Recent and future BSM searches in LHC

of my interest

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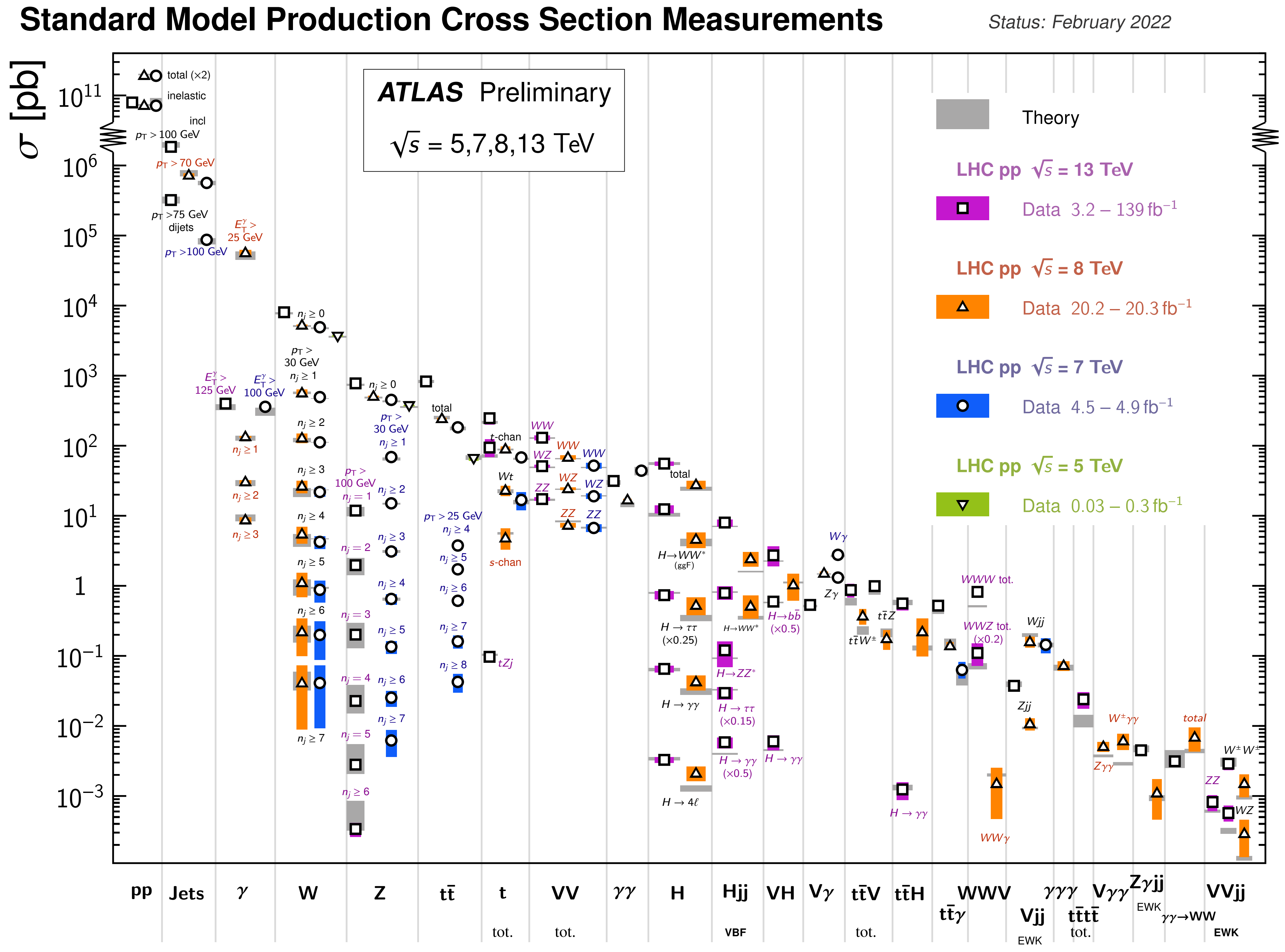
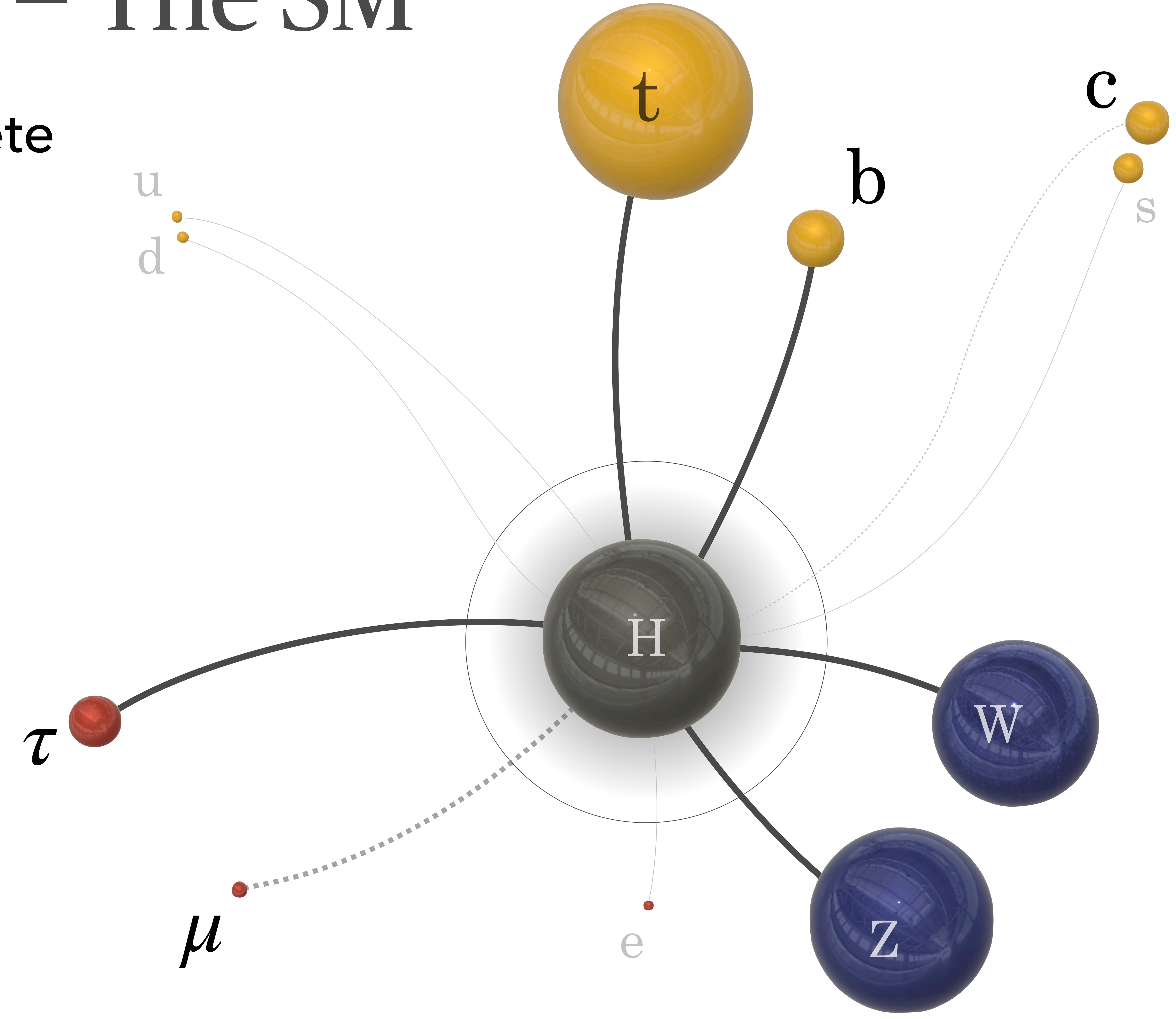
Essences of the talk

- LHC in the intensity fronter vs. BSM search
- Long-lived particle searches in ATLAS and underlying techniques
- Recent search result: pixel dE/dx
- Some HL-LHC prospects

Preamble – The SM

- Ths SM of particle physics is a UV-complete renormalizable theory with a extremely strong support of expriments.



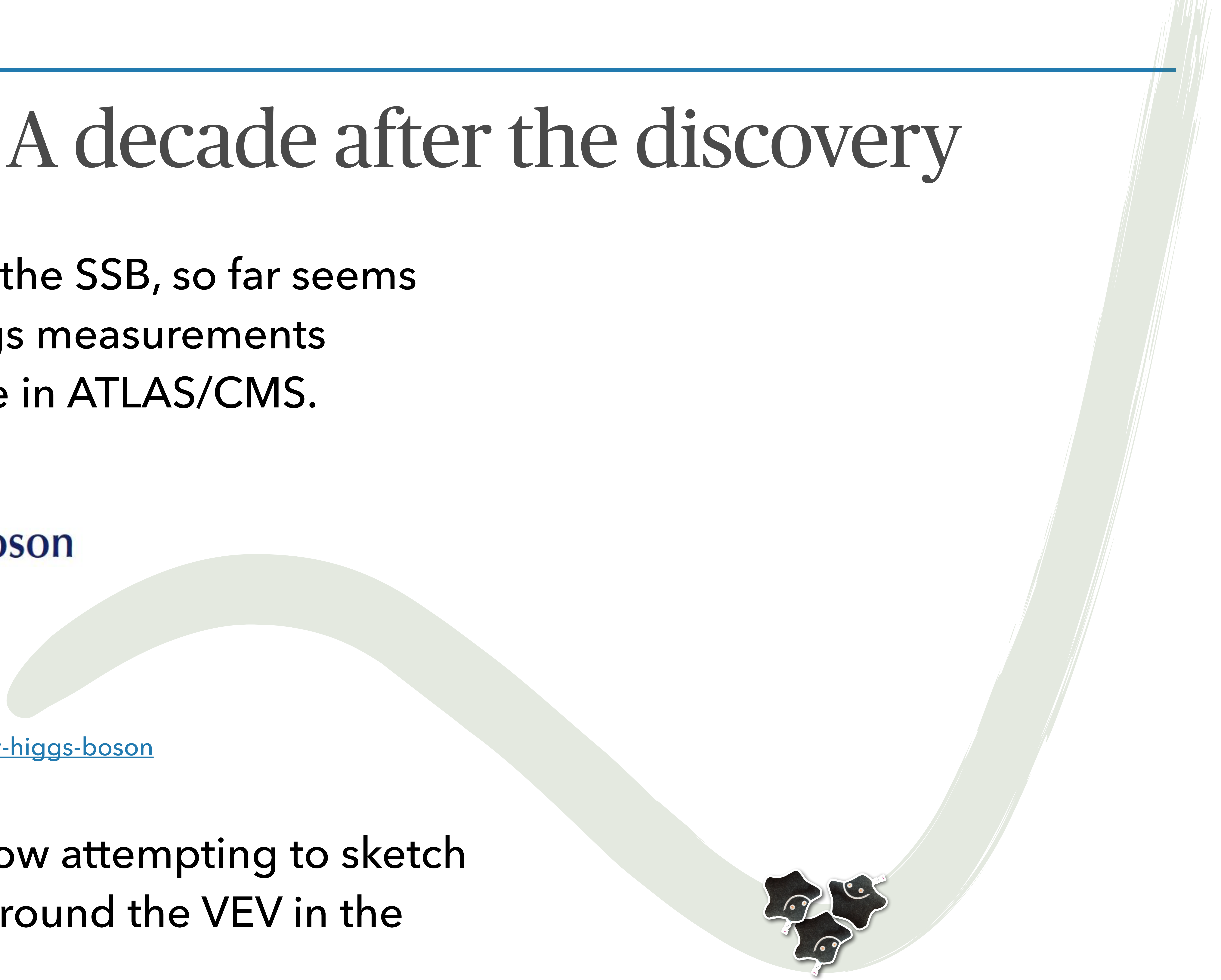


(*) The volume of the sphere roughly corresponds to the mass.

Preamble – A decade after the discovery

- The key of the SM concept, the SSB, so far seems valid by **quasi-precise** Higgs measurements scrutinied in the last decade in ATLAS/CMS.

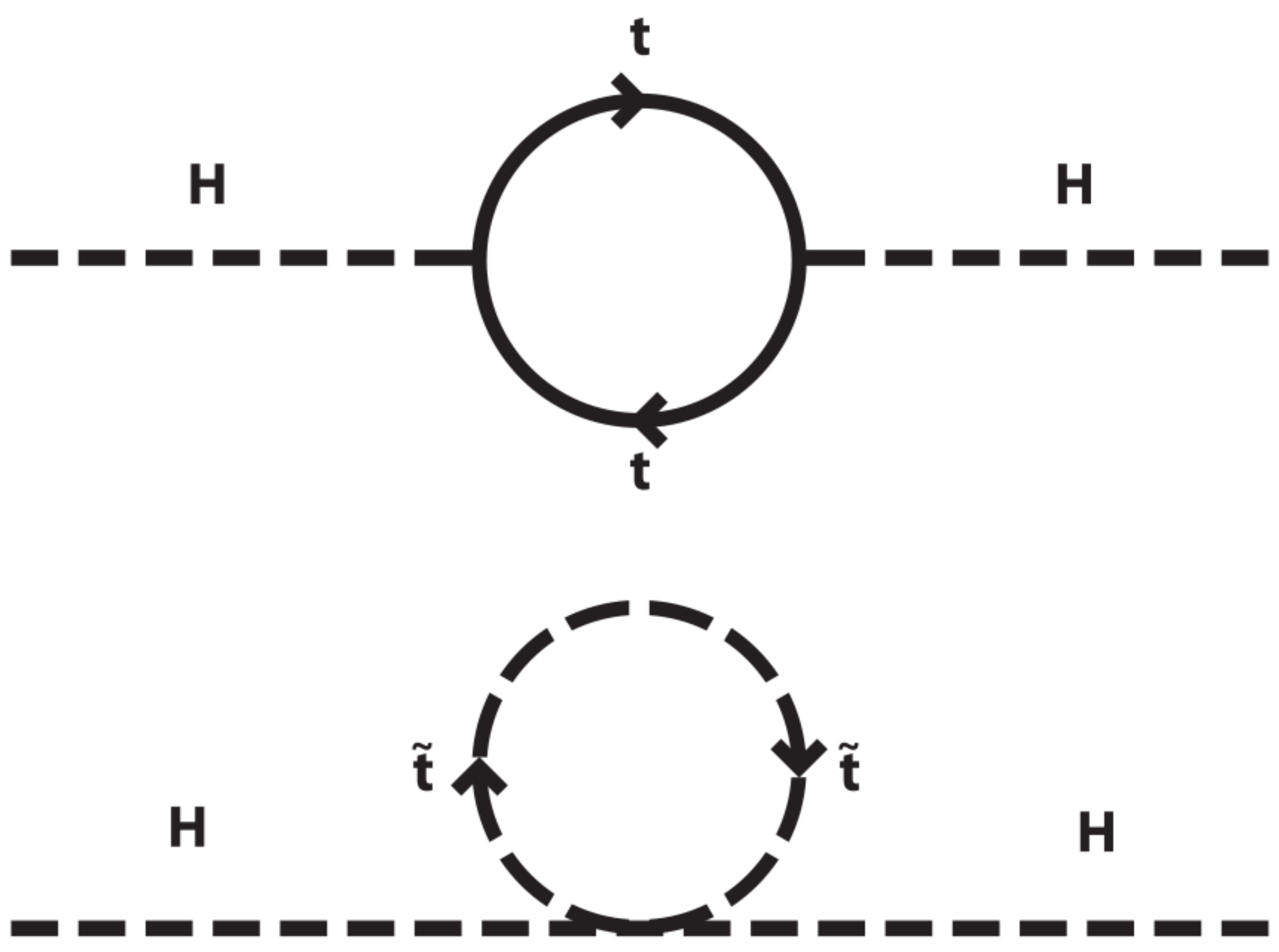
https://home.cern/events/anniversary-discovery-higgs-boson

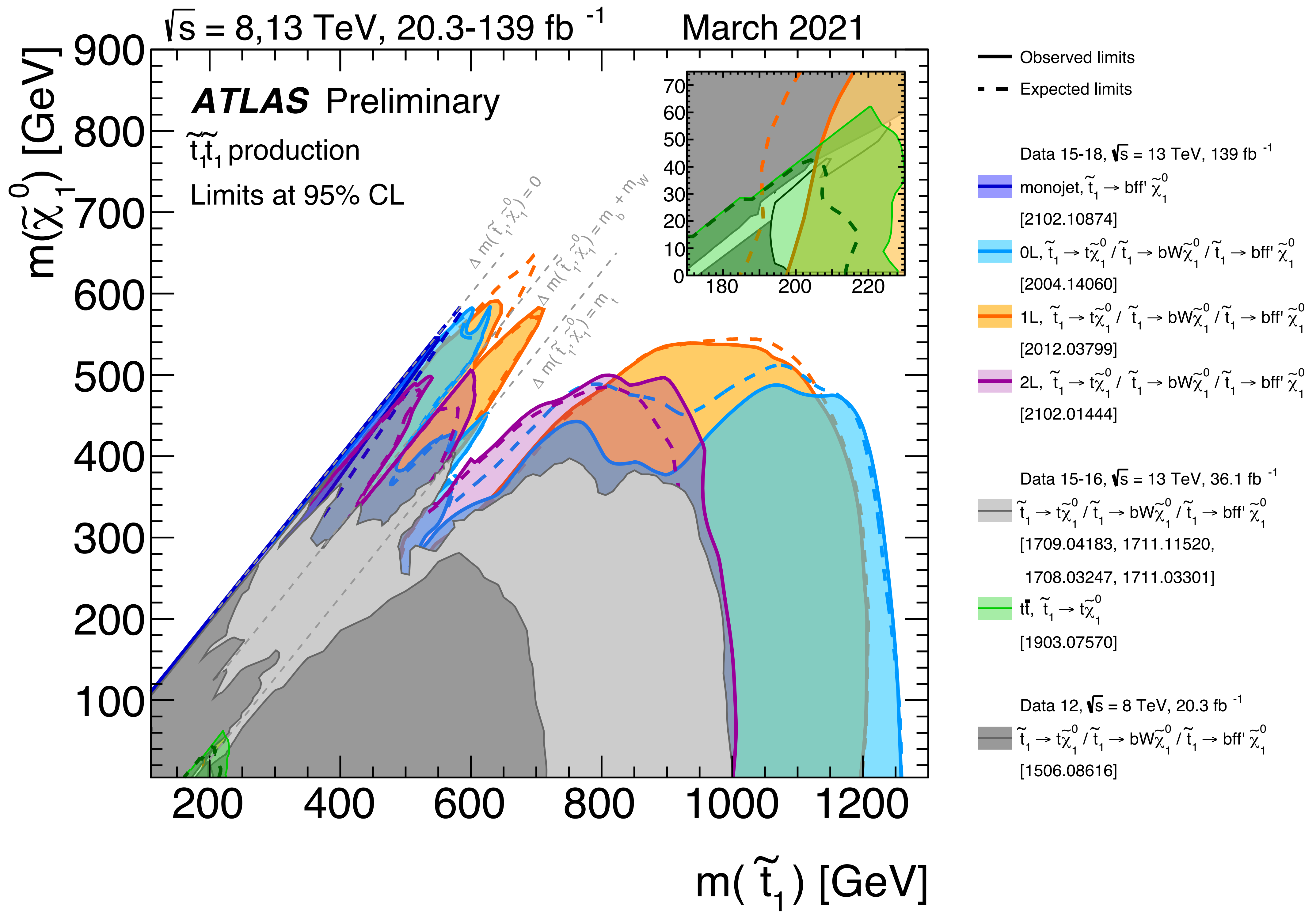


- The LHC experiments are now attempting to sketch the shape of the potential around the VEV in the next decade.

Preamble – The problematic problem

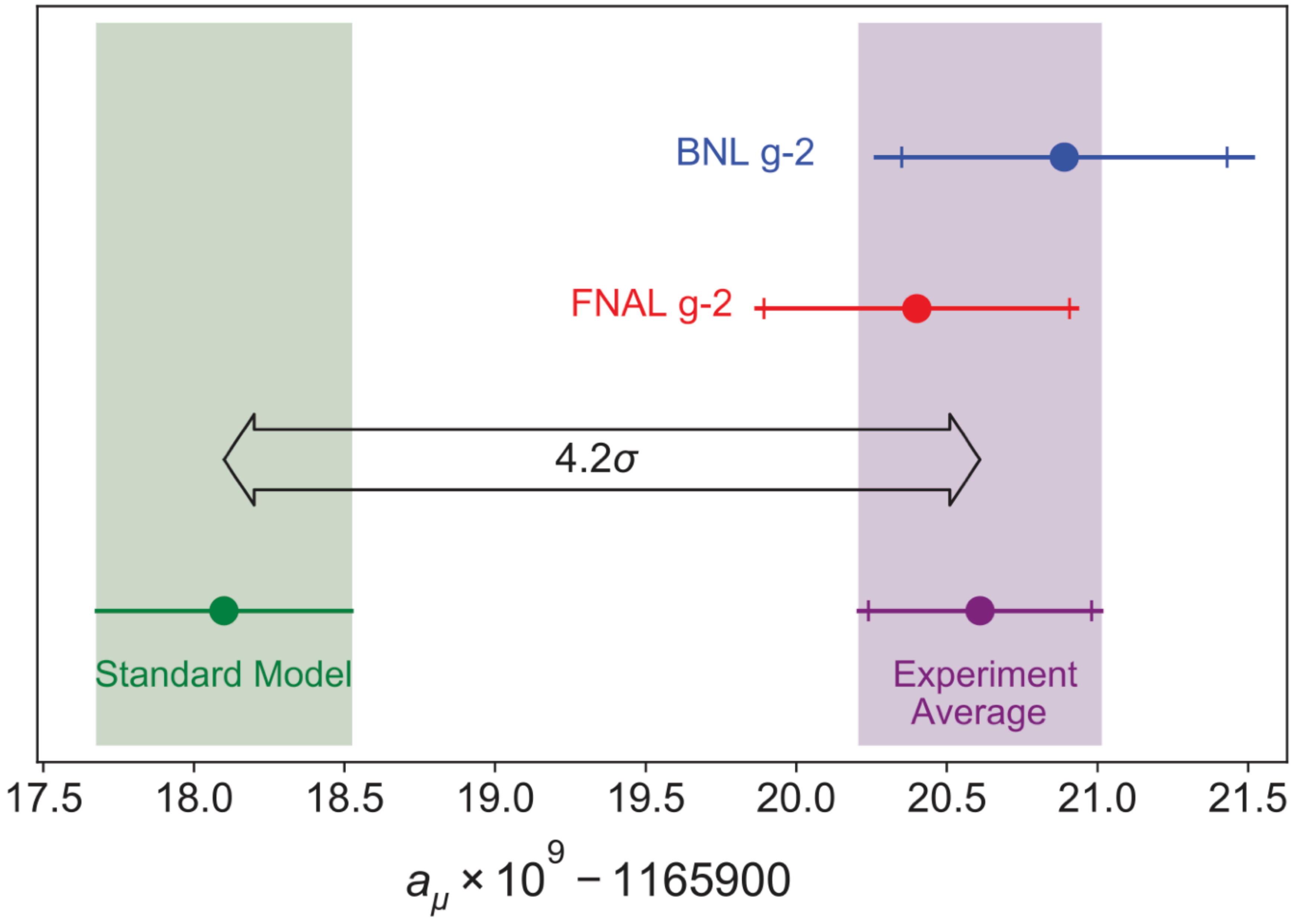
- The ***faith*** that the hierarchy problem should be the first-priority agenda has been threathened through the last decade.

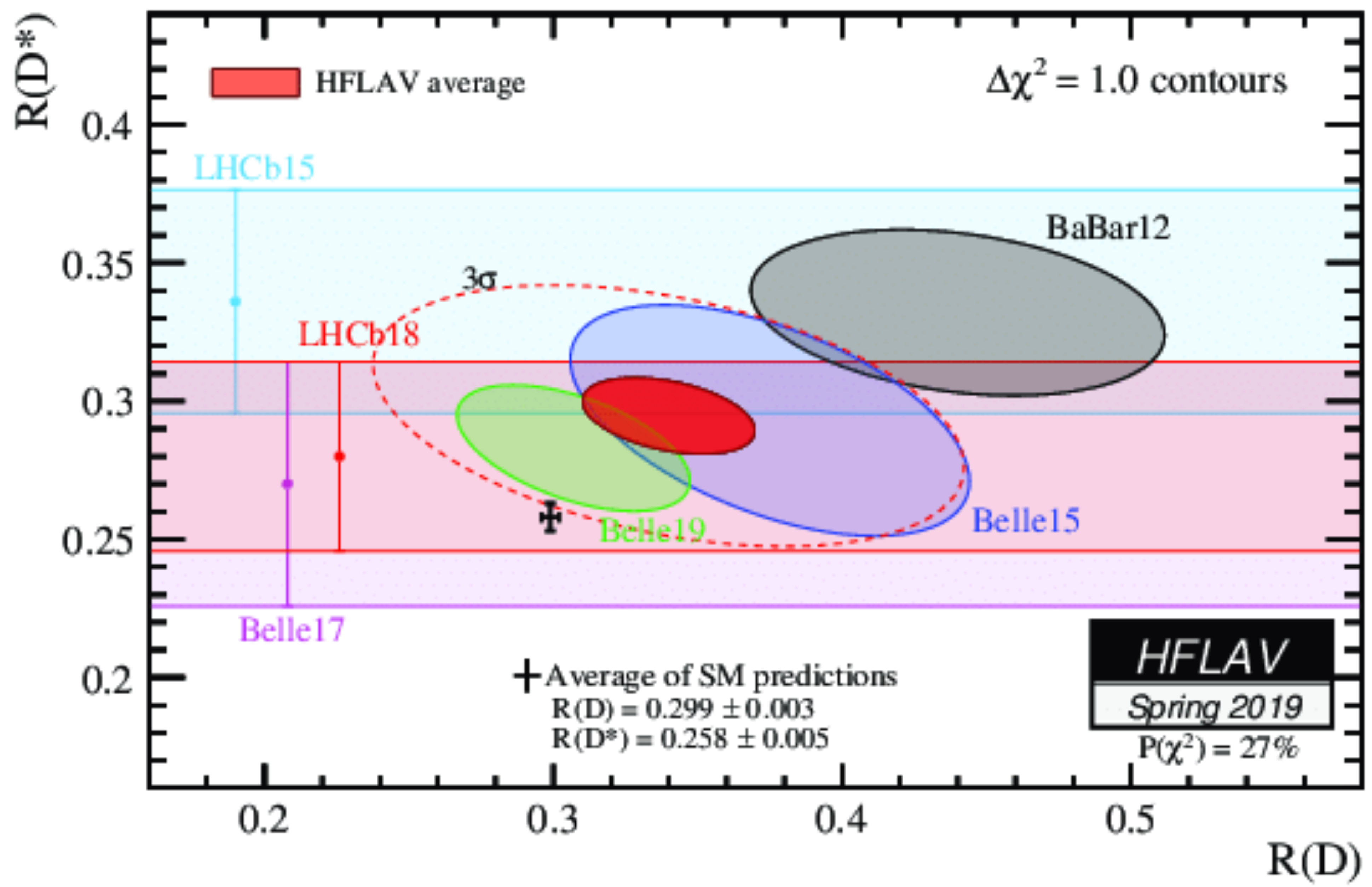




Preamble – Indications of BSM

- However, SM is *a priori* unsatisfactory to accommodate with gravity.
- But also, SM is *empirically* unsatisfactory, too.
- The most overwhelming and reliable evidence is DM.
- Recent several experimental anomalies stimulating the HEP field as well.





Breakthrough has been awaited, so long...

- Although it seems less stressed in these days than the past… but we know,

The impact of **direct discovery** of a new particle is enormous, once happened.

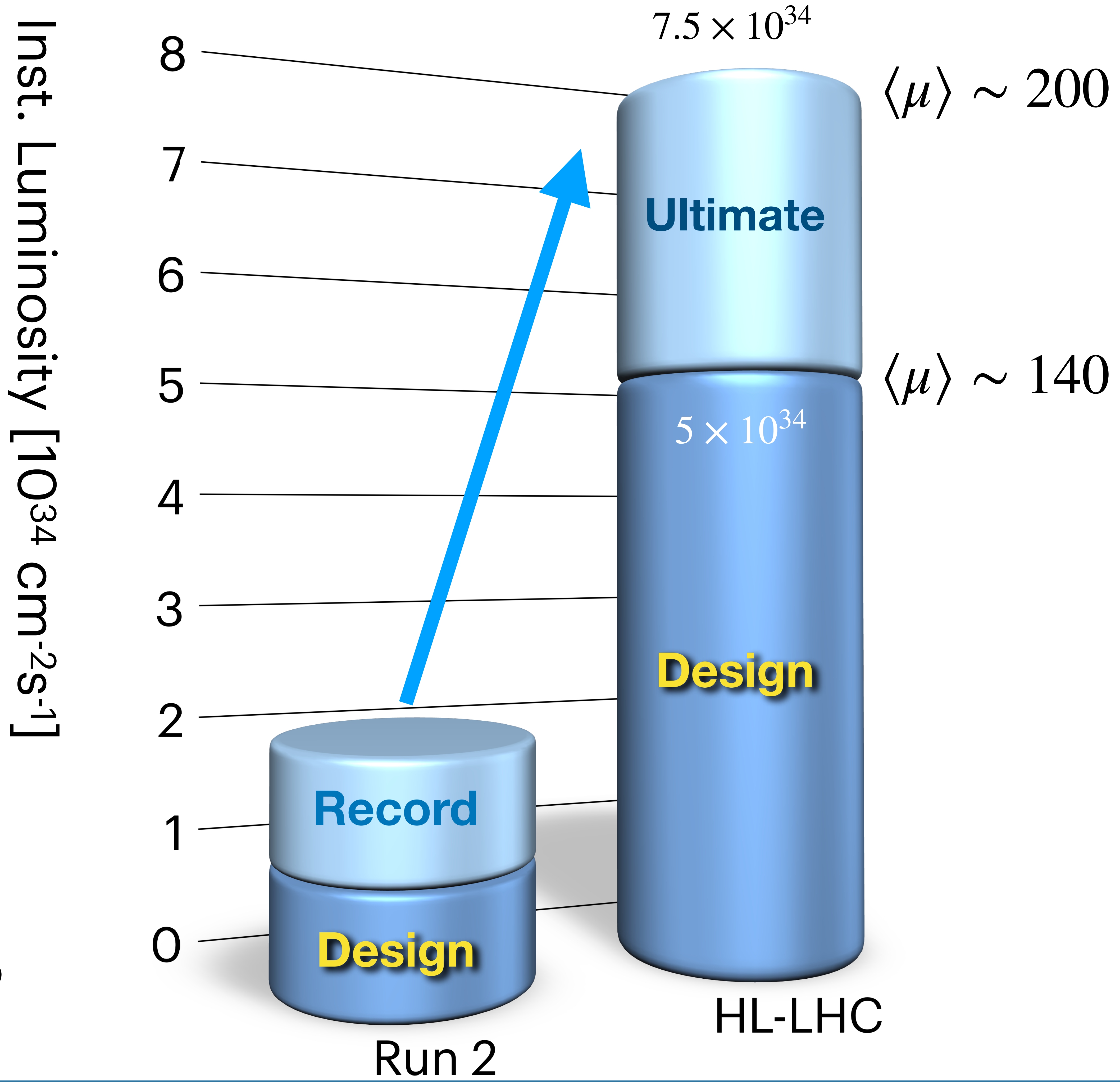
→ It would become the driving force to enterprise the next fundamental projects of the HEP field.

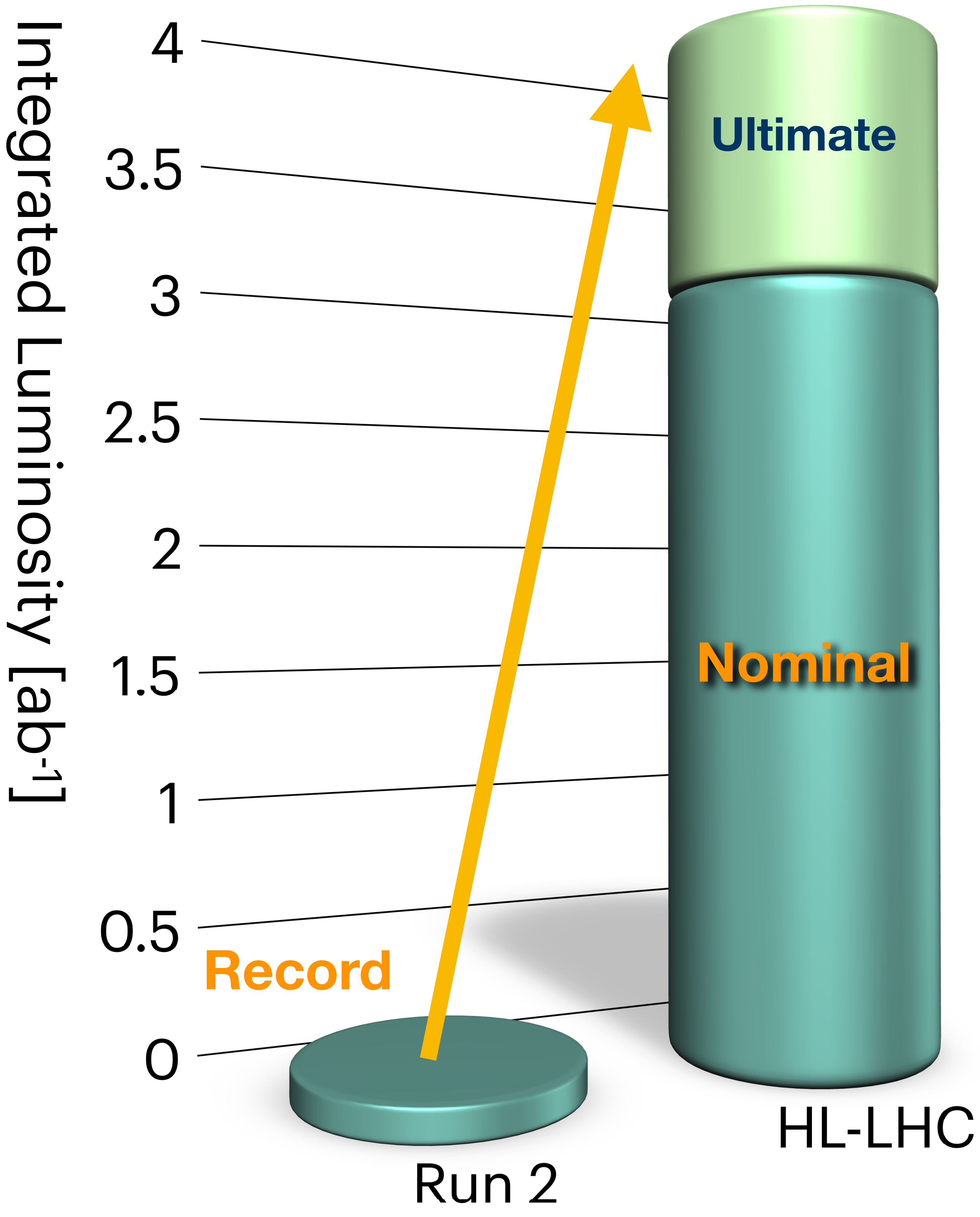
- Moreover, the degree of surprise (aka. “cross-entropy”) to physics will be larger if the discovery takes place in a form which is less anticipated to happen.

This does not mean the well-anticipated sectors should not be de-prioritized.
But we need to search **wider** than that.

LHC as an intensity frontier

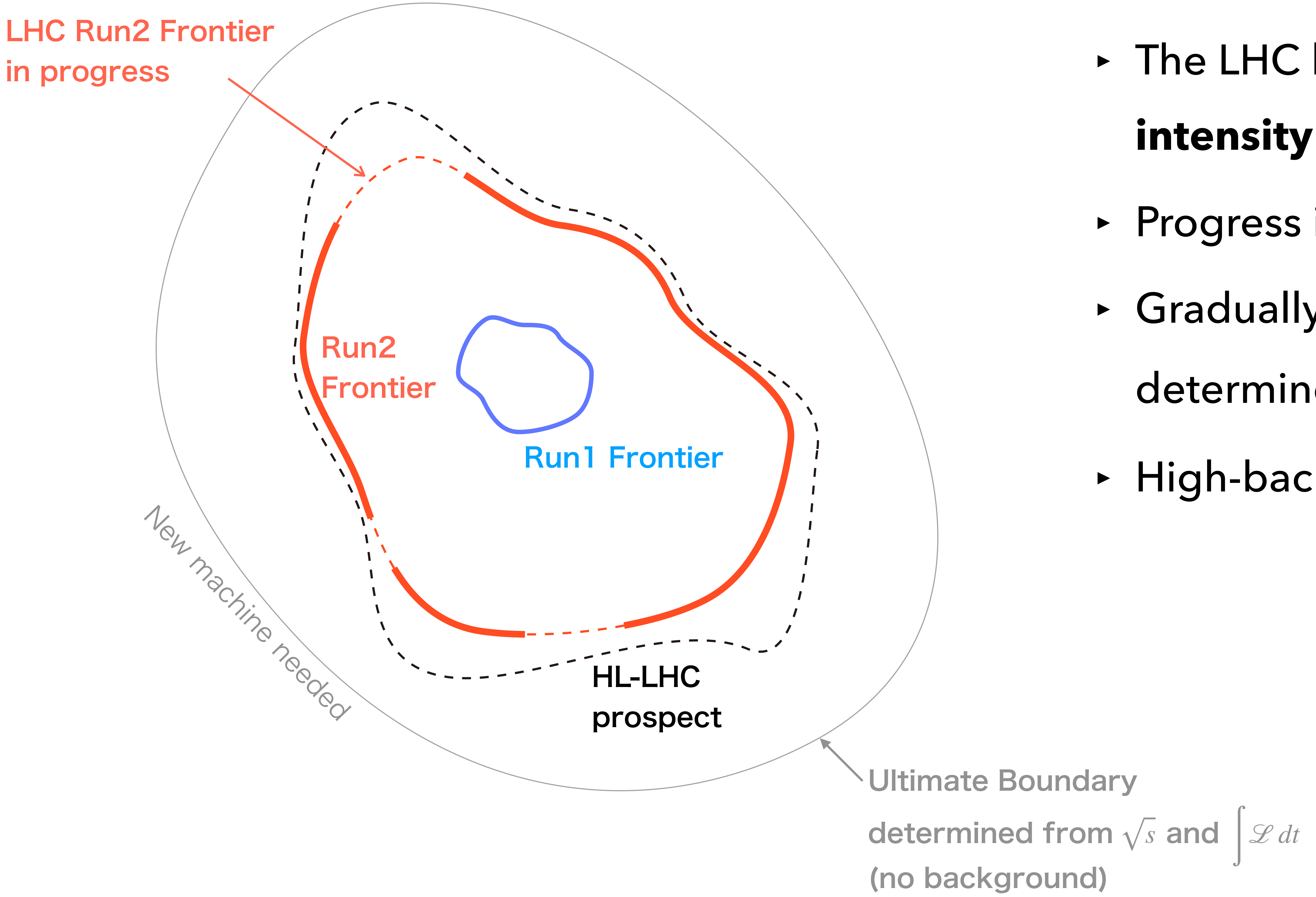
Name	Nominal value	Unit
Levelled luminosity	5×10^{34}	$cm^{-2}.s^{-1}$
Beam energy	7	TeV
Beam emittance	2.5	µm
β*	20	cm
1 σ bunch length	1.2 (9)	ns (cm)
Half-crossing angle	295	µrad
Bunch intensity	2.2×10^{11}	protons
Beam intensity	6×10^{14}	protons
Luminosity lifetime	5	hours





Planned to start in 2029

Search frontiers from now on

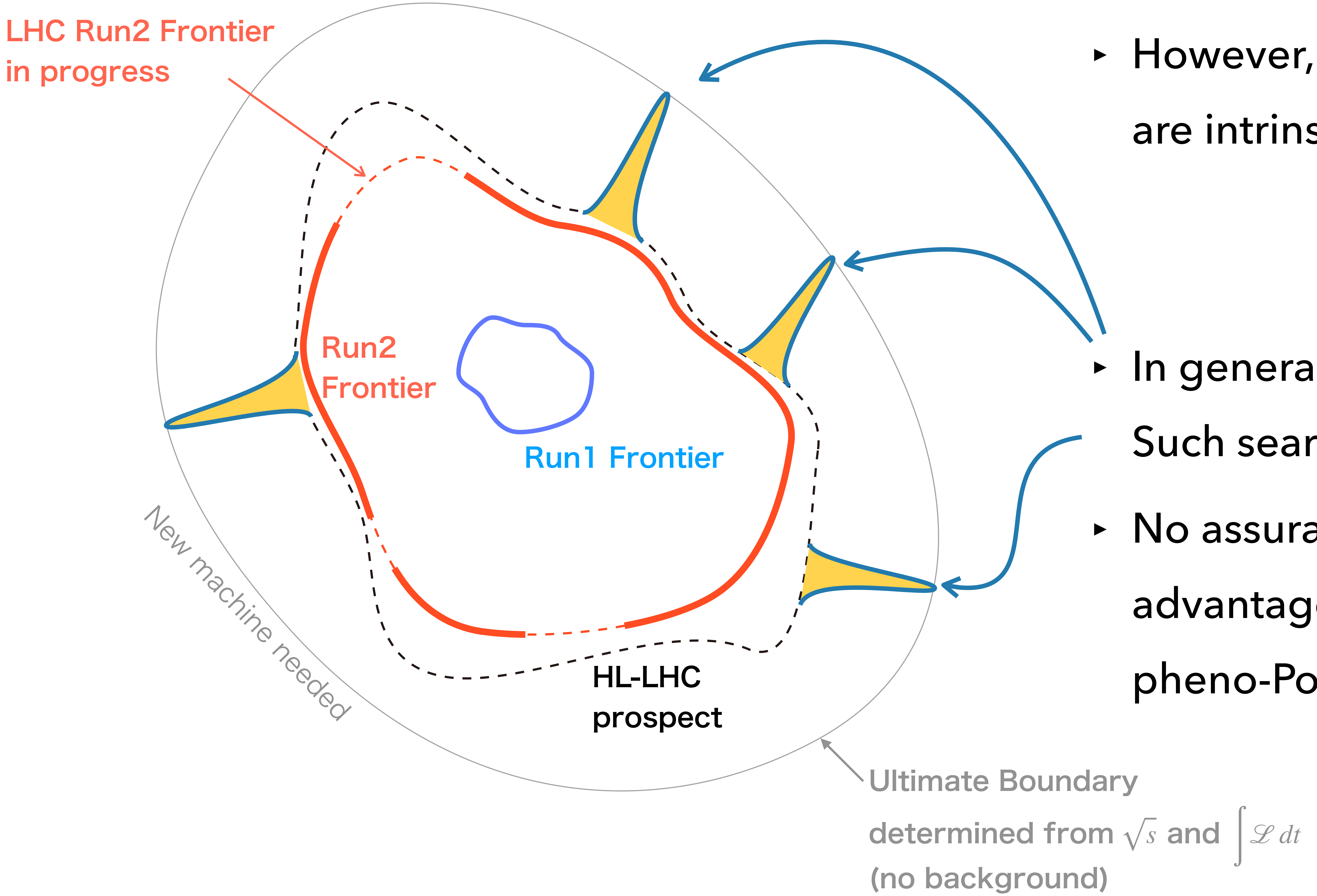


- The LHC has now transited to the **intensity frontier** machine.
- Progress is certain, but **slow**.
- Gradually approaching to the limit determined by $\sqrt{s}$ and luminosity.
- High-background channels **saturate earlier**.

Significance $\propto \sqrt{\mathscr{L}}$

There's a popular trend to push this further, e.g. by sophisticated algorithms represented by ML technologies.

Search frontiers from now on



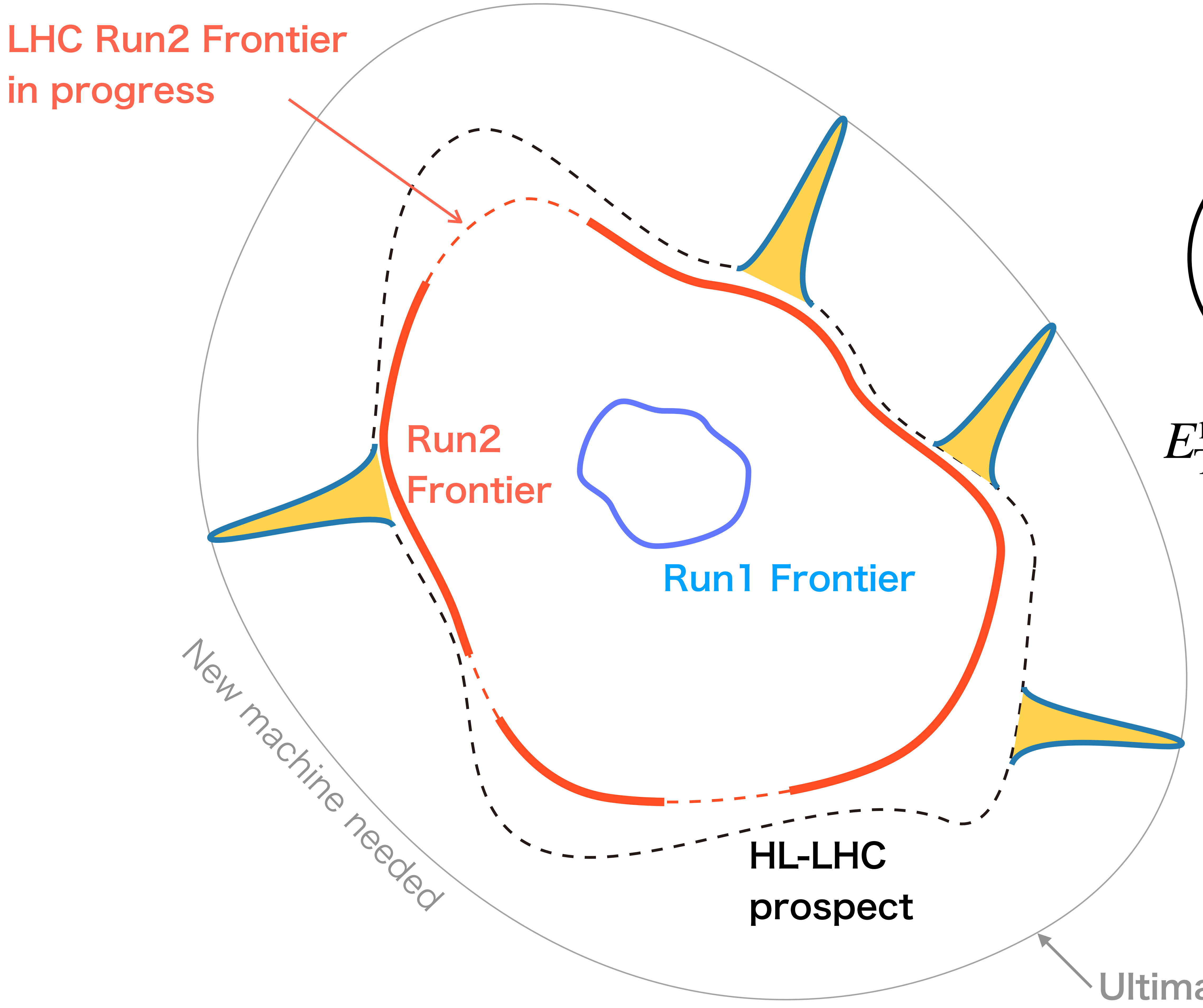
- However, **low-background** search channels are intrinsically more hopeful.

Significance $\propto \mathscr{L}$

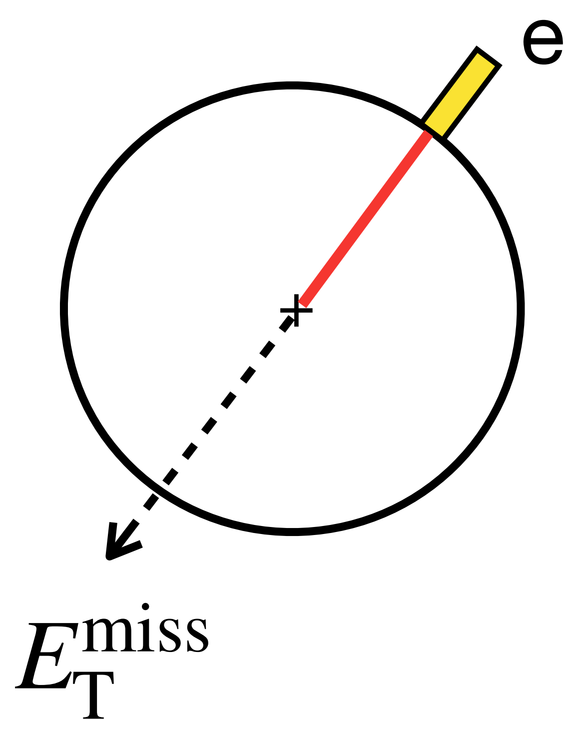
- In general, LHC = "dirty collider"
  Such search channels are rather niches.
- No assurance that such experimentally advantageous searches will meet BSM from the pheno-PoV, but we may have a luck!

IMHO: Experiments should cultivate such search windows.

Example (I): Explore the dessert

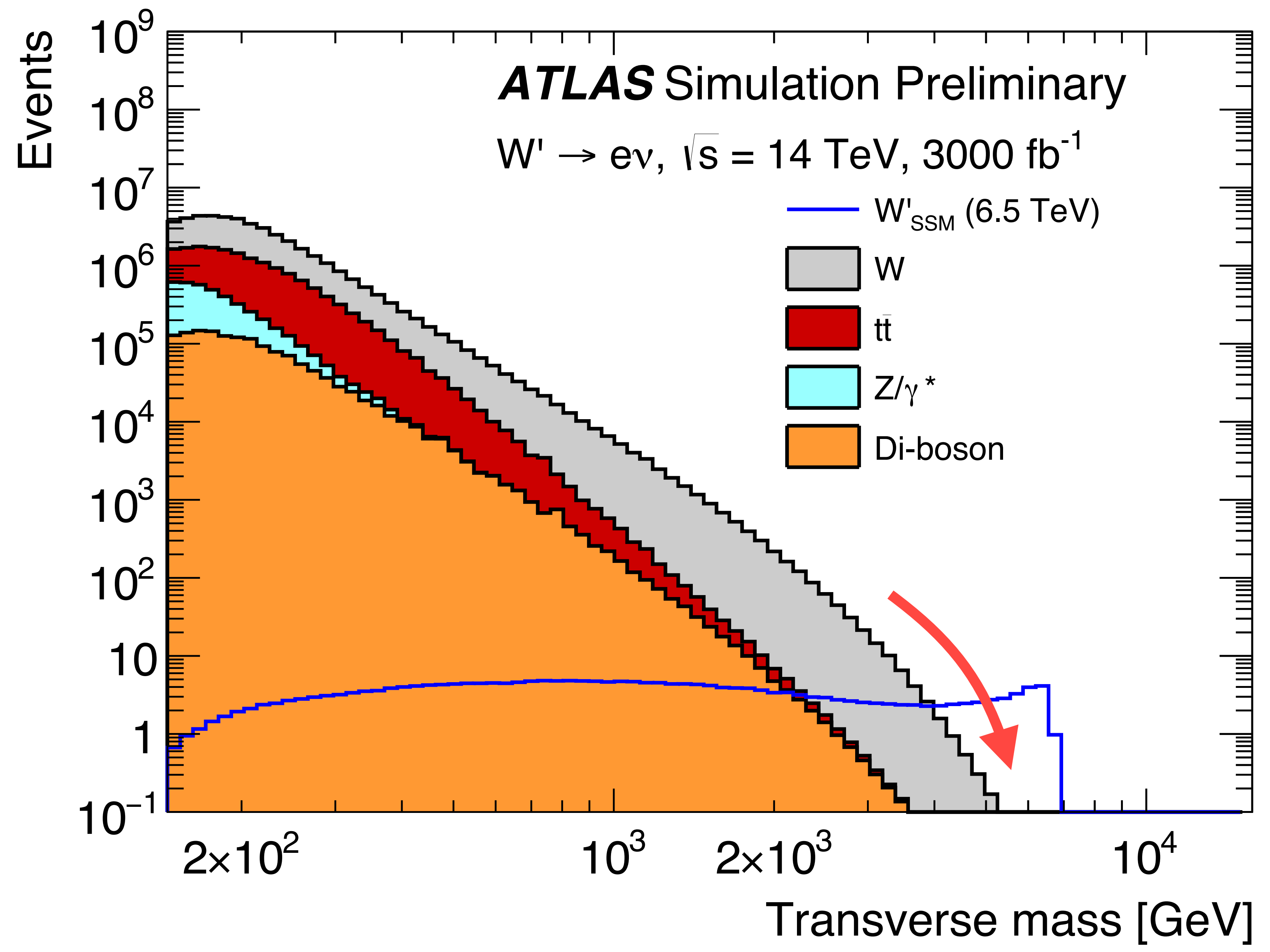


- One such example: extinction of SM backgrounds.



HL-LHC Prospect

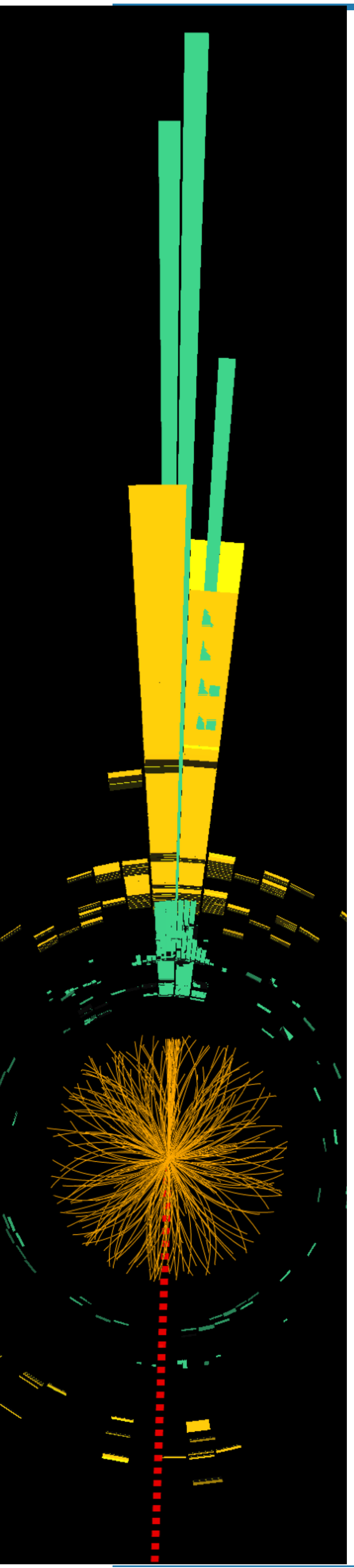
ATL-PHYS-PUB-2018-044



Transition to a "clean search" regime.

Possible to exclude m(W′) < 7.6 TeV!

→ But we have more cases.

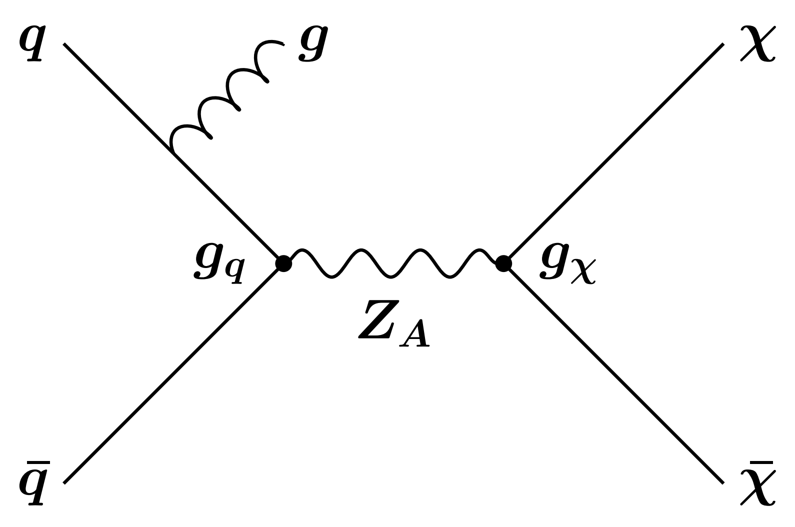


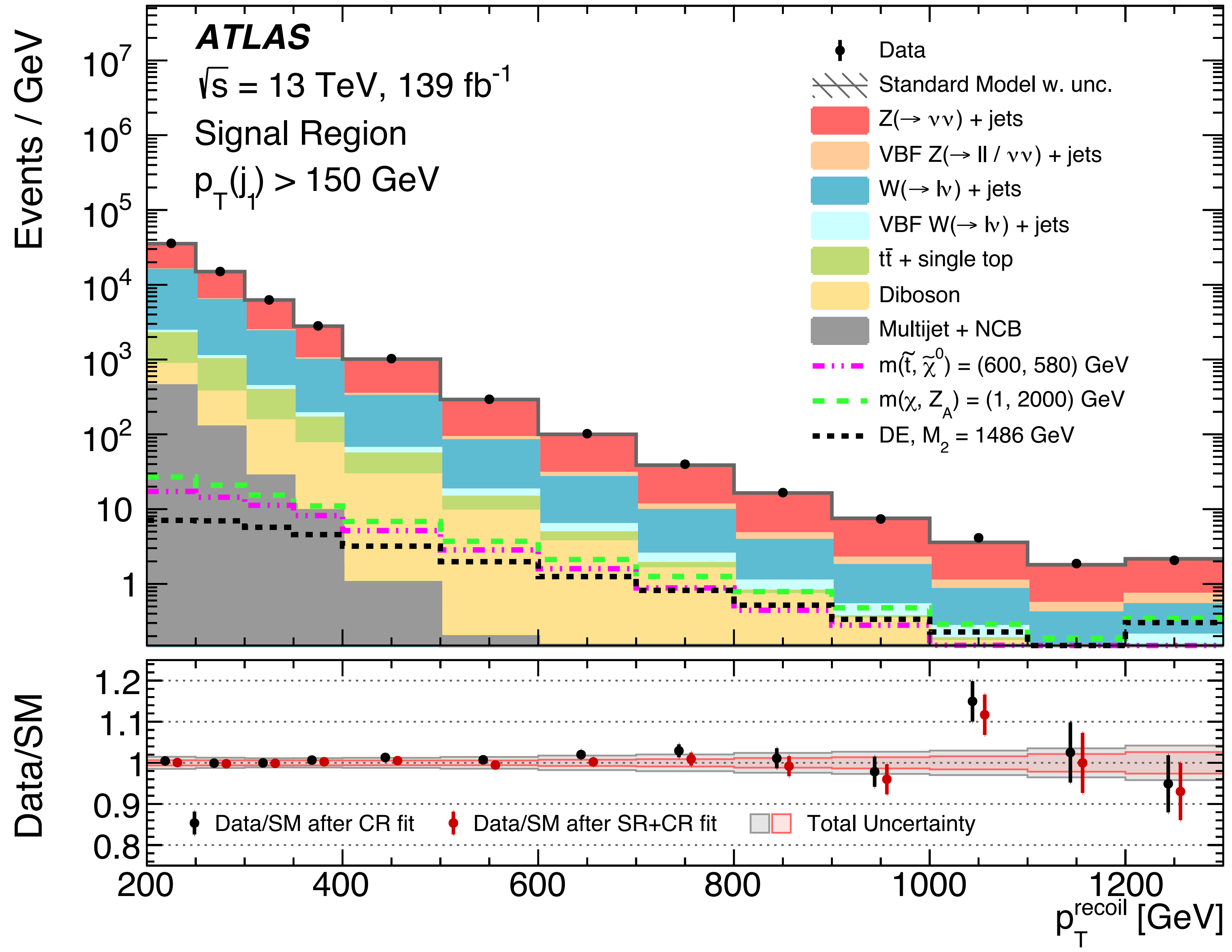
Example (II): Dig the detail

- Model-independnet searches have wide acceptance and applicability.
- e.g. mono-jet DM search was simple and model-independent!
- But they are feature-less and inevitable to suffer from the SM bkg…

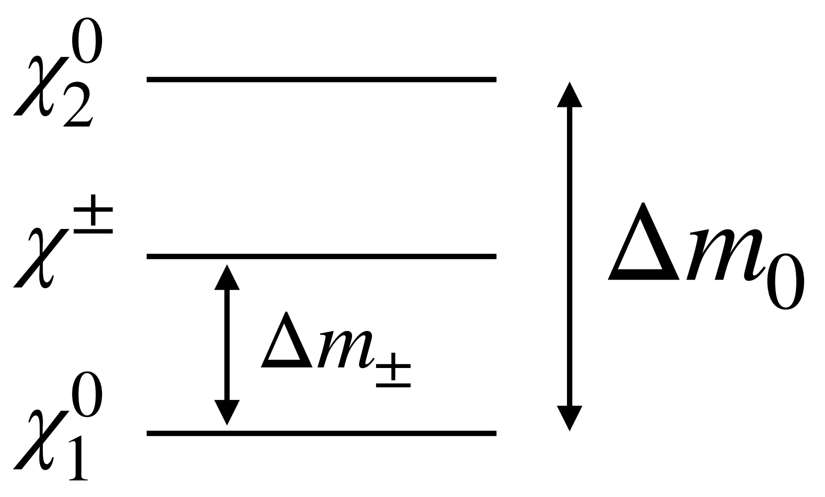
  For instance, mon-jet is hard to probe the **Higgsino DM** scenario.

