Exotics and BSM (non SUSY, non DM) in ATLAS and CMS

Corfu Summer Institute: Workshop on the Standard Model and Beyond

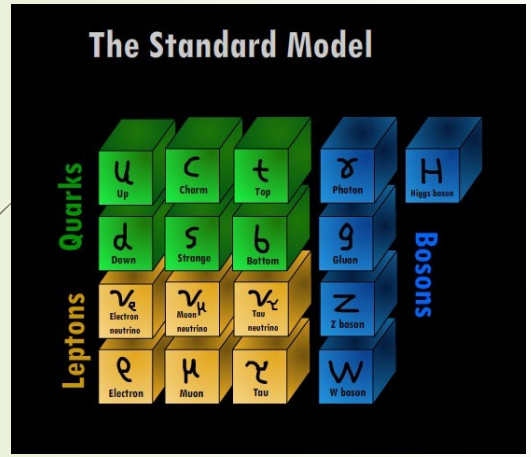
25 August to 4 September 2024

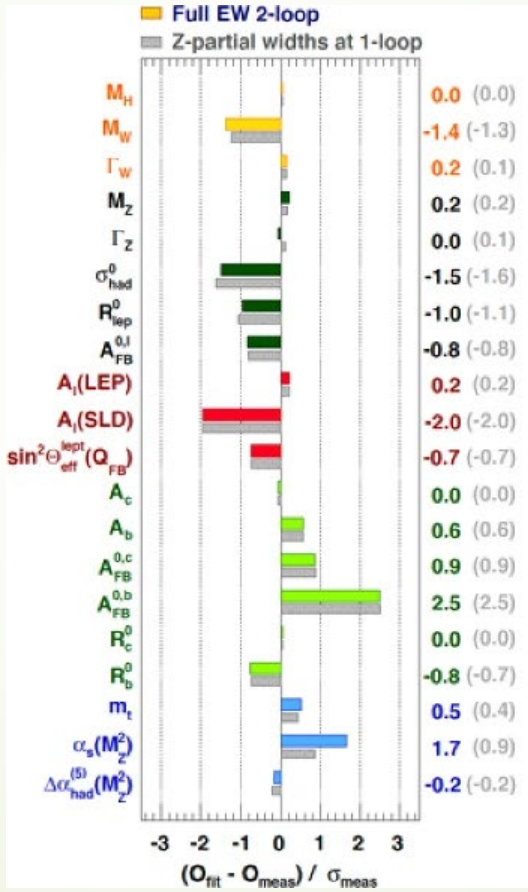
Andrea Perrotta (INFN Bologna)

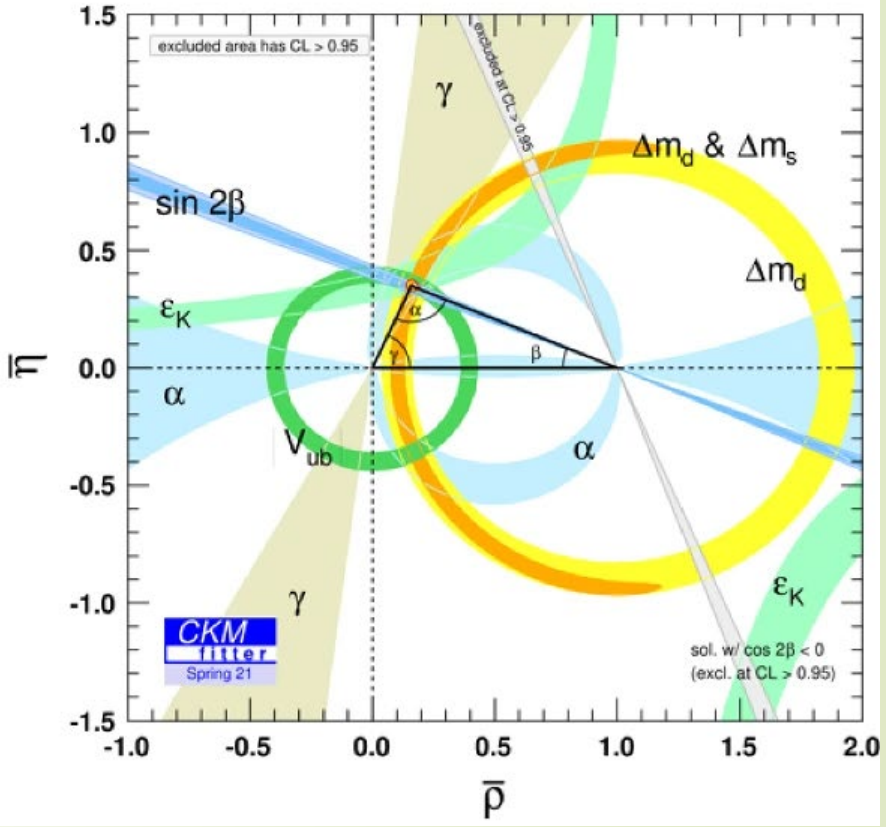
on behalf of the CMS and ATLAS collaborations

Why to look for new Physics?

- SM extraordinarily successful in describing the World we live in







Harlander, R., Martinez, JP. & Schiemann, G. "The end of the particle era?". *EPJ H* **48**, 6 (2023)

Why to look for new Physics?

- SM extraordinarily successful in describing the World we live in
- Still, several observations suggest that this cannot be the end of the story
  - Neutrino masses
  - Baryon/anti-baryon asymmetry
  - Dark mass and dark energy
  - Not to mention the hint of discrepancies appearing in various measurement:
    - g_μ-2
    - nuclear anomalies
    - …

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    - …
- Also theoretically a few questions remain unanswered and make the SM an "un-natural" theory
  - Why three generations?
  - Hierarchy problem
  - …

Which kind of new Physics to look for?

- The SM must be an "effective theory" that extends into something more general in some so far unattaigned energy scale
- Many extentions of the SM have been invented to cope with its weaknesses while trying to remain in agreement with the experimental observations:
  - Supersymmetry (SUSY)
  - Extra-Dimensions
  - Compositeness
  - LeptoQuarks
  - Vector-like quarks
  - …

Supersymmetry (SUSY)

- Very well studied and formalized theory
- A lot of theoretical developments
- After LEP we were convinced that it was only the matter of switching on LHC to start getting evidence of SUSY phenomenology
- *Quoting myself from SUGRA2003*:

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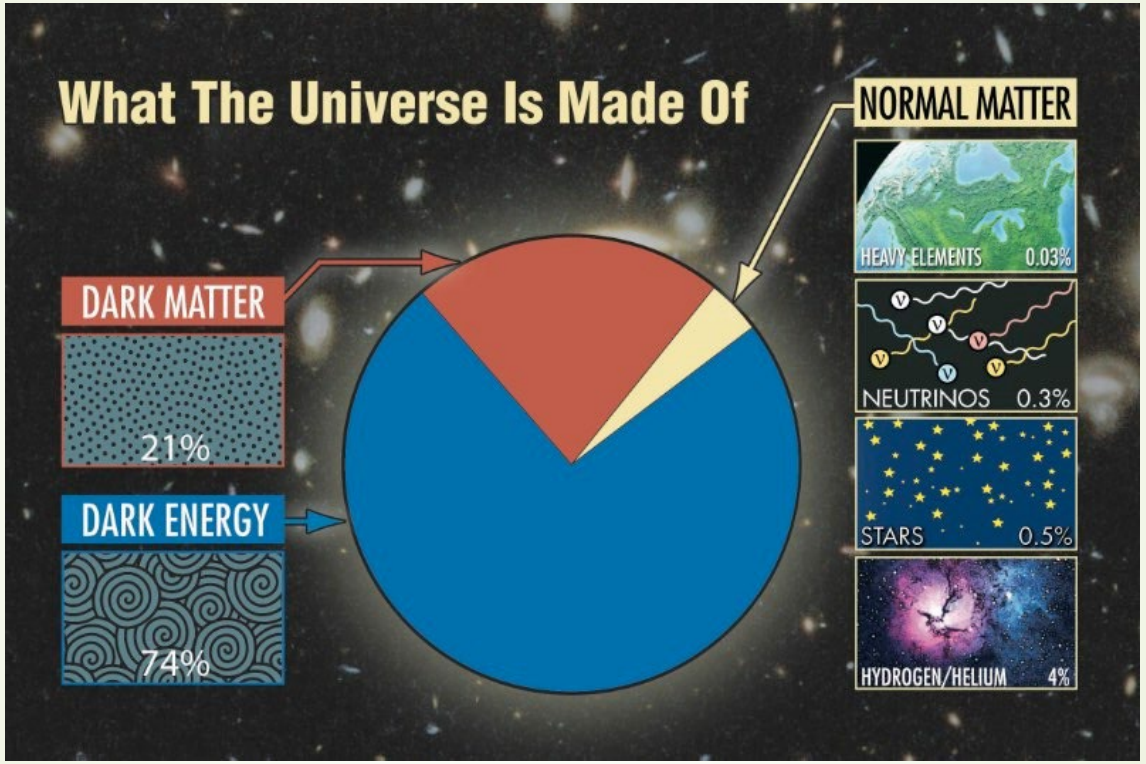
For SUSY searches at ATLAS and CMS see the interesting talk of *Yuya Mino right before mine in agenda*

