Selected Highlights of New Physics Searches in ATLAS

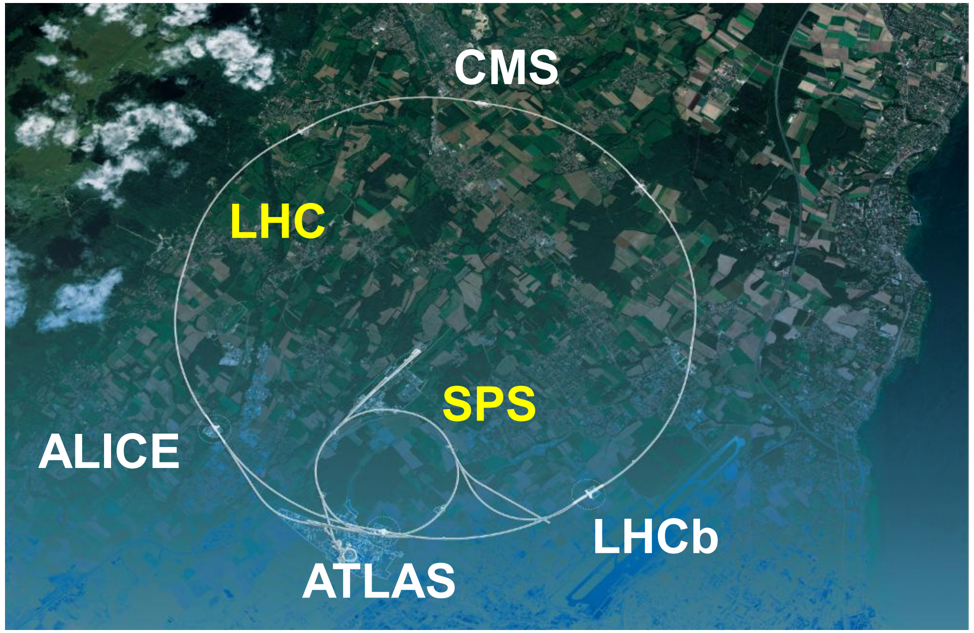
Cosmo-Astro-Particle Symposium (CAP 2025) & 19th TeV Workshop,

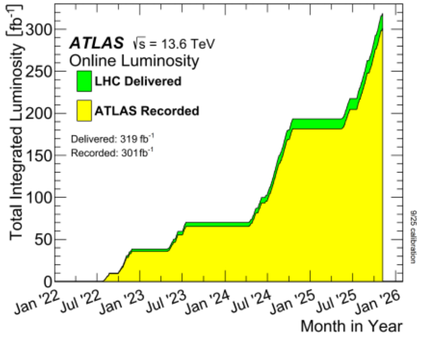
December 11-15, 2025

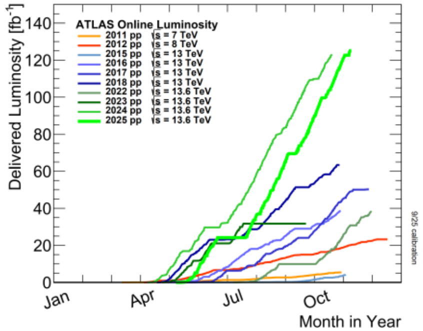
OKAWA (大川) Hideki (英希)

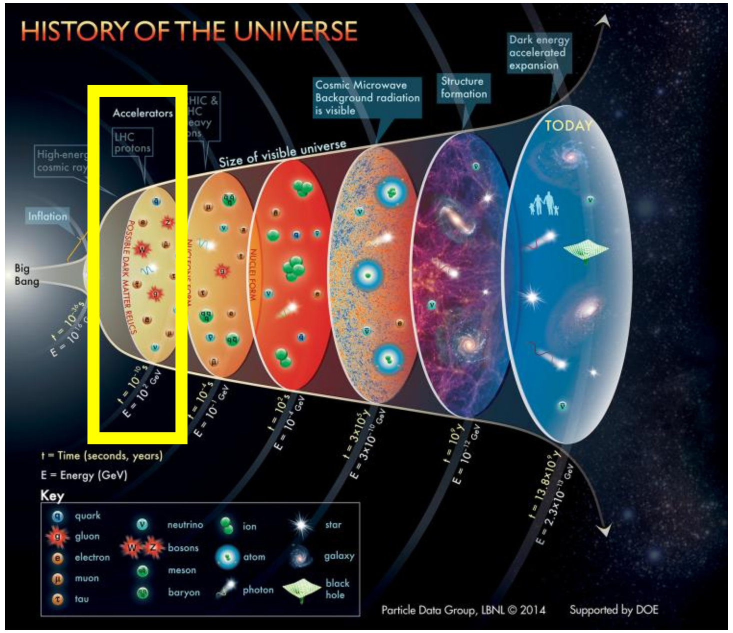
Institute of High Energy Physics, Chinese Academy of Sciences

Large Hadron Collider (LHC)



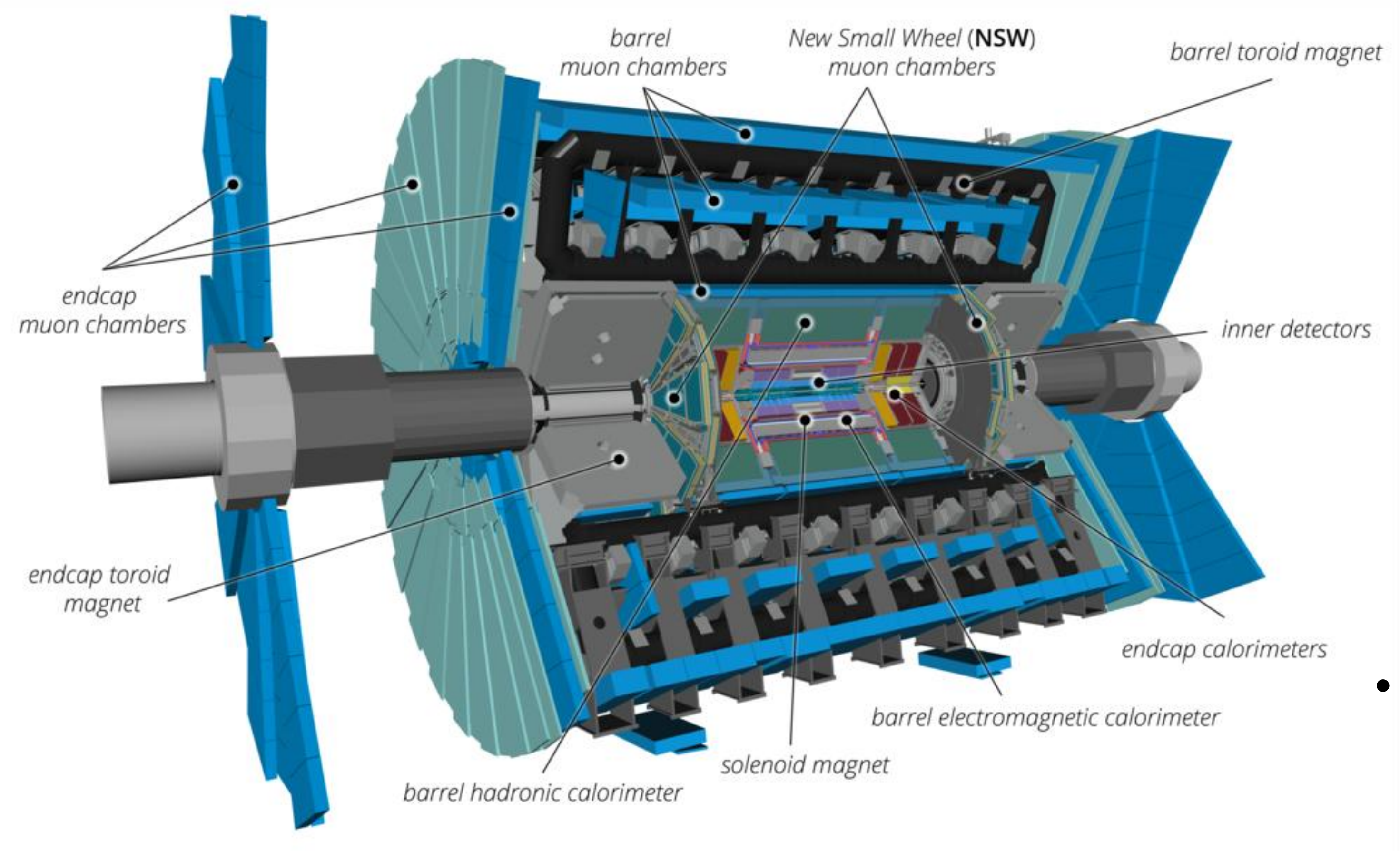


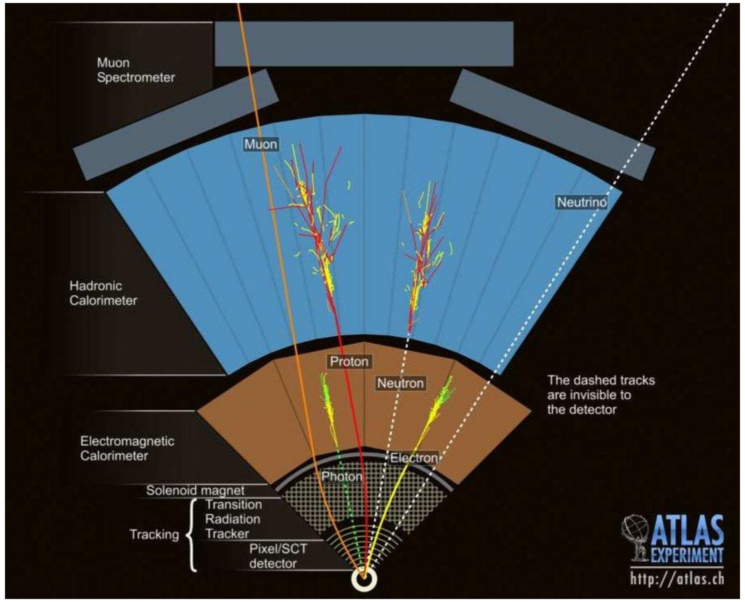




- The only operating collider at the energy frontier. Hosted at CERN in Geneva, Switzerland.
- p-p collisions at 7/8 TeV (Run 1: 4.8/20.3 fb^{-1}), 13 TeV (Run 2: 140 fb^{-1}), 13.6 GeV (Run 3: targeting 350 fb^{-1}). Four large-scale detectors at the collision points.
- Providing a unique microscopic probe with a mystic link to the history of the Universe.

ATLAS Detector





- One of the two general-purpose detectors at the LHC along with CMS.

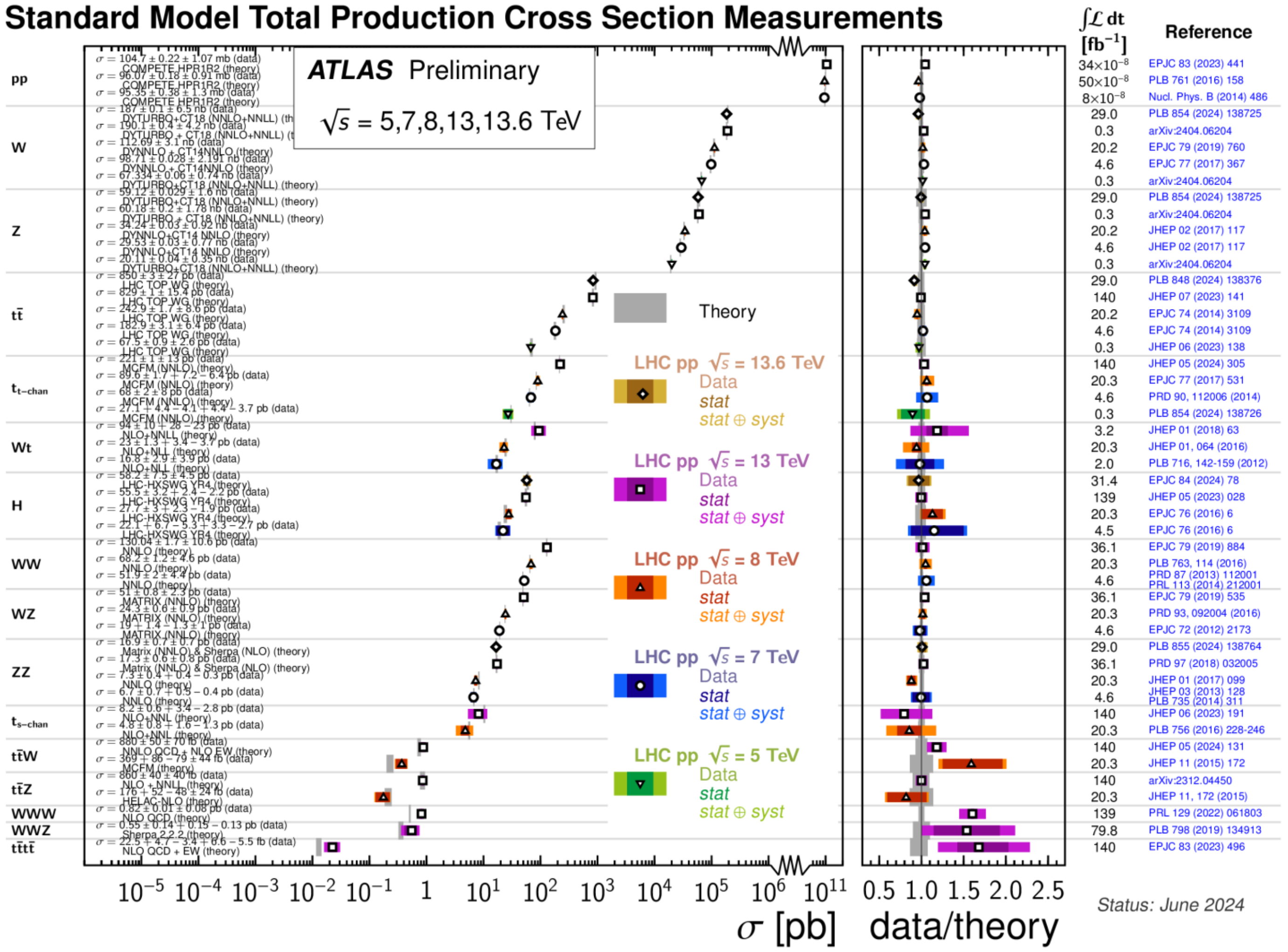
- **<u>Significant upgrade (Phase-I) completed during Long Shutdown 2 in 2019-2022</u>**: New Small Wheel muon chambers, new muon RPC, LAr calorimeter front-end electronics, TDAQ

ATLAS China

- 3 independent institutes: IHEP, USTC, Tsinghua
- 3 clusters: Nanjing + Sun Yat-Sen, SJTU + TDLI, Shandong + Zhengzhou + Nankai
- 1 technical associate: SINANO, CAS

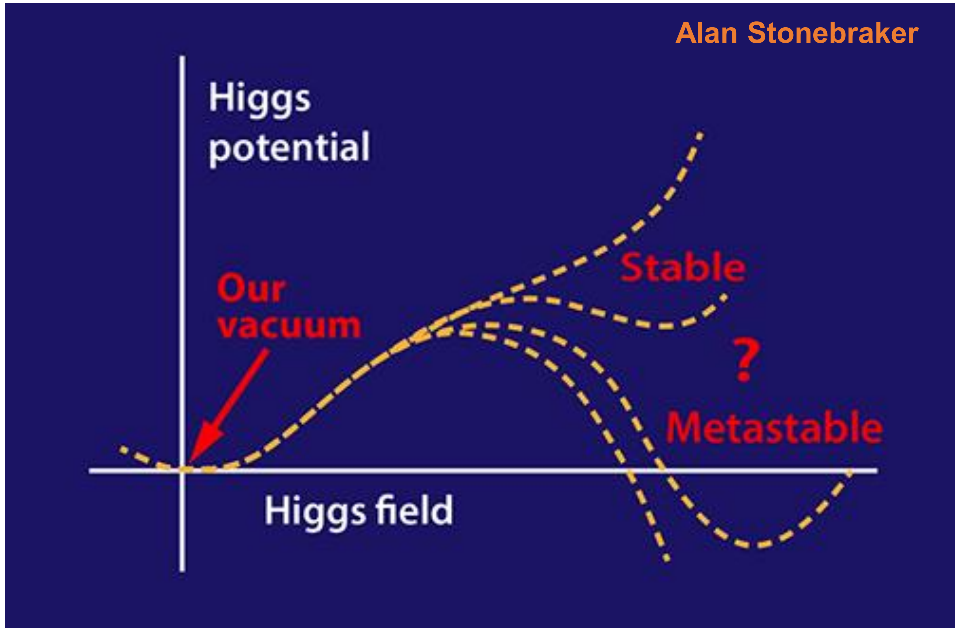
- 273 / 5971 ATLAS members (4.5%), 112 / 2846 ATLAS physics authors (3.8%), 72 PhD students (6.2%).