EXOT-2018-06





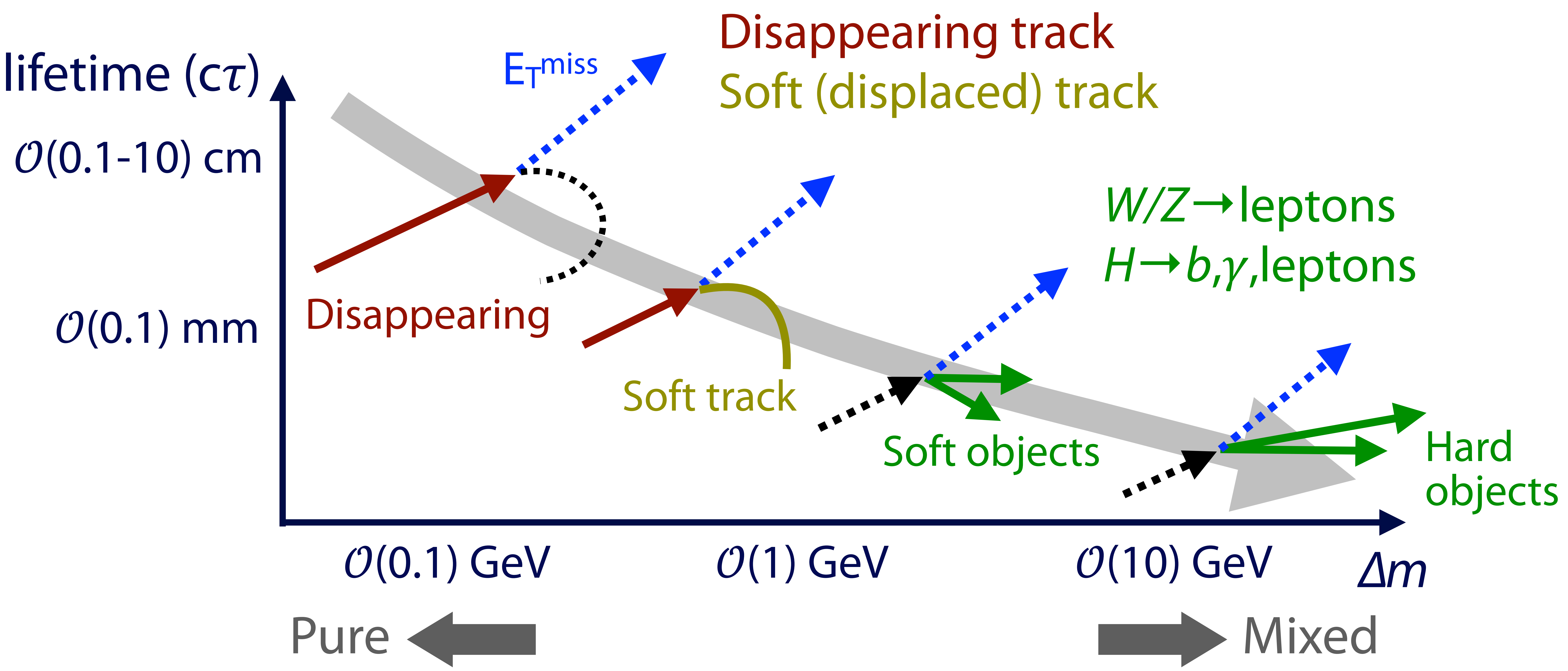
Example (II): Dig the detail



$$\Delta m_0^{\rm tree} \simeq M_Z^2 \left(\frac{c_W^2}{M_2} + \frac{s_W^2}{M_1} \right)$$

μ

Diagram by K.Terashi



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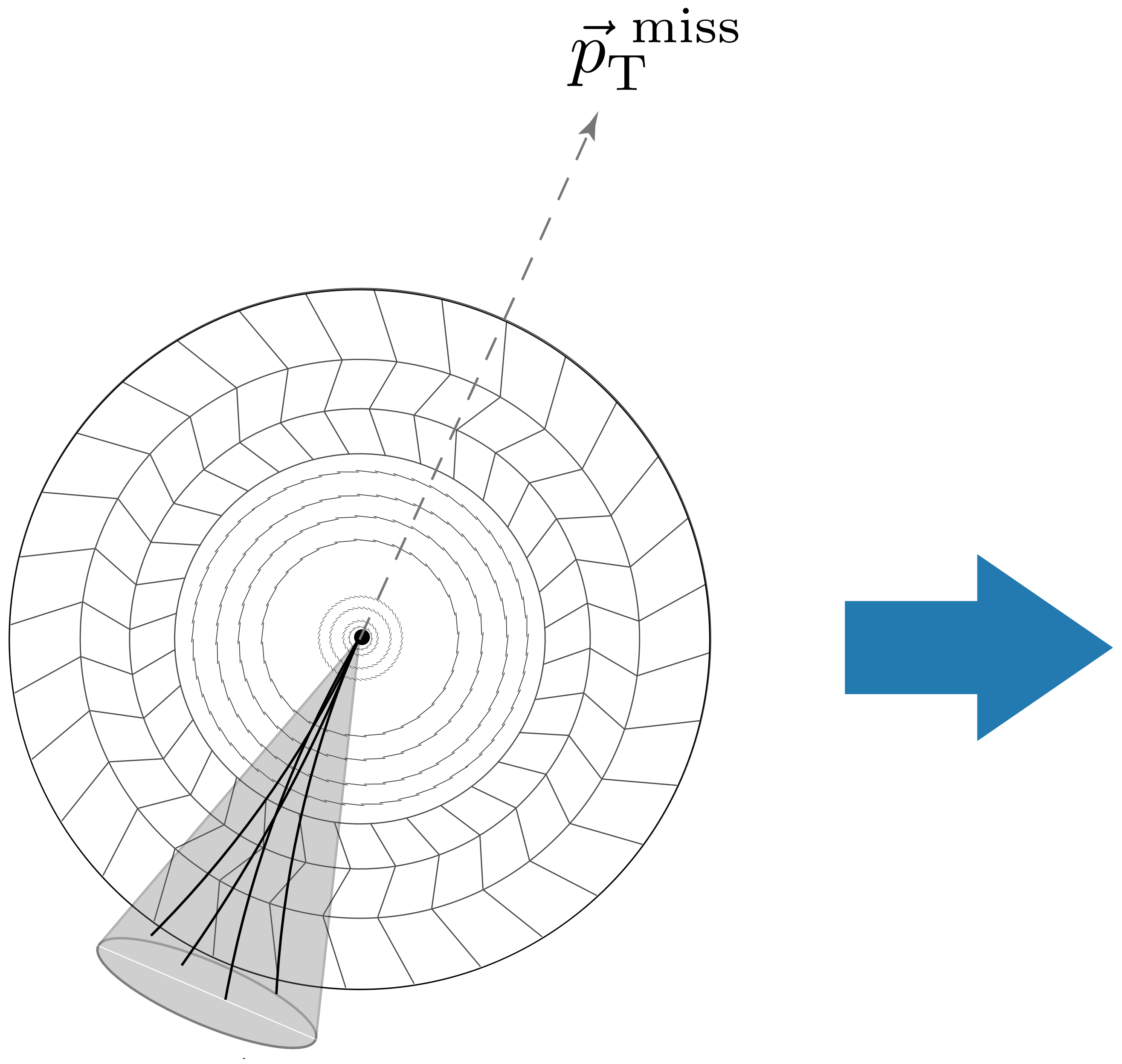
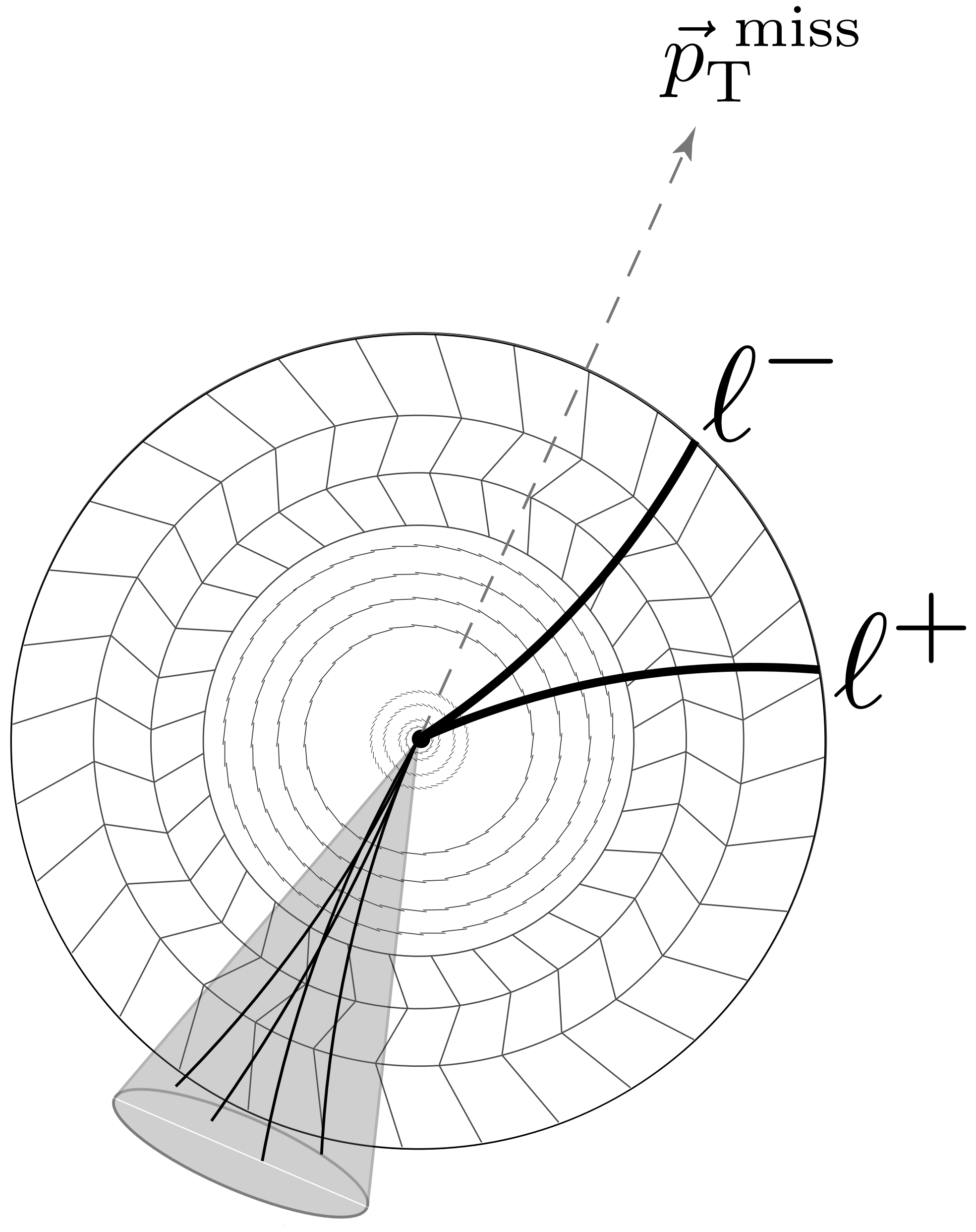
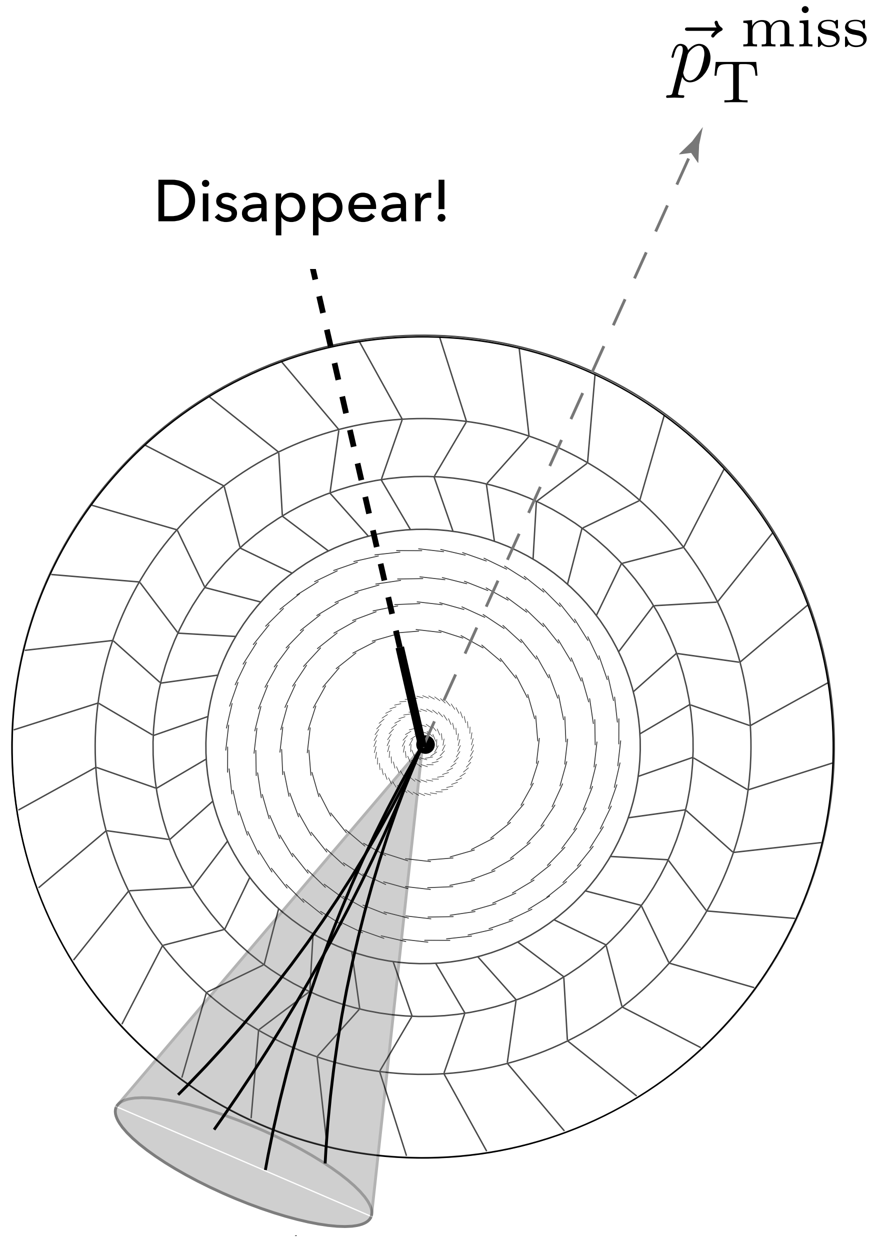


Mono-jet: the archetype



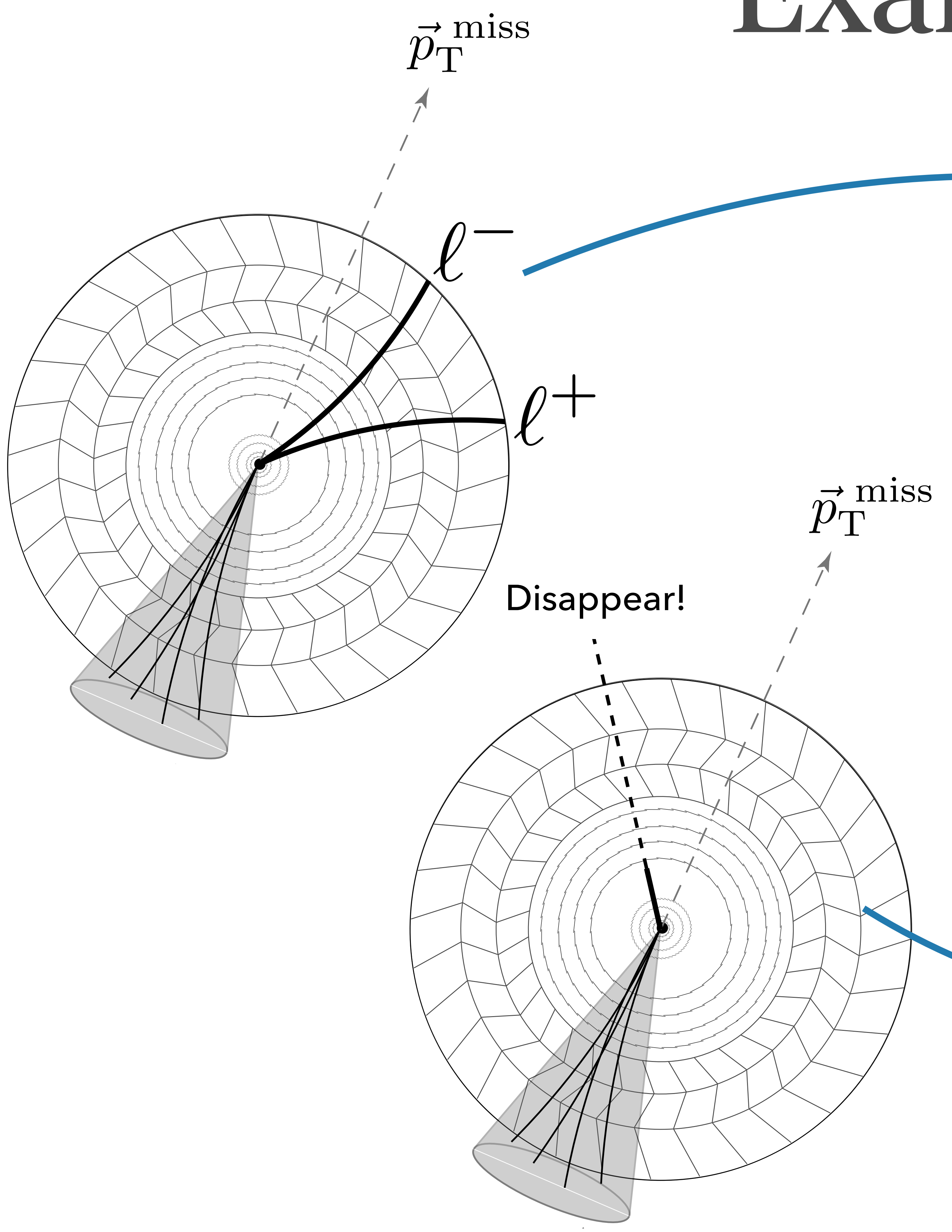
Soft di-lepton

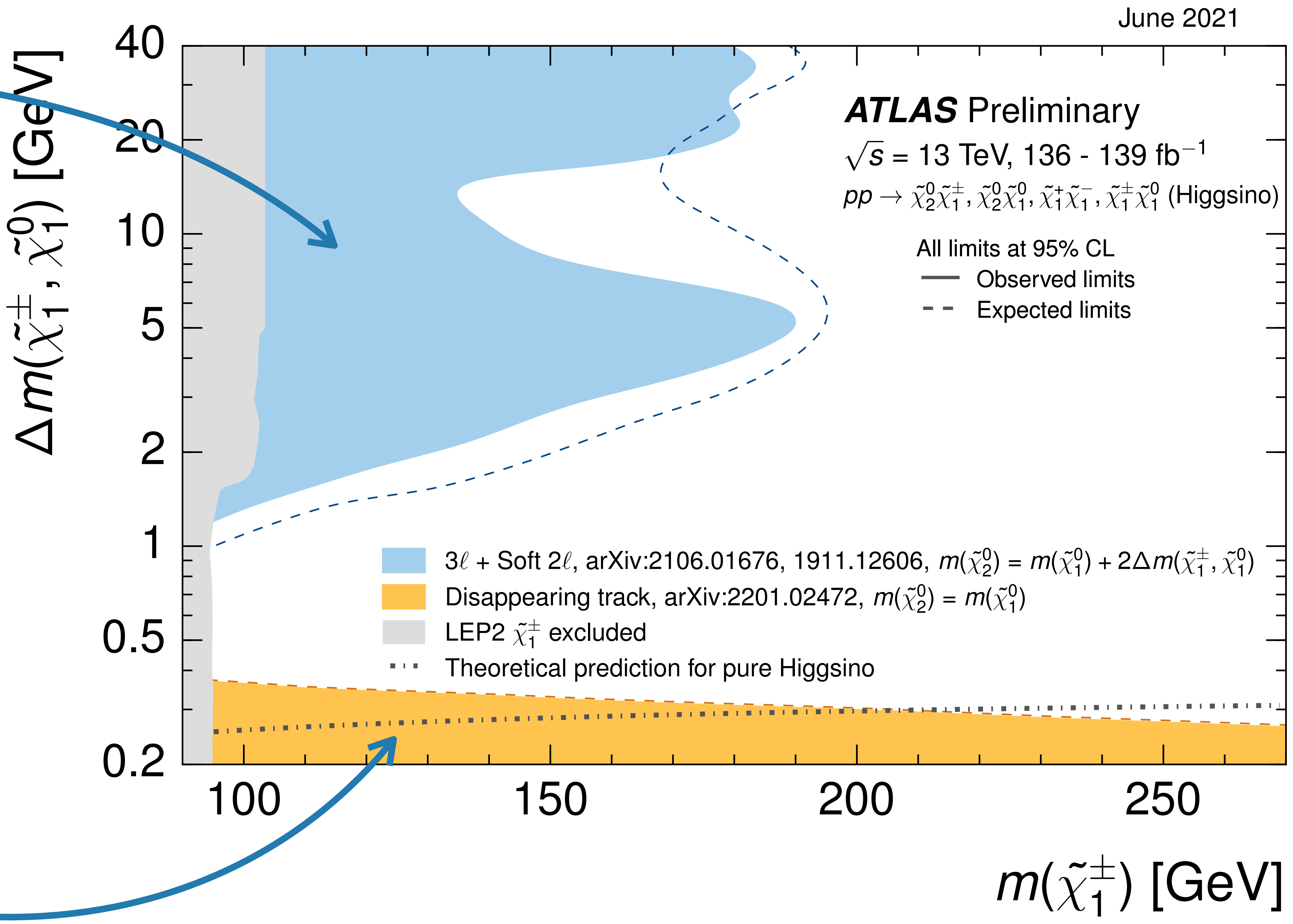


Disappearing Track

- Lesson: additional requirement of the **detail** of the event features can significantly extend the sensitivity by strong bkg. rejection.

Example (II): Dig the detail



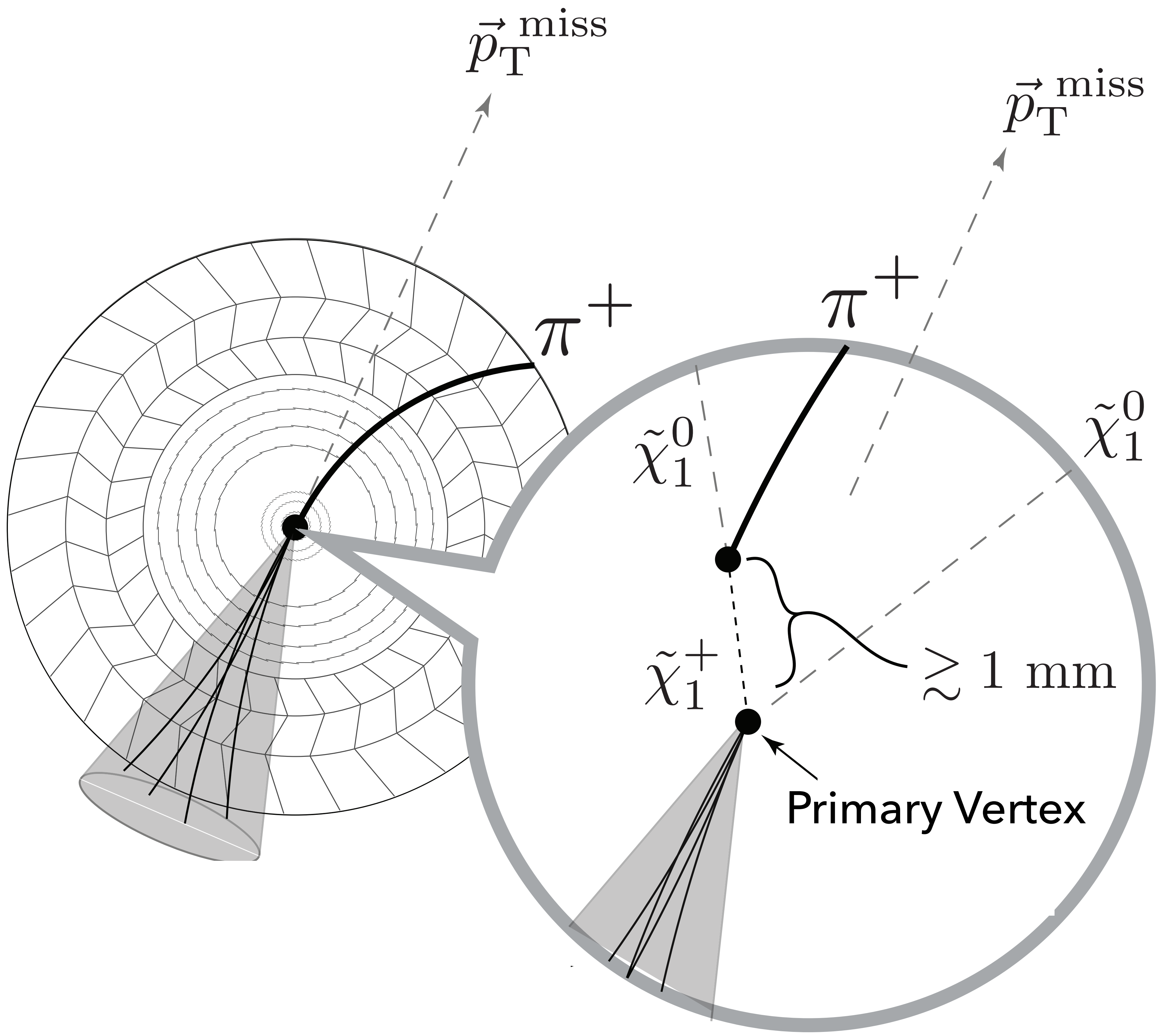


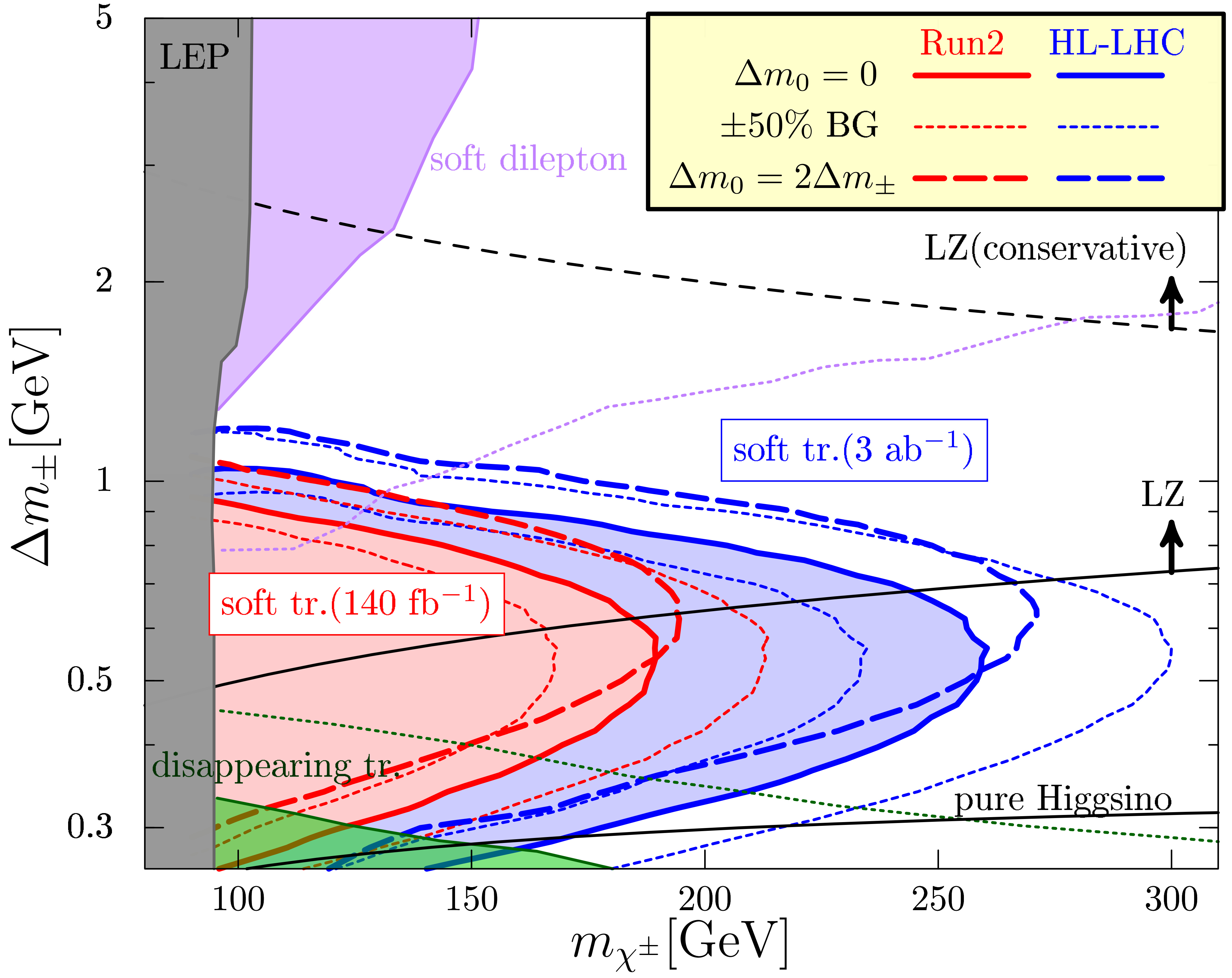
The 3rd detail channel, using a micro-displaced soft pion has been proposed.

H. Fukuda, S. Shirai, N. Nagata, H. Otono, HO [PRL 124, 101801 (2020)]

→ Studies in-progress in ATLAS.

Example (II): Dig the detail





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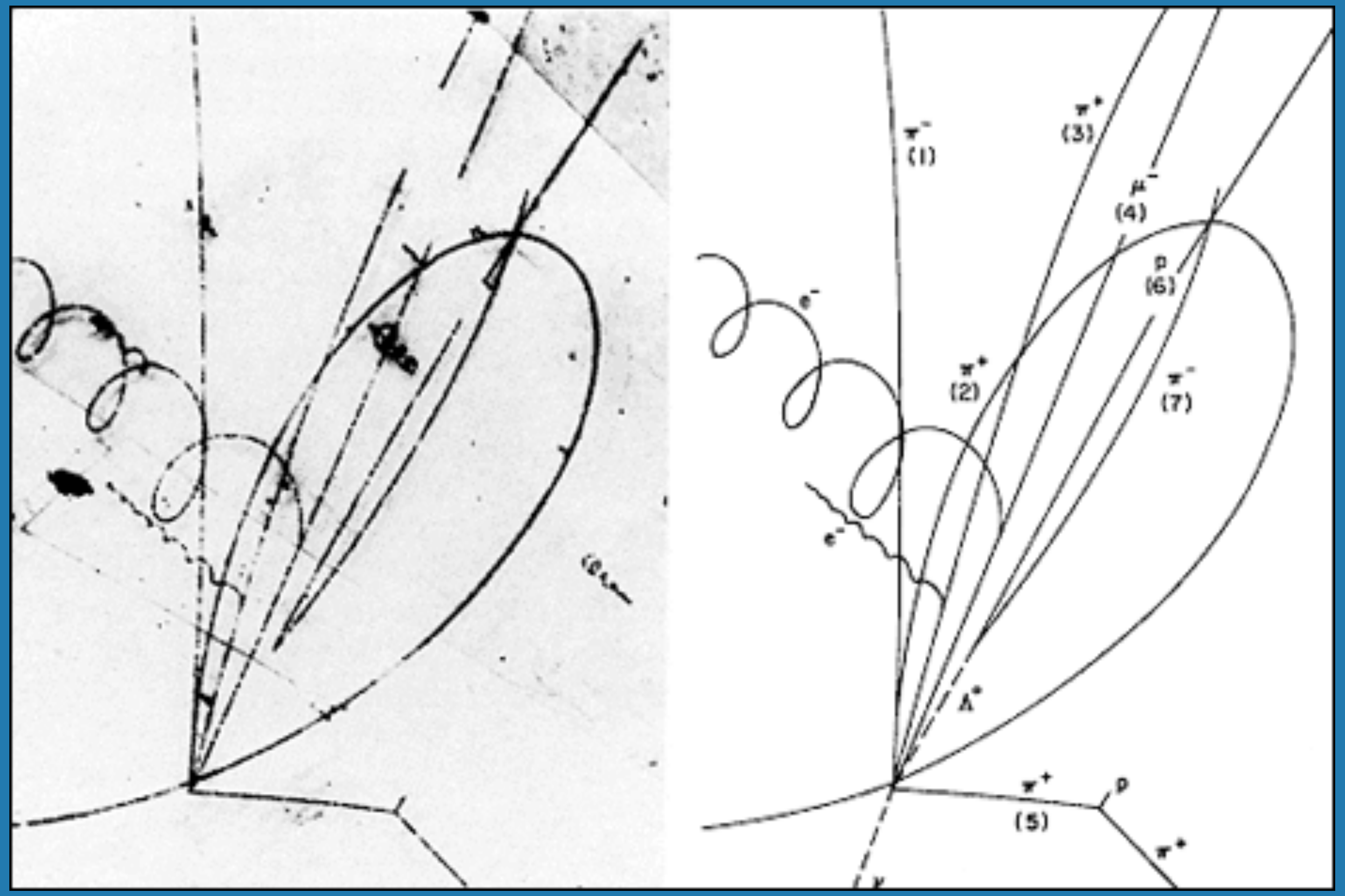
Key points

- LHC: transition to the intensity frontier.
- Previous flagship searches do not end,
  but are inevitably slow down.
- More focus to the **low-background** frontier.
- Using **event details** is one of the quick paths
  in order to get to the low-background frontier.
- Gen.purpose colliders not primarily designed to tag event details.

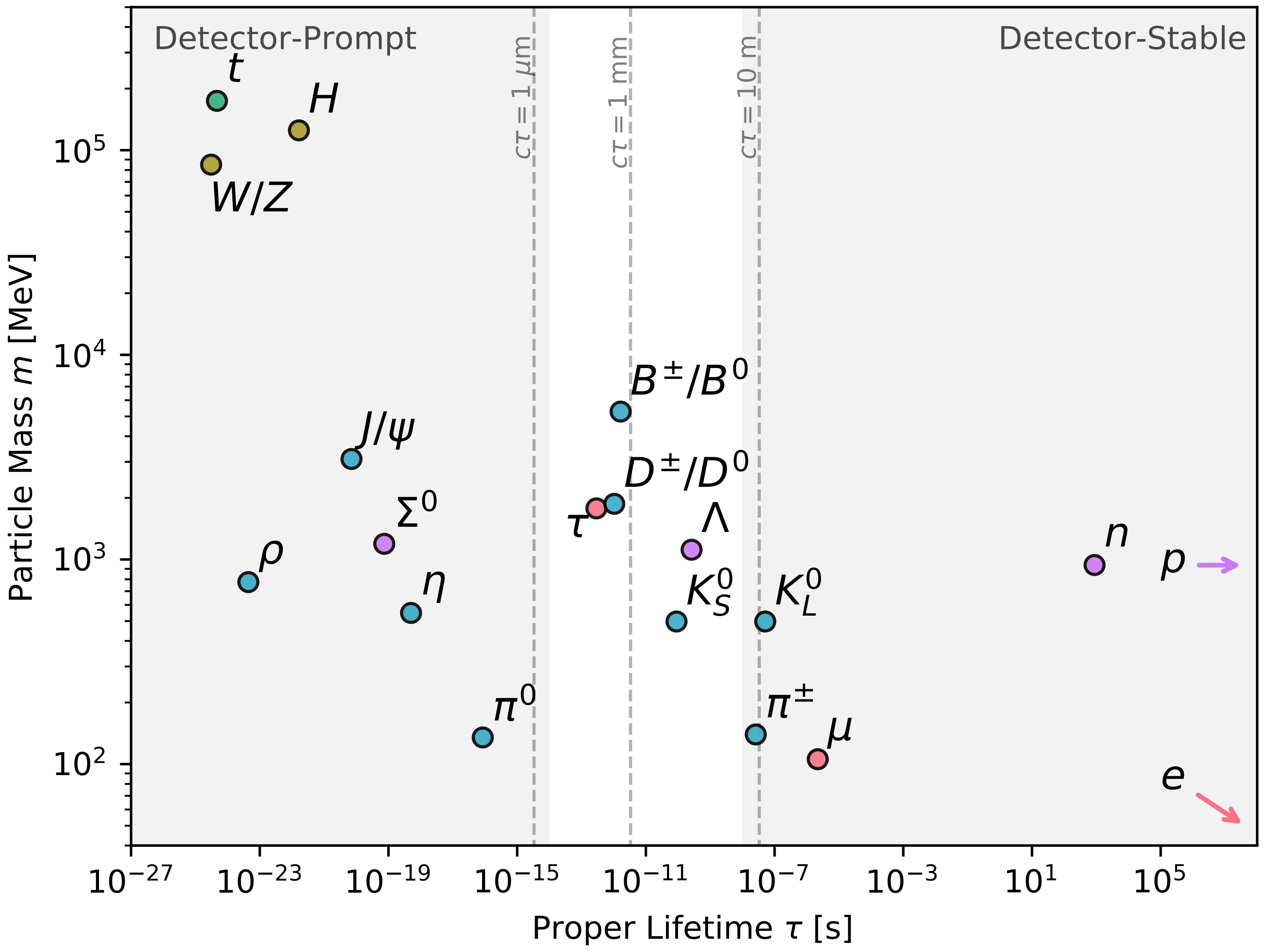
The Lifetime Frontier:

The Modern Bubble Chamber



Many known particles are long-lived

L. Lee, C. Ohm, A. Soffer, T. Yu, JPPNP 3695 (2019)

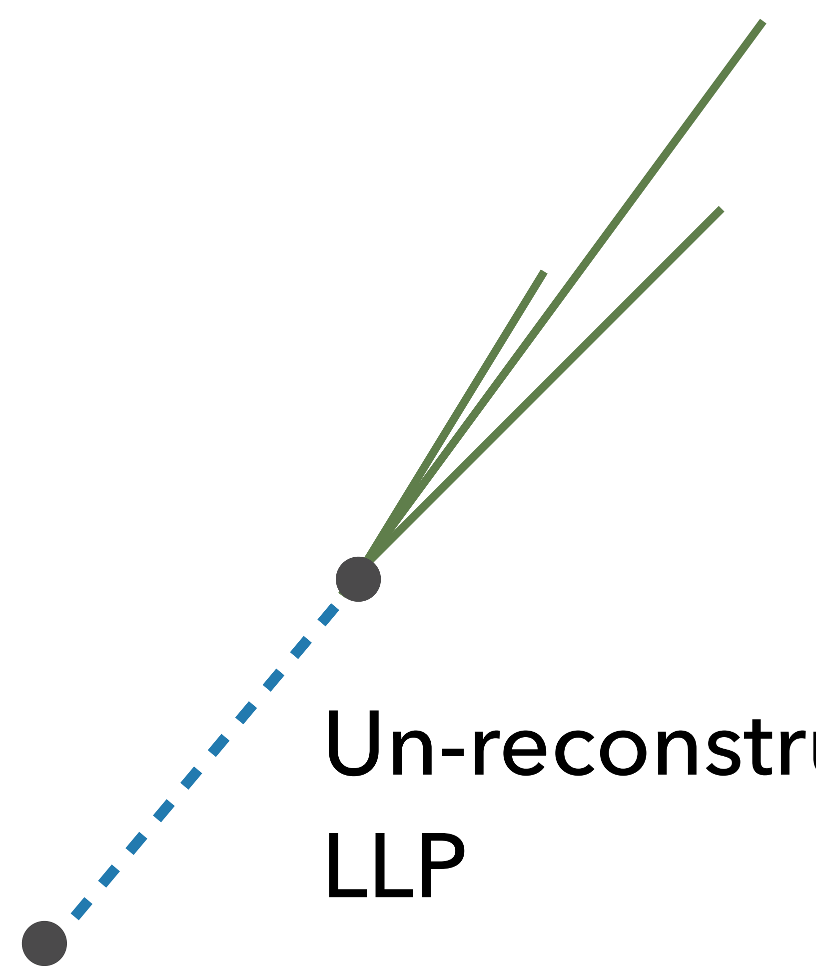


- In the SM, a number of elementary particles or hadrons have narrow decay widths.
- Is this only a peculiar coincidence of the SM, or it can be in BSM sectors?
- Multiple mechanisms of having narrow widths: mass hierarchy, phase space, degeneracy, feeble coupling, …
- These are all "building blocks" of phenomenology.

Very distinctive signatures...

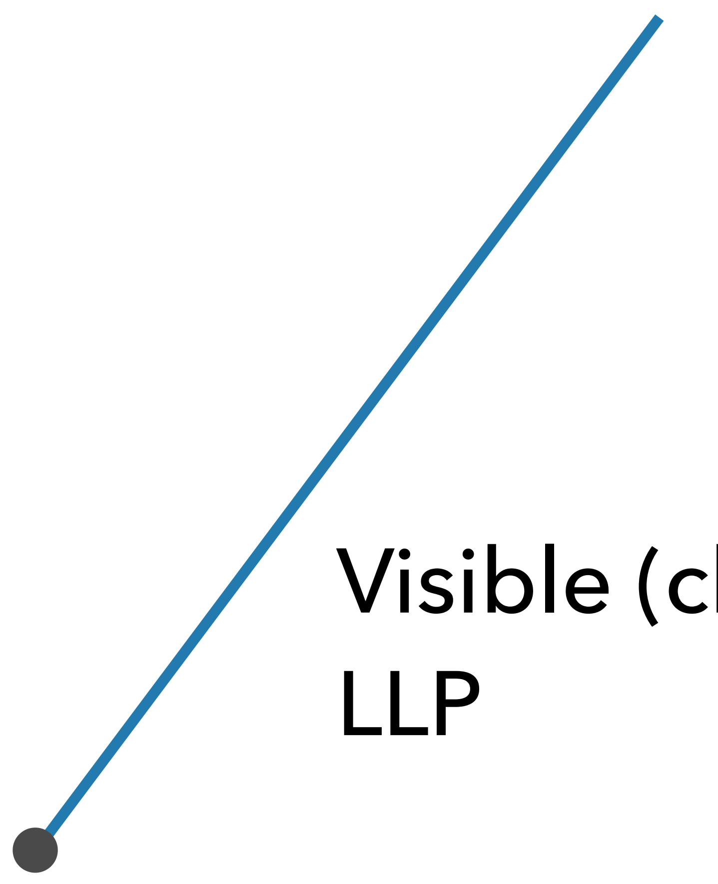
- Observe decays of LLP
- Observe LLP itself
- Observe anomalous global event topology

Visible particles



Un-reconstructible LLP

IP



Visible (charged) LLP

IP

Less jetty energy flow

SUEP, emerging jet, dark shower…

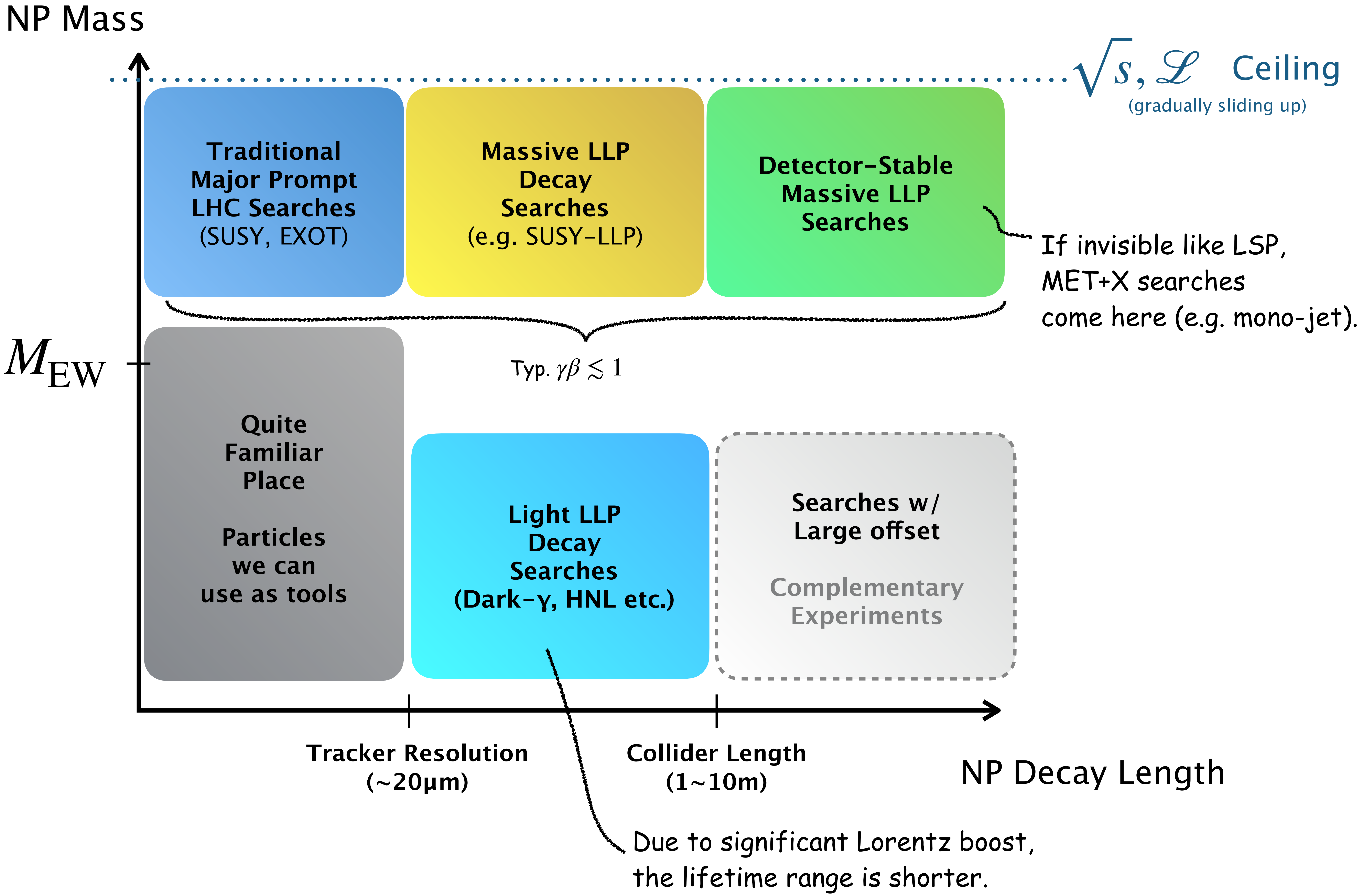
Soft Unclustered Energy Patterns

See e.g. [J. Nelson's talk]

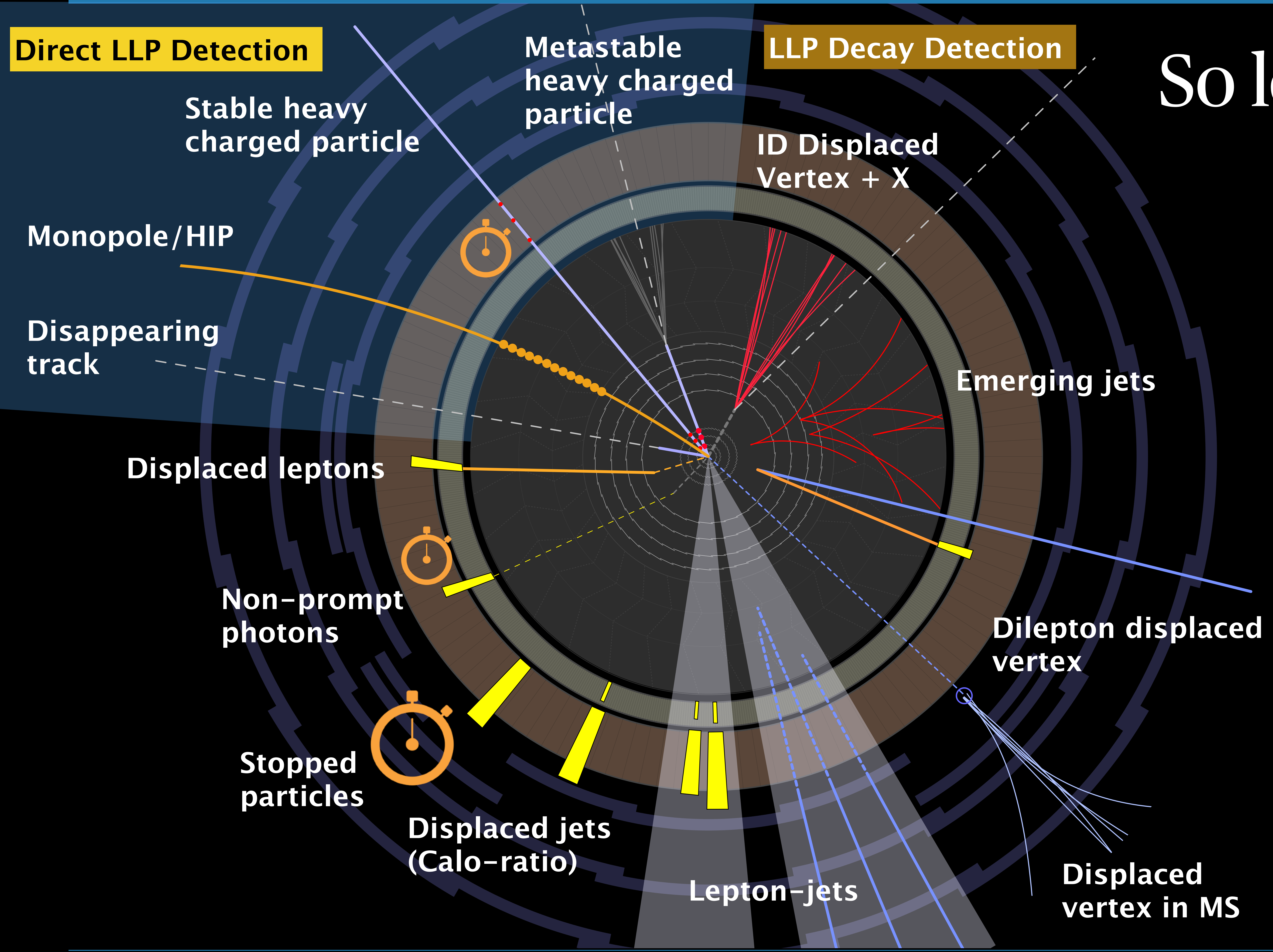
... lead to clean environments

- The orthodox search programs assume classification of BSM signal vs. SM backgrounds.
- But for LLP searches, SM backgrounds are typically **not** our main subjects of concern anymore.
- Major backgrounds arise from the instrument itself, where **MC generators are less helpful**.
- **Data-driven approach** is required
  – might not be so "fun" situation for pheno-theorists since sensitivity projection is tough to draw outside of the collaboration?

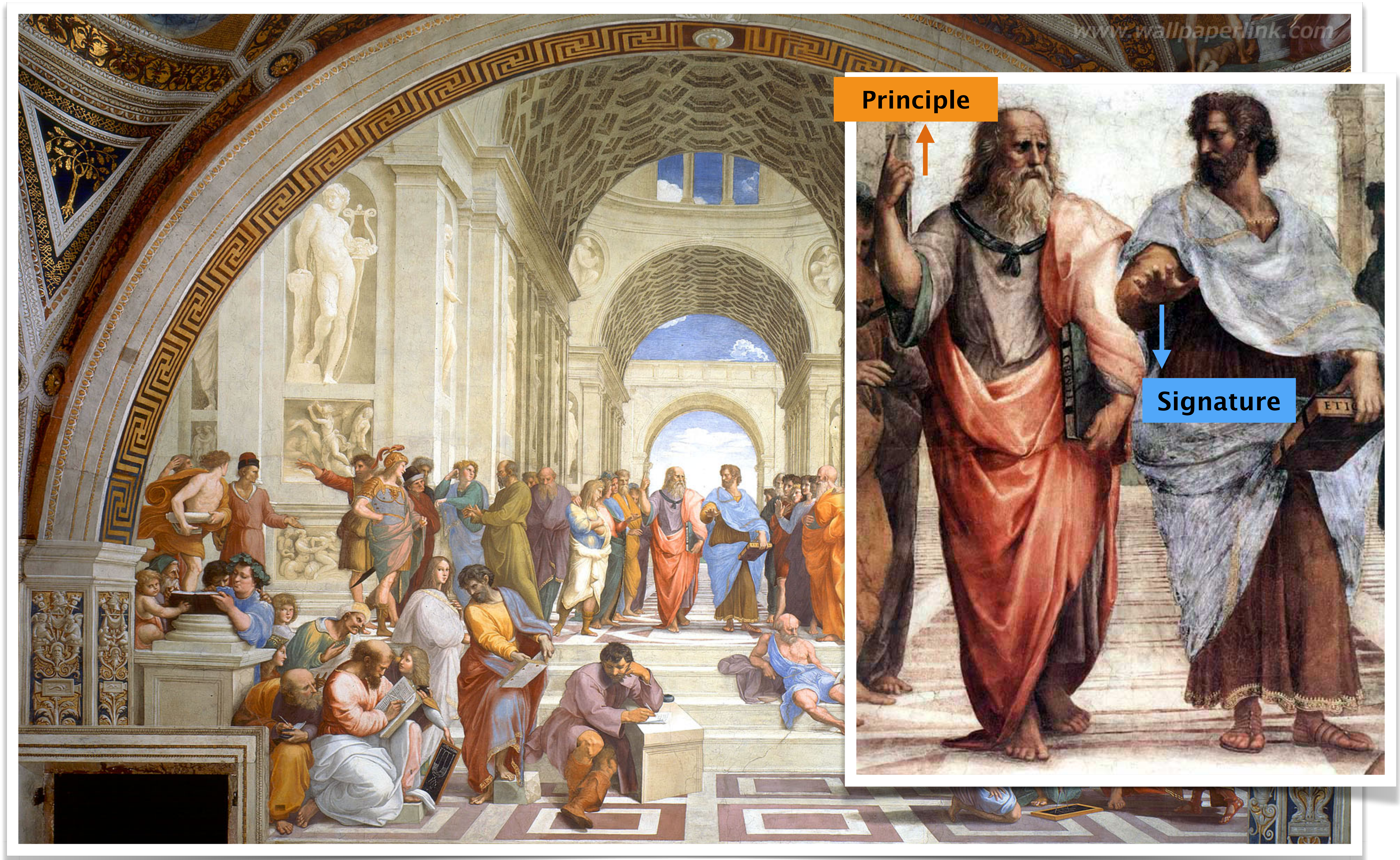
LHC Lifetime Frontier



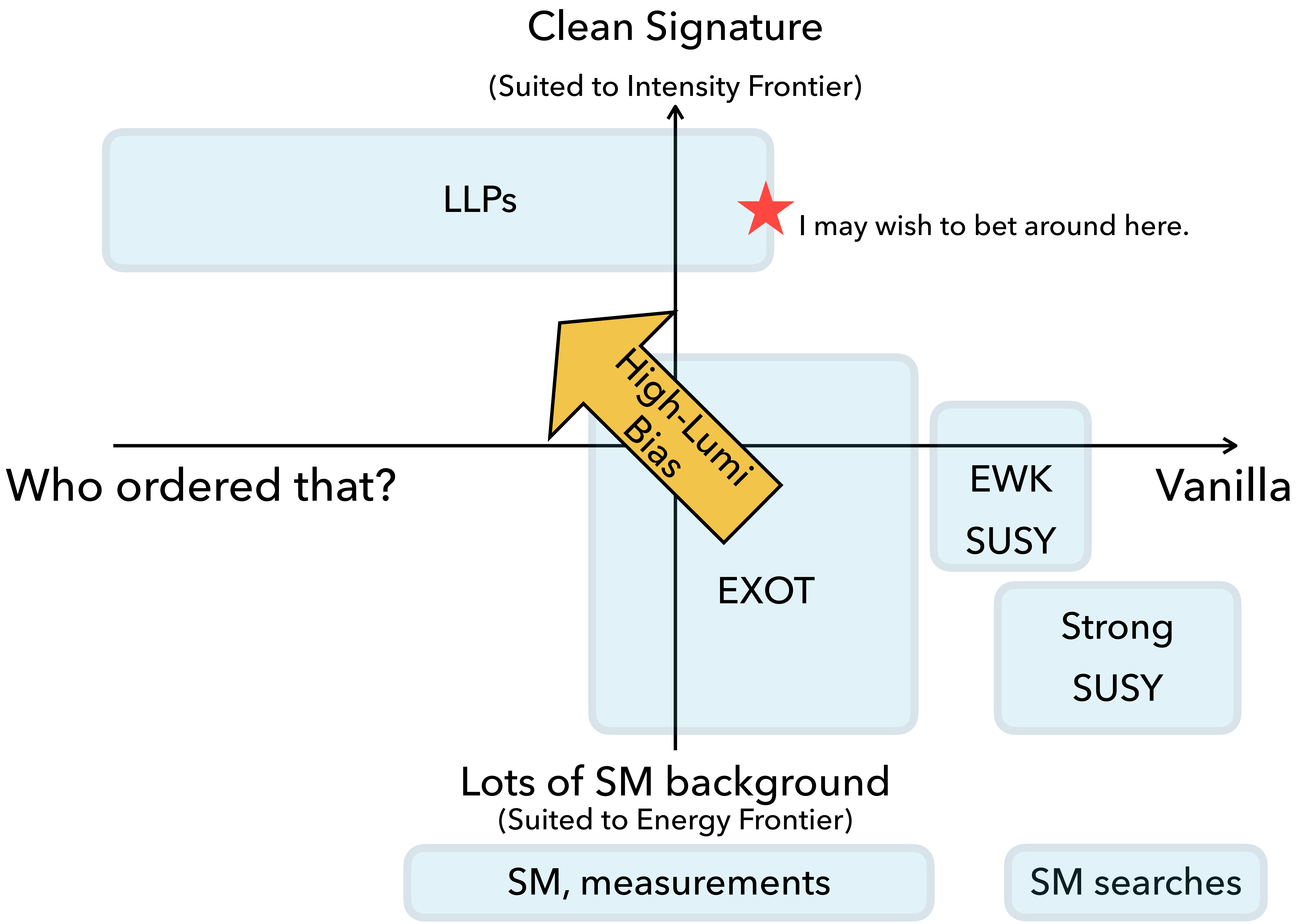
So let the “LLP Zoo” be...



- In a signature-driven manner, quite many of search classes can be enumerated.
- Discovery-first
  be model-independent. not too late to think of physics afterwards...
- Need to be careful. Not all signatures would have robust theoretical backbones.

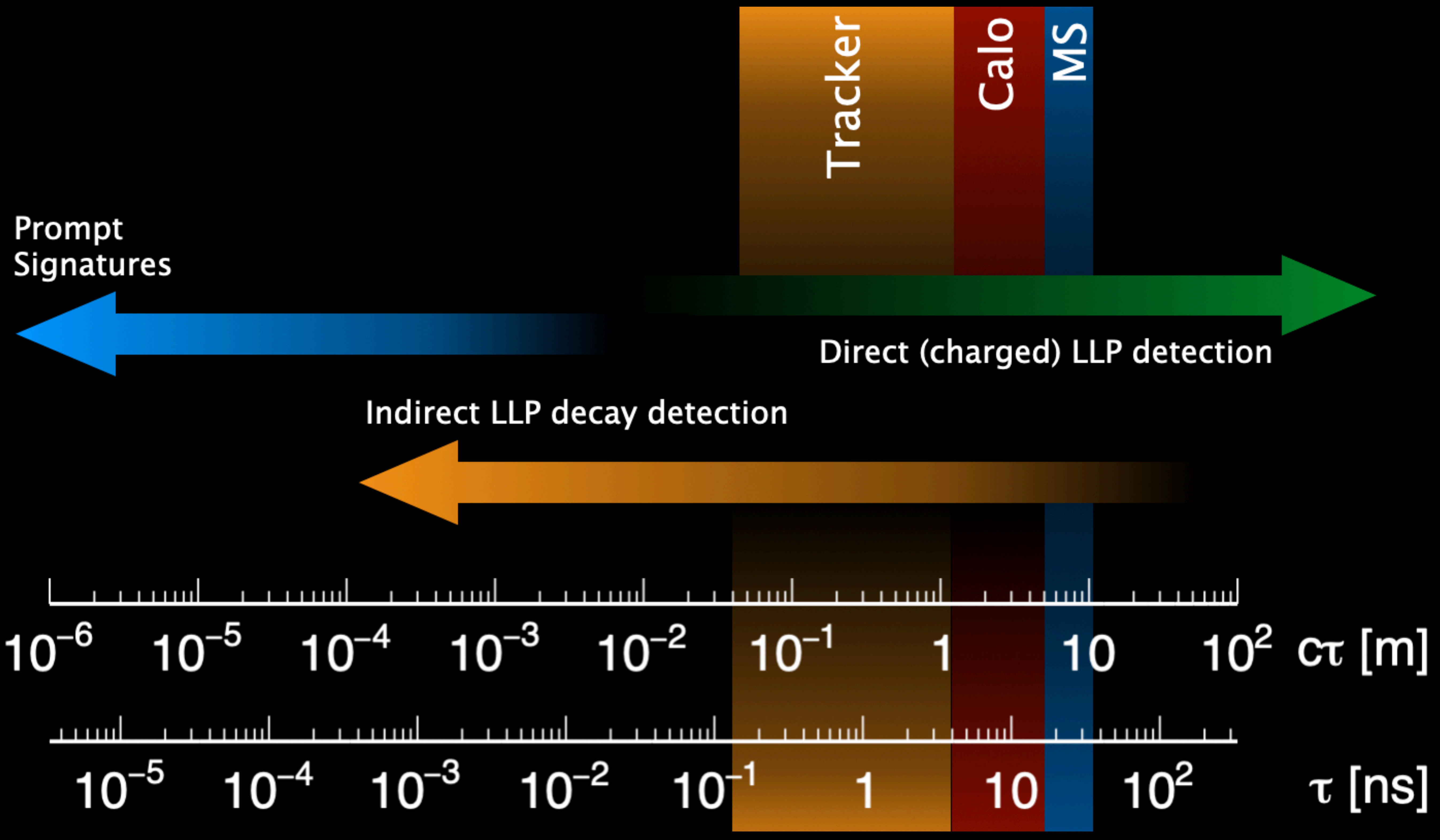

www.wallpaperlink.com
Principle
Signature

Transition of the search trend



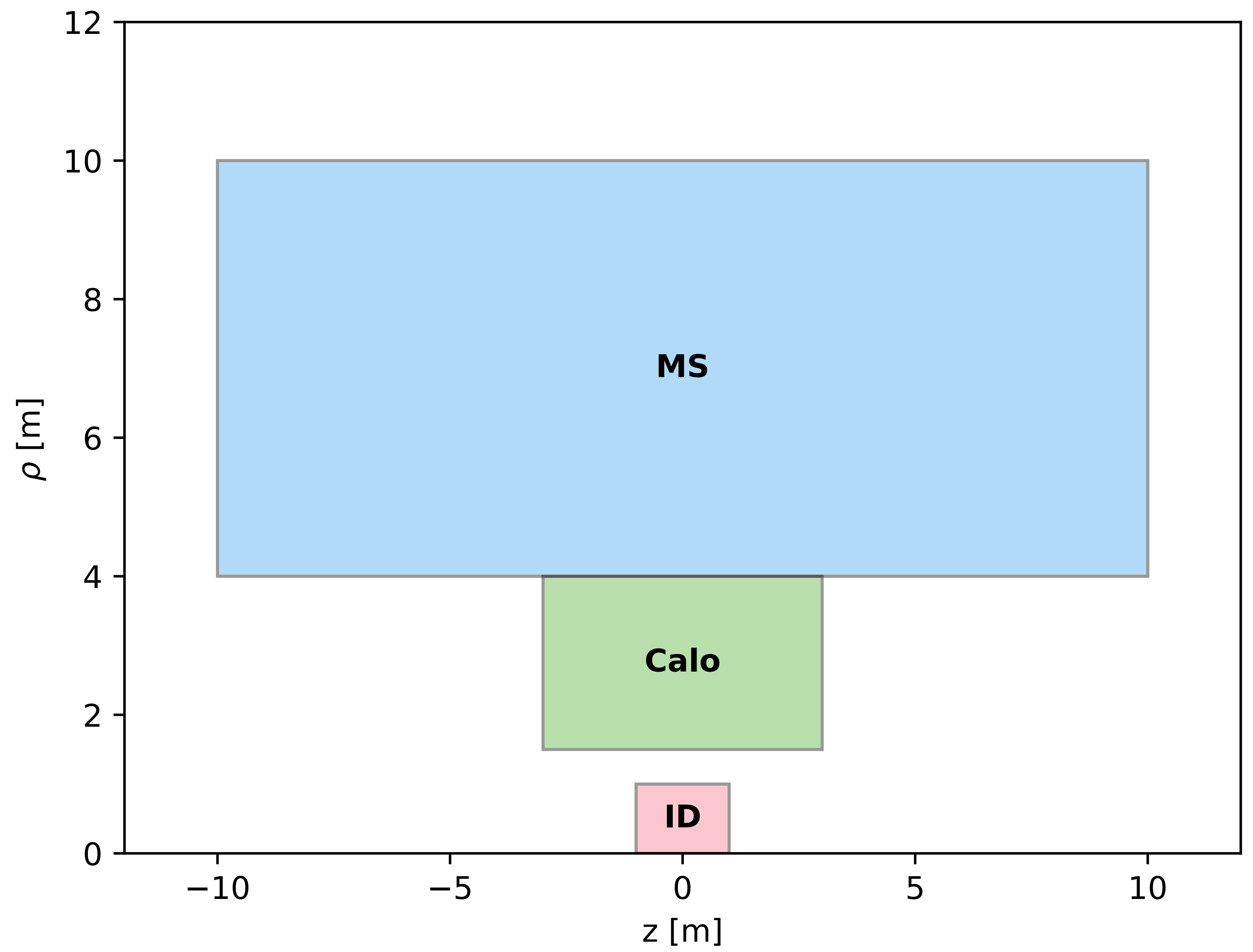
- Historically, the progress of paritlce physics was a mixture of glorious success (vanilla) and surprises (who ordered that?)
- Searches have been largely biased to discovery of “vanilla”.
- But “who ordered that?” is also valuable, since it imposes big unanswered questions that has been driving motivations to continue exploration.
- Do we want more awkward discoveries or not??

Dimension of instruments

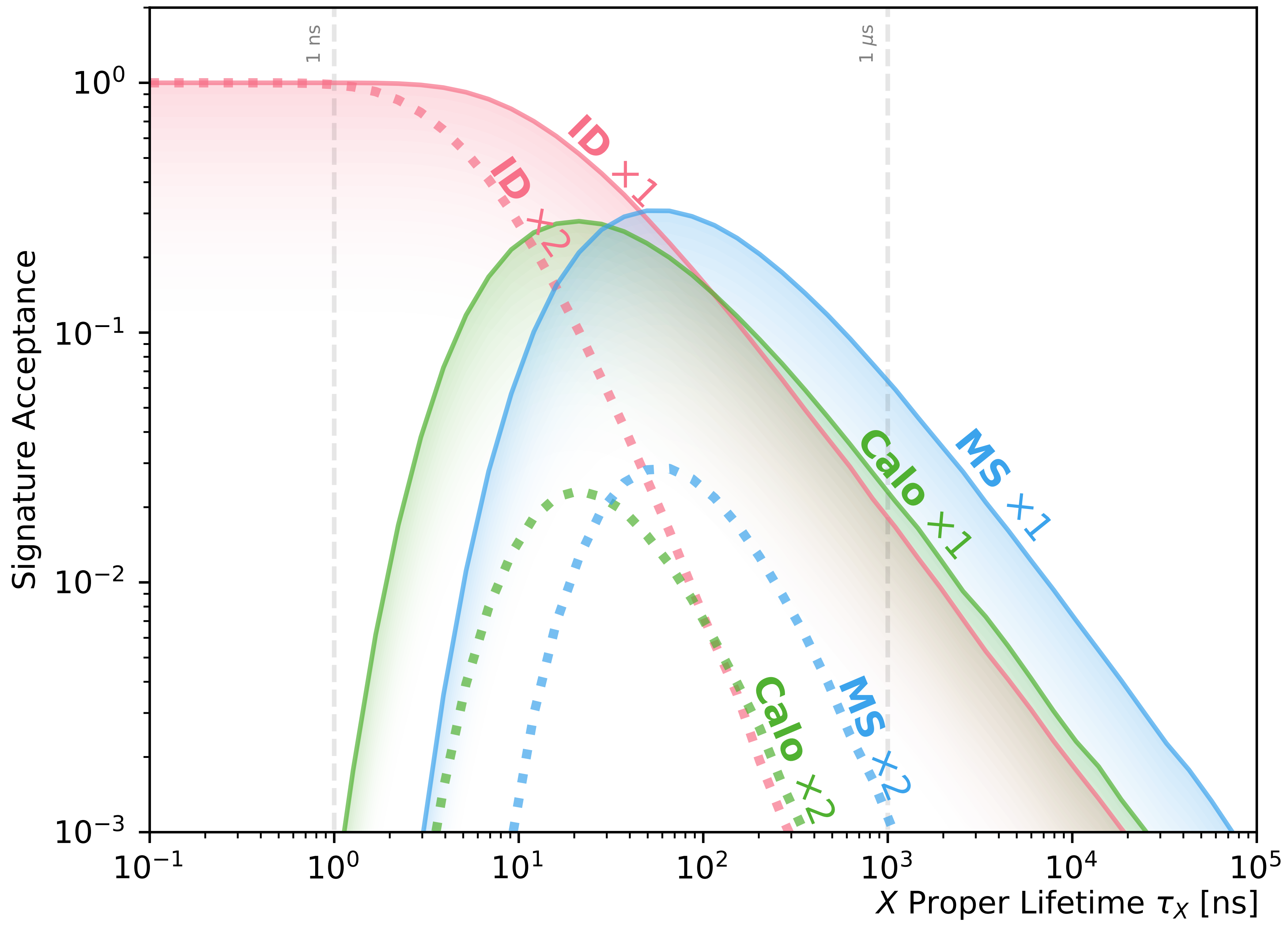


- The most prompt SM particle (W/Z) is **10** orders of magnitude smaller than the position resolution of the collider.
- In the collider instruments, we have approx. **6** orders of magnitude of the decay length dynamic range. (10 μm – 10 m)
- Making use of this instrumental length scale adds 6 on top of 10. Seems not so bad deal.

Importance in smaller radii



L. Lee, C. Ohm, A. Soffer, T. Yu, JPPNP 3695 (2019)



- For the decay detection, due to exponential distribution of the decay position, inner detector is quite competitive for longer lifetime.
- In addition, particle characteristic identification using outer subsystems is available.
- Tracker is an indispensable system for charged LLP searches.

