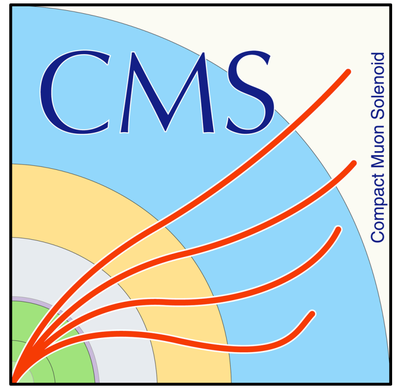
Searches for Dark Matter and other exotic particles from ATLAS and CMS

LA THUILE 2025 - Les Rencontres de Physique de la Vallée d'Aoste

On behalf of the ATLAS and CMS collaborations
Michael Holzbock (CERN)
March 14, 2025

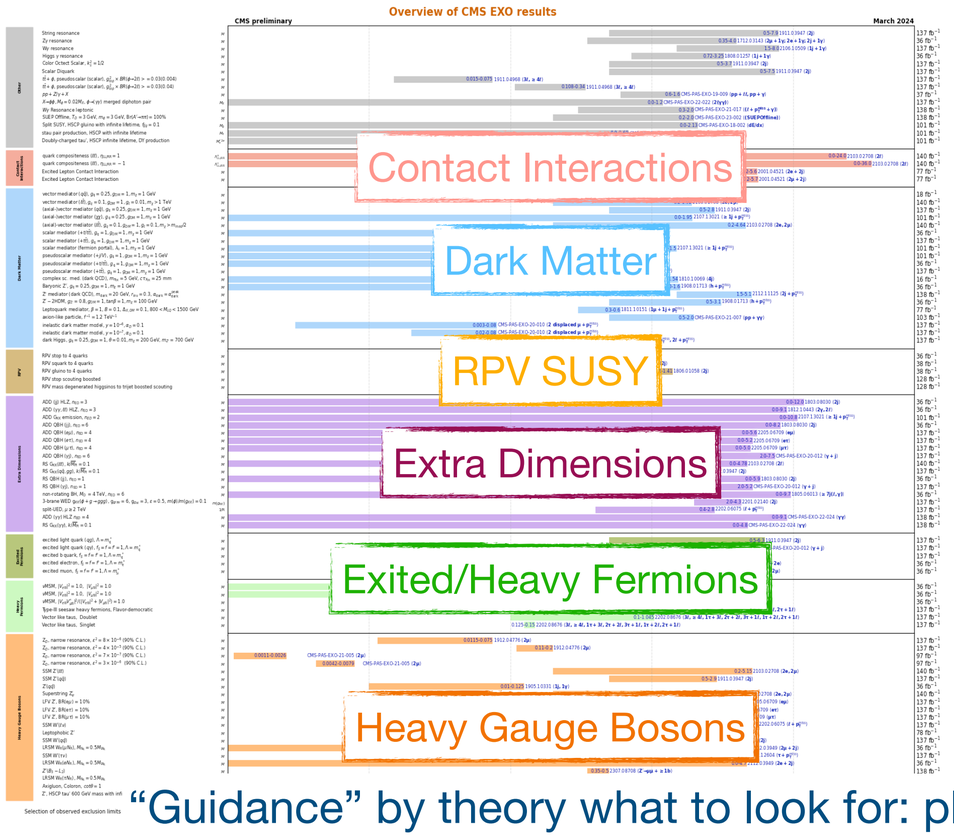


LHC Searches: Needle in the Haystack?

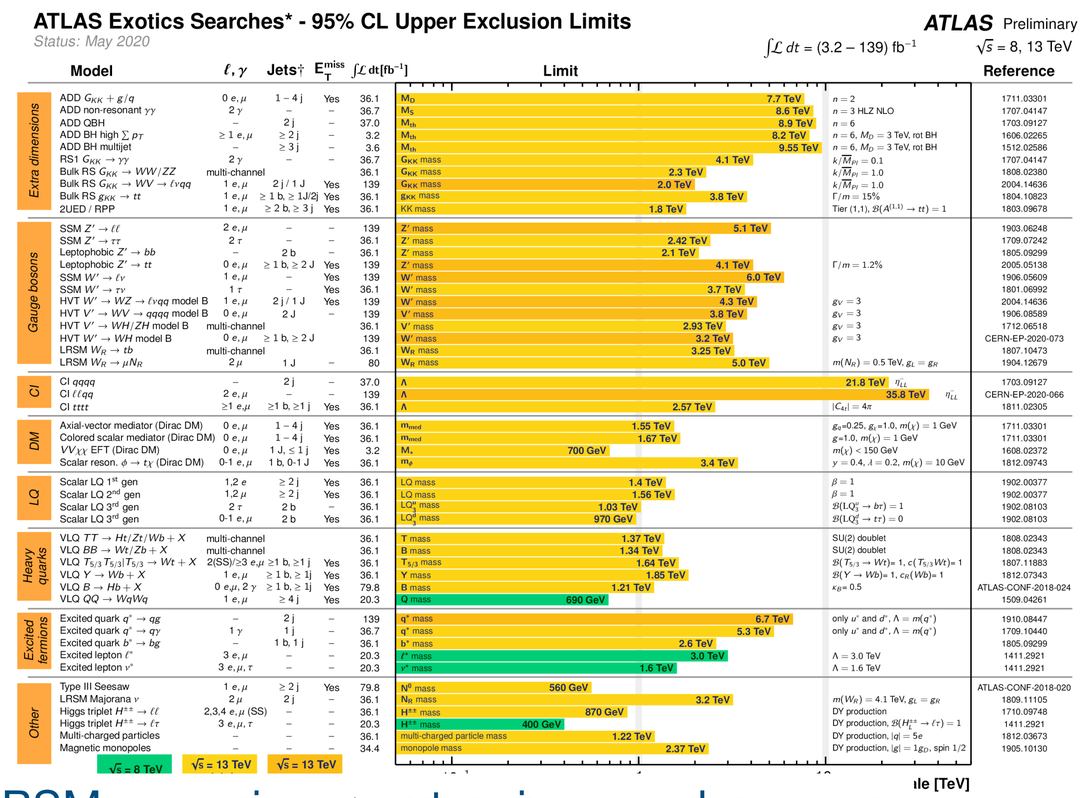
- Countless experimental & theoretical motivations for physics beyond the SM
  - Dark Matter, baryon asymmetry, neutrino masses, metastability of SM vacuum, …

→*Do signals of BSM physics exist in the LHC data?*

CMS Summary Plot



ATLAS Summary Plot



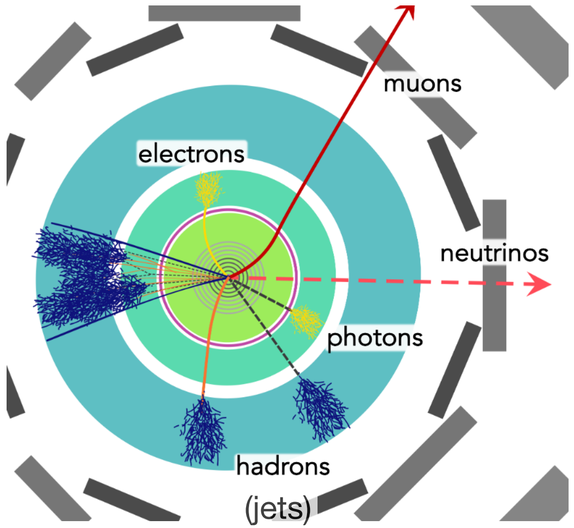
"Guidance" by theory what to look for: plethora of BSM scenarios → extensive search program

LHC Searches: Quo Vadis?

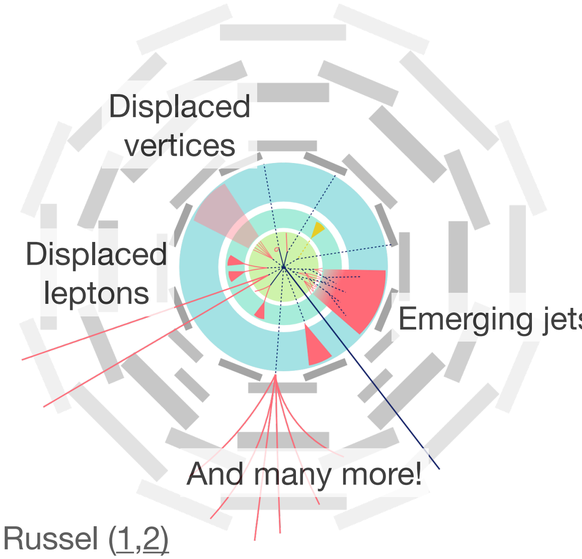
- Nearly endless ways how NP could be realised in LHC data, no "smoking gun" from theory
  - Seems like ball is in the court of the experimentalists!
- Advantages of ATLAS & CMS: general-purpose experiments, sensitive to variety of signatures
  - Empirically scan "standard final states" in Run2 & Run3 data for NP
  - Target “unconventional signatures” predicted by BSM scenarios
  - Access new phase space via specialized data acquisition: data scouting (CMS), TLA* (ATLAS), delayed reco**

Standard Objects

Decays of BSM particles prompt and into SM particles: **Electrons**, **photons**, **muons**, **taus** and **jets** in the final state



Unconventional Signatures



Often from **long-lived particles (LLPs)** predicted in e.g. hidden sector models

BSM particles acquire lifetimes by small couplings or small decay phase space

Image credits: Heather Russel (1,2)

*Trigger Level Analysis

** data parking (CMS) & delayed stream (ATLAS)

LHC Searches: Quo Vadis?

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  - Seems like ball is in the court of the experimentalists!
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Standard Objects

Some **selected highlights** of recent searches that **probe new phase space**, **close existing sensitivity gaps**, **extend previous results** …

Experiment	Reference	Title
ATLAS	EXOT-2023-09	Search for dark mesons decaying into top and bottom quarks
ATLAS	SUSY-2023-26	Search for chargino-neutralino pair production with small mass splittings in VBF topologies
ATLAS	EXOT-2021-31	Search for vector-like electrons and muons
CMS	EXO-21-018	Search for a dilepton resonance produced with a massive vector boson or top quark-antiquark pair
CMS	SUS-23-008	Search for dark matter produced in association with a pair of bottom quarks

+ many more!

Unconventional Signatures

Experiment	Reference	Title
ATLAS	HMBS-2024-68	Search for long-lived particles with Pixel dEdx and low beta or two highly-ionizing tracks
ATLAS	EXOT-2018-55	Prompt lepton jet search
ATLAS	SUSY-2022-11	Displaced e/mu lepton pairs
CMS	EXO-23-013	Search for light long-lived particles decaying to displaced jets
CMS	EXO-21-008	Search for long-lived particles decaying in the CMS muon detectors

+ many more!

