EPISODE III
BEYOND
MET-BASED SEARCHES

MAURIZIO PIERINI
CERN

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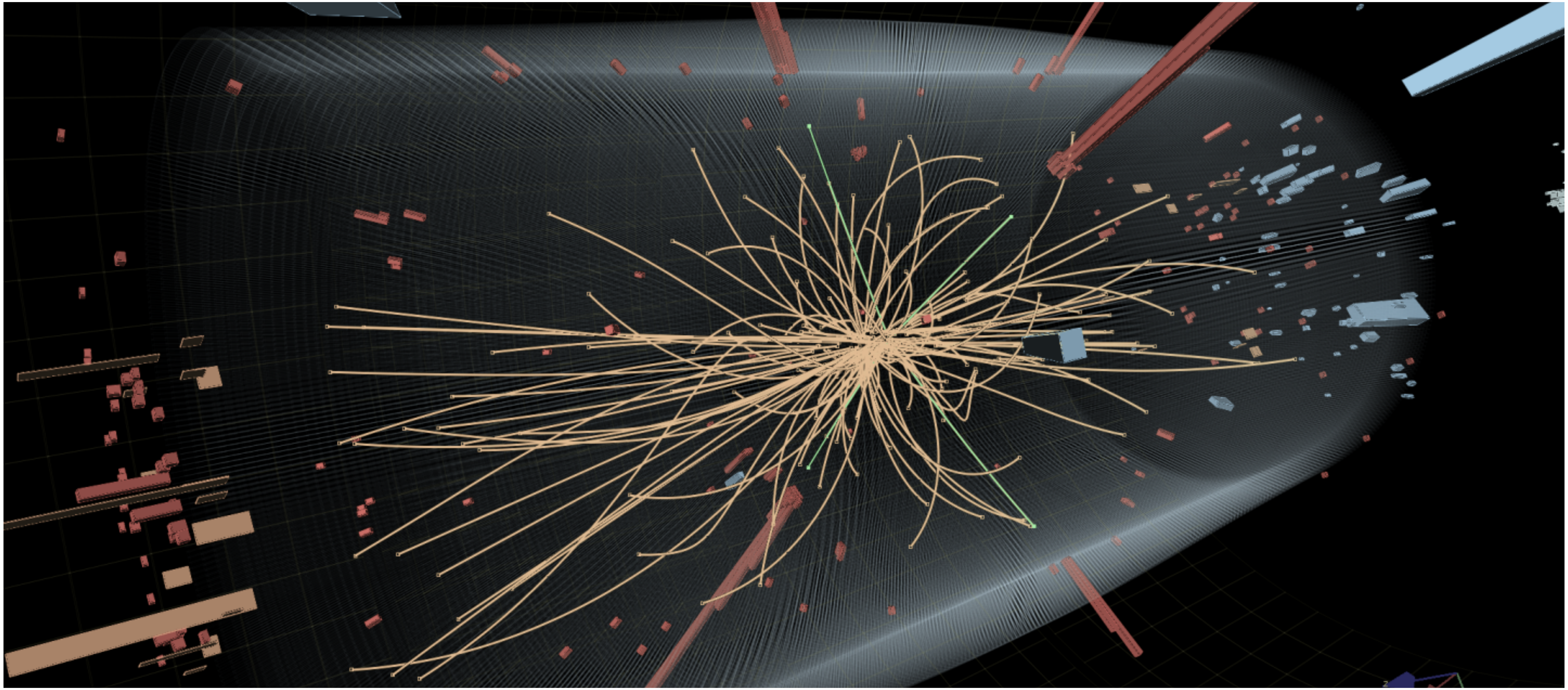
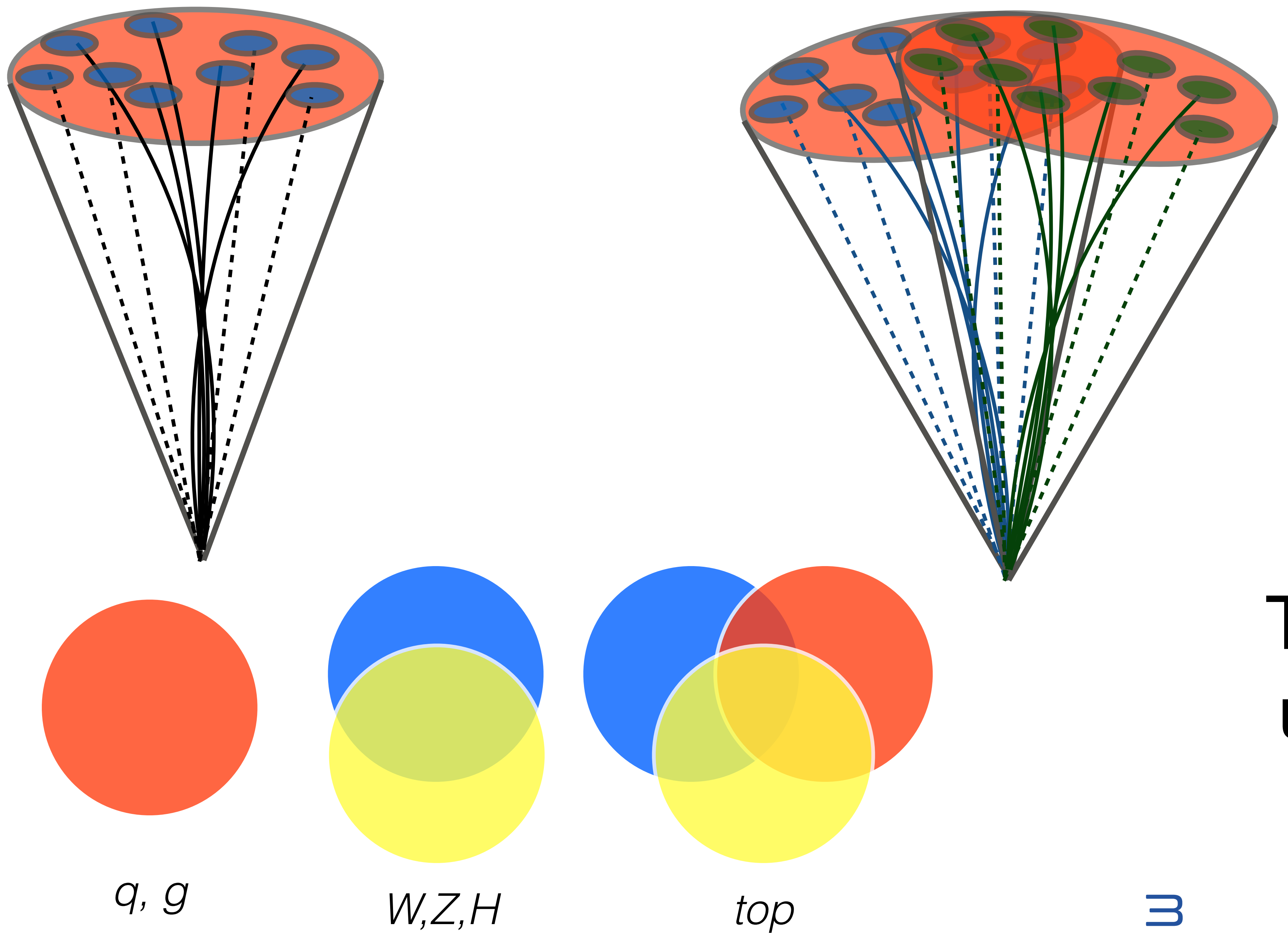


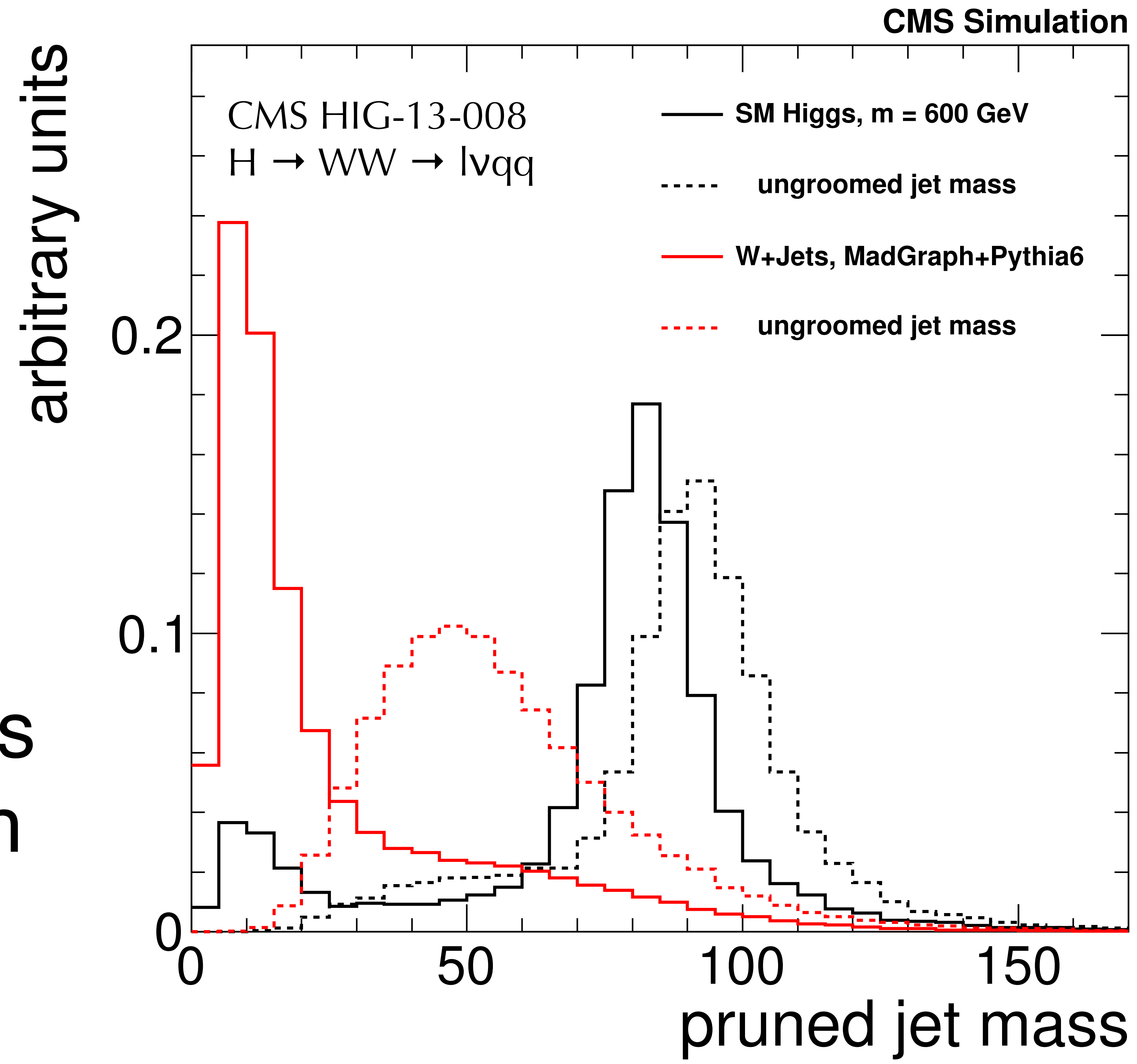
I open a Parenthesis here to tell you about jet substructure

FROM JETS TO BOOSTED JETS

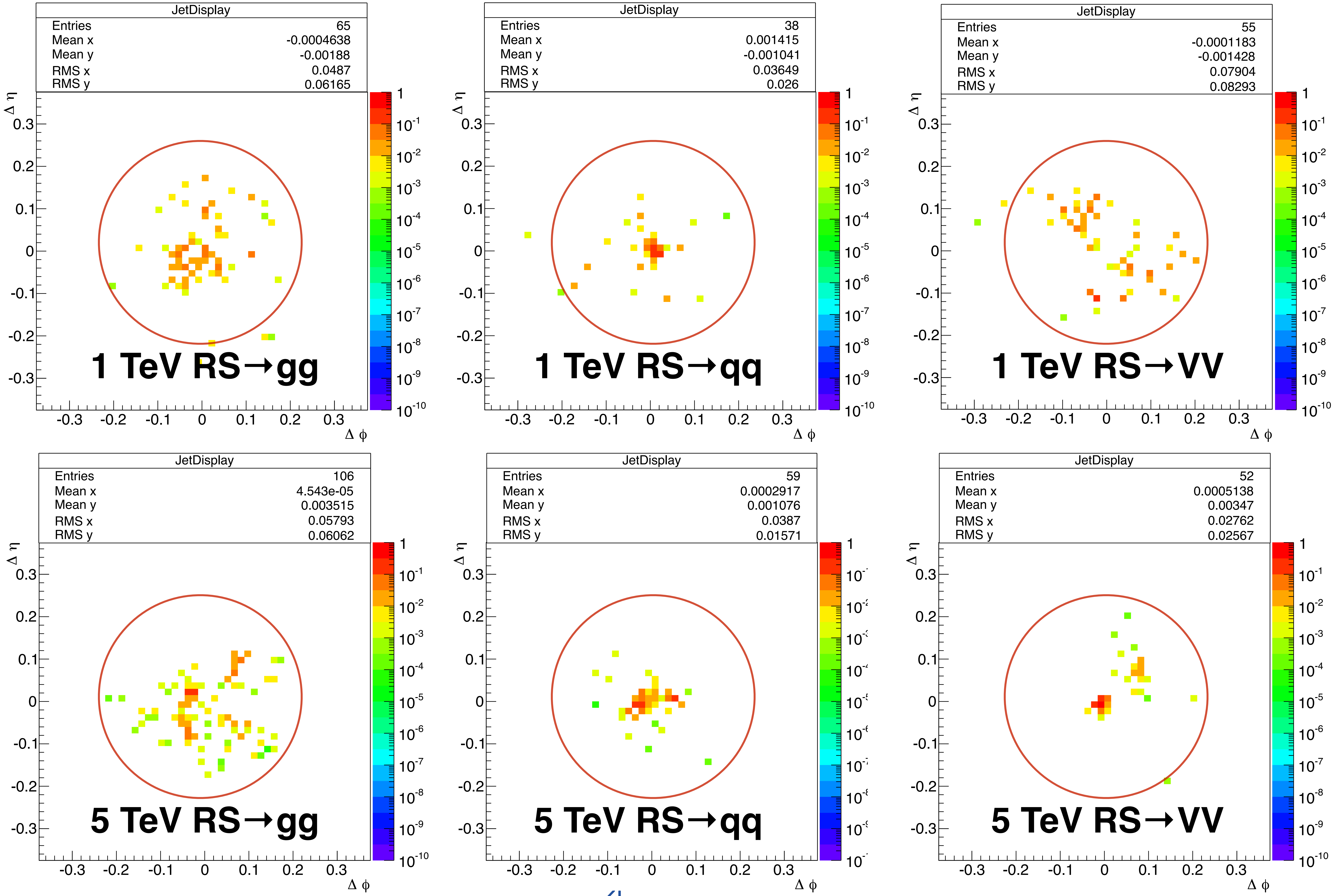
- Heavy particles (e.g., W, Z, and H bosons, top quark) can decay to 2q/3q/4q final states, giving normally multi-jet signatures
- For large enough pT, the decay products might merge into a single jet
- These jets are special: the mass of the jet peaks at the "right" value (unlike QCD jets, for which large mass values are generated by QCD)



$\Delta R \sim 2\ M_W/p_T$ (to be compared with jet size R) Typically large jets used (Anti-Kt with R=0.8)



JET SUBSTRUCTURE



SUBSTRUCTURE VARIABLES

- *Several jet-shape variables proposed to quantify this behaviour (see ongoing BOOST conference for a full overview)*

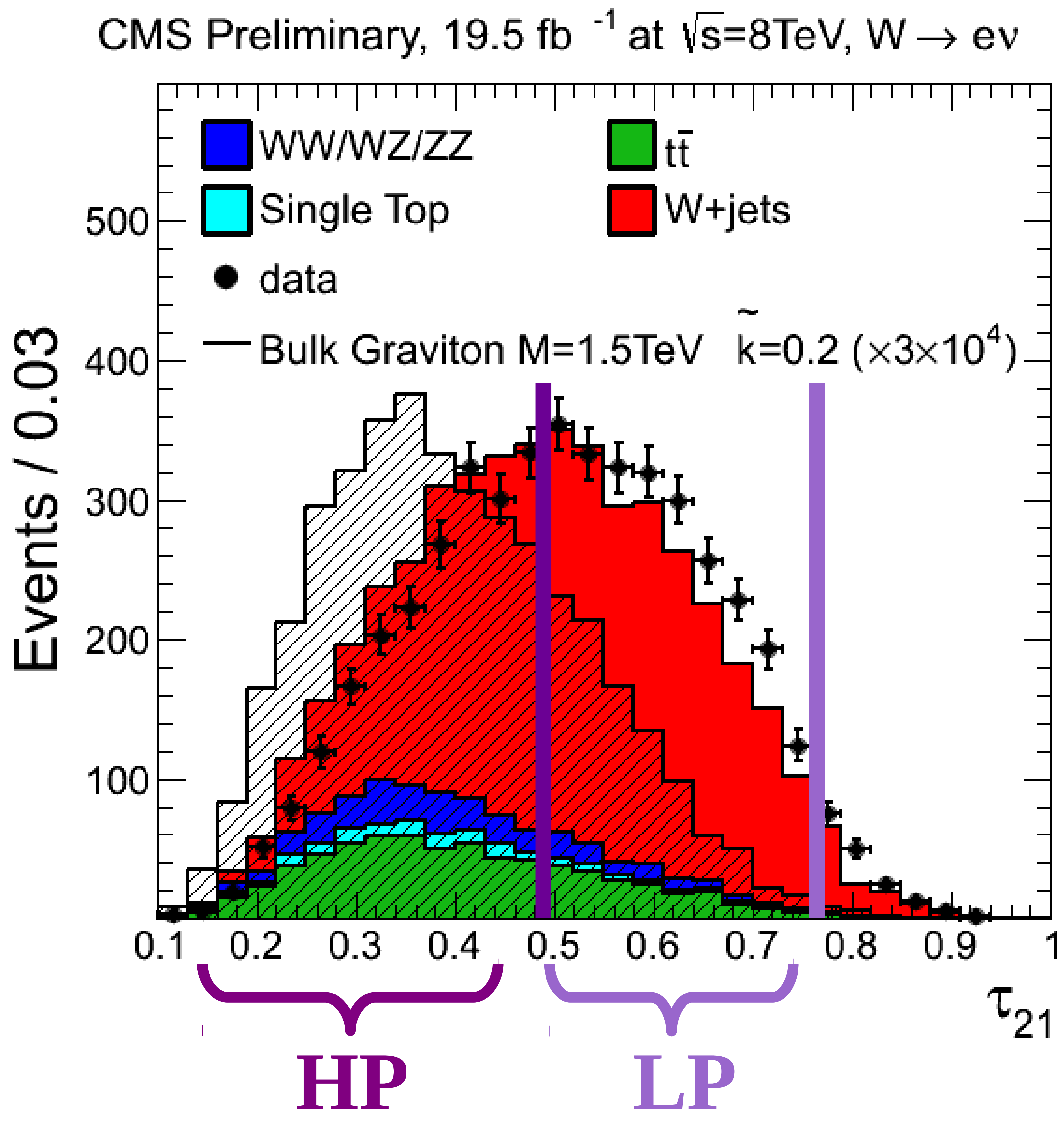
- *N-subjettiness is among the most popular*

  - *Quantify how well the constituents of a jet can be arranged in N subjects*

$$\tau_N^{(\beta)} = \frac{1}{p_{TJ}} \sum_{i \in \mathrm{Jet}} p_{Ti} \min\left\{R_{1i}^{\beta}, R_{2i}^{\beta}, \ldots, R_{Ni}^{\beta}\right\}$$

J. Thaler and K. Van Tilburg http://arxiv.org/abs/1011.2268

  - *Can construct a complete basis by computing τN it for several N*



2-body: $\tau_1^{(1)}, \tau_1^{(2)}$

3-body: $\tau_1^{(0.5)}, \tau_1^{(1)}, \tau_1^{(2)}, \tau_2^{(1)}, \tau_2^{(2)}$

4-body: $\tau_1^{(0.5)}, \tau_1^{(1)}, \tau_1^{(2)}, \tau_2^{(0.5)}, \tau_2^{(1)}, \tau_2^{(2)}, \tau_3^{(1)}, \tau_3^{(2)}$

5-body: $\tau_1^{(0.5)}, \tau_1^{(1)}, \tau_1^{(2)}, \tau_2^{(0.5)}, \tau_2^{(1)}, \tau_2^{(2)}, \tau_3^{(0.5)}, \tau_3^{(1)}, \tau_3^{(2)}, \tau_4^{(1)}, \tau_4^{(2)}$

6-body: $\tau_1^{(0.5)}, \tau_1^{(1)}, \tau_1^{(2)}, \tau_2^{(0.5)}, \tau_2^{(1)}, \tau_2^{(2)}, \tau_3^{(0.5)}, \tau_3^{(1)}, \tau_3^{(2)}, \tau_4^{(0.5)}, \tau_4^{(1)}, \tau_4^{(2)}, \tau_5^{(1)}, \tau_5^{(2)}$

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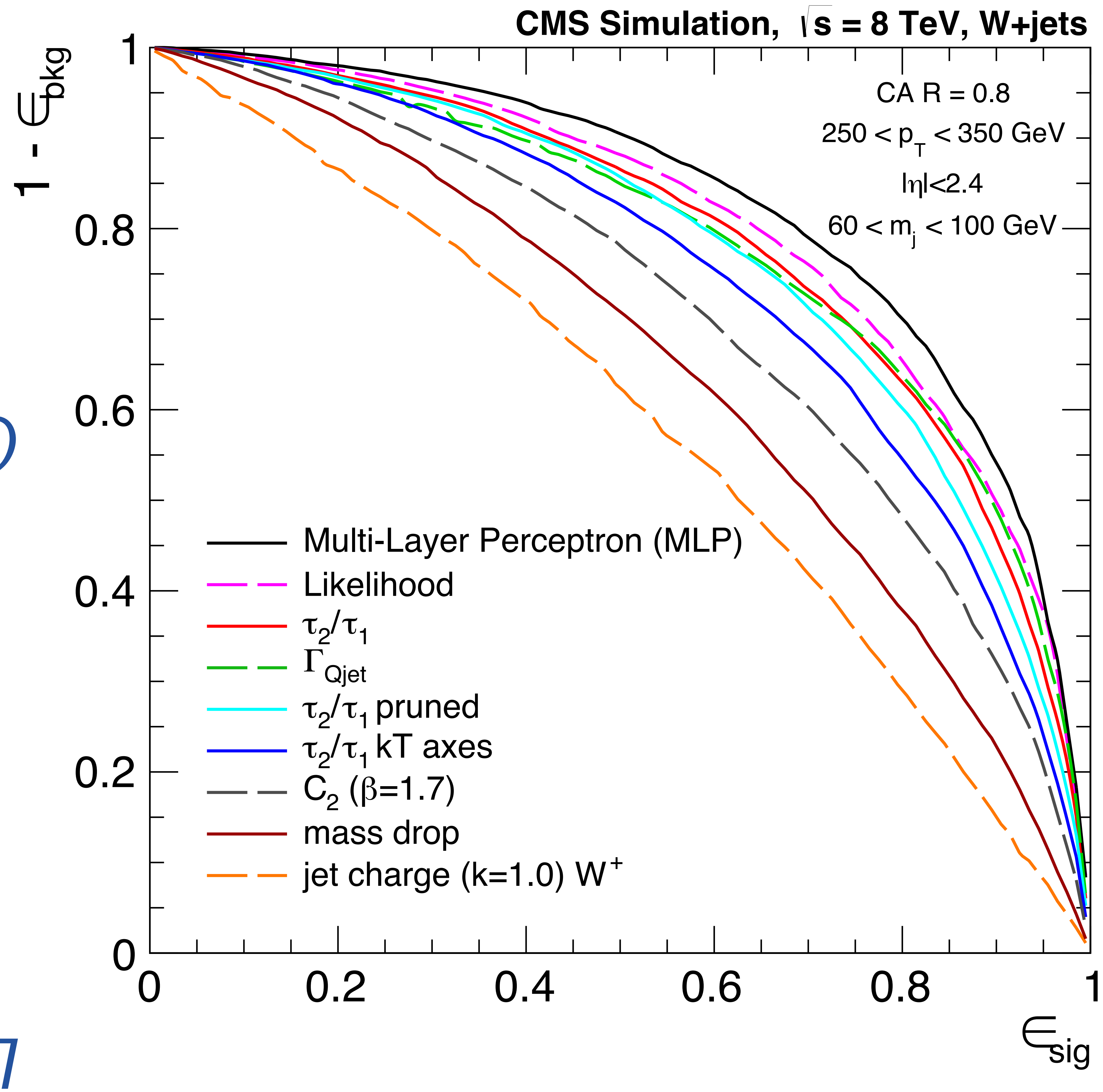
A DIJET TAGGER

- A typical tagger would consist of
  - A jet grooming procedure (trimming, pruning, soft drop) to remove soft radiation in the jet (and pileup, to some extent)
  - A (post-grooming) jet mass cut
  - A cut on an appropriate set of substructure variables
  - For instance, S vs B discrimination in CMS is optimal for di-subjet (W/Z/H) when $\tau2/\tau1$ ratio is considered

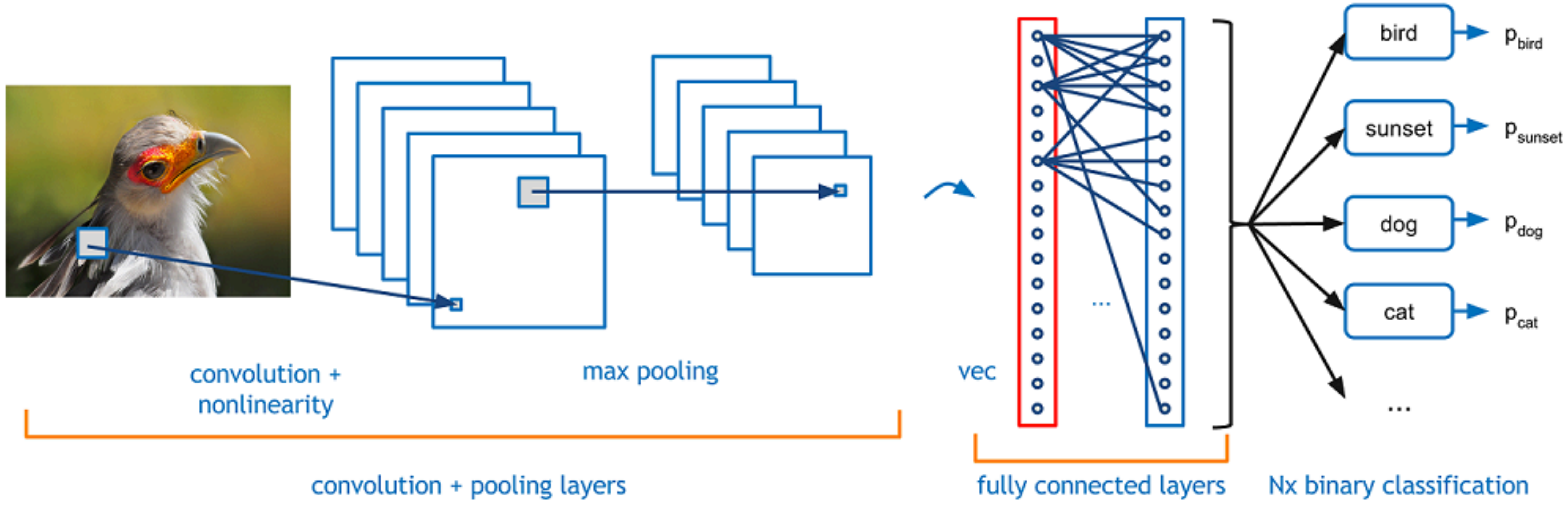


CMS-PAS-JME-13-006

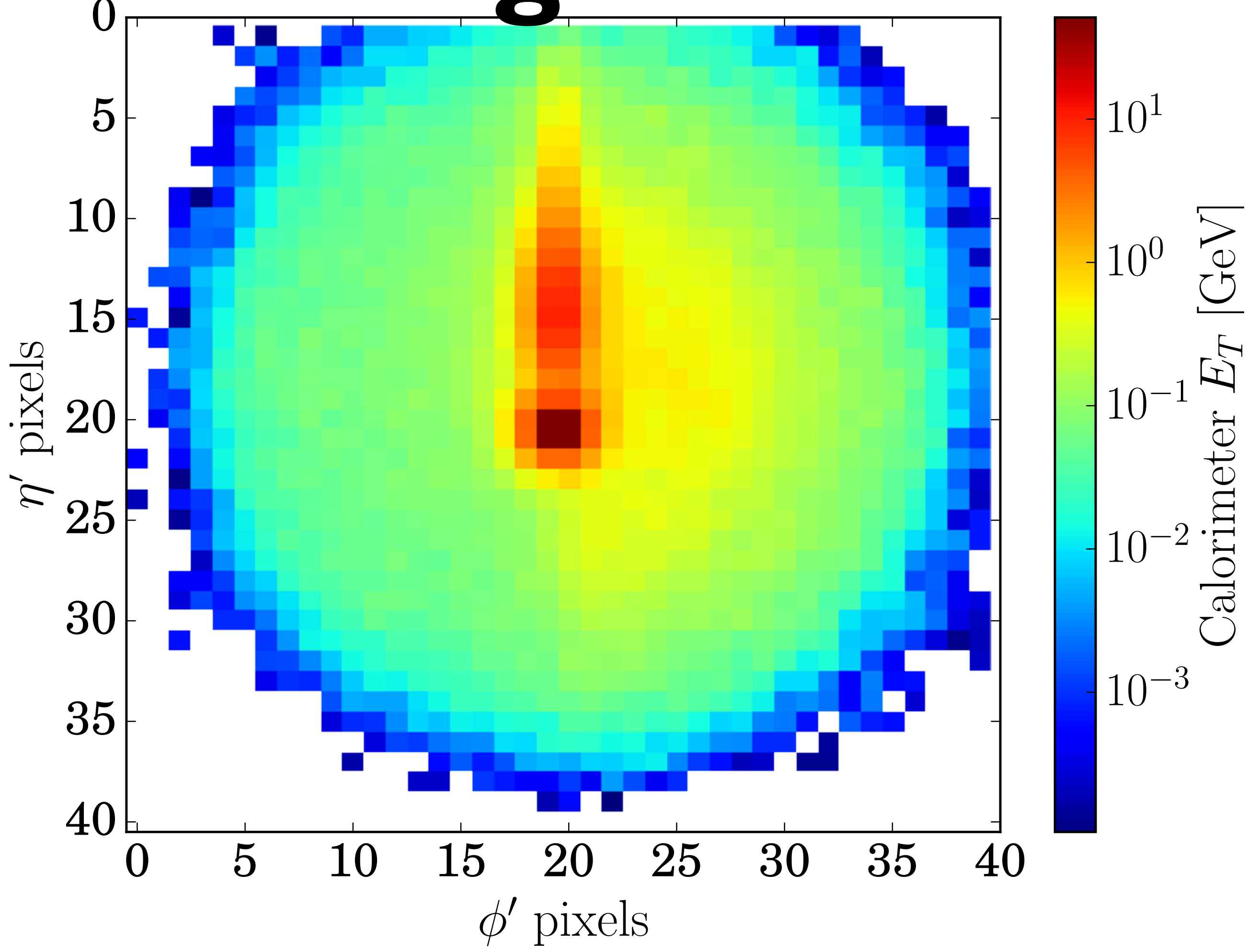
DEEP LEARNING TAGGING

- One can imagine a jet as an image impressed by energy deposits on calorimeters

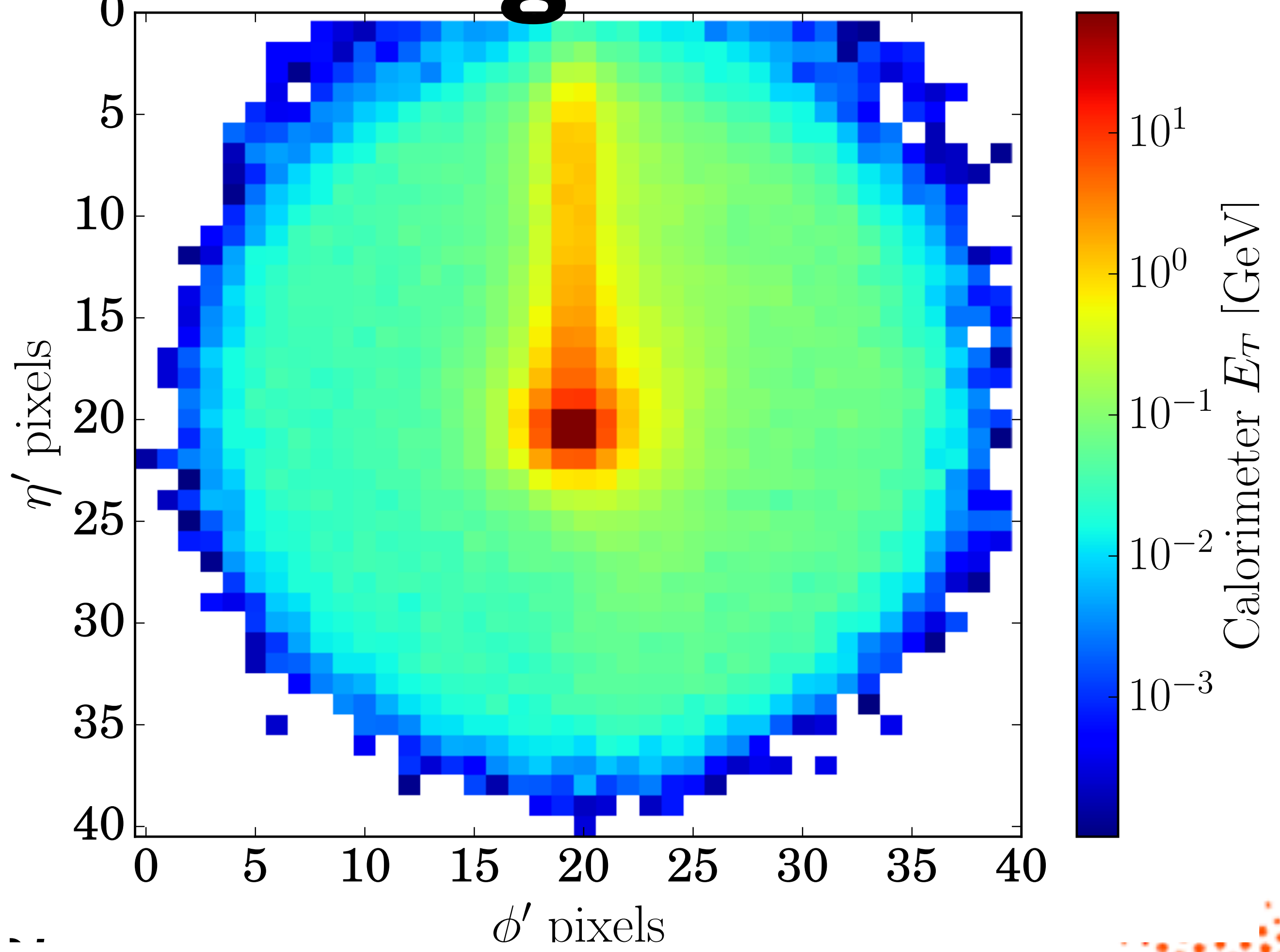
- On this image, one can apply modern computing-vision techniques, e.g., Convolutional Neural networks



