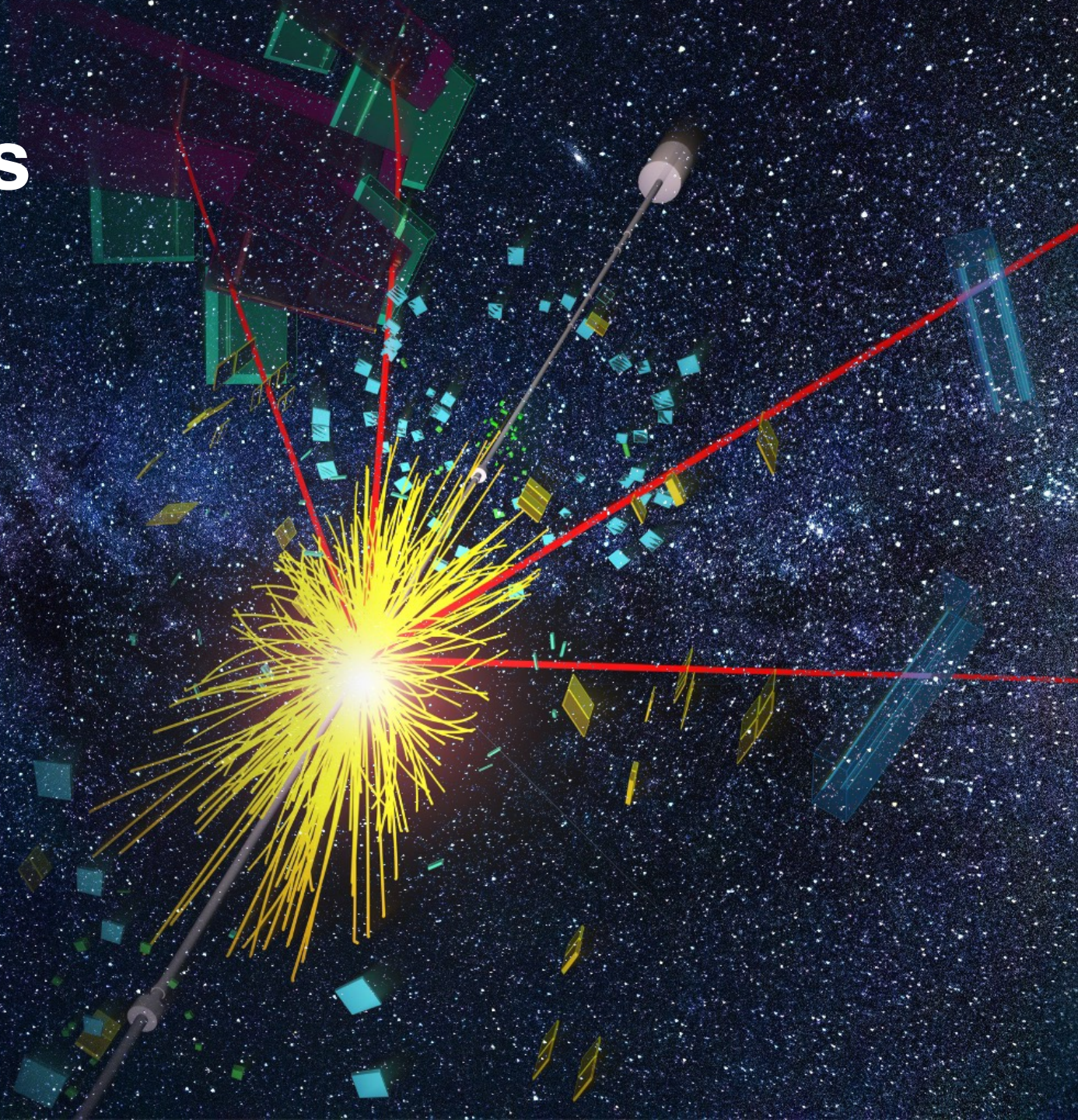


Experimental Physics at the LHC (4)

Andreas Hoecker (CERN)

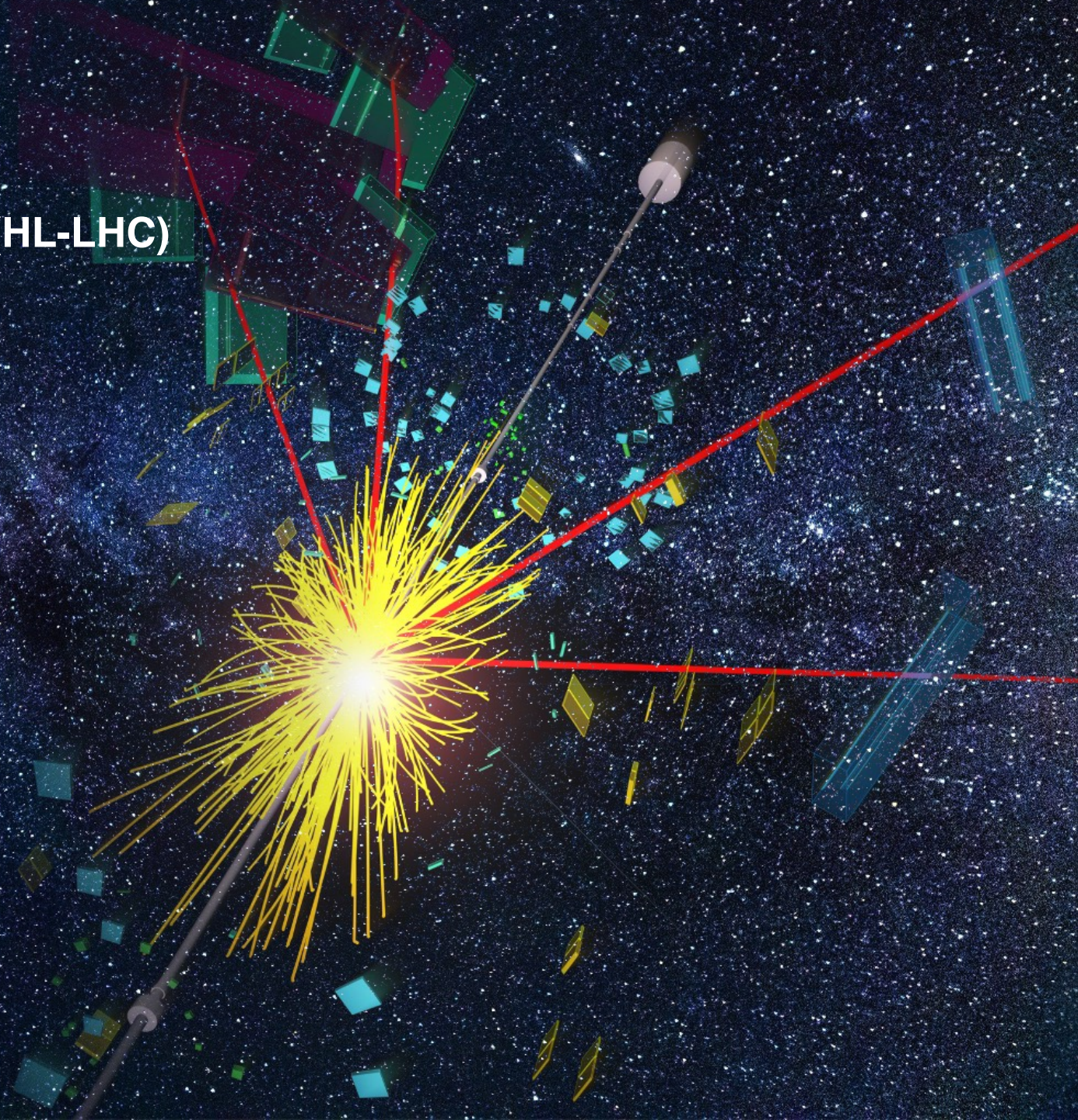
57. Herbstschule HEP

1–11 September 2026, Bad Honnef, Germany



Today's lecture:

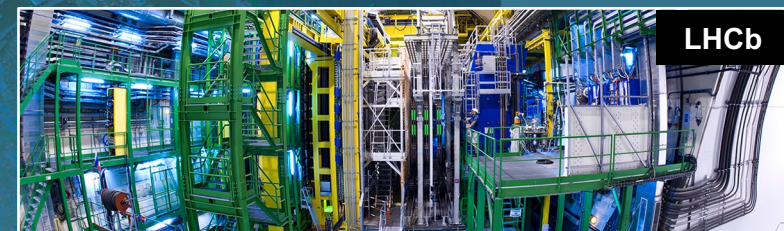
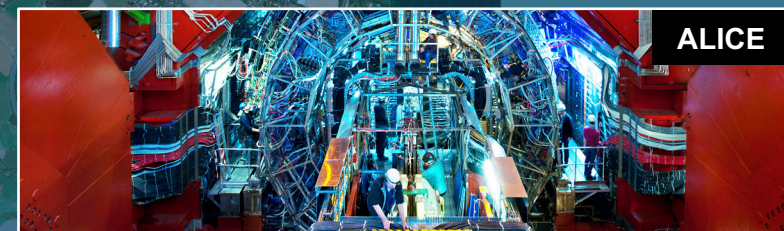
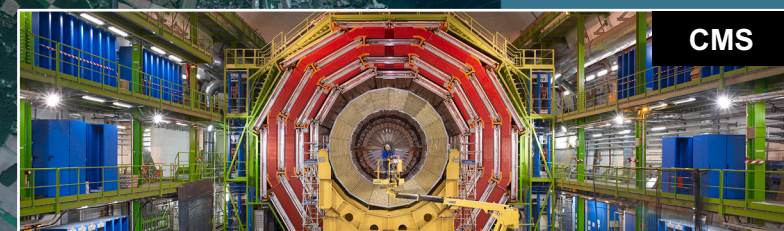
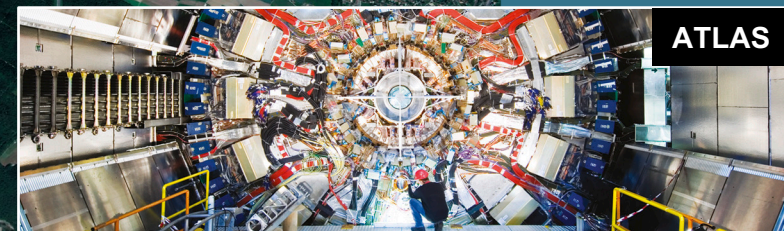
- Upgrade to the High-Luminosity LHC (HL-LHC)
- Physics opportunities



LHC: the next phase



Areal view

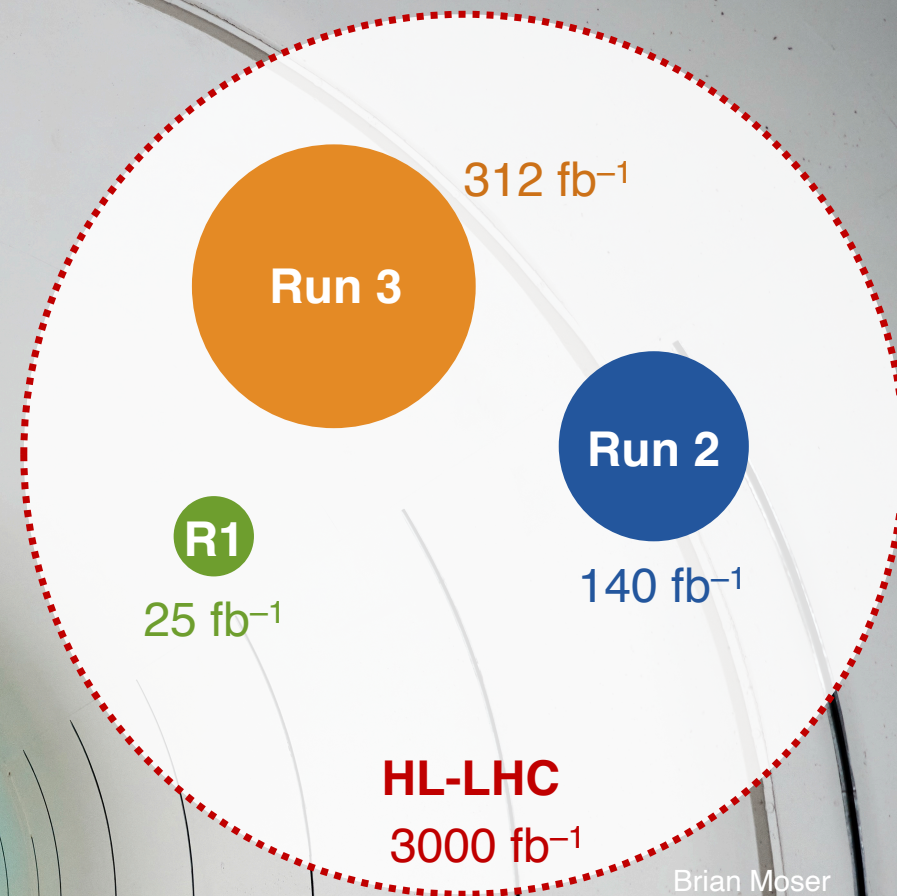


Not shown: additional smaller experiments

High-Luminosity LHC

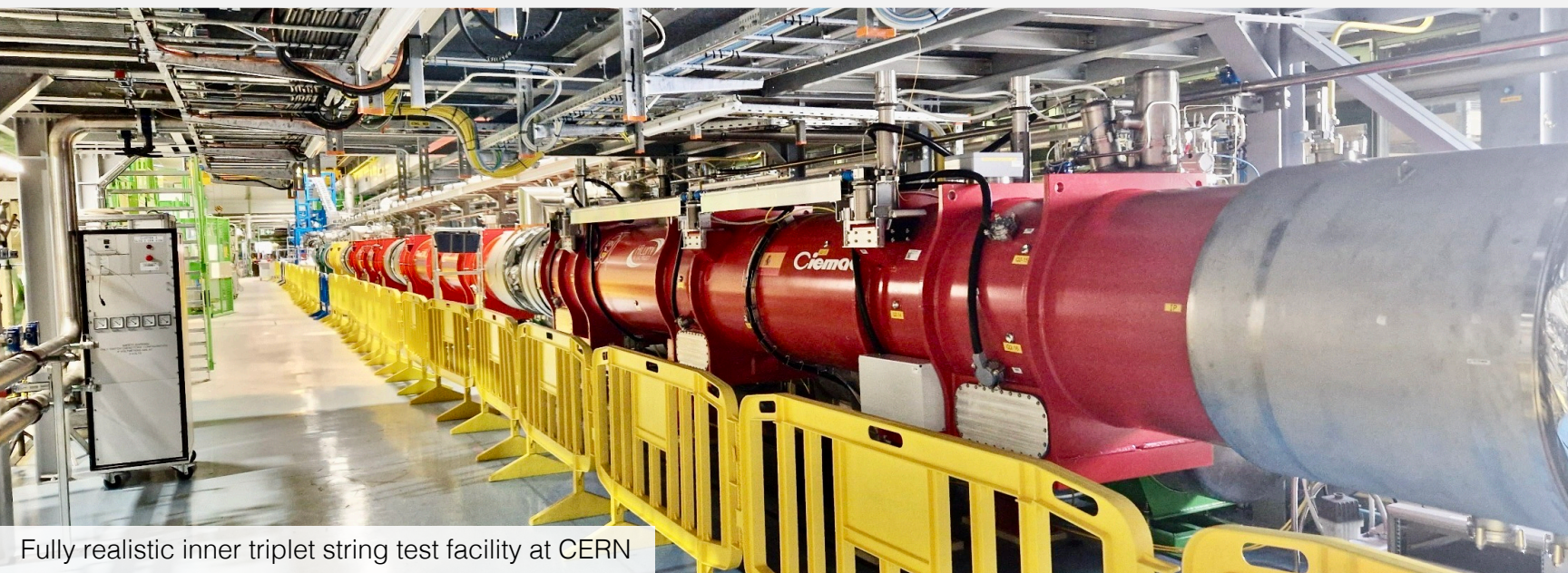
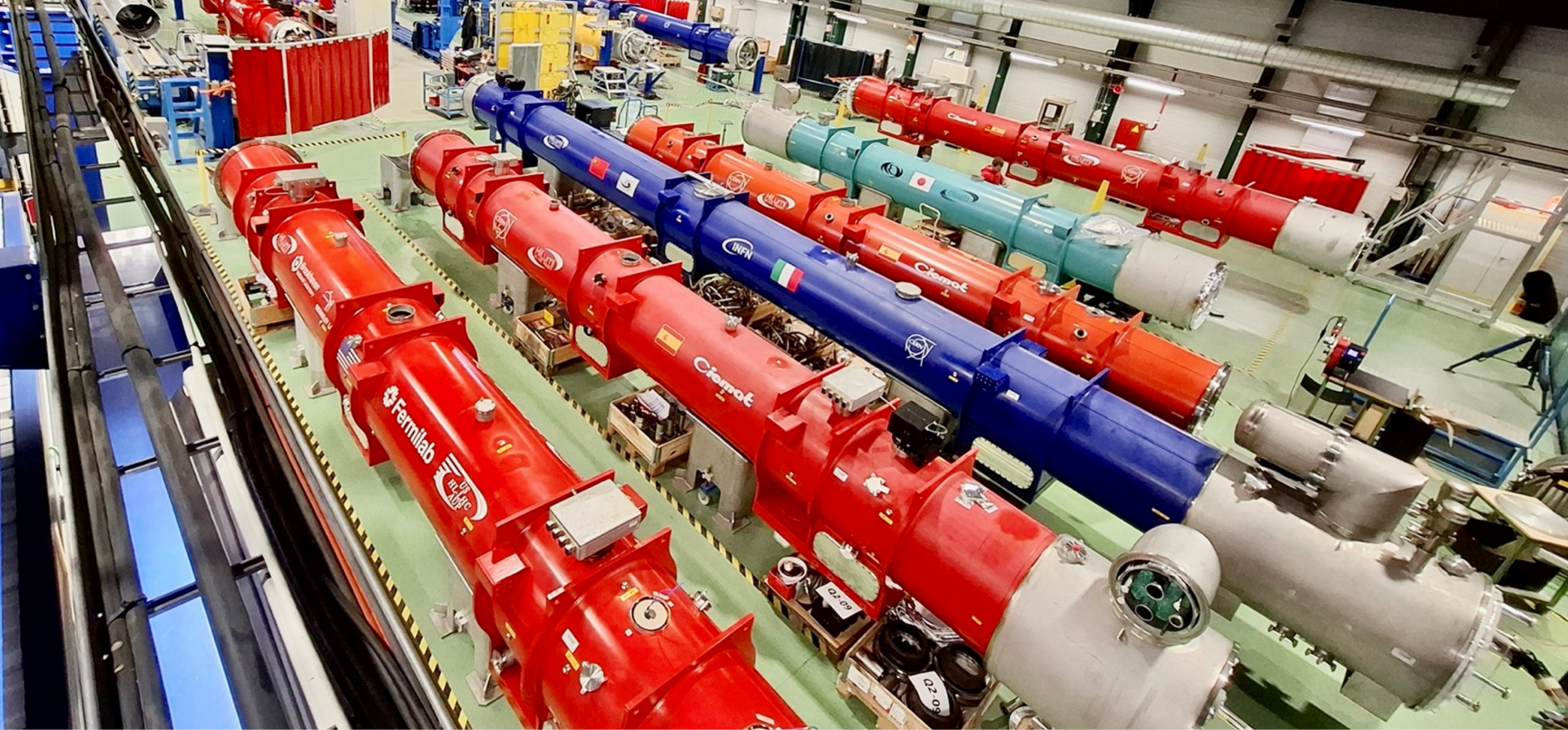
New underground LHC service gallery at Point 5 (CMS) to accommodate higher radiation levels, Increased power consumption, complex electronics, cooling, and cryogenic systems

High-Luminosity LHC



Brian Moser
(Freiburg), 2026

New underground LHC service gallery at Point 5 (CMS) to accommodate higher radiation levels, Increased power consumption, complex electronics, cooling, and cryogenic systems



Upgrade to the High-Luminosity LHC is under way

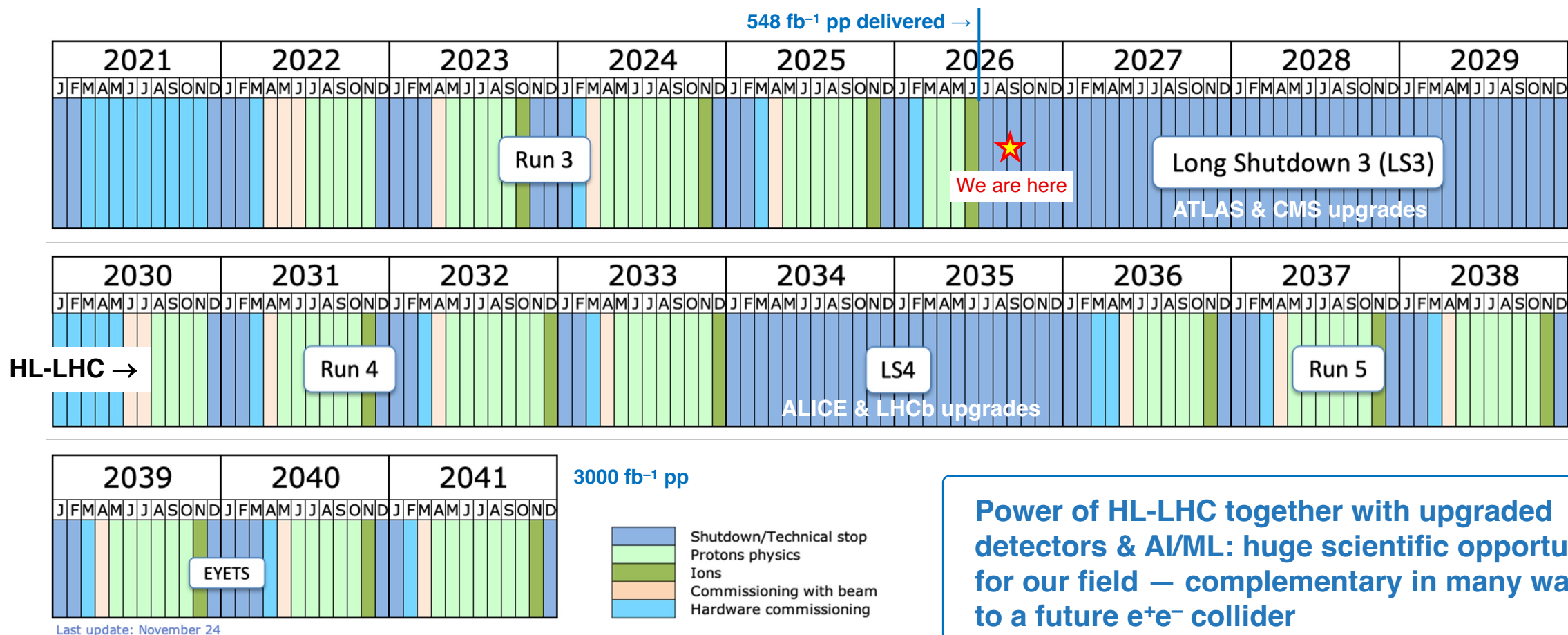
- The HL-LHC will use new technologies to provide up to 6 times more luminosity than the LHC
- The detectors are also being upgraded
- It will give access to rare phenomena, greater precision and discovery potential (350M H, 240k HH, 13B top, 720M WW, ...)
- It is scheduled to start operating in 2030 and run until 2041
- **Largest construction project at CERN for almost 20 years**

Fully realistic inner triplet string test facility at CERN

LHC and High-Luminosity-LHC (HL-LHC) project timeline

HL-LHC and experiment upgrades

Large-scale ATLAS & CMS upgrades under construction for Run 4, ALICE & LHCb plan significant upgrades for Run 5



HL-LHC — Brighter beams and stronger focusing to deliver 3 ab⁻¹

Ambitious goal: $L_{\text{int}} > 2500 \text{ fb}^{-1}$ in 9 years of operation (for a total delivered luminosity of 3 ab⁻¹)

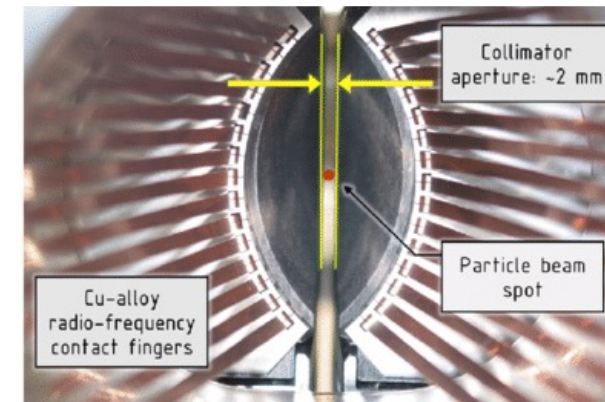
Expect no increase in pp collision energy beyond current 13.6 TeV for Run 4; and later?

$$\mathcal{L} \propto \frac{n_b N_p^2}{\epsilon_n \beta^*} R_{\text{crossing}}$$

	Bunch intensity [protons / bunch]	β^* [cm]	Levelled lumi [cm ⁻² s ⁻¹]	Pileup $\langle \mu \rangle$	Int. lumi / year / IP [fb ⁻¹]
LHC design	$1.15 \cdot 10^{11}$	55	$1 \cdot 10^{34}$	23	30
LHC Run 3	$1.8 \cdot 10^{11}$	60/18	$2.2 \cdot 10^{34}$	64	120
HL-LHC	$2.2 \cdot 10^{11}$	15	$5\text{--}7 \cdot 10^{34}$	140–200	up to 300

↑
LIU (during LS2) provides brighter, more intense bunches ($B_{\text{beam}} \equiv N_p / \epsilon_n$); upgraded collimation, machine protection and cryogenics handle the increased beam current, losses and heat loads*

*New shafts, caverns and 300-m power-converter galleries at Points 1 and 5 house power converters, cryogenics and services



Front-view of an LHC collimator showing the size of jaw aperture in operation

RF fingers provide continuous, low-impedance electrical path through mechanical gaps and moving joints (suppress beam-coupling impedance and localized RF heating or electrical discharges)

HL-LHC — Brighter beams and stronger focusing to deliver 3 ab⁻¹

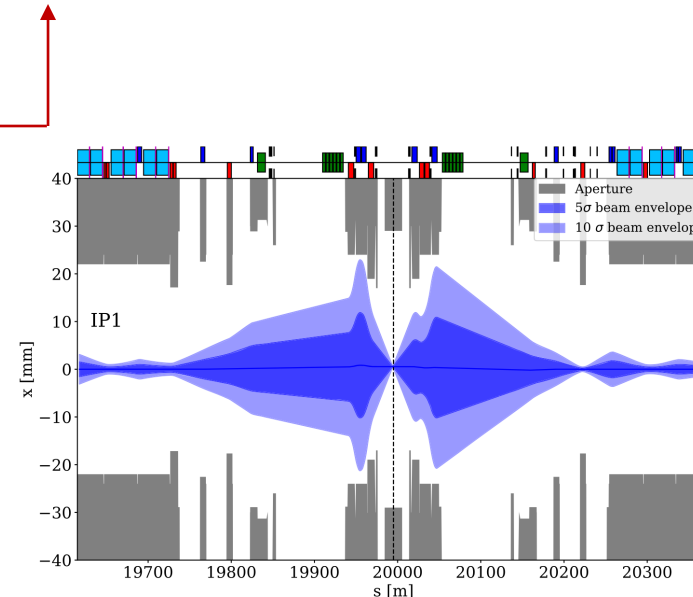
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Stronger focusing: 12 new Nb₃Sn “inner-triplet” quadrupoles at ATLAS & CMS squeeze the beams to $\beta^* = 15 \text{ cm}$ (B-field: 8 T → 11.3 T = 16.2 kA, aperture: 70 → 150 mm)



Rapid growth of the beam envelope away from IP:

$$\beta(s) \simeq \beta^* + \frac{s^2}{\beta^*}$$

A smaller β^* at IP increases beam inside final-focus quadrupoles

Note: beam size is: $\sigma(s) = \sqrt{\varepsilon \beta(s)}$

HL-LHC — Brighter beams and stronger focusing to deliver 3 ab⁻¹

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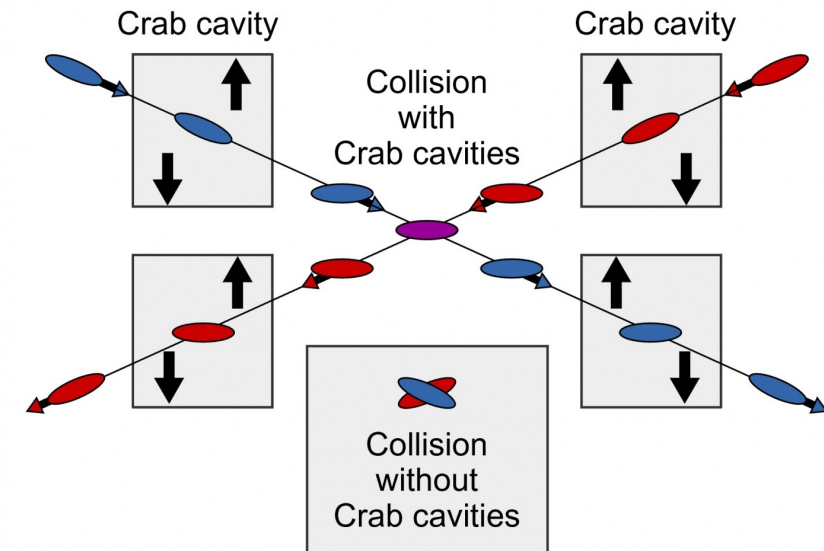
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RF crab cavities tilt the bunches via time-dependent transverse kicks, restoring their overlap despite the larger crossing angle

- 16 (8 around ATLAS/CMS) superconducting RF cavities tilt proton bunches through application of a time-dependent transverse voltage (3.4 MV/cavity) across the bunch such that they effectively collide head-on despite the crossing angle (uncorrected: luminosity loss of up to 30% at HL-LHC)
- Leading (trailing) edge of the bunch gets a kick in one (opposite) direction → rotation of the bunch in the transverse plane
- Already successfully used at SuperKEKB, but never at hadron colliders



HL-LHC — Stronger focusing

HL-LHC final focus: large-aperture Nb₃Sn quadrupoles

- NbTi (known since 1962) is a ductile (malleable) alloy, while Nb₃Sn (1954!) is a brittle intermetallic compound, which cannot be bent or plastically deformed once formed
- This requires a “wind-and-react” process:
 - Cable:** Nb and Sn precursor filaments in a copper-stabilised Rutherford cable
 - Wind:** form the coil while the precursor remains ductile
 - React:** heat-treat at 650–700 °C to form brittle Nb₃Sn (entire coil must survive high-temperature treatment without distortion or contamination, any mismatch in thermal expansion can induce stress or cracking)
 - Support:** vacuum-impregnate with epoxy and apply precise mechanical preload
- Small conductor movements can initiate **quenches**; Nb₃Sn magnets may require more training quenches than NbTi to reach nominal field, and they could show de-training after thermal cycling [or possibly not, see [this article](#) from July 21, 2026]

NbTi: $T_c \sim 9.2$ K, $B_c \sim 10\text{--}11$ T (0 K), $B_{\text{practical}} \sim 8\text{--}9$ T (4.2 K)

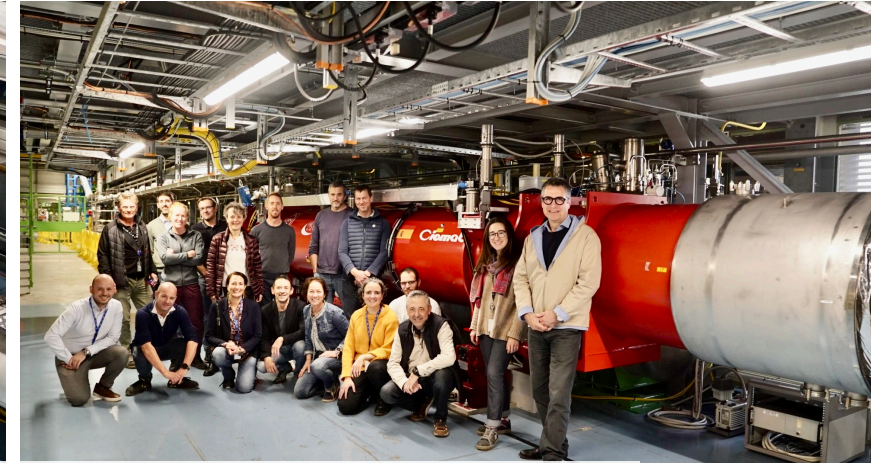
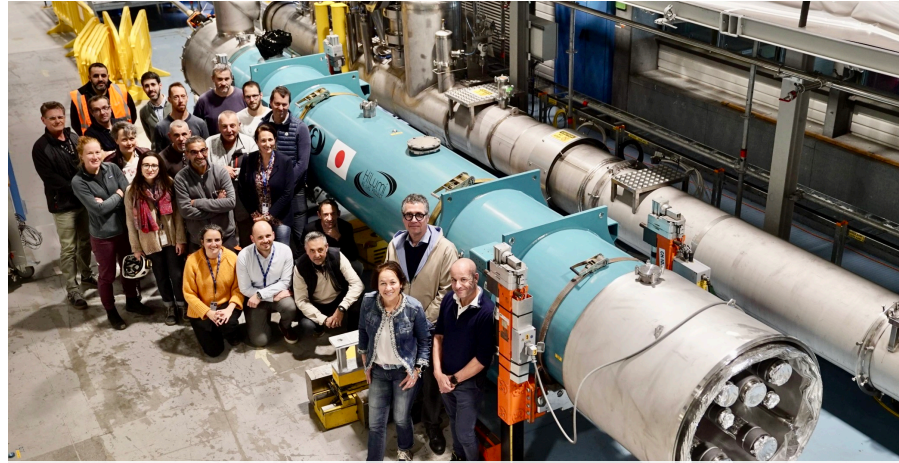
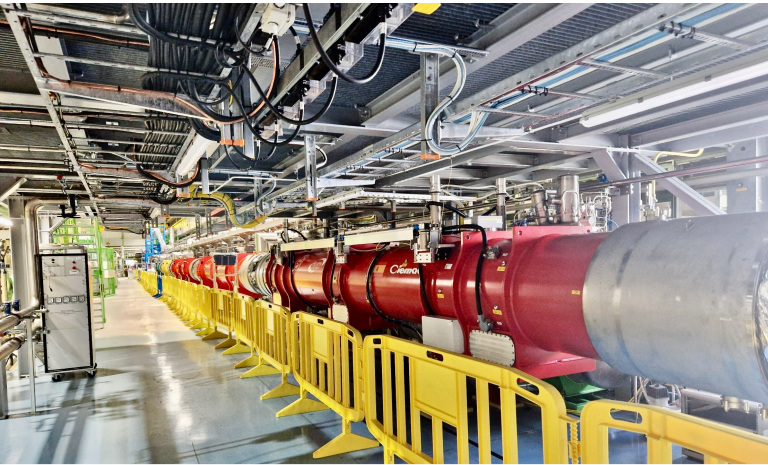
Nb₃Sn: $T_c \sim 18$ K, $B_c \sim 25\text{--}30$ T (0 K), $B_{\text{practical}} \sim 15\text{--}20$ T (4.2 K)



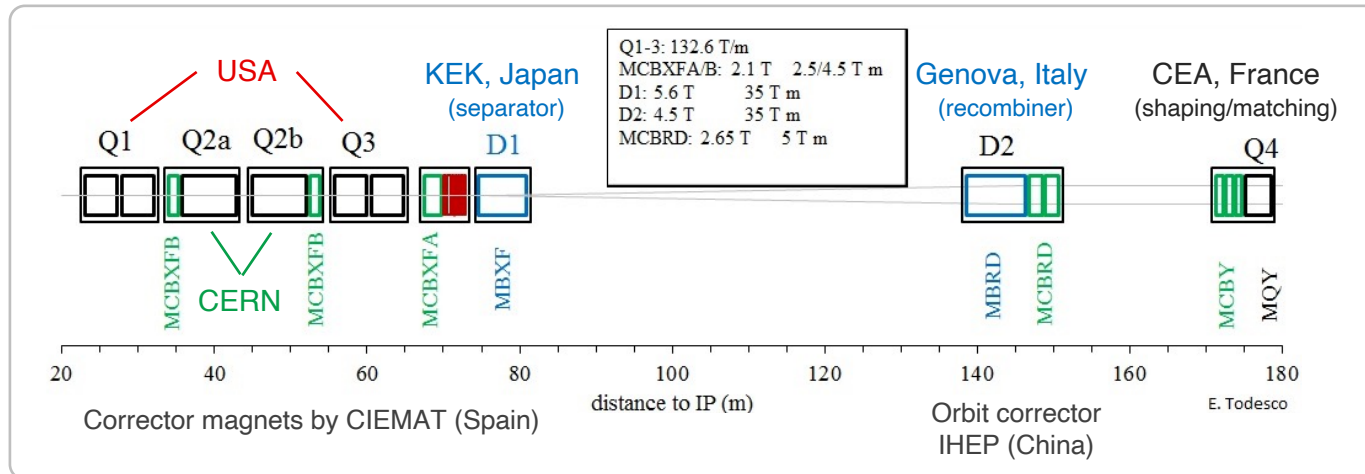
Nb₃Sn cable with single strands and glass-fibre insulation (partially unwrapped). Winding of magnet coil with glass-fibre insulated cables made of multi-filamentary wires that contain Nb and Sn precursors in a Cu matrix. Heat treatment of coil so that precursor elements react chemically and form the desired Nb₃Sn superconducting phase. To protect the then extremely fragile coil, a polymer is injected, which fills the interstitial spaces among cables, and is subsequently cured to become a matrix of hardened plastic providing cohesion and support to the cables

HL-LHC — Stronger focusing

New Nb₃Sn “inner triplet” quadrupoles



Fully realistic inner triplet string test facility at CERN, from left to right: installation of superconducting link, installation of D1 and Q2a cryo-assemblies, tests to start in Oct 2025



Nb₃Sn technology for new high-field superconducting quadrupole magnets successfully demonstrated for HL-LHC!

