Searches for BSM physics at the LHC

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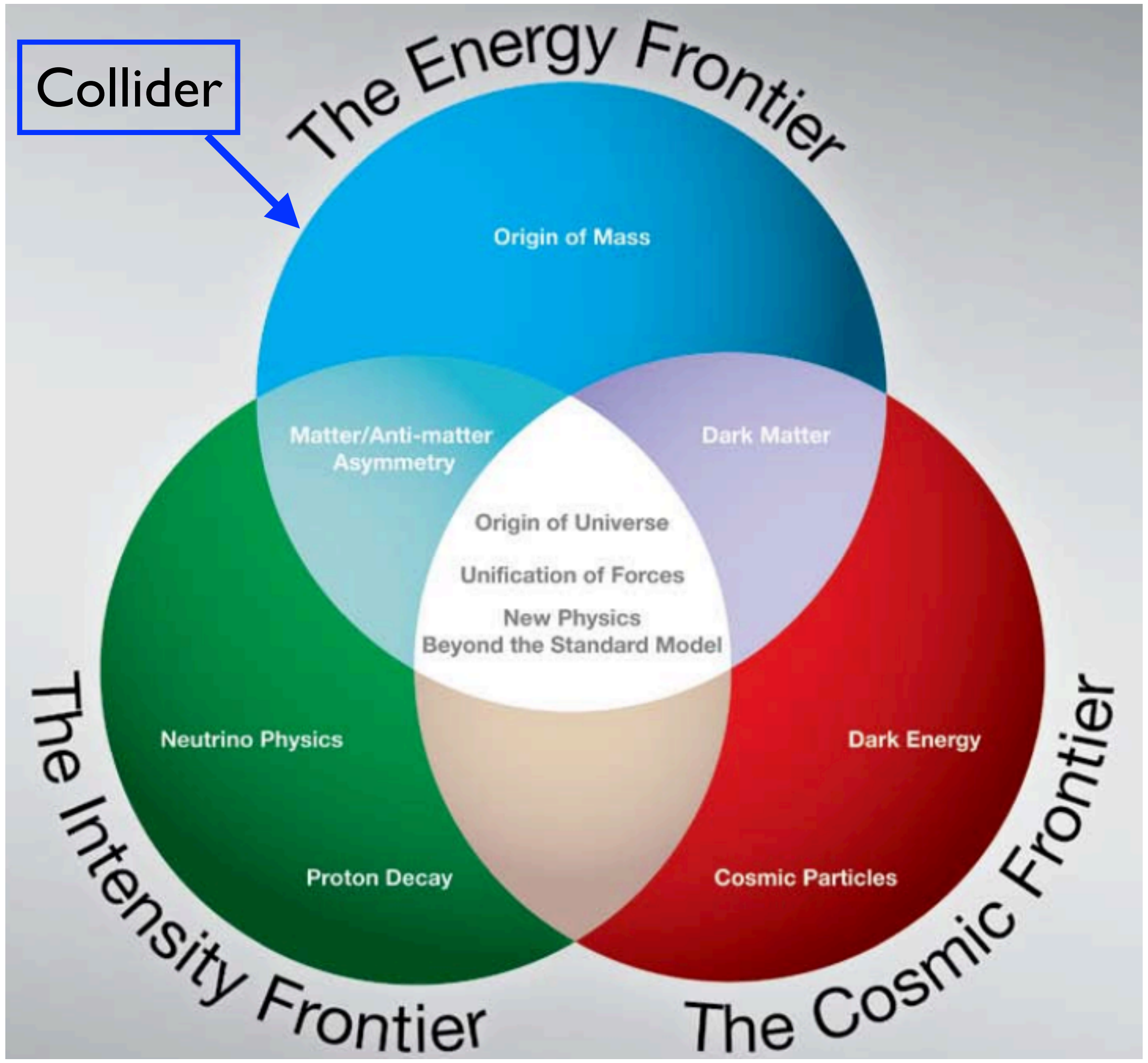
12-April-2021

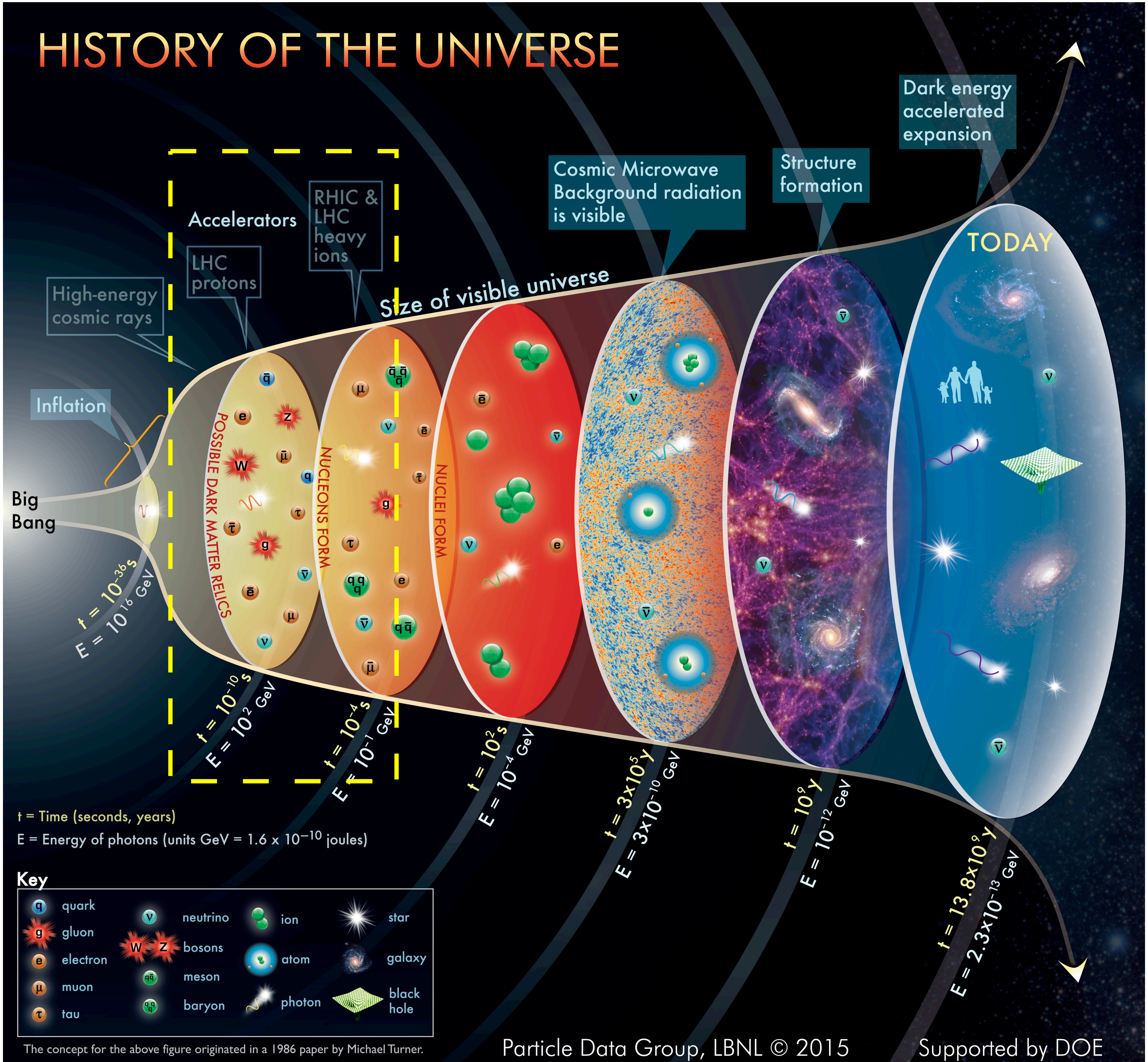
IoP Joint APP, HEPP and NP Conference 2021

Setting the theme - BSM searches

- Dark matter and dark energy
- Abundance of matter over anti-matter
- Neutrino masses and origin
- Origin of EW symmetry breaking
- A more "natural" solution to the hierarchy problem
- Strong CP problem



"There is no experiment nor facility, proposed or conceivable, in the lab or in space, accelerator or non-accelerator driven, which can guarantee discoveries beyond the SM, and answers to the big questions of the field" (M.Mangano, 98th ECFA, November 2015)



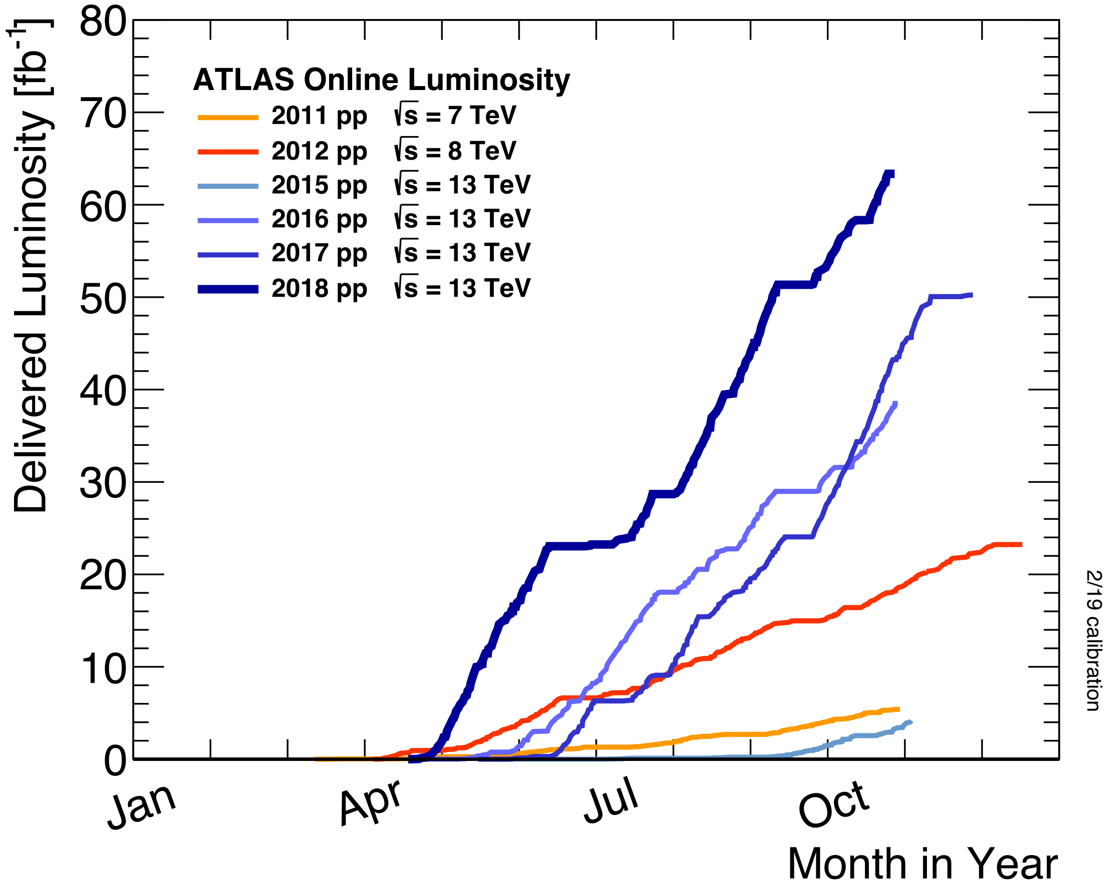
HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Cosmic Microwave Background radiation is visible
Structure formation
TODAY
Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy cosmic rays
Size of visible universe
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
t = 10^2 s
E = 10^-4 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 2.3x10^-13 GeV
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6 x 10^-10 joules)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
The concept for the above figure originated in a 1986 paper by Michael Turner.
Particle Data Group, LBNL © 2015
Supported by DOE

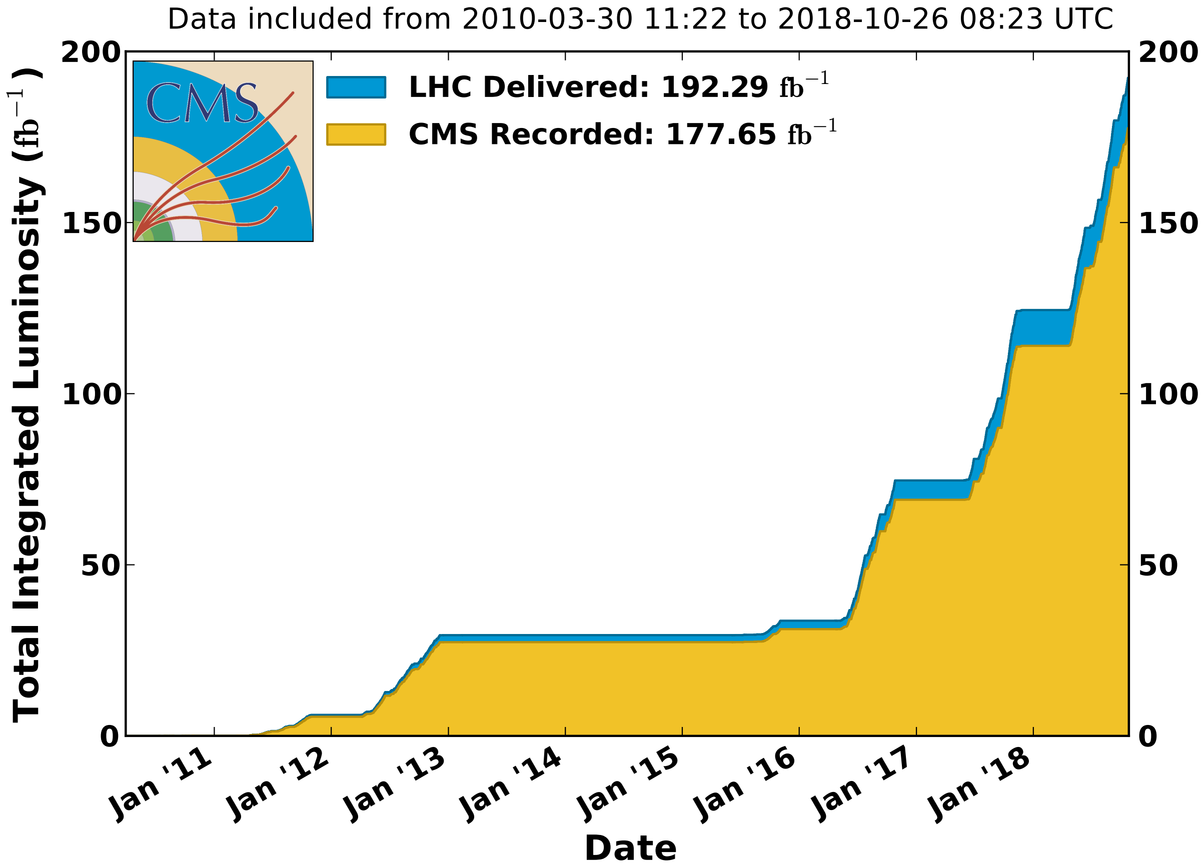
Setting the theme - BSM searches at the LHC

- There is an overwhelmingly large collection of BSM models to choose from
    - Non exhausted list: SUSY, extra dimensions, vector-like quarks, lepto-quarks…
    - Also: simplified models, minimal models, and EFT
    - Gauge invariance, UV-completion, existing experimental results provide the best guidance
        - The constraint can be very loose: many caveats and work-around
- LHC searches are signature-driven as a first principle
    - Search for excesses in number of events in a plethora of kinematic regions and for resonances from new particles, exploring the highest mass range possible → main focus of this talk
    - Perform precision measurements of SM parameters to search for deviations → not covered
- Challenges in interpreting LHC search results
    - There are numerous results with similar final states → not trivial to correlate or compare
    - Many searches take advantage of machine learning algorithms → non-trivial to interpret
    - ⇒ Present, and preserve, physics object efficiency/resolutions, and particle-level results

Run 1+2 pp collision data

[Link to ATLAS Lumi public plot]





- Many key analyses are based on full Run1+Run-2 data

ATLAS/CMS: 140 fb^{-1} at $\sqrt{s} = 13\,\text{TeV}$

- Expect more results: many analyses are still analysing this legendary dataset

Highlight of the search results

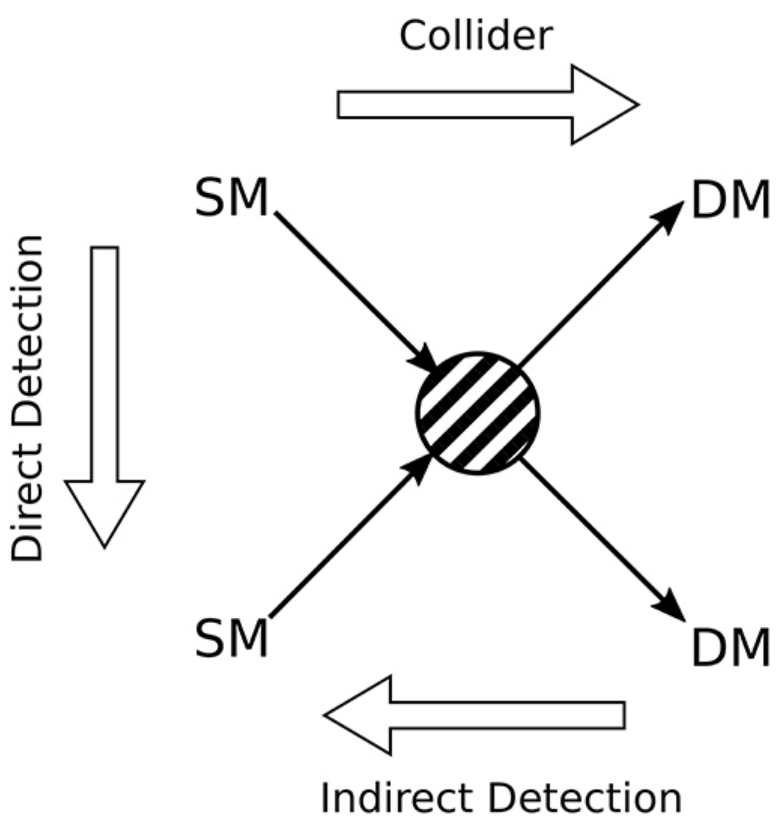
- General remarks on the LHC DM searches, embedded in many BSM searches
- Highlight of recent searches results in
  - High mass/pT regions
  - SUSY
  - Long-lived particles (LLP)
- Areas not covered
  - BSM searches in dedicated quark-flavour sector → Eva Gersabeck's talk earlier
  - Dark sector scenarios → Phil Ilten's talk next
  - BSM searches using Higgs boson → Kristin Lohwasser's talk tomorrow
- For detailed information, especially the "how", tune in the relevant parallel sessions
  - Also follow these experimental public webpages for complete list of results

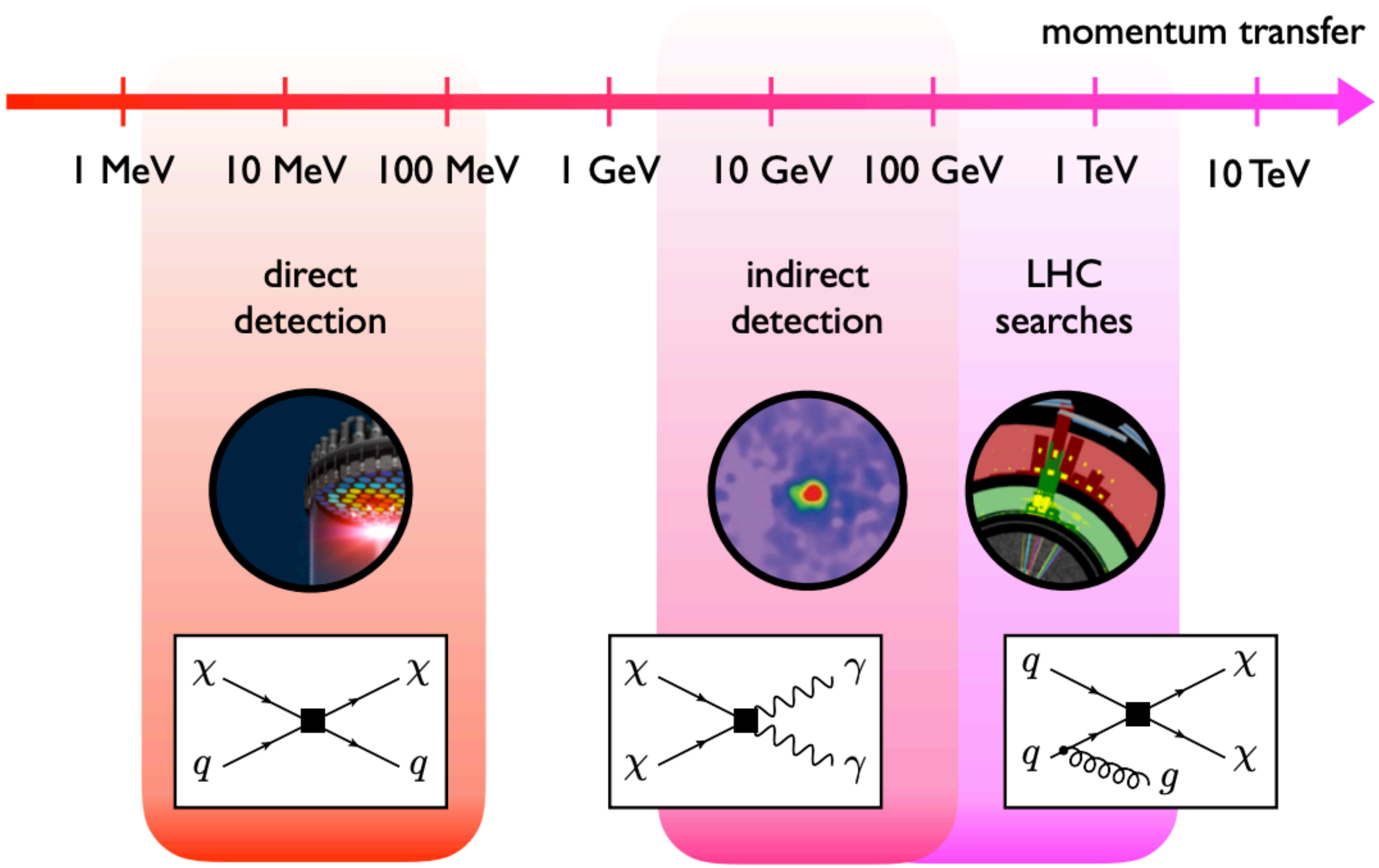
ATLAS public results *CMS public results*

General remark on DM searches

- Dark matter represents one of the clear guidance for BSM physics
  - Embedded in many BSM models, e.g. R-parity conserving SUSY, dark sector…
  - LHC searches have gone much beyond the traditional MET+X regions

LHC Dark Matter Working Group: joint ATLAS/CMS/theory forum
Recommend: benchmark signal models, LHC DM results presentation and comparison with non-collider frontiers

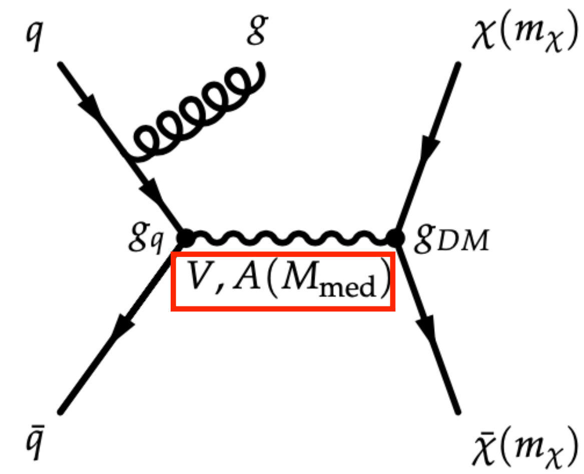




LHCDMWG: 1810.09420

DM searches - models and signatures*

$\not{E}_T + X(\mathrm{g/q}/\gamma/V)$



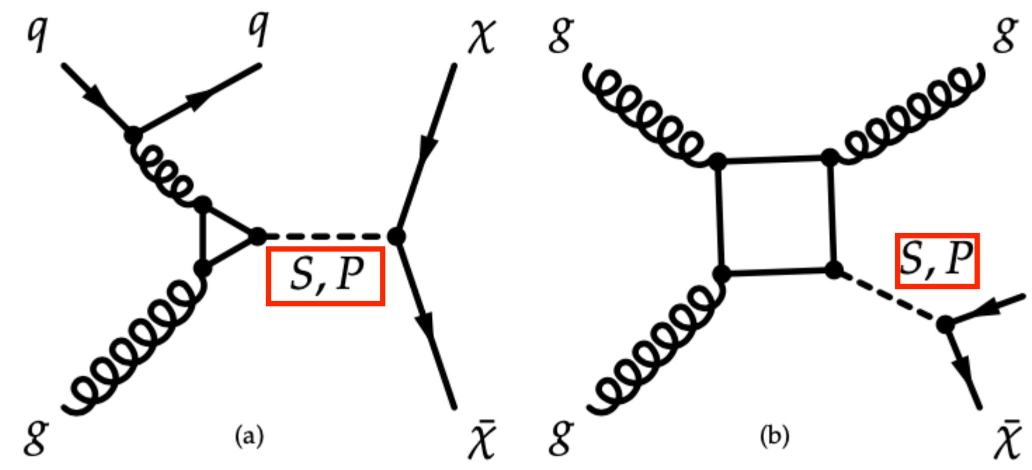
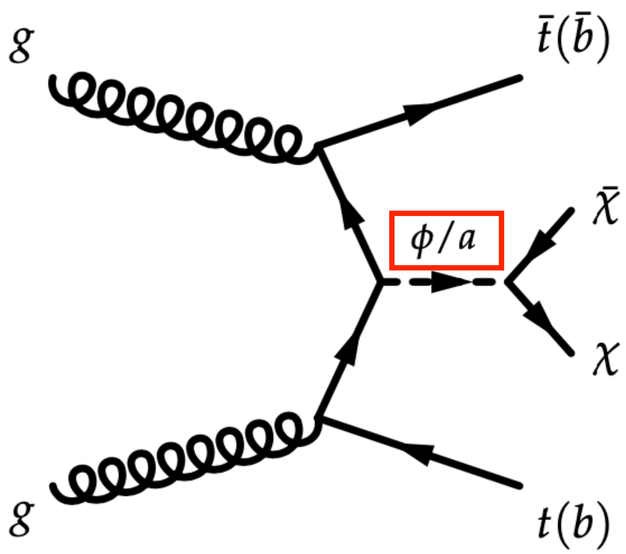
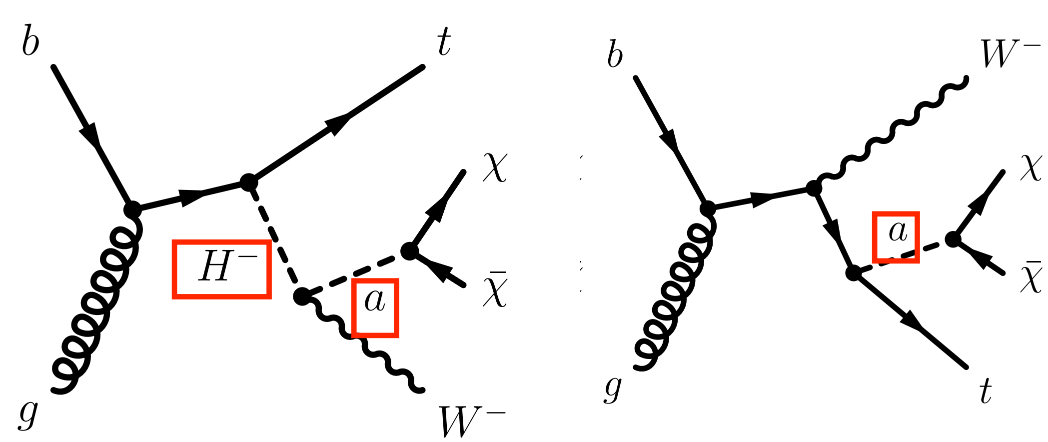


Figure 2.14: One-loop diagrams of processes exchanging a scalar (*S*) or pseudoscalar (*P*) mediator, leading to a mono-jet signature.

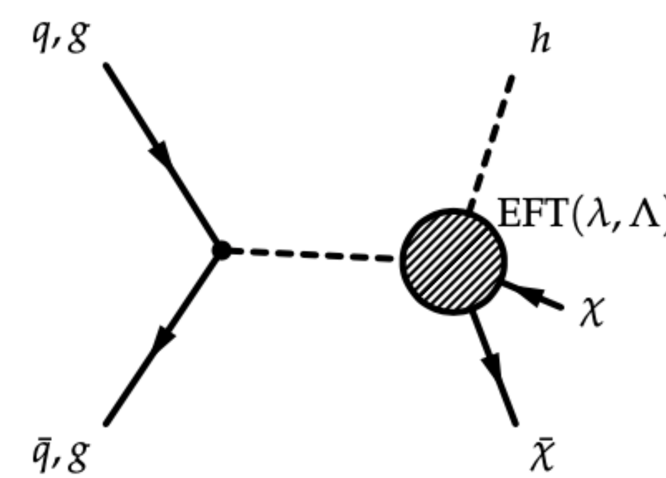
$\not{E}_T + \mathrm{t\bar{t}/b\bar{b}}$



$\not{E}_T + \mathrm{tW}$ 2HDM $+ a$



$\not{E}_T + h$ EFT



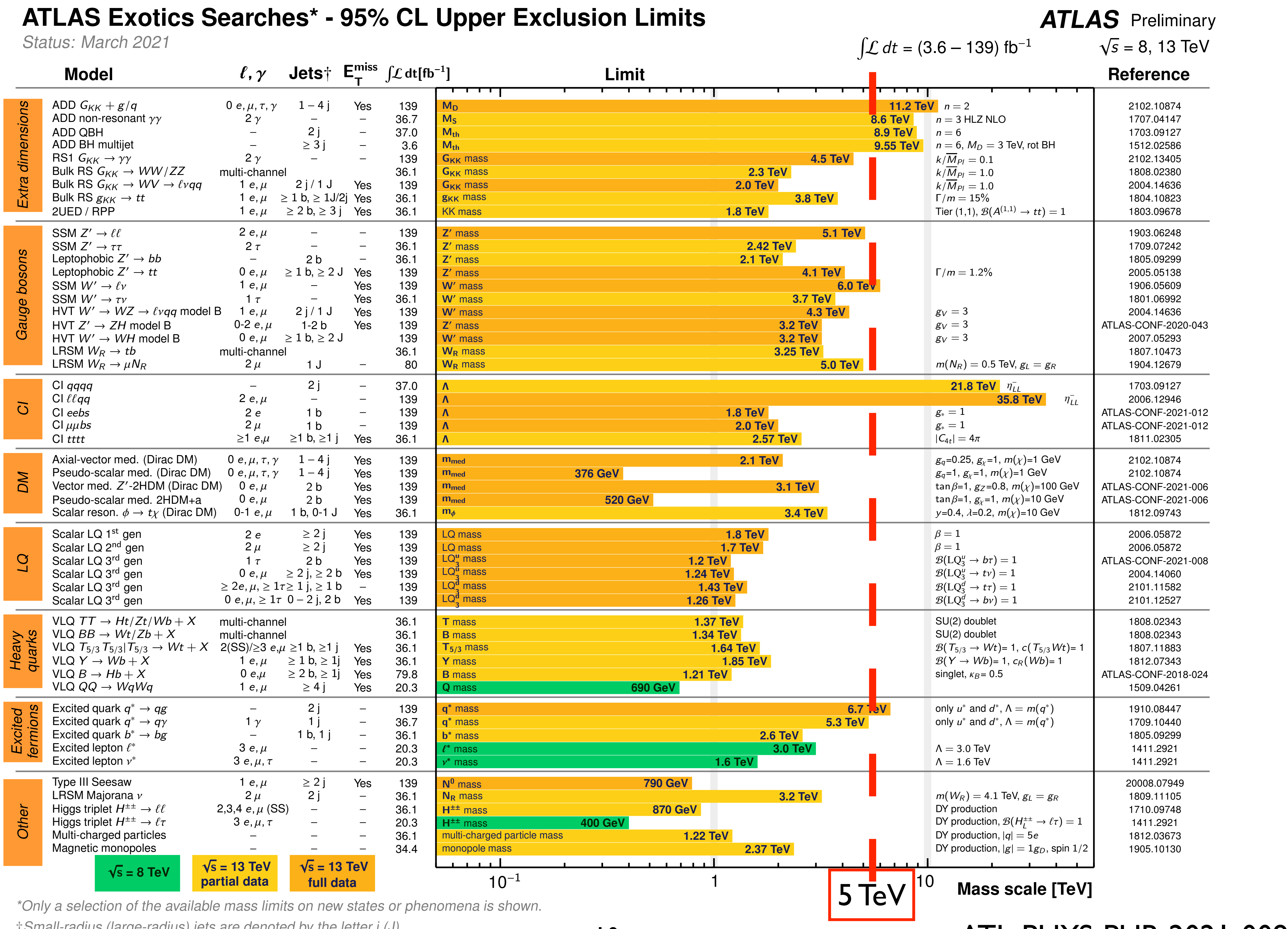
Can search for these BSM particles (mediators) in visible decays as well!