Signal



Background



arXiv: 1701.08784

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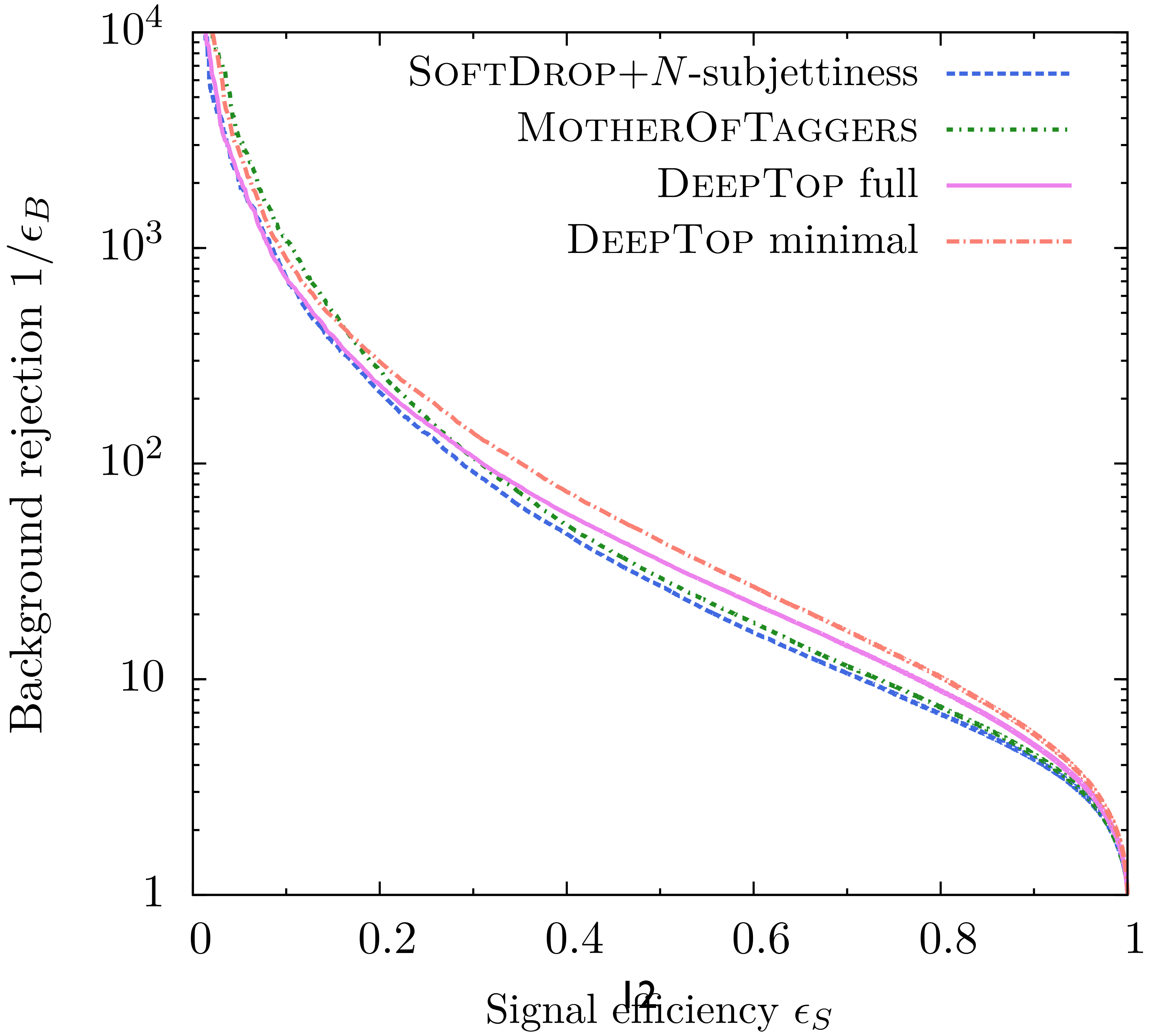

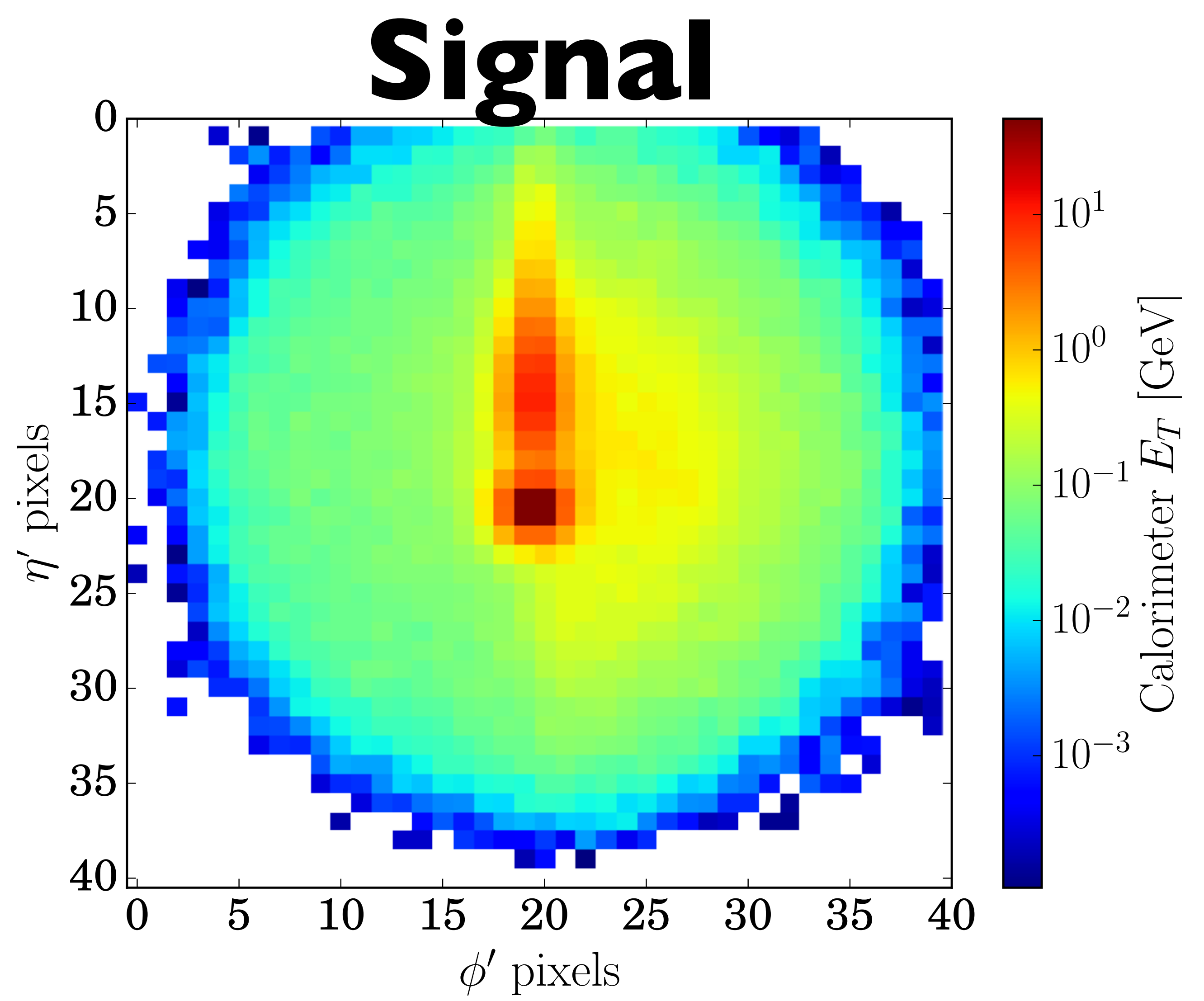

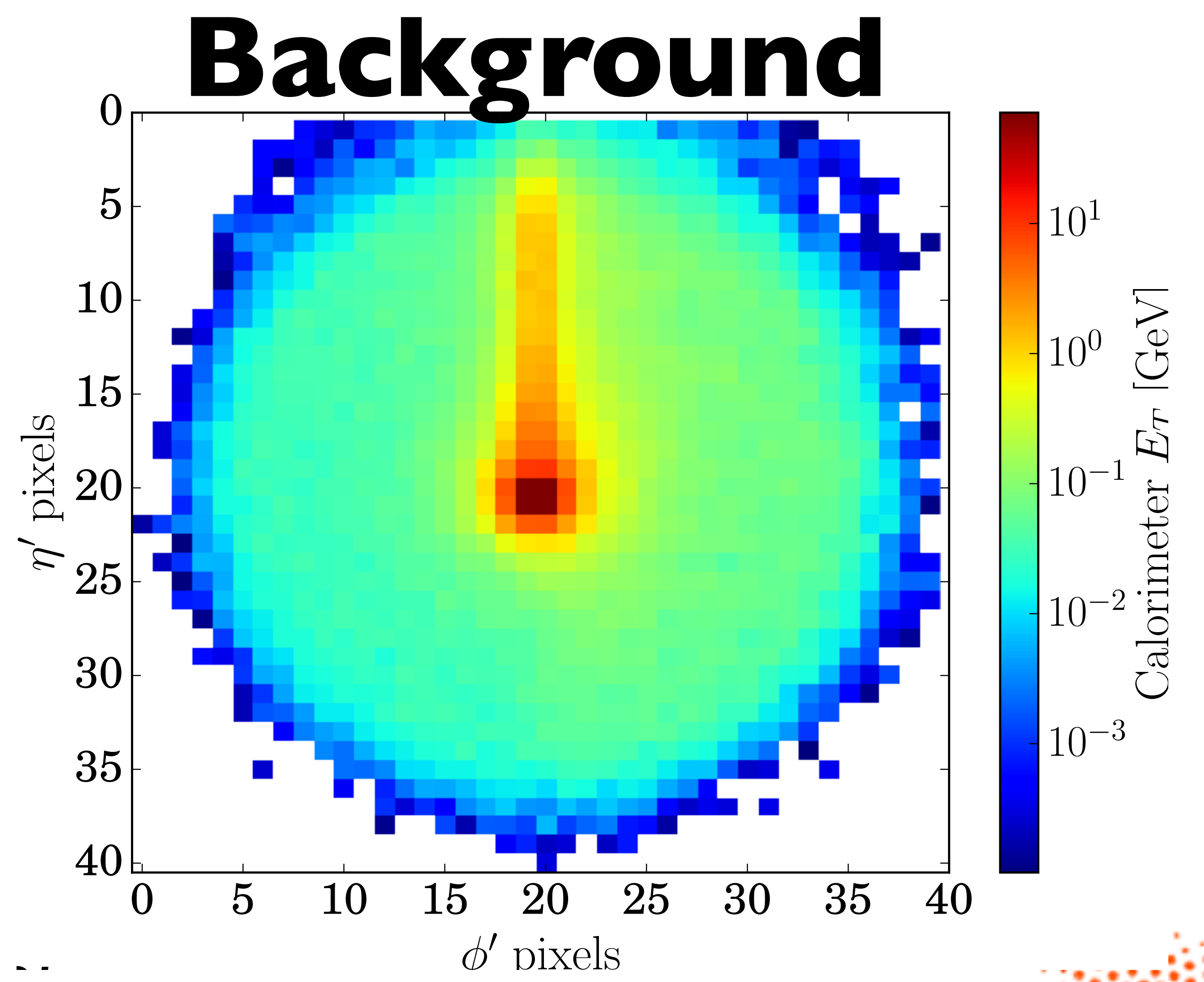

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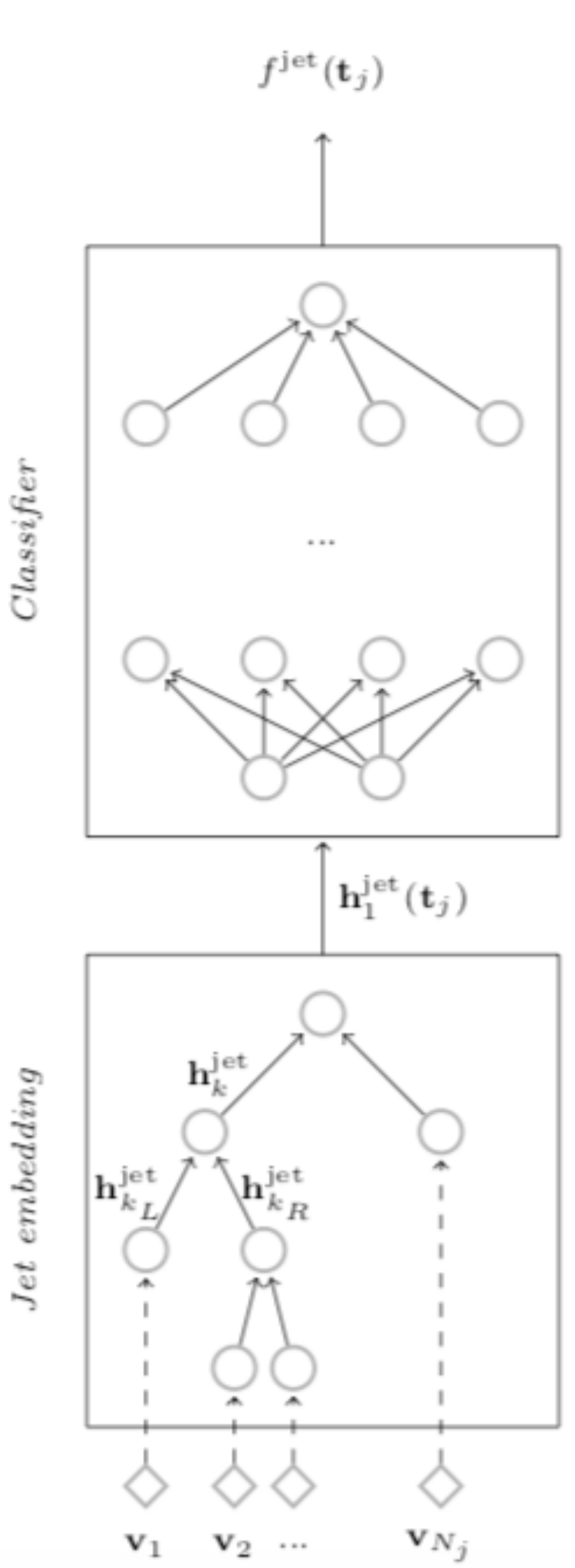
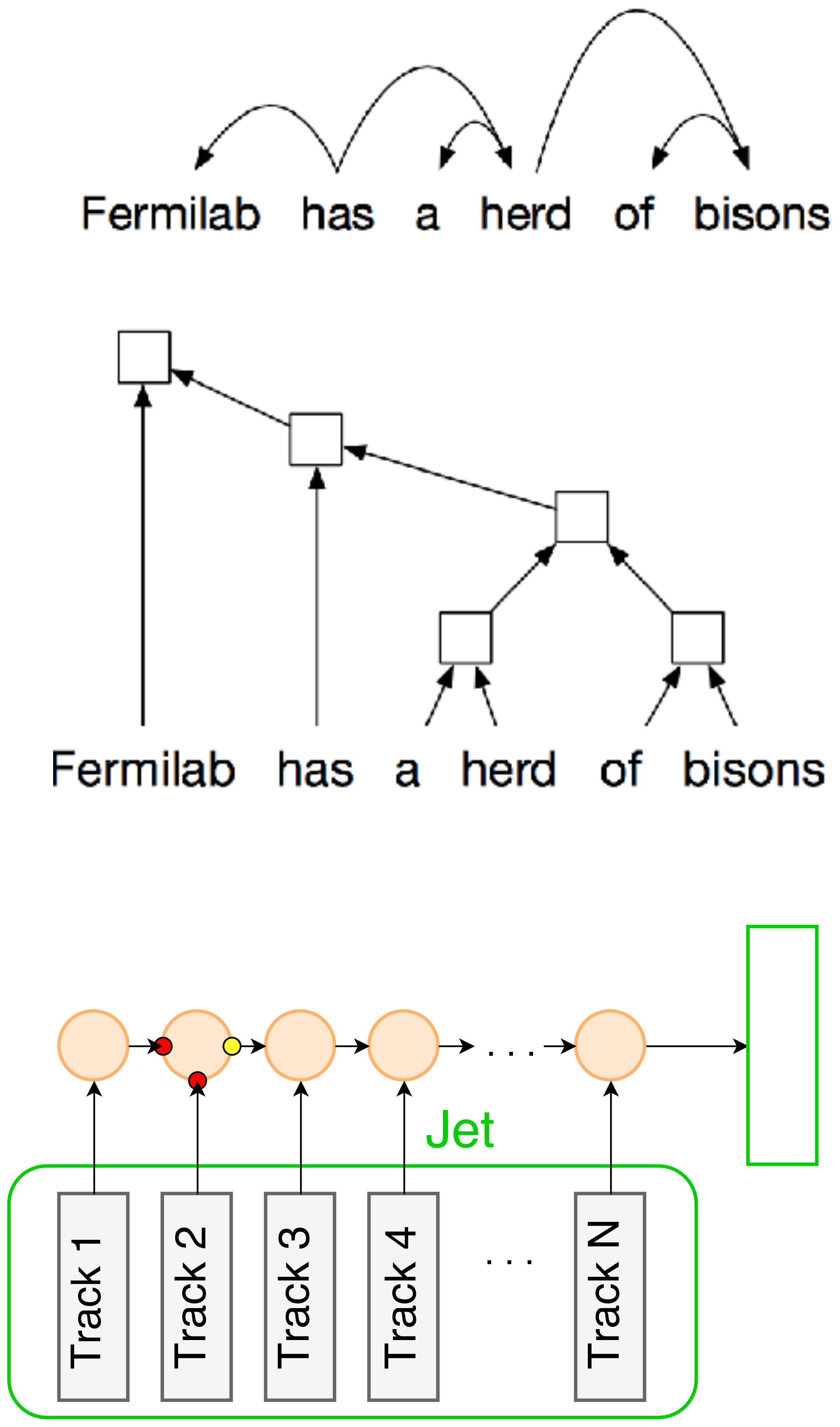
DEEP LEARNING TAGGING

- One can also represent a jet as a list of particles, ordered by QCD laws
  - Similar to words arranged in a sentence
  - Can use language processing techniques to tag a jet
- Deep learning offer a few opportunities (recurrent NN, recursive NN,…)
- Advantages:
  - No need to bin the image → can exploit the full angular resolution (e.g., tracking)
  - Very convenient for PF jets and track jets





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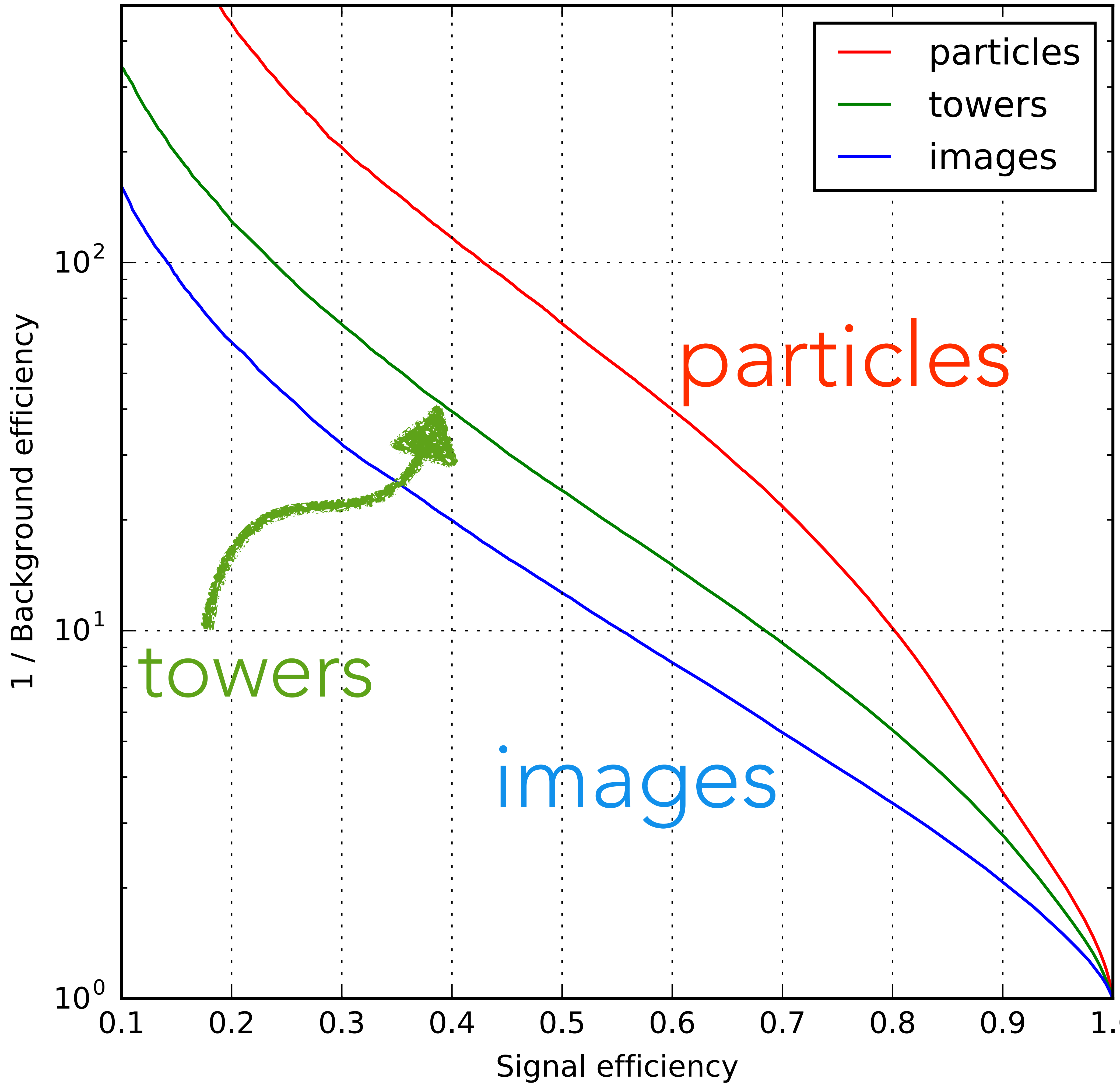
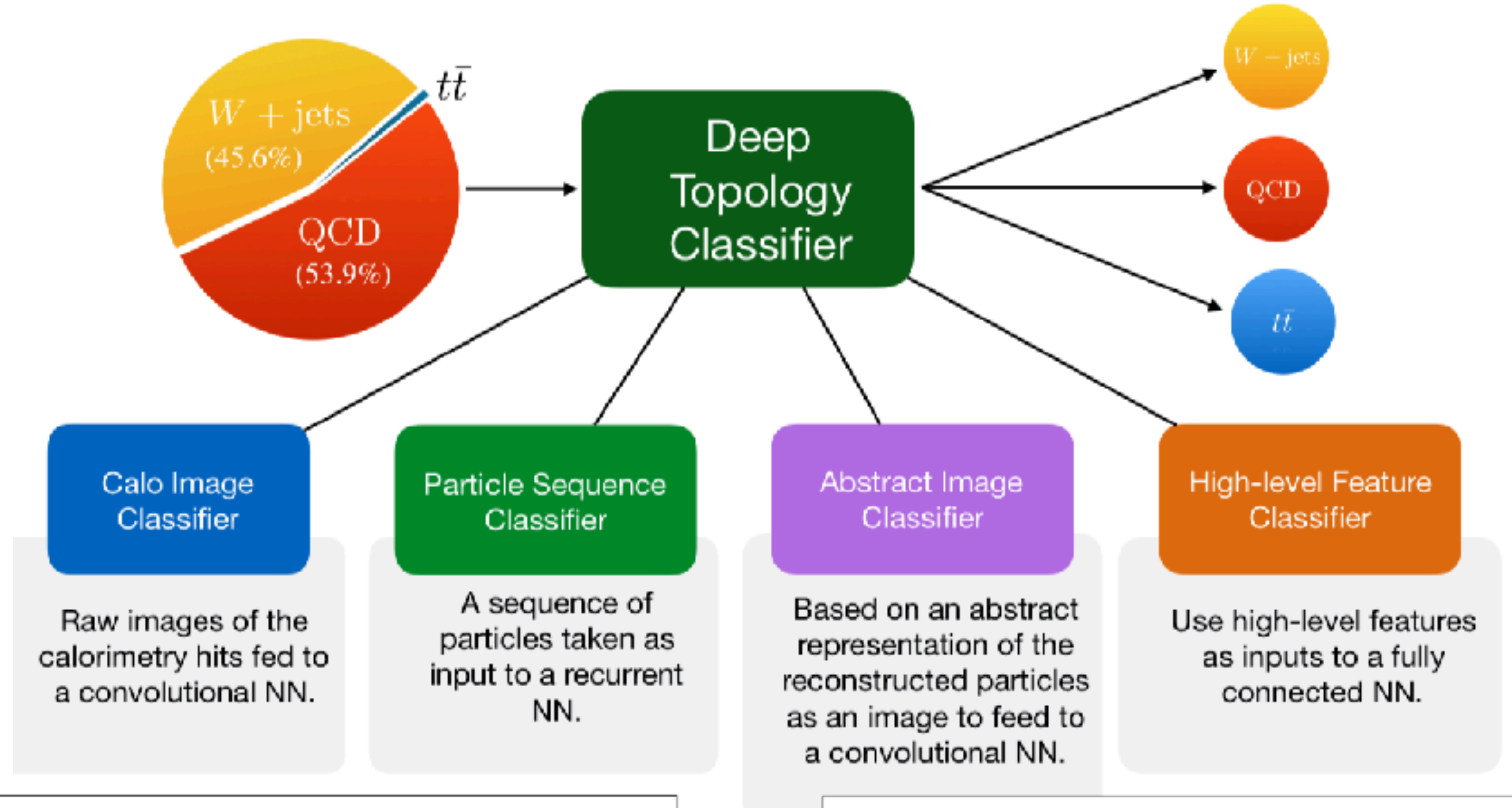


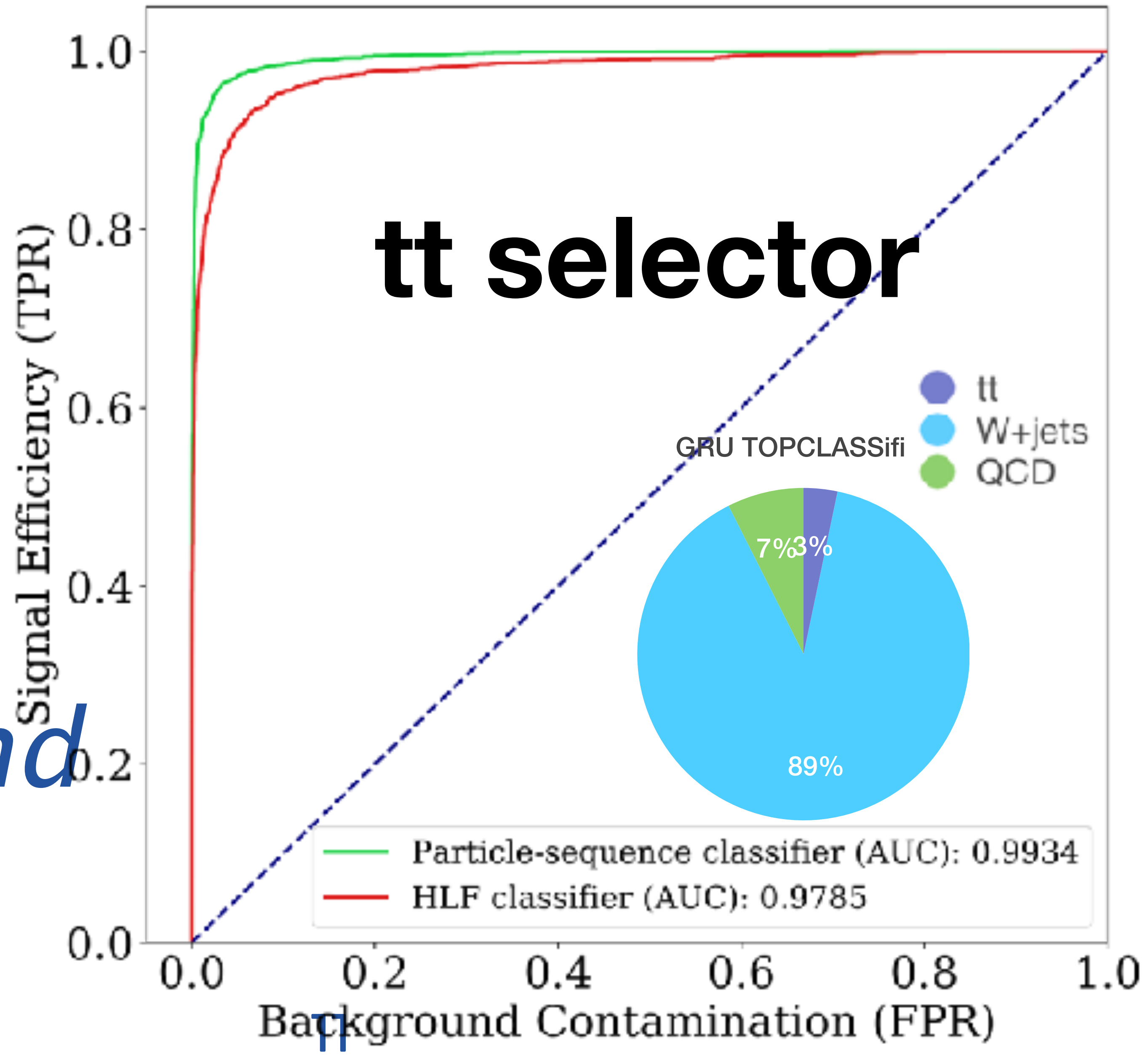
EVENT TAGGING WITH RNN

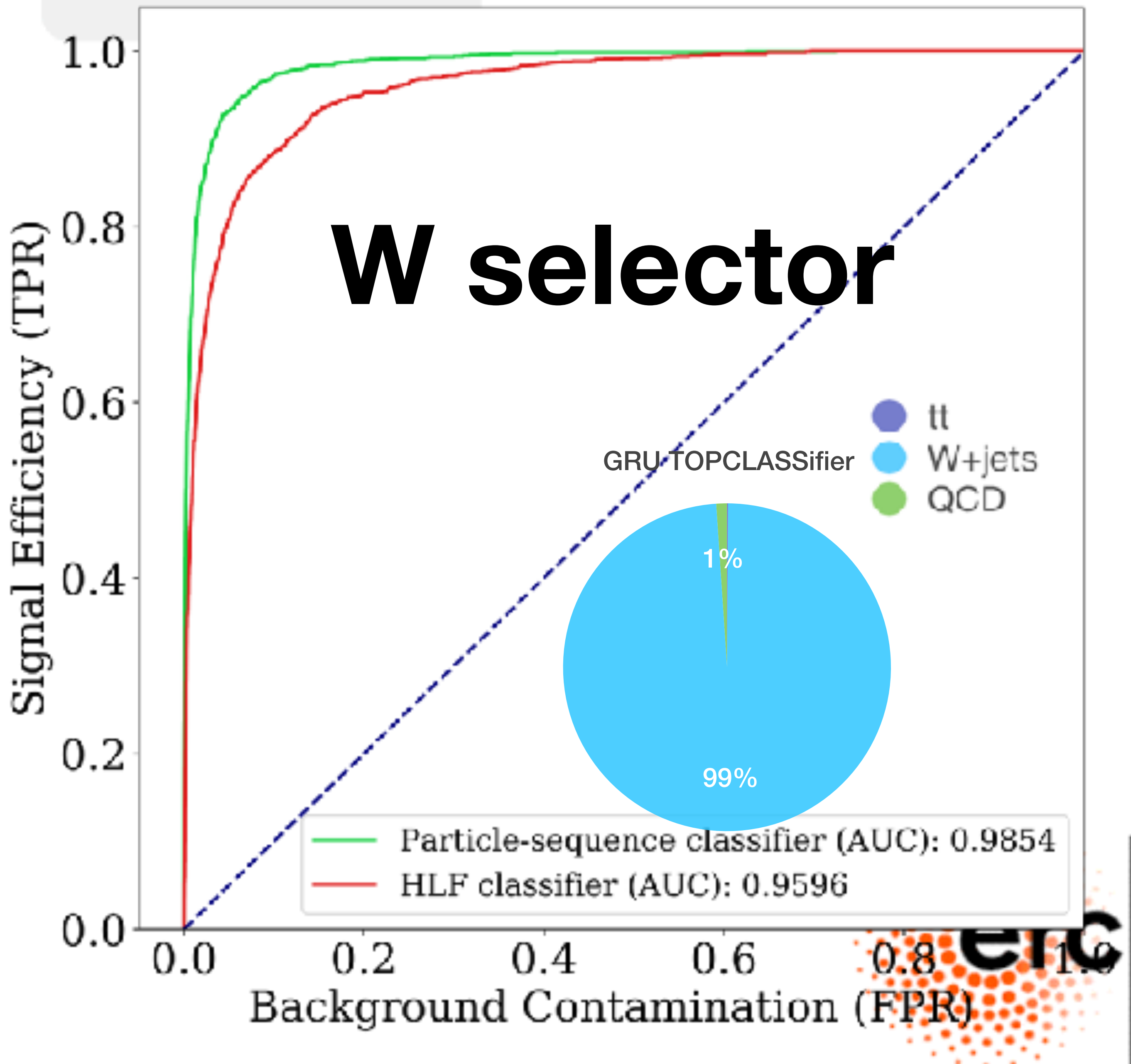
- One can push this approach beyond jet, building a topology tagger for the full event

- Tested with simulated events, as a way to implement a more efficient trigger strategy

- Could have impact on the way we process and analyze data in the future







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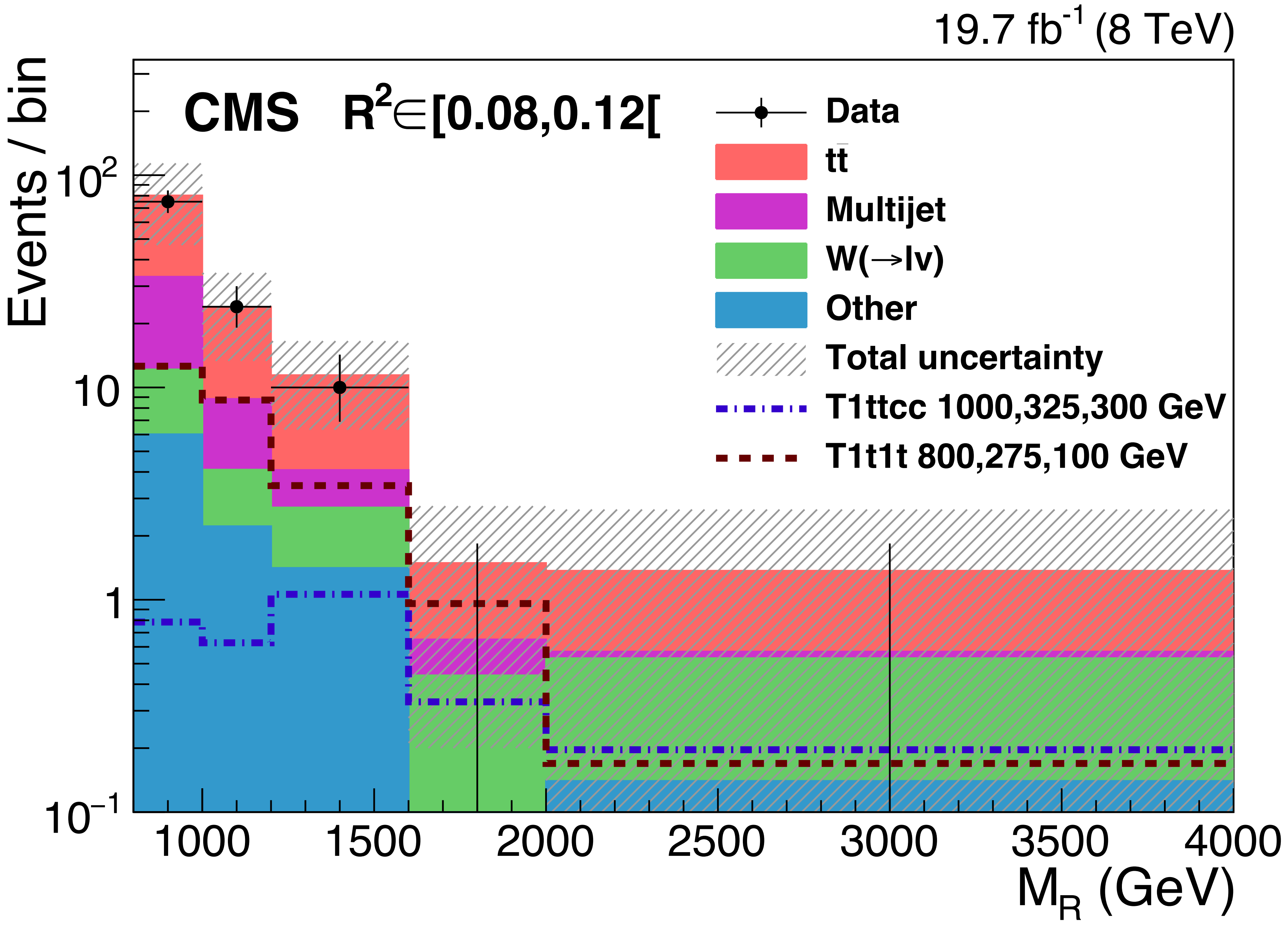
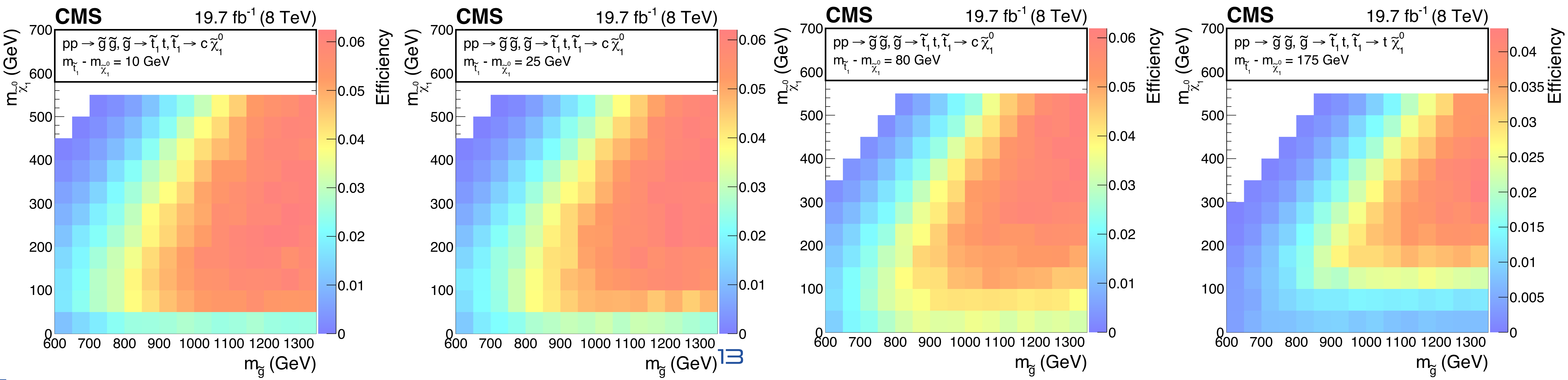
Parenthesis closed