HL-LHC (aka Phase-2) upgrades of ATLAS and CMS

HL-LHC's high luminosity (pileup $\rightarrow$ 200) requires unprecedented detector and computing technologies, realised through very ambitious and challenging upgrades

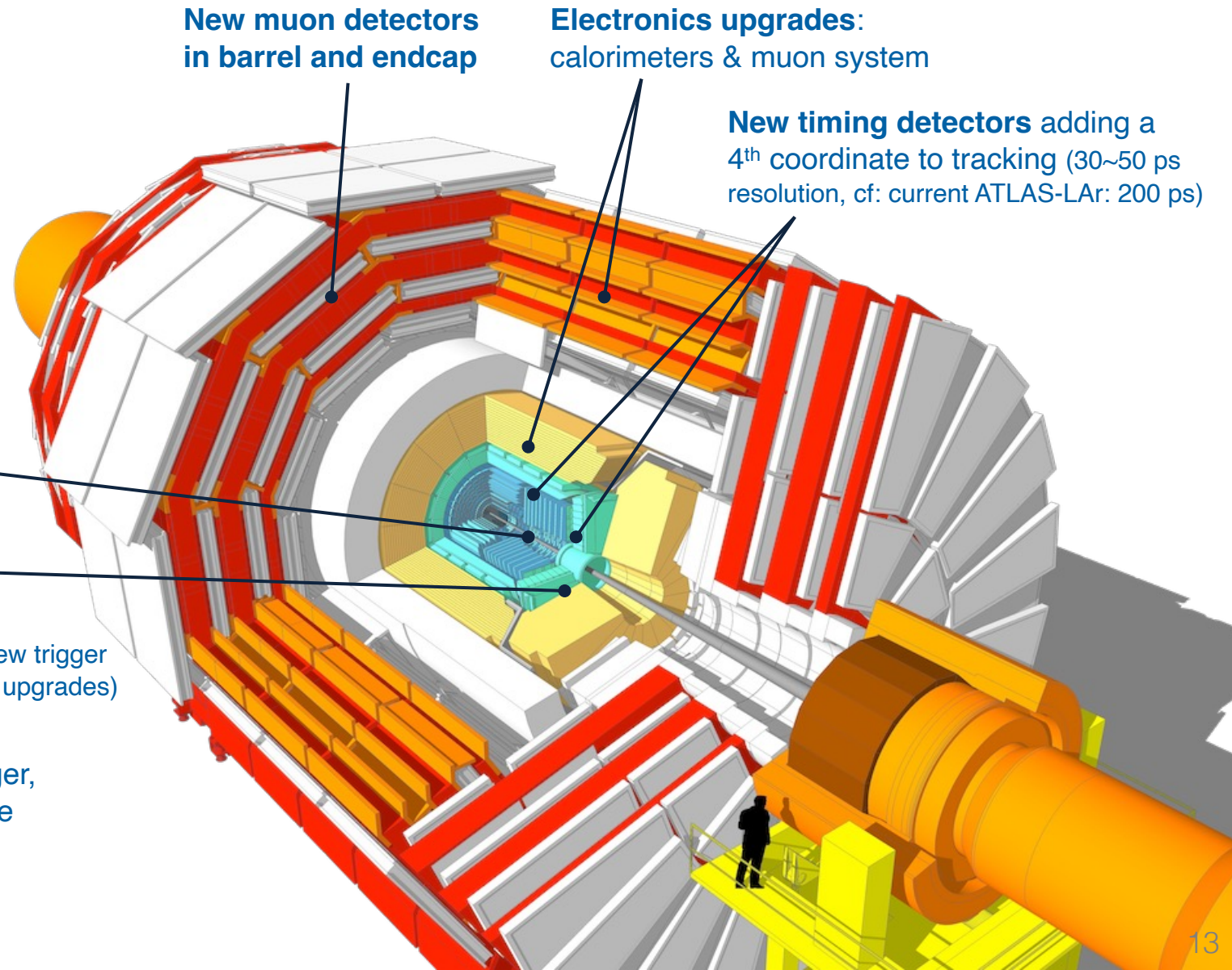
$\rightarrow$ **Top priority for ATLAS & CMS**

New **silicon pixel and strip inner trackers** with increased granularity and forward acceptance to $|\eta| \sim 4$

New **high-granularity endcap calorimeter** (CMS)

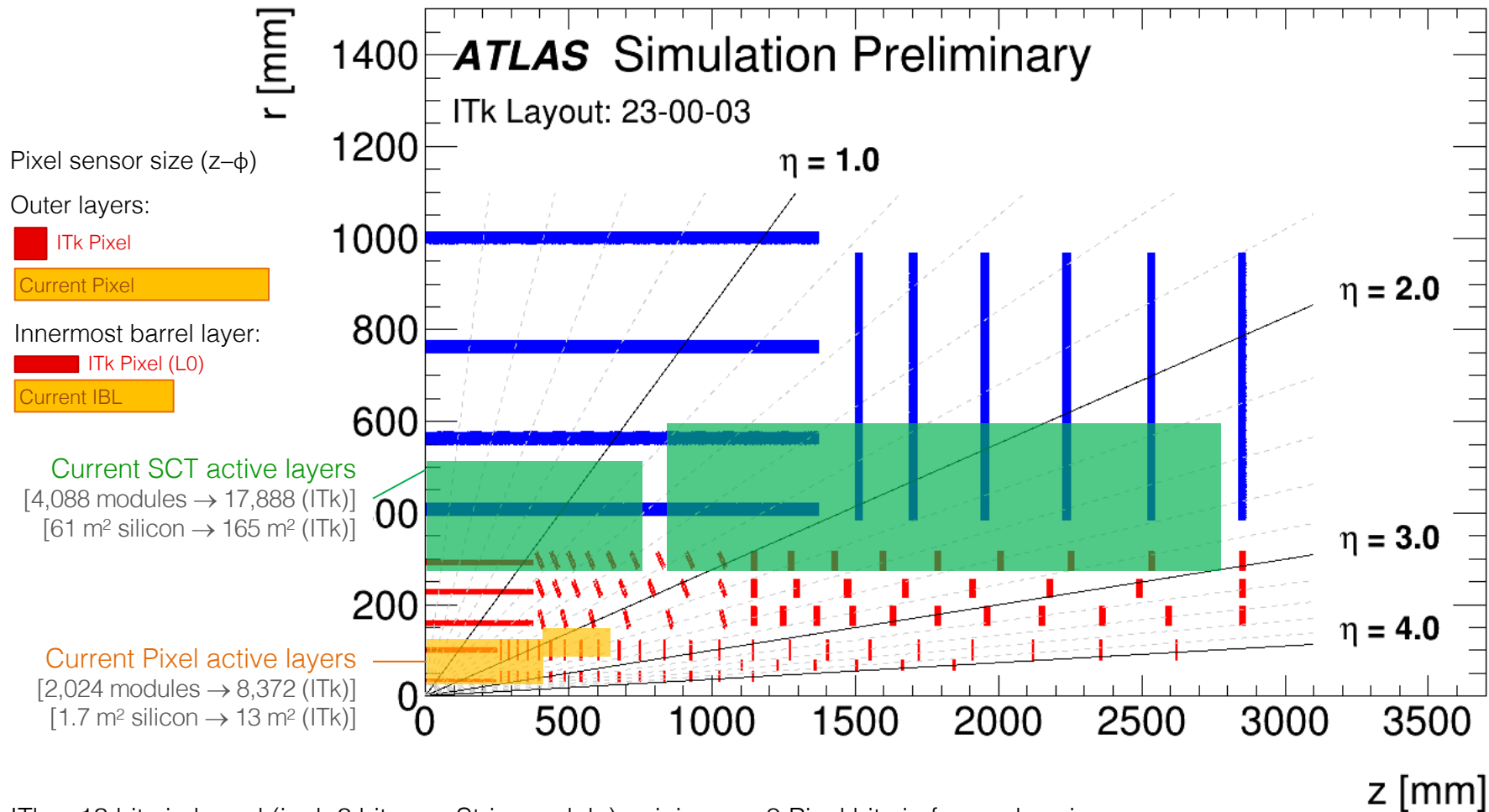
Upgraded trigger and data acquisition systems (new trigger requirements (increased latency) drive most of the electronics upgrades)

Extensive **software (incl. ML) developments** in trigger, reconstruction, and analysis needed to fully exploit the new capabilities

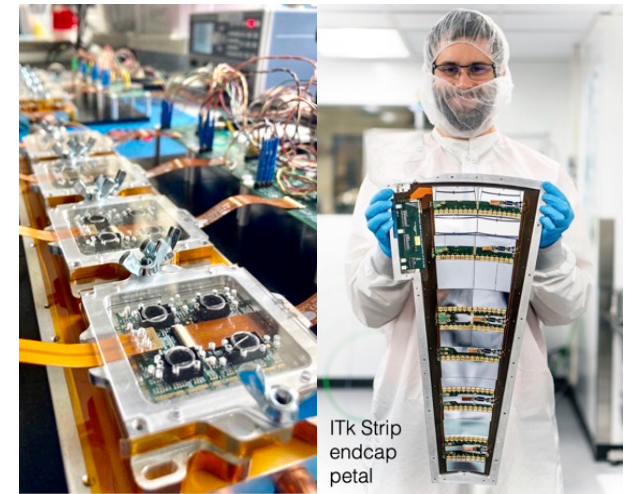


New ATLAS Inner Tracker (ITk)

New ATLAS silicon pixel and strip tracker (5B channels, $|\eta| \leq 4$: e.g. in VBF, 30 GeV central-jet veto efficiency rises from 26% to 82% owing to better pileup mitigation)

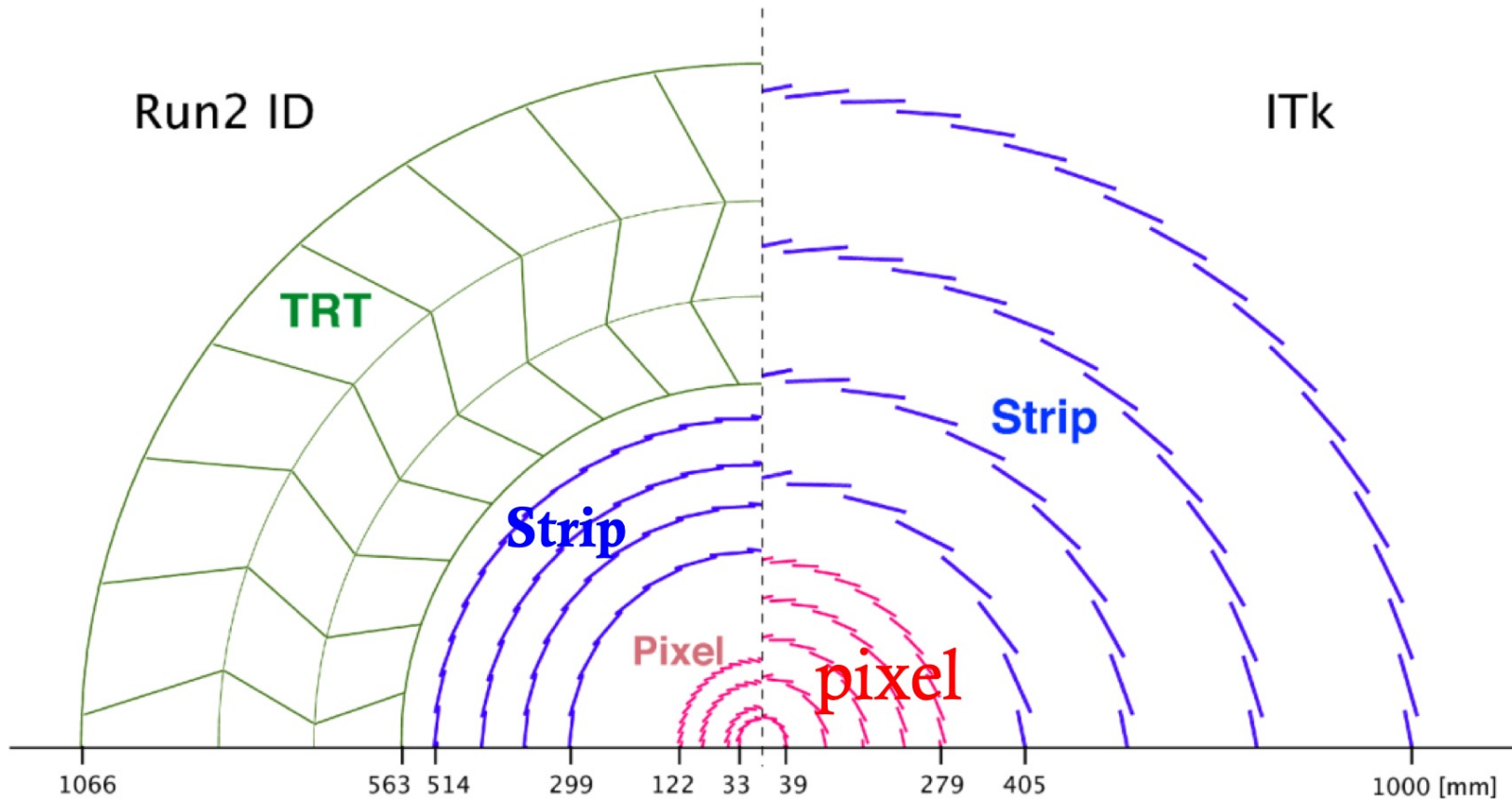


ITk: ~ 13 hits in barrel (incl. 2 hits per Strip module), minimum ~ 9 Pixel hits in forward region

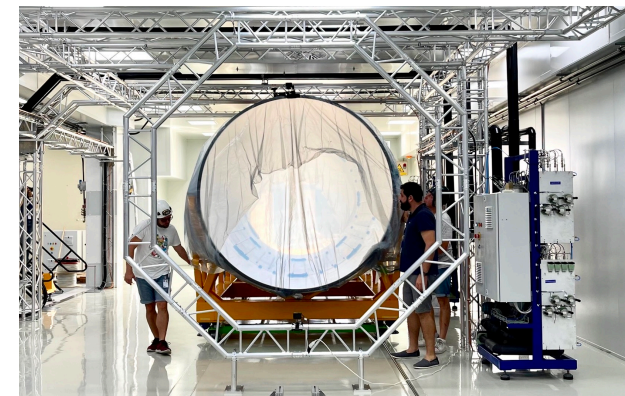
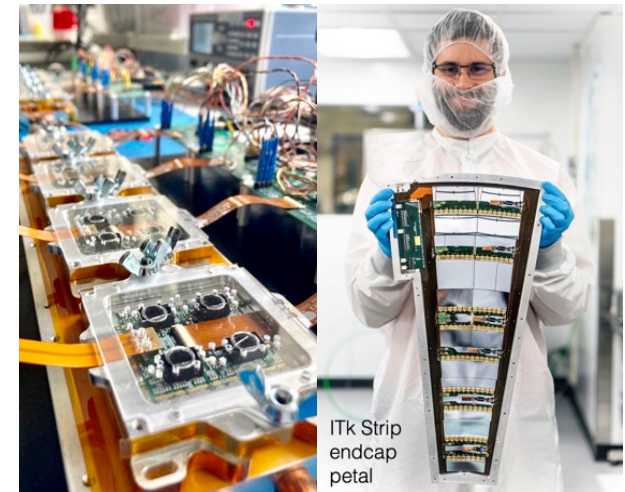


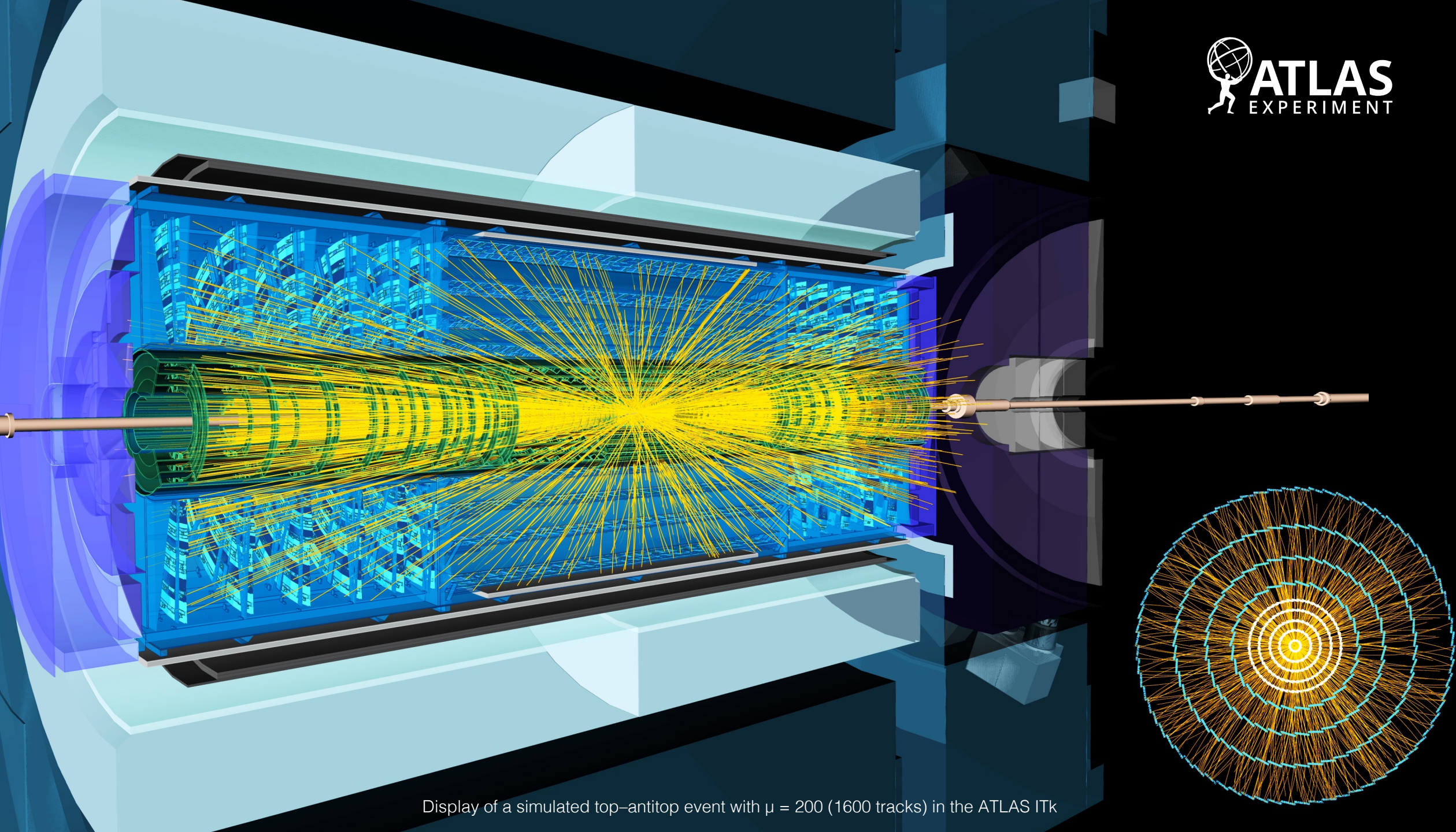
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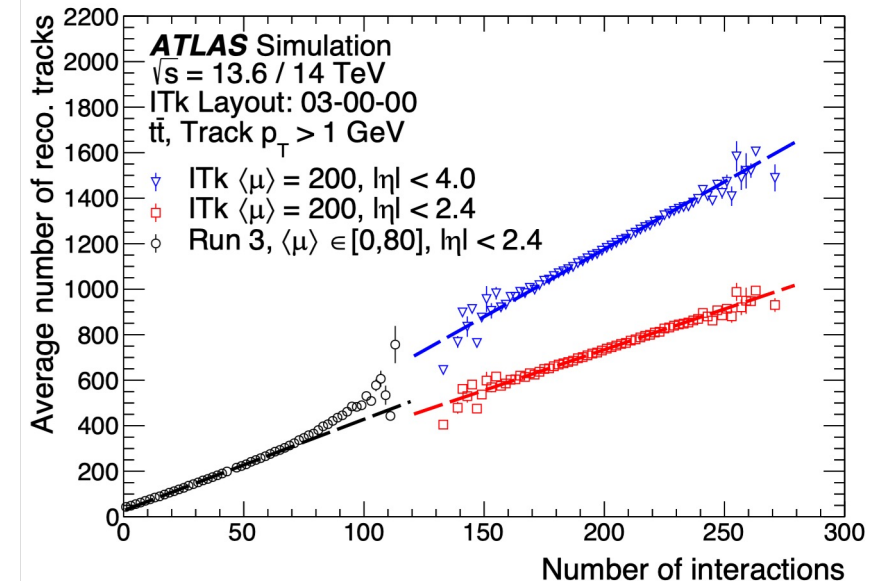
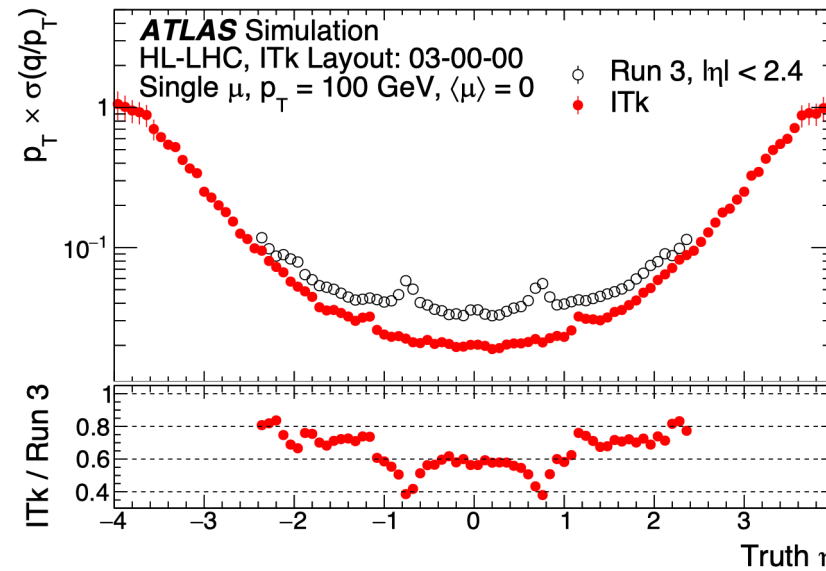
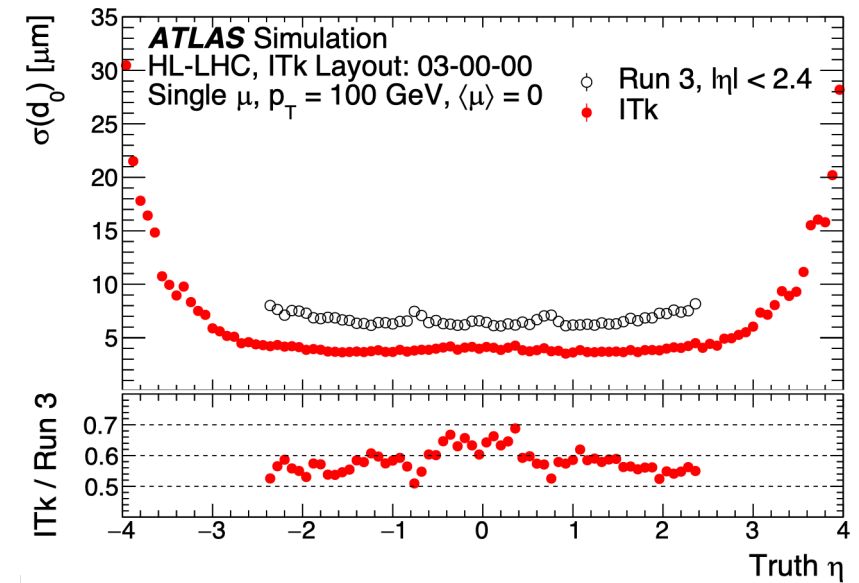
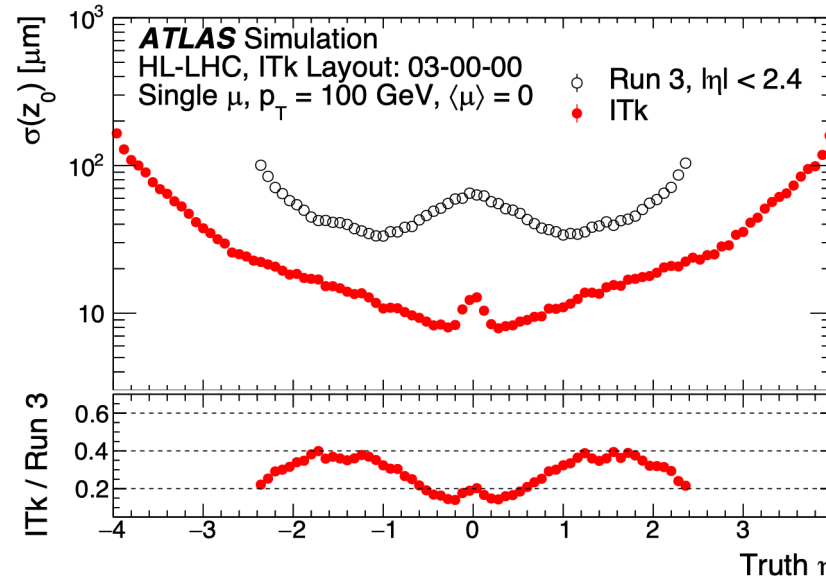
Display of a simulated top-antitop event with $\mu = 200$ (1600 tracks) in the ATLAS ITk

Performance of ATLAS ITk

JINST 20 (2025) P02018

For 100 GeV muons, z_0 resolution improves by up to $\times 5$, enhancing pileup rejection; d_0 and p_T resolutions also improve, benefiting flavour tagging and $H \rightarrow \mu\mu$ (smaller gains at low p_T due to multiple scattering)

Quasi-linear scaling of track multiplicity with pile-up



SR1 at Point 1: cleanroom for ITk Pixel and Strip integration



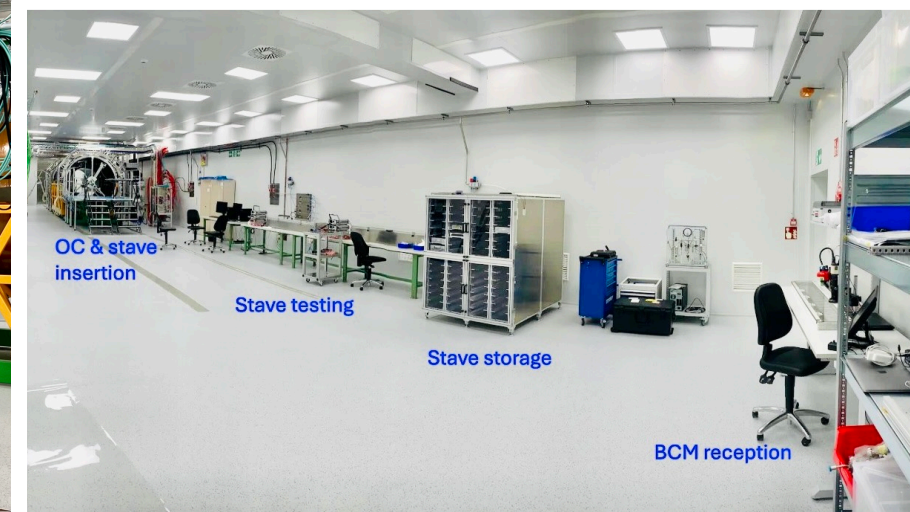
Top: ITk Outer Cylinder

Outer Barrel loaded local support reception test stand

Outer Barrel integration area

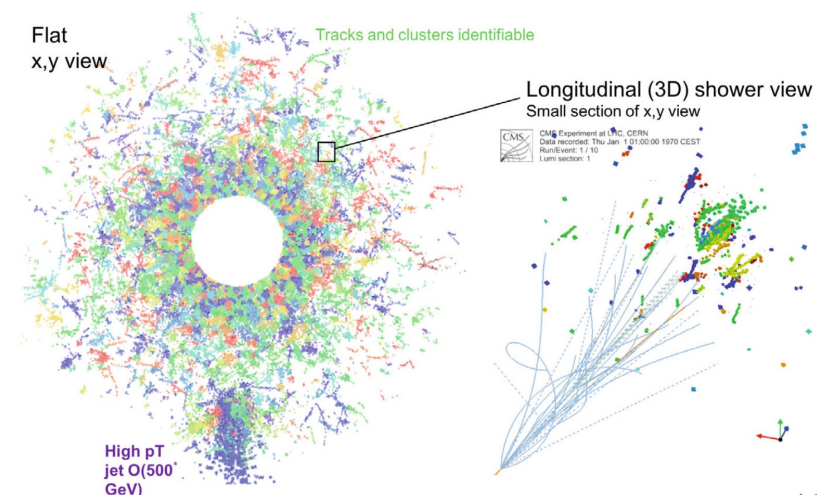
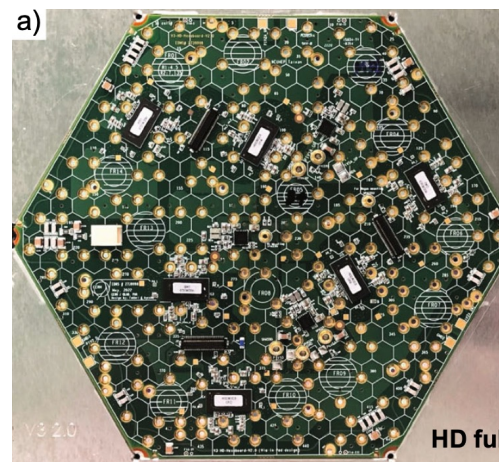
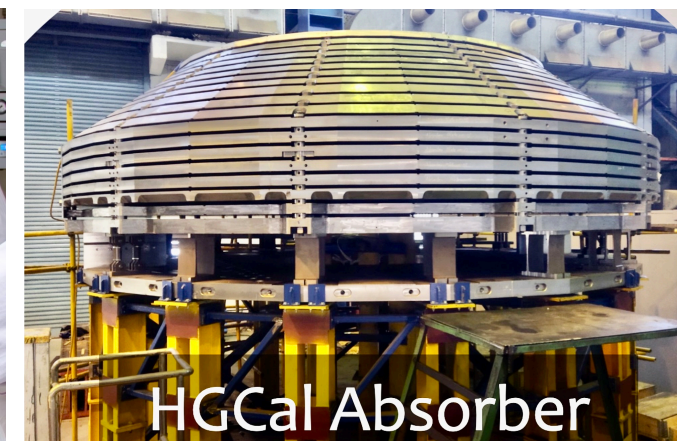
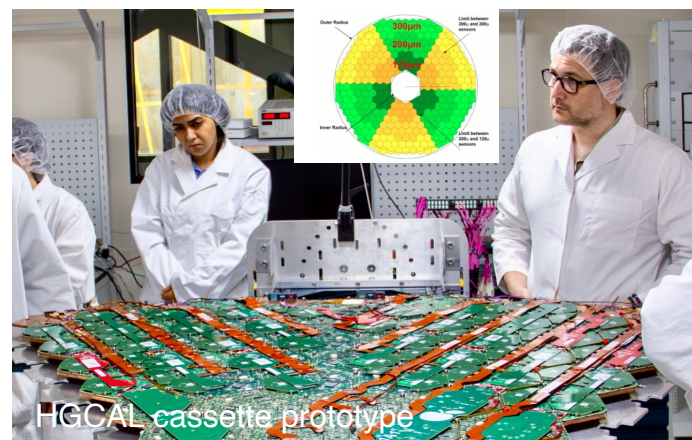
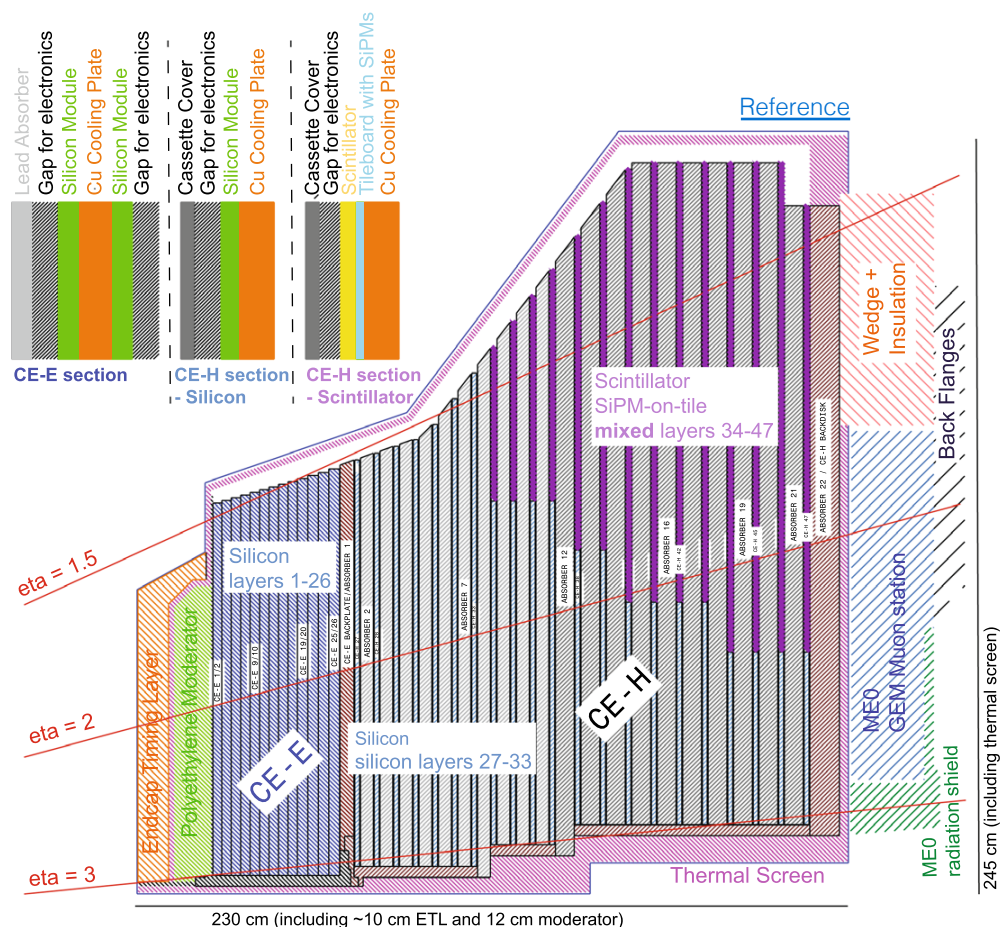


