

Review on Exotics Physics ATLAS



Monica Verducci - Universita' di Pisa and INFN

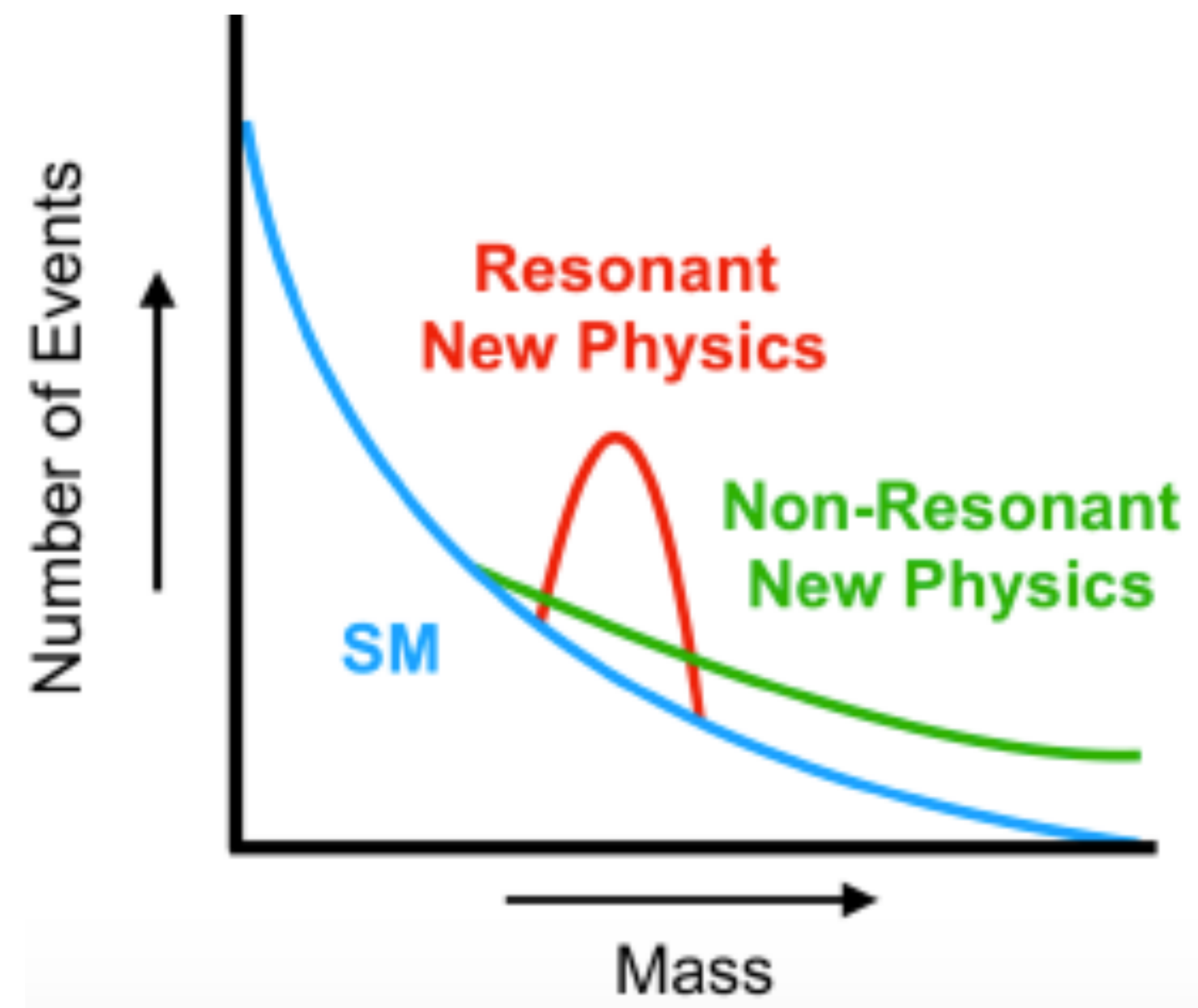
COMPOSE-IT 27-28 January 2020

Dipartimento di Fisica e Geologia, Università degli Studi di Perugia



Outline

- ATLAS detector and data-taking from 2015-2018
 - A look at High Luminosity LHC plans
- Exotics searches with Run2 data and prospects for High Luminosity LHC:
 - **Searches for heavy resonances.**
 - **Searches for long-lived particles (LLPs)**
 - **Higgs portal dark photons.**
 - **Heavy Neutral Leptons.**
 - **Monopoles.**
- Summary

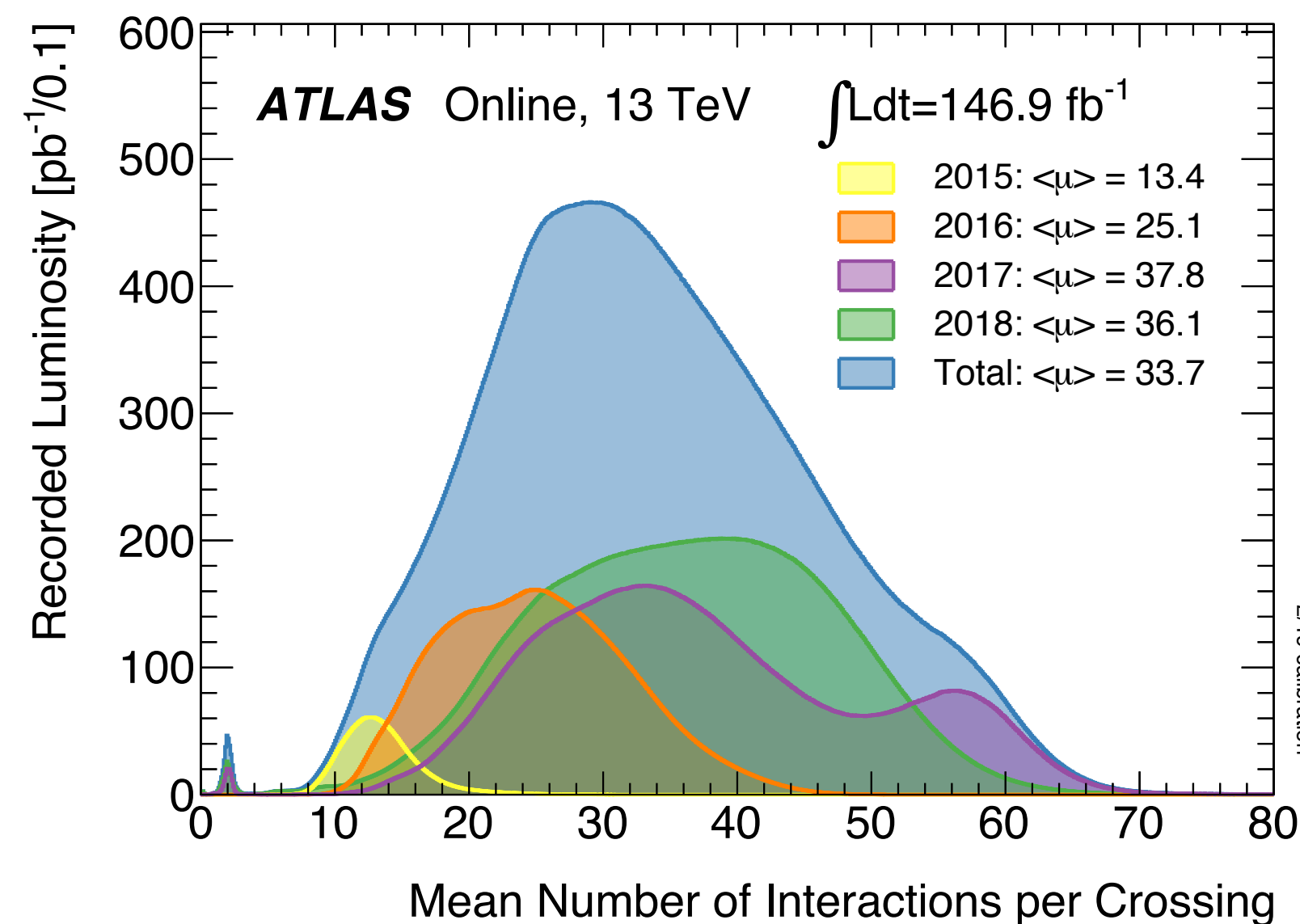
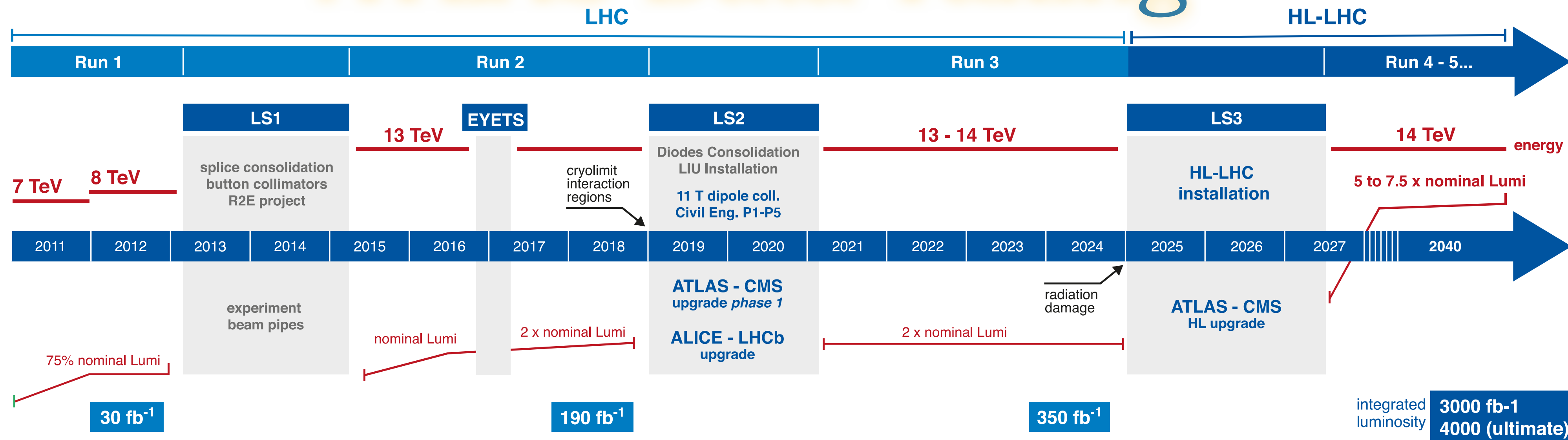


More ATLAS results tomorrow:

- “Search in ATLAS for excited lepton and di-lepton high mass” A. Sidoti
- “Diboson search in ATLAS” F. Ciotto

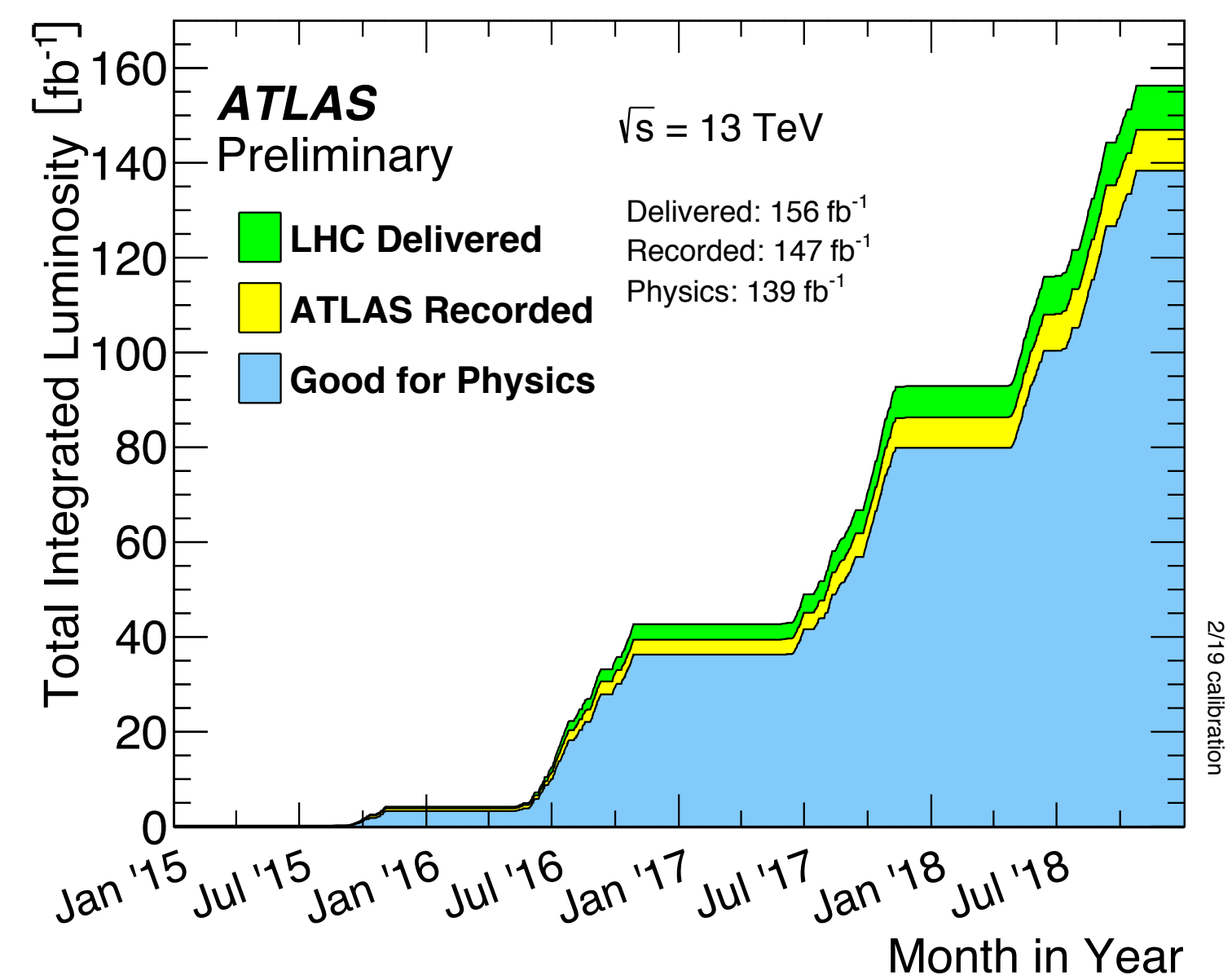
News from LHC plans: “Present status of LHC and perspectives for Run3 and HL” M.Tosi

ATLAS Data Taking

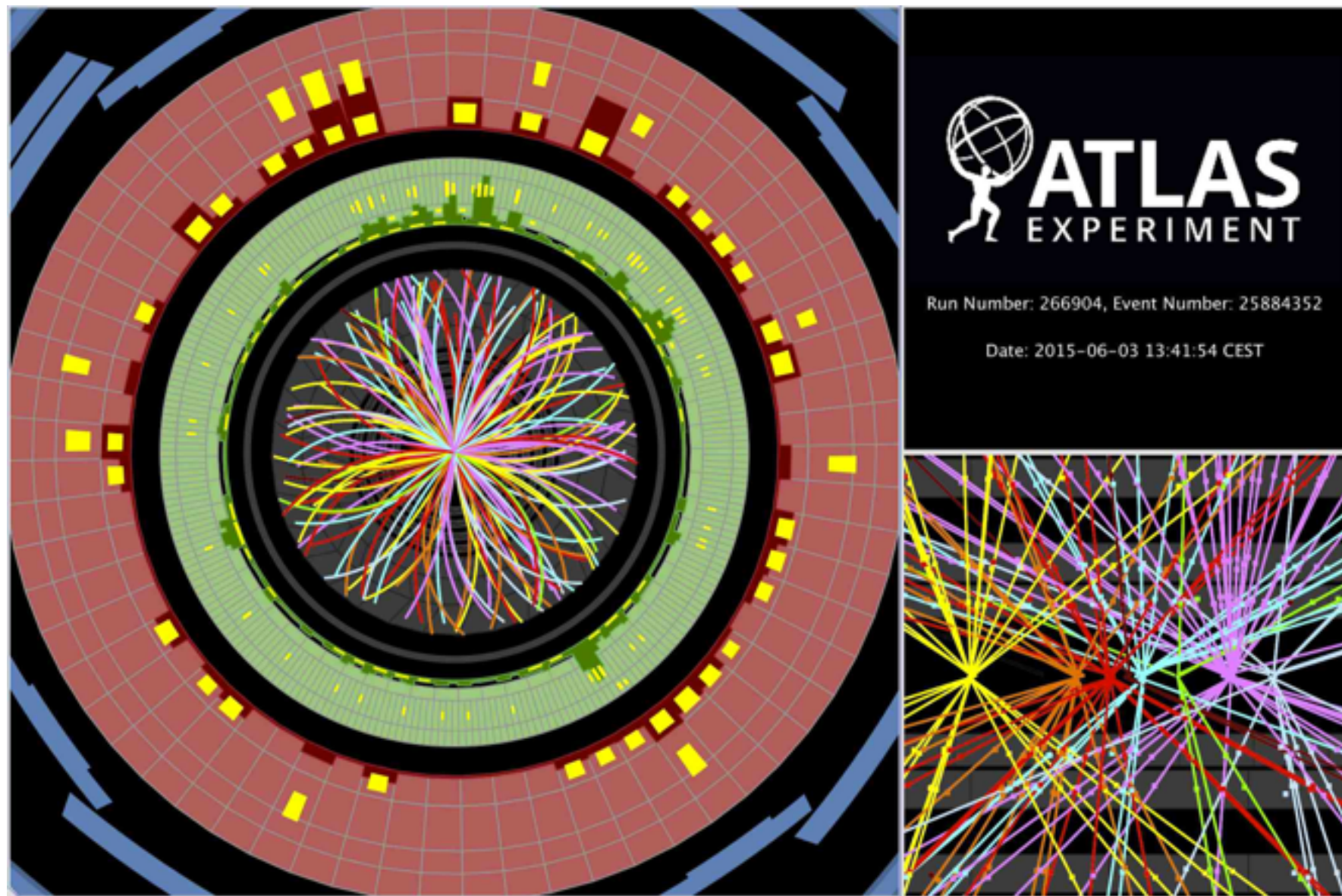


Both LHC and ATLAS performed extremely well in Run-2.

- Maintained ~94% data-taking and data-quality efficiency despite harsh pileup conditions.
- Provides huge opportunity for discovery of New Physics!
- HL-LHC projections under study by using Run 2 data



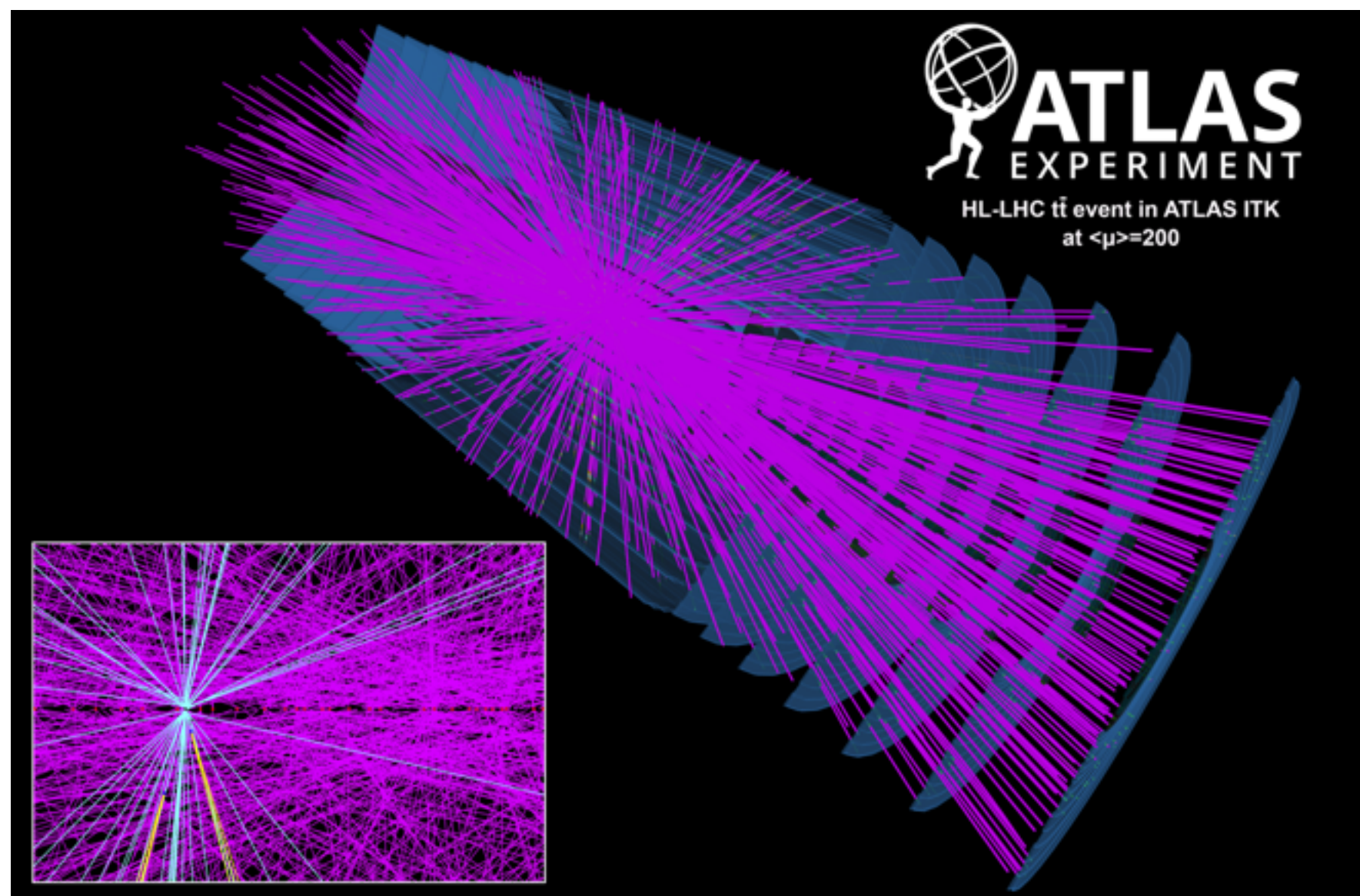
The Challenge of High Luminosity



The $5\text{-}7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ instantaneous luminosity is beyond the capabilities of the current detectors: this requires very granular detectors, very good vertex reconstruction capabilities and bunch crossing identification, fast trigger -> **Detector Upgrade**.

High luminosity means a big number of simultaneous events:
 $\langle \mu \rangle = 140\text{-}200$

Very High Radiation doses: replace several parts to achieve a robuster, faster, radiation harder and lighter detector. **Detectors ageing** very quickly and having to be replaced/refurbished.



HL-LHC projections are obtained by:

1. **scaling the signal and background datasets used for the Run 2 analyses (36 fb^{-1}), to the HL-LHC expected integrated luminosity (3000 fb^{-1}) and center-of-mass energy ($\sqrt{s} = 13 \text{ TeV} \rightarrow \sqrt{s} = 14 \text{ TeV}$). Scale factors are applied to event yields and systematics uncertainties.**
2. **using truth-level 14 TeV upgrade samples with $\mu=200$ and smearing function for detector performance**

The ATLAS detector (HL-LHC Upgrade)

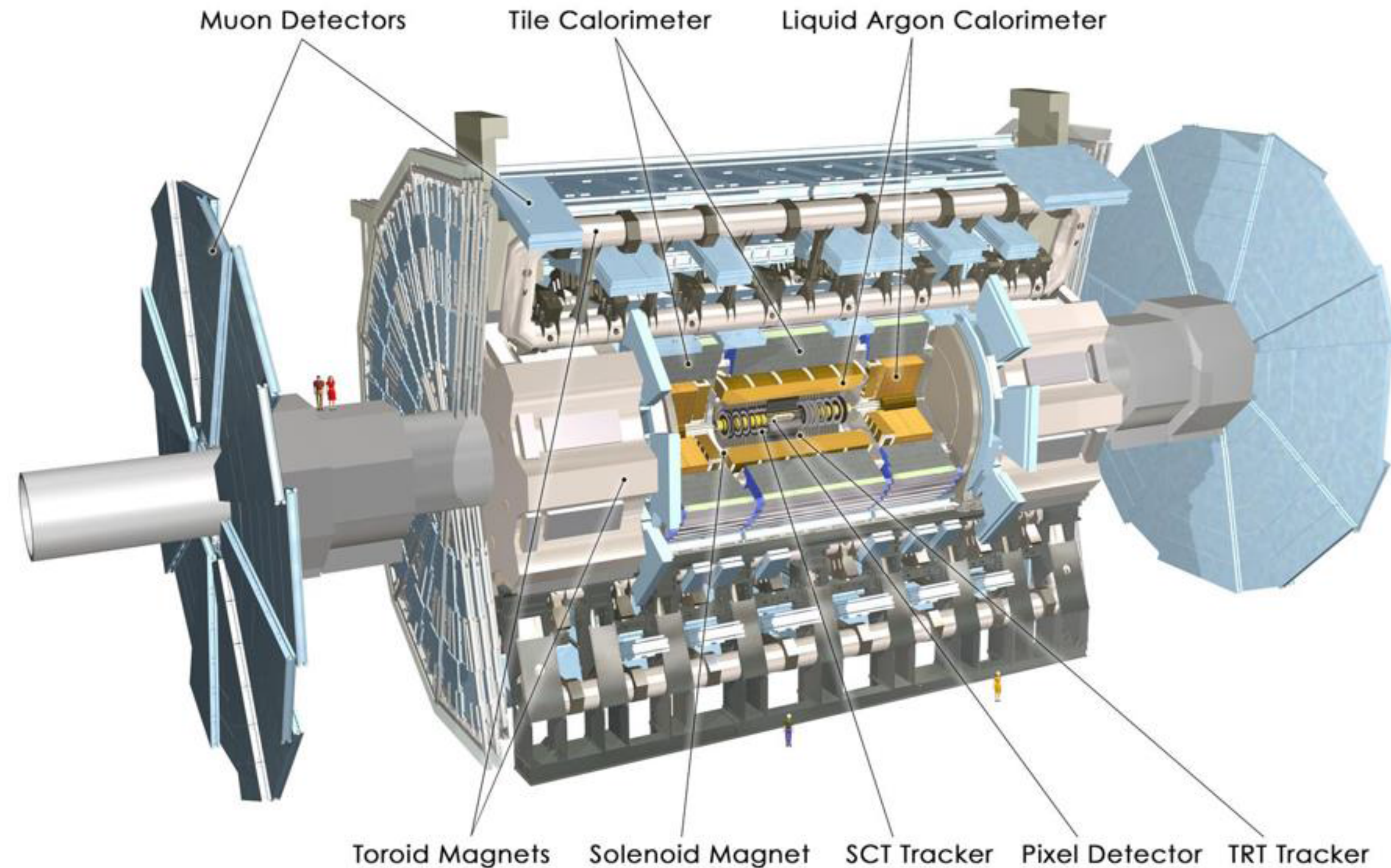
TDAQ upgrade

→ Increased latencies and rates

Proposals for adding in forward regions a muon tagger and a timing detector

Inner Detector: full replacement by a all-silicon one (165m²), extending up to $|\eta|=4$
At most 1.75 X₀

Muon readout and trigger upgrades.
New Barrel trigger layer.
New end cap inner Muon station (nSW) (Phase I)

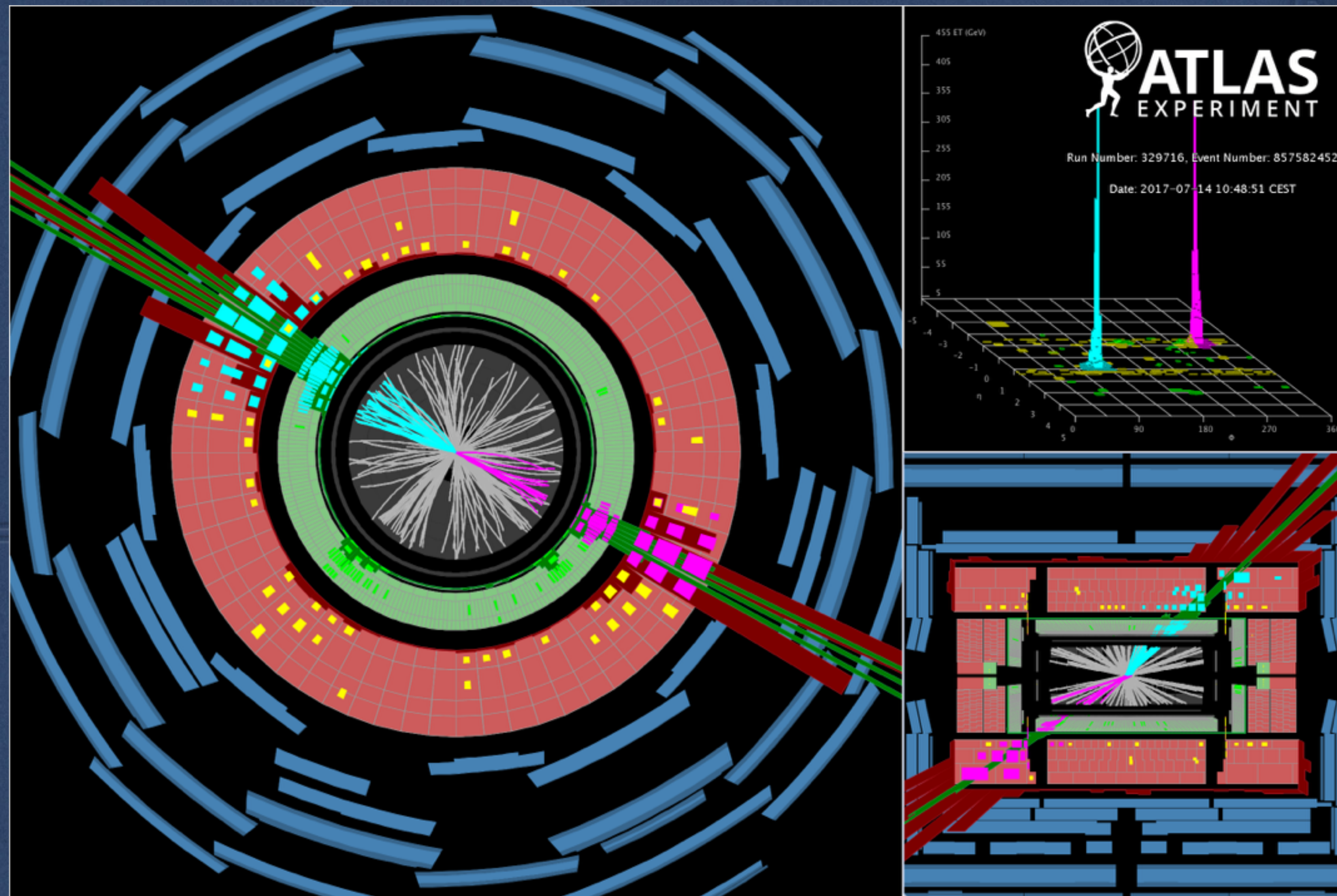


ATLAS
Detector
Upgrade for
HL-LHC

LArg: new FrontEnd and BackEnd electronics for faster readout
High granularity LAr (Phase I)
Tile Calorimeter : upgrade of electronics and HV distribution

Resonance Search

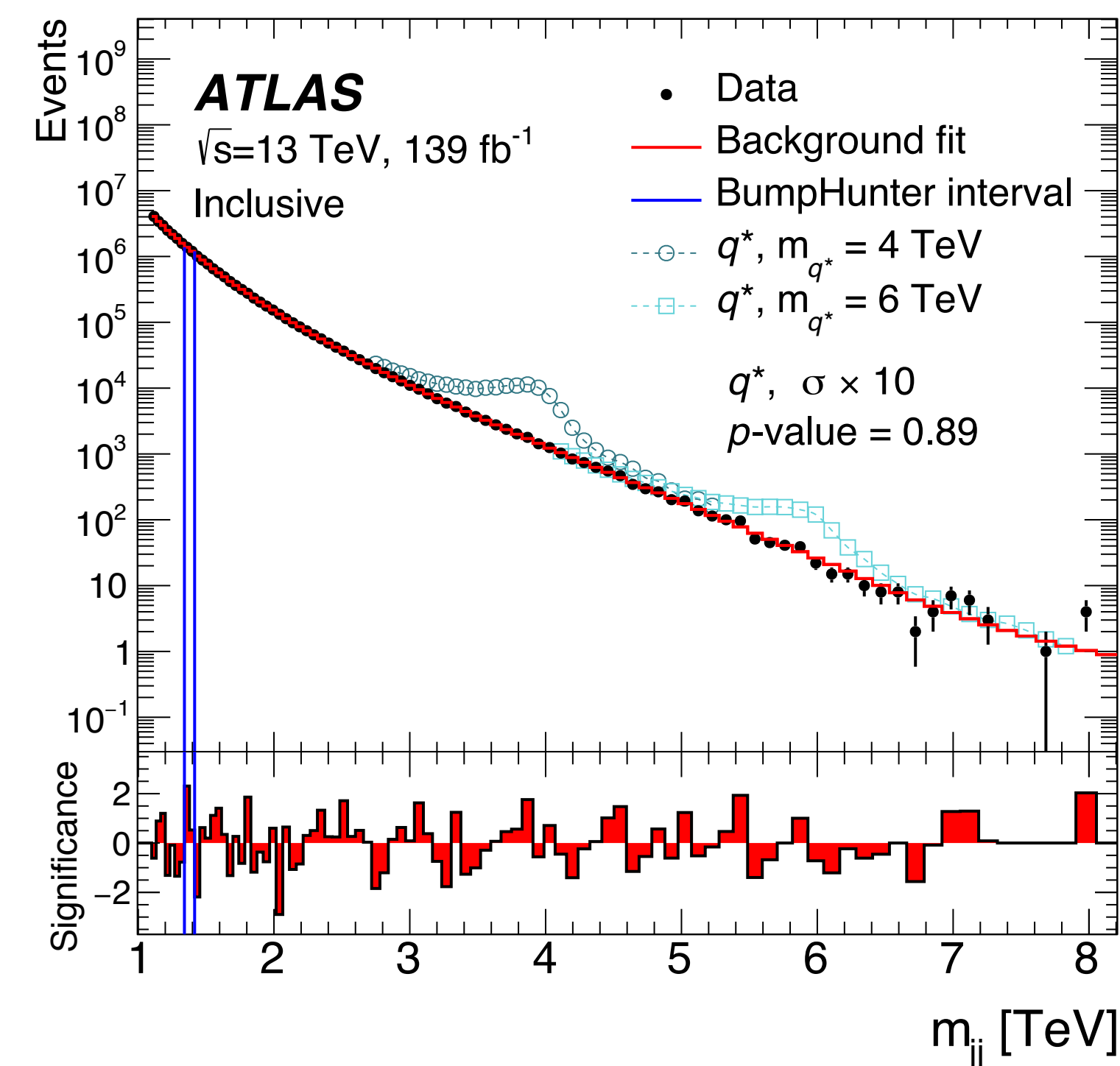
- Di-jets
- Di-bjets
- W'
- Z'



Di-jets Resonance

Searches for heavy dijet + di b-jet resonances:

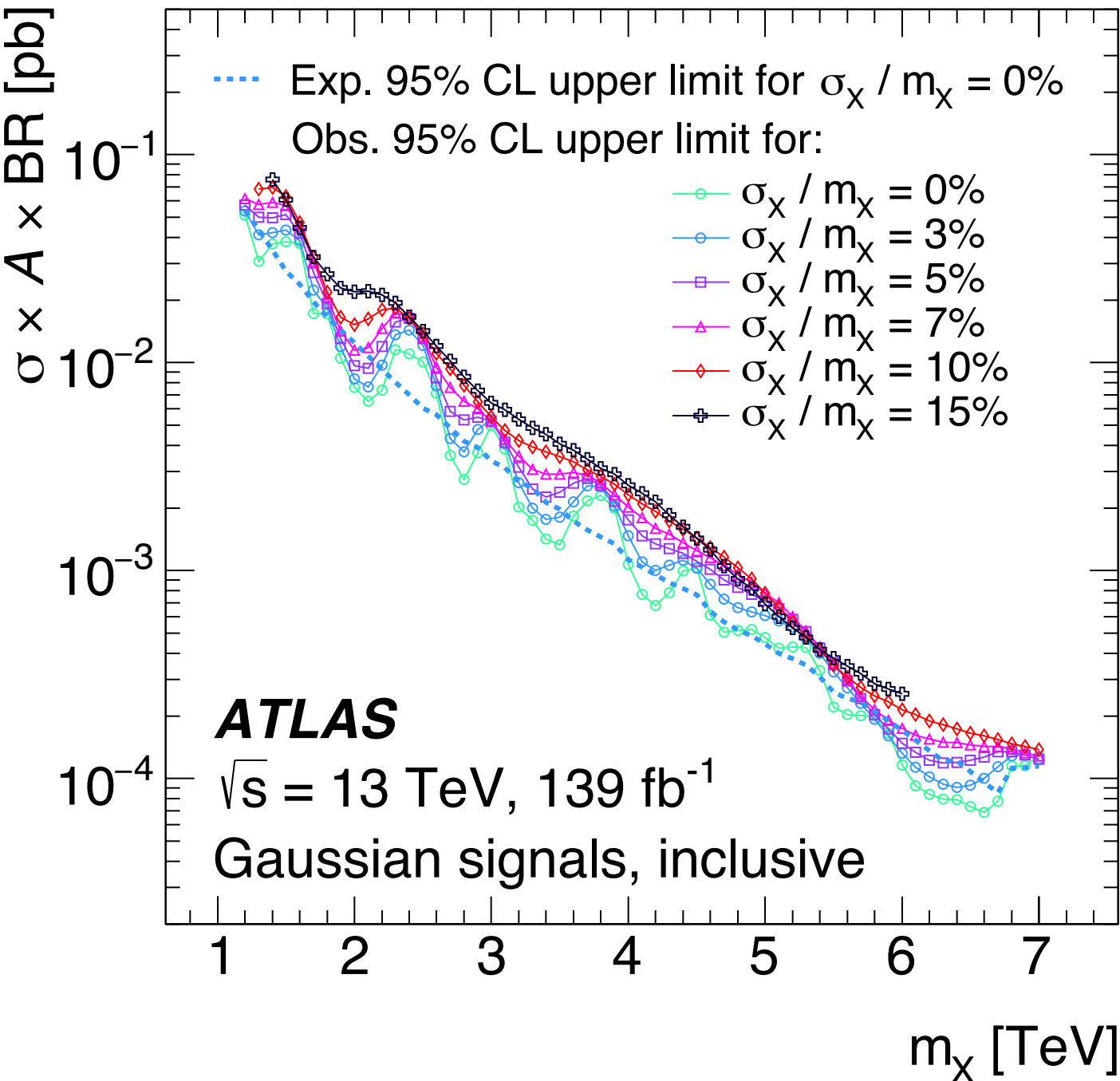
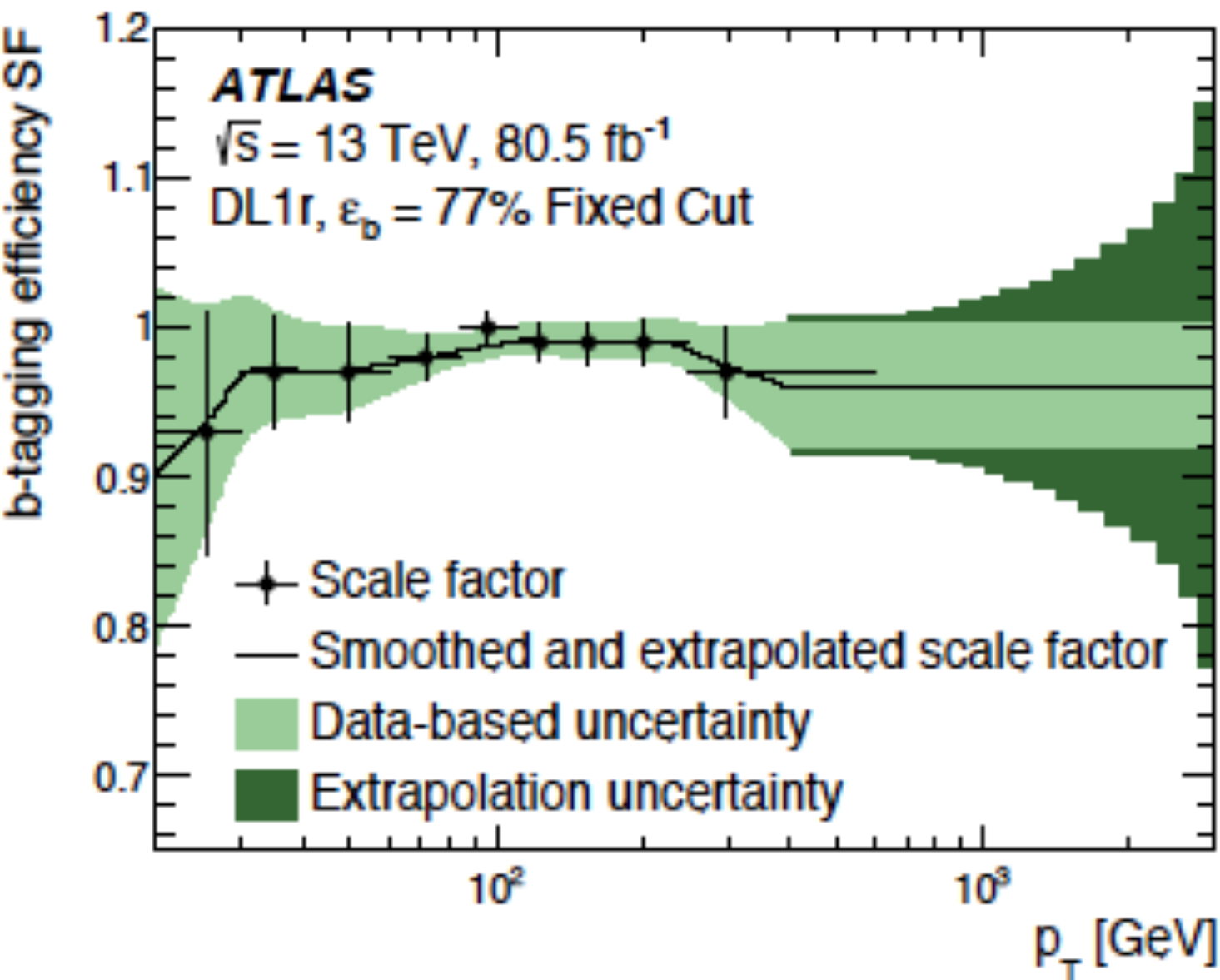
- Excited quarks (q^*) in models of compositeness.
- Test generic Gaussian signal shapes.
- SSM Z' + DM Z' mediator (bb).
- The **distribution of the invariant mass of the two leading jets** is examined for local excesses above a data-derived estimate of the Standard Model background.
- In addition to an **inclusive dijet search**, events with **jets identified as containing b-hadrons** are examined specifically (one or exactly two b-jets).
- Event Selection:** single-jet trigger that requires at least one jet with $p_T > 420$ GeV, the lowest p_T unprescaled single-jet trigger. **At least two jets** with $p_T > 150$ GeV and the azimuthal angle between the two leading jets must be greater than 1.0.



Category	Inclusive		1b	2b
Jet p_T	> 150 GeV			
Jet ϕ	$ \Delta\phi(jj) > 1.0$			
Jet $ \eta $	-		< 2.0	
$ y^* $	< 0.6	< 1.2	< 0.8	
m_{jj}	> 1100 GeV	> 1717 GeV	> 1133 GeV	
b-tagging	no requirement		≥ 1 b-tagged jet	2 b-tagged jets
Signal	DM mediator Z'	W^*	b^*	DM mediator Z' ($b\bar{b}$)
	W'		Generic Gaussian	SSM Z' ($b\bar{b}$)
	q^*			graviton ($b\bar{b}$)
	QBH			Generic Gaussian
	Generic Gaussian			

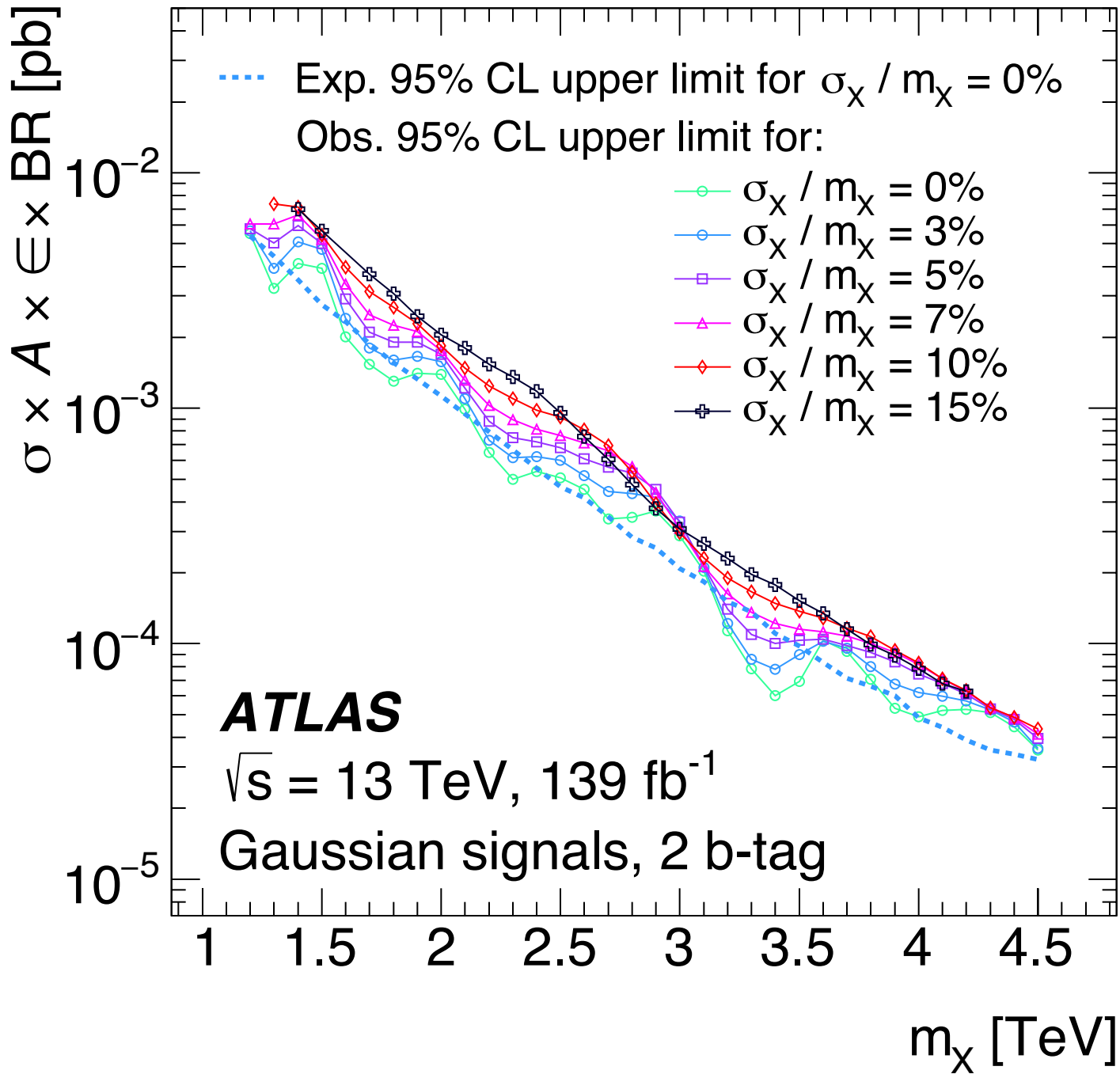
Di-Jets Results

- **Dominant background contribution from QCD processes**
 - selection based on rapidities difference between the two jets y^* : s-channel for QCD (large y^*) while t-channel for signal (small y^*).
- Additional scaling factor for b-tagging



Interpretations:

- Excited quarks (q^*) excluded up to 6.7 TeV.
- SSM Z' (bb) excluded up to 2.7 TeV.
- DM Z' mediator up to 2.9 TeV.