Searches for Dark Matter



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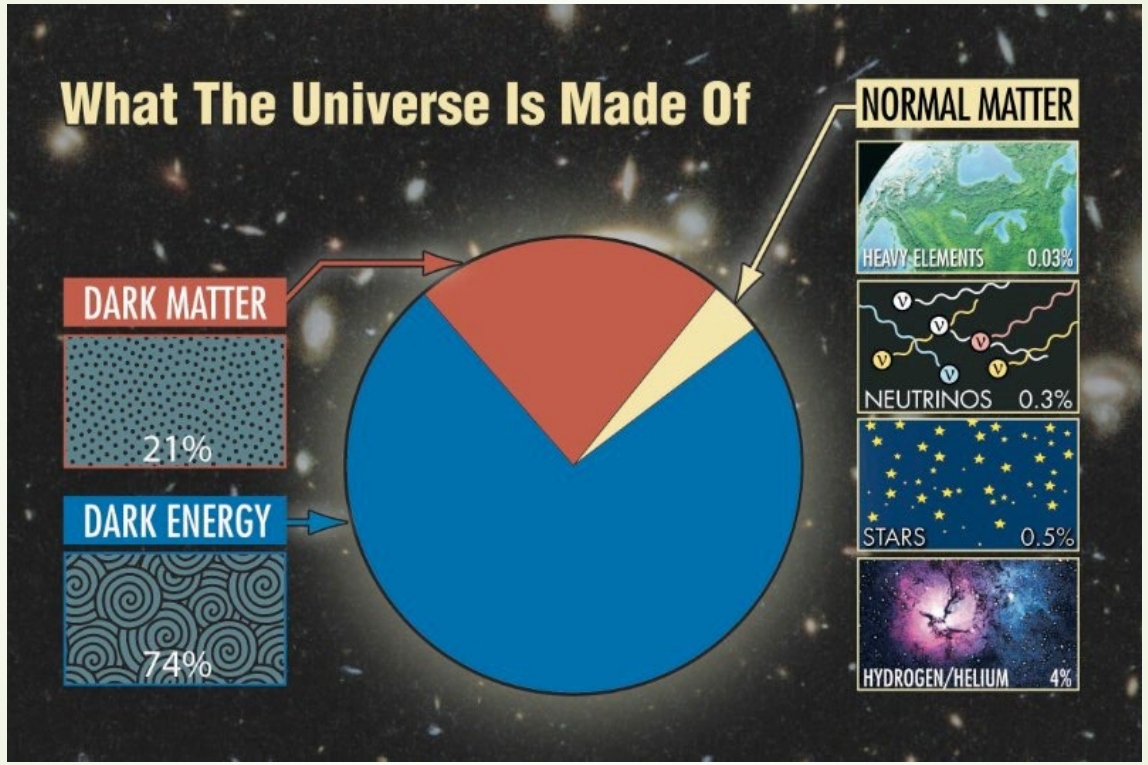
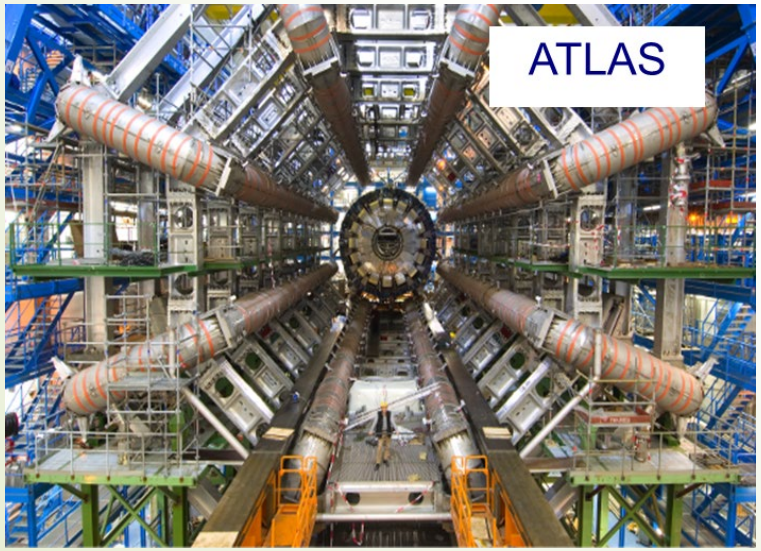
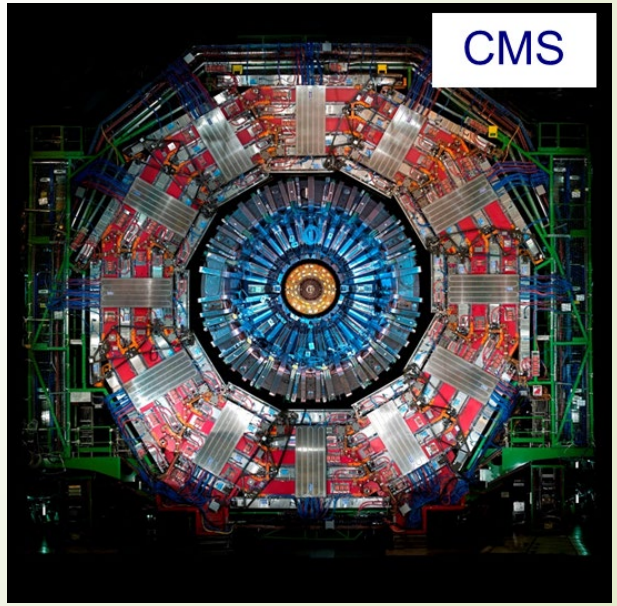


For Dark Matter searches at ATLAS and CMS see the interesting talk of *Xinhui Huang in agenda on Friday*

Where to look for new physics?

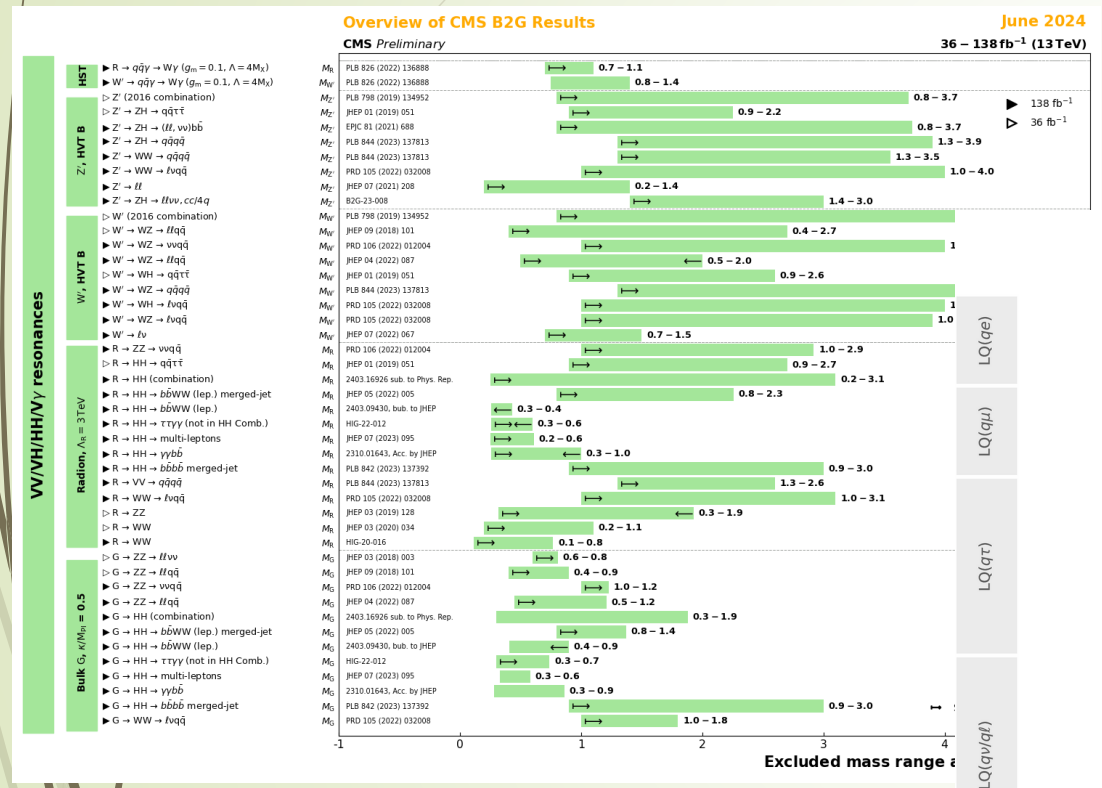
- Of course, quite several different experiments can look for new physics, and we have presentations about them in the agenda of this conference
- The **multi-purpose** experiments **ATLAS** and **CMS** at the **LHC p-p and Heavy Ion collider** are extremely powerful tools intended to explore at 360° the phenomenologies that can witness evidence of new physics (see also the reviews of Alexander Oh and Greg Landsberg from the first day of this conference)





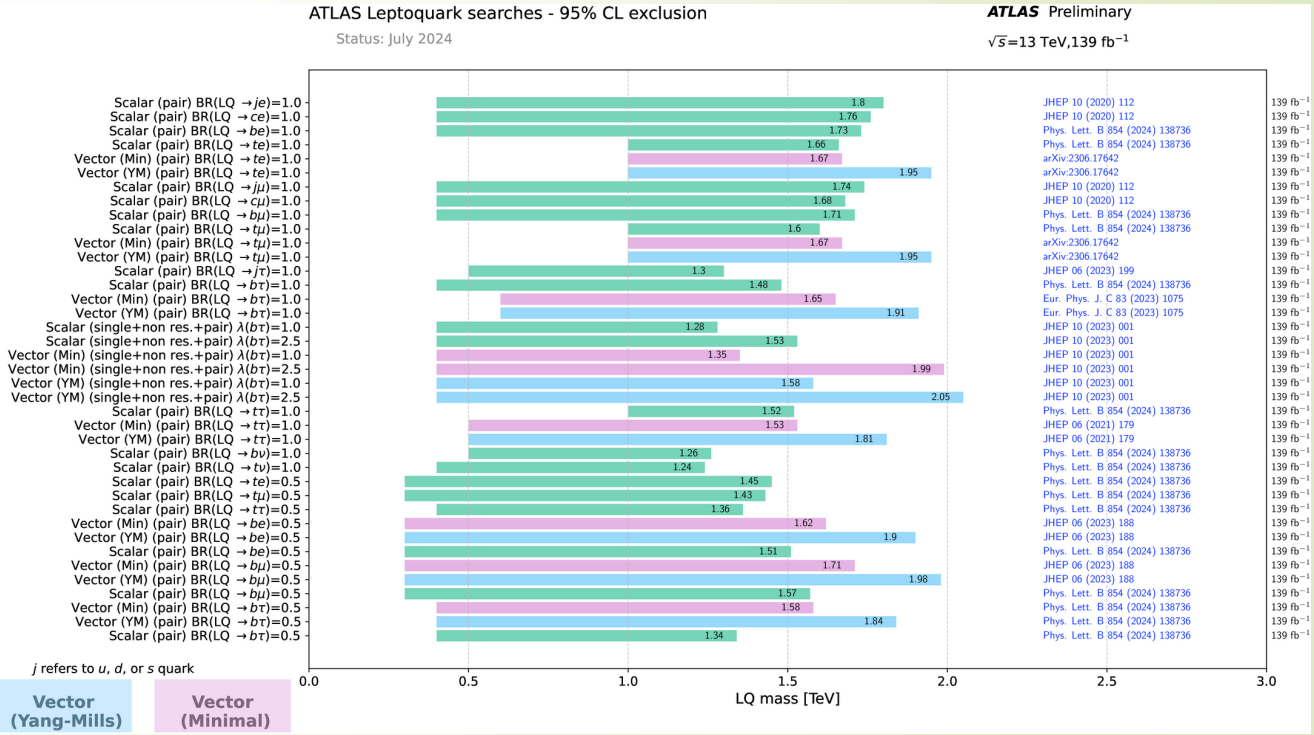
Searches for new physics in ATLAS and CMS

- Mostly done by **hunting for excesses above the SM expectations**



CMS limits from the searches for di-boson resonances

ATLAS limits from the searches for LeptoQuarks



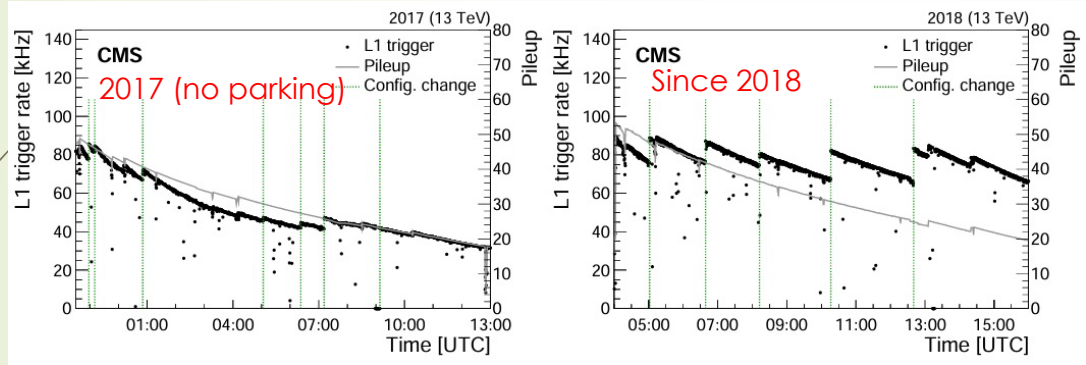
Searches for new physics in ATLAS and CMS