Bottom: ITk Strip integration area



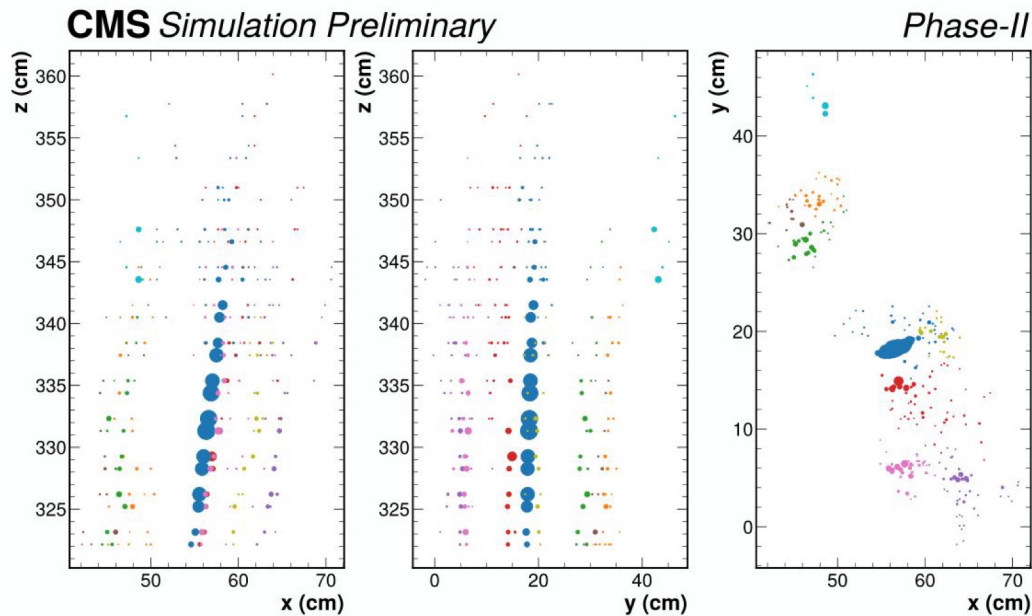
New High-Granularity Silicon CMS Endcap Calorimeter

New CMS endcap calorimeter (HGCAL, $1.5 < \eta < 3$) — highly segmented, 5D imaging sampling calorimeter with 26 Si + Pb/CuW/Cu layers in EM section (CE-E), and 7 Si plus 14 scintillator + steel/Cu layers in HAD section (CE-H), to provide precise energy, position, and timing measurements in high-radiation forward region, 6M channels, 27k Si modules, 620 m² of silicon (ATLAS tracker: 180 m²)



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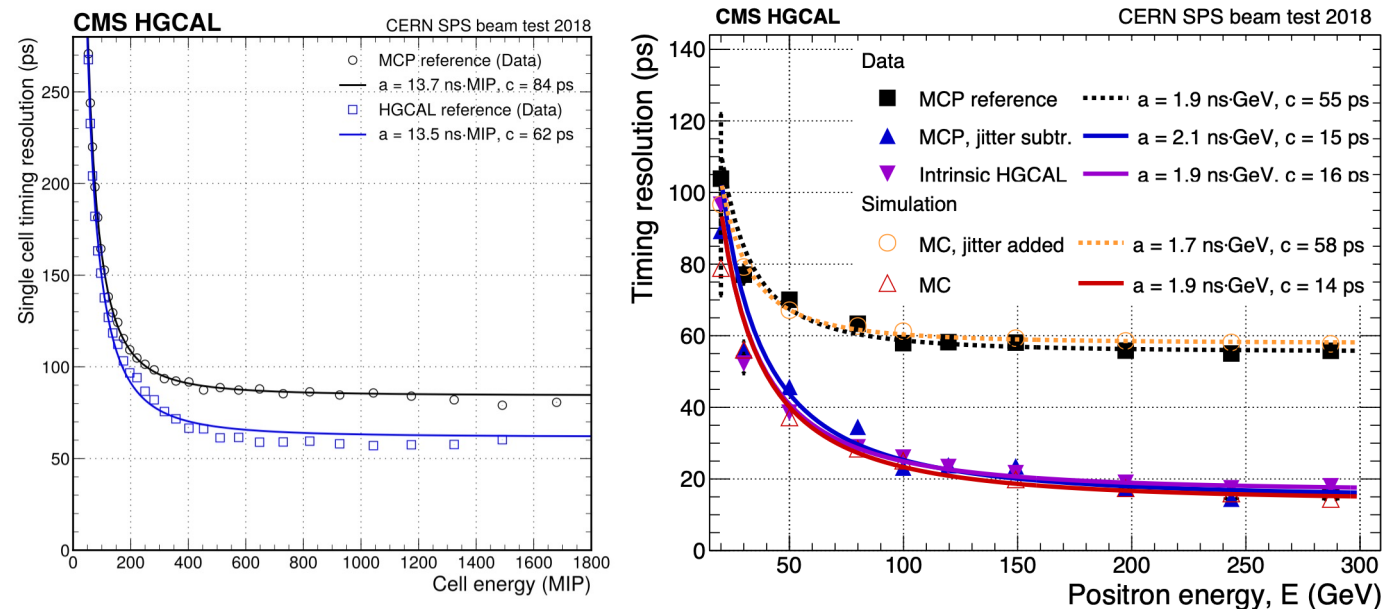
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[CMS DP -2024/124](#)

Event display in the HGCAL of an electron. Each circle represents a Layer Cluster (LC) and its radius is proportional to its energy. The LCs forming a trackster* are identified with the same colour

*trackster is reconstructed 3D representation of a particle shower (or shower fragment) in HGCAL



[arXiv:2312.14622](#)

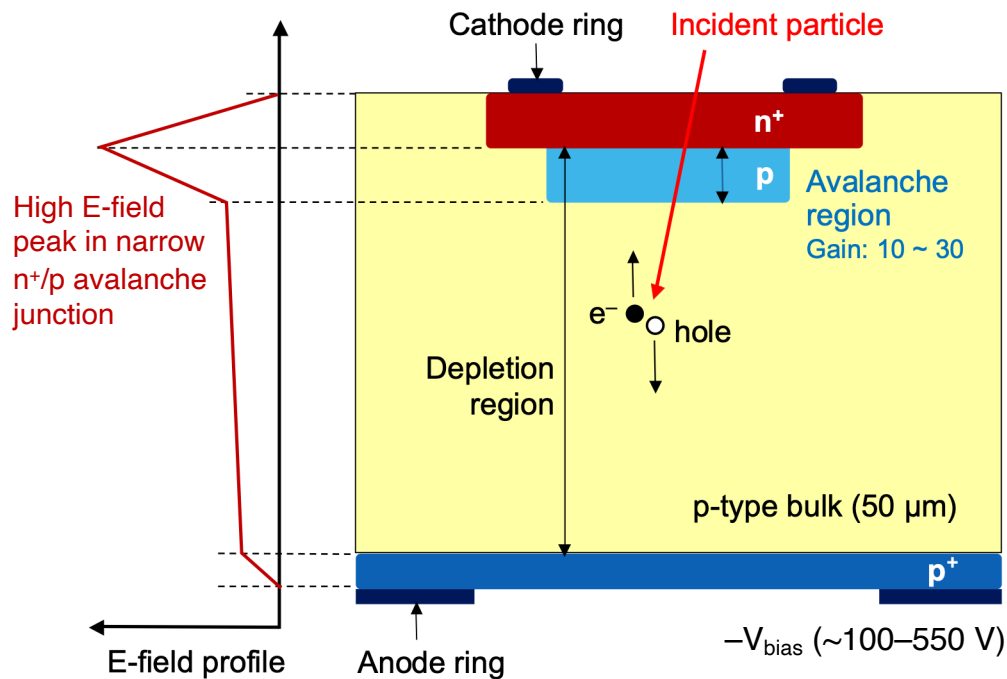
Timing results from 2018 positron beam tests of an HGCAL prototype. If sufficient energy, reaching 60 ps single channel and 20 ps full shower resolution

A 4th tracking coordinate: precision timing

*LGAD = Low-Gain Avalanche Detector
LYSO** is a fast rad hard scintillating crystal

ATLAS (forward) and CMS (endcap) construct LGAD* based timing layers (CMS barrel uses LYSO+SiPM)**
with $\sigma_t = 30\text{--}50$ ps timing resolution per track for pileup mitigation / primary vertex identification

Equivalent z_0 resolution per track: $\sigma^{\text{equiv}}(z_0) = c \cdot \sigma_t / |\tanh(\eta)| \approx 9\text{--}15$ mm (for $|\eta| > 2.4$) light-travel distance: an independent fourth coordinate for pileup rejection



Mechanism: Gain layer → fast rise time; thin sensor → fast charge collection, less fluctuations; **together: precision timing**

Rad-mitigation: Engineered gain layer, active cooling, higher V_{bias}

ATLAS HGTD at a glance

- **Geometry:** Two double-sided disks per endcap at $z \approx \pm 3.5$ m; $2.4 < |\eta| < 4.0$; 2–3 hits per track
- **Granularity:** 50 μm sensors; $1.3 \times 1.3 \text{ mm}^2$ pads; 3.6 M channels in 8'032 modules
- **Readout:** ASIC measures time of arrival and time over threshold; ToT corrects timewalk
- **Reconstruction:** Time-of-flight correction + calibrated offsets → track time; associated tracks determine vertex t (primary vertex t_0 required → barrel timing layer (CMS) helpful)
- **Lifetime:** ~ 30 ps/track initially → ~ 50 ps at $2.5 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$

What sets the time resolution

$$\sigma_t^{\text{total}} = \underbrace{\sigma_t^{\text{Landau}}}_{< 25 \text{ ps thin sensor}} \oplus \underbrace{\sigma_t^{\text{jitter}}}_{< 25 \text{ ps } t_{\text{rise}}/(S/N)} \oplus \underbrace{\sigma_t^{\text{timewalk}}}_{< 10 \text{ ps ToT correction}} \oplus \underbrace{\sigma_t^{\text{TDC}}}_{< 10 \text{ ps digitisation}} \oplus \underbrace{\sigma_t^{\text{clock}}}_{< 10 \text{ ps distribution}}$$

Impact of radiation on silicon detectors

$\Phi_{eq} = 1 \text{ MeV neutron-equivalent fluence}$
 $1 \text{ MGy} = 1 \text{ MJ per kg absorbed energy}$

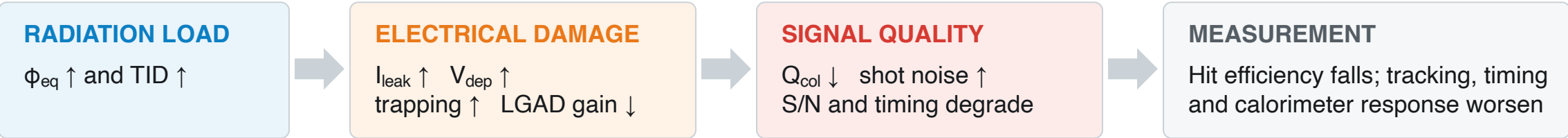
Detectors face harsh radiation fields varying with radial distance and pseudorapidity. Exposure is quantified by **Non-Ionizing Energy Loss (NIEL fluence Φ_{eq})** [unit: 1 MeV n_{eq}/cm^2] and **Total Ionizing Dose (TID)** [MGy]

Impact on silicon

BULK · NIEL	Displacement defects in silicon lattice → p-type carrier generation ($I_{leak} \uparrow$), trapping $\uparrow$ ($Q_{col} \downarrow$), space-charge changes ($V_{dep} \uparrow$)
SURFACE · TID	Oxide / interface charge builds up → surface leakage ($I_{leak} \uparrow$), insulation, ASIC transistor threshold voltage shifts
LGAD	Gain-layer acceptors are removed → multiplication gain $\downarrow$, timing jitter $\uparrow$

Maximum doses (4 ab^{-1})

DETECTOR REGION	$\Phi_{eq} [n_{eq}/\text{cm}^2]$	TID
ATLAS/CMS Inner Pixels	2×10^{16}	10 MGy
CMS HGCAL silicon	1×10^{16}	6 MGy
ATLAS HGTD (sensor)	2.5×10^{15}	2 MGy
ATLAS ITk Strips	1.5×10^{15}	0.75 MGy



Recover charge collection during operation

$V_{bias} \uparrow \rightarrow$ deeper depletion + stronger field + faster drift $\rightarrow Q_{col}$ and efficiency recover
Cold operation ($-35 \text{ }^\circ\text{C}$ CO_2 set point) suppresses I_{leak} and prevents thermal runaway

But bias has a ceiling (limiting det. lifetime)

Sensor breakdown and HV insulation limits, thermal runaway, excessive shot noise, LGAD single-event burnout SEB ($< 550 \text{ V}$)

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Non-Ionizing Energy

Impact on silicon

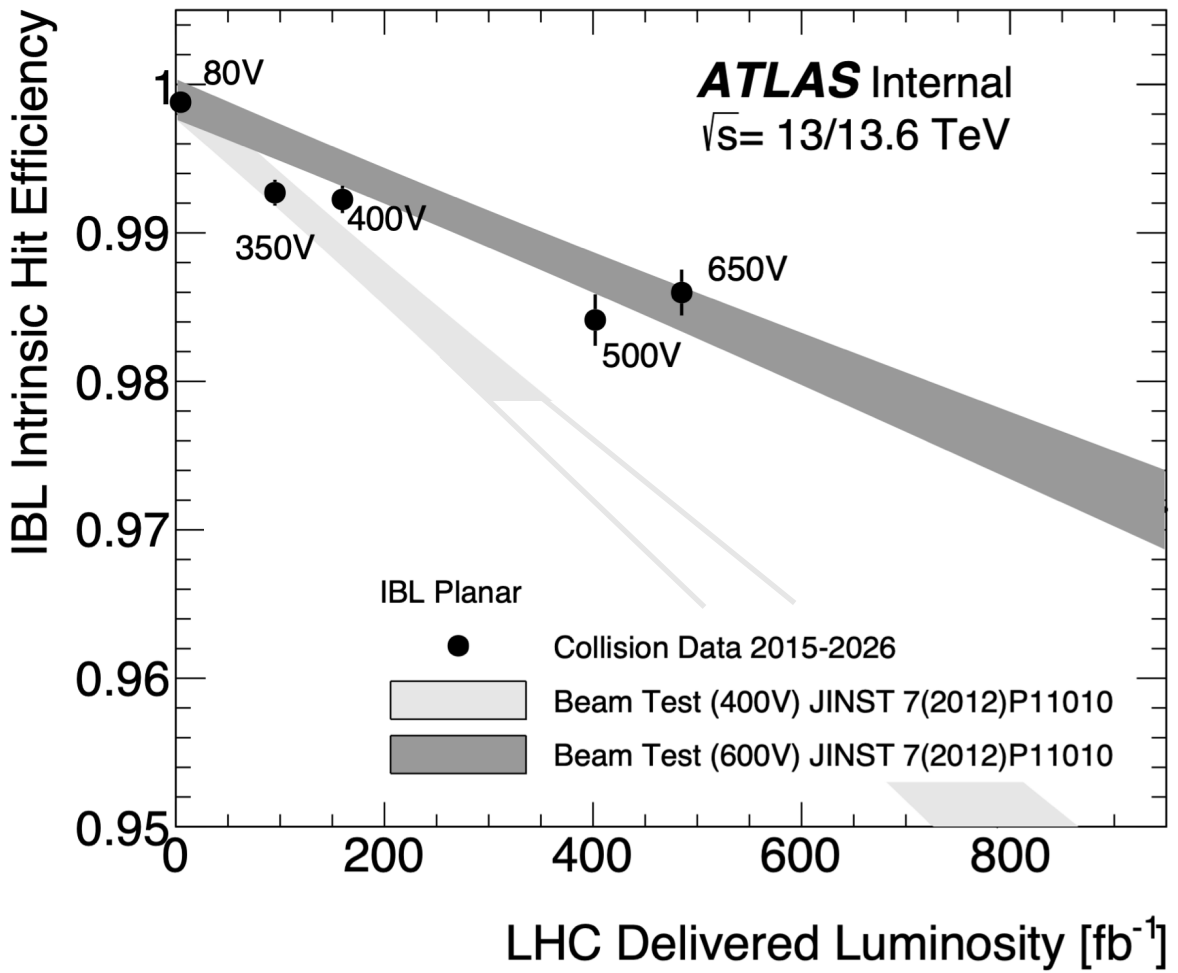
- BULK · NIEL** Displacement
trapping
- SURFACE · TID** Oxide /
ASIC tr
- LGAD** Gain-la

RADIATION LOAD

$\Phi_{eq} \uparrow$ and TID $\uparrow$

Recover charge col

$V_{bias} \uparrow \rightarrow$ deeper dep
Cold operation ($-35\text{ }^{\circ}\text{C}$)



antified by
[MGy]

Φ_{eq} [$\text{n}_{eq}/\text{cm}^2$]	TID
$< 10^{16}$	10 MGy
$< 10^{16}$	6 MGy
$\times 10^{15}$	2 MGy
$\times 10^{15}$	0.75 MGy

EMENT

cy falls; tracking, timing
meter response worsen

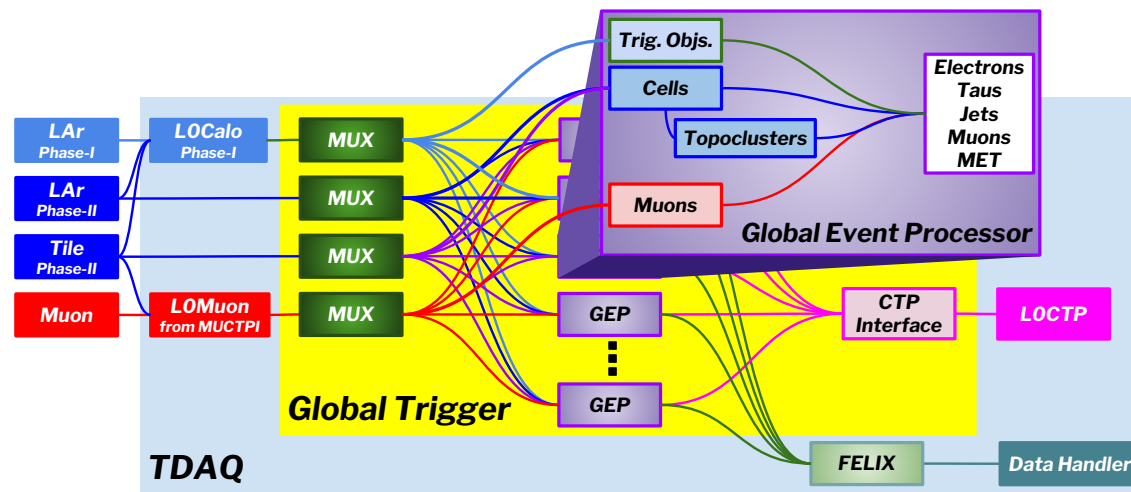
g (limiting det. lifetime)

d HV insulation limits,
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ATLAS and CMS Trigger and Data Acquisition Upgrade

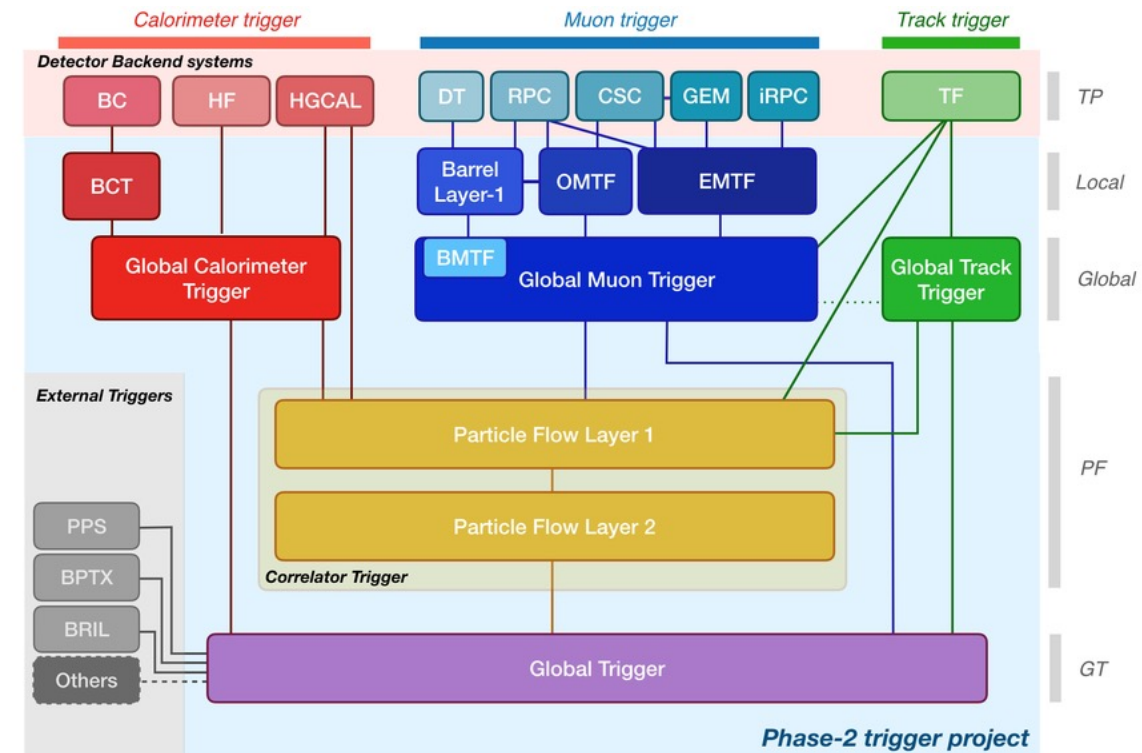
Significantly improved TDAQ especially for the first hardware level: throughput of 1 MHz (ATLAS), 750 kHz (CMS), much more detailed object-level, topological, and global event selection capabilities, including ML, based on powerful FPGAs

Aim: keep and improve over Run-2 selections (low thresholds) in much harder HL-LHC environment, and offer new opportunities



New ATLAS L0 Global Trigger: offline-quality reconstruction using input from calorimeters and muon systems built upon digital improvements realised during Phase-I upgrade

ATLAS Global Common Module prototype (v3)

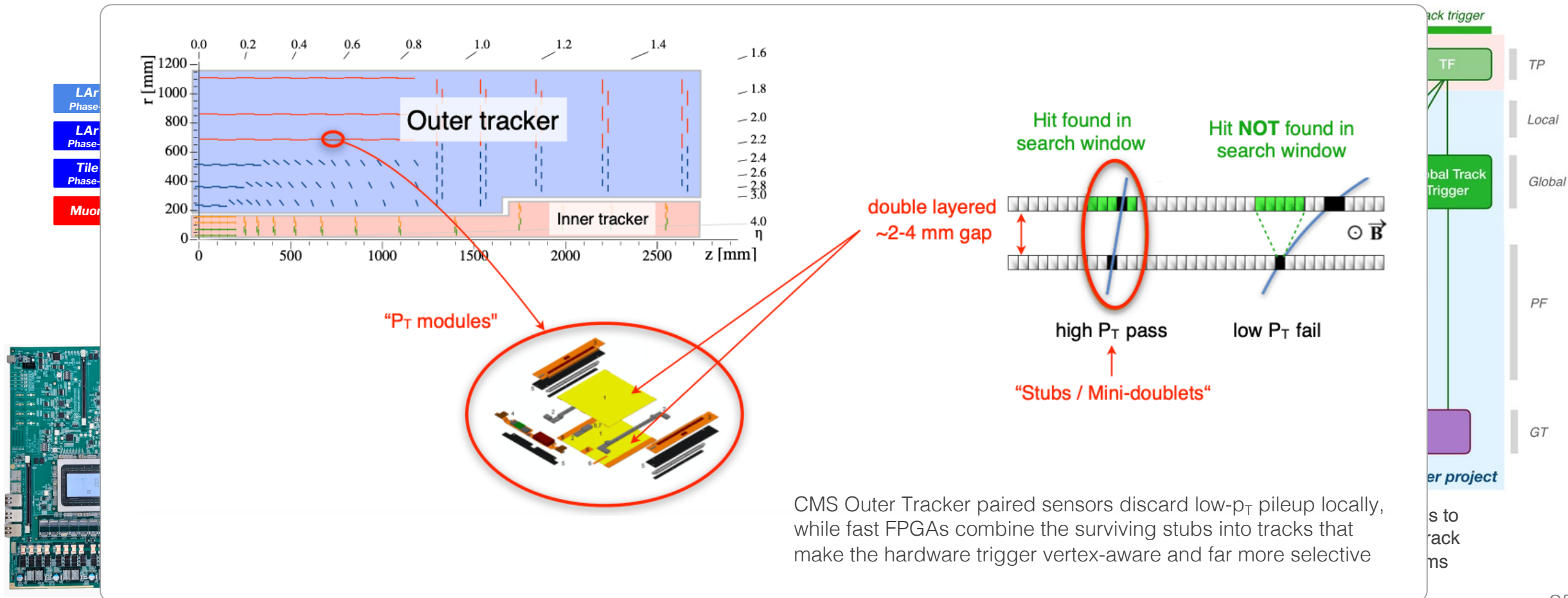


New CMS L1 trigger design: the Global Muon Trigger matches muons to tracks built from outer tracker stubs in the Track Finder, the Global Track Trigger reconstructs the primary vertex, the Correlator Trigger performs particle-flow, and the Global Trigger makes the final decision

ATLAS and CMS Trigger and Data Acquisition Upgrade

Significantly improved TDAQ especially for the first hardware level: throughput of 1 MHz (ATLAS), 750 kHz (CMS), much more detailed object-level, topological, and global event selection capabilities, including ML, based on powerful FPGAs

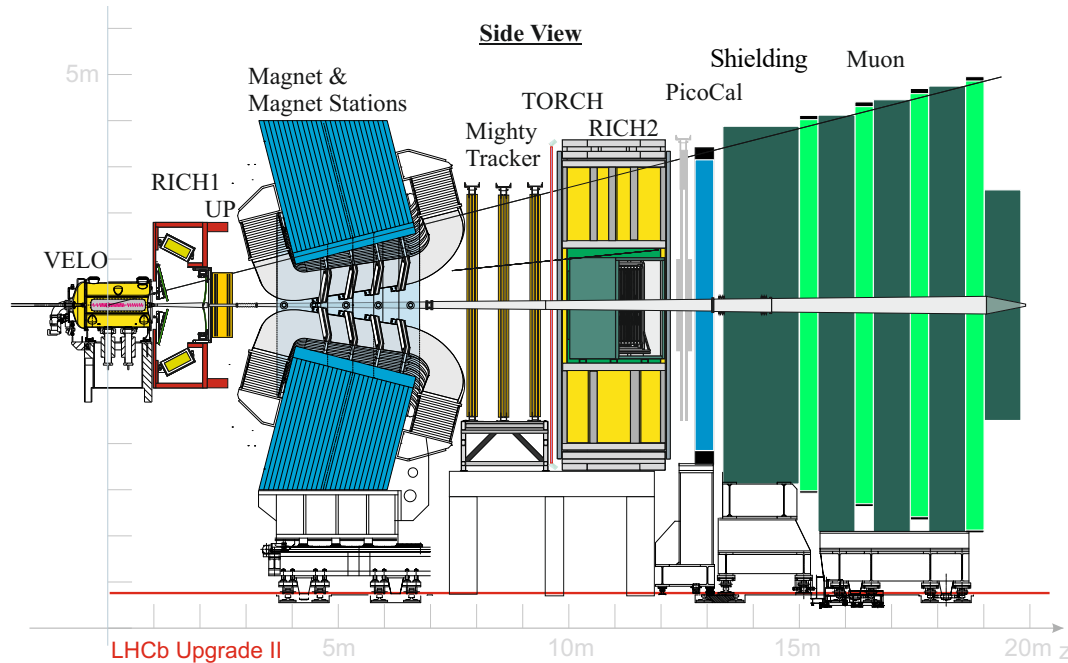
Aim: keep and improve over Run-2 selections (low thresholds) in much harder HL-LHC environment, and offer new opportunities



Ambitious LHCb Upgrade II and ALICE 3 for Run 5 (2036–2041)

LHCb Upgrade II [\[LHCb Upgrade II scoping document\]](#)

- Goal: enable operating at $L_{\text{inst}} = 1.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ (currently $0.23 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$), for $L_{\text{int}} > 300 \text{ fb}^{-1}$
- Challenge: pileup of 42 (current: ~ 6) $\rightarrow$ efficient tracking and vertexing, excellent PID, precise timing

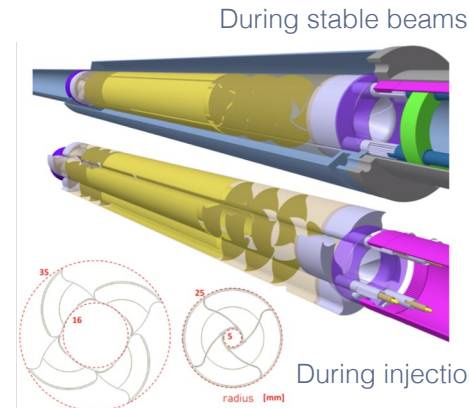
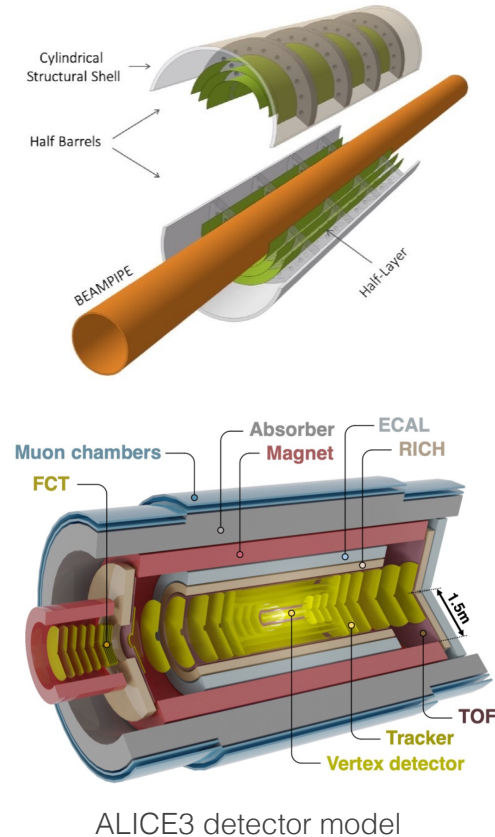


ALICE upgrades during LS3

- New ITS3 (MAPS) and forward calorimeter

ALICE 3 [\[ALICE 3 scoping document\]](#)

- Key goals: early-stage temperature with dielectrons, properties and hadronisation of QGP with heavy flavour hadrons, low- p_T hadron reconstruction required
- Compact low-mass all-silicon tracker, excellent vertex reconstruction, wide acceptance $|\eta| < 4$, PID in wide p_T range, high readout rate in A-A and pp