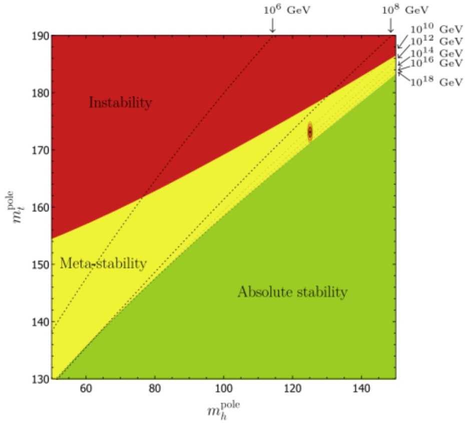
A Discovery & Precision Machine



- LHC will continue to search at the energy frontier.
- In parallel, with its unprecedented large statistics, we are beginning to enter **a new precision era**.
- LHC is a Higgs boson factory, a top-quark factory, with accessibility to rare production & decays.

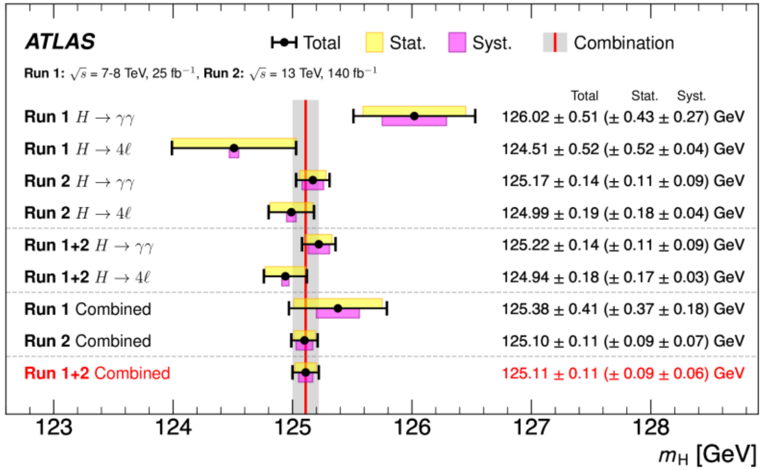
Higgs, Top & Stability of the Universe



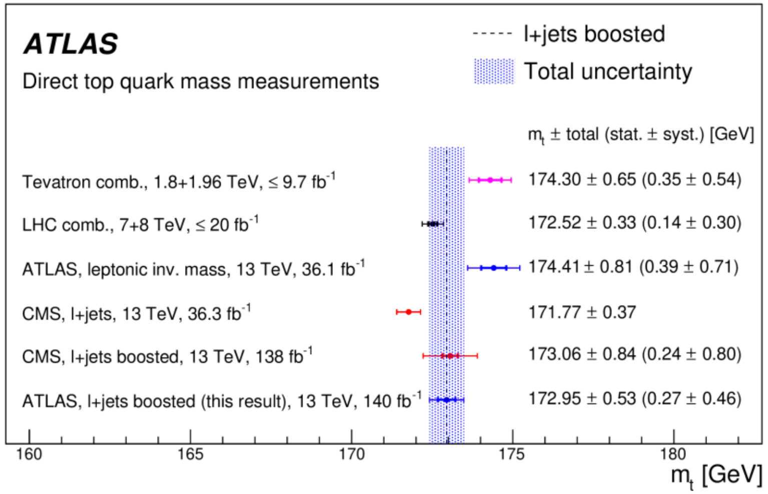


A. Andreassen, W. Frost, M. Schwartz PRD 97, 056006 (2018)

Phys. Rep. 1116 (2025) 4 - 56



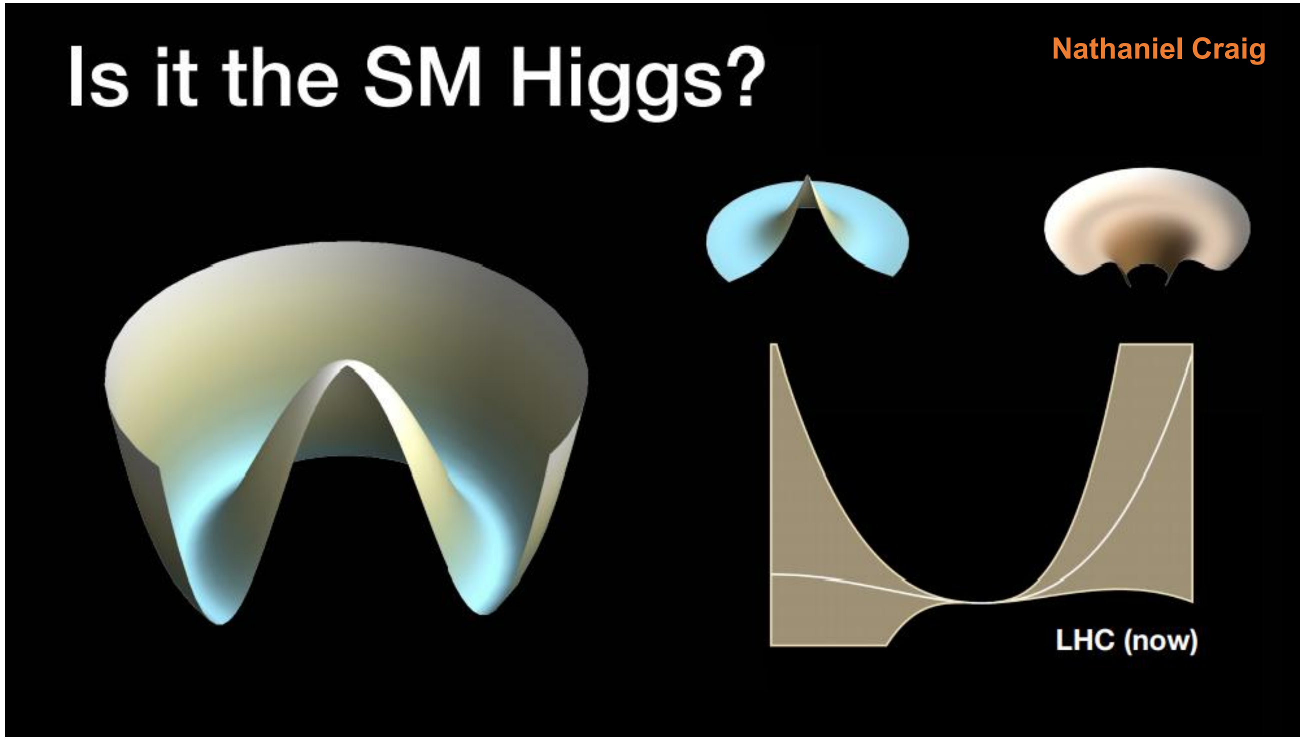
Phys. Lett. B 867 (2025) 139608



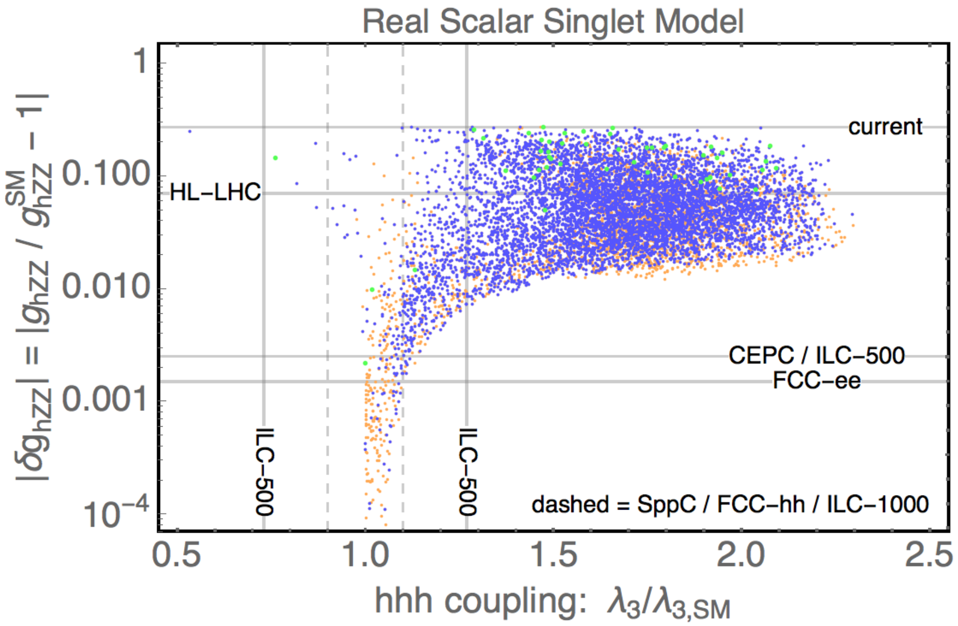
- **Higgs boson mass is already measured at per-mille level.**
- **Latest semi-leptonic boosted analysis provides the most precise measurement from a single channel: 172.95 ± 0.53 GeV.**
- The current LHC measurements point to the boundary of meta-stability/stability, if no BSM.

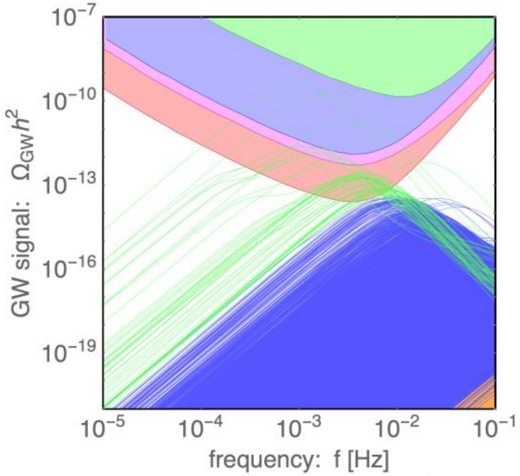
See also talks by Baihong Zhou & Shu Li

Shaping the Higgs Potential



P Huang, AJ Long, LT Wang, PRD 94 (2016) 075008

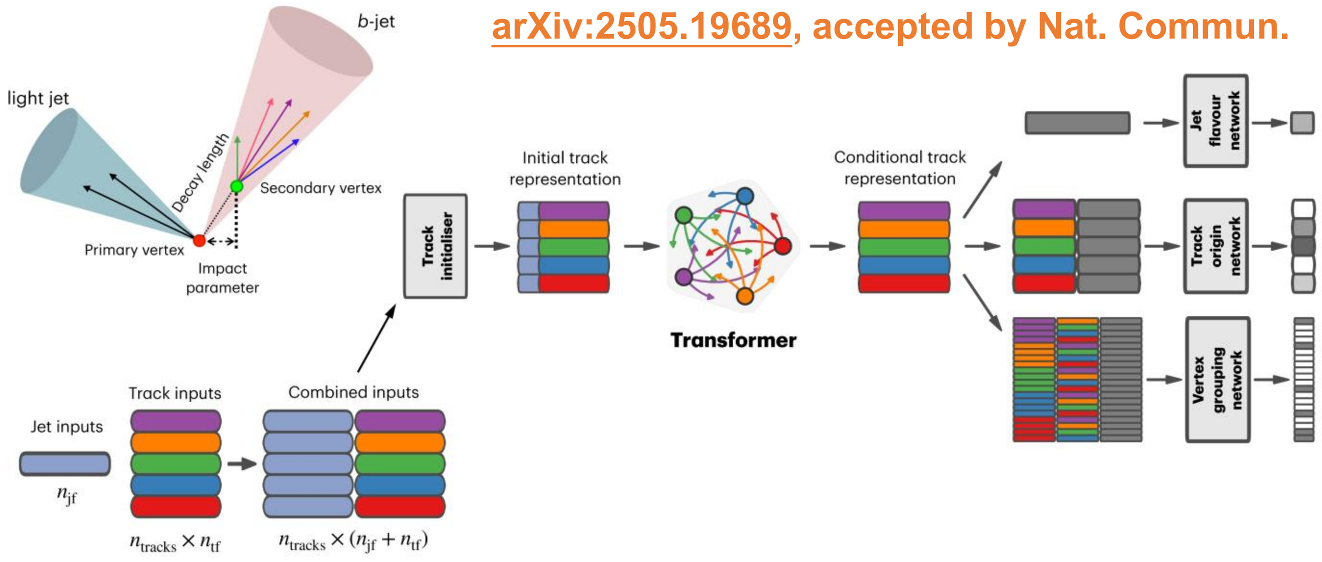


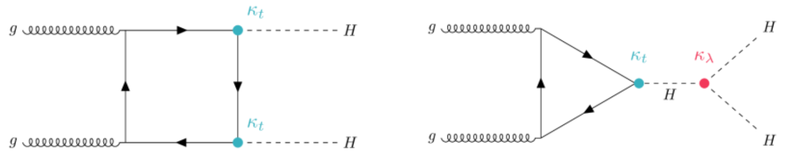


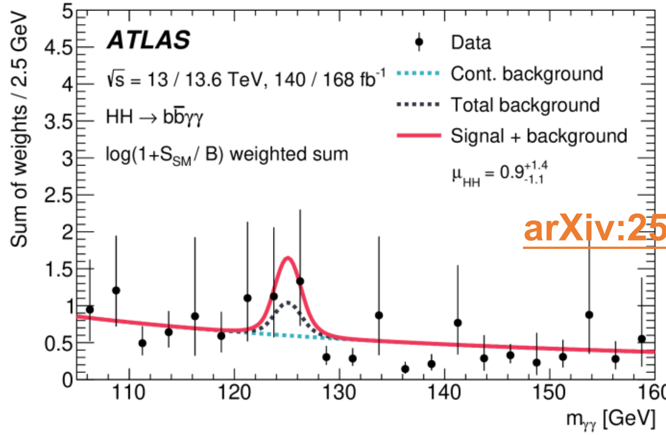
- Higgs boson self-coupling will tell us about the Higgs potential shape.
- **It is sensitive to various BSM, and has important connections to the electroweak phase transition & gravitational waves.**

