Nordita Workshop: Is There Still Room For Naturalness (April 18-29th 2022, Stockholm)

Non-natural Signatures in the Pursuit of Naturalness

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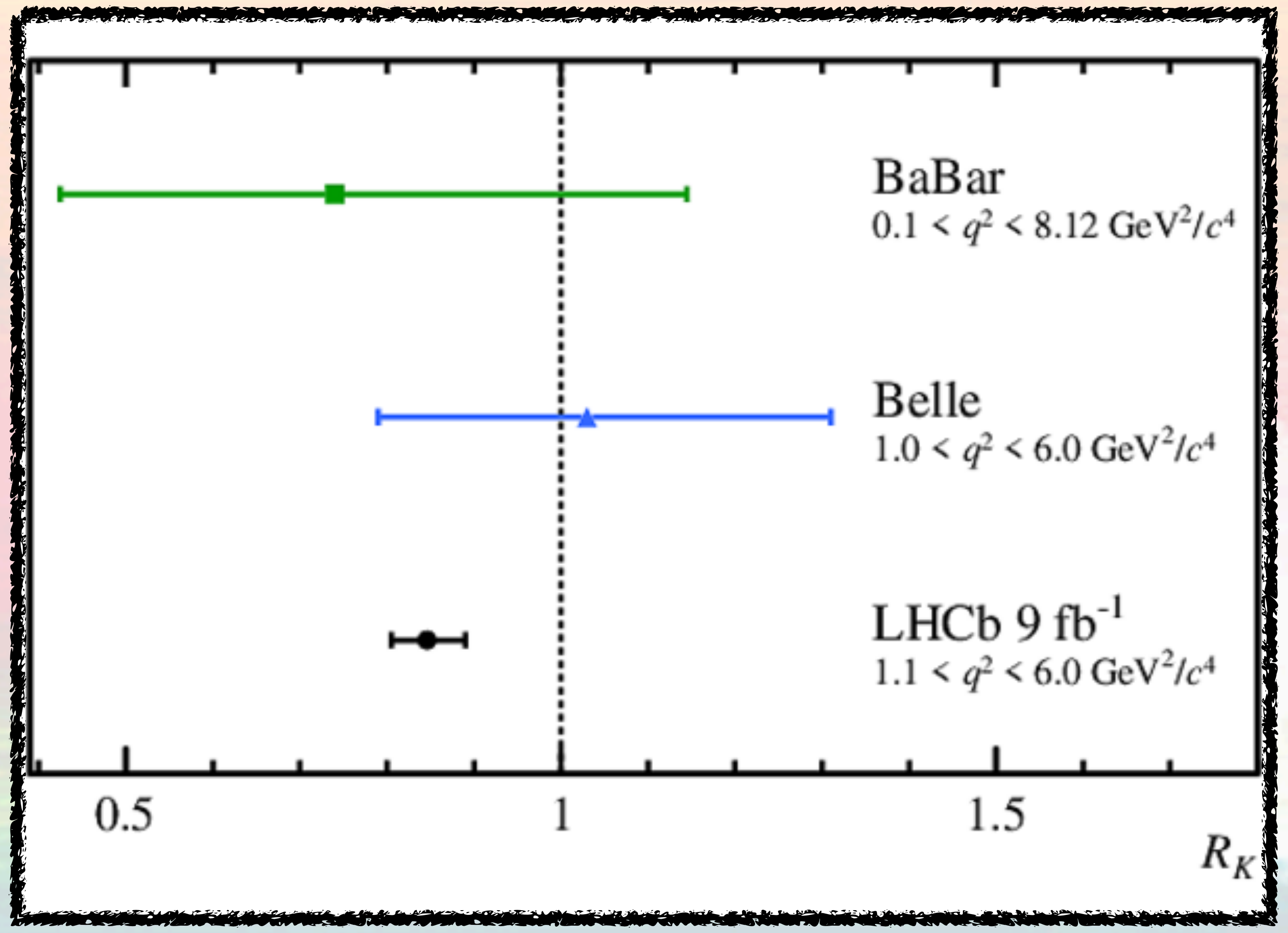
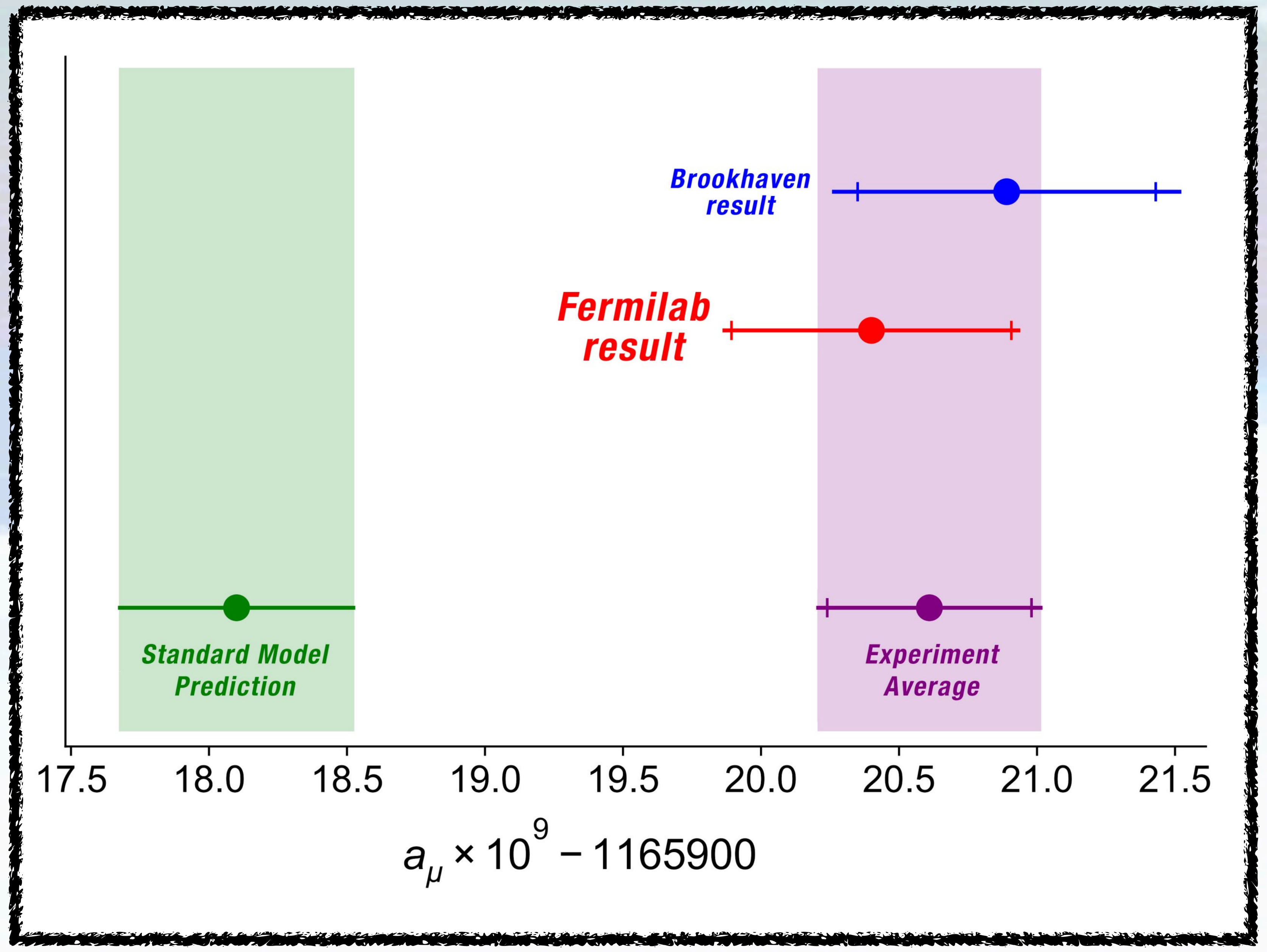
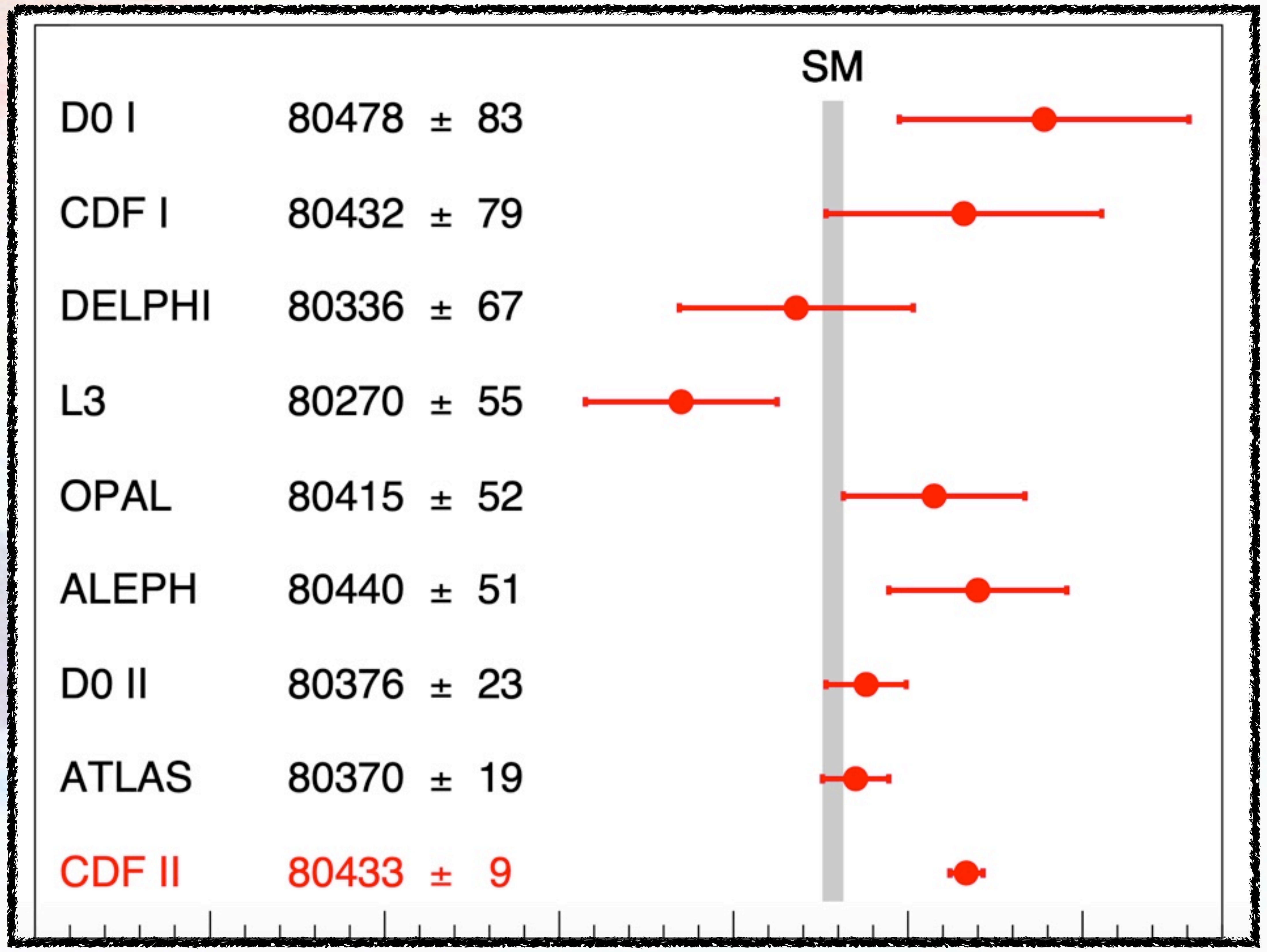
ATLAS EXPERIMENT

SFU SIMON FRASER UNIVERSITY

Exciting Time!



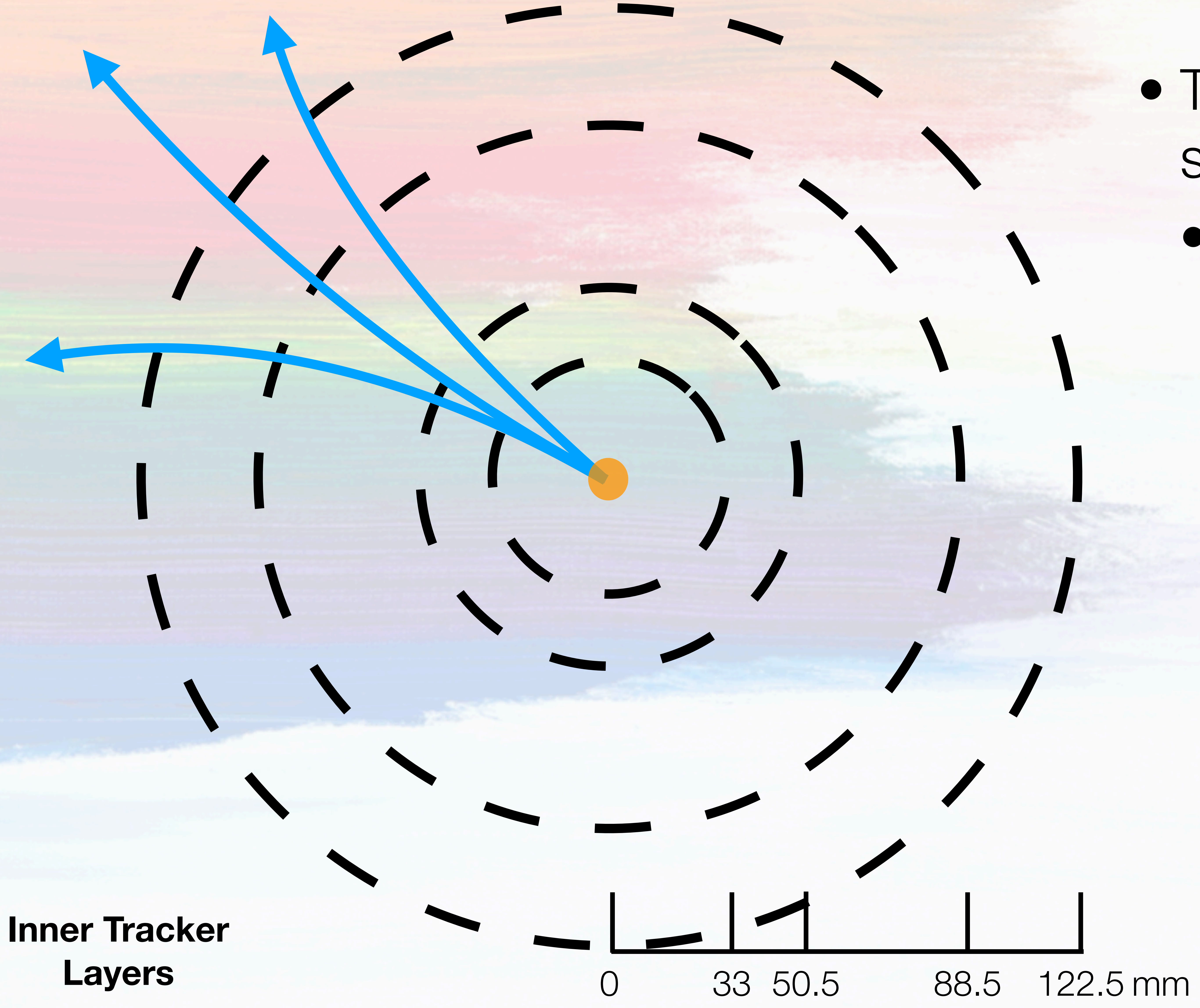




Hmmm..Ok what do these tell me. It looks like searches involving third generation is important, precision measurement is also vital and maybe something a bit more crazy???? So....

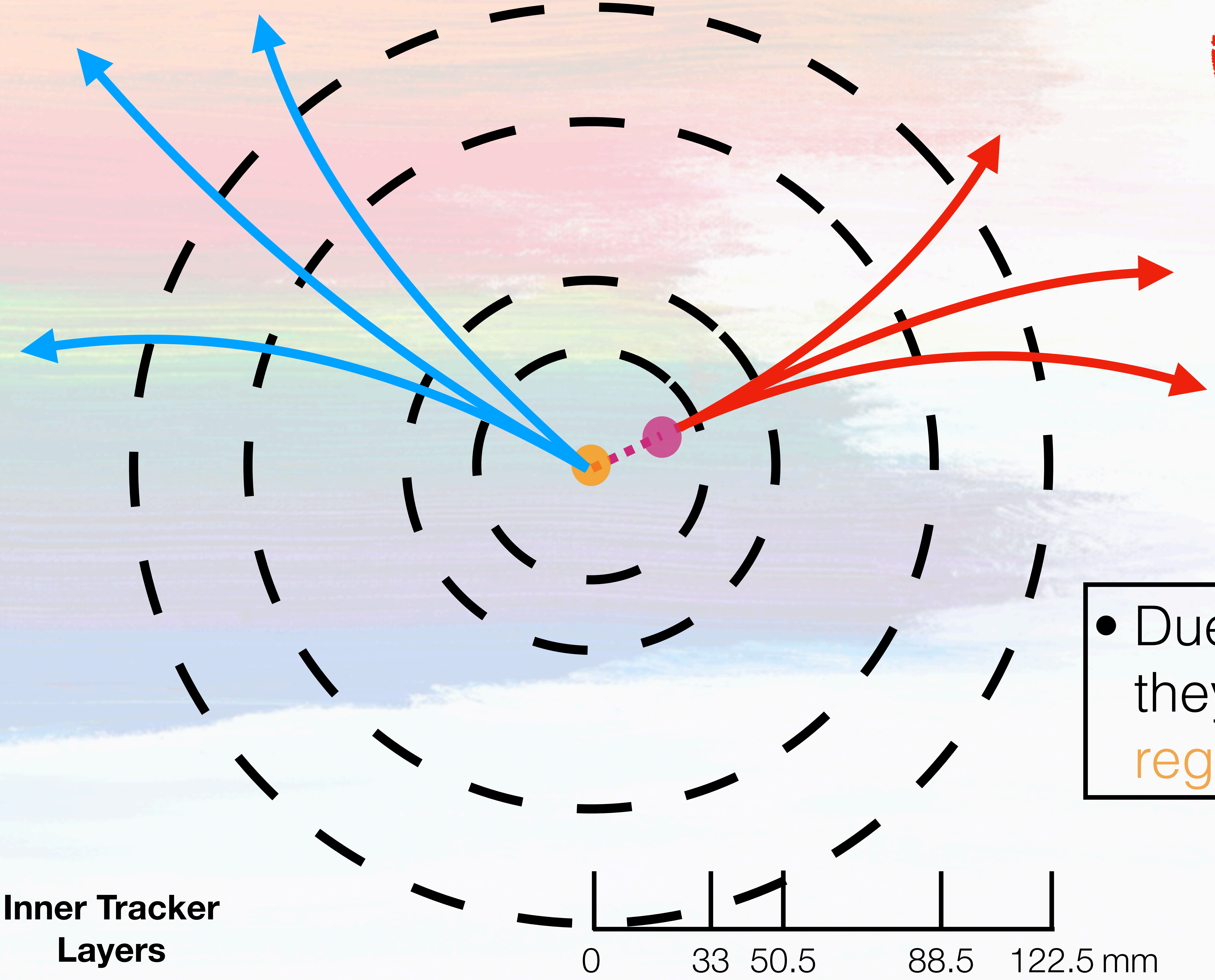
Is there still room for naturalness?

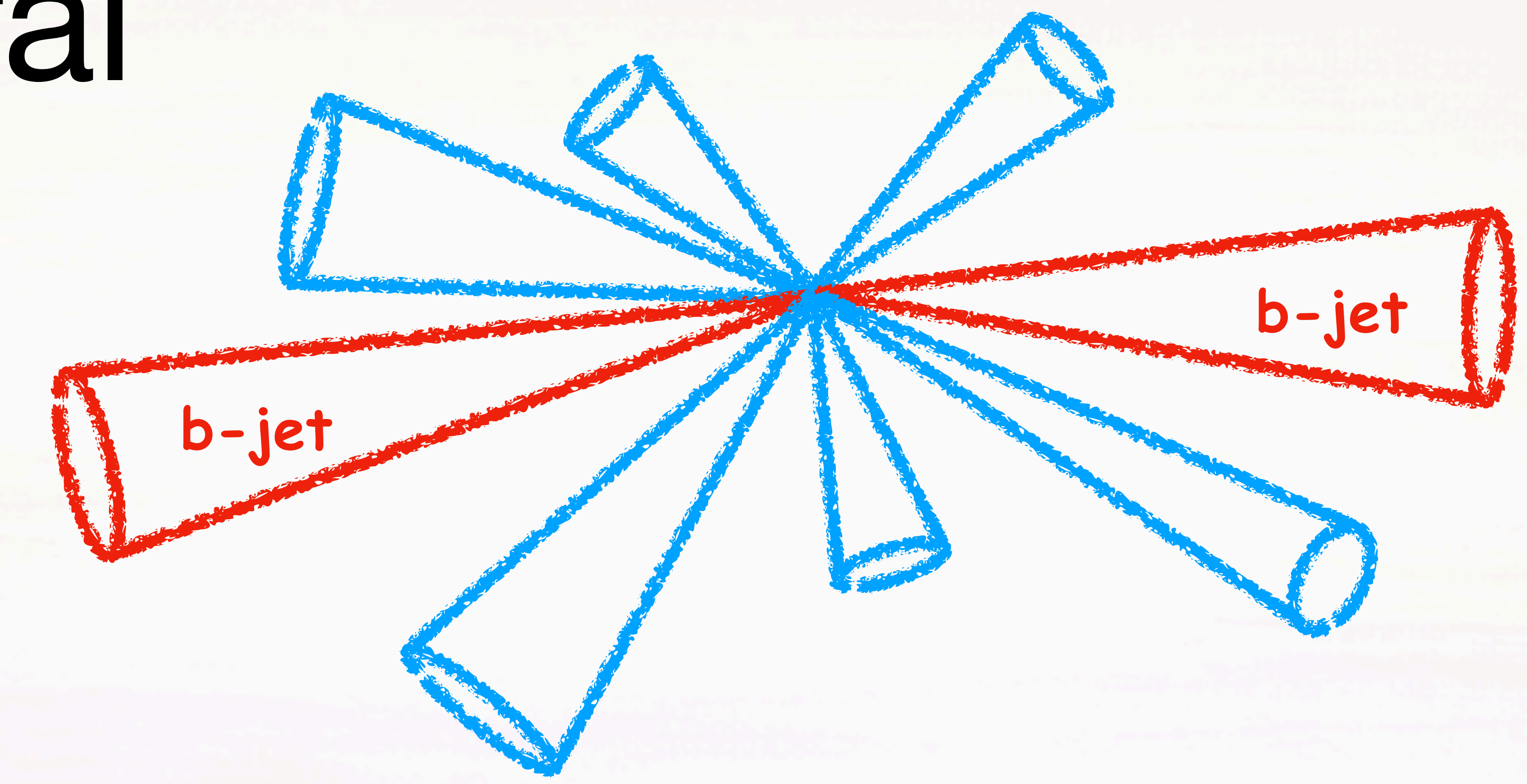
Definition of Naturalness…A Different Point of View



- The detectors are cylindrically symmetric
  - A natural physics object is originated from the luminous region

B-hadron Decay: A bit non-natural

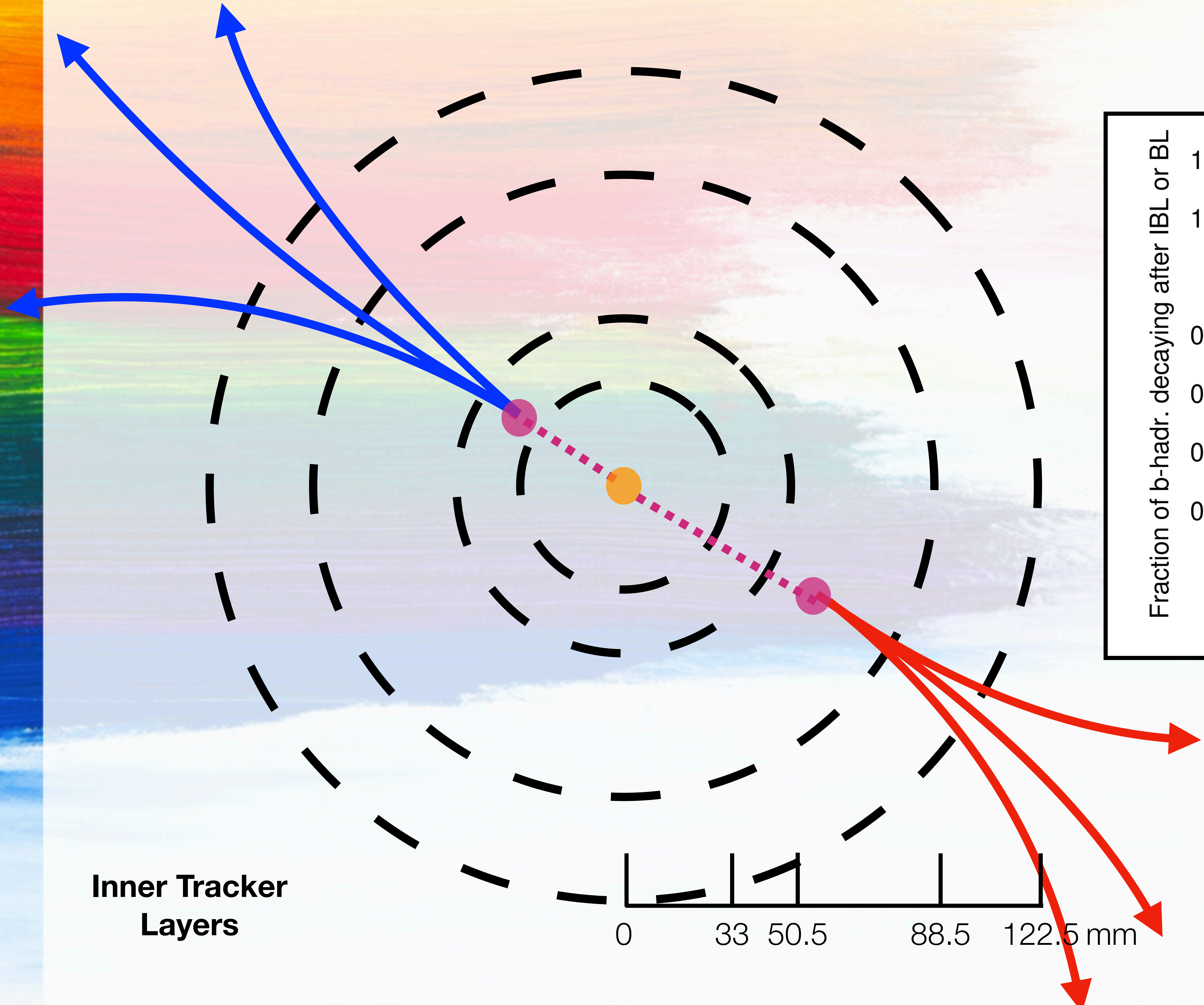




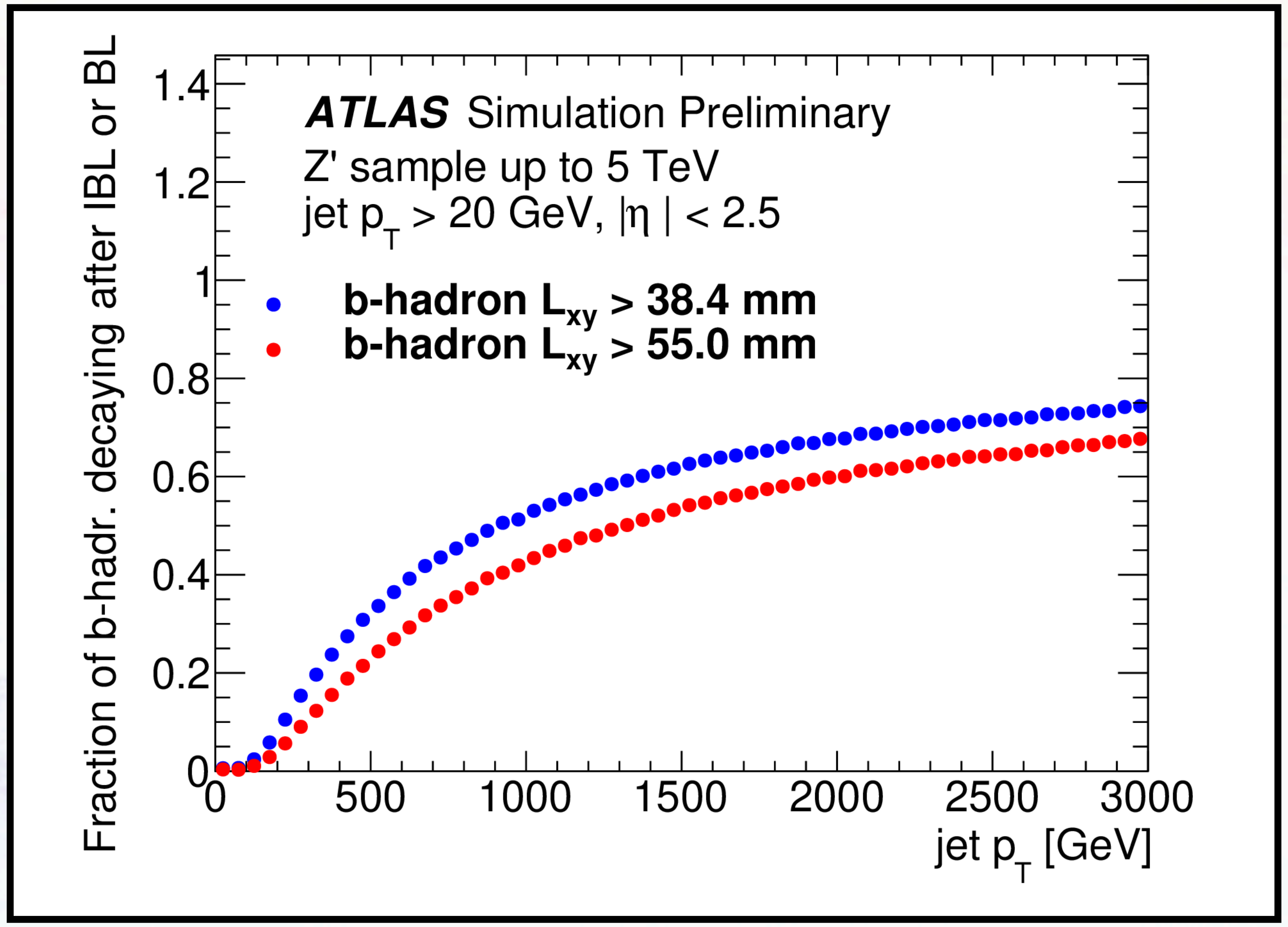
- Due to b-hadrons' long lifetimes, they decay outside the luminous region

