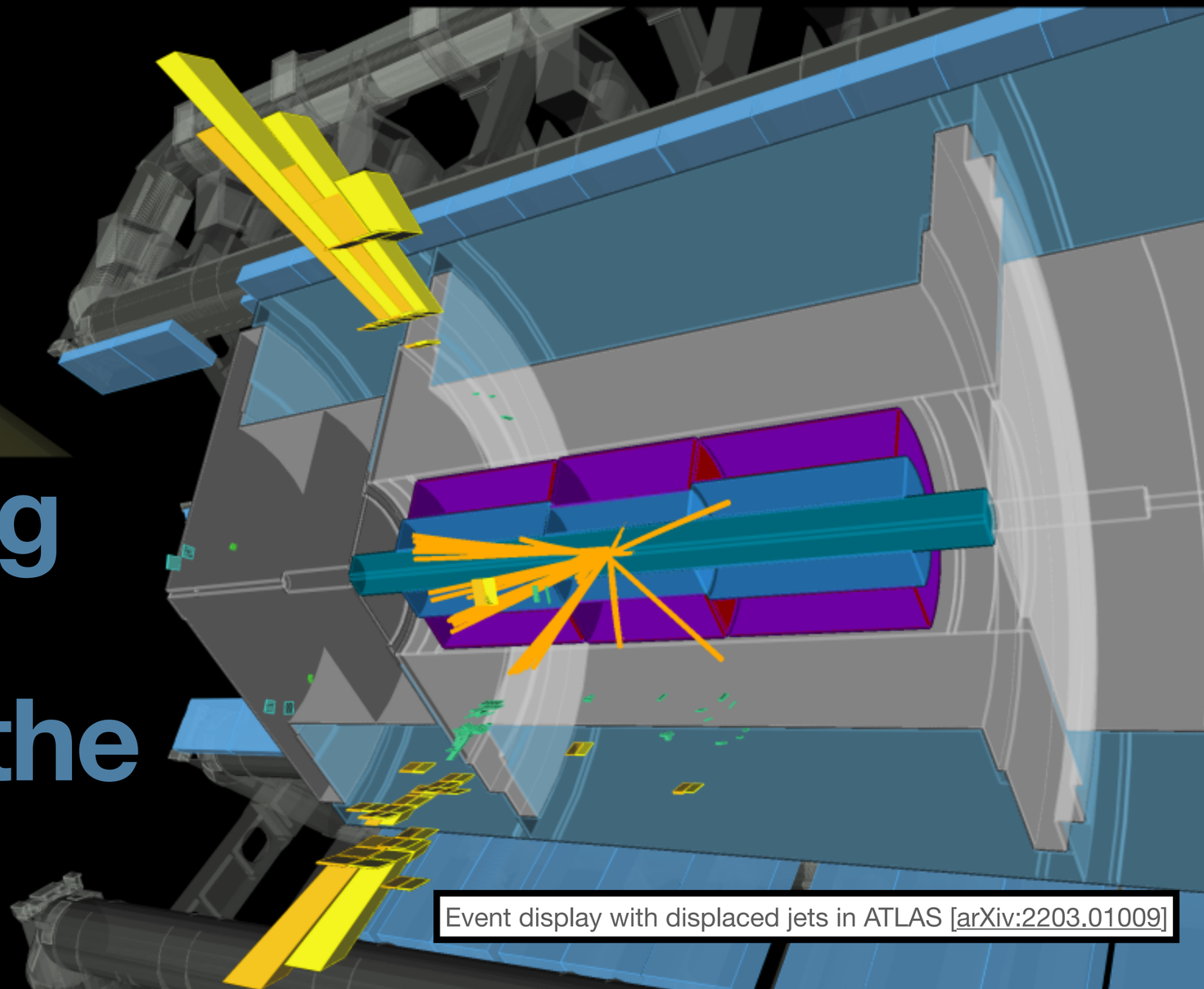
Searches for BSM physics

using challenging and long-lived signatures with the ATLAS detector



Event display with displaced jets in ATLAS [arXiv:2203.01009]

Elena Pompa Pacchi on behalf of the ATLAS collaboration

Why Long-Lived-Particles (LLPs)?

- approximate symmetries
- effective higher order dimension operators

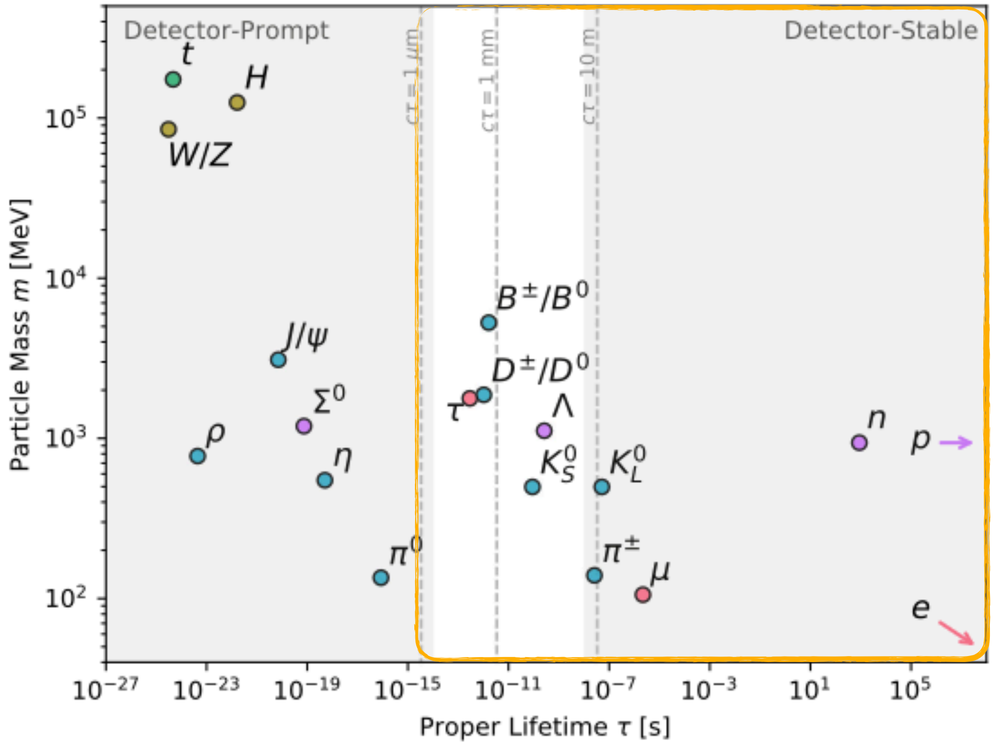
- mass-degenerate spectra
- highly virtual intermediate state

Long Lived Particles can arise when:

$$\tau^{-1} = \Gamma = \frac{1}{2m_X}\int d\Pi_f \left|\mathscr{M}\left(m_X \to \{p_f\}\right)\right|$$

Small phase space or small matrix element

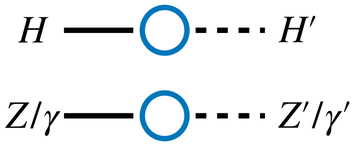
Lots of SM particles are LLPs!



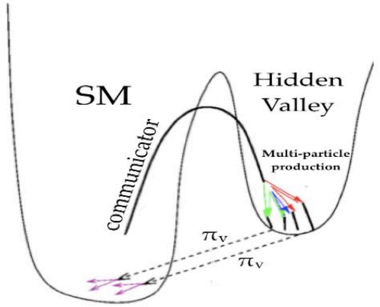
Many BSM theories foresee LLPs too!

SUSY

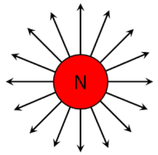
Portal models



Hidden Valleys



HECO and monopoles



Selected BSM LLPs searches in ATLAS

Inner Detector (ID)
Electromagnetic CALorimeter (ECAL)
Hadronic CALorimeter (HCAL)
Muon Spectrometer (MS)

HECO and monopoles

Multi-Charged Particles

ATLAS-CONF-2022-034

Unconventional $\frac{dE}{dx}$ in Pixel Detector (PD), Transition Radiation Tracker (TRT) and Muon Drift Chambers (MDT)

SUSY

Displaced vertices + jets

arXiv:2301.13866

SUSY

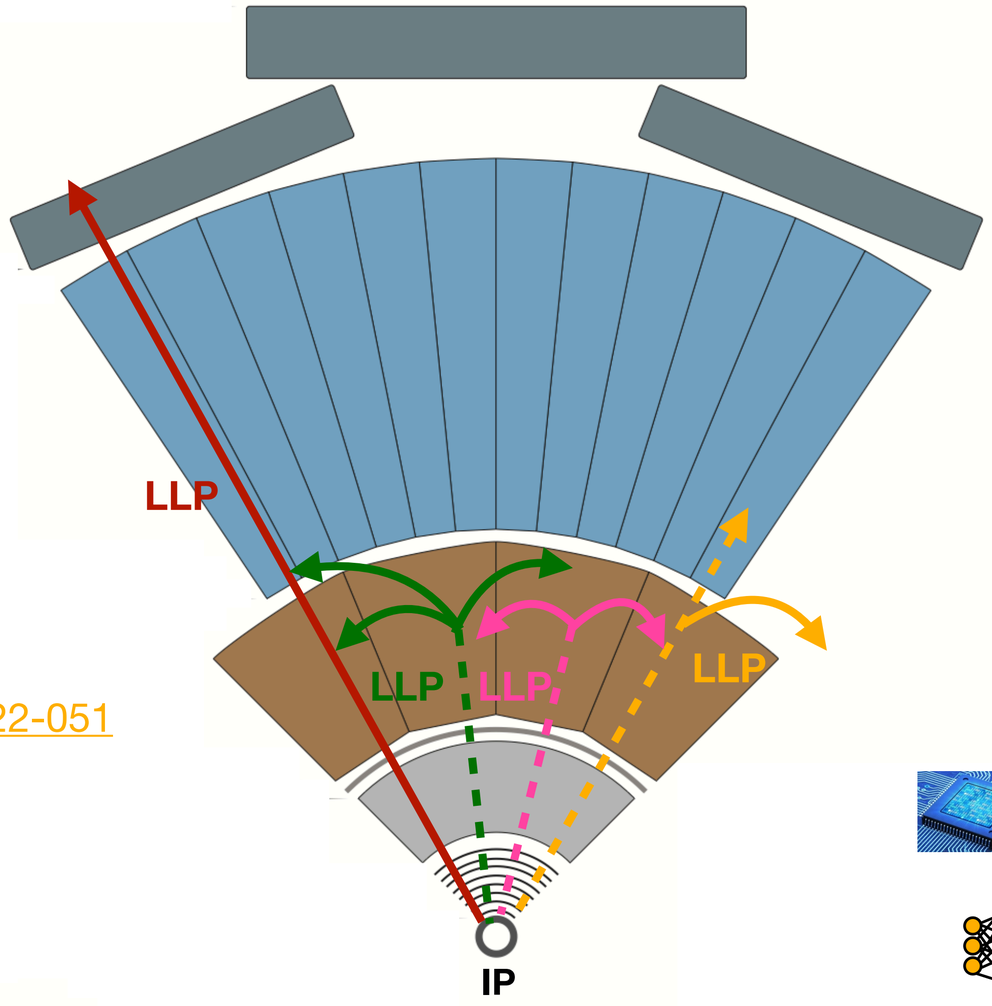
Displaced photons

From the same decay: ATLAS-CONF-2022-051
From different decays: arXiv:2209.01029

SUSY

Slightly displaced muons

ATLAS-CONF-2023-018



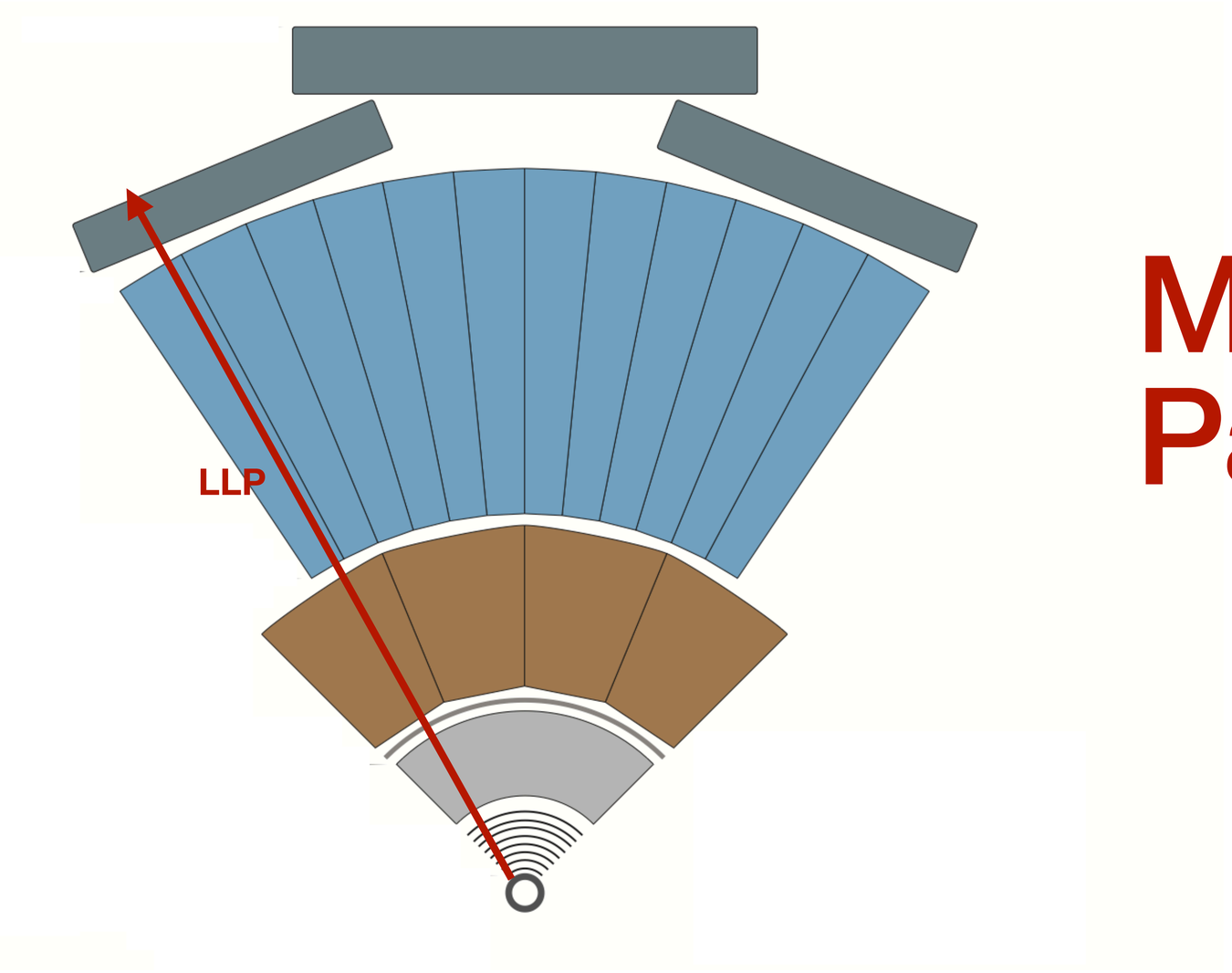
How to overcome challenges in LLP detection?

Custom object reconstruction (all these searches)

Data-driven background estimations (all these searches)

Dedicated trigger algorithms

ML tools



Multi-Charged Particles (MCPs)

NEW

ATLAS-CONF-2022-034: 23/03/2023

Signature and SRs

Signature:

MCP traverse the whole detector interacting with it

→ muon-like signature → muon triggers

$$\frac{dE}{dx} \propto \frac{Z^2}{\beta^2}, Z \geq 2 \text{ and } \beta \ll 1$$

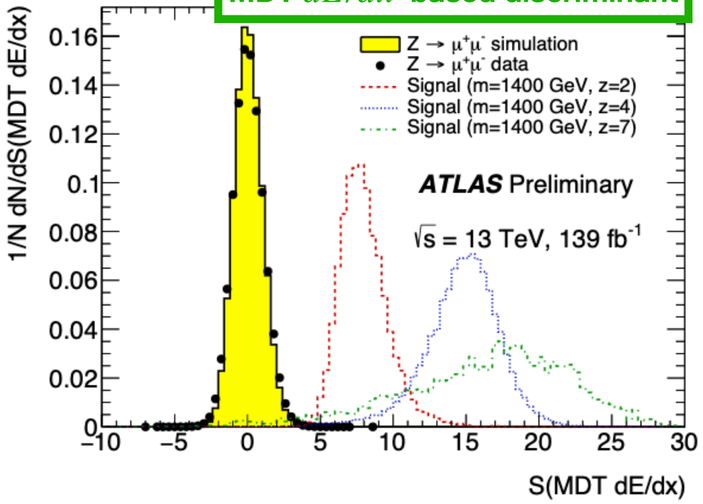
→ highly-ionising and slow particles

⇓

$\frac{dE}{dx}$ based discriminants

E_T^{miss} and late muon triggers

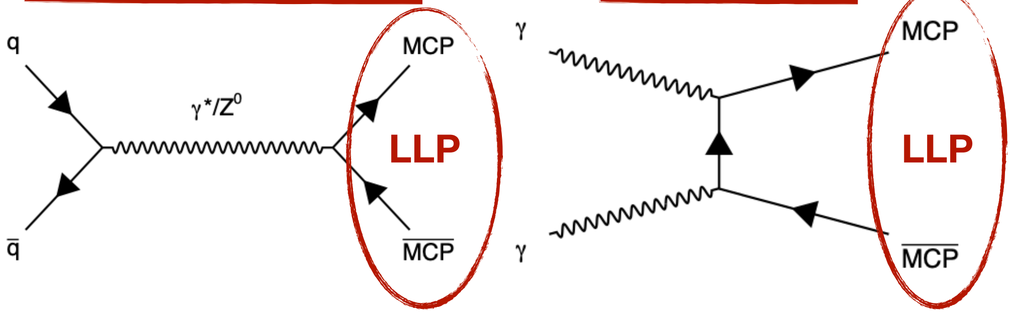
MDT dE/dx based discriminant



$m_{MCP} \in [500,2000]$ GeV

$Z_{MCP} \in [2e,7e]$

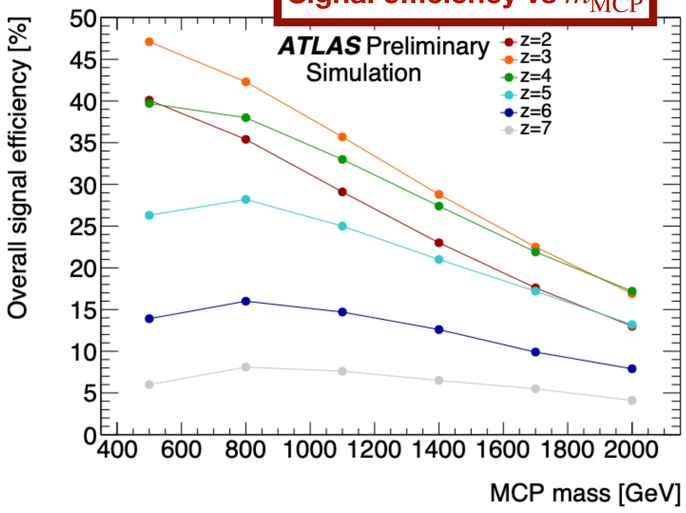
HECO and monopoles



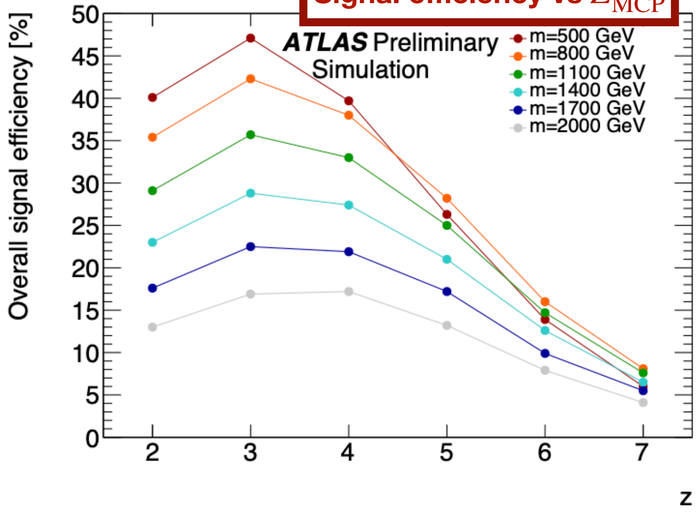
SRs:

- ≥ 1 highly energetic and isolated muon (MS matched to ID)
- 2 SRs optimised for different z_{MCP}

Signal efficiency vs m_{MCP}



Signal efficiency vs Z_{MCP}

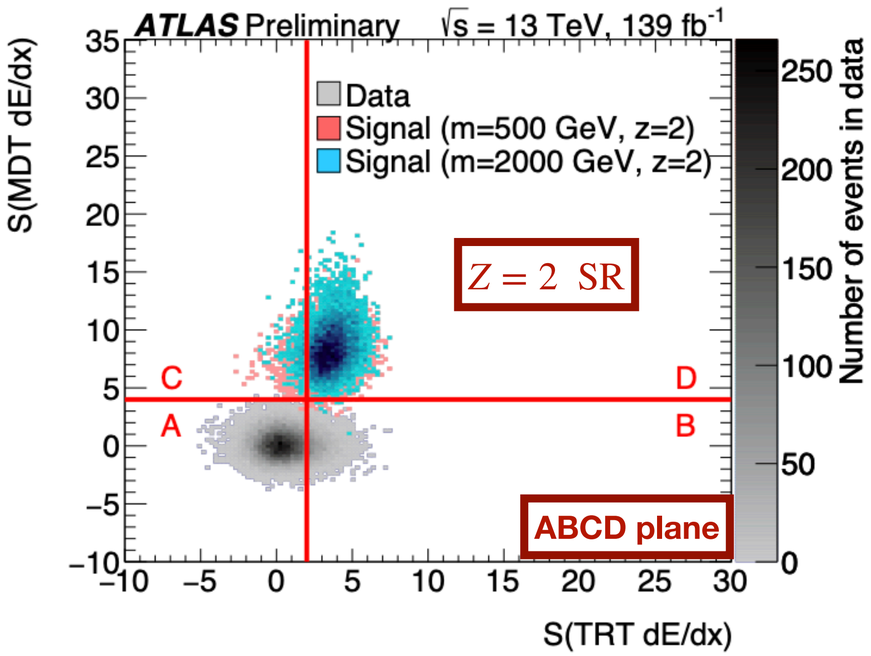


Background and results

Background:

- Energy fluctuations for highly energetic muons
- δ-rays

→ data driven estimation using ABCD method

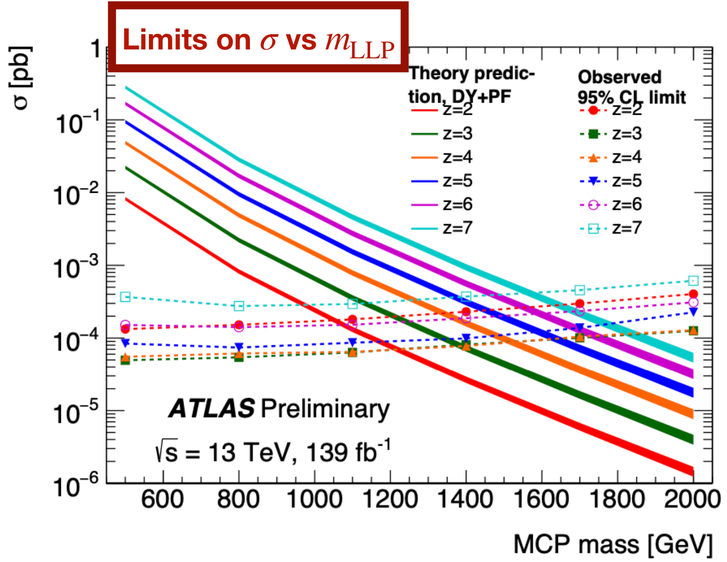


Results:

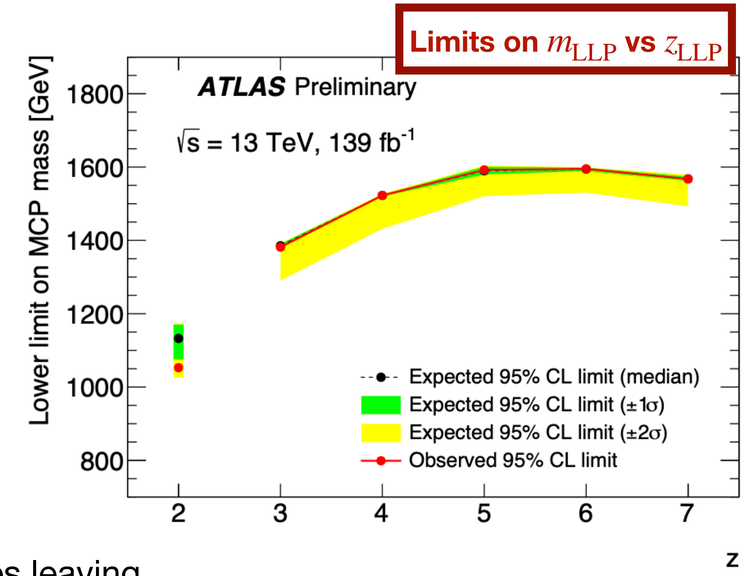
No excess found over SM prediction

→ exclusion limits on σ vs m_{MCP} and Z_{MCP}

Limits on σ vs m_{LLP}



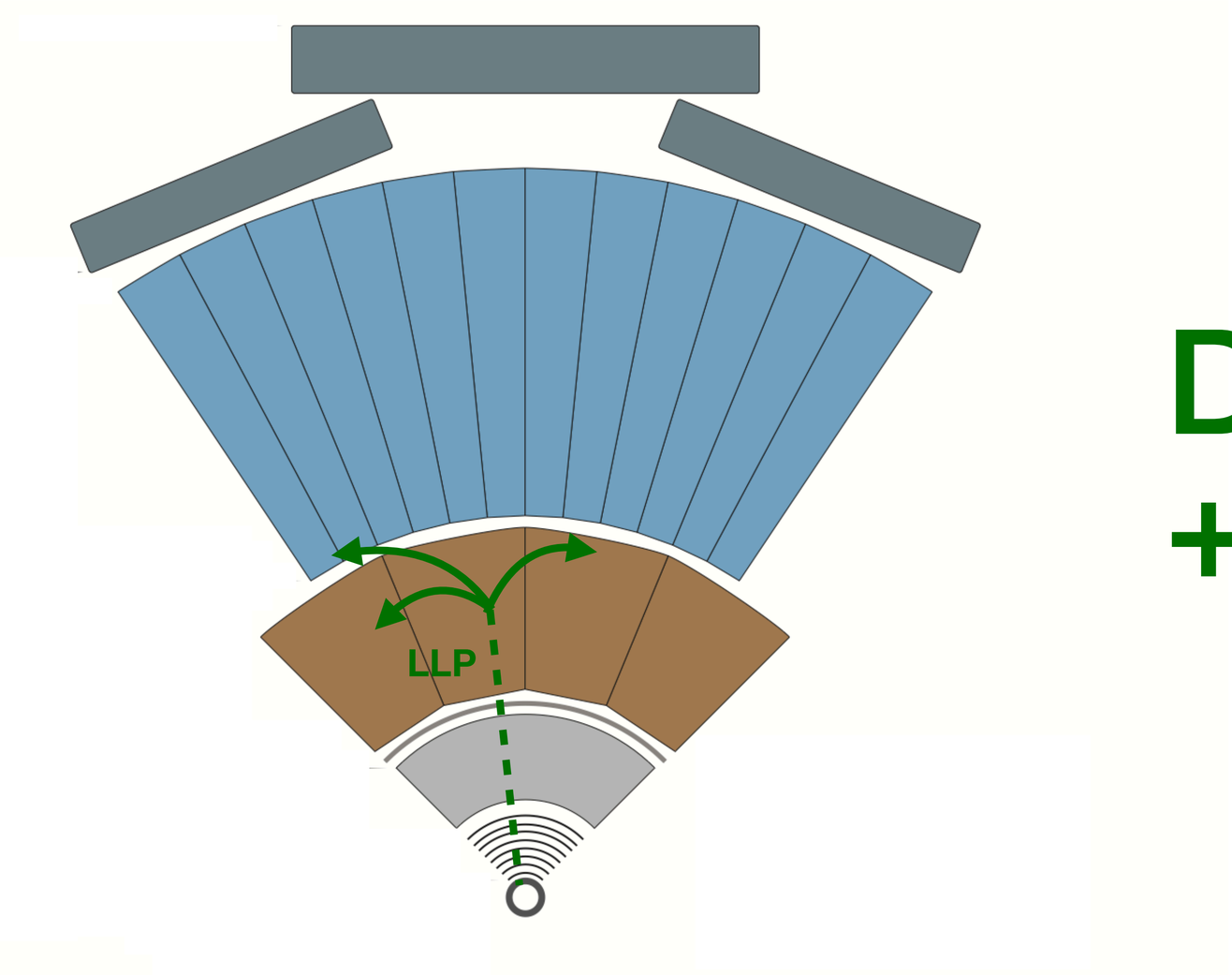
Limits on m_{LLP} vs z_{LLP}



Comparison wrt ATLAS early Run2: Extended sensitivity

- Late muon trigger
- Photon Fusion production mode added
- γ^* virtual boson exchange added

Events found in search for particles leaving high energy loss in pixel have too small $\frac{dE}{dx}$ both in MDT and TRT to be in SR

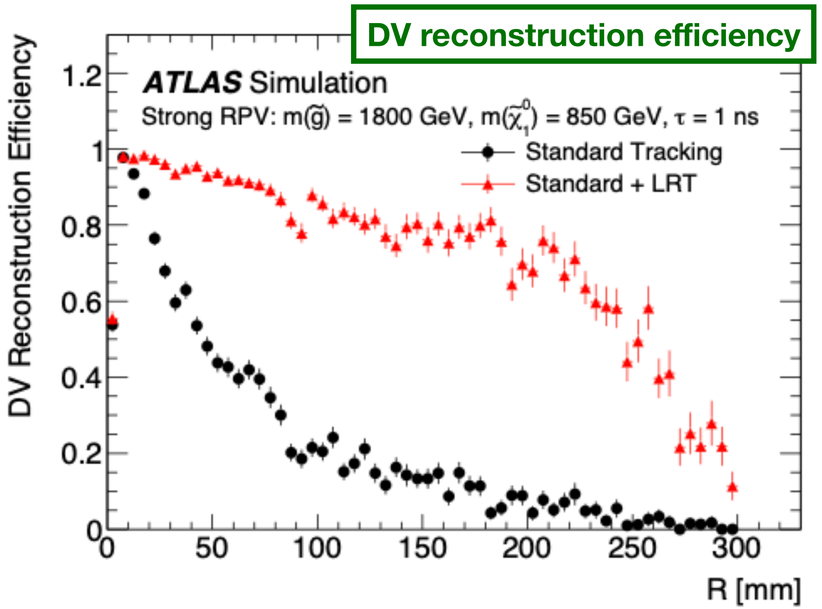


Displaced vertices + jets (DV+jets)

arXiv:2301.13866: 01/02/2022

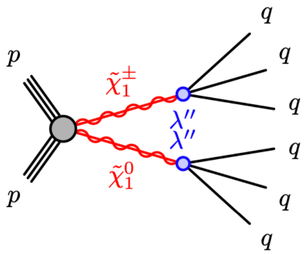
Signature and SRs

Signature:
LLP decay displaced into hadrons
→ displaced vertices (DVs) and multi-jets
→ jet triggers
→ DVs reconstructed using Large Radius Tracking, LRT
(looser requirements on tracks impact parameter)



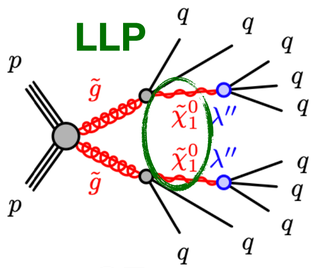
$m_{\tilde{\chi}_1^0} \in [100,1700]$ GeV

RPV EWK SUSY



$m_{\tilde{\chi}_1^0} \in [10,2500]$ GeV; $m_{\tilde{g}} \in [1.6,2.6]$ TeV

RPV STRONG SUSY

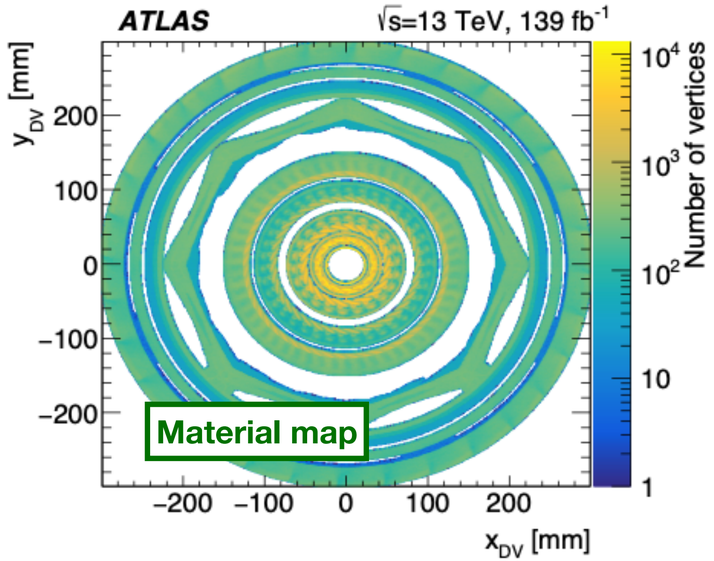


SRs:

At least 1 DV:

- With large m_{DV} and $n_{\mathrm{DV}}^{tracks} \geq 5$
- Reconstructed within fiducial volume
- **Material map**-veto satisfied

→ **2SRs** targeting RPV EWK or RPV Strong SUSY



Background and results

Background:

- Hadronic interaction with detector material
- Accidental crossings
- Merged vertices

→ **data driven estimation**

$$p^{SR}_{\mathrm{DV-jet}} = p^{CR}_{\mathrm{DV\leftrightarrow track-jet}} f^{CR\rightarrow SR}$$

Results:

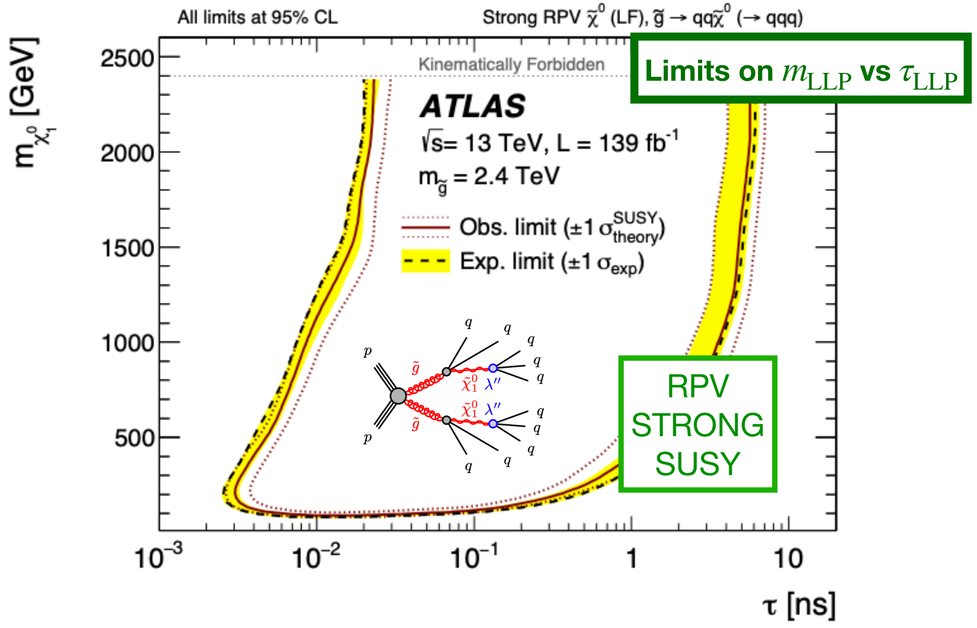
No excess found over SM prediction

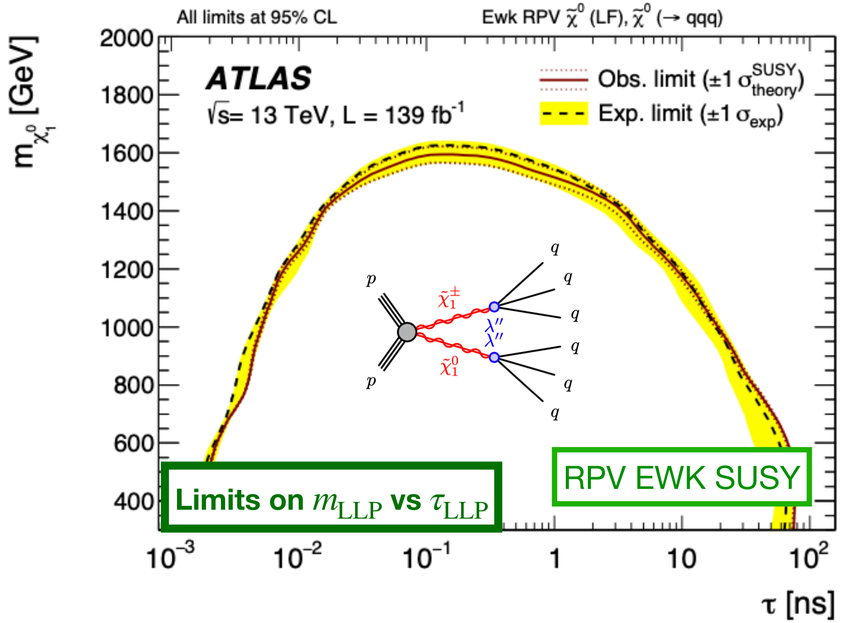
→ exclusion limits on $m_{\tilde{\chi}^0_1}$ and $\tau_{\tilde{\chi}^0_1}$