Di-Higgs Searches with Transformers

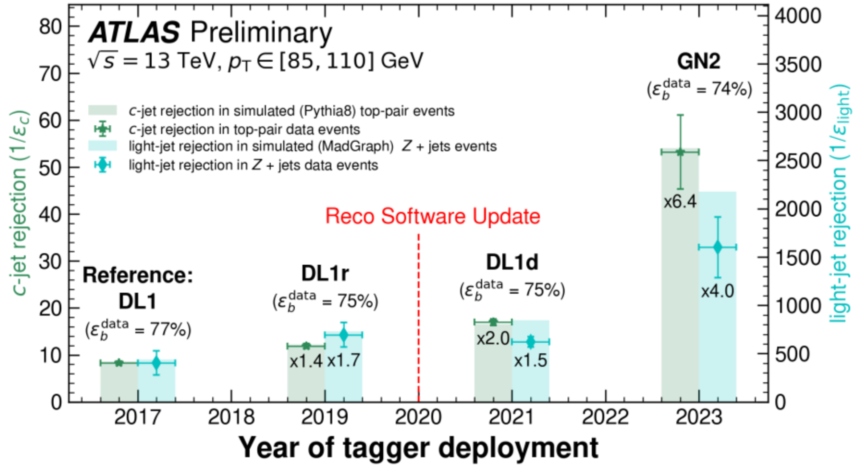
arXiv:2505.19689, accepted by Nat. Commun.







arXiv:2507.03495



- **Transformers improves the c- & light- jet rejection by several factors from previous versions.**
- **Transformer-based b-jet tagging (GN2) alone brings 20% improvement to HH→bbγγ analysis.**
- Signal strength for di-Higgs production: $\mu_{HH} = 0.9^{+1.4}_{-1.1}$ [obs] ($1.0^{+1.3}_{-1.0}$ [exp])
- **Higgs self-coupling: $-1.7 < \kappa_\lambda < 6.6$ [obs] ($-1.8 < \kappa_\lambda < 6.9$ [exp])**

Higgs as a Portal to New Physics

Phys. Rep. 1116 (2025) 184

Low mass — **125 GeV** — **High mass**

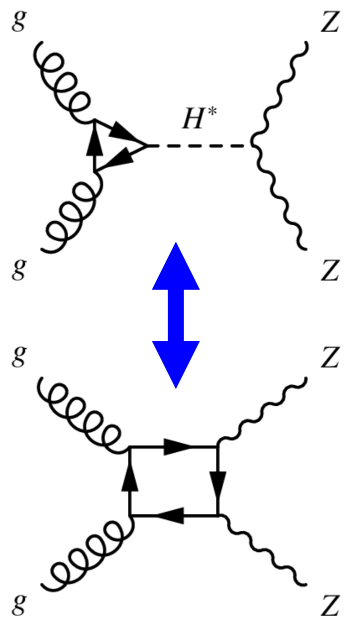
Haifeng Li's talk for H→μμ

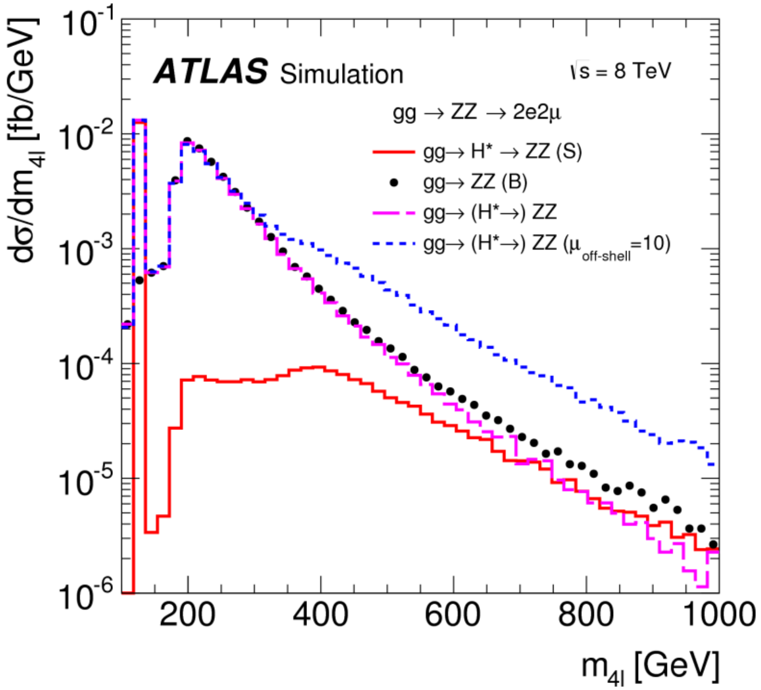
Low mass	125 GeV	High mass
$pp \rightarrow a$	h_{125} rare decays	$pp \rightarrow H/A$, $pp \rightarrow H^{\pm}$
$h_{125} \rightarrow aa$, $h_{125} \rightarrow a_1 a_2$	h_{125} exotic decays	$H \rightarrow h_{125} h_{125}$
$h_{125} \rightarrow Za$	$h_{125} \rightarrow invisible$	$H \rightarrow Sh_{125}$, $H \rightarrow SS$
		$A \rightarrow ZH$, $A \rightarrow Zh_{125}$

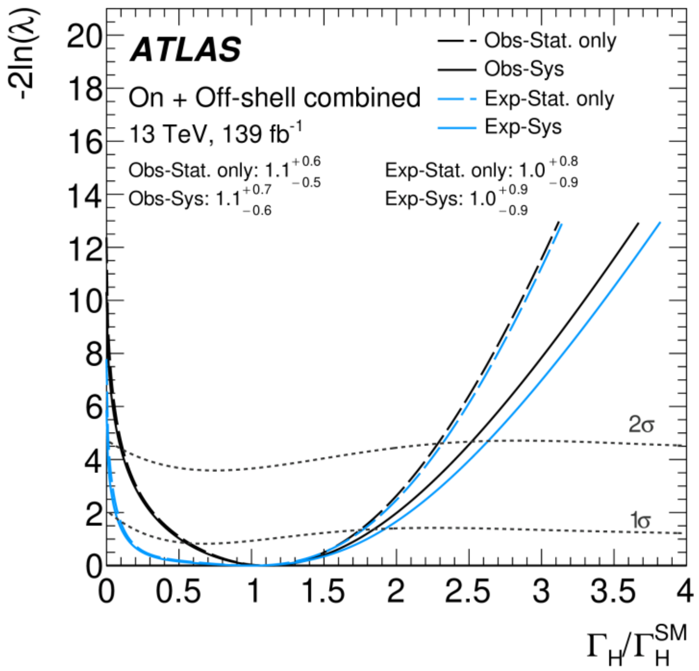
- Higgs boson is a promising portal to new physics. Its sign could show up as **exotic decays, enhancement of rare decays** and/or as an existence of **additional Higgs bosons and/or other high mass resonances**.
- Searches for rare decays can be performed via:
  1. **Inclusive model-independent search** → measure the Higgs boson decays width
  2. **Exclusive channel-by-channel searches**

Phys. Lett. B 846 (2023) 138223

Evidence of Off-Shell Higgs Boson







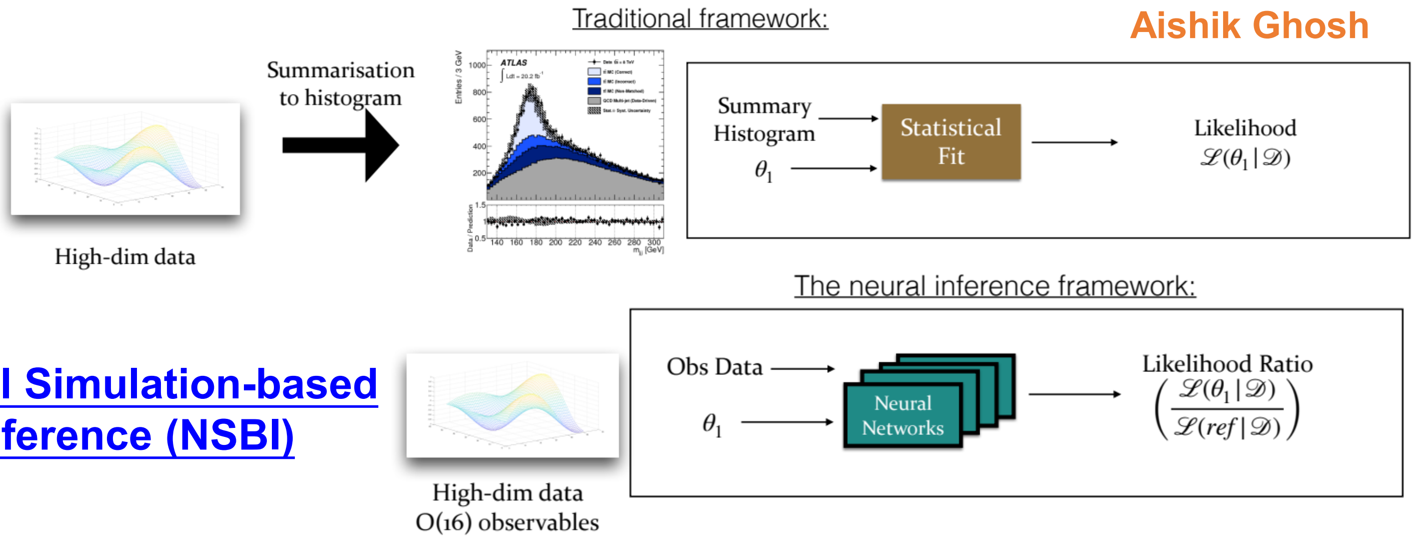
- Decay width is a model-independent probe for BSM, but **SM Higgs boson decay width (Γ_H=4.1 MeV) is well below the GeV-level detector resolution**.
- However, **the off-shell contribution is highly sensitive to the decay width, allowing us to constrain it by a few orders of magnitude.**
- Evidence of the off-shell Higgs boson production is obtained both by ATLAS & CMS.

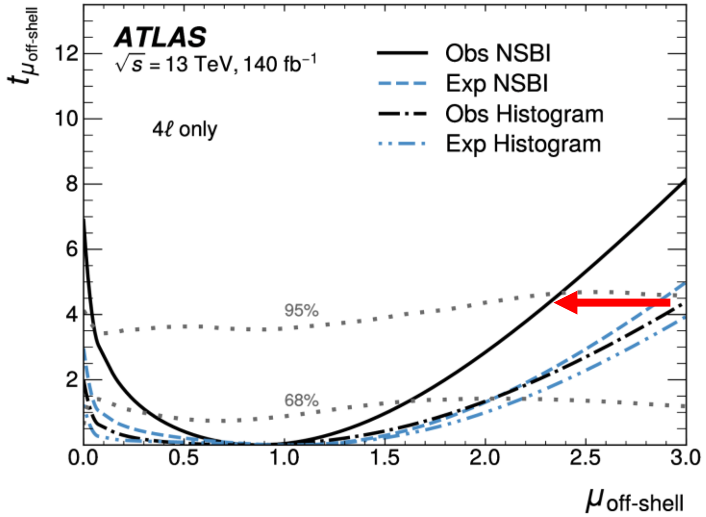
Rep. Prog. Phys. 88 (2025) 057803

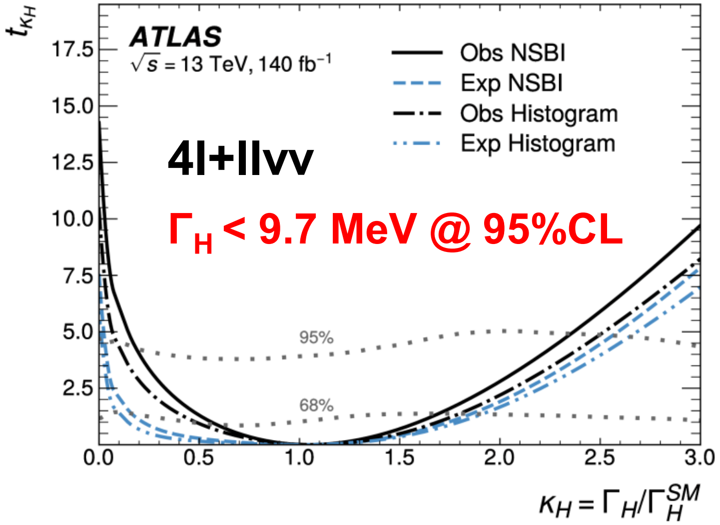
Off-Shell Higgs Boson + NSBI

Aishik Ghosh

Neural Simulation-based Inference (NSBI)

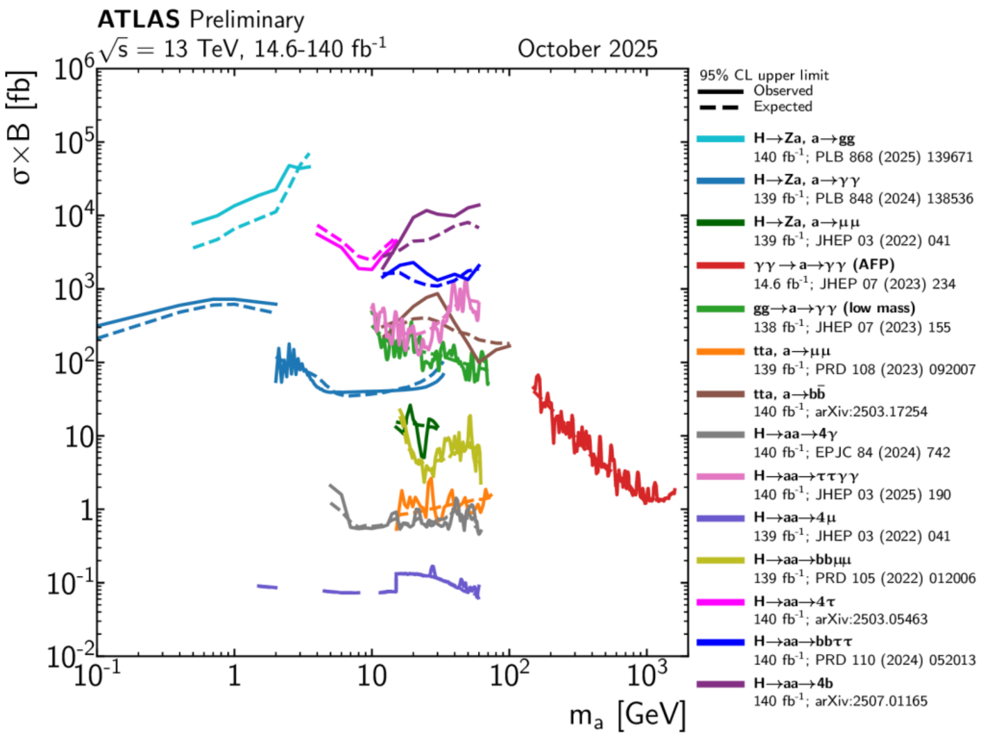




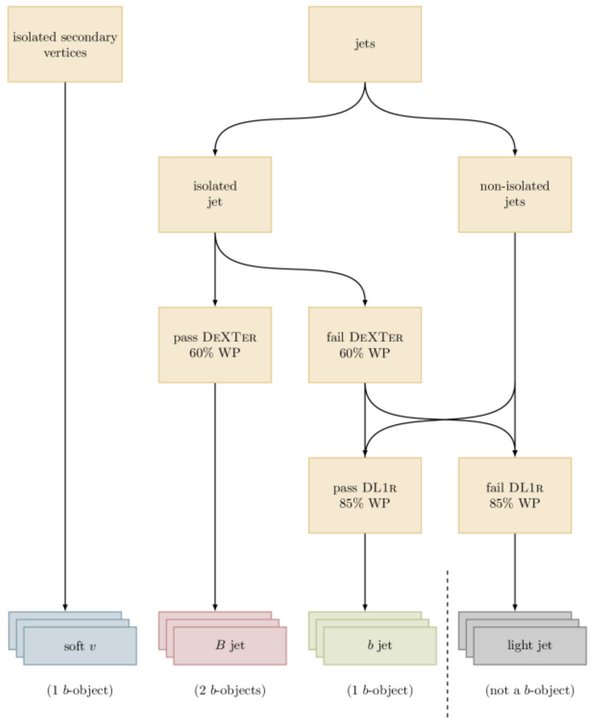


- In neural simulation-based inference (NSBI), **the NN output is directly used for the statistical treatment →** no information loss from 1D dimensional reduction & histogram binning
- It can also handle parametrized signals & complicated signal/BG interference.
- **Notable improvement from the traditional histogram-based method: 3.3σ → 3.7σ (combined with llvv)**