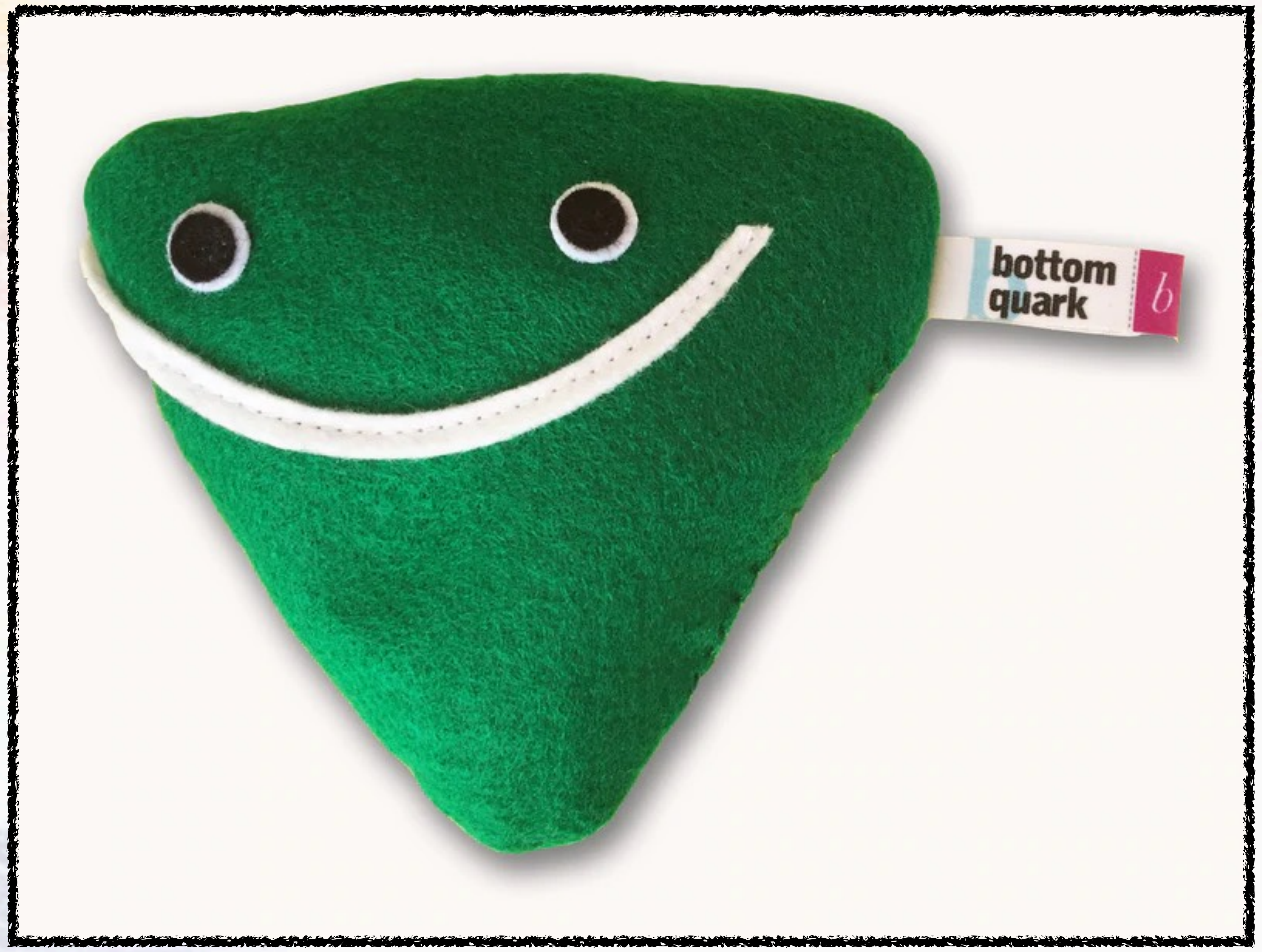
B-hadron Decay: A bit non-natural

FTAG-2020-002



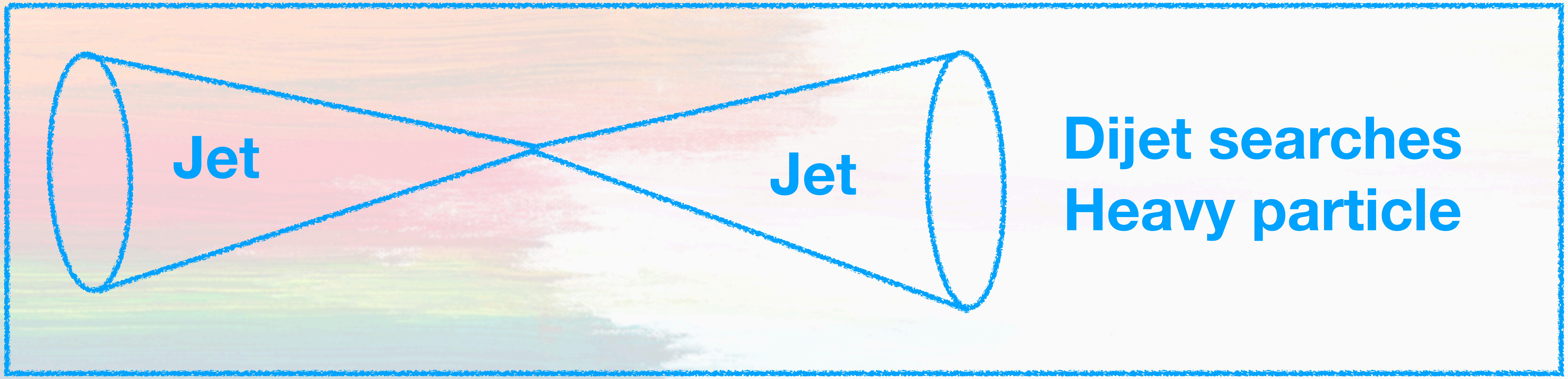
Inner Tracker Layers

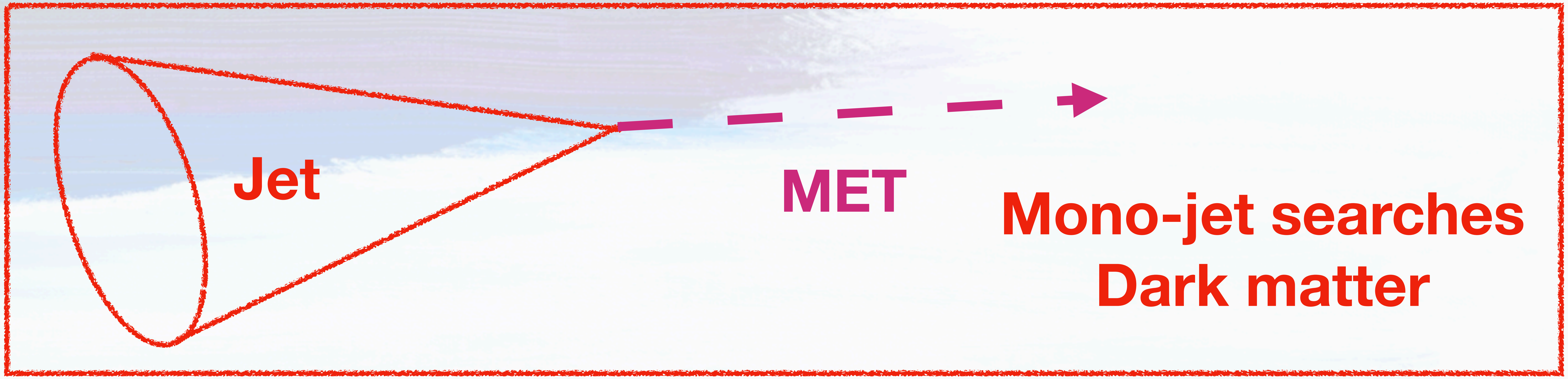




Inclusive search with heavy flavor quarks

Flagship Inclusive Searches

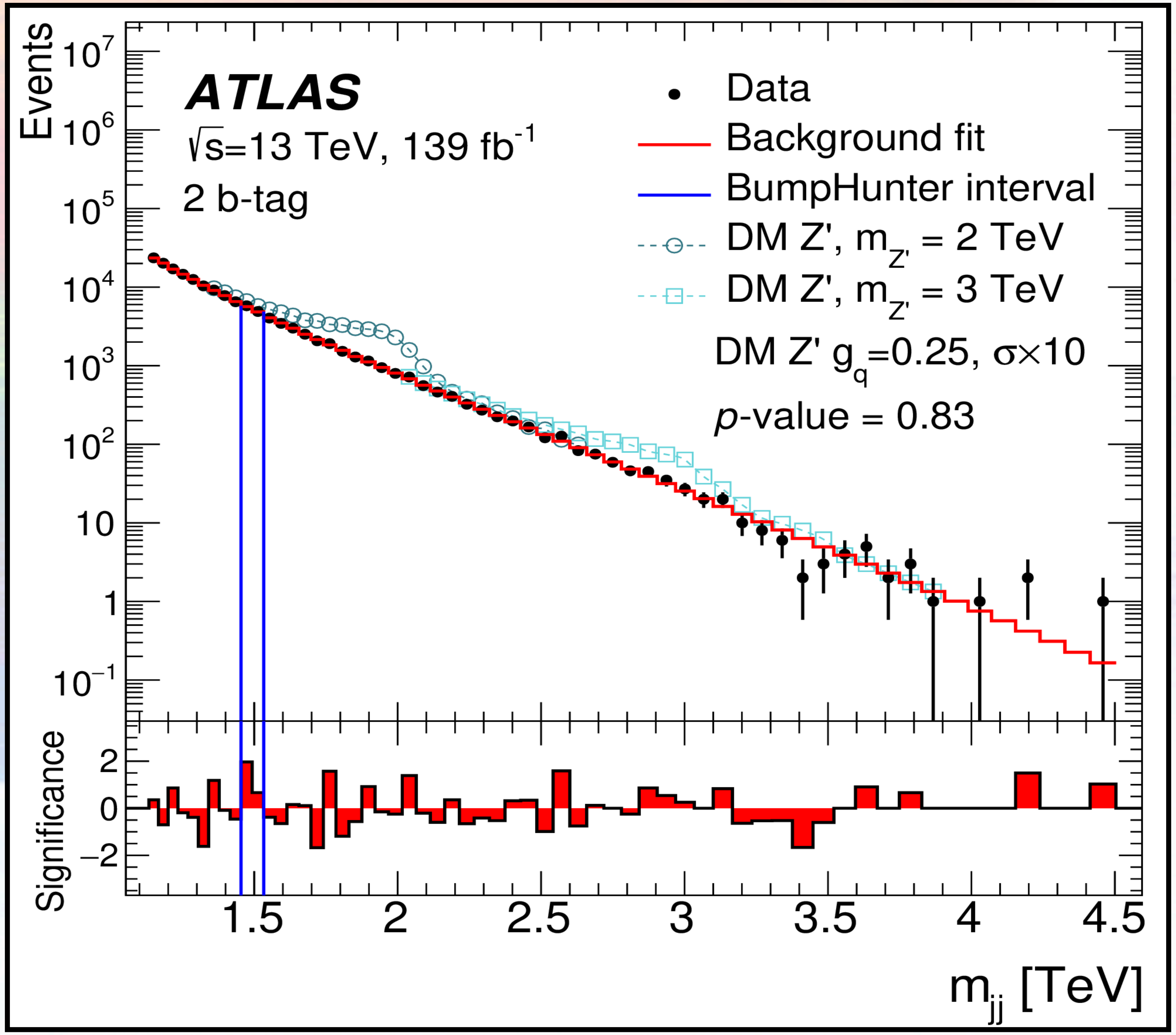




Inclusive Di-(*b*)-jet Search

JHEP03(2020)145

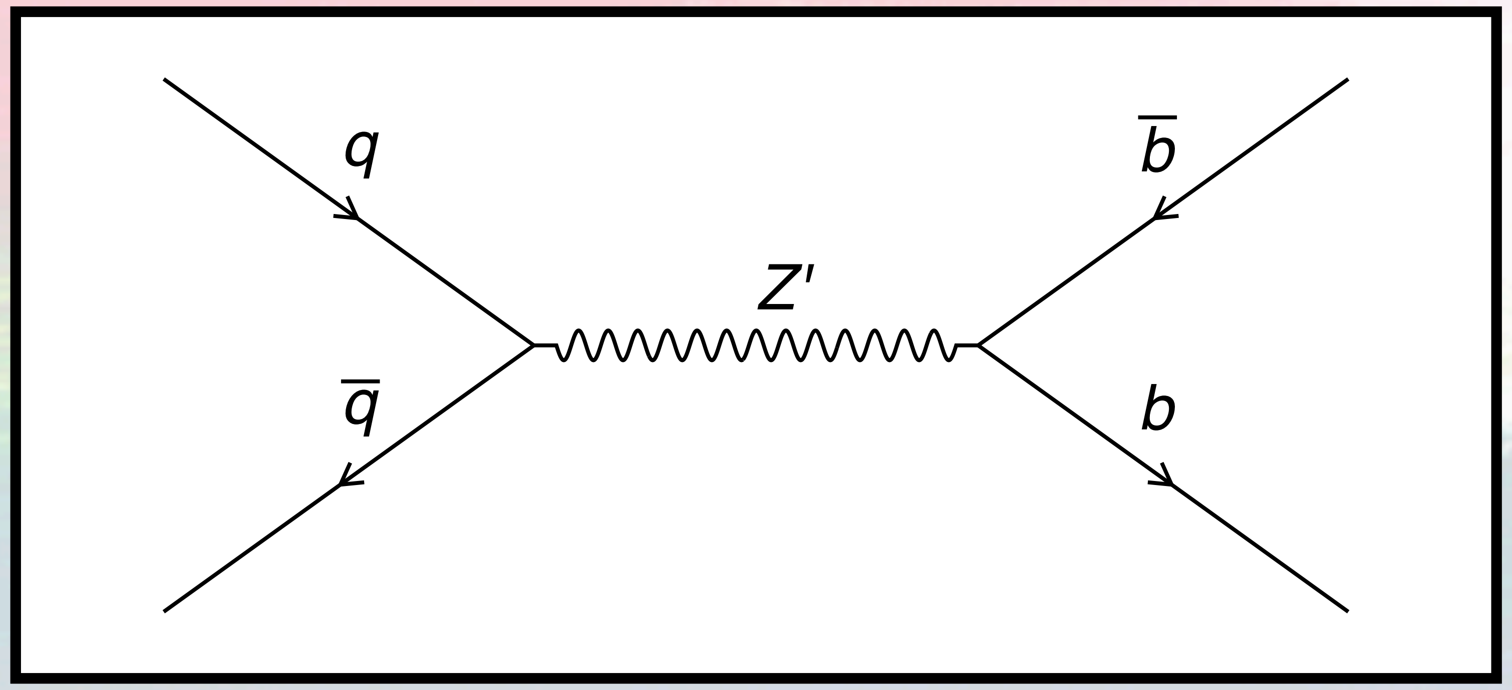
- ATLAS has published the full Run 2 inclusive di-(*b*)-jet search

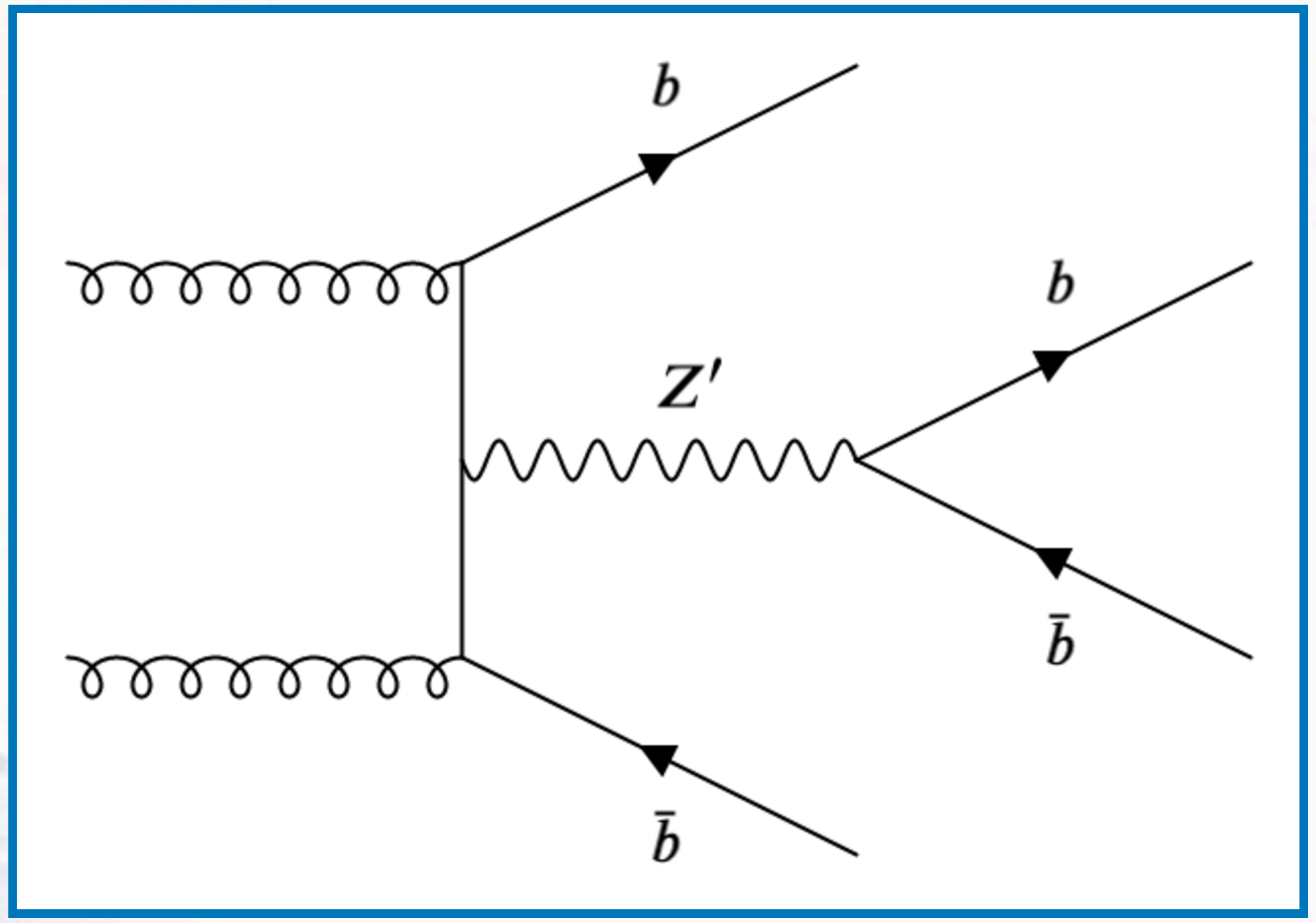


- Very powerful/important search
- Setting the most stringent limits on models with narrow heavy resonances in the hadronic final states

Heavy Particle Search with Associated *b*-quarks

- What if the new heavy particle is exclusively coupled to third generation



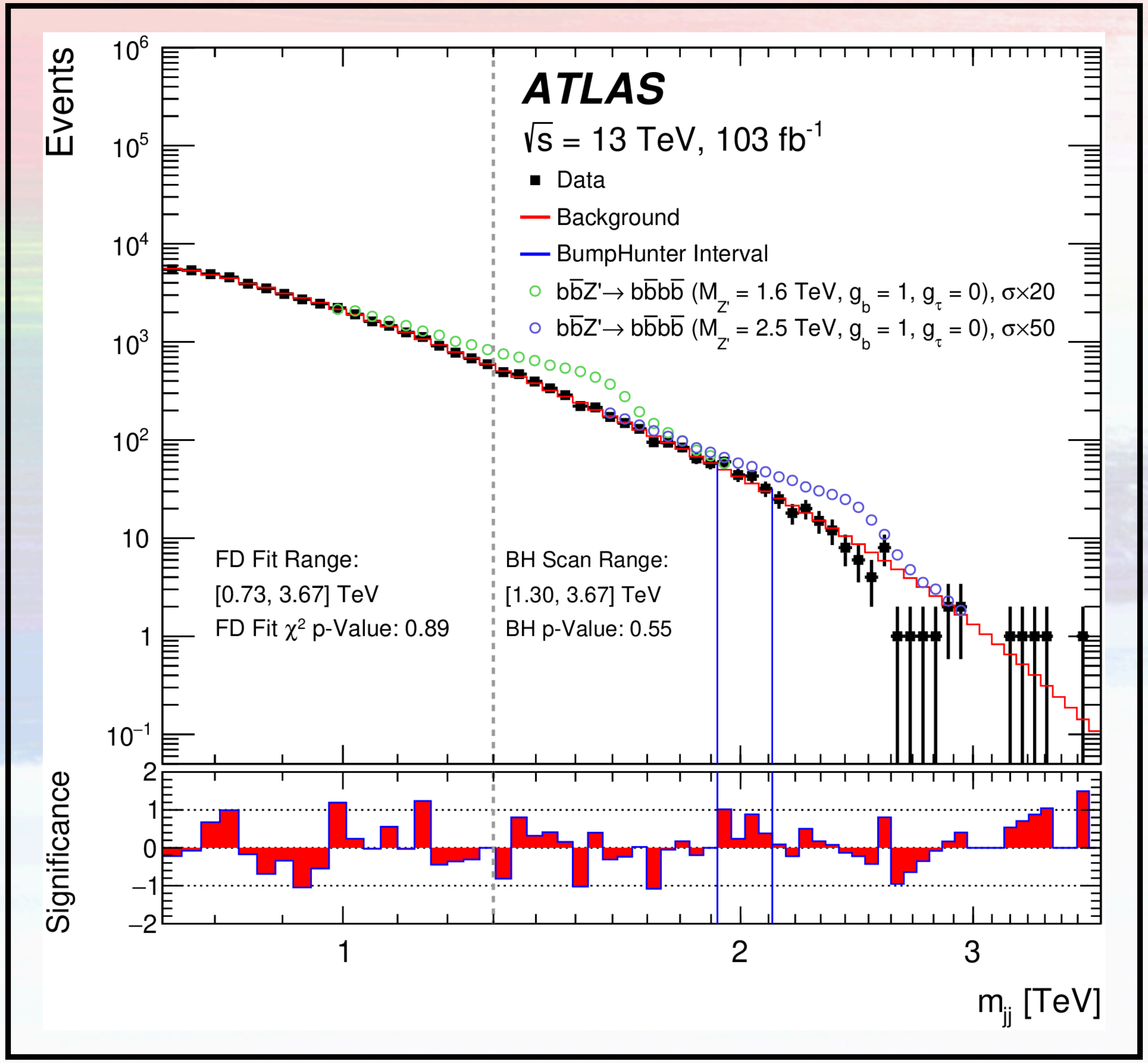


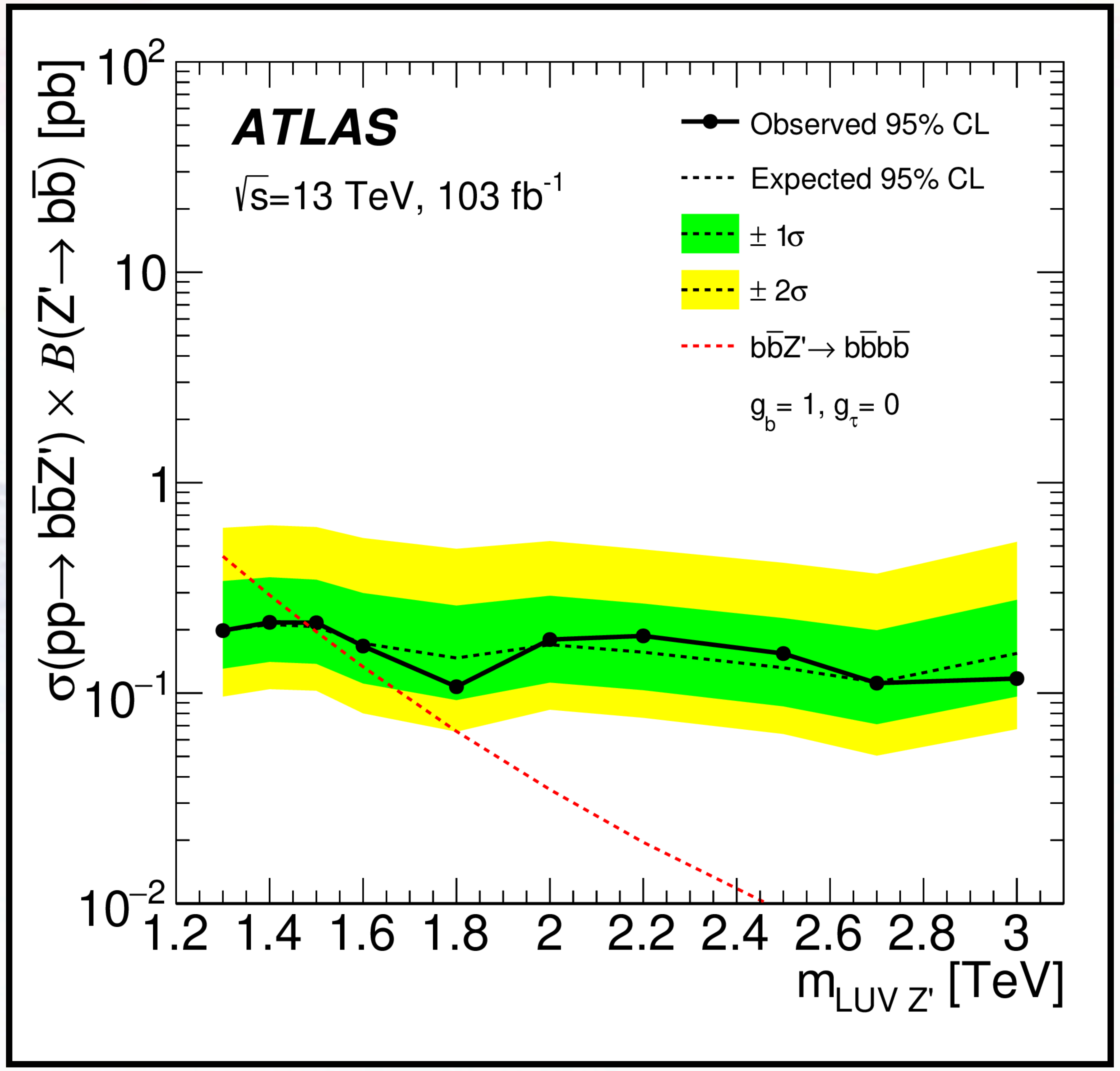
- It has to be produced in association with additional *b*-quarks at the LHC
  - Multi-*b*-jet final state, two from the heavy particle decay and two from the spectator quarks
- This type of Z' can incorporate the flavor physics anomalies observed in LHCb
  - Lepton Universality Violating Z' [JHEP07(2015)142, Admir, et.al]

Lepton Universality Violating (LUV) Z’

PhysRevD.105.012001

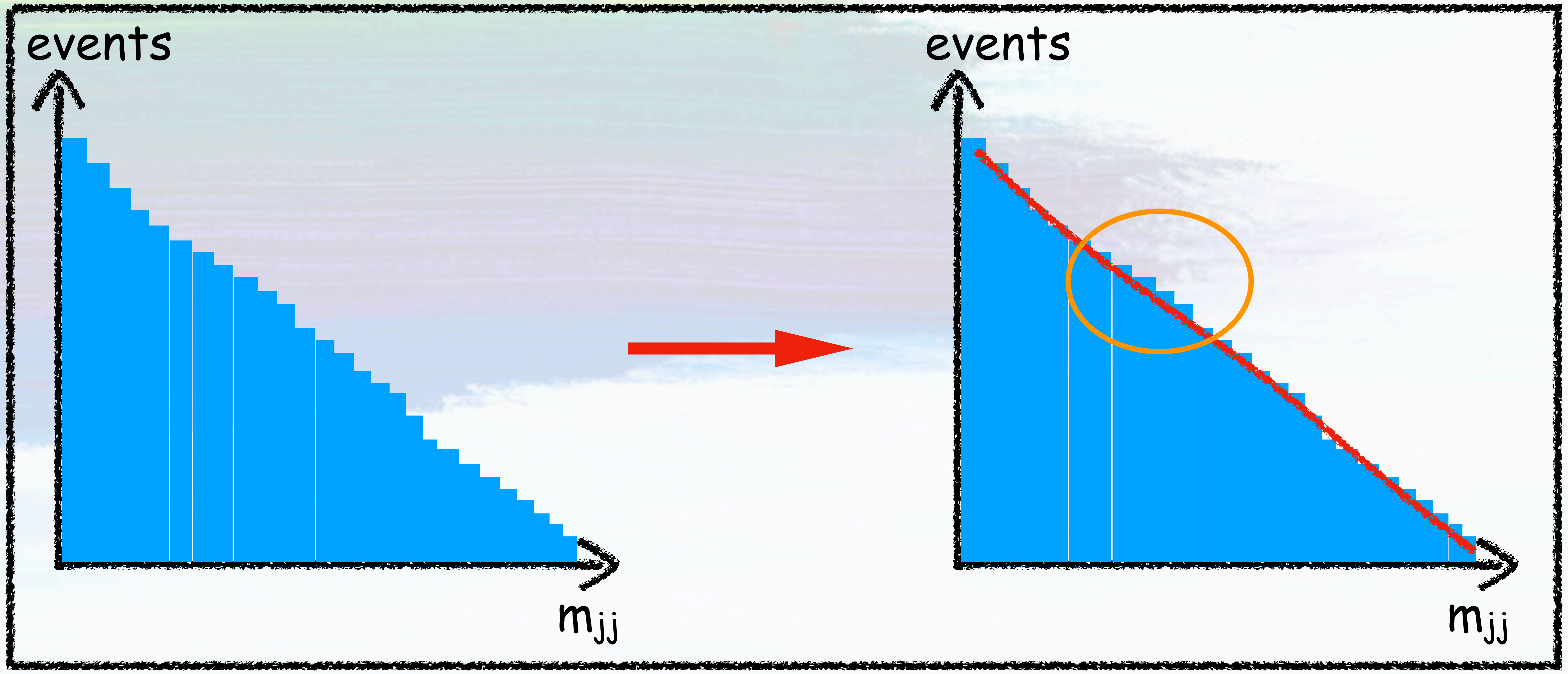
- No significant deviations are observed, limits are set on LUV Z’
- First coverage up to 3 TeV in this final state





Traditional Approach: Functional Fit

- Heavy particle searches in hadronic final states usually have to deal with an enormous multi-jet background
  - Multi-jet simulation has large theoretical uncertainties and limited sample size
- Functional fit is widely applied



- Apply empirical functions to fit the data spectrum
- And look for significant deviations in data compared with the background fit

Traditional Approach: Functional Fit

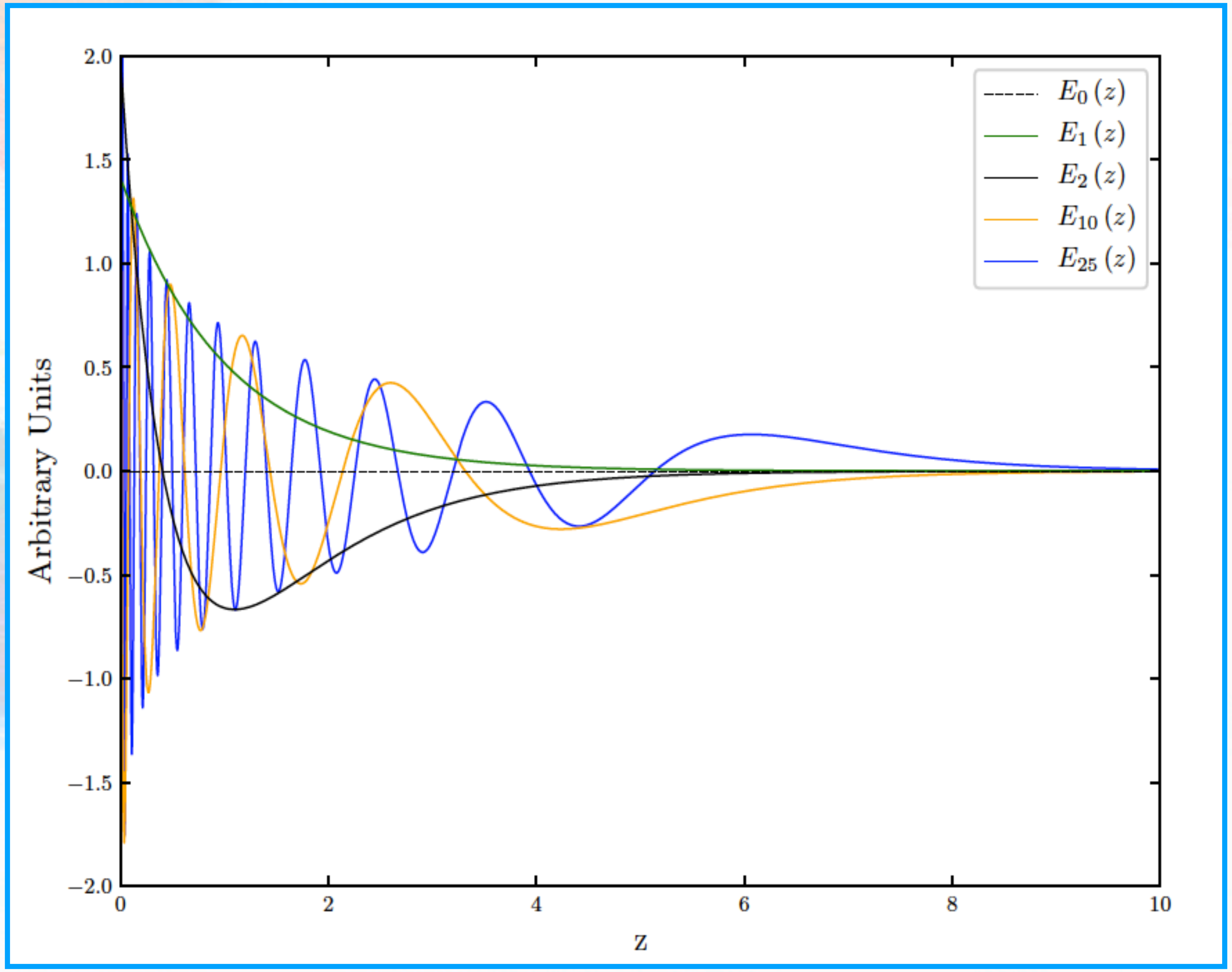
- Heavy particle searches in hadronic final states usually have to deal with an enormous multi-jet background
  - Multi-jet simulation has large theoretical uncertainties and limited sample size

But empirical functions may break

Is there a more universal approach?

