BSM Physics at ATLAS

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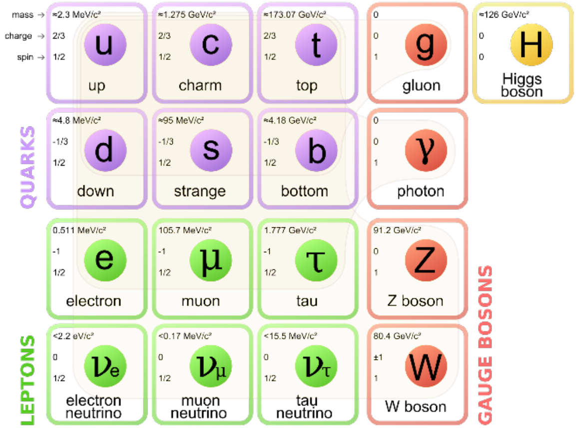
The 15th workshop of TeV physics working group

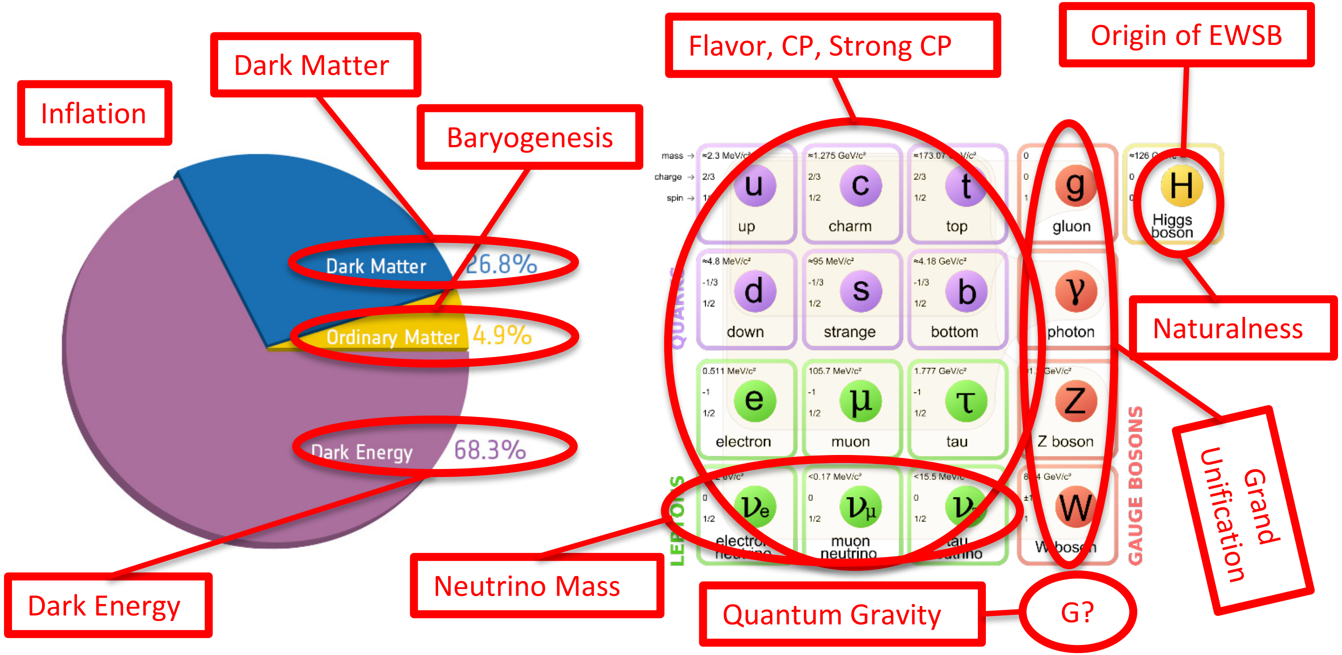
Standard Model

- Standard Model (SM), including the experimental tests, great achievement in human history
- Discovery of Higgs boson makes SM self-consistent



Beyond Standard Model

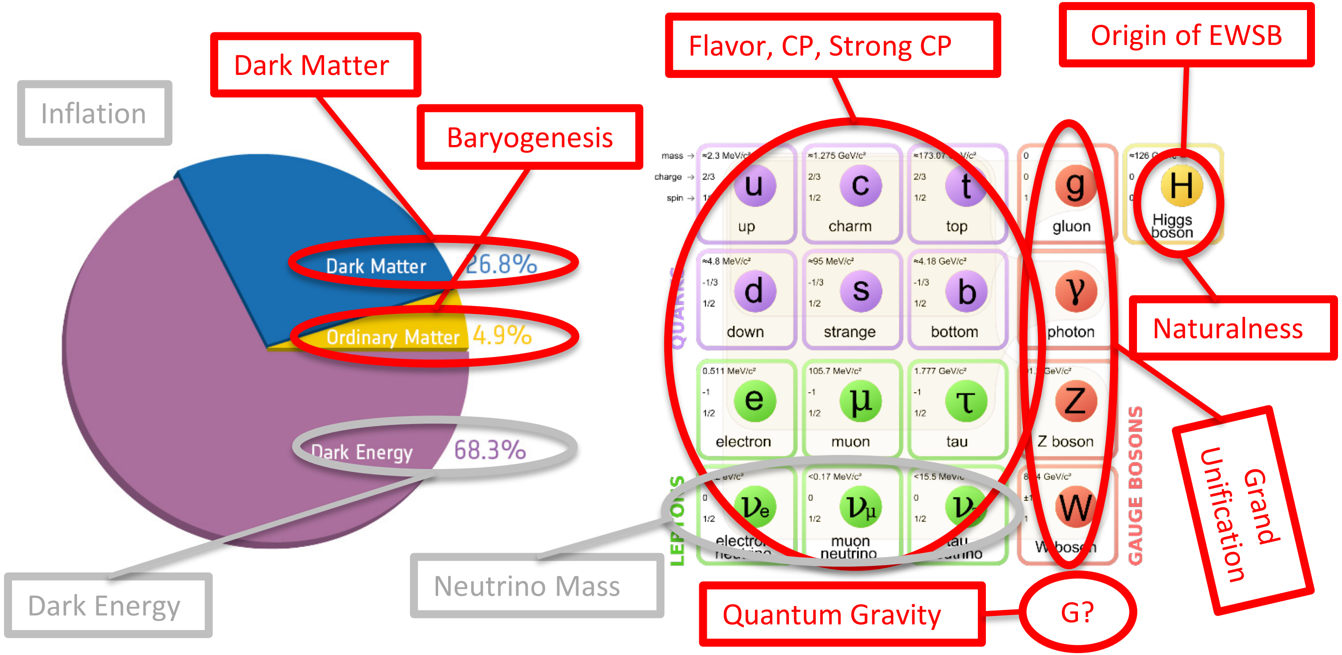
➢ Standard Model can not answer many questions



Picture modified from Jonathan Feng at 2017 ICFA Seminar

Exploration at energy frontier

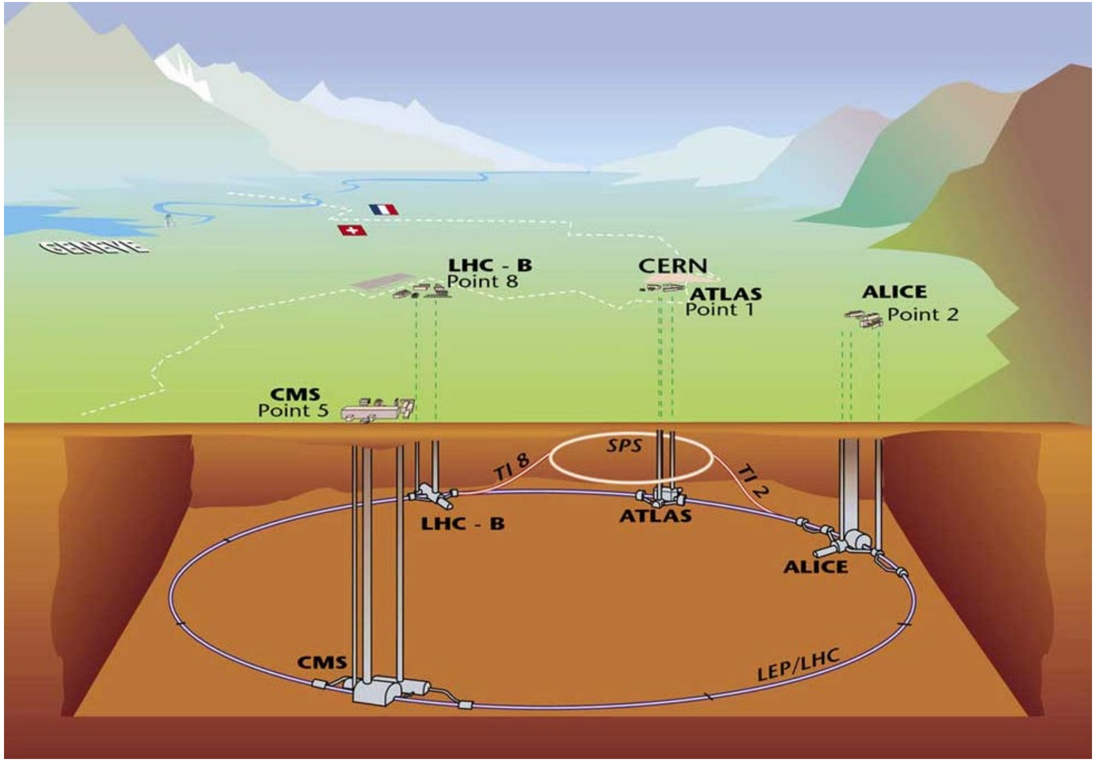
- LHC-ATLAS experiment hopefully could give some hints



Picture modified from Jonathan Feng at 2017 ICFA Seminar

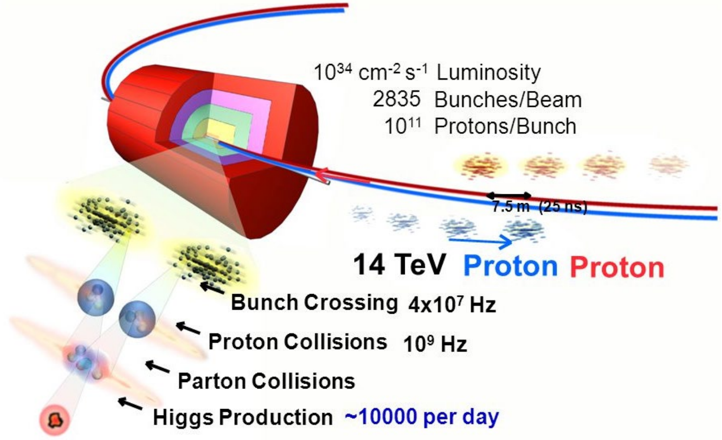
Large Hadron Collider

- Powerful discovery machine with four major experiments



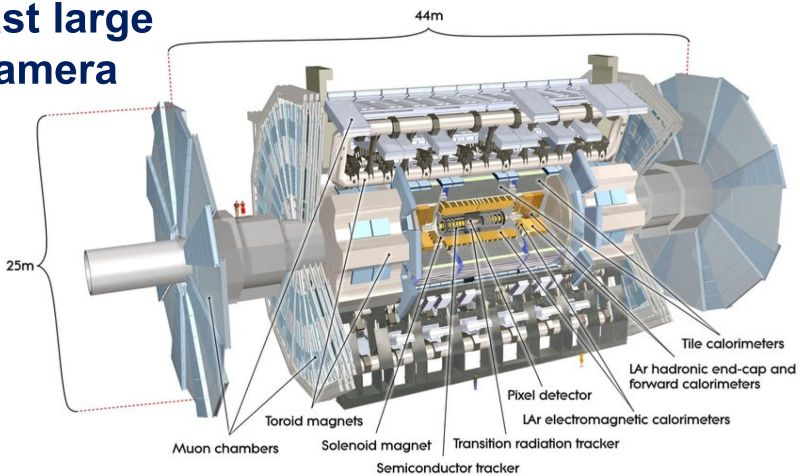
Energy frontier experiments

ATLAS and **CMS**

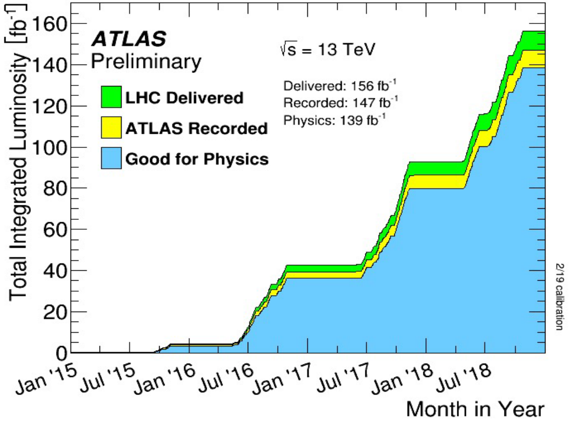


ATLAS experiment

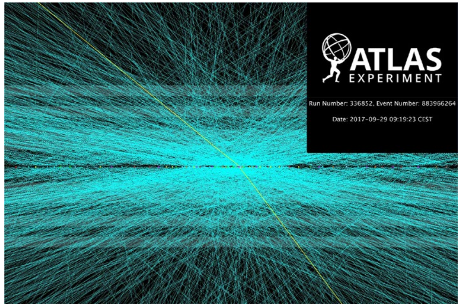
Ultra fast large 3D camera



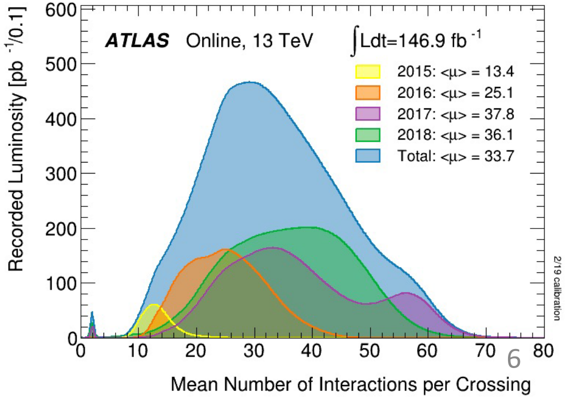
Huge dataset



Busy environment

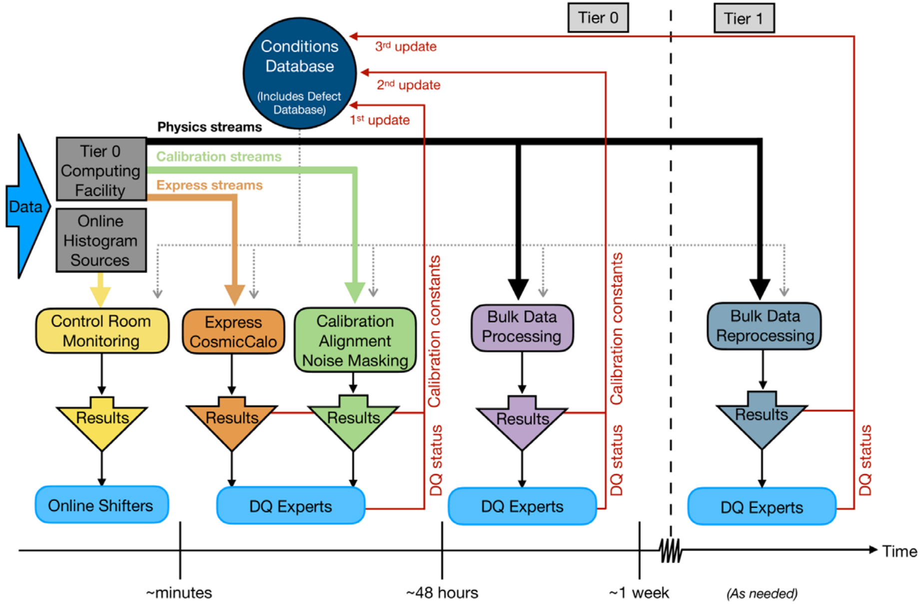


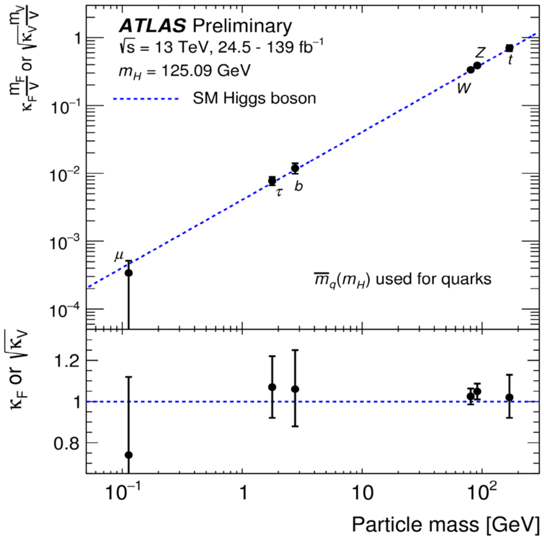
Pileup events



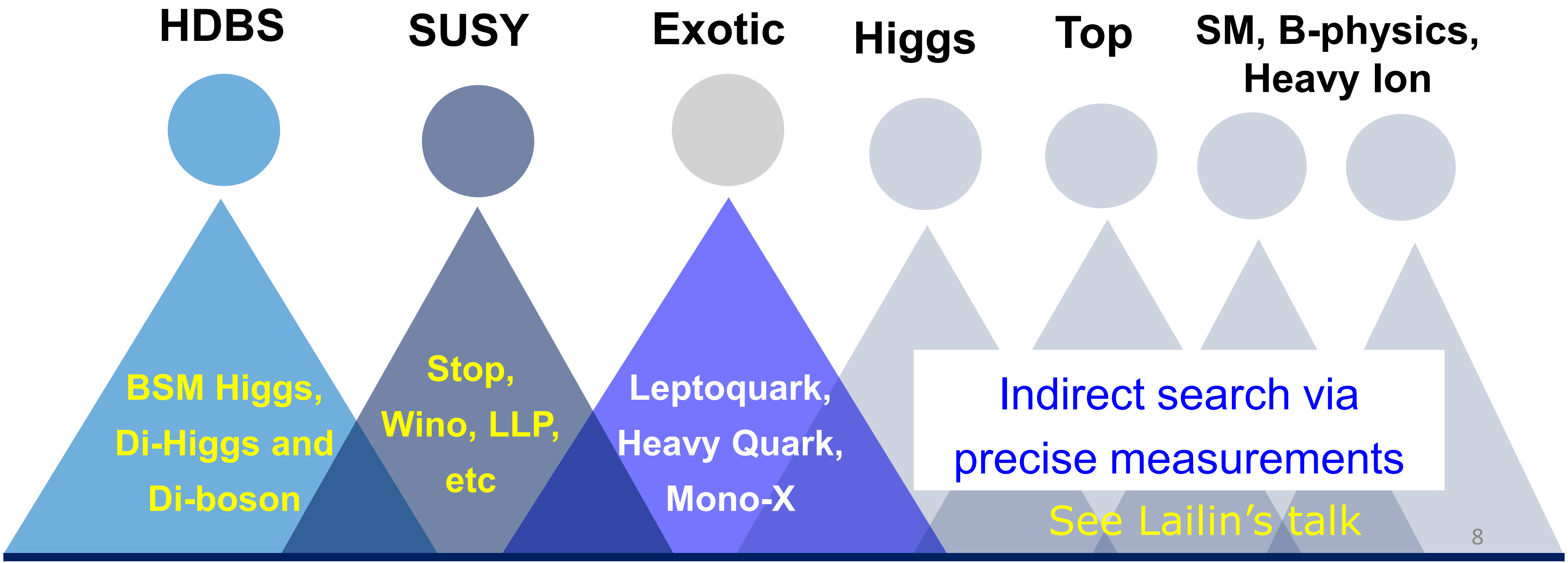
Data-Quality for Physics [JINST 15 (2020) P04003]

- Given the complex of LHC-ATLAS, multi-stage DQ deployed
  - **1)** Online monitor, **2)** Express stream, **3)** Bulk processing,
  - **4)** Alignment and calibrations, **5)** Bulk Reprocess





New Physics searches at ATLAS



New Physics searches at ATLAS

No one doing old physics !

