

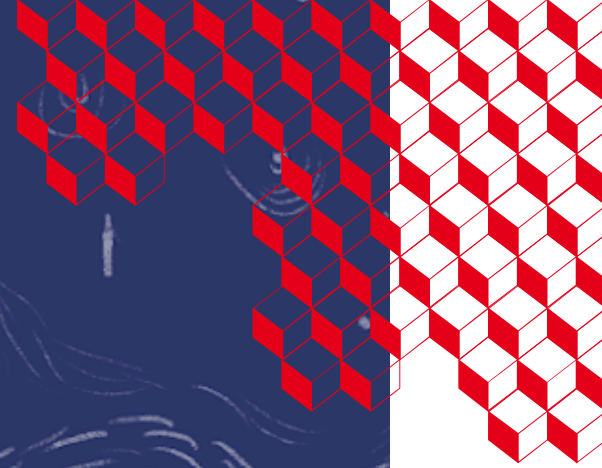


Status of LLP and dark sector searches with the ATLAS and CMS experiments

Marianna Liberatore – 16 May 2023

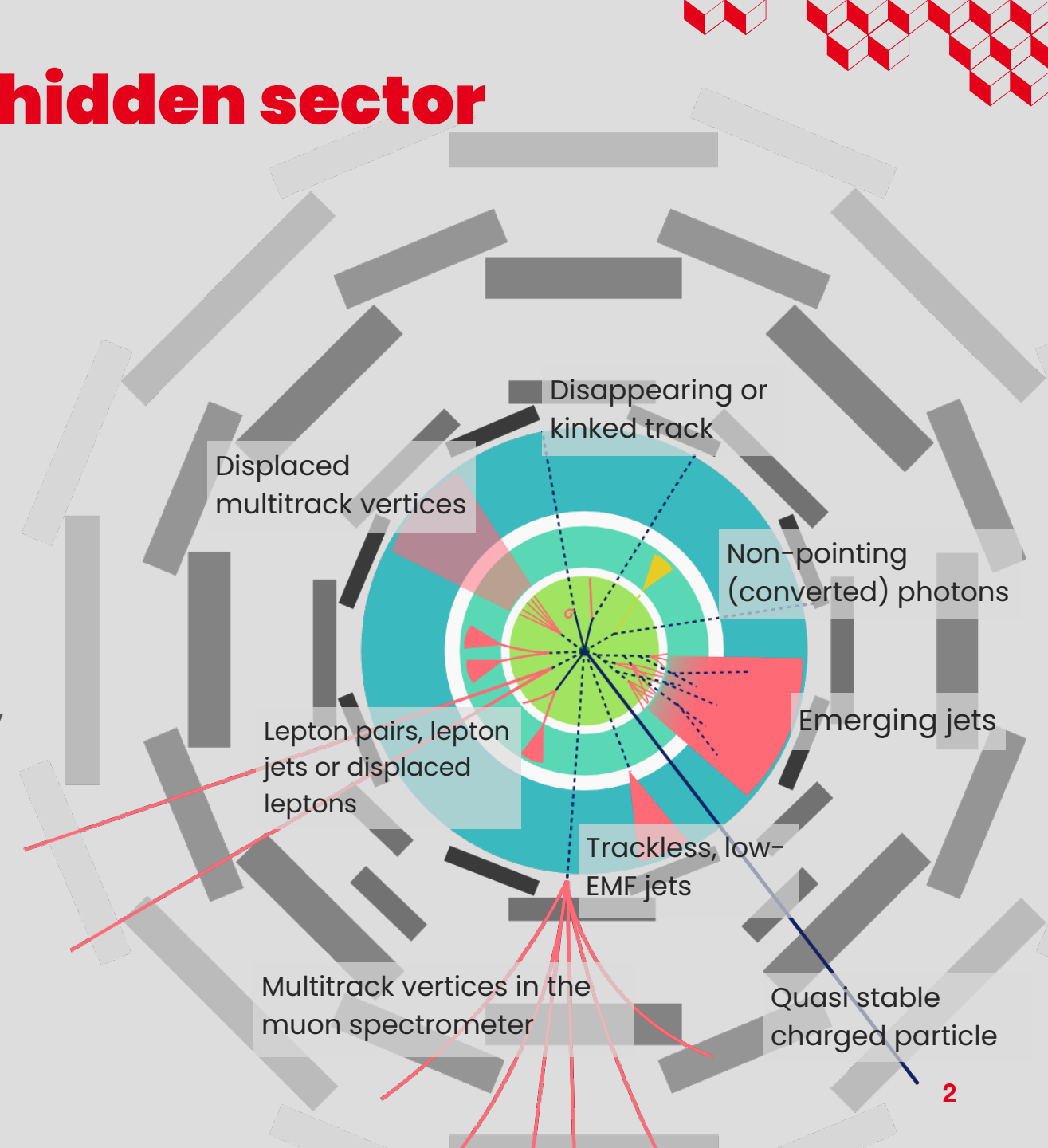
Rencontres de Blois 2023

On behalf of the **ATLAS** and **CMS** collaborations



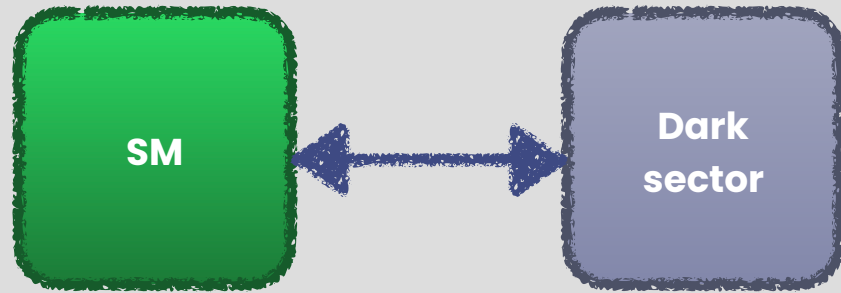
Long Lived Particles and hidden sector

- LLPs → **Beyond the Standard Model (BSM)** particles with **long lifetime**
 - Decay products **far away from collision point**
 - Plenty of SM “LLPs” (kaons, b-hadrons, muon, neutron, pions...) mechanisms understood
 - Suppressed decays via small coupling, heavy virtual particles mediating the decay or small phase space
 - Should also occur in BSM extensions
 - **Non-conventional signatures**



Long Lived Particles and hidden sector

- Dark Matter → part of **larger hidden/dark sector**



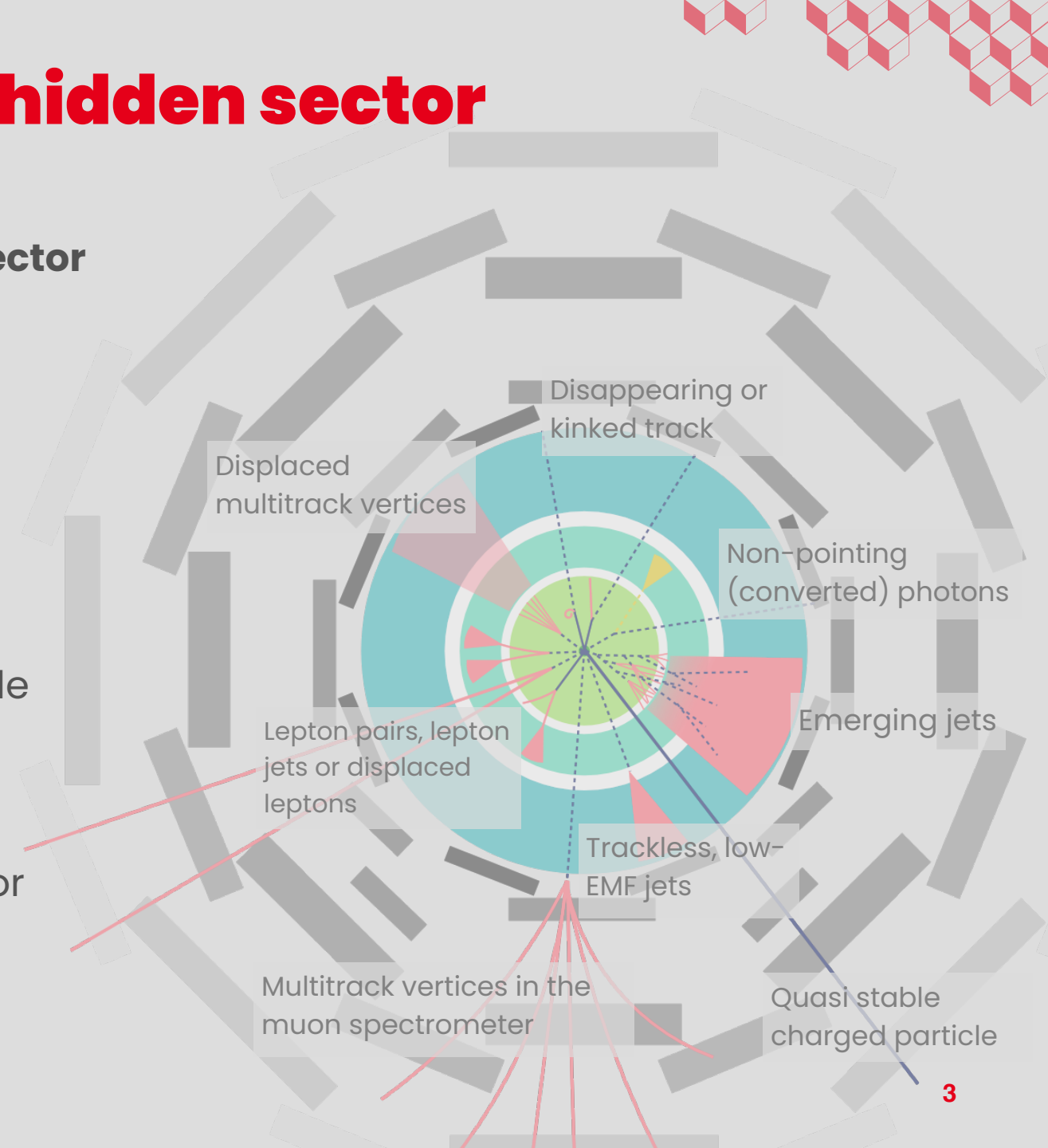
Vector portal → Dark photon, dark Z'

Scalar portal → Dark Higgs, scalar ϕ

Pseudo scalar portal → Axion-like particle (ALP)

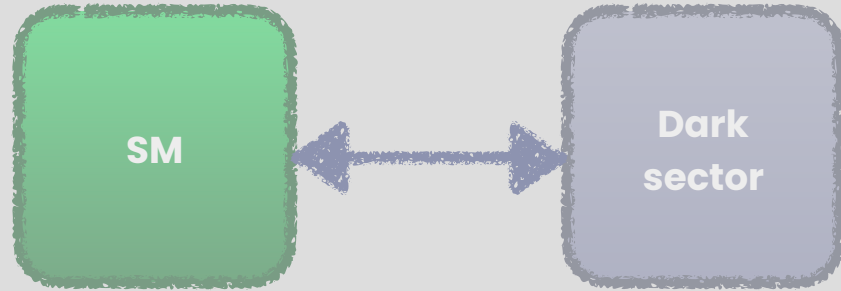
Neutrino portal → sterile neutrinos

- **Mediators** between SM-DM candidates or candidates **themselves**



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Scalar

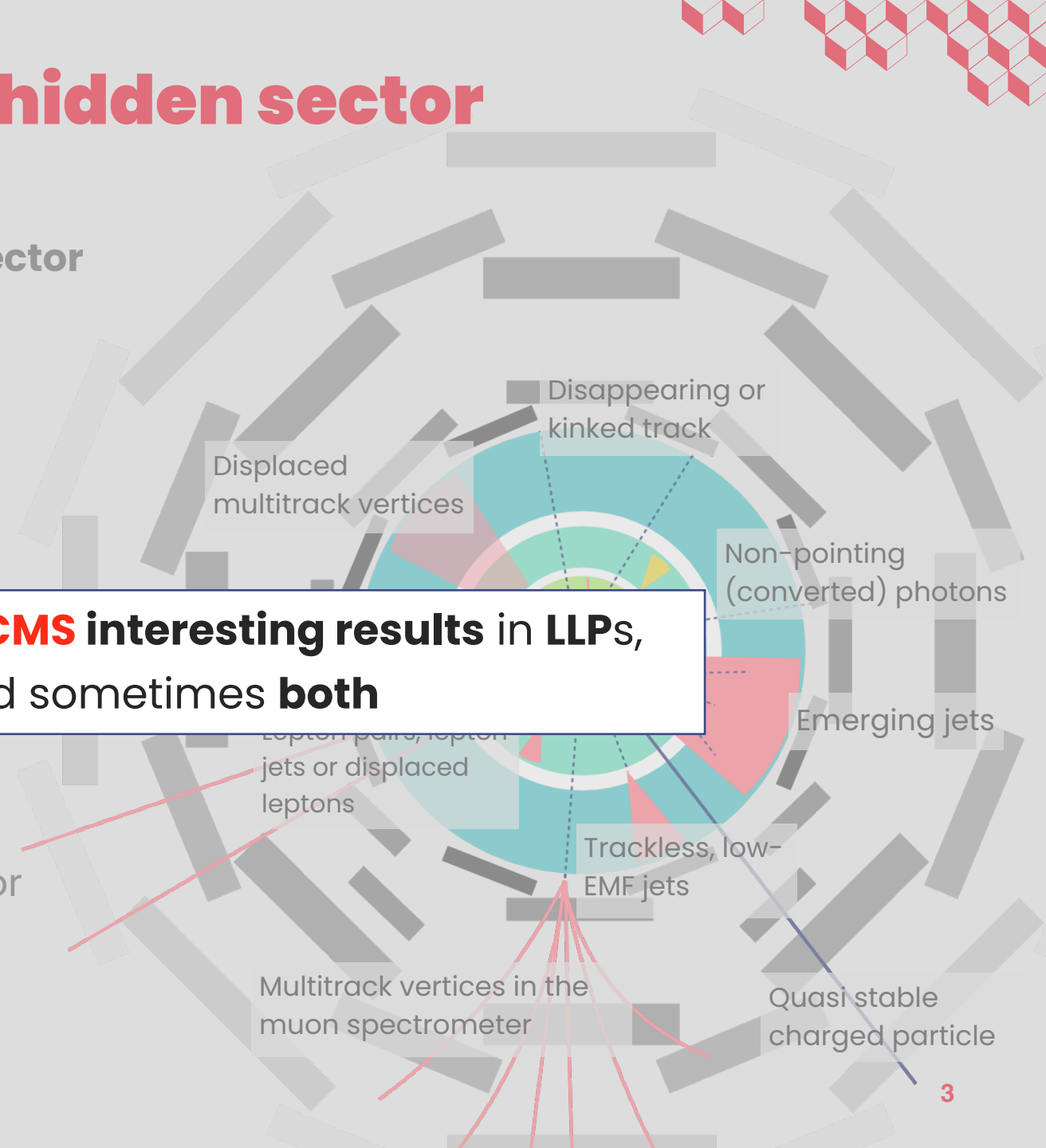
Pseudoscalar

(ALP)

Neutrino portal → sterile neutrinos

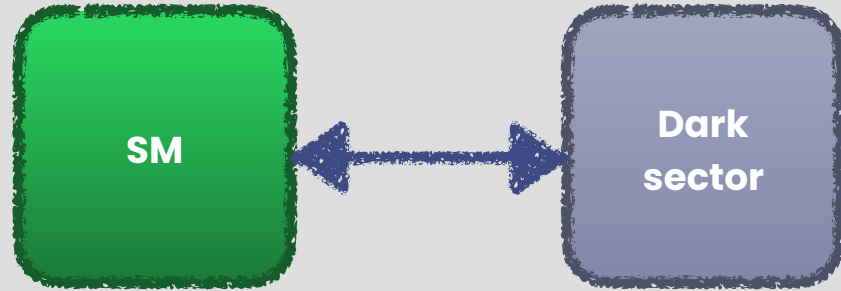
- **Mediators** between SM-DM candidates or candidates **themselves**

Showing **latest ATLAS** and **CMS** interesting results in **LLPs**,
dark sector and sometimes **both**



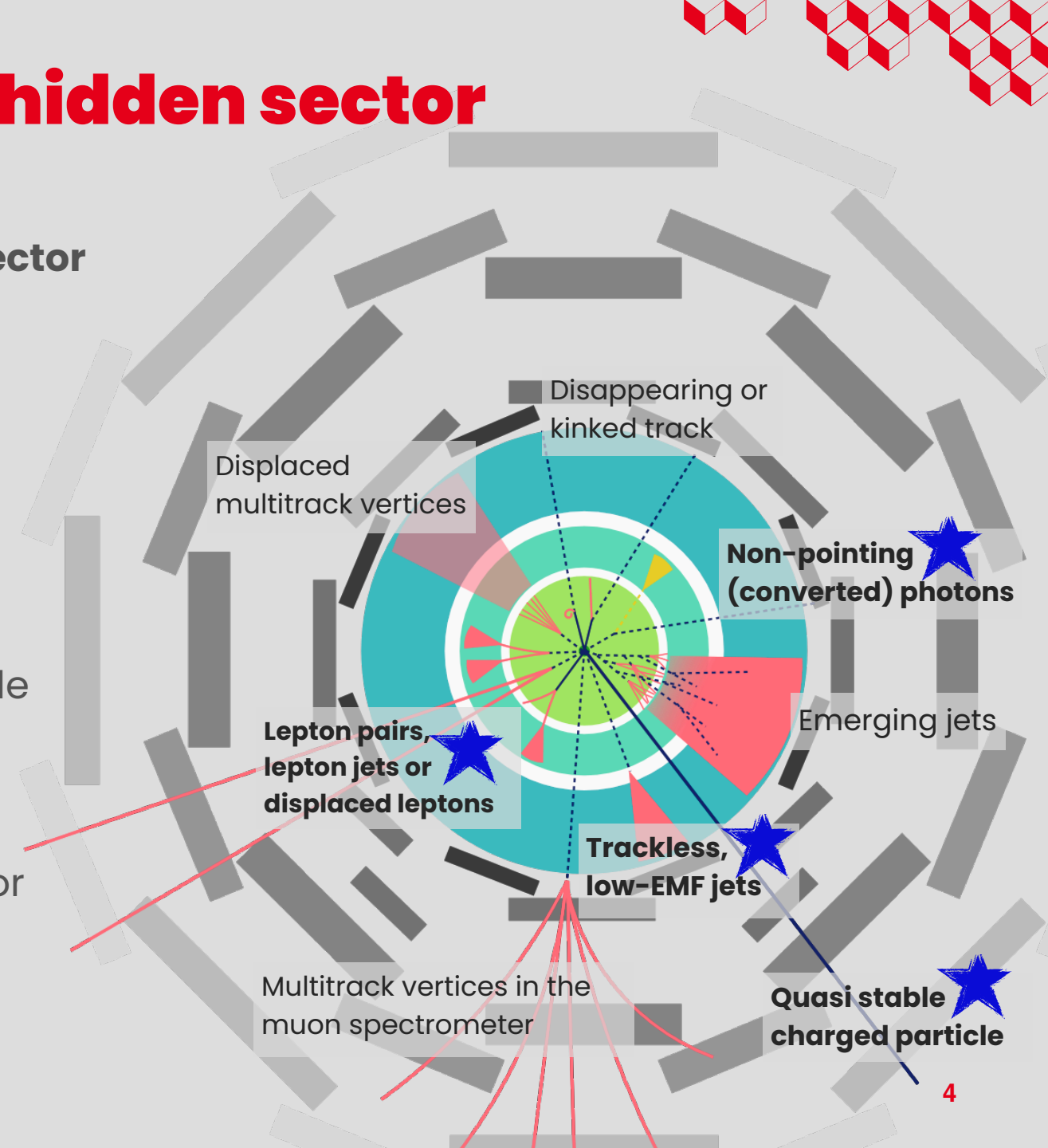
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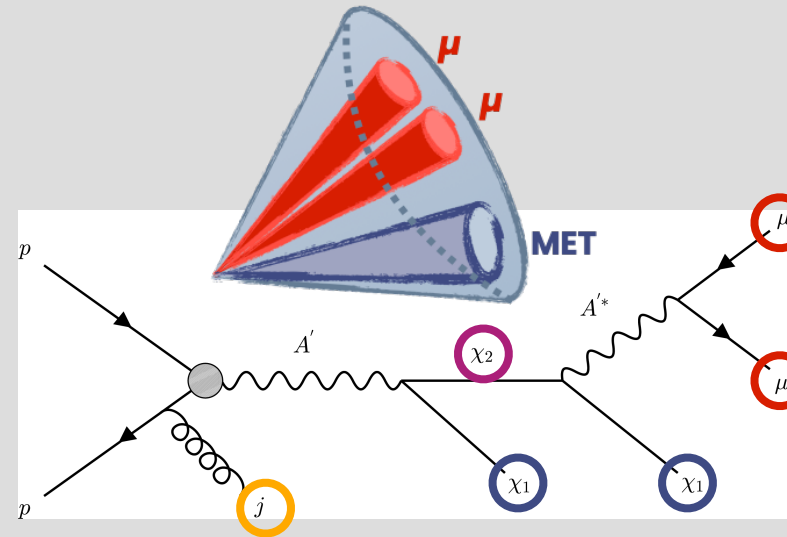


Inelastic Dark Matter with displaced muons

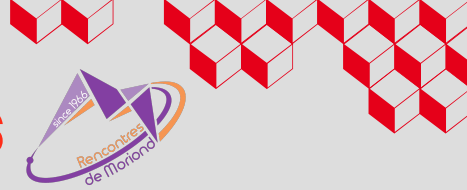


- **First search for inelastic DM at a hadron collider!**

- ≥ 2 DM states (χ_1, χ_2) + dark photon A'
- $\Delta \equiv m_1 - m_2$ small $\rightarrow \chi_2$ **LLP**
- **1 displaced muon pair**, large **MET**, **≥ 1 boosted jet (initial state radiation)**

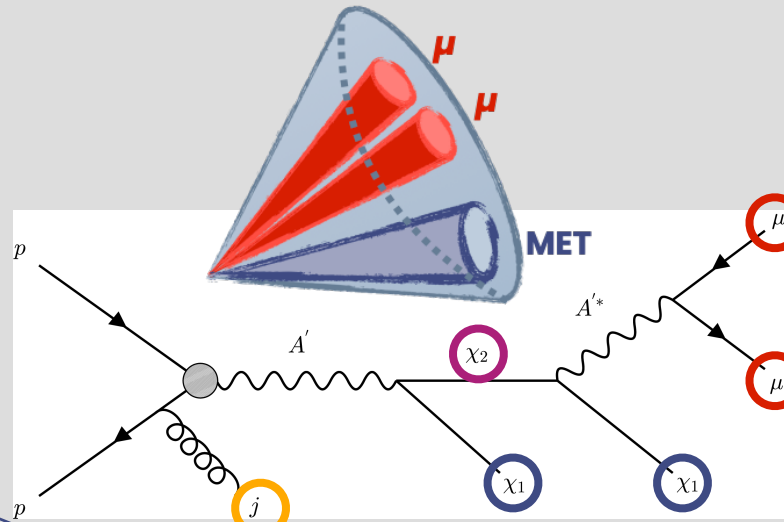


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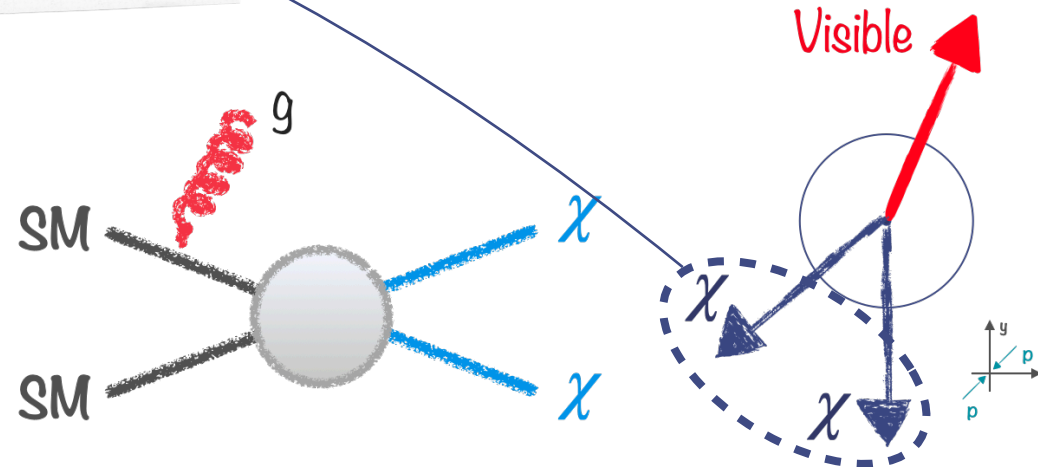


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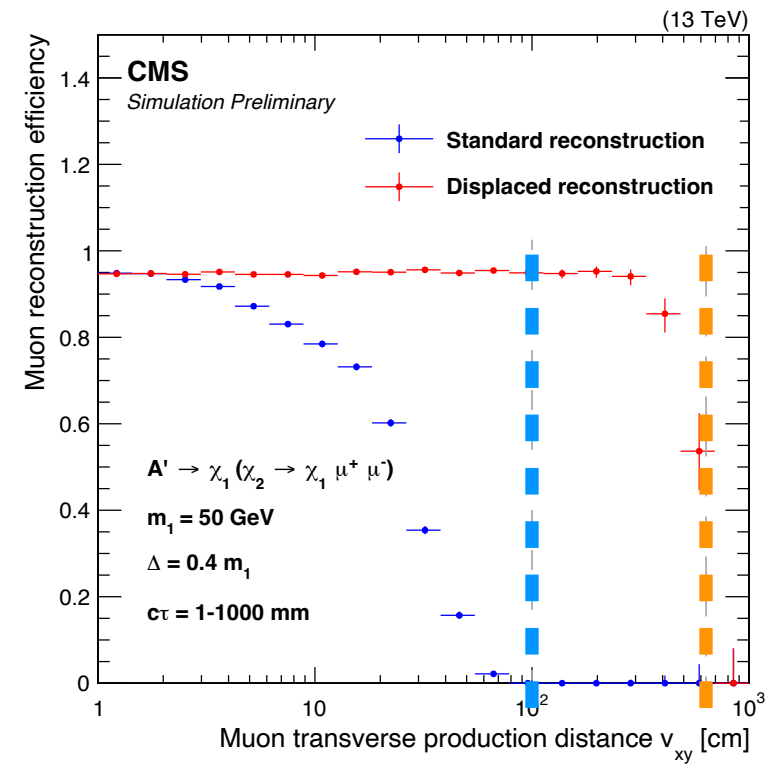
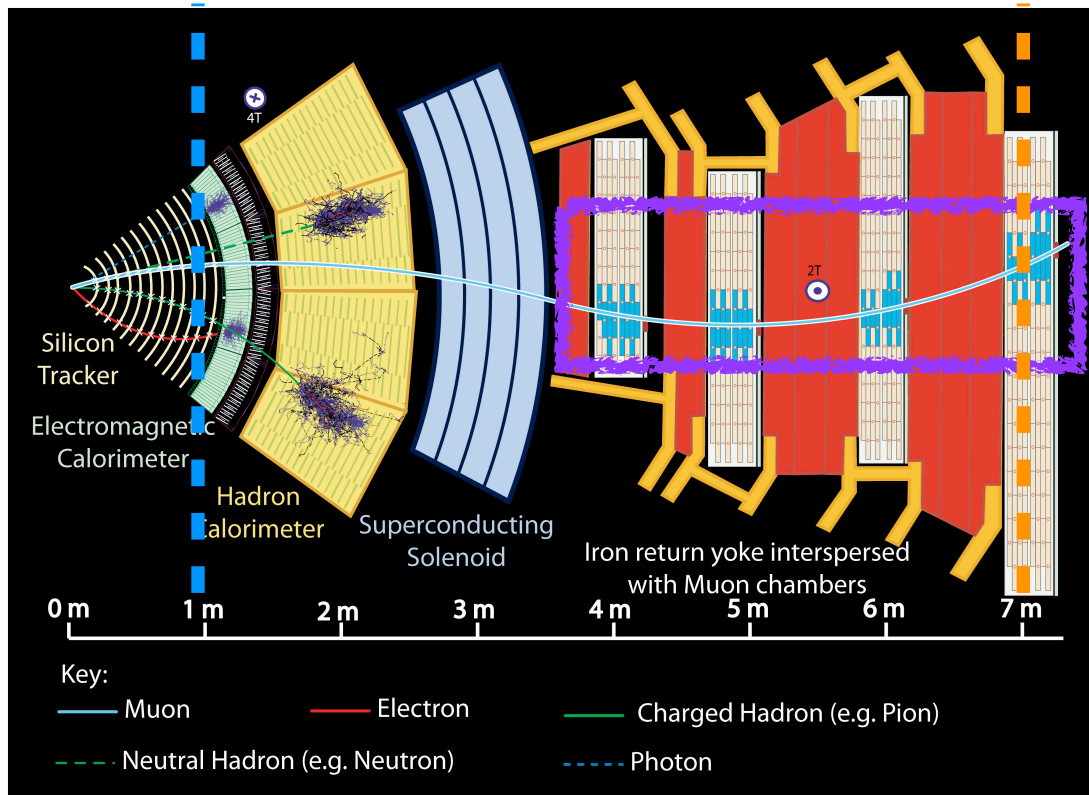
- **sum of all event momenta at initial state in xy plane = 0**
- Detected as **missing transverse momentum** ($p_T^{\text{miss}}/E_T^{\text{miss}}/\text{MET}$)



