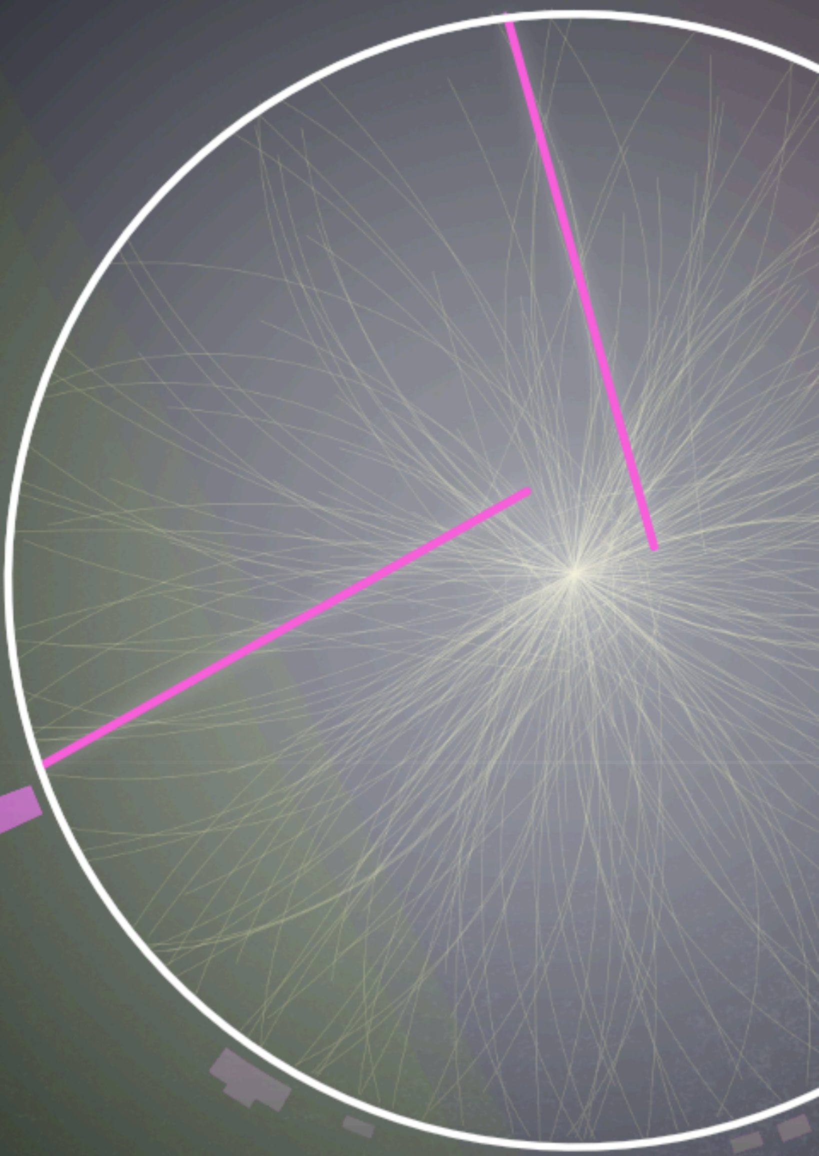
The Lifetime of the Long-Lived Particle Era

LAWRENCE LEE



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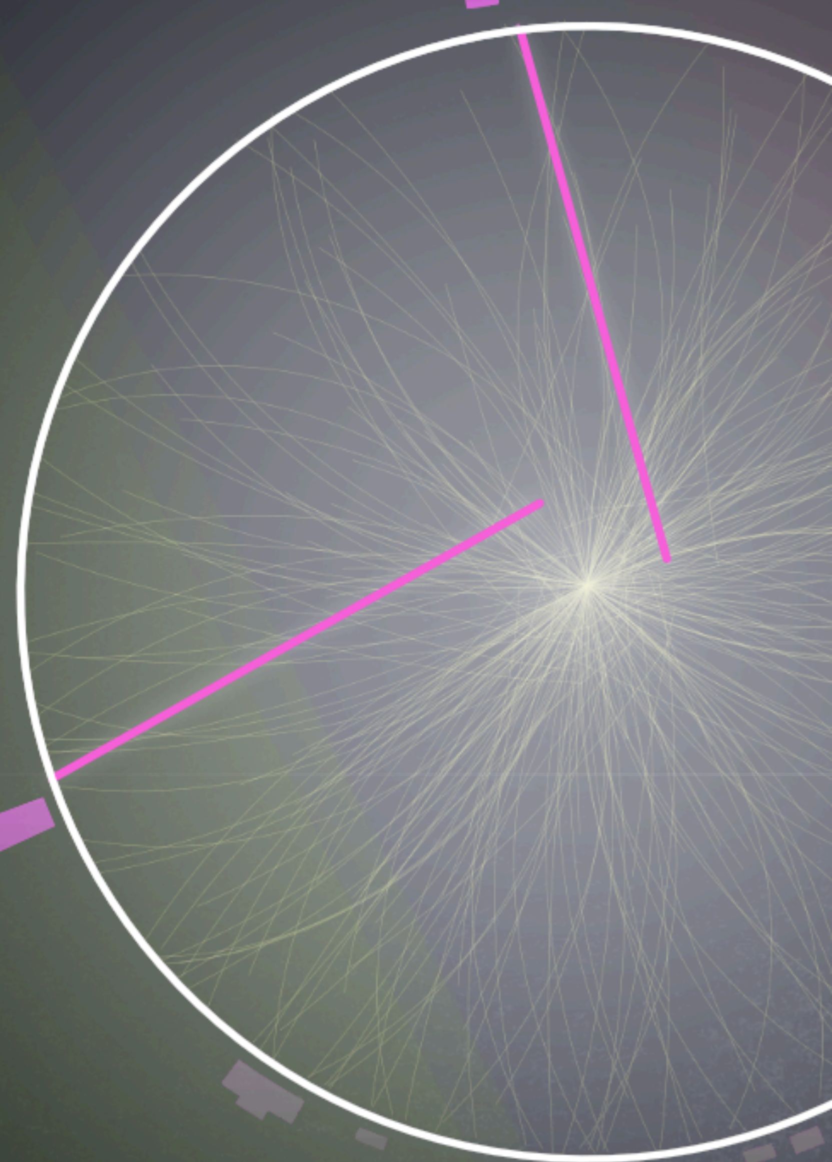

24 March 2021 - A Rainbow of Dark Sectors - Aspen Center for Physics

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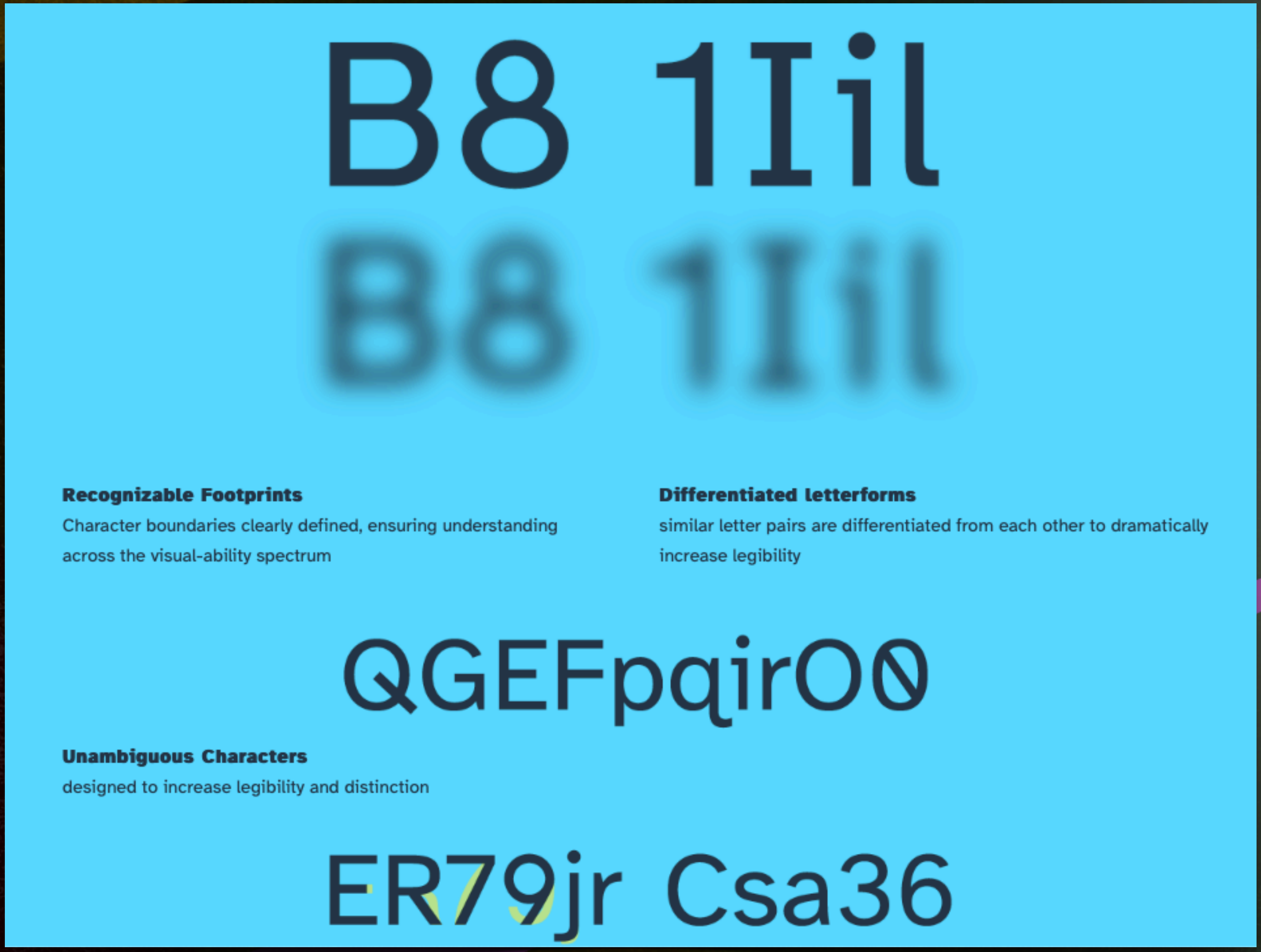
Atkinson Hyperlegible

