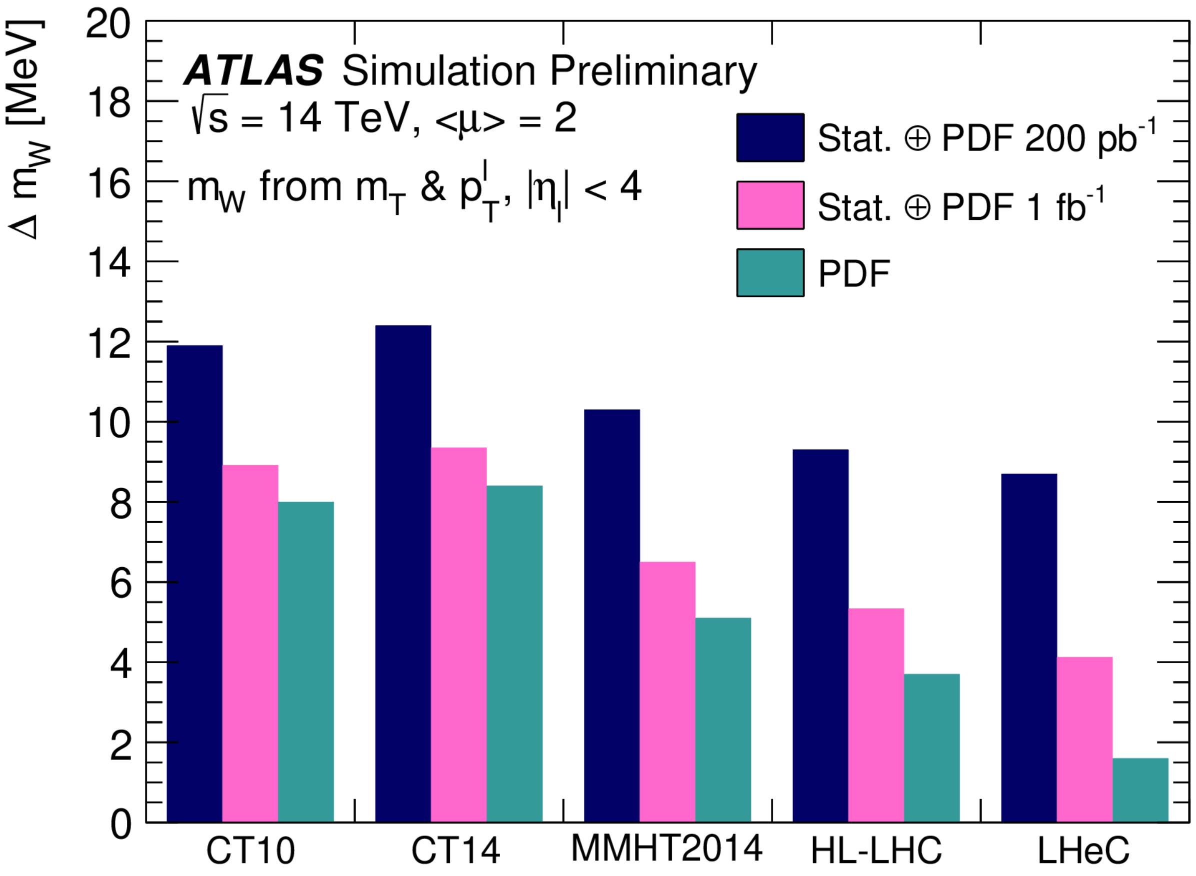
- Rediscover the SM, and measure properties with higher precision
- Improve measurements of Higgs production and branching ratios, with a target of percent-level uncertainties for range of decay modes
- Some Holy Grails:
  - Improve measurements of WW scattering
  - Access the Higgs self coupling
- Use the Higgs boson to search for BSM physics
- Extend searches for
  - SUSY, long-lived particles, Heavy new bosons (W'/Z'), exotic Higgs bosons, and much, much more!

Precision Standard Model: W boson mass

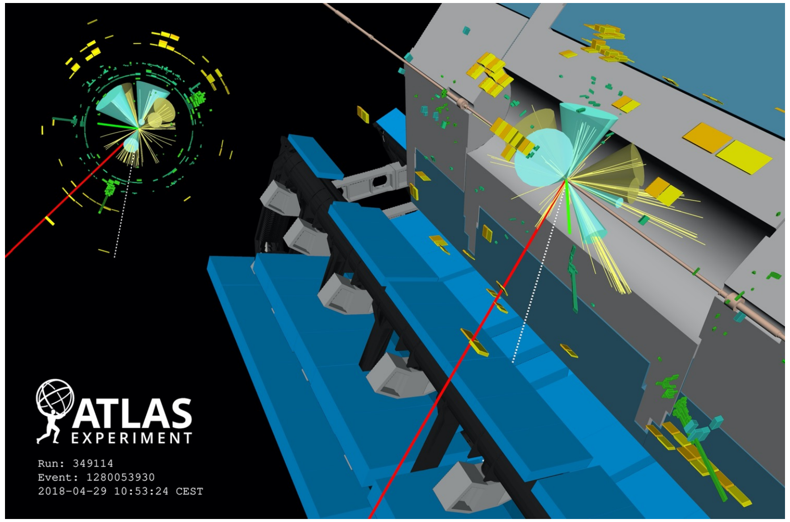
There has been renewed interest in the W mass measurement due to the recent CDF result.



At HL-LHC, requires a dedicated low pile-up dataset. The analysis benefits from improved forward lepton ID, and is very dependent on PDF knowledge.

