

ATLAS Highlights

F. Cerutti LBNL

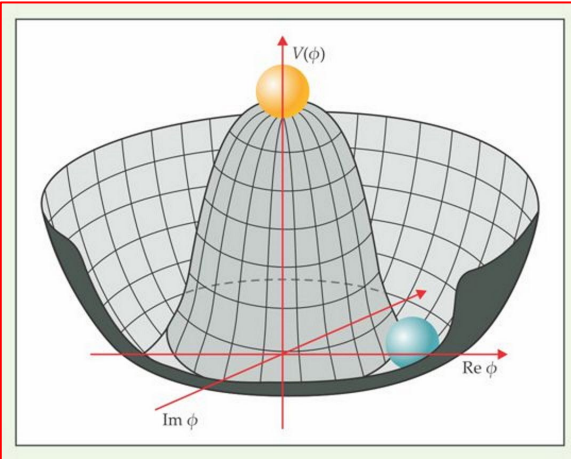
On behalf of the **ATLAS Collaboration**



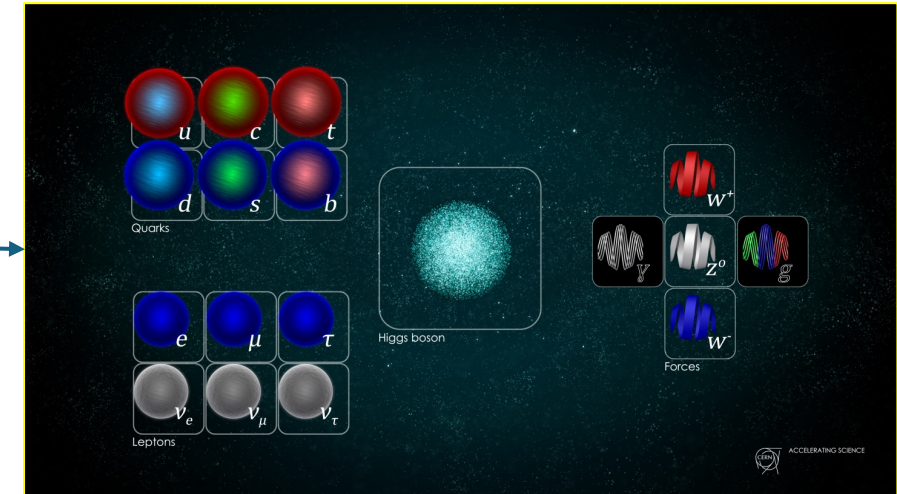
EPS-HEP CONFERENCE
07-11 JULY, 2025
PALAIS DU PHARO
MARSEILLE, FRANCE

Addressing fundamental questions ...

$$SU(3)_{\text{QCD}} \times SU(2)_L \times U(1)_Y$$



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

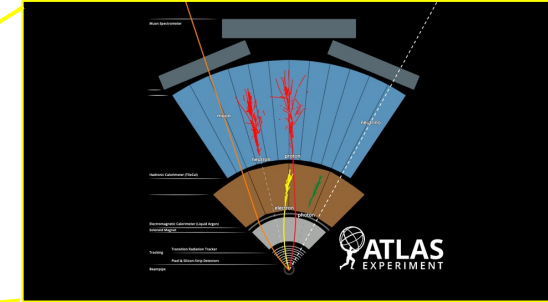
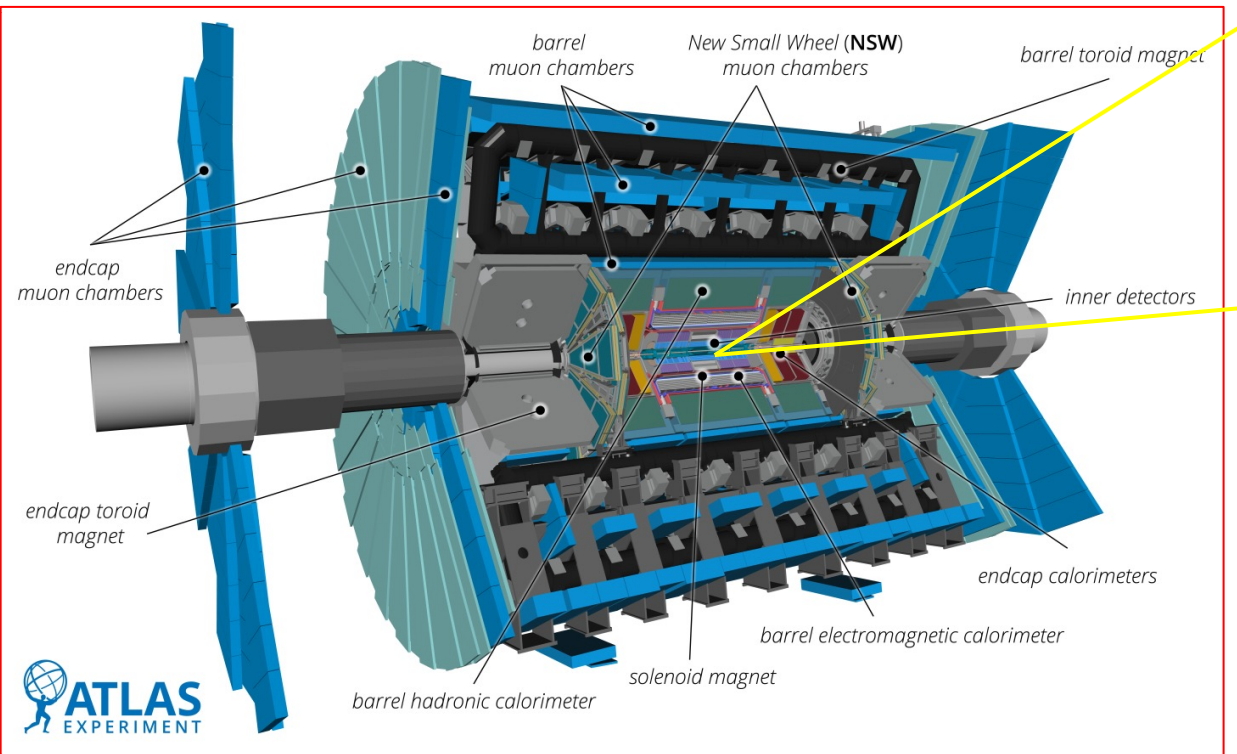
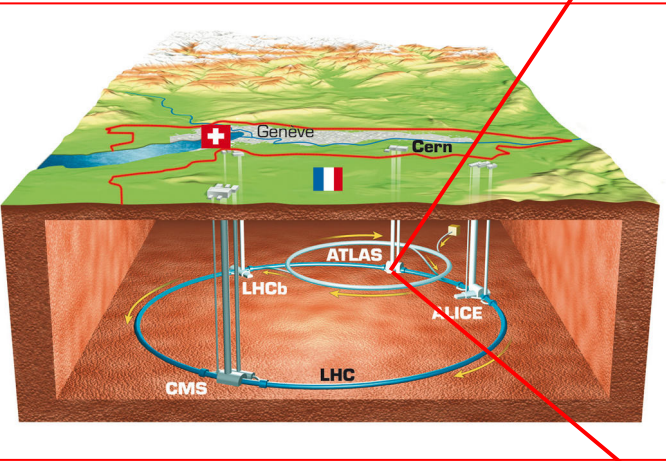


Interactions between elementary particles described by a quantum field theory based on invariance under local Gauge symmetries: the **Standard Model**

SU(2) symmetry spontaneously broken by BEH mechanism: generates vector bosons (W and Z) and fermion masses, and a new scalar H → well behaved perturbative computation and renormalizability → precise predictions that can be experimentally tested

There are several indications that the SM is a low energy approximation of a more complete UV theory: hierarchy problem, fermion mass hierarchy (ν), matter-antimatter asymmetry, dark matter, dark energy

The ATLAS experiment



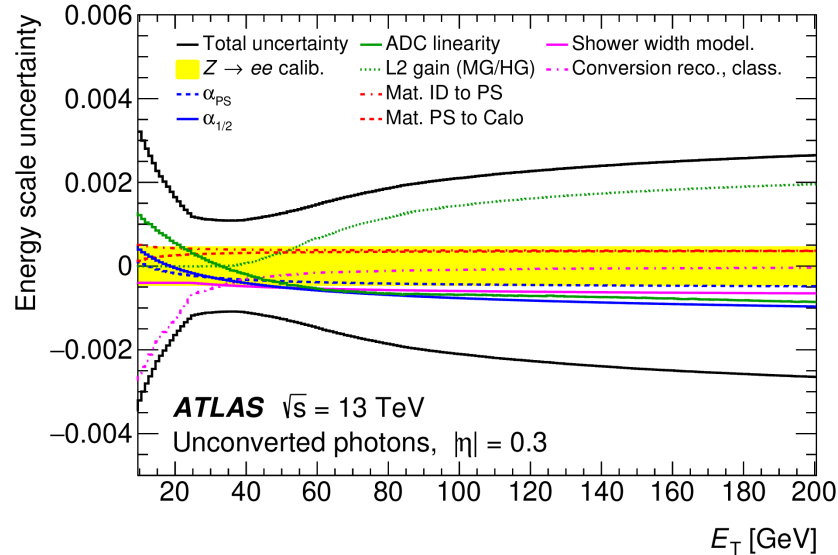
The **ATLAS** experiment is designed to shed light on elementary particle interactions: test the SM and search for phenomena beyond it

ATLAS is a general-purpose detector running at the LHC collider with excellent reconstruction, identification and energy-momentum measurement of electrons, photons, muons, taus, jets and flavor-tag covering a wide energy range (sub-GeV $\rightarrow$ TeV)

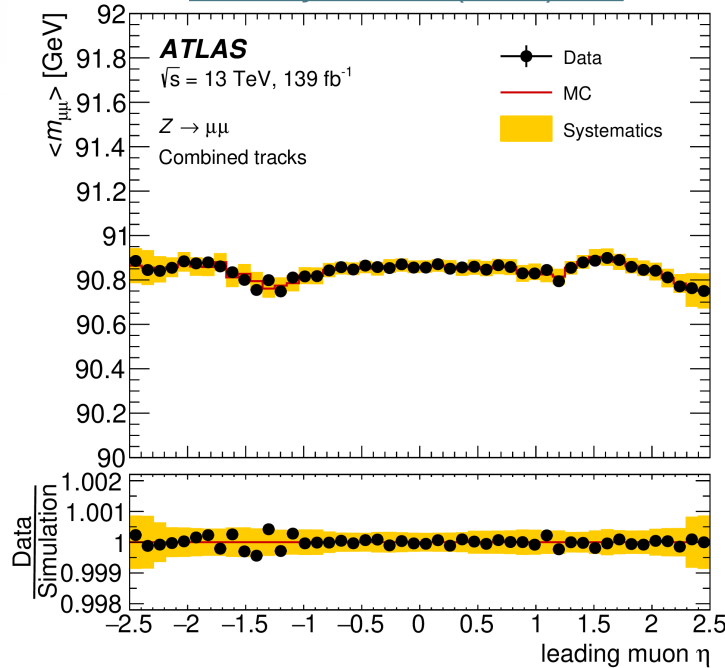
Collecting proton-proton collisions at $E_{\text{CM}} = 13.6$ TeV (world record collider energy) at instantaneous luminosity $\sim 2 \times 10^{34} \text{ s}^{-1} \text{ cm}^{-2}$ with ~ 60 minimum bias interactions per bunch crossing (well above the design value of 20)

Physics Objects calibration

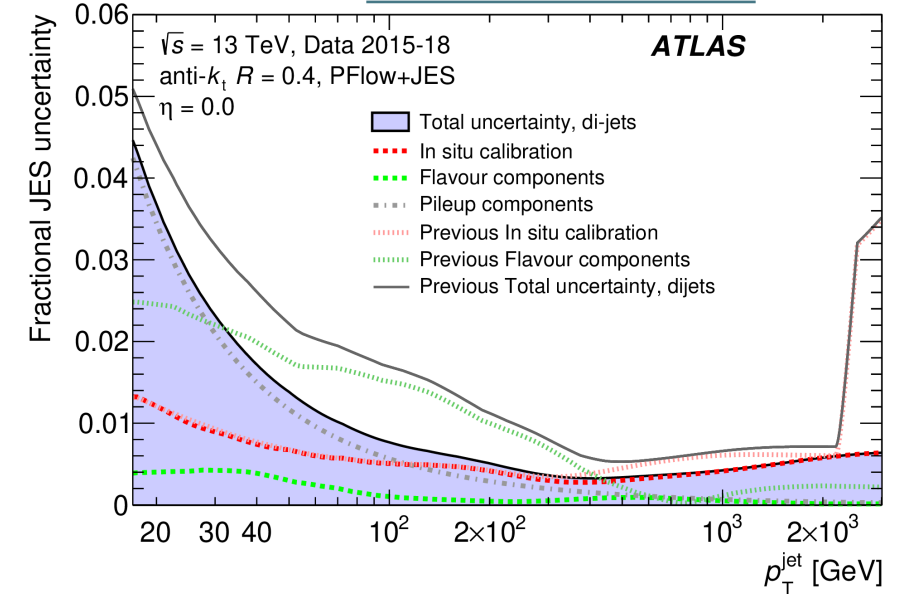
JINST 19 (2024)



Eur. Phys J. C 83 (2023) 686



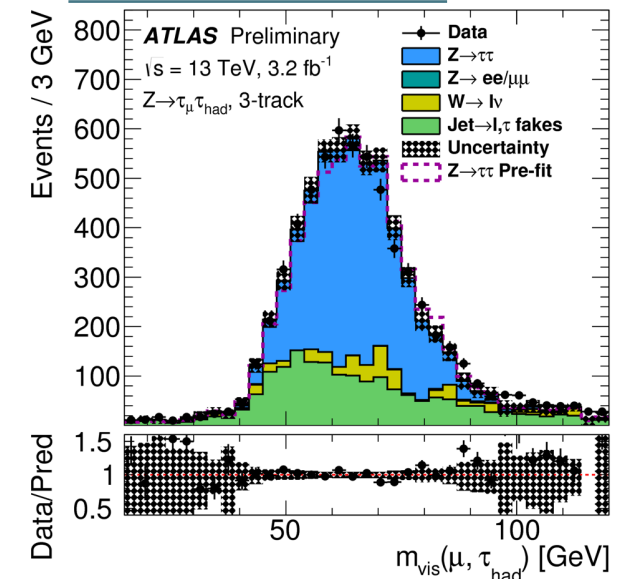
2407.15627 Subm. EPJC



➤ The excellent performance requires **excellent calibrations**:

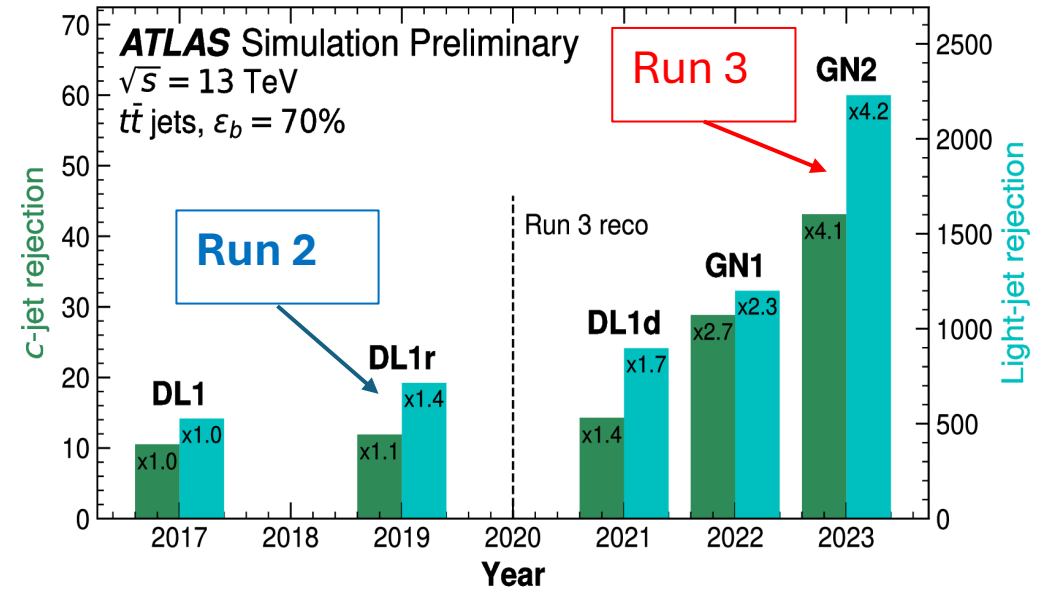
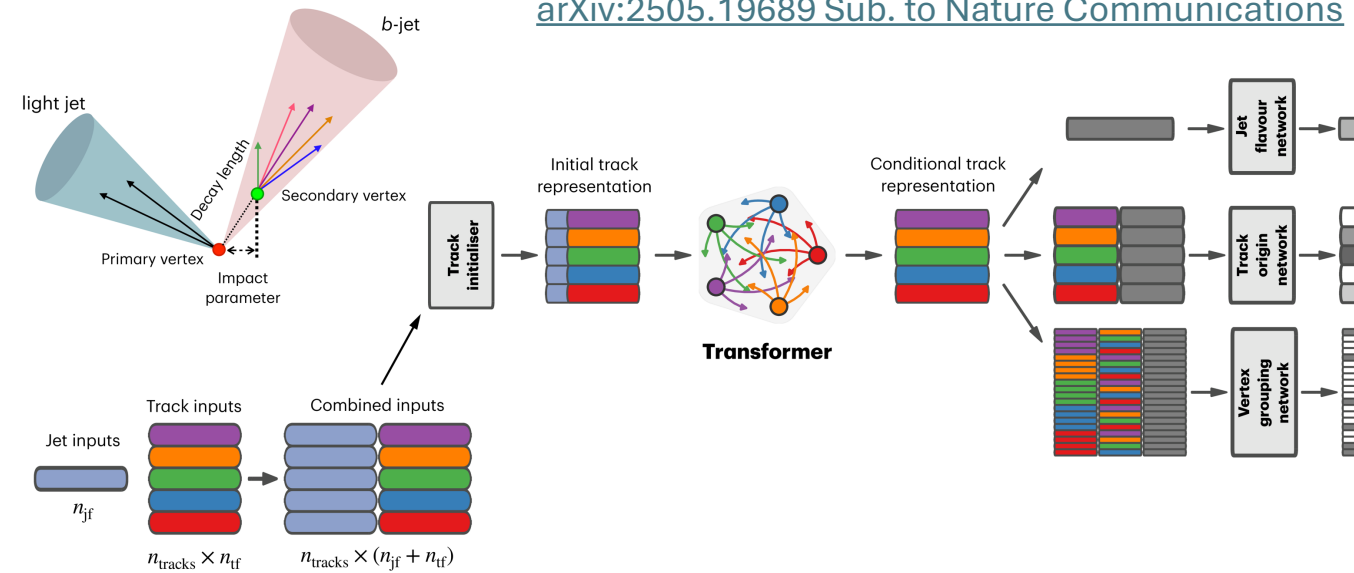
- γ : energy calibration **0.2%** at 60 GeV, **e** energy calibration **0.05%** at 45 GeV
- μ : energy scale calibration at **0.1-0.05%**
- **Jet**: energy calibration scale at **(better than) 1%** level for p_T above 60 GeV
- τ : energy scale calibrated at **~1%** level