- In these searches one must look for very unconventional signatures: they are therefore an ideal training ground to explore new ideas and methods, attempt new usages of the detectors, and to invent new tools!
  - New triggers
  - Intensive usage of AI/NN techniques
  - Search for long lived particles
  - Identify merged objects
  - Ultraperipheral HI collision used as photon-photon collider
  - Data scouting
  - Data parking tecniques
  - …
- Gain in luminosty and improved detector performances (together with a small E_{cms} increase) enhance the potential of discovery of **LHC Run3** wrt previous LHC runs

arXiv:2403.16134

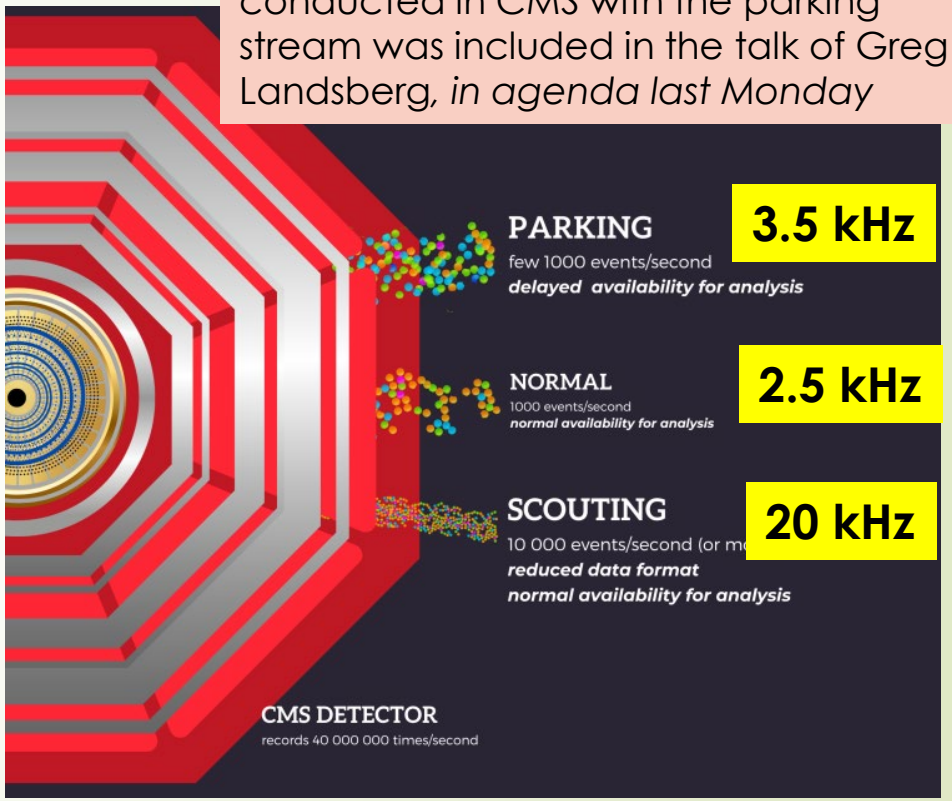
Rethinking data taking strategies

- **Parking Stream** to work around computing constraints: store extra data on tape and reco them when extra computing resources are available



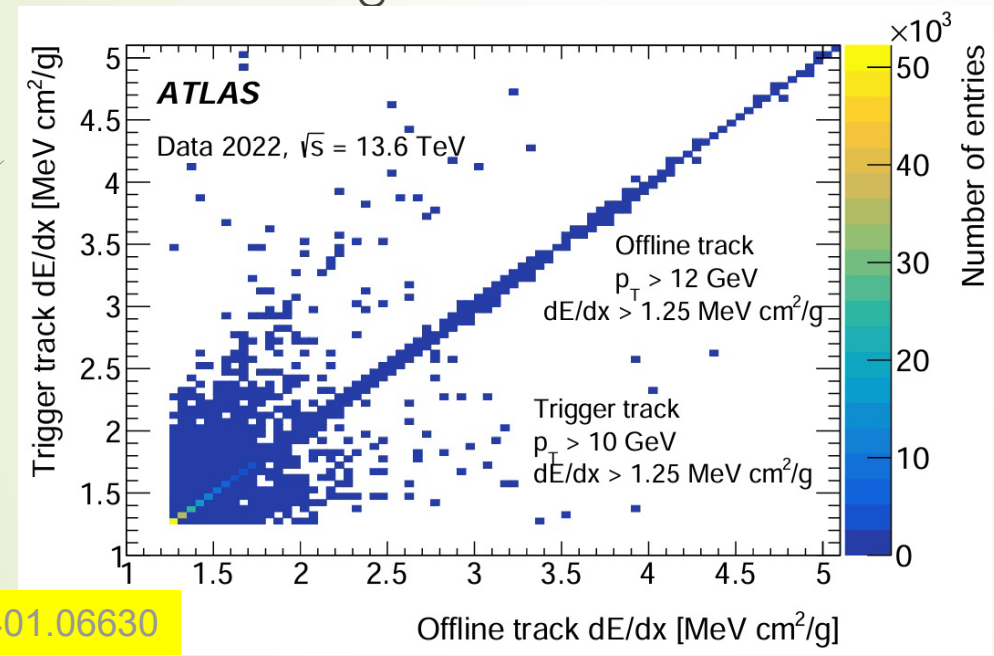
- **Scouting Stream** to work around trigger constraints: store 10 kB of HLT reco objets rather than the full RAW event (~1 MB): it now covers about 20 kHz of the 100 kHz incoming L1T rate

A nice review of a few searches conducted in CMS with the parking stream was included in the talk of Greg Landsberg, *in agenda last Monday*



Innovative Trigger strategies

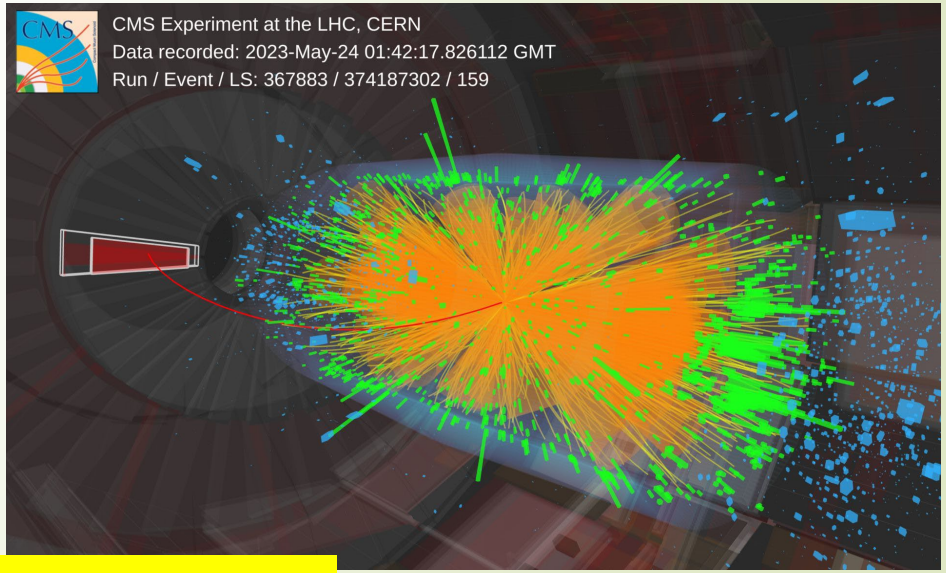
- Trigger is the first, non-reproducible, level of selection
- Triggers for unconventional signatures must be defined before the start of the data taking



arXiv:2401.06630

dE/dx at trigger level, to select Heavy Charged highly ionizing particles

*AXOL1TL **anomaly detection algorithms** for the level-1 trigger based on AI: able to select unique events relative to existing L1T*



CMS-DP-2023-079

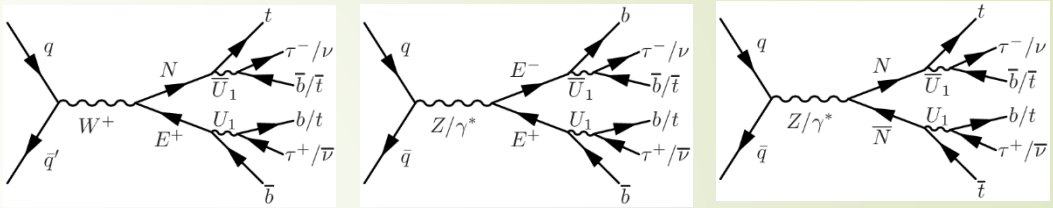
A collection of a few recent results of those searches in ATLAS and CMS

- As prepared by the two Collaborations for the Summer 24 Conferences

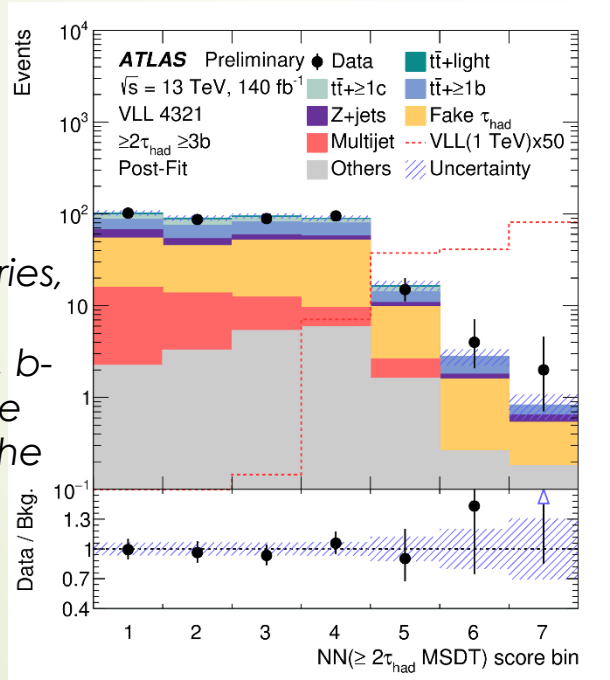
ATLAS-CONF-2024-008

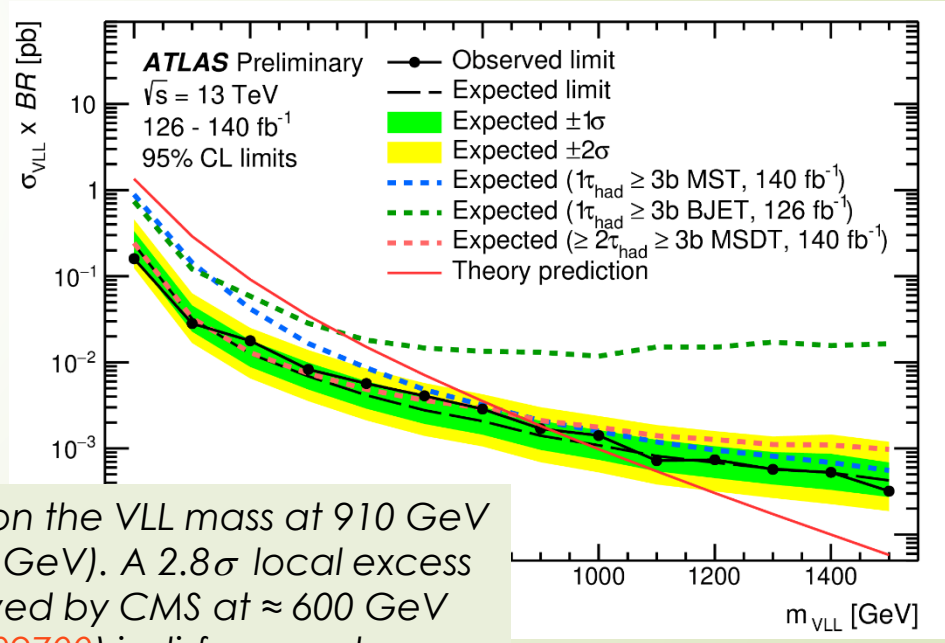
Vector-Like Leptons (VLL)