EXO-20-010 $\int L = 138 \text{ fb}^{-1}$

Muon reconstruction

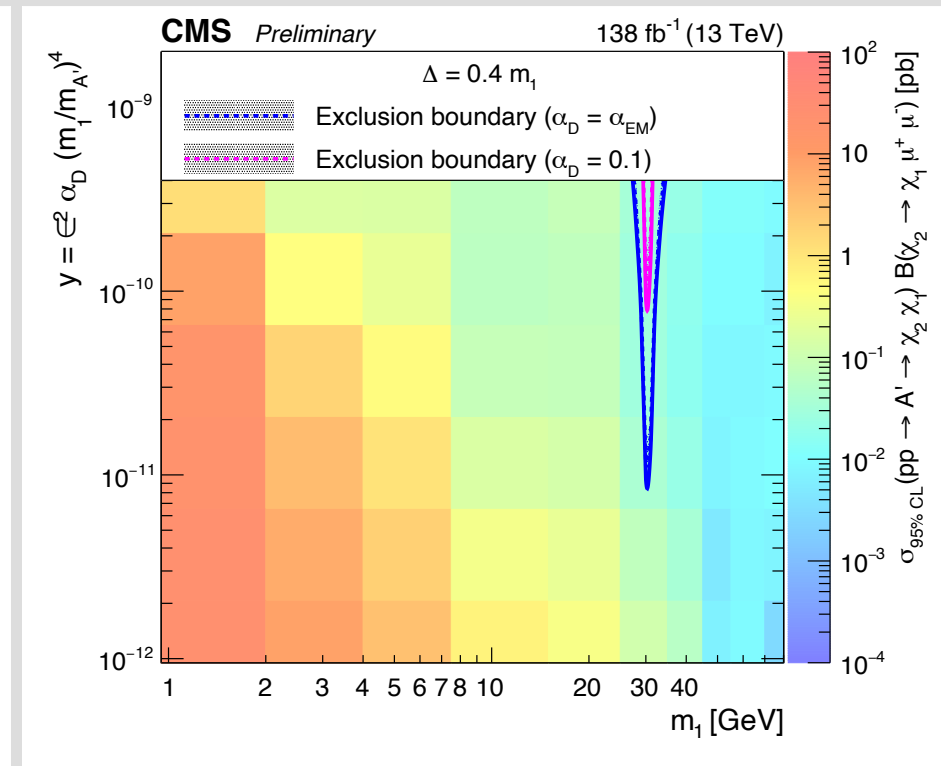
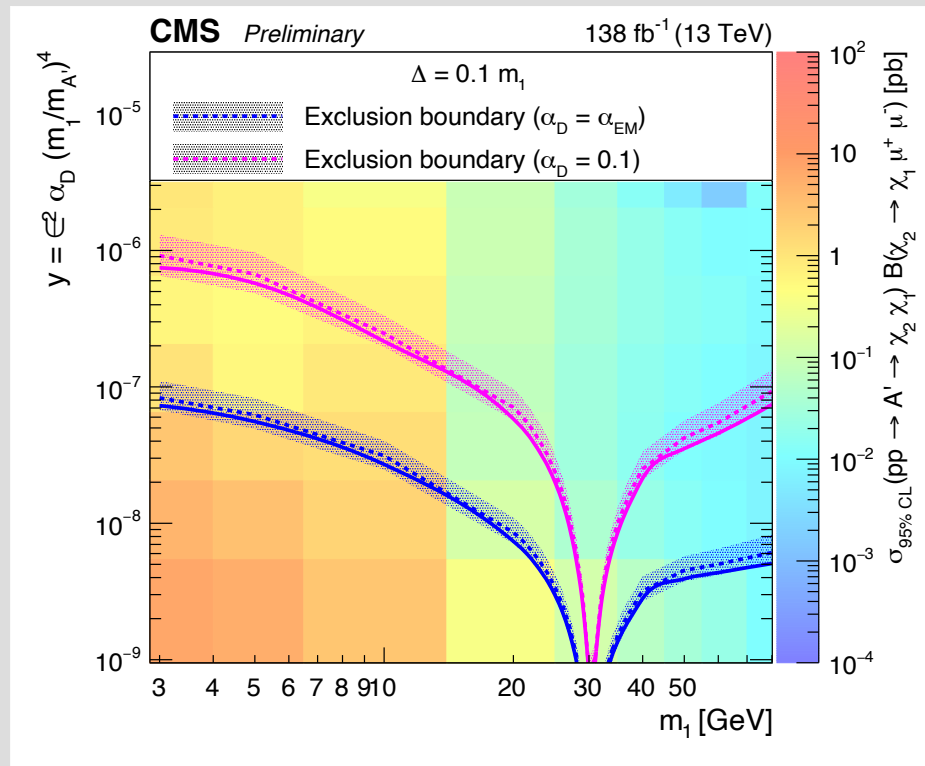
- F Dedicated displaced standalone muon reconstruction



Inelastic Dark Matter with displaced muons



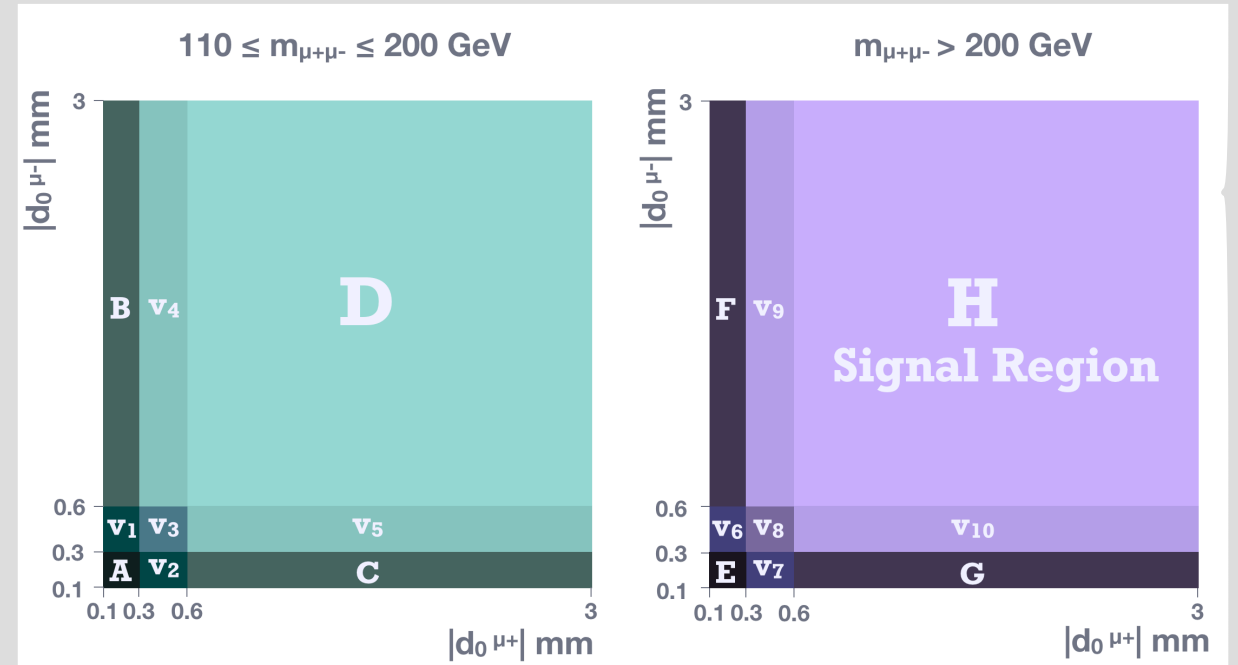
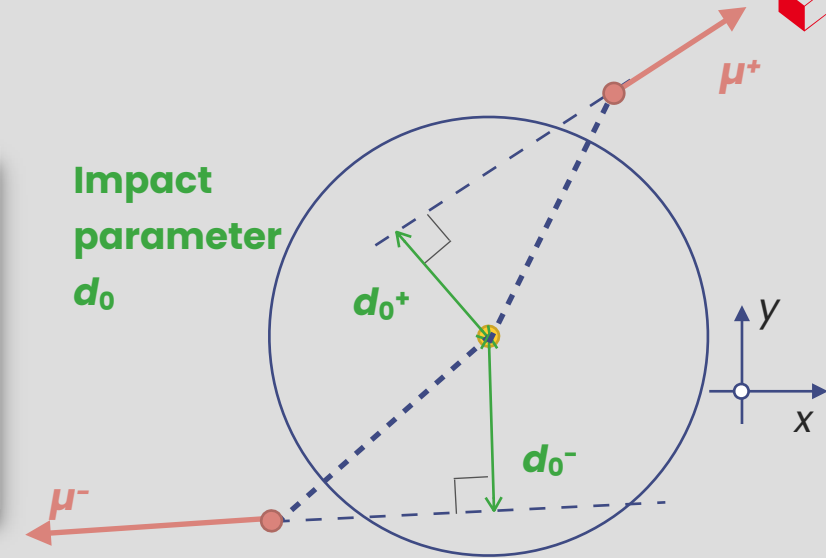
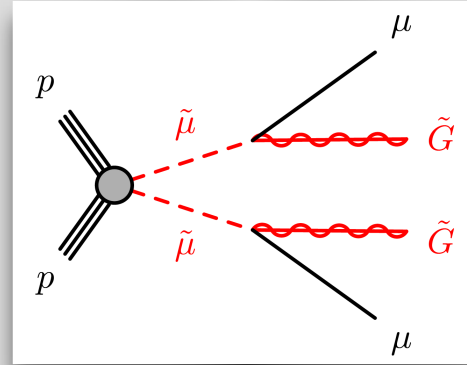
- Upper limits set on $\sigma(pp \rightarrow A' \rightarrow \chi_2 \chi_1) \mathcal{B}(\chi_2 \rightarrow \chi_1 \mu^+ \mu^-)$ as function of m_1 and **interaction strength**
 $y \equiv \epsilon^2 \alpha_D (m_1/m_{A'})^4$ @ 95% Confidence Level (CL)
- $e^2 \rightarrow$ **kinematic mixing** SM/dark photons and $a_D \rightarrow$ **coupling strength** to dark sector



Micro-displaced muons



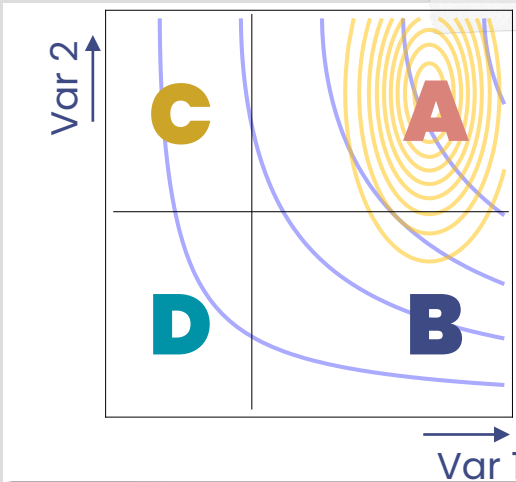
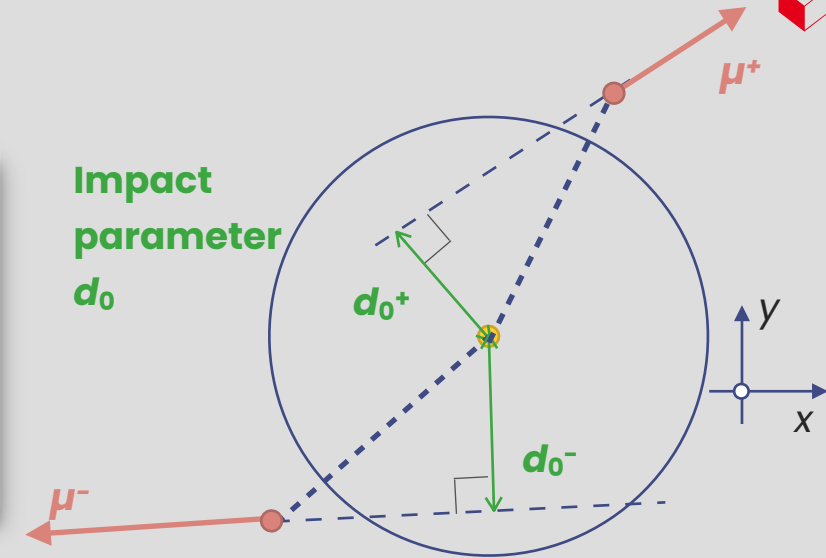
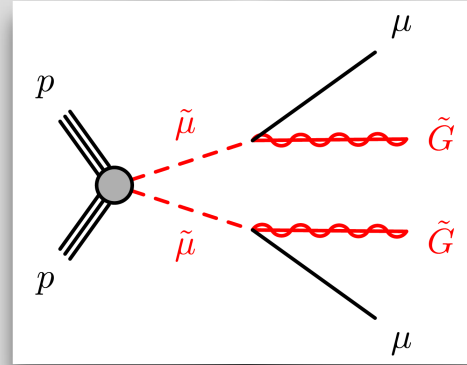
- Search for smuons $\tilde{\mu}$ with “intermediate” lifetime $\mathcal{O}(1-10)$ ps in Gauge-mediated SUSY breaking model (GMSB)
 - Signature with **2 non-prompt muons**
 - $0.6 < |d_0| < 3$ mm
- Main backgrounds → semileptonic **B-hadron** decays $b\bar{b} \rightarrow \mu^+\mu^-$
 - **ACBD method** → $(d_0^+, d_0^-, m_{\mu^+\mu^-})$



Micro-displaced muons

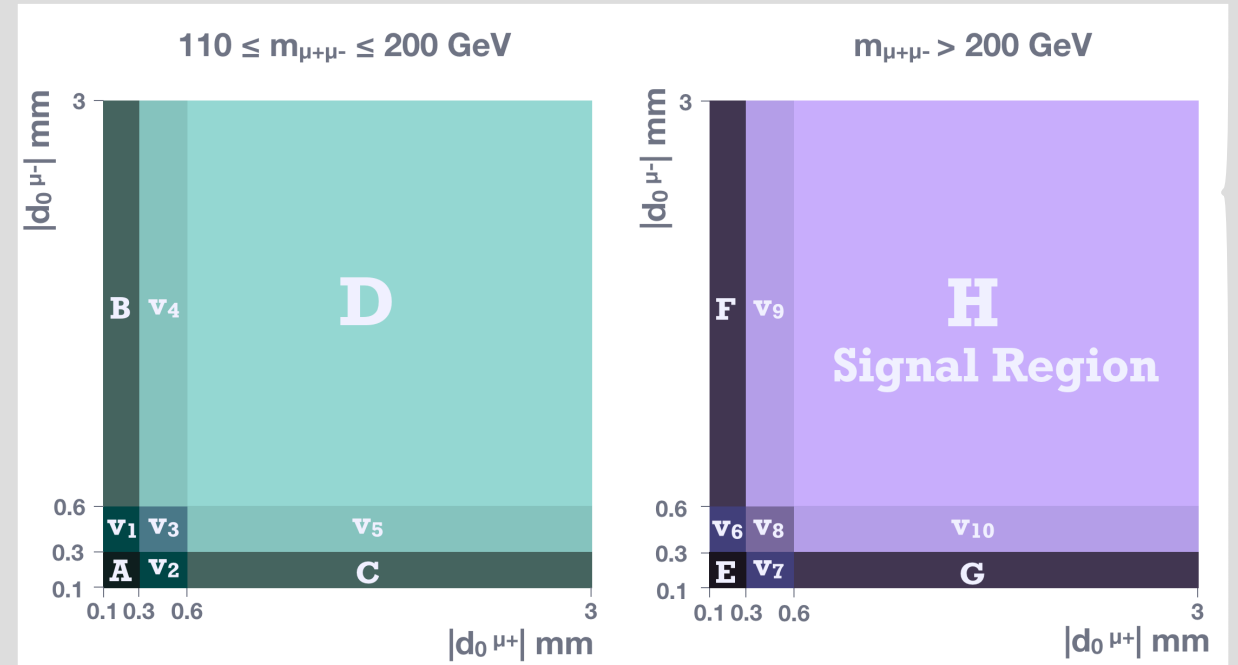


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A signal region, **B, C, D** control regions \rightarrow statistically independent

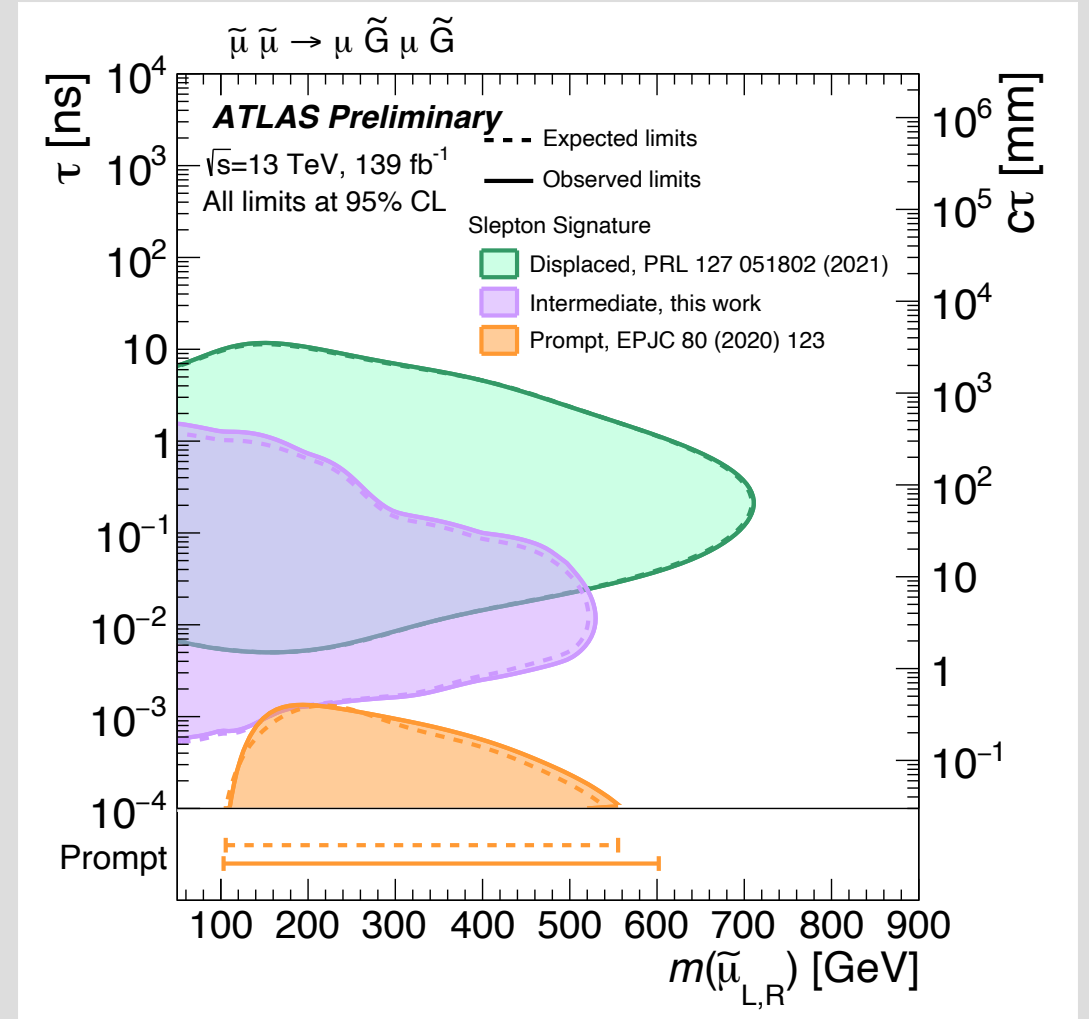
$N_A = N_B \times N_C / N_D$



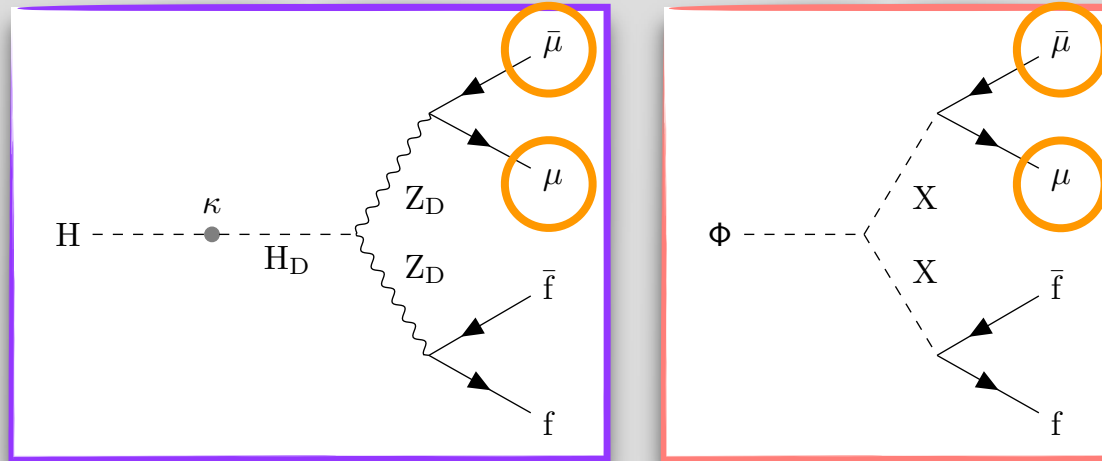
Micro-displaced muons



- No excess found → **limit sets** on $\tilde{\mu}$ mass **up to 100(520)GeV** for lifetimes down to **1(10)ps @ 95% CL**
 - Fills gap between **displaced** and **prompt** lepton searches
 - **First reinterpretation** of prompt lepton searches **in long-lived regime** in **ATLAS**



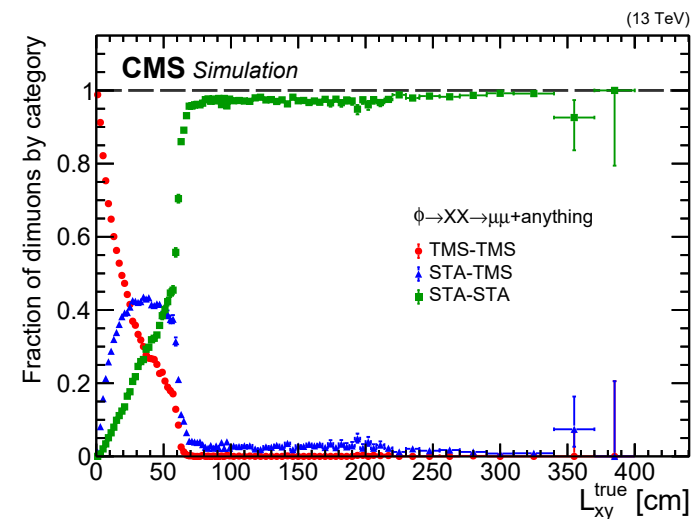
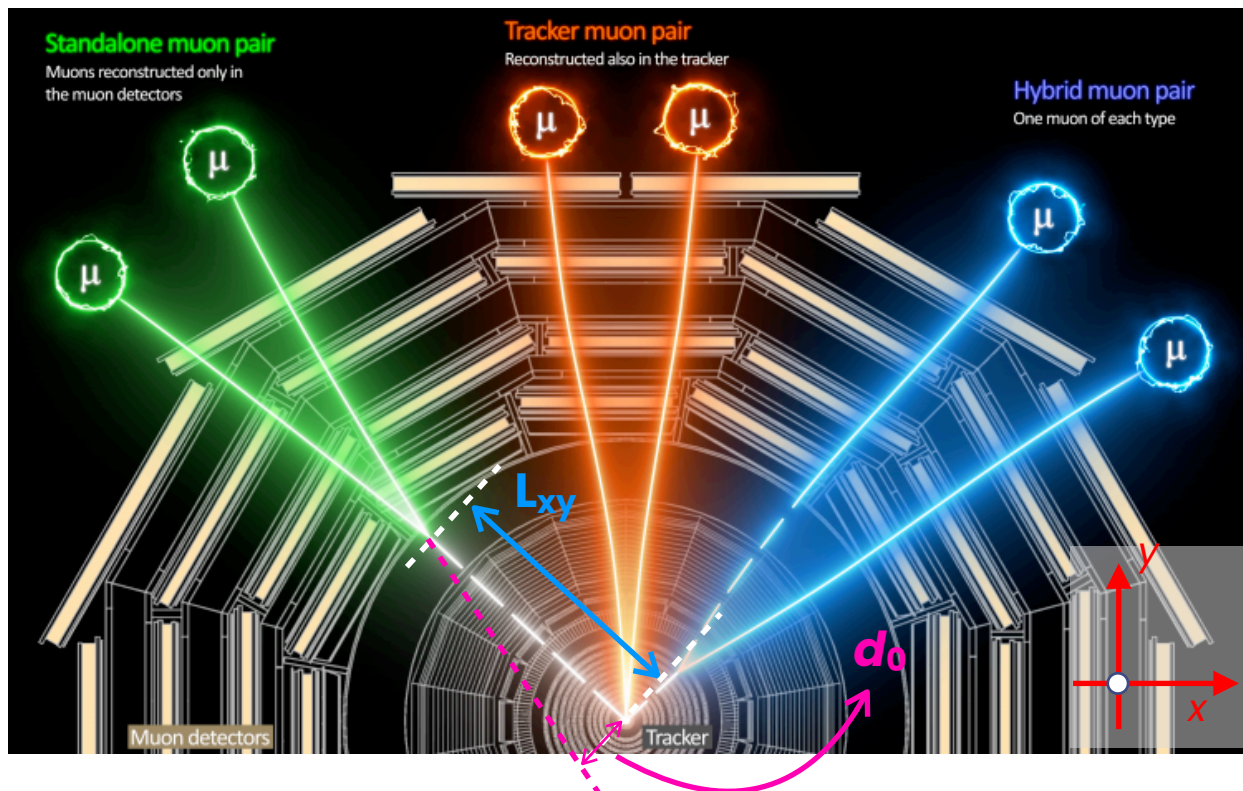
LLPs to muon pairs



- Search for long-lived exotic particles decaying to **muon pair**
 - Higgs to **dark photons Z_D** (hidden Abelian Higgs Model)
 - Scalar ϕ to LL exotic **heavy neutral scalar bosons X** (simplified model)