In many cases, the visible decay dominate the sensitivity

* *non-exclusive list, much more at arXiv:1507.00966 (LHCDMWG)*

High pT/mass region

A summary of search results - mass scale (non-SUSY)



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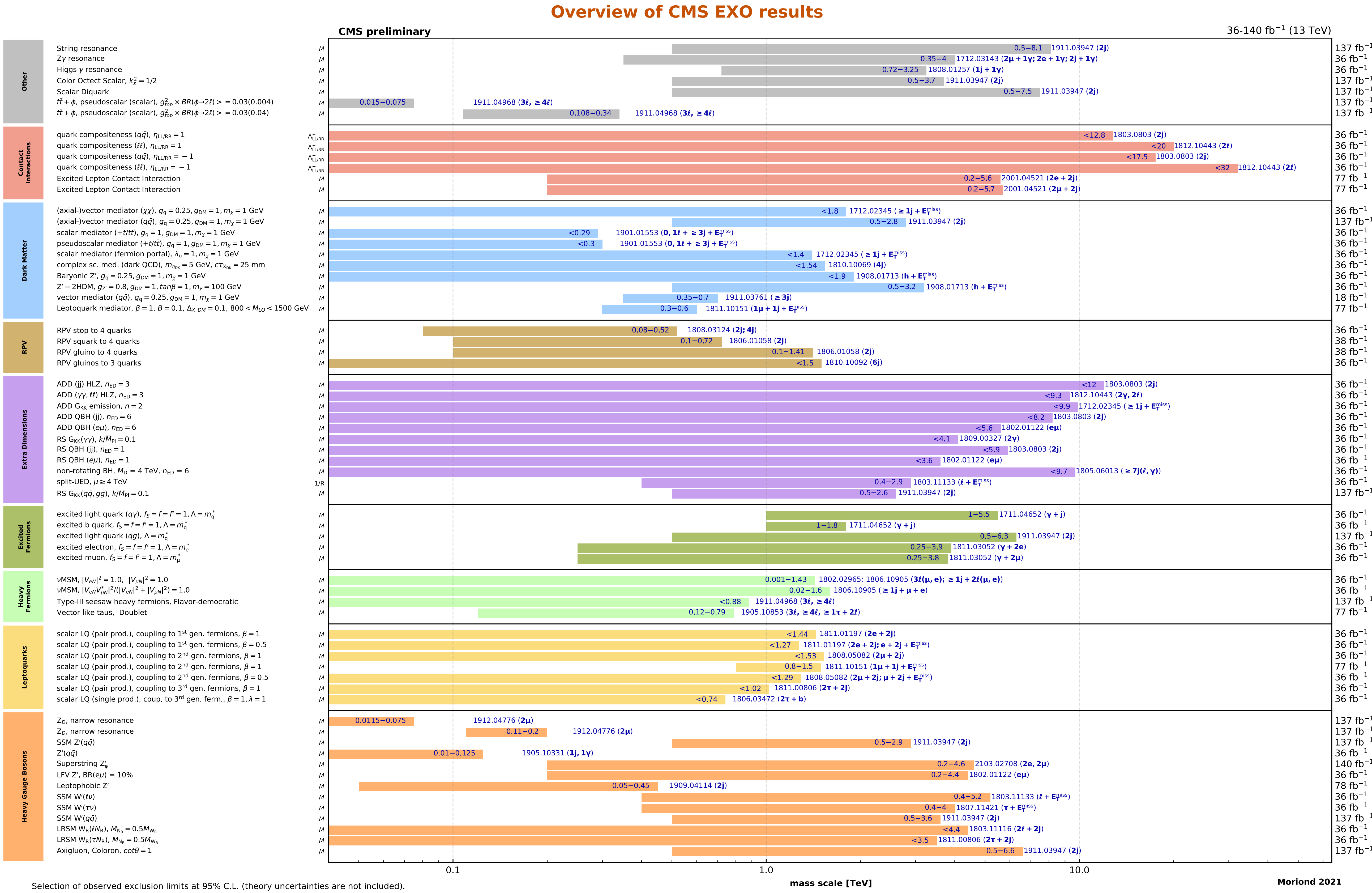
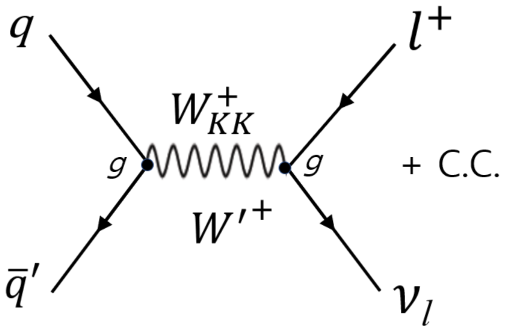
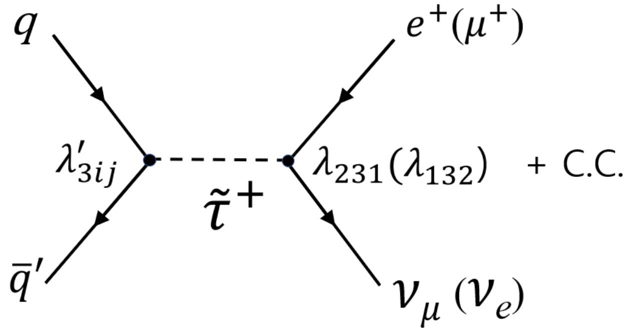
A summary of search results - mass scale (non-SUSY)

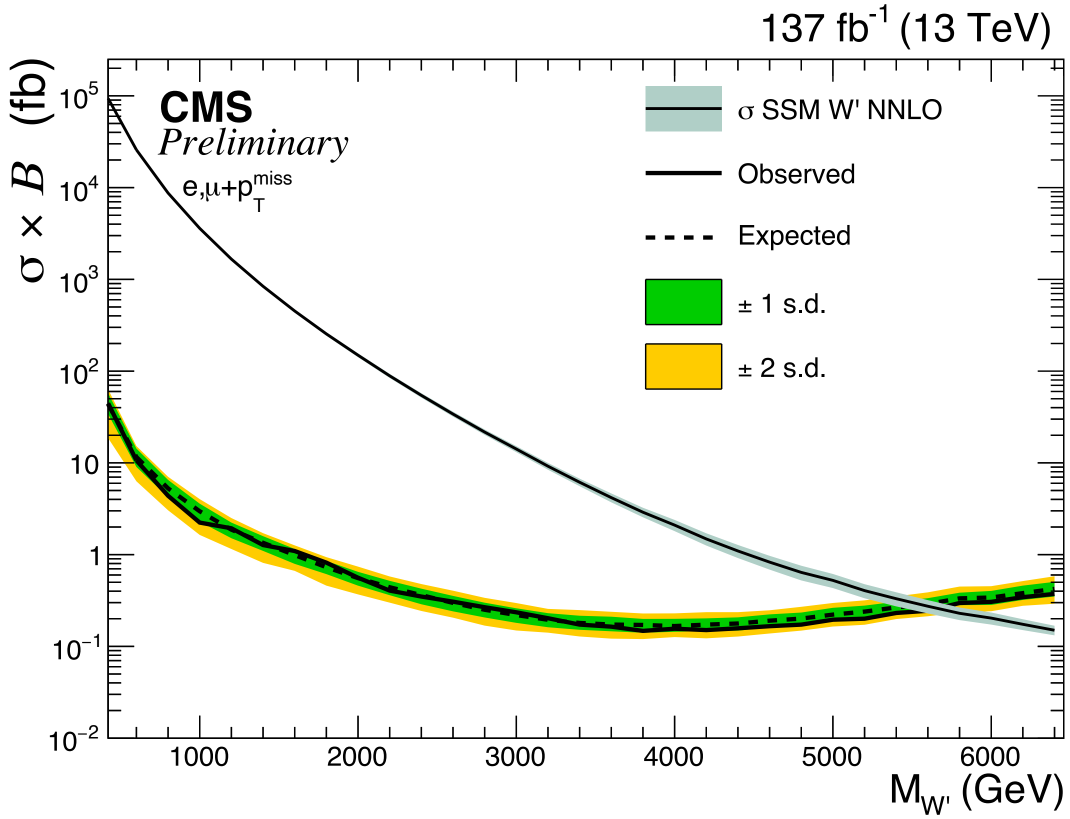


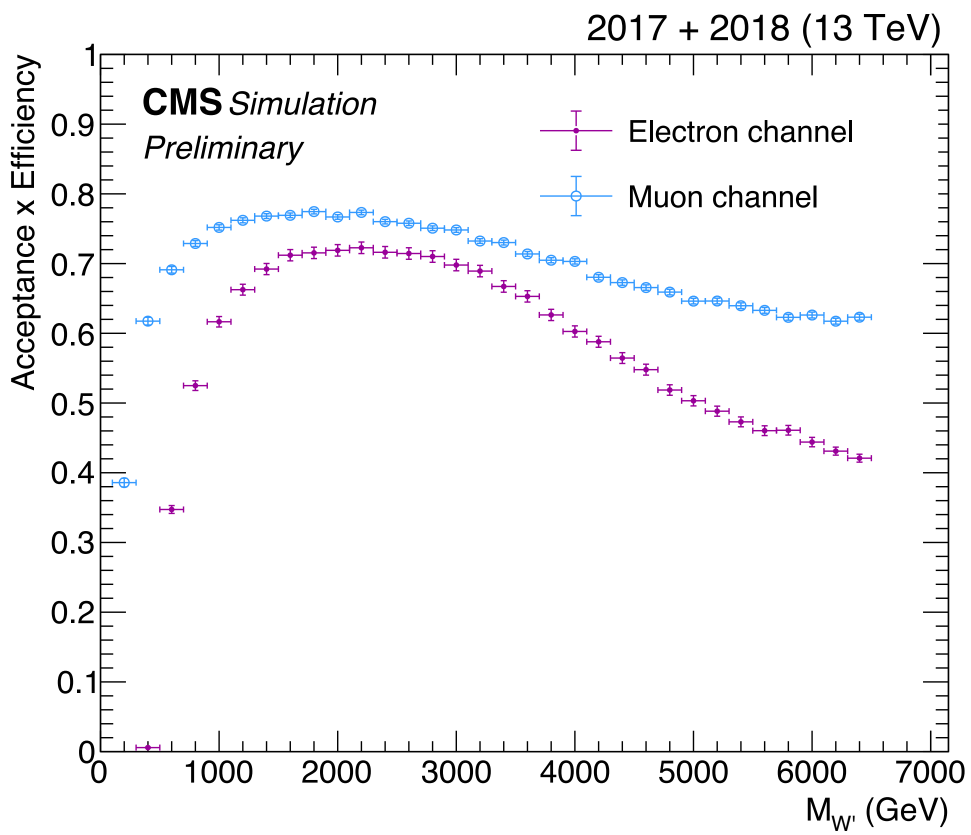
CMS Exotica summary

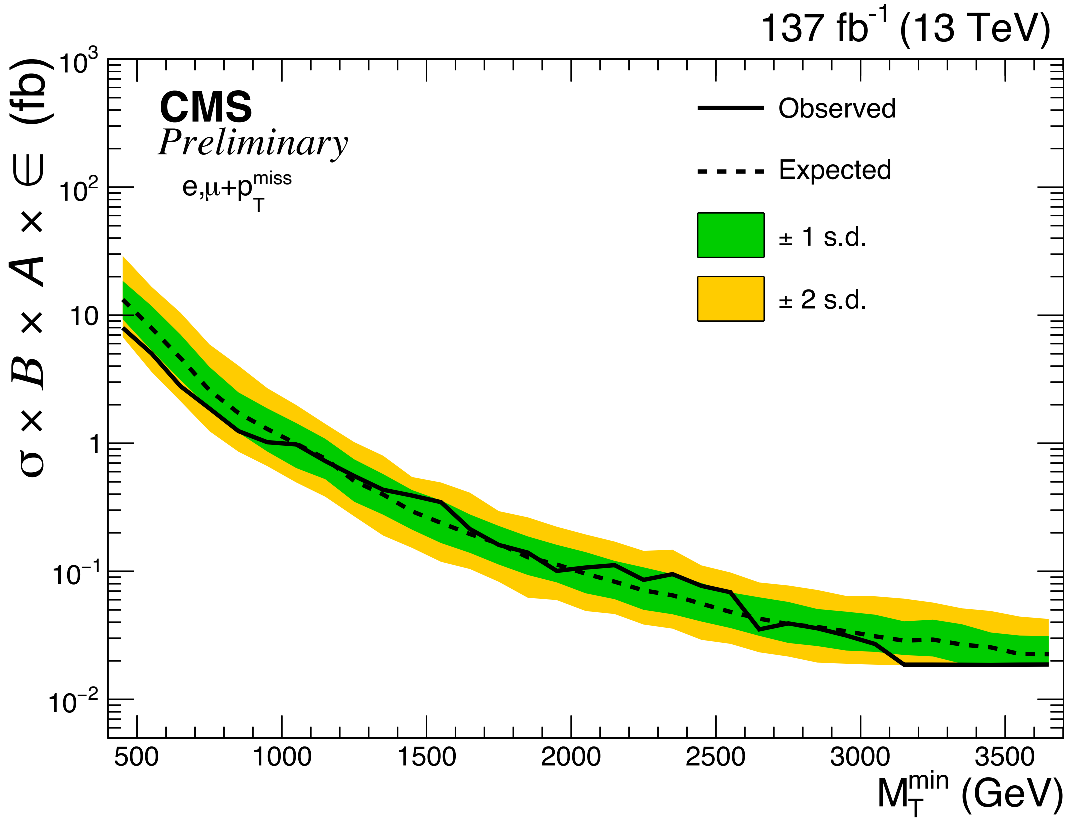
Single lepton + $\not{E}_T$







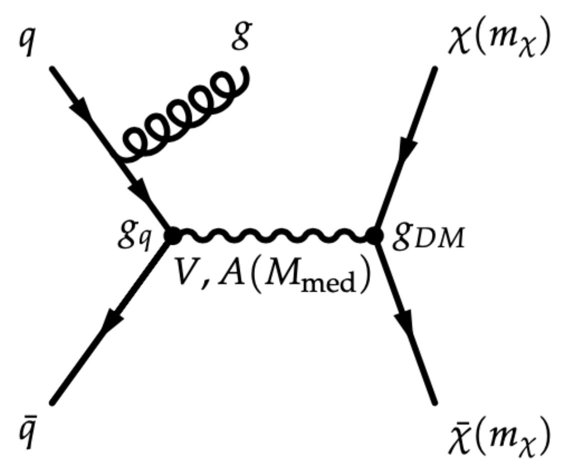




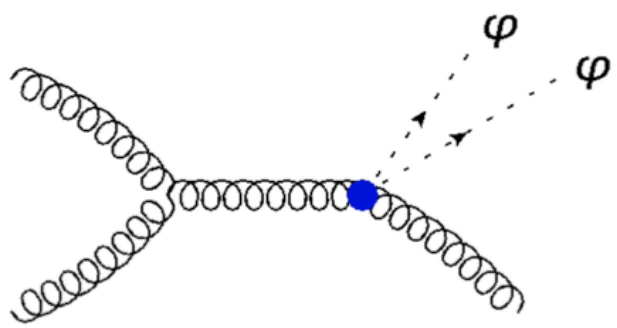
EXO-19-017

Mono-jet + E_T^{miss}

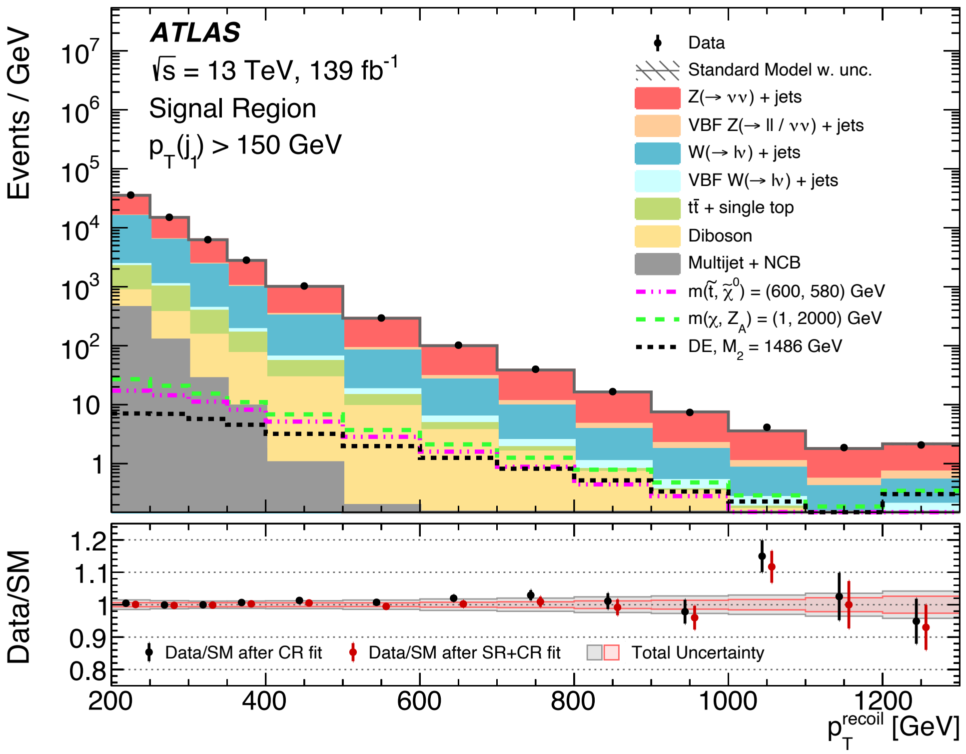
- Flagship high-pT DM search for invisible particles



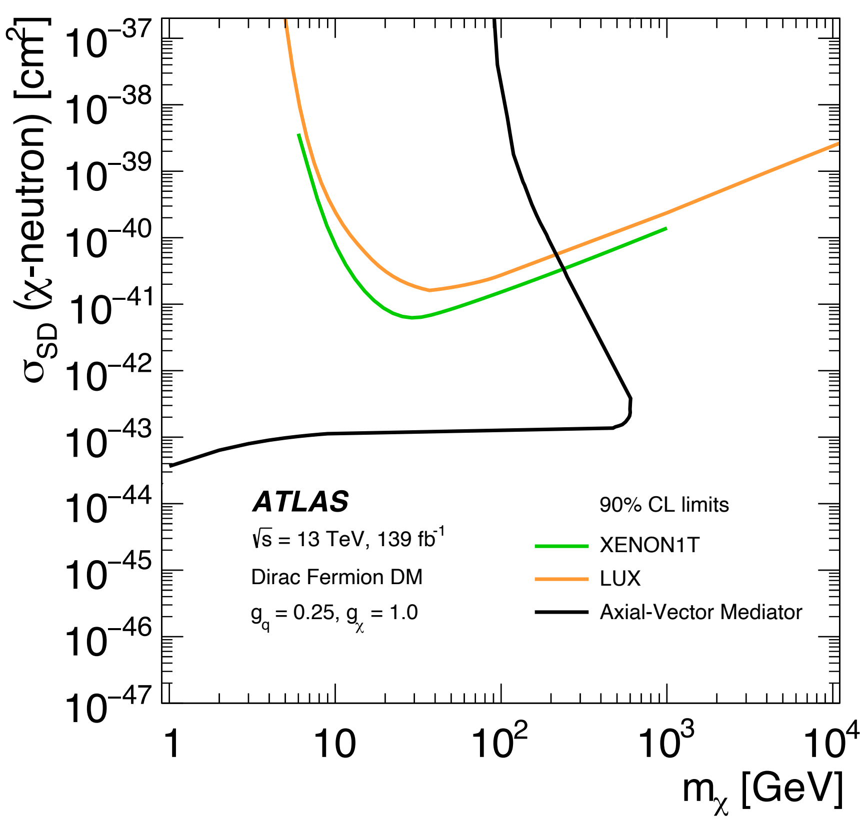
Simplified Minimal Model



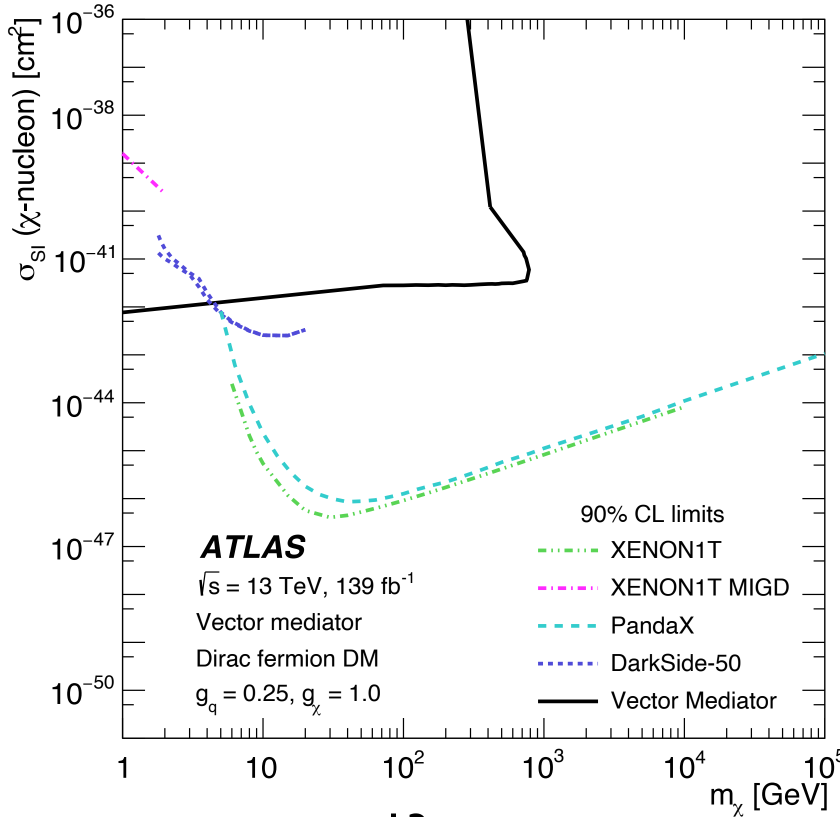
DE inspired scalar field



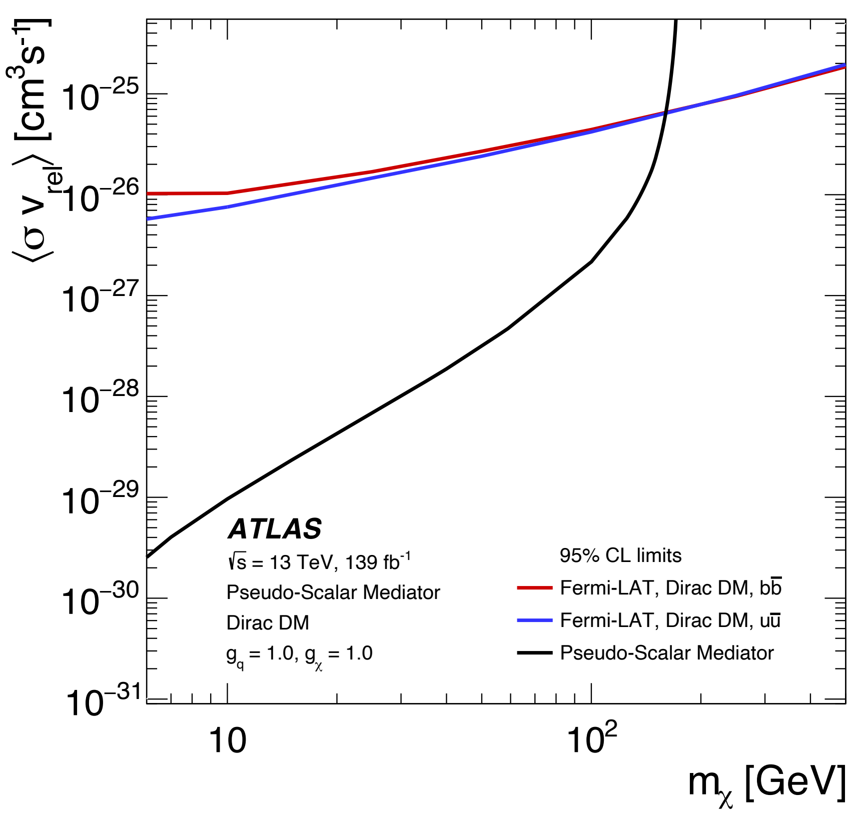
spin-dependent
Axial-Vector mediator



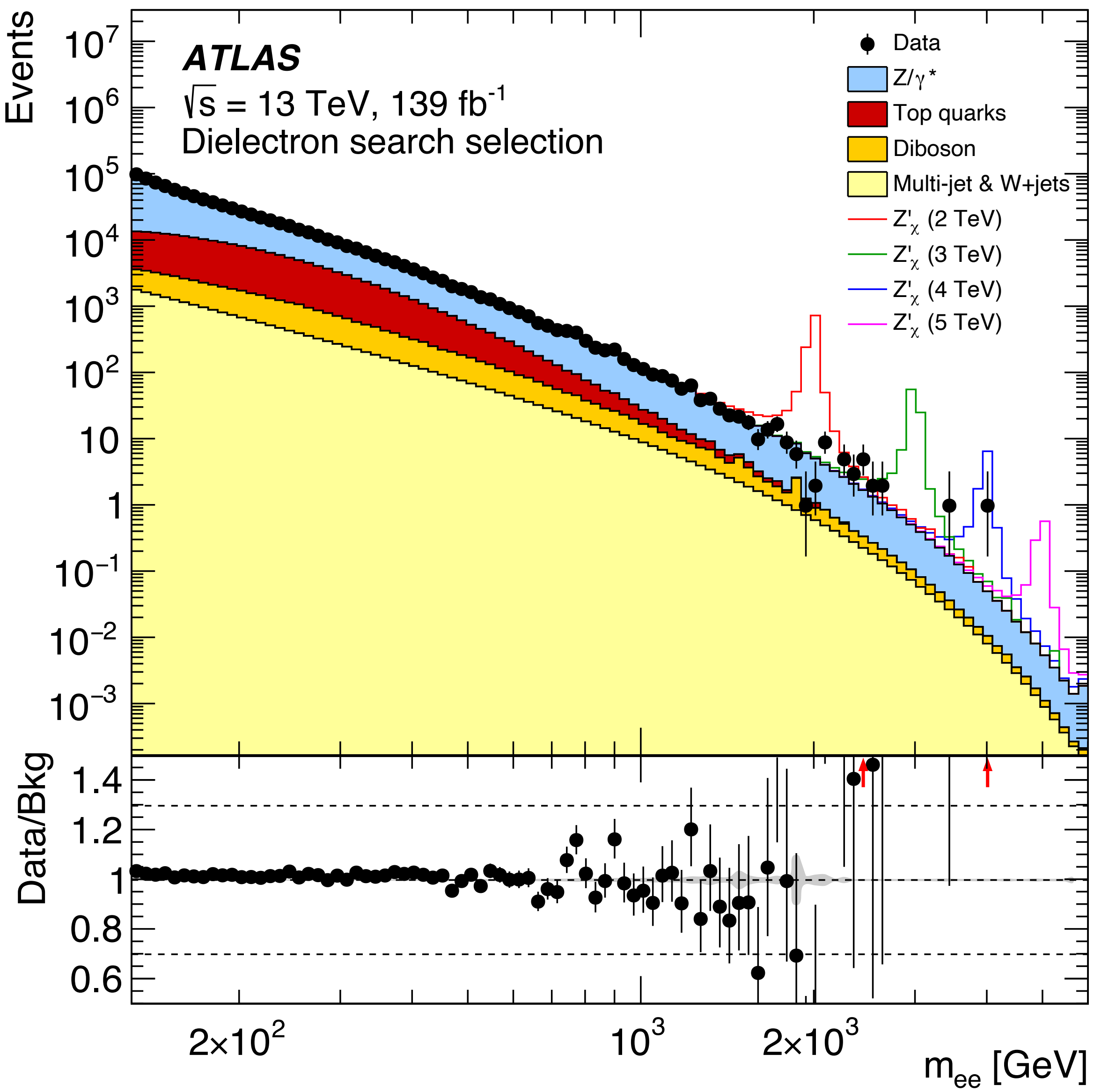
spin-independent
Vector mediator



pseudoscalar mediator



Di-lepton searches



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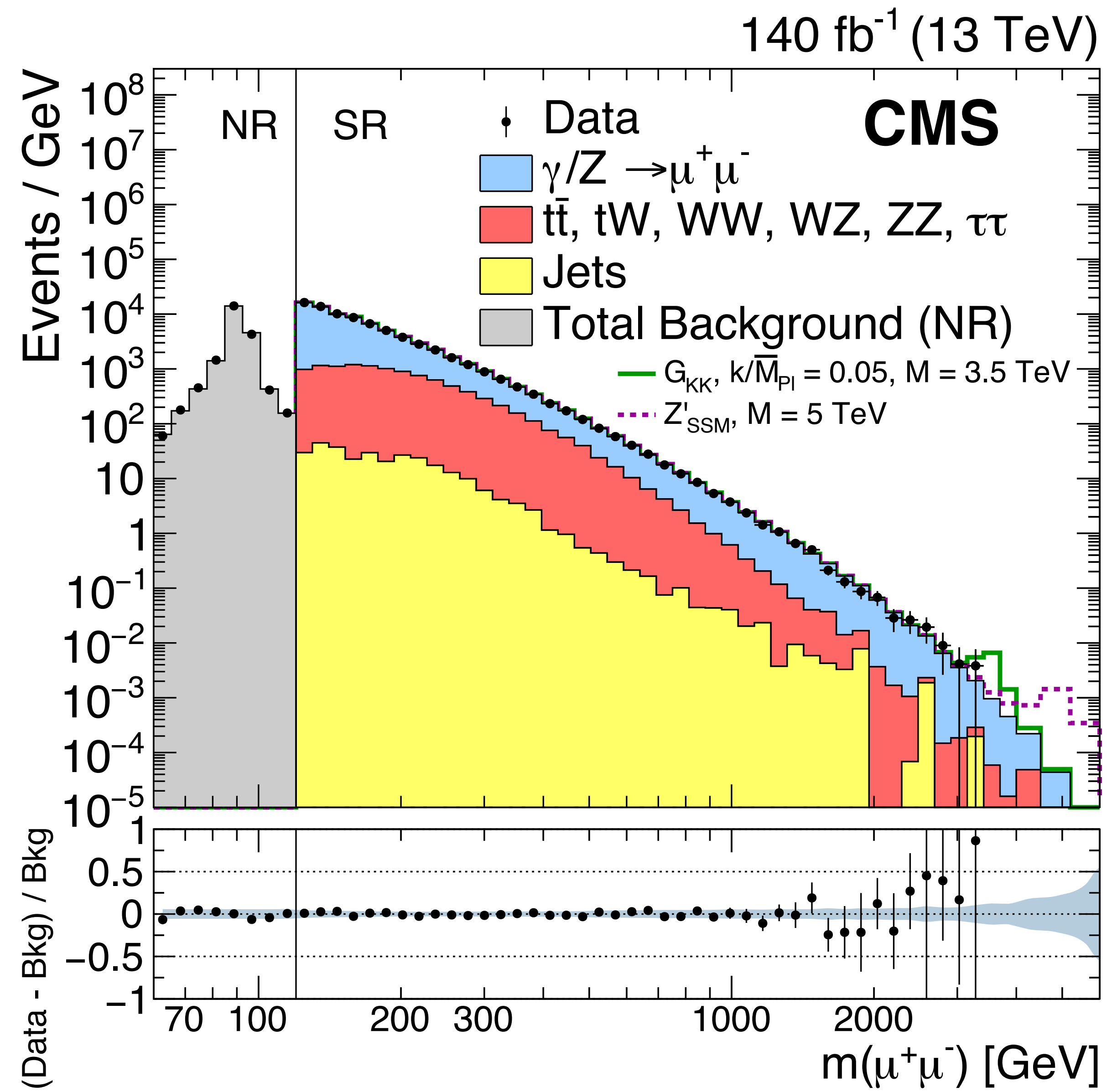
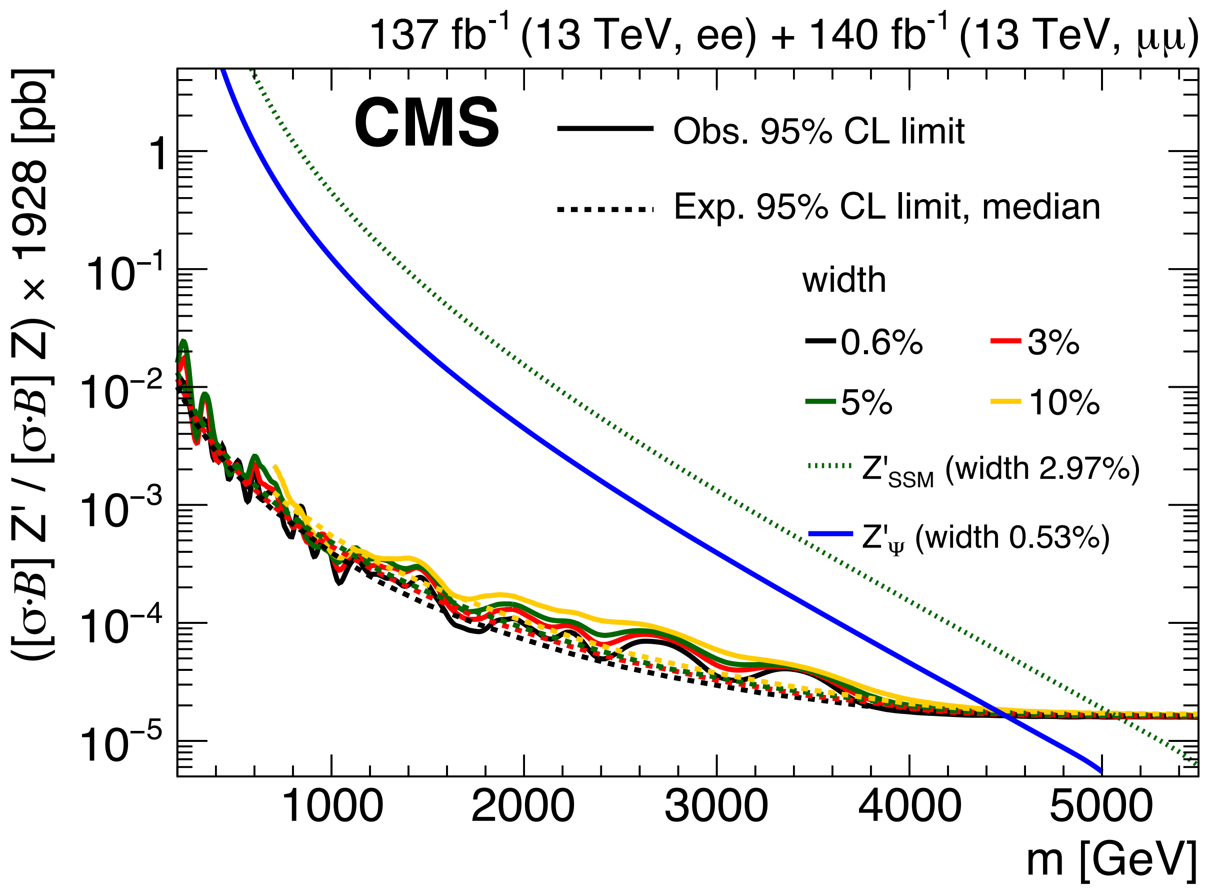
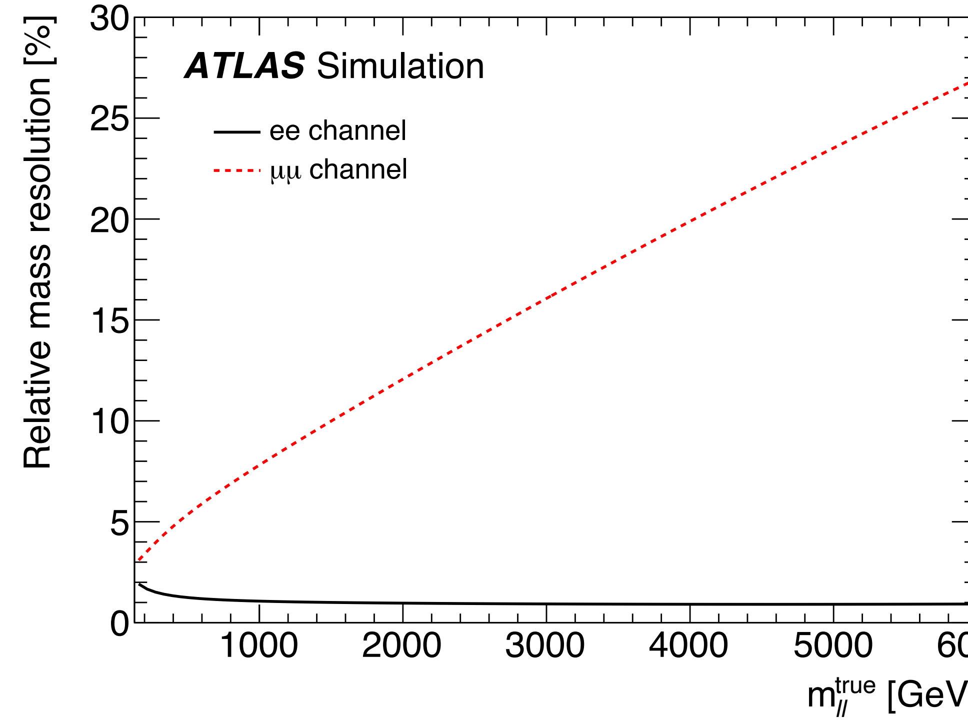


2103.02708

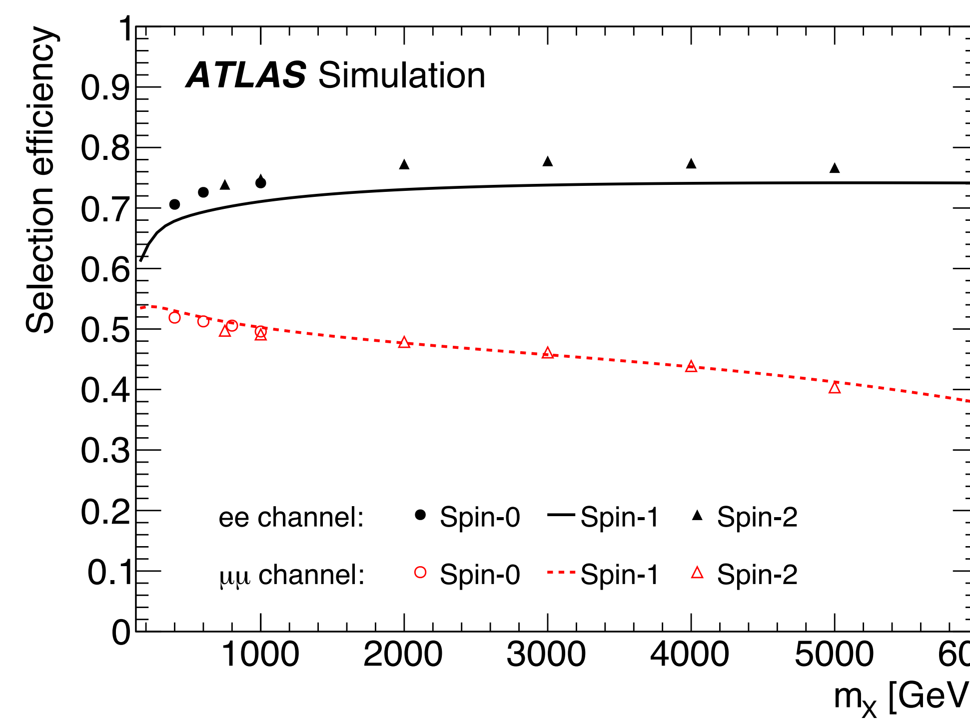
Interpretation of search results



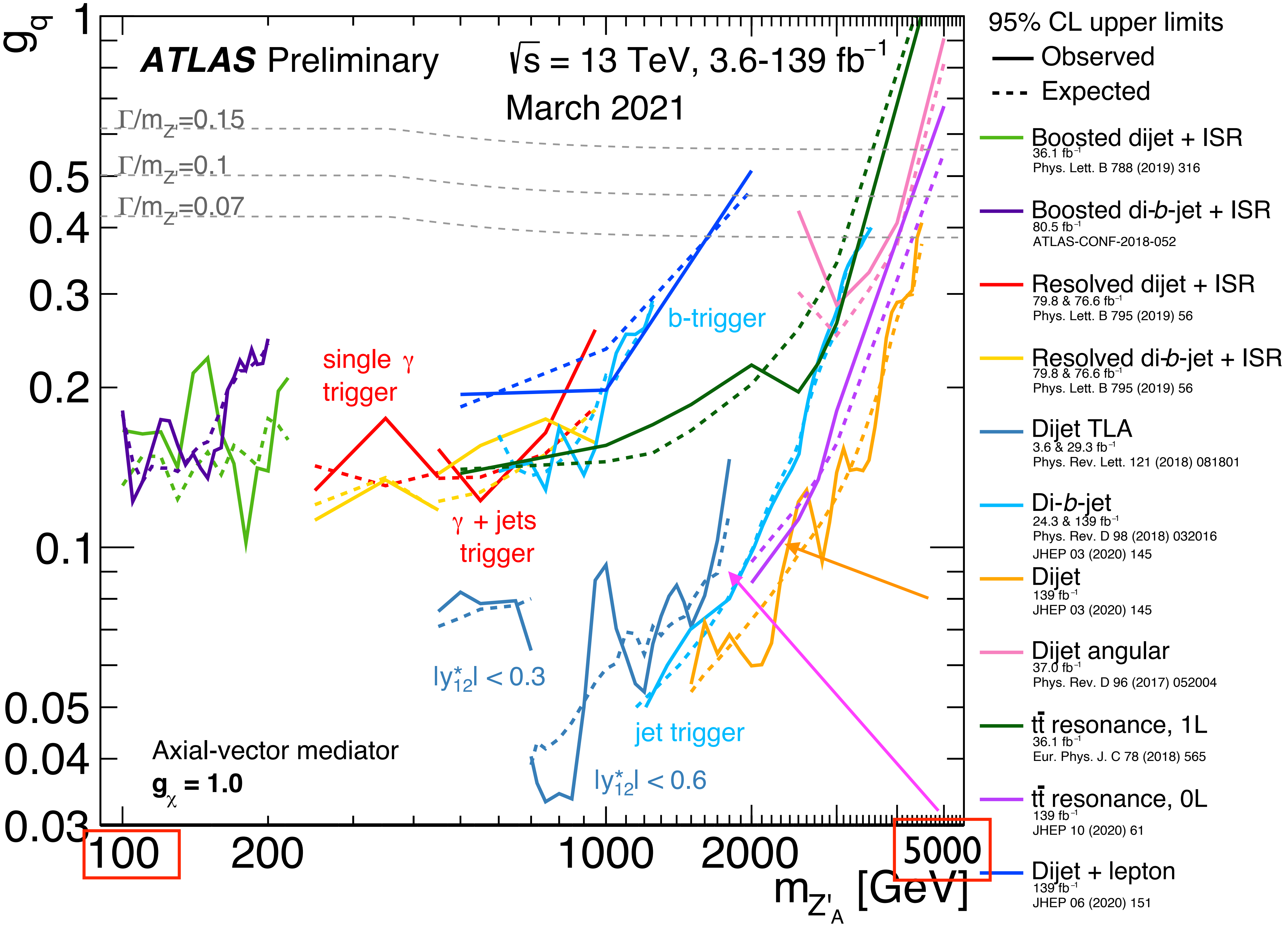


ATLAS

Model	Lower limits on $m_{Z'}$ [TeV]					
	ee		$\mu\mu$		$\ell\ell$	
	obs	exp	obs	exp	obs	exp
Z'_{ψ}	4.1	4.3	4.0	4.0	4.5	4.5
Z'_{χ}	4.6	4.6	4.2	4.2	4.8	4.8
Z'_{SSM}	4.9	4.9	4.5	4.5	5.1	5.1