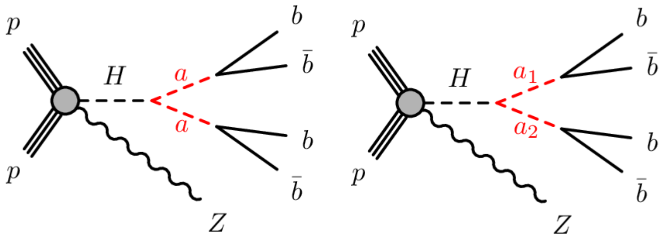
BSM Rare Decays to Low-Mass Scalars

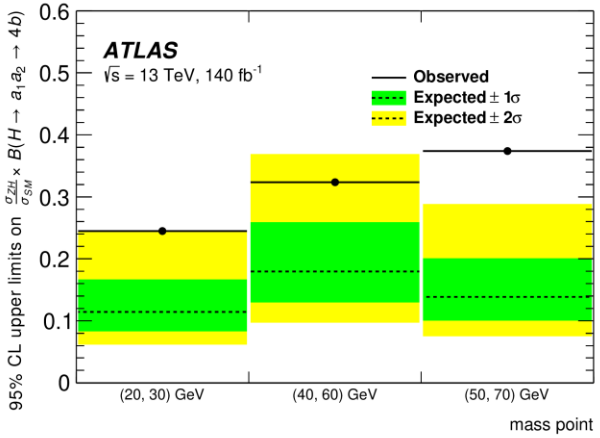


Jet tagging with DeXTer



Phys. Rev. D 112 (2025) 072005

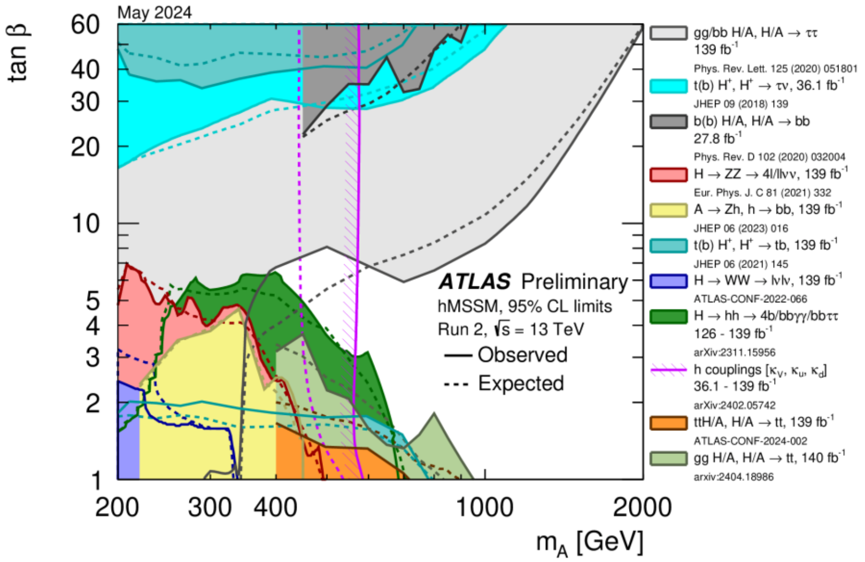


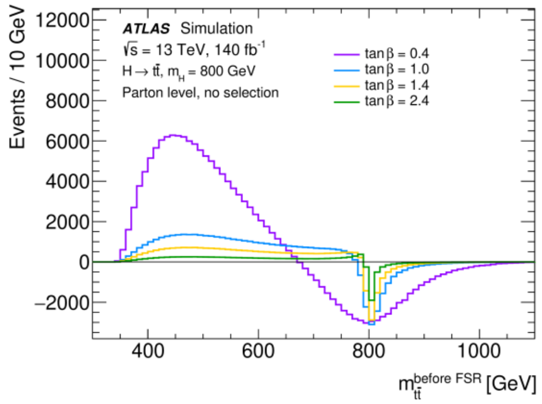


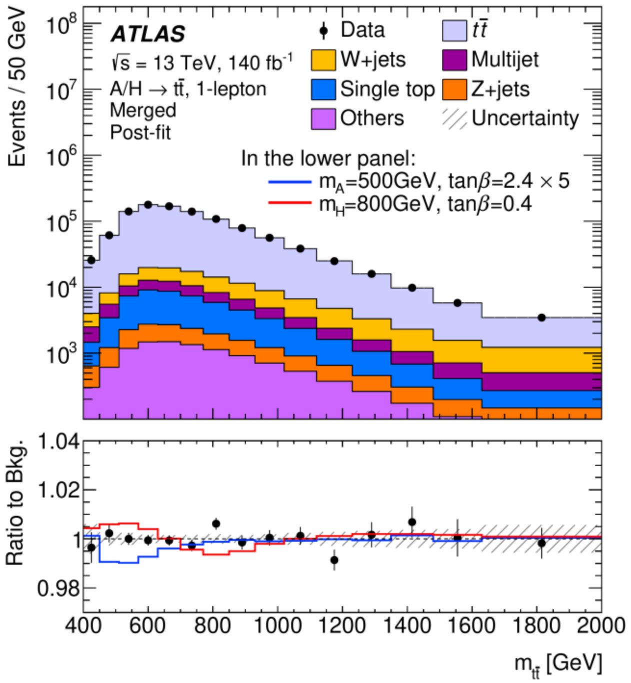
- Higgs BSM decays through low mass (pseudo-)scalars often lead to highly collimated signatures.
- Deep Sets based neural networks (DeXTer) designed for low p_T double b-tagging.
- Small excess seen in $H \rightarrow a_1 a_2 \rightarrow 4b$ search: Global (local) significance of 3.28 (2.57) σ for (m_{a1}, m_{a2}) = (50, 70) GeV.

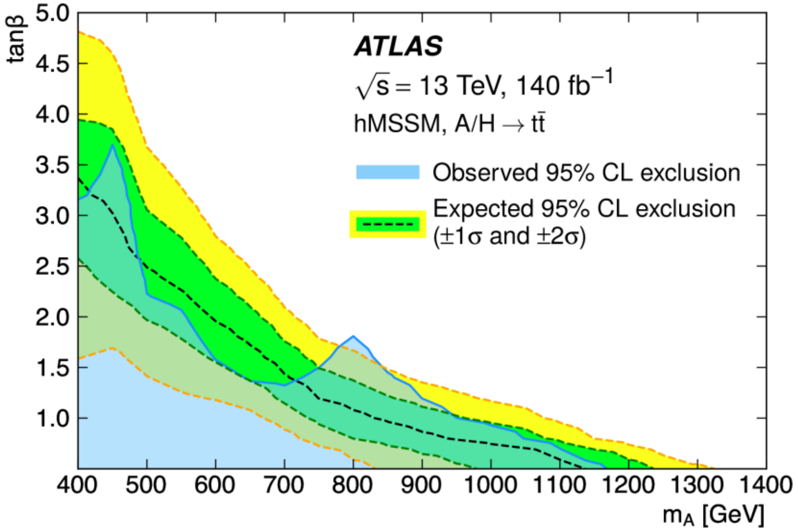
JHEP 08 (2024) 013

More Higgs Bosons?







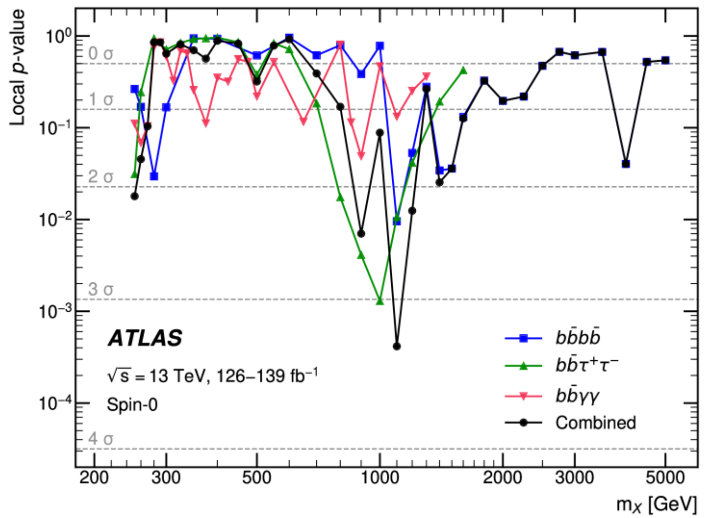


- Heavy Higgs boson decays to $t\bar{t}$ are dominated for low tan β in Two Doublet models, but are challenging due to large BG & interference.
- $t\bar{t}$ threshold region is not considered (see Haifeng Li's talk for the toponium observation)
- Small excess seen around 800 GeV.

Other Heavy Resonance Searches

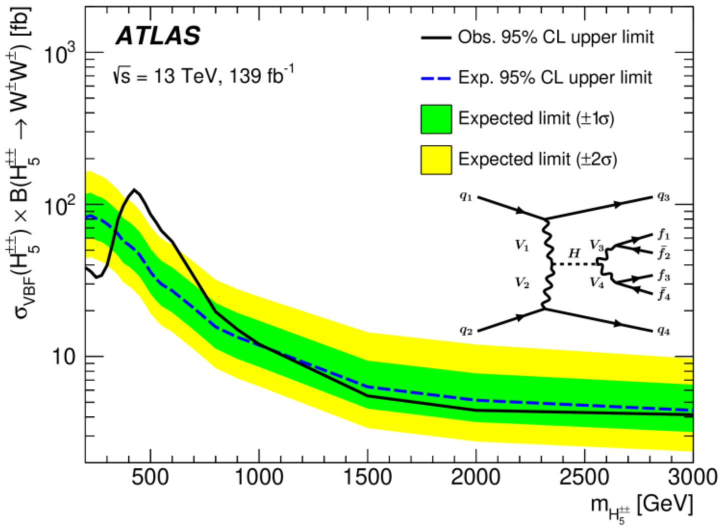
Di-Higgs resonance

PRL 132 (2024) 231801



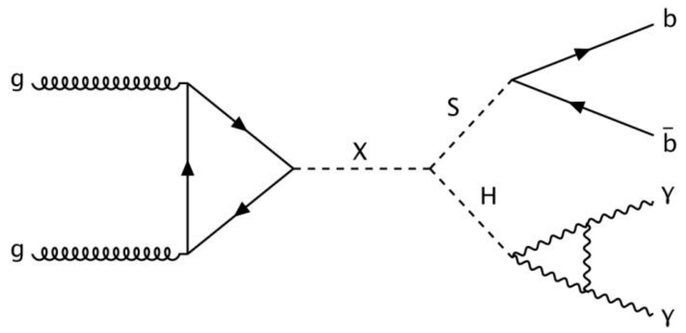
VBF doubly-charged Higgs

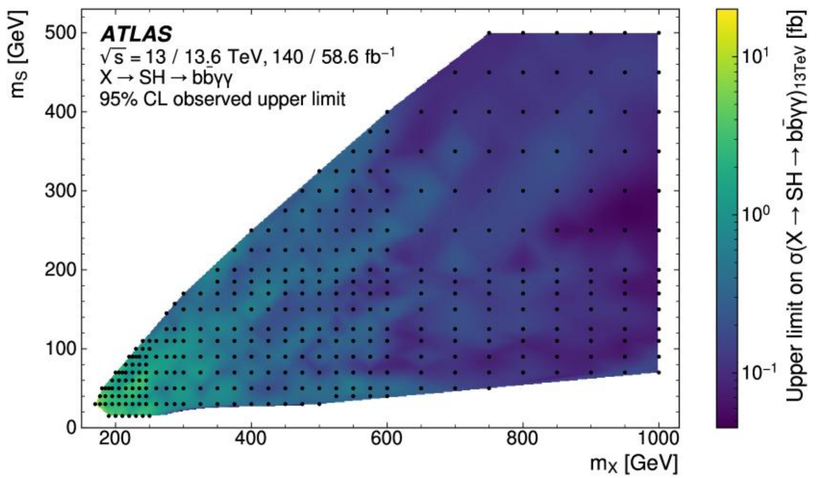
JHEP 04 (2024) 026, PLB 860 (2025) 139137



Scalar extensions (X→SH)

arXiv:2510.02857

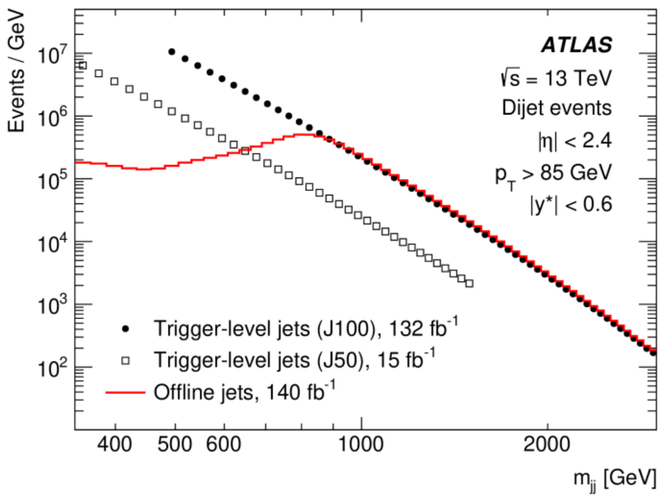


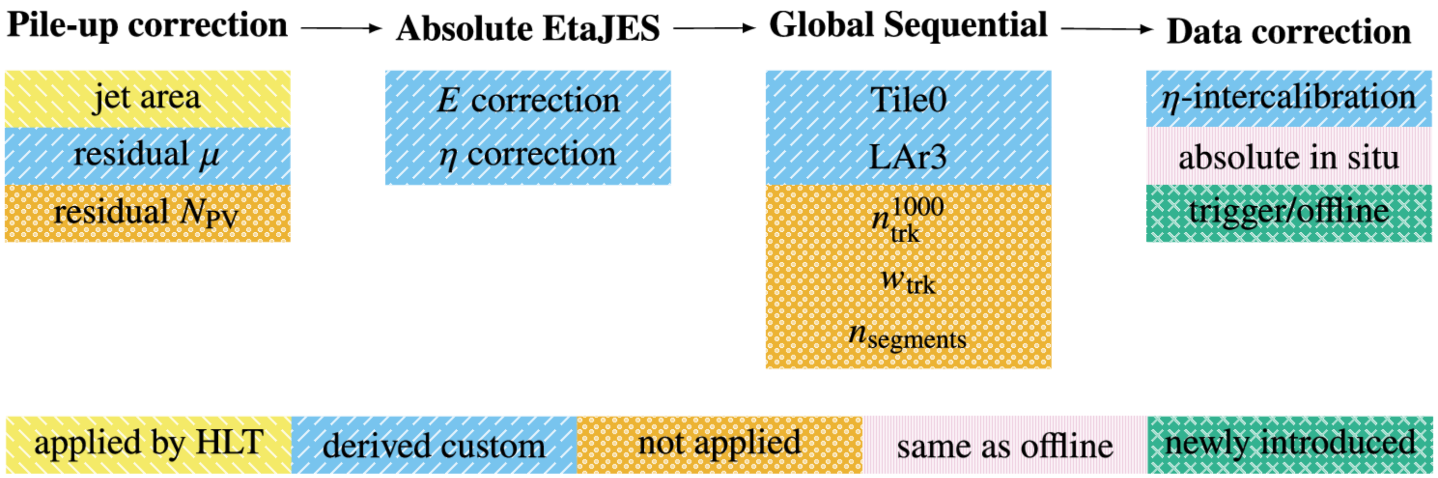


- **Di-Higgs resonance:** global (local) excess 2.1σ (3.3σ).
- **VBF doubly-charged Higgs:** global (local) 2.5σ (3.3σ).
- **Scalar extensions (X→SH):** CMS saw global (local) excess of 2.8σ (3.8σ) at (m_X, m_S)=(650, 90) GeV [JHEP 05 (2024) 316]. Not seen by ATLAS.