- Consider their decays into a third-generation SM quark and a vector leptoquark (U_1) as predicted by an ultraviolet-complete extension of the Standard Model ('4321 model', first ATLAS result on this model)



NN applied on five different signal categories, all with a large number of jets, b-jets, τ_h: here the NN scores for the SR [$\geq 2\,\tau_h$, ≥ 3b]

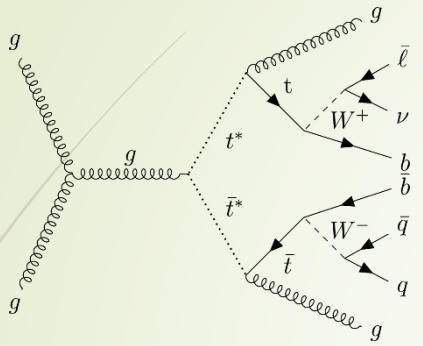




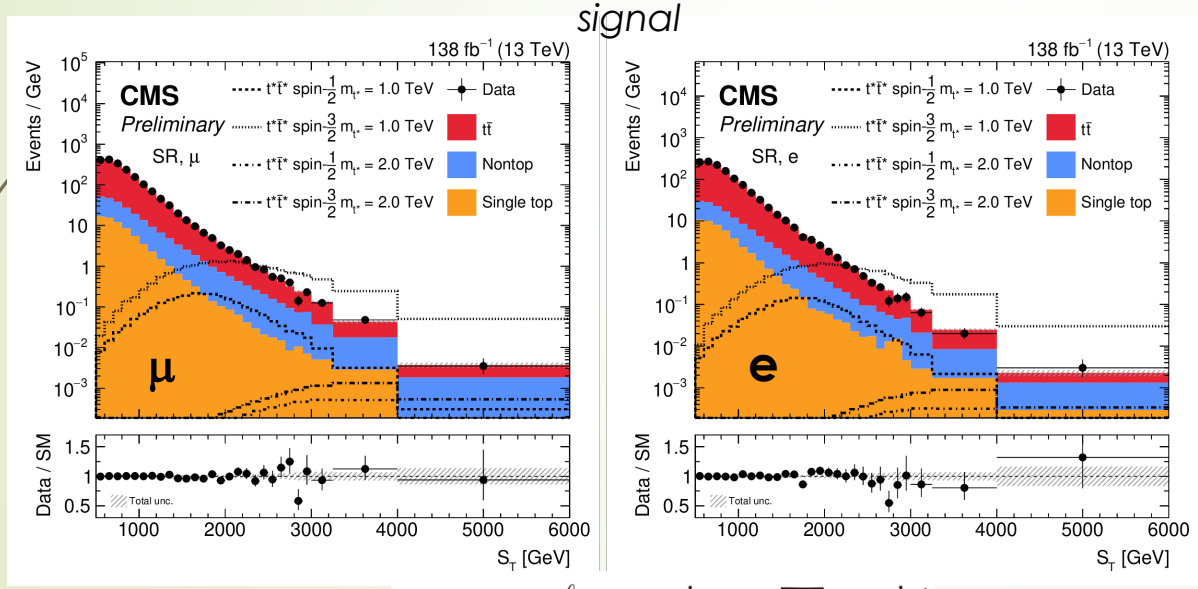
Observed limit on the VLL mass at 910 GeV (expected: 970 GeV). A 2.8σ local excess that was observed by CMS at ≈ 600 GeV (arxiv.org:2208.09700) is disfavoured

CMS-PAS-B2G-22-005

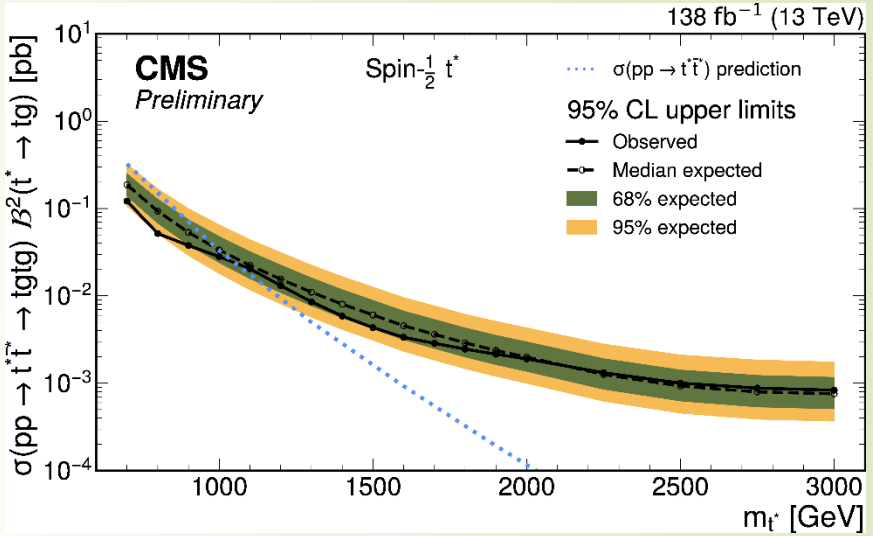
Pair production of excited top (t*)

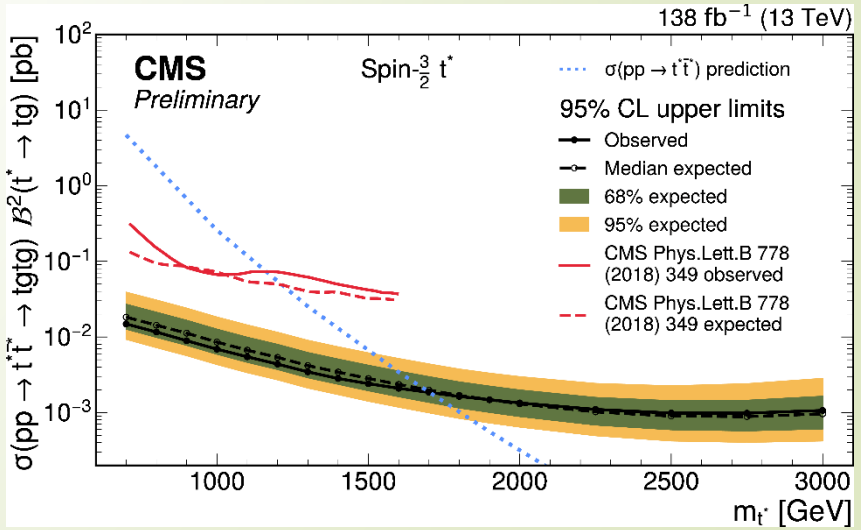


- *Variable-radius jets (with substructures) to describe the hadronic top decays*
- *Use a deep NN to enrich the sample of signal-like events*
- *Analyze distributions in the scalar sum of the transverse momenta of all reconstructed objects in search for a signal*



$$S_{\mathrm{T}} = p_{\mathrm{T}}^{\ell} + p_{\mathrm{T}}^{\mathrm{miss}} + \sum_{i} p_{\mathrm{T},i}^{\mathrm{jet}}$$