Di-“jet” summary $X \to q\bar{q}/qg/gg/b\bar{b}/t\bar{t}$



Creative trigger strategy is a must → See Elena Villhauer’s talk on how ATLAS can keep improving L1-jet trigger in Run-3

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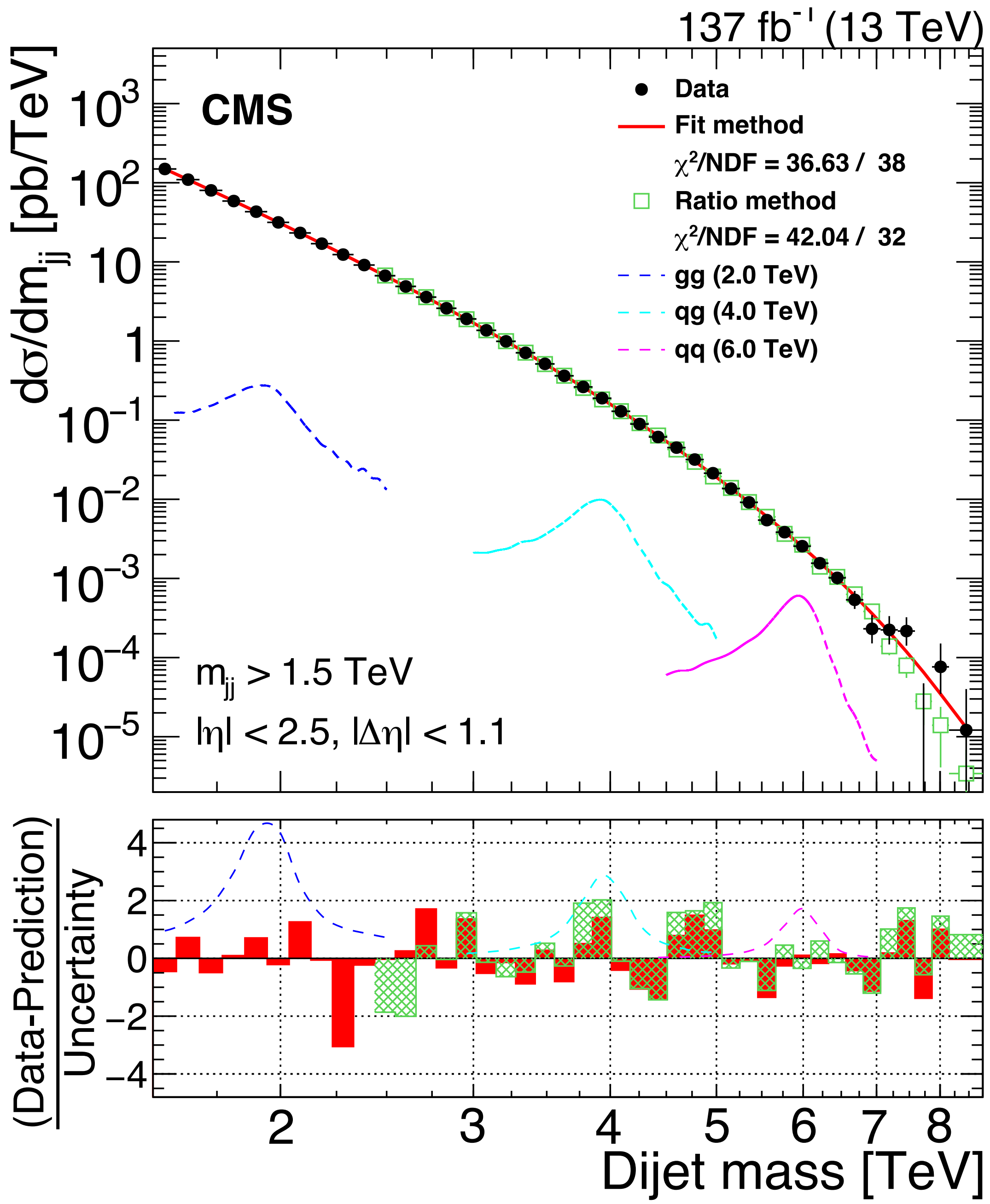
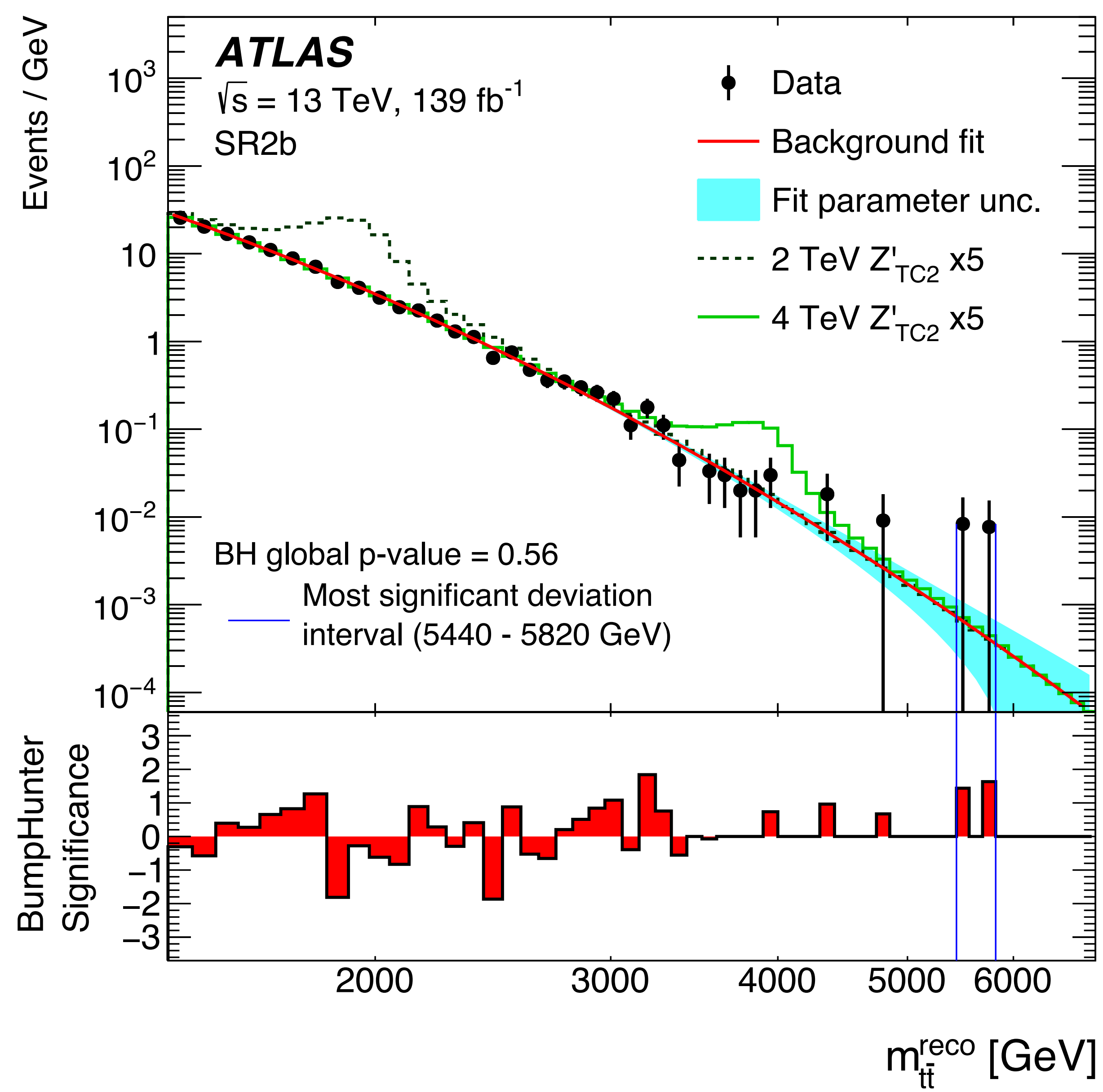
Two examples of di-“jet” searches

$pp \rightarrow X \rightarrow q\bar{q}/gg/qg$



JHEP 05 (2020) 033

$pp \rightarrow X \rightarrow t\bar{t}(\mathrm{all-had})$



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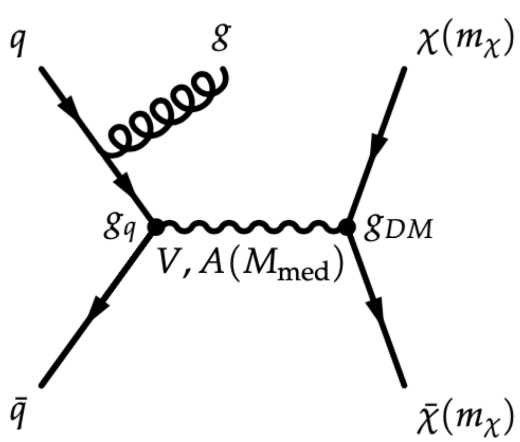
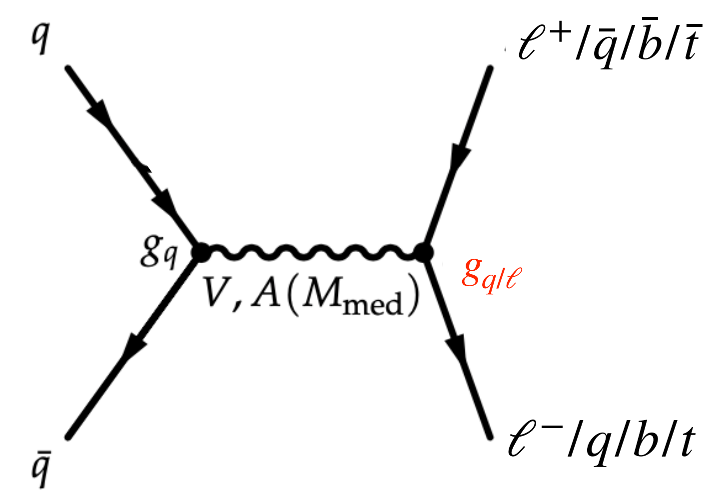
Dilepton and Dijet implications on DM searches

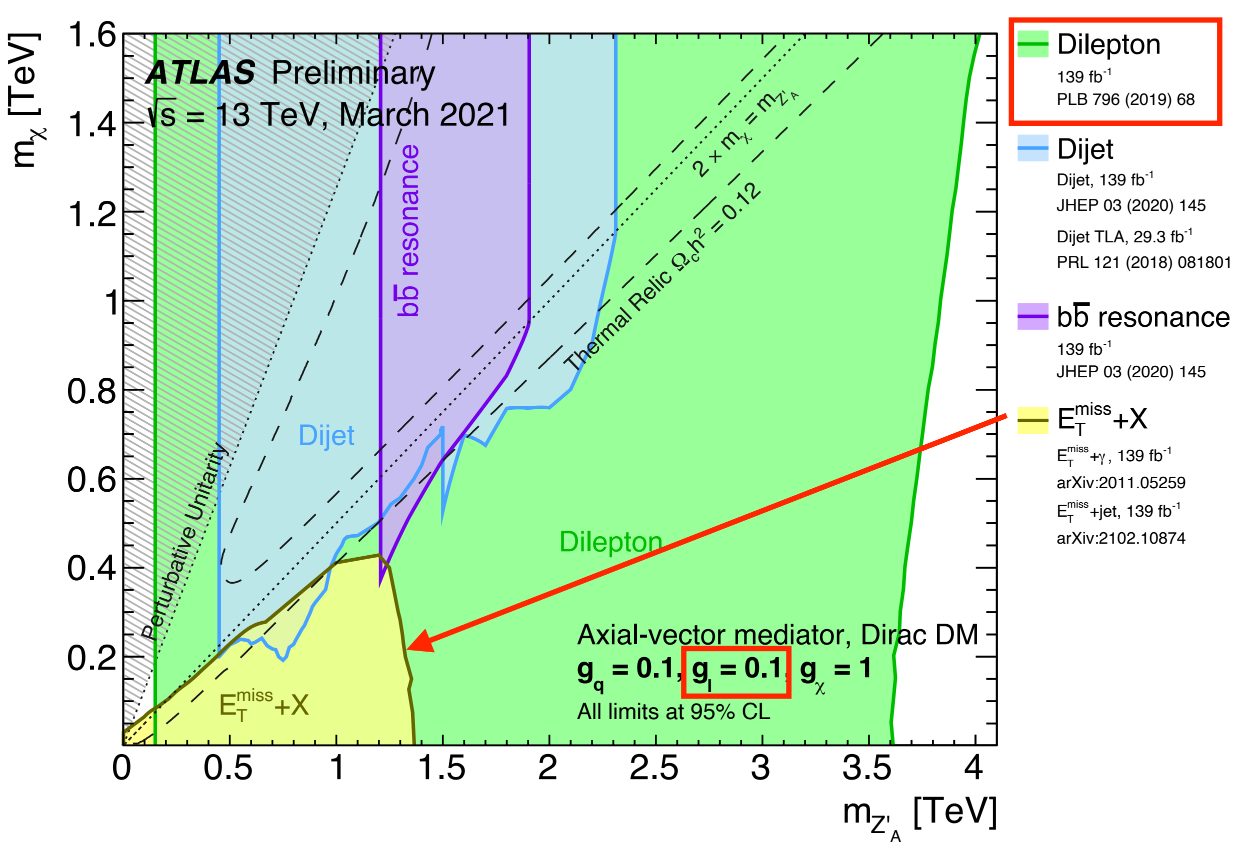
$\not{E}_T + X$

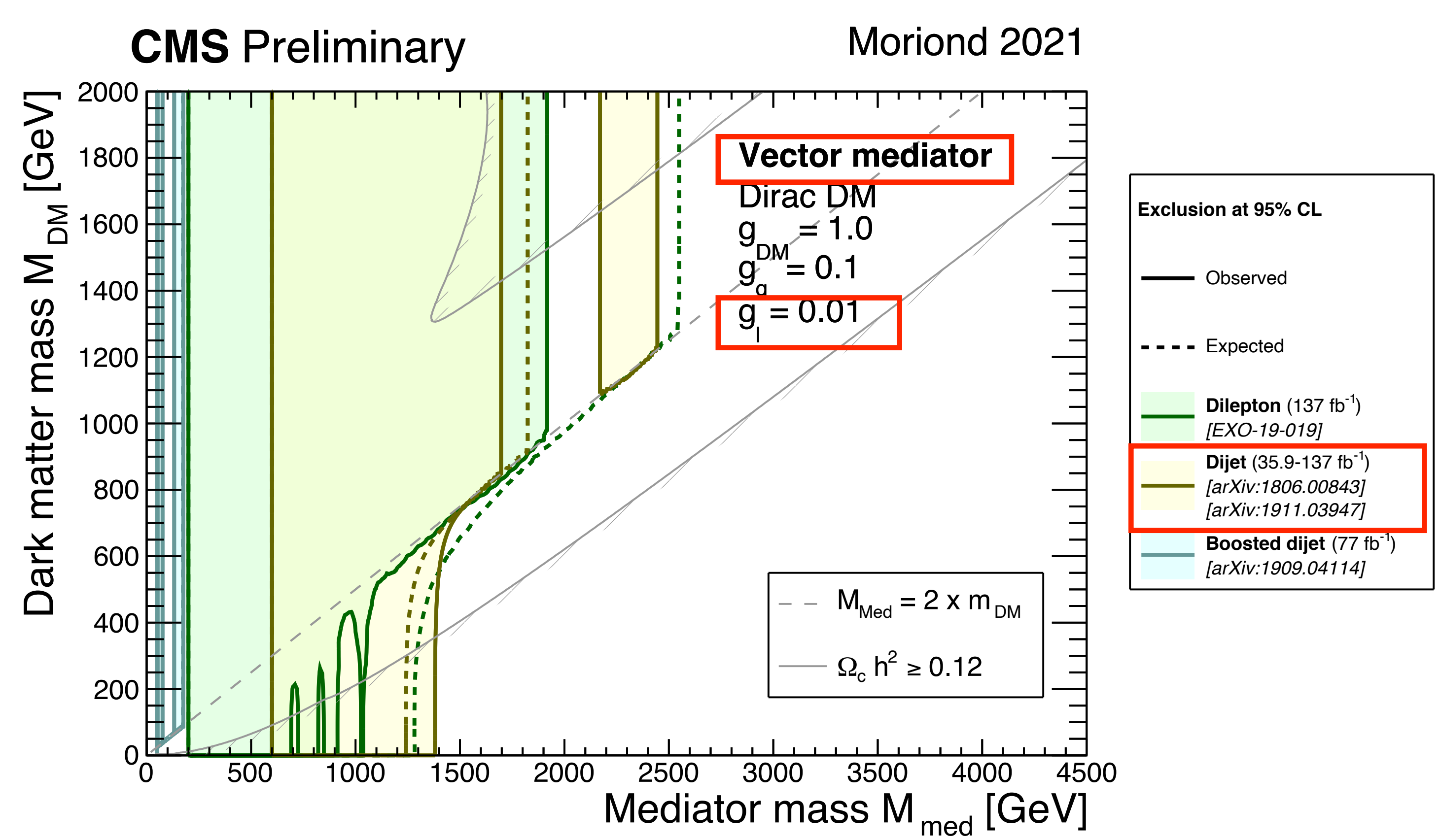


+

no intrinsic $\not{E}_T$: dilepton/dijet







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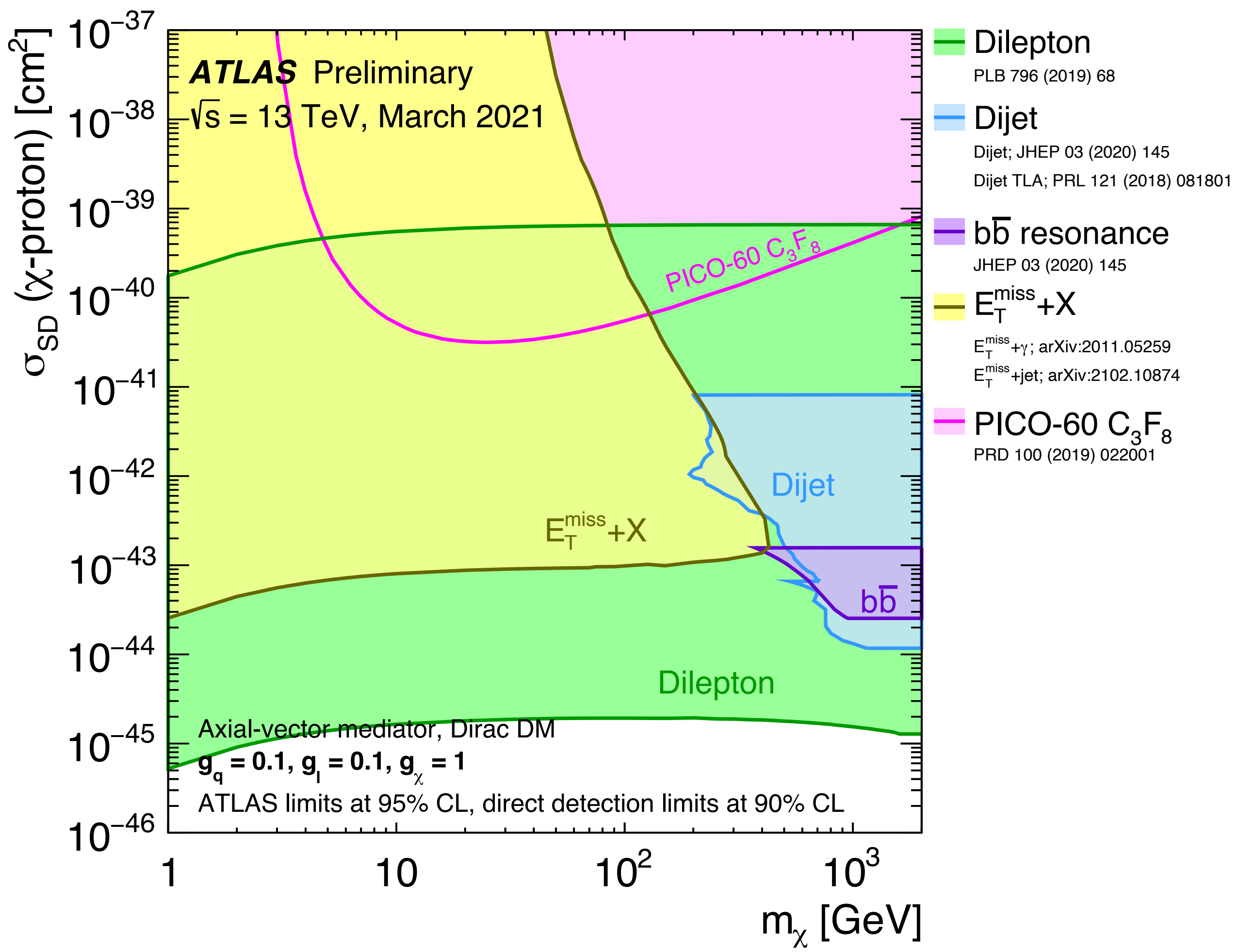
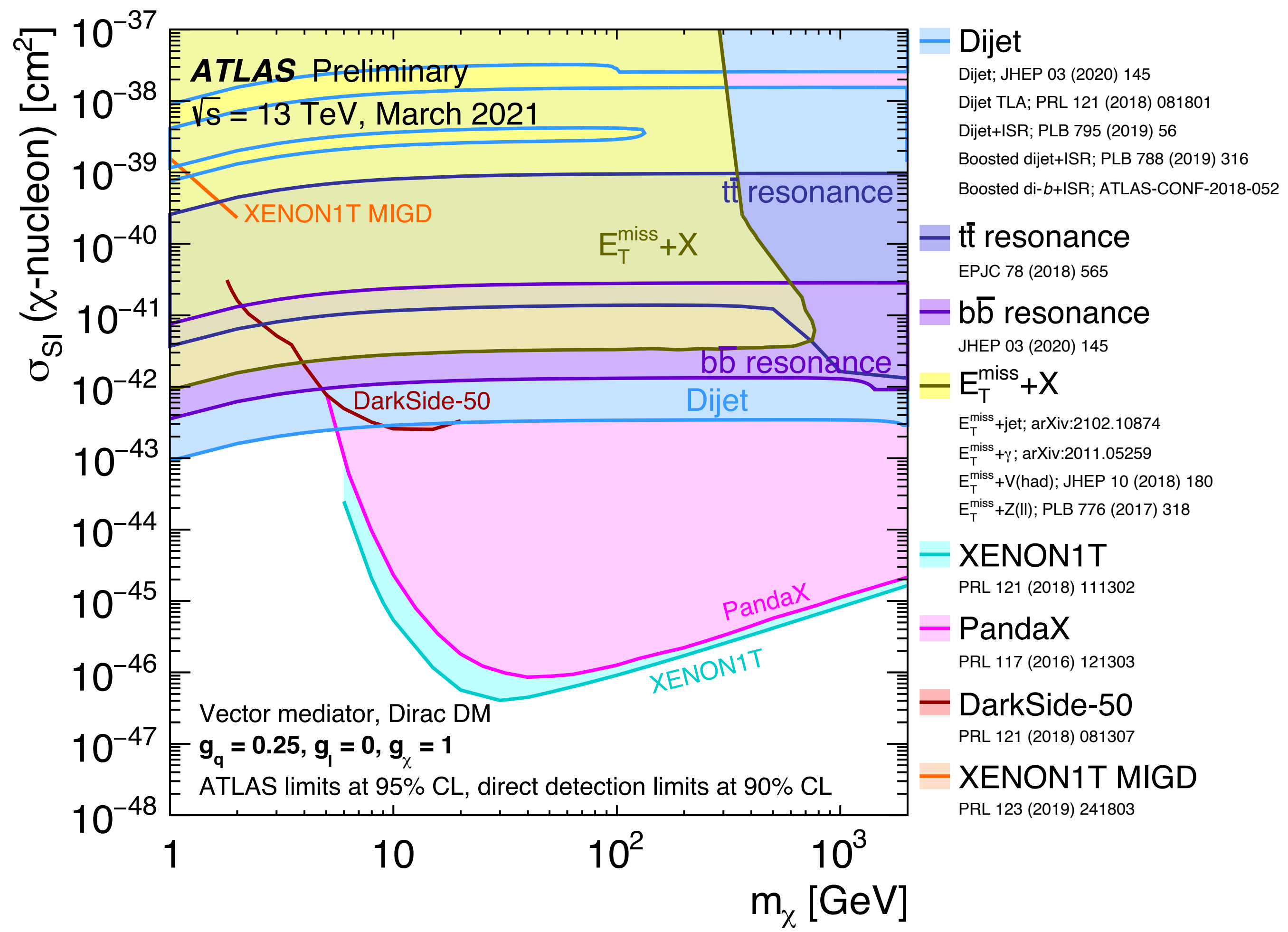
CMS EXO Summary

LHC DM searches vs non-Collider approaches

Spin-dependent
Universal fermion coupling



Spin-independent
Lepotonphobic couplings



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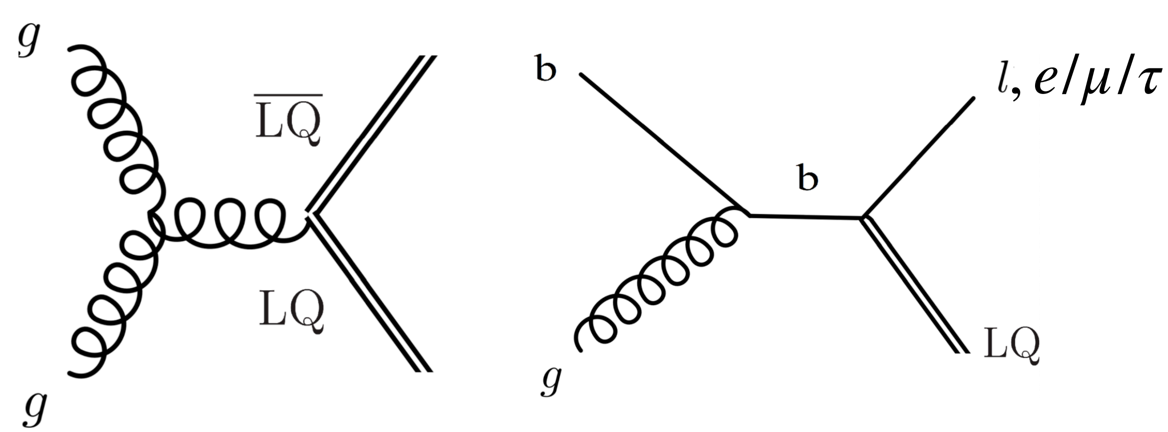
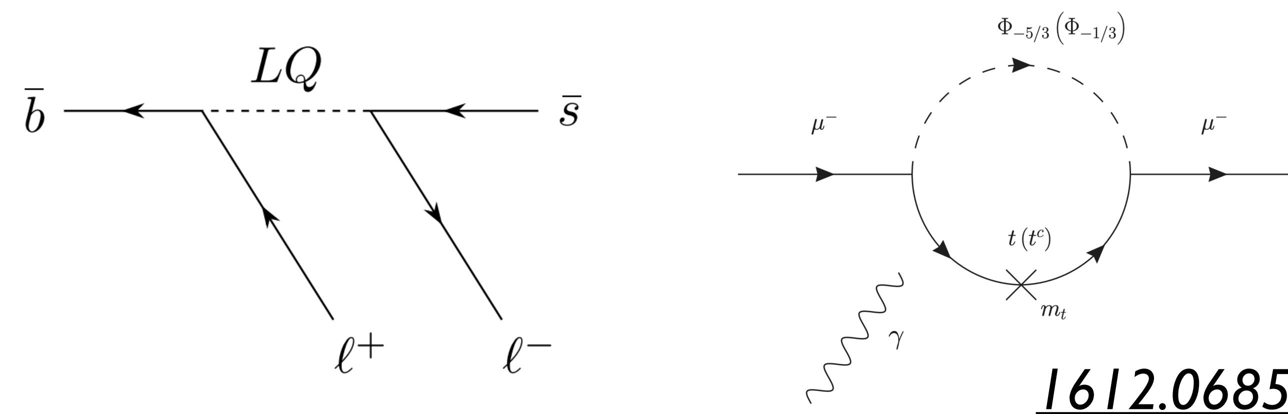
Lepto-quark searches

Productions at the LHC



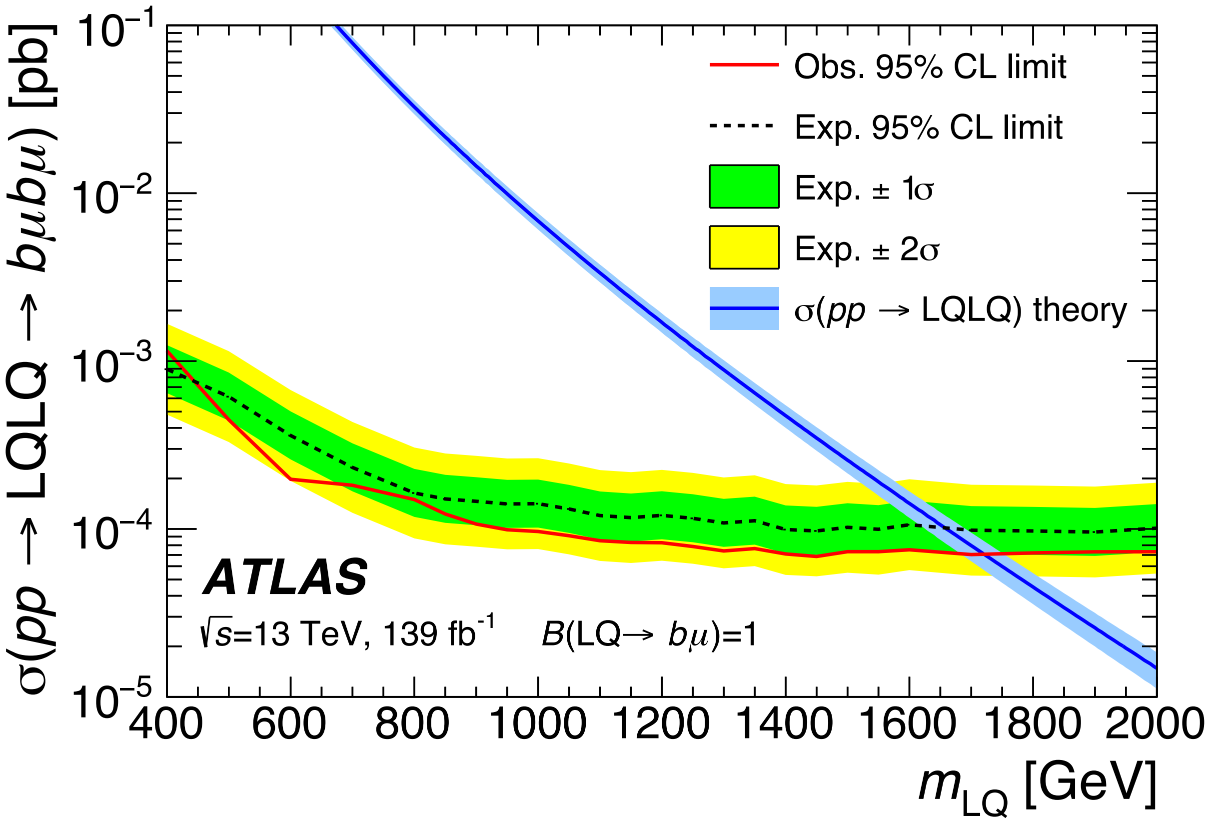
Potential contributions to anomalies



1612.06858

Two latest results focusing on third-generation fermion LQ

$\mathscr{B}(\mathrm{LQ_S} \to b\mu) = 100\,\%$



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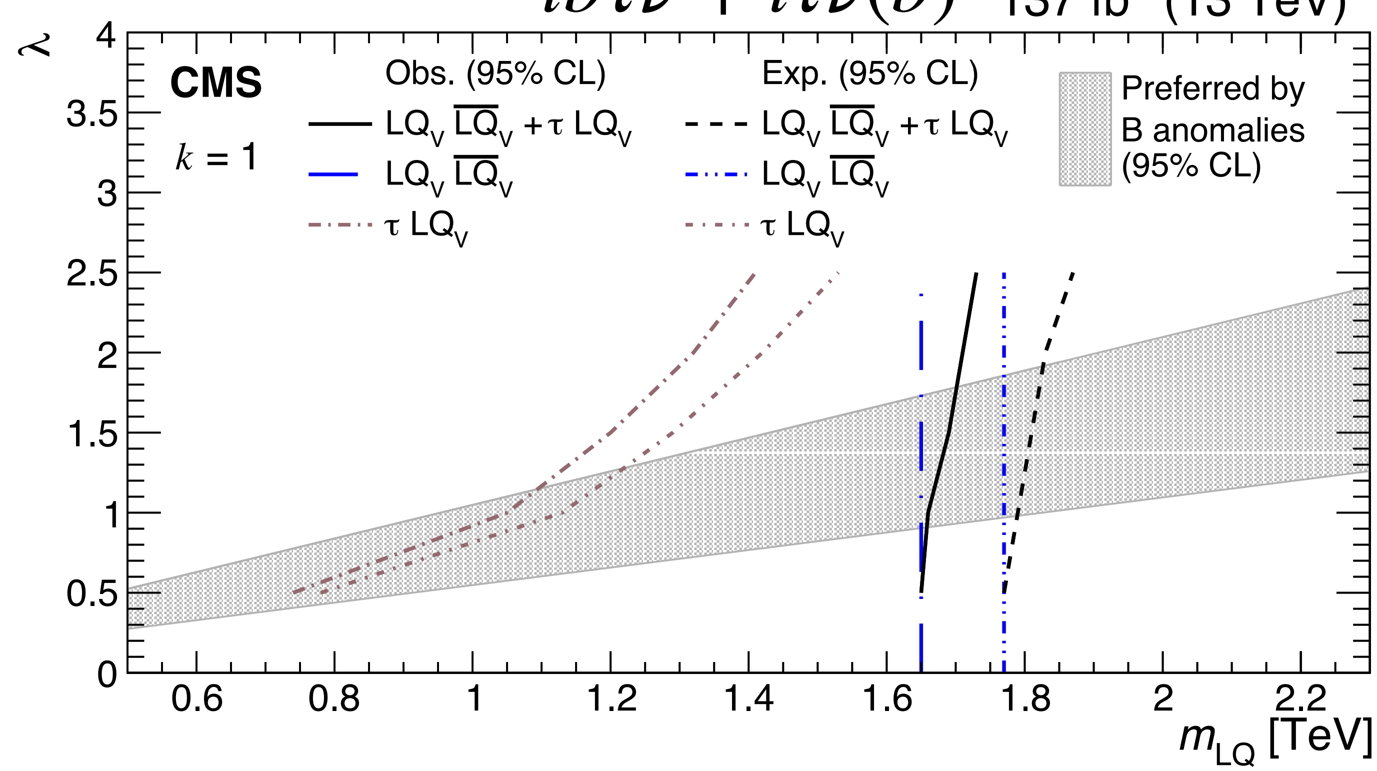
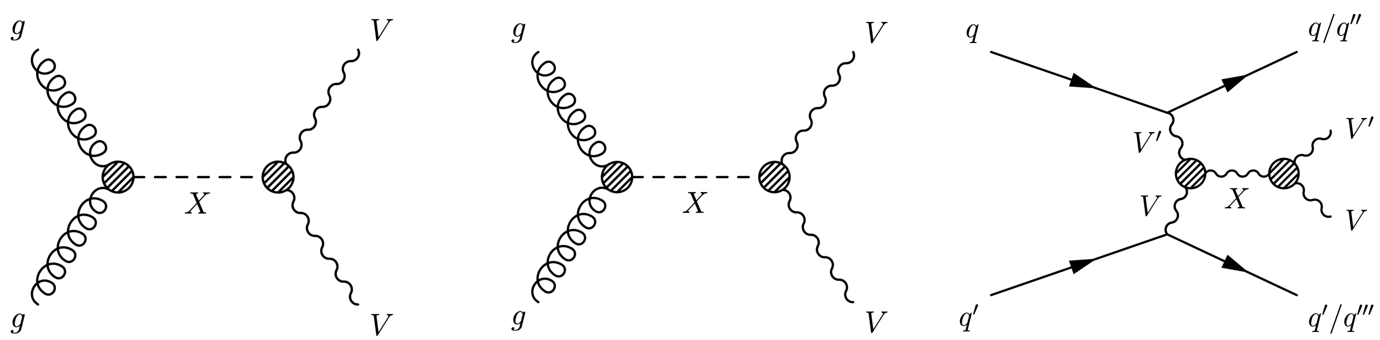
$tb\tau\nu + t\tau\nu(b)$ 137 fb^{-1} (13 TeV)