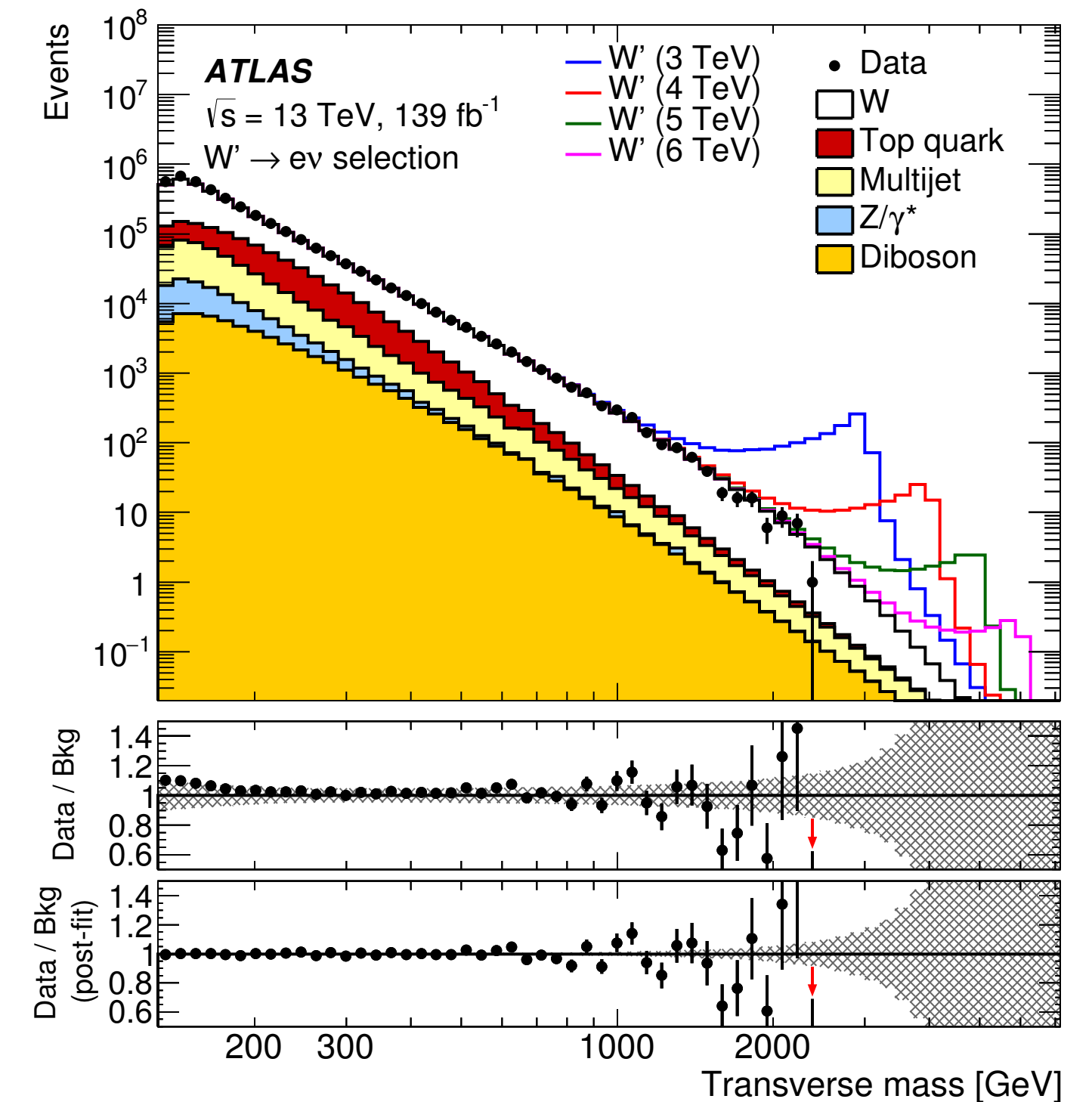
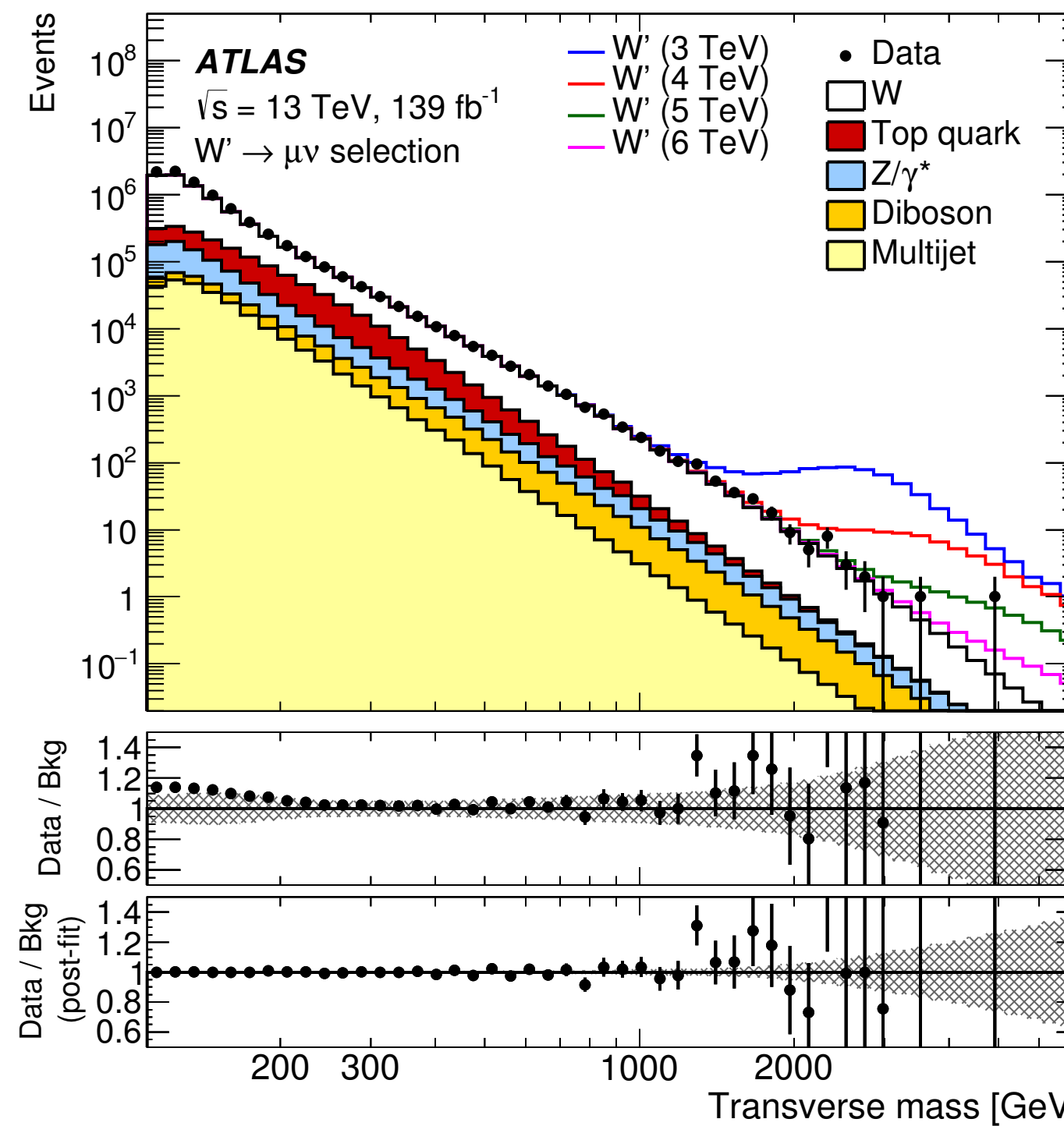
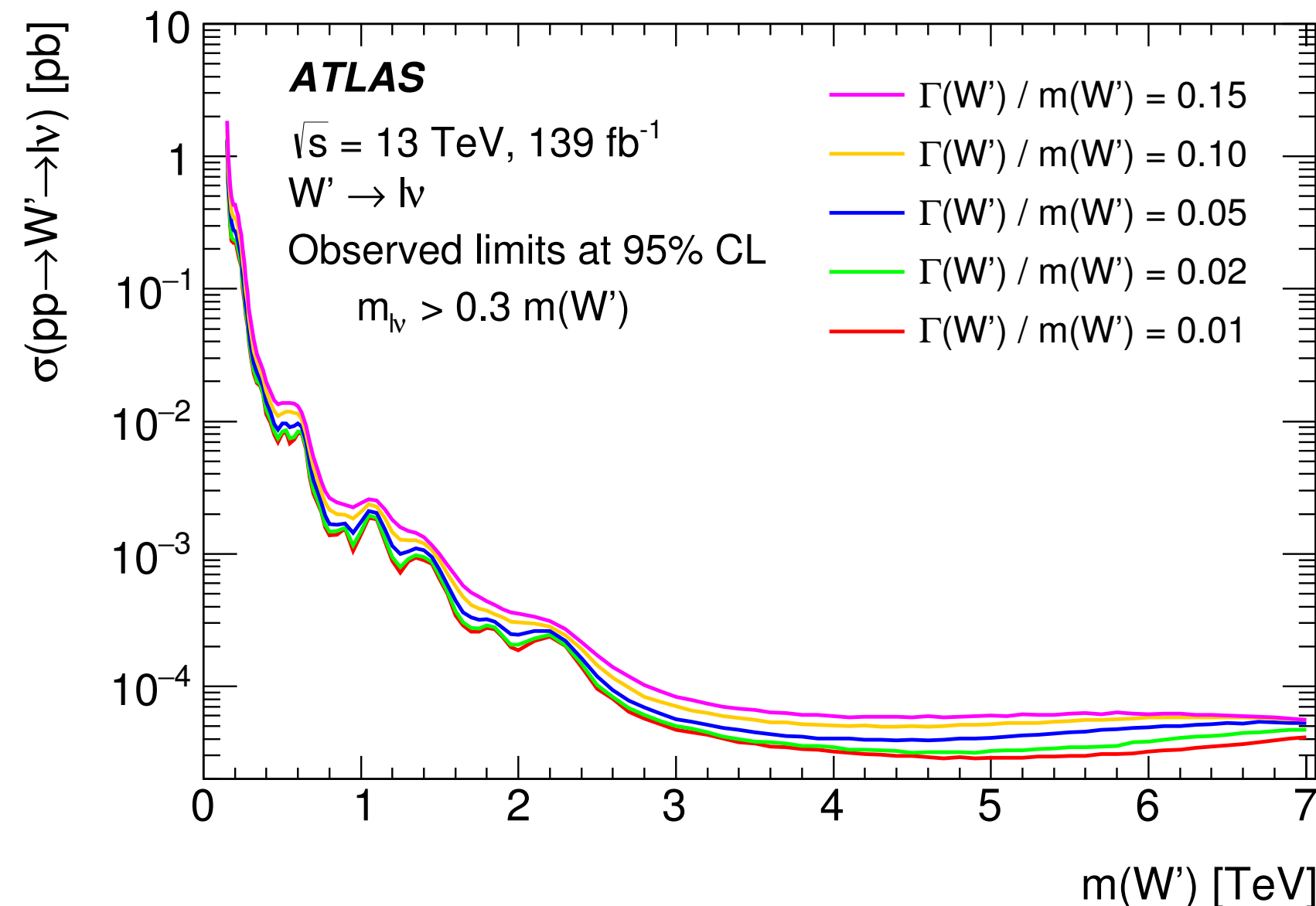


Searches for new resonances: W'

W' predicted by many New Physics models:

- GUT models.
- L-R symmetry models.
- Little Higgs models.

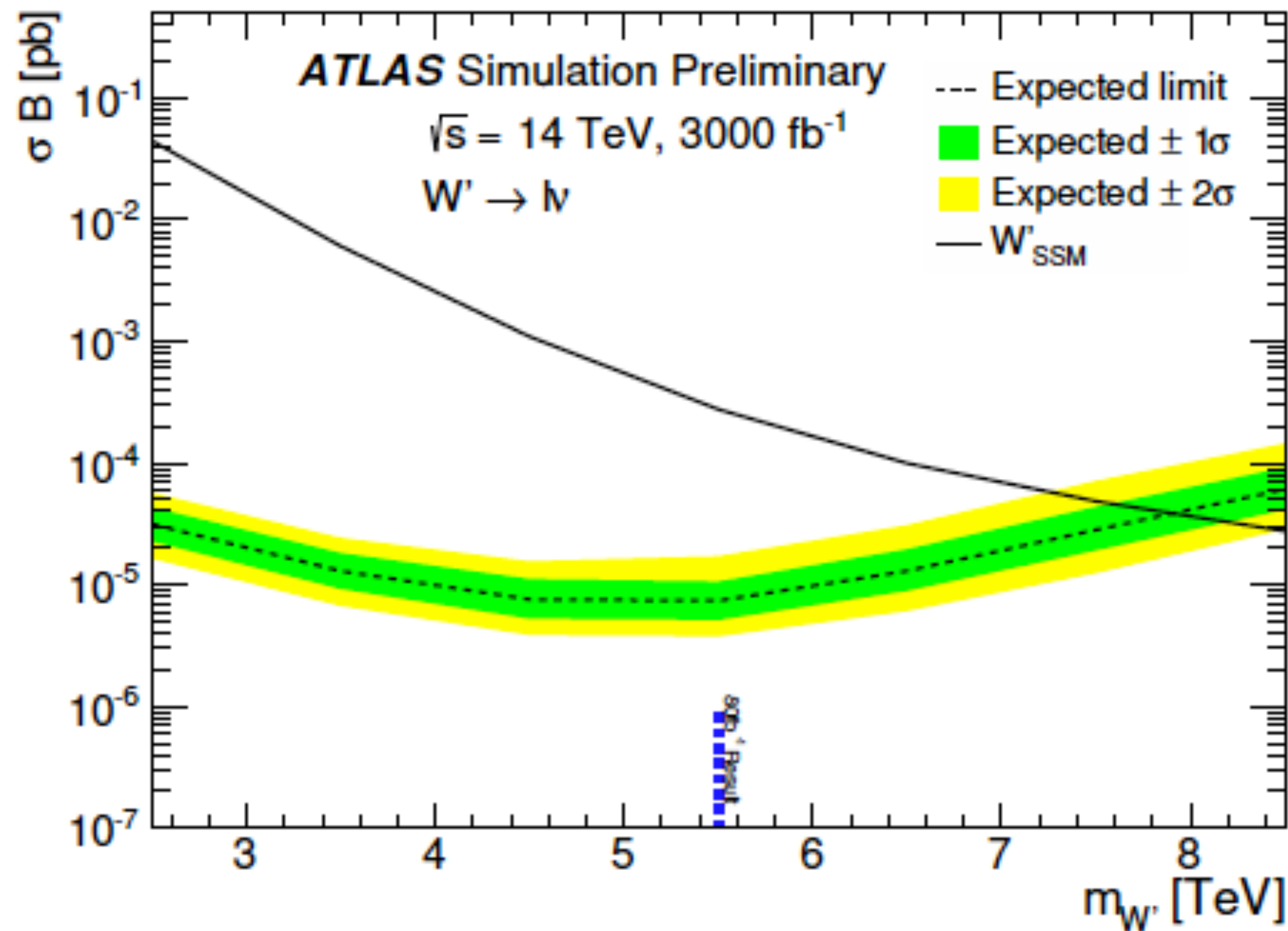
Search for resonances in transverse mass m_T in lepton +MET channel.



Use MC estimate of major backgrounds, data-driven fake leptons estimate.

Excluded to 6 (5.1) TeV in electron (muon) channel

W' in HL-LHC



Decay	Exclusion [TeV]	Discovery [TeV]
$W'_{\text{SSM}} \rightarrow e\nu$	7.6	7.5
$W'_{\text{SSM}} \rightarrow \mu\nu$	7.3	7.1
$W'_{\text{SSM}} \rightarrow \ell\nu$	7.9	7.7

W' bosons can be excluded up to masses of 7.6 TeV (7.3 TeV) in the electron (muon) channel

- The **combination** of the two channels increases the limits to just over 7.9 TeV

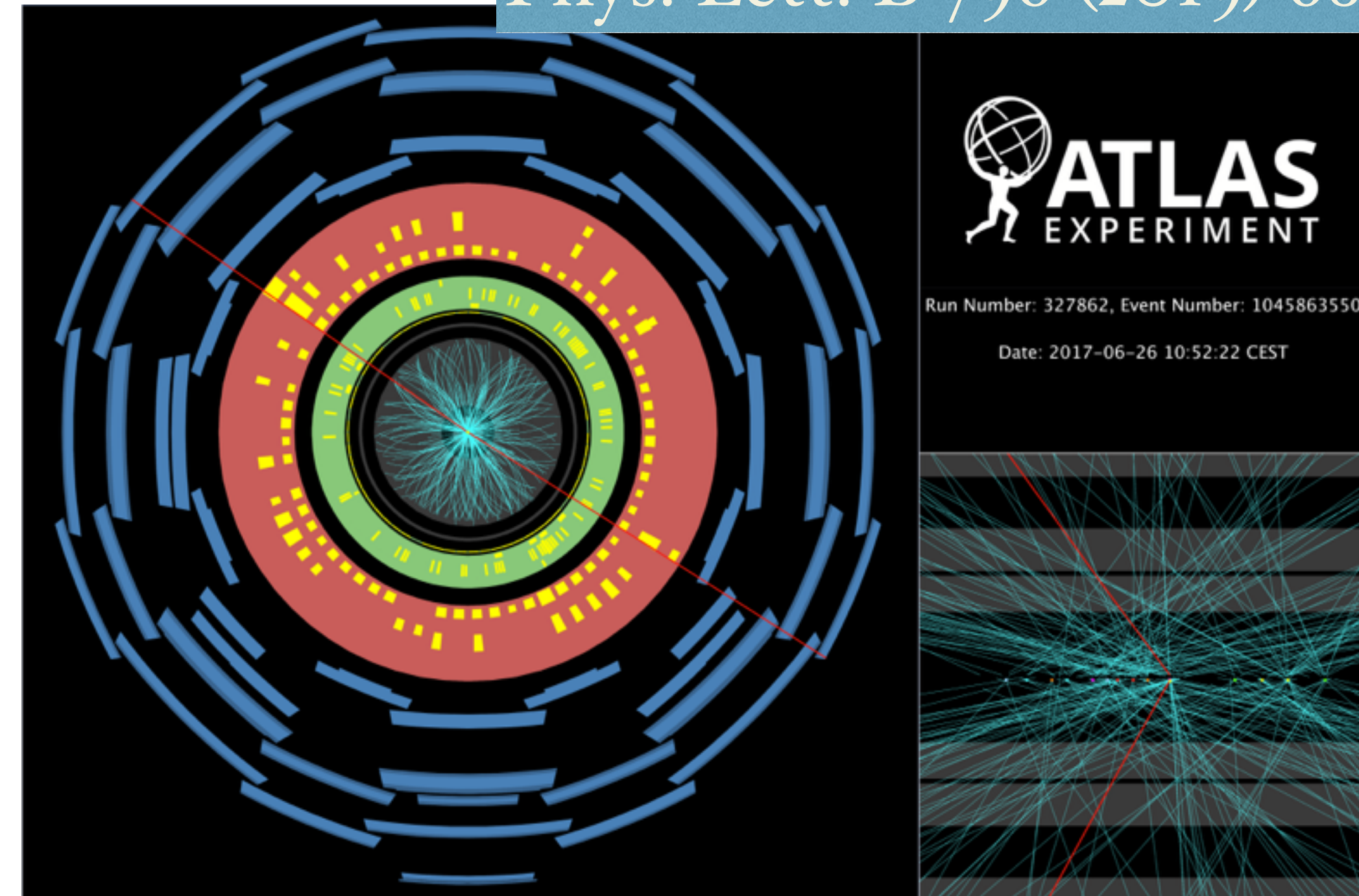
- **2 TeV of improvement wrt Run2 results!**

- Based on **5σ significance**, it is found that **W'** with masses up to **4.3 TeV** can be discovered (**increase of 1.2 TeV** when **assuming 300 fb^{-1}**)

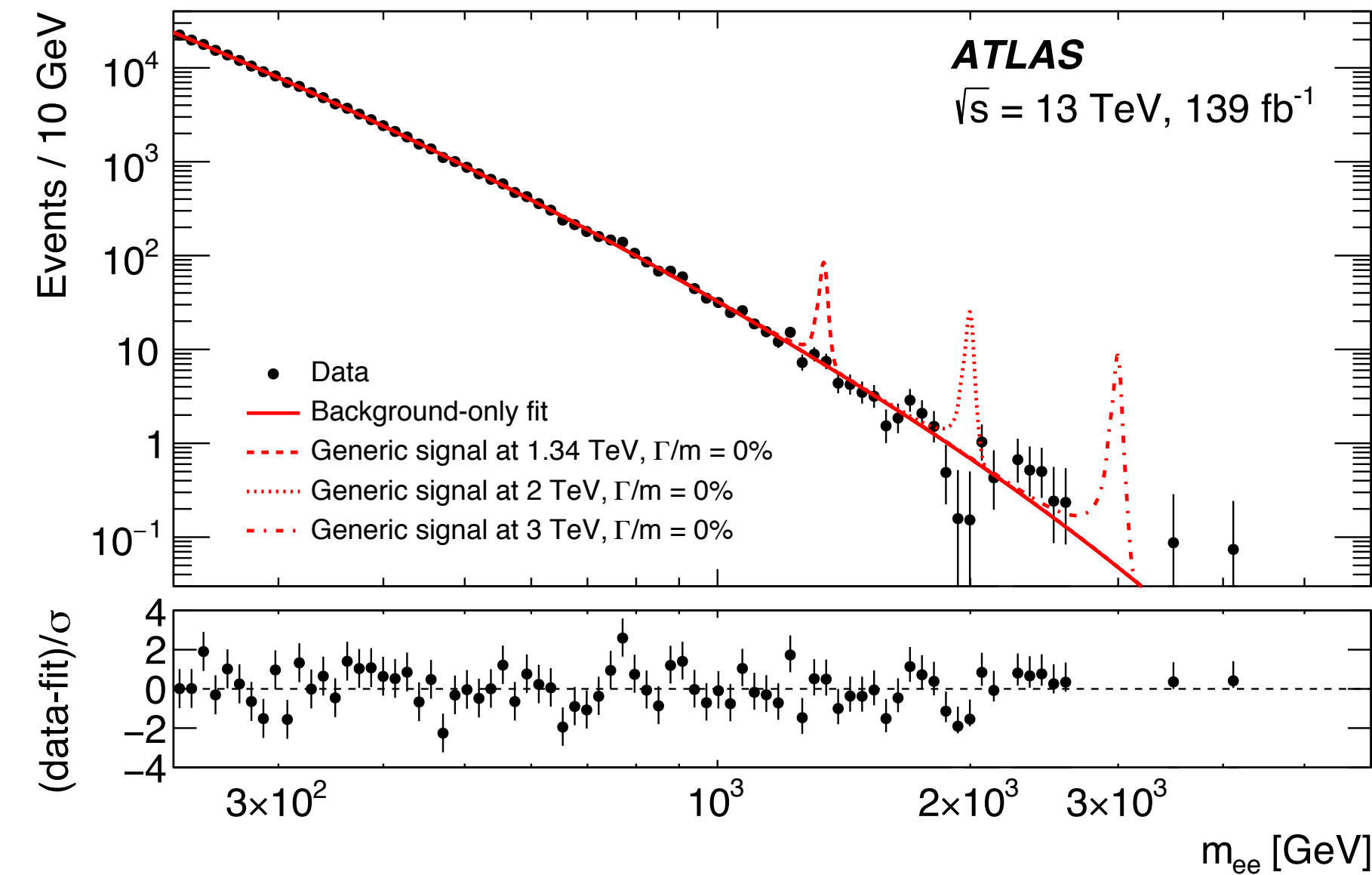
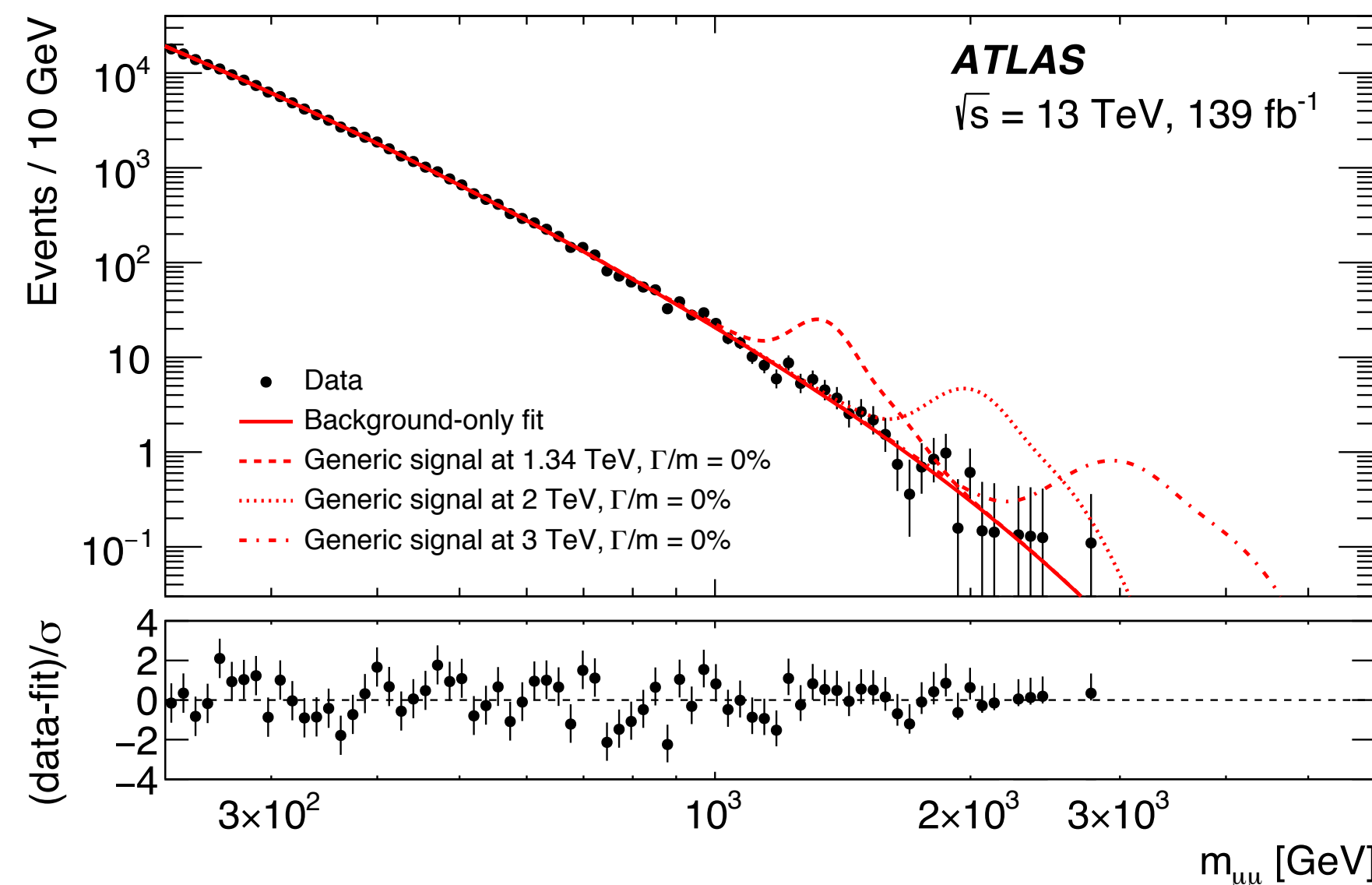
Searches for new resonances: Z'

Searches for **new heavy gauge boson Z'** predicted by the physics models:

- SSM Z' .
- GUT Z' or Z'_ψ
- New SU(2) triplet: Z'_{HVT}
- **New**: search for signals on smoothly-falling background-fit from data, a generic signal shape is used to determine the significance of observed deviations from this background estimate.

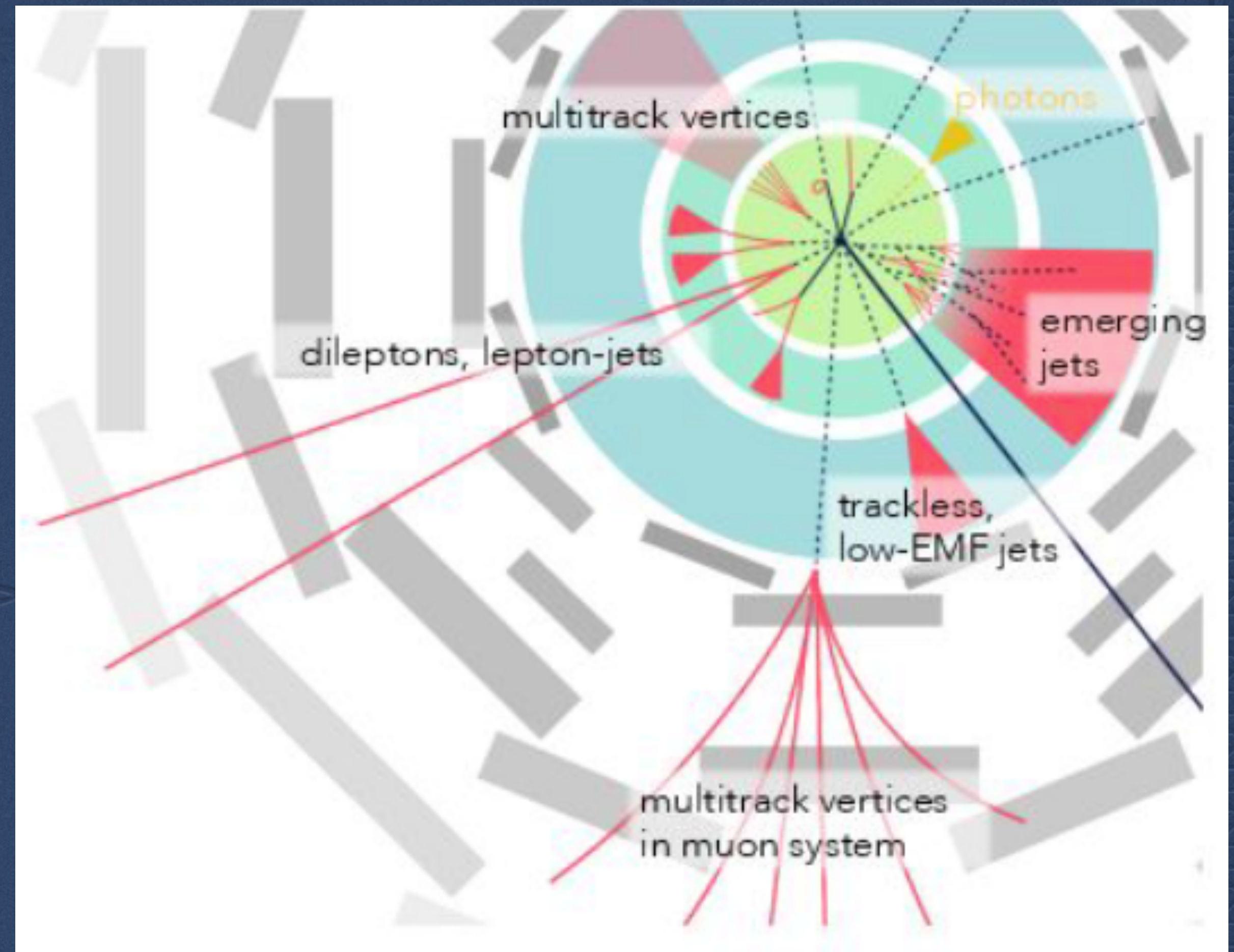


No significant deviation from SM interpretations:
 Z' (SSM) excluded to 5.1 TeV
 $Z'\psi$ excluded to 4.5 TeV
 The derived limits are shown to be applicable to spin-0, spin-1 and spin-2 signal hypotheses



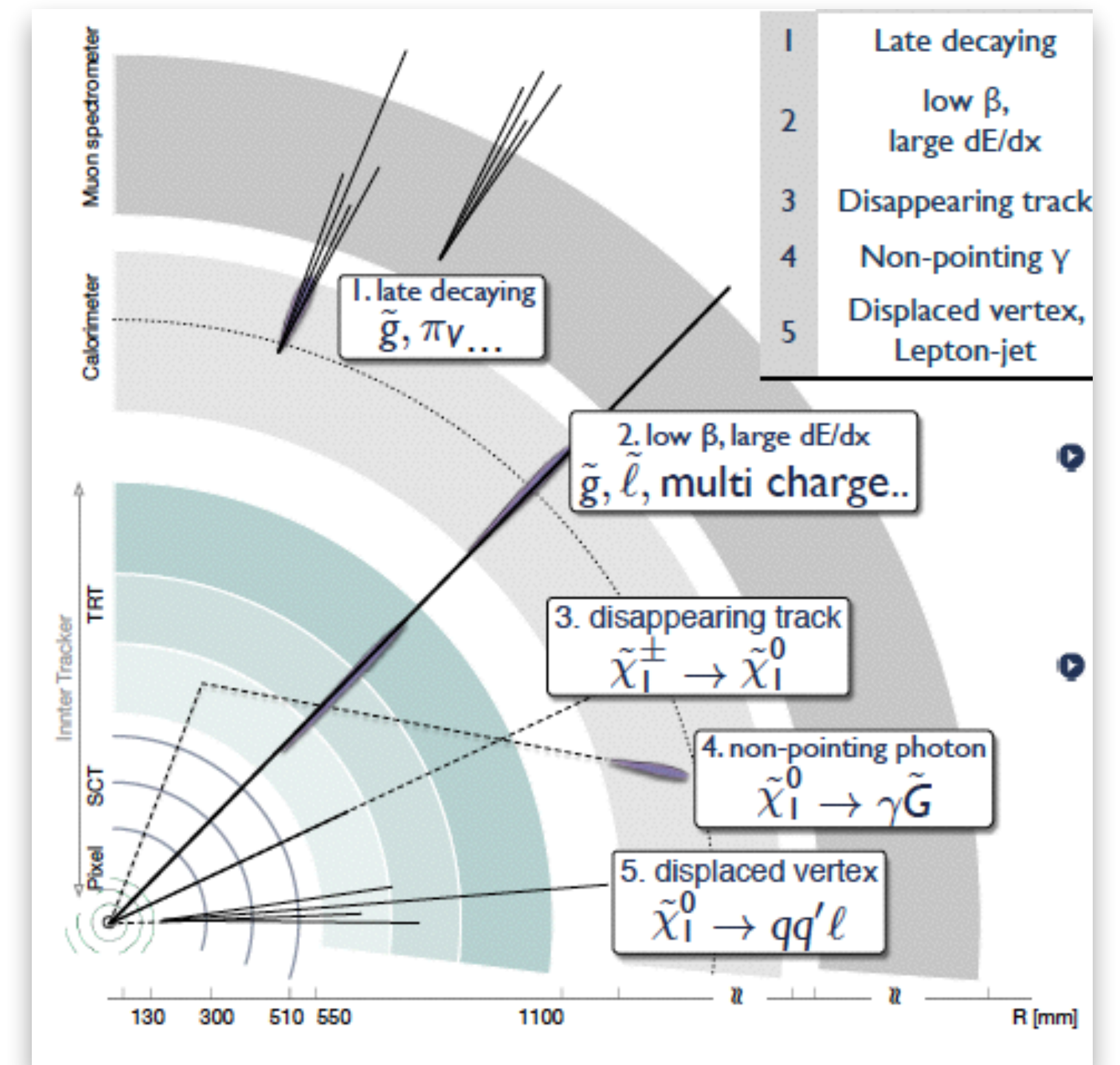
Long-Lived Particles

- Displaced Jets
- Displaced Leptons Jets
- Heavy Neutral Leptons
- Monopoles



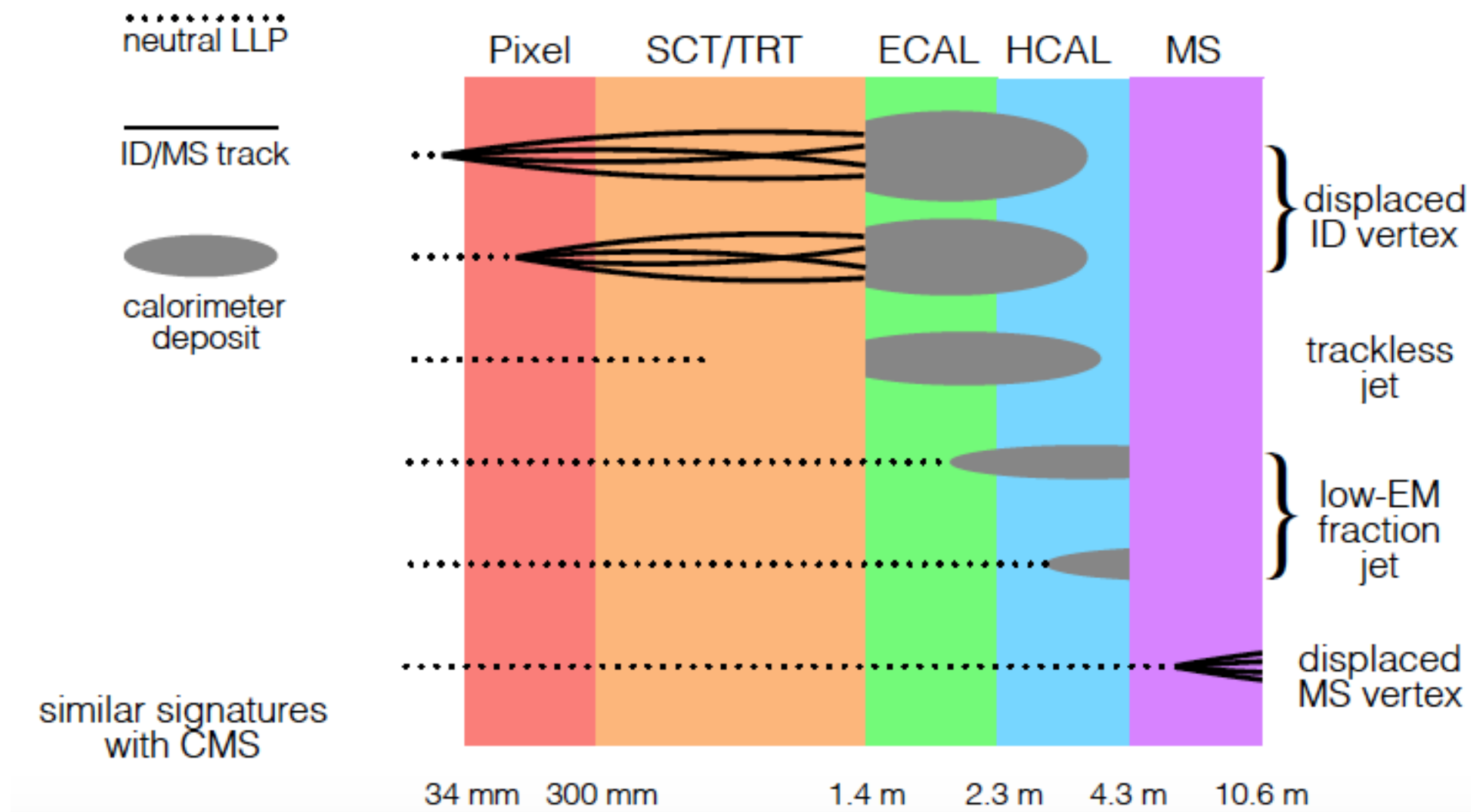
Introduction to LLP

- **A wide variety of BSM models** (Hidden Sectors, RPV violating decays, Split-SUSY, AMSB, GMSB, etc.) **predict the existence of Long Lived Particles (LLP), *new particle with long life-time*, enabling direct measurements.**
- LLP have unusual and interesting signatures, extremely challenging due to the non-standard final topologies. The signal event reconstruction and selection, as the background estimation, use dedicated, unique and very specialised technicalities.
 - **Detector-signature based search.** Experimentally very diverse, depending on particles' properties (dE/dx, Time-of-flight, kinked or disappearing tracks, displaced vertex)
 - **May require customised trigger and self-made objects reconstruction algorithm**
 - Requires **non-standard analysis strategies and tools**



	Signature	Scenario	decay-length sensitivity
1	Late decaying	split SUSY, Hidden Valley	—
2	low β , large dE/dx	GMSB, Split-SUSY, Stealth SUSY, Multi-charged	>1000mm
3	Disappearing track	AMSB (wino-LSP)	O(100-1000)mm
4	Non-pointing γ	GMSB	O(100-1000)mm
5	Displaced vertex, Lepton-jet	RPV, GMSB, Hidden Valley	O(10-100)mm

Displaced Jet Signatures



Displaced ID vertex: a displaced vertex not reconstructed by the standard tracking (relaxing do and zo cuts)

Low-EM fraction jet: an atypical jet with no tracks in the inner tracker and would deposit no energy in the electromagnetic calorimeter

Displaced MS vertex: displaced vertexes in the MS originated by decays in calorimeter. Optimised tracking algorithm.

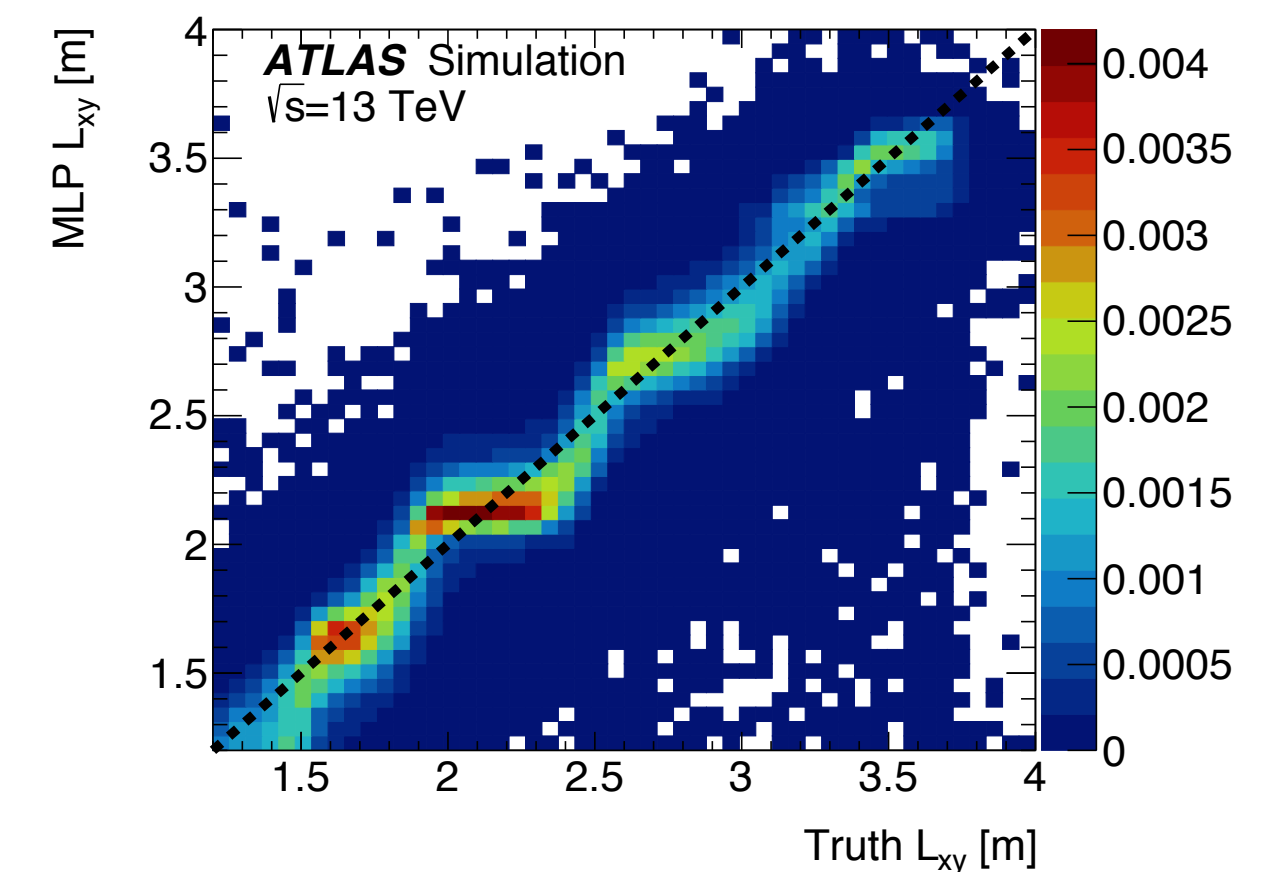
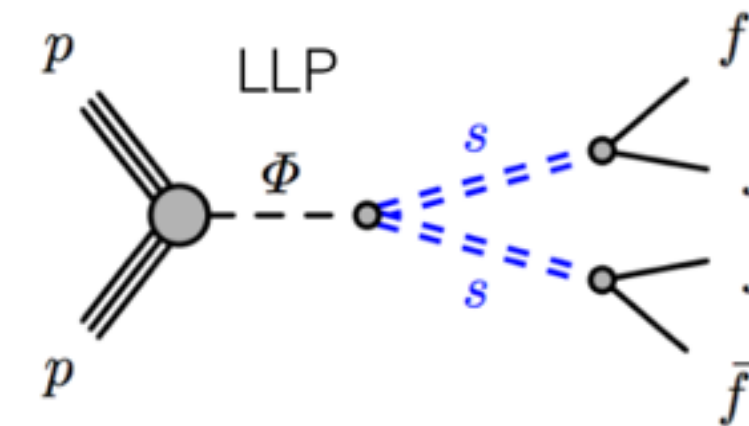
Three different analyses: 2 displaced MS vertexes, 2 low-EM fraction jets, one displaced MS vertex and one displaced ID vertex

Exclusion limits set from the combination of them.

Interpretation in term of Hidden Valley and Stealth SUSY Models

Displaced Jet in Hadronic Calorimeter

Model Interpretation: Weakly coupled Hidden Sector (HS) communicates with the SM via neutral LLP that decays within the ATLAS detector.