Muon reconstruction

- 3 categories of muon pair events → **standalone**, **tracker+MS**, **hybrid**



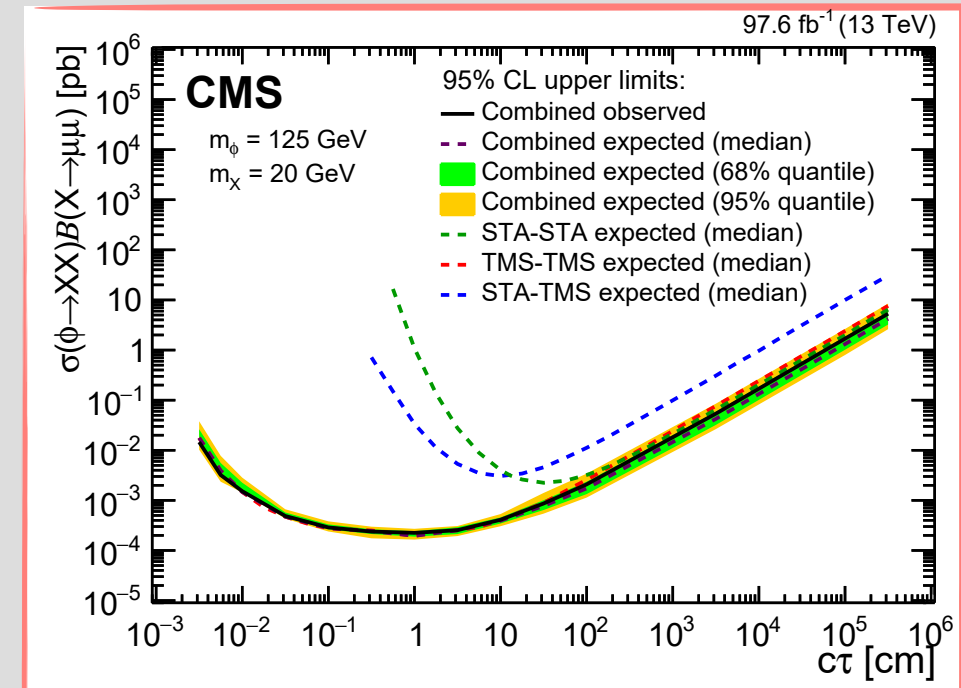
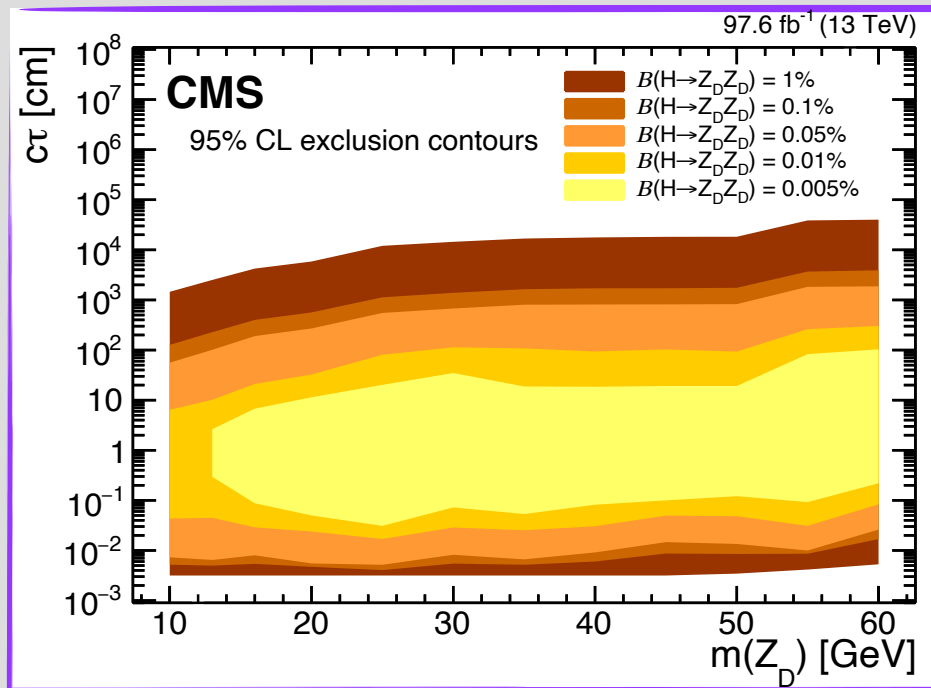
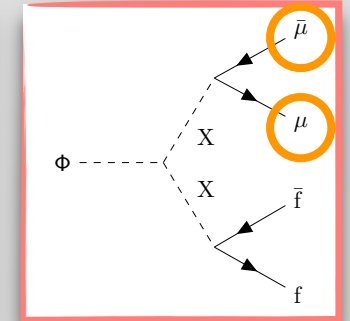
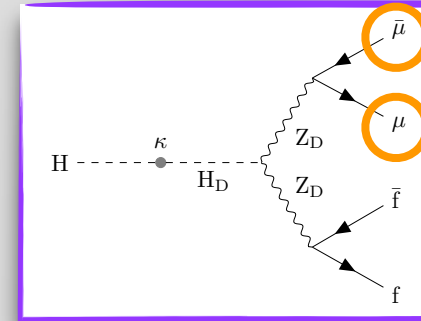
L_{xy} , $d_0/\sigma(d_0)$ and

$$\Delta\Phi(\vec{p}_T^{\mu\mu}, \vec{L}_{xy}) \rightarrow$$

discriminating variables against non-prompt/fake displaced muons

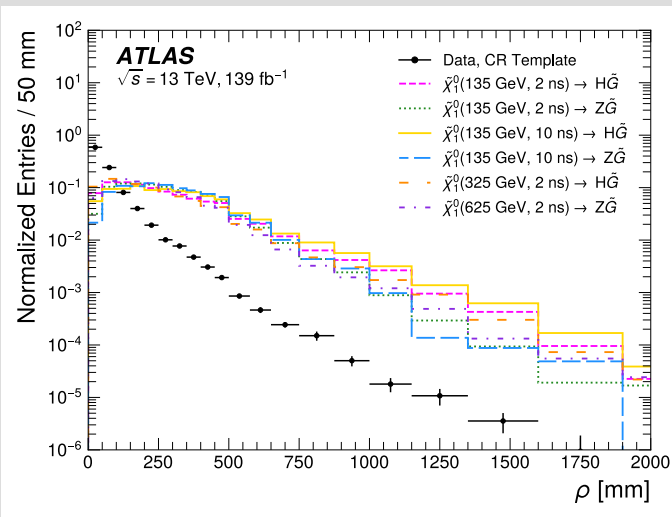
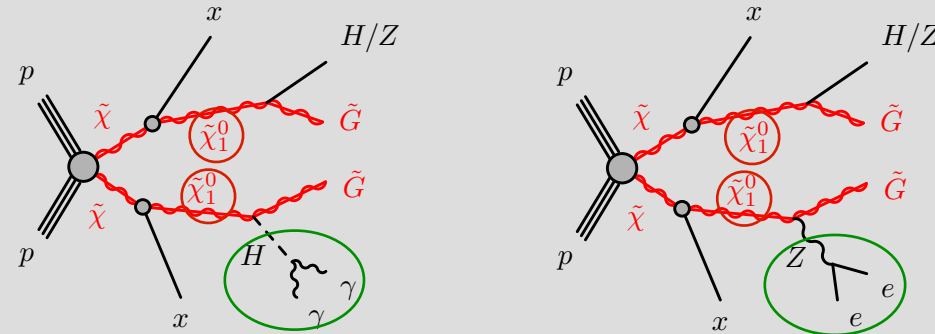
LLPs to muon pairs

- Search in $m_{\mu\mu}$ bins \rightarrow no excess found
 - Limits set on $B(H \rightarrow Z_D Z_D)$ as function of m_{Z_D} and $c\tau_{Z_D}$ and $\sigma(\phi \rightarrow XX)B(X \rightarrow \mu\mu)$ as function of $c\tau$
 - Best limits to date for $20 \text{ GeV} < m_{Z_D} < \frac{1}{2}m_H$ and $m_\phi > m_H$

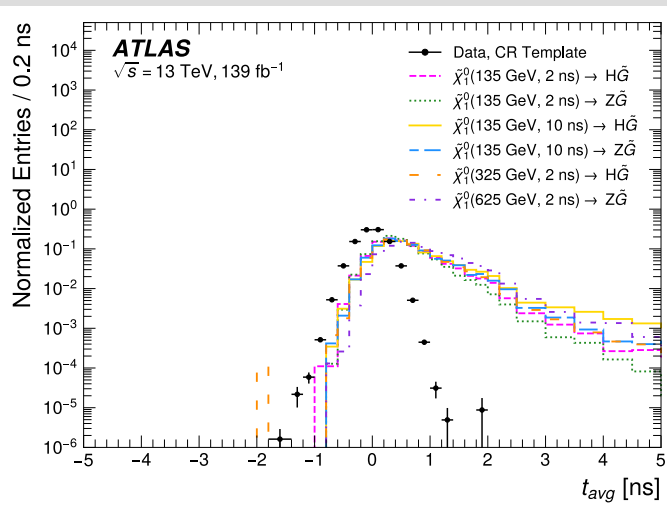


Displaced diphoton/dielectron vertex

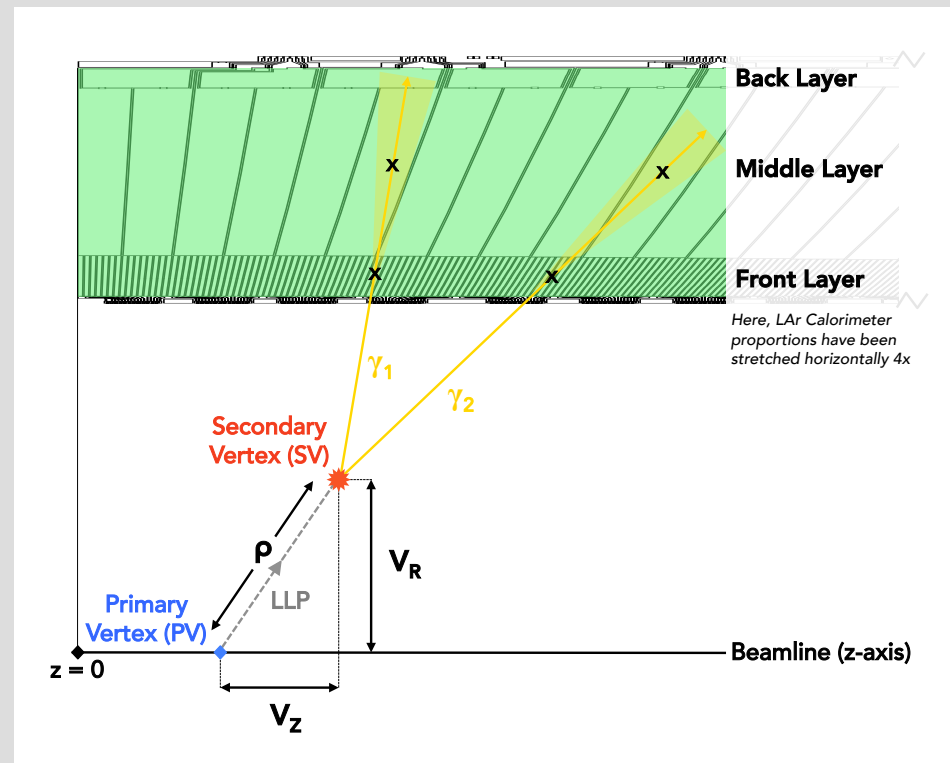
- GMSB model: $\tilde{\chi}\tilde{\chi} \rightarrow \text{LLP } \tilde{\chi}_1^0 \rightarrow H(\gamma\gamma) \text{ or } Z(ee)$
 - Only **calorimeter information**
 - Displaced** and **delayed** diphoton vertex \rightarrow use **pointing** for reconstruction in (R-z) plane
- Main background \rightarrow real photons misreconstructed as displaced/fake photons



Categorize events with **pointing** $\rightarrow \rho = \sqrt{(V_R^2 + V_Z^2)}$

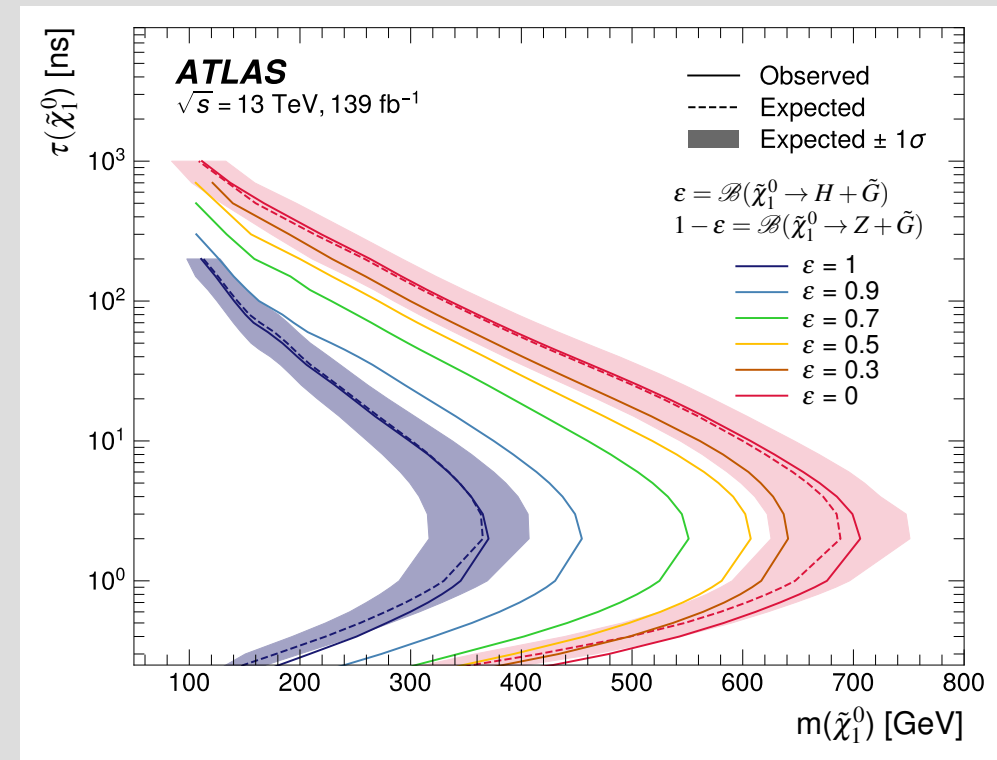
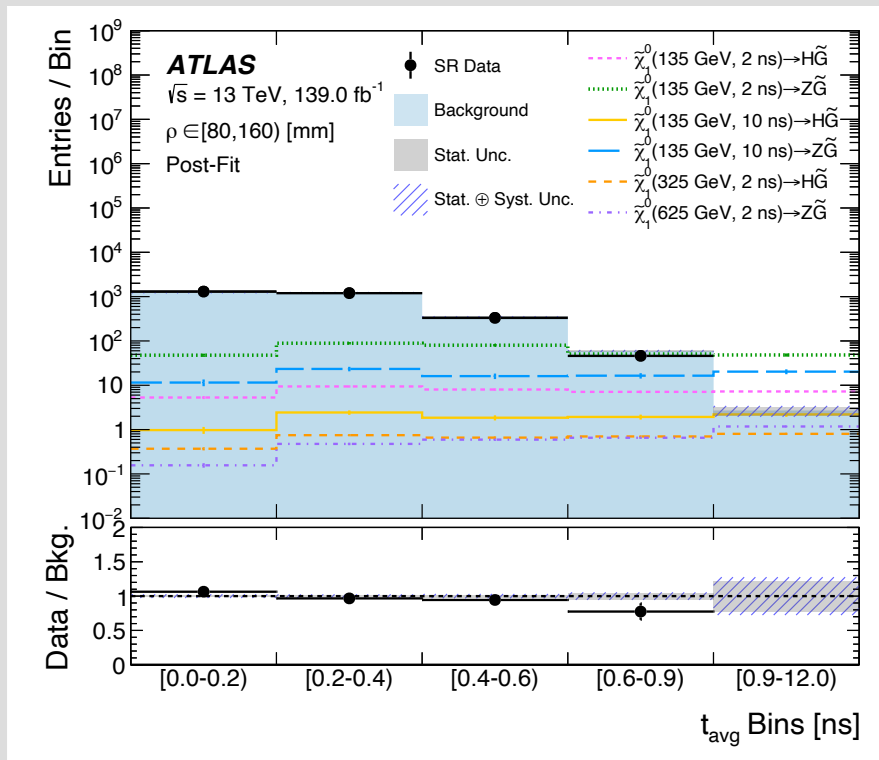


Fit background **timing** $t_{\text{avg}} = (t_{\gamma 1} + t_{\gamma 2})/2$ distribution in each category to data

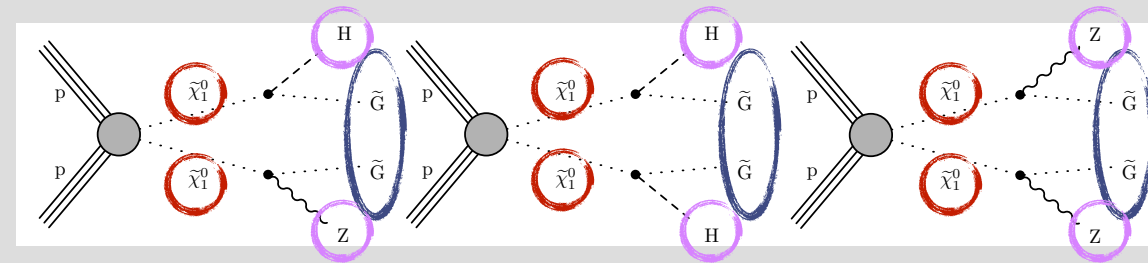
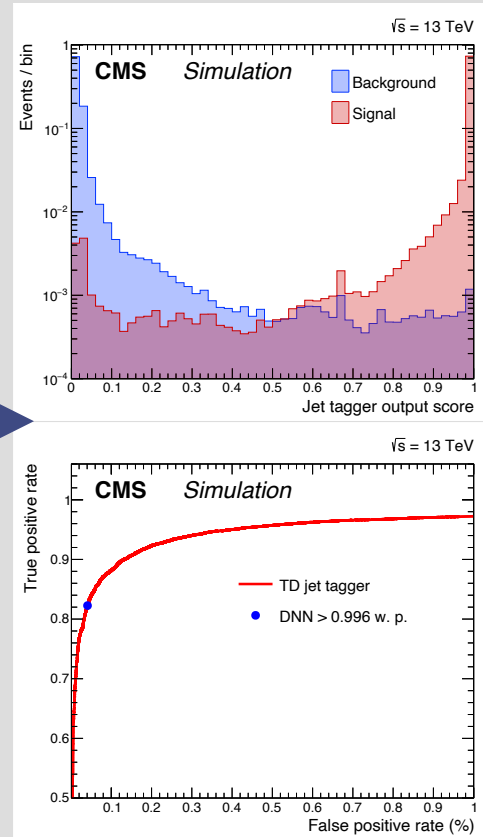
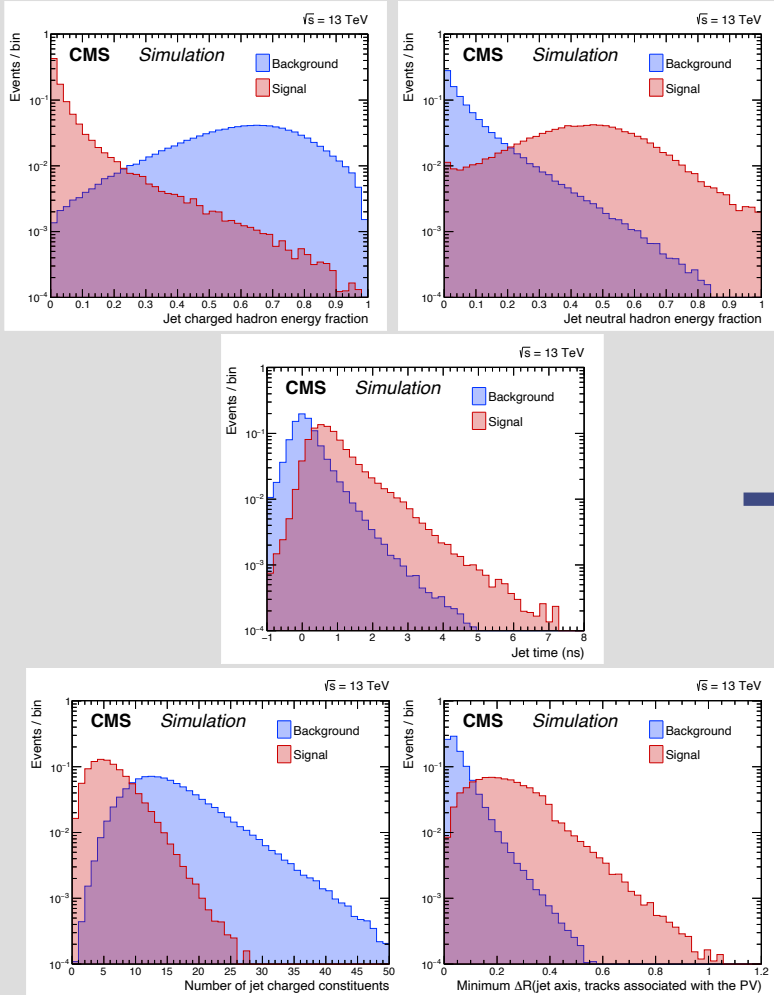


Displaced diphoton/dielectron vertex

- Good agreement between background prediction and data
- Limits as function of $m(\tilde{\chi}_1^0)$ and $\tau(\tilde{\chi}_1^0)$ for various BR to H and Z

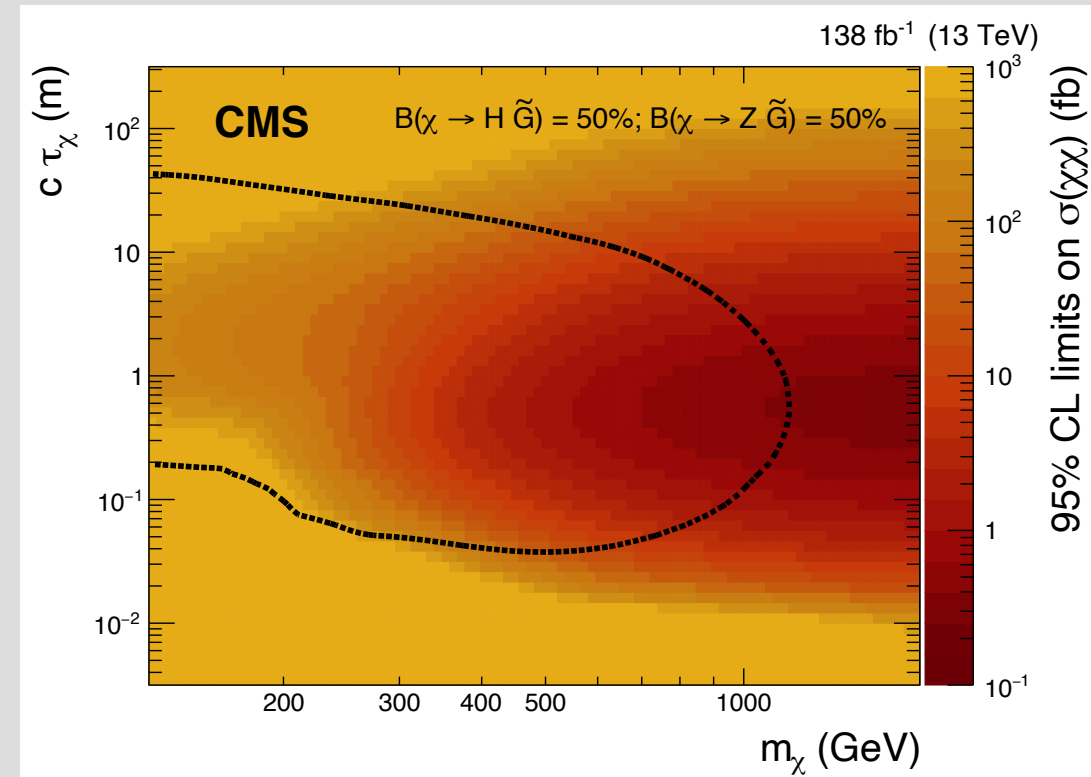
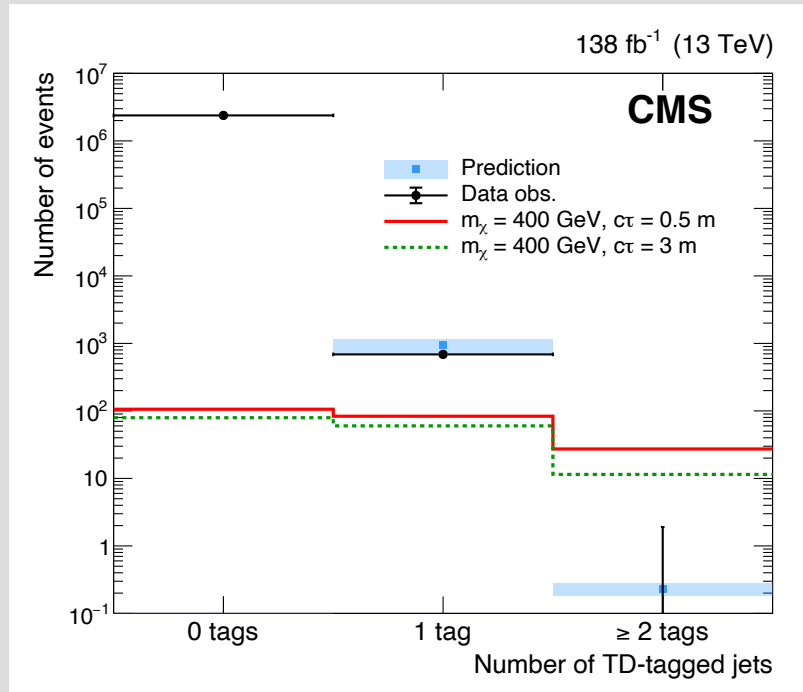


LLPs out of time trackless jets



- GMSB model \rightarrow neutralino to HZ, HH, ZZ and large MET
- Combine trackless and delayed (TD) jet information into Deep Neural Network \rightarrow TD-tagged
- $3\times$ background jet rejection while 80% signal efficiency
- Background estimation \rightarrow extrapolate tagger's misidentification probability to signal regions

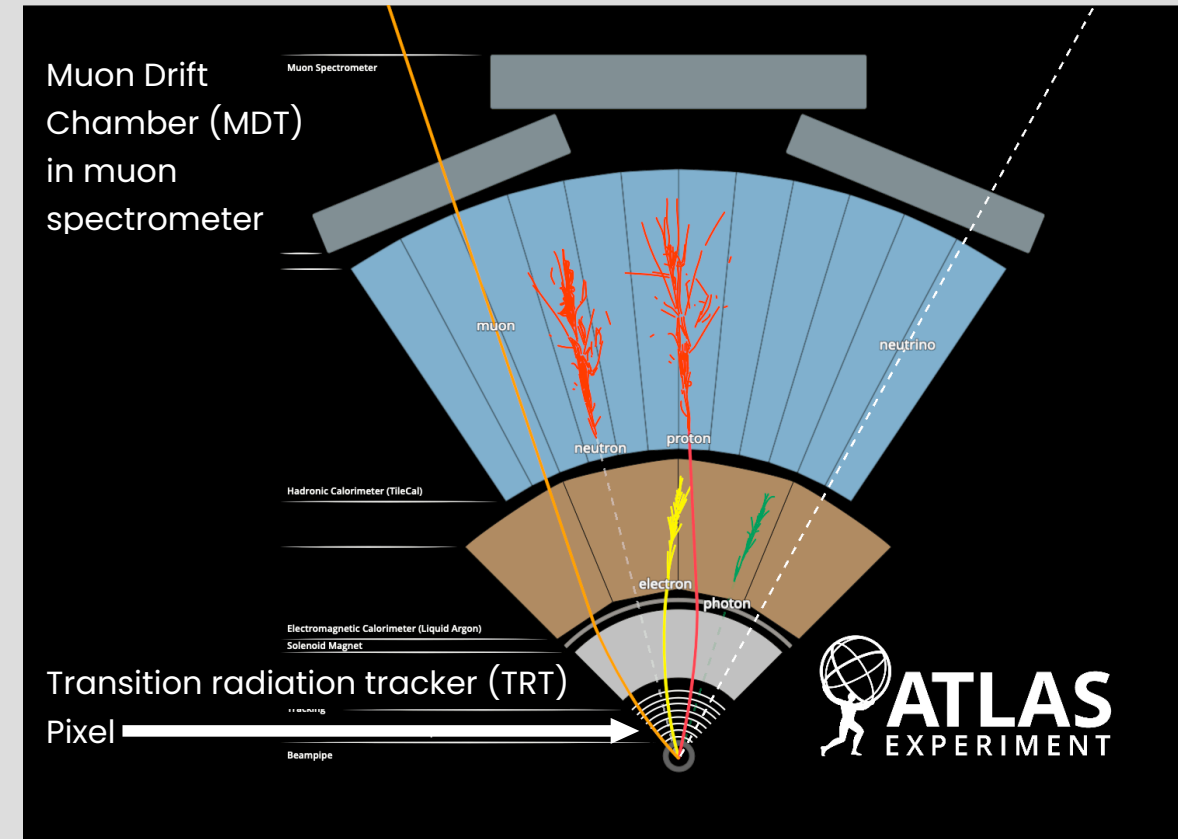
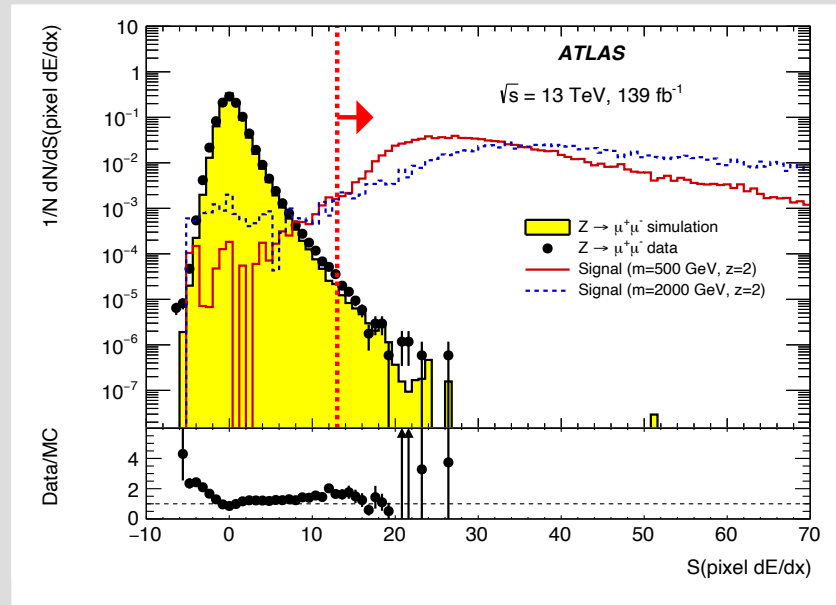
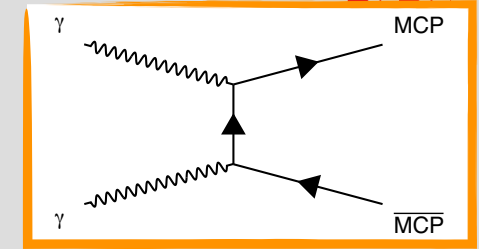
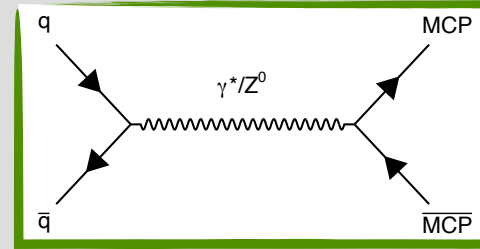
LLPs out of time trackless jets