New Approach: Functional Decomposition

- Functional Decomposition
  - Using orthonormal basis
  - Analogous to Fourier Analysis
- An infinite series can describe any given spectrum
- Truncate the series so that it is sufficient to describe the background not incorporating new physics

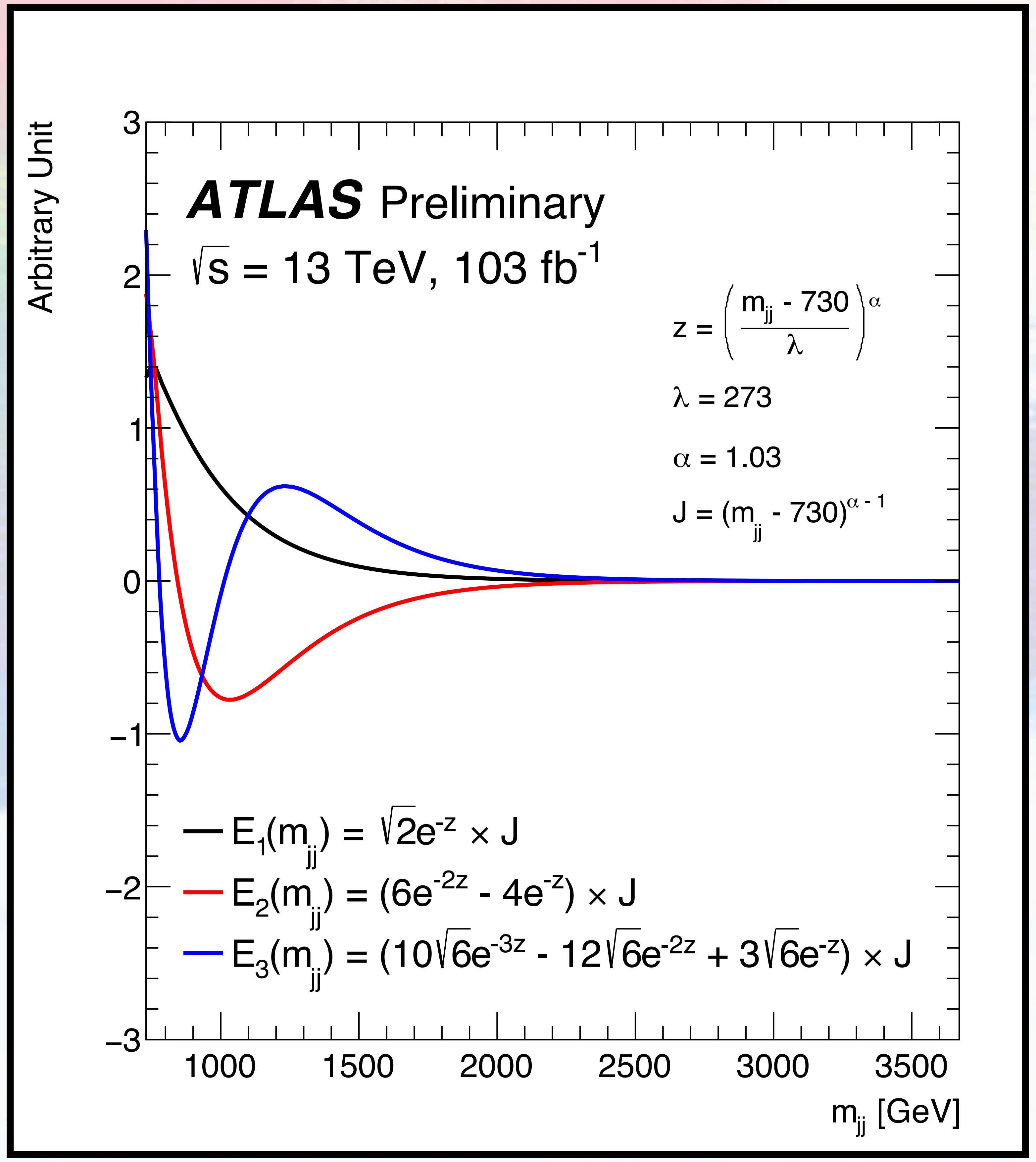


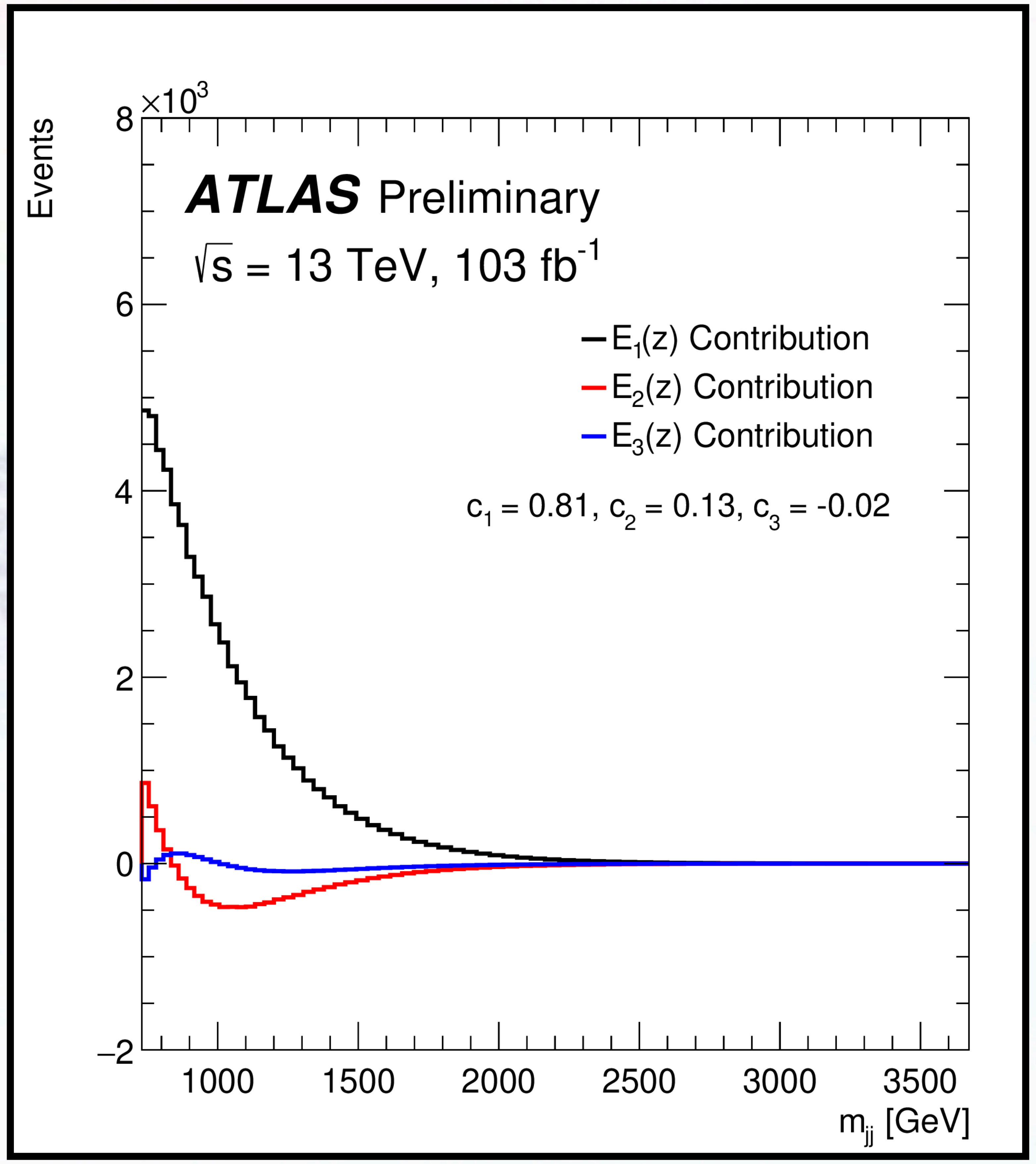
arXiv:1805.04536

Decomposed Background

PhysRevD.105.012001

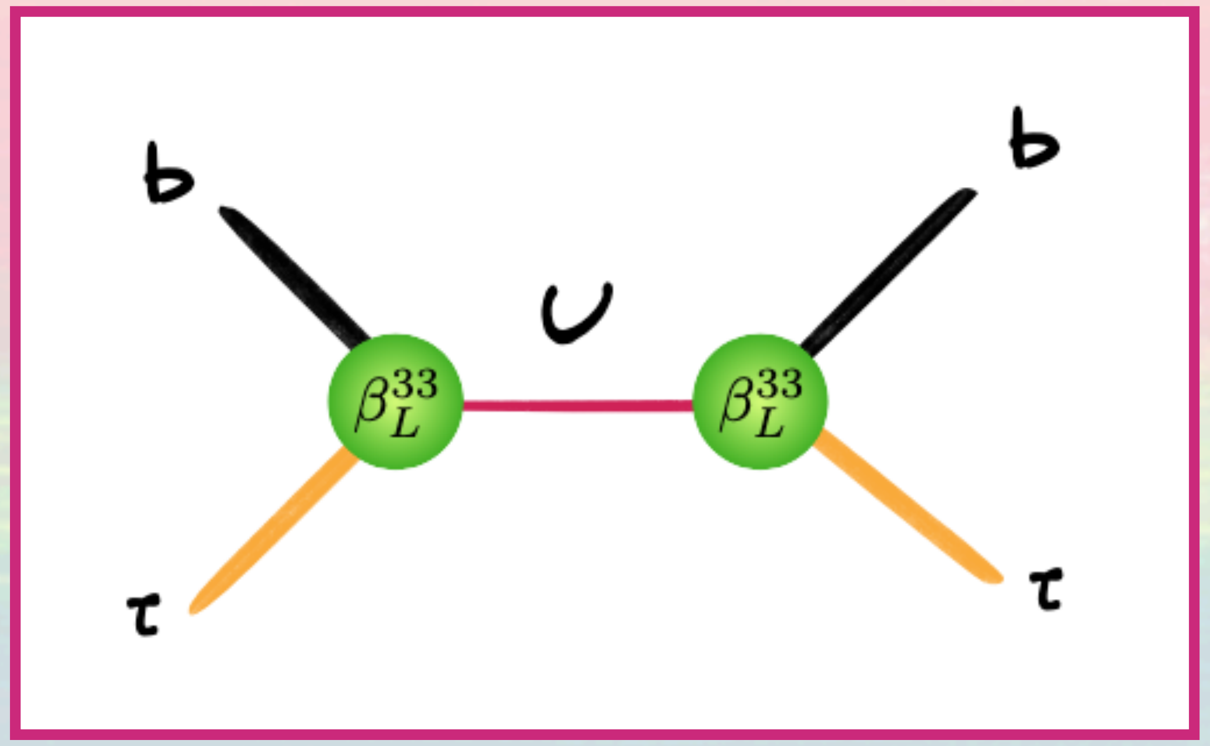
- Using three moments is sufficient to describe the background
- The background components are not physical as they come from mathematical forms

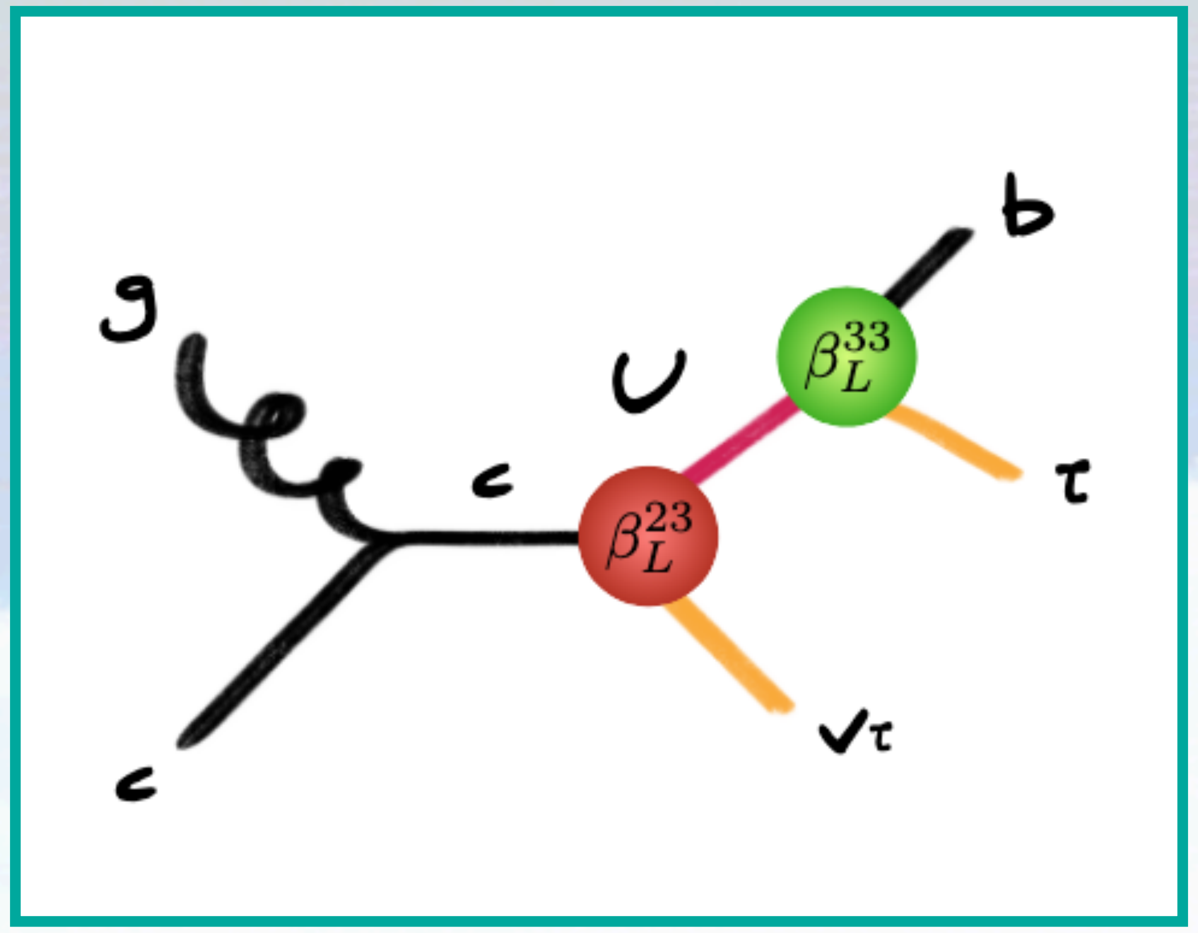


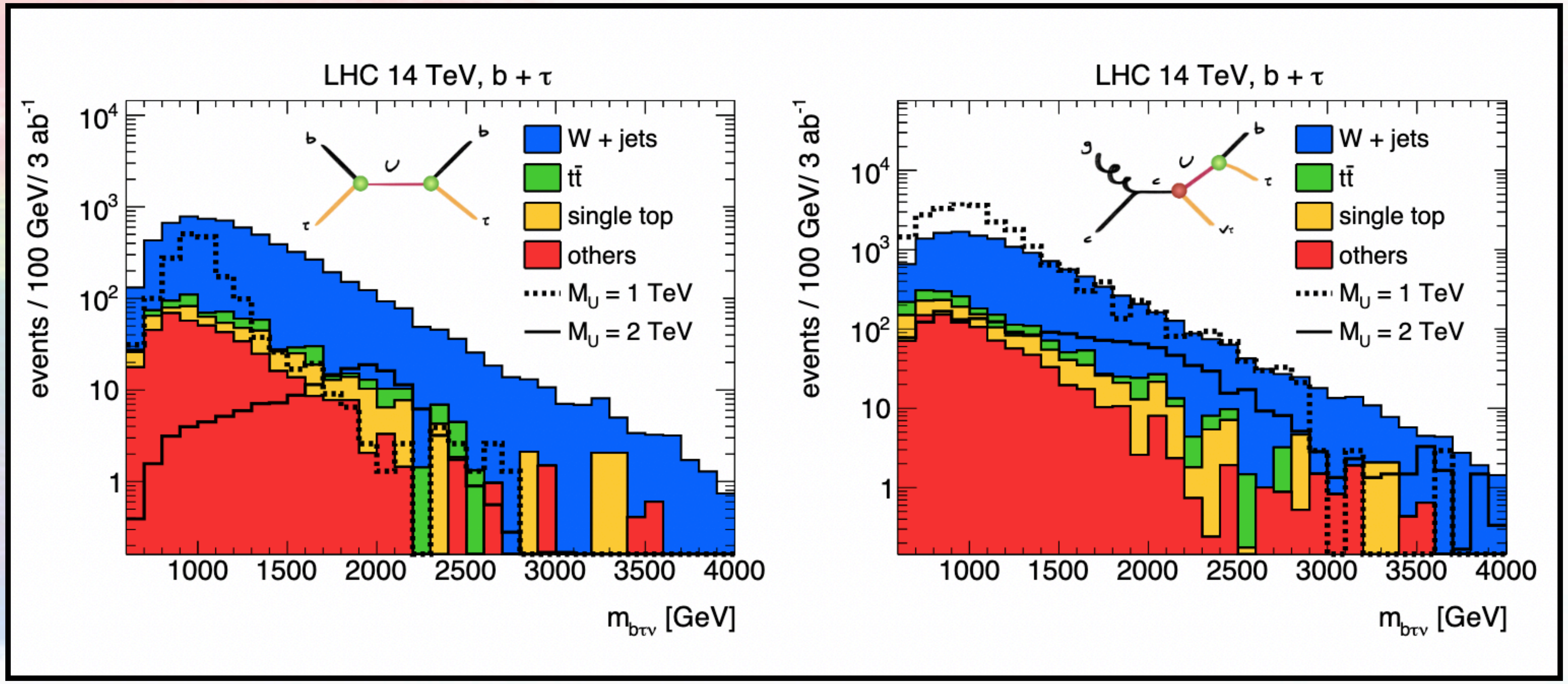


Lepton Universality Violating Leptoquark

- Resonant leptoquark production gives peaks in the lepton-jet mass spectrum
- Models explaining the *b*-anomalies predicts $b\tau$ ($b\tau\nu$) final states







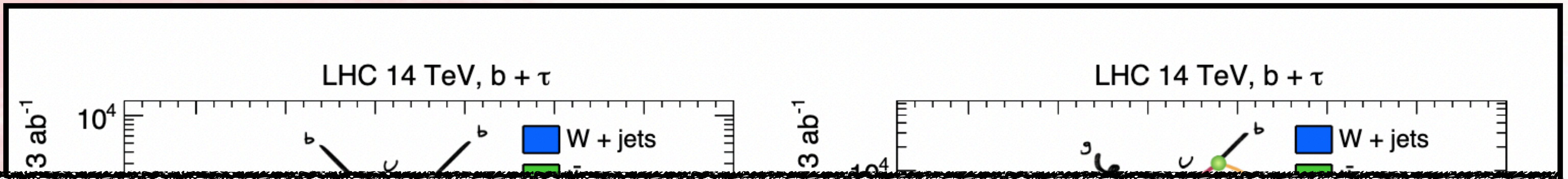
- Need separate approaches for these two final states

JHEP05(2021)057

Uli's talk

How About Mono-jet?

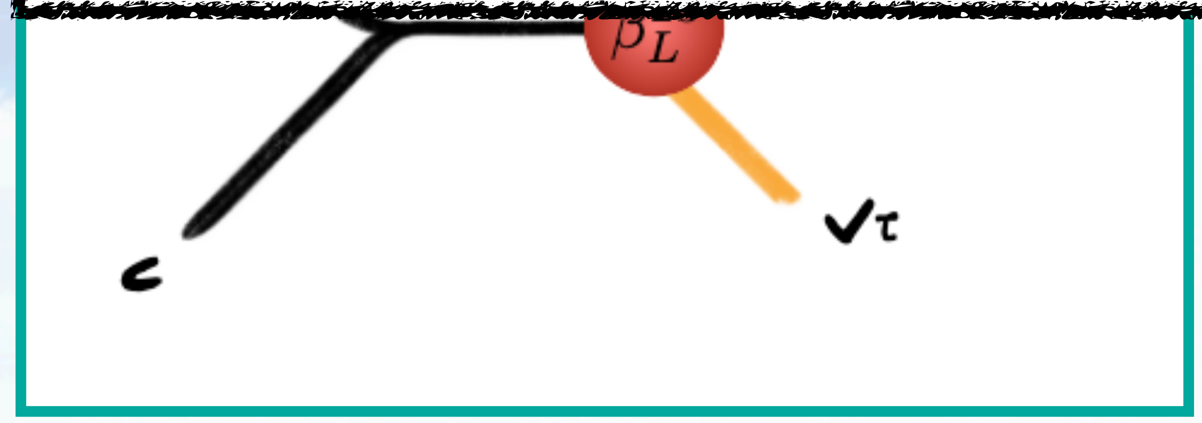
- Resonant leptoquark production gives peaks in the lepton-jet mass spectrum
- Models explaining the b-anomalies predicts $b\tau$ ($b\tau\nu$) final states



$$\Gamma(U \to b\tau^+) \simeq \frac{g_U^2}{48\pi}\left(|\beta_L^{33}|^2 + |\beta_R^{33}|^2\right) M_U\,, \qquad \Gamma(U \to t\bar{\nu}_\tau) \simeq \frac{g_U^2}{48\pi}|\beta_L^{33}|^2 M_U\,,$$

$$\Gamma(U \to s\tau^+) \simeq \frac{g_U^2}{48\pi}|\beta_L^{23}|^2 M_U\,, \qquad \Gamma(U \to c\bar{\nu}_\tau) \simeq \frac{g_U^2}{48\pi}|\beta_L^{23}|^2 M_U\,.$$

Mono-charm!



- Need separate approaches for these two final states

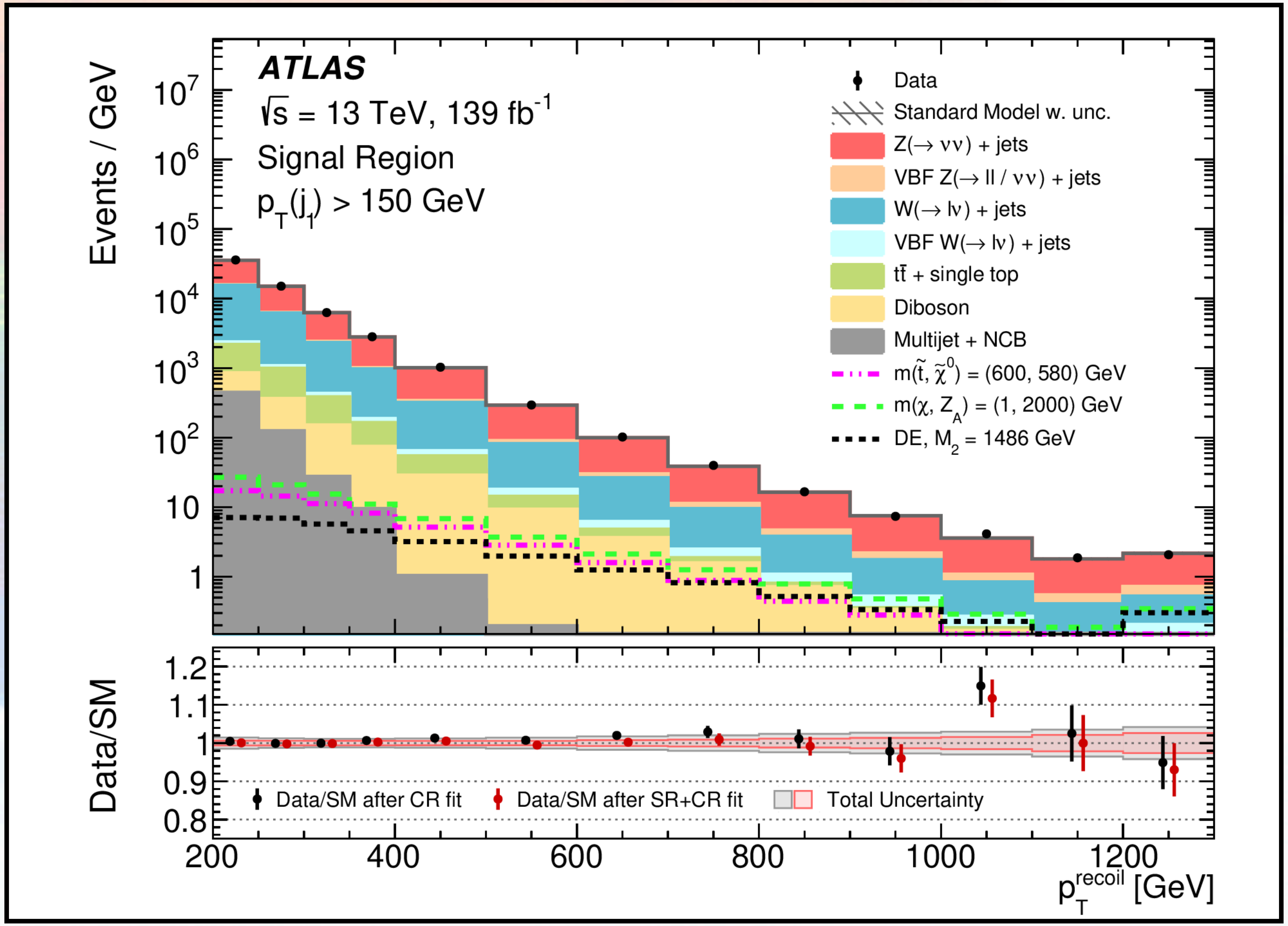
JHEP05(2021)057

Uli's talk

Inclusive Mono-jet

PhysRevD.103.112006

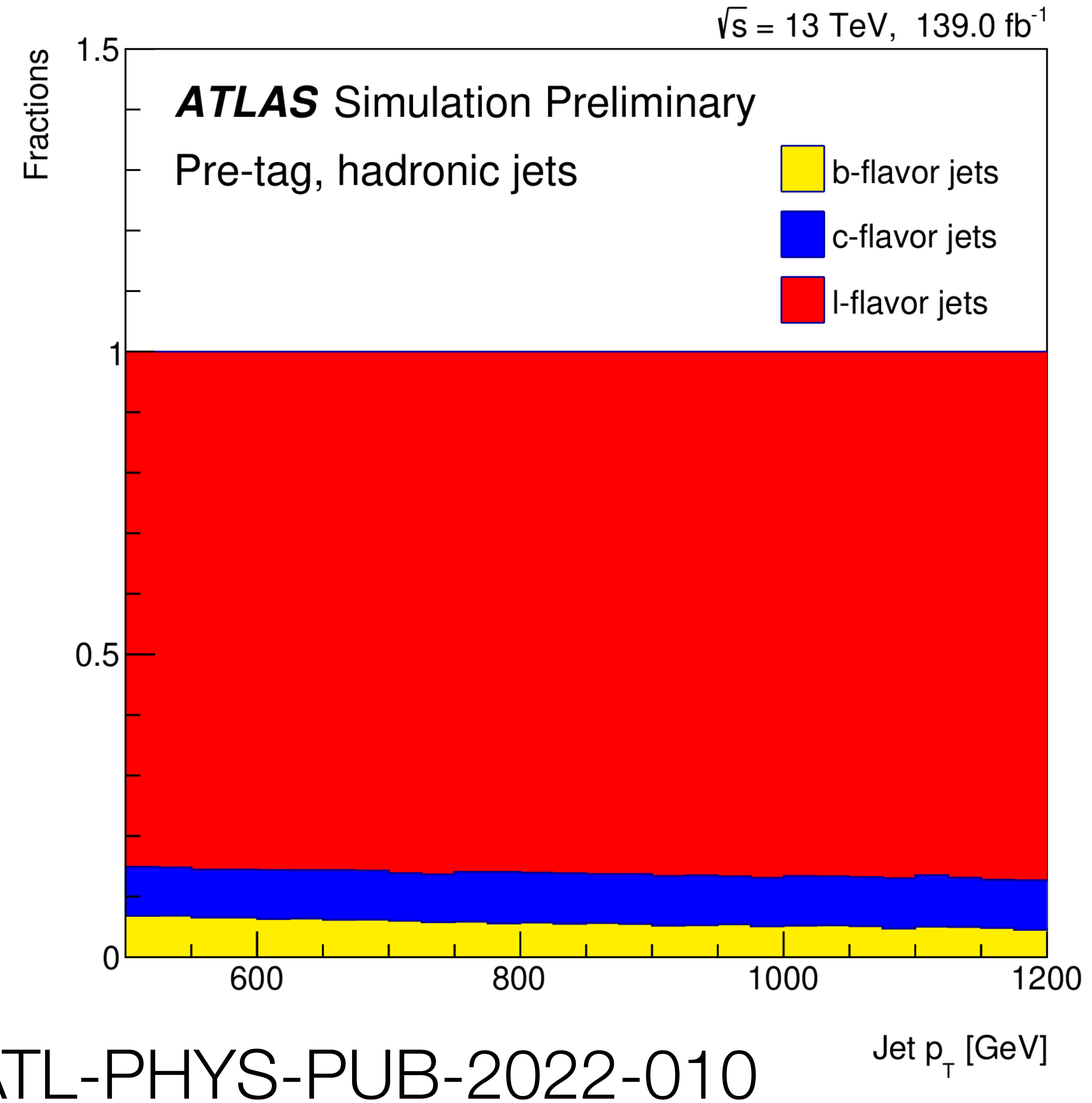
- ATLAS has published the full Run 2 inclusive mono-jet search



- Excellent work done by the theorists
  - Amazing precise V + jets background estimation using MC
- Mono-HF (*b* or *c*) could have been hiding here given the large light jet contribution from V + jets

Inclusive Mono-jet

- Multi-jet and V + jets are dominated by light flavor jets



ATL-PHYS-PUB-2022-010

- Better sensitivities can be achieved via bottom/charm-tagging
- However V + HF measurements and simulations are not as well studied as the inclusive case
- Theory inputs are very important and good opportunity to collaborate again

Heavy flavor associated production mode

Flavor tagging performance at high energy scale

Heavy flavor modeling at high energy scale

New *b*-Tagger For Run 3

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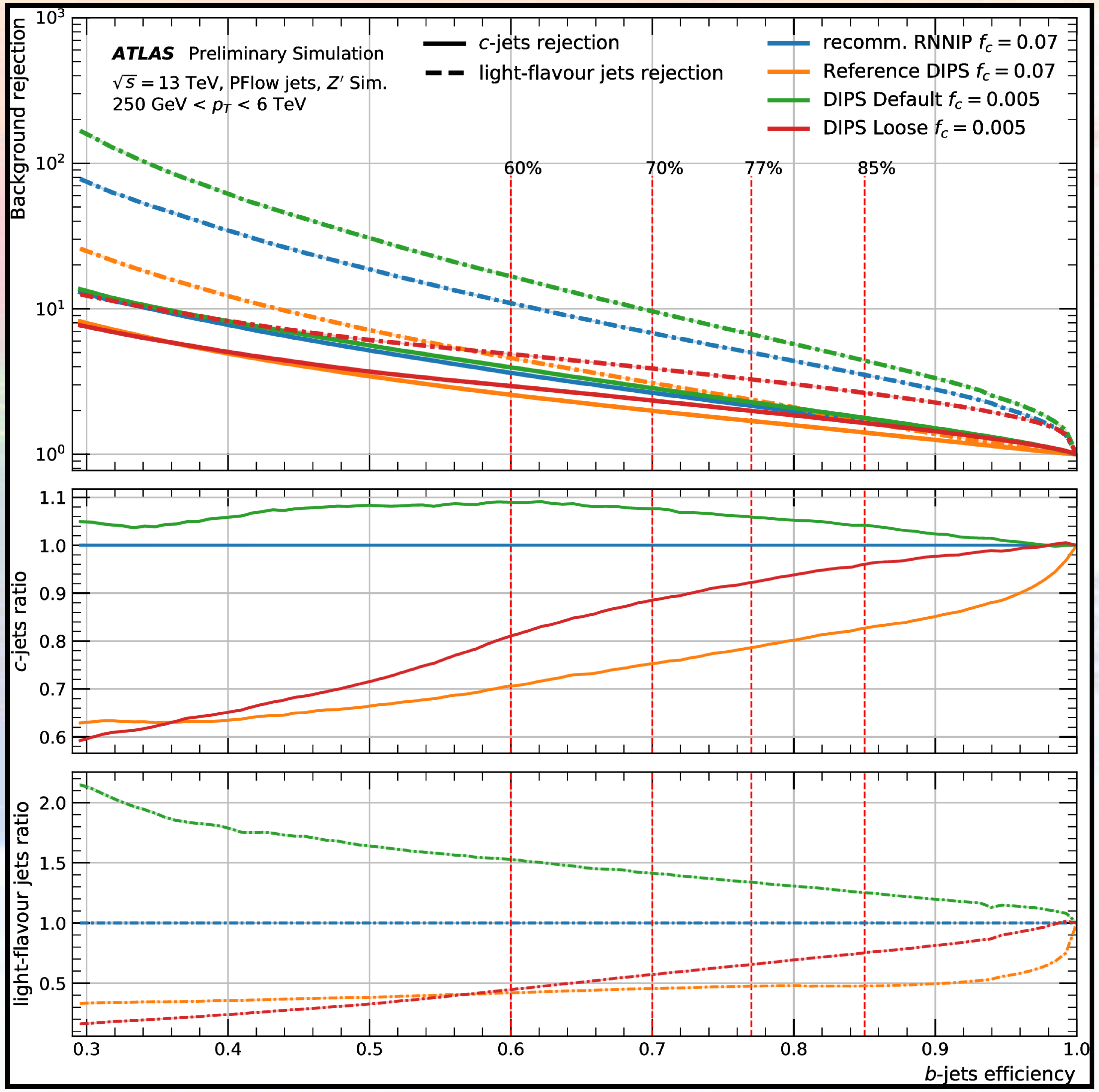
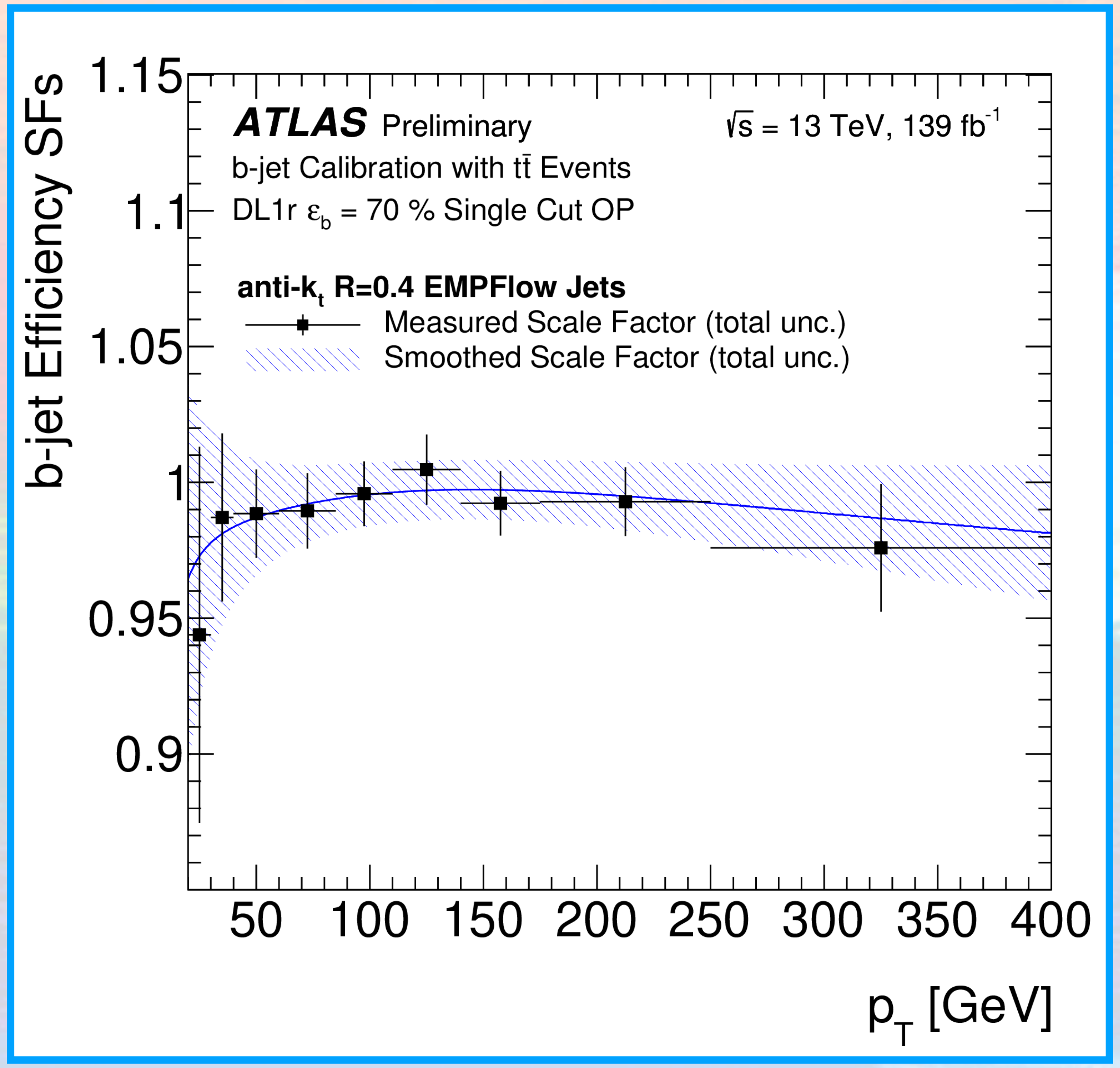


- New *b*-taggers for ATLAS Run 3 physics programs are being developed
- Already seen great improvement in preliminary results for high pT jets
- The reason why projected sensitivities are often pessimistic
  - Performance improvement!