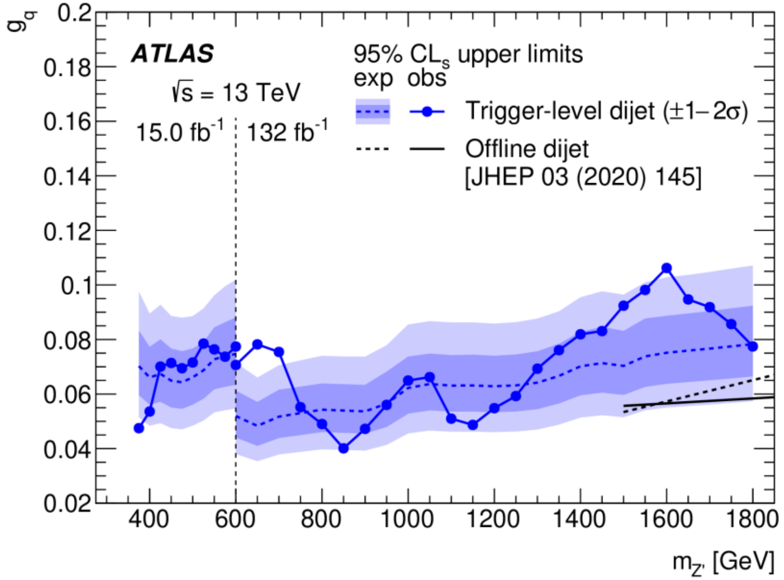
Phys. Rev. D 112 (2025) 092015

Trigger-level Analysis for Dijet



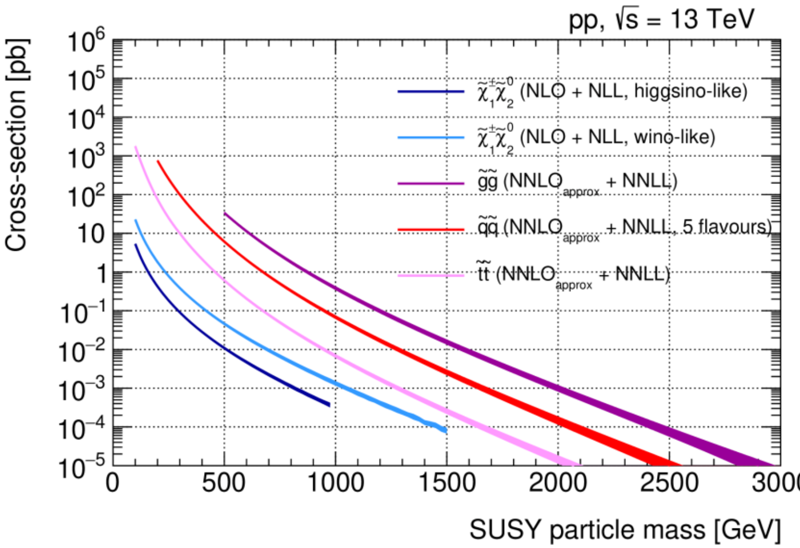


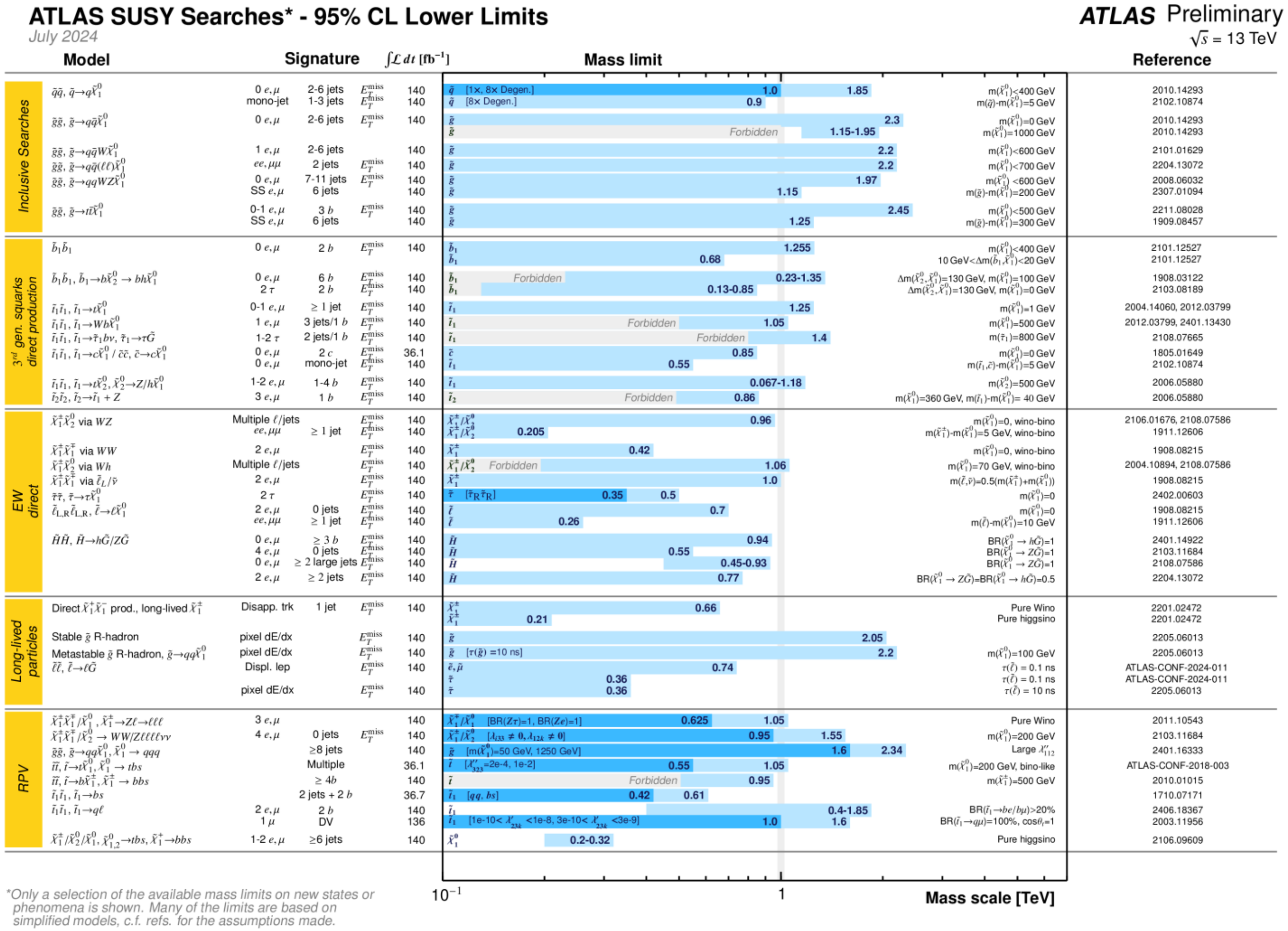
- Very challenging to search for resonances decaying to quarks.
- We need to perform analysis at the trigger level to go below ~1.5 TeV. → Need to apply custom jet calibration
- Global (local) excess: 2.2σ (3.4σ) for $m_{Z'}$=650 GeV.



Supersymmetry

Note that relevant BRs are often assumed to be 1 in the simplified models





- Direct electroweak productions are becoming more accessible due to large dataset.
- Searches for challenging scenarios such as compressed mass scenarios and long-lived decays are also actively performed.

Compressed Scenarios

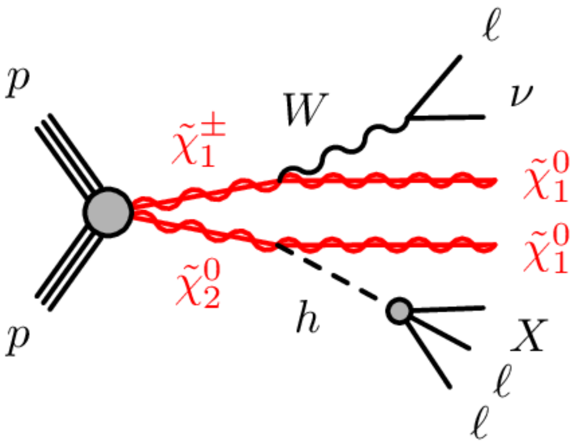
[Electroweakino search]

- Mild excess of ~2σ observed.
- A similar excess seen for the same final state in CMS (PRD 109 (2024) 112001).

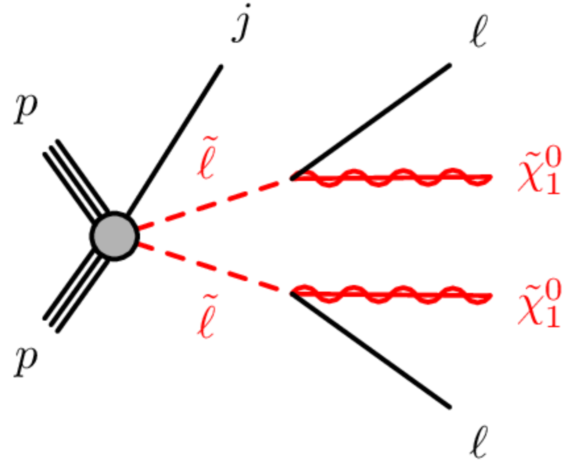
[Slepton search]

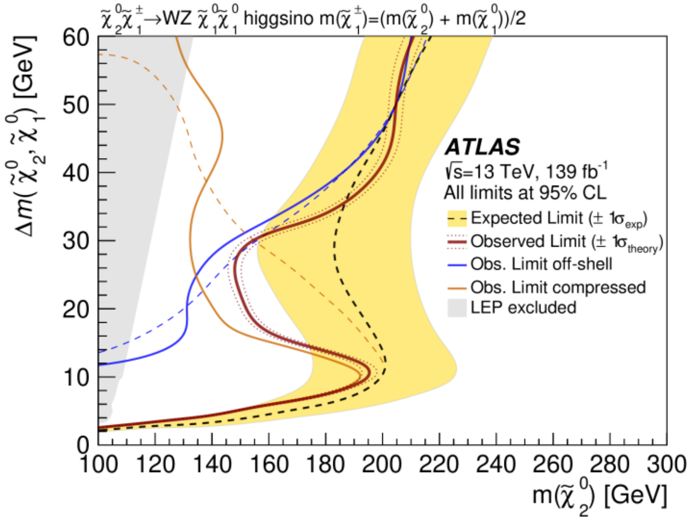
- Challenging phase space ("corridor" region) due to small cross section & compressed mass sparticle mass hierarchly. Events are tagged with ISR jets.
- Small excesses in both e- (μ-) channels: local significance 2.0σ (2.4σ)