HDBS

BSM Higgs, Di-Higgs and Di-boson

SUSY

Stop, Wino, LLP, etc

Exotic

Leptoquark, Heavy Quark, Mono-X

Higgs

Top

SM, B-physics, Heavy Ion

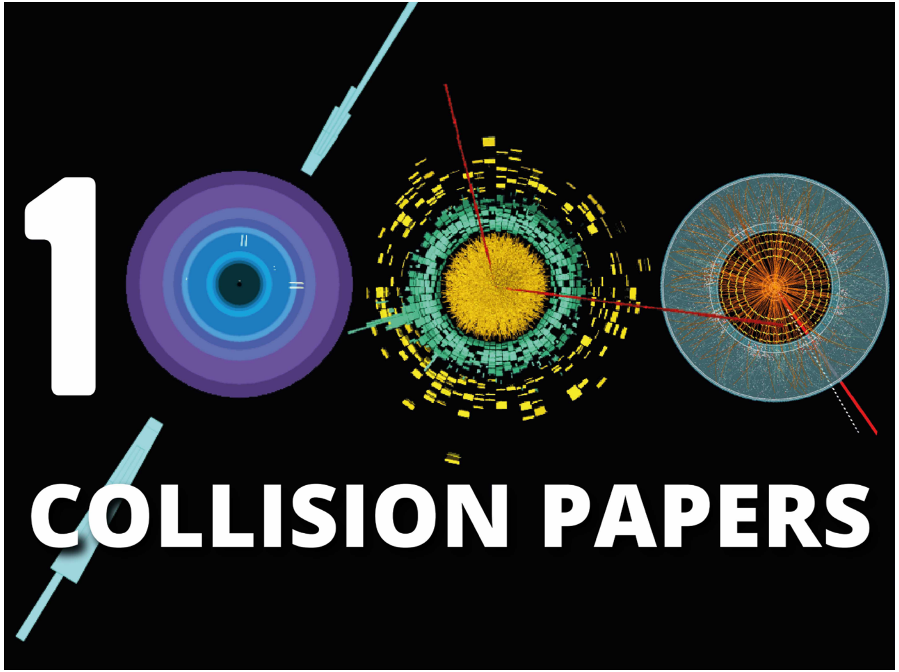
Indirect search via precise measurements

See Lailin's talk

New Physics search at ATLAS

- ATLAS produced more than 1000 papers
- Try to overview the whole field while highlighting new results
  - Can not cover every topics
  - Selective and based on personal preference
  - Apologies if any relevant topic missed

[ATLAS celebrates results of 1000 collision papers](#)



Searches dirven by big questions

01 Origin of EWSB

Di-Higgs, extra Higgs and scalars

02 GUT, Extra-Dim

Di-boson resonance, W’, Z’, Vector-Like Quark, etc.

03 Anomalies driven

LFV, g-2, ν-mass, Leptoquark, etc

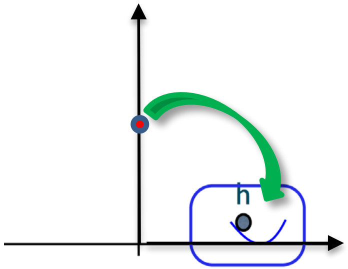
04 Dark matter driven

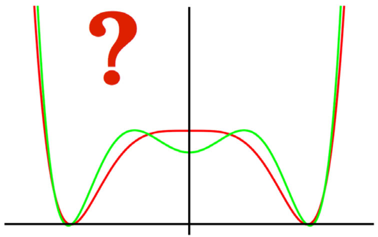
Invisible decay, mono-jet, -H, -Z, Wt, 2HDM+a, etc

05 SUSY inspired

SUSY particles,
Long Lived Particle, etc.

Origin of EWSB





- Thermal history of EWSB
  - Probe the Higgs potential, via Higgs self-coupling

- Extended Higgs sector
  - Impact the Higgs potential, leads first order phase transition
  - Predict extra Higgs bosons

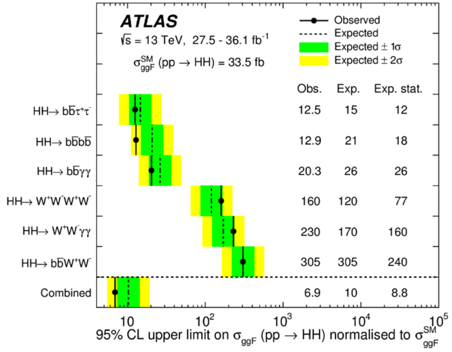
$$V_{\rm CxSM} = \frac{m^2}{2}\mathrm{H}^\dagger\mathrm{H} + \frac{\lambda}{4}(\mathrm{H}^\dagger\mathrm{H})^2$$

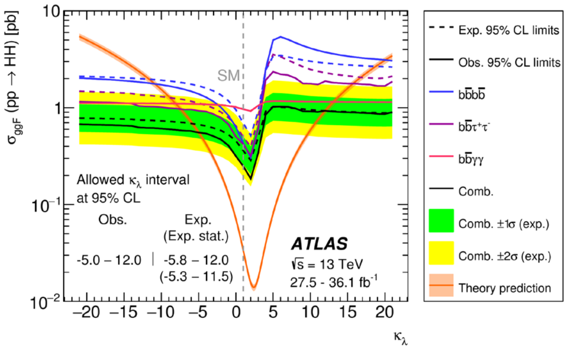
Example:
Complex singlet extension

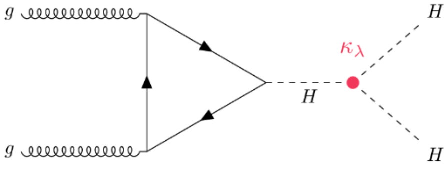
$$+\frac{\delta_2}{2}\mathrm{H}^\dagger\mathrm{H}|\mathbb{S}|^2 + \frac{b_2}{2}|\mathbb{S}|^2 + \frac{d_2}{4}|\mathbb{S}|^4 + \left(\frac{b_1}{4}\mathbb{S}^2 + a_1\mathbb{S} + c.c.\right)$$

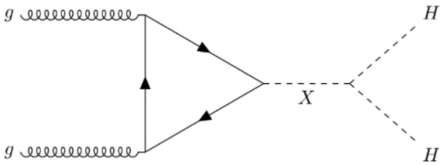
Di-Higgs production (summary plots)

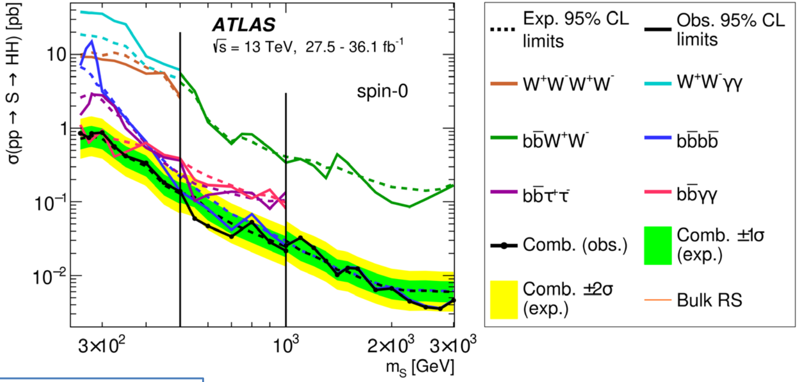
- At LHC, self-coupling probed via di-Higgs (HH) production
- HH also sensitive to BSM heavy scalars or Graviton







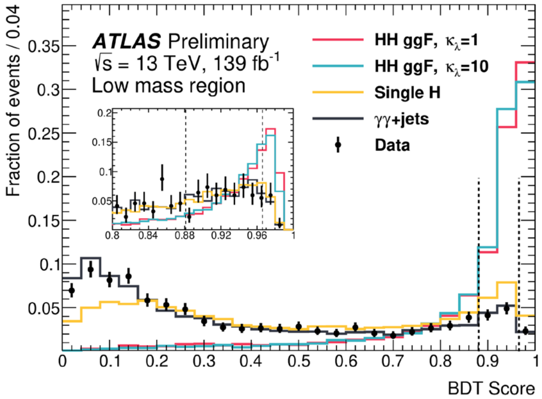


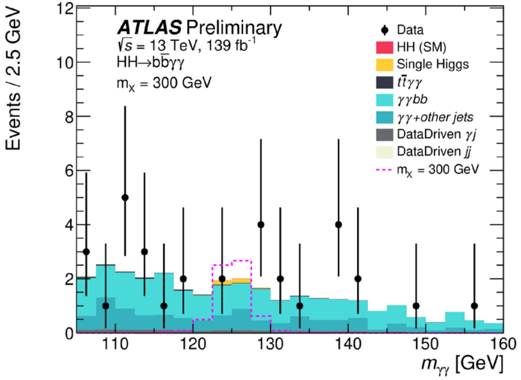


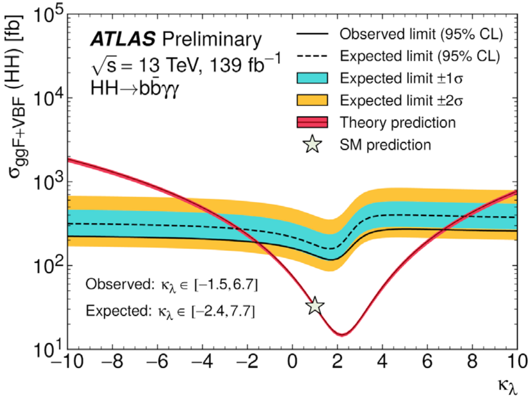
See Xiaohu's talk

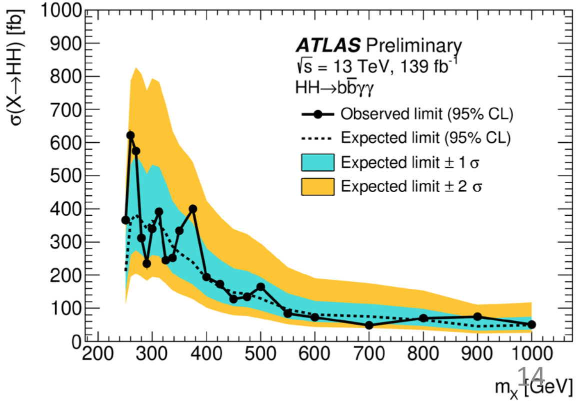
HH→bbγγ ATLAS-CONF-2021-016

- Both ggF and VBF modes explored
- BDT used to define signal regions
- Final discriminant: $m_{\gamma\gamma}$
- Constrained κ_λ into [-1.5, 6.7]
- Most sensitive for m_X below 400 GeV



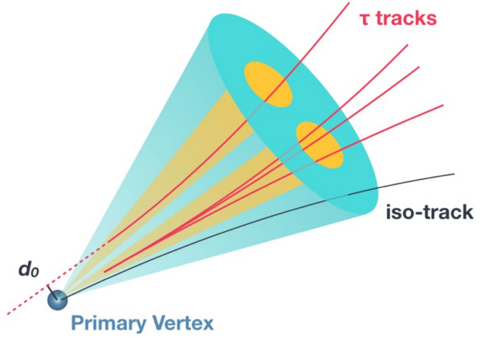


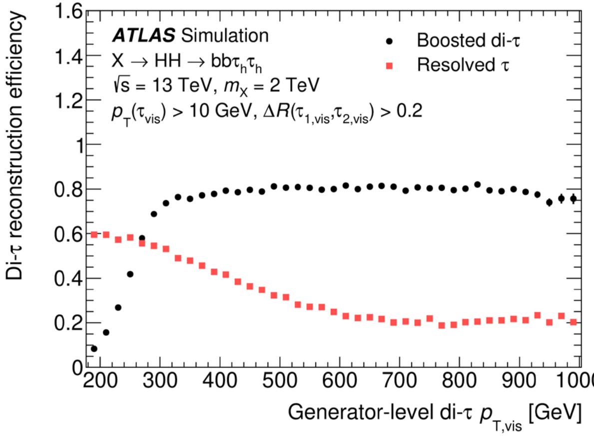


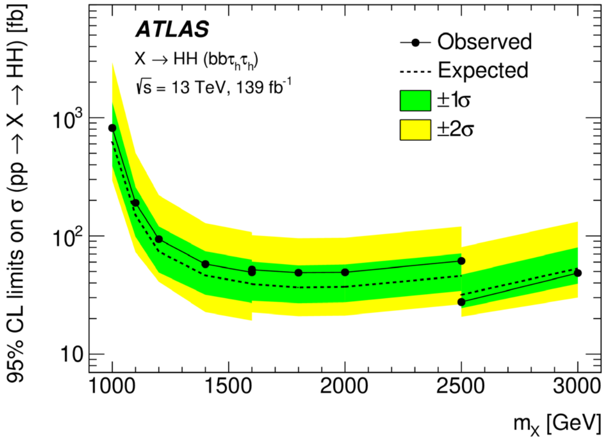


Boosted HH→bbττ JHEP 11 (2020) 163

- First boosted di-tau tagger at ATLAS
  - Reconstructed as R=1.0 jet with R=0.2 sub-jets
  - Identified against q/g initiated jets by BDT
- Complement resolved analysis for m_X > 1.2TeV







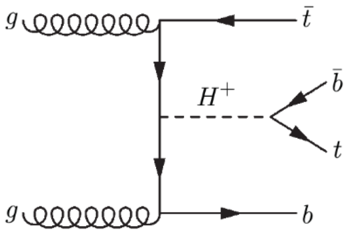
Extended Higgs sector

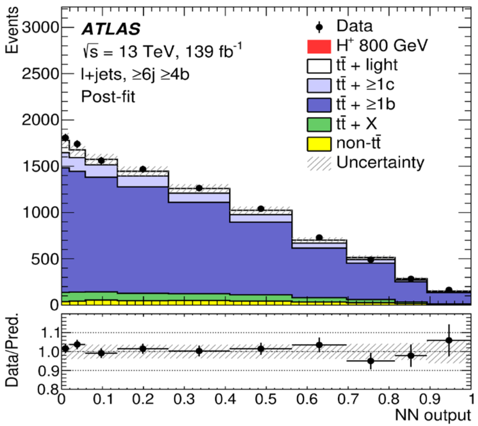
- Many models: MSSM, 2HDM, triplet, etc
- Benchmark models: MSSM-like
  - Five Higgs bosons: h, H, A, $H^{\mp}$
  - Two free parameters at tree level: m_A, $\tan\beta = \nu_u/\nu_d$

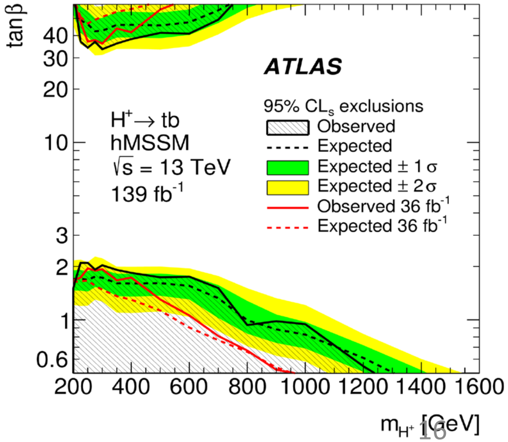
$$\phi_u = \begin{pmatrix} \phi_u^+ \\ \phi_u^0 \end{pmatrix}$$

$$\phi_d = \begin{pmatrix} \phi_d^0 \\ \phi_d^- \end{pmatrix}$$

Charged Higgs: $H^{\mp} \rightarrow tb$ [JHEP 06 (2021) 145]