Uncovered Phase Space

FTAG-2021-001



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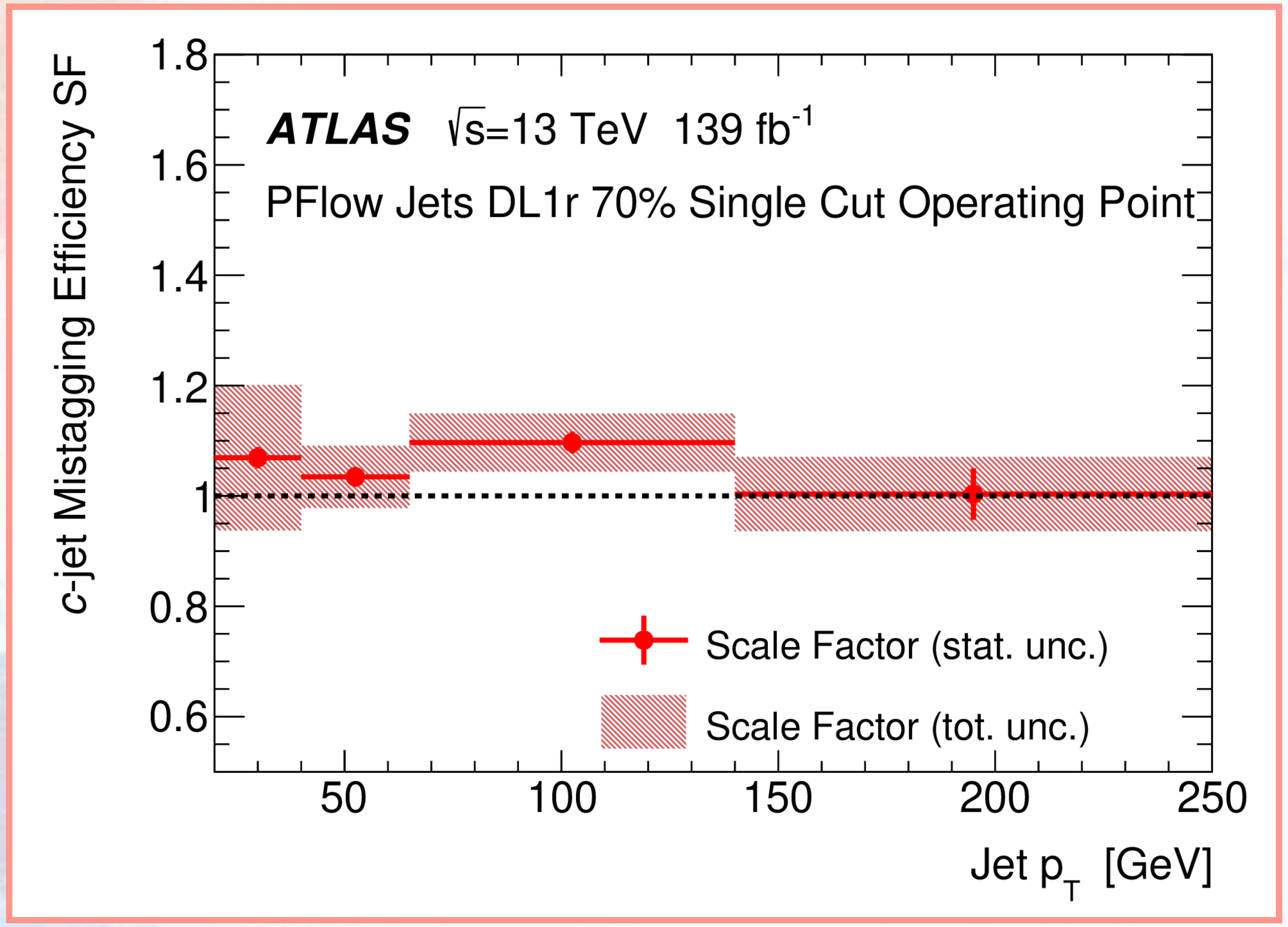
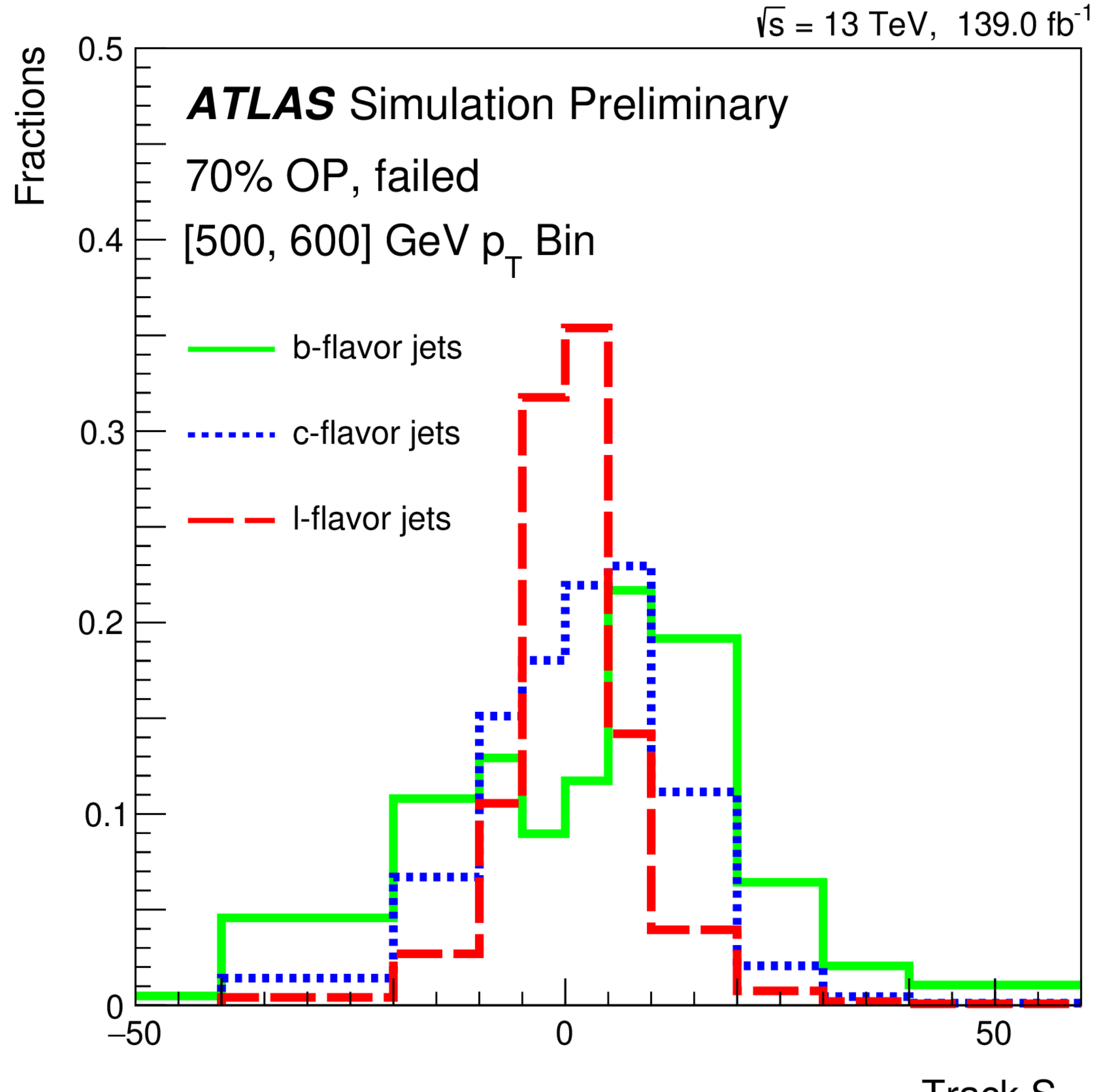


- TeV scale jets are considered in these searches but the tagging performance is only studied up to a few hundreds GeV in data

b-tagging Calibration in Multi-jet Events

- Due to b-hadrons' longer lifetimes they would have tracks with positive large S_{d_0}



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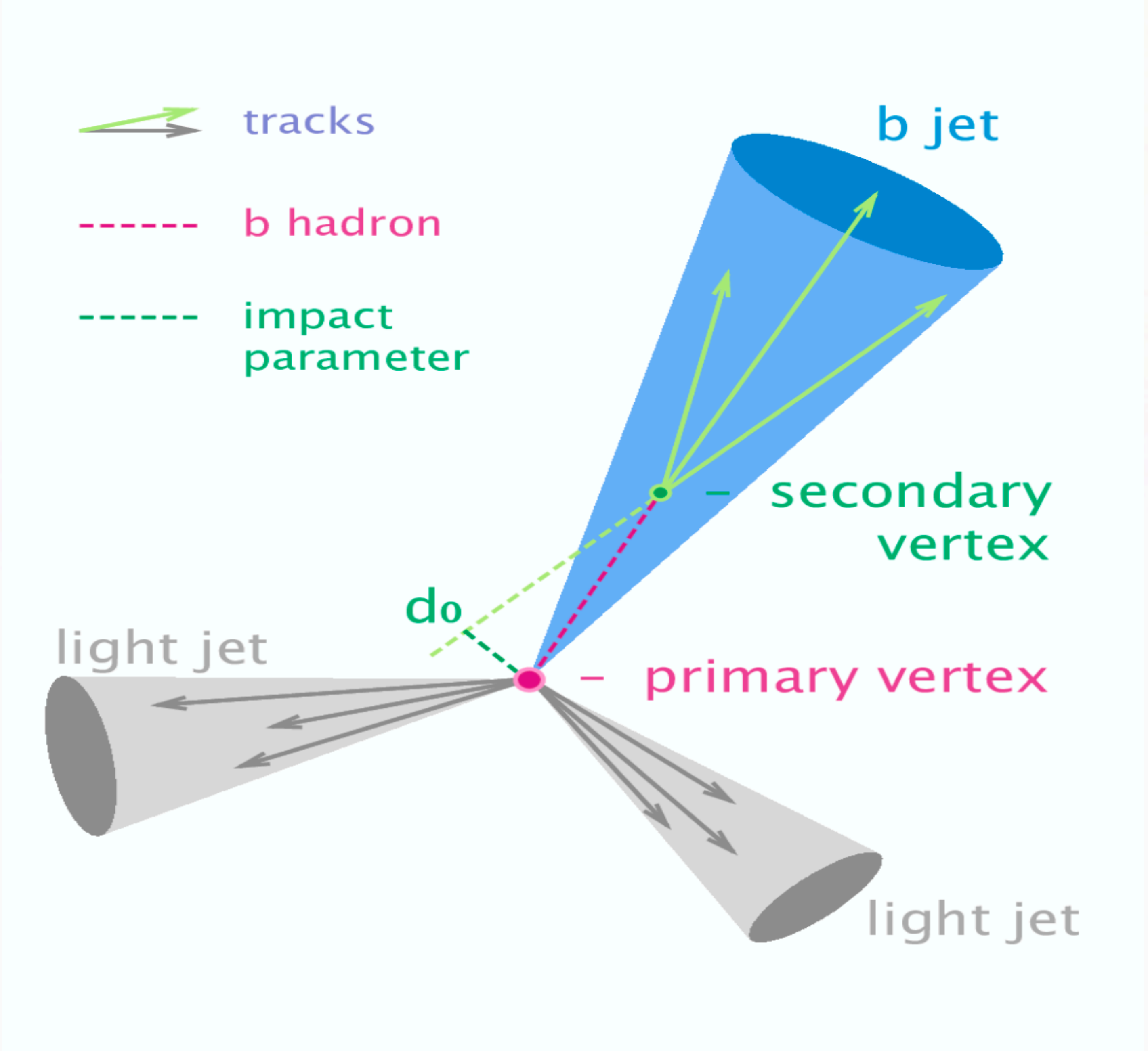
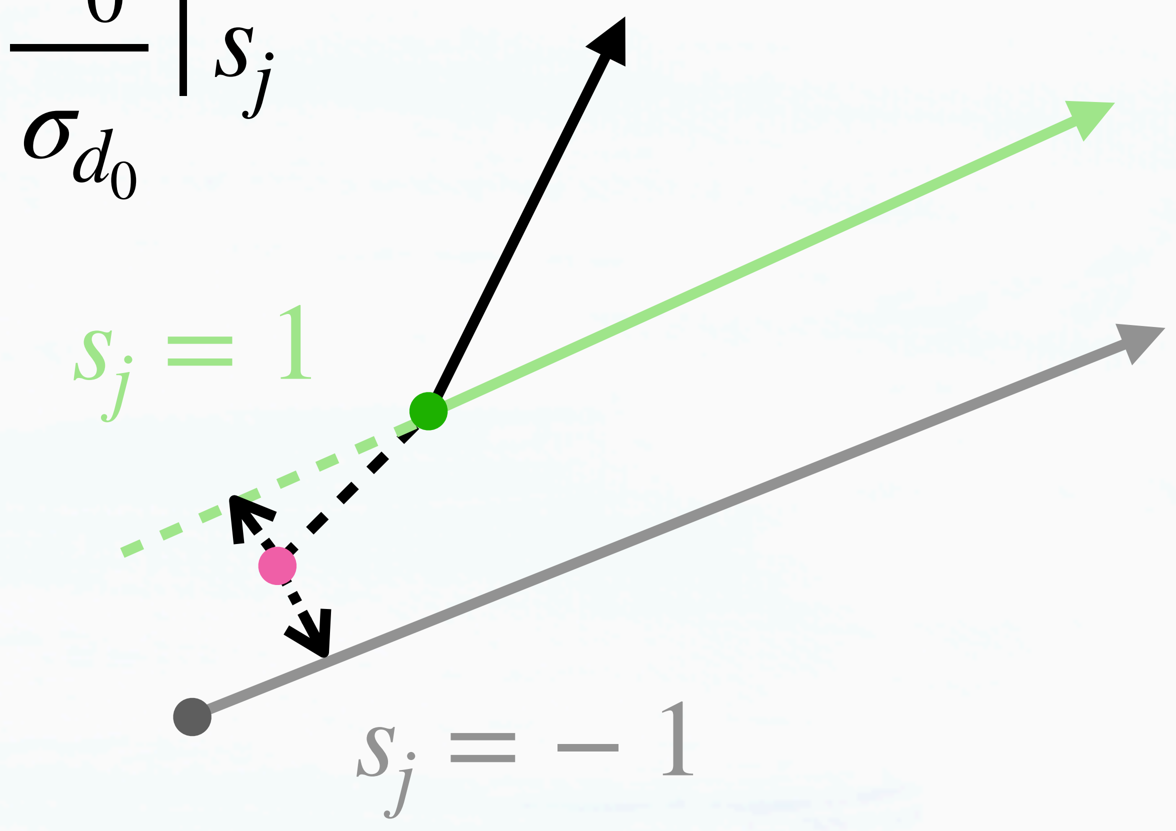
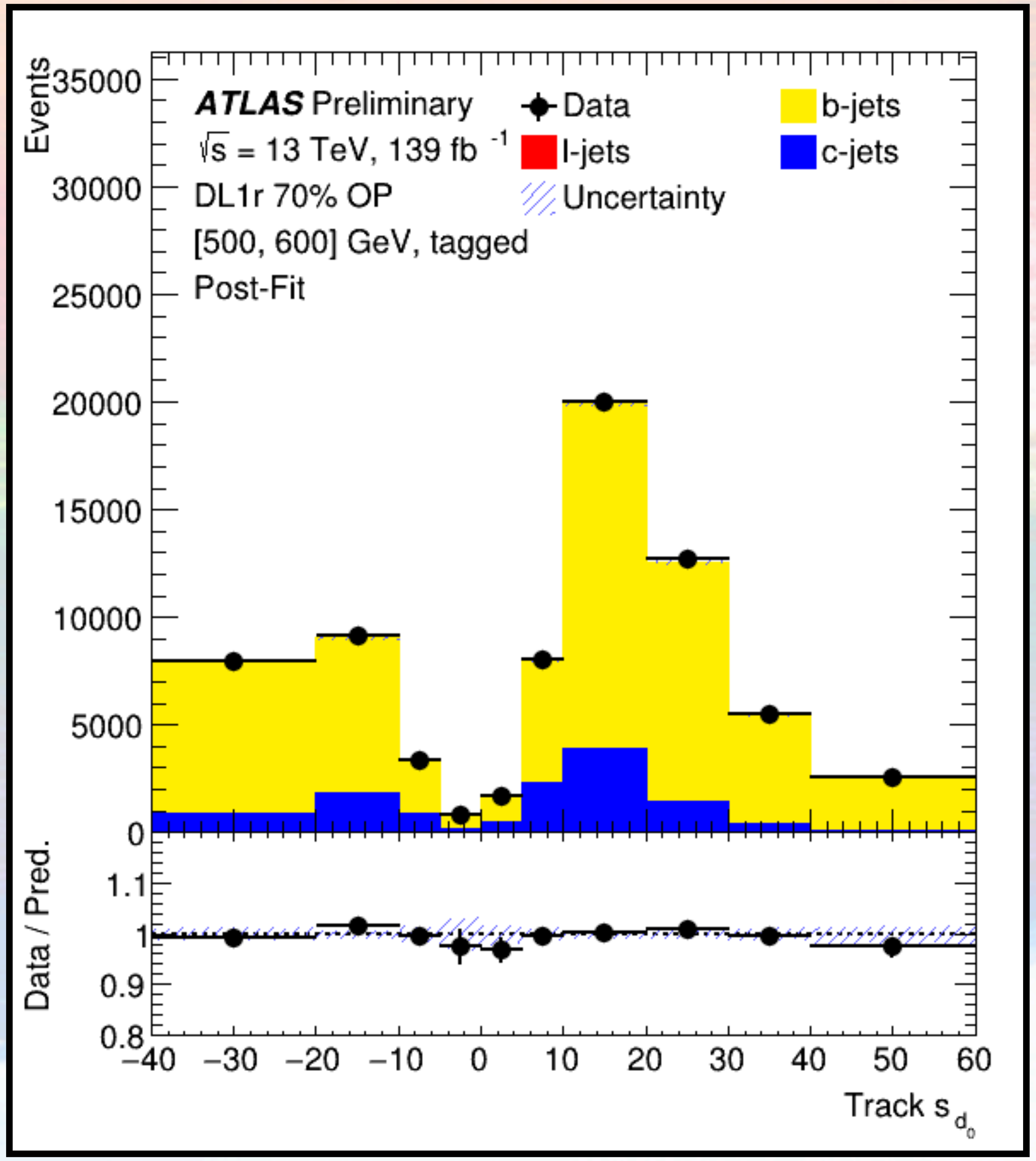
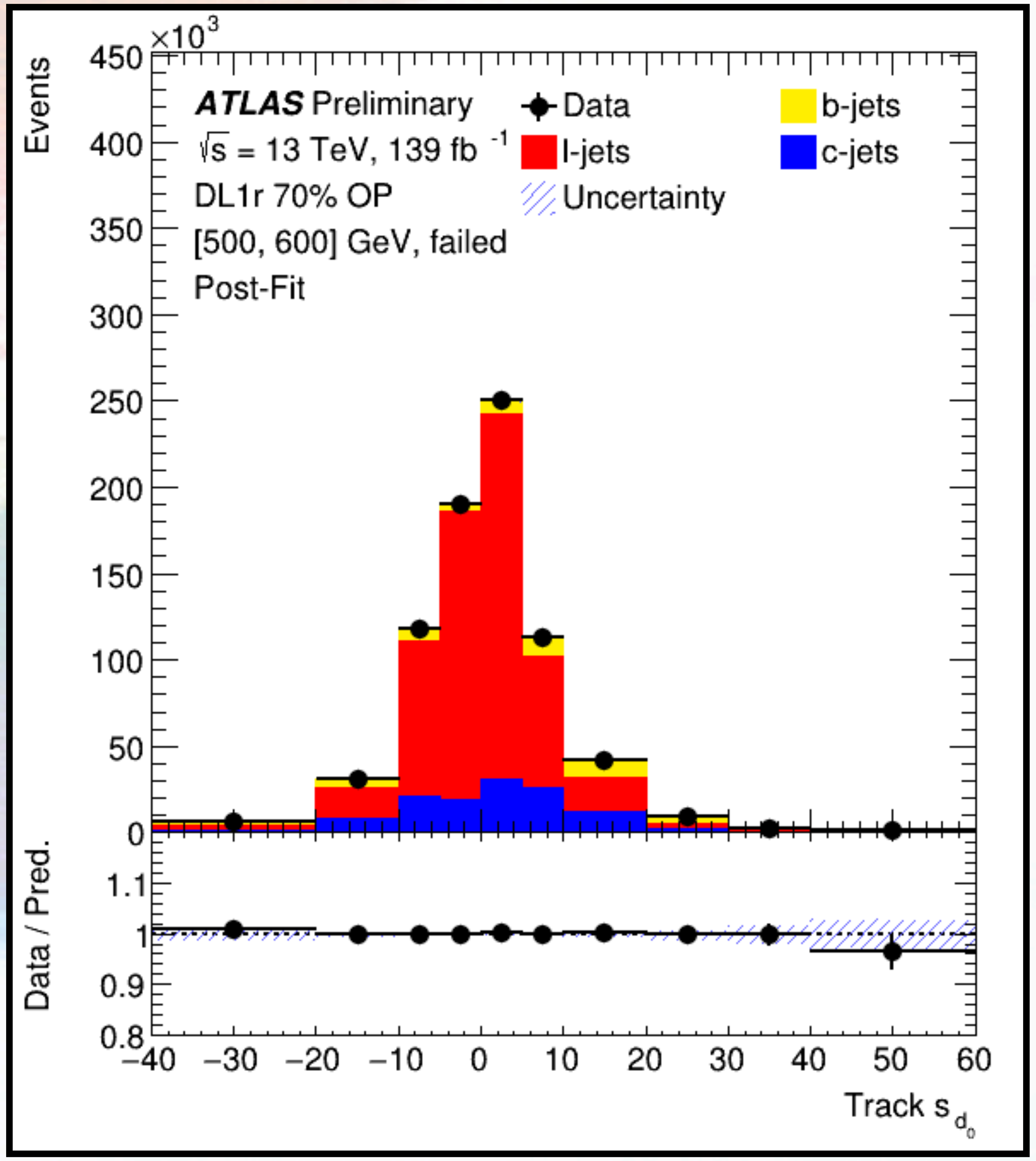


$$S_{d_0} = \left|\frac{d_0}{\sigma_{d_0}}\right| s_j$$



b-tagging Calibration in Multi-jet Events





$$\epsilon_b = \frac{N_{\text{tagged}}}{N_{\text{tagged}} + N_{\text{failed}}}$$

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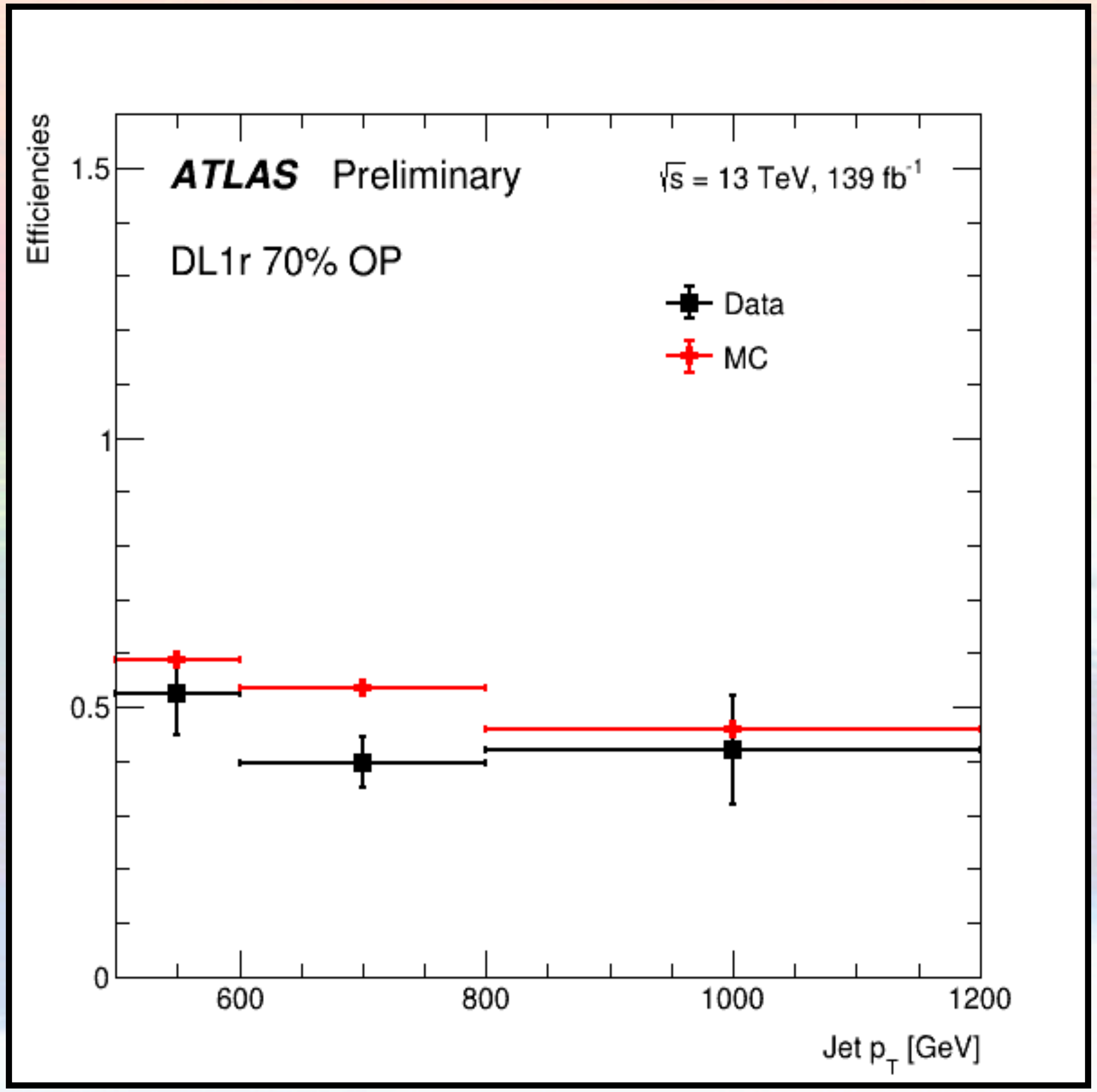
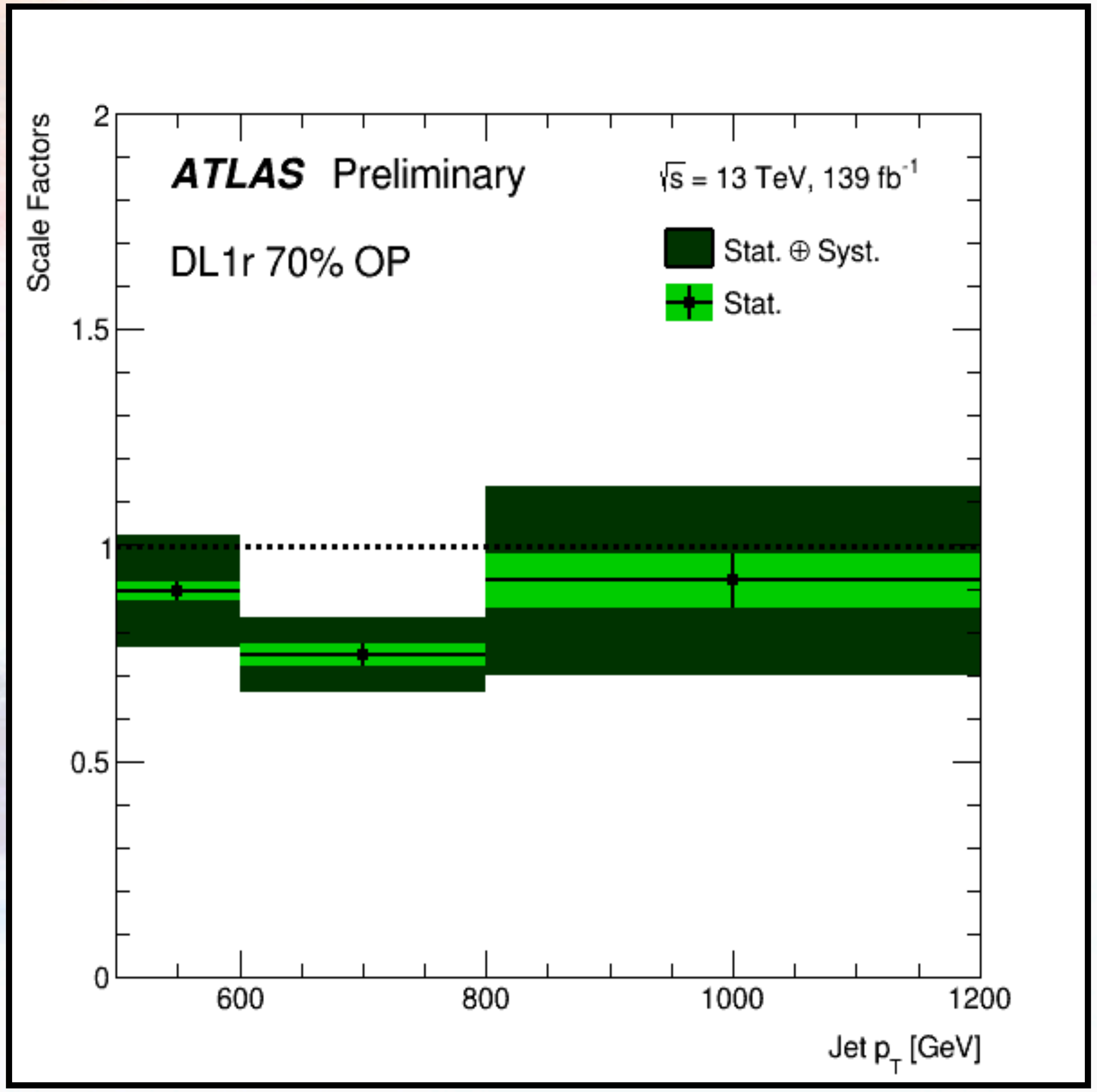
b-tagging Calibration in Multi-jet Events





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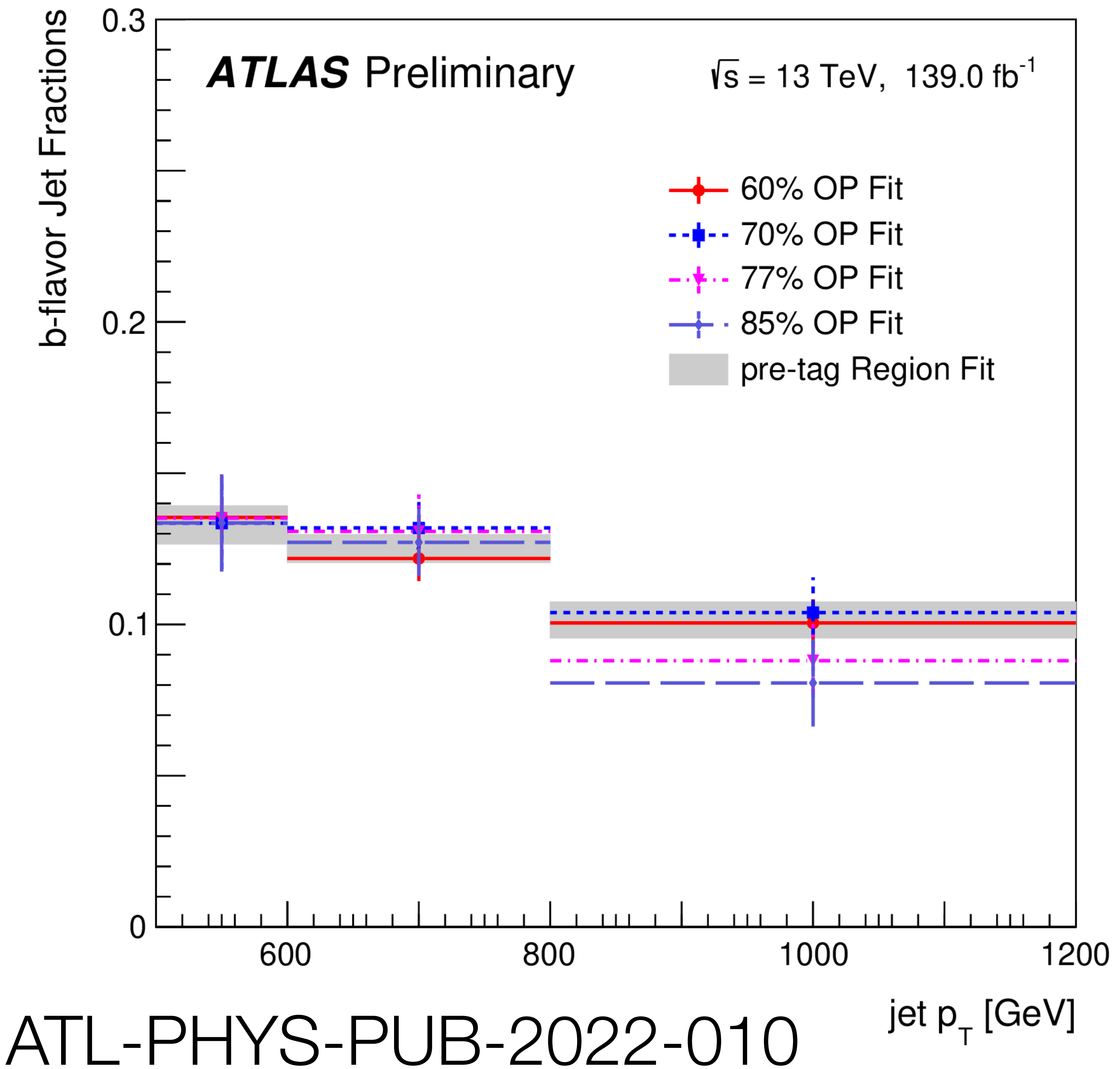
- The performance at TeV scale is not optimal. Need to improve