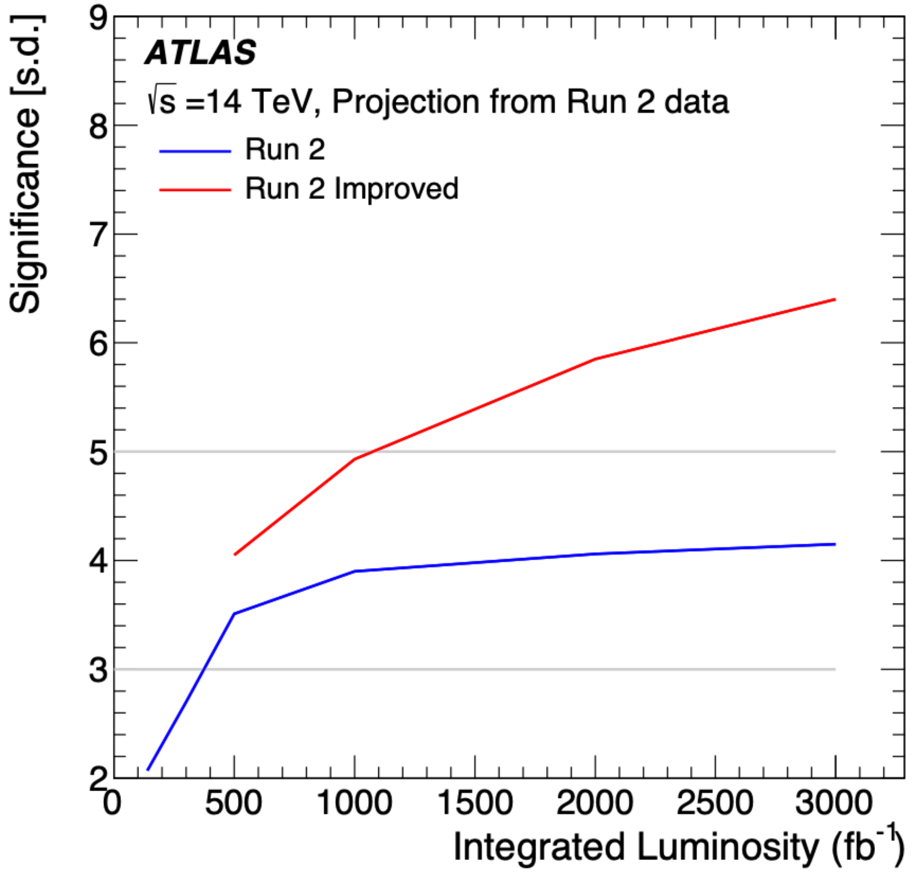


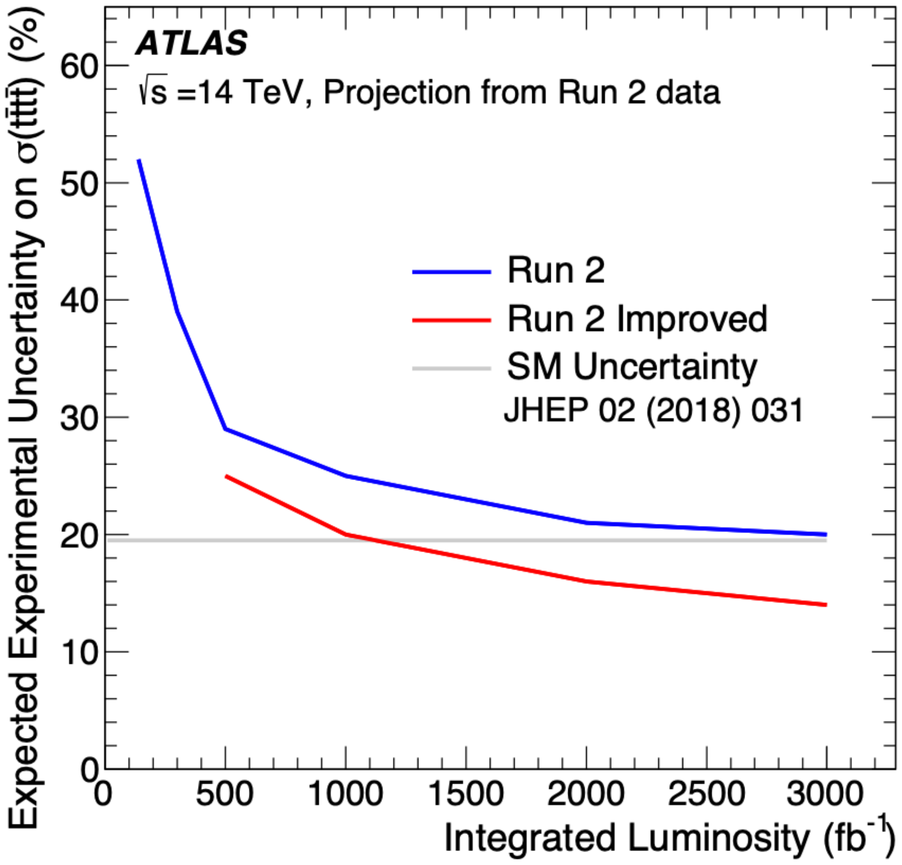
Four top cross section



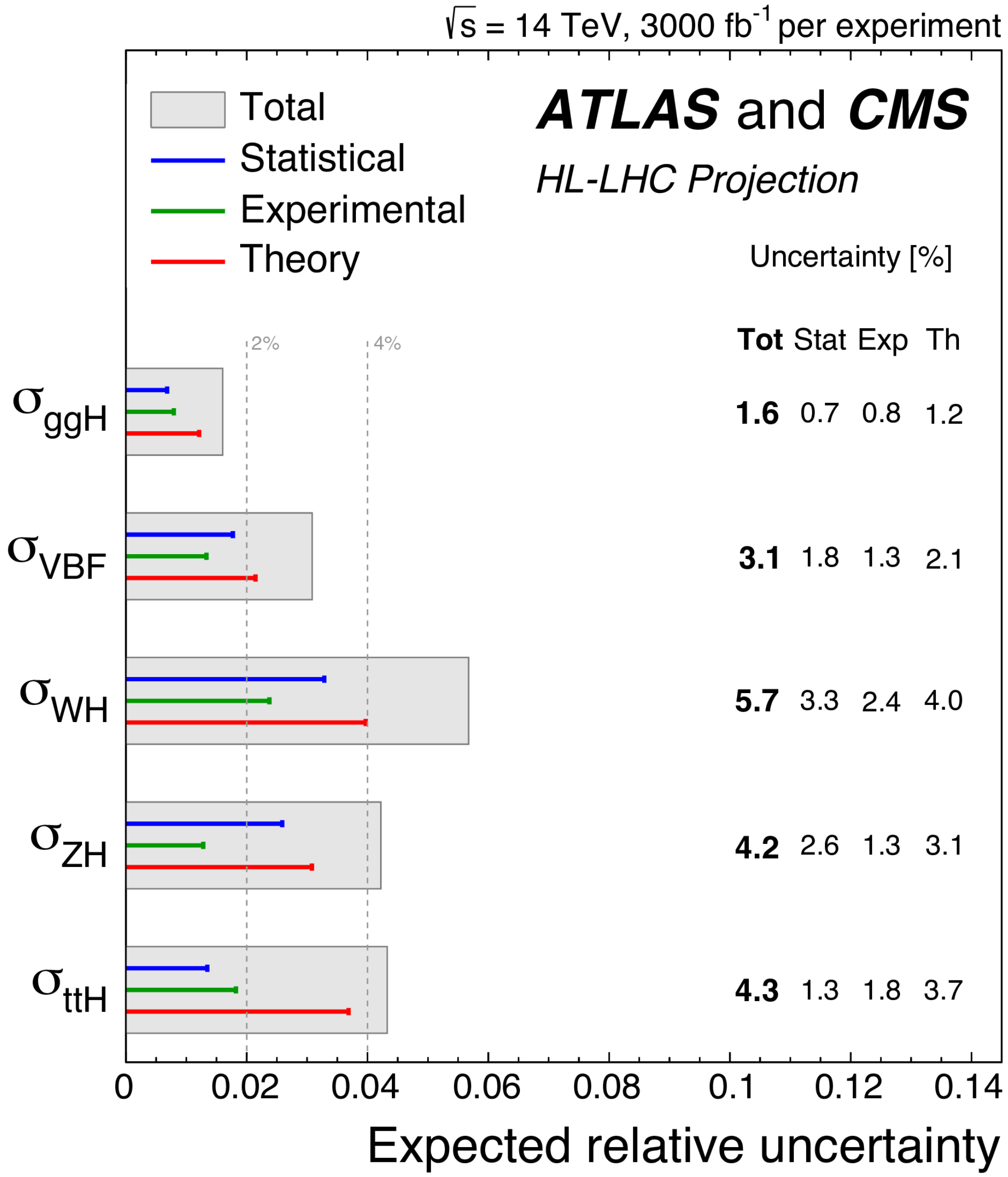
Run 2 analysis improvements enabled ATLAS to update our HL-LHC projection

