Searches for BSM physics using challenging and long-lived signatures with the ATLAS detector

Neža Ribarič, 10.01.2023 at HEP2023 conference, Valparaíso, Chile

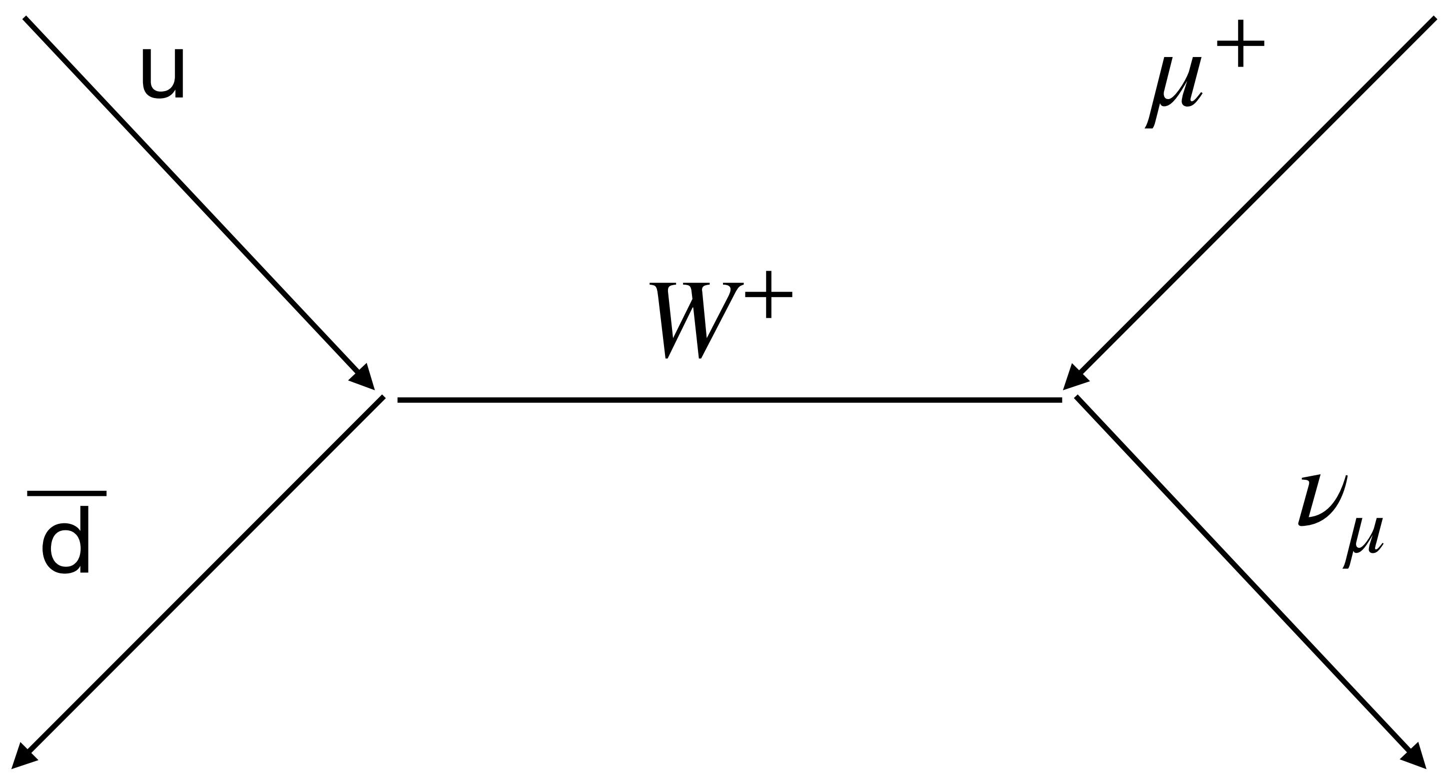
Overview

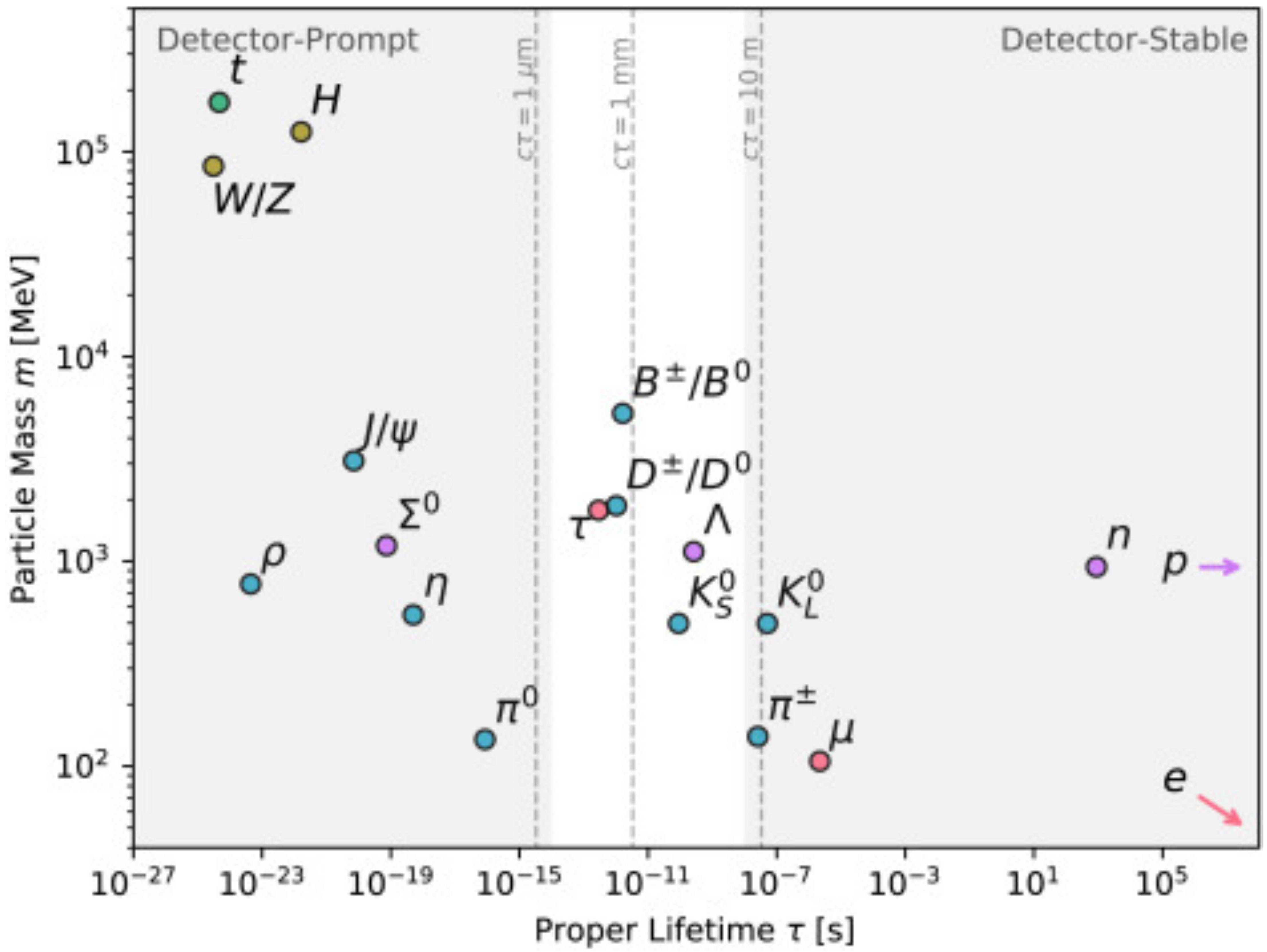
- What are long-lived particles and what generates larger lifetimes?
- Why are searches for long-lived particles difficult?
- 5 intriguing analysis results on full Run2 data

Long-lived particles in SM

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

- $\frac{1}{\tau_{\pi^+}} = \Gamma_{\pi^+} \approx g_W^2 (\frac{m_{\pi^+}}{m_W})^4 \, m_\pi$
- small decay width -> large lifetime
- helicity suppressed decay -> smaller phase space
- off-shell, virtual W -> large m_W





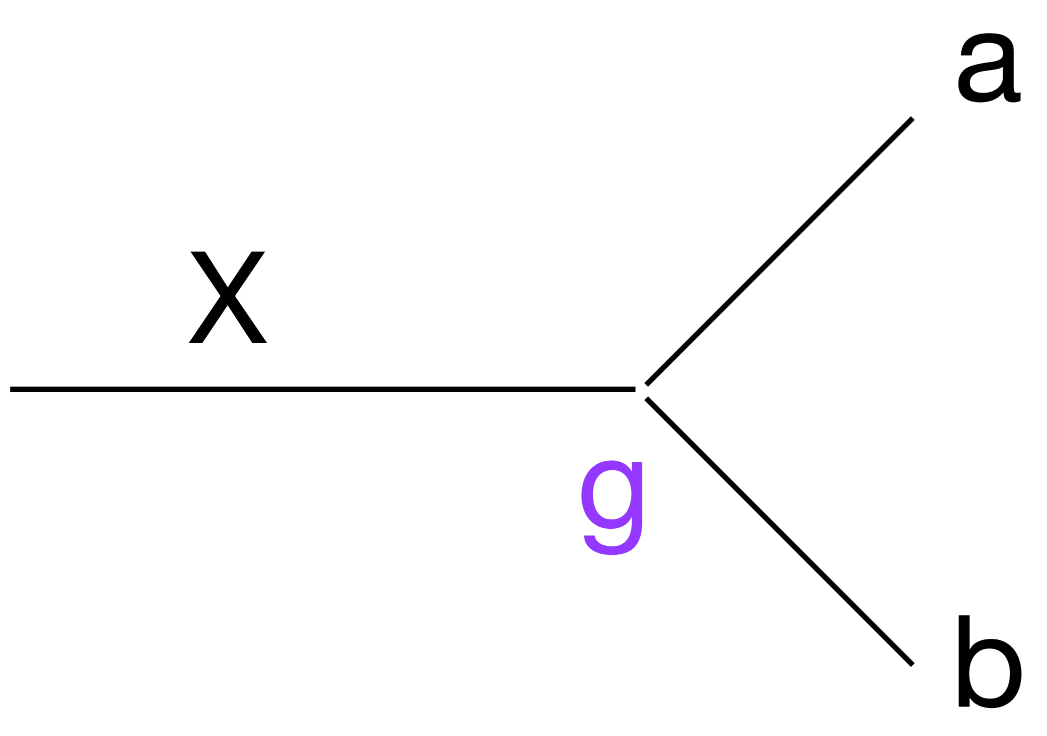
Long-lived particles in BSM

- fewer possible decay modes

$$\tau = \frac{1}{\sum_{decay\ modes} \Gamma_{decay\ mode}}$$

- small coupling constants
- off-shell mediator
- less phase space (suppression, small mass-splitting)

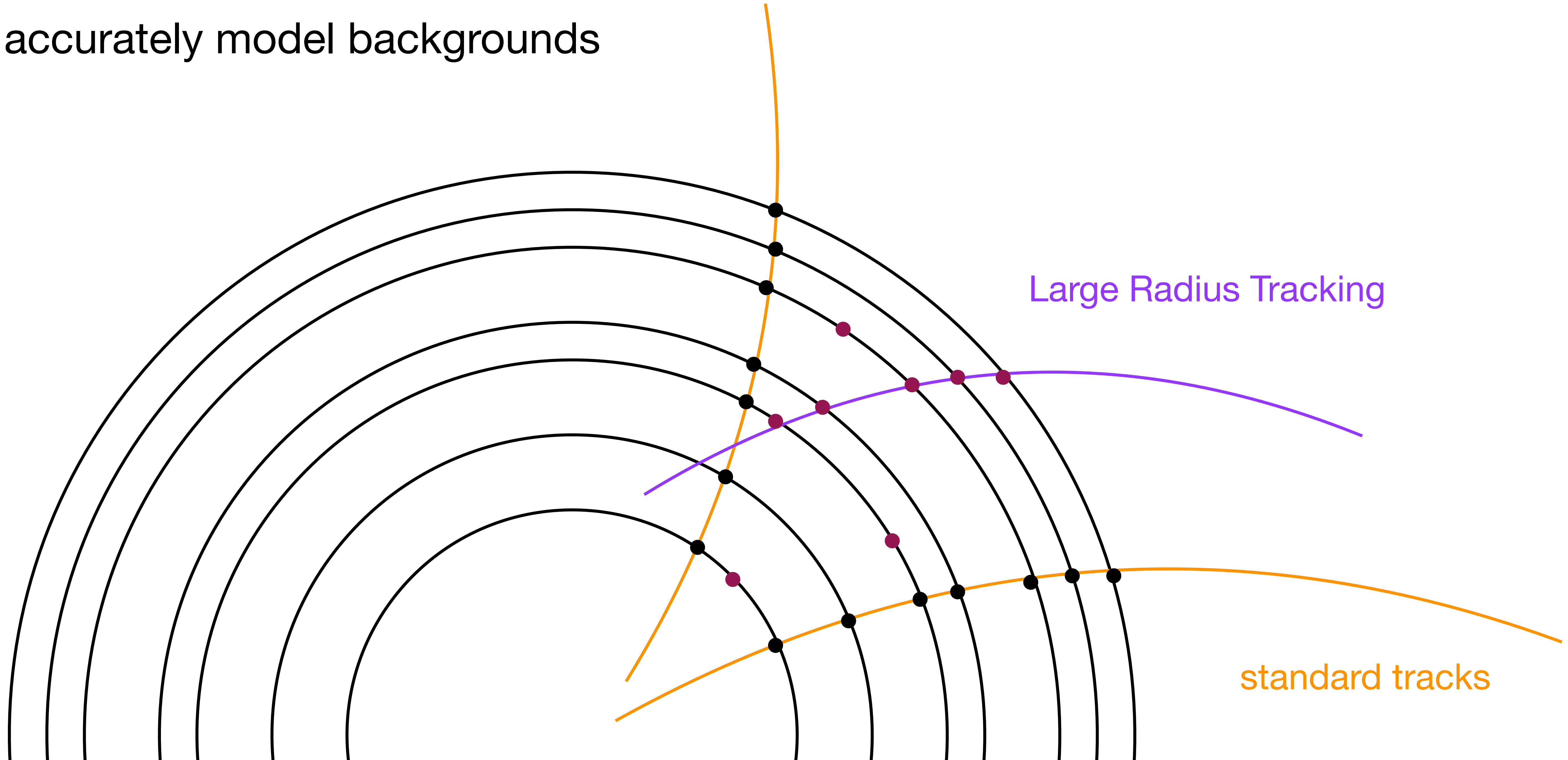
$$\Gamma_{decay\ mode} \propto \frac{|\vec{p}\,|}{m_X} |M|^2 \propto \frac{\sqrt{(m_X^2 - m_a^2)^2 + (m_X^2 - m_b^2)^2 - m_X^4 - 2m_a^2 m_b^2}}{m_X^2} |M|^2$$



$$\Gamma_{decay\ mode} \propto |M|^2 \longrightarrow M \propto g$$

Long-lived particles in ATLAS
What makes these searches difficult?