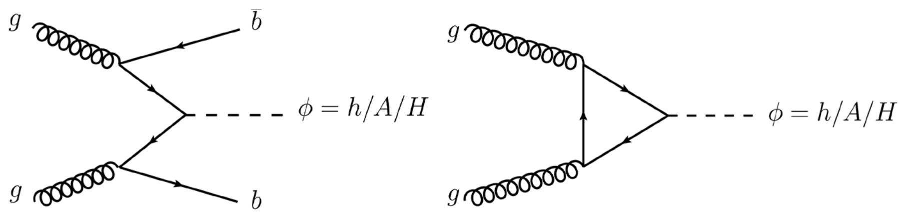


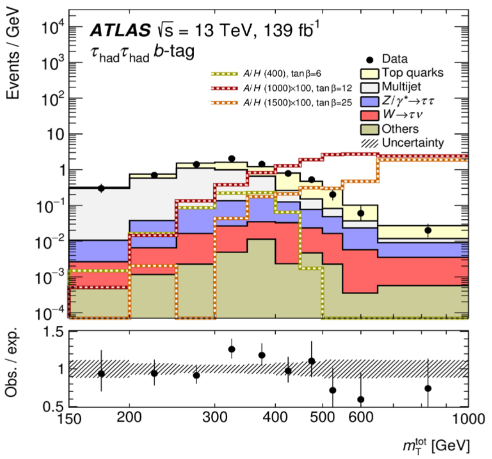


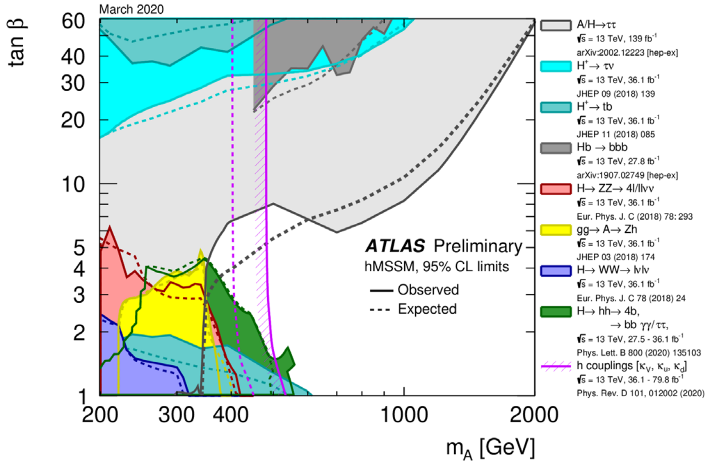
- Sensitive at high mass and low tan β

A/H→ττ [PRL 125 (2020) 051801]

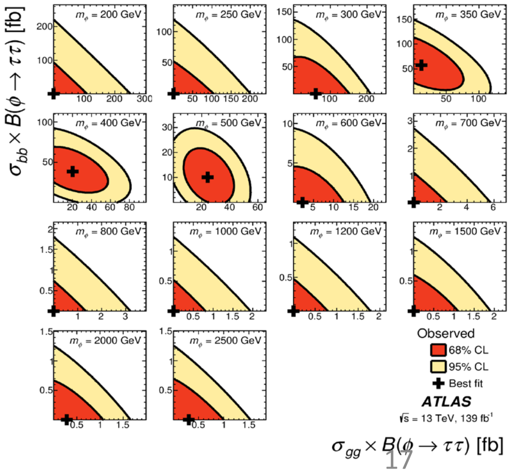
- Down type fermion, sensitive to high tan β regime
- "Flag-ship" analysis in BSM Higgs searches





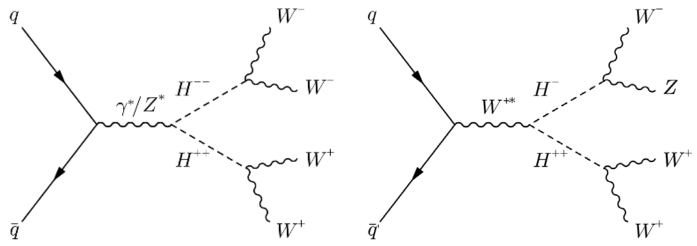


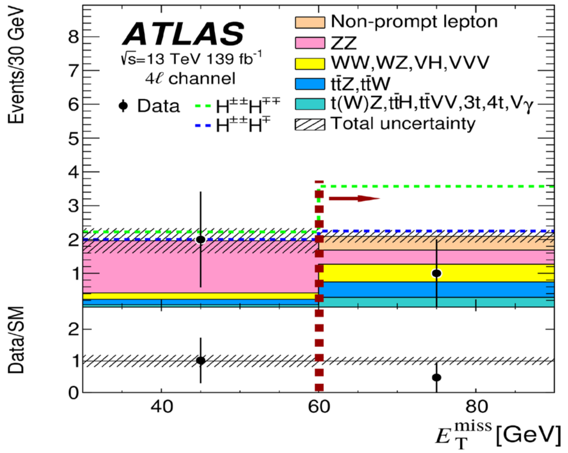
3D likelihood

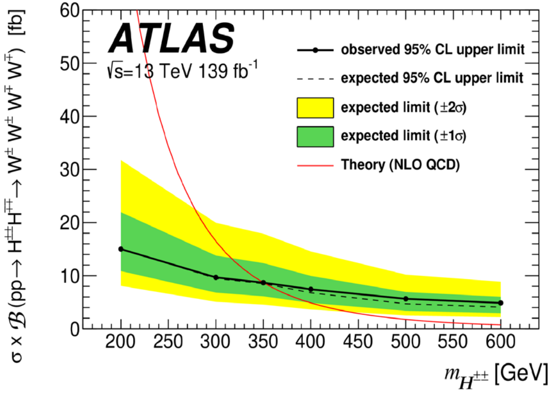


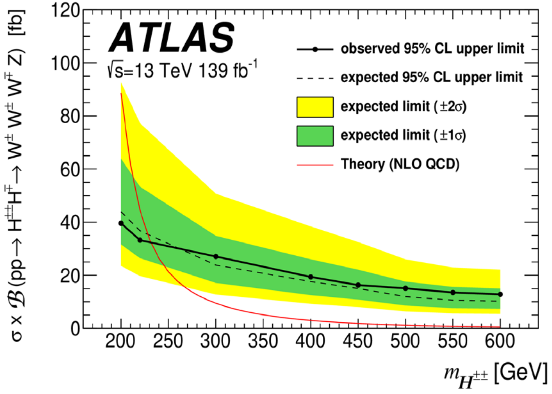
Doubly charged $H^{++} \rightarrow WW$ [JHEP 06 (2021) 146]

- Additional Triplet of scalar fields
  - Account for neutrino masses through type-II seesaw mechanism
- Final states: multi-lepton





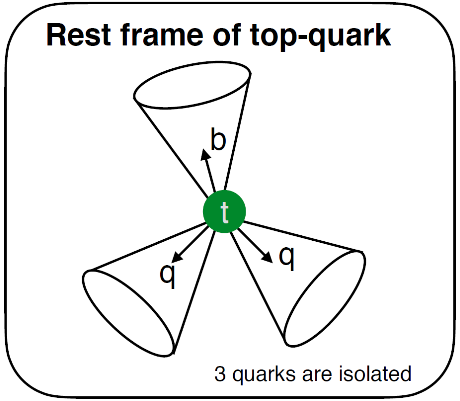


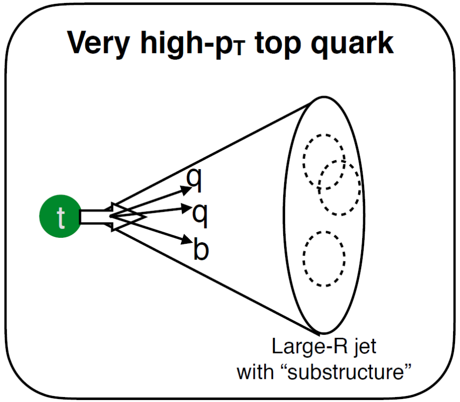


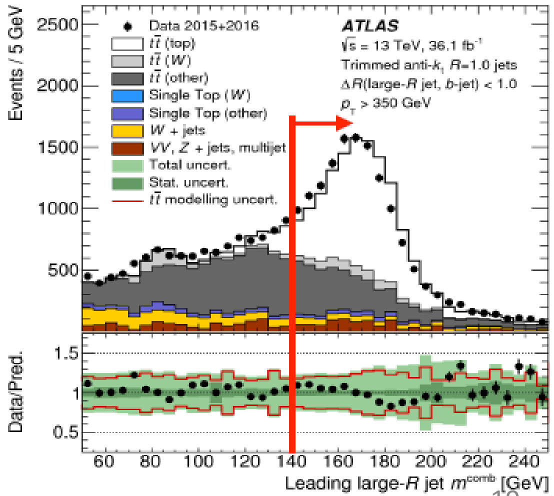
Exclusion up to 350 (230) GeV
for pair (associated) production modes

High mass resonance searches

- New resonances at TeV energy scale predicted by many BSM
- Boosted object tagging: important technique at m>1TeV
  - Hadronically-decaying W/Z bosons and top quarks reconstructed as one large-R jet (R=1.0)

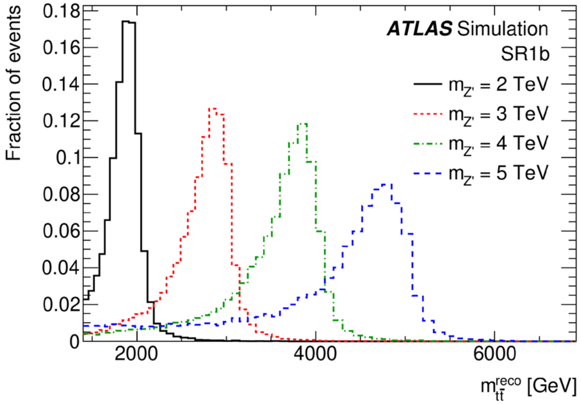


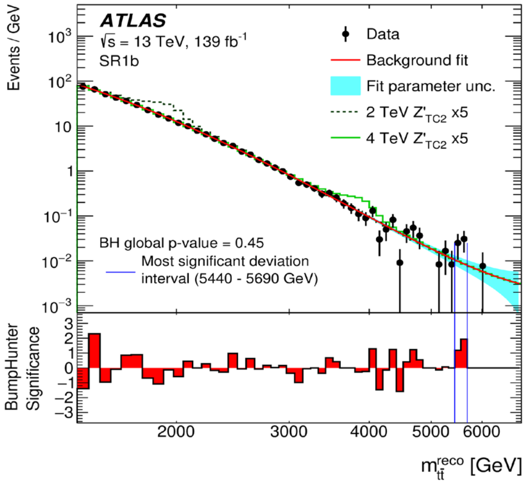


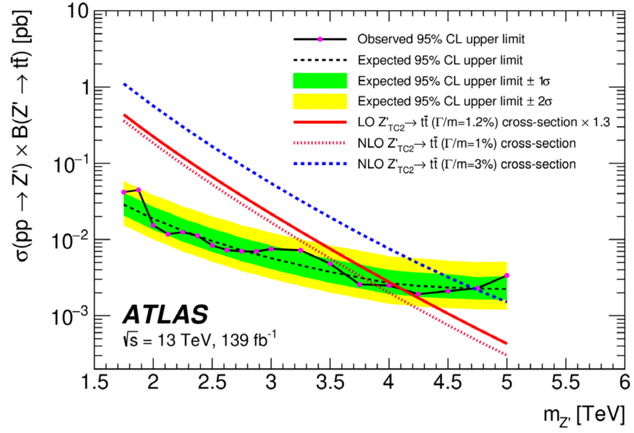


Full hadronic $t\bar{t}$ resonance [JHEP 10 (2020) 61]

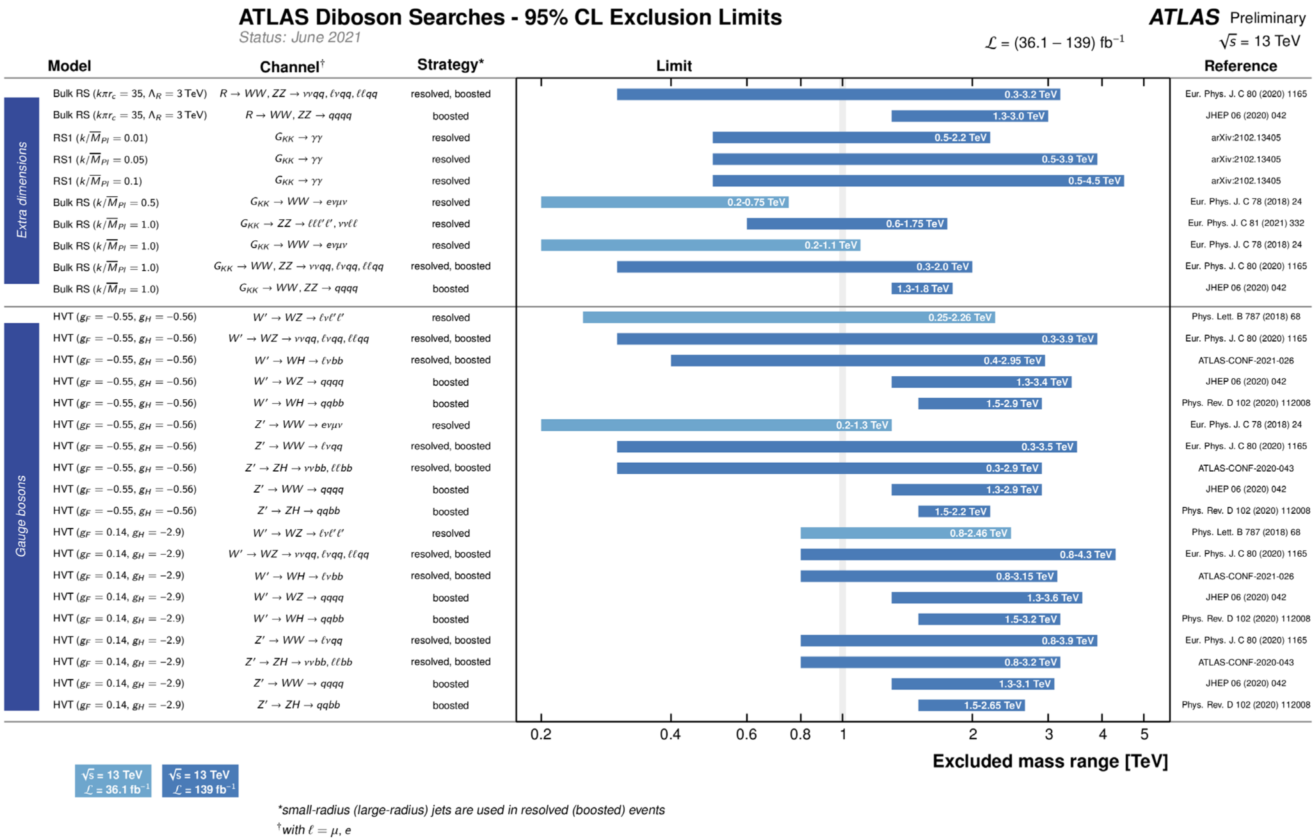
- Explored models:
  - Leptophobic Z’ and KK gluon decaying to $t\bar{t}$
- A few channels probe up to 5 TeV



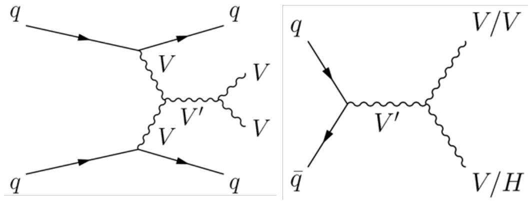




Di-boson resonance searches [ATL-PHYS-PUB-2021-018]

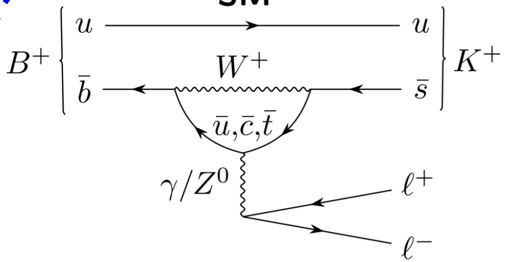


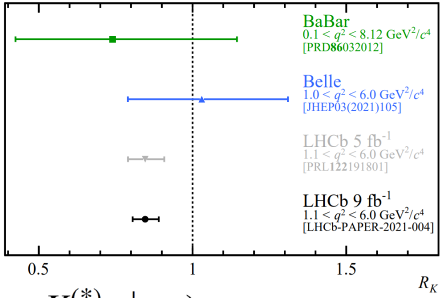
- Spin-2 bulk RS Graviton $G_{KK} \to WW/ZZ$
- Heavy Vector Triplet (HVT)



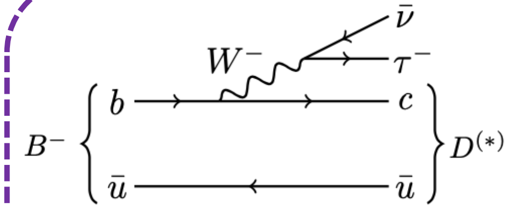
Anomalies in lepton sector

SM



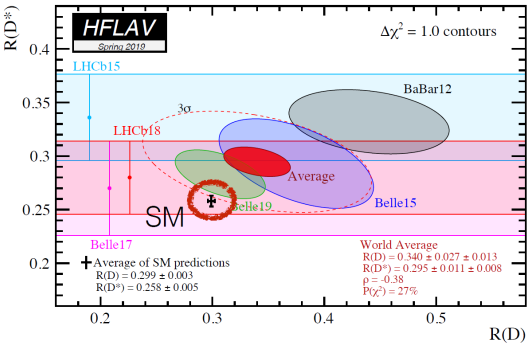


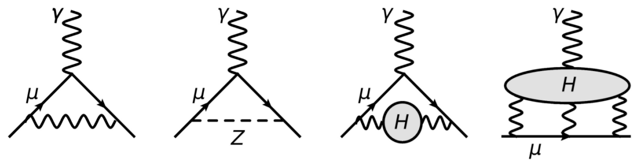
$$R(K^{(*)}) = \frac{\mathscr{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathscr{B}(B \to K^{(*)}e^+e^-)}$$

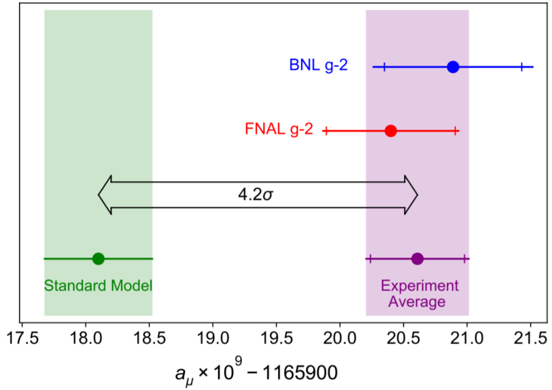


$$R(D^{(*)}) = \frac{\mathscr{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathscr{B}(B \to D^{(*)}\ell\nu_\ell)}$$