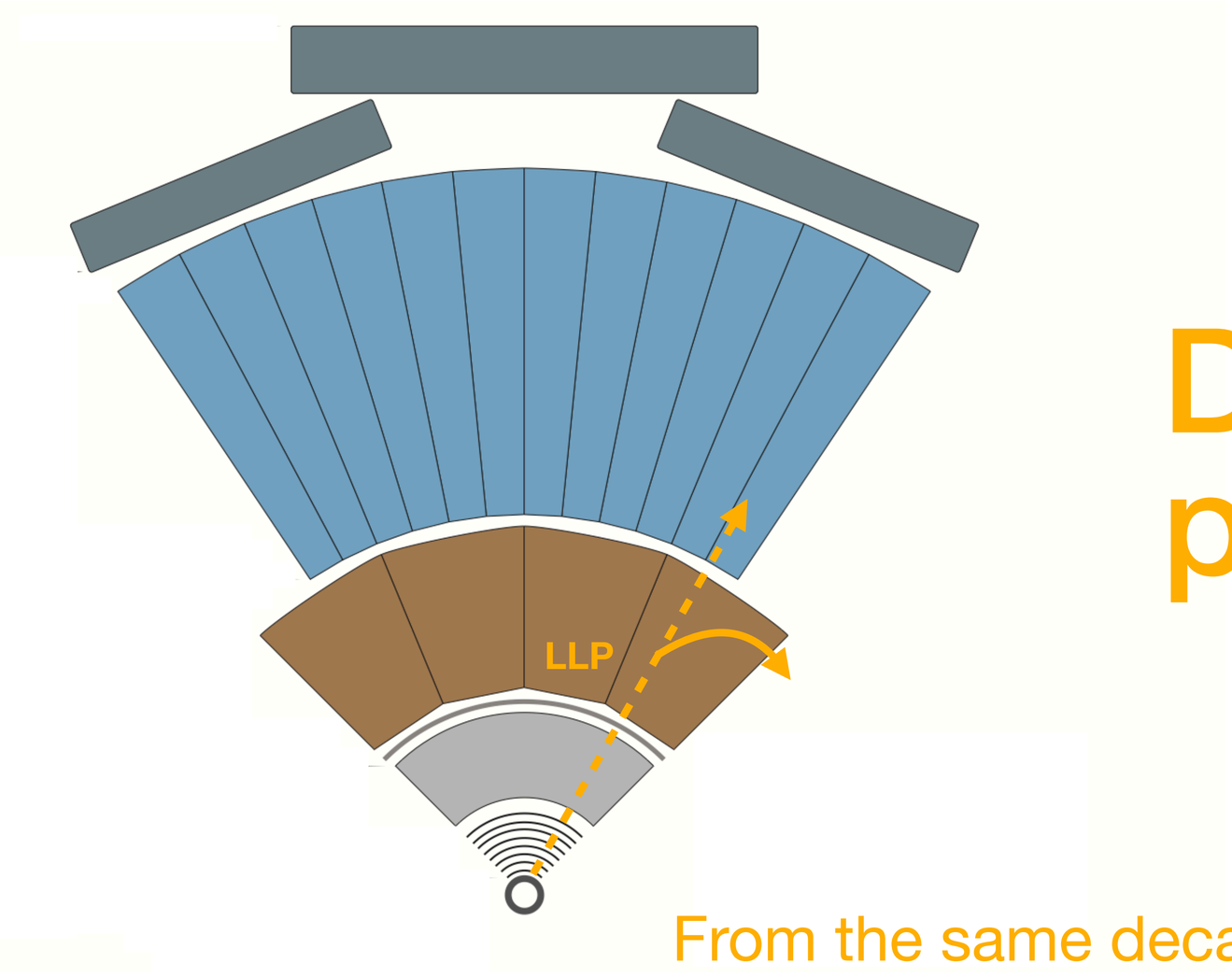
Comparison wrt ATLAS Run1:

Extended sensitivity

- Large Radius Tracking
- Novel background estimation technique
- First time interpreted in EWK SUSY







Displaced non-pointing photons

From the same decay: ATLAS-CONF-2022-051 12/07/2022
From different decays: arXiv:2209.01029 02/09/2022

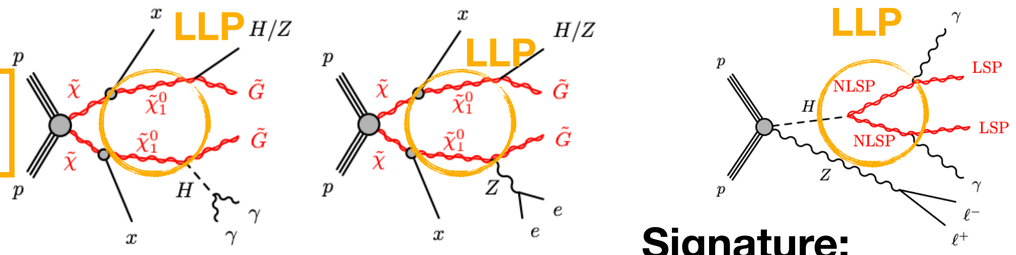
Signature and SRs

From same decay

$m_{\tilde{\chi}_1^0} \in [100,725]$ GeV

From different decays

SUSY GMSB



$m_{\mathrm{NLSP}} \in [30,60]$ GeV
$m_{\mathrm{NLSP}} \in [0.5,50]$ GeV

Signature:

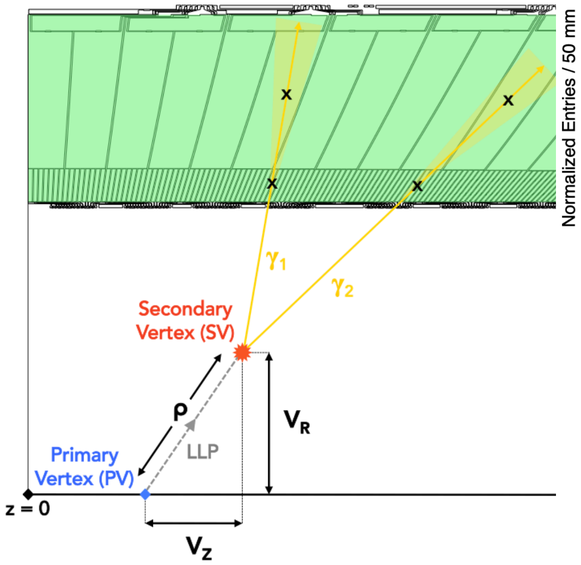
Same decay:

two photons produced in decays of LLPs

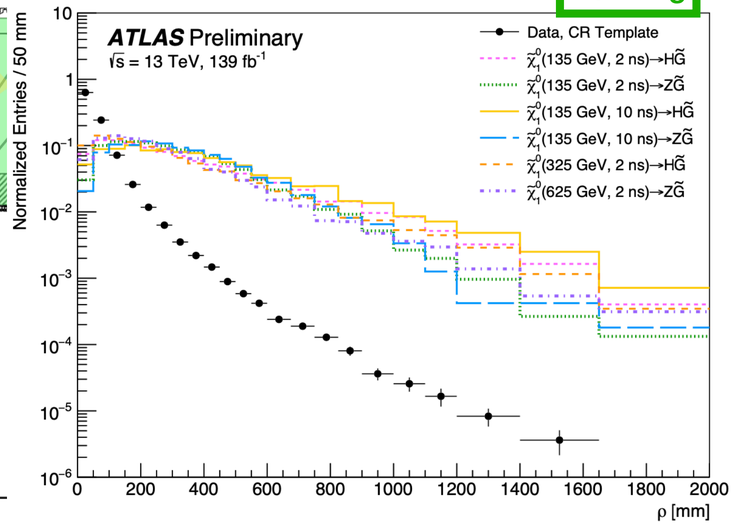
→ **photon triggers**

Non pointing photons coming from same LLP

→ vertexing $\rho = \sqrt{V_R^2 + V_Z^2}$



Pointing



Signature:

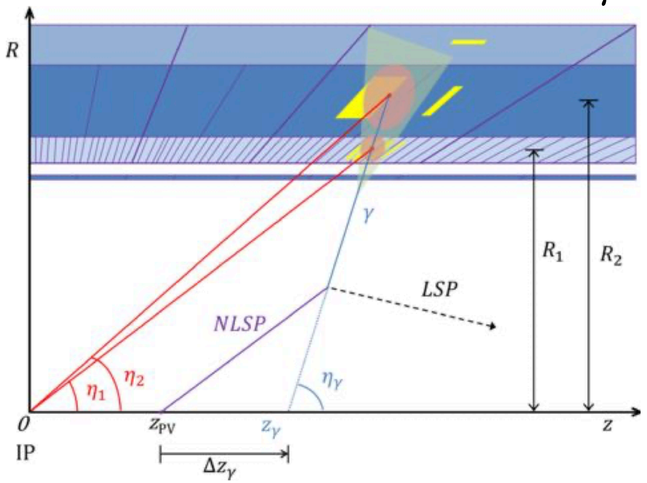
Different decays:

two photons produced in different of LLPs in association with leptons

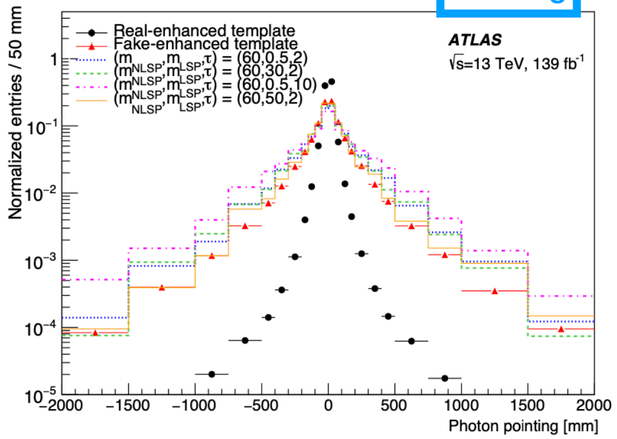
→ **lepton triggers**

Non pointing photons coming from different LLPs

→ pointing $\Delta z_\gamma = |z_\gamma - z_{PV}|$



Pointing



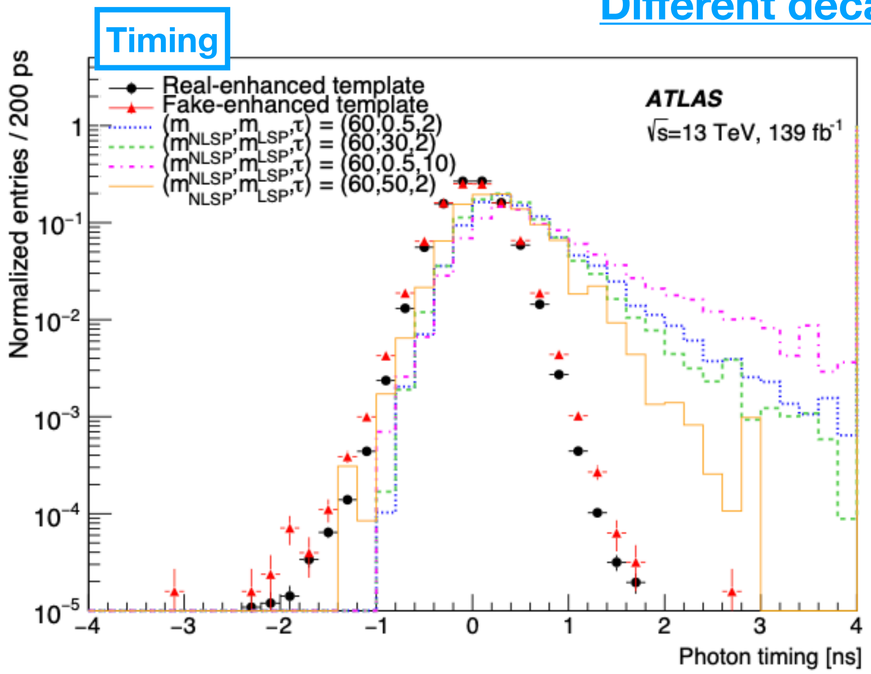
Signature, SRs and background

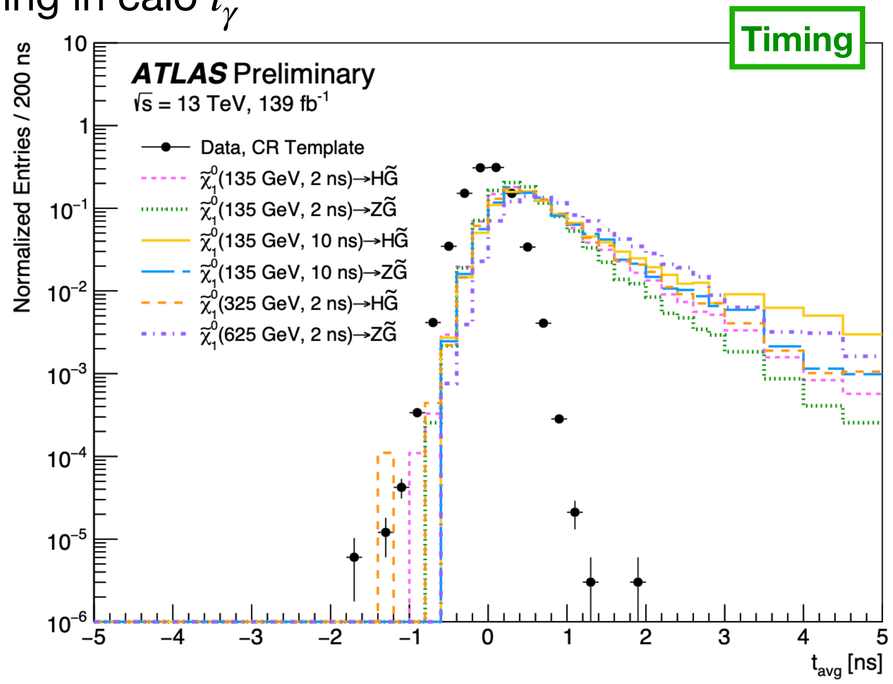
Signature: displacement

Timing information in calo (resolution $O(100\,\mathrm{ps})$)

Same decay: →average timing in calo $t_{avg} = (t_{\gamma 1} + t_{\gamma 2})/2$

Different decays: →per photon timing in calo t_γ





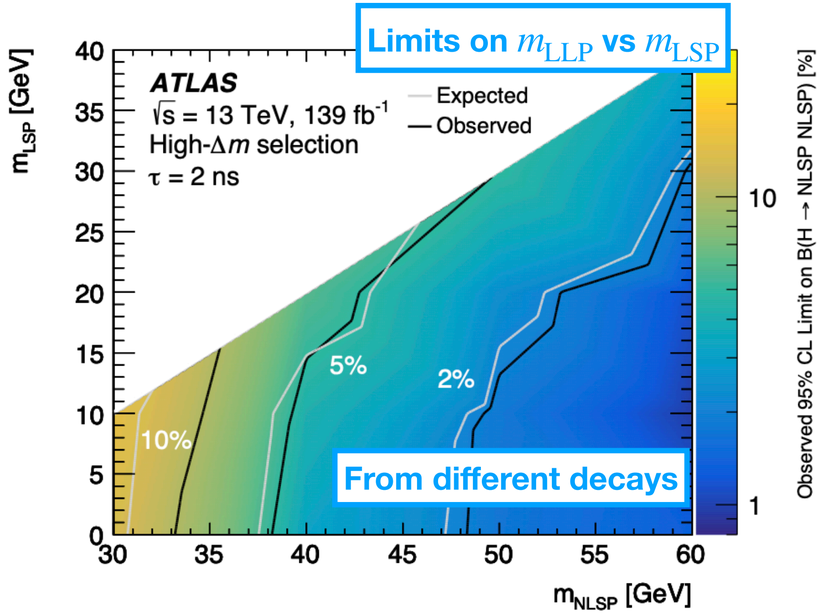
Background:

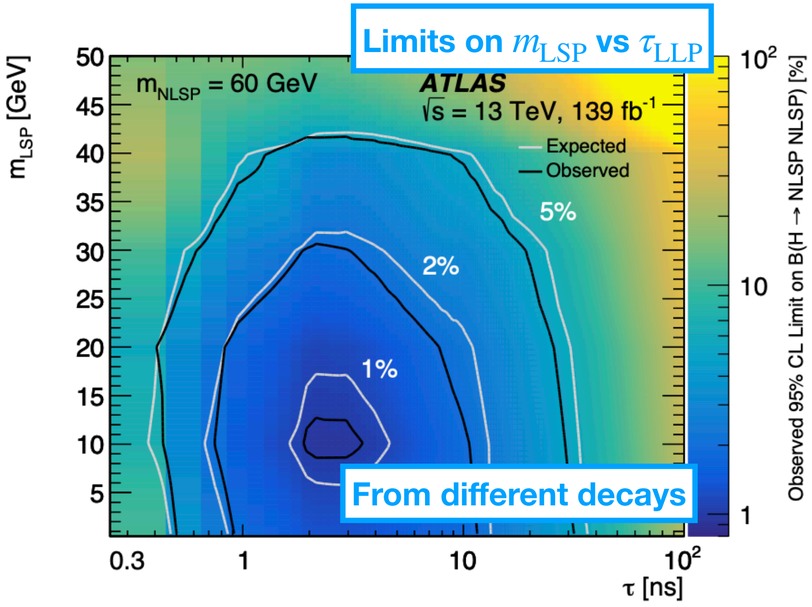
- Real prompt photons
- Fake photons (electrons and jets)

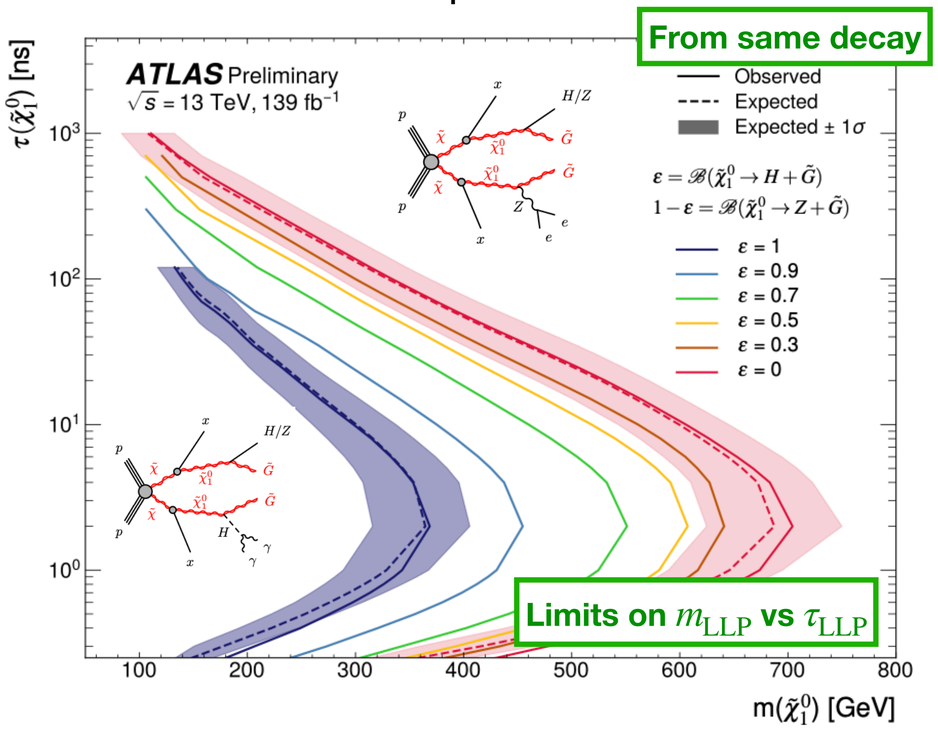
→ shape fit performed in fake-enhanced and genuine-enhanced photon data samples over t_γ (t_{avg}) spectrum for different $|\Delta z_\gamma|$ bins (ρ)

Results

Results:
No excess found over SM prediction
→ exclusion limits on free parameters of the models