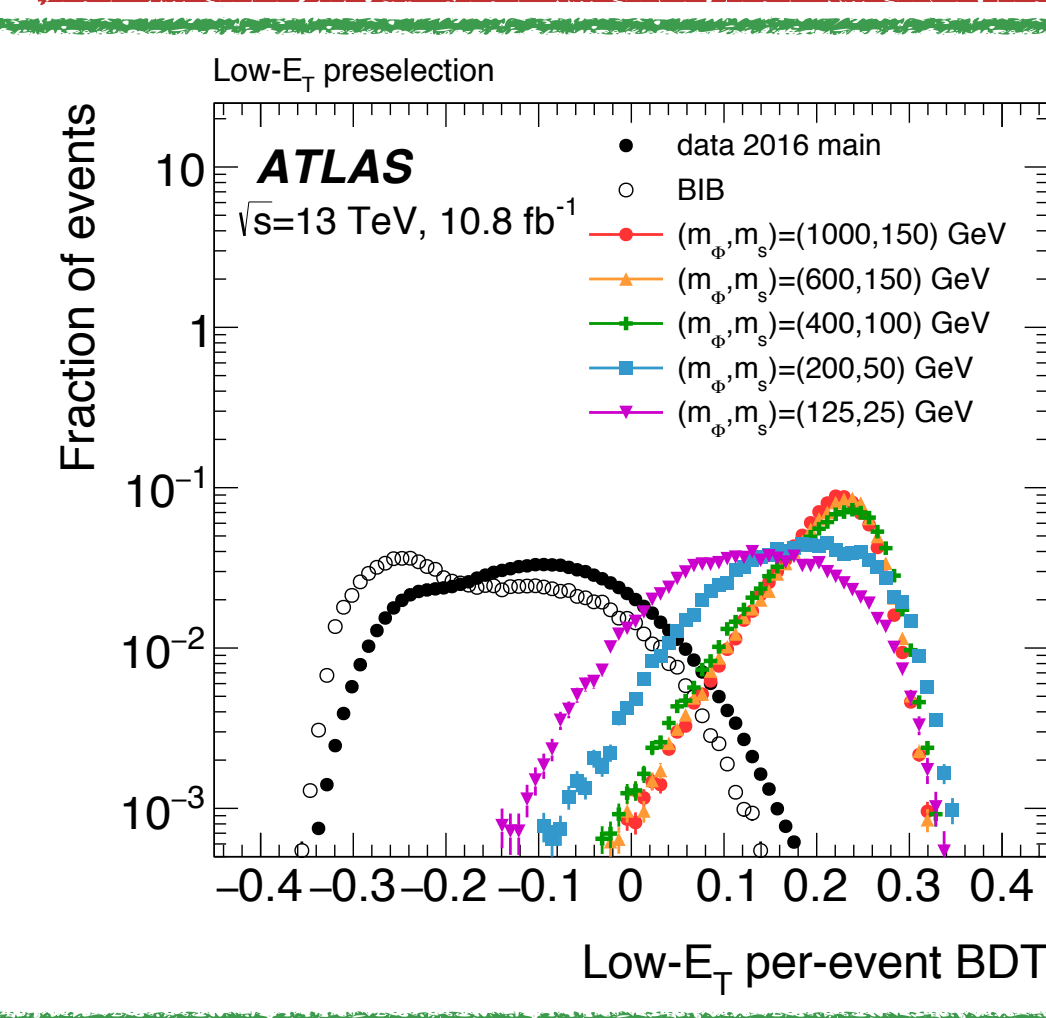
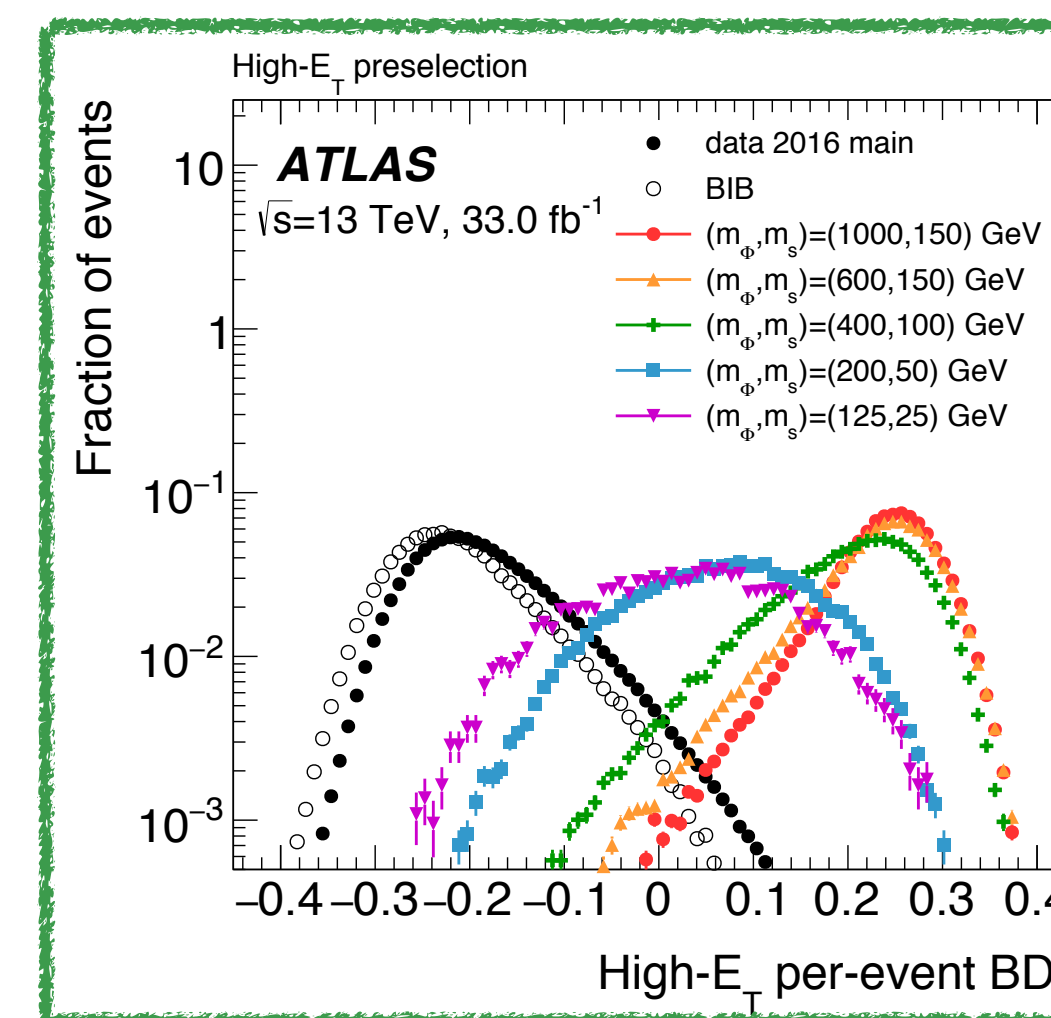
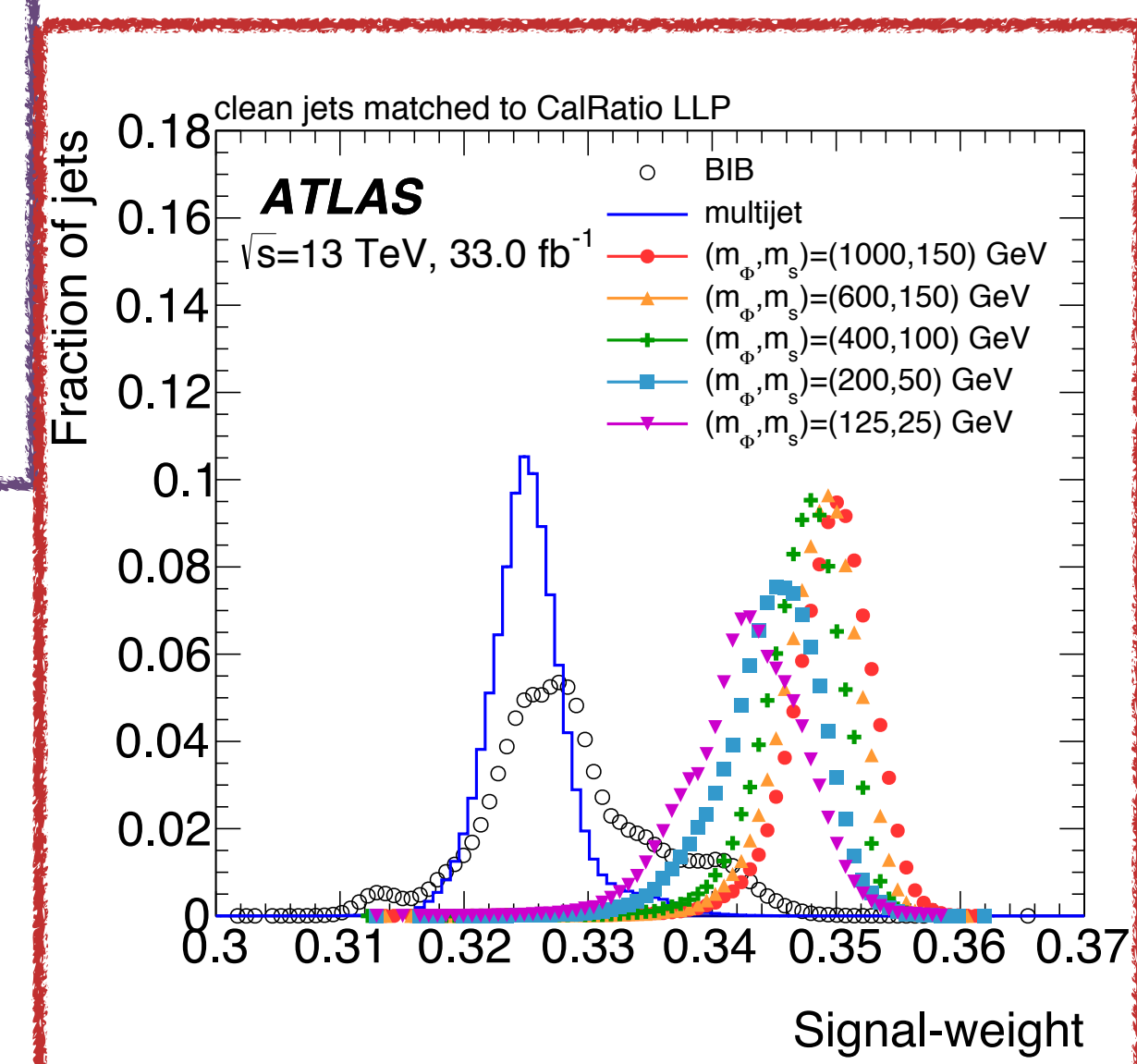
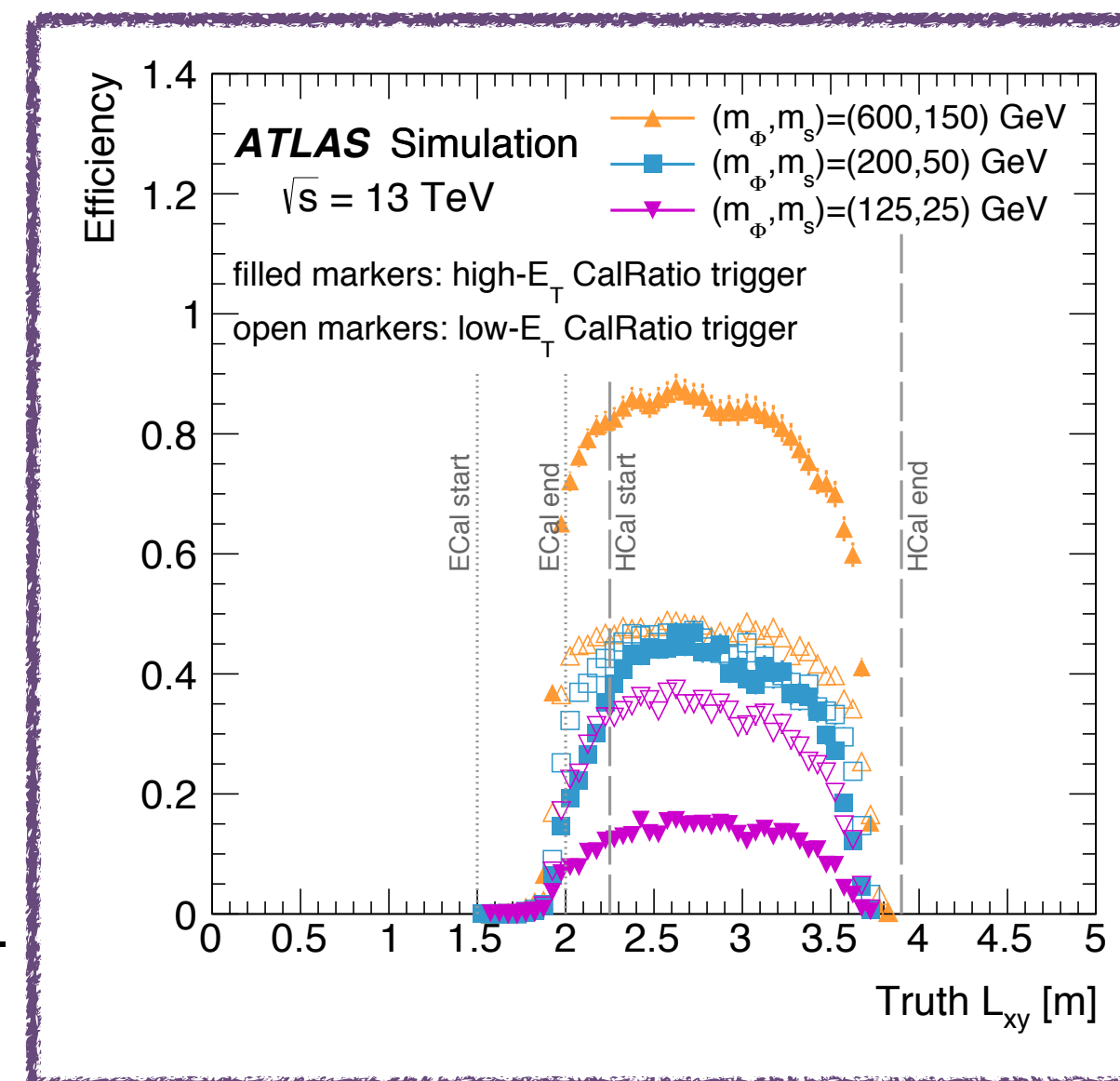
- This analysis explores signature, where both neutral LLPs decaying in the hadronic calorimeter, resulting in **an atypical jet topology**:

- Produce **narrower cone** than typical SM jets originating from the IP
- Ratio of energy in the HCal (E_H) to the energy in the ECal (E_{EM}) is large (**large $\log(E_H/E_{EM})$**)
- No associated ID tracks to the jet** –large ΔR_{min} between the jet direction and the tracks

Each clean jet is evaluated by a multilayer perceptron (MLP) to predict the radial and longitudinal decay positions (L_{xy} and L_z) of the particle that produced the jet, using the jet's fraction of energy deposited in each of the ECal and HCal layers as input variables. Input for a BDT study per jet and then BDT per event.

Analysis Strategy

- Dedicated signature-driven trigger: “**CalRatio Trigger**”.
 - Although the jets from neutral LLP decays pass standard jet triggers, the high prescales of these triggers and the high multijet and other background-process cross-sections required a dedicated trigger selection.
- **Event Selection: BDT per jet and cut of BDT per event**
 - Boosted Decision tree (BDT) is used to select signal based on kinematics of the jets
- **Modifying Jet quality cuts and systematics**
- **Non standard background:** cosmics and beam induced background are quite relevant, along with multijets
 - Background estimation from ABCD Method



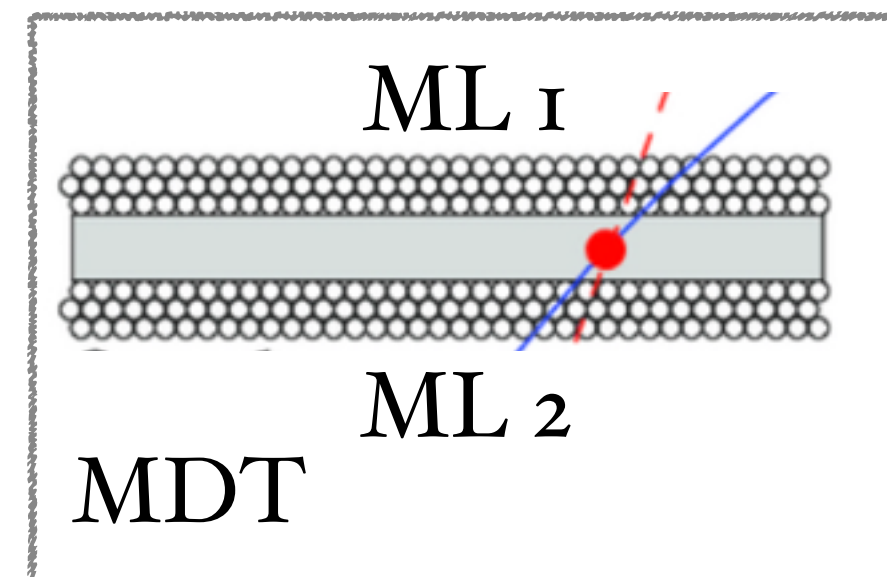
Displaced Jets in MS

This analysis look for: **one or two displaced vertexes in the MS**

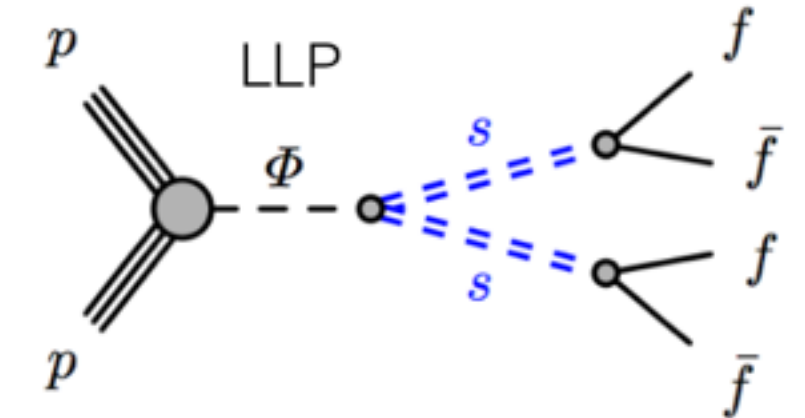
- **One/Two vertexes for inclusive and Hidden Valley Models searches**
- **Two vertexes with 2 jets for Stealth SUSY Model searches**
- **MS vertex is obtained by a dedicated algorithm** using hits from each tracking station MDT (a tracklet) matched with trigger chamber to extract the line of flight and then the track parameter. Quality cuts are applied on the trackless to reduce fake vertexes

Main backgrounds:

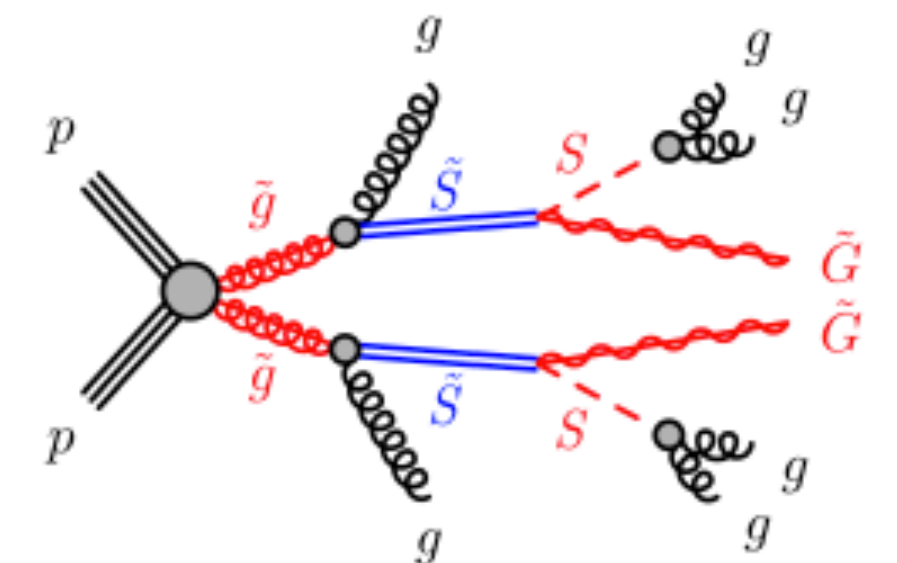
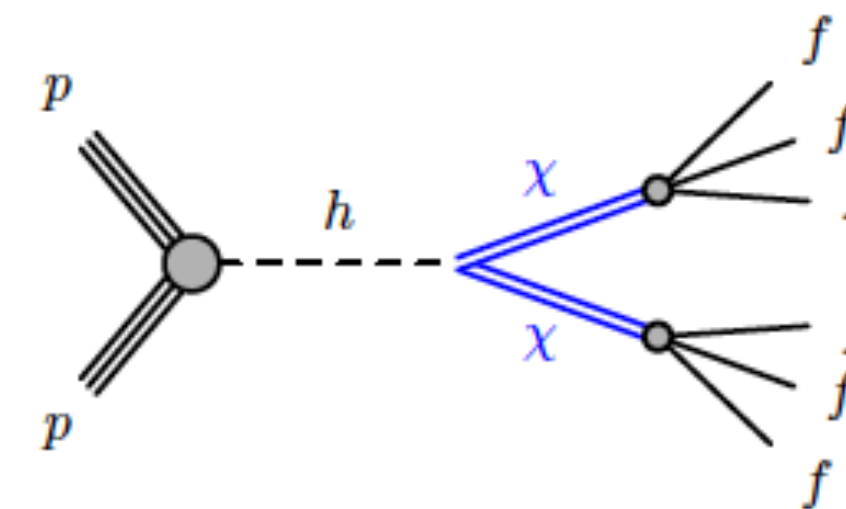
- QCD multi-jets
- Beam Halo,
- cosmons.



Model Interpretation: **Weakly coupled Hidden Sector (HS)** communicates with the SM via neutral LLP that decays within the ATLAS detector.



Model Interpretation: **Stealth SUSY and Higgs portal Baryogenesis model**



Quality cuts on tracklet

	Barrel	Endcaps
Precision chamber hits	$300 < n_{\text{MDT}} < 3000$	
Trigger chamber hits	$n_{\text{RPC}} > 250$	$n_{\text{TGC}} > 250$
Isolation from $p_T > 5$ GeV tracks	$\Delta R > 0.3$	$\Delta R > 0.6$
Σp_T of tracks in $\Delta R = 0.2$ cone	< 10 GeV	< 10 GeV
Isolation from $p_T > 30$ GeV jets	$\Delta R > 0.3$	$\Delta R > 0.6$
MSVx $ \eta $	$ \eta_{\text{MSVx}} < 0.7$	$1.3 < \eta_{\text{MSVx}} < 2.5$

Displaced Jets in ID and MS

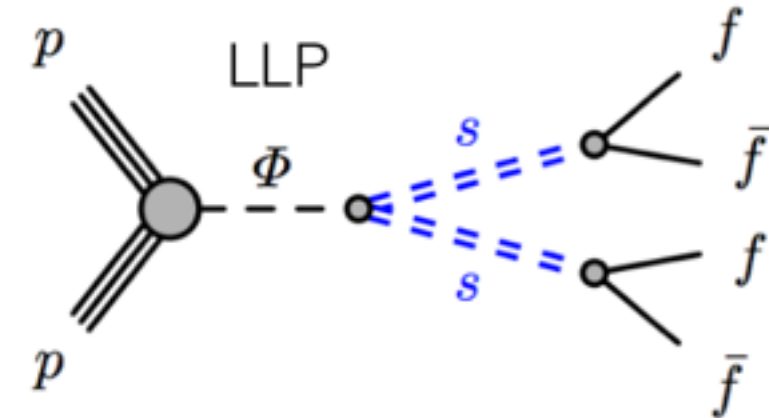
This analysis look for: **two displaced vertexes**, one in the MS and one in the ID

- **A vertex in the MS isolated wrt jets and tracks** (as displaced MS analysis)
- **Displaced ID vertex is computed by using the Large Radius Tracking (LRT) algorithm.** LRT is a dedicated second pass of the tracking ran on leftover hits from the standard track but with **looser cut on d_0 and z_0** algorithm.
- Additional cuts on the mass (A) and number of tracks (B) belonging to each vertex.

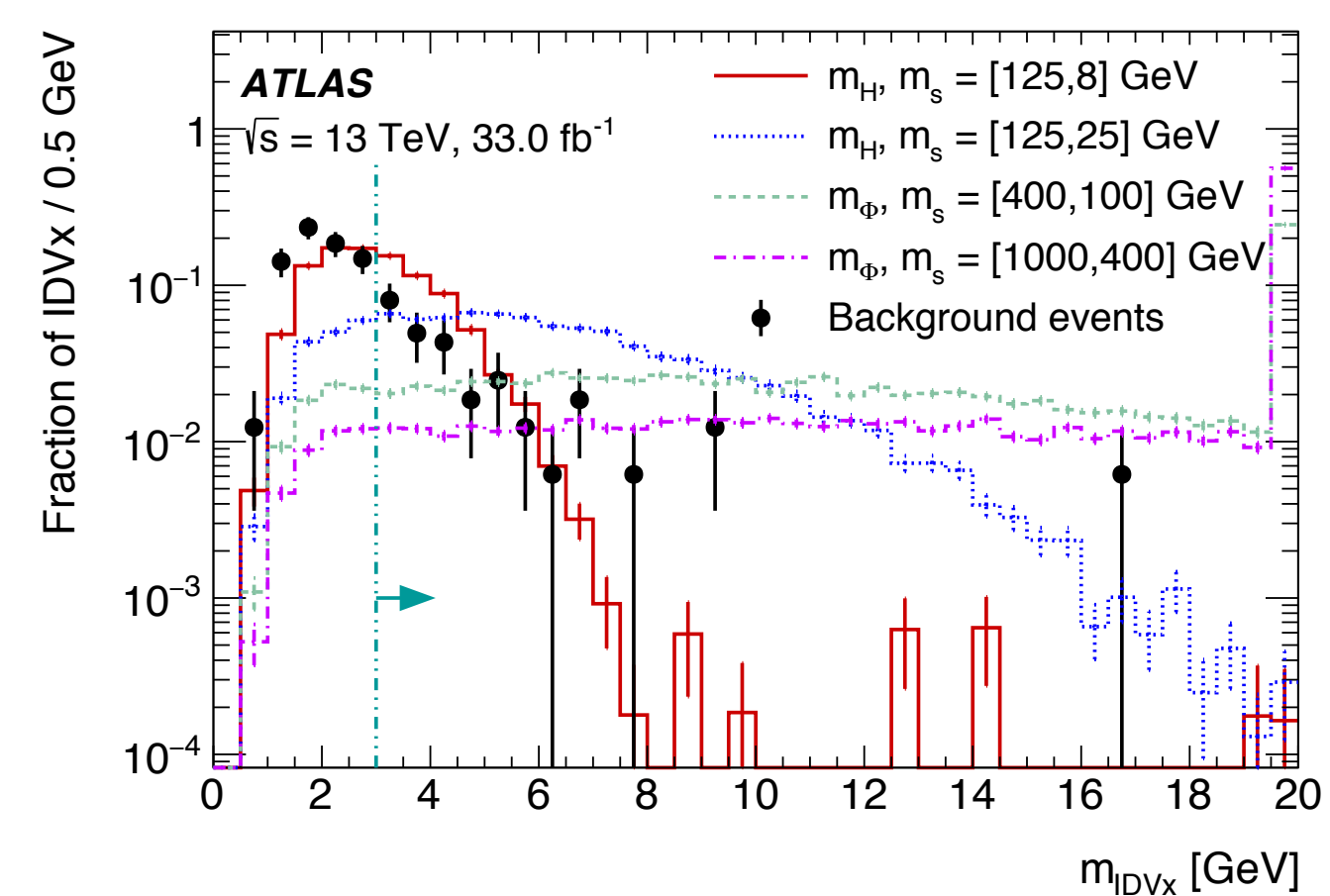
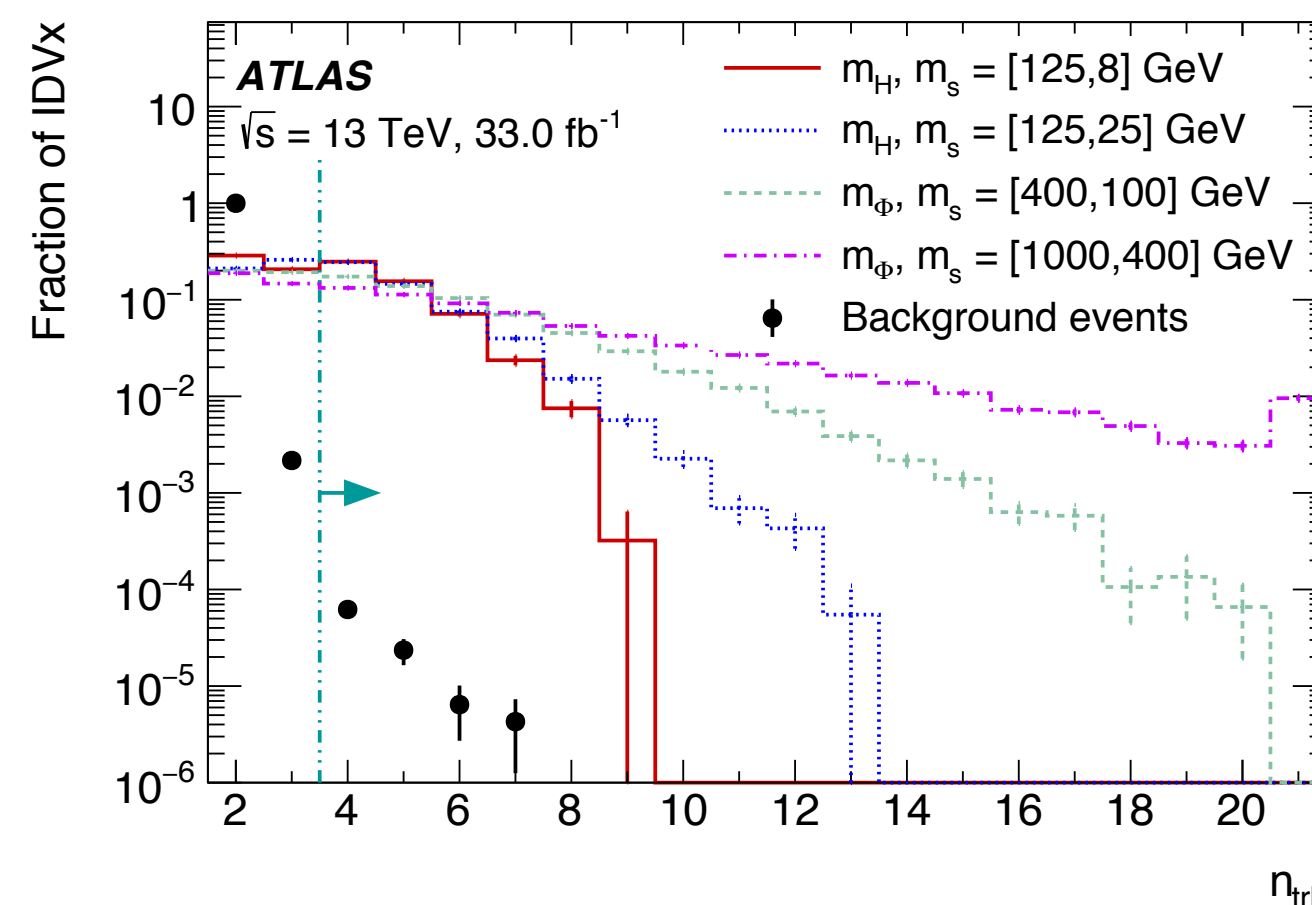
Main backgrounds:

- ID vertex background from hadrons interaction with detector material. Create a 3D map of the dense material region of the ID and veto vertices in these regions.

Model Interpretation: Weakly coupled Hidden Sector (HS) communicates with the SM via neutral LLP that decays within the ATLAS detector.

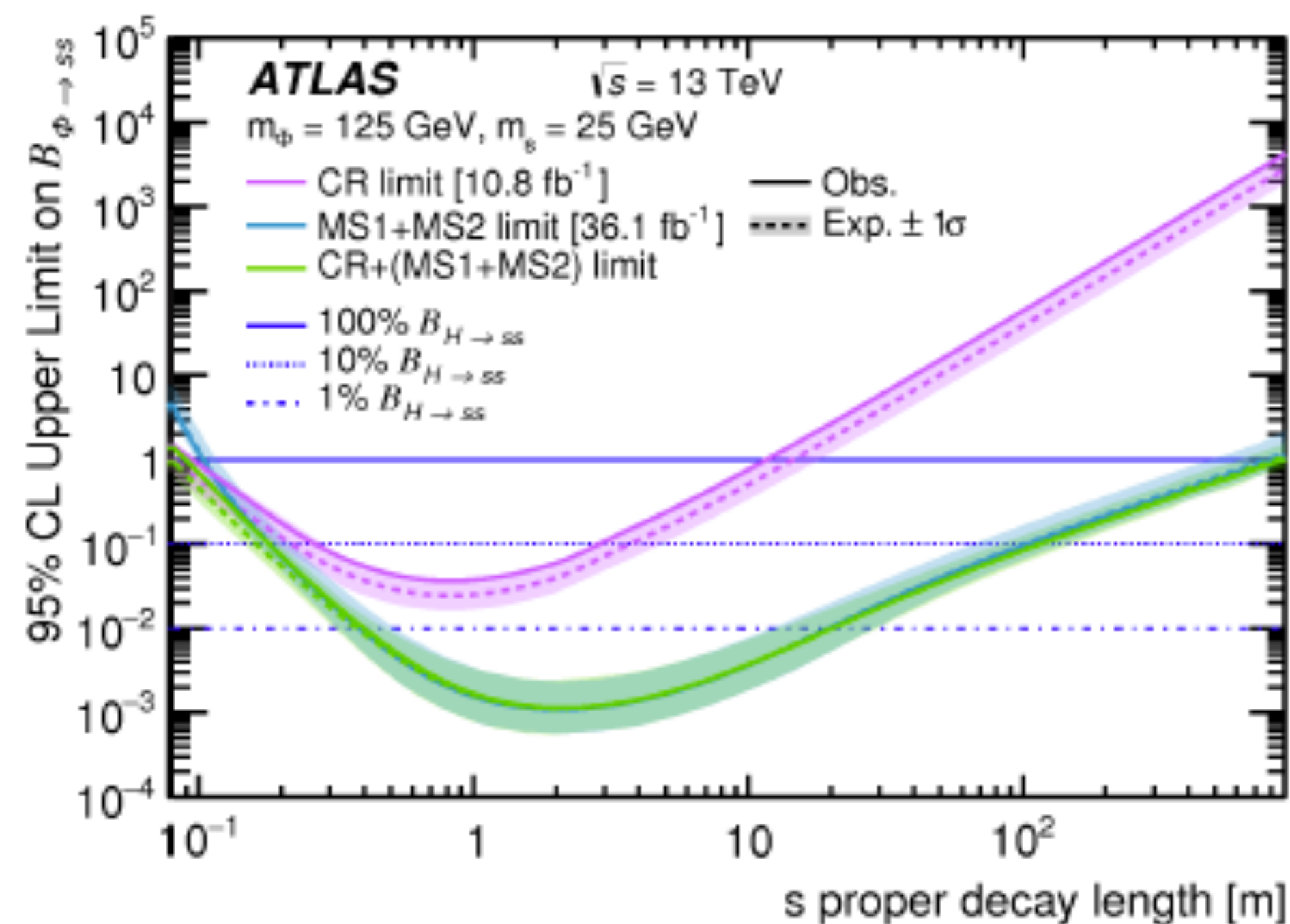


Track parameter	Standard	Large radius
Maximum $ d_0 $	10 mm	300 mm
Maximum $ z_0 $	250 mm	1500 mm
Minimum p_T	400 MeV	500 MeV
Maximum track $ \eta $	2.7	5.0
Minimum silicon hits	7	7
Minimum unshared silicon hits	6	5

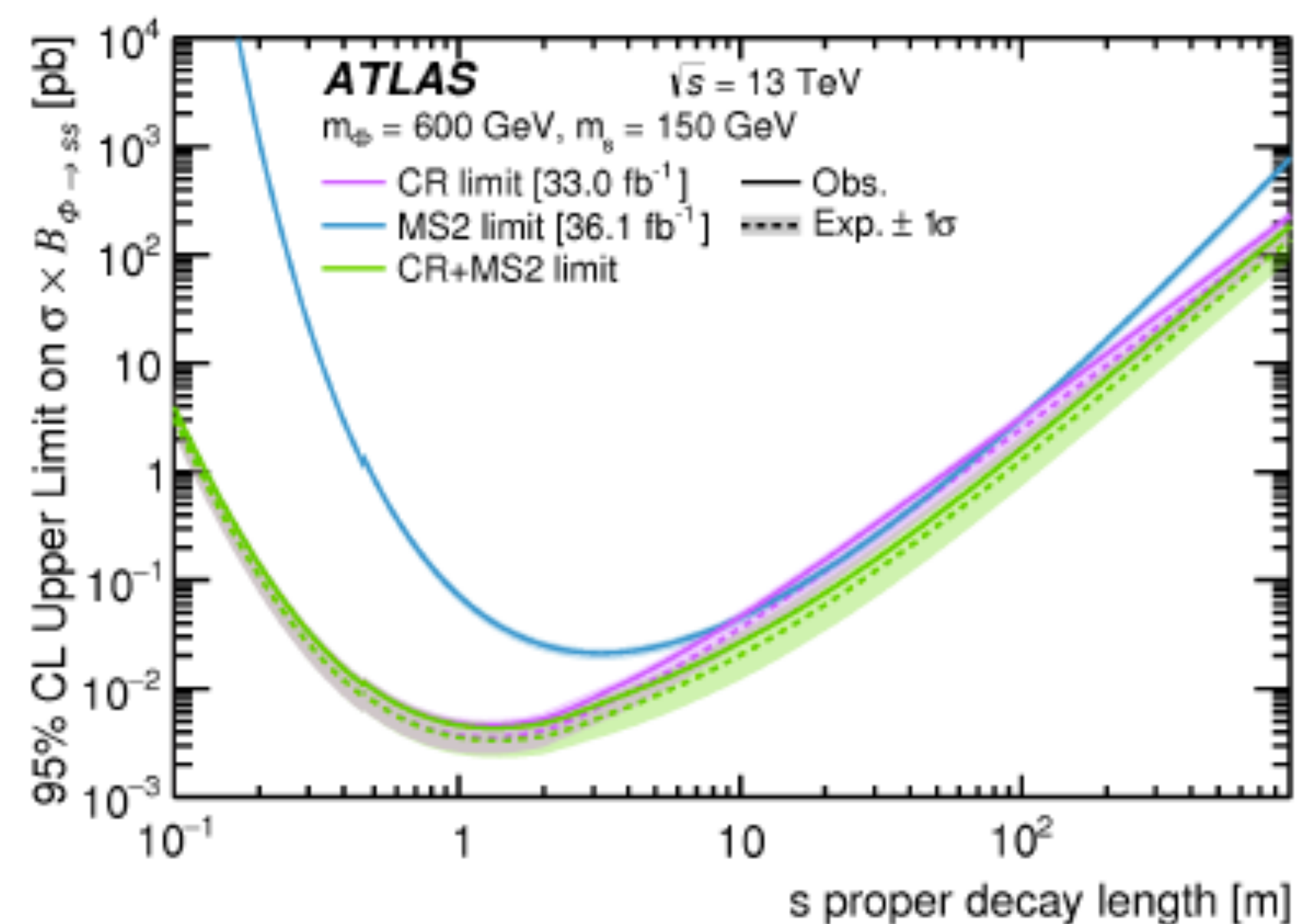


Displaced Jet Combined Limits

H(125)



H(600)



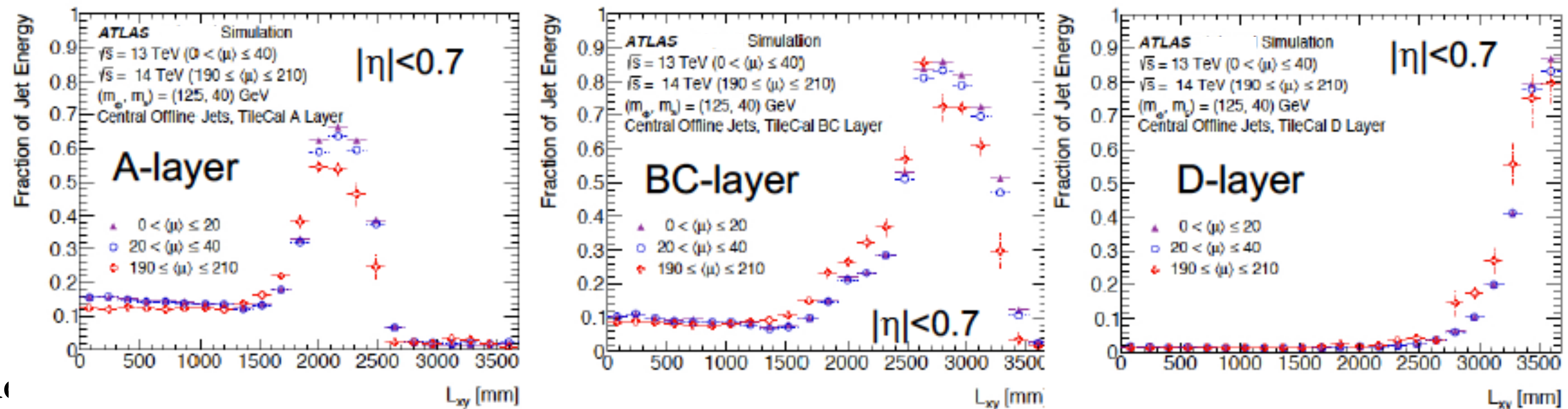
Displaced Jets in HL-LHC

Current Run2 trigger:

- Dedicated L1 trigger based on tau candidates + low EMfrac.

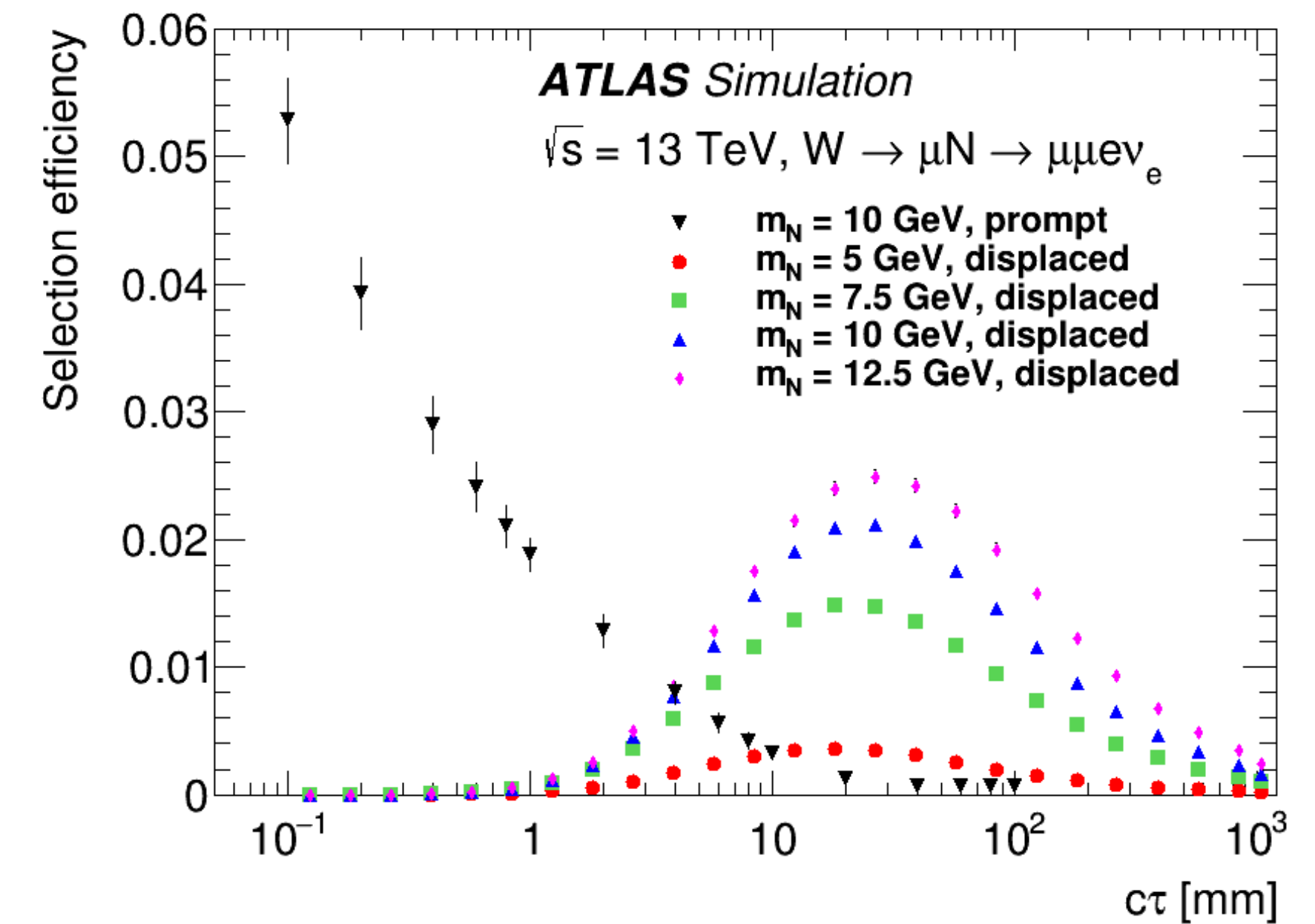
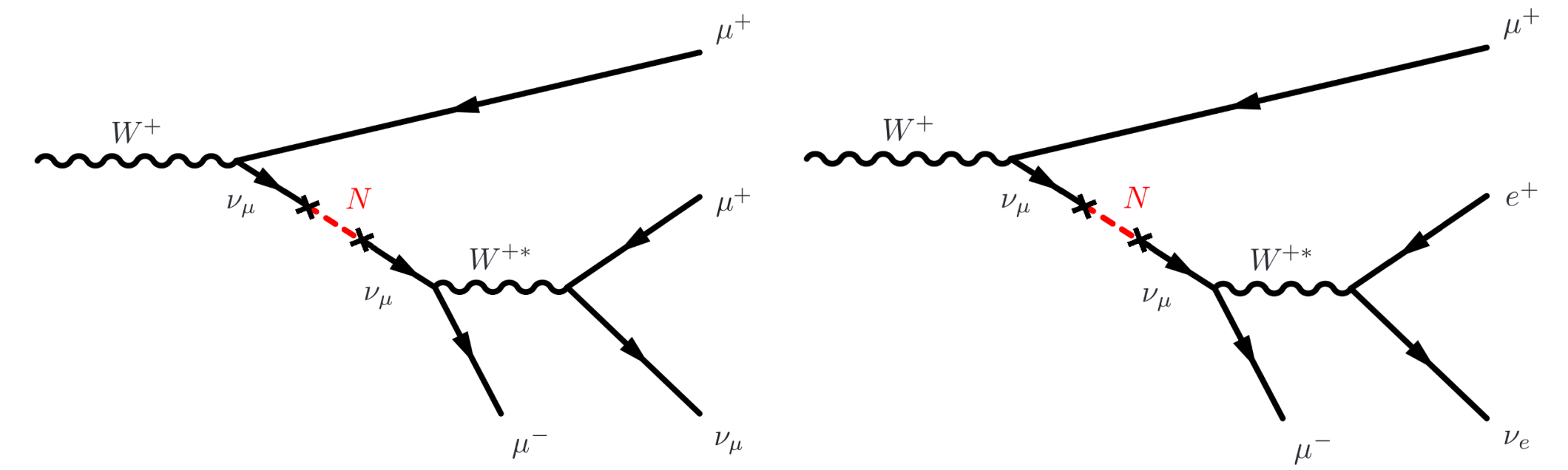
Upgraded (Phase2) trigger ideas:

- **Expected high pile-up activity in EM calorimeter: low EMfrac jets will become problematic.**
- **Increased longitudinal L1 granularity in Tile:**
 - Compare energy deposit per layer will reduce sensitivity to pileup.
 - The energy deposit per layer could be use to identify the exact decay point



Heavy Neutral Lepton HNL

- **Search for heavy neutral leptons (HNLs)** that are produced through mixing with muon or electron neutrinos (Right-handed neutrinos with Majorana masses below the electroweak scale: see-saw mechanism). **HNLs could explain SM neutrino masses, matter-antimatter asymmetry, and is a DM candidate**
- **Prompt and displaced leptonic decay signatures are investigated.**
 - **The prompt signature requires three leptons** produced at the interaction point (either $\mu\mu e$ or $e\mu\mu$) with a veto on same-flavour opposite-charge topologies.
 - **The displaced signature looks for a prompt muon from the W boson decay and the requirement of a di-lepton vertex** (either $\mu\mu$ or μe) **displaced** in the transverse plane by 4–300 mm from the interaction point.