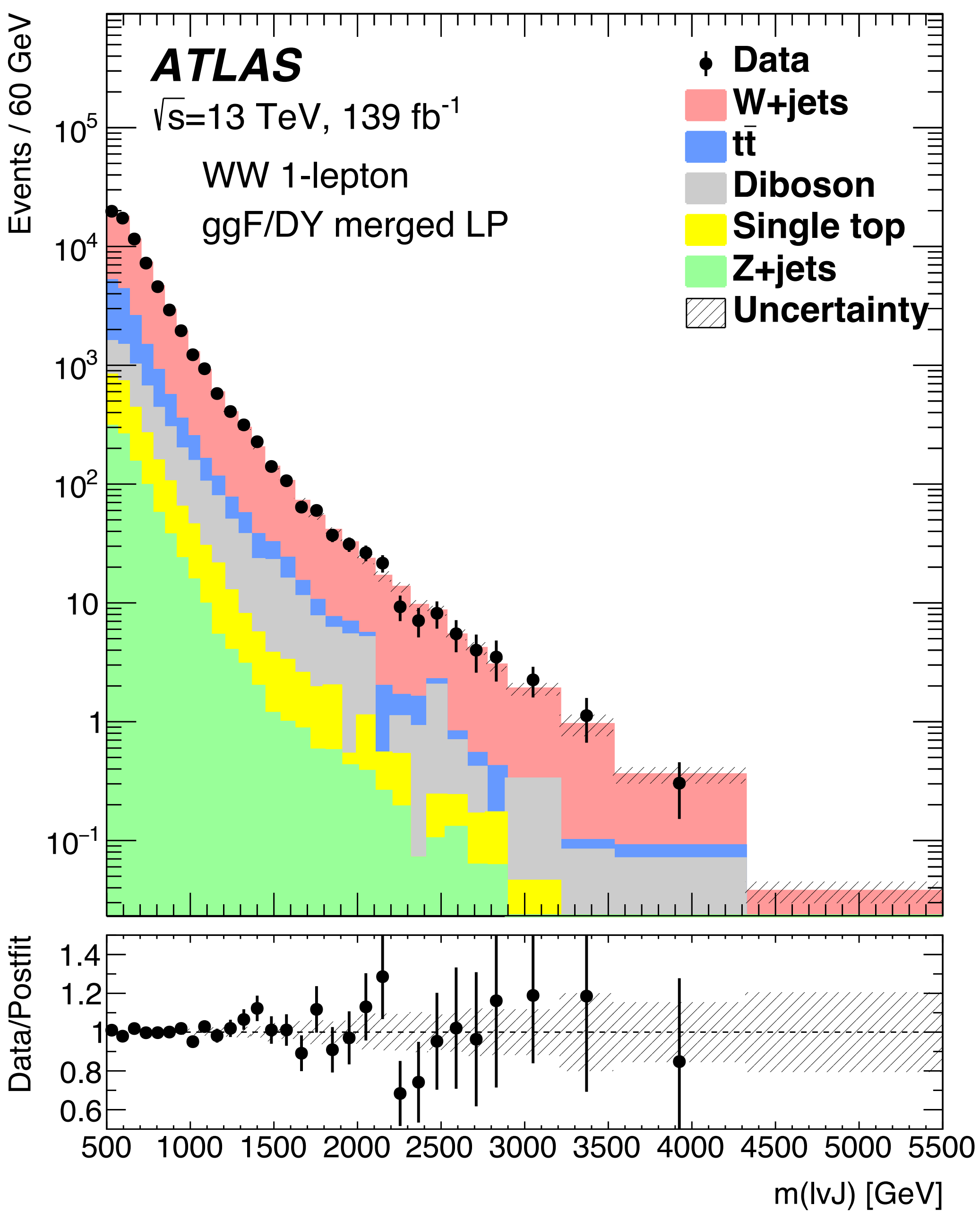


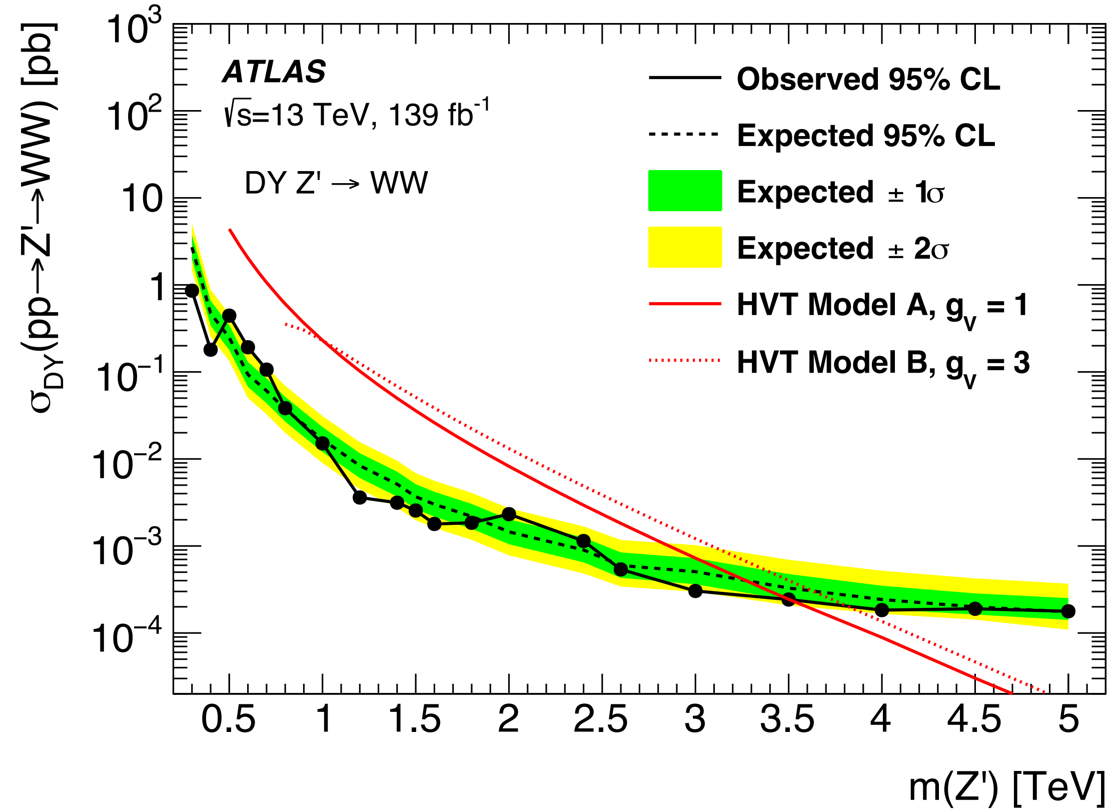
$\mathrm{LQ_V(LQ_S)} \to t\tau(t\nu)$ $\mathrm{LQ_V(LQ_S)} \to b\nu(b\tau)$

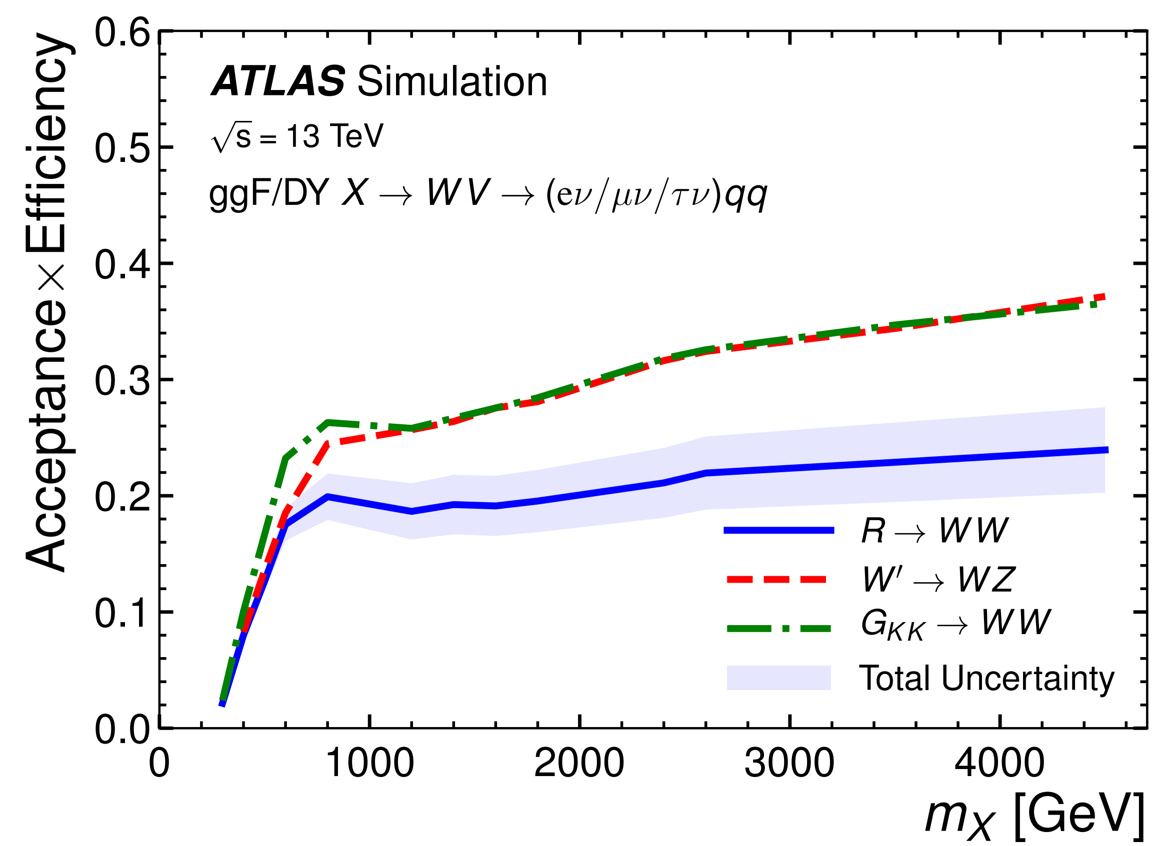
2012.04178

Diboson searches





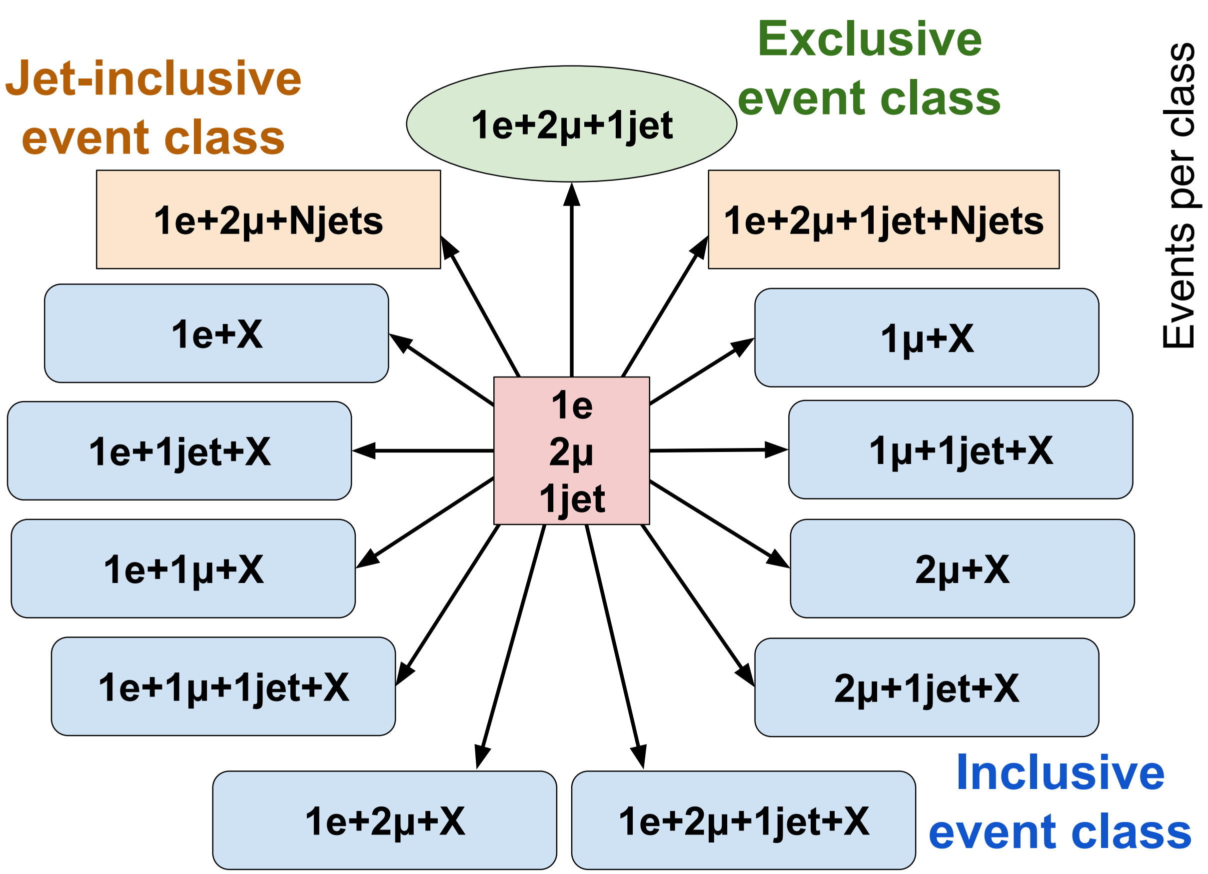


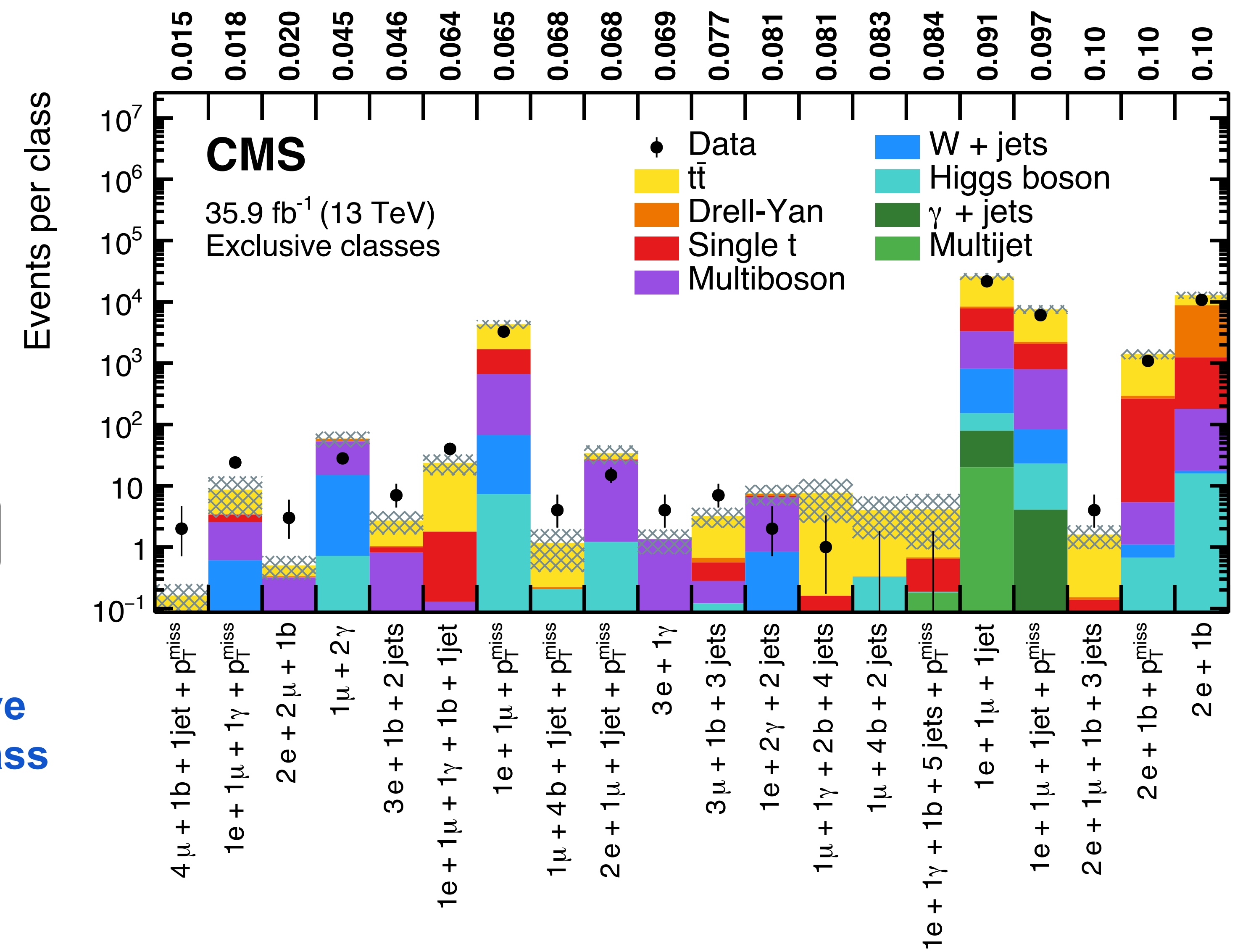


2004.14636

Model Unspecific Search in CMS (MUSiC)

Input: several hundred final states and multiple kinematic distributions





2010.02984

Supersymmetry

General remark on SUSY searches

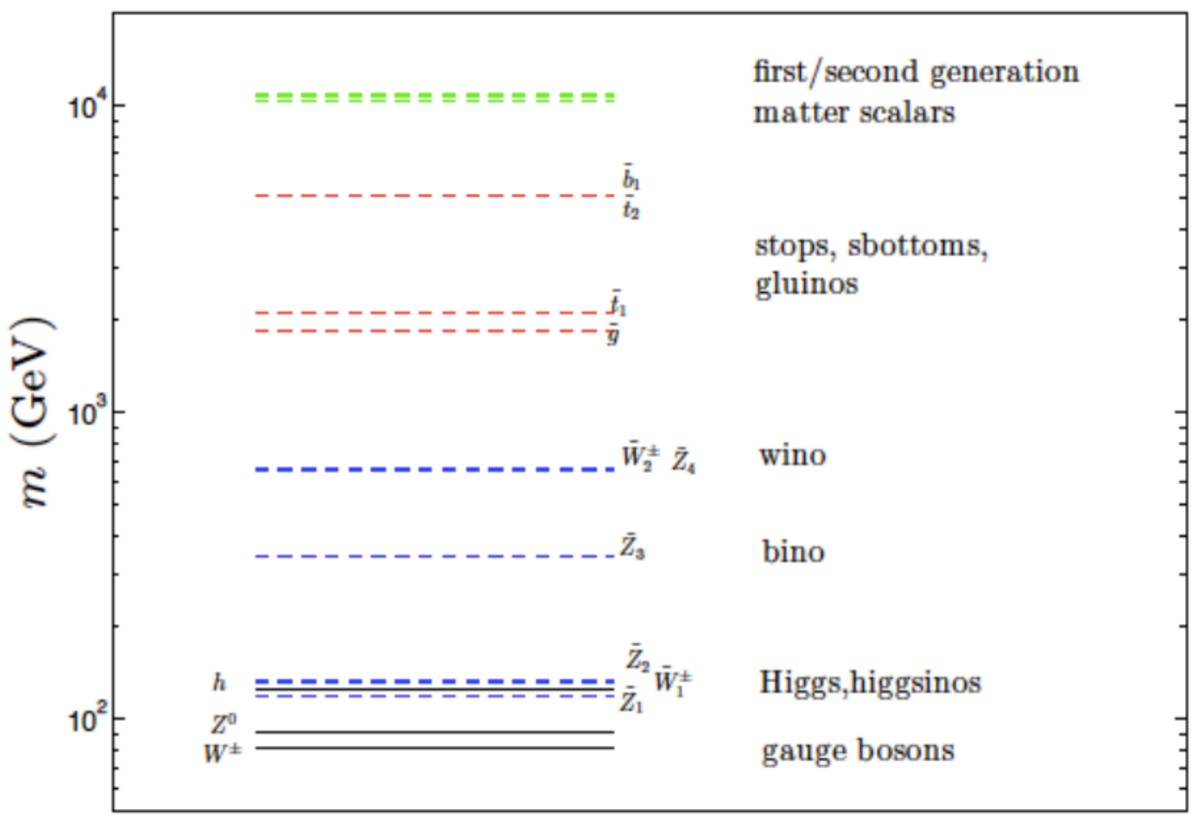
- One of the long-term favourite of both theorists and experimentalists
  - Elegant solution to hierarchy problem, stabilising the Higgs boson mass
  - DM candidates in R-parity violation scenarios
  - Gauge coupling unifications

M. Carena, SUSY 2014

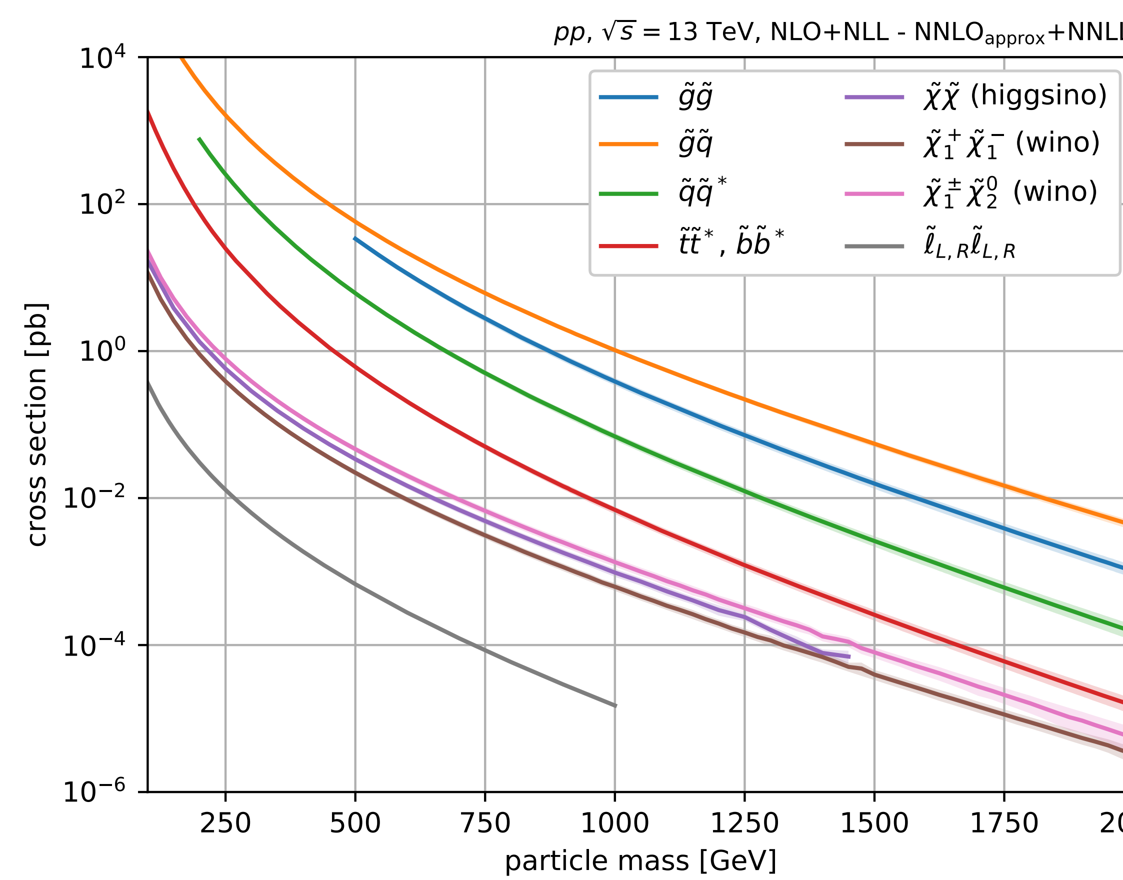
If $M_{SUSY} \sim M_{weak}$ ⟶ Natural SUSY
If $M_{SUSY} \ll M_{GUT}$ ⟶ big hierarchy problem solved

- No SUSY particles seen yet at the LHC ⇒ a blow to the much hoped favoured "natural" region
  - SUSY breaking varies → wide range of predictions on signal parameters at EWK
  - There is no rigours definition of naturalness ⇒ **SUSY searches continue, and more creatively!**

Typical spectrum for low Δ_{EW} models

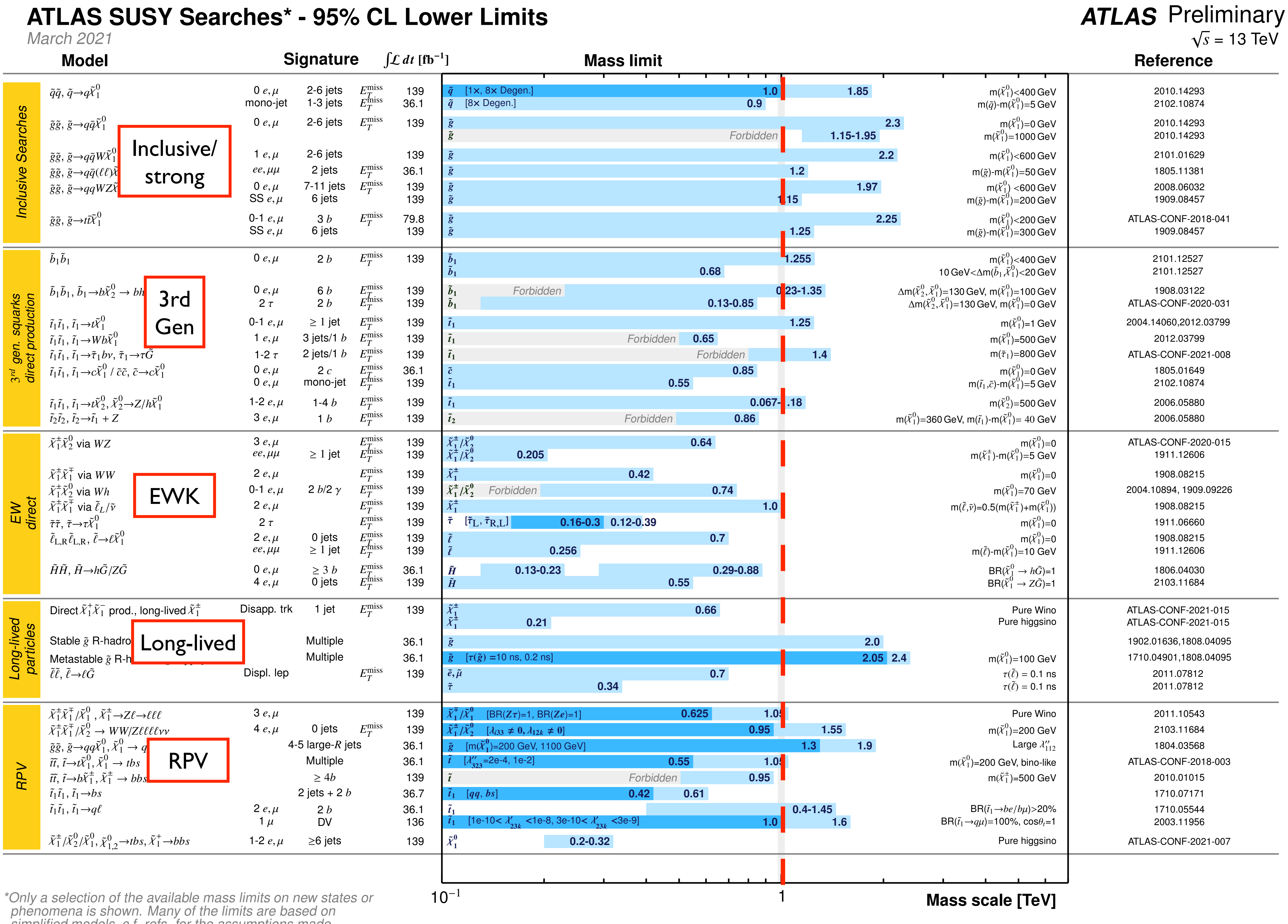


H. Baer, FNAL HL/HE-LHC workshop



LHC SUSY Cross-section Working group

A snapshot of search summary



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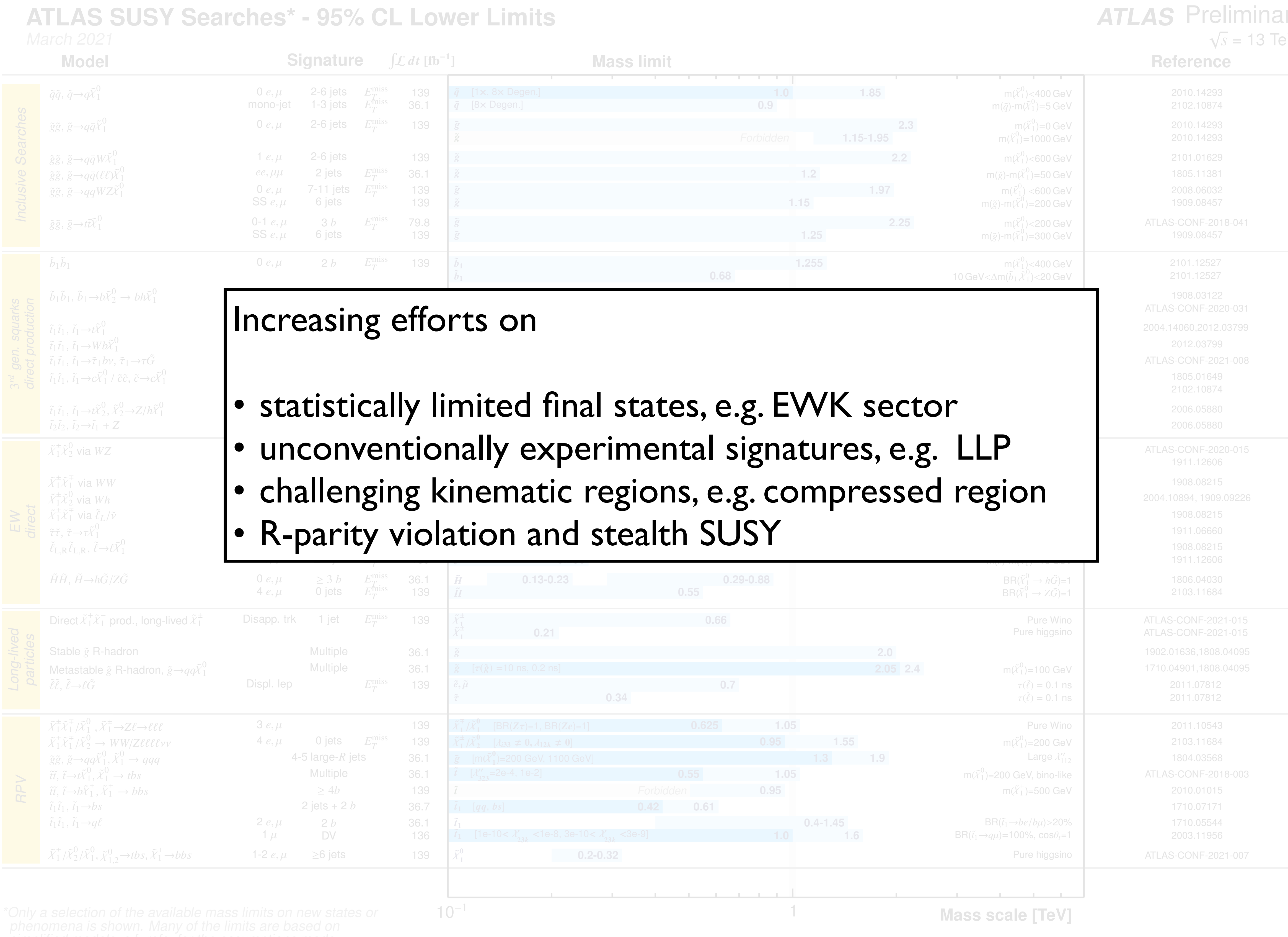
A snapshot of search summary

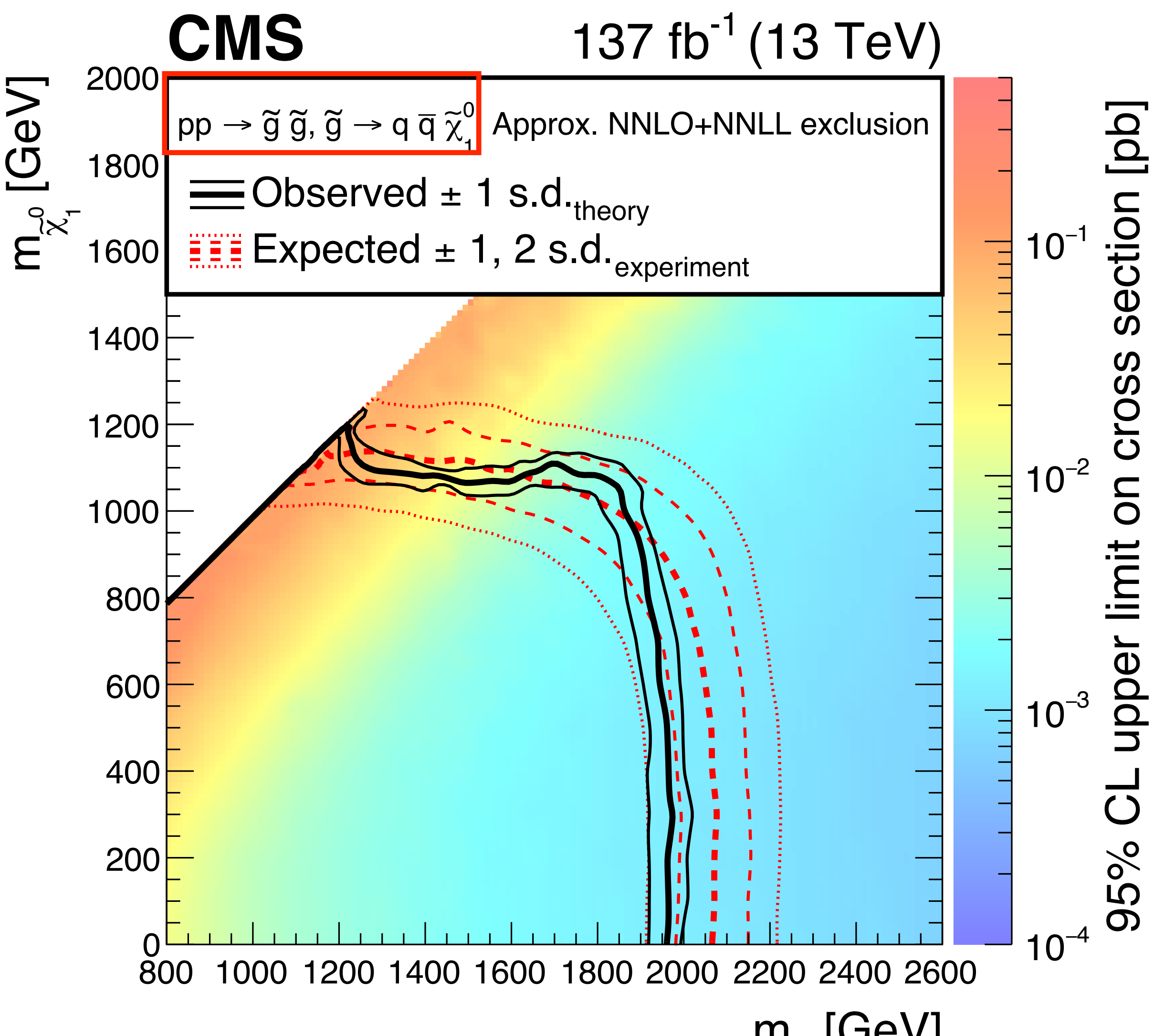


Increasing efforts on

- statistically limited final states, e.g. EWK sector
- unconventionally experimental signatures, e.g. LLP
- challenging kinematic regions, e.g. compressed region
- R-parity violation and stealth SUSY