BRAILLE INSTITUTE



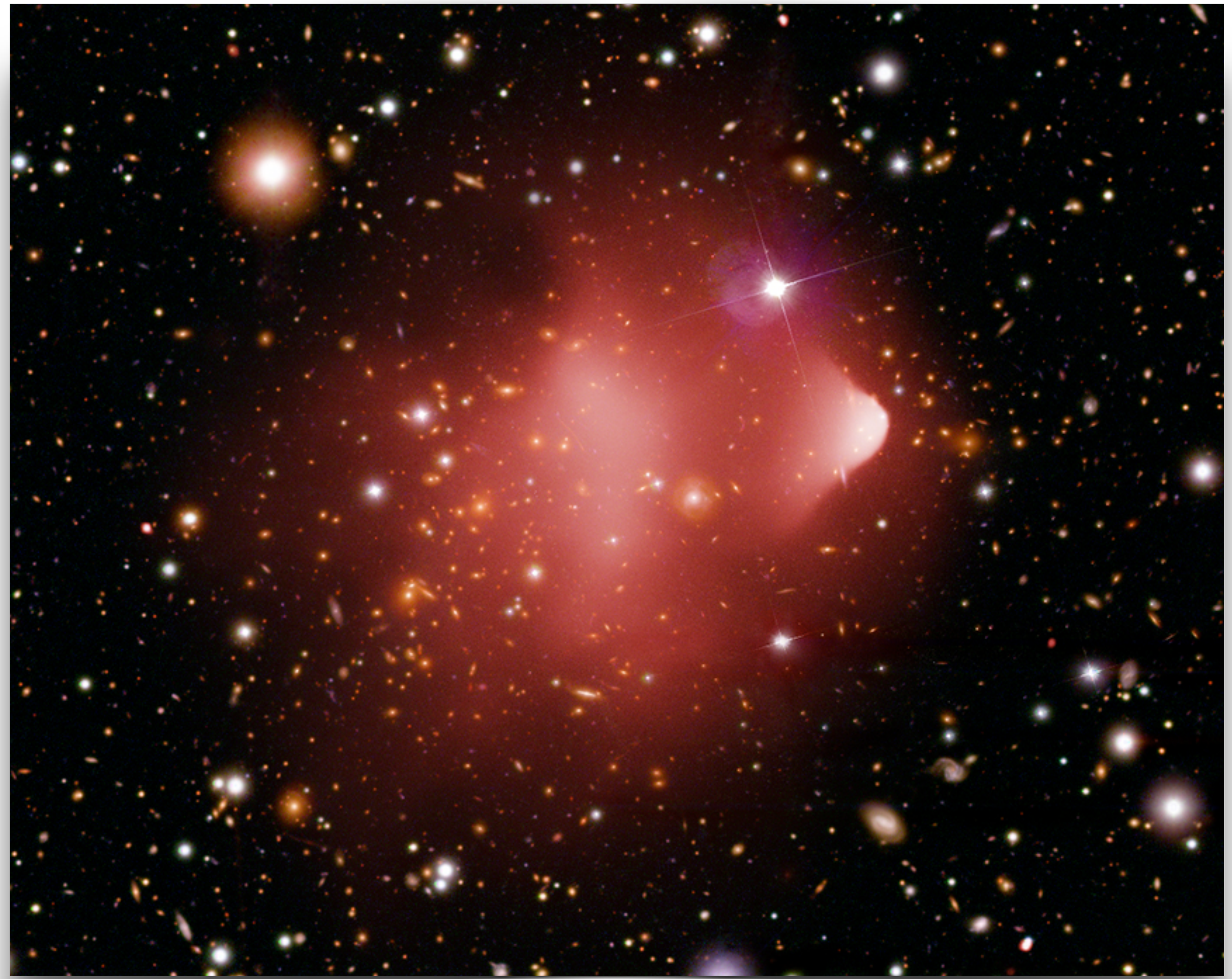
THE STANDARD MODEL'S GOT ISSUES

$$\Delta m_H^2 / m_H^2 \gg 1$$

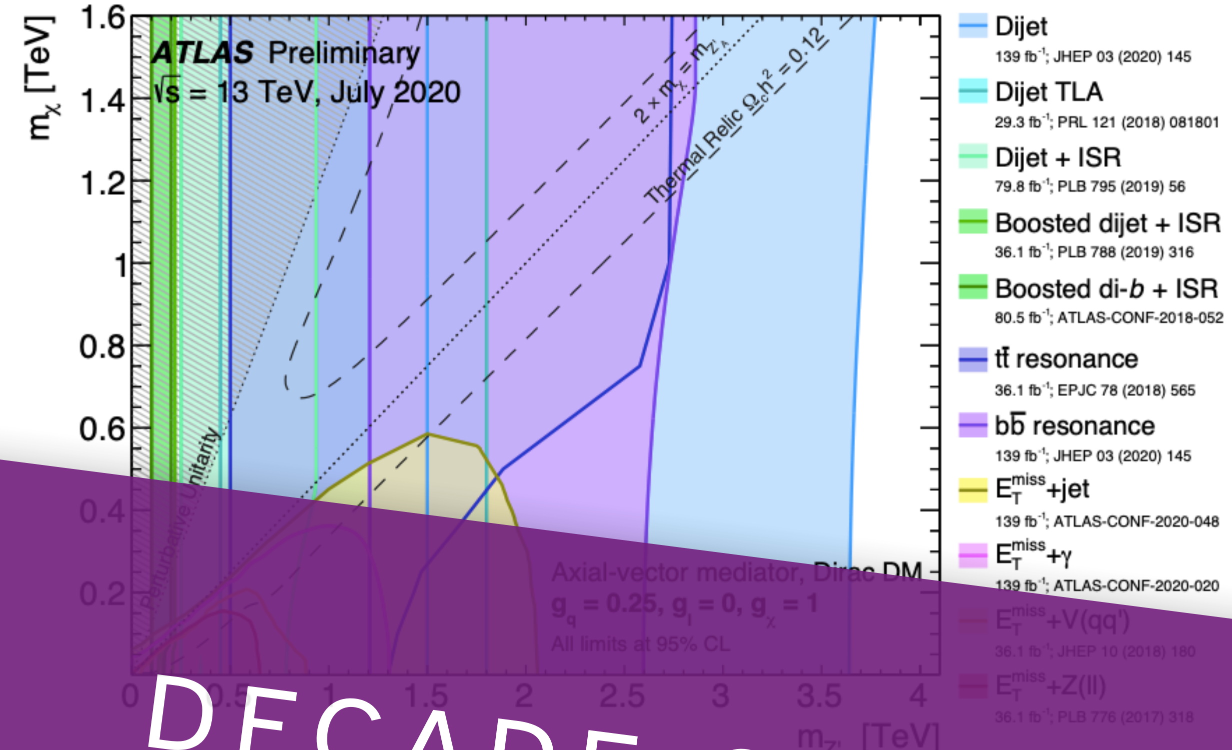
$$v \ll M_{Pl}$$

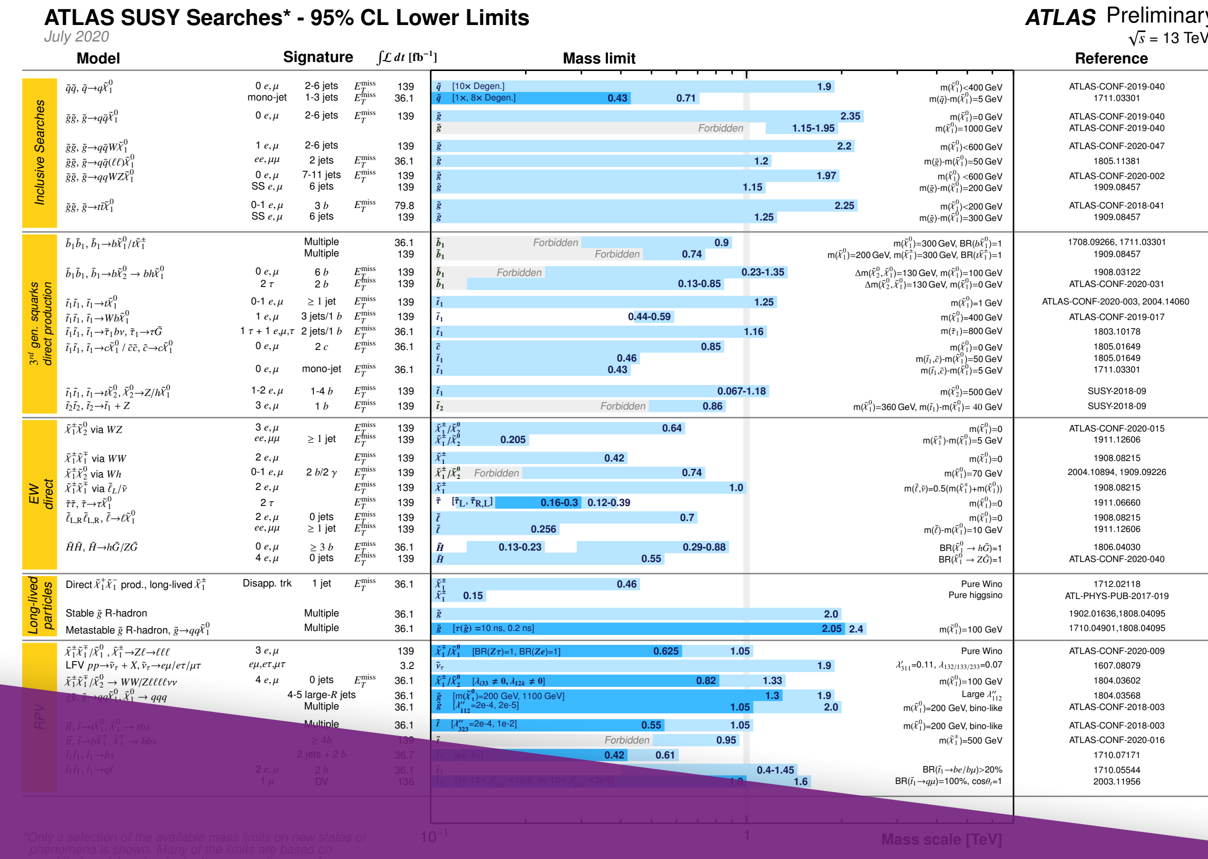
$$\theta_{QCD} \approx 0$$