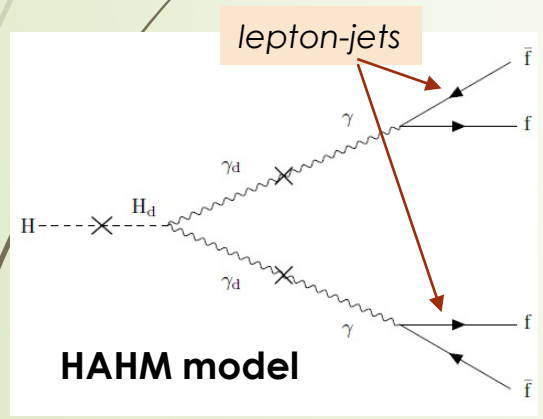


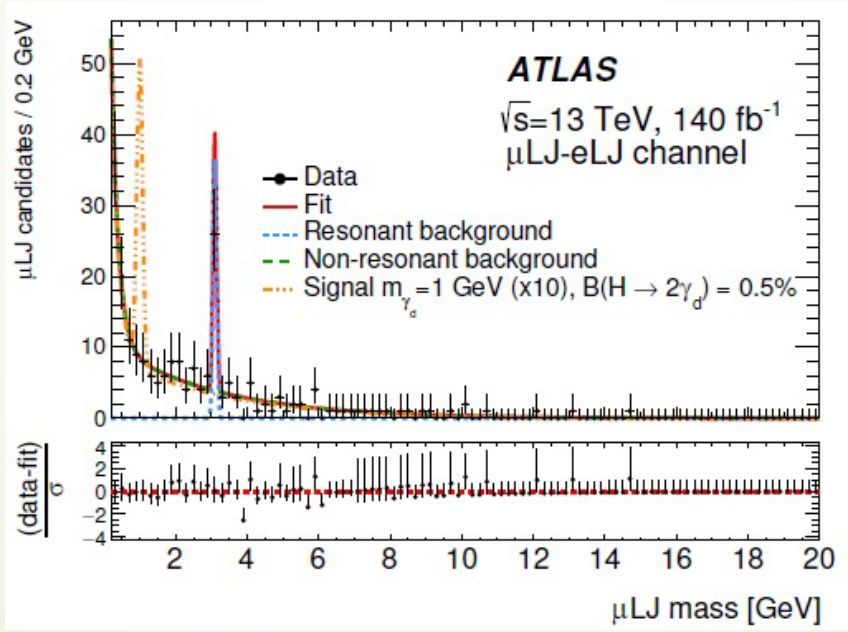


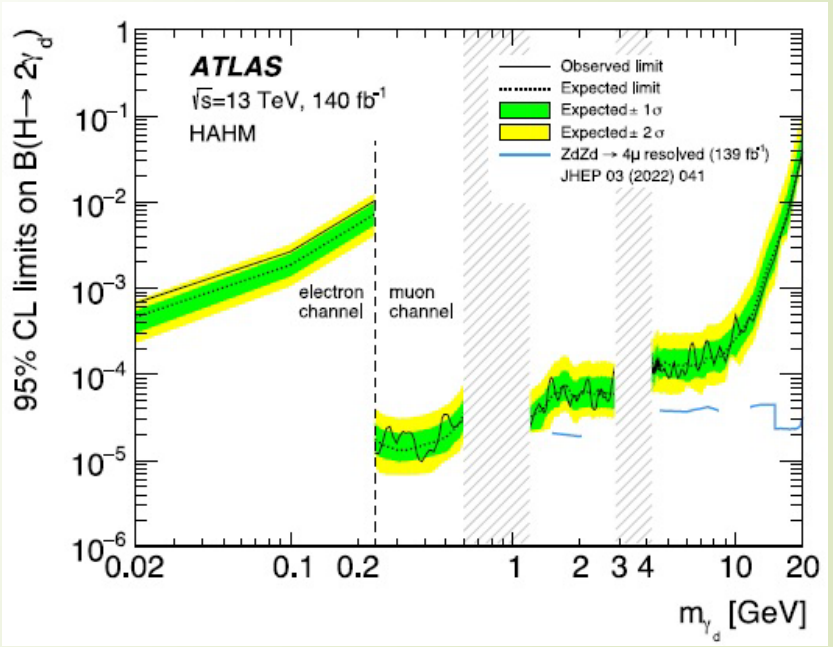
arXiv:2407.09168

Search for neutral particles decaying promptly to collimated pairs of leptons

- A search for a dark photon, a new light neutral particle which decays promptly into collimated pairs of electrons or muons
- Dedicated reconstruction and ID of merged di-lepton pairs

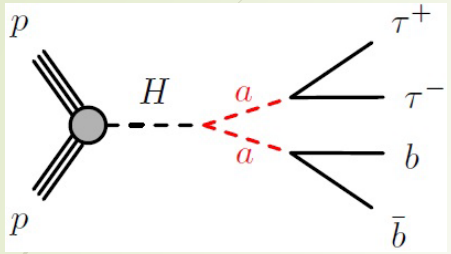




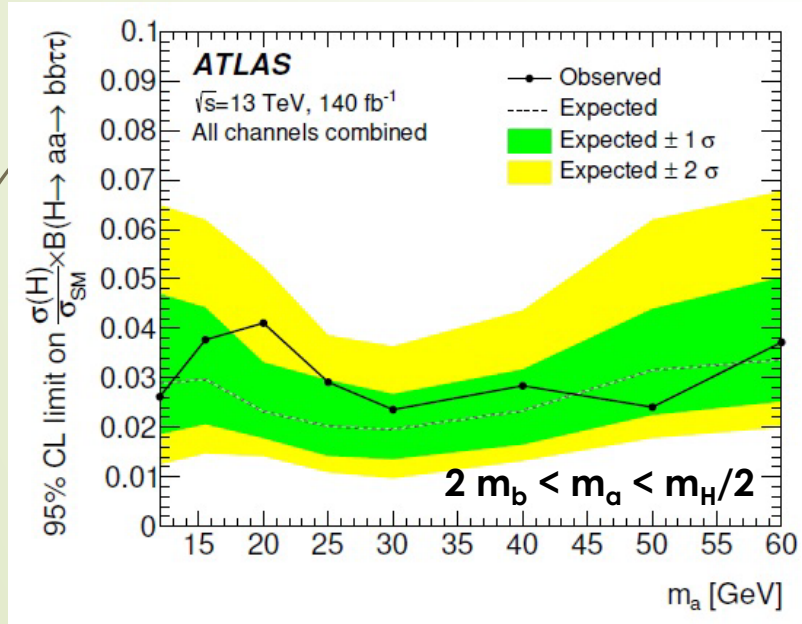


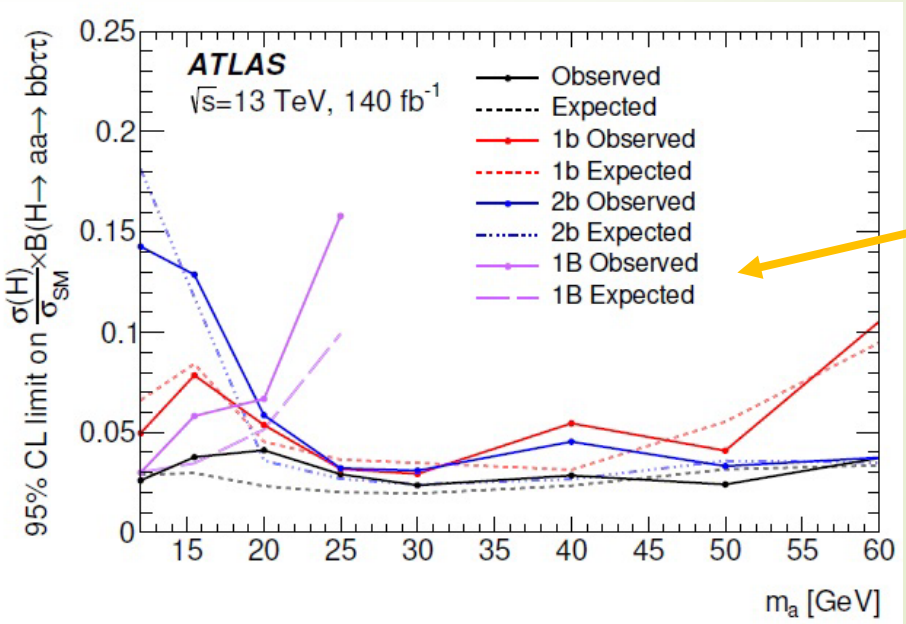
arXiv:2407.01335

Exotic decays of the SM Higgs boson



- Search for decays of the Higgs boson into a pair of pseudoscalar particles decaying into bb$\tau\tau$
- *Different exclusive analysis categories defined depending on the τ-lepton decay mode and the number of b- or B- jets*

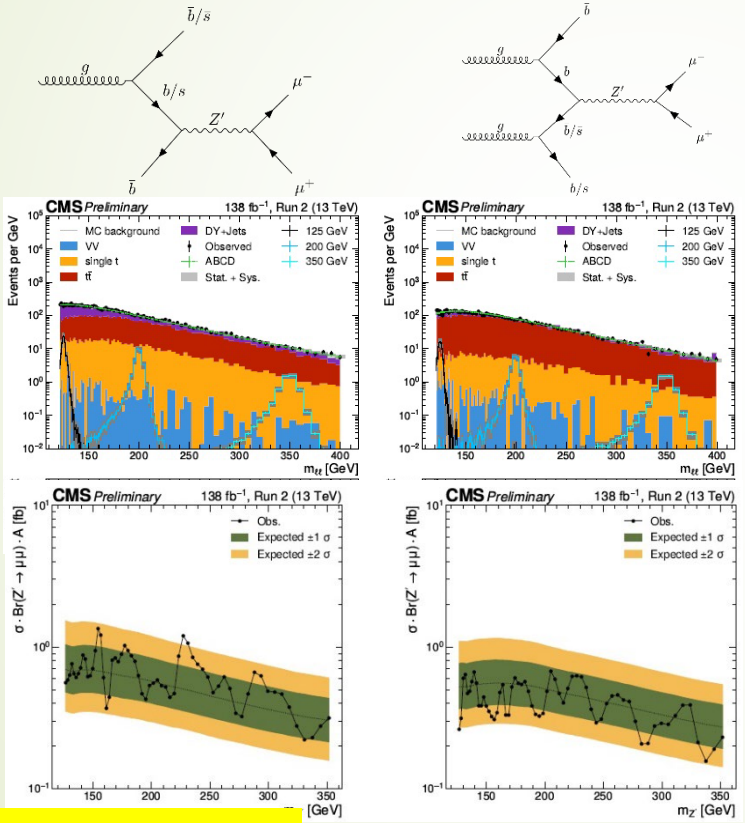




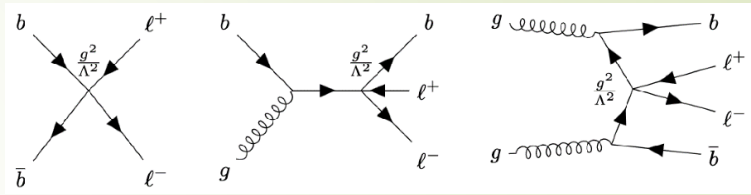
Novel, dedicated algorithm to identify low mass merged, "double b" jets → "1B" category

Searches for energetic dileptons with b-jets

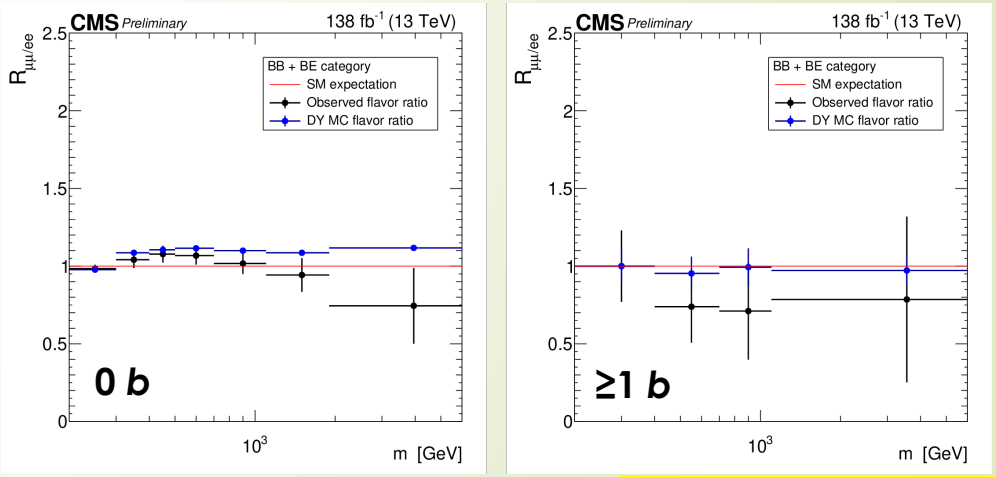
- Tools to study Lepton Flavour Violation and its connection with third quark generation
- Resonant di-lepton (Z') + b-jets