General remarks on SUSY results

- Typical result: exclusion limits as functions of two masses
  - Strong assumptions on the remaining signal parameters
  - Extra information, e.g. efficiencies in signal regions, are provided to allow for re-interpretation
- Interpretations in many different signal models, even beyond SUSY



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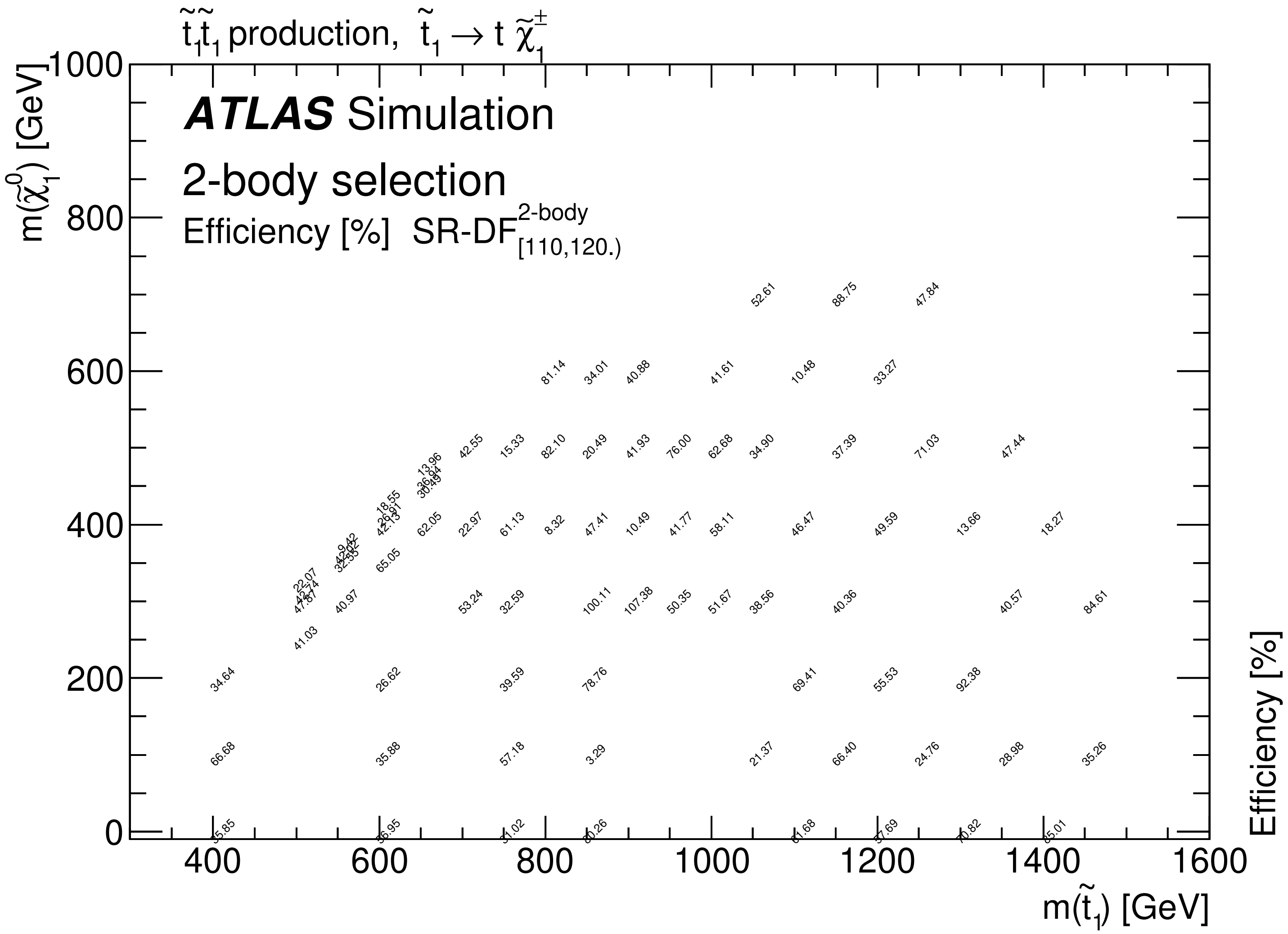
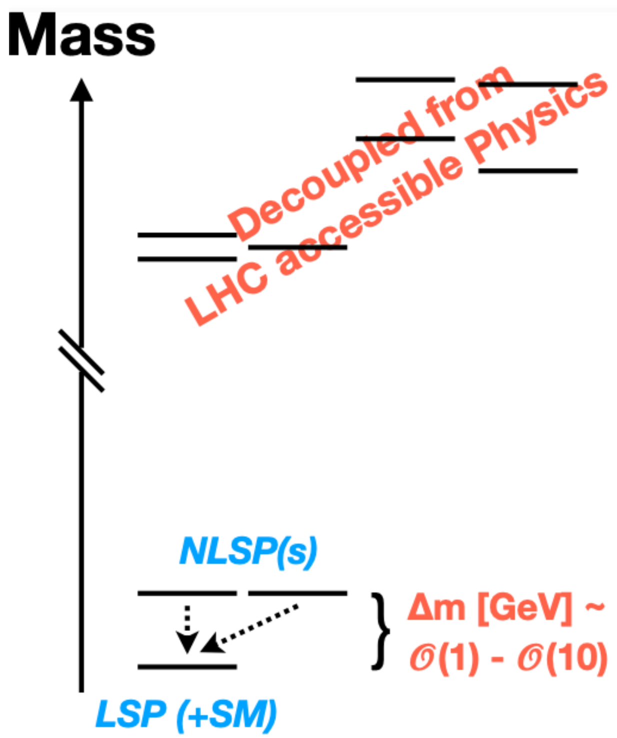


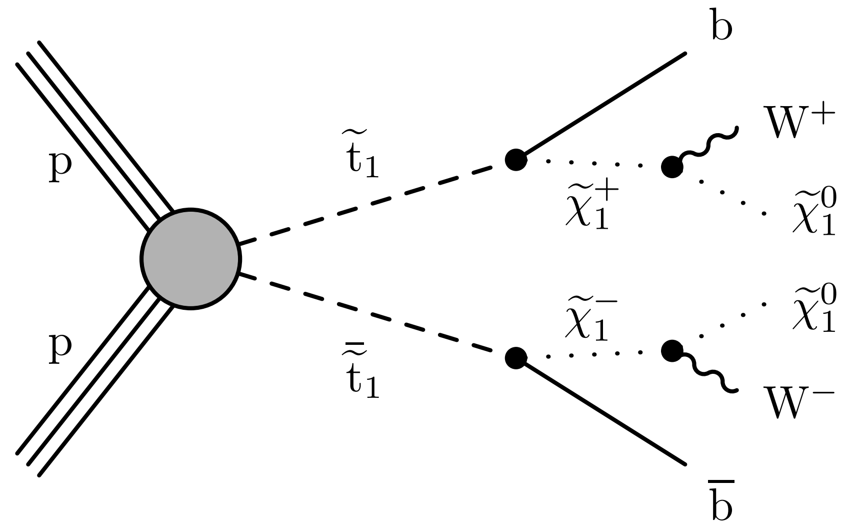
2102.01444

Compressed Region - $\tilde{t}$ in the top corridor



top corridor region

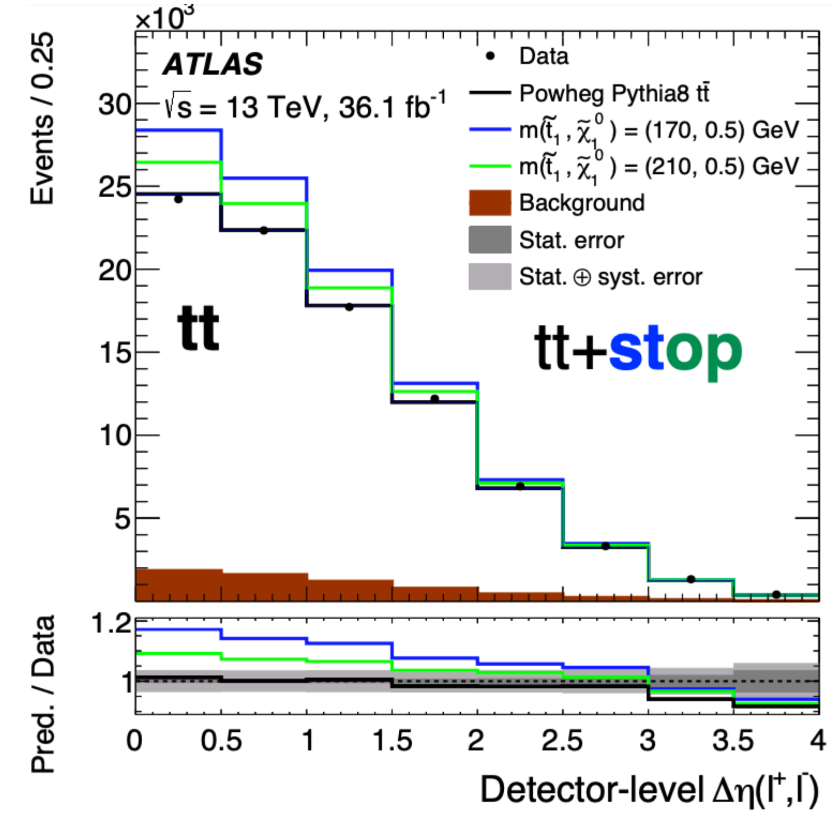
$$m(\tilde{t}) - m(t) \sim m(\tilde{\chi}_1^0)$$

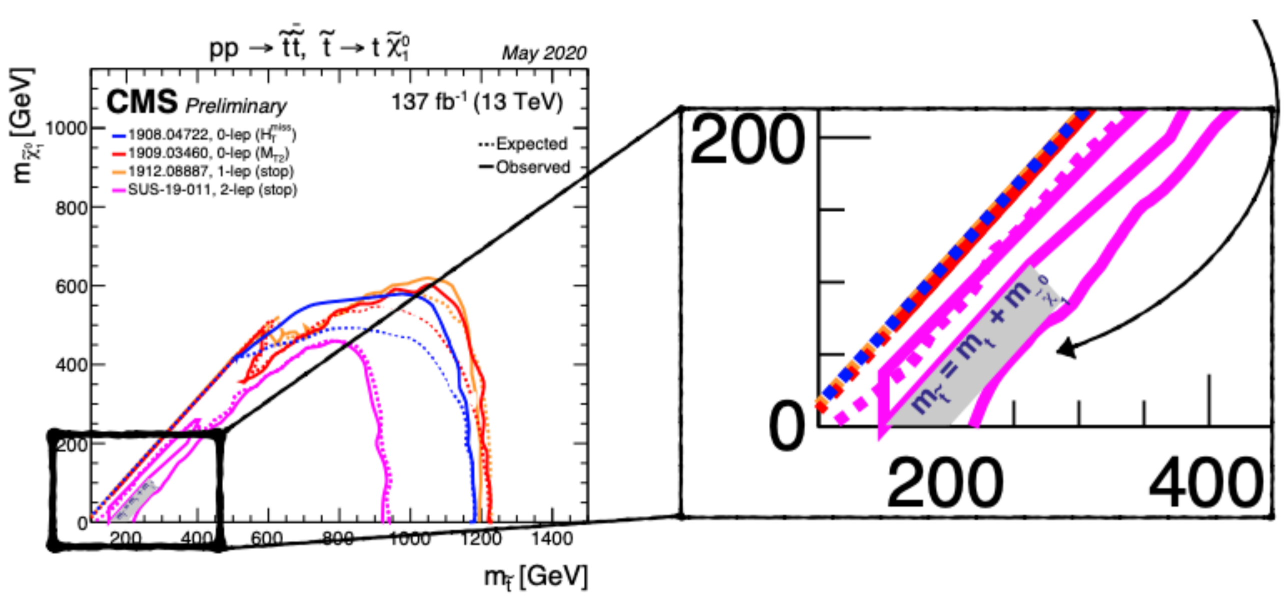


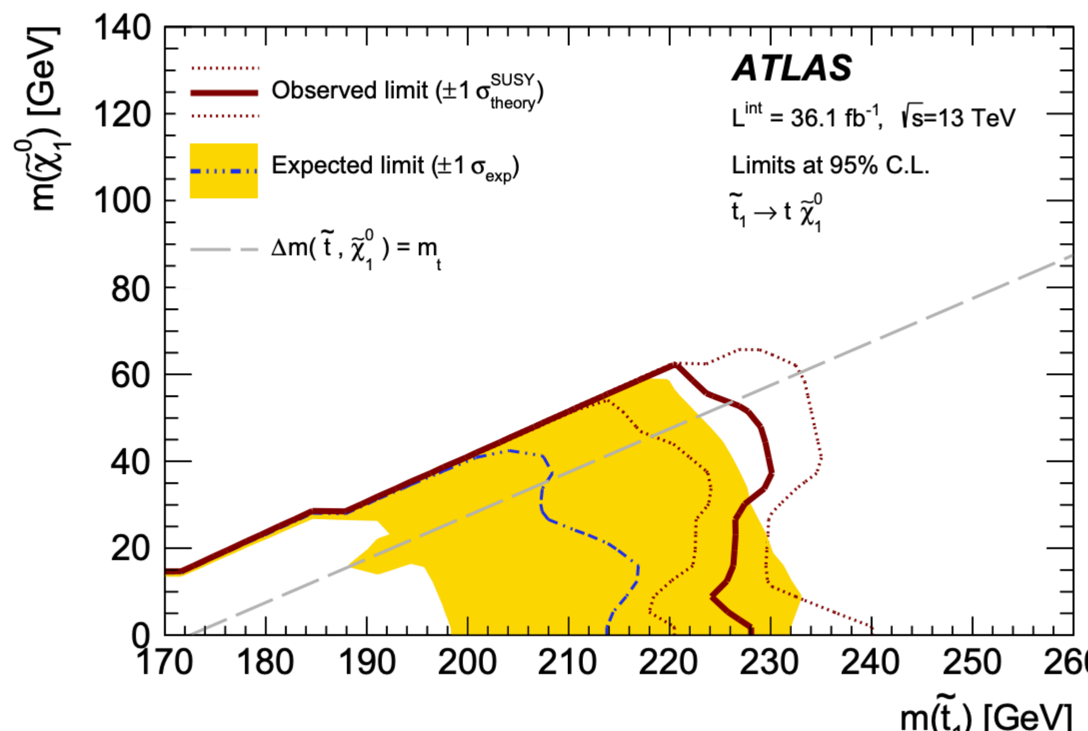
very little p_T^{miss}

signal resembles to $t\bar{t}$ background

ATLAS explores top quark spin correlations



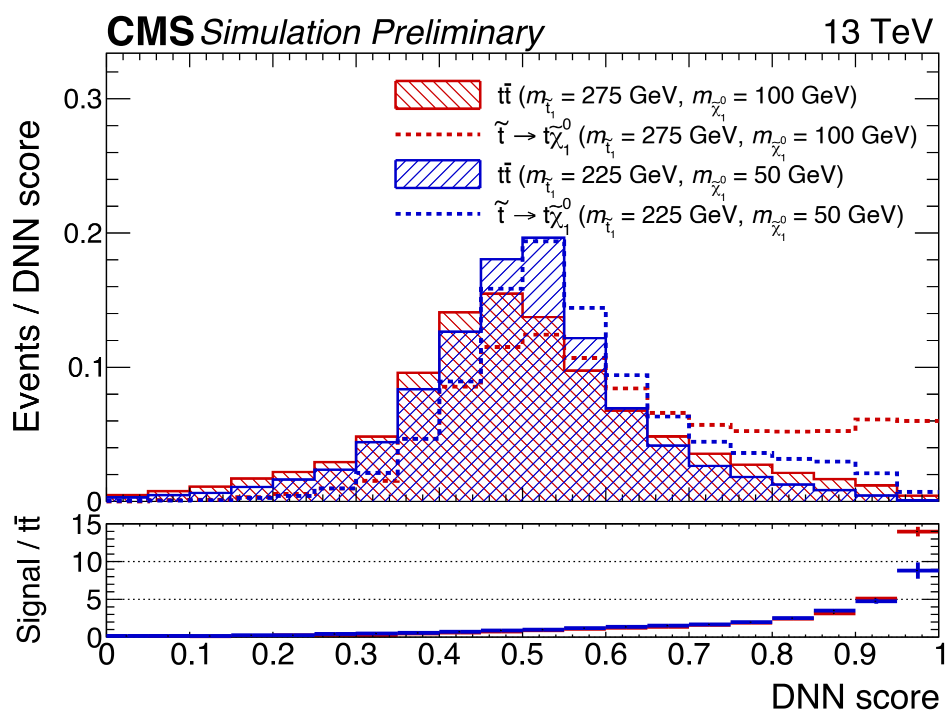


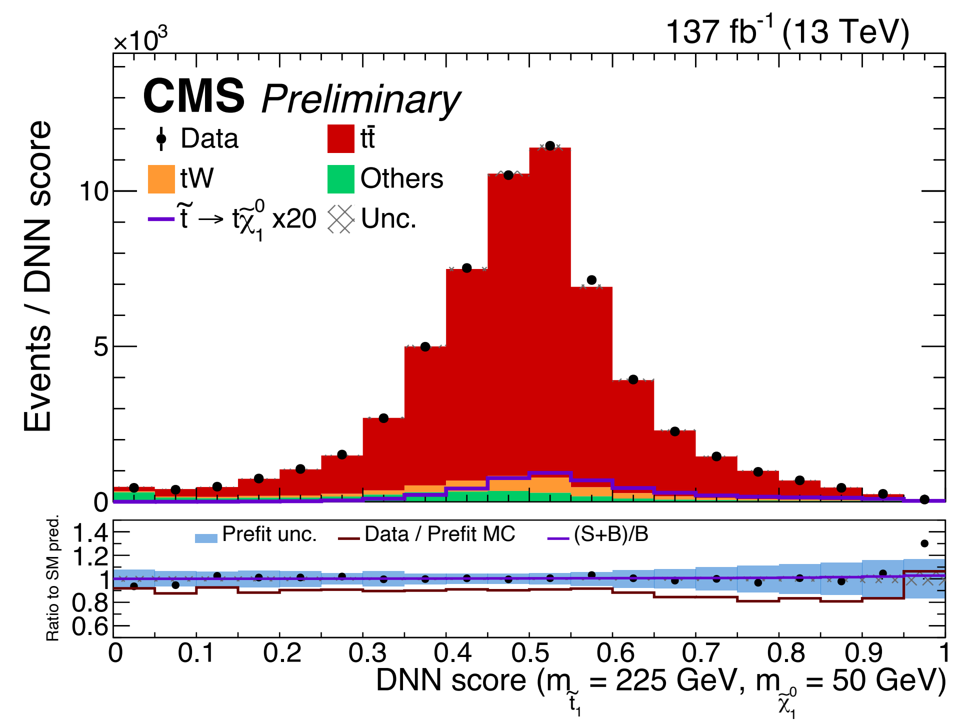


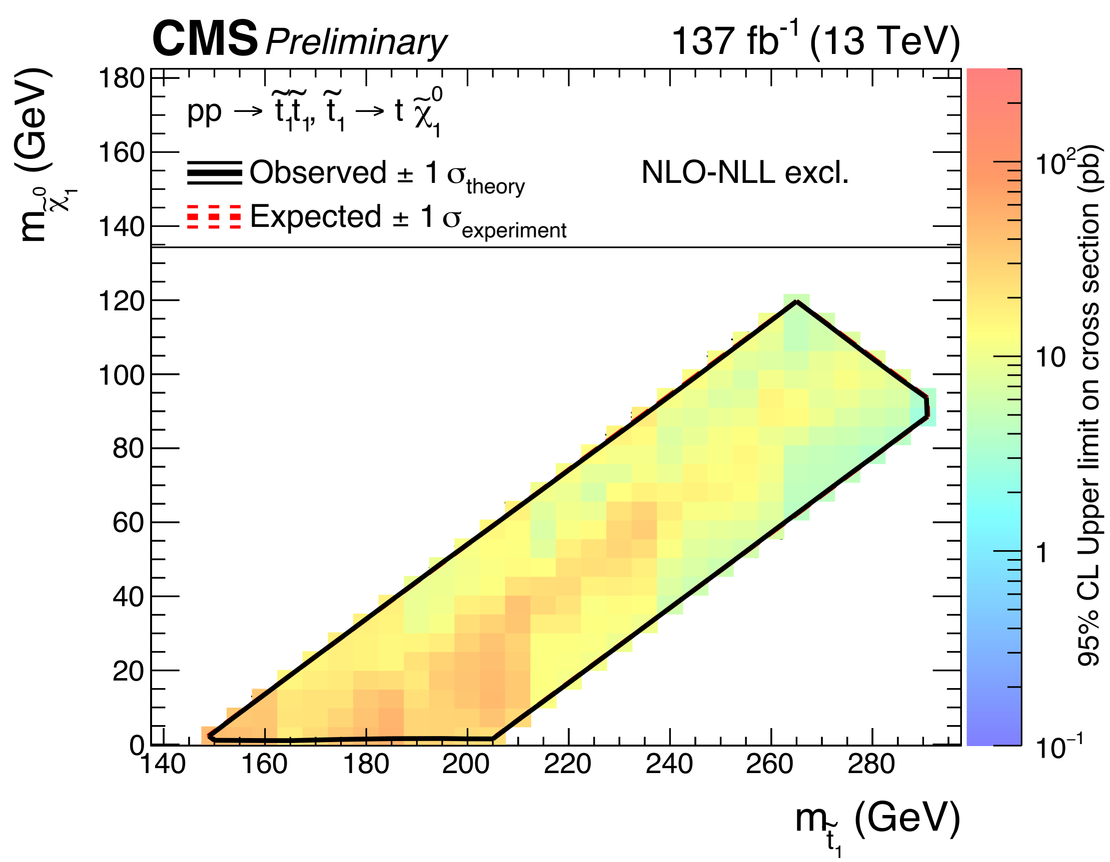
1903.07570

$\tilde{t}$ in the compressed "top corridor"

- Multivariate analysis: 11 input variables 7 hidden layer DNN







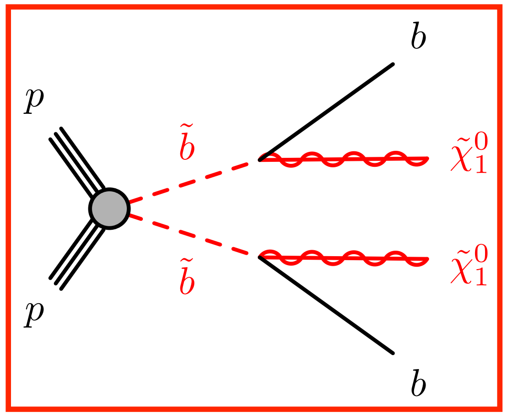
Entire corridor excluded for the first time in CMS

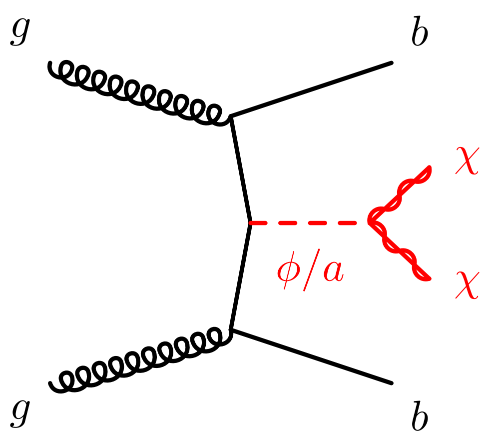
$$|m_{\tilde{t}_1} - m_t - m_{\tilde{\chi}_1^0}| < 30\text{ GeV}$$

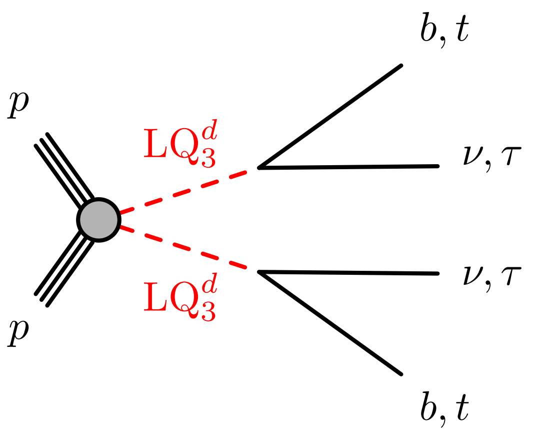
$$m_{\tilde{\chi}_1^0} < 120\text{ GeV}$$