- No excess → limits in **GMSB EWK model**
- **Best results to date** in mass range constrained by m_H **up to 1.8 TeV**

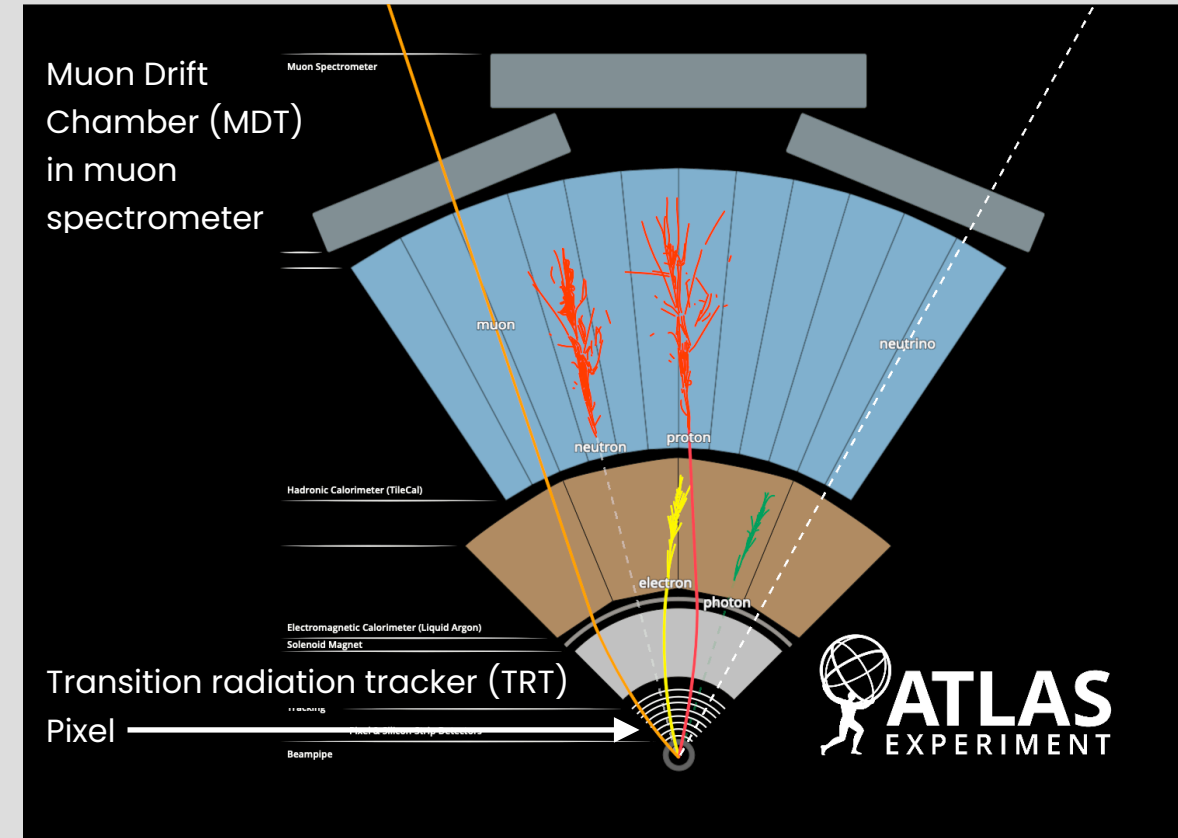
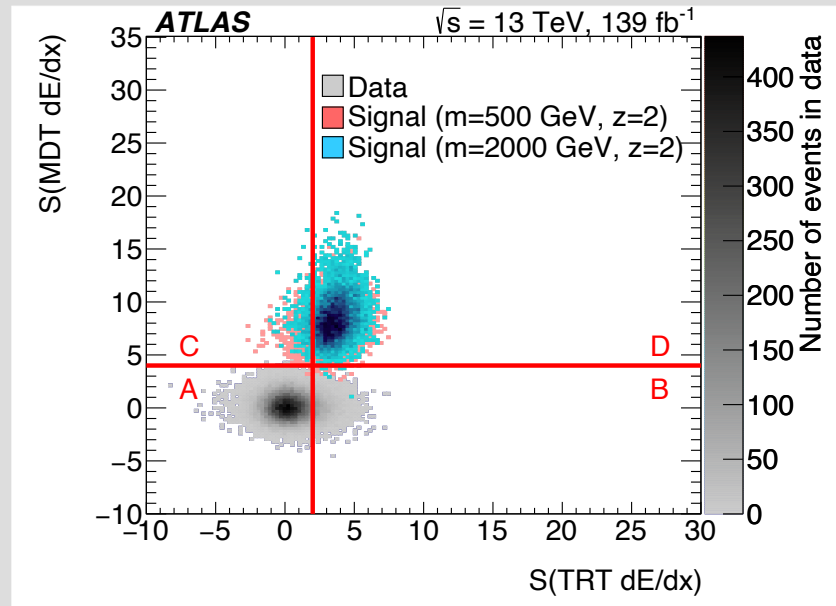
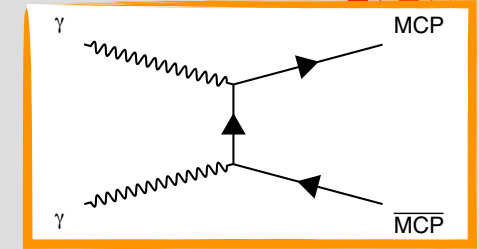
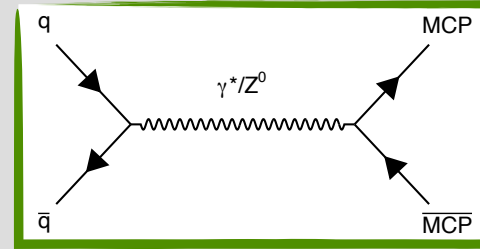
Multi-charged particles

- LL **highly ionizing** heavy fermions with $|q|=ze$ ($2 \leq z \leq 7$)
 - Predicted in many theories
 - **Drell-Yan** or **Photon Fusion**
- Muon-like track going **through whole detector**
 - **dE/dx** \rightarrow MCP **high ionization signature** in sub-detectors



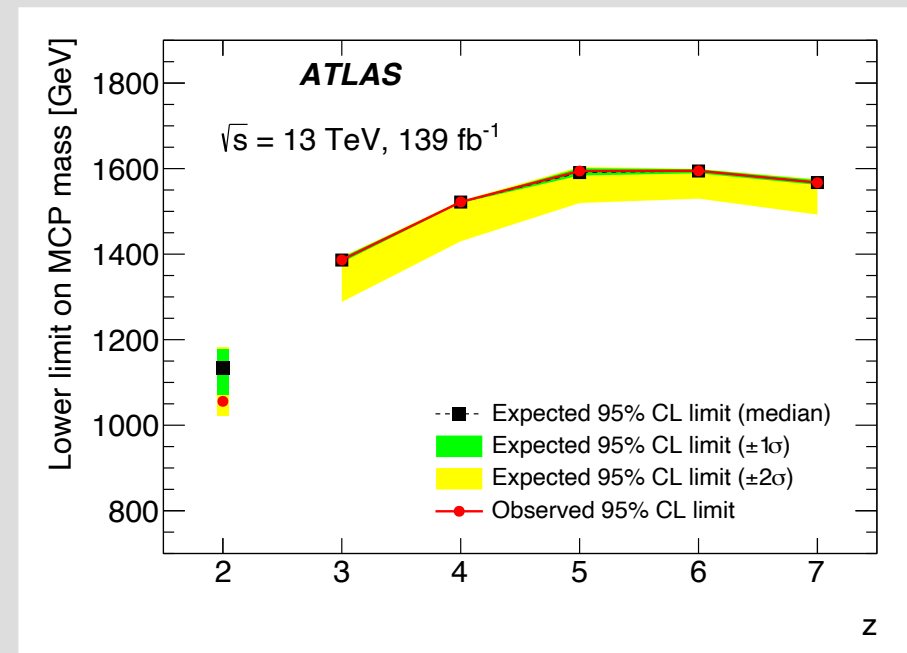
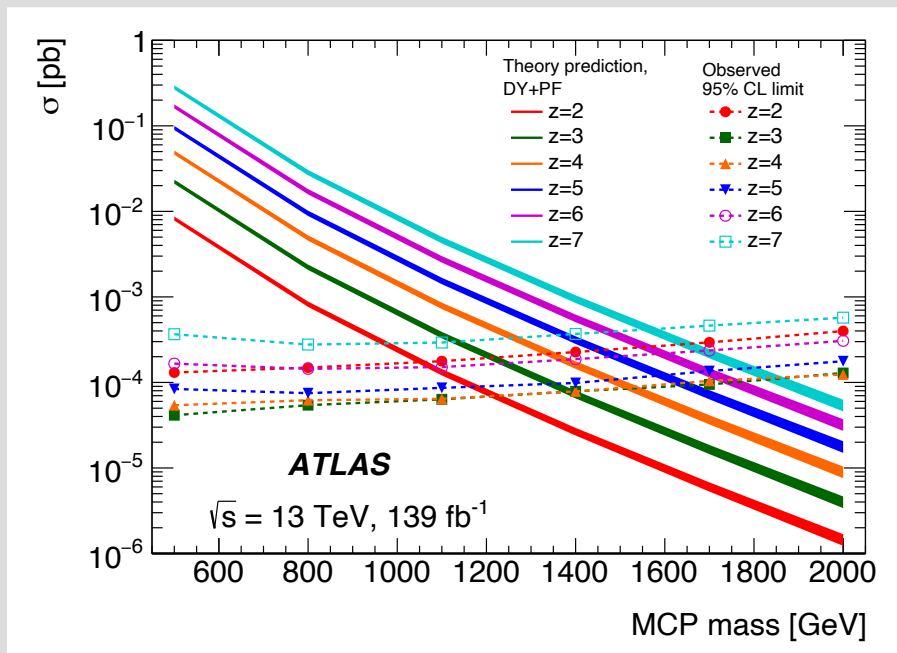
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- Main backgrounds \rightarrow detector occupancy effects, δ -rays
 - ABCD method in $[S(\text{MDT } dE/dx), S(\text{TRT } dE/dx)]$ plane

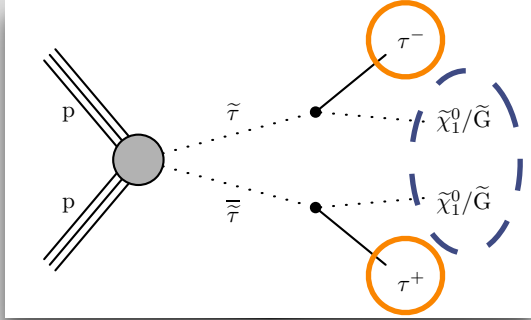


Multi-charged particles

No excess \rightarrow limits set on production cross section for MCP masses **up to 500 GeV** and **1060–1600 GeV**

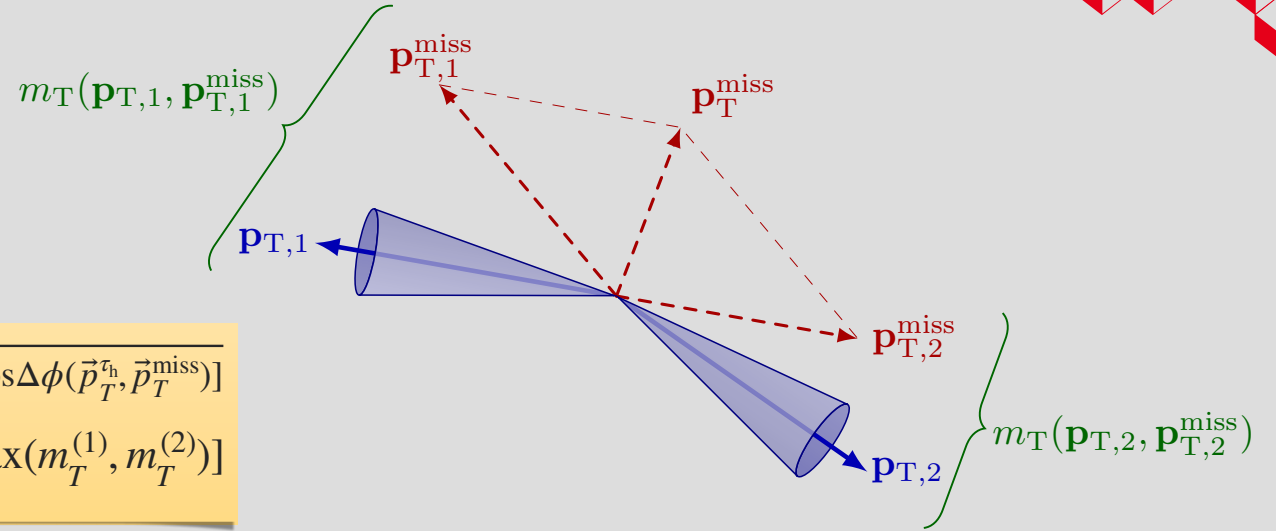


Sleptons to $\tau\tau$ + MET

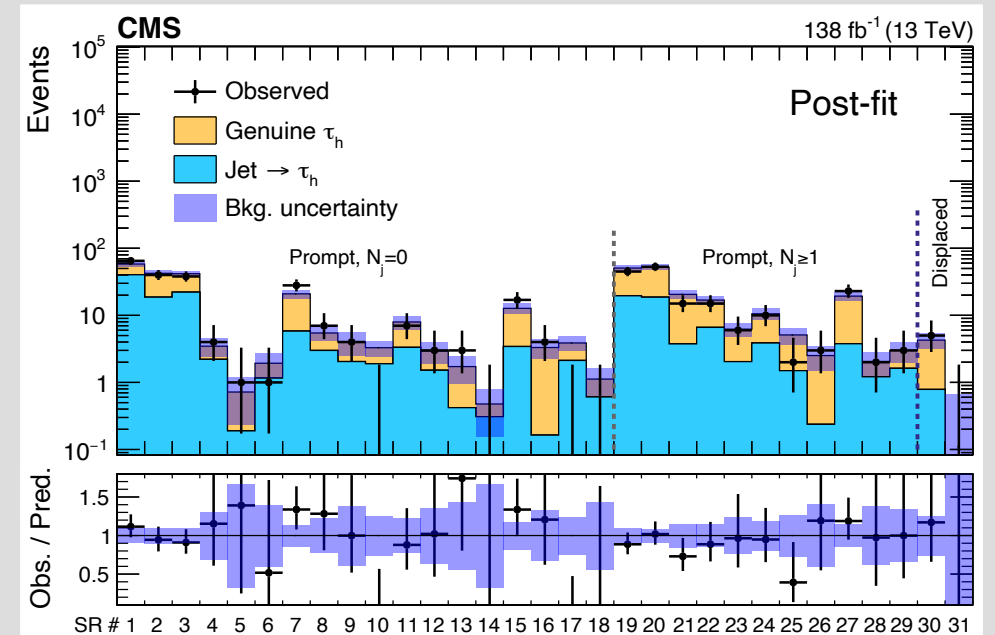


$$m_T(\tau_h) = \sqrt{2p_T^{\tau_h} p_T^{\text{miss}} [1 - \cos\Delta\phi(\vec{p}_T^{\tau_h}, \vec{p}_T^{\text{miss}})]}$$

$$m_{T2} = \min_{\vec{p}_T^{X(1)} + \vec{p}_T^{X(2)} = \vec{p}_T^{\text{miss}}} [\max(m_T^{(1)}, m_T^{(2)})]$$



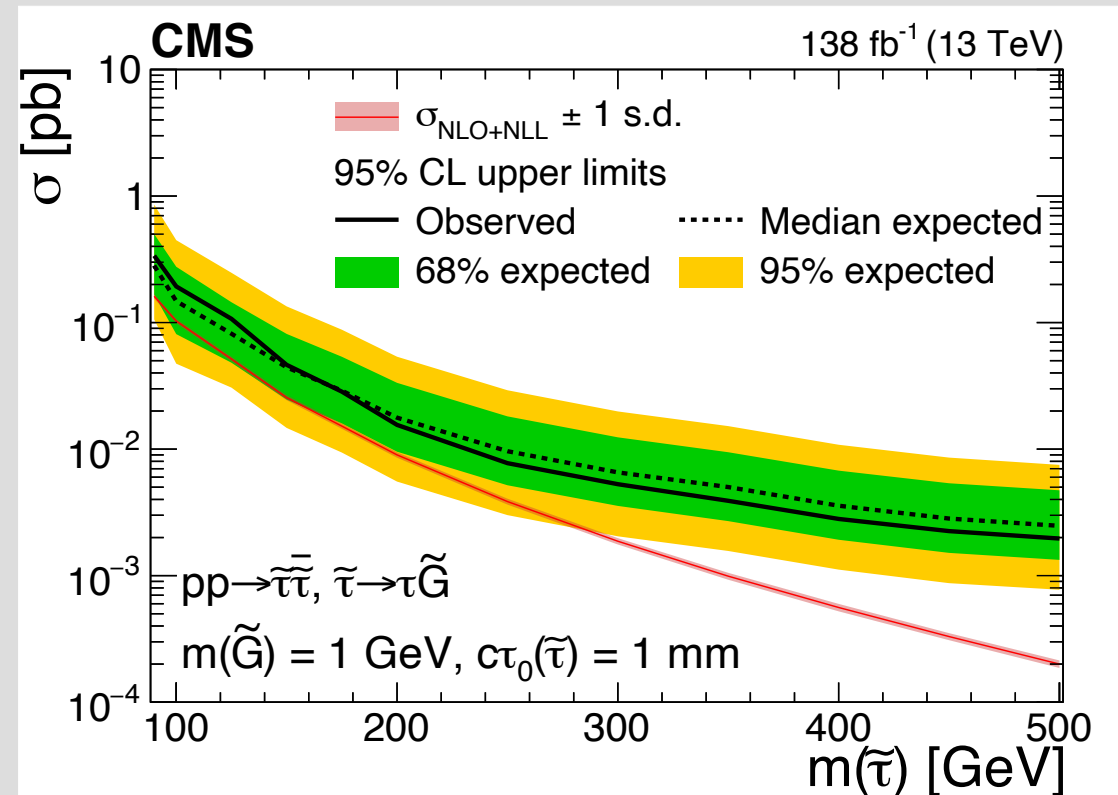
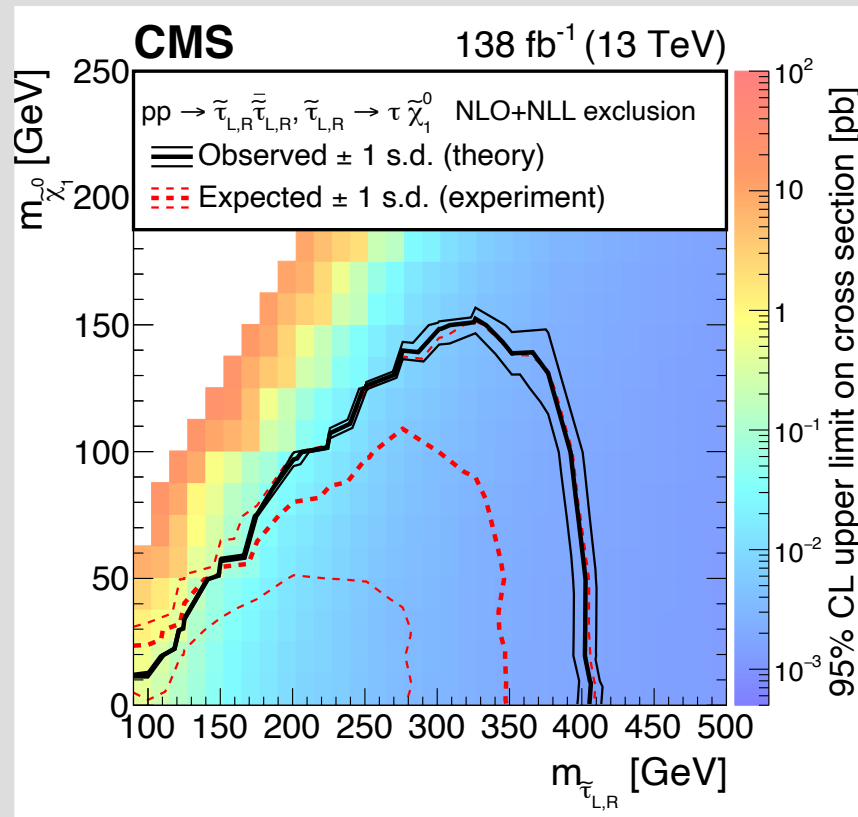
- Stau to **tau** (\rightarrow hadronic) τ_h + high MET
 - Purely left-handed, degenerate (L+R) + LLP interpretation \rightarrow **first search on displaced τ**
- **31 SRs = 29** for prompt $\tilde{\tau}$ and **2** for displaced $\tilde{\tau}$
 - Main discriminants $\rightarrow \Sigma m_T = m_T(1) + m_T(2), m_{T2}, p_T^{\tau_h}$



[arXiv:2207.02254](https://arxiv.org/abs/2207.02254)

$\int L = 138 \text{ fb}^{-1}$

Sleptons to $\tau\tau$ + MET



- Good agreement with SM \rightarrow **strongest limits** on LH and degenerate production scenarios so far + **limits on LLP $\tilde{\tau}$ mass**



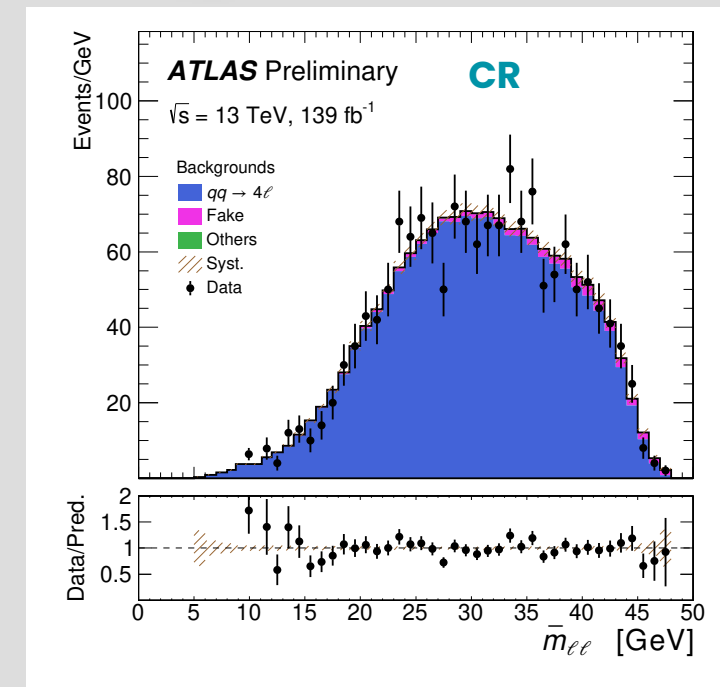
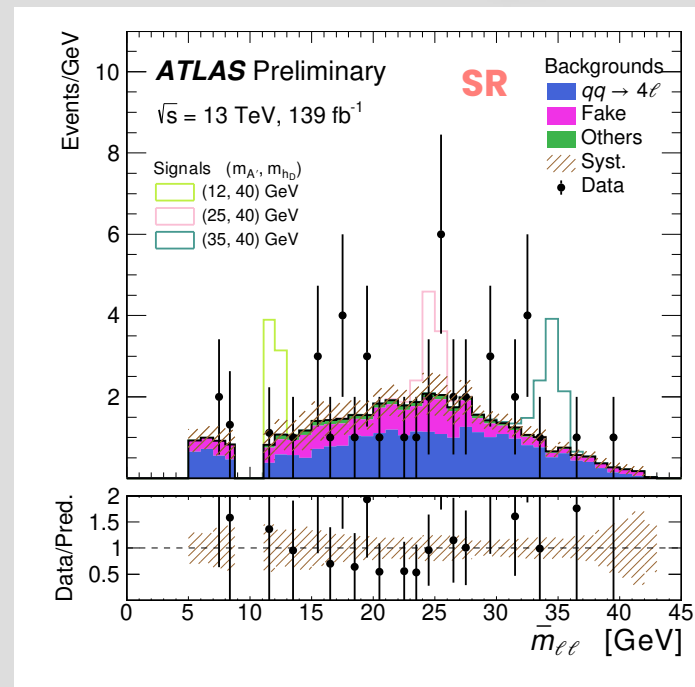
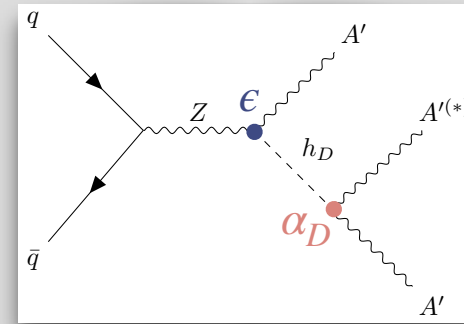
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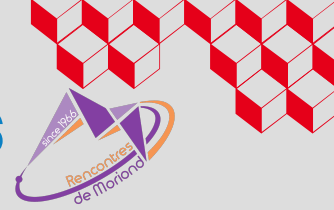
Search for dark photons in rare Z boson decays



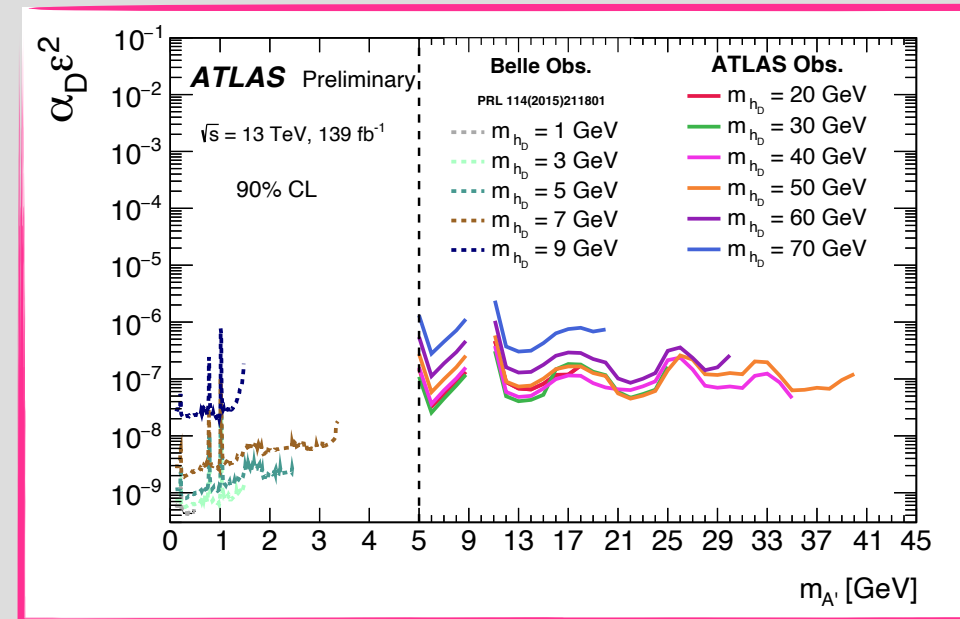
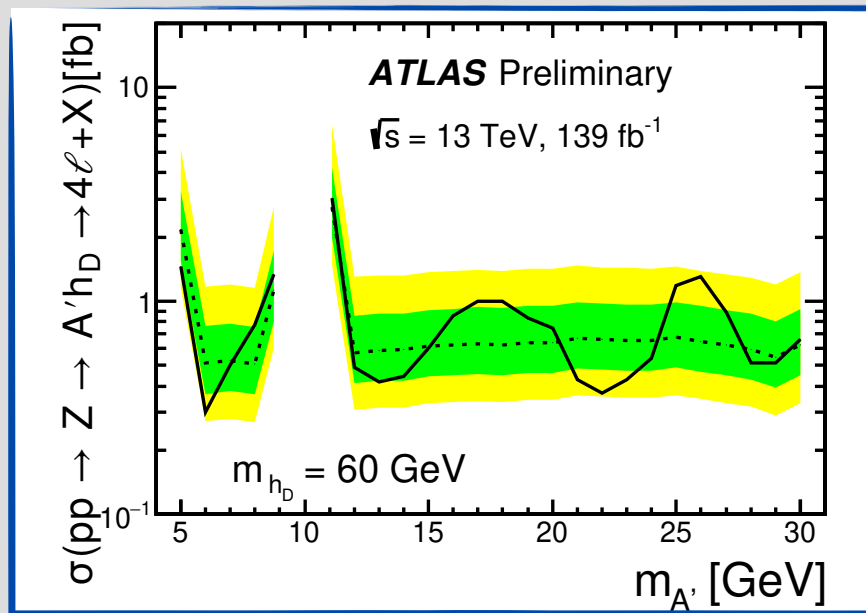
- Dark Abelian Higgs model
 - $m_Z < m_{h_d} < m_{A'}$
- ≥ 2 on-shell $A' \rightarrow \ell^+ \ell^-$ (e/μ)
- Main backgrounds $qq \rightarrow 4\ell$ and fakes
- Discriminant variable $\rightarrow m_{4\ell}$
 - **SR**: veto Z boson, **CR**: select Z boson candidates
- Additional contamination from quarkonia Υ
 - \rightarrow veto on dilepton mass
- Simultaneous fit on average invariant mass $\bar{m}_{\ell\ell} = (m_{\ell_1\ell_2} + m_{\ell_3\ell_4})/2$



Search for dark photons in rare Z boson decays

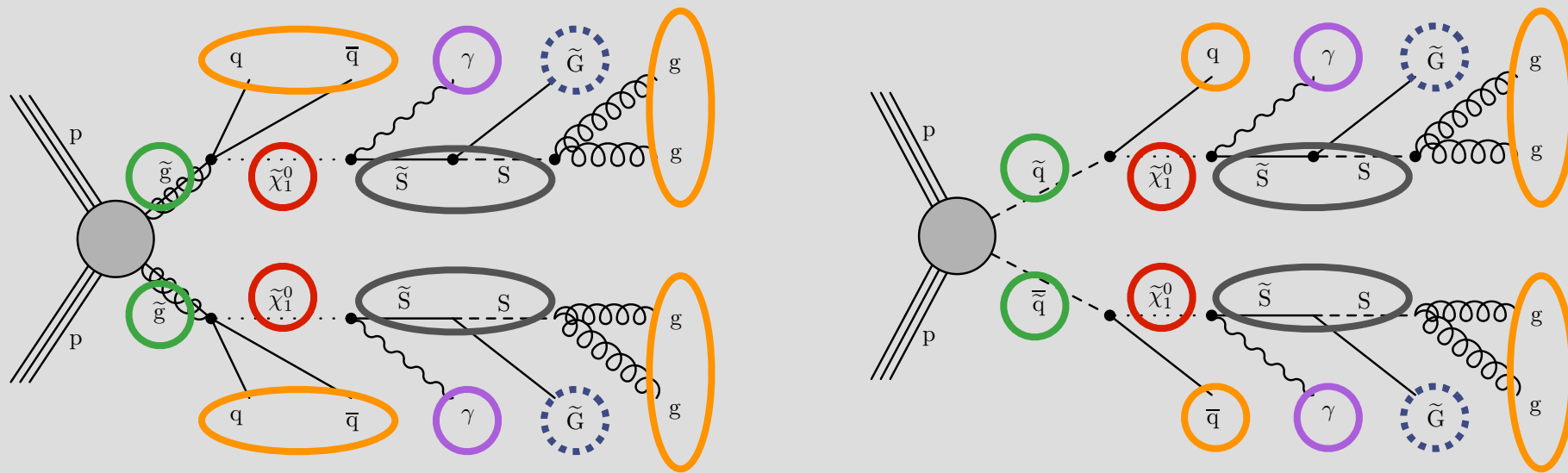


- Limits on $\sigma(\text{pp} \rightarrow \text{Z} \rightarrow \text{A}'h_d \rightarrow 4\ell + \text{X})$ for $20 < m_{h_D} < 70$ GeV and $\alpha_D \epsilon^2$ for $5 < m_{A'} < 40$ GeV and $20 < m_{h_D} < 70$ GeV



Significantly wider ranges than previous experiments!