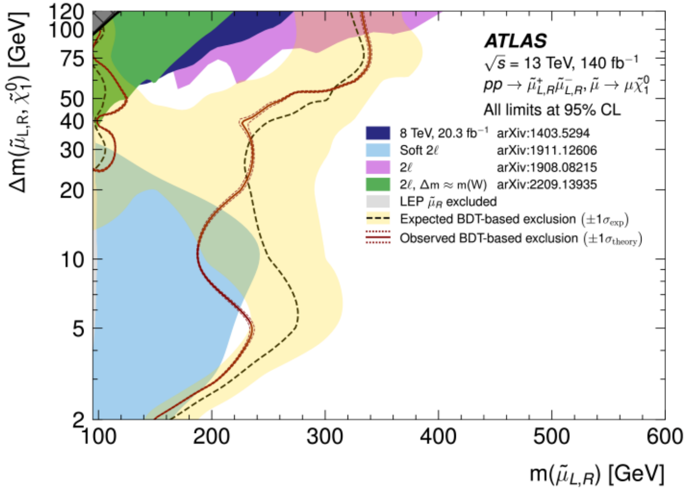
Eur. Phys. J. C 81 (2021) 1118



JHEP 08 (2025) 053



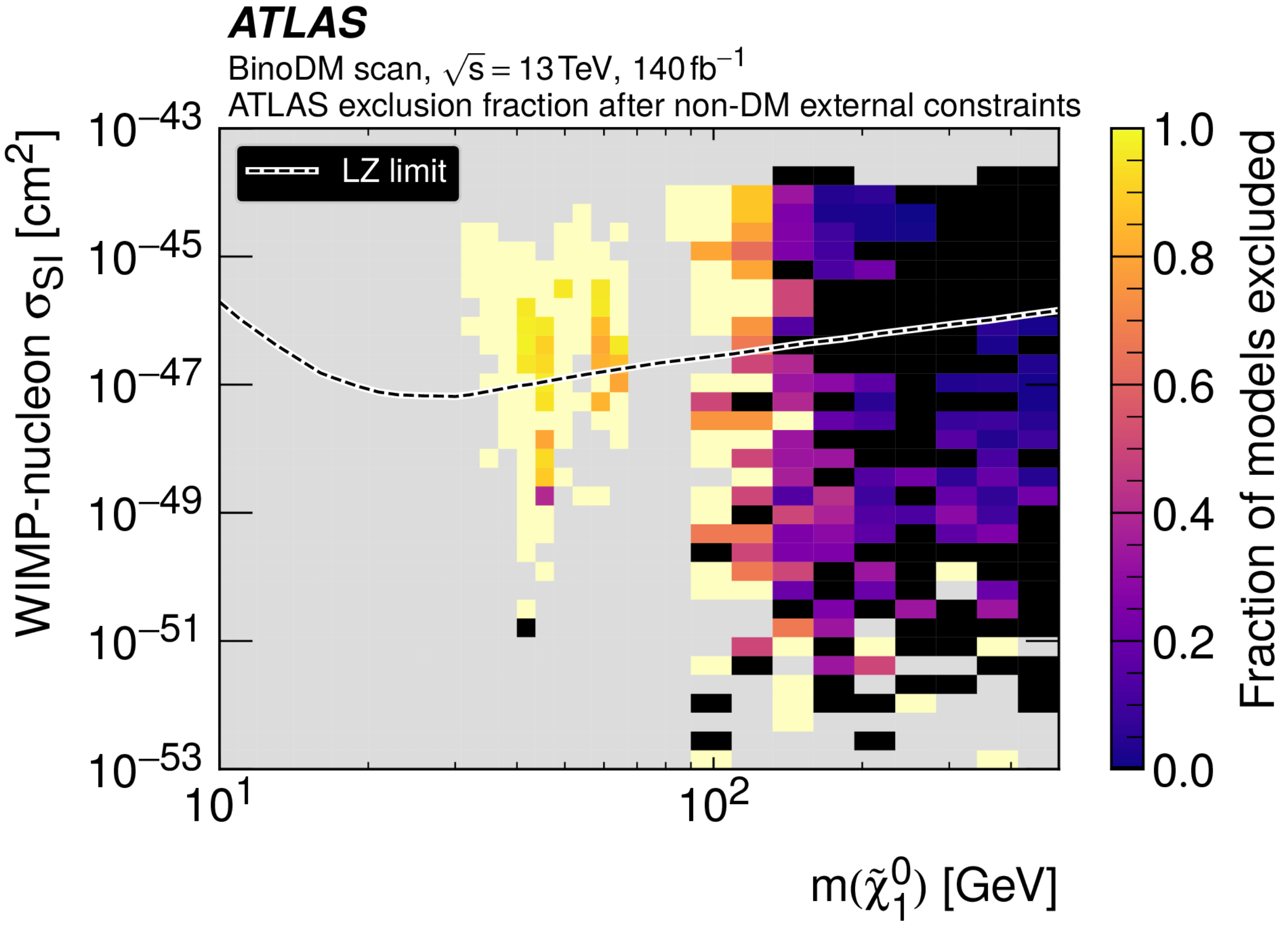




pMSSM & Dark Matter Searches

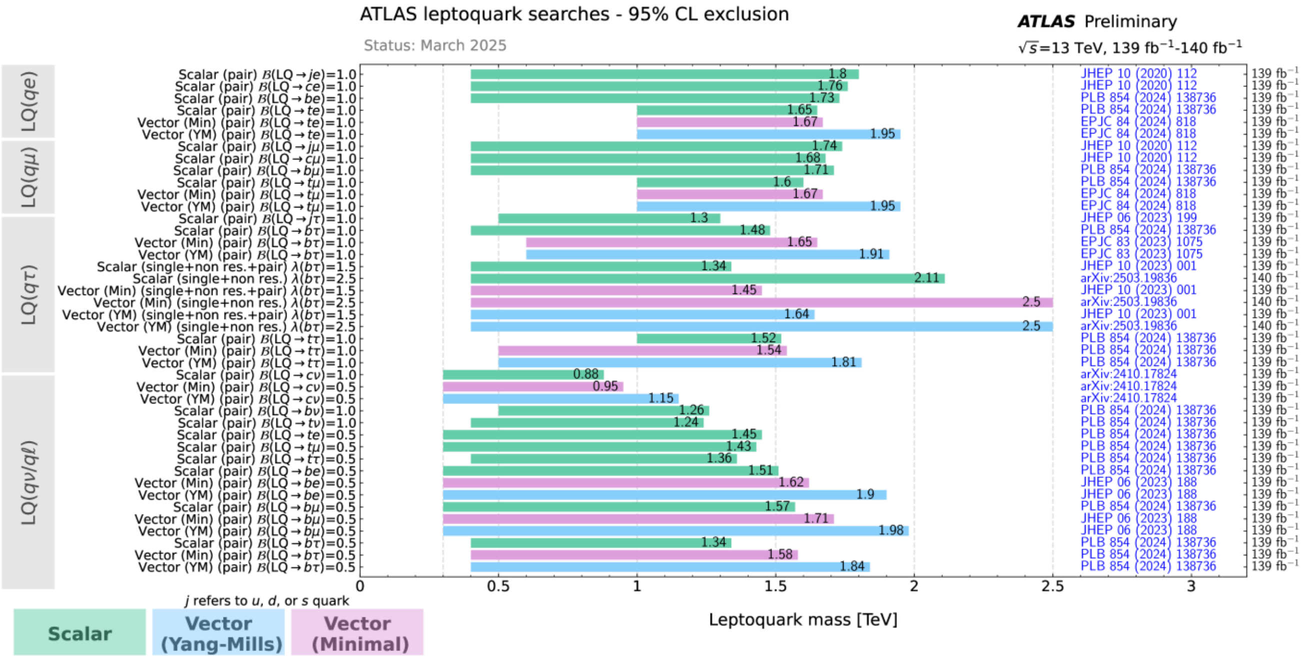
Phys. Rep. 1116 (2025) 261

- Phenomenological MSSM (pMSSM) varies a limited set of parameters affecting the electroweak sector.
- Parameter regions are excluded based on the global likelihood of models relevant for explaining the DM relic density.
- Complementary to direct DM detection experiments in the O(100) GeV region.

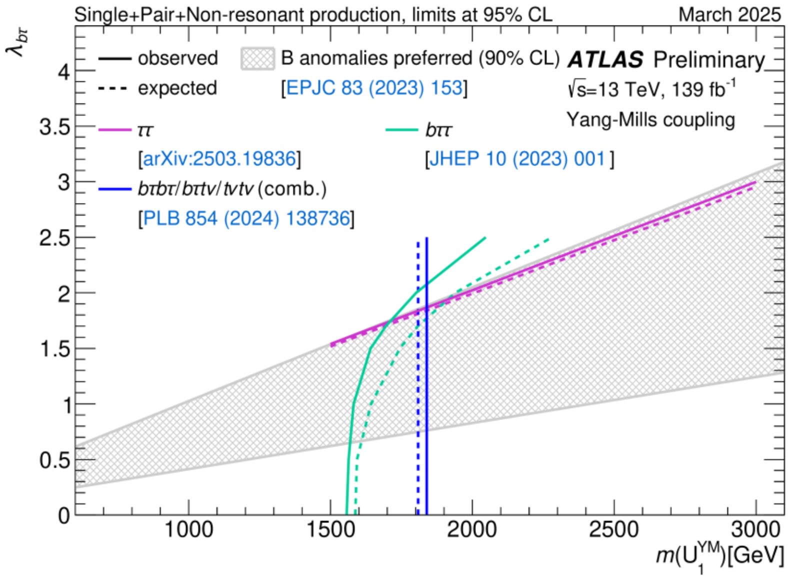


Leptoquarks

ATL-PHYS-PUB-2025-013

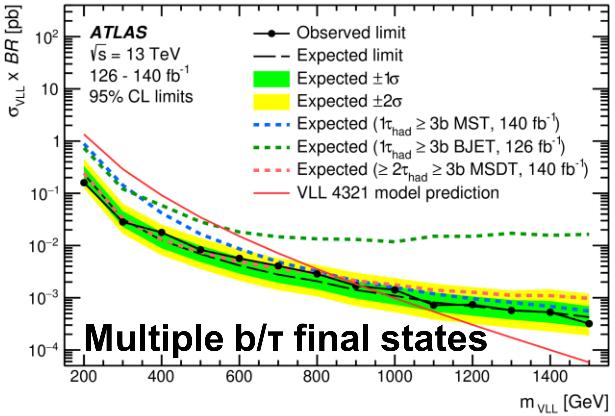


$$R(D^{(*)}) = \frac{\mathcal{B}(\overline{B} \to D^{(*)}\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\overline{B} \to D^{(*)}\ell^-\overline{\nu}_\ell)}$$

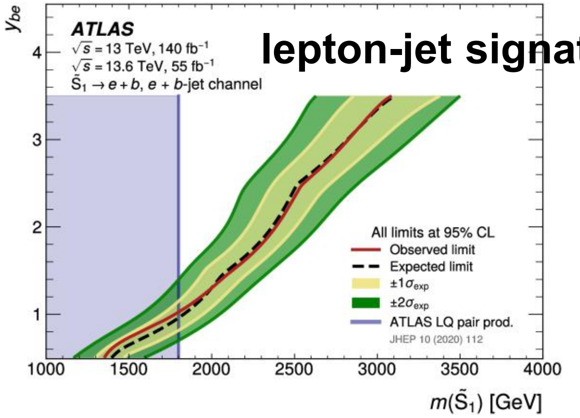


- Leptoquarks may explain the R(D)/R(D*) anomalies seen at the b-factories.
- Searches are extensively performed via various final states, but no significant sign so far.
- **We are starting to reach the phase space preferred by the R(D)/R(D*) anomaly.**

Eur. Phys. J. C 85 (2025) 1335

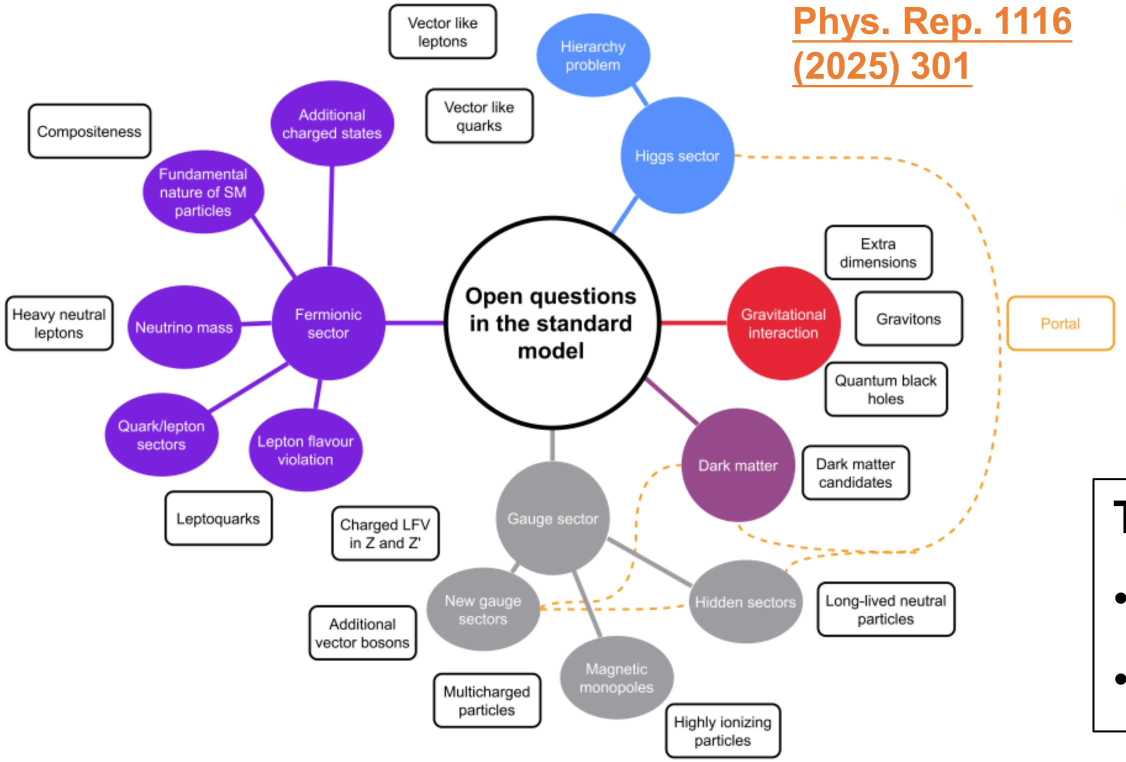


arXiv:2507.03650

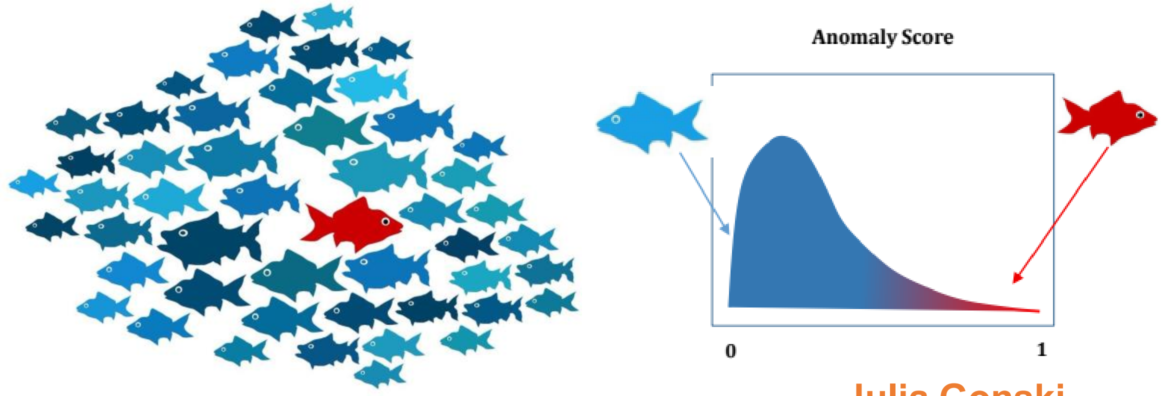


lepton-jet signatures

Anomaly Detection



[Phys. Rep. 1116 (2025) 301]



Julia Gonski

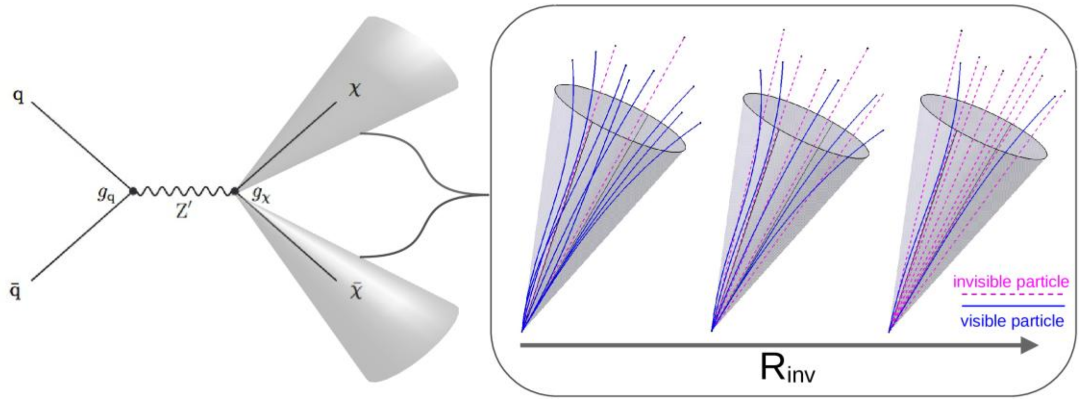
Two classes of anomaly detection

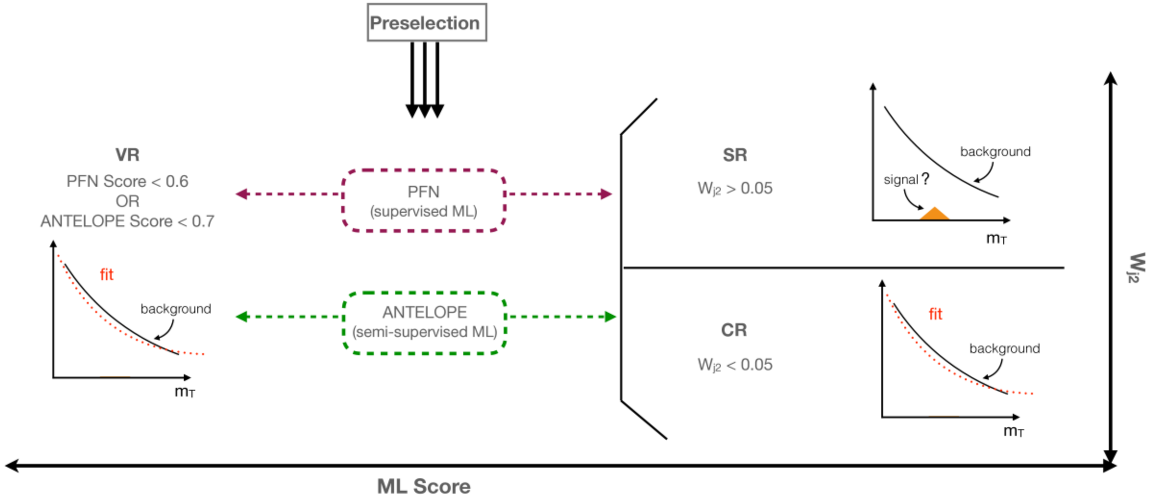
- **Weakly supervised**: trained on a reference data
- **Unsupervised**: directly identify rare events

- Possible BSM scenarios are diverse. Simplified Models have been extensively used at the LHC to suppress model-dependent biases.
- AI is now providing an alternative/complementary approach to search for new physics.