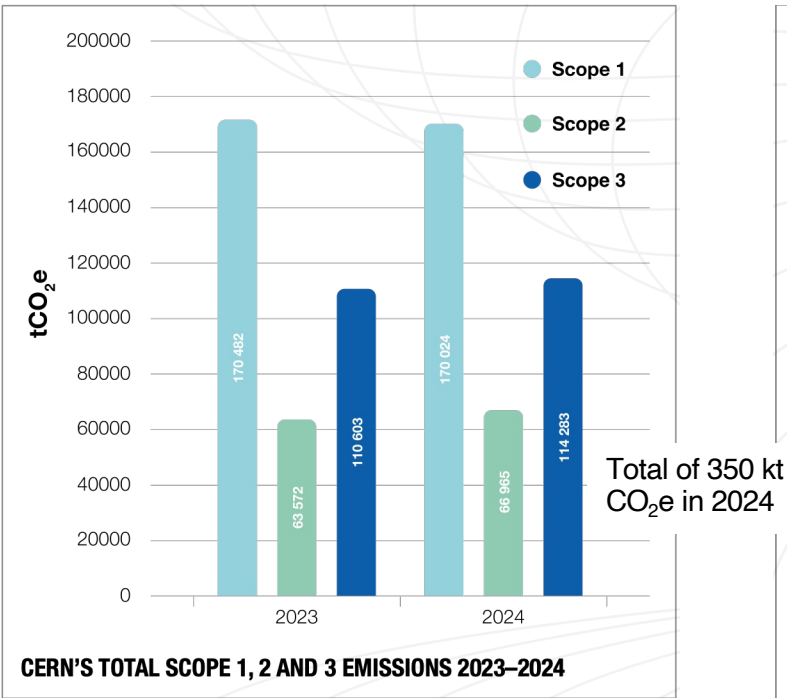
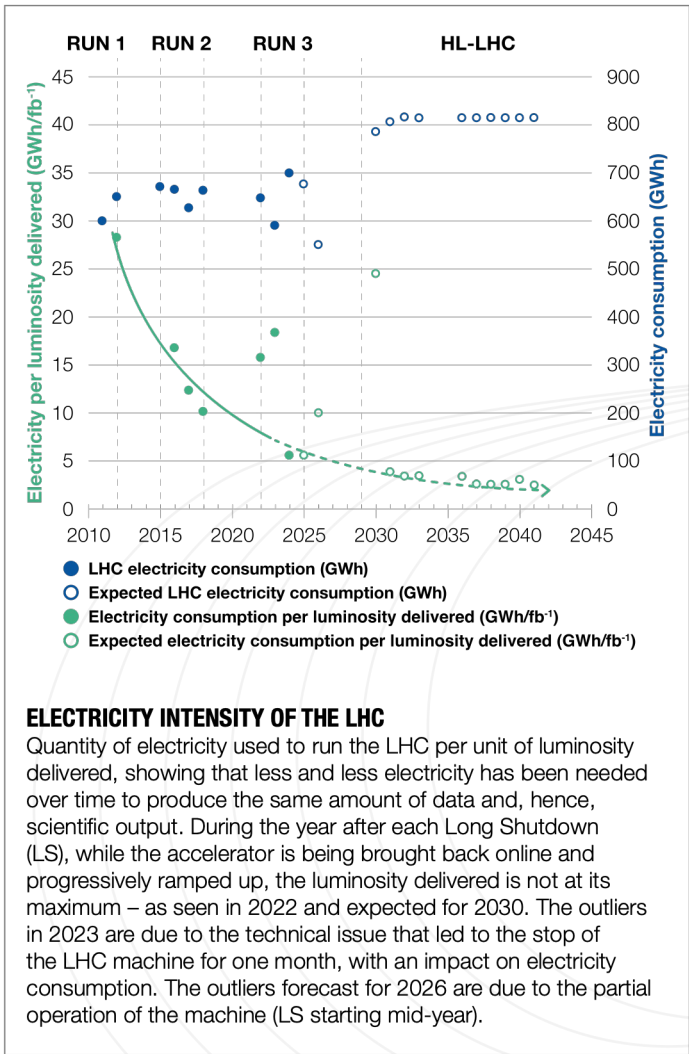


Retractable silicon vertex detector at 5 mm (15 mm during injection) from beam, giving $< 10 \mu\text{m}$ pointing resolution for $p_T > 200 \text{ MeV}$ in high-multiplicity environment at ALICE3

Environmental impact of LHC / HL-LHC operation

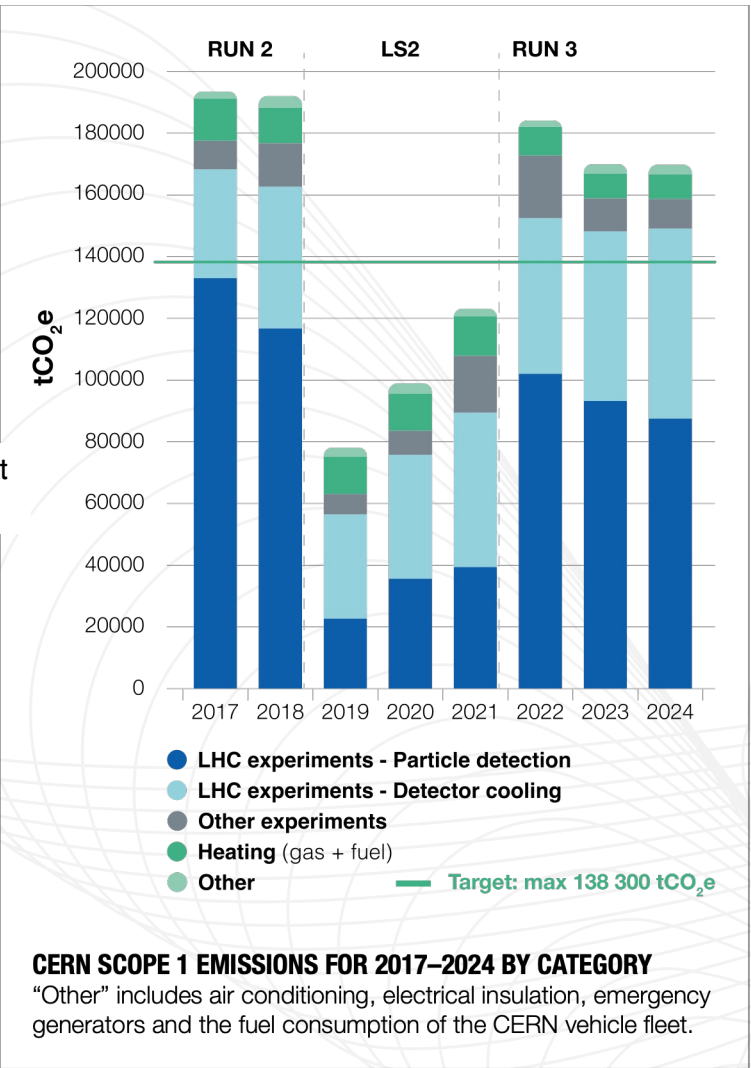
Source: [CERN Environmental Report 2023–2024](#)

CERN’s total annual power consumption is ~1.3 TWh dropping to ~0.4 TWh when LHC is not operating



- Scope 1: direct emission of greenhouse gases*
- Scope 2: indirect emission via purchased electricity
- Scope 3: all other indirect emission (procurement, ...)

*F-gas impact mainly from RPC losses and detector cooling; HL-LHC reductions from leak repairs, gas dilution, and new CO₂ cooling plants

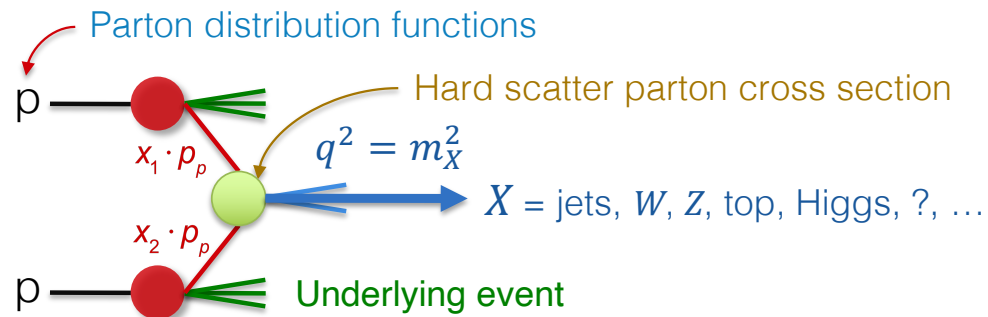


New opportunities at the HL-LHC

20 times more luminosity than Run 2 and better detectors offer significantly enhanced physics reach

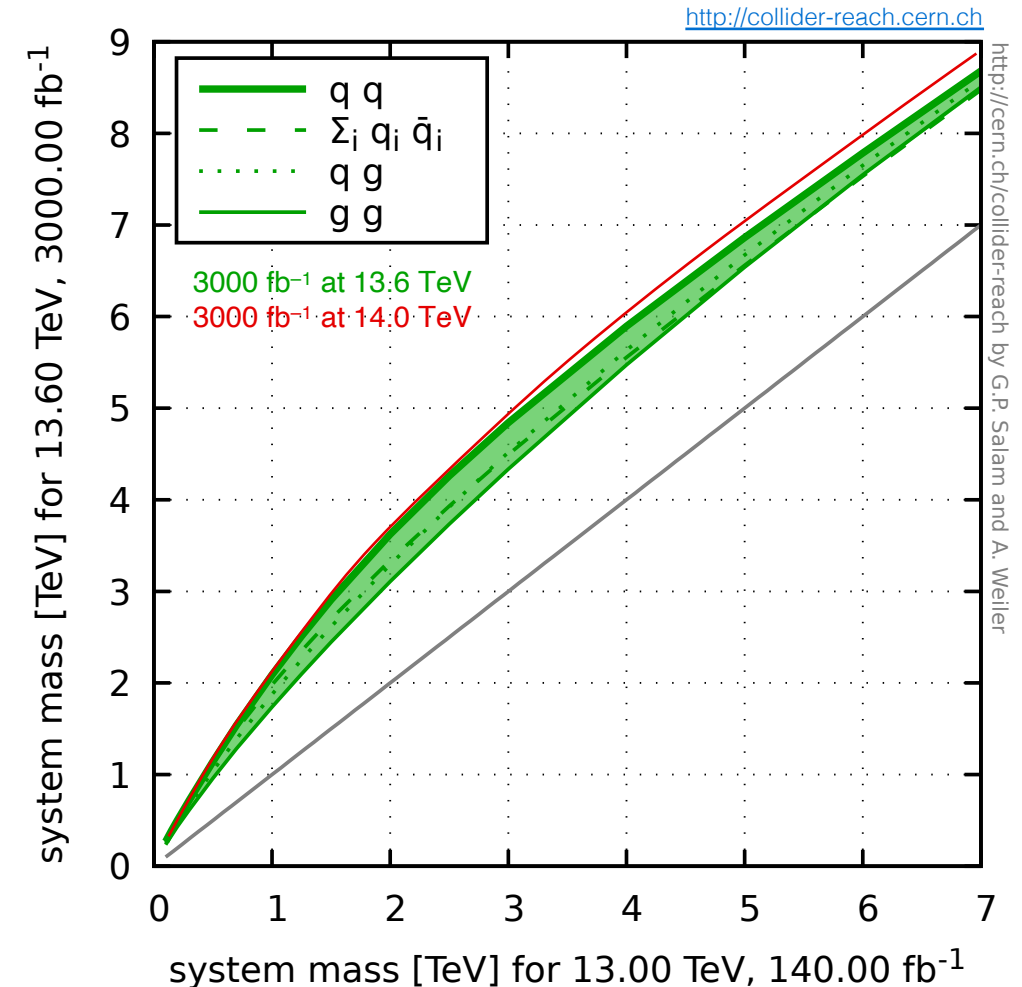
- Sensitivity increase by up to 2 TeV for searches

Proton–proton collisions correspond to a convolution of Parton Density Functions (PDF) with parton–parton scattering matrix element



CM energy-squared of parton collision: $\hat{s} = M_X^2 = x_1 \cdot x_2 \cdot s_{\text{LHC}}$

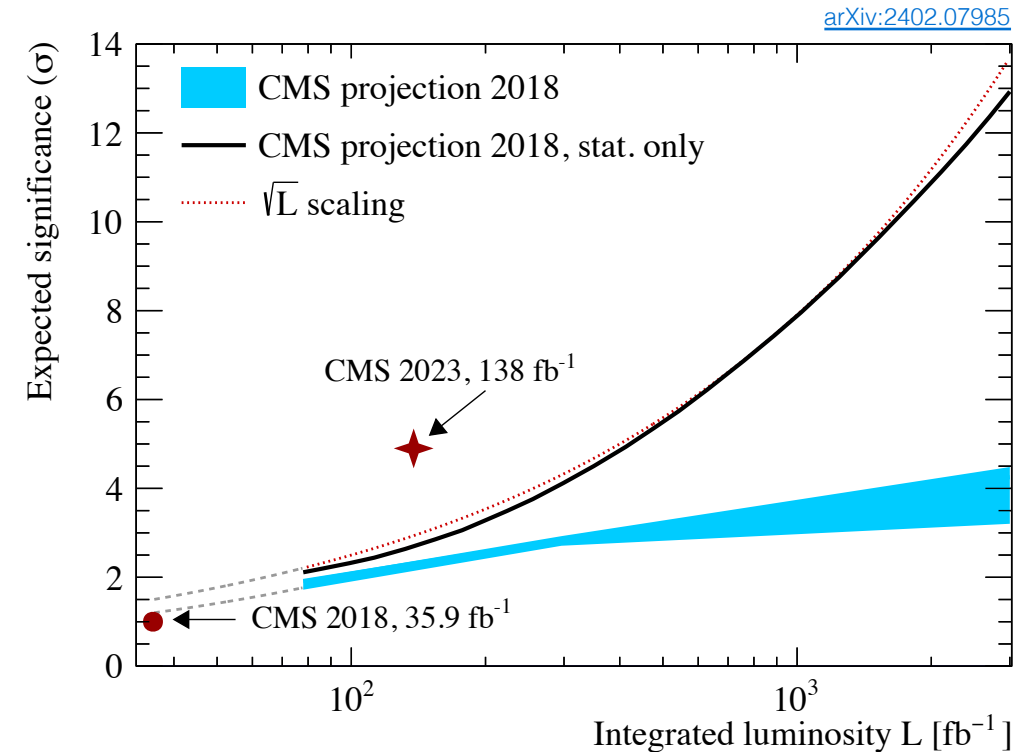
More luminosity allows to explore the high- x tails of the PDFs and thus reach higher parton collision energies



New opportunities at the HL-LHC

20 times more luminosity than Run 2 and better detectors offer significantly enhanced physics reach

- Sensitivity increase by up to 2 TeV for searches
- $\sqrt{L}$ or better sensitivity increase to new physics with weak or suppressed couplings (eg, EW SUSY, WIMPs, or feebly interacting particles)
- Sensitivity to new SM processes, extended phase space, and improved precision in Higgs, multiboson, top, flavour, ... probes



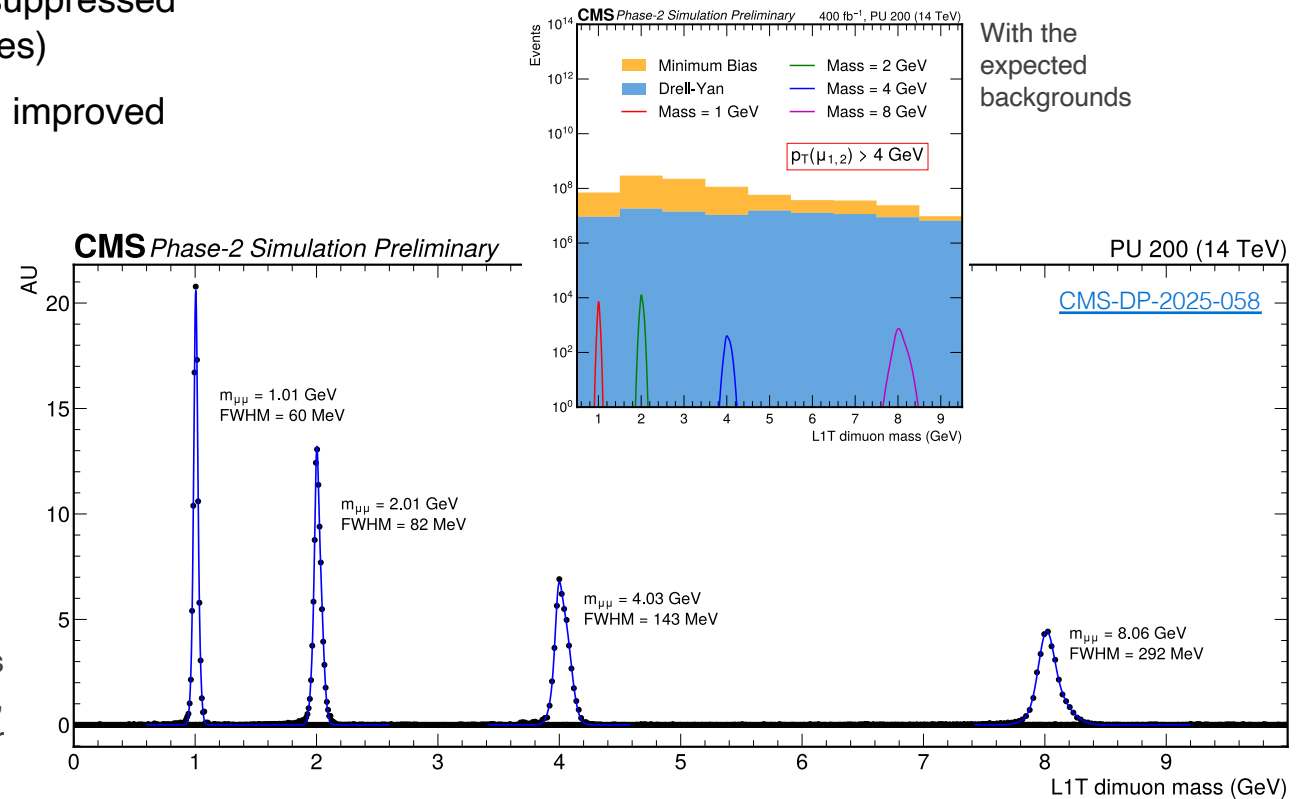
Evolution of the expected significance in CMS 4 top search, and what really happened

New opportunities at the HL-LHC

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- Increased trigger acceptance and selection capabilities for low-mass, soft, unconventional signatures

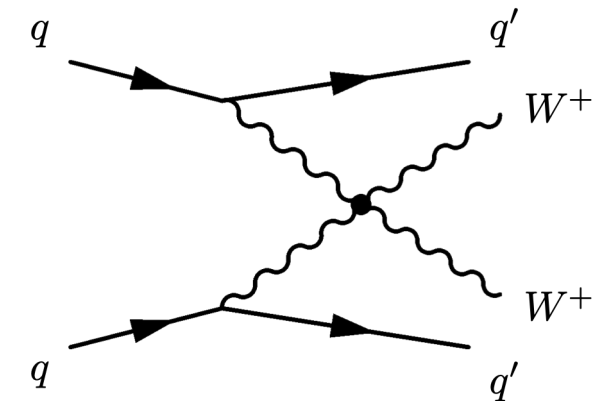
L1 data scouting prospects for low-mass $\mu\mu$ resonance search (eg, dark photon), excellent resolution owing to track trigger



New opportunities at the HL-LHC

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- Increased forward acceptance of trackers allows improved reconstruction of VBF/VBS topologies, constraints on PDFs, and control of pileup
- New timing detectors with 30 ~ 50 ps resolution help mitigate pileup and improve the detection of long-lived particles

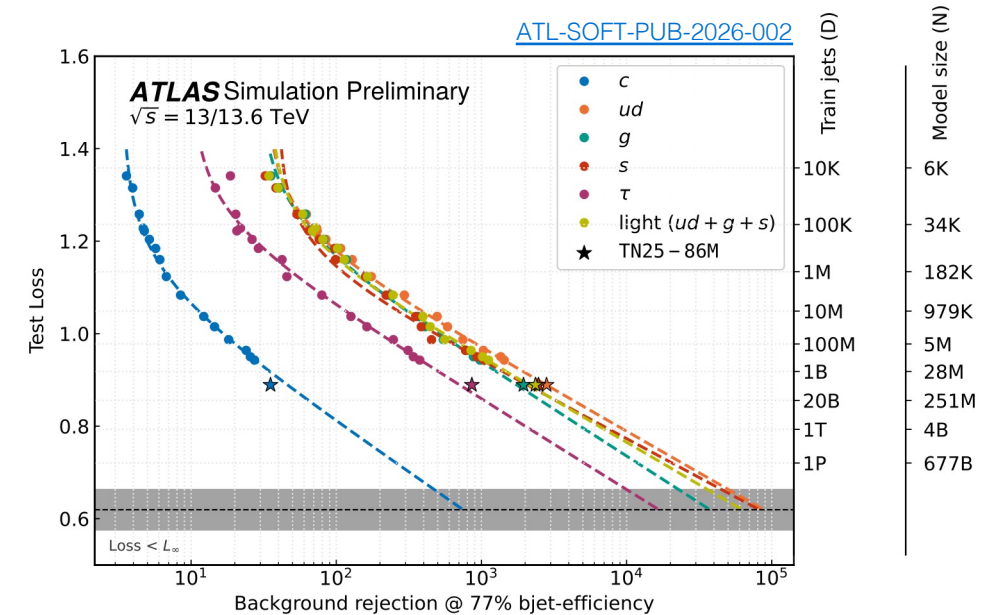


Vector boson scattering diagramme

New opportunities at the HL-LHC

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- New timing detectors with 30 ~ 50 ps resolution help mitigate pileup and improve the detection of long-lived particles
- Machine learning and AI will continue to boost detector, reconstruction, and analysis performance, as well as our work efficiency



HL-LHC Physics prospects — Higgs

Higgs physics is one of the science drivers of the HL-LHC

Huge experimental programme. Some channels suffer from large backgrounds, big improvements from smart analysis techniques and machine learning

Channel categories		BR	ggF	VBF	VH	ttH
Cross Section (13 TeV)			48.6 pb	3.8 pb	2.3 pb	0.5 pb
$\gamma\gamma$	0.2 %	✓	✓	✓	✓	
ZZ	2.6%	✓	✓	✓	✓	
WW	21%	✓	✓	✓	✓	
$\tau\tau$	6.3 %	✓	✓	✓	✓	
$b\bar{b}$	58%	✓	✓	✓	✓	
$Z\gamma$ (& $\gamma\gamma^*$)	0.2 %	✓	✓	✓	✓	
$\mu\mu$	0.02 %	✓	✓	✓	✓	

Higgs couplings

Higgs coupling prospects

Coupling strength modifiers ($\kappa_i^2 \equiv \sigma_i/\sigma_i^{\text{SM}}$, assuming SM Γ_H)

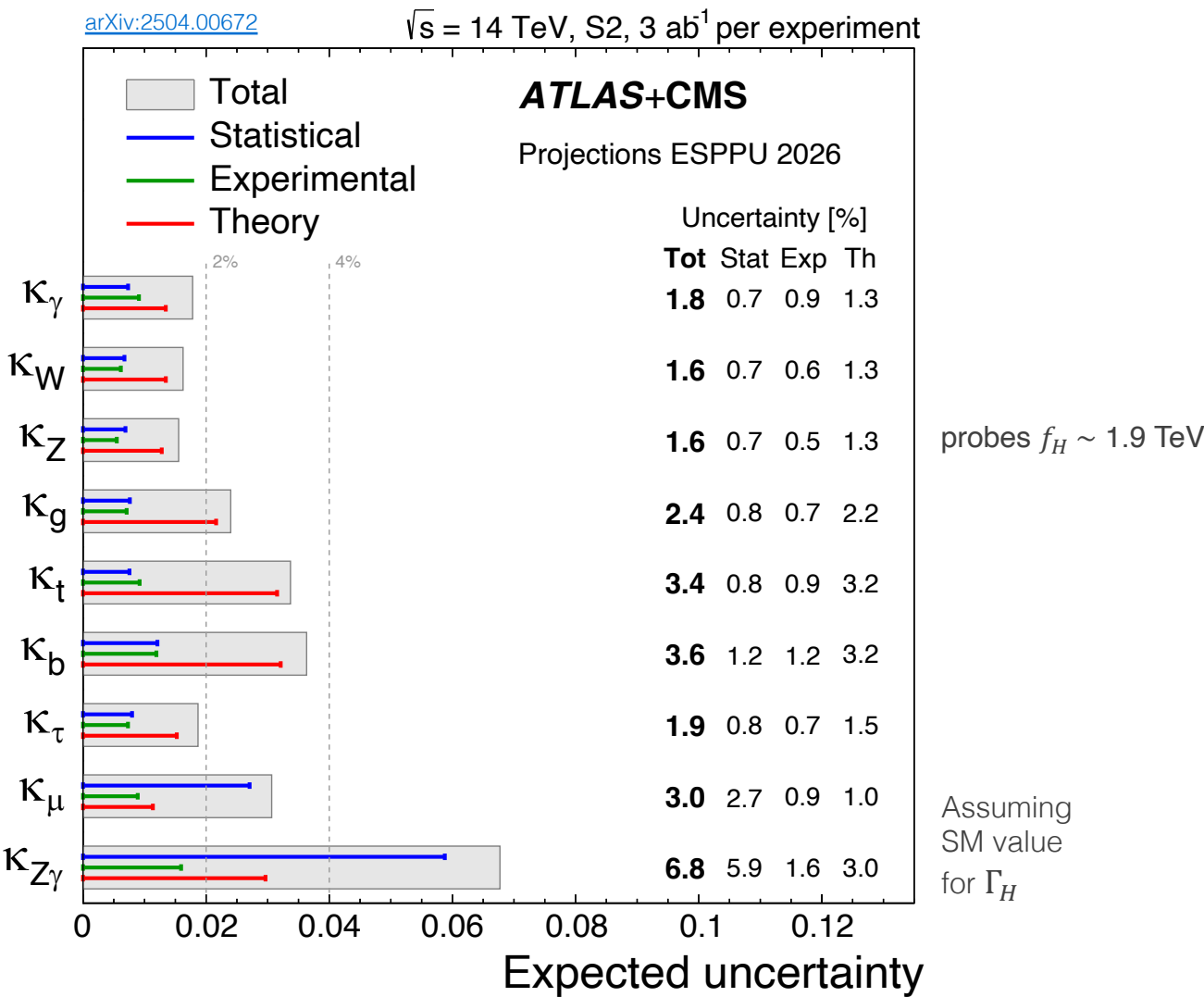
Remember: the best measured coupling probes compositeness of the Higgs boson

Current status:

Coupling modifier	ATLAS ($\Gamma_{H\rightarrow\text{inv}/\text{und}} = 0, \kappa_c = \kappa_t$) [arXiv:2608.07332]	CMS ($\Gamma_{H\rightarrow\text{inv}/\text{und}} = 0, \kappa_c = \kappa_t$) [arXiv:2602.18611]
κ_Z	0.97 ± 0.05	1.06 ± 0.06
κ_W	$1.01^{+0.05}_{-0.04}$	1.03 ± 0.06
κ_γ (effective)	0.99 ± 0.06	1.07 ± 0.07
κ_τ	$0.95^{+0.07}_{-0.06}$	$0.93^{+0.08}_{-0.07}$
κ_t	0.86 ± 0.08	0.80 ± 0.09

5.0 (0.1)% precision on κ_i probes $f_H \sim 0.8$ (5.5) TeV

Coupling strength modifiers: $\kappa_i^2 \equiv \sigma_i/\sigma_i^{\text{SM}}$ or $\kappa_i^2 \equiv \Gamma_i/\Gamma_i^{\text{SM}}$



Higgs couplings

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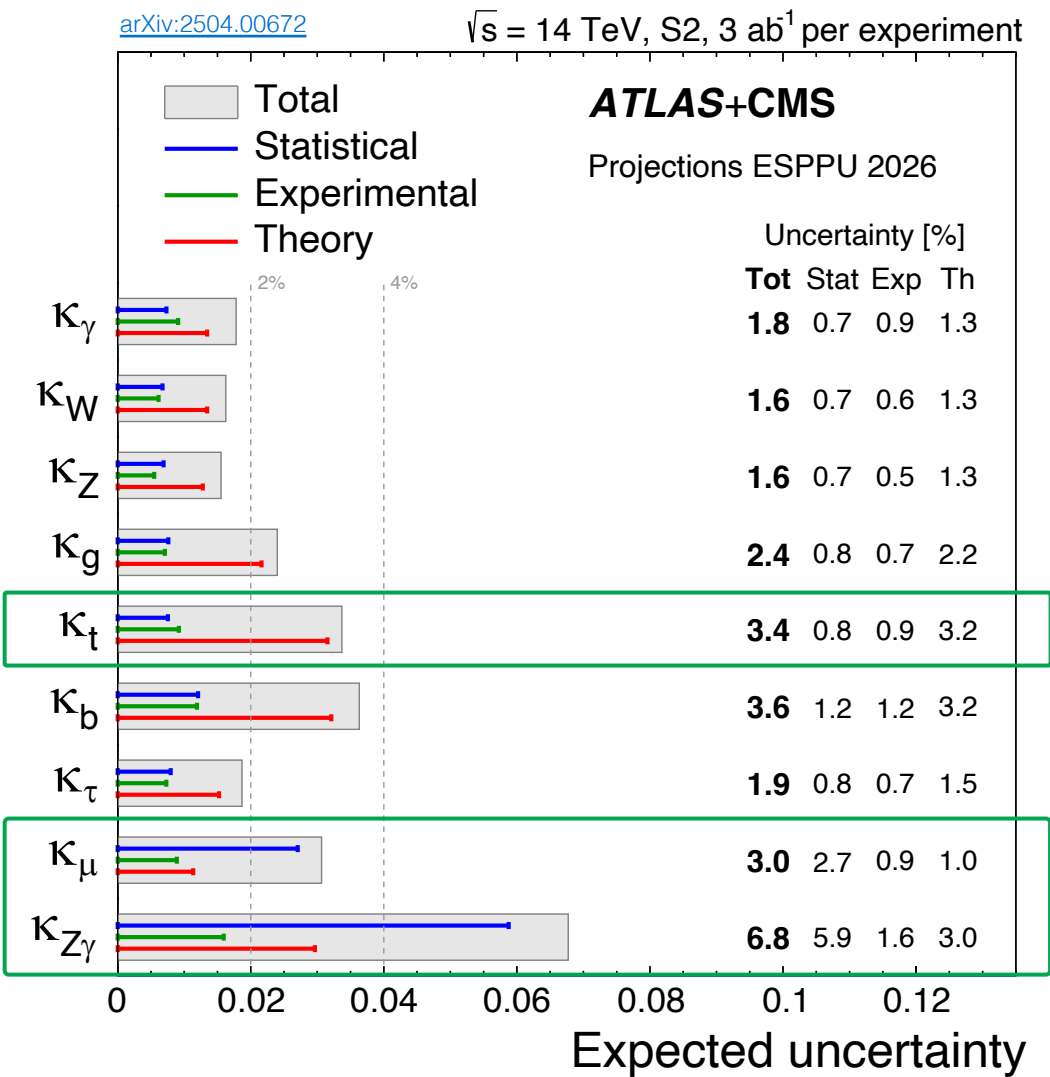
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Higgs couplings

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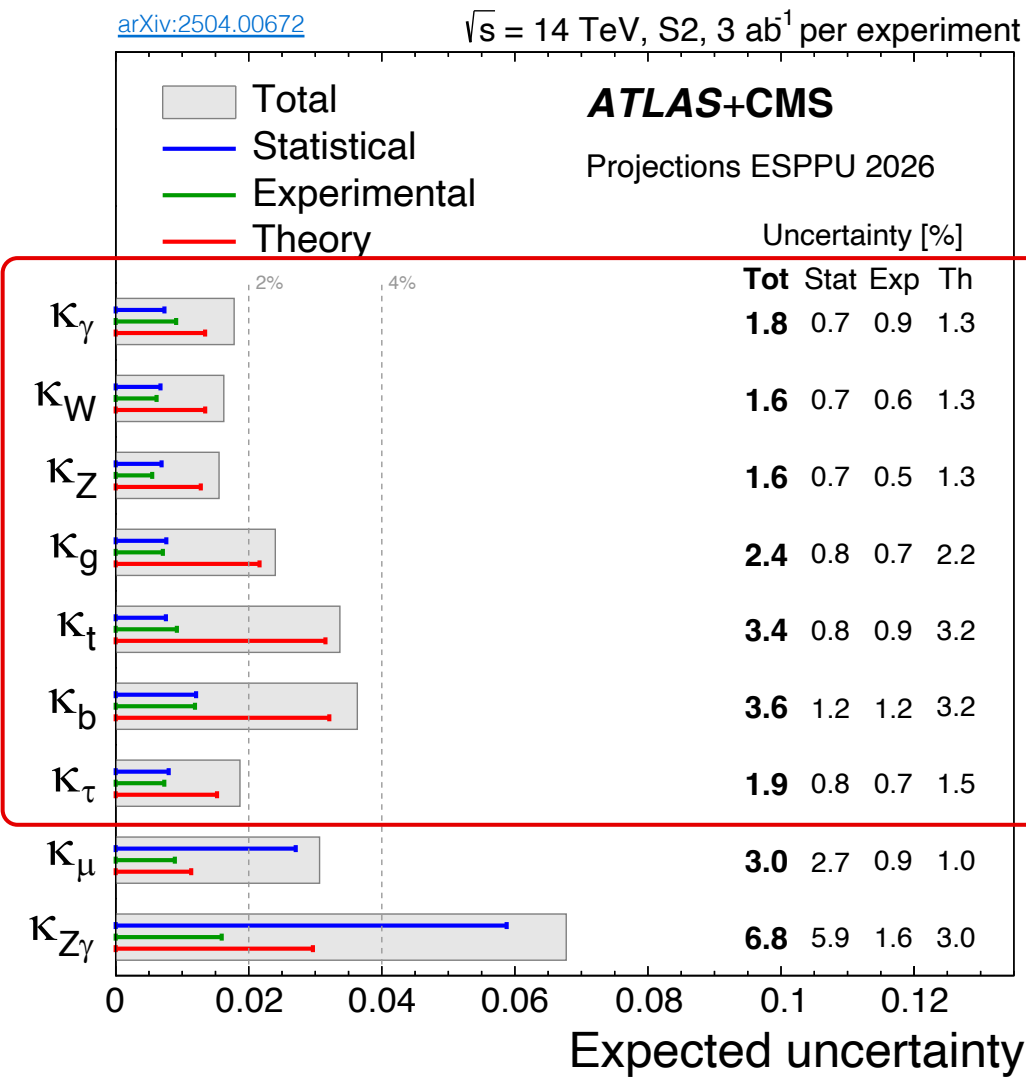
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BSM Higgs