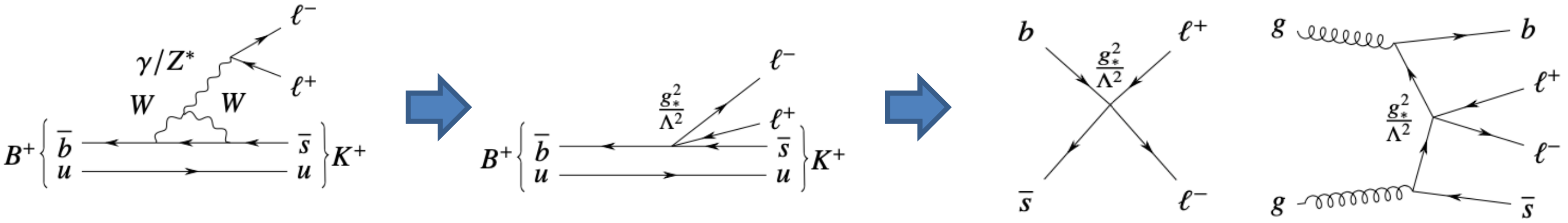
$(\ell = e, \mu)$



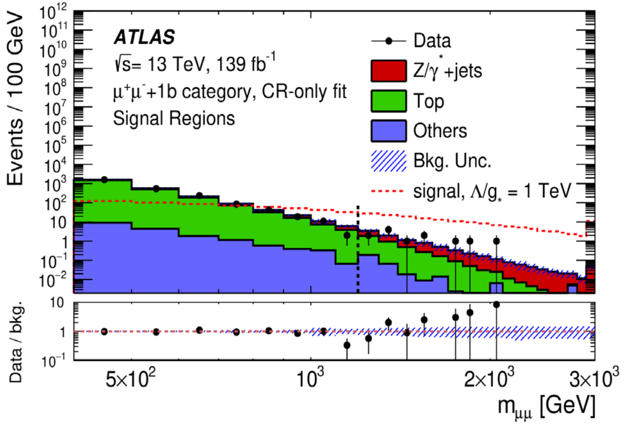


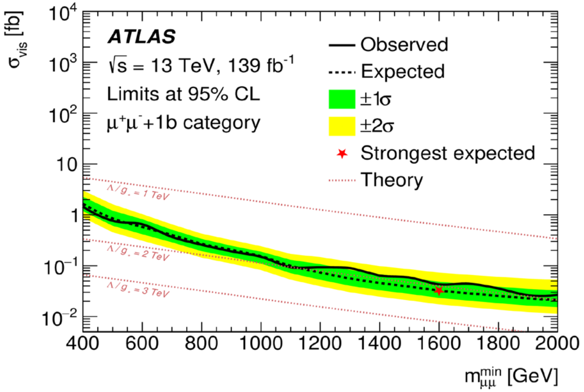


New physics search in $ee/\mu\mu+0/1b$ arXiv:2105.13847



- Model: $bs\ell\ell$ contact interaction motivated by B anomalies
- Strategy: looking for deviation at the high mass tail

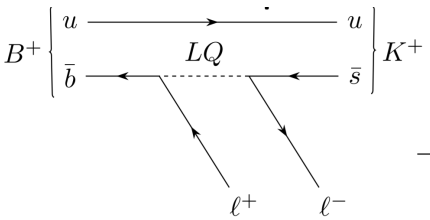


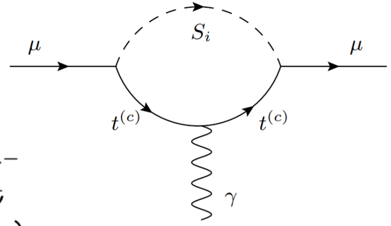


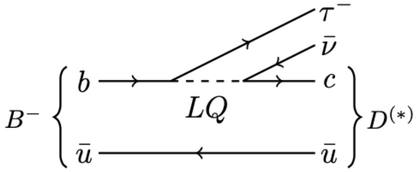
Λ/g_* excluded up to ~2 TeV, scale indicated by B anomalies at ~30 TeV

Search for 3rd Leptoquarks

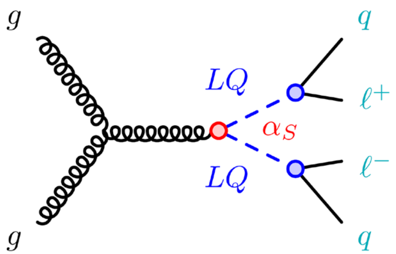
- Leptoquarks(LQ)
  - Scalar or vector bosons, predicted by many GUT-like models
  - Non-zero baryon and lepton numbers
  - Could explain B anomalies and μ g-2

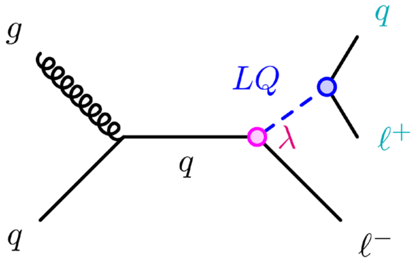


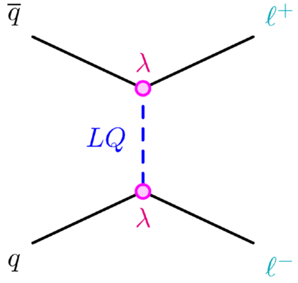




- At LHC: Pair production | Single production | Off-shell production

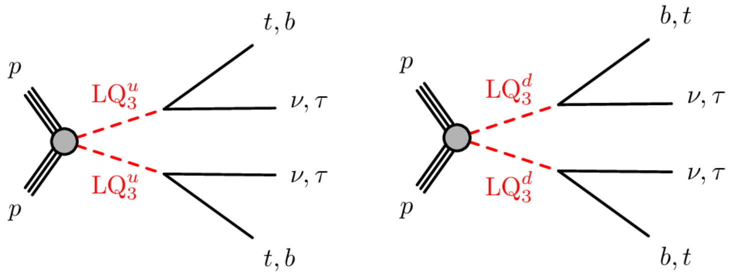




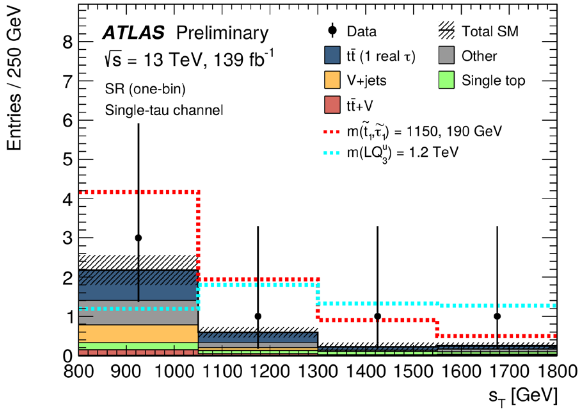


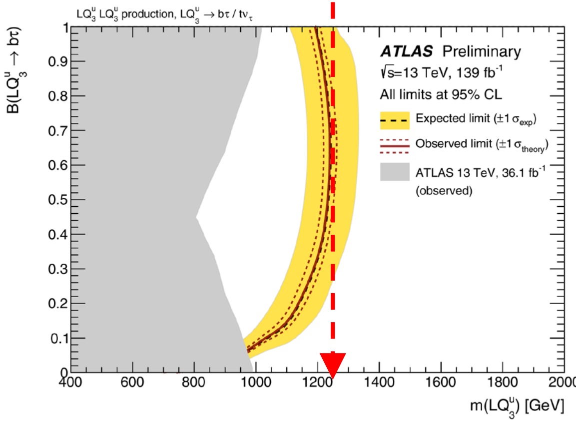
Search for 3rd Leptoquarks ATLAS-CONF-2021-008/

- Pair produced LQ $\rightarrow t\nu/b\tau$ or $t\tau/b\nu$
- Minimal BRW model
  - Yukawa-type couplings to or $q\ell$ $q\nu$ [*PLB* 191 (1987) 442-448]

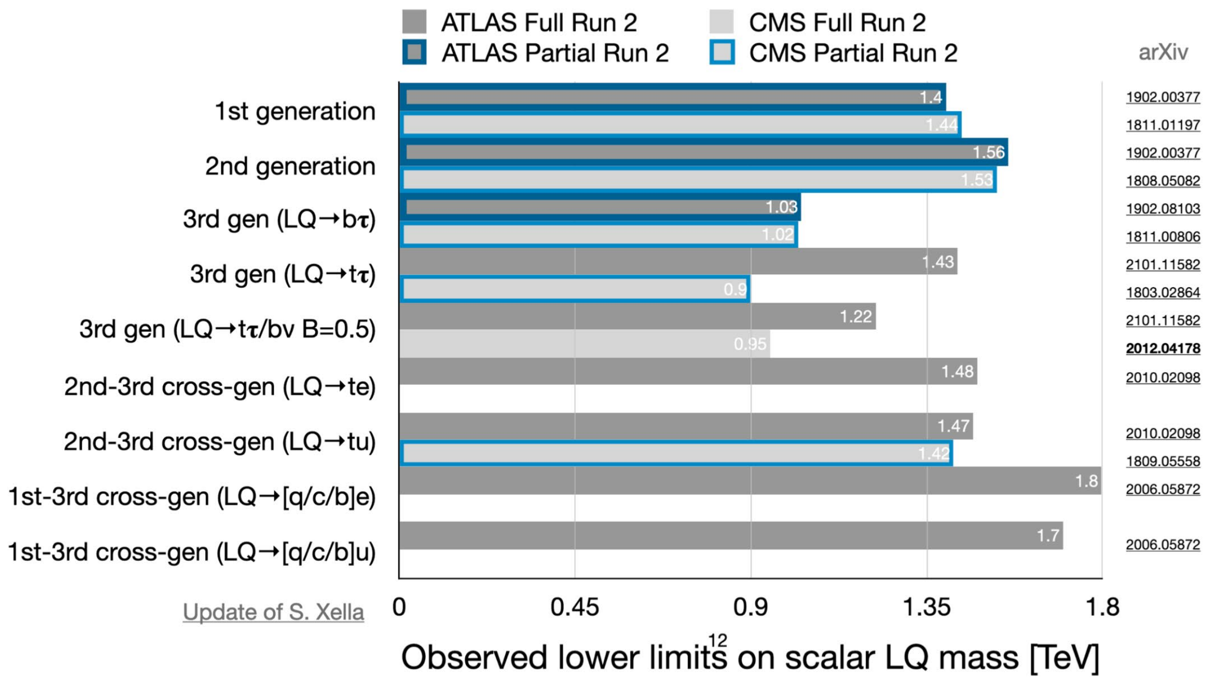


- Strategy
  - E_T^{miss}> 250 GeV
  - Categorized on N_{bjet} and $N_{\tau\text{-had}}$

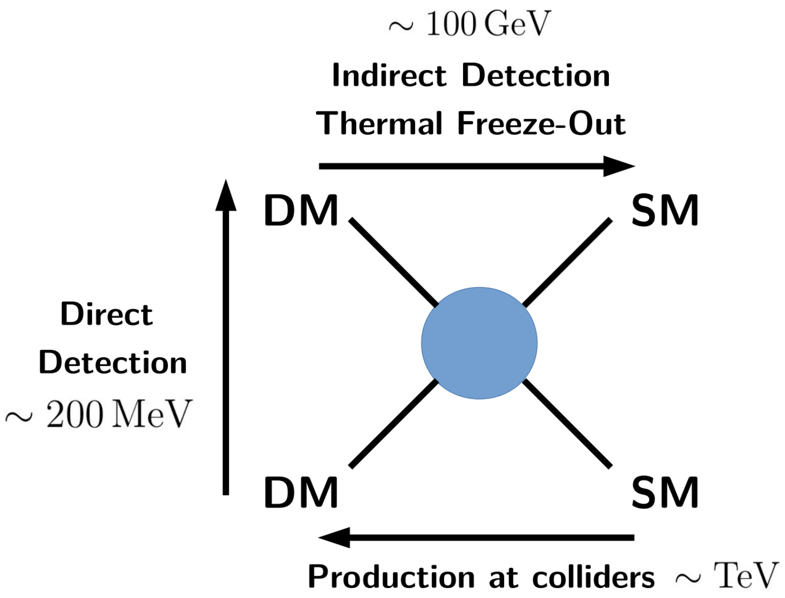




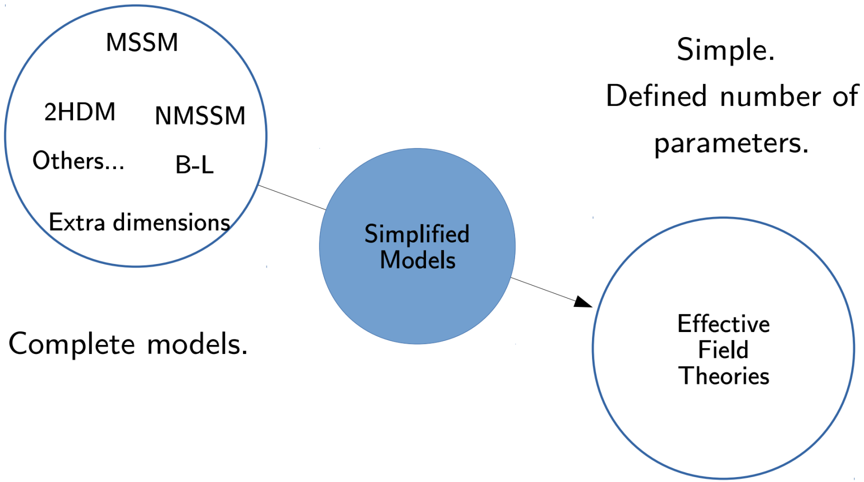
Summary of Leptoquark searches



Dark matter



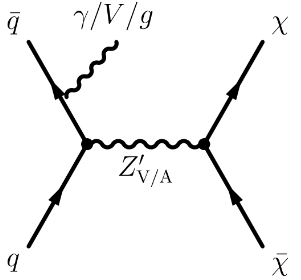
$\sim 100\,\mathrm{GeV}$
Indirect Detection
Thermal Freeze-Out
DM
SM
DM
SM
Direct
Detection
$\sim 200\,\mathrm{MeV}$
Production at colliders $\sim \mathrm{TeV}$

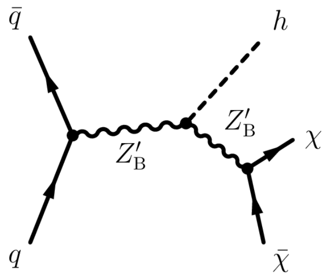


MSSM
2HDM
NMSSM
Others...
B-L
Extra dimensions
Complete models.
Simplified Models
Simple.
Defined number of parameters.
Effective Field Theories

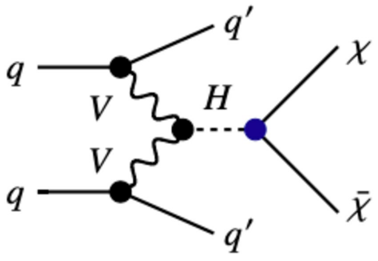
Dark matter at LHC

mono-jet, -W/Z, -H searches

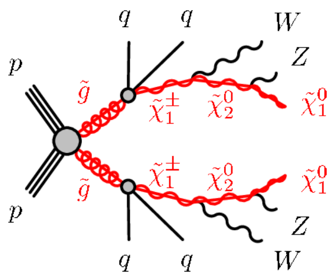




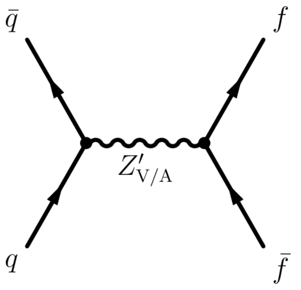
Higgs portal

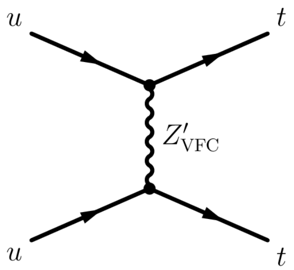


SUSY LSP

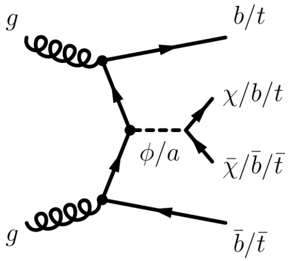


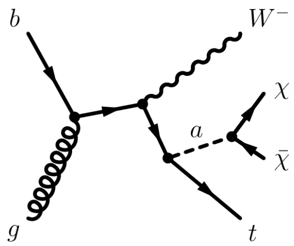
Resonant mediator searches





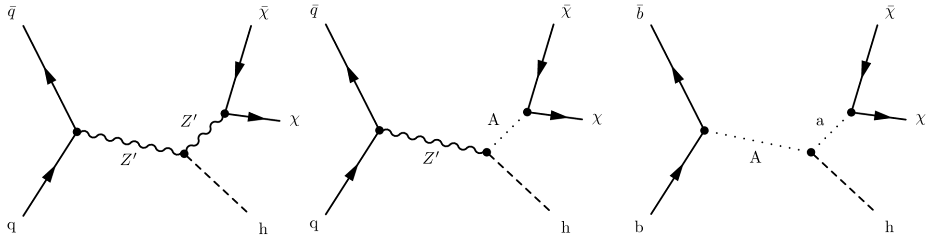
Associated productoin



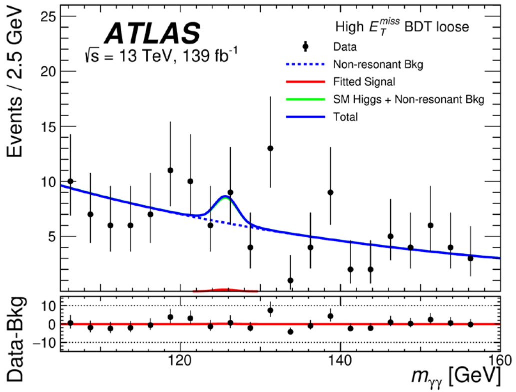


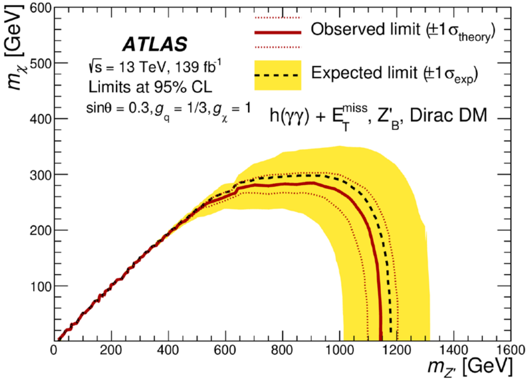
Mono-Higgs ($H \to \gamma\gamma$) [arXiv:2104.13240]