- Non-resonant di-lepton + b-jets



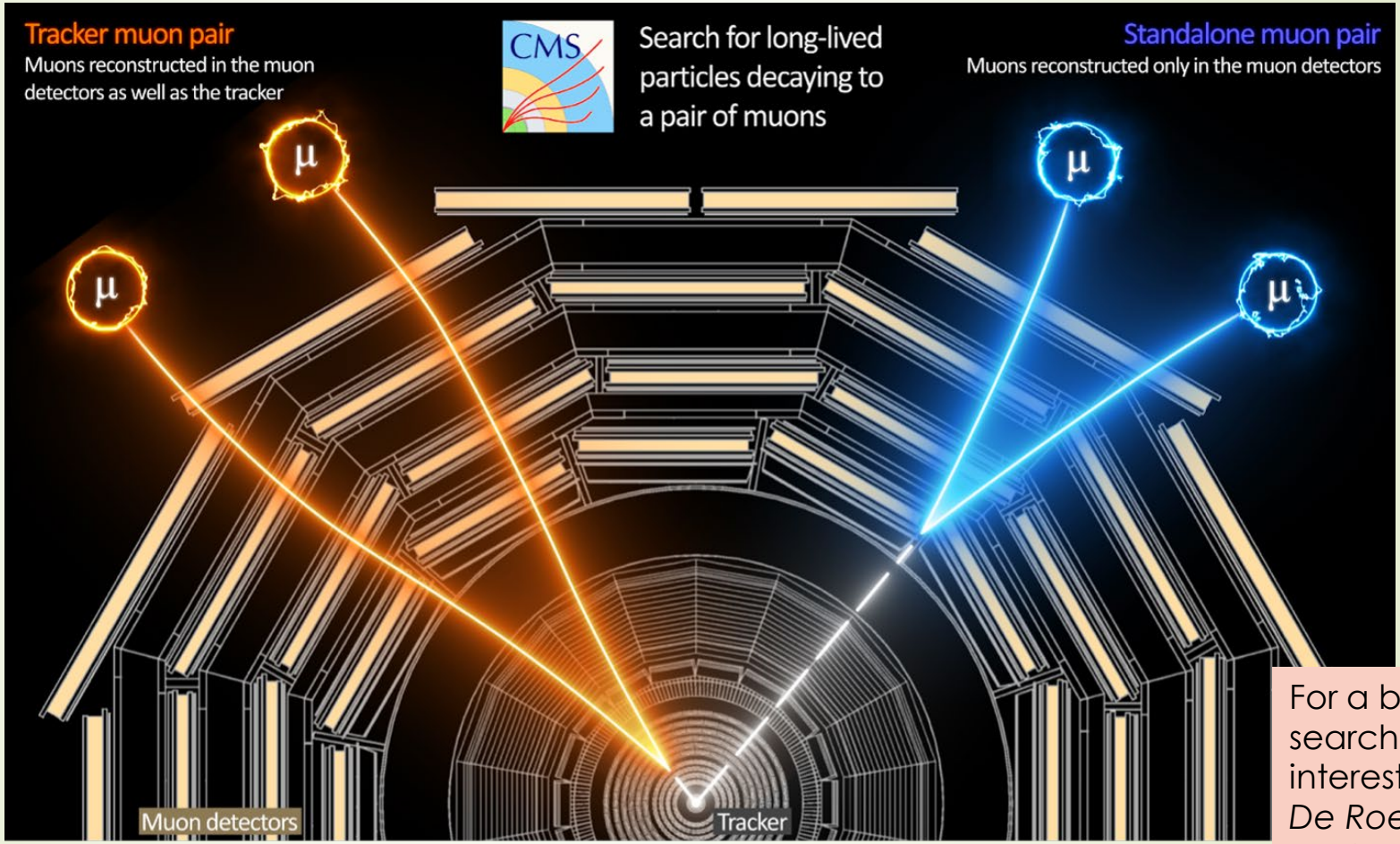
- LFV tested by comparing (unfolded) di-electron and di-muon mass spectra:



CMS-PAS-EXO-22-006

CMS-PAS-EXO-23-010

Searches for Long Lived Particles

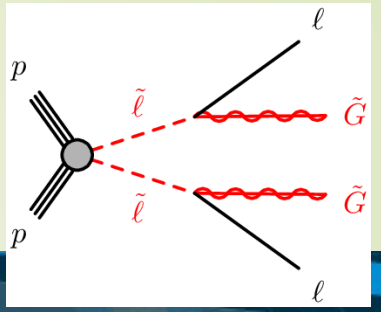


For a broader review of searches for LLP see the interesting talk of *Albert De Roeck, in agenda earlier this morning*

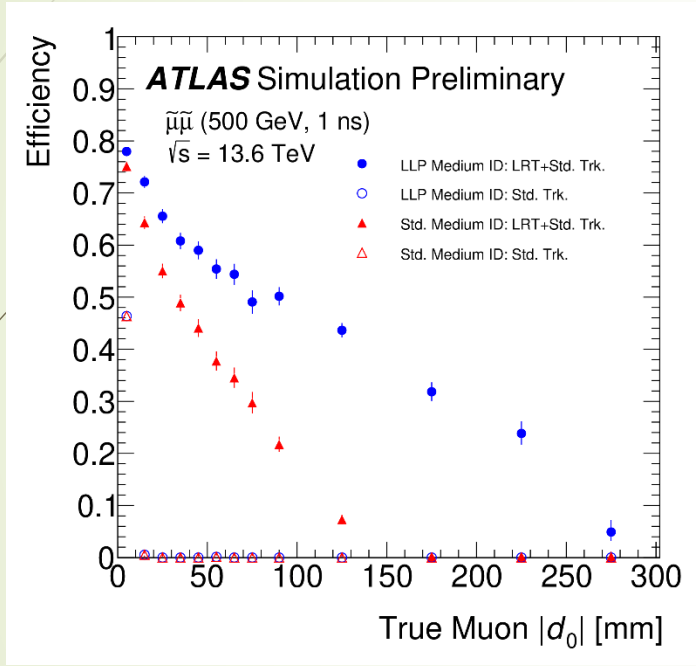
Search for Displaced Leptons

ATLAS-CONF-2024-011

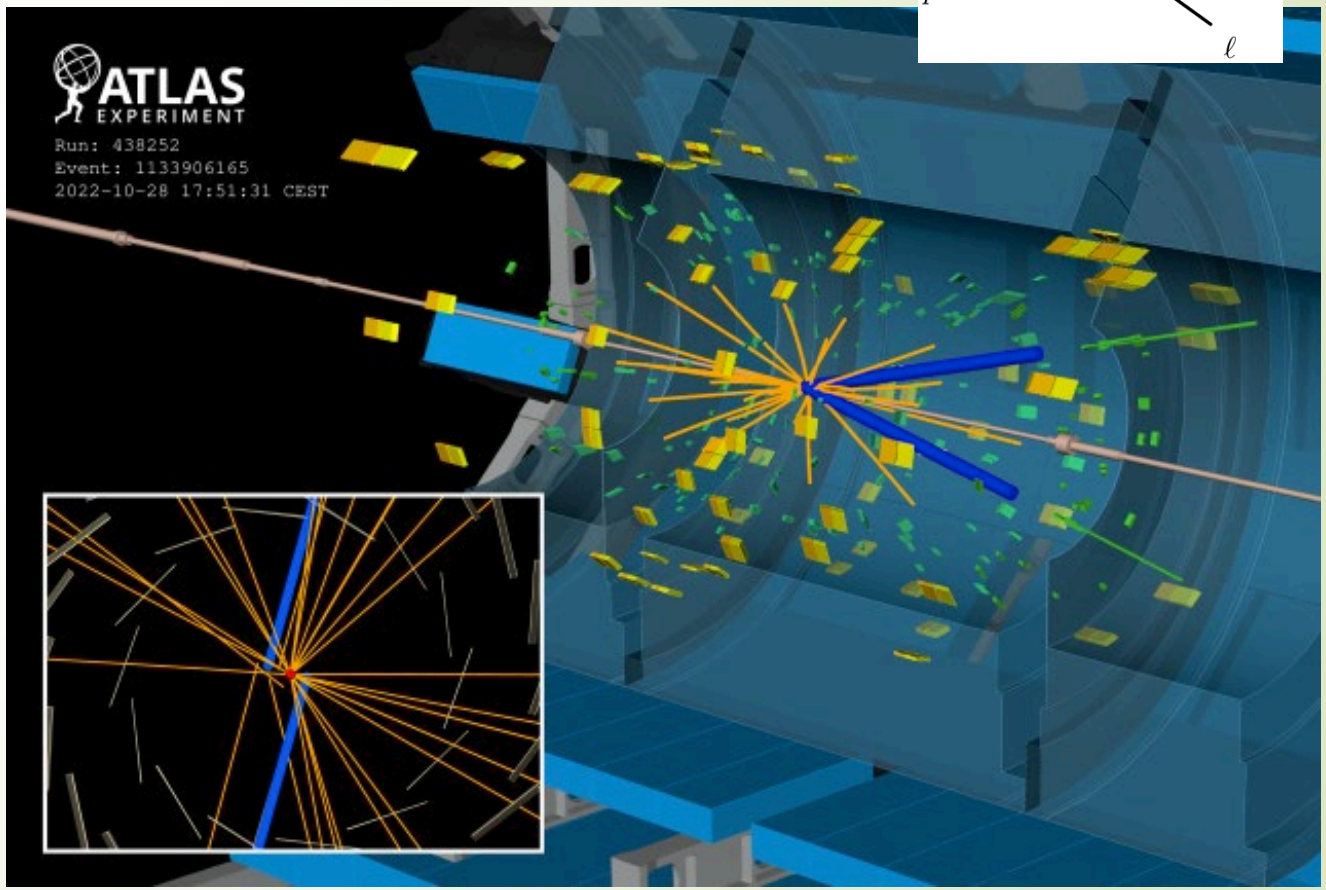
Run2 + (22+23) Run3



- Large Radius Tracking: run in the HLT for the first time at Run 3



Improved tracking efficiency for the decay products of LLPs with LRT



Search for Displaced Leptons

ATLAS-CONF-2024-011

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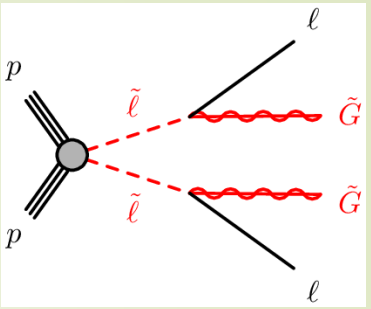