ATLAS-CONF-2017-029



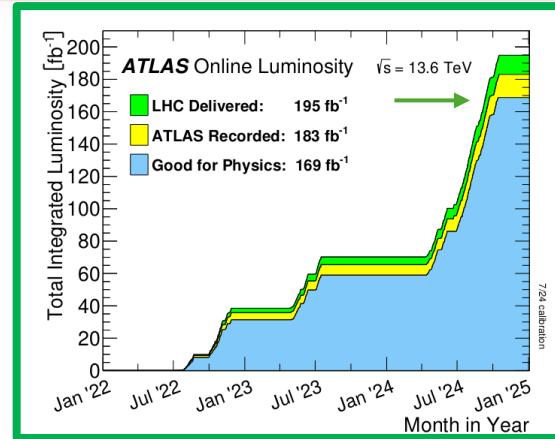
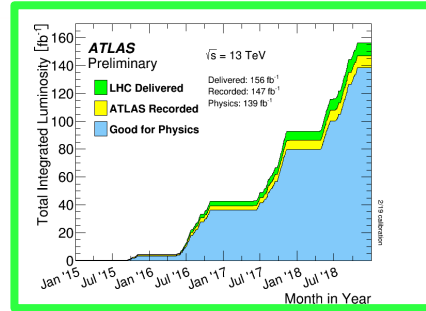
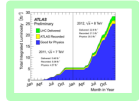
Improvements in Flavor Tag

[arXiv:2505.19689](https://arxiv.org/abs/2505.19689) Sub. to Nature Communications



- **Traditional approach** (DL1r): low-level quantities based on tracks followed by high-level multivariate classifier
- **New approach** (GN2): directly process **track and jet information**. In addition to the **primary training target** (jet flavor prediction) **auxiliary training objectives** are introduced to reconstruct the internal structure of a jet by grouping tracks originating from a common vertex
- **GN2** used in **Run 3** analyses and **reprocessed Run 2** → you will see few examples ...

This talk ...



~90% of LHC delivered luminosity used in physics analyses

ATLAS reached **1400** publications: [AtlasPublicResults](https://atlaspublicresults.cern.ch/)

Run 1:
25 fb⁻¹ @ 7+8 TeV

Run 2:
140 fb⁻¹ @ 13 TeV

Run 3: 2022-2024
168 fb⁻¹ @ 13.6 TeV

HL-LHC:
3 ab⁻¹ @ 13.6 TeV

- This talk will **highlight** a **few results** focusing on what is **new** (shown for the **first time** at this conference ) and of **highest impact on particle physics** → Some results using Run 2 + Run 3 data up to 2024 → **308 fb⁻¹** in total

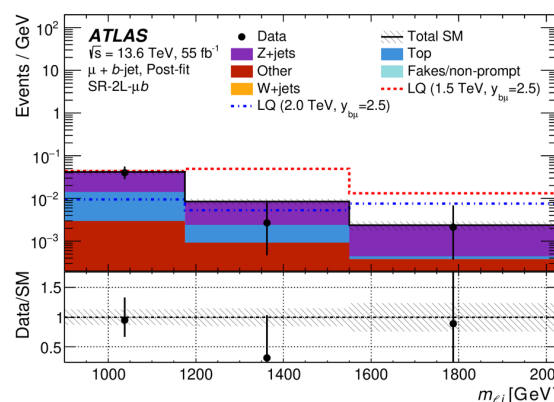
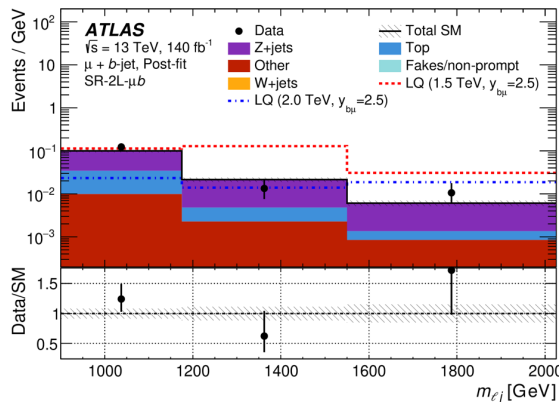
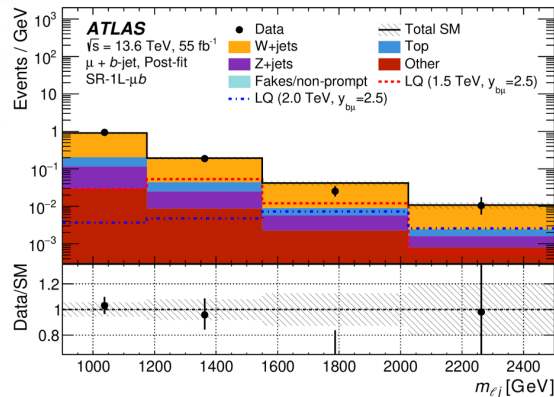
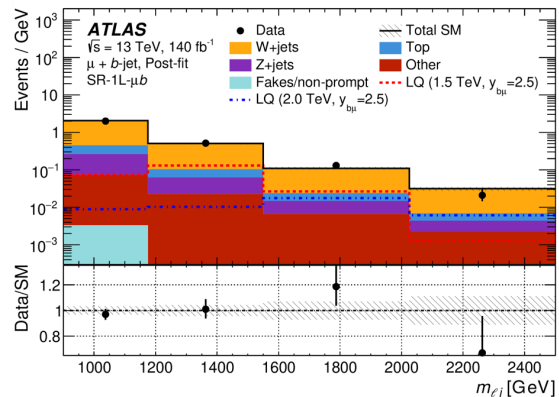
21 NEW results released for this conference

More details of the ATLAS results in other plenary talks by Emanuele Di Marco, Timothy Gershon, Josh Bendavid, Francesco Prino and Tamara Vazquez + the 56 ATLAS talks in parallel sessions + 18 ATLAS posters

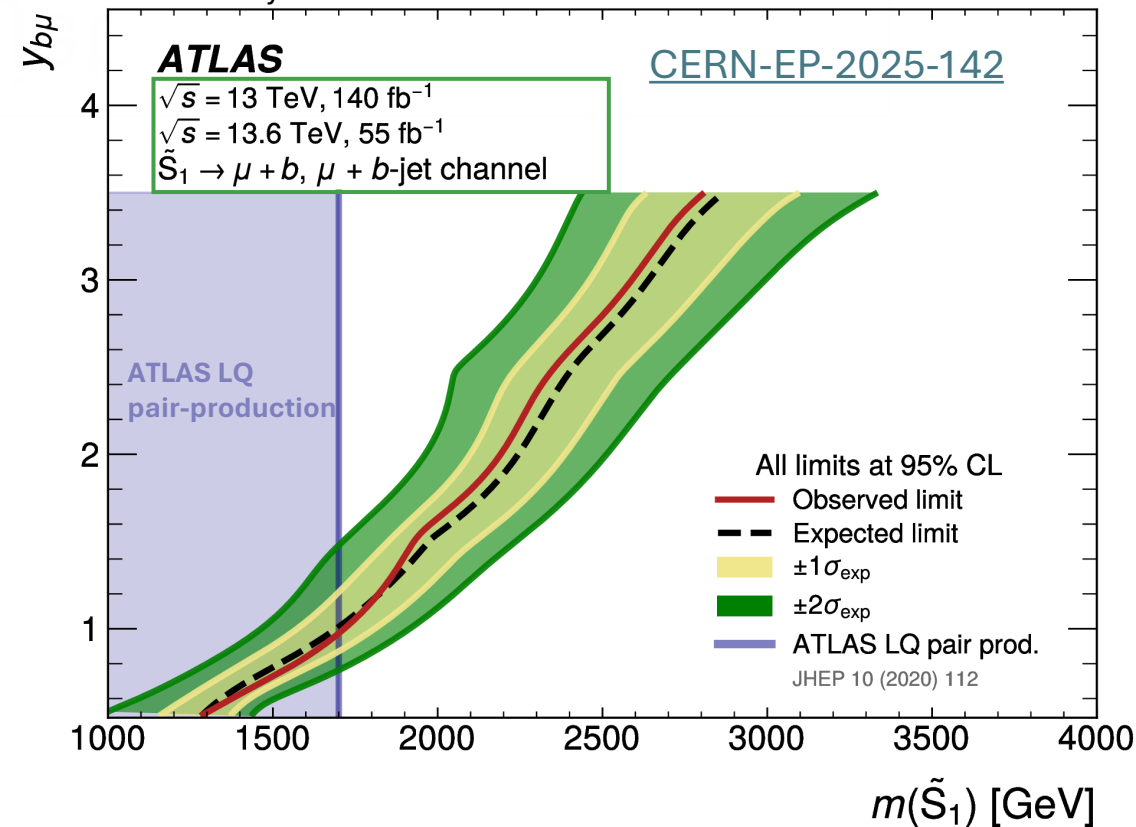
BSM searches

Many More results in **Tamara Vazquez Schröder's** talk on **Friday**

Search for resonant LQ in l+jet

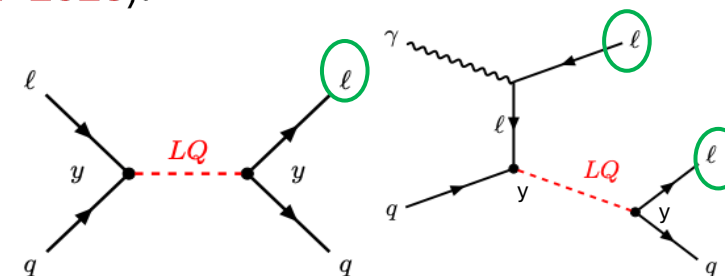


Parallel Session talk by [Monica Wieters](#)



➤ LQ s-channel production via lepton PDF of the proton using Run 2+Run 3(2022+2023):

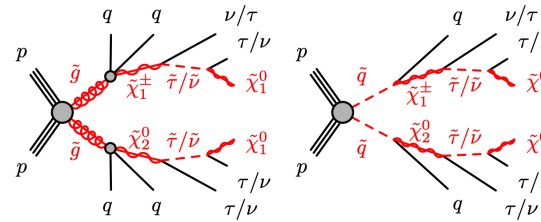
- lepton+jet resonances in $m_{l,j}$, **untagged-jet** and **b-tagged categories**
- 1- and 2-lepton channels
- No significant excesses: limits on LQ mass vs y coupling derived



Search for strong produced SUSY

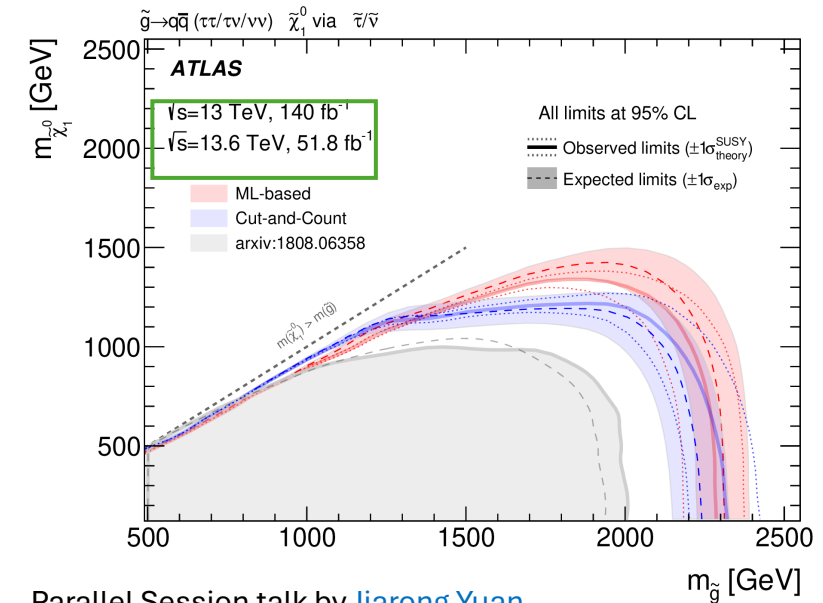
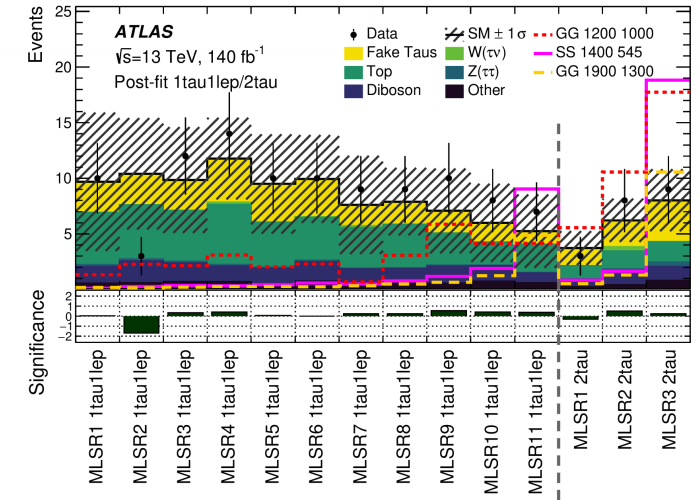


- SUSY offers a natural solution to the *hierarchy problem* and (if RP is conserved) a natural WIMP dark matted candidate
- SUSY partner of the gluon and quarks have large σ at the LHC, and are usually searched in jets + MET but for some region of SUSY parameter space decay chains involving final states with τ 's are dominant



- Select events with 1 or 2 τ , at least 2 jets and large MET (>200 GeV)
- 2 new analyses dividing events into (1 τ ,0l), (1 τ ,1l) (2 τ):
 - ML-learning based (more sensitive)
 - cut-based (less model depended and optimized for mass-compressed scenario)
- No excess found in Run 2 + Run 3 (2022-2023) data, 95% CL limits in gluino-LSP and squark-LSP planes largely improving on previous results