HF Measurement at High Energy Scale



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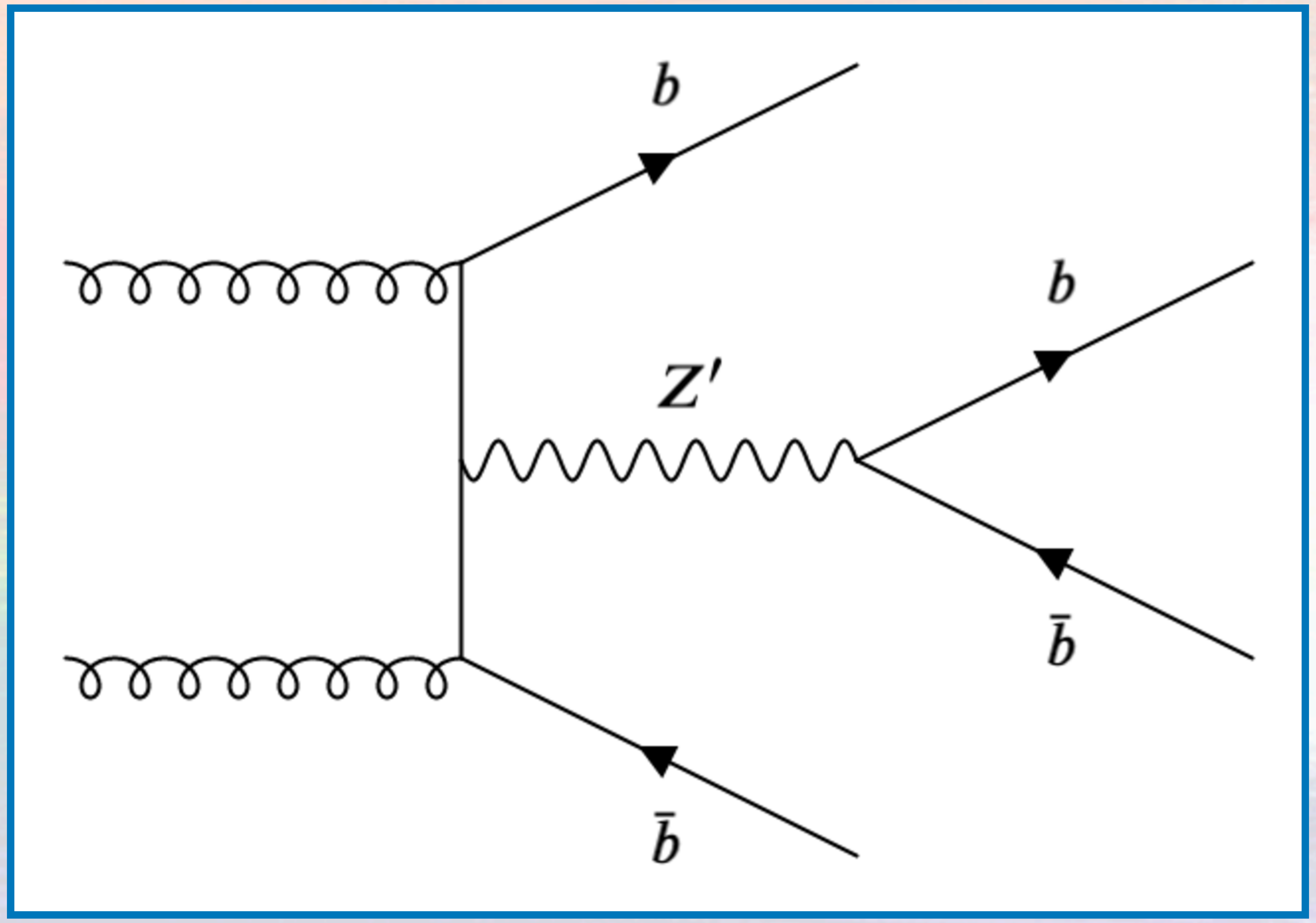
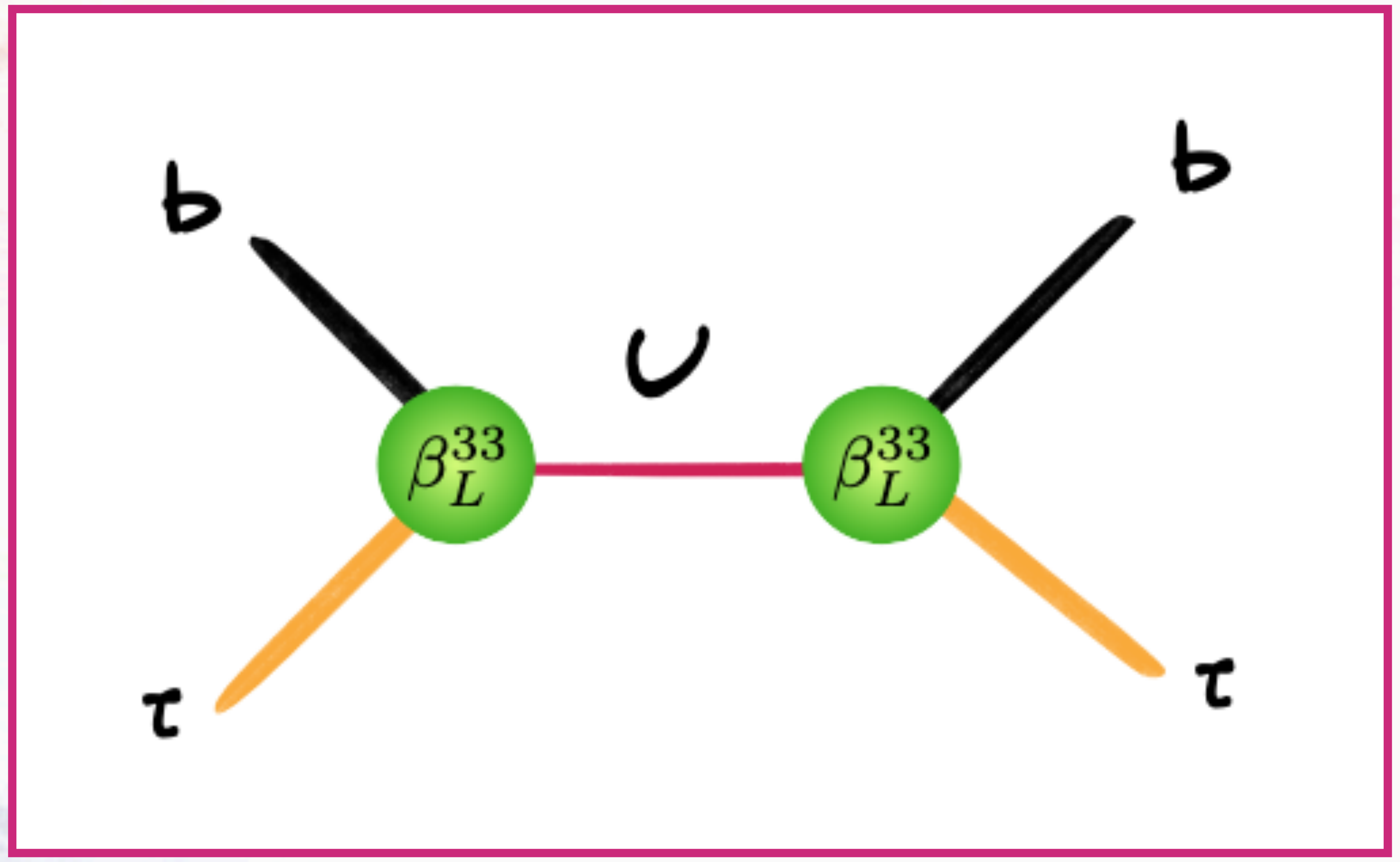
- Tuning the jet flavor fractions in simulation to match the data will significantly reduce the background estimate uncertainties
- Had a look at a specific phase space (jets containing muons) in this calibration work
- A thorough measurement would be ideal

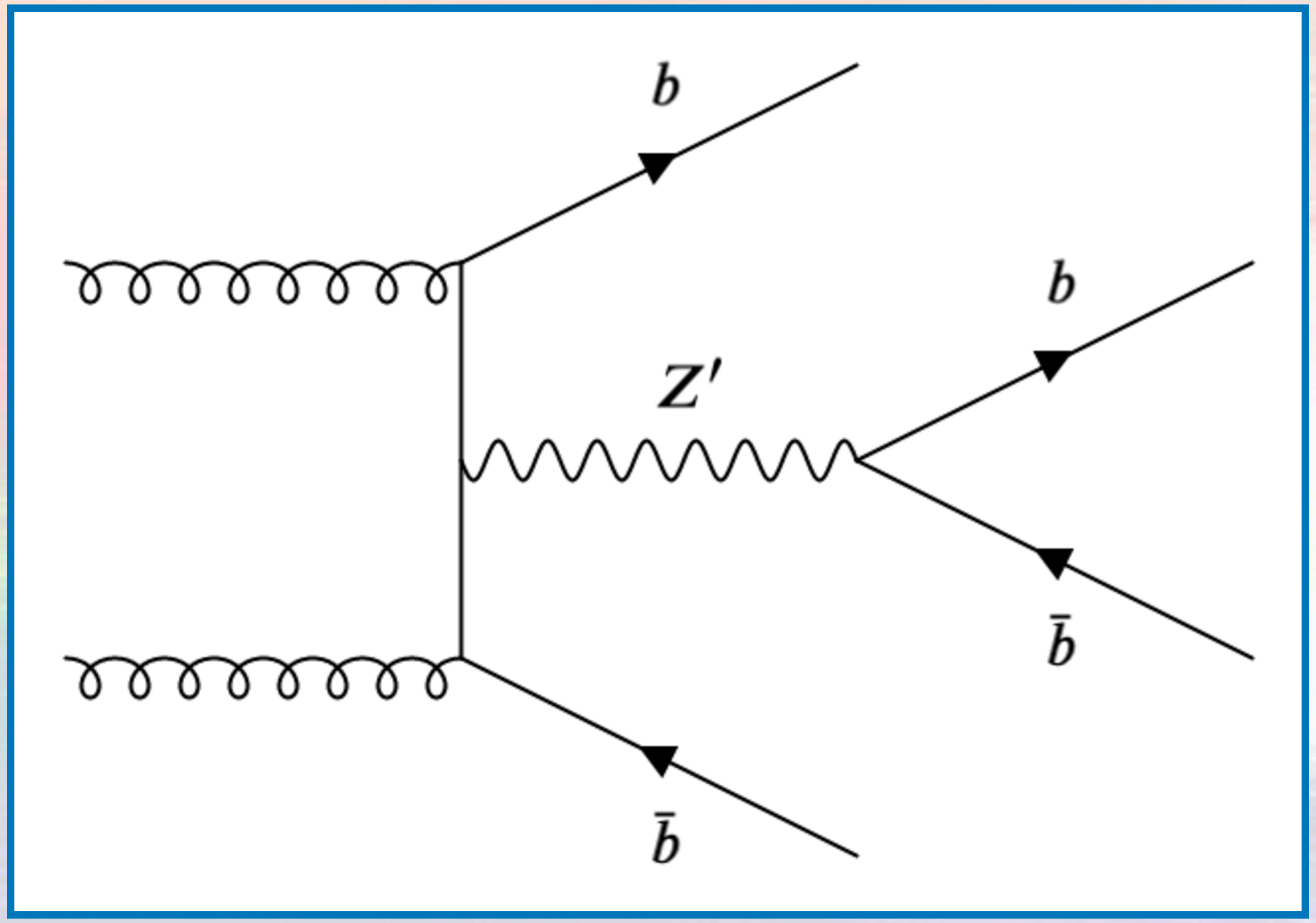
HF Flavor Associated Production

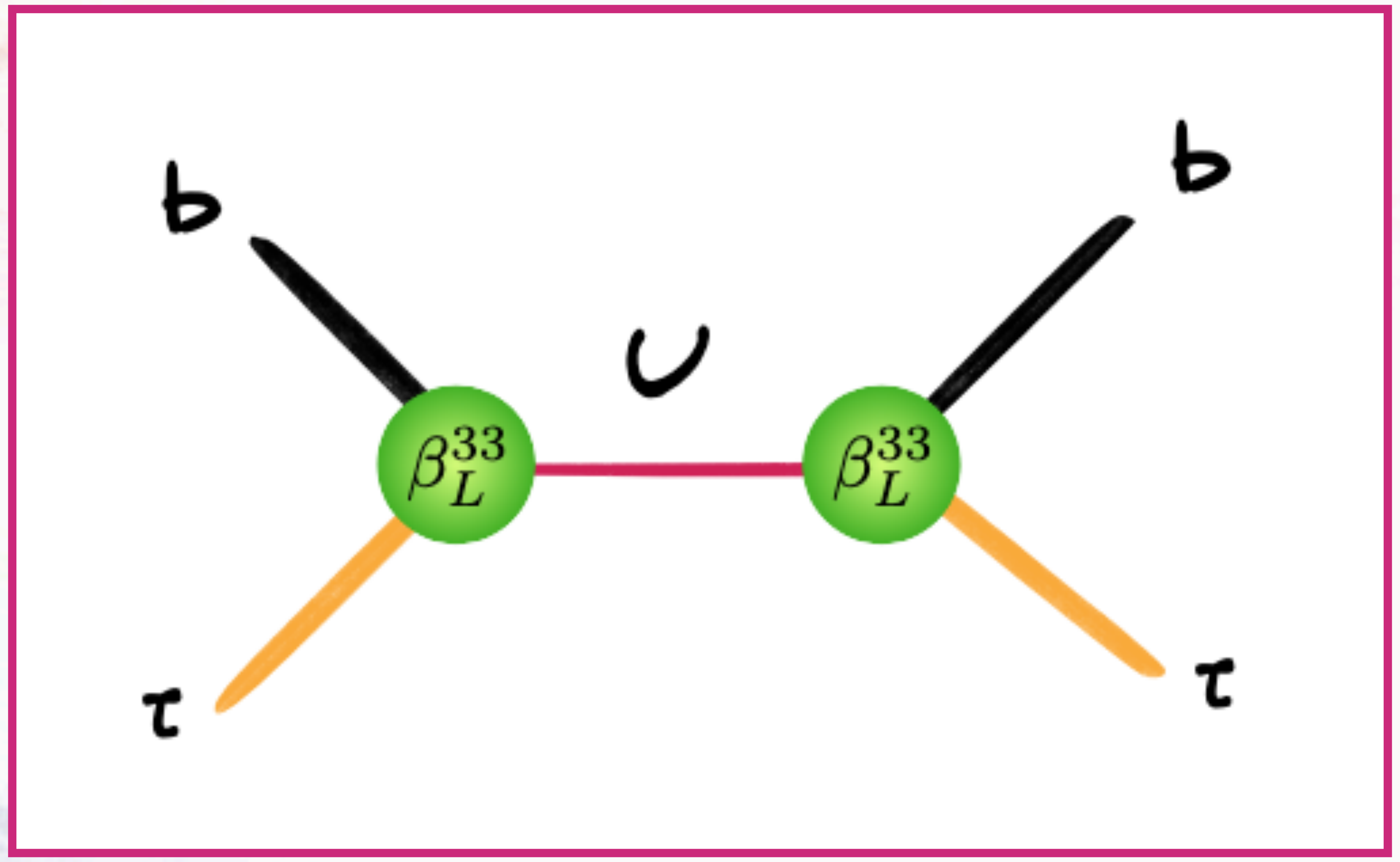




- Due to LHC PDF, soft additional heavy flavor quarks are produced
  - Extra objects to trigger on
  - Additional heavy flavor quarks can go beyond the current tracker coverage
    - Tracker Upgrade (ITK) and forward flavor tagging

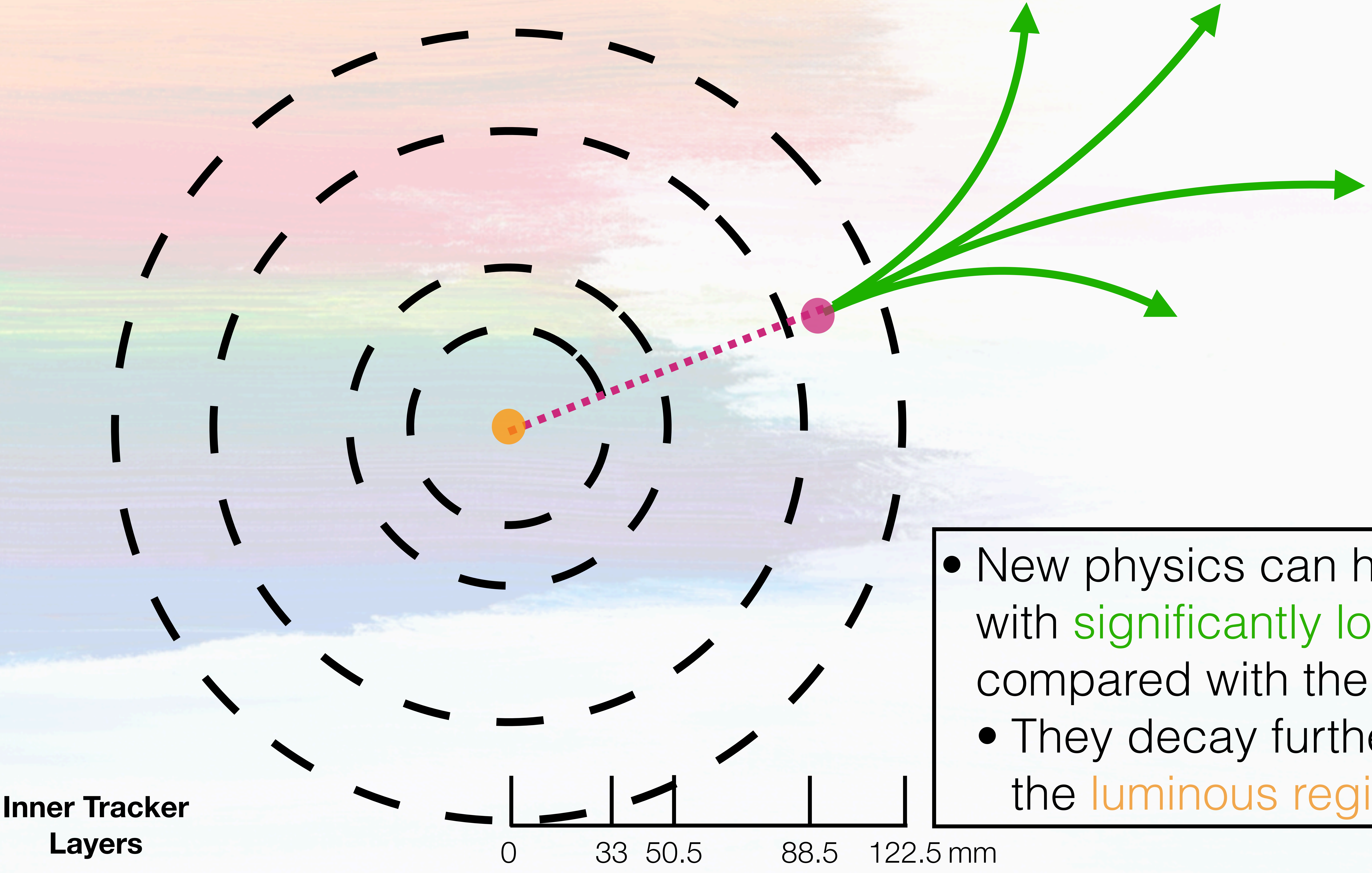
HF Flavor Associated Production





Plenty room to optimize this scenario!

BSM Long-lived Particles (LLPs) Decay



- New physics can have particles with significantly longer life-time compared with the b-hadrons
  - They decay further away from the luminous region

Long-lived Particle Search

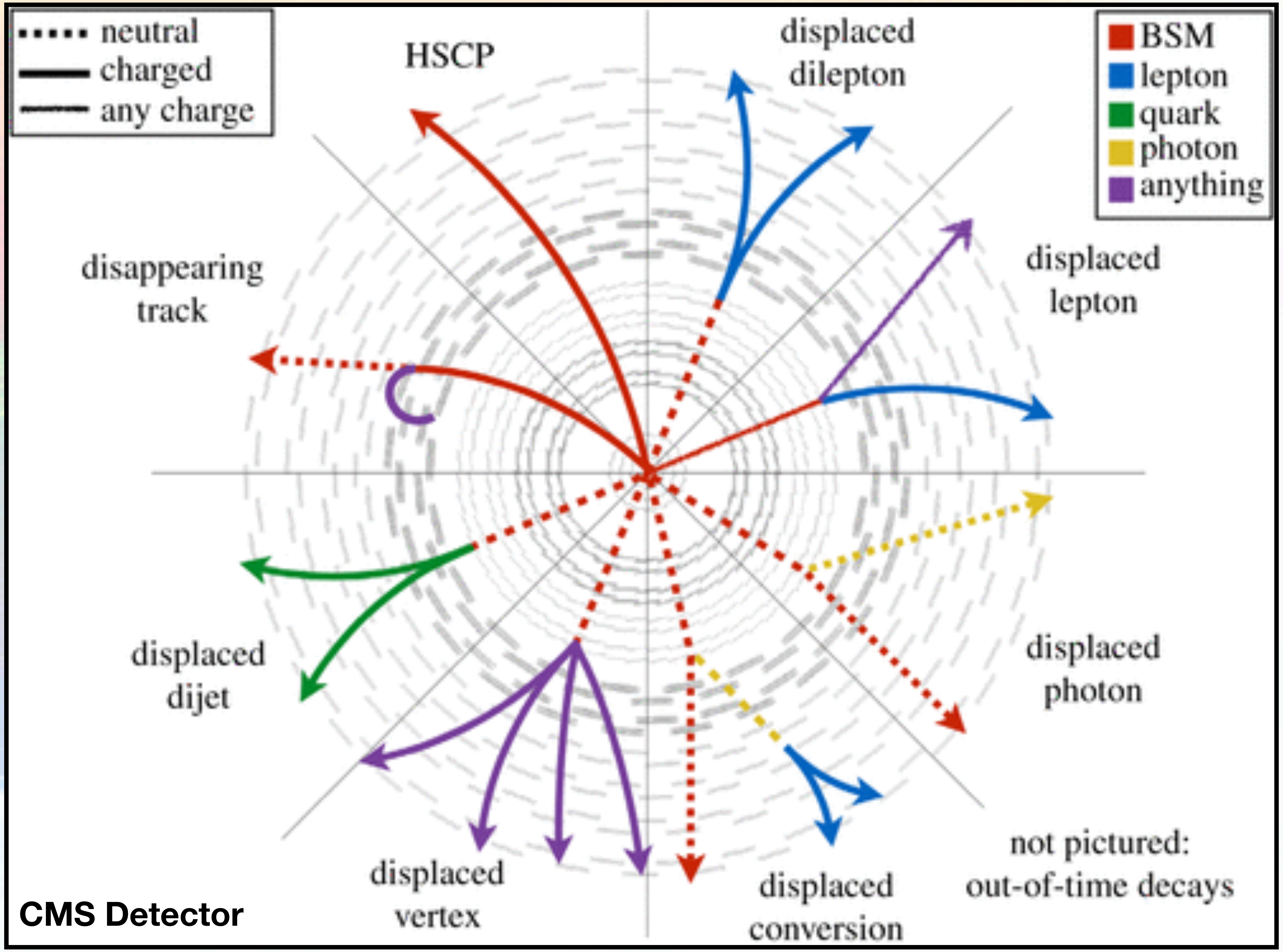
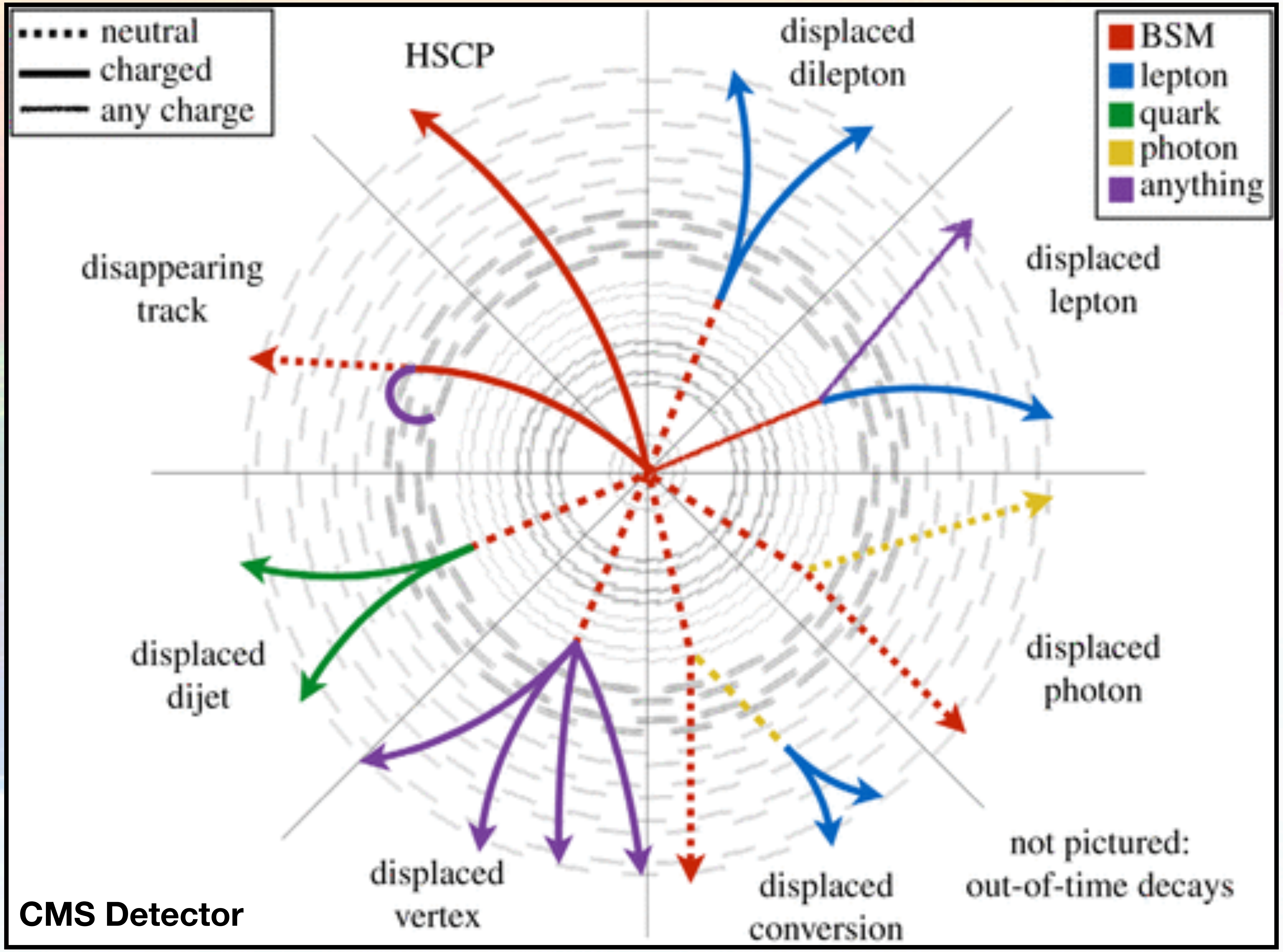


Figure credit: J. Antonelli

- Often categorize long-lived particle searches by where the particle decays and what the decay products are
  - Displaced objects
    - Jets, leptons, photons, vertices
  - Non conventional objects
    - Highly ionizing track, disappearing track

Long-lived Particle Search



Signature Driven:

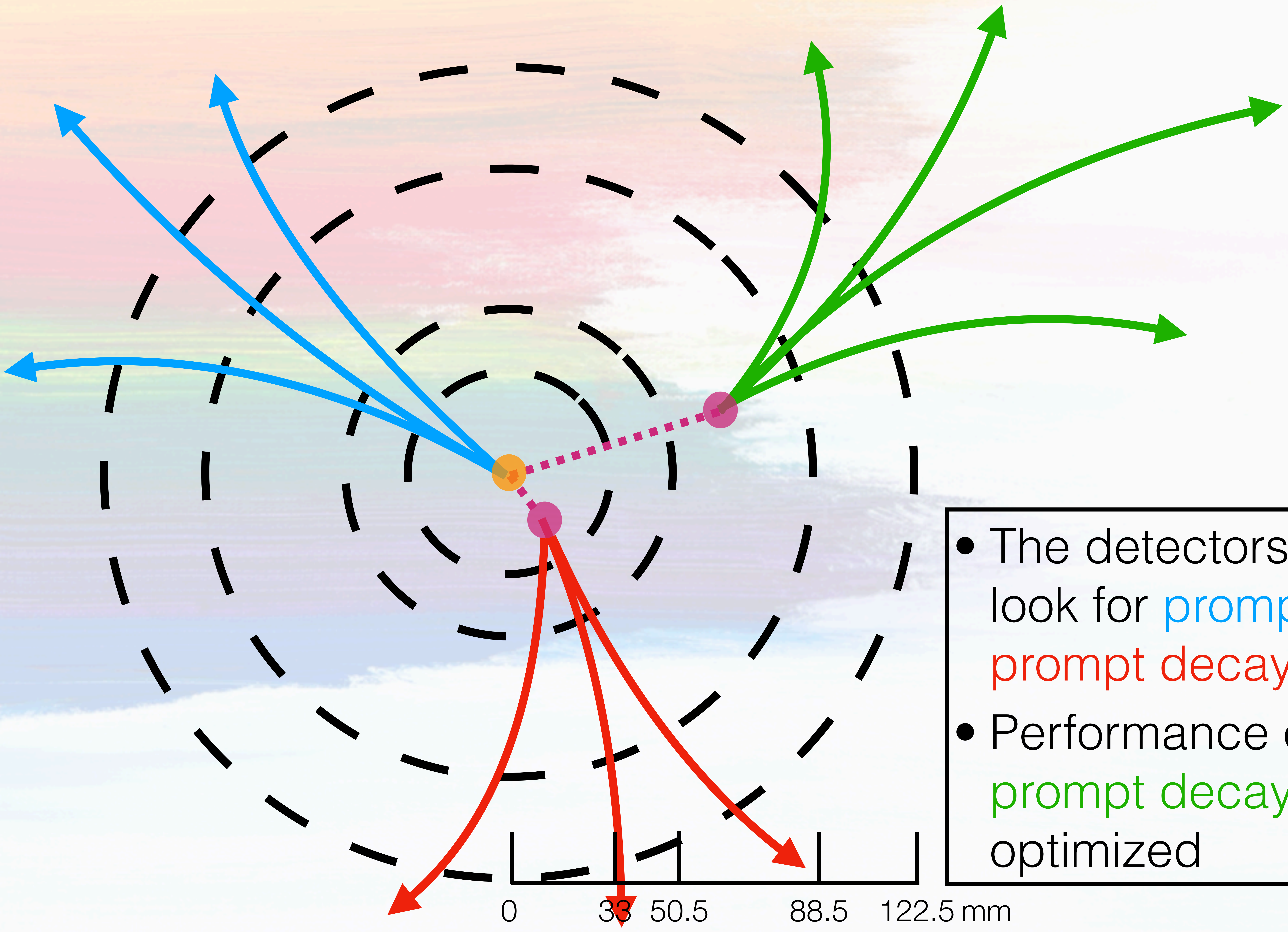
Look for special signatures in the detector that have not been searched before

Figure credit: J. Antonelli

Long-lived Particle Search

- They are also well motivated theoretically
  - Predicted in many scenarios
- R-parity violated Supersymmetry
  - The lightest supersymmetric particles (LSP) can decay to SM particles whose mean lifetimes are free parameters
    - Becoming more important as traditional SUSY searches have excluded a large parameter space
- Hidden valley scenarios
  - A hidden sector is connected with SM and the new particles in the decay chain can have long lifetimes
    - Higgs is very sensitive to this scenario
- Many other models as well
  - Anomaly Mediated SUSY Breaking (AMSB), etc

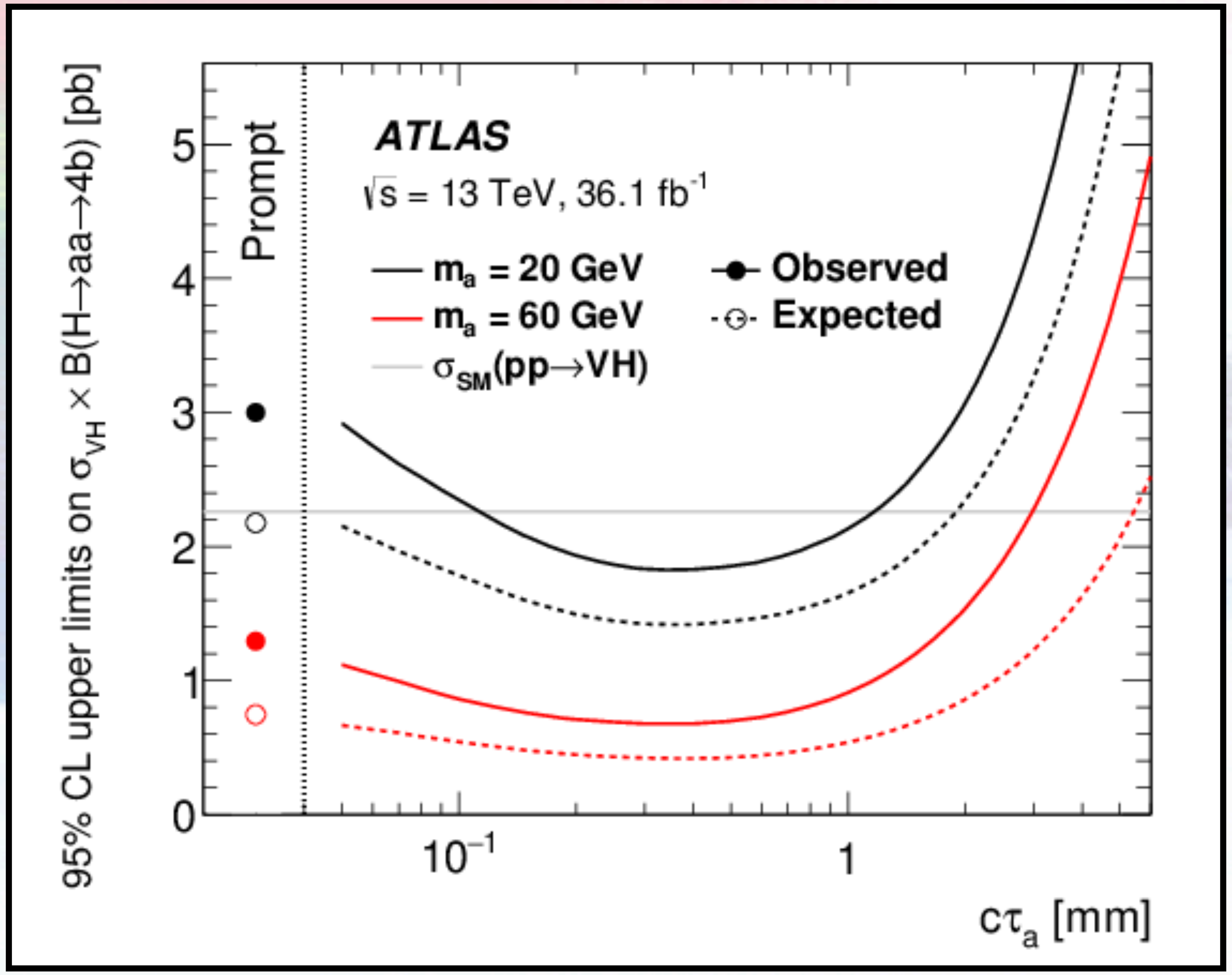
Challenging!



