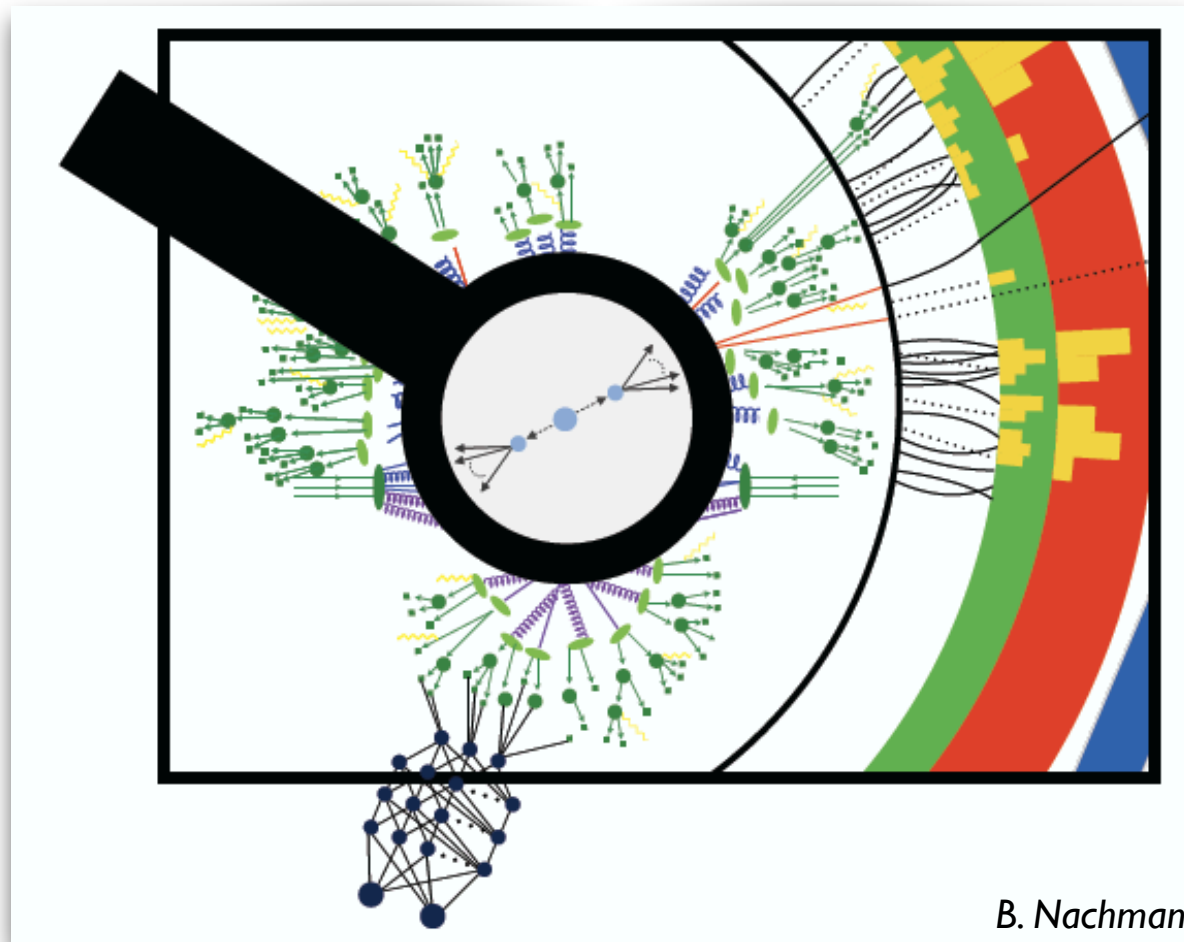


Searching for What Lies Beyond the Standard Model



Robin Erbacher - University of California, Davis

ICHEP 2022 - Bologna, Italy - July 12

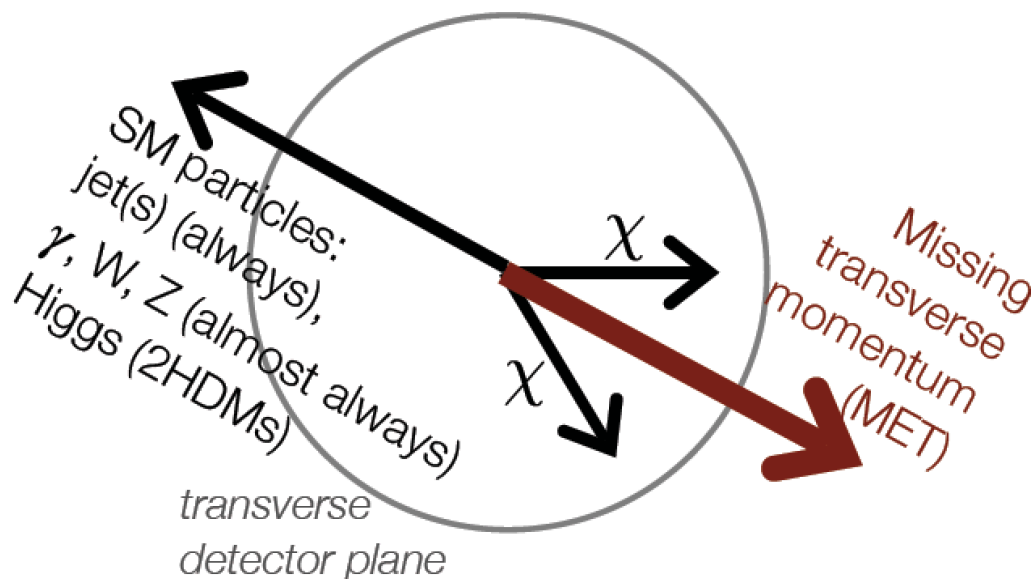
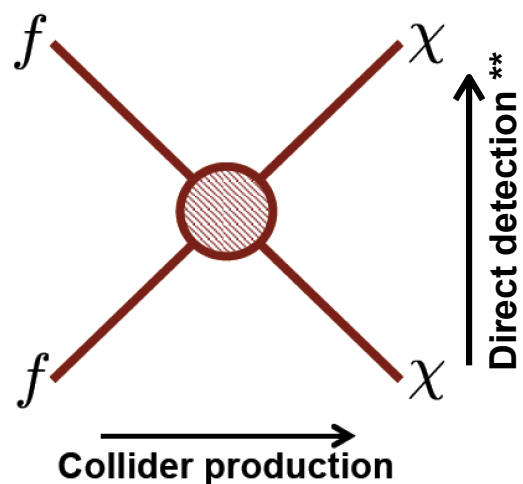
HIGGS FOUND

LHC

What motivates new physics searches?

Dark Matter!

Definitive evidence for something beyond the SM—we know something exists to explain!



O. Brandt

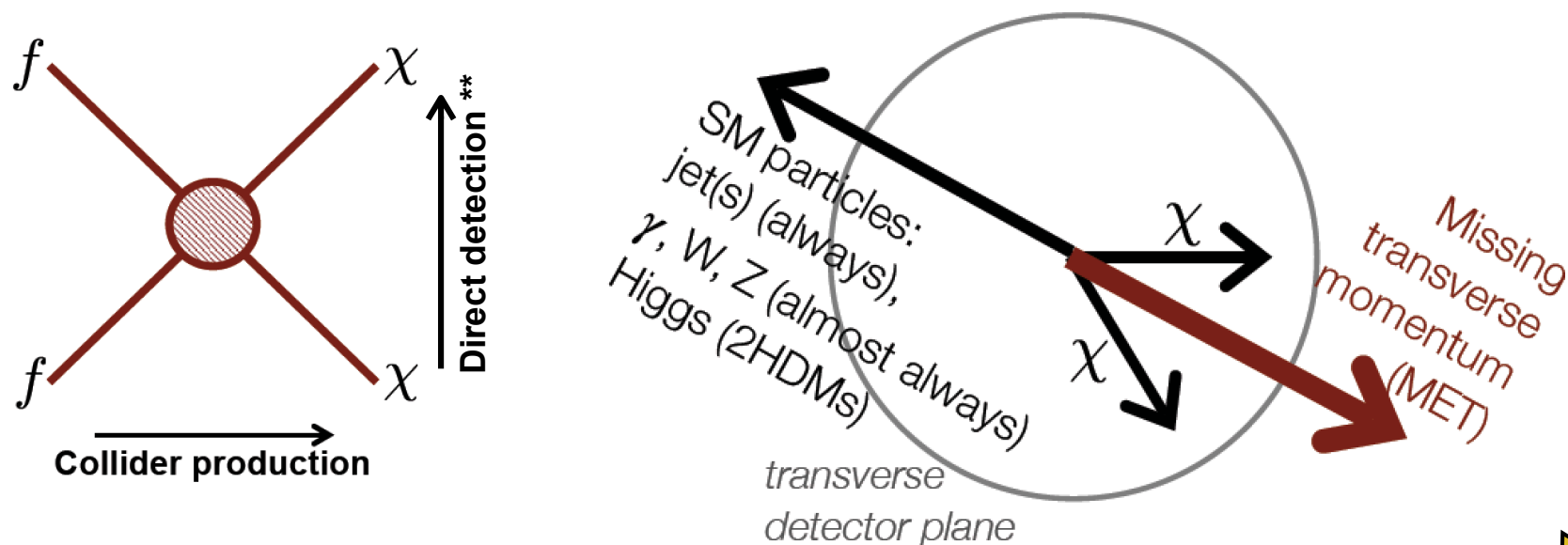
** for astrophysical DM searches, see [talk by Marradón](#) Monday

Dark Matter!

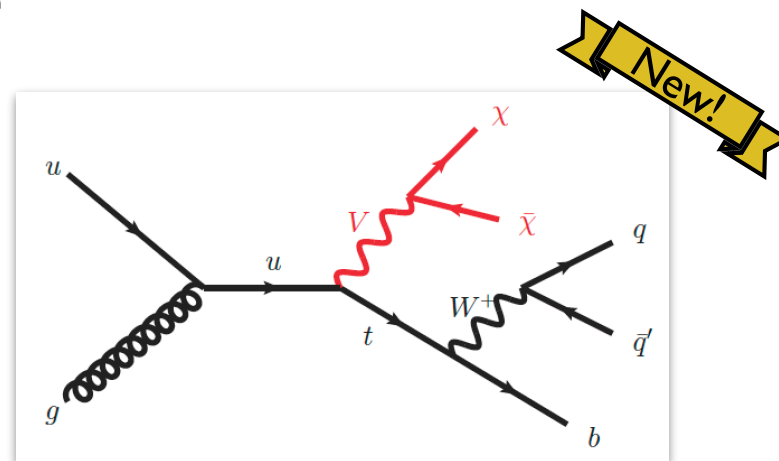
Definitive evidence for something beyond the SM—we know something exists to explain!



O. Brandt



Ex: ATLAS “mono-top”
shown by [G. Unal](#) Monday

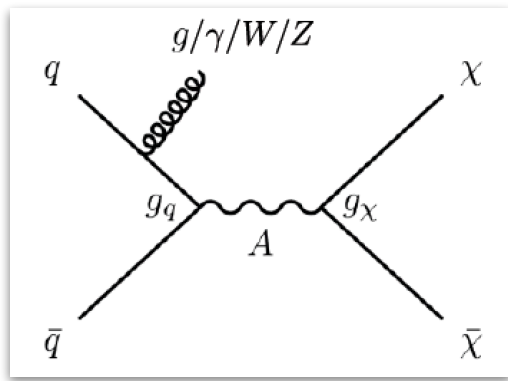


ATLAS-CONF-2022-036

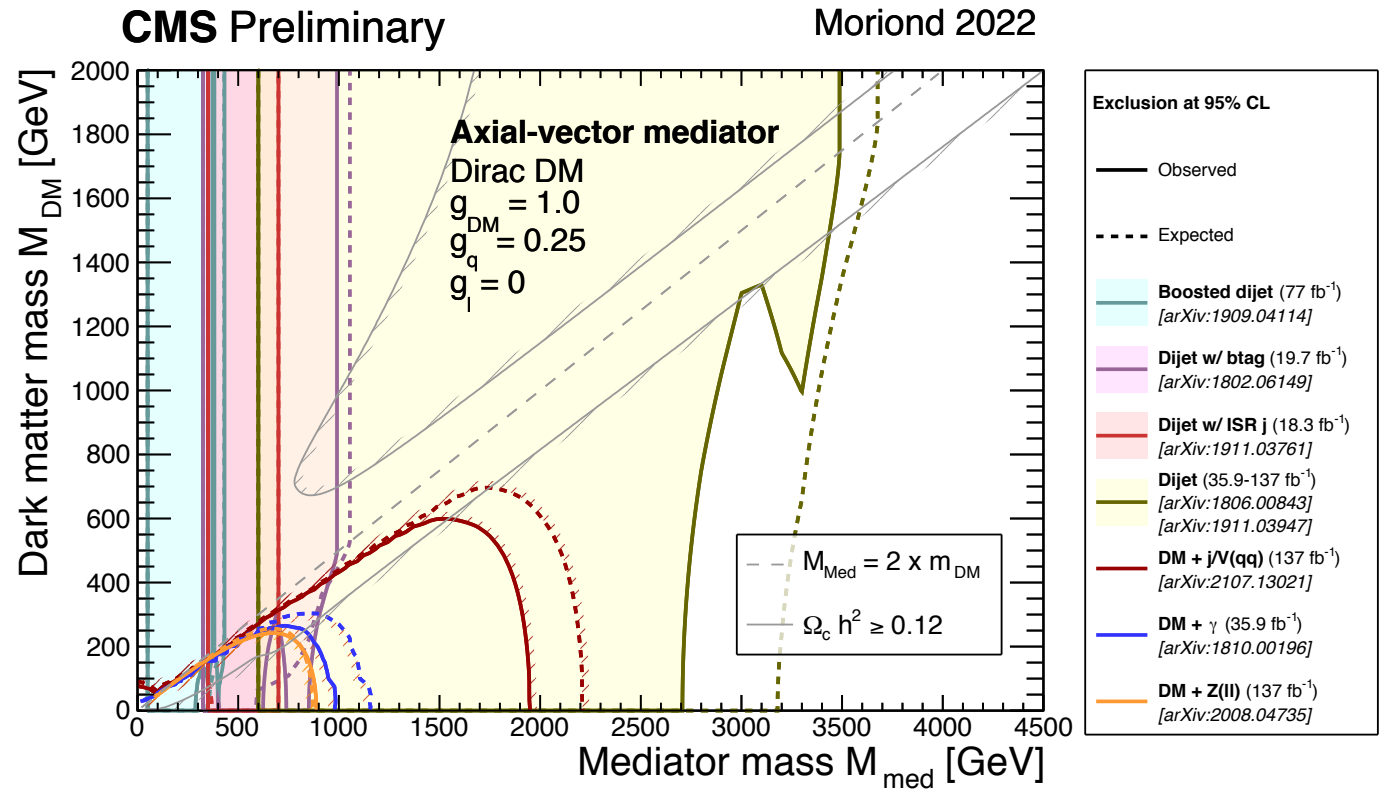
** for astrophysical DM searches, see [talk by Marradón](#) Monday

Dark Matter!

- Axial-vector, vector, or scalar mediation?
- Use effective field theories (EFT), or now more common: Simplified Models.



LHC DM WG recs:
[arXiv:1603.04156](https://arxiv.org/abs/1603.04156)
[arXiv:1703.05703](https://arxiv.org/abs/1703.05703)

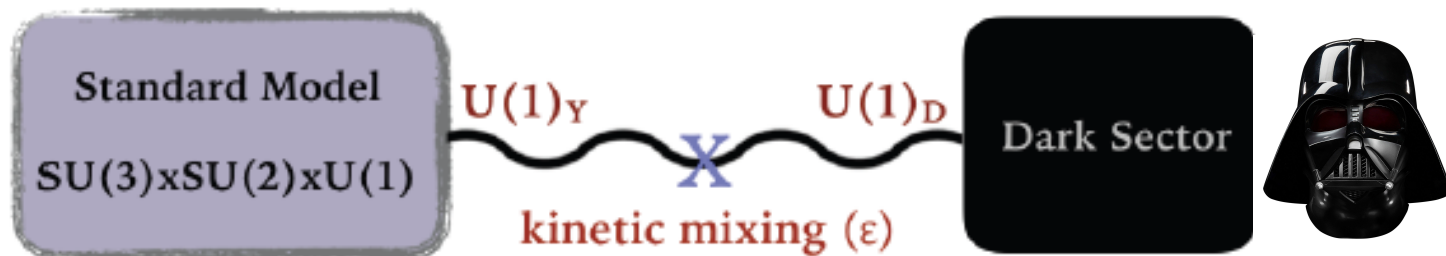
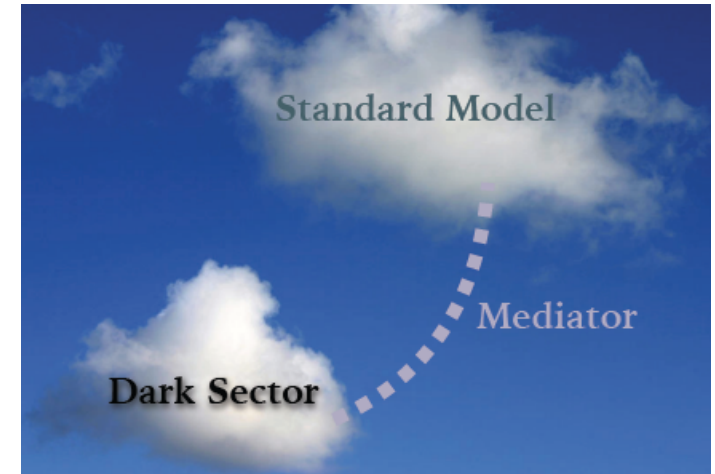


CMS and ATLAS have full programs of DM searches
 using missing transverse energy/momentum (**MET/p_{Tmiss}**) or di-jets

Dark Matter & the Dark Sector

S. Mukherjee

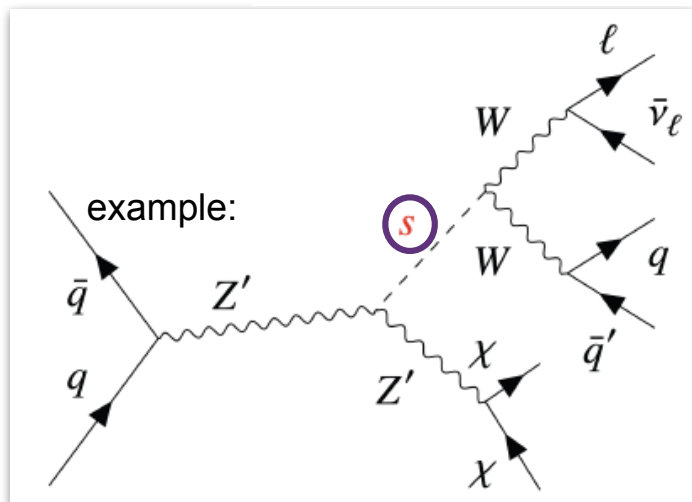
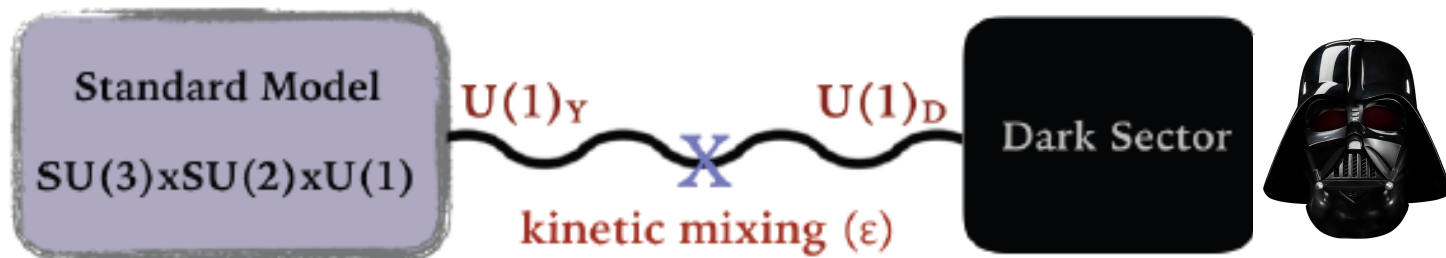
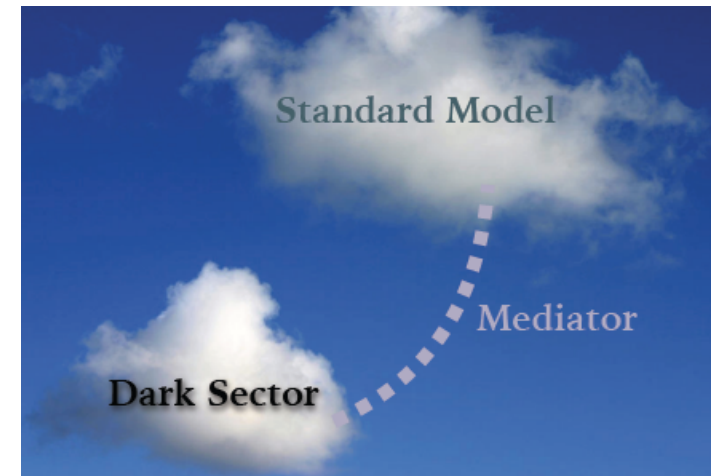
- Popular in BSM: Dark sector (hidden sector) models often predicted by string theory, & motivated in part by dark matter.
- Interactions w/ SM: weak, indirect, or through gravity.



Dark Matter & the Dark Sector

S. Mukherjee

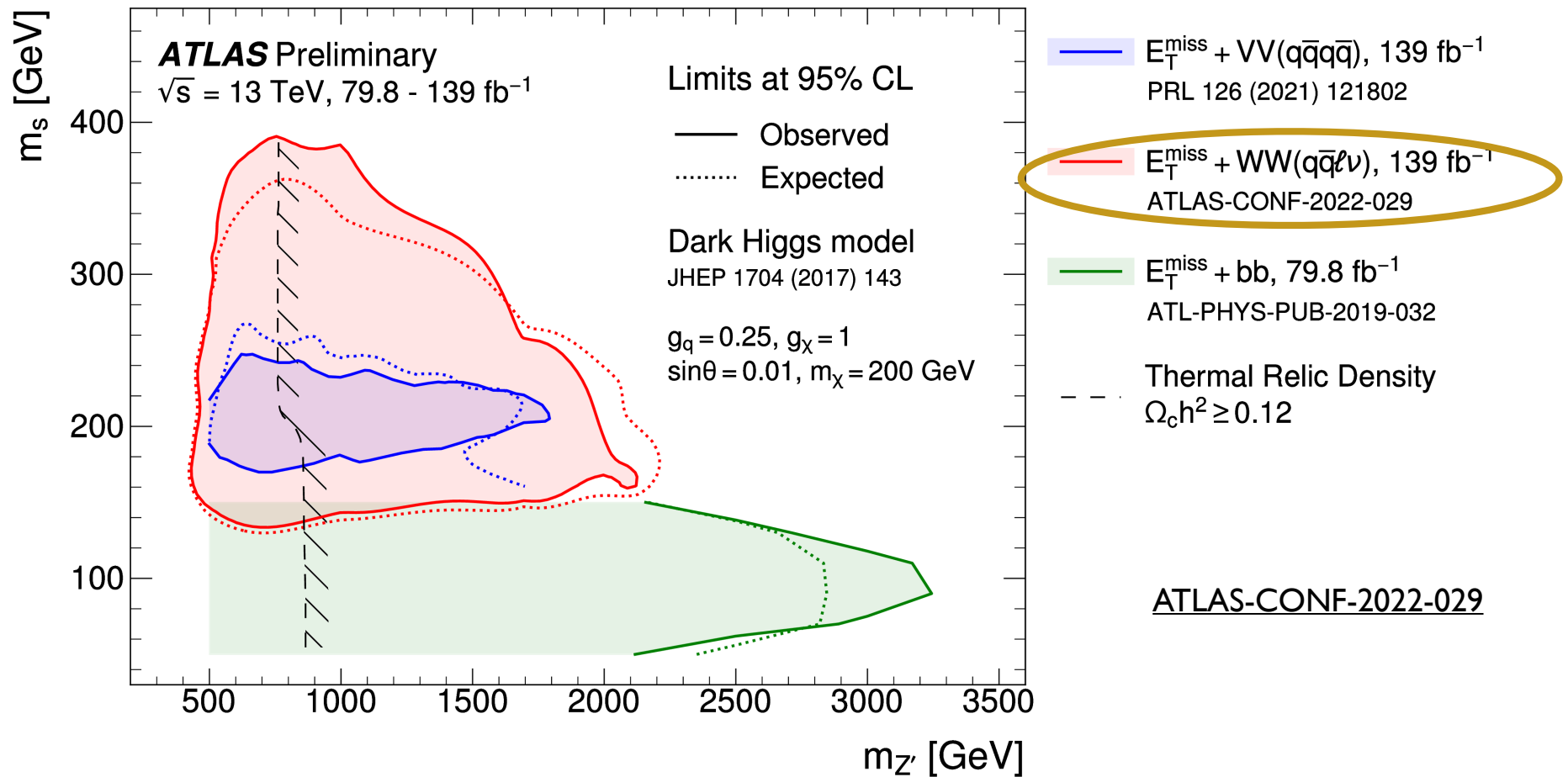
- Dark sector (hidden sector) models can be predicted by string theory, and motivated in part by dark matter.
- Interactions w/ SM: weak, indirect, or through gravity.



Model: $U(1)_{\text{dark}}$ symmetry where kinetic mixing to SM broken by a “dark Higgs boson S ”.

Dark Matter & the Dark Sector

July 2022



ATLAS searches for “Dark Higgs” $S + \text{DM}$: $S \rightarrow W^+W^- \rightarrow q\bar{q}\ell\nu$



Semi-visible Jets
 ATLAS-CONF-2022-038

CMS fully leptonic result: CMS-PAS-EXO-20-013

Dark Photons

Dark Sector particles can include axions, sterile neutrinos, dark photons...