Stealth SUSY

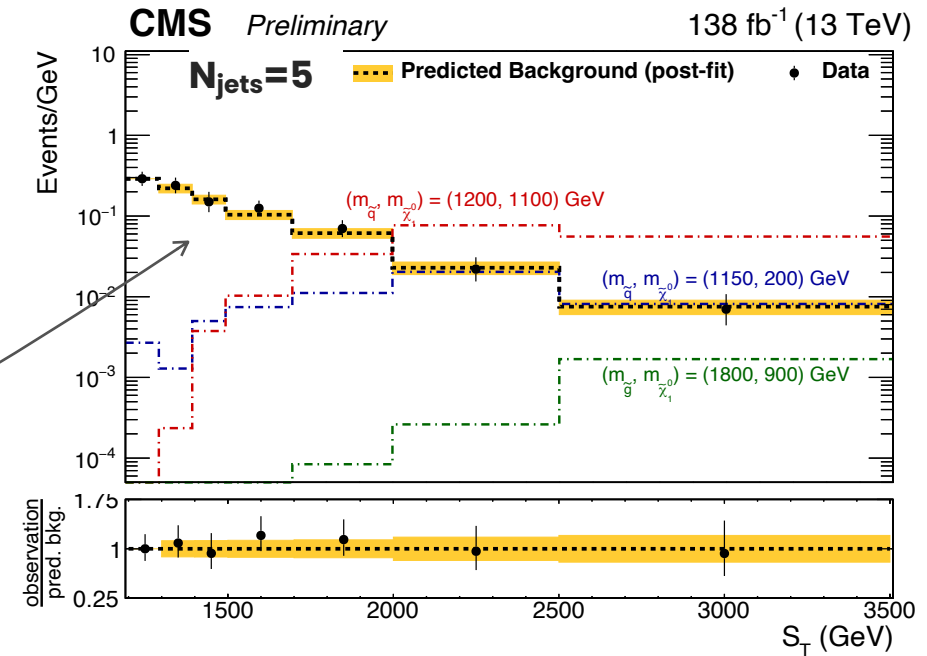
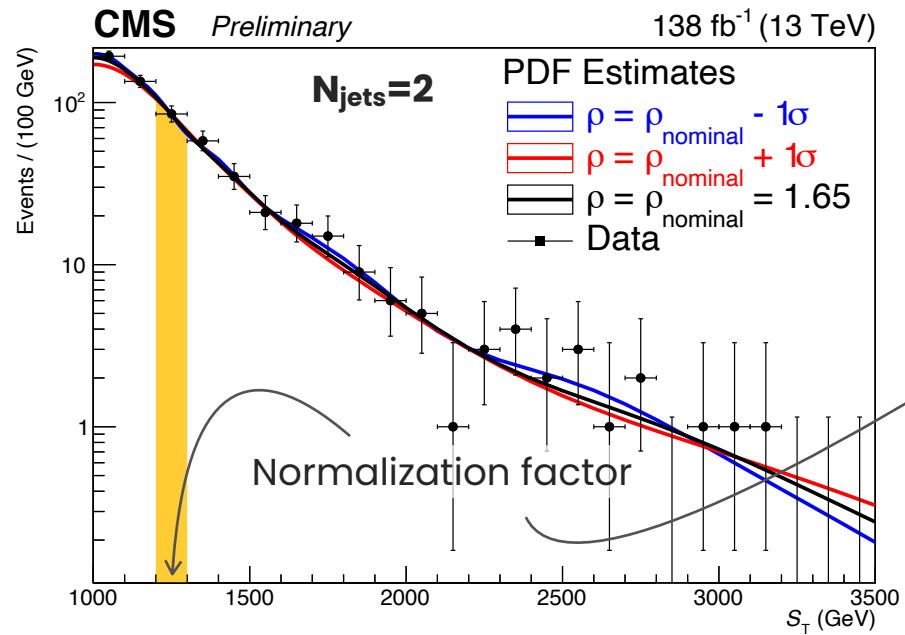


- Minimal SUSY model (MSSM) + light hidden/**stealth sector** → singlet boson S /singlino \tilde{S}
 - **gravitino** \tilde{G} as LSP → DM candidate
- Events with **2 photons**, **≥4 jets** and **low MET**
- Scan over the (**neutralino**, **gluino/squark**) mass 2D plane
- Main backgrounds → **multijets+diphotons** events → $S_T = \sum_i |p_T^i|$ (i =jets, photons, MET...), N_{jets}



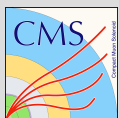
SUS-19-001 $\int L = 138 \text{ fb}^{-1}$

S_T invariance shape



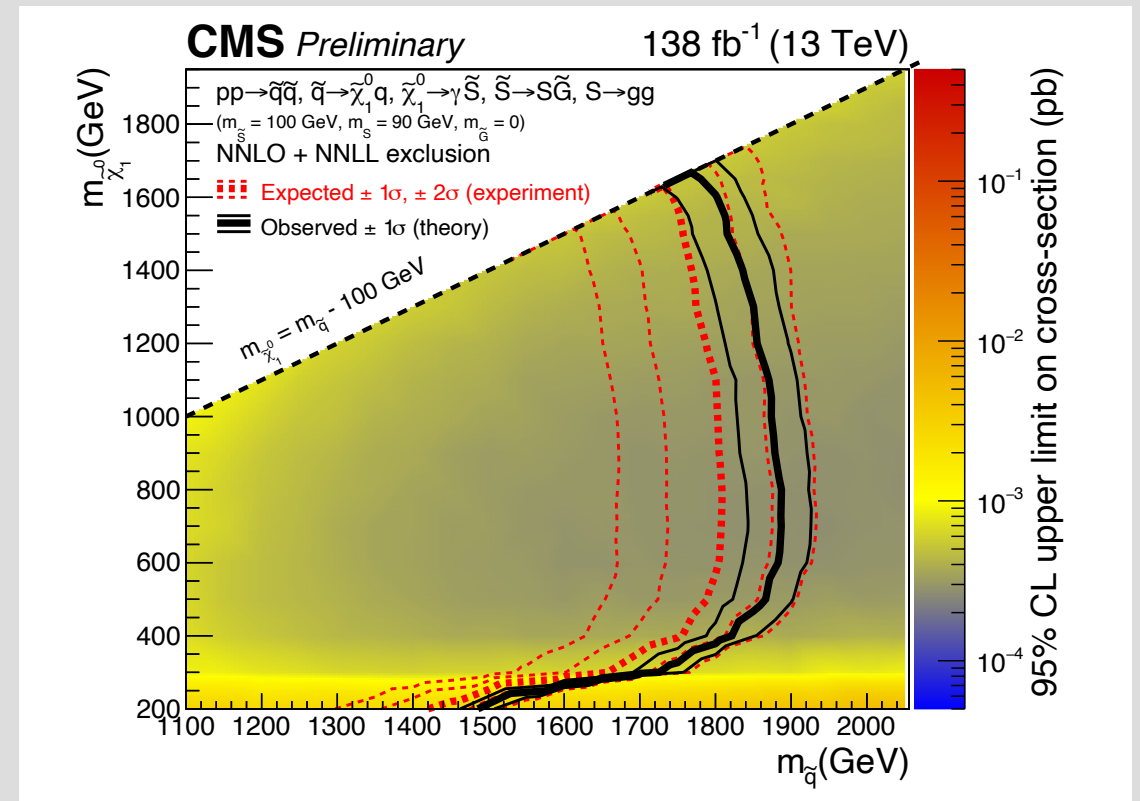
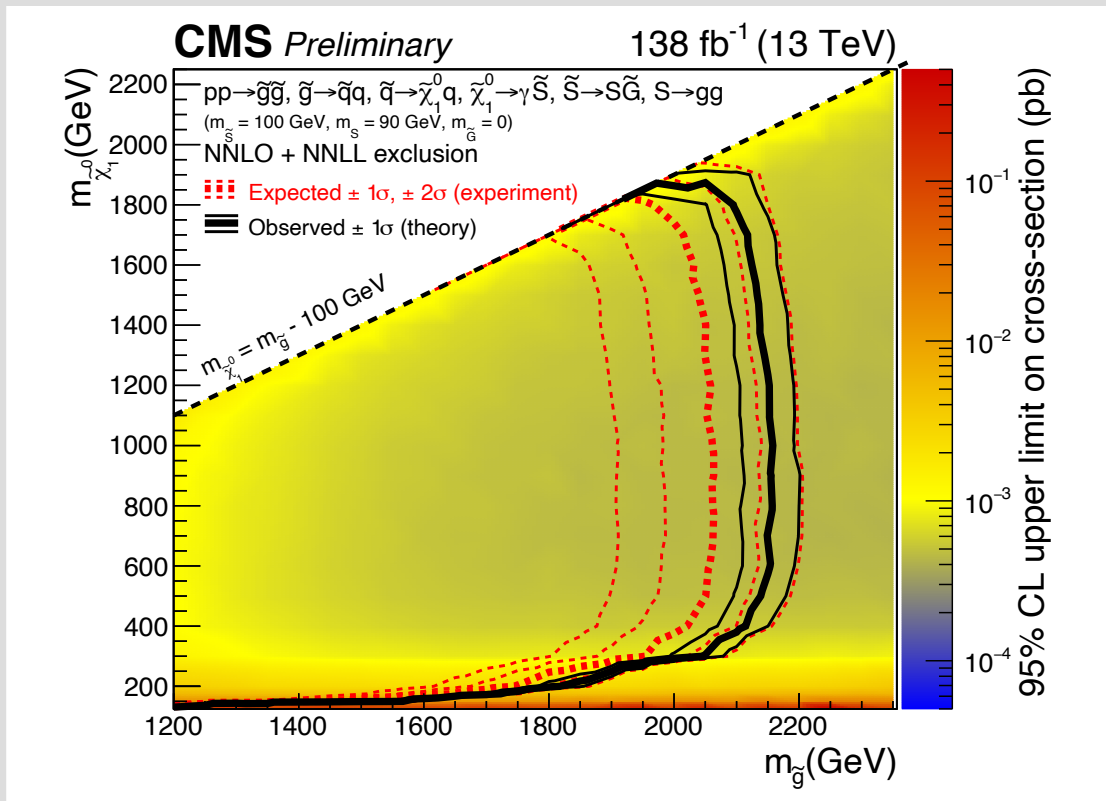
- Minimal
- grav
- Events w
- Scan ove
- Main bac

- Distribution invariant for **high N_{jets}** → normalisation factor from **S_T distribution @ low N_{jets}** + corrections via **MC simulations**



Stealth SUSY

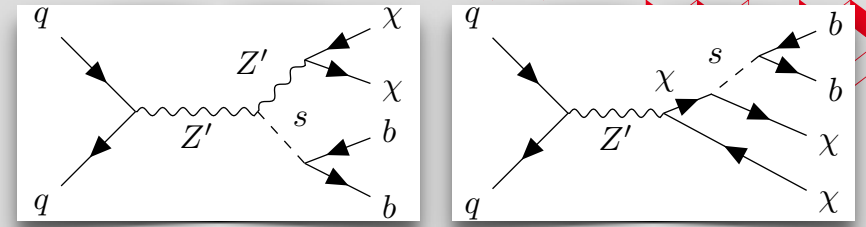
Limits set on **gluino(squark) mass** at 95% CL \rightarrow **$\sim 70\%$ improvement** in exclusion contour + **most stringent limits** to date



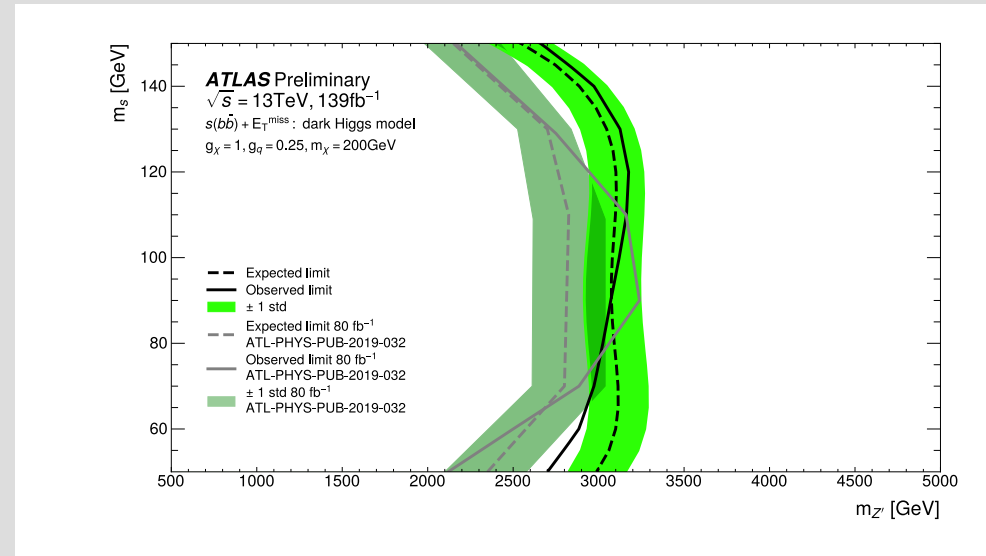
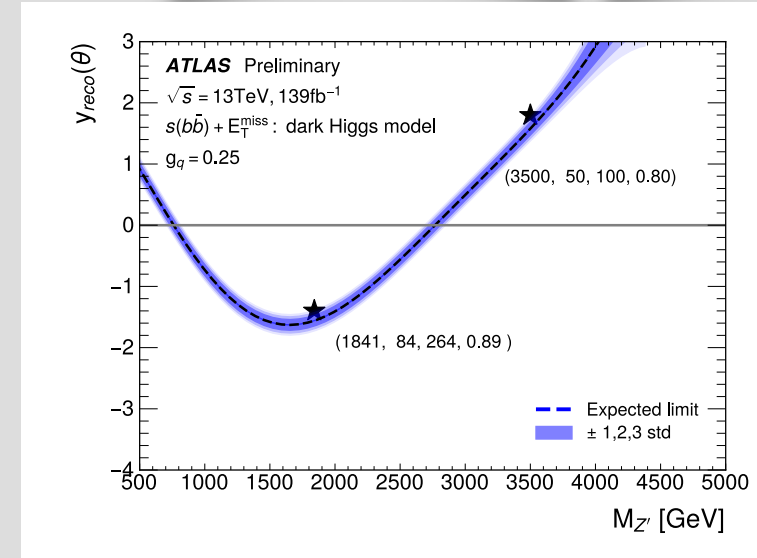
SUS-19-001

$\int L = 138$ fb⁻¹

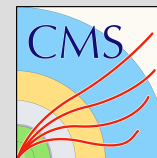
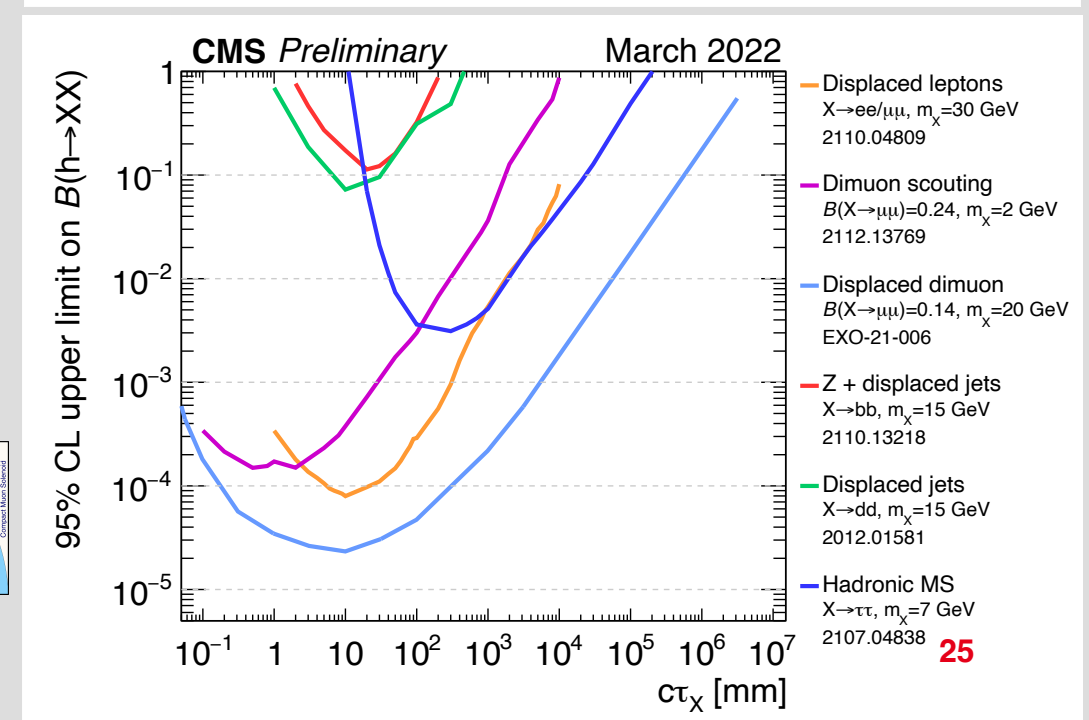
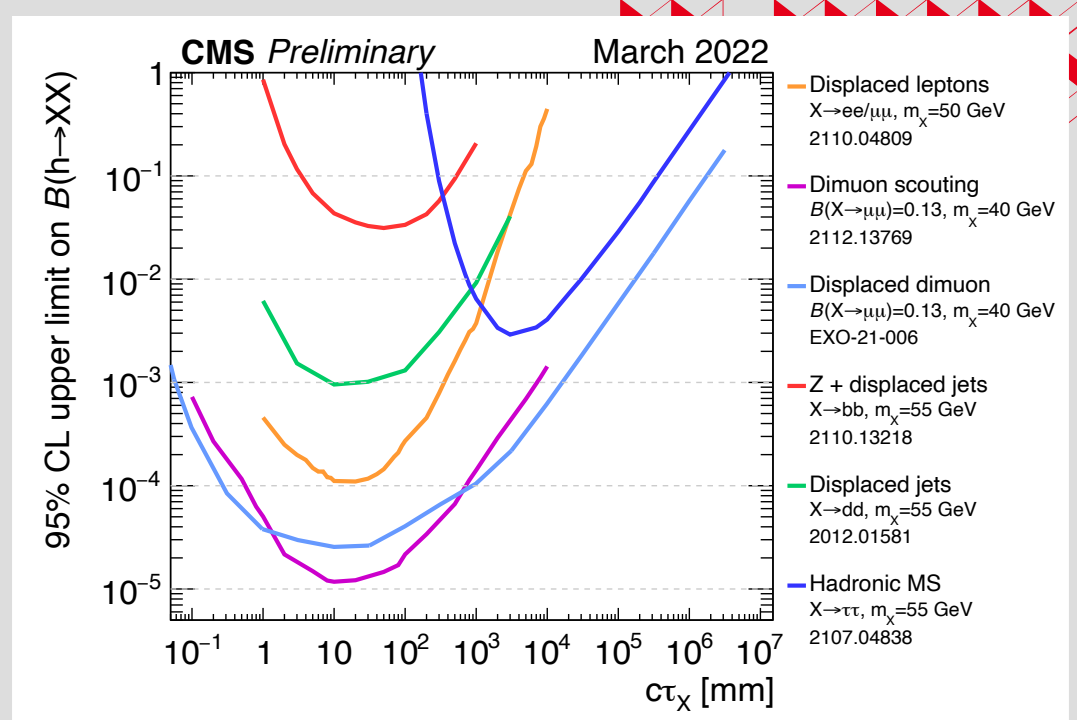
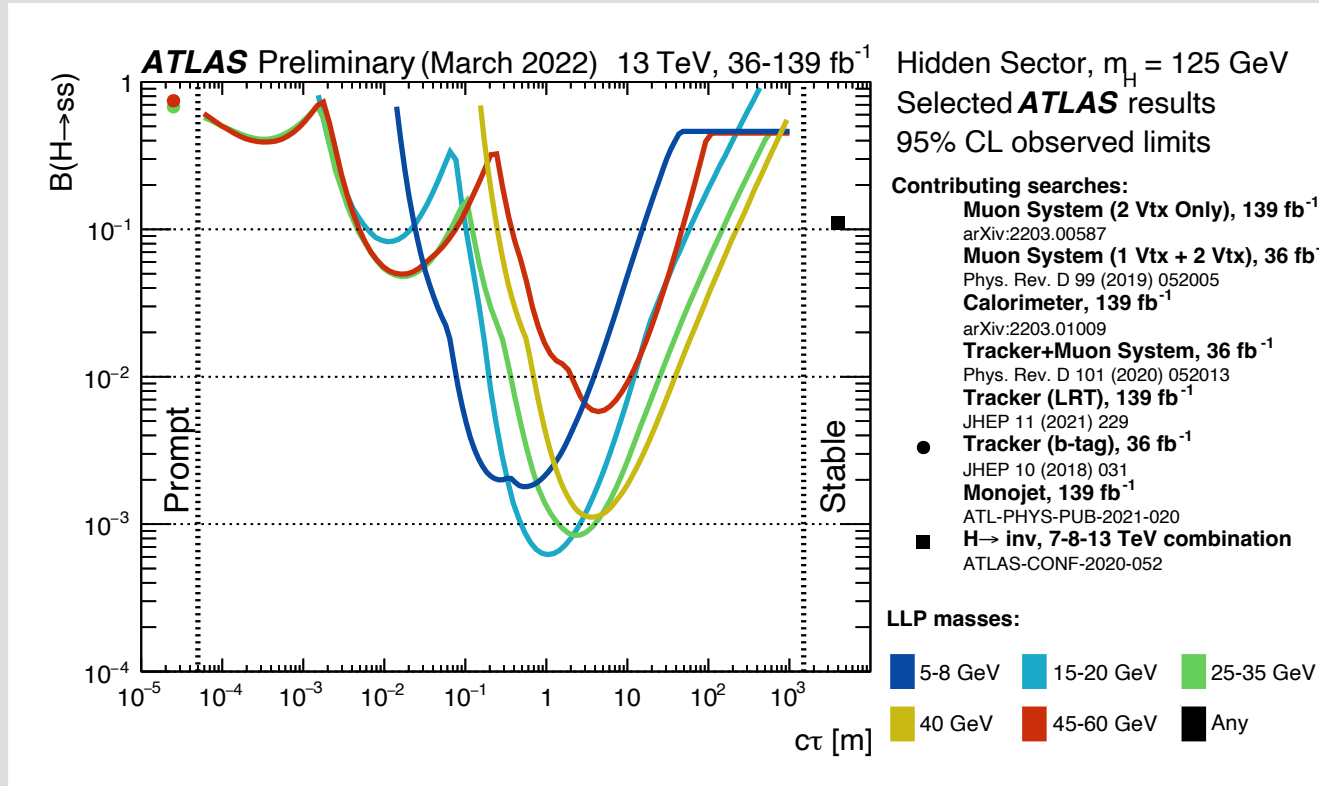
Active Learning reinterpretation