Heavy Neutral Lepton HNL

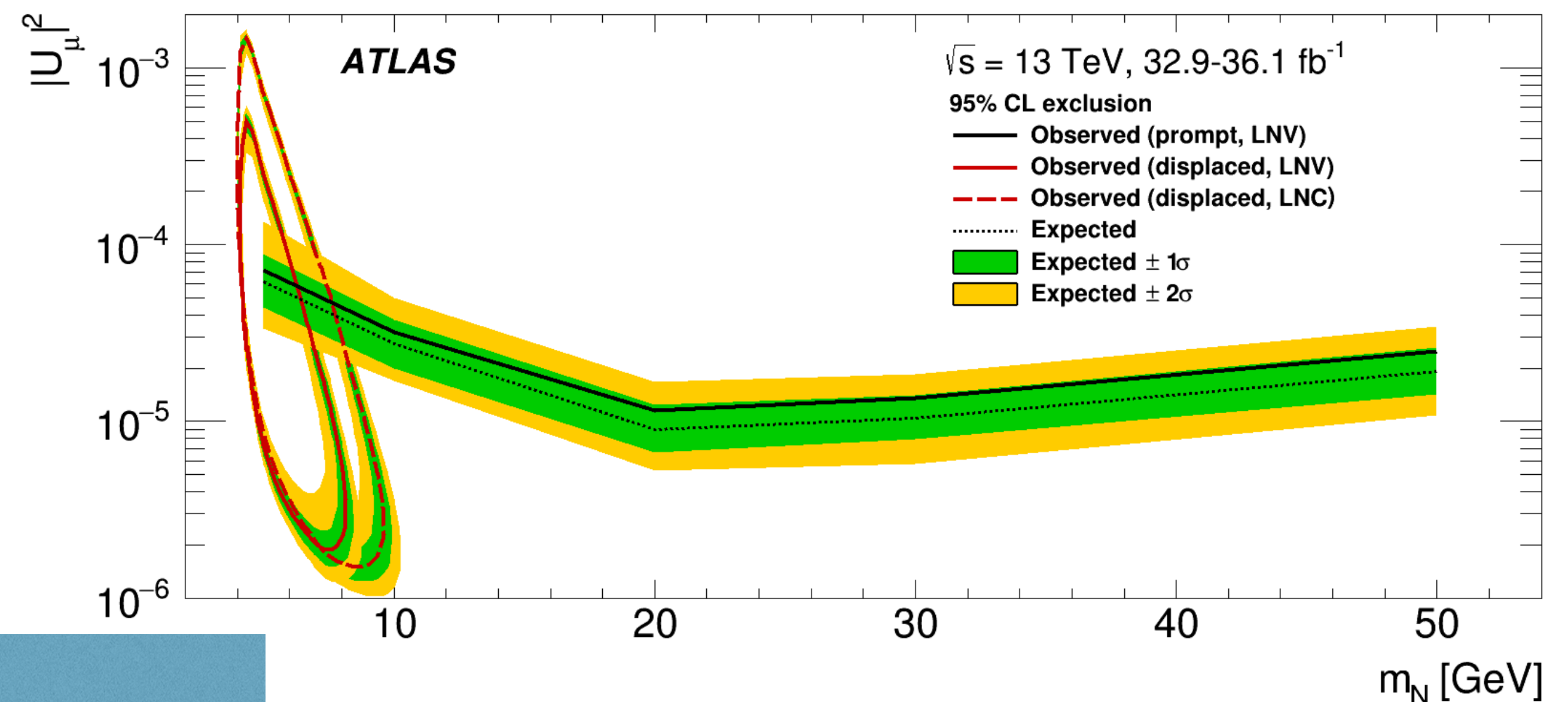
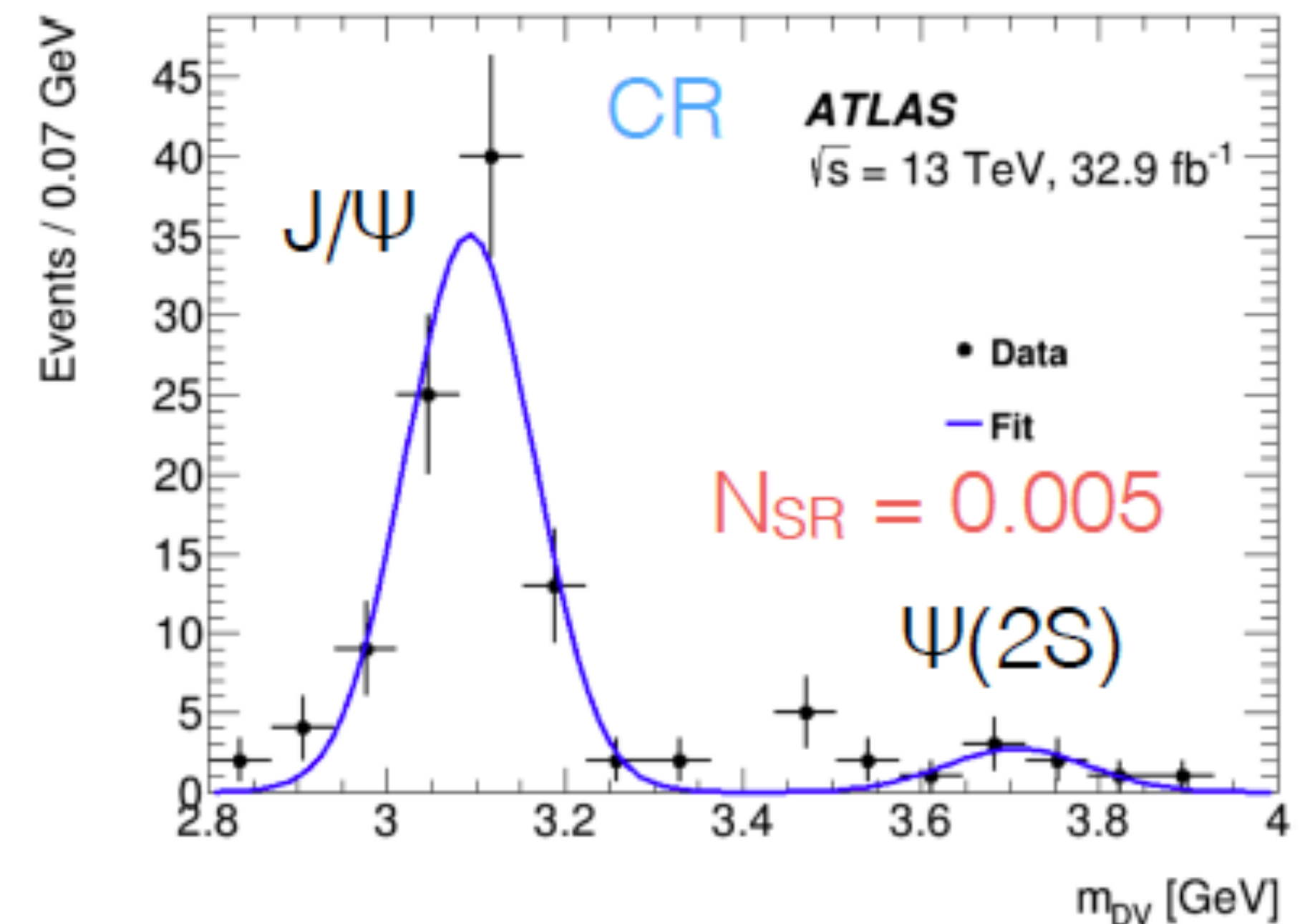
- Signal Region in displaced search:**

- Exactly 2 OS tracks
- Tight* electron or muon
- $m_{DV} > 4 \text{ GeV}$
- $4 < R < 300 \text{ mm}$

- Signal Region in prompt search:**

- 3 leptons from PV, cut on $m(l\bar{l}l)$
- Displaced ID vertex (DV) is computed by using the Large Radius Tracking (LRT)

Backgrounds from interaction with inert material and metastable states (negligible for $m_{DV} > 4 \text{ GeV}$), random track crossing background modelled with ABCD method



No evidence for HNLs observed:

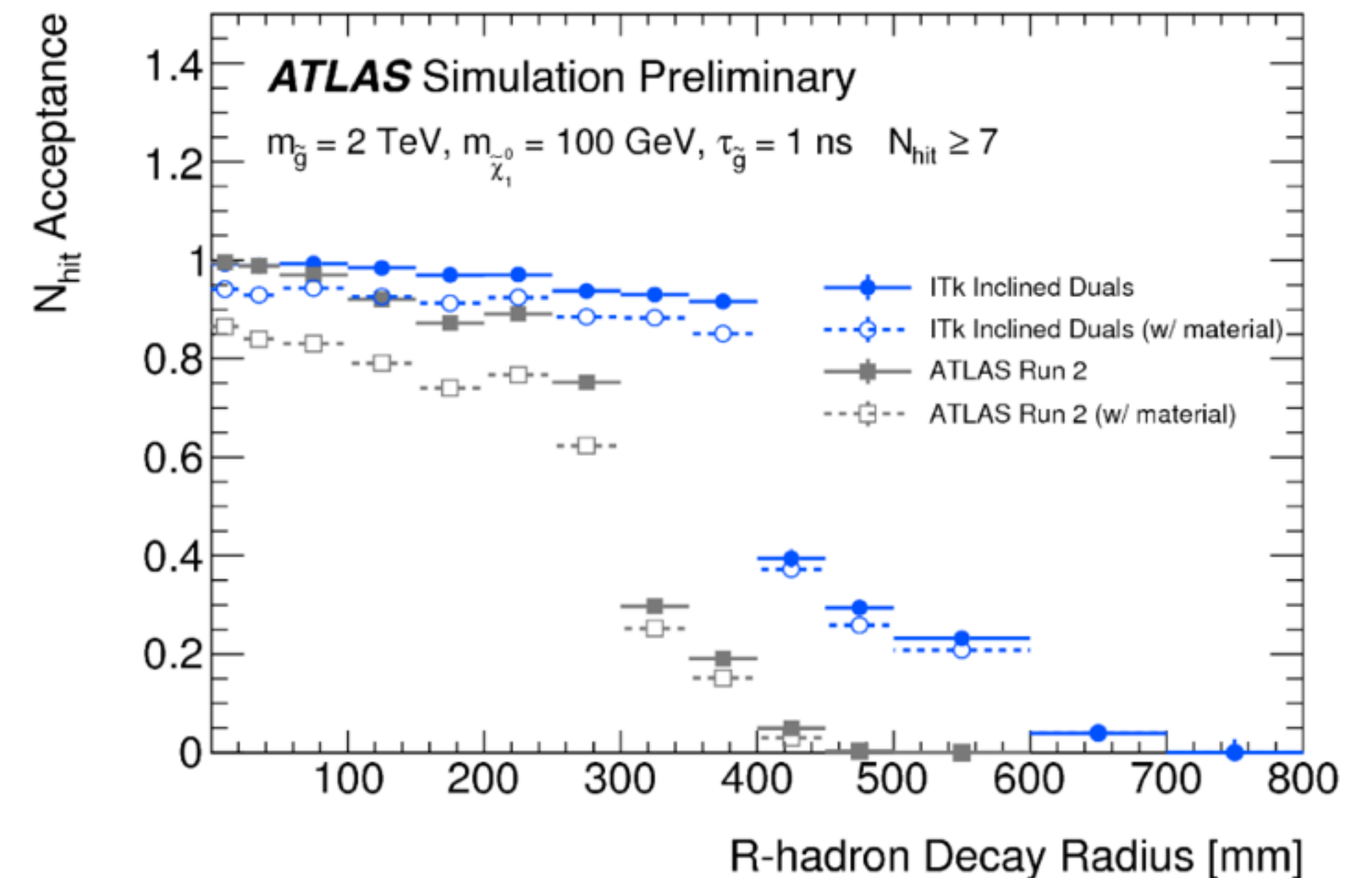
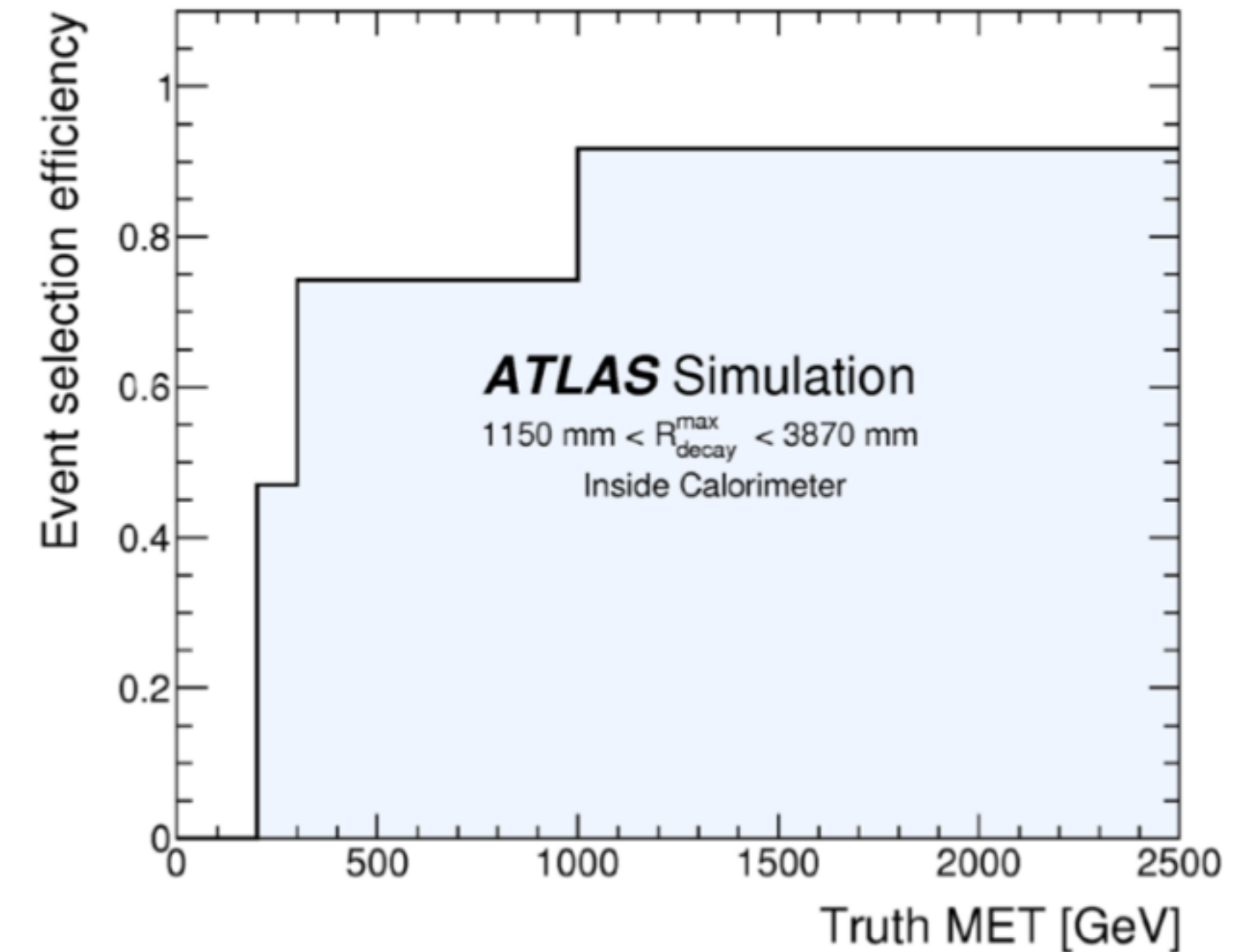
Displaced signatures: excluded coupling strength to 1.5×10^{-6}

Prompt signatures: excluded coupling strength to 1.1×10^{-5}

Displaced Vertices in HL-LHC

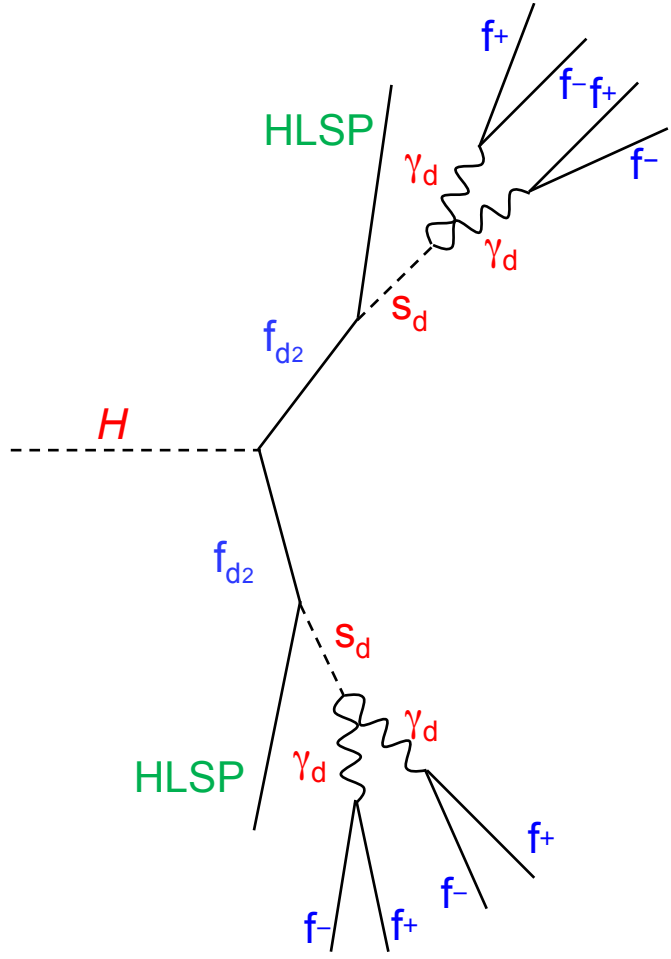
Selection (taken from Run 2 analysis):

- Relies on reconstructing displaced tracks and displaced vertices from those.
- Veto of vertices in detector material & MET above 200 GeV.
- Requires at least one vertex with at least 5 tracks & DV mass at least of 10 GeV.
- Reconstruction efficiency (reach) for displaced tracks increases up to 400 (500) mm.**

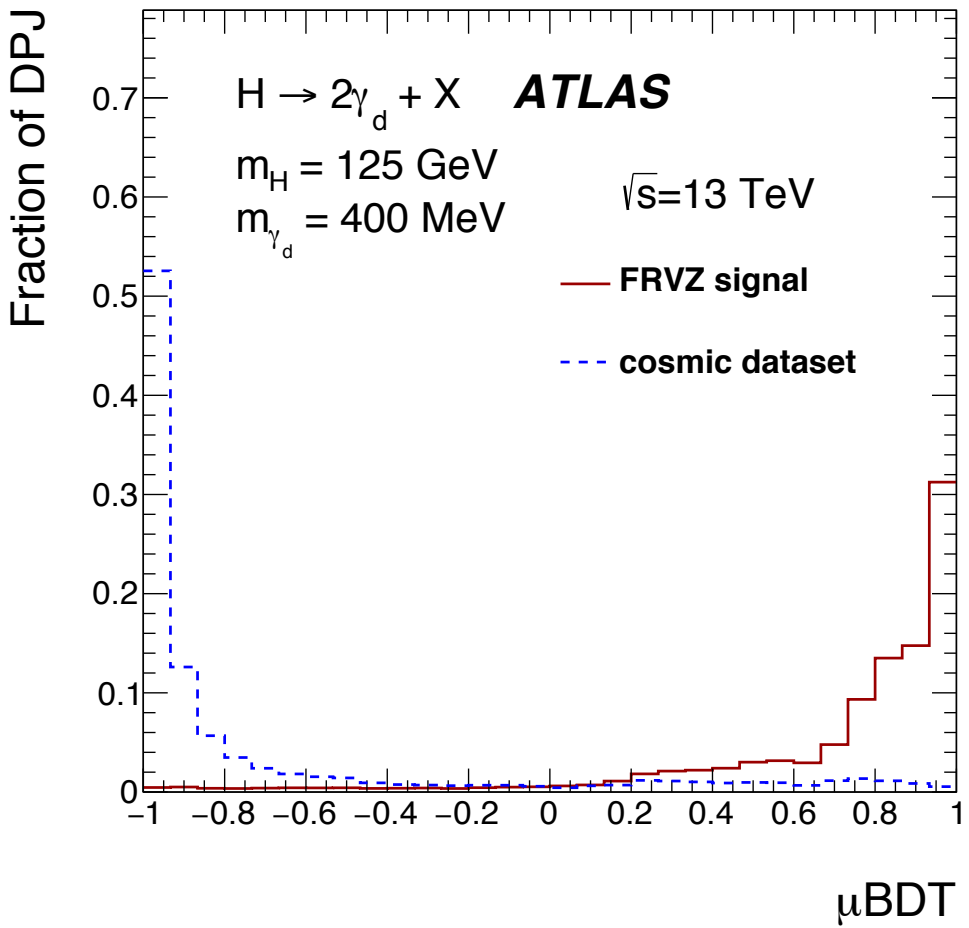
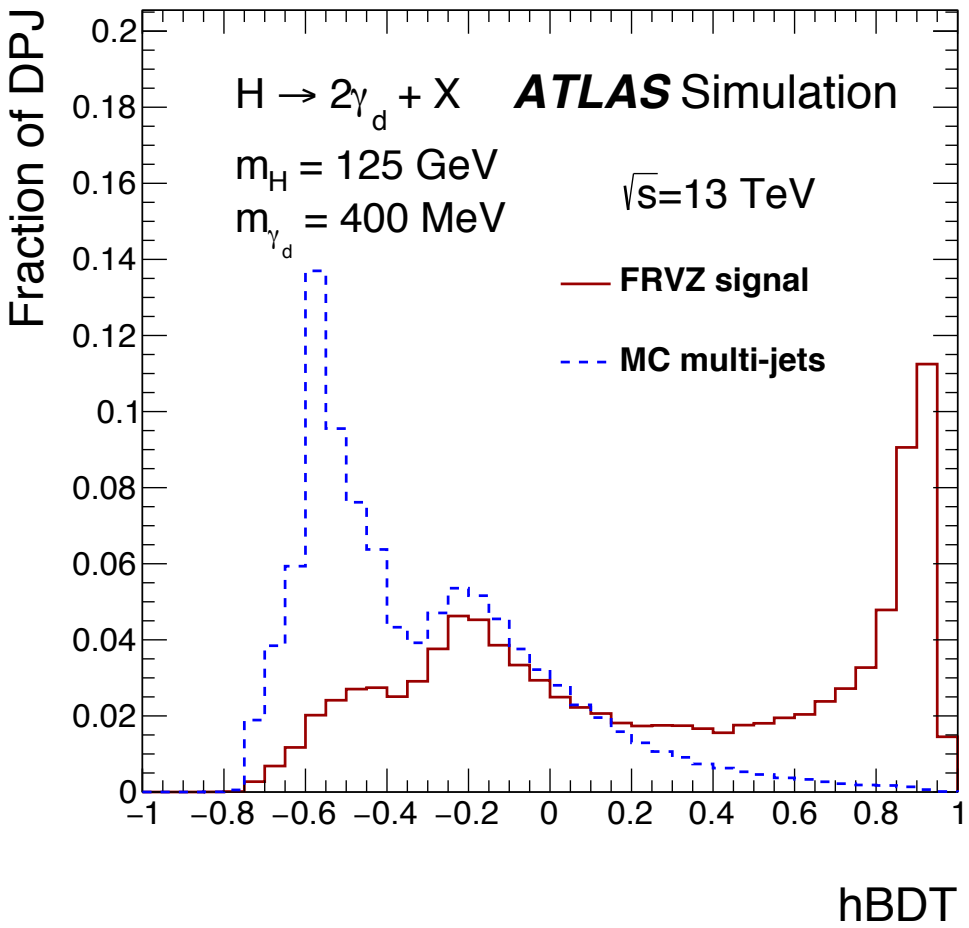
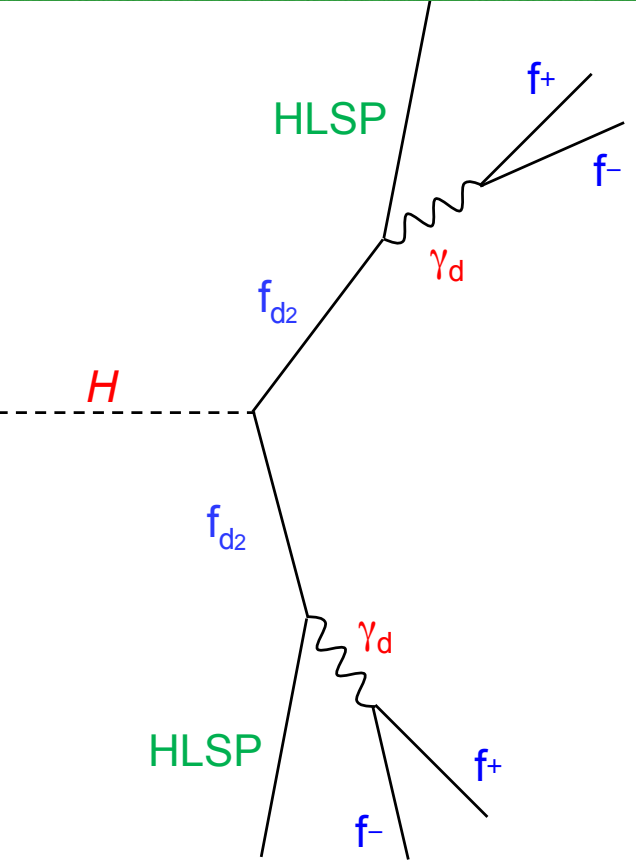


Dark Photons

- Several models of physics beyond the Standard Model predict the existence of **dark photons, light neutral particles decaying into collimated leptons or light hadrons**.
- **This search looks for a long-lived dark photons produced from the decay of a Higgs boson or a heavy scalar boson and decaying into displaced collimated Standard Model fermions.**
- The analysis exploits **multivariate techniques for the suppression of the main multi-jet background**, optimised for the different DPJ channels
 - **muonic-DPJ (μ DPJ)** – DPJs decays into muons, at least **two muons are required and no jets are allowed in the cone**.
 - **hadronic-DPJ (hDPJ)** – DPJs decays into electron or pion pairs in the HCAL, **one jet is required and no muons are allowed to be in the cone**.



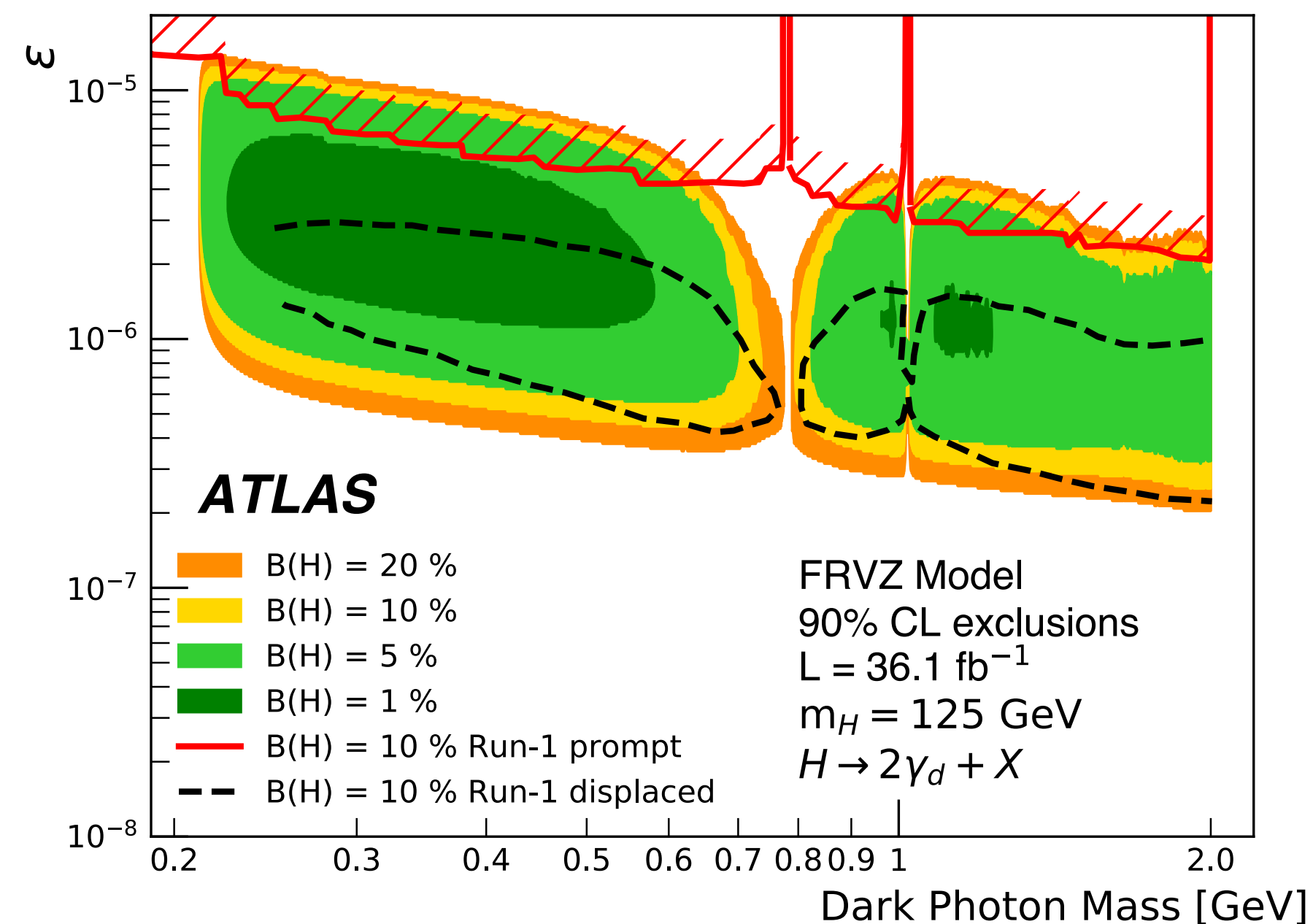
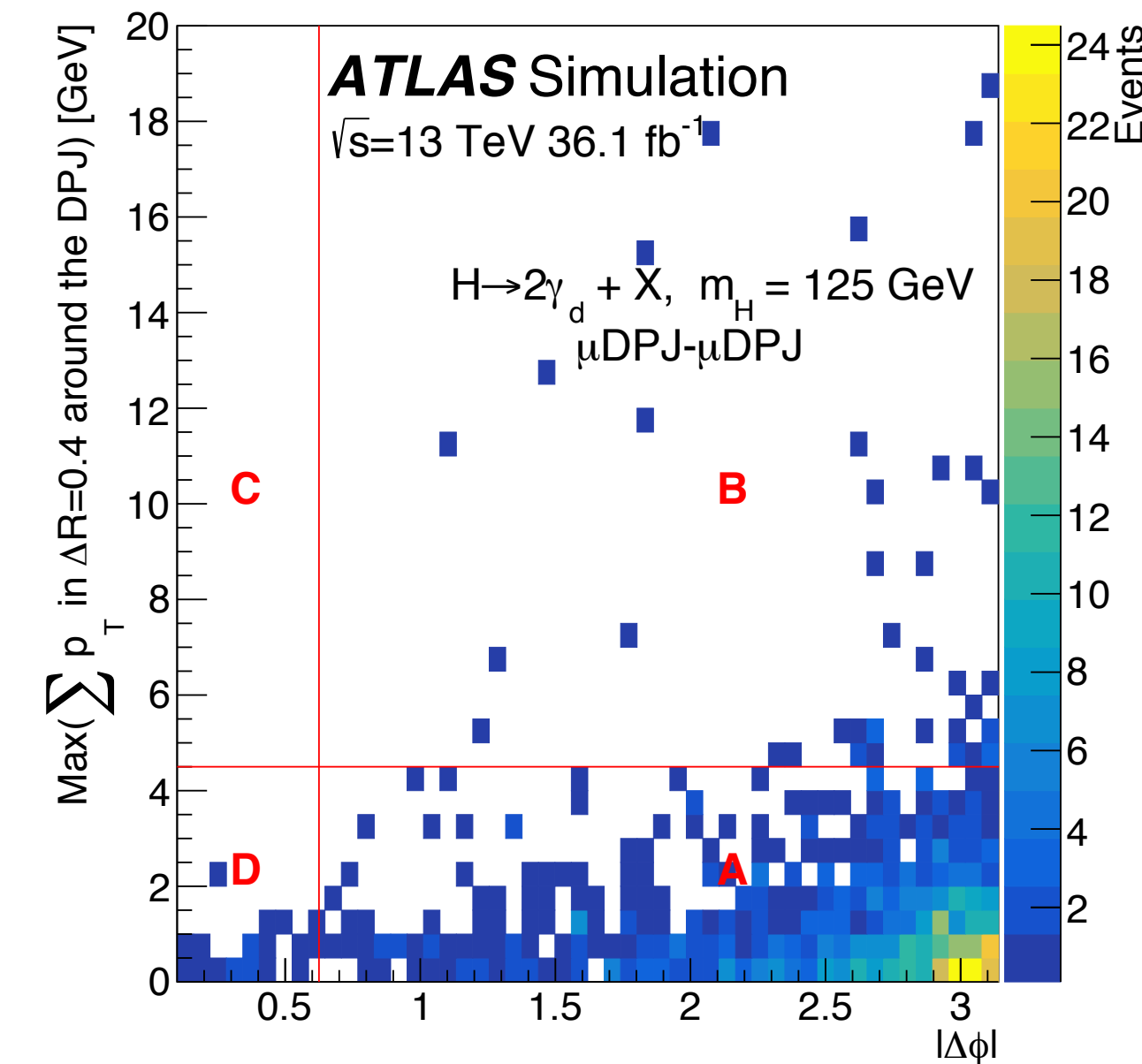
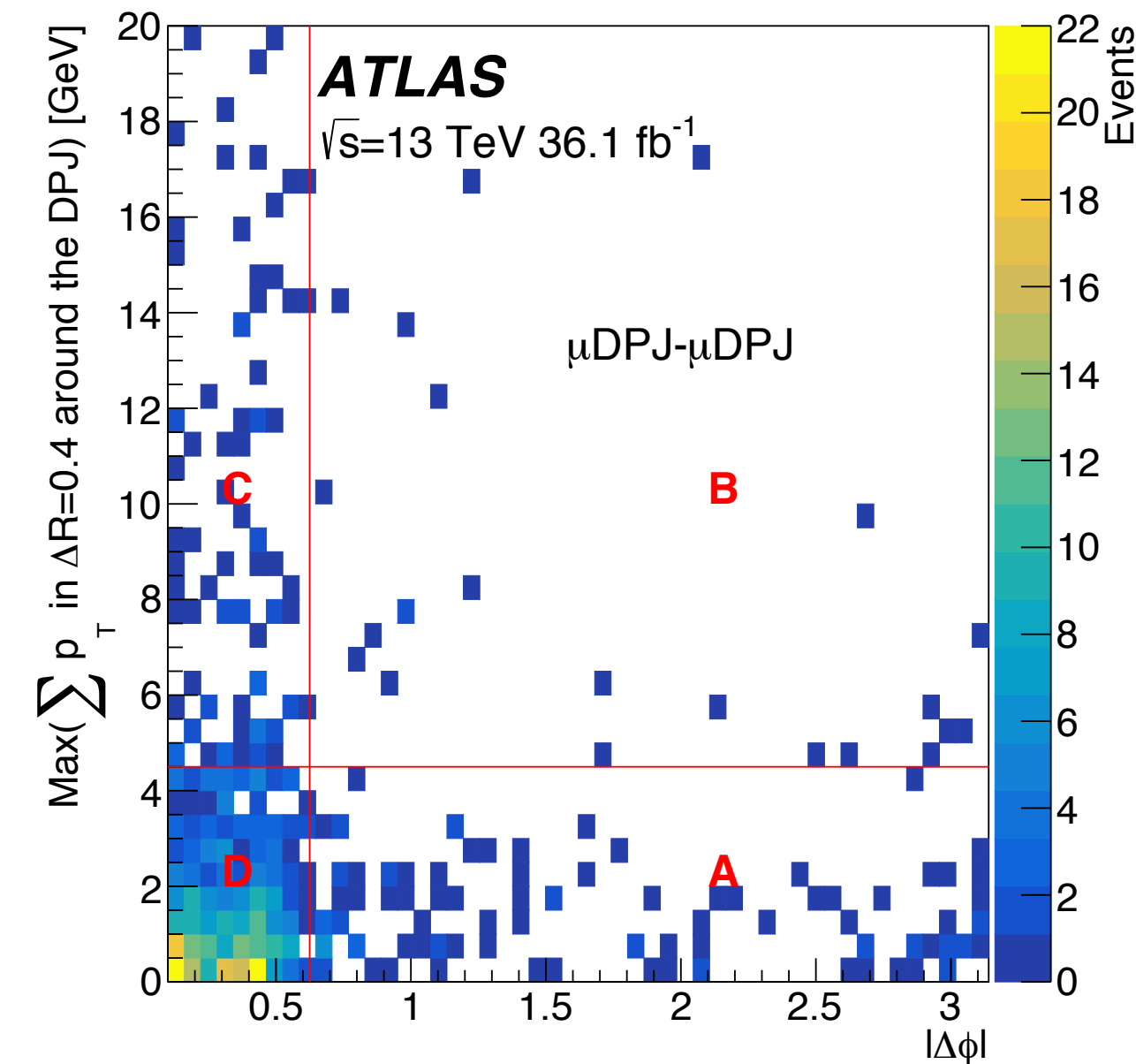
FRVZ signal sample



Region	Channel	Criteria
SR	μ DPJ- μ DPJ	μ BDT > 0.21 for both DPJs
	μ DPJ-hDPJ	μ BDT > 0.21 and hBDT > 0.91
	hDPJ-hDPJ	hBDT > 0.91 for both DPJs

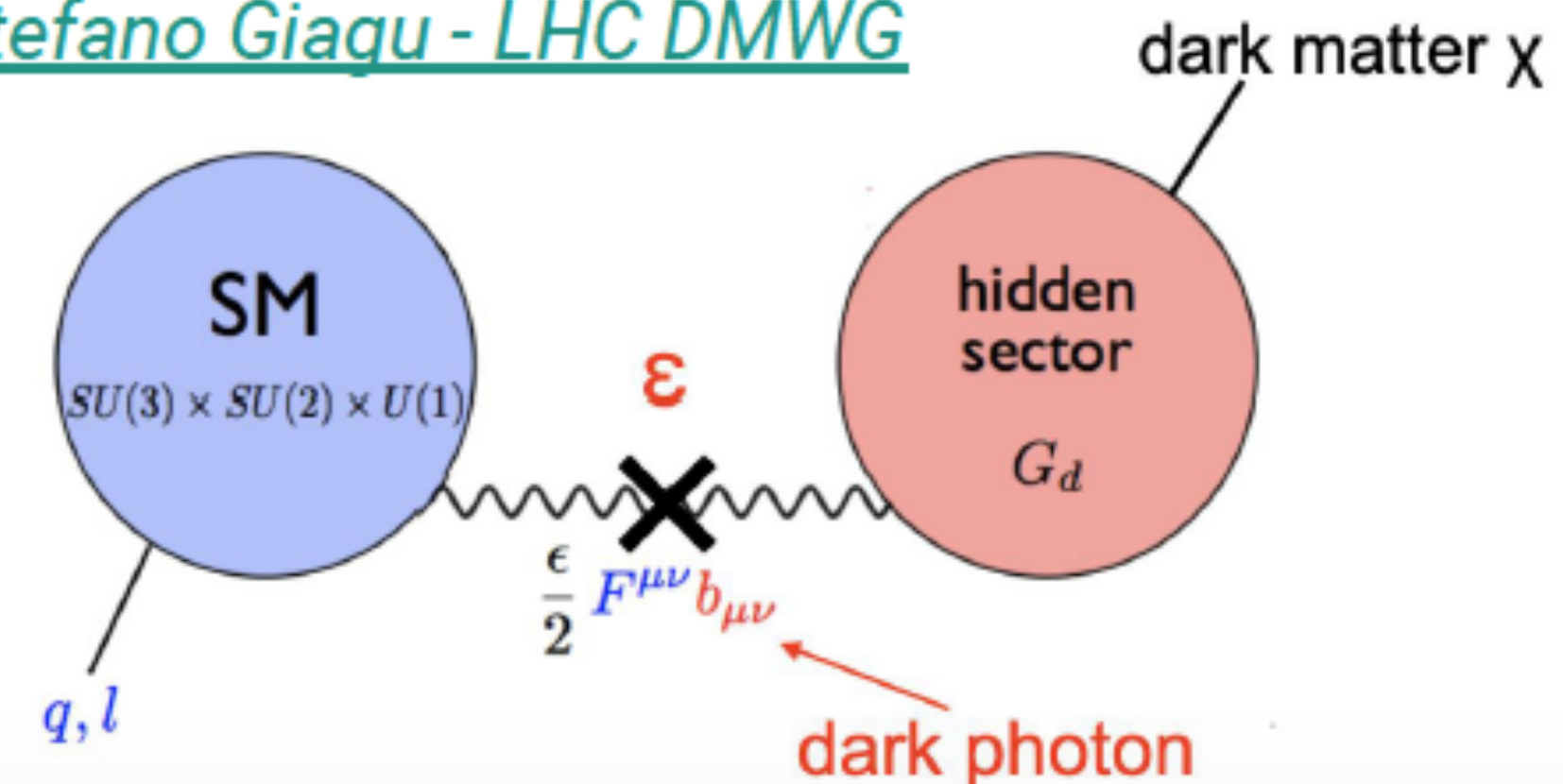
Dark Photons

- BDT for **muonic-DPJ** (μ DPJ) – background from cosmics-muon event
- BDT for **hadronic-DPJ** (hDPJ) – background from Beam-Induced Background BIB and QCD
- **A data-driven ABCD method is used to estimate the multi-jet background in each of the three channels**



The 90% CL exclusion regions for the decay $H \rightarrow 2\gamma_d + X$ of the Higgs boson as a function of the γ_d mass and of the kinetic mixing parameter