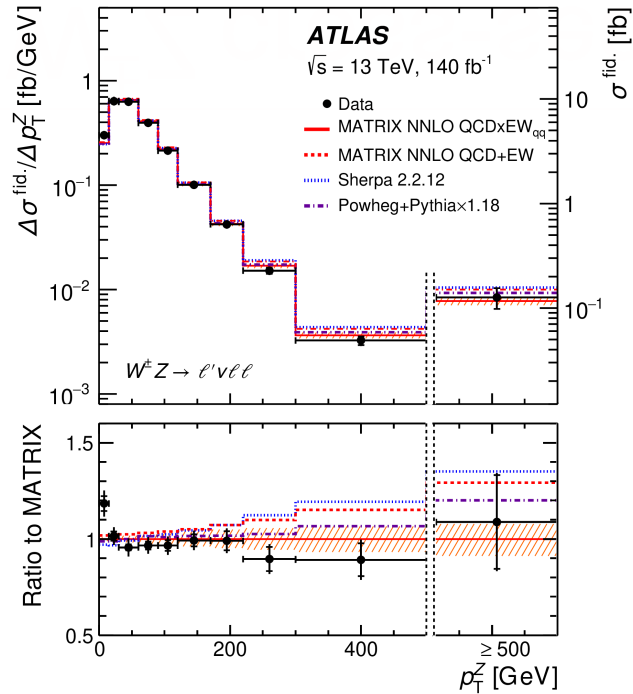
CERN-EP-2025-132 Sub. EPJC



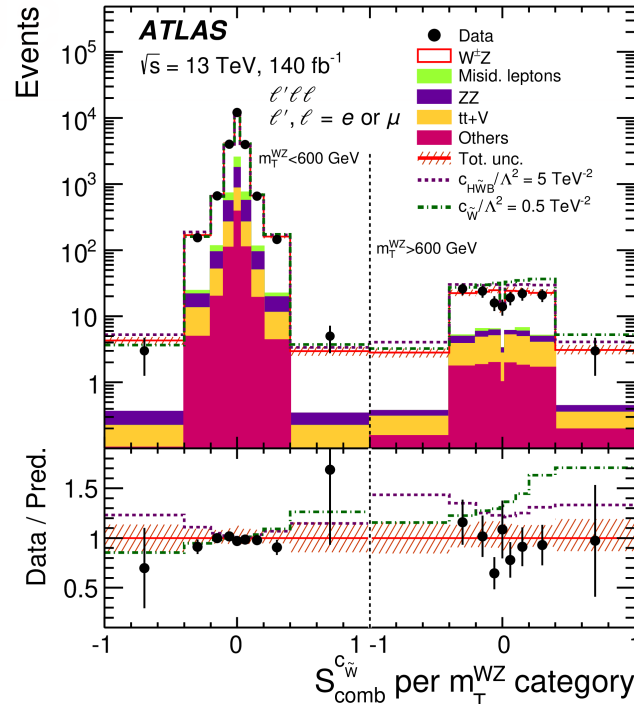
SM and Top Measurements

Many more results in **Josh Bendavid's** talk on **Wednesday**

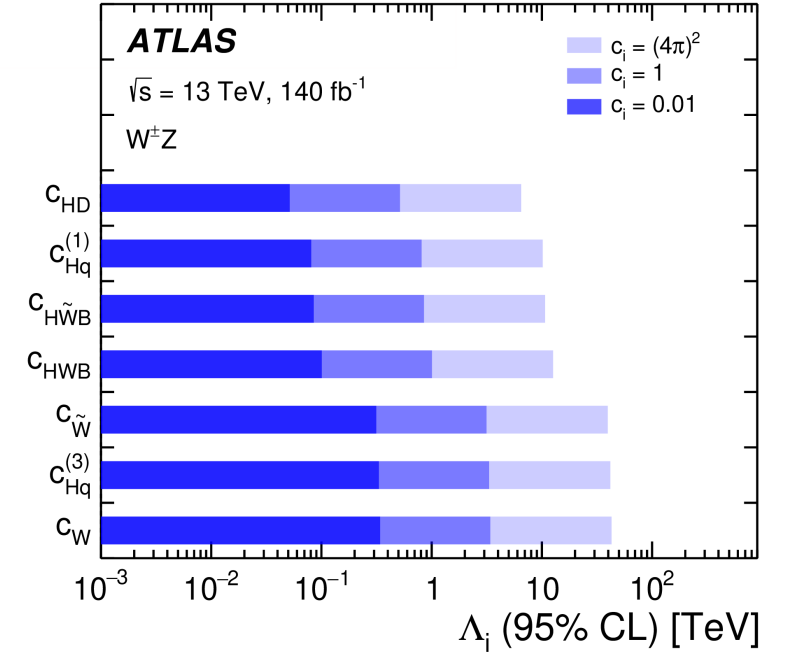
$W^\pm Z$ cross-sections



CERN-EP-2025-145 sub. JHEP



Parallel Session talk by Hannes Mildner



➤ WZ cross-section sensitive to V-boson interaction with V and H entering in the precision domain:

➤ Inclusive WZ xs measured with **4% accuracy** $\sigma_{W^\pm Z \rightarrow \ell' \nu \ell \ell}^{\text{fid.}} = 60.7 \pm 0.5 \text{ (stat.)} \pm 1.4 \text{ (exp. syst.)} \pm 1.8 \text{ (mod. syst.)} \pm 0.6 \text{ (lumi.) fb}$

➤ In agreement with SM NNLO QCD x NLO EW = $61.4 \pm 1.3 \text{ fb}$

➤ **15 observables** (including CP-odd) compared with **state-of-the-art predictions**

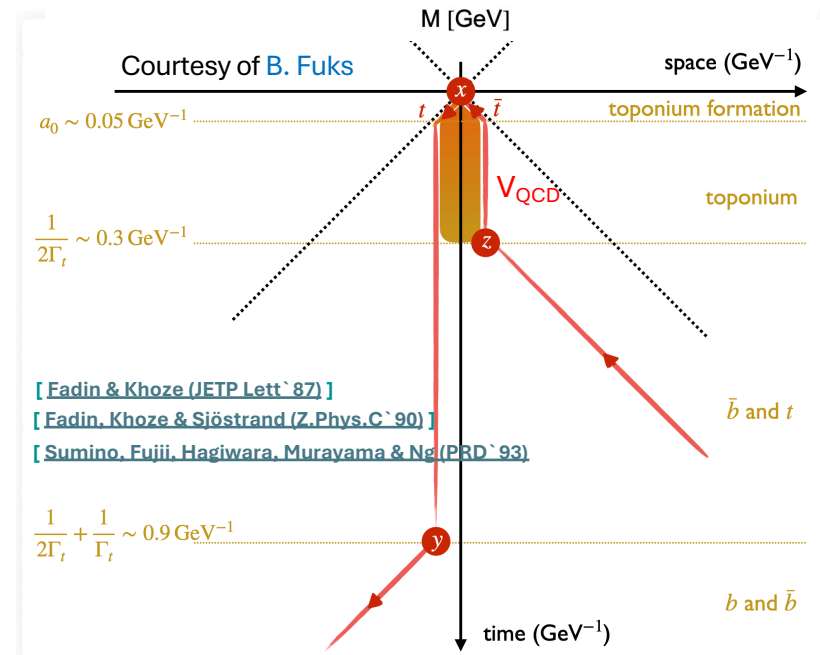
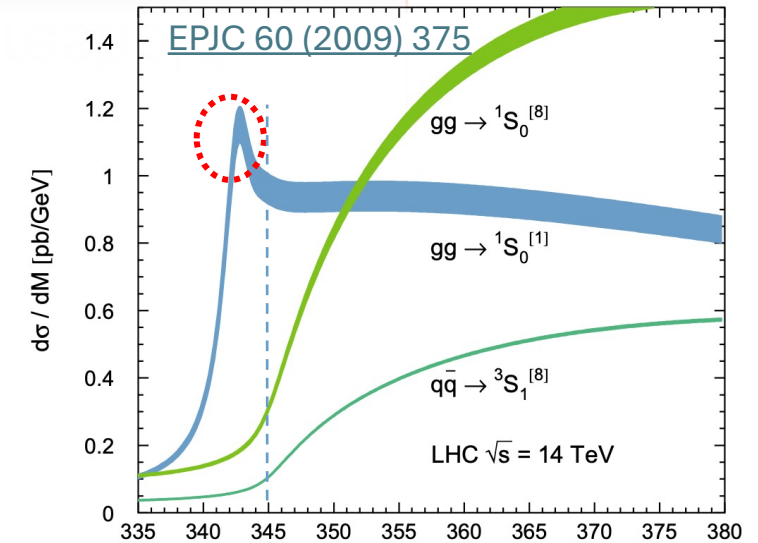
➤ Dedicated “**CP-odd**” BDT (detector level) to **constrain EFT CP-odd** operators: testing energy scales **above 10 TeV**

Observation of a $t\bar{t}$ cross-section enhancement at threshold

New



- Non-Relativistic QCD predicts the formation at threshold ($m_{t\bar{t}} \sim 2m_t \sim 345$ GeV) of **quasi-bound-state** (*Toponium*): spin-singlet - color-singlet $^1S_0^{[1]}$
- Our baseline $t\bar{t}$ modeling - PS-matched pQCD predictions reweighted to NNLO-QCD+NLO-EW – is missing these NRQCD states
- Experimentally **extremely challenging**: small effect (1% of total xs) in a $m_{t\bar{t}}$ region **much smaller** than experimental resolution
- **New modeling** of NRQCD effects via the re-weighting of the $t\bar{t}$ production MEs through the non-relativistic QCD Green's function and projection to color singlet (Fuks et al. EPJC 85 (2025) 157) used as “signal”
- CMS measurement based on **simplified model** (pseudo-scalar resonance η_t)
 - $\sigma(\eta_t) = 8.8^{+1.2}_{-1.4}$ pb $> 5\sigma$ observation [arXiv:2503.22382](https://arxiv.org/abs/2503.22382)



Observation of $t\bar{t}$ cross-section enhancement at threshold

New



- Use $t\bar{t} \rightarrow \ell\nu b \ell\nu b$ leptonic decay:

- Reconstruction of $m_{t\bar{t}} \rightarrow$ mass resolution **~20%** at threshold
- Enhance sensitivity using **lepton angular variables** sensitive to $t\bar{t}$ spin correlation (c_{hel} and c_{han}) **signal** behaves as “*pseudo-scalar*”

- Fit to the data in 9 SR with $m_{t\bar{t}}$ bins (300-500 GeV)

- Background Model: baseline pQCD
- **Signal Model: NRQCD** (from Fuks et al.)

- Bkg.-only hypothesis rejected at **7.7σ**

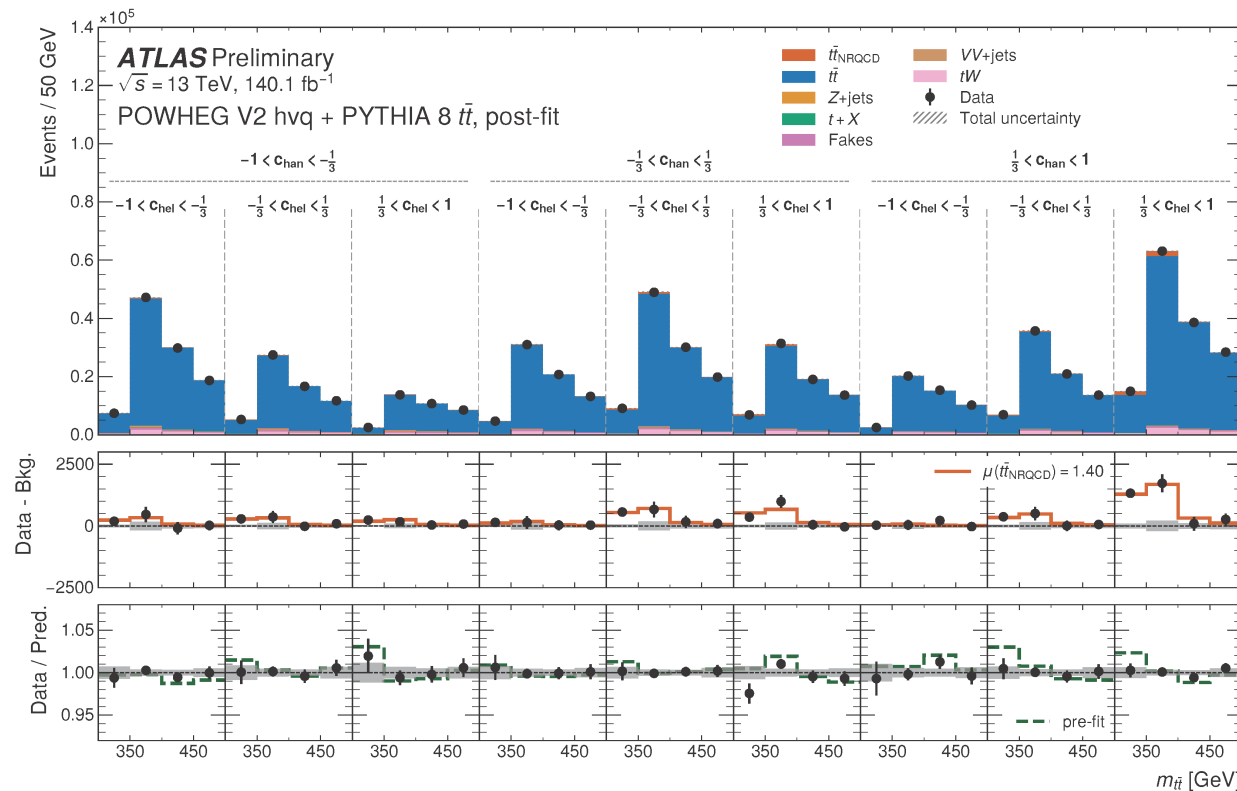
$$\sigma(t\bar{t}_{NRQCD}) = 9.0 \pm 1.3 \text{ pb (expected 6.4 pb, } 5.7\sigma)$$

ATLAS **observed** this *elusive* NRQCD phenomena

more work is needed on **theory side** (off-shell effects, matching pQCD and NRQCD, other NRQCD effects, ...) to better establish the properties of the **observed signal**

ATLAS-CONF-2025-008

Physics Briefing



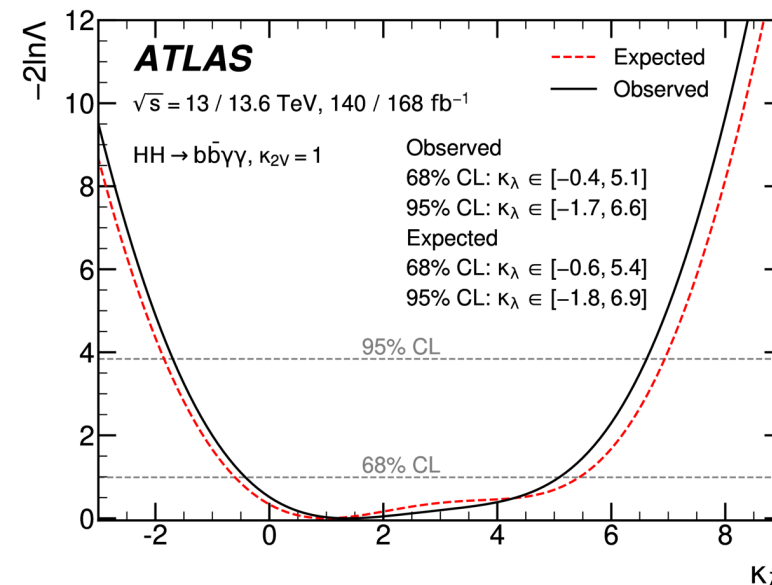
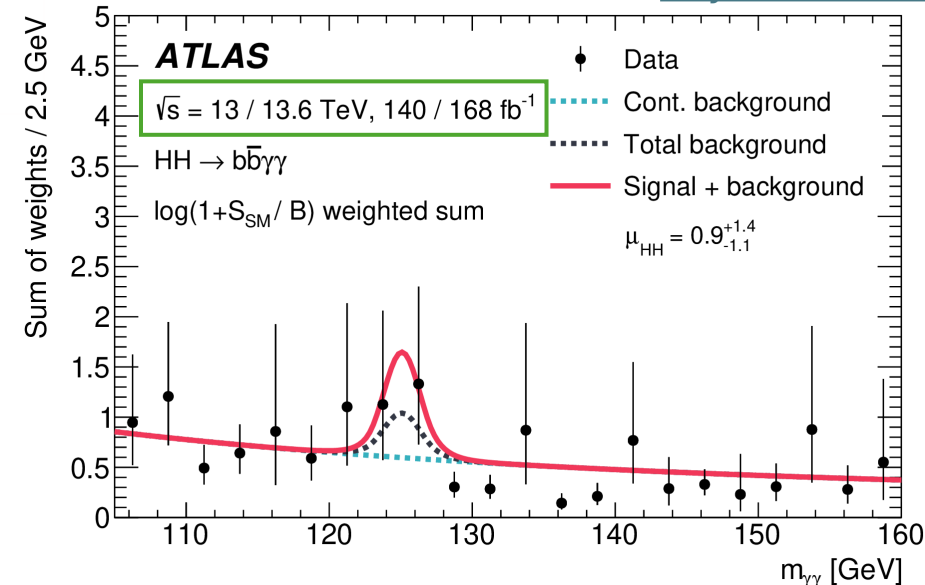
Parallel Session talk by Haifeng Li

Higgs Boson Physics

Many more results in **Emanuele Di Marco** talk on **Tuesday**

Search for $HH \rightarrow b\bar{b}\gamma\gamma$

- New measurement using reprocessed Run 2 + Run 3 (2022-2024!) → Total **308 fb⁻¹**
- **Timely calibration of physics objects** for Run 3 (up to 2024!)
- **Improvements on HH sensitivity** relative to Run 2 legacy analysis:
 - Additional data: **50%**
 - New flavor tag algorithm **GN2: 20%**
 - Analysis preoptimization: **10%**
 - $m_{b\bar{b}}$ kinematic fit : **5%**
- Signal extracted by a fit to $m_{\gamma\gamma}$ in 7 BDT categories
 - Observed $\mu(\sigma/\sigma_{SM})_{HH} = 0.9^{+1.4}_{-1.1}$
 - **0.8 σ** significance (1.0 expected)
 - **Similar sensitivity** of Legacy Run 2 combination (5 chan.)
- Higgs boson **self-coupling modifier** (coupling normalized to its SM prediction) $\kappa_\lambda \in [-1.7, 6.6]$ @95% CL



$H \rightarrow Z\gamma$



- Rare decay loop-suppressed in the SM with $BR=1.5 \times 10^{-3} \rightarrow$ Sensitive to **BSM** effects

- Intriguing **ATLAS+CMS** in Run 2: $\mu(\sigma/\sigma_{SM})=2.2 \pm 0.7$ (Obs./Exp. Significance $3.4/1.6\sigma$ - about 2σ above SM prediction) [Phys. Rev. Lett. 132 \(2024\) 021803](#)

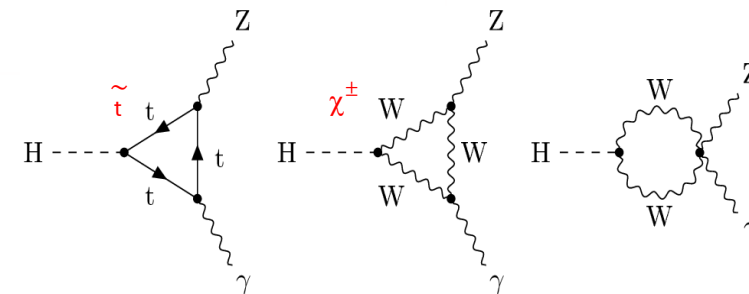
- Use **Run 3** up to **2024!**

- Fit to $m_{Z\gamma}$ **2 leptons** $Z \rightarrow \ell(\ell, \mu)$ + **isolated photon** in **13 Categories**