Volume 166B, number 2

PHYSICS LETTERS

9 January 1986

An old idea: if there is an additional $U(1)$ symmetry, the new vector boson A' kinetically mixes with the SM photon

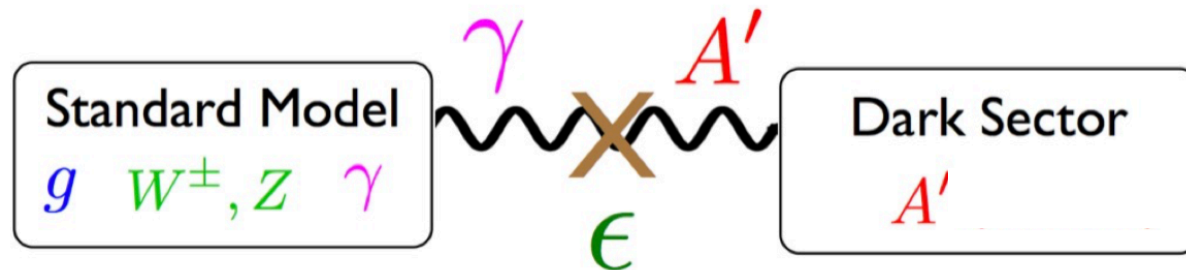
TWO $U(1)$ 'S AND ϵ CHARGE SHIFTS

Bob HOLDOM

Department of Physics, University of Toronto, Toronto, Ontario, Canada M5S 1A7

Model: $U(1)_{\text{dark}}$ symmetry w/ kinetic mixing to SM hypercharge: a “dark photon” (A' , Z_D , γ_d)

A' acts as a “portal” between the SM and the new sector



Dark Photons: colliders

LHCb prompt A' search

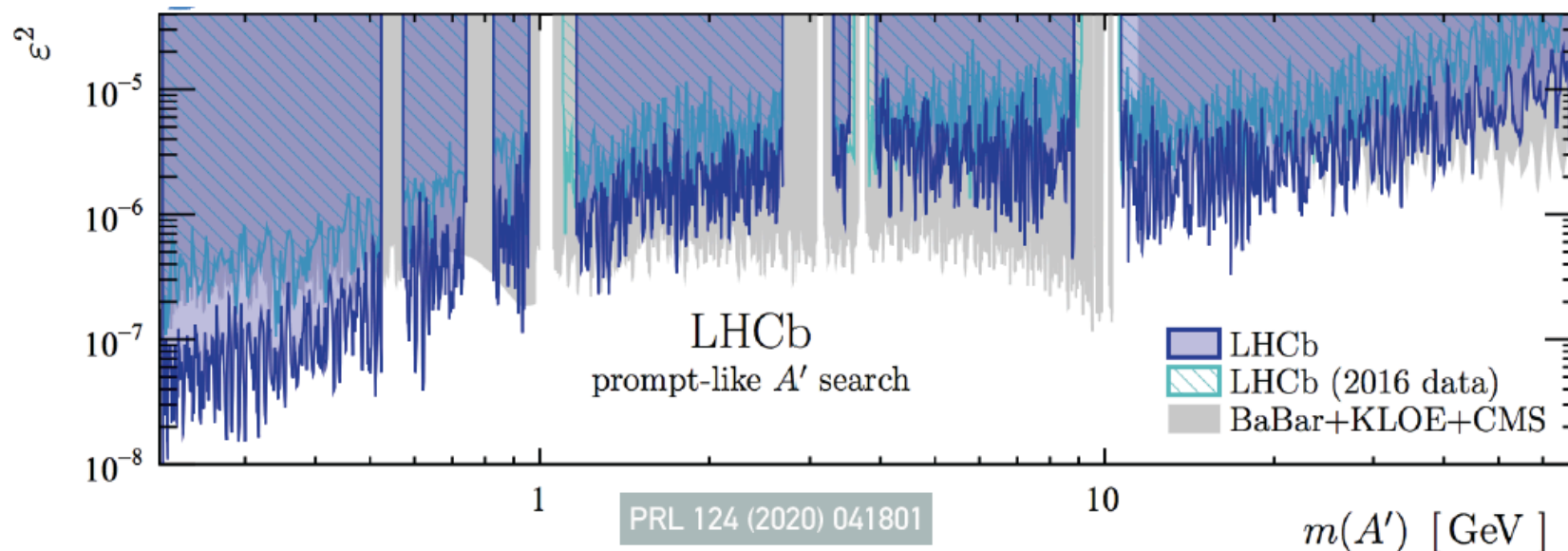
PRL 124 (2020) 041801 *turbo stream muons*

CMS prompt Z_D search

arXiv:2205.08582 *scouting muons*

Search for dark photon decaying to a pair of muons with real-time reco.

(Both use special triggers to accept more “low mass” events: partial reconstruction)

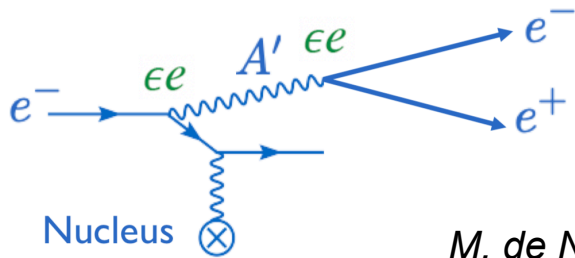


Prompt search up to 70 GeV. most stringent limit: 214-730 MeV

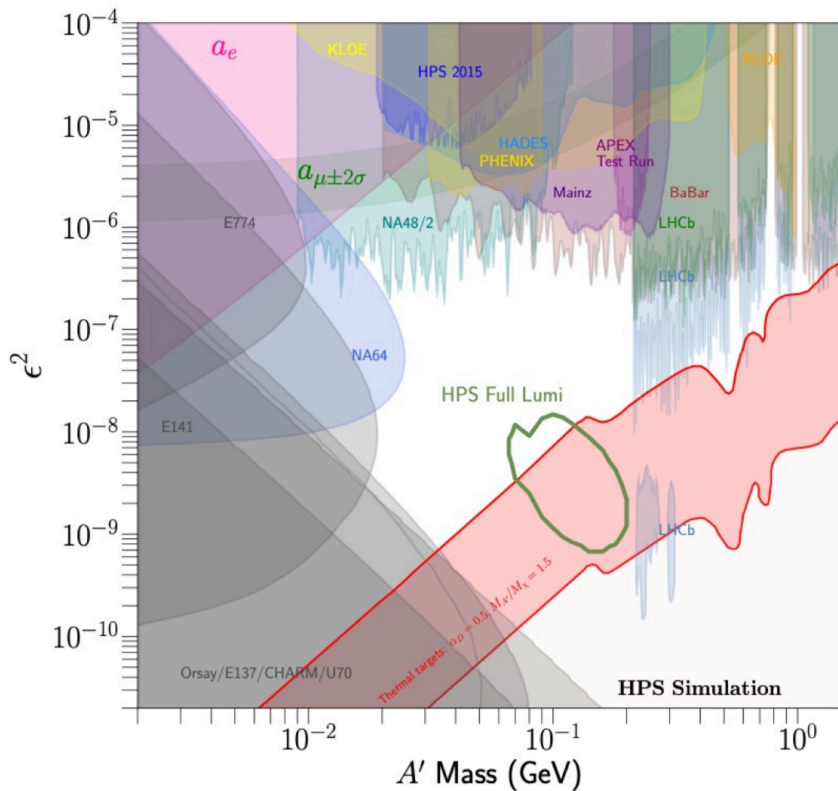
Large # of dark photon/dark sector searches at ATLAS, CMS, LHCb

Dark Photons: HPS / NA62

Heavy Photon Search- JLAB



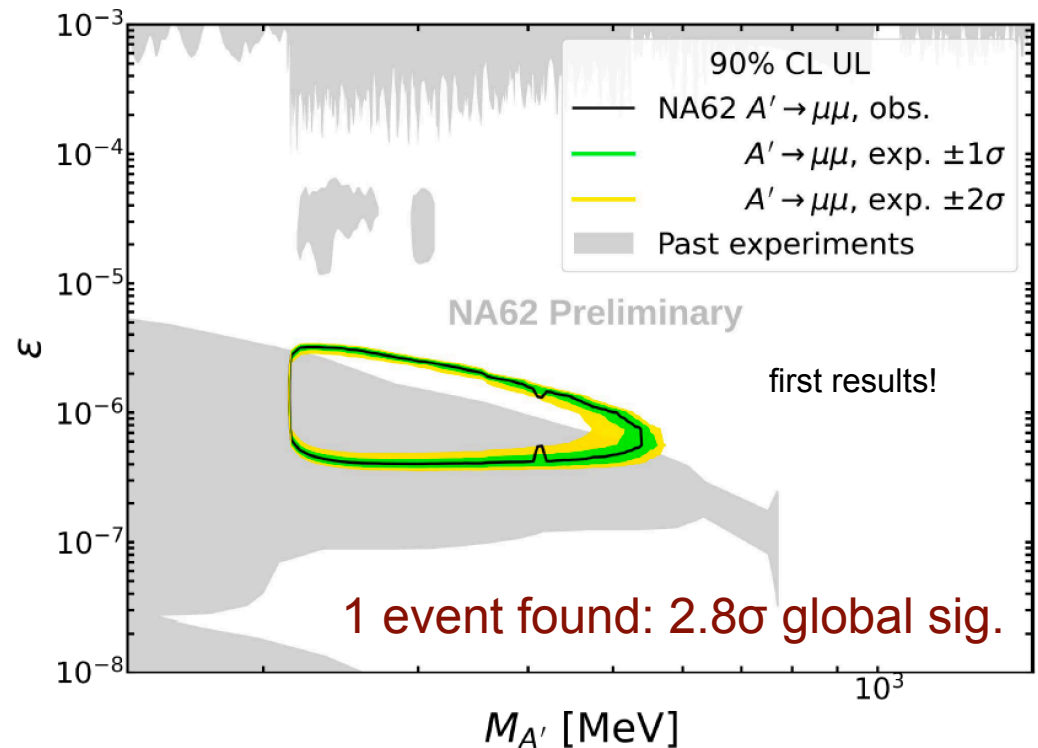
M. de Napoli



NA62: Beam Dump mode

main goal: rare/forbidden K decays
spin-off: dark portal particles!

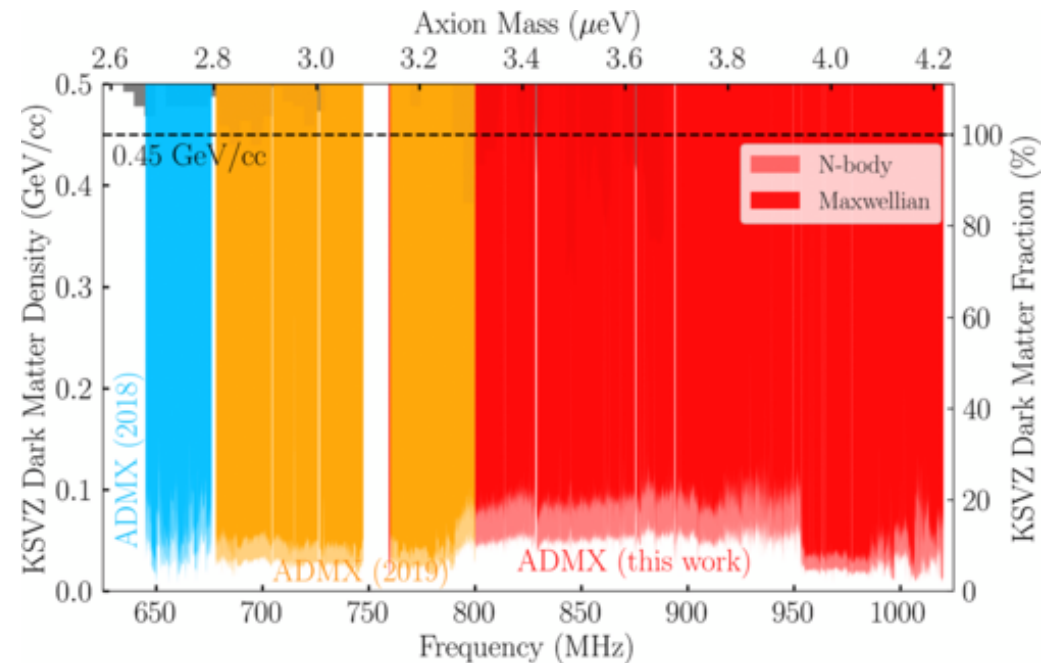
E. Minucci



μ BooNE
PADME

Axion-like Particles (ALPs)

Peccei-Quinn solution to the strong CP problem requires the existence of an axion - a potential dark matter candidate



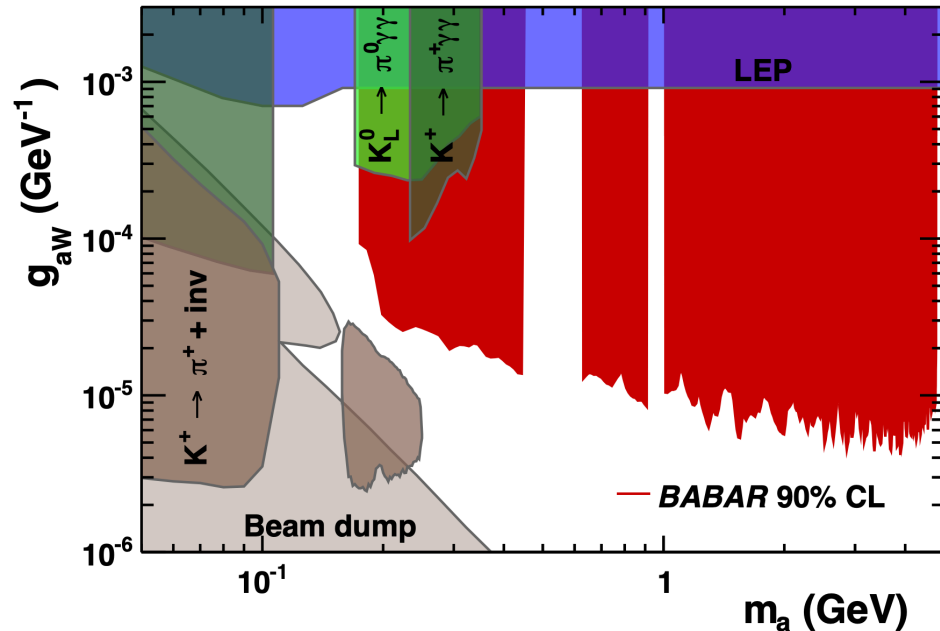
ADMX experiment uses ultra-low-noise quantum electronics to look for axions converted to microwave photons in strong magnetic field.

ADMX rules out axion densities which are less than 20% of the total galactic matter in μeV range.

Axion-like Particles (ALPs)

Peccei-Quinn solution to the strong CP problem requires the existence of an axion - a potential dark matter candidate

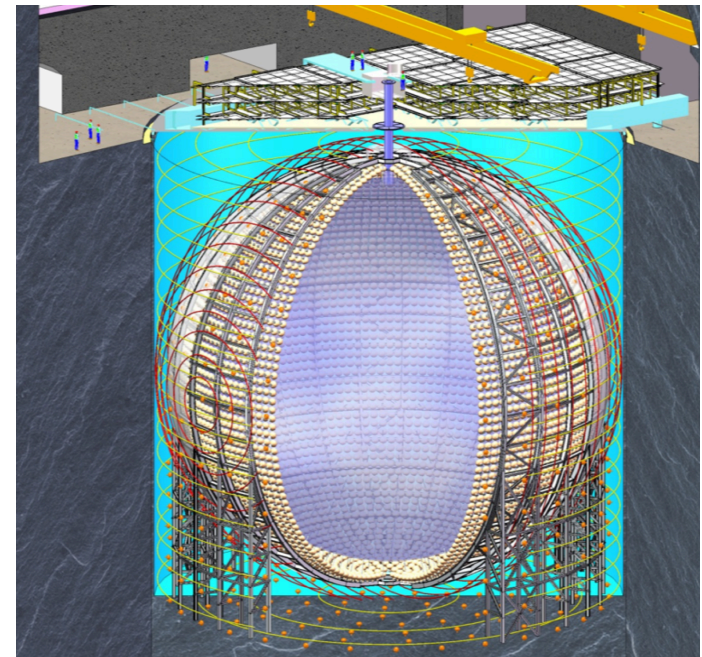
BaBar: Search for $B \rightarrow K a$, $a \rightarrow \gamma\gamma$



sensitive to $m_a = [0.1-4.78]$ GeV

Parallel talk: A. Lusiani

JUNO: 20 kton (Jiangmen, CN)
future underground liquid scintillator

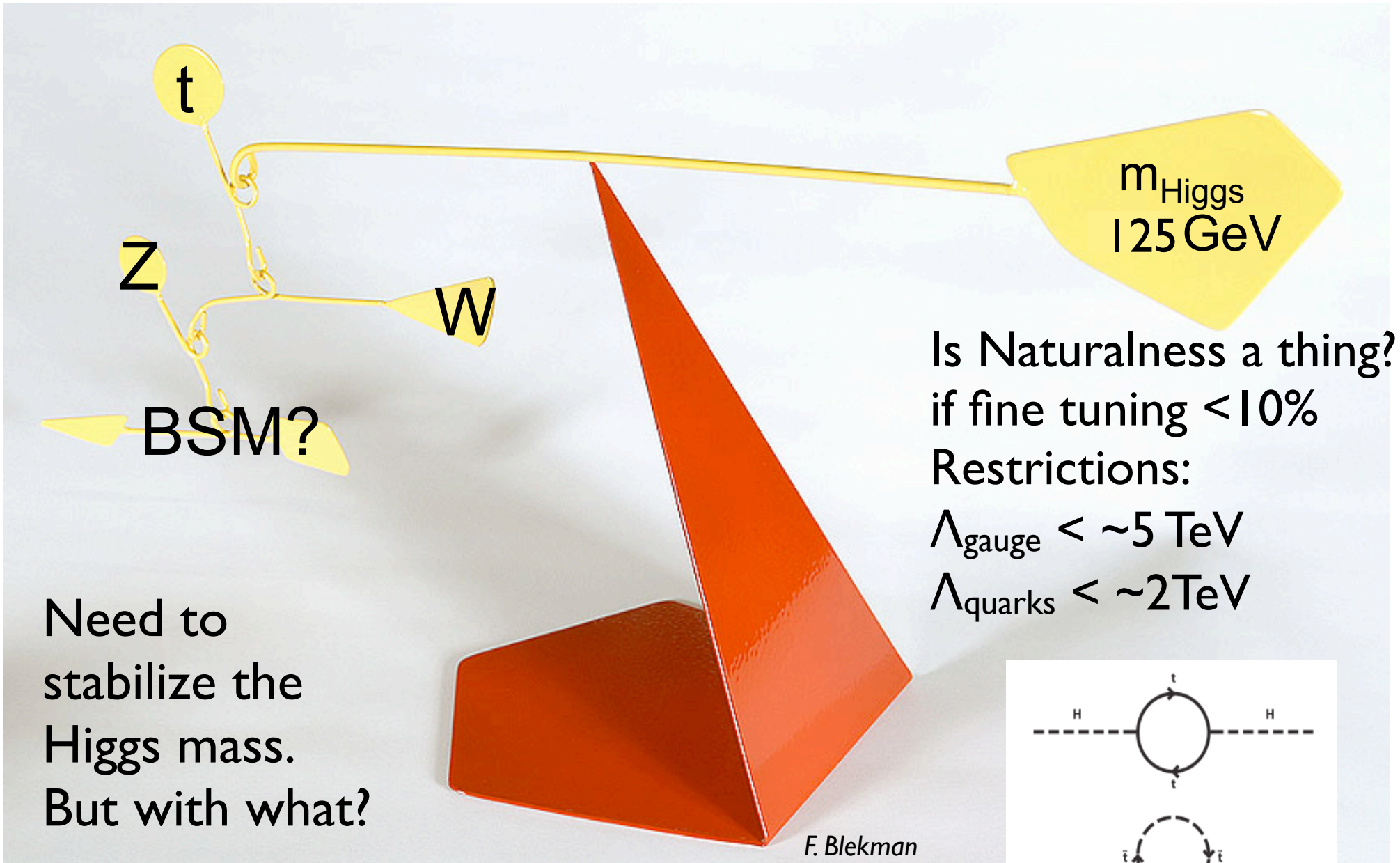


Parallel talk: N. Nath

Coherent Captain-Mills Parallel talk: D. Newmark

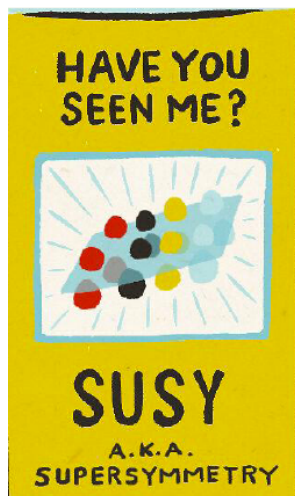
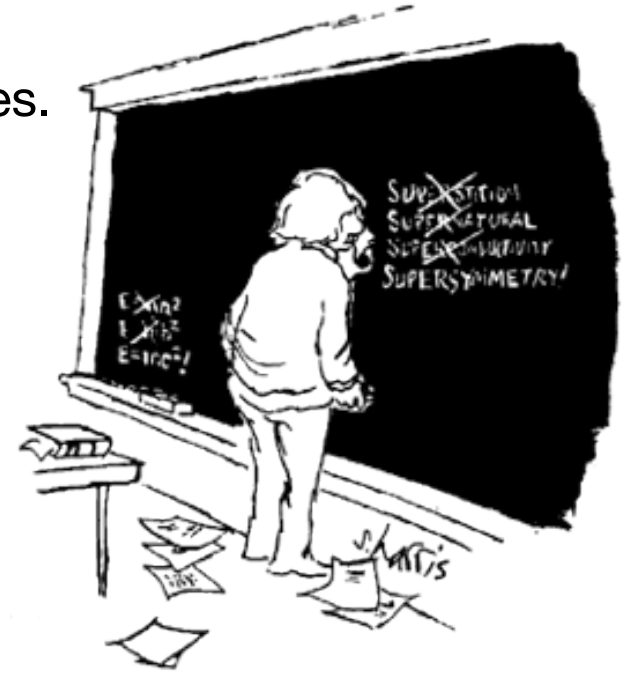
liquid Ar scintillator LANL

Hierarchy Problem: Naturalness

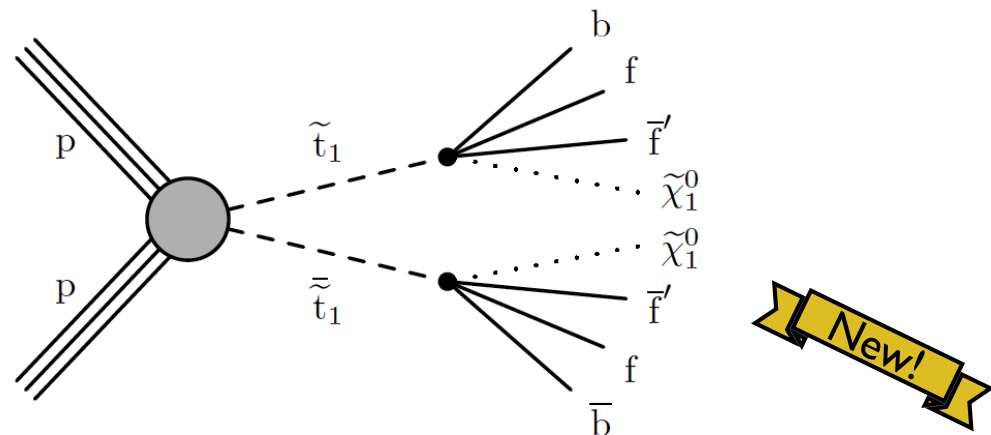


Supersymmetry (SUSY)

- Broken SUSY: a solution to the hierarchy problem— SM particle partners (sparticles) loops cancel divergences.
- Two main production modes:
 - strong (squarks, gluinos)
 - electroweak (gauginos, sleptons)
- Spectra can be inverted (light stop/stau), compressed (giving LLPs)...there are no theoretical constraints!
- Lightest SUSY particle still a contender for **dark matter**
- Dozens of searches at the LHC!