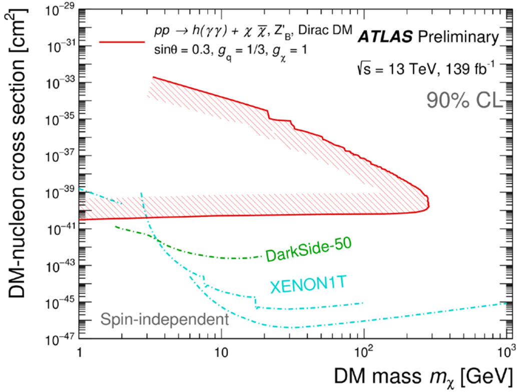
- Analysis strategy
  - Require 2 γ + large E_t^{miss}
  - Final fit on $m_{\gamma\gamma}$



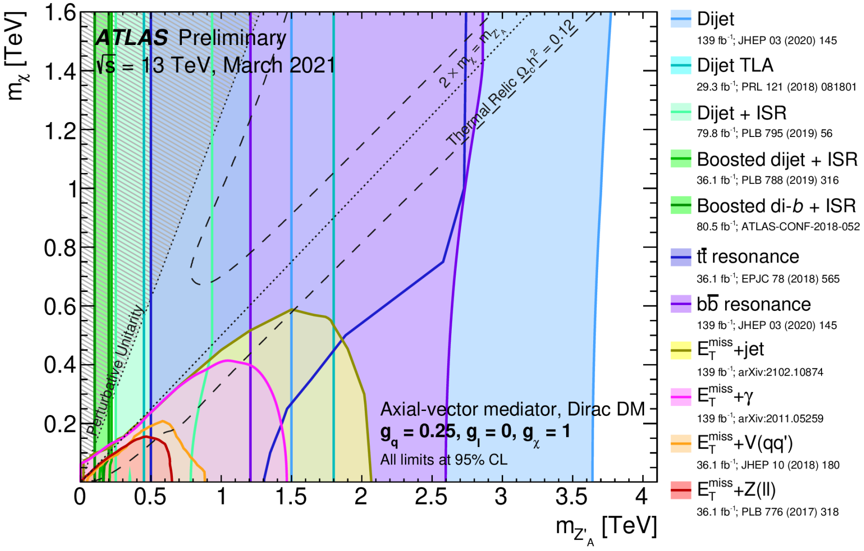
- Explored models: Z'_B, Z'-2HDM, 2HDM+a

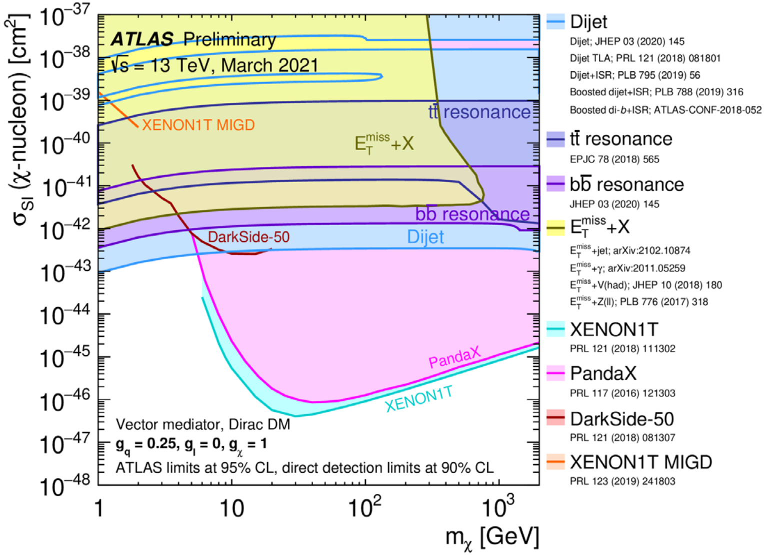






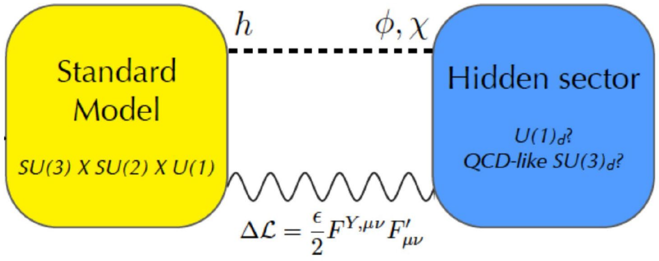
Summary of DM mediator searches ATL-PHYS-PUB-2021-006/

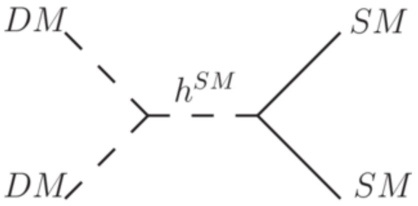




Exotic Higgs Boson Decays

- Higgs portal to hidden sector

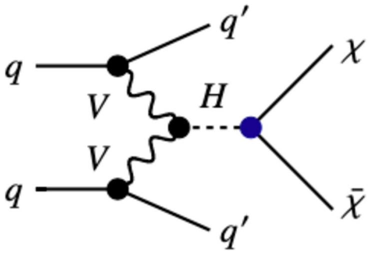


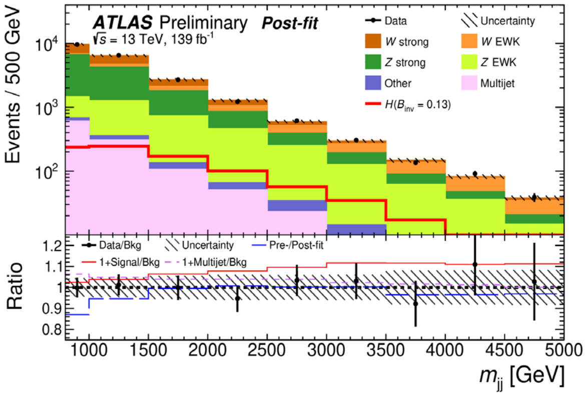


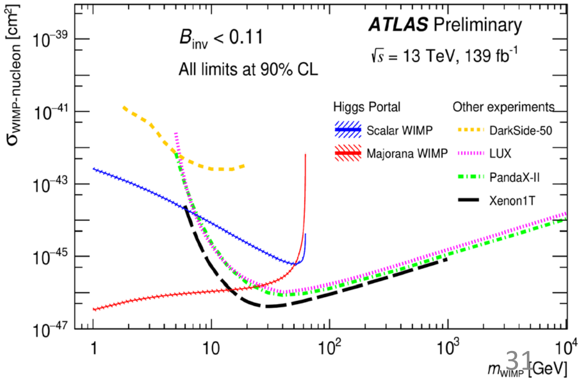
Higgs invisible decay

ATLAS-CONF-2020-008

- Upper limit on Br(H→inv) is 13 %

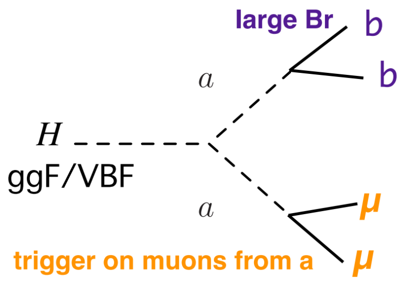


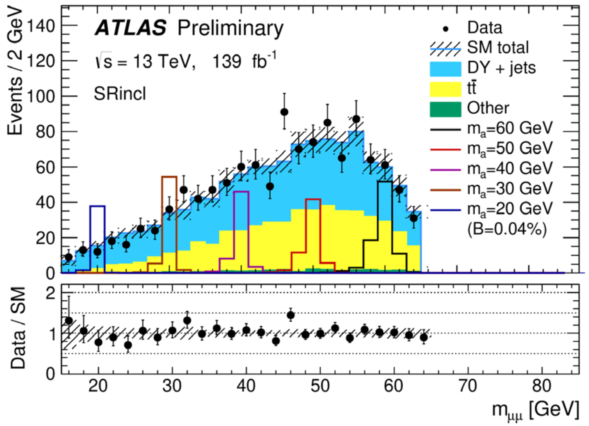


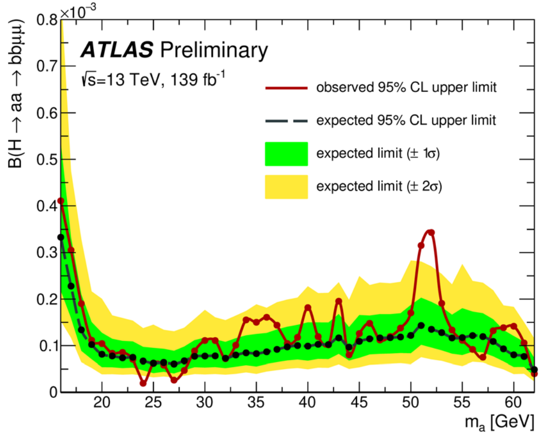


H→aa→bbμμ [ATLAS-CONF-2021-009]

- Higgs decaying to 2 pseudoscalar
- Large Br(a→bb) and a clean a→μμ signature
  - Cut-and-count analysis on $m_{\mu\mu}$
  - BDT trained in multiple $m_{\mu\mu}$ windows



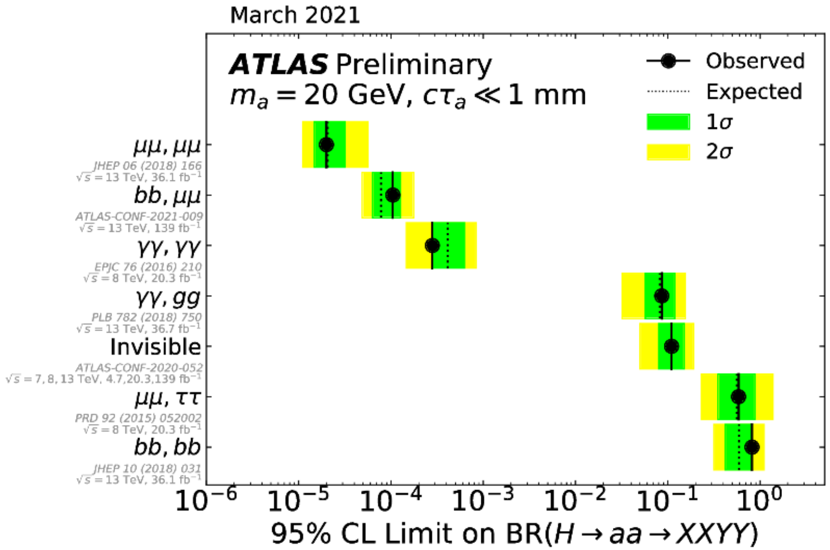


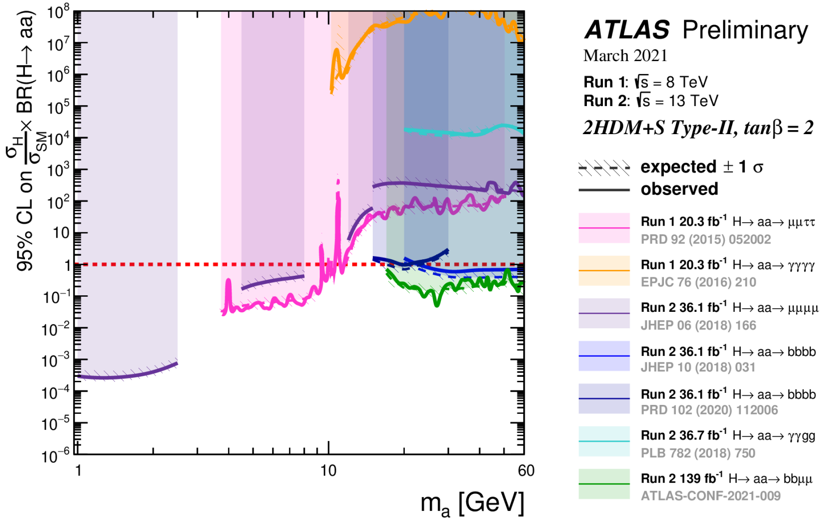


Excess at 52 GeV:

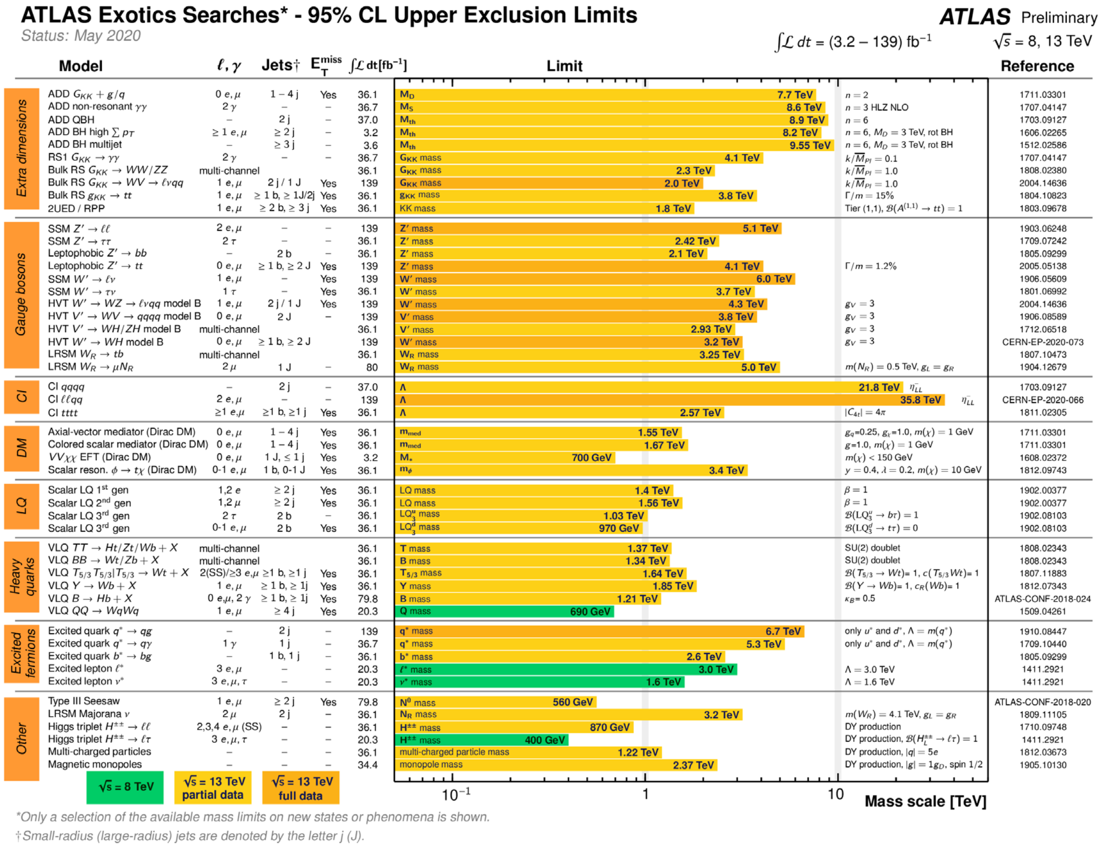
- 3.3 (1.7) σ local (global) significance

H→aa summary [ATL-PHYS-PUB-2021-008/]





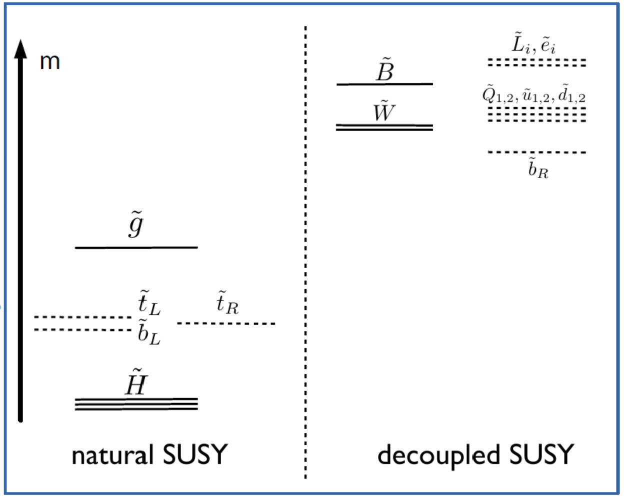
New resonance searches [ATL-PHYS-PUB-2021-009]



SUSY

- SUSY, a well motivated theory
  - Why Higgs mass so light?
  - How can the forces of nature be unified?
  - What about the nature of Dark Matter?
  - …

- Natural SUSY with relatively light stops, gluinos and higgsinos.