Key points

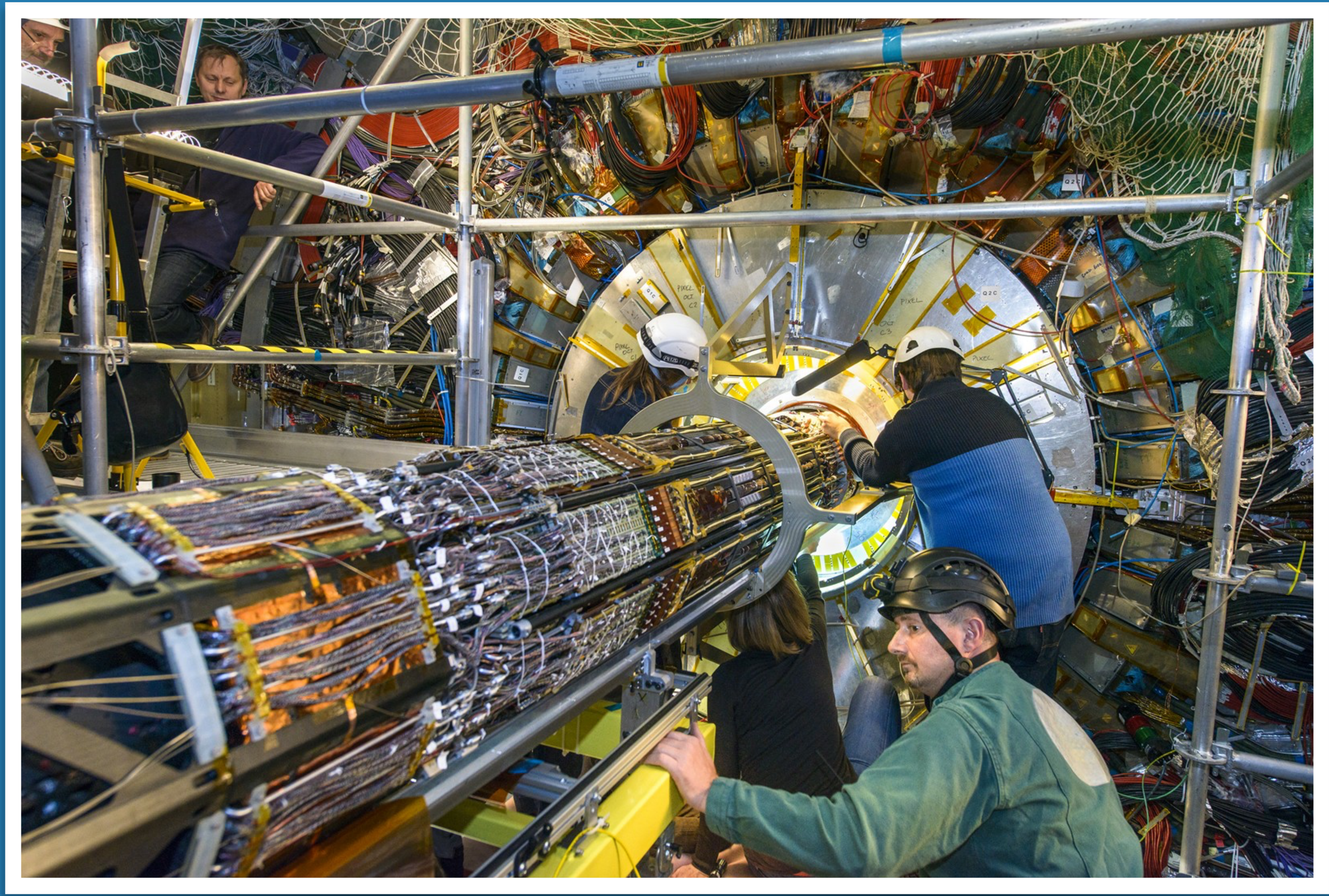
Intrinsically
Low
Backround

Access to
Fine
detail of events

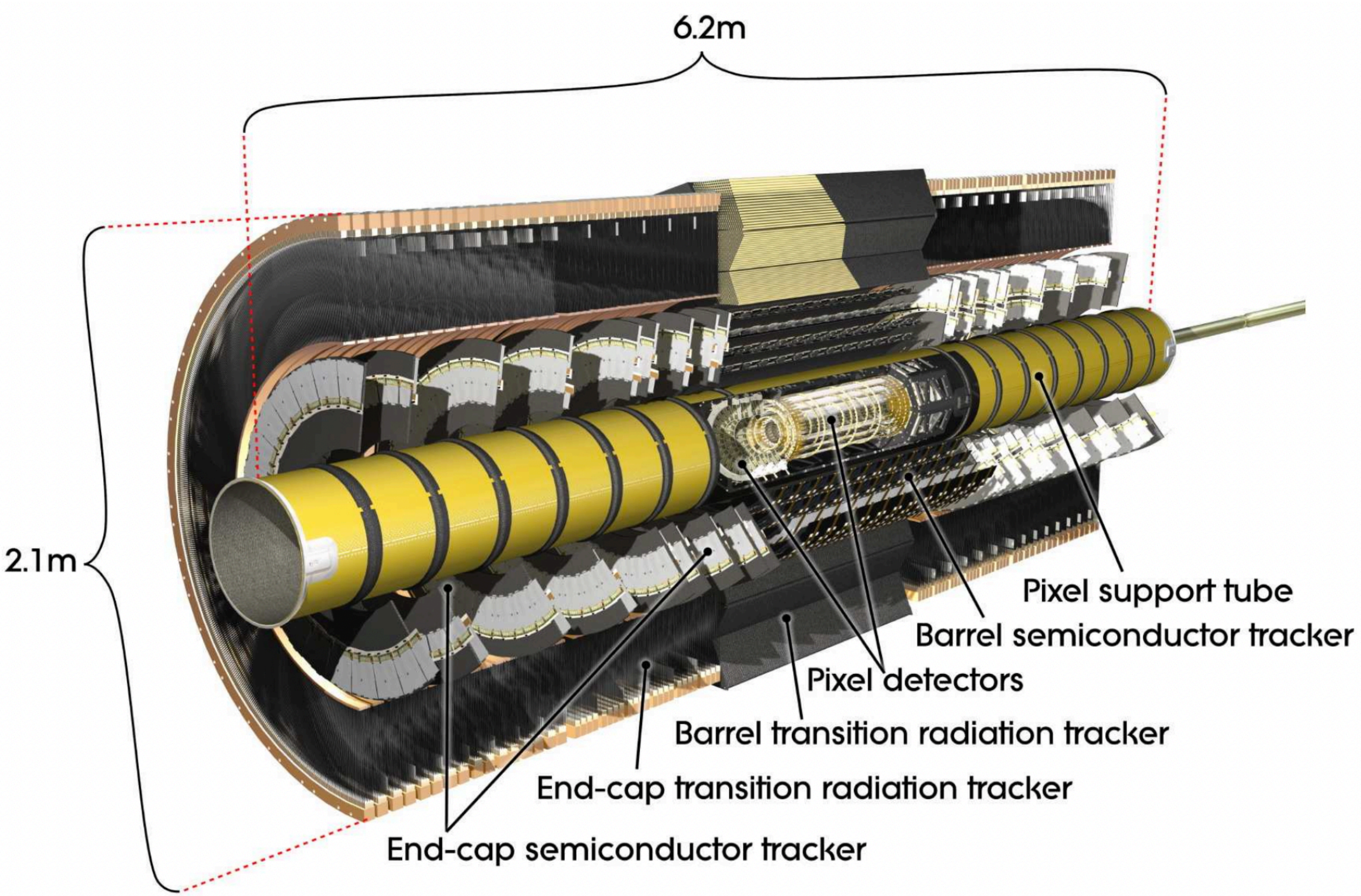
Ensure
Wide
acceptance

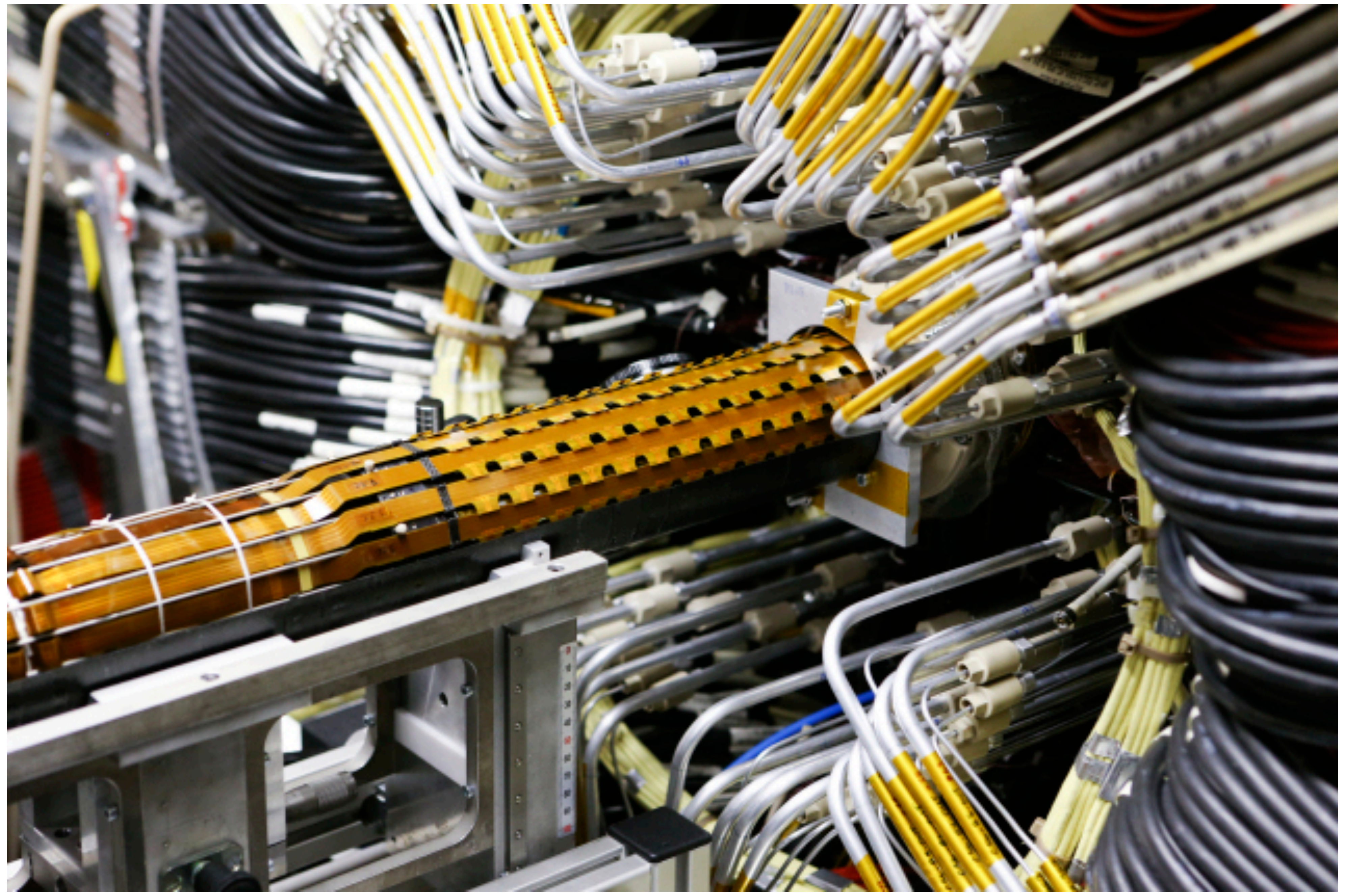
→ LLP searches in focus on the tracker

ATLAS Tracker



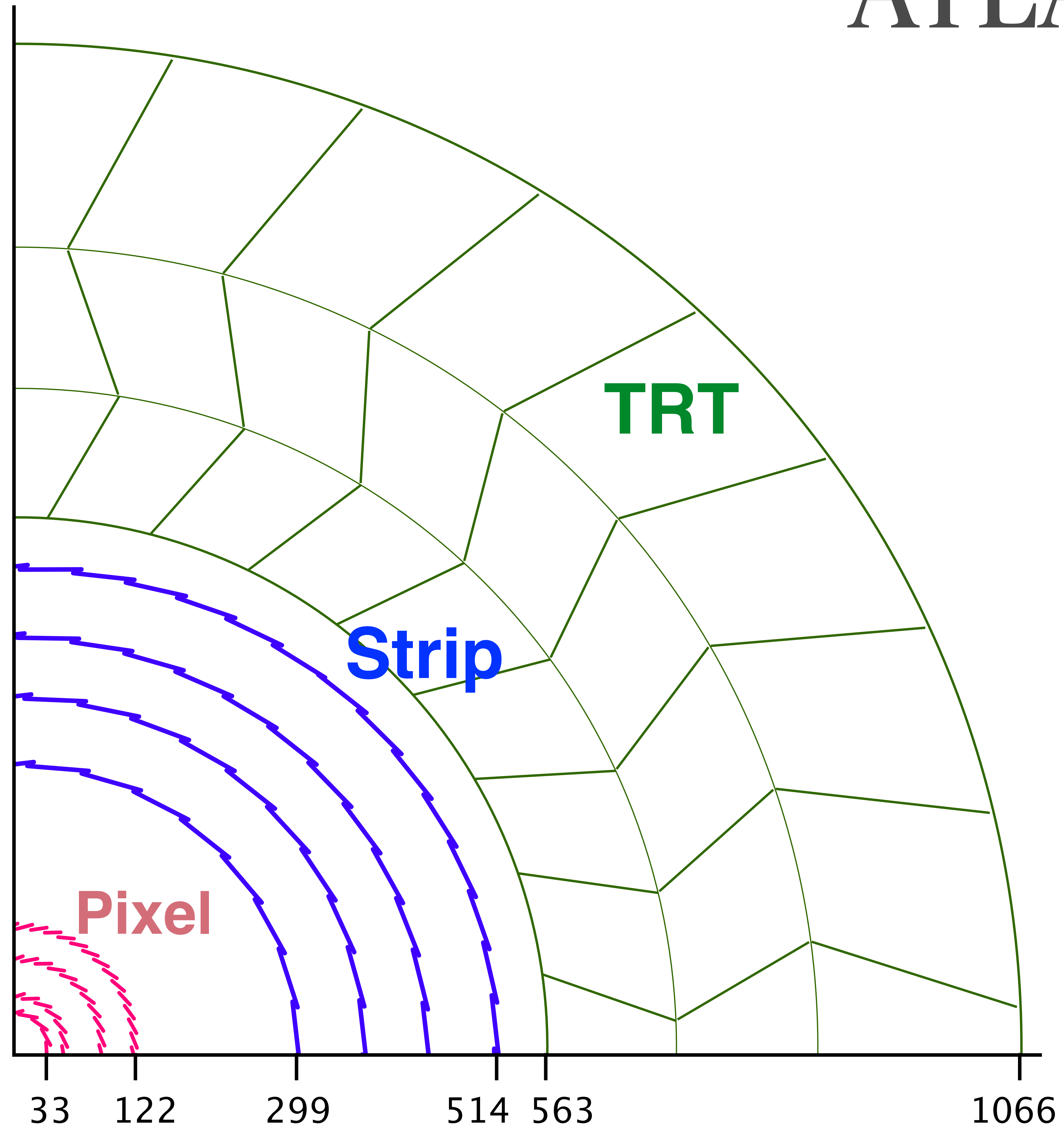
ATLAS Tracker





The great Run2 results of ATLAS have been supported by a successful opeartion of the innermost pixel layer IBL installed in 2014.

ATLAS Tracking



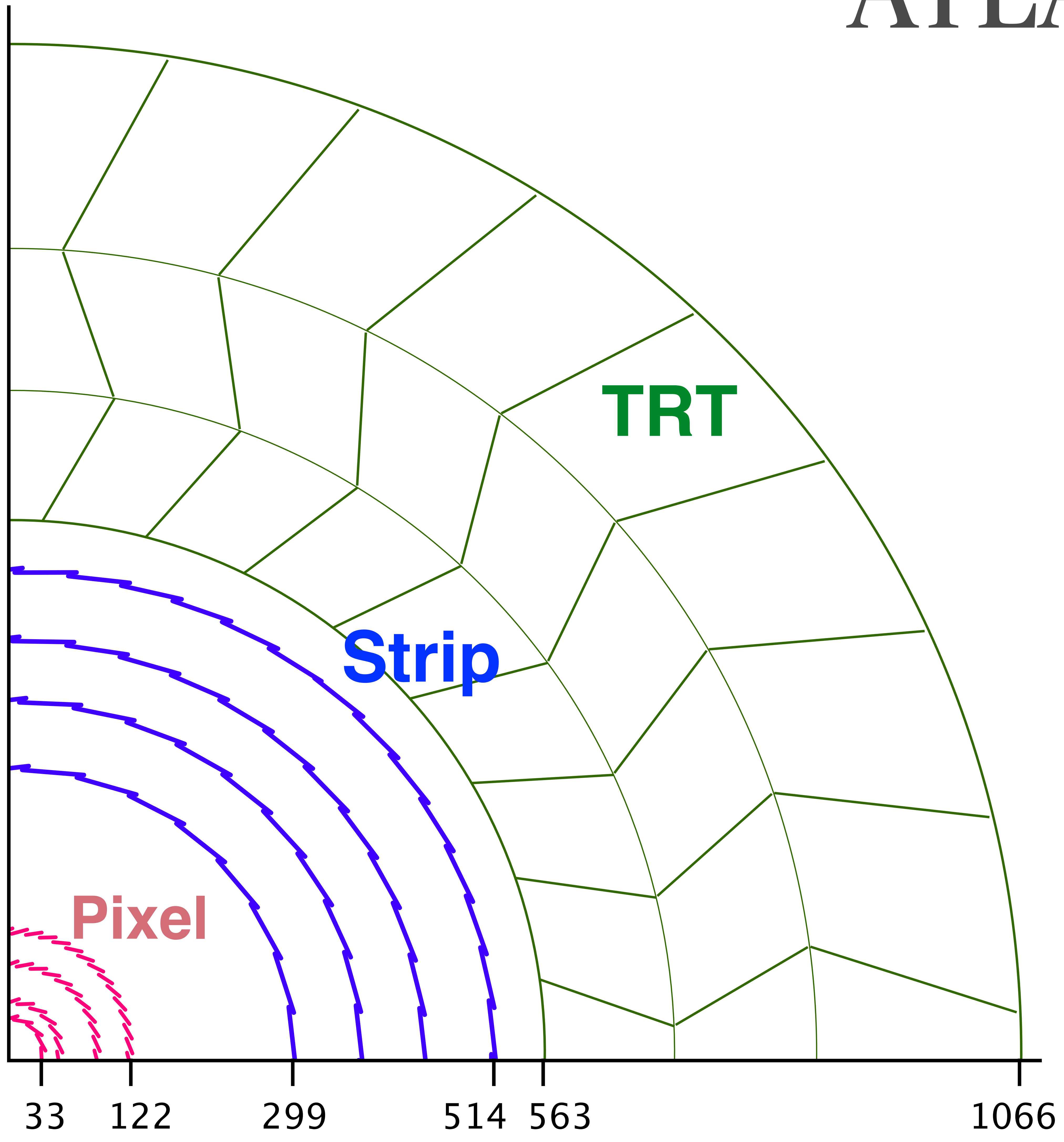
- 4 barrel layers of **silicon** pixel detector: r = 3.3 cm – 12.5 cm
- 4 barrel layers of **silicon** strip detector with a stereo angle: r = 30 cm – 50 cm
- O(30) straw drift tube (TRT)

1. The track needs to be seeded using ≥3 consecutive layers of silicon detector hits.
2. In order to have a track to be genuine (not fake), at least 7 or 8 silicon hits are required.

(*) Algorithm of seeding from TRT (back-tracking) exists but it is less efficient.

(**) Strip layers are double-sided (2 hits / layer)

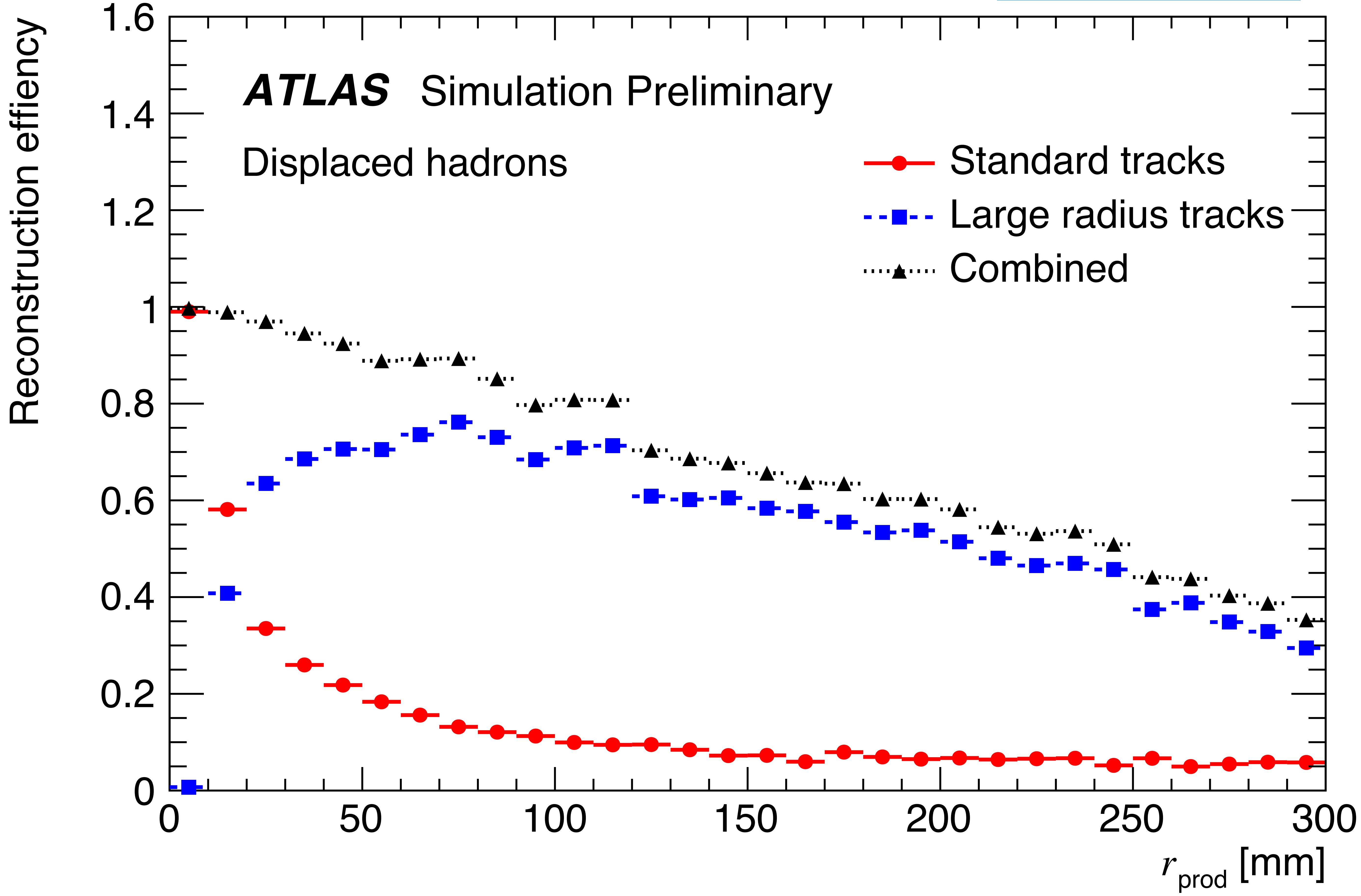
ATLAS Tracking



- These constraints impose limits on the impact parameters and the decay position.
- The maximum decay position radius is the first strip layer, r = 30 cm.
- $\max(d_0) = 300$ mm, $\max(z_0) = 1500$ mm
- In reality, the seed-finding algorithm further narrows down the search scope.
- Standard ATLAS tracking limited to $|d_0| < 10$ mm. This limit is somewhat arbitrary but related to computing resource constraints for track reconstruction and data saving.

The large-d_0 tracking

ATL-PHYS-PUB-2017-014

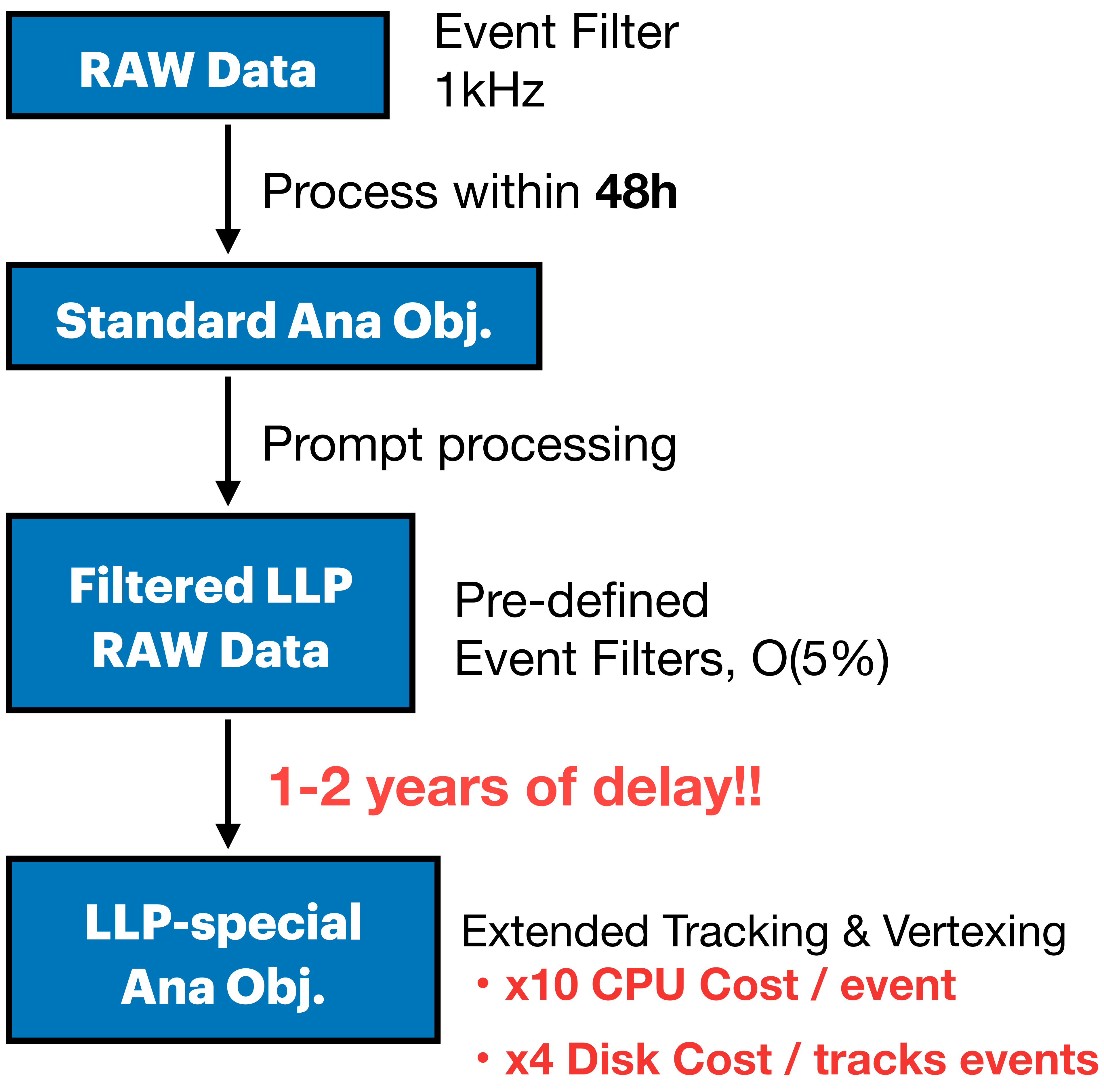


- Using left-over hits by the standard tracking algorithm.
- Expands the acceptance of the lifetime range drastically.

The large-d_0 tracking: cons

- Much broader track-finding phase space.
- In Run2:
  - 10x more CPU intensive
  - 4x more of disk consumption
- Impossible to apply to all physics data.
- An additional offline event filter
  - cherry-pick events of interests for LLPs (typ. only **5-7%** of all physics dataset).
- Event filters based on:
  E_T^{miss}, multijet, leptons, etc.

ATLAS Run2 Data Flow

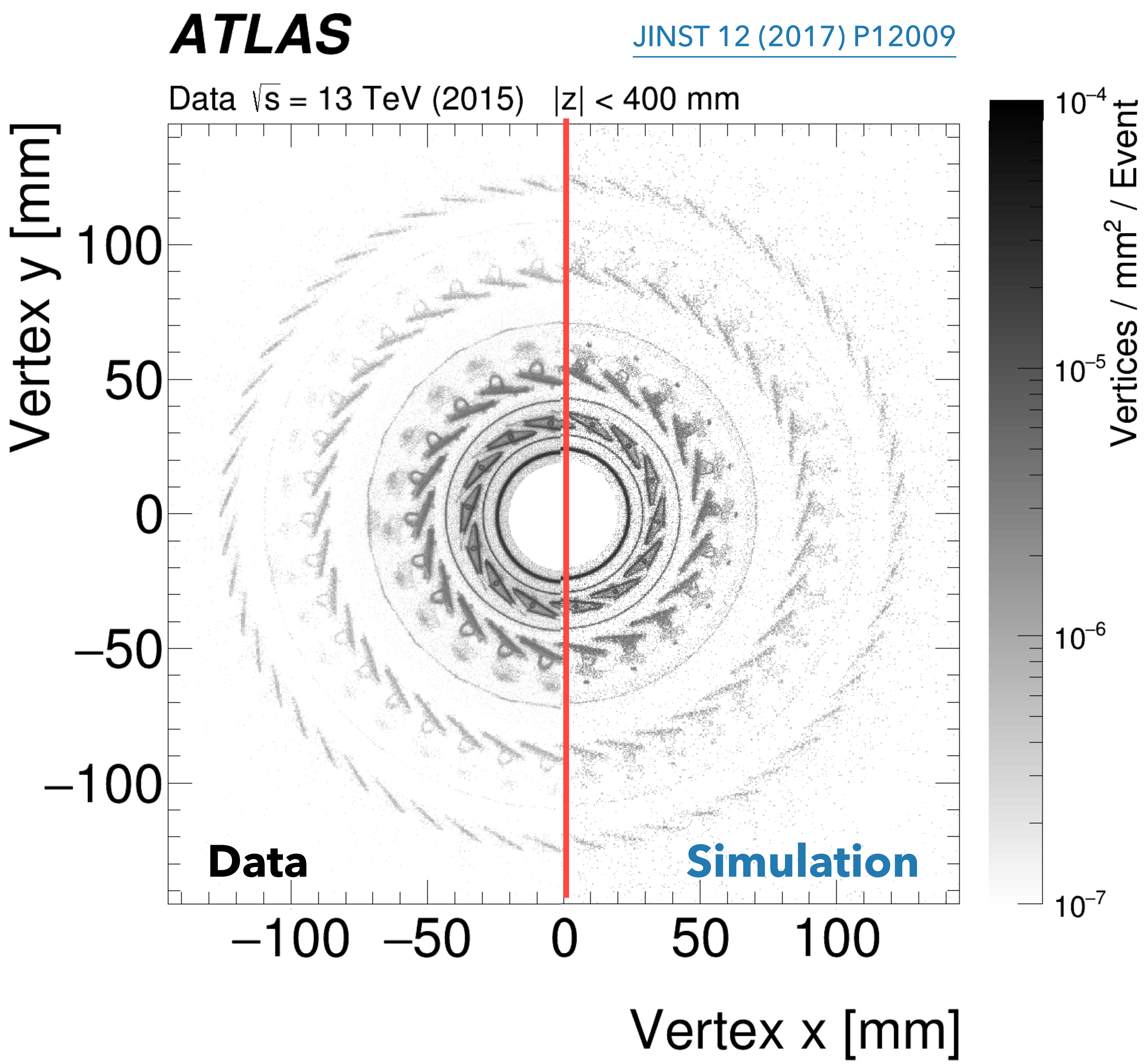


Vertexing

- ATLAS primary vertex reconstruction uses a so-called adaptive multi-vertex finder and fitter (**AMVF**).
- Primarily important for pileup rejection through the jet-vertex tagger (JVT).
- AMVF is only applicable around the primary vertex due to the presence of the beam-spot location constraints in the xy-plane in the seed finding step.
- Explicit reconstruction of secondary vertexing is not under the central support of the ATLAS data model.
- For example, B-tag secondary vertexing is only applied inside the jet cone.
- Contrary to primary vertexing, multiple directions of optimizations can be possible for secondary vertices.

Secondary vertexing for LLP searches

- Algorithm: VrtSecInclusive
- The basic algorithm is the same was what was used for the material study.
- Seeded from all large-d_0 tracks satisfying the basic selection criteria, try $C(n,2)$ numbers of combinations aiming at high efficiency.
- Rather accepts random vertexing eventually cleaned up by the offline selection.

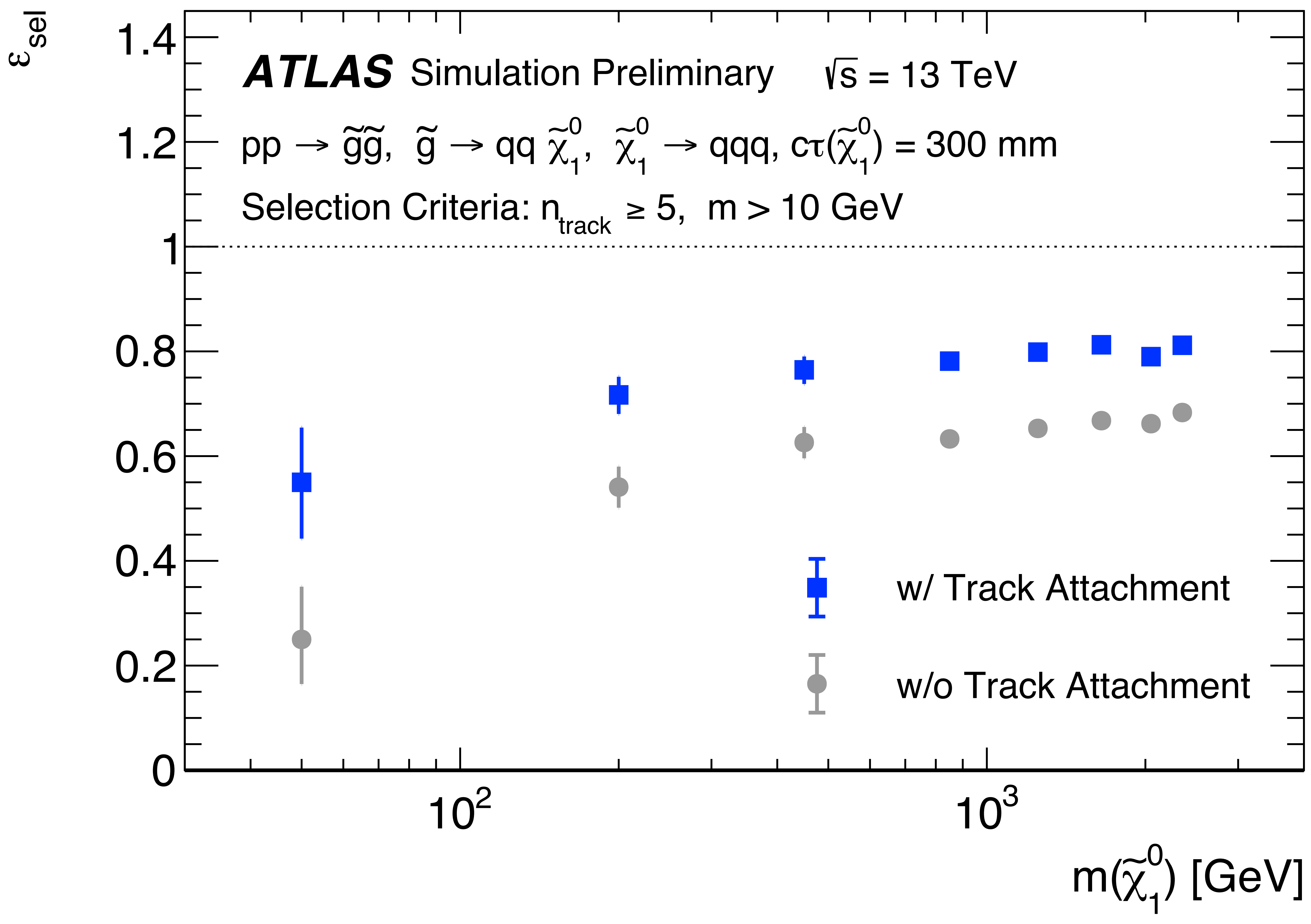


Secondary vertexing for LLP searches – Performance

- A feature dedicated to LLP towards the full-Run2 dataset:
- Attach small-d_0 tracks not selected by the initial selection to the found vertex to enrich the associated tracks and vertex priperties.
- Another option to feed tracks of more specified collections: e.g. leptons.

Displaced vertex selection efficiency

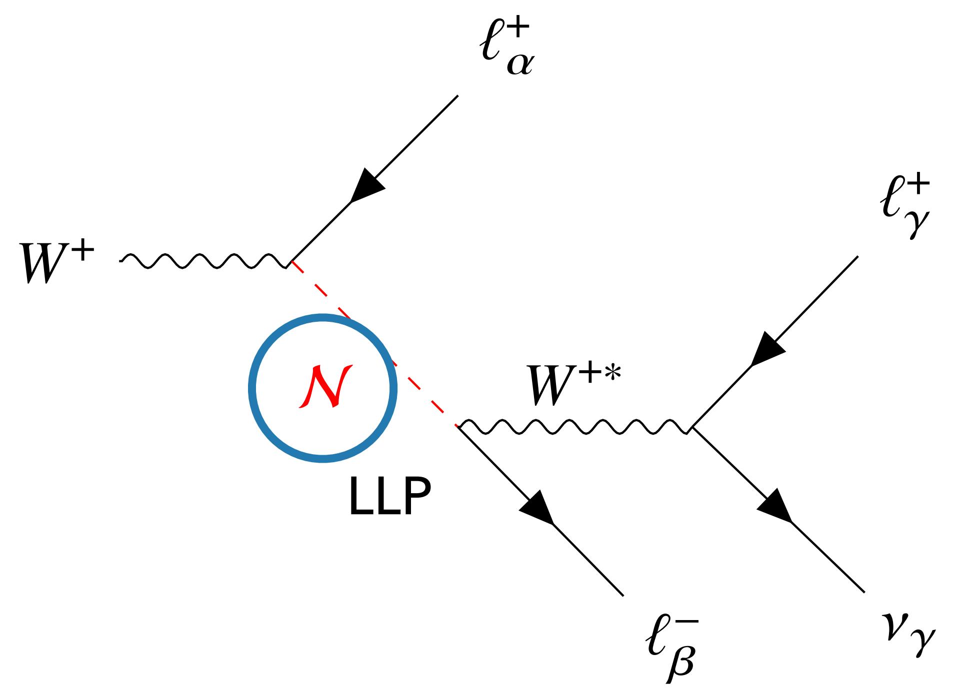
ATL-PHYS-PUB-2019-013

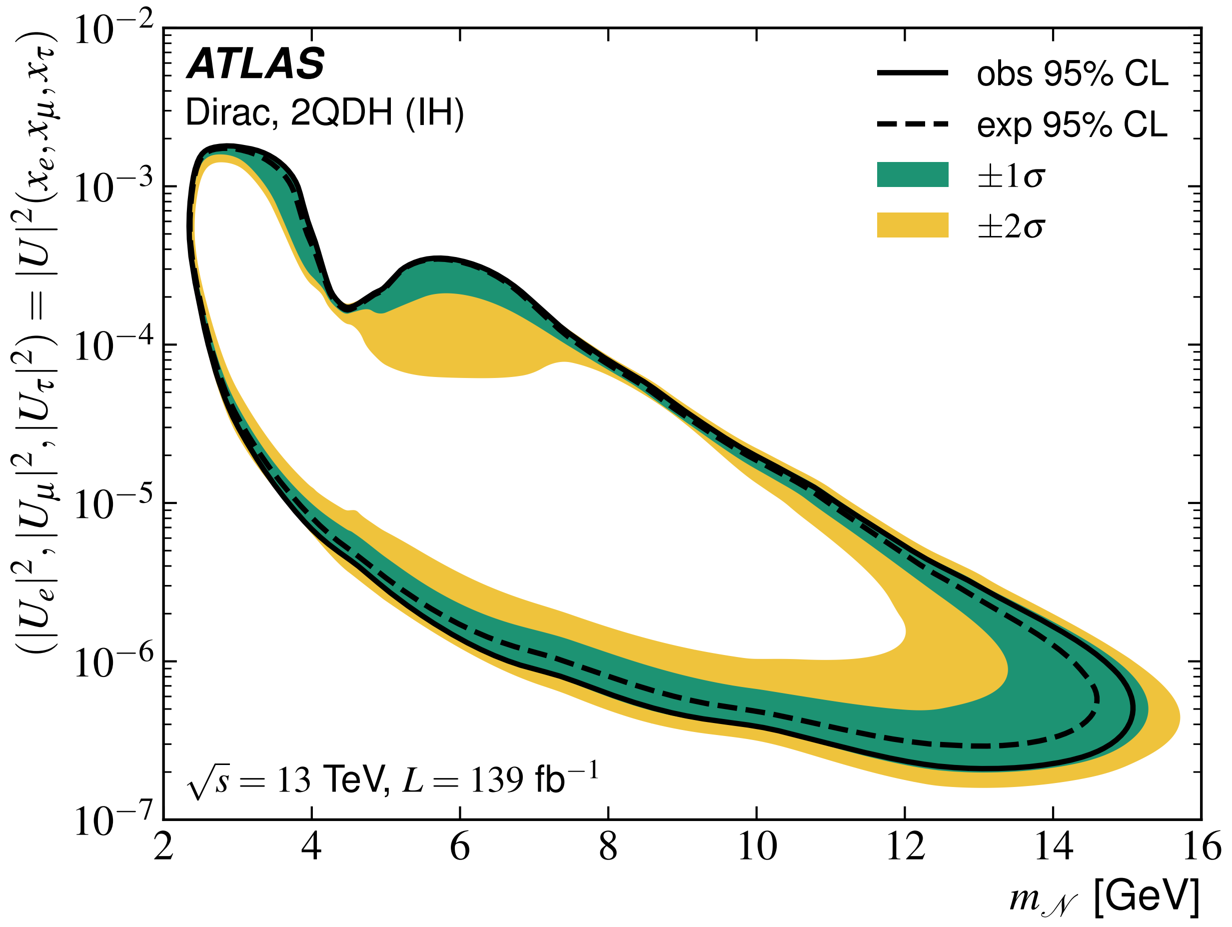


Secondary vertexing for LLP – Applications

dHNL: displaced dilepton DV + prompt lepton

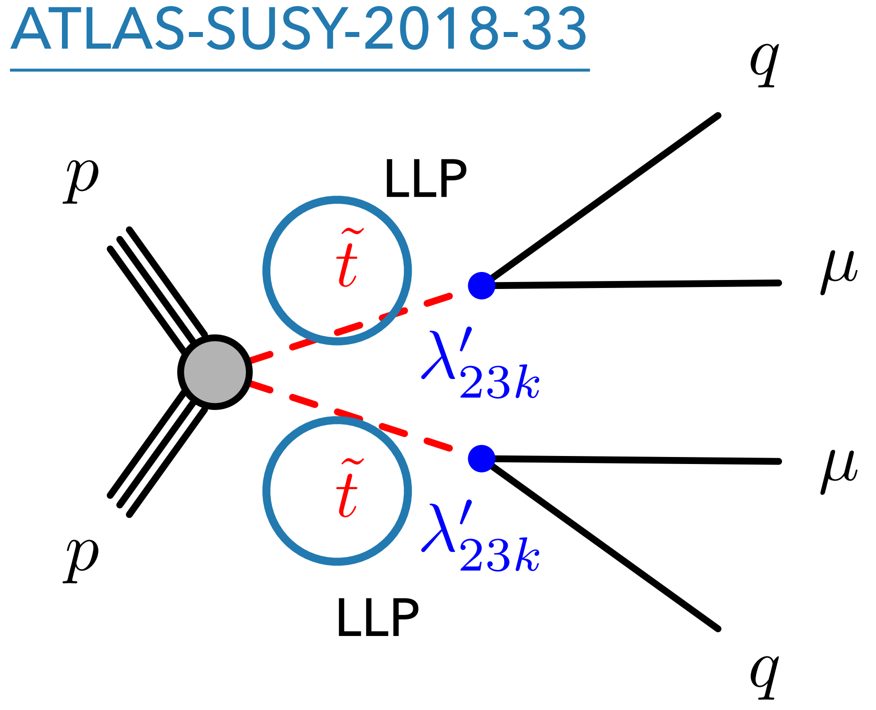
ATLAS-EXOT-2019-29

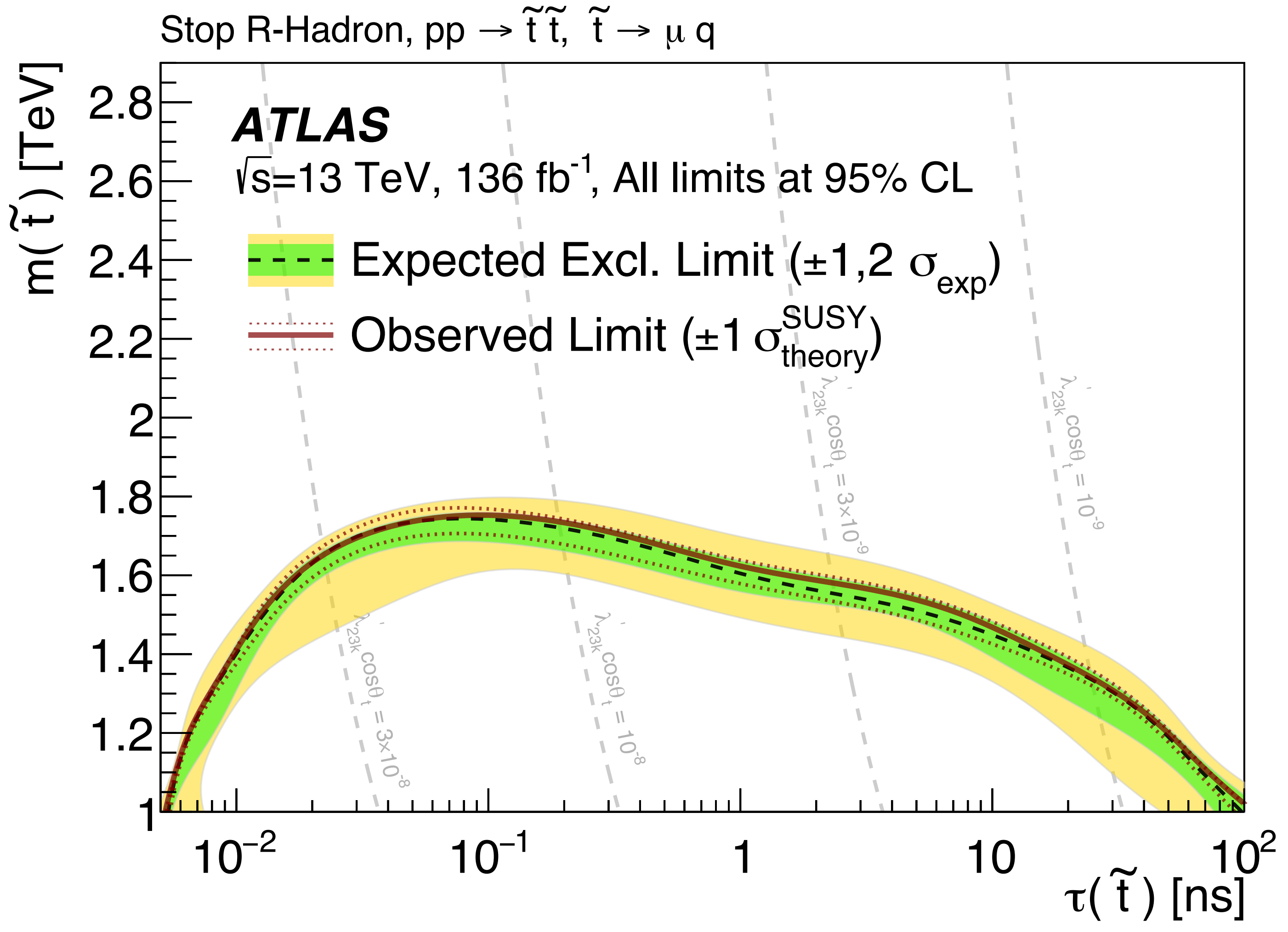




DV+μ: RPV stop (LQD)

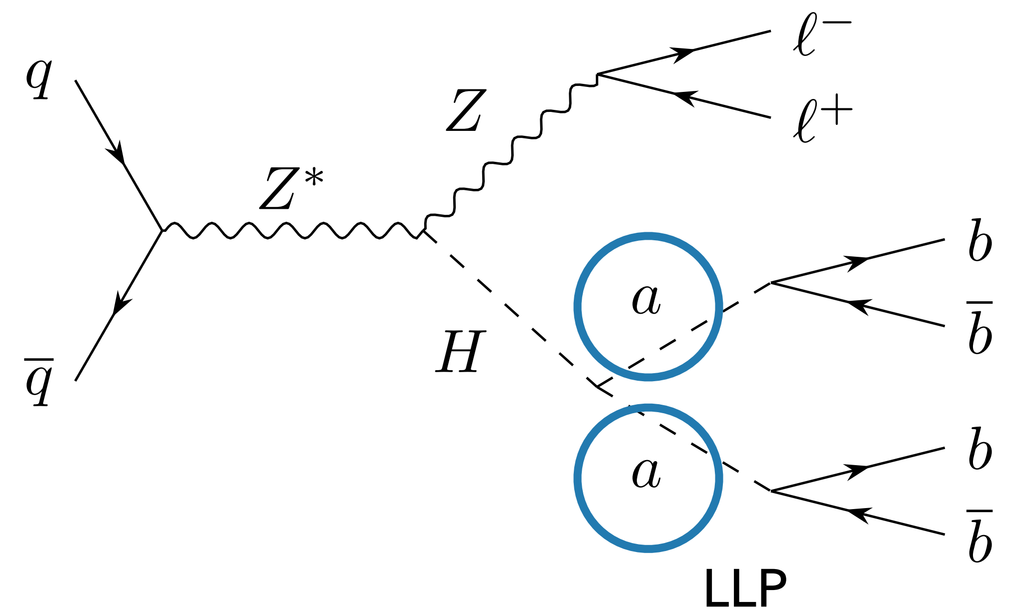
ATLAS-SUSY-2018-33

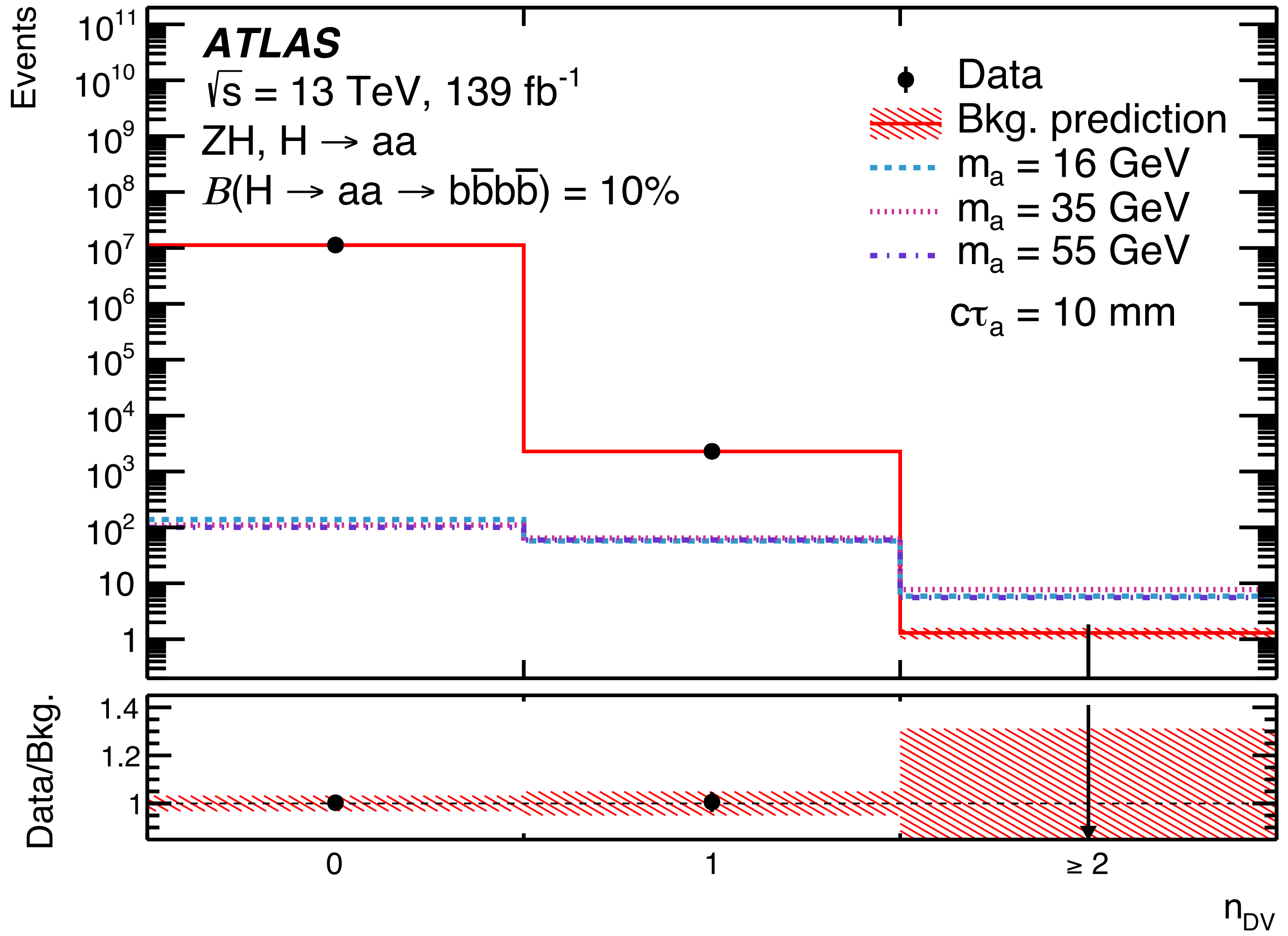




2x b-rich DVs from H(125)

ATLAS-EXOT-2018-57

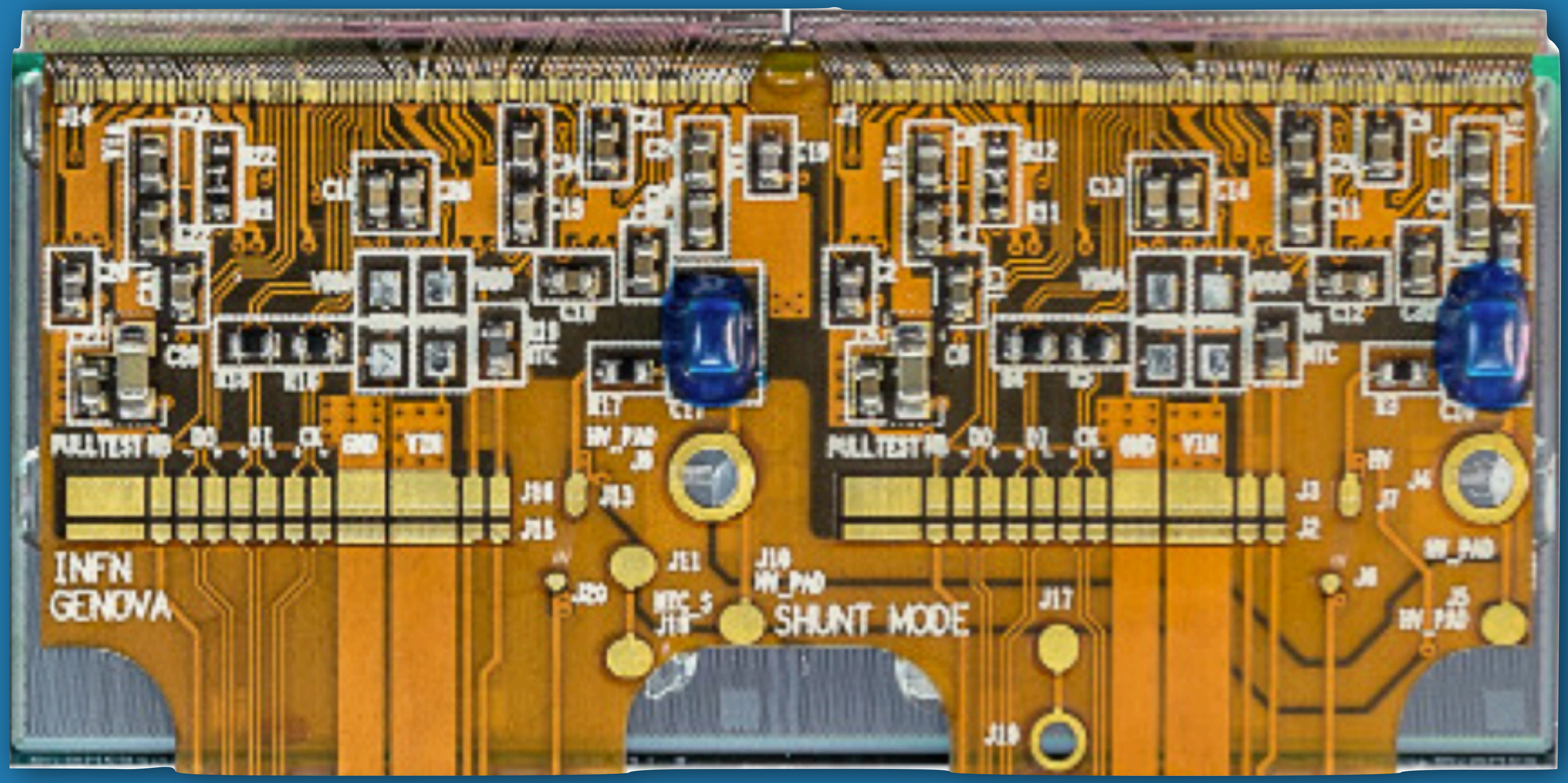




- Several papers using VrtSecInclusive with full Run2 dataset the have been released.
- And more searches are ongoing!

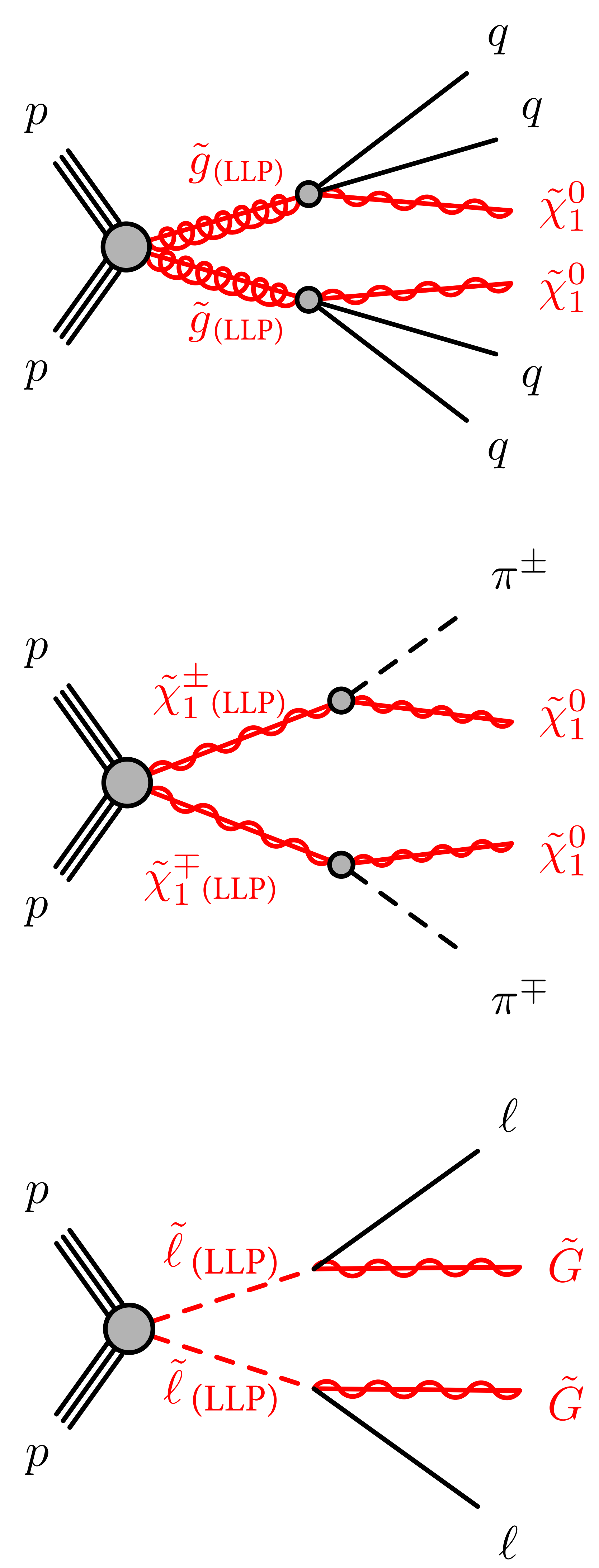
A recent result:

search with pixel dE/dx



ATLAS IBL FE-I4 Double-Planar Pixel Module

ATLAS-SUSY-2018-42, arXiv:2205.06013



Pixel dE/dx

Massive charged LLP

→ Typically $\beta < 1$

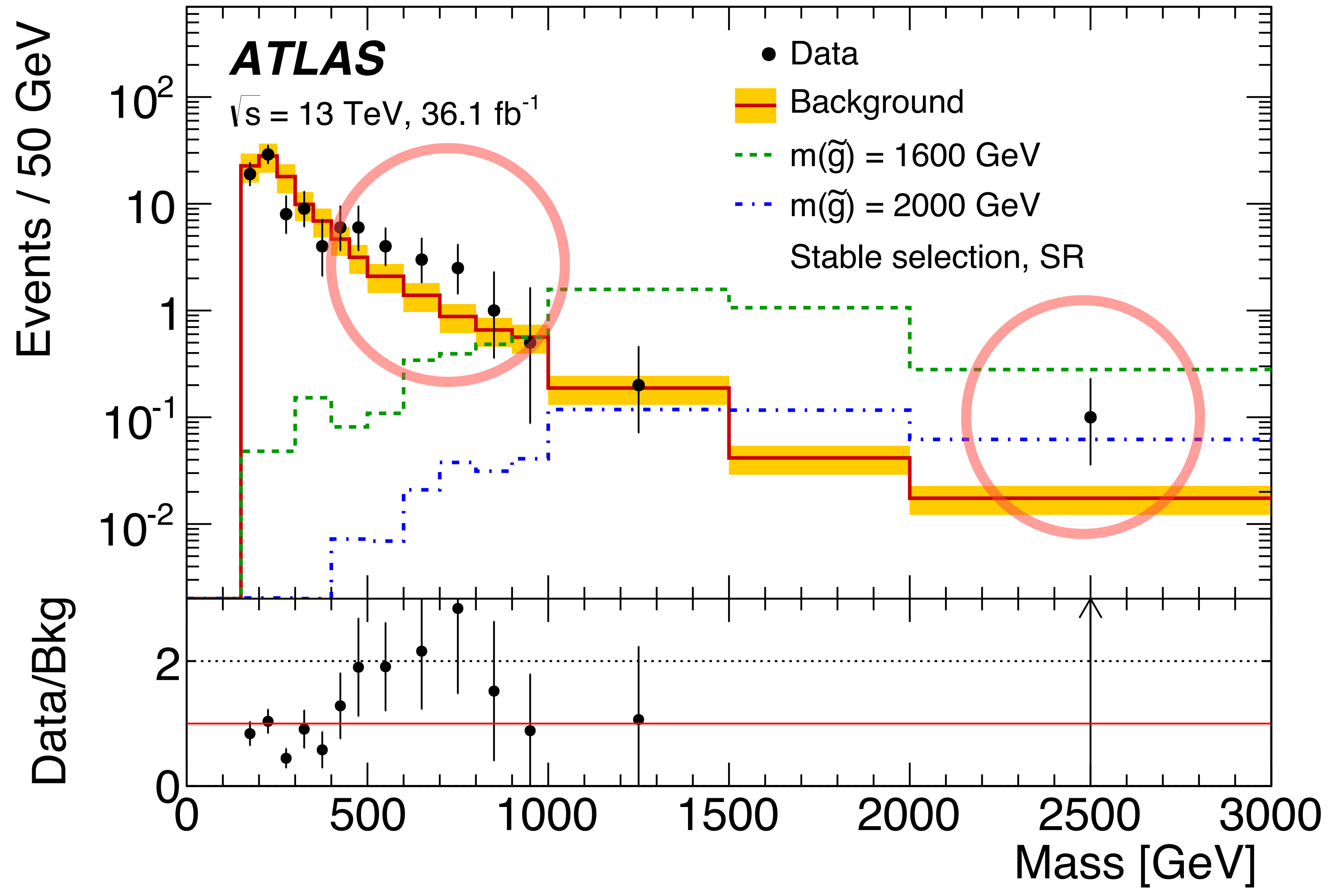
→ Anomalously large specific ionization loss.

- Events triggered by E_T^{miss}
- Offline $E_T^{miss} > 170$ GeV
- Has a well-isolated track or muon satisfying $p_T > 120$ GeV, $|\eta| < 1.8$
- Hadron and electron veto
- Requires anomalously large pixel dE/dx

Main discriminant:

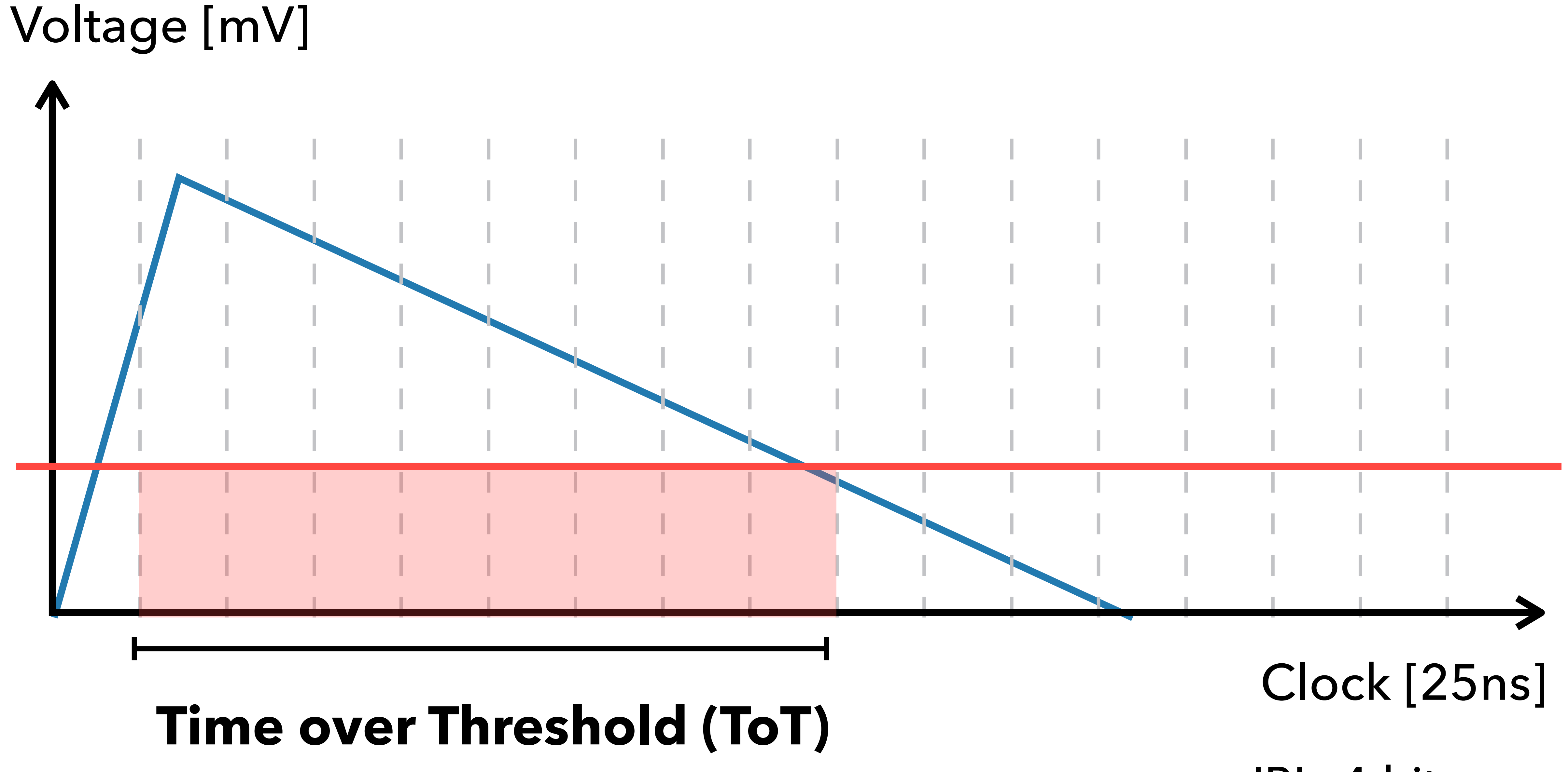
$$\boxed{m_{dE/dx} = \frac{p_{\mathrm{tracker}}}{\beta\gamma_{\langle dE/dx \rangle}}}$$

ATLAS-SUSY-2016-31



In the previous round of the search (mid-Run2), a mild excess of 2.4σ (local signif.) was present in one of the two SRs at around 600 GeV. Also 2 events at the high-mass end.