Way too many to cover them all in one talk - will exemplarily introduce the ones highlighted in orange

*Trigger Level Analysis

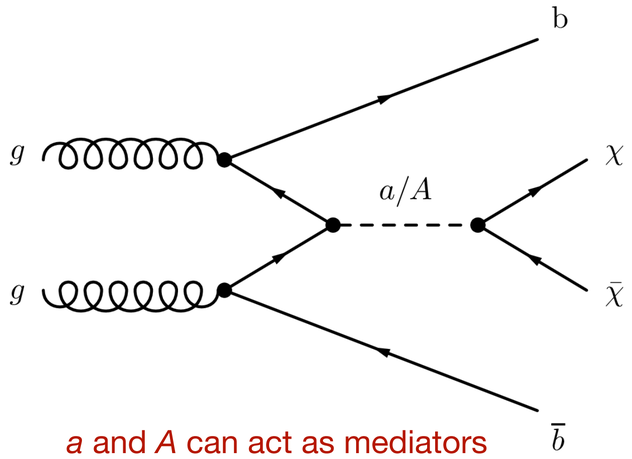
** data parking (CMS) & delayed stream (ATLAS)

SUS-23-008

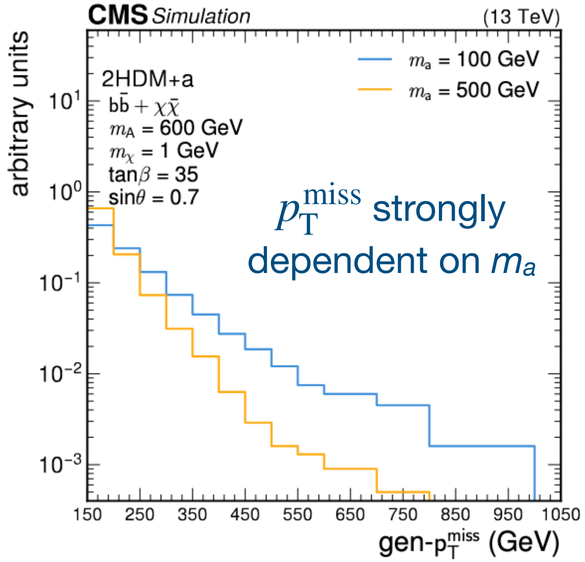
CMS Search for DM with $b\bar{b}$

- DM searches at LHC require **DM χ to interact via some kind of mediator** (Higgs, …)
  - Results in typical $\underbrace{p_{\mathrm{T}}^{\mathrm{miss}}}_{\text{From DM}} + \underbrace{X}_{\text{From Mediator}}$ signatures for DM searches

- CMS considered first search for **DM + non-resonant $b\bar{b}$ pair**
  - Interpretation in 2HDM+*a* model: 5 Higgses ($h, H, A, H^{\pm}$), 1 pseudo-scalar *a* + 1 fermion χ



a and *A* can act as mediators



$p_{\mathrm{T}}^{\mathrm{miss}}$ strongly dependent on m_a

Several **parameters** in this model (m_a, m_χ, …):

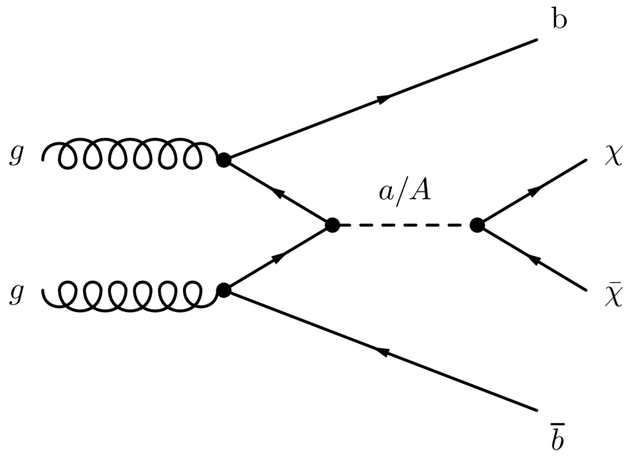
→ Use recommendations of **LHC Dark Matter Working Group** (1810.09420)

Results in **5 free parameters**:

$m_a, m_A, m_\chi, \tan\beta, \sin\theta,$

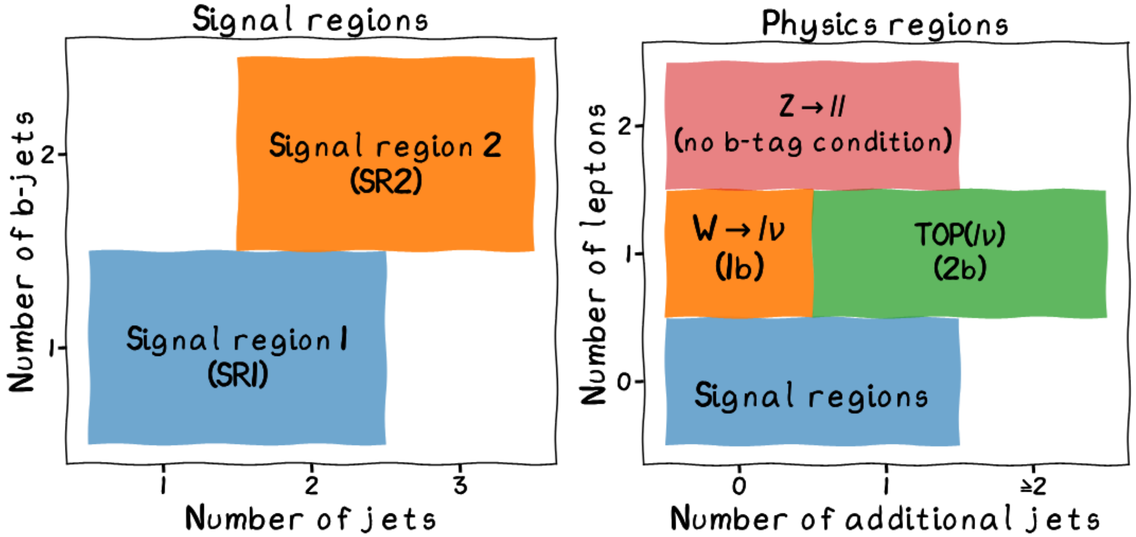
Search capitalises **high couplings of pseudo scalars and b-quarks** at large $\tan\beta$

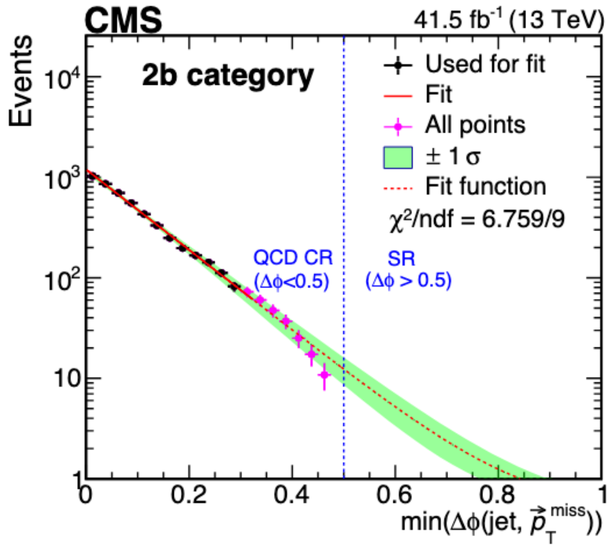
CMS Search for DM with $b\bar{b}$



SUS-23-008

- Select events triggered in Run 2 by $p_{\mathrm{T}}^{\mathrm{miss}}$ signature
- Classify events with **either 1 or 2 identified b-jets**
  - Veto events with e/μ for SRs, apply $p_{\mathrm{T}}^{\mathrm{miss}} > 250$ GeV*
- Constrain $Z \to \ell\ell$, $W \to \ell\nu$ and top backgrounds via 2ℓ and 1ℓ events
- QCD multijet background estimated via fit of $\min(\Delta\phi(\mathrm{jet}, p_{\mathrm{T}}^{\mathrm{miss}}))$ spectra to data



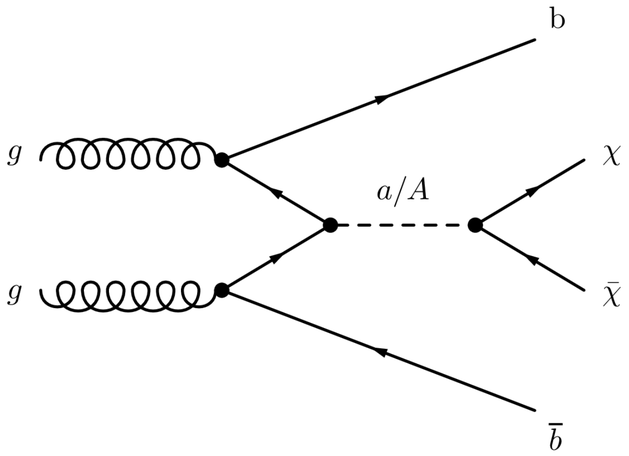


Multijet yields extrapolated from **low (QCD-CR) to high $\Delta\phi$ (SR)** values

* For events with leptons , $p_{\mathrm{T}}^{\mathrm{miss}}$ is replaced with the recoil U

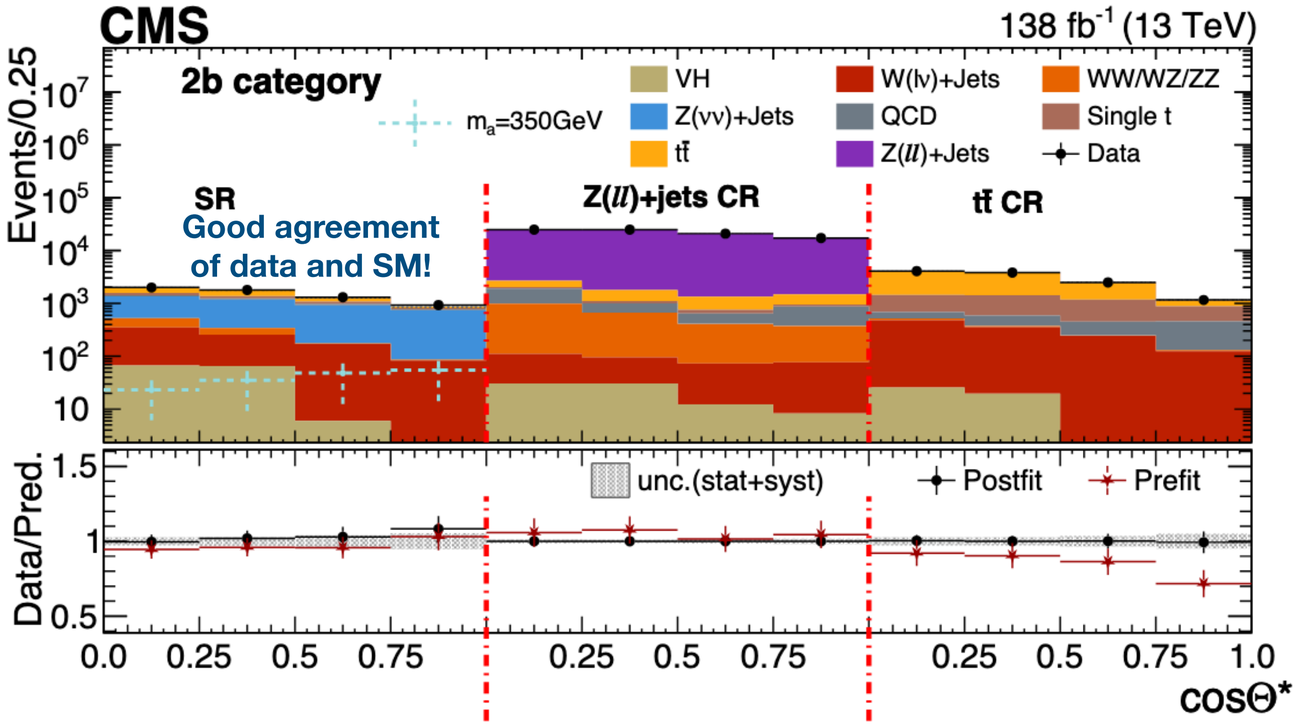
$$U = |\vec{U}| = \left| -\left(\vec{p}_{\mathrm{T}}^{\mathrm{miss}} + \sum \vec{p}_{\mathrm{T}}^{\mathrm{lep}}\right)\right|$$