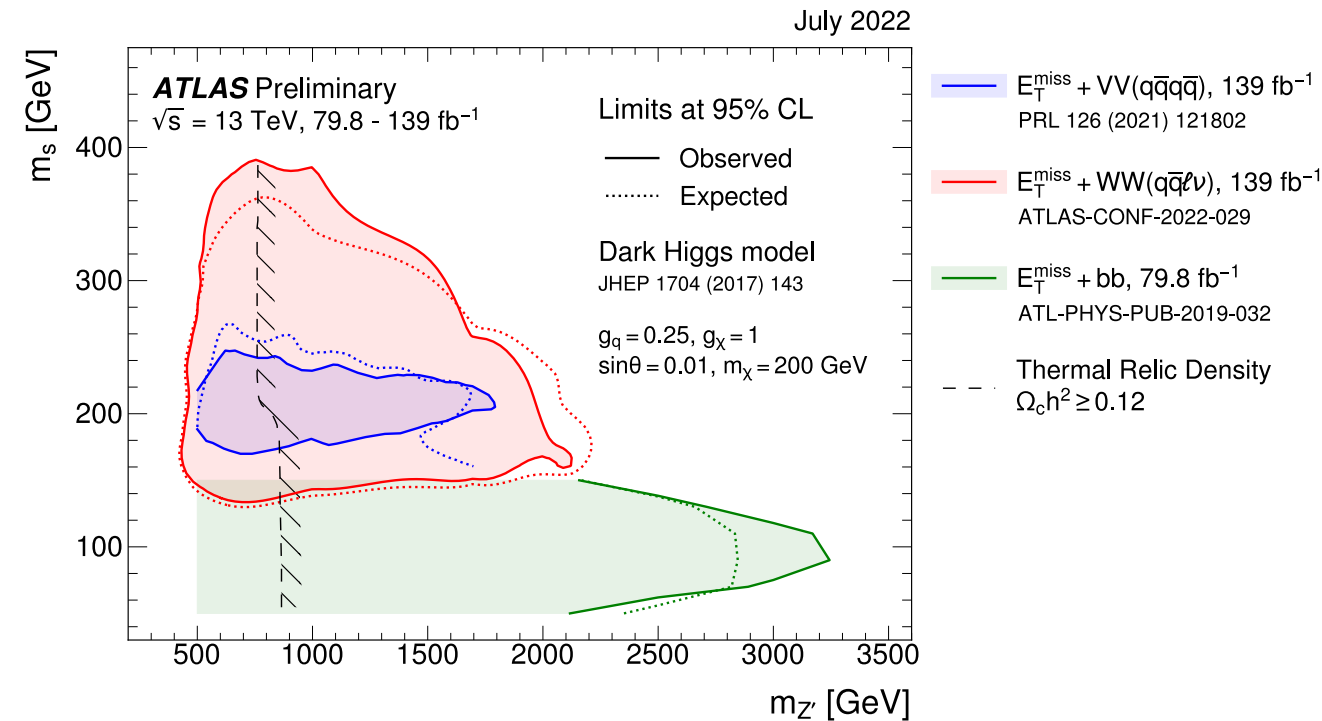
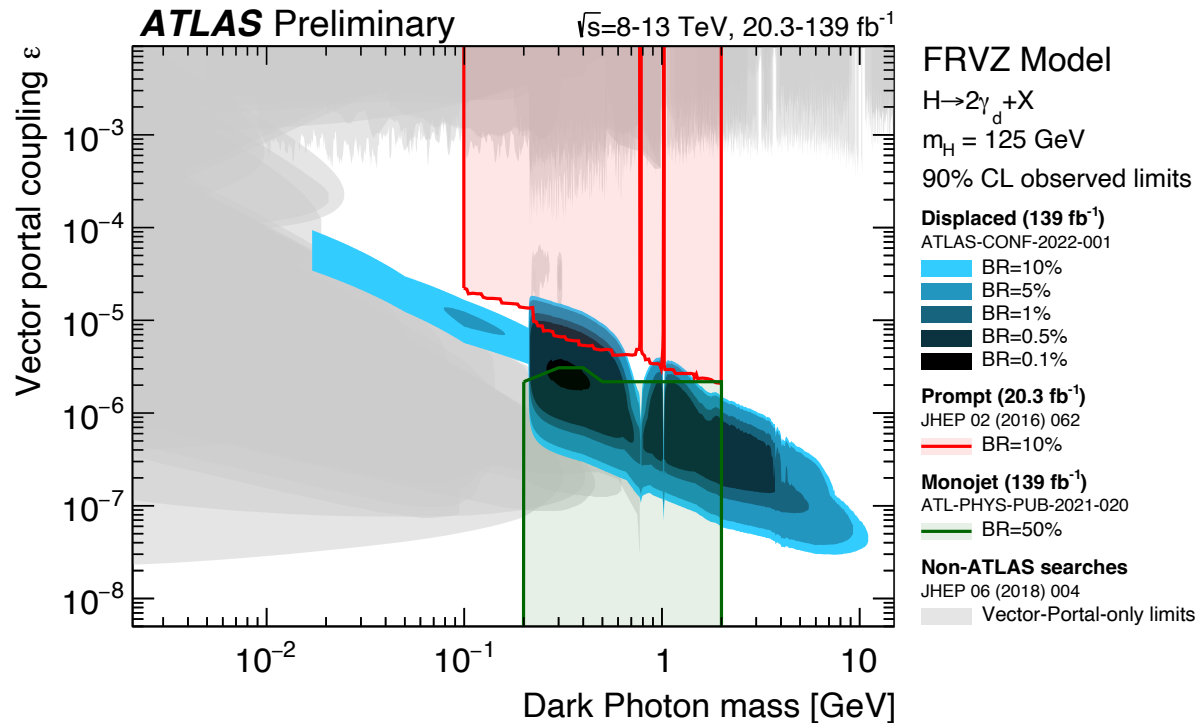
- Mono- $H(b\bar{b})$ reinterpretation \rightarrow **dark Higgs** model $s + Z' + \chi$
 - ≥ 2 **b-jets** + **MET**
- **Active Learning** approach \rightarrow **Gaussian Process** fits the upper limit on the signal strength + uncertainty
 - Iterative approach \rightarrow **RECAST** protocol to compute exclusion limits with full accuracy
 - Computationally **inexpensive**
 - $m_s, m_{Z'}, m_\chi, g_\chi$ free parameters
- Exclusion contour across whole new physics parameter space under investigation



H → LLPs



Dark photons, dark Higgs

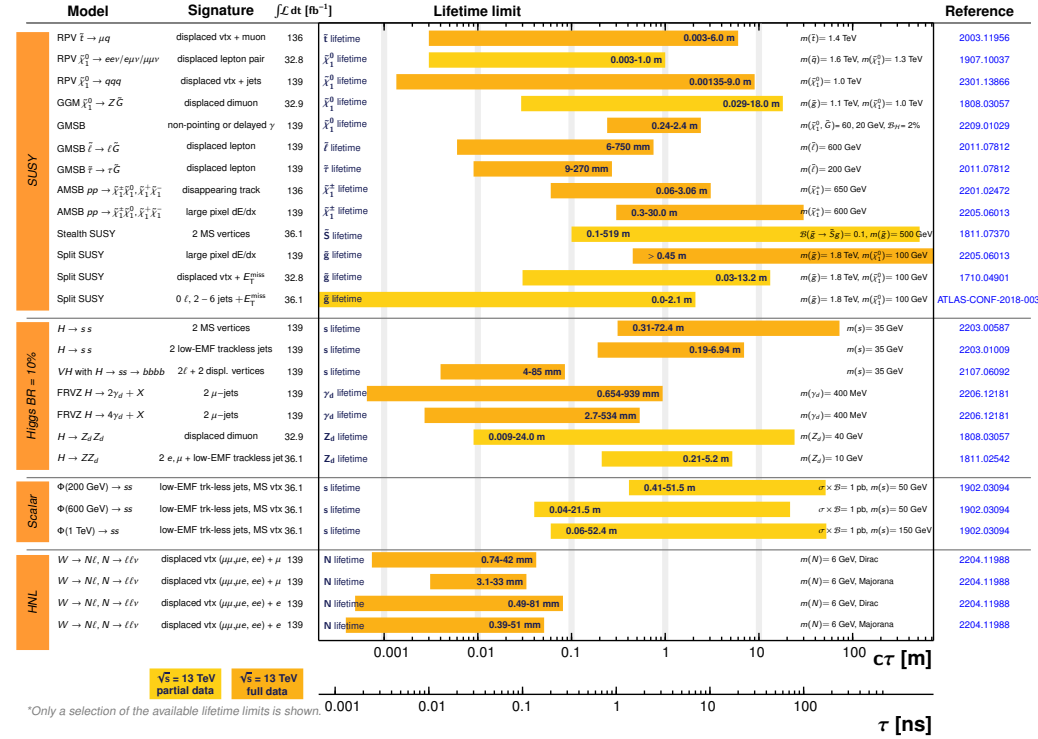


Current status @ ATLAS and CMS

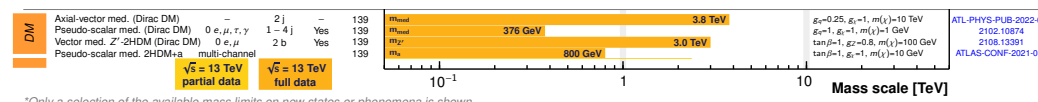
ATLAS Long-lived Particle Searches* - 95% CL Exclusion

Status: March 2023

ATLAS Preliminary
 $\int \mathcal{L} dt = (32.8 - 139) \text{ fb}^{-1}$ $\sqrt{s} = 13 \text{ TeV}$



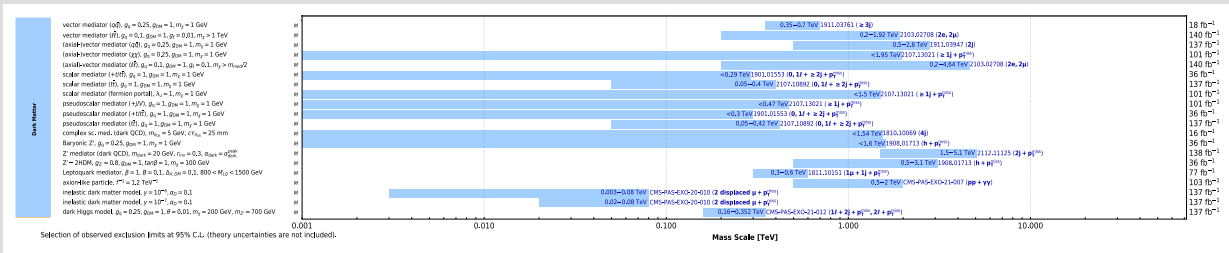
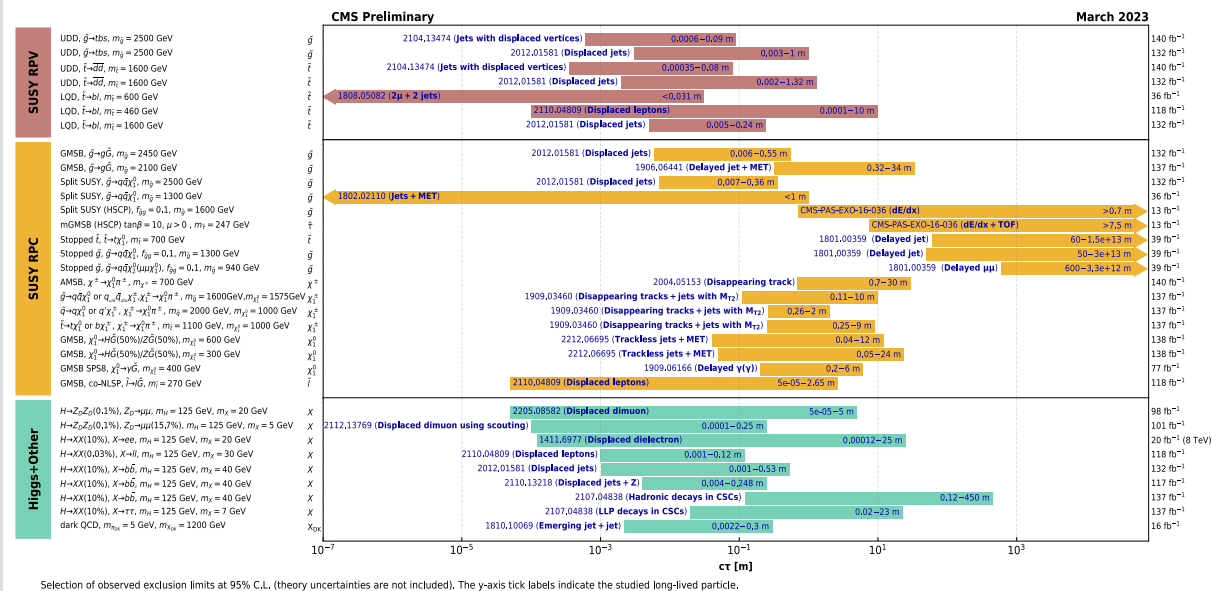
*Only a selection of the available lifetime limits is shown.



*Only a selection of the available mass limits on new states or phenomena is shown.

† Small-radius (large-radius) jets are denoted by the letter J.

Overview of CMS long-lived particle searches



- Spanning over large energy scale/lifetime
- Novel techniques exploited → pushed boundaries even further
- Let's see Run 3 → HL-LHC → FCC...!





Thank you!

Marianna Liberatore

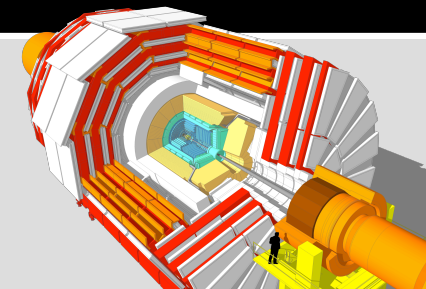
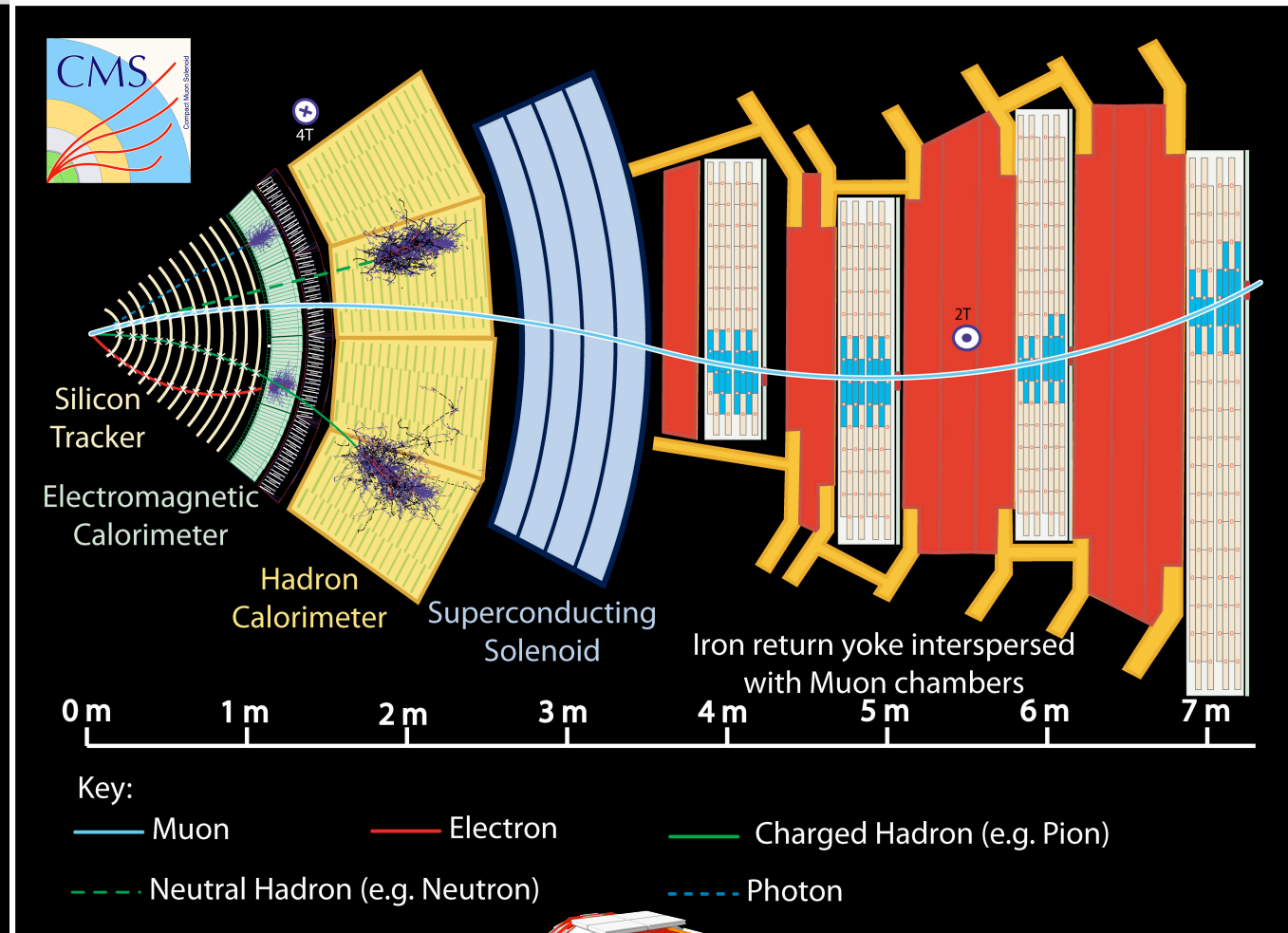
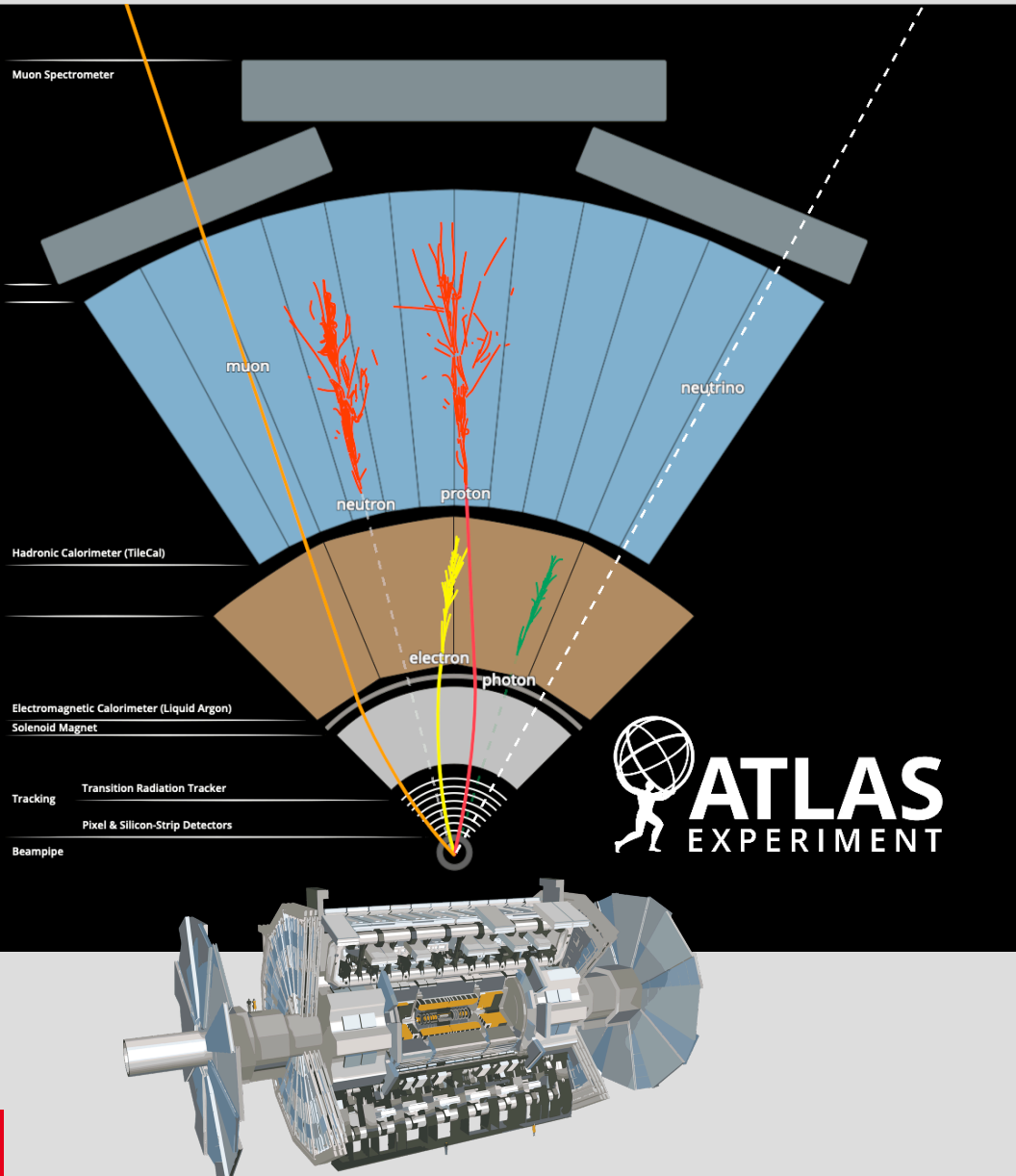
ATLAS group @ Irfu CEA Saclay

marianna.liberatore@cern.ch

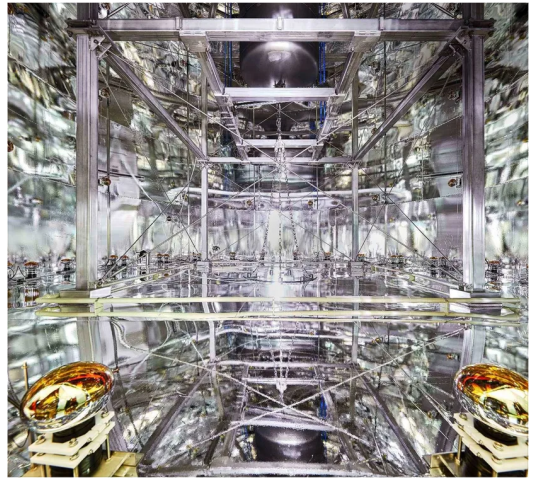


■ Backup

ATLAS and CMS detectors



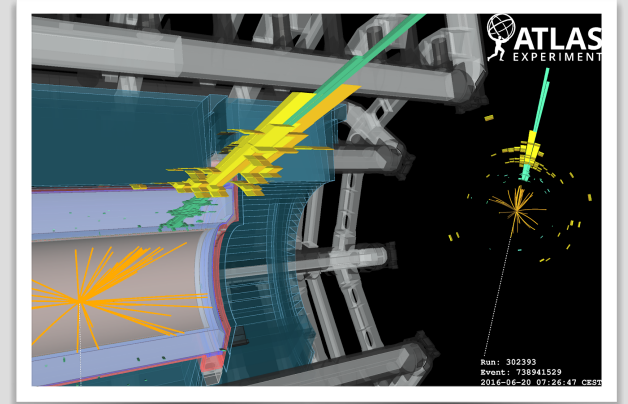
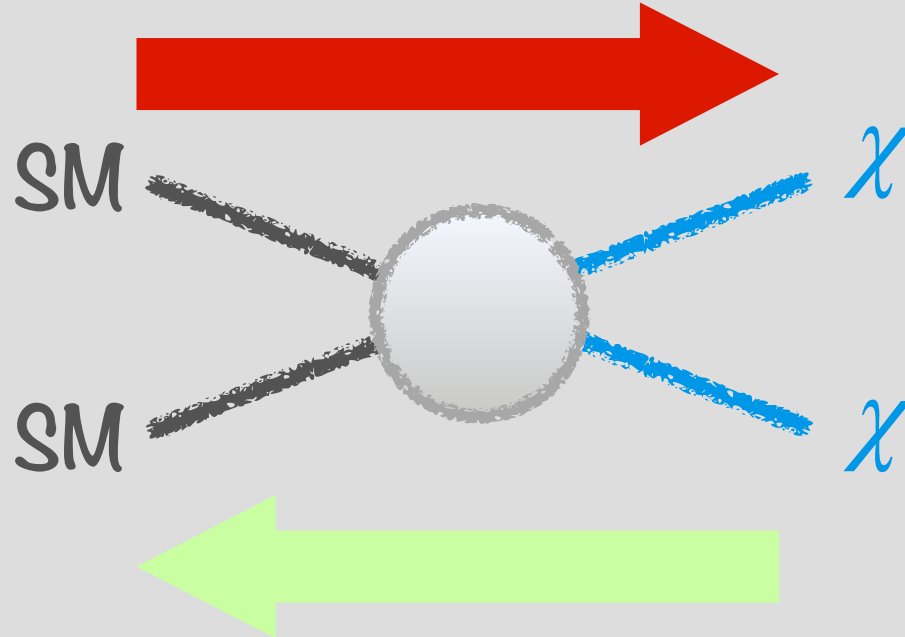
Looking for DM in all directions



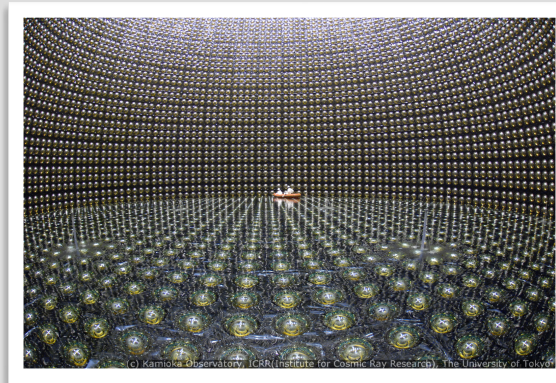
Direct detection



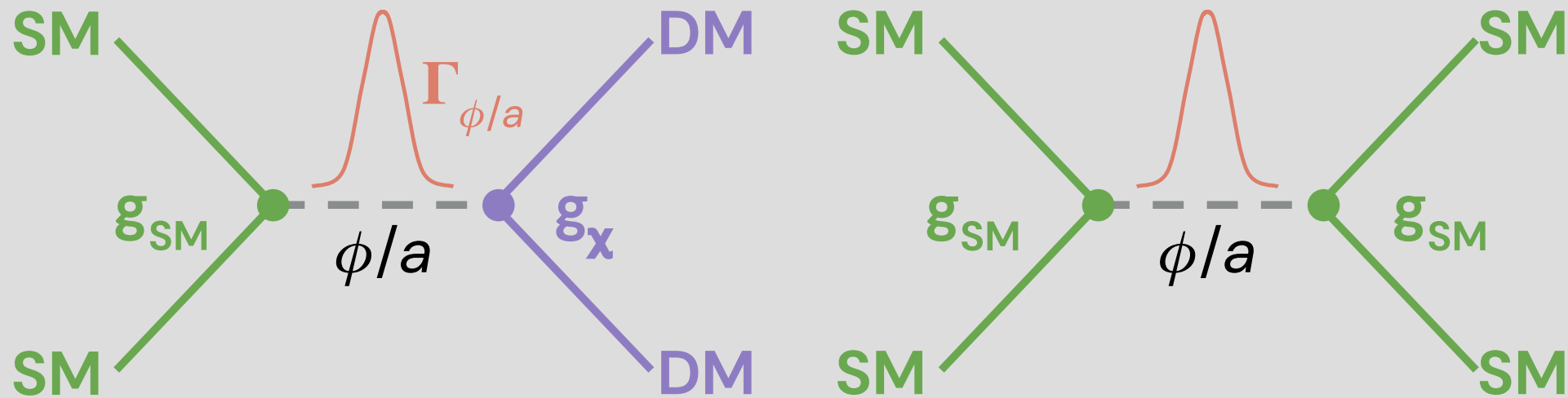
Production @ colliders



Indirect detection

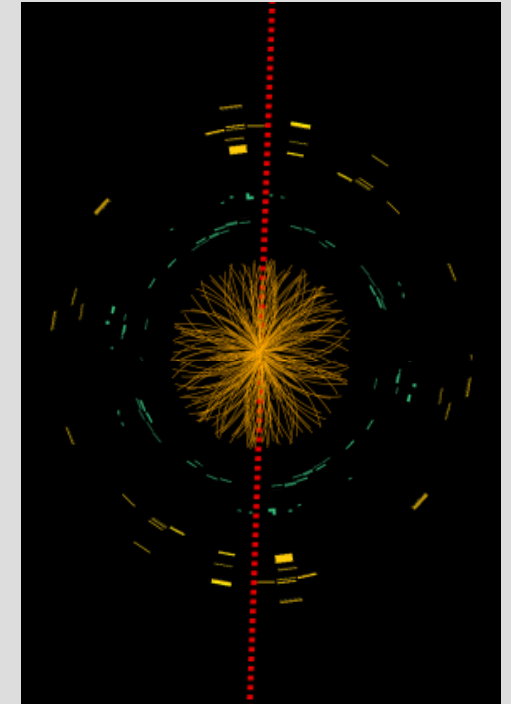
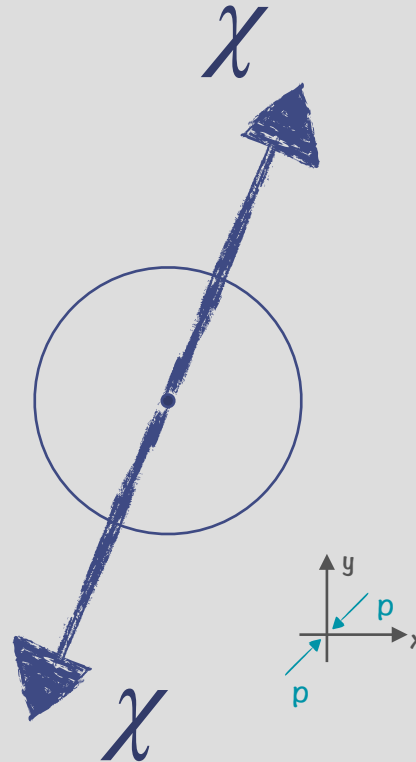
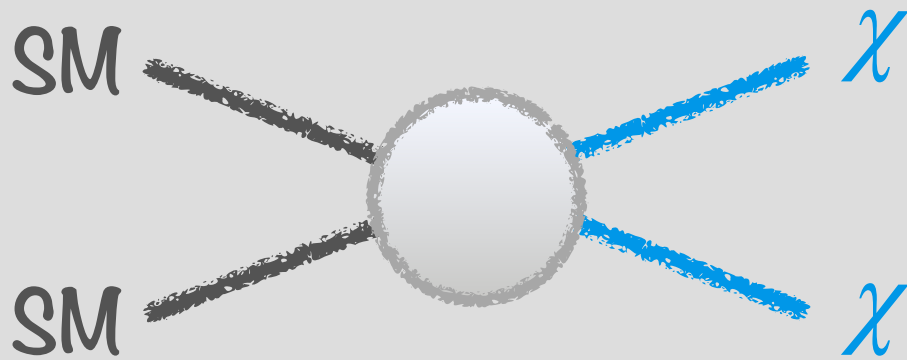