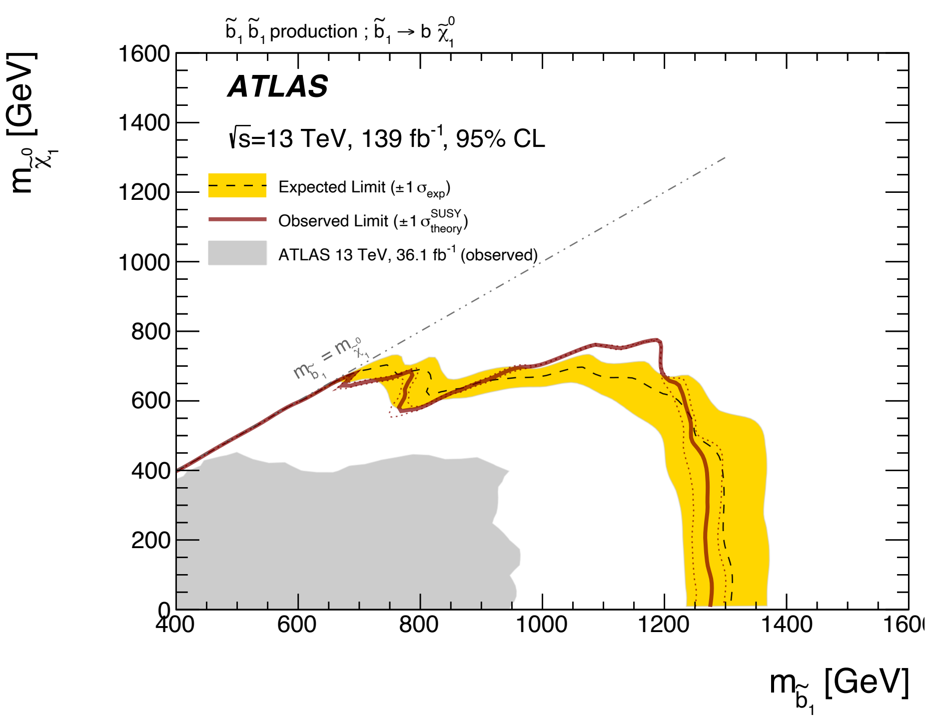
CMS-PAS-SUS-20-002

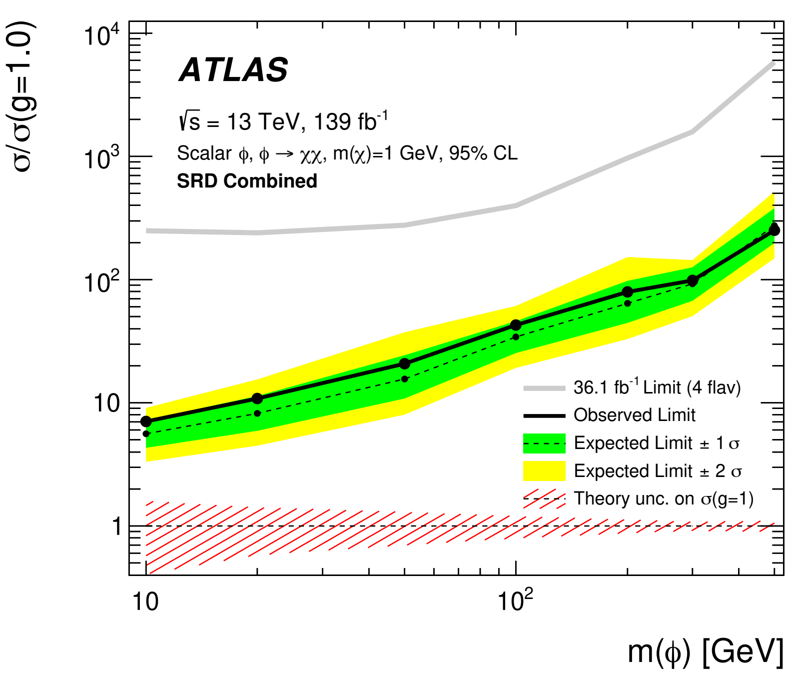
$b\bar{b} + \not{E}_T$

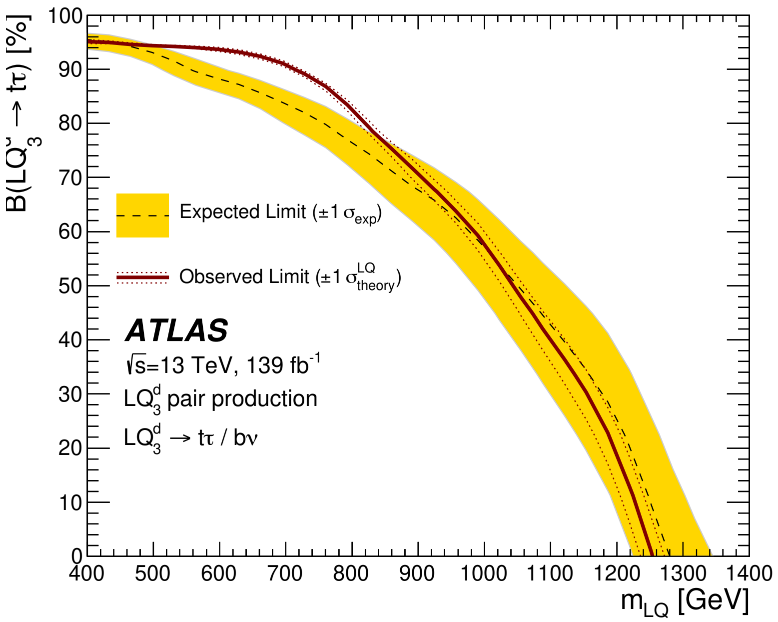






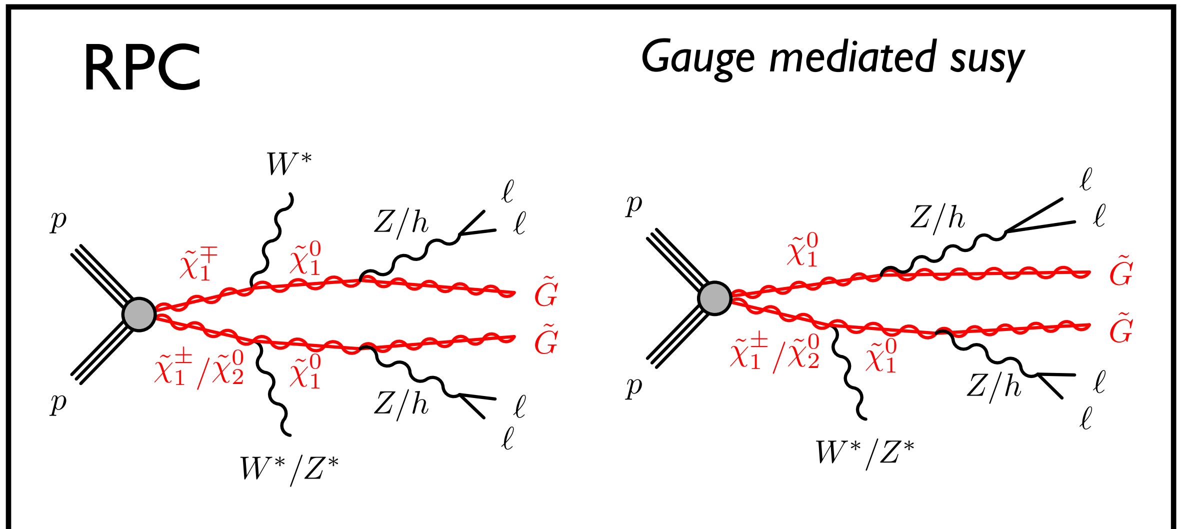


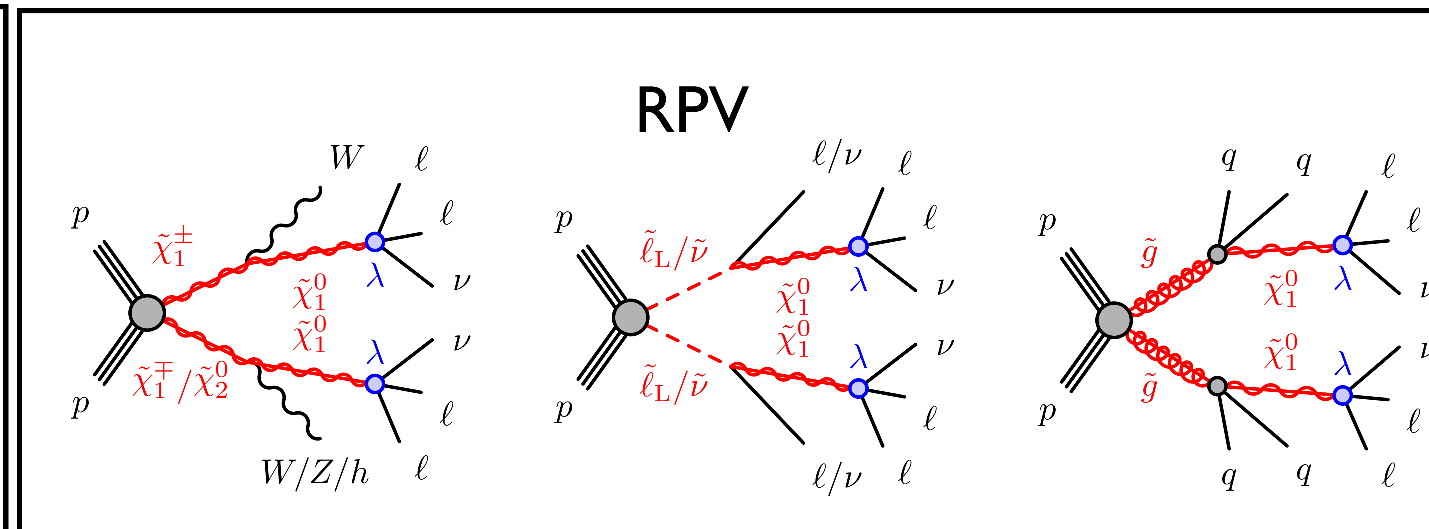


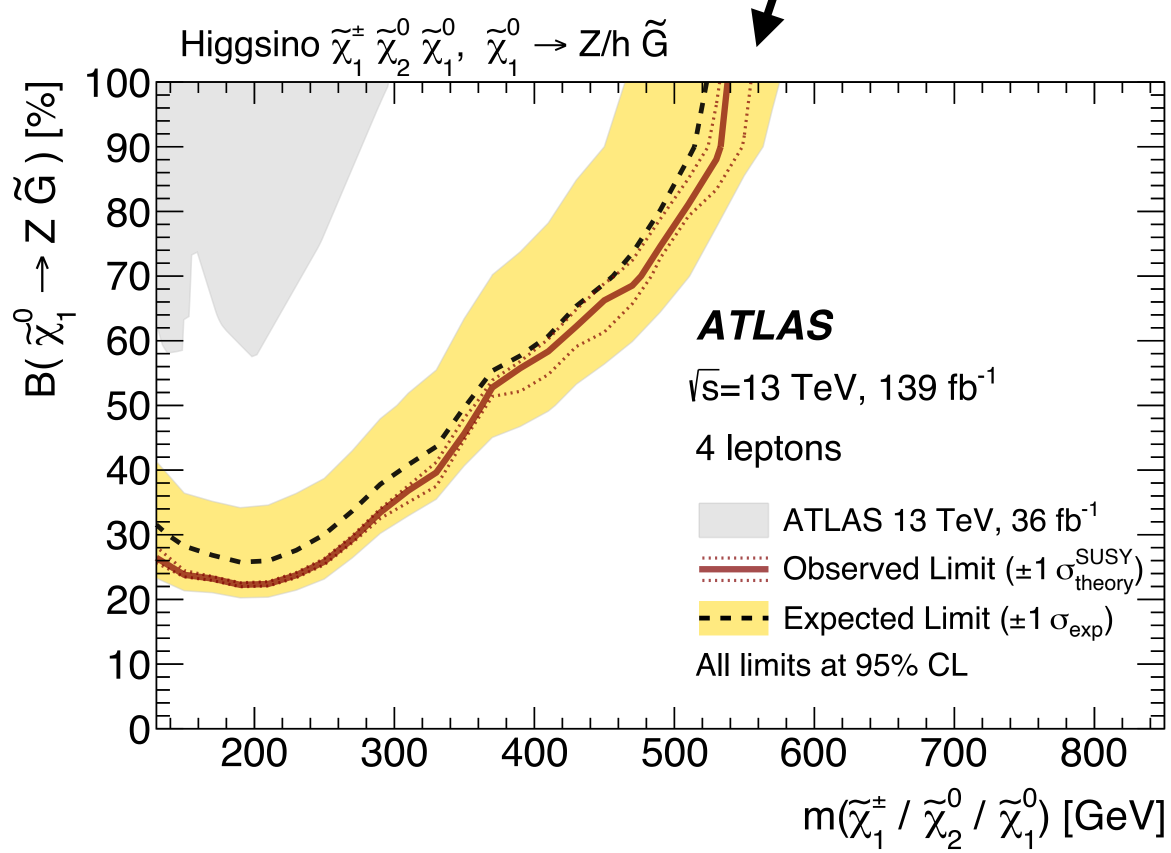


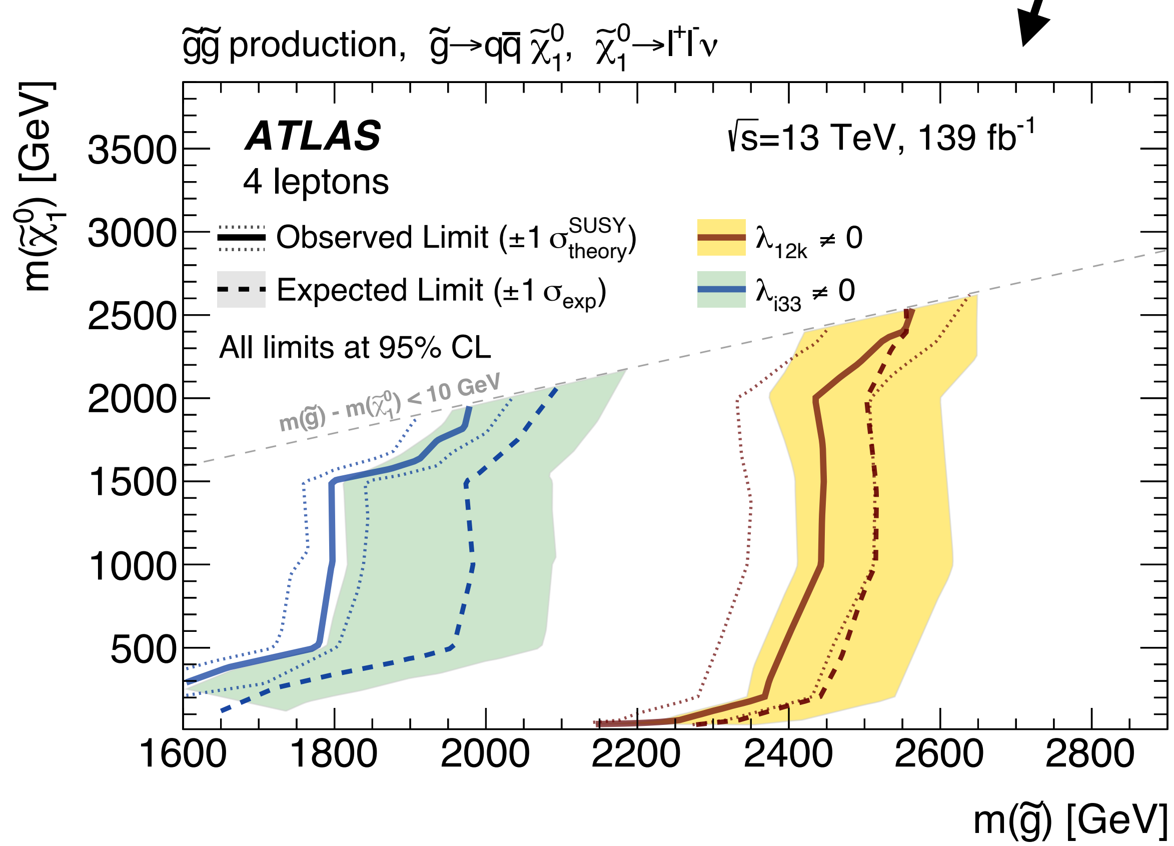
ATLAS: JHEP 06 (2020) 46

Tackling rare final states $4\ell + E\!\!\!/_T$





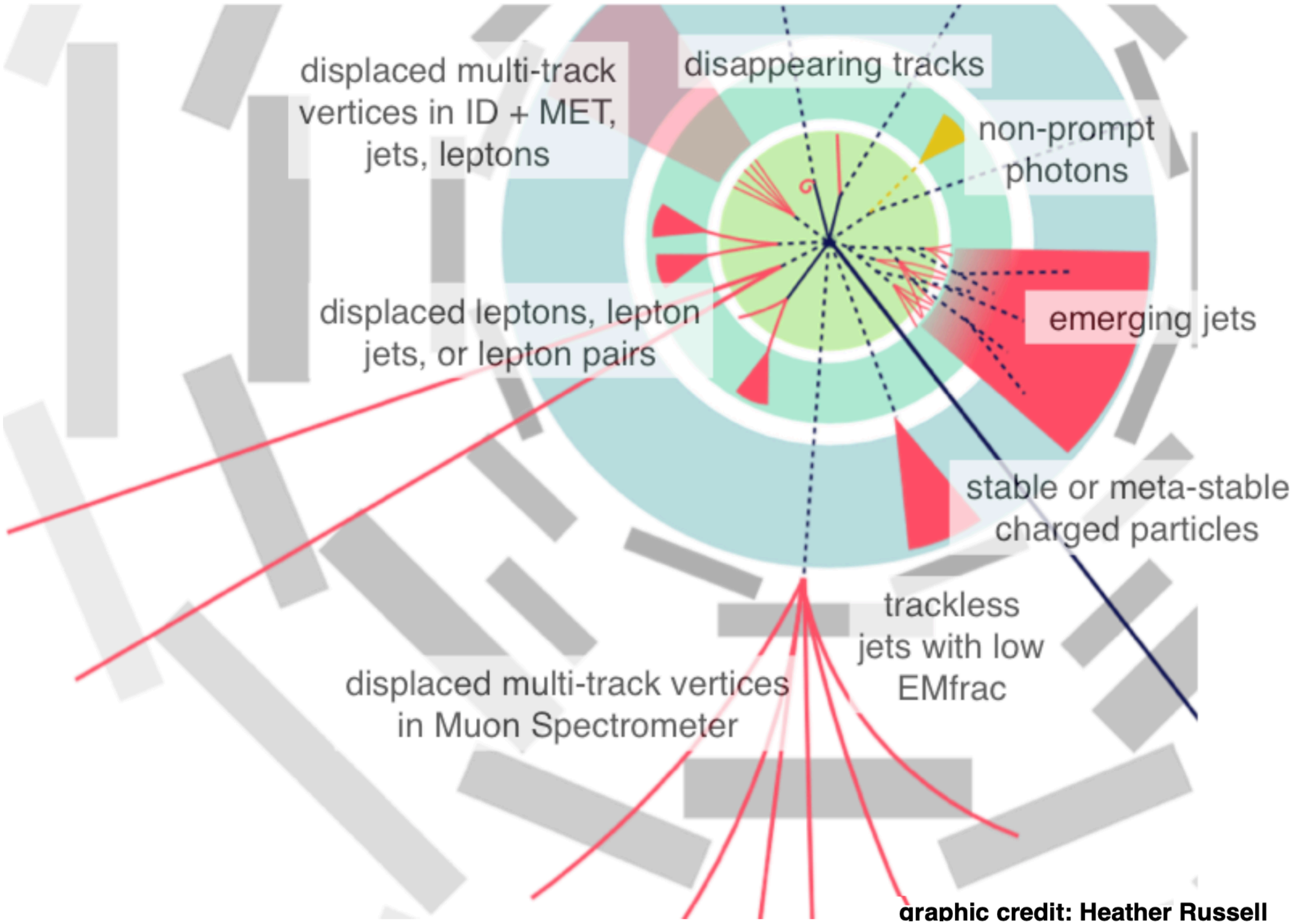




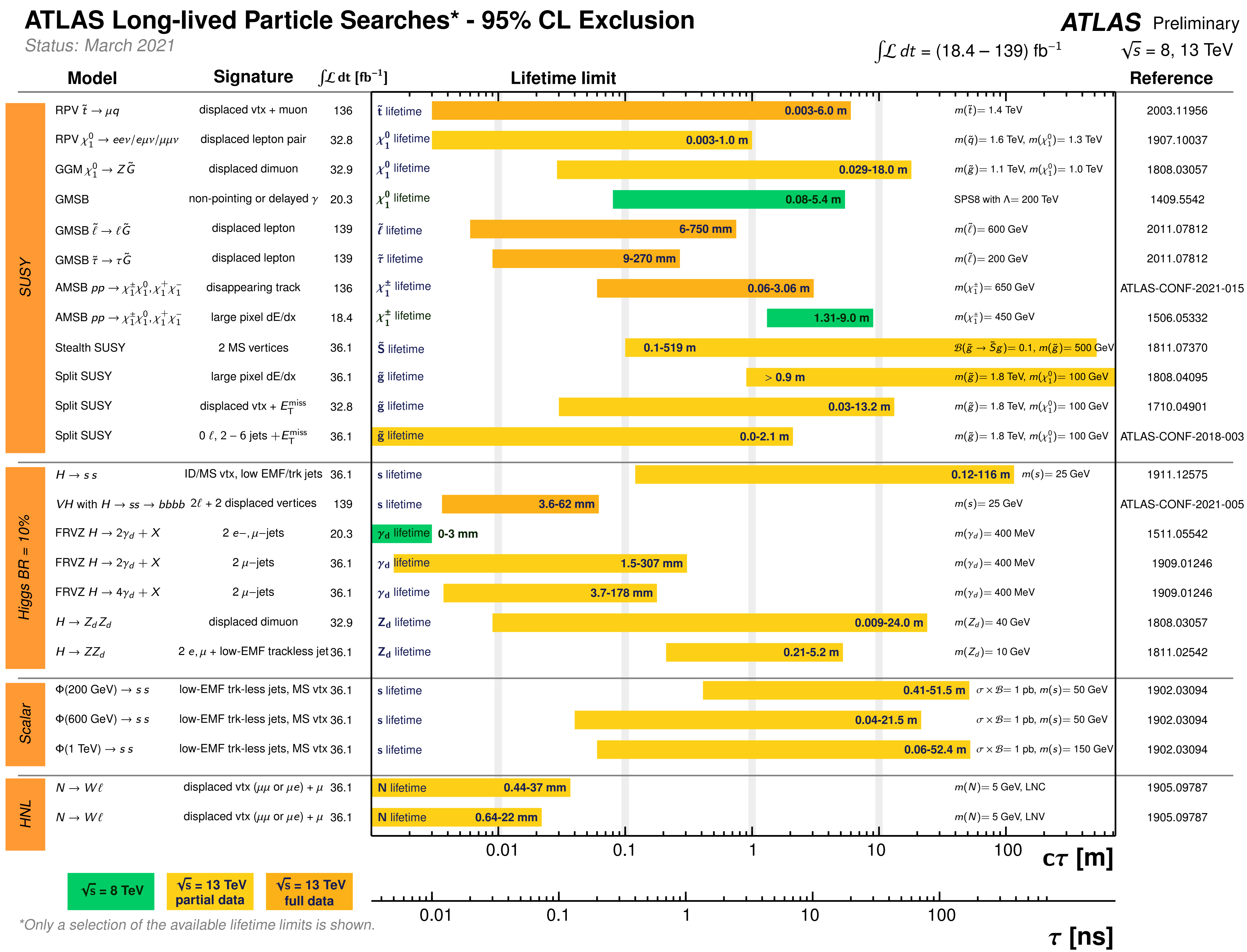
ATLAS: arXiv:2103.11684

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2018-02/

Long-lived particles

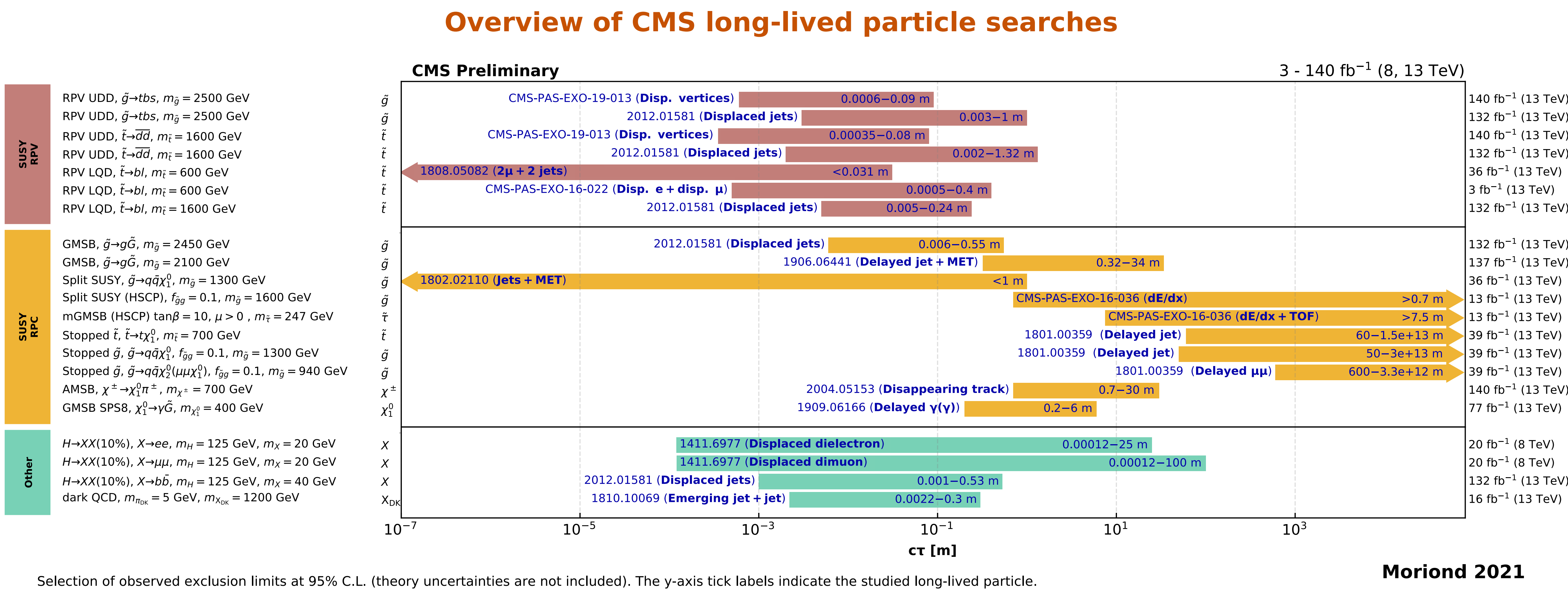


A summary of search results - $c\tau$

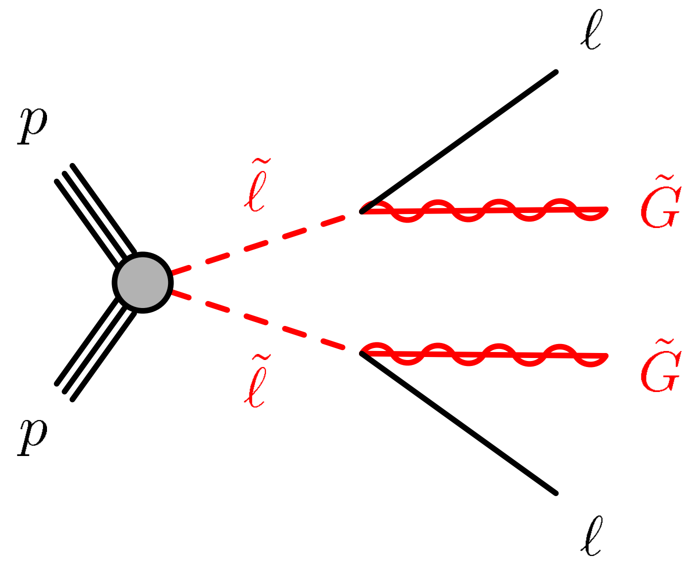


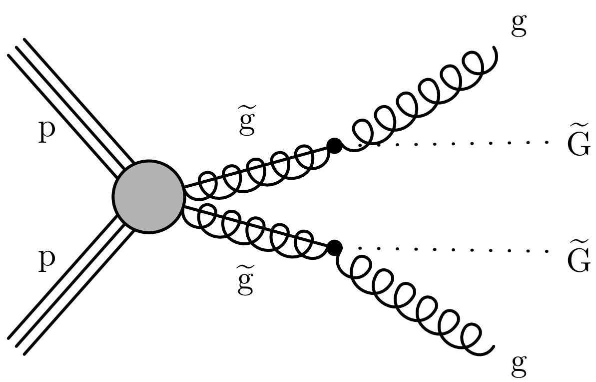
ATL-PHYS-PUB-2021-009/

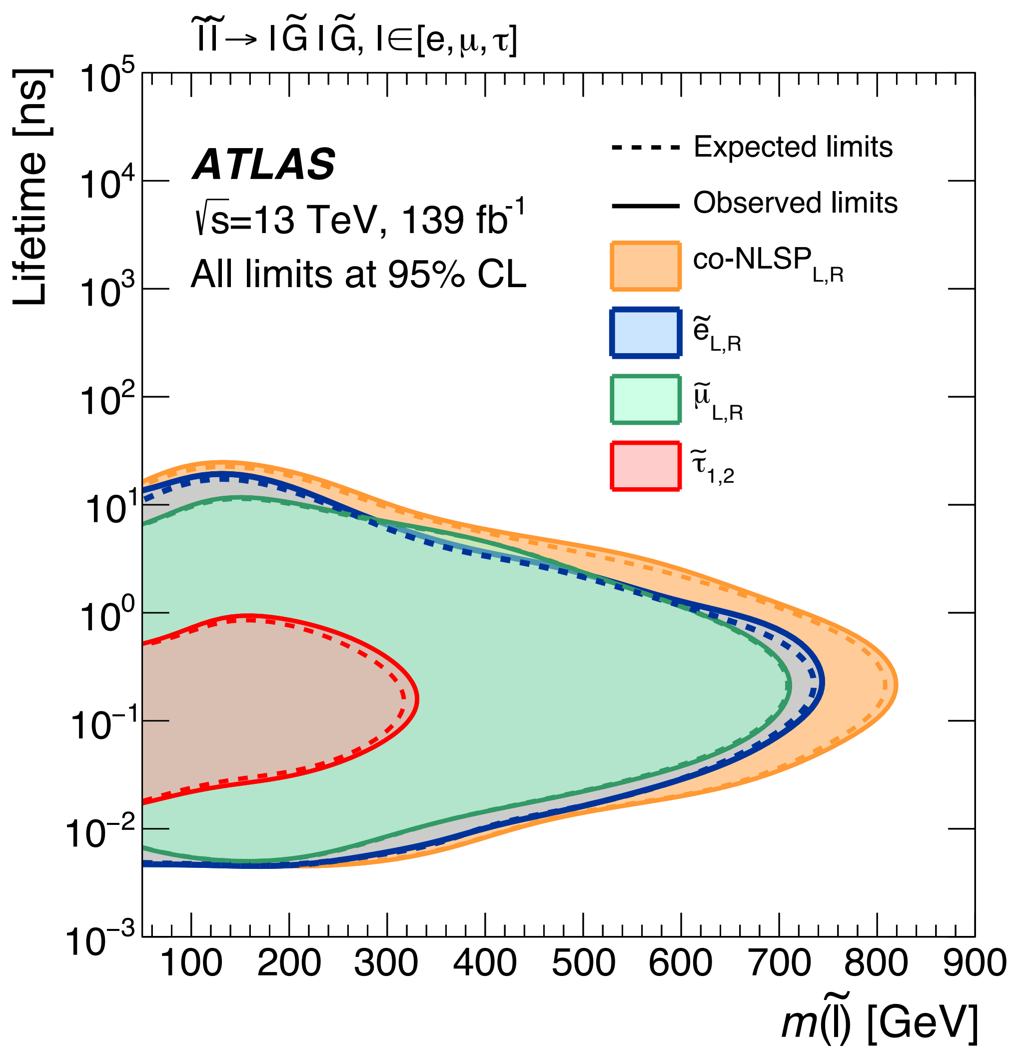
A summary of search results - $c\tau$

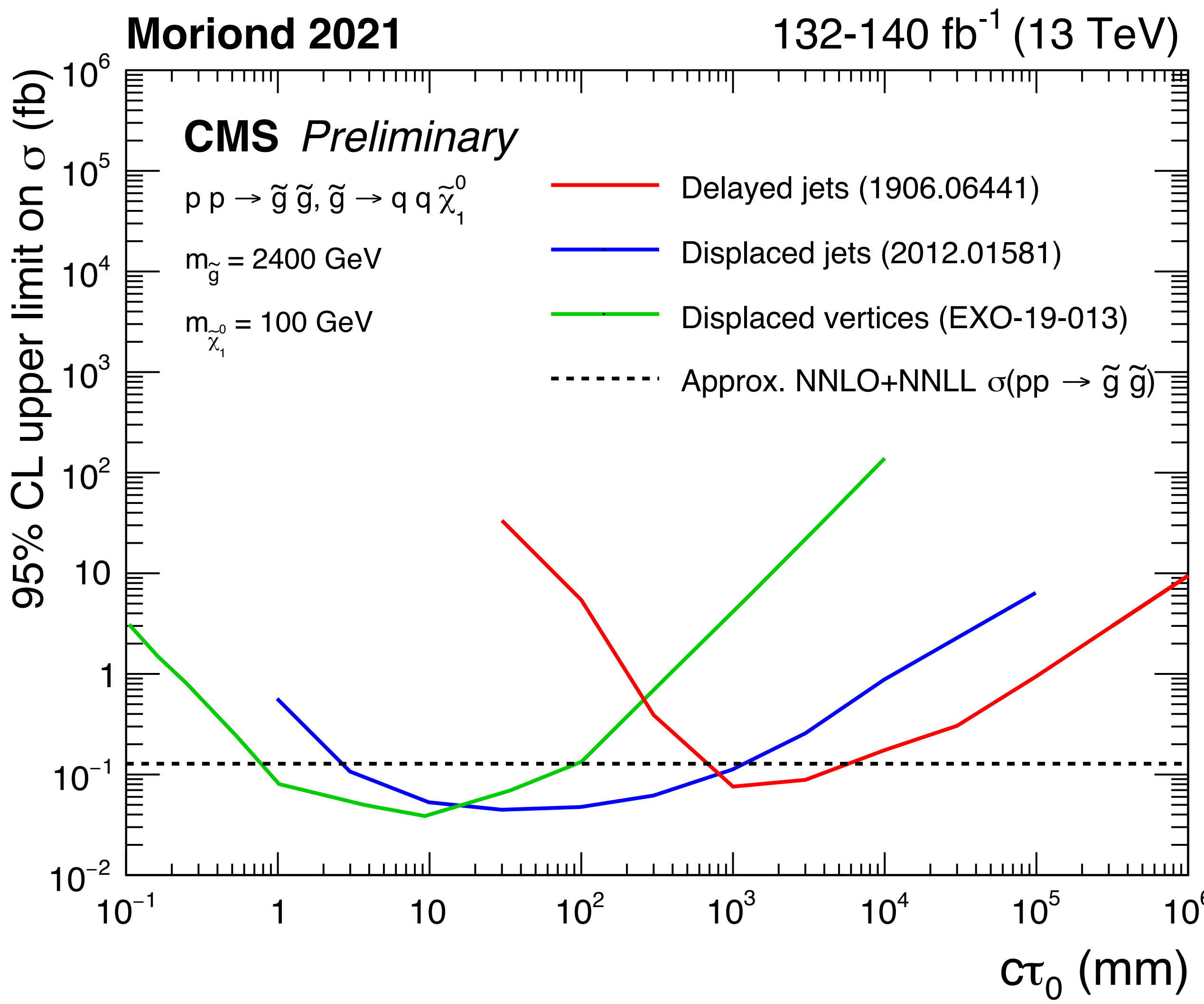


Displaced signatures in high pT/mass region



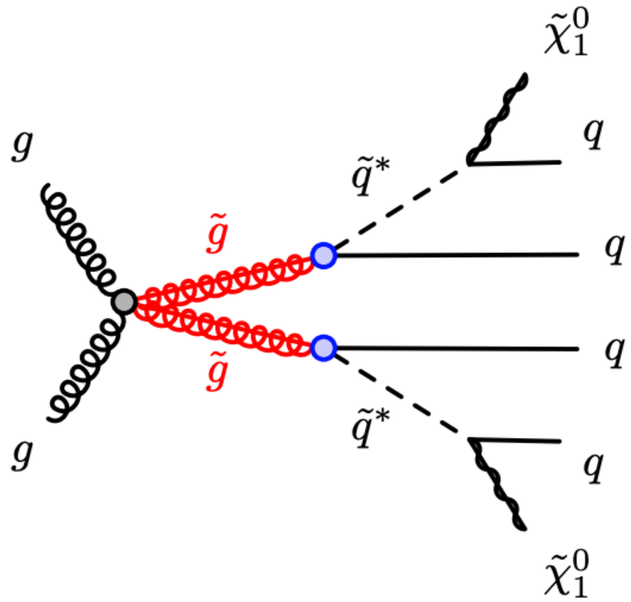






2011.07812

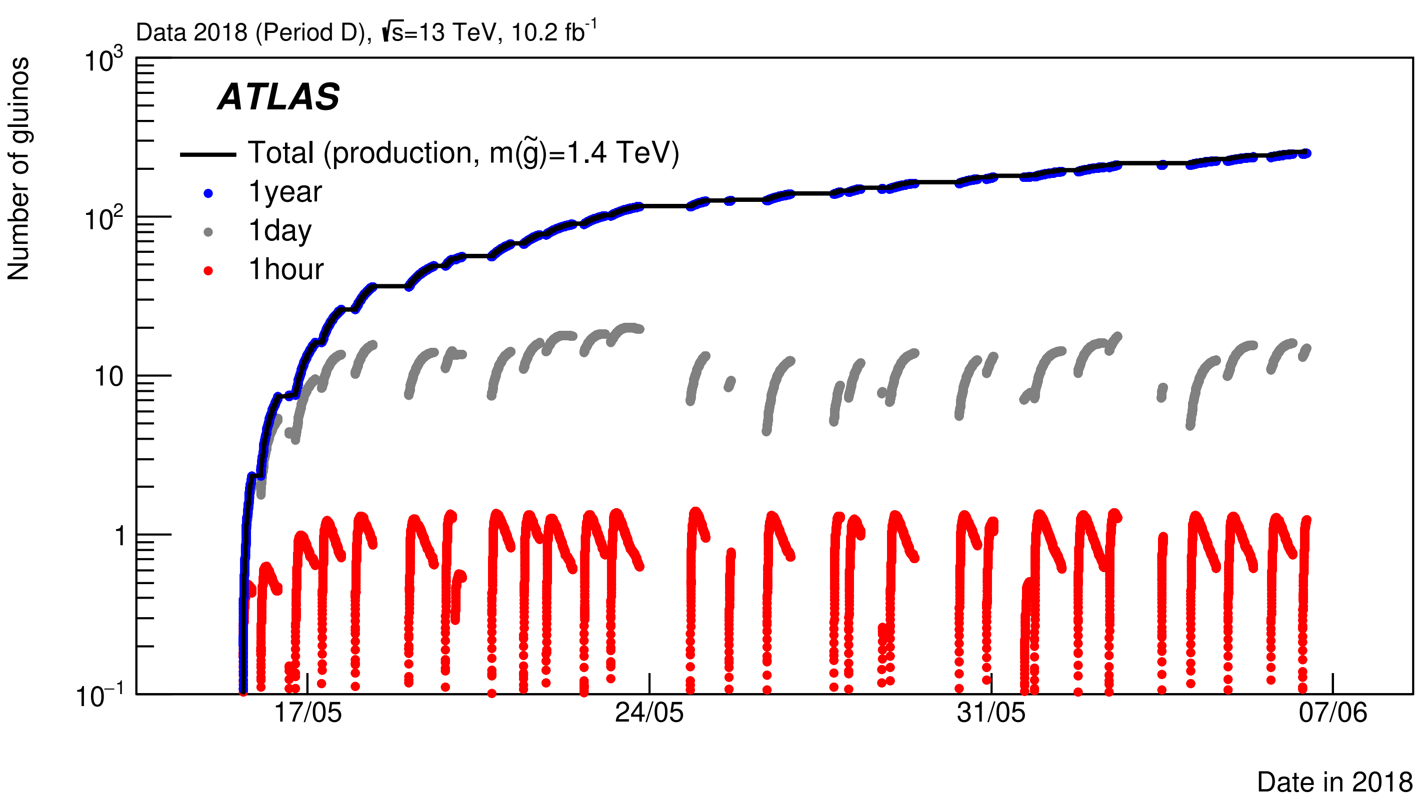
Stopped LLP in bunch crossings with no collision