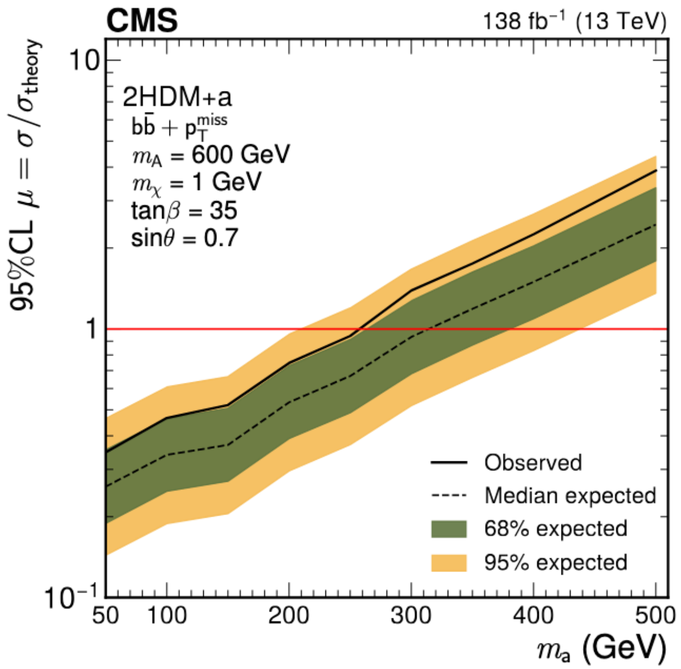
CMS Search for DM with $b\bar{b}$



SUS-23-008

- Signal extraction via **simultaneous fit of SR and CRs** of
  - $p_{\mathrm{T}}^{\mathrm{miss}}$ spectra in 1b category
  - $\cos\Theta^* = |\tanh((\eta_1 - \eta_2)/2)|$ spectra in 2b category*





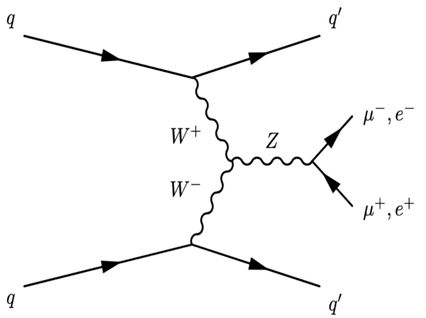
Sensitivity reach for m_a up to 260 GeV! (with m_A = 600 GeV & $m_\chi = 1$ GeV)

* Better S/B discrimination than $p_{\mathrm{T}}^{\mathrm{miss}}$ in 2b category

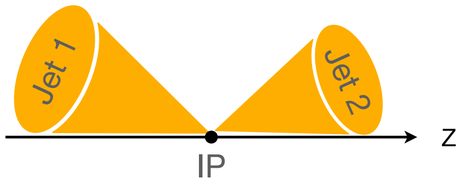
ATLAS SUSY VBF Search

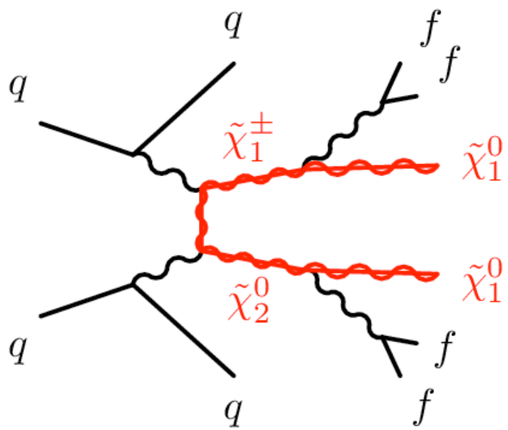
SUSY-2023-26

- Vector boson fusion (**VBF**) allows to study **pure-electroweak processes** at LHC, e.g. Ewk V+jet production
  - Distinctive VBF topology: **2 forward jets with large** m_{jj}
  - Well established probe of SM electroweak sector (and BSM)
- Supersymmetry (SUSY) well-studied extension of SM
  - Naturalness, gauge coupling unifications, attractive DM candidate, …
- SUSY scenarios with **close-in-mass electroweakinos*** $(\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_1^\pm)$ partly still unprobed since LEP



Example for electroweak Z production



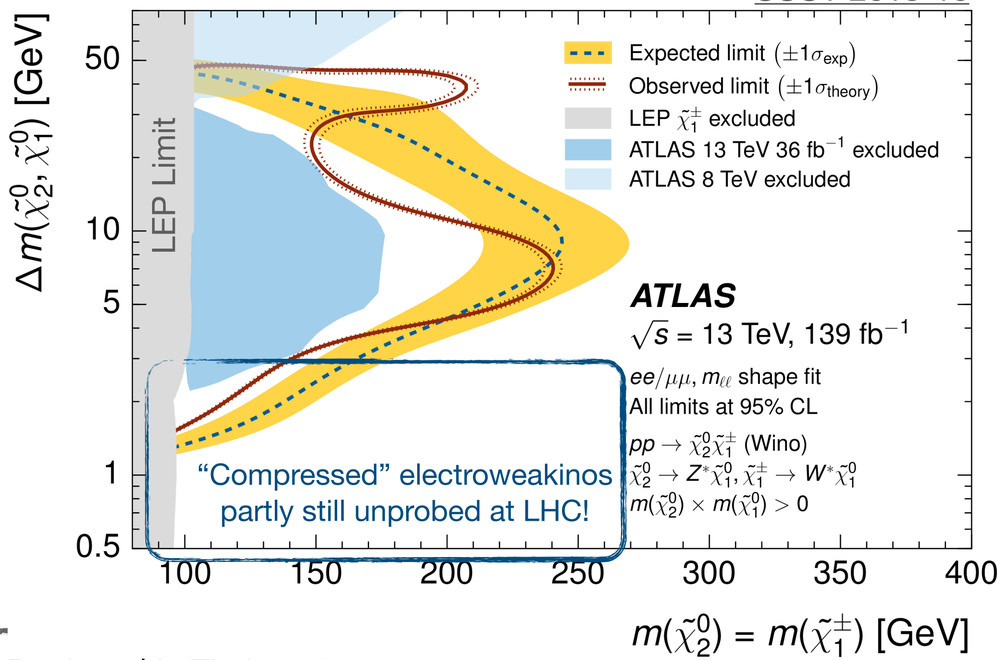


Utilise **VBF production of electroweakinos**

Consider **all-hadronic** final state:
No sensitivity loss due do
lepton reconstruction thresholds

First VBF SUSY search at ATLAS**!

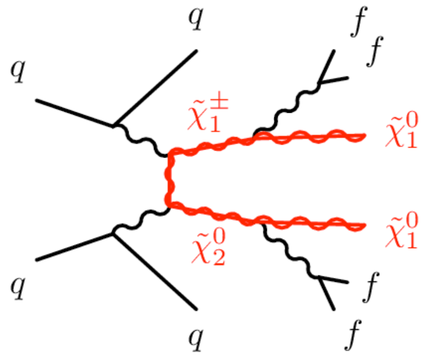
SUSY-2018-16



*superpartners of SM gauge/higgs fields mix to form electroweakinos $\tilde{B}^0, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0 \to \tilde{\chi}_{1,2,3,4}^0$ and $\tilde{W}^1, \tilde{W}^2 \to \tilde{\chi}_{1,2}^\pm$

** inspired by CMS

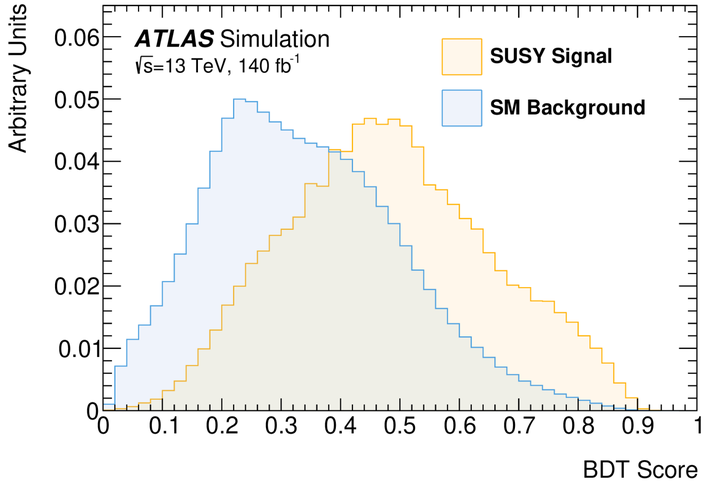
ATLAS SUSY VBF Search

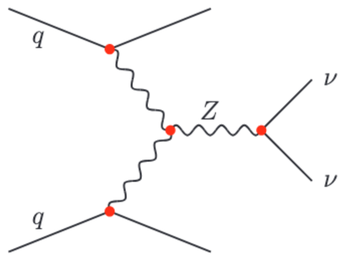


ATLAS EXPERIMENT

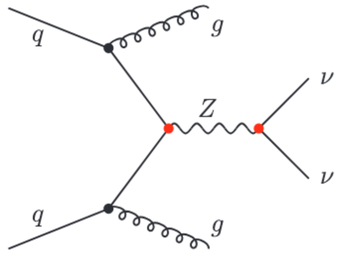
SUSY-2023-26

- Select events triggered by $p_{\mathrm{T}}^{\mathrm{miss}}$ signature in Run 2
- Apply requirements to **enforce VBF topology** (e.g. $m_{jj} > 600$ GeV), lepton veto
  - Enhance signal/background separation with BDT trained on $p_{\mathrm{T}}^{\mathrm{miss}}$, jet and angular variables
  - SR split into $2j$ and $\geq 3j$ categories; signal extraction via fit of BDT tail
- Main backgrounds: **Strong and electroweak** $Z \to \nu\nu$ and $W \to \ell\nu^*$ events
  - Constrained via CRs using 2ℓ and 1ℓ events (using $p_{\mathrm{T}}^{\mathrm{miss}}$ with invisible leptons)