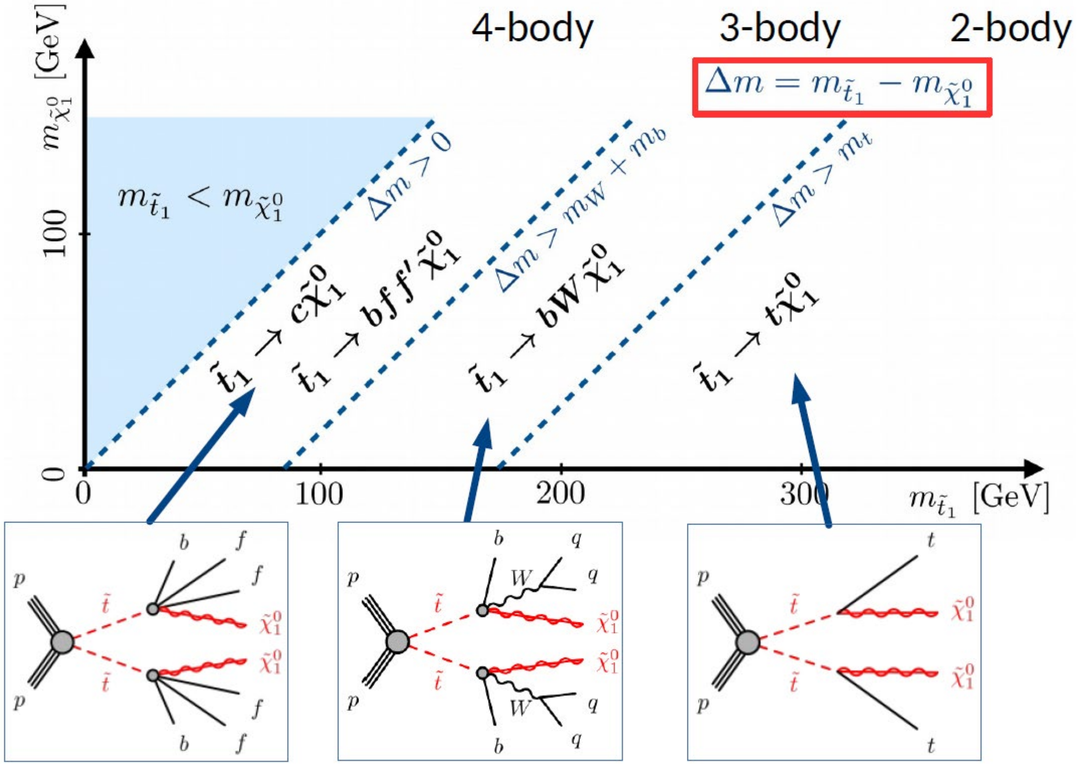


[JHEP 1209 (2012) 035]

SUSY top partner

- R-Parity Conservation
  - +1 for SM particles
  - –1 for superpartners
  - LSP stable, neutral one could be DM candidate

- Difficulties around
  - $\Delta m = m_{top}$
  - $\Delta m < m_b + m_W$



Squeezing the corners of STop

low-energy ("soft")

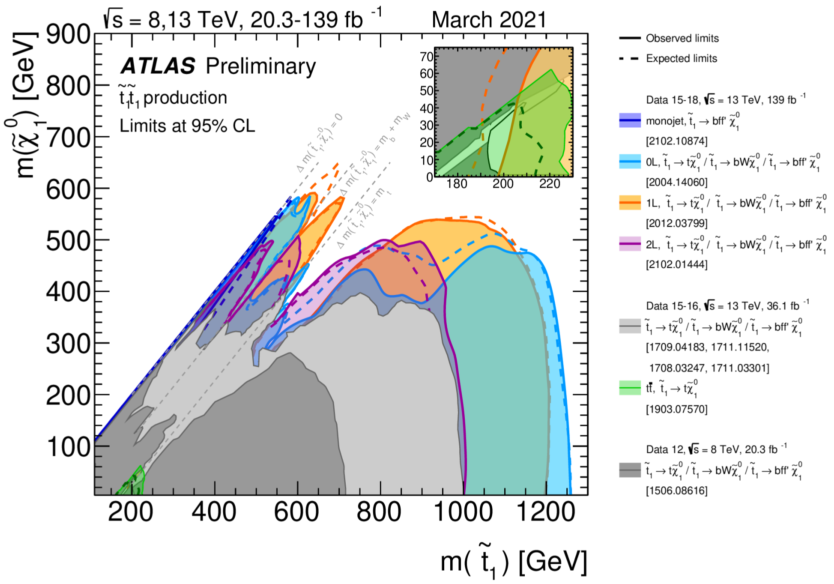
Soft b-tagging

- track jets with pT> 5 GeV
- Secondary vertices using only tracks

Irreducible ttbar backgrounds

Precise ttbar measurement

- Spin correlation

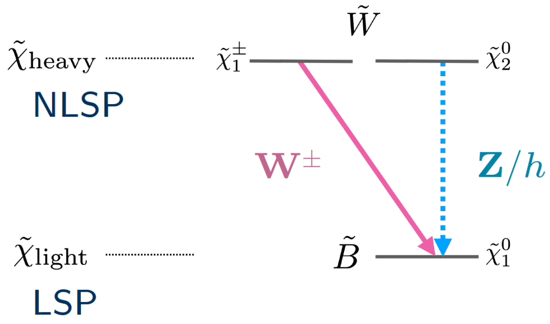


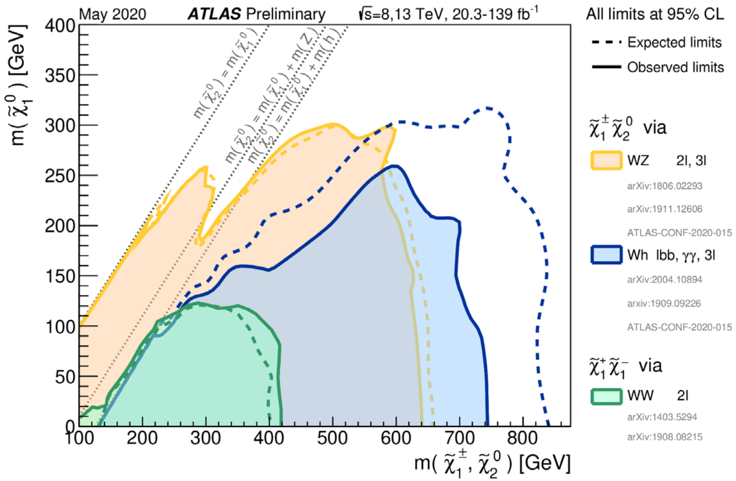
High-energy frontier

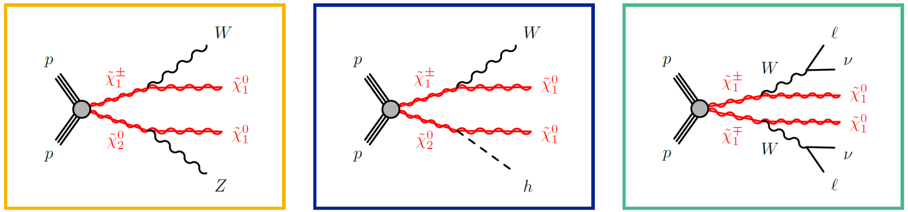
("boosted") particles

EW SUSY

- Smaller cross section, comparing to the strong production

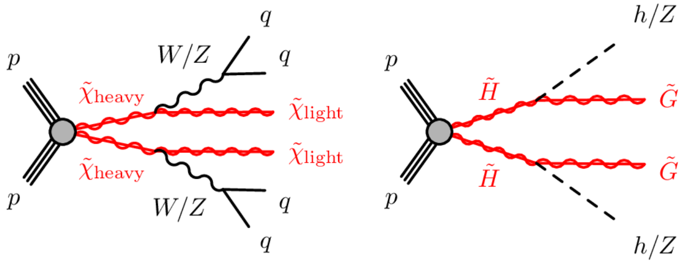


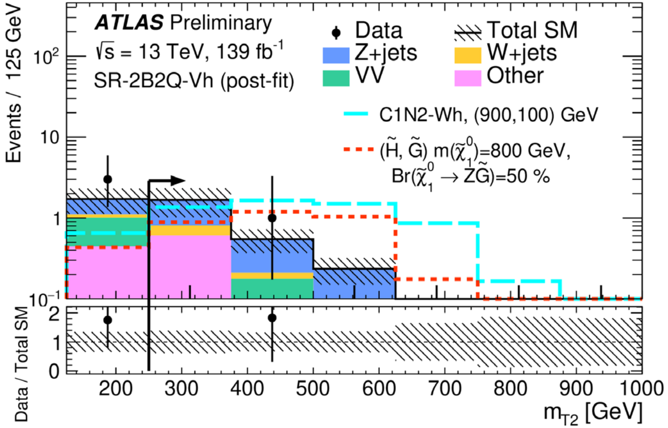


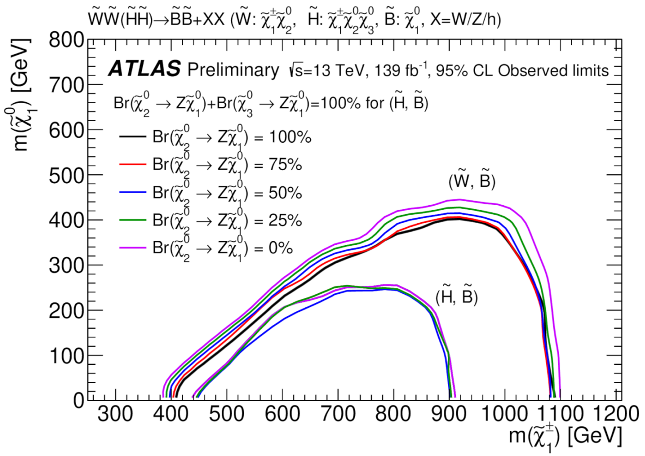


Boosted bosons ATLAS-CONF-2021-022

- Signature: two boosted W/Z/h + E_T^{miss}
  - First search for 4q fully hadronic signature at LHC
- $\tilde{\chi}_{heavy}$ exclusion reaches up to 1 TeV

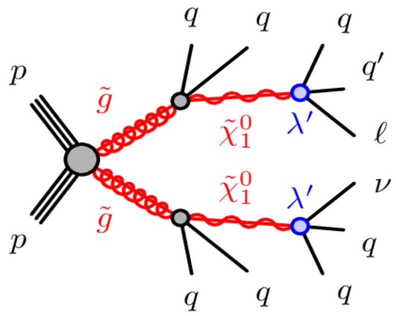


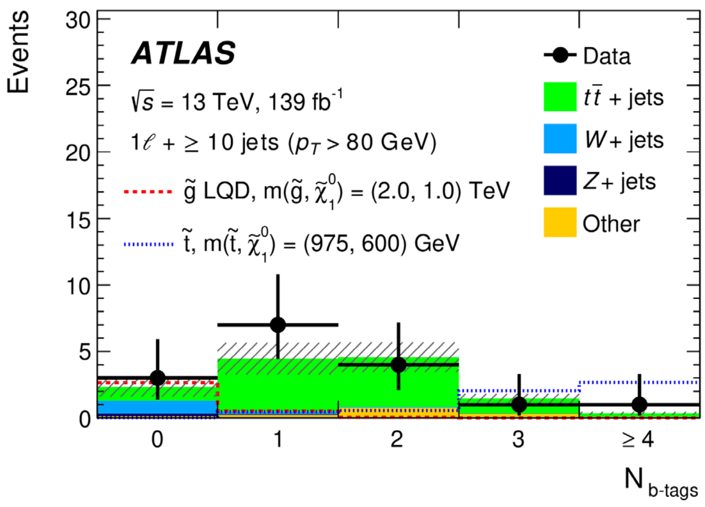


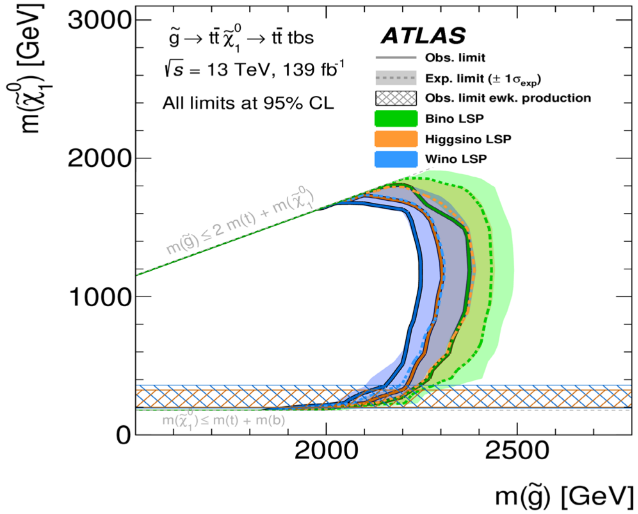


R-Parity Violation arXiv:2106.09609

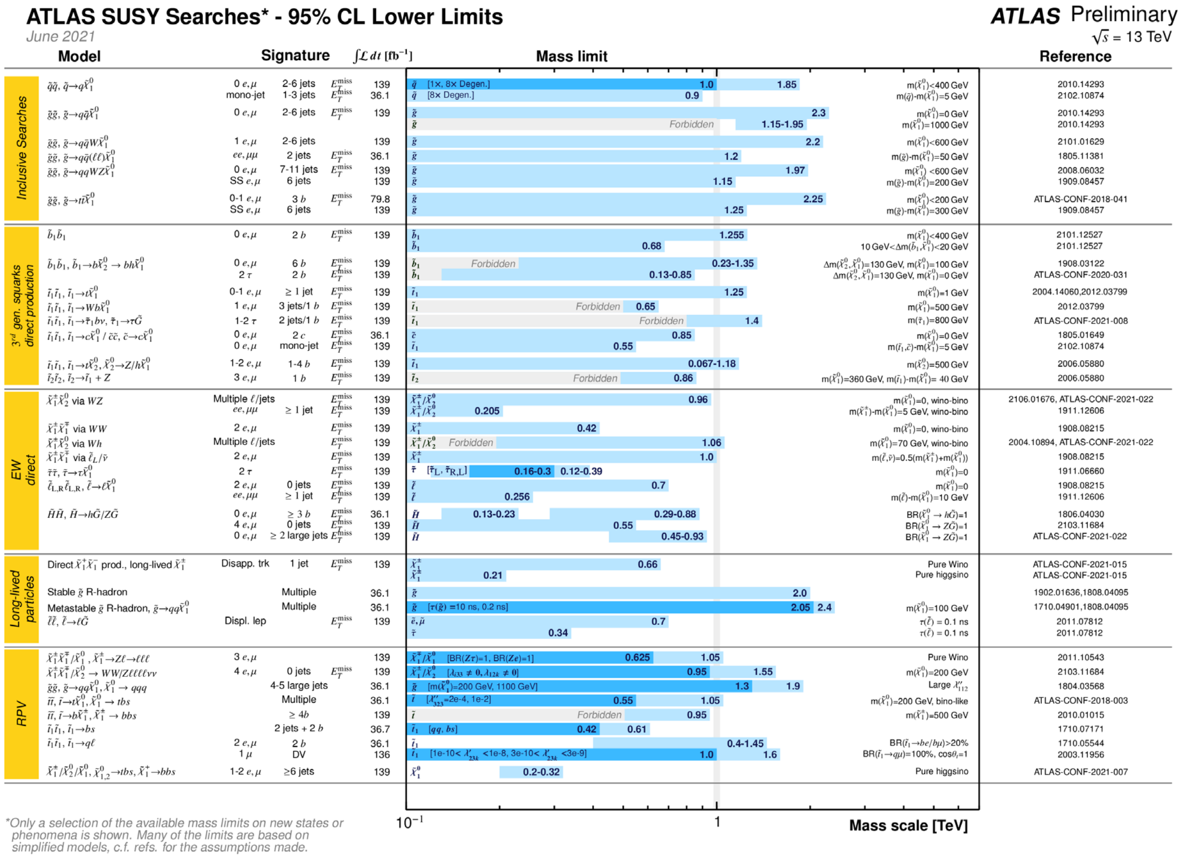
- Strong and EW production with RPV decays
  - Final state: 1lepton plus multijets
  - High $N_{jet/b\text{-}jet}$, no E_t^{miss}







SUSY summary ATL-PHYS-PUB-2021-019



Long Lived Particles

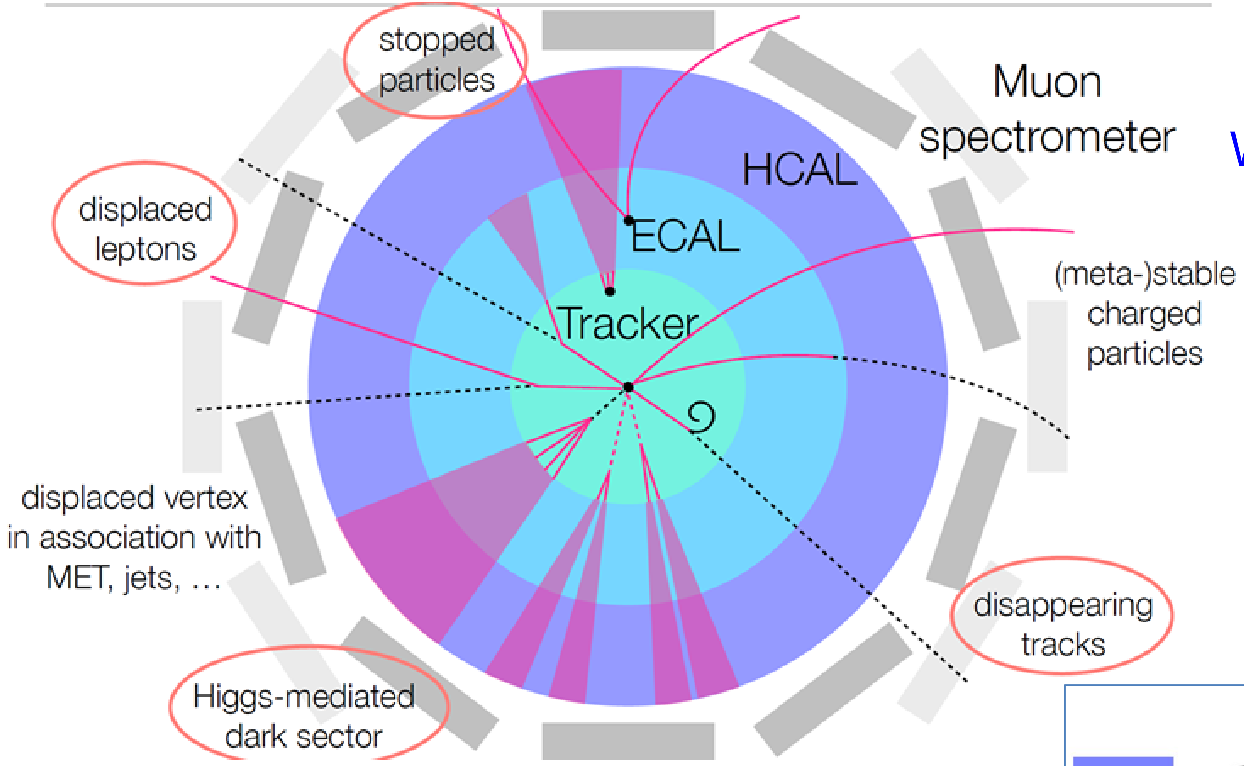
- Long Lived Particles (LLPs) predicted by any model with
  - Small couplings
  - Small mass splitting
  - Decays via off-shell particles

Small couplings
e.g. R-parity violating SUSY

Limited phase space
e.g. compressed SUSY scenarios

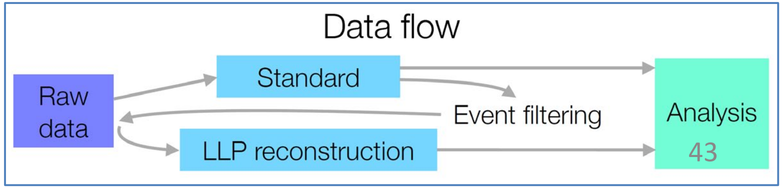
Decays via heavy particle
e.g. heavy neutrinos

Long Lived Particles at ATLAS



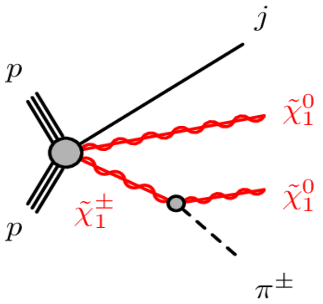
What makes LLPs so difficult?