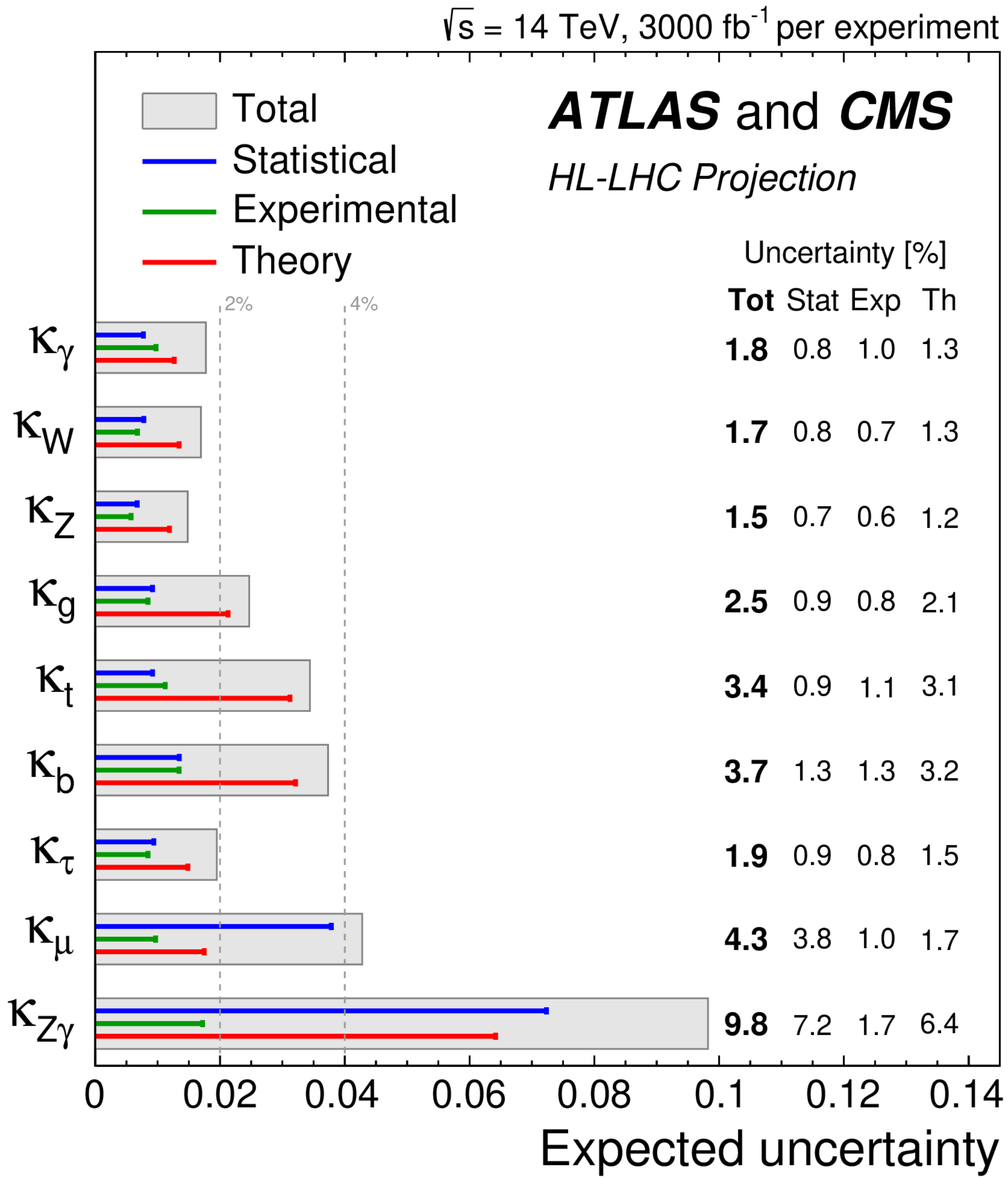
Our experimental uncertainty approaches, or dips below, the current uncertainty from theory.