BOOSTED-JETS SUSY SEARCH

- *Regime already probed in Run I (update ongoing)*
- *Will become more relevant with HL-LHC and higher-energy colliders (if any)*





SUMMARY OF EPISODE II

- *When R-parity is postulated, the lightest SUSY particle becomes stable (a natural dark matter candidate)*
- *Dark matter cannot be detected*
- *But LHC can probe dark matter production using balance on transverse plane*
    - *direct production, when high-pT jet/photon/etc is radiated*
    - *in cascade, from the production of other SUSY partners*
- *Several new methods proposed since LHC started*
- *A large part of the parameter space was explored, particularly in the context of Natural SUSY*
- *Now looking at the corners of the parameter space, where experimental conditions are more complicated*
- *Deep learning (e.g., for jet tagging) will help us to deal with this*

THE PLAN

- Lecture 1: **SETTING UP A SEARCH AT THE LHC**
  - Searching for SUSY in practice: strategy, trigger, reconstruction
  - Designing a search: Simplified Models
  - Building a search: signal region, control regions, statistics tools

- Lecture 2: R -Parity Conserving SuSY
- DM direct production
- DM cascade production

- Lecture 3: **BEYOND MET-BASED SEARCHES**
  - RPV SUSY
  - Displaced particles

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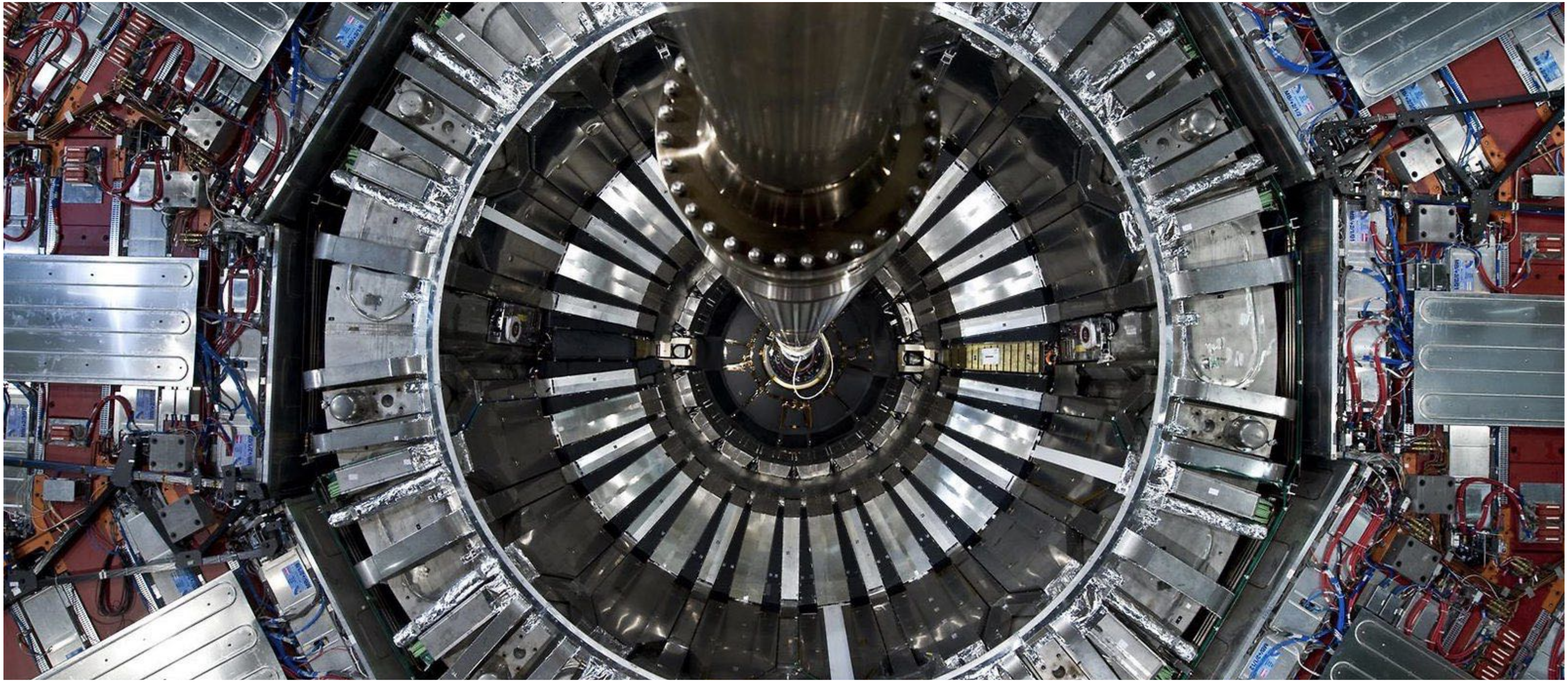
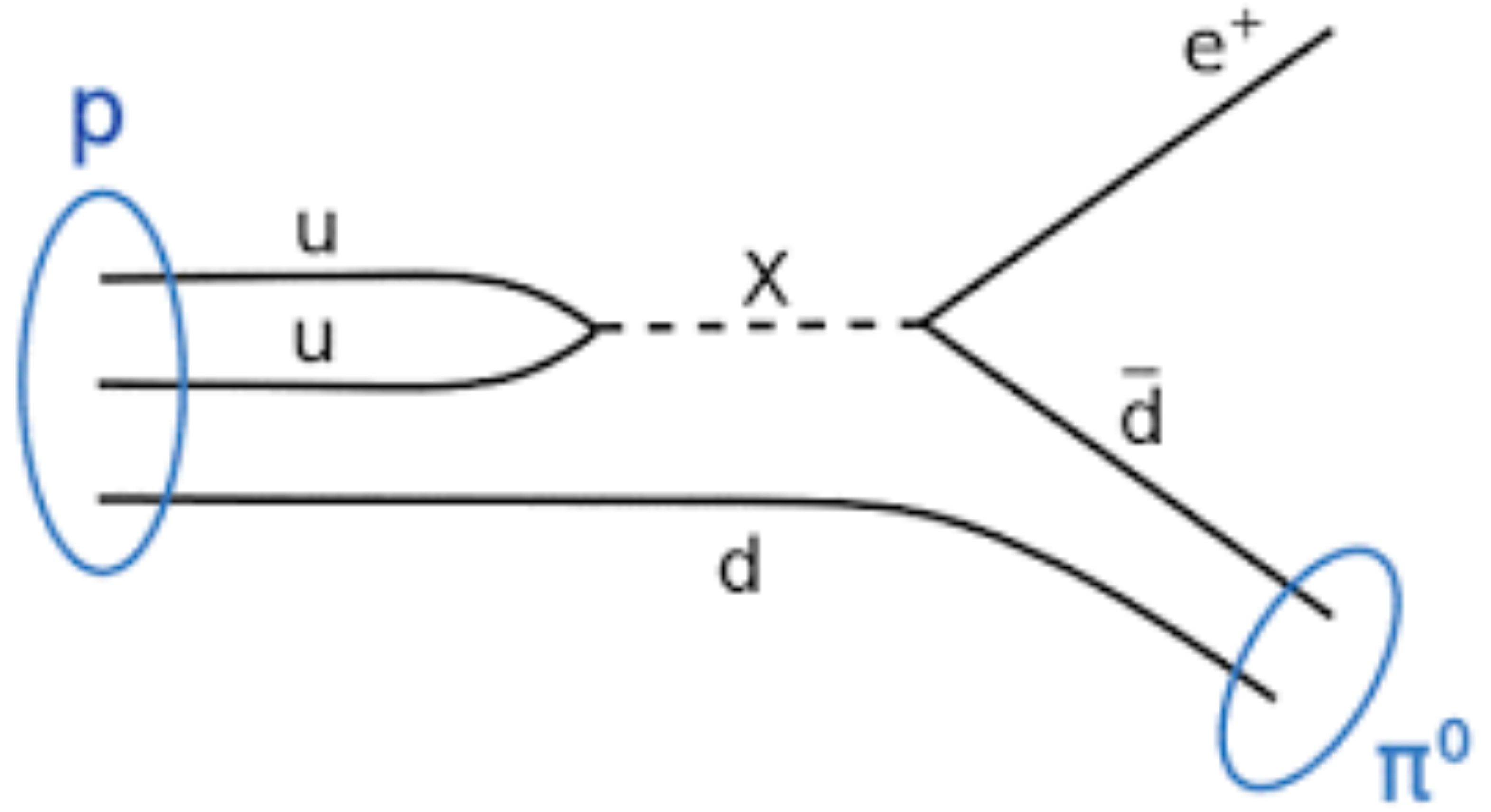


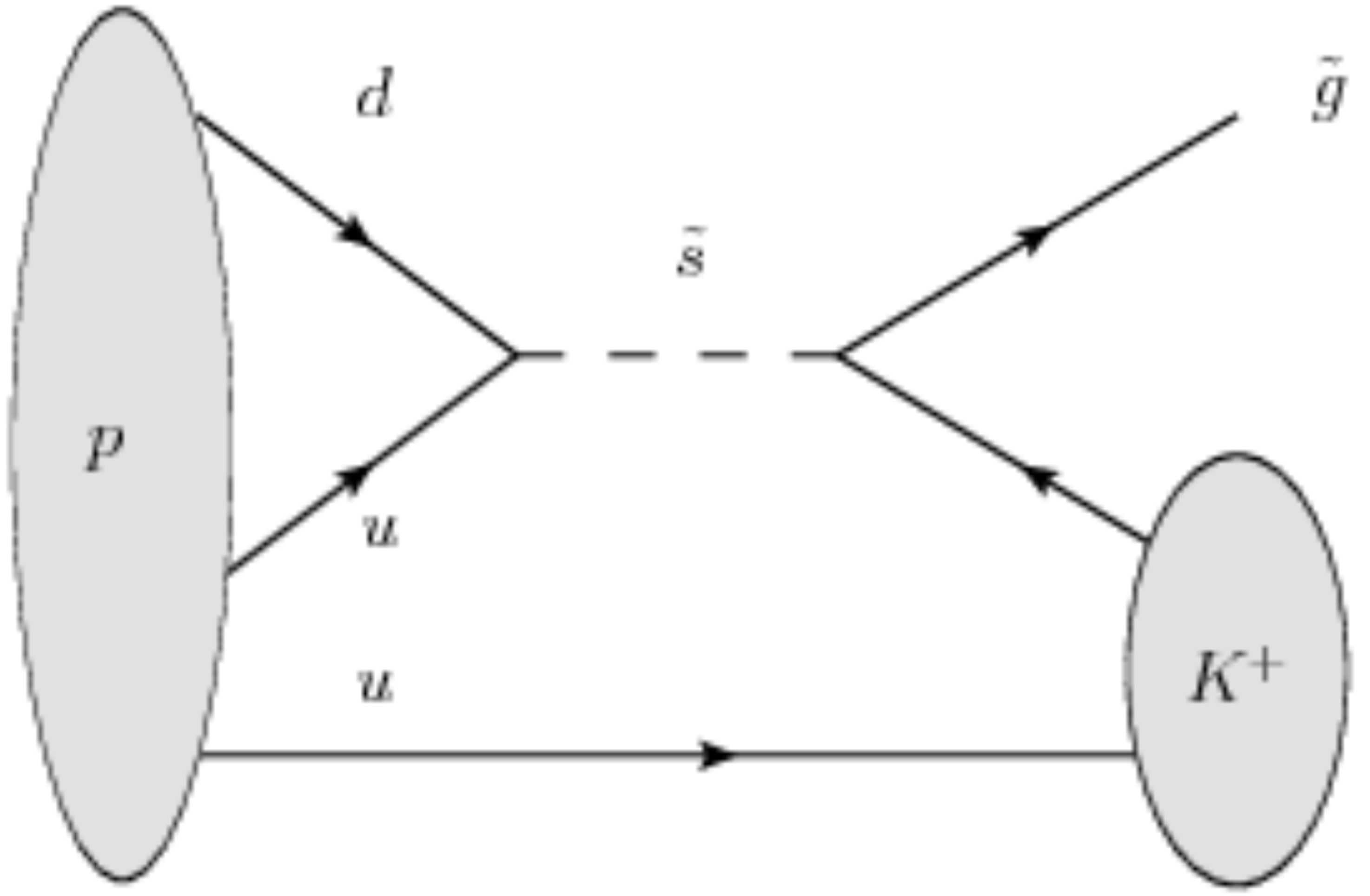
RPV SUSY SEARCHES

WHY R-PARITY AT ALL?

$$R = (-1)^{3B+L+2S}$$

- *R-parity prevents proton from decaying*
- *What people like of R-parity is that DM comes "for free"*
- *Still, it might be that SUSY has nothing/little to do with Dark Matter*
- *Can we renounce to R-parity in view of no R-parity conserving (RPC) SUSY?*
  - *Yes, but coupling have to be kept small(*) / fine-tuned*
  - ***Even better if we have a mechanism that keeps the couplings small***





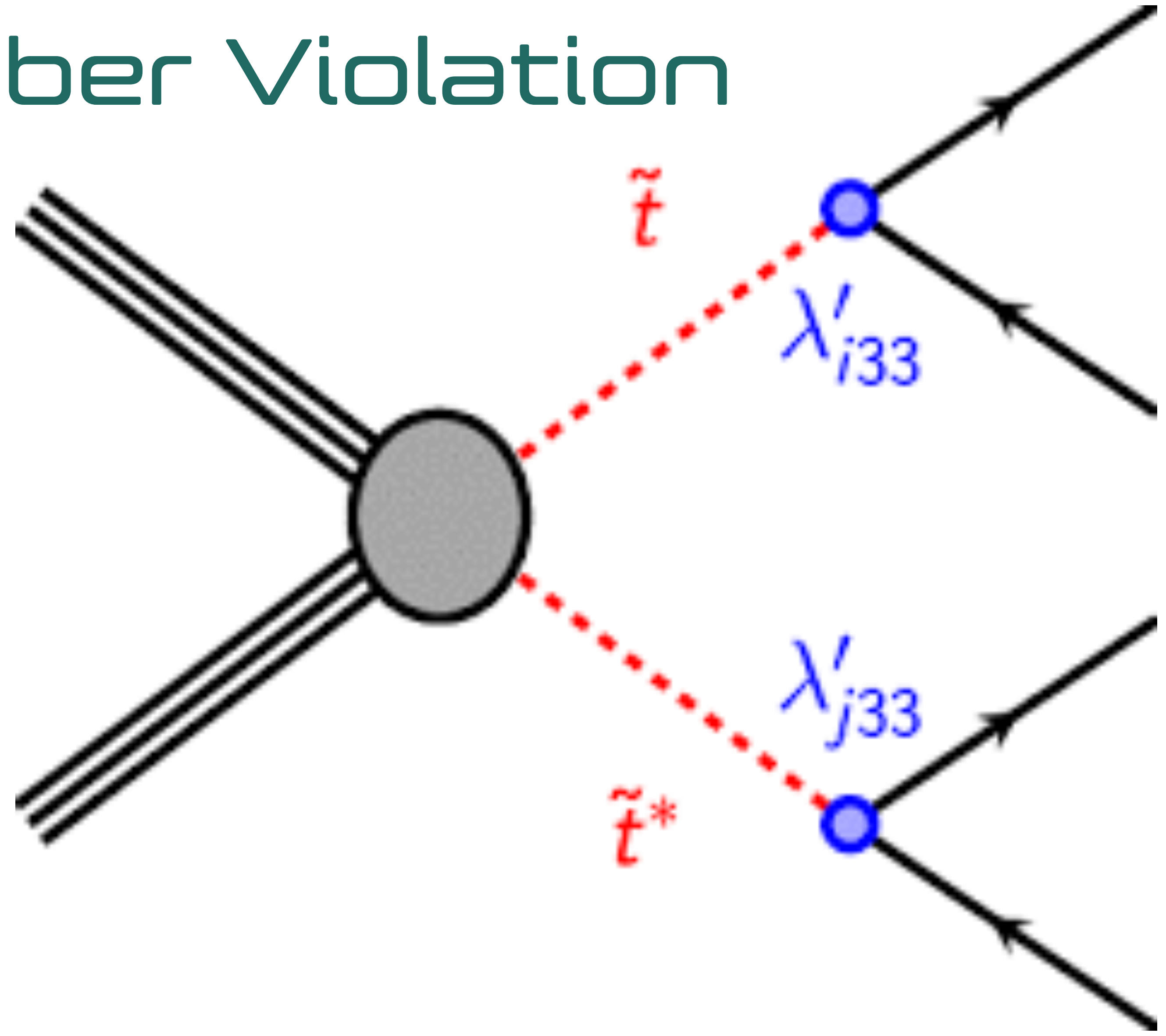
(*) **For very small couplings, particle might become long living (see tomorrow)**

HOW TO BRAKE R-PARITY

Lepton Number Violation

$$W = \frac{1}{2}\lambda_{ijk}L_iL_jE^c_k + \lambda'_{ijk}L_iQ_jD^c_k + \frac{1}{2}\lambda''_{ijk}U^c_iD^c_jD^c_k + \mu'_iL_iH_u$$

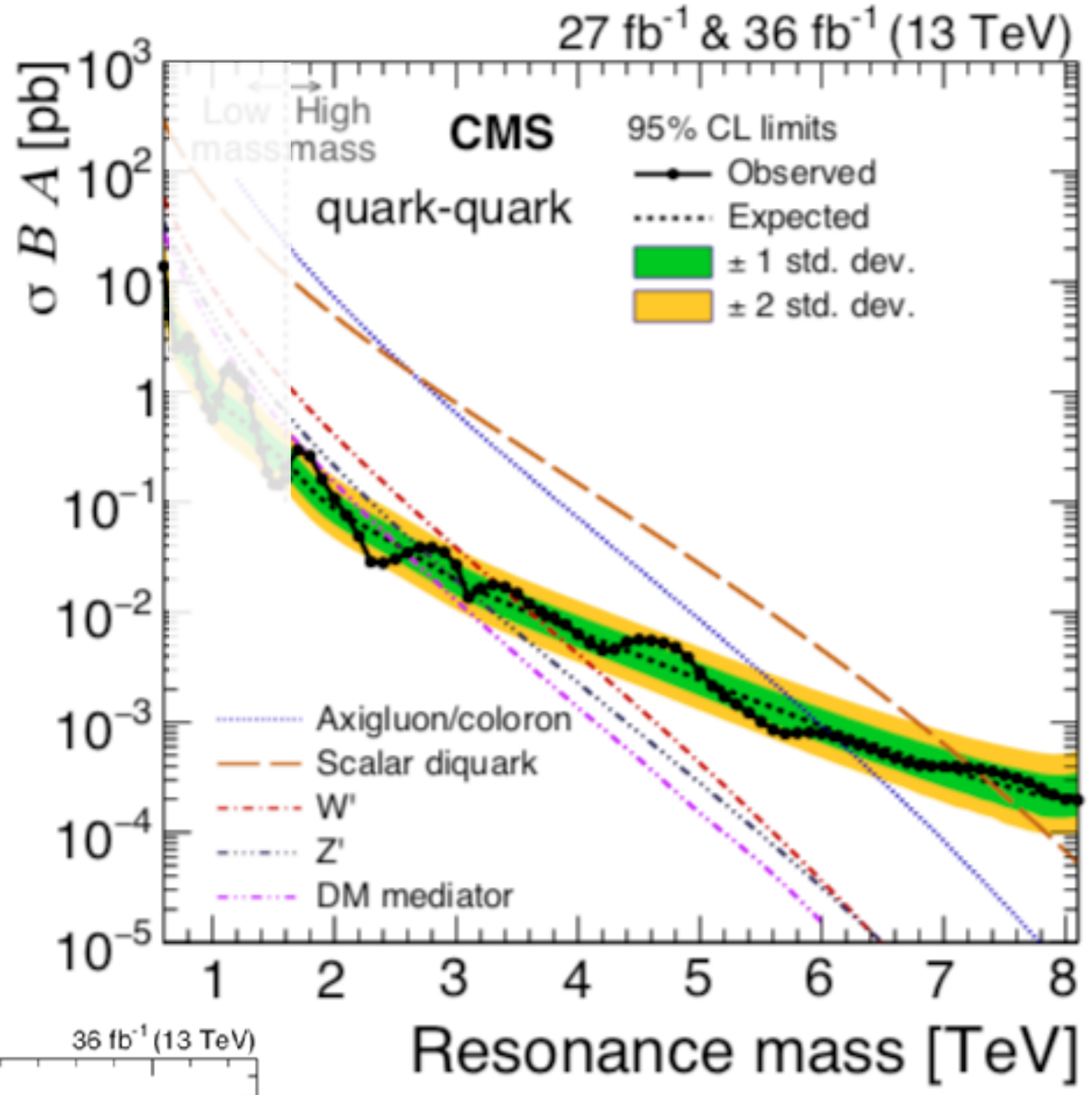
Baryon Number Violation

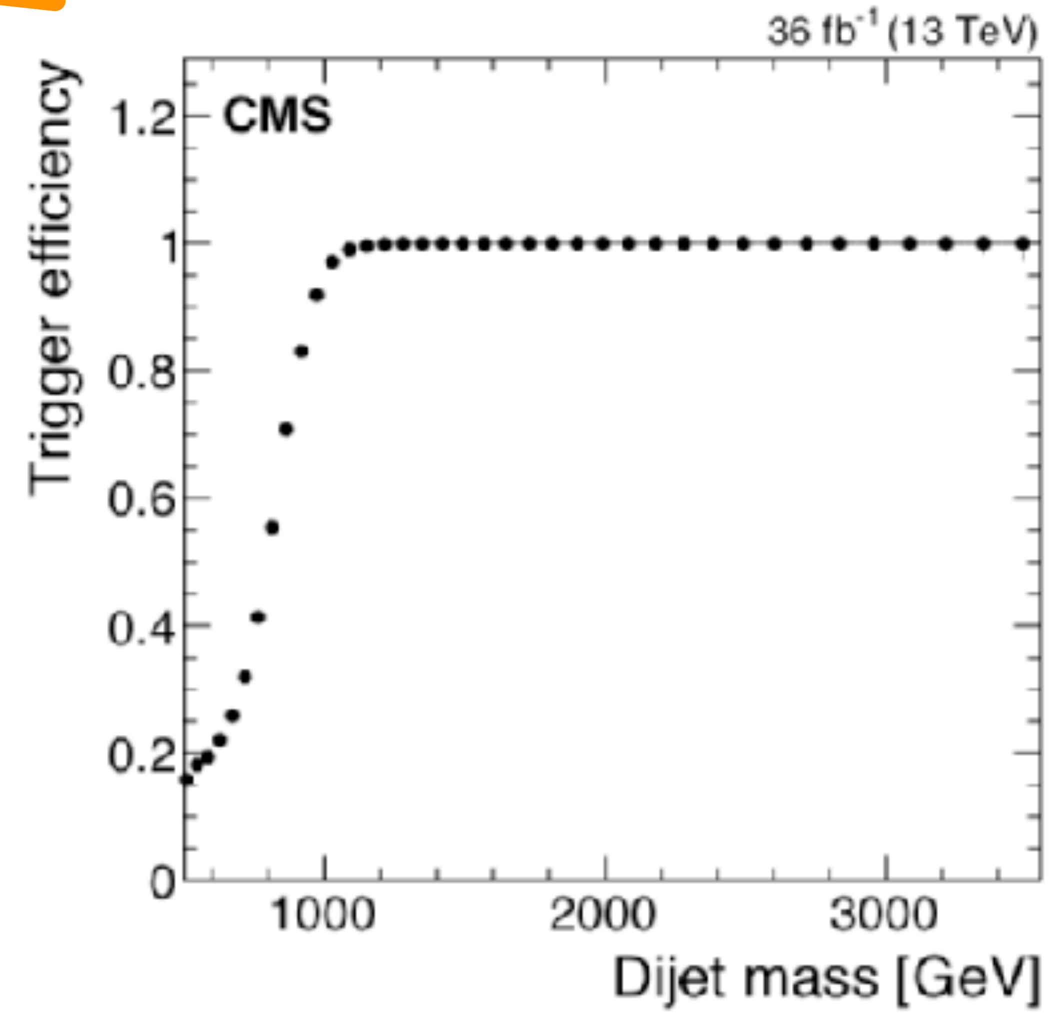


- *Leptonic RPV is easy to look for, thanks to charged leptons in the final states (similar to LQ searches, **not much to say**)*
- ***Hadronic RPV more complicated:** all jets final states at moderate masses*
    - *single production (complicated because of trigger)*
    - *pair production easier to access (more objects in the final state, more trigger handles)*

SINGLE-PRODUCED RPV SQUARK

- *aka dijet resonance search*
- *Traditional (easiest) LHC BSM search*
- *Main limitation is trigger*
  - *standard strategy limited > 1 TeV*
  - ***scouting introduced to go around this problem. Works OK down to ~500 GeV (then L1 becomes an issue)***
  - *ISR searches (same trick as monojet) to push sensitivity to very-small masses*





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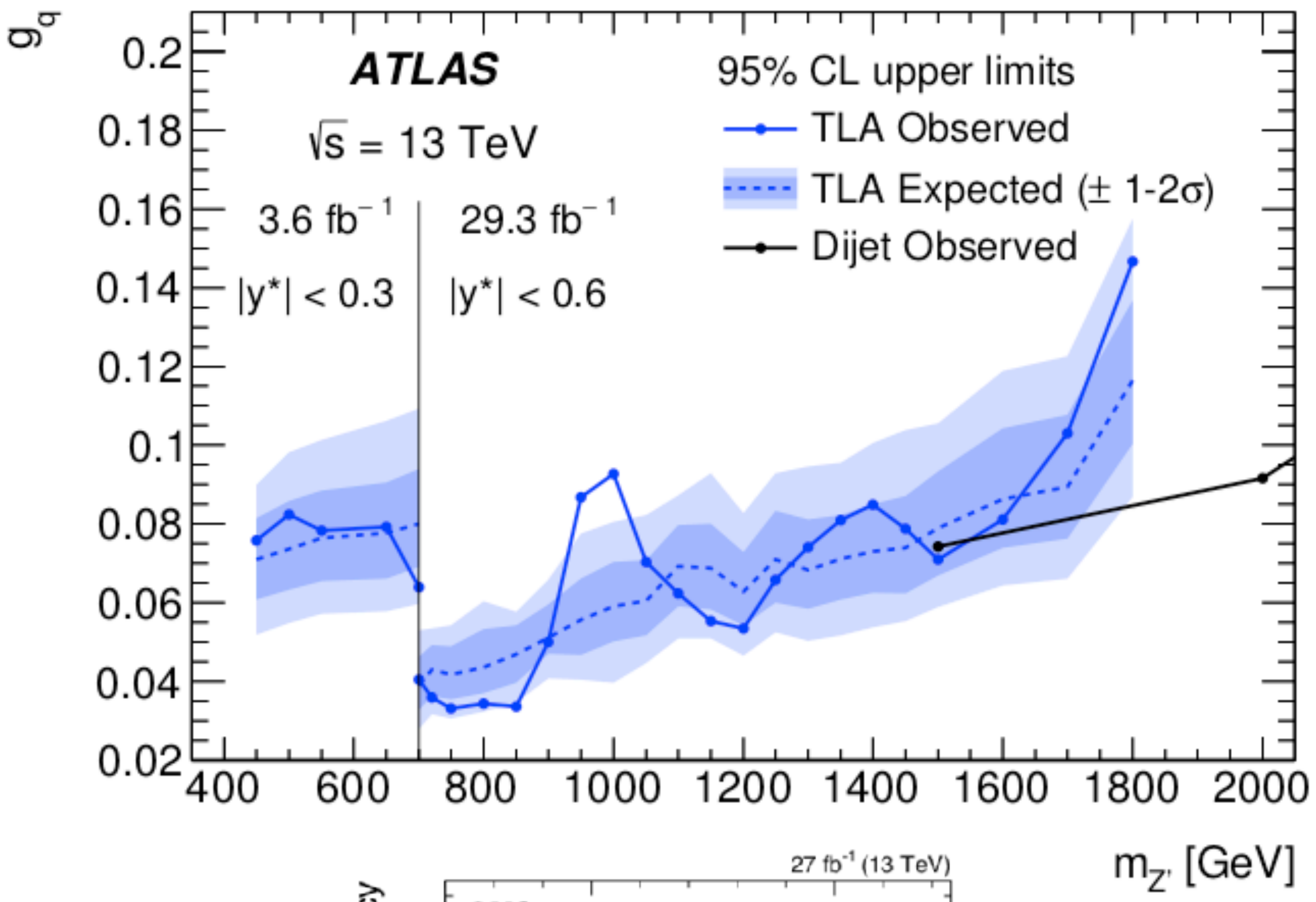