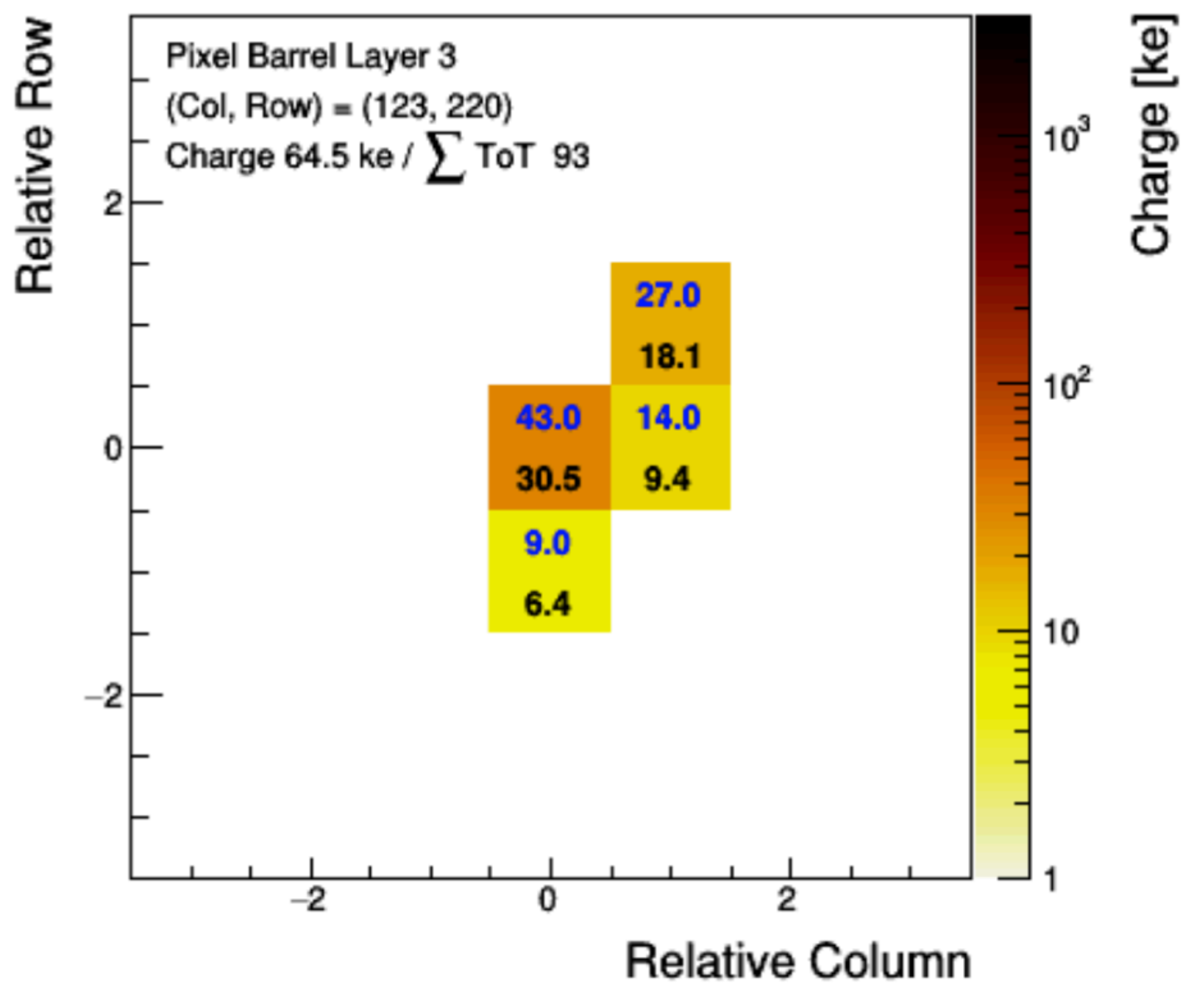
Pixel dE/dx



(Proxy of the deposit charge on the pixel.)

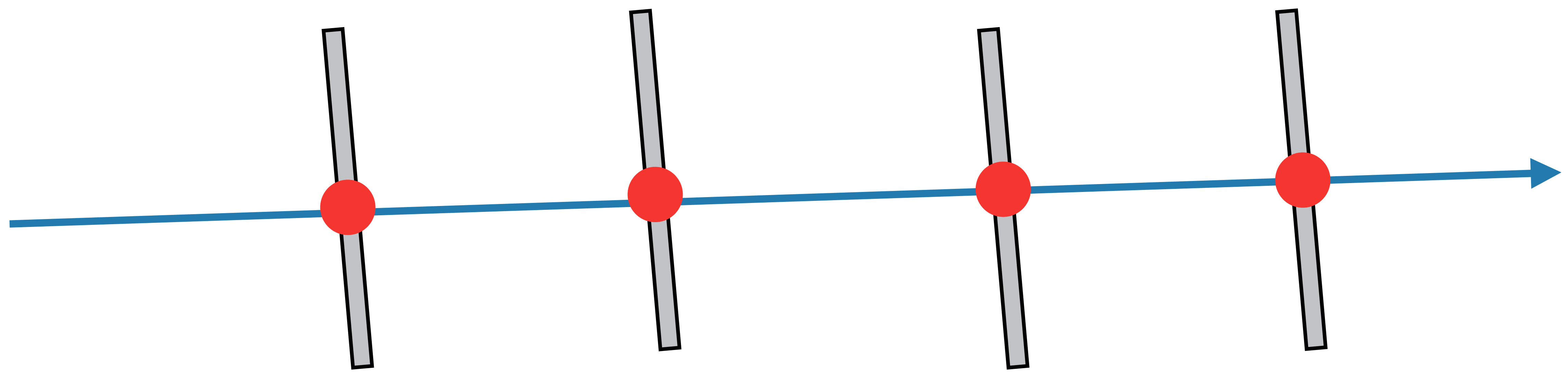
IBL: 4-bit

Outer Pixel: 8-bit



Pixel hits are clustered by concatenation.

Cluster charge = analog sum of the ToT calibrated to the charge.

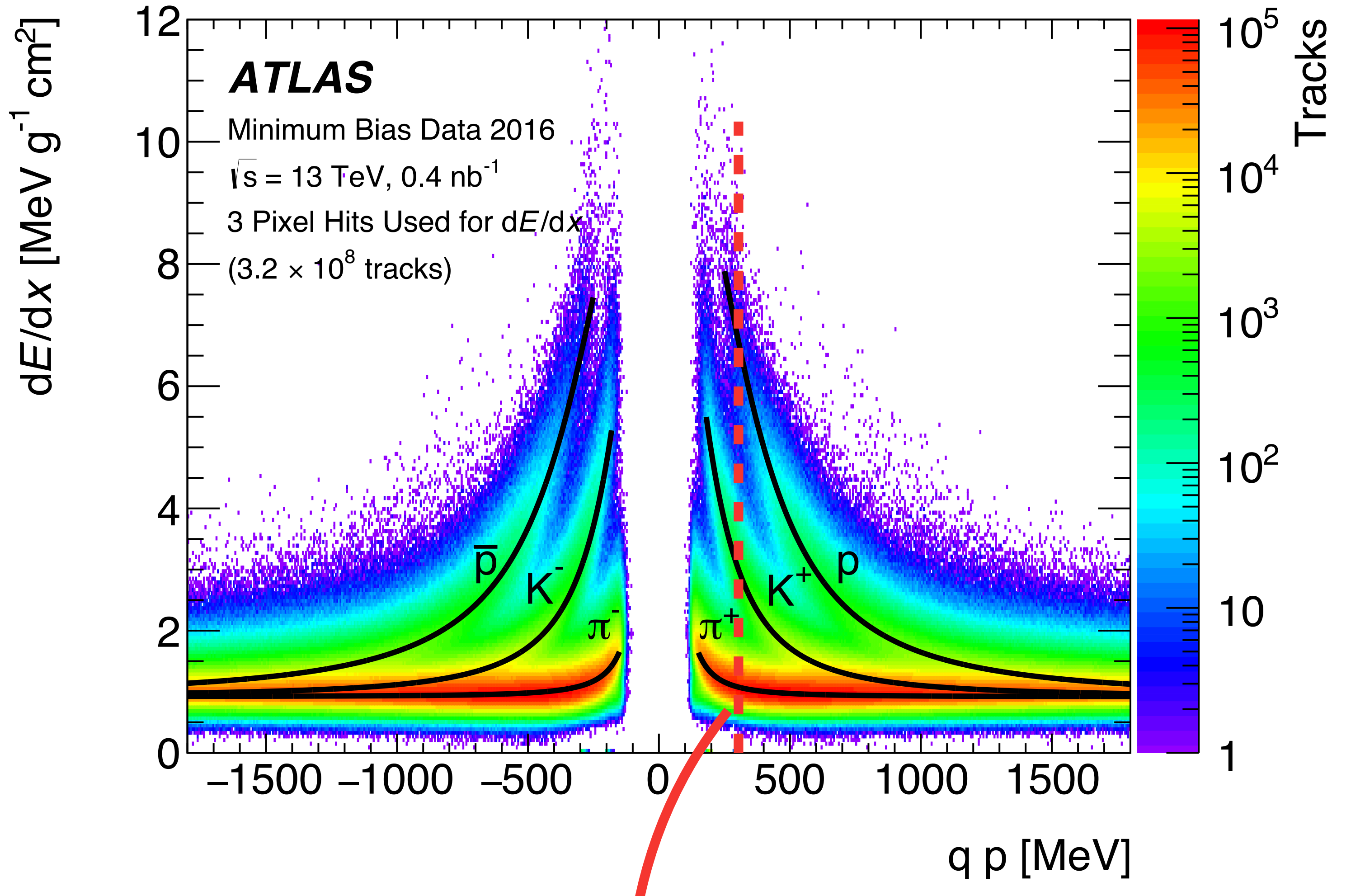


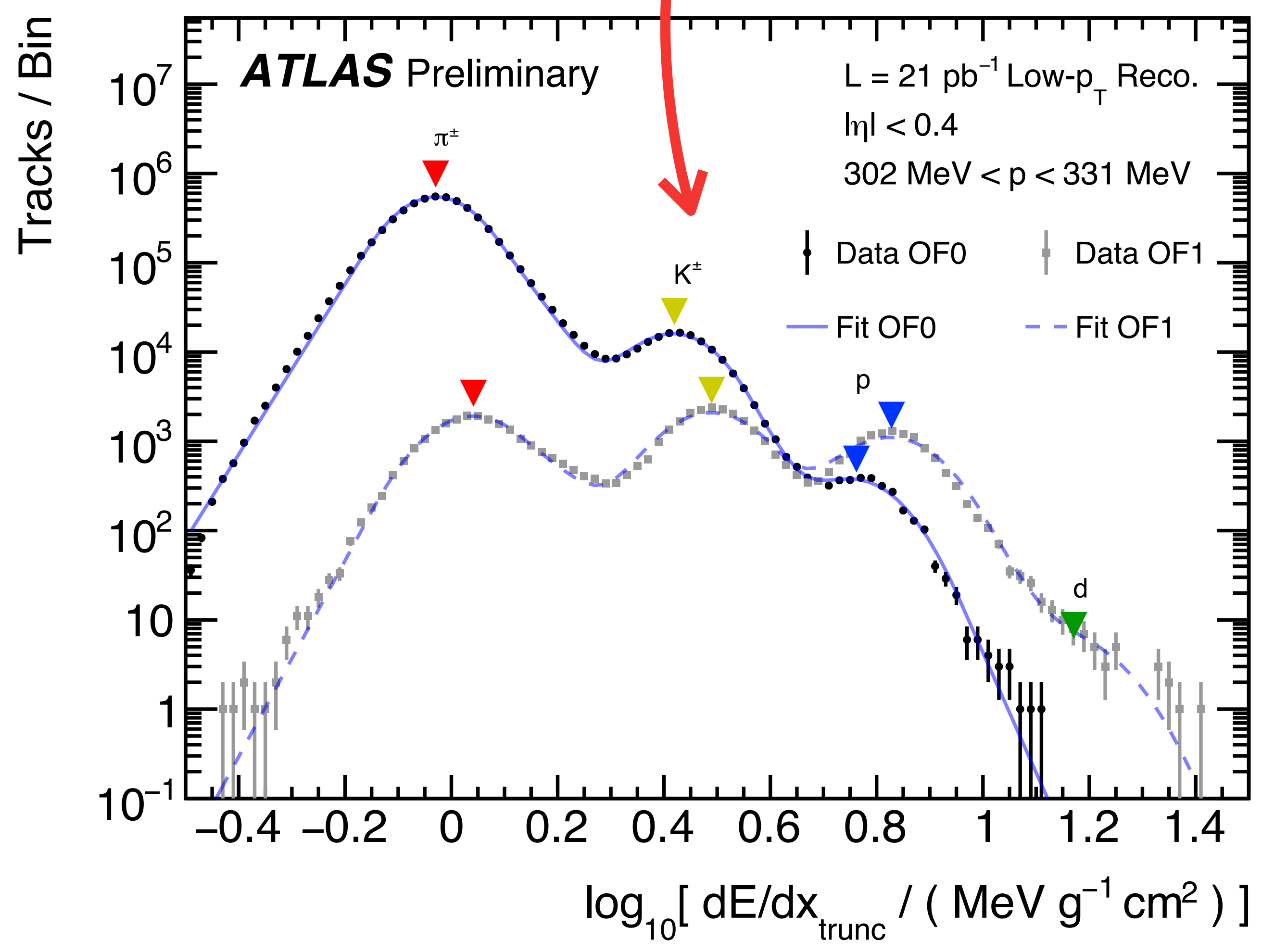
Array of cluster-level dE/dx is available for a track.

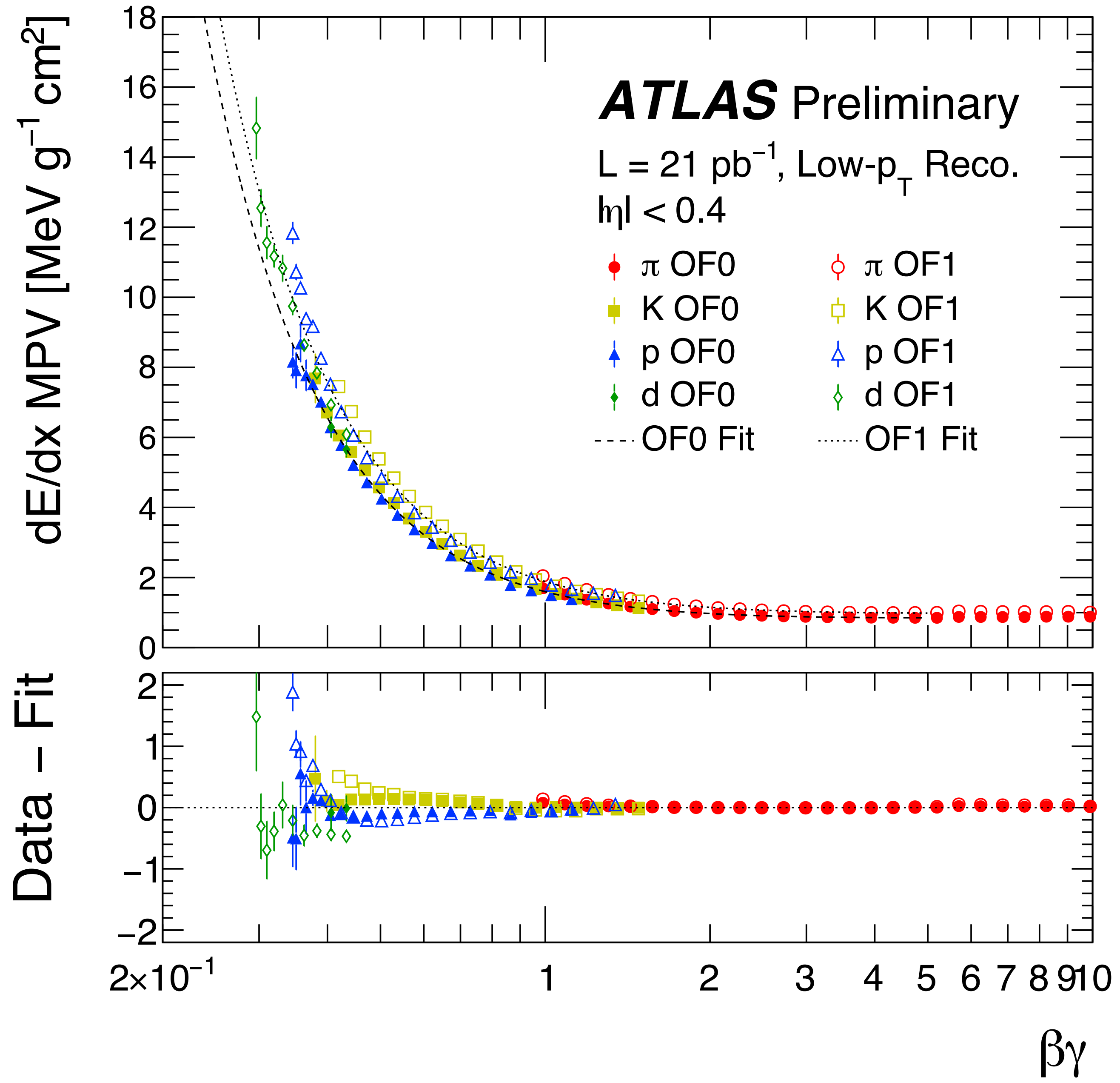
→ Take a truncated mean of the cluster dE/dx as the dE/dx of the track.

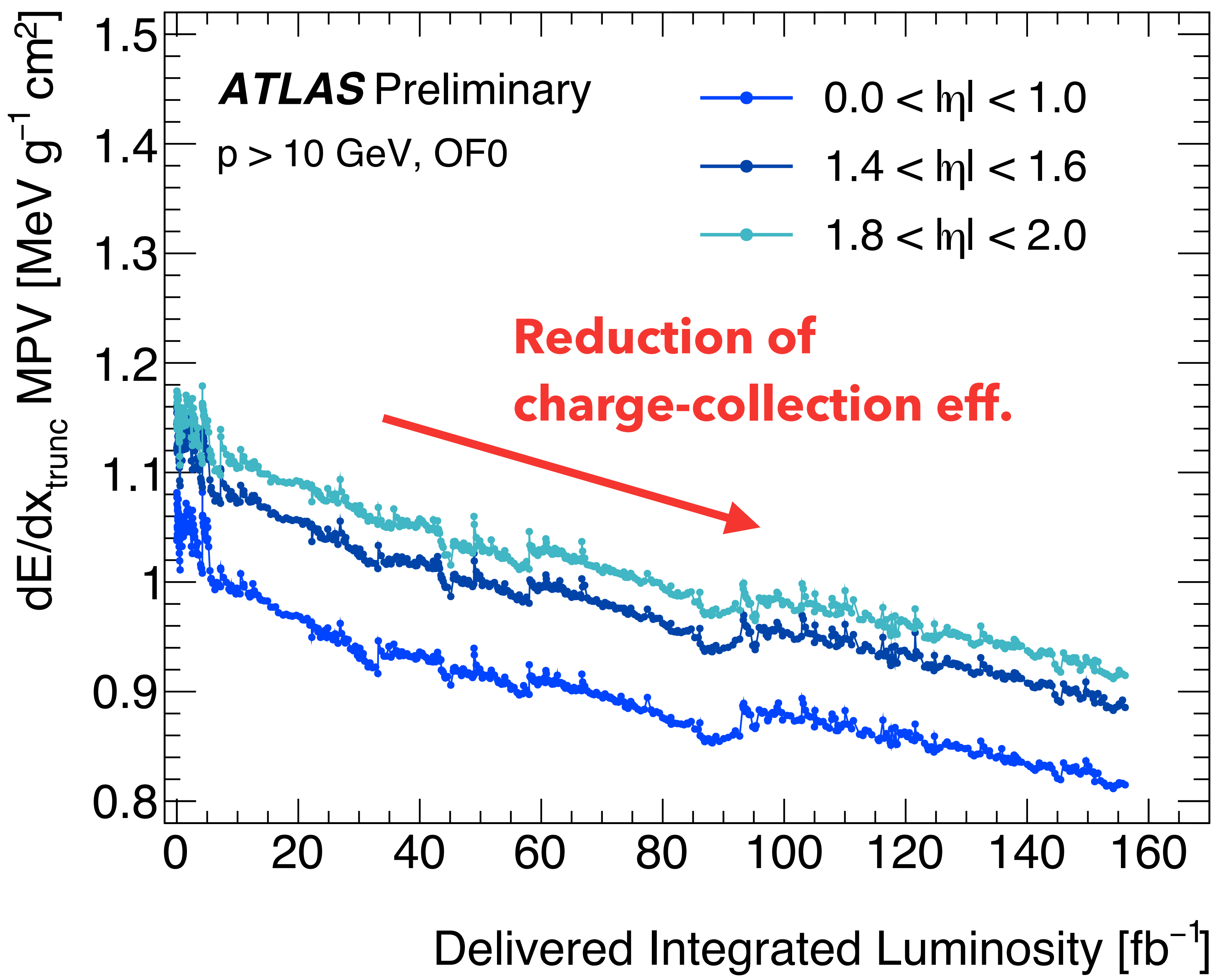
Effective to trim the Landau tail of MIP.

Bethe-Bloch Calibration



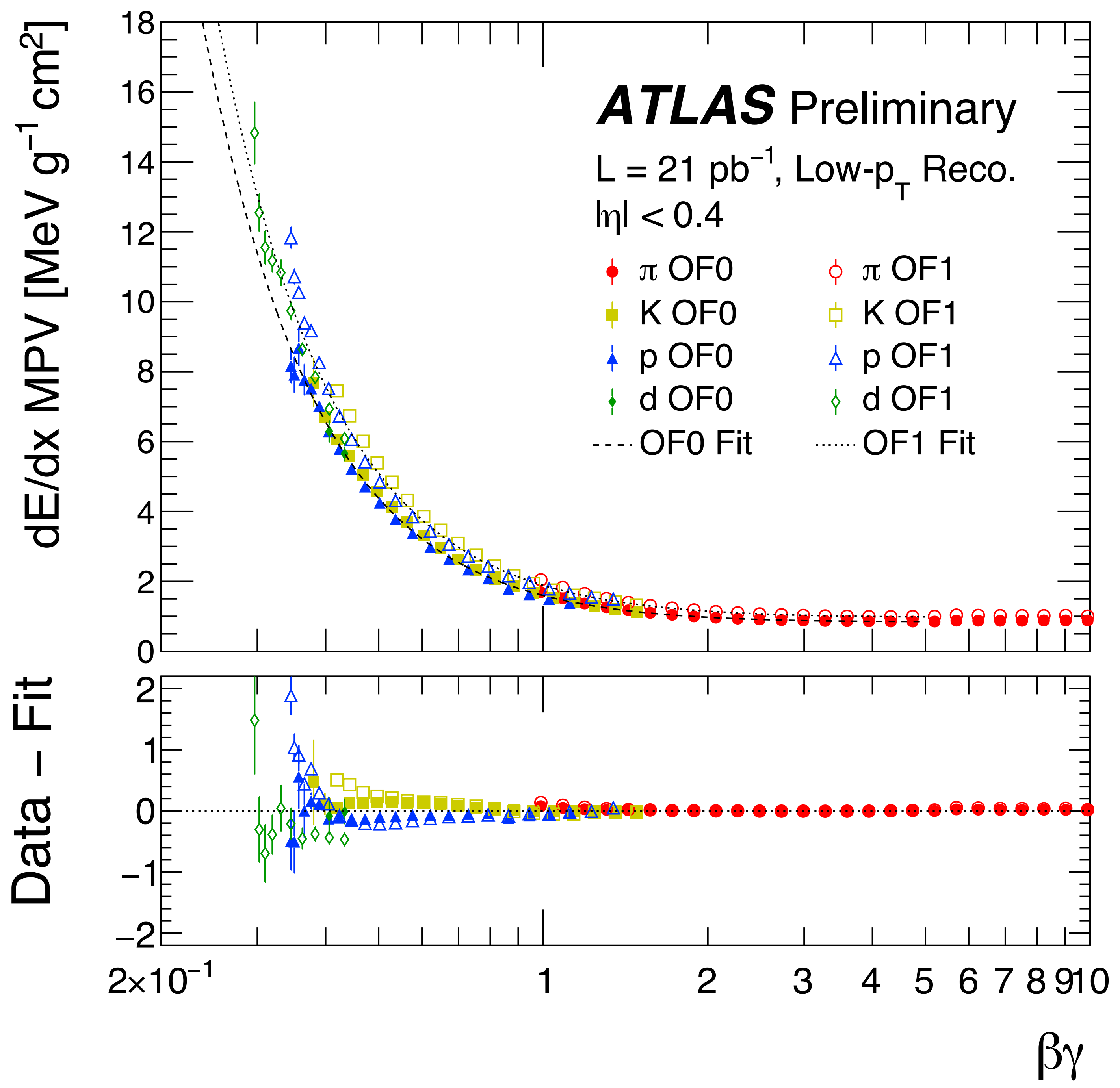


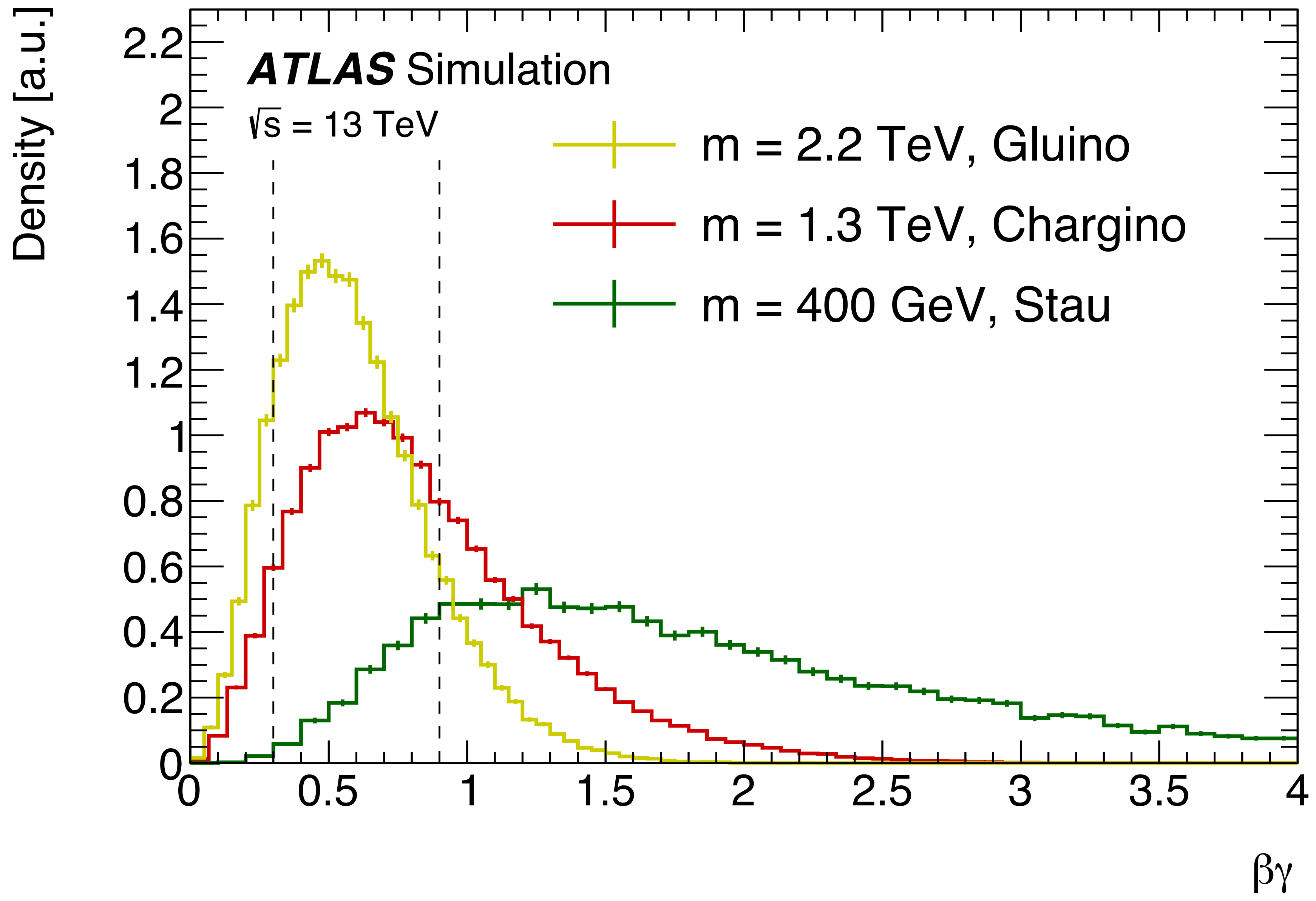


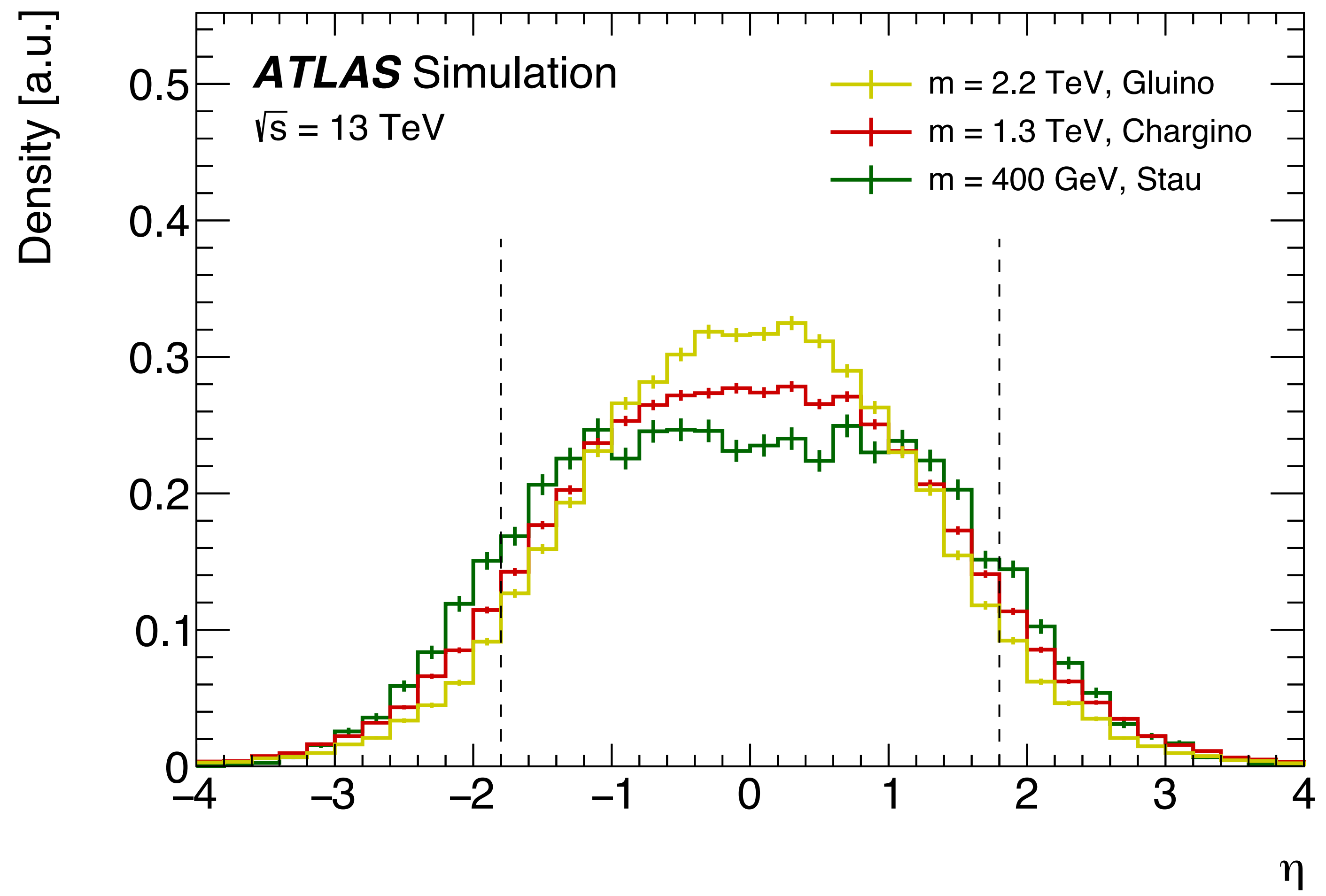


- Tracing Bethe-Bloch curve using a special low-$\langle \mu \rangle$ run enabling $p_\mathrm{T} > 100$ MeV reconstruction (standard: $p_\mathrm{T} > 500$ MeV).
- Time-dependent MIP-MPV reflecting radiation damage is compensated.
- Pixel $\mathrm{d}E/\mathrm{d}x$ is rather tough to model.
  → Landau distribution templated from data & applied for signal models.

Universal Acceptance

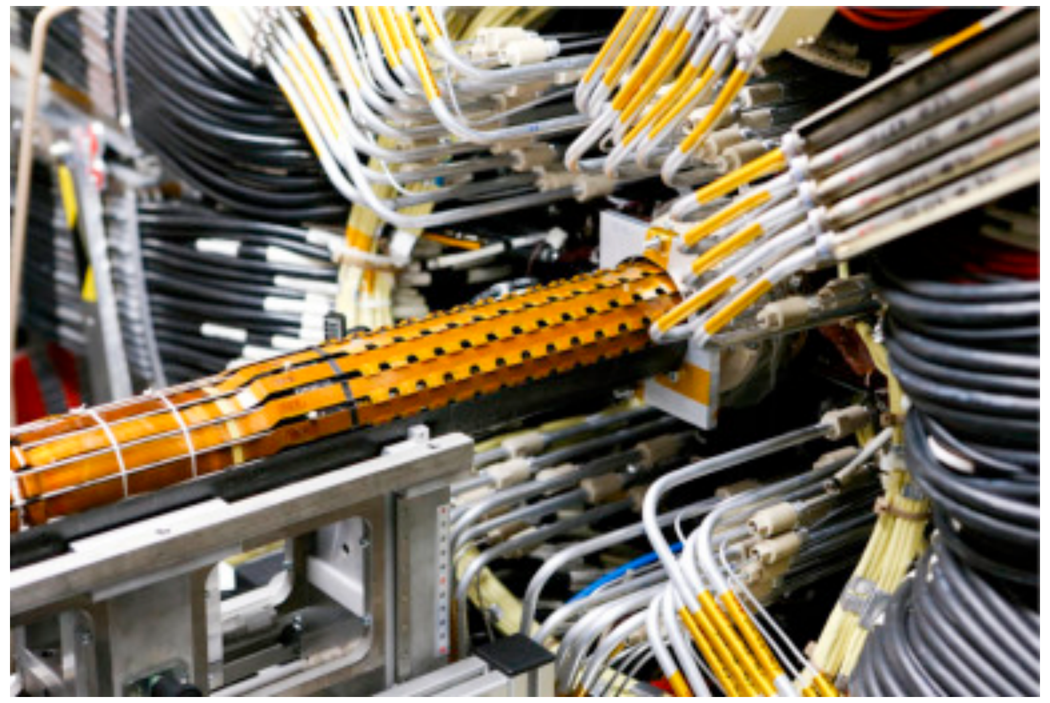






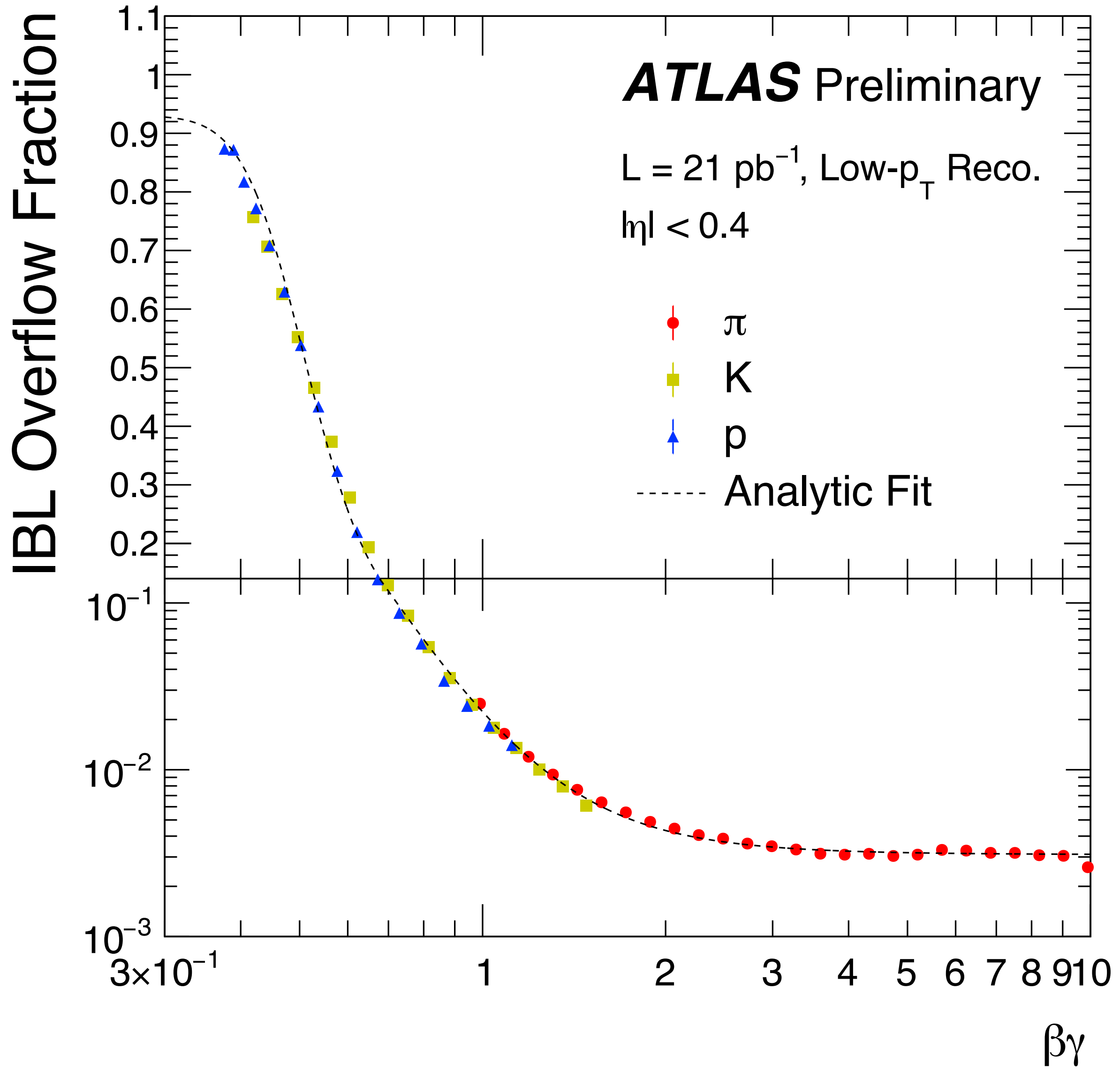
- The simplest assumption is that LLPs are likely produced in pairs (incl. C1N1 case).
- General two-body production with a mass threshold leads to similar kinematic distribution.
  (a peak structure reflecting phase-space opening, then a long tail reflecting PDF).
- The acceptance is dependent on mass but not strongly dependent on the microscopic phenomenology.

Signal Region Binning

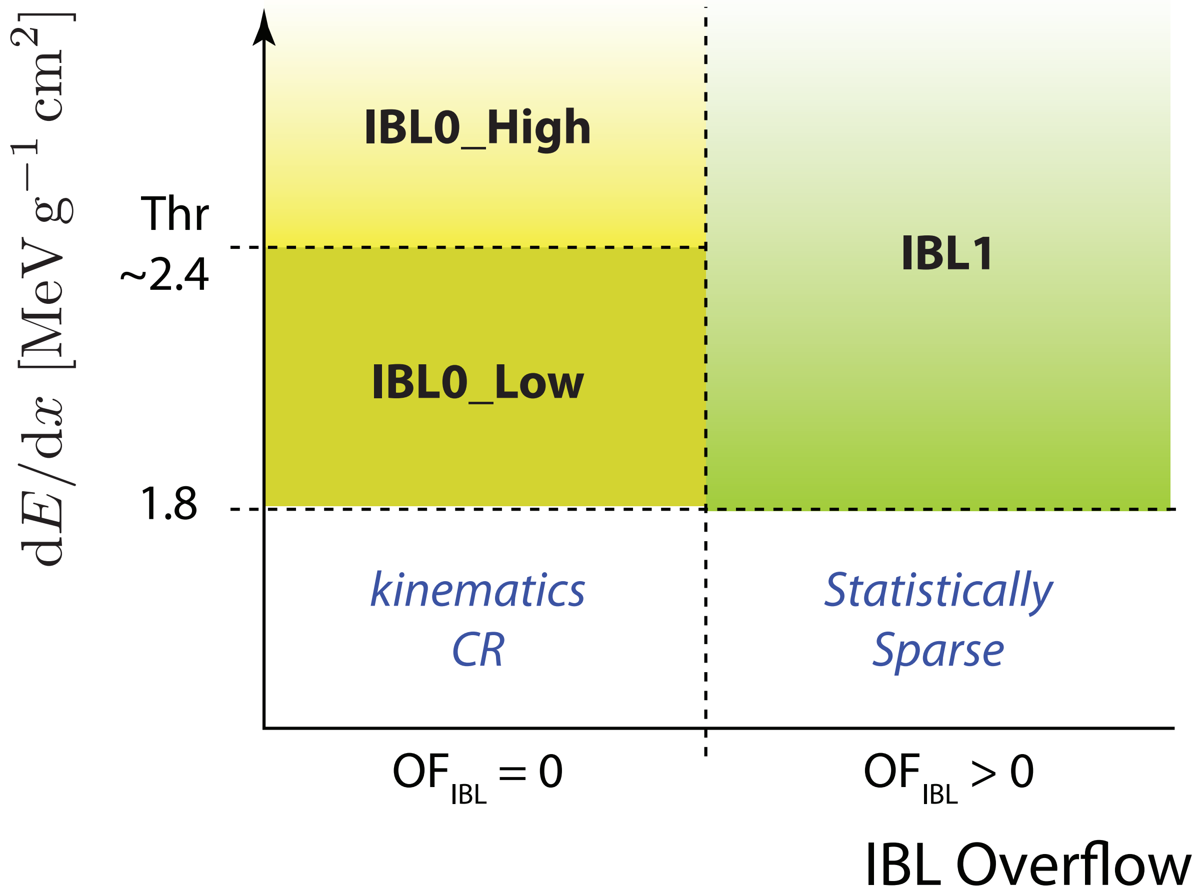


ATLAS Innermost Layer is IBL.
It uses a newer FE chip (**FE-I4**) than outer layers.

Time-over-threshold (**ToT**) of FE-I4 is only 4-bit.
It saturates earlier than other layers having 8-bit dynamic range. For IBL, an overflow flag is issued.



The IBL **ToT overflow flag** has a strong discrimination power for slow charged particles from MIP!



For limit setting, divide SR bins like the left figure.
Also, classified as muon tracks or not: total **6 SR bins**.

For discovery, allocate 2 bins:
- dE/dx in [1.8, 2.4]
- dE/dx > 2.4

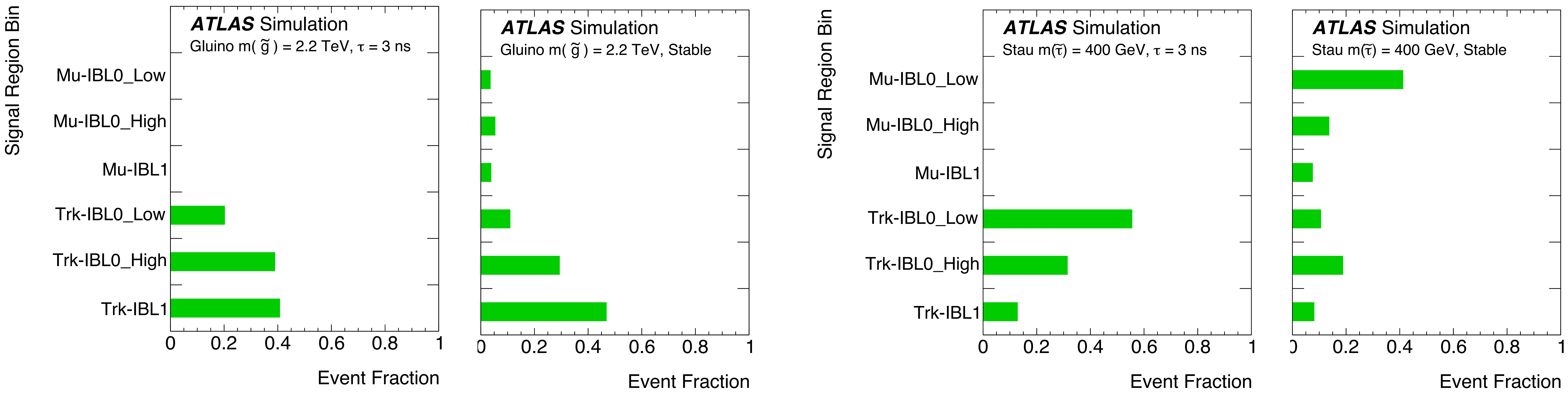
SR name	Discovery	Limit setting	Track category	IBL overflow	dE/dx [MeV g^{-1}cm^2]
SR-Inclusive_Low	✓		inclusive	yes or no	[1.8, 2.4]
SR-Inclusive_High	✓				> 2.4
SR-Trk-IBL0_Low		✓	track	no	[1.8, 2.4]
SR-Trk-IBL0_High		✓		no	> 2.4
SR-Trk-IBL1		✓		yes	> 1.8
SR-Mu-IBL0_Low		✓	muon tracks	no	[1.8, 2.4]
SR-Mu-IBL0_High		✓		no	> 2.4
SR-Mu-IBL1		✓		yes	> 1.8

→ For each signal CLLP mass value, allocate two sets of mass windows in SR covering ~70% of the signal, depending on the lifetime of CLLPs.

Signal Region Binning

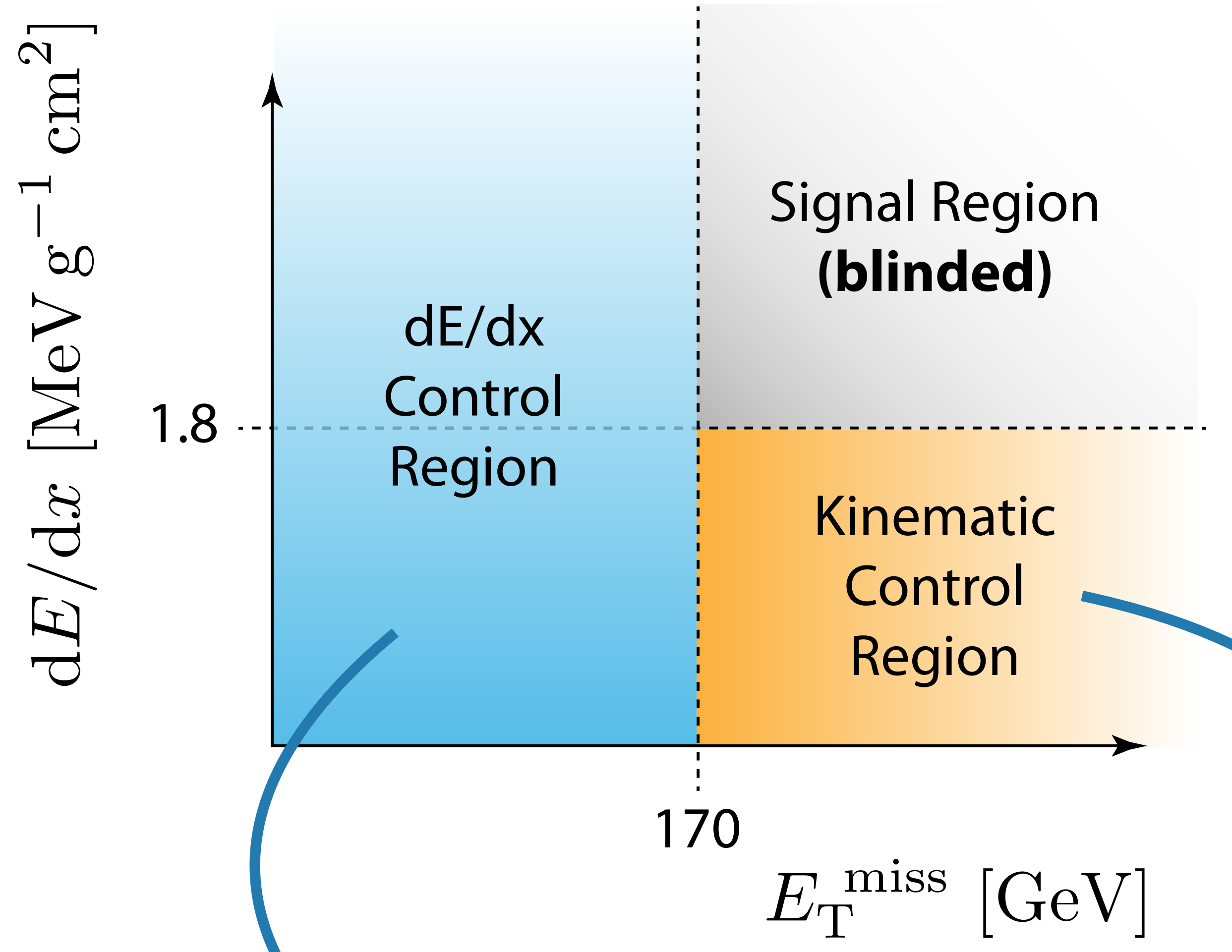
Gluino R-hadron, 2.2 TeV

GMSB Stau, 400 GeV



- The binning strategy fits to various BSM hypotheses and lifetime assumptions.

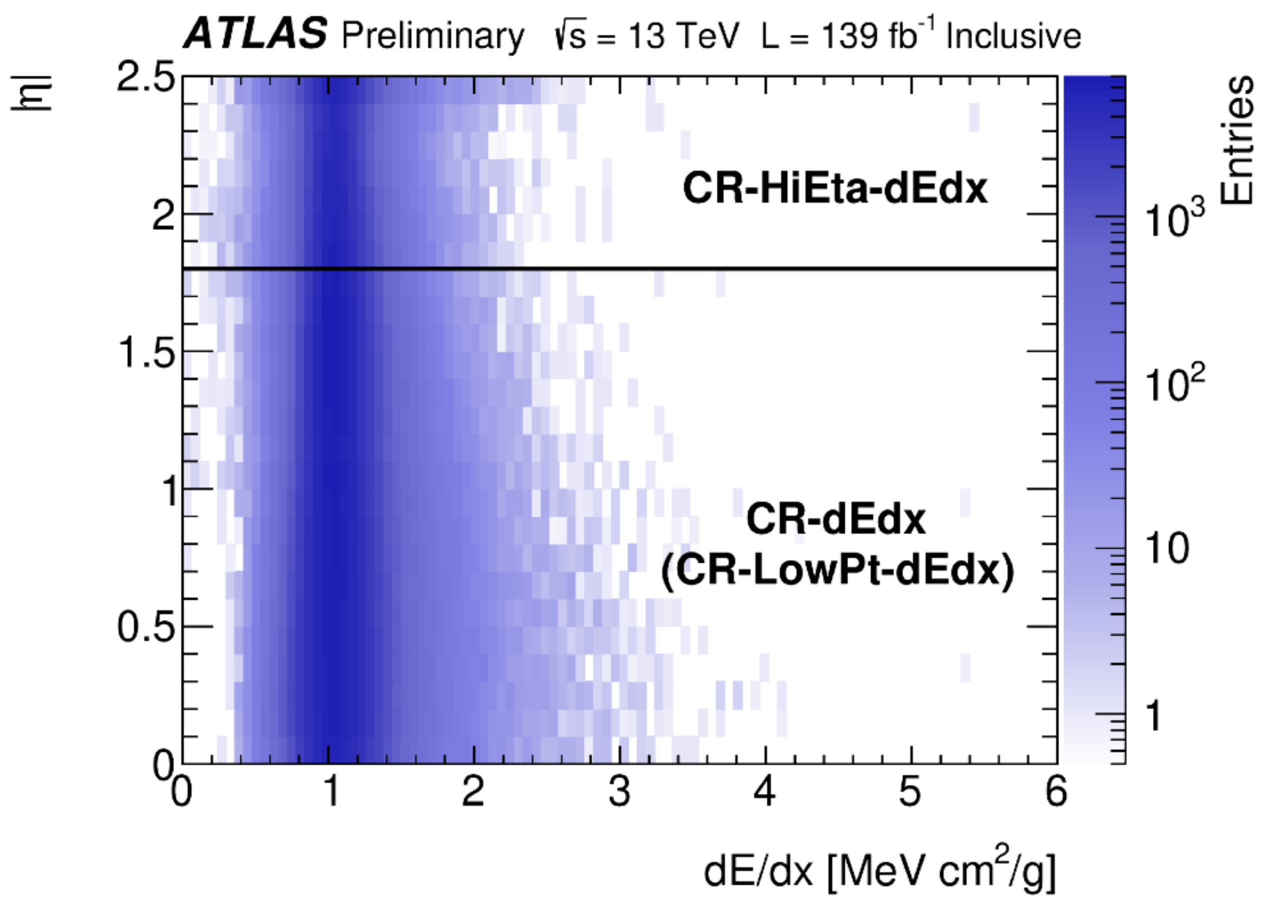
Background Estimation



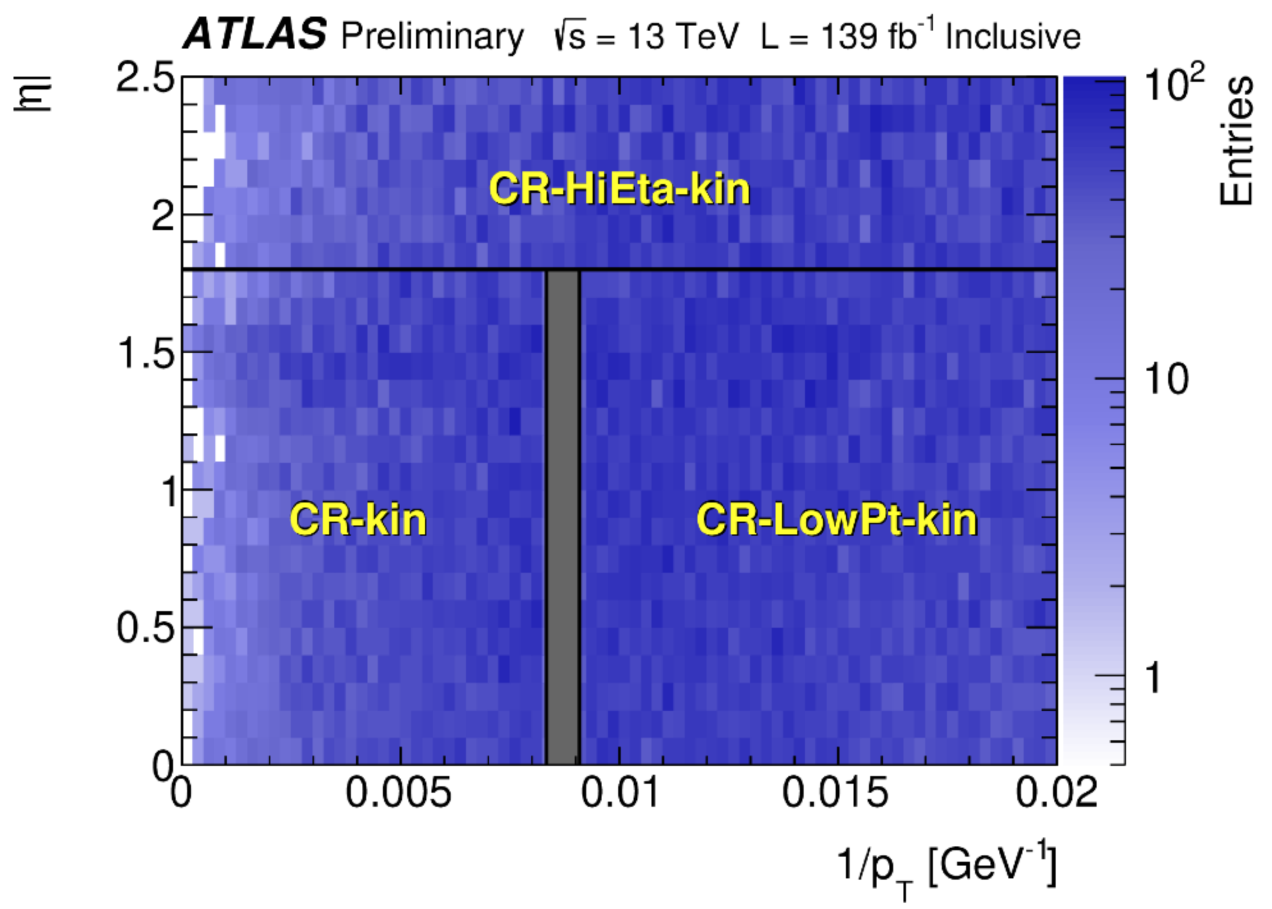
Basic assumption for data-driven estimation:
SM particles are ~MIP.
→ Kinematics and dE/dx response are independent.

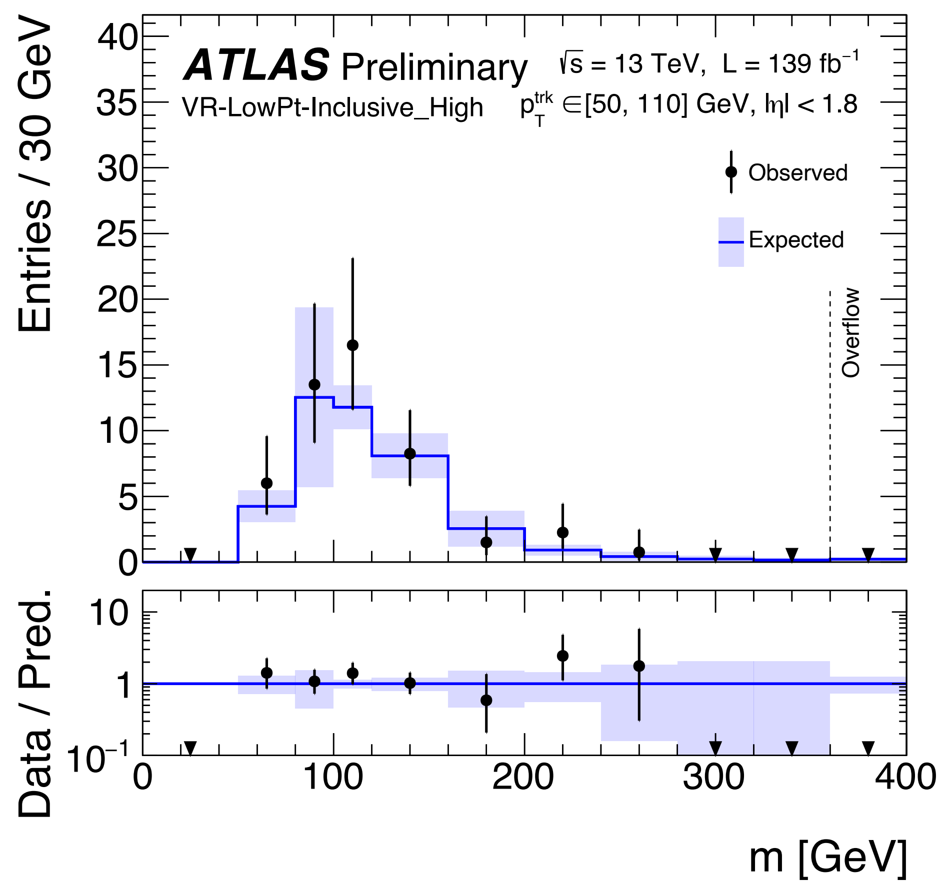
- (1) Random picking of (p_{T}, η) from the kinematic template.
- (2) Random picking of $\mathrm{d}E/\mathrm{d}x$ from the same η of the dE/dx template.
- (3) Construct mass and normalize events at $m < 160$ GeV.

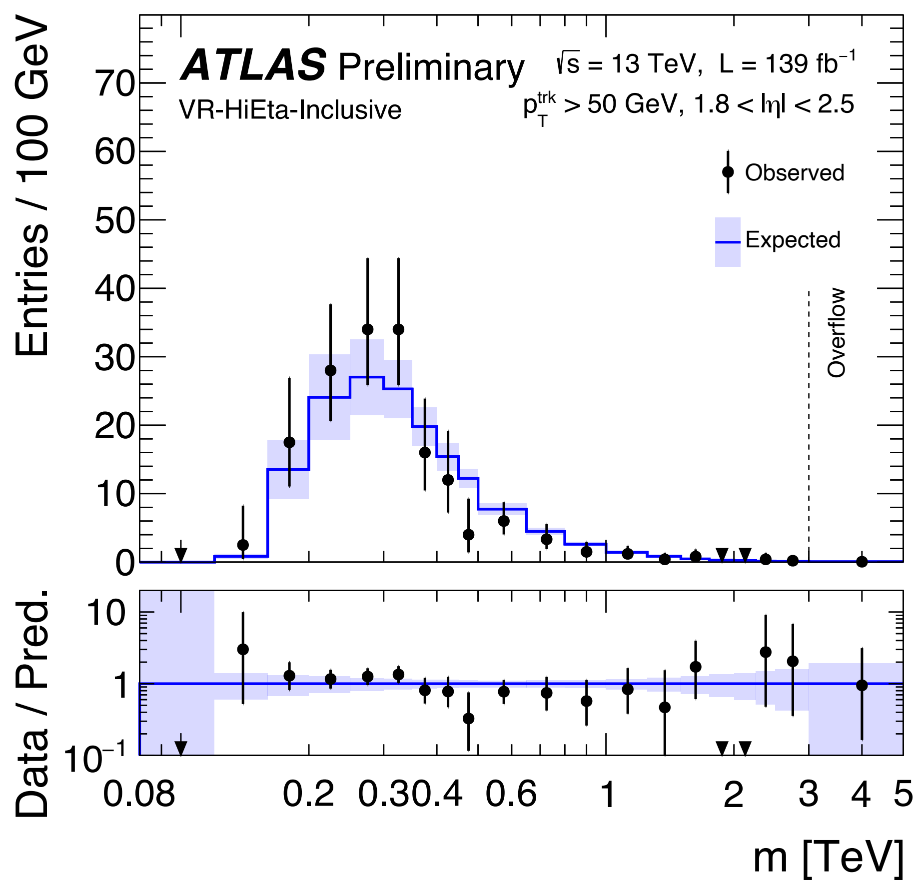
Extract dE/dx response



Extract Track Kinematic distr.

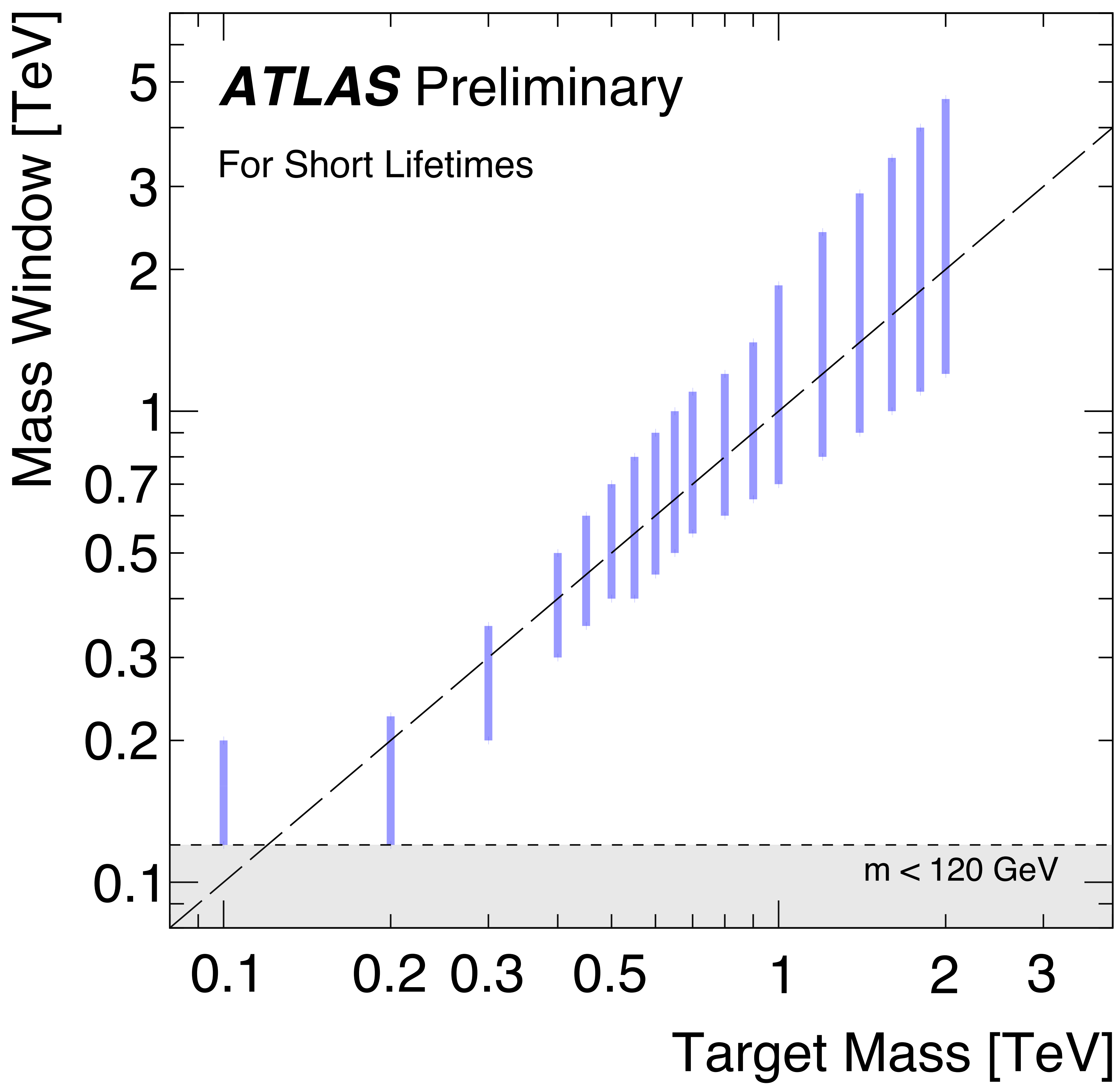


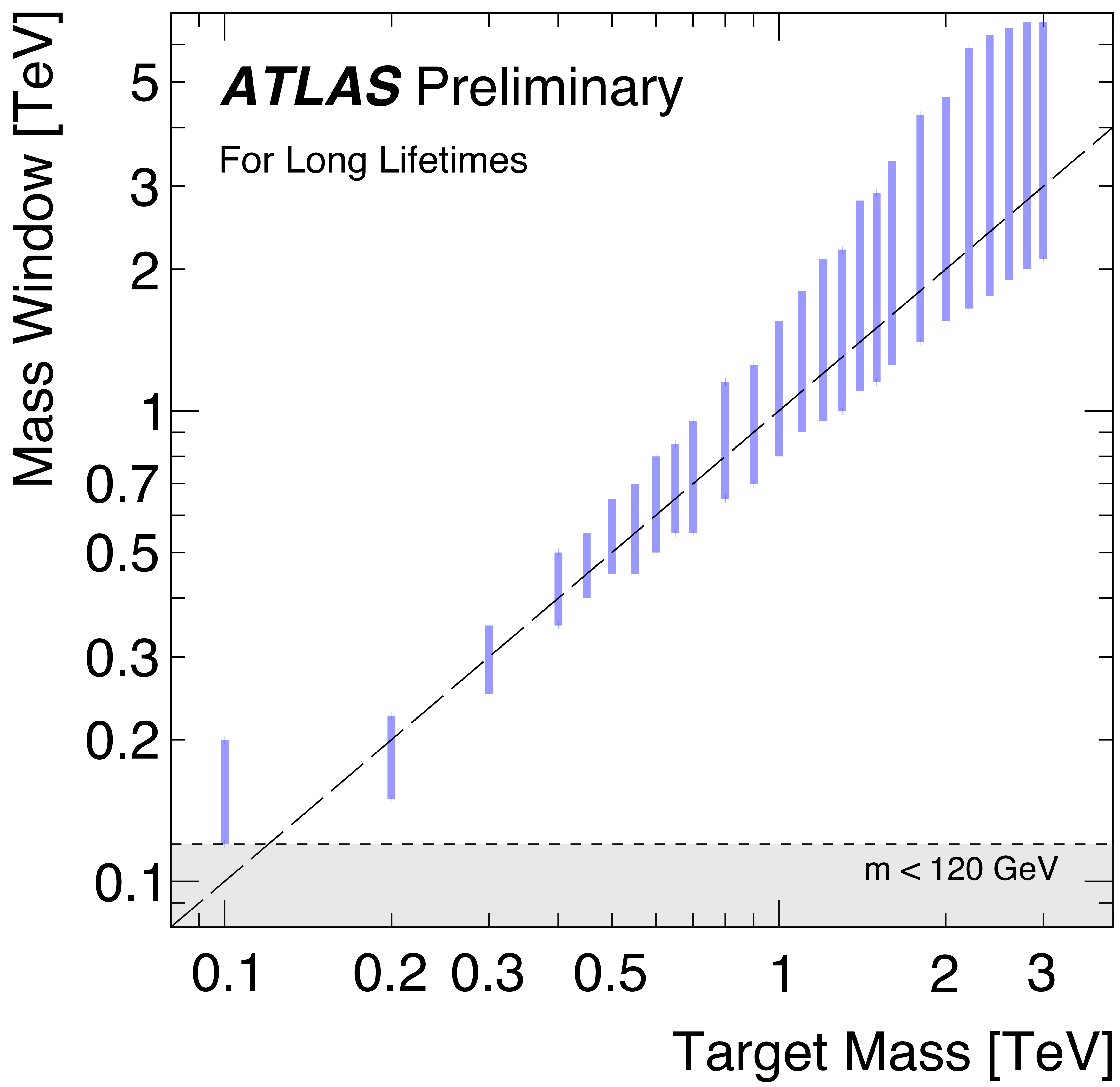




Good prediction closure in Low-p_{T} and High-$|\eta|$ VRs.