- ATLAS was designed to detect particles and their decays that originate from interaction point
  - SM LLPs have well understood experimental signatures
- BSM LLPs have unusual signatures
  - excellent prospects for discovery
  - standard reconstruction algorithms may reject the events
  - atypical signatures resemble noise, pile-up, mis-reconstruction
- the rarity of such mis-reconstruction, MC simulations may not accurately model backgrounds
- Solution:
  - use innovative trigger strategies
  - custom reconstruction
  - ML for background elimination
  - fully data-driven background estimation techniques

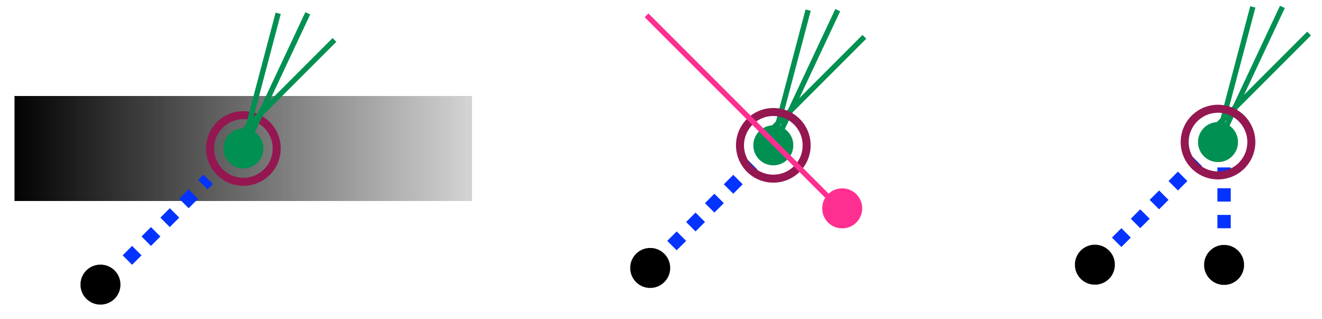


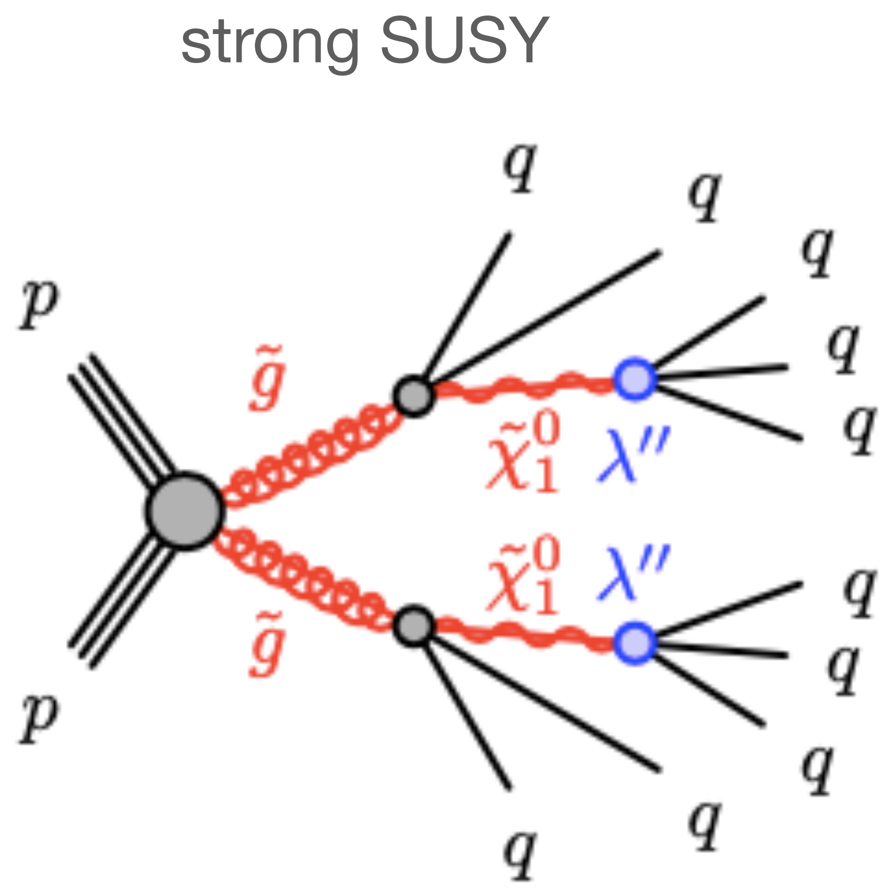
Displaced vertex + jets

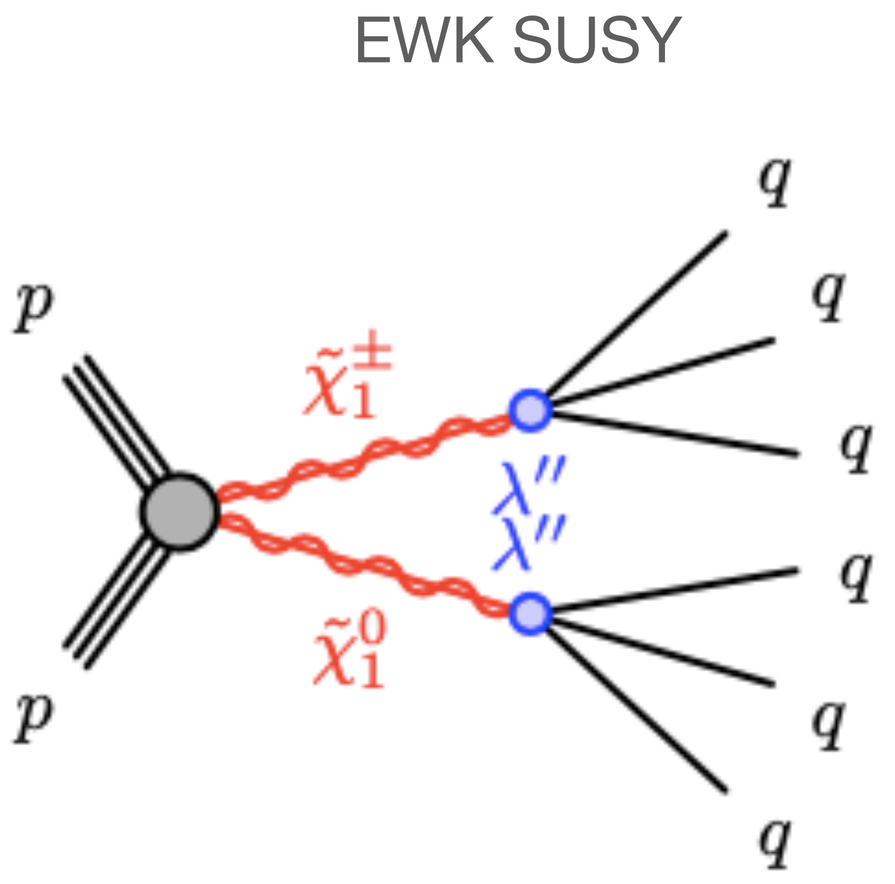
[CONF note]

Analysis overview and Run2 improvements

- benchmark models are SUSY scenarios:
  - neutralino $\tilde{\chi}^0$ decaying via small RPV coupling to three SM quarks
  - production via gluinos $\tilde{g}$ that each promptly decay to two SM quarks and $\tilde{\chi}^0$
- no SM processes that produce high-pT jets and a massive, multi-track displaced vertex
- background sources:
  - hadronic interactions in detector material
  - accidental crossings
  - merged vertices







- previous searches required different signatures with the displaced vertex
- previous searches required two displaced vertices
- improvement in the vertex finding algorithm and bkg. estimation

Event selection

- one displaced vertex and jets, no requirement for them to be linked
- LRT is computationally expensive
- two filters: trackless jet and high-pT jet

Signal regions

High-pT SR

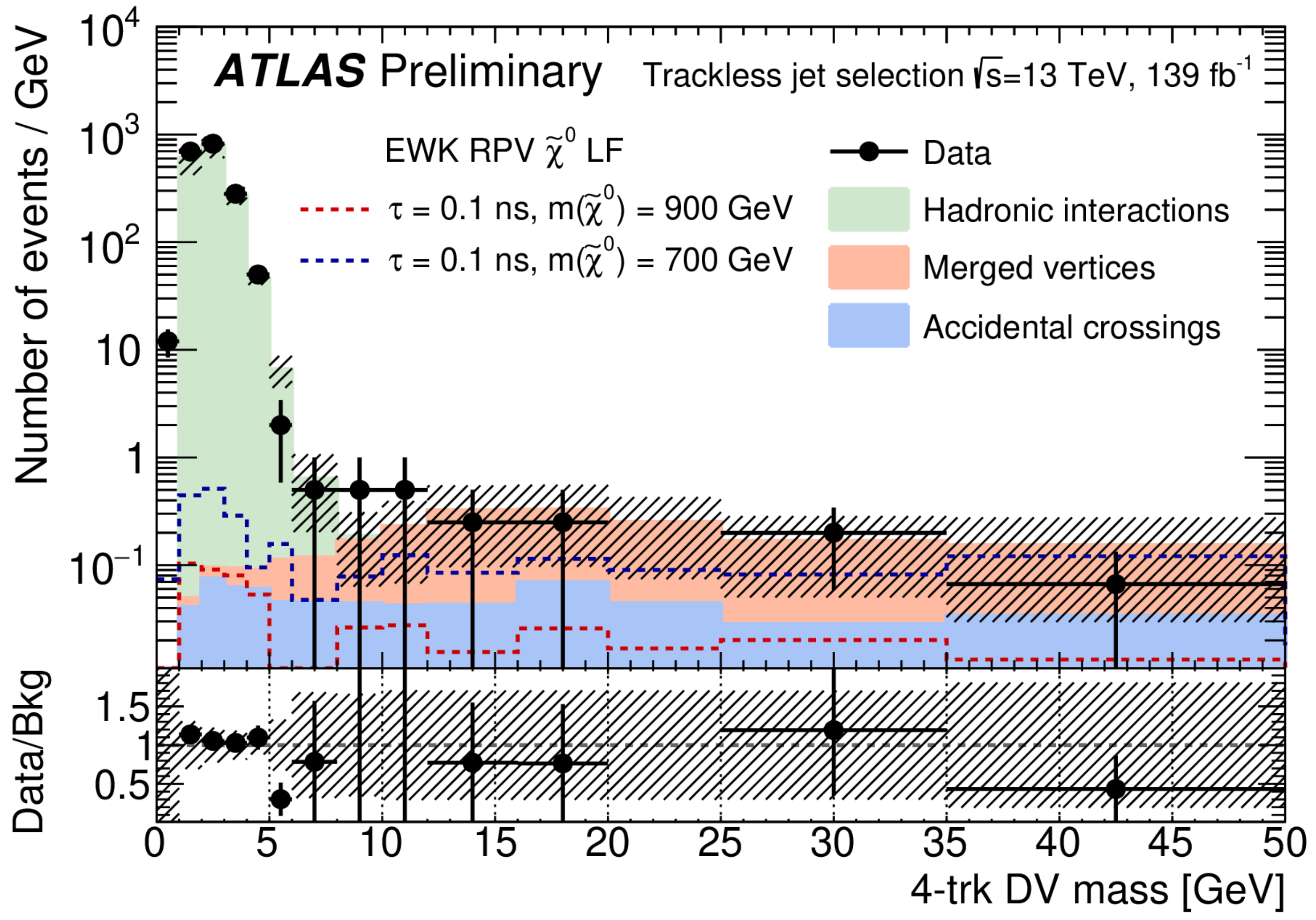
- pass high-pT jet selection
- at least one DV passing full DV selection