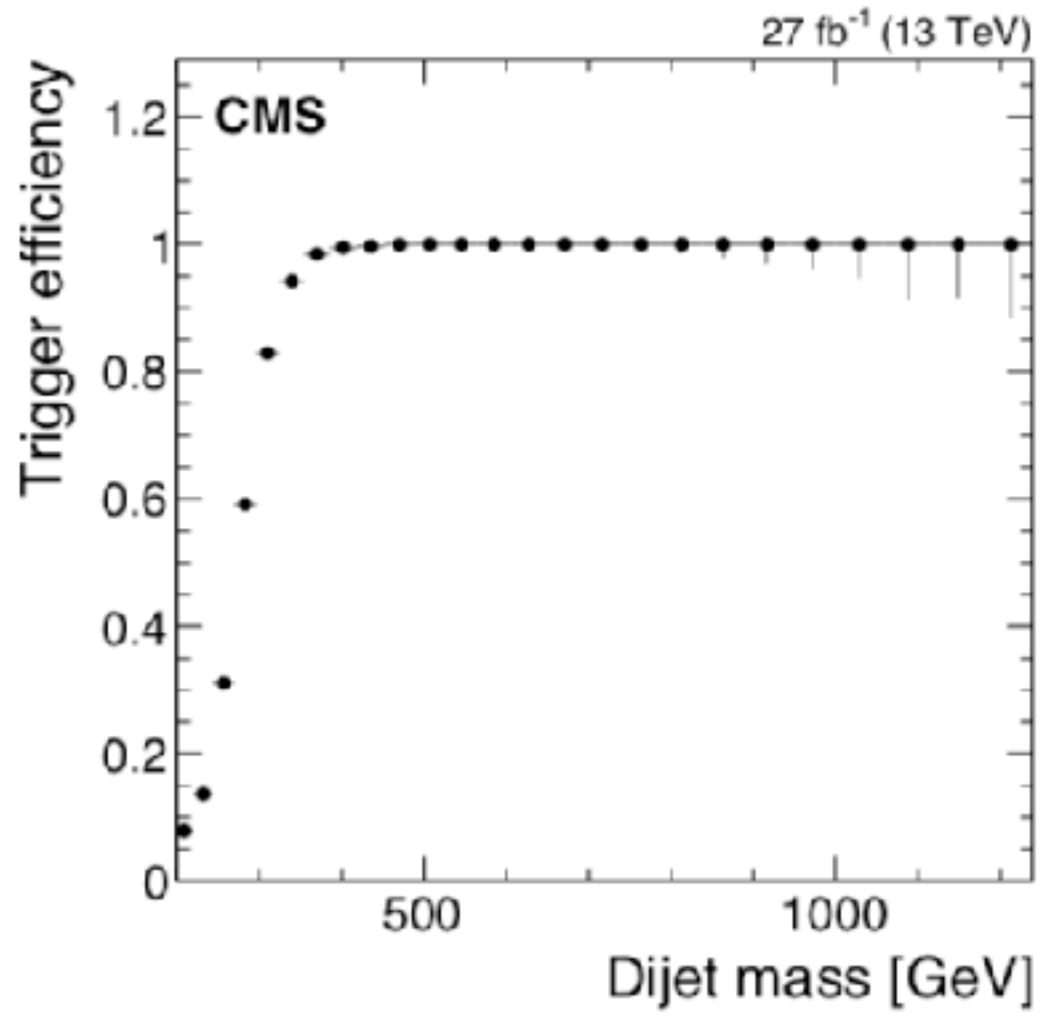

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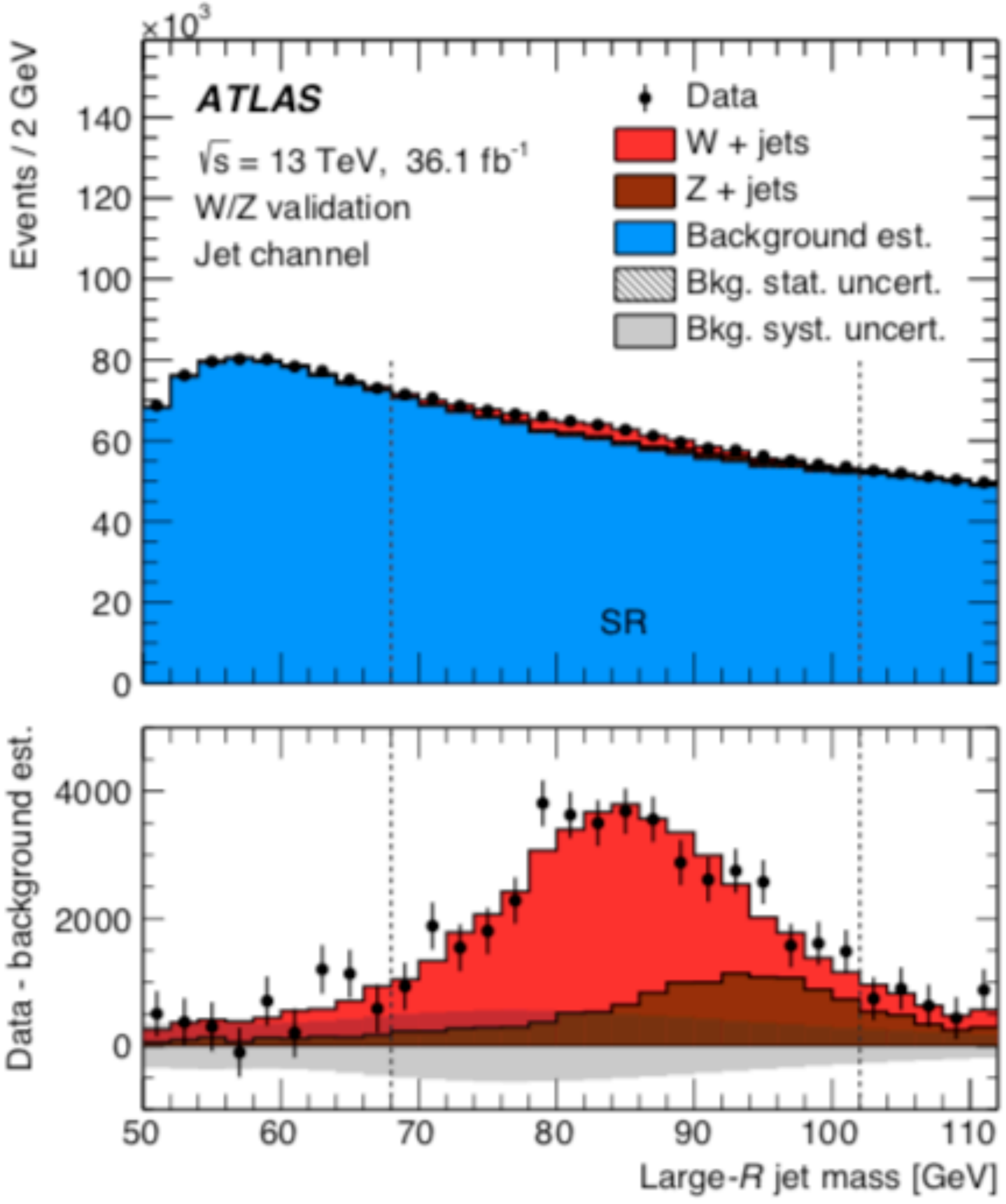
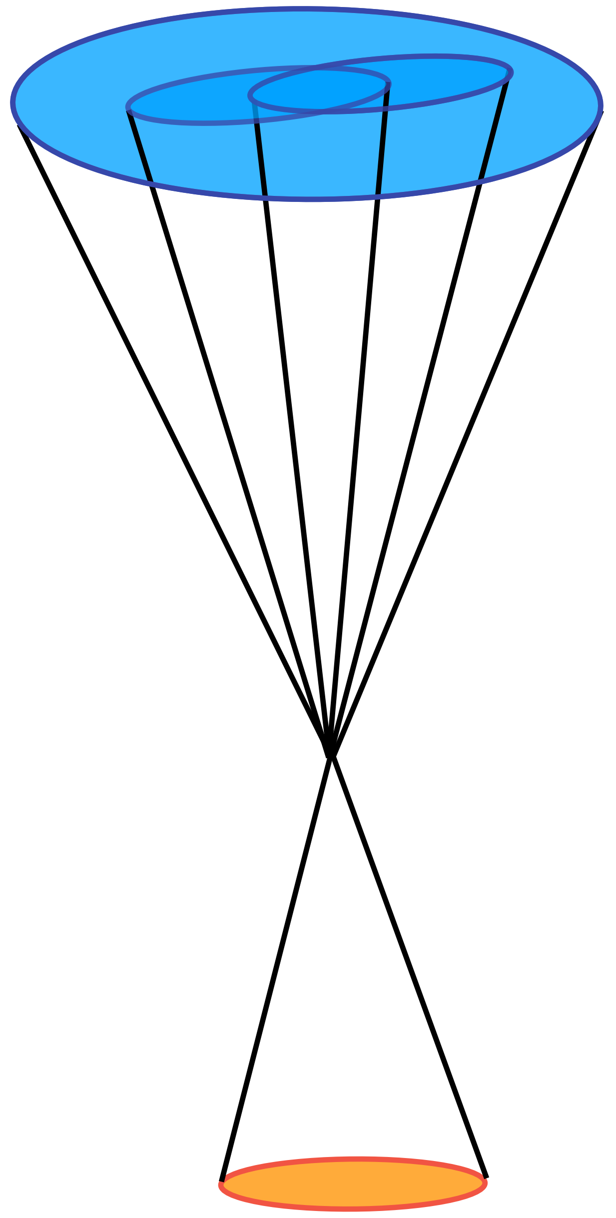
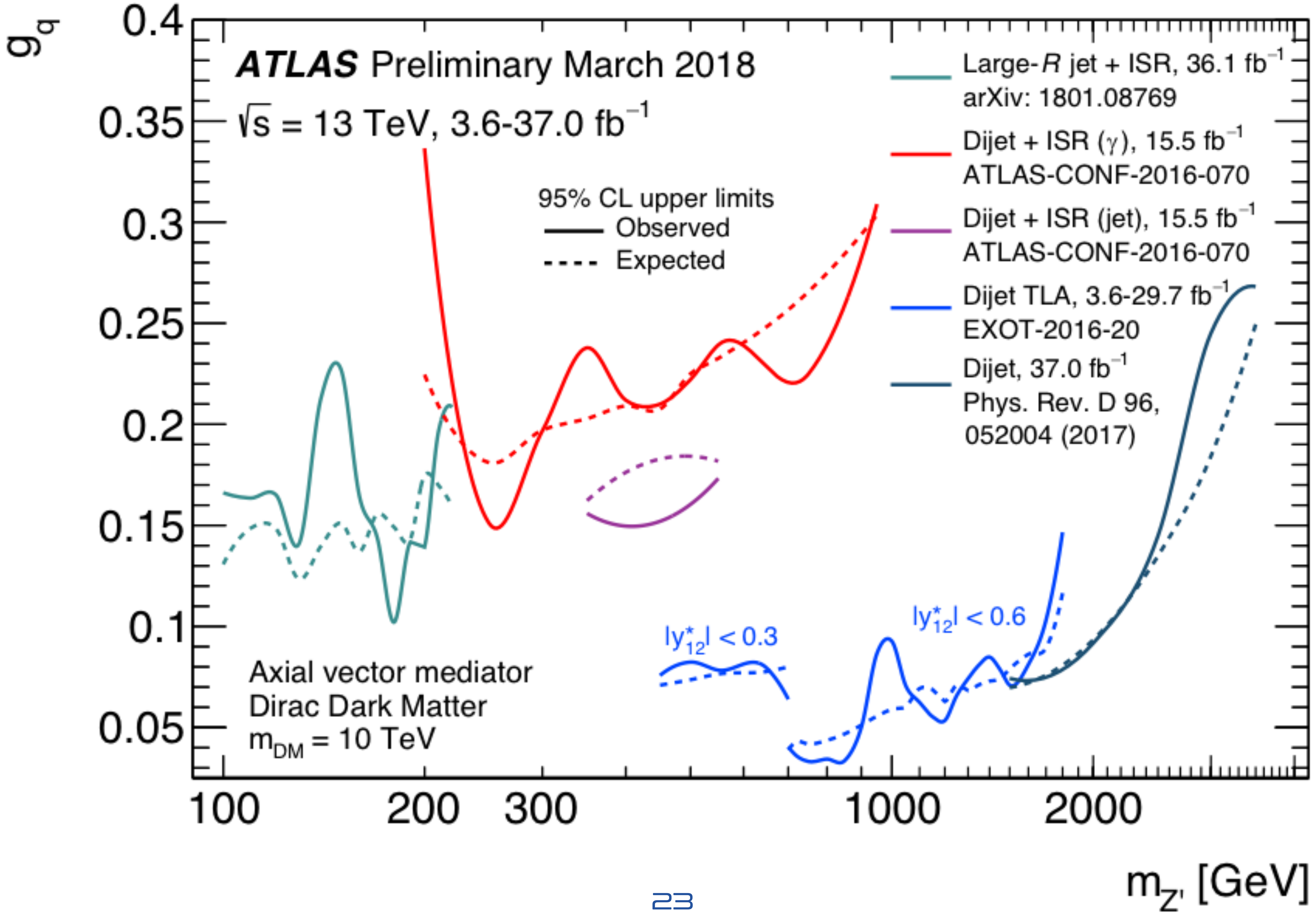


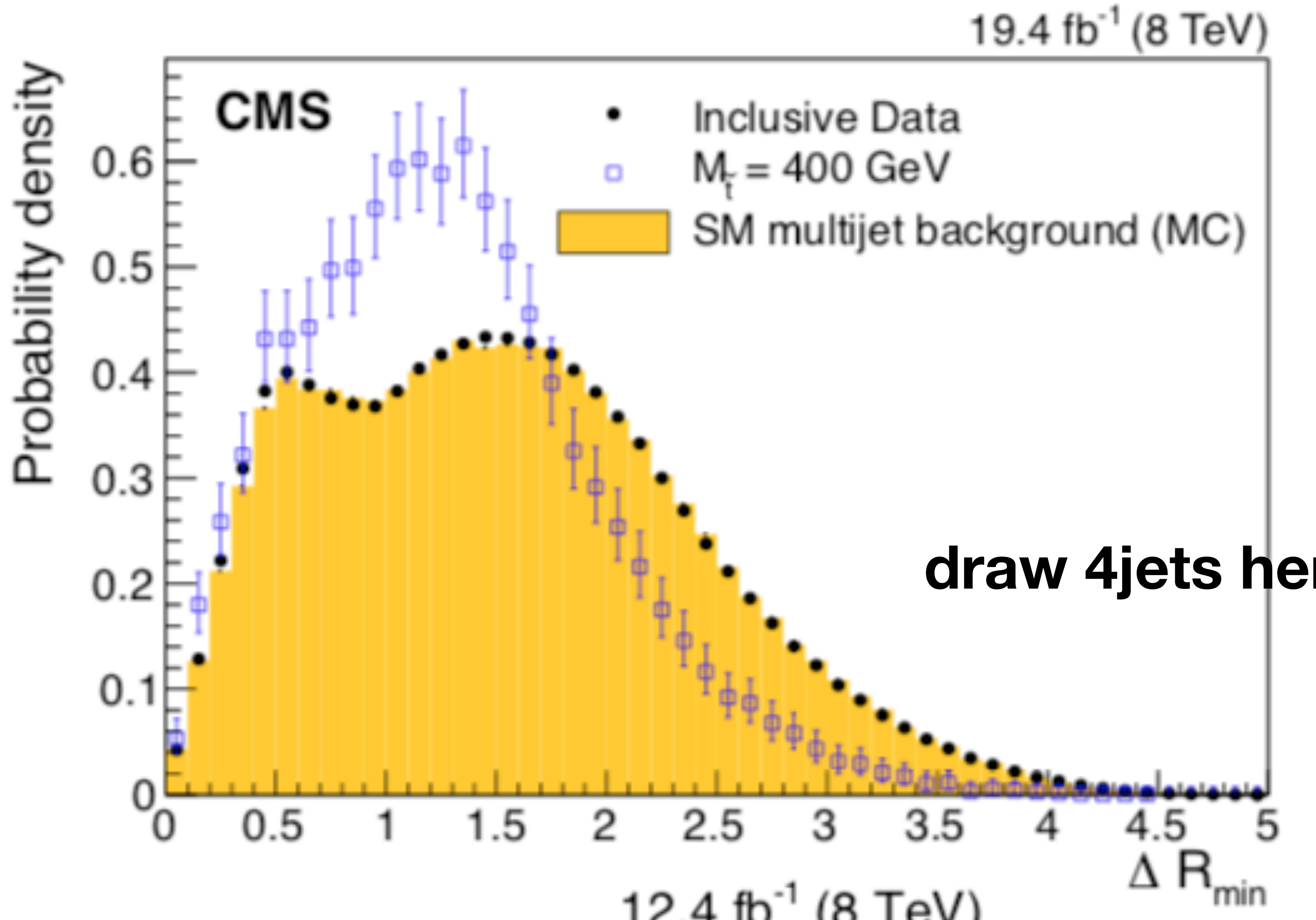


PUTTING ALL TOGETHER

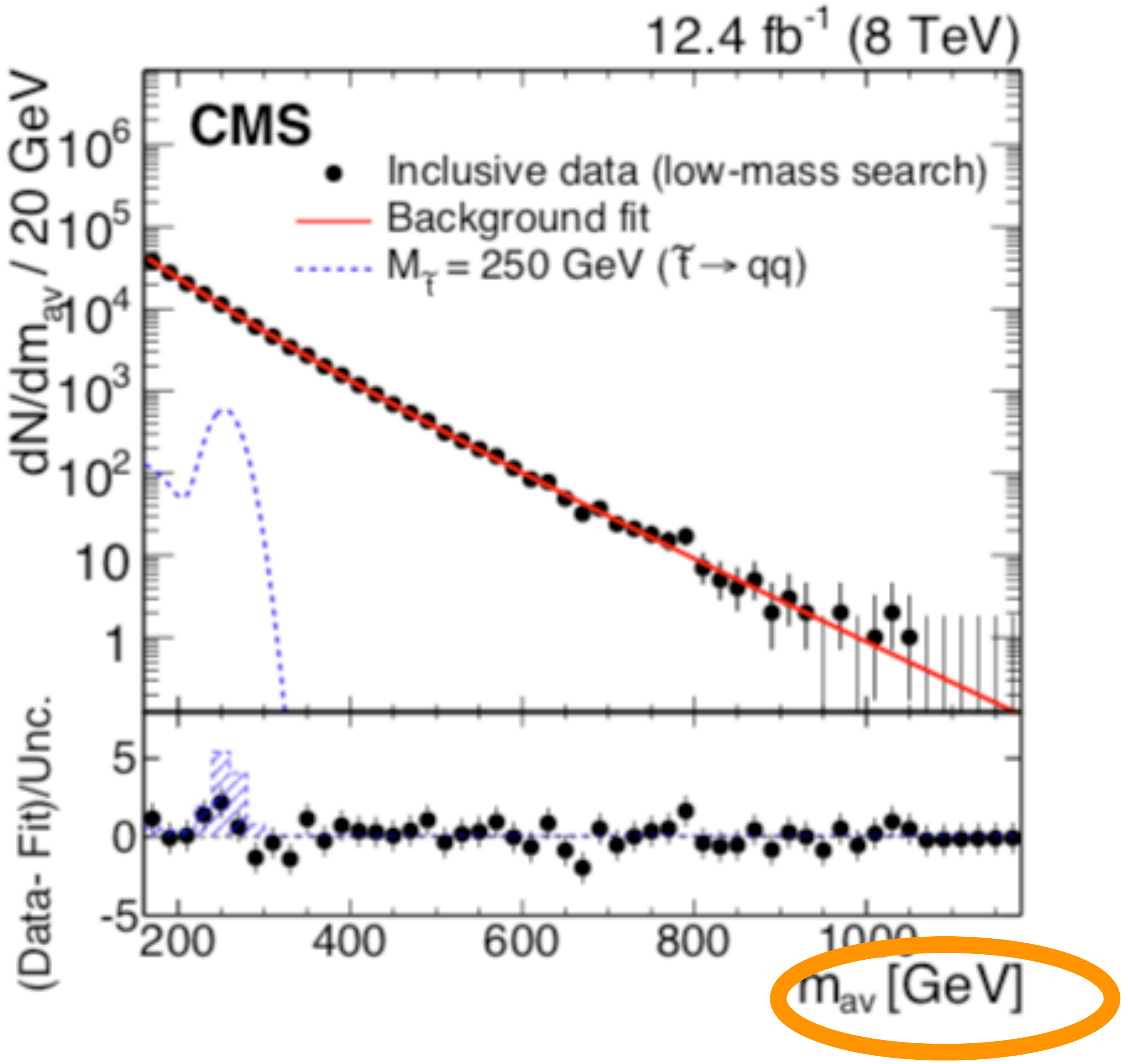


PAIR-PRODUCED RPV STOP

- *Two jet pairs in the final state, with similar masses*
- *Quite complicated combinatoric + large background*
- *Two strategies:*
  - *resolved dijet pairs: some combinatoric issue to find best pairing. Then simple bump hunt on average mass*
  - ***merged dijet pairs: simpler topology (no combinatorics) and extra handles (jet substructure)***



draw 4jets here



Fit done on the average dijet mass

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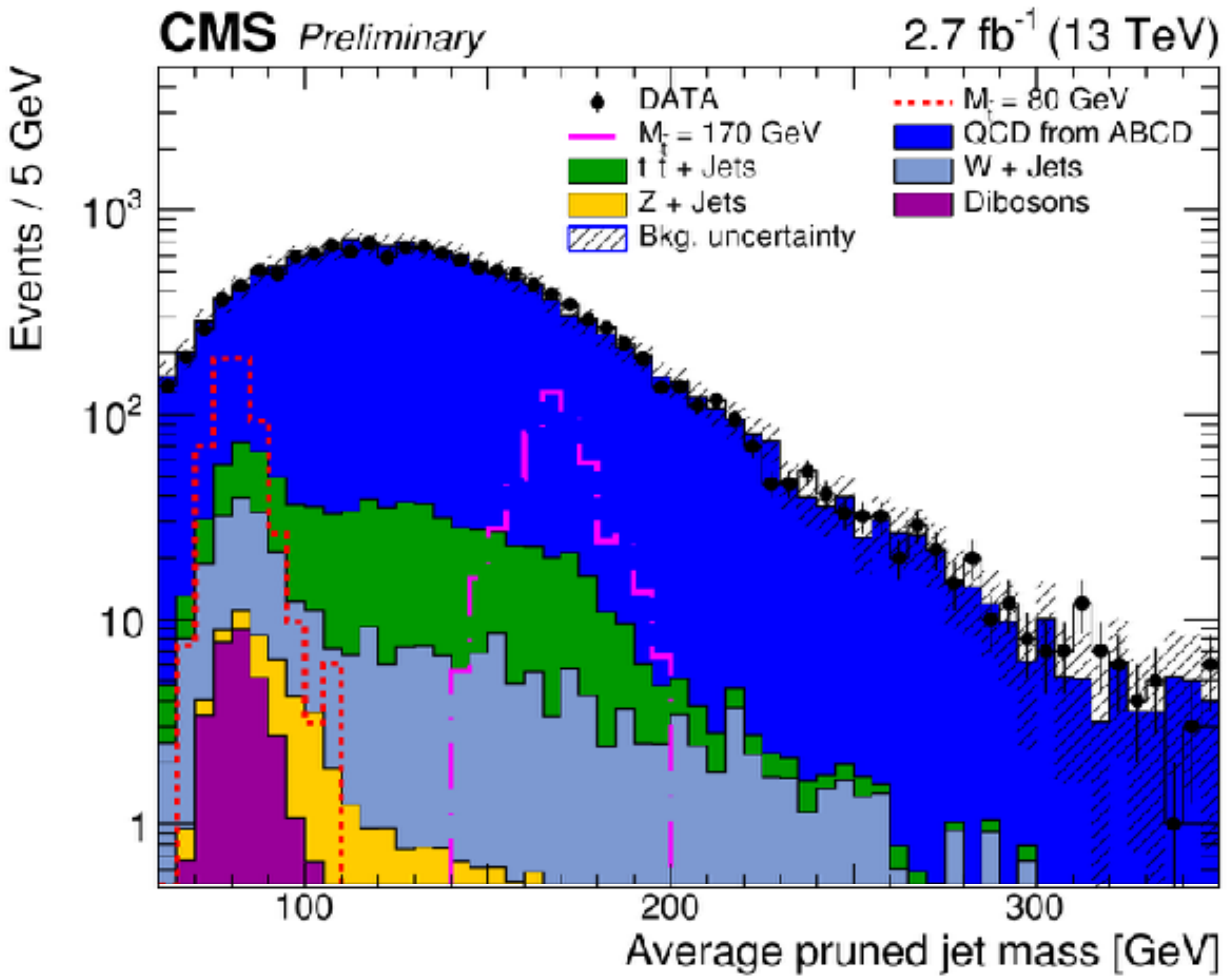
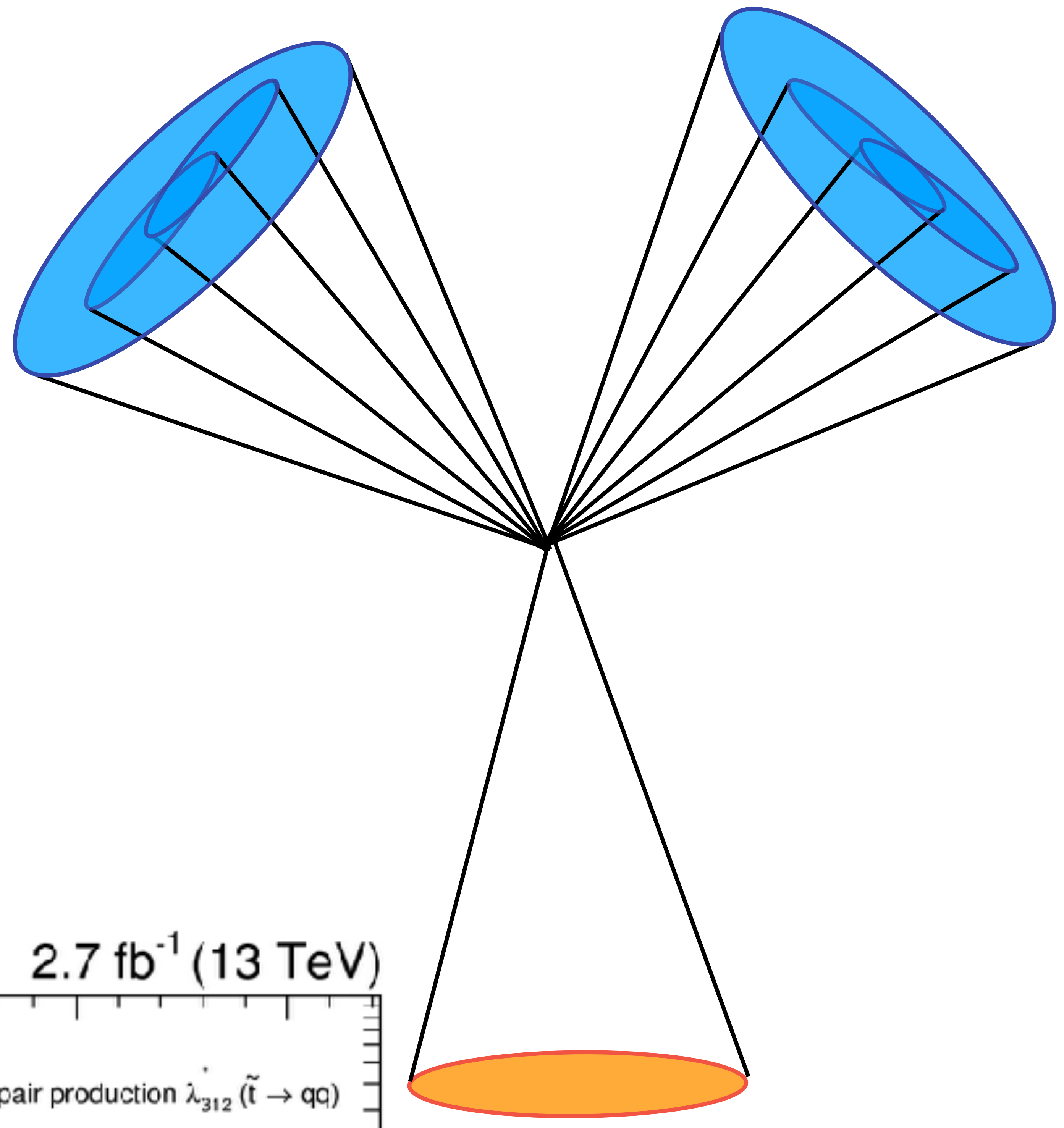
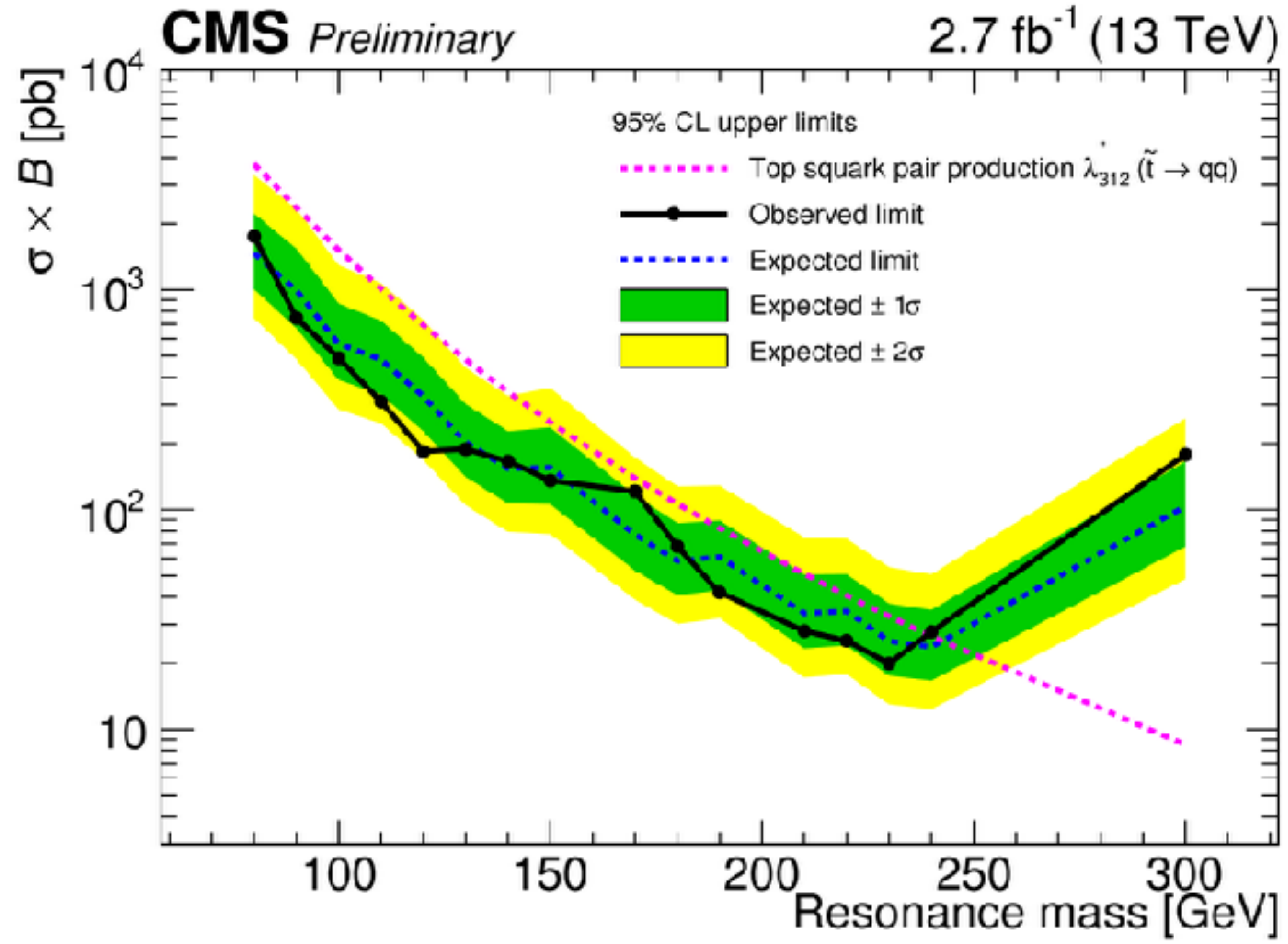
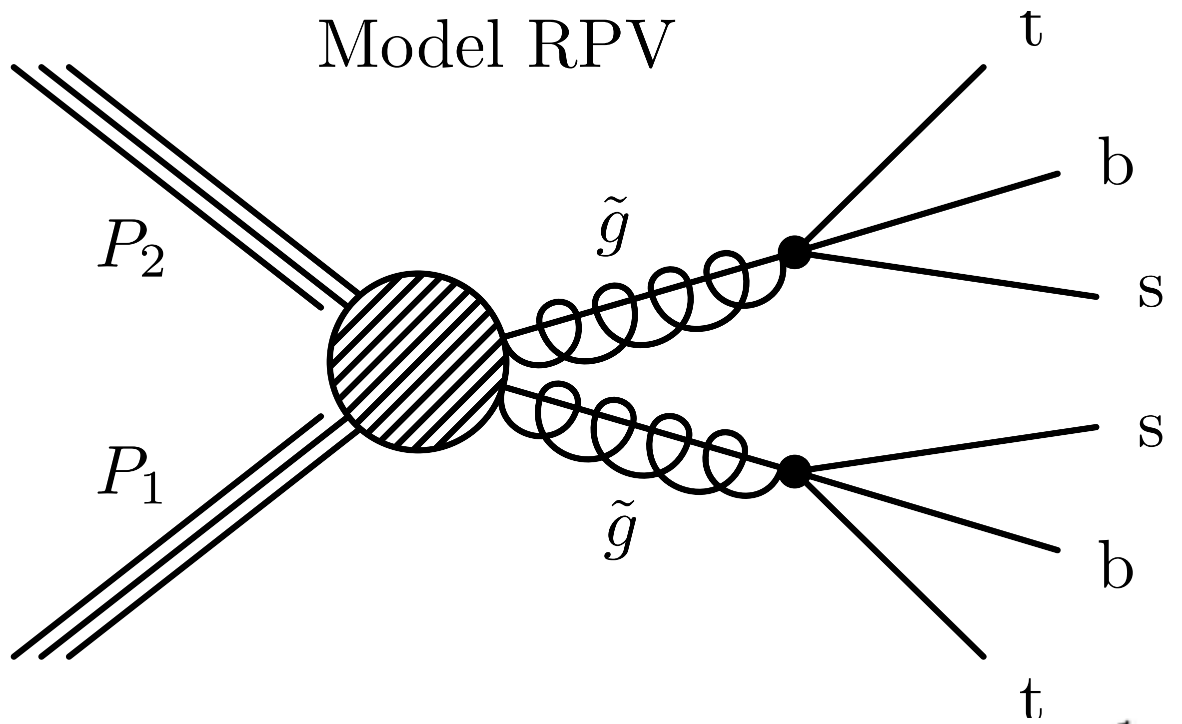




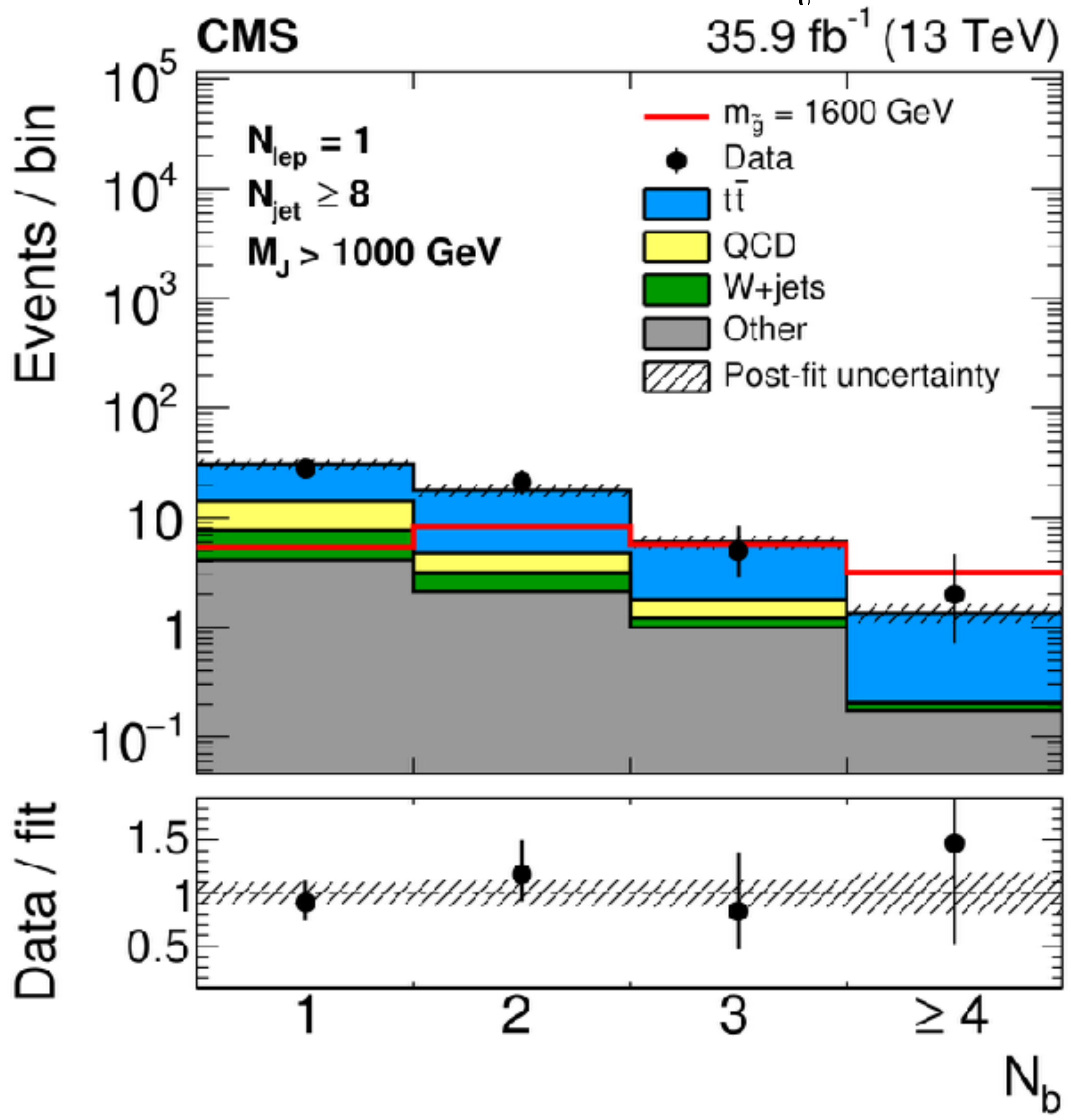


MFV SUSY

- MFV is a kind of RPV SUSY in which RPV couplings are making small
- This is achieved requiring the couplings to scale ~ CKM factors
  - 1st-generation couplings stay small and proton is safe
  - RPV confined to 3rd generation
- MFV SUSY comes with top and bottom quarks
- One of the main motivations to look into jet multiplicity as a discriminating variable



8 jets (4b) in 1-lepton final state



https://arxiv.org/abs/1111.1239

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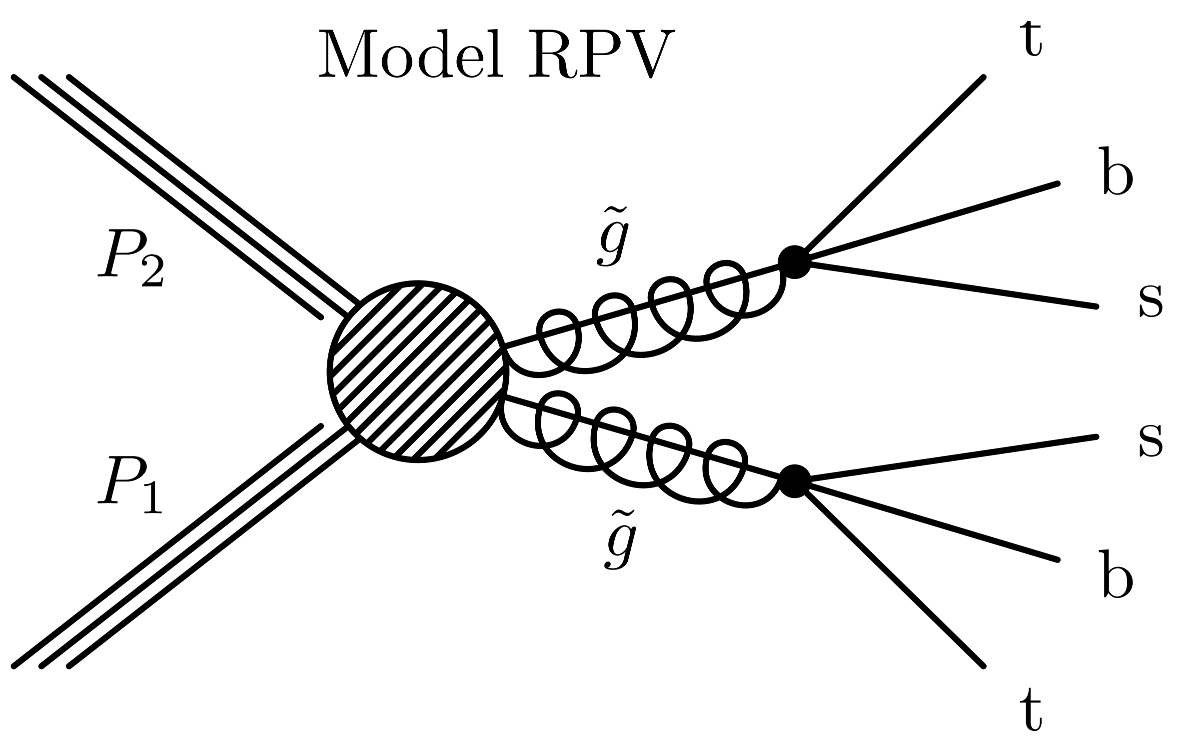