- The detectors were designed to look for prompt decays or non-prompt decays expected by SM
- Performance on exotic BSM non-prompt decays were not optimized

b-tagging Long-lived Particles

- Long-lived particles can have lifetimes similar as *b*-hadrons
  - Can be *b*-tagged
  - Standard searches with *b*-tagging have sensitivities to such LLPs



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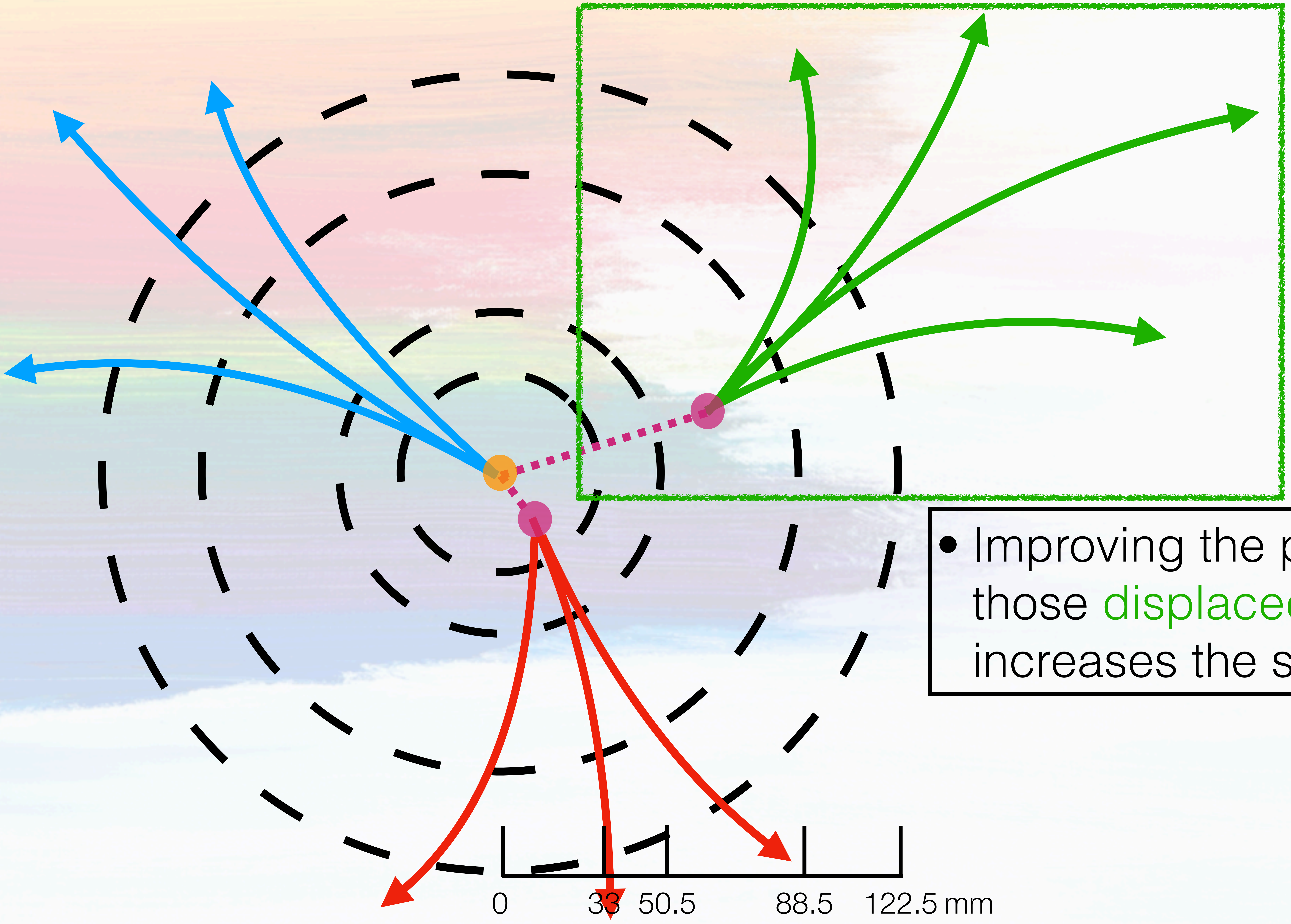
- We performed a re-interpretation of the $VH(H \to aa \to b\bar{b}b\bar{b})$ search
- Without changing analysis strategy, the search is sensitive to $c\tau_a$ up to 1mm
  - Usually consider $c\tau$ as a parameter of the signal
- Very exciting to see the potential of dedicated taggers targeting intermediate lifetimes

Challenging but Really Rewarding!

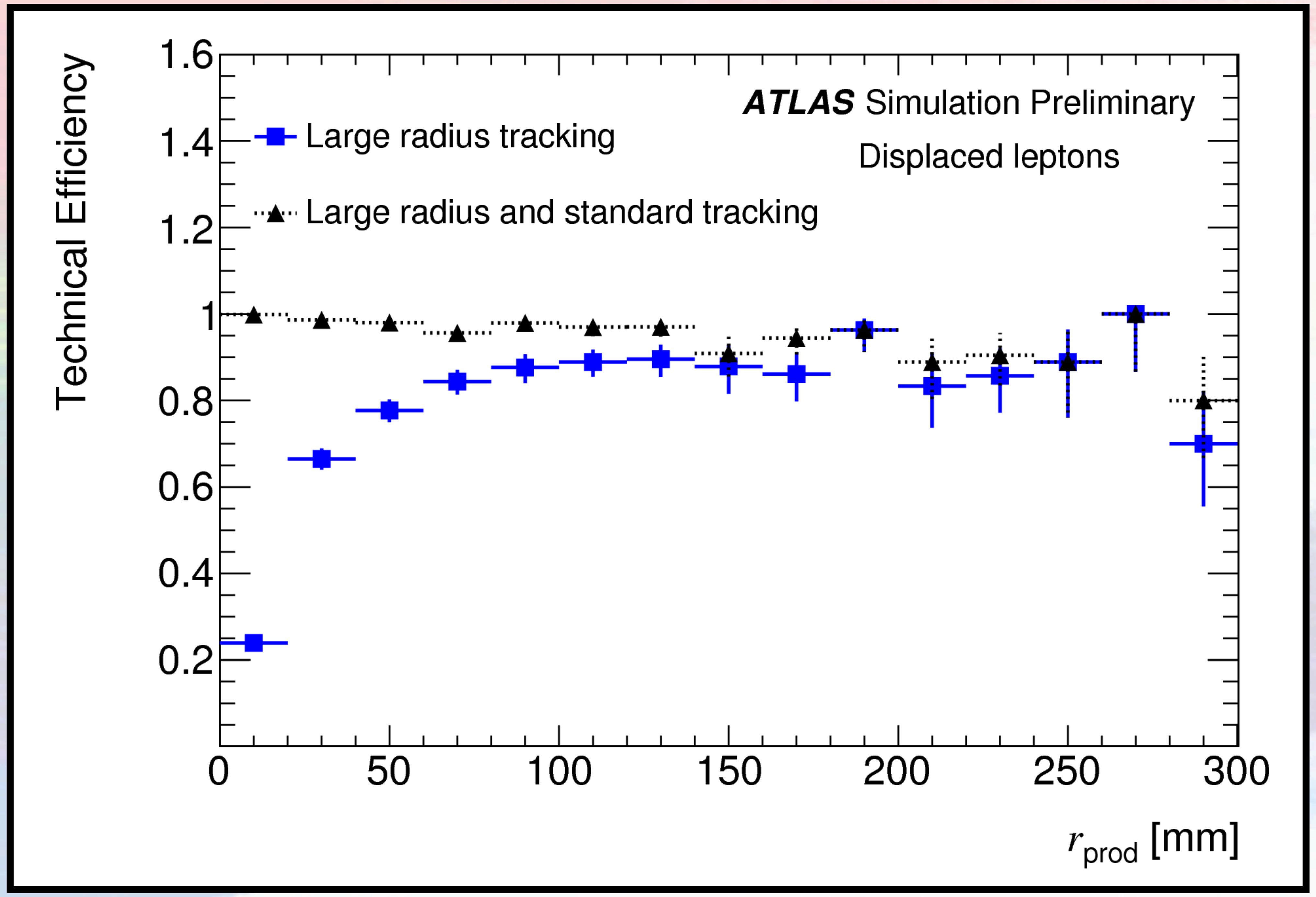


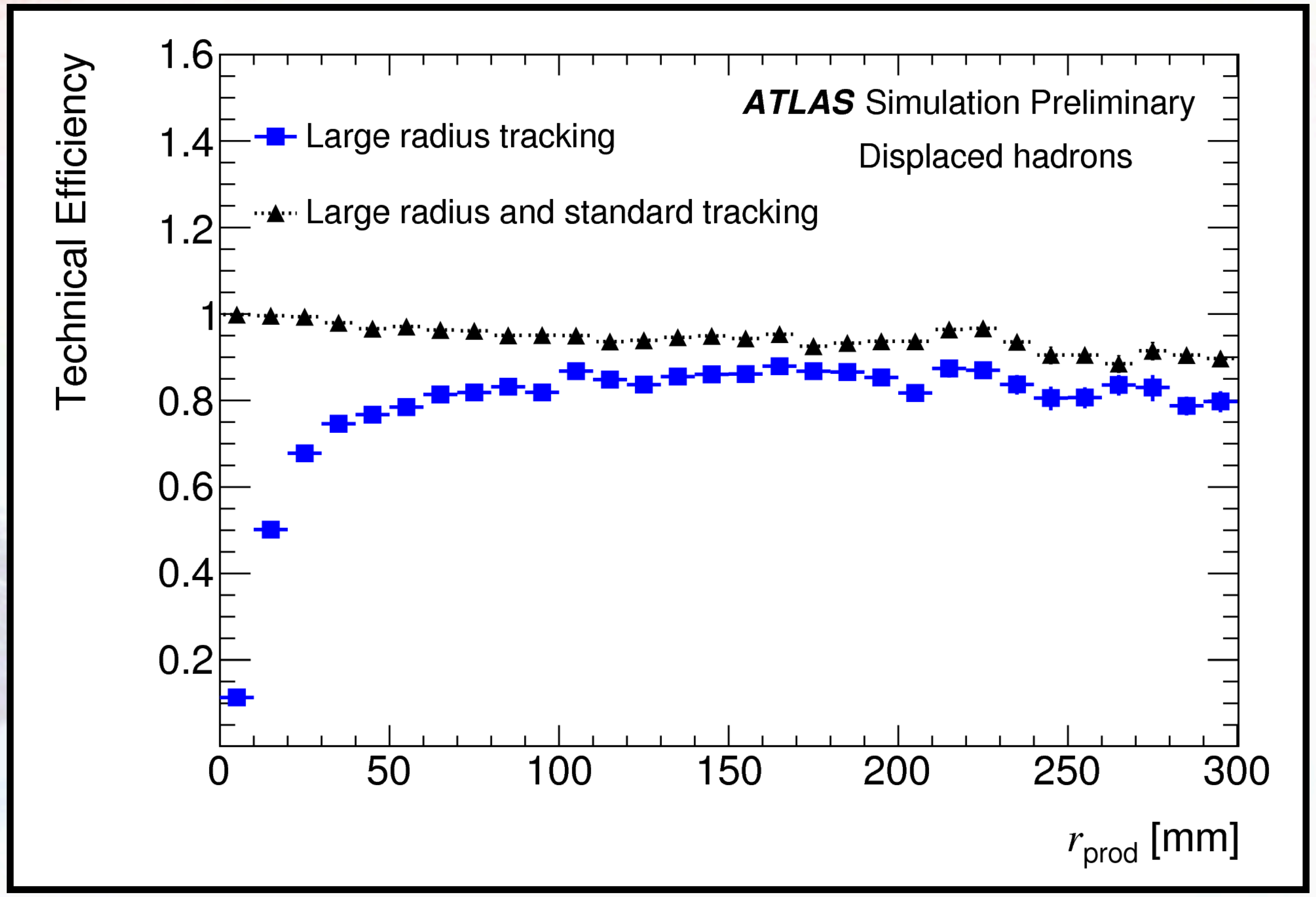
- Improving the performance on those displaced signature increases the search sensitivity

Large Radius Tracking in ATLAS

- Large Radius Tracking (LRT) is a special tracking algorithm for long-lived particle (LLP) searches

ATL-PHYS-PUB-2017-014

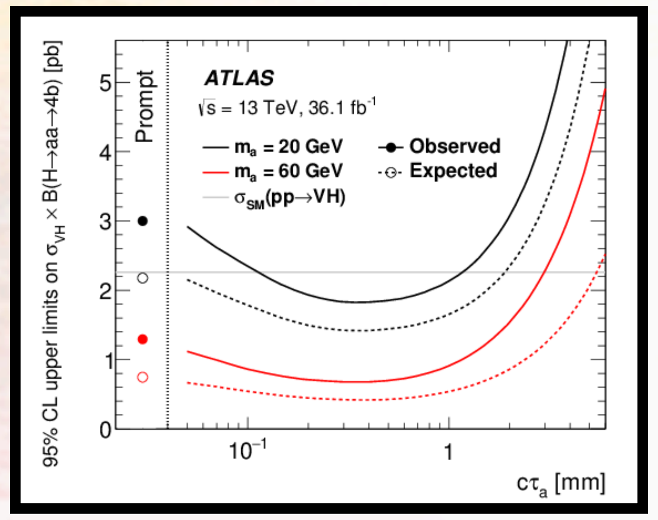




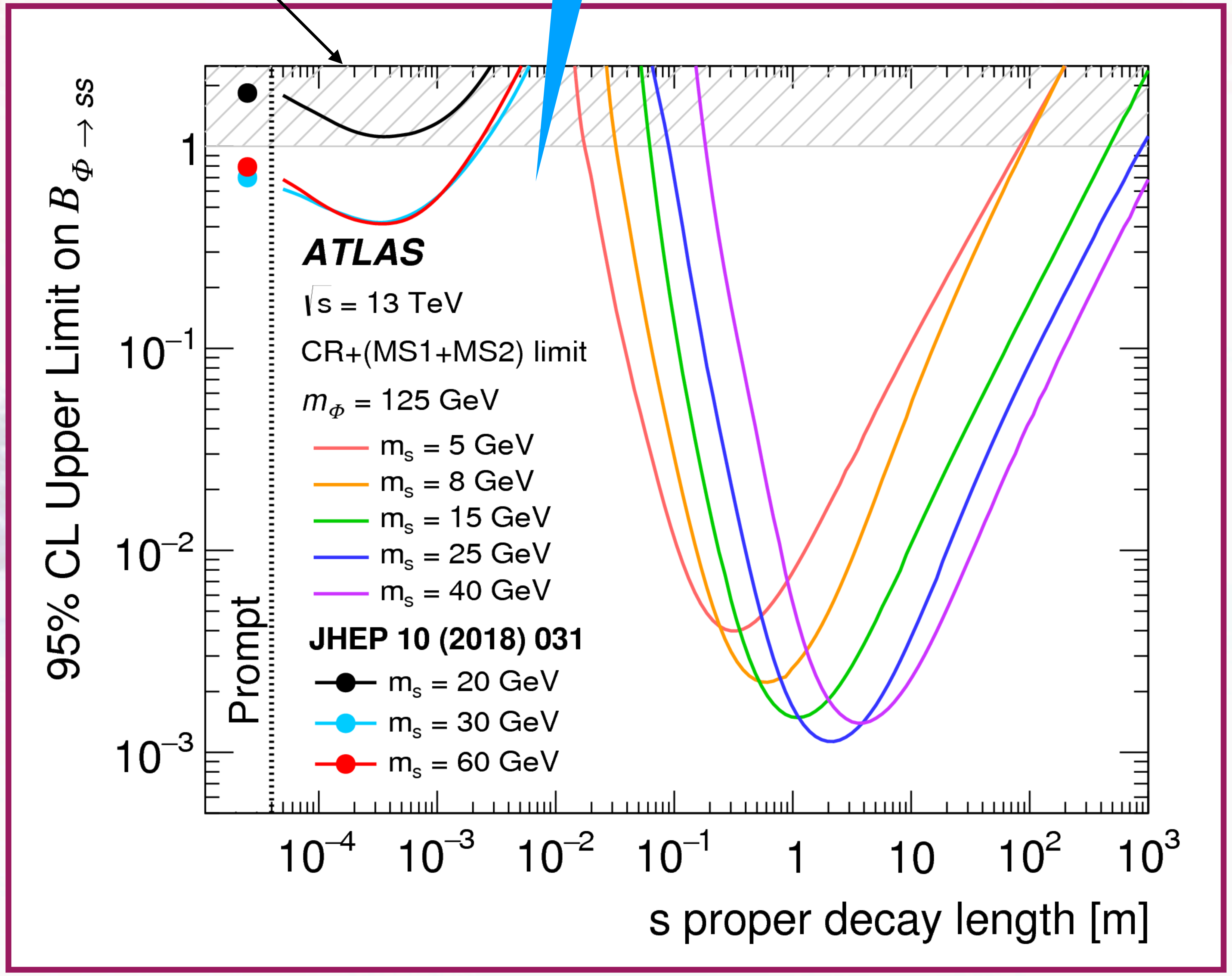
- It has been applied in many Run2 LLP searches
  - Good efficiency up to production radius ~ 300 mm!

VH4b Dedicated LLP Search

- Intermediate lifetime region has not been covered well
  - Displaced decays within the tracker volume
- We did a dedicated search using LRT to cover this gap
  - Searching for V+Higgs -> aa (long-lived) -> 4 *b*-quarks via displaced vertices (DV) reconstructed using LRT



A Clear Gap!



Eur. Phys. J. C 79 (2019) 481

VH4b Dedicated LLP Search

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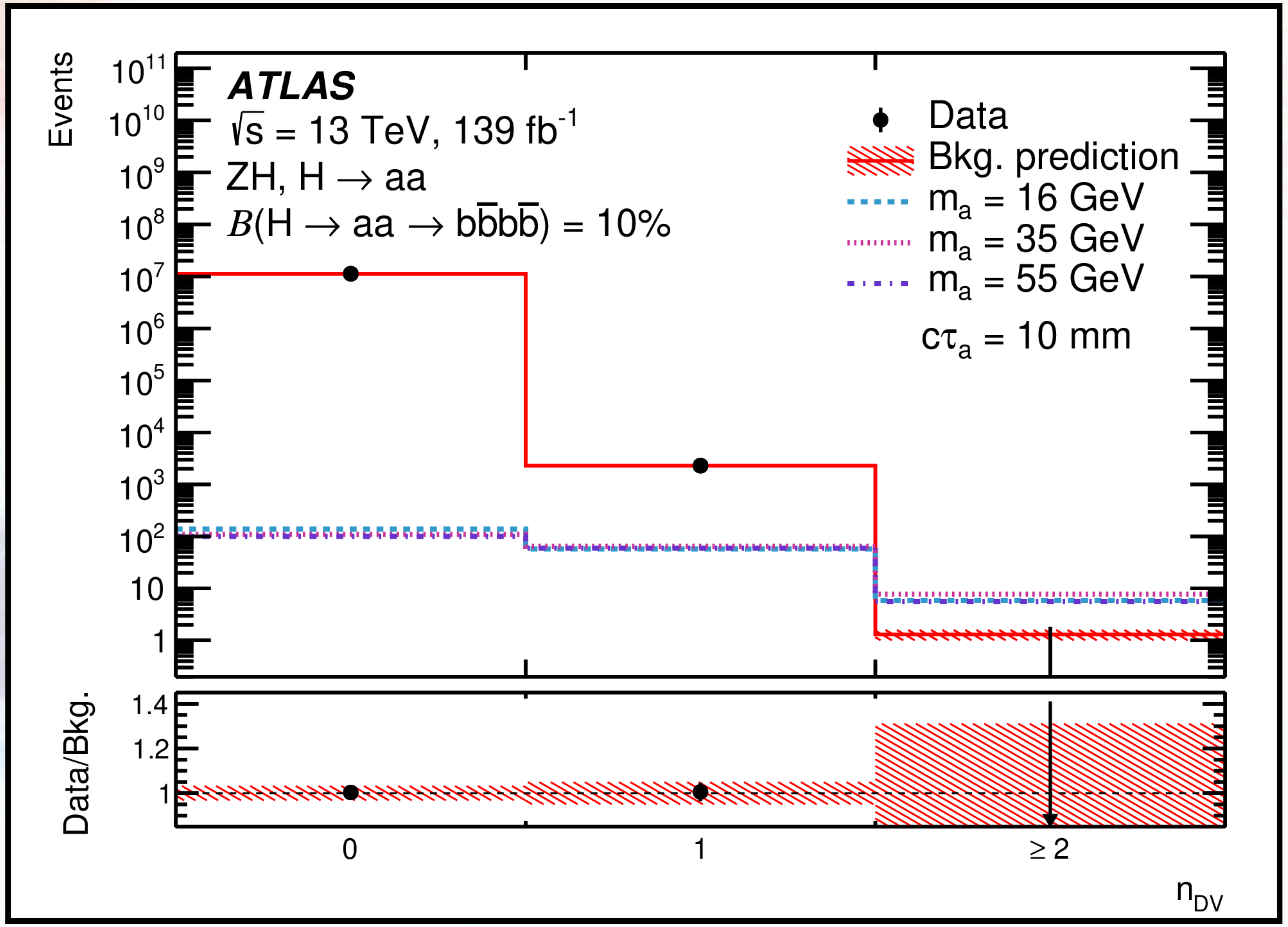
  - Signal region requires at least two DVs



JHEP11(2021)229

VH4b Dedicated LLP Search

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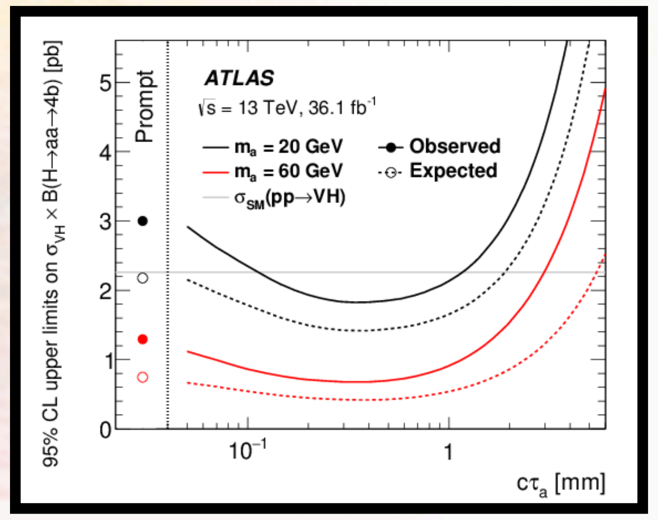
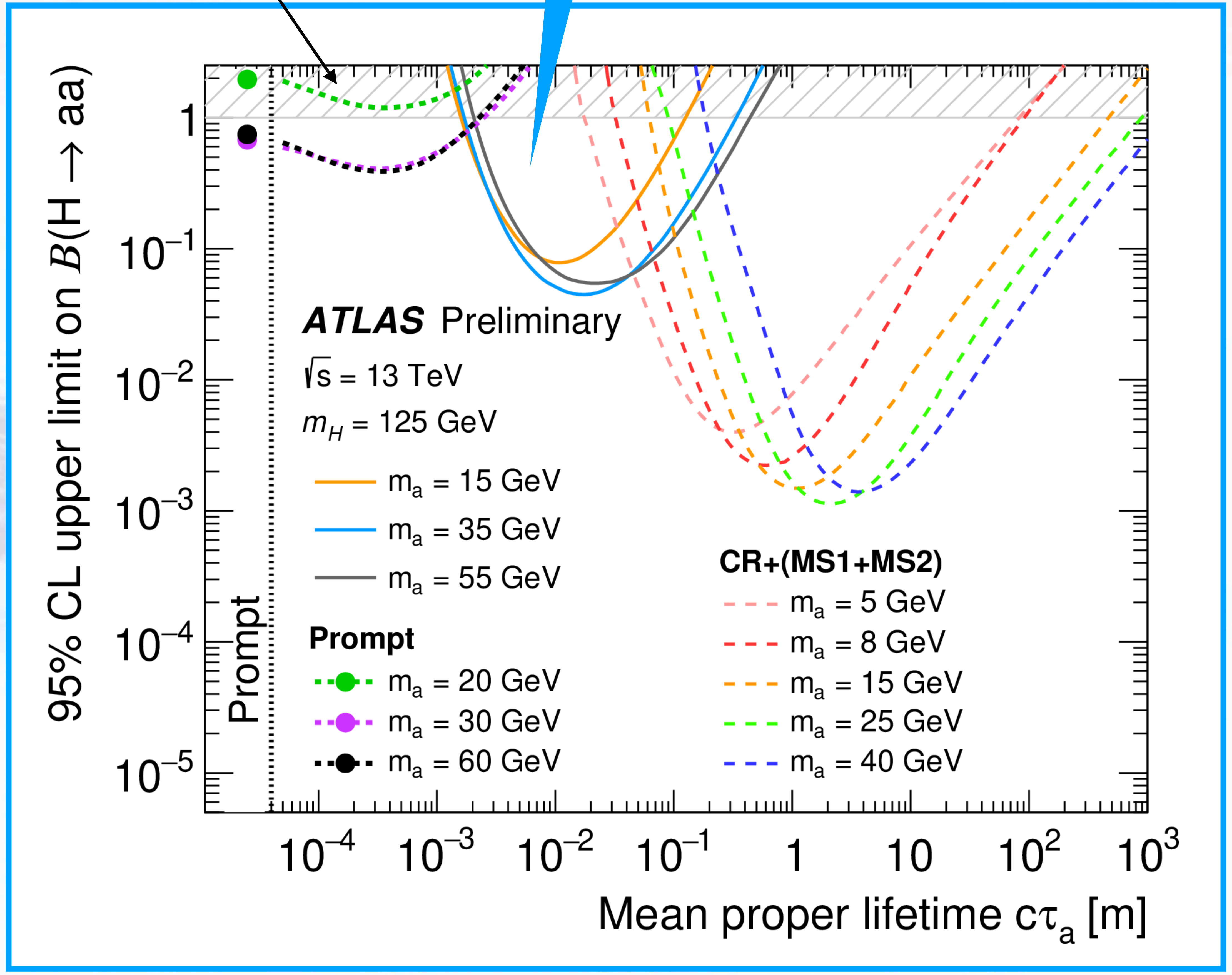
- We did a dedicated search using LRT to cover this gap
  - Searching for V+Higgs -> aa (long-lived) -> 4 *b*-quarks via displaced vertices (DV) reconstructed using LRT
- Aiming at **filling this gap**
- And it did fill this gap



Gap filled!