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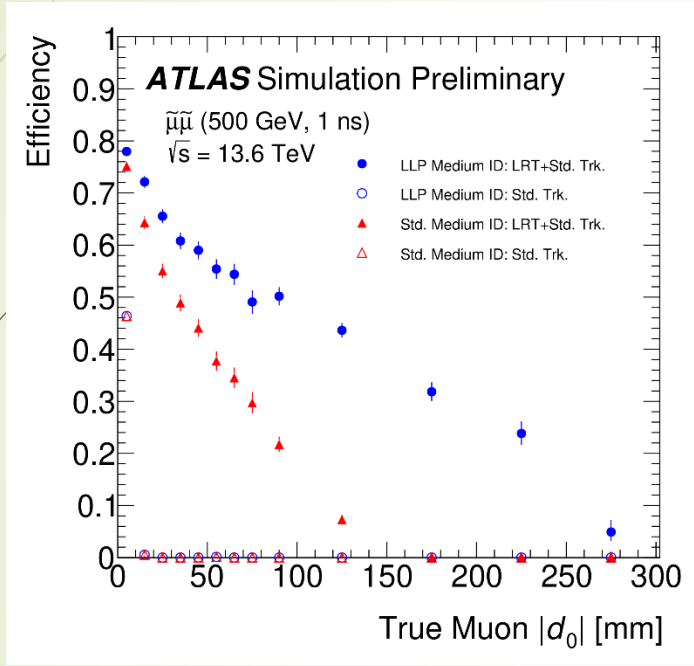
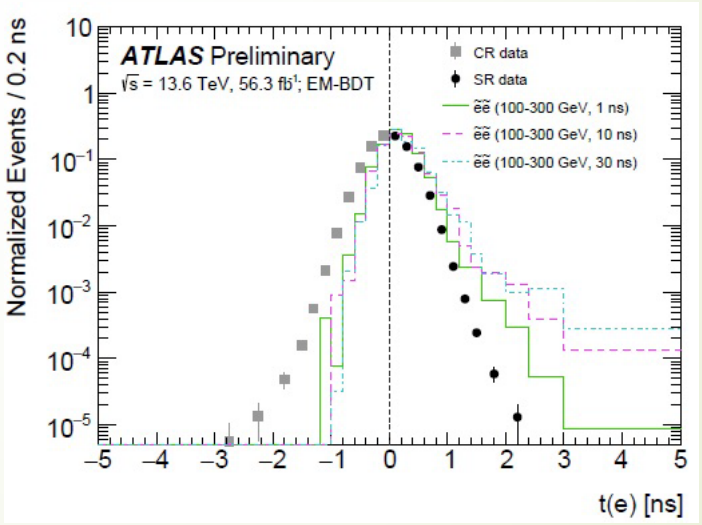
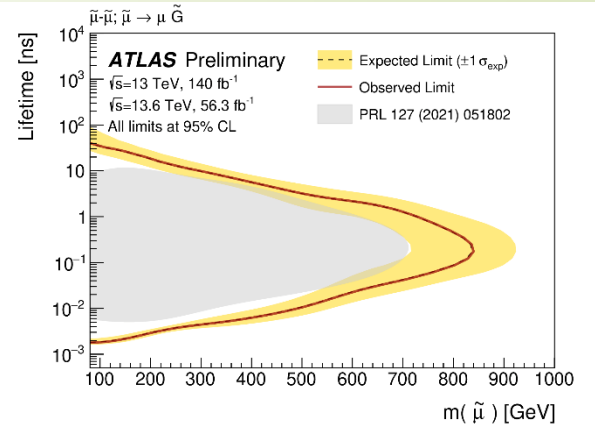


Improved tracking efficiency for the decay products of LLPs with LRT

Enhanced discovery reach beyond prior searches through several novel additions: photon reconstruction, multivariate techniques (EM BDT), …



LAr timing

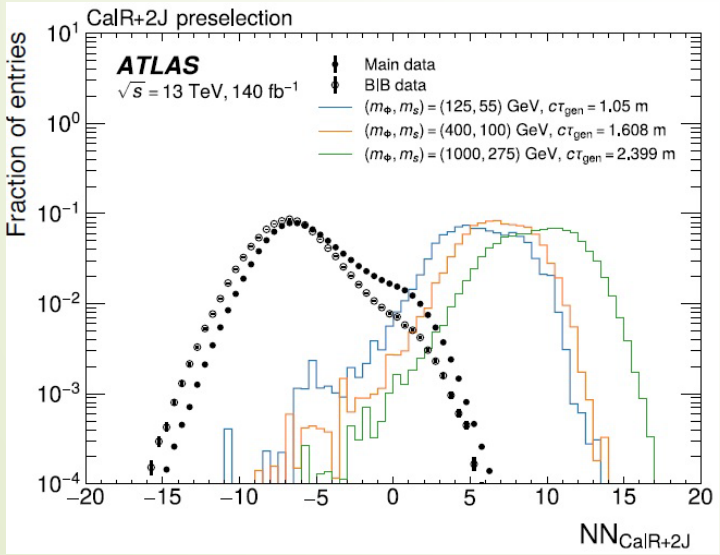


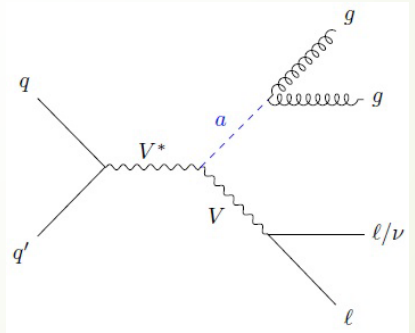
Limits derived for GMSB as a benchmark… but they can be derived also for other exotic models

arXiv:2407.09183

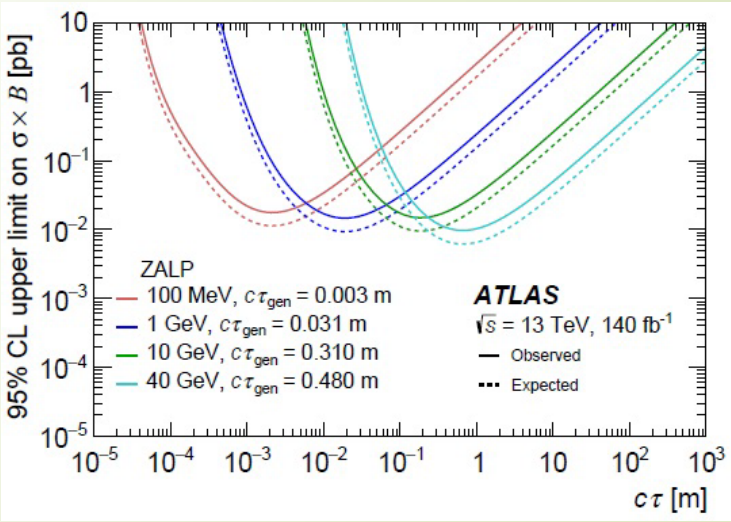
Search for *neutral long-lived particles that decay into* displaced jets in the calorimeters

- LLPs that decay after the electromagnetic calorimeter have very low electromagnetic component: **CalRatio** ("CalR") triggers and tagger
- Three channels: the first targets pair-produced LLPs, where one LLP is produced with sufficiently low boost that its decay products can be resolved as separate jets ("CalR + 2J"); the second and third channels target LLPs respectively produced in association with a W ("CalR + W") or q Z ("CalR + Z") boson that decay leptonically.





Several models tested: here ALPs in "CalR+Z"

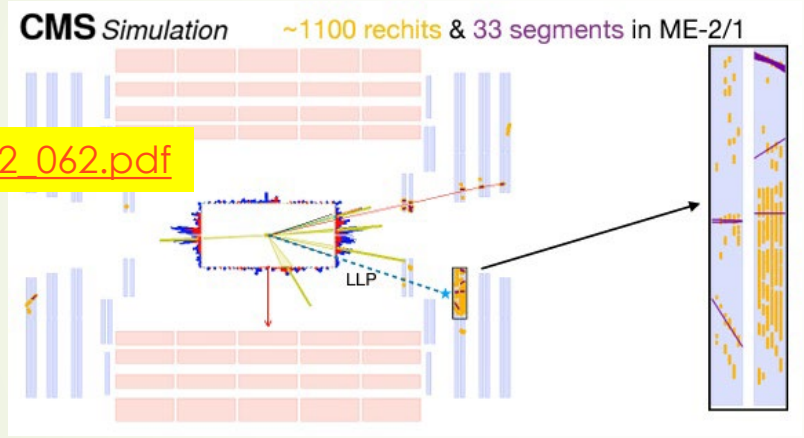


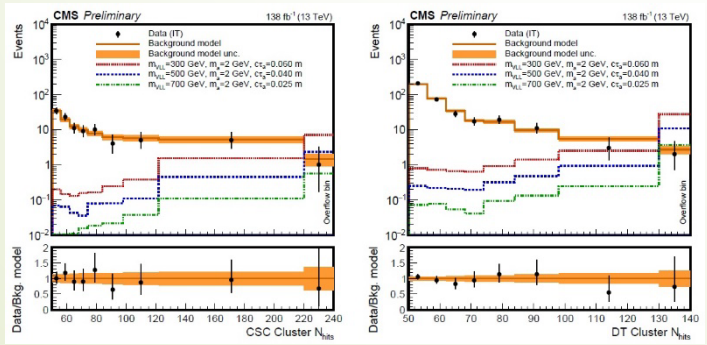
CMS-PAS-EXO-23-015

Search for decays in the muon detectors

- Muon Detector Showers: cascade of secondary particles produced by high energy particles crossing the muon detectors

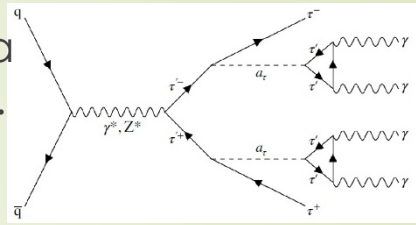
CMS-DP2022_062.pdf

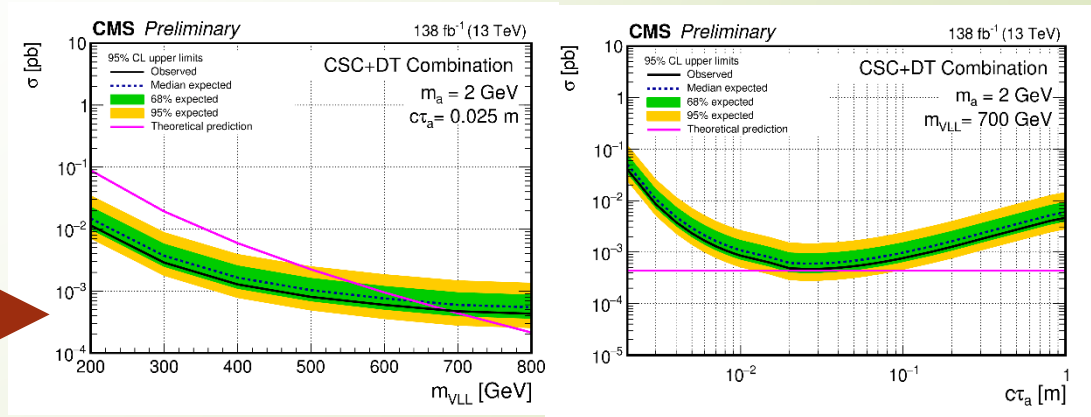




Nr of hits in clusters for CSC/DT

- Search for vector-like leptons (VLLs), which in turn decay into a long-lived pseudoscalar and a standard model τ lepton. The pseudoscalar exclusively decays into a pair of photons, and is identified using the Muon Detector Shower signature