- **Run 3**: $\mu(\sigma/\sigma_{SM})=0.9^{+0.7}_{-0.6}$ significance 1.4σ (exp. SM 1.5σ)

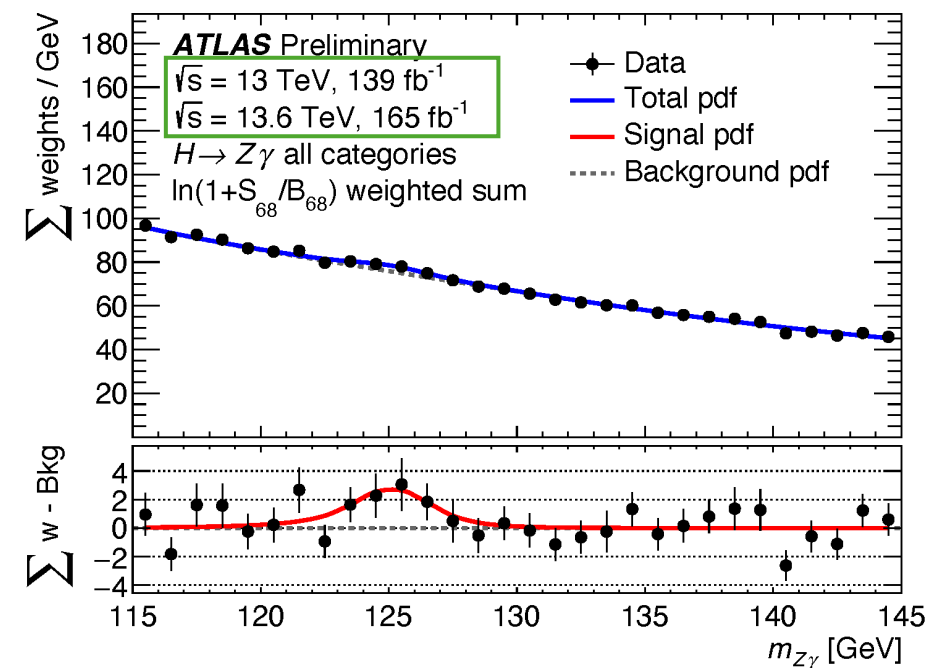
- **Combined Run2+Run3**: $\mu=1.3^{+0.6}_{-0.5}$ significance 2.5σ (exp. SM 1.9σ)

Sensitivity improved by **60%** relative to **Run 2** and by **20%** relative to **ATLAS+CMS combination**



[ATLAS-CONF-2025-007](#)

[Physics Briefing](#)



$H \rightarrow \mu\mu$

New

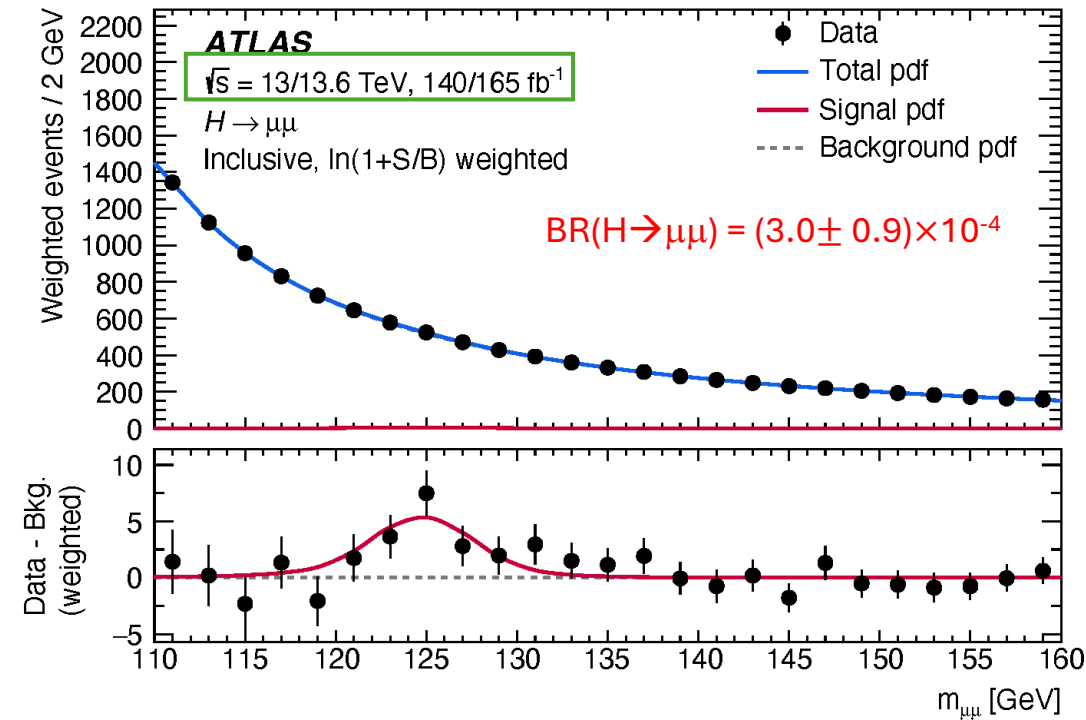
- Test **SM Yukawa sector** on **2nd Fermion generation**
- Rare decay **$BR \sim 2 \times 10^{-4}$** with huge DY background: **S/B inclusive $\sim 0.2\%$**
- **23 Categories** based on **Higgs production mode** and **kinematic** (BDT/NN) to enhance **S/B**
- Use **Run 3** up to **2024!**
- **Run 3:** $\mu(\sigma/\sigma_{SM}) = 1.6 \pm 0.6 \rightarrow 2.8 \sigma$ (Exp. 1.8σ)
- **Combined Run 2+Run 3:** $\mu(\sigma/\sigma_{SM}) = 1.4 \pm 0.4 \rightarrow 3.4 \sigma$ (2.5σ)

[CERN-EP-2025-149 sub. PRL](#)

[Physics Briefing](#)

STRONG evidence for $H \rightarrow \mu\mu$ decay in agreement with SM

Sensitivity improved by $\sim 50\%$ relative to **Run 2 analysis**



Run 2 Higgs coupling combination



ATLAS-CONF-2025-006

- Added new Run 2 measurements relative to [Nature 607 \(2022\) 52](#)

$ttH \rightarrow bb$, $VH \rightarrow bb, cc$, $H \rightarrow \tau\tau$, $H \rightarrow WW^*$

- $\mu(\sigma_{\text{obs}}/\sigma_{\text{SM}}) = 1.023^{+0.056}_{-0.053}$ (0.028(stat)±0.026(exp)±0.039(th))

- Main improvements on σ (BR fixed to SM)

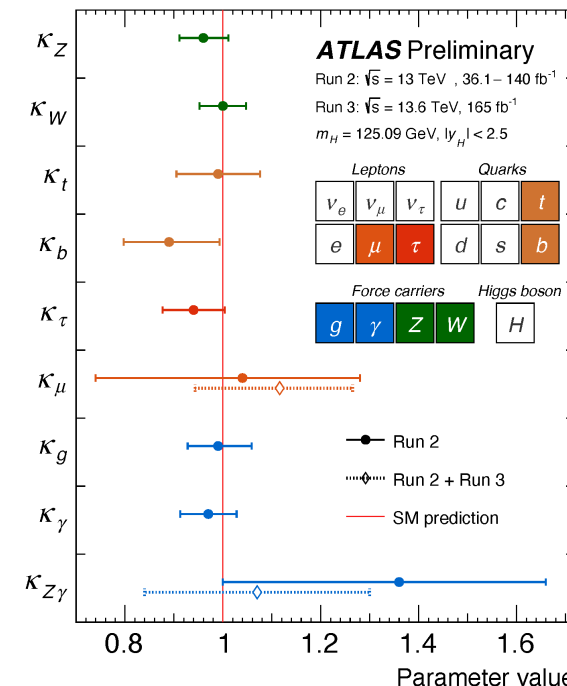
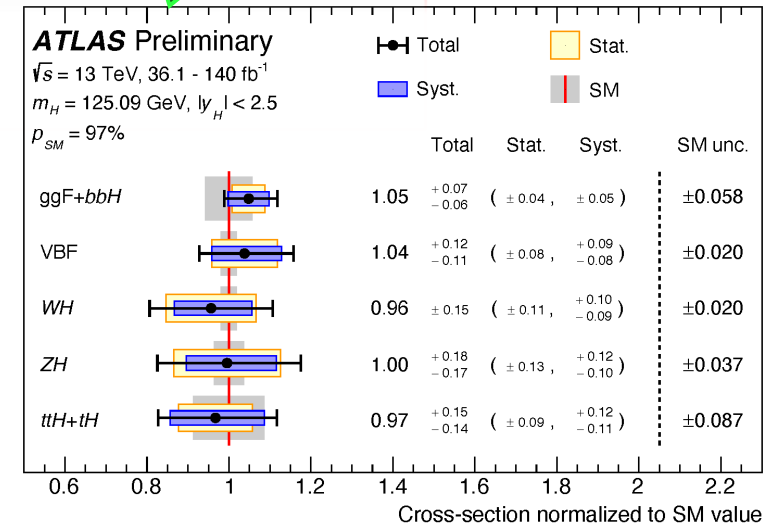
- WH/ZH reduced by **30/20%** new $V(H \rightarrow bb)$

- ttH+tH reduced by **25%** new $tt(H \rightarrow bb)$

- Test SM with coupling modifiers κ (coupling normalized to its SM prediction)

$$\sigma_i \times B(H \rightarrow f) = \frac{\sigma_i \times \Gamma_f}{\Gamma_H} = \frac{\kappa_i^2 \kappa_f^2}{\kappa_H^2} \sigma_i^{\text{SM}} \times B^{\text{SM}}(H \rightarrow f)$$

Achieved precision* ranging from **5-10%** (p_{SM} 89%)

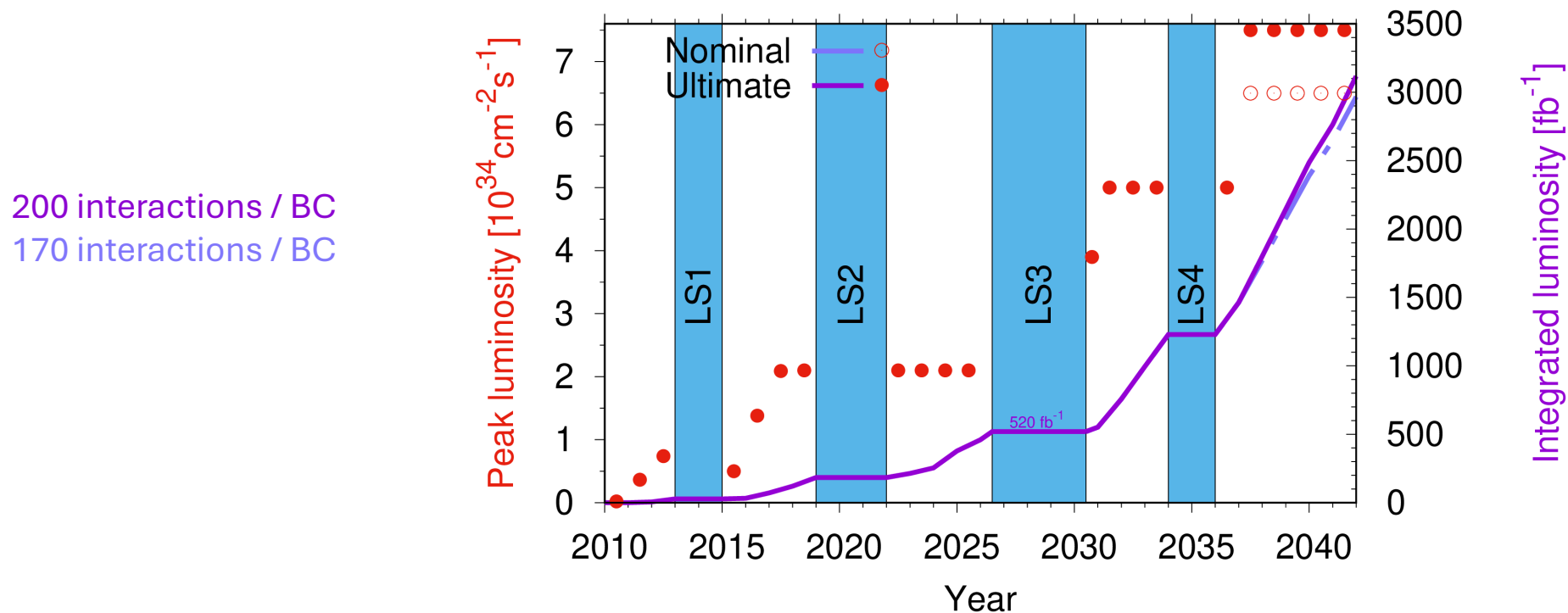


*No BSM contributions to Higgs boson width

A bright Future

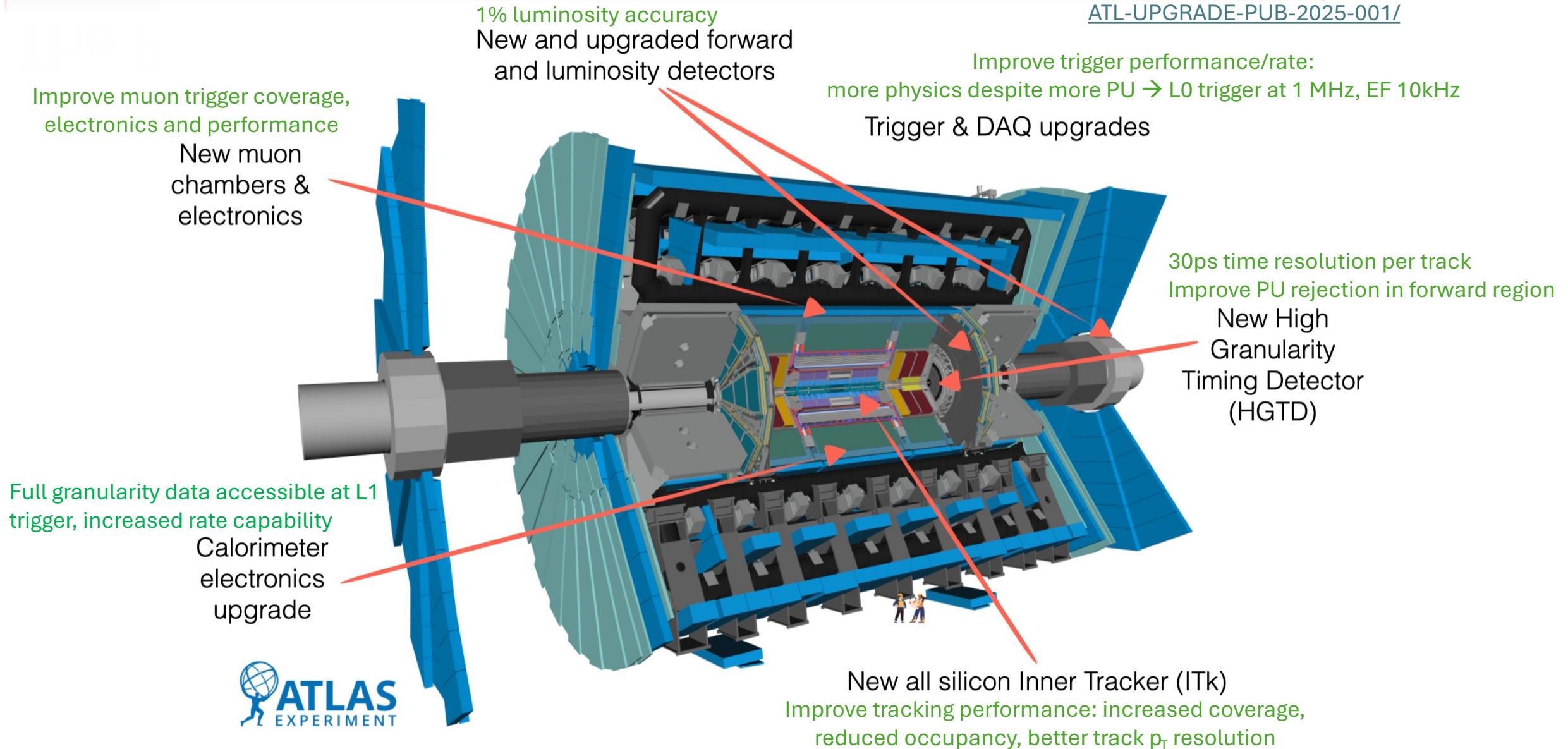
The Phase II upgrade program

- ATLAS is working on an ambitious **Phase II upgrade** aiming to keep the detector performance (and in some cases **improve** them) in the harsh high-luminosity LHC running conditions
- Designed to cope with up to **200 interactions per bunch crossing** to reach **3 ab⁻¹** *good for physics*