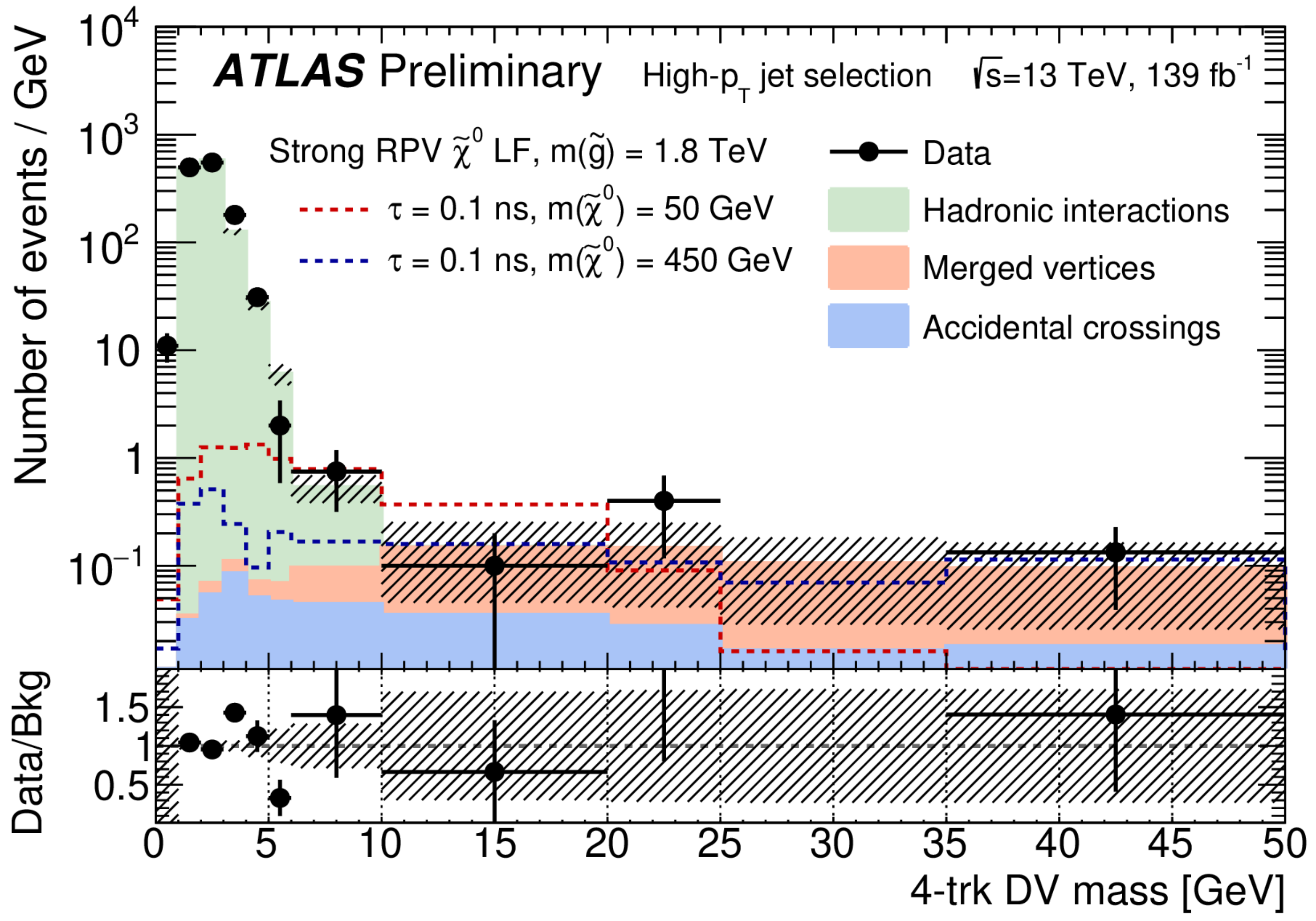
Trackless SR

- pass trackless jet selection
- fail high-pT jet selection
- at least one DV passing full DV selection

Background estimation

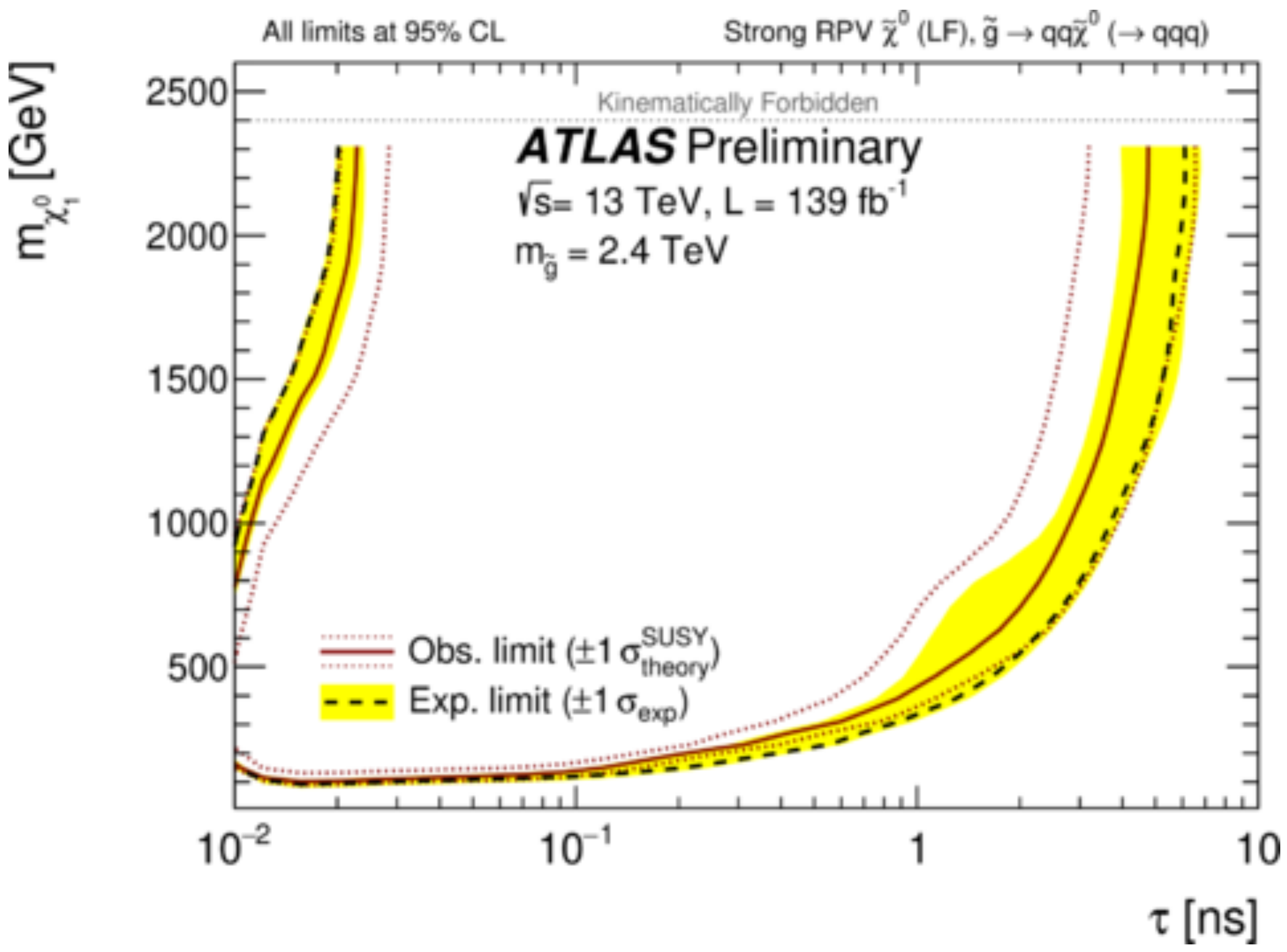
- fully inclusive data driven bkg. estimate
- relies on assumption that in a multijet final state, DV production is correlated to presence of jets
- done in two steps:
    1. calculate probability of a SR-like DV is produced in proximity to a jet using track jets in CRs
    2. apply probability to track jets in events passing event-level SR selection

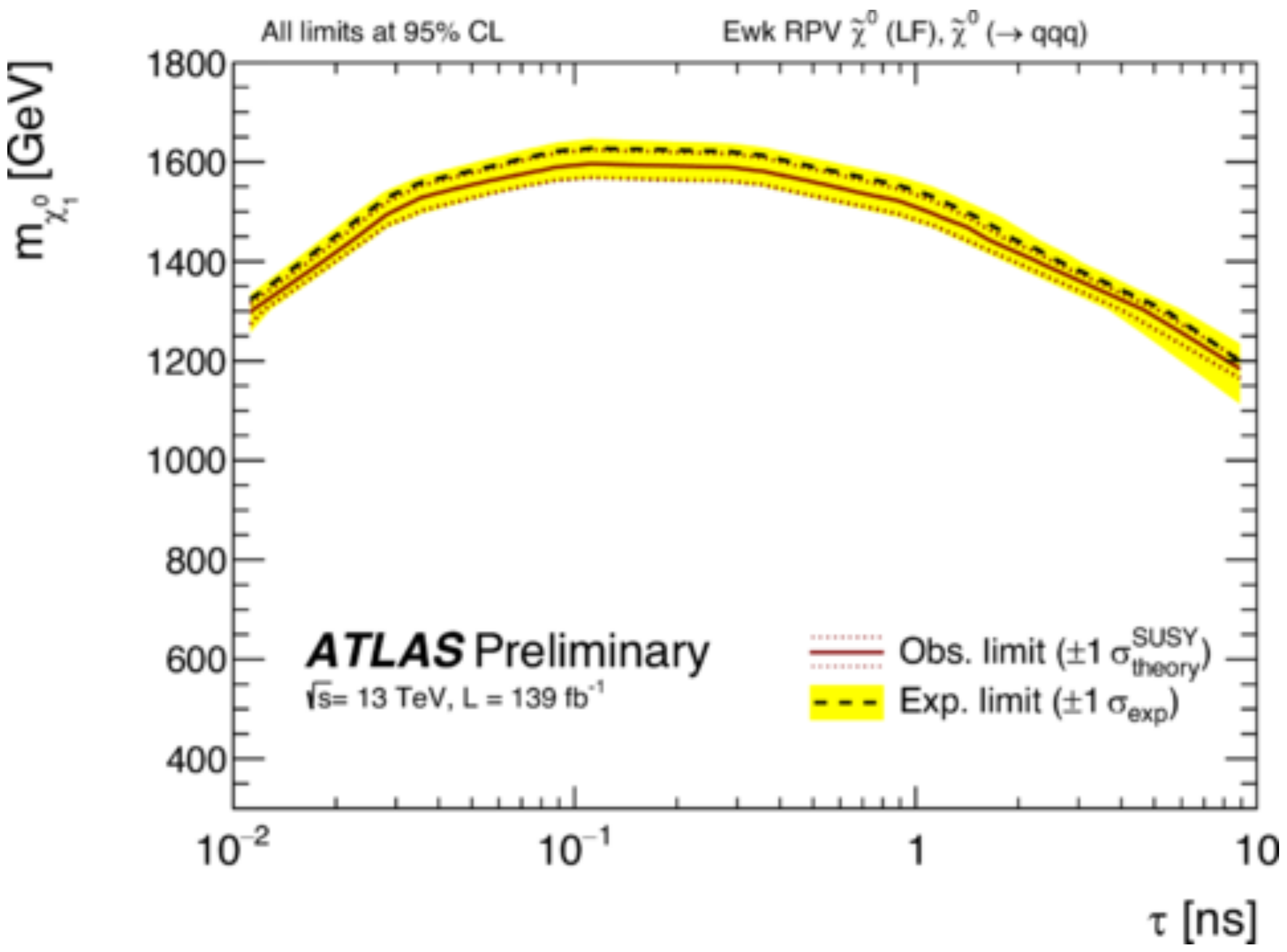




Results

- observation consistent with the background-only hypothesis
- exclusion limits derived for several R-parity-violating SUSY models with long-lived neutralinos





Non-pointing and delayed photons

Non-resonant [paper]

Resonant [CONF Note]

Analysis overview and Run2 improvements

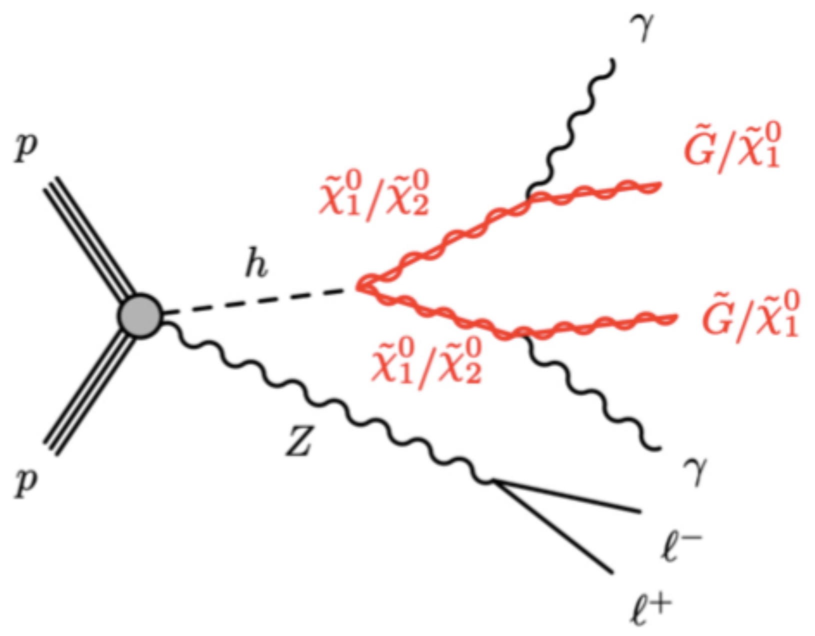
Non-resonant

- benchmark model is a SUSY scenario:
  - SM higgs decay to NLSP which decays to LSP and photon
  - associate production of SM Higgs with W,Z or top-antitop system
- NLSP lifetime is a free parameter
- associate production due to E_T^{photon}, E_T^{miss} not large enough for triggering

Resonant

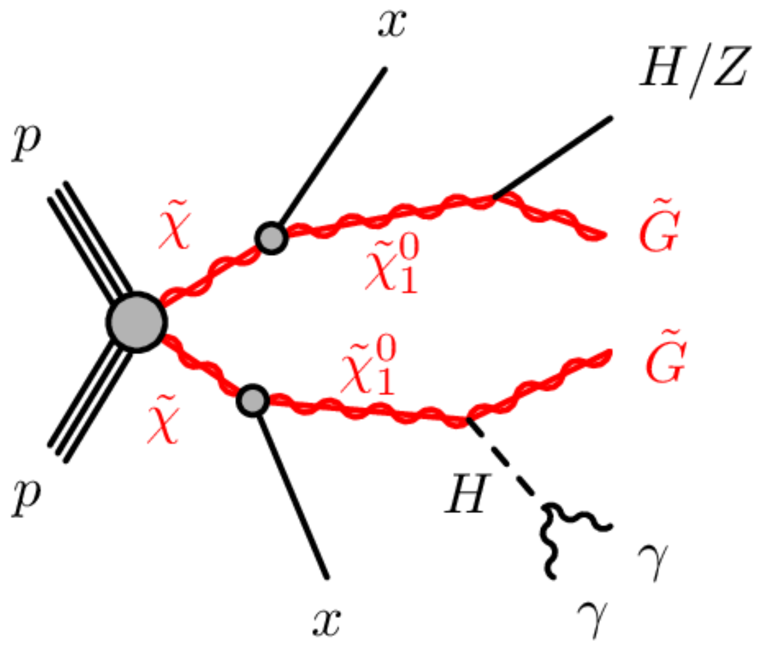
- benchmark models is a SUSY scenarios:
  - pair production of SM EW SUSY partners
  - each decaying to to NLSP and SM particle
  - NLSP decaying via $\tilde{\chi}_1^0 \rightarrow H/Z + \tilde{G} \rightarrow \gamma\gamma/ee + \tilde{G}$
- weak coupling of NLSP to the gravitino LSP
- no SM process produces a displaced diphoton vertex with significant invariant mass