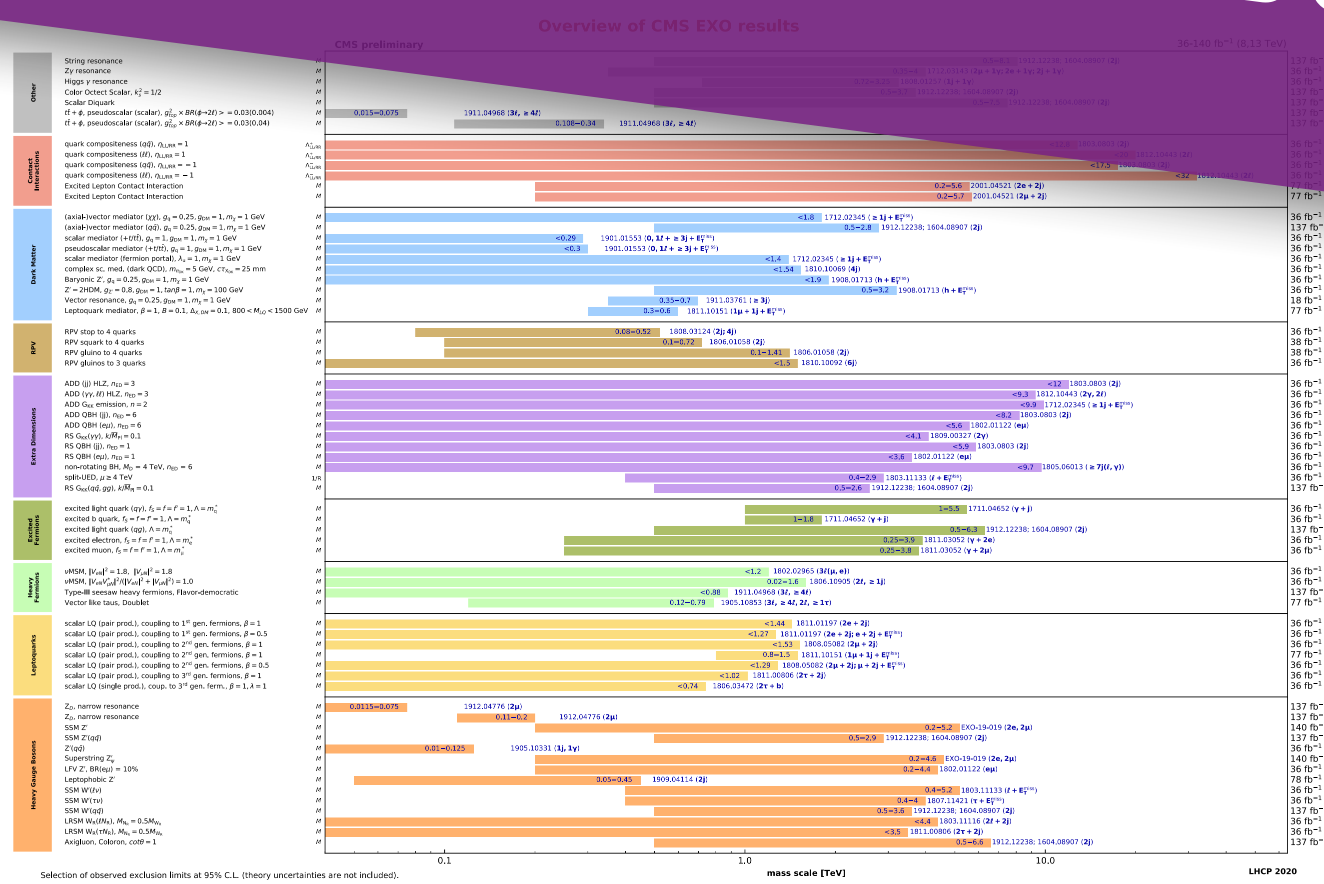
$$m_\nu > 0$$

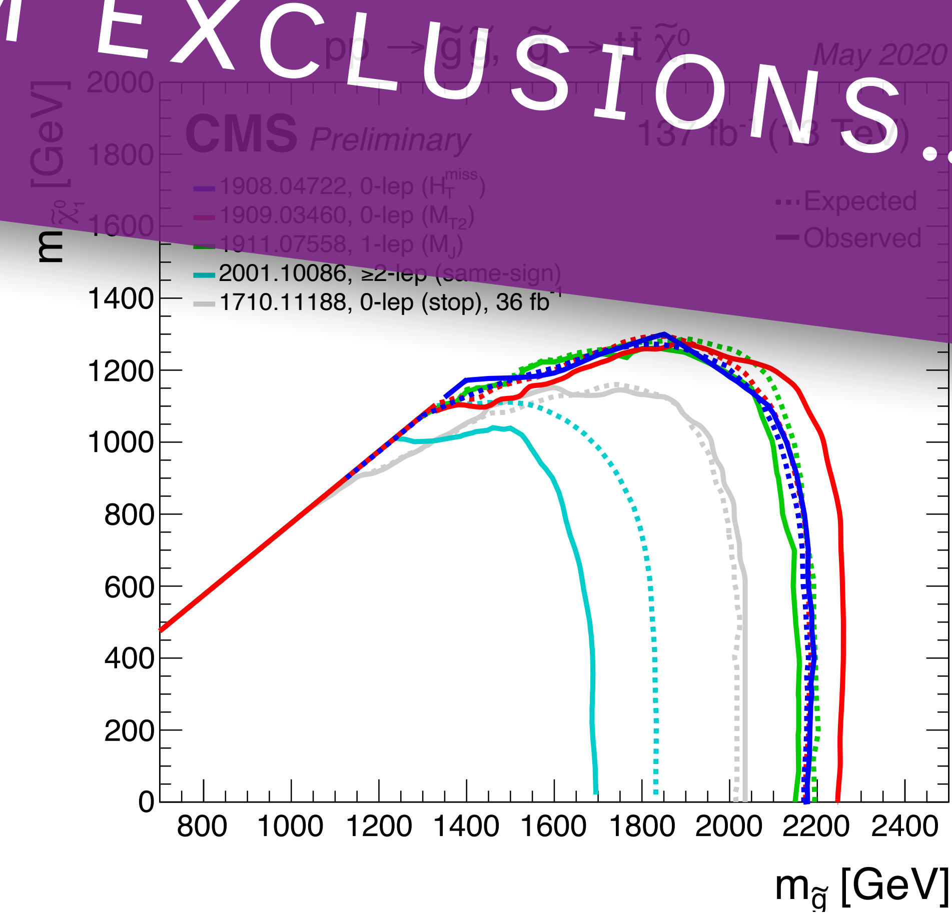


DECADE OF LHC BSM EXCLUSIONS…

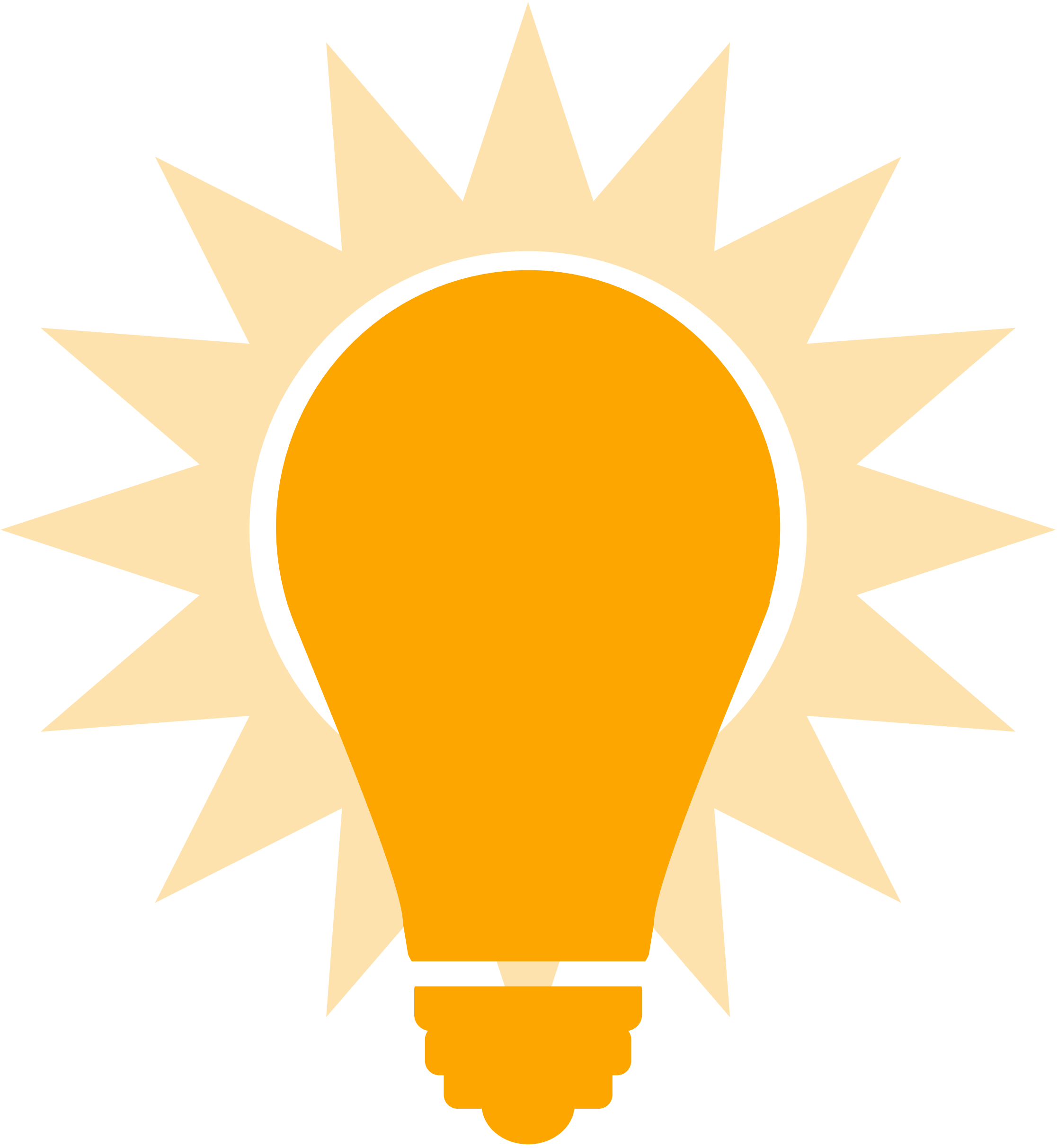


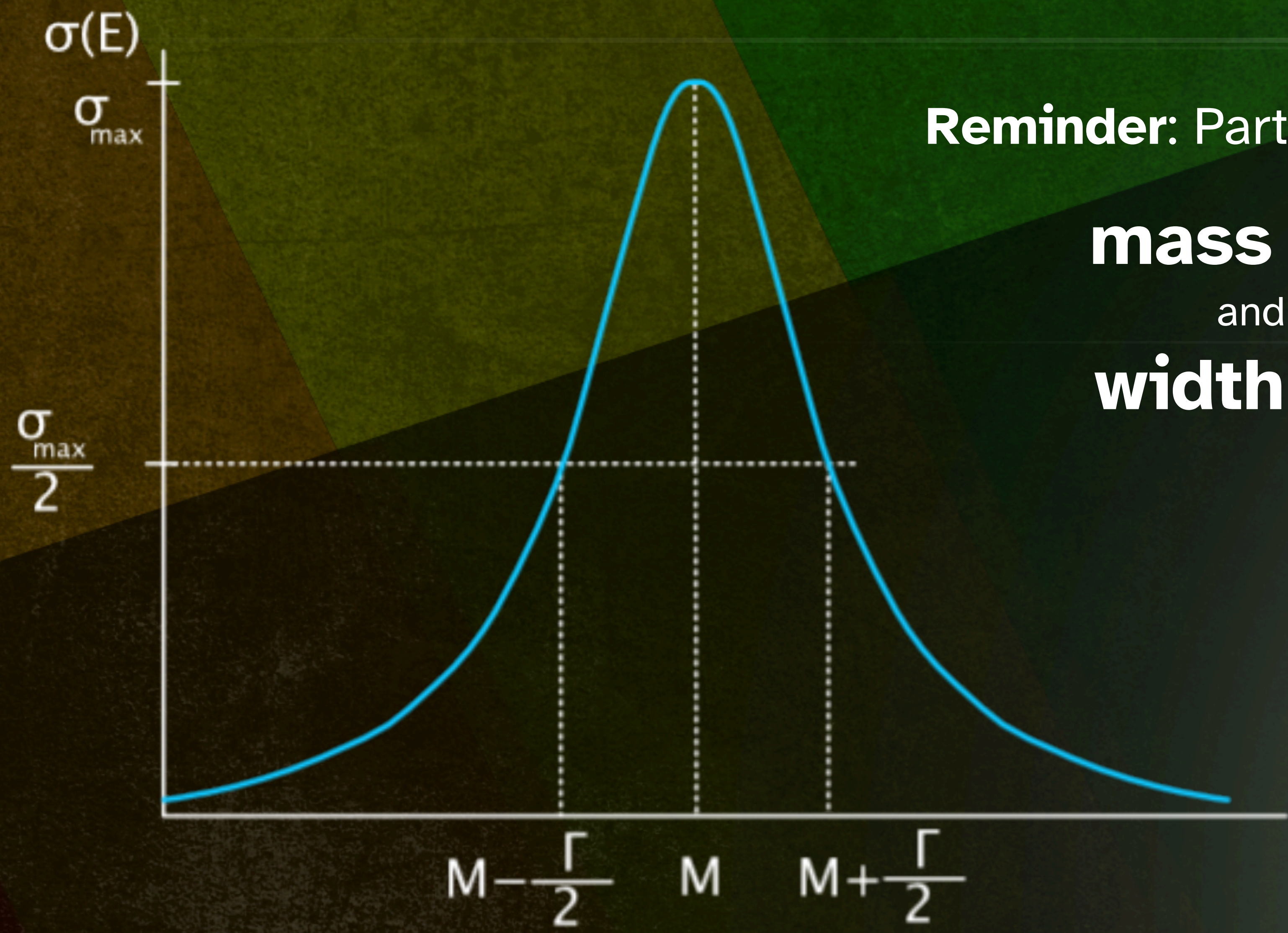






- We have no answers to these problems after all this searching…