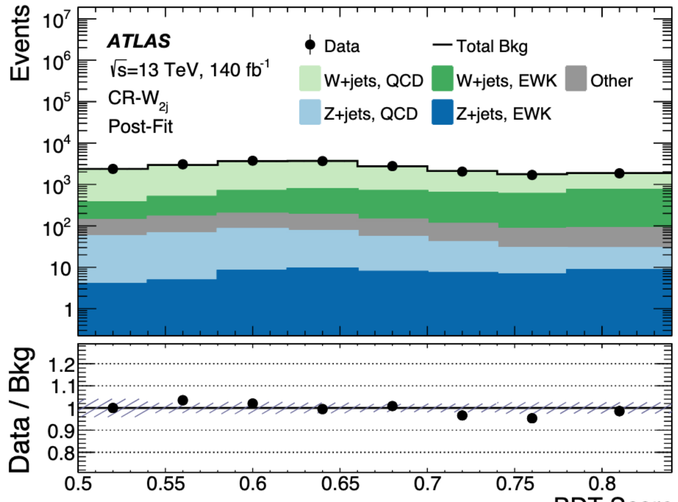




Ewk Z background



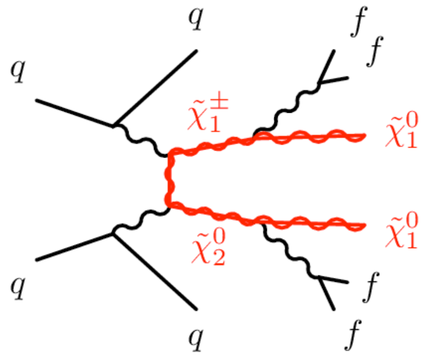
Strong Z background



W-CR for 2j events

* where lepton from *W* is not reconstructed

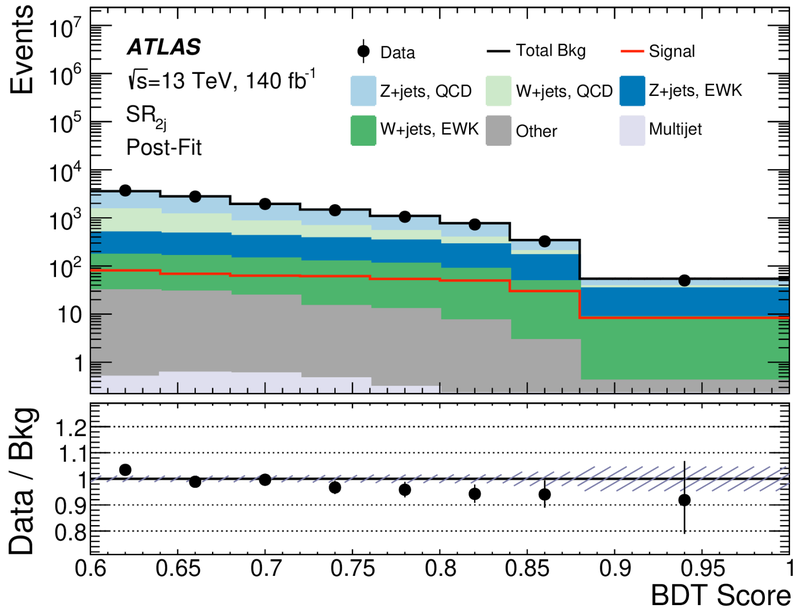
ATLAS SUSY VBF Search



ATLAS EXPERIMENT

SUSY-2023-26

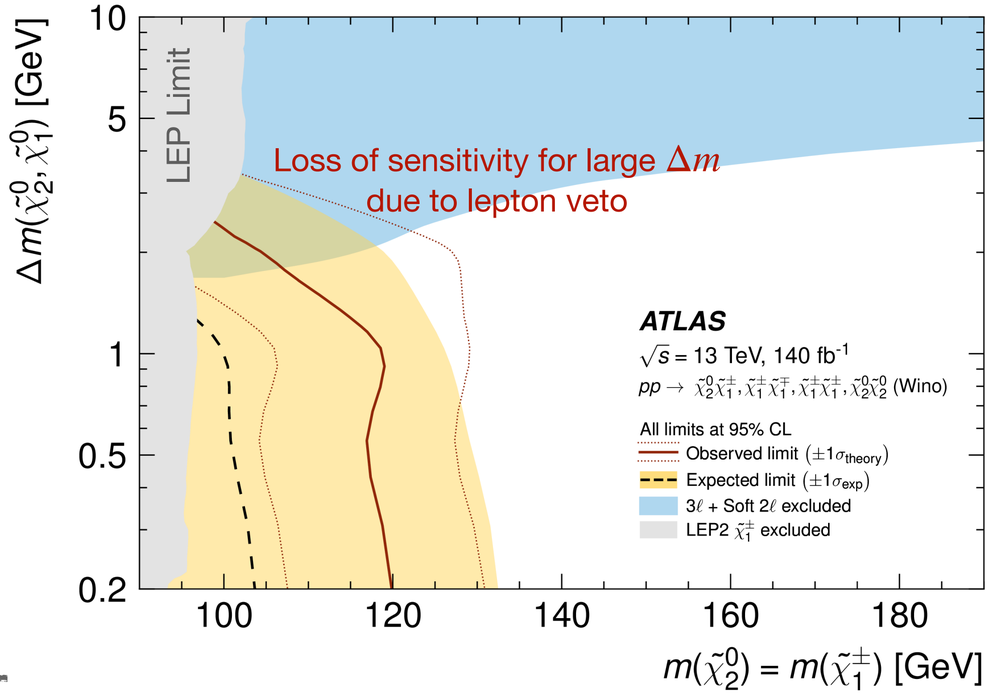
- Extracting signal via simultaneous fit of $2j$ and $\geq 3j$ SRs and CRs
  - Agreement of data and SM predictions within uncertainties
- Results interpreted in simplified model of electroweakino production
  - Assuming wino-like $\tilde{\chi}_2^0, \tilde{\chi}_1^{\pm}$ and bino-like $\tilde{\chi}_1^0$
  - Sensitivity to mass differences $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) < 1$ GeV!



SR for 2j events

Sensitivity to $\tilde{\chi}_2^0, \tilde{\chi}_1^{\pm}$ **masses up to 120 GeV** for such scenarios (finally surpassing LEP!)

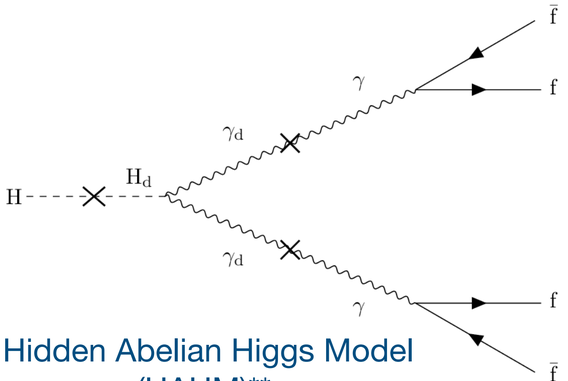
No drop of exclusion reach for $\Delta m < 1$ GeV! (in contrast to leptonic signatures)



EXOT-2018-55

ATLAS Prompt Lepton Jets Search

- Hidden sectors at electroweak scale compelling BSM scenarios
  - Associated particles could be produced at LHC (interaction with SM via mediator)
- Baseline benchmark model: **additional broken U'(1)** gauge symmetry
  - Mediated by massive vector boson: **dark photon** γ_d
  - Kinetic mixing with SM γ with coupling ϵ
  - Dark Higgs H_d drives symmetry breaking of U'(1)
- Targeting **prompt** γ_d **decays*** with masses $\mathcal{O}(10\ \text{MeV}) - \mathcal{O}(10\ \text{GeV})$
  - Search for $\gamma_d \to ee/\mu\mu$ decays
  - Decay products highly collimated: Lepton-Jet (LJ) signatures



Hidden Abelian Higgs Model (HAHM)**

* corresponds to $\epsilon \geq 10^{-5} - 10^{-3}$

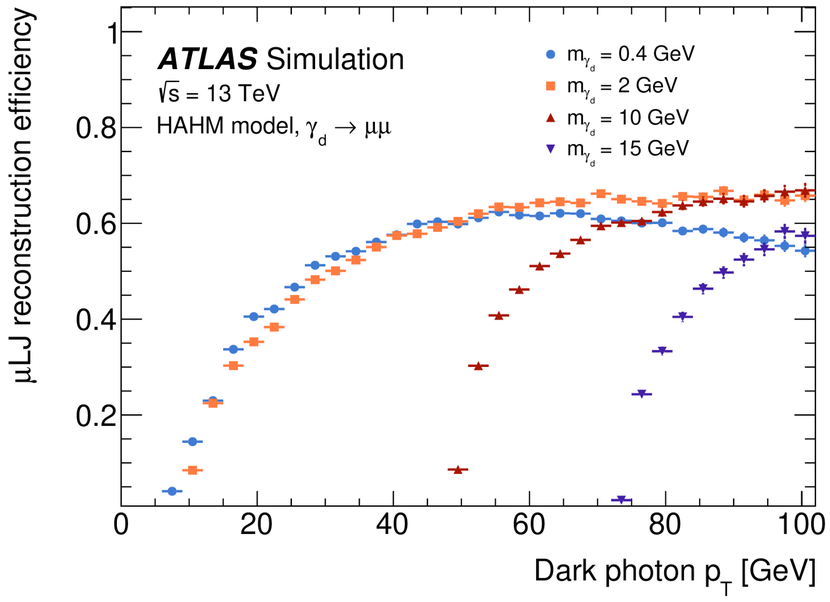
** FRVZ model also considered

EXOT-2018-55

ATLAS Prompt Lepton Jets Search

- Trigger on muon and electron signatures in Run 2
- **Identify leptons** using “standard-like” criteria
  - Combined (ID+MS) muons with custom isolation variable
  - EM clusters with one or more associated ID tracks (showers from close-by e^- may merge)
- **Build LJs objects** using established clustering algorithm* with $\Delta R = 0.4$ from those leptons
  - μLJ: constructed from at least two muons ← Next Slide
  - eLJ: at least one electron and ≥ 2 ID tracks ← Backup
  - Zero total charge, LJ mass calculated from constituents
- Consider several **orthogonal analysis categories**
  - Muon channel: ***μ*LJ-*μ*LJ** and ***μ*LJ-eLJ**
  - Electron channel: **eLJ-eLJ**
    (optimised for $m_{\gamma_d} < 2m_\mu$)

Performance of μLJ reconstruction



* Cambridge-Aachen

EXOT-2018-55

ATLAS Prompt Lepton Jets Search

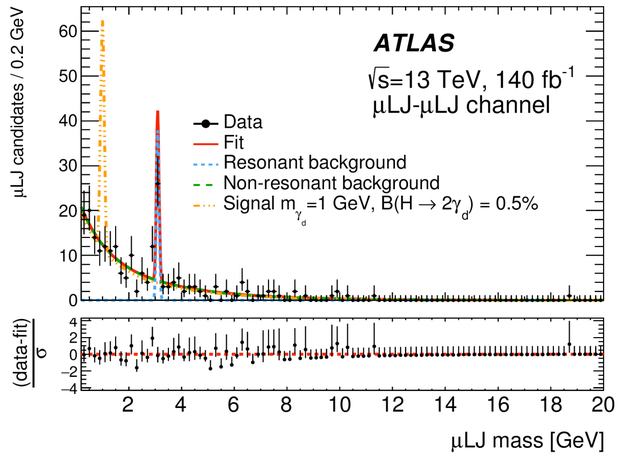
- Analysis strategy for muon channel: unbinned max. likelihood fit of μLJ invariant mass*
  - SM background has non-resonant (virtual γ) and resonant (J/ψ, …) component

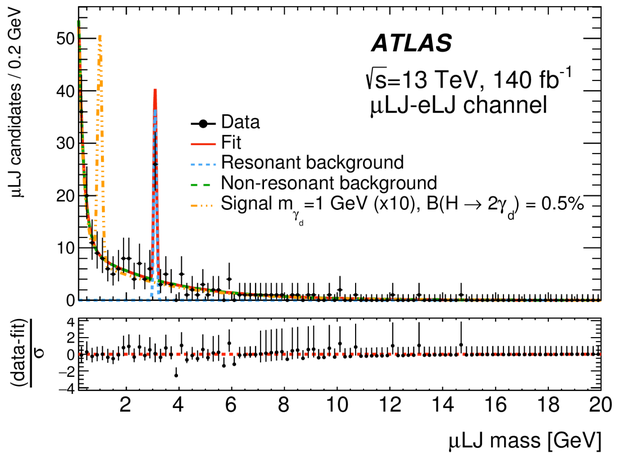
$$B(m_{\mu\mathrm{LJ}}) = N_{\mathrm{exp1}} e^{-m_{\mu\mathrm{LJ}}/\tau_2} + N_{\mathrm{exp2}} e^{-m_{\mu\mathrm{LJ}}/\tau_1}$$ Continuum: double exponential