- background sources:
  - real prompt photons
  - fake photons (electrons or jets faking photons)



- previous Run1 searches focused on prompt photons
- previous Run1 search focused on VBF production
- no previous ATLAS search with this exact signal

- no previous ATLAS search with this exact signal
- previous searches without vertex requirements

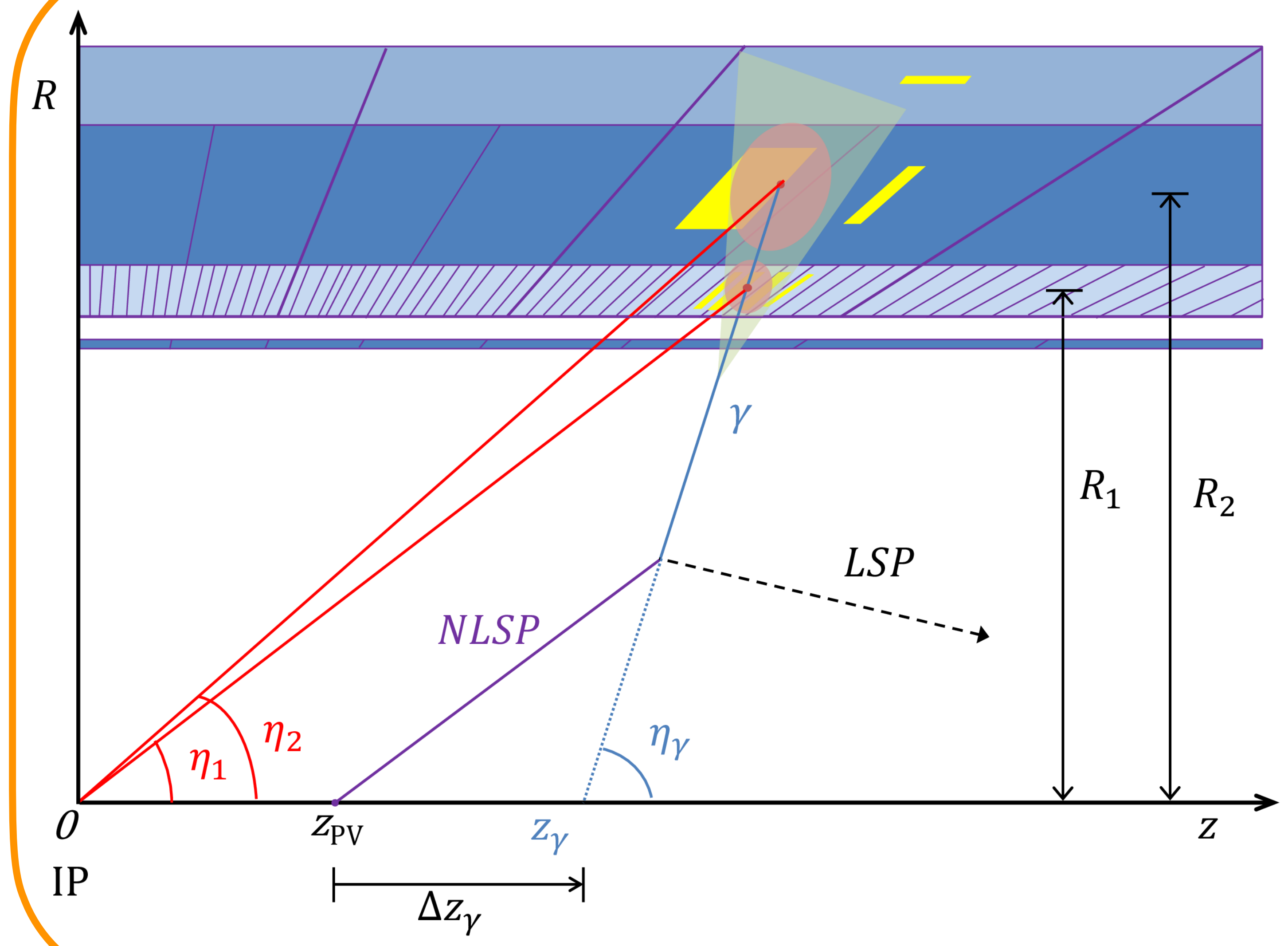


Timing measurement

- arrival time of EM objects measured using second-layer EM calo cell with largest eng. deposit

Non-resonant

Pointing measurement



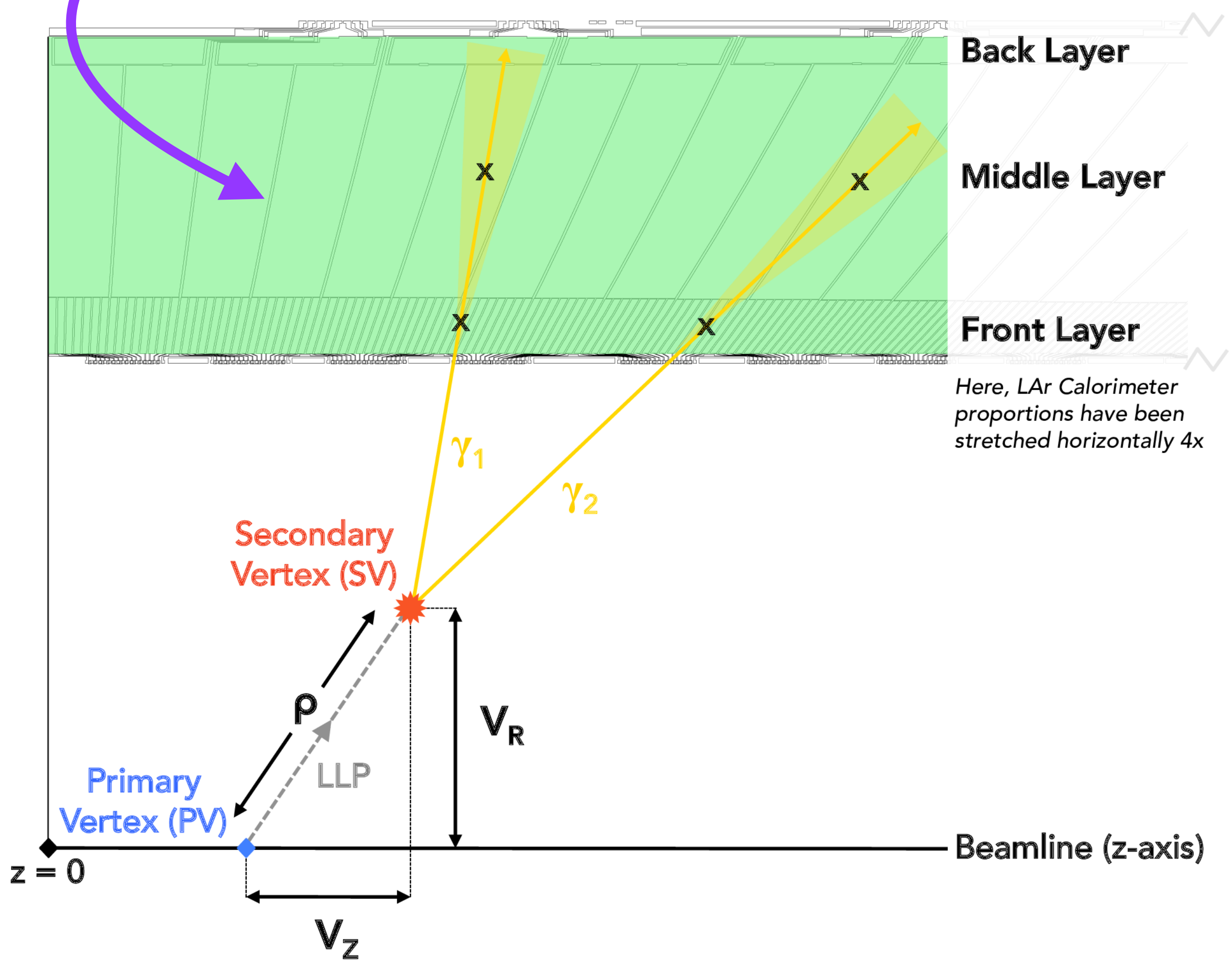
- measuring the centroids of the EM shower in first and second EM calo layers
- $\Delta z_\gamma = z_\gamma - z_{PV}$

Fitting procedure

- 1photon and 2photon channels
- likelihood fit is performed over timing distribution in non-overlapping categories of $|\Delta z_\gamma|$

Resonant

Pointing measurement



- intersection of the two photon paths determined by pointing defines the location of reconstructed secondary vertex

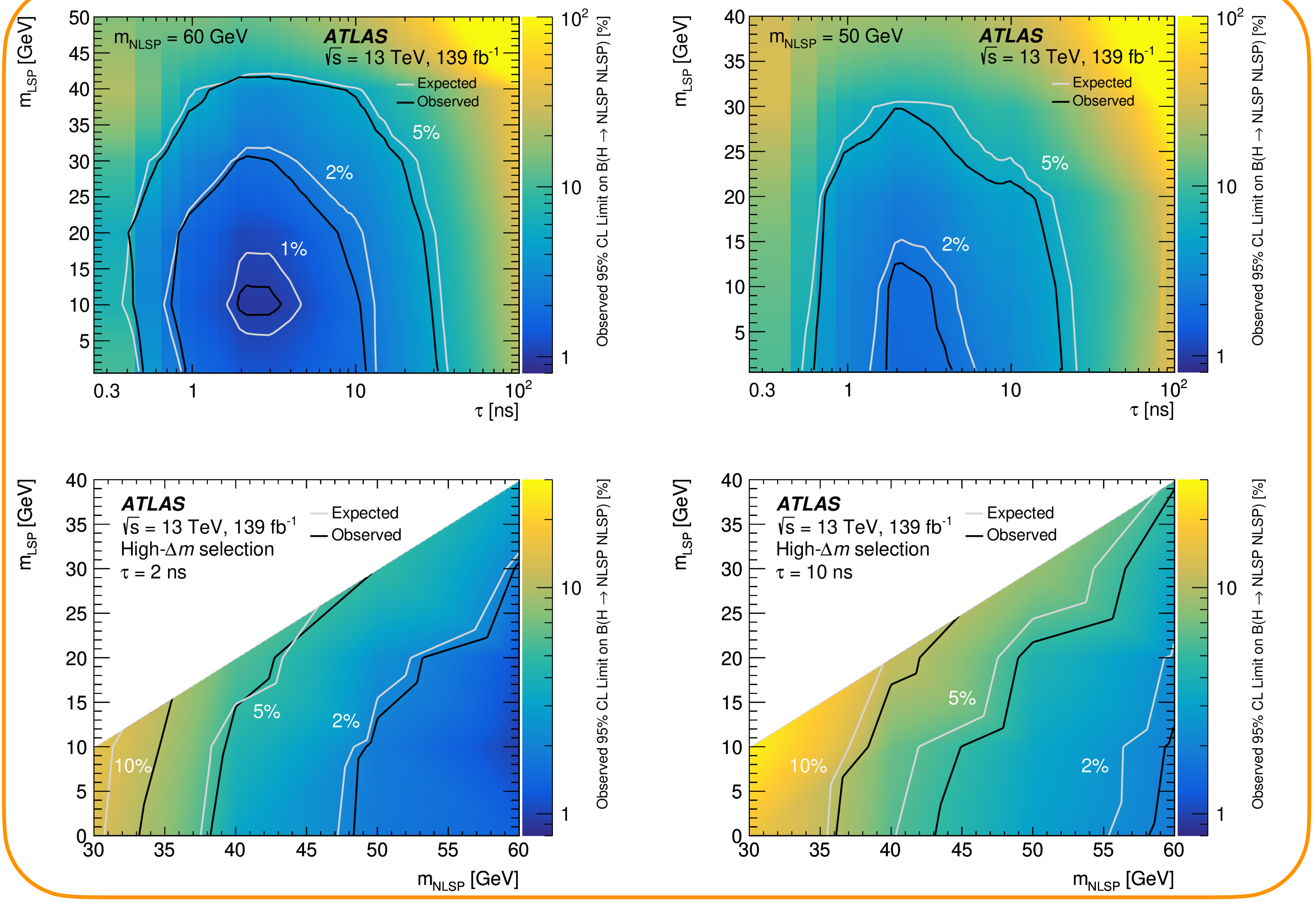
Fitting procedure

- $t_{avg} = (t_{\gamma_1} - t_{\gamma_2})/2$
- likelihood fit is performed over t_{avg} distribution in non-overlapping categories of ρ, where $\rho = \sqrt{v_r^2 + v_z^2}$