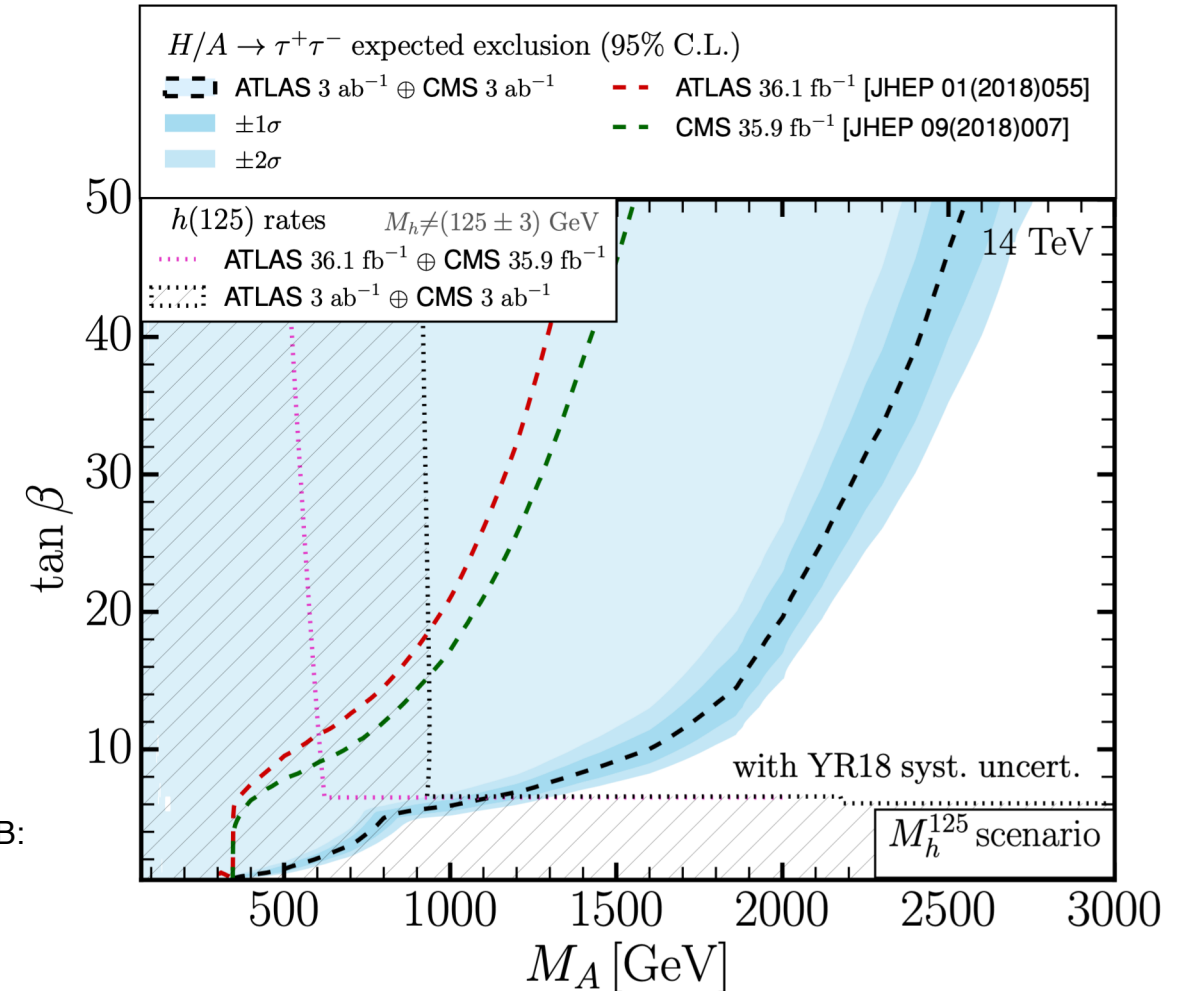
Higgs width from off-shell measurement and invisible decays, Higgs sector extensions (2HDM)

- Γ_H via $\mu_{\text{off-shell}} / \mu_{\text{on-shell}}$ in $H \rightarrow 4\ell$ & $2\ell 2\nu$ with $< 20\%$ uncertainty
- $\text{BR}(H \rightarrow \text{invisible}) < 2.5\%$
- Discover or exclude MSSM two Higgs doublets scenario deep into TeV scale for $\tan\beta > 6$

2 Higgs doublets, H_u, H_d with VEVs $v^2 = v_u^2 + v_d^2$

$$\tan\beta \equiv \frac{v_u}{v_d}, y_{t/b} = \frac{\sqrt{2} m_{t/b}}{v \sin/\cos\beta} \quad \text{Five Higgs bosons after EWSB: } h, H, A, H^+, H^-$$

[ATLAS & CMS Snowmass White Paper](#)



Higgs self-coupling

Higgs self-coupling via Higgs pair production: complex final states, eldorado for ML enthusiasts, strongest channels: $HH \rightarrow b\bar{b}\gamma\gamma$ (0.27%), $b\bar{b}\tau\tau$ (7.3%), $b\bar{b}b\bar{b}$ (34%); best sensitivity to λ at low m_{HH}

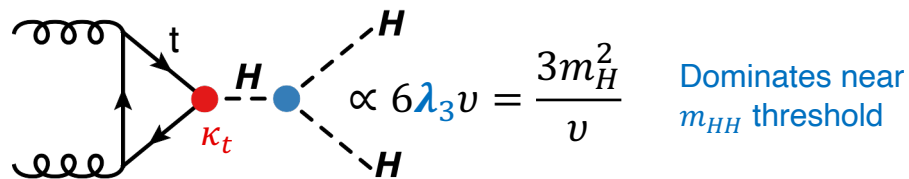
Higgs potential: $V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$

After expansion around minimum:

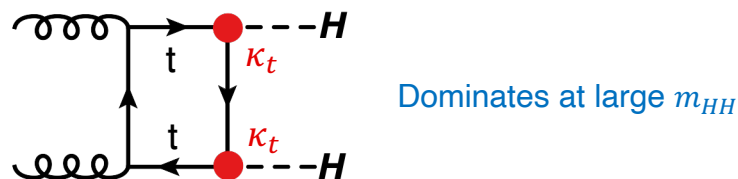
$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4}\lambda_4 H^4$$

where: $\lambda_3^{\text{SM}} = \lambda_4^{\text{SM}} = \lambda^{\text{SM}}$ and: $\kappa_\lambda \equiv \lambda_3^{\text{obs}}/\lambda^{\text{SM}}$

HH production via gluon fusion and triple-Higgs coupling

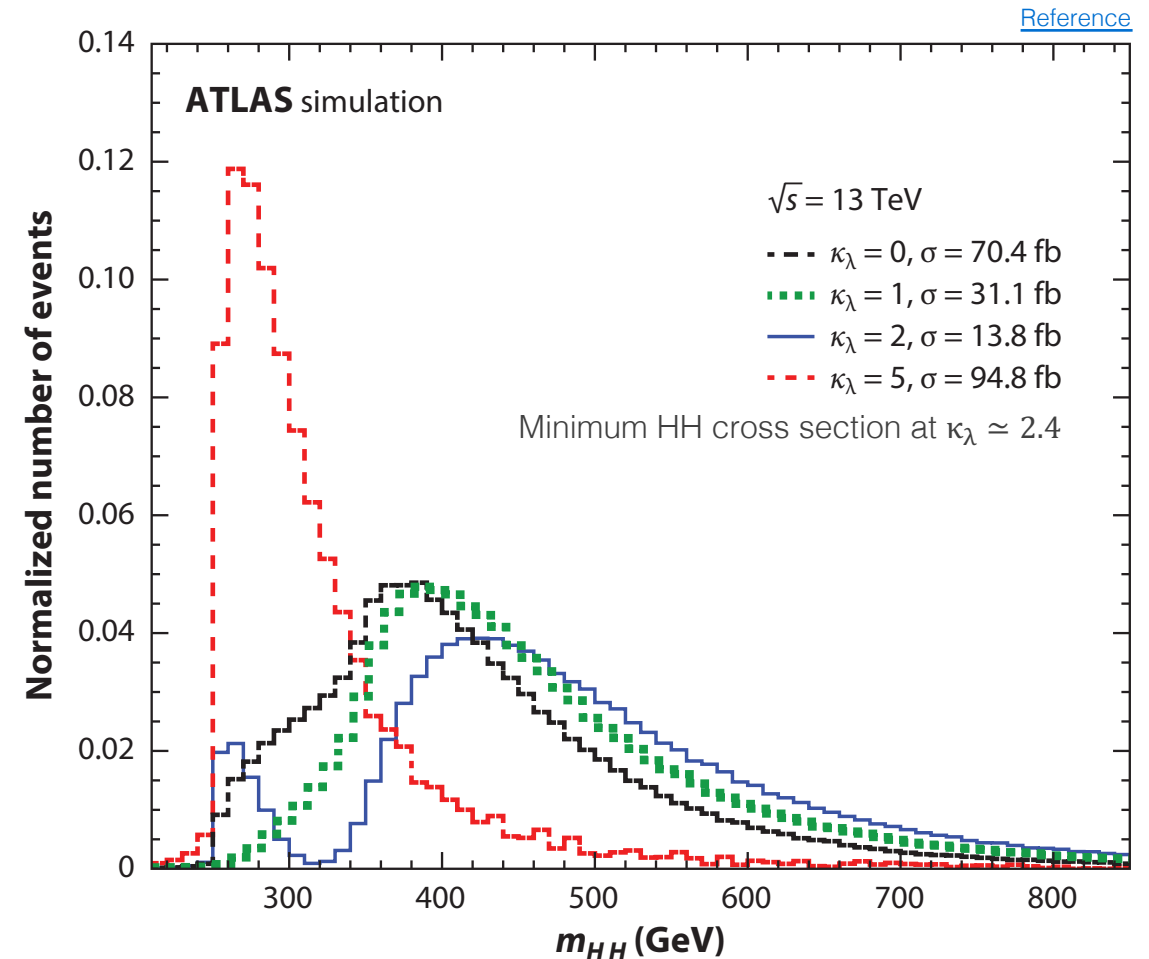


Destructive interferes with box diagram:



leads to small HH SM cross section of 32.5 (36) fb at 13 (13.6) TeV

Minimum HH cross section at $\kappa_\lambda \approx 2.3$



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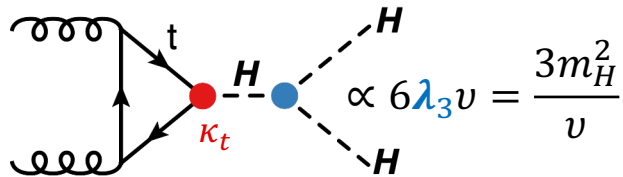
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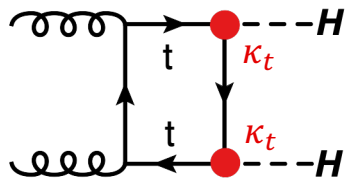
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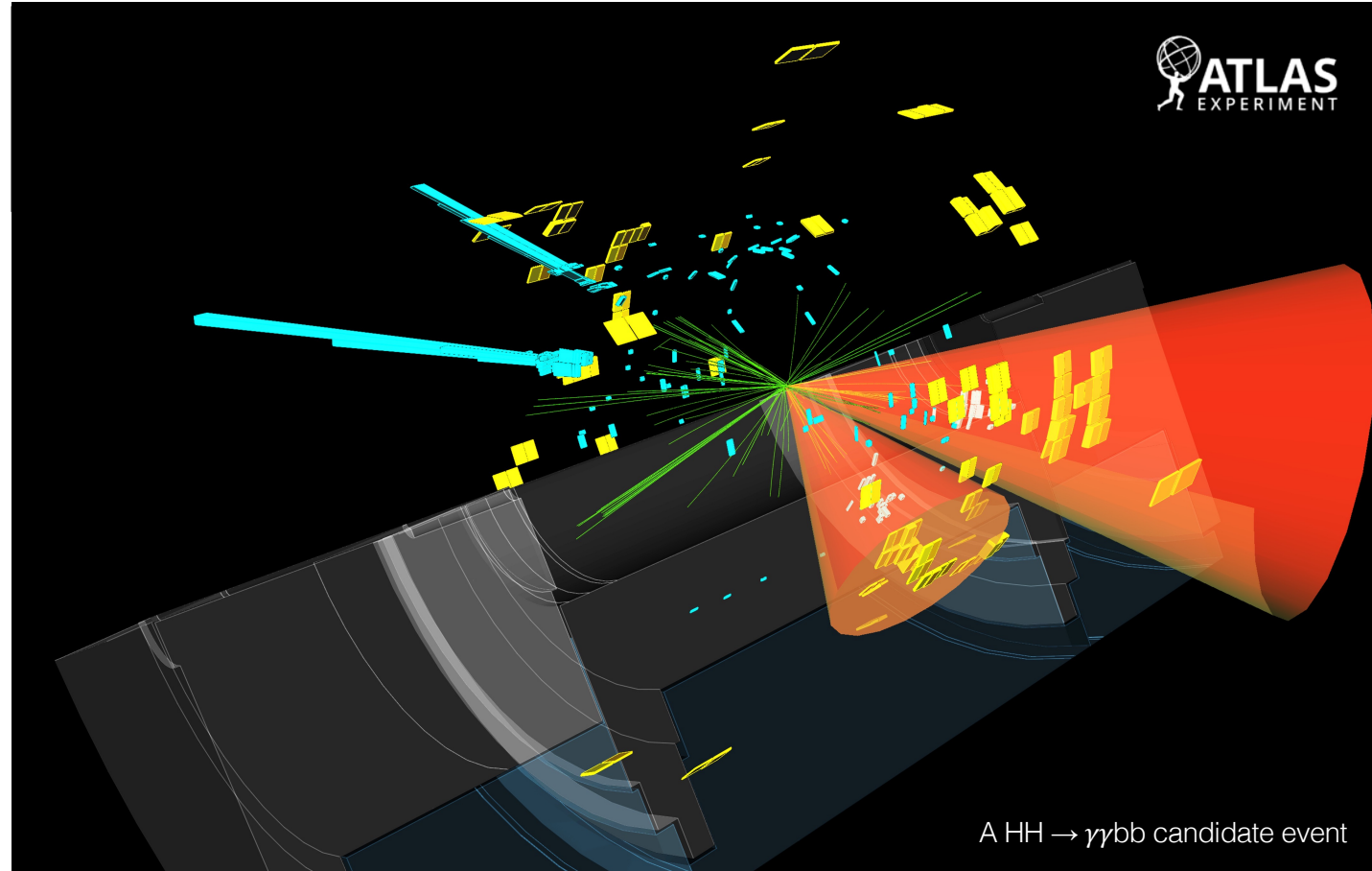


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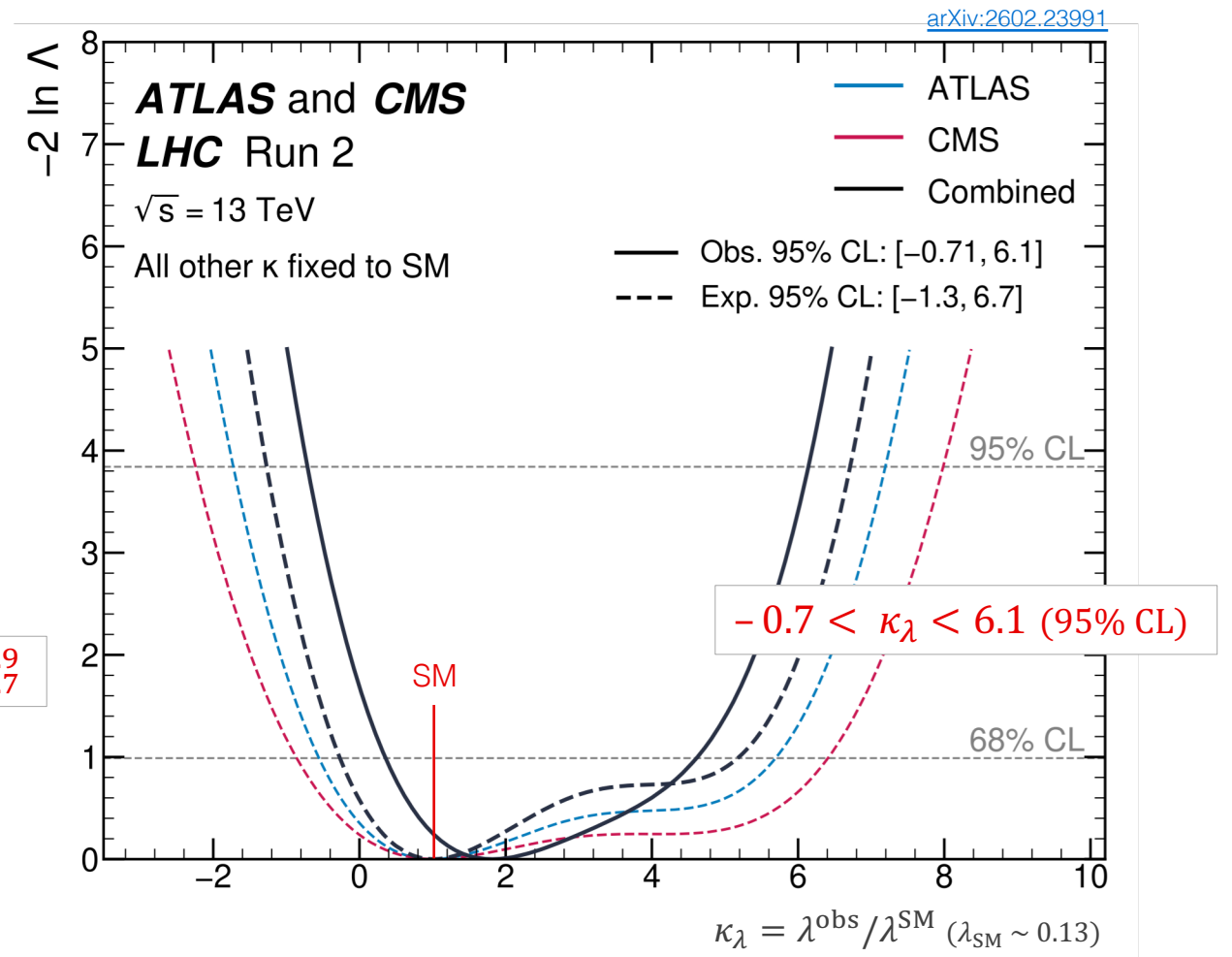
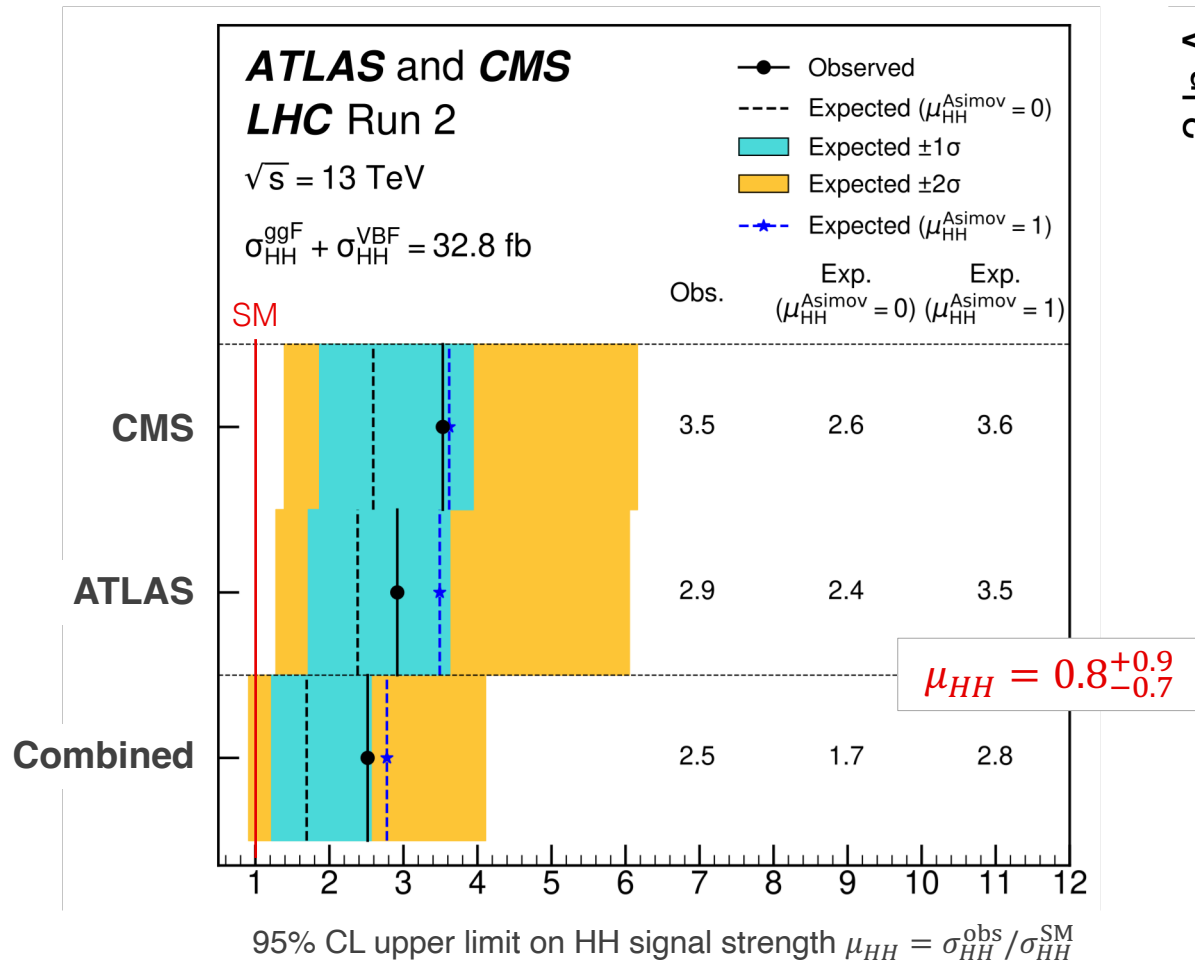
Minimum HH cross section at $\kappa_\lambda \approx 2.3$



A $HH \rightarrow \gamma\gamma b\bar{b}$ candidate event

Higgs self-coupling

First ATLAS & CMS combination of HH production using Run-2 datasets

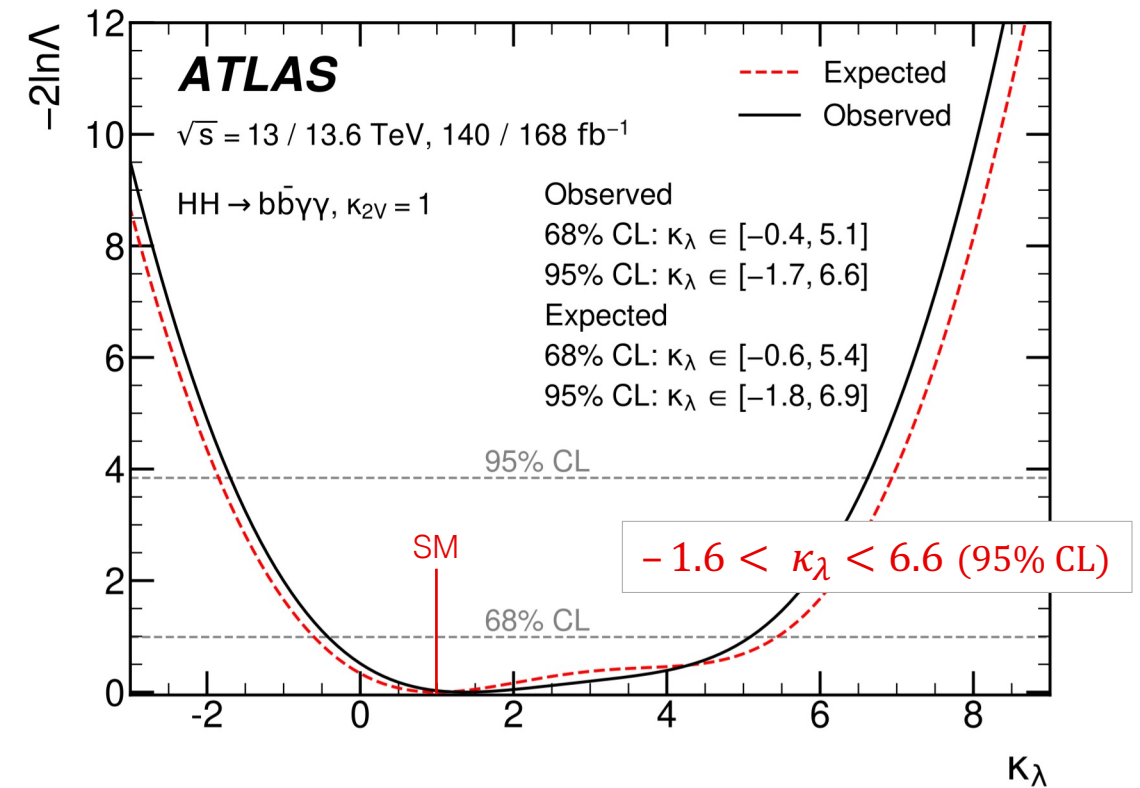
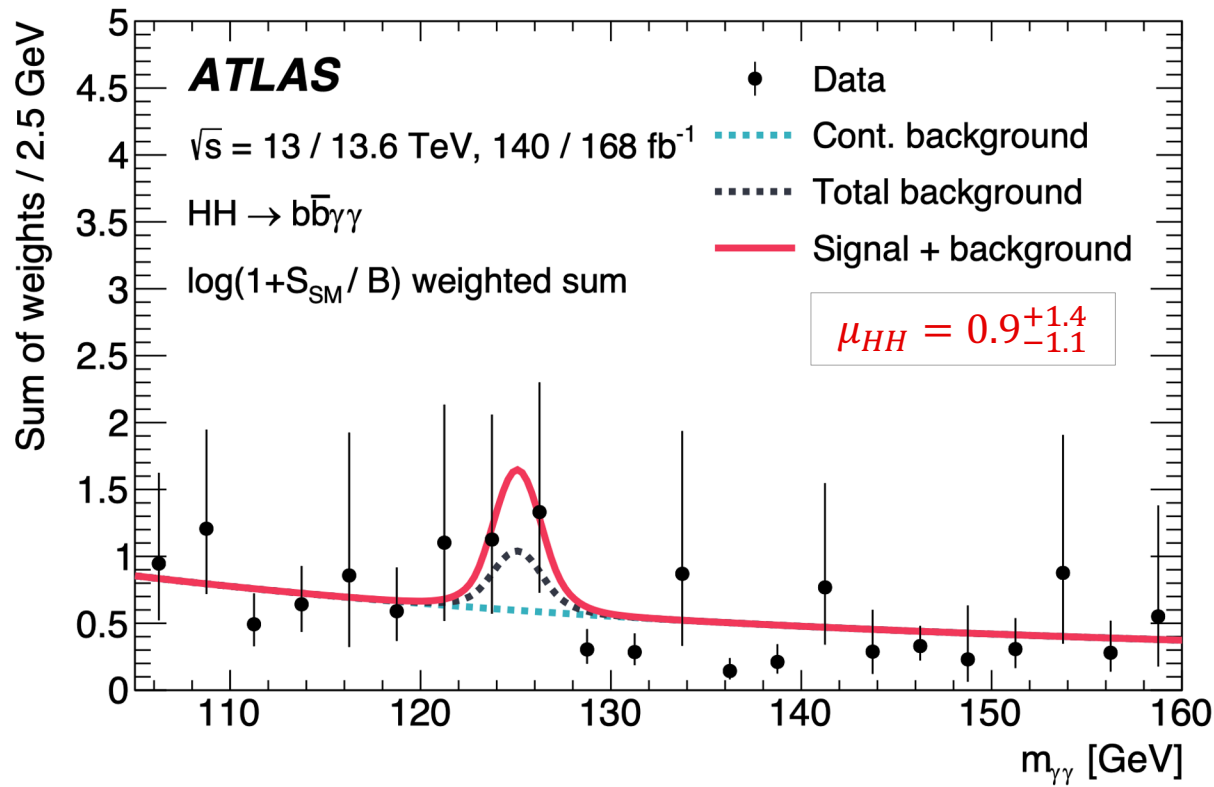


Higgs self-coupling

PLB 876 (2026) 140280

New ATLAS result on $HH \rightarrow b\bar{b}\gamma\gamma$ with 308 fb^{-1} (Run 2 + 2022–2024 of Run 3 data)

Improvements: more data (50%), better b-tagging (20%), analysis optimisation (15%)



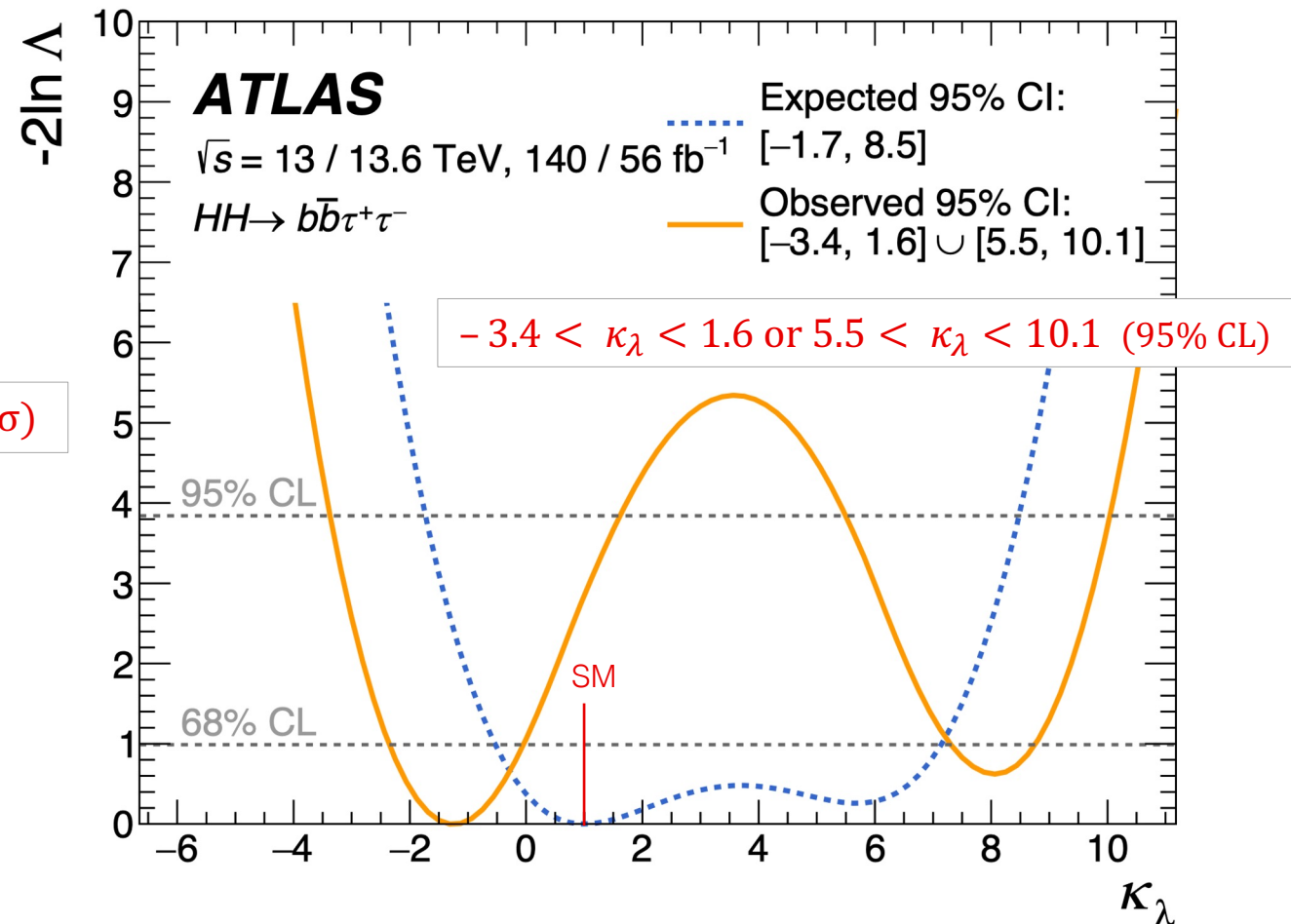
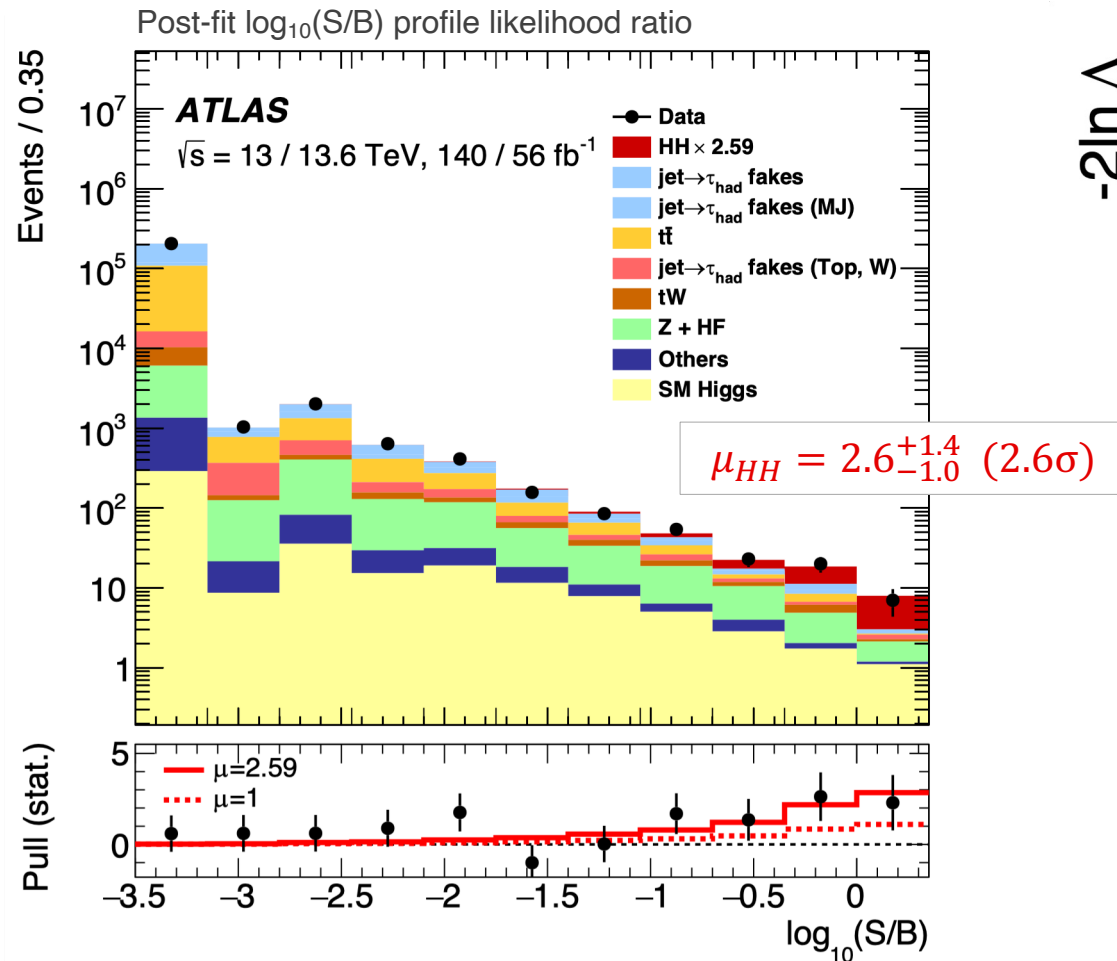
Single channel as sensitive as ATLAS' full Run-2 combination