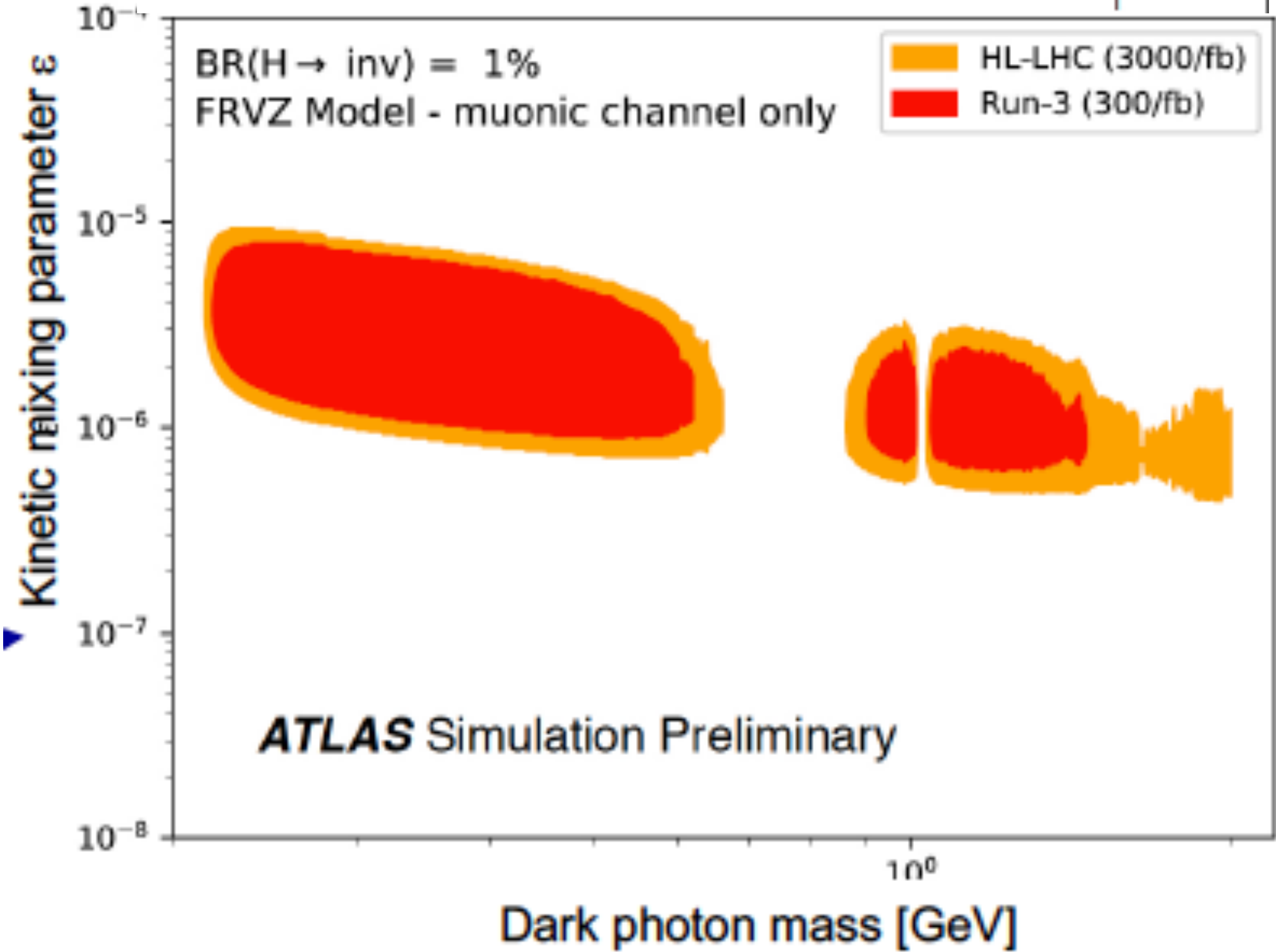
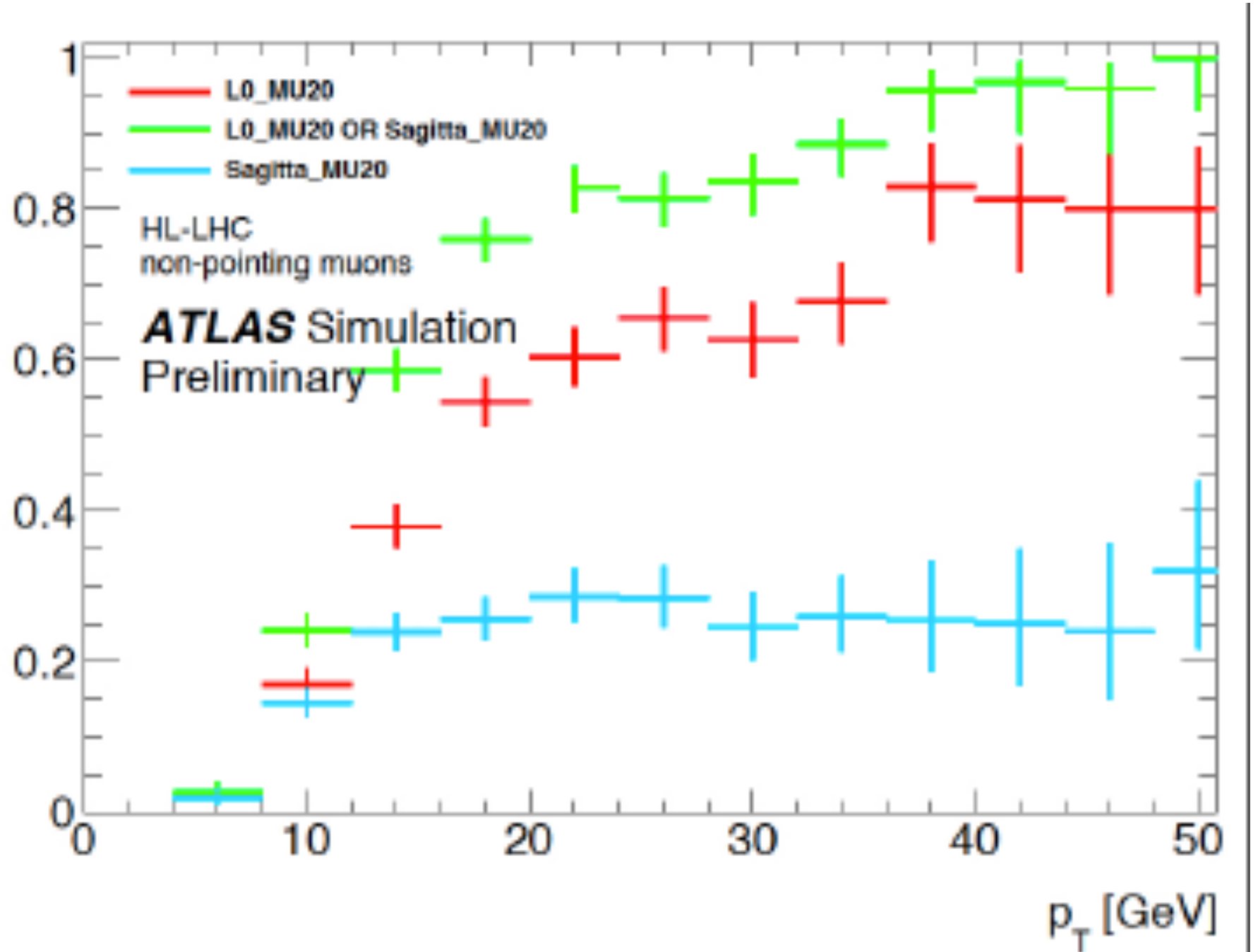
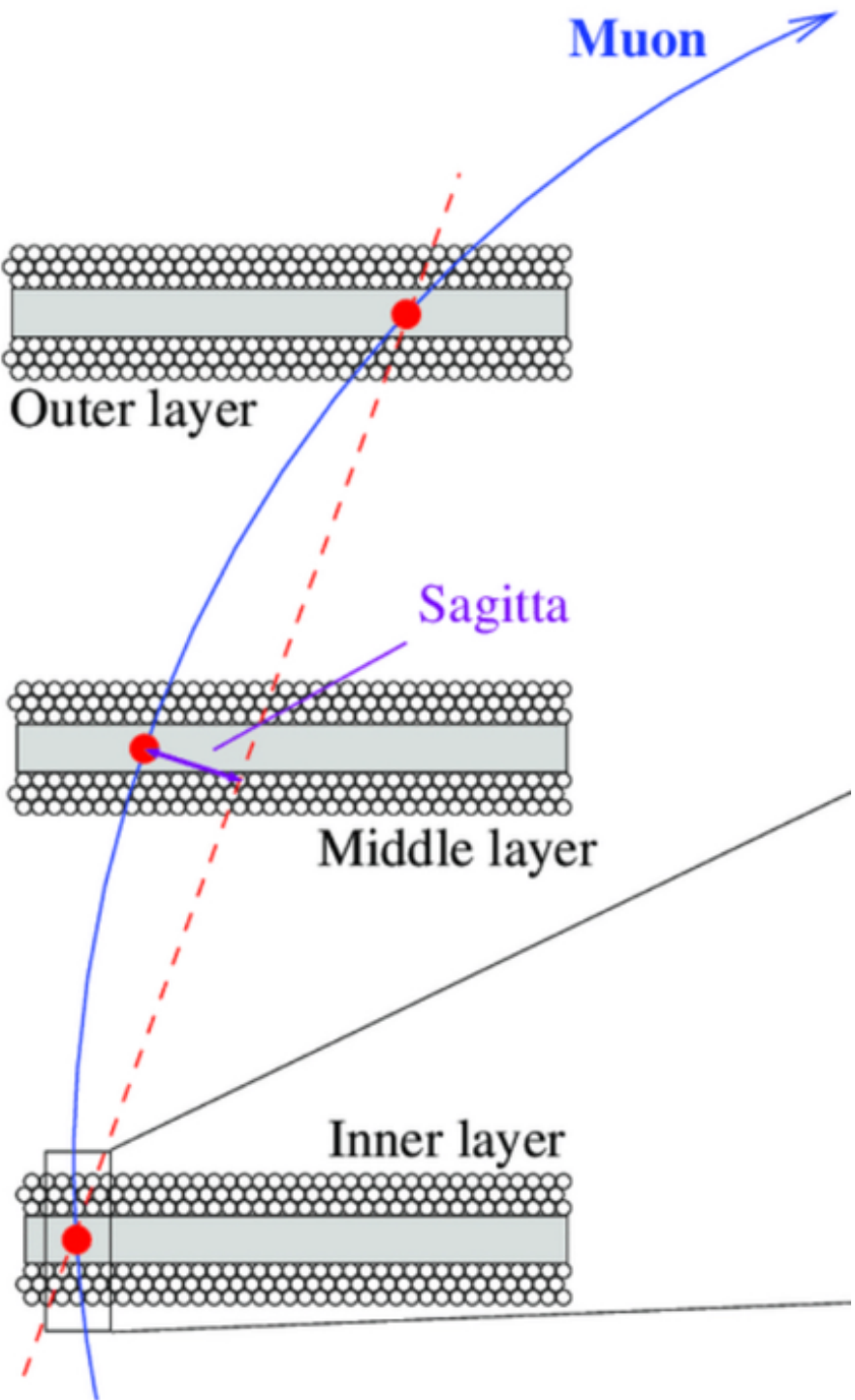
Stefano Giauq - LHC DMWG



Dark Photons at HL-LHC

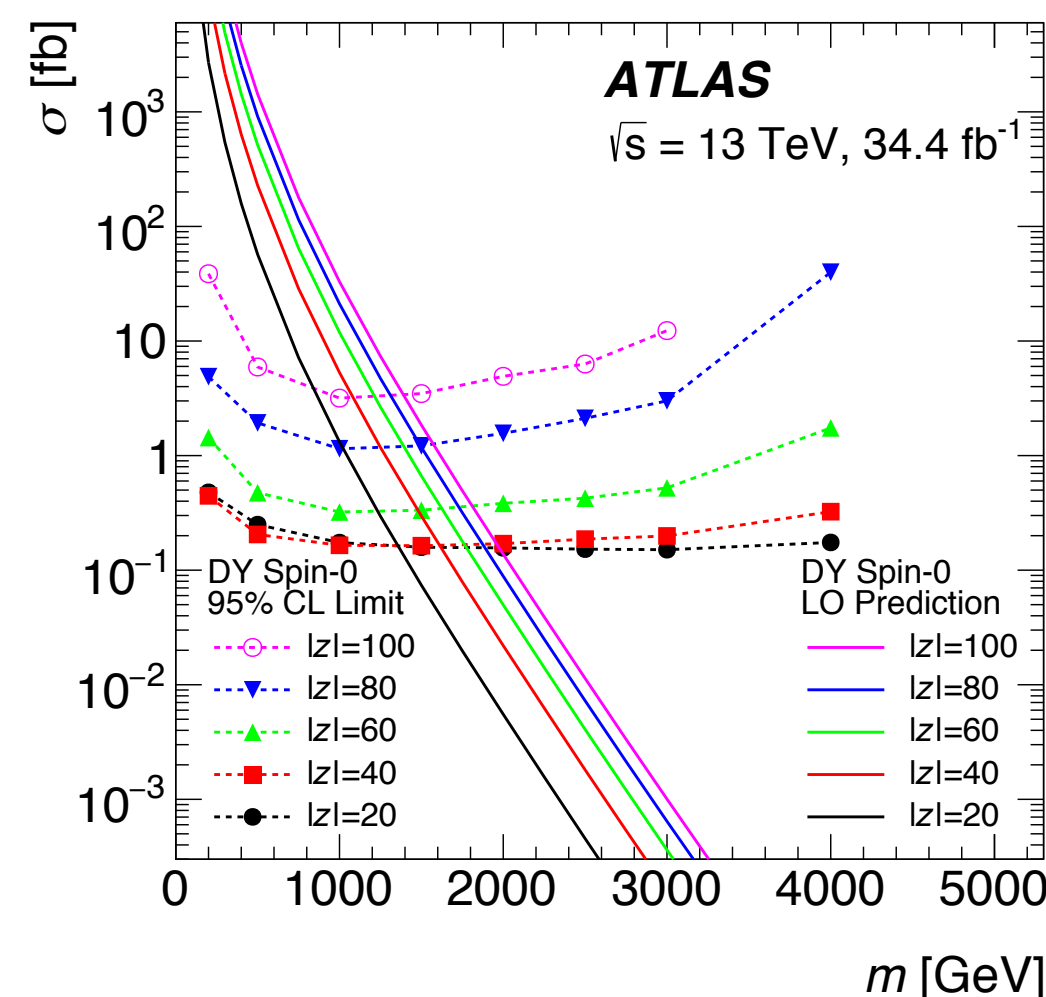
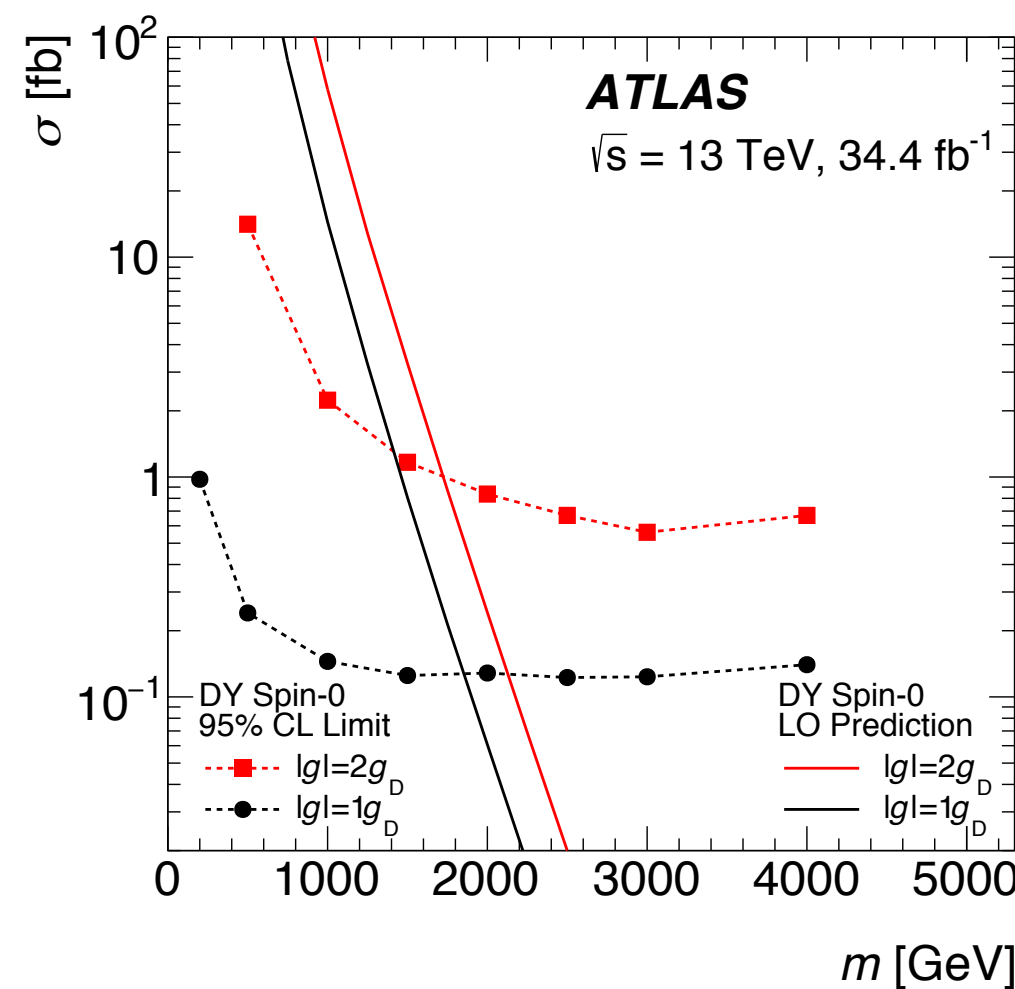
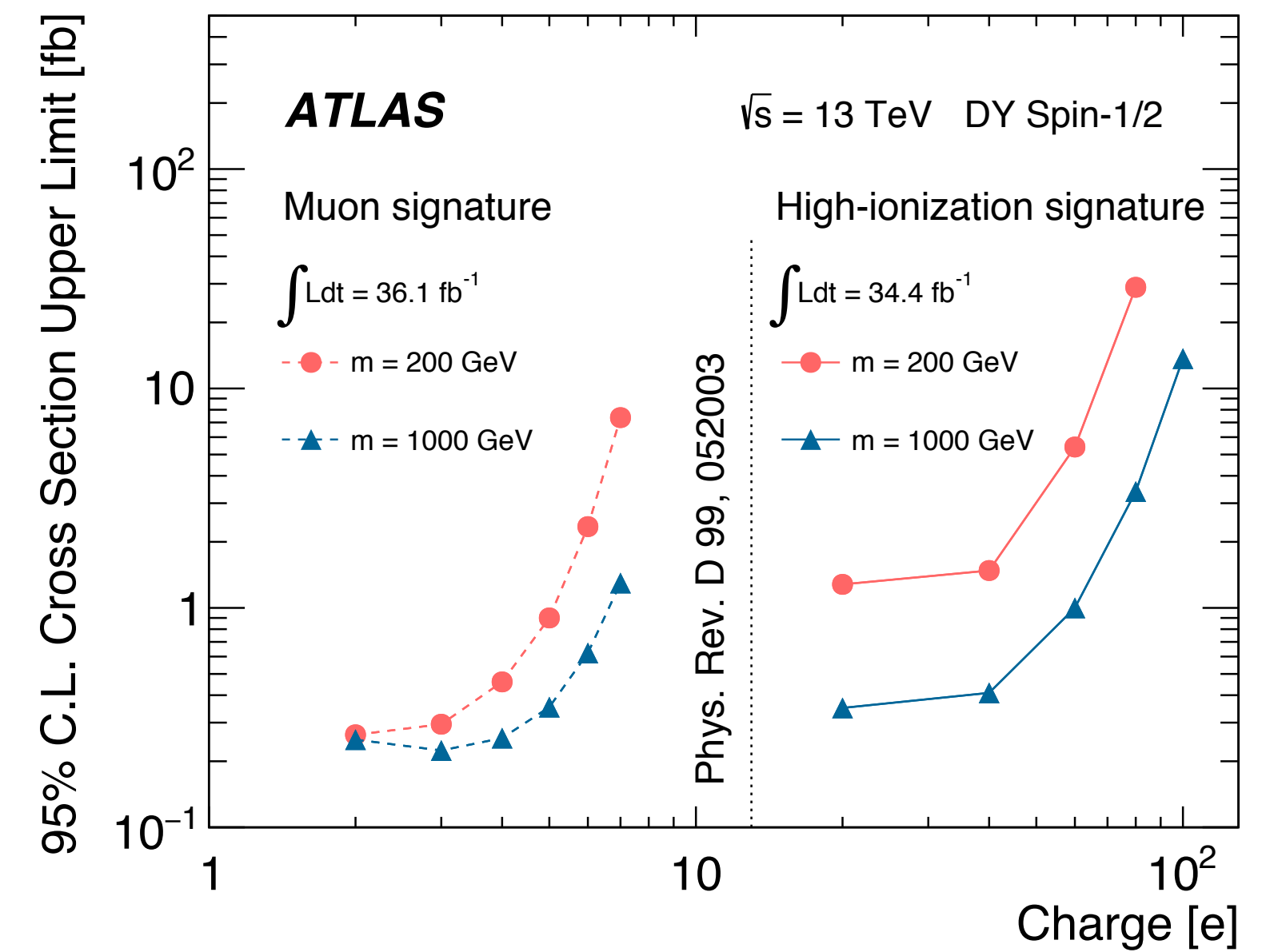
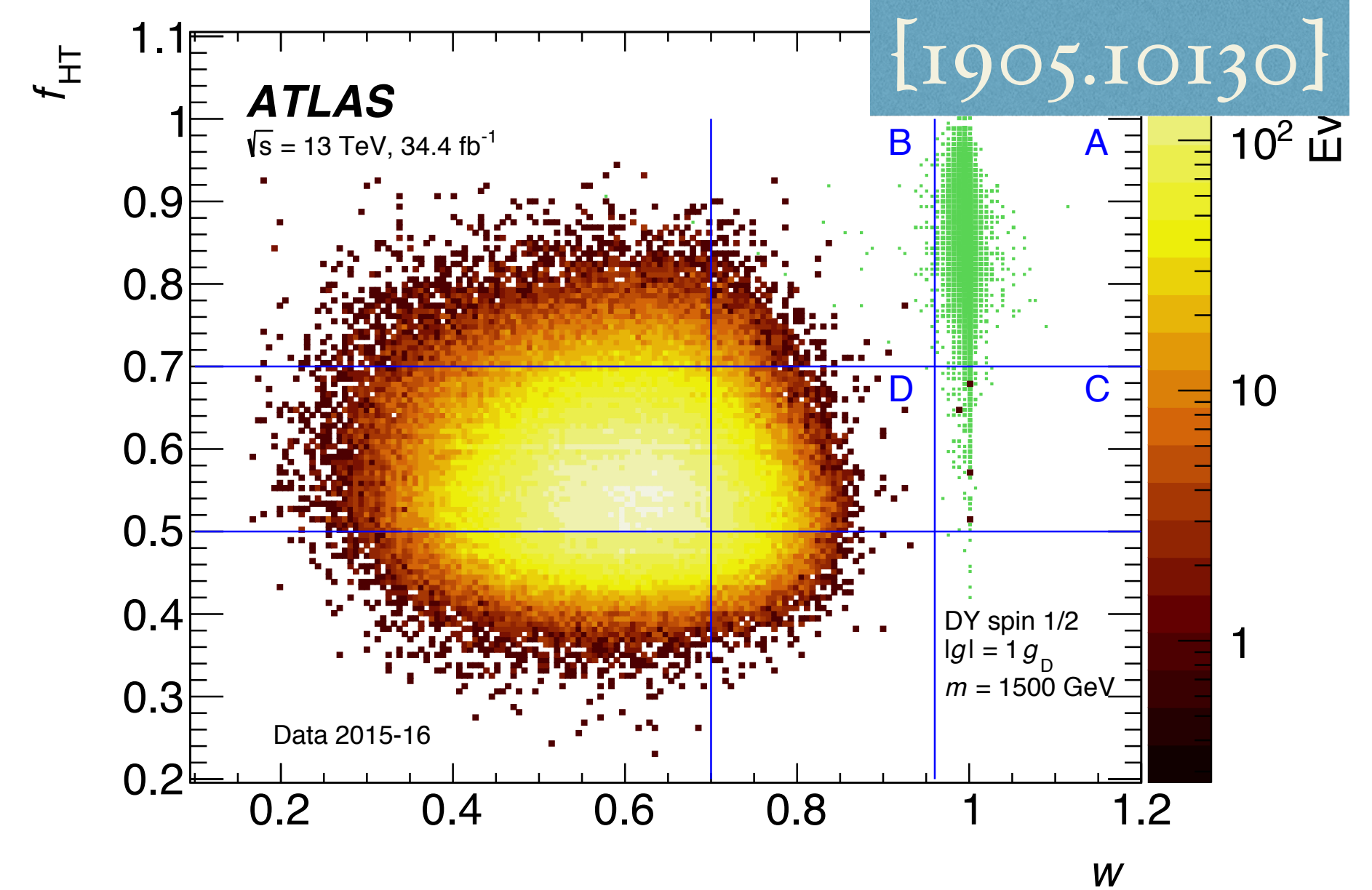
Muon Spectrometer triggering improved by additional thin-gap RPCs resulting in increase in acceptance from 75% to 95% at Lo

Two dedicated muon trigger: multi-muon scan and Lo sagitta (not-boosted objets)



Magnetic Monopole

- ❖ **Magnetic monopoles and high-electric-charge objects** are interpreted in **Drell-Yan pair production** of stable particles with two spin hypotheses (0 and 1/2) and masses ranging from 200 GeV to 4000 GeV.
- ❖ The considered signature is based upon **high ionization in the transition radiation tracker (TRT)** of the inner detector associated with a **pencil-shape energy deposit in the EM calorimeter**.
 - Dedicated trigger based on the tracker high-threshold hit capability.
 - EM cluster seed with $E_{\tau} > 18$ GeV
- **Background modelling with ABCD method:** Fraction of nearby HT TRT hits and EM cluster energy dispersion used in for the ABCD plane



Lower limits on the mass of Drell-Yan magnetic monopoles and HECOs [GeV]

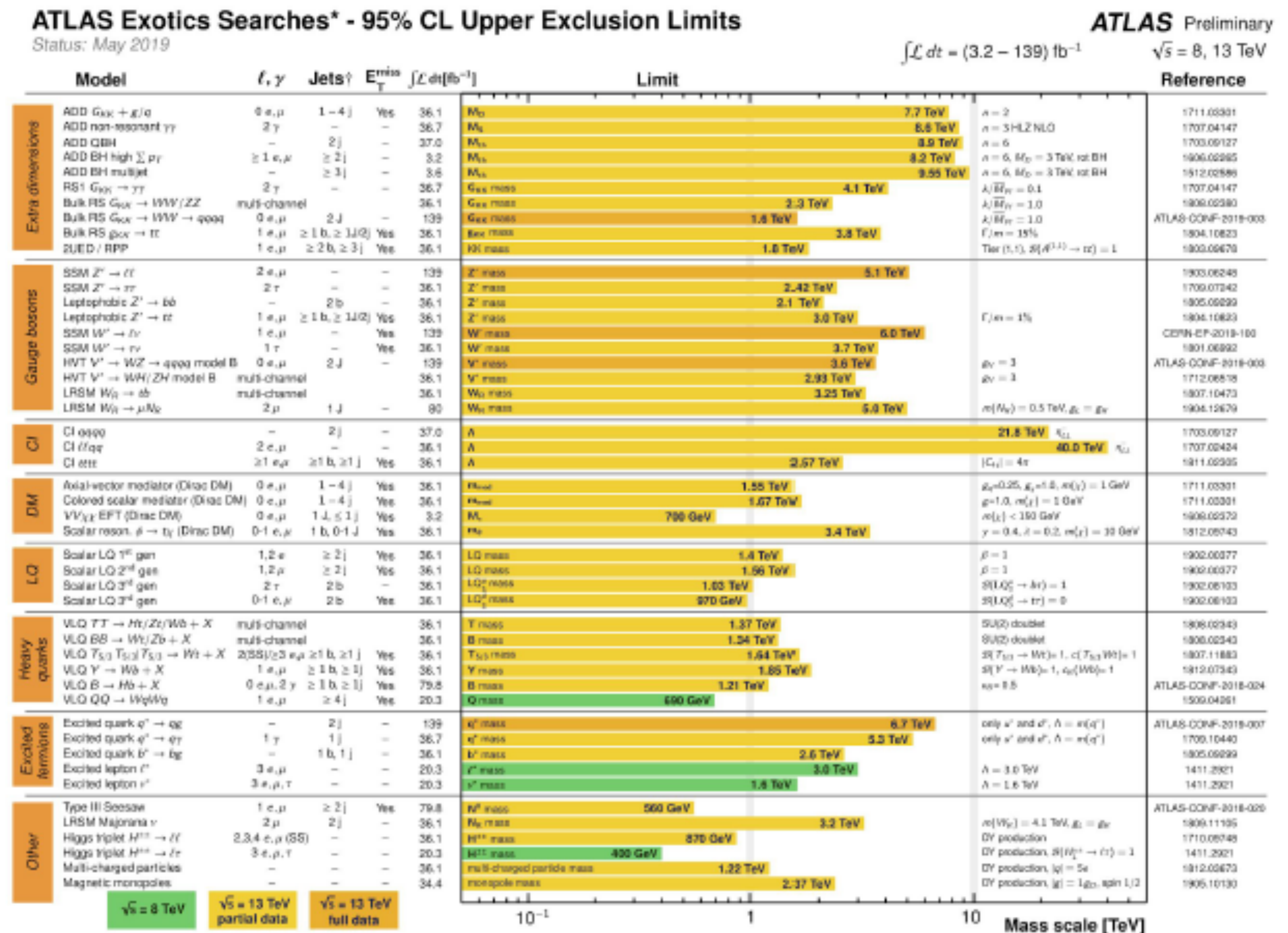
	$ g = 1g_D$	$ g = 2g_D$	$ z = 20$	$ z = 40$	$ z = 60$	$ z = 80$	$ z = 100$
Spin-0	1850	1725	1355	1615	1625	1495	1390
Spin-1/2	2370	2125	1830	2050	2000	1860	1650

Conclusions

- Many exotics searches have been reviewed in this talk:
 - Searches using heavy resonances (with full Run2), Displaced Jets, HNL, Dark Photons (2015-2016 data)**

- The results presented explored Run2 Data Taking and future perspectives from HL- LHC:**

- Run 2 results achieved a large increase in sensitivity with respect to Run 1 results
 - But no significant deviation observed yet**
- Significant effort to extend our experimental reach and coverage for Phase 2 HL-LHC Projections

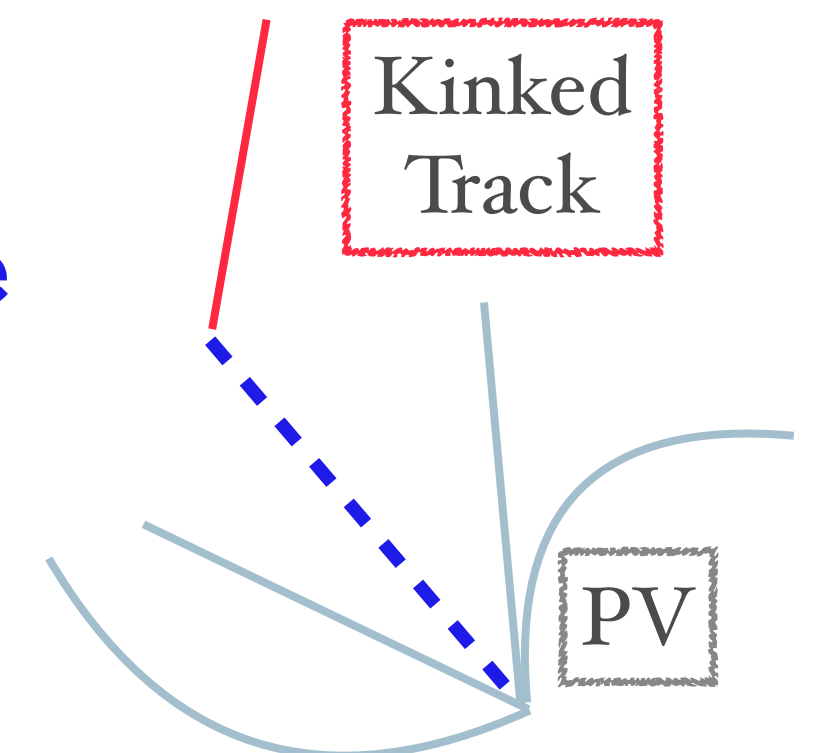
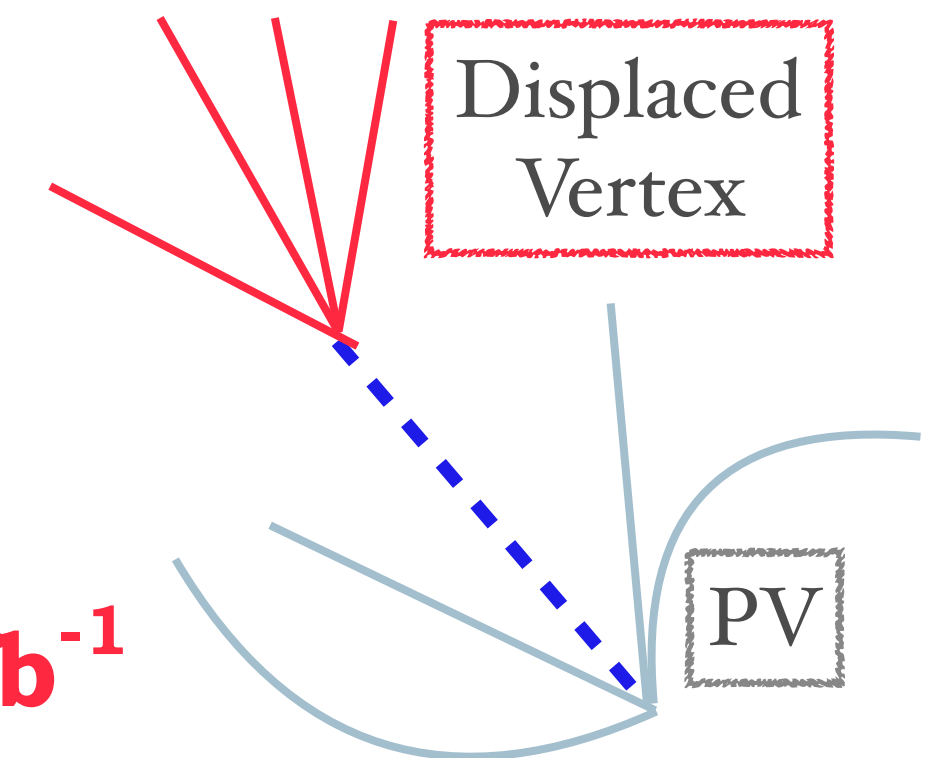
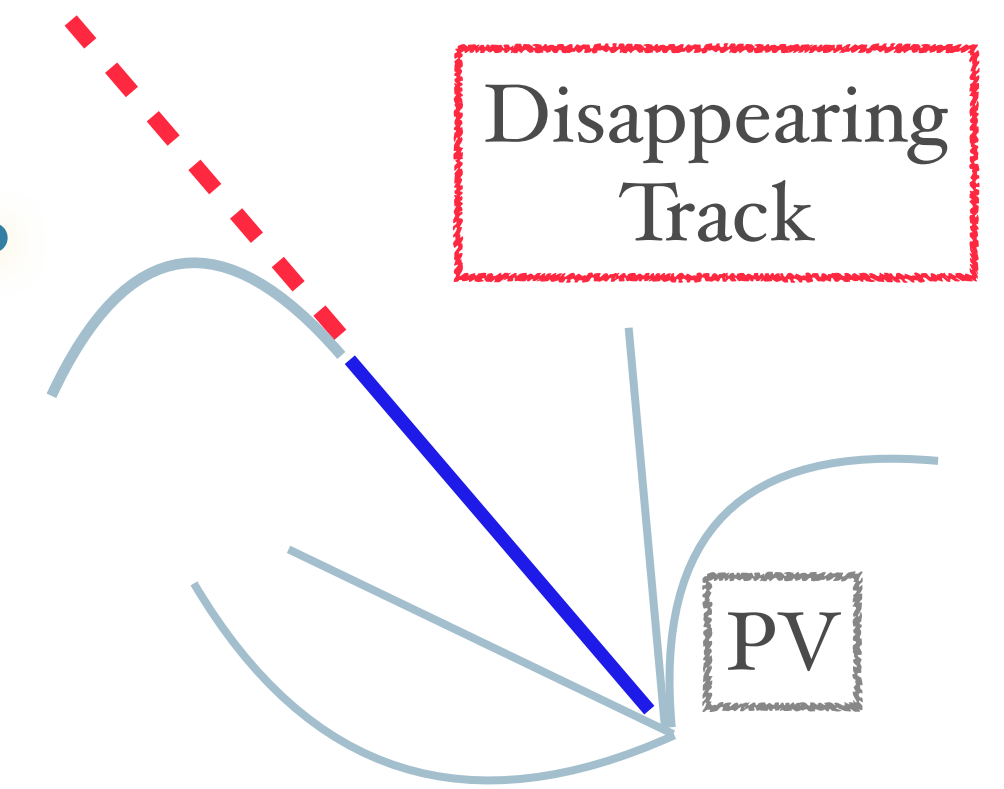


Backup



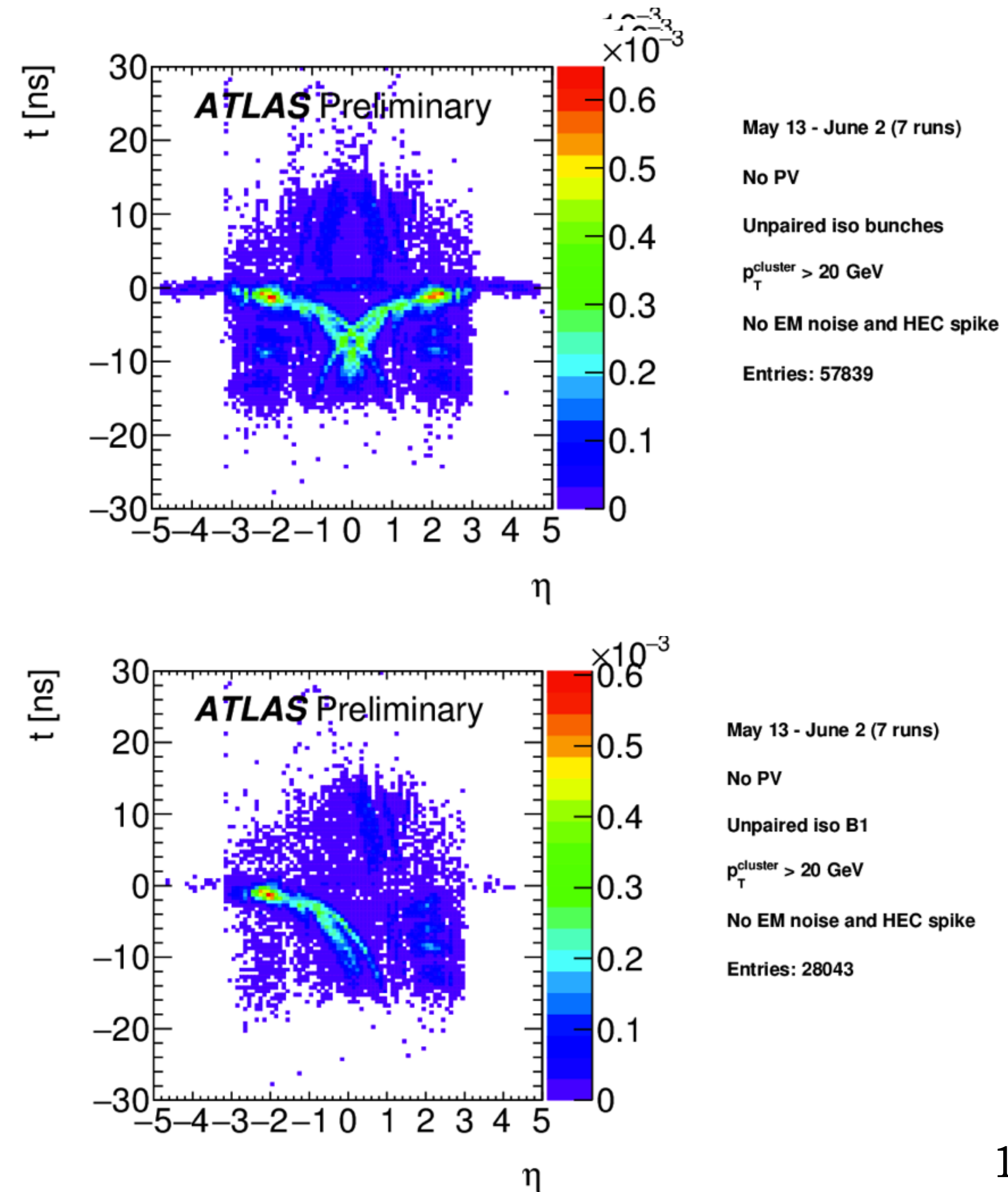
LLP analysis in this talk...

- ❖ Highlight Run2 results and their perspectives at HL-LHC for:
 - ❖ **Disappearing tracks and displaced vertices**
 - ❖ **Displaced Jets**
 - ❖ **Large dE/dx**
- ❖ **In these analyses, the signal event reconstruction and selection, as the background estimation, use dedicated, unique and very specialised technicalities.**
 - ❖ **Run2 results include 2016 and/or 2015 data taking (from few fb^{-1} up to 36 fb^{-1})**
 - ❖ **HL-LHC projections are obtained by scaling the signal and background datasets used for the Run 2 analyses (36 fb^{-1}), to the HL-LHC expected integrated luminosity (3000 fb^{-1}) and center-of-mass energy ($\sqrt{s} = 13 \text{ TeV} \rightarrow \sqrt{s} = 14 \text{ TeV}$). Scale factors are applied to event yields and systematics uncertainties.**



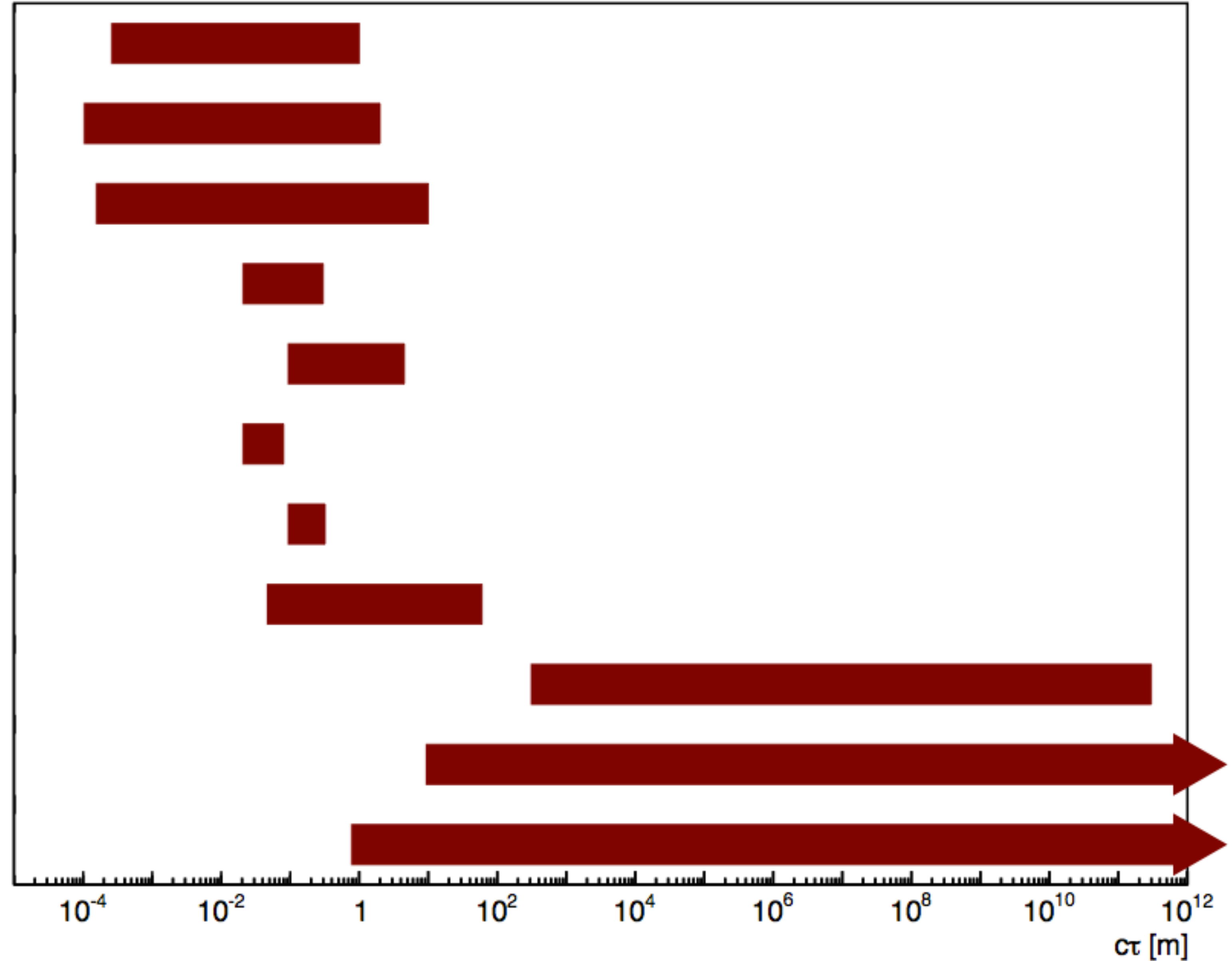
BIB in A

Interactions between beam protons and beam collimators upstream of the IP are a source of **high-momentum muons, denoted beam-induced-background (BIB) muons**, that can enter the ATLAS detector nearly parallel to the beam axis. Most MS tracks and jets generated by this process are identified and rejected.



CMS long-lived particle searches, lifetime exclusions at 95% CL

- RPV SUSY, $\tilde{t} \rightarrow b\ell$, $m(\tilde{t}) = 420$ GeV
8 TeV, 19.7 fb^{-1} (displaced leptons)
- $H \rightarrow XX$ (10%), $X \rightarrow ee$, $m(H) = 125$ GeV, $m(X) = 20$ GeV
8 TeV, 19.6 fb^{-1} (displaced leptons)
- $H \rightarrow XX$ (10%), $X \rightarrow \mu\mu$, $m(H) = 125$ GeV, $m(X) = 20$ GeV
8 TeV, 20.5 fb^{-1} (displaced leptons)
- GMSB SPS8, $\tilde{\chi}_1^0 \rightarrow \tilde{G} \gamma$, $m(\tilde{\chi}_1^0) = 250$ GeV
8 TeV, 19.7 fb^{-1} (disp. photon conv.)
- GMSB SPS8, $\tilde{\chi}_1^0 \rightarrow \tilde{G} \gamma$, $m(\tilde{\chi}_1^0) = 250$ GeV
8 TeV, 19.1 fb^{-1} (disp. photon timing)
- RPV SUSY, $m(\tilde{g}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 150$ GeV
8 TeV, 18.5 fb^{-1} (displaced dijets)
- RPV SUSY, $m(\tilde{g}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 500$ GeV
8 TeV, 18.5 fb^{-1} (displaced dijets)
- AMSB $\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 + \pi^\pm$, $m(\tilde{\chi}_1^\pm) = 200$ GeV
8 TeV, 19.5 fb^{-1} (disappearing tracks)
- cloud model R-hadron, $m(\tilde{g}) = 1000$ GeV
8 TeV, 18.6 fb^{-1} (stopped particle)
- AMSB $\tilde{\chi}_1^\pm$, $\tan(\beta) = 5$, $\mu > 0$, $m(\tilde{\chi}_1^\pm) = 800$ GeV
8 TeV, 18.8 fb^{-1} (tracker + TOF)
- AMSB $\tilde{\chi}_1^\pm$, $\tan(\beta) = 5$, $\mu > 0$, $m(\tilde{\chi}_1^\pm) = 200$ GeV
8 TeV, 18.8 fb^{-1} (tracker + TOF)



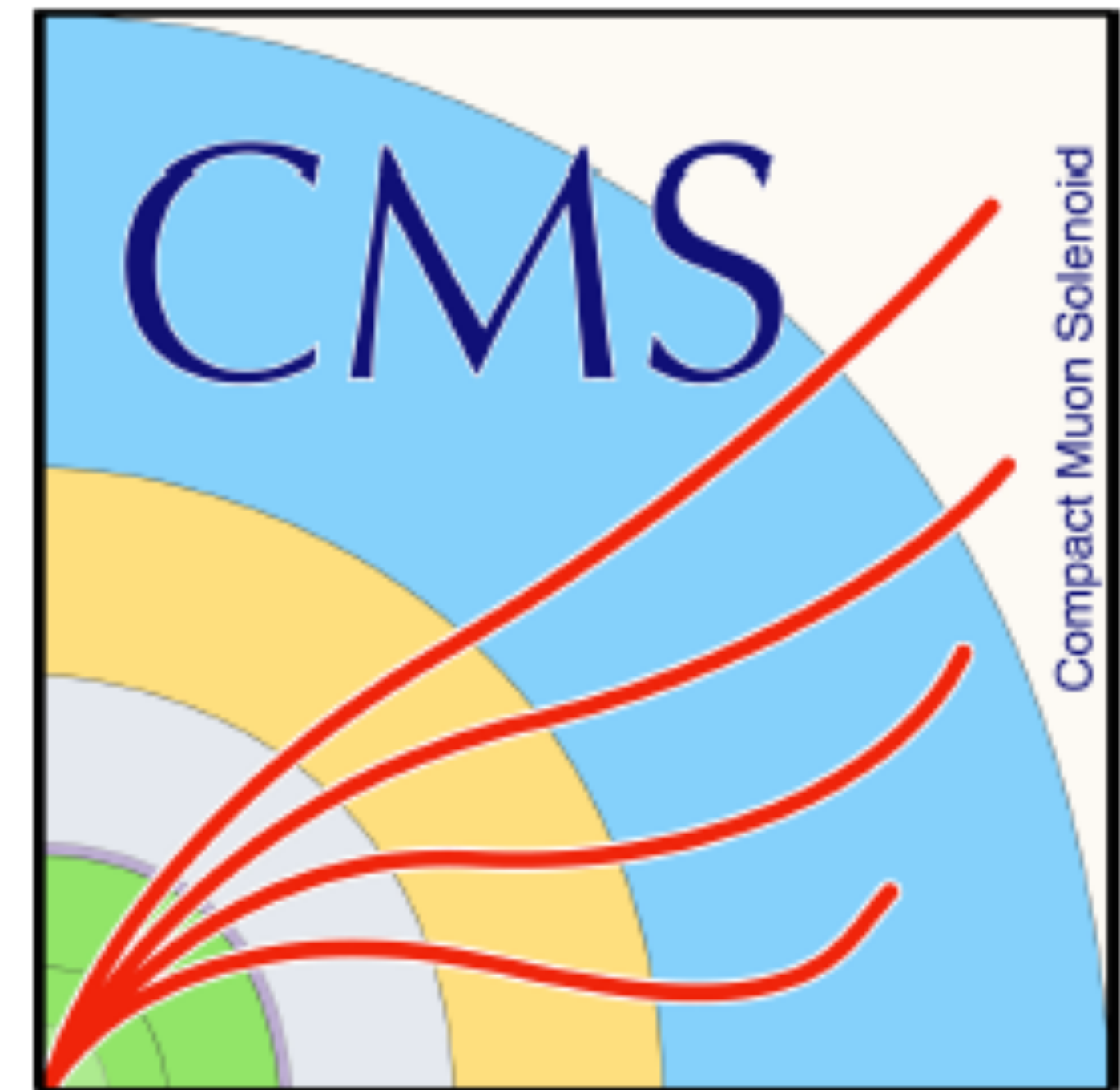
LHCb Upgrade

- Aim for complementarity w.r.t. ATLAS and CMS:
 - Forward acceptance \rightarrow low masses.
 - Excelling vertexing capabilities \rightarrow low lifetimes.
- Upgraded trigger, tracker and VELO:
 - Instrumentation studies for Phases 1 and 2.
- Massive LLPs decaying to $\mu + \text{jets}$:
 - Physics projection studies for yellow report.
- Massive LLPs decaying to jet pairs:
 - Physics projection studies for yellow report.
 - Interest in pile-up studies (jet reco efficiencies).
- Extended reach for LLPs (CODEX-b + LHCb):
 - New detector to operate interfaced with LHCb.
 - Greatly extend reach for LLP searches.