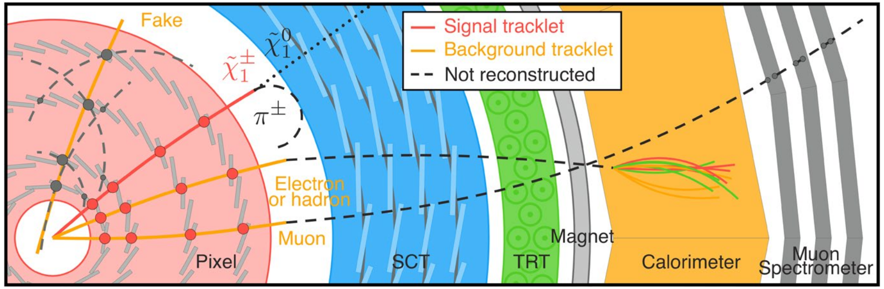
- Not triggered by conventional ones
- Need special reconstruction
- Non-standard Backgrounds, non-simulated



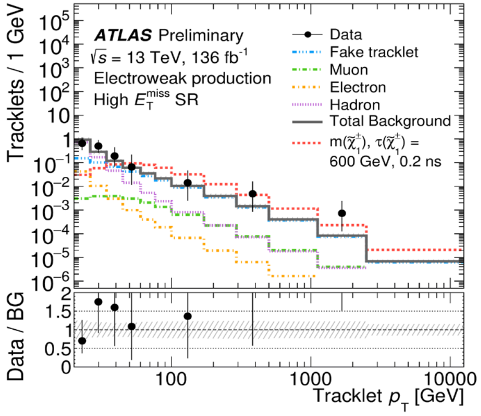
Disappeared track ATLAS-CONF-2021-015

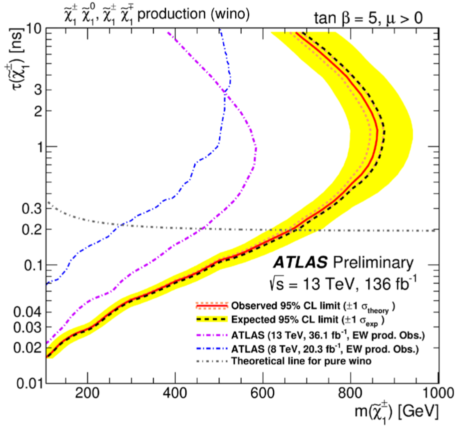
- Small mass gap between $\tilde{\chi}^{\pm 1}$ and $\tilde{\chi}^{01}$, long lifetime for $\tilde{\chi}^{\pm 1}$





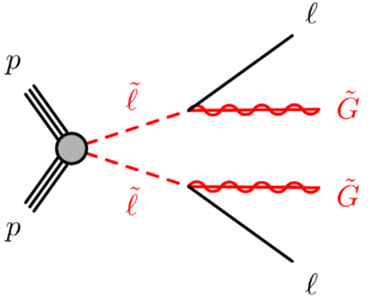
- Analysis strategy
  - ≥ 1 “disappearing” tracklet, with only pixel layer hits

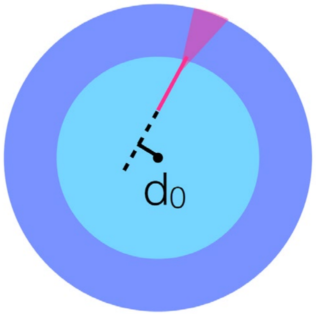




Displaced leptons arXiv:2011.07812

- Benchmark model
  - Sleptons $\tilde{l}$ in GMSB model
  - Small coupling to gravitino gives $\tilde{l}$ a long lifetime



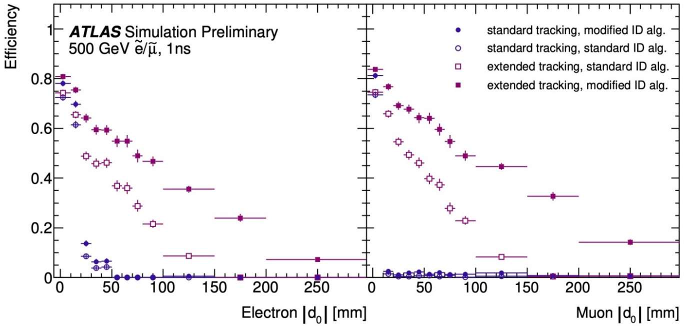


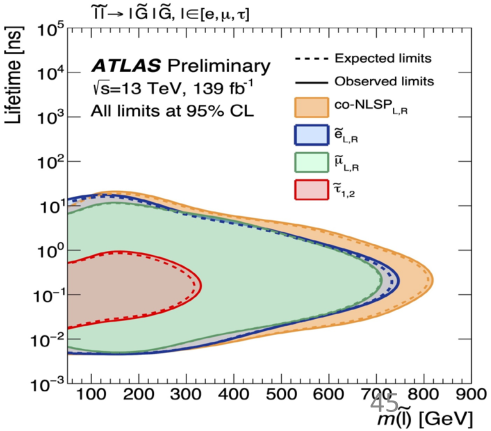
- Light leptons not pointing to primary vertex

- Two triggers
  1. Muon spectrometer
  2. Single/di-photon

  No ID track required

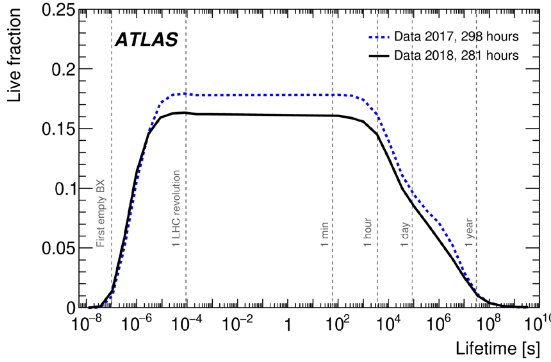
Large Radius Track

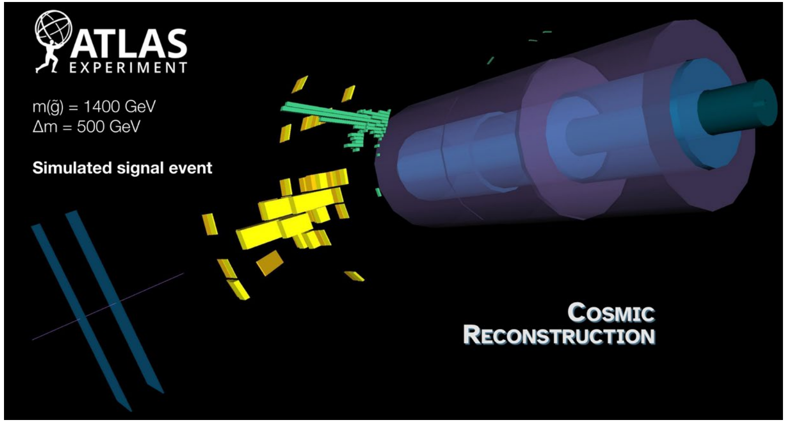


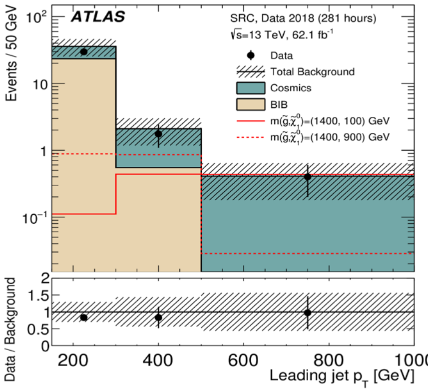


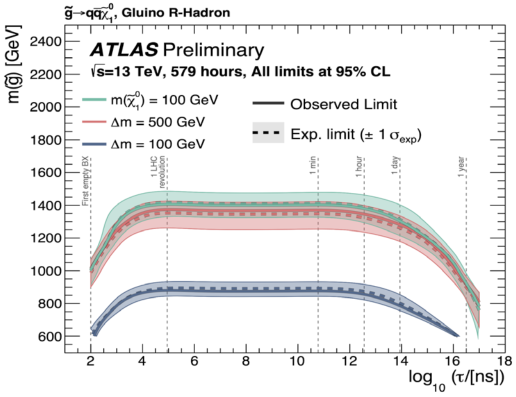
Stopped particles: R-hadron [arXiv:2104.03050]

- SUSY LLP hadronised (R-hadrons)
  - Stopped in the detector, decay later
- Search for jets in empty bunch crossings
  - Low backgrounds - Low trigger thresholds

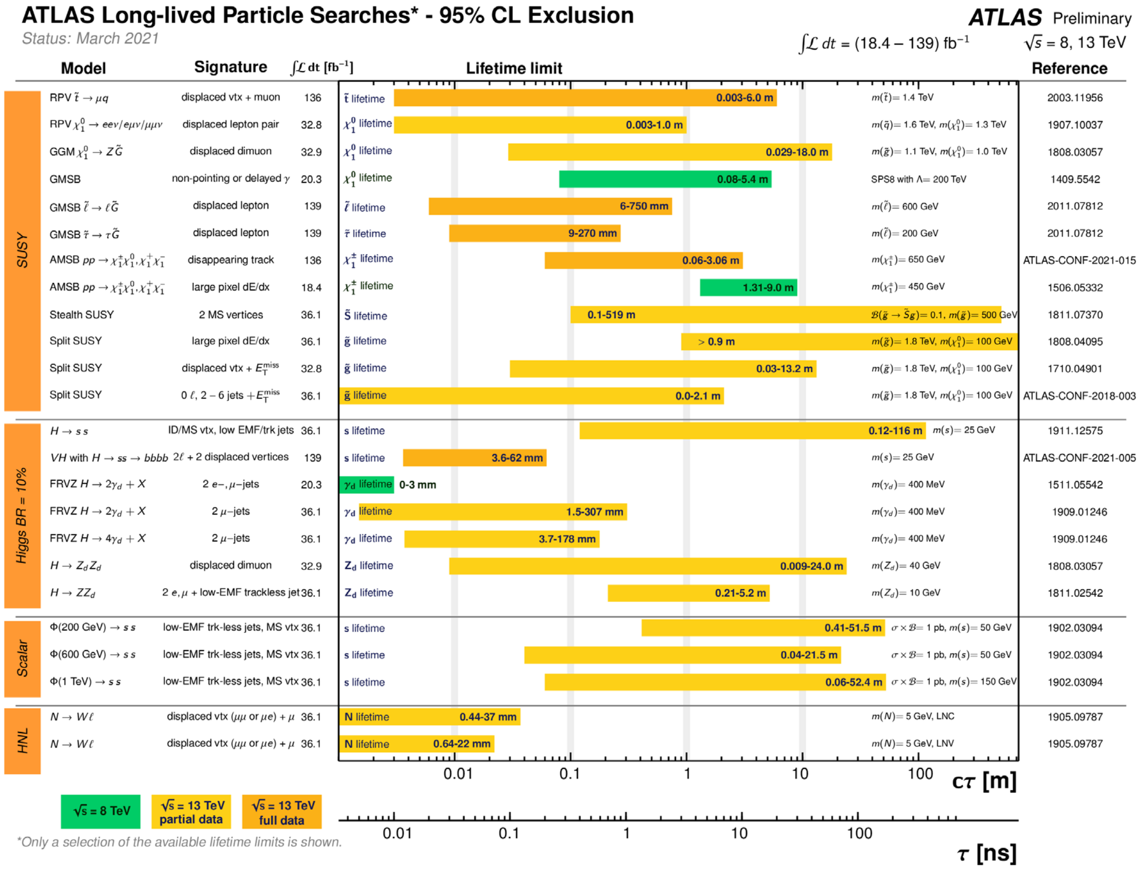






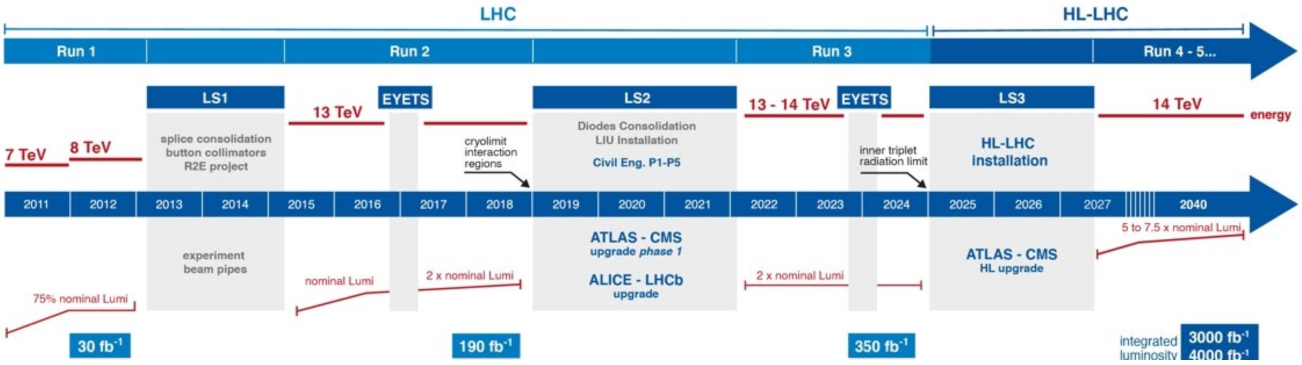


LLP summary ATL-PHYS-PUB-2021-009



Summary

- ➢ BSM new physics extensively searched at ATLAS
  - Direct searches for new resonances
  - Indirectly searches via precise measurements
  - Unconventional signature to cover the phase space gap
- ➢ Knowledge on the physics at TeV scale significantly improved
- ➢ The job is clearly not done yet! New ideas needed on both theoretical and experimental sides



Workshop on Higgs physics, Nanjing, 27-31 August

- Higgs potential and BSM opportunity
  - https://indico.ihep.ac.cn/event/14180/
- Scope including
  - Higgs precise measurements, Higgs potential, EWPT, extra Higgs or scalars, etc.

Let's meet, drink
and excite more Higgs bosons

BSM New Physics

- LHC-ATLAS hopefully could give hint to those big questions

Dark Matter

Baryogenesis

Flavor, CP, Strong CP

Dynamics of Higgs mechanism

- Precise Higgs measurement, BSM interpretation, EFT, etc
- H invisible, Mono-H, -Z,tW, etc

- Z’,W’
- SUSY,
- Extra Higgs

Naturalness

- ALP
- LQ

Grand Unification

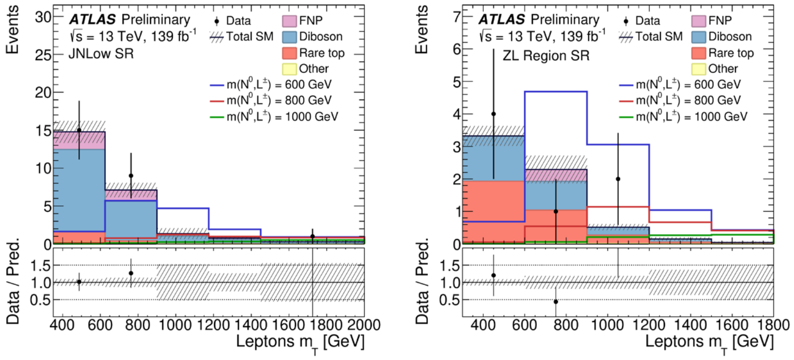
- KK Graviton,etc

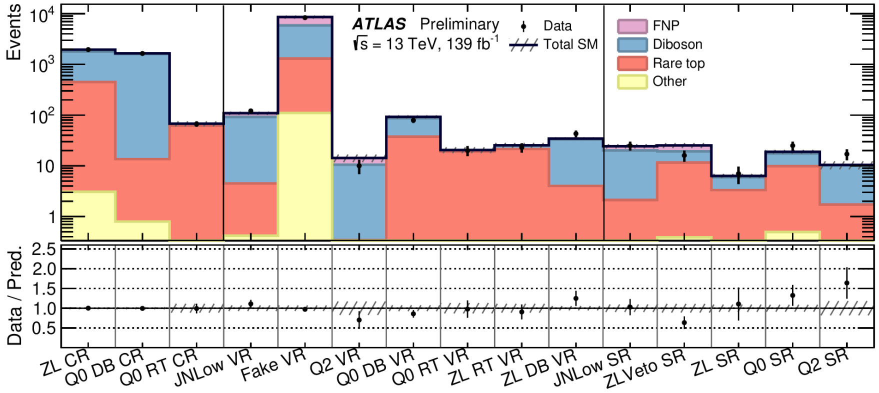
Quantum Gravity

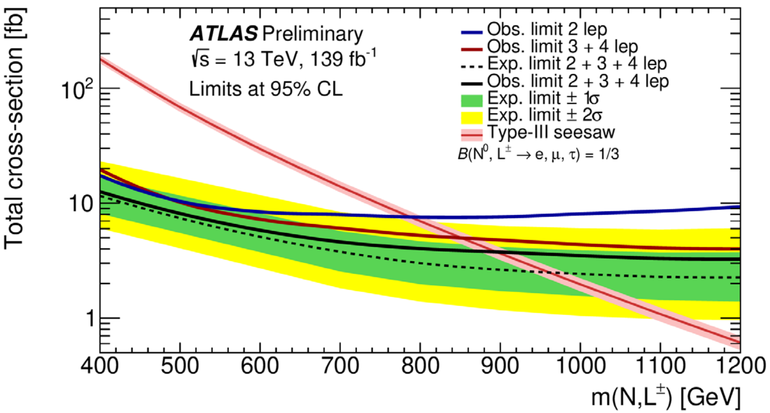
G?