LHC SUSY summaries shown by J. Heikkilä

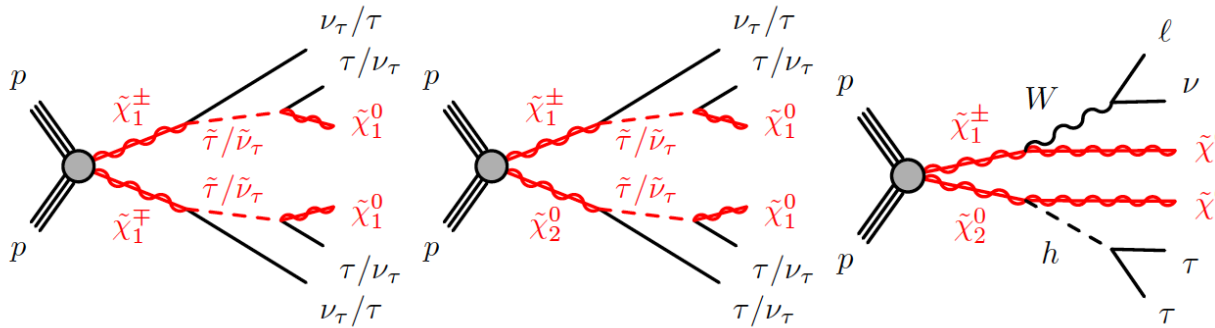


CMS new search for stop squarks
in 4-body decays, talk by A. Rizzi

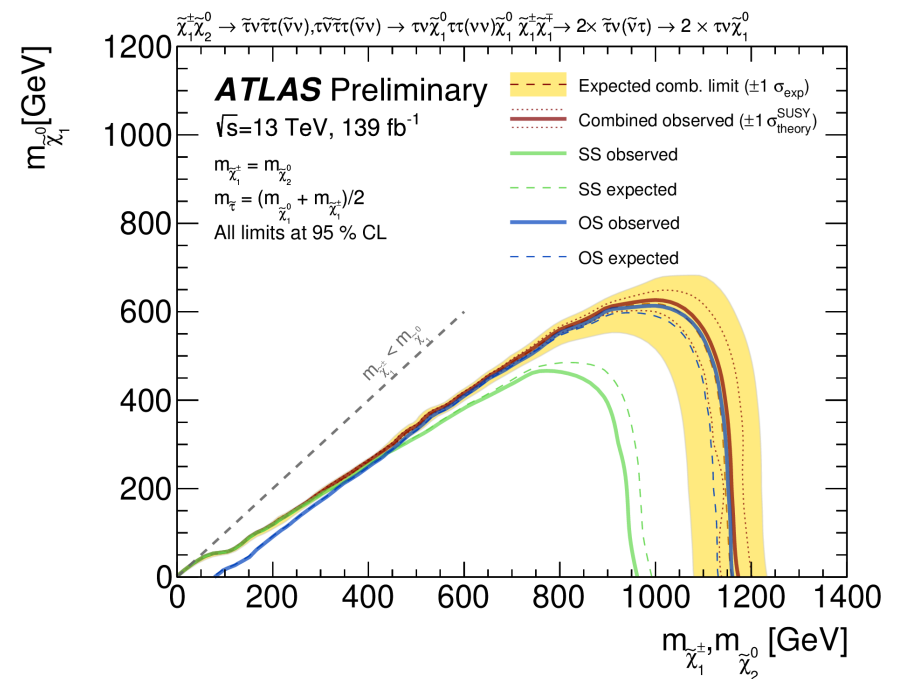
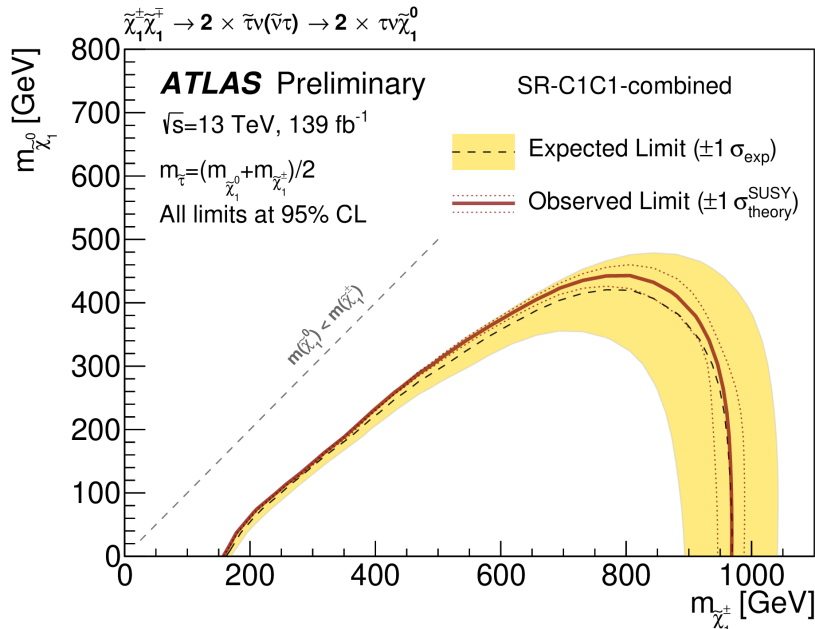
SUSY (Colliders)

Electroweak SUSY production is challenging: smaller cross sections.
Helped by new techniques, and combinations, and full Run 2 datasets.

ATLAS-CONF-2022-042



New!

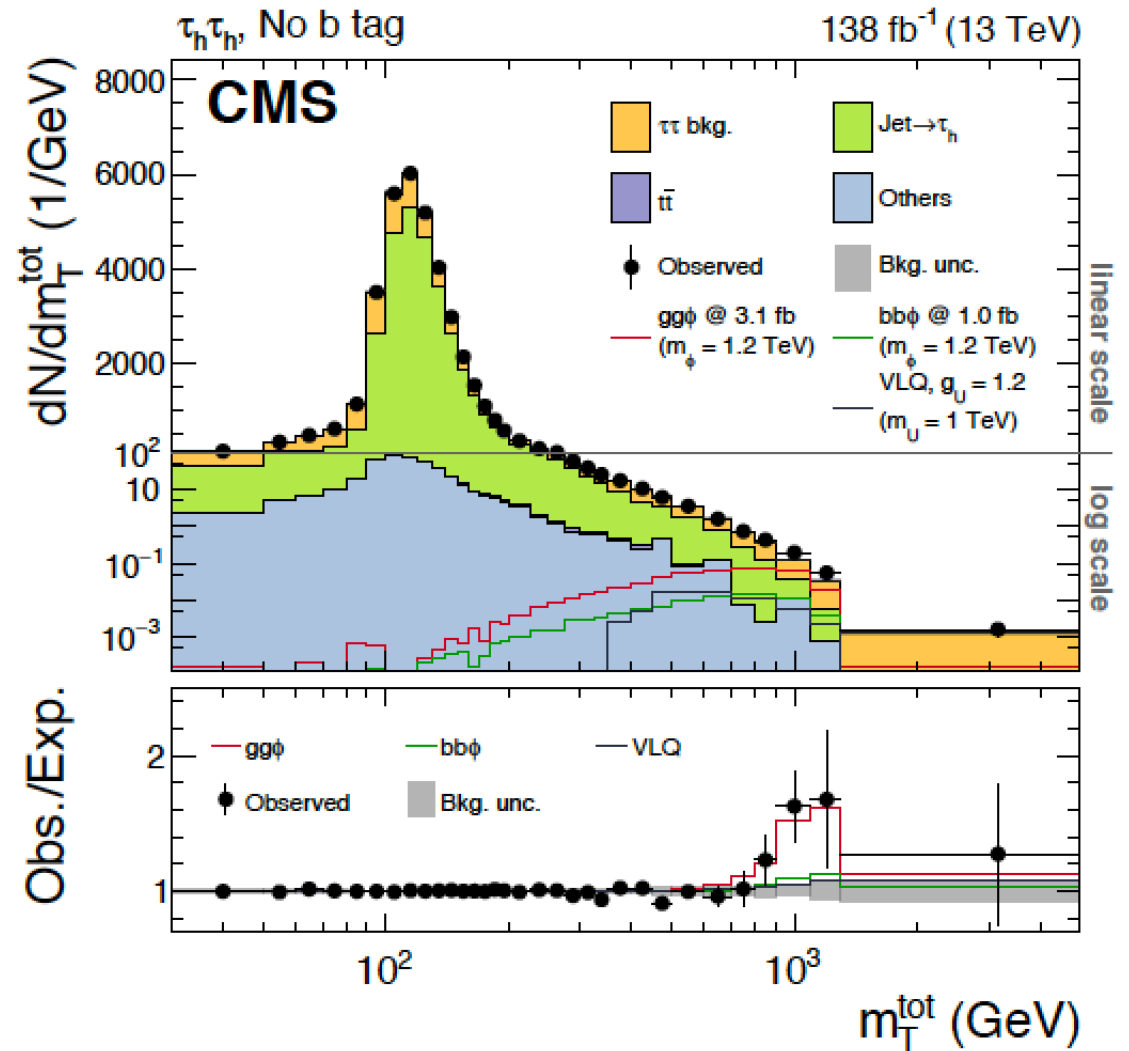
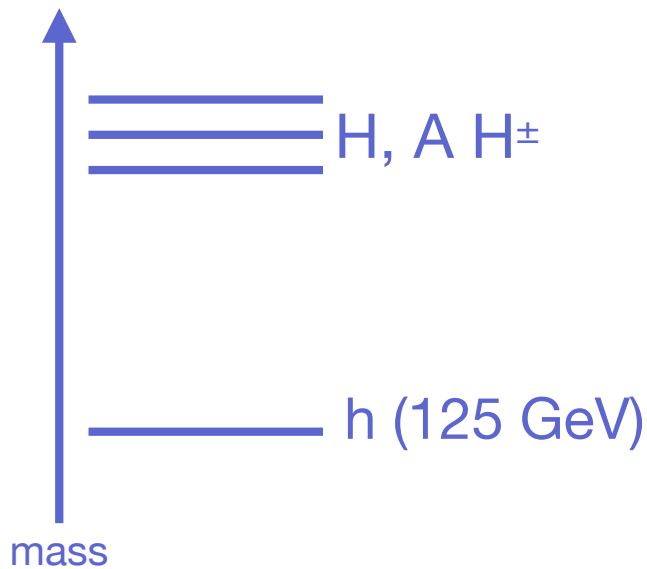


ATLAS: Gaugino pair prod. \rightarrow final state taus. Into compressed region.
Light staus: interesting for μ g-2 & M_W anomalies, and dark matter.

Exotic Higgs? MSSM

Minimal Supersymmetric SM

Two Higgs doublets
give five Higgs states;
can get SM-like h
at 125 GeV!

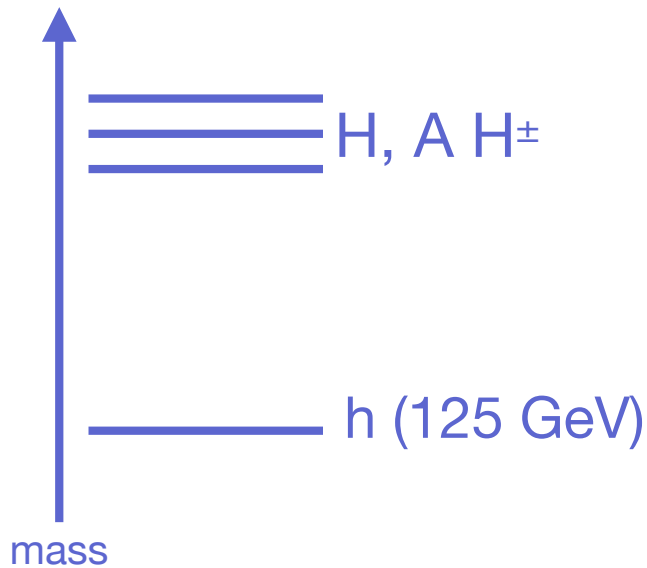


Most sensitive channel at high $\tan\beta$ is $H/A \rightarrow \tau\tau(+b)$

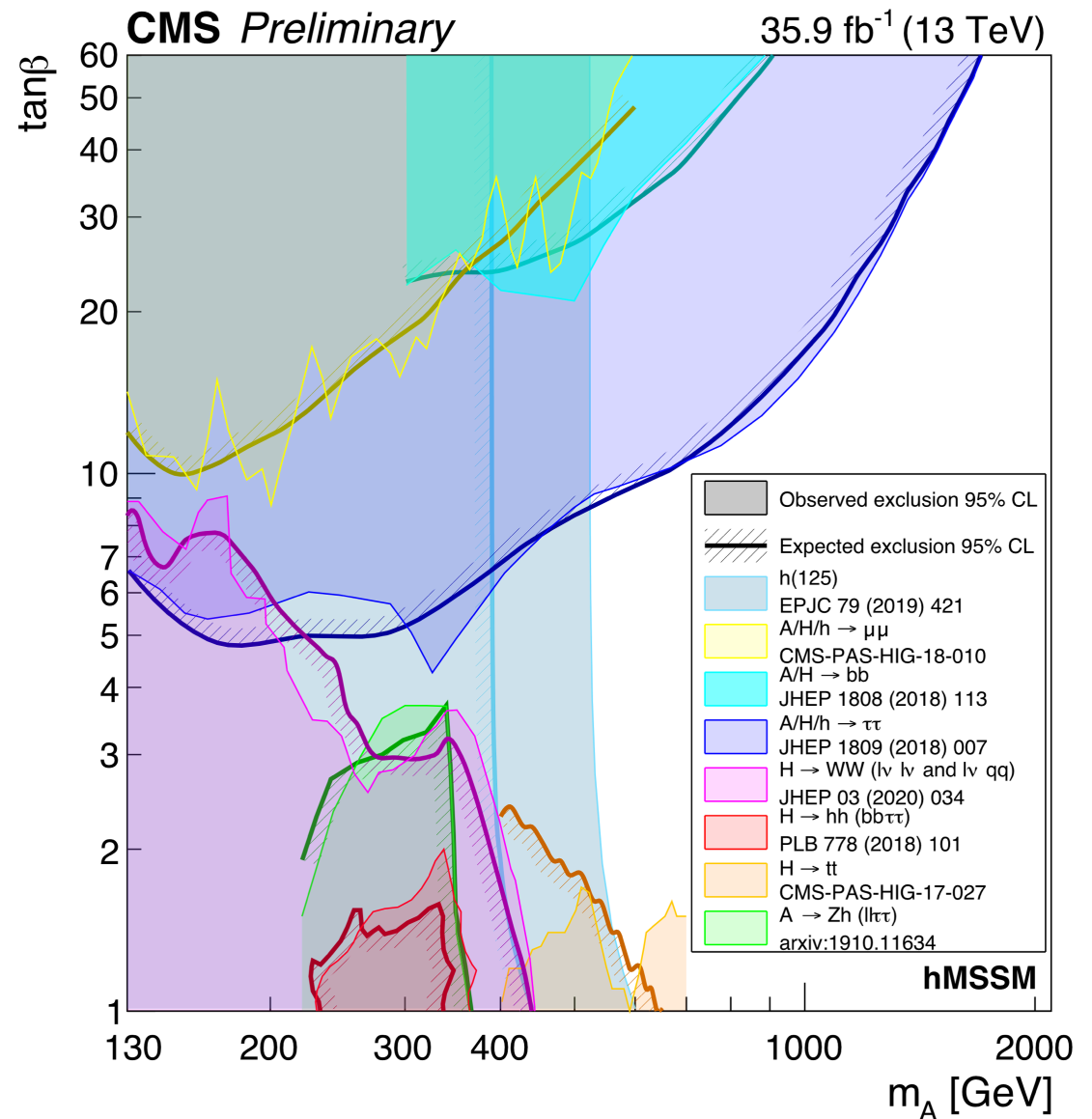
Exotic Higgs? MSSM

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Putting together multiple analyses CMS covers $m_A < 500$ GeV

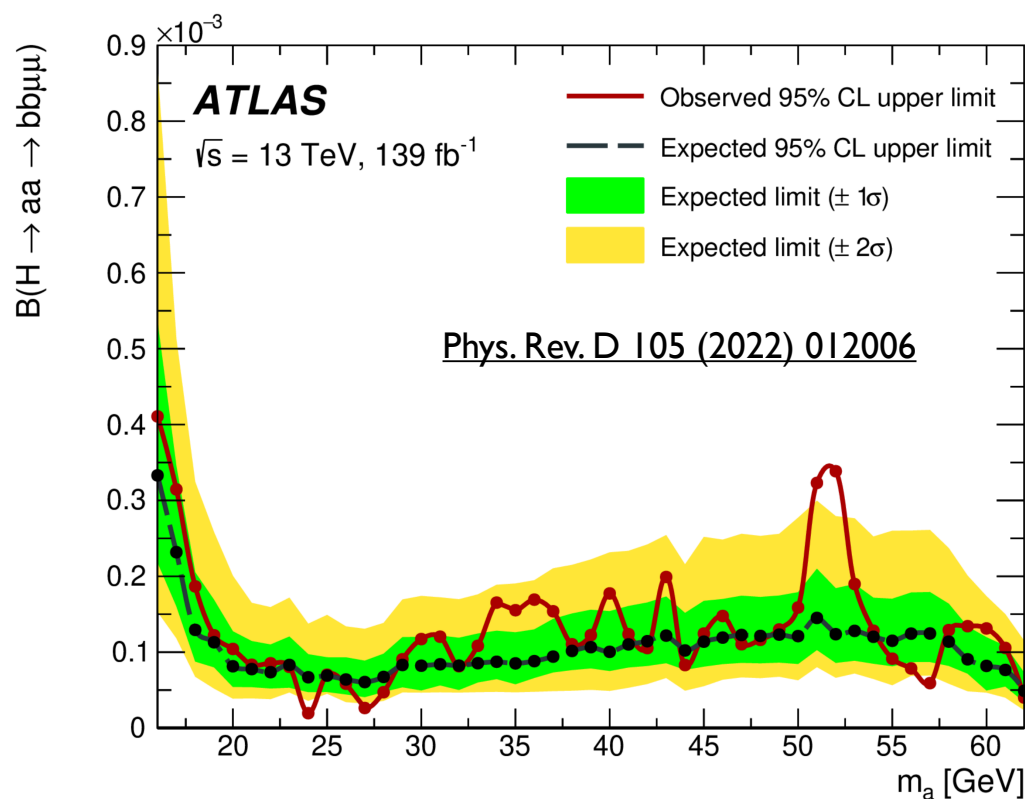
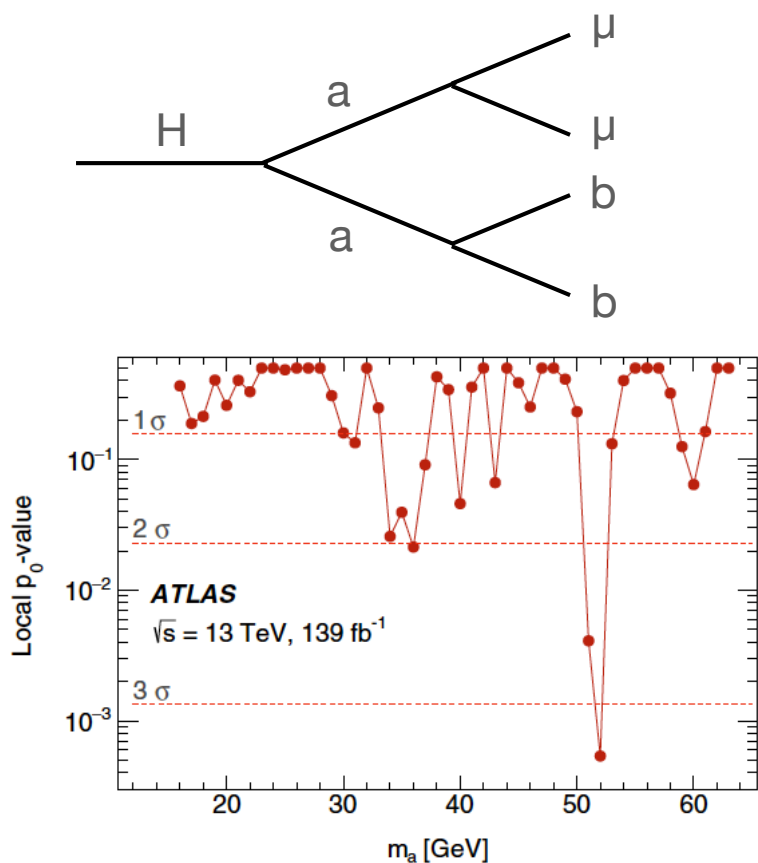


Exotic Higgs: nMSSM

- nMSSM = MSSM + additional Higgs singlet (J. Gunion) which helps solve the “little hierarchy problem” in the MSSM
- can get H(125), but can have lighter and heavier states such as light pseudoscalar a; H(125) \rightarrow aa has been key experimental target

Exotic Higgs: nMSSM

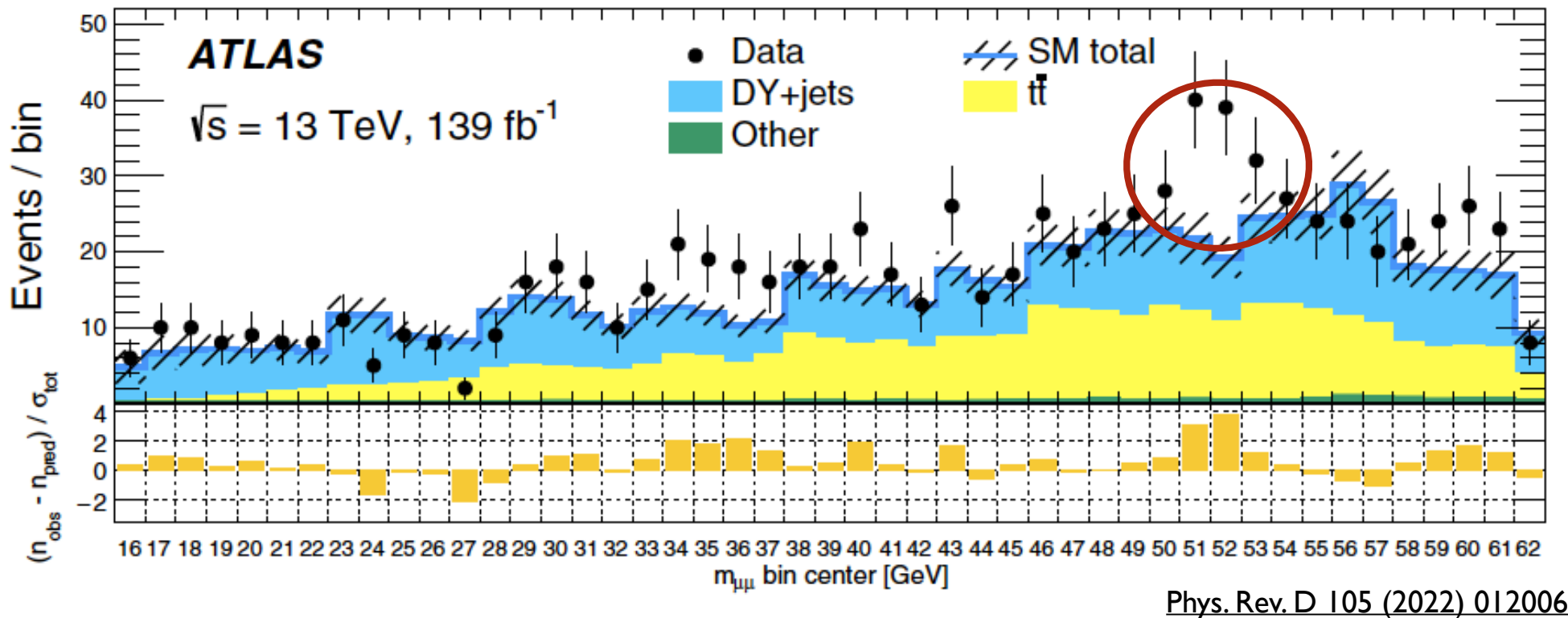
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In Run 2 data, ATLAS sees intriguing excess in $bb\mu\mu$ final state at $m_a \sim 52$ GeV.

Exotic Higgs: nMSSM

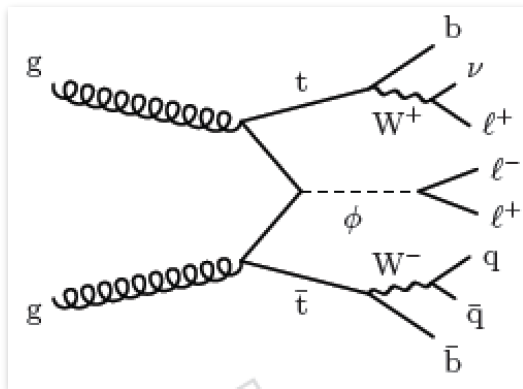
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In Run 2 data, ATLAS sees intriguing excess in $bb\mu\mu$ final state at $m_a \sim 52 \text{ GeV}$.

Light Neutral Boson?

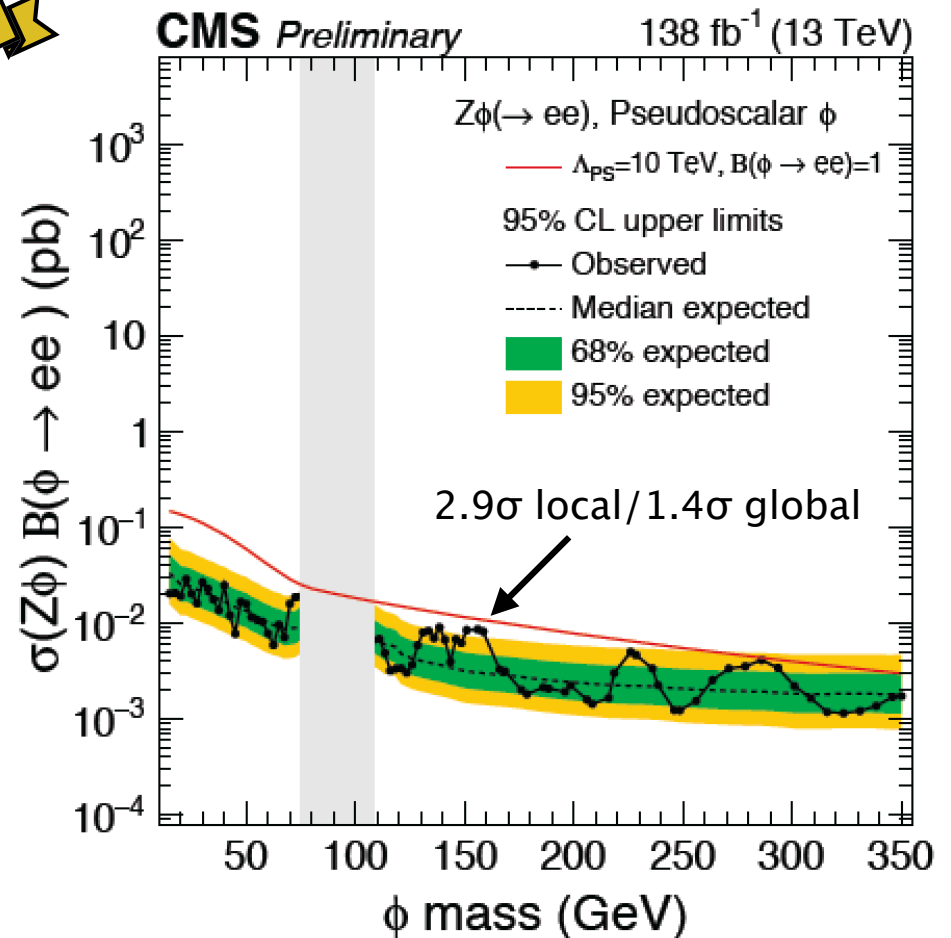
- A neutral, light boson ϕ would be a minimal SM Higgs sector extension.
- Scalar, ps, or H-like couplings, or associated prod $X\phi$ ($X=W,Z,tt$). [arXiv:1507.07004](#)
- CMS searches for $X\phi$, with ϕ decaying to lepton pairs in narrow resonances.



CMS-PAS-EXO-21-018

Probe 24 (W/Z/tt) ϕ signal models
(37 dilepton masses)

New!

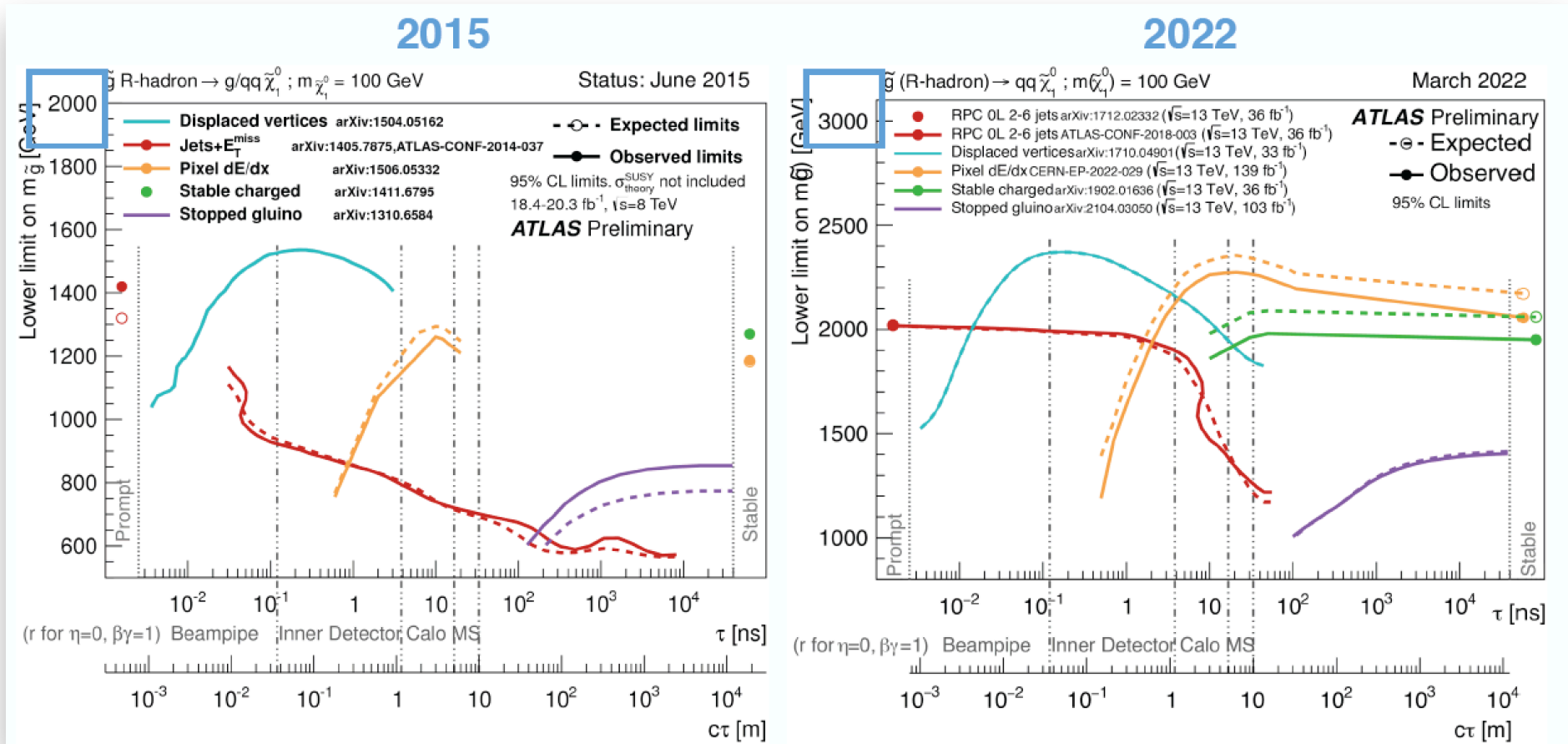


Long-lived Particles

LLPs arise in models of SUSY (compressed spectra or weakly-coupled RPV), Hidden Valleys, QCD axions, dark matter, dark portal particles, heavy neutral leptons... Very popular experimental topic in the last years!

Long-lived Particles

LLPs arise in models of SUSY (compressed spectra or weakly-coupled RPV), Hidden Valleys, QCD axions, dark matter, dark portal particles, heavy neutral leptons... Very popular experimental topic in the last years!



Territory explored for long-lived SUSY gluinos

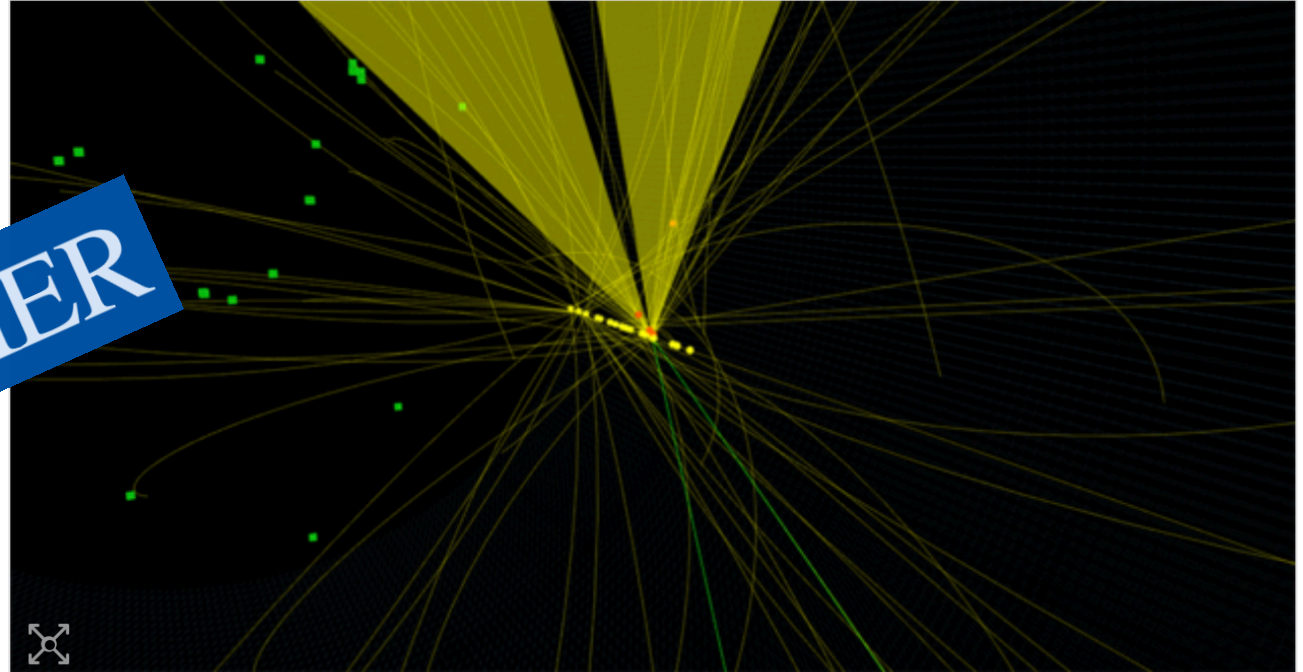
Long-lived Particles

CERN COURIER

SEARCHES FOR NEW PHYSICS | MEETING REPORT

Long-lived particles gather interest

21 July 2021



LLP candidate A CMS candidate event for the decay of a Higgs boson into a pair of LLPs which decay into jets (yellow cones) containing secondary vertices (orange circles), in association with $Z \rightarrow e^+e^-$ (green tracks). Credit: CMS / cms3d.web.cern.ch/EXO-20-003/

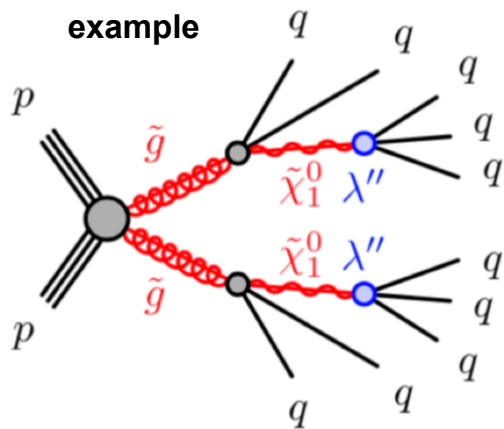
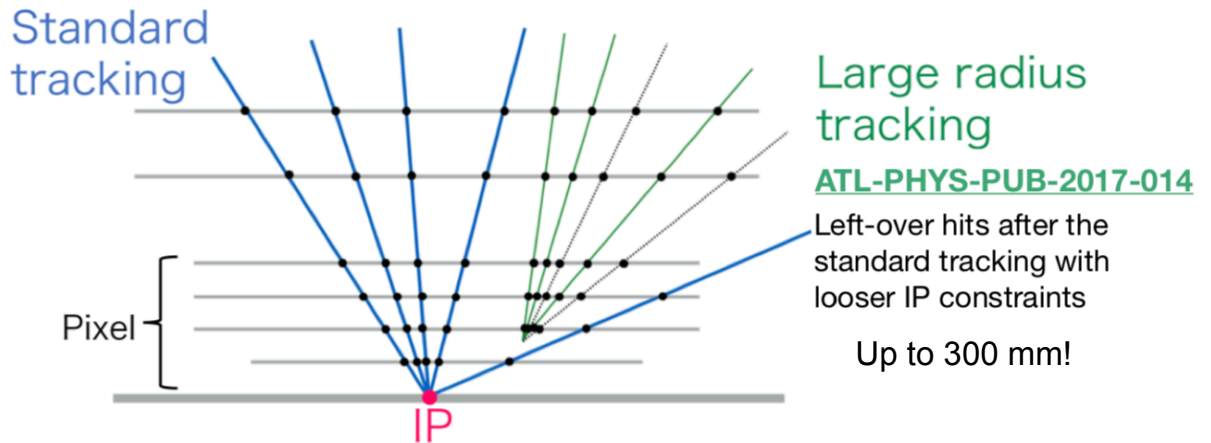
From 25 to 28 May, the long-lived particle (LLP) community marked five years of stretching the limits of searches for new physics with its ninth and best-attended workshop yet, with more than 300 registered participants.

LLP9 played host to six new results, three each from ATLAS and CMS. These included a remarkable new ATLAS paper searching for stopped particles – beyond-the-Standard Model (BSM) LLPs that can be produced in a proton–proton collision and then get stuck in the detector before decaying minutes, days or weeks later. Good hypothetical

Long-lived Particles

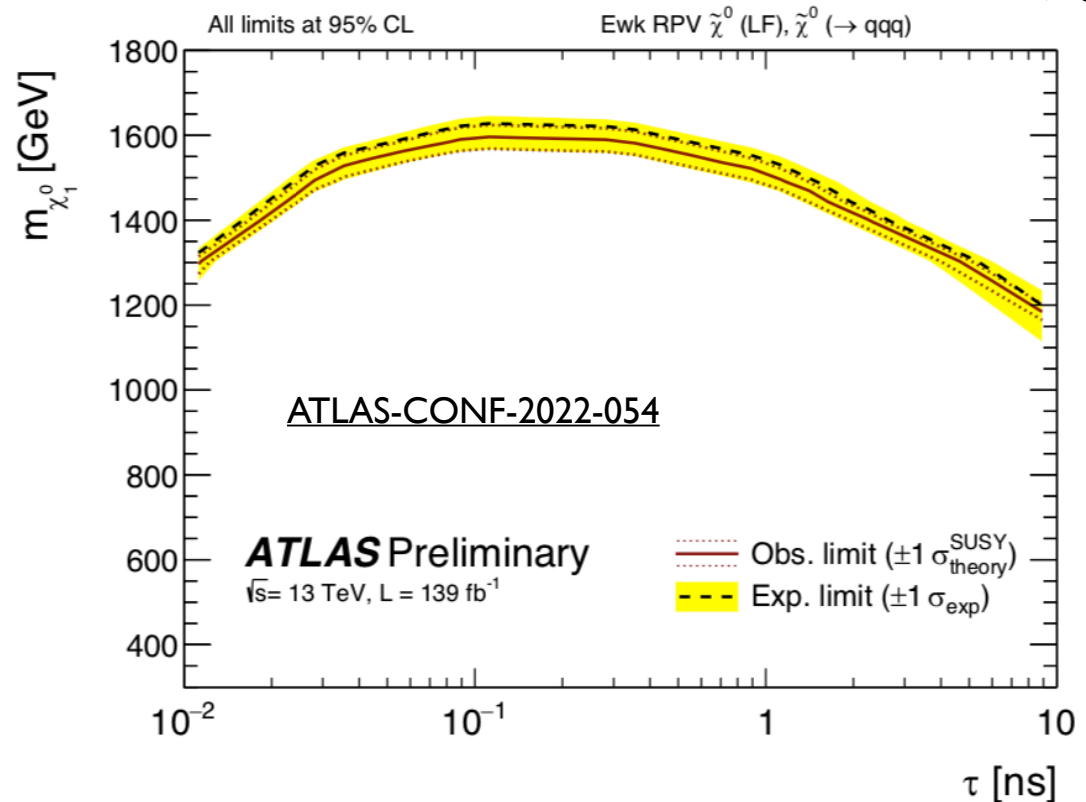
LLPs at LHC:

- displaced vertices
- long time-of-flight
- unusual energy deposits



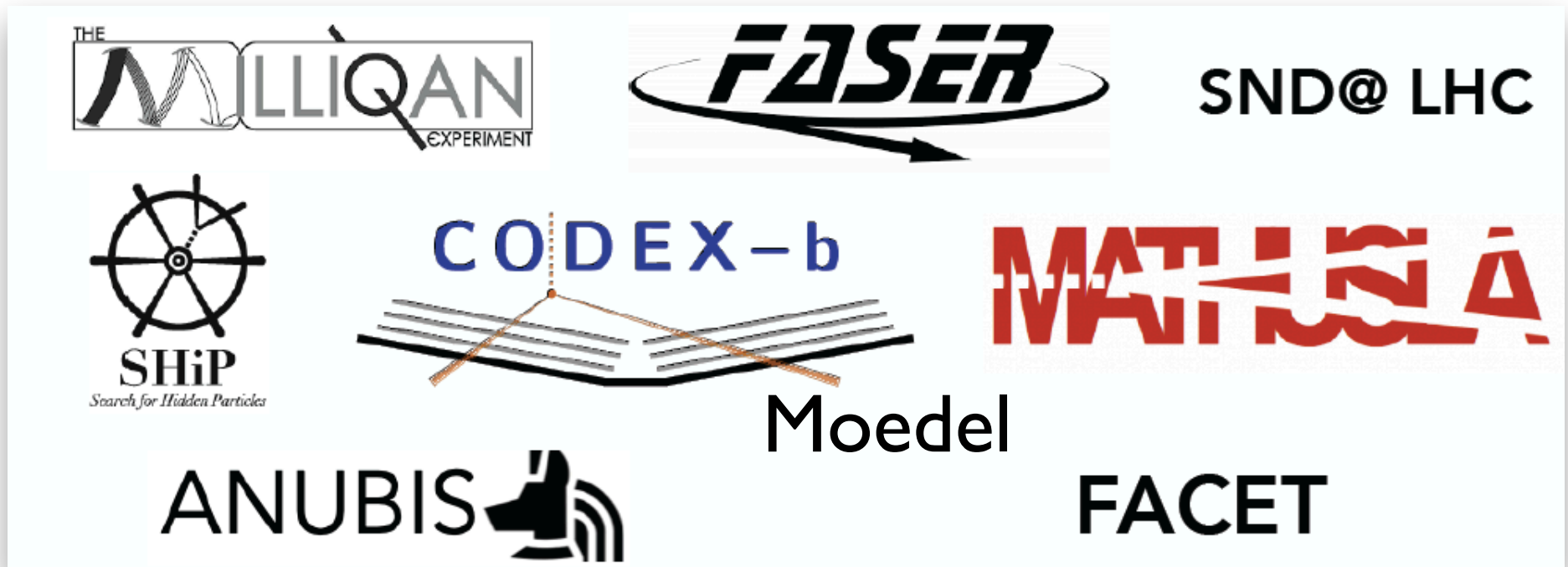
ATLAS: search for displaced vertices plus jets signatures

I. Longarini



Long-lived Particles

- Theorists began to model and reinterpret (HEPdata) LLP signals.
- 2000's: theory/exp collaborations blossomed, Moedel began in 2010
- Last decade+, many experiments, including several initiated by theorists! (LLPs and Portals both)



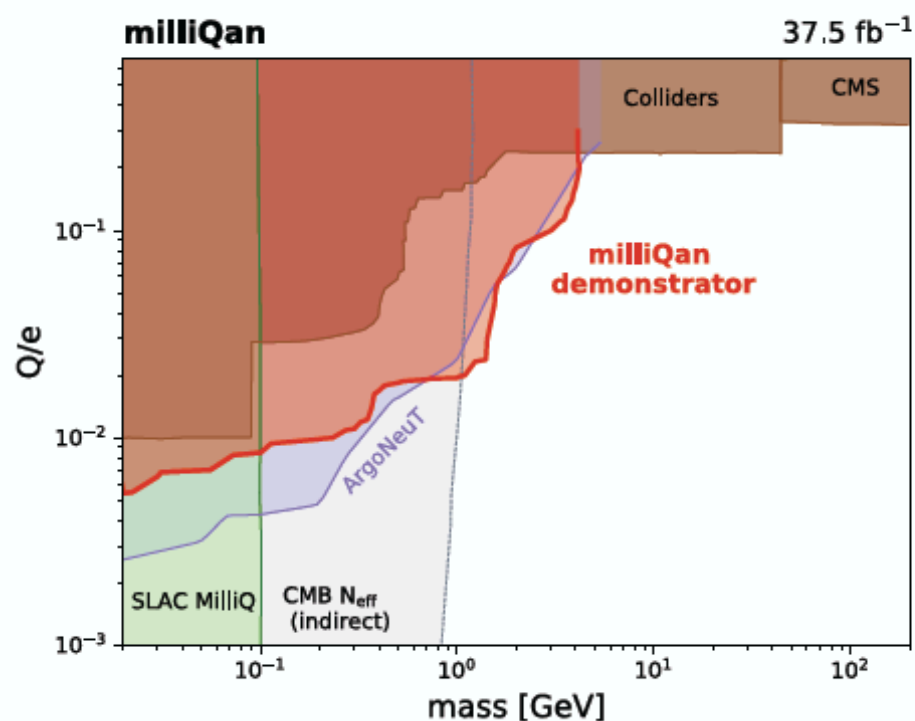
“Every Theorist has an experiment!”

Long-lived Particles

Upcoming: First data in test runs!



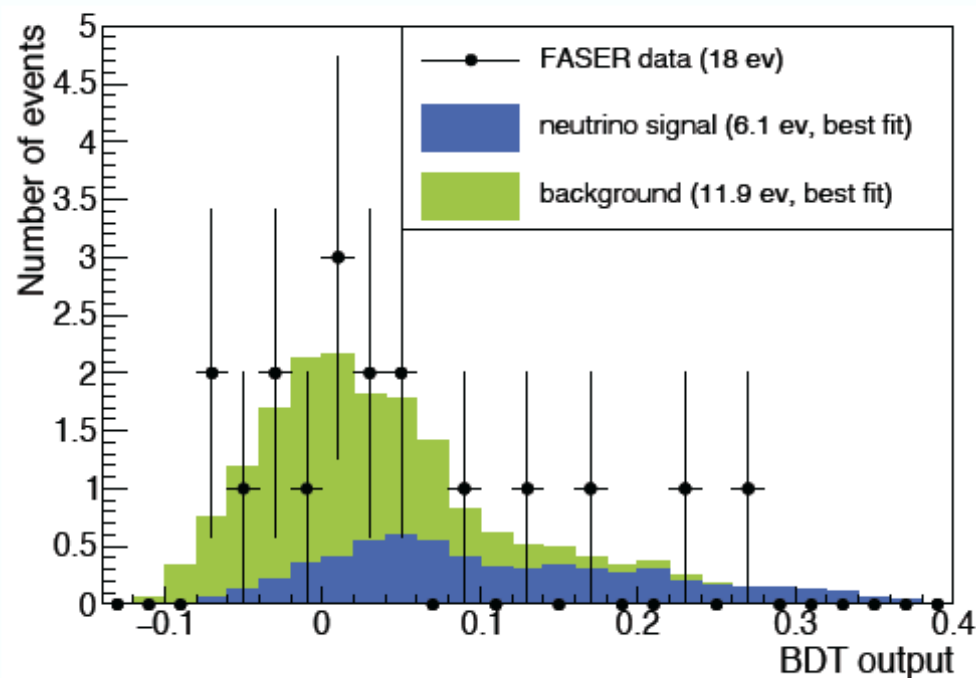
milliQan, 2005.06518 [PRD]



17



FASER, 2105.06197 [PRD]



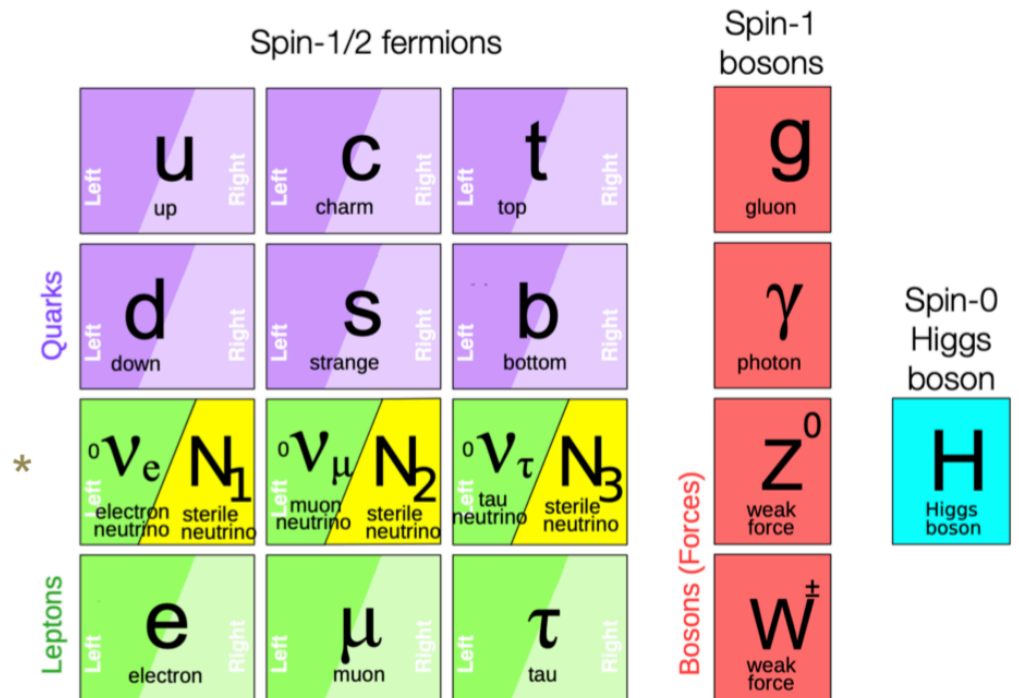
Heavy Neutral Leptons

- RH sterile neutrinos lead to HNLs when mixing with LR states. Majorana or Dirac.

- Could explain:

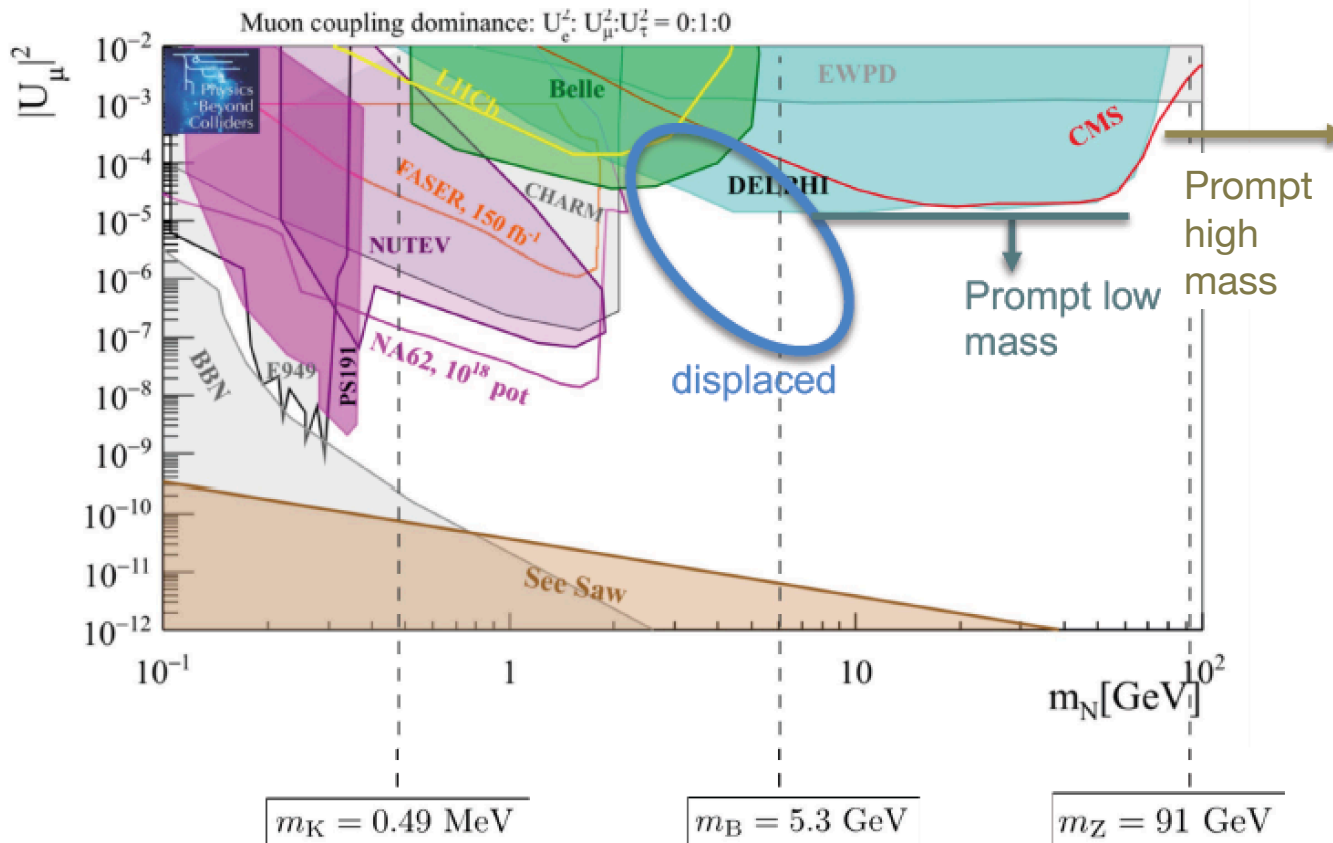
- ν masses
- Seesaw mechanism
- matter/anti-matter asymmetry
- dark matter candidate
- Majorana: LFV

SM Extension with 3 HNLs



Heavy Neutral Leptons

physics beyond colliders
CERN-PBC-REPORT-2018-007



How to search?

Below Kaon mass

- Kaon decays (e.g. NA62)

Below B or D masses

- Heavy flavor decays (e.g. Belle, LHCb, FASER)

Below W, Z masses

- Displaced & prompt searches (e.g. LEP, LHC)

Above W, Z masses

- Decays to on shell bosons (e.g. LHC)

Heavy Neutral Leptons

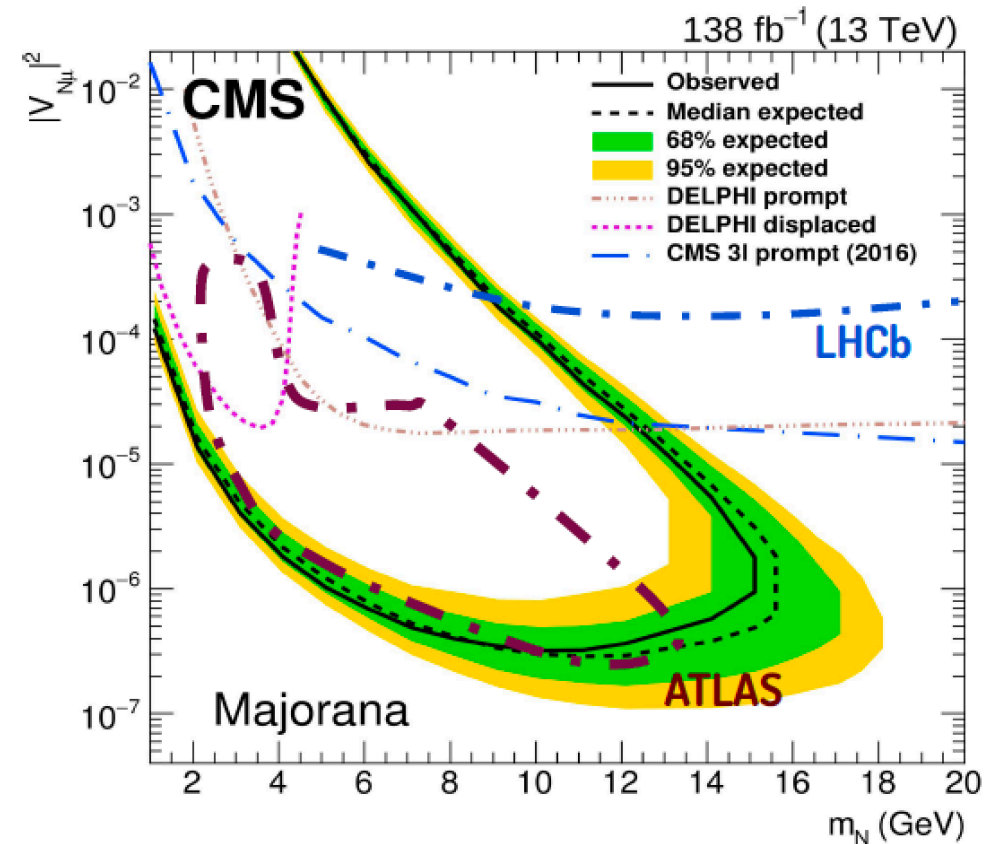
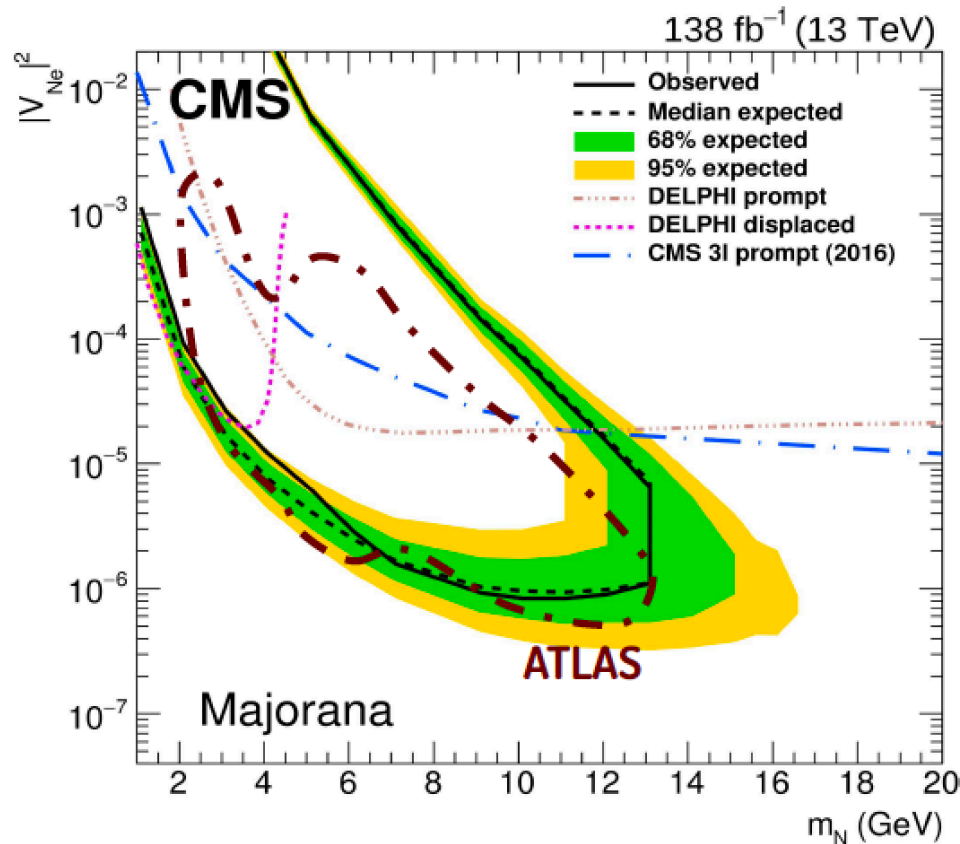
A. Escalante del Valle, LLP Workshop, May 2022

Hand-drawn comparison between ATLAS, CMS, LHCb, and DELPHI results

CMS arXiv:2201.05578

ATLAS-CONF-2019-029

LHCb arXiv:2011.05263

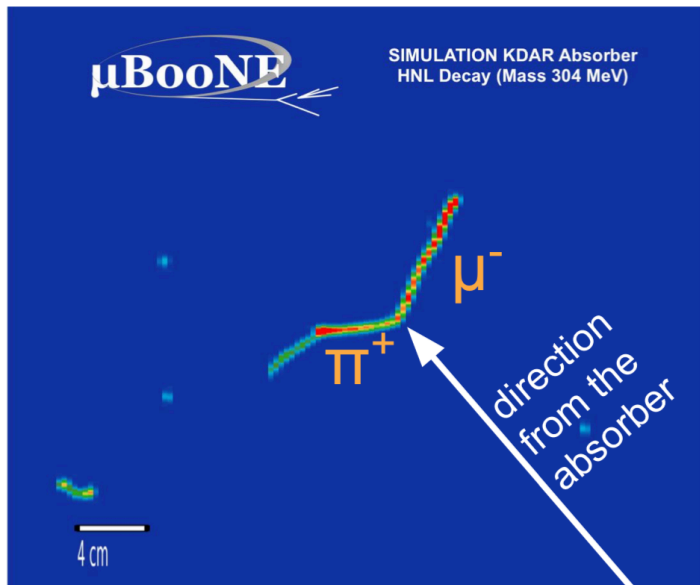


Territory explored by colliders recently

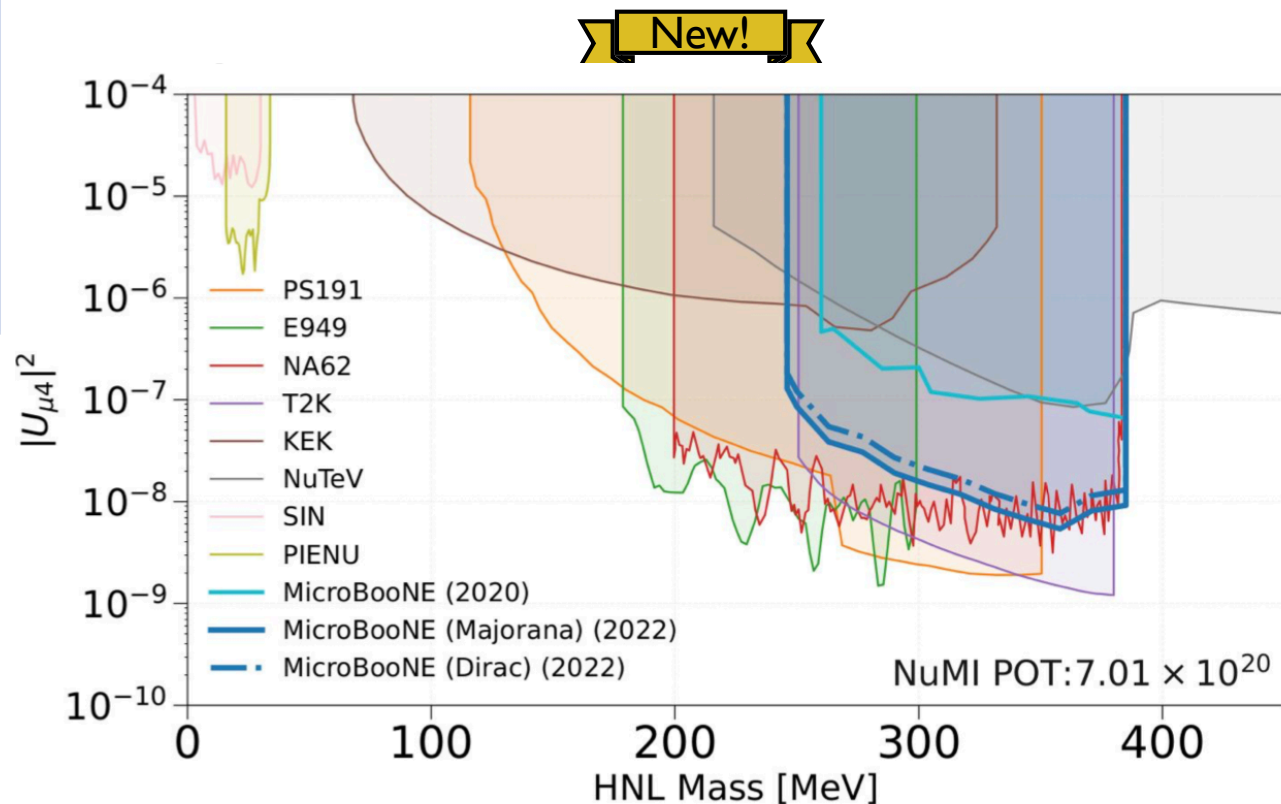
many HNL results shown at ICHEP!

Neutrino Detectors as BSM tools

- long-lived searches (late trigger)
- beam dump searches: kaons decaying at rest



- HNLs and HPS (higgs portal scalars)



- new beam dump results
- x10 increase in reach

compositeness?
extra dimensions?

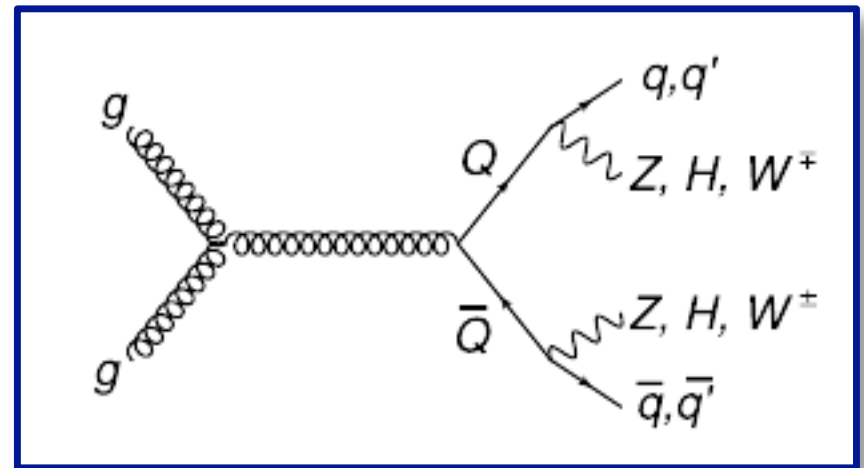


Vector-like Quarks

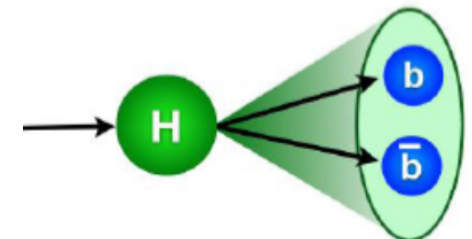
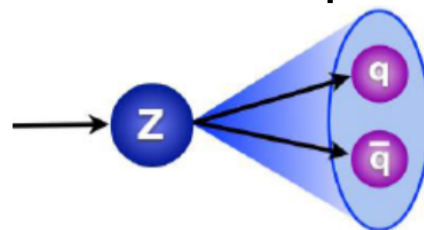
- Higgs- good agreement with SM: Hard to accommodate new particle masses.
- Vector-like fermions: Dirac masses— decouple from EWK scale at large mass.
- Motivated by string theory or extra dimensions.

Weak multiplets (isospin_{hypercharge})

Singlets	Doublets	Triplets
$1_{2/3} = T$	$2_{1/6} = \begin{pmatrix} T \\ B \end{pmatrix}$	$3_{2/3} = \begin{pmatrix} X \\ T \\ B \end{pmatrix}$
$1_{-1/3} = B$	$2_{7/6} = \begin{pmatrix} X \\ T \end{pmatrix}$	$3_{-1/3} = \begin{pmatrix} T \\ B \\ Y \end{pmatrix}$
	$2_{-5/6} = \begin{pmatrix} B \\ Y \end{pmatrix}$	



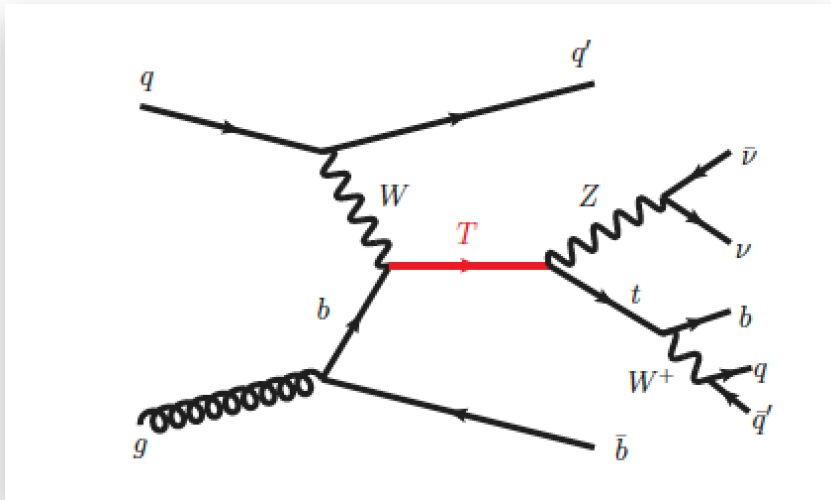
boosted final state particles



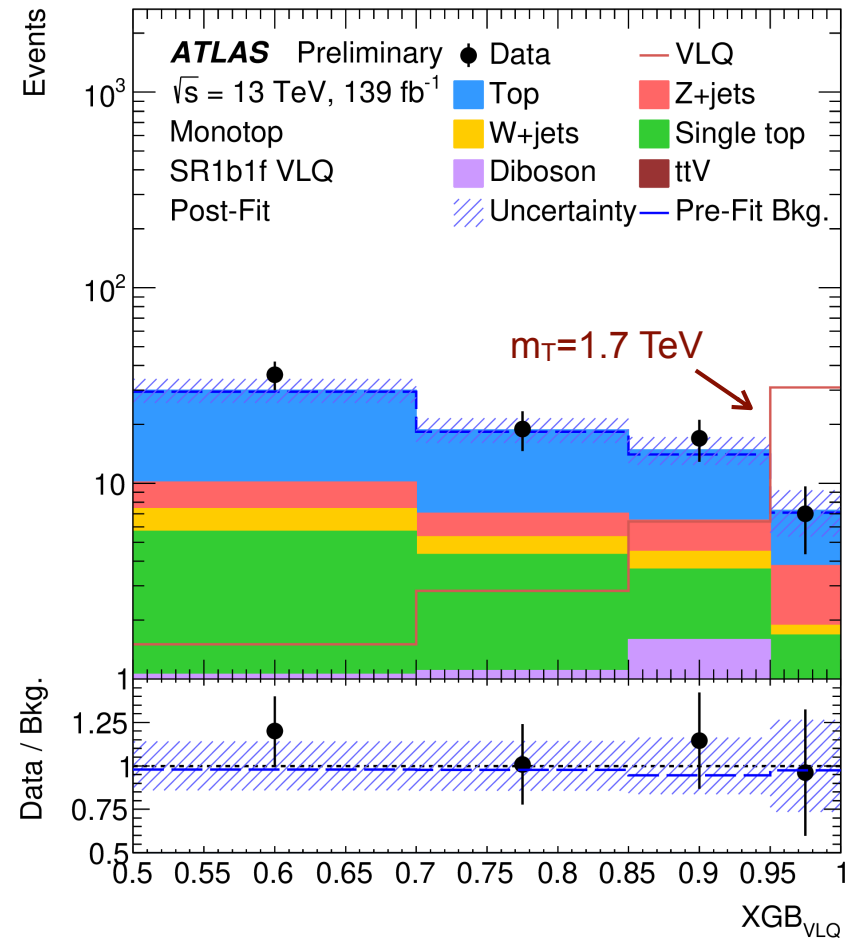
Vector-like Quarks

New!

New “monotop” search from ATLAS
([G. Unal](#)) also looks for single VLQ
production: most sensitive at the LHC!



Use a BDT classifier to look at
benchmark coupling $\kappa_T=0.5$ and
 $BR(T \rightarrow tZ) = 25\%$



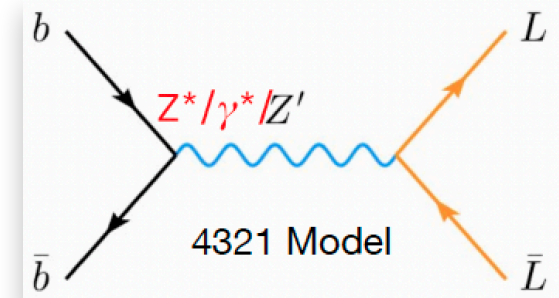
Limit: m_T (singlet) > 2.2 TeV
(500 GeV gain!)

CMS VLQs: see talks by [J. Bonilla](#) and [A. Rizzi](#)

Vector-like Leptons

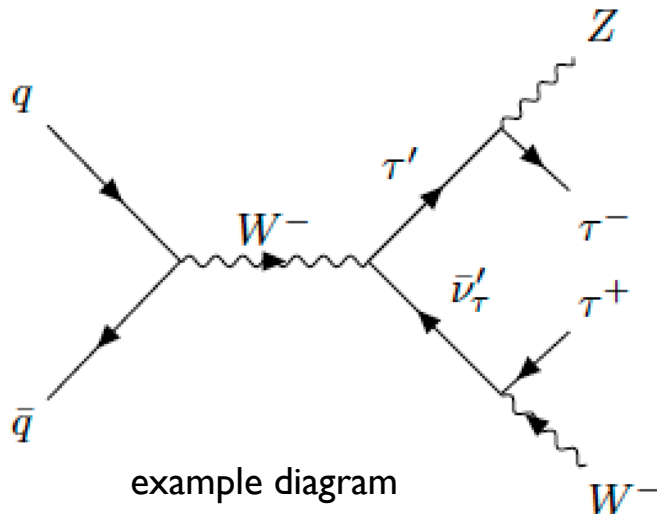
Additional motivation from recent B flavor anomalies. Relevant: **Searches for 3rd gen L!**

D. Faroughy talk



ATLAS:

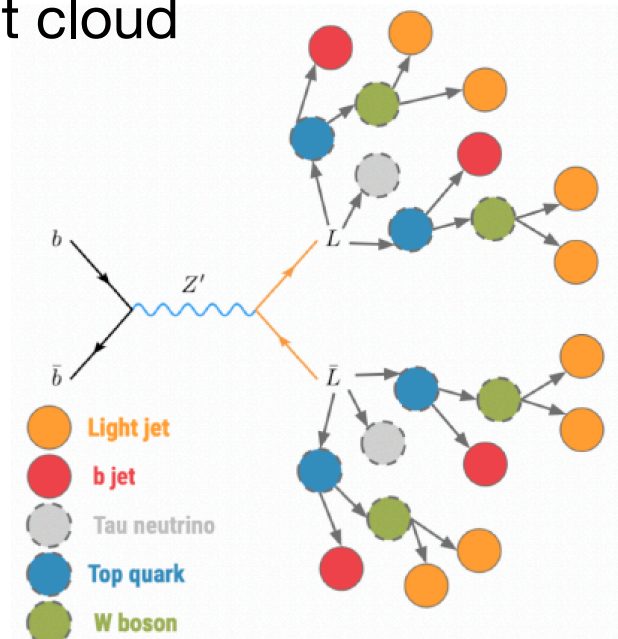
- Doublet $L' = (\nu'_\tau, \tau')$, $\nu'_\tau \rightarrow W^+ \tau^-$, $\tau' \rightarrow H/Z \tau^-$
- final state: at least 2 light e/μ , $\geq 0 \tau_{\text{had}}$, momentum imbalance
- Uses BDT to tag b and tau



example diagram

CMS:

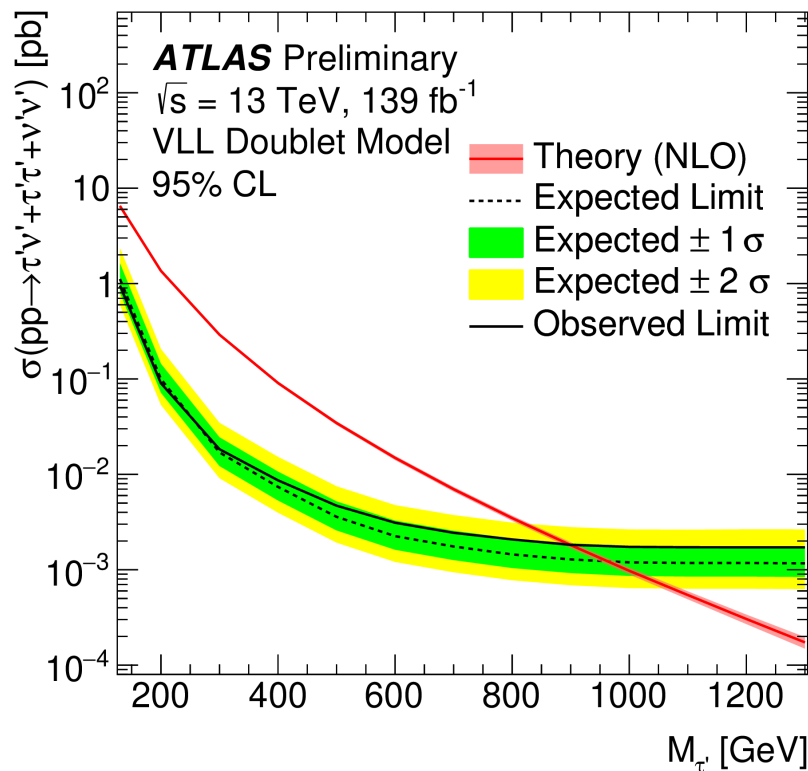
- EWK focus: $L' \rightarrow t\bar{t}$ (ν_τ/τ), $t \rightarrow qq\bar{b}$
- Uses 2 graph NN (bkg, signal)
- represent hadronic event as point cloud



Vector-like Leptons

ATLAS:

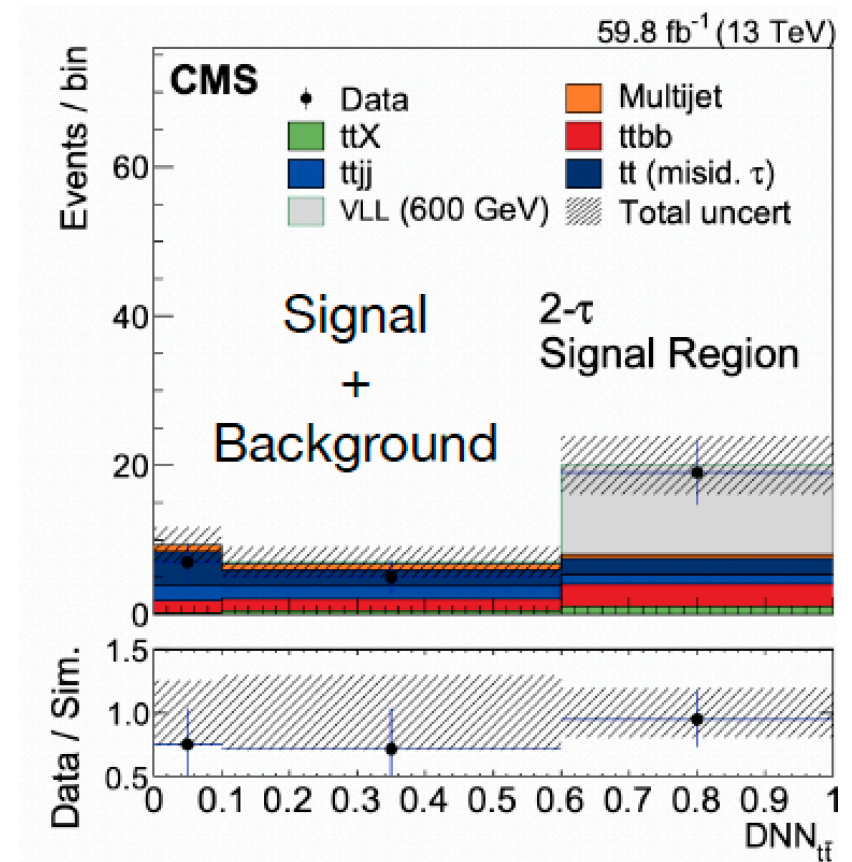
- Limits on σ v. $m_{\tau'}$:
967 GeV (exp) / 898 GeV (obs)



ATLAS-CONF-2022-044

CMS:

- Fit prefers signal at 2.8σ for a representative 600 GeV VLL



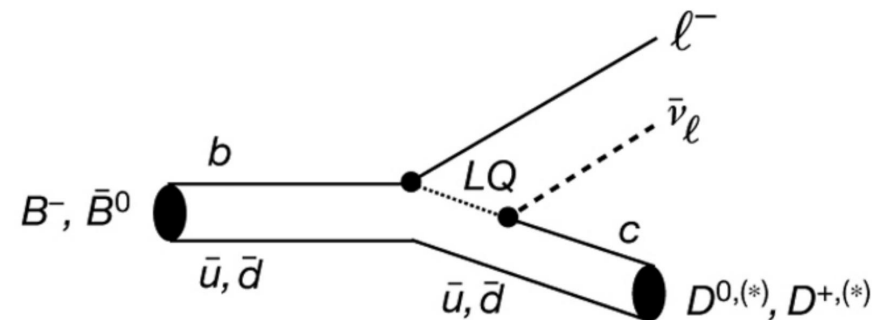
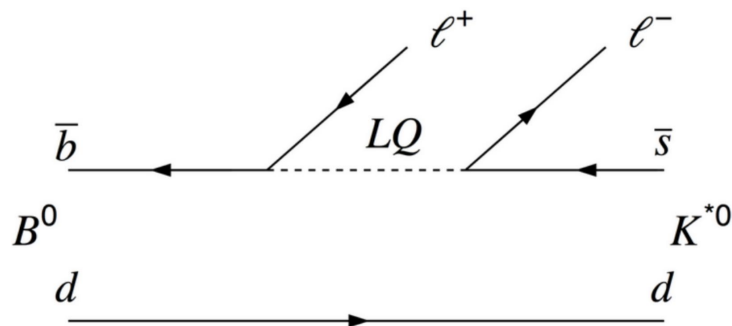
CMS-PAS-B2G-21-004

flavor violation?



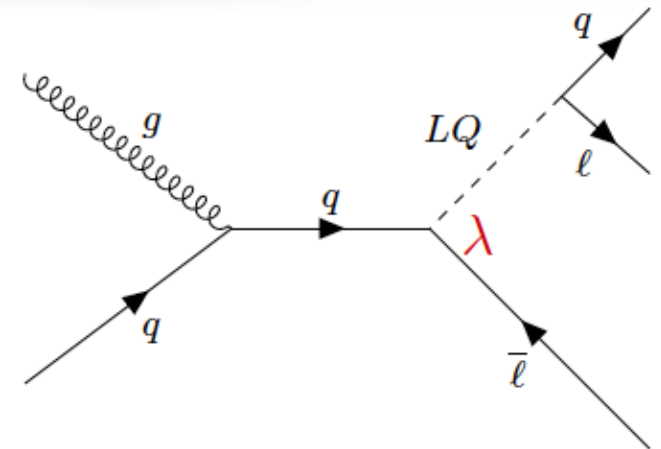
Leptoquarks

- New scalar (spin 0) or vector (spin 1) particle with fractional electric charge.
- LQs appear in RPV SUSY, GUTs, Technicolor, composite models. Expected at the TeV scale.



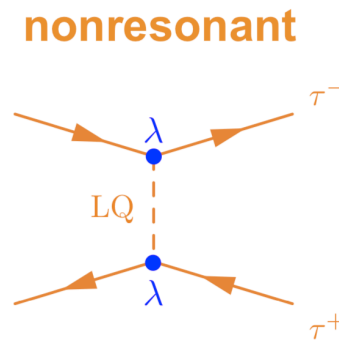
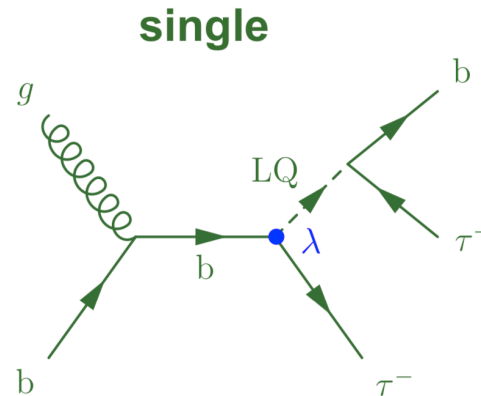
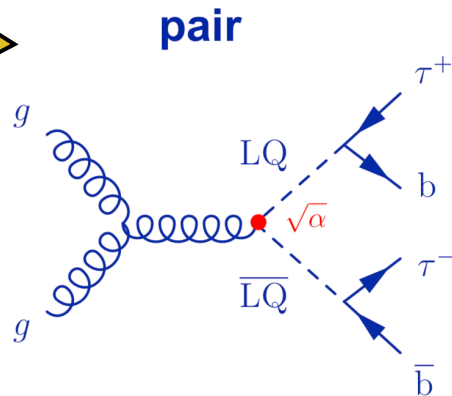
Popular! Candidates to explain some flavor anomalies in B meson decays: possible hints of lepton flavor non-universality.

- Pair (strong) production: \sim depends on M_{LQ}
- Single (radiation): \sim depends on M_{LQ} and $LQ \rightarrow lq$ coupling λ



Leptoquarks

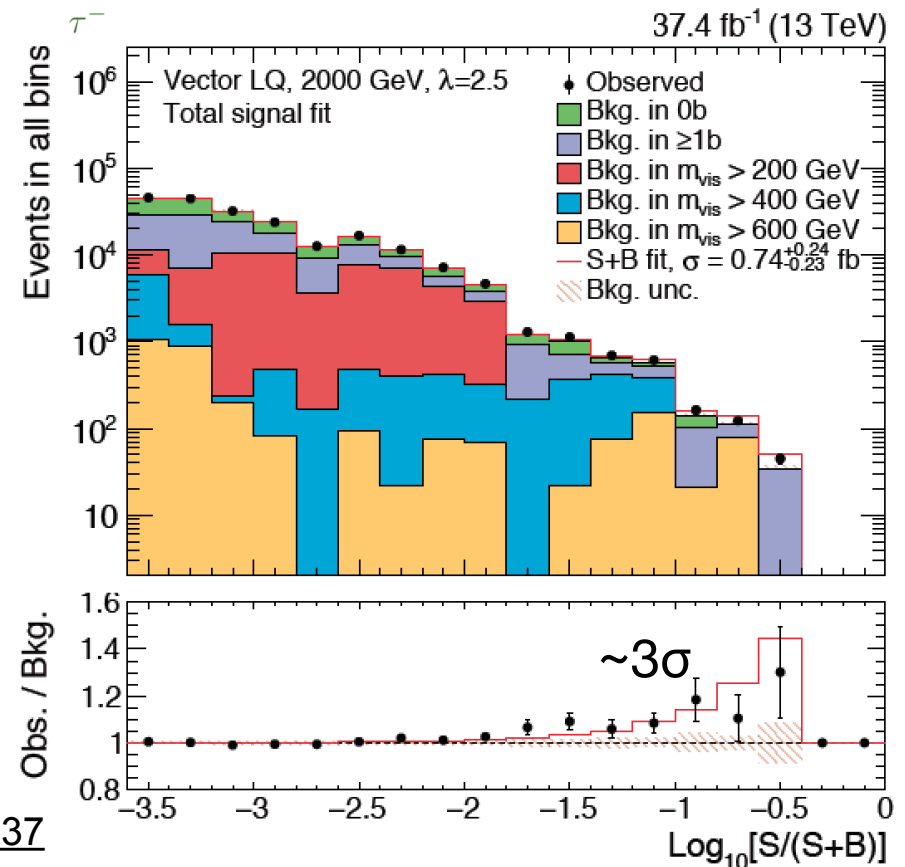
CMS: new search for combined b-tau LQ production



E. Tziaferi
O. Karacheban

CMS-PAS-EXO-19-016

- limits on scalar and vector LQs with varied couplings
- slight excess ($\sim 3\sigma$) in categories compatible with the $H \rightarrow \tau\tau$ result driven by non-res categories

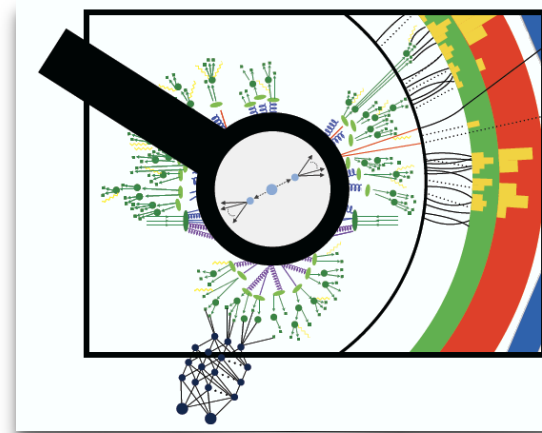


New ATLAS b-tau LQ resonant result: ATLAS-CONF-2022-037

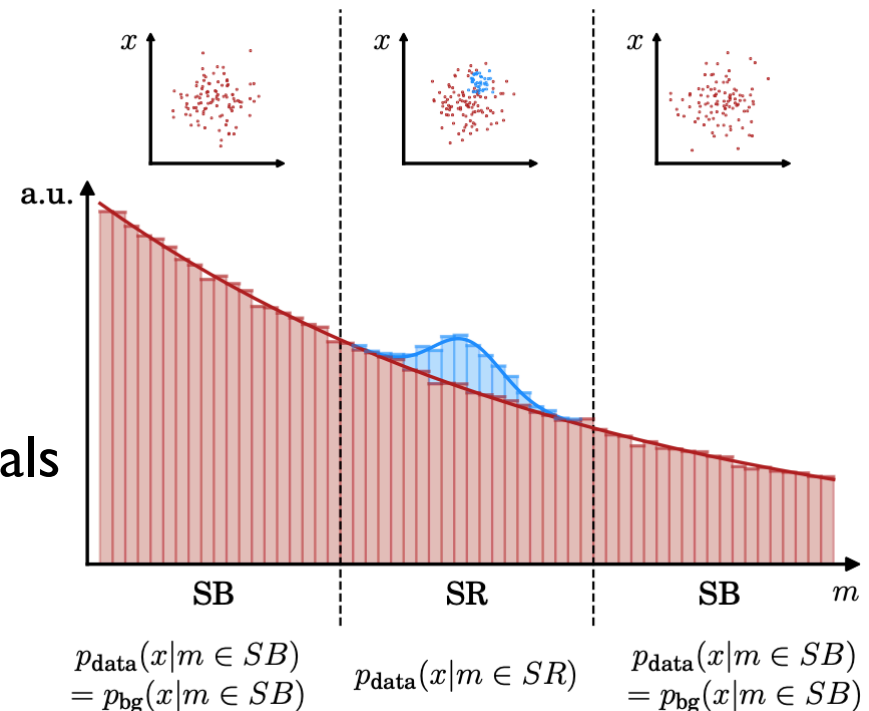


Anomaly Detection

- What do we do when we don't have a specific model to look for?
- AI/ML used since start of LHC for jet tagging/corrections, particle ID, and signal/background selection
- New approach: anomaly detection via
 - bump hunting (a la $H \rightarrow \gamma\gamma$) with background from data
 - unsupervised networks (autoencoders, adversarial nets, ...)
 - weakly or semi-supervised networks
- 2020 LHC Olympics: blinded samples w/ signals
- 2021 Dark Machine Challenge
- May 2022: PHYSTAT Anomalies Workshop

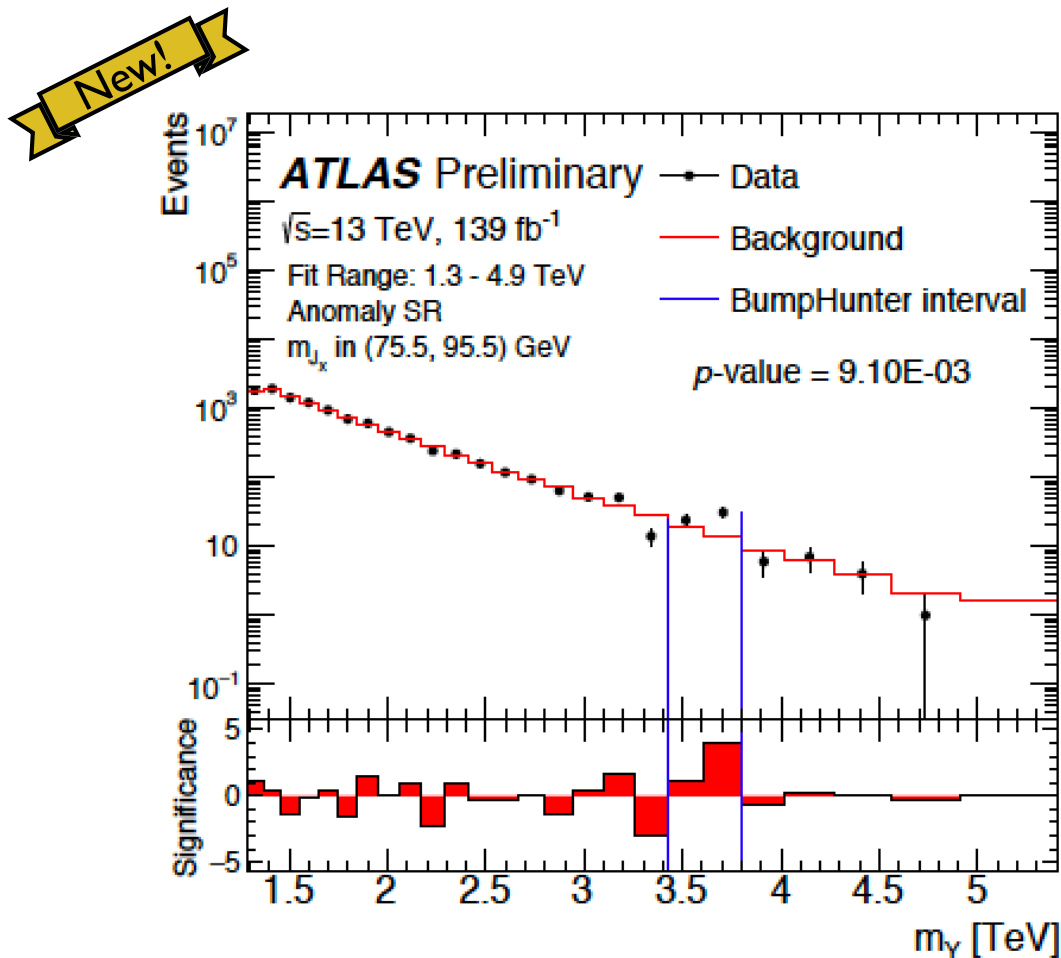


B. Nachman



Anomaly Detection

- ATLAS: search for boosted diboson “dijet” resonances with unsupervised NNs.
- Look for $Y \rightarrow X + H_{(\rightarrow bb)}$ (BSM particles $Y_{(\text{high mass})}$ and $X_{(1 \text{ or } 2 \text{ body})}$) in hadronic decays.
- Use boosted particle (jet substructure) techniques/taggers, and ML.



Results of background
only fit to all m_X categories.

Largest deviation in m_X [75.5-95.5 GeV]

Bumphunter interval: m_Y [3424-3805 GeV]

Global 1.47σ after trials factor

Could not cover

- plenty of other new results for ICHEP, SUSY, LHCP
- (please see also backup slides)
- many types of resonances, including $X \rightarrow (\text{dilepton}, VV, qq, HH)$, others
- touched on current trends at the expense of many classic searches
- areas of recent interest where I could not show the depth (LLPs, LQs, DM, dark sector, VLQs, HNLs...)
- BSM physics in many other non-accelerator venues— see parallel talks!
- indirect constraints by testing the SM (top quark/EWK sector, rare flavor processes, $g-2$, $\mu 2e$, EDMs...)
- interesting analysis techniques like jet substructure, machine learning, ...

Join us at BOOST 2022



14th International Workshop on Boosted Object Phenomenology,
Reconstruction, Measurements and Searches in HEP

15–19 Aug 2022
University of Hamburg

Enter your search term



15-19 August! Learn about novel analysis and reco techniques

Near future...



- This month! Gathering in Seattle, Washington, U.S.A., July 2022
- Many contributed papers on future BSM prospects at LHC and other facilities and frontiers: Energy, Cosmic, Neutrino, Rare, Computing...
- See also European Strategy Report 2020

Near future...



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- See also European Strategy Report 2020



Shout out to
LHC Run 3!

Final thoughts...

- This is a unique time in history: we have no solid prediction of what might come next (unlike W/Z, top, Higgs).
- The ICHEP BSM sessions had 75 parallel talks, each with several individual results. Community is working hard to explore all sectors!
- Collider experiments still dominate the search space: a number of intriguing results to watch & follow up in Run 3 and beyond.
- New, specialized experiments are demonstrating their “street cred”, and will soon contribute to the story.

This is a great time to search for surprises!

Fine!

Thank you to the ICHEP Local and International Organizing Committees!

Thank you to the BSM Conveners for great sessions and discussion!



Thank you to the BSM speakers for your inspiration!

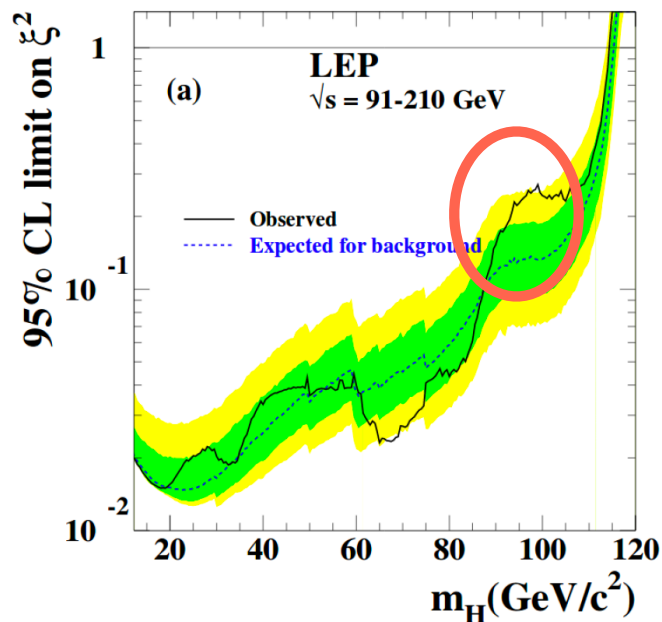
Backup Slides



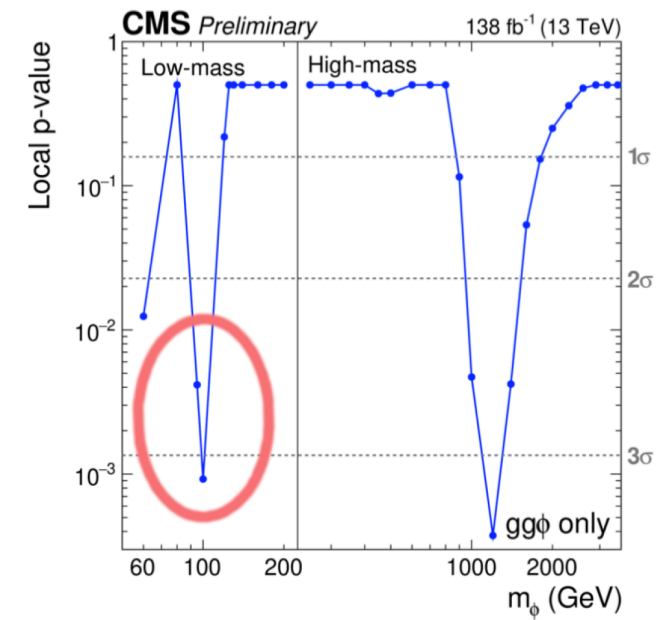
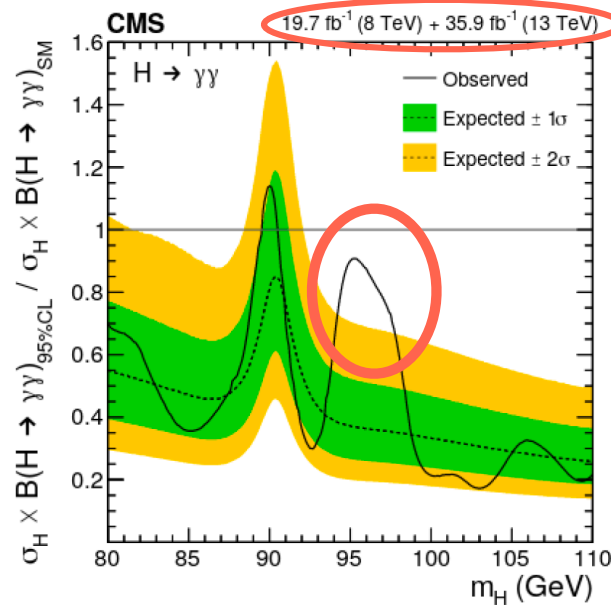
← Sam

Exotic Higgs: 95 GeV state?

- Longstanding but weak excess near the Z pole from LEP (bb)
- Excesses from CMS in $\gamma\gamma$ (old) and $\tau\tau$ channels (new)
- Much interest in this question in parallel sessions



[LEP: hep-ex/0306033]

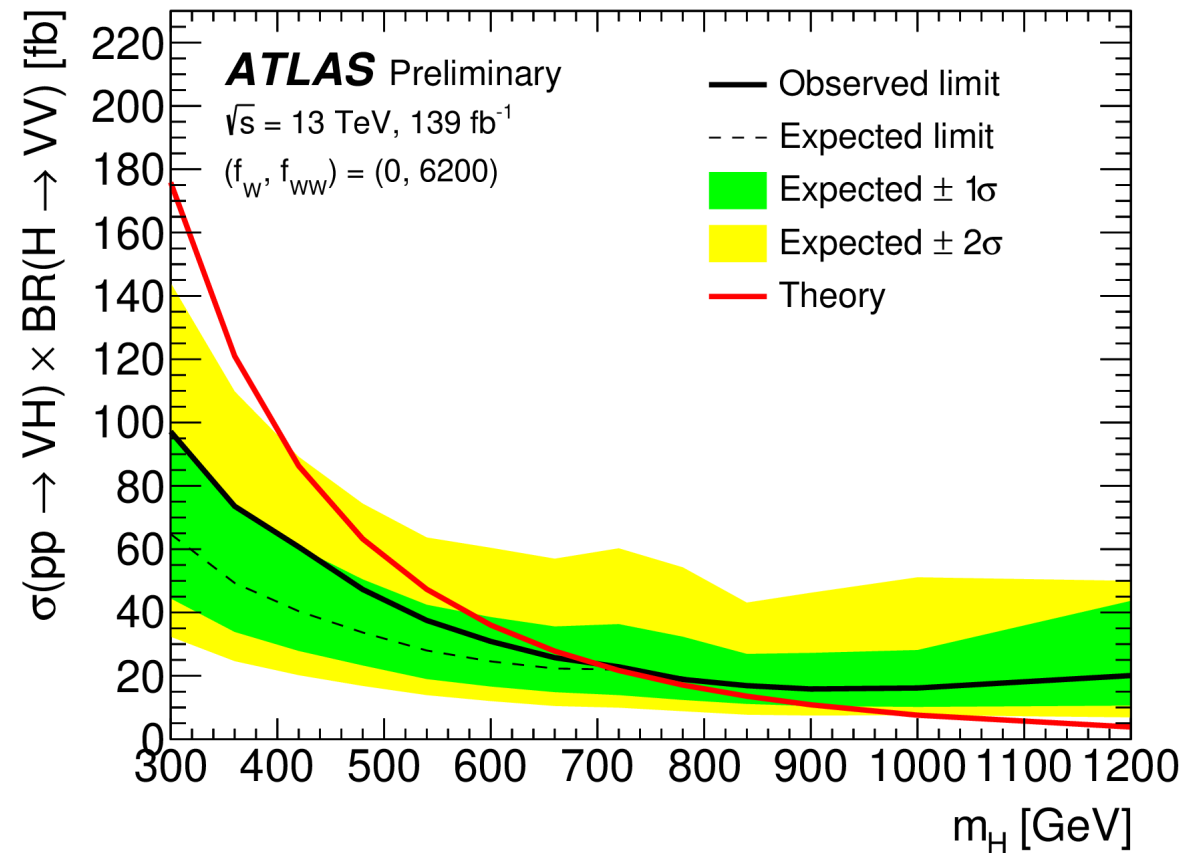
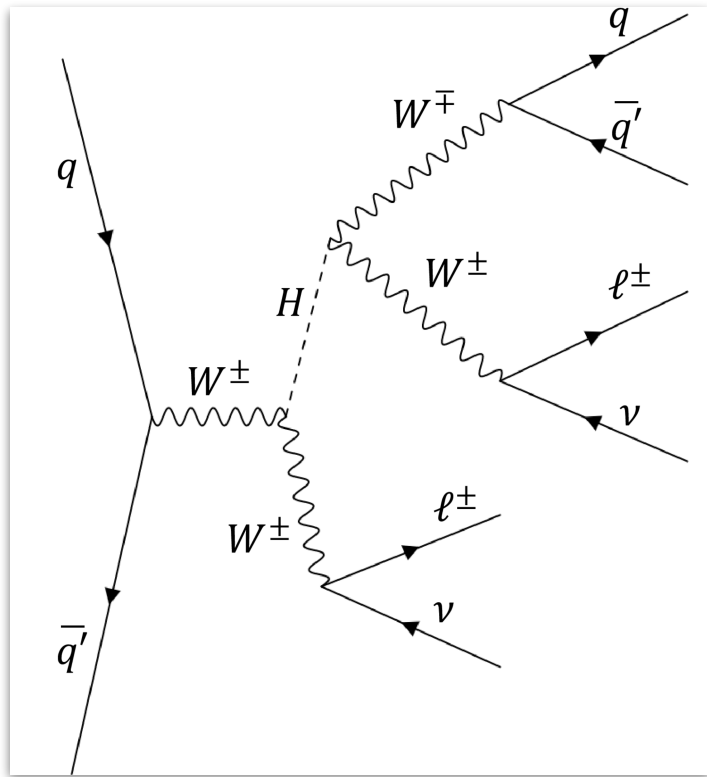


- Biekötter/Heinemeyer/Weiglein talk: can accommodate in N2HDM
- Boukidi talk: can accommodate in Type III 2HDM

Stay tuned for full Run 2 and Run 3!

Exotic Higgs: Heavy $(W)H \rightarrow (W)WW$

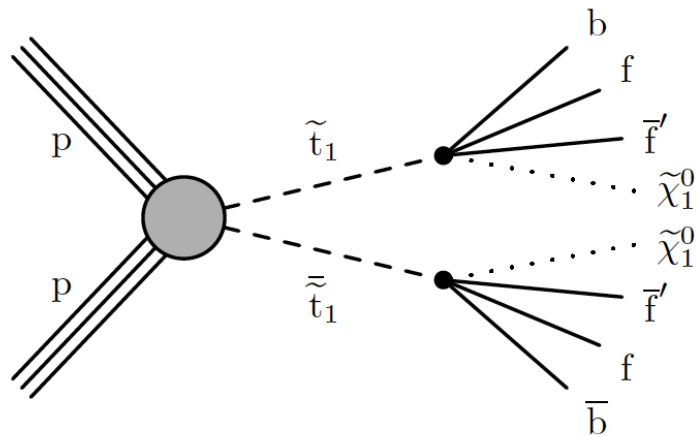
Clean same-sign dilepton signature from leptonic W decays.



ATLAS: limits on m_H and anomalous couplings H, WW

SUSY (Colliders)

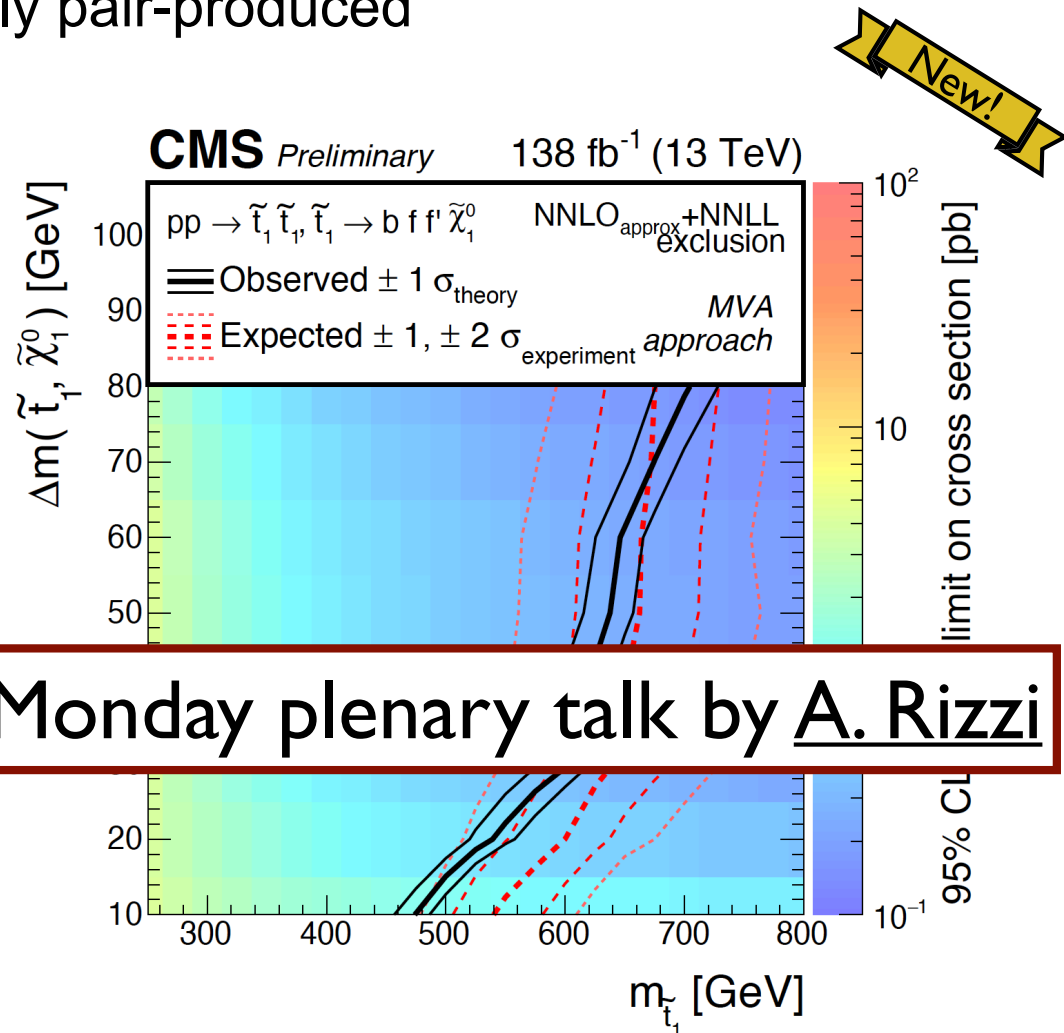
A light stop quark (or is it top squark?) could be key to solving the hierarchy problem - should be readily pair-produced



Similar to top quark pair production, but with extra missing E_T .

As $m(\chi)$ approaches $m(\tilde{t})$, sensitivity decreases

Limits expressed in terms of $m(\tilde{t})$ and Δm



See Monday plenary talk by A. Rizzi

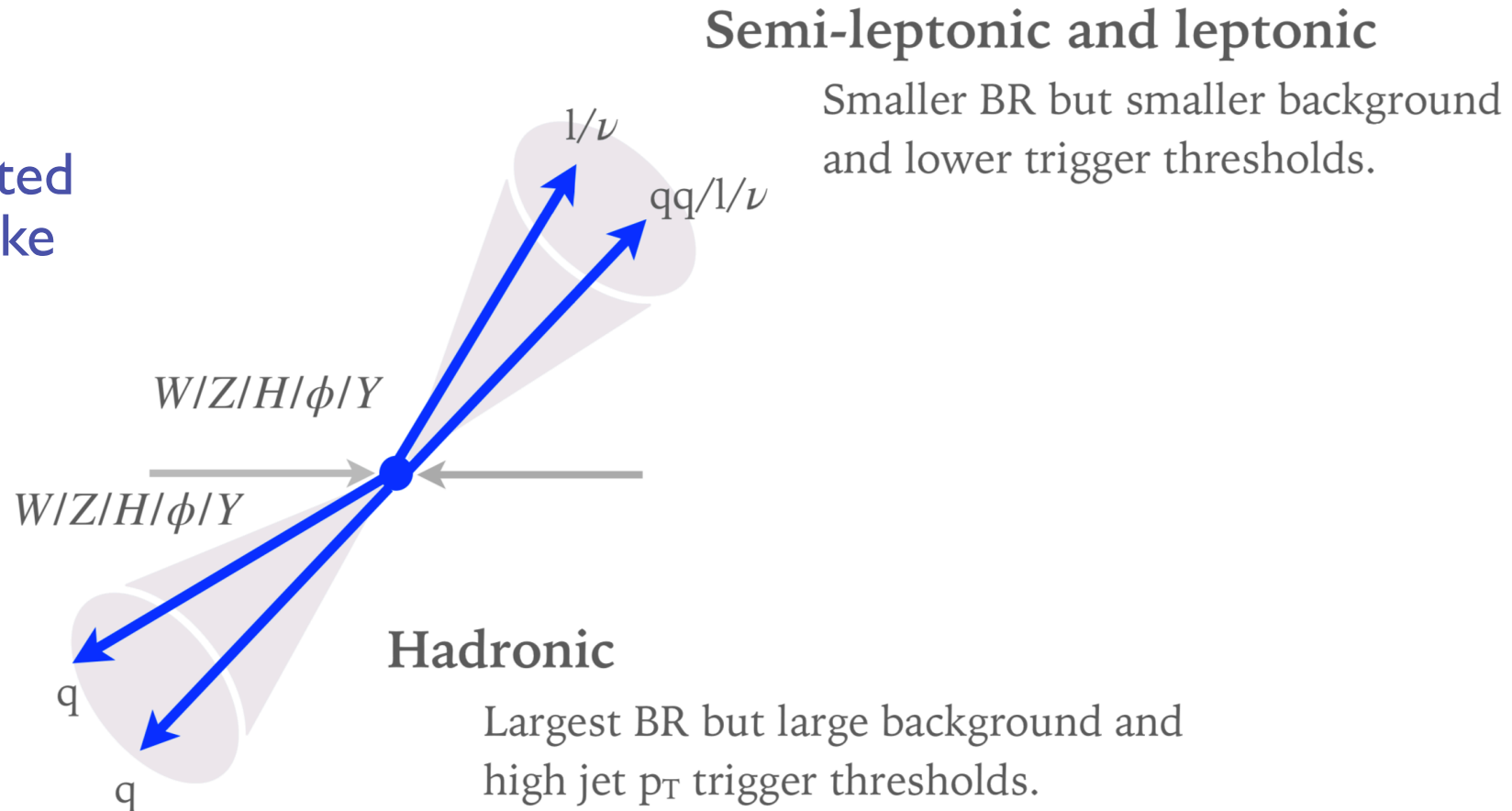
CMS uses an MVA to search for stop in 4-body decays

Di-boson Resonances

Searches cover range of models:

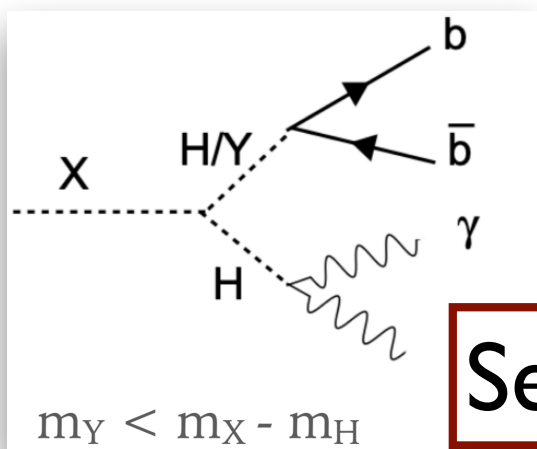
- Spin 0: extended Higgs, warped extra dimensions(w.e.d.), 2HDM
- Spin 1: heavy vector triplet(HVT), extensions of w.e.d.
- Spin 2: warped extra dimensions

Highly-boosted
often dijet-like
final states!



Di-boson Resonances

CMS searches for $X \rightarrow HH/HY \rightarrow bb\gamma\gamma$ (Y new light scalar).



X interpreted either in
RS bulk model or NMSSM

New!

See Monday plenary talk by A. Rizzi

$M_X = 650 \text{ GeV}$

$M_Y = 90 \text{ GeV}$

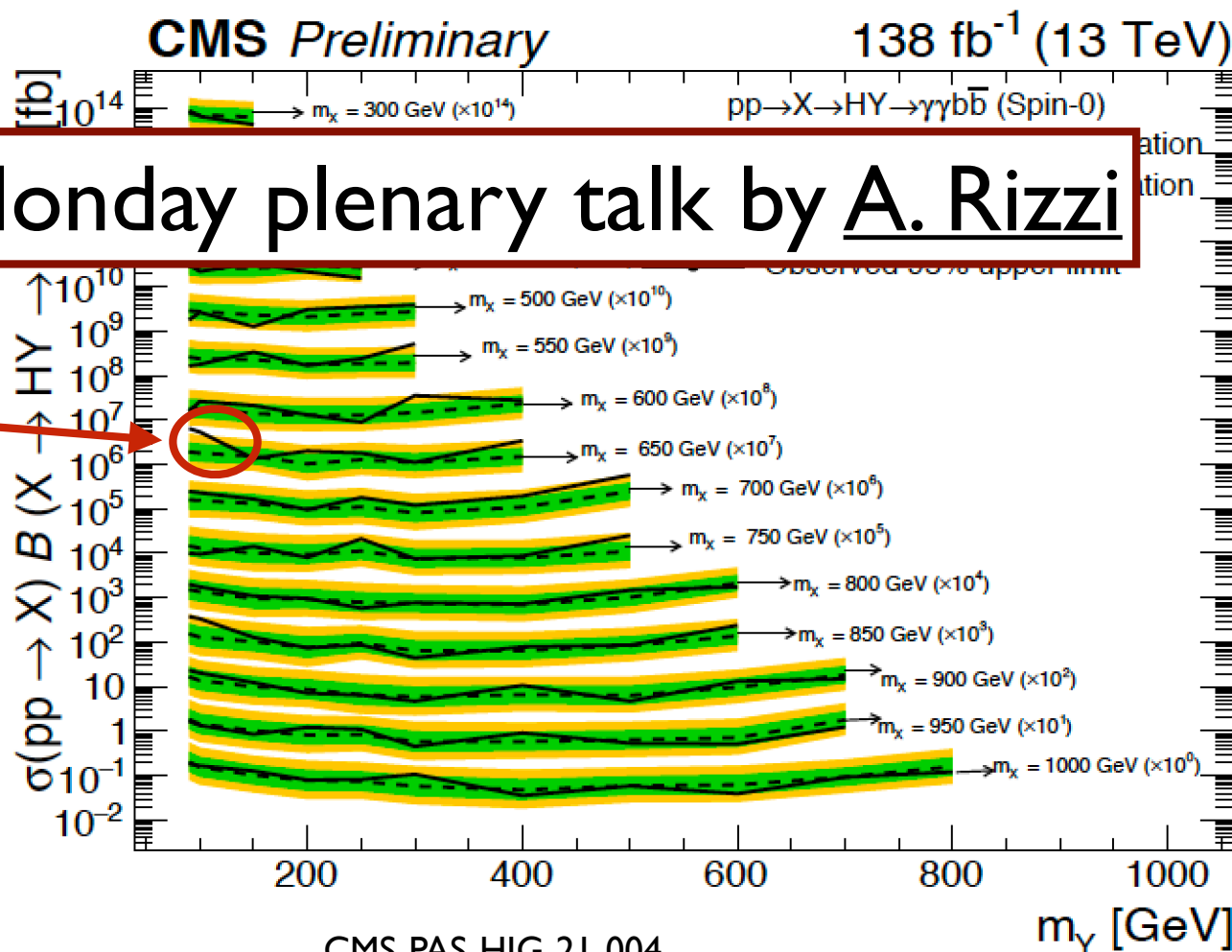
local sig: 3.8σ

global sig: 2.6σ ($M_Y < 150 \text{ GeV}$)

global sig: 3.5σ @ $M_Y = 100 \text{ GeV}$

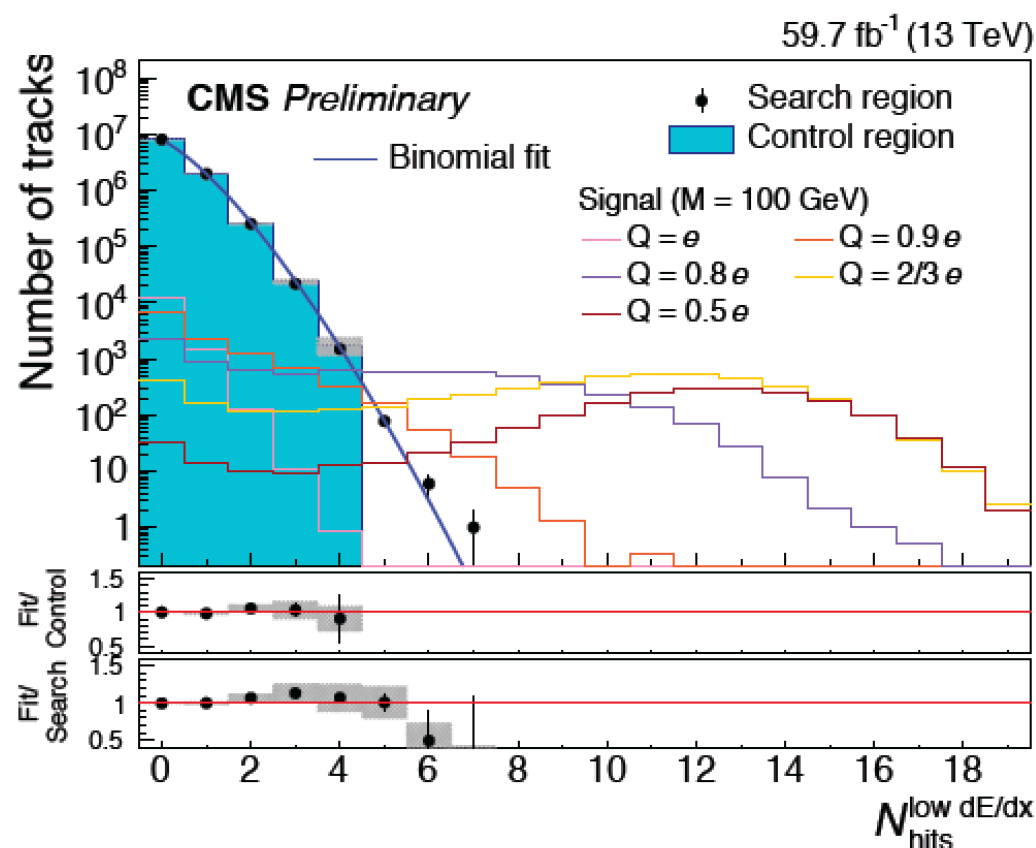
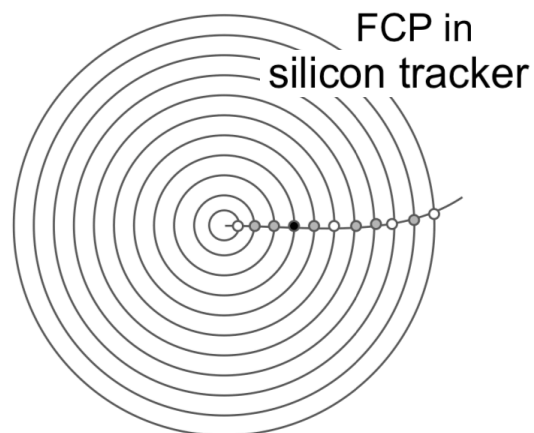
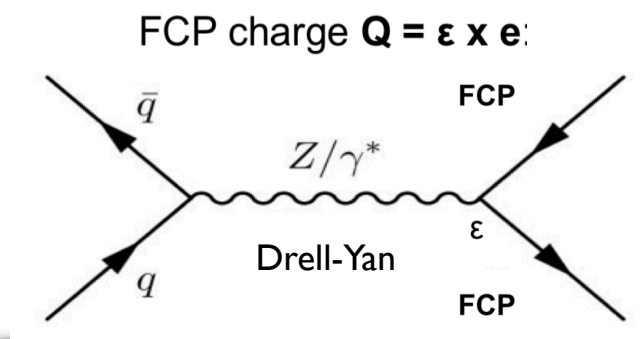
Consistent with local excesses @:

- Low mass $H(\gamma\gamma)$ @ 95 GeV
- High mass $H(WW)$ @ 650 GeV
- $A(\tau\tau)$ @ 100 GeV



Fractional Charges

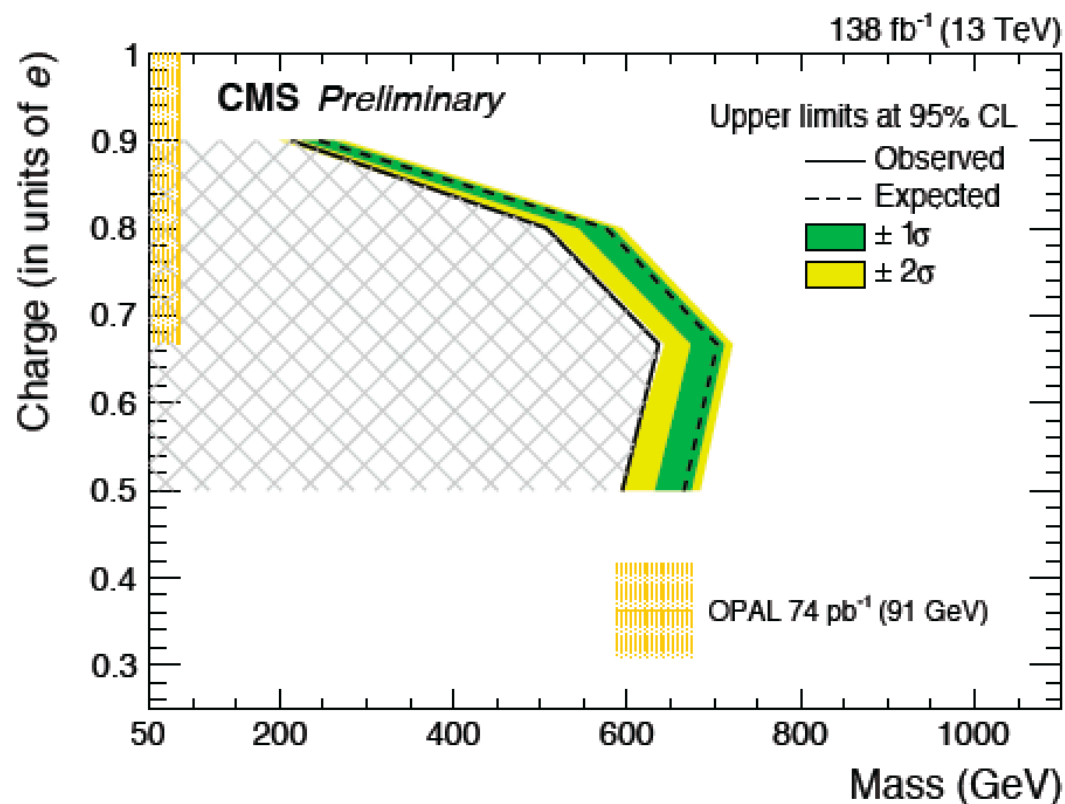
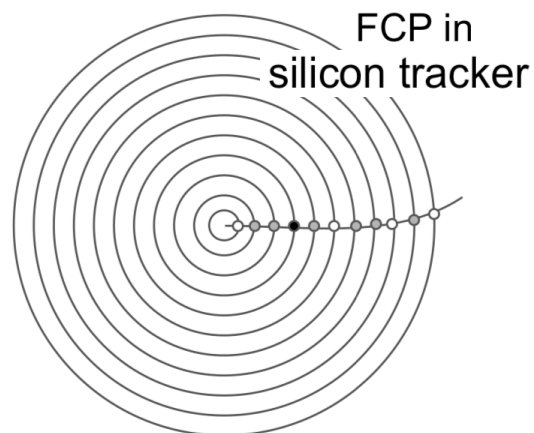
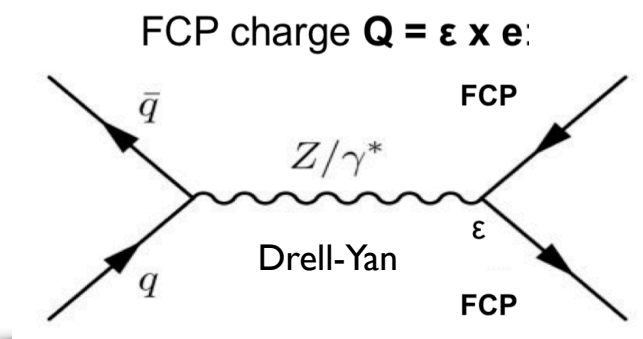
- Limited constraints on free fractional charges at LHC masses.
- Motivated in some weakly-connected scenarios: e.g. “portals” with new U(1) symmetry with boson=dark photon, mixing with SM hypercharge.
- CMS: weakly ionizing particles in tracking detector probing $Q=[1/2 \text{ to } 1]e$.