CMS Upgrade

- Tracker & RPC upgrade for HSCP:
[CMS-TDR-17-001] [CMS-TDR-17-003]
 - HSCPs have a distinct signature in the detector.
 - Exploit RPC time resolution & OT capabilities.
- Displaced muons:
[CMS-TDR-17-003]
 - New forward muon detectors to improve trigger.
 - New tracking algorithms for displaced muons.
- Signatures with delayed photons/ Z^0 bosons:
 - Sensitivity strongly limited by time resolution.
 - New MTD → new possibilities for LLP searches.



ATLAS Upgrade

- **Interplay between searches and upgraded detector:**
 - Performance of ID, ITk, calo and muon triggers.
 - Works towards TDR → go for PUB note before yellow report.
- **Disappearing tracks:**
 - Physics projection studies in Pixel TDR.
- **Multi-track displaced vertices in ID + MET:**
 - Tracking studies in Pixel TDR.
 - Physics projection studies yet to be done.
- **Displaced vertices in muon spectrometer:**
 - Muon trigger studies in TDAQ TDR.
- **Jets in HCAL with low EM fraction:**
 - Calo trigger studies in Tile TDR.
- **High Granularity Timing Detector (HGTD):**
 - Works toward a TDR.
 - Very interesting concept for LLPs.



Simulating Physics channels at HL-LHC

Two possible ways:

CASE 1

- 1) **Extrapolate from Run1,2 results.** Scale both signal and background to 14TeV and 3000 fb⁻¹
- 2) **Assume similar detector performances** and apply same analyses

or

CASE 2

- 1) **Smear event-generator level particles** with parameterised functions
- 2) Functions are determined from full simulation of the upgraded ATLAS detector and reconstructed assuming pileup of 140 (5x10³⁴) or 200 (7x10³⁴)
- 3) **Analyses as for 8 and (or) 13TeV** with some updates for high luminosity

What about systematics? Difficult to predict.

Experimental Systematics: so far , scaled from current knowledge

Theory Systematics : current numbers, half of them, or none.

HL-LHC Systematics Guideline

- ✦ **Statistics-driven sources: data $\rightarrow \sqrt{L}$, simulation $\rightarrow 0$**
 - ✦ account for large statistics available
 - ✦ assume will overcome limitations in generating large simulations
- ✦ **Intrinsic detector limitations stay ~constant**
 - ✦ usage of full simulation tools for detailed analysis of expected performance, thanks to the large effort for TDRs preparation
 - ✦ detector simulation advances and operational experience may compensate for e.g. detector aging
- ✦ **Theory uncertainties tentatively halved**
 - ✦ applies to both normalisation (x-sec) and modelling
 - ✦ more dedicated discussions with inputs from theorists welcome!
- ✦ **Extrapolation based mostly on methods available now**
 - ✦ challenges as pile-up compensated by algorithmic improvements

ATLAS HL-LHC analysis techniques

CASE 2

ATLAS HL-LHC studies have to consider:

- upgraded ATLAS detector + trigger systems
- collision energy, $\sqrt{s} = 14$ TeV
- high pile-up, $\langle\mu_{\text{PU}}\rangle$, of 140 or 200

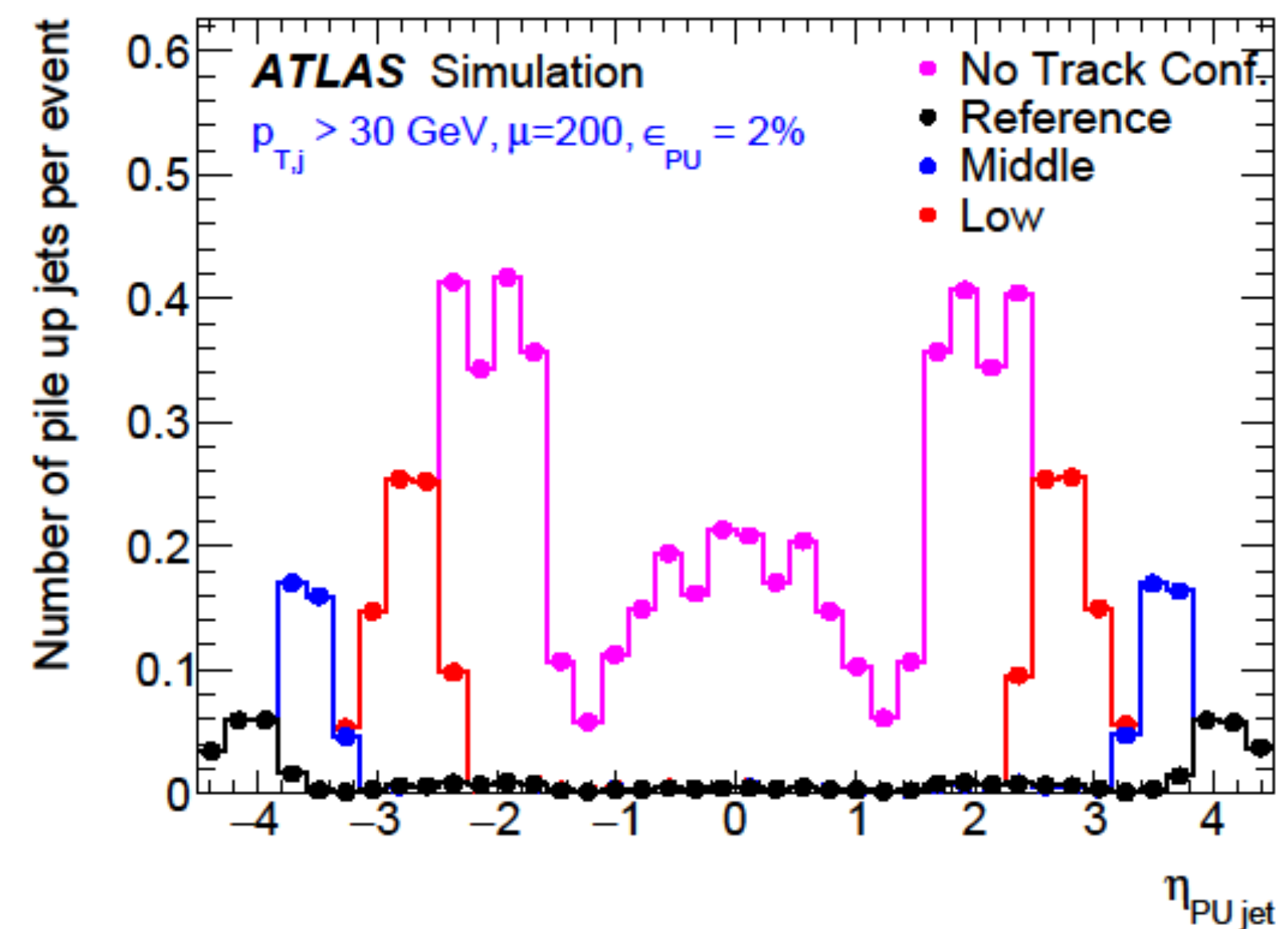
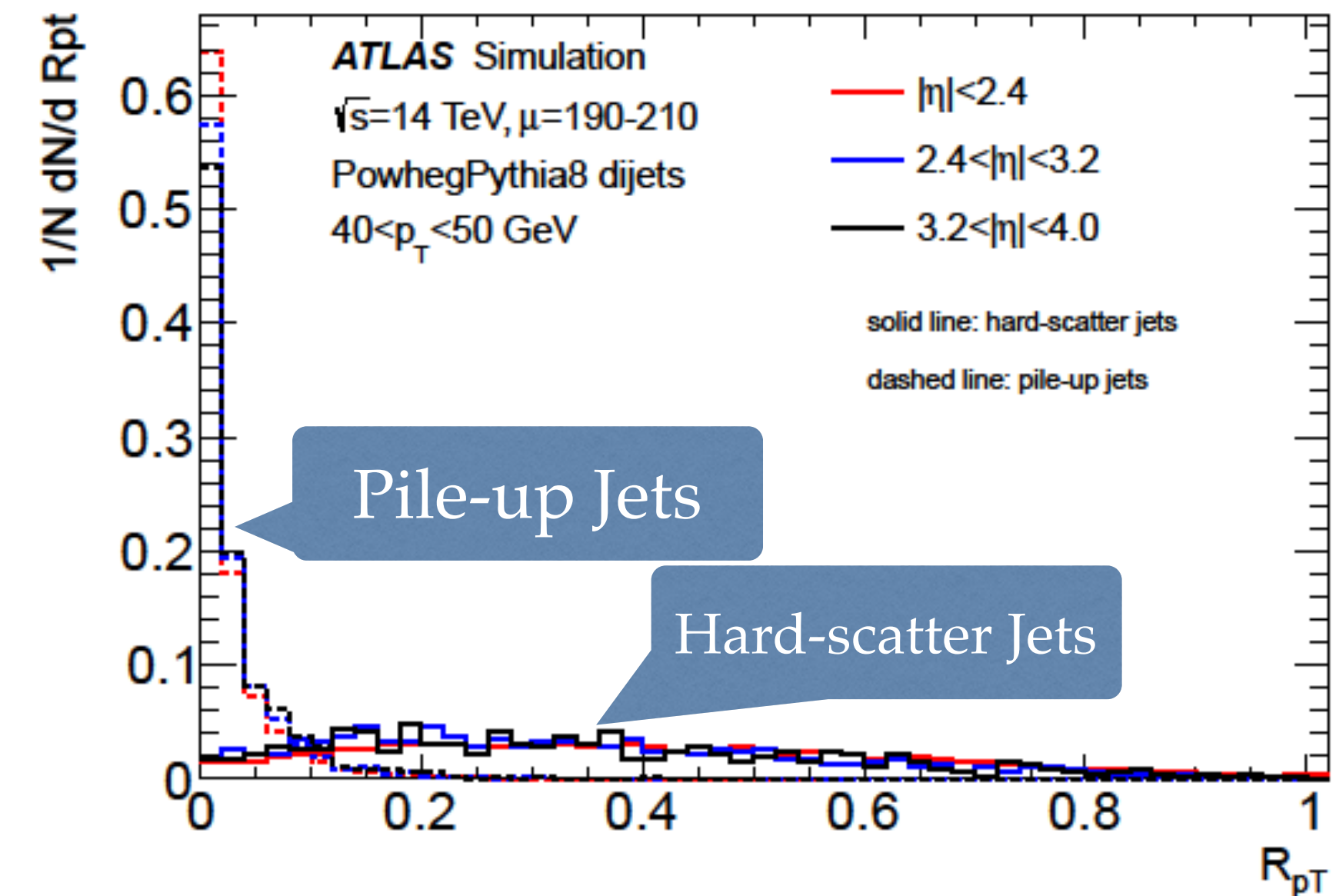
- We use **generator-level $\sqrt{s} = 14$ TeV Monte Carlo** samples
 - Overlay with jets from dedicated **pile-up library**
 - pile-up library contains fully simulated pile-up jets with $\langle\mu_{\text{PU}}\rangle = 140$ or 200
 - Reconstruct electron, muons, jets, photons and missing-ET from generator + overlay information
- **To simulate the response of the detector:**
 - smear p_T and energy of reconstructed physics objects using **smearing functions based on fully simulated samples**
 - apply **reconstruction efficiencies** for electrons, muons and jets
- **To emulate triggers: apply **trigger efficiency functions****

Pile-up Mitigation

- Typical jet selections require $p_T(\text{jet}) > 30$ GeV, $|\eta(\text{jet})| < 3.8$
- For $\langle \mu_{\text{PU}} \rangle = 200$, expect 4.8 pileup jets with $p_T > 30$ GeV, $|\eta| < 3.8$ per event
- **To reduce sensitivity to pile-up in jets we apply a parameterised **track-confirmation requirement**, based selecting on charged vertex fraction, R_{pT} .**

$$R_{pT} = \frac{\sum_{\text{tracks}} p_T}{p_T(\text{jet})}$$

- Applied to all non b-tagged jets with $p_T < 100$ GeV and $|\eta| < 3.8$
- **Reduces pile-up by factor $\sim 50 \rightarrow 0.2$ selected pile-up jets per event.**



Physics Object Performance

Tracking

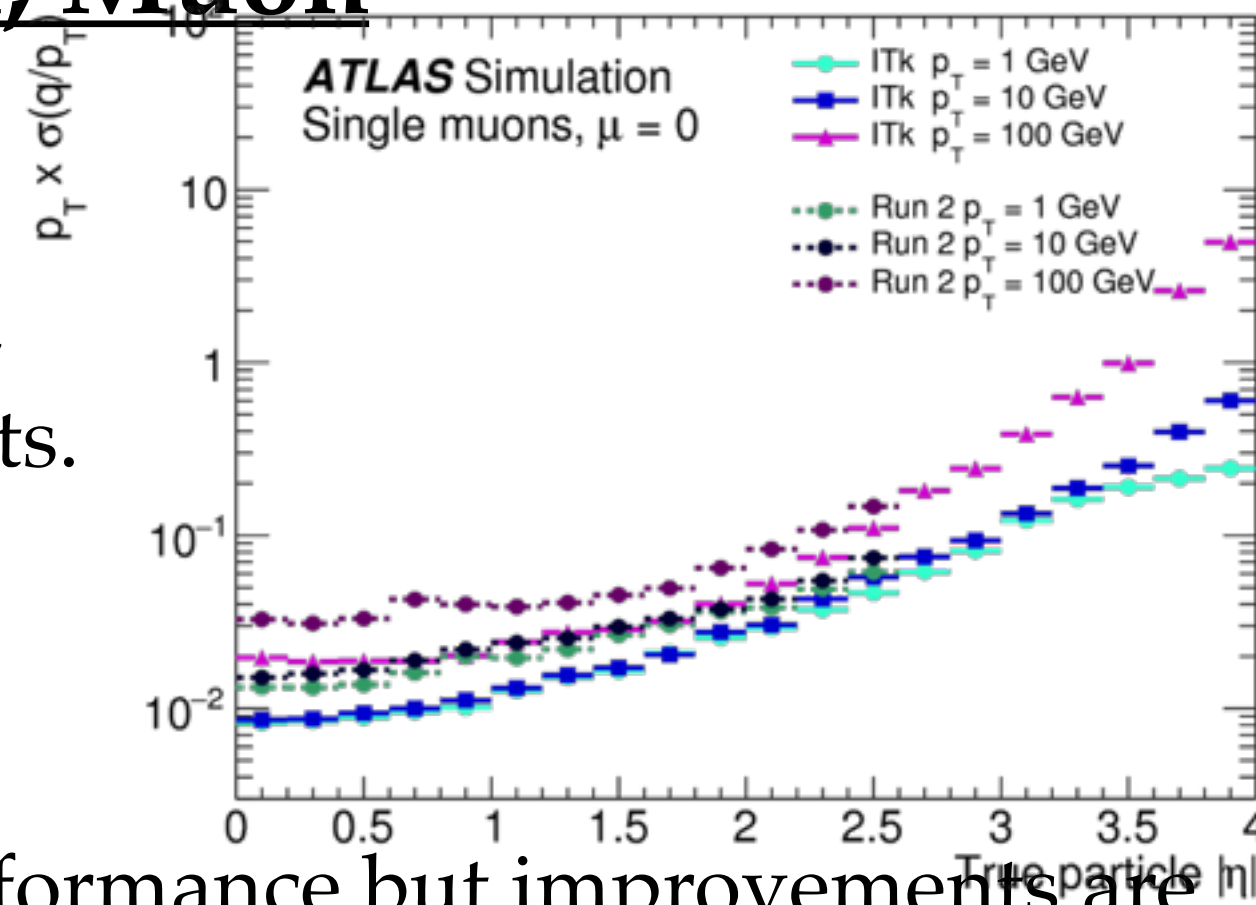
The large η extension of the tracker has a significant impact on the identification of physics objects and on pileup mitigation \rightarrow most visible contributions are in the area of jets and missing ET performance.

Inclined and Extended Layout as possible options.

Electron, Photon, Muon

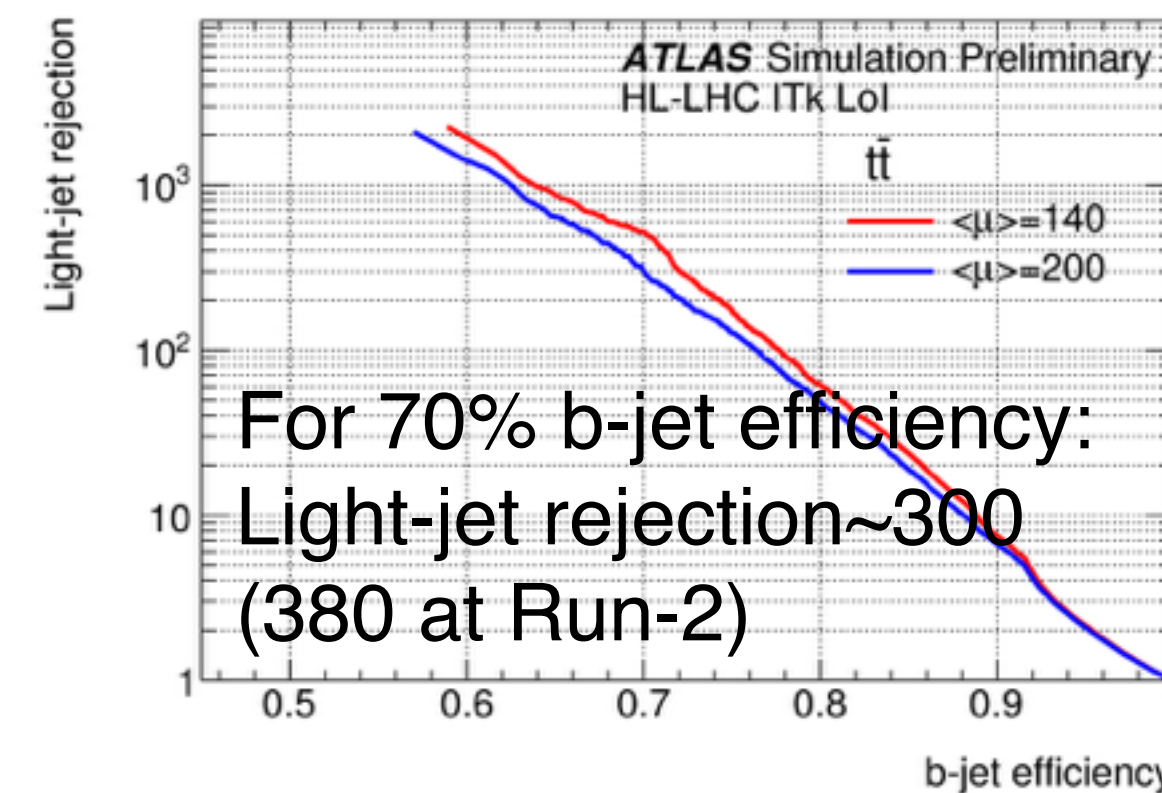
Electron and Photon performances are in line with Run2 results, room for improvements.

Upgrades of the MS are not expected to change significantly the reconstruction performance but improvements are foreseen in the resolution for combined (ITk+MS) muons and in the large η region.



BTagging

The performance is estimated to be similar to the one of the Inner Detector in Run2 conditions.



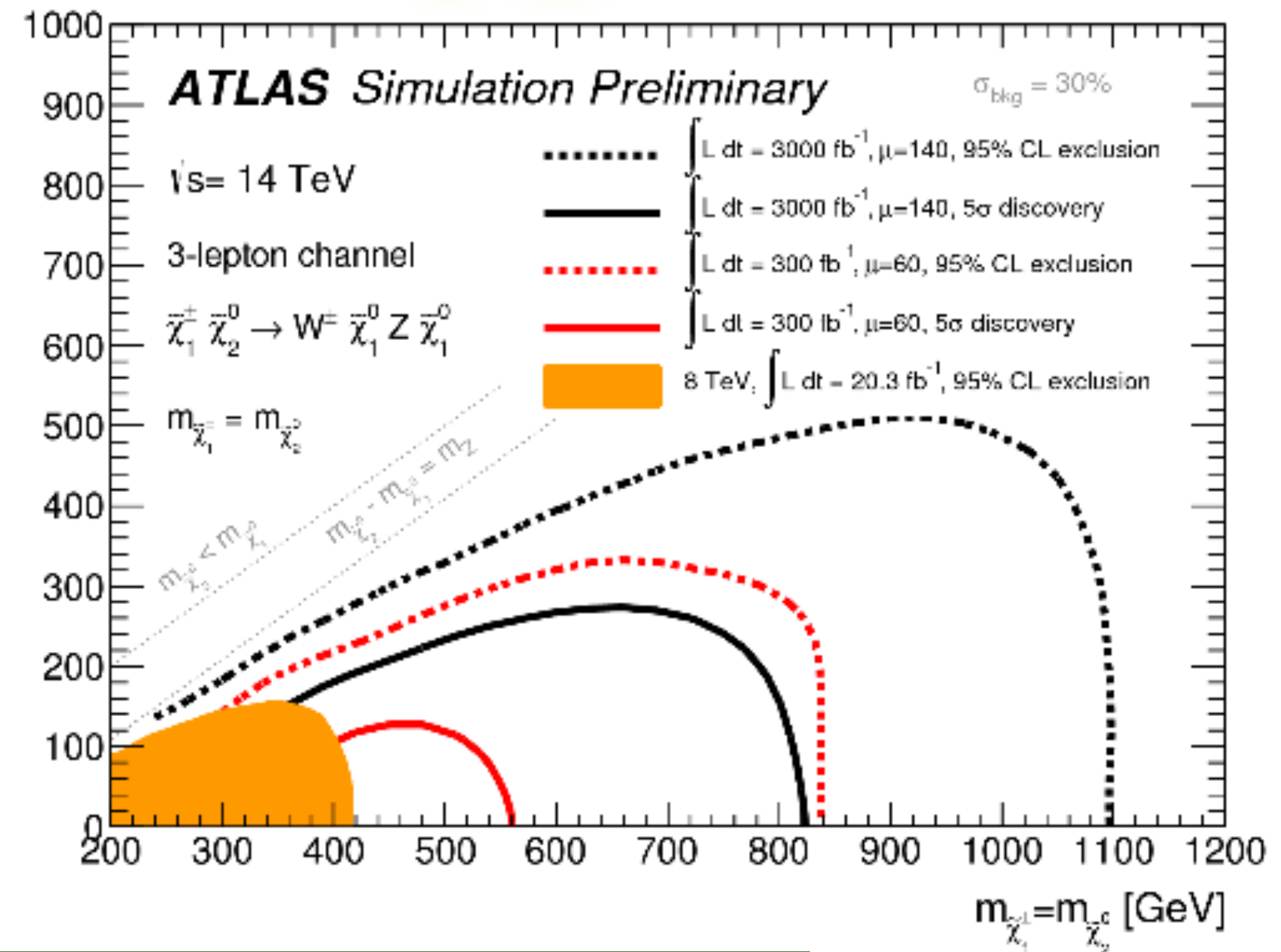
Jet and MET

The tracking extensions improves the resolution of MET. Large impact of pile-up jets in the jets reconstruction. Timing measurements via HGTD.

Motivation for the Upgrades

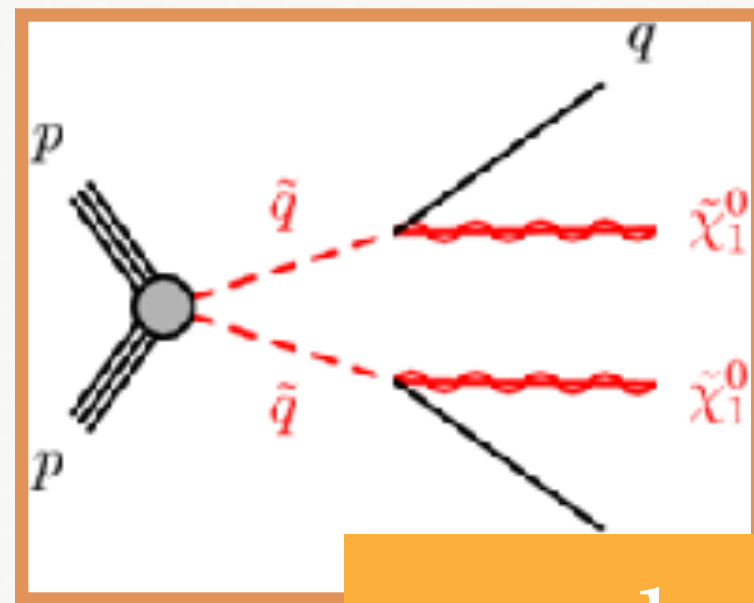
❖ Maximise physics performance for:

- Precision measurements in the 125 GeV Higgs Boson Sector as **Higgs coupling**.
- Search for **rare Higgs Boson decay** modes as $H \rightarrow \mu\mu$ or **self-coupling Higgs** from double Higgs events.
- Study of **low production cross section Standard Model** processes.
- **New phenomena beyond the Standard Model.**

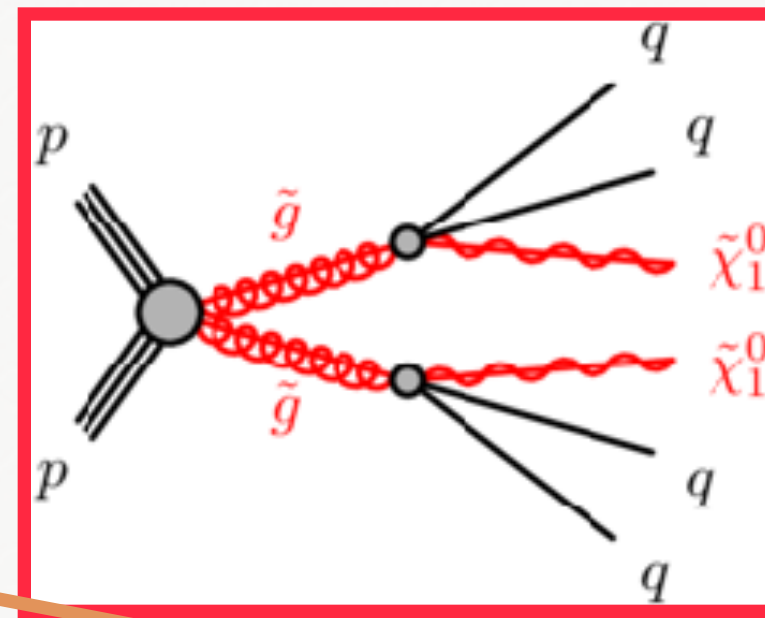


ATLAS projection	gluino mass	squark mass	stop mass	sbottom mass	$g_{kk} \rightarrow tt$ RS 95% CL	Dark Matter M^*
300 fb^{-1}	2.0 TeV	2.6 TeV	1.0 TeV	1.1 TeV	4.3 TeV	2.2 TeV
3000 fb^{-1}	2.4 TeV	3.1 TeV	1.2 TeV	1.3 TeV	6.7 TeV	2.6 TeV

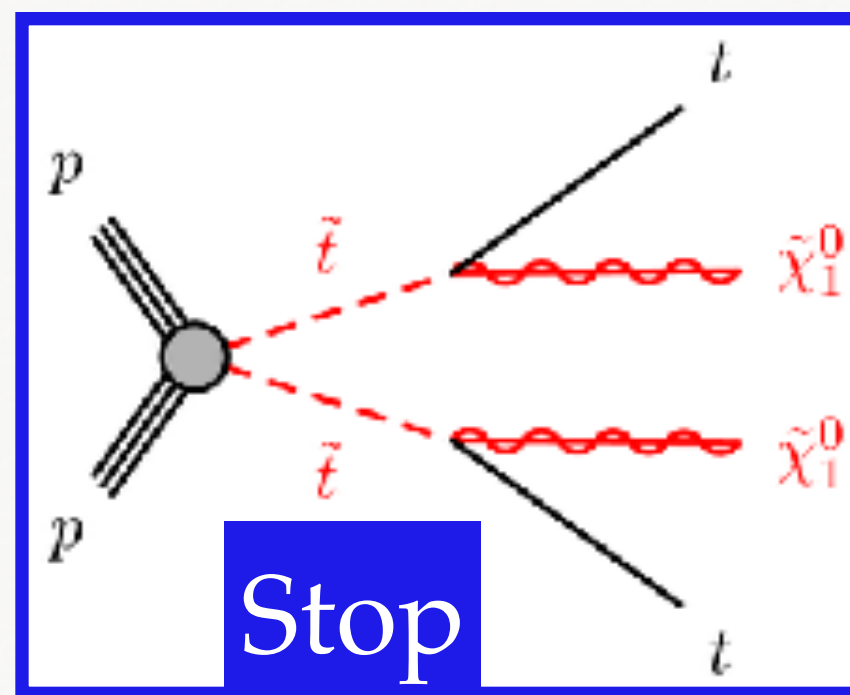
SUSY production at the LHC



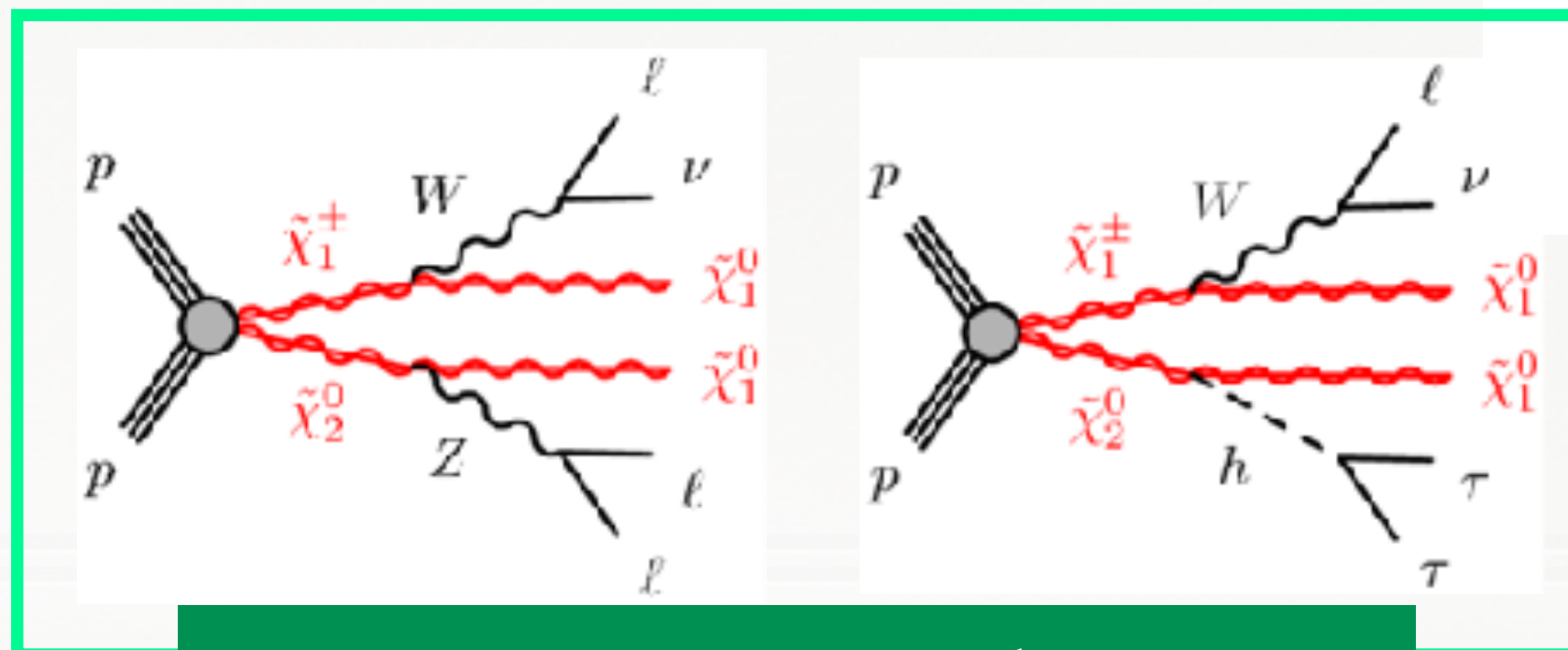
squarks



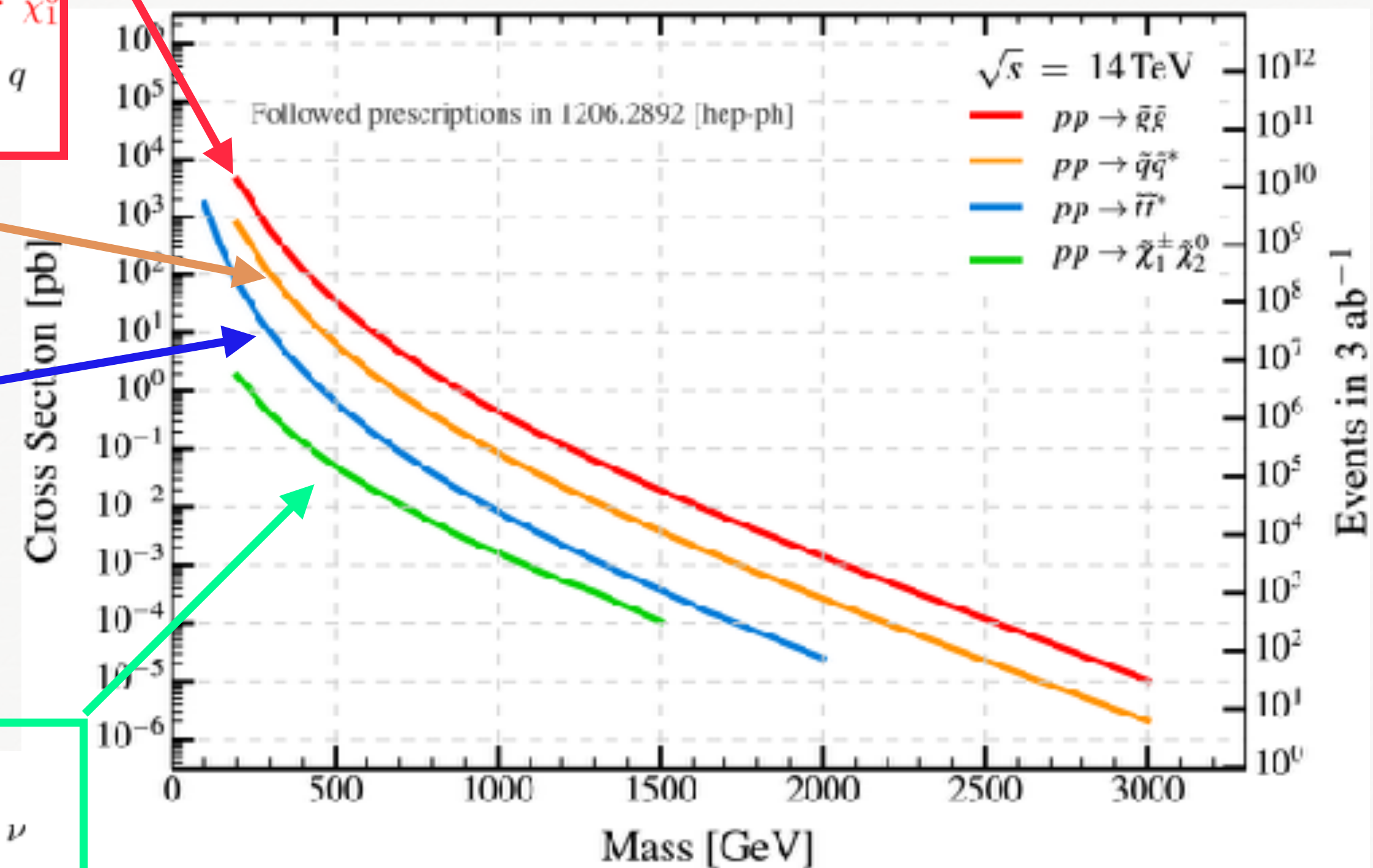
gluinos



Stop



Neutralinos and charginos



The lightest neutralino (LSP) is a candidate to explain dark matter.

W' Systematics

Source	Electron channel		Muon channel	
	Background	Signal	Background	Signal
	$m_T = 2$ (6) TeV	$m_T = 2$ (6) TeV	$m_T = 2$ (6) TeV	$m_T = 2$ (6) TeV
Trigger	negl. (negl.)	negl. (negl.)	1.1% (1.0%)	1.2% (1.2%)
Lepton reconstruction and identification	4.1% (1.4%)	4.3% (4.3%)	8.9% (37%)	6.6% (38%)
Lepton momentum scale and resolution	3.9% (2.7%)	2.7% (4.5%)	12% (47%)	13% (20%)
E_T^{miss} resolution and scale	<0.5% (<0.5%)	<0.5% (<0.5%)	<0.5% (<0.5%)	<0.5% (<0.5%)
Jet energy resolution	<0.5% (<0.5%)	<0.5% (<0.5%)	<0.5% (0.6%)	<0.5% (<0.5%)
Multijet background	4.4% (420%)	N/A (N/A)	0.8% (1.5%)	N/A (N/A)
Top-quark background	0.8% (1.9%)	N/A (N/A)	0.7% (<0.5%)	N/A (N/A)
Diboson extrapolation	1.5% (47%)	N/A (N/A)	1.3% (9.7%)	N/A (N/A)
PDF choice for DY	1.0% (10%)	N/A (N/A)	<0.5% (1.0%)	N/A (N/A)
PDF variation for DY	8.1% (13%)	N/A (N/A)	7.4% (14%)	N/A (N/A)
EW corrections for DY	4.2% (4.5%)	N/A (N/A)	3.7% (7.0%)	N/A (N/A)
Luminosity	1.6% (1.1%)	1.7% (1.7%)	1.7% (1.7%)	1.7% (1.7%)
Total	12% (430%)	5.4% (6.4%)	17% (62%)	15% (43%)

Searching for LLP...

Unconventional signatures require challenging analysis methods

- **Detector-signature based search**

- Experimentally very diverse, depending on particles' properties (dE/dx , Time-of-flight, kinked or disappearing tracks, displaced vertex)
- Identification/discriminating variables depends on properties of the LLP. Lifetime? Charge? Decay products? Decay position in detector?

- Standard trigger are not designed for **unusual objects**

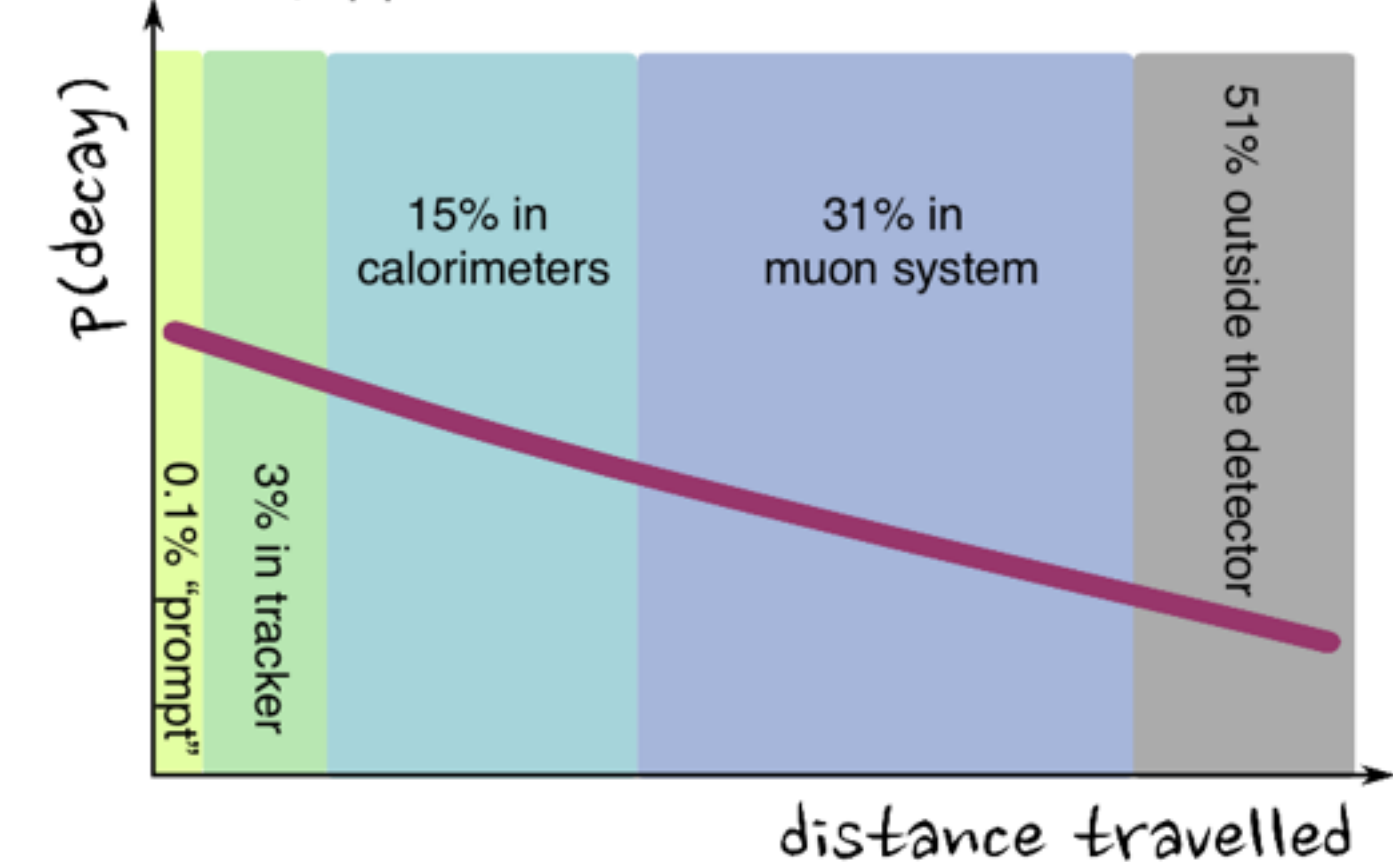
- **Self-made objects reconstruction is required**

- **Requires non-standard analysis strategies and tools**

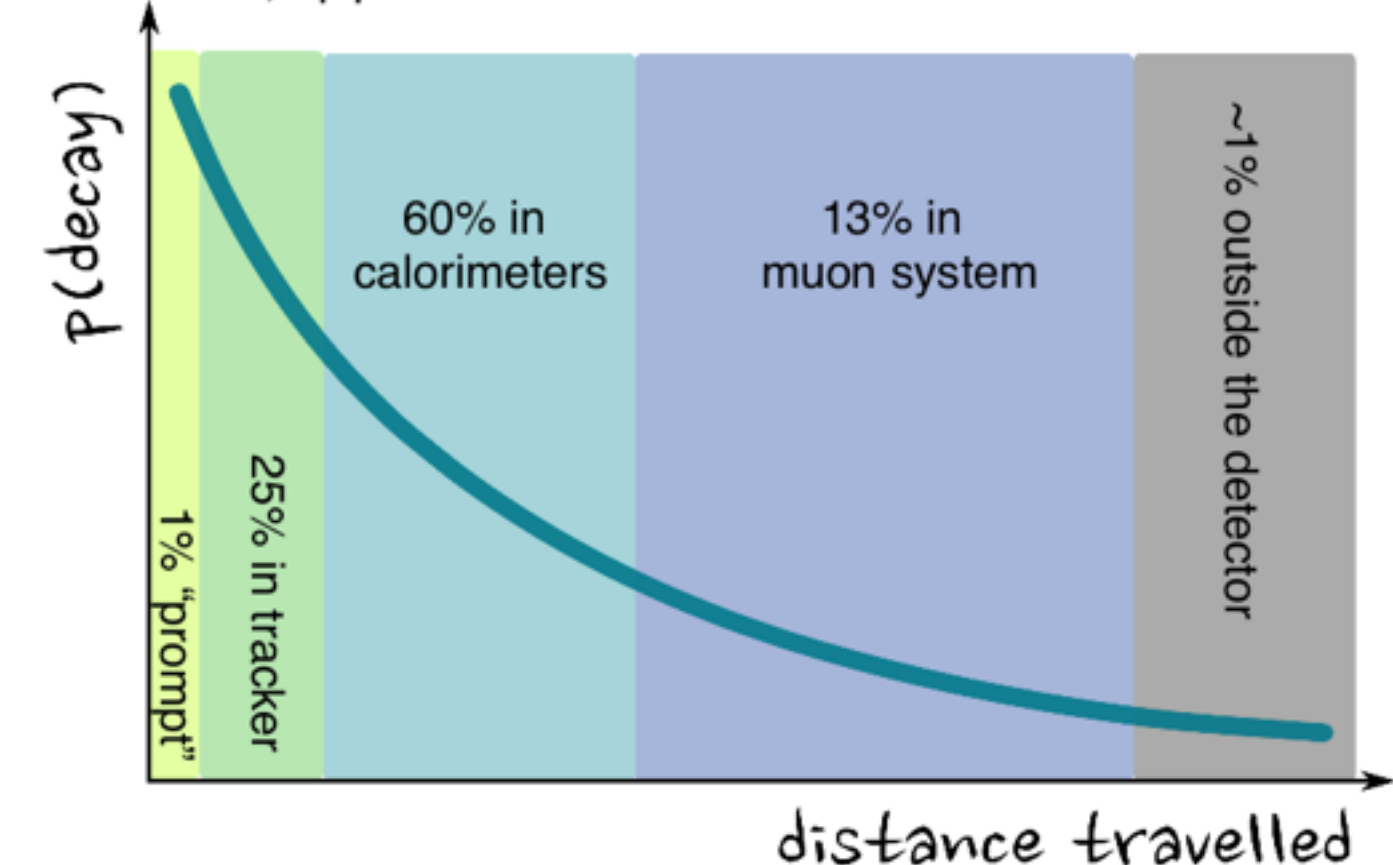
- Custom made MC simulation
- **Non-standard background, generally data-driven estimation**

- **Claim discovery if statistically significant excess is found or, if not, interpret the result in term of constraints on selected models.**

e.g. for $c\tau = 50$ cm, $\langle\beta\gamma\rangle \sim 30$ A graphic example for ATLAS by H. Russell:



e.g. for $c\tau = 5$ cm, $\langle\beta\gamma\rangle \sim 30$ A graphic example for ATLAS by H. Russell:

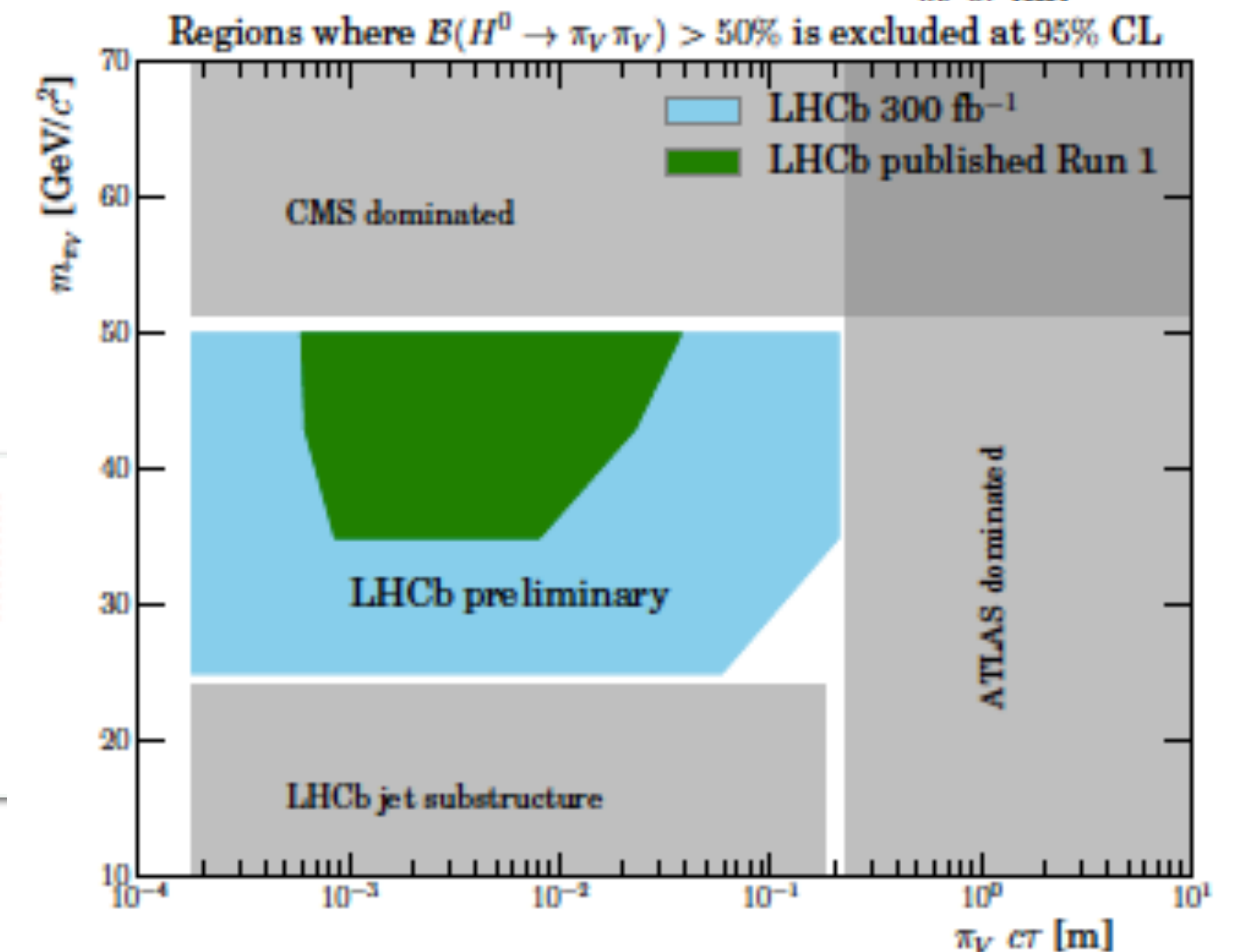
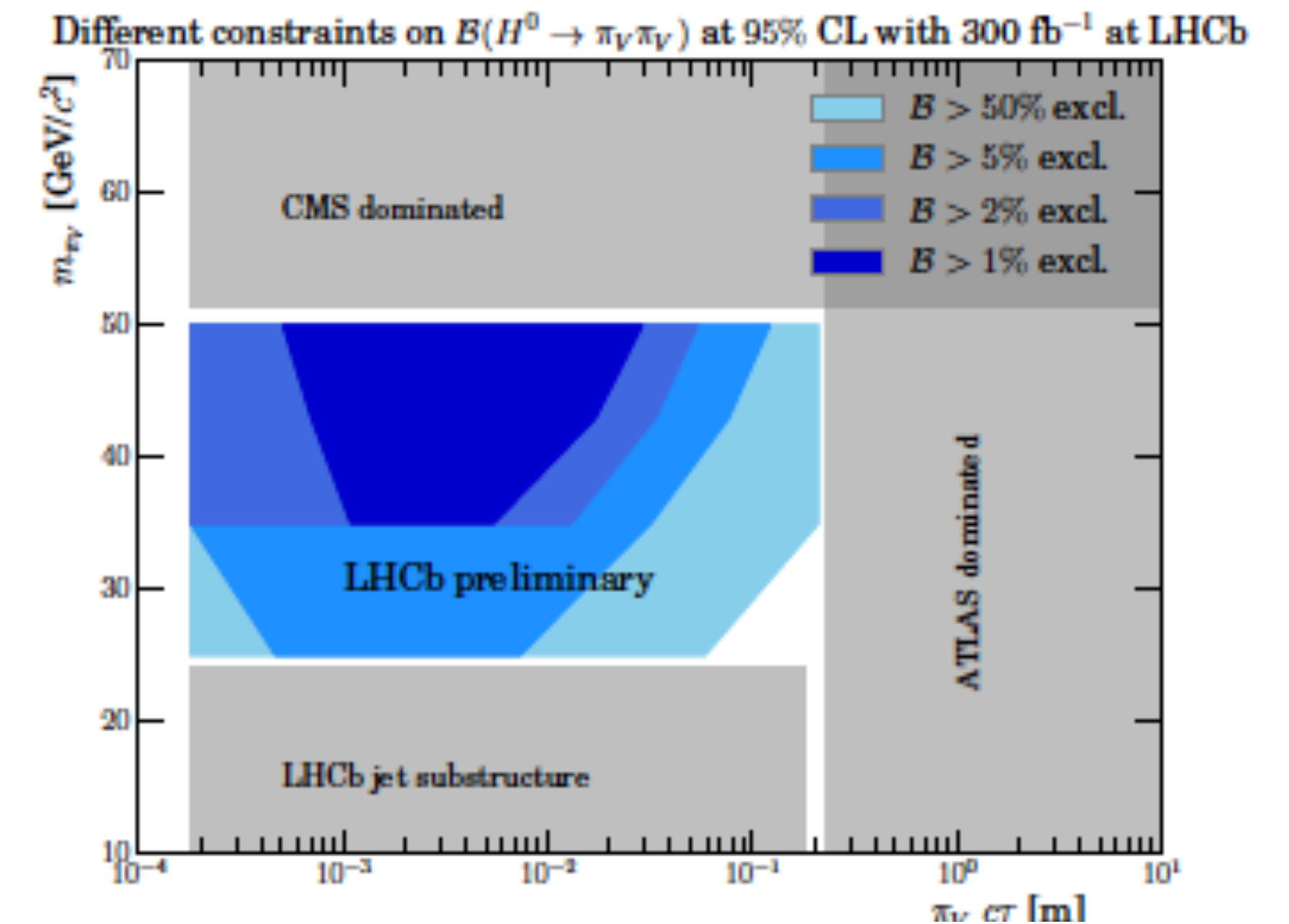
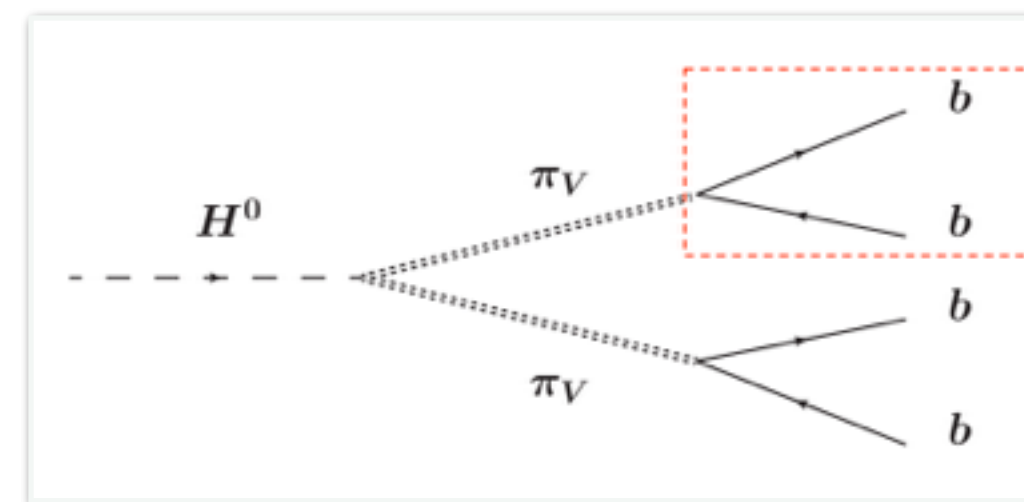


Displaced jets in HL-LHC - (LHCb)

Phase 2 prospects start from Run 1 results [EPJC (2017) 77:812]

- ✳ **Signature:** Displaced Vertex with two associated heavy flavour jets
 - **Dedicated trigger lines for displaced jets & jet substructure tools to reach lower masses.**
- ✳ Background dominated by $b\bar{b}$ and material interactions.
- ✳ **Sensitive to several benchmark production models, focus on the decay of a Higgs-like particle into two π_V .**

Pile-up in Phase 2 will probably affect jet reconstruction.



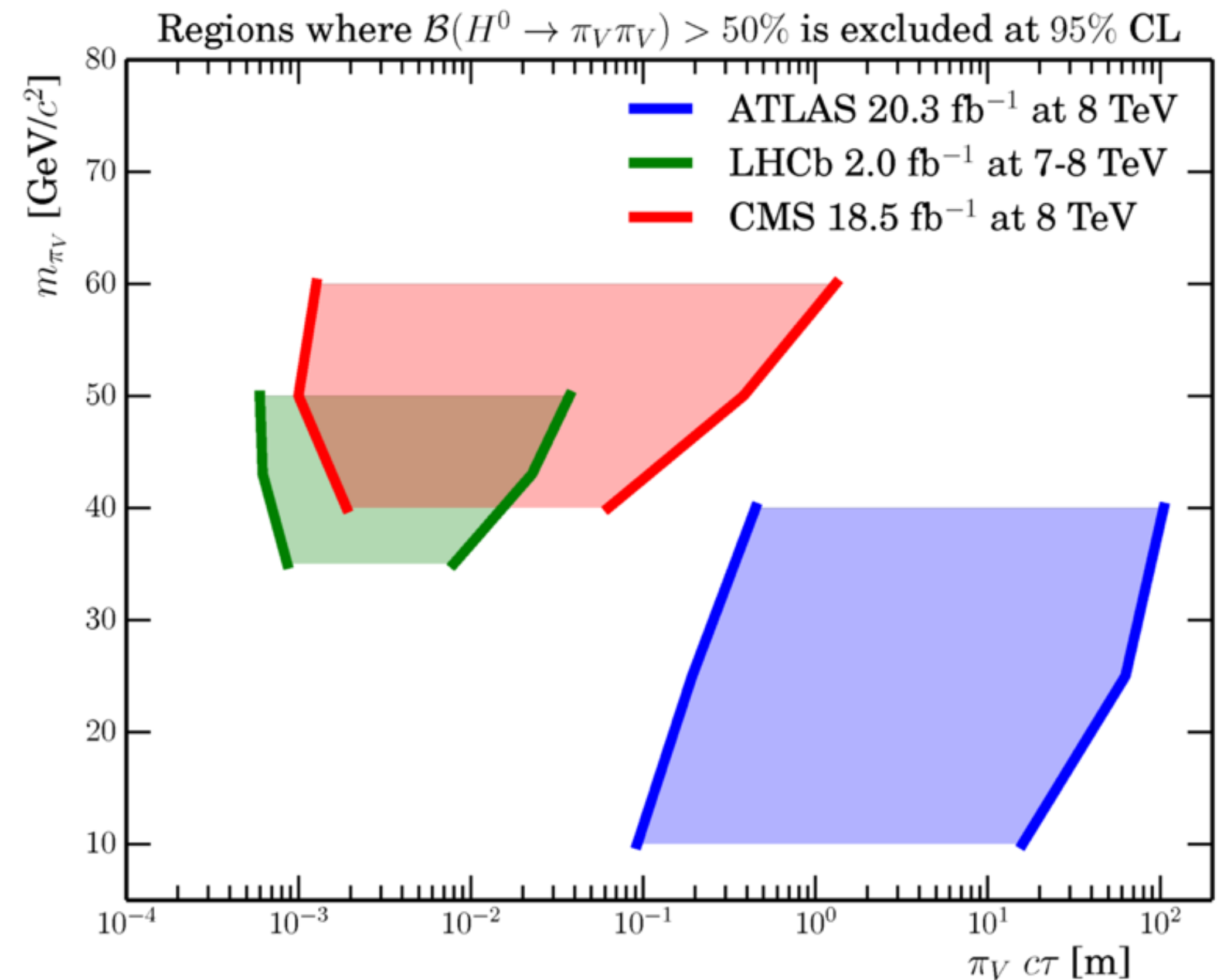
Comparison LHCb, CMS and ATLAS

Keep complementarity between LHCb, ATLAS and CMS:

- ✳ Detector acceptance and vertexing capabilities play an important role.
- ✳ LHCb can reach lifetime and masses that ATLAS & CMS can not and vice-versa.

An example Run 1 search for pair produced Hidden Valley via SM Higgs decay:

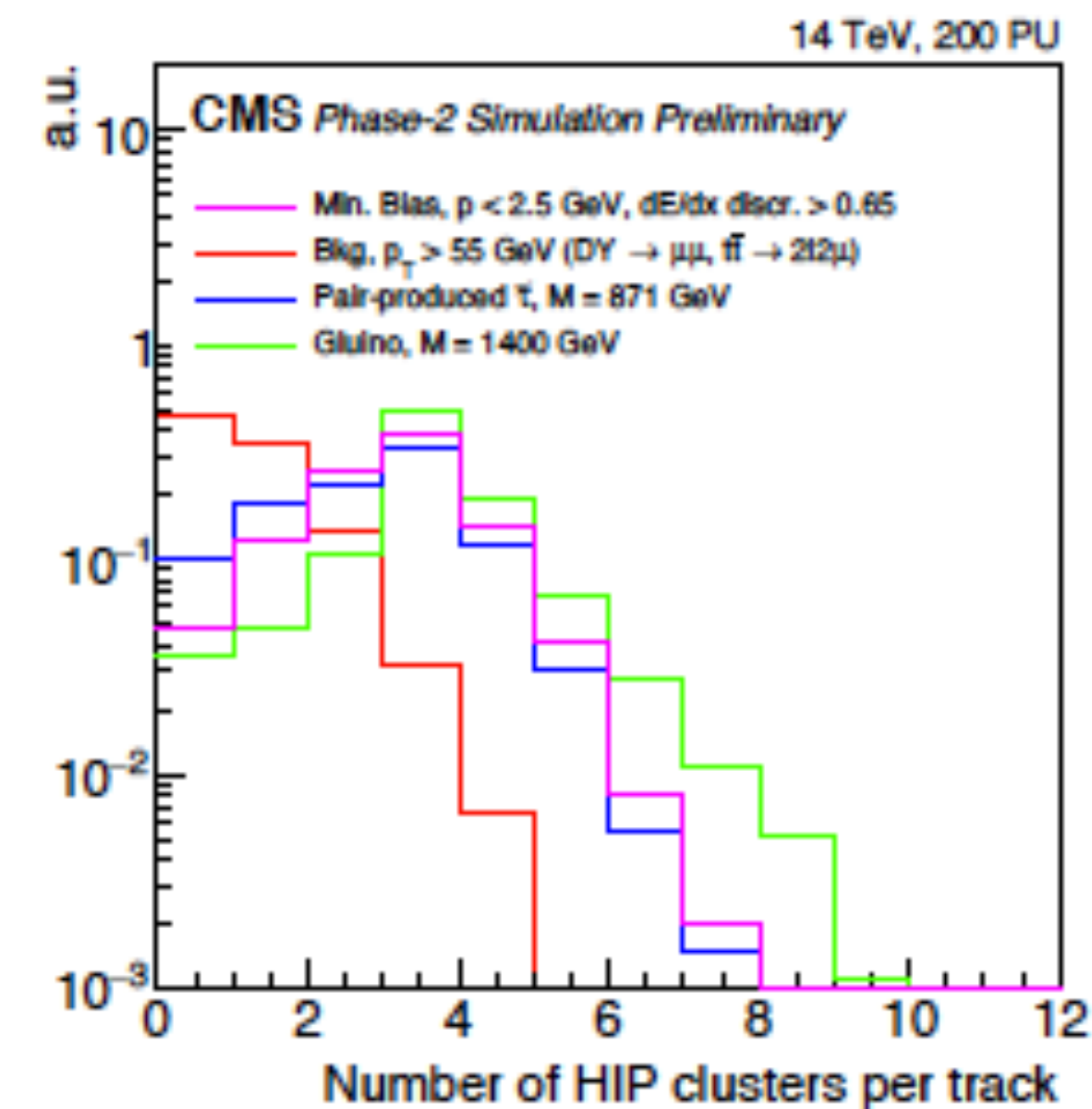
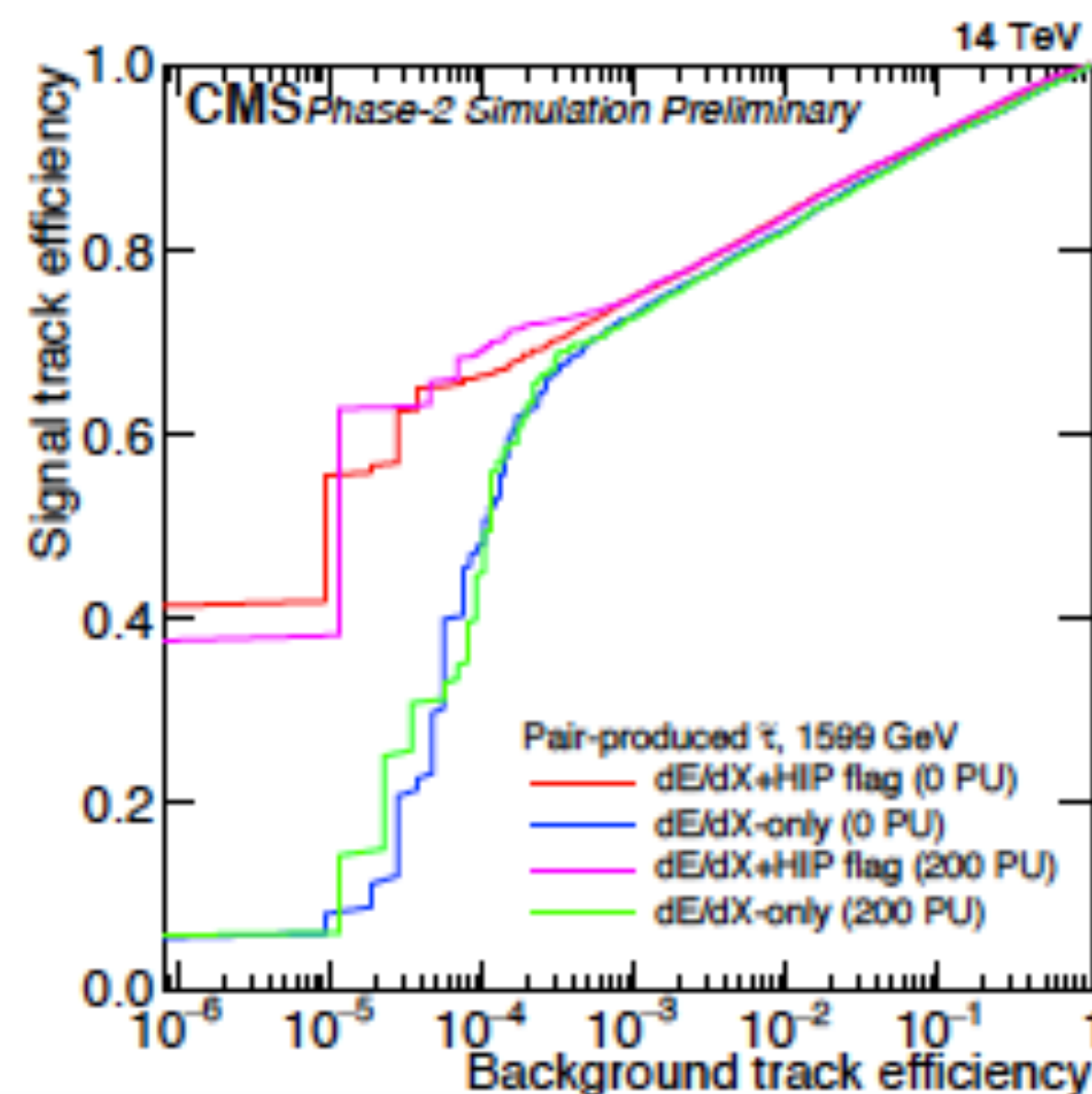
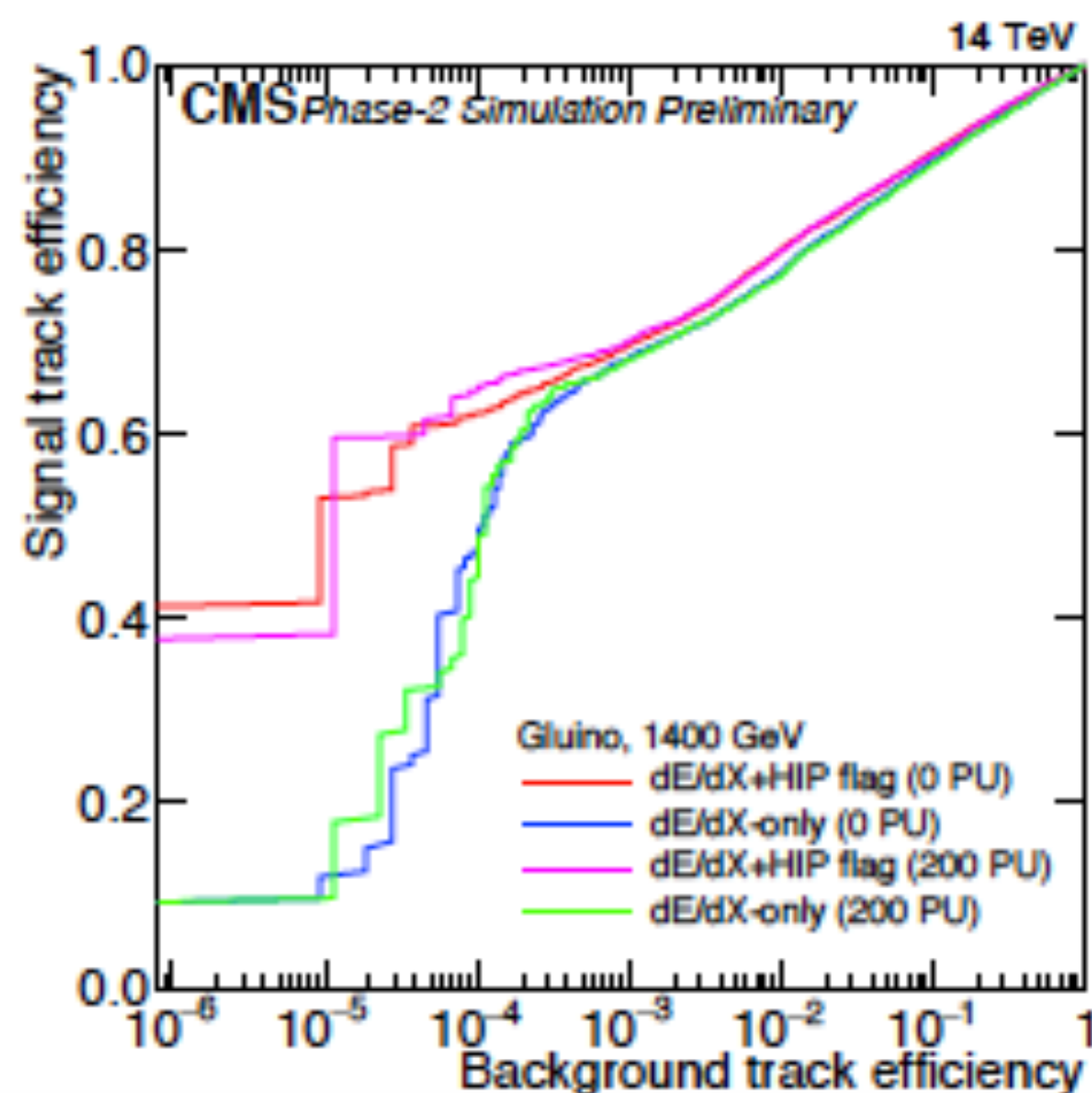
- ✳ **CMS 18.5 fb⁻¹ [PRD 91 (2015) 012007], recast [PRD 92 (2015) 073008]**
- ✳ **ATLAS 20.3 fb⁻¹ [PRD 92 (2015) 012010] [PLB 743 (2015) 15-34]**
- ✳ **Parameter space $\text{BR}(H \rightarrow \pi_V \pi_V) > 50\%$ is excluded at 95% confidence level**



HSCP at HL-LHC

Exploit intrinsic time resolution of the RPC system (trigger chambers) and upgraded tracker:

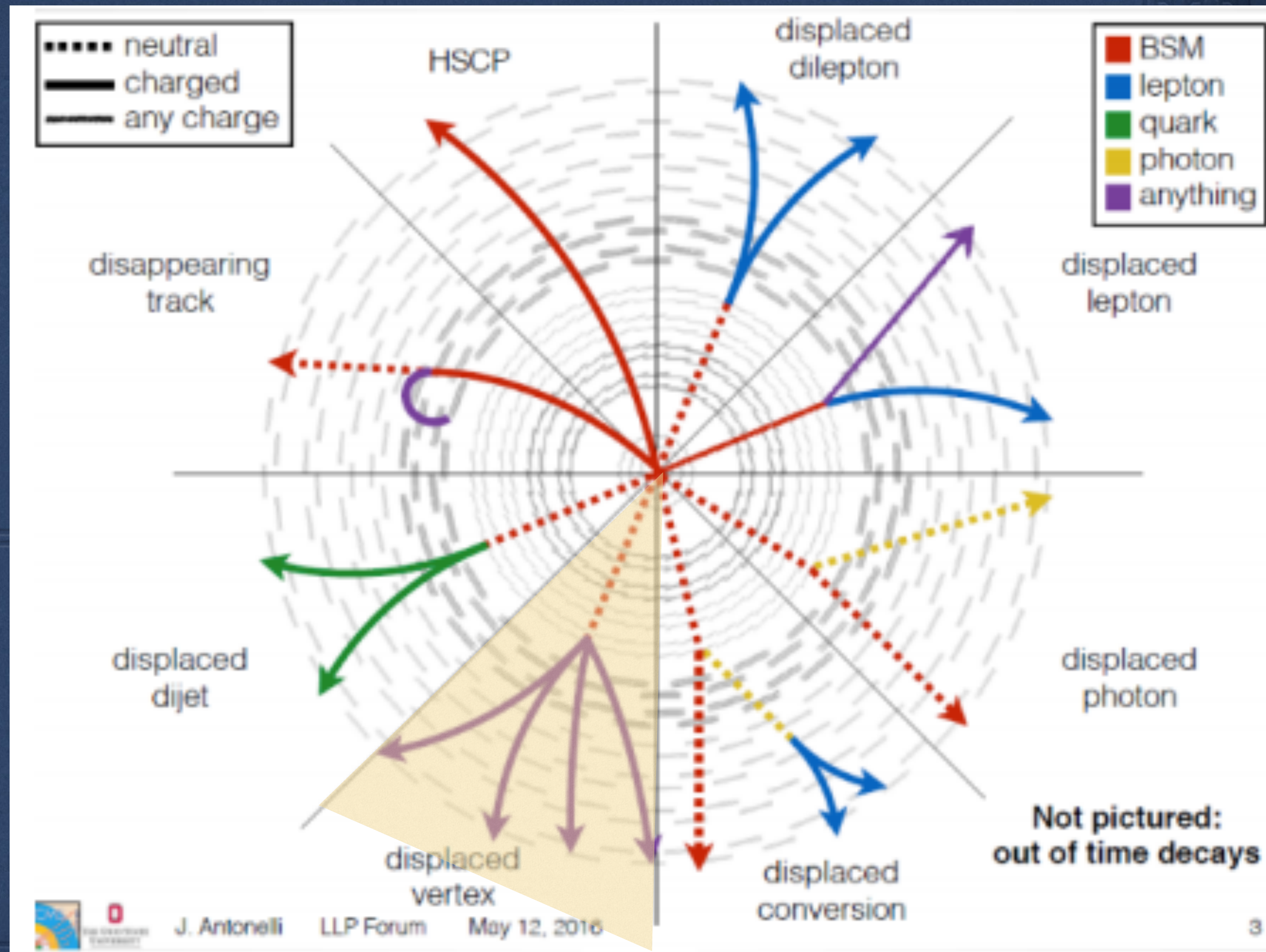
- HSCPs look like slow muons \rightarrow RPC triggers HSCPs with $\beta \sim 0.25$.
- Use trackers to identify signal tracks looking for anomalously high energy loss measurements (IT vs. OT) \rightarrow **HIP Flag**.
- Improved performance of dE/dx discriminator for Phase 2
- **ROC curve(*) for gluino (1.4 TeV) and stau (1.599 TeV)**



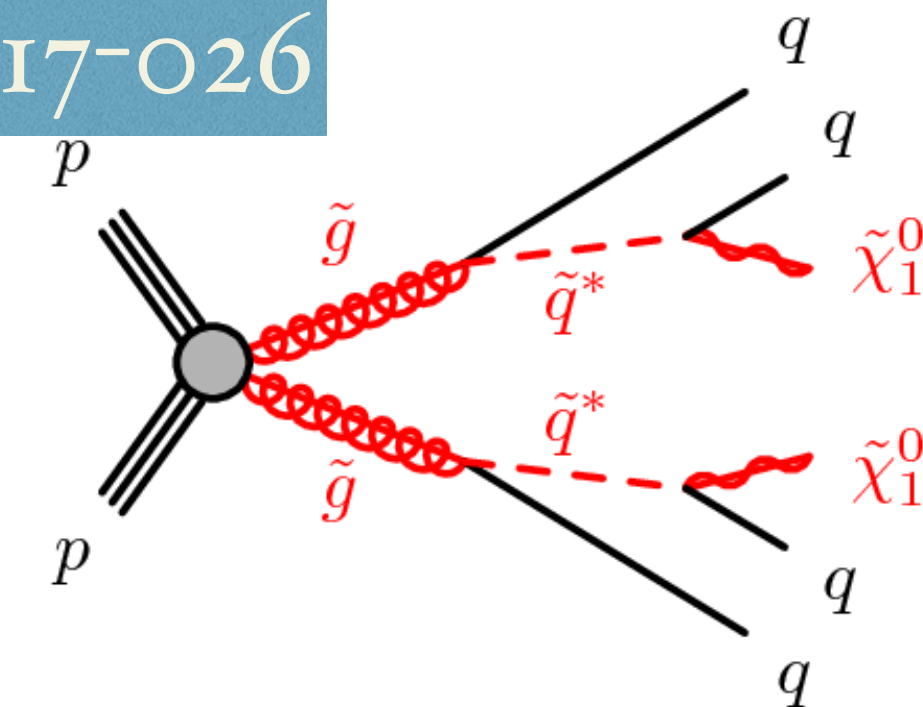
(*) Receiver Operating Characteristic curve, i.e. ROC curve, is a graphical plot that illustrates the diagnostic ability of a binary classifier system as its discrimination threshold is varied. 47

Displaced Vertex

ATLAS-CONF-2017-026
CMS-EXO-17-018
CERN-LHCC-2017-021
arXiv:1808.03057



Displaced Vertices - ATLAS

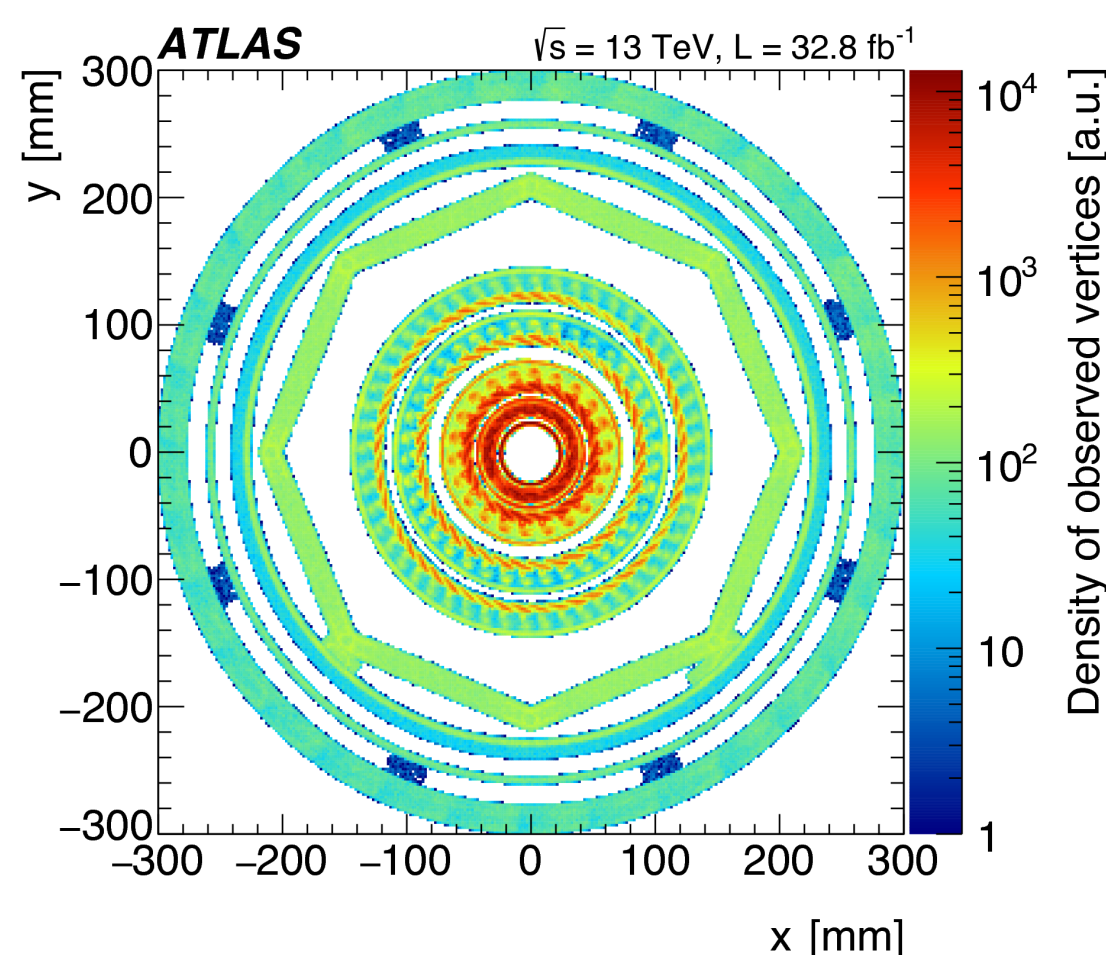
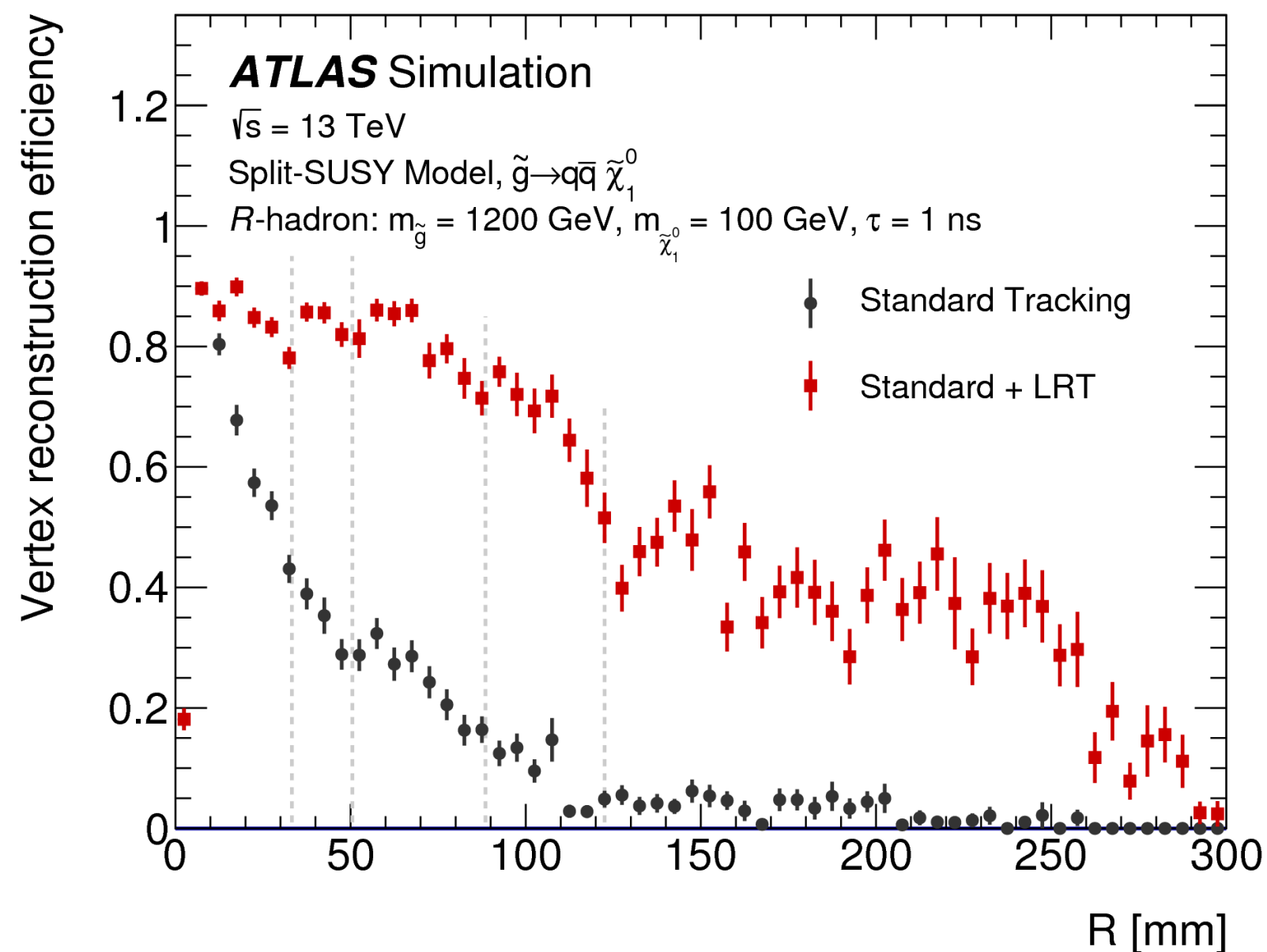


R-hadrons decaying within the ID can be reconstructed as a Displaced Vertex (DV)

- Long-lived Gluinos are present in Mini-split SUSY models
- Analysis sensitive to decay length up to 300 mm
- **Large MET is expected and used for trigger and selection.**

Standard Tracking has low efficiency:

- Standard cuts on transverse (d_0) and longitudinal (z_0) impact parameters with respect to the IP remove displaced decay (large impact parameters)
- **Large radius tracking (LRT).** A dedicated second pass of the tracking is ran on leftover hits from the standard track -much like for the disappearing-track analysis -but with **looser cut on d_0 and z_0** algorithm.
- Final selection: $MET > 250$ GeV at least one good DV with mass $m_{DV} > 10$ GeV and number of associated tracks $n_{trk} \geq 5$
 - Main background from hadrons interaction with detector material. Create a 3D map of the dense material region of the ID and veto vertices in these regions



Production of long-lived gluinos with masses up to 2.37 TeV and lifetimes of $O(10^{-2})$ - $O(10)$ ns in a simplified model inspired by split supersymmetry.

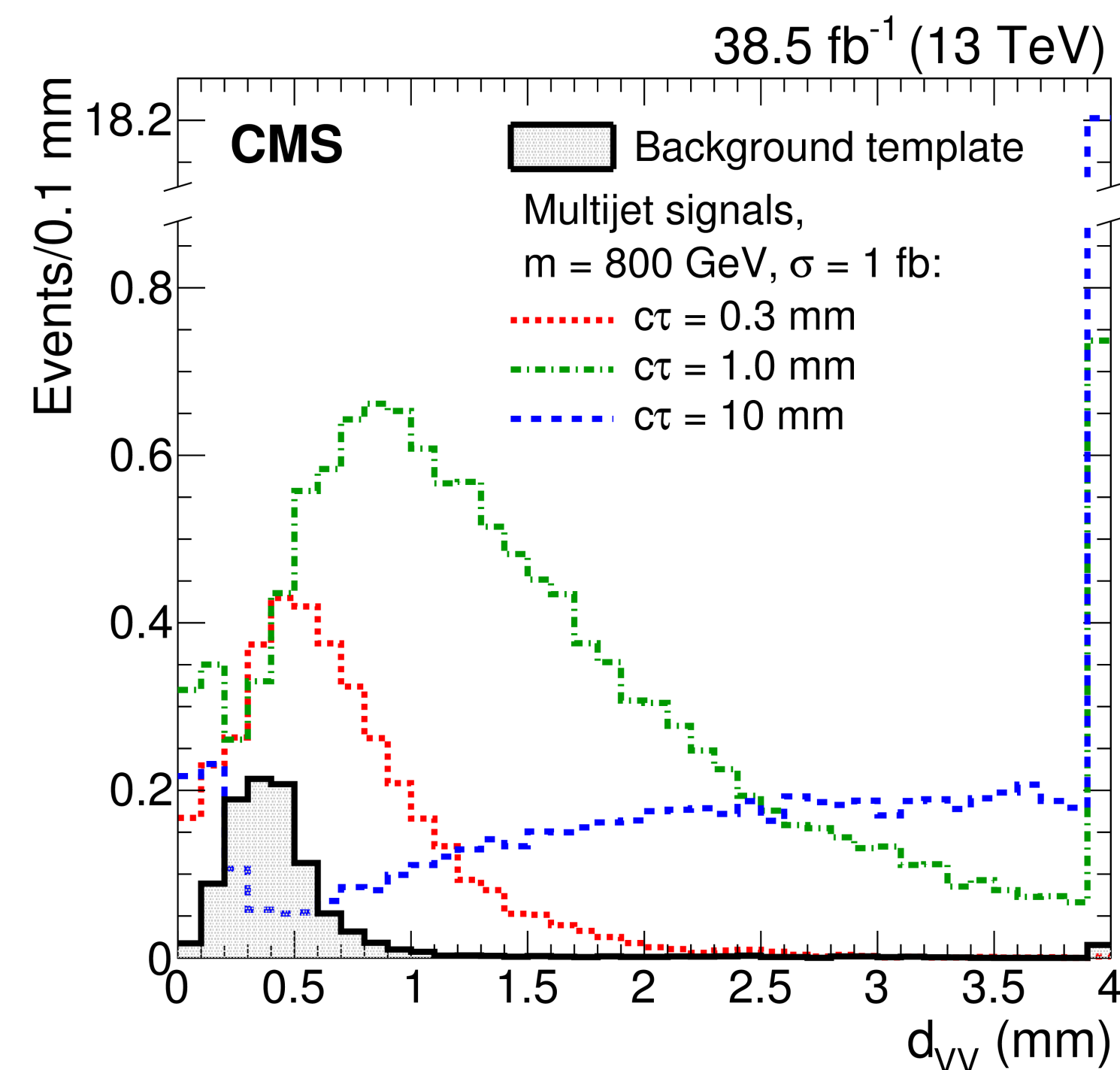
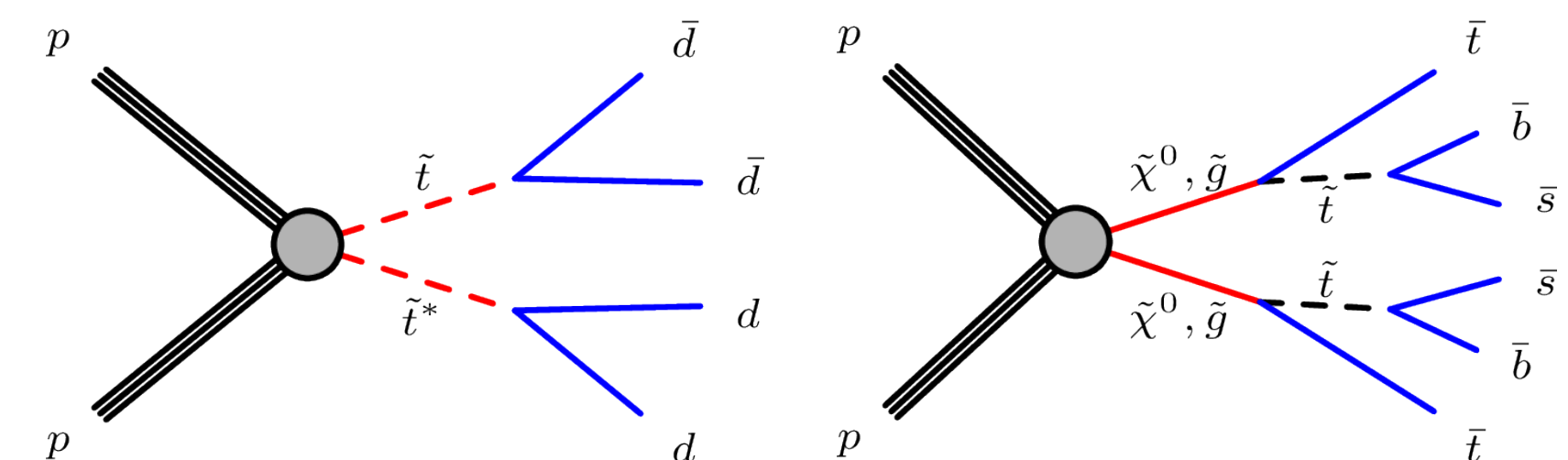
Displaced Vertices in Multijet Events - CMS

Search for long-lived resonance decaying to a pair of jets (RPV Model):

- Dijet (stop channel)
- Multijet (gluino, neutralino channel)

Analysis Strategy

- No MET but large number of hard jets is expected.
- For trigger (selection) $H_T > 800, 900 (1000)$ GeV
(H_T is the scalar sum of hard jets transverse momenta)
- Use d_{VV} - distance between pair of vertices.
Only DV vertices inside beam pipe are considered.
- Fit background (multijets & $t\bar{t}$) and signal d_{VV} templates



The data exclude cross sections above approximately 0.3 fb for particles with masses between 800 and 2600 GeV and mean proper decay lengths between 1 and 40 mm. For mean proper decay lengths between 0.6 and 80 mm, gluino masses below 2200 GeV and top squark masses below 1400 GeV are excluded.