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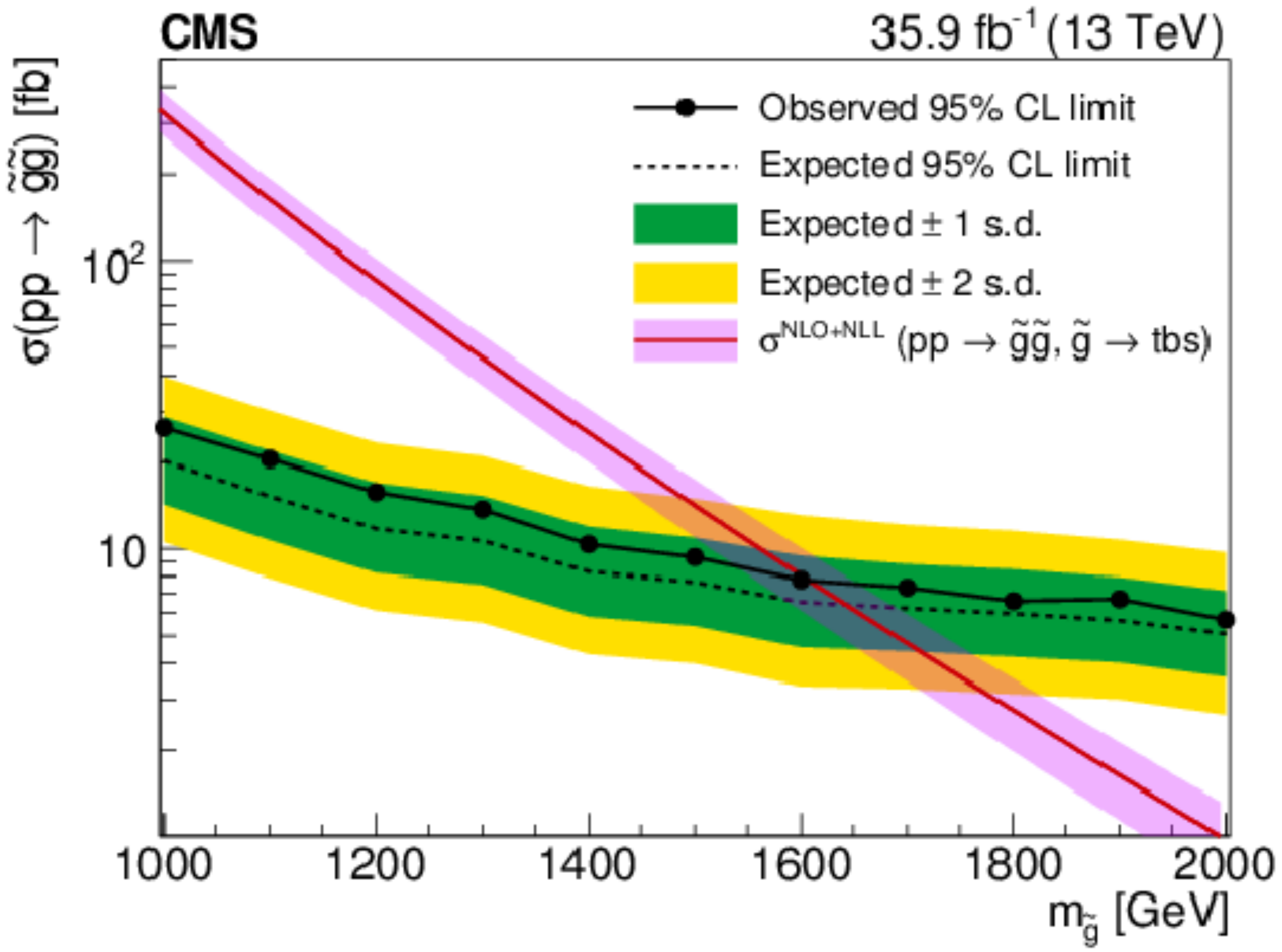

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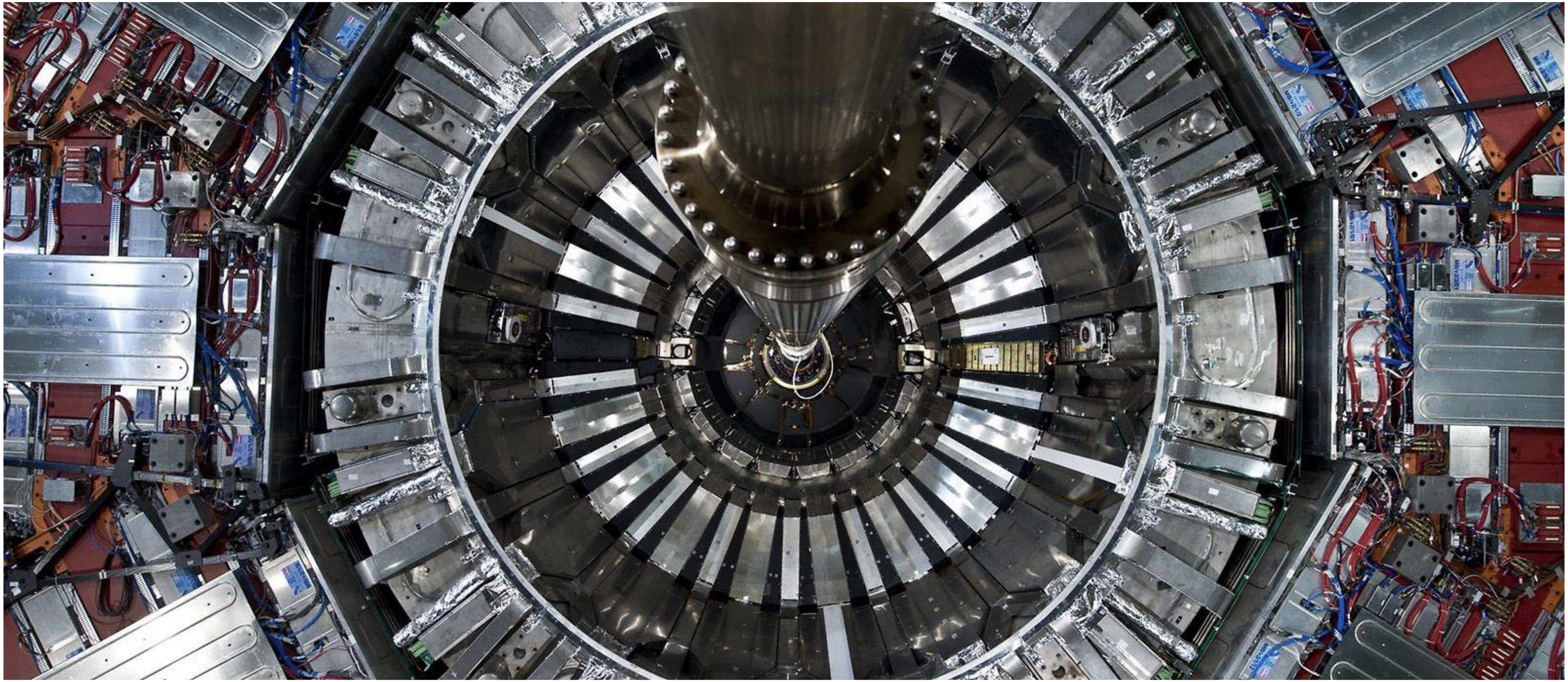
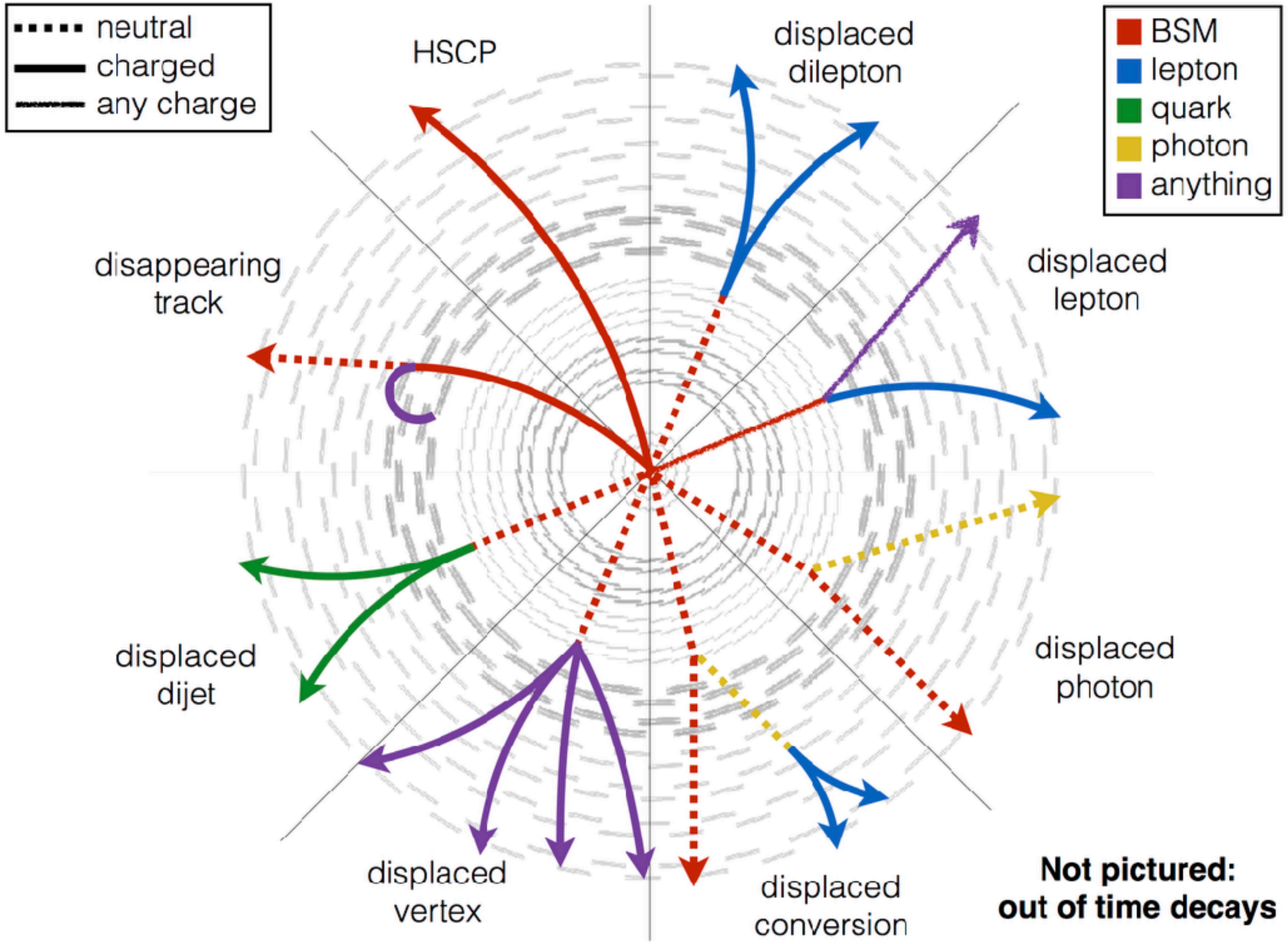


LONG-LIVING PARTICLES

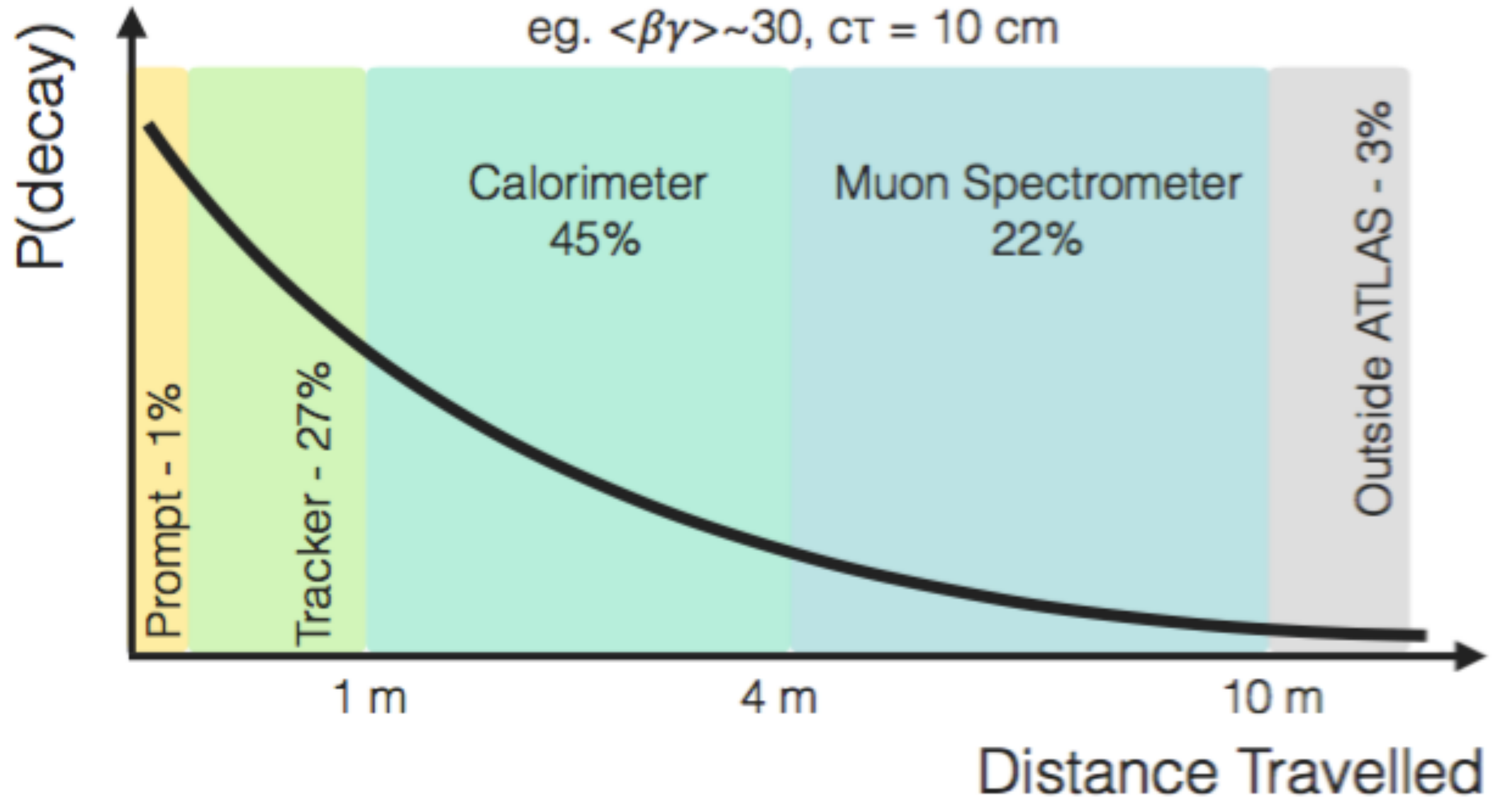
LONG-LIVING PARTICLES IN A DETECTOR

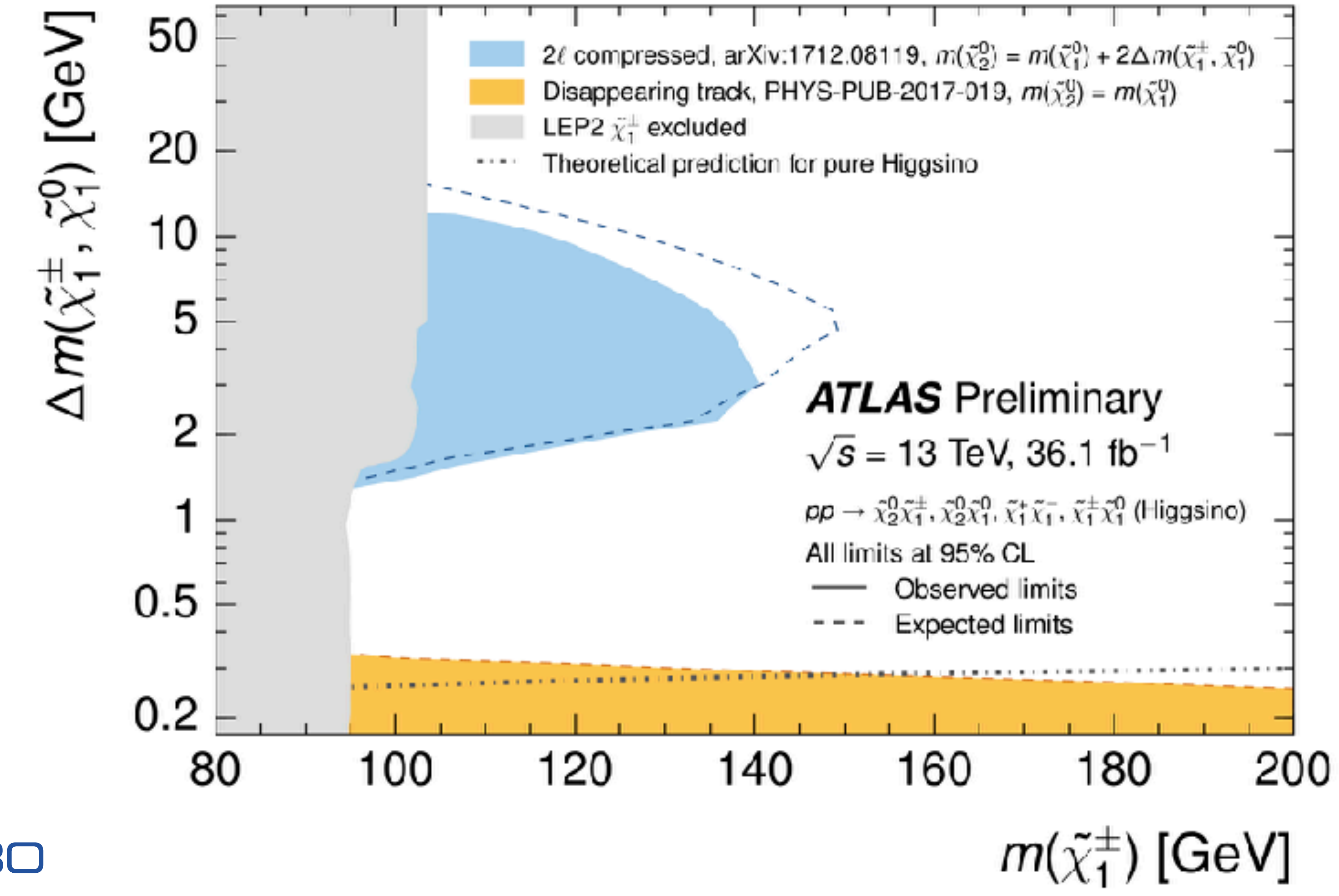
- *Signature depends on charge and lifetime*
  - *muon-like particle with large mass (large dE/dx)*
  - *track segment*
  - *displaced particles (track leptons, jets)*
  - *…*
  - *(for very long lifetimes) particles can be stuck in the calorimeter and decay months after*



WHAT A LLP LOOKS LIKE IN A DETECTOR

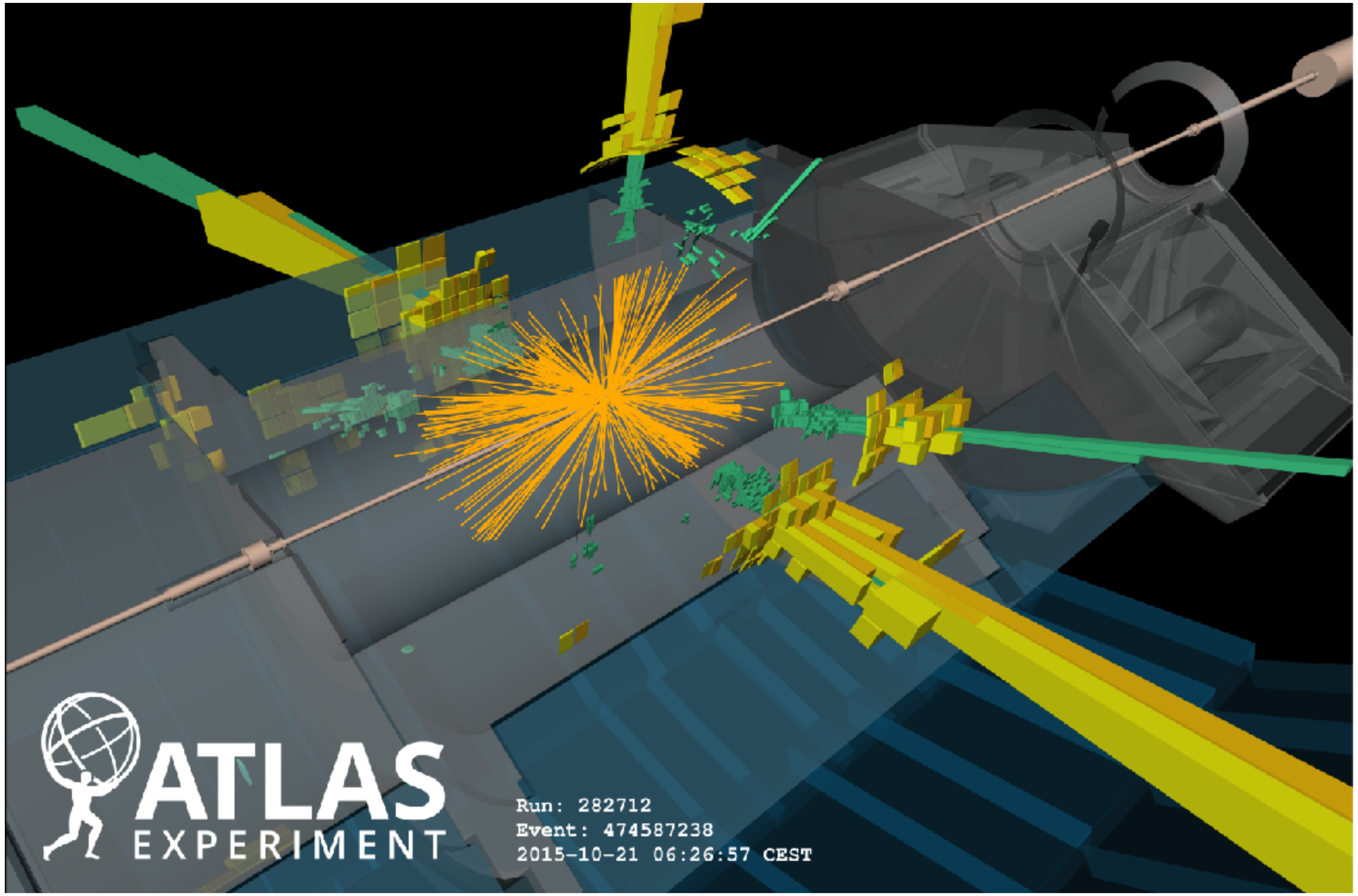
- Signatures can be very tricky
- Depending on the lifetime, different detector components are involved
- Some of these detectors cannot be operated in L1 trigger (and sometimes also at HLT)
  - Trigger can be a challenge
  - More than one analysis is needed for a given model, depending on the parameter space





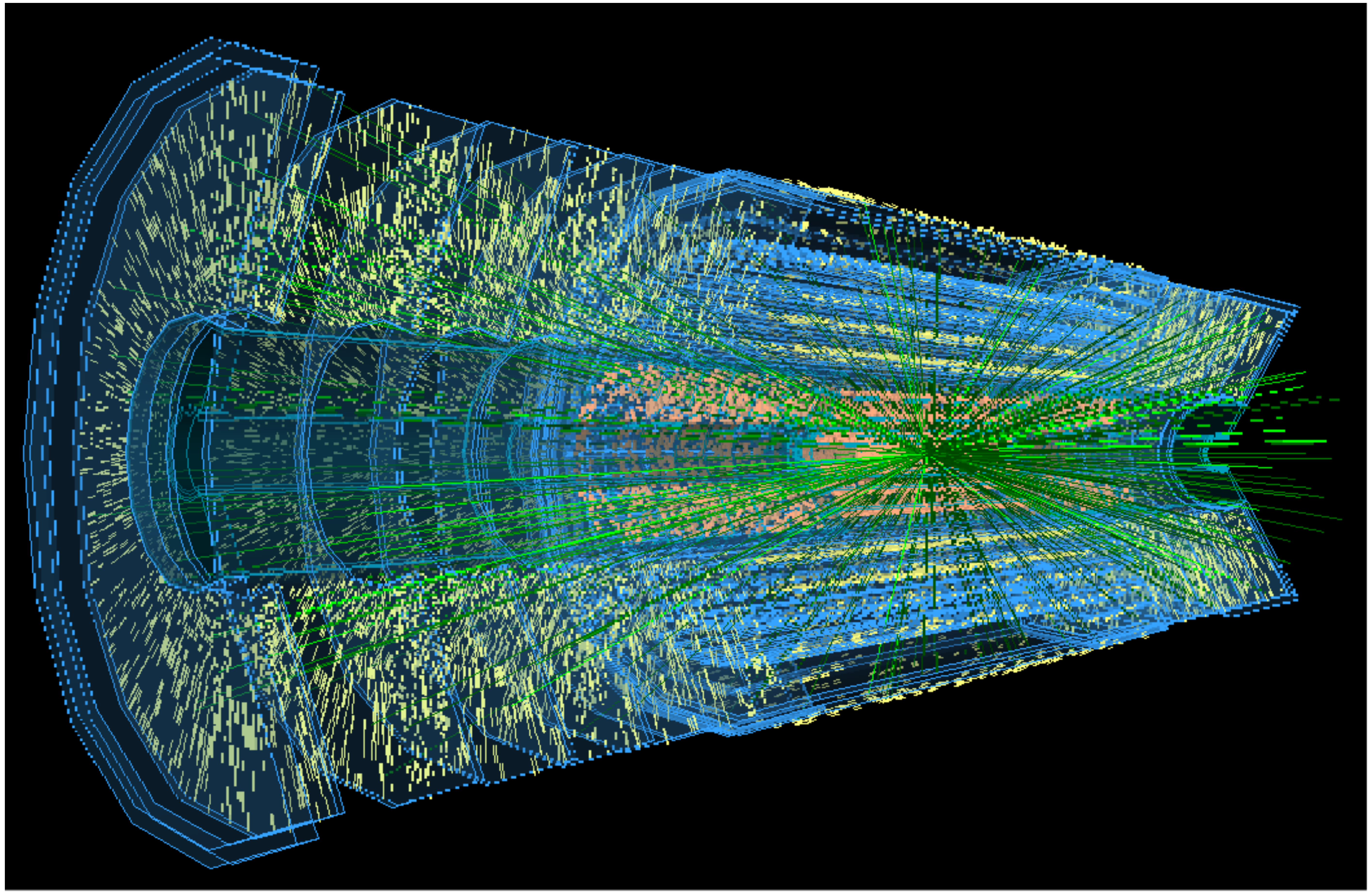
THE TRIGGER PROBLEM

- No track information @L1
  - need to trigger on something else (e.g., jet+MET - the ISR trick)
- At HLT, full information can be used (with some pre-selection on the rest of the event, to keep CPU under control)
- So far this works, because the L1 seed is inclusive enough



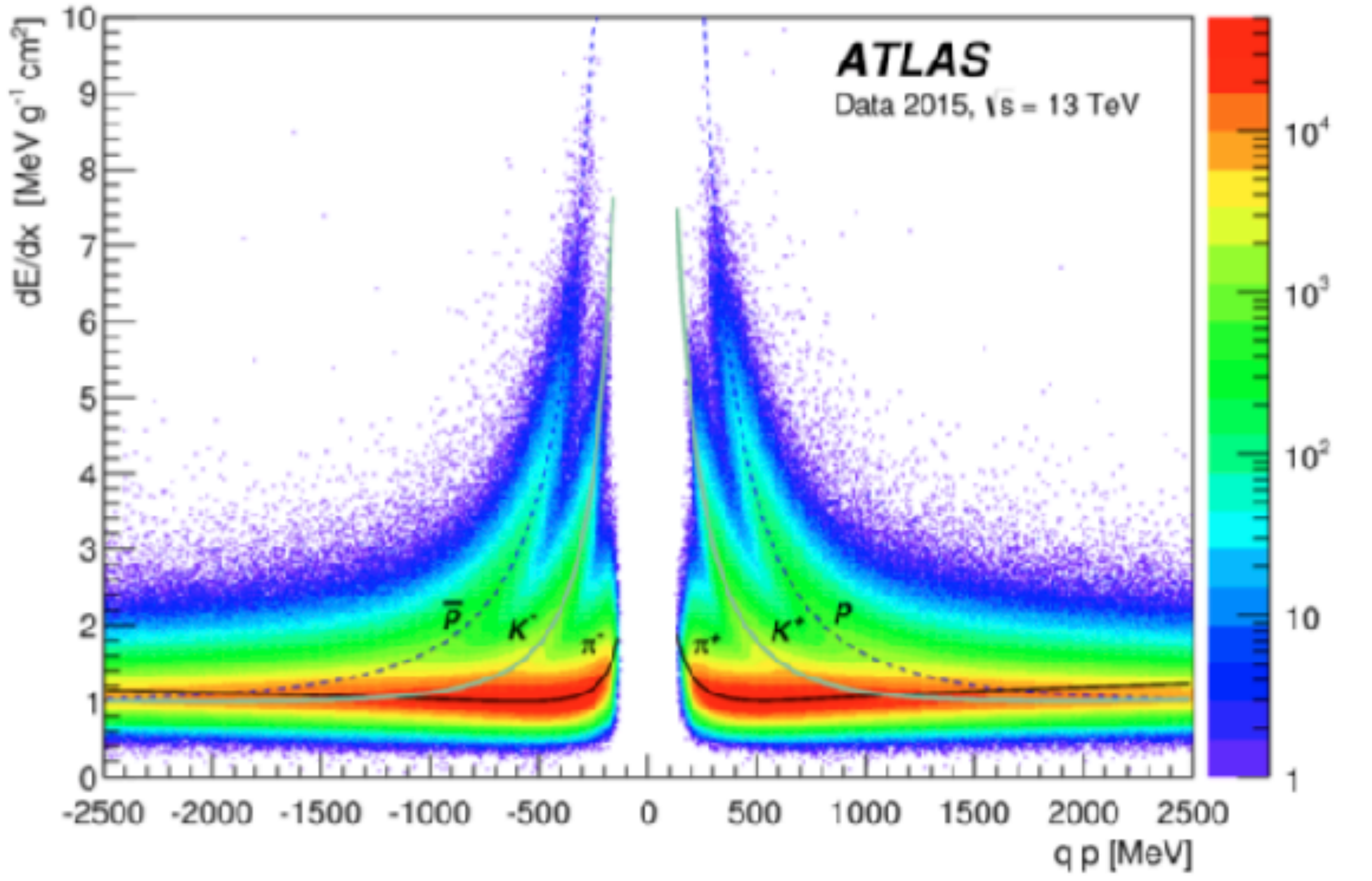
THE TRIGGER PROBLEM

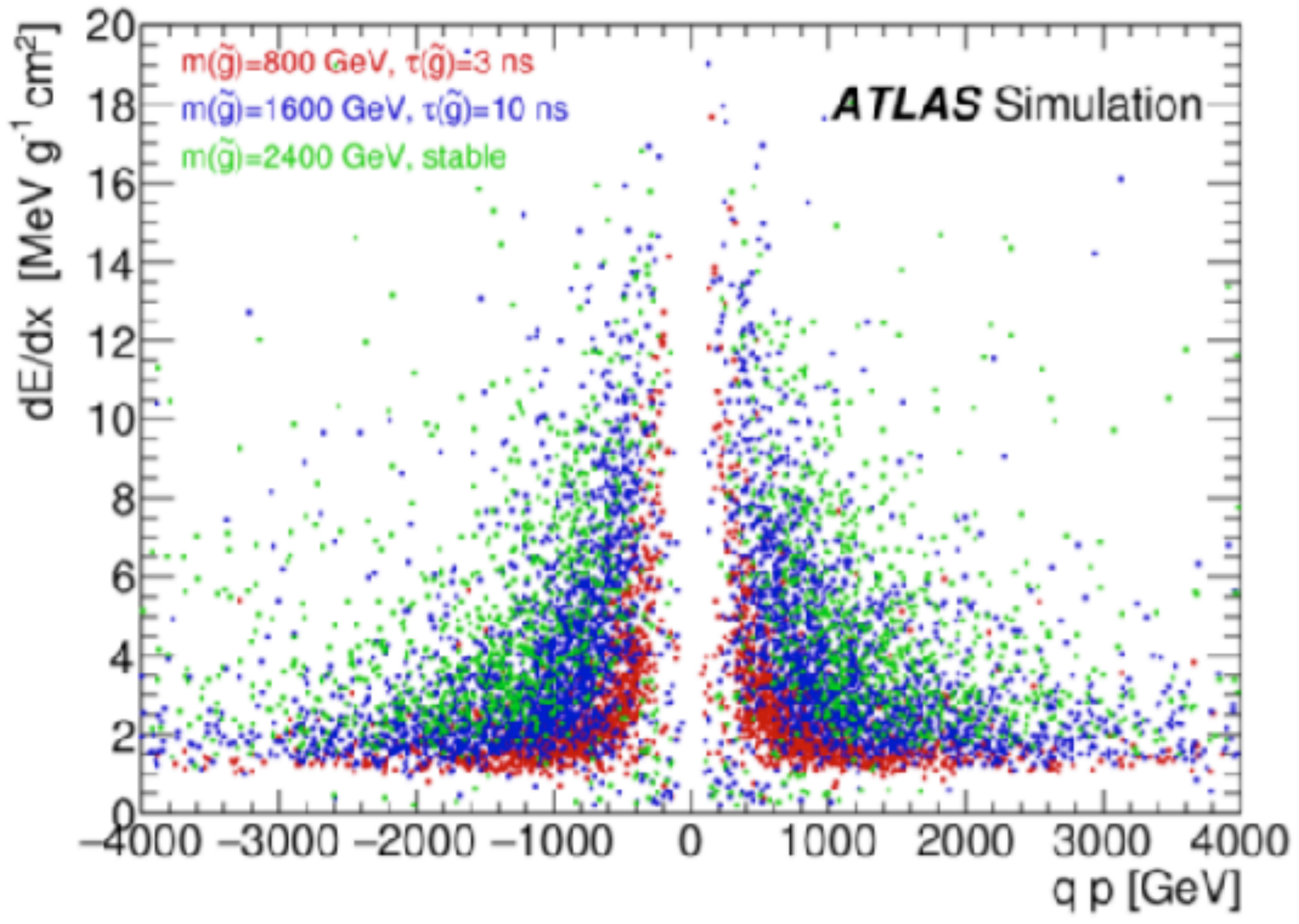
- *This might become a problem in the future*
  - *L1 trigger challenged by 200 pile-up interactions*
  - *New trackers might not provide dE/dx information (too many hits to read-out in non-digital mode)*
- *Sensitivity to these signatures might be at danger in the future*