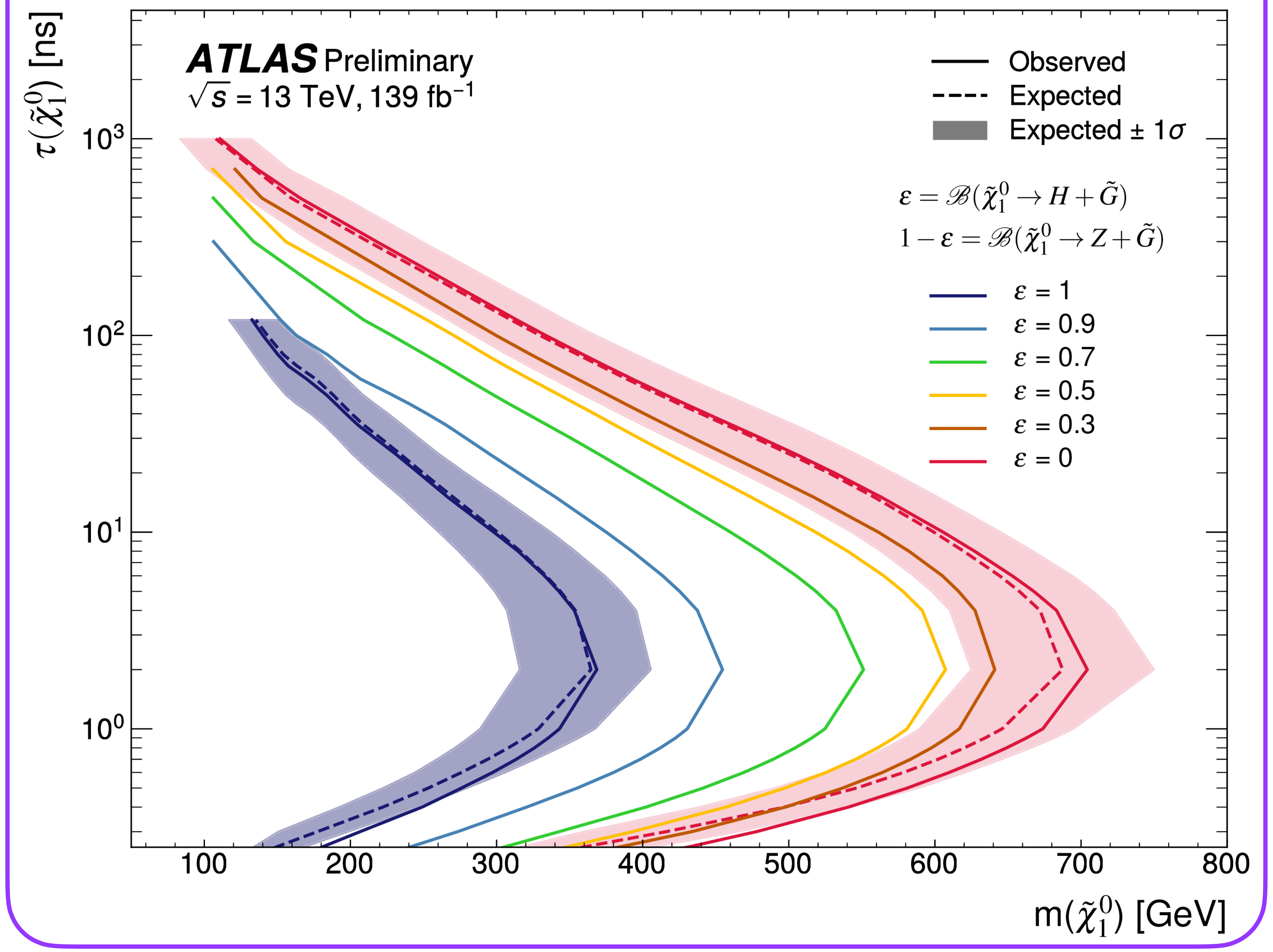
Results

- no significant excess over the expected background

Non-resonant

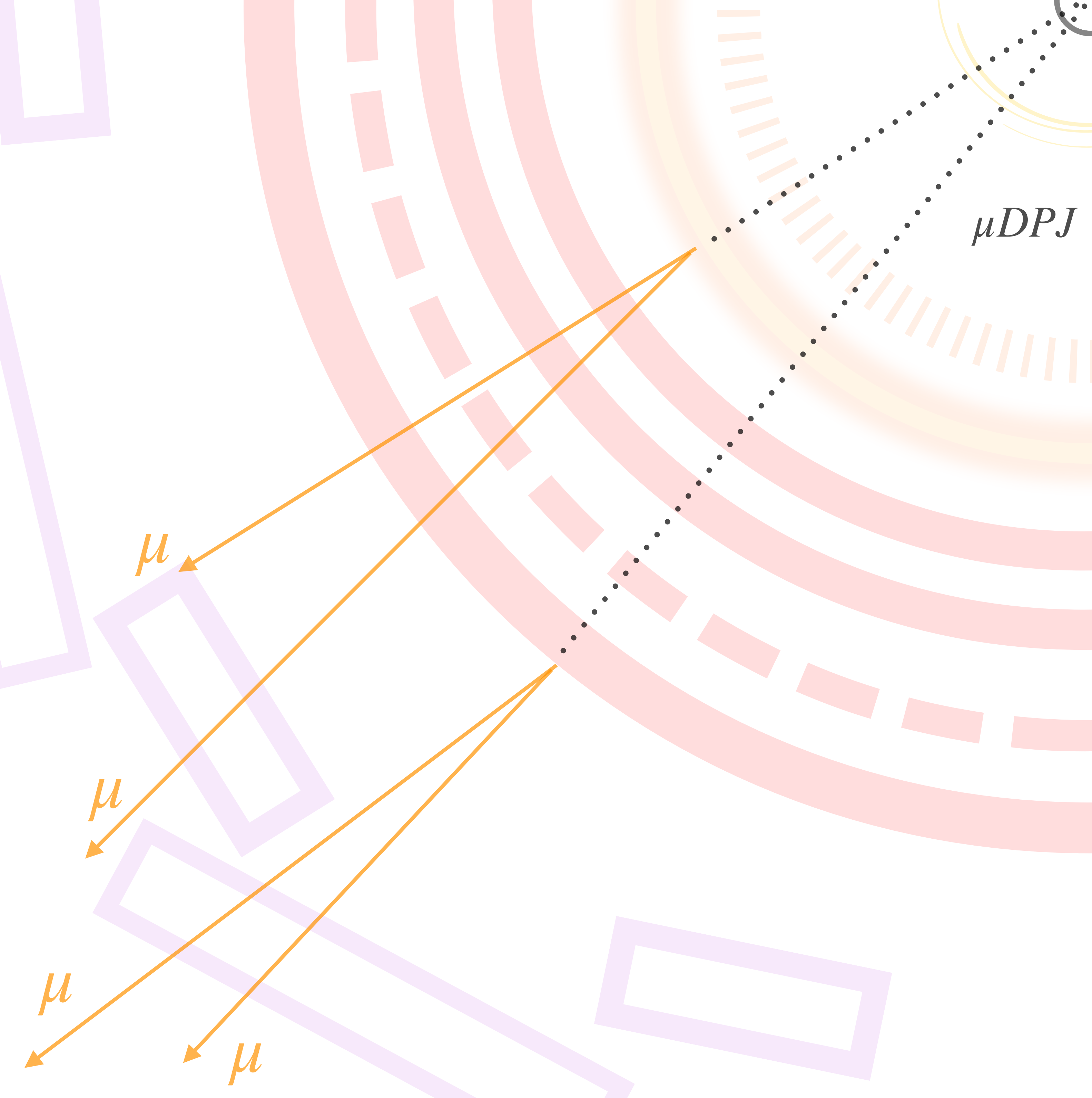


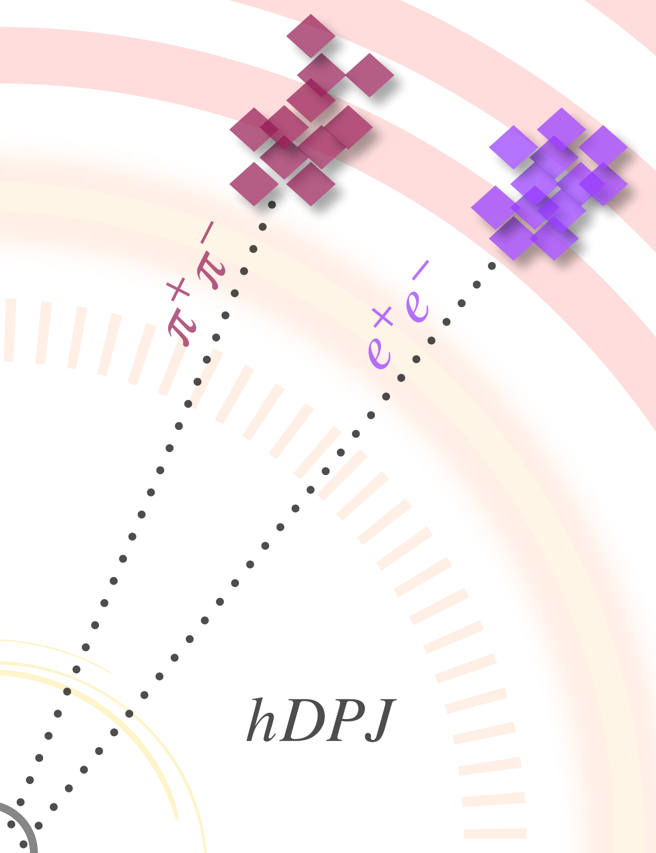
Resonant



Displaced collimated pairs of leptons or light hadrons

[paper]



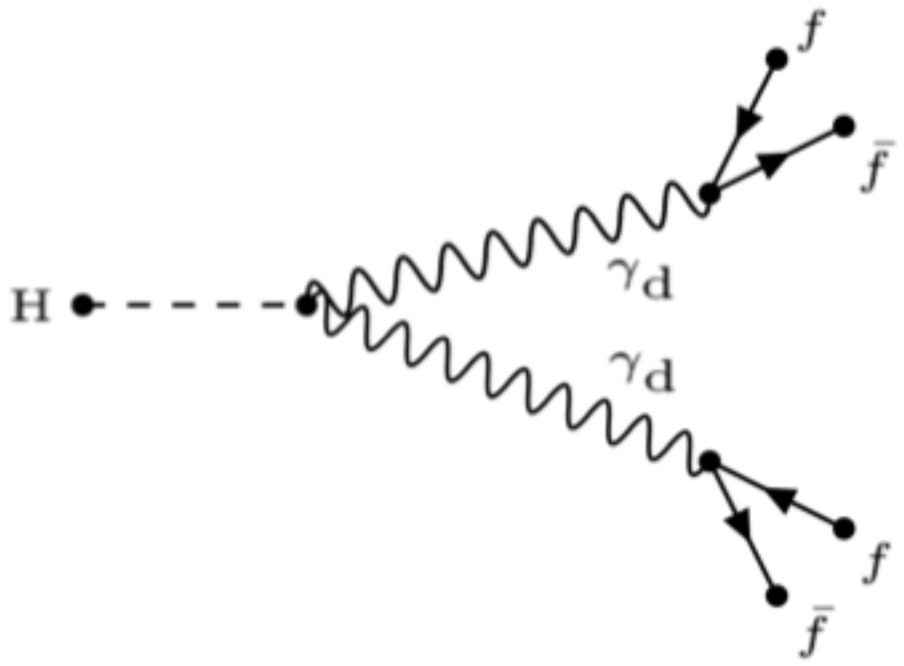


Analysis overview and Run2 improvements

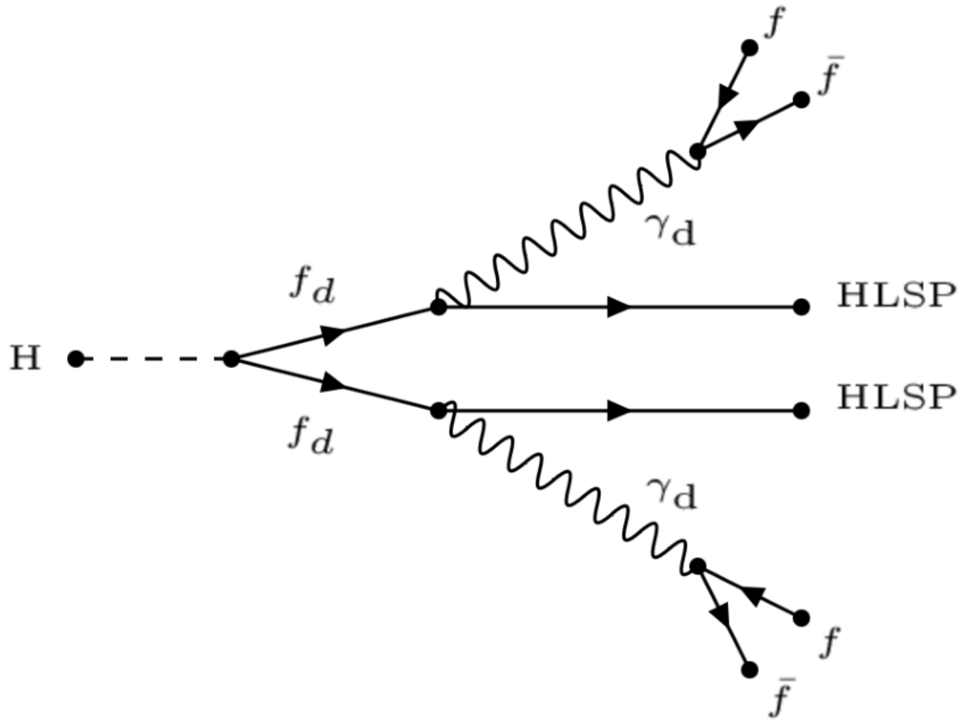
- dark sector weakly coupled to SM via vector portal
- dark photon mixes with SM photon and decays to SM leptons and light quarks;

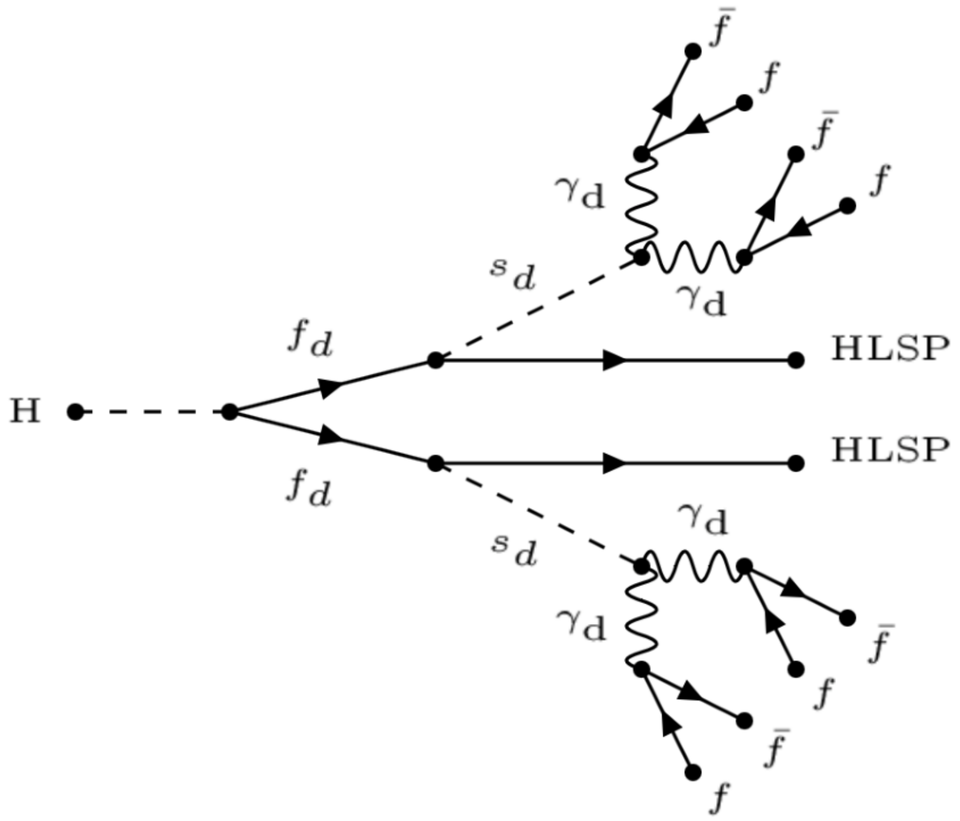
$$\tau \propto (\frac{10^{-4}}{\epsilon})^2 (\frac{100\ MeV}{m_{\gamma_d}})^2\ [s]$$

$$\epsilon < 10^{-5},\ MeV < m_{\gamma_d} < 15\ GeV$$



- using ML techniques to reject majority of background processes
- outstanding background contributions are estimated using ABCD method