Higgs self-coupling

[arXiv:2607.26879](https://arxiv.org/abs/2607.26879), [Physics briefing](#)

New ATLAS result on $HH \rightarrow b\bar{b}\tau\tau$ with 196 fb^{-1} (Run 2 + 2022–2023 of Run 3 data)

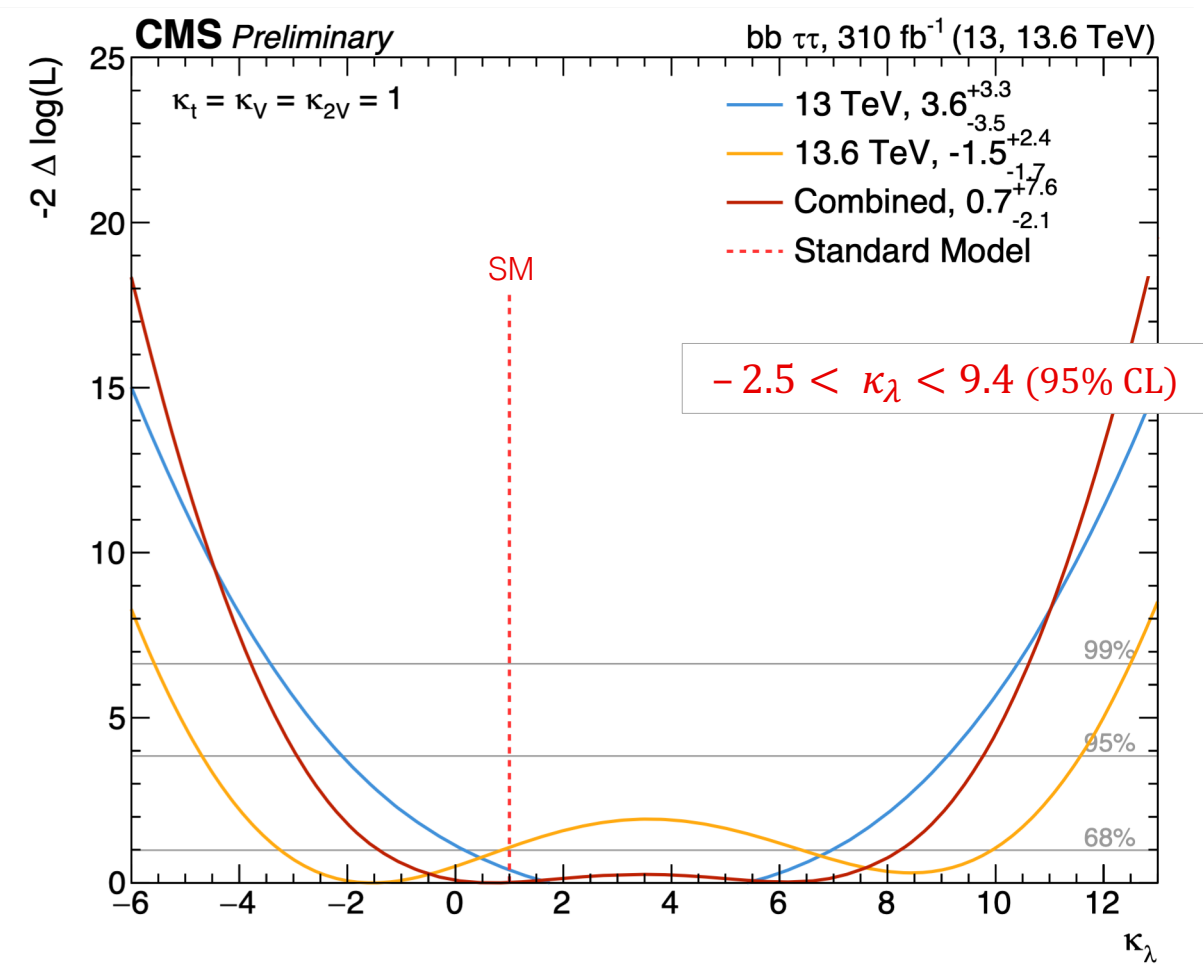
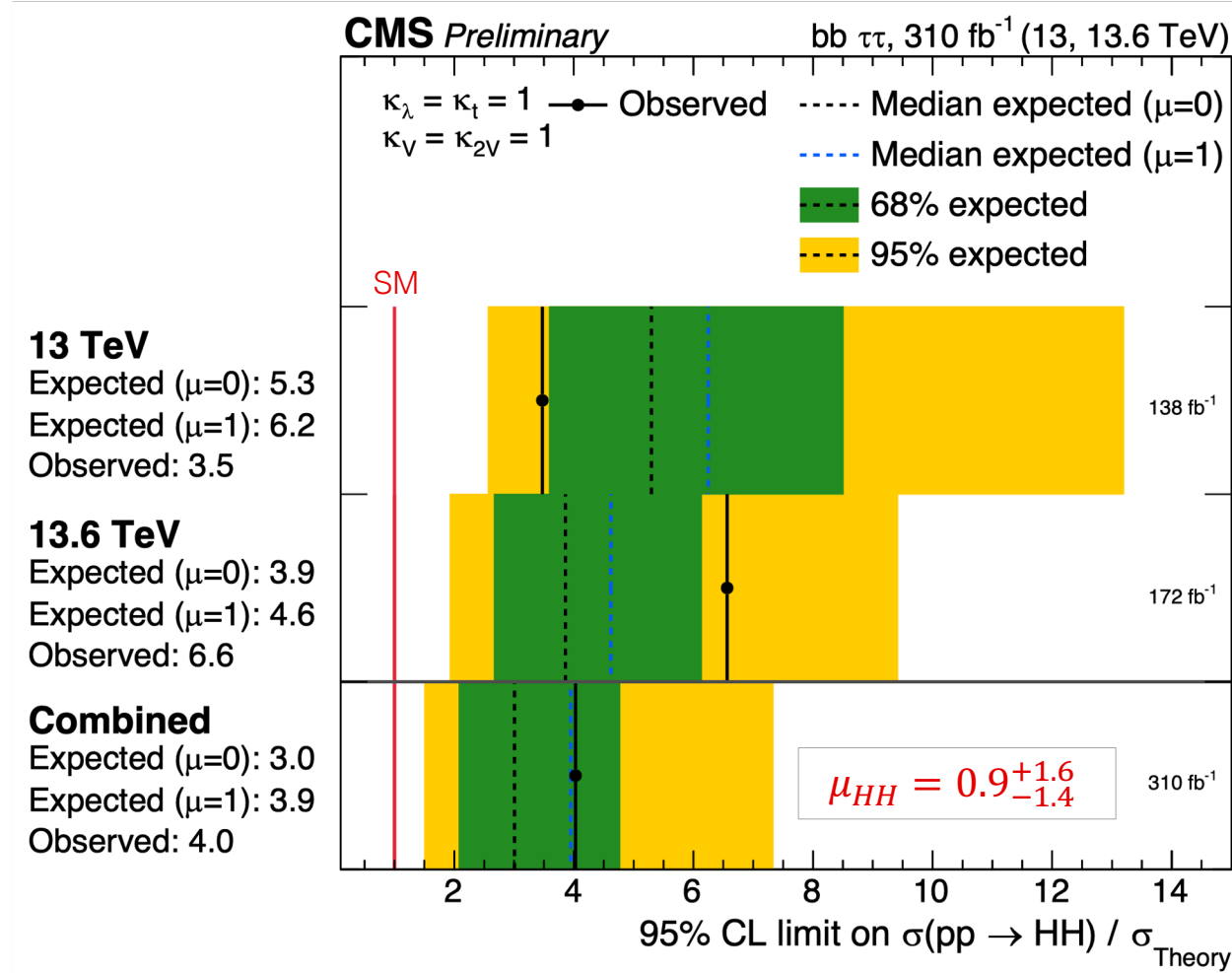
Improvements: additional triggers, improved b-tagging, τ -id, and ML-based event classification $\rightarrow$ 40% better than expected luminosity scaling



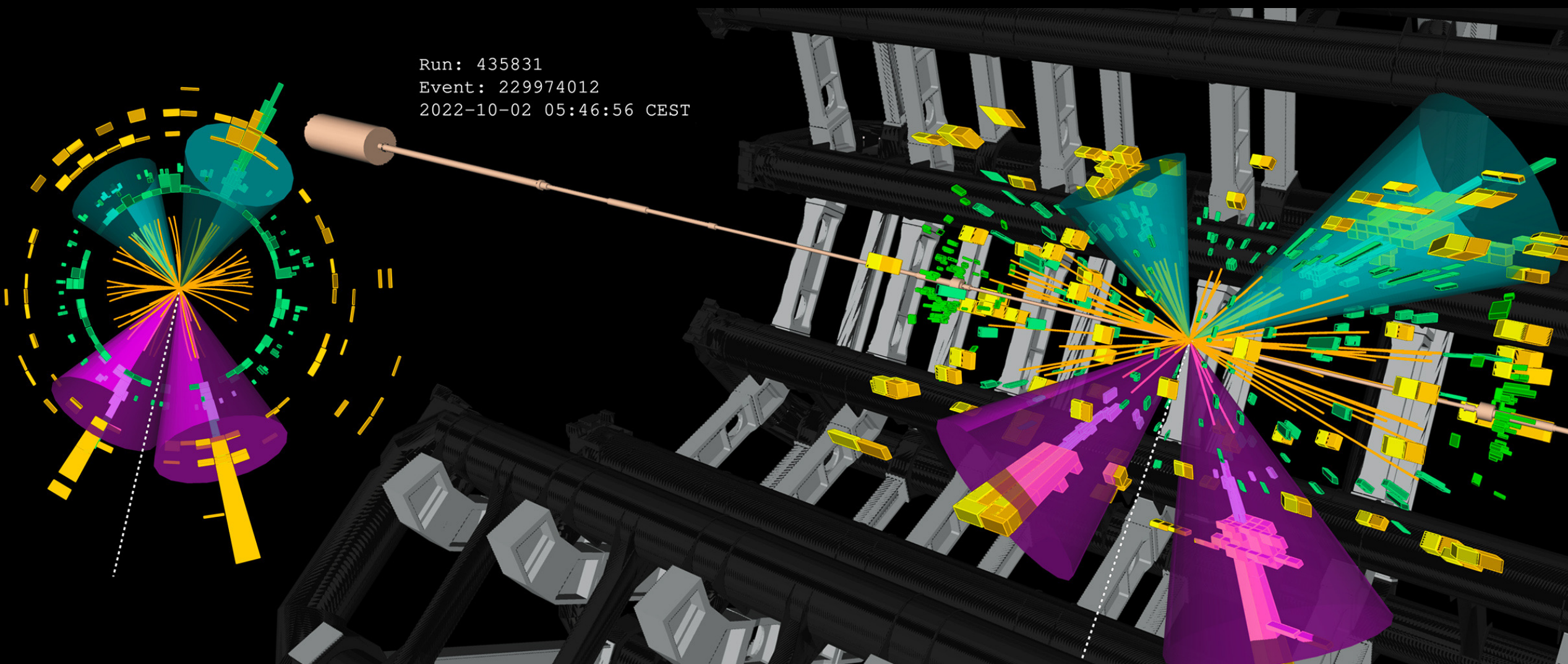
Higgs self-coupling

New CMS result on $HH \rightarrow b\bar{b}\tau\tau$ with 310 fb^{-1} (Run 2 + 2022–2024 of Run 3 data)

Improvements: improved triggering, recovery of boosted $\tau\tau$ events, ggHH / VBF classifiers, better fake- τ modelling $\rightarrow$ 20% > luminosity scaling



Run: 435831
Event: 229974012
2022-10-02 05:46:56 CEST

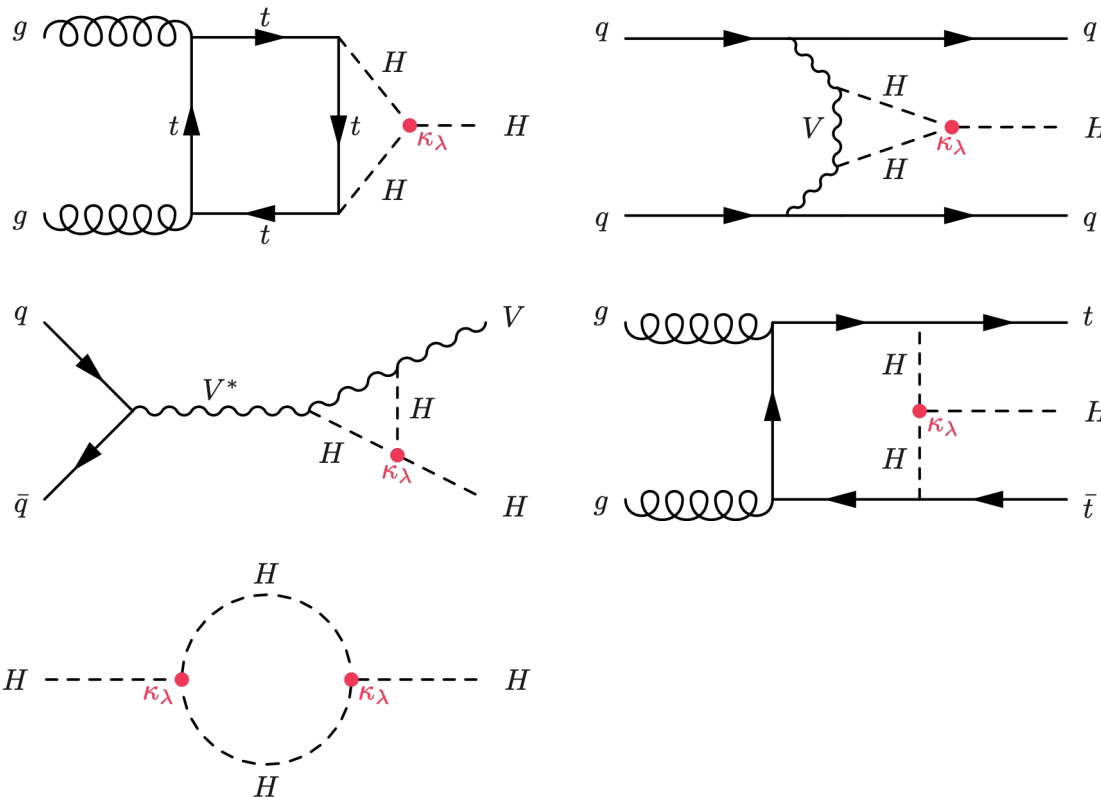


A $HH \rightarrow b\bar{b}\tau\tau$ candidate event

Higgs self-coupling

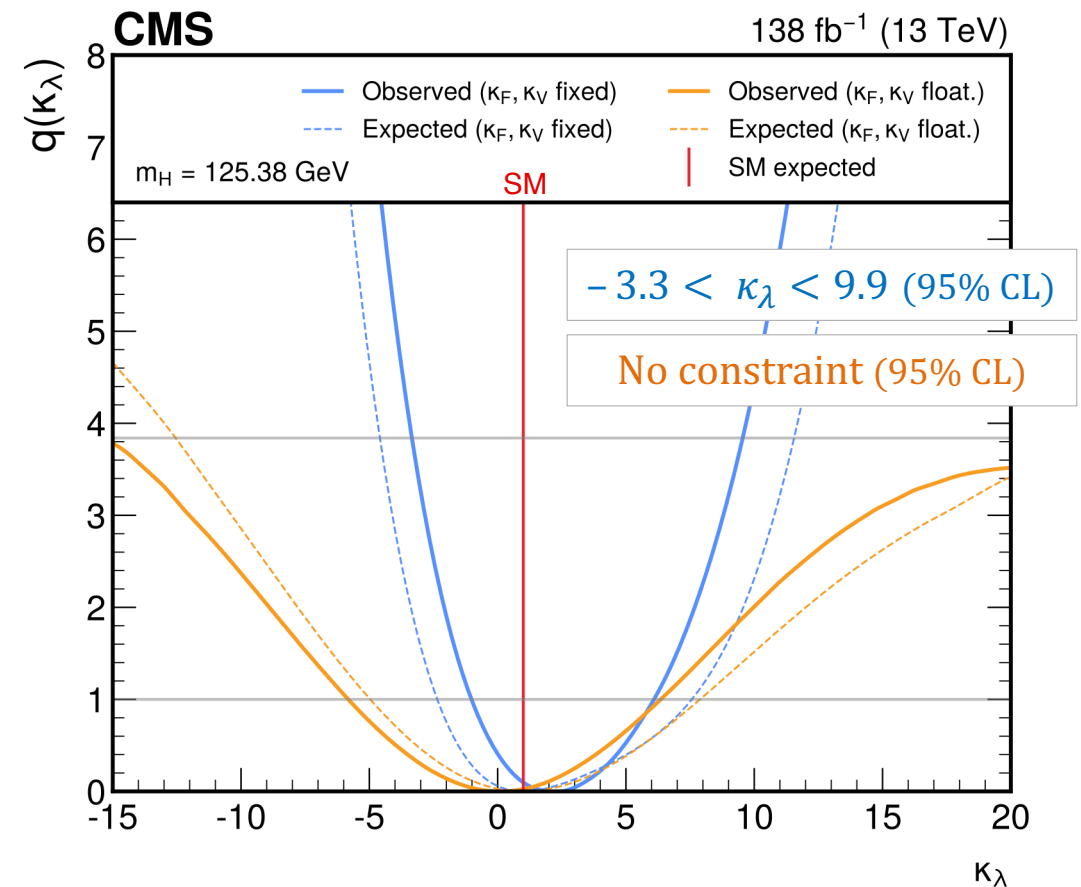
ATLAS: [arXiv:2608.07332](https://arxiv.org/abs/2608.07332), CMS: [Rep. Prog. Phys. 89 \(2026\) 087801](https://arxiv.org/abs/2608.07332)

Precise single Higgs production measurements can constrain κ_λ through loops



Loop diagrams involving Higgs self-coupling.
From left to right ggF, VBF, HV, ttH, Higgs self energy

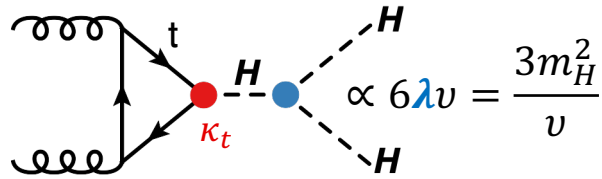
Results varying only κ_λ (blue) or varying $\kappa_\lambda, \kappa_F, \kappa_V$ (orange)



Higgs self-coupling — HL-LHC prospects

Combination of expected ATLAS and CMS yields for 3 ab⁻¹

Note: prospects tend to be conservative as future analysis improvements not included

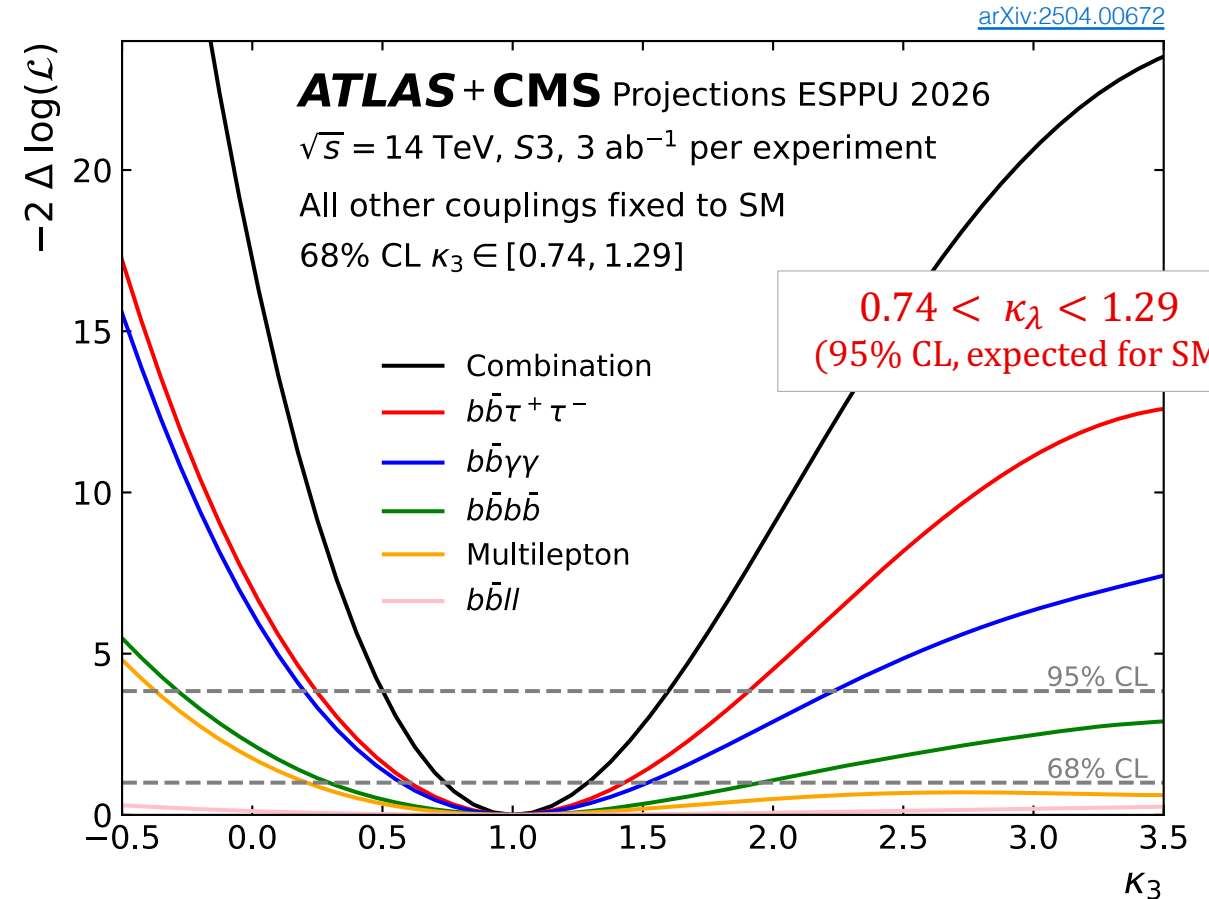


$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$$

$$\kappa_\lambda \equiv \lambda_3^{\text{obs}} / \lambda^{\text{SM}}$$

For SM:

- Expect HH observation > 7σ
- κ_λ precision better than 30%



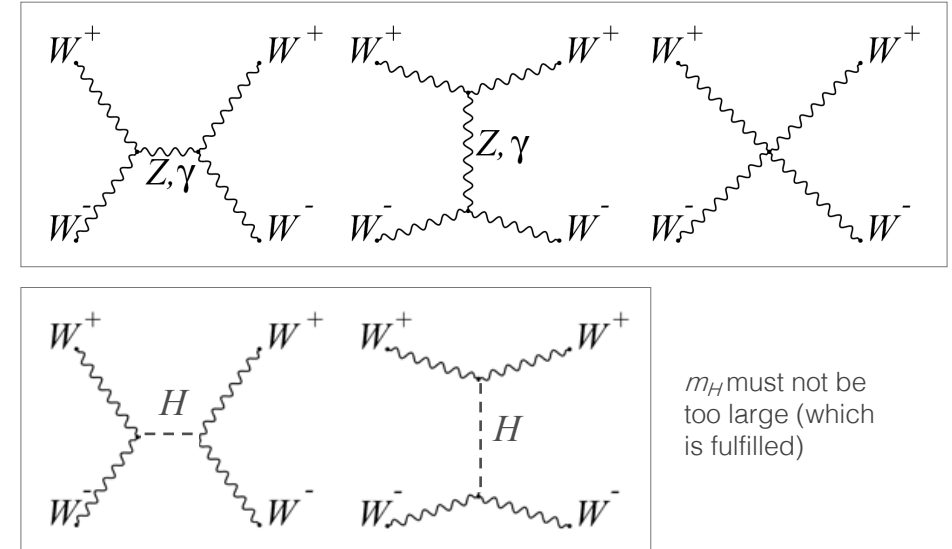
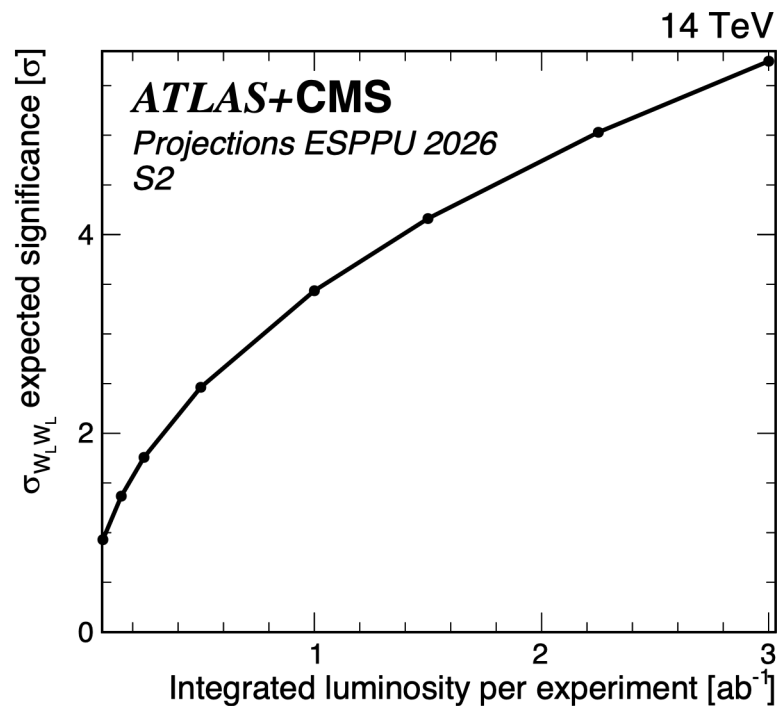
HL-LHC Physics prospects — vector boson scattering

Longitudinal VV scattering tests whether the observed Higgs boson really completes the electroweak theory

Status so far:

- Using Run-2 dataset, ATLAS reported first 3.3σ evidence for at least one longitudinally polarised W boson in $W^\pm W^\pm$ scattering
- Using Run 2 plus part of Run-3 dataset, ATLAS reported observation with 6.5σ of electroweak $Z_L Z_L$ production

Extrapolation
to HL-LHC

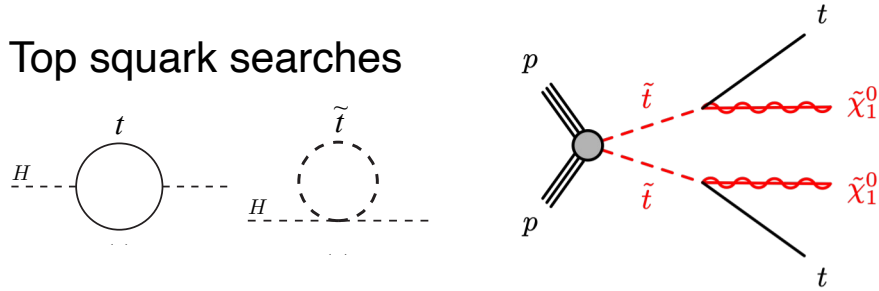


ATLAS & CMS expect to observe with $> 5\sigma$ and measure $W_L W_L jj$ at the HL-LHC with a precision better than 20%

[arXiv:2504.00672](https://arxiv.org/abs/2504.00672), see also: [CMS PAS FTR-21-001](https://cds.cern.ch/record/2811113/files/CMS-PAS-FTR-21-001)

SUSY stop search

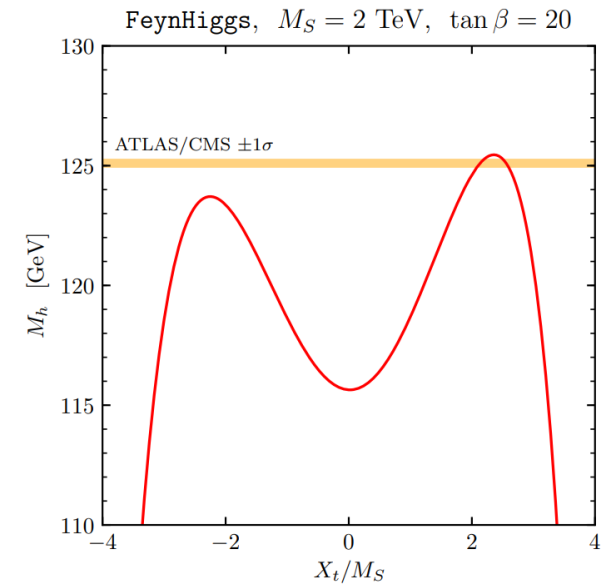
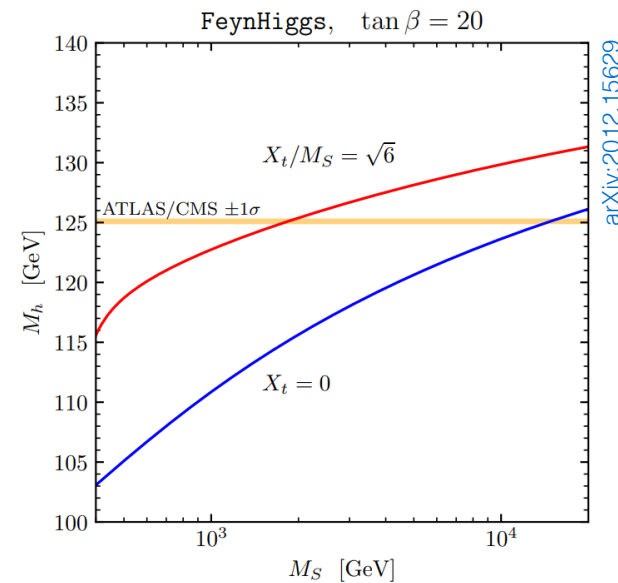
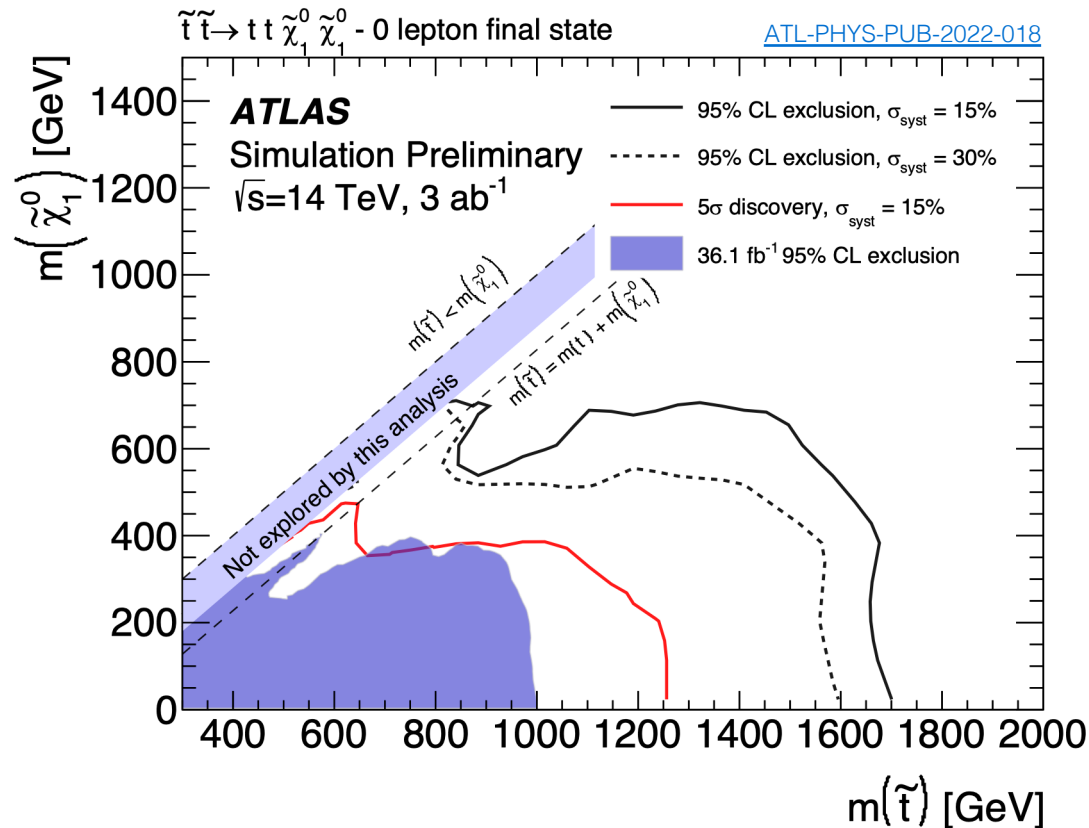
Top squark searches



Remember: $m_h = 125$ GeV requires large radiative corrections, putting strong constraints on stop mass $M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$ and left-right mixing parameter $X_t = A_t - \mu \cot \beta$

$$(\Delta m_h^2)_{O(\alpha_t)} \approx \frac{3 m_t^4}{4\pi^2 v^2} \left[\ln \left(\frac{M_S^2}{m_t^2} \right) + \frac{X_t^2}{M_S^2} - \frac{X_t^4}{12 M_S^4} \right]$$

For $m_{\tilde{t}_{1,2}} = \sqrt{M_S^2 + m_t^2 \mp m_t |X_t|}$, $M_S = 2$ TeV and maximum LR mixing: $\Delta m_{\tilde{t}_{1,2}} \sim 0.4$ TeV