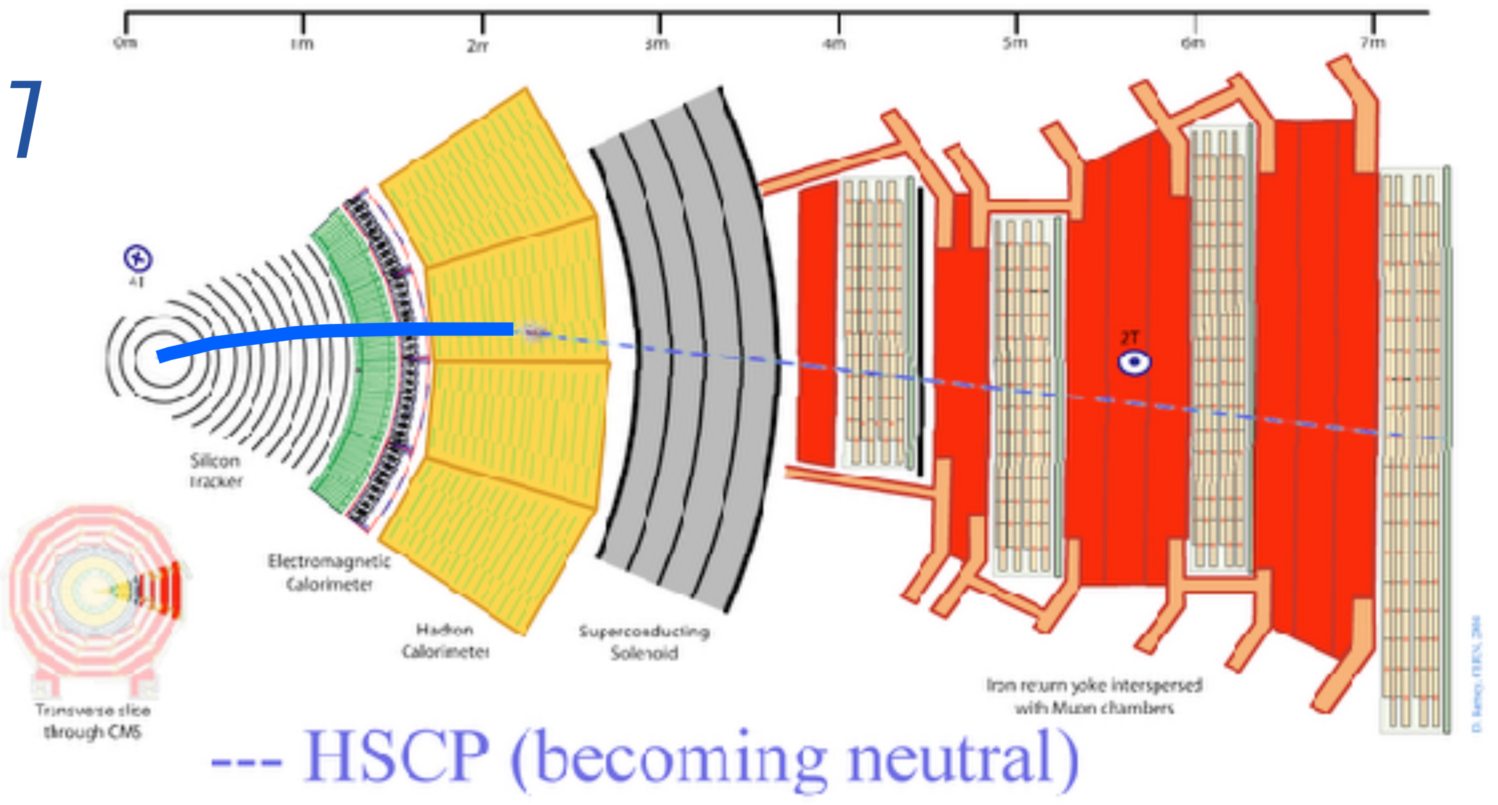


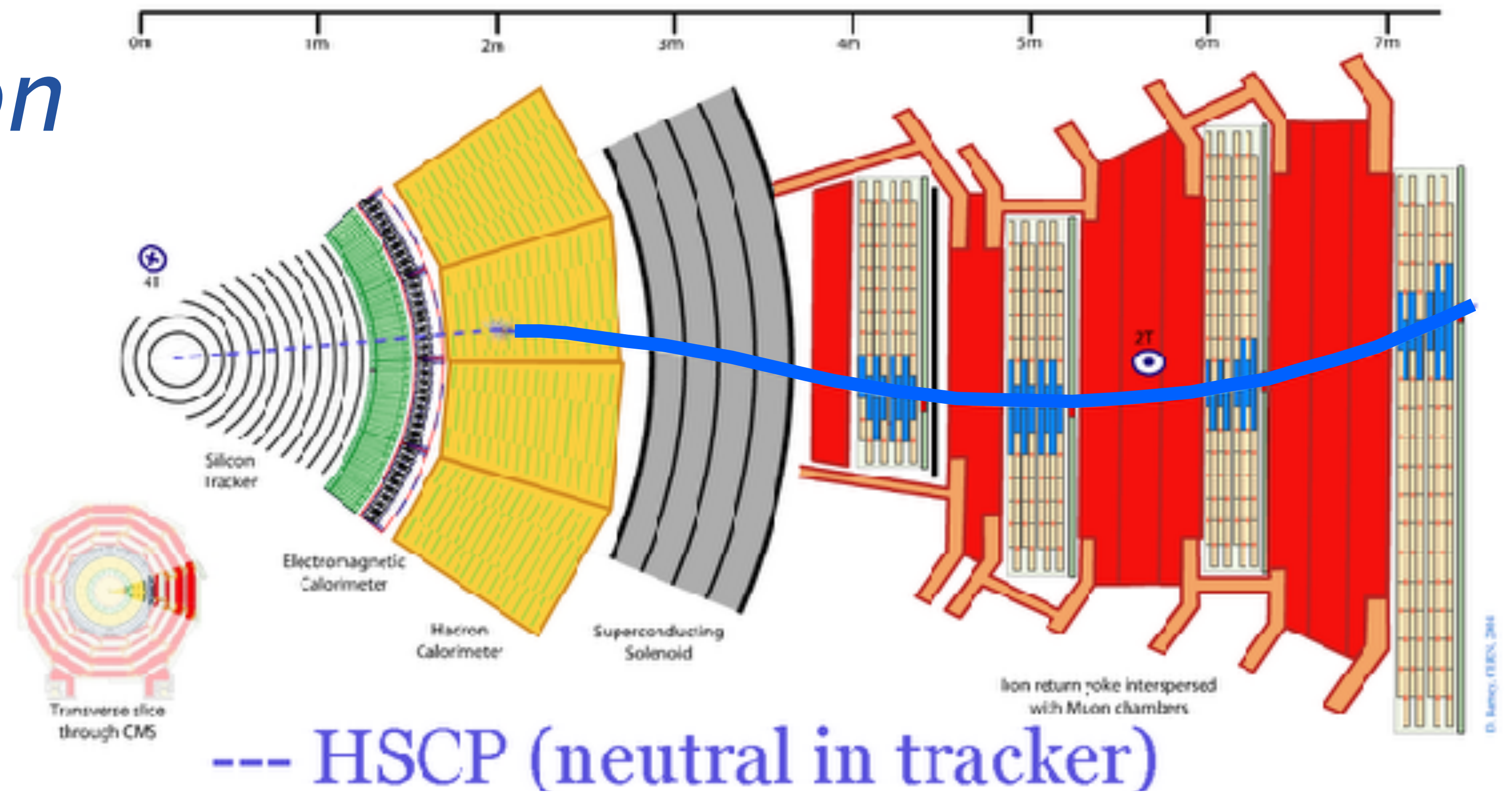
HEAVY STABLE CHARGE PARTICLES

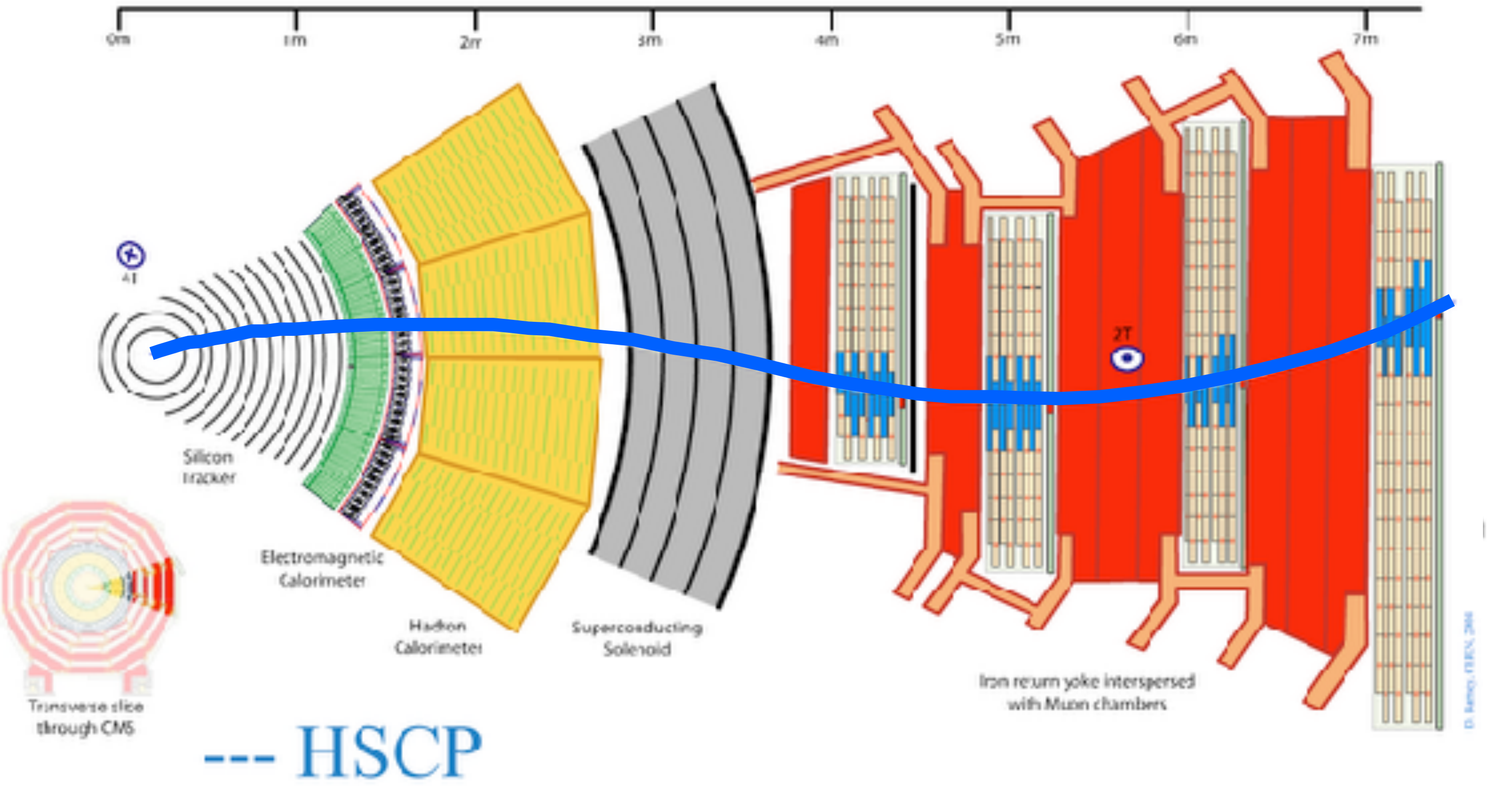
- Depending on lifetime, particles could cross several detectors
  - Good to have detector-specific searches
  - Good to put them together as well
- These particles will deposit more energy than a muon
- dE/dx crucial to isolate the signal





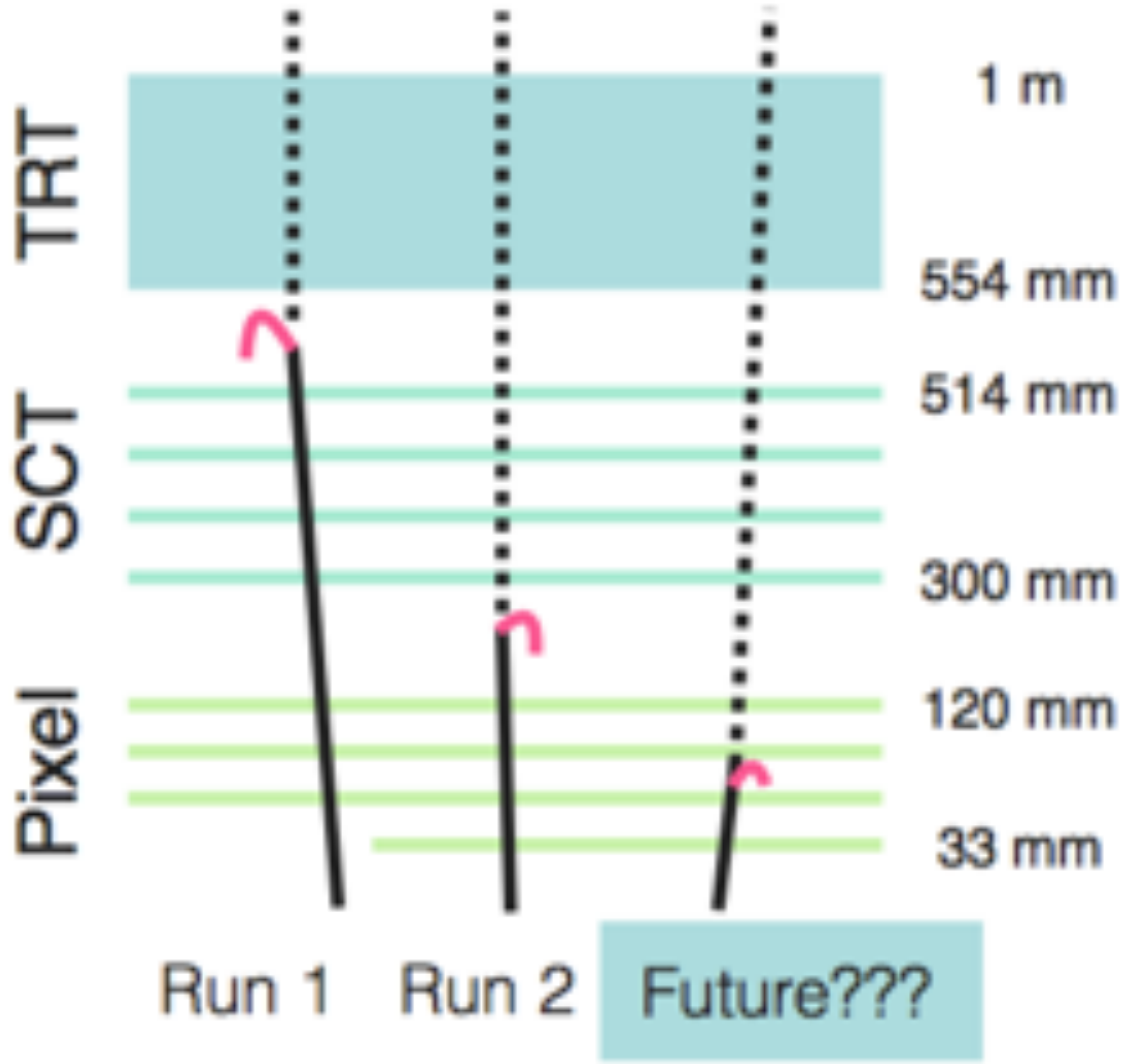






DISAPPEARING TRACKS

- *Disappearing tracks happen when*
  - *the LLP comes with charge*
  - *it decays to an invisible particle*
  - *the mass difference is small (i.e., any other decay product is undetectable)*
- *Can be exploited with different detectors, depending on lifetime*
- *That's why it is important to go closer and closer to the beam*



The emerging particle (a pion) is typically too soft to be reconstructed

DISAPPEARING TRACKS

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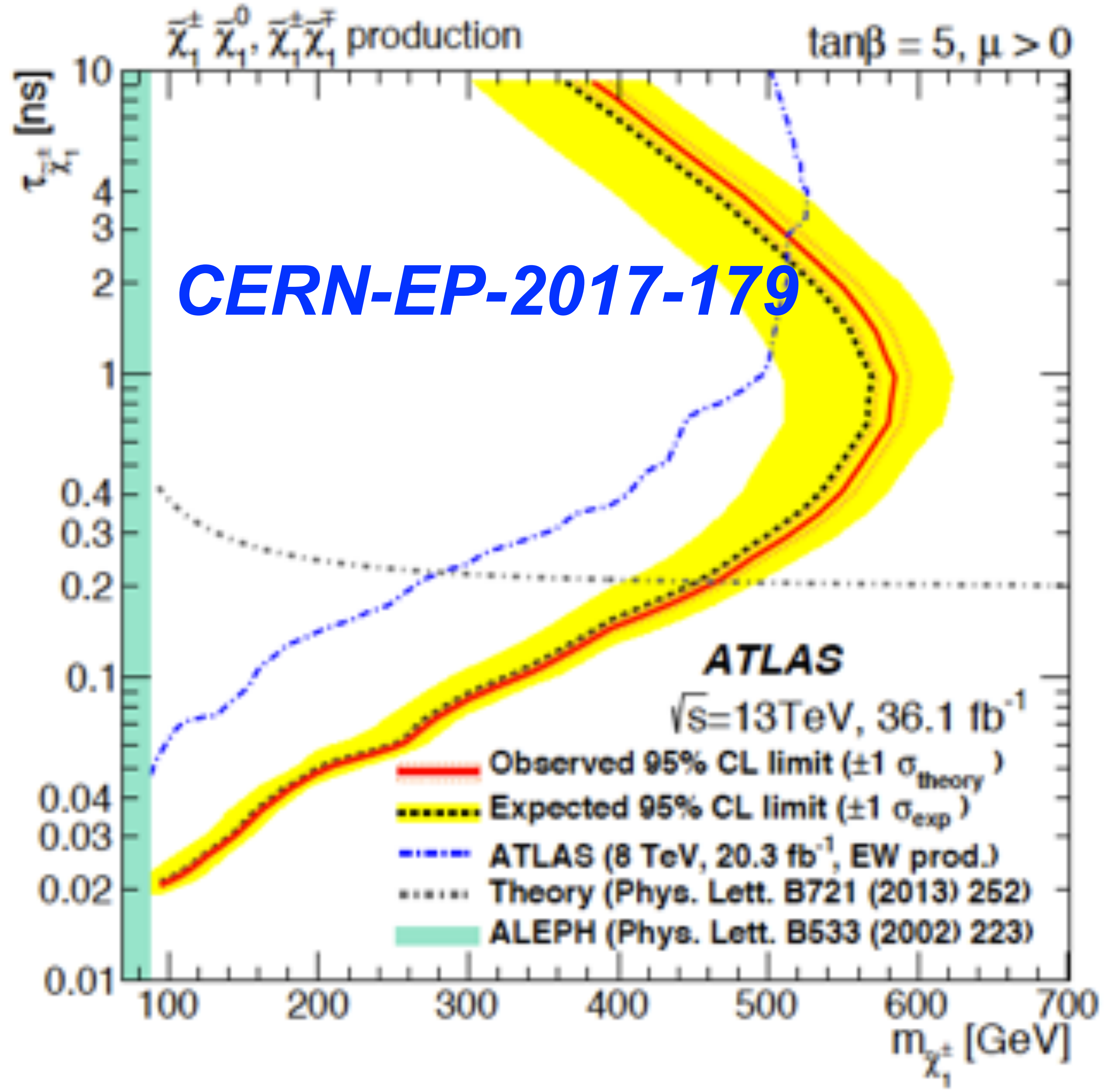
Very clean signature->can be ~ background-free search

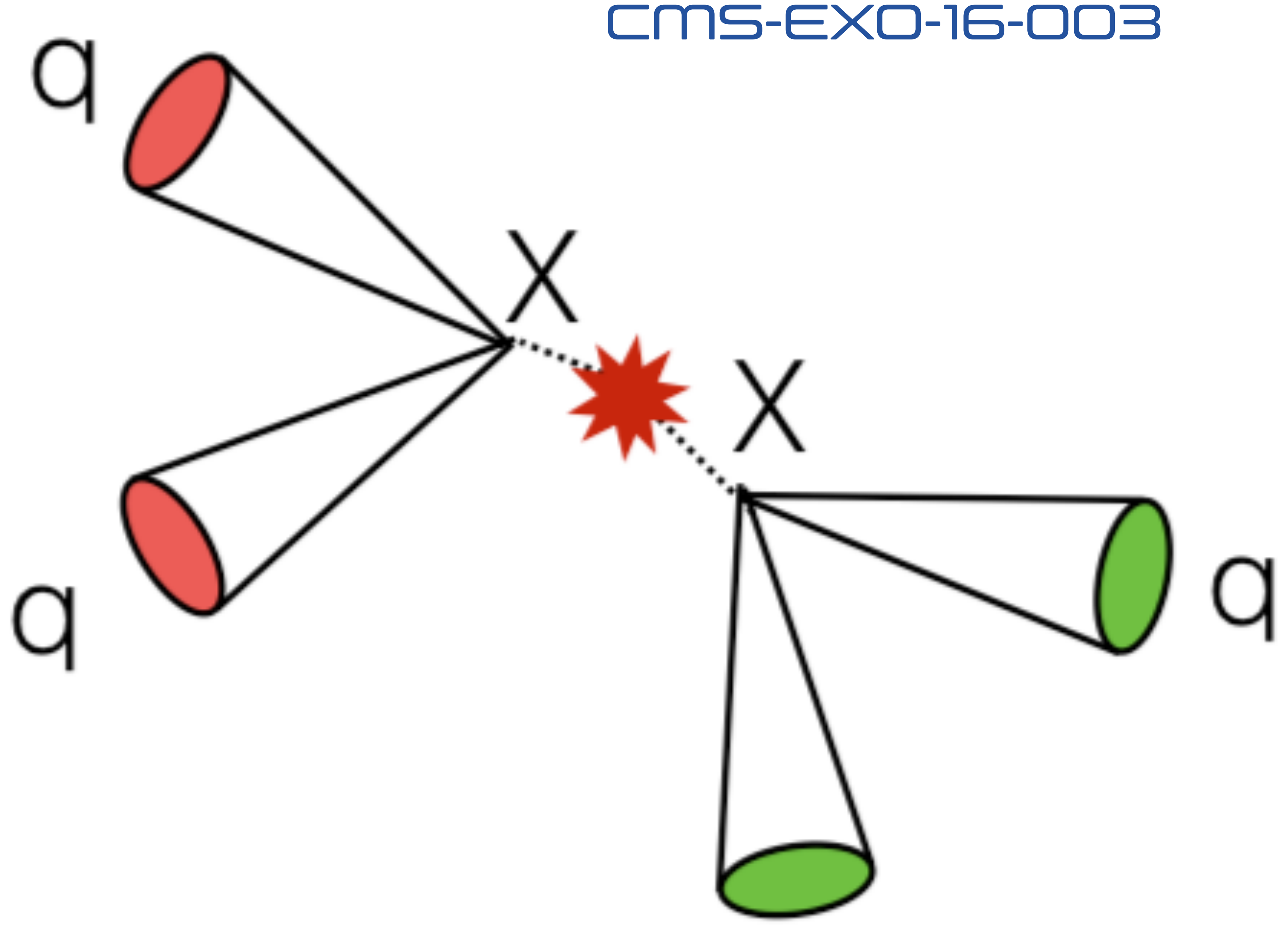
run period	est. event count			observation
	leptons	fake tracks	total	
2015	$0.12^{+0.11}_{-0.08} \pm 0.01$	$0^{+0.079}_{-0}{}^{+0.025}_{-0}$	$0.12^{+0.14}_{-0.08}{}^{+0.03}_{-0.01}$	1
2016B+C	$1.99 \pm 0.42 \pm 0.11$	$0.38 \pm 0.19^{+0.41}_{-0.38}$	$2.38 \pm 0.46^{+0.43}_{-0.40}$	2
2016D-H	$3.07 \pm 0.63 \pm 0.22$	$0.91 \pm 0.35 \pm 0.91$	$3.98 \pm 0.71^{+0.93}_{-0.94}$	4
total	$5.18 \pm 0.76 \pm 0.25$	$1.3 \pm 0.4 \pm 1.0$	$6.48 \pm 0.86 \pm 1.03$	7

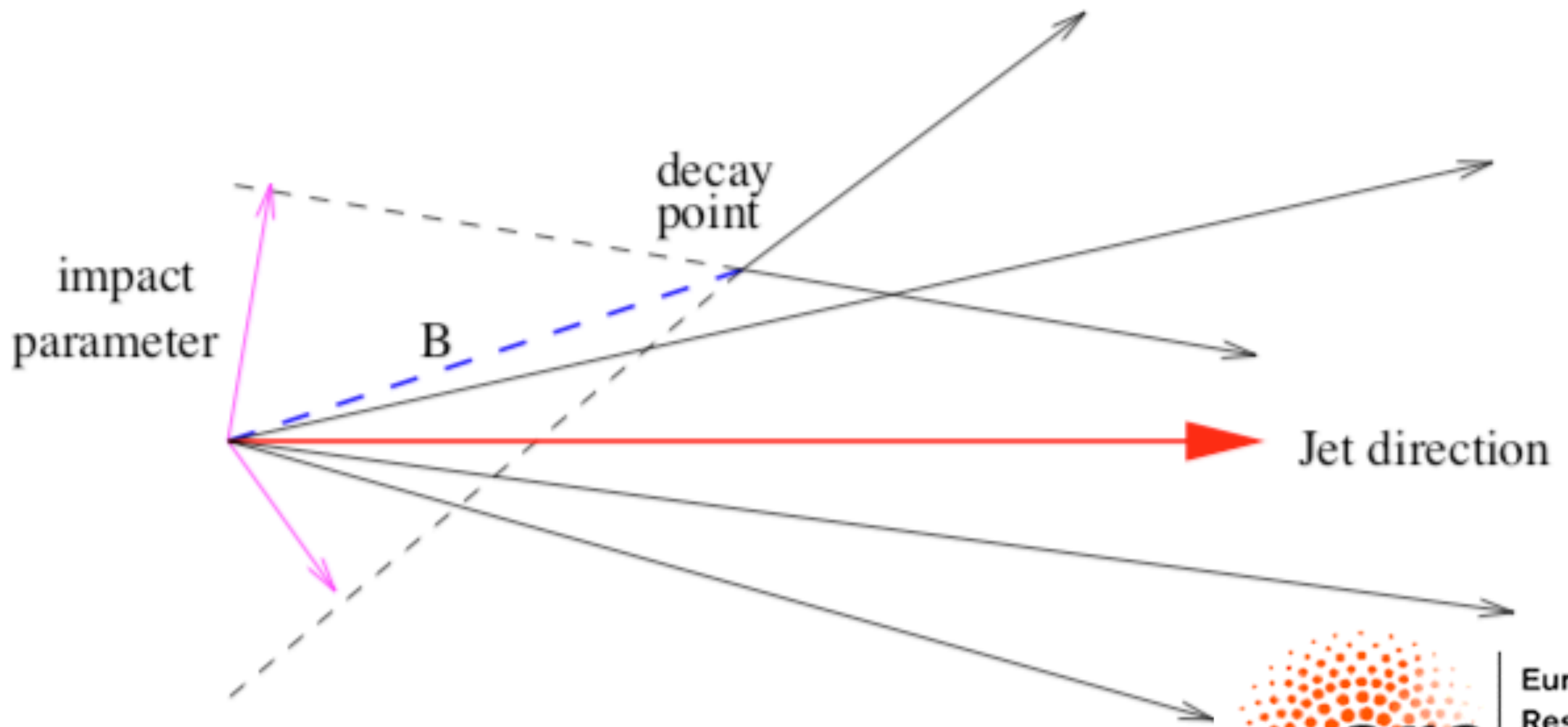


DISPLACED JETS

CMS-EXO-16-003

- Reconstruction of displaced jets has very specific challenges
  - physics background from b and τ jets
  - Projective geometry of the jet compromised (problematic e.g. for association of tracks to jets in particle flow)
  - Displacement exploitable in trigger only starting from HLT
- Despite these difficulties, several analyses exist that probe this scenario.





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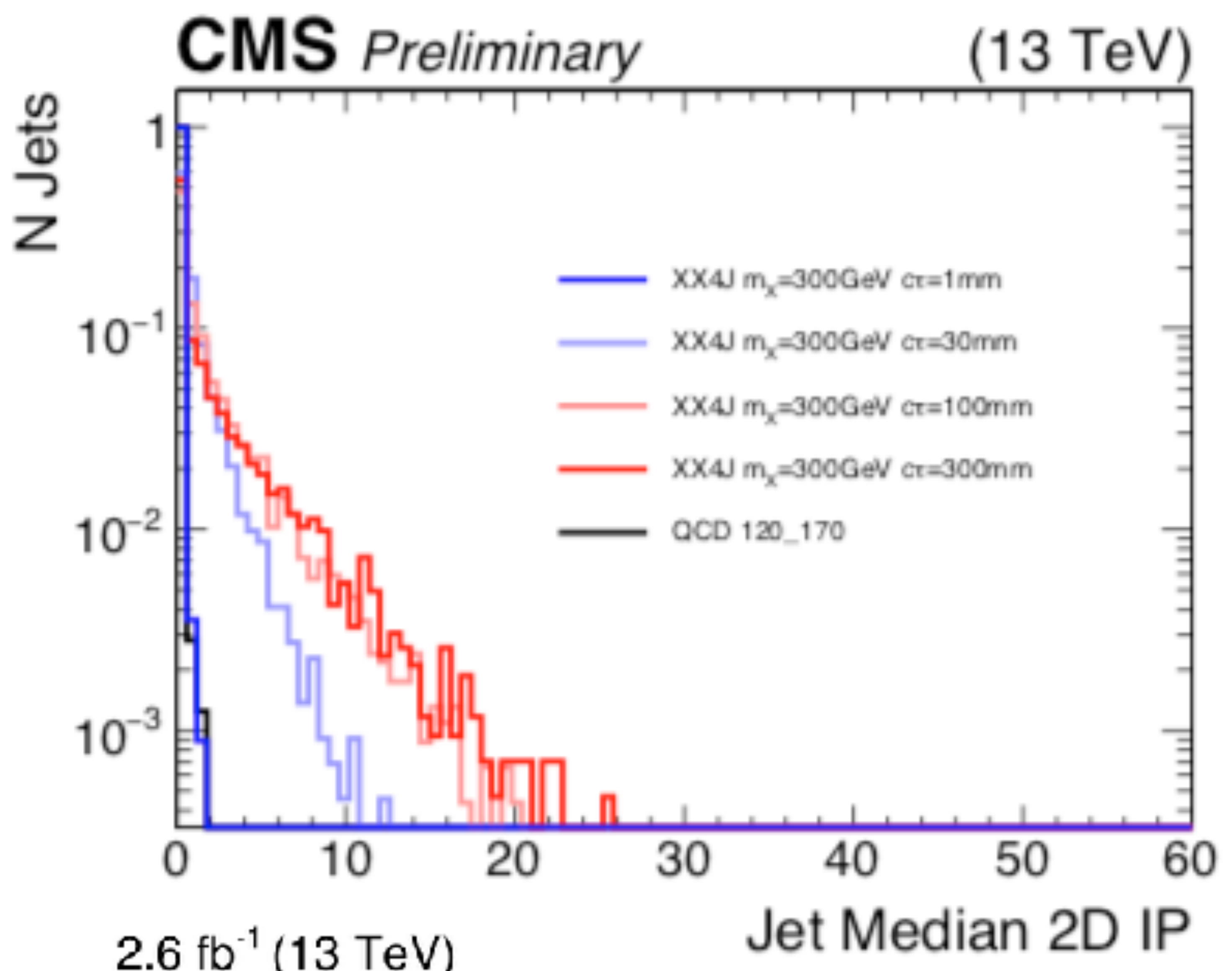
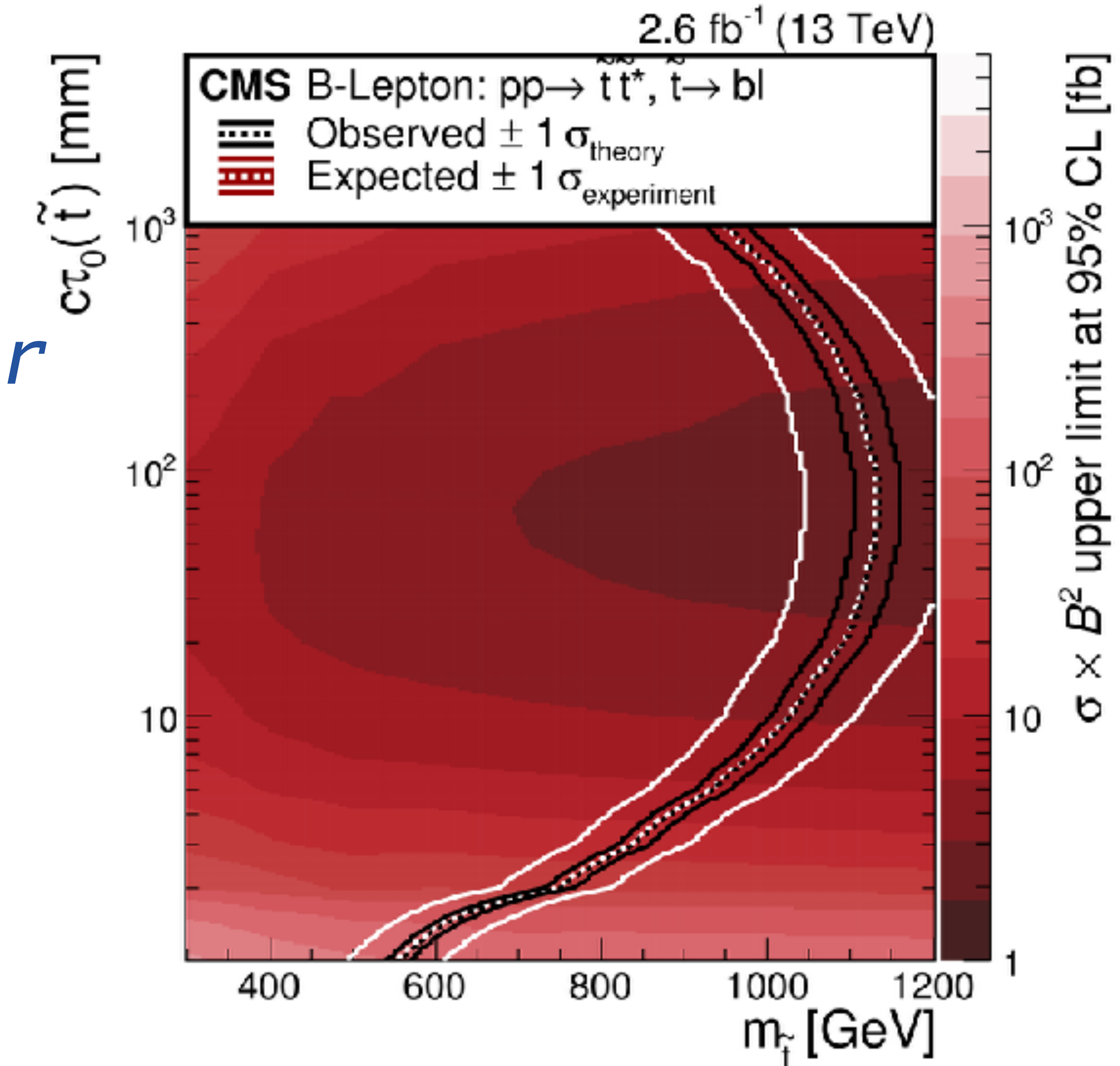
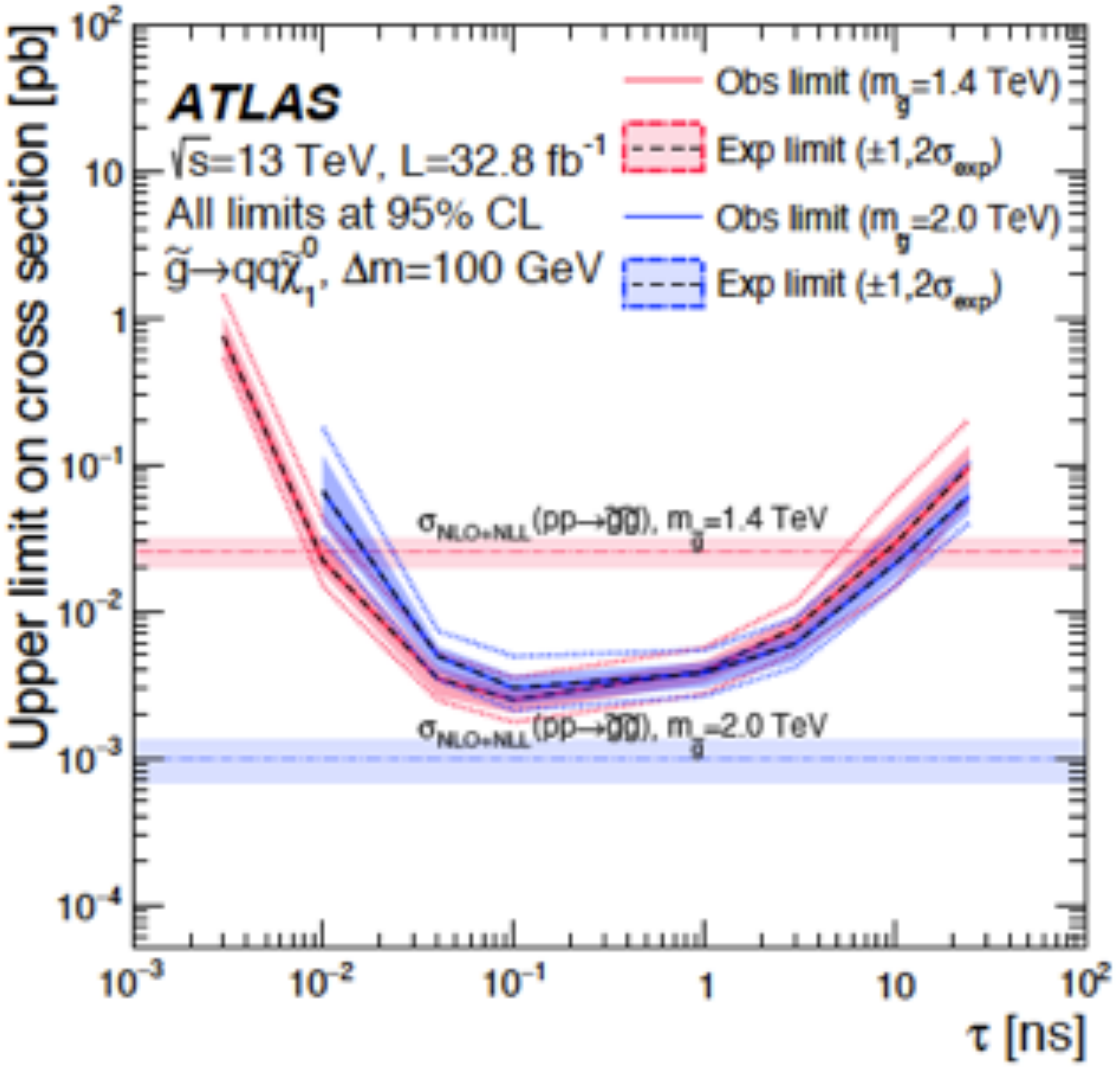
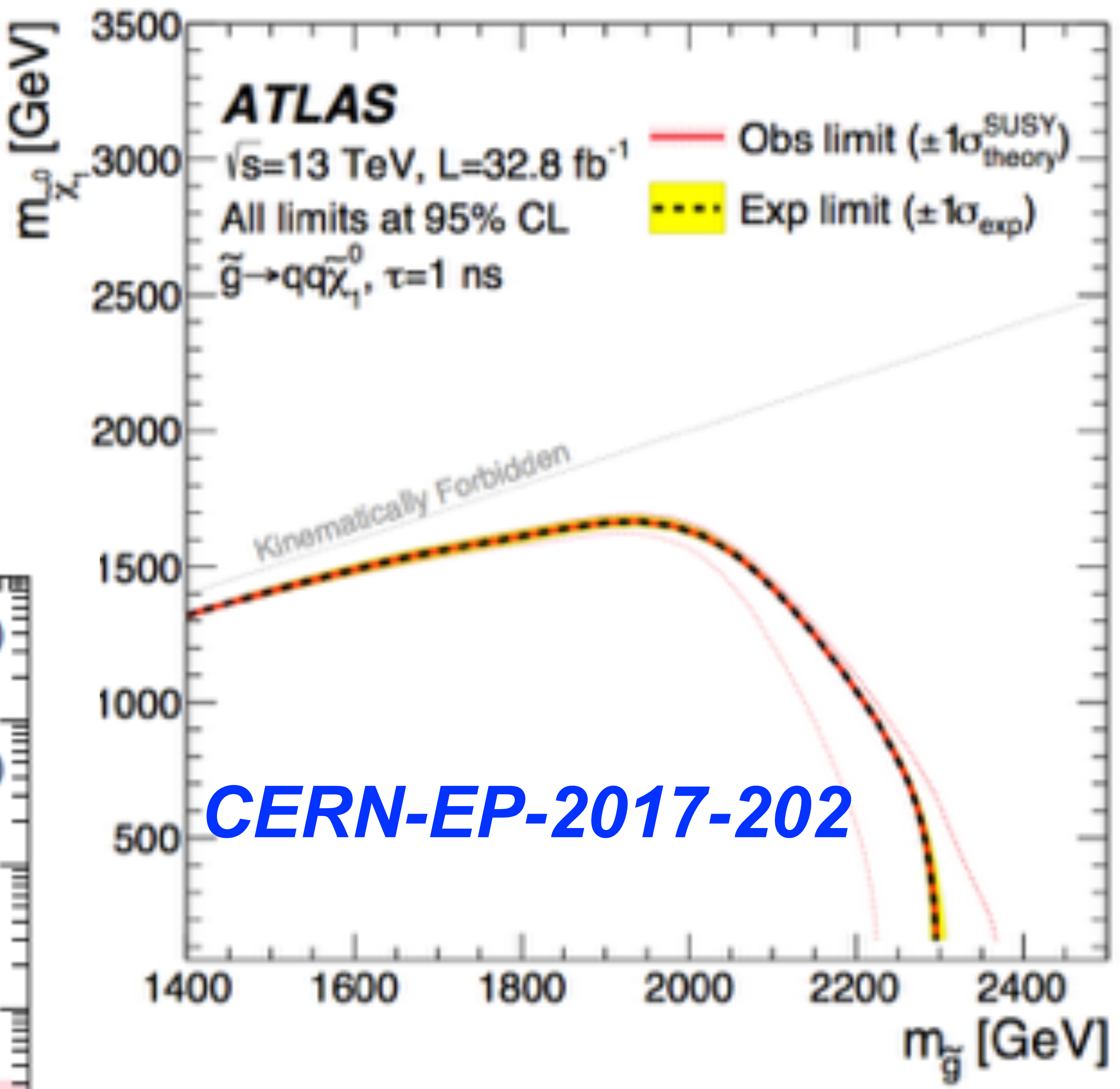