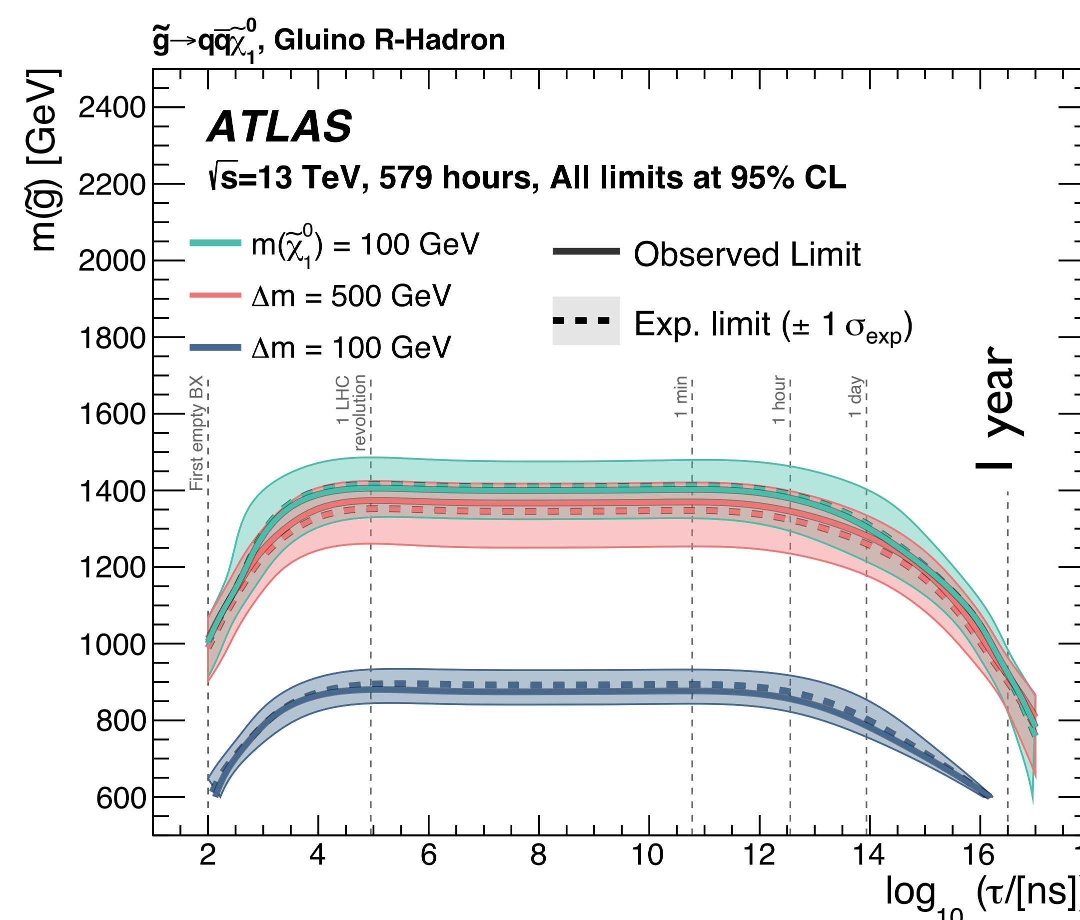


small $\Delta m(\tilde{g} - \tilde{q}^*)$
→ Gluino R-hadron LLP

Hadronise to R-hadron and stopped

Signature: Large out-of-time energy deposits in the calorimeter

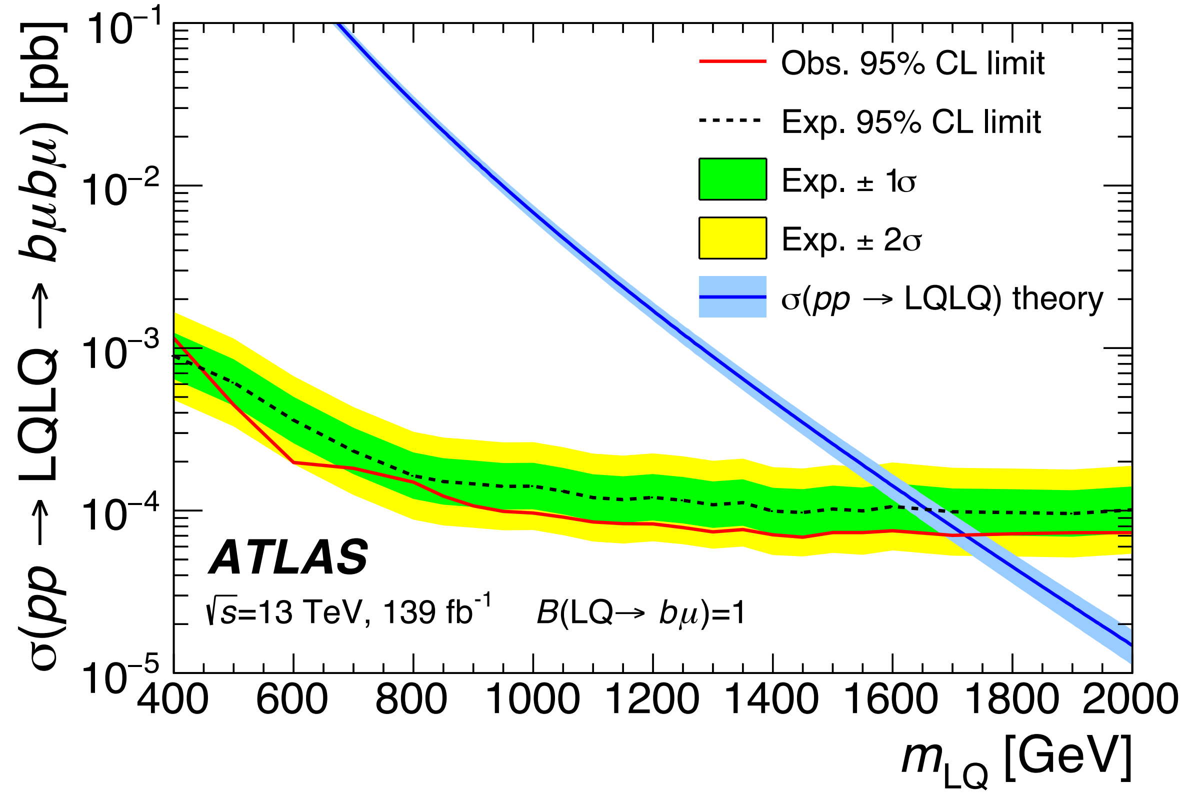


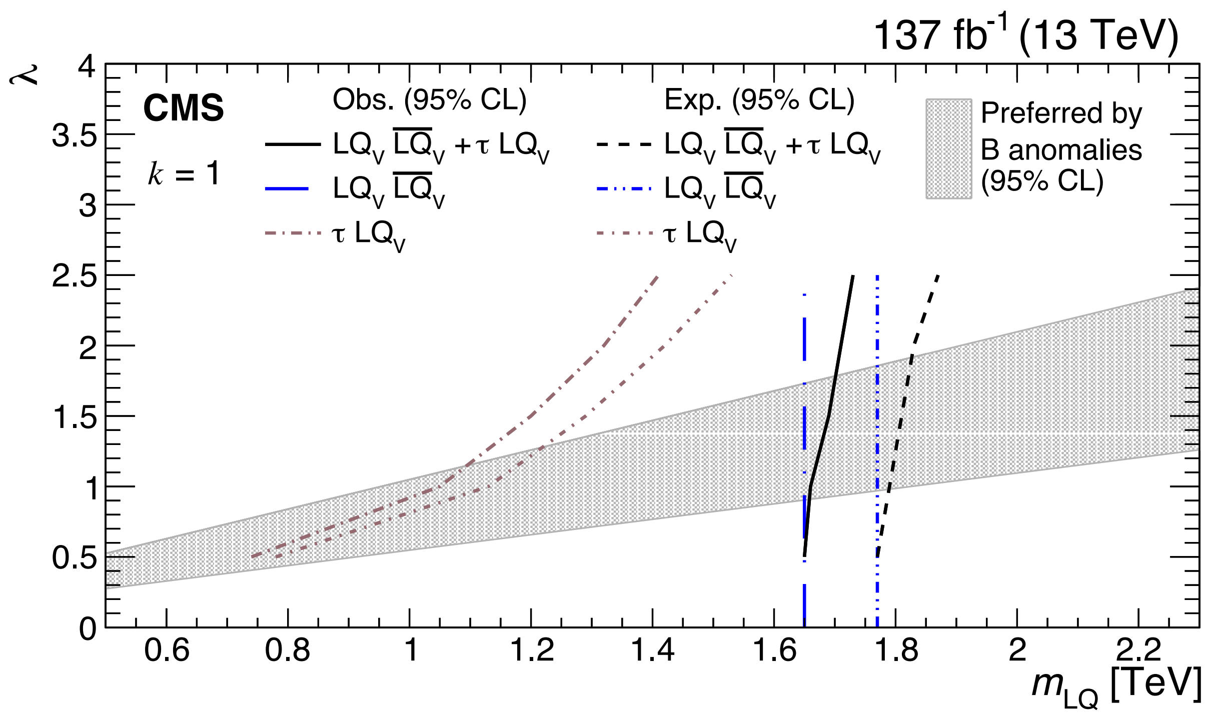


2104.03050

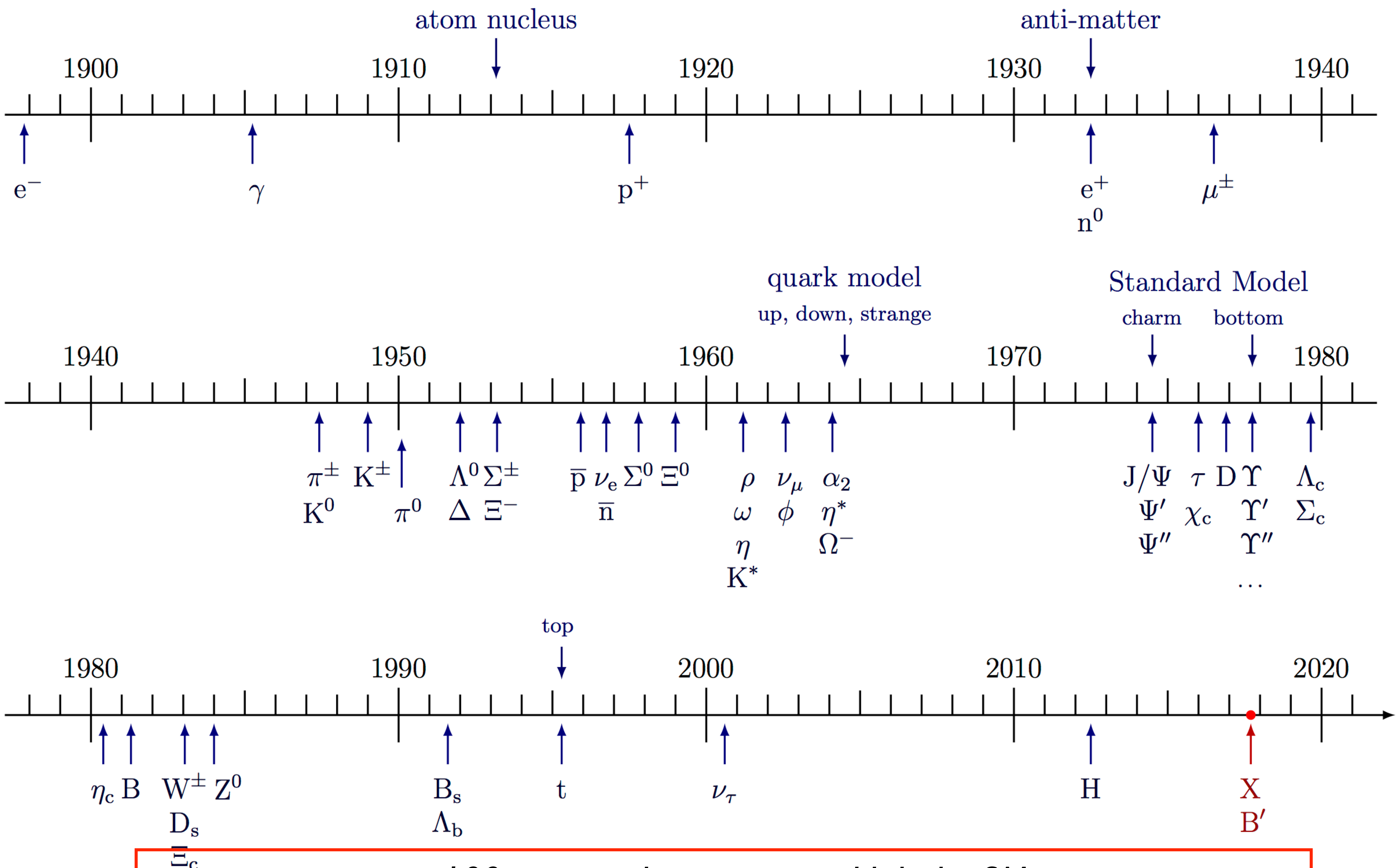
Summary

- A vast programme of BSM physics searches has been carried out based on the successful LHC Run 1+2 data-taking
- ATLAS and CMS explored a huge chunk of the phase-space at multi- TeV scale
  - More efforts are now devoted to challenging kinematic regions and theoretical phase-space
    - Closing up the gaps!
  - Presenting and preserving this legendary dataset are also becoming mainstream
- Several intriguing anomalies in the flavour sector, led by the LHCb experiment, may just be what we need to go behind the SM
  - Muons appear to be "acting up" in several places, and will surely shake/shape the LHC BSM physics programme
- This is really just the beginning …





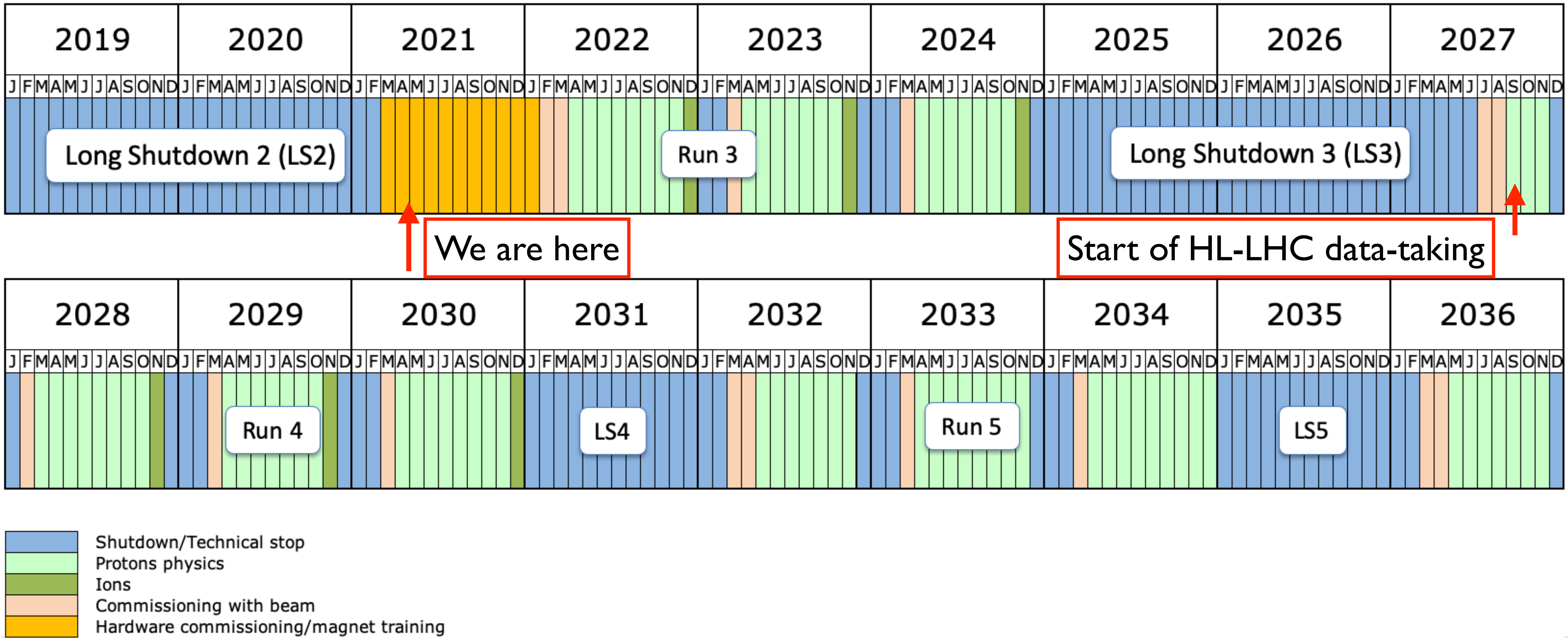
A historical perspective



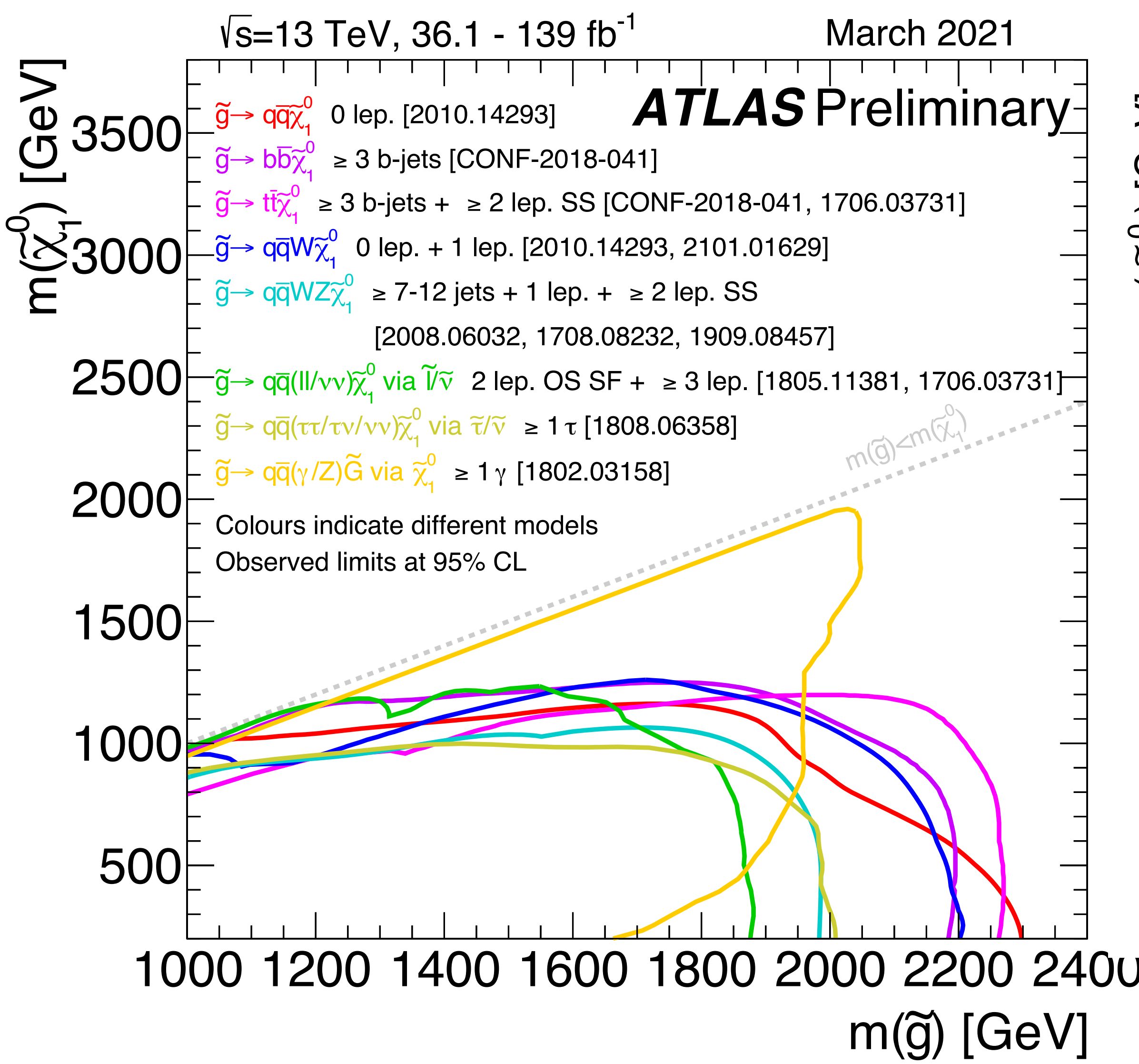
>100 years endeavour to establish the SM
Now we are starting a completely new chapter.
The challenges we face now are much more compared with the start of the LHC.

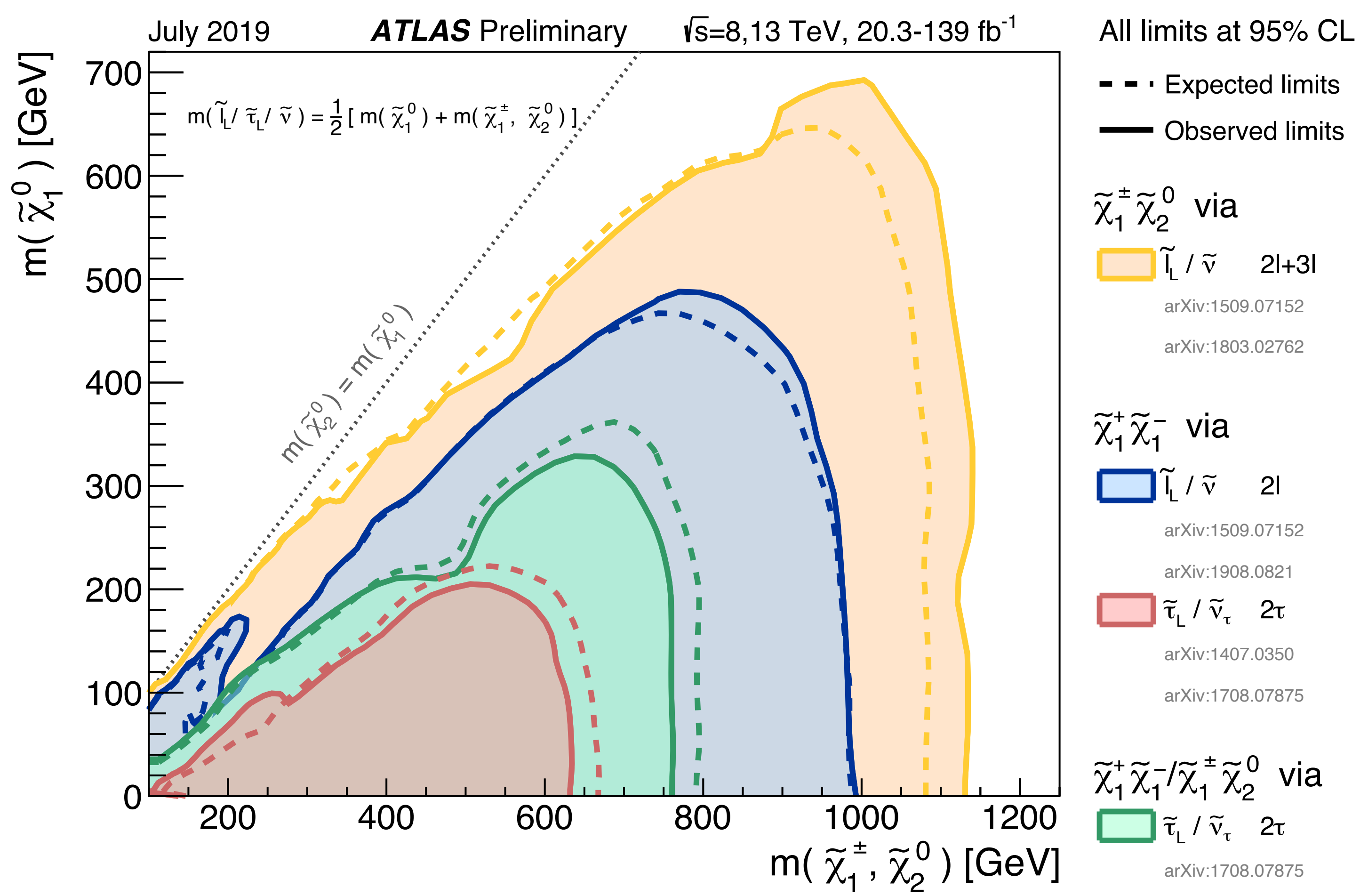
Backup slides

LHC schedule



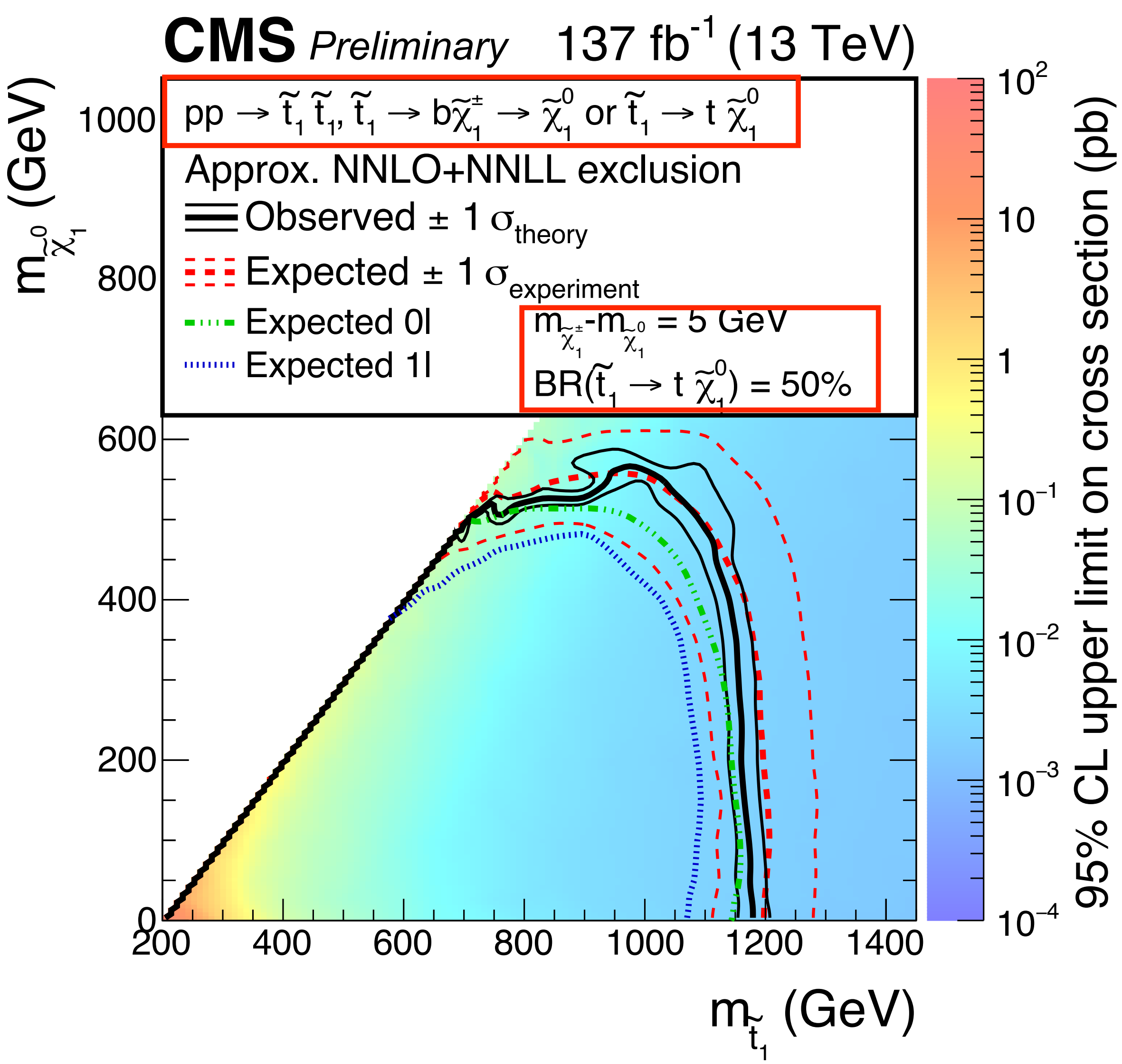
ATLAS SUSY summary results

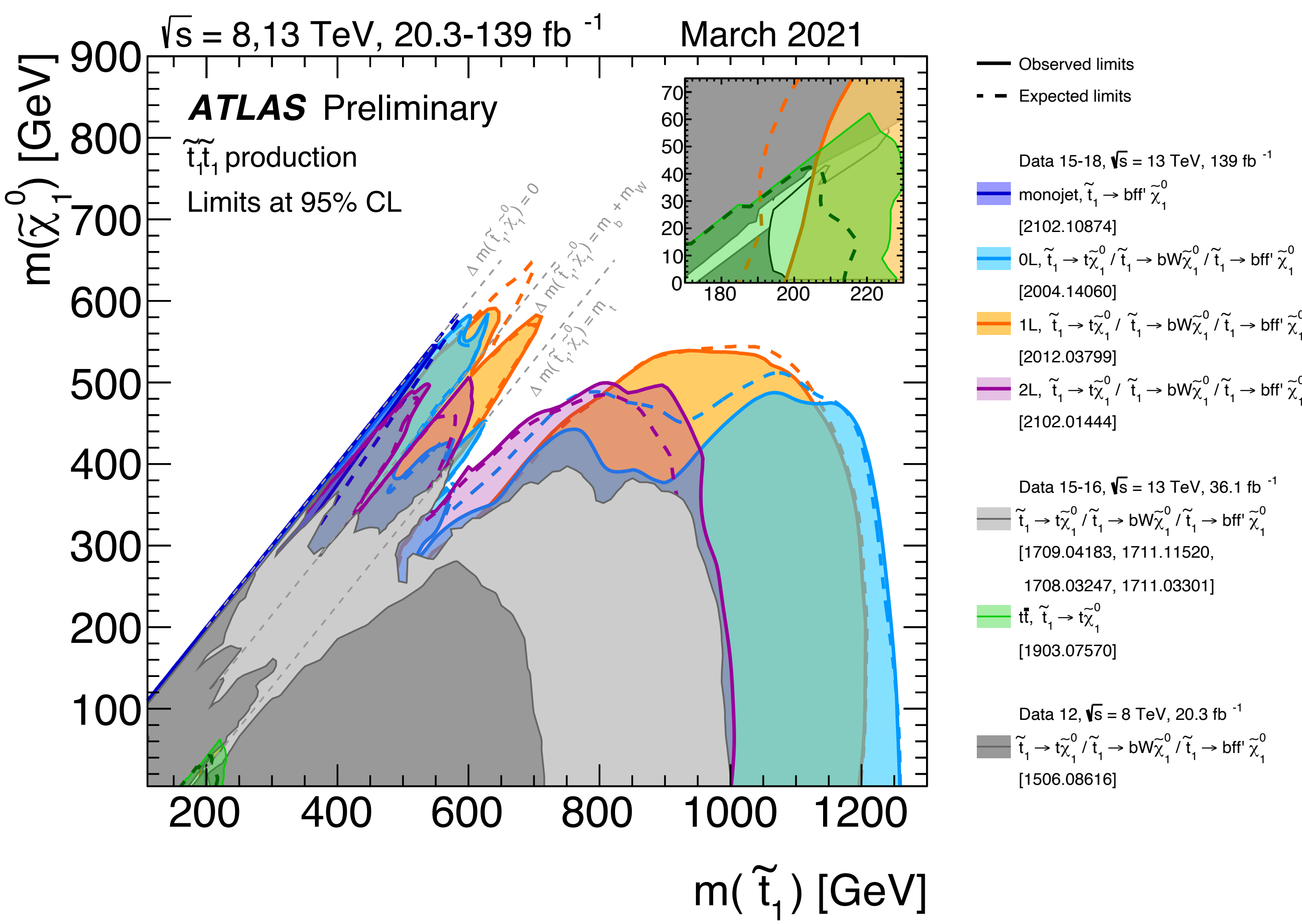




ATL-PHYS-PUB-2021-007

Third-generation $\tilde{t}\tilde{t}$



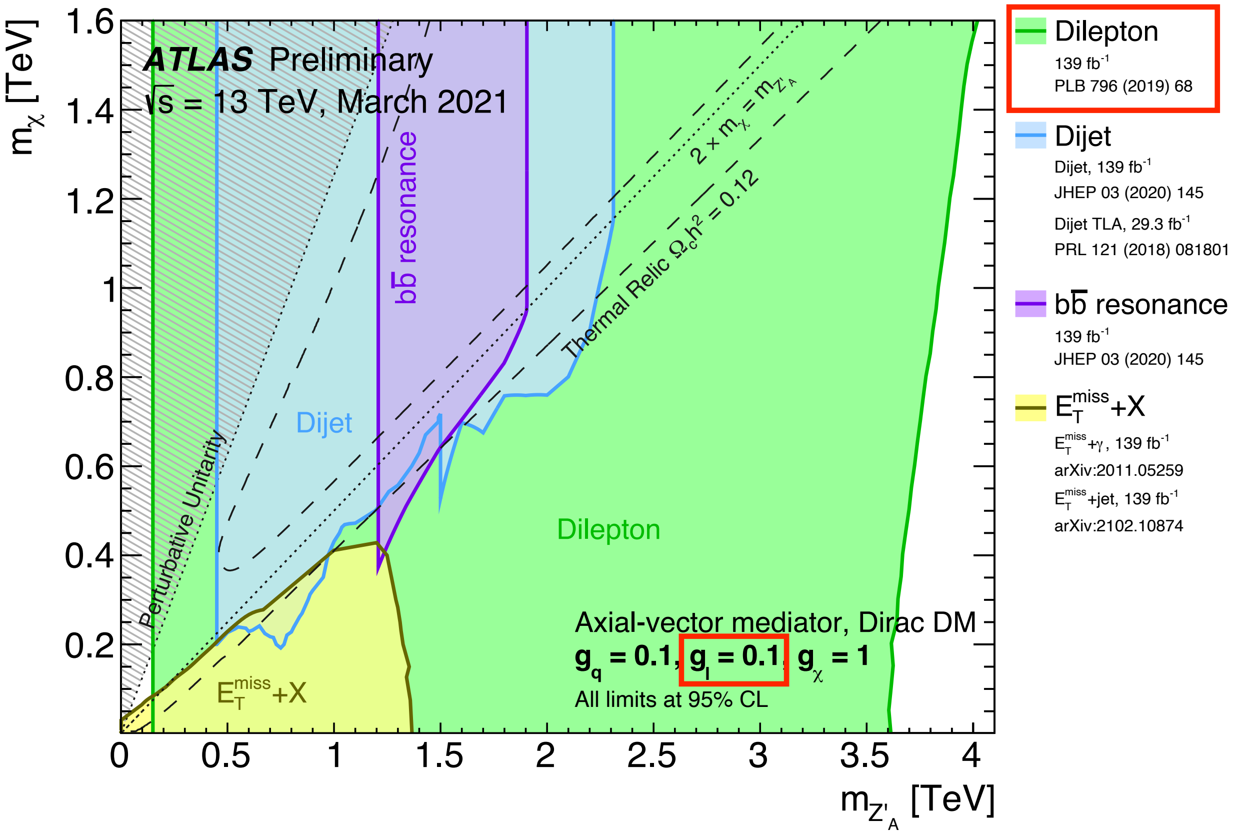


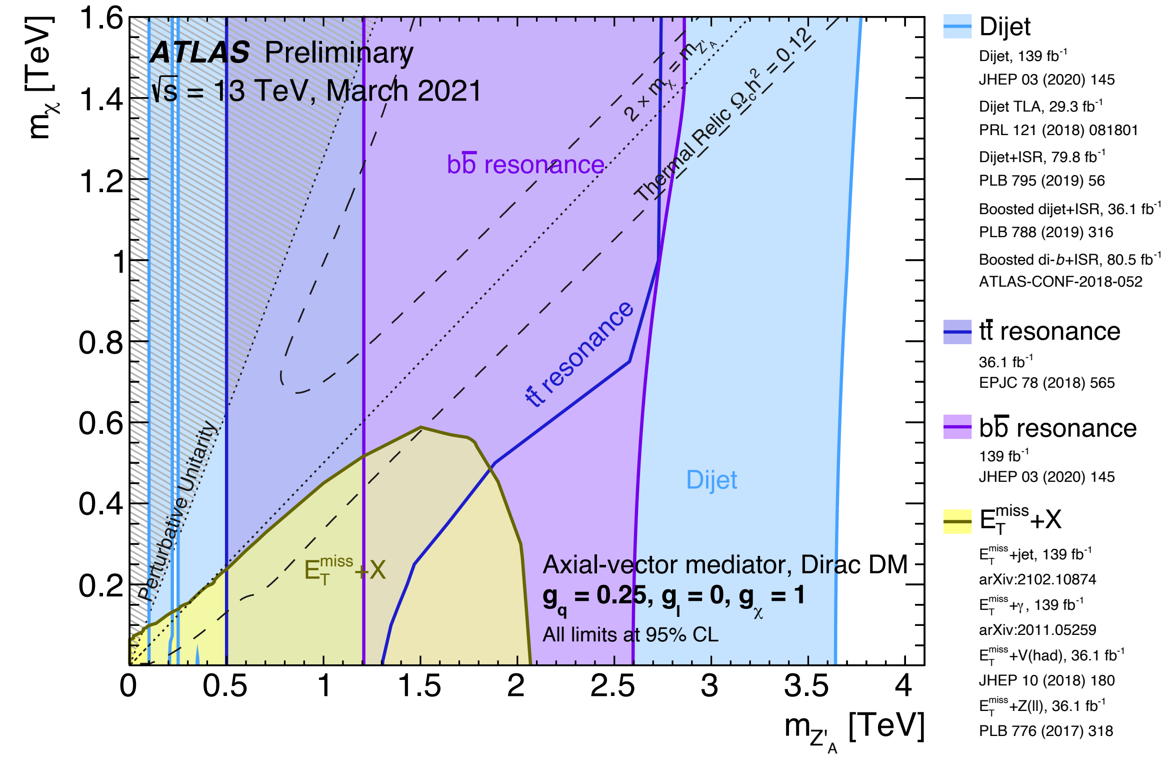
CMS-PAS-SUS-20-002

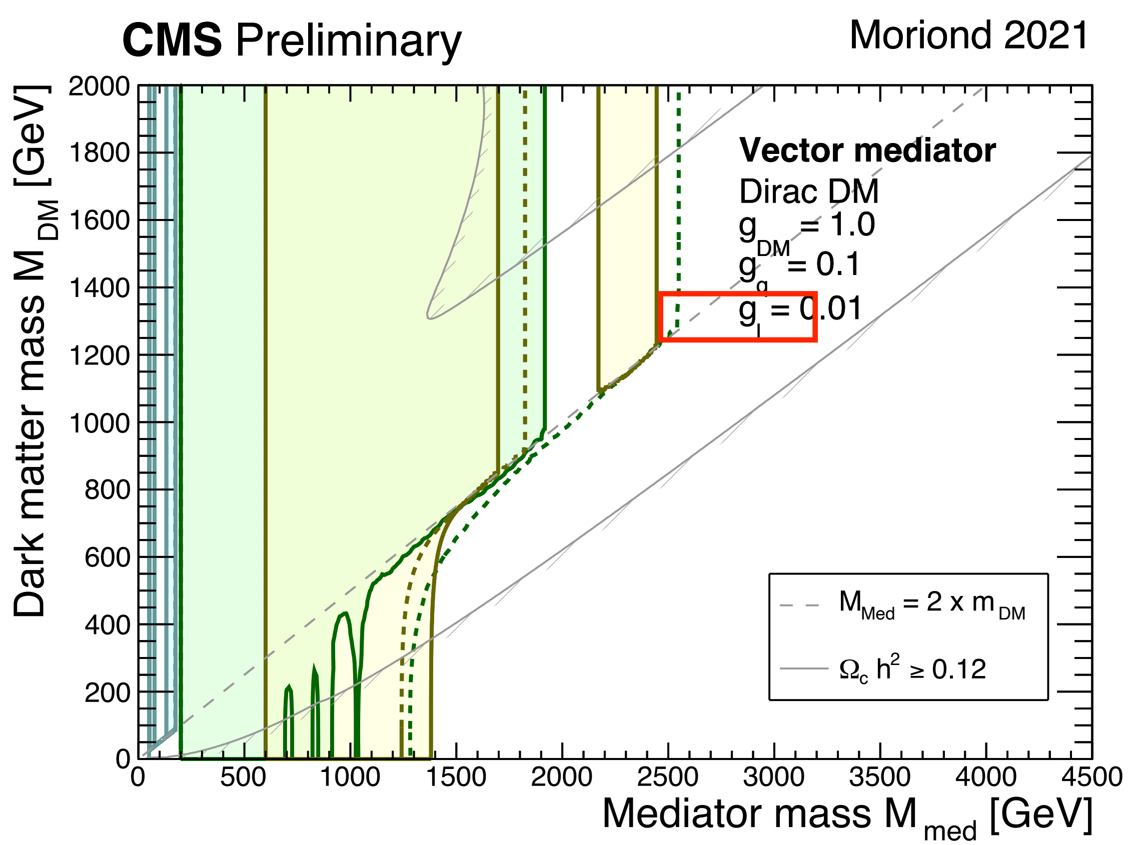
ATL-PHYS-PUB-2020-020

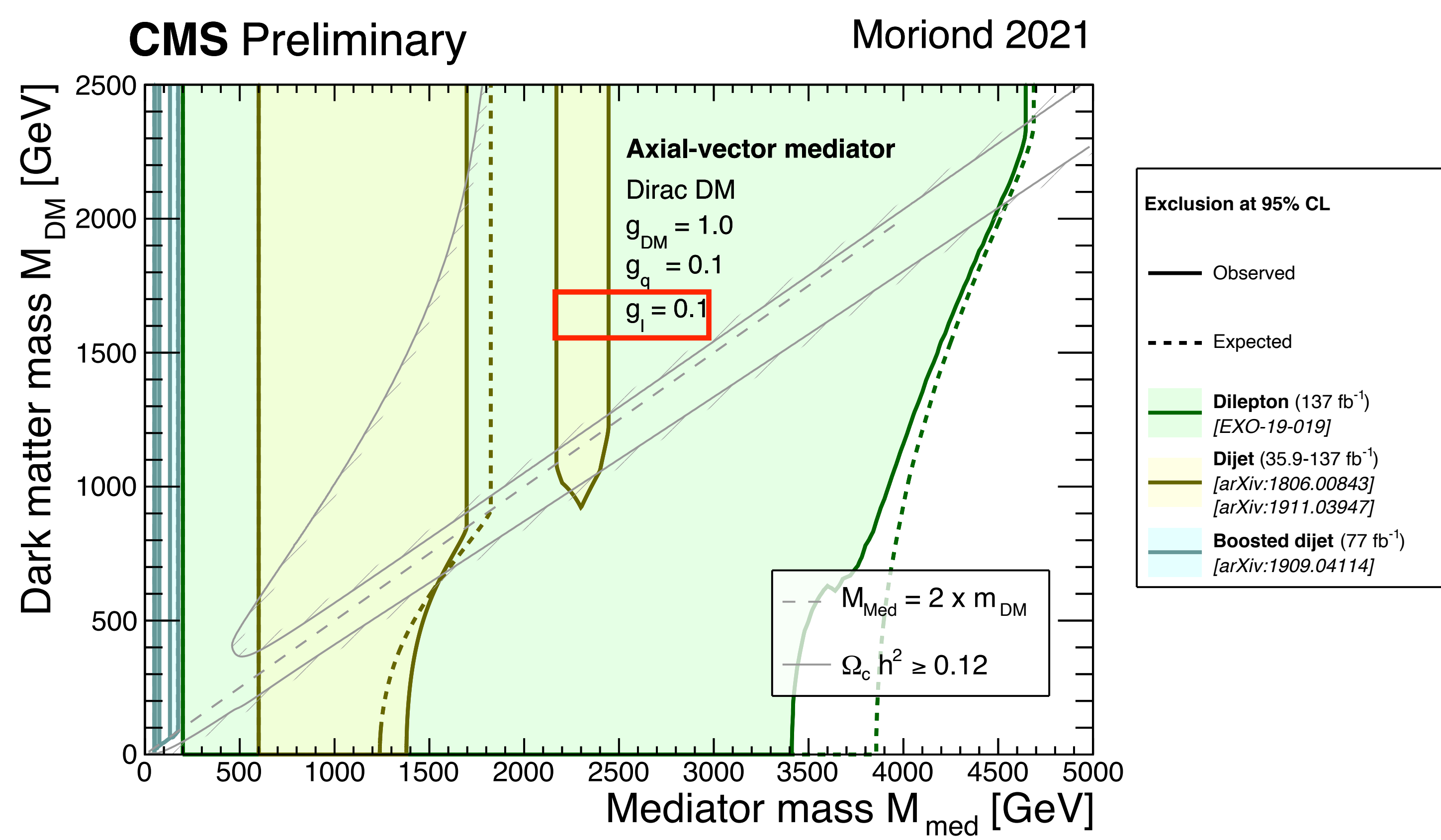
Dilepton and Dijet implications on DM mediators