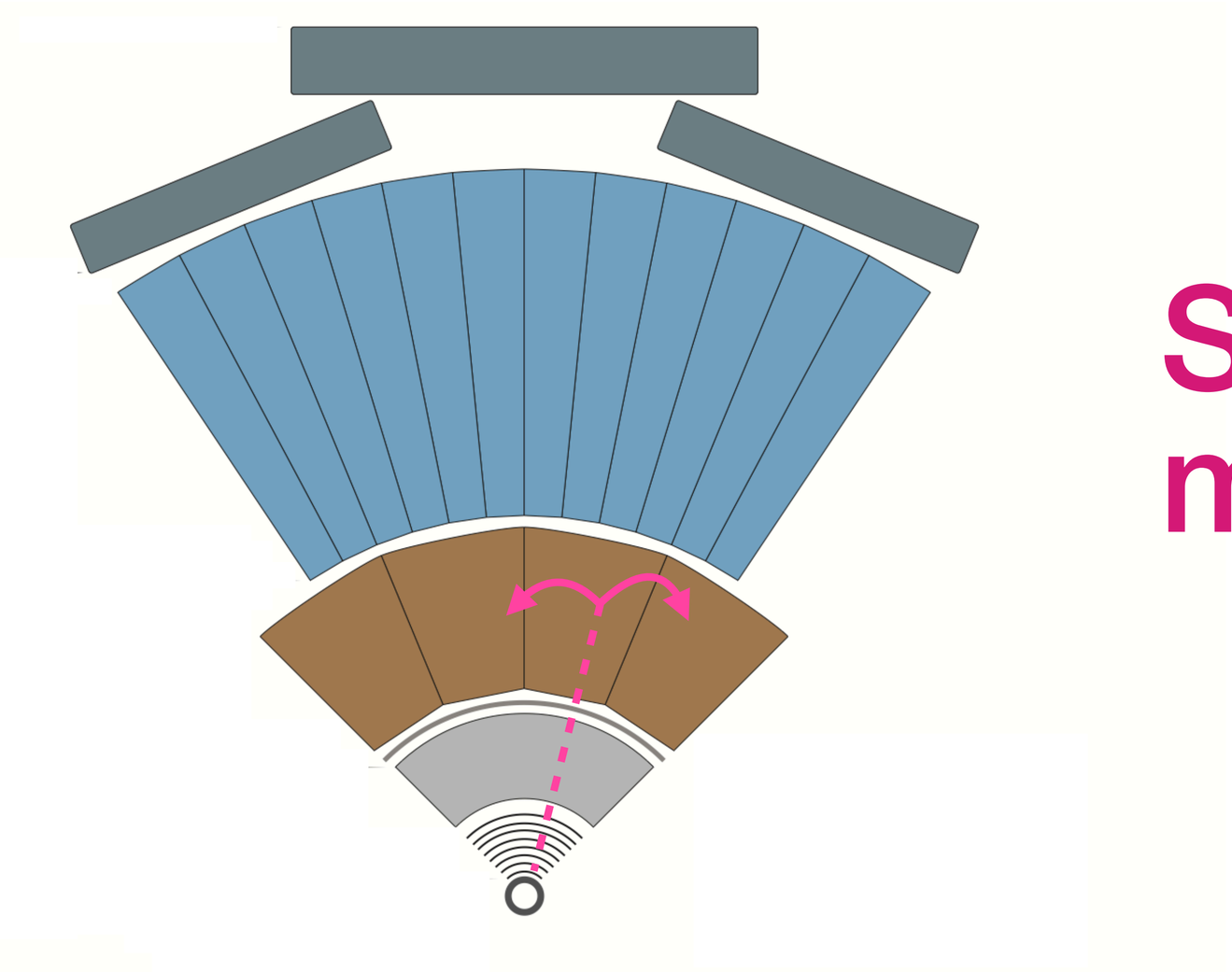
Comparison with previous searches:

- First time it is looked for photon final states with VH and displaced photons

Comparison with previous searches:

- **First time** it is looked for di-photon final states with photons coming from same vertex
- First time ρ requirements

NEW

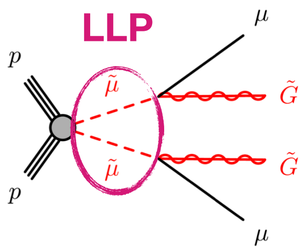


Slightly displaced muons

ATLAS-CONF-2023-018: 23/03/2023

Strategy and results

SUSY GMSB



$m_{\tilde{\mu}} \in [80,520]$ GeV

Signature:

LLPs decaying **slightly displaced** in the ID in **muons**

→di-muon triggers

→ large impact parameter

SRs:

SR1: $m_{\mu^+\mu^-} \geq 120\,\text{GeV} \rightarrow 0.6\,\text{mm} \leq |d_0| \leq 1.3\,\text{mm}$

SR2: $m_{\mu^+\mu^-} \geq 140\,\text{GeV} \rightarrow 0.6\,\text{mm} \leq |d_0| \leq 3\,\text{mm}$

SR3: $m_{\mu^+\mu^-} \geq 200\,\text{GeV} \rightarrow 0.6\,\text{mm} \leq |d_0| \leq 3\,\text{mm}$

Background:

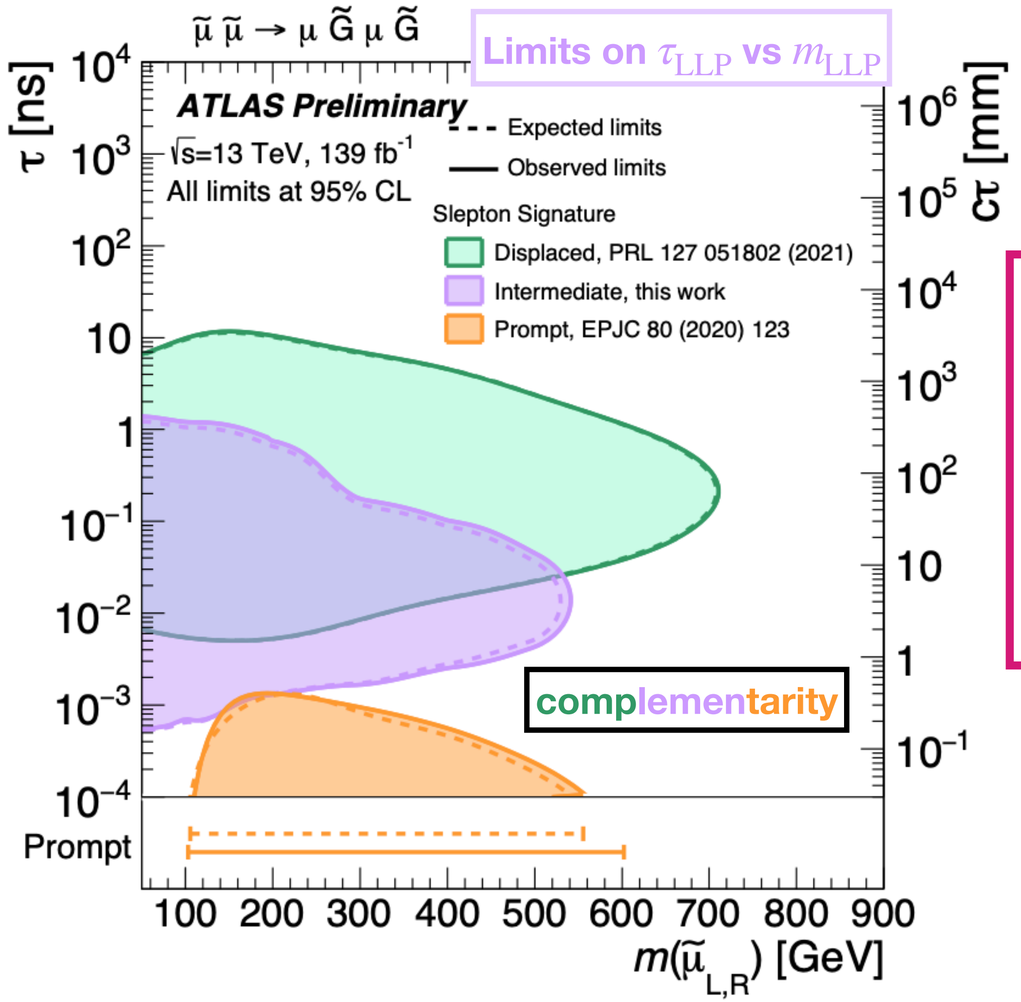
B-hadron decays ($b\bar{b} \rightarrow \mu^+\mu^-$)

→ABCD data driven method using $d_0^{\mu^+}$ and $d_0^{\mu^-}$ as discriminating variables

Results:

No excess found over SM prediction

→ **exclusion limits on free parameters of the models**



Comparison wrt other searches:

- Different d_0 requirements
- Complementarity with other ATLAS searches ()

Summary and conclusion

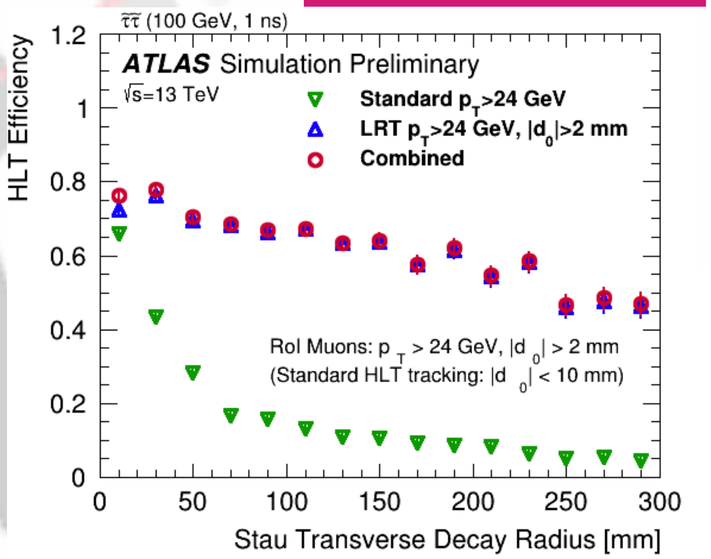
LLP exist in SM, why not in BSM too? LLP searches great challenge for HEP experiments (optimised for prompt objects)!

Unconventional reconstruction, novel trigger algorithm, very good knowledge of detectors are needed…

ATLAS looking for LLPs with direct detection (MCPs…) and indirect detection (displaced vertices, displaced non pointing photons, displaced leptons/light hadrons), see here for all ATLAS BSM results

No evidence of BSM LLP so far, but new techniques brought to light and better understanding of detector achieved

Trigger LRT performance



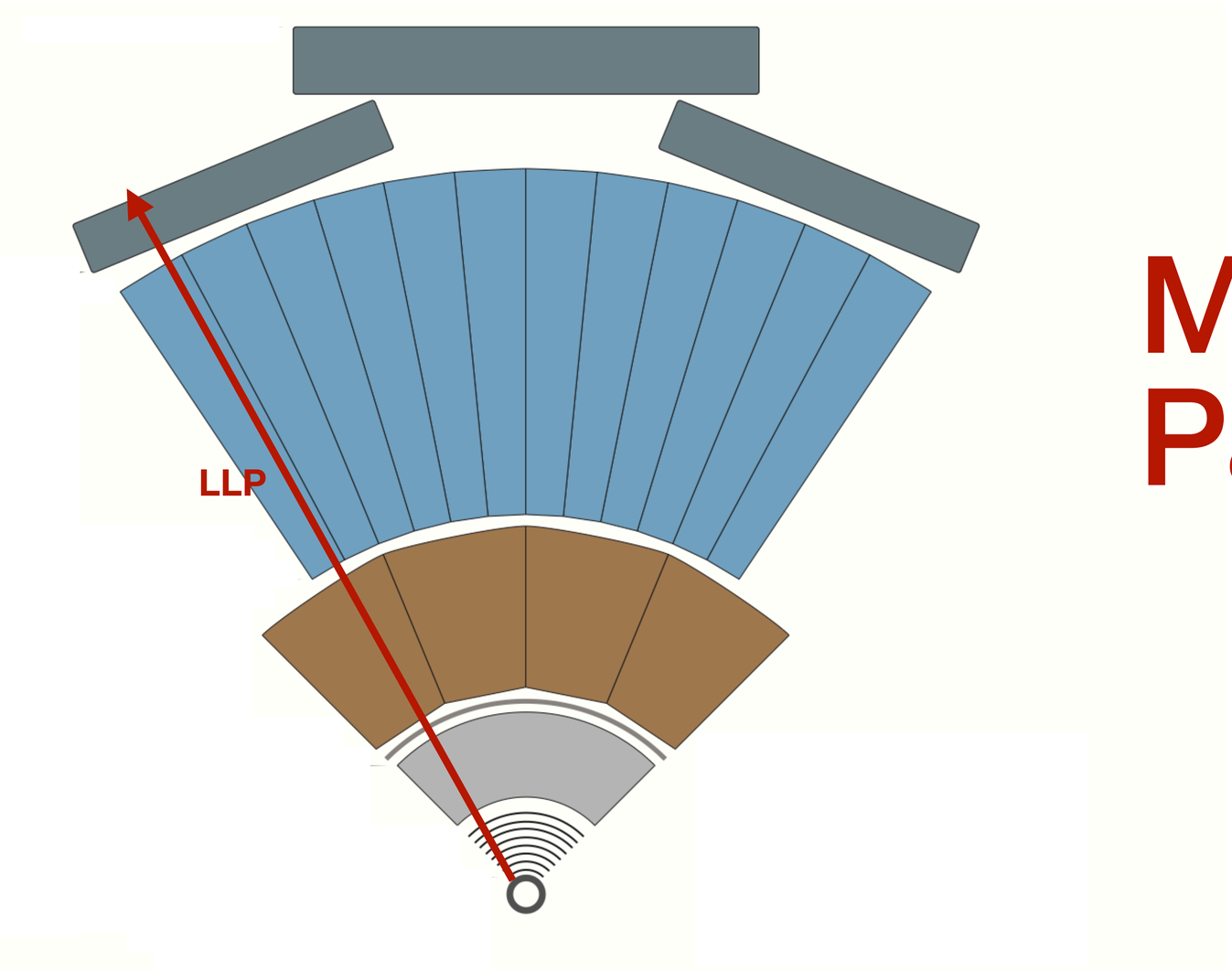
Now we are in Run3 → more data, novel trigger and reconstruction algorithms ongoing: exciting prospect for LLP searches!

Long live the Long Lived

DIS23

MICHIGAN STATE UNIVERSITY®

Backup



Multi-Charged Particles (MCPs)

CONF Note 19/05/2022

MCPs

Signature:

MCP traverse the whole detector interacting with it

→ muon-like signature → muon triggers

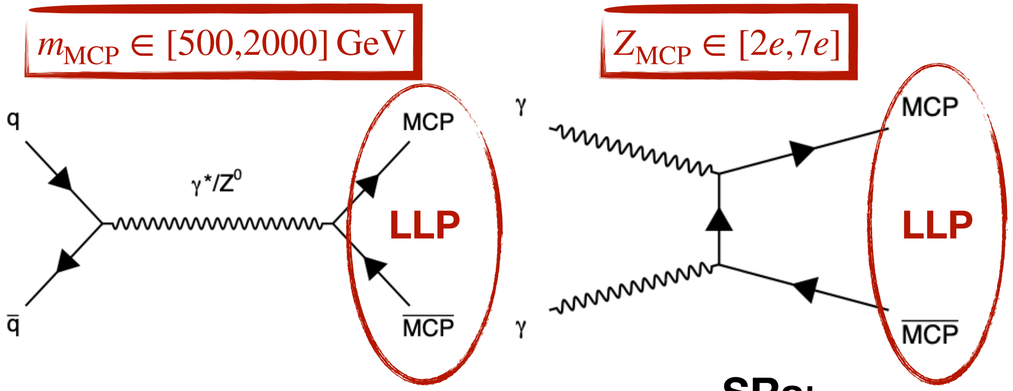
$$\frac{dE}{dx} \propto \frac{Z^2}{\beta^2}, Z \geq 2 \text{ and } \beta \ll 1$$

→ highly-ionising and slow particles

⇓

$\frac{dE}{dx}$ based discriminants

E_{T}^{miss} and late muon triggers

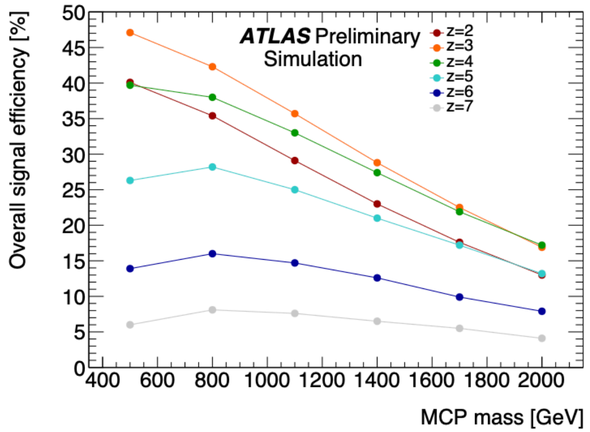


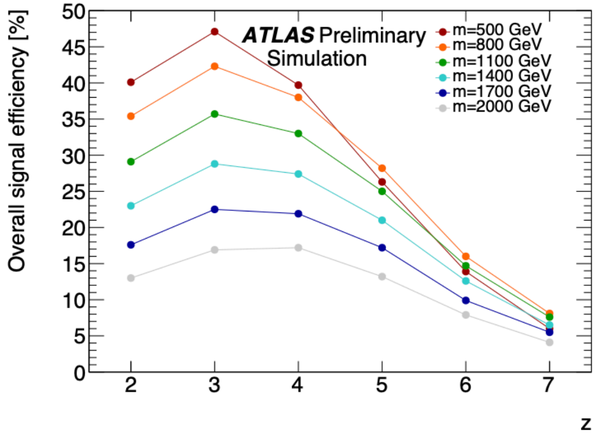
SRs:

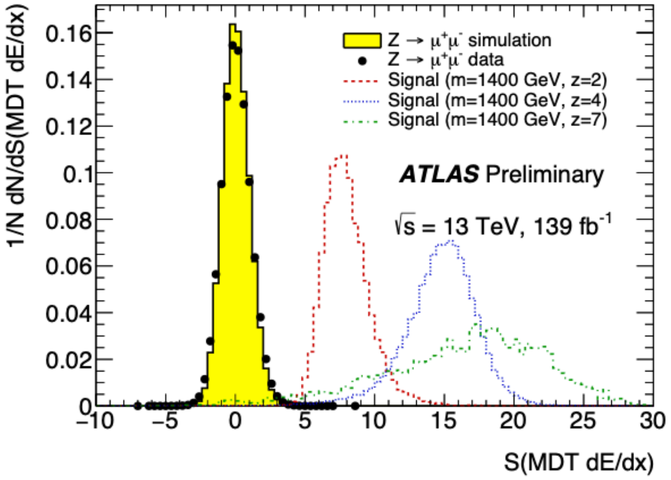
- ≥ 1 highly energetic and isolated muon (MS matched to ID)