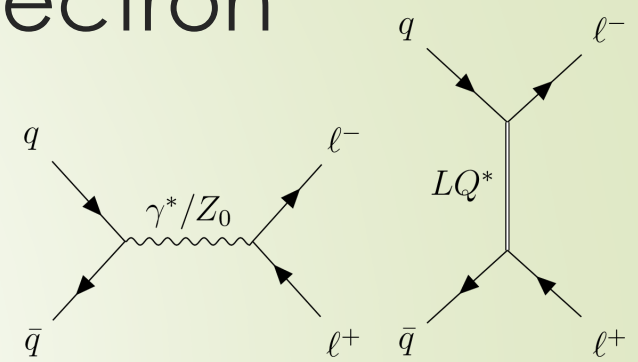


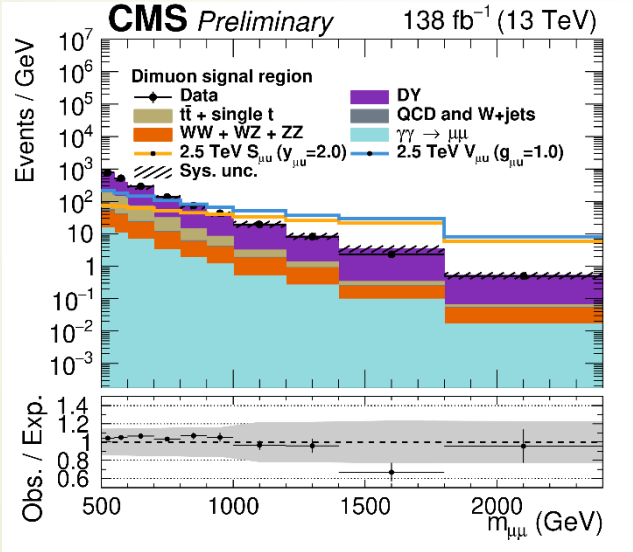


CMS-PAS-EXO-22-013

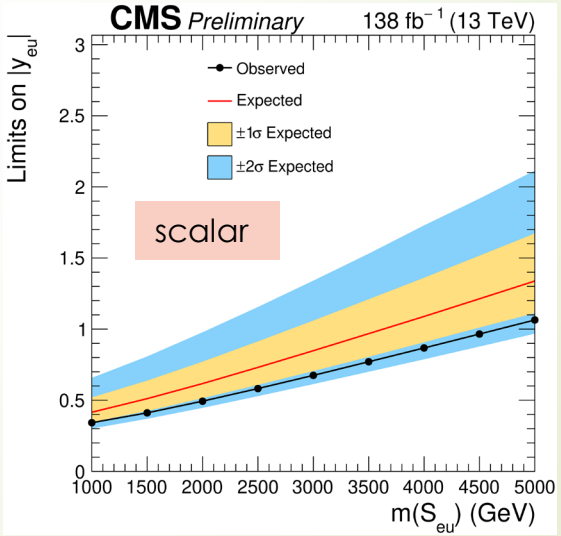
t-channel scalar and vector leptoquarks in the high mass di-muon and di-electron

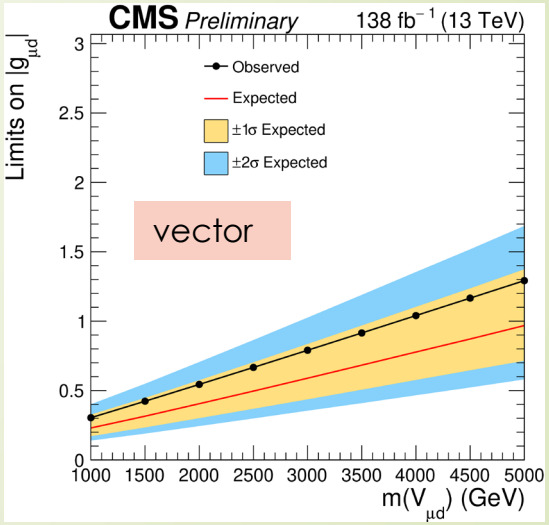
- Non-resonant production of electron or muon pairs
- Differential distributions of di-lepton events fit to templates built from reweighted samples of simulated SM events





- Limits obtained on the LQ-fermion couplings





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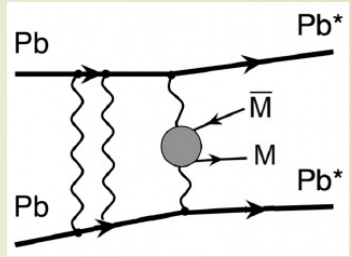
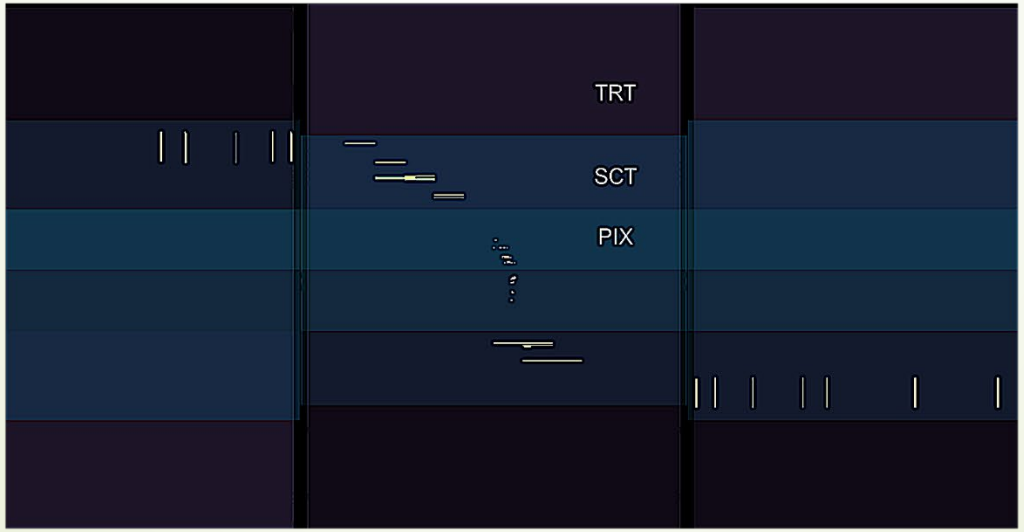
HI Run3 (2023)

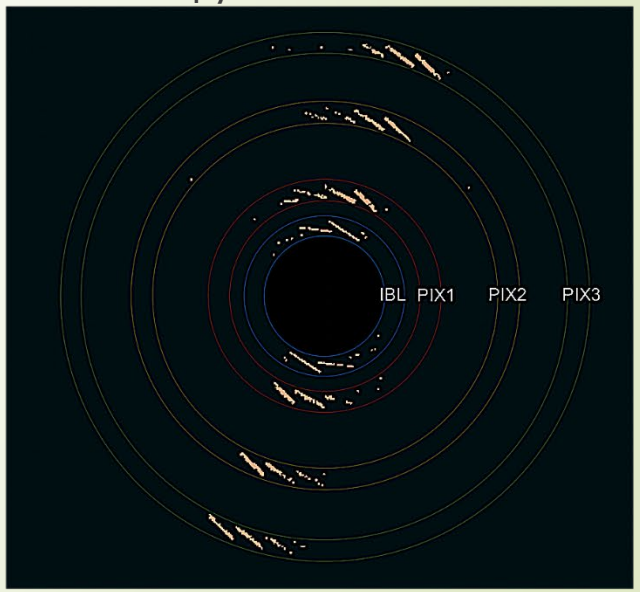
Magnetic monopoles in UltraPeripheral lead-lead Collisions



- UPC in Heavy Ion runs are a source of photon-photon collisions
- In such collisions, magnetic fields as high as 10^{16} T can be produced
- Signature: large ionization clouds in an otherwise empty detector, parabolic trajectory in the r-z plane (rather than helics in r-φ)

ATLAS simulation:
50 GeV Monopoles





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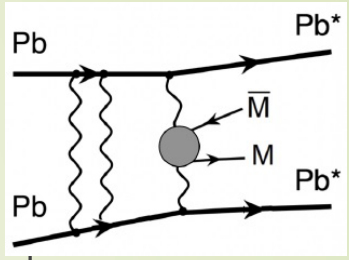

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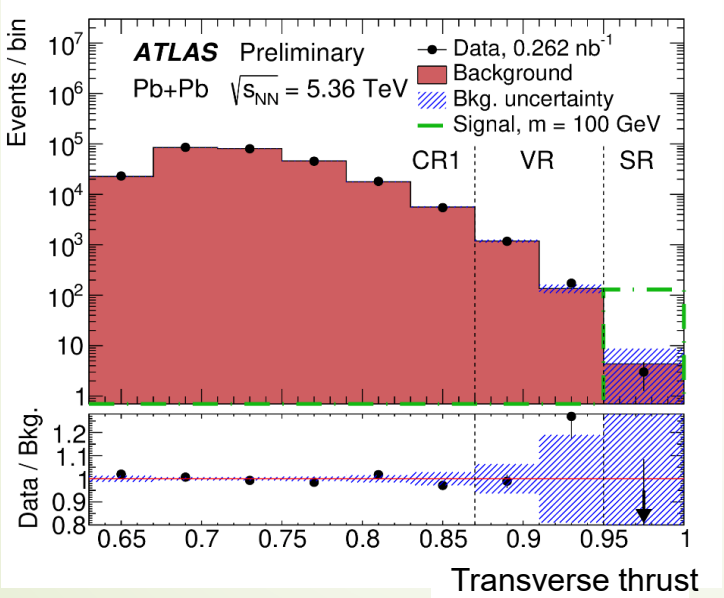

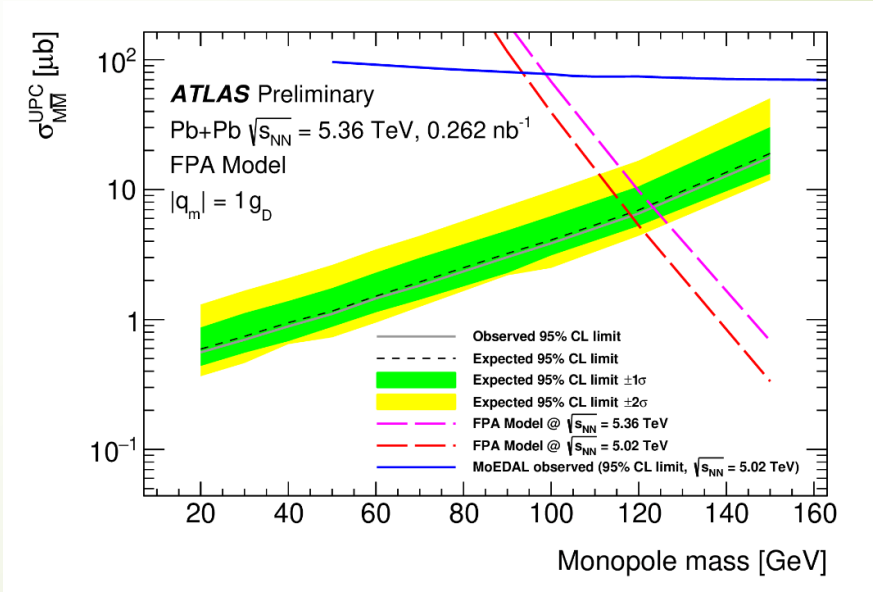

Conclusions

- LHC **Run 2 and 3** provide a powerful platform to explore new physics through combination of **higher energy, increased luminosity, and improved experimental techniques** with respect to previous LHC runs and other experimental facilities
- It is an **ideal training ground** to explore new ideas and methods, to attempt new usages of the detectors, and to invent new tools: a lot of possibilities still open for young and curious researchers in the field, and a lot of fun granted in inventing and implementing them!
- **HL-LHC** will significantly further increase the physics reach: gains will from **high luminosity and new detector capabilities**, but certainly also from so far unexplored new experimental techniques and new ideas
- And, who knows? Maybe one of those models that are tested will eventually turn out being true…

Thank you!