Higgs boson Production and Decay Modes

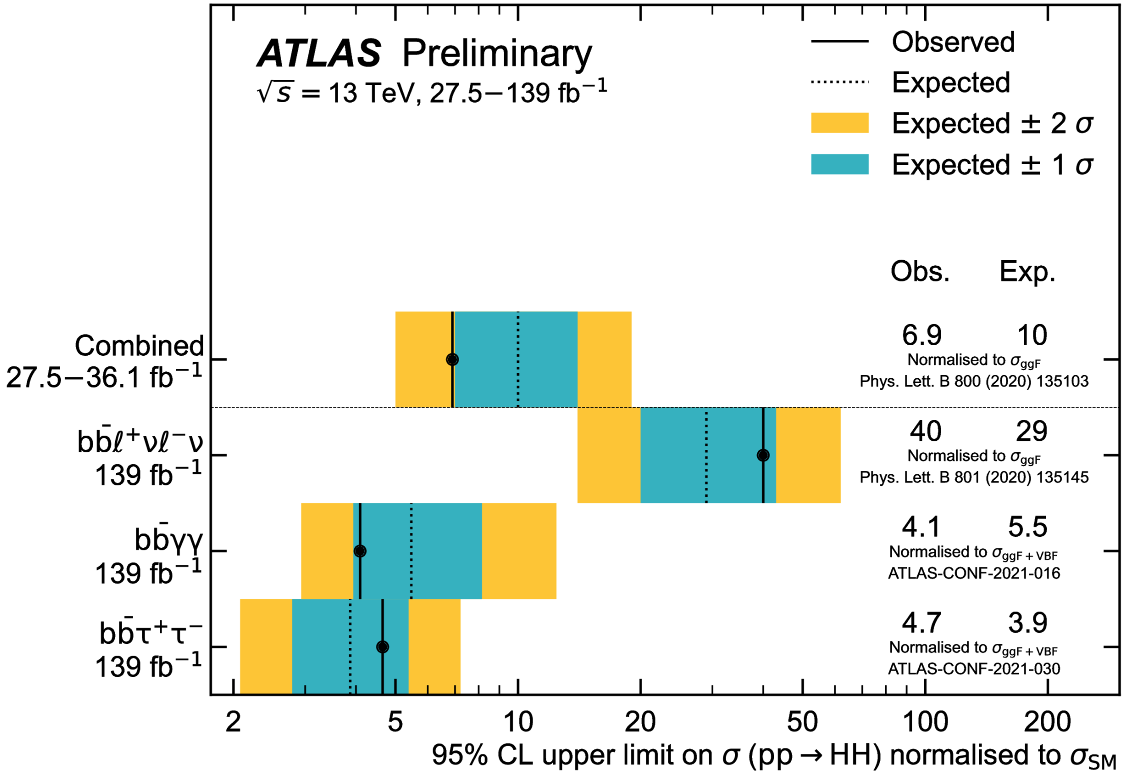


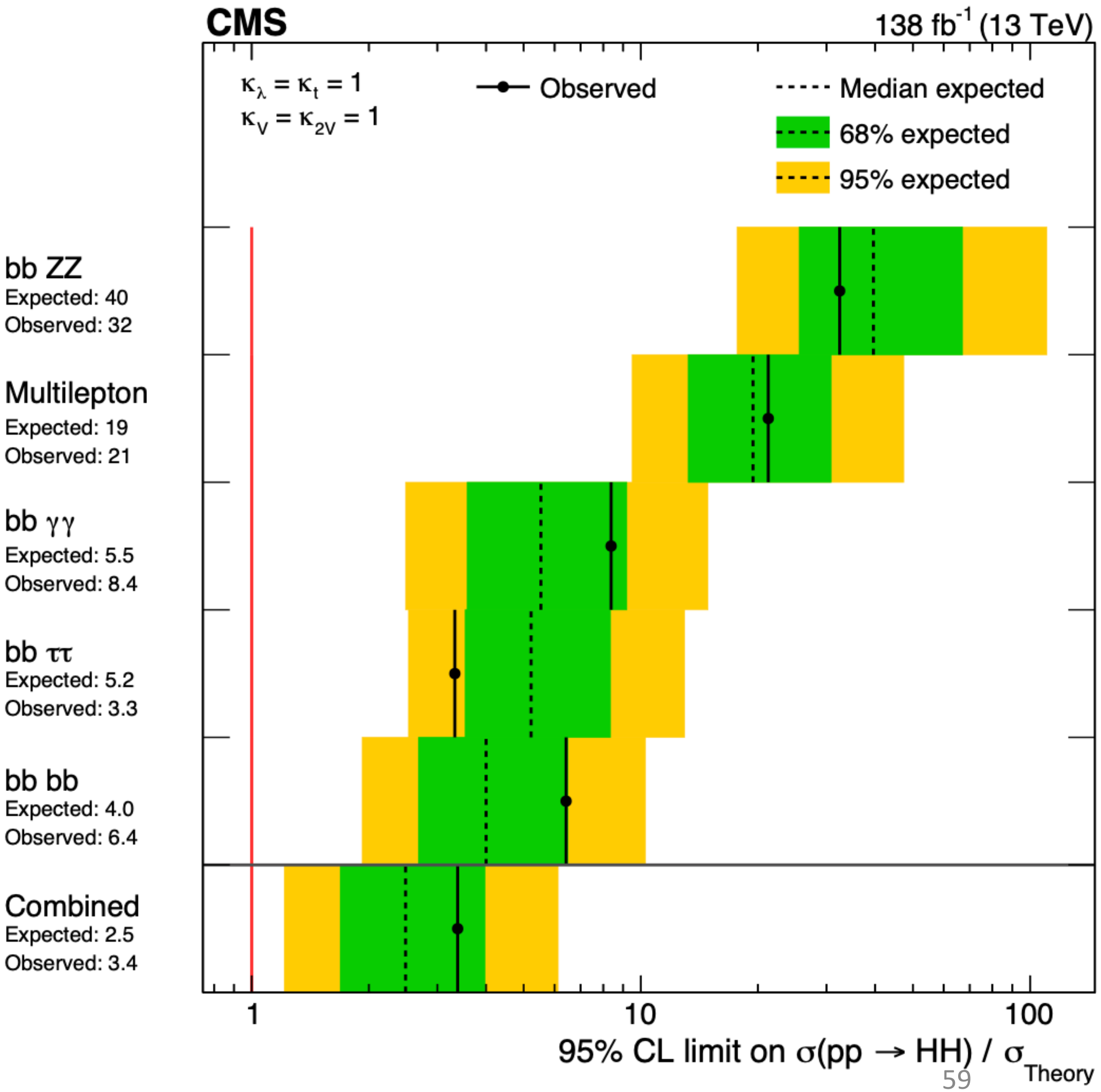


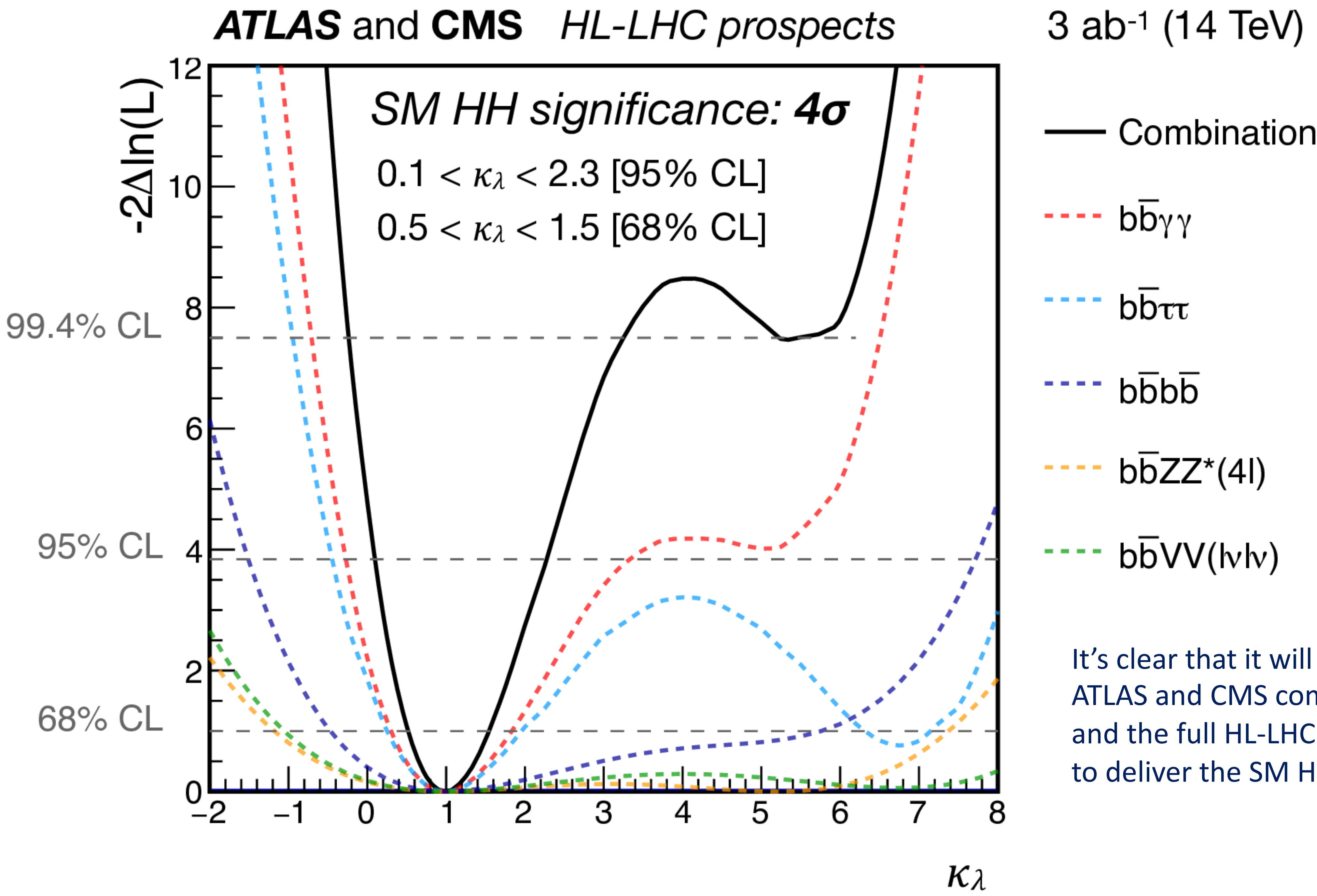
Higgs boson self-interaction

- Accessing the Higgs boson self-interaction is a primary goal of the HL-LHC
  - Central to our understanding of the vacuum instability and inflation
- Measuring λ_{HHH} would constrain the shape of the Higgs potential and contribute to our understanding of EW symmetry breaking
  - new dynamics at higher energy scales could modify the Higgs self coupling
- HH production provides our most sensitive window at the HL-LHC
- Extremely challenging measurement, since the rate is a factor of 1000 smaller than single Higgs production. We need to exploit all modes and combine ATLAS and CMS measurements to reach sensitivity.