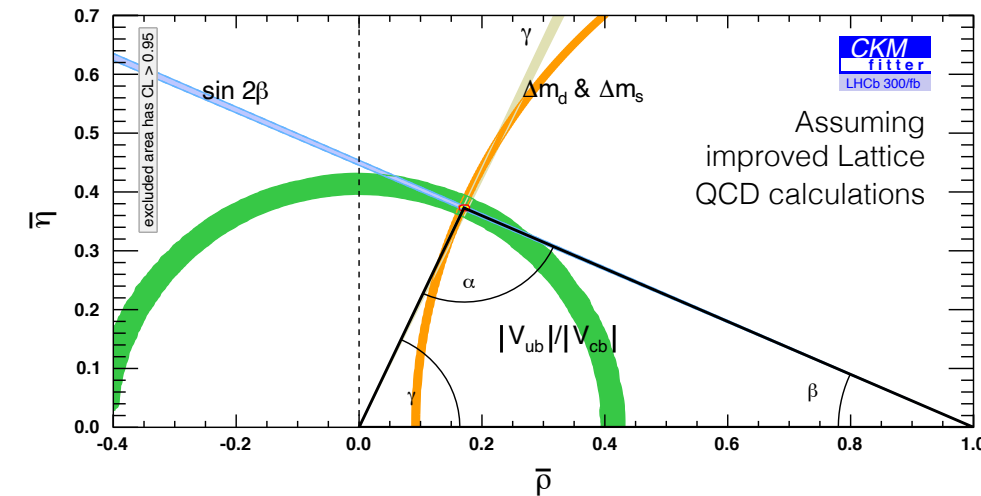
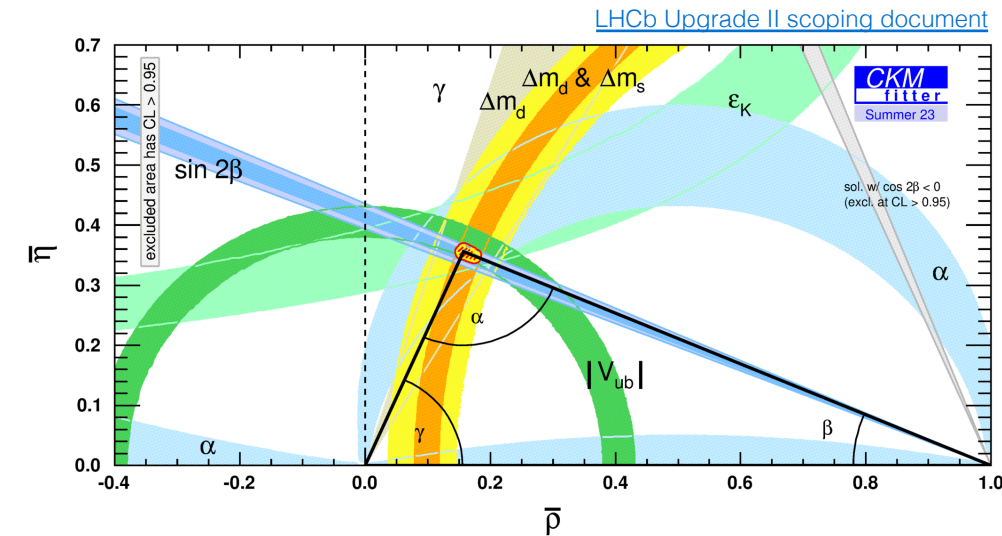
HL-LHC Physics prospects — flavour

Huge opportunities in flavour sector with LHCb Upgrade II

> ×5 Run 3/4 instantaneous luminosity, integrated luminosity of 300 fb⁻¹

Observable	Current LHCb (up to 9 fb ⁻¹)	Upgrade I (23 fb ⁻¹)	Upgrade I (50 fb ⁻¹)	Upgrade II (300 fb ⁻¹)
CKM tests				
γ ($B \rightarrow DK$, etc.)	2.8° [20, 21]	1.3°	0.8°	0.3°
ϕ_s ($B_s^0 \rightarrow J/\psi\phi$)	20 mrad [24]	12 mrad	8 mrad	3 mrad
$ V_{ub} / V_{cb} $ ($\Lambda_b^0 \rightarrow p\mu^-\bar{\nu}_\mu$, etc.)	6% [56, 57]	3%	2%	1%
Charm				
ΔA_{CP} ($D^0 \rightarrow K^+K^-, \pi^+\pi^-$)	29×10^{-5} [27]	13×10^{-5}	8×10^{-5}	3.3×10^{-5}
A_Γ ($D^0 \rightarrow K^+K^-, \pi^+\pi^-$)	11×10^{-5} [31]	5×10^{-5}	3.2×10^{-5}	1.2×10^{-5}
Δx ($D^0 \rightarrow K_S^0\pi^+\pi^-$)	18×10^{-5} [58]	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}
Rare decays				
$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-)/\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)$	69% [32, 33]	41%	27%	11%
$S_{\mu\mu}$ ($B_s^0 \rightarrow \mu^+\mu^-$)	—	—	—	0.2
$A_T^{(2)}$ ($B^0 \rightarrow K^{*0}e^+e^-$)	0.10 [59]	0.060	0.043	0.016
$S_{\phi\gamma}$ ($B_s^0 \rightarrow \phi\gamma$)	0.32 [60]	0.093	0.062	0.025
α_γ ($\Lambda_b^0 \rightarrow \Lambda\gamma$)	$^{+0.17}_{-0.29}$ [61]	0.148	0.097	0.038

[LHCb Upgrade II scoping document](#), see also [arXiv:1808.08865](#)



HL-LHC Physics prospects — flavour

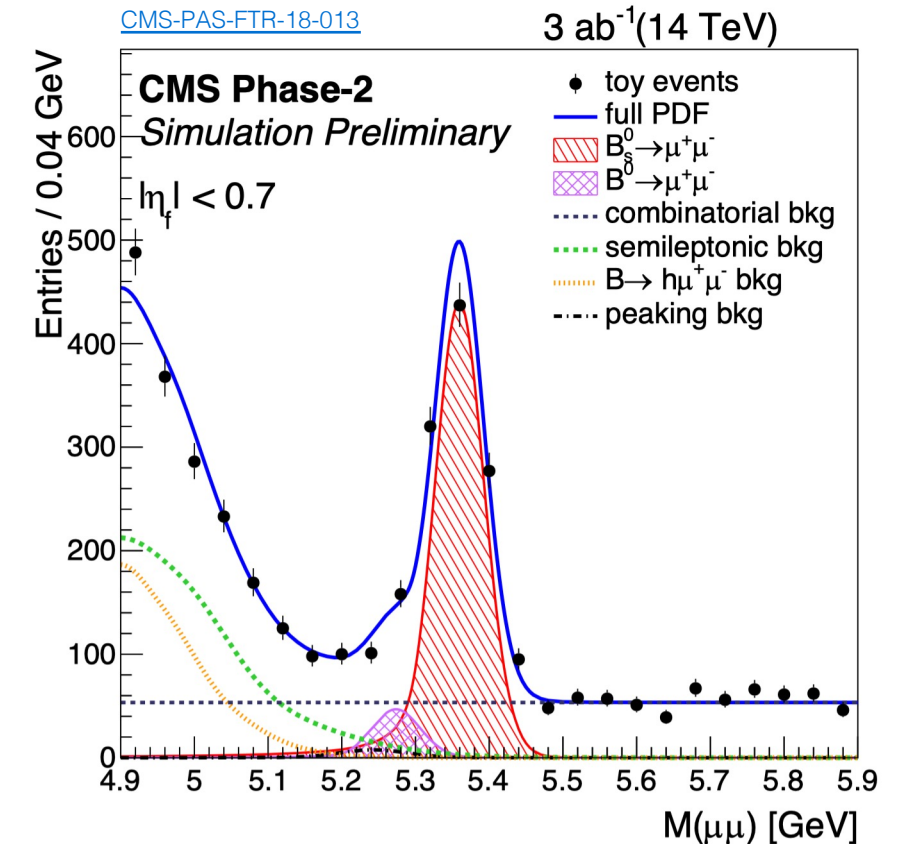
Huge opportunities in flavour sector with LHCb Upgrade II

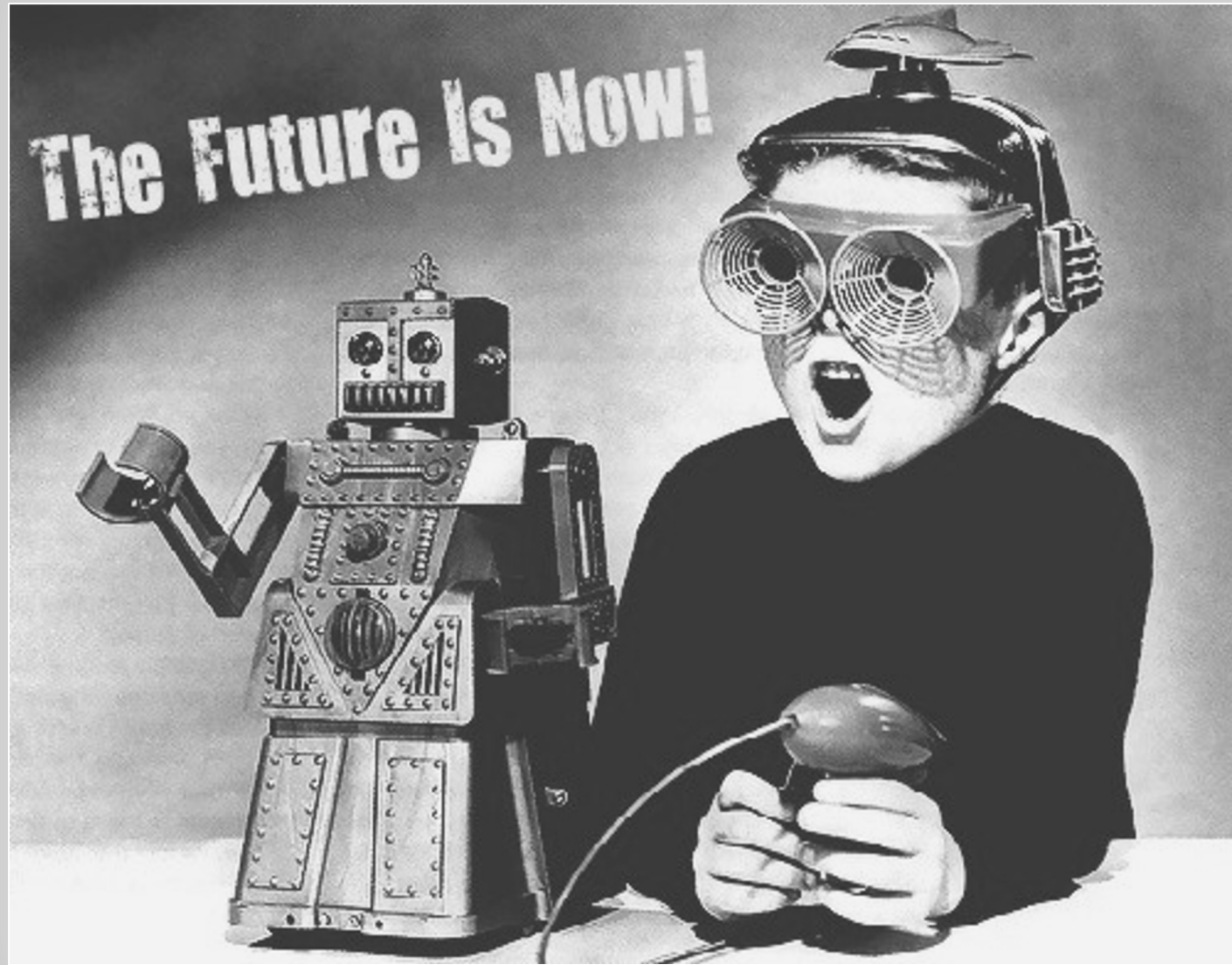
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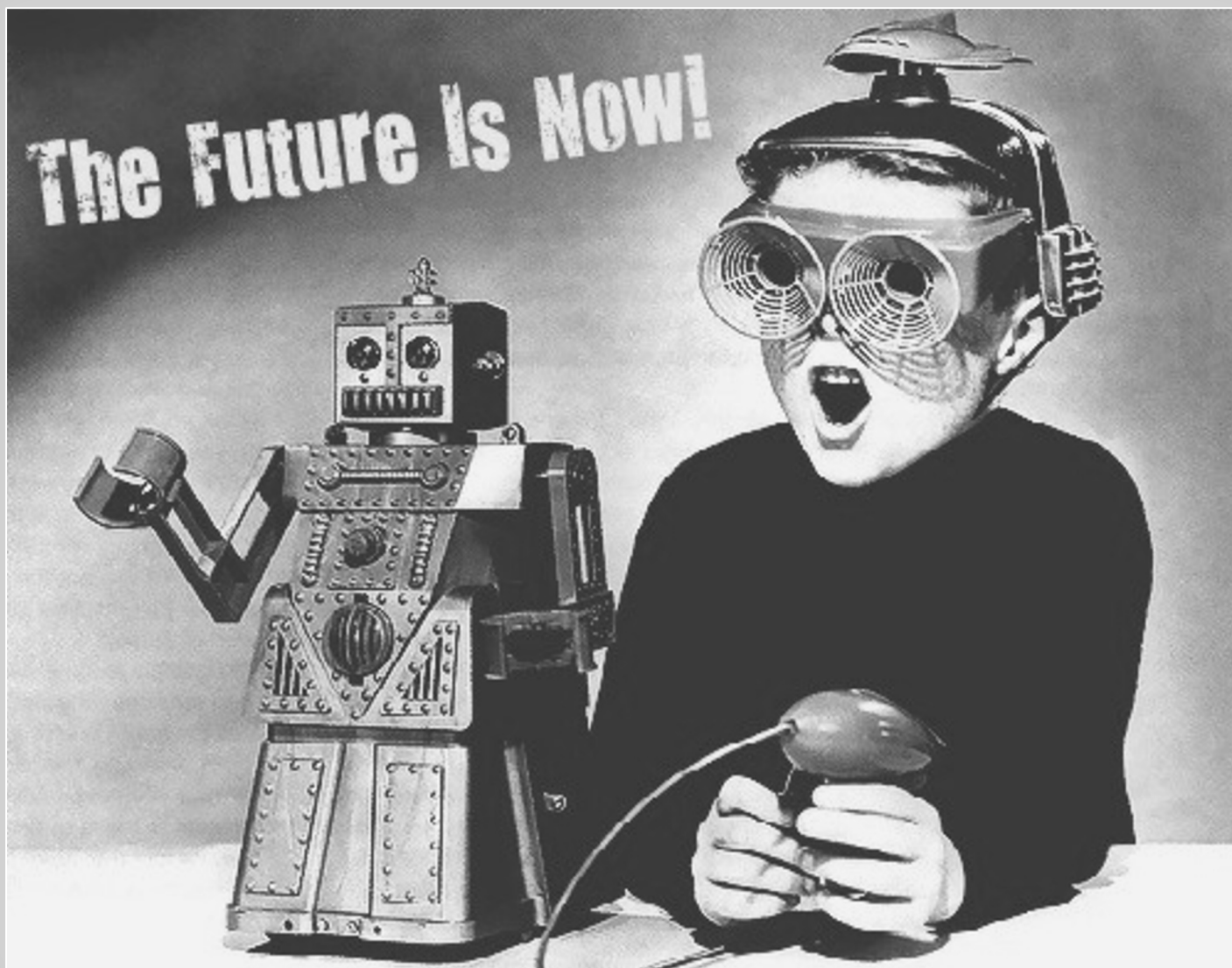
CMS projection: expect to observe $B_d^0 \rightarrow \mu^+\mu^-$ decay with > 5σ (LHCb with Upgrade II should be even better)





Robert the Robot toy produced by the Ideal Toy Corporation in the 1950s (NOT an AI picture!)

"The composition captures mid-century retro-futuristic optimism, reflecting how post-war popular culture and early science fiction imagined the dawn of the robotic age" (Google AI)



WE ARE IN A (TECHNICAL & INTELLECTUAL?) REVOLUTION

→ Jan Kieseler's talk on ML in HEP

LLMs are already permeating every aspect of our work and research, and today's models are only the weakest we will ever get to use

We are clearly 'learning by doing', at the minimum, AI will accelerate our work (and publications)

We must uphold our scientific principles and integrity during this learning process!

Use AI transparently and critically: acknowledge its use, document reproducible workflows, independently verify outputs and possible hallucinations, retain human accountability, and avoid undue vendor dependence

Lecture summary

- The LHC is the greatest fundamental science machine ever built. Its accelerator and experiments are unique marvels of engineering, made to advance physics *and* technology
- It is the result of the vision and talent of thousands of people from across the world who have worked together for decades towards this common goal
- Today, we are privileged to exploit and further improve the LHC and its detectors, while we operate and exploit many other experiments worldwide, and design ambitious new projects — to answer the deep questions in our field, we need more experiments, not less
- You are part of this adventure. Stay curious, question boldly, and aim high — compelling ideas attract collaborators and support



Extra slides

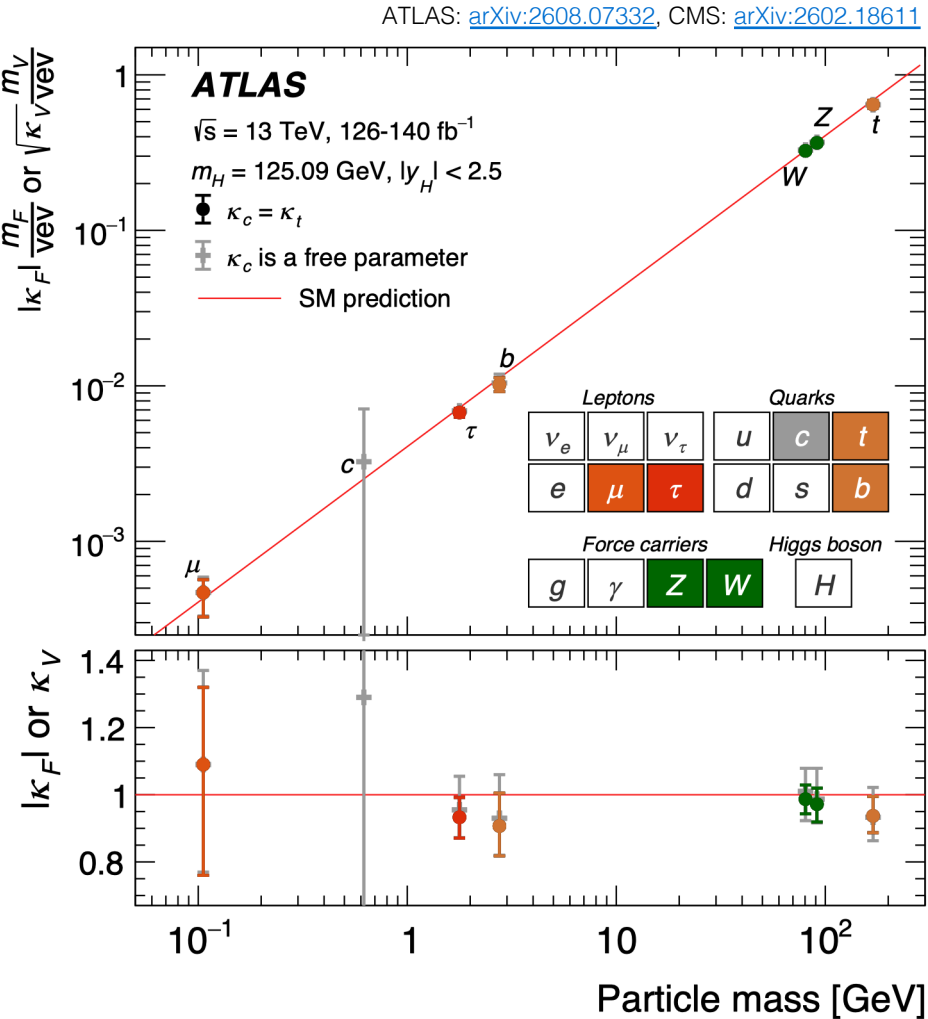
The LHC showed that the Brout-Englert-Higgs mechanism is real

Discovery of Higgs boson enables the direct study of electroweak symmetry breaking and the process of mass generation

$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \not{D} \psi + h.c. + \chi_i y_{ij} \chi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi) + \dots$

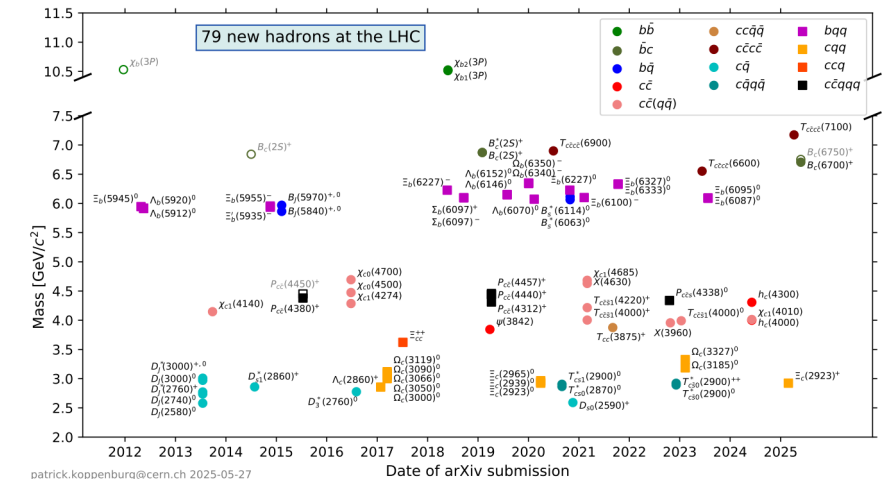
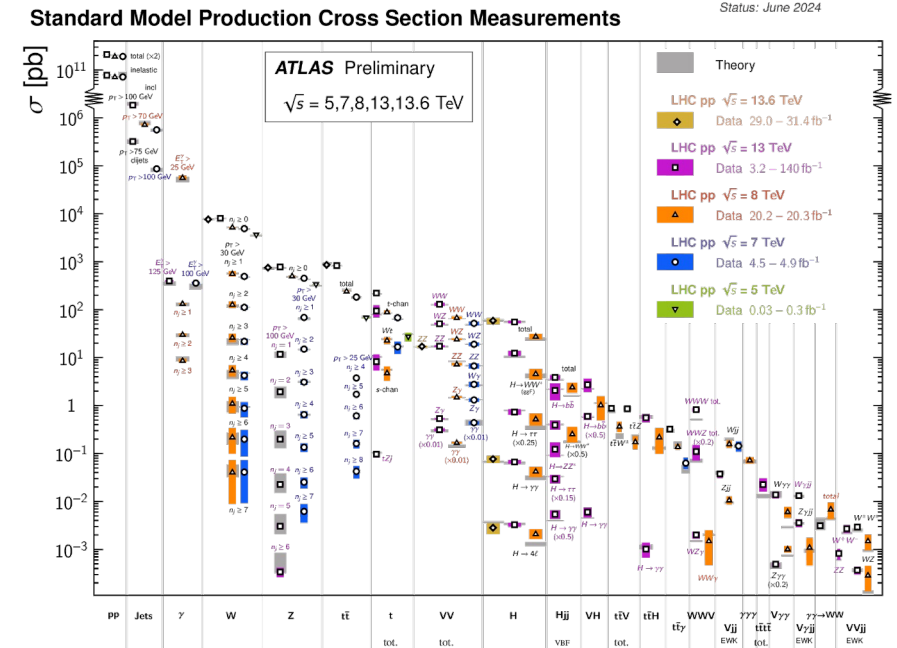
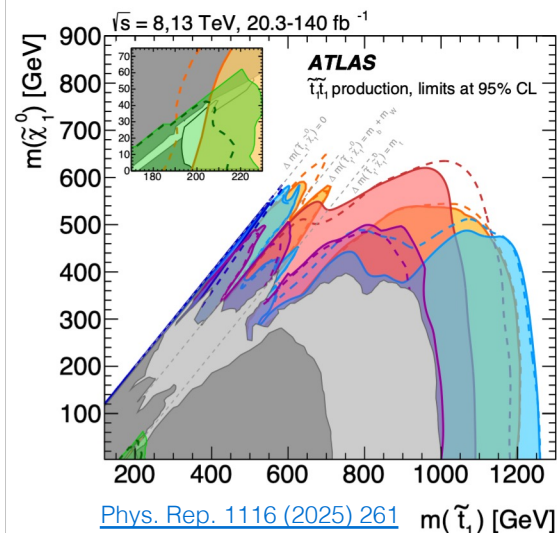
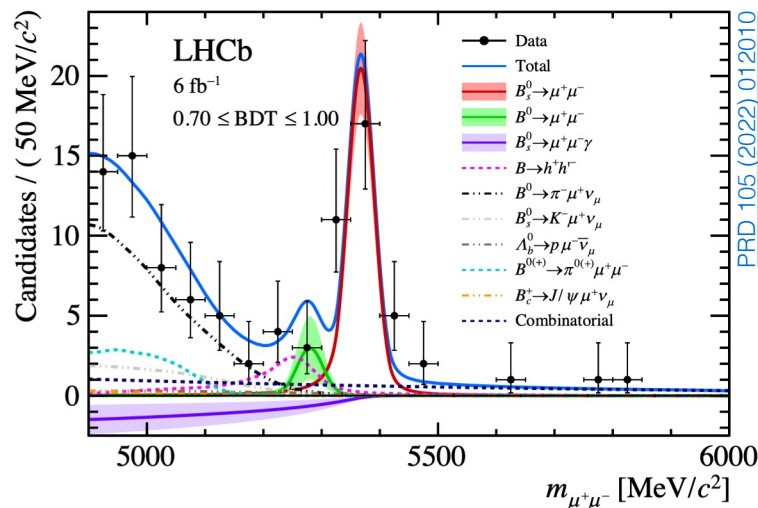
Unpleasant scalar sector (23 parameters, large hierarchy) — key to many mysteries

Coupling strength modifiers: $\kappa_i = \kappa_i^{\text{obs}} / \kappa_i^{\text{SM}}$



We have learned so much more at the LHC ...

- A plethora of measurements, some involving extremely rare and sensitive processes, others reaching very high precision, deepen our understanding and confirm the predictive power of the SM
- 82 new hadronic bound states discovered so far, 28 of which exotic, the heaviest being the quasi-bound state toponium
- Heavy-ion collisions enabled unprecedented insights into the properties of the quark-gluon plasma
- Searches for new phenomena have set tight constraints on some of the most popular SM extensions, thus completely changing the field of beyond the SM physics



What are the next goals in collider physics?

Scalar sector and EWBS

- Higgs coupling measurements from 10% $\rightarrow$ % $\rightarrow$ ‰ level to test BEH mechanism
- Establish second (and first?) generation Yukawa couplings; probe width, CP, and rare/exotic decays
- Begin mapping the Higgs potential through the trilinear self-coupling λ_3
- Establish longitudinal VBS and probe extended or composite Higgs sectors

Precision SM and QCD

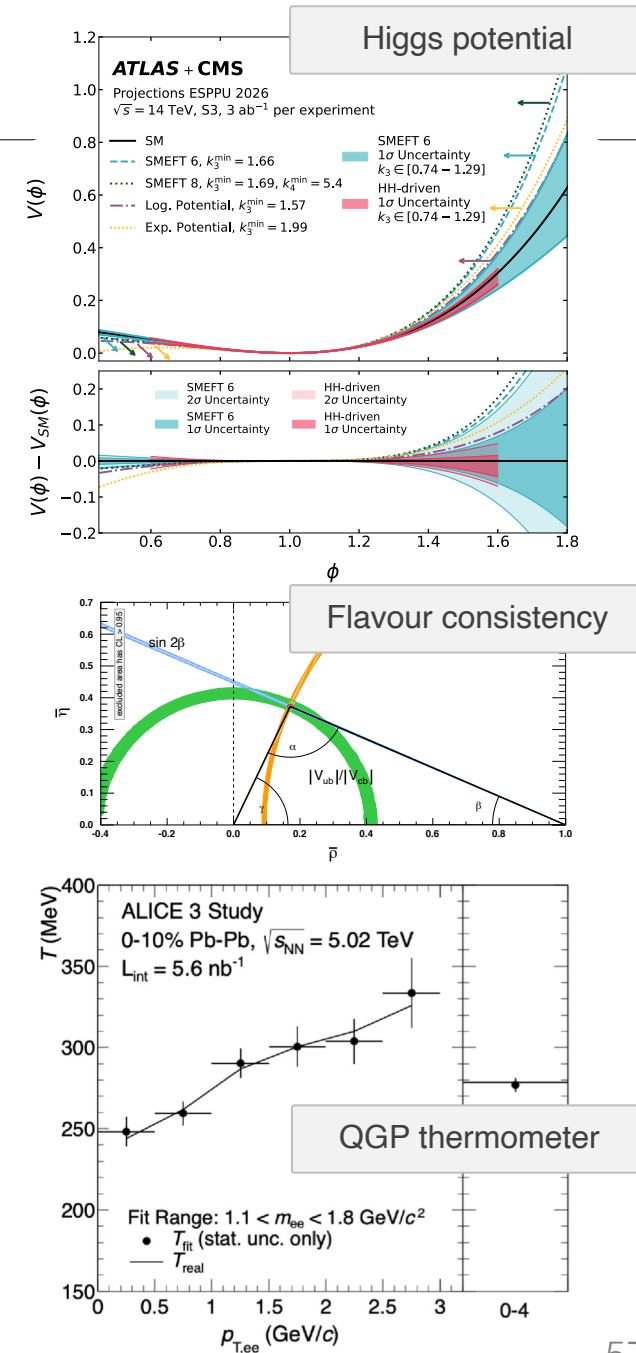
- Push the precision of electroweak, top, flavour, and Higgs observables
- Deepen understanding of SM dynamics, pert. and nonpert. QCD, hadron structure, and spectroscopy
- Probe high scales indirectly through precision observables and energetic tails
- *Match experimental precision with higher-order calculations and improved event generators*

Discovery frontier

- Search directly for new particles and interactions across masses and coupling strengths
- Explore dark sectors, LLPs, FIPs, HNLs, and exotic Higgs decays
- Test possible origins of dark matter, neutrino mass, baryogenesis, and electroweak hierarchy

Heavy ion collisions

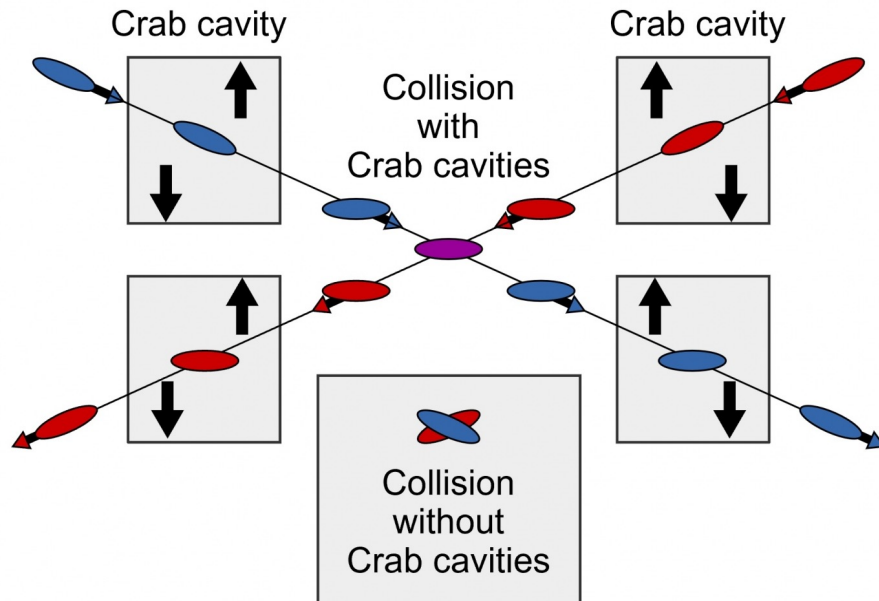
- Determine QGP transport properties and temperature evolution
- Study jets, heavy flavour, quarkonia and electromagnetic radiation in QGP
- Probe small-x nuclear dynamics and map the accessible QCD phase structure



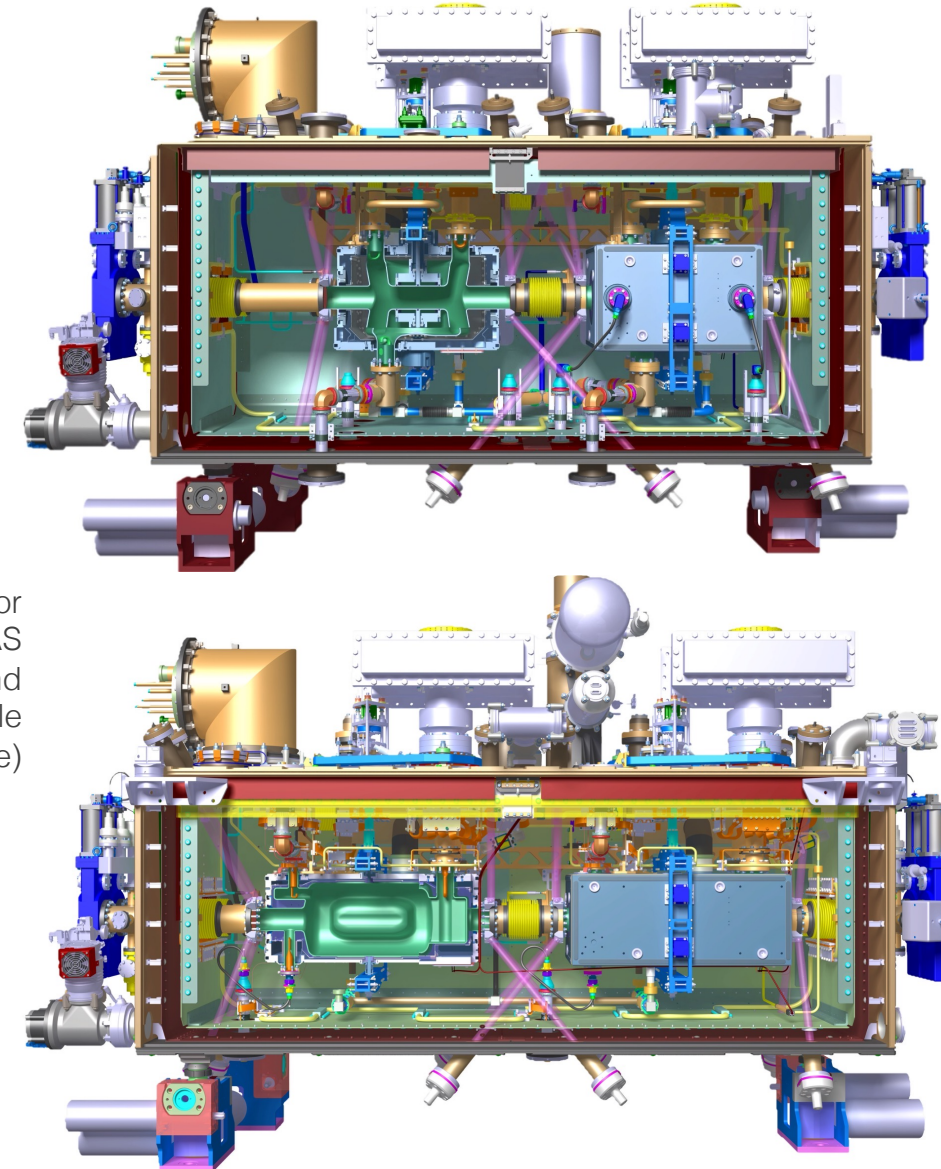
HL-LHC — Higher peak luminosity

Crab cavities at ATLAS and CMS

- 16 (8 around ATLAS/CMS) superconducting RF cavities tilt proton bunches through application of a time-dependent transverse voltage (3.4 MV/cavity) across the bunch such that they effectively collide head-on despite the crossing angle (uncorrected: luminosity loss of up to 30% at HL-LHC)
- Leading (trailing) edge of the bunch gets a kick in one (opposite) direction → rotation of the bunch in the transverse plane
- Already successfully used at SuperKEKB, but never at hadron colliders