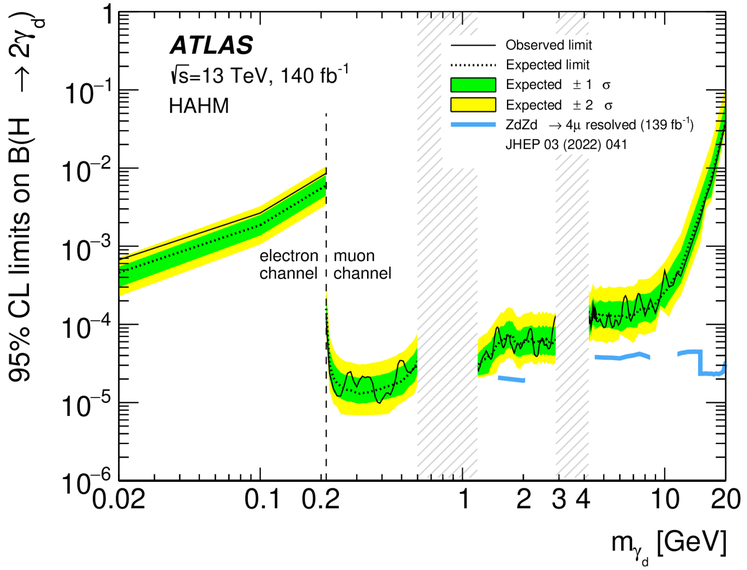
$$+ N_{J/\psi} e^{-\left(\frac{m_{\mu\mathrm{LJ}}-\mu_{J/\psi}}{\sigma_{J/\psi}}\right)^2} + N_{\psi(2S)} e^{-\left(\frac{m_{\mu\mathrm{LJ}}-\mu_{\psi(2S)}}{\sigma_{\psi(2S)}}\right)^2} + N_{\phi} e^{-\left(\frac{m_{\mu\mathrm{LJ}}-\mu_{\phi}}{\sigma_{\phi}}\right)^2},$$ Resonances: Gaussians

- Fit functions validated in two CRs with one μLJ + two extra electrons or muons

Post-fit μLJ spectra in μLJ-μLJ and μLJ-eLJ







Sensitivity down to BRs for $H \to 2\gamma_d\gamma_d + X$ **as low as 0.001%!** (x50 improvement w.r.t Run 1)

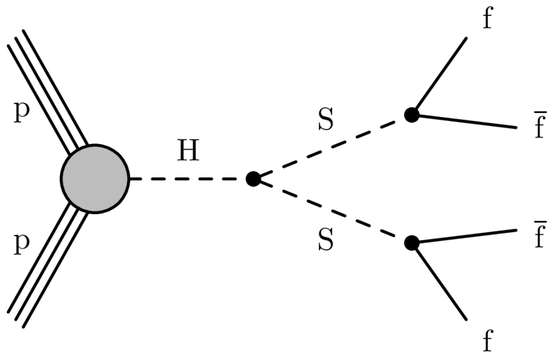
Excellent **complementarity** to **displaced LJ** search! (see backup)

* in μLJ-μLJ each event provides two entries

CMS Search for Displaced Jets

EXO-23-013

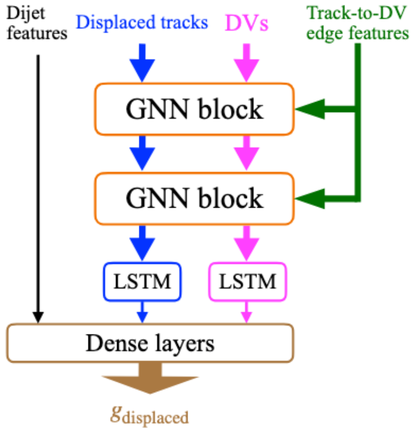
- Hadronically decaying LLPs (decay length ≥ 0.1 mm) appear in many BSM scenarios
  - Dark sectors, SUSY, heavy neutral leptons, …
- Yield distinct **displaced jet signature**
- Benchmark scenario: SM Higgs portal
  - Higgs decay into 2 neutral scalars S, S $\rightarrow f\bar{f}$
  - Appears in e.g. “neutral naturalness” models (where S would be a hidden glueball)
- Search targets on scenarios with $m_{\text{LLP}} < 60$ GeV
  - Focus on hadronic final states via $S \rightarrow b\bar{b}, d\bar{d}, \tau\tau$

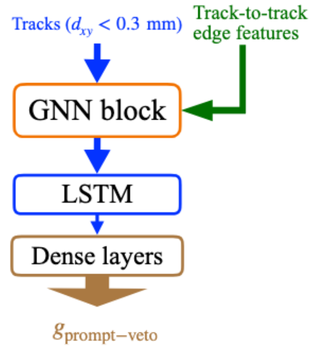


EXO-23-013

CMS Search for Displaced Jets

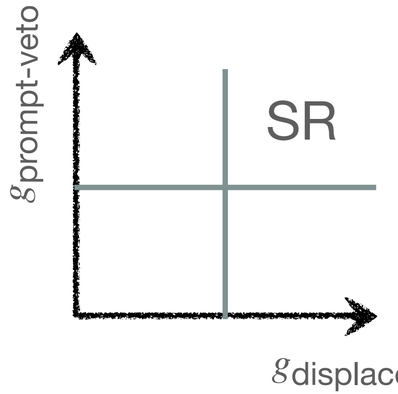
- Dedicated **displaced jet triggers** in Run 3 targeting light LLPs
  - 2 trigger types: based either only on H_T (scalar sum of jet p_T) or H_T+muon
  - Overall trigger efficiencies around 0.4-1.0%
- Construct analysis inputs **dijet candidates**:
  - Form dijet candidates from all jet pairs in the event
  - Associate tracks to each dijet candidate via angular distance
  - Reconstruct displaced vertices* (DVs) for displaced tracks for each dijet candidate
- Dijet candidates, **DVs and tracks** used to train GNNs
  - Graph nodes: tracks & DVs
  - Graph edges: track-to-vertex, track-to-track, … relations
- **2 types of GNNs**
  - "Displaced" GNN: associated displaced tracks and DVs
  - "Prompt-veto" GNN: associated prompt tracks (small d_{xy})
- Both GNNs trained to separate $S \to b\bar{b}$ from multijet





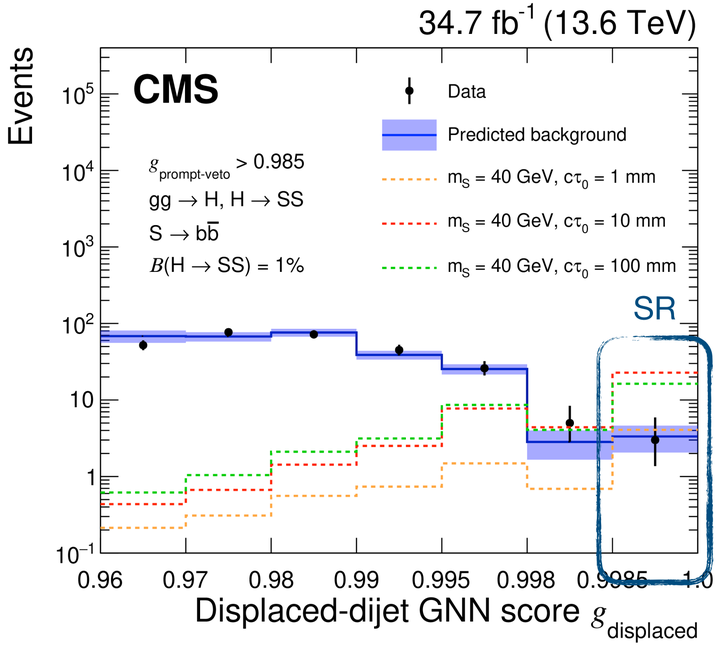
* Two reconstruction algorithms are used: adaptive vertex reconstruction & using points of closest approach

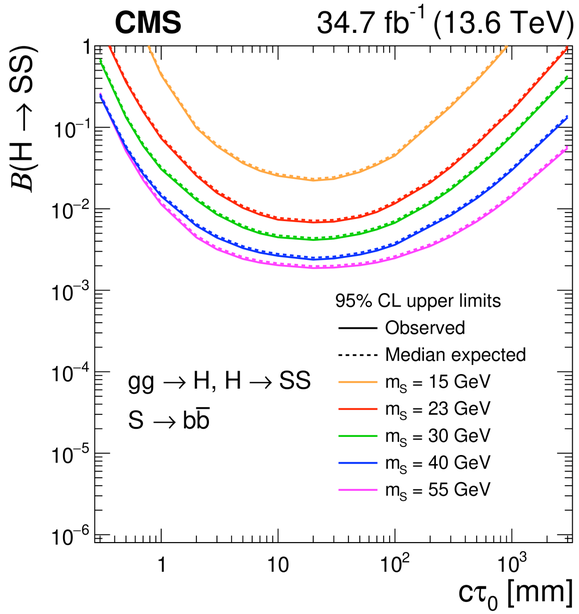
CMS Search for Displaced Jets

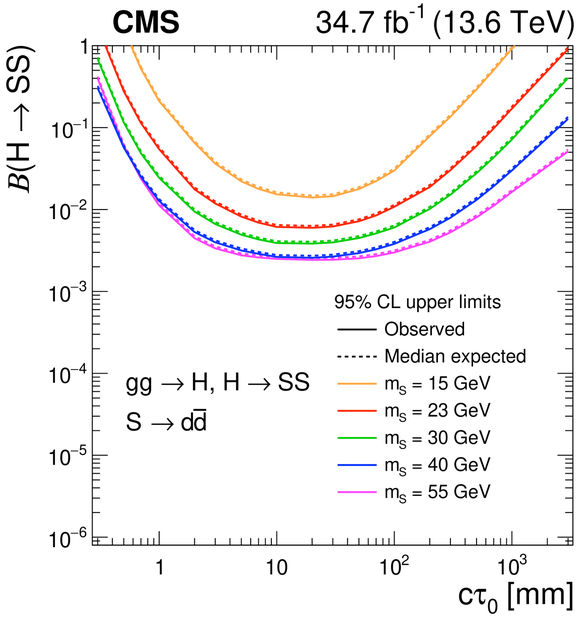


EXO-23-013

- Select events with at least one dijet candidate with well reconstructed DV
- Require **large displaced and prompt-veto GNN scores** for SR
- Estimate backgrounds via ABCD method using plane spanned by both GNN scores
  - Good agreement in SR between prediction and observed data
- Up to **x10 improvements by new techniques** (triggers, reco, GNNs) w.r.t. previous results







Further key achievement (see backup):

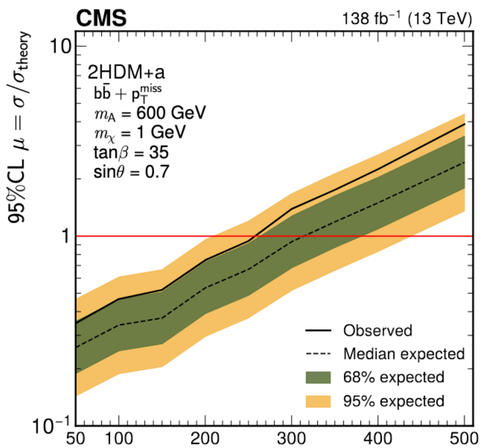
First exclusions of hadronically decaying displaced tau leptons arising from LLPs with decay lengths ≤ 1m

Very similar sensitivity for $S \to b\bar{b}$ and $S \to d\bar{d}$!