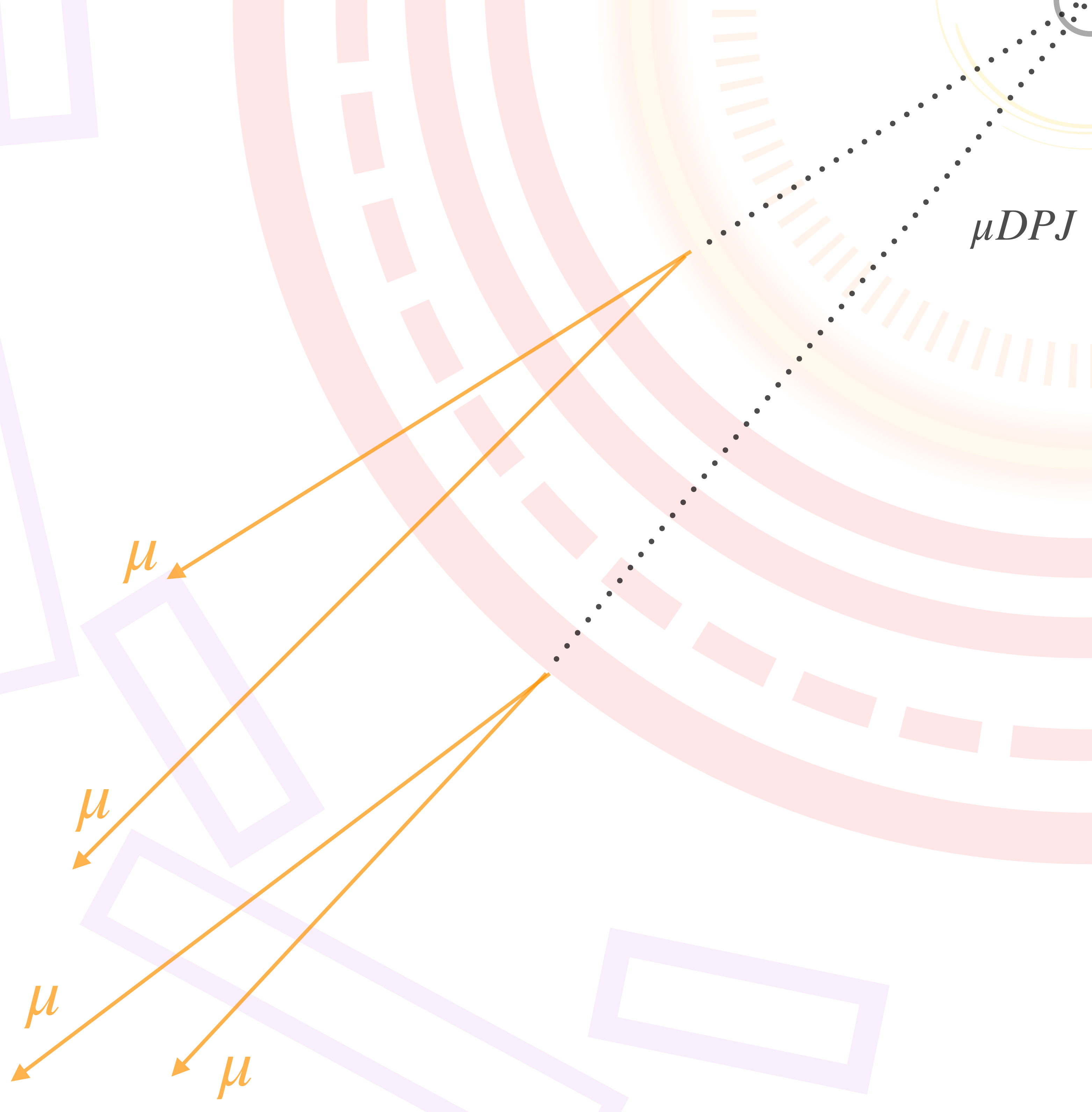


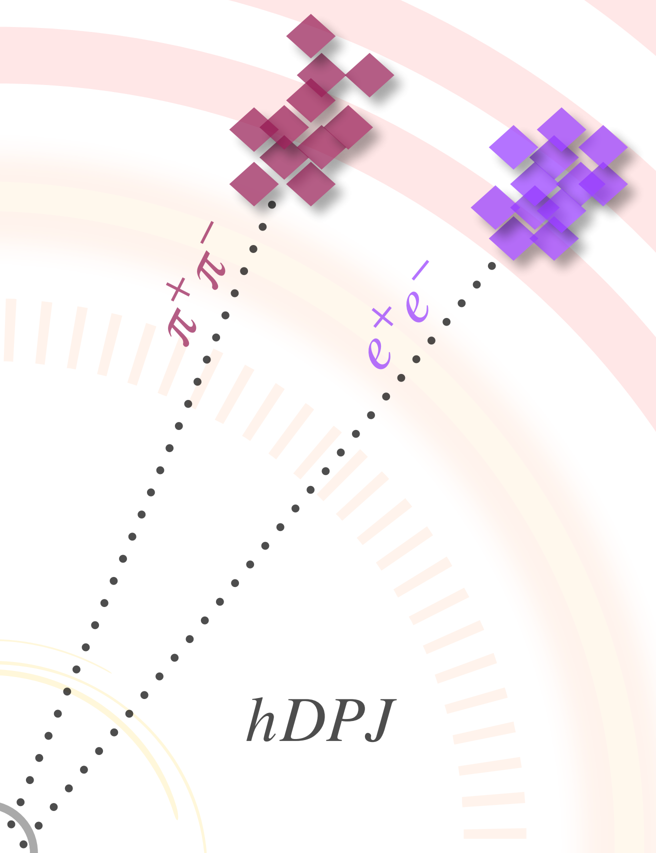
- overcoming the bottleneck of trigger selection
- considering an additional Higgs production mode: WH, making use of more efficient standard triggers
- making use of multi-muon and two dedicated LLP search triggers: Narrow-scan and CalRatio

Object definitions

μDPJ

- decays beyond the last pixel layer
- two or more collimated stand-alone MS tracks
- reconstructed using a clustering alg. seeded by highest pT muon
- main background source are cosmic-ray muons
- discriminated using DNN trained on cosmic dataset and MC





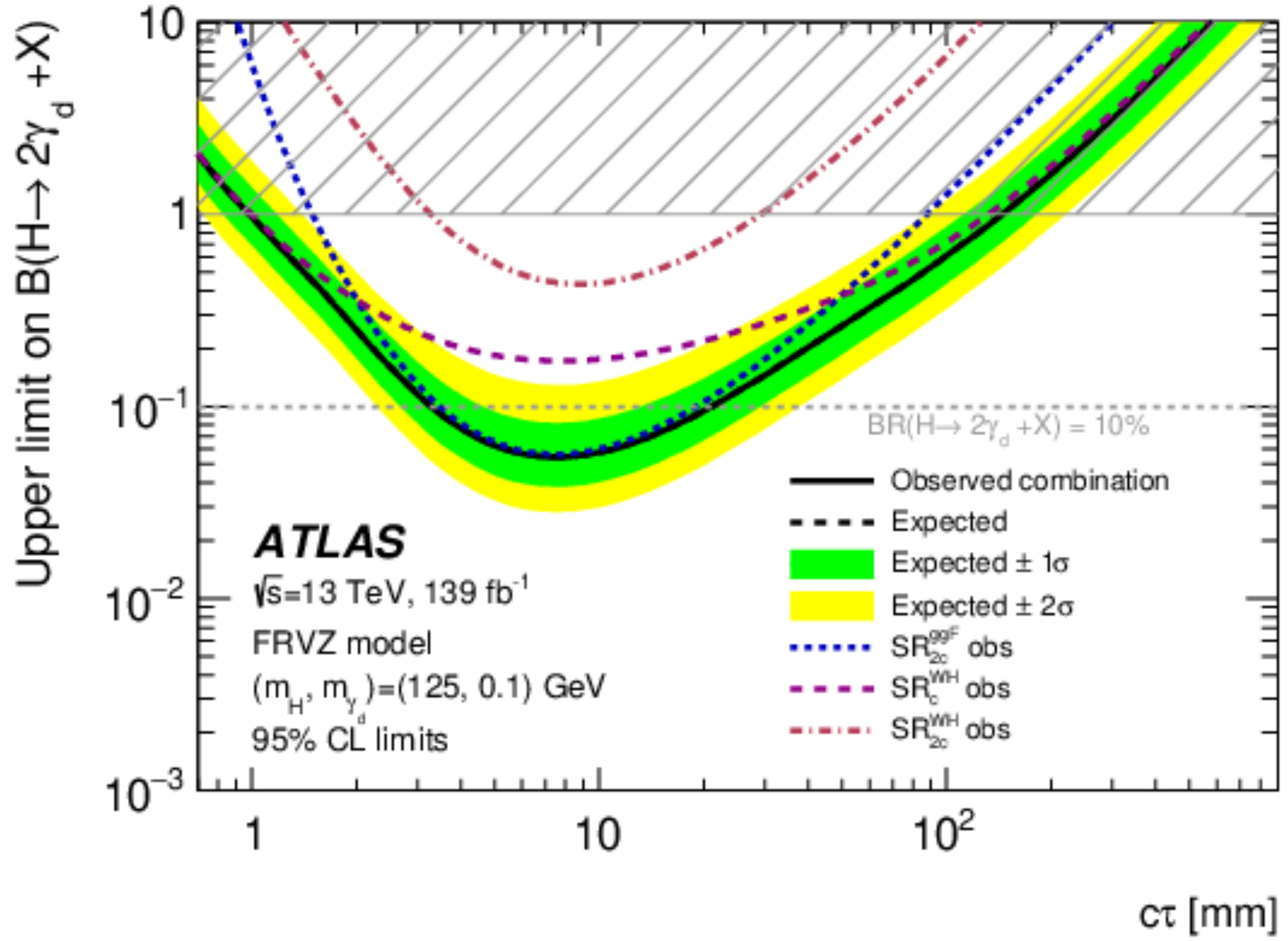
hDPJ

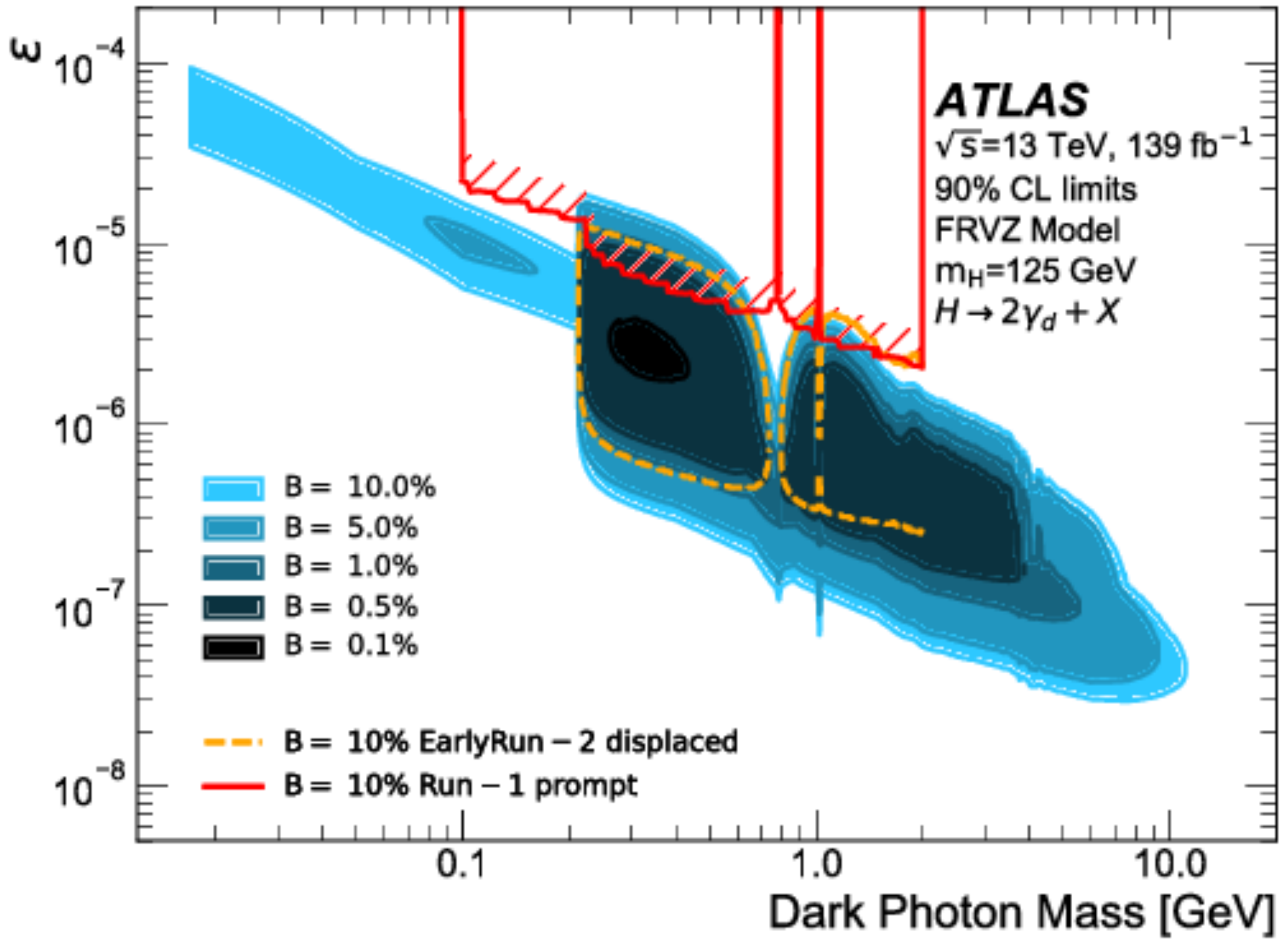
- jet with low EM fraction
- main background sources are rare QCD processes, cosmic rays and beam induced background
- discriminated using
  - cuts: tile gap ratio, timing cut, jet width, jet vertex tagger
  - QCD rejection using CNN trained on signal and QCD MC
  - BIB rejection using CNN trained on collision BIB dataset and signal MC