  - Let’s eke out as much sensitivity from our LHC lamp post as possible
  - Searches for **Long-Lived Particles (LLPs)** huge part of this program



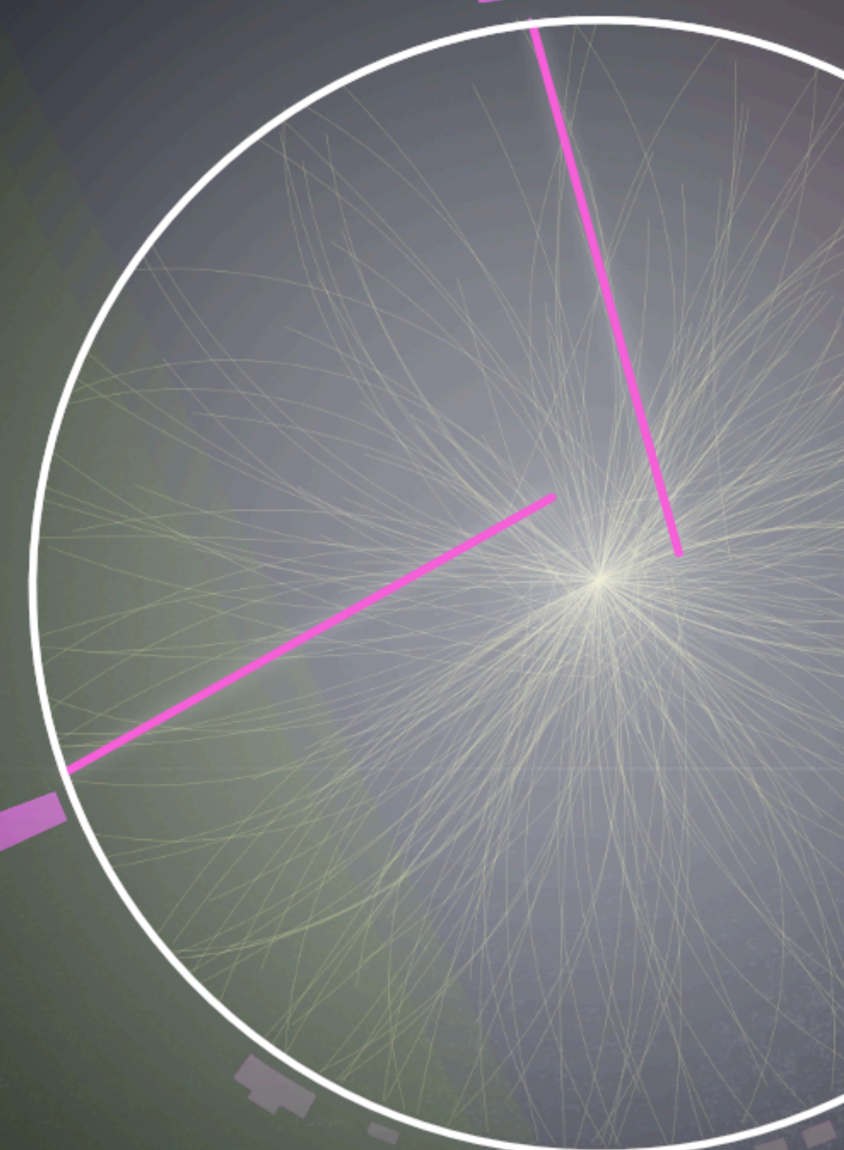


Reminder: Particles have a:

mass (M)

and

width (Γ)