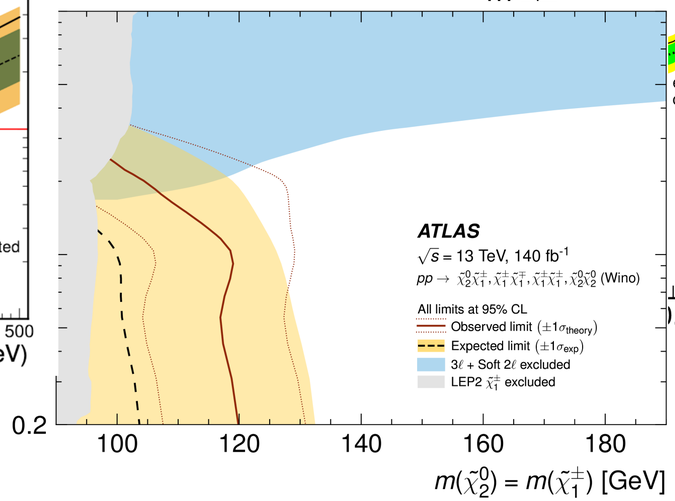
Wrap-up

- **Vibrant program** at the LHC to discover BSM physics
  - No “smoking gun” from theory, need to carefully comb through our datasets!
  - Using both “standard” final states as well as unconventional signatures
- Presented recent, (only very few!) **selected highlights** examples of ATLAS & CMS collaborations

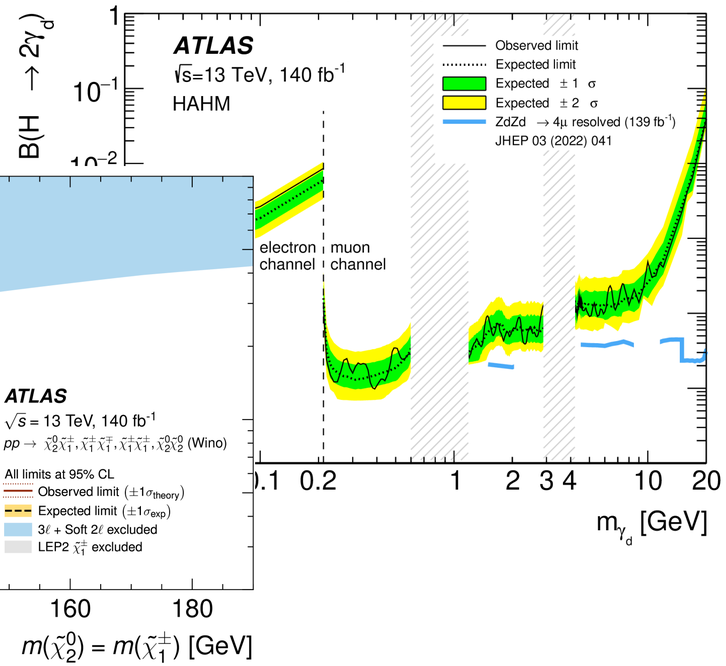
DM $p_T^{miss} + b\bar{b}$



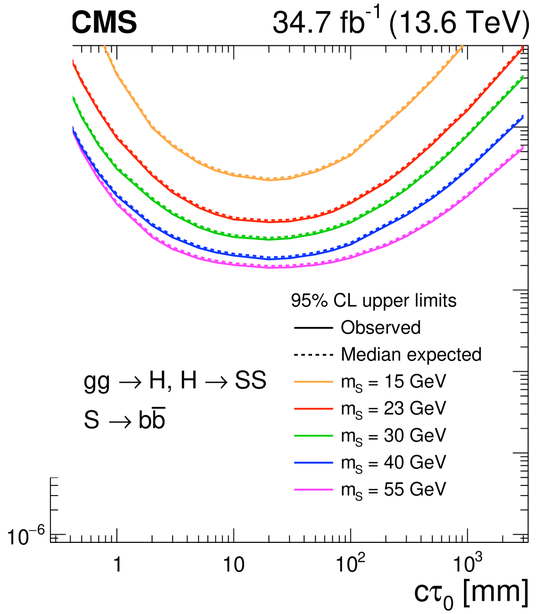
VBF SUSY



Prompt Lepton Jets



Displaced Jets



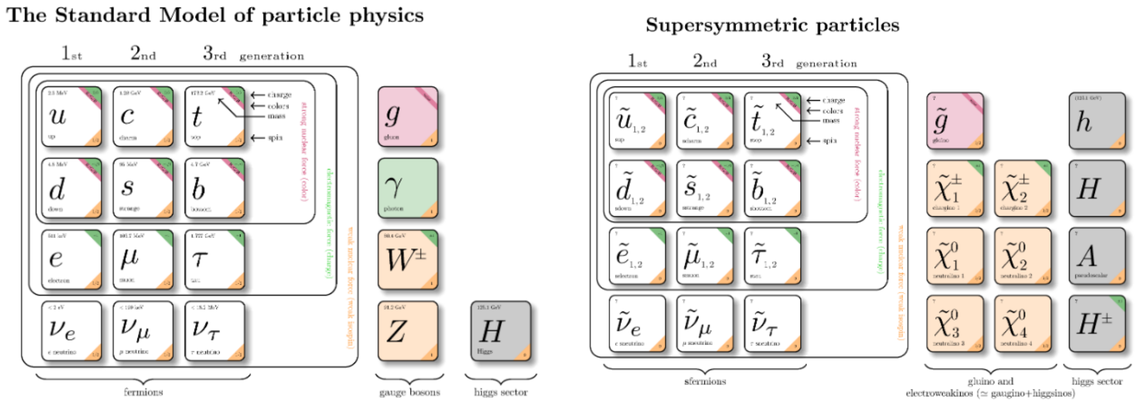
Extras

Recent ATLAS/CMS Searches for DM & LLP

Experiment	Reference	Title
ATLAS	SUSY-2018-25	Search for new physics in the cc+MET final state
ATLAS	EXOT-2020-26	Dark matter search in ETmiss + dark Higgs → bb
ATLAS	EXOT-2021-35	VLQ TT→Wq+X
ATLAS	EXOT-2022-33	Search for low-mass hadronic resonances produced in association with a photon
ATLAS	SUSY-2018-37	Stop pair; 2 leptons, b-jets, RPV
ATLAS	EXOT-2023-09	Search for dark mesons decaying into top and bottom quarks
ATLAS	SUSY-2023-26	Search for chargino-neutralino pair production with small mass splittings in VBF topologies
ATLAS	EXOT-2021-31	Search for vector-like electrons and muons
CMS	SUS-23-008	Search for dark matter produced in association with a pair of bottom quarks

Experiment	Reference	Title
ATLAS	HMBS-2024-68	Search for long-lived particles with Pixel dEdx and low beta or two highly-ionizing tracks
ATLAS	EXOT-2018-55	Prompt lepton jet search
ATLAS	SUSY-2022-11	Displaced e/mu lepton pairs
CMS	EXO-23-013	Search for light long-lived particles decaying to displaced jets
CMS	EXO-21-008	Search for long-lived particles decaying in the CMS muon detectors

The MSSM



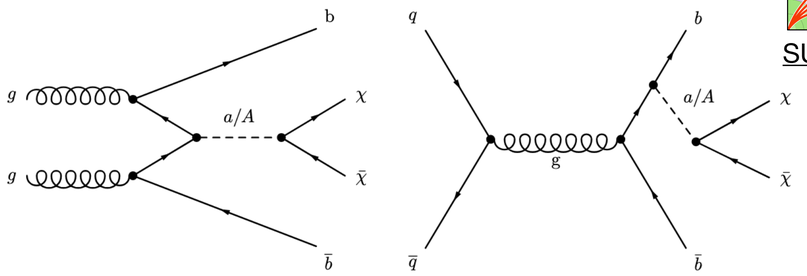
A few important phenomenological features

- After EWSB, gauginos and higgsinos mix to form the neutralinos ($\tilde{\chi}^0_{1,2,3,4}$) and the charginos ($\tilde{\chi}^\pm_{1,2}$)
- The Higgs sector is a two Higgs-doublet (2HDM) of type-II. Physical spectrum is composed of two neutral CP-even Higgs (h and H), one neutral CP-odd Higgs (A) and two charged Higgses ($H^\pm$)
- The light Higgs mass is *predicted* in the MSSM (in terms of the other parameters). The tree level upper bound is m_Z, however radiative corrections are very important and allow to reach the observable value

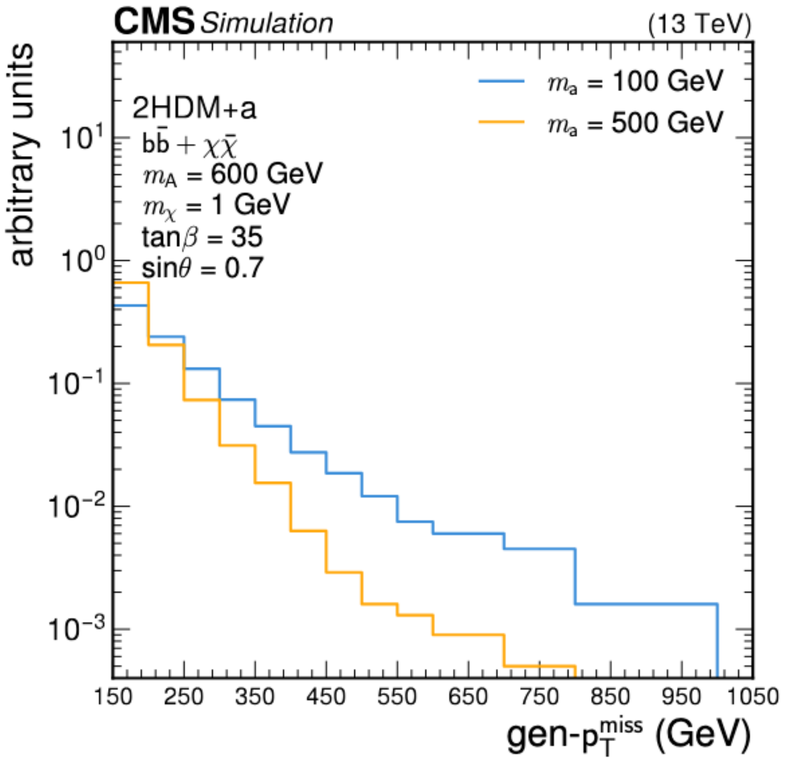
- Slide stolen from Emanuele A. Bagnaschi