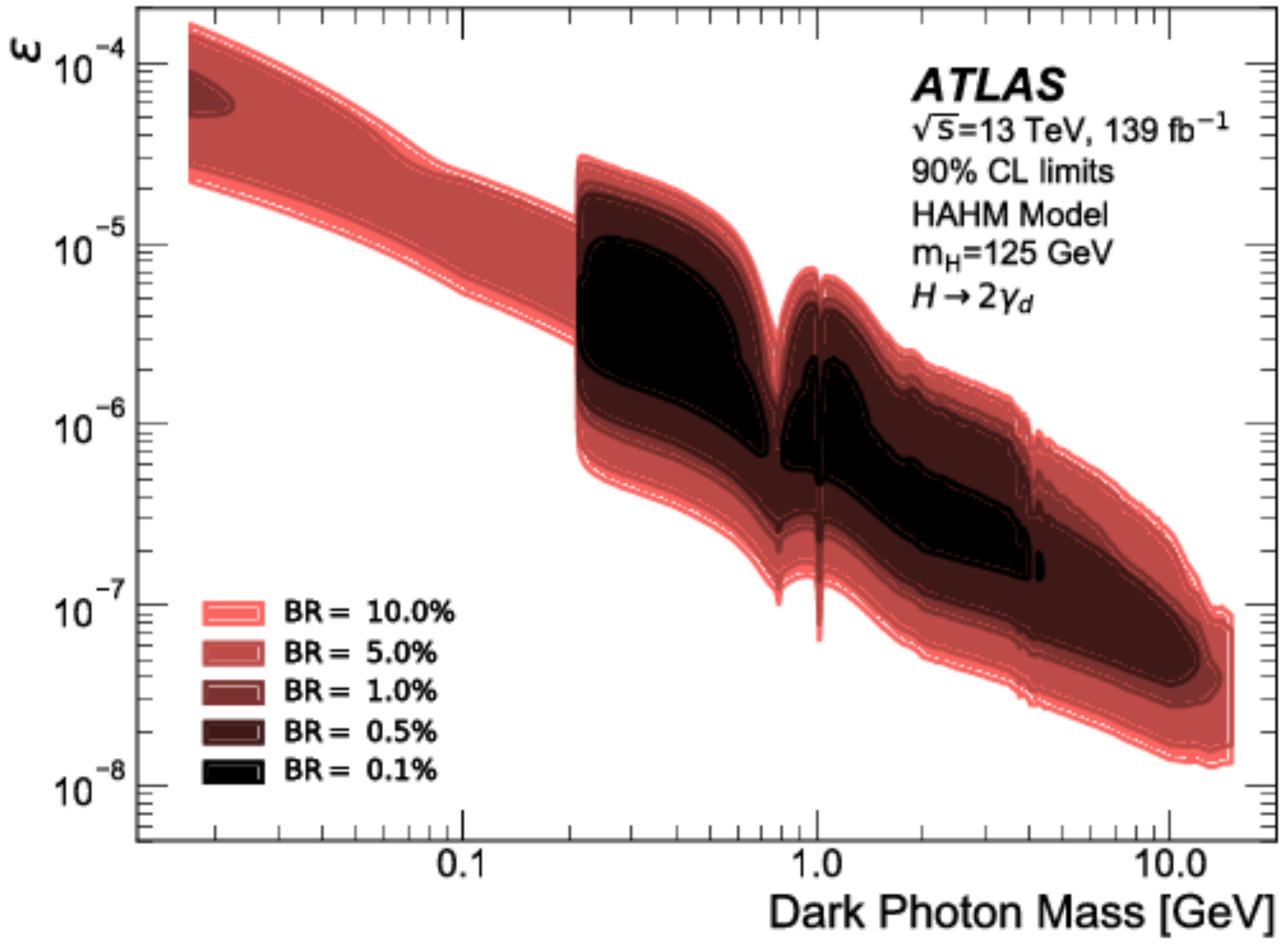
ggF		WH
• trigger: NarrowScan, CalRatio, $3\mu6$ msOnly • veto mJJ > 1 TeV and MET > 225 GeV • signal lepton veto	**Event selection**	• single lepton trigger • $\lesssim$ 3 jets with pT > 30 GeV • exactly one signal lepton • B-jet veto, veto mJJ > 1 TeV • MET > 30 GeV • mT (lepton-MET) > 40 GeV
• $2\mu DPJ$ • $hDPJ + \mu DPJ$ • $2hDPJ$	**Signal regions**	• $hDPJ$ • $hDPJ + \mu DPJ$ • $2hDPJ$
• ABCD method for multi-jet and cosmic-ray bkg. estimation • isolation in InDet • DPJ $\Delta\phi$ • NN tagger score	**Background estimation**	• ABCD method for V+jets bkg. estimation • $\Delta\phi(MET - DPJ)$ • NN tagger score

Results

- improve exclusion limits for γ_d masses and lifetimes across analysis channels
- set limits on BR for all channels for Higgs-like, Higgs and γ_d masses
- more stringent results for hDPJ:
  - combining the hadronic channels 1hDPJ and 2hDPJ in WH analysis
  - combining the hadronic channel 2hDPJ-ggF, 1hDPJ-WH and 2hDPJ-WH in both analysis







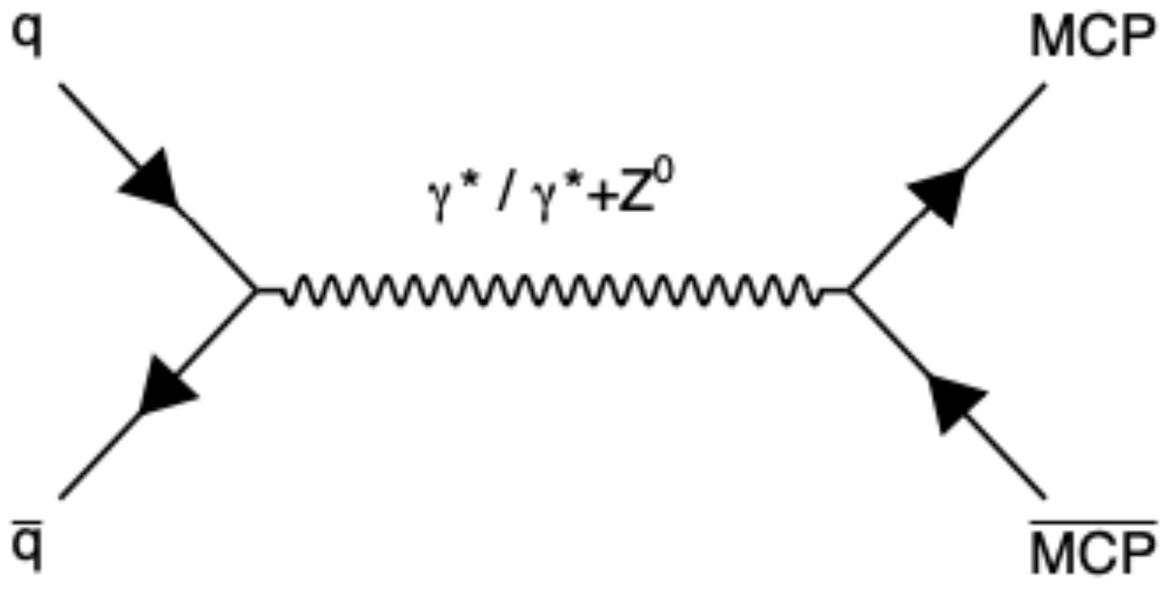
Multi-charged particles: MCP

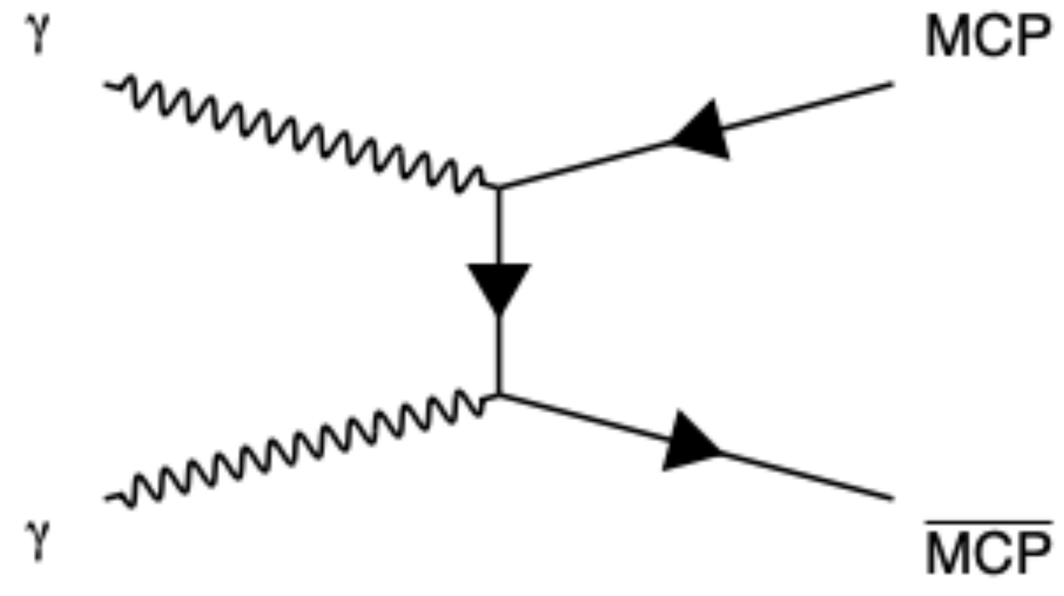
[CONF note]

Analysis overview and Run2 improvements

- MCPs predicted by several BSM theories to tackle DM compositeness question or adding new symmetries to SM
- signature is a muon-like object with high ionisation losses in both InDet and MS
- background sources:
    - muons with random ionisation fluctuations towards larger values
    - detector occupancy effects
    - δ -ray yields
    - radiation background
    - sporadic-noise events
- dE/dx measured in Pixel, TRT and MS

- inclusion of photon fusion production mode
- virtual boson exchange
- make use of new late-muon trigger





Event selection and bkg. estimation

- at least one combined muon
- triggers: single muon, E_T^{miss}, late-muon trigger
- at least 6 ‘good’ TRT hits
- ID track not in close proximity with another track
- additional tight selection for z = 2 candidates