HH Current Picture

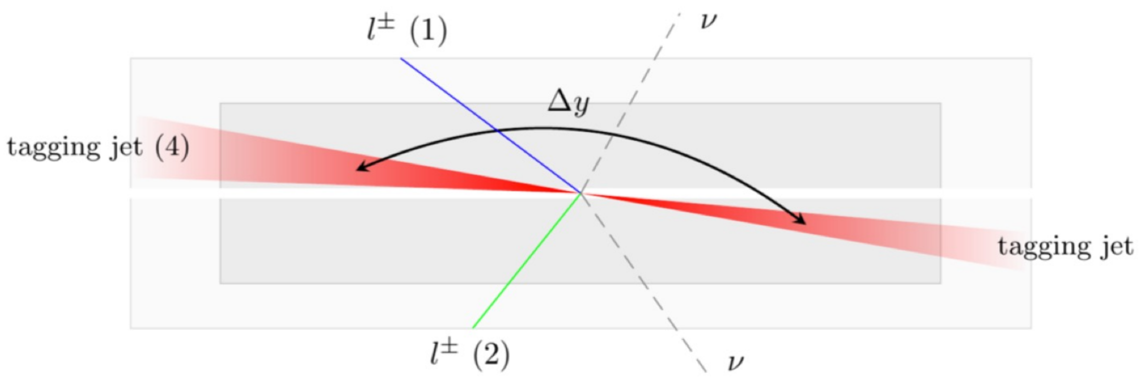


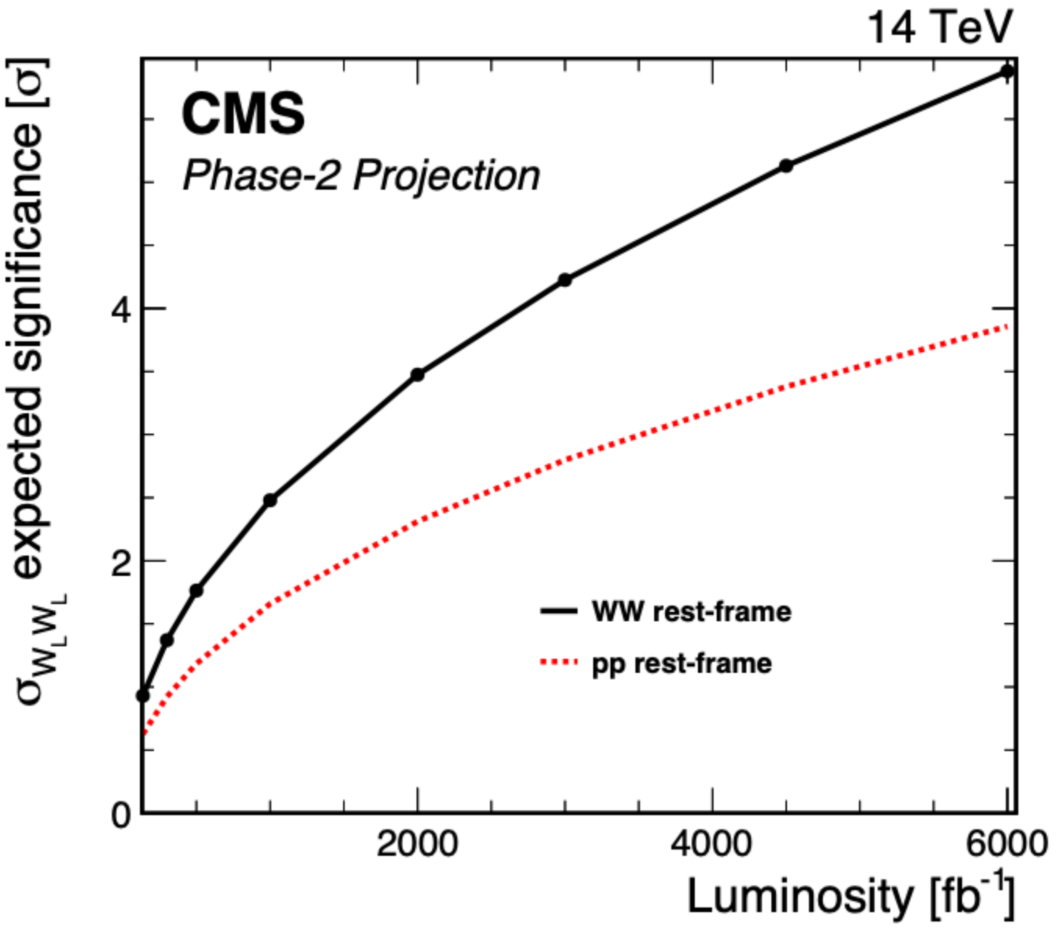


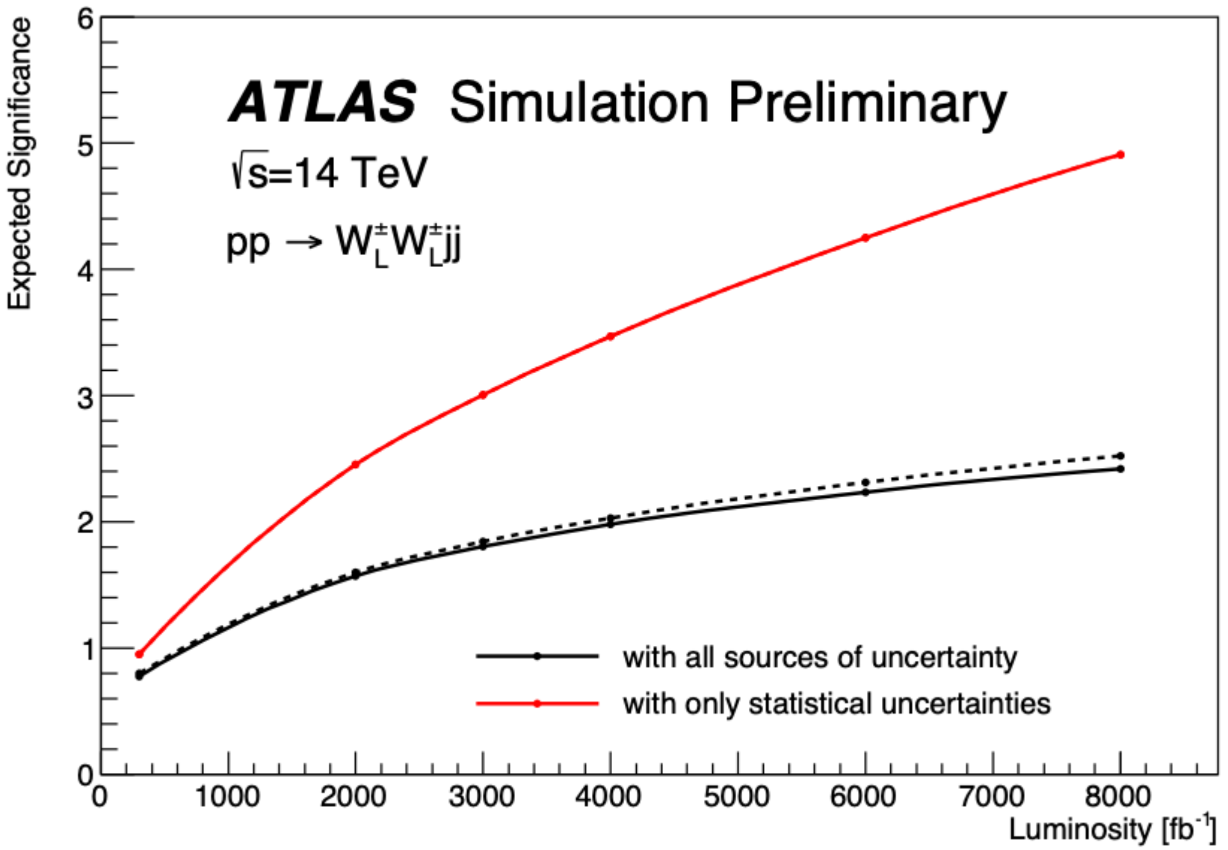


It's clear that it will take an ATLAS and CMS combination and the full HL-LHC dataset to deliver the SM HH signature

Vector boson Scattering: **longitudinal** mode



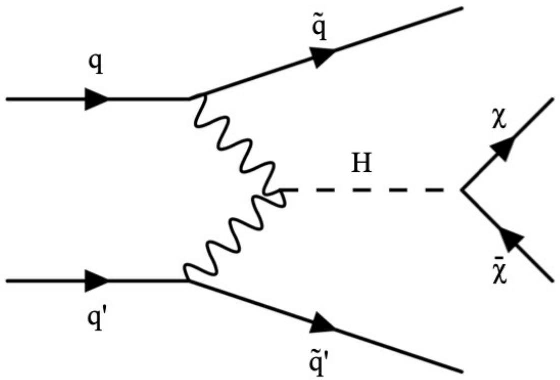




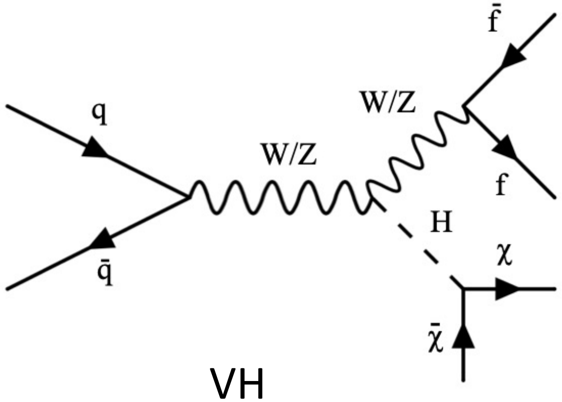
Invisible Width of the Higgs

A challenge at a hadron collider is the inability to measure the full width of objects produced. Without a known collision-by-collisions center-of-mass energy, we can’t know the # of Higgs bosons produced.