Scalar/pseudoscalar mediator



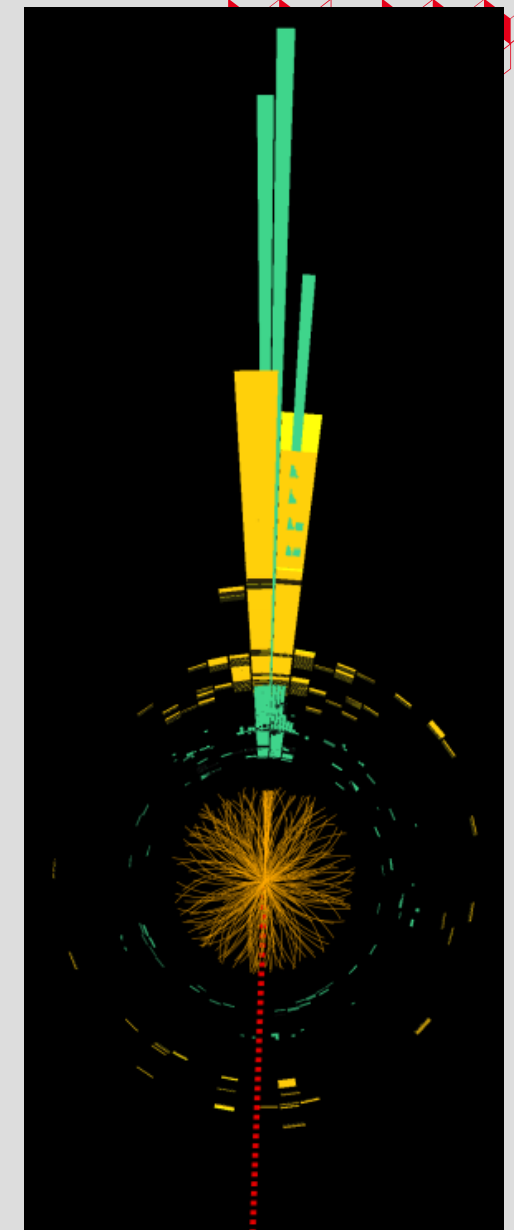
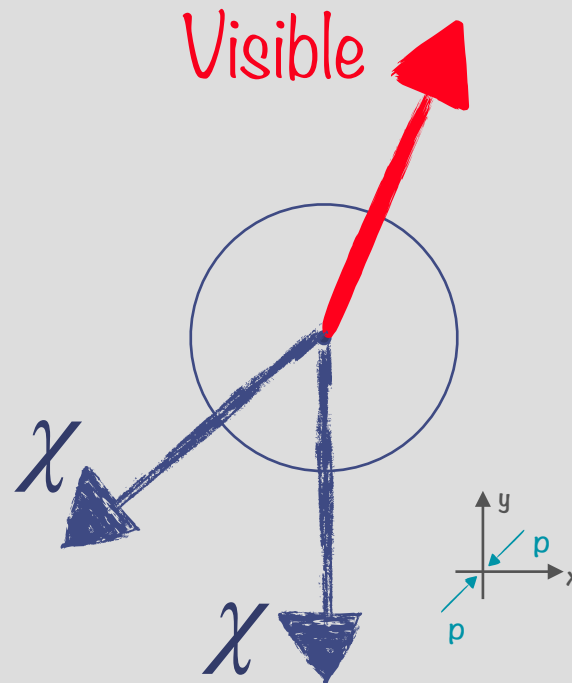
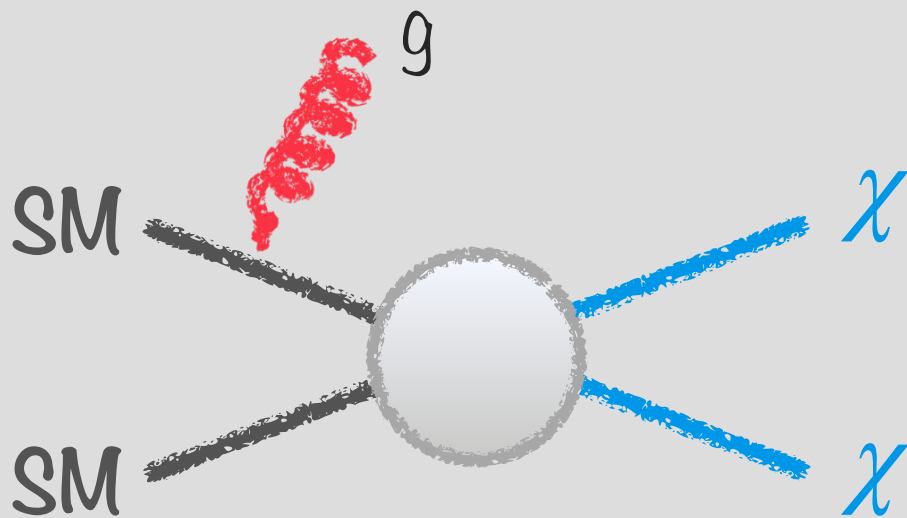
Missing transverse momentum

- Events with only non-interactive particles in final state \rightarrow cannot be detected



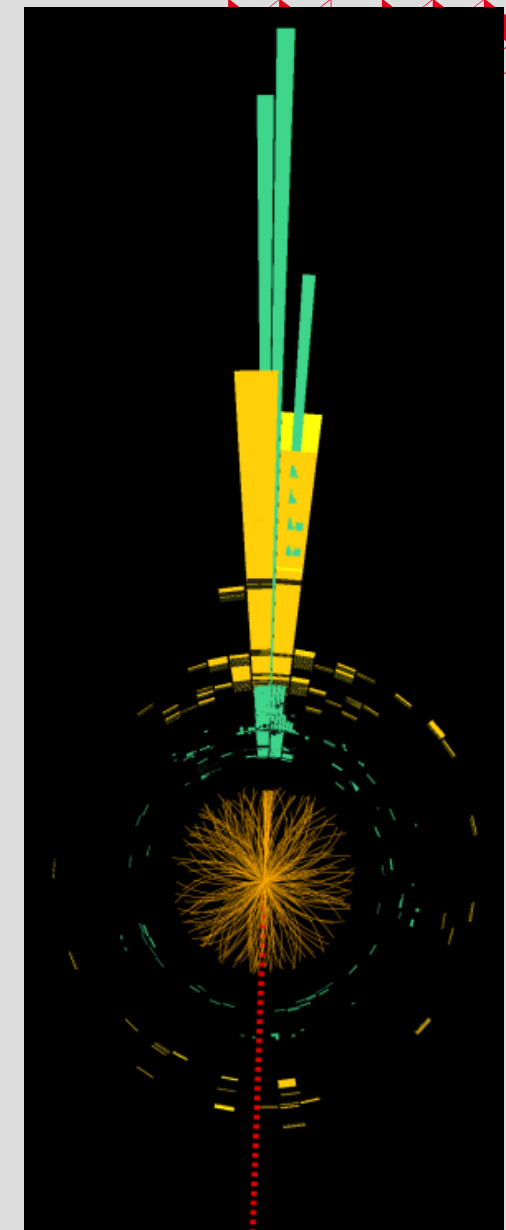
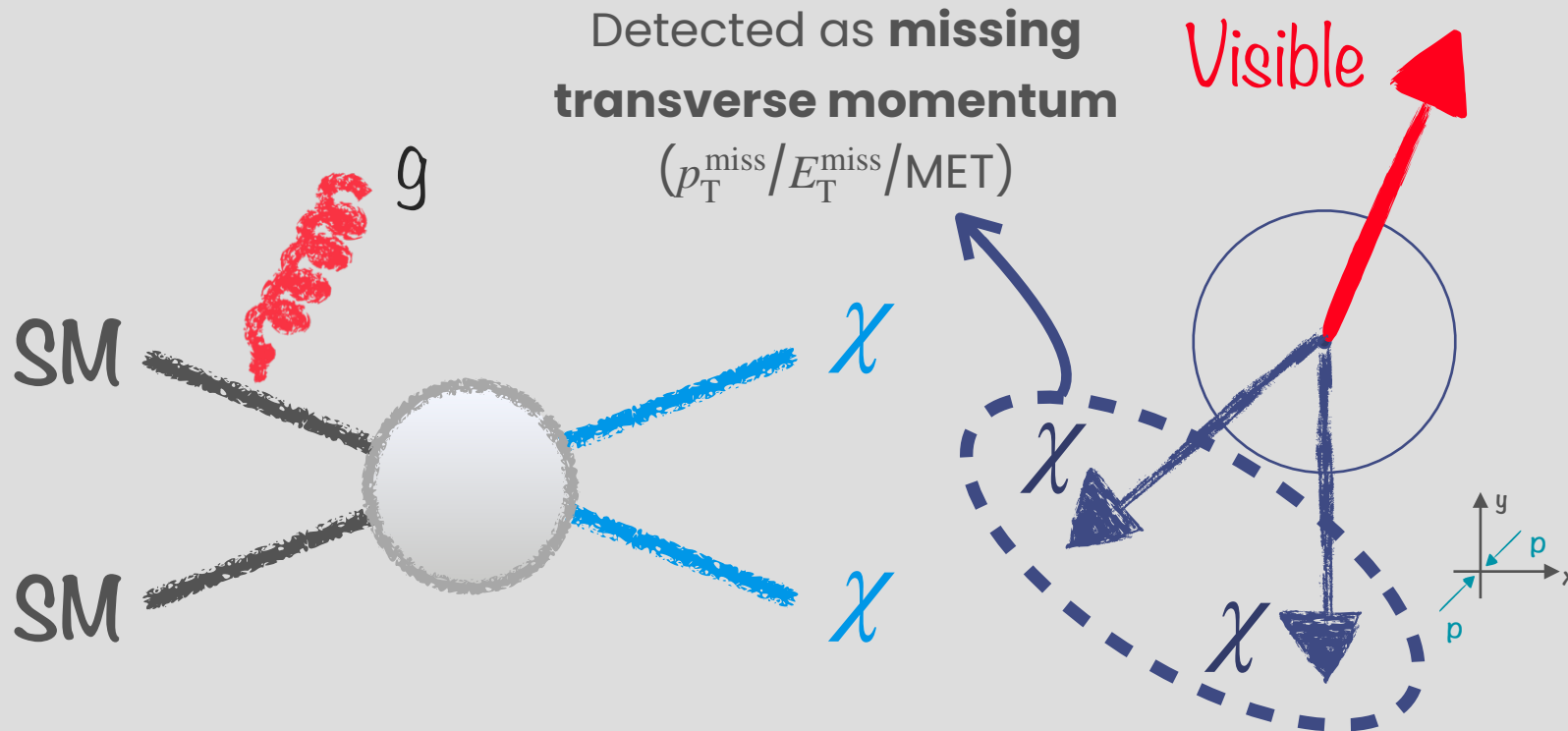
Missing transverse momentum

- Events with only non-interactive particles in final state \rightarrow cannot be detected
- Rely on *visible* objects from **initial state radiation** or associated production to detect *invisible* particles



Missing transverse momentum

- Events with only non-interactive particles in final state \rightarrow cannot be detected
- Rely on *visible* objects from **initial state radiation** or associated production to detect *invisible* particles
- **sum of all event momenta in transverse plane = 0**



Theoretical framework

Simpler models

- Generic searches
- Few model assumptions

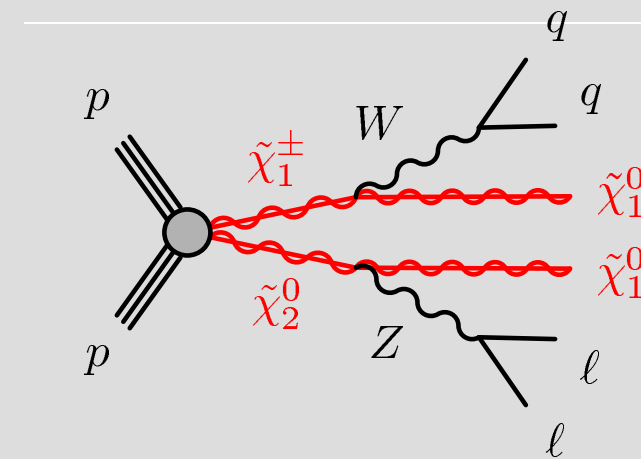
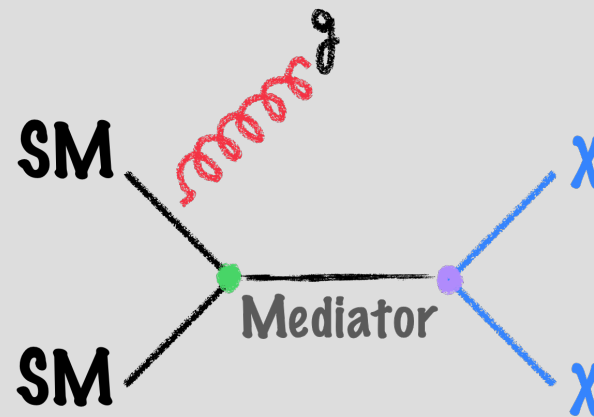
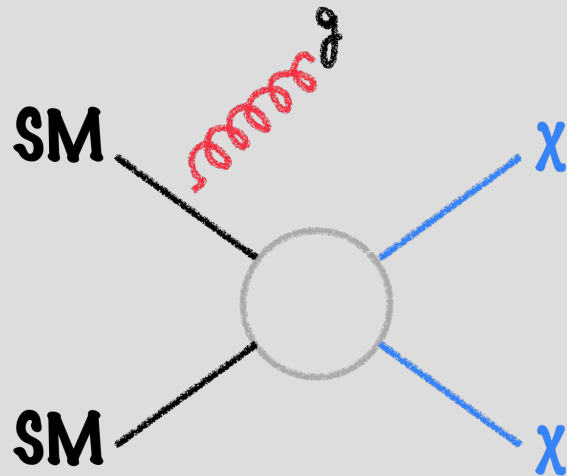
More complex/complete models

- More sensitive to specific models
- More reliant on model assumptions

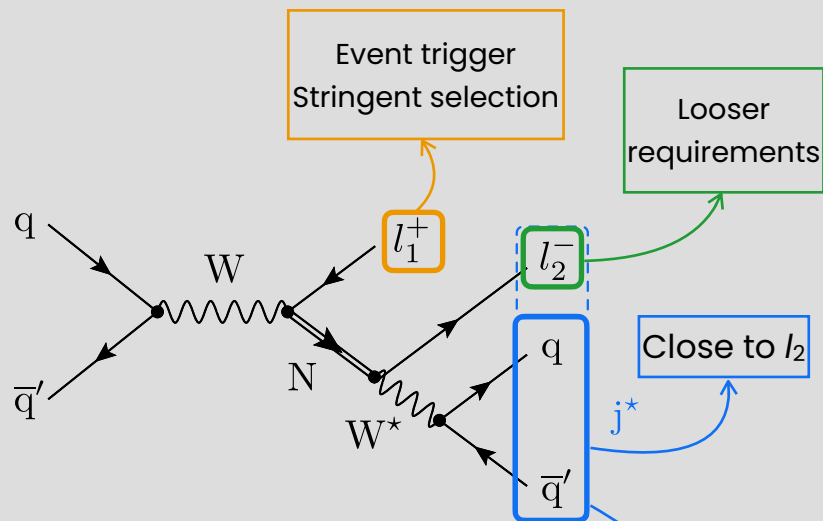
Effective field theories

Simplified models

Complete theories (e.g. SUSY)



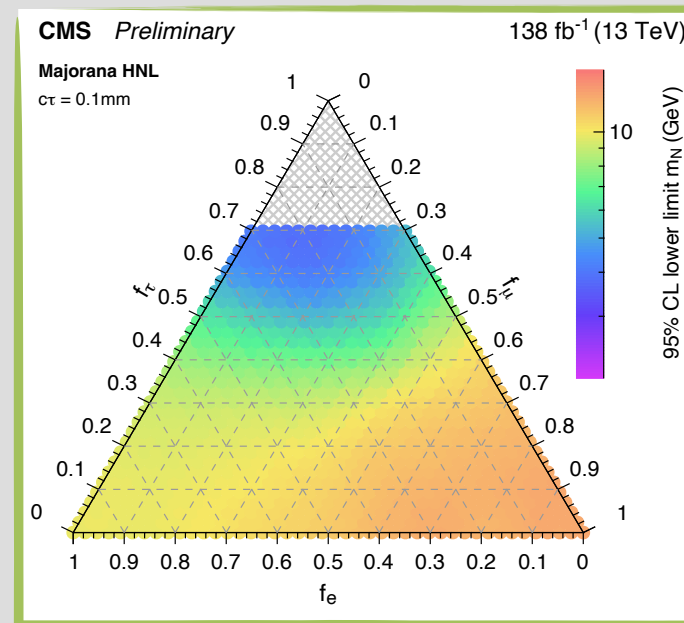
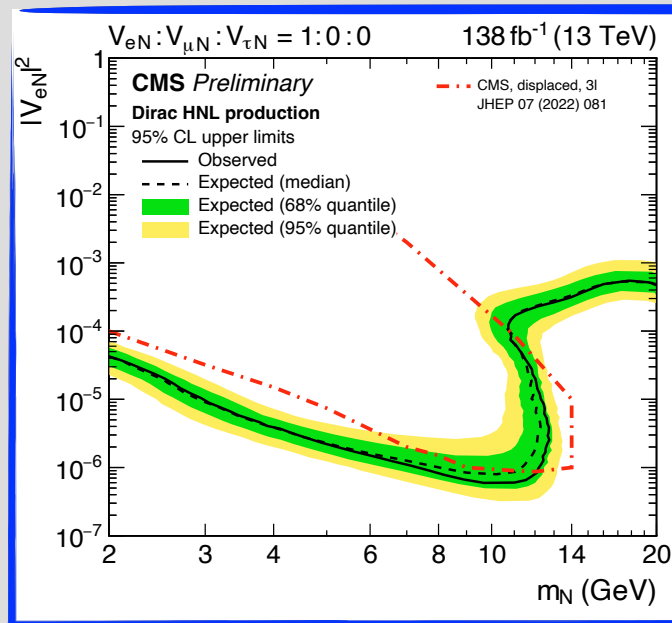
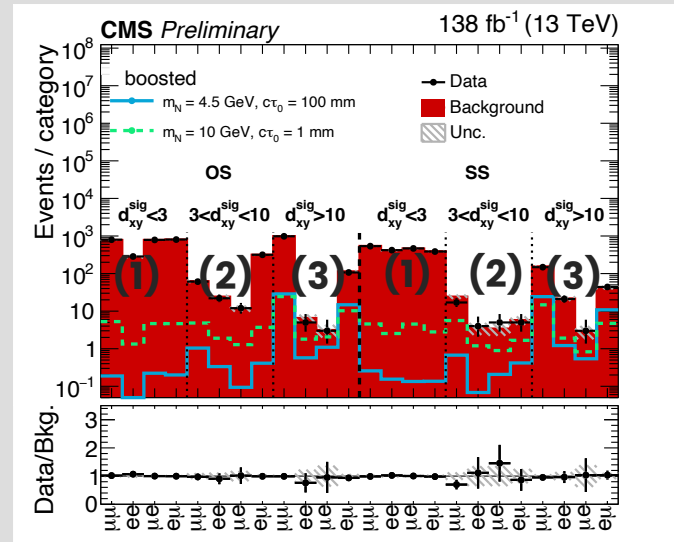
Heavy neutral leptons to jets and leptons



- **Dirac** or **Majorana** HNL coupling to $e/\mu/\tau$ for $2 < m_N < 20$ GeV
 - **1 prompt** + **1 displaced** leptons (e/μ) + **≥ 1 displaced jet j^*** , $\tau \rightarrow e/\mu$ only
- SRs with **opposite-** or **same-**sign leptons (OS,SS), *Boosted* or *resolved* j^* , Prompt-like **(1)**, displaced **(2)**, very displaced l_2 **(3)**
- Main background $\rightarrow Z/\gamma^* + \text{jets} \rightarrow \text{CR with } m_{ll} > 80 \text{ GeV}$
 - ABCD method in $(P_{q,l}(j^*), m_{ll}(j^*))$ plane

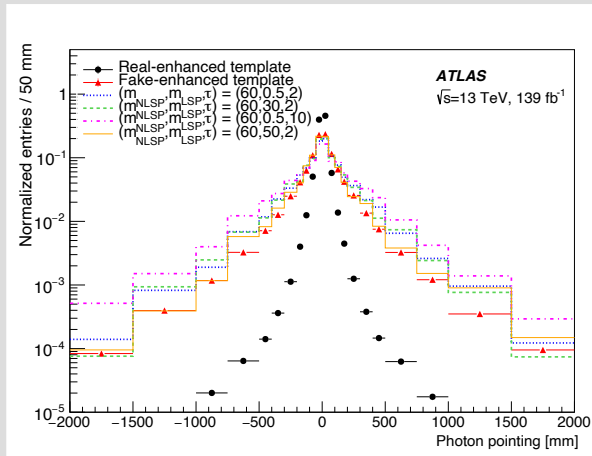
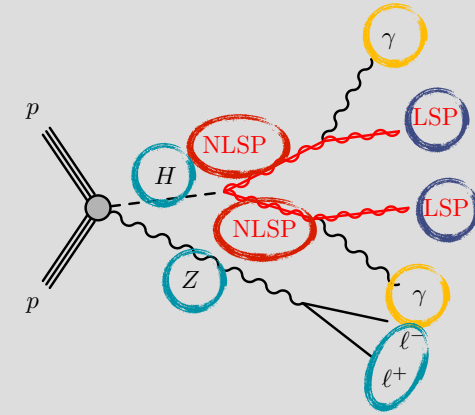
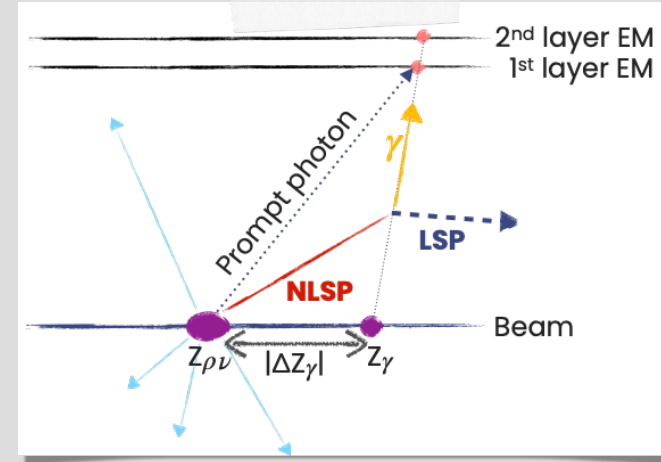
Identified via NN with $\sim 330k$ parameters
 \rightarrow jets features + constituent particles
 \rightarrow tagger score for resolved $P_q(j^*)$ or boosted regime $P_l(j^*)$ ($l=l_2=e, \mu$)

Limits on Dirac(Majorana) **HNL production xsec** as function of m_N and $|V_{lN}|^2$ + limits on $|V_{lN}|^2 \rightarrow$ best limits for $|V_{\mu N}|^2 > 5(4) \times 10^{-7}$ for $m_N=10$ GeV @ 95% CL

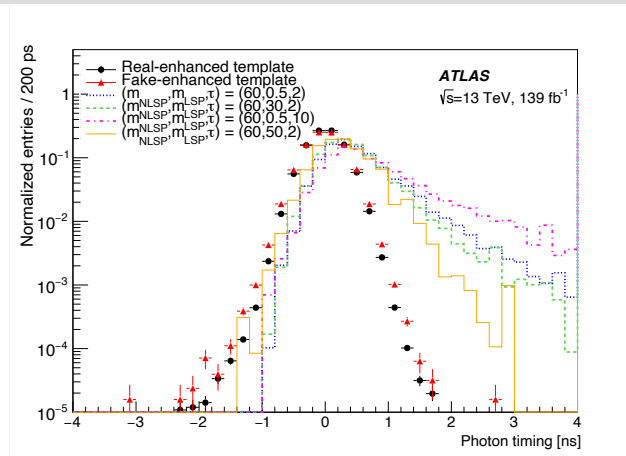


Non-pointing and delayed photons

- SM Higgs production (ZH , WH , ttH) with exotic decay \rightarrow **lepton trigger from W, Z, t**
- Higgs to **Long-Lived Next to Lightest SUSY particle (NLSP)** \rightarrow **delayed and non-pointing photons** + **LSP as MET**
- Main backgrounds \rightarrow **prompt photons** (modelled with $Z \rightarrow ee\gamma$) and **fake photons** (modelled with $MET < 30\text{GeV}$)

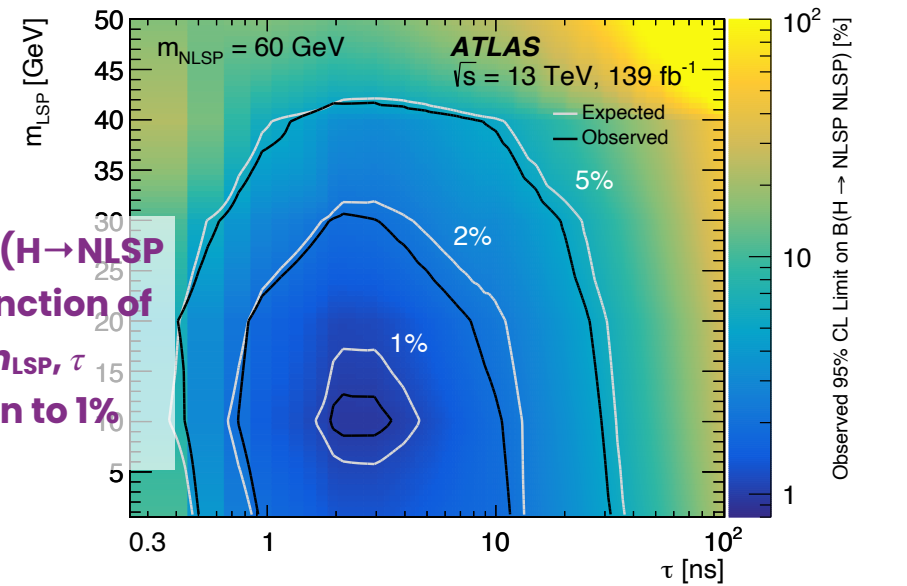


Categorize events with **pointing** $\rightarrow |\Delta Z_\gamma|$

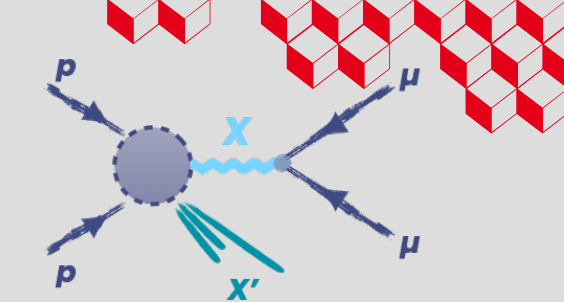


Fit background **timing** distribution in each category to data

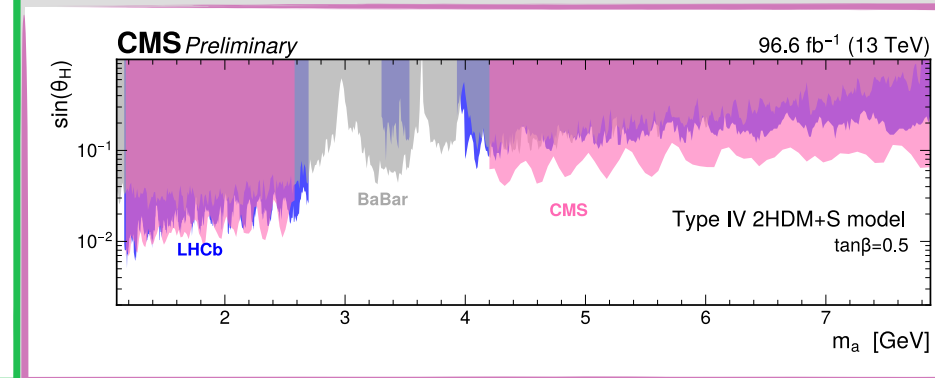
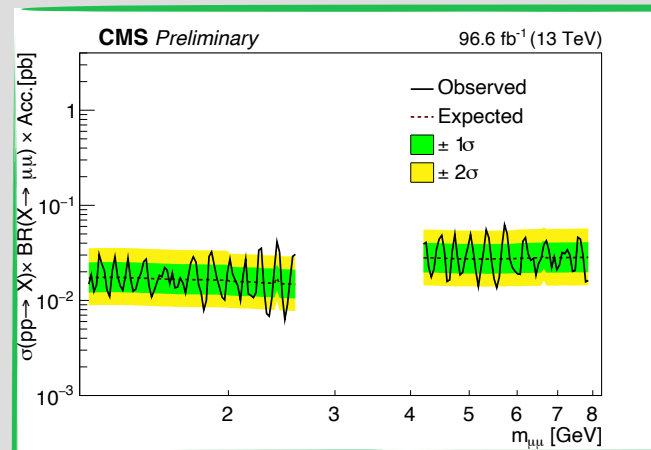
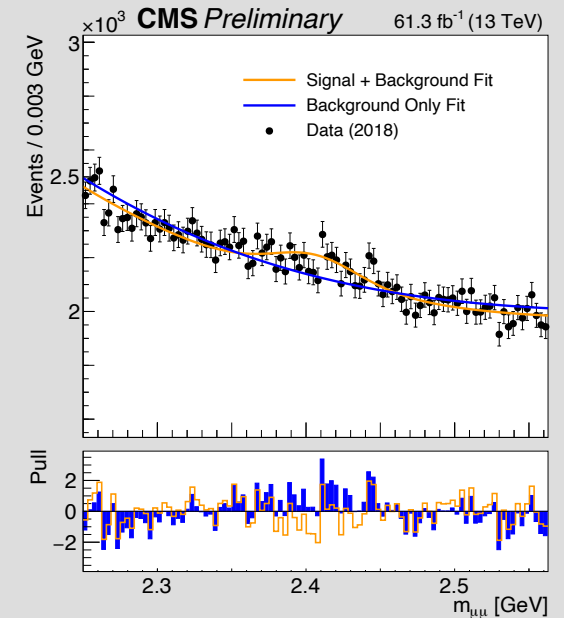
Limits on $BR(H \rightarrow NLSP NLSP)$ as function of m_{NLSP}, m_{LSP}, τ
 \rightarrow BR down to 1%