Mass Windows

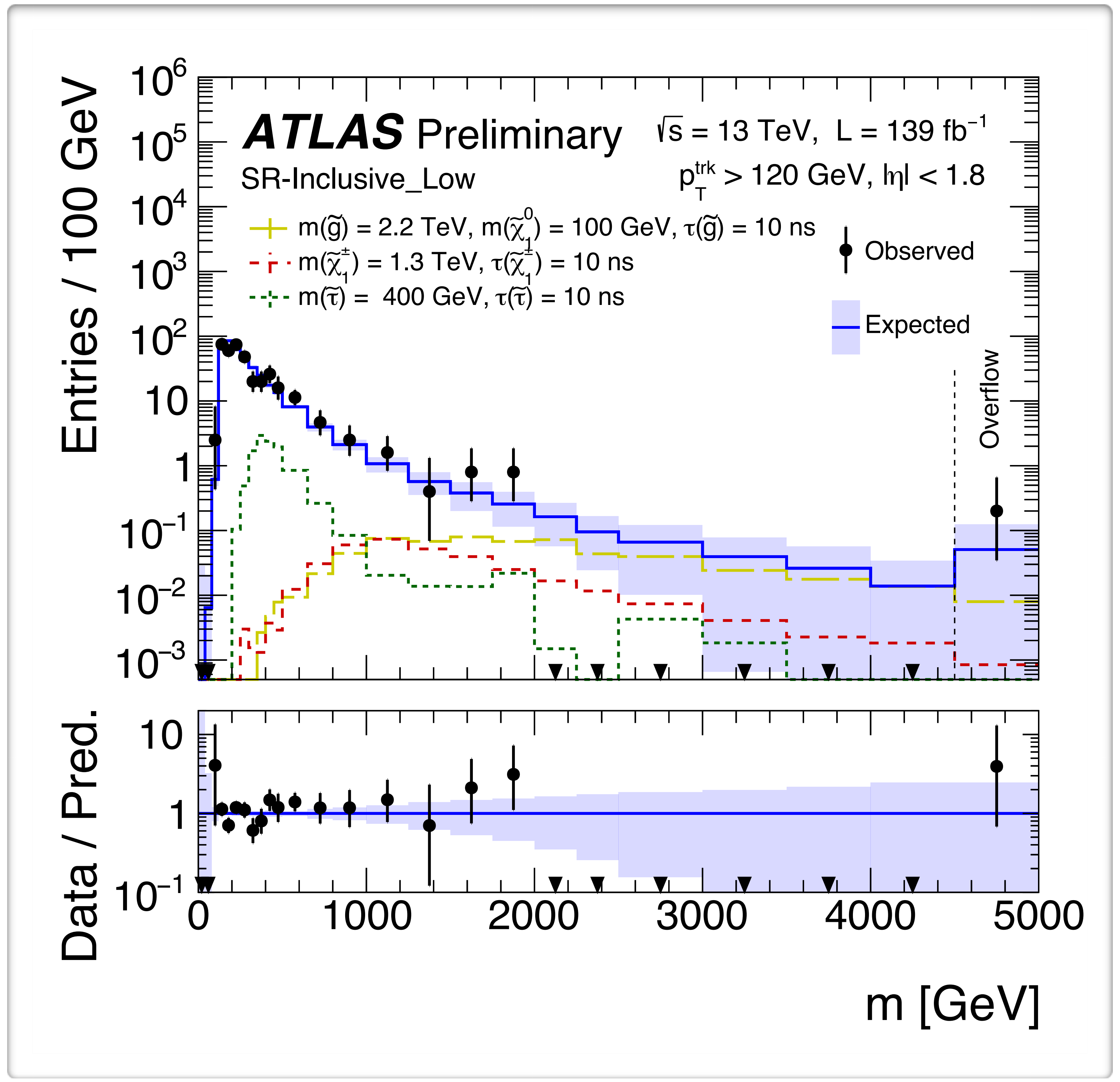




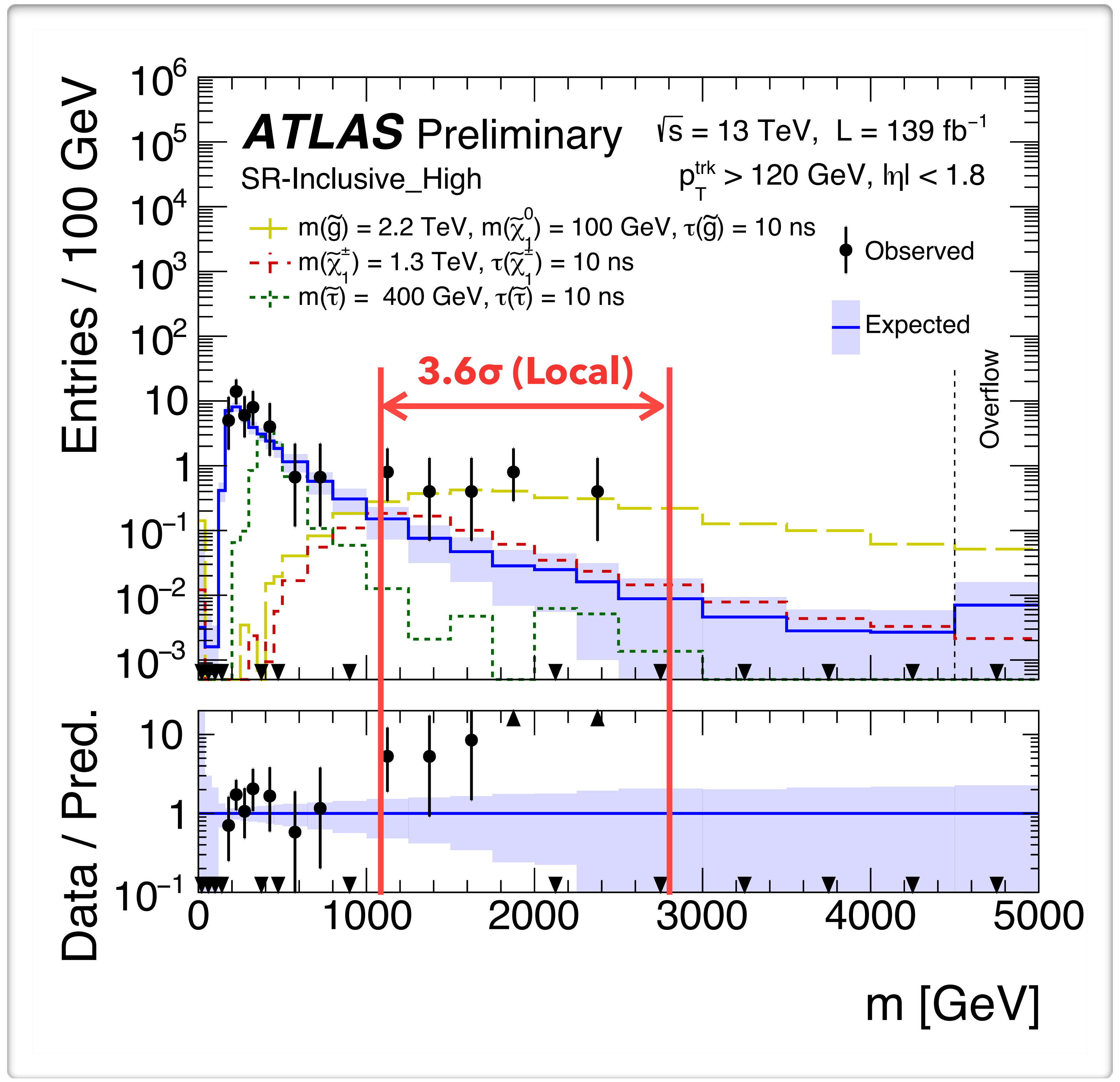
ATLAS-SUSY-2018-42, arXiv:2205.06013

Result

1.8 < dE/dx < 2.4



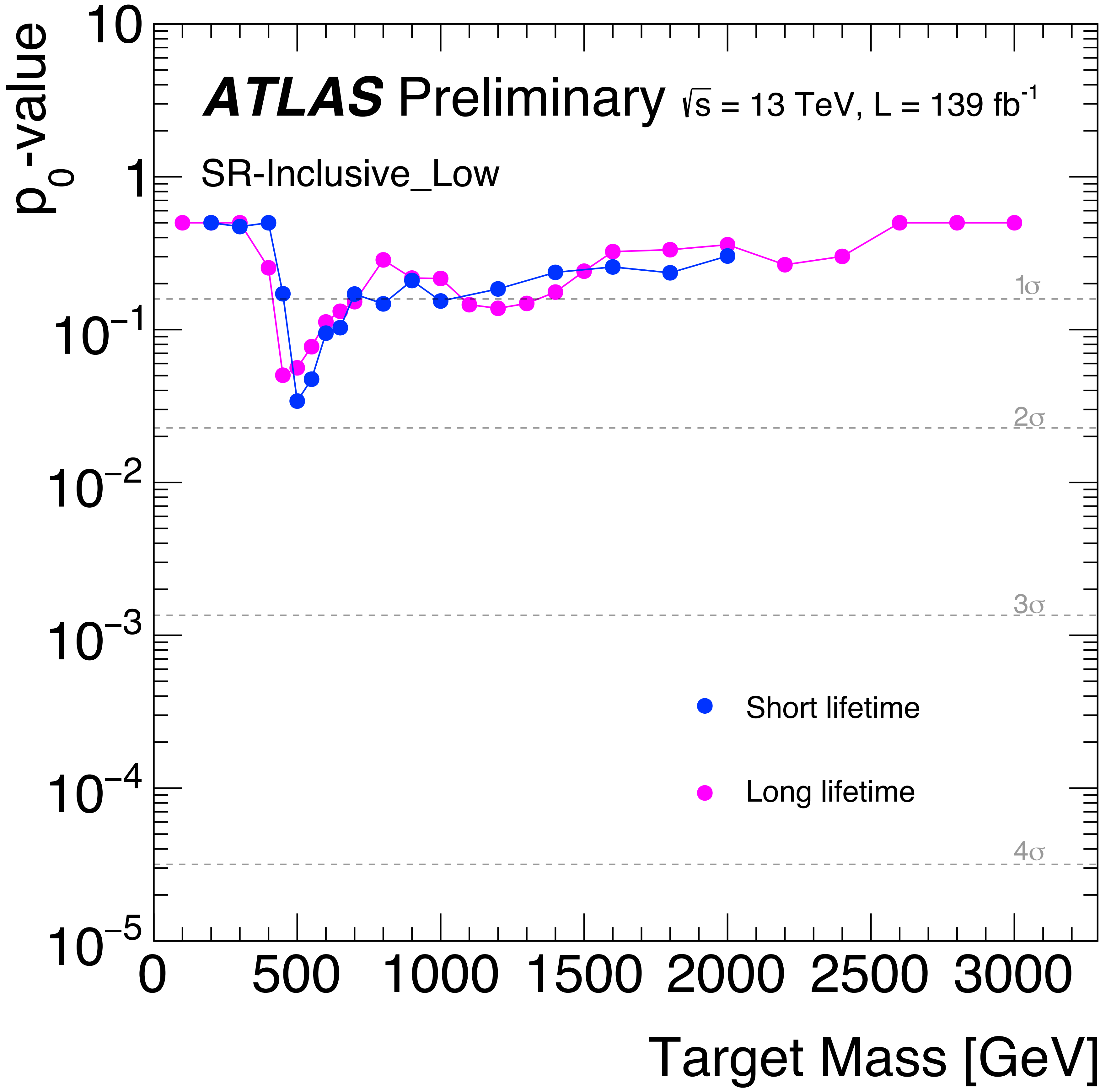
dE/dx > 2.4



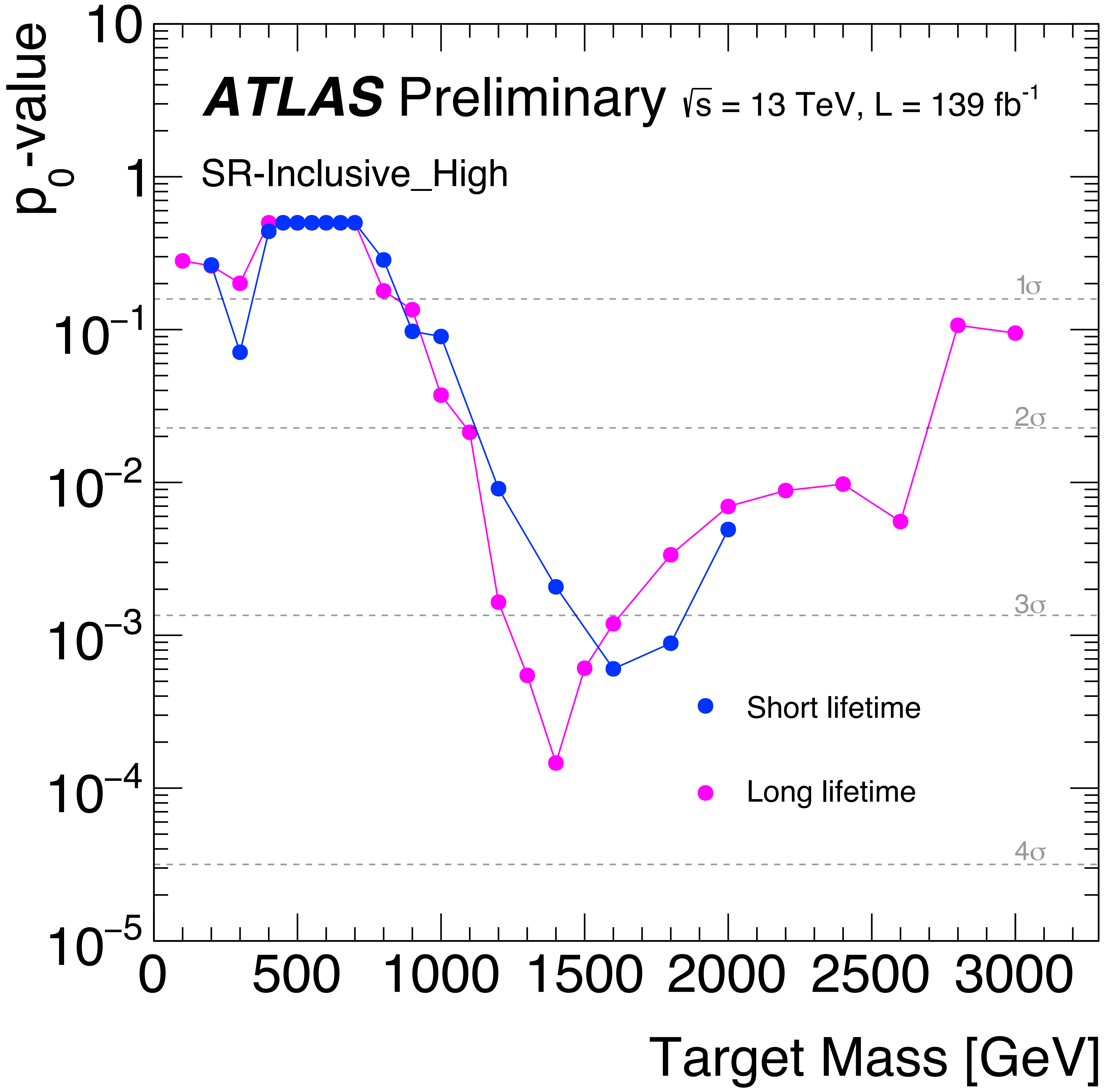
- For most of the SR, the observed data agrees well with the predicted background.
- No excess around $m \sim 600$ GeV.
- **Largest significance of 3.6σ** is observed for a pre-defined mass window [1.1, 2.8] TeV in high-dE/dx SR. Global significance: 3.3σ.
- **No instrumental pathologies** were found in the observed tracks and individual pixel cluster shapes.
- **Crosscheck of momentum** reconstruction between ID and MS for muon candidate tracks.

p_0-value

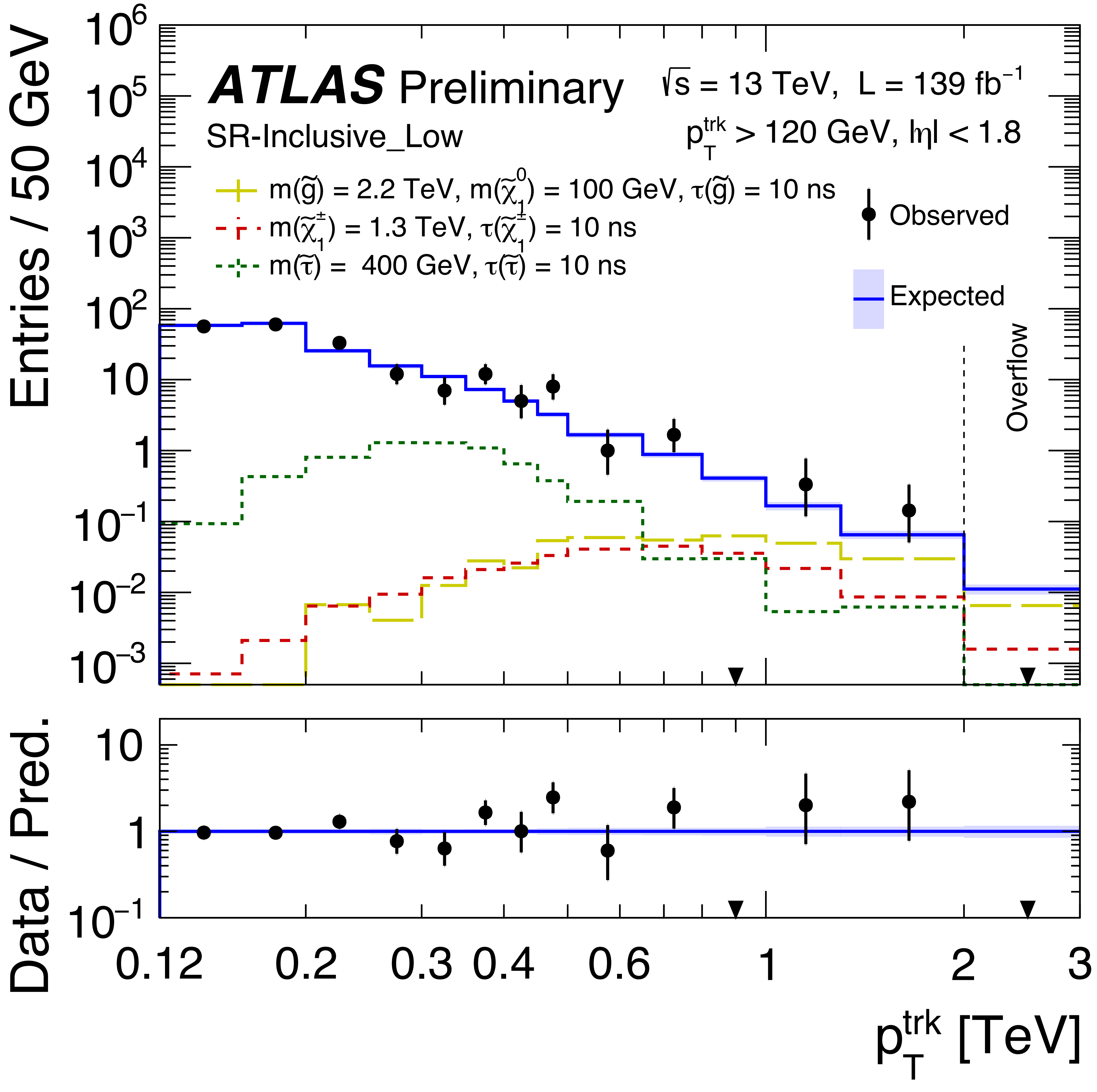
1.8 < dE/dx < 2.4

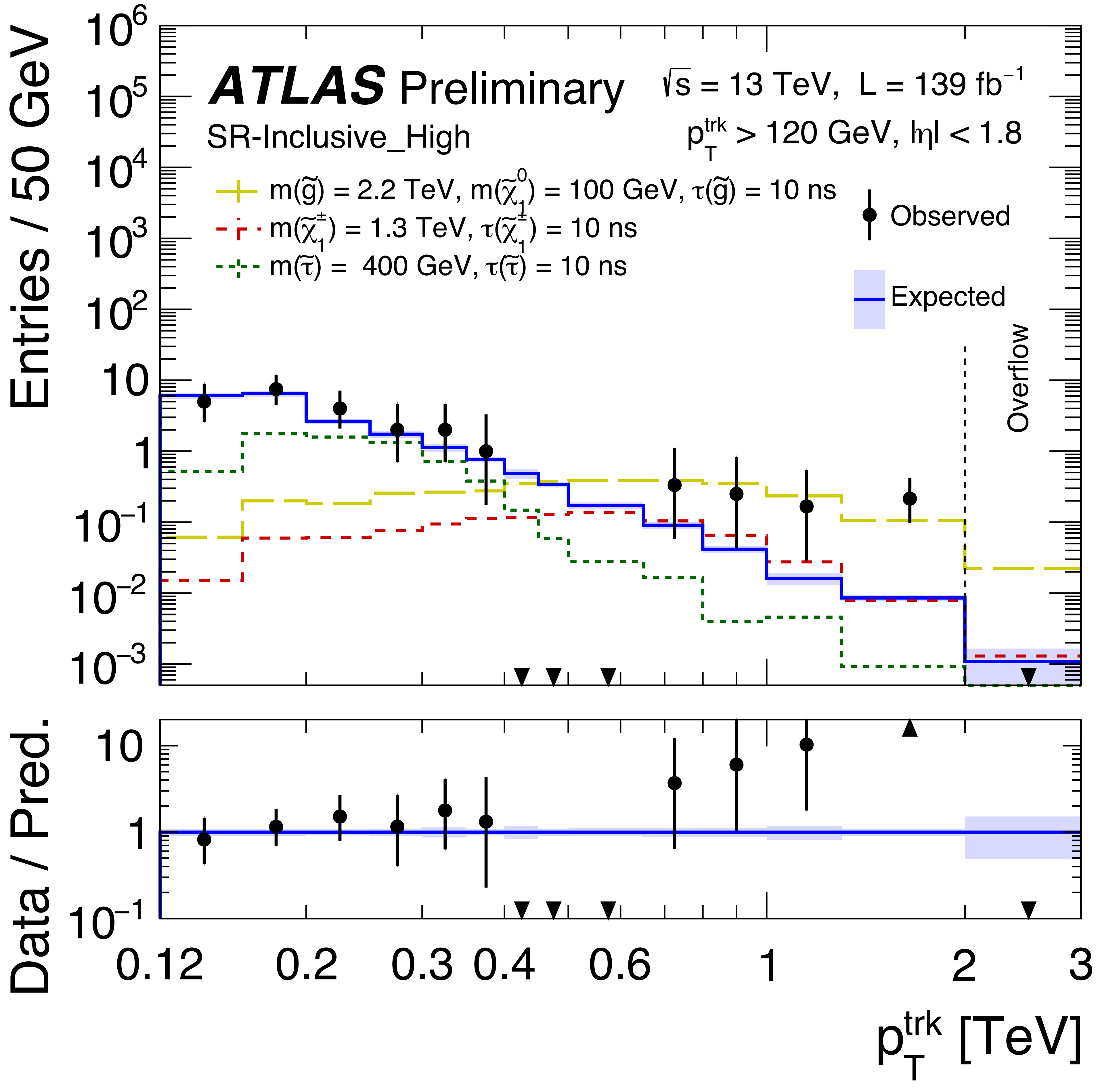


dE/dx > 2.4

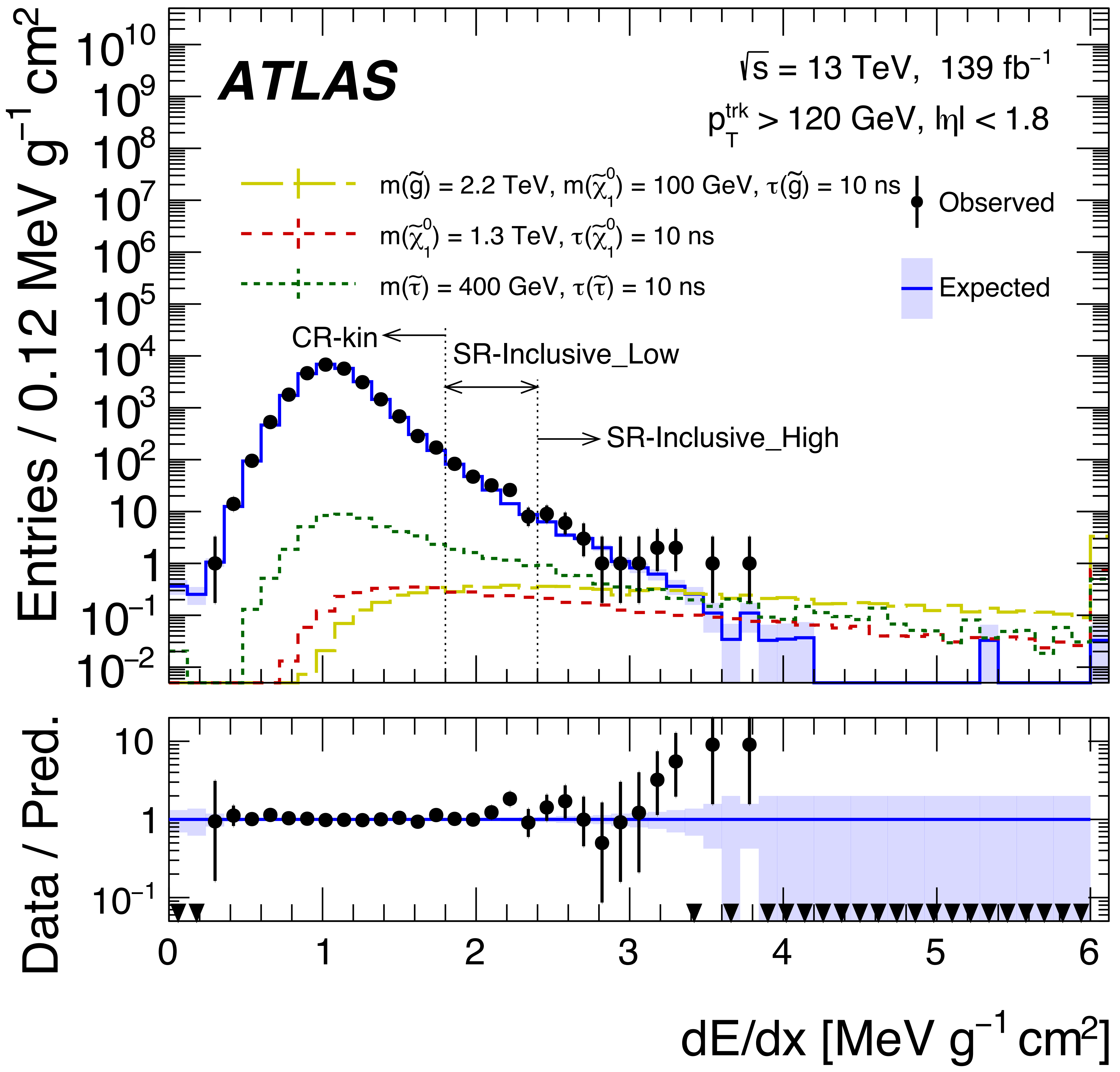


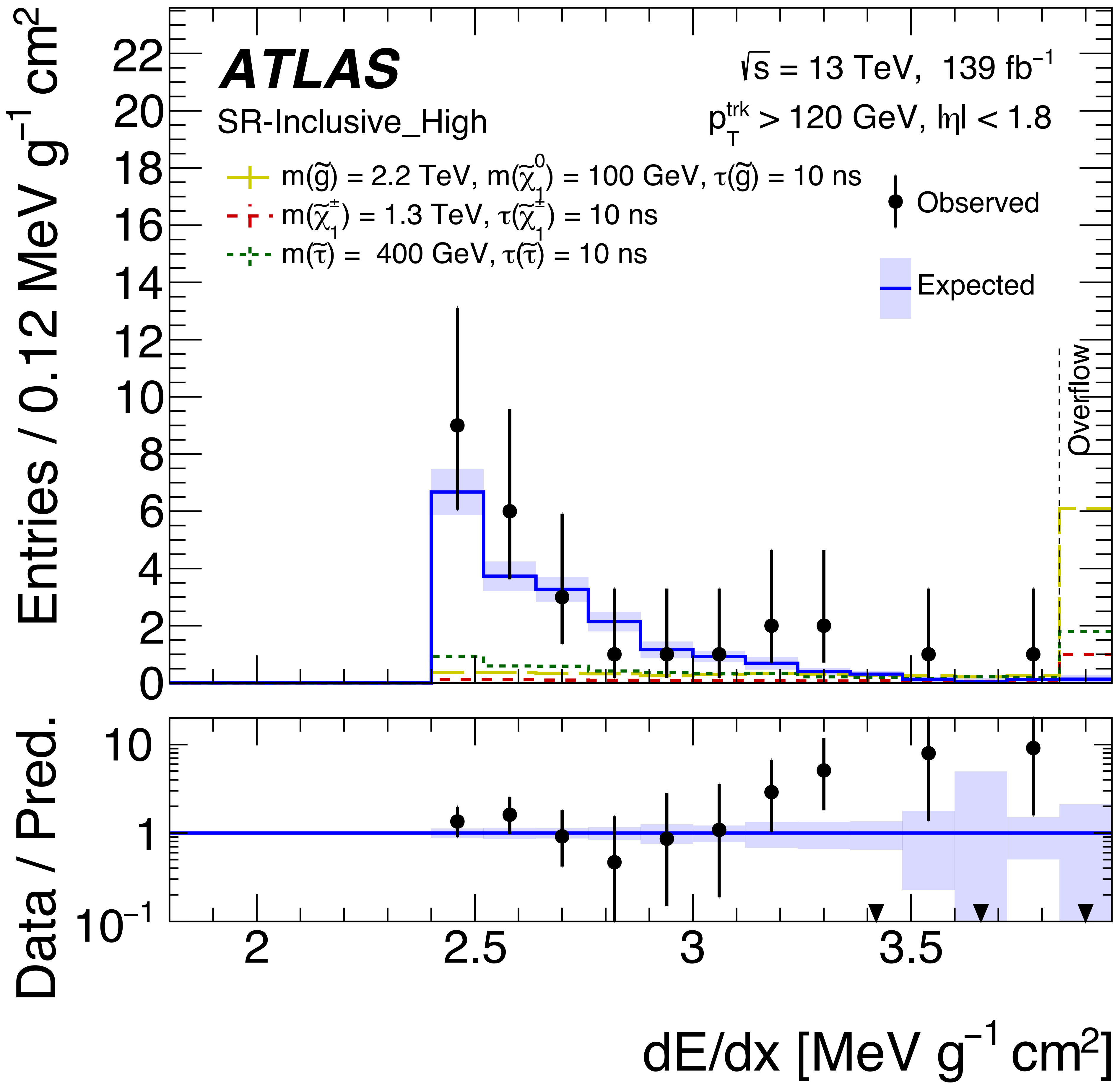
Signal Region Events





Signal Region Events



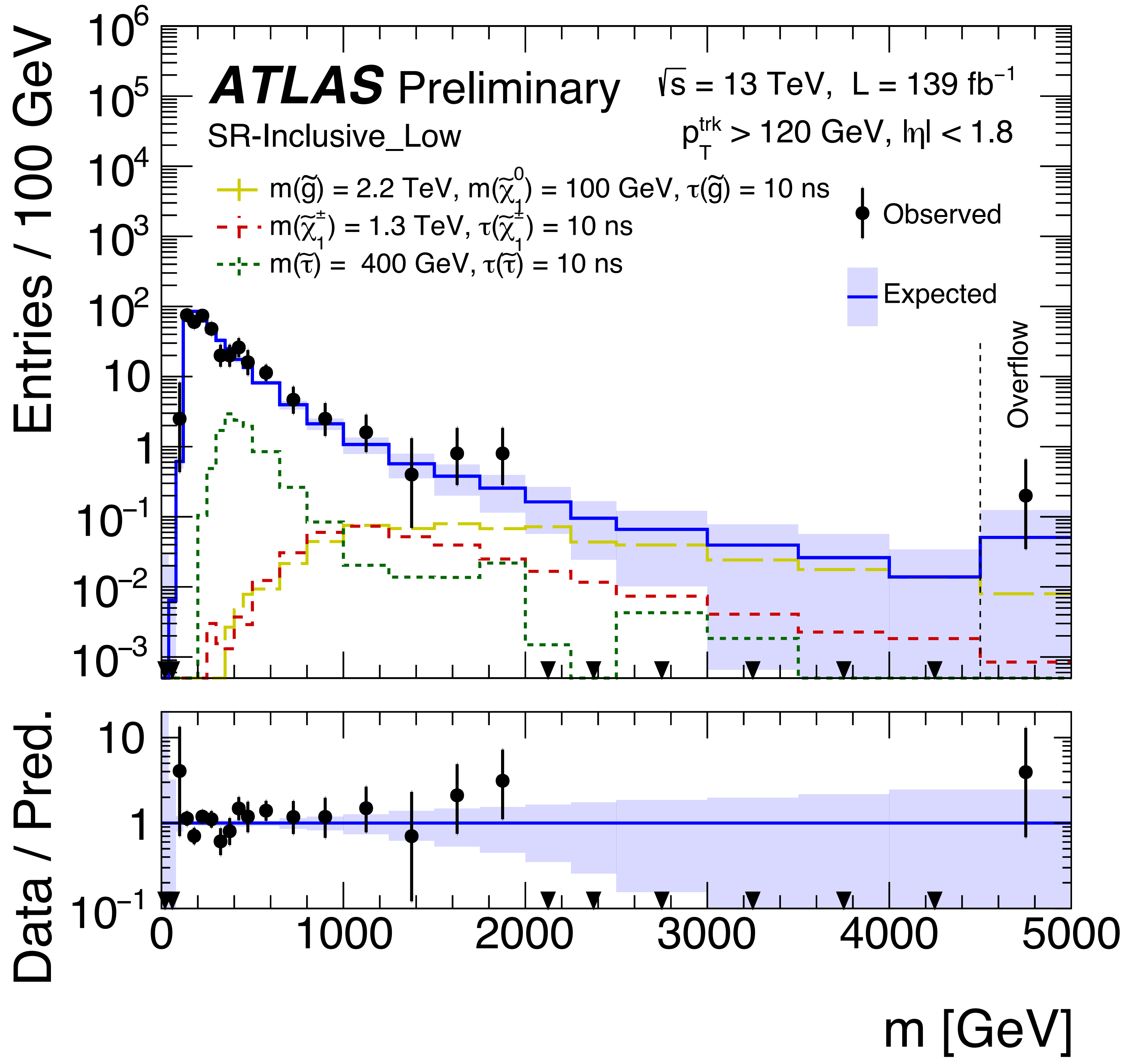


Timing variable crosscheck

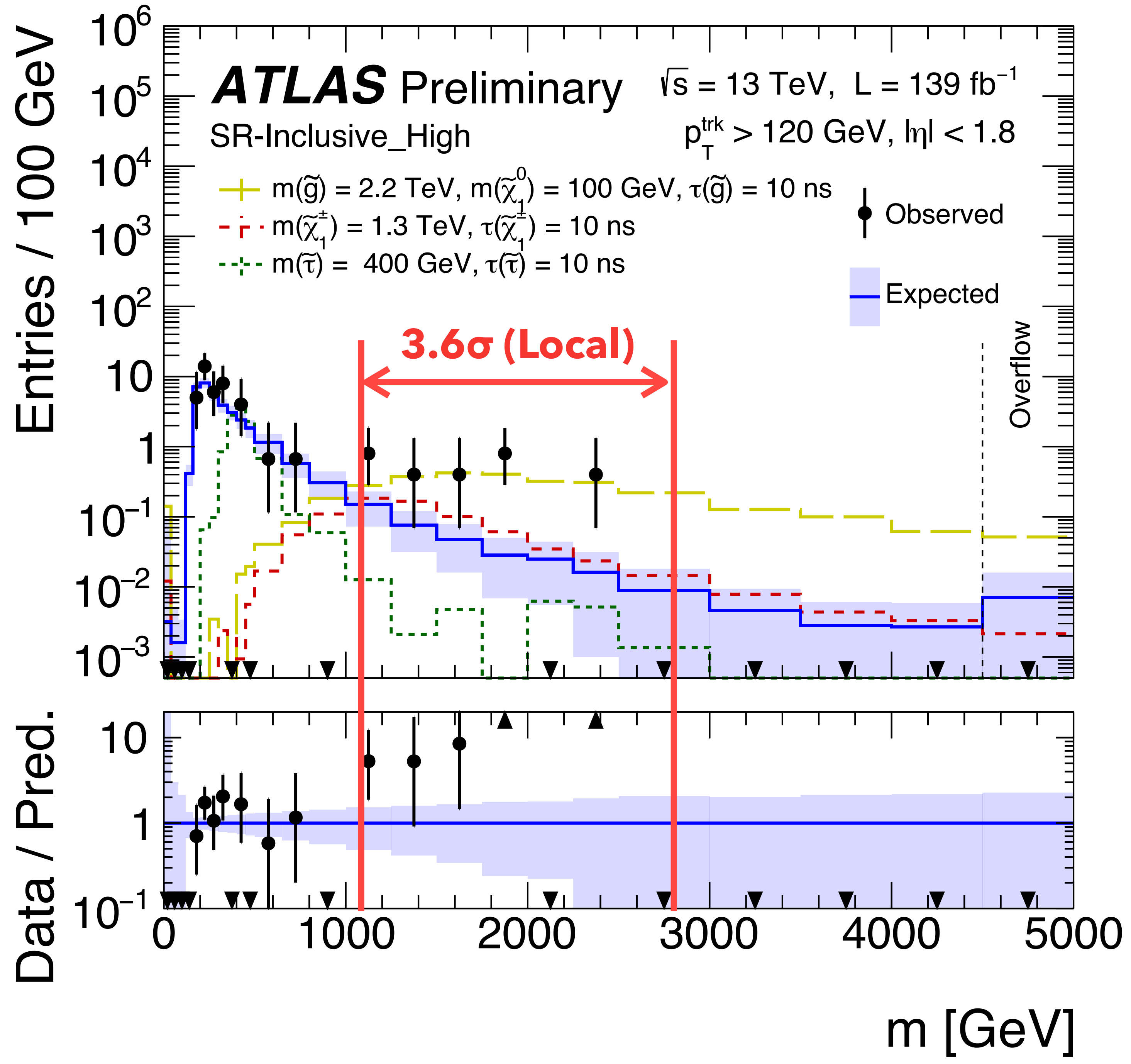
- Two β values were examined:
  - β_{MS}: measured by the muon spectrometer by slow-muon reconstruction
  - β_{calo}: obtained from calorimeter cell hits associated with the candidate track by taking the average ToF weighted by the timing resolution of the cells
- The probability distributions of these two β variables for the $\beta = 1$ SM particles are modelled from the CR-kin dataset.
- Both β probability distributions exhibit non-Gaussianity with approximately symmetric side-lobes.
- Resolution (FWHM/2.35):
  0.045 for β_{MS}, 0.075 (0.050) for β_{calo} in CR-kin-Mu (CR-kin-Trk) samples.

Result – Conclusion

1.8 < dE/dx < 2.4

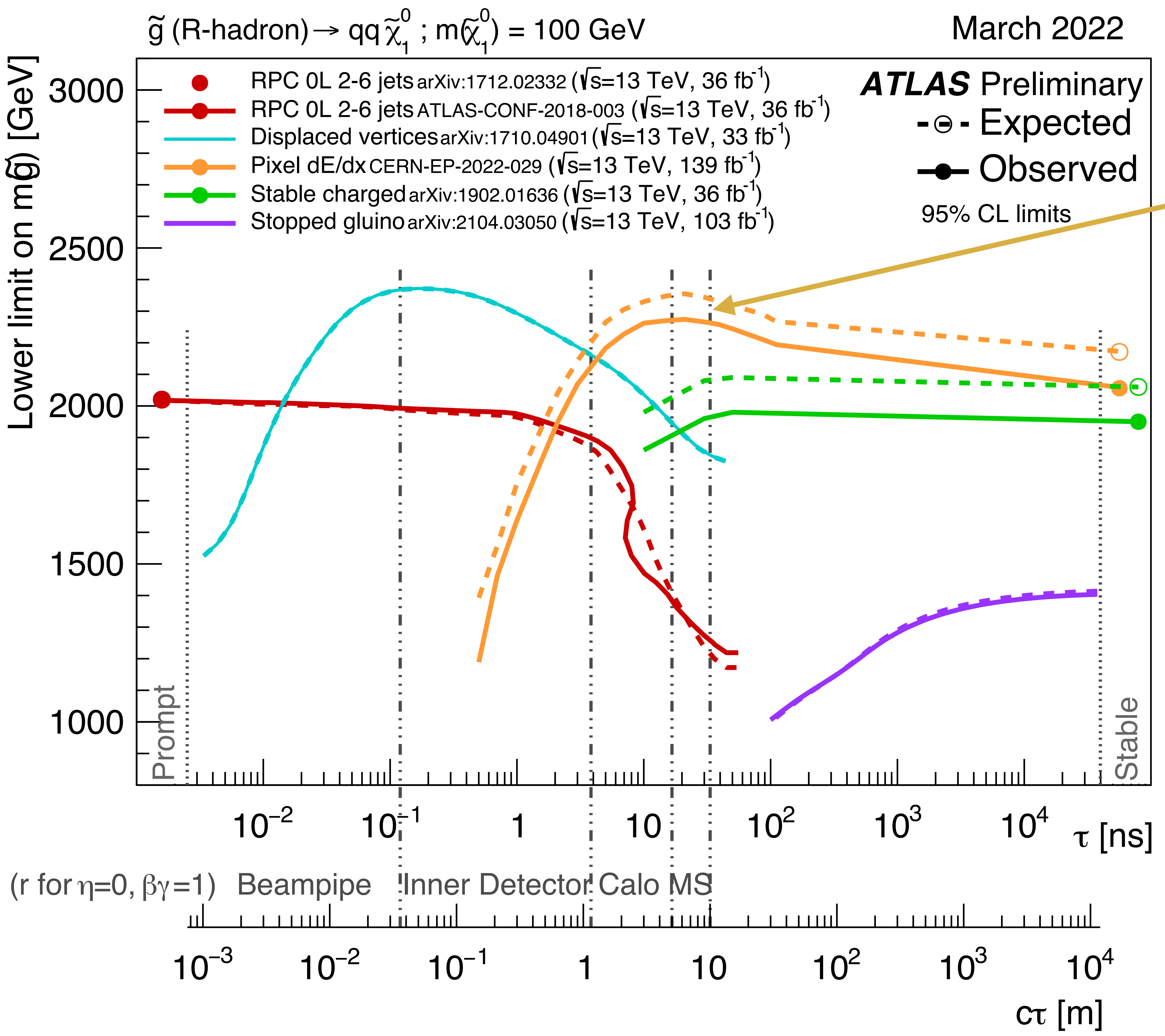


dE/dx > 2.4

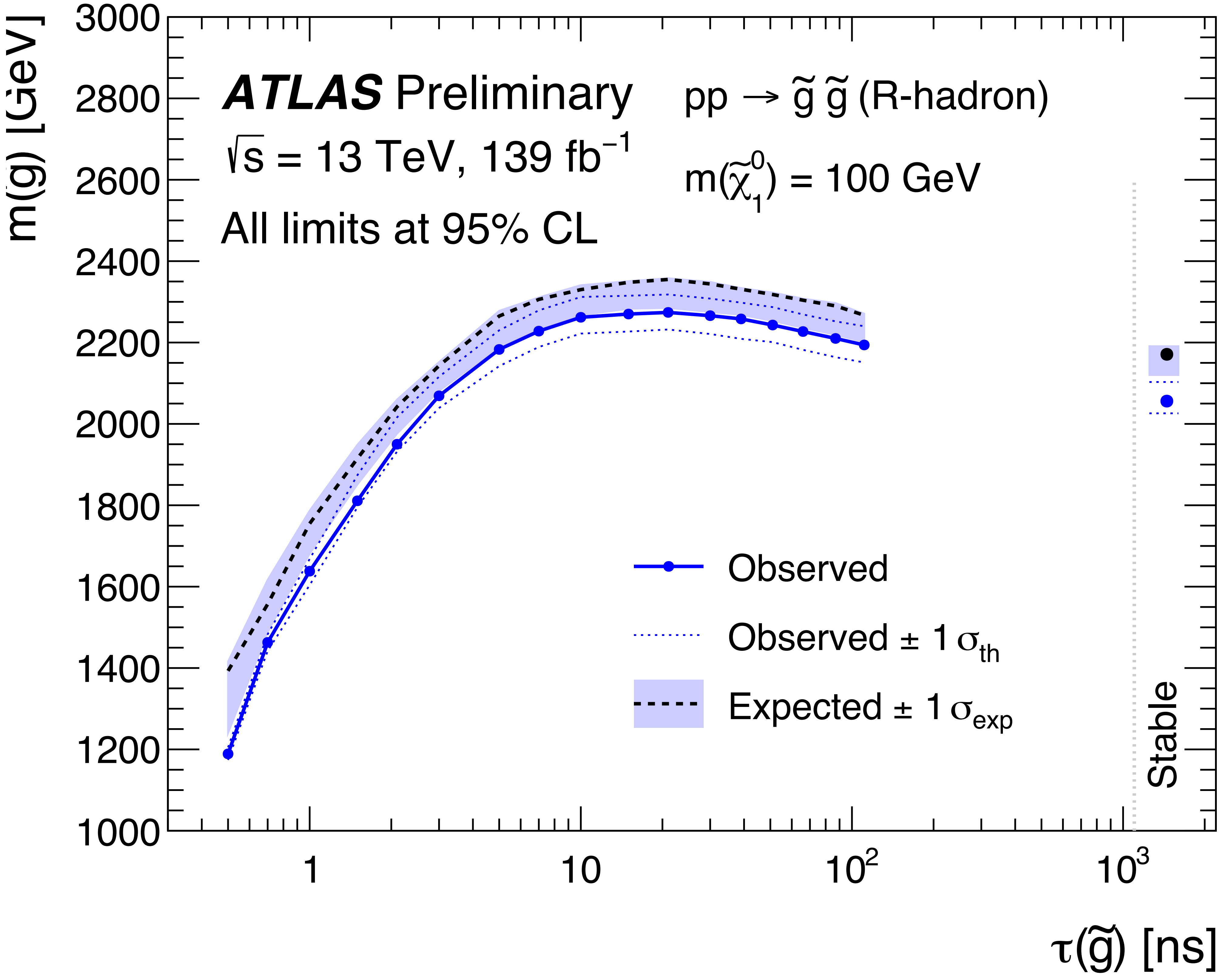


- All of excess events candidate tracks were observed to be **well consistent** with $\beta = 1$ within the data-driven timing resolution.
- The excess events are concluded **not compatible** with the benchmark signal models considered in this search.

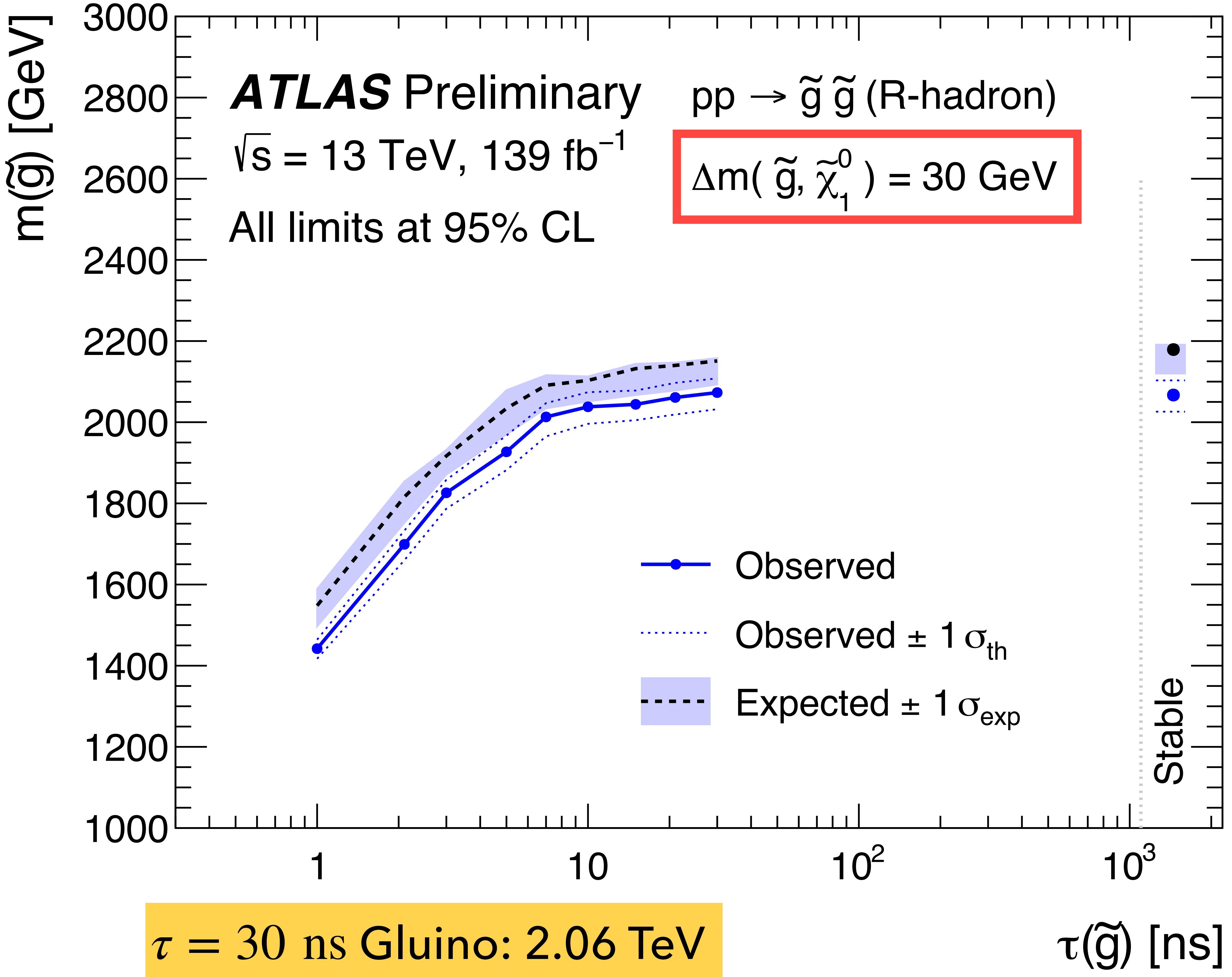
Limits



$\tau = 20$ ns Gluino: 2.27 TeV
($\tilde{\chi}_1^0$ mass = 100 GeV)

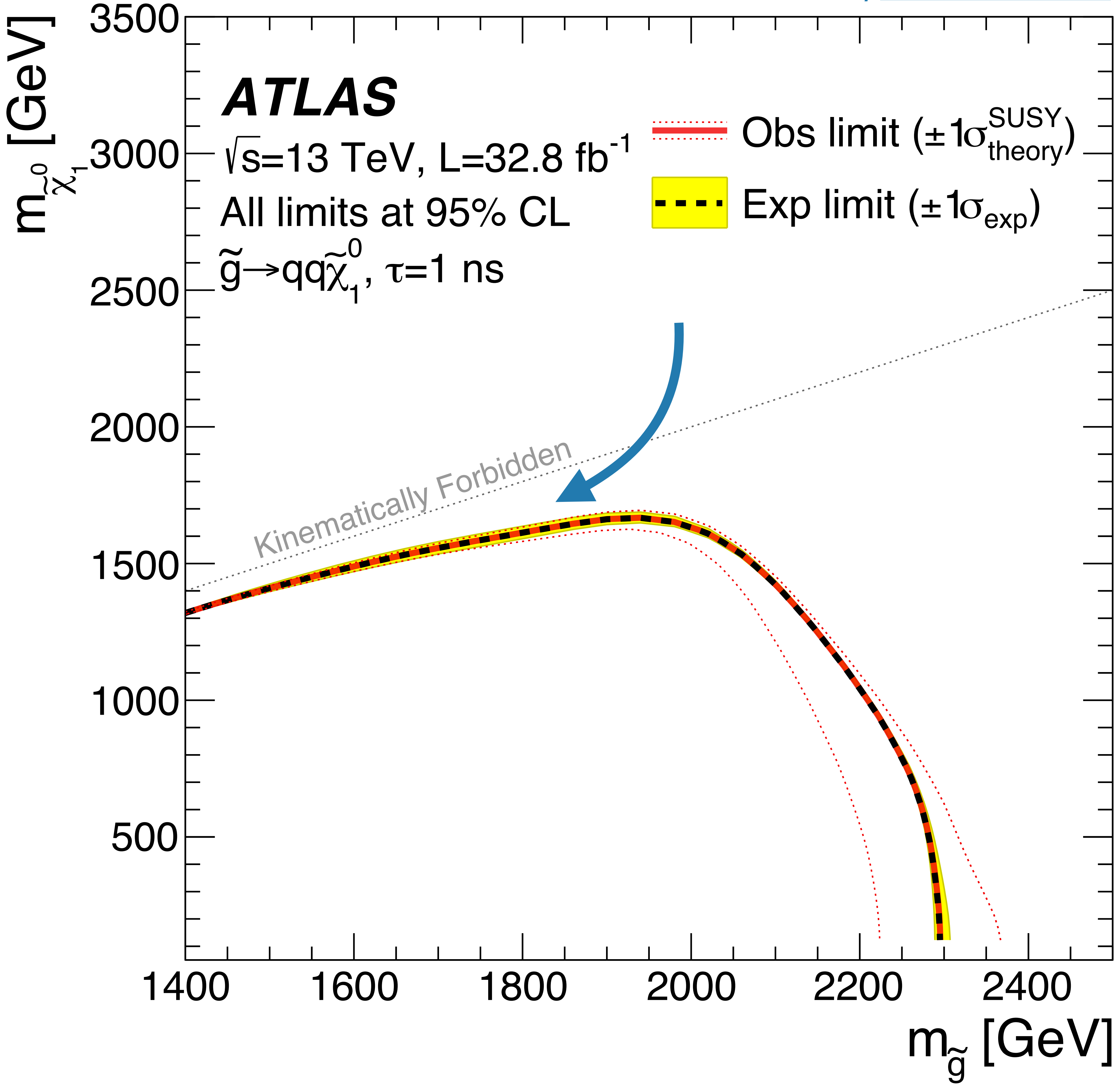


Limits



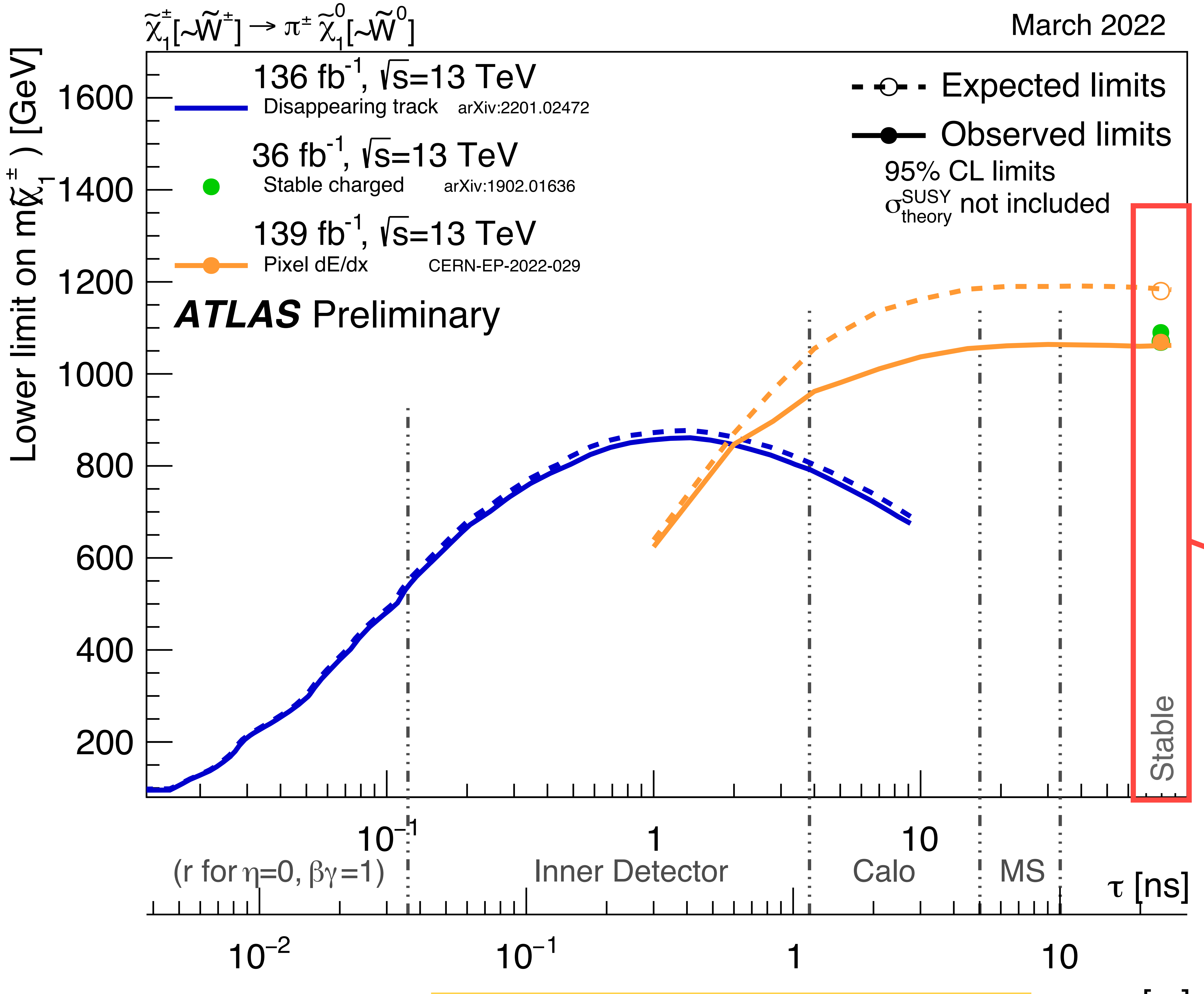
$\tau = 30$ ns Gluino: 2.06 TeV
($\Delta m(\tilde{g}, \tilde{\chi}^0_1) = 30$ GeV)

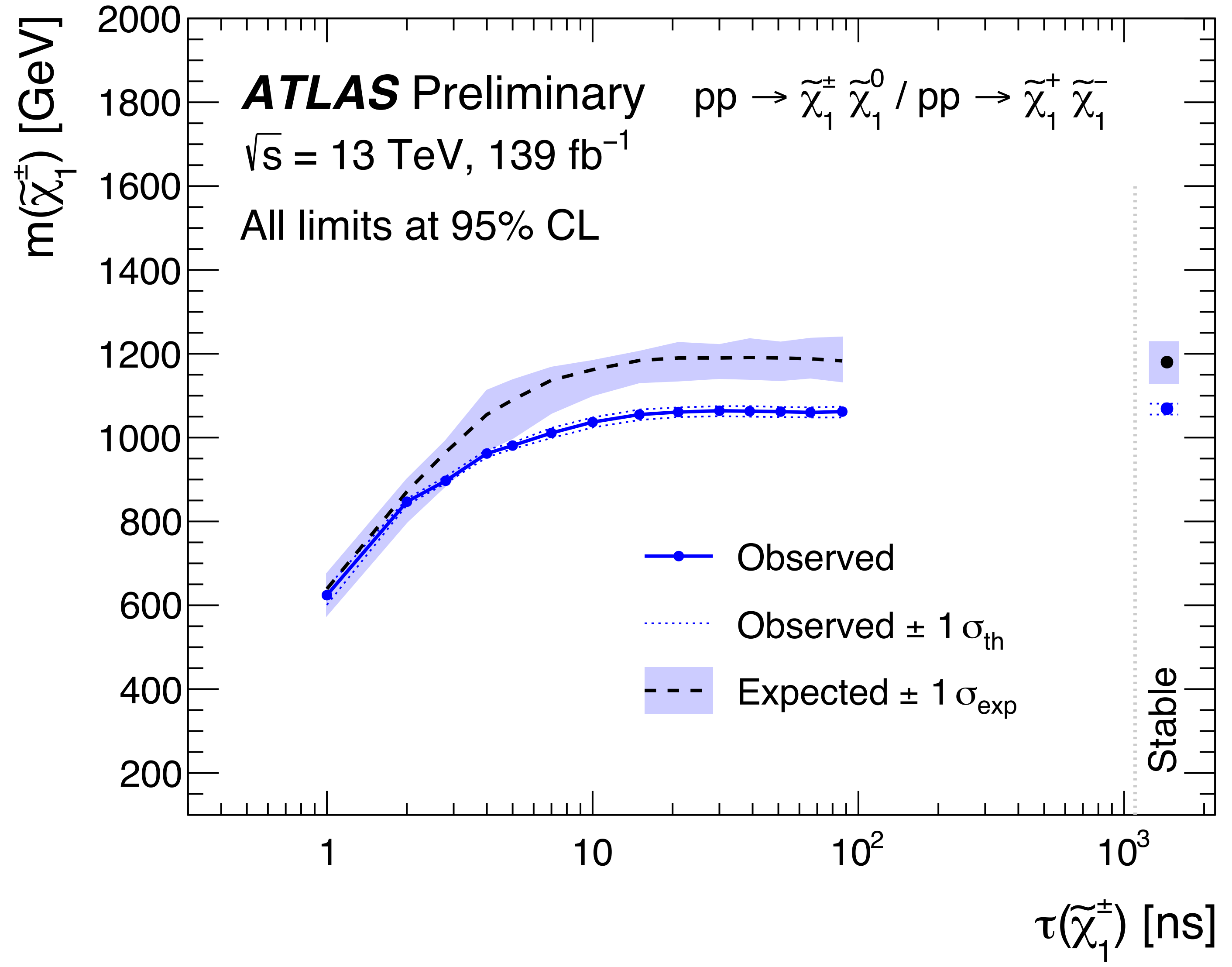
Last DV+MET search result, SUSY-2016-08

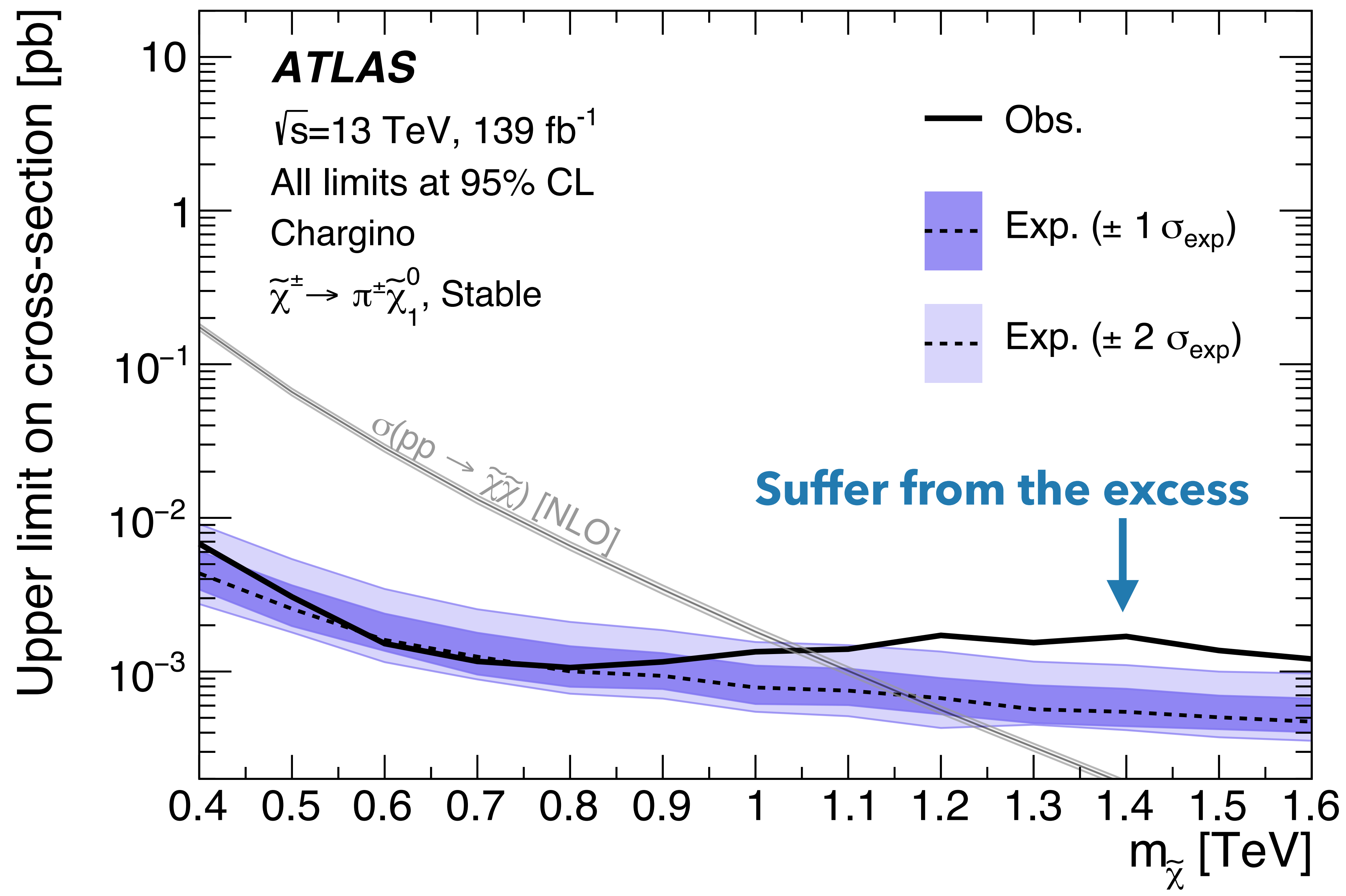


Powerful and complementary access to the compressed R-hadron regime!