The Phase II upgrade program

ATL-UPGRADE-PUB-2025-001/



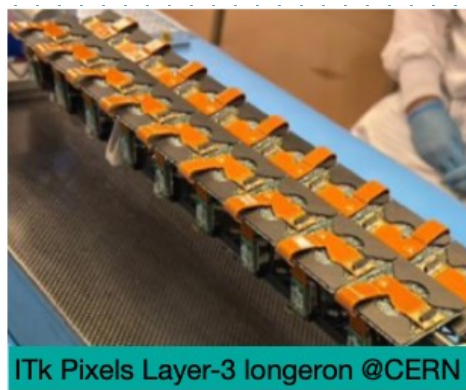
The Phase II upgrade program



ITk Pixels triplet module



ITk Pixels Layer-0 stave @SLAC



ITk Pixels Layer-3 longeron @CERN



Tile calib. system testbench



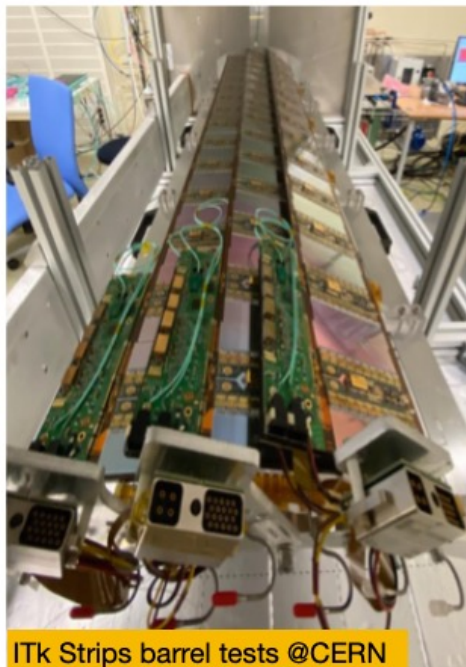
HGTD demonstrator



Trigger L0Calo prototype



ITk Strips end-cap tests @DESY



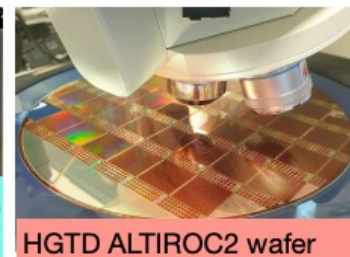
ITk Strips barrel tests @CERN



ITk Strips module assembly @USBC



Tile FENICS card



HGTD ALTIROC2 wafer



LAr FEC system



Muon pilot sector installation

The Phase II upgrade program



New and upgraded forward and luminosity detectors

New muon

Trigger & DAQ upgrades

Several technical issues addressed

All projects making progresses and entering the **pre-production/production** phase

The schedule is tight, but we are on track to make it

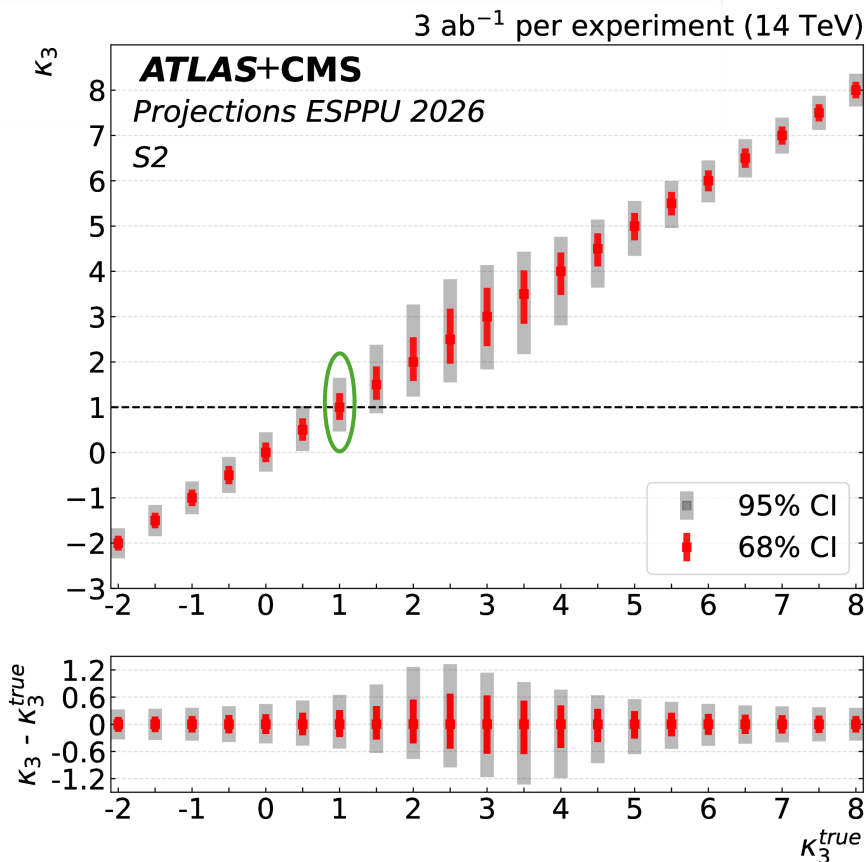
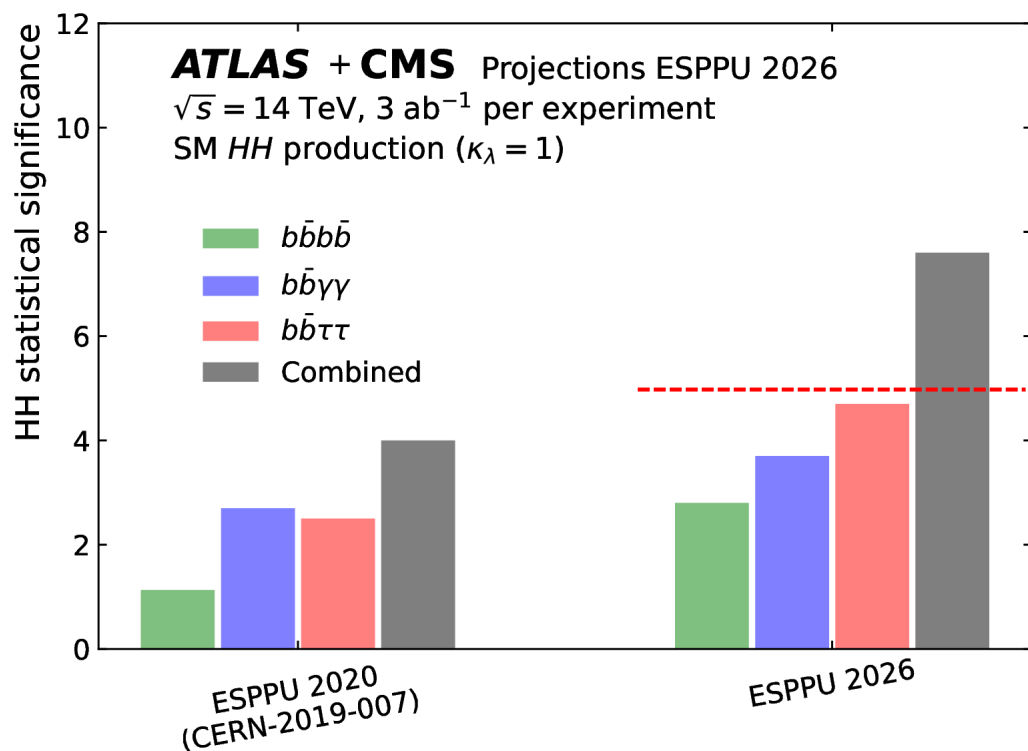
(more details in backup slides)



New all silicon Inner Tracker (ITk)

Why we are doing that ...

[ATL-PHYS-PUB-2025-018/](#)



Among the **main physics goals** of the **HL-LHC program** one is the **Observation** of the **HH process** and measurement of the **Higgs boson self-coupling** with a **30% accuracy** → we need **3ab^{-1} good for physics** to achieve them

- The ATLAS experiment continue to provide outstanding contributions to elementary particle physics:
 - Precision measurements as test of the foundations of the SM: steady improvements brought by the ingenuity of our collaborators investing resources in innovative analysis techniques, including the physics objects identification and calibration
 - A broad BSM search program: deeply explore the well-motivated models (SUSY, dark matter and dark sector, quantum black holes), but also look for the unexpected no stones unturned (model independent signals, LLP and AD, etc.)
 - Already profiting of the wonderful Run 3 data set with timely release of high-profile results
 - A bright future is in front of us thanks to the HL-LHC and Phase II upgrade projects ...

Backup

Addressing fundamental questions ...

Fundamental questions in particle physics

Is the BEH mechanism the (only) responsible of the EW symmetry breaking?

Are the Higgs interactions as described by the SM and the only origin of all elementary particle masses?

Is the Higgs boson an elementary particle, and the only elementary scalar?

What is the origin of the matter-anti-matter asymmetry (1st order phase transition + CP violation needed)

Cosmological implications of the SM (Higgs potential)

What is the origin of dark matter?

Is QCD correct and what are the properties of the Quark-Gluon plasma?

ATLAS physics program

Measurement a wide range of processes at energy scales up to few TeV involving jets, W, Z bosons, Top quark

Precisions Tests of the EW sector and measurement of “input” observables: m_W , $\sin^2(\theta_W)$, α_s , m_{top} , m_H

Measurement of the Higgs boson properties and interactions wit other SM particles (including self-interactions)

Search for BSM phenomena in model driven and model independent approaches

Study of flavor physics and CP violation in B-sector but also in the Higgs and EW sector

Study of the quark gluon plasma in heavy ion collisions

Search for direct production of dark matter particles

This talk ...

QCD	Observation of double parton scattering in same-sign W boson pair production
EW	Measurements of WZ production
EW	Modeling of longitudinal-longitudinal polarization in ZZ
Top	Measurement of $t\tau\gamma$
Top	Differential cross sections in $WbWb$
Top	Top pole mass in $t\bar{t}+1\text{jet}$
Top	Observation of cross section enhancement at $t\bar{t}$ threshold
Higgs	Higgs couplings combination
Higgs	CP in Higgs VBF production with $H\rightarrow\tau\tau$
Higgs	Evidence for $H\rightarrow\mu\mu$
Higgs	Search for $H\rightarrow Z\gamma$
Higgs	Search for di-Higgs decaying to $b\bar{b}\gamma\gamma$

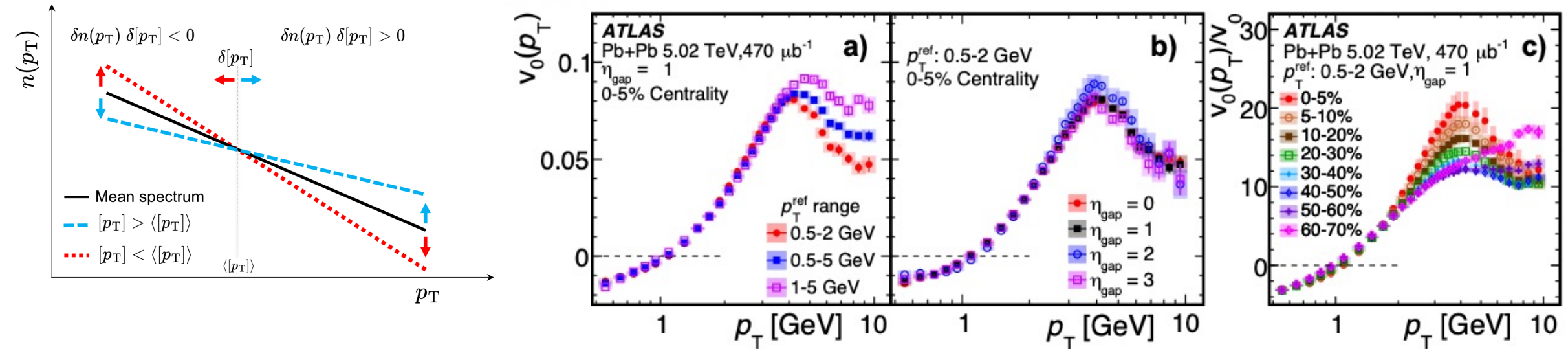
Search	Search for resonant $SH\rightarrow b\bar{b}\gamma\gamma$
Search	Search for Higgs boson decays to scalars decaying to $4b$ or $6b$
Search	Search for DM in association with dark Higgs in $3b$ and $4b$ final states
Search	Search for single production of vector-like quarks decaying into $W(\ell\nu)b$
Search	Search for resonant leptoquark production in lepton+jet signatures
Search	Search for squarks and gluinos in events with taus, jets, and MET
Performance	Identification of boosted Higgs boson decays to collimated tau pairs
Performance	Statistical uncertainties in jet eta intercalibration
Performance	Study of deep-learning flavor tagging with integrated gradients

21 NEW results for EPS

102 papers submitted to journals in the last year

Radial flow in Pb+Pb

[arXiv:2503.24125 sub. PRL](https://arxiv.org/abs/2503.24125)

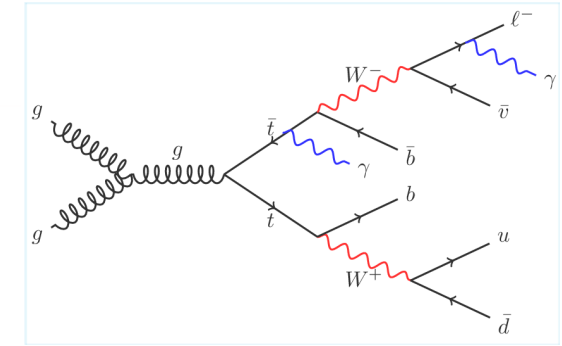


- At LHC Pb+Pb collision produce quark gluon plasma: a state of matter where quarks and gluons are deconfined with a fluid-like behaviour
- Measurement aiming to study collective effects in the isotropic QGP expansion “radial flow”: new observable $v_0(p_T)$ study the correlation between the fraction of particles in a given p_T range and the average p_T in each event
- Collective behavior proven by three key signatures:
 - Radial flow factorization in (reference) p_T
 - No dependency on rapidity gap (long range)
 - Centrality independent shape (at low p_T)

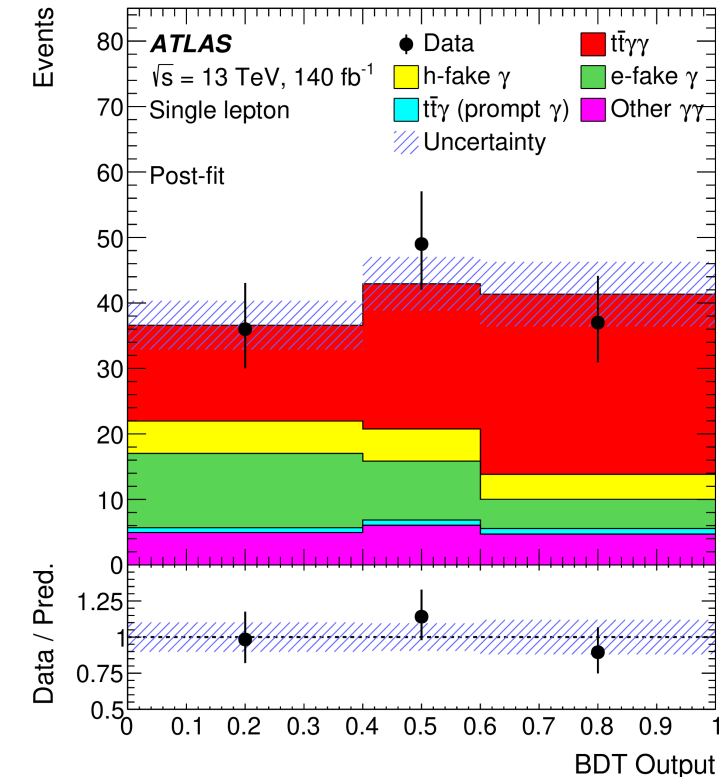
Observation of $t\bar{t}\gamma\gamma$ process



- Study production of top anti-top in association with two prompt γ
- Very rare process: expected cross-section $\sim$ few fb
- Select events with 1 leptons, 2 isolated photons and at least 4 jets of which at least one b-tagged
- Use BDT based on photon and other event variables (19 in total) to enhance backgrounds rejection (mainly fake photons in $t\bar{t}$ events)
- Measured fiducial cross-section $\sigma(t\bar{t}\gamma\gamma) = (2.42^{+0.58}_{-0.53})$ fb
- Prediction from LO MC $1.5^{+0.4}_{-0.5}$ fb x estimated k-factor ~ 1.7
- Observed significance 5.2σ



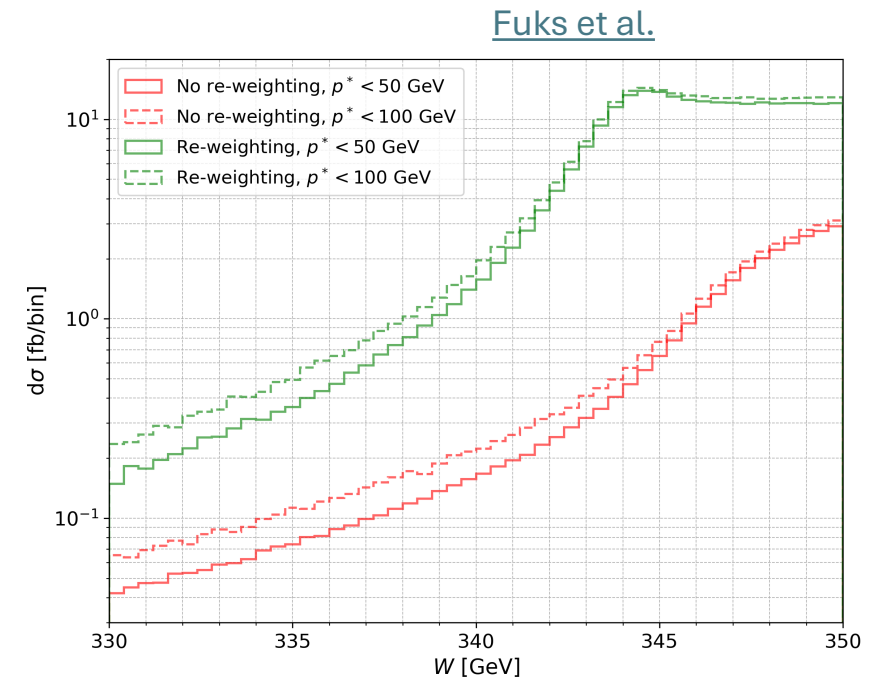
[arXiv:2506.05018](https://arxiv.org/abs/2506.05018) sub. to PLB