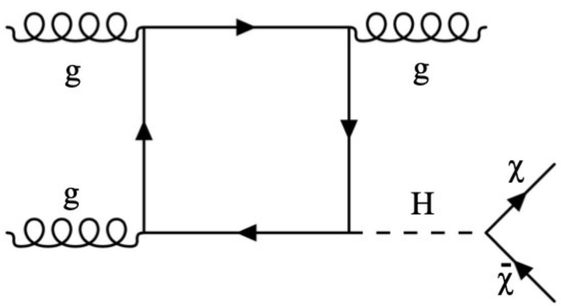
Current limits are at the level of 10%. We expect, with the HL- LHC, to measure $B(H \rightarrow inv) < 2.5\ \%$.



VBF

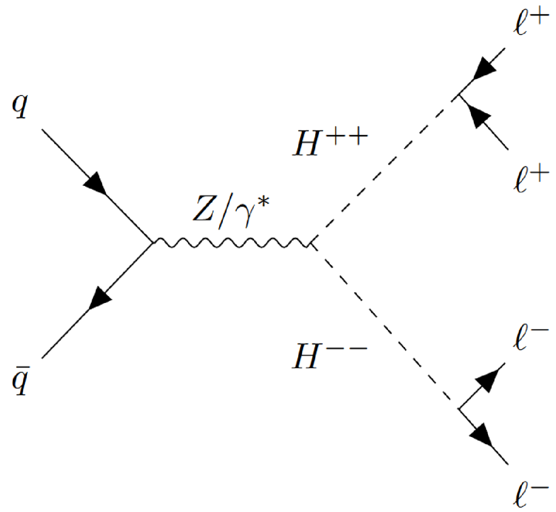


VH

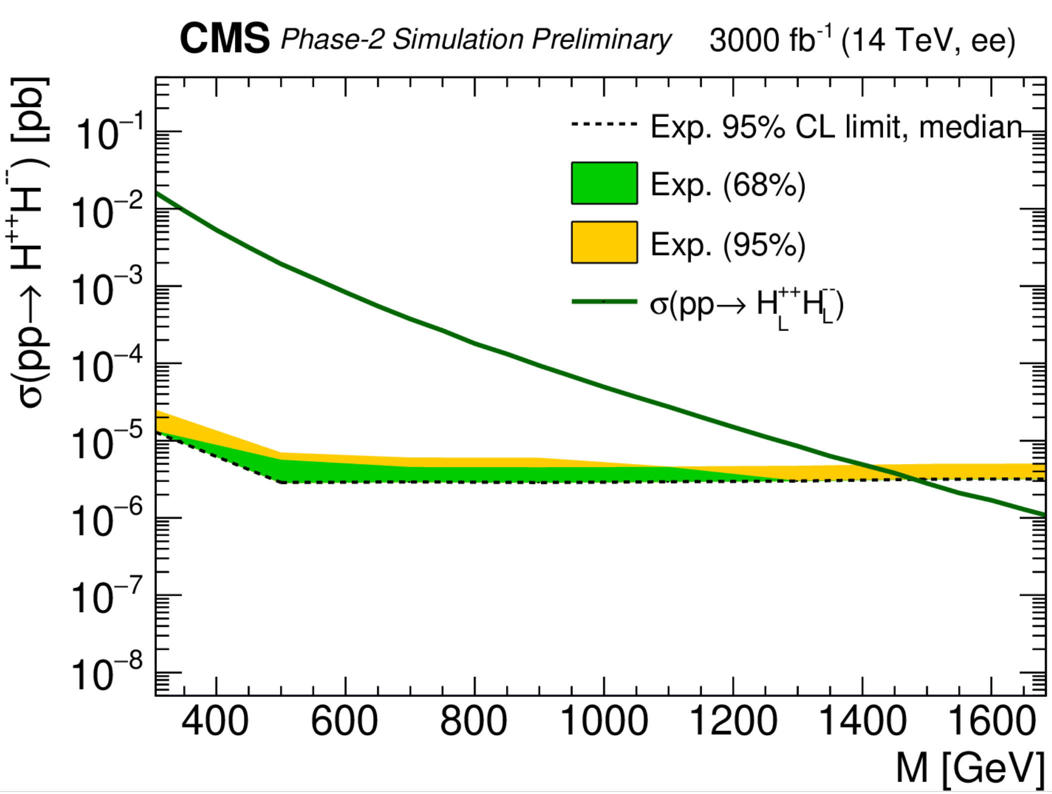


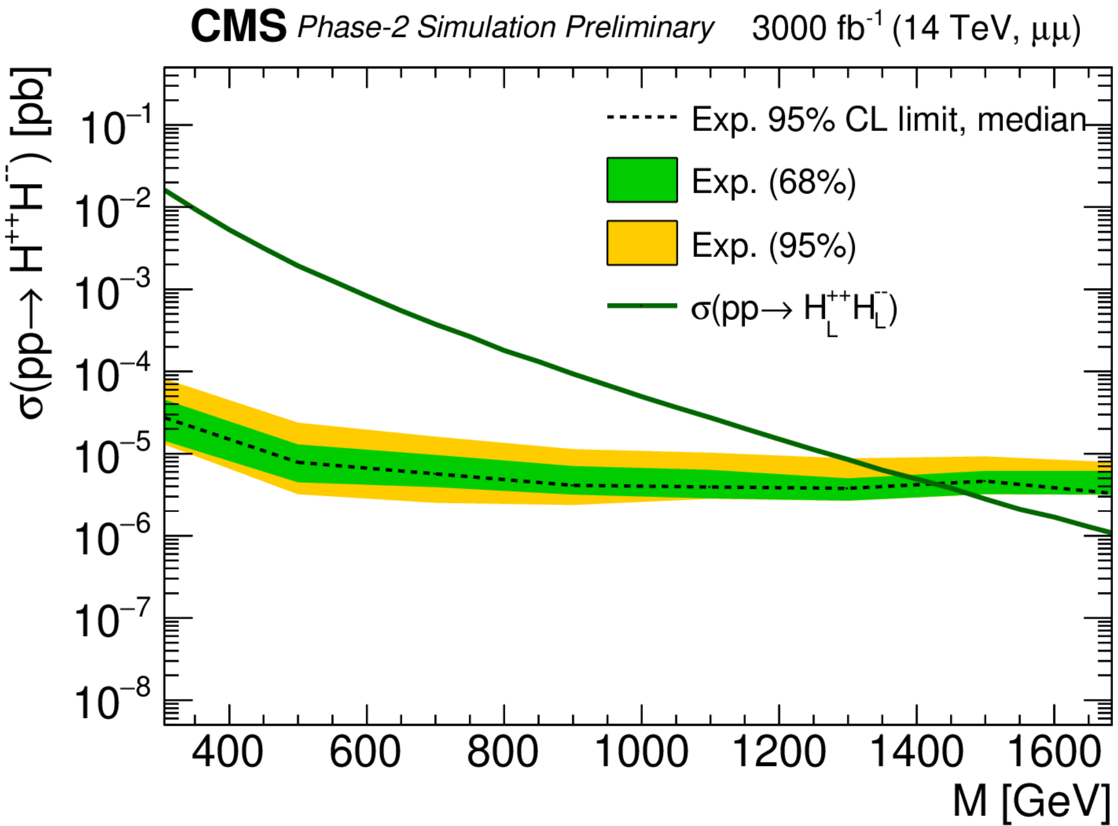
ggH

CMS Search for H^{++}/H^{--}

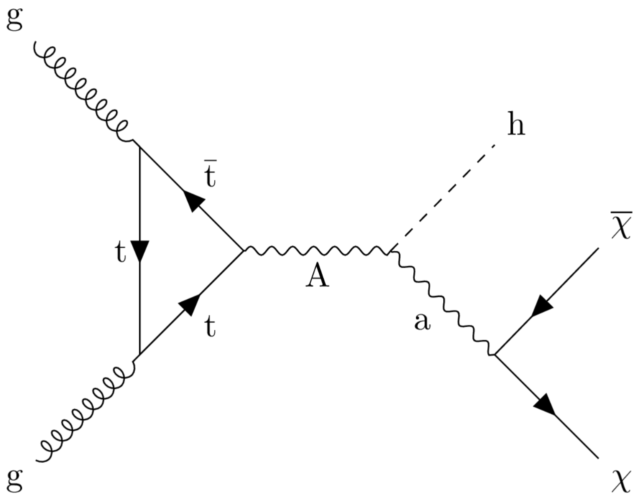


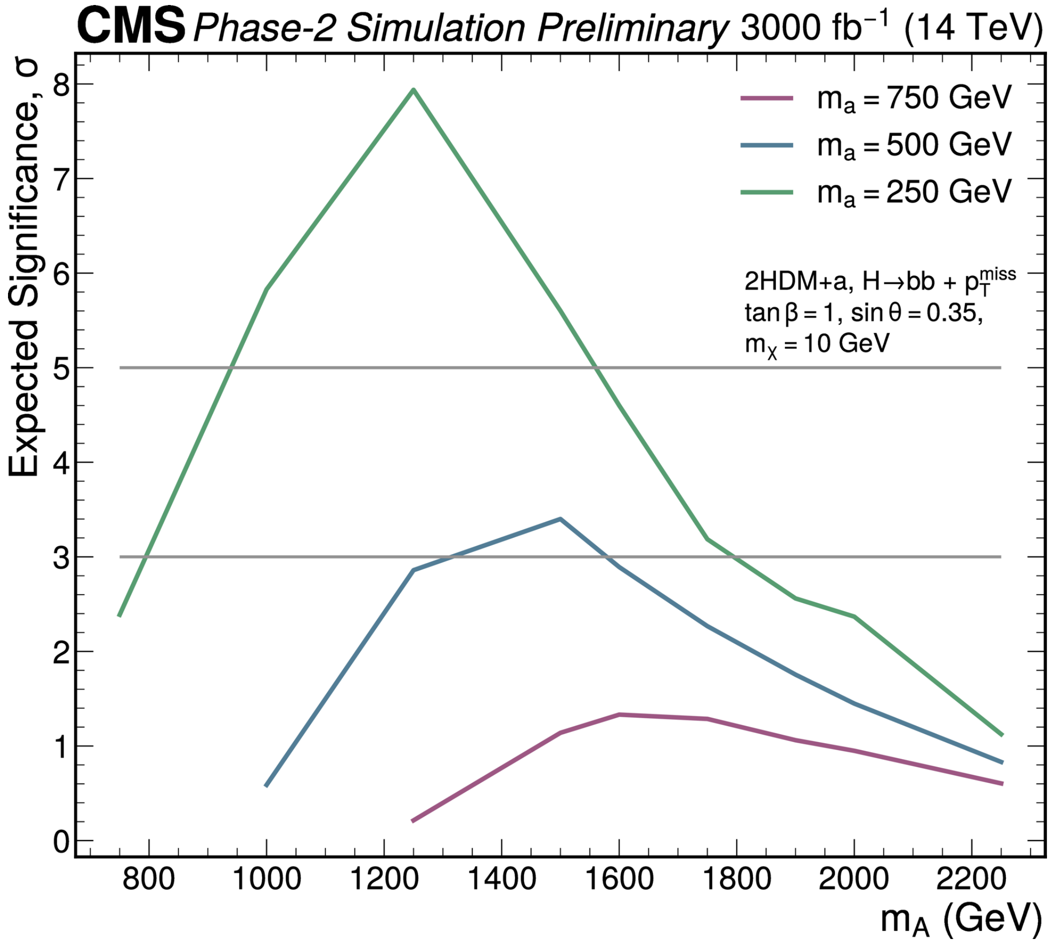