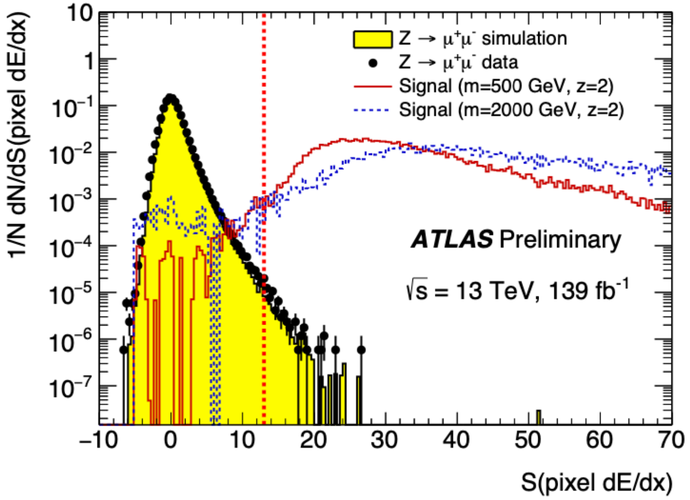
$Z = 2$ SR:
- $S(\mathrm{pix}\, dE/dx) > 13$
- $S(\mathrm{TRT}\, dE/dx) > 2$
- $S(\mathrm{MDT}\, dE/dx) > 2$

$Z > 2$ SR:
- $f^{\mathrm{HT}} > 0.7$
- $S(\mathrm{MDT}\, dE/dx) > 7$







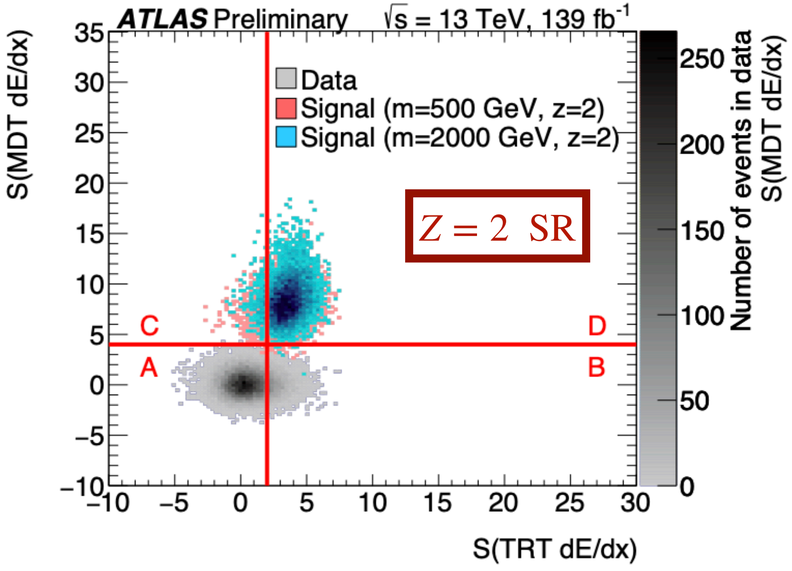


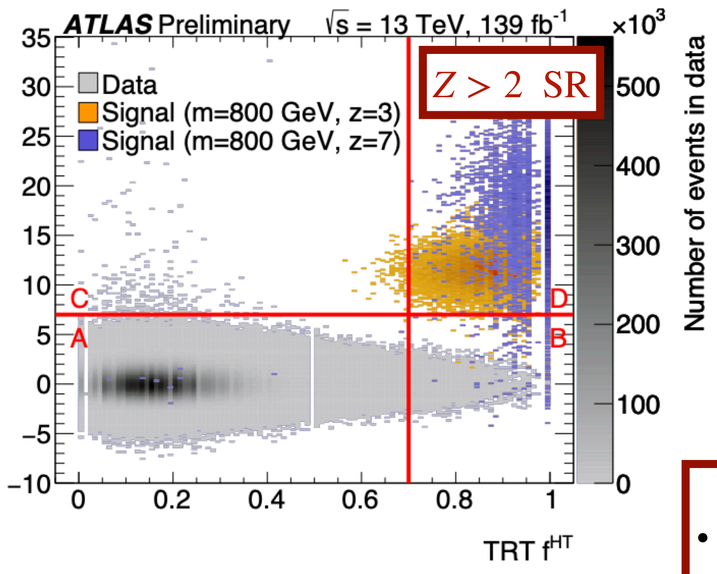
Background and results

Background:

- Energy fluctuations for highly energetic muons
- δ-rays
- Detector noise
- Radiation background

→ data driven estimation using ABCD method

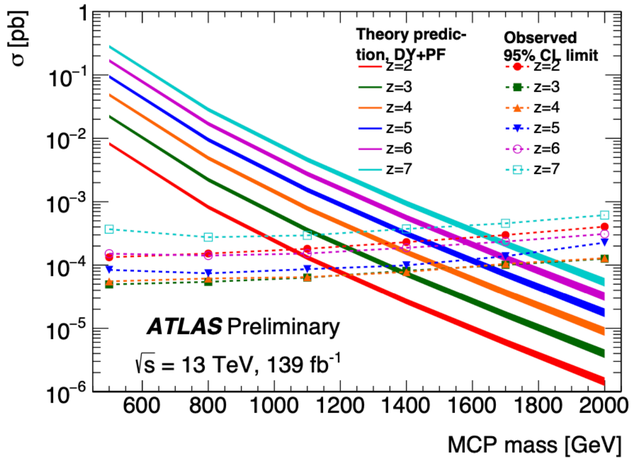


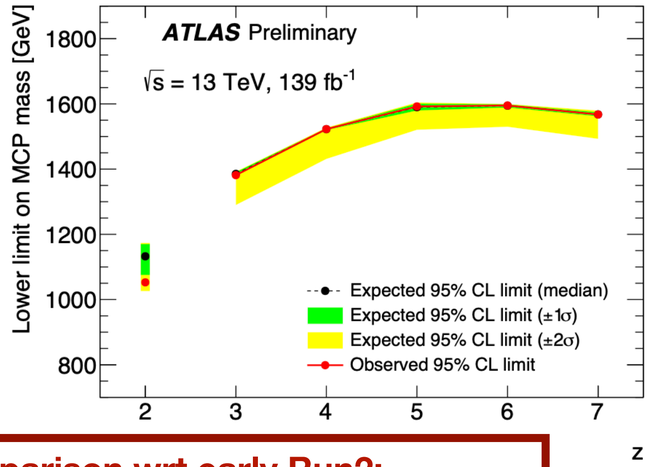


Results:

No excess found over SM prediction

→ exclusion limits on σ vs m_{MCP} and Z_{MCP}





Comparison wrt early Run2:

- Late muon trigger
- Photon Fusion production mode added
- γ^* virtual boson exchange added

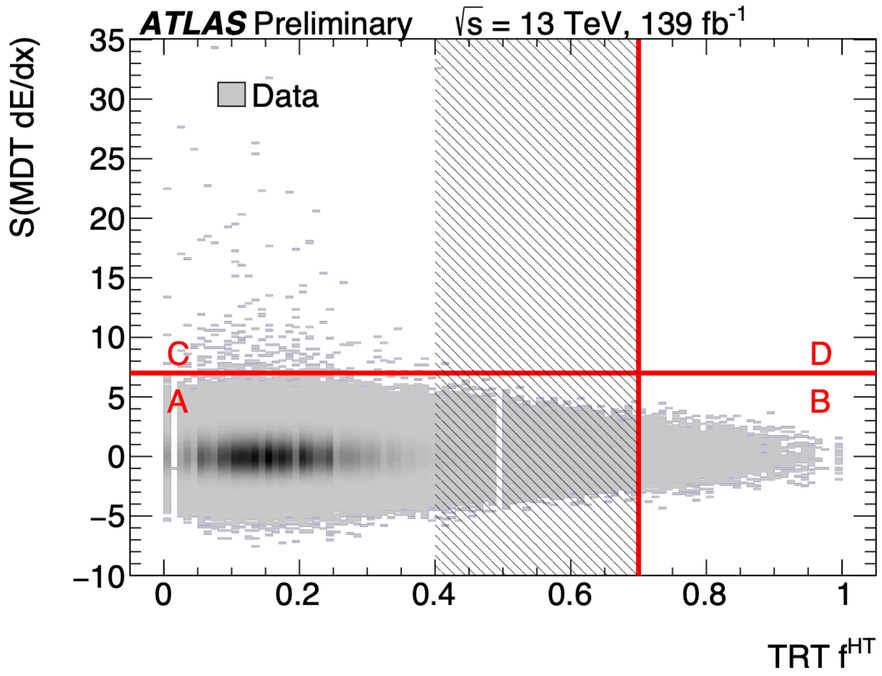
Uncertainties

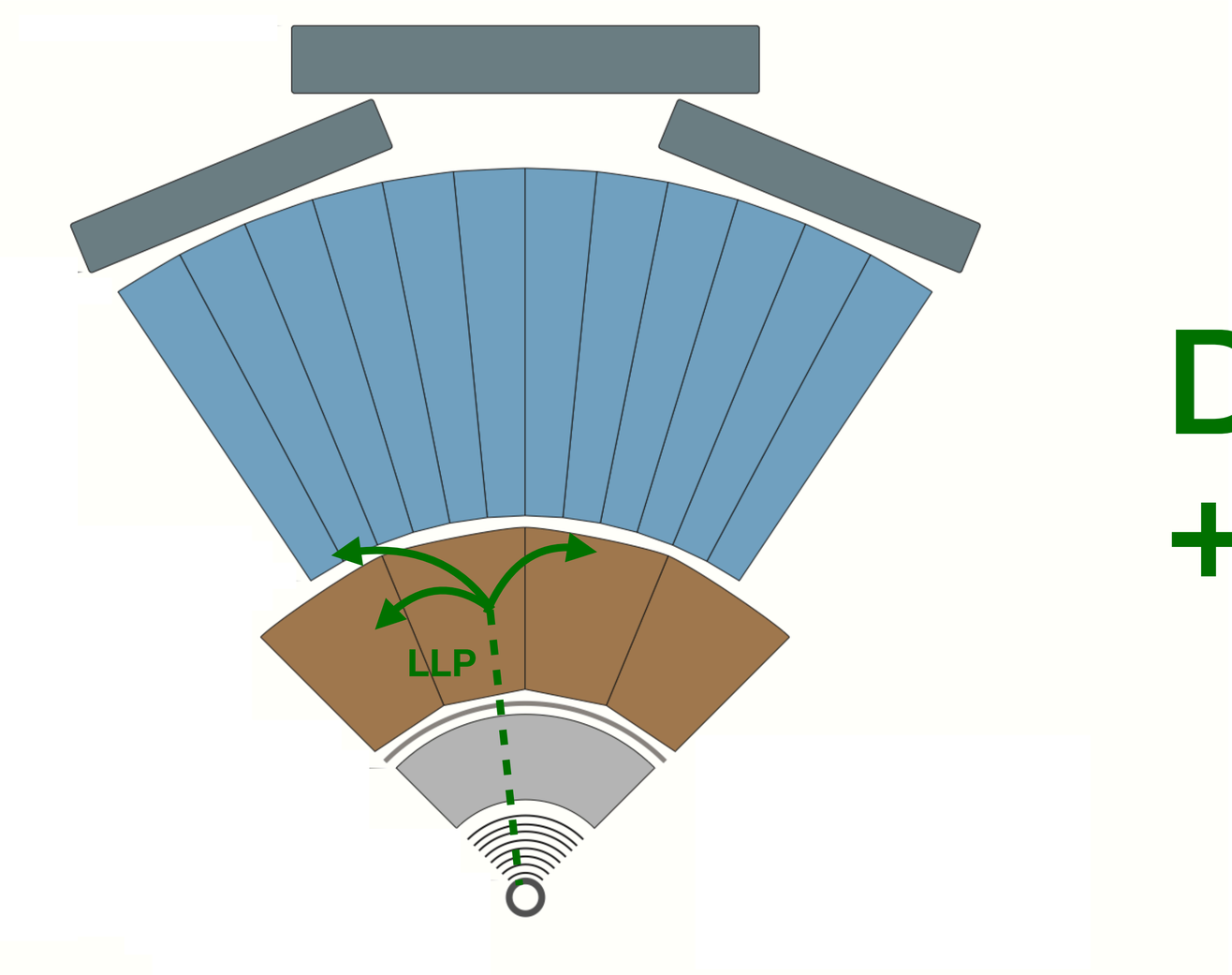
Signal:

- Offline quantities: mis-modelling of discriminators
  - Uncertainty on material in front of MS
  - Mis-modelling on $\frac{dE}{dx}$ and f_{TRT}^{HT} $\rightarrow \in [0.5\,\%, 3\%]$
- Online quantities: mis-modelling of triggers
  - Muon triggers: difference in timing to reach RPCs (no mis-modelling in TGC triggers) $\rightarrow 1\,\%$
  - E_{T}^{miss} triggers
- Luminosity $\rightarrow 1.7\,\%$

Background:

- Closure uncertainty due to ABCD method $\rightarrow \in [12\,\%, 33\%]$



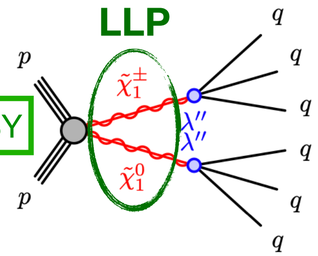


Displaced vertices + jets (DV+jets)

DV+jets

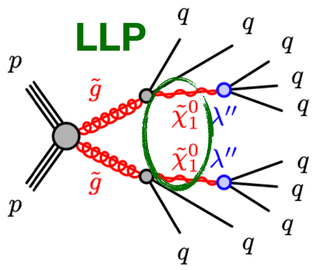
$m_{\tilde{\chi}_1^0} \in [100,1700]$ GeV

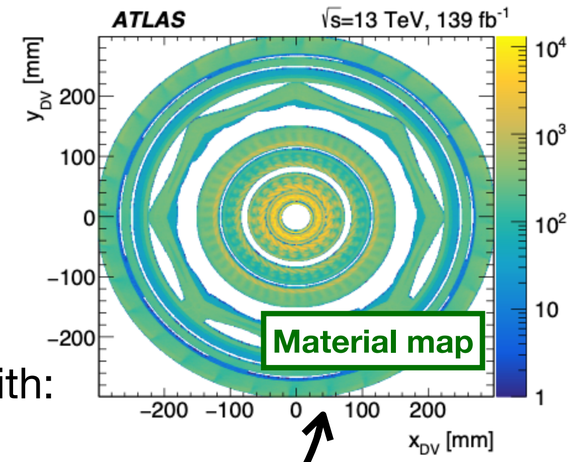
RPV EWK SUSY



$m_{\tilde{\chi}_1^0} \in [10,2500]$ GeV; $m_{\tilde{g}} \in [1.6,2.6]$ TeV

RPV STRONG SUSY

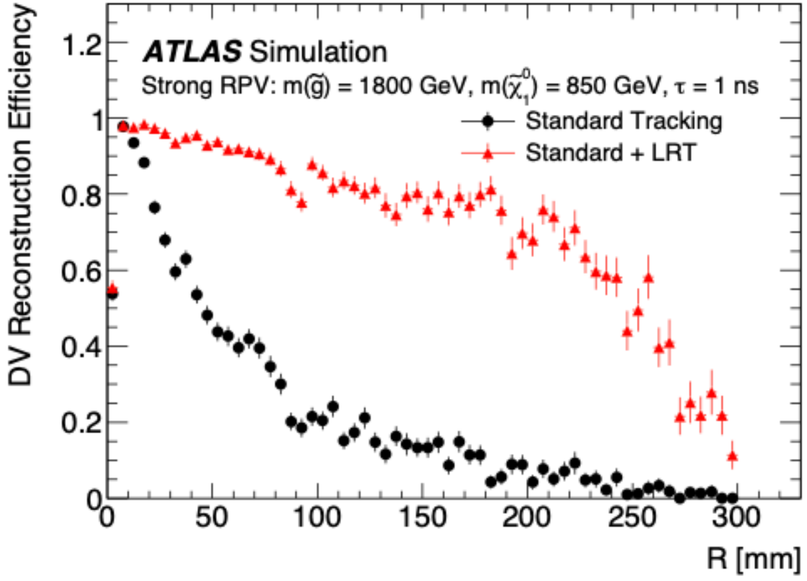




Signature:
LLP decay displaced into hadrons
→ displaced vertices (DVs) and multi-jets
→ jet triggers
→ DVs reconstructed using Large Radius Tracking, LRT
(looser requirements on tracks impact parameter)

SRs:
At least 1 DV with:

- $m_{\mathrm{DV}} > 10$ GeV
- $n_{\mathrm{DV}}^{tracks} \geq 5$
- $R_{\mathrm{DV}} < 300$mm, $z_{\mathrm{DV}} < 300$mm
- **Material map**-veto satisfied
  (reject DVs due to hadronic interactions with detector)



High-pT SR:
Targeting Strong SUSY

- $n_{\mathrm{jet}}^{250} \geq 4$ or $n_{\mathrm{jet}}^{195} \geq 5$ or $n_{\mathrm{jet}}^{116} \geq 6$ or $n_{\mathrm{jet}}^{90} \geq 7$

Trackless-jet SR:
Targeting EWK SUSY

- Fail High-pT selection
- $n_{\mathrm{jet}}^{137} \geq 4$ or $n_{\mathrm{jet}}^{101} \geq 5$ or $n_{\mathrm{jet}}^{83} \geq 6$ or $n_{\mathrm{jet}}^{55} \geq 7$
- $n_{\mathrm{trackless-jet}}^{70} \geq 1$ or $n_{\mathrm{trackless-jet}}^{50} \geq 2$

Signal jet:= reconstructed from energy cluster using anti-k_t algorithm with $\Delta R = 0.4$ ($p_{\mathrm{T}} > 20$ GeV, $|\eta| < 2.5$)

Track-less jet:= jet whose $\sum p_{\mathrm{T}} < 5$ GeV (using standard tracks)

DV+jets

Background:

- Hadronic interaction with detector material
- Accidental crossings
- Merged vertices

→ **data driven estimation**

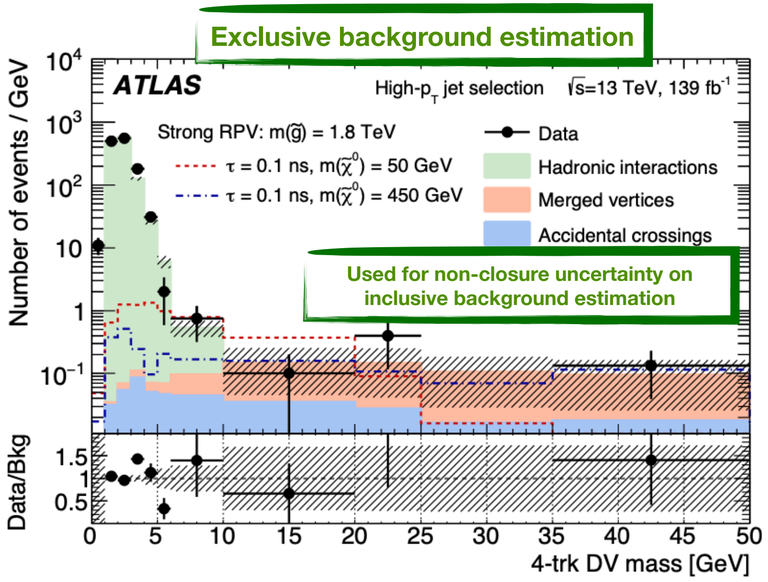
$$p^{SR}_{\mathrm{DV-jet}} = p^{CR}_{\mathrm{DV\leftrightarrow track-jet}} f^{CR\rightarrow SR}$$