Limits

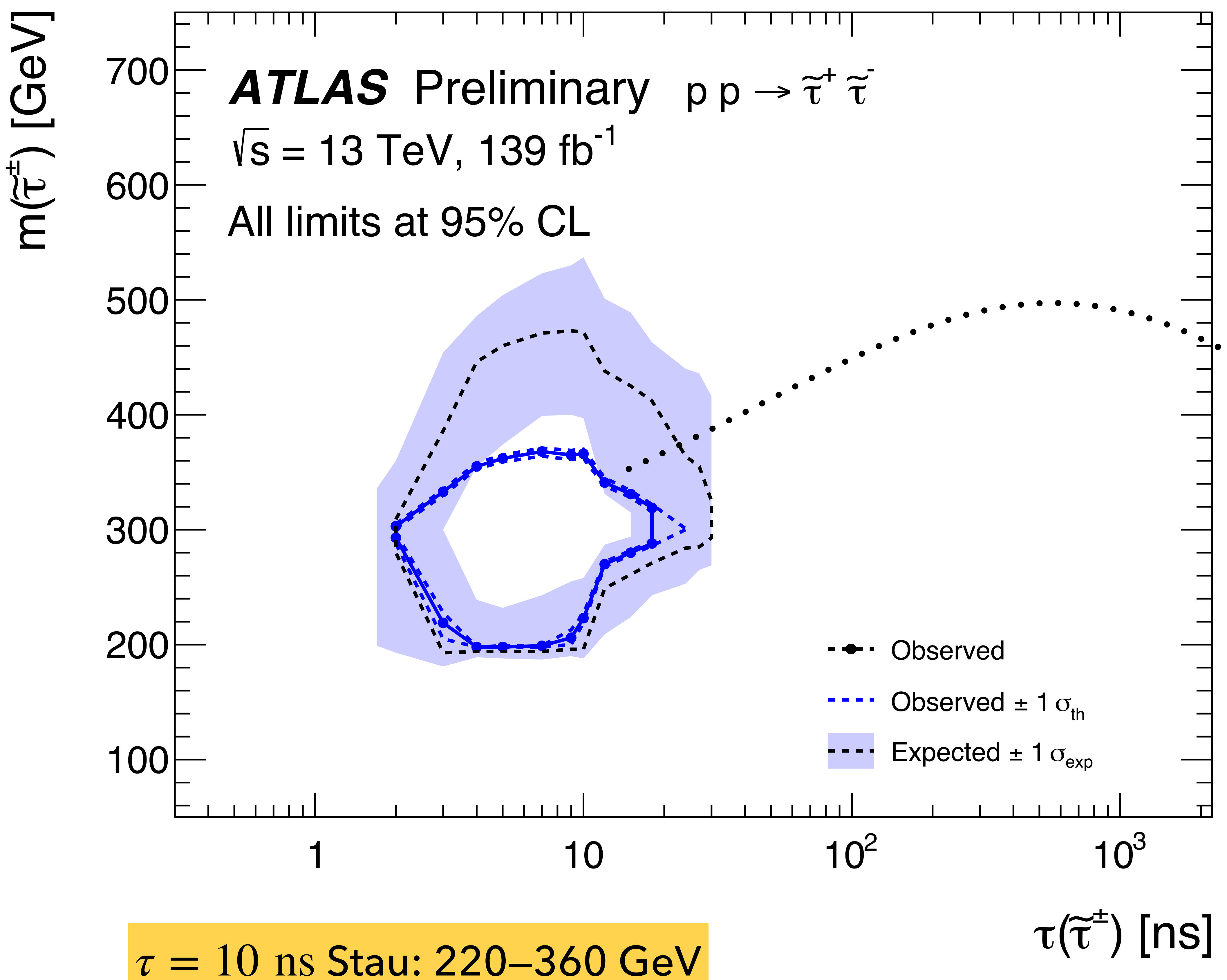




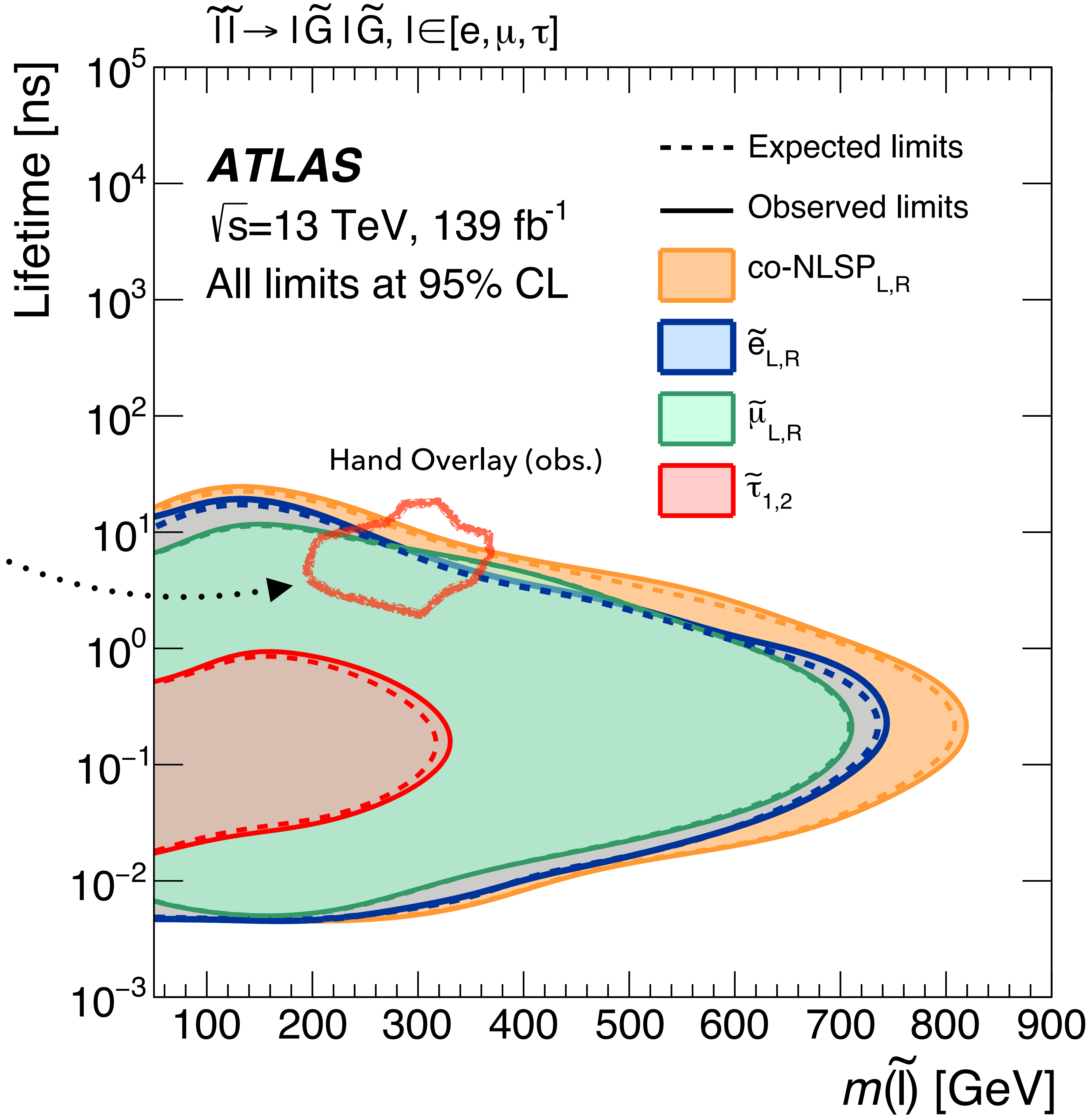


$\tau = 30$ ns Chargino (Wino): 1.07 TeV

Limits



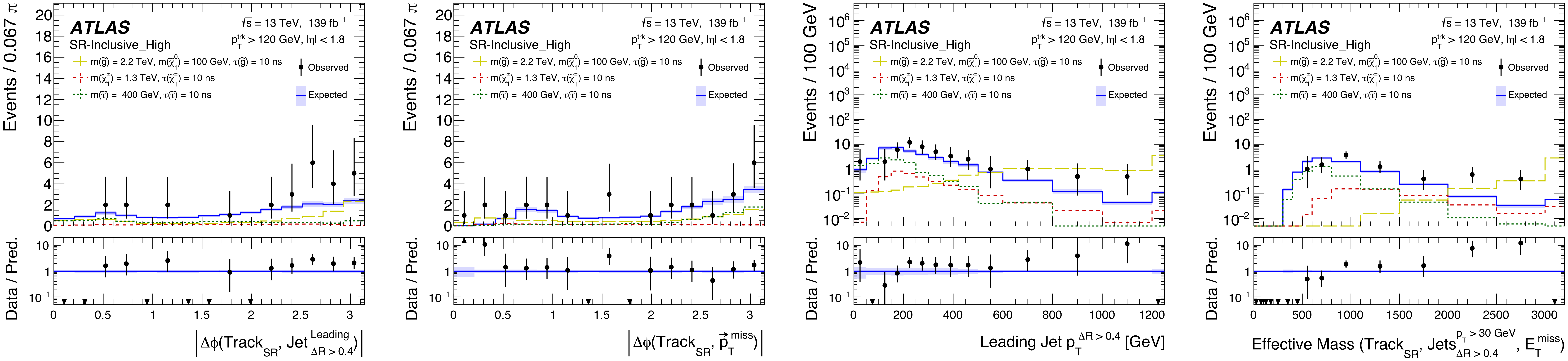
$\tau = 10$ ns Stau: 220–360 GeV



Complementary to disp.leptons search

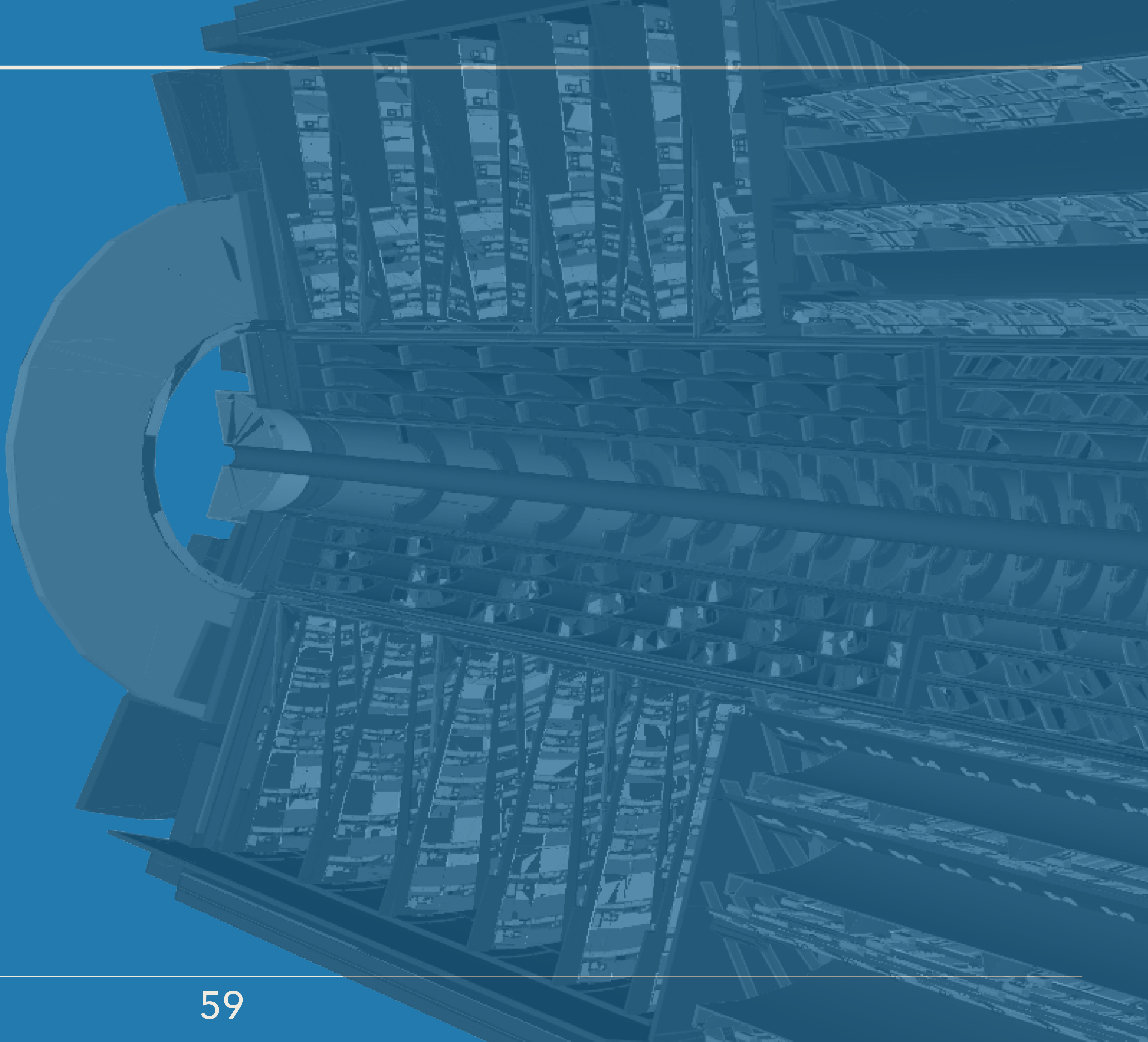
Next steps

- It's ATLAS homework to followup in Run3 with further understanding of dE/dx.
- Wish to see CMS update (has not been released since 3.2 fb^{-1})
- Multi-charged particles search in ATLAS scoping $z = 2$ and $3 \leq z \leq 7$ has just released for LHCP2022 (CONF avaialble in few days).



For your sake, we also provide various distributions of event kinematics/topology of the SR events apart from the SR track inforamtion.

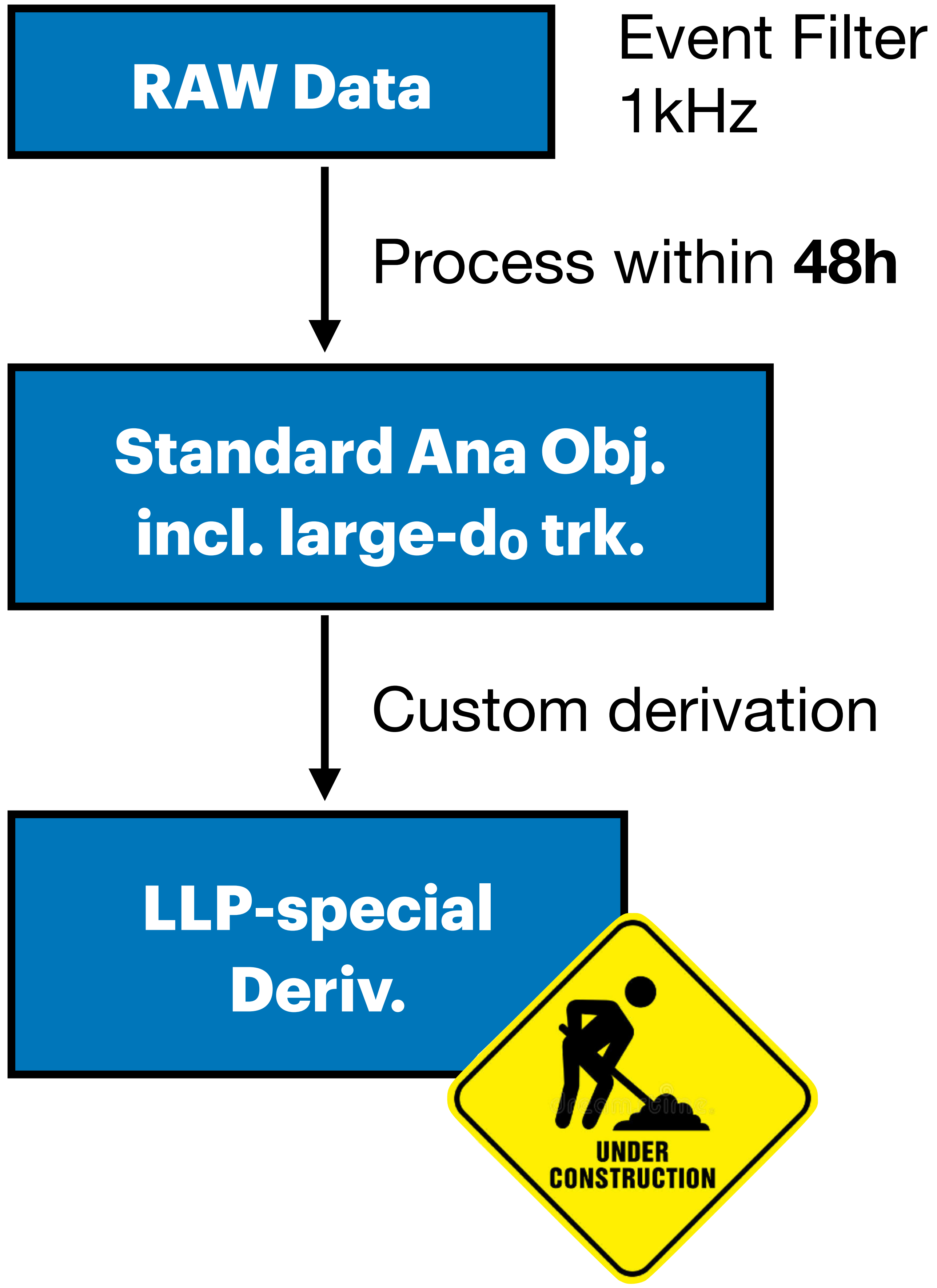
Looking ahead



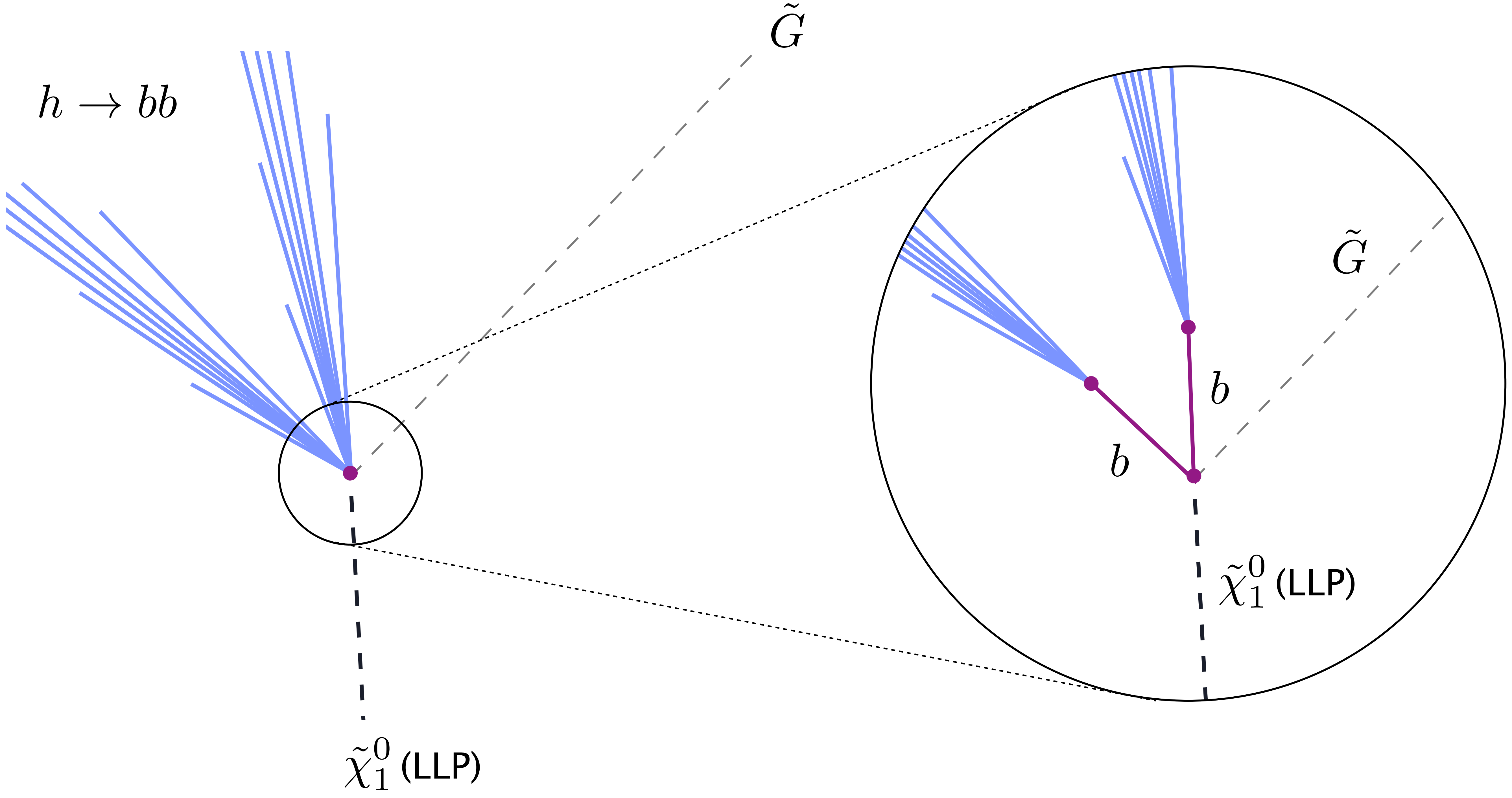
Run3 ATLAS Tracking and Reconstruction

- Big gain: large-d_0 track reconstruction runs in the standard reconstruction, with much improved fake rejection algorithm.
- However, the common standard data-reduction scheme in Run3 skims out informations needed for LLP analyses.
- The same new data model was applied to the entire Run2 dataset, enabling smooth combination of Run2+Run3.

ATLAS Run3 Data Flow

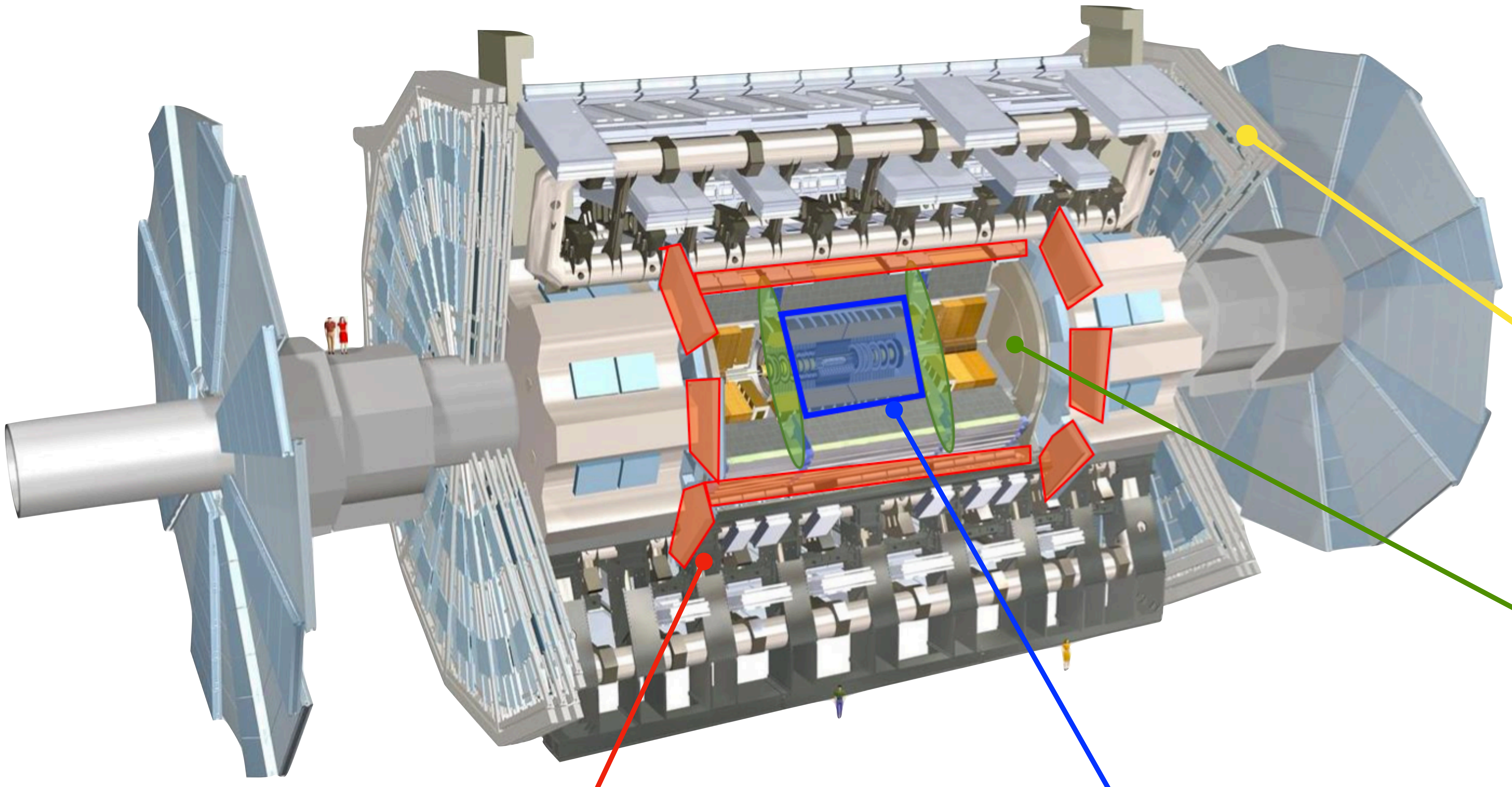


Secondary Vertexing for LLP



- Often in BSM models, heavy flavors are present in the decay product of the LLP.
- The present ATLAS secondary vertexing algorithm is not very inclusive about for such cases resulting in limited efficiencies.
- Development for “fuzzy vertexing” is ongoing with a PhD student (R. Ushioda) in Tokyo Tech.

HL-LHC Upgrade (ATLAS Phase-II)



Upgraded Trigger and Data Acquisition System

- Single Level Trigger with 1 MHz output
- Improved 10 kHZ Event Farm

Electronics Upgrades

- On-detector/off-detector electronics upgrades of LAr Calorimeter, Tile Calorimeter & Muon Detectors
- 40 MHz continuous readout with finer segmentation to trigger

High Granularity Timing Detector (HGTD)

- Precision time reconstruction (30 ps) with Low-Gain Avalanche Detectors (LGAD)
- Improved pile-up separation and bunch-by-bunch luminosity

New Muon Chambers

- Inner barrel region with new RPCs and sMDTs, and new Inner Endcap TGCs
- Improved trigger efficiency/momentum resolution, reduced fake rate

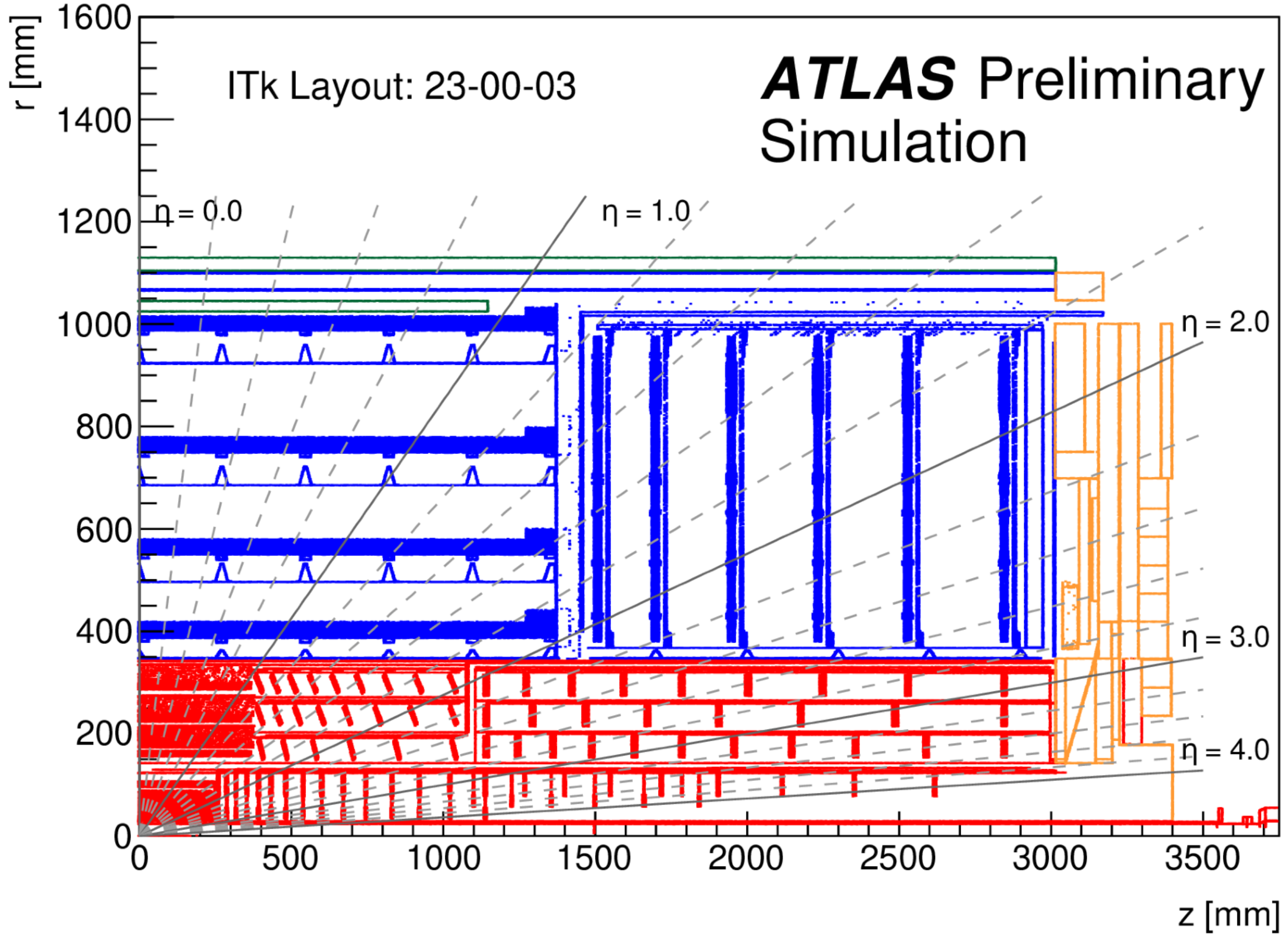
New Inner Tracking Detector (ITk)

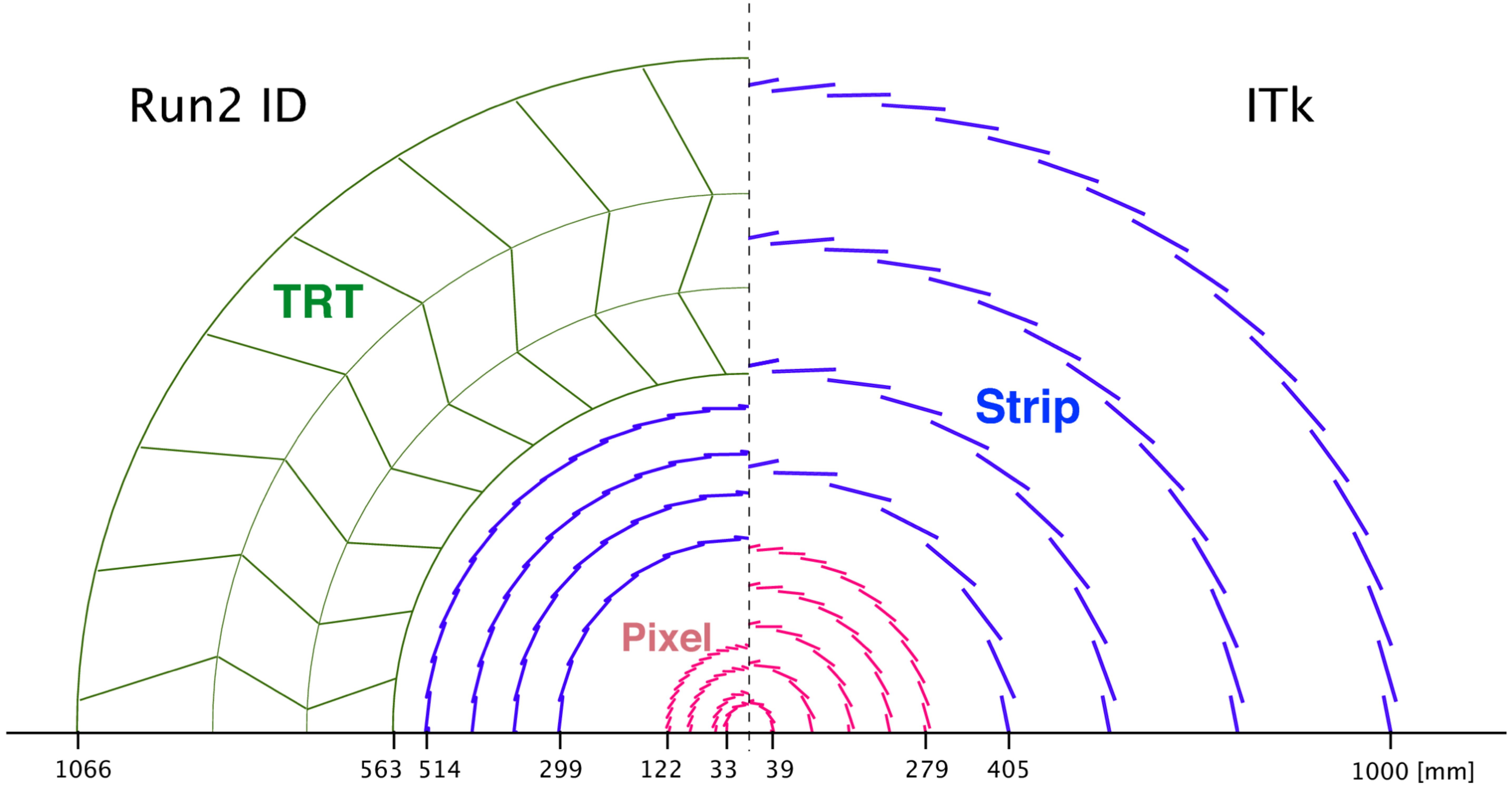
- All silicon with at least 9 layers up to $|\eta| = 4$
- Less material, finer segmentation

Additional small upgrades

- Luminosity detectors (1% precision)
- HL-ZDC (Heavy Ion physics)

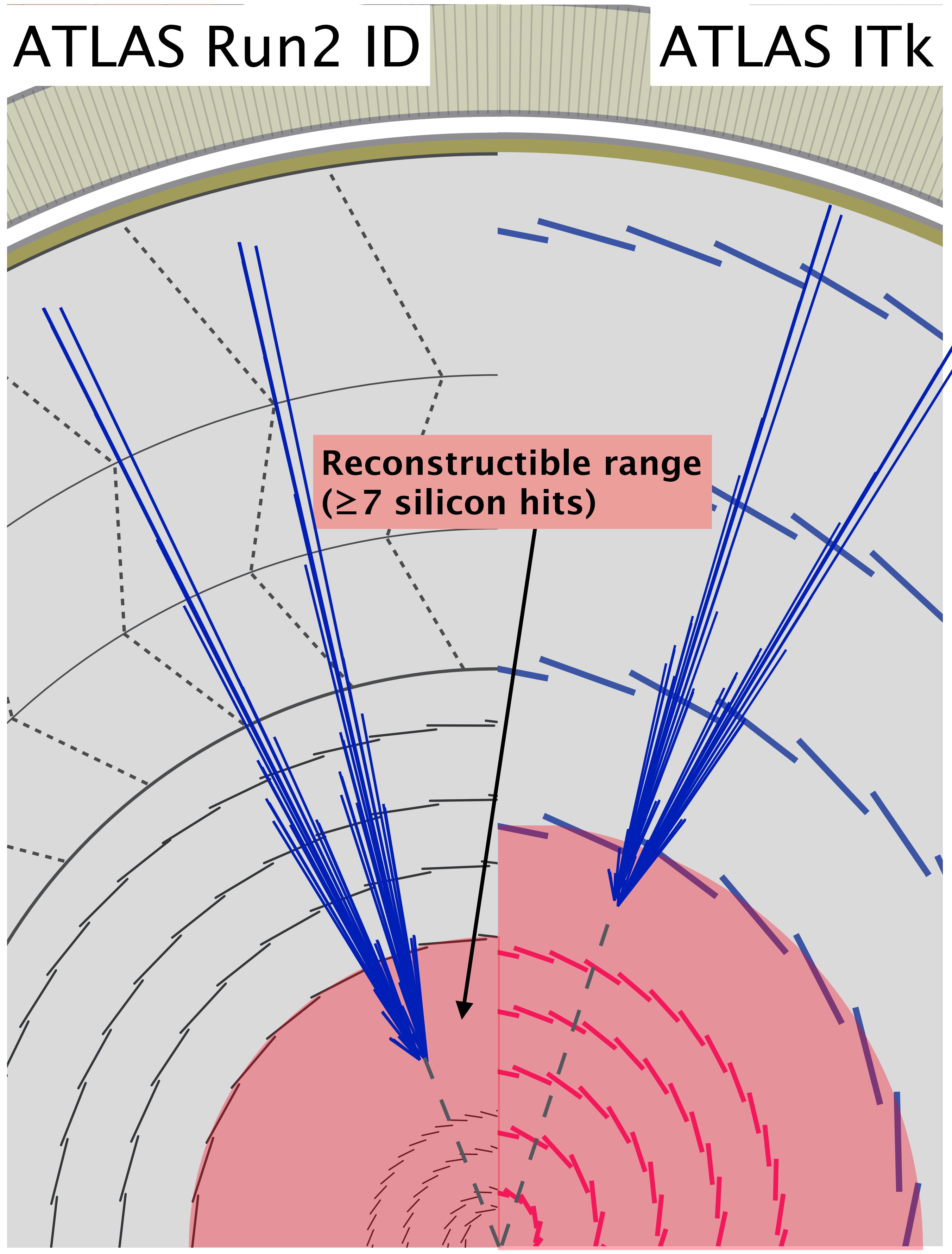
ATLAS Tracker Upgrade (ITk)

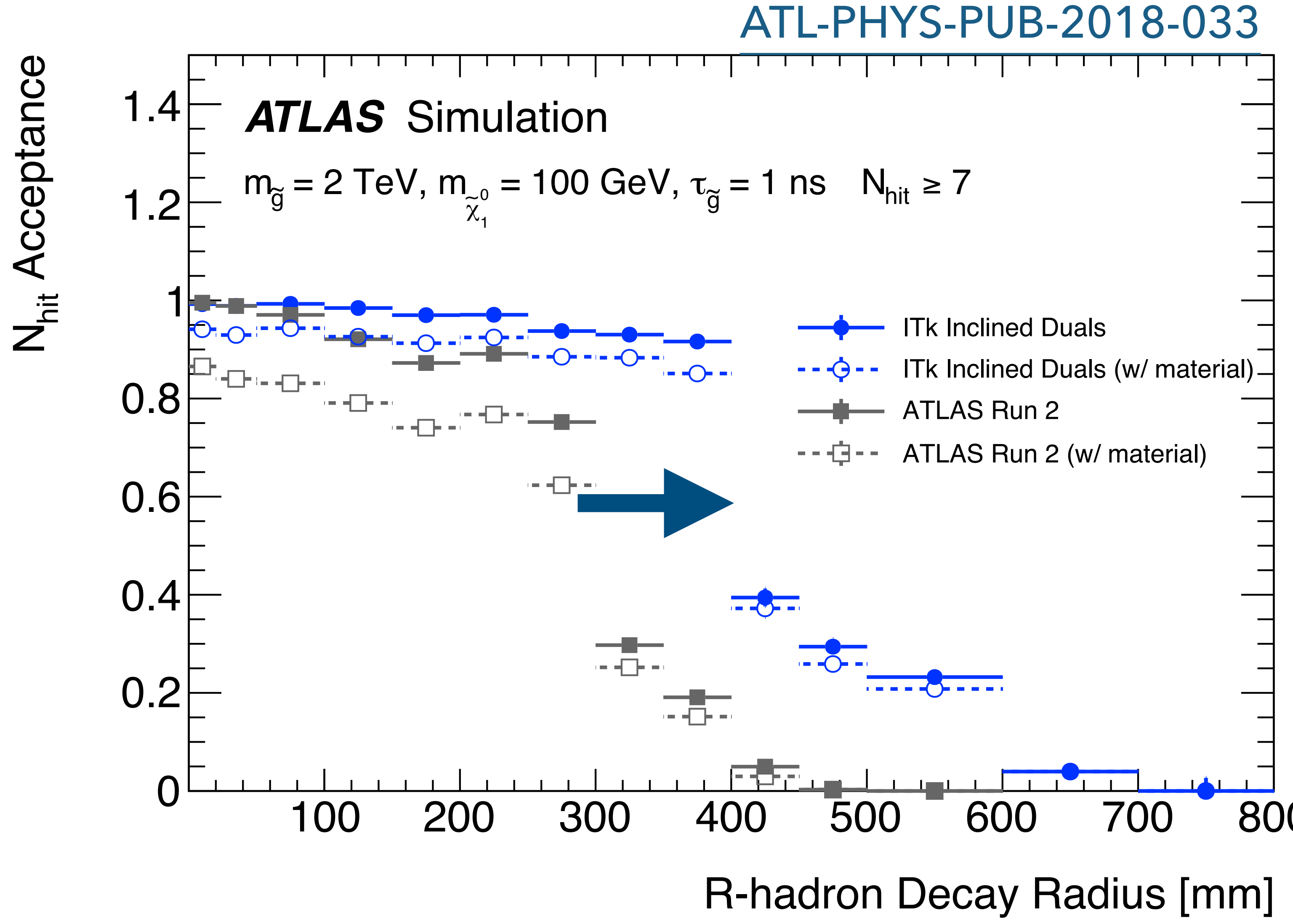


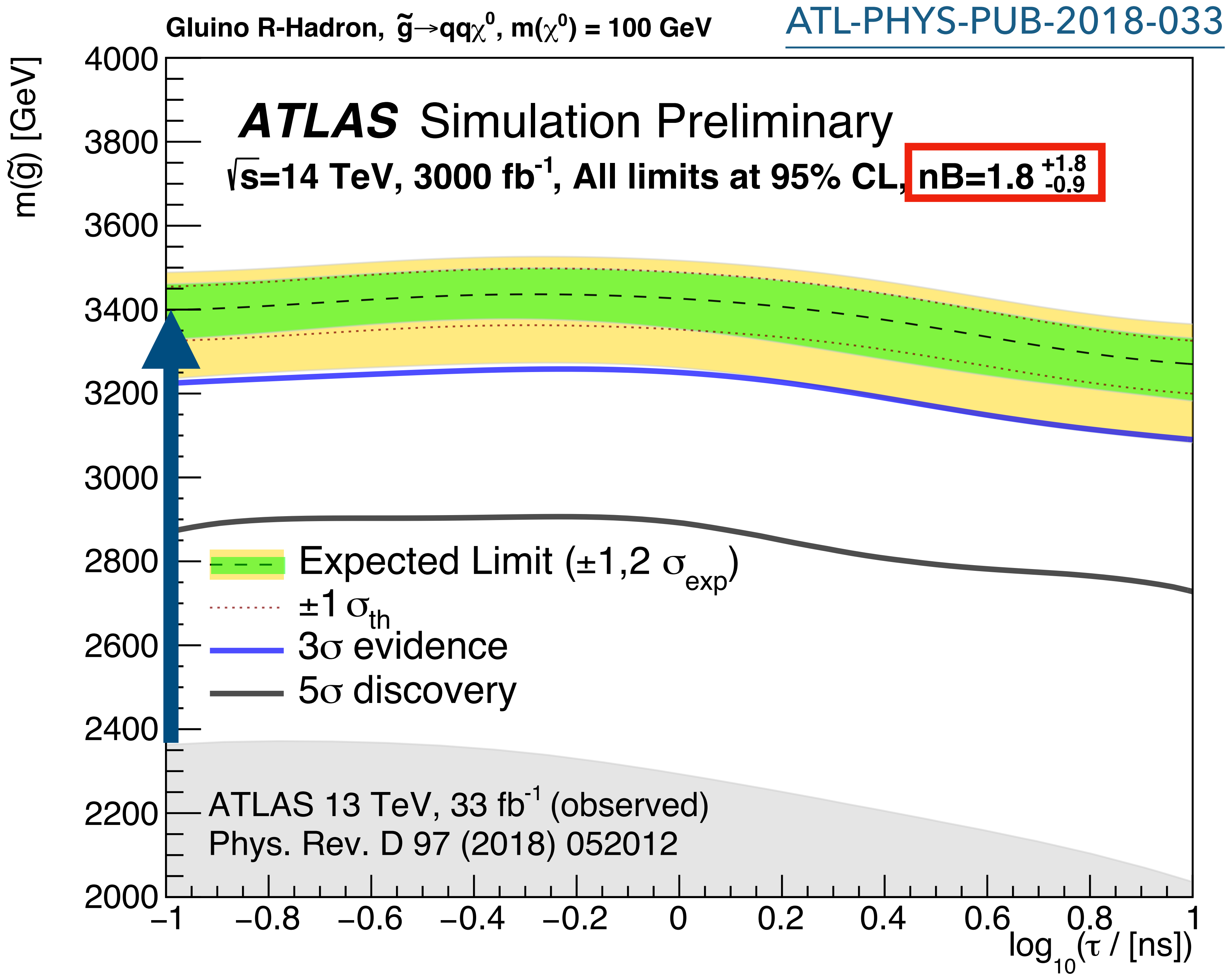


HL-LHC: Long-lived Gluino Search

DV $N_{track} \geq 5$
DV mass > 10 GeV
MET > 250 GeV

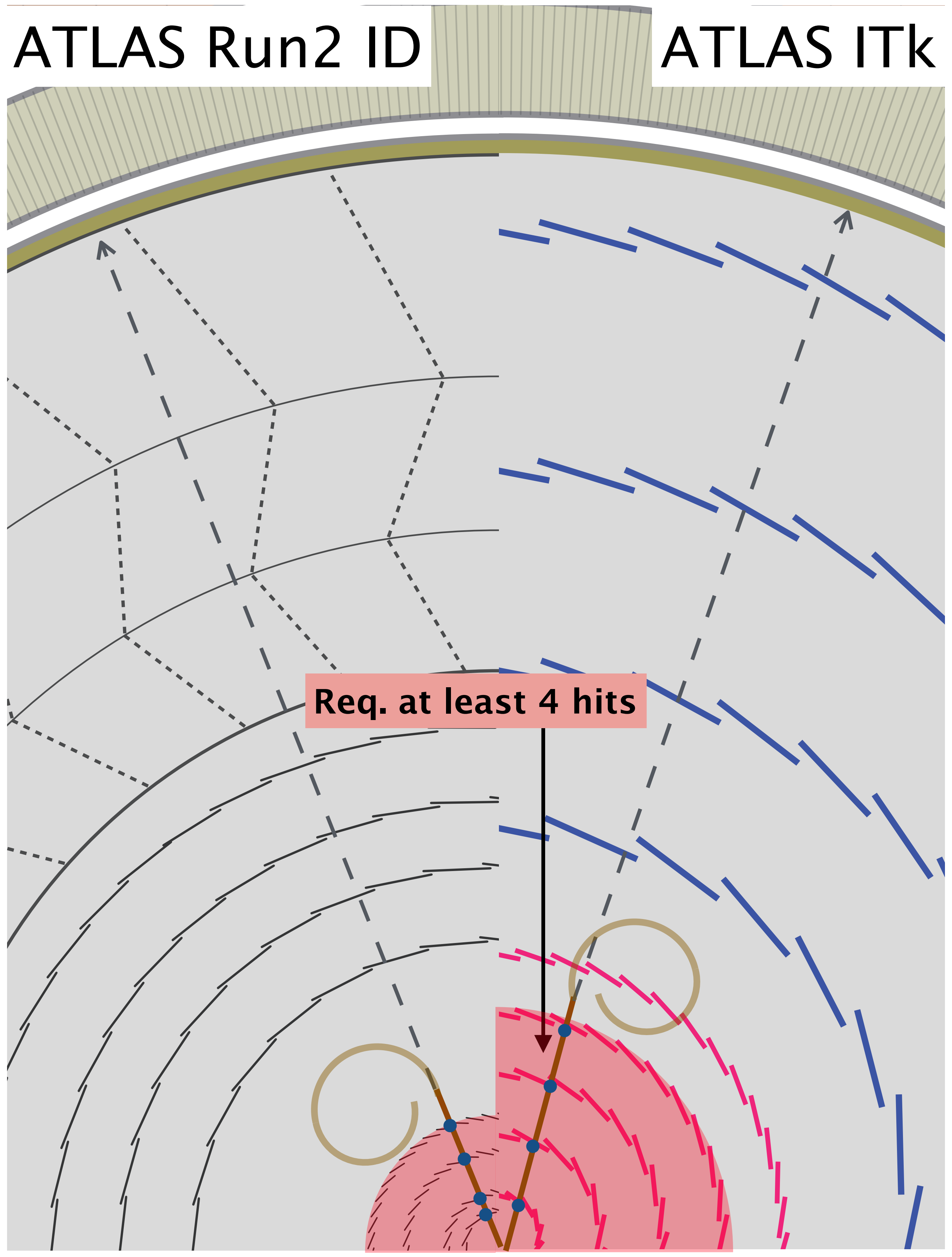


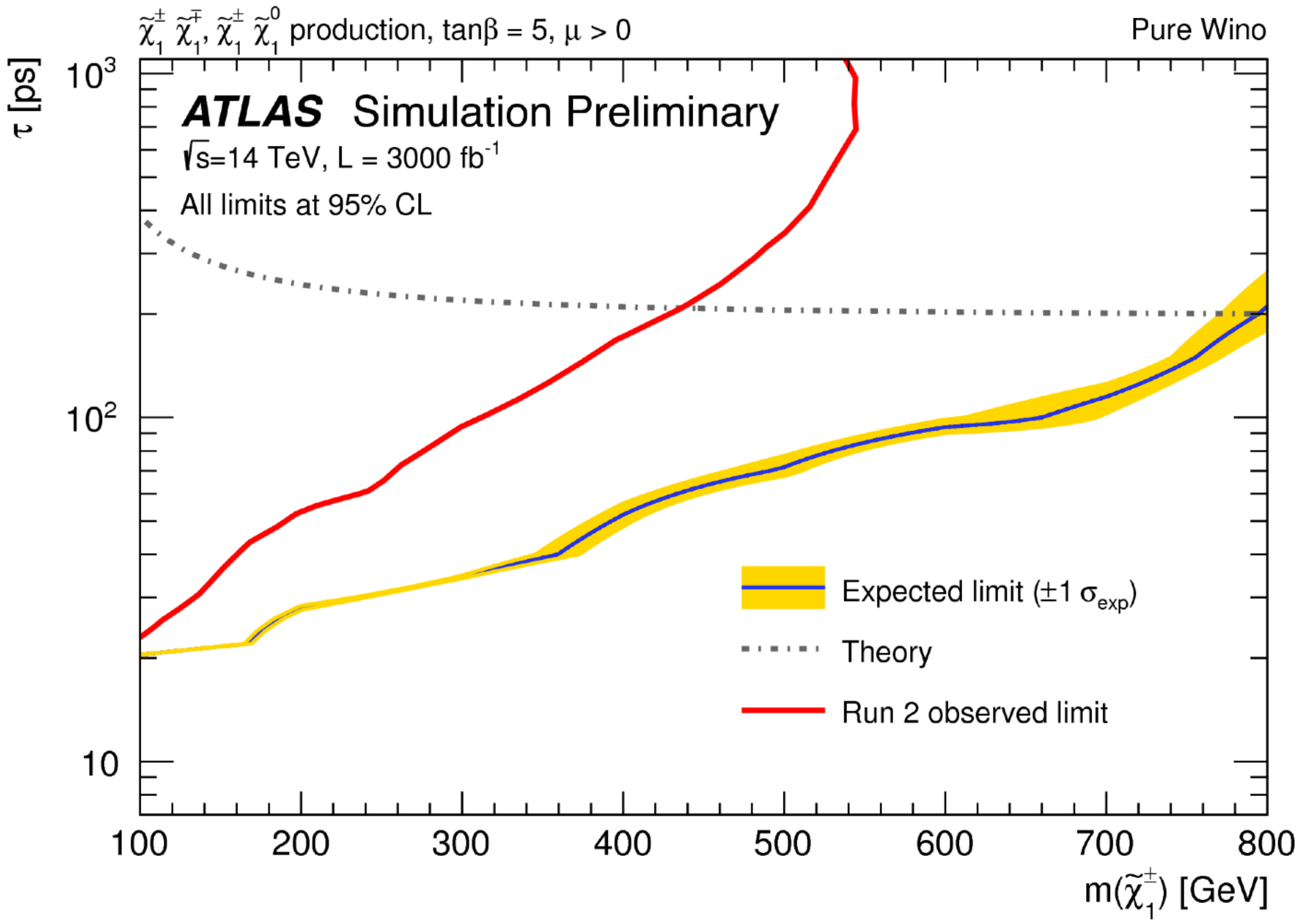




- **Grain of salt**: prospects are tough to estimate: Concrete reco-algorithm does not exist yet.
- The maximim decay radii inflates from 300 mm to 400 mm.
- May be able to exclude up to 3.4 TeV gluino *R*-hadron.

HL-LHC: Disappearing Track Search





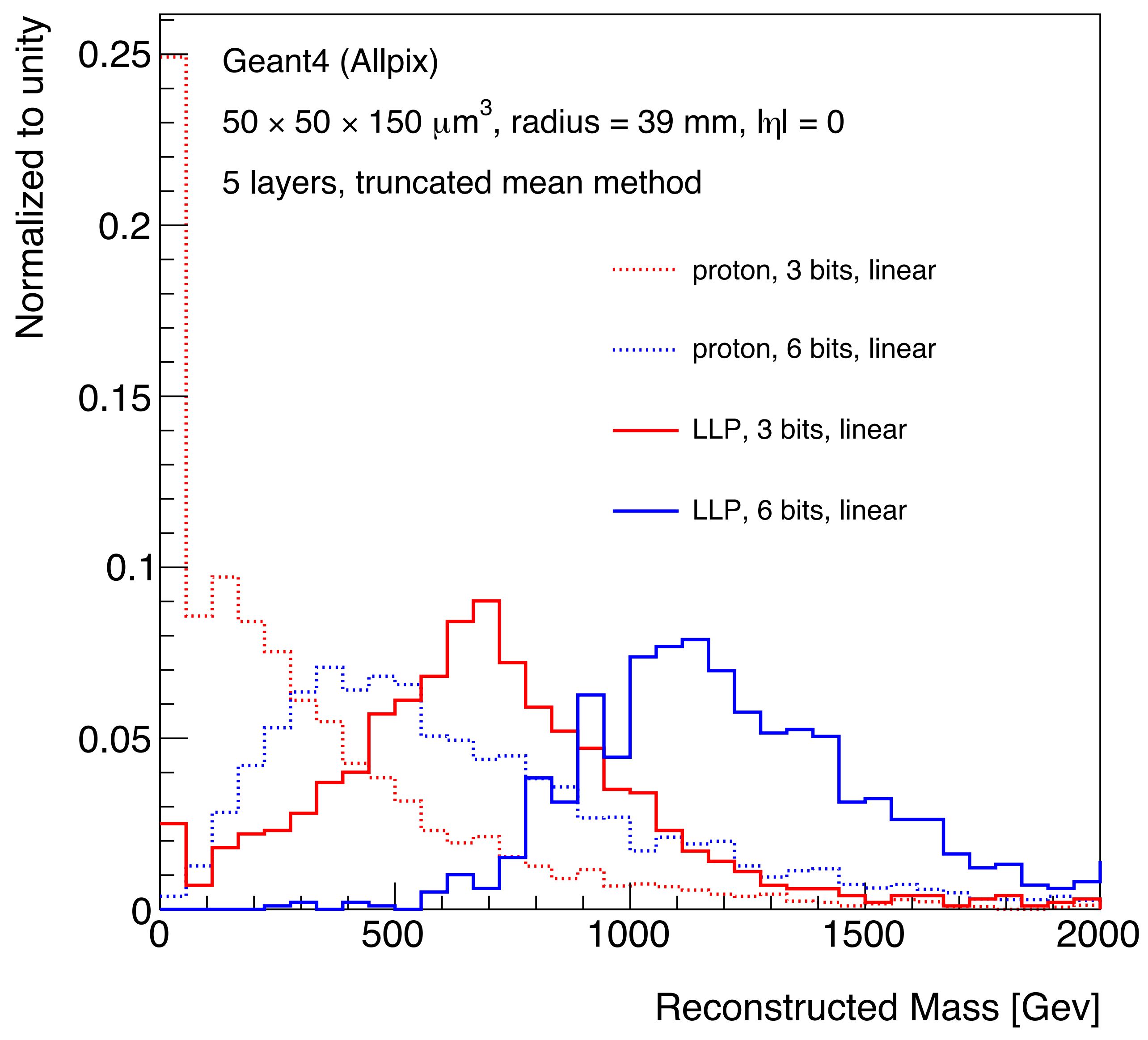
Pure wino: > 800 GeV

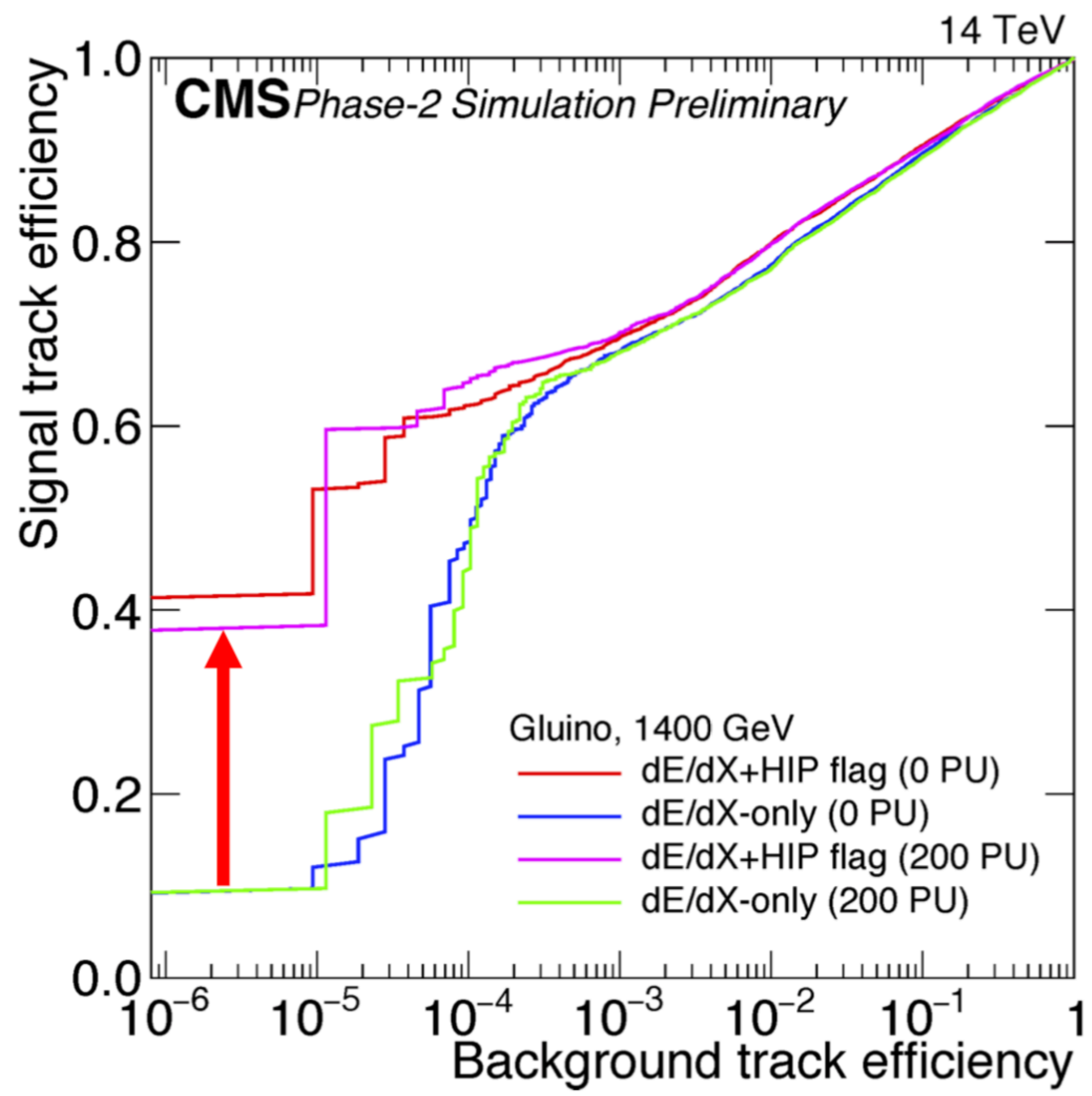
Pure higgsino: > 250 GeV

- ATLAS inner tracking detectors have a new layout: different implications depending on the signature.
- Disappearing track (long-lived chargino search): need tracking using only innermost layers
  → decrease of acceptance is expected.

HL-LHC: dE/dx measurement

- The ITk pixel detector of 50x50 μm² pitch:
  only 4 bit dynamic range can be accommodated.
- Also the data bandwidth limits the data bits/hit to be read-out.
- An early study [1710.02582] prospects:
  A reasonable classification of large-dE/dx signals is feasible,
  with a deteriorated mass resolution.
- CMS Phase-II strip tracker high-threshold hits is powerful.
- We can keep some abilities to push this search.
- Optimization of the operation condition must be studied.