Γ is determined by
how the particle decays

e.g. lifetime:

$$\tau \sim 1/\Gamma$$

Particles can gain a large lifetime (small Γ) a number of ways

$$\Gamma \sim \varepsilon^2 \left(\frac{m}{\Lambda}\right)^{2n} \Phi$$

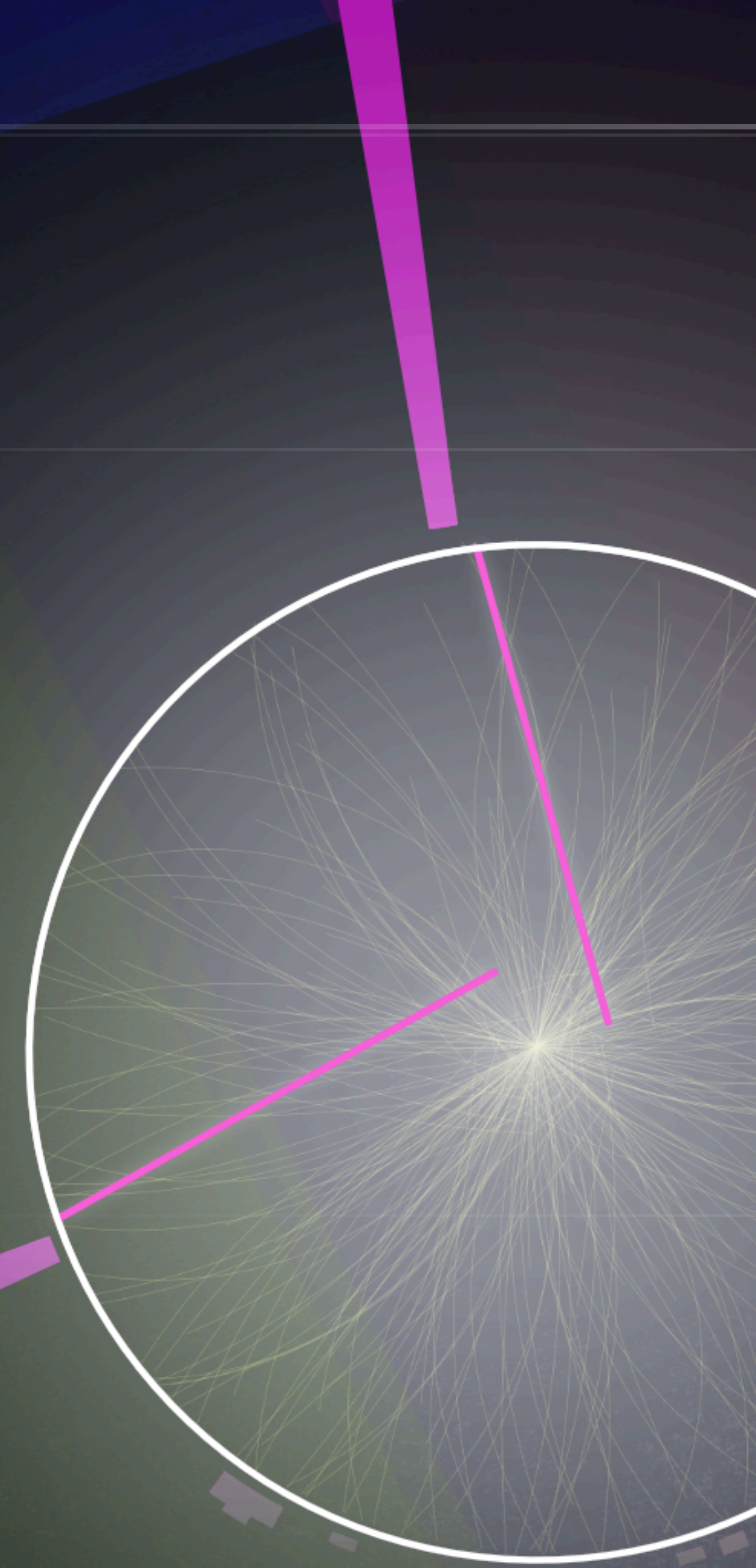
Small couplings

(e.g. RPV decays)

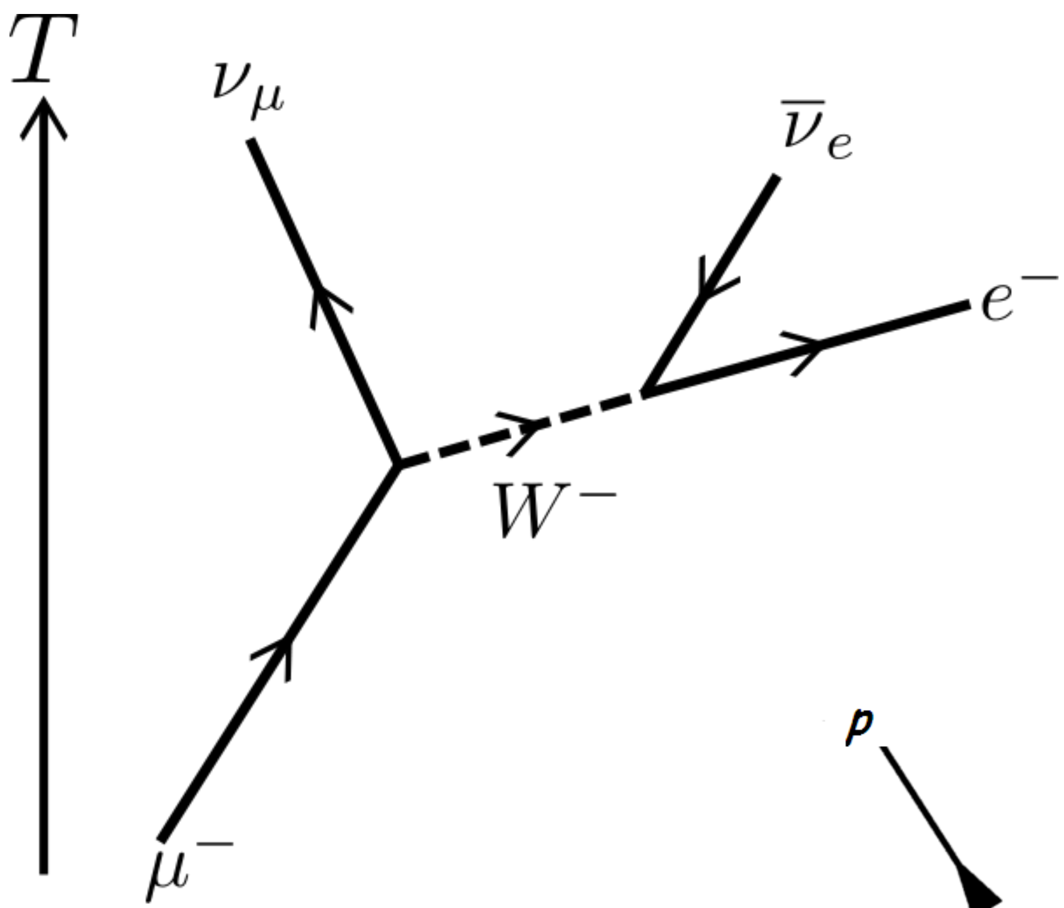
Effective Coupling

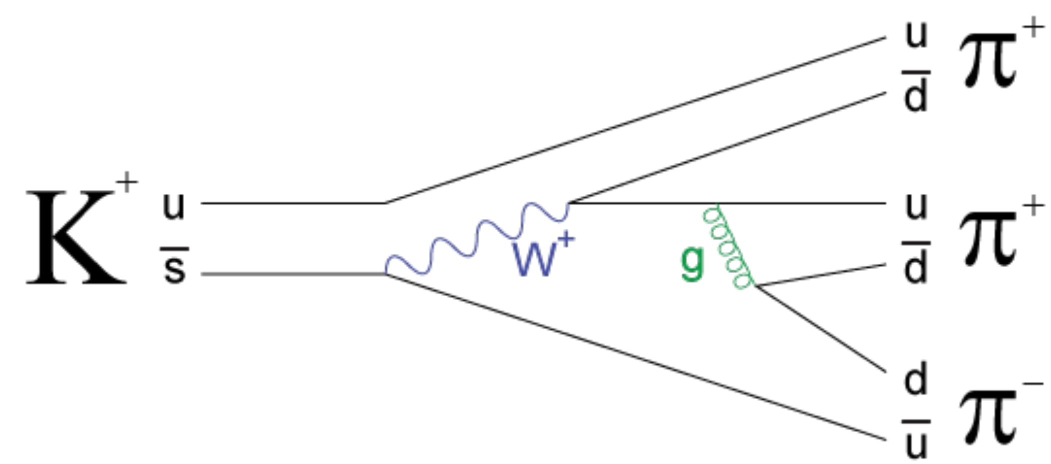
(+Loop Suppression)