Displaced Muons

GGM Scenario and Higgs decays Models

Two searches: High mass ($Z\mu\mu$) and Low mass ($Z_D\mu\mu$)

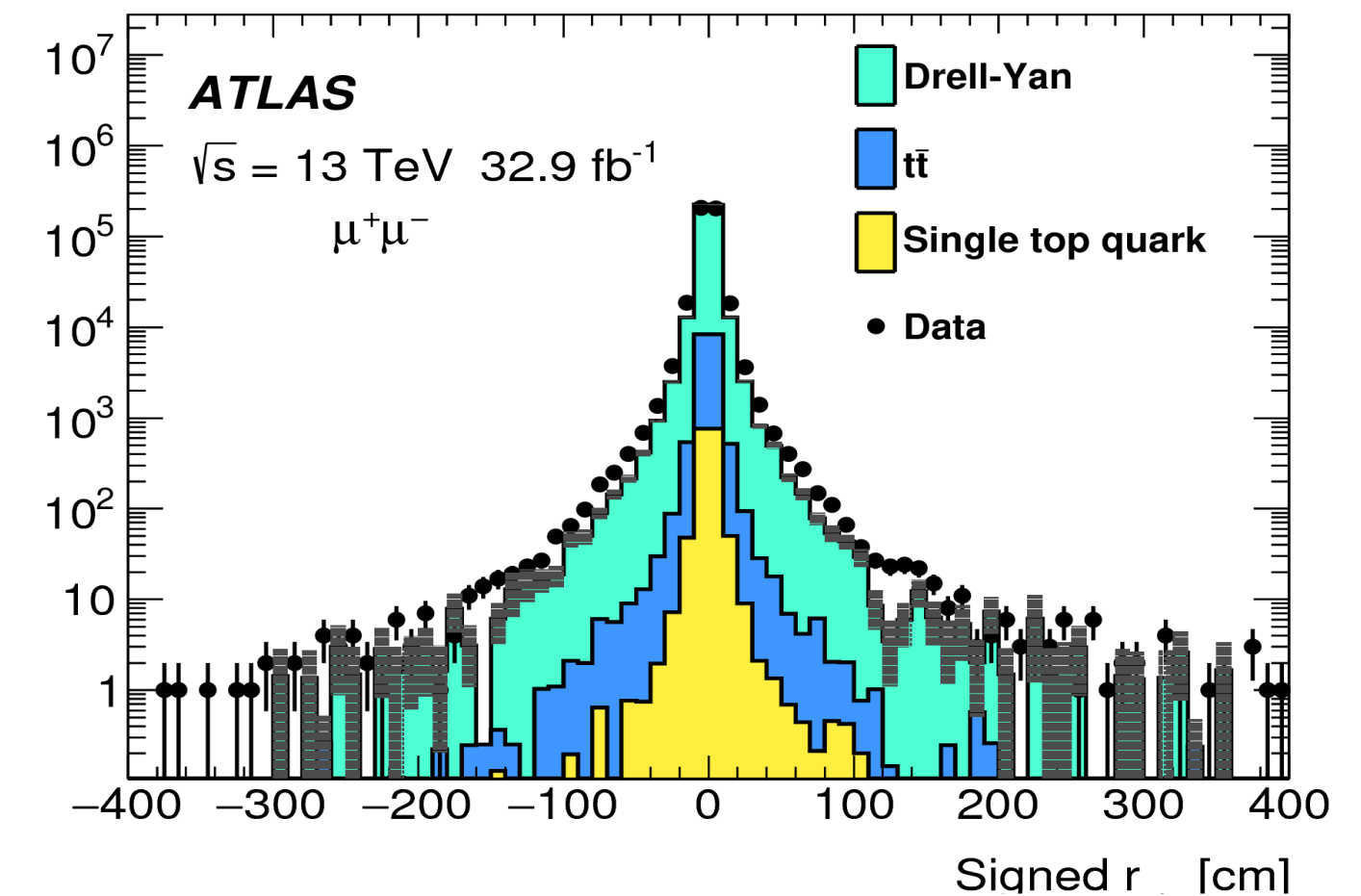
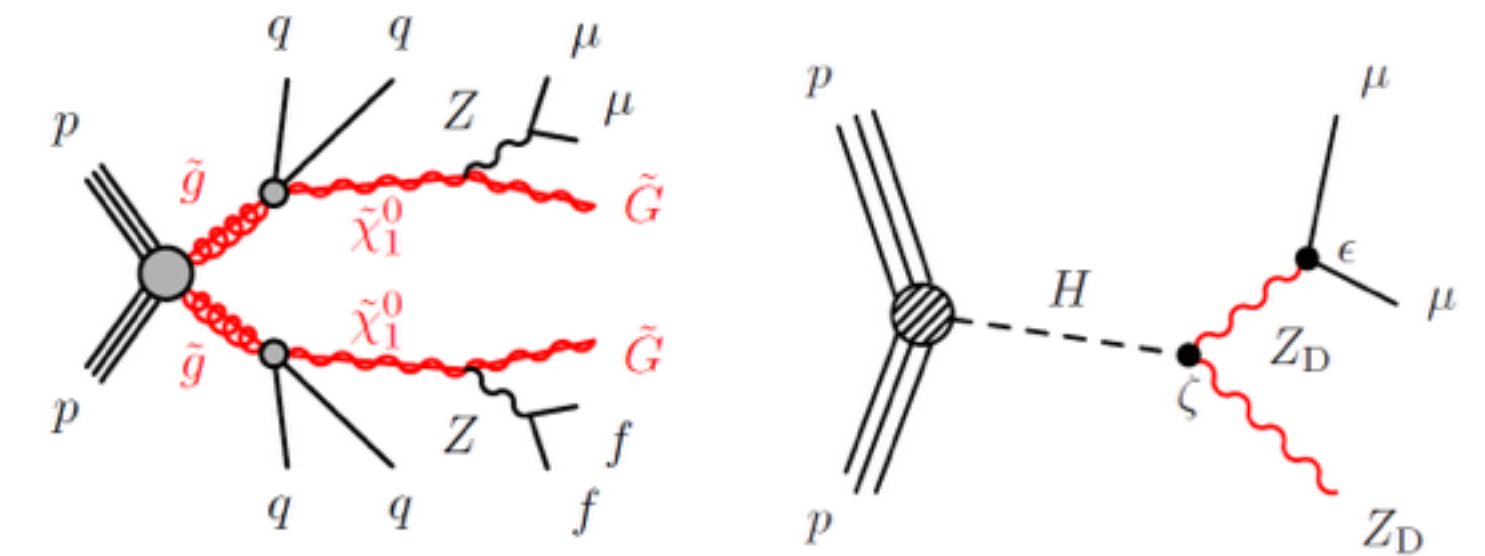
- Opposite-signed muons with vertex up to 4m from interaction point

Trigger: OR of MET, and 1, 2, 3 muon(s).

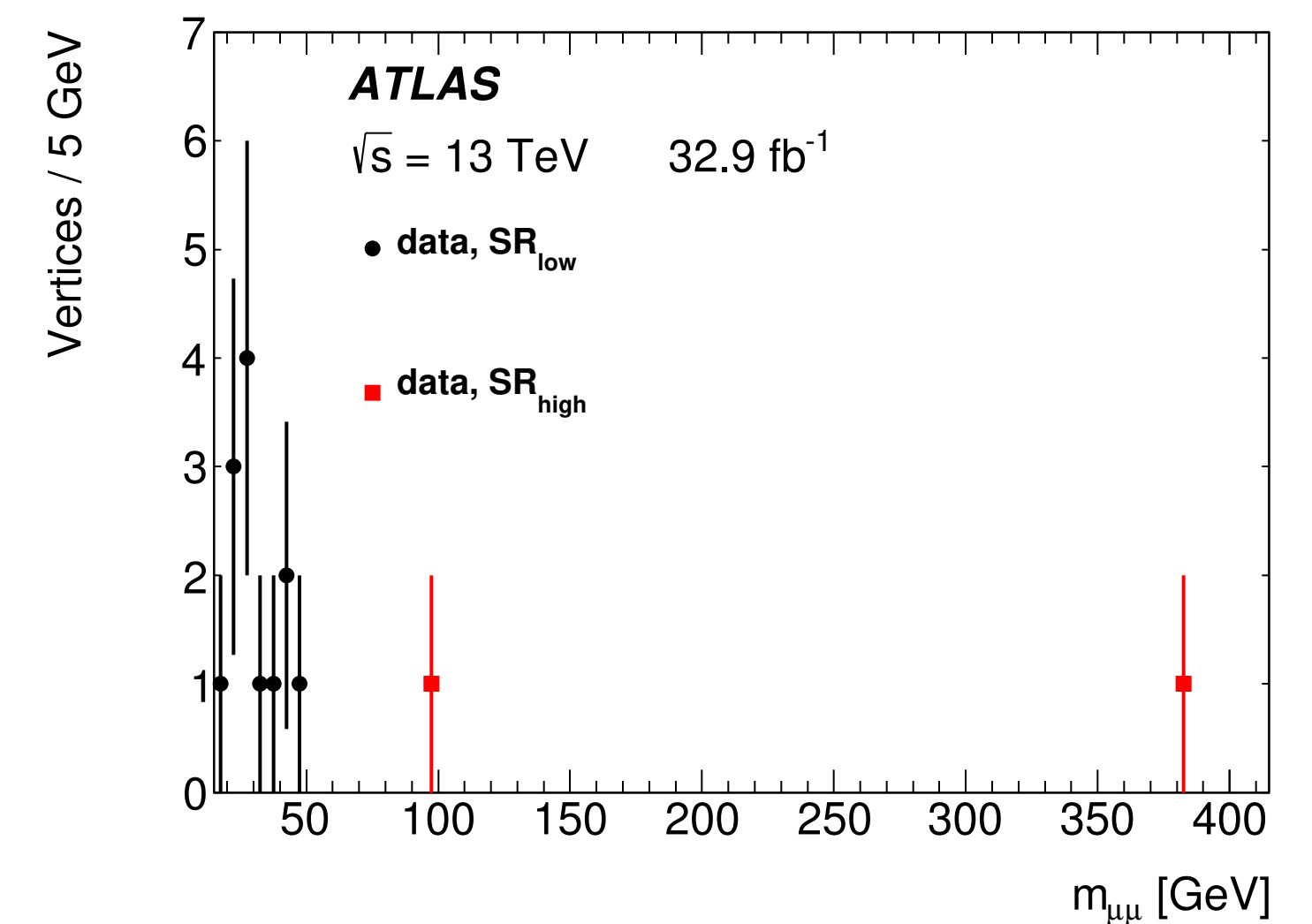
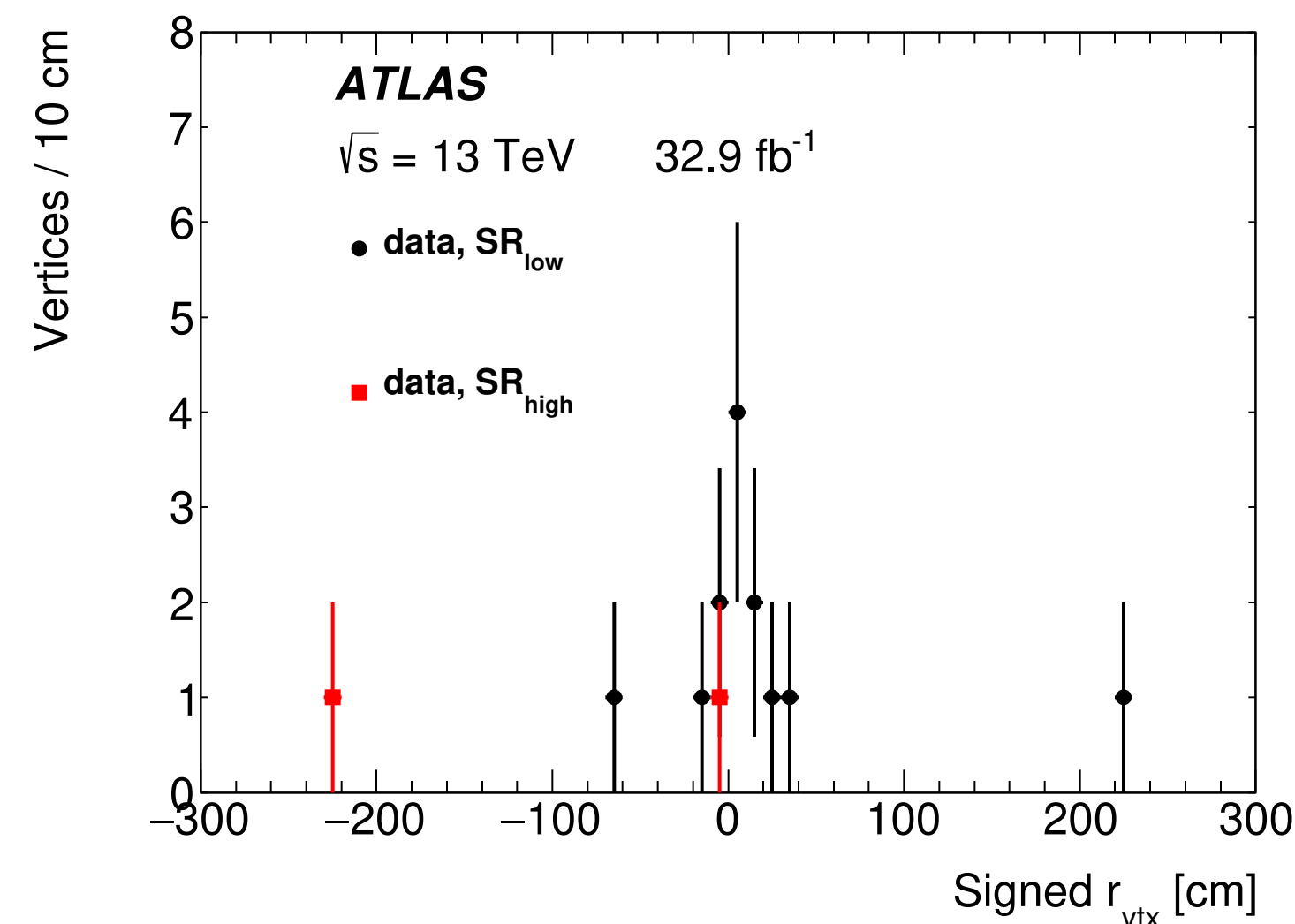
Signal Region-low,high: pair of isolated OS Muon Spectrometer only

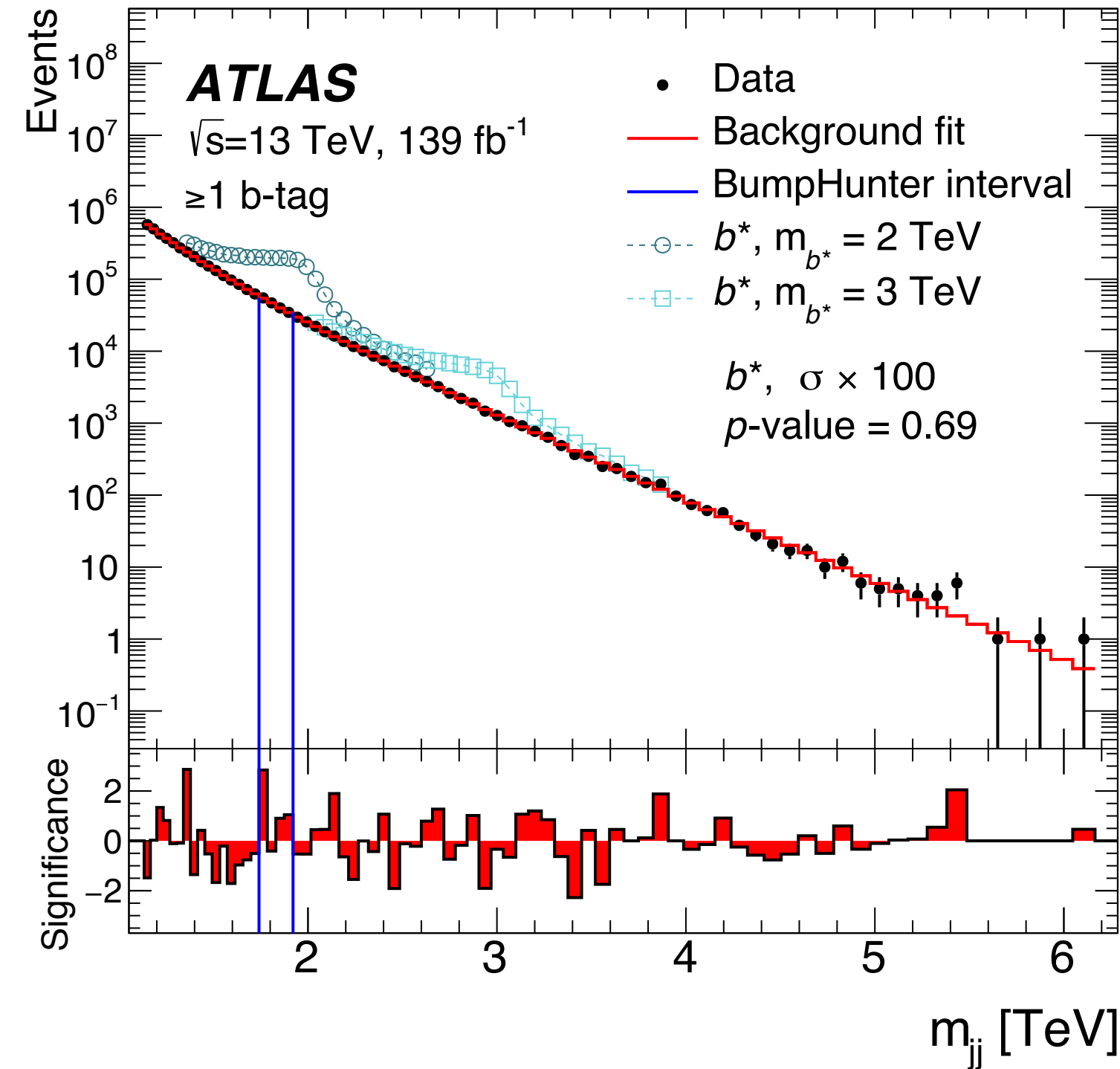
Data Driven Background

- MOnly & MScomb muons
- OS & SS pair of muons - isolated vs non-isolated - pairs. The main background is from accidental pairing, beam-induced background and Cosmic Ray muons.

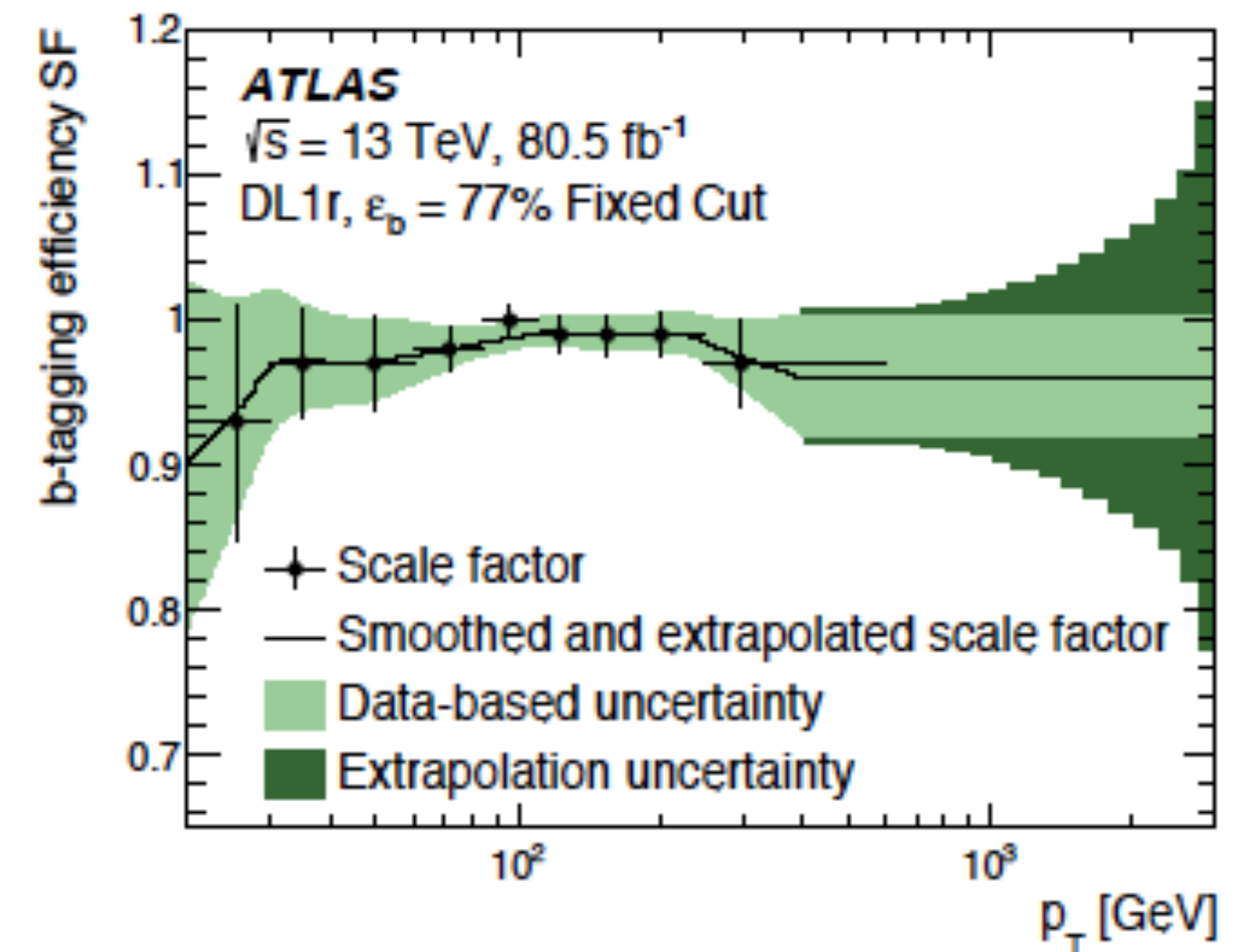
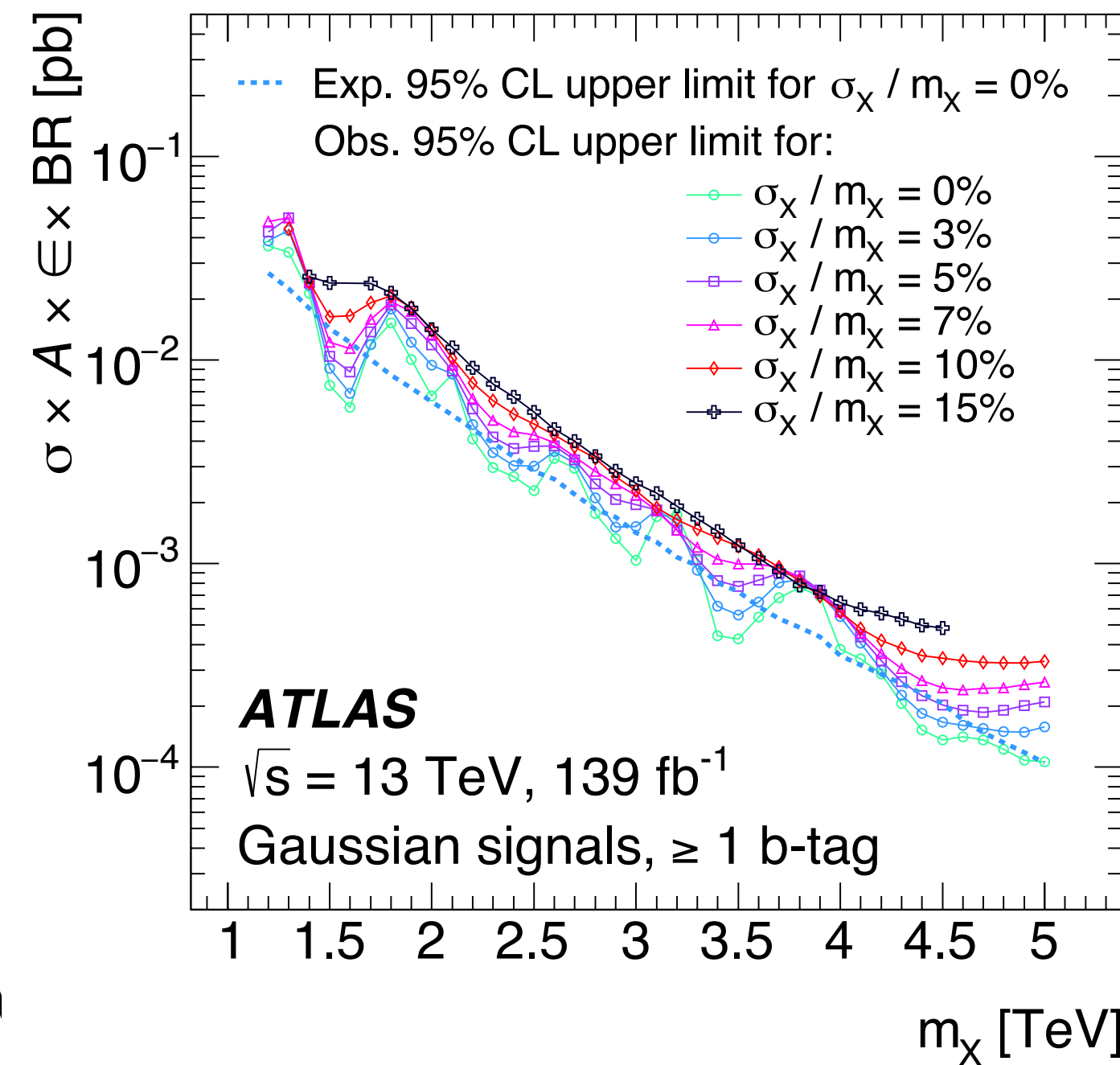
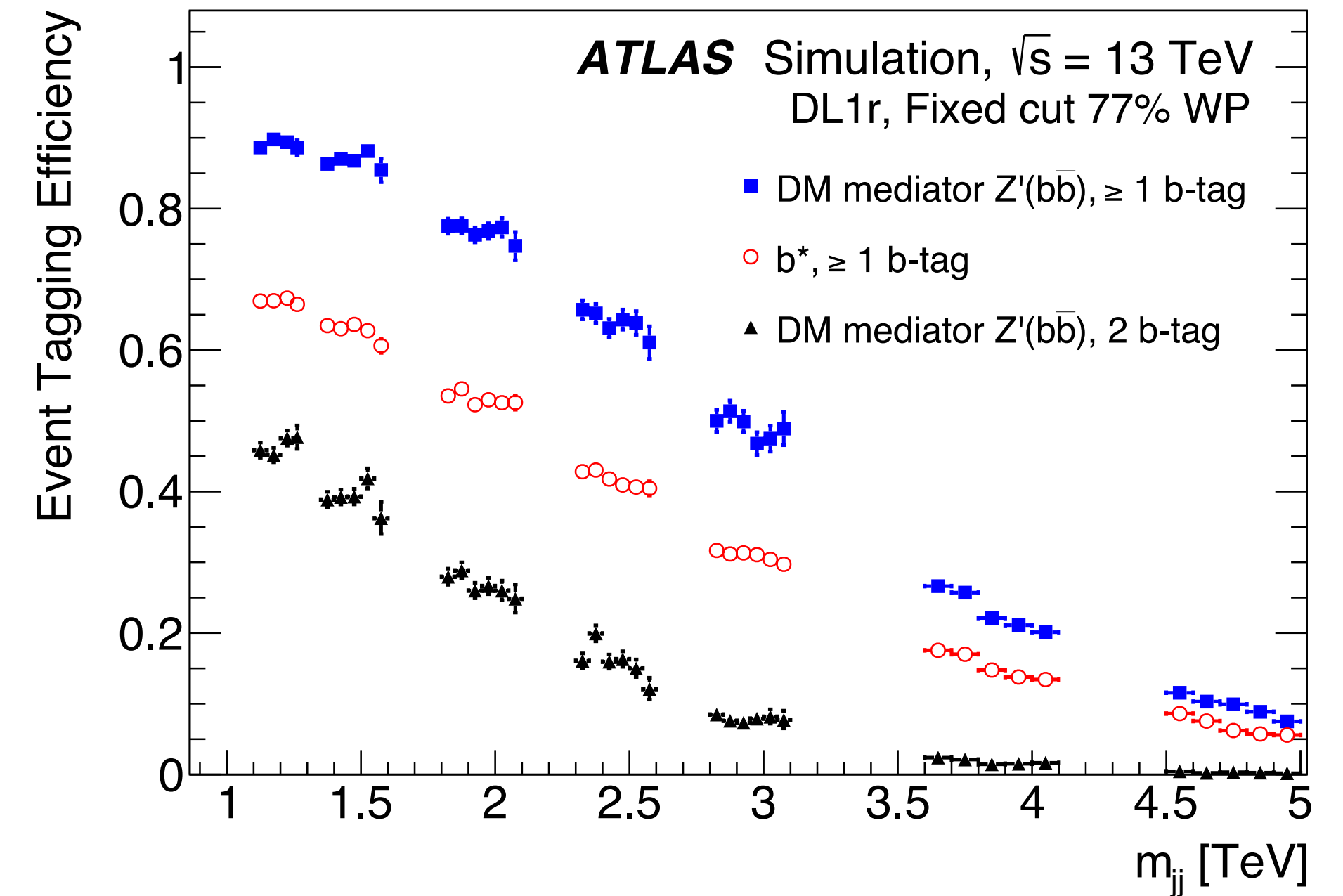


Lifetimes in the range
 $c\tau = 1 - 2400$ cm are
 excluded, depending on
 the parameters of the
 model.





Di-Jets Analysis



Dark Photons

❖ Inclusive search for Dark Photons (A') in $\mu\mu$ only with LHCb 2016 dataset

- ❖ The model predicts A' light, produced as γ^*
- ❖ Two searches: prompt and displaced muons
- ❖ Large fraction in forward region, very soft p_T . Online reconstruction of candidates, no pre-scale down to threshold $2m_\mu$. Isolation cut applied above 1 GeV/c.
- ❖ Backgrounds from same sign μ , fits to IP χ^2

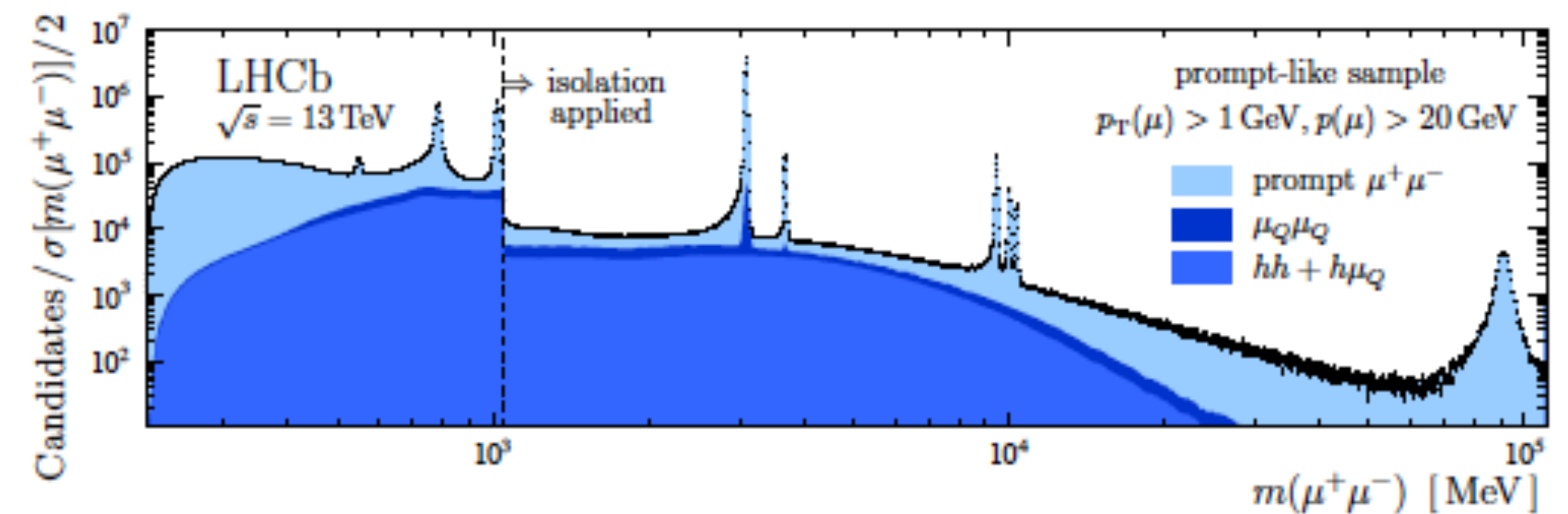
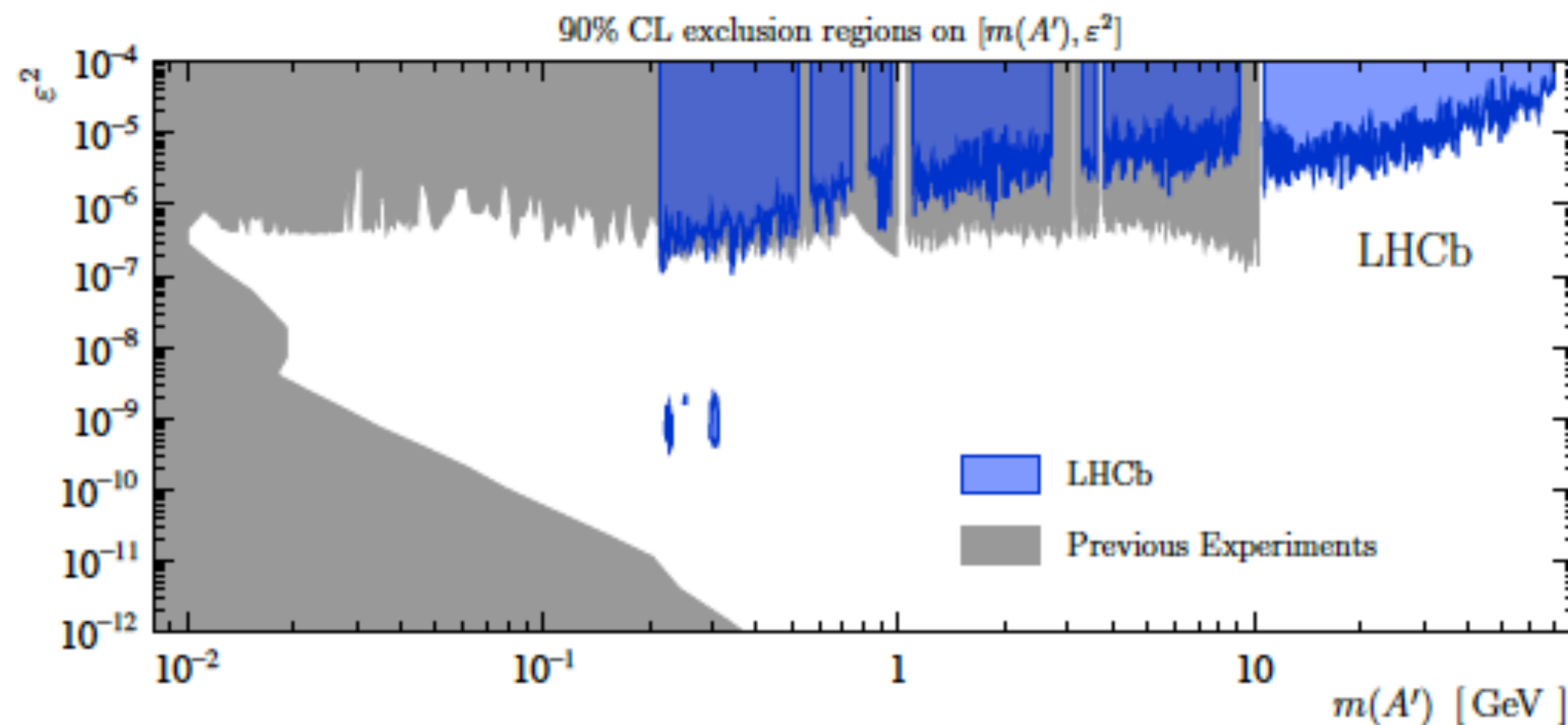
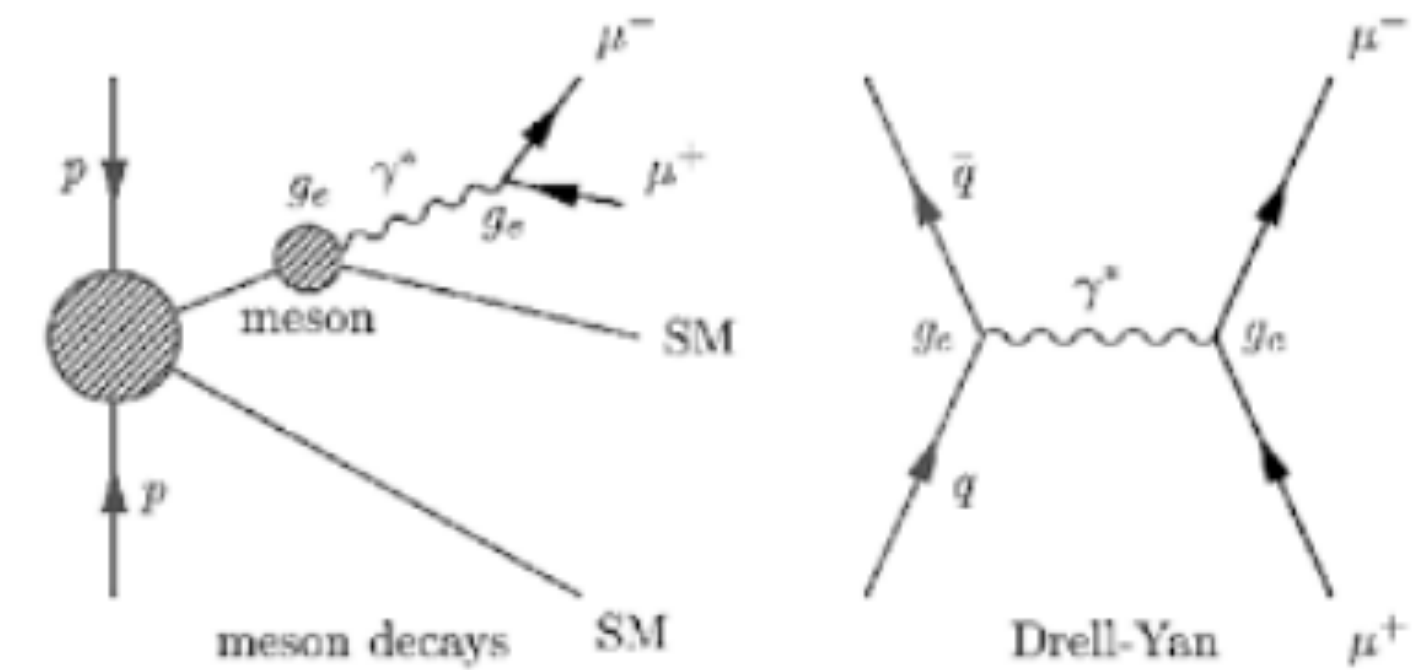


Table 2: Summary of the definitions of the signal regions (SRs) and validation regions (VRs) used in the ABCD method.

Region	Channel	Criteria
SR	$\mu\text{DPJ}-\mu\text{DPJ}$	$\mu\text{BDT} > 0.21$ for both DPJs
	$\mu\text{DPJ}-h\text{DPJ}$	$\mu\text{BDT} > 0.21$ and $h\text{BDT} > 0.91$
	$h\text{DPJ}-h\text{DPJ}$	$h\text{BDT} > 0.91$ for both DPJs
VR	$\mu\text{DPJ}-\mu\text{DPJ}$	$-0.75 < \mu\text{BDT} < 0.35$ for leading μDPJ , $\mu\text{BDT} > -0.7$ for subleading μDPJ
	$\mu\text{DPJ}-h\text{DPJ}$	$-0.5 < \mu\text{BDT} < 0.8$ and $0.2 < h\text{BDT} < 0.8$
	$h\text{DPJ}-h\text{DPJ}$	$h\text{BDT} < 0.91$ for both DPJs

Dark Photons

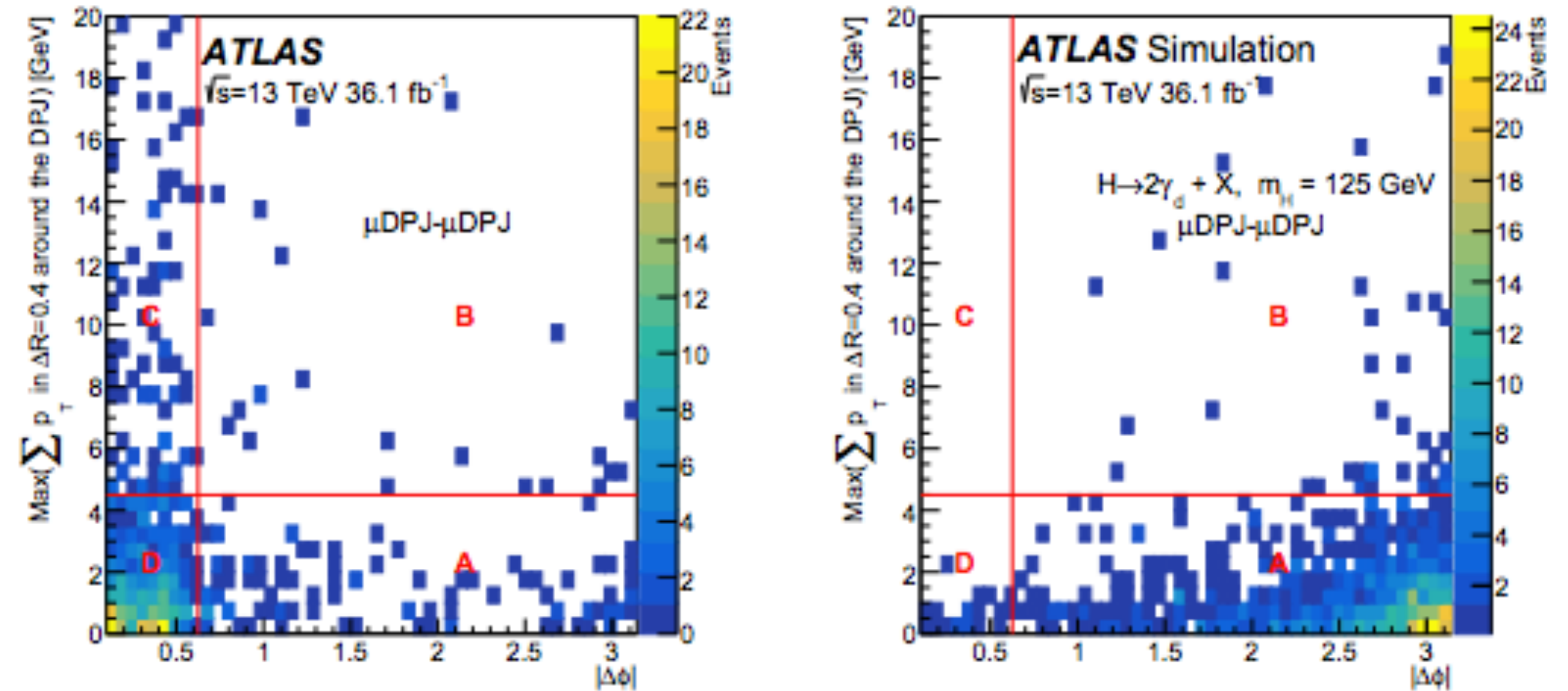
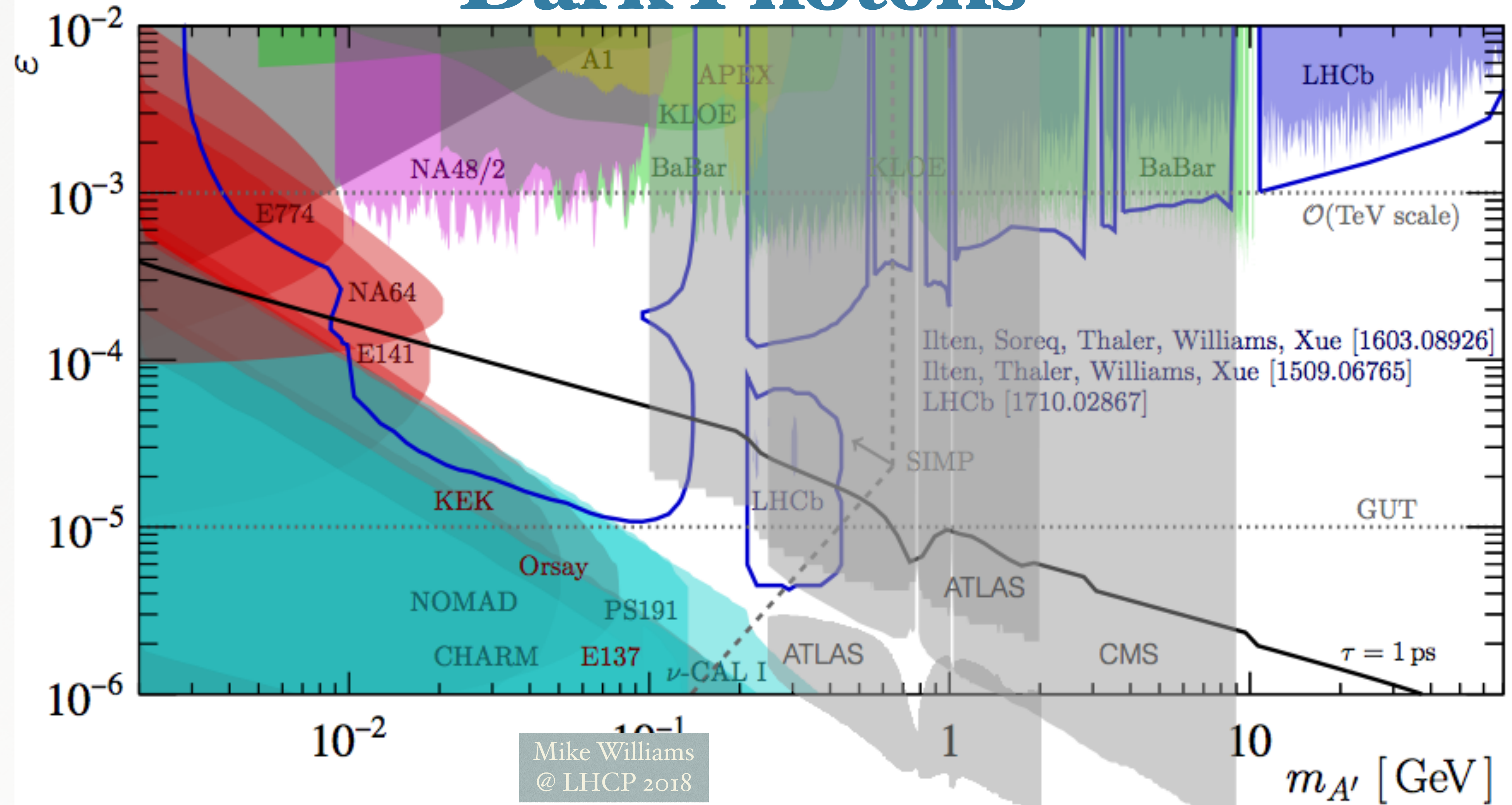


Figure 3: Opening angle between the two DPJs, $|\Delta\phi|$, vs inner-detector isolation, $\text{max}(\Sigma p_T)$, in the $\mu\text{DPJ}-\mu\text{DPJ}$ channel for data (left) and MC signal $H \rightarrow 2\gamma_d + X$ with $m_H = 125 \text{ GeV}$ (right), assuming a 10 % Higgs boson decay branching fraction into γ_d . The red (solid) lines show the boundaries of the ABCD regions.

Dark Photons



ATLAS/CMS limits shown here assume $B(H \rightarrow f_D f_D) = 10\%$.

ATLAS [1511.05542] (see also 1505.07645.CONF-2016-042). CMS [PAS-HIG-16-035].