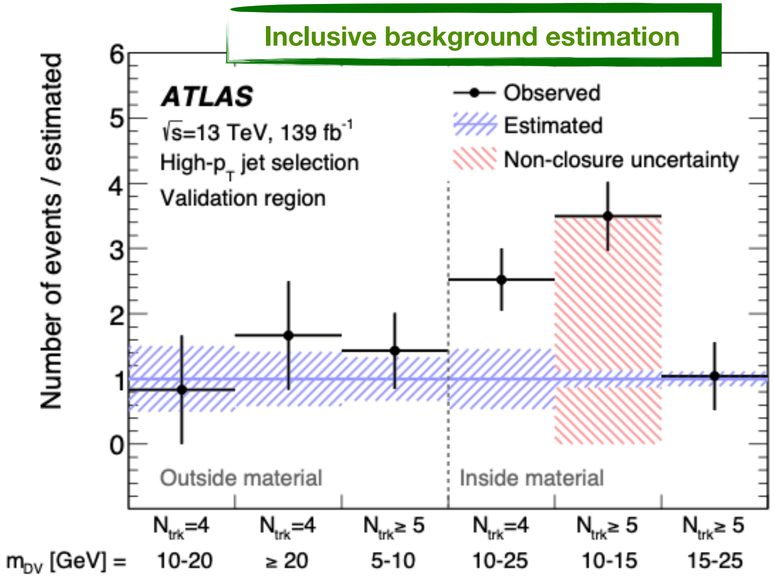
$$\rightarrow p^{CR}_{\mathrm{DV\leftrightarrow track-jet}} \in [6\times10^{-7}, 2\times10^{-6}]$$

CR:

- γ triggers;
- High-pT and Trackless-jet SRs jet requirement failed;
- ≥ 3 track-jets with $p_{\mathrm{T}} > 20\,\mathrm{GeV}$

Track-jets:
Background DVs correlated with track-density, correlated with jets multiplicity

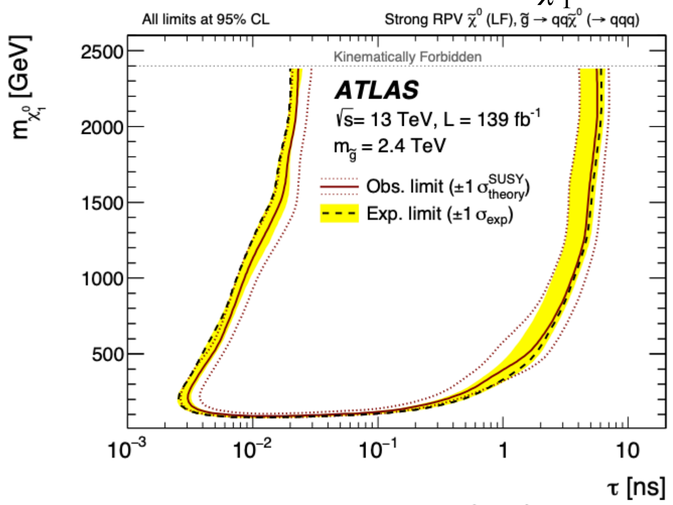


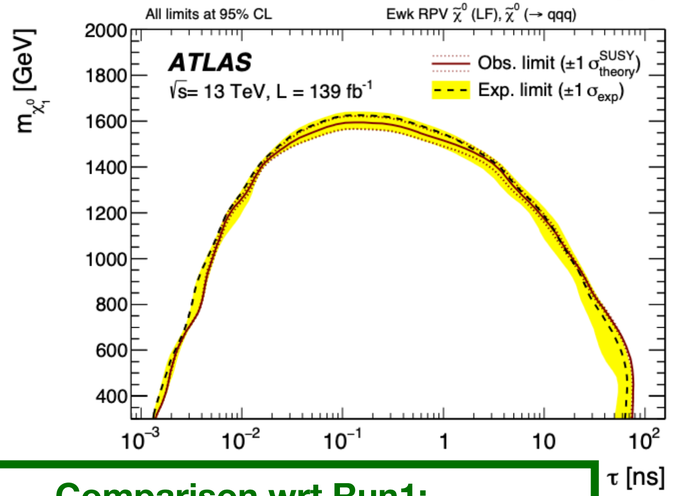


Results:

No excess found over SM prediction

→ exclusion limits on $m_{\tilde{\chi}^0_1}$ and $\tau_{\tilde{\chi}^0_1}$





Comparison wrt Run1:

- Large Radius Tracking
- Novel background estimation technique
- First time interpreted in EWK SUSY

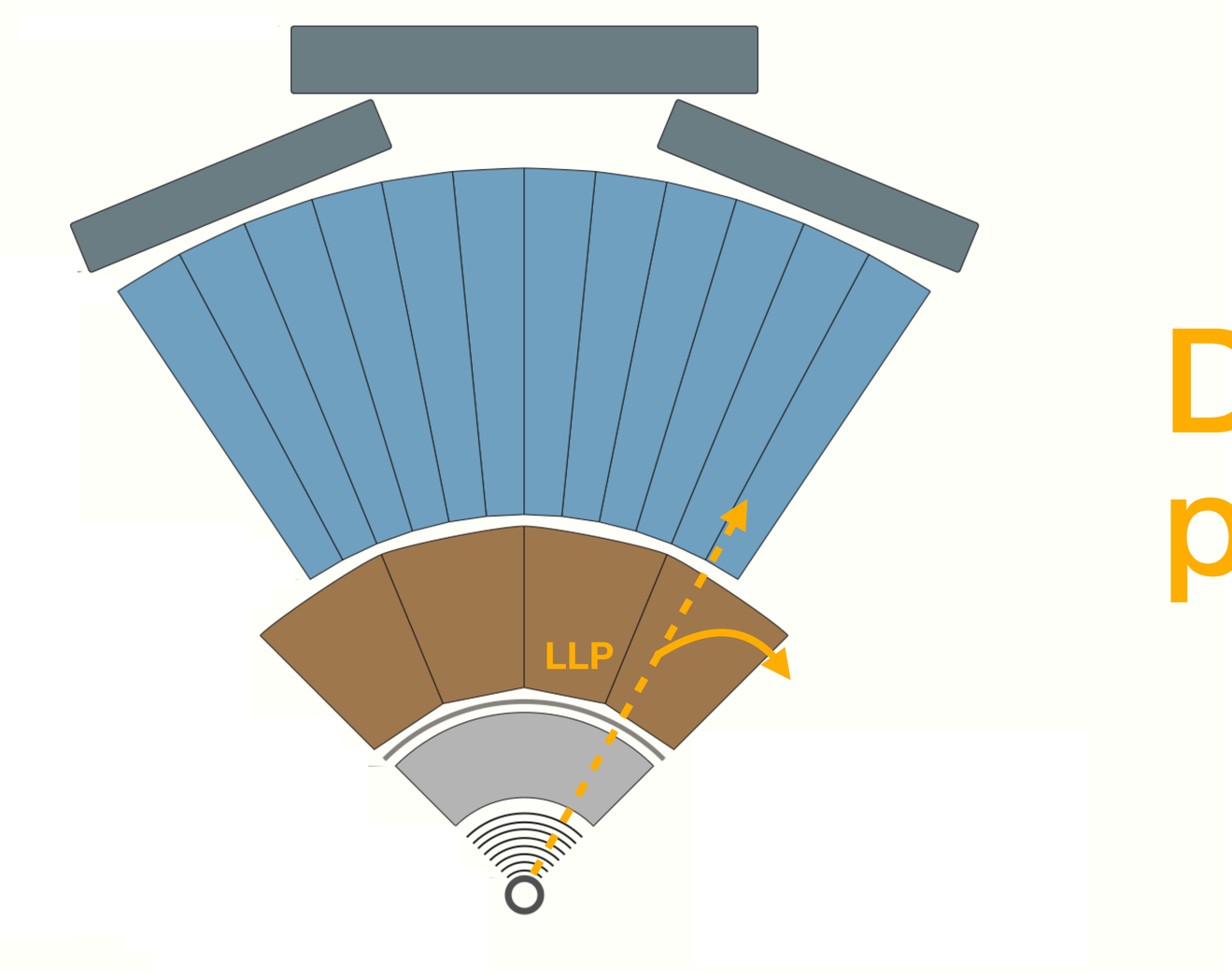
Uncertainties

Signal:

Source of uncertainty	Relative impact signal yield [%]	
	Gluino pairs	Electroweakino pairs
Total	17 – 20	20 – 31
Tracking and vertex reconstruction	14 – 17	
ISR modelling in MC simulation	< 1	1 – 24
Jet energy scale and resolution	1	10
Integrated luminosity of data sample	1.7	

Background:

Region	Uncertainty source			
	CR statistical	Non-linearity	VR non-closure	Pile-up
High-p_T jet SR	± 58%	$^{+10\%}_{-27\%}$	± 4%	± 5.9%
Trackless jet SR	± 58%	$^{+6.3\%}_{-17\%}$	–	± 20%



Displaced non-pointing photons

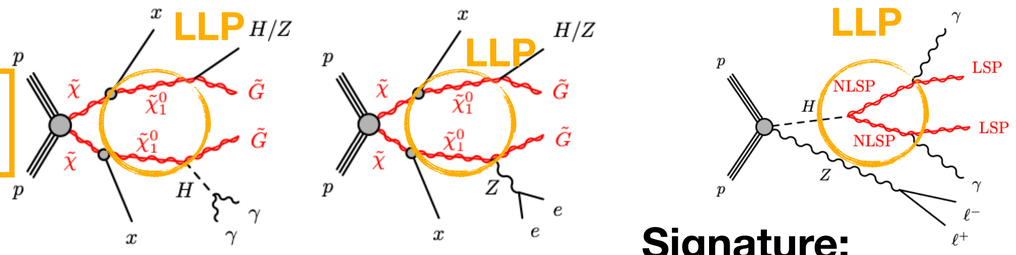
Displaced photons

From same decay

$m_{\tilde{\chi}_1^0} \in [100,725]$ GeV

From different decays

SUSY GMSB



$m_{\mathrm{NLSP}} \in [30,60]$ GeV
$m_{\mathrm{NLSP}} \in [0.5,50]$ GeV

Signature:

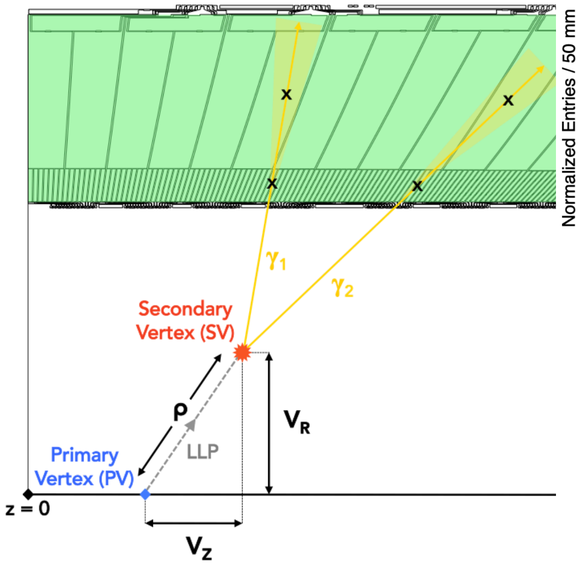
Same decay:

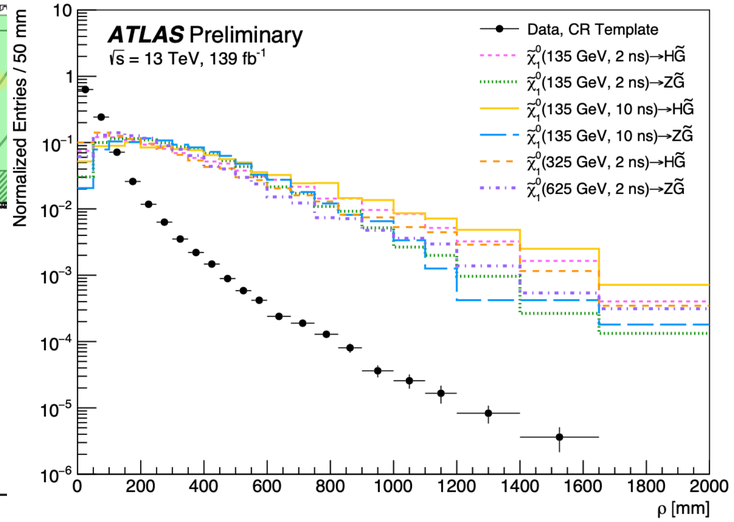
two photons produced in decays of LLPs

→ **photon triggers**

Non pointing photons coming from same LLP

→ vertexing $\rho = \sqrt{V_R^2 + V_Z^2}$





Signature:

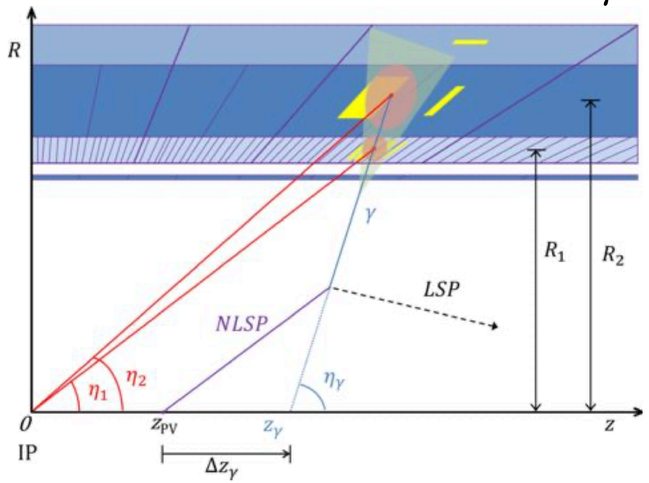
Different decays:

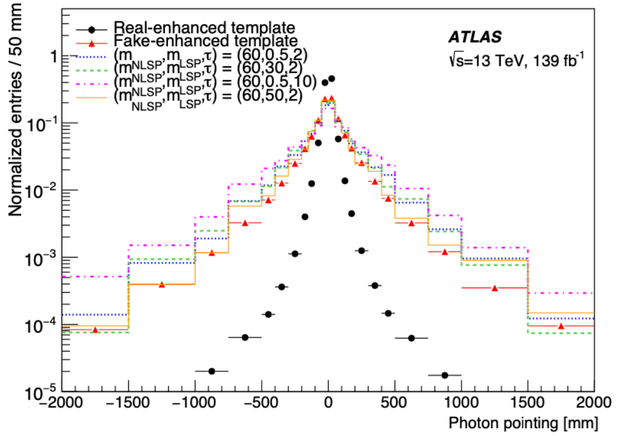
two photons produced in different of LLPs in association with leptons

→ **lepton triggers**

Non pointing photons coming from different LLPs

→ pointing $\Delta z_\gamma = |z_\gamma - z_{PV}|$





Displaced photons

Signature: displacement

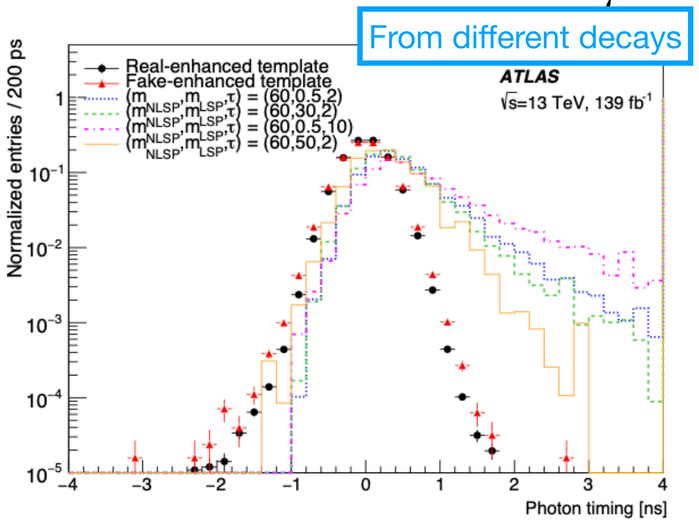
Timing information in calo (resolution $O(100\,\mathrm{ps})$)

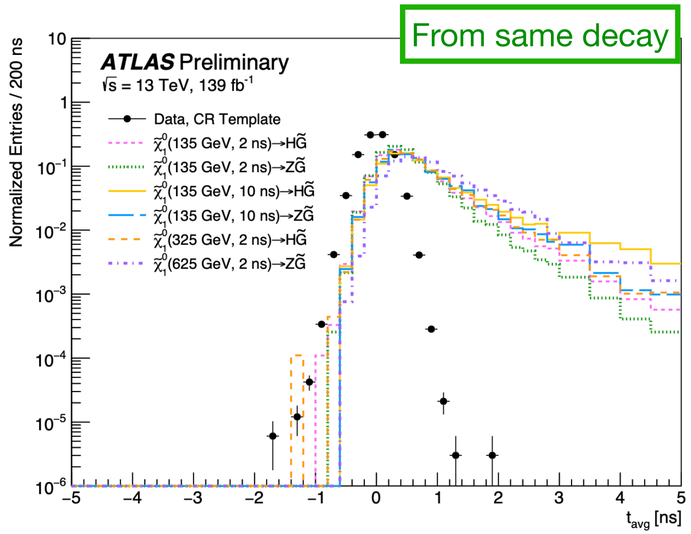
Same decay:

→average timing in calo $t_{avg} = (t_{\gamma 1} + t_{\gamma 2})/2$

Different decays:

→per photon timing in calo t_γ





Background:

- Real prompt photons
- Fake photons (electrons and jets)

→ shape fit performed in fake-enhanced and genuine-enhanced photon data samples over t_γ (t_{avg}) spectrum for different $|\Delta z_\gamma|$ bins (ρ)

Different decays SR:

4 SRs with at least one γ in EMB

- $1\gamma, m_{NLSP} - M_{LSP} = 10\,\mathrm{GeV}$
- $\geq 2\gamma, m_{NLSP} - M_{LSP} = 10\,\mathrm{GeV}$

$t_\gamma > 0\,\mathrm{ns}$ → $E_T^{miss} > 80\,\mathrm{GeV}$, $E_{cell} > 7\,\mathrm{GeV}$

- $1\gamma, m_{NLSP} - M_{LSP} > 10\,\mathrm{GeV}$
- $\geq 2\gamma, m_{NLSP} - M_{LSP} > 10\,\mathrm{GeV}$

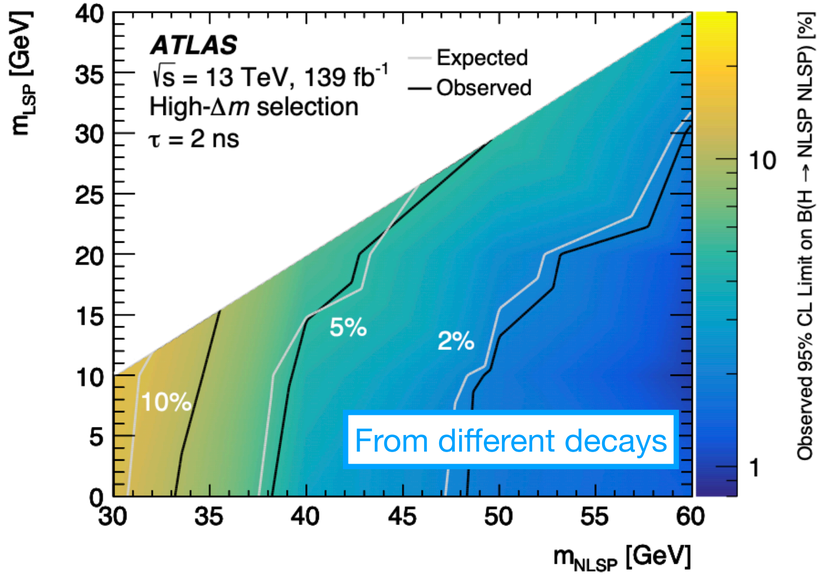
$t_\gamma > 0\,\mathrm{ns}$ → $E_T^{miss} > 80\,\mathrm{GeV}$, $E_{cell} > 10\,\mathrm{GeV}$