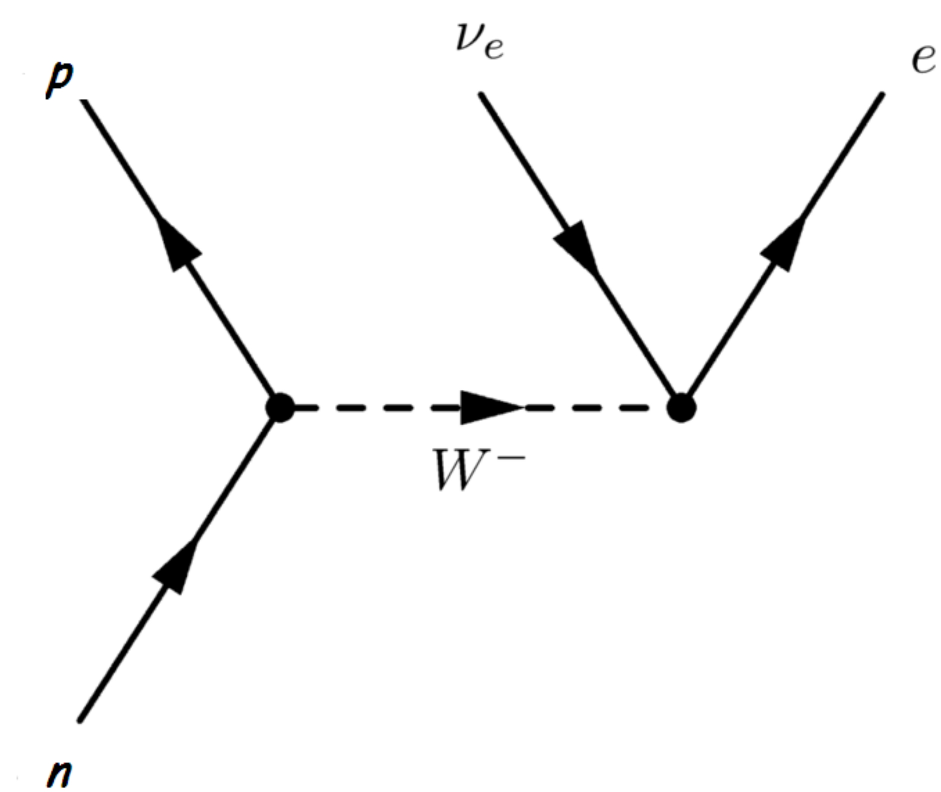
Small phase space



And particles do in the SM!







[JPPNP 3695 (2019)] - LL, C. Ohm, A. Soffer, T. Yu

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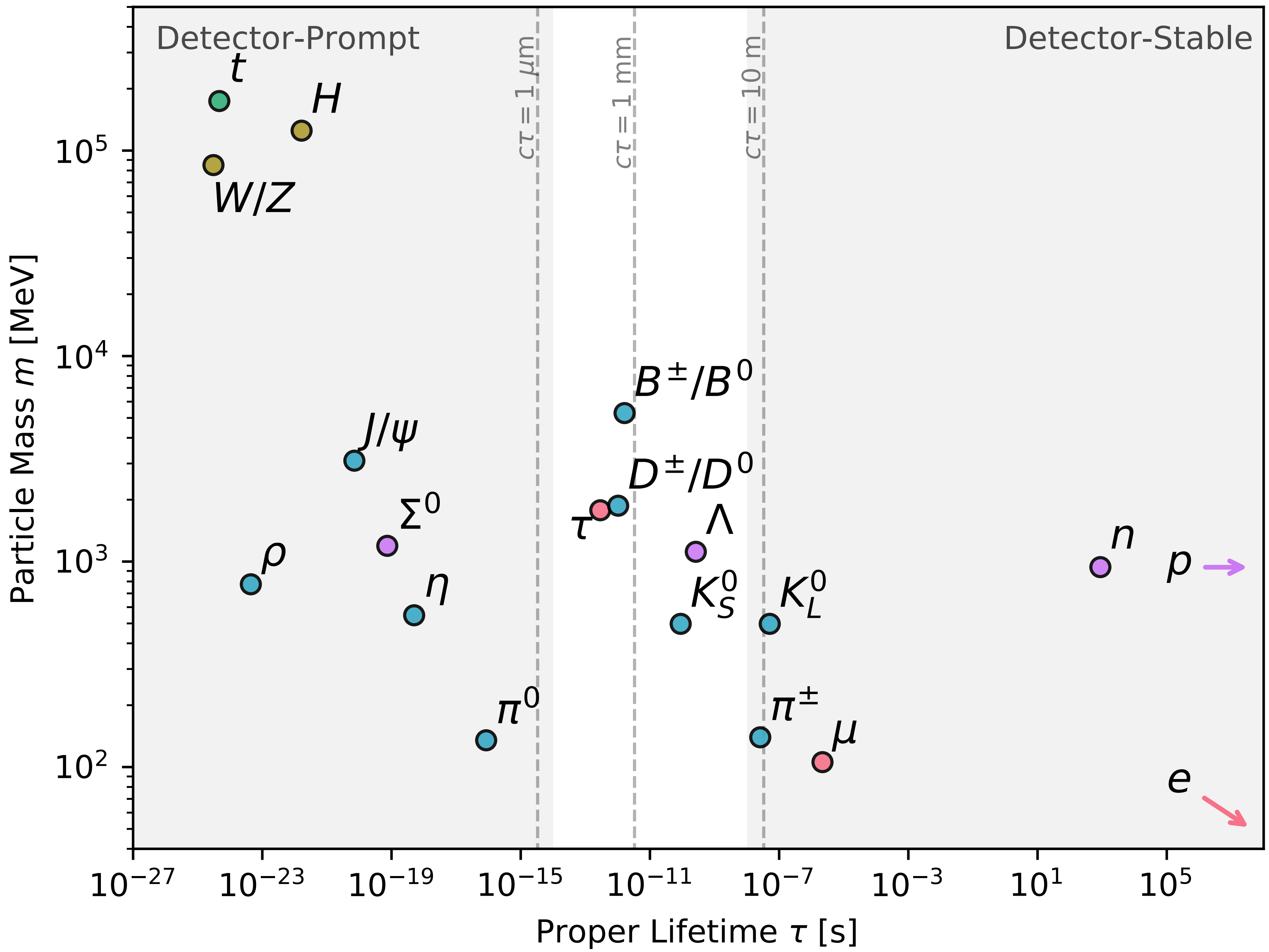
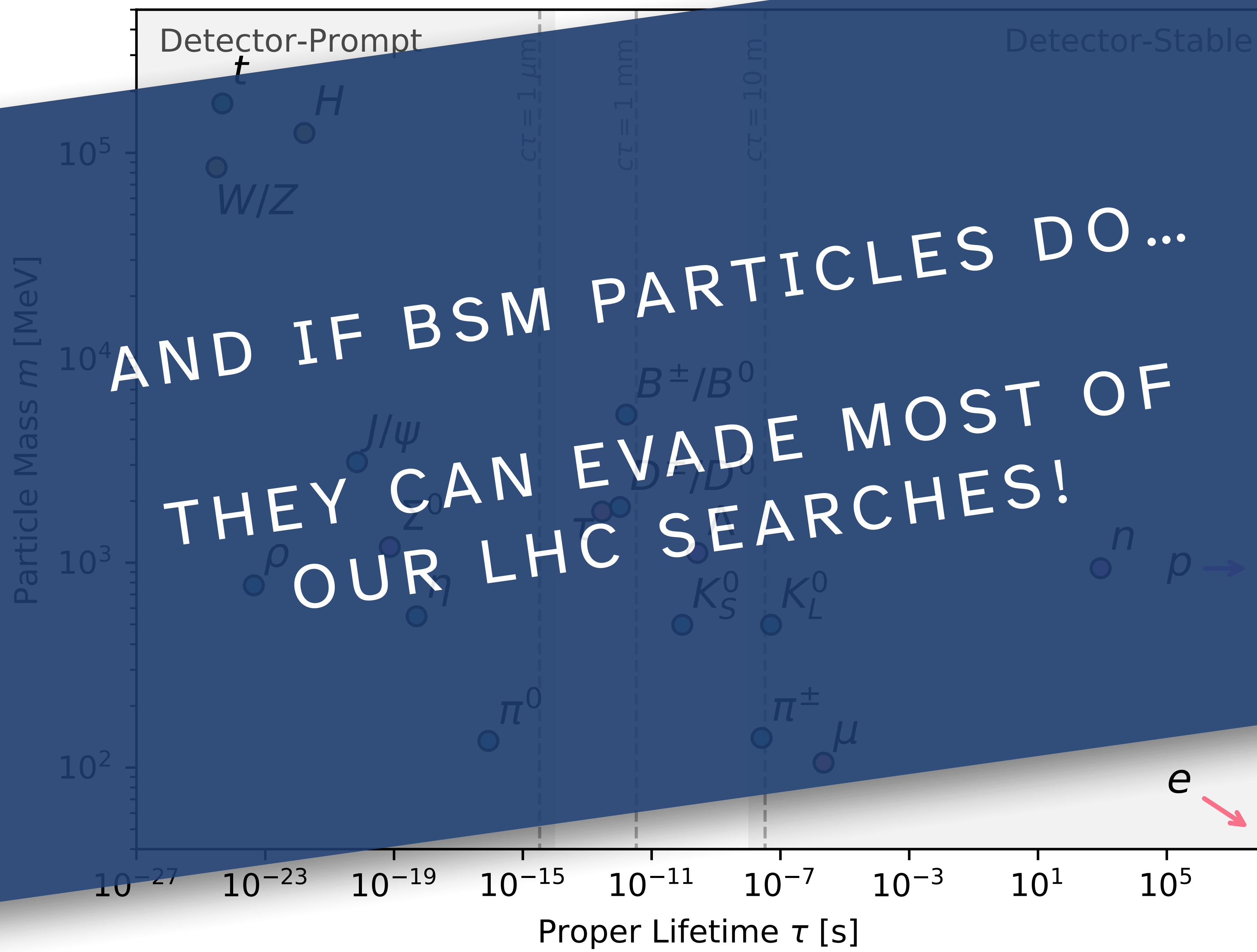


[JPPNP 3695 (2019)] - LL, C. Ohm, A. Soffer, T. Yu

And particles do in the SM!

AND IF BSM PARTICLES DO…

THEY CAN EVADE MOST OF OUR LHC SEARCHES!