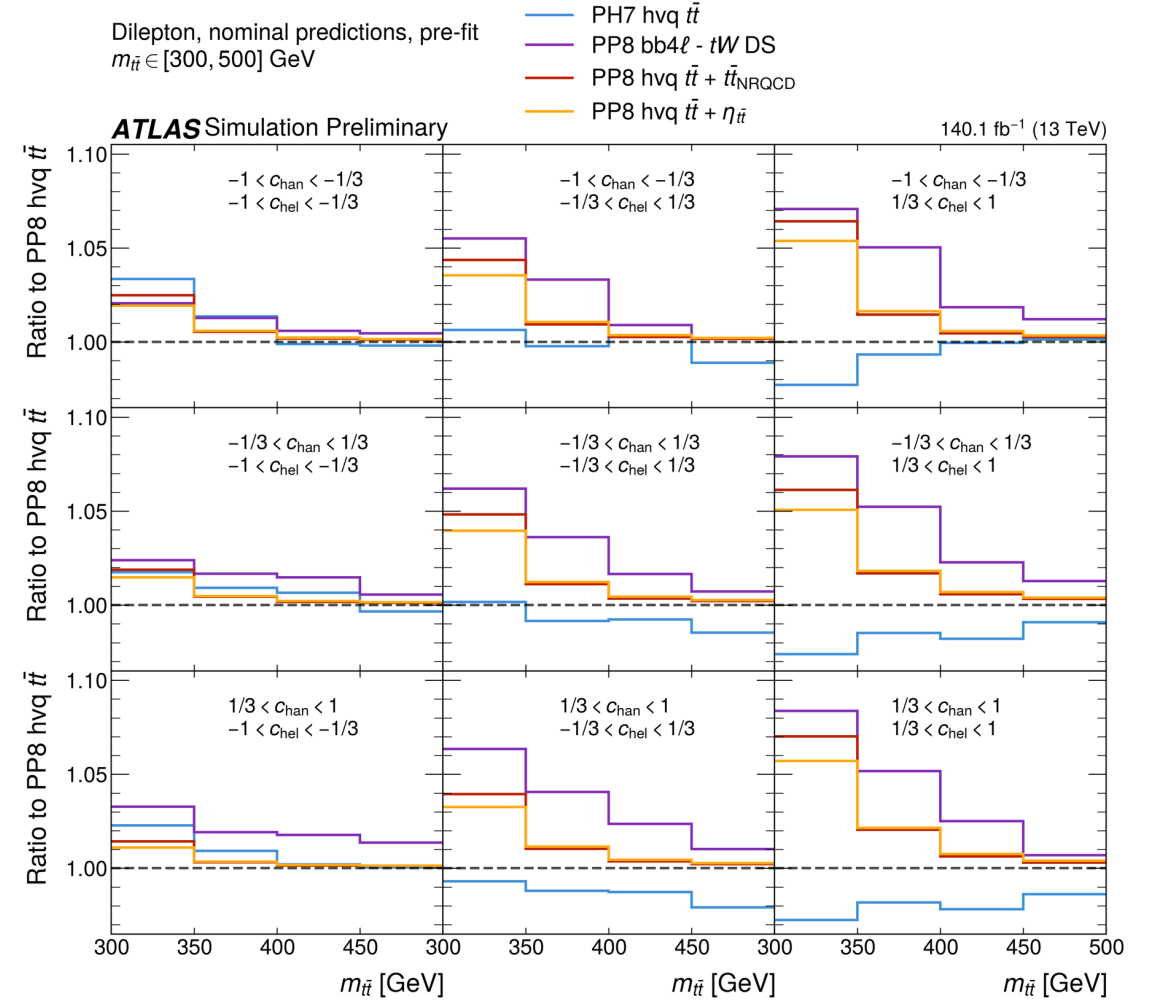
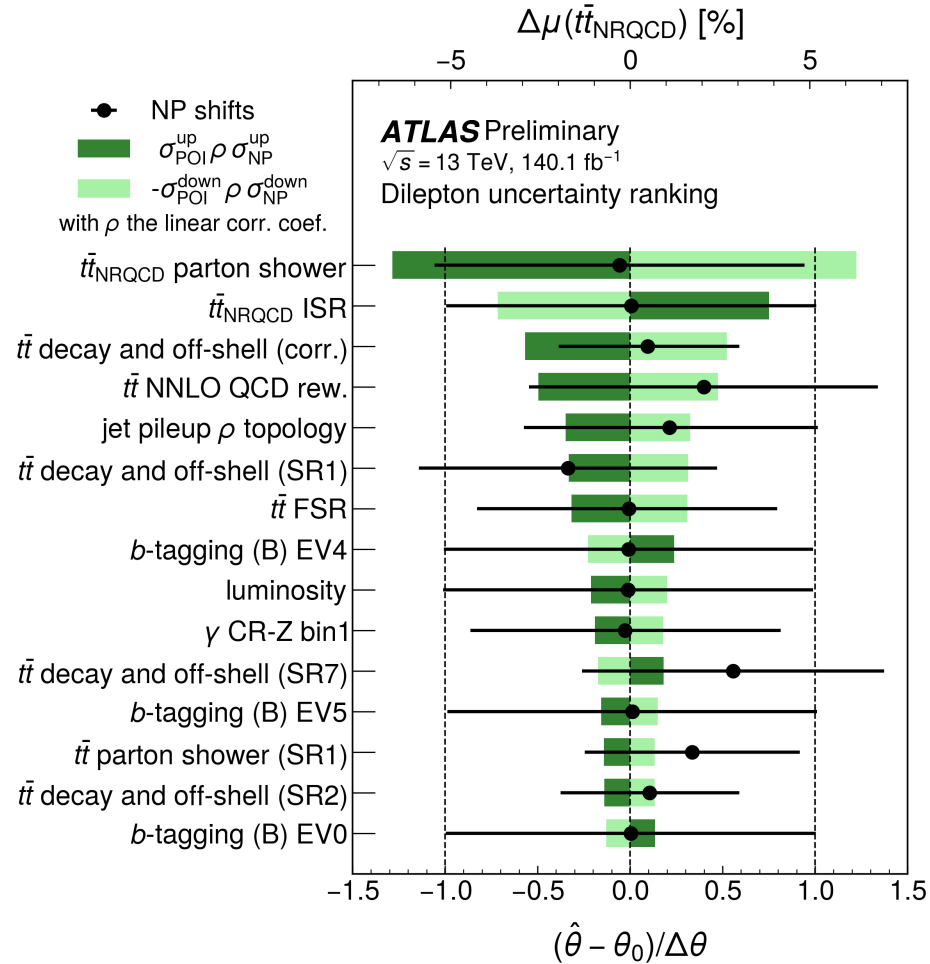
Observation of $t\bar{t}$ cross-section enhancement at threshold



- Top-quark pair production at threshold ($m_{t\bar{t}} \sim 2m_t \sim 350$ GeV):
 - of **colour-singlet, S-wave, pseudo-scalar quasi-bound-states** (*Toponia*) with masses just below the production threshold. Given the small top lifetime these states do not form a BW resonances but rather a cross-section enhancement
- This study uses an improved MC modeling of **NR-QCD effects** described via the re-weighting of the $t\bar{t}$ production MEs through the **non-relativistic QCD Green's function** ([Fuks et al.](#))

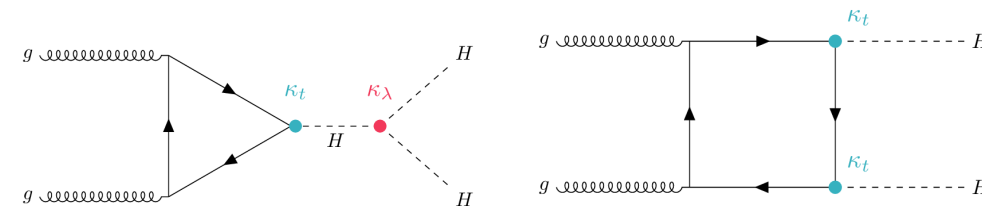
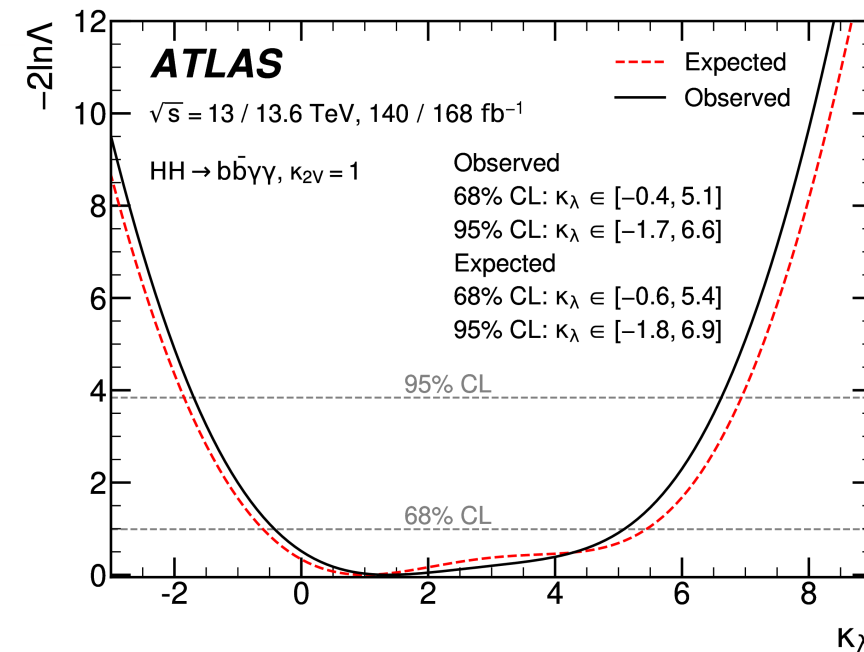
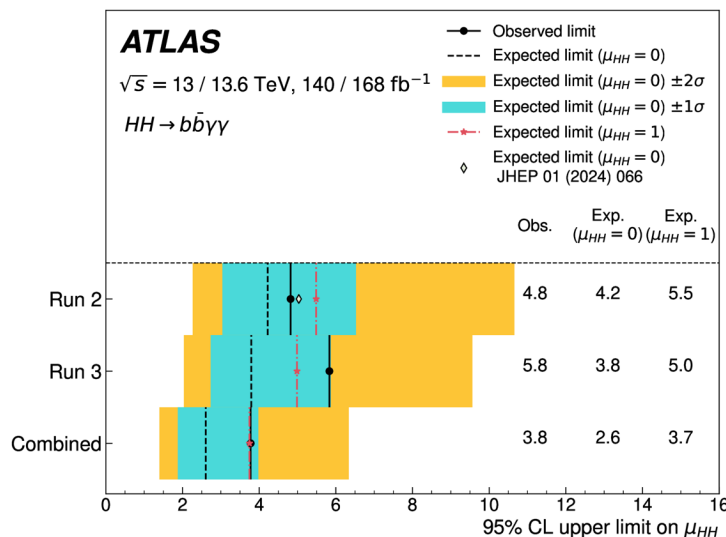
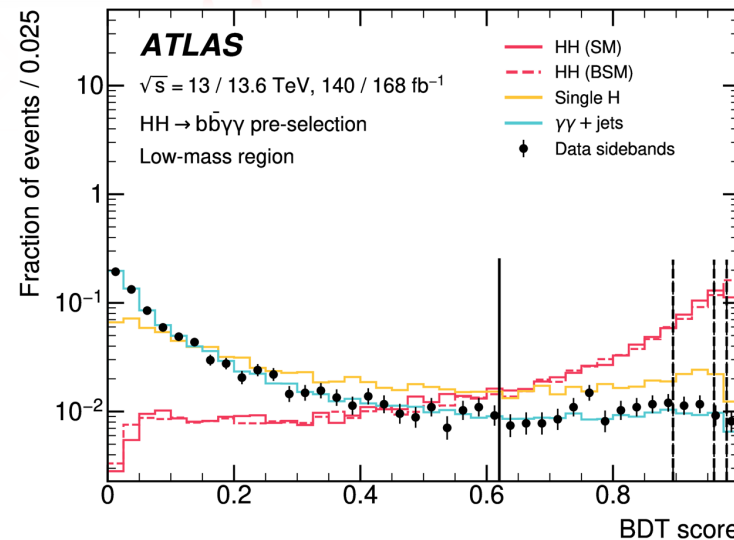
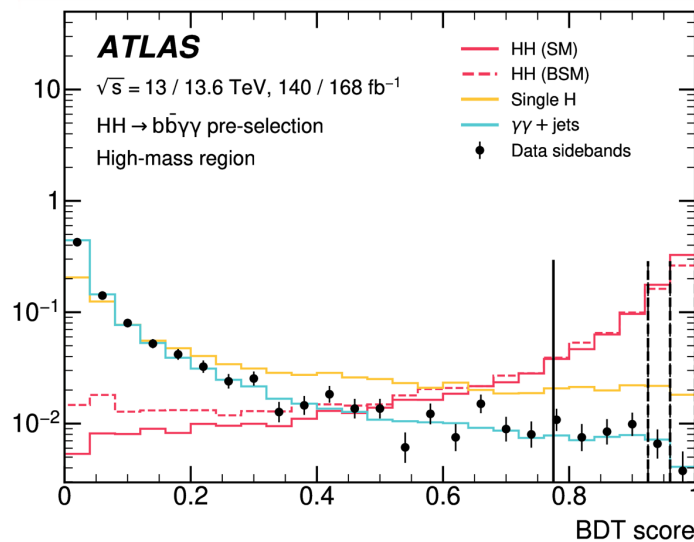


Observation of $t\bar{t}$ cross-section enhancement at threshold



Search for $HH \rightarrow b\bar{b}\gamma\gamma$

Fraction of events / 0.04

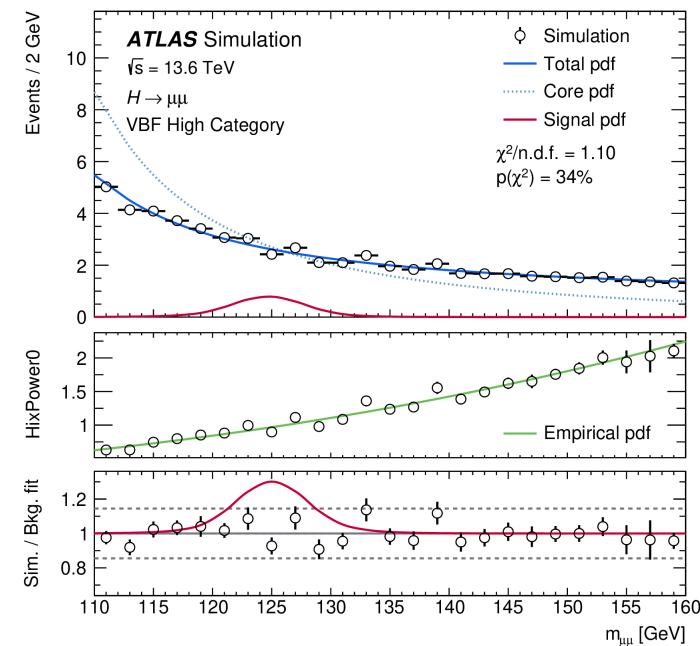


➤ Higgs boson self coupling modifier $\kappa_\lambda \in [-1.7, 6.6]$ @95% CL (assuming all other couplings are SM like)