We can continue the hunt for a doubly-charged Higgs boson. This search benchmarks scenarios where decays are exclusively to electrons (left) or to muons (right)





Using the Higgs boson: searches for dark matter



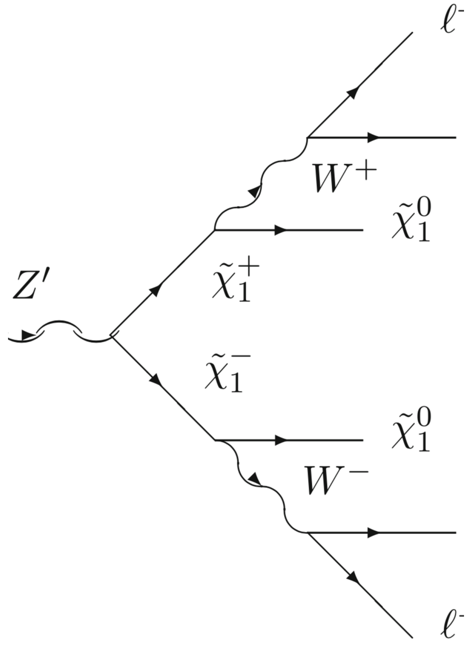


Using boosted events where the higgs decays to a pair of b quarks, with that final state reconstructed in a large radius jet

Interpretation in the 2HDM+a model

Important to remember that we have clear discovery potential for a wide range of new physics with the HL-LHC