ATL-PHYS-PUB-2021-006









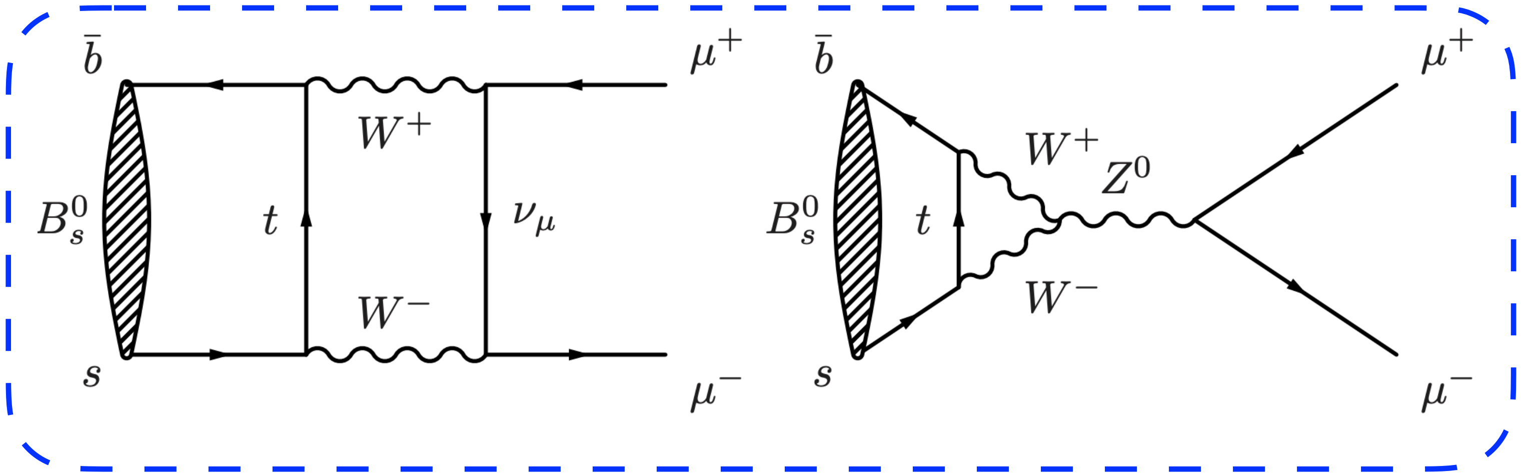
CMS EXO Summary

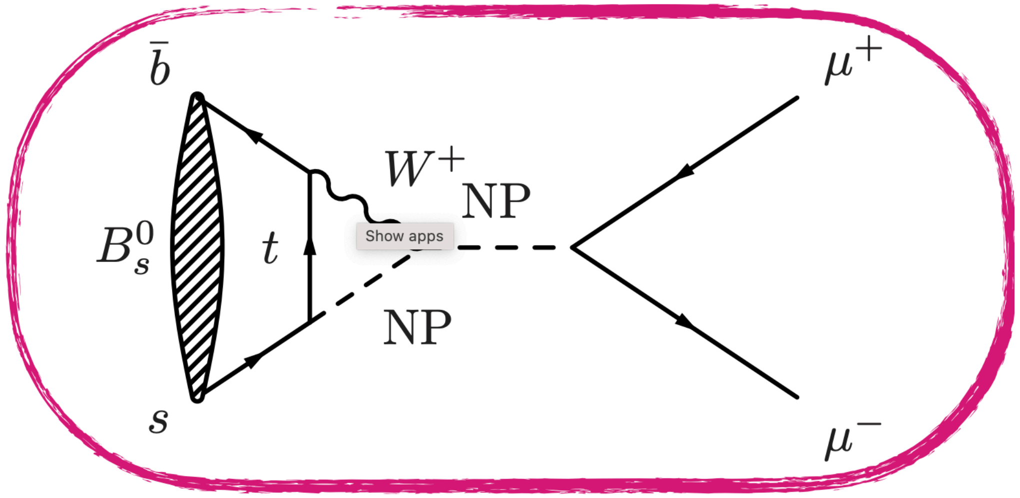
BSM searches in b-decays

Dedicated quark-flavour results in Eva Gersabeck's talk earlier

$B_s \to \mu^+\mu^-$

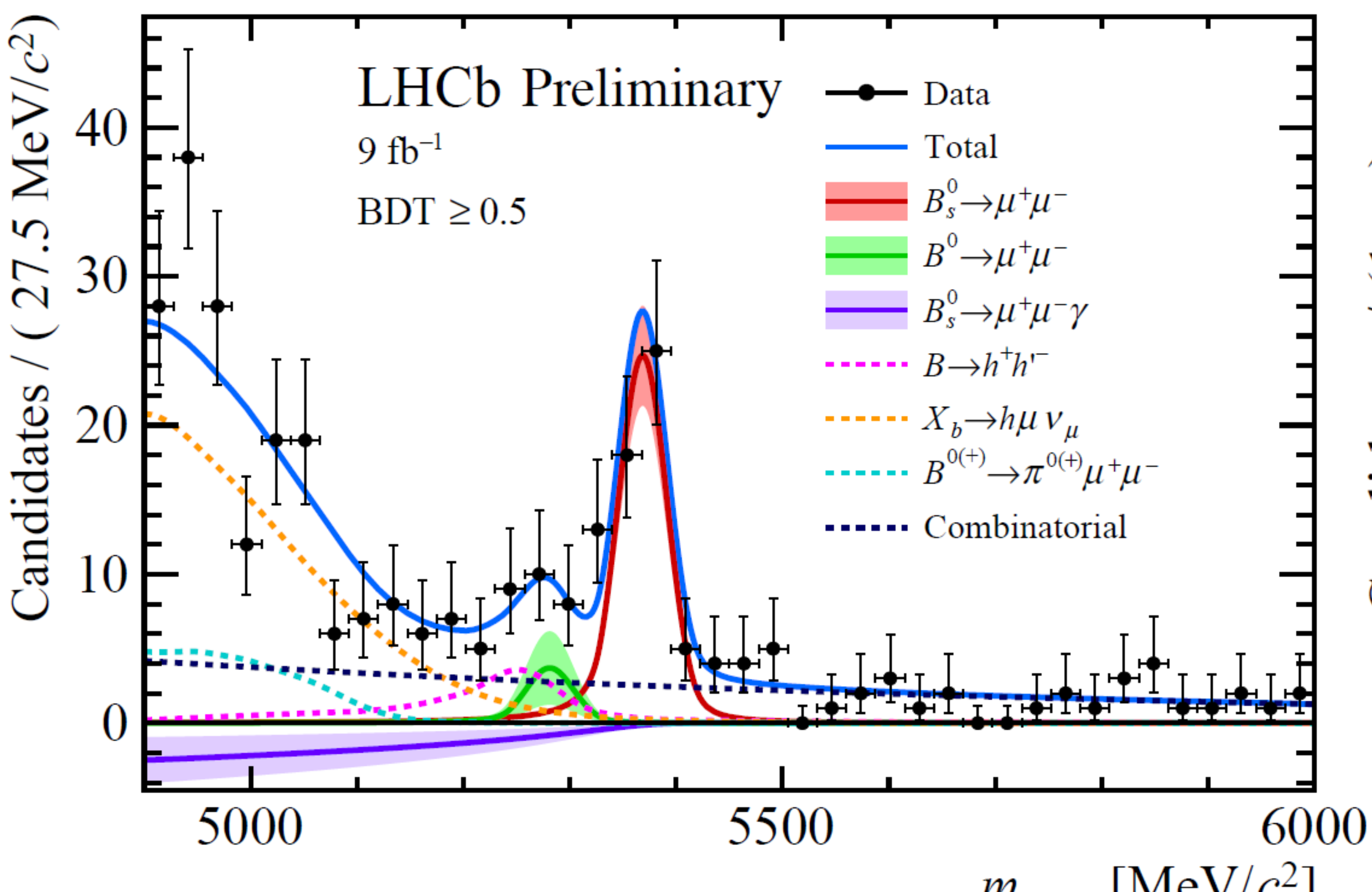
- Very rare and experimentally clean final states, particularly sensitive to NP

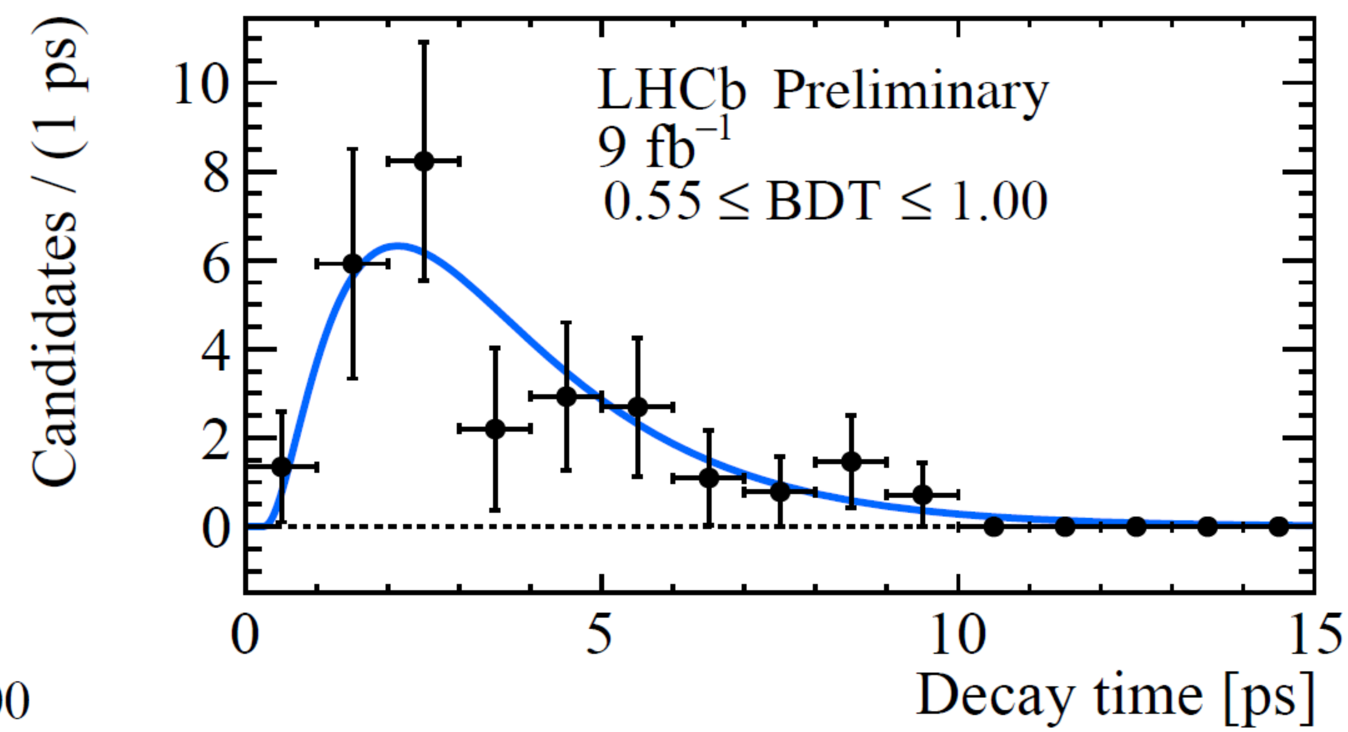




$$\mathscr{B}(B_s^0 \to \mu^+\mu^-)_{\mathrm{SM}} = 3.66 \pm 0.14 \times 10^{-9}$$

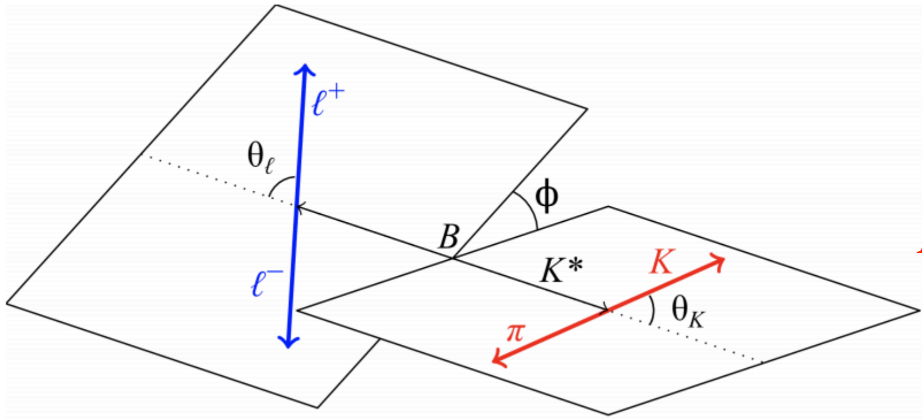
$$\mathscr{B}(B_s^0 \to \mu^+\mu^-) = (3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9} \quad (10.8\sigma)$$





LHCB-PAPER-2021-007

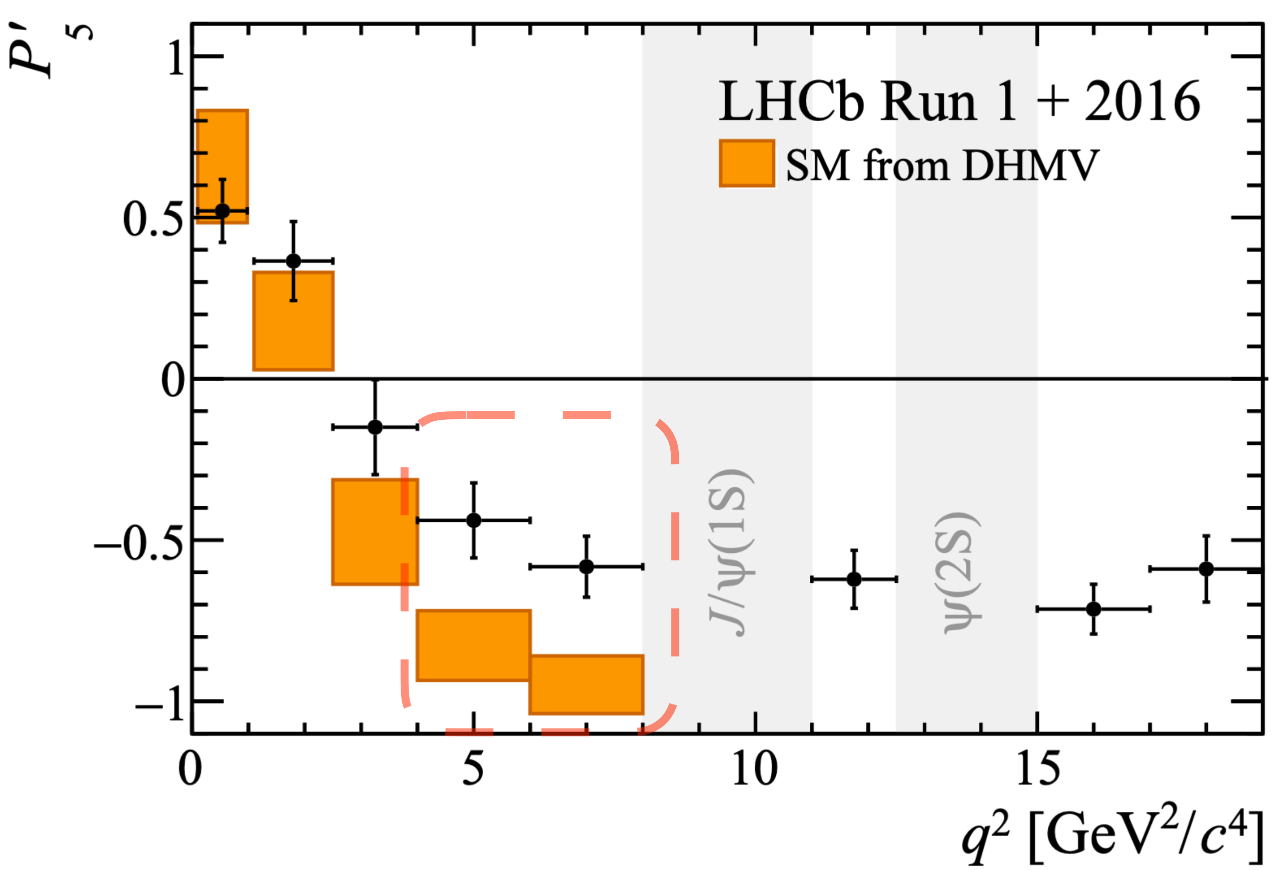
Angular anomaly in $B \to K^*\mu^+\mu^-(P_5')$



$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}}\bigg|_{\mathrm{P}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l$$
$$-F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+\tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

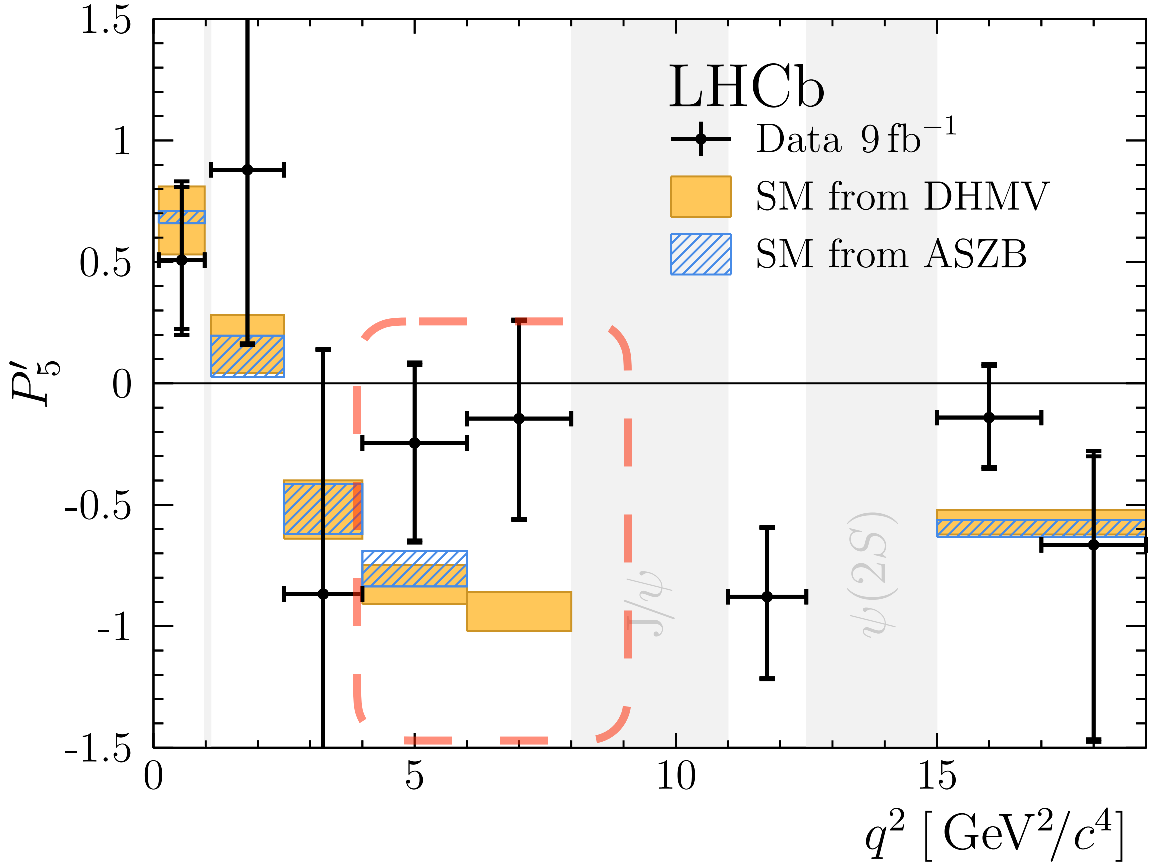
$$P_5' = S_5/\sqrt{F_L(1-F_L)}$$

$B^0 \to K^{*0}\mu\mu$ 4.7 fb^{-1}



Phys. Rev. Lett. 125, 011802

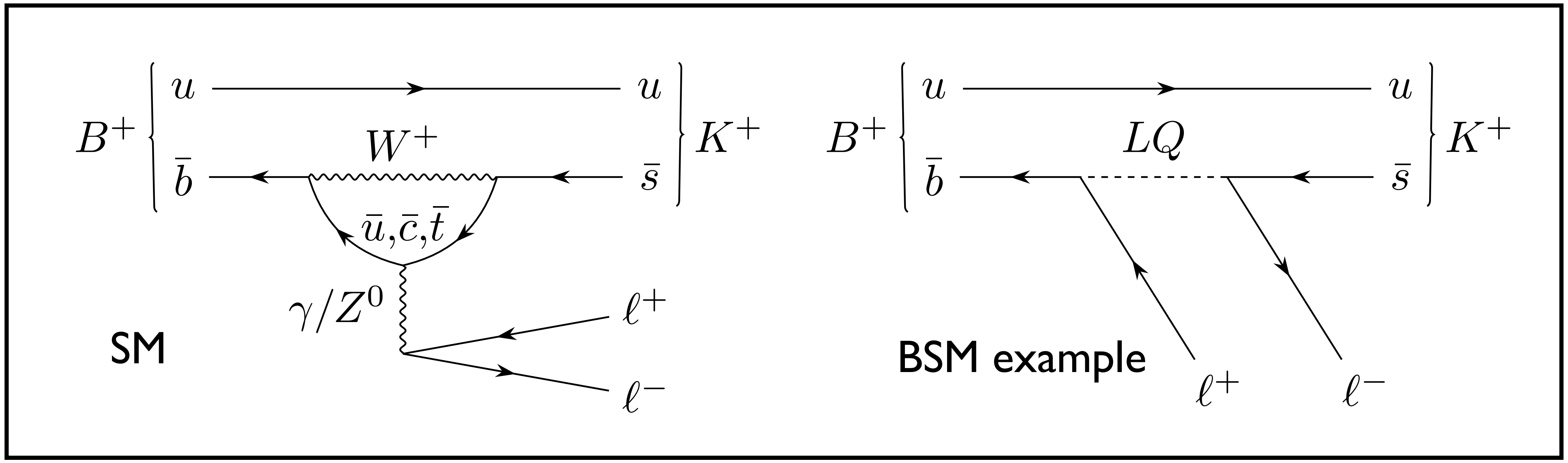
$B^+ \to K^{*+}\mu\mu$ 9 fb^{-1}



2012.13241

Test of lepton flavour universality R_K

- Many experiments are testing LFU → 2 dedicated sessions in Parallel Stream 2
  - In particular LHCb has revealed a range of anomalies known as $R_K, R_{K^*}, R_{D^*}^{\tau,\ell}$



$$R_K = \frac{\int_{1.1\,\mathrm{GeV}^2}^{6.0\,\mathrm{GeV}^2} \frac{\mathrm{d}\mathcal{B}(B^+\to K^+\mu^+\mu^-)}{\mathrm{d}q^2}\mathrm{d}q^2}{\int_{1.1\,\mathrm{GeV}^2}^{6.0\,\mathrm{GeV}^2} \frac{\mathrm{d}\mathcal{B}(B^+\to K^+e^+e^-)}{\mathrm{d}q^2}\mathrm{d}q^2}$$

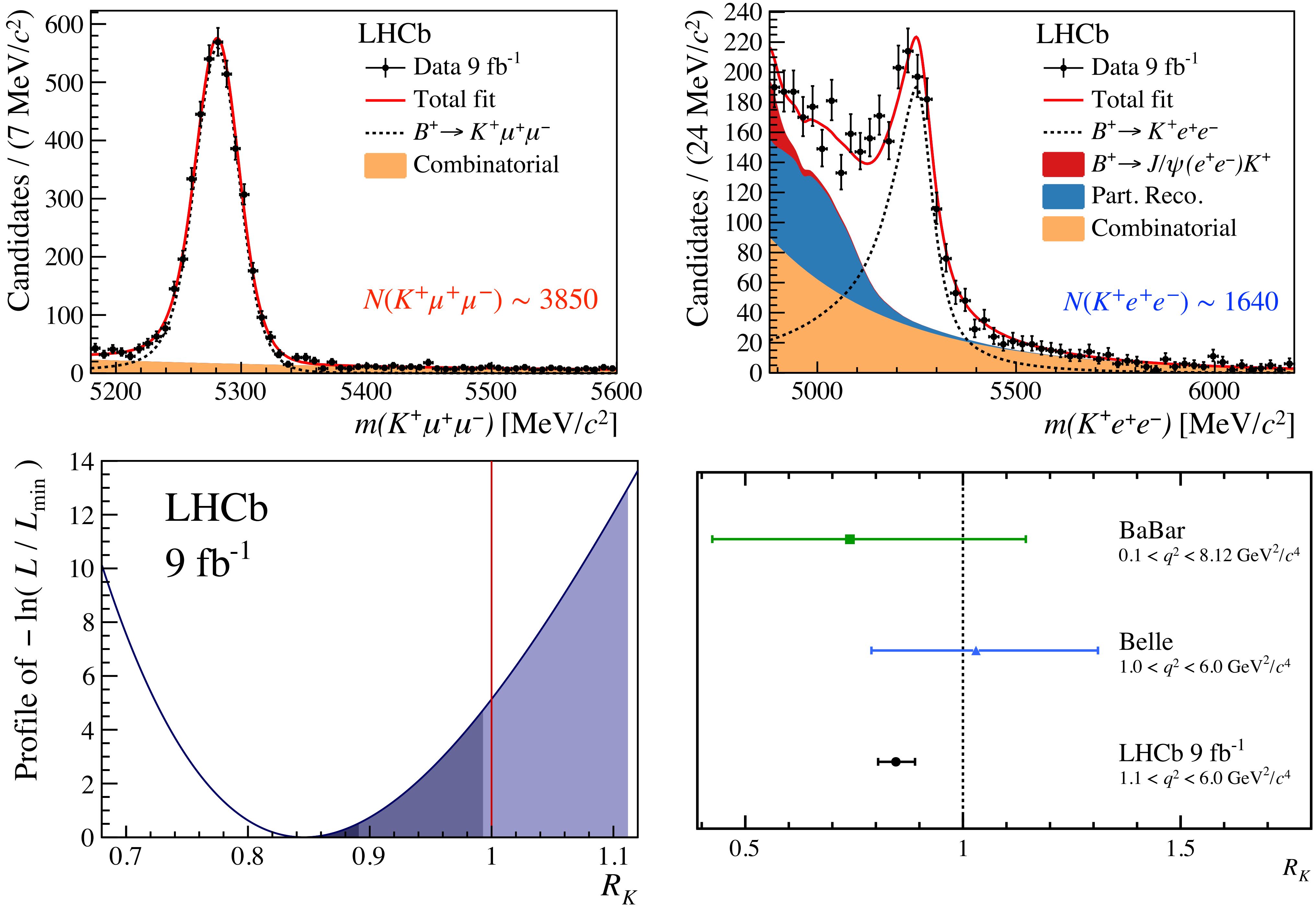
Double-ratio approach → cancel out most systematic uncertainties

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+J/\psi(\mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to K^+J/\psi(e^+e^-))} = \frac{N^{\mathrm{rare}}_{\mu^+\mu^-}\ \varepsilon^{J/\psi}_{\mu^+\mu^-}}{N^{J/\psi}_{\mu^+\mu^-}\ \varepsilon^{\mathrm{rare}}_{\mu^+\mu^-}} \times \frac{N^{J/\psi}_{e^+e^-}\ \varepsilon^{\mathrm{rare}}_{e^+e^-}}{N^{\mathrm{rare}}_{e^+e^-}\ \varepsilon^{J/\psi}_{e^+e^-}}$$

LHCb-PAPER-2021-004

More in Razvan-Daniel Moise's talk in PS

Test of lepton flavour universality in $B^+ \to K^+\ell^+\ell^-$



- What does this mean for BSM searches?
  - Dedicated resonance searches (e.g. LQ, Z' at ATLAS CMS)
  - Global fit **EFT** Lagrangian for $b \to s\ell\ell$: $\mathcal{L}_{\rm eff} \propto \frac{4G_F}{\sqrt{2}} \sum_k C_k(\mu) O_k(\mu)$

J. Kriewald, Moriond 2021

Input to the global fit on $b \to s\ell\ell$

Results: V_1 leptoquark & non-unitary mixing from **VL** leptons

~ 350 Observables taken into account:

Lepton Flavour Violation: $(\mu - e)$-conversion, $\ell \to \ell'\gamma$, $\ell \to \ell'\ell'\ell'$, $\tau \to (\rho, \phi)\ell$,
$B_{d,s} \to \ell^\pm \ell'^\mp$, $K_L \to \mu^\pm e^\mp$, $B \to (K, K^*, \pi)\ell^\pm \ell'^\mp$, $K \to \pi \ell^\pm \ell'^\mp$, $(B \to K\nu\bar{\nu}$, $K \to \pi\nu\bar{\nu})$

EW Precision Observables: g_V^ℓ, g_A^ℓ, Γ_Z^ℓ, $Z \to \ell\ell^{(\prime)}$

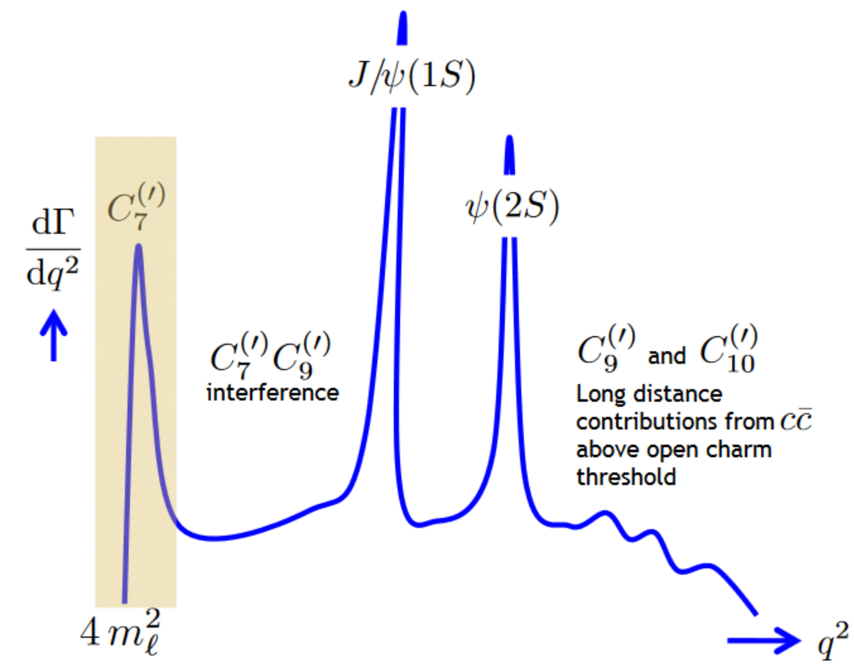
Semi-leptonic decays: $B_{d,s} \to \mu\mu$, $B_s \to \phi\mu\mu$, $B \to K^{(*)}\mu\mu$, $B \to K^{(*)}ee$, $B \to D^{(*)}\tau\nu$,
$D_{(s)} \to \ell\nu$, $D \to \pi\ell\nu$, $D \to K\ell\nu$, $K \to \ell\nu$, $\tau \to (K, \pi)\nu$, $B \to \ell\nu$, $B \to \pi\ell\nu$

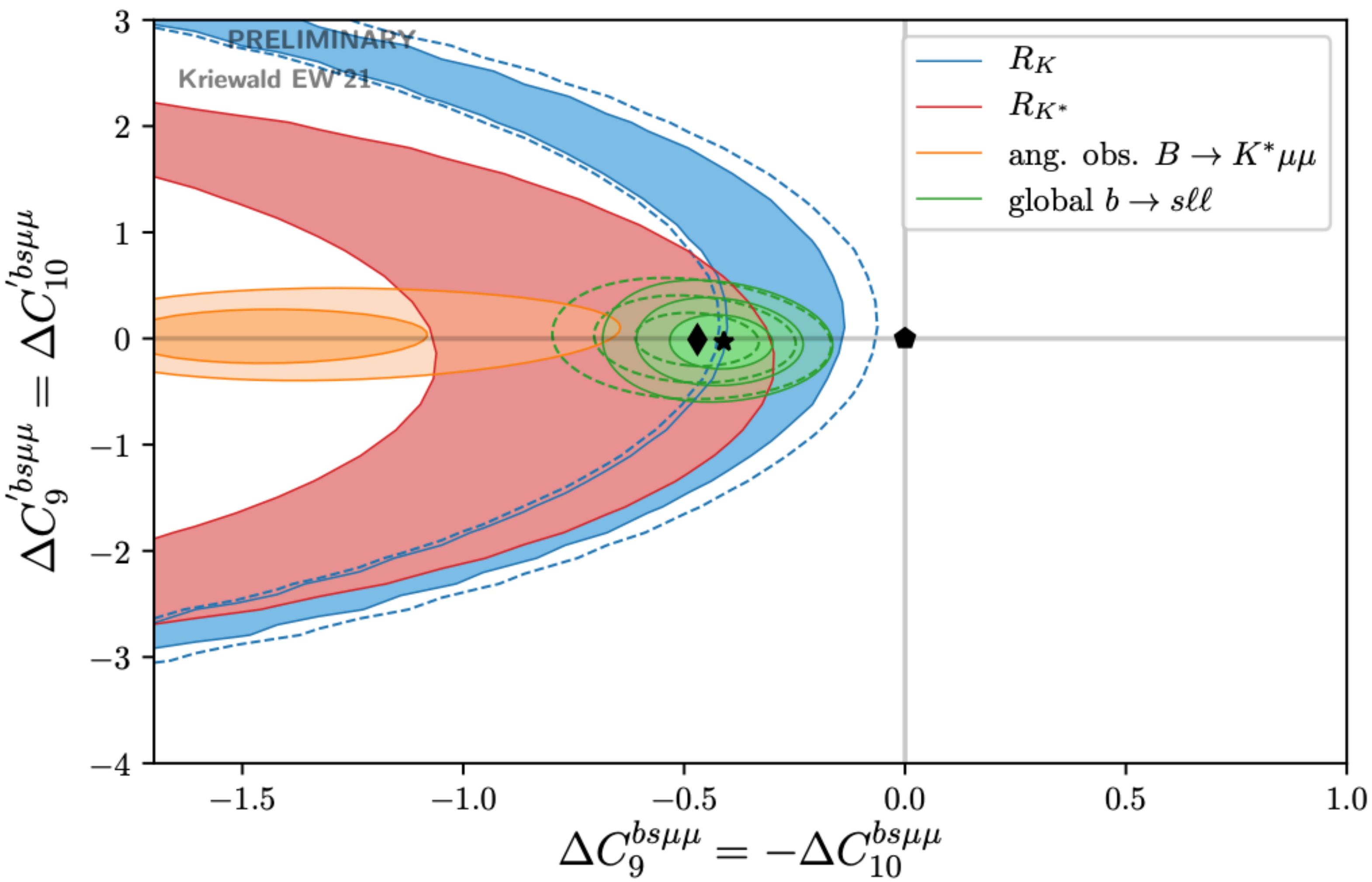
LFU Violation: $R_{K^{(*)}}$, $R_{D^{(*)}}$, angular observables and asymmetries in $b \to s\ell\ell$ à la P_5'

Direct searches (colliders): $m_{V_1} \gtrsim 1.5\,\mathrm{TeV}$

Global EFT fit for $b \to s\ell\ell$

EFT Lagrangian for $\boldsymbol{b \to s\ell\ell}$: $\mathcal{L}_{\text{eff}} \propto \frac{4G_F}{\sqrt{2}} \sum_k C_k(\mu) O_k(\mu)$





- - -: old data
⬠: SM
◇: former best fit (B.F.)
★: new B.F.

J. Kriewald, Moriond 2021