- Hit from significant energy loss: $dE/dx > 3 \text{ MeV/cm}$
- Hit from feeble energy loss: $dE/dx < 3 \text{ MeV/cm}$
- Missing hit: $dE/dx \ll \text{threshold}$

Fractional Charges

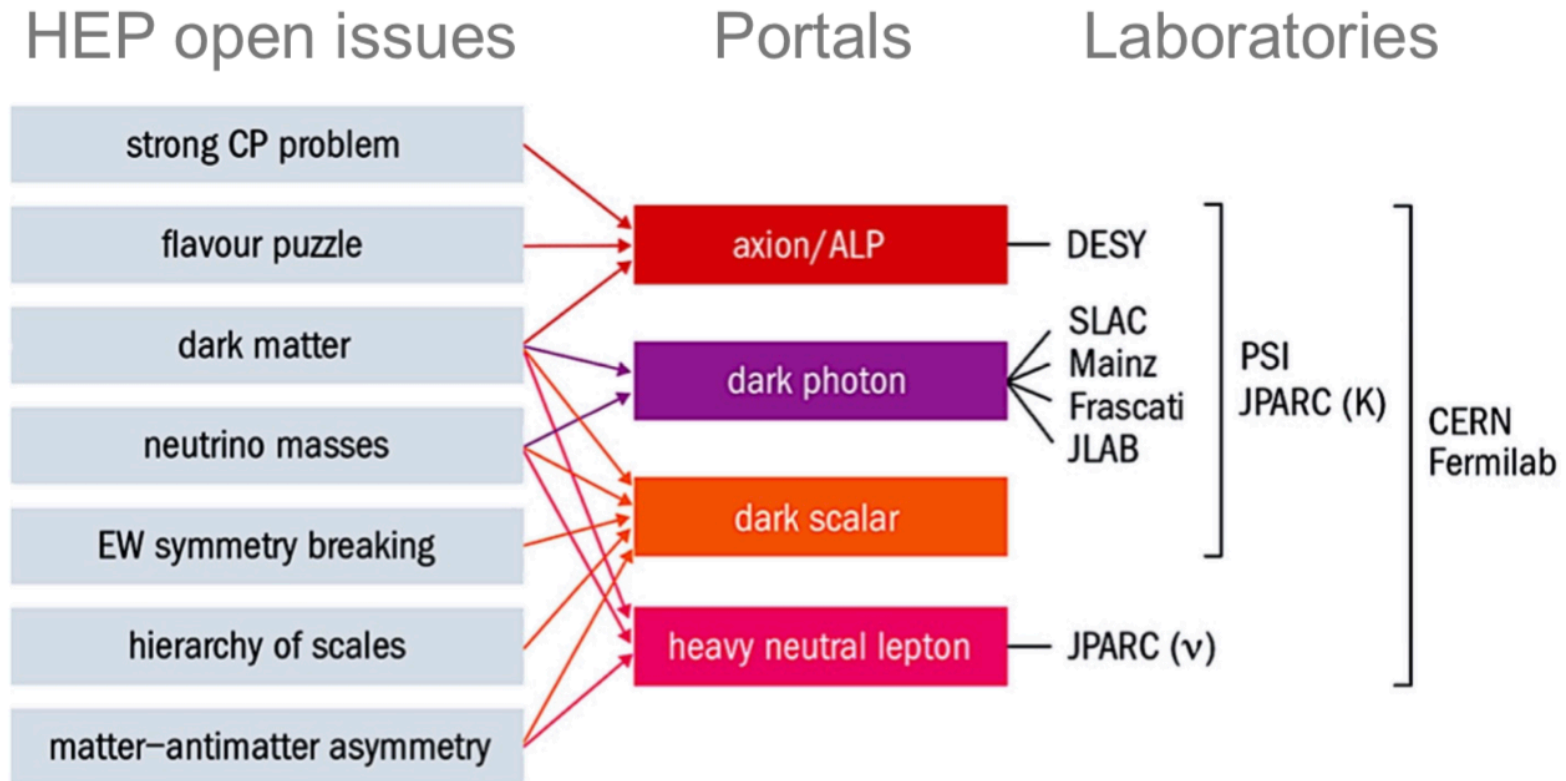
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New!

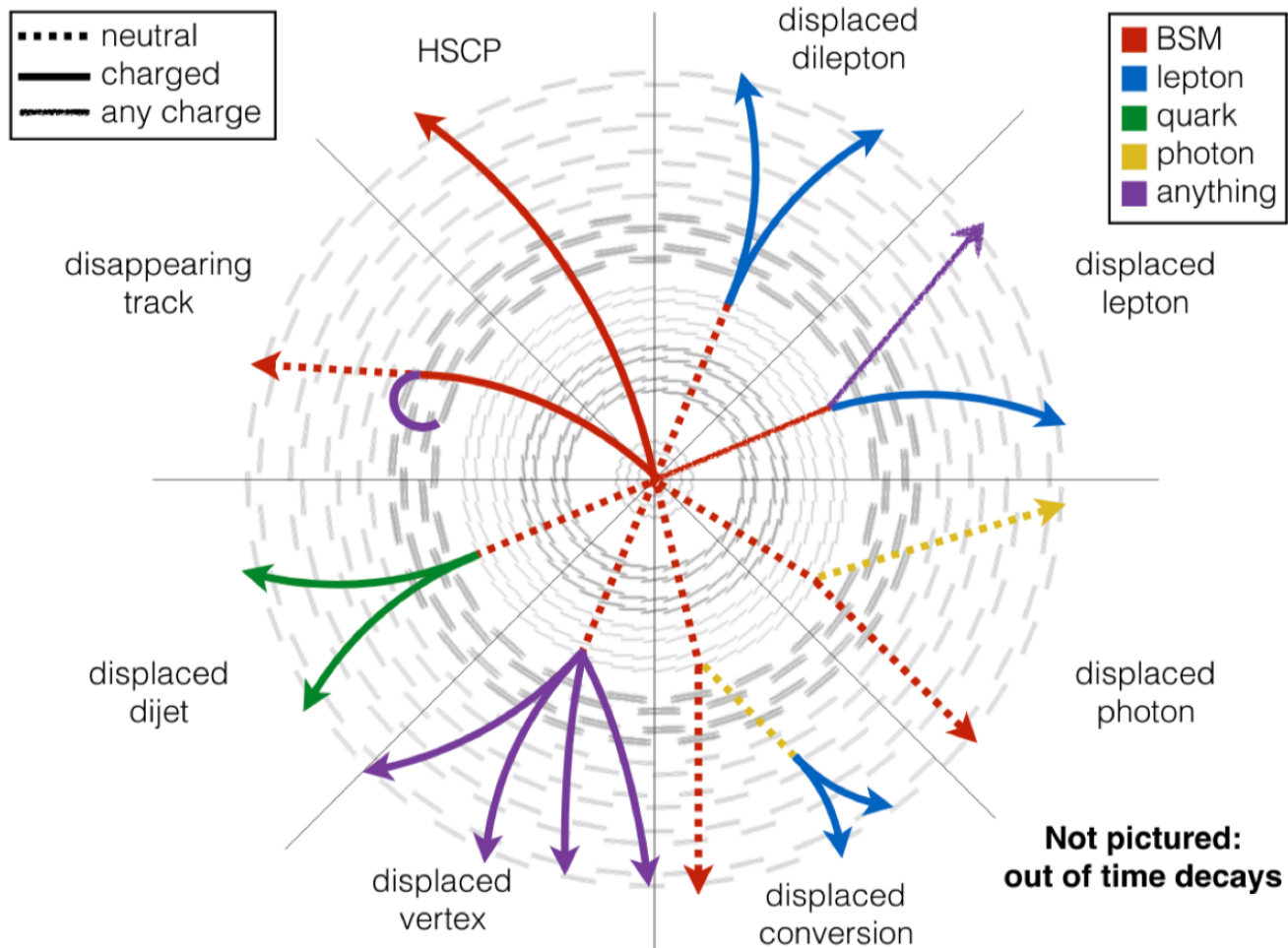
- Hit from significant energy loss: $dE/dx > 3 \text{ MeV/cm}$
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- Missing hit: $dE/dx \ll \text{threshold}$

Dark Portals



Adapted from B. Batell, G. Lanfranchi/M. Rayner, T. Lin

Long-lived Particles

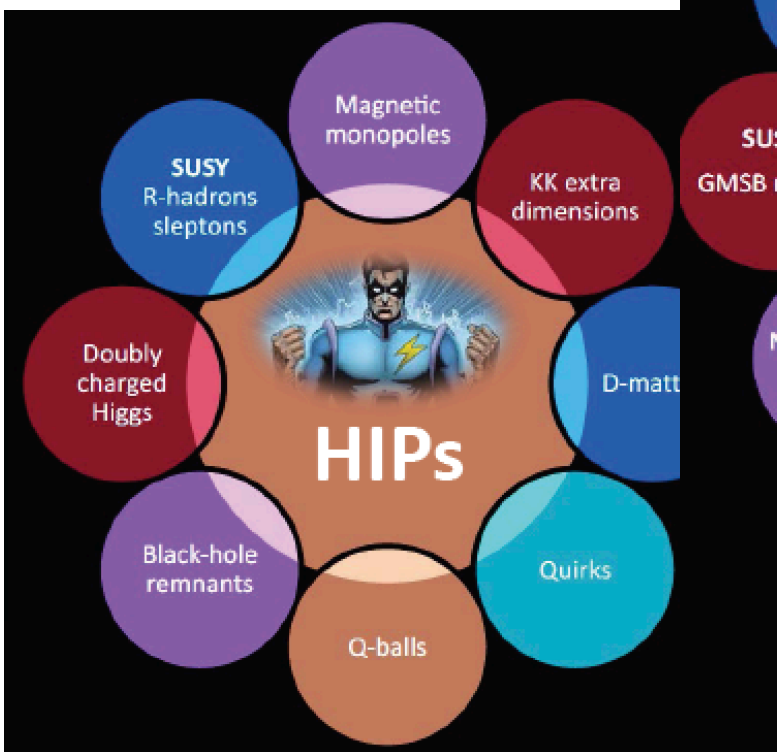


Beyond LLPs: MoEDAL-MAPP

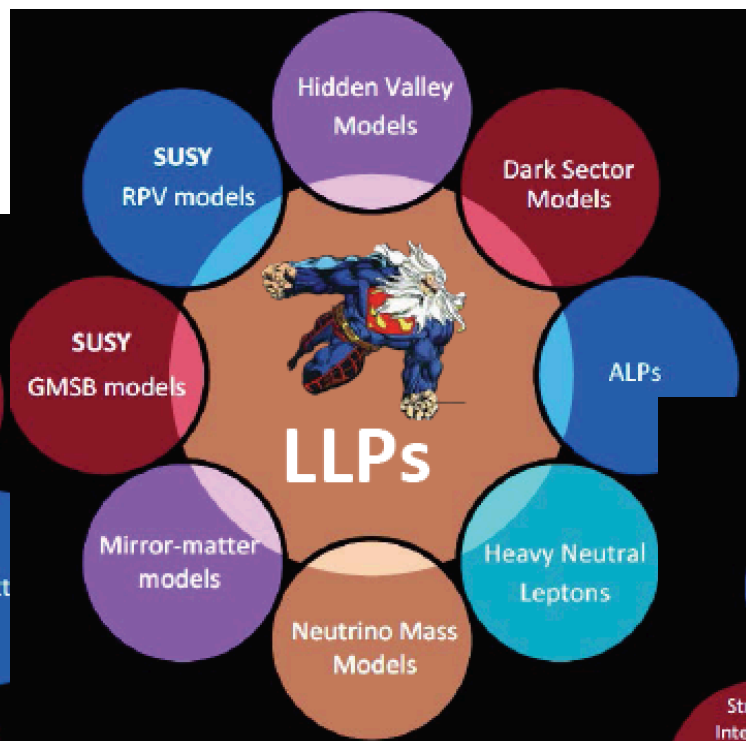
LHC's first dedicated search experiment- first data in 2015



highly-ionizing



long-lived



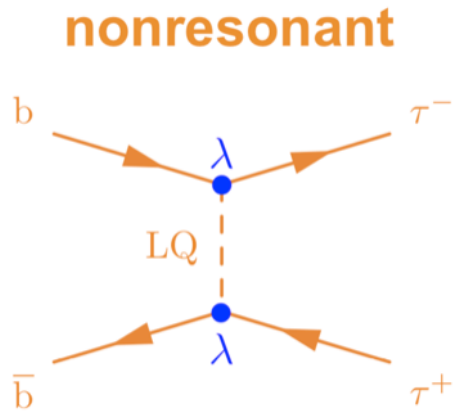
feebly-interacting



Phase I MoEDAL-MAPP
ready for Run 3!

Leptoquarks

CMS: new search for combined b-tau LQ production

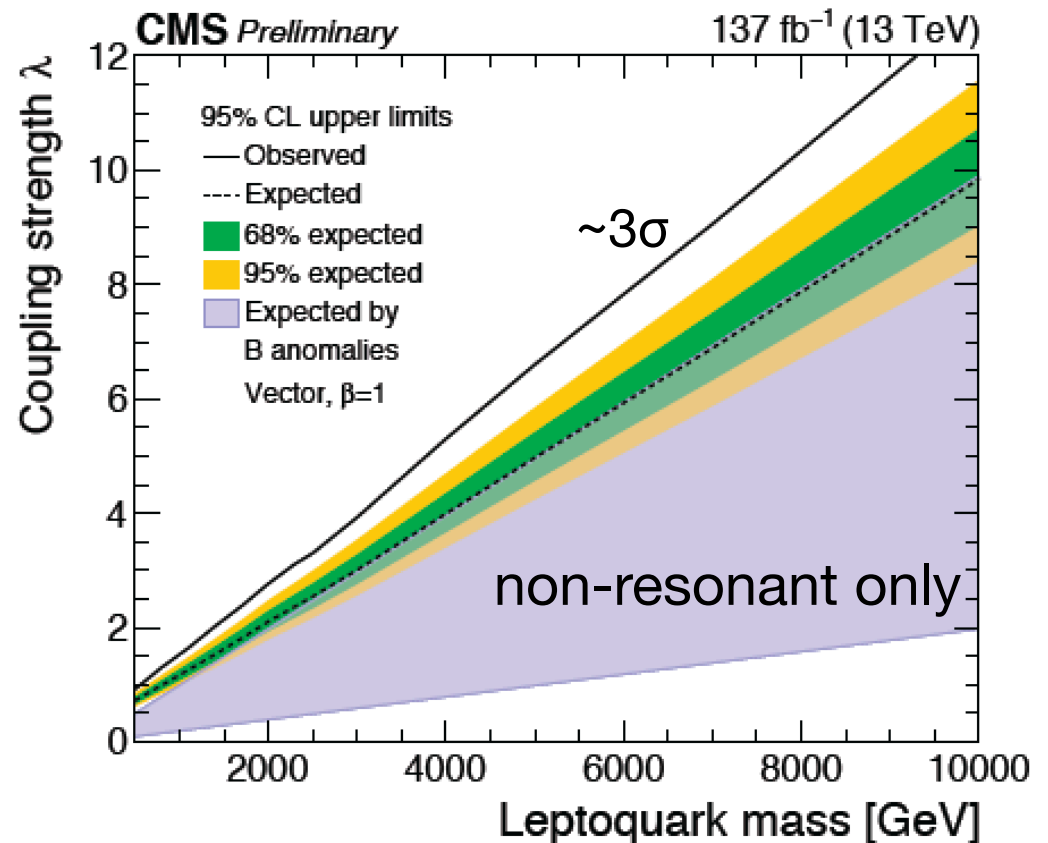


- t-channel gives access to 2-10 TeV range!

CMS-PAS-EXO-19-016

New!

E. Tziaferi
O. Karacheban

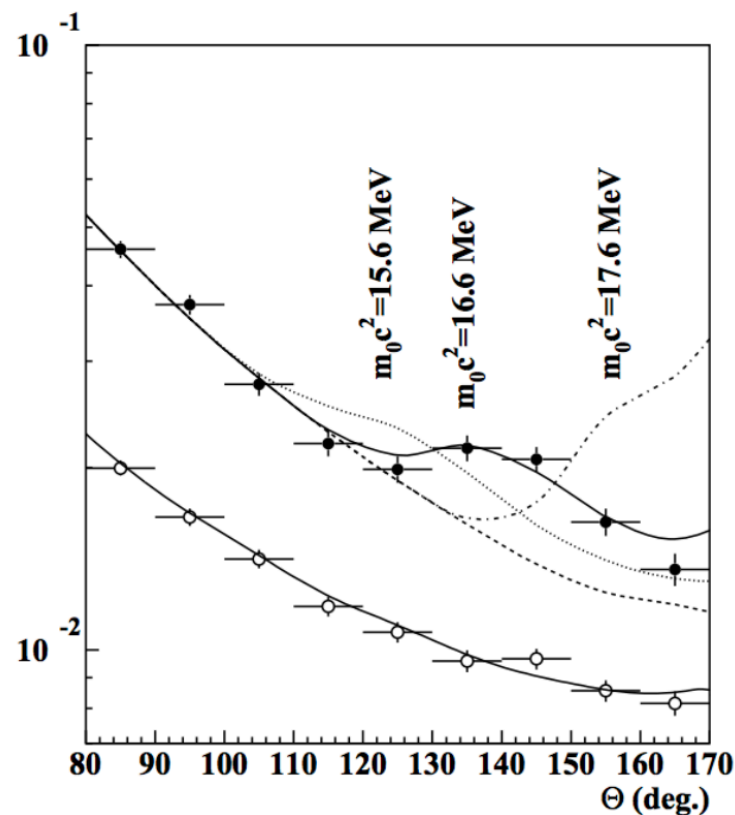
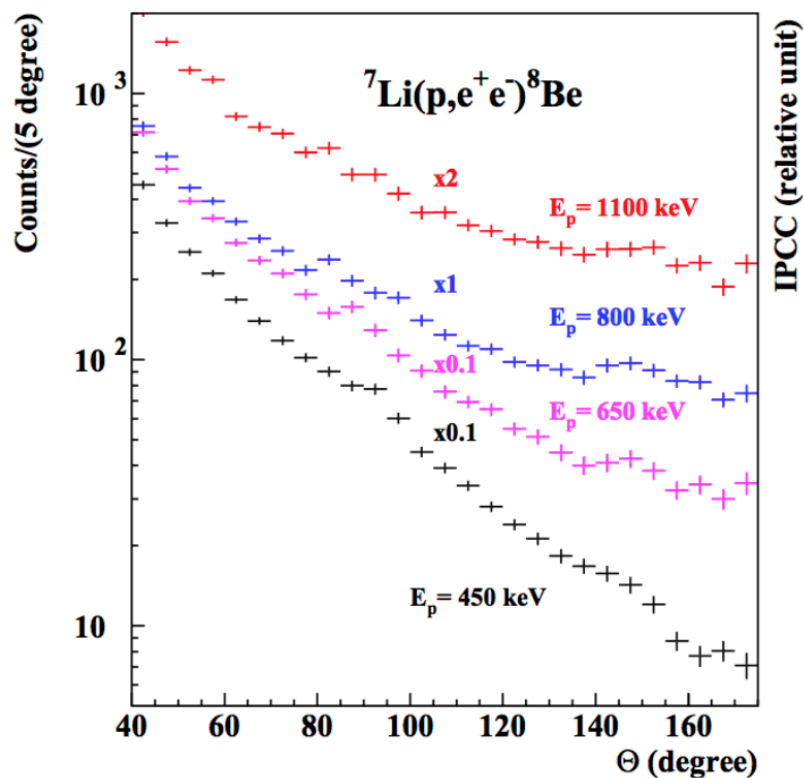
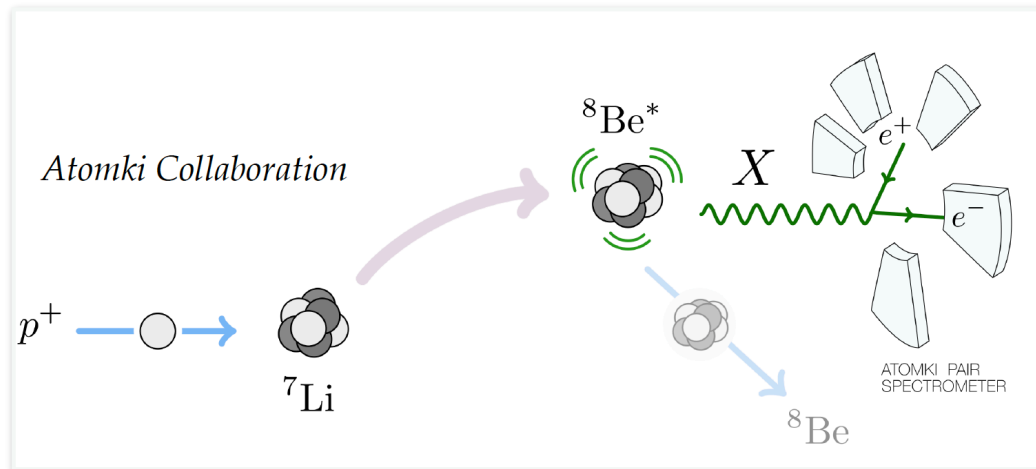


New!

New ATLAS resonant result: ATLAS-CONF-2022-037

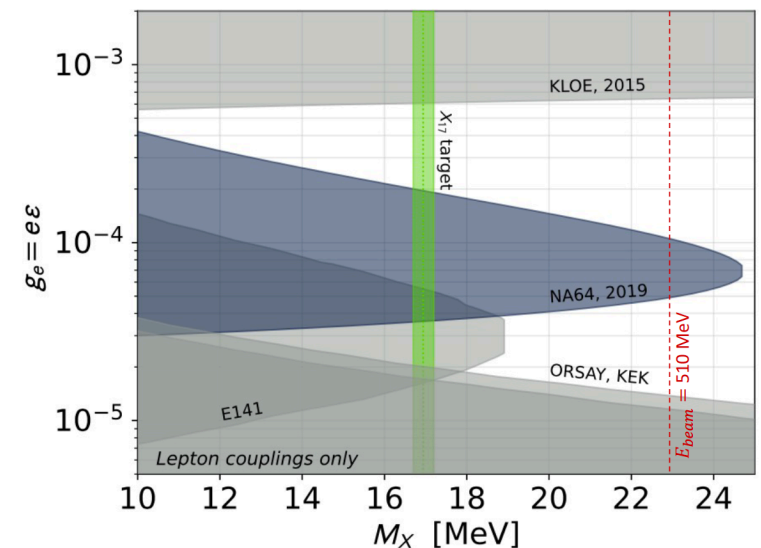
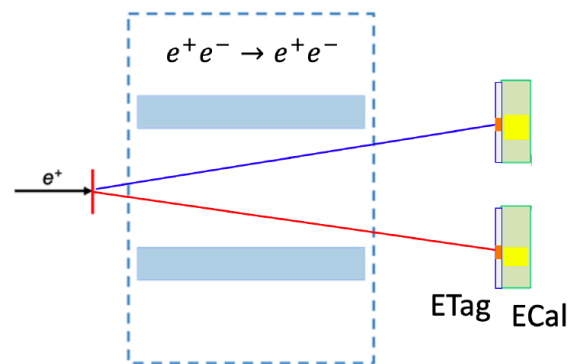
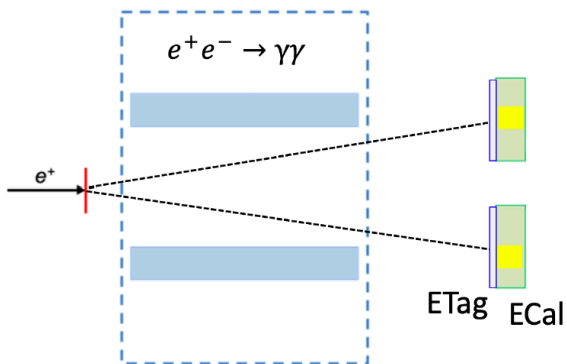
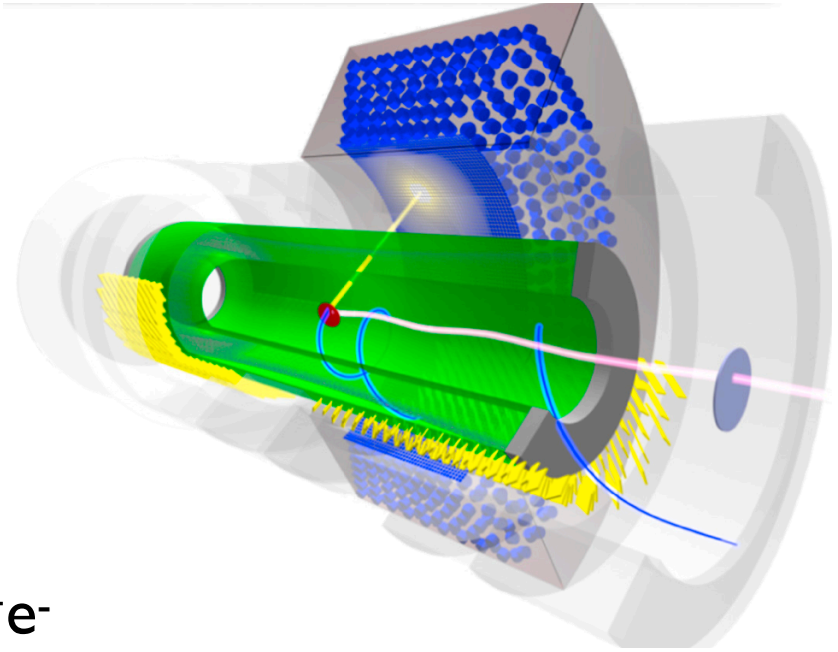
Beryllium (X17) Anomaly

Original Atomiki observation:
17 MeV bump in ${}^7\text{Li}(p, e^+e^-){}^8\text{Be}$



Beryllium (X17) Anomaly

- **MEG-II** expt. analyzing data to confirm Atomiki result
- X17 dedicated target
- Results soon!
- **PADME** experiment will look for e^+e^- resonance at positron energy of 283 MeV: running this summer... (B field off)



Anomaly Detection

- ATLAS: search for dijet resonances with weakly supervised neural nets
- Look for $A \rightarrow BC$ for BSM particles A, B, C with $m_C \ll m_A$
- Obtain up to 10x sensitivity of inclusive dijet search!