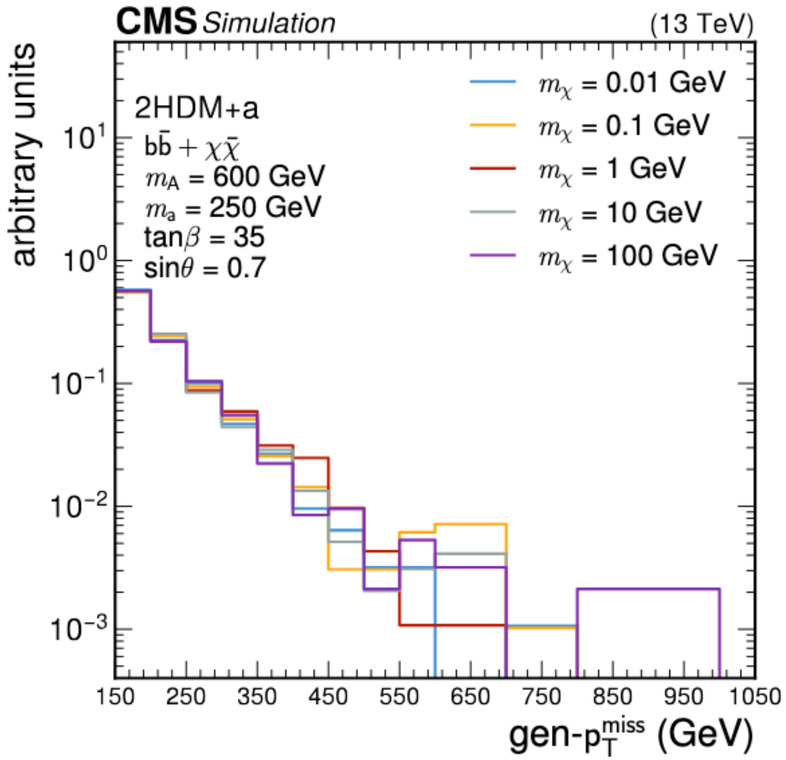
CMS Search for DM with $b\bar{b}$

SUS-23-008



- Dependence on event kinematics across signal grid

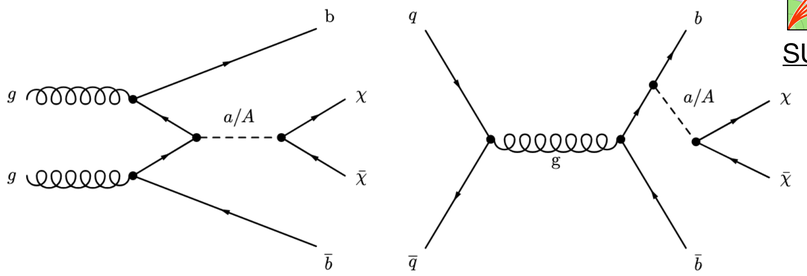


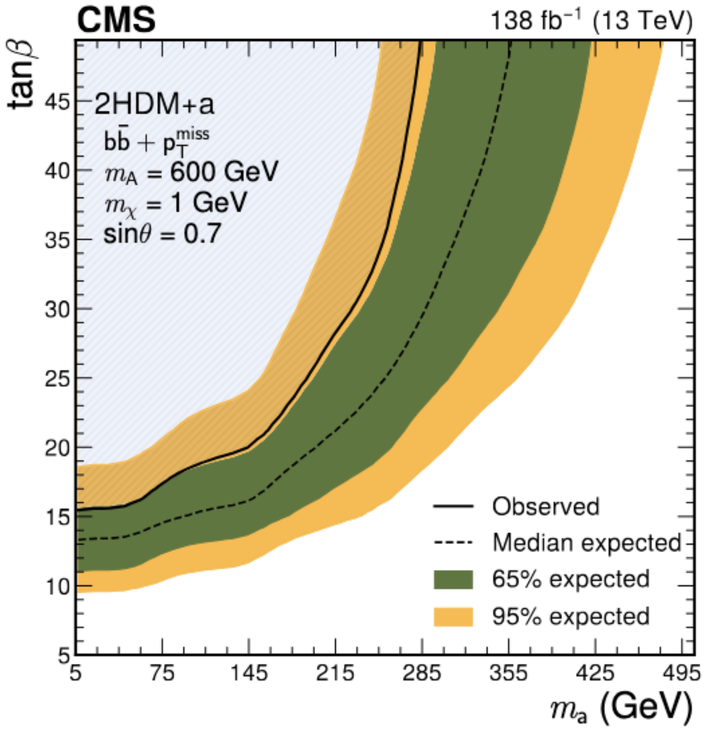


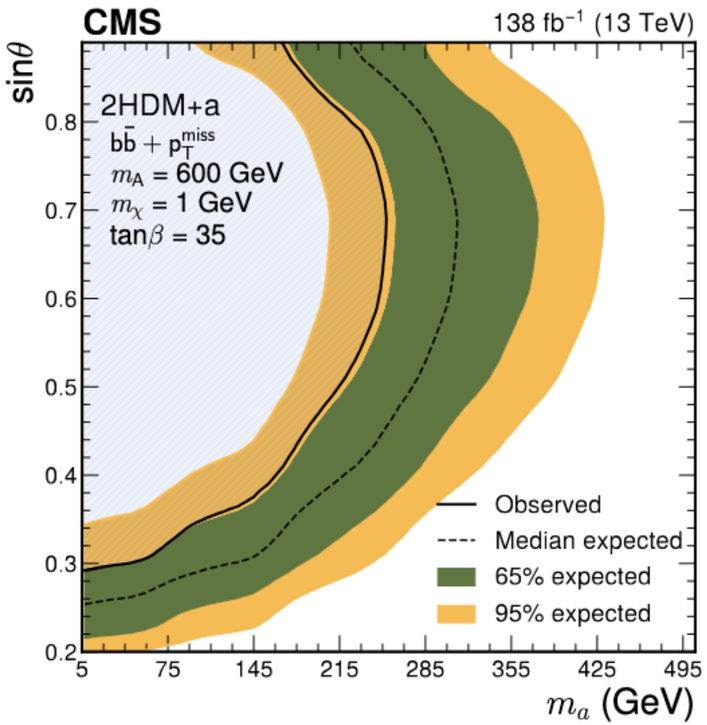
CMS Search for DM with $b\bar{b}$

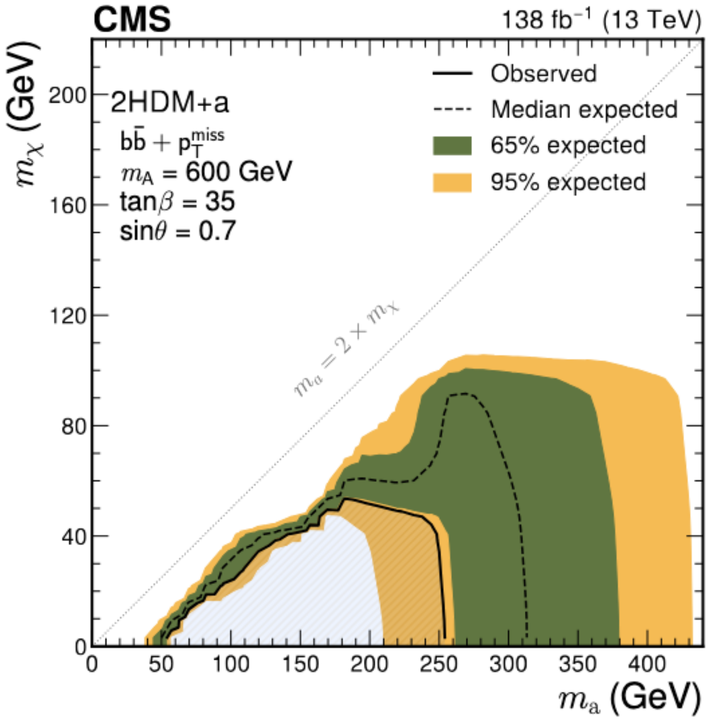
SUS-23-008

- Additional interpretations





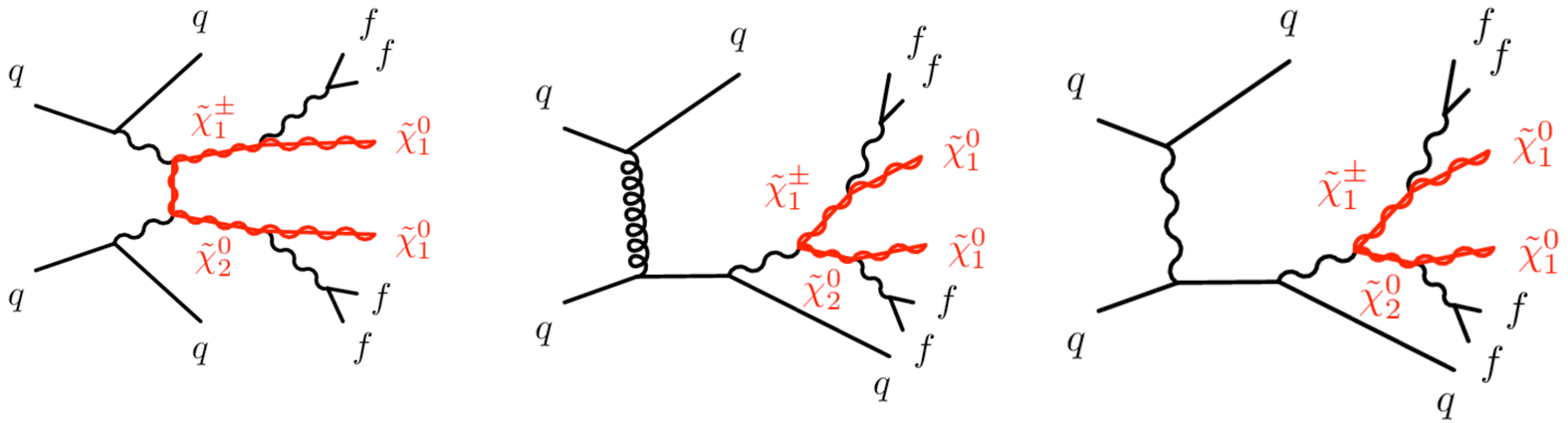




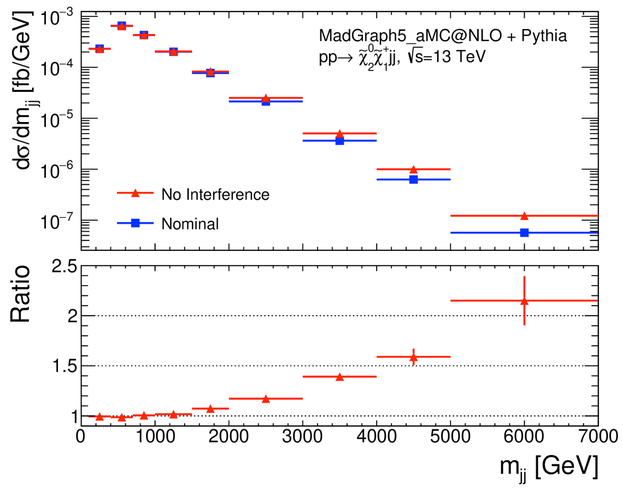
SUSY-2023-26

ATLAS SUSY VBF Search

- Large interference of pure electroweak and strong diagrams for VBF SUSY production