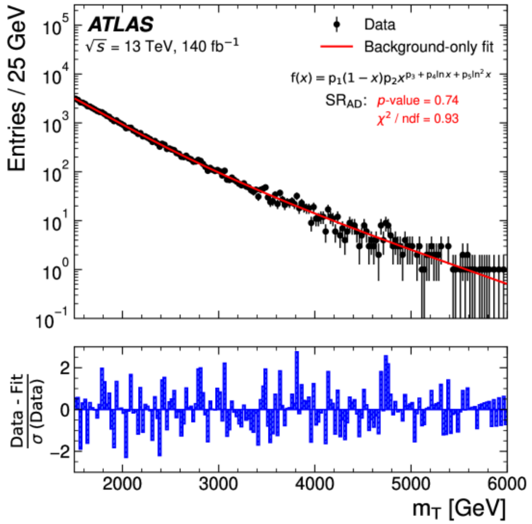
Phys. Rev. D 112 (2025) 012021

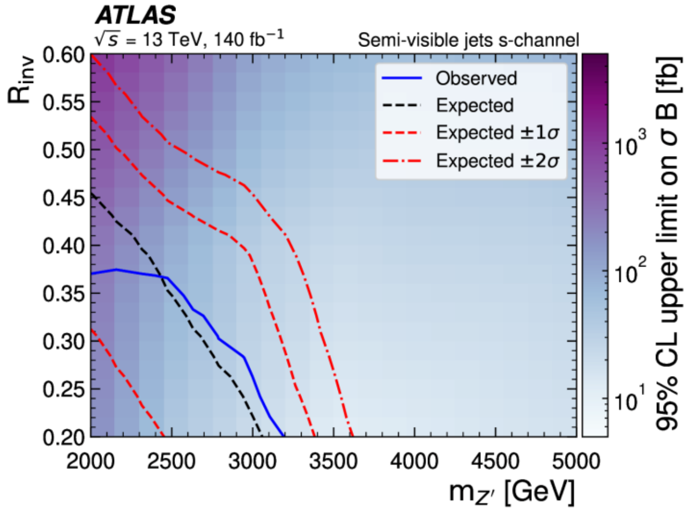
Jets from the Dark Side





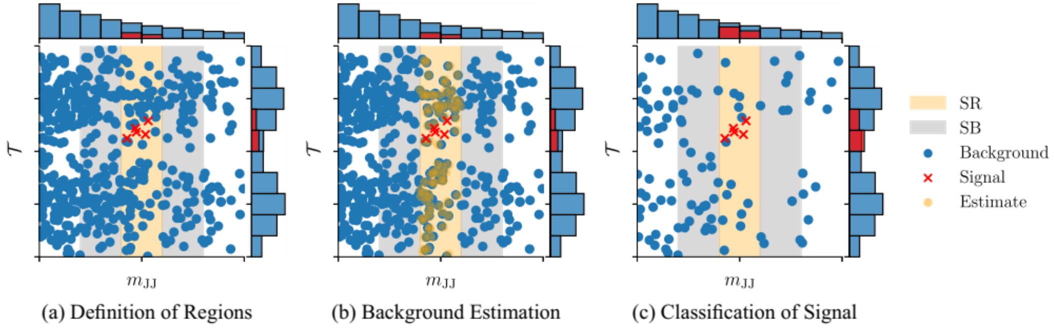
- Strongly-coupled hidden dark sector via resonant production of a mediator Z´ can create invisible/semi-visible jets.
- Supervised technique with Particle Flow Network & semi-supervised anomaly detection are independently considered.
- Cutting-edge AI allows us to search to highly unconventional signatures.





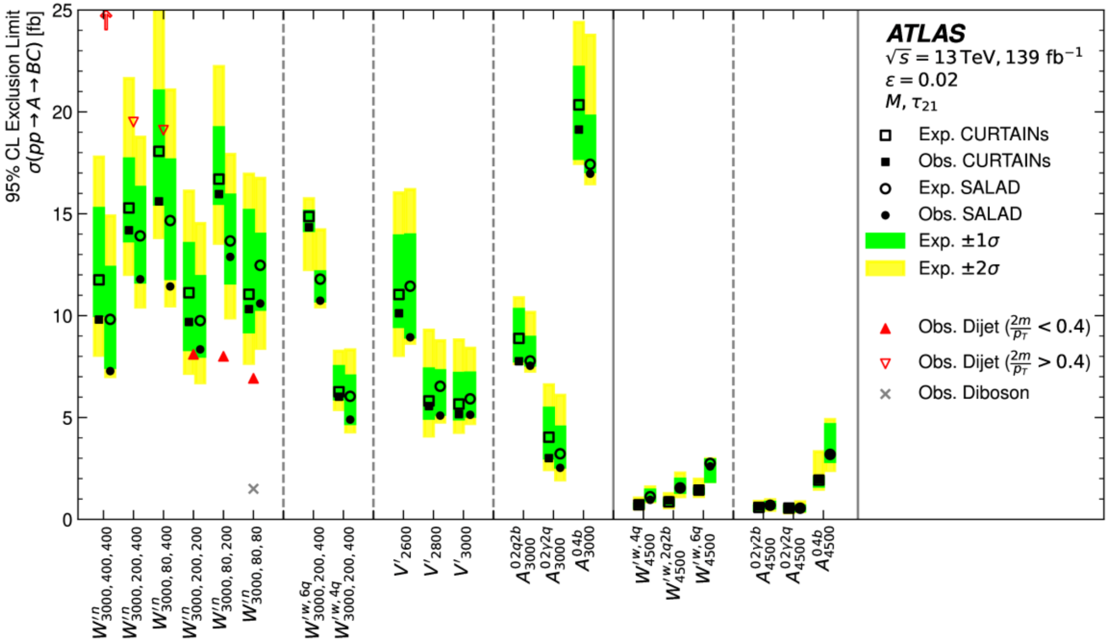
Anomaly Detection in Boosted Dijets

Subsets of observables (e.g. jet mass, substructures)



(a) Definition of Regions (b) Background Estimation (c) Classification of Signal

Phys. Rev. D 112 (2025) 072009

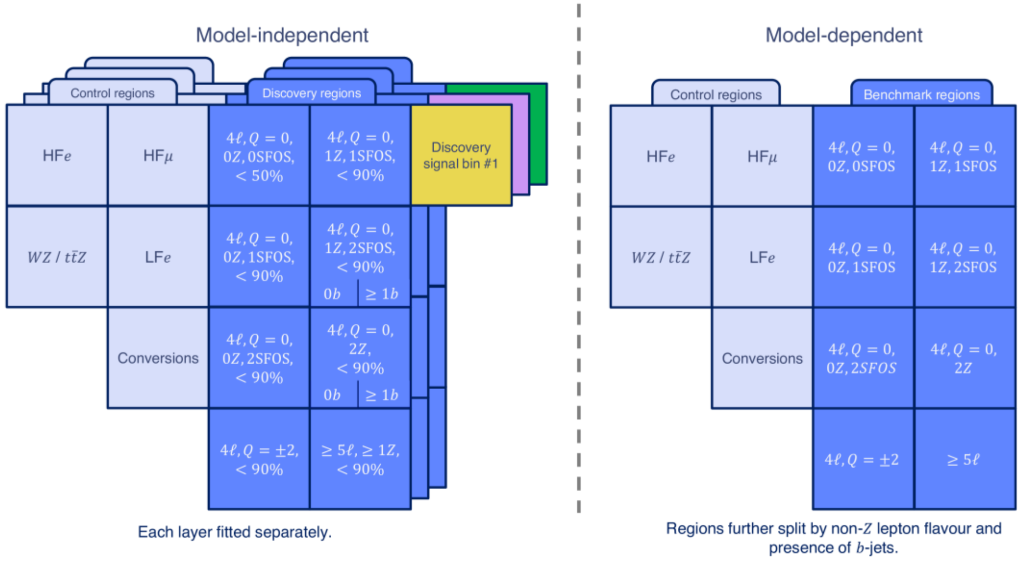


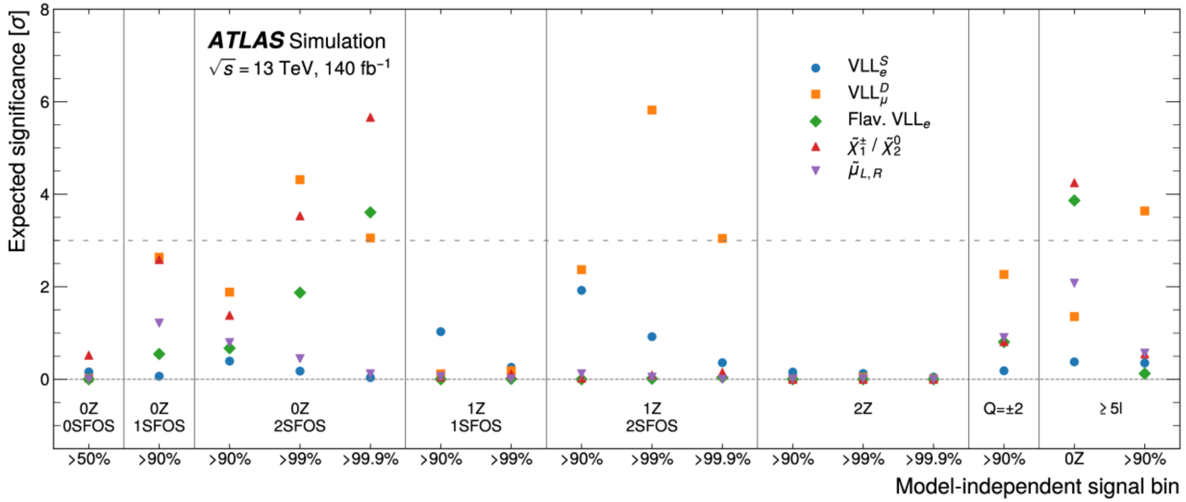
1. Define signal region & sideband
2. Create BG template from sideband using SALAD (simulated prior) or CURTAINs (fully data-driven)
3. Train weakly supervised ML classifier to suppress BG & enhance the fraction of signal (CWOLA paradigm)
4. Perform statistical inference in the signal region

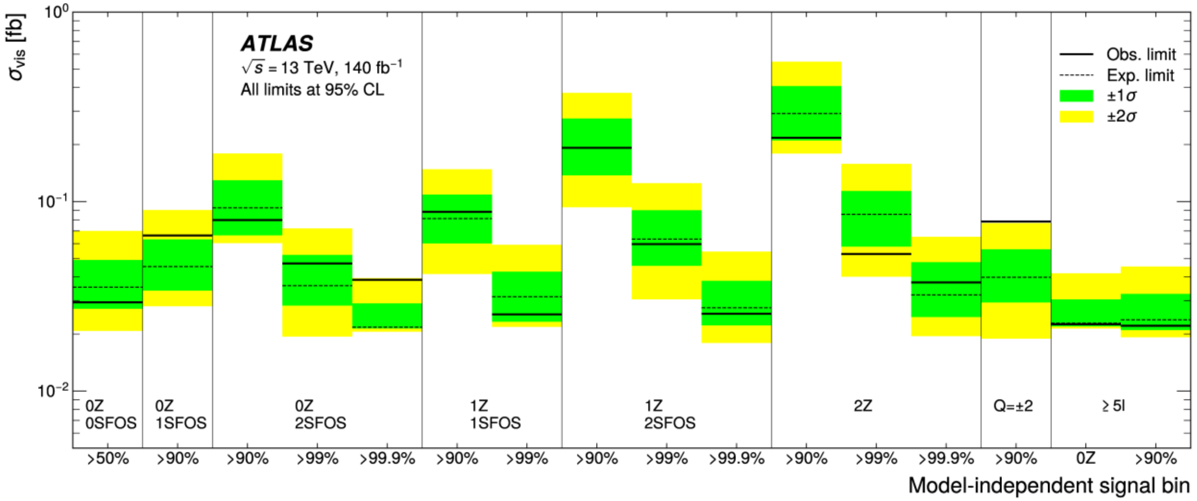
- No significant excess is seen.
- The obtained limits are generally at the same level of magnitude as the previous results but are improved by an order of magnitude for large daughter mass difference cases.

Anomaly Detection in ≥4-lepton Events

arXiv:2508.19778







- Model-independent analysis used an event-level **unsupervised anomaly detection based on normalizing flows**.
  - The flow is trained on the BG MC only with high-level kinematic variables.
- Small excess in 4-lepton SR with a total charge of ±2.

See talk by Chen Zhou

Towards HL-LHC

Andreas Hoecker

	Bunch intensity [protons / bunch]	β* [cm]	Peak lumi [$cm^{-2}s^{-1}$]	Pileup ⟨μ⟩	Int. lumi / year [fb^{-1}]
LHC design	$1.15 \cdot 10^{11}$	55	$1 \cdot 10^{34}$	23	30
LHC today	$1.6 \cdot 10^{11}$	60/18	$2.2 \cdot 10^{34}$	64	120
HL-LHC	**$2.2 \cdot 10^{11}$**	**15**	**$5–7 \cdot 10^{34}$**	**140–200**	**up to 300**

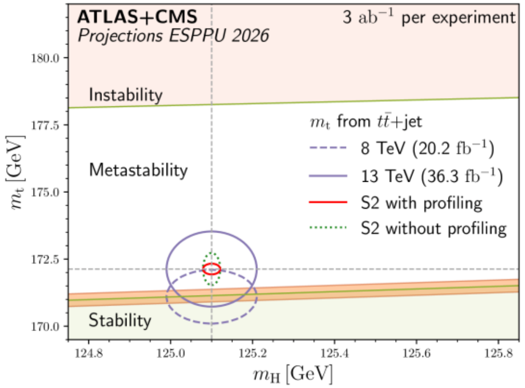
Improved crygenic cooling and collimators, make all systems more radiation hard

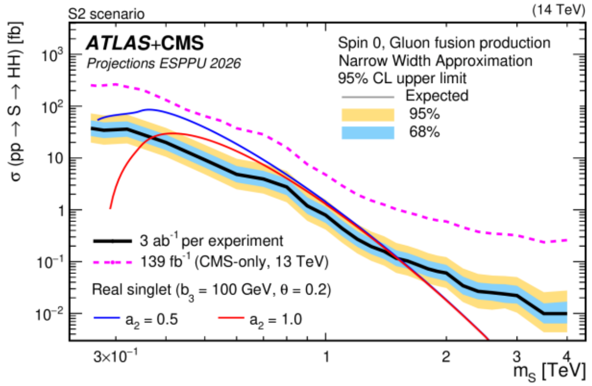
Stronger focussing: 12 new Nb_3Sn "inner triplet" quadrupoles at ATLAS & CMS (aperture: 70 → 150 mm, B-field: 8 → 11.5 T)

RF crab cavities to restore effective head-on collisions, LIU high-brightness programme during LS2

- HL-LHC is aiming to collect >2500 fb^{-1} of data in 9 years: **LHC+HL-LHC → 3 ab^{-1}**
- Phase-II detector upgrade is actively ongoing, to cope with the HL-LHC conditions & enhance capability with innovative technology.
- HL-LHC will provide unprecedented precision for measurements & sensitivities to BSM!