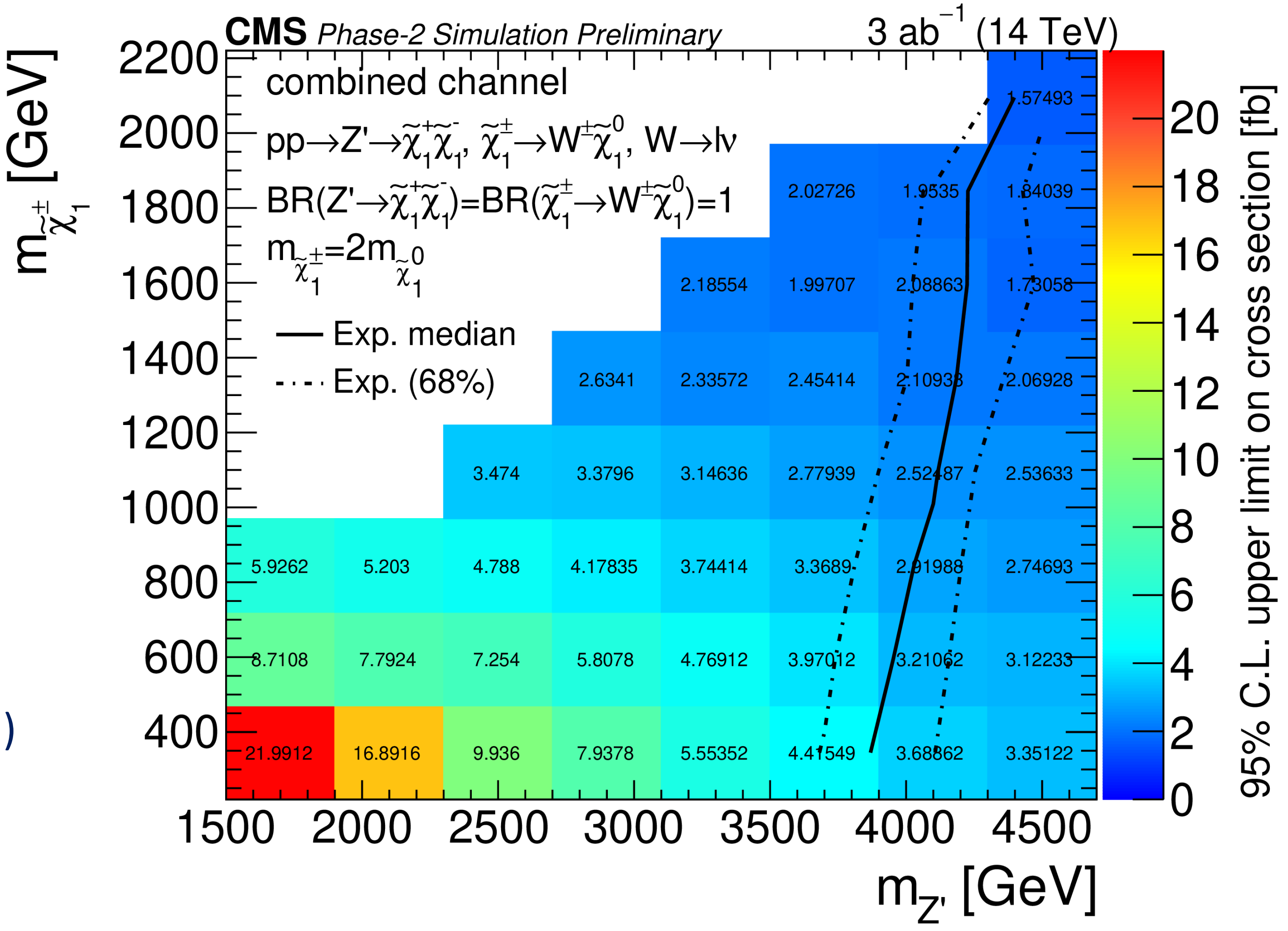
Search for a "leptophobic" Z'



Search motivated by extensions to SUSY

Communicating the results is a challenge, as is optimizing the analysis, due to the huge potential phase space covered (BRs, masses, etc.)

Deep NN used for signal extraction



Conclusions (1)

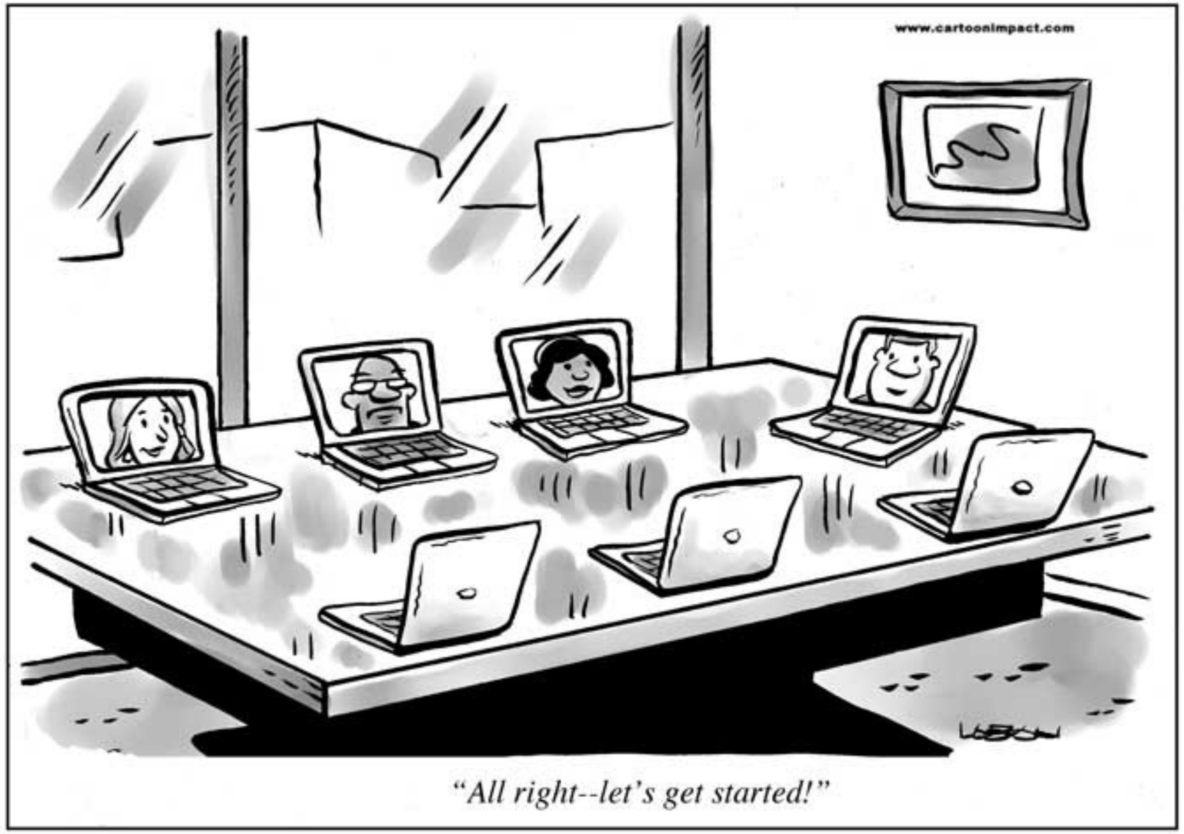
- Run 3 is well underway. We expect our Run 2 dataset to be significantly expanded.
- Improvements for all LHC experiments will extend the physics reach beyond what a simple extension of Run-2-like data would enable
  - Be on the lookout for combinations of Run 2 and Run 3 data, in both searches and measurements!

- The challenging HL-LHC high-pileup conditions will be supported by many new detector components from the LHC experiments.
  - More sophisticated triggers, with tracking information available early and more analysis moved online, will help select the optimal dataset for physics exploration within the constraints.
  - Hallmarks include higher granularity information and improved resolutions, along with a new category of information via dedicated timing detectors.

Conclusions (2)

- There is uncertainty in our near-term, and long-term, futures.
- We are not isolated from our environments:
  - CERN, like the rest of Europe, is impacted by the invasion on the continent and the energy crisis. This impacts our integrated luminosity.
- Long term: we carry the future of the energy frontier with us, collectively. We must extract as much as we can from LHC and HL-LHC data as early as we can to best inform the path forward.
- The experience of the pandemic has influenced all of us.
  - We learned some lessons about taking care of ourselves and each other that we should not forget as things return more to “normal”.
- It’s an incredibly exciting time at CERN, as we launch into the third run of the LHC and have the HL-LHC to look forward to. It is useful to keep in mind **that there are few better generators of creativity than challenges and constraints.**

Thank you for your attention,
and nice to be with you in person!



And thank you to colleagues across many experiments
for the beautiful papers/notes/talks that informed or populated these slides!

Additional Material

- Machine Learning
  - New PDG Chapter
  - Living Review: https://iml-wg.github.io/HEPML-LivingReview/
- Run 3 Prospects
  - CMS Briefing
- HL-LHC Prospects
  - "Yellow Report" input for European Strategy
  - ATLAS & CMS Snowmass input