DISPLACED VERTICES

- For smaller lifetimes, displacement becomes typically small
- NP particles would decay in the inner tracker
  - can use pixel vertexing in all its power
  - have physics-induced SM backgrounds to deal with

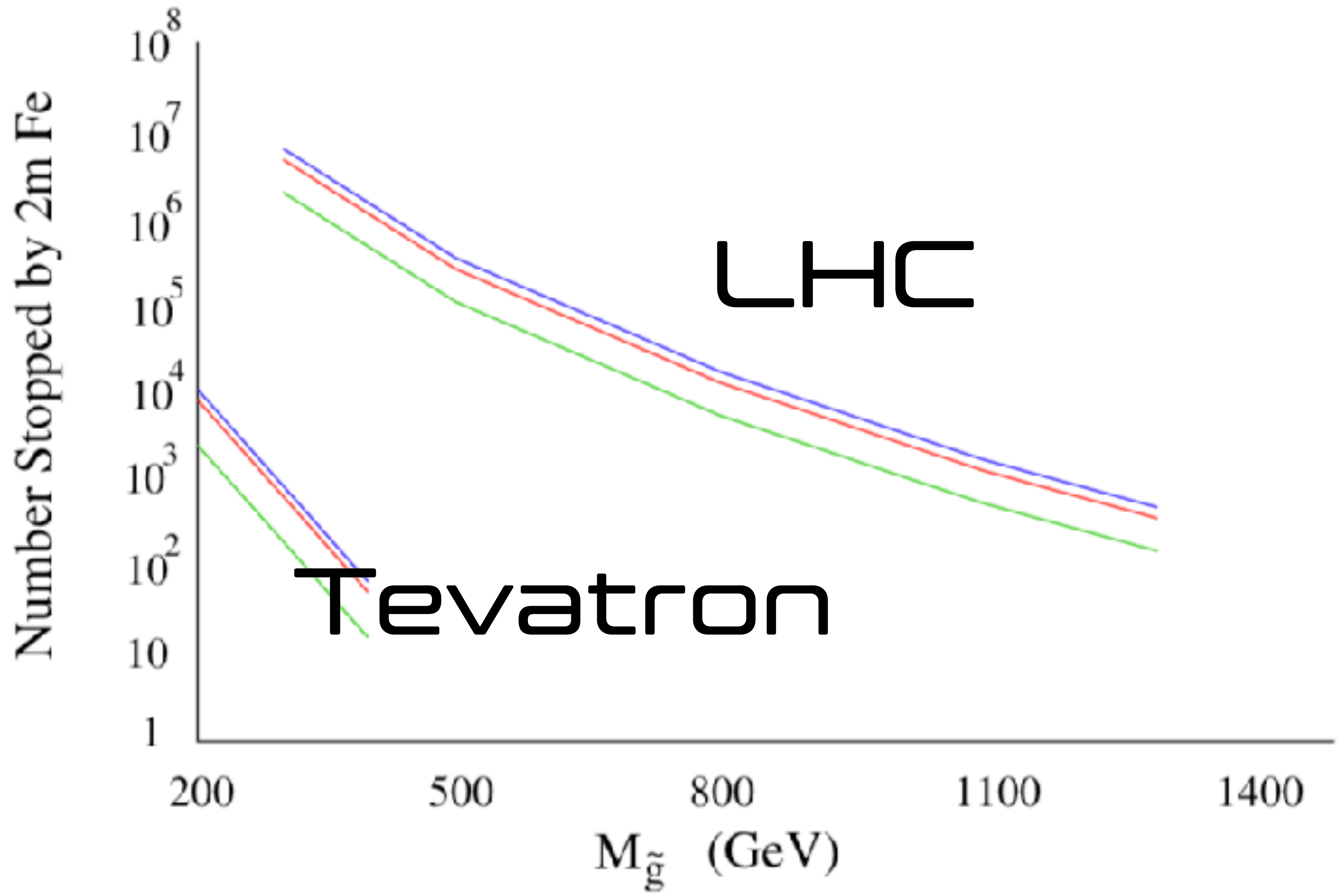


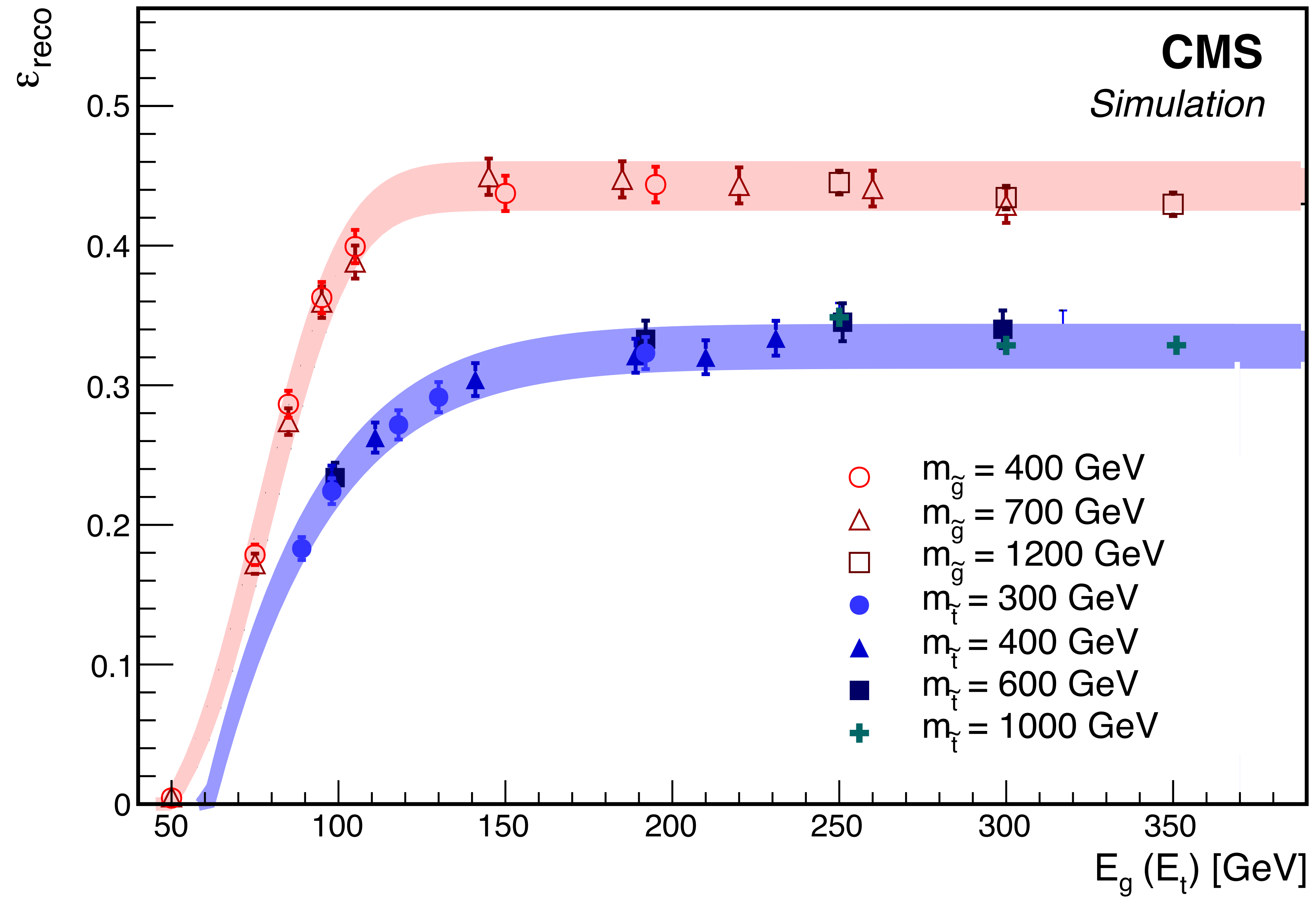


CERN-EP-2017-202

STOPPING PARTICLES

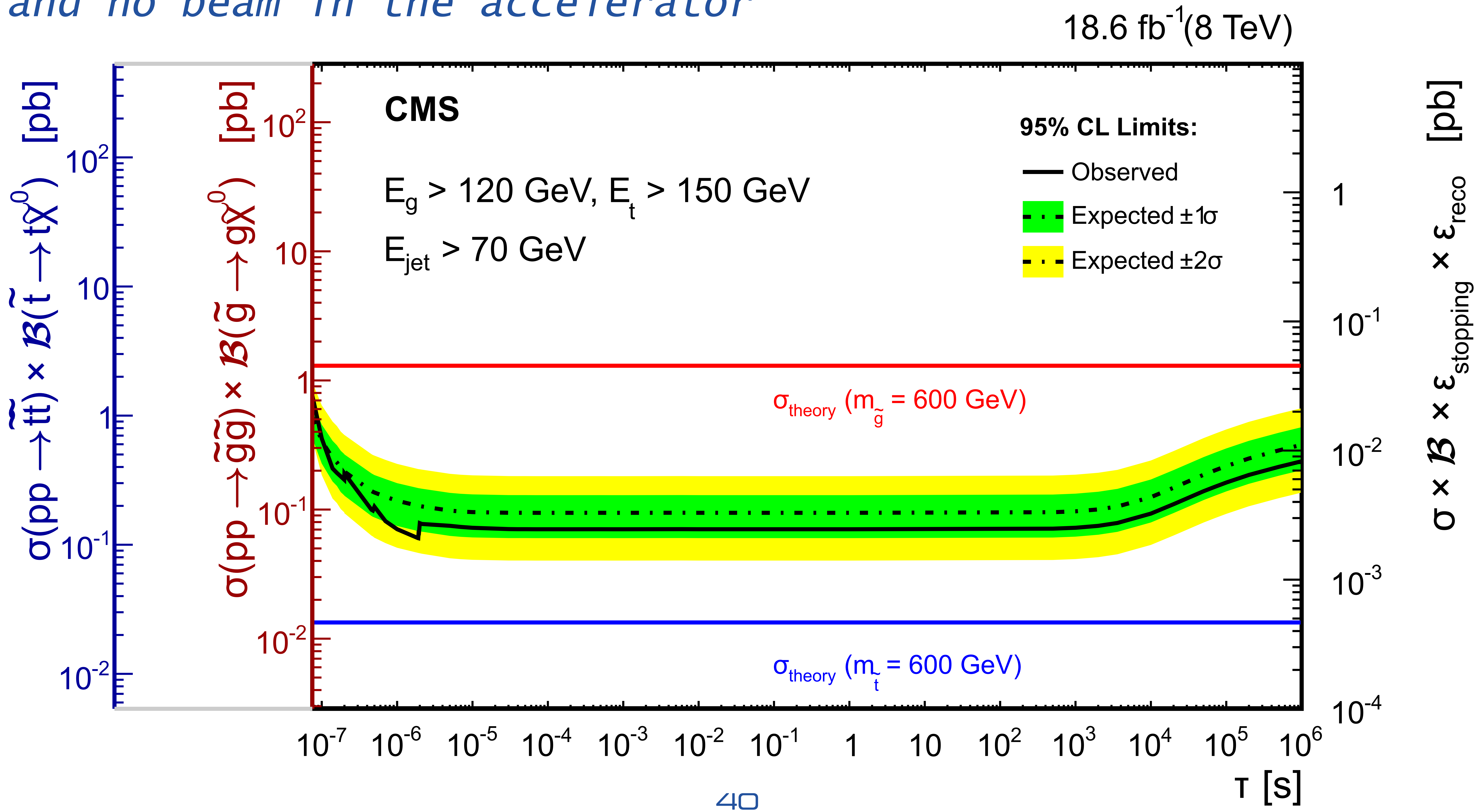
- *Heavy colored particles (gluinos, stop, etc) can be trapped by nuclei of the calorimeter*
- *Once there, depending on the lifetime, it could take hours/days/months before it decays*
- *The signature is energy in the calorimeter and no beams*
- *Could happen during shutdown, when LHC is filling, etc*
- *Your trigger should run all time!*





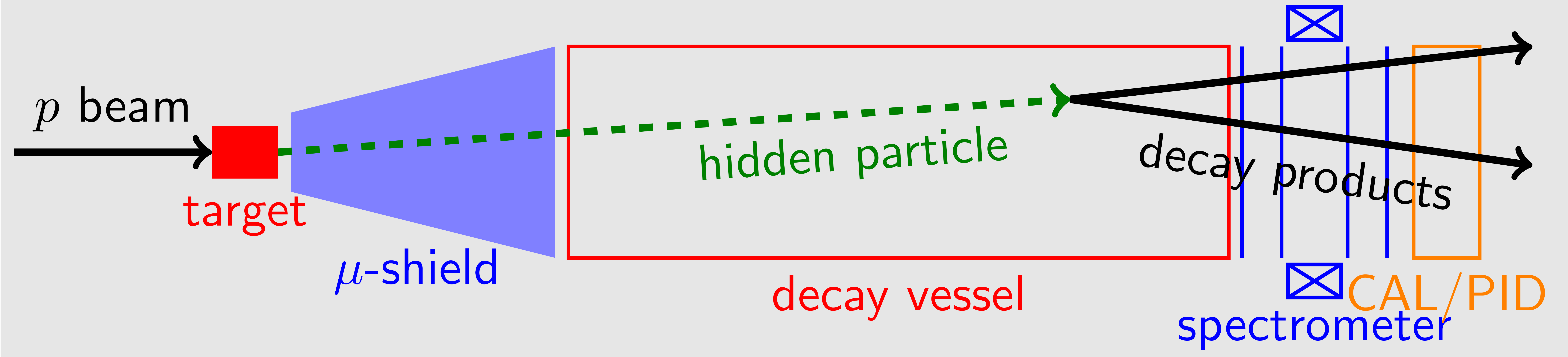
STOPPING PARTICLES

- *A typical trigger consists in asking for energy in the calorimeter and no beam in the accelerator*



NEW IDEAS: SHIP

- *Advanced proposal for an experiment at the CERN SpS*
  - *Designed mainly to look for right-handed neutrinos (e.g., predicted by νMSM)*
  - *Can be used to probe generic long-living particles*



https://arxiv.org/abs/1708.09389

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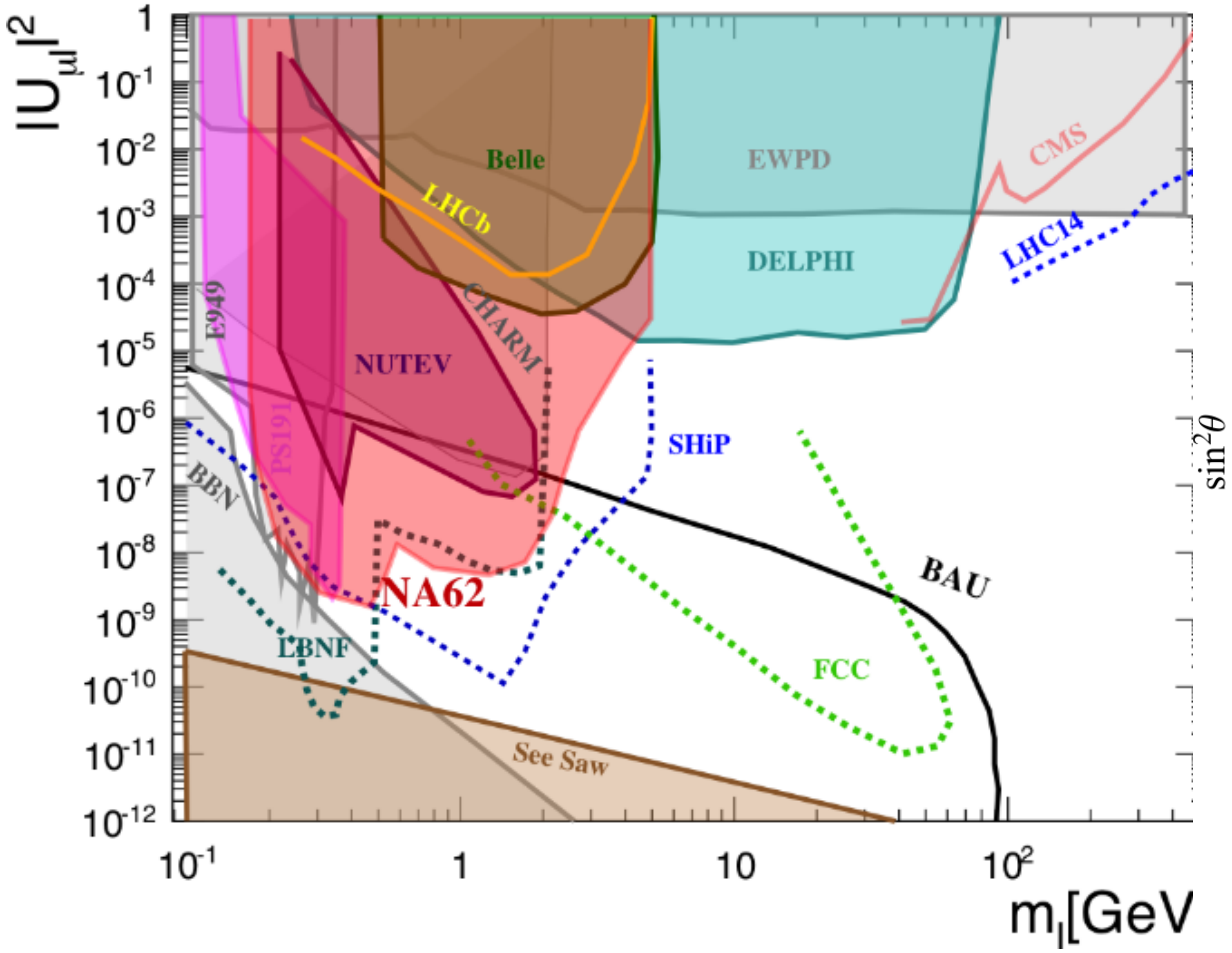

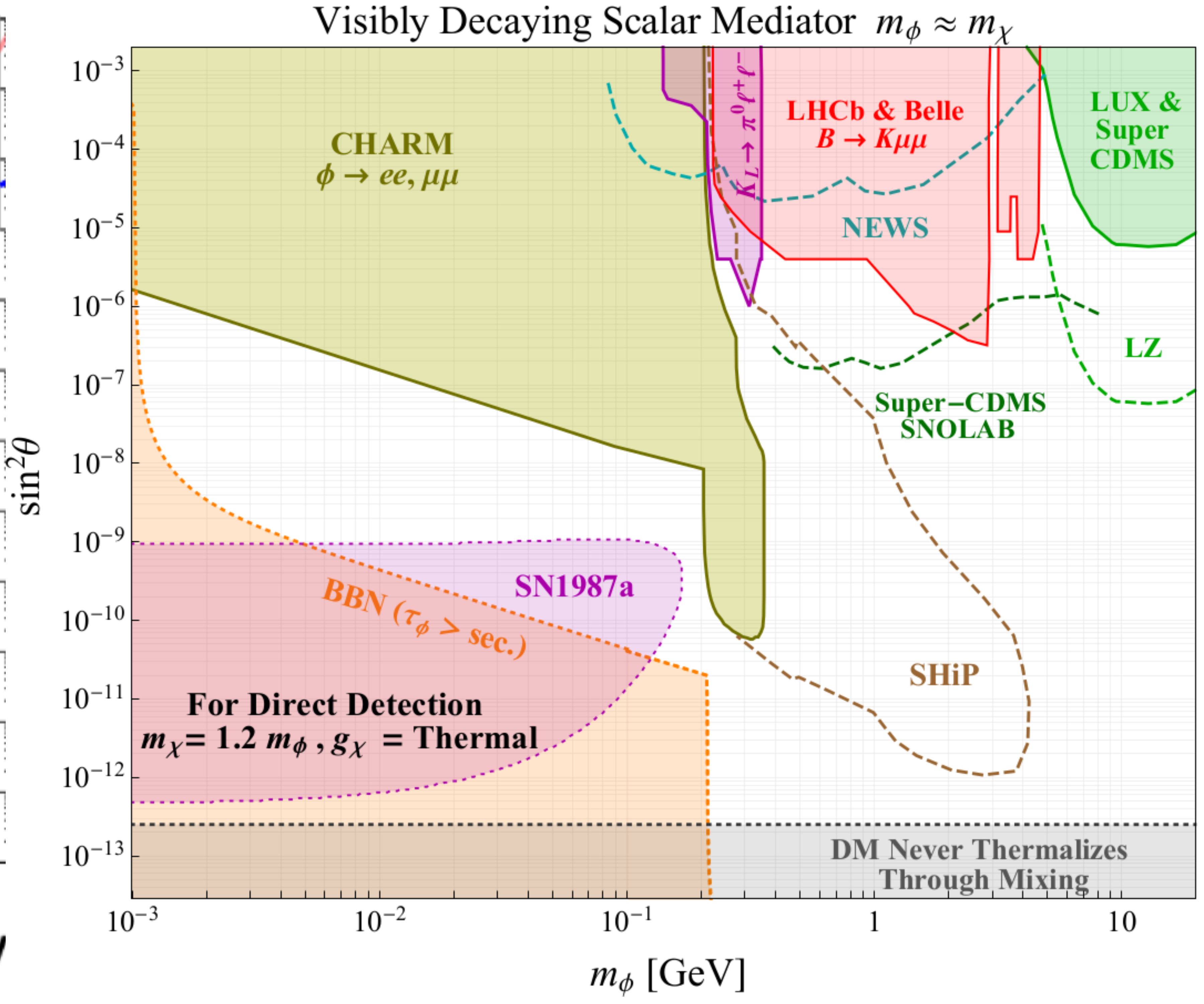

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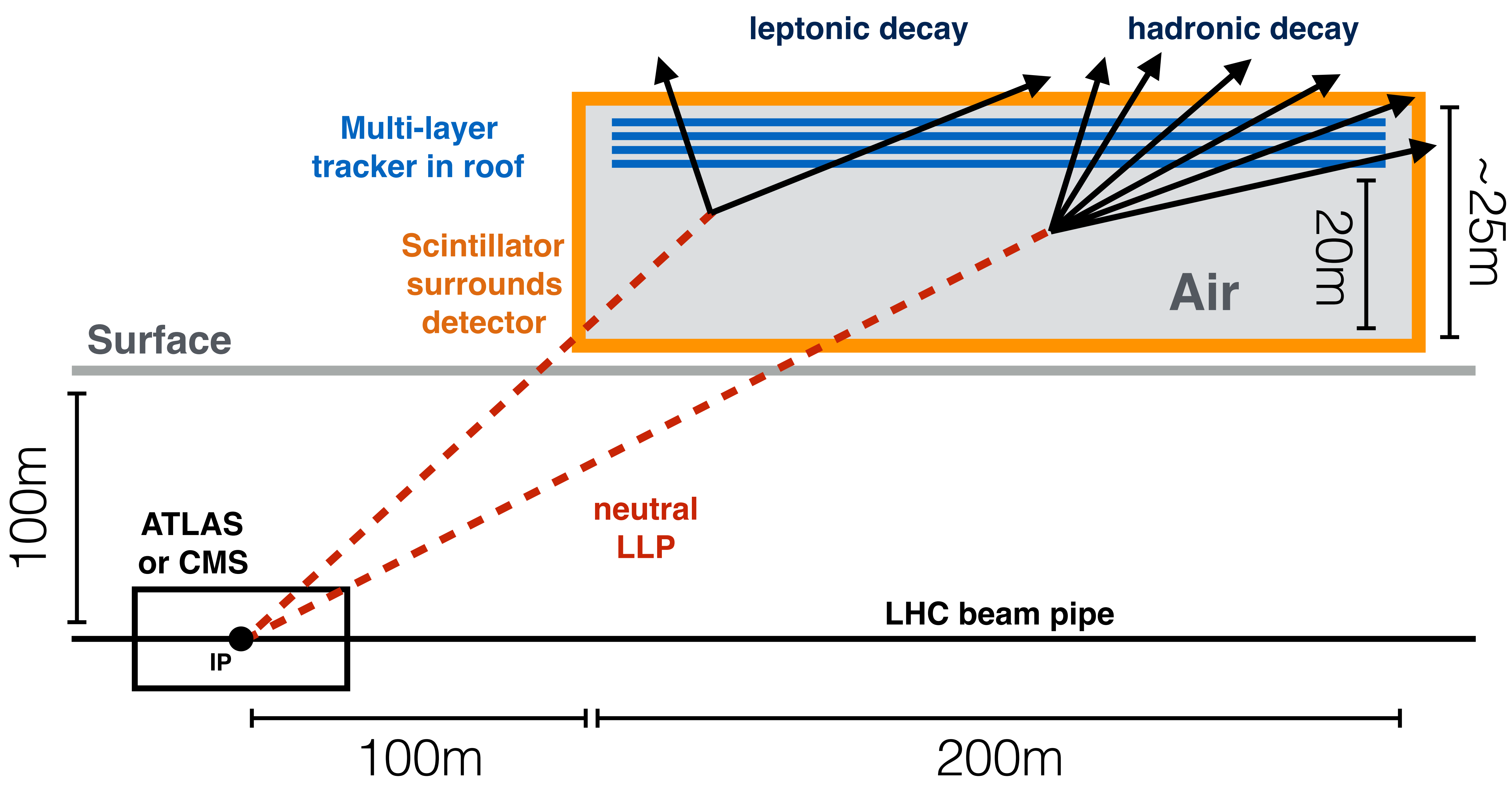
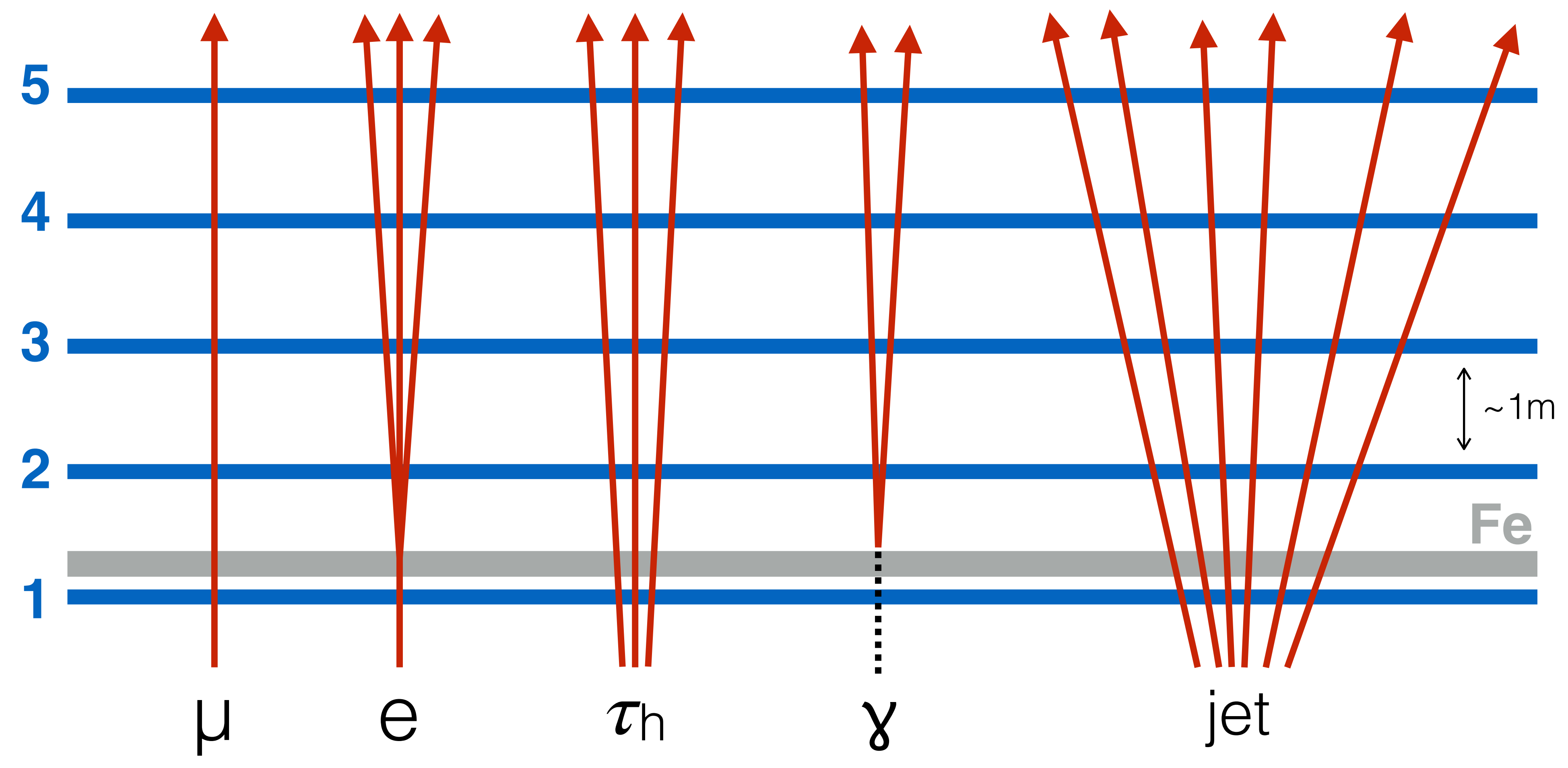
European Research Council