ATL-PHYS-PUB-2025-018, CMS-HIG-25-002





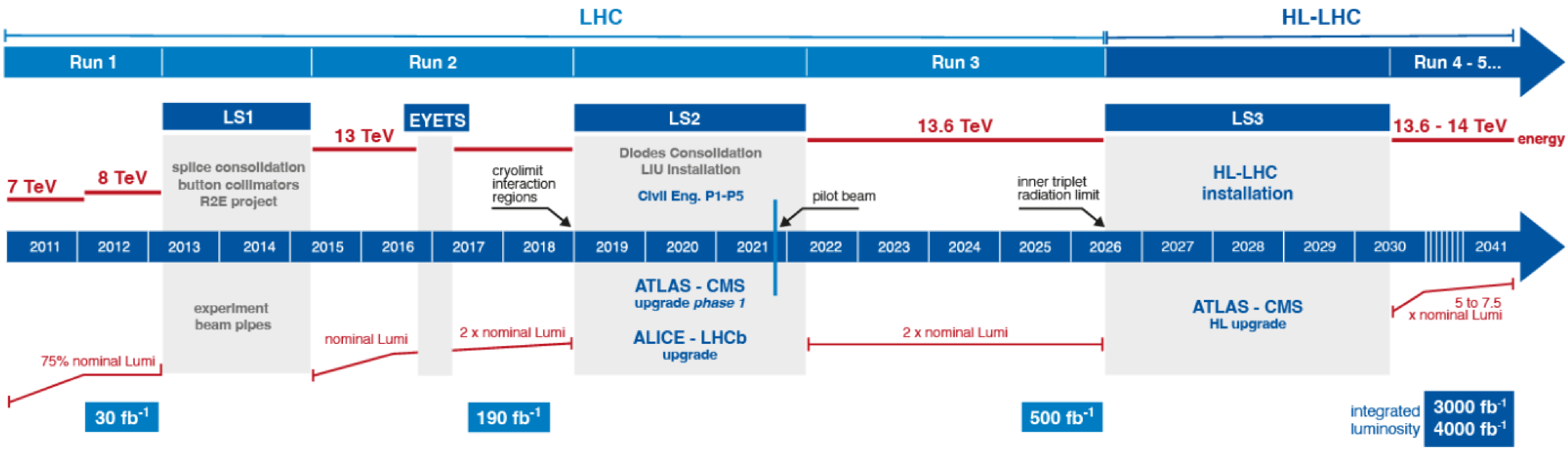
Summary

- Presented selected highlights of new physics searches from various perspectives.
- There are small excesses in various channels. Further investigations & inter-experimental consistency checks are mandatory.
- Foreseeing the complete LHC/HL-LHC program, we have only looked at <~10% of the expected dataset so far!
- With the innovations from the detector upgrades & analysis techniques (particularly AI), rich physics programs are still waiting ahead.

For the full list of LHC excesses, see: https://lhc-bsm-wg.docs.cern.ch/excesses/

Backup

LHC & HL-LHC Schedule



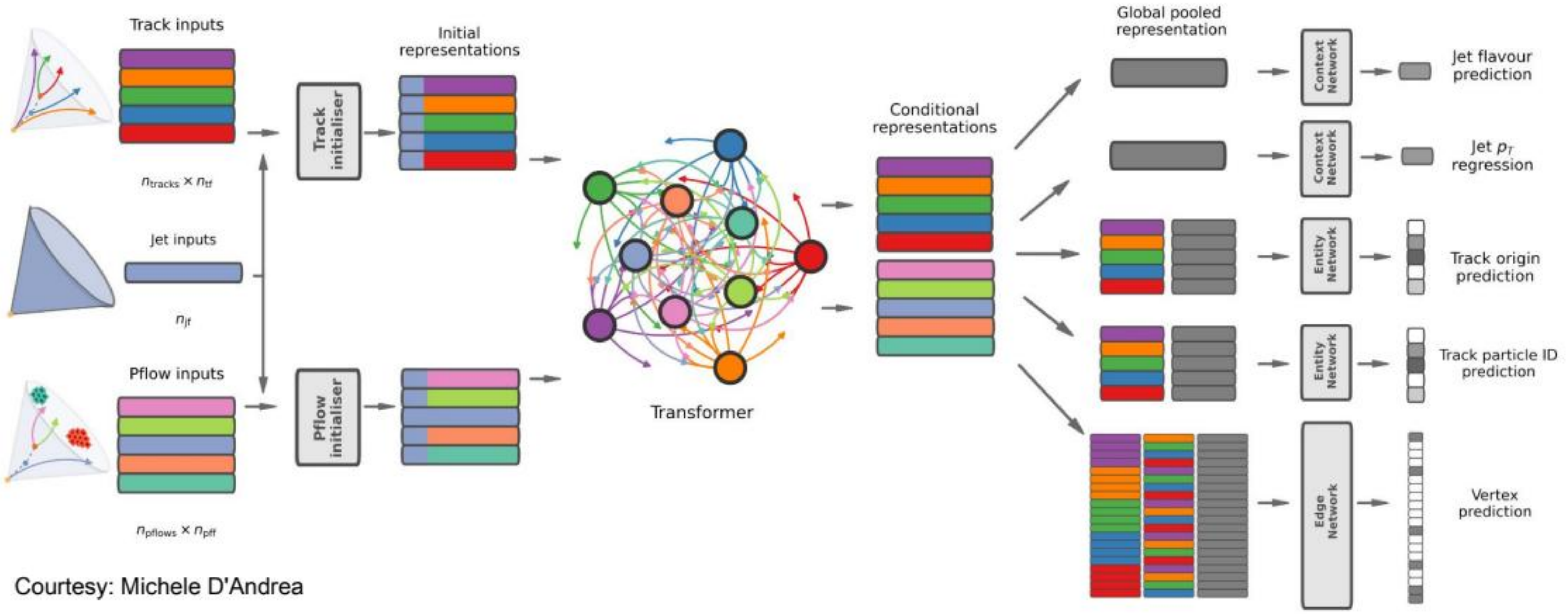
List of LHC Excesses

ATLAS

Physics Group	Final state	Nature of excess	Local (global) significance [σ]	Dataset	Reference	Does the other experiment see it?
HMBS	Compressed sleptons $\to$ 2L	m($\mu\mu$) 5-10 GeV 2.0 (SR2-BDTmm5+10)	2.4	Run 2	HMBS-2024-64	
HMBS	Compressed EWKinos $\to$ 2L	mll ~ 20GeV (SR-E)	2.7	Run 2	SUSY-2018-16	yes SUS-19-012
HMBS	EWKinos $\to$ multib	2017 in SR with MET>200 Meff>860	2.6	Run 2	SUSY-2020-16	
HMBS	VBF Charged Higgs $\to$ 2-3L	mH = 375GeV	3.3 (2.5)	Run 2	HDBS-2023-19	
HMBS	Charged Higgs $\to$ cb	mH+ = 130 GeV	3	Run 2	HDBS-2019-24	
HMBS	VBF Diboson $\to$ 1L2j	mT ~ 1.5TeV	2.8	Run 2	HDBS-2018-10	
EXO	dE/dX		3.6	Run 2	SUSY-2018-42	
EXO	displaced HNLs	mN of 5 GeV in the 2QDH model	3.1	Run 2	EXOT-2022-12	
EXO	high mass dilepton resonance	ee+1b	2.6	Run 2	EXOT-2018-16	
EXO	dijet with isolated lepton		2.6	Run 2	EXOT-2018-32	
EXO	TLA dijets	at 650 GeV	3.4	Run 2	EXOT-2018-39	
HDBS/ HMBS	g2HDM flavourful	mH = 900 GeV and couplings ρ_{tt} = 0.6, ρ_{tc} = 0.0, and ρ_{tu} = 1.1	2.8	Run 2	HDBS-2020-03	
HIGP	Resonant X $\to$ HH combination (4b, bb$\gamma\gamma$, bb$\tau\tau$)	mX=1.1 TeV	3.3 (2.1)	Run 2	HDBS-2023-17	
HIGG/HIPG	Low mass X $\to$ $\gamma\gamma$	95 GeV	1.7	Run 2	HIGG-2023-12	
HIGG/HIPG	LFV in Higgs decay ($\mu\tau$ and $e\tau$)	BR(H $\to$ $\mu\tau$) - BR(H $\to$ $e\tau$)	2.5	Run2	HIGG-2019-11	

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/FTAG-2025-01/

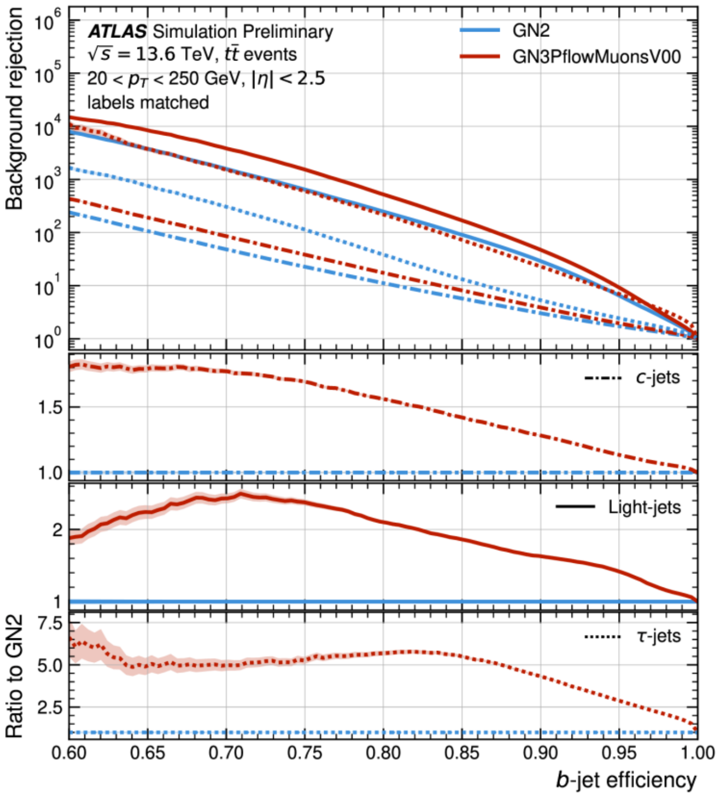
GN3 Tagger

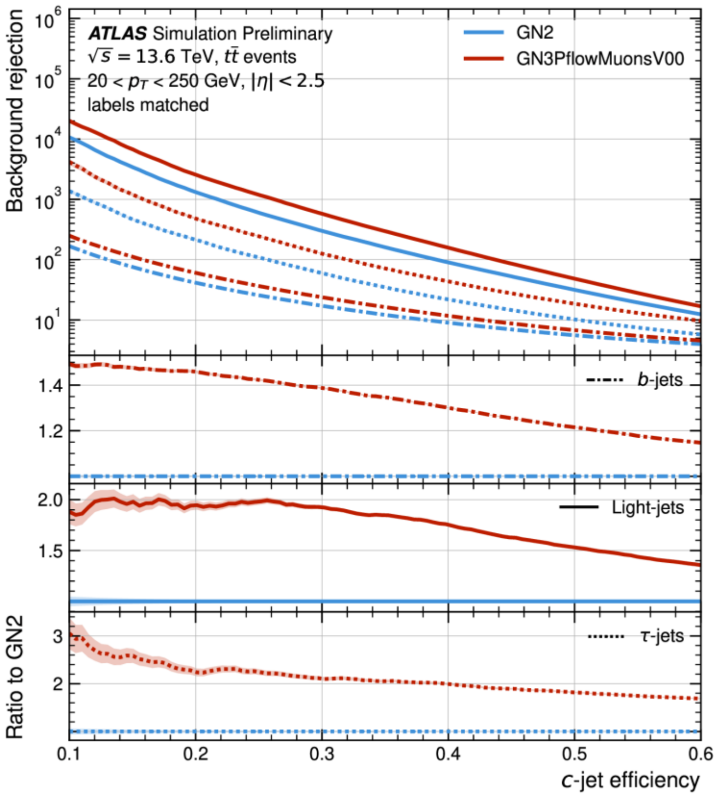


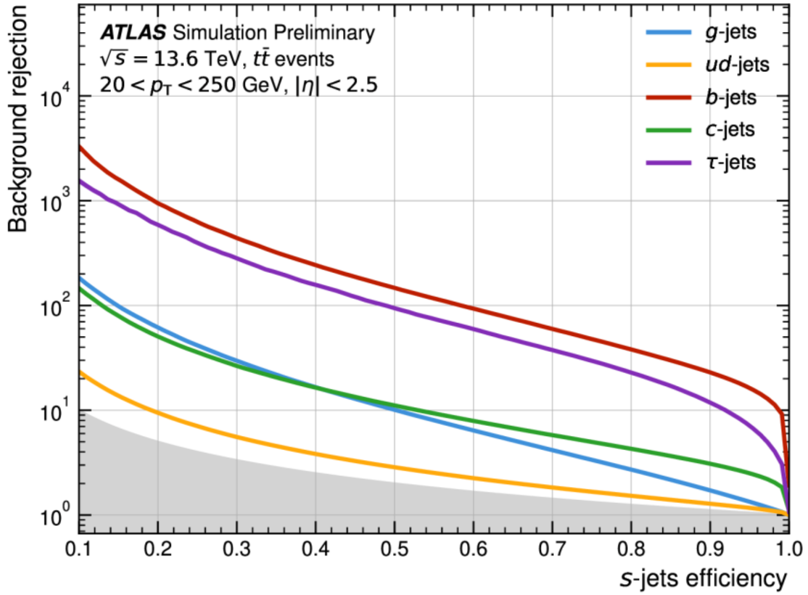
Courtesy: Michele D'Andrea

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/FTAG-2025-01/

GN3 Tagger







Component	GN2	GN3
Track–jet association	ΔR–based association	Ghost-association
Track selection	d_0 < 3.5 mm, 40 tracks	d_0 < 5 mm, 50 tracks
Inputs	Jets and tracks	Jets, ghost-associated tracks, soft muons, PFlow objects
Activation function	ReLU	SiLU
Initialisation layers	256	512
Transformer encoder	4 scaled dot-product attention	4 Flash Attention, Gated Linear Units, 8 register tokens
Embedding dimension	256	512
Jet classification	4 classes: b, c, ℓ, τ	6 classes: b, c, ud, s, g, τ
Loss balancing	Fixed weights per task	Geometric mean of losses (GLS)
Optimiser	AdamW	Lion

Higgs Invisible Decay / Higgs-portal