- Signal cross section depends on properly taking into account interference

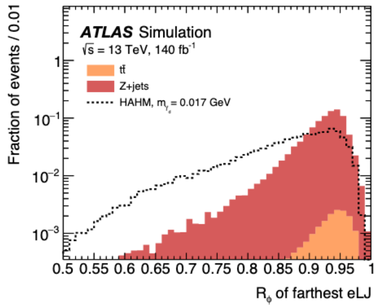


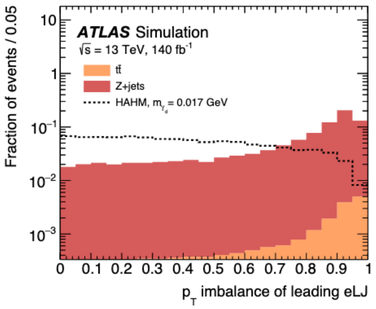
ATLAS Prompt Lepton Jets Search

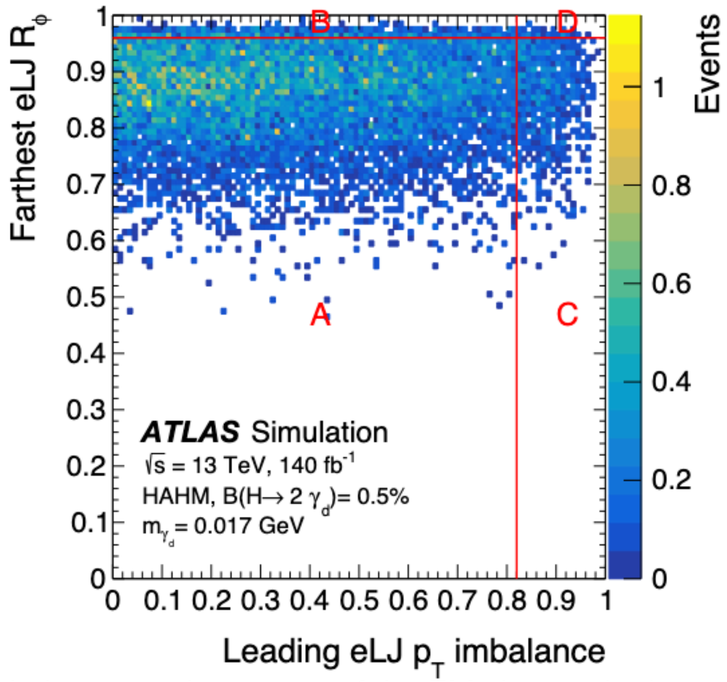
EXOT-2018-55

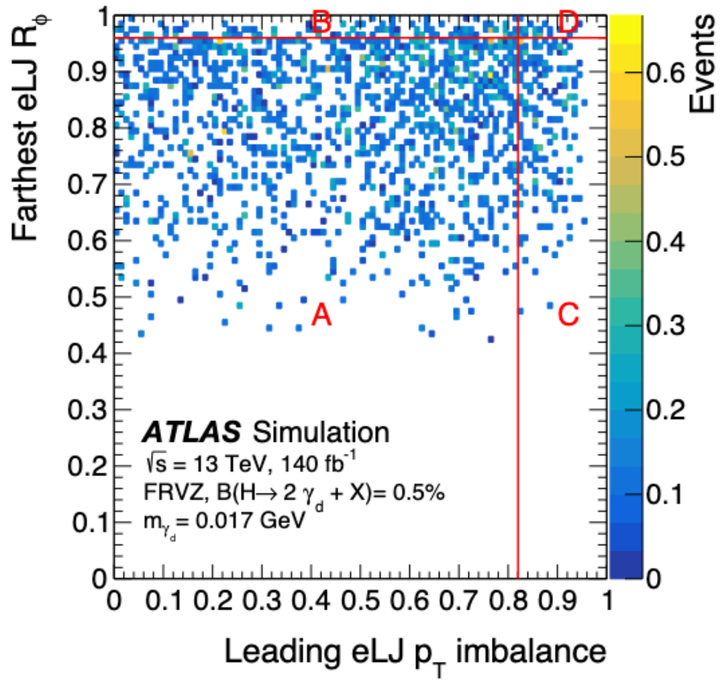
- Analysis strategy for electron channel: cut-and count in SR
  - Cuts on p_{T} imbalance and R_{ϕ}*
- Background estimate via ABCD method

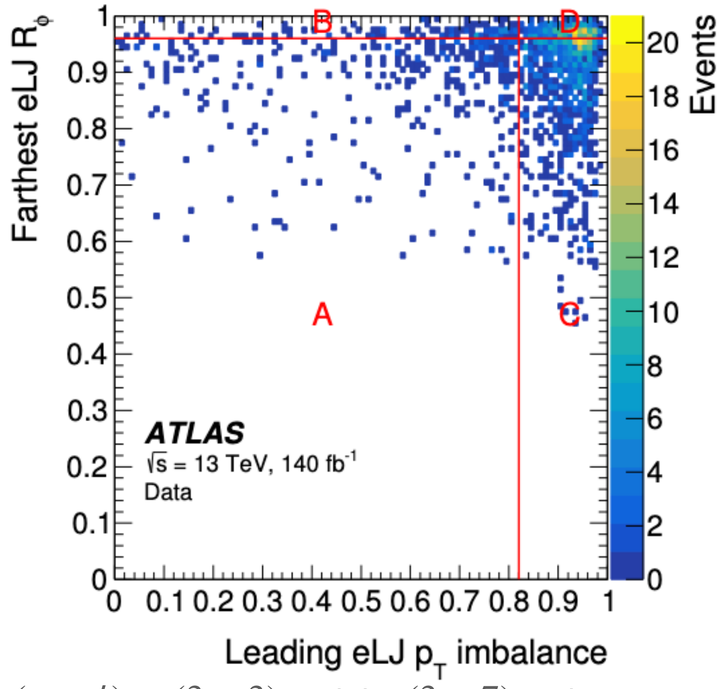
Region	CR B	CR C	CR D	SR expected *a priori*	SR expected *a posteriori*	SR observed
*e*LJ–*e*LJ	125	862	356	303 ± 33	334 ± 17	351









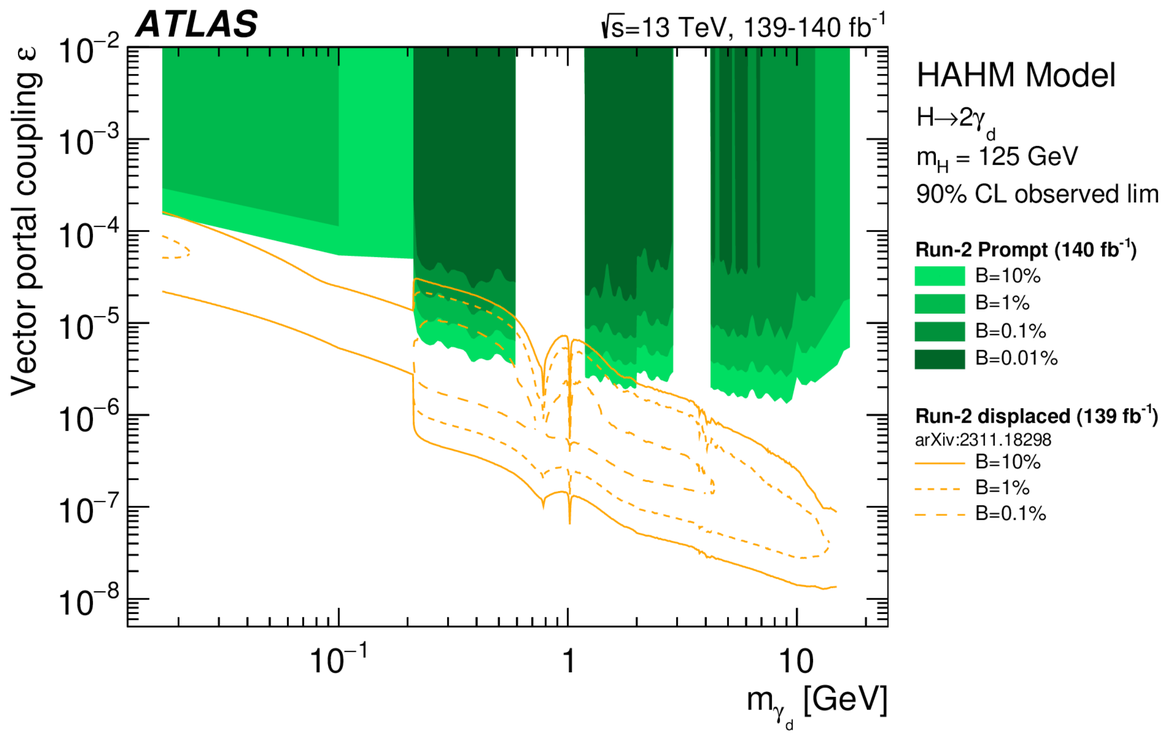


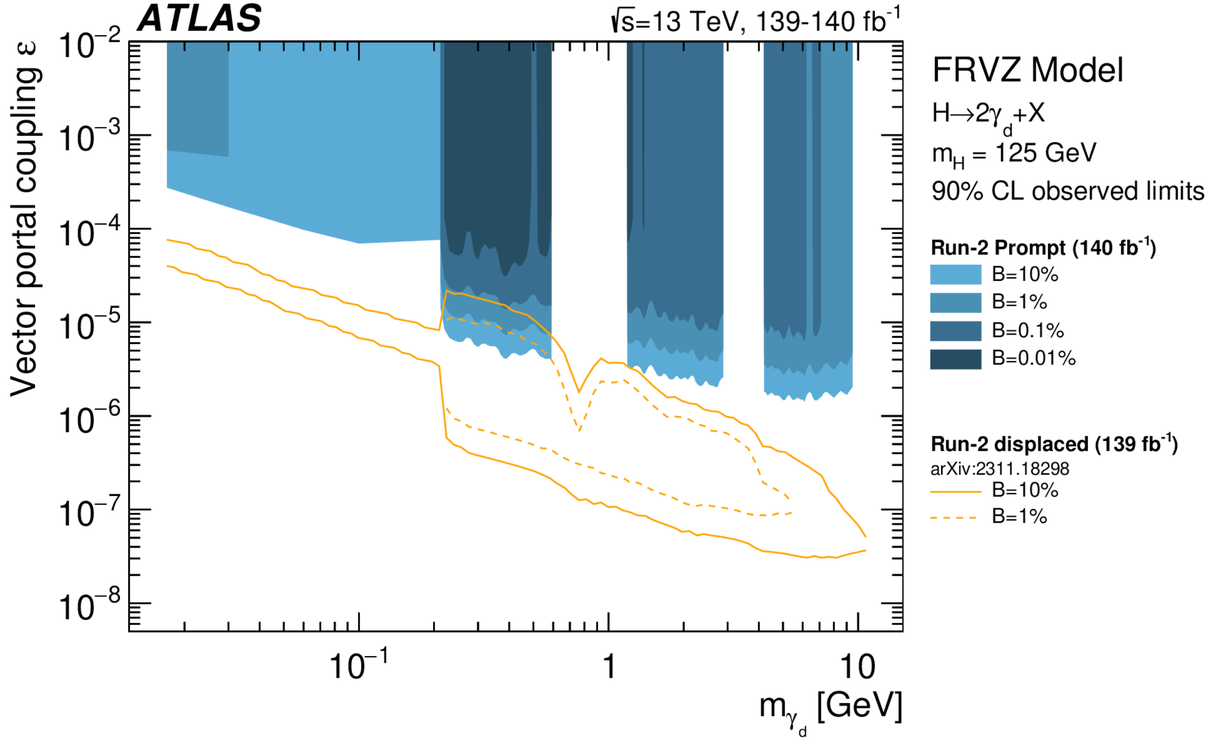
* Ratio between the energy of the EM shower, in the cells around the most energetic energy cluster measured in a $(\eta \times \phi) = (3 \times 3)$ and the (3×7) region

EXOT-2018-55

ATLAS Prompt Lepton Jets Search

- Comparison of prompt and displaced LJ results





CMS Search for Displaced Jets

EXO-23-013