$$H \rightarrow \mu\mu$$

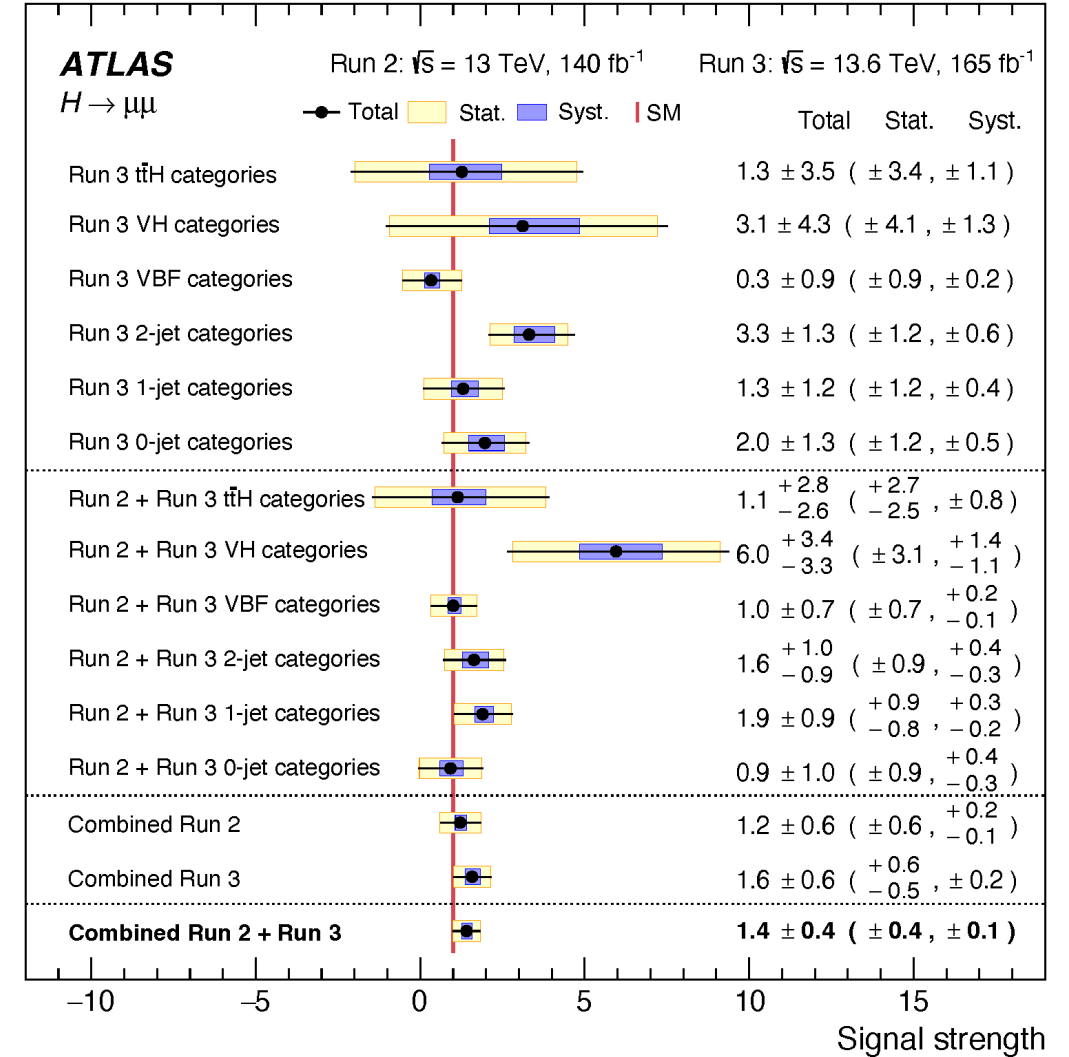
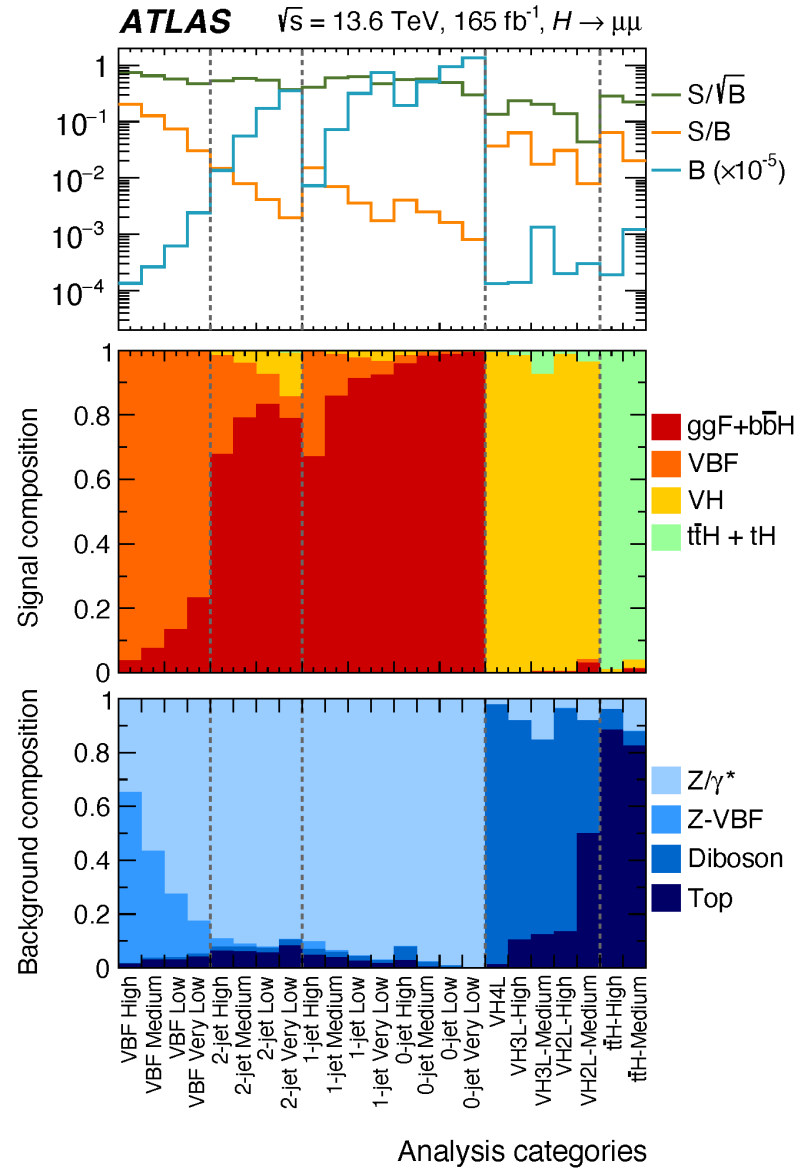


- Signal extracted via an **analytical fit** to $m_{\mu\mu}$ **spectra**
- Bkg. Modeling based on **Core** x **Empirical** analytic fit or spectra
 - **Core** DY same for all categories (no free DOF)
 - **Empirical**: flexible enough to adapt to mass distortions caused by selection, between 1 and 4 shape DOF depending on category (plus normalization)
- Required **good quality fit** on: MC, data SB, MC systematic variations
- Uncertainties implemented via **Spurious Signals** (signal yields obtained from a fit to the background-only MC spectra) → Kept below **20% stat. uncertainty**



Uncertainty source	$\Delta\mu$	
Statistical uncertainty	-0.40	+0.41
Systematic uncertainty	-0.12	+0.15
Spurious signal	-0.09	+0.09
Theory	-0.07	+0.10
Luminosity	-0.02	+0.04
Muon	-0.02	+0.04
Jets, flavor tagging	-0.01	+0.01
Other	-0.02	+0.03
Total	-0.42	+0.43

H → μμ



$$H \rightarrow Z\gamma$$



➤ Important to **timely check** with **Run 3** data, need **2022-2024** sample **$\sim 165\text{fb}^{-1}$**

➤ Select 2 isolated leptons compatible with $Z \rightarrow \ell\ell$ (e, μ) (10 GeV mass window) and isolated photon

➤ Relative to Run 2 analysis:

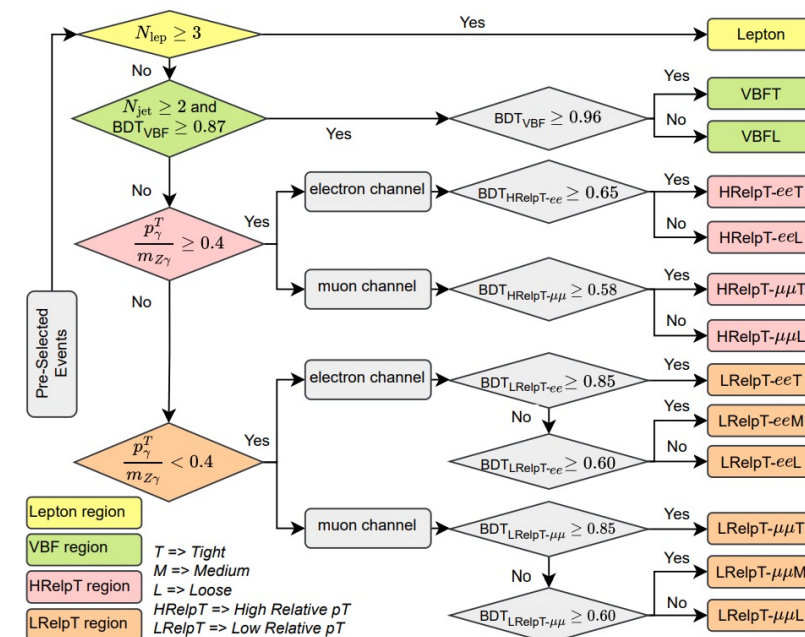
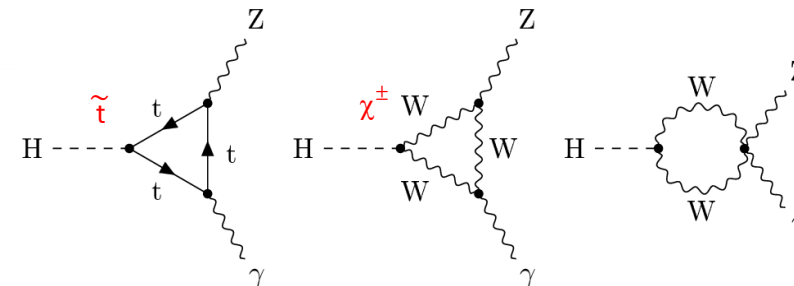
➤ Improved mass resolution including FSR

➤ Improved categorization 13 categories 1 3L (target VH, ttH), 2 VBF categories, 5 BDT-based categories x 2 lepton flavors

➤ Signal extracted by **analytical fit** to the $m_{\ell\ell\gamma}$ spectra (13 cat.)

➤ Background modeling functions and systematics based on Spurious Signal test (S+B fit on bkg.-Only templates) $\rightarrow$ mainly of statistical nature, kept small relative to stat. unc.

➤ Other systematics includes signal modeling and main exp. uncertainties



$$H \rightarrow Z\gamma$$



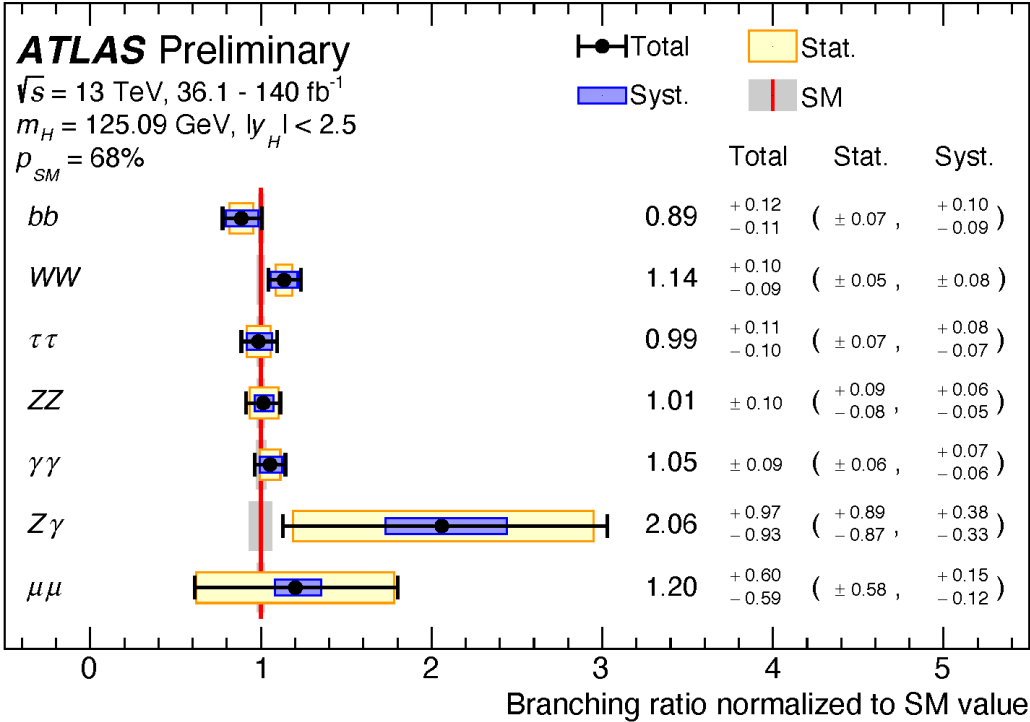
Category	Data	S	B	$S/B [10^{-2}]$	$S/\sqrt{S+B}$
Lepton	168	2.6	173	1.5	0.20
VBFT	5	2.8	3	93.1	1.16
VBFL	67	5.1	68	7.4	0.59
HRelpT- ee T	19	2.2	20	11.0	0.46
HRelpT- ee L	139	5.2	135	3.9	0.44
HRelpT- $\mu\mu$ T	58	4.4	50	8.7	0.59
HRelpT- $\mu\mu$ L	154	4.3	142	3.1	0.36
LRelpT- ee T	607	16.2	593	2.7	0.65
LRelpT- ee M	6 191	51.1	6 161	0.8	0.65
LRelpT- ee L	29 463	42.4	29 509	0.1	0.25
LRelpT- $\mu\mu$ T	241	8.9	233	3.8	0.57
LRelpT- $\mu\mu$ M	6 093	61.1	6 032	1.0	0.78
LRelpT- $\mu\mu$ L	38 378	64.8	38 635	0.2	0.33
Inclusive	81 583	271.1	81 754	0.3	0.95

Uncertainty sources	$\Delta\mu$	
	Expected	Observed
Statistical uncertainty	0.70	0.64
Systematic uncertainty	0.17	0.17
Spurious signal	0.11	0.10
QCD scale, PDF+ α_S , parton shower	0.09	0.06
Branching ratio	0.08	0.05
Luminosity	0.05	0.03
Photon efficiency	0.05	0.03
Jet	0.04	0.07
Electron and photon energy scale and resolution	0.02	0.02
Electron efficiency	0.02	0.02
Muon	0.02	< 0.01
Trigger	0.02	< 0.01
Total	0.70	0.67