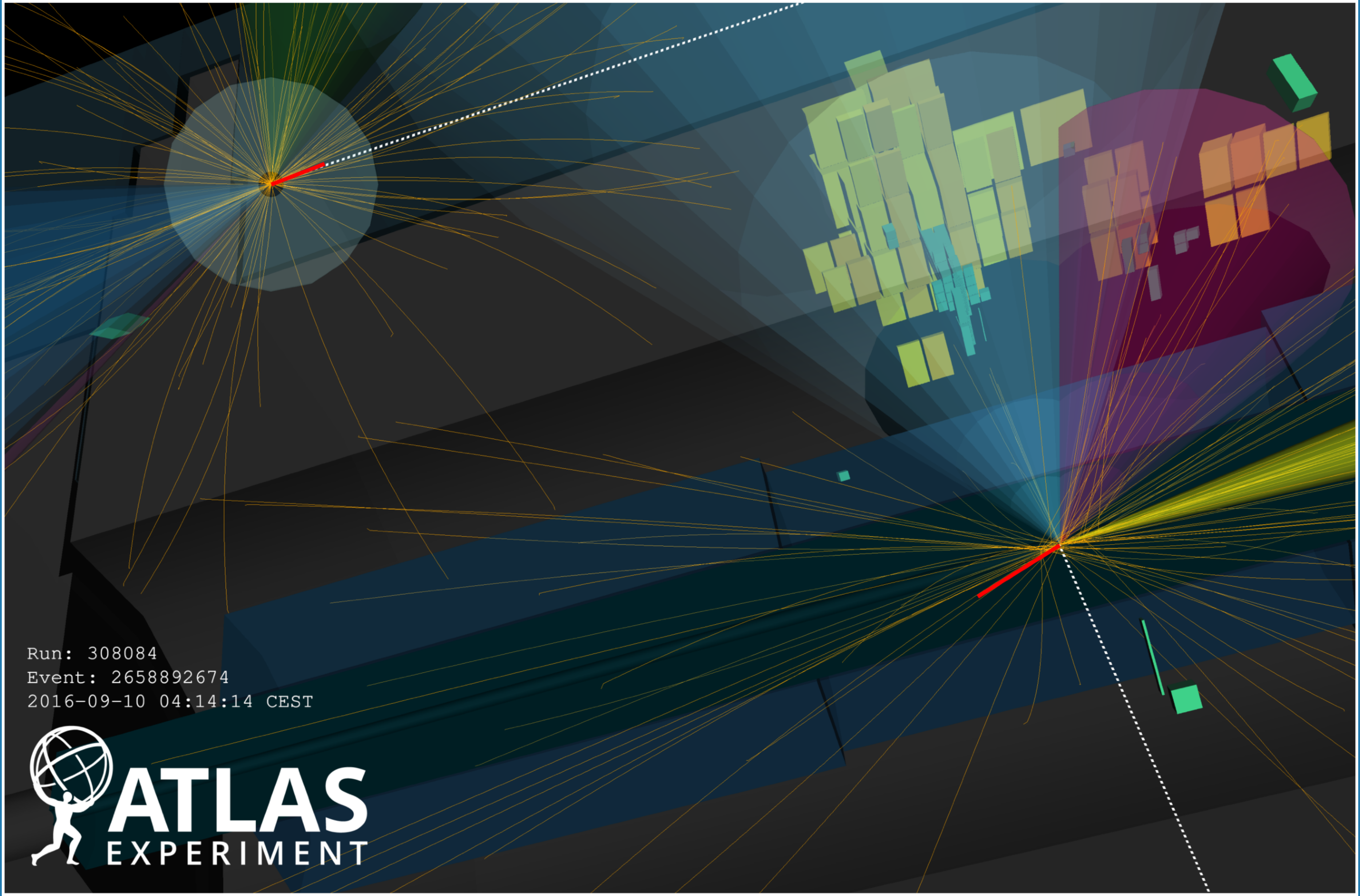




Summary

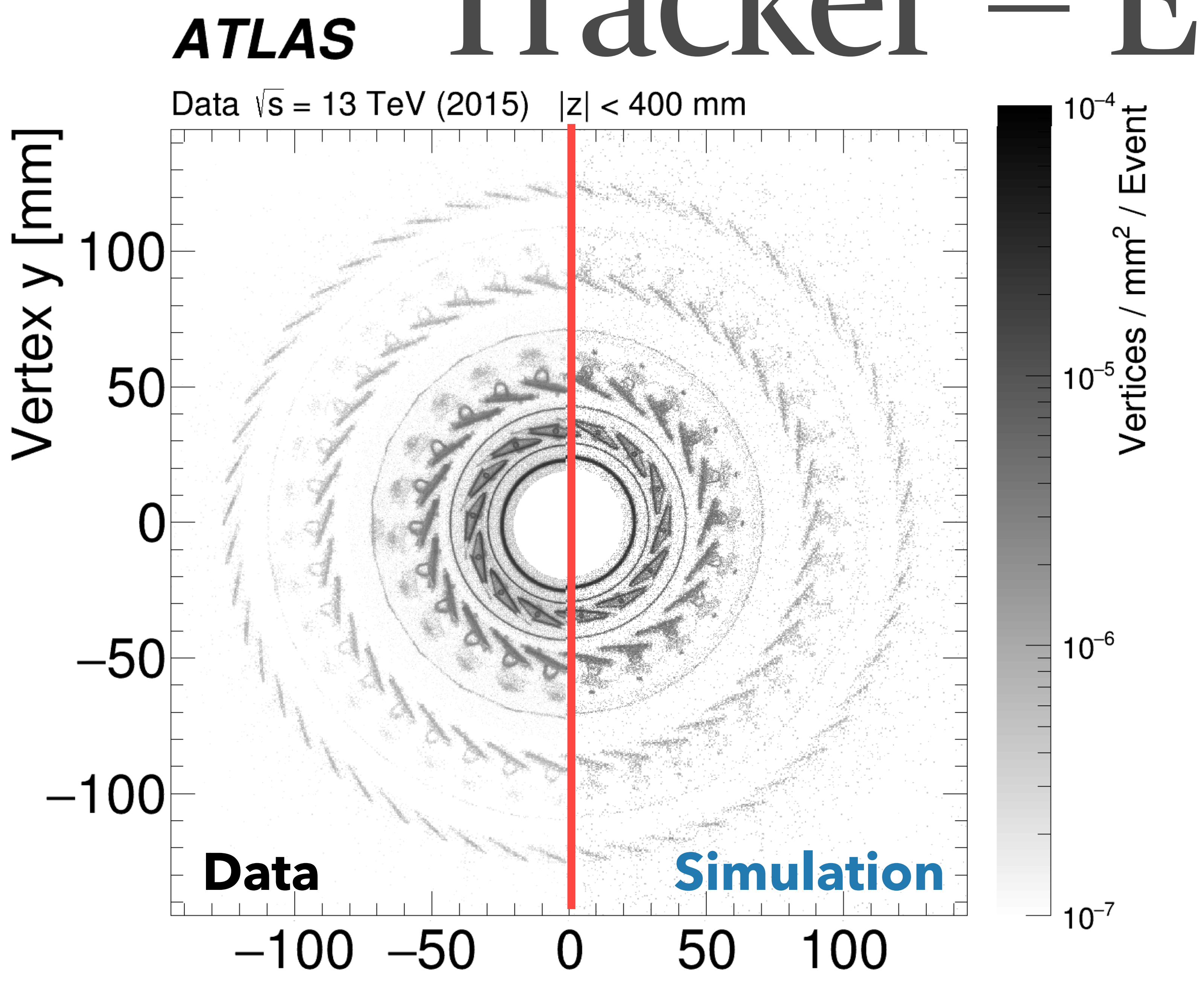
- Low-background searches are important.
- A number of attractive BSM scenarios predict charged LLP as a new particle.
- Advanced use of the collider detector technologies enables searches for these particles in wide range of the scenarios in the model-independent manner.
- Not all of the full-Run2 analyses have been released, and Run3 is imminent to start.
- Promising sensitivity extension in HL-LHC.

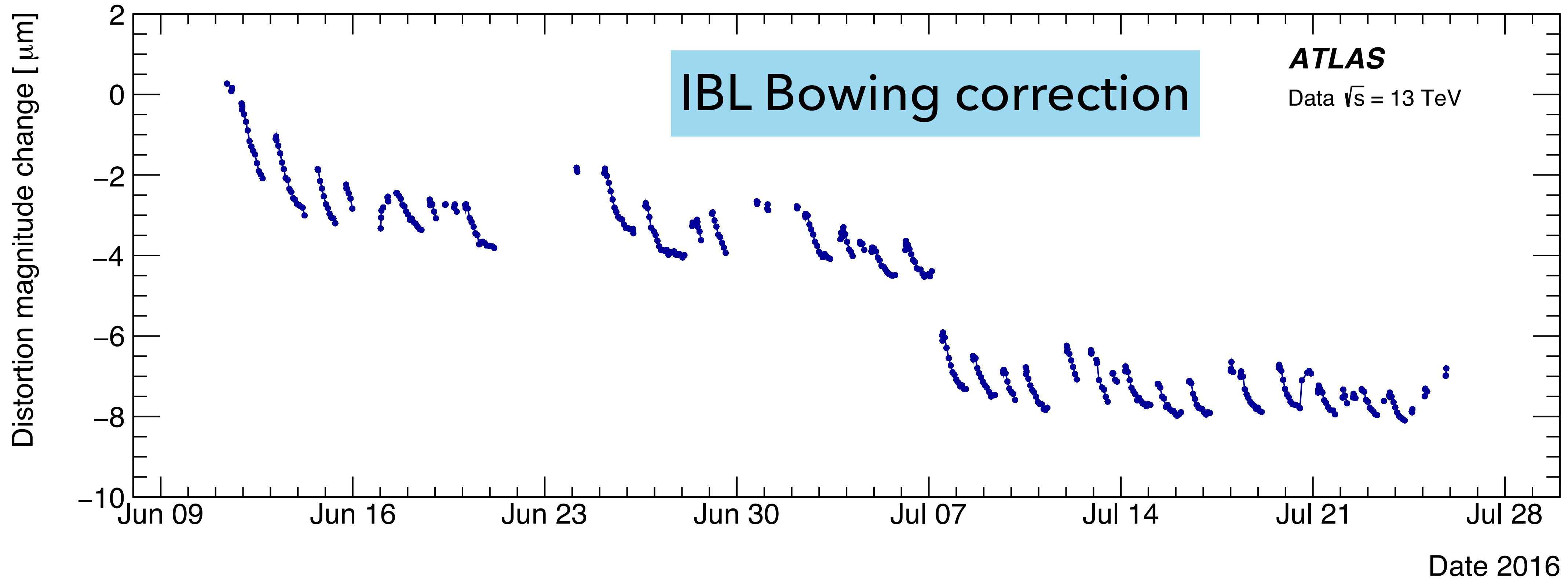
Backup

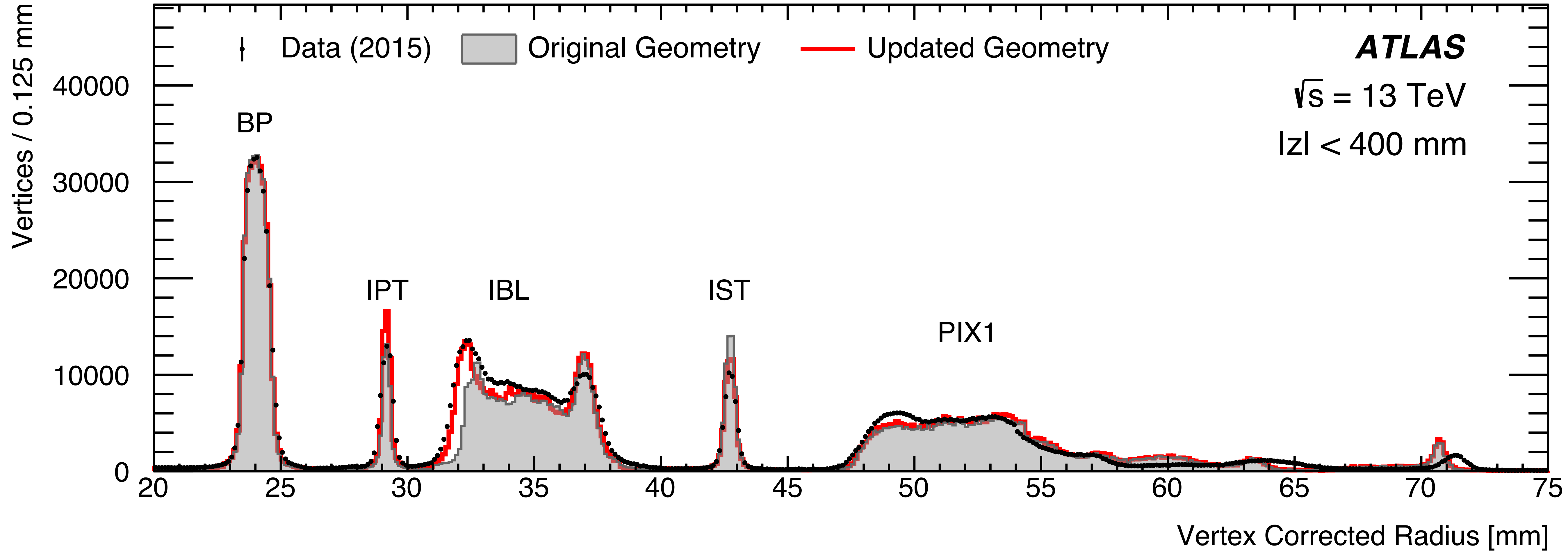

Run: 308084
Event: 2658892674
2016-09-10 04:14:14 CEST
ATLAS
EXPERIMENT

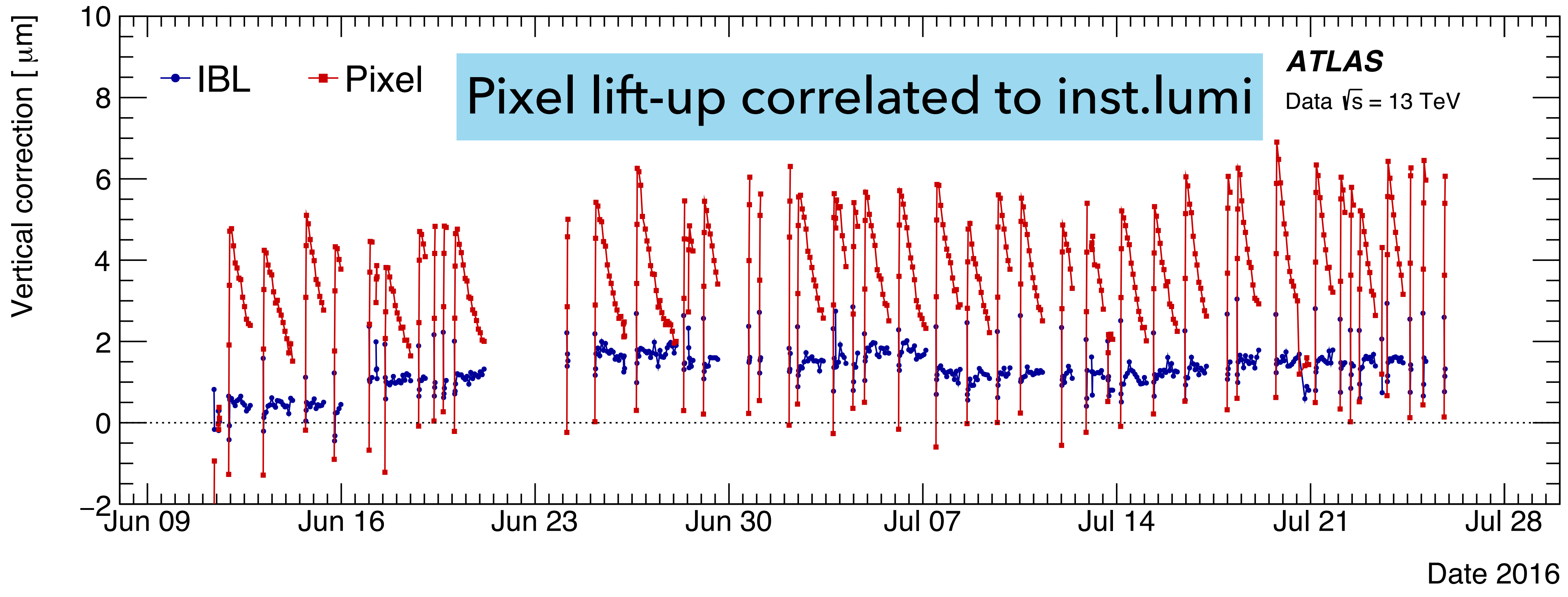
Tracker – Early Characterization in Run2

- Geometry establishment: ~ 2015.
- Alignment establishment: ~2016.









Disclaimer

- Personal invitations to seminars about ATLAS results can be accepted by any ATLAS collaborator on a private basis with the responsibility to present ATLAS in a fair and scientifically correct way, and to only use approved material.
- Despite the generic title (sorry!), this seminar talk is **not** intended to represent the work of the entire LHC collaborations, but is rather largely weighted on the speaker's research orientations as a member of the collaboration.
- All contents are totally organized by HO.
  The contents are not reviewed by any of the LHC collaborations.
- **Please**: audiences are guided to refer to the official presentations in major HEP conferences for state-of-the-art of the entire experiment.

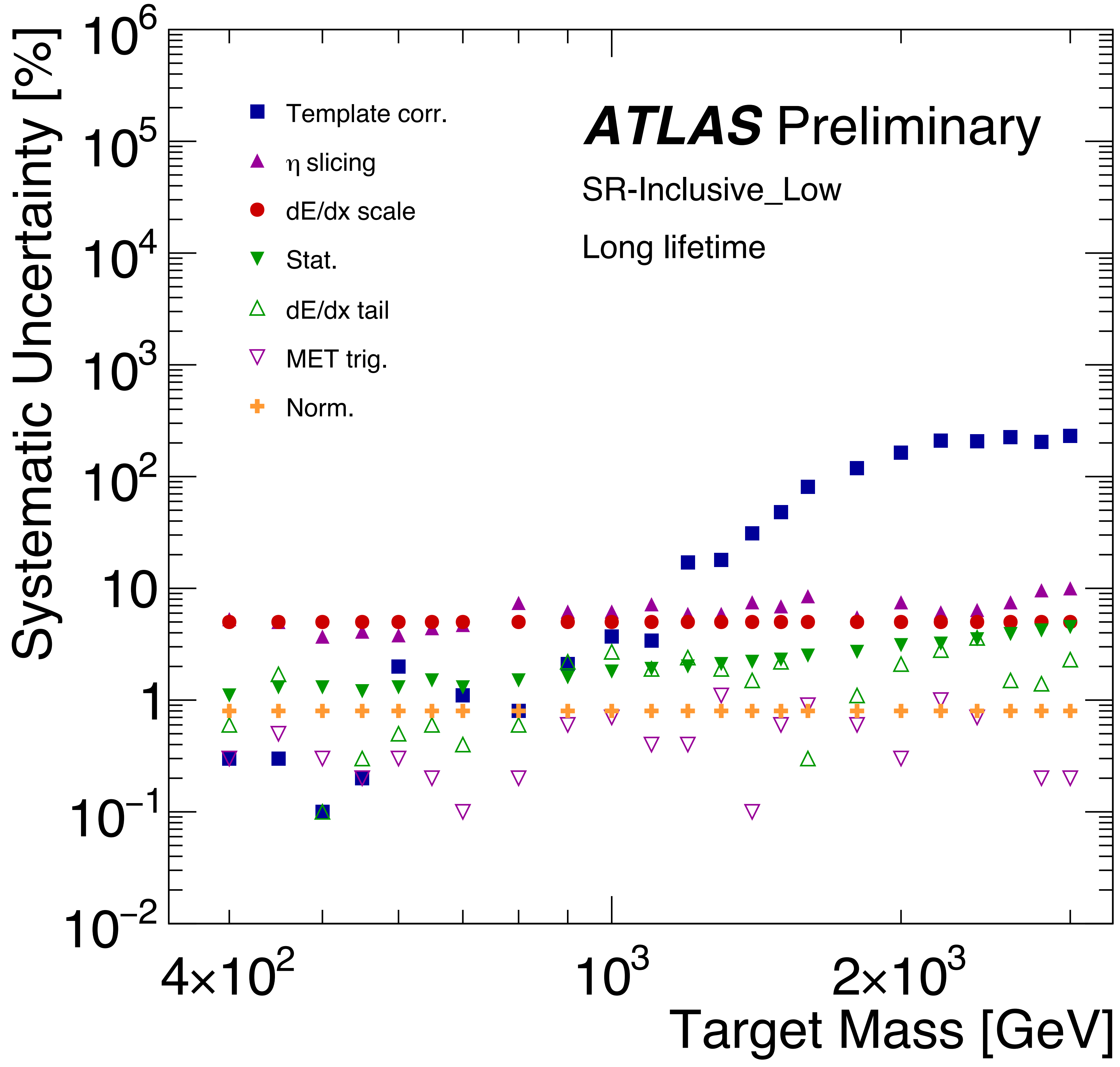
Signal Selection

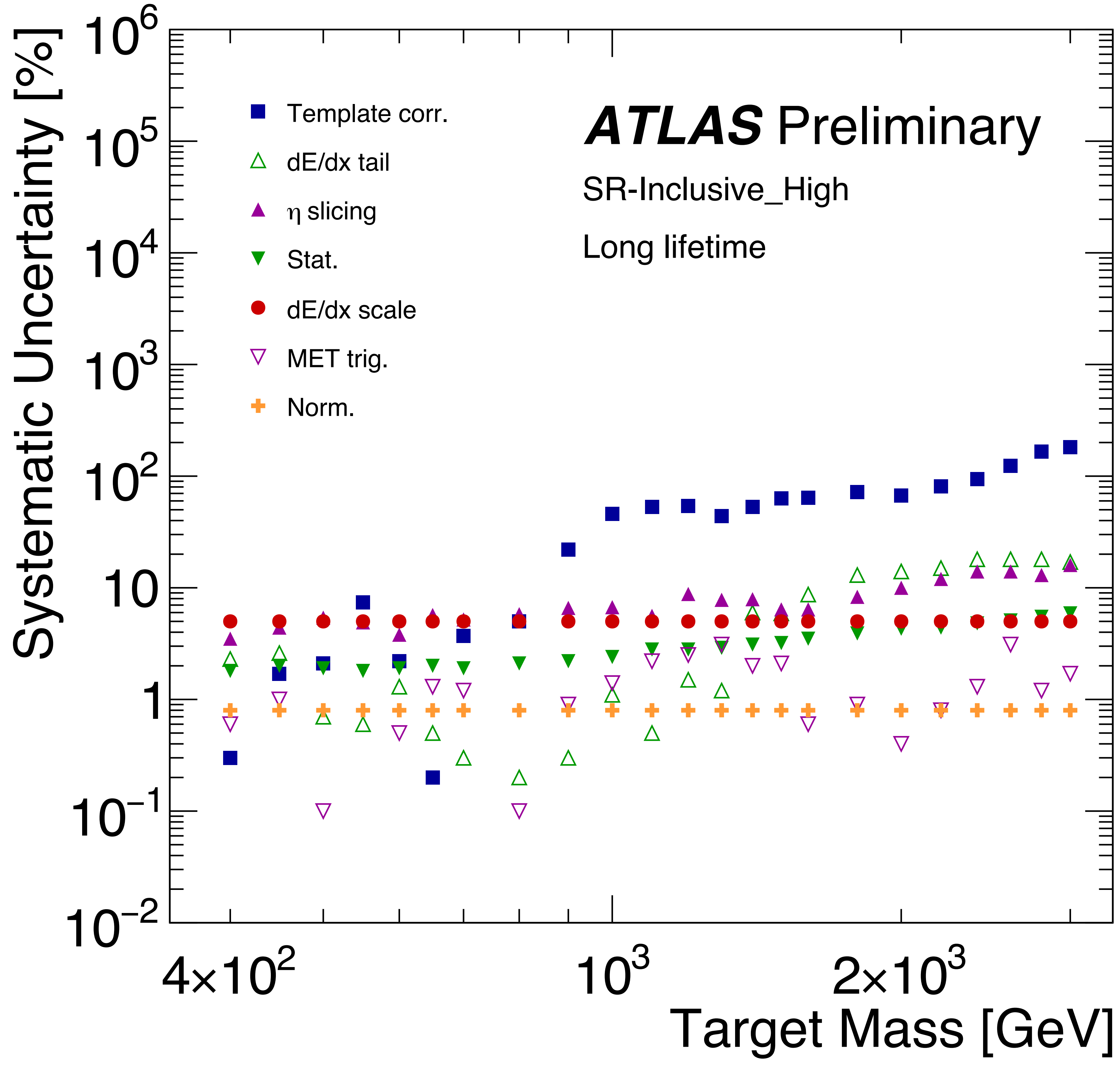
Category	Item	Description
Event topology	Trigger	Unprescaled lowest-threshold $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger
	$E_{\mathrm{T}}^{\mathrm{miss}}$	$E_{\mathrm{T}}^{\mathrm{miss}} > 170$ GeV
	Primary vertex	The hard-scatter vertex must have at least two tracks
Events are required to have at least one track fulfilling *all* criteria listed below; tracks sorted in p_{T} descending order		
Track kinematics	Momentum	$p_{\mathrm{T}} > 120$ GeV
	Pseudorapidity	$\lvert\eta\rvert < 1.8$
	$W^{\pm} \to \ell^{\pm}\nu$ veto	$m_{\mathrm{T}}(\mathrm{track}, \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}) > 130$ GeV
Track quality	Impact parameters	Track matched to the hard-scatter vertex; $\lvert d_0\rvert < 2$ mm and $\lvert\Delta z_0 \sin\theta\rvert < 3$ mm
	Rel. momentum resolution	$\sigma_p < \max\left(10\%, -1\% + 90\% \times \frac{\lvert p\rvert}{\mathrm{TeV}}\right)$ and $\sigma_p < 200\%$
	Cluster requirement (1)	At least two clusters used for the $\langle \mathrm{d}E/\mathrm{d}x\rangle_{\mathrm{trunc}}$ calculation
	Cluster requirement (2)	Must have a cluster in the IBL (if this is expected), or a cluster in the next-to-innermost pixel layer (if this is expected while a cluster is not expected in IBL)
	Cluster requirement (3)	No shared pixel clusters and no split pixel clusters
	Cluster requirement (4)	Number of SCT clusters > 5
Vetoes	Isolation	$\left(\sum_{\mathrm{trk}} p_{\mathrm{T}}\right) < 5$ GeV (cone size $\Delta R = 0.3$)
	Electron veto	EM fraction < 0.95
	Hadron and τ-lepton veto	$E_{\mathrm{jet}}/p_{\mathrm{track}} < 1$
	Muon requirement	`SR-Mu`: MS track matched to ID track; `SR-Trk`: otherwise
Pixel $\mathrm{d}E/\mathrm{d}x$	Inclusive	`Low`: $\mathrm{d}E/\mathrm{d}x \in [1.8, 2.4]$ MeV g^{-1}cm^2
		`High`: $\mathrm{d}E/\mathrm{d}x > 2.4$ MeV g^{-1}cm^2
	Binned	`IBL0_Low`: $\mathrm{d}E/\mathrm{d}x \in [1.8, 2.4]$ MeV g^{-1}cm^2 and $\mathtt{OF}_{\mathrm{IBL}} = 0$
		`IBL0_High`: $\mathrm{d}E/\mathrm{d}x > 2.4$ MeV g^{-1}cm^2 and $\mathtt{OF}_{\mathrm{IBL}} = 0$
		`IBL1`: $\mathrm{d}E/\mathrm{d}x > 1.8$ MeV g^{-1}cm^2 and $\mathtt{OF}_{\mathrm{IBL}} = 1$

Signal Selection: CR, VR, SR

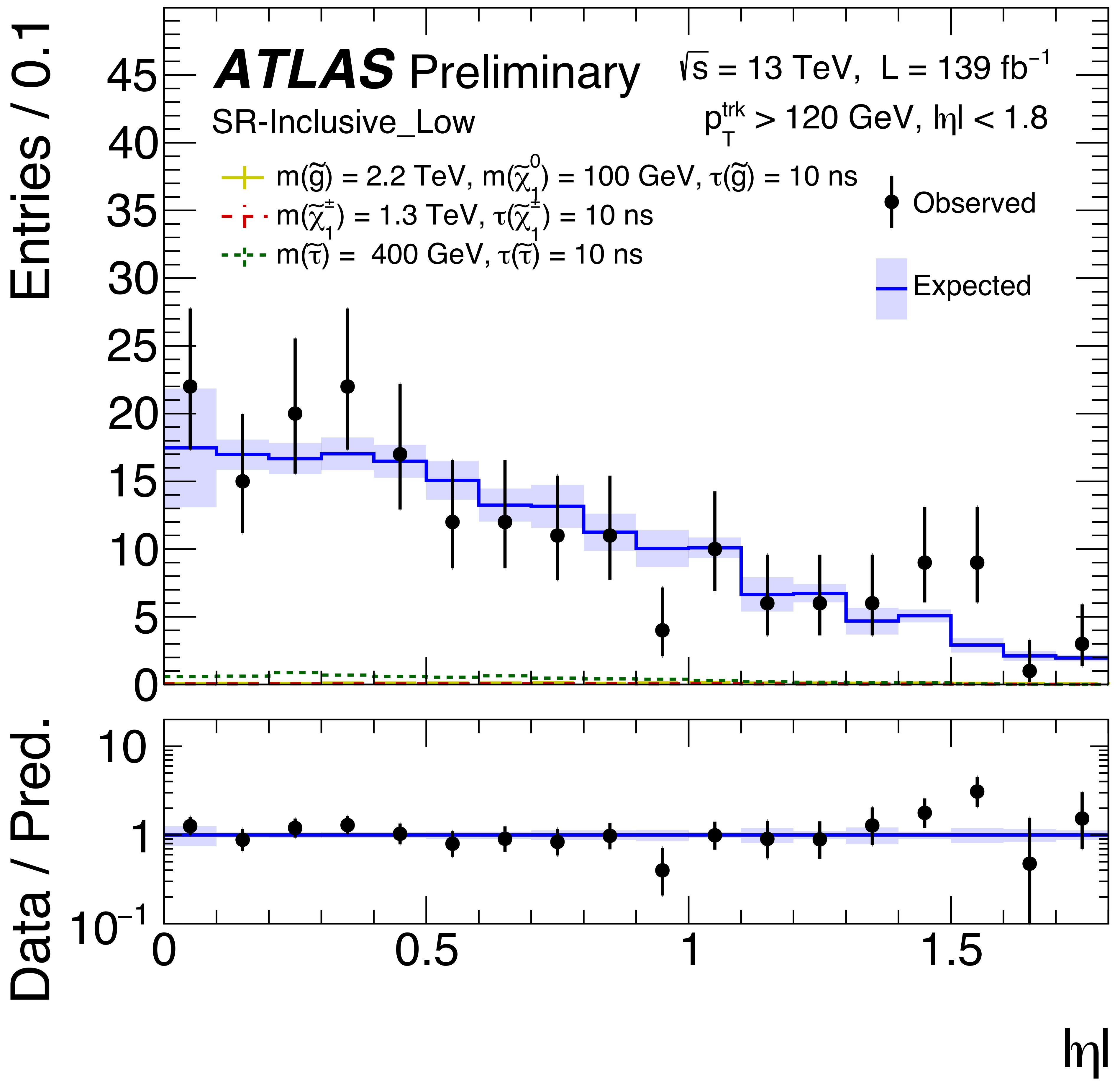
Region	p_{T} [GeV]	$\|\eta\|$	$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	$\mathrm{d}E/\mathrm{d}x$ [MeV g^{-1}cm^{2}]
`SR`			> 170	> 1.8
`CR-kin`	> 120	< 1.8	> 170	< 1.8
`CR-dEdx`			< 170	> 0
`VR-LowPt`			> 170	> 1.8
`CR-LowPt-kin`	$[50, 110]$	< 1.8	> 170	< 1.8
`CR-LowPt-dEdx`			< 170	> 0
`VR-HiEta`			> 170	> 1.6
`CR-HiEta-kin`	> 50	$[1.8, 2.5]$	> 170	< 1.6
`CR-HiEta-dEdx`			< 170	> 0

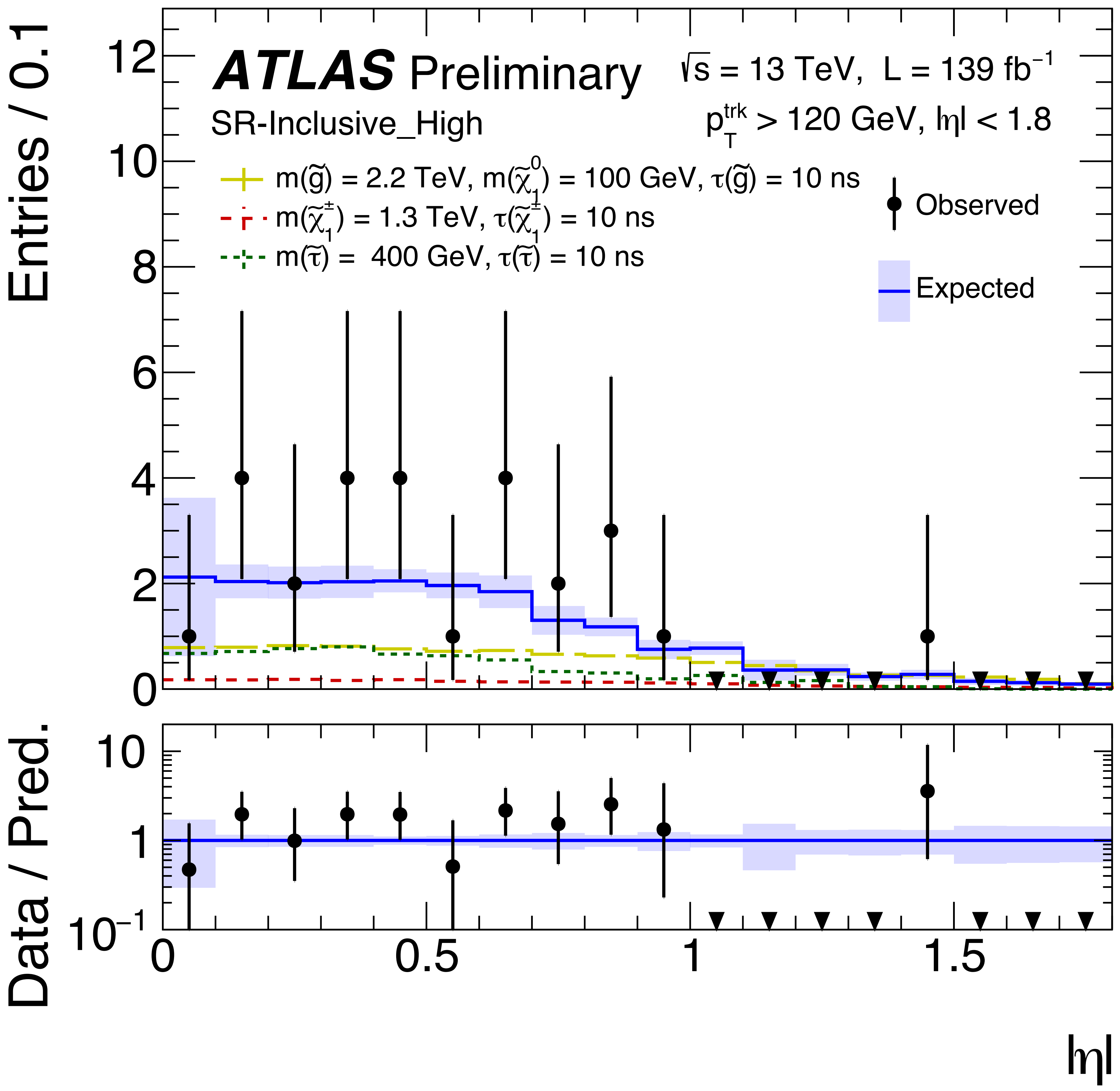
Systematic Uncertainties



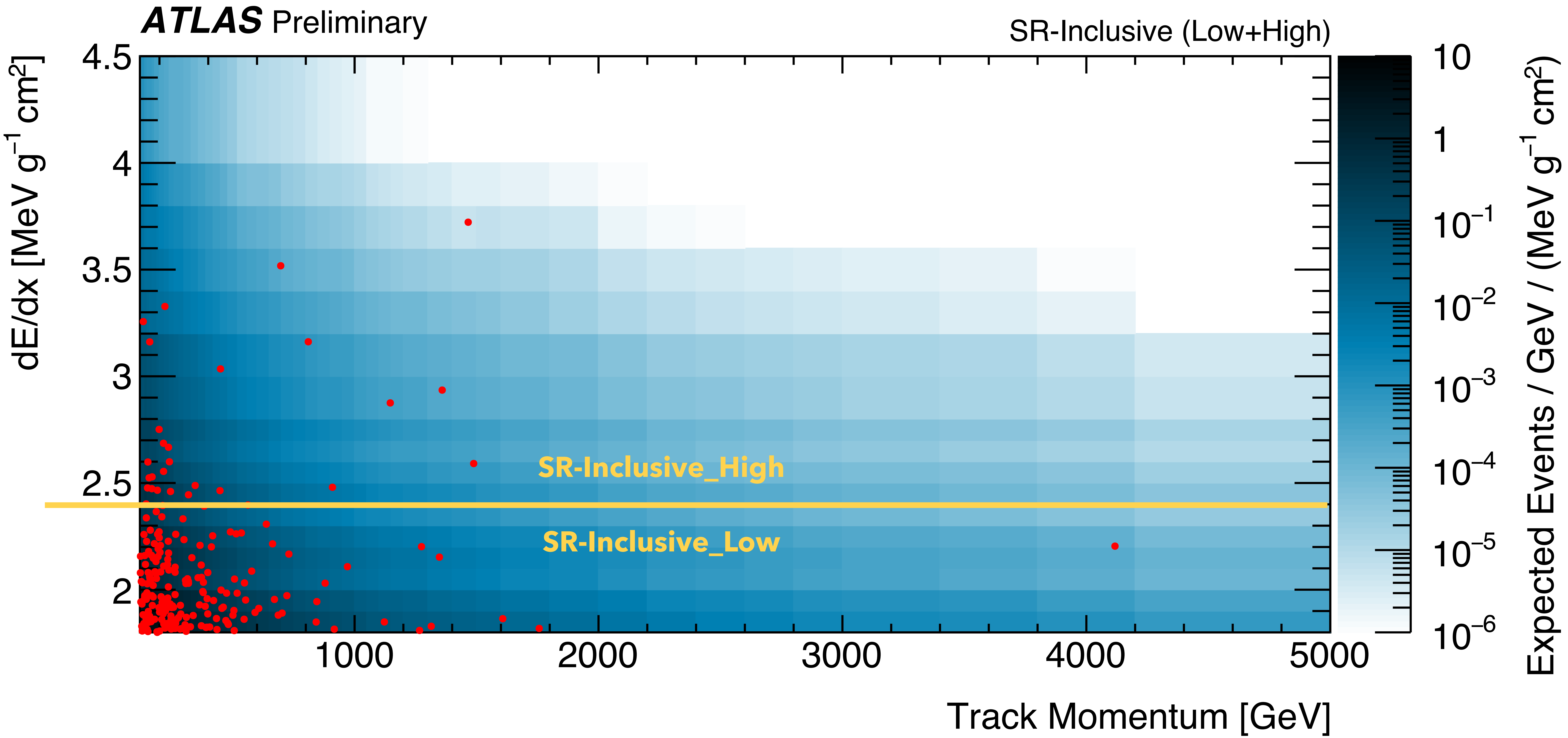


Signal Region Events





Signal Region Events

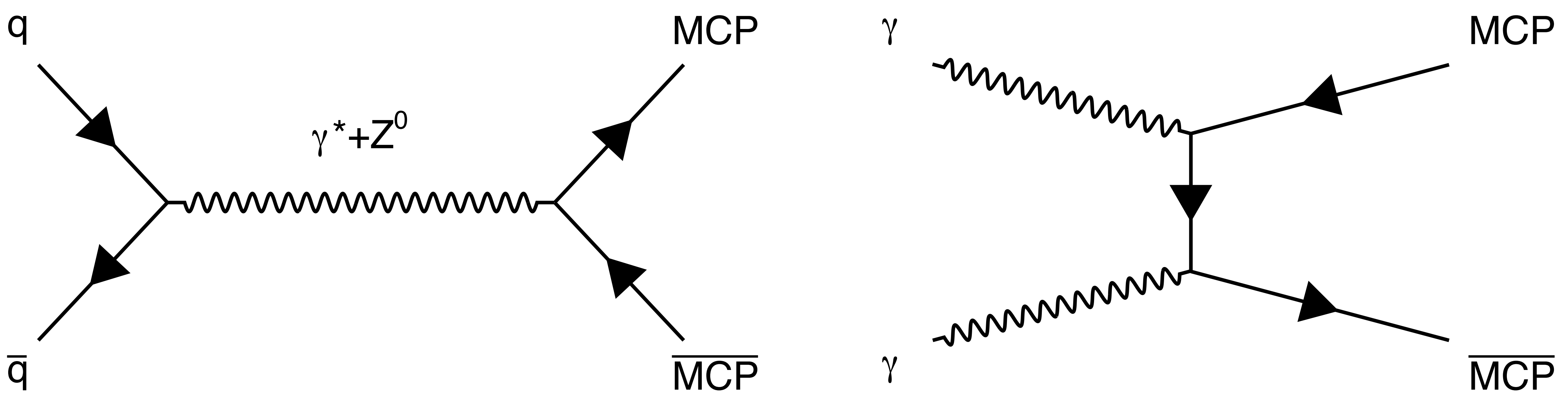


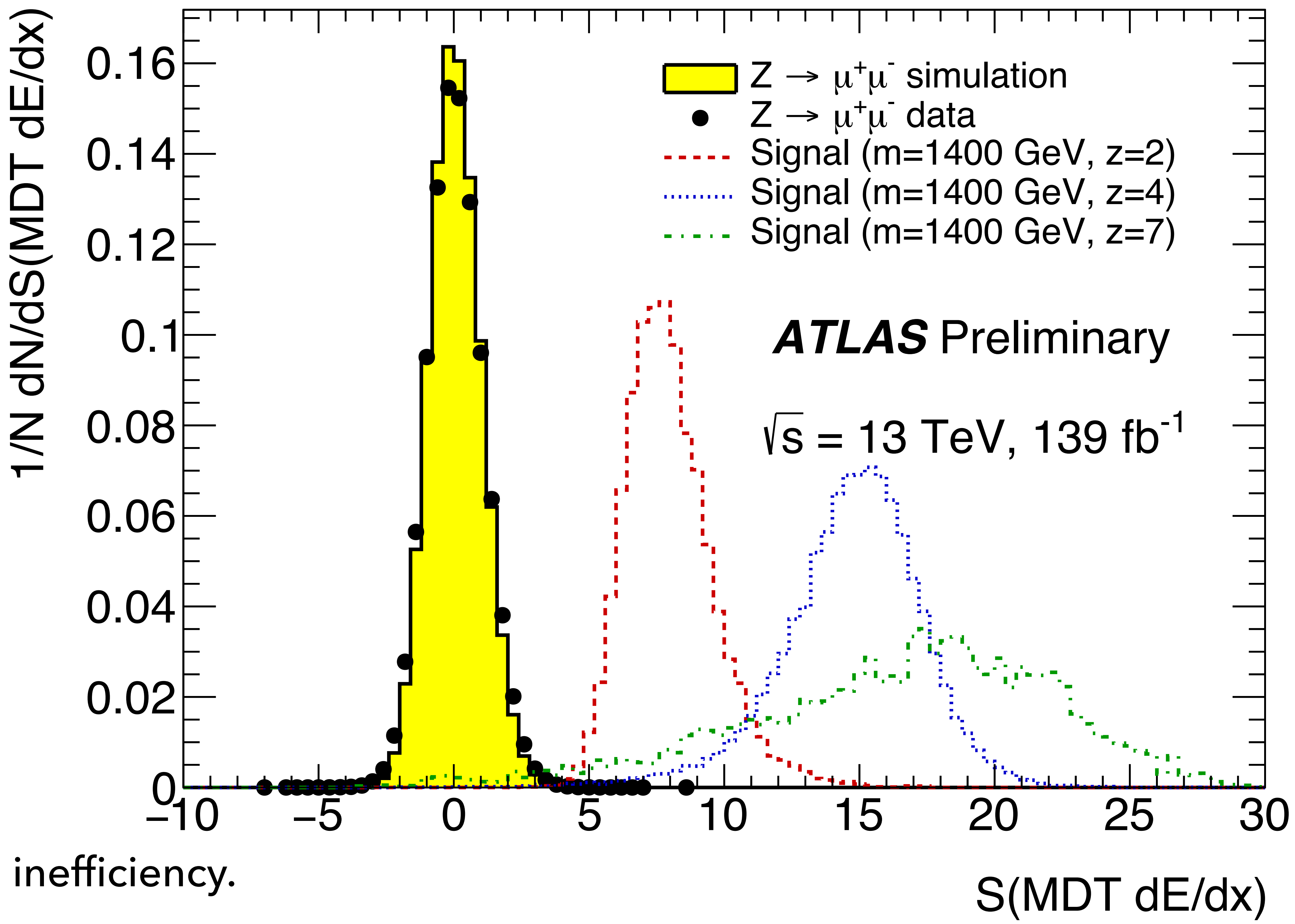
Excess events examinations

- 7 events in the mass window with the lowest p_0-value were examined.
  - 4 events in the SR-Mu category w/o IBL overflow
  - 2 events are in the SR-Trk category w/ IBL overflow
  - 1 event is in the SR-Trk category w/o IBL overflow.
- 1 event in the SR-Trk category has a matched muon which does not satisfy the identification criterion applied in this analysis.
- Candidate tracks are well isolated both at the track level and at the calorimeter cluster level, as required by the signal selection.
- The two reconstructed momentum values from ID-only and IS+MS (combined track) are compatible with each other for all 4+1 events reconstructed as a muon.
- The visual inspection of the individual pixel clusters did not show an obvious trace of merging of multple charged particles injection.

Multi-charged dE/dx (in multiple subsystems)

- A generic multi-charged particles (MCP) produced in pairs via Drell-Yan or photon-fusion processes.
- Scope: $z = 2$ and $3 \leq z \leq 7$.
- Single muon trigger supplemented by the E_T^{miss} trigger and the "late muon" trigger.
- Require at least one track with $p_T/z > 50$ GeV in $|\eta| < 2.0$ identified as an isolated muon.
- Require anomalously large $\mathrm{d}E/\mathrm{d}x$ significance $\mathcal{S}(\mathrm{d}E/\mathrm{d}x)$ in multiple subsystems:
  - $z = 2$: $\mathcal{S}(\mathrm{d}E/\mathrm{d}x, \text{pixel}) > 13.0$, then $\mathcal{S}(\mathrm{d}E/\mathrm{d}x, \text{TRT}) > 2.0$ & $\mathcal{S}(\mathrm{d}E/\mathrm{d}x, \text{MDT}) > 4.0$
  - $z > 2$: TRT high-threshold hits fraction $(f_{HT}) > 0.7$ & $\mathcal{S}(\mathrm{d}E/\mathrm{d}x, \text{MDT}) > 7.0$



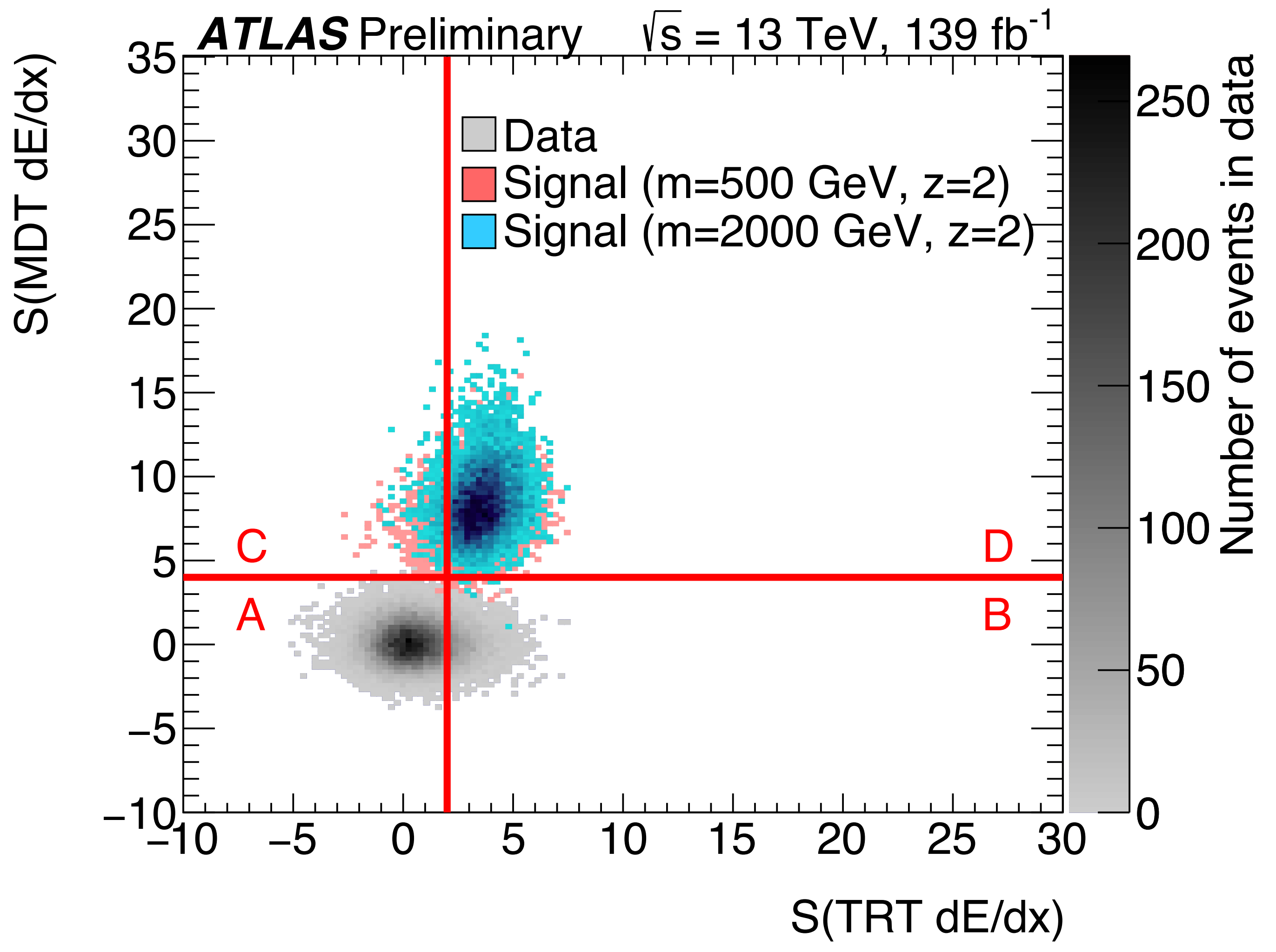


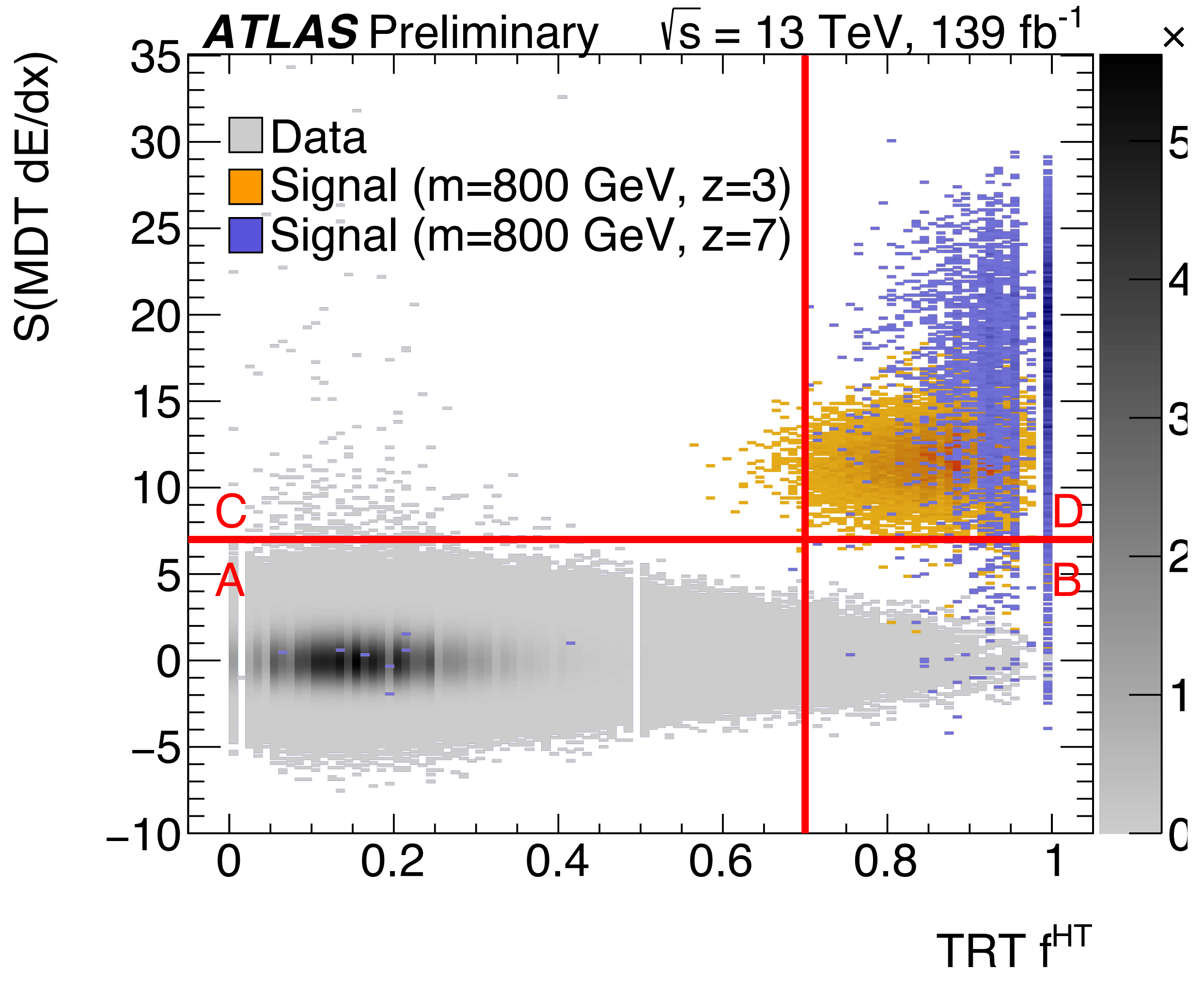
(*) Pixel dE/dx unused due to saturation and inefficiency.

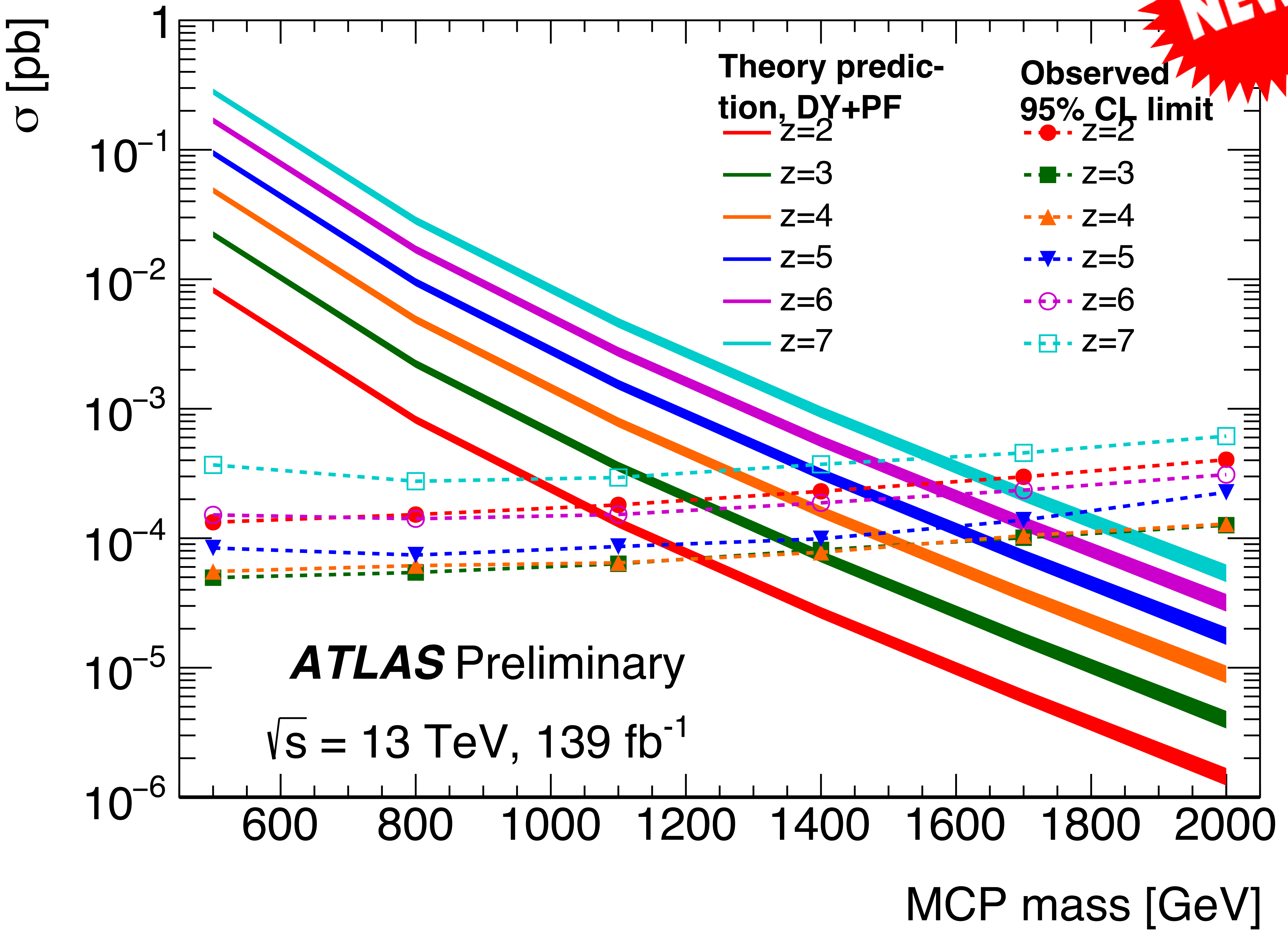
Multi-charged dE/dx (in multiple subsystems)

NEW!

- Background estimation: the ABCD method assuming two final discriminants are orthogonal each other.
- $z = 2$: $\mathcal{S}(\mathrm{d}E/\mathrm{d}x, \mathrm{TRT})$ & $\mathcal{S}(\mathrm{d}E/\mathrm{d}x, \mathrm{MDT})$
- $z > 2$: f_{HT} & $\mathcal{S}(\mathrm{d}E/\mathrm{d}x, \mathrm{MDT})$





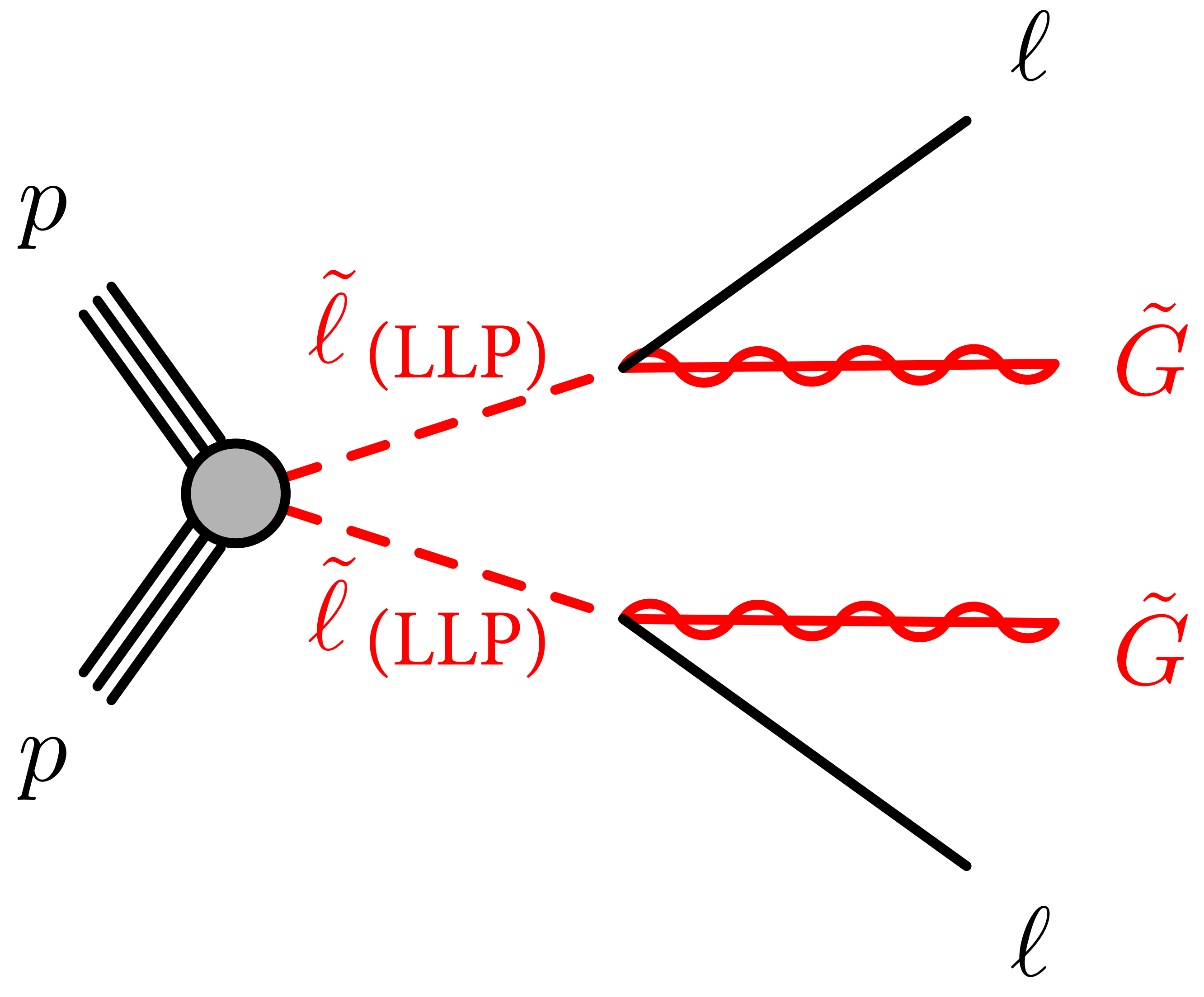


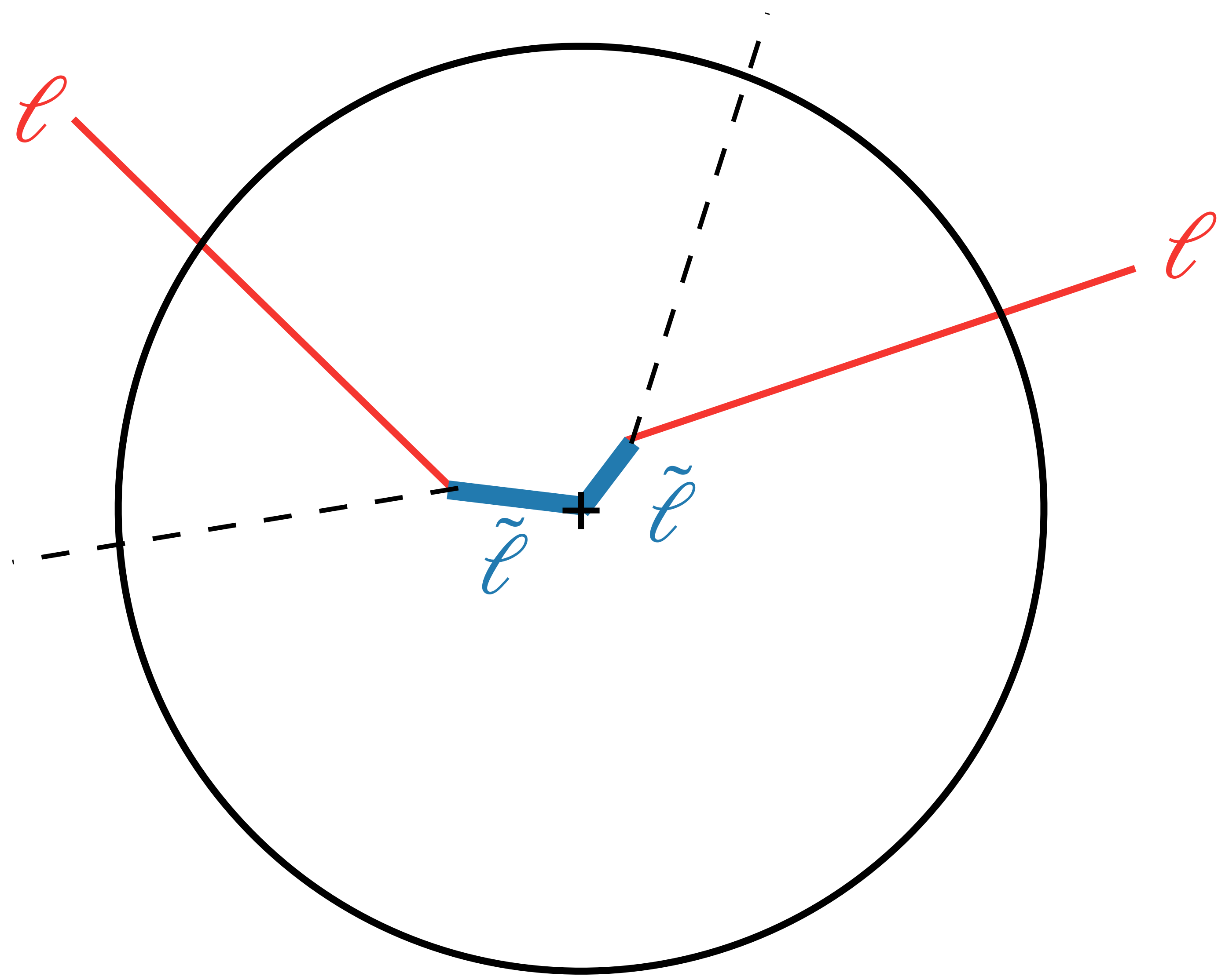
Selection	$N^{\mathrm{A\ observed}}_{\mathrm{data}}$	$N^{\mathrm{B\ observed}}_{\mathrm{data}}$	$N^{\mathrm{C\ observed}}_{\mathrm{data}}$	$N^{\mathrm{D\ expected}}_{\mathrm{data}}$	$N^{\mathrm{D\ observed}}_{\mathrm{data}}$
$z = 2$	24 294	4039	9	1.5 ± 0.5 (stat.) ± 0.5 (syst.)	4
$z > 2$	192 036 934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

- Observed events in SR well consistent with the estimation.
- Put stringent limits to MCPs

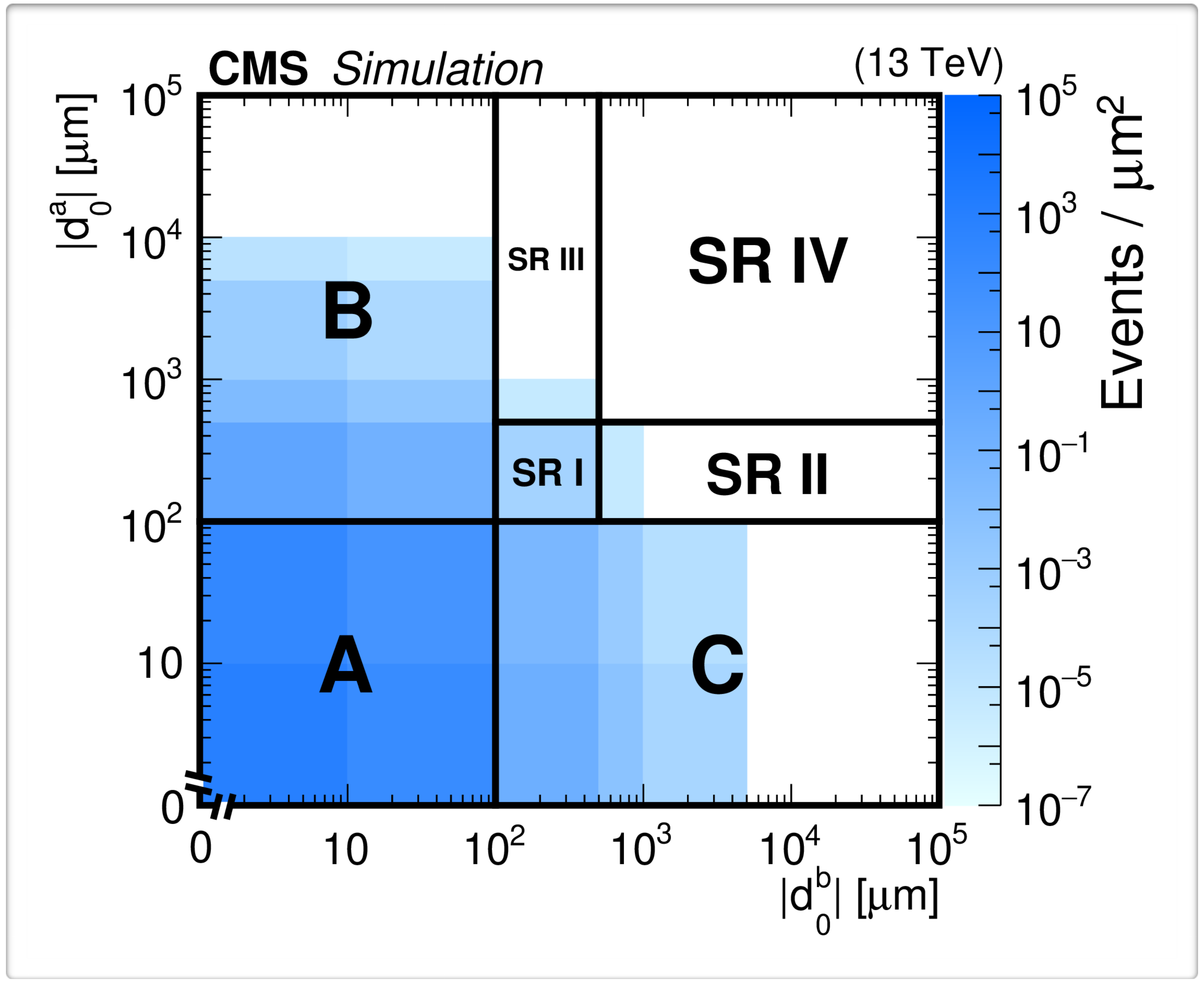
Displaced Leptons

- **Model**
  - GMSB-inspired slepton pair-production.
  - Slepton decays to a lepton and a massless LSP (gravitino).
  - Signature: 2x leptons (e or μ) with significant displacement from IP.