NEW IDEAS: MATHUSLA

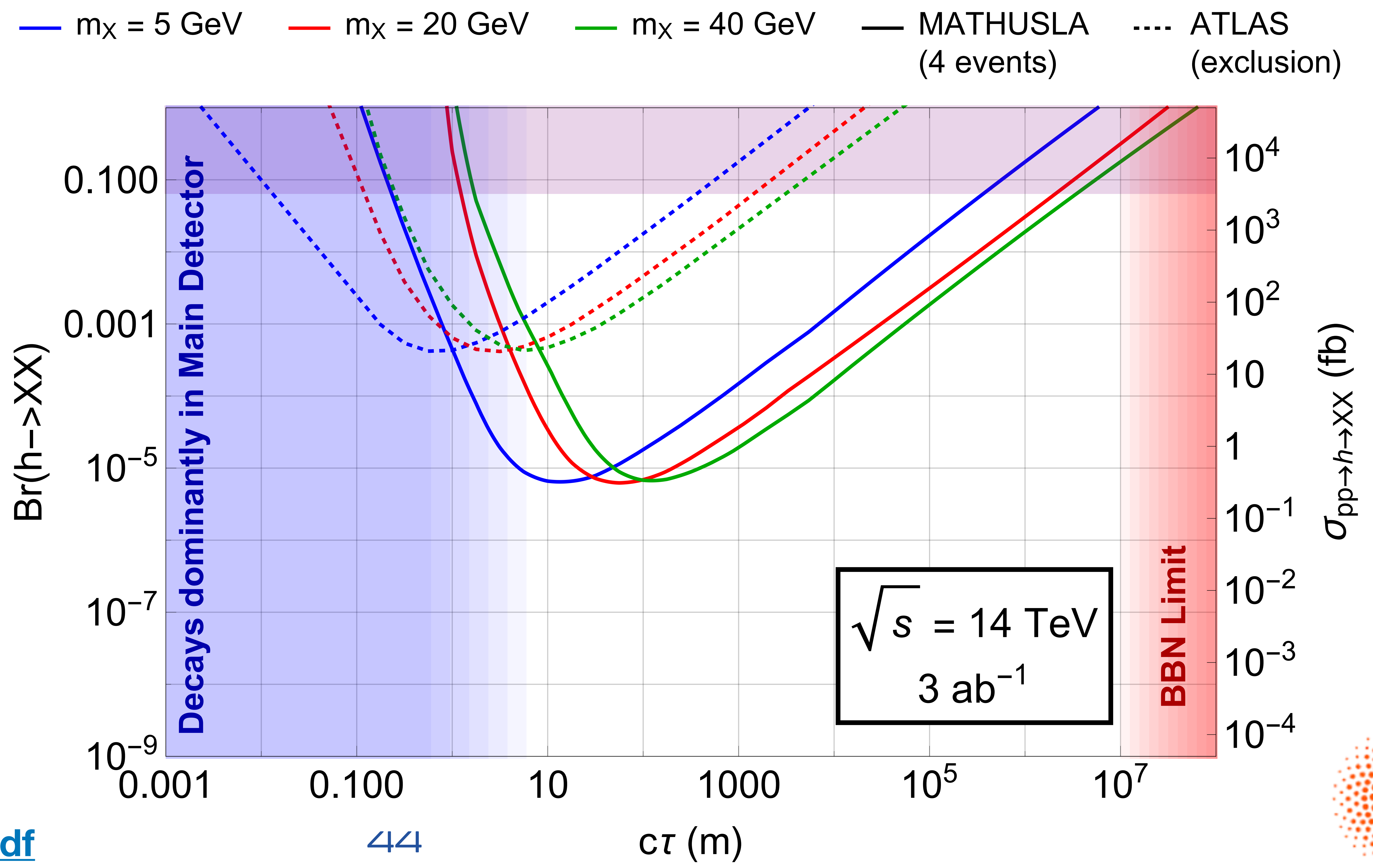
- *A detector on surface, capable of collecting decay of long-living particles produced at LHC*
- *No magnetic field, but particle possible thanks to track topology*





NEW IDEAS: MATHUSLA

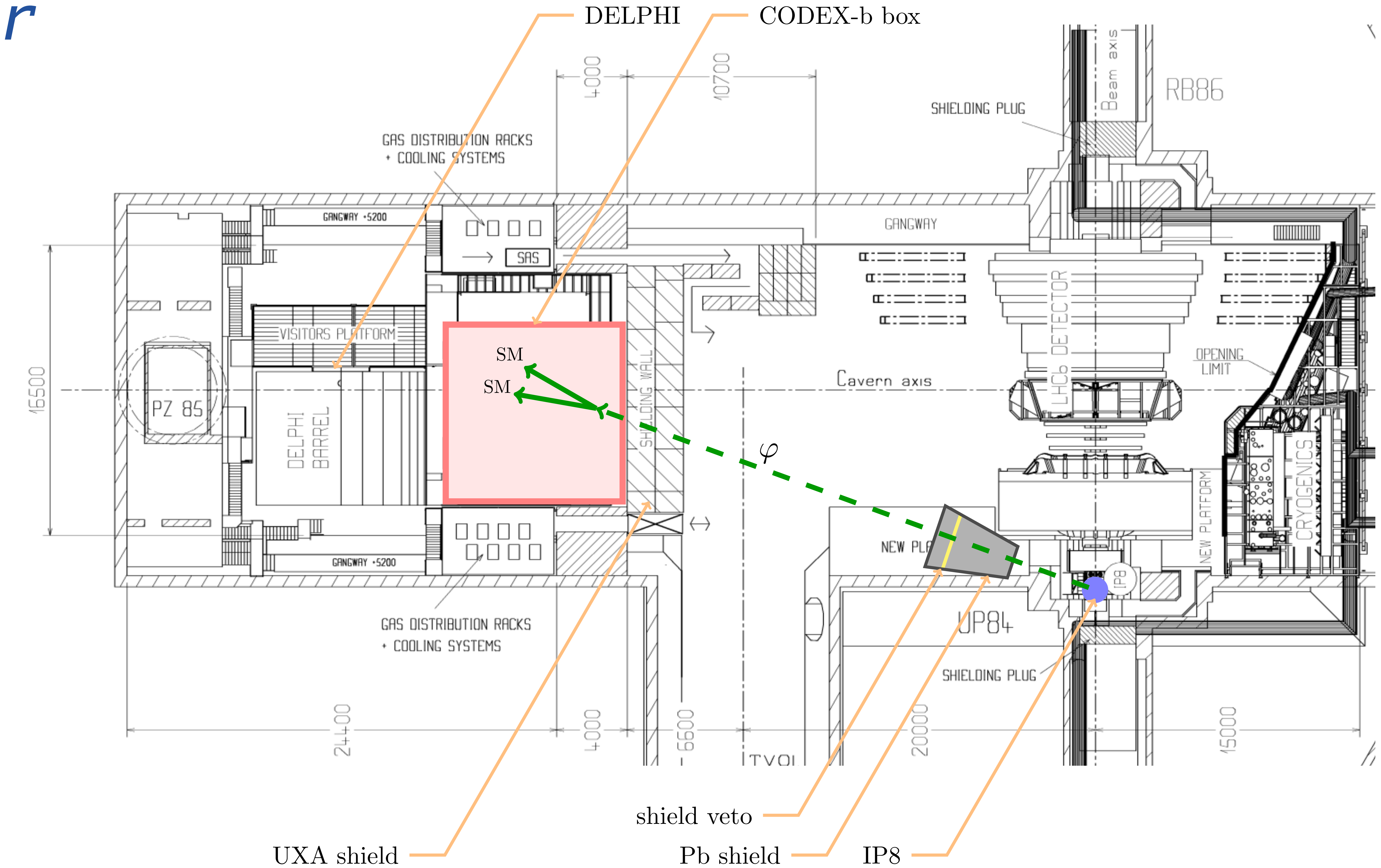
- *A detector on surface, capable of collecting decay of long-living particles produced at LHC*
- *No magnetic field, but particle possible thanks to track topology*
- *Could probe long-living particles, e.g., from Higgs decays*



https://arxiv.org/pdf/1606.06298.pdf

NEW IDEAS: CODEX

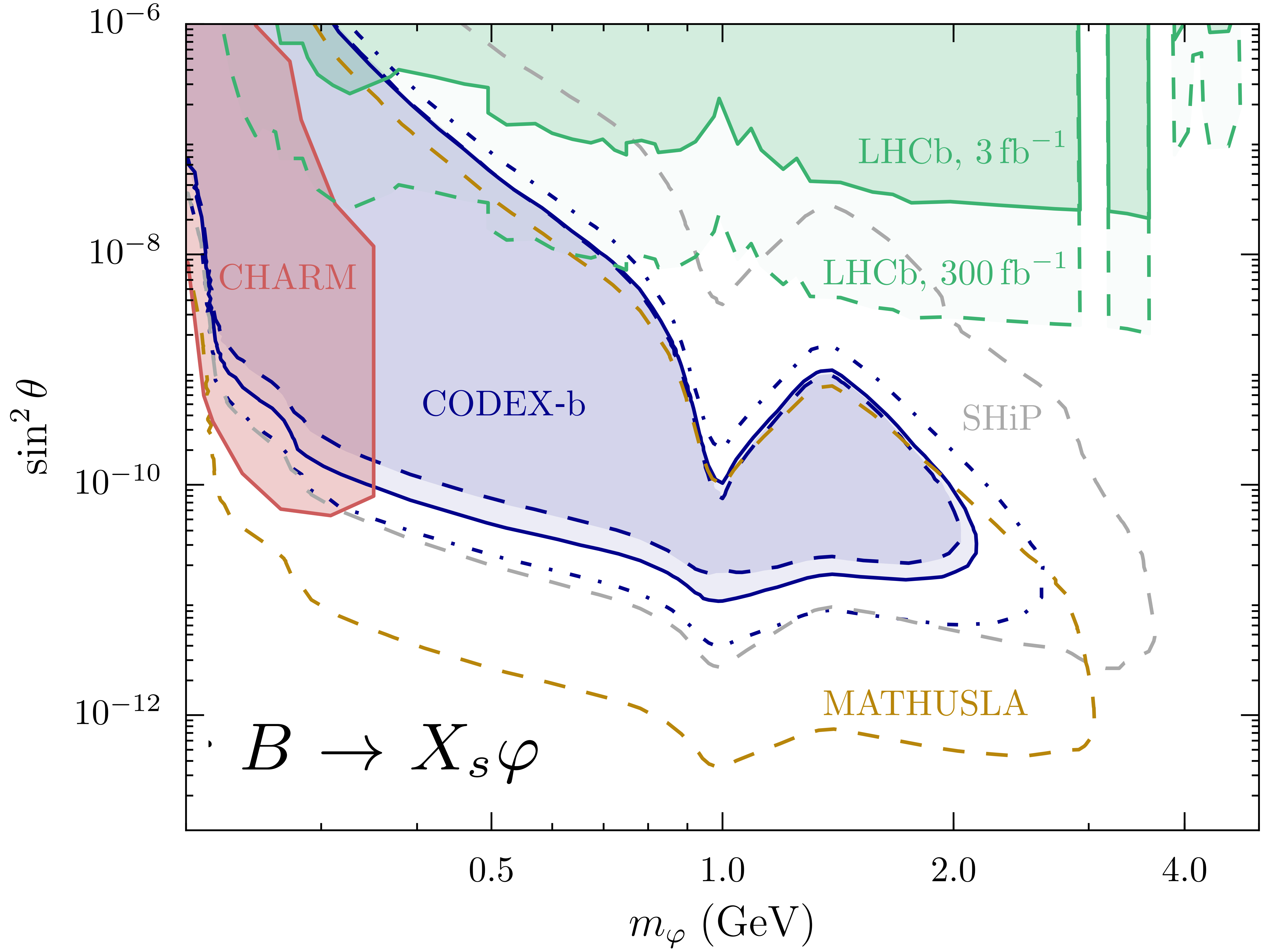
- *LHCb is moving HLT farm out of the detector area*
- *Free space could be used to host a small Mathusla-like detector*



https://arxiv.org/pdf/1708.09395.pdf

NEW IDEAS: CODEX

- *LHCb is moving HLT farm out of the detector area*
- *Free space could be used to host a small Mathusla-like detector*
- *Could be used to probe light long-living particles produced at LHC (e.g., in b decays)*



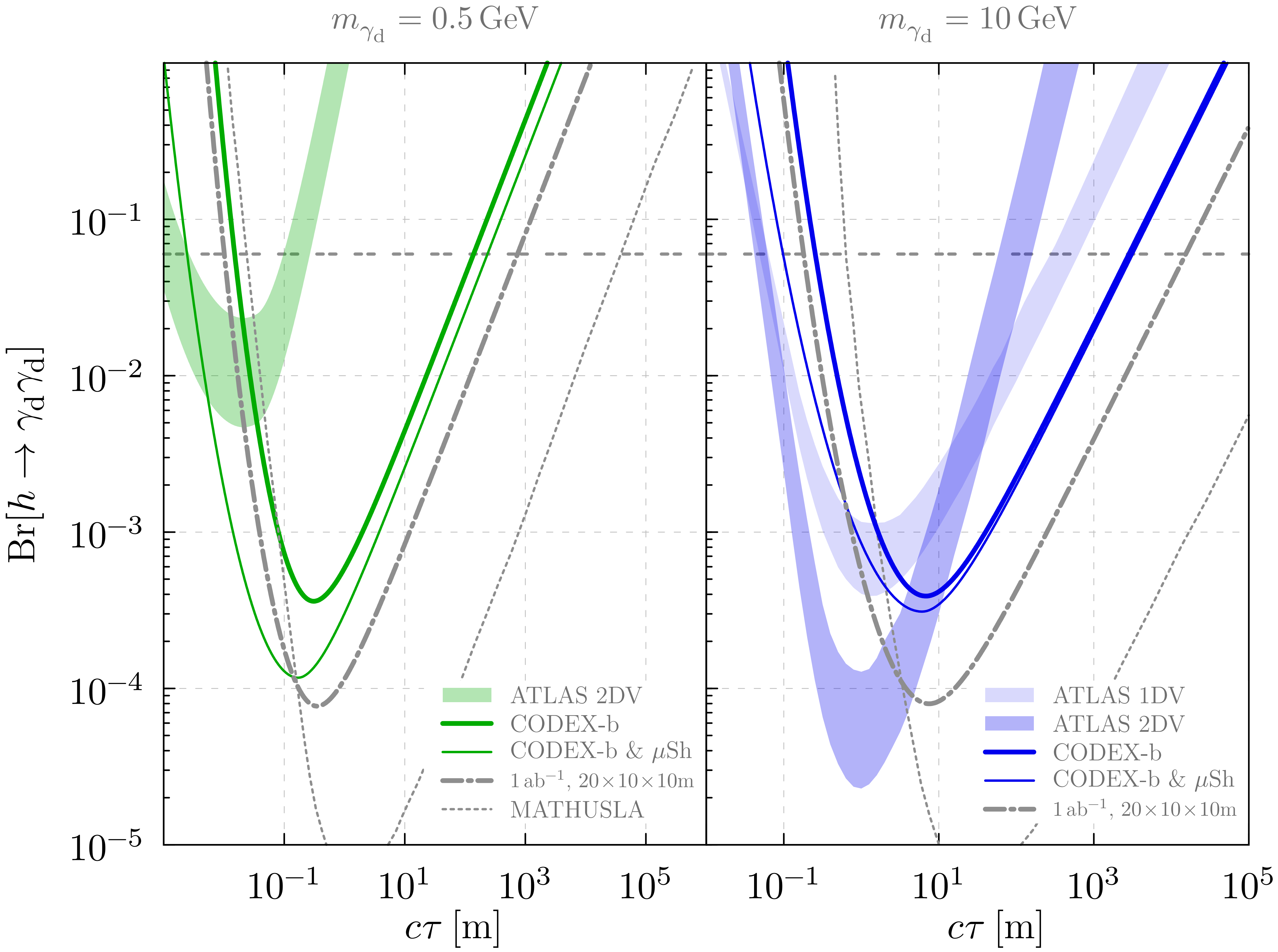
https://arxiv.org/pdf/1708.09395.pdf

NEW IDEAS: CODEX

- *LHCb is moving HLT farm out of the detector area*

- *Free space could be used to host a small Mathusla-like detector*

- *Or probe long-living particles from Higgs decays*



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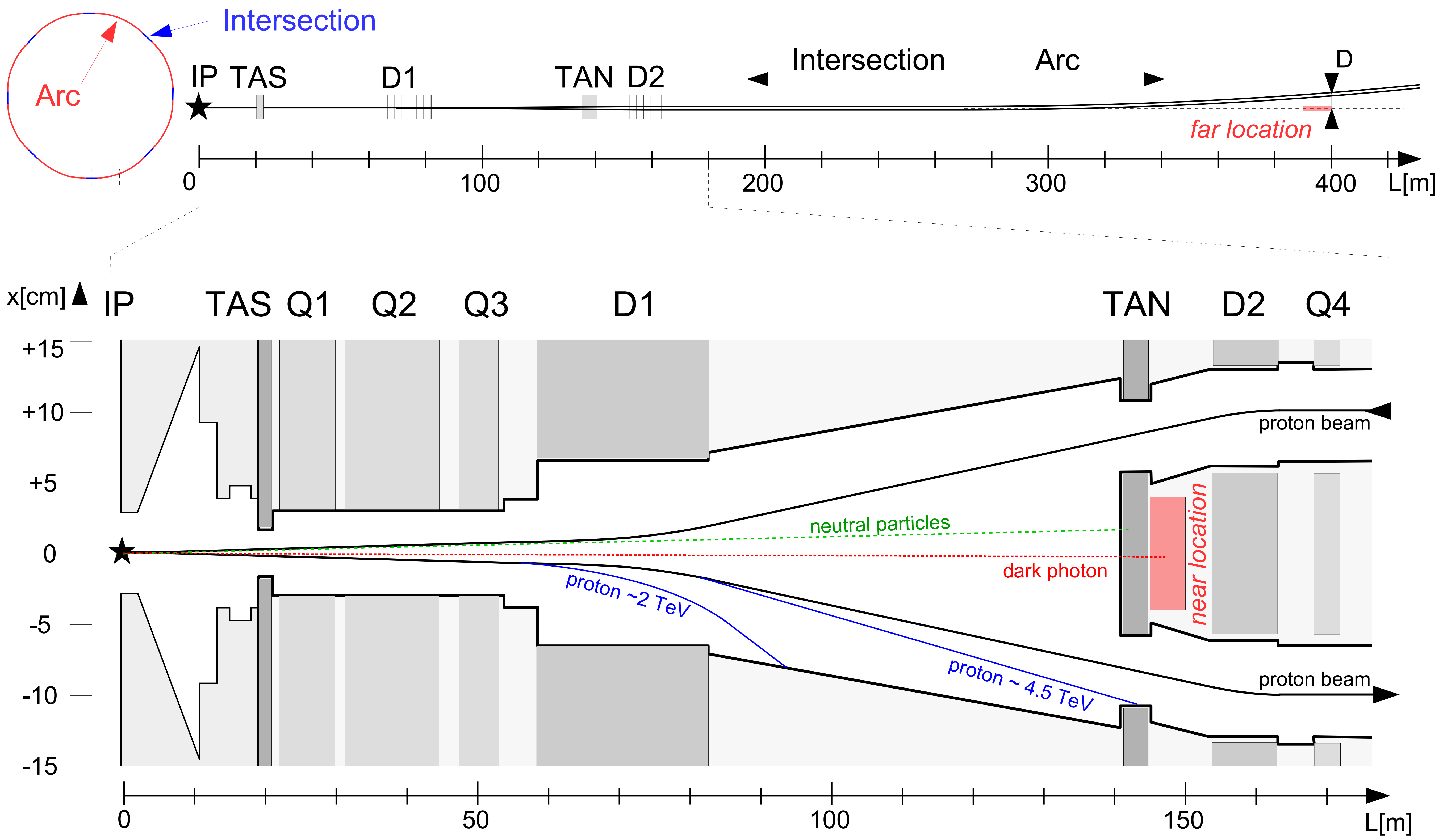
NEW IDEAS: FASER

- Small detector, to be installed side-by-side the LHC tunnel, pointing to the detector interaction point

- Same target physics (dark photons, etc) but different scale, budget, and reach



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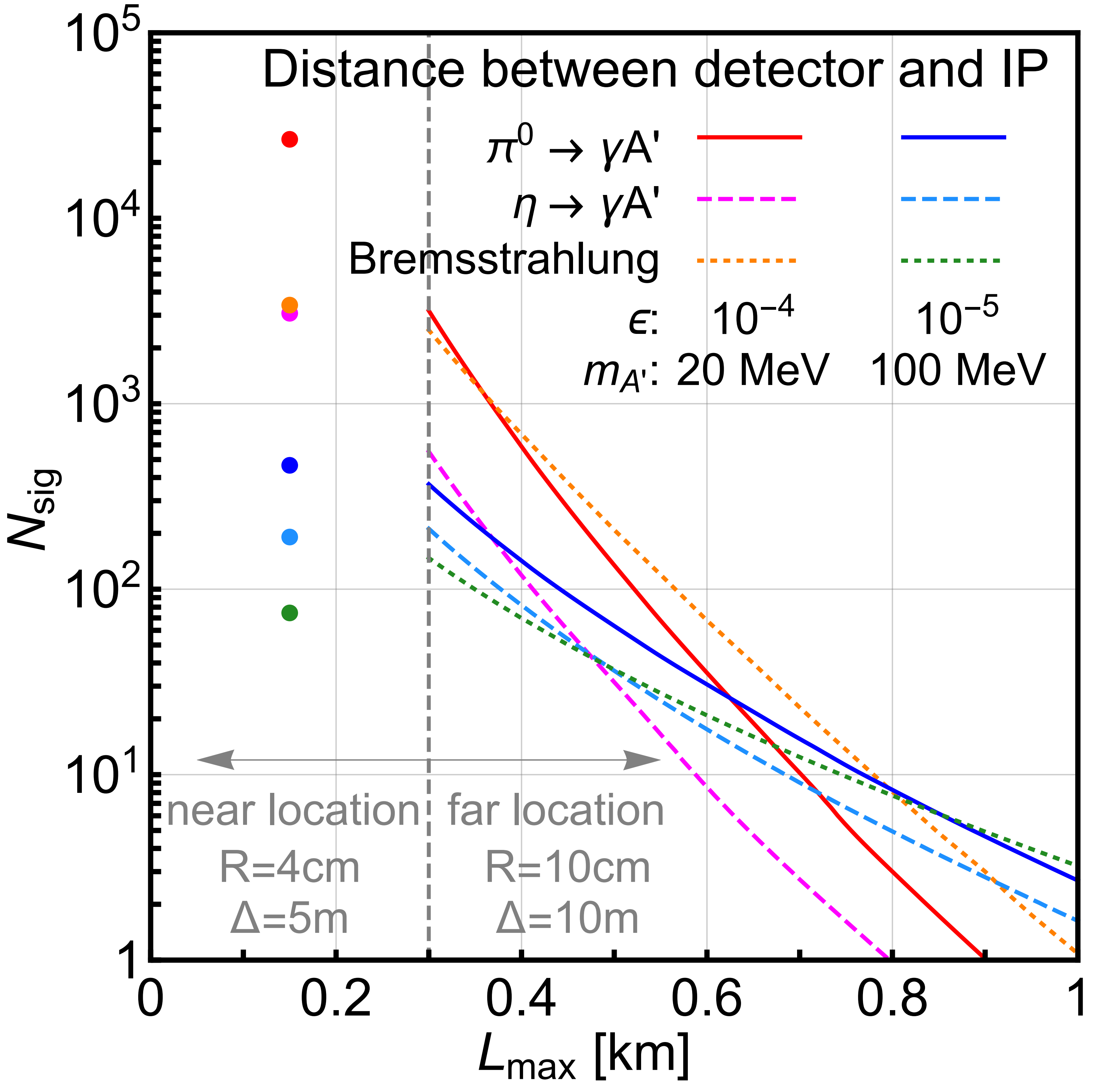

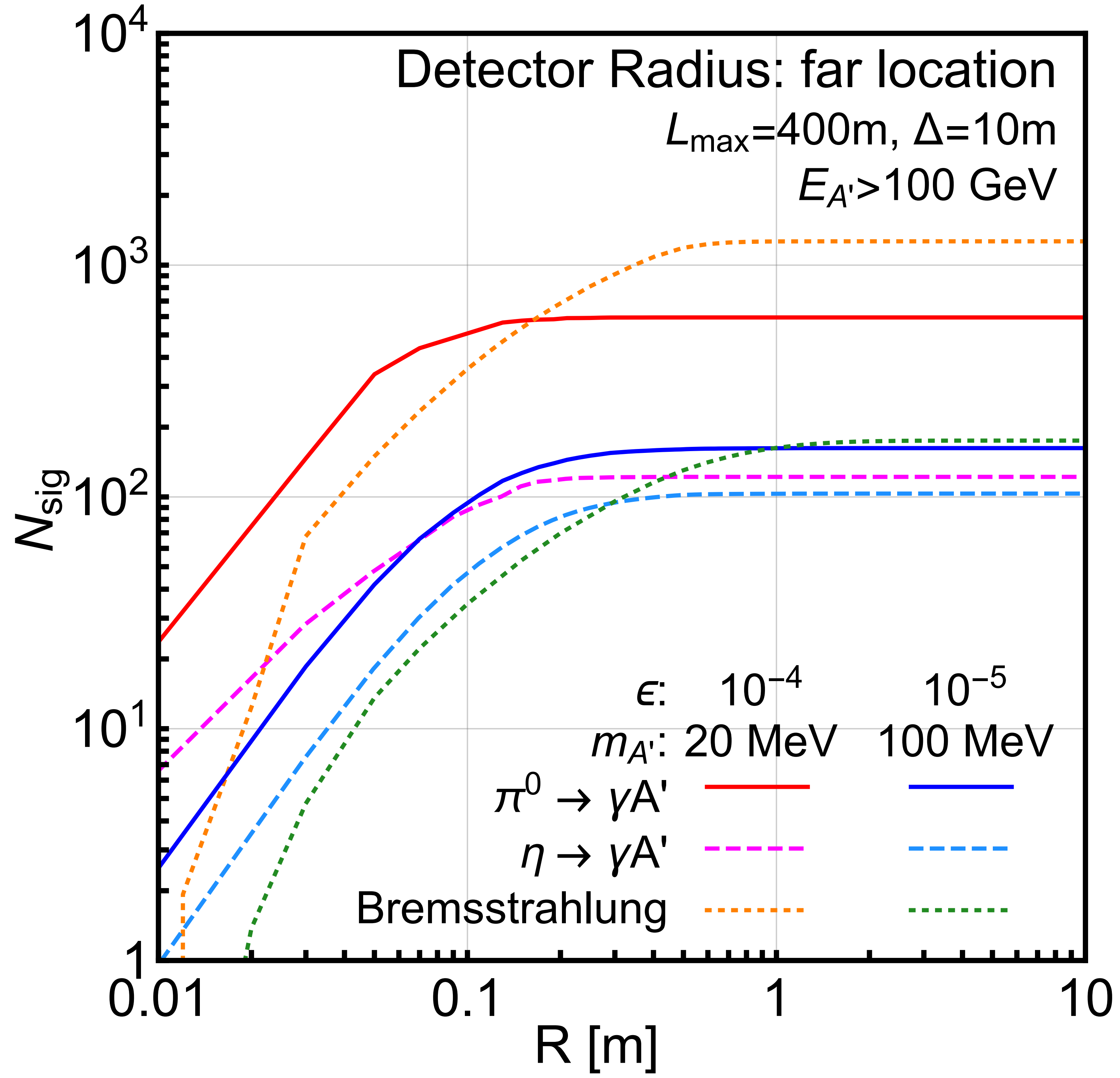

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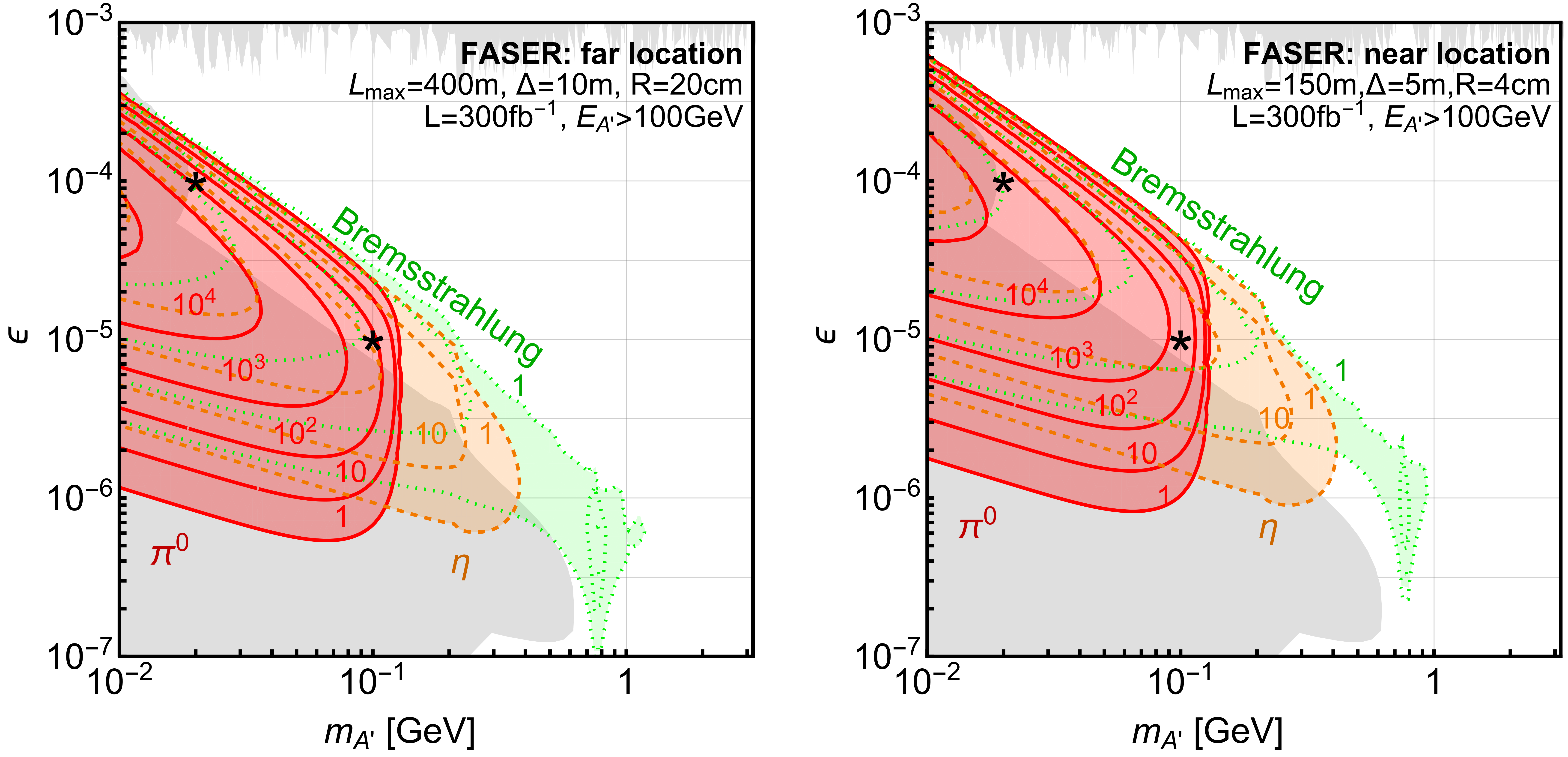

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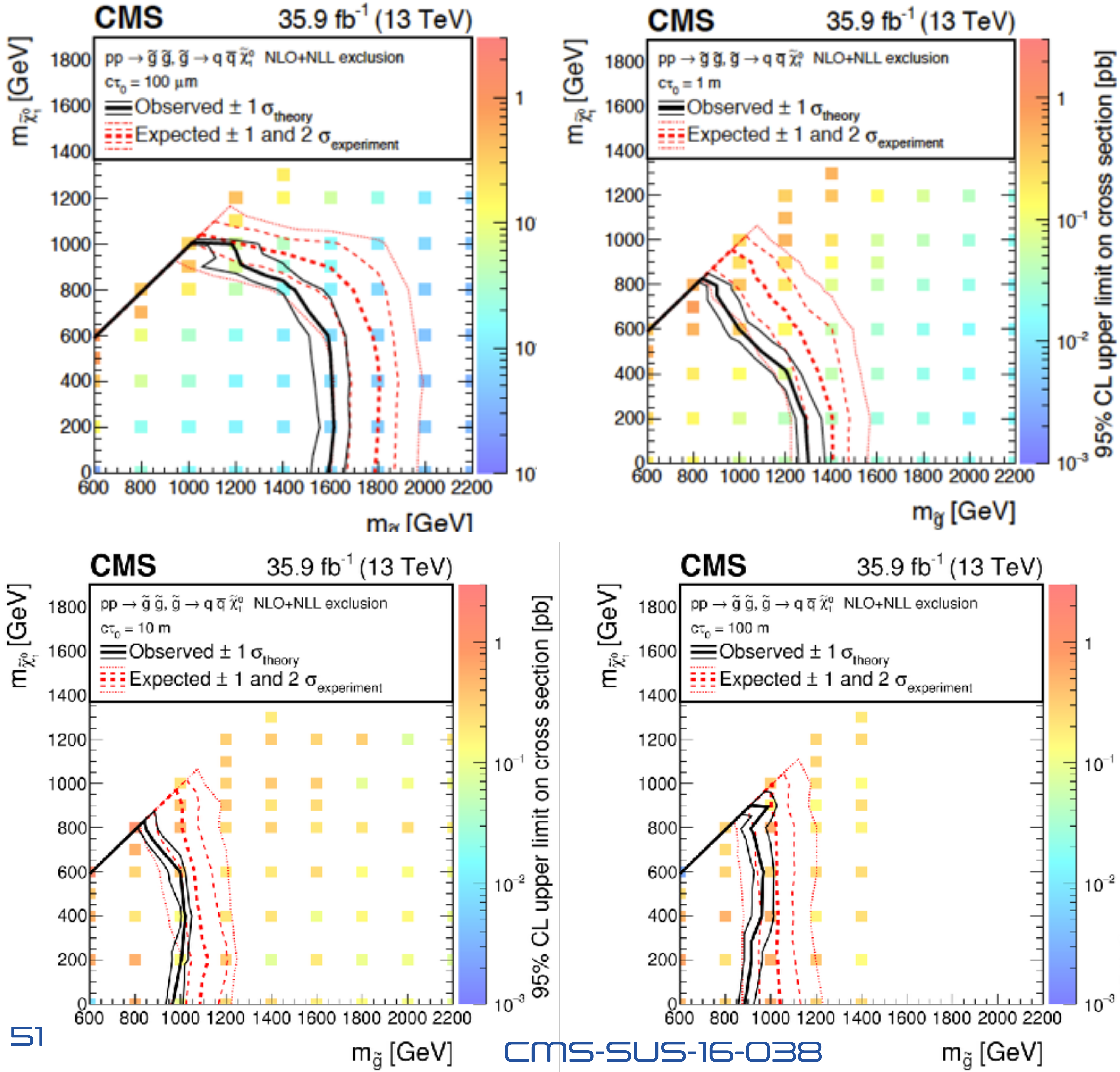
Reinterpreting Prompt Searches

- Prompt analyses are sensitive to small displacements (i.e., to small lifetime)
- This is why some traditional prompt analysis was recasted to long-living particle scenarios
- The result is already good in probing large portion of parameter space
- The deterioration of sensitivity with lifetime is less pronounced than what would expect



CMS-SUS-16-038

SUMMARY OF EPISODE III

- LHC (SUSY) searches are much more than MET-based searches
  - RPV SUSY: single & double production == new resonance searches (bump hunts, boosted jets, …)
  - Large set of exotic signatures emerging from long-living particles
    - SUSY compressed spectra
    - Dark sector
  - Searches program in place
  - New ideas to extend LHC reach with new detectors
  - But don’t underestimate the sensitivity of even the more classic searches

BACKUP SLIDES