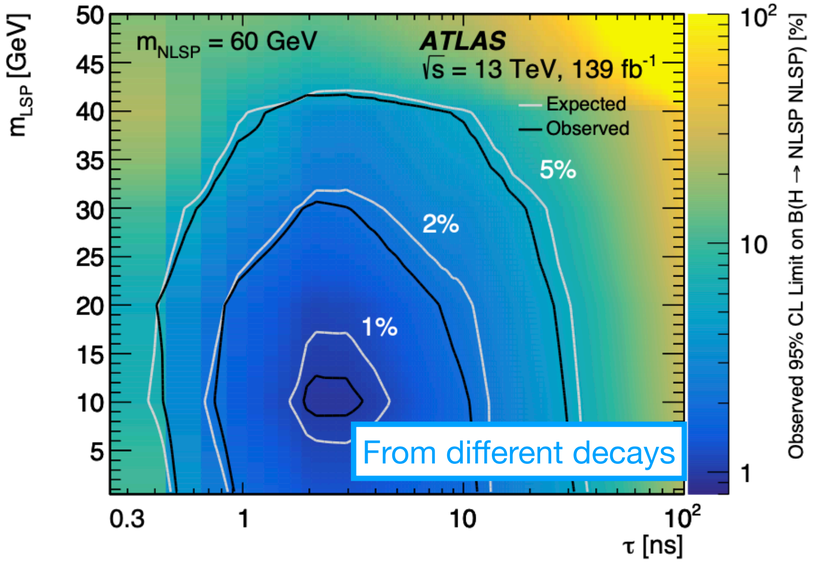
Same decay SRs:

- $\geq 2\gamma$ energetic
- $E_{cell}(\gamma_1), E_{cell}(\gamma_2) > 5\,\mathrm{GeV}$
- $m_{\gamma\gamma} > 60\,\mathrm{GeV}$
- $V_r < 1500\,\mathrm{mm}$, $V_Z < 3740\,\mathrm{mm}$
- $t_{\gamma_1}, t_{\gamma_2} > 0$

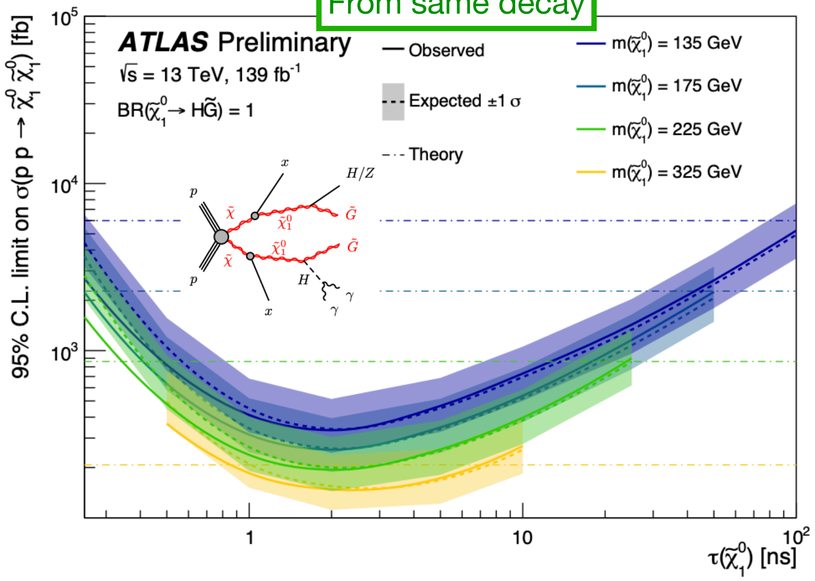
Displaced photons

Results:
No excess found over SM prediction
→ exclusion limits on free parameters of the models

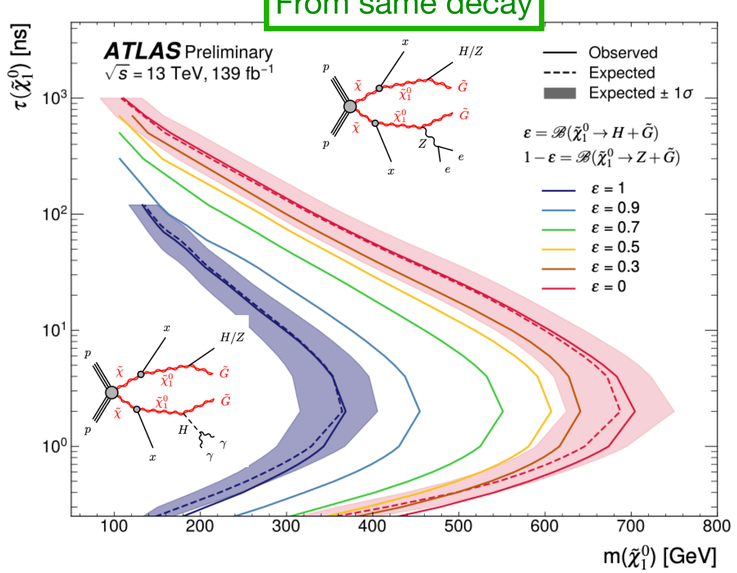




From same decay



From same decay



Comparison with previous searches:
- First time it is looked for photon final states with VH and displaced photons

Comparison with previous searches:
- First time it is looked for di-photon final states with photons coming from same vertex
- First time ρ requirements

Uncertainties

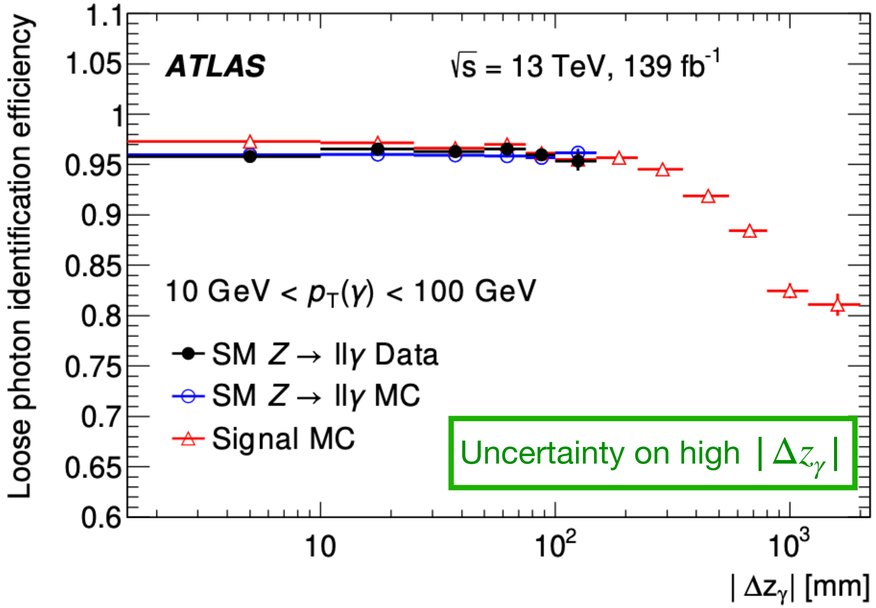
Signal, different decays:

- Normalisation uncertainty:
  - Instrumental uncertainties → $O(1\%)$
  - Theoretical uncertainties (α_s, renormalisation and factorisation scale variations, PDFs choice) → $17\,\%$
  - Luminosity → $1.7\,\%$
- Shape uncertainty → nuisance parameter in fit
  - Photon ID, timing and pointing mismodelling

Background, different decays:

Background shape uncertainties:

- Fluctuations of events in CRs
- Choice of events yielding in fake-enhanced and fake-enhanced CRs
- Non closure uncertainty → $\in [0\,\%, 40\%]$



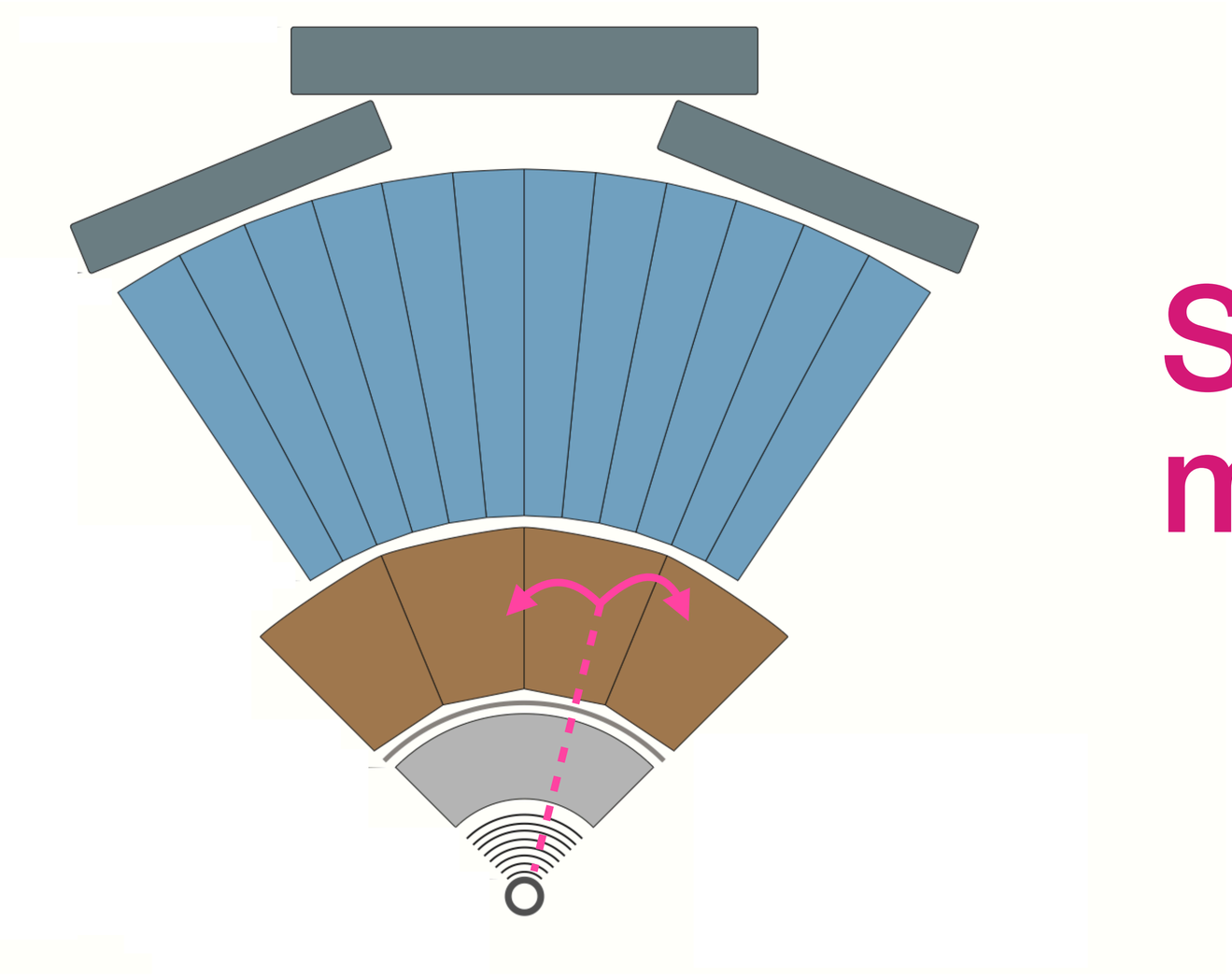
Signal, same decay:

- Instrumental uncertainties → $\in [2.5\,\%, 3\%]$
- Theoretical uncertainties (α_s, renormalisation and factorisation scale variations, PDFs choice) → $12.6\,\%$
- Luminosity → $1.7\,\%$

Background, same decay:

Background shape uncertainties:

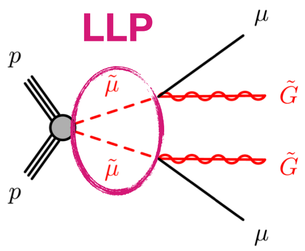
- Purity of genuine enhanced and fake enhanced samples → $\in [1\,\%, 10\%]$
- Pile-up → $10\,\%$



Slightly displaced muons

Signature, SRs and background

SUSY GMSB



$m_{\tilde{\mu}} \in [80,520]$ GeV

Signature:

LLPs decaying **slightly displaced** in the ID in **muons**

→di-muon triggers

→ large impact parameter

SRs:

SR1: $m_{\mu^+\mu^-} \geq 120\,\text{GeV} \rightarrow 0.6\,\text{mm} \leq |d_0| \leq 1.3\,\text{mm}$

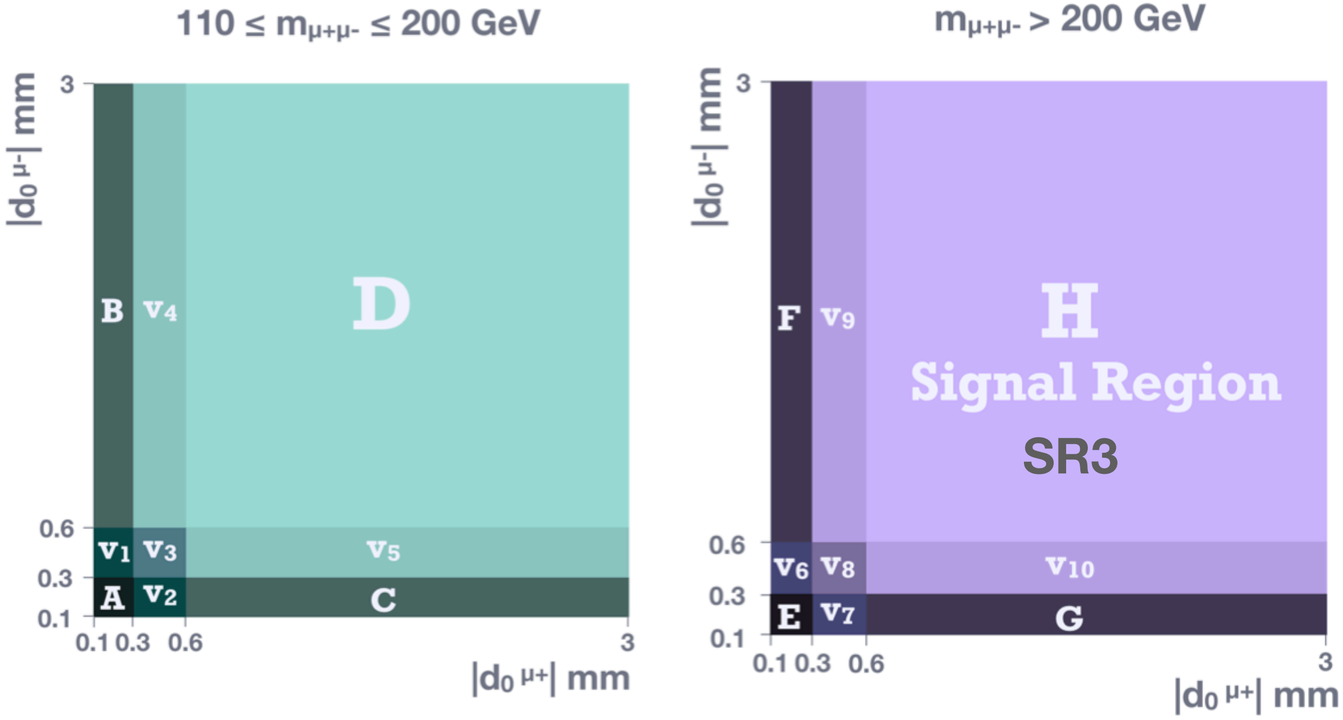
SR2: $m_{\mu^+\mu^-} \geq 140\,\text{GeV} \rightarrow 0.6\,\text{mm} \leq |d_0| \leq 3\,\text{mm}$

SR3: $m_{\mu^+\mu^-} \geq 200\,\text{GeV} \rightarrow 0.6\,\text{mm} \leq |d_0| \leq 3\,\text{mm}$

Background:

B-hadron decays ($b\bar{b} \rightarrow \mu^+\mu^-$)

→ABCD data driven method

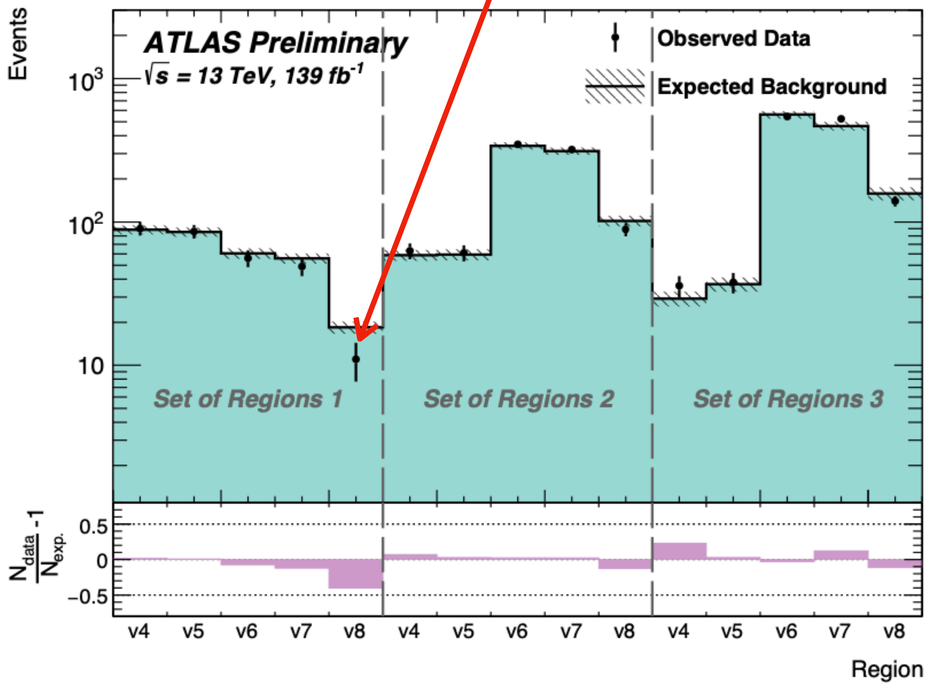


$$N_{SR}^{\text{data}} = N_D^{\text{data}} \frac{N_E^{\text{data}}}{N_A^{\text{data}}} \quad \text{where} \quad N_D^{\text{data}} = N_A^{\text{data}} \frac{N_C^{\text{data}}}{N_A^{\text{data}}} \frac{N_B^{\text{data}}}{N_A^{\text{data}}}$$

Background and results

Background estimation validation:

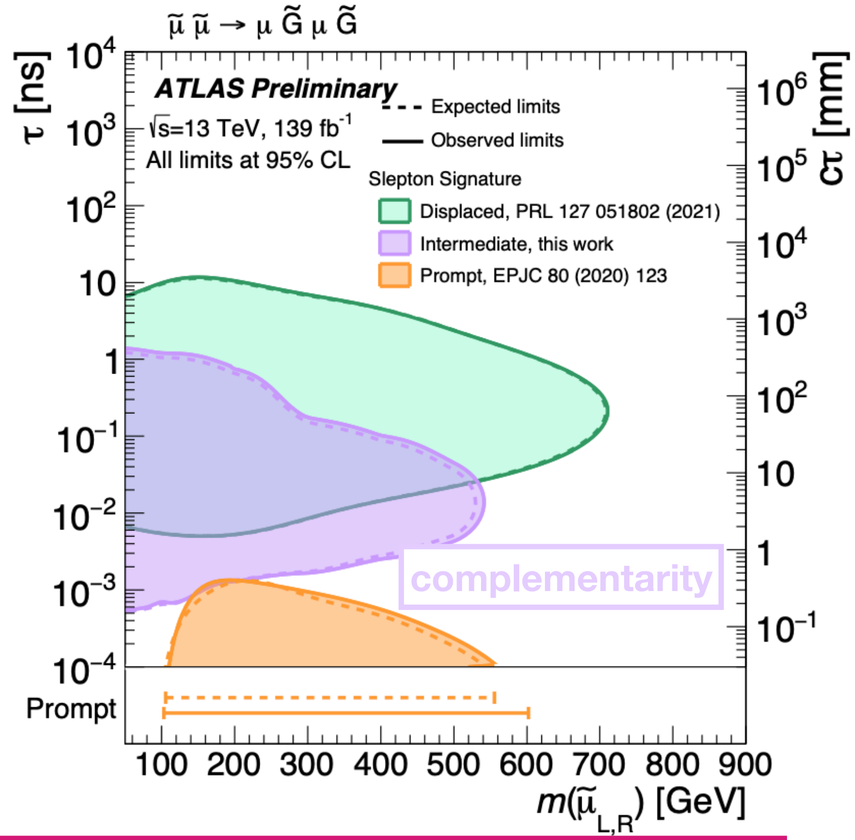
4 VRs for the 3 SRs→ conservative 40% non-closure uncertainty assigned



Results:

No excess found over SM prediction

→ exclusion limits on free parameters of the models



Comparison wrt other searches:

- Different d_0 requirements
- Complementarity with ATLAS/CMS/LEP searches

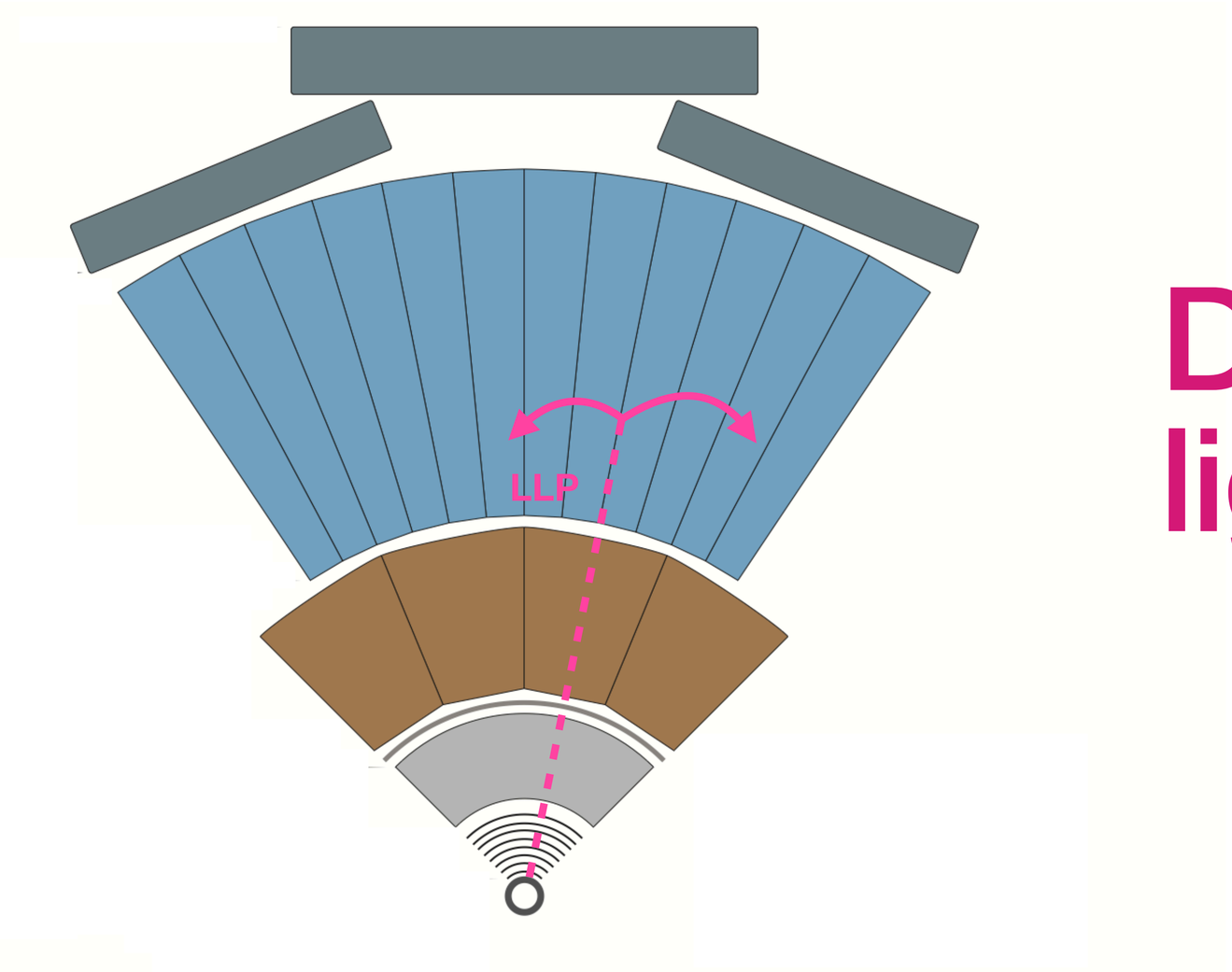
Uncertainties

Signal:

- Offline quantities: mis-modelling of discriminators
  - negligible
- Online quantities: mis-modelling of triggers
  - $< 5\,\%$
- Luminosity $\rightarrow 1.7\,\%$
- Theoretical (only xSec) $\rightarrow \in [1.6\,\%, 3.9\%]$

Background:

- $40\,\%$ non closure uncertainty

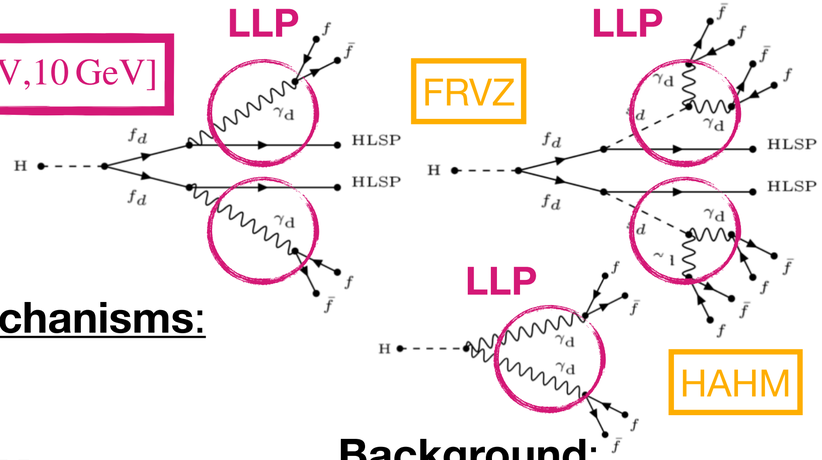


Displaced leptons/ light hadrons

Paper 24/06/2022

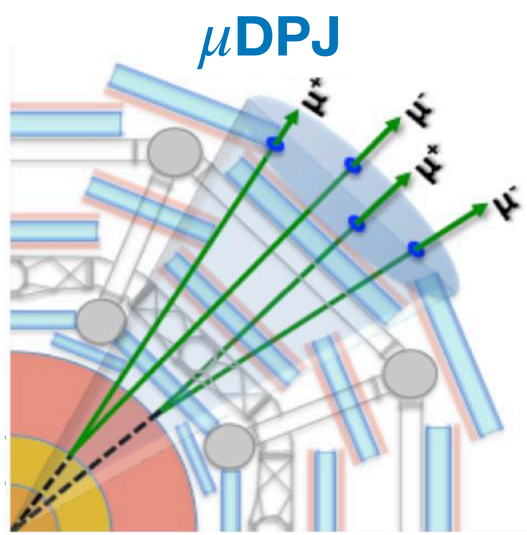
Displaced leptons/light hadrons

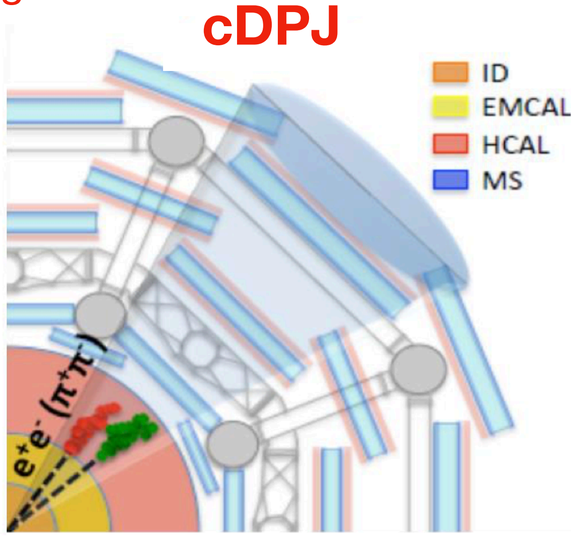
$m_{\gamma_d} \in [17\,\text{MeV}, 10\,\text{GeV}]$

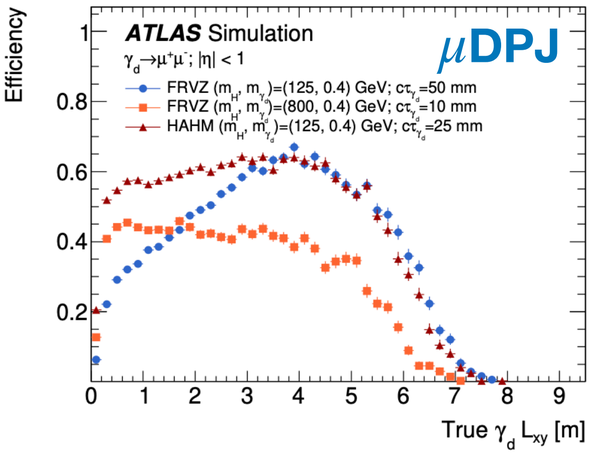


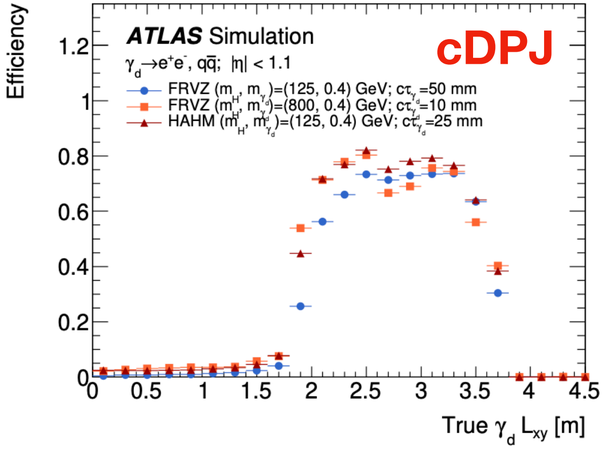
Signature:

LLP decaying after ID either in muons/electrons/light hadrons









Two Higgs production mechanisms:

ggF:

Triggers:

- 3 muons with $p_T > 6\,\text{GeV}$
- Close-by muons
- Narrow jets

3 SRs:

$$SR^{ggF}_{2\mu},\ SR^{ggF}_{\mu+c},\ SR^{ggF}_{2c}$$

WH:

Triggers:

- Single lepton triggers

3 SRs:

$$SR^{WH}_{2c},\ SR^{WH}_{\mu+c},\ SR^{WH}_{c}$$

Background:

- QCD multi-jet (cDPJ)
- Beam Induced Background (cDPJ)
- Cosmic ray background (μDPJ)

→ Reduced using:

- cDPJ isolation, timing and Jet Vertex tagger
- ML discriminants

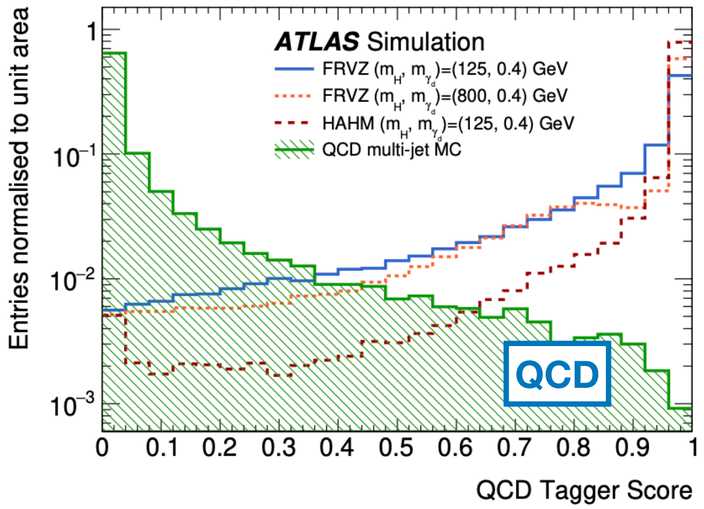
→ Evaluated via:

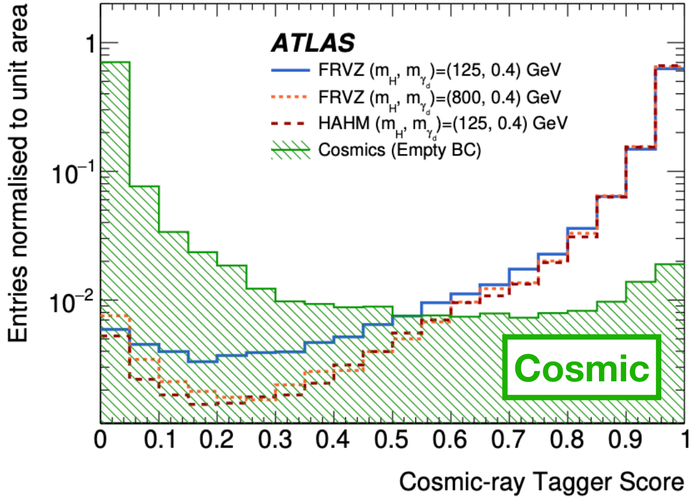
- ABCD in empty bunches for cosmic ray, subtracted from data
- ABCD data

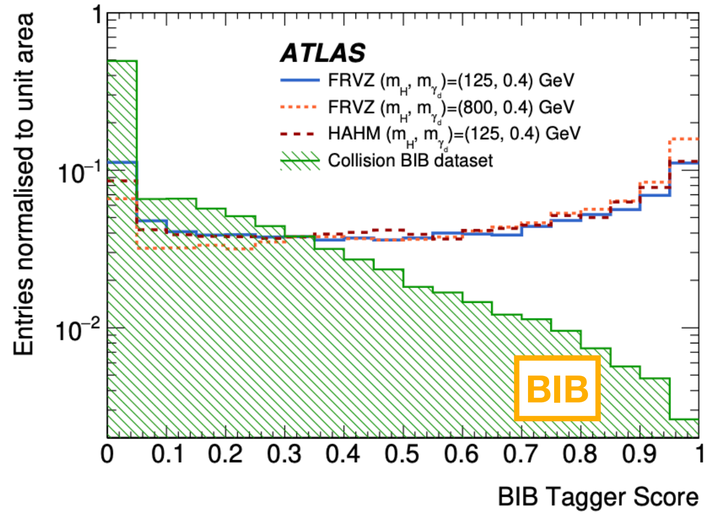
Displaced leptons/light hadrons

QCD (BIB) tagger based on 3D calorimeter images trained on signal and multi-jet MC (BIB data)

Cosmic ray tagger based on z_0, η, ϕ, time of MS tracks in μDPJ trained on signal and cosmic data



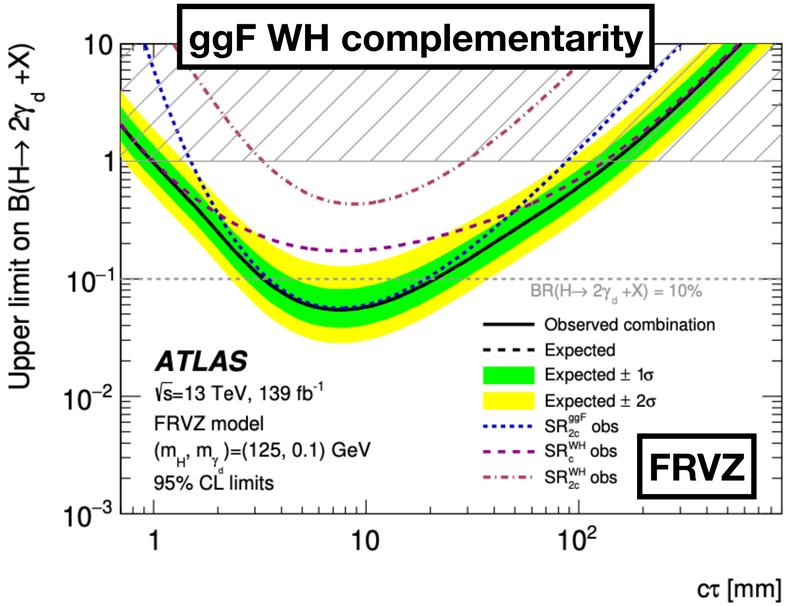
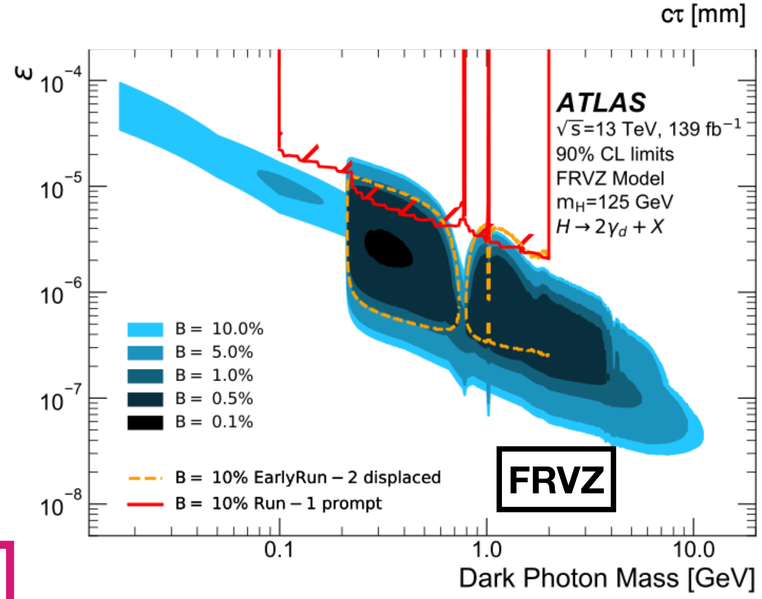




Results:

No excess found over SM prediction

→ exclusion limits on free parameters of the models

Comparison wrt partial Run2:

- ML techniques
- Inclusion of WH production method