Search for Heavy Leptons

- Exclusion limits at $m(N, L^{\pm}) > 910$ GeV
- Most stringent limits on type-III seesaw models at LHC

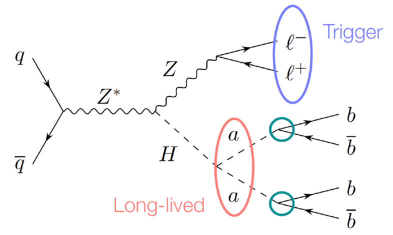




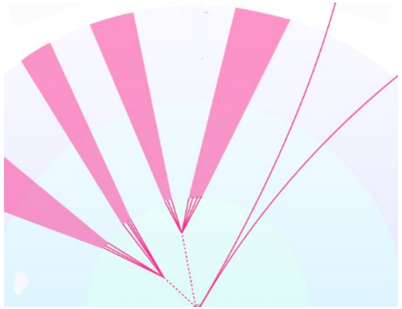


$H \rightarrow aa \rightarrow bbbb$

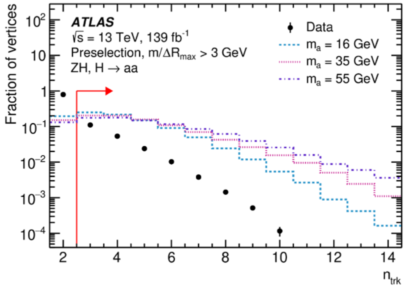
- Motivation
  - uncoloured + neutral LLPs produced in SM Higgs decay
  - scalar/pseudoscalar mediators to a dark sector
- Benchmark: pseudoscalars, $15<m_a<55$ GeV, 10mm $<c\tau<$ 1m
- Higgs production mode
  - ZH allows leptons to trigger and suppress QCD backgrounds

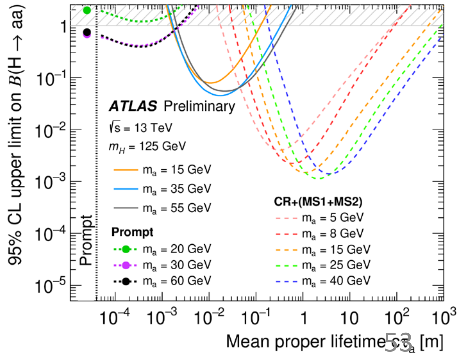


Less prompt tracks



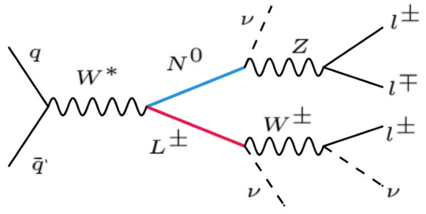
>=3 tracks to suppress SM vertiex

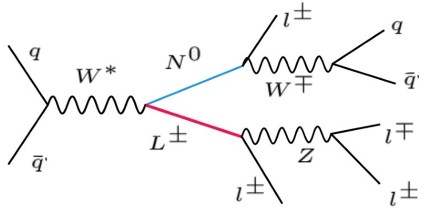


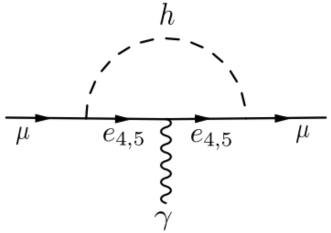


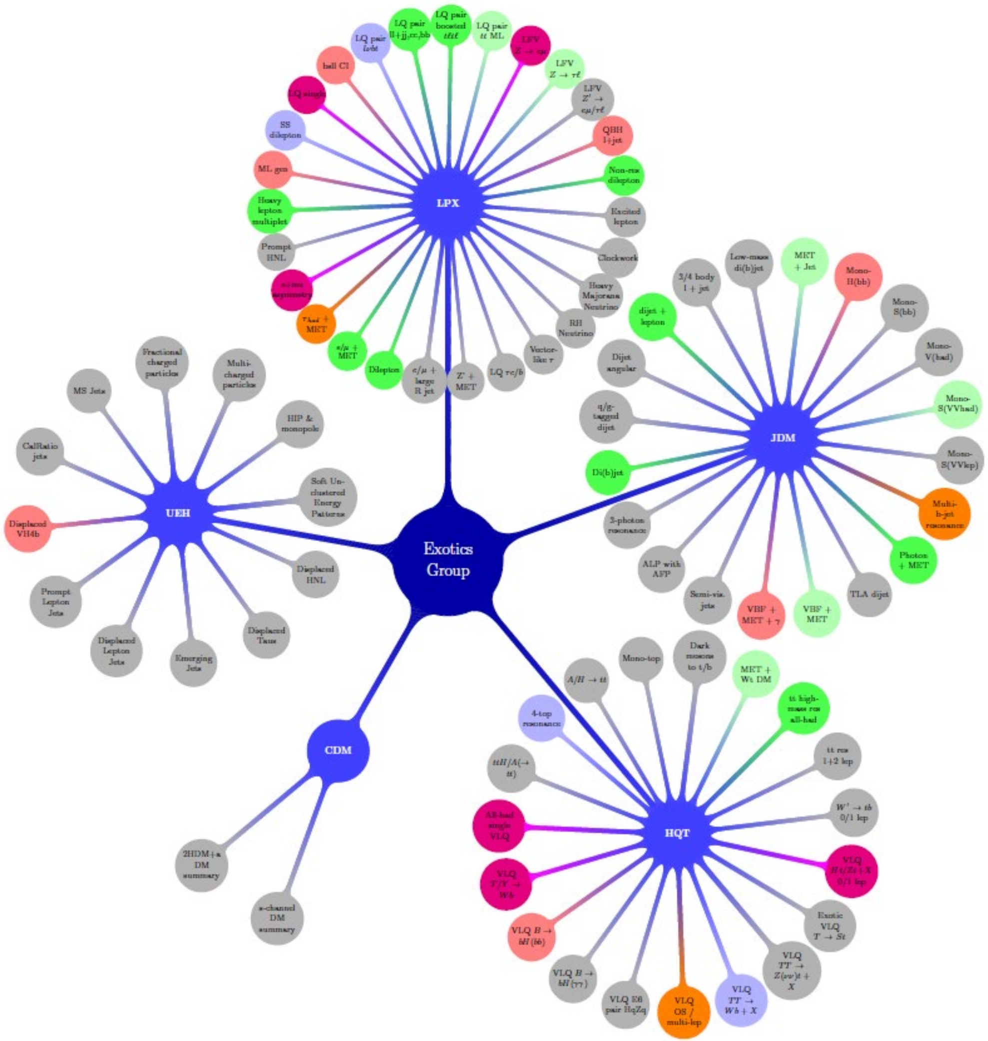
Search for Heavy Leptons

- Search for heavy leptons in events with 3/4 leptons
- Benchmark model
  - **Type-III seesaw model** which provides a heavy Majorana neutrino that could explain small neutrino mass
  - Extra fermionic $SU(2)_L$ triplet coupled to W, Z, H bosons
- Phenomenology similar to other models with heavy leptons, like **Vector-Like Lepton** triplets that could be linked to g-2 anomaly
- Dominant backgrounds: *WZ*, *ZZ* (diboson) and "rare top" production (*ttV*, *ttH*, *tWZ*)



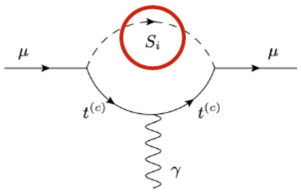


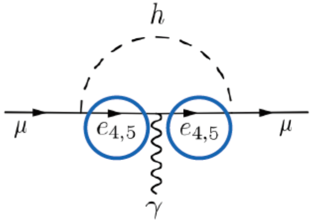


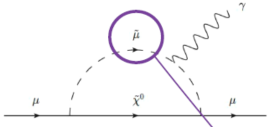

Exotics Group
LPX
LQ pair
ll+jj,cc,bb
LQ pair boosted
LQ pair
tt ML
LFV
LFV
Z → τℓ
LFV
Z′ →
eμ/τℓ
QBH
l+jet
Non-res dilepton
Excited lepton
Clockwork
Heavy Majorana Neutrino
RH Neutrino
Vector-like τ
LQ τc/b
Z′ + MET
e/μ + large R jet
Dilepton
e/μ + MET
τ_had + MET
asymmetry
Prompt HNL
Heavy lepton multiplet
ML gm
SS dilepton
LQ single
ll CI
LQ pair
JDM
3/4 body
l + jet
Low-mass di(b)jet
MET + Jet
Mono-H(bb)
Mono-S(bb)
Mono-V(had)
Mono-S(VVhad)
Mono-S(VVlep)
Multi-b-jet resonance
Photon + MET
TLA dijet
VBF + MET
VBF + MET + γ
Semi-vis. jets
ALP with AFP
3-photon resonance
Di(b)jet
q/g-tagged dijet
Dijet angular
dijet + lepton
UEH
Fractional charged particles
Multi-charged particles
HIP & monopole
Soft Un-clustered Energy Patterns
Displaced HNL
Displaced Taus
Emerging Jets
Displaced Lepton Jets
Prompt Lepton Jets
Displaced VH4b
CalRatio jets
MS Jets
CDM
2HDM+a DM summary
s-channel DM summary
HQT
Mono-top
Dark mesons to t/b
MET + Wt DM
tt high-mass res all-had
tt res
1+2 lep
W′ → tb
0/1 lep
VLQ
Exotic VLQ
T → St
VLQ
TT →
Z(νν)t +
X
VLQ
TT →
Wb + X
VLQ
OS /
multi-lep
VLQ E6 pair HqZq
VLQ B →
bH (γγ)
VLQ B →
bH (bb)
VLQ
T/Y →
Wb
VLQ
ttH/A(→
tt)
4-top resonance
A/H → tt

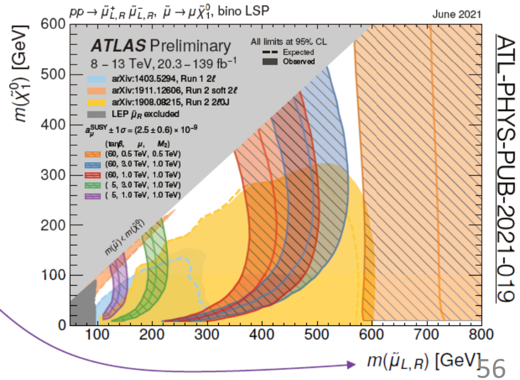
Muon g-2

- Discrepancy may be explained by
  - **Leptoquark**
  - **Vector-like leptons**
  - **SUSY smuons, …**



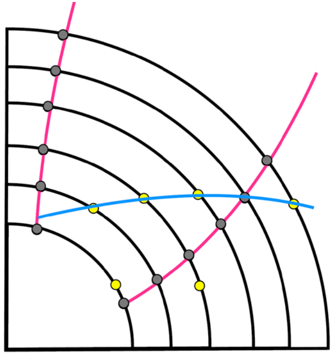


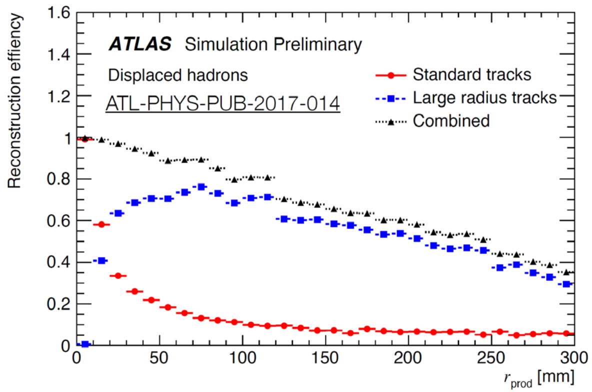


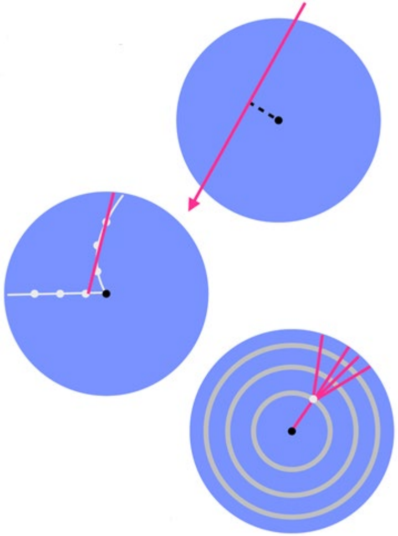


Long Lived Particles at ATLAS

- For selected subset of events, run dedicated “large radius tracking” (LRT), excluding the hit used by prompt tracking







- Backgrounds
  - Cosmic muons
  - Mis-reconstructed objects (fake tracks, pileup contamination, …)
  - Material interactions in detector components
  - Beam-induced backgrounds
- Not possible to simulate them well

arXiv:2103.16558

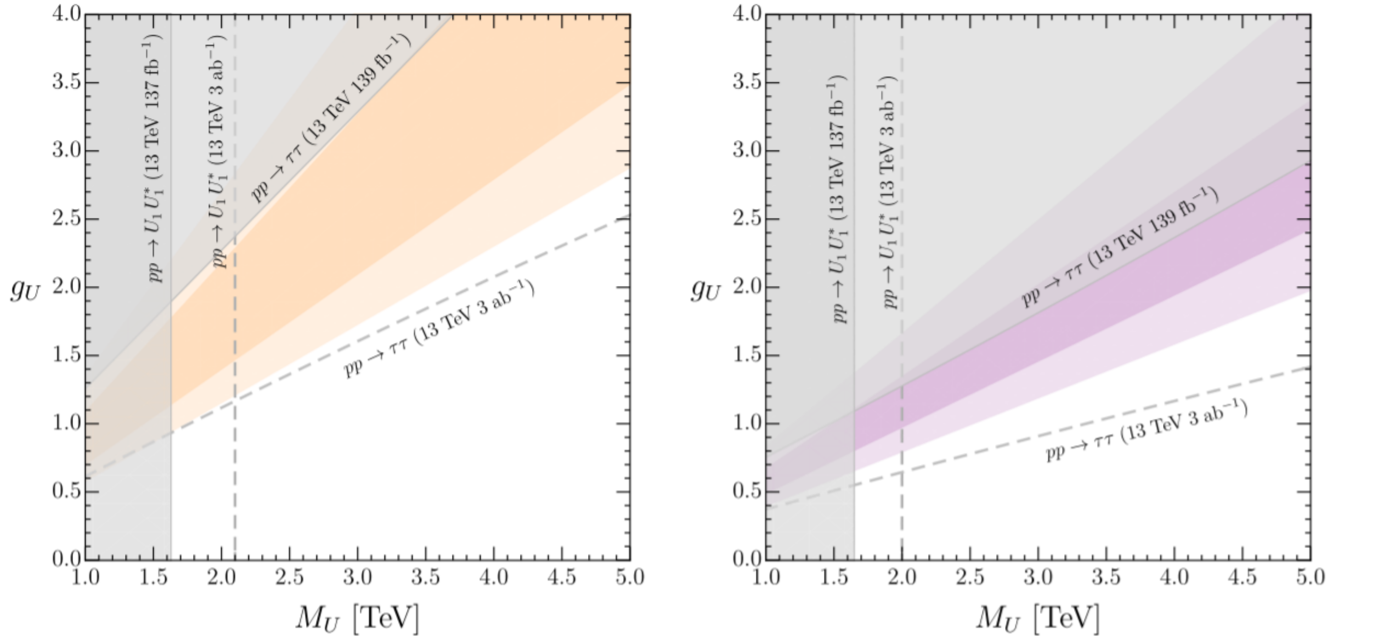
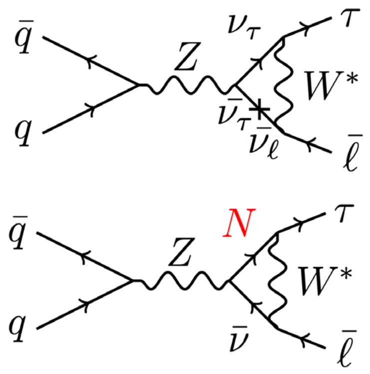
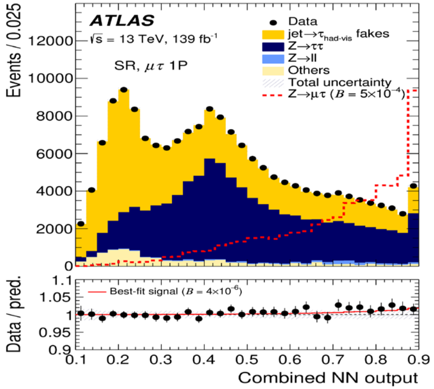


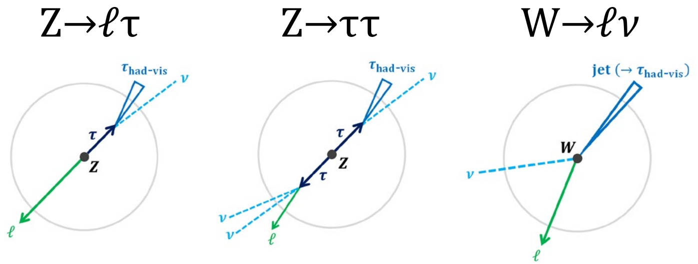
Figure 3.3: LHC constraints for the U_1 vector leptoquark for the benchmark scenarios with $\beta_R^{b\tau} = 0$ (left) and $\beta_R^{b\tau} = -1$ (right). The 1σ and 2σ regions obtained from the fit to low-energy data are also shown.

Search for LFV decays Z→lτ EXOT-2018-36/



- Z→ℓτ via neutrino mixing at $\mathcal{B}r \approx 10^{-54}$ in SM, enhanced significantly in BSM





- Z→ℓτ search complements low-energy searches, eg τ→γμ,3μ