ABCD parameters

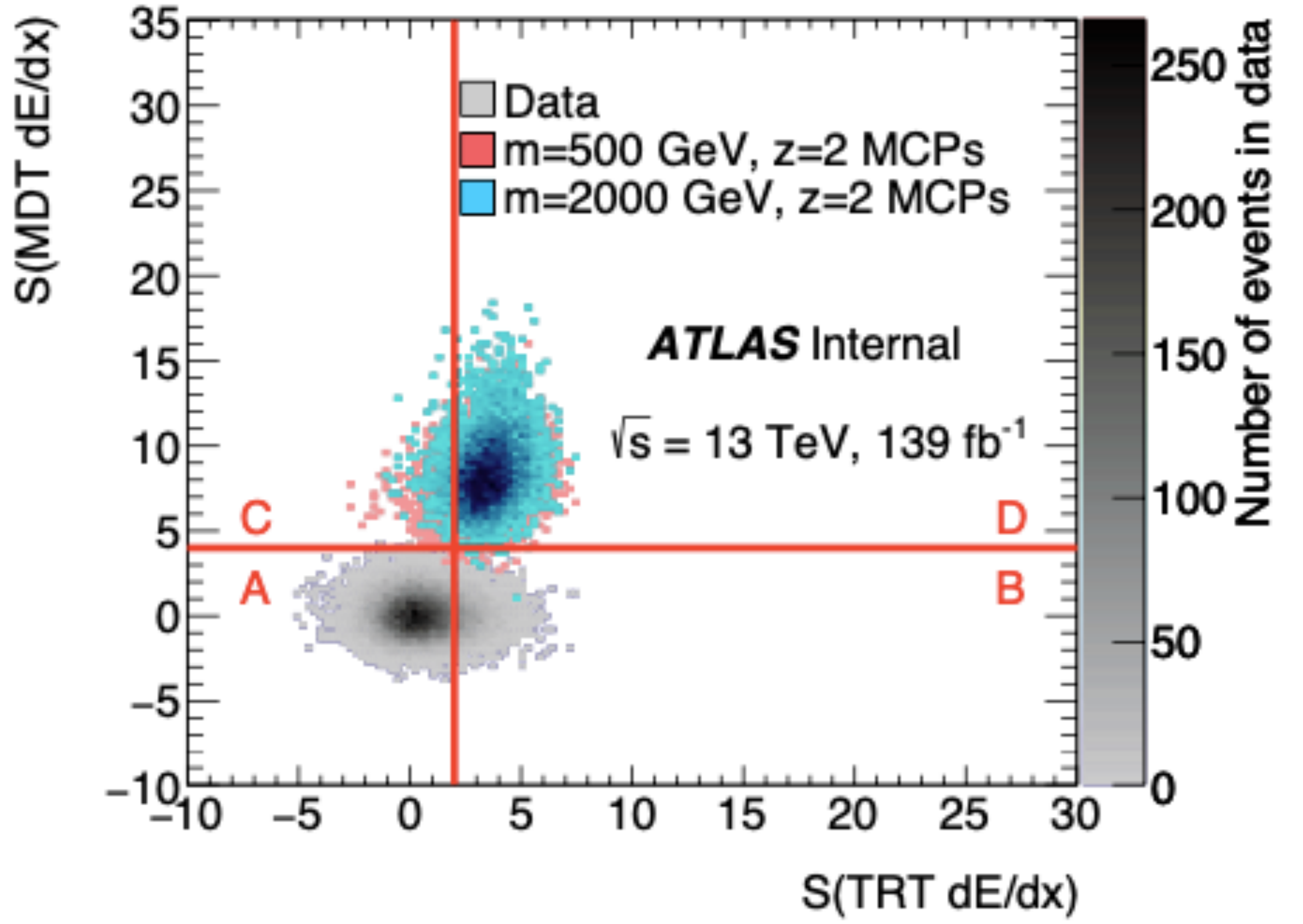
z = 2

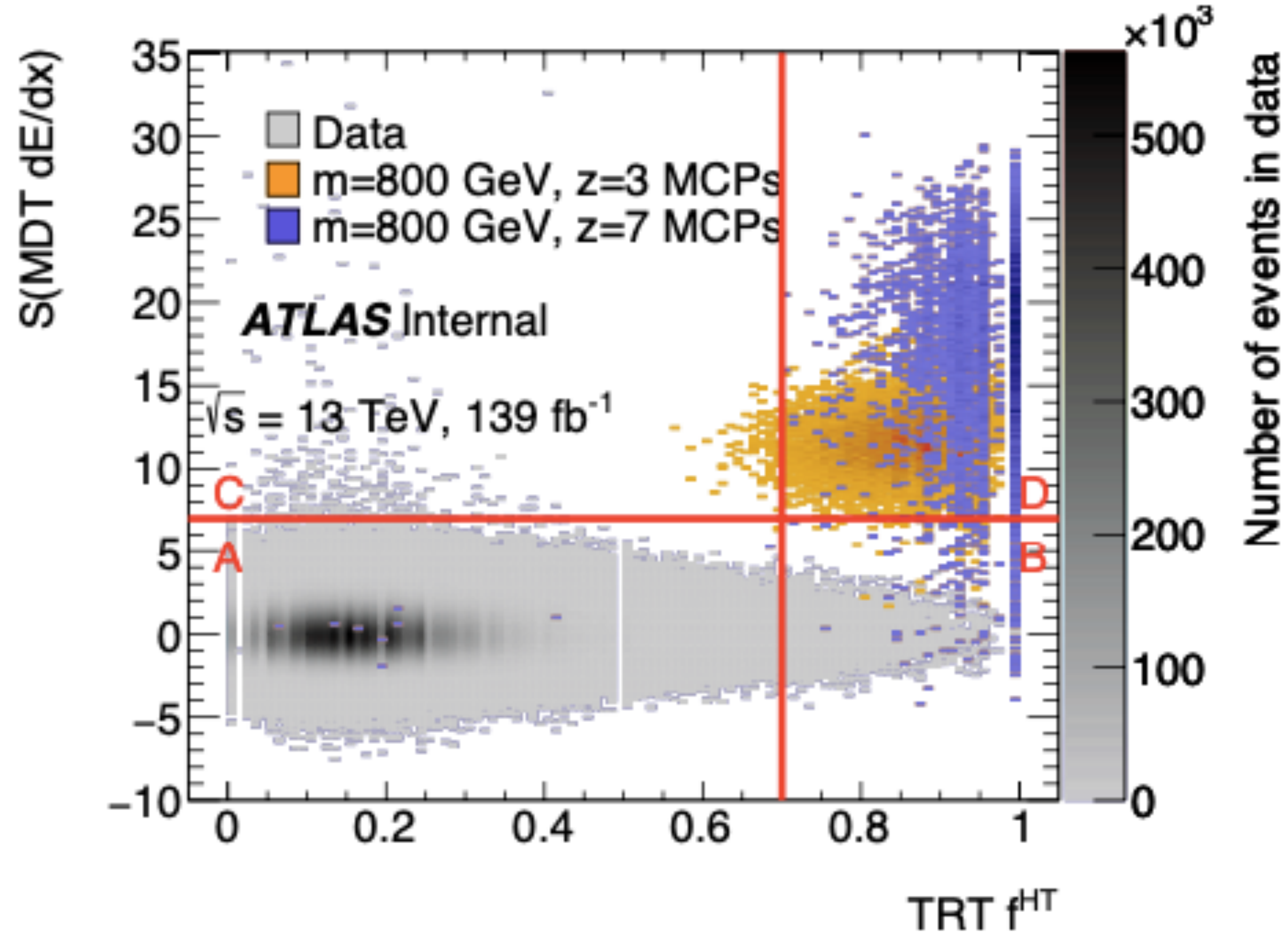
$S(TRT\ dE/dx) \geq 2.0,\ S(MDT\ dE/dx) \geq 4.0$

$$S(dE/dx) = \frac{dE/dx - \langle dE/dx \rangle_\mu}{\sigma(dE/dx)_\mu}$$

z > 2

$TRT\ f^{HT} \geq 0.7,\ S(MDT\ dE/dx) \geq 7.0$

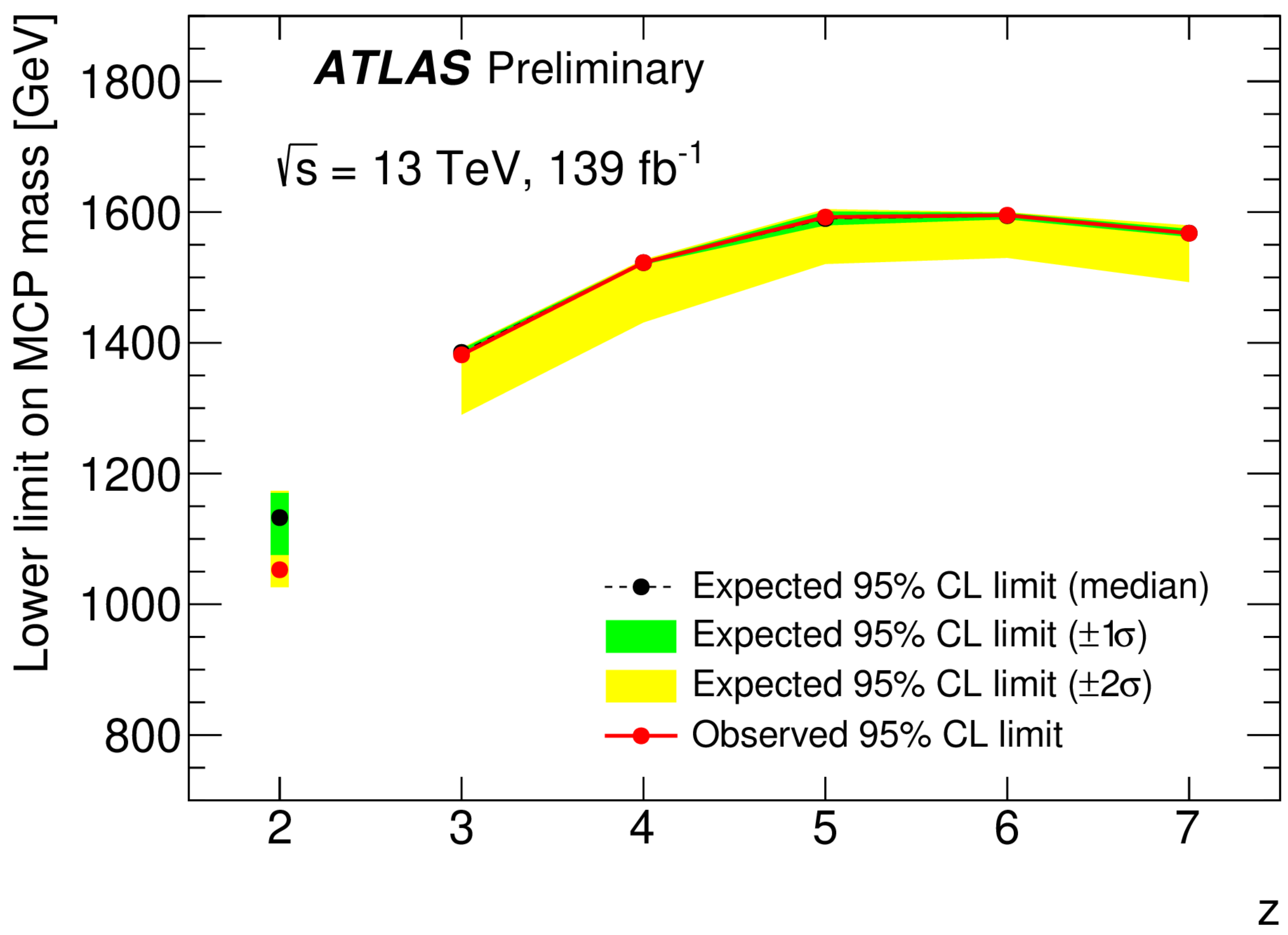


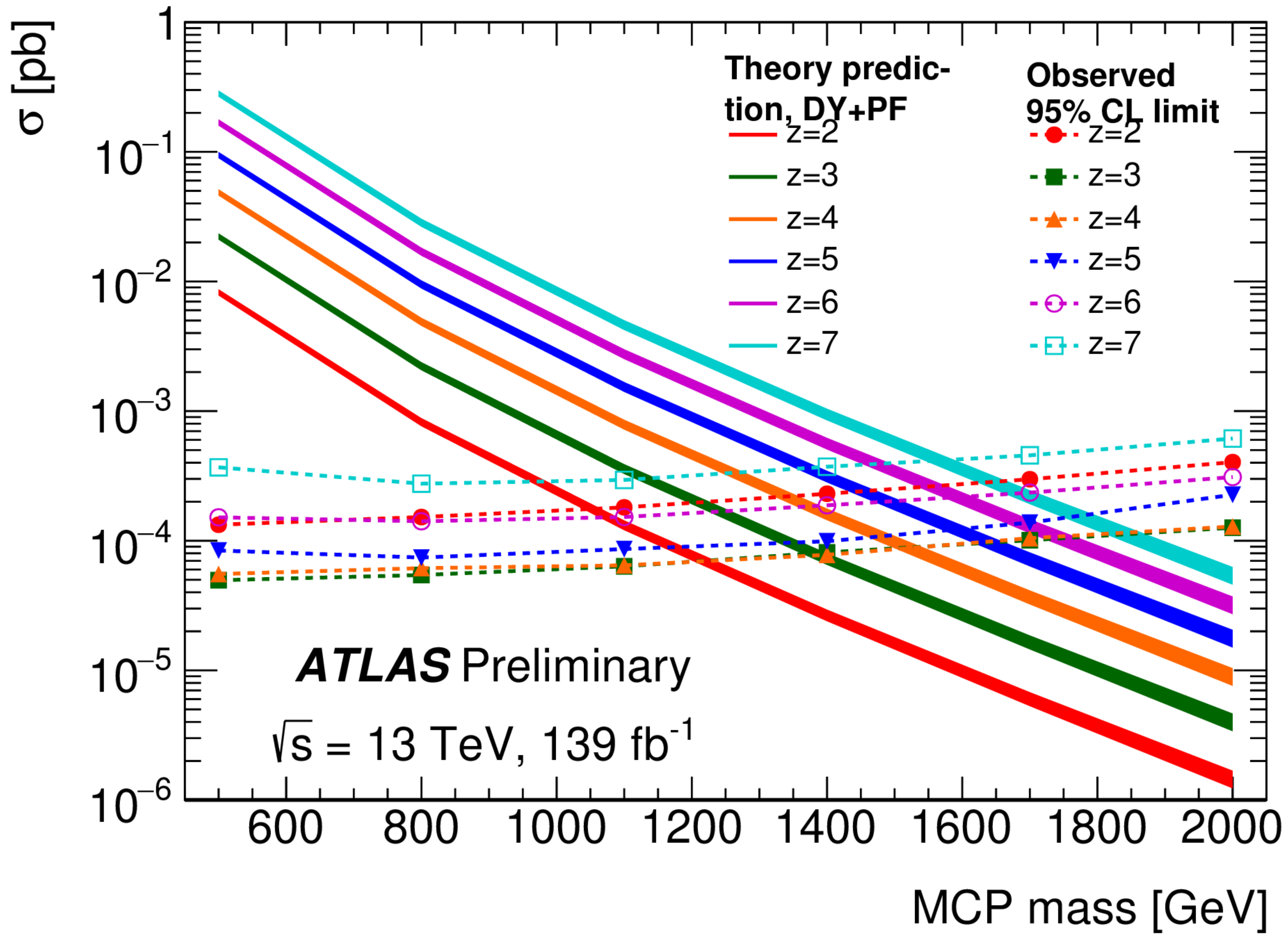


Results

- no significant excess observed
- limits set in cross section, mass and charge of new potential particles

Selection	$N_{data}^{A\ observed}$	$N_{data}^{B\ observed}$	$N_{data}^{C\ observed}$	$N_{data}^{D\ expected}$	$N_{data}^{D\ observed}$
$z = 2$	24 294	4039	9	1.5 ± 0.5 (stat.) ± 0.5 (syst.)	4
$z > 2$	192 036 934	15 004	441	0.034 ± 0.002 (stat.) ± 0.004 (syst.)	0





Summary

- In Run2 we searched for displaced vertices, displaced lepton / light hadron jets, non-pointing photons and multi-charged particles (this talk) among other interesting signatures [SUSY results] [EXOTICS results]
- no significant excess observed → stringent limits placed on BSM particles
- Run3 is here!
  - more statistics for rare decays
  - dedicated LLP triggers

Thank you for listening

Pixel dE/dx

- no significant excess observed in dE/dx analysis using pixel, TRT and MDT (MCP)
- similar ATLAS search using pixel dE/dx observed 7 events where 0.7±0.4 were expected [3.6σ local, 3.3σ global excess]
- MCP analysis sees 2 of these events as having good enough dE/dx in pixel, but does not see sufficient dE/dx in TRT or MDT
- dE/dx $\in [2.42{,}3.72]\ MeVg^{-1}cm^{2} \rightarrow \beta \in [0.62 - 0.52]$, particles have longer time-of-flight than SM
- directly measuring β from calorimeter and MS consistent with 1 → low particle speed is not consistent