[JPPNP 3695 (2019)] - LL, C. Ohm, A. Soffer, T. Yu

LLPs are strongly motivated and are generically predicted in many DM solutions

		Small coupling	Small phase space	Scale suppression
SUSY	GMSB			✓
	AMSB		✓	
	Split-SUSY			✓
	RPV	✓		
NN	Twin Higgs	✓		
	Quirky Little Higgs	✓		
	Folded SUSY		✓	
DM	Freeze-in	✓		
	Asymmetric			✓
	Co-annihilation		✓	
Portals	Singlet Scalars	✓		
	ALPs			✓
	Dark Photons	✓		
	Heavy Neutrinos			✓

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	Dark Photons	✓		
	Heavy Neutrinos			✓

$$\chi_2 \to \chi_1 + X$$

[JPPNP 3695 (2019)] - LL, C. Ohm, A. Soffer, T. Yu

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	ALPs			✓
	Dark Photons	✓		
	Heavy Neutrinos			✓

THERM. Eq.

DM

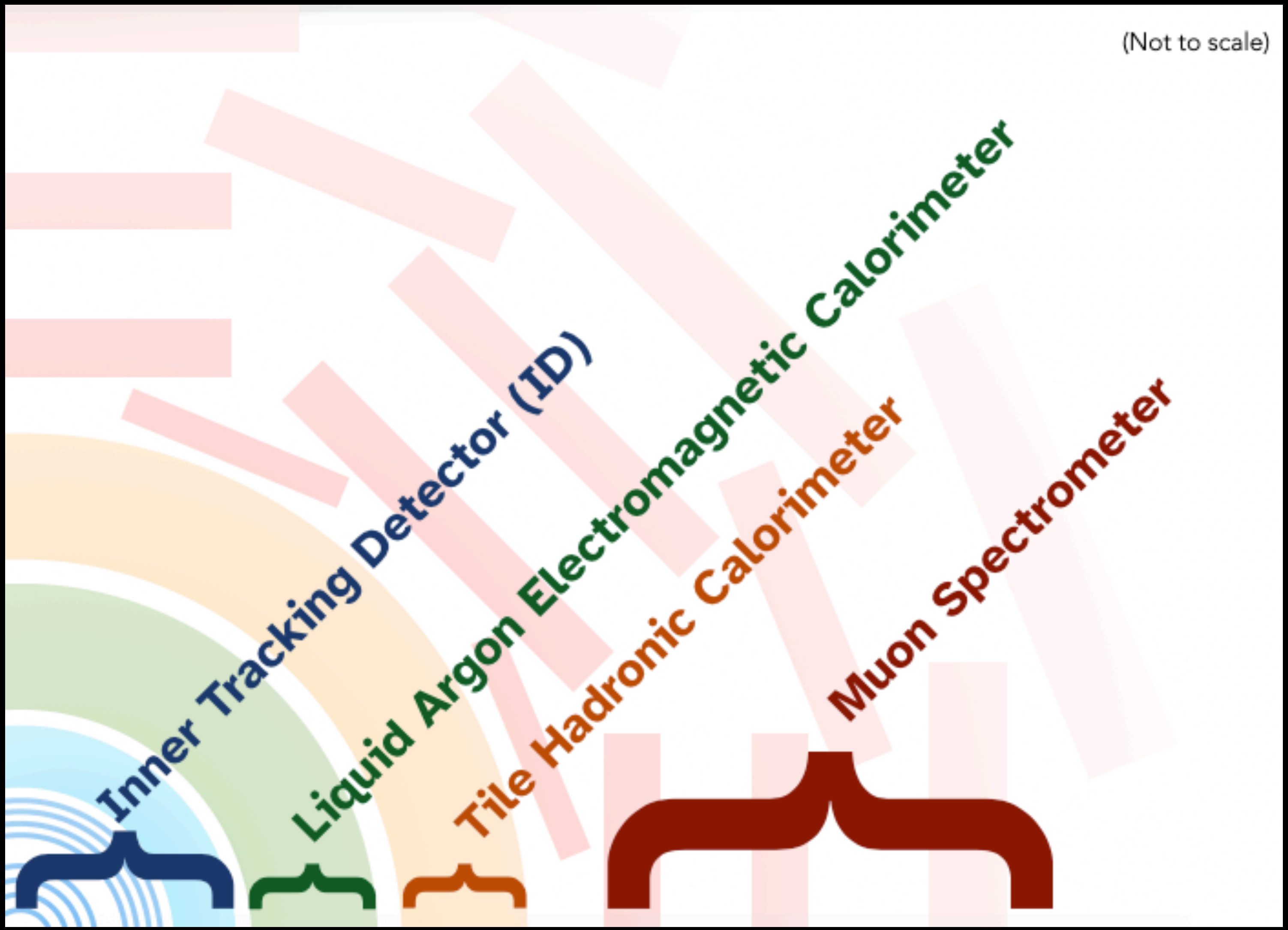
$$\chi_2 \rightarrow \chi_1 + X$$

[JPPNP 3695 (2019)] - LL, C. Ohm, A. Soffer, T. Yu

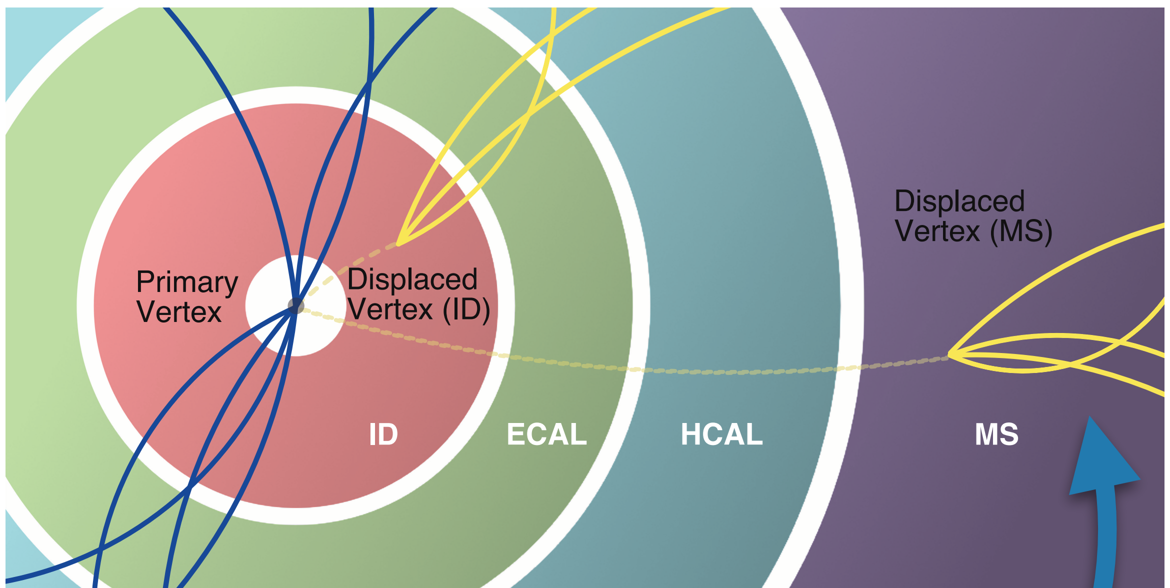
Why is this hard?

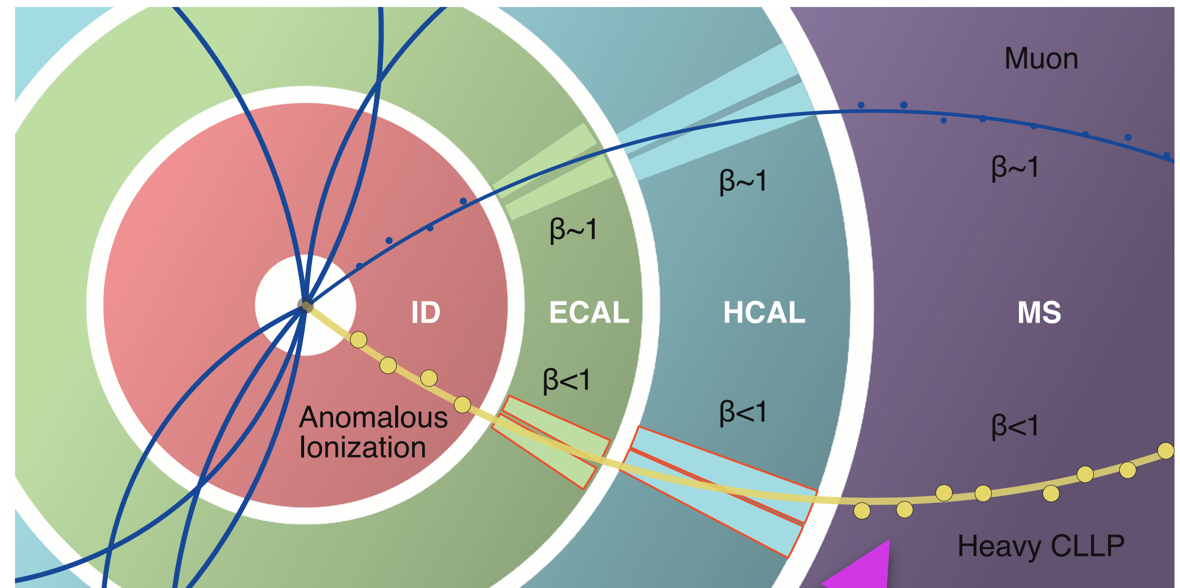
ATLAS/CMS were **not designed** to look for **displaced** new physics

Reconstruction algorithms, cylindrical **geometry**, **trigger**, all designed assuming particles emerge from the collision point



A Long-Lived Particle could break any of these!
Existing mass limits may be much weaker!





Indirect Detection

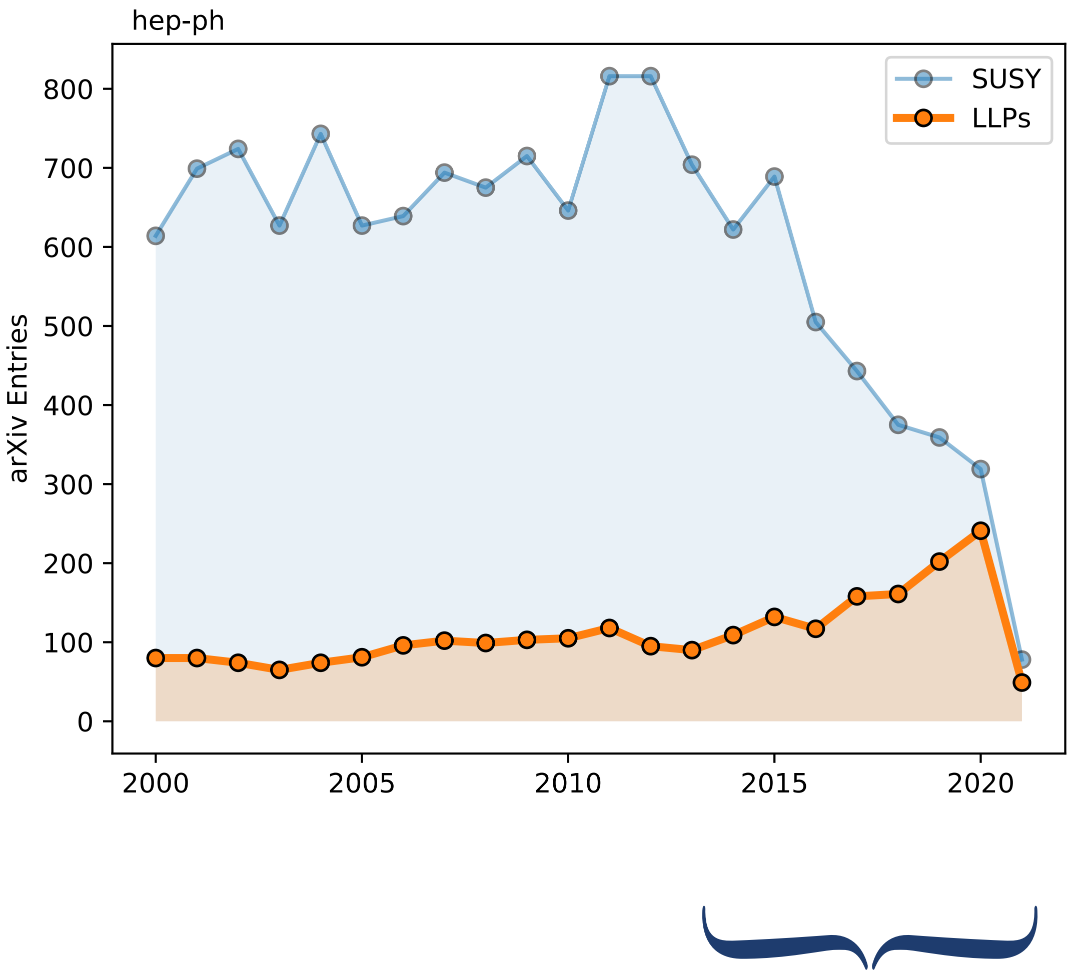
Look for SM decay products of LLP

Direct Detection

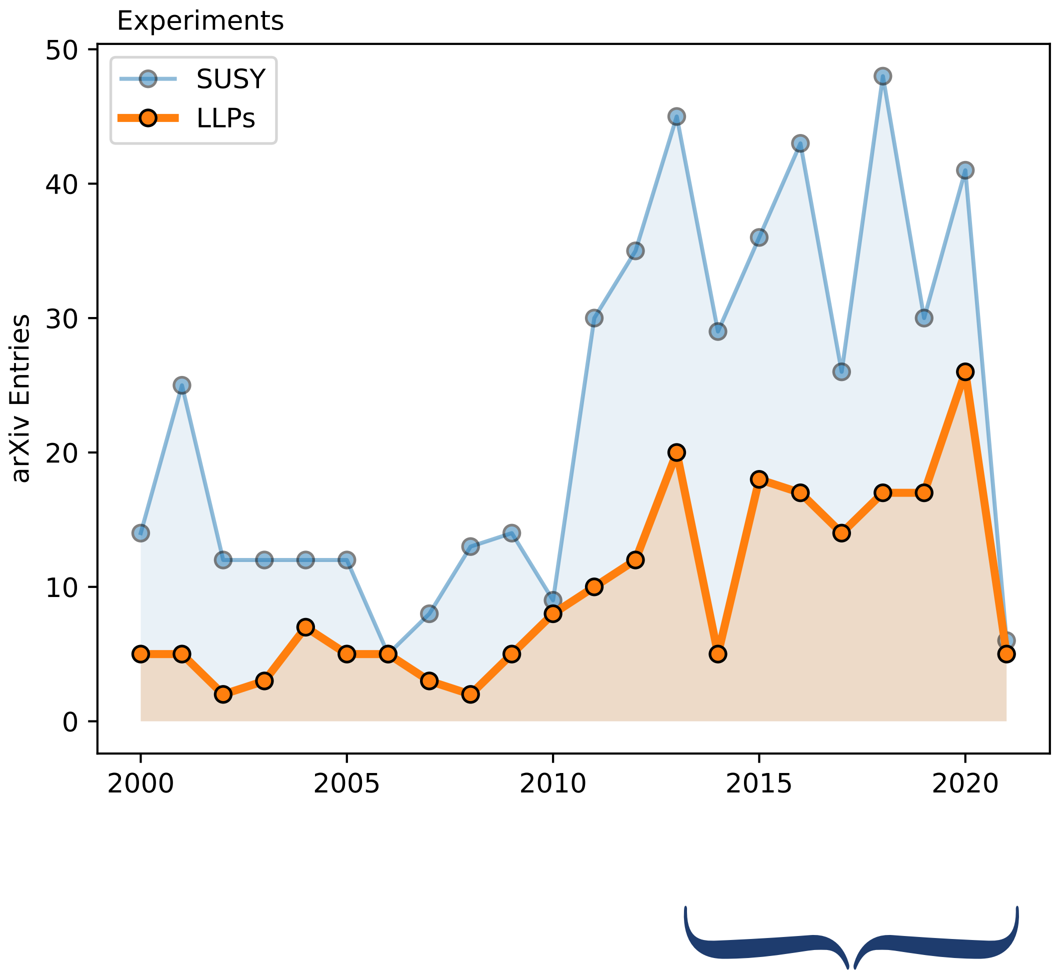
If LLP carries SM charge, look for its interactions with the detector

[JPPNP 3695 (2019)] - LL, C. Ohm, A. Soffer, T. Yu

Pheno



Experiments

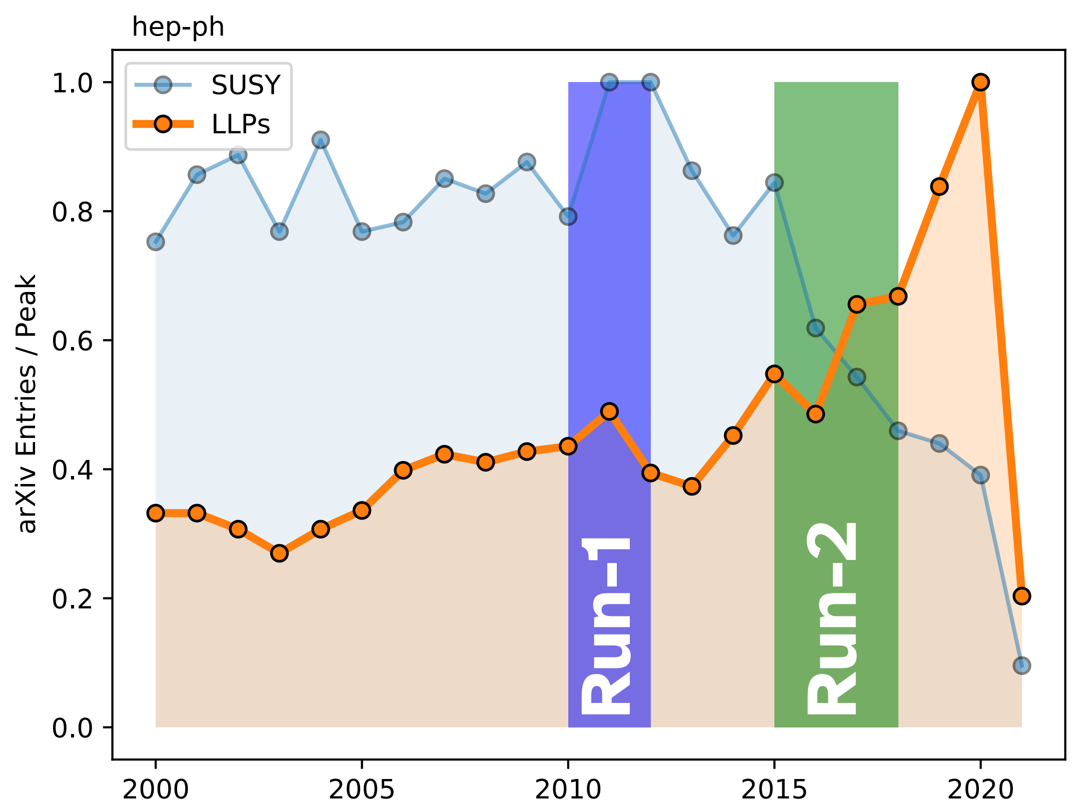