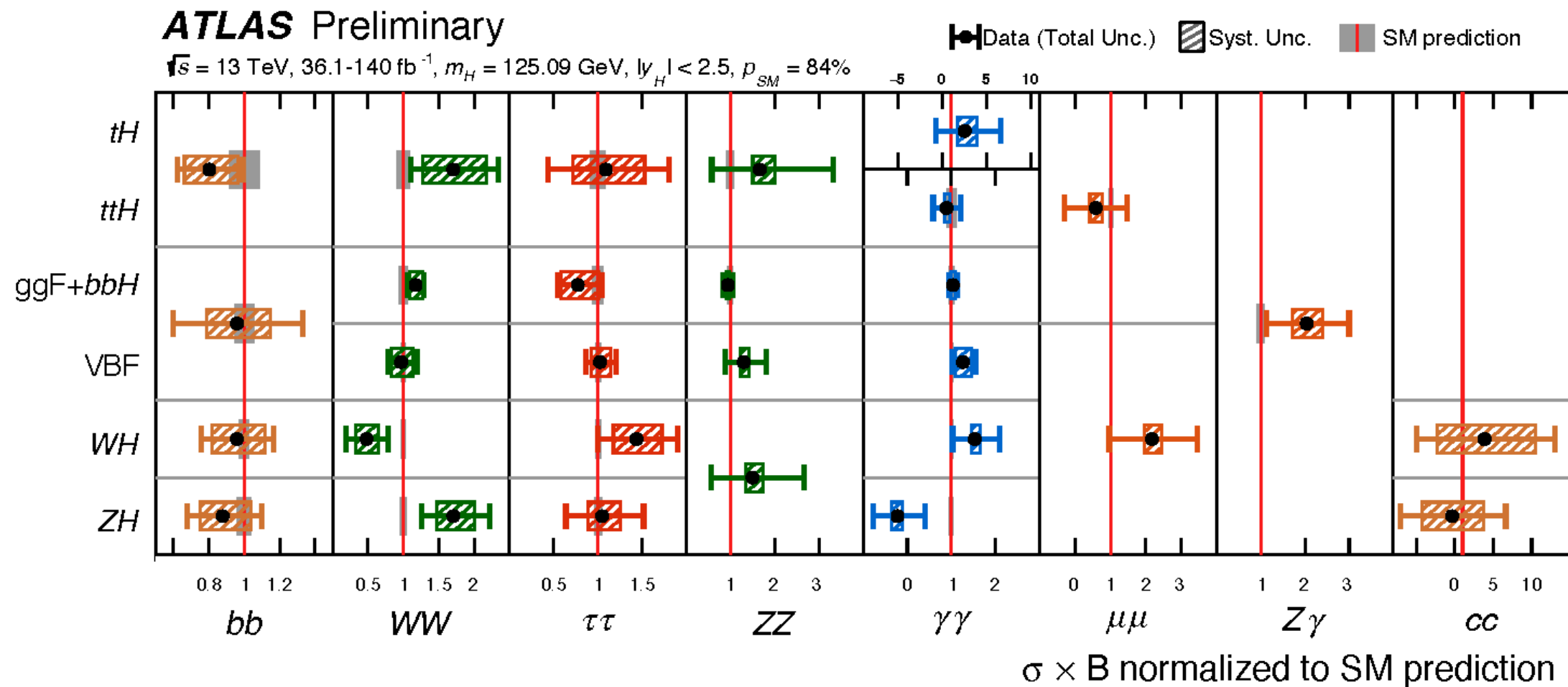
Run 2 Higgs coupling combination



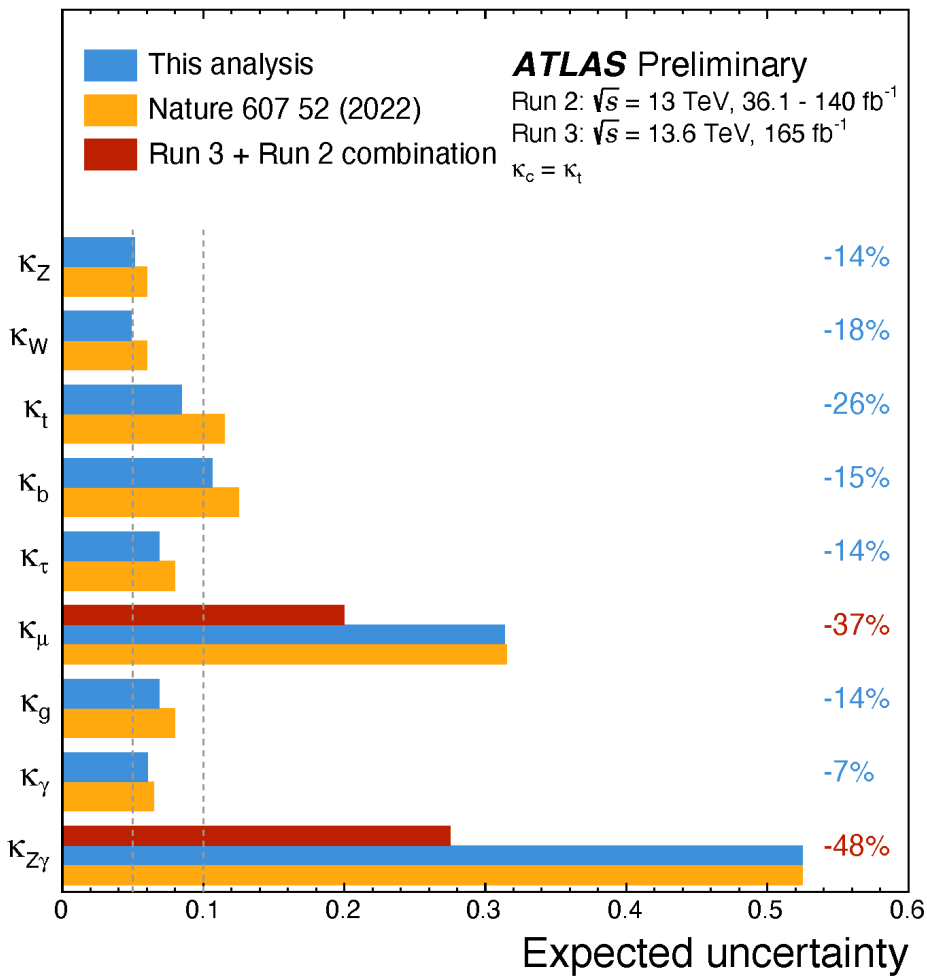
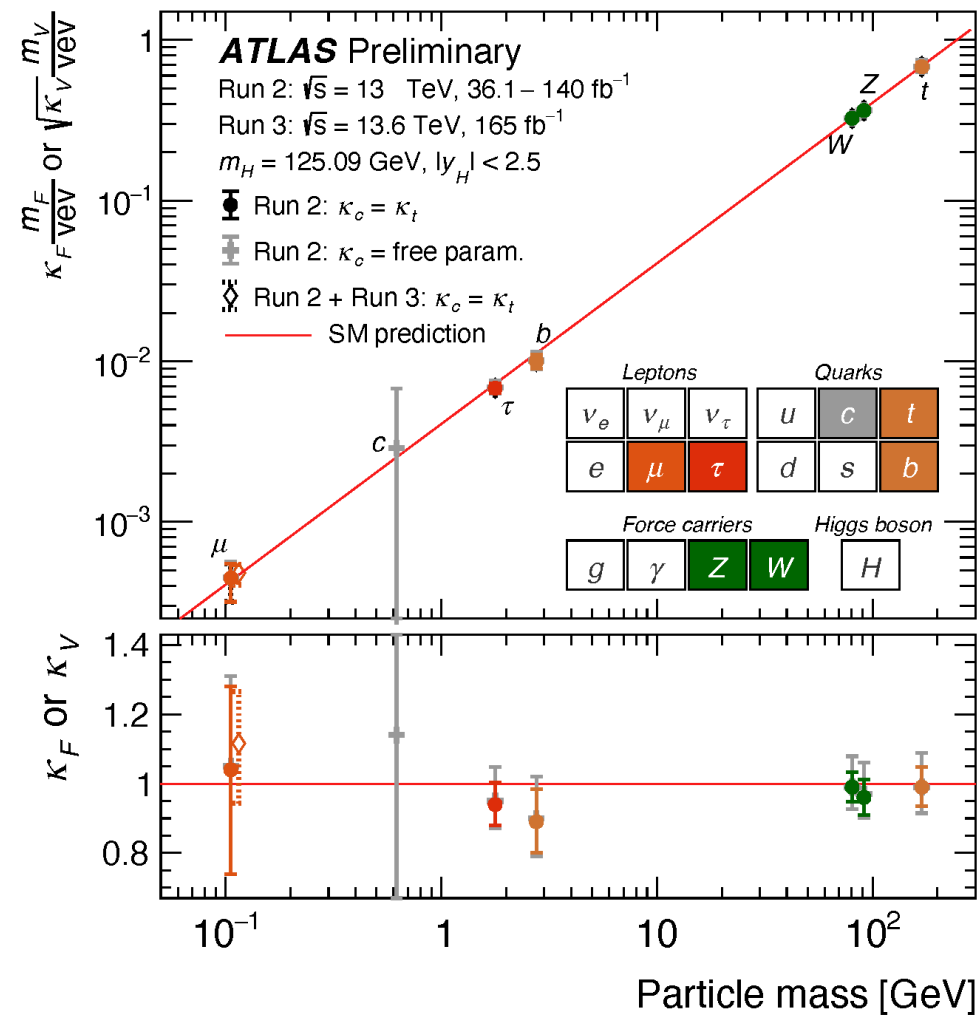
Analysis	Prod. modes	$\mathcal{L}$ (fb ⁻¹)	Reference	STXS stage	Improvements relative to Ref. [5]
$H \rightarrow \gamma\gamma$	All	140	[13]	1.2	-
$H \rightarrow ZZ^* \rightarrow 4\ell$	All	140	[14]	1.2	-
$H \rightarrow \tau\tau$	All	140	[15]	1.2	Reanalysis
$H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$	ggF,VBF	140	[16]	1.2	Reanalysis
$H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$	VH	140	[17]	1.2	Full Run 2
$H \rightarrow bb$	VBF	126	[7]	1.2	-
$H \rightarrow bb, cc$	VH	140	[18]	1.2	Reanalysis
$H \rightarrow \text{multileptons}$	ttH	36.1	[6]	1.2	-
$H \rightarrow bb$	ttH	140	[19]	1.2	Reanalysis
$H \rightarrow \tau\tau$	VH	140	[20]	0	New analysis
$H \rightarrow Z\gamma$	All	140	[21]	0	-
$H \rightarrow \mu\mu$	All	140	[22]	0	-



Run 2 Higgs coupling combination



Run 2 Higgs coupling combination



Production	Loops	Main interference	Effective modifier	Resolved modifier
$\sigma(\text{ggF})$	✓	t - b	κ_g^2	$1.040 \kappa_t^2 + 0.002 \kappa_b^2 - 0.038 \kappa_t \kappa_b - 0.005 \kappa_t \kappa_c$
$\sigma(\text{VBF})$	-	-	-	$0.733 \kappa_W^2 + 0.267 \kappa_Z^2$
$\sigma(qq/qg \rightarrow ZH)$	-	-	-	κ_Z^2
$\sigma(gg \rightarrow ZH)$	✓	t - Z	-	$2.456 \kappa_Z^2 + 0.456 \kappa_t^2 - 1.903 \kappa_Z \kappa_t$ $- 0.011 \kappa_Z \kappa_b + 0.003 \kappa_t \kappa_b$
$\sigma(WH)$	-	-	-	κ_W^2
$\sigma(ttH)$	-	-	-	κ_t^2
$\sigma(tHW)$	-	t - W	-	$2.909 \kappa_t^2 + 2.310 \kappa_W^2 - 4.220 \kappa_t \kappa_W$
$\sigma(tHq)$	-	t - W	-	$2.633 \kappa_t^2 + 3.578 \kappa_W^2 - 5.211 \kappa_t \kappa_W$
$\sigma(b\bar{b}H)$	-	-	-	κ_b^2
Partial decay width				
Γ^{bb}	-	-	-	κ_b^2
Γ^{WW}	-	-	-	κ_W^2
Γ^{gg}	✓	t - b	κ_g^2	$1.111 \kappa_t^2 + 0.012 \kappa_b^2 - 0.1 \kappa_t \kappa_b$
$\Gamma^{\tau\tau}$	-	-	-	κ_τ^2
Γ^{ZZ}	-	-	-	κ_Z^2
Γ^{cc}	-	-	-	κ_c^2
$\Gamma^{\gamma\gamma}$	✓	t - W	κ_γ^2	$1.589 \kappa_W^2 + 0.072 \kappa_t^2 - 0.674 \kappa_W \kappa_t$ $+ 0.009 \kappa_W \kappa_\tau + 0.008 \kappa_W \kappa_b$ $- 0.002 \kappa_t \kappa_b - 0.002 \kappa_t \kappa_\tau$
$\Gamma^{Z\gamma}$	✓	t - W	$\kappa_{Z\gamma}^2$	$1.118 \kappa_W^2 - 0.125 \kappa_W \kappa_t + 0.004 \kappa_t^2 + 0.003 \kappa_W \kappa_b$
Γ^{ss}	-	-	-	$\kappa_s^2 (= \kappa_b^2)$
$\Gamma^{\mu\mu}$	-	-	-	κ_μ^2
Total width				
Γ_H	✓	-	κ_H^2	$0.581 \kappa_b^2 + 0.215 \kappa_W^2 + 0.082 \kappa_g^2 + 0.063 \kappa_\tau^2$ $+ 0.026 \kappa_Z^2 + 0.029 \kappa_c^2 + 0.0023 \kappa_\gamma^2$ $+ 0.0015 \kappa_{(Z\gamma)}^2 + 0.0004 \kappa_s^2 + 0.00022 \kappa_\mu^2$

The Phase II upgrade program

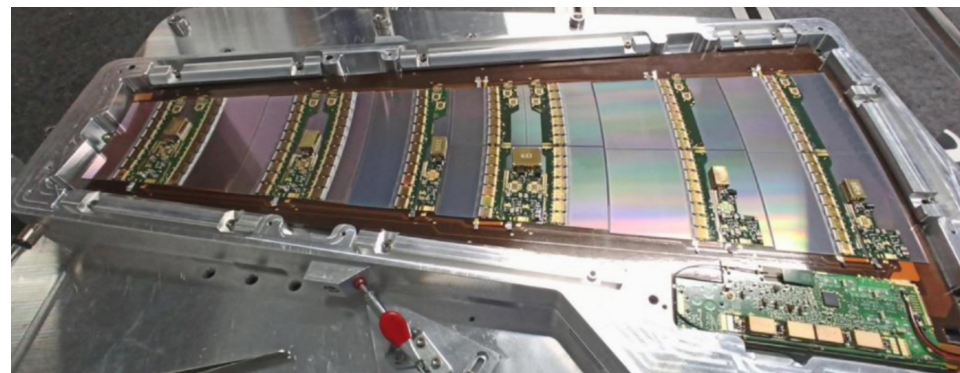
- **ITk Pixel**
 - **Pre-production and production underway**, incl. sensors, ASICs, on-detector local supports
 - Solving (small) residual technical issue
- **ITk Strips**
 - **Pre-production and production underway**, incl. sensors, ASICs, on-detector local supports
 - Main technical issue (sensor cracking) solved adding Kapton interposer
- **HGTD:**
 - **sensor production started**, solving technical problems on ASIC wafer probing
- Muon spectrometer:
 - **sMDT very advanced**, testing final choice for **RPC (trigger) electronics**
- **Calorimeter electronics:**
 - In **production** of electronic components
- **TDAQ:**
 - **Finalizing prototype for final readout system (FELIX) and L0 global trigger**
 - Progresses on the choice of the Event Filter tracking technology

The schedule is tight, but we are on track to make it

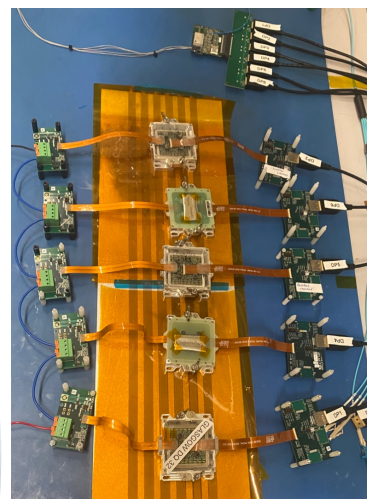
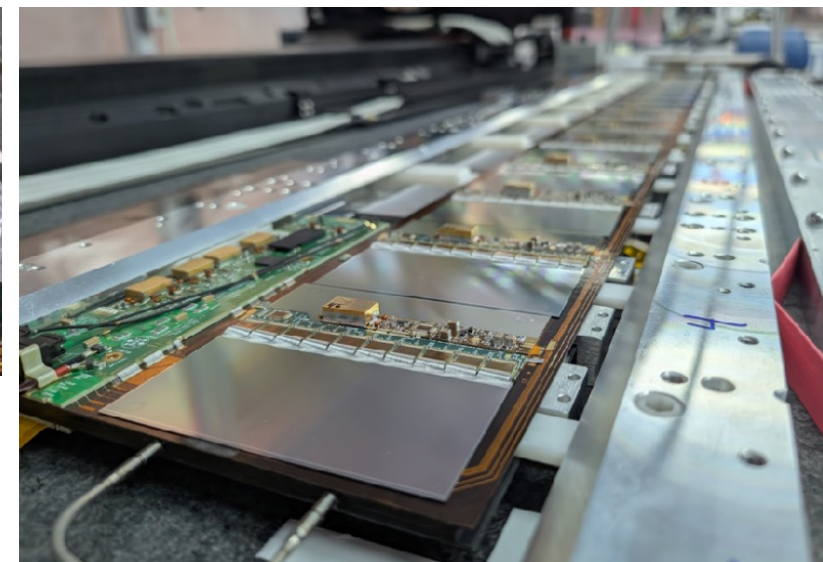
Phase II upgrade highlights



Major progress with CO₂
cooling plant for ITk & HGTD
Infrastructure installed at P1



ITk strip ASIC production quasi-complete;
endcap and barrel staves under production;
irradiation tests; thermal cycling tests



ITk pixel module production
ramping up; DAQ setups
ready for testing

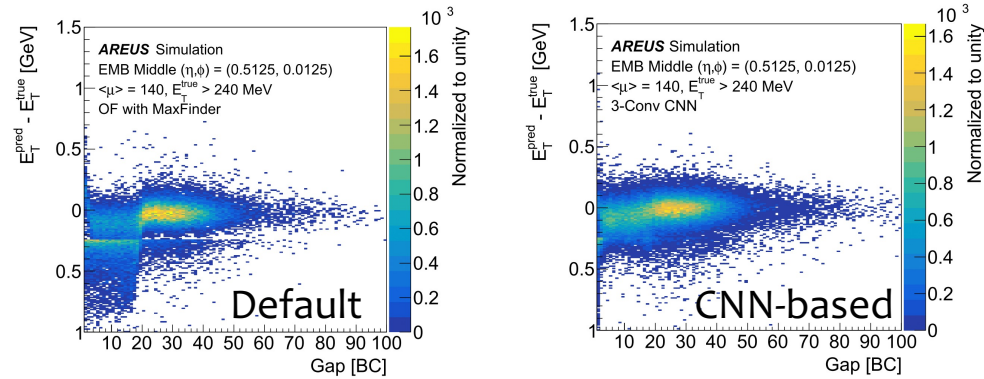


HGTD LGAD sensors
in production,
continued tests
with demonstrator

Moving from preparing to producing!

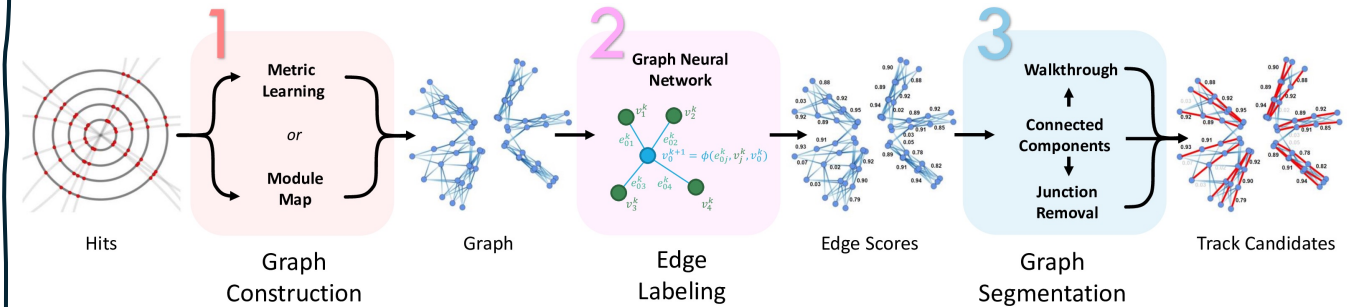
Phase II upgrade highlights

New **LAr** electronics allow improved ML-based energy reconstruction

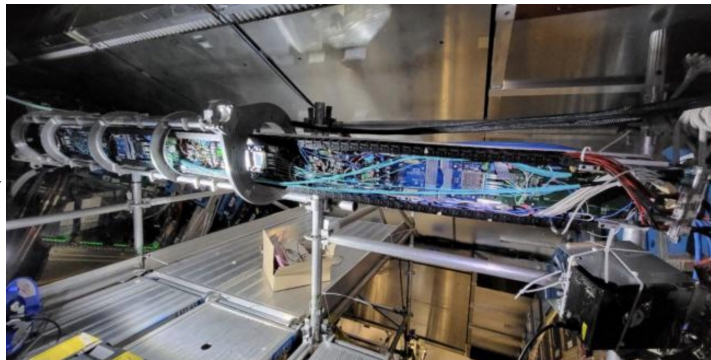


Comput Softw Big Sci 5, 19 (2021)

Progress in all **TDAQ** aspects; Prototyping continues for hardware components; Event Filter technology choice coming up later this year: GPU and FPGA accelerators under consideration.



Very active algorithmic development for all platforms !



TileCal electronics steadily progressing;
Demonstrator set up operating in Run 3
proven to be extremely valuable.

Good progress across all **muon system** upgrades: replacement of on-detector electronics for MDT, RPV and TGCs; new small MDT chambers under commissioning; TGC chambers built; power system prototypes under testing