Prompt low-mass dimuon resonances



- Search for narrow **resonance to dimuon** in mass range $m_{\mu\mu} \in [1.1-2.6]$ **GeV** and **[4.2-7.9] GeV** (veto Υ and J/ψ)
 - divided in **inclusive** and **boosted** selection
 - Since 2015 CMS collects events with ≥ 2 muons via loose-selection, high-rate trigger, \rightarrow **DiMuon Scouting stream**
 - Data driven BDT \rightarrow trained on $\Upsilon, J/\psi$
- Background modelled on Bernstein polynomials + $D \rightarrow KK(K\pi)$ misreconstructed as dimuon \rightarrow estimated by fit in control region
- **No excess** except in high- p_T region @ **2.41 GeV** with **3.2 σ** (compatible with LHCb result @ 2.42 GeV with 3.1 σ [JHEP 10 \(2020\) 156](#))
- **Model independent** limits on $\sigma \times B \times Acc$ for inclusive and high- p_T dimuon selection
- Exploited to constrain **dark photon** and **2HDM+S** scenarios

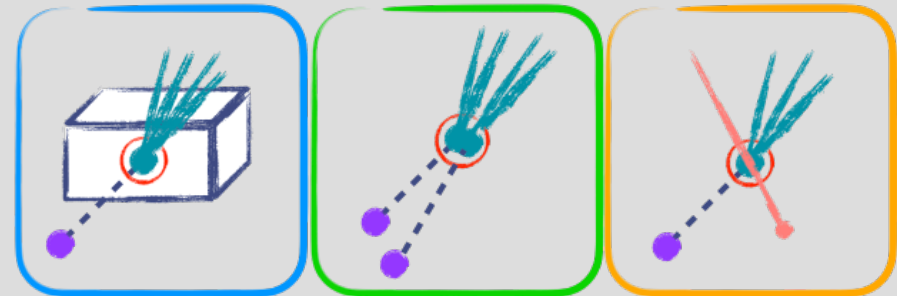
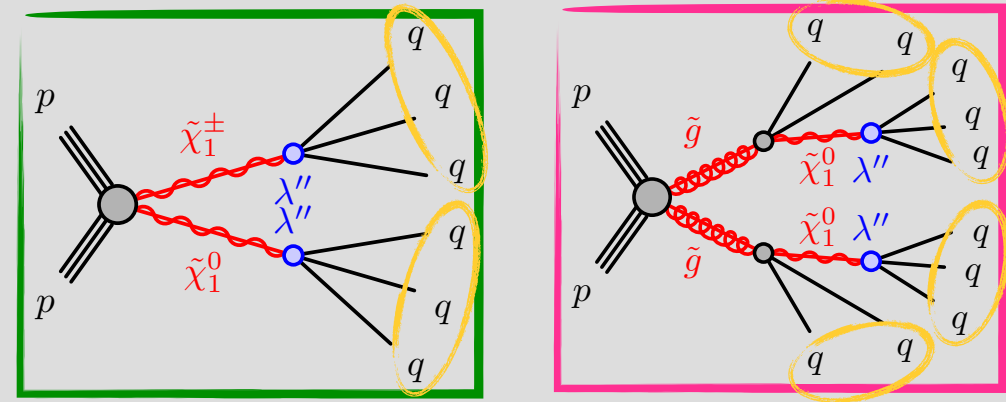


EXO-21-005 $\int L = 96.6 \text{ fb}^{-1}$



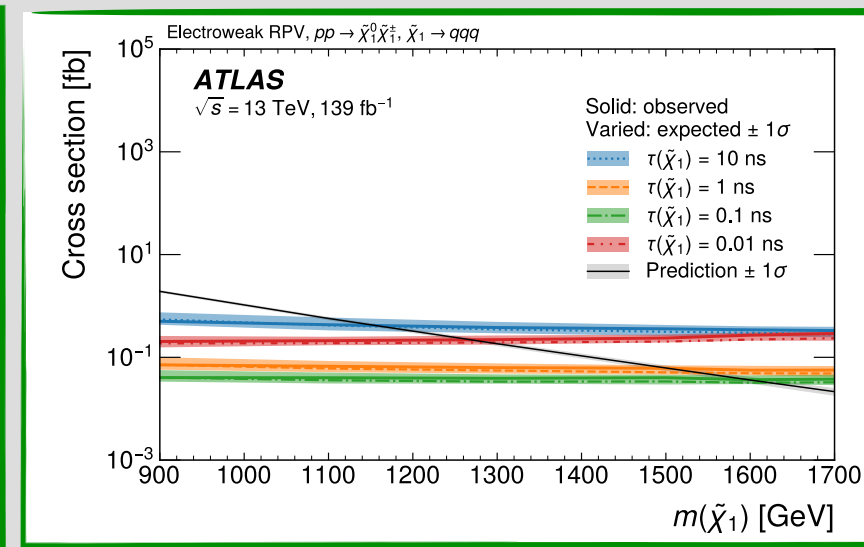
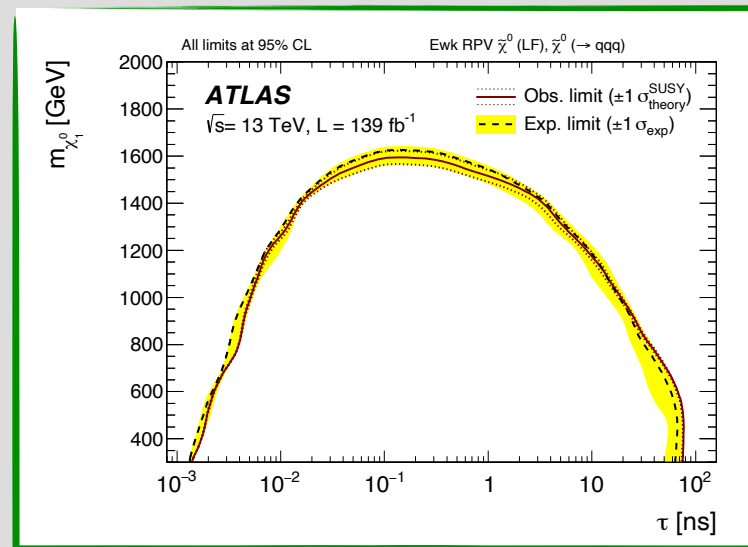
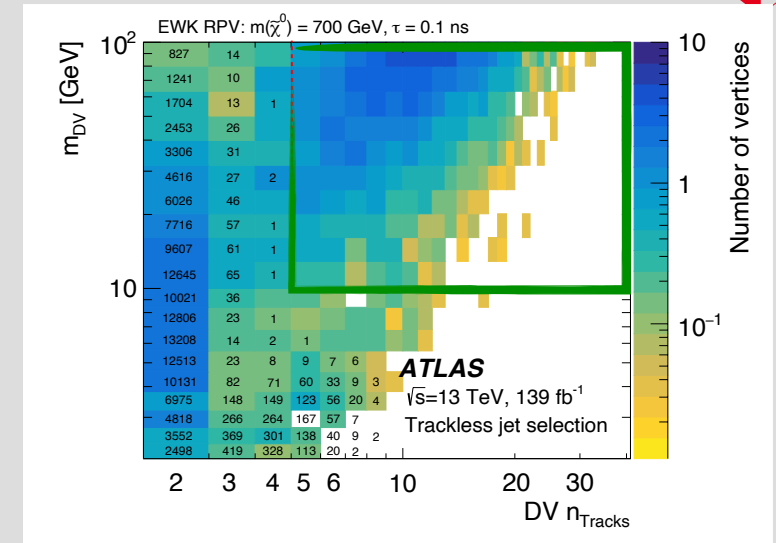
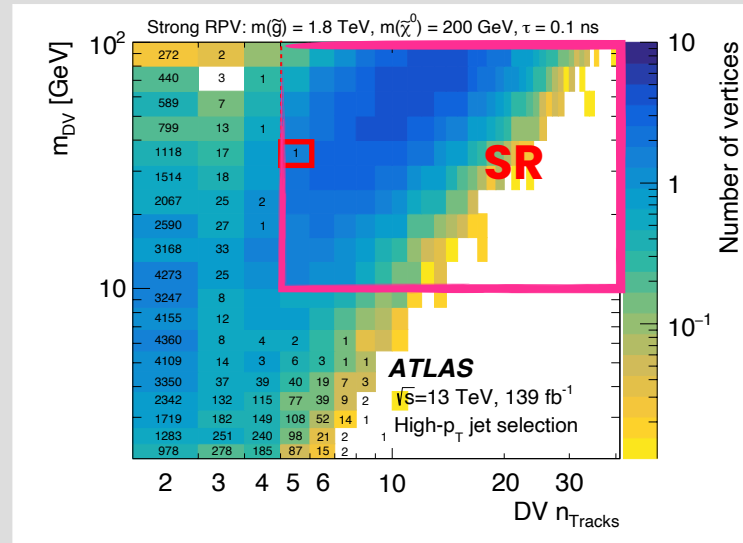
Displaced jets

- Search for LLPs in **EWK** and **Strong** R-parity violating (RPV) models → lifetime up to $\mathcal{O}(10)$ ns
- Events with massive multitrack **displaced vertex** and **multiple jets**
 - **Large-radius** vs standard tracking
- **Trackless jet SR** and **high- p_T jet SR**
- Backgrounds → **hadronic interactions**, **merged vertices**, **accidental crossing**
- **Inclusive data-driven technique** + alternative DD estimation for each bkg source



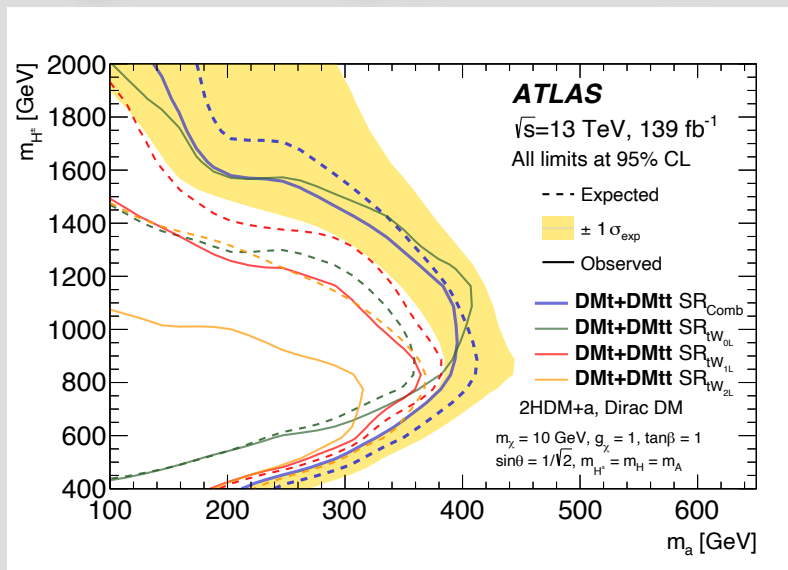
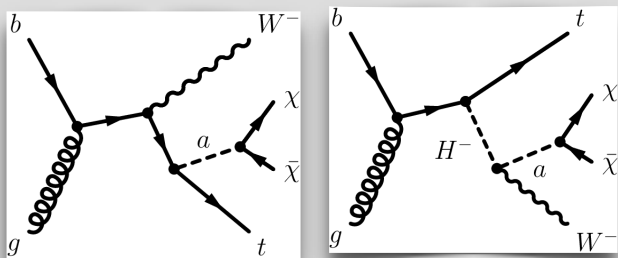
Displaced jets

- **No event** in the **trackless jet SR**, **1 event** observed in the **high- p_T SR**,
- Limits set on $m(\tilde{\chi}_1^0)$ up to **1.58 TeV** for $\tau=0.1$ ns and **visible xsec** for strong(EWK) model up to **0.03(0.02)fb**
- Sensitivity to **EWK RPV SUSY** models demonstrated **for the first time**



Dark matter searches with top quarks

tW +MET in 2HDM+a model

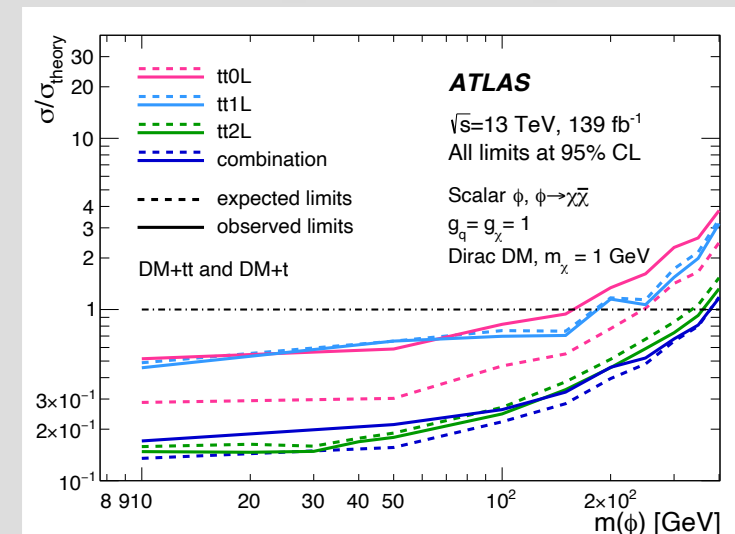
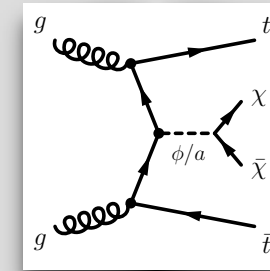


- With $0/1/2$ leptons in the final state
- Combining searches and signals \rightarrow 2HDM+a \leftrightarrow simplified model reinterpretation
- Main backgrounds \rightarrow $t\bar{t}$, W/Z +jets, $t\bar{t}Z$
- Discriminant variable depending on signature: m_T , BDT, m_{T2}
- Limits on $\sigma/\sigma_{\text{theory}}$ as function of free parameters

Analysis	Best fit $\mathcal{B}_{H \rightarrow \text{inv}}$	Observed upper limit	Expected upper limit
tt0L	$0.48^{+0.27}_{-0.27}$	0.95	$0.52^{+0.23}_{-0.16}$
tt1L	$-0.04^{+0.35}_{-0.29}$	0.74	$0.80^{+0.40}_{-0.26}$
tt2L	$-0.08^{+0.20}_{-0.19}$	0.36	$0.40^{+0.18}_{-0.12}$
$t\bar{t}H$ comb.	$0.08^{+0.15}_{-0.15}$	0.38	$0.30^{+0.13}_{-0.09}$

$H \rightarrow \text{inv.}$ interpretation

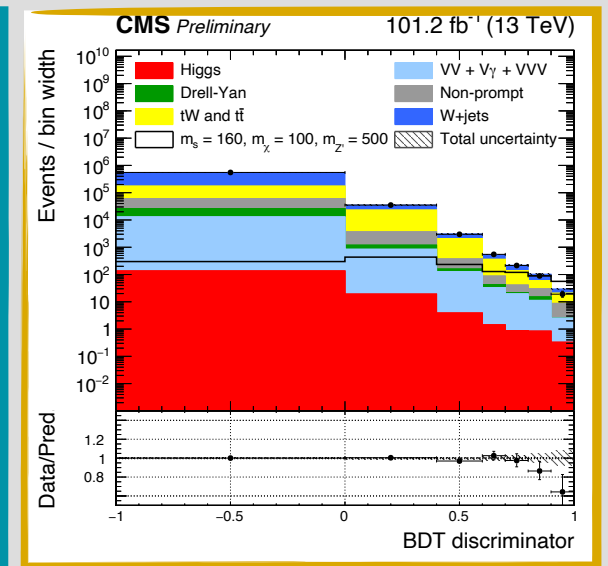
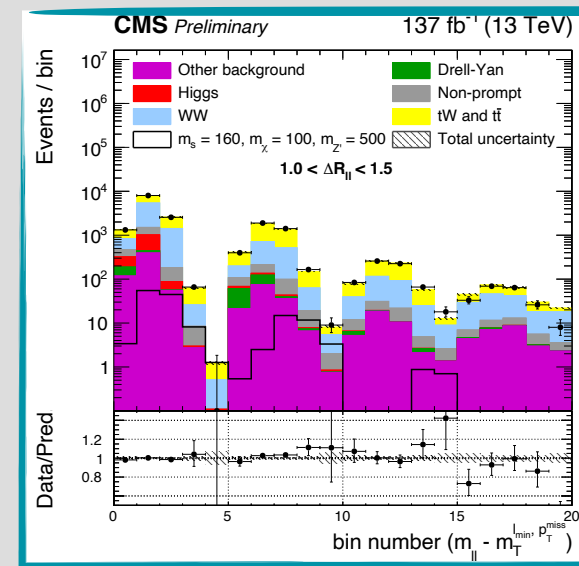
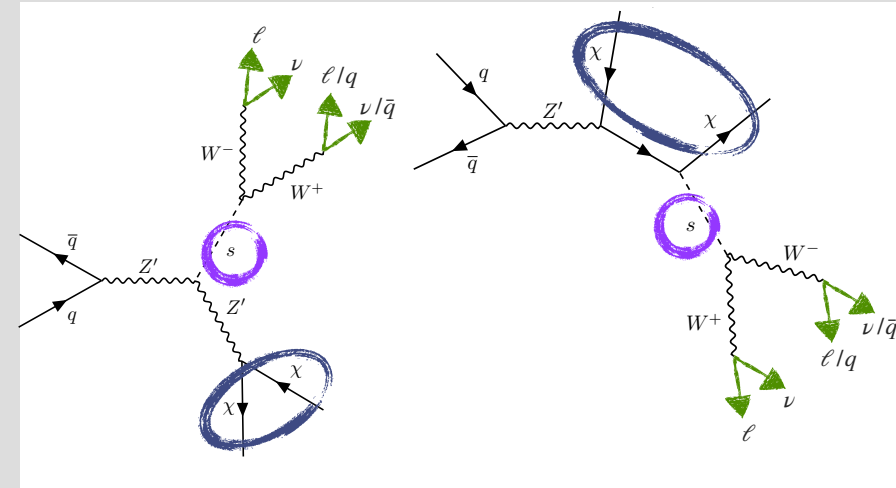
$t\bar{t}$ +MET in Simplified model



See also ATLAS [HIGG-2021-05](#) and CMS [HIG-21-007](#) for latest $H \rightarrow \text{inv}$ combination results

Dark matter searches in W^+W^-+MET

- **spin-1 vector mediator Z' to Dark Higgs s** → $WW \rightarrow \ell\nu(\ell\nu \text{ or } qq) + MET$ ($m_s, m_{Z'}, m_\chi$ free parameters)
- Discriminant variables
 - **Dilepton**: $m_T^{p_{\ell}^{\min}, p_T^{\text{miss}}}$
 - **Semilepton**: **BDT** based on 13 variables with best signal/background separation power
 - SR binning optimized for 2016 and 2017–2018 data-taking
- Dominating backgrounds → **W^+W^-** and **Drell-Yan** for **dilepton**, **W +jets** for **semilepton**, **tW** and **$t\bar{t}$** for **both** → dedicated CRs

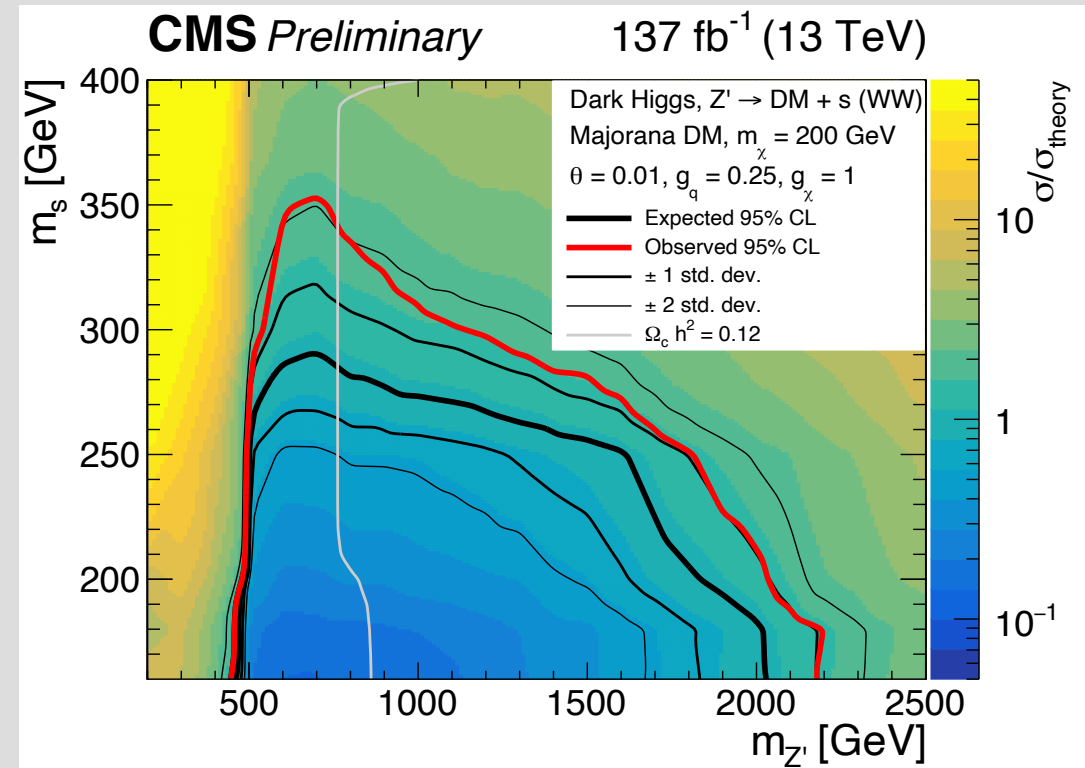


EXO-21-012 $\int L = 137 \text{ fb}^{-1}$

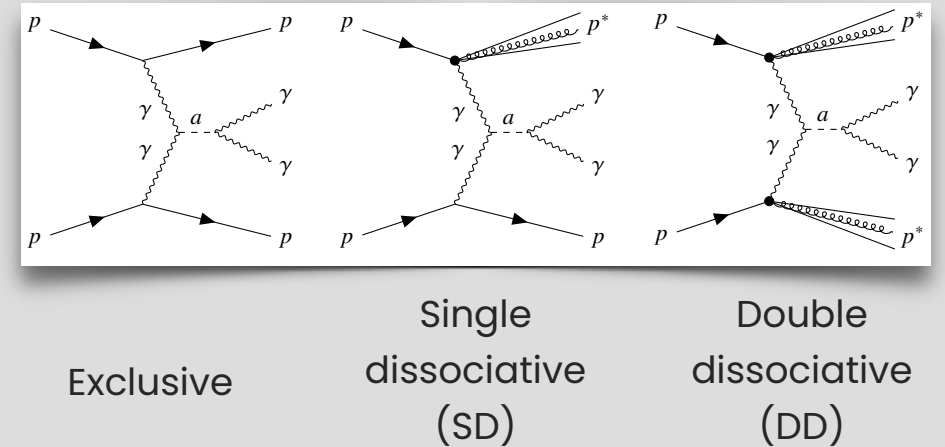
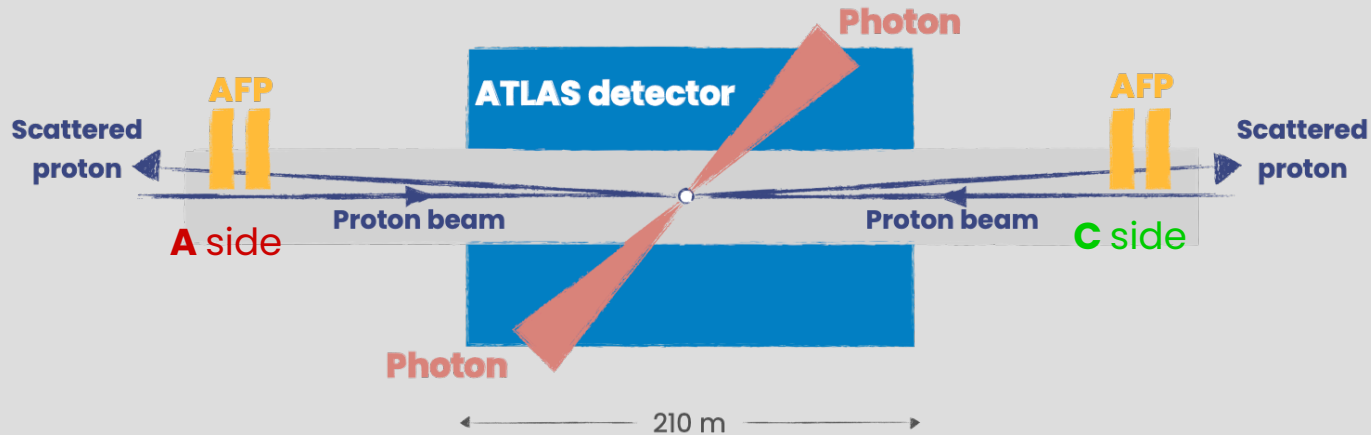
See also **ATLAS results** in [arXiv:2211.07175](https://arxiv.org/abs/2211.07175)

Dark matter searches in W^+W^-+MET

- Limits set on DM production cross section
 - **Wider** DM mass range **100** → **300 GeV** + limits on $m_{Z'}$ + **most stringent limits** @ $m_{DM}=200$ GeV on m_s and $m_{Z'}$



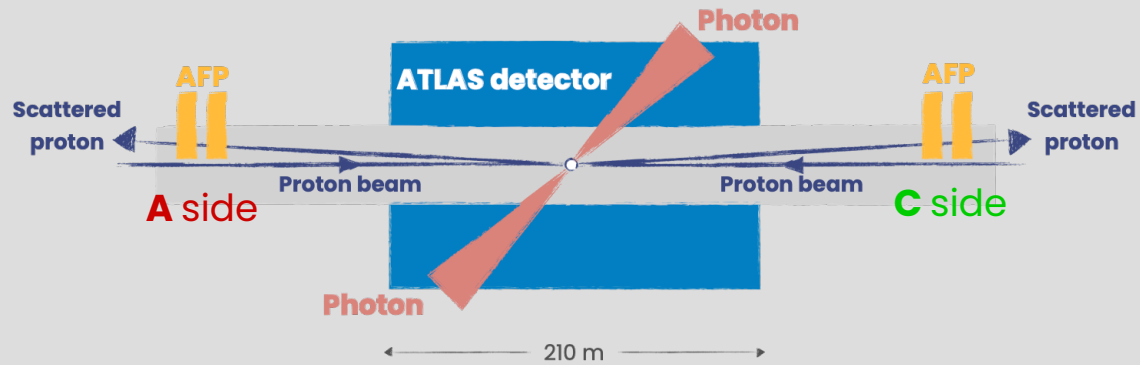
ALPs in the ATLAS Forward Spectrometer



- **Diphoton resonance** search in light-by-light scattering in pp collisions $\rightarrow 150 < m_{\gamma\gamma} < 1600$ GeV

- Main discriminant \rightarrow **Fractional energy loss**
 $\xi_{\text{AFP}} = (1 - E_{\text{scattered}}/E_{\text{beam}})_{\text{calibrated}}$ of forward proton matching with $\xi_{\gamma\gamma}$ inferred from photon pair + in both **A** and **C** sides

ALPs in the ATLAS Forward Spectrometer



- Upper limits on **ALP coupling constant** in **[0.04-0.09] TeV⁻¹** range @ 95% CL for $\mathcal{B}(a \rightarrow \gamma\gamma) = 100\%$