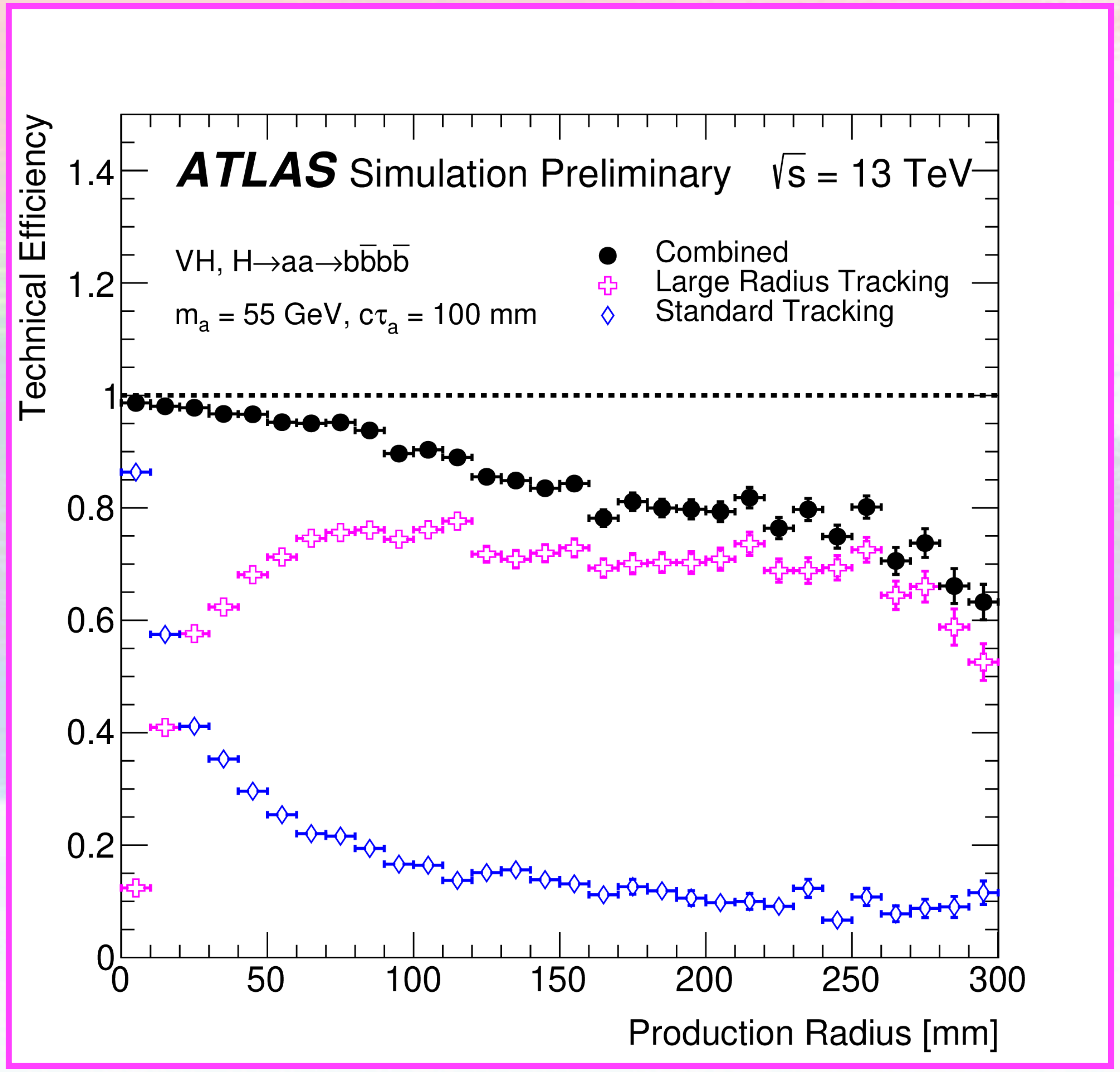


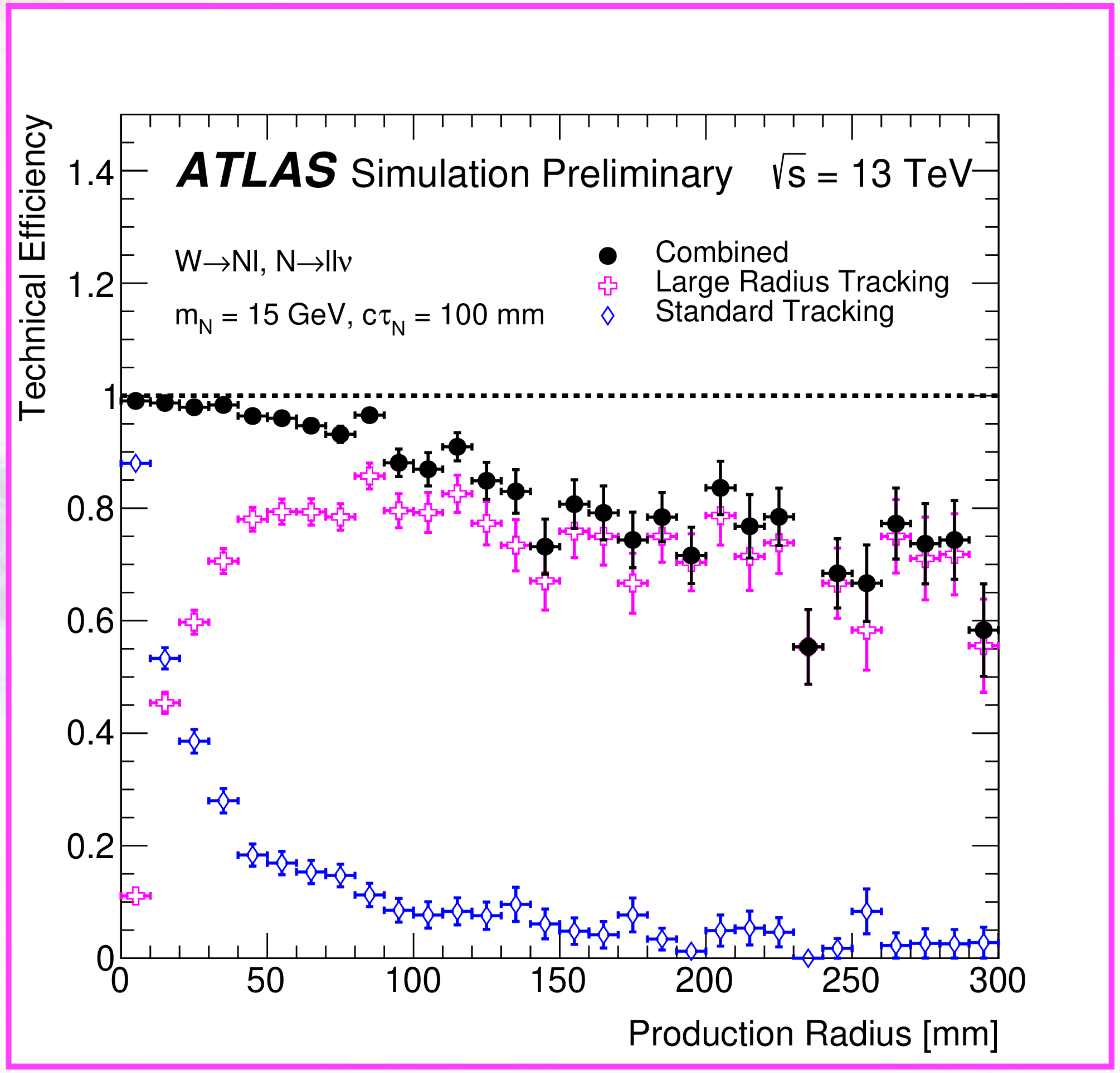
JHEP11(2021)229

NEW Large Radius Tracking in ATLAS

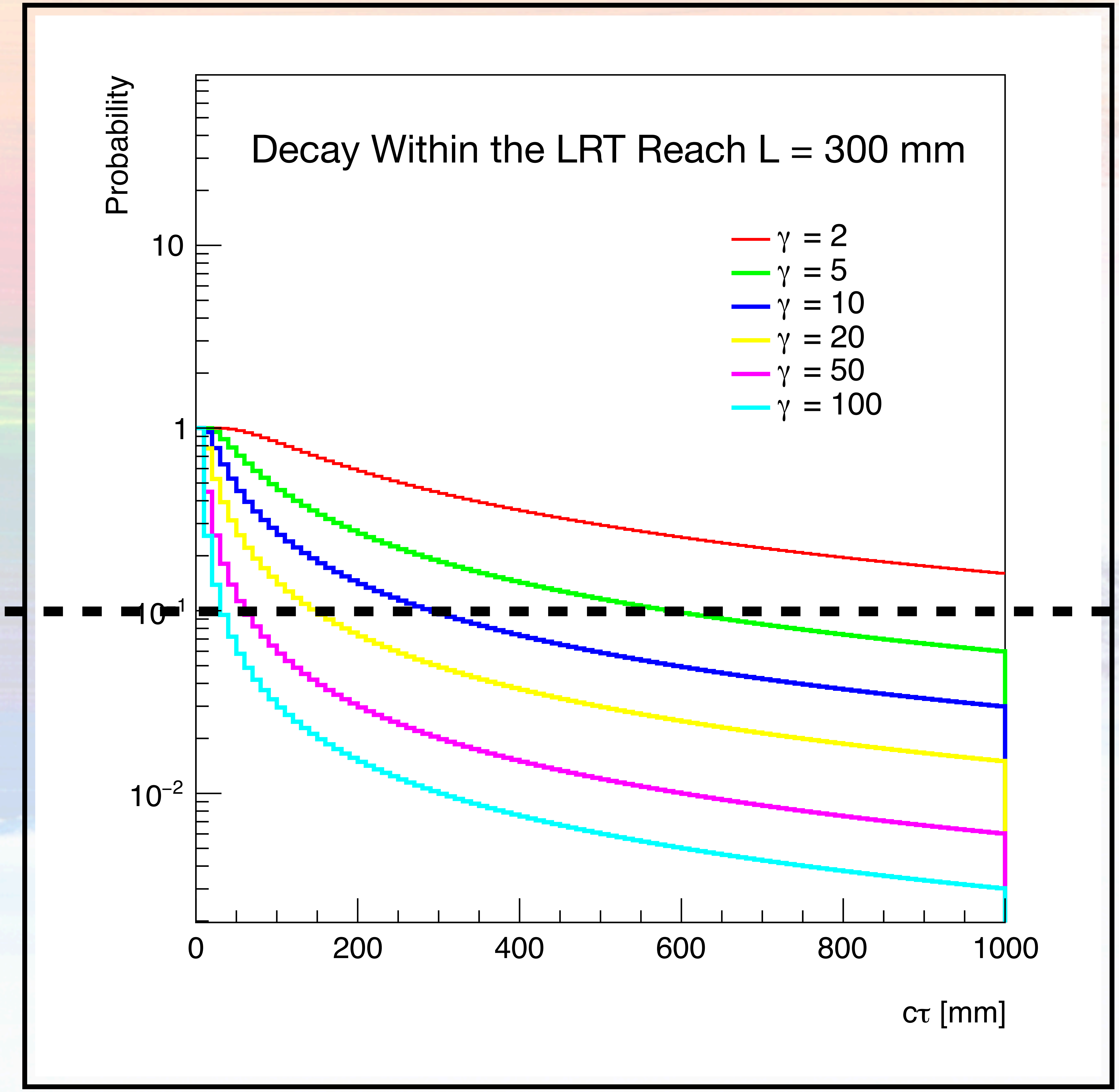
IDTR-2021-003

- LRT has been significant updated/improved for Run3!
  - Run2 LLP program can also benefit it from reprocessing





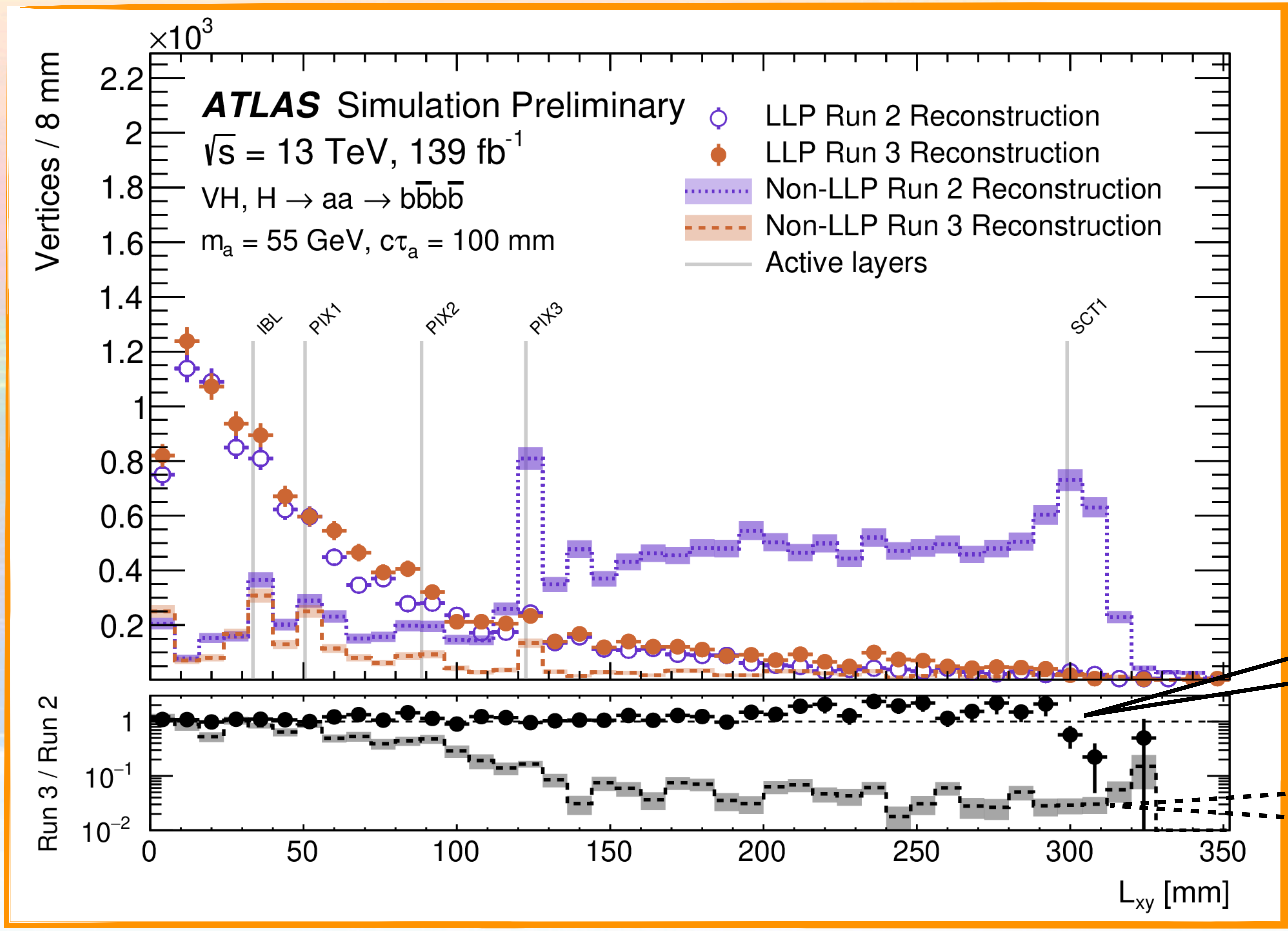
NEW Large Radius Tracking in ATLAS



- Distance traveled before decaying: $\mathrm{L} = c\beta\gamma t$
- Save to assume a heavier mass leads to a smaller γ
- Given the exponential nature of the decays, the probability of a LLP decaying within the LRT reach (L = 300 mm) is significant for a large part of the parameter space
- Expecting good acceptance!

NEW Large Radius Tracking in ATLAS

IDTR-2021-003



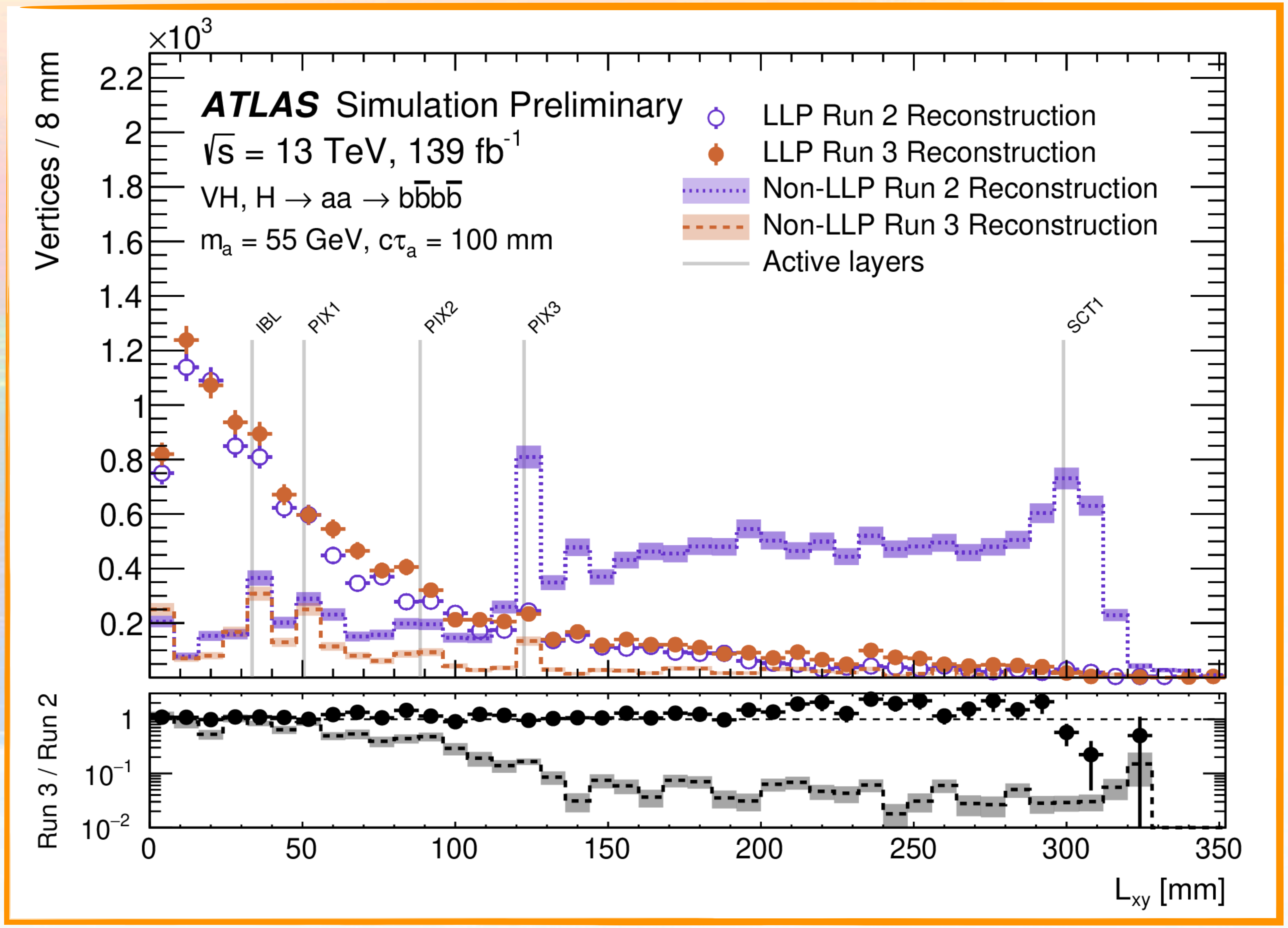
- The displaced vertex performance is improved significant

Similar/Higher signal efficiencies

Much lower fake rates

NEW Large Radius Tracking in ATLAS

IDTR-2021-003

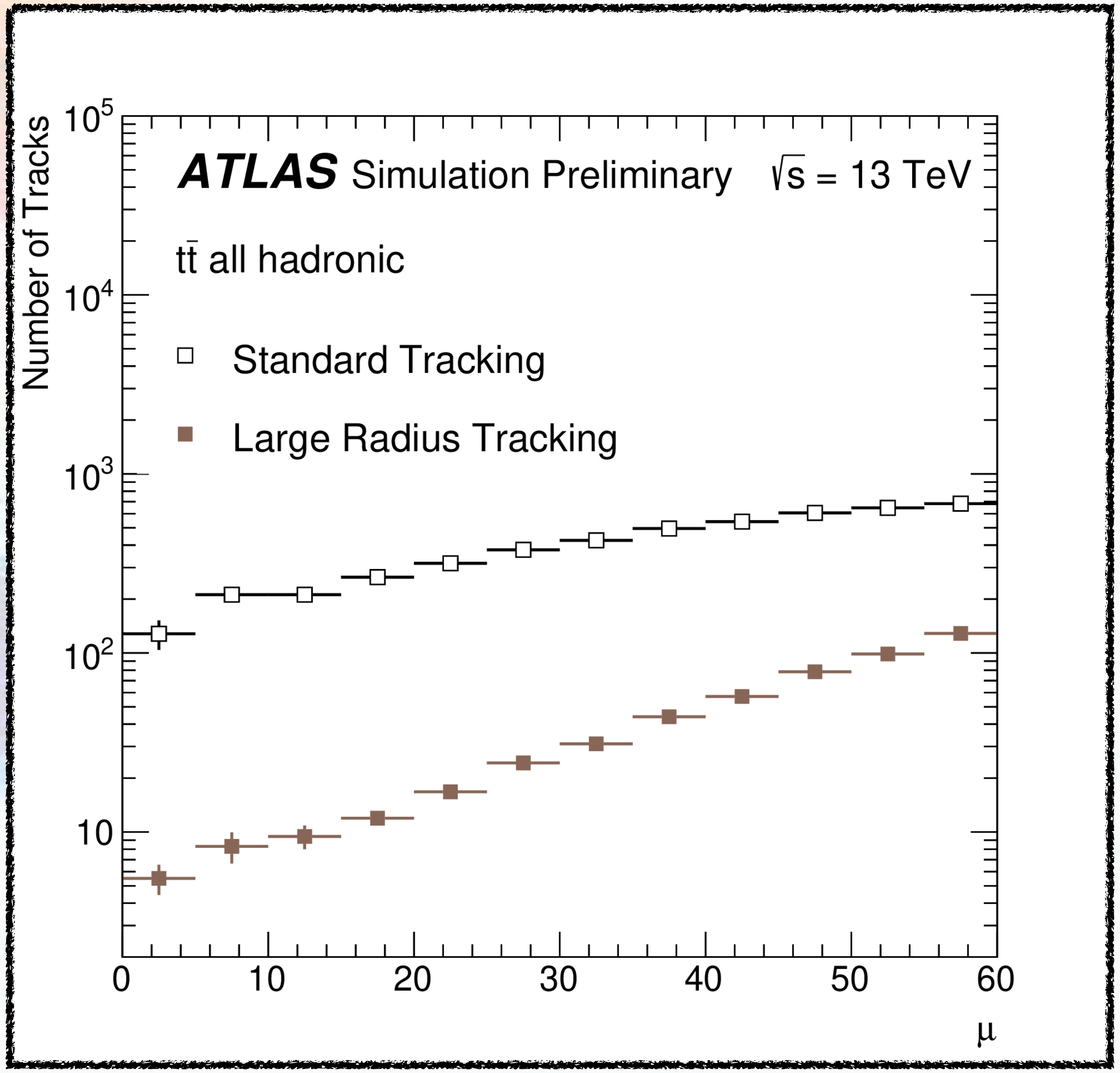


Sensitivities of LLP searches using the inner tracker will be amazing!

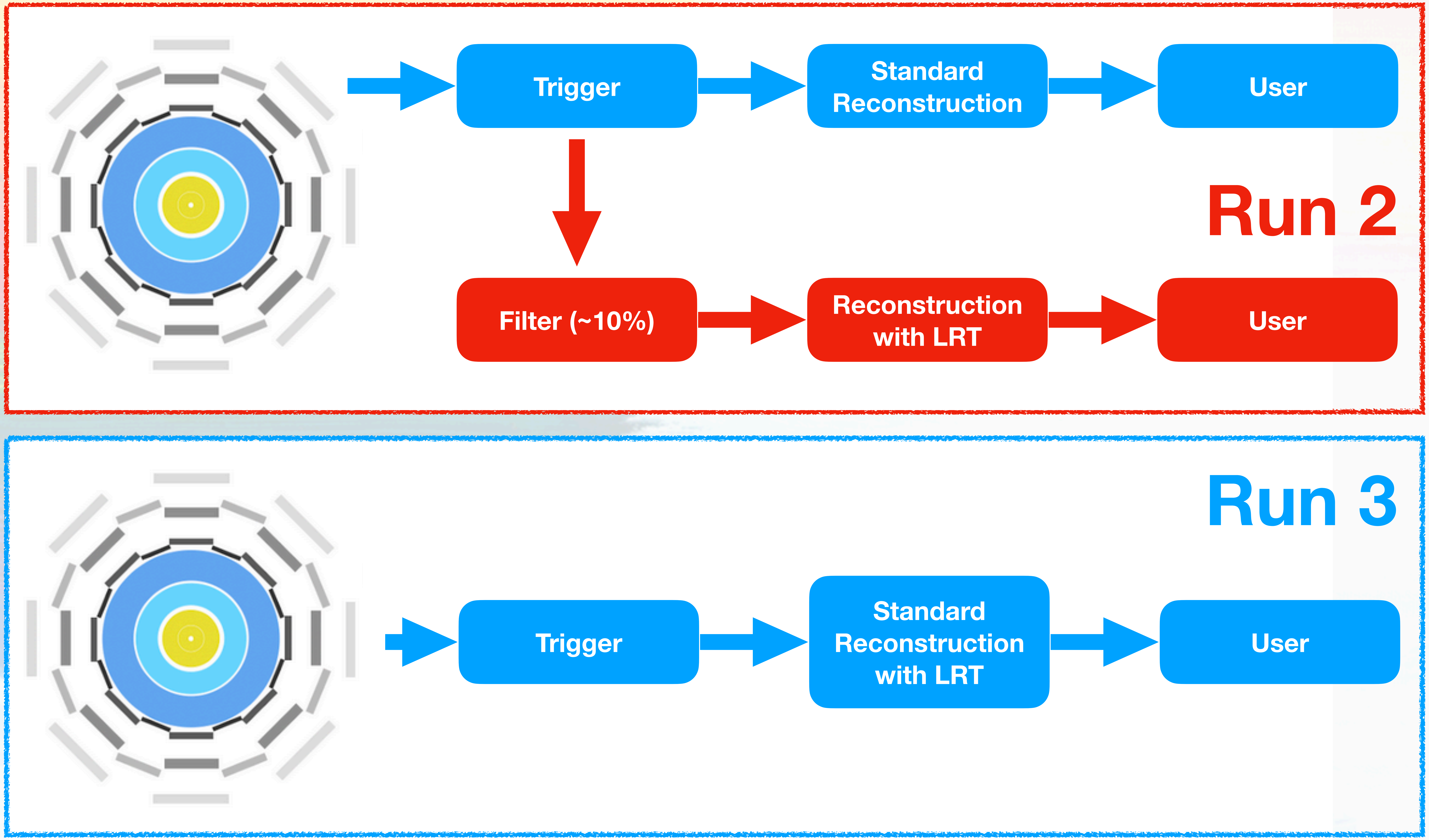
NEW Large Radius Tracking in ATLAS

IDTR-2021-003

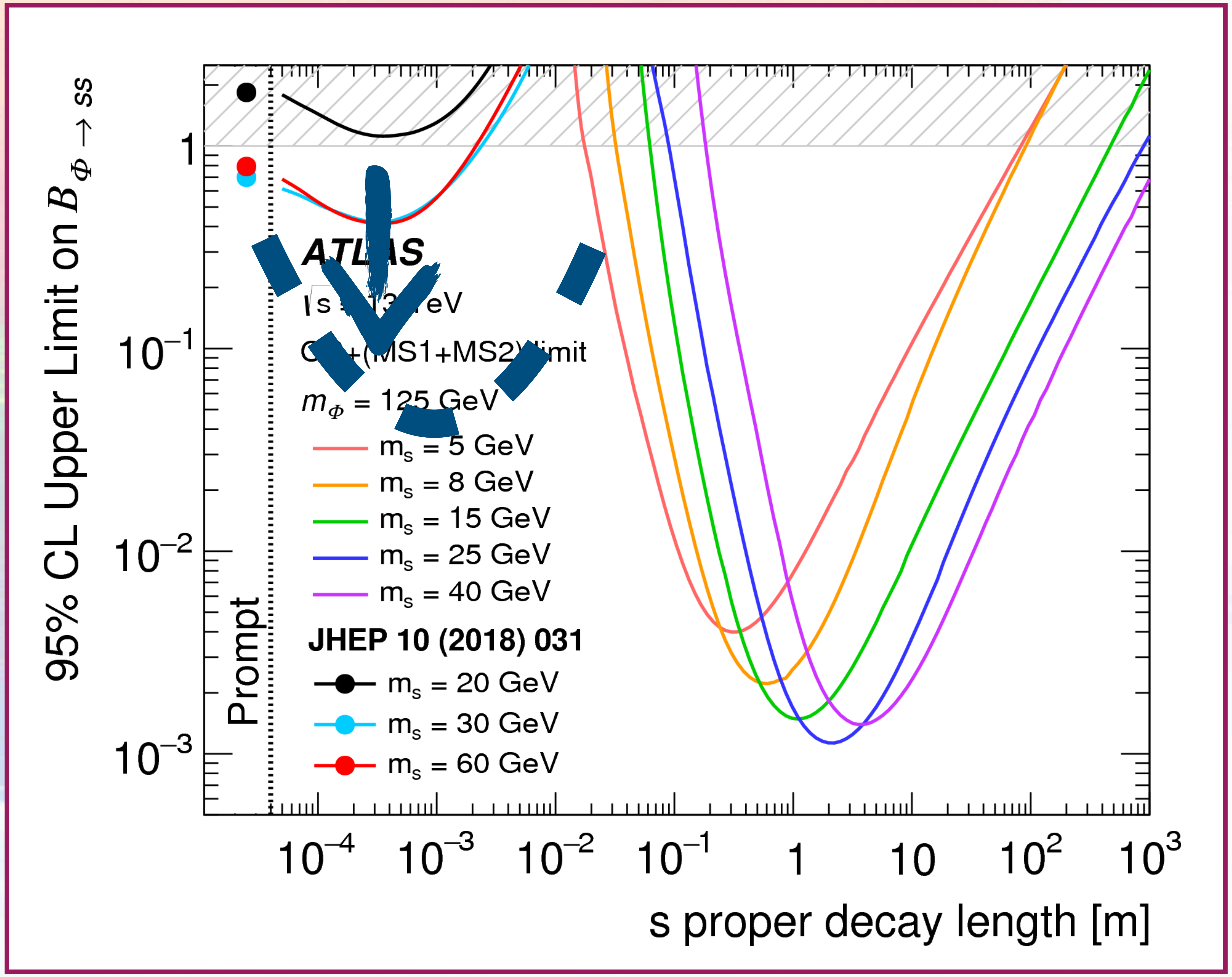
- The new algorithm only adds ~10% more tracks on average in each event
- It is enabled for every single event collected by ATLAS
  - No additional filtering or processing is needed
  - Save computational resource and person power
- Previously LRT was only applied to ~10% of the events collected by ATLAS



Bingxuan Liu

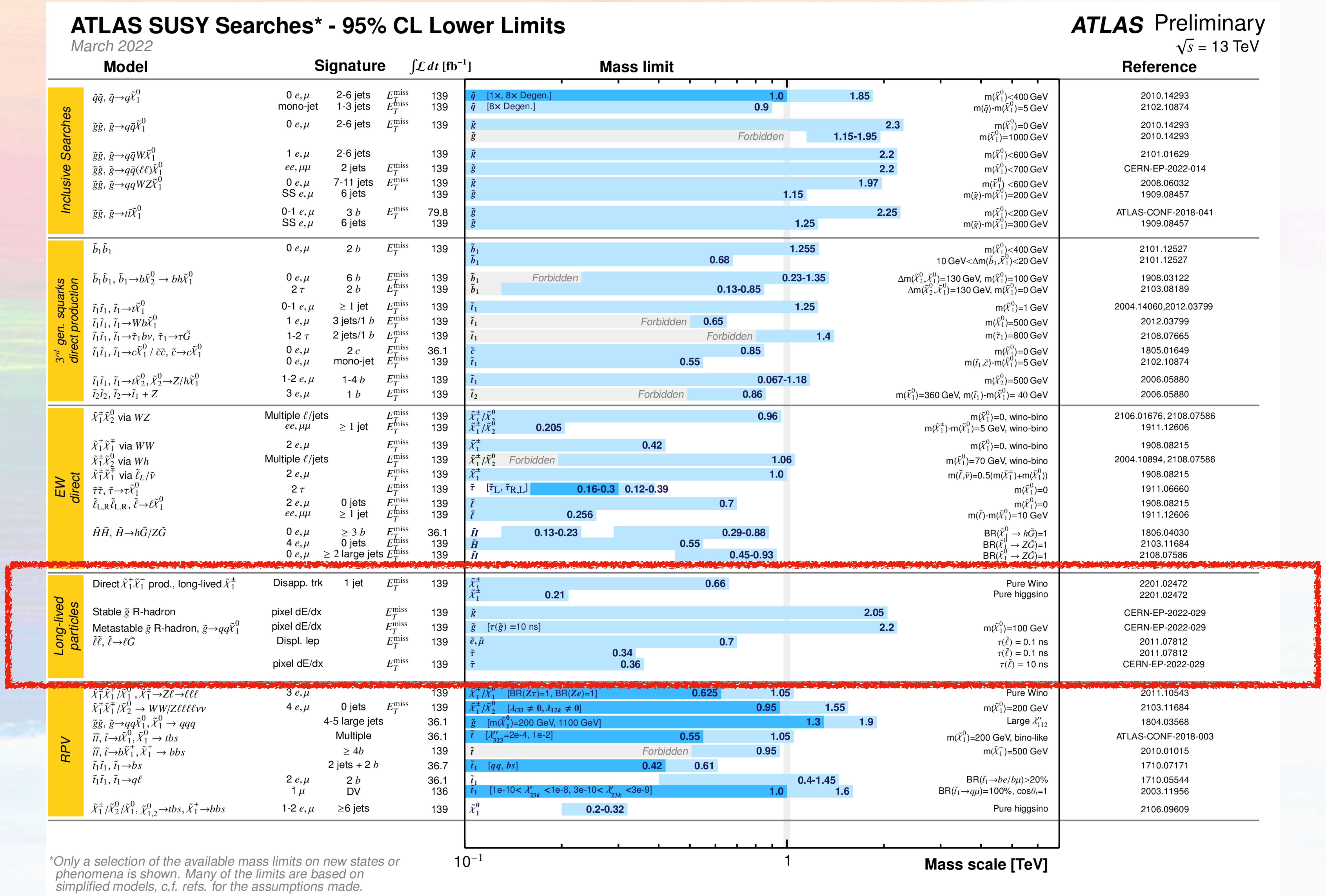

Trigger
Standard Reconstruction
User
Run 2
Filter (~10%)
Reconstruction with LRT
User
Run 3
Trigger
Standard Reconstruction with LRT
User

Make Traditional Searches More Sensitive to LLP



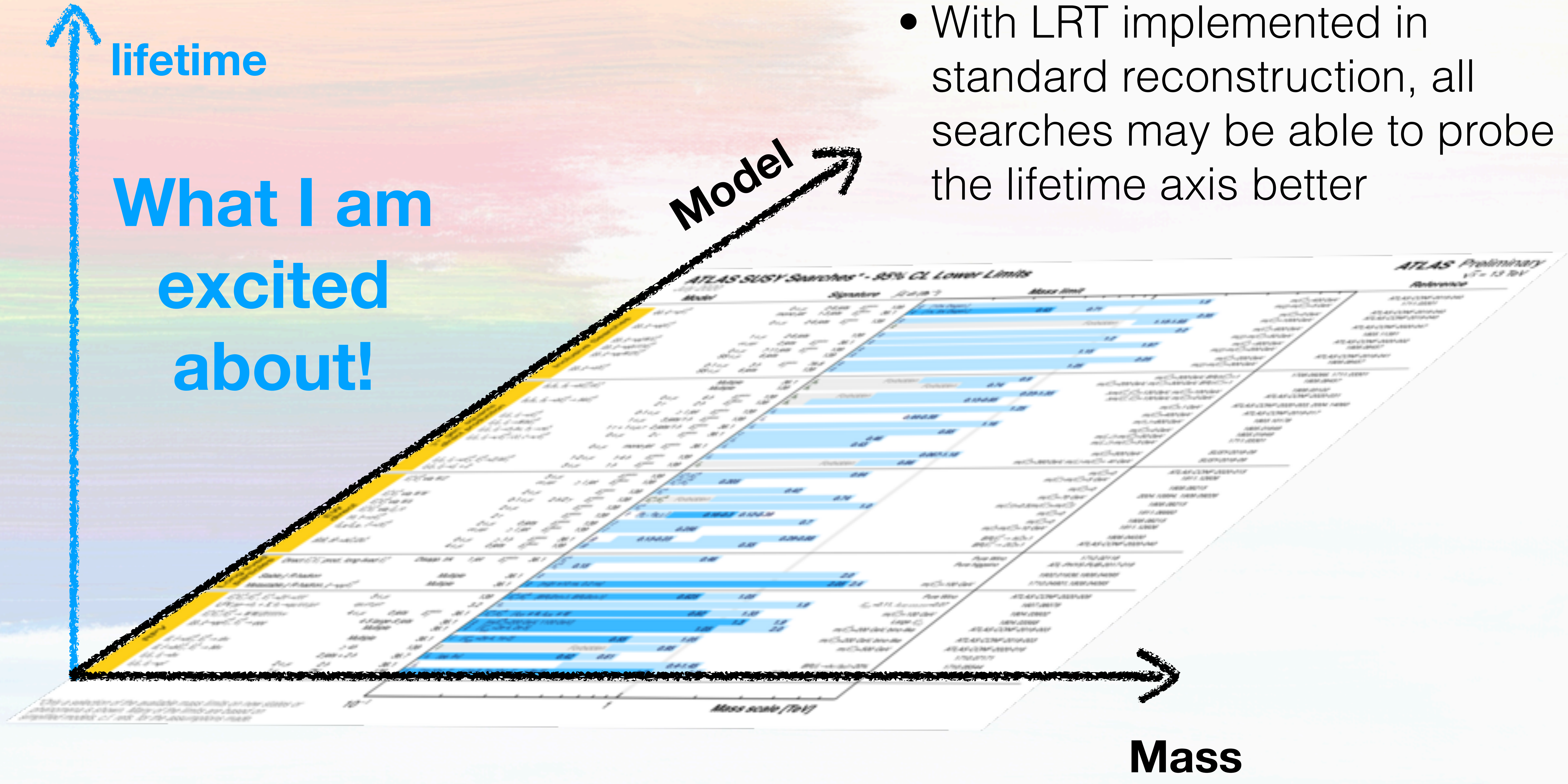
- Standard *b*-tagging is clearly already sensitive to LLP in a given phase space
- With the new LRT, we could make it more sensitive!
- A simultaneous coverage extension!