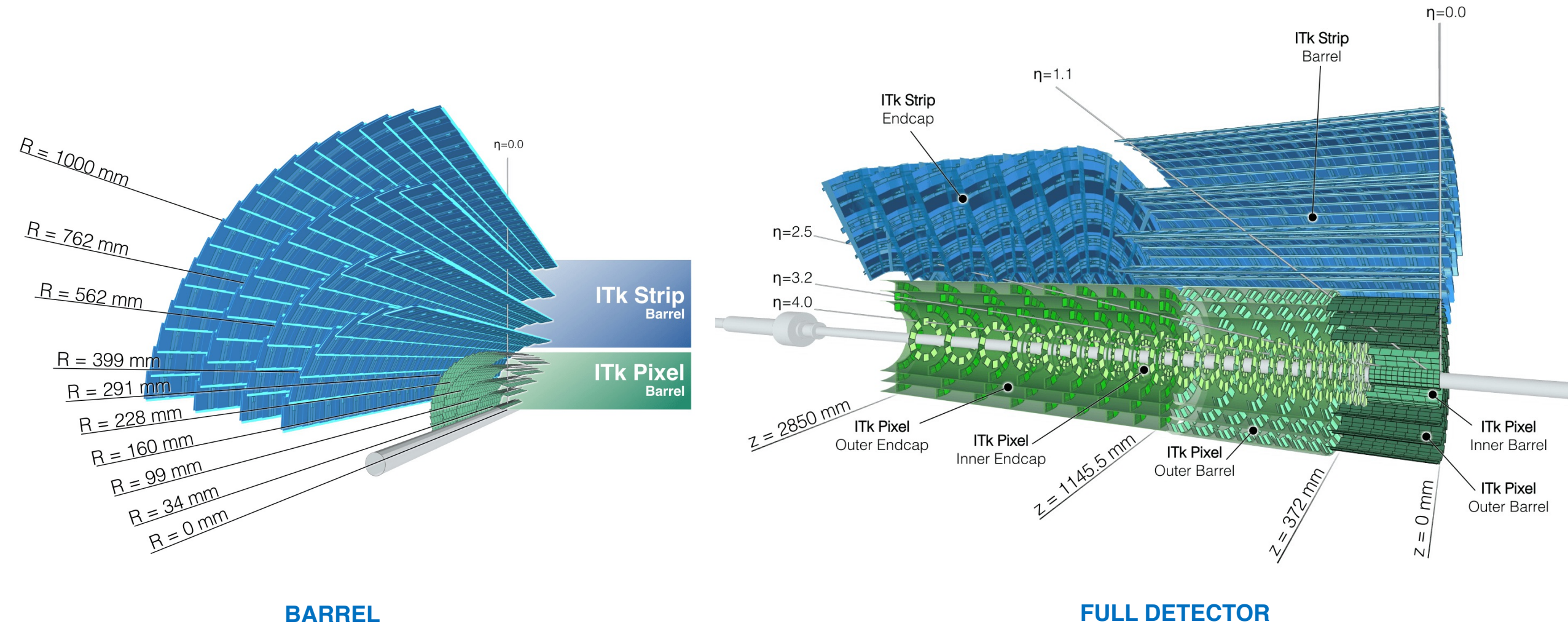
Right: cryomodule designs for crab cavity chain at ATLAS (top, RFD — RF Dipole) and CMS (bottom, DQW — Double Quarter-Wave)



New ATLAS Inner Tracker (ITk)

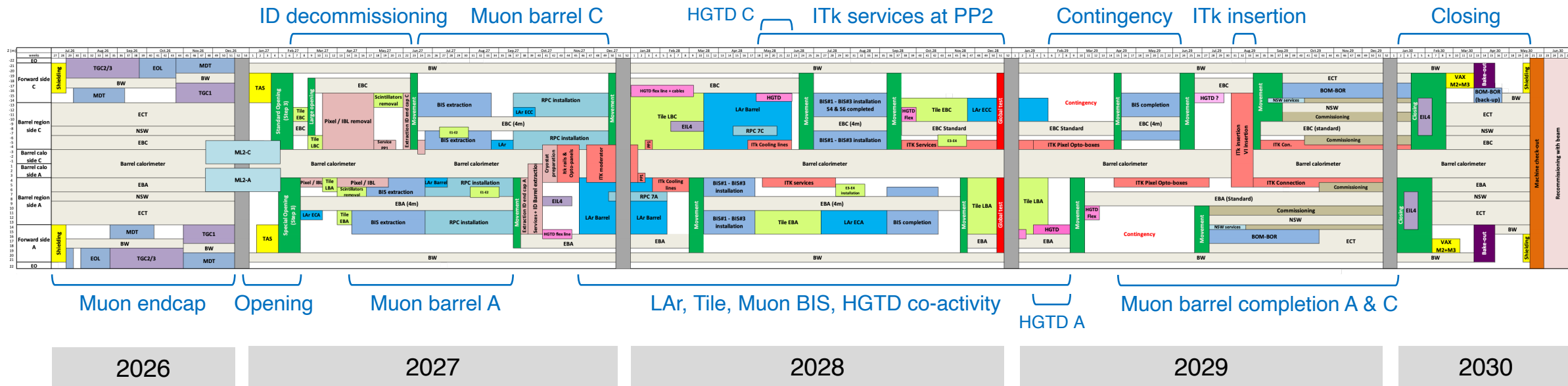
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New ATLAS silicon pixel and strip

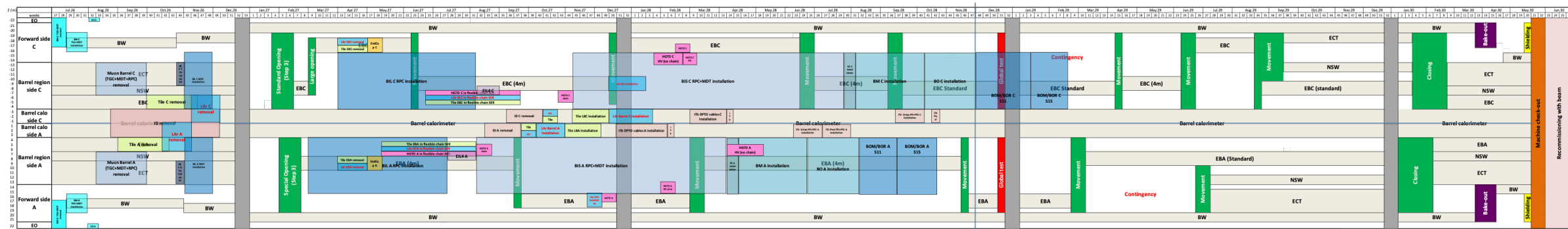


LS3 installation schedule — Example ATLAS, overseen by ATLAS Technical Coordination

Detector in UX15 (Point 1 cavern) — Schedule includes > 7,500 tasks



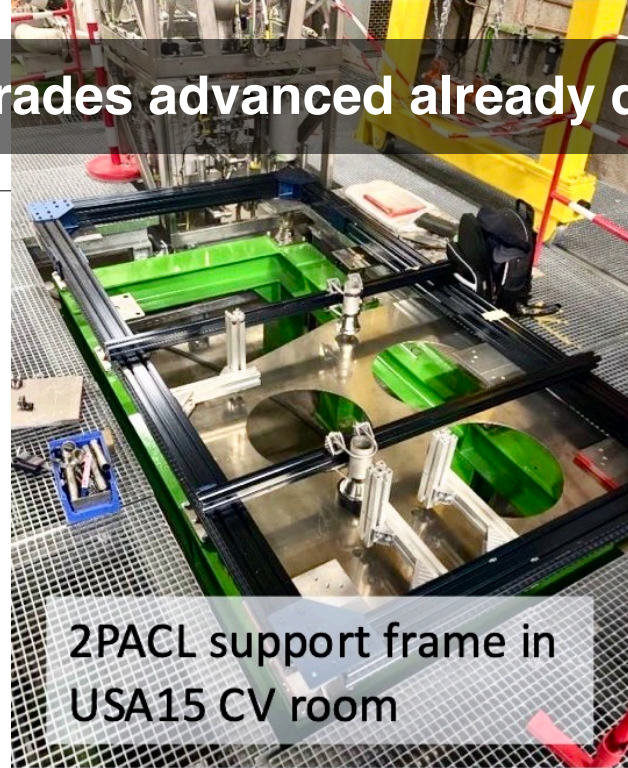
Services in UX15 — 6 teams working in parallel



Infrastructure upgrades advanced already during Run-3 YETS



2PACL installation
(March 2025)



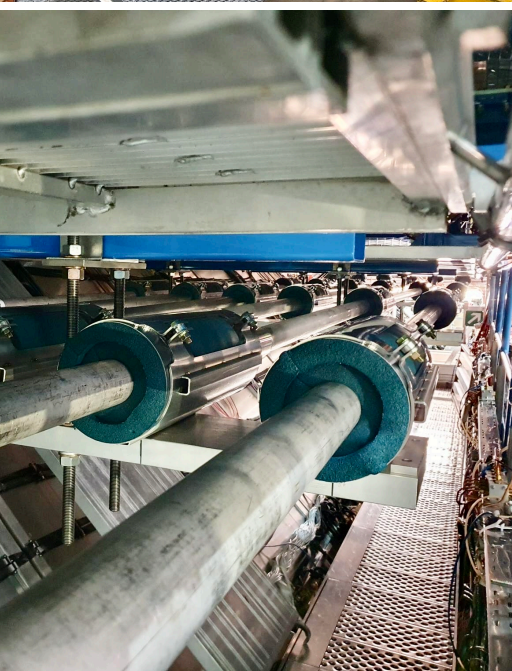
2PACL support frame in
USA15 CV room



R744 units installed in SXS1



2PACL control cabinets in
USA15 CV room



Main CO₂ transfer line UX15

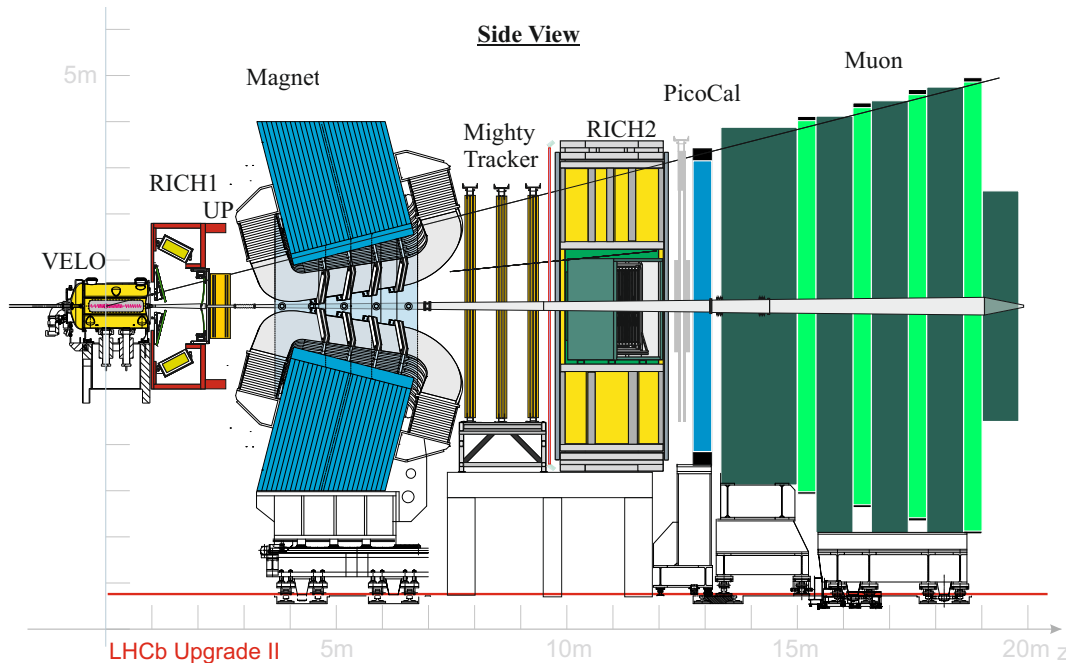


Main CO₂ transfer line
USA15 – UX15

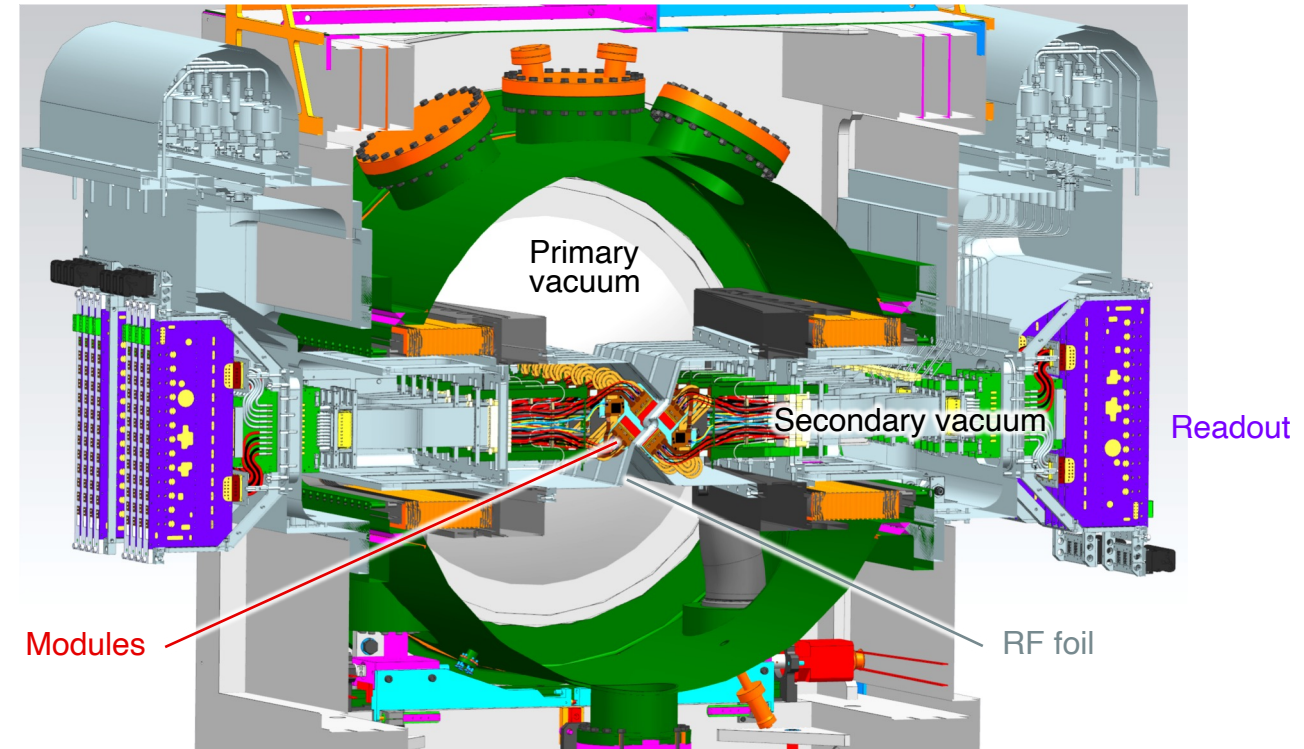
Ambitious LHCb Upgrade II and ALICE 3 for Run 5 (2036–2041)

LHCb Upgrade II [\[LHCb Upgrade II scoping document\]](#)

- Goal: enable operating at $L_{\text{inst}} = 1.0 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ (currently $0.23 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$), for $L_{\text{int}} \sim 300 \text{ fb}^{-1}$
- Challenge: pileup of 30 (current: ~ 6) $\rightarrow$ efficient tracking and vertexing, excellent PID, precise timing



A new vertex detector (VELO) including timing



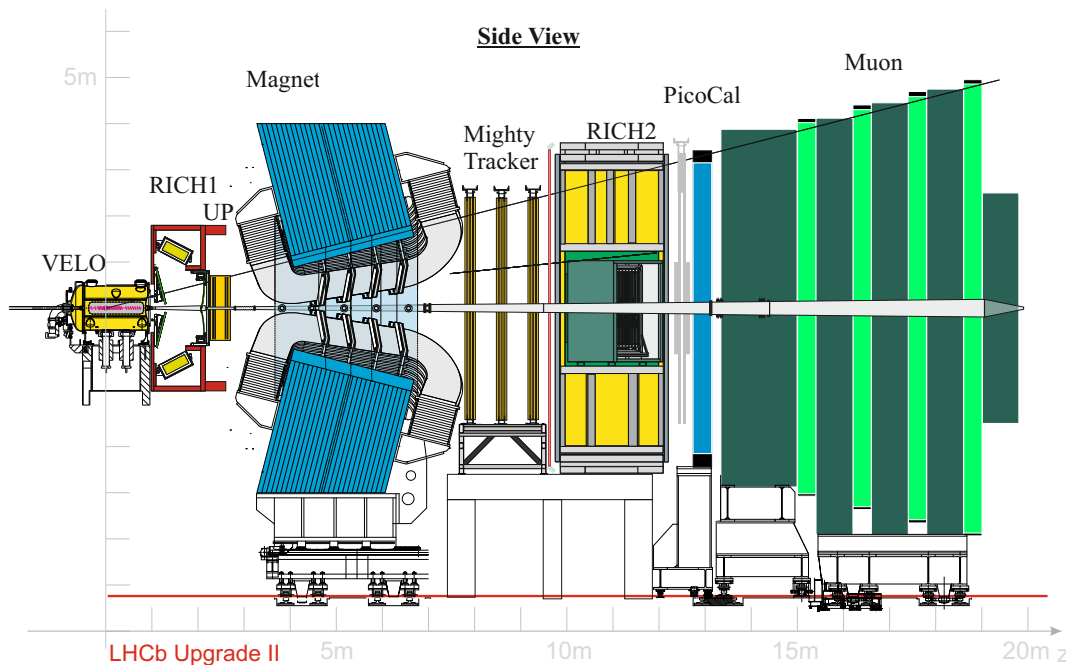
Run-3 VELO, closest active pixel sensor: 5.1 mm from beam, 55 μm pixel pitch

- Move VELO to $O(7 \text{ mm})$, to limit fluence ($\sim 10^{16} n_{\text{eq}}/\text{cm}^2$), offset by finer pixels (45–50 μm), a 75- μm RF foil (250 μm in Run 3) and less material
- Fast 3D sensors with 28-nm ToT/ToA “PicoPix” ASIC (current VeloPix: 130 nm) target $\sim 50 \text{ ps/hit}$ and $\sim 20 \text{ ps/track}$ resolution from 6–8 hits

Ambitious LHCb Upgrade II and ALICE 3 for Run 5 (2036–2041)

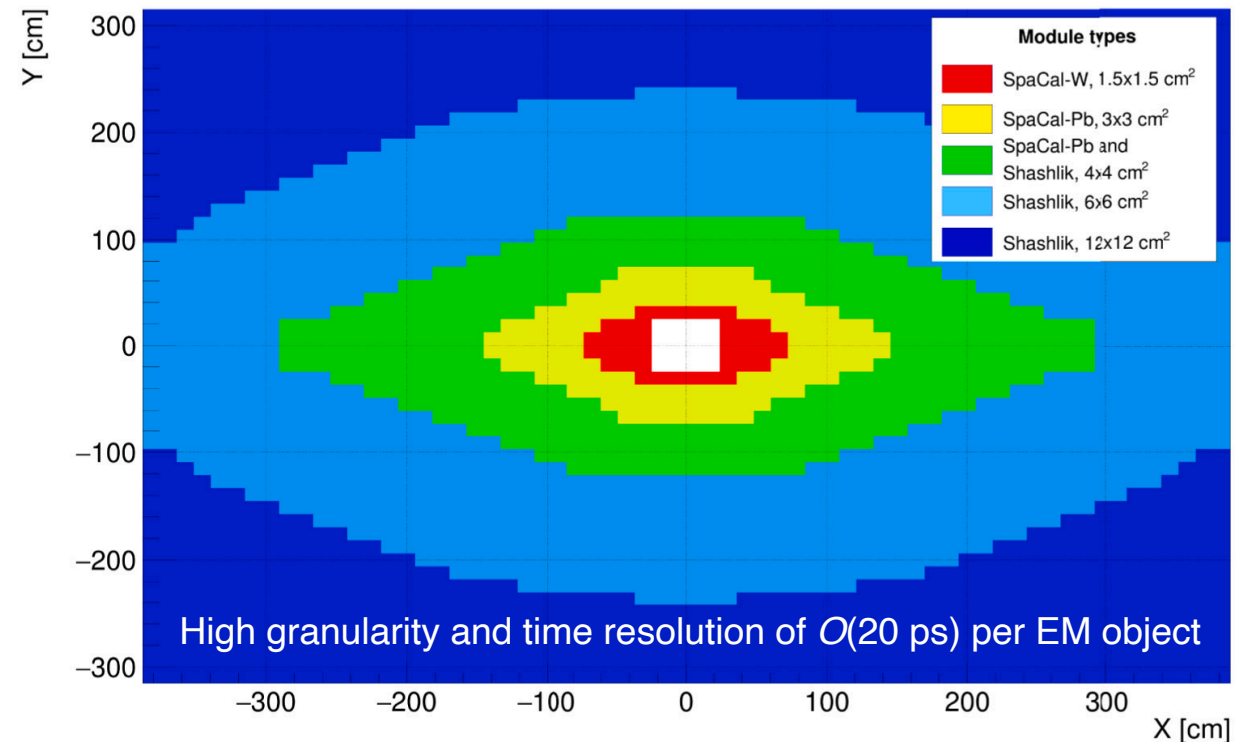
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A new high-granularity 4D calorimeter replacing ECAL: PicoCal

PicoCal 2024 - baseline



- SpaCal-W, tungsten absorber with radiation-hard crystal fibres
- SpaCal, lead absorber with plastic scintillating fibres
- Upgraded Shashlik, alternating lead and plastic-scintillator plates with faster wavelength-shifting fibres

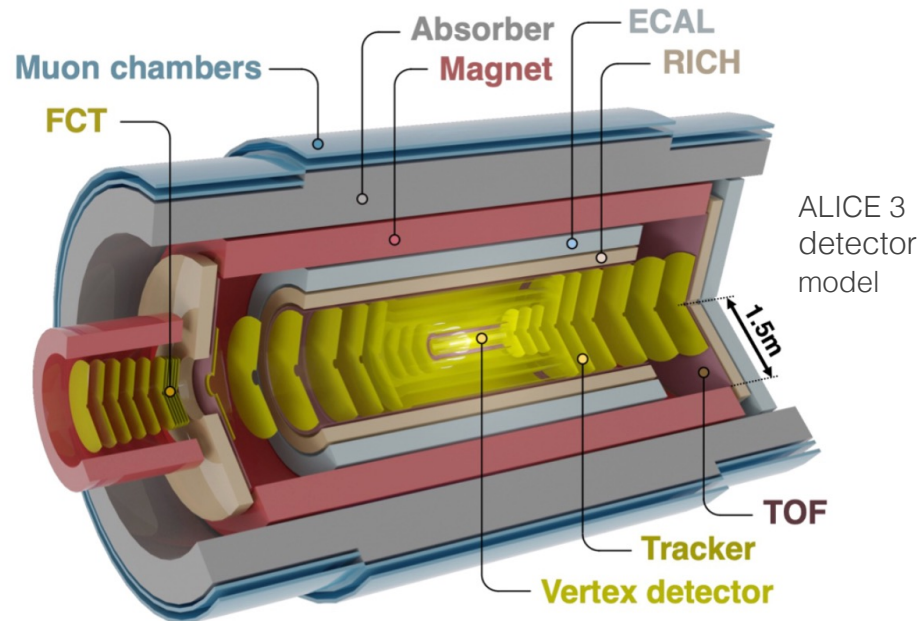
Ambitious LHCb Upgrade II and ALICE 3 for Run 5 (2036–2041)

ALICE upgrades during LS3

- New ITS3 (MAPS) and forward calorimeter

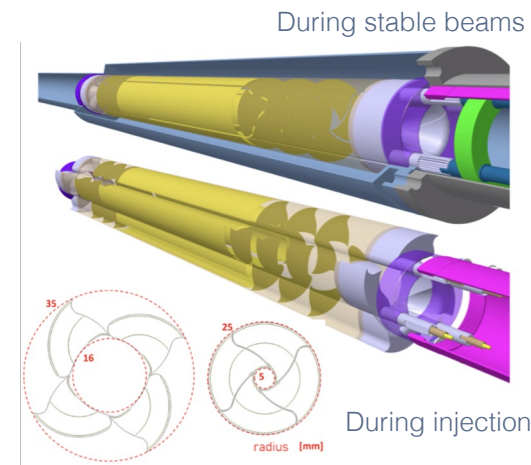
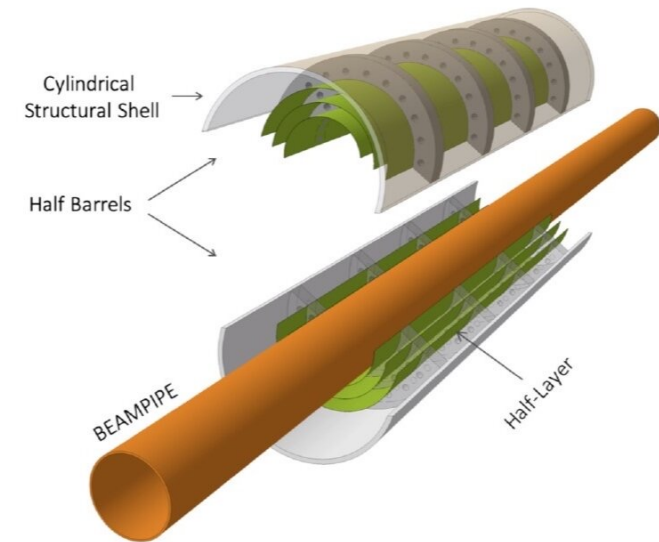
ALICE 3 [\[ALICE 3 scoping document\]](#)

- **Physics:** QGP temperature from dielectrons; heavy-flavour transport and hadronisation in QGP; low- p_T hadron reconstruction required
- Compact compact, low-mass all-silicon tracker with precision vertexing, broad PID and high-rate readout



Among the new systems, new MAPS detectors

- 3-layer ITS3 uses ultra-thin, wafer-scale Monolithic Active Pixel Sensors (MAPS) bent into cylinders, integrating sensor and readout electronics on one CMOS wafer, without bump bonding
- “Stitching” joins multiple lithographic fields into one O(25 cm)-long wafer-scale sensor
- After fabrication, sensors are thinned to O(50 μ m) and bent

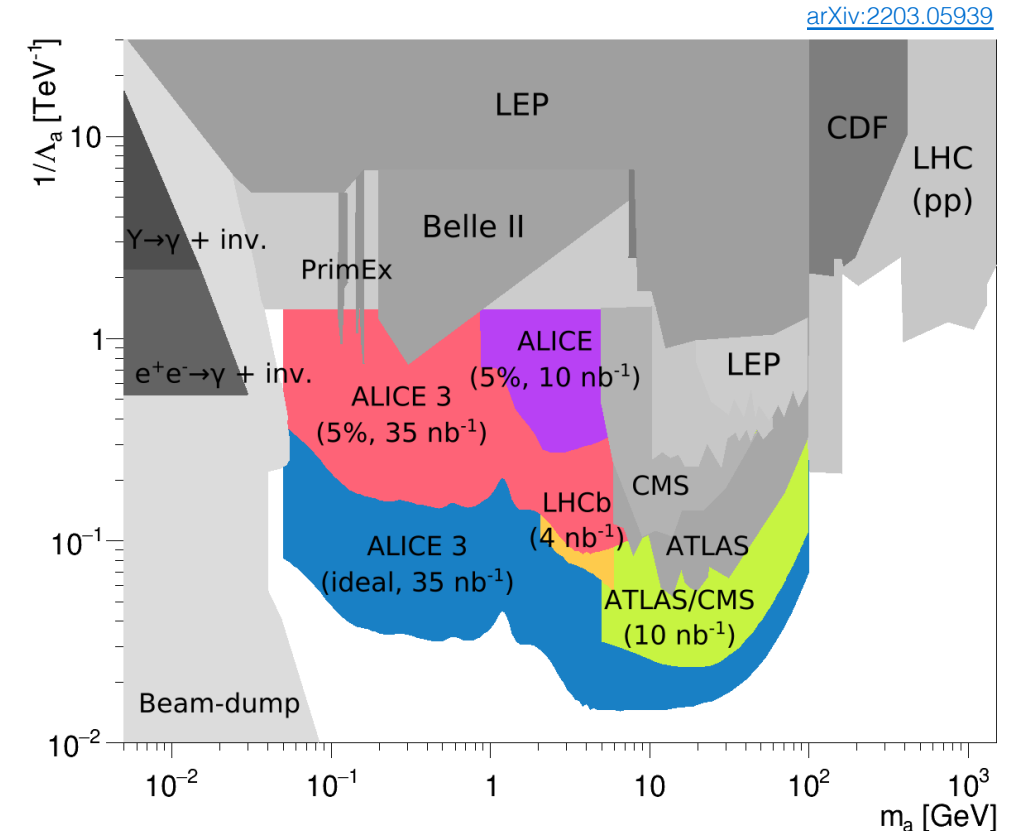


Retractable silicon vertex detector at 5 mm (15 mm during injection) from beam, giving $< 10 \mu\text{m}$ pointing resolution for $p_T > 200 \text{ MeV}$ in high-multiplicity environment at ALICE3

New opportunities at the HL-LHC

20 times more luminosity than Run 2 and better detectors offer significantly enhanced physics reach

- Sensitivity increase by up to 2 TeV for searches
- $\sqrt{L}$ or better sensitivity increase to new physics with weak or suppressed couplings (eg, EW SUSY, WIMPs, or feebly interacting particles)
- Sensitivity to new SM processes, extended phase space, and improved precision in Higgs, multiboson, top, flavour, ... probes
- Increased trigger acceptance and selection capabilities for low-mass, soft, unconventional signatures, and AD
- Increased forward acceptance of trackers allows improved reconstruction of VBF/VBS topologies, constraints on PDFs, and control of pileup
- New timing detectors with 30 ~ 50 ps resolution help mitigate pileup and improve the detection of long-lived particles
- Machine learning (and AI?) will continue to boost detector, reconstruction, and analysis performance
- The higher luminosity (LHCb) and increased low- p_T acceptance (ALICE) will improve sensitivity in direct searches for feebly interacting particles



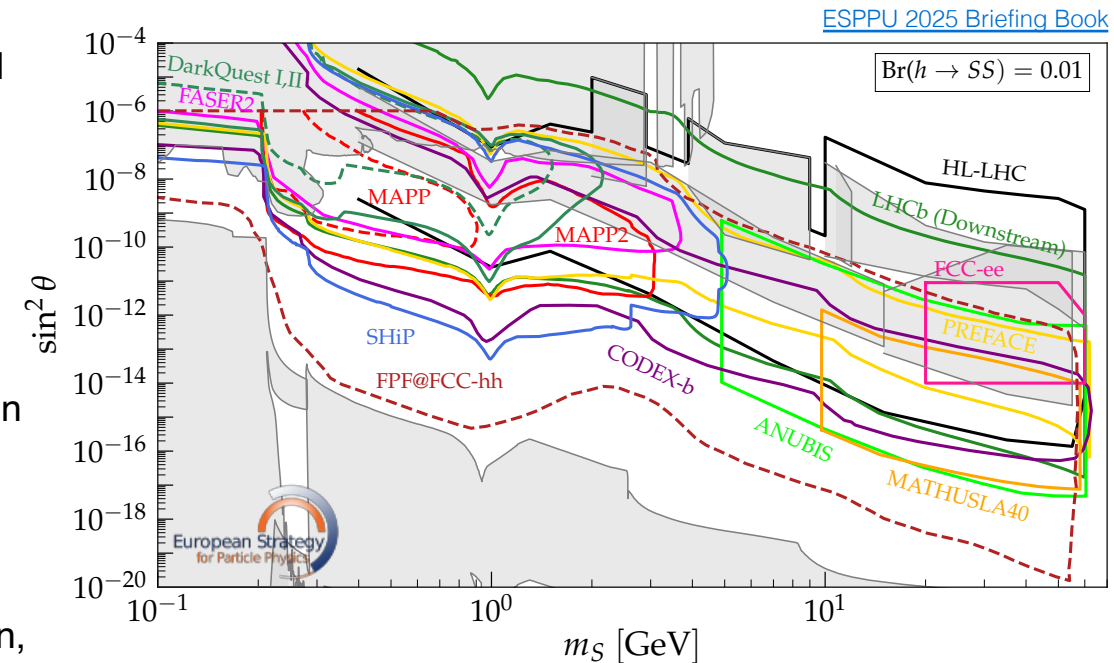
ALICE 3 sensitivity to ALPs from light-by-light scattering extending significantly to low masses. PbPb collisions also offer unmatched sensitivity to some magnetic monopole processes

(ALICE 3 constraints estimated in two scenarios of 5% and 100% photon reconstruction efficiency corresponding to photons registered via conversions or in an ideal calorimeter)

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- And, of course, the next generation HNL/FIP experiments at the LHC will significantly extend the sensitivity in coupling and mass

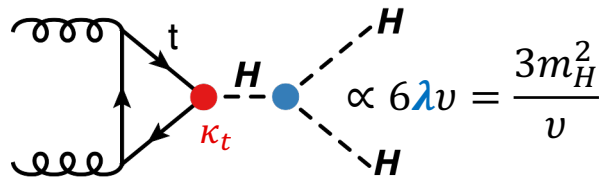


Projection of future searches for dark scalars ($\sin^2\theta$ sets the mixing strength between the SM Higgs and S)

Higgs self-coupling — HL-LHC prospects

Combination of expected ATLAS and CMS yields for 3 ab⁻¹

Note: prospects tend to be conservative as future analysis improvements not included



$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4 \quad \kappa_\lambda \equiv \lambda_3^{\text{obs}}/\lambda^{\text{SM}}$$

The measurement of λ allows to constrain SM extensions that produce a 1st order electroweak phase transition to allow possible EW baryogenesis (SM: 2nd order = continuous)