Signal Selection and Background Estimation



Signal region

- ee, $\mu\mu$ and $e\mu$ (no charge requirement)
- SR sub-divided into 4 bins by $|d_0|$

Signal selection

(*) Proxy of electron triggers to be more inclusive.

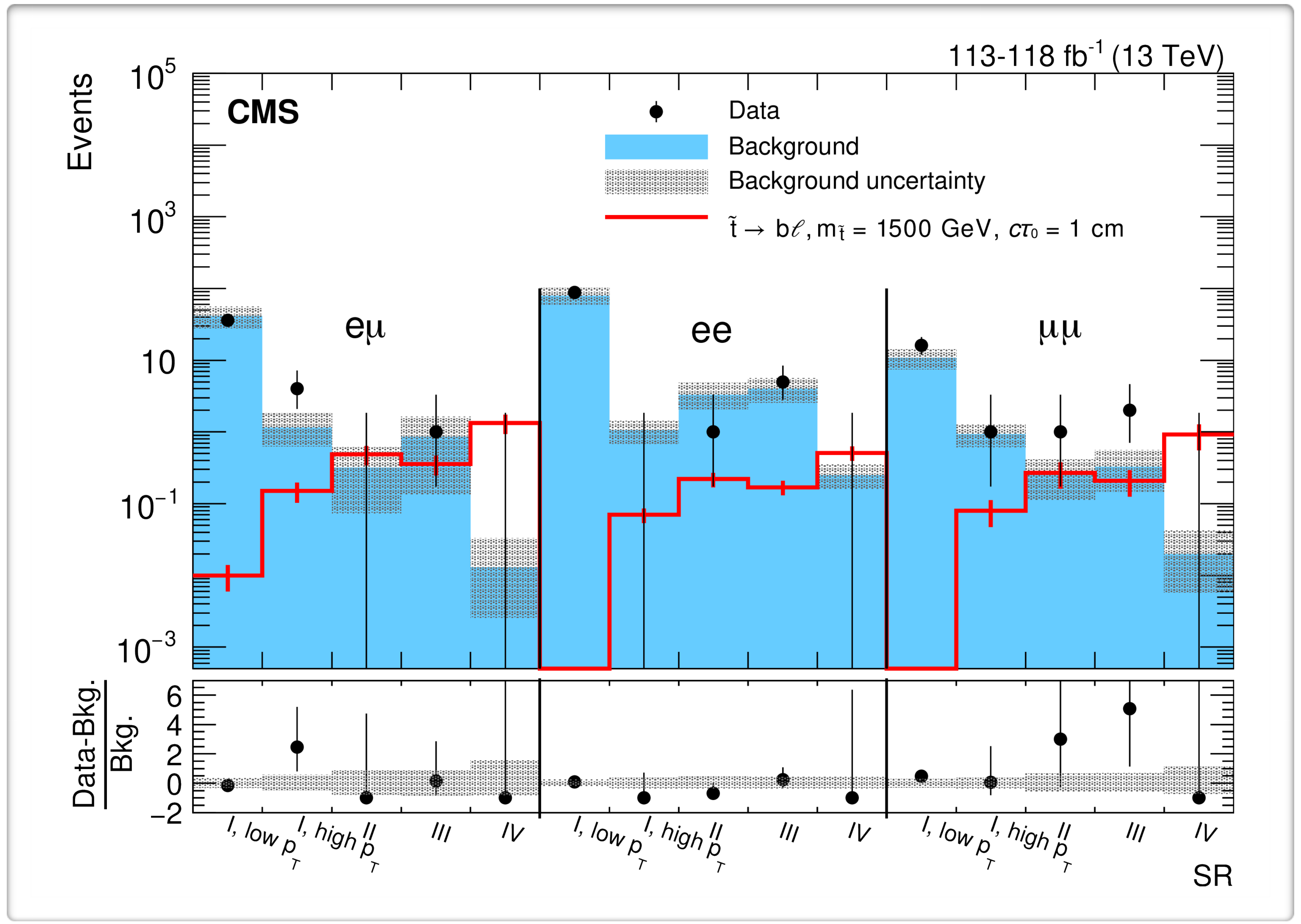
- Muon and photon(*) triggers. No IP requiement.
- 2x isolated high-pT good-quality leptons
- Minimum pT depending on each flavor's turn-on
- $|\eta| < 1.5$
- Impact parameter: $100\ \mu\mathrm{m} < |d_0| < 10\ \mathrm{cm}$

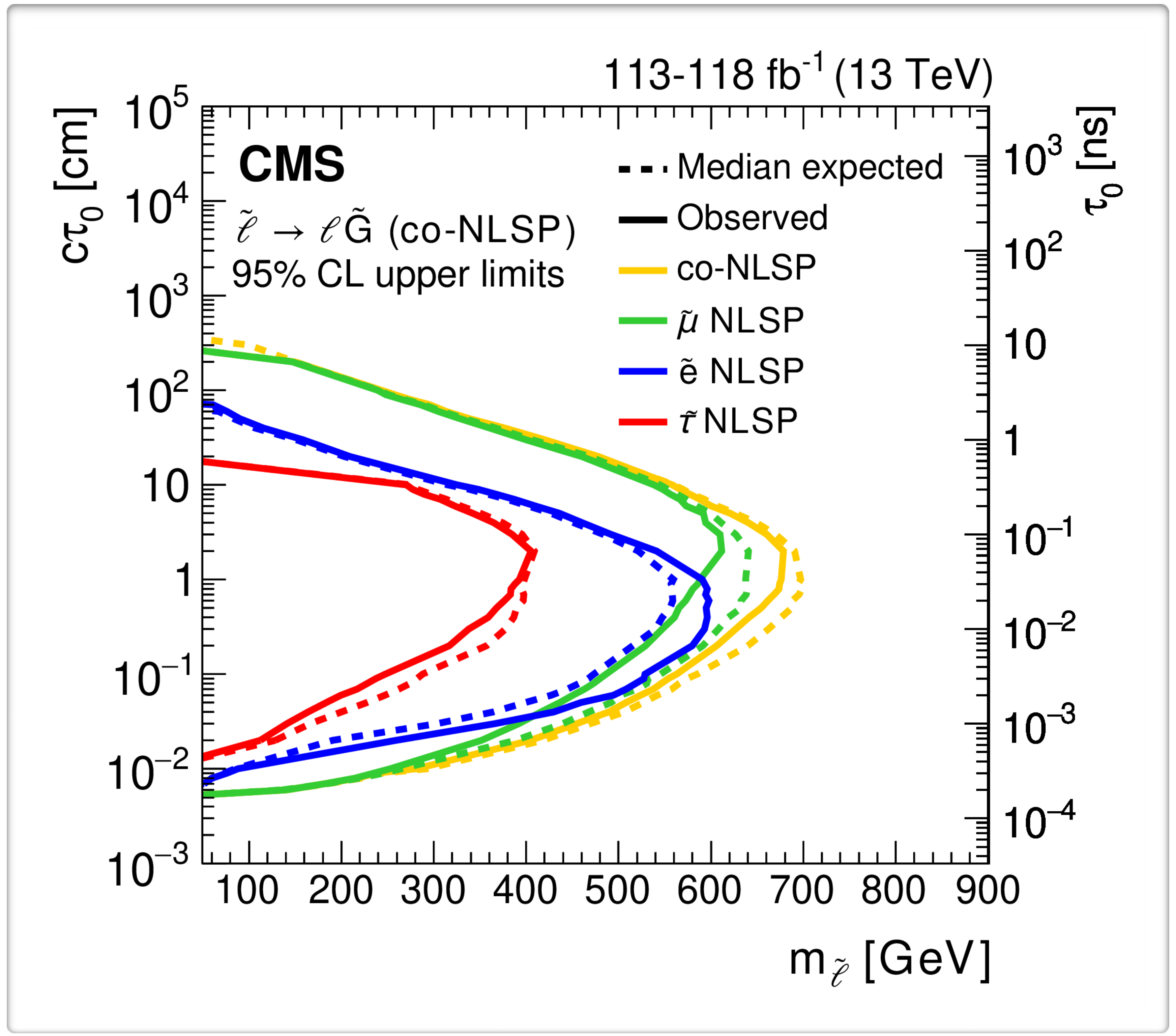
Background estimation

- Source: poorly measured prompt leptons
  Semi-leptonic decays of tau, heavy-flavor decays
- A binned ABCD method assuming impact parameters of 2 candidate leptons are uncorrelated.

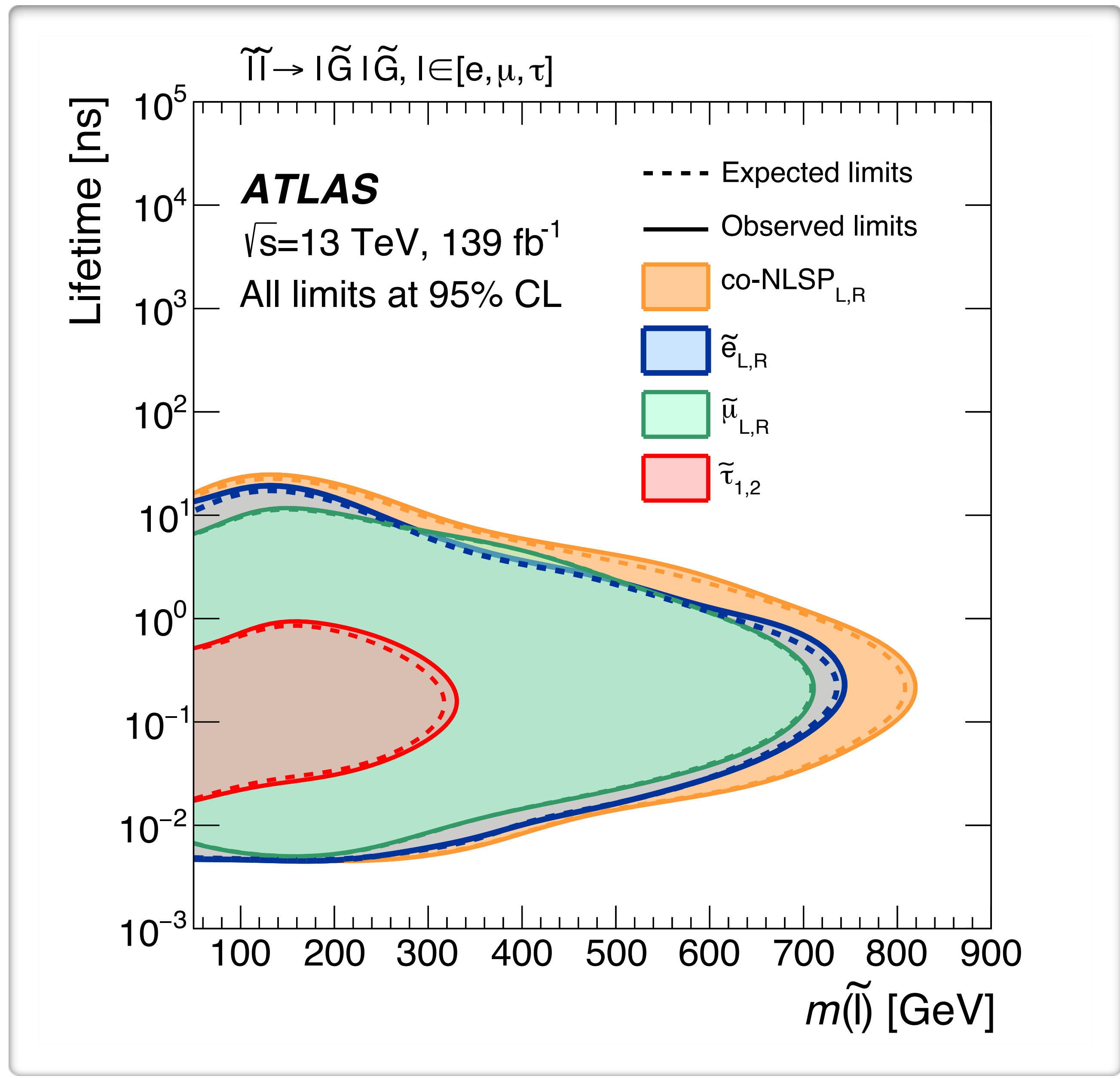
$$N_{\mathrm{SR}}^{(i)} = N_B^{(i)} \times N_C^{(i)}\ /\ N_A^{(i)} \quad (i = \mathrm{I, II, III, IV})$$

Results & Limits



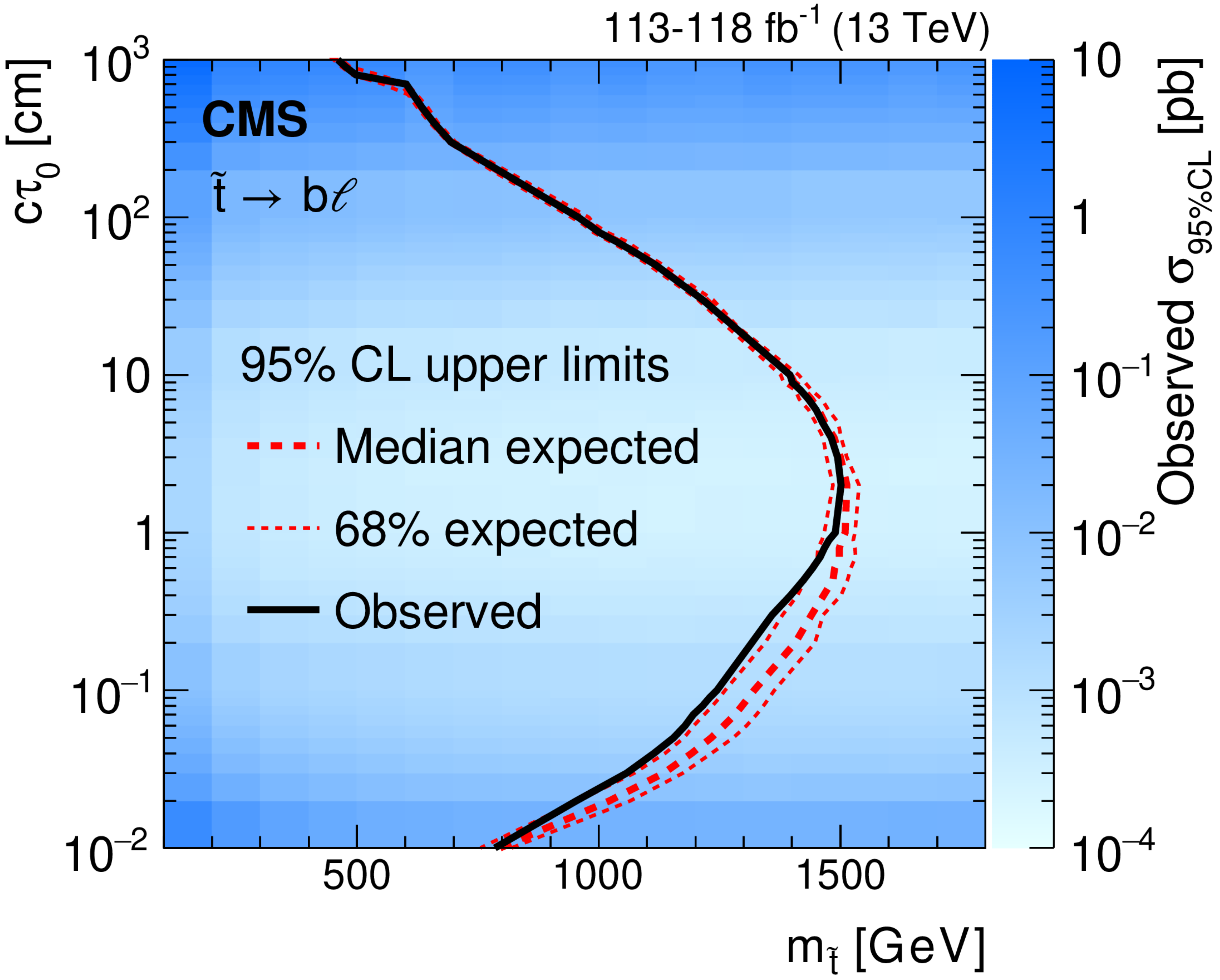


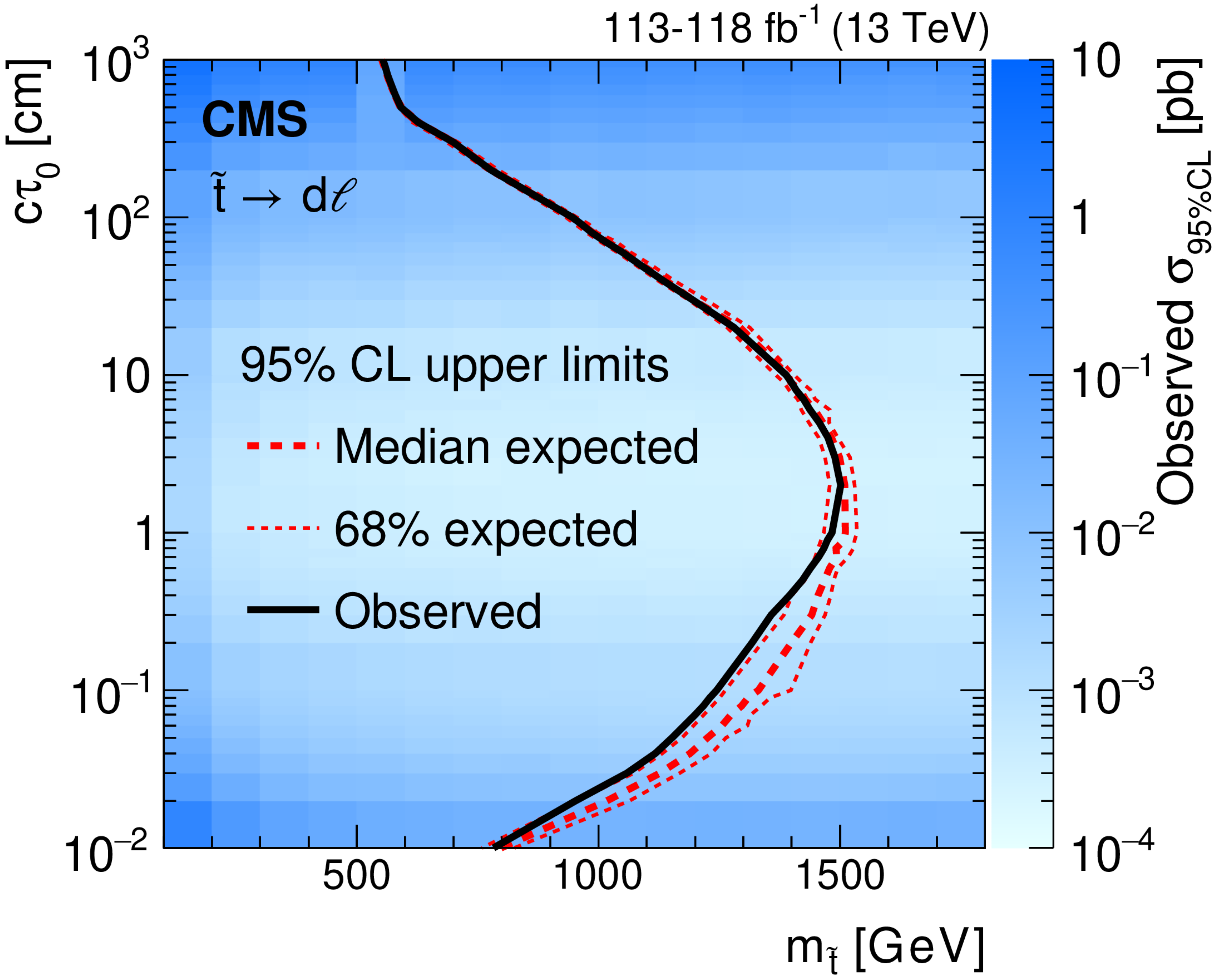
ATLAS-SUSY-2018-14, PRL 127 (2021) 051802



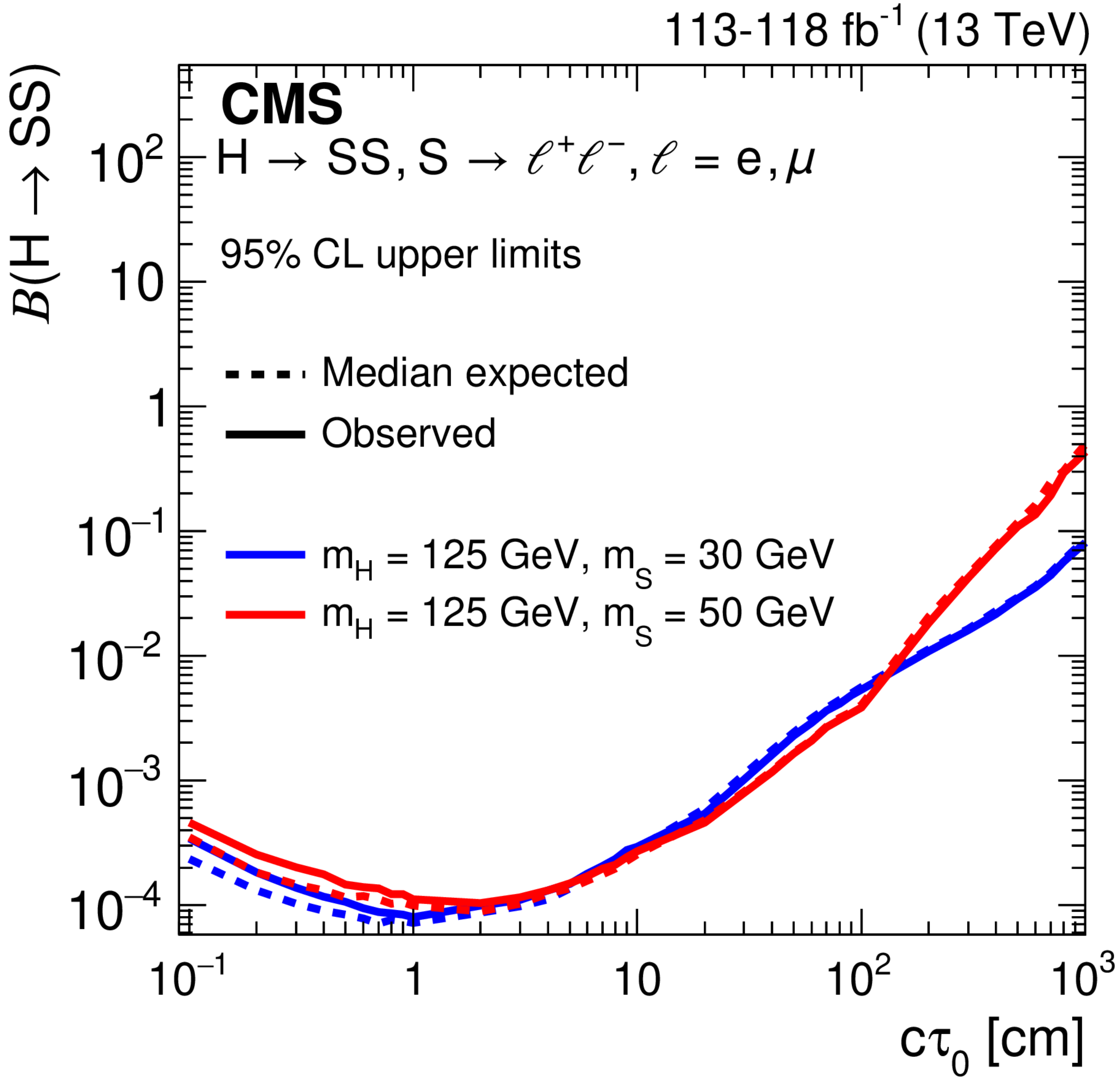
- Observed SR event yields agree well with the prediction in all bins.
- Very stringent limits to all slepton flavors in quite a wide lifetime scales down to ~ 100 μm of the decay length! (extending the ATLAS earlier result)

Limits for RPV (LQD) $\tilde{t} \to q\ell$

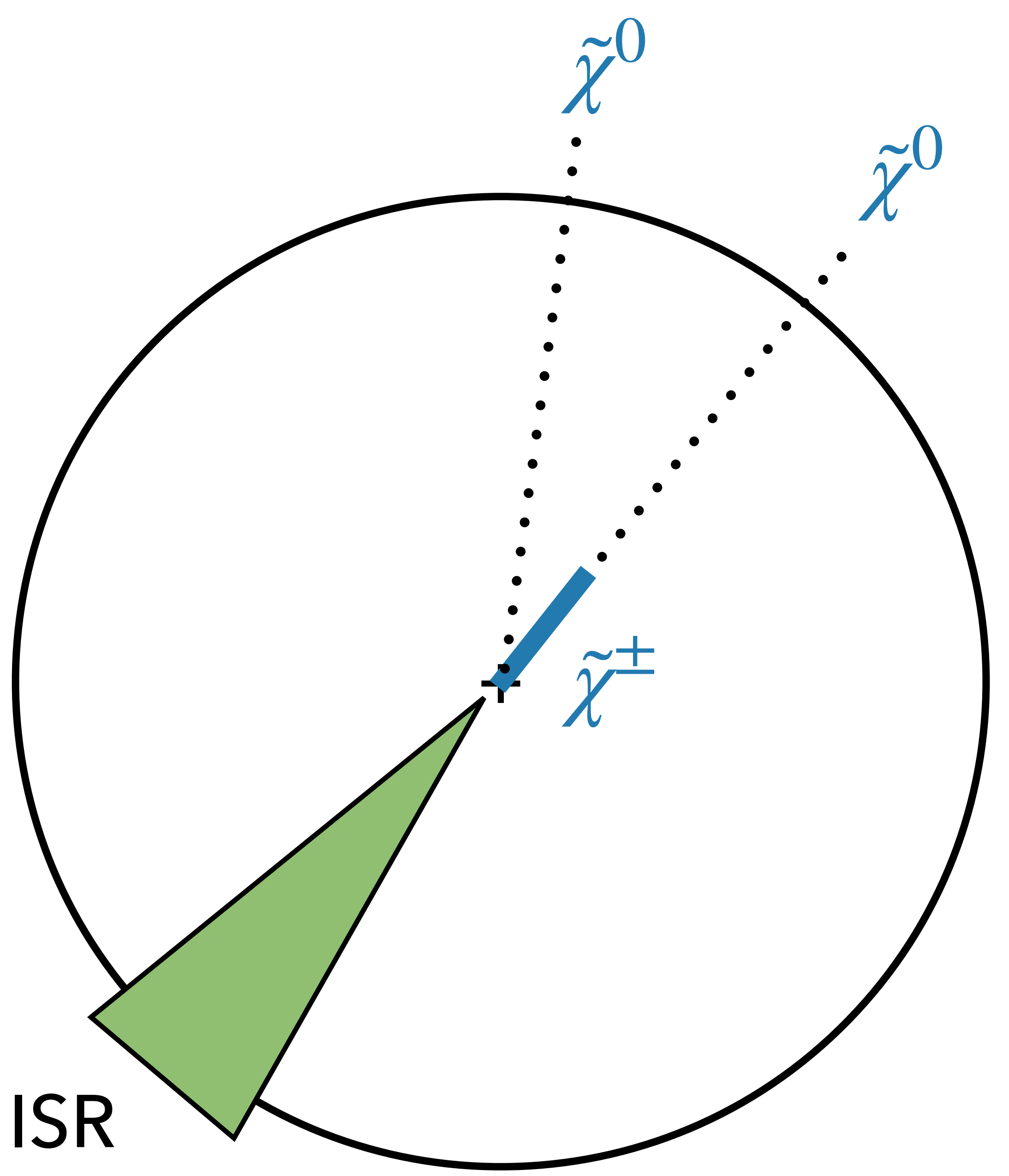




Limits for $H \to SS, S \to \ell^+\ell^-$



Disappearing Track



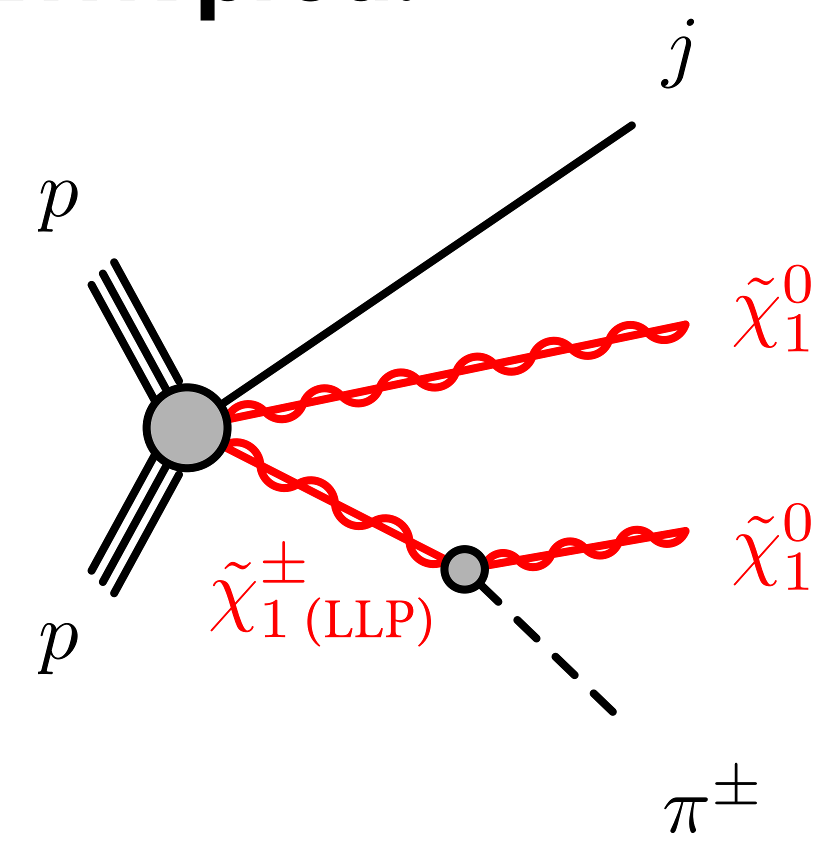
Scenario: Decay phase-space highly suppressed by degeneracy

- AMSB pure-wino case: $\Delta m(\tilde{\chi}^\pm, \tilde{\chi}^0) \simeq 160$ MeV, $c\tau(\tilde{\chi}^\pm) \sim 60$ mm
- Pure-higgsino case: $\Delta m(\tilde{\chi}^\pm, \tilde{\chi}^0) \simeq 340$ MeV, $c\tau(\tilde{\chi}^\pm) \sim$ 6-15 mm
- DM abundance argument accepts up to 3 TeV (1 TeV) for wino (higgsino).

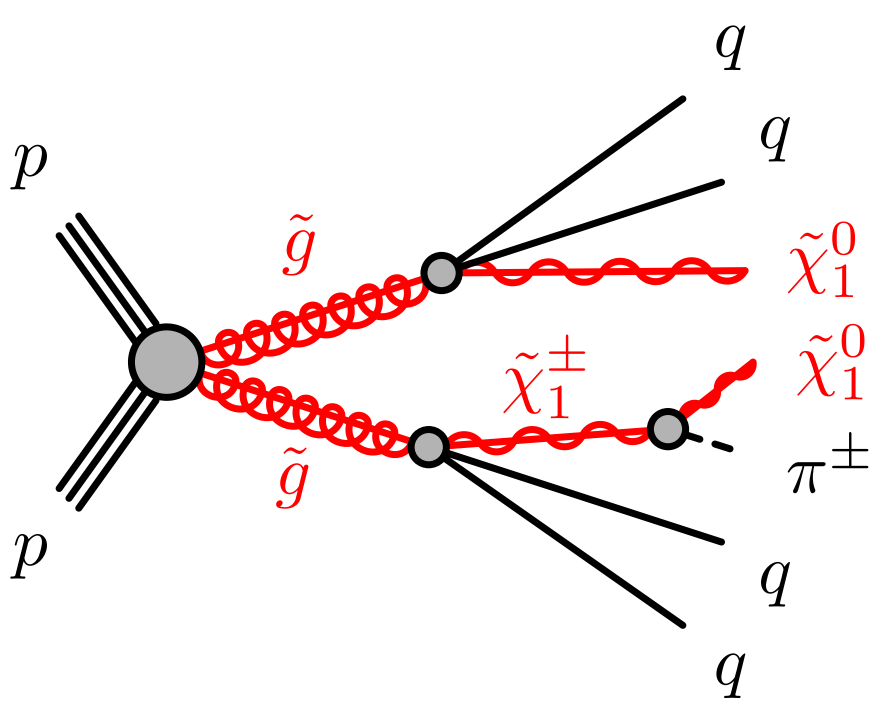
Signature

- Even with the ISR recoil boost, the CLLP can pass only first several layers of the inner tracking system before decay.
- Decay objects (pion) are too soft to be identified.
- Main signature: $E_{\mathrm{T}}^{\mathrm{miss}}$ + jet(s) + well-isolated **tracklet**.
- Production: direct (**EWK**) or production via gluino (**Strong**).

EWK prod.

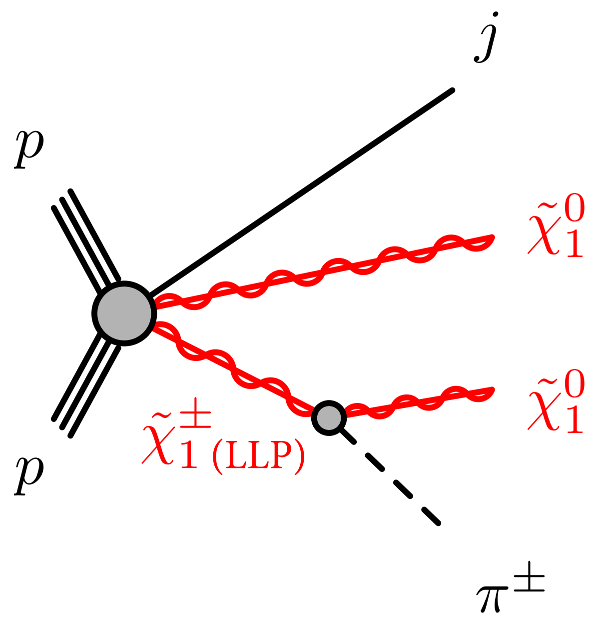


Strong prod.



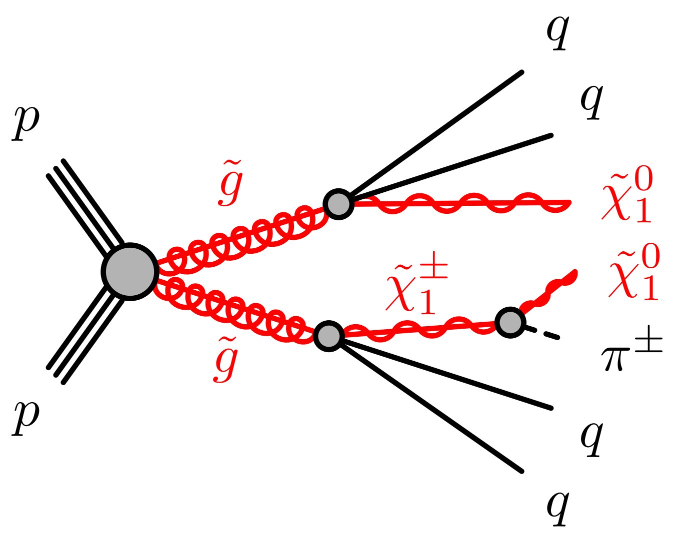
Signal Selection and Background

SR for EWK



- $E_T^{miss} > 200$ GeV
- ≥ 1 jet w/ $p_T > 20$ GeV
- $\Delta\phi(E_T^{miss}, \text{jet}) > 1.0$

SR for Strong



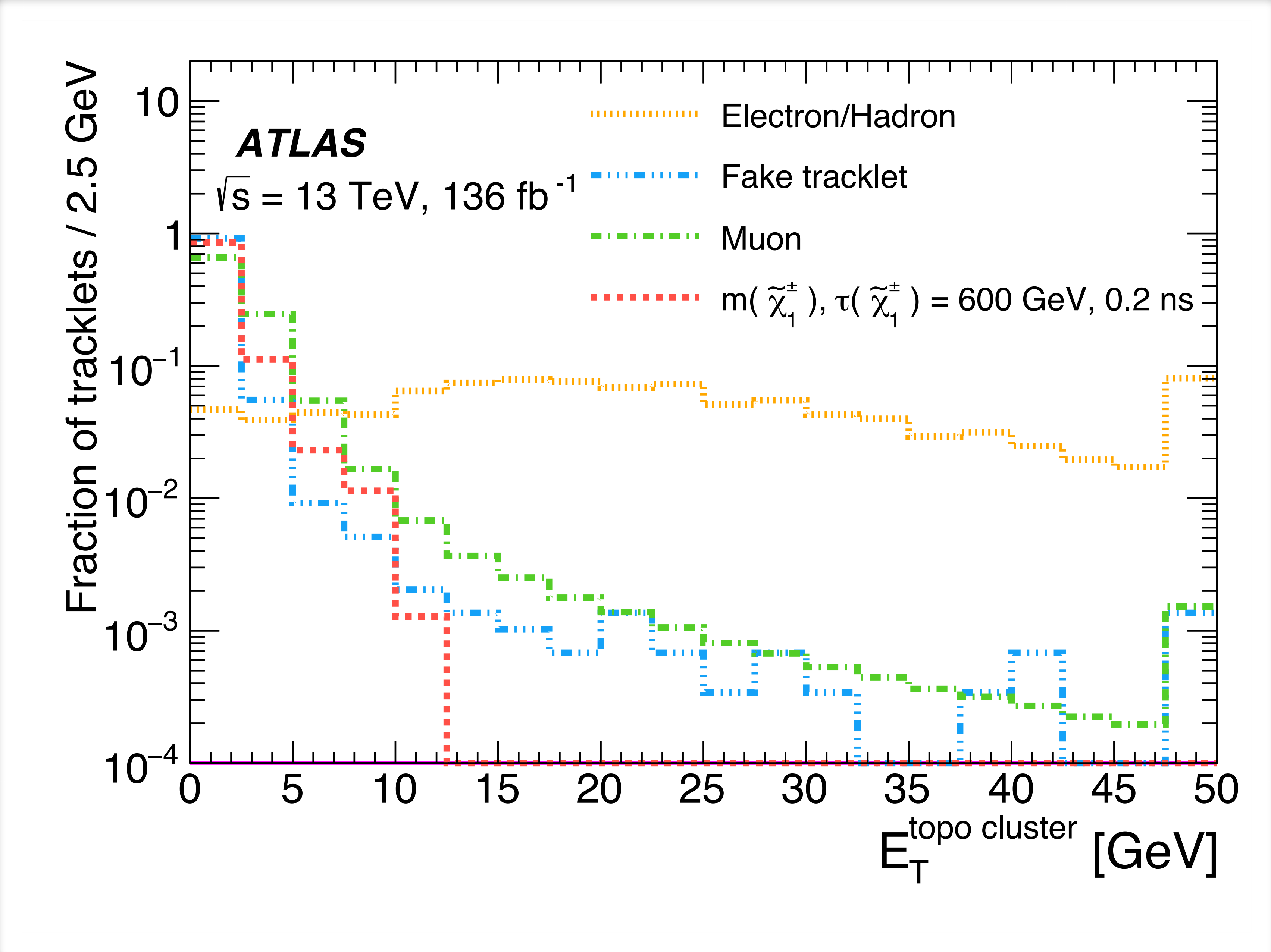
- $E_T^{miss} > 250$ GeV
- ≥ 3 jet w/ $p_T > 20$ GeV
- $\Delta\phi(E_T^{miss}, \text{jet}) > 0.4$

3 Major Backgrounds

- Charged hadrons
- Electrons
- Fake Tracklets

Signal Selection

- Tracklets reconstructed using left-over hits after the standard tracking within the Pixel detector ($r < 12$ cm).
- Requires hits in 4 (barrel) layers and isolation.
- Veto hits in outer strip layers.
- Vecto activities in the extrapolated calorimeter cell (new).
  → Effective to reduce hadrons and electrons background.

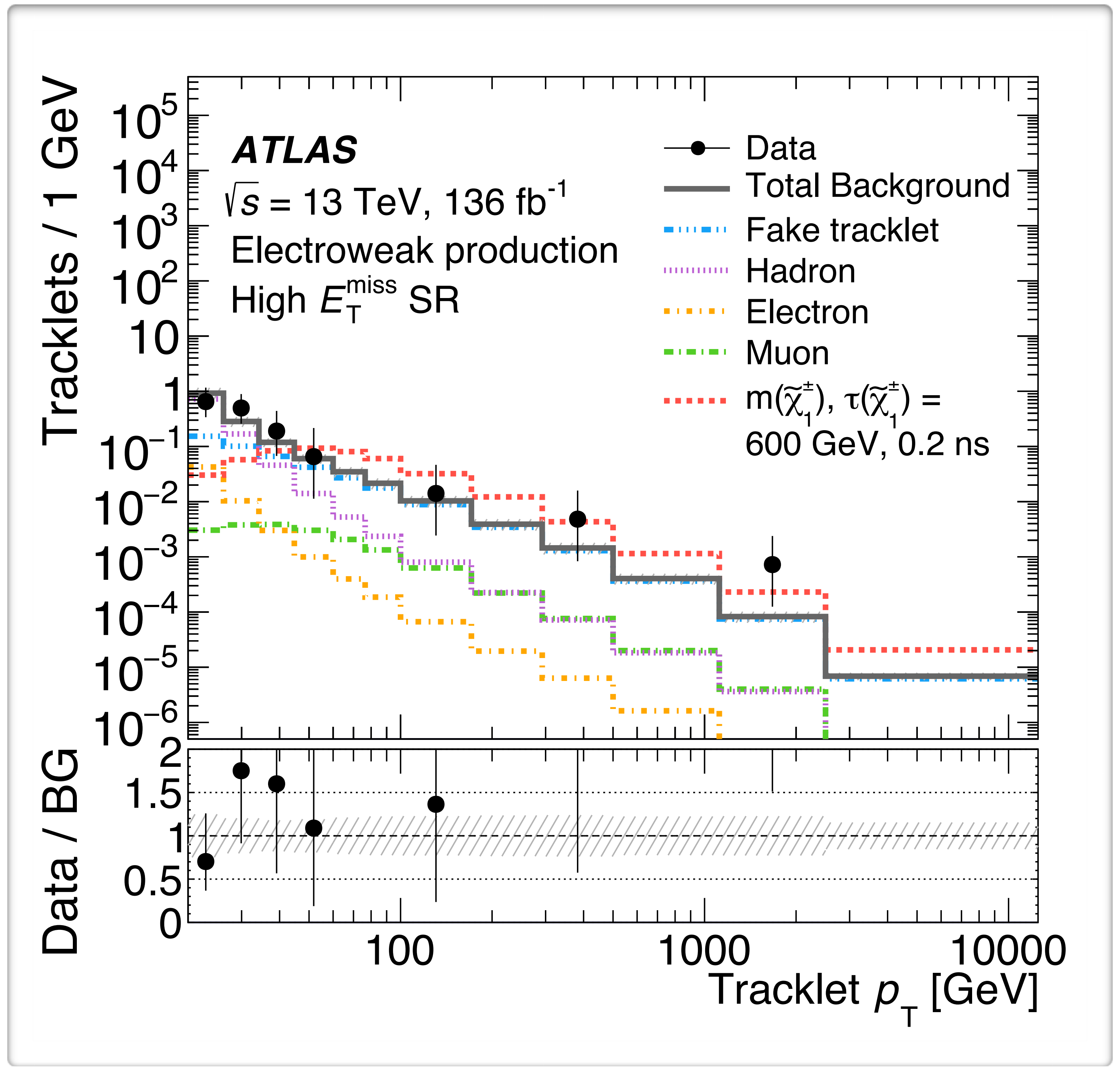


Results

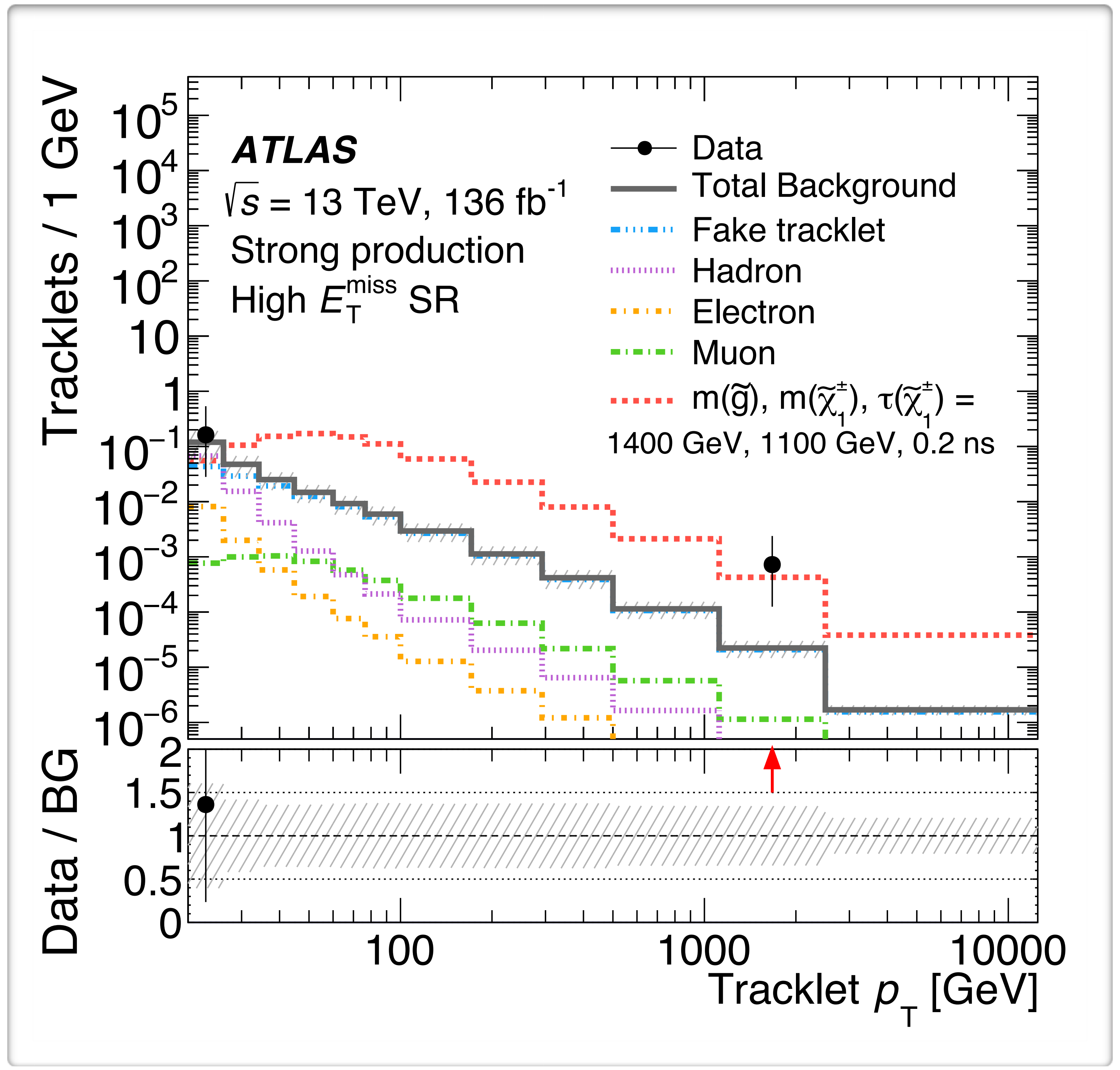
Background Estimation

- Full data-driven approach
- The template p_T spectrum is extracted from control regions for each source of the bkg. component.
- Simultaneous fit of the spectrum in SR and sideband VRs.
- High-p_T SR dominated by fake tracklet backgrounds.
- The observed data perfectly agree with the estimation for both signal regions.

Electroweak SR



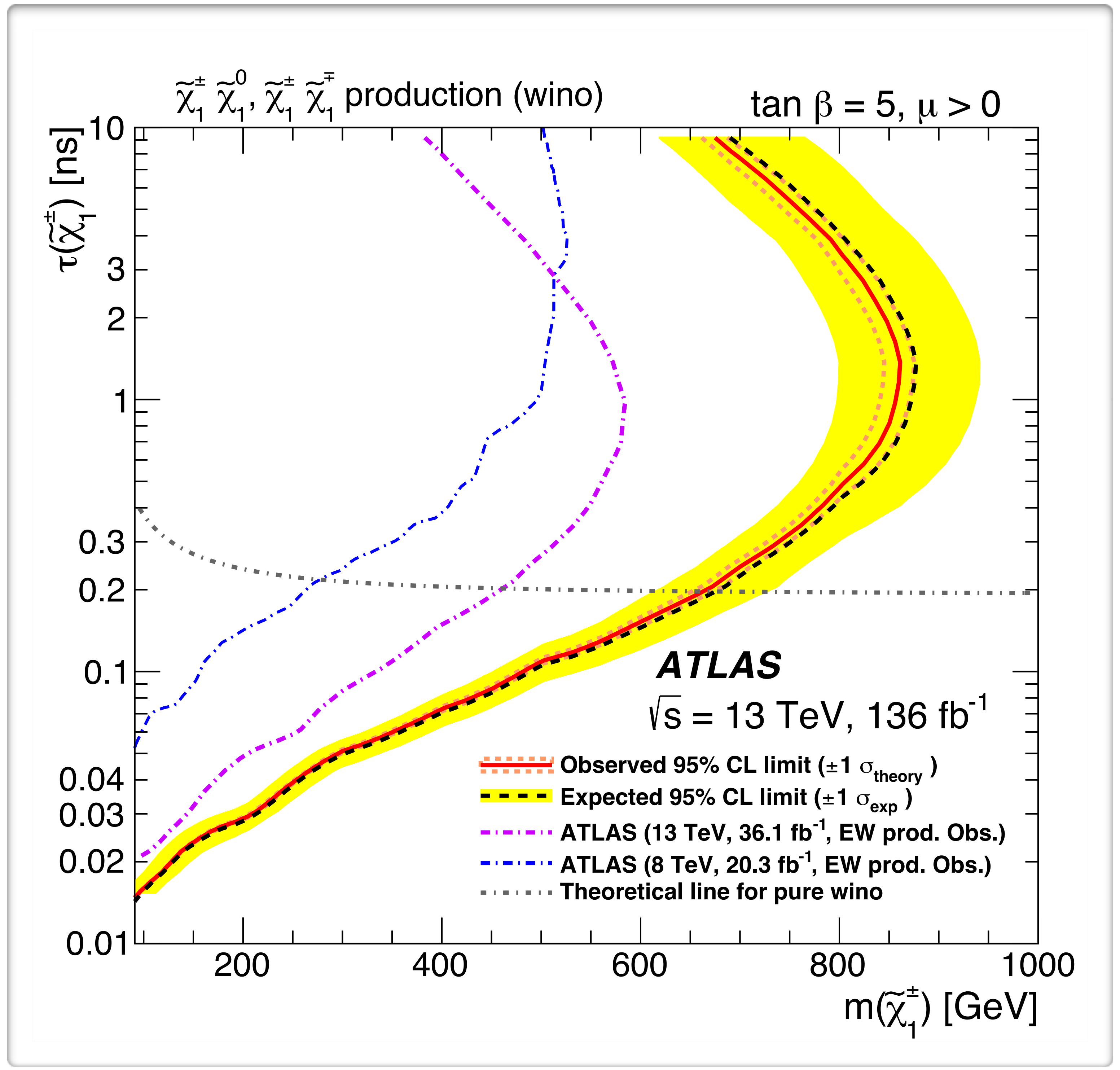
Strong SR



ATLAS-SUSY-2018-19, arXiv:2201.02472

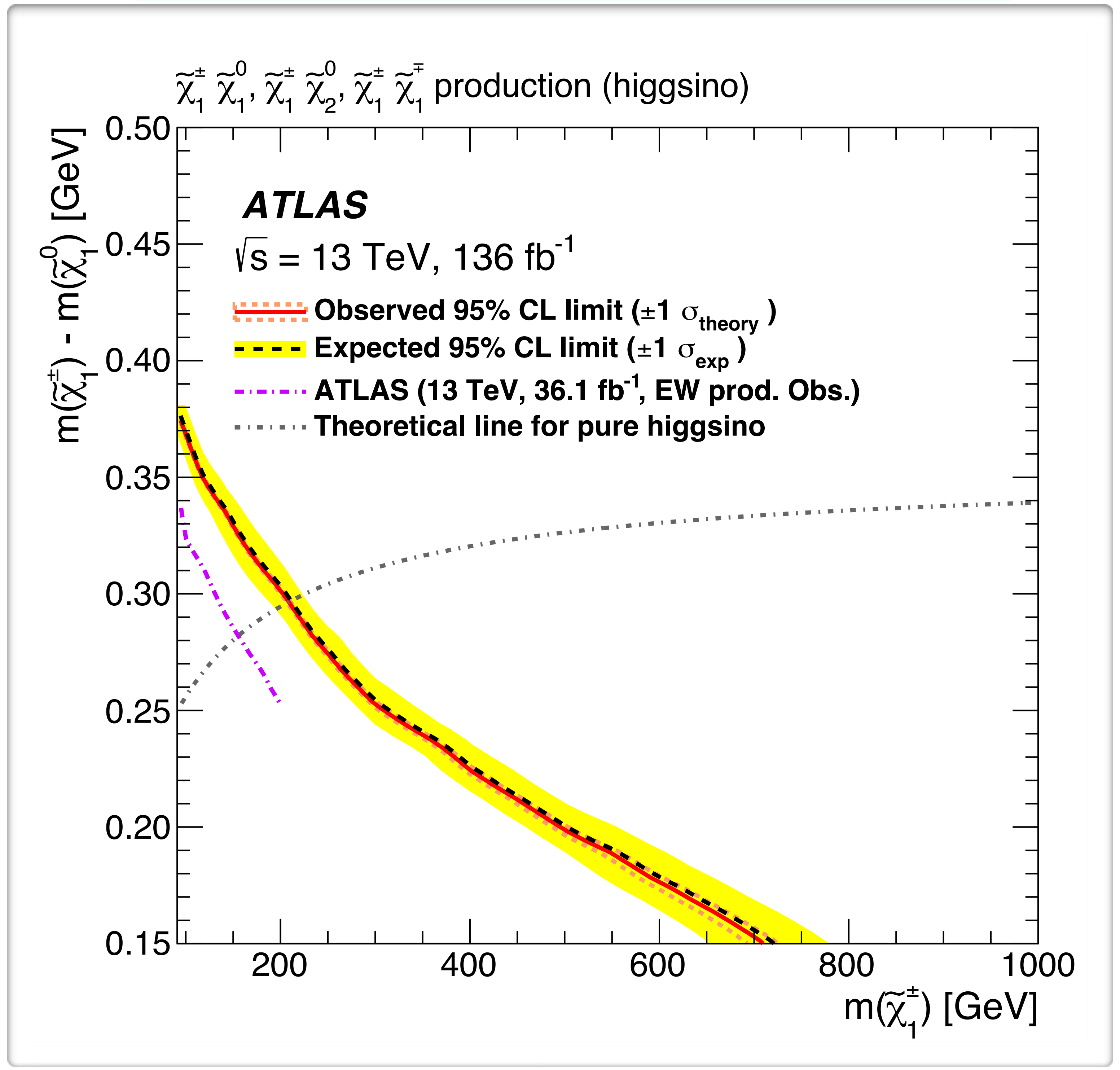
Limits

EWK Production (Pure-Wino/AMSB)



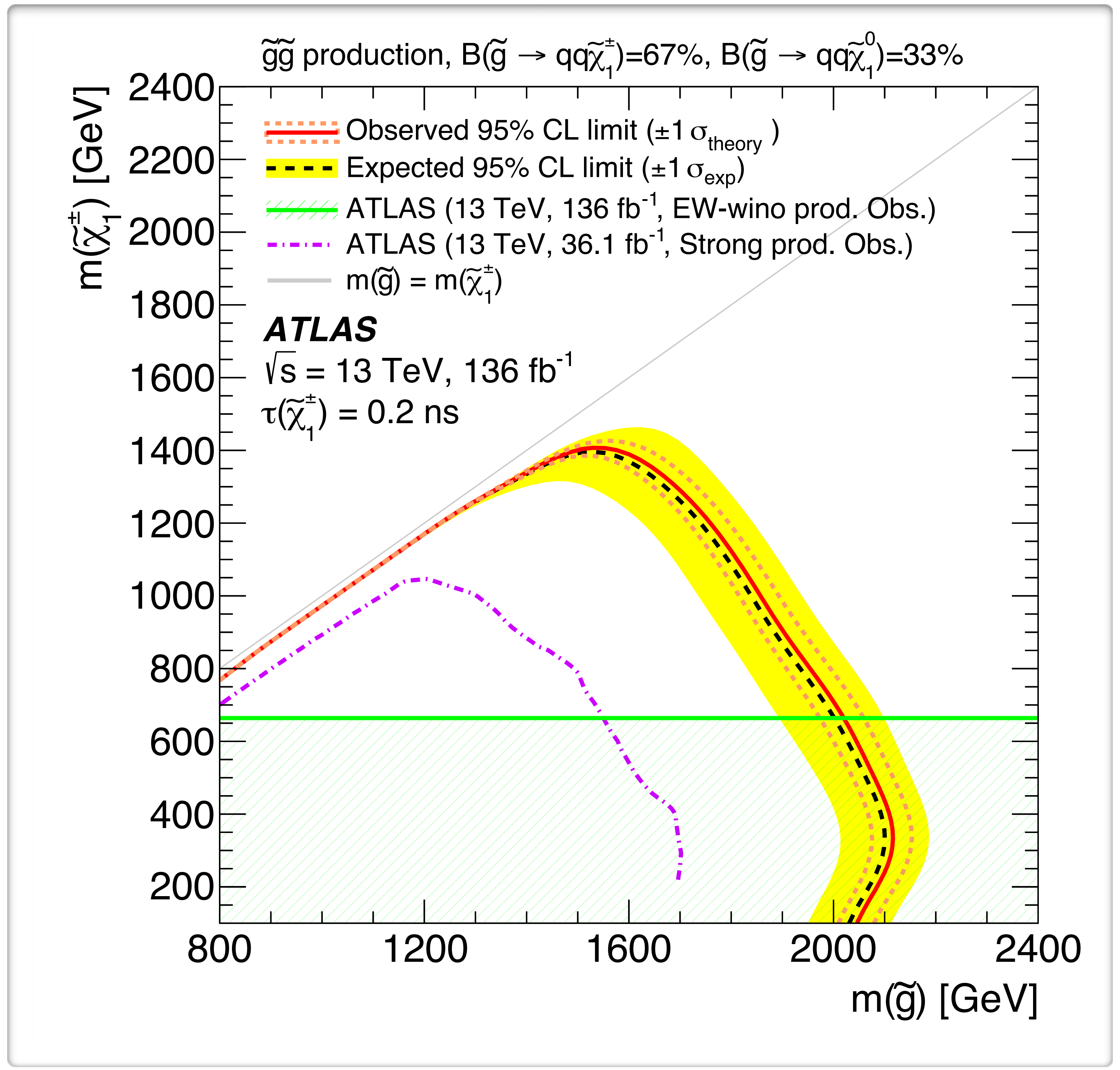
Excluded <660 GeV Wino

EWK Production (Pure-Higgsino)



Excluded <210 GeV Higgsino

Strong Production

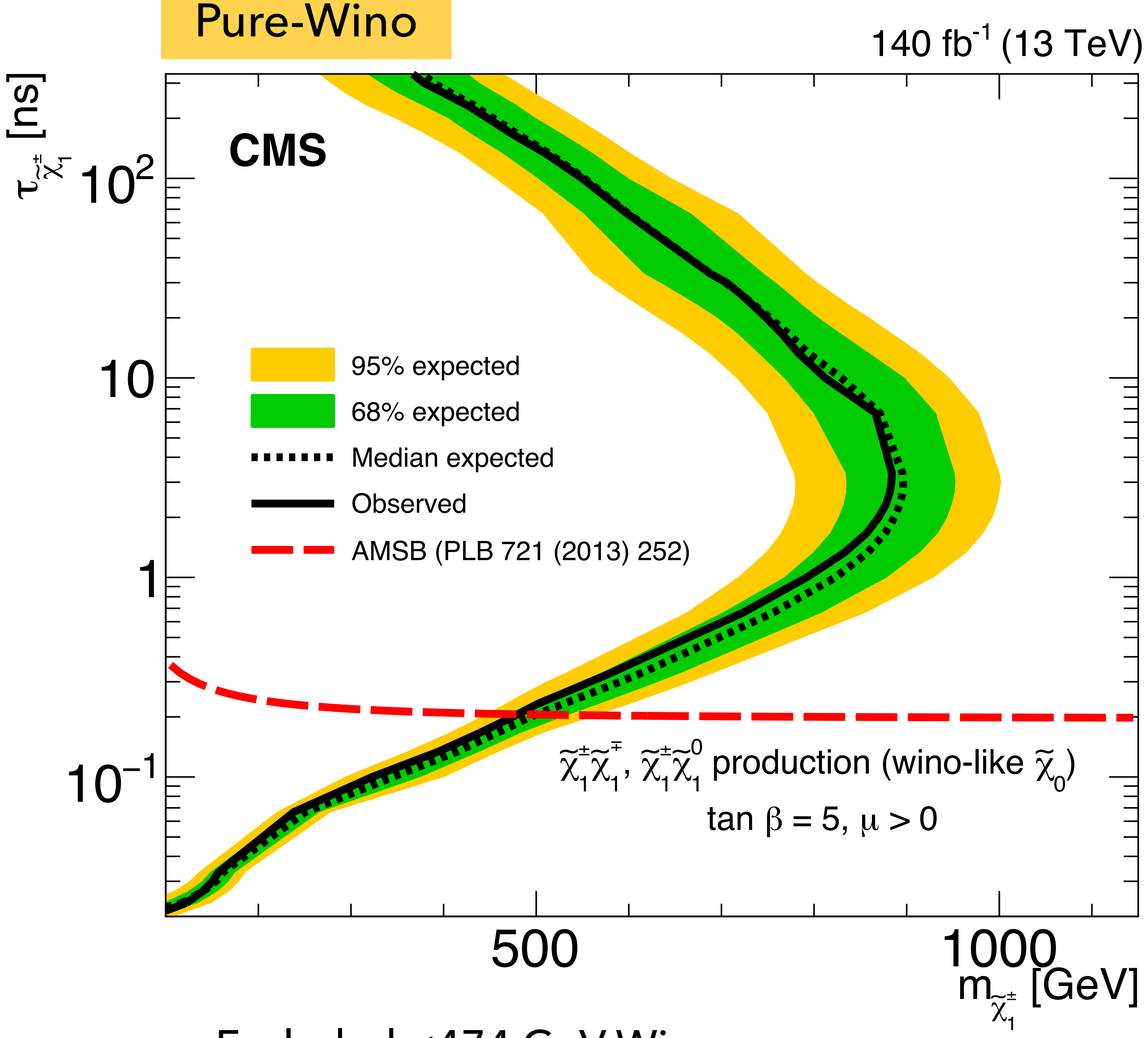


Excluded <2.1 TeV gluino for 300 GeV chargino

- Stringent limits to well-inspired DM scenarios by a dedicated search!

CMS Disappearing Track Limits

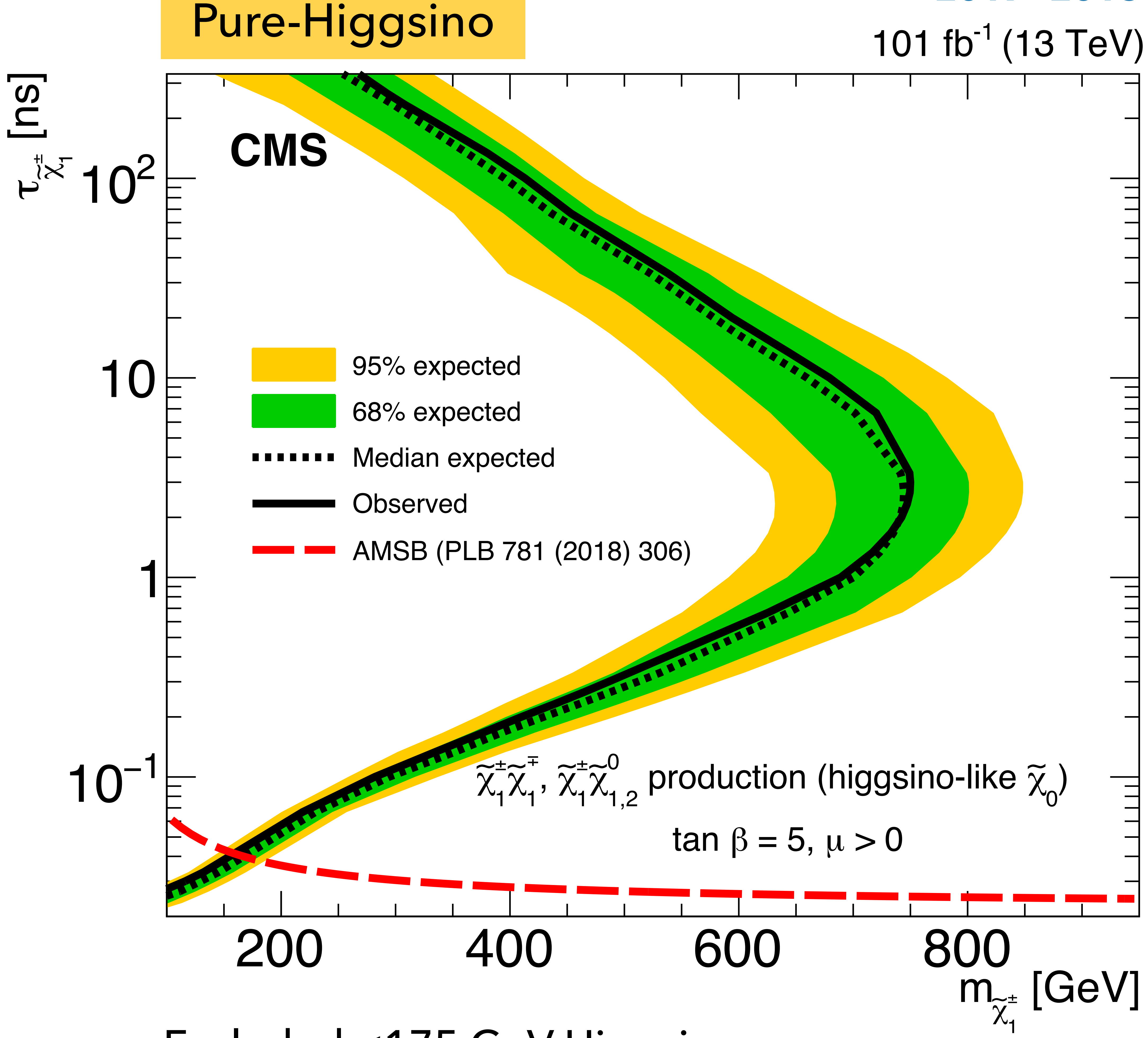
Pure-Wino



Excluded <474 GeV Wino

Pure-Higgsino

2017+2018



Excluded <175 GeV Higgsino