Greatly Extend the Parameter Space



- Taking the SUSY search program at ATLAS as an example
- Long-lived particle search is only a small category of the search program

Greatly Extend the Parameter Space

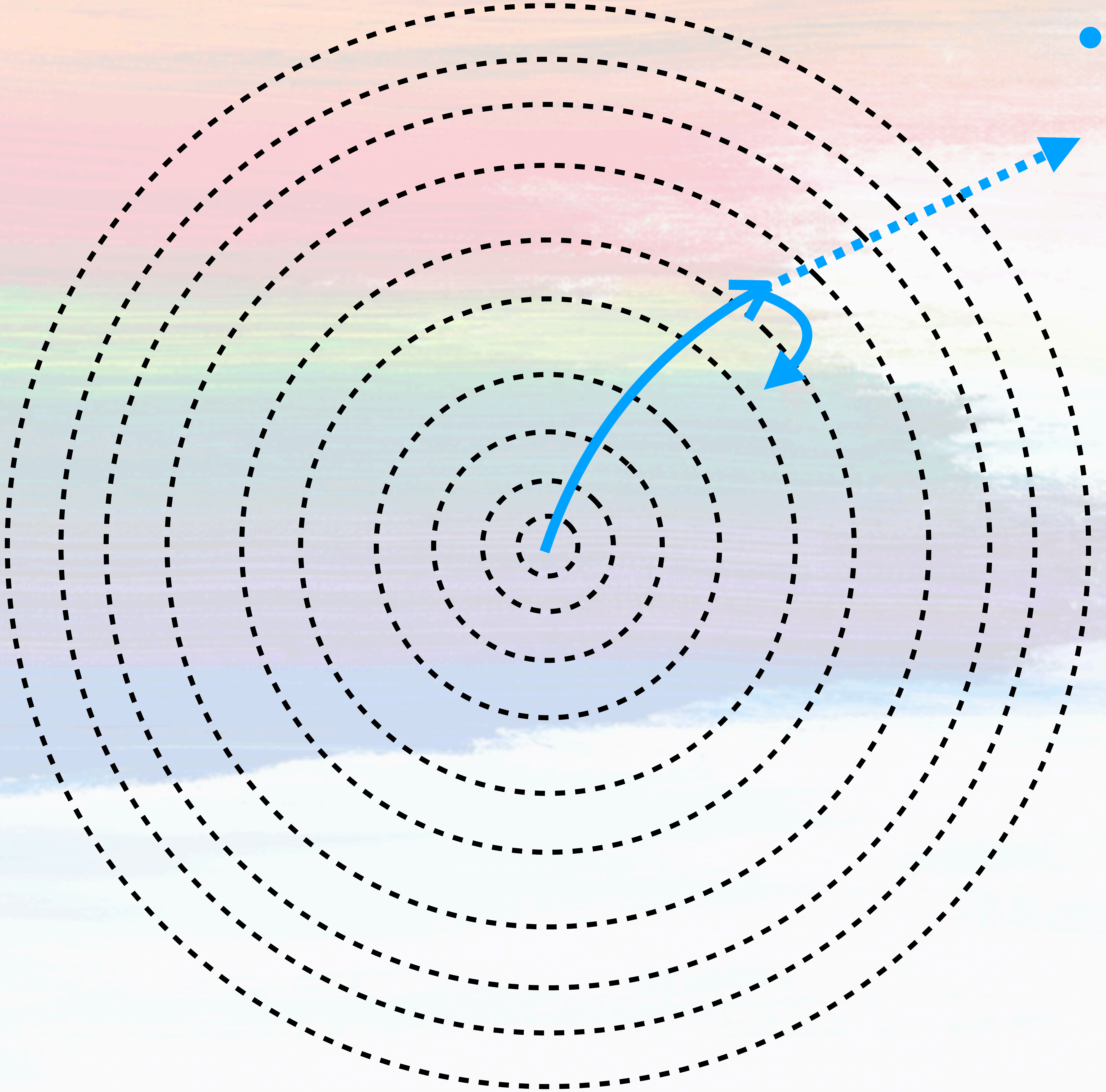


- With LRT implemented in standard reconstruction, all searches may be able to probe the lifetime axis better

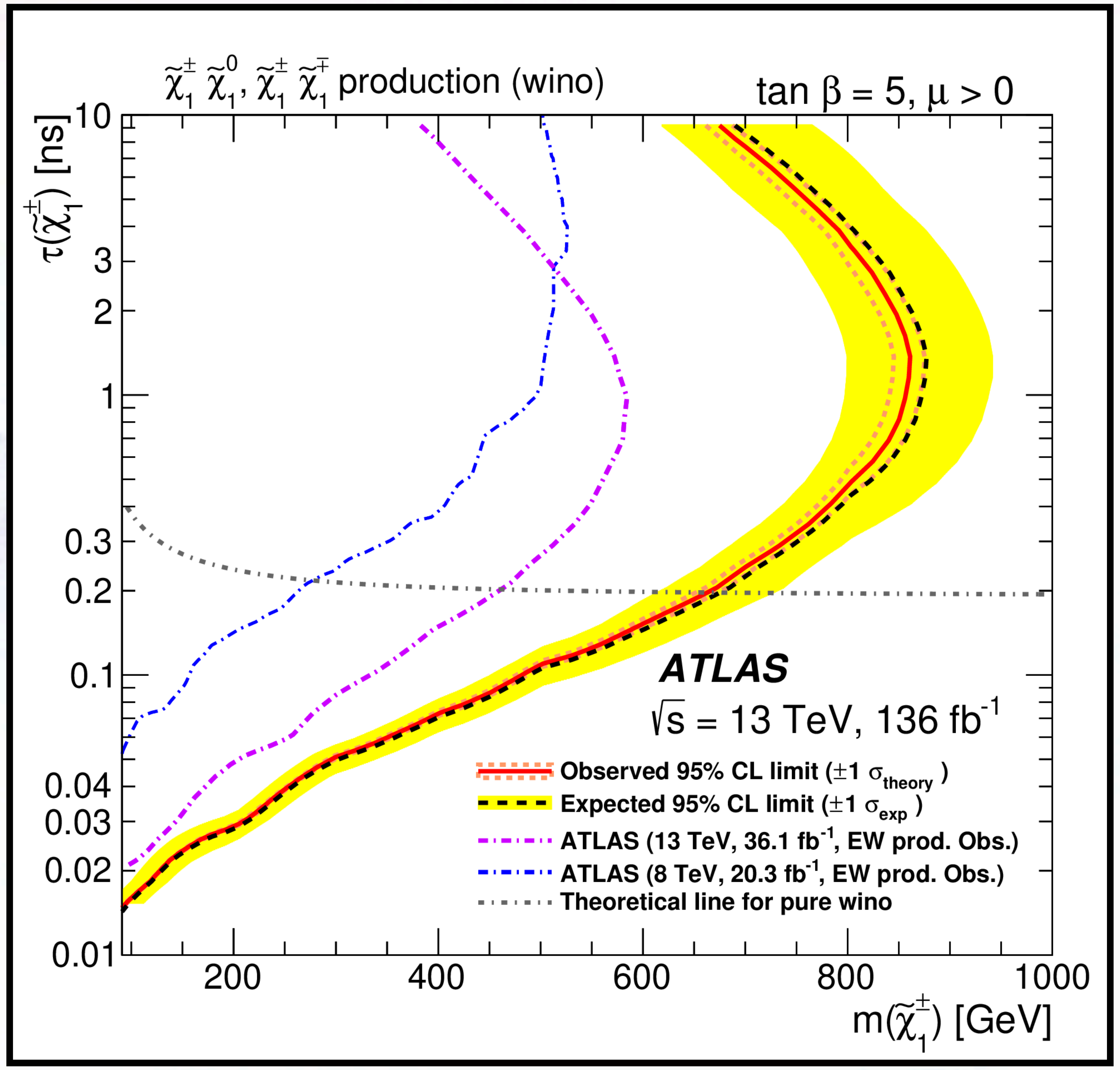
LLP searches will gradually become part of the mainstream program

Which means….we can consider more

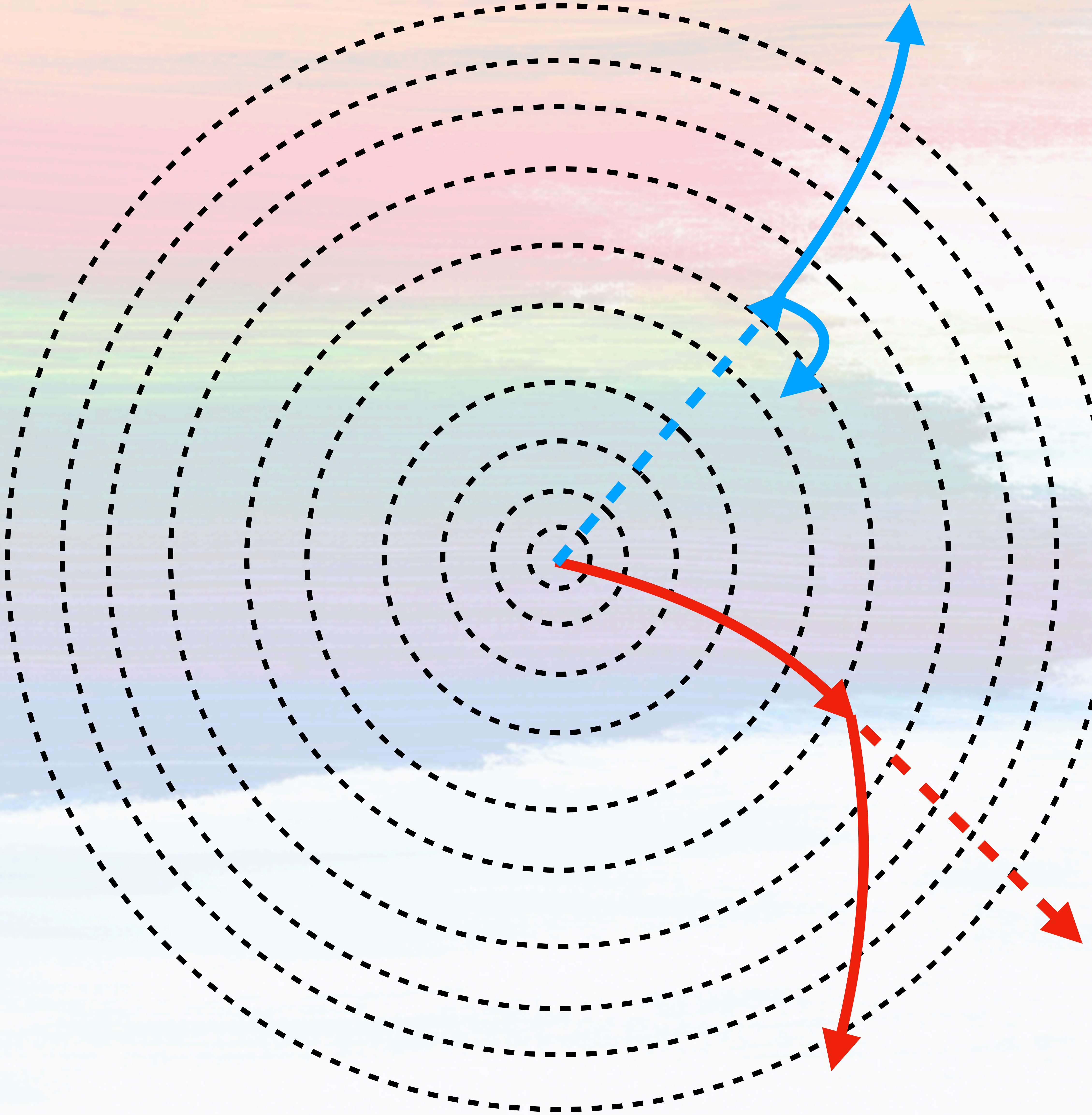
Strange Things We Have Probed



- Disappearing Track:
  - Charged LLP decays to a neutral particle + soft charged particle



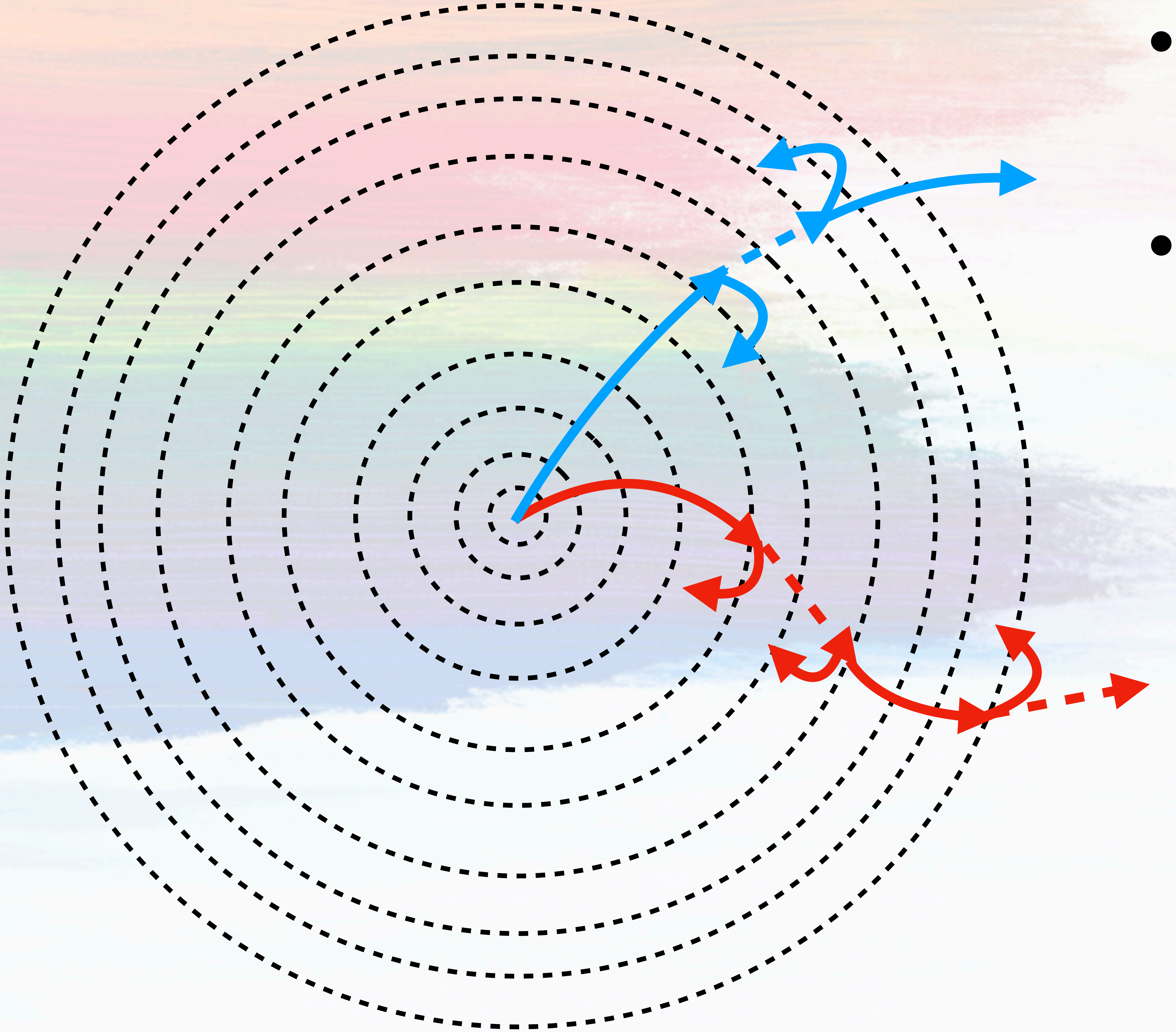
Exotic Tracks: Appearing/Kinked Tracks



- Appearing Track:
  - Neutral LLP decays to a charged particle + soft charged particle: not able to form a displaced vertex
- Kinked Track:
  - A charged LLP decays to a neutral particle and a charged particle

More Exotic: Dashed Tracks

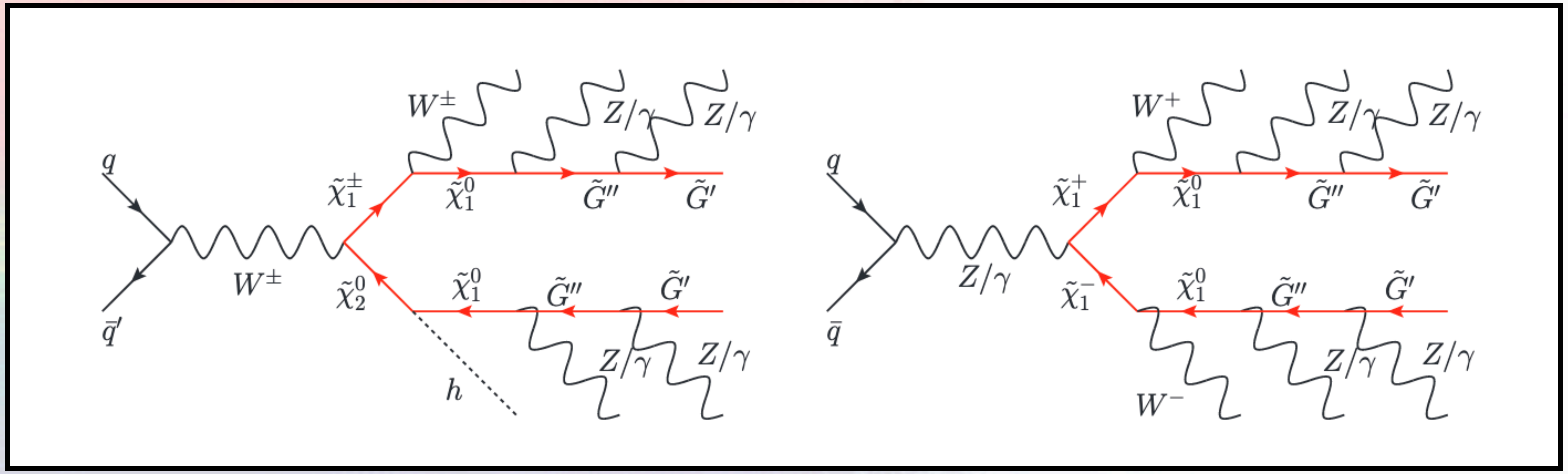
- Oscillation between charge and neutral particles with measurable lifetimes



- A unique signature rises
  - Disappearing-reappearing-disappearing patterns
- Track characteristics:
  - Missing inner hits along the tracks or holes on tracks in general
    - If they are reconstructed as one single track
  - Track pairs with the same trajectory separated by a few tracker layers
    - If they are reconstructed as various tracks

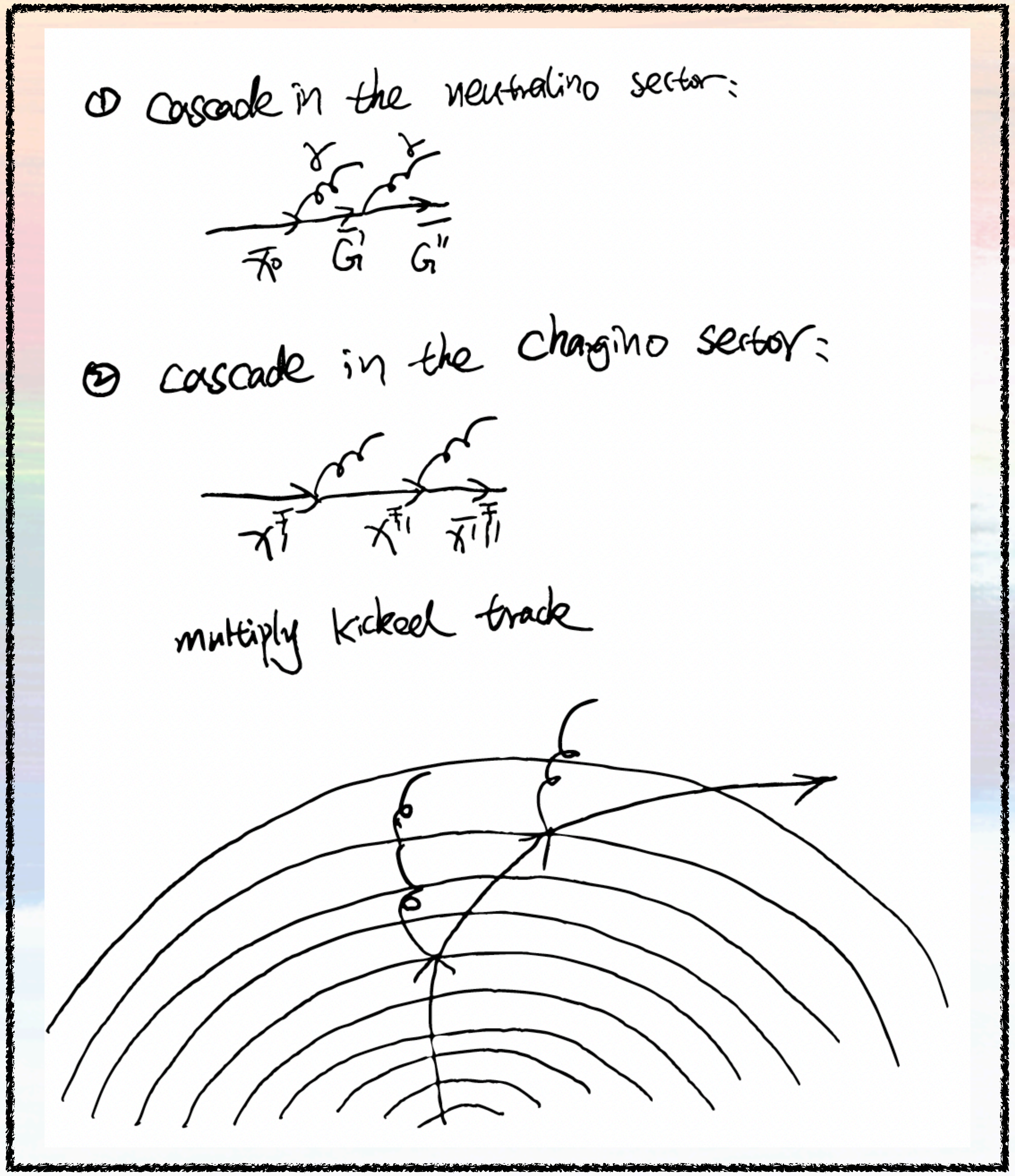
Also This is Why I am Here Today:)

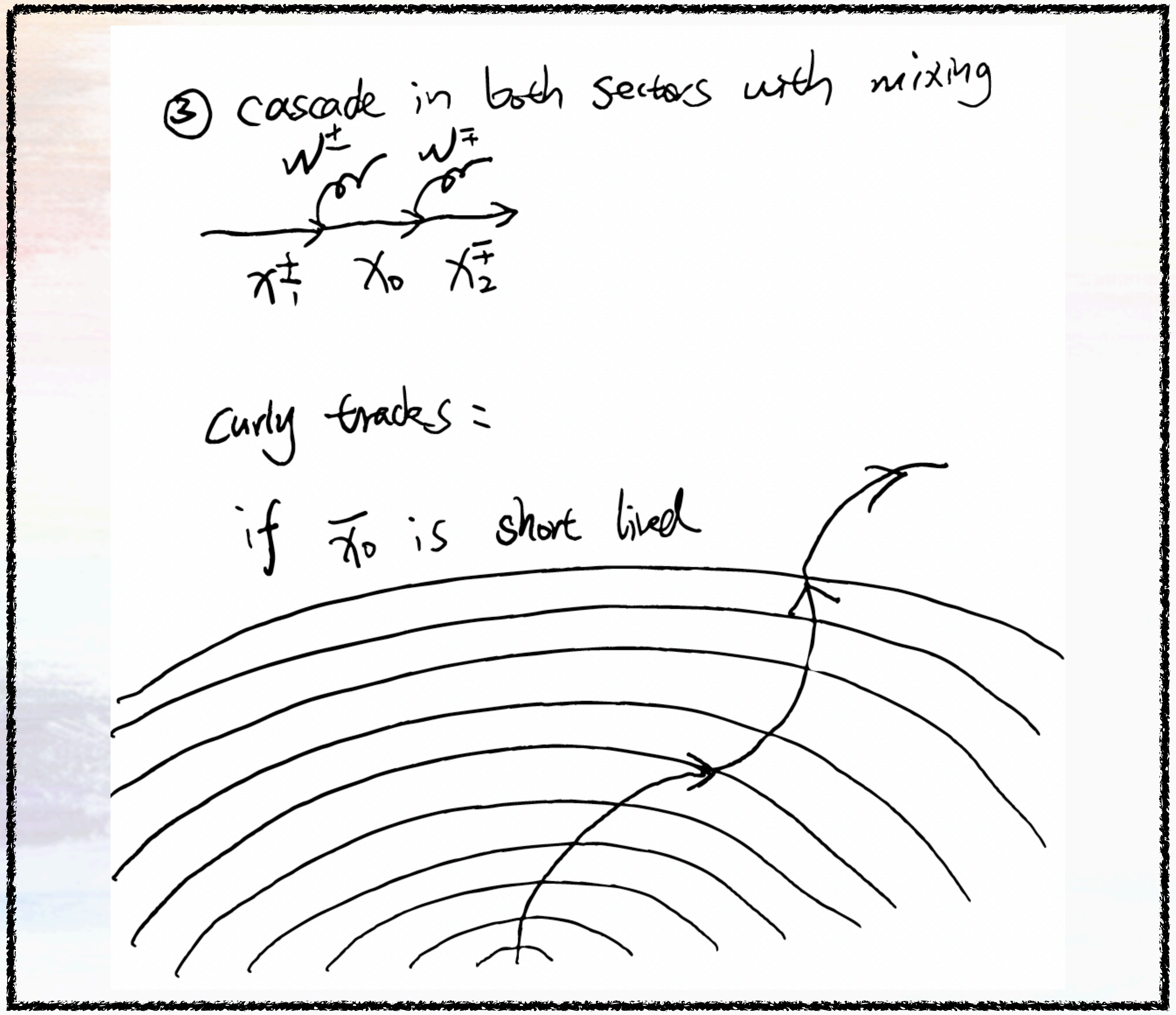
- Diogo, Gabriele, Ellen and Sara investigated similar structures in the neutral sector [arxiv:2111.04775]



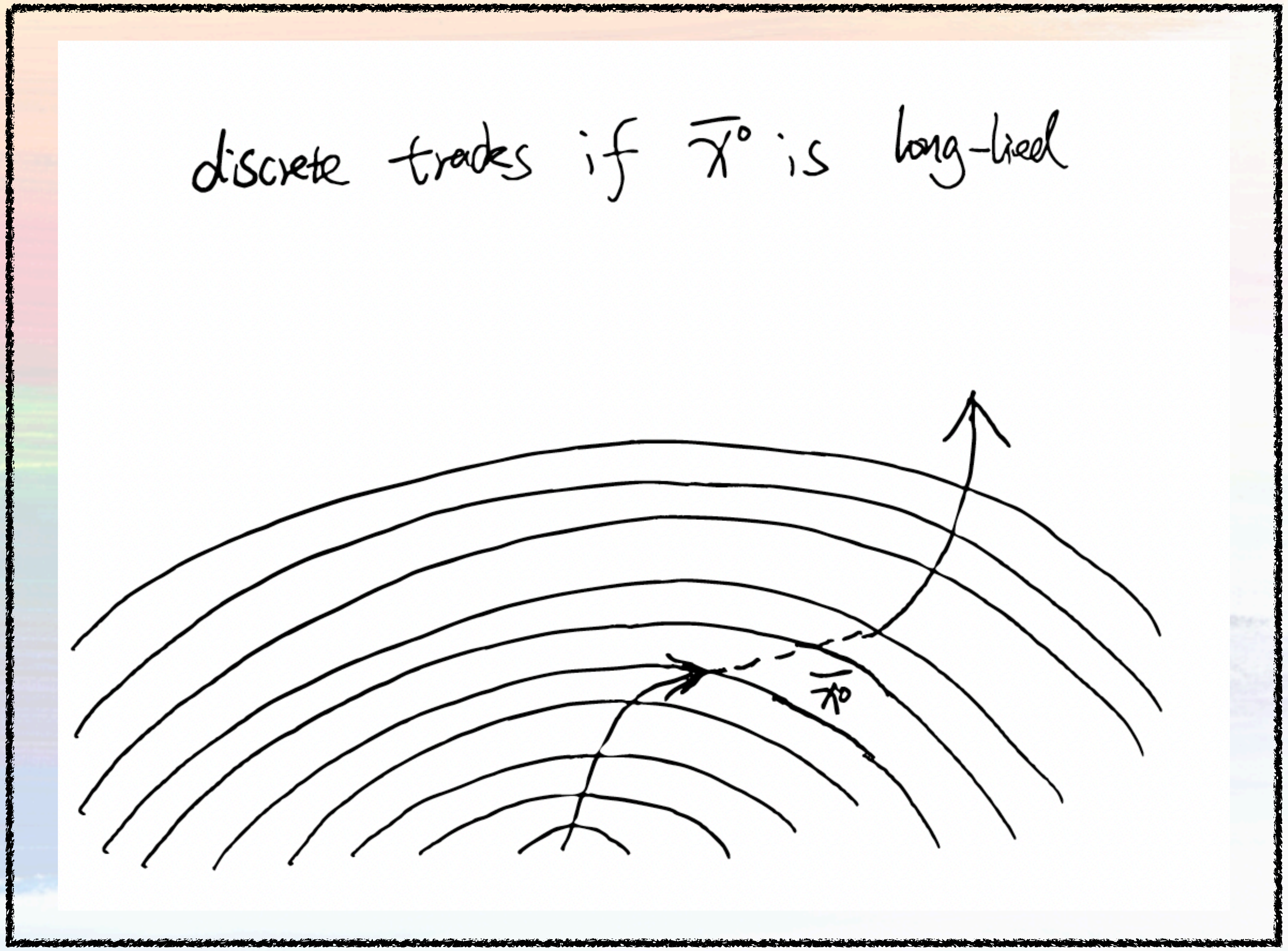
- I read this paper and wondered whether the model can have a similar charged sector

Also This is Why I am Here Today:)





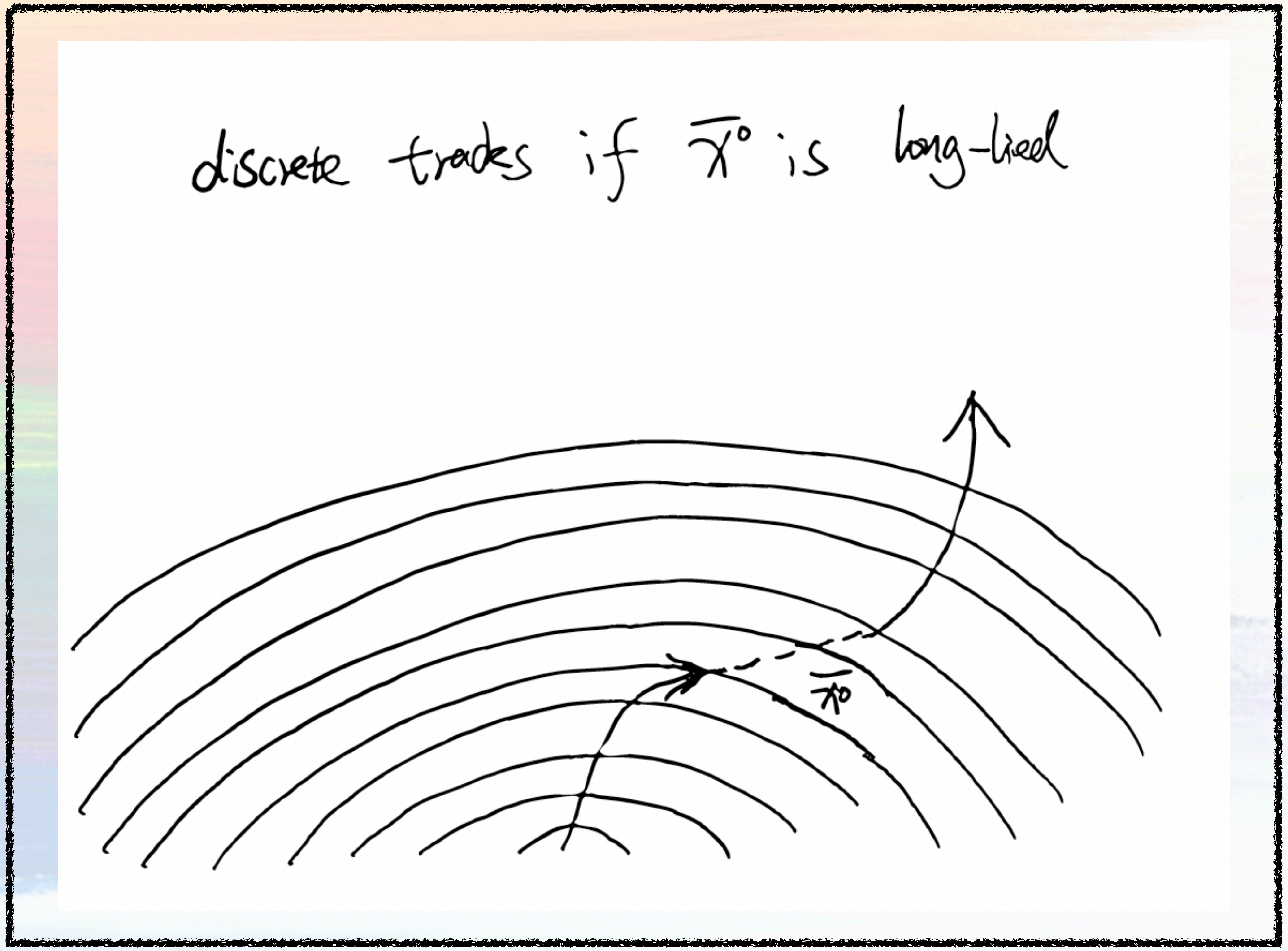
Also This is Why I am Here Today:)



- Hard to be realized in arxiv:2111.04775

- Other possible candidate: baryon genesis ….and maybe your model?

Also This is Why I am Here Today:)



- Hard to be realized in arxiv:2111.04775

- Other possible candidate: baryon genesis ….and maybe your model?

Bold Claims

There is definitely room for non-natural signatures!

Searching for them is a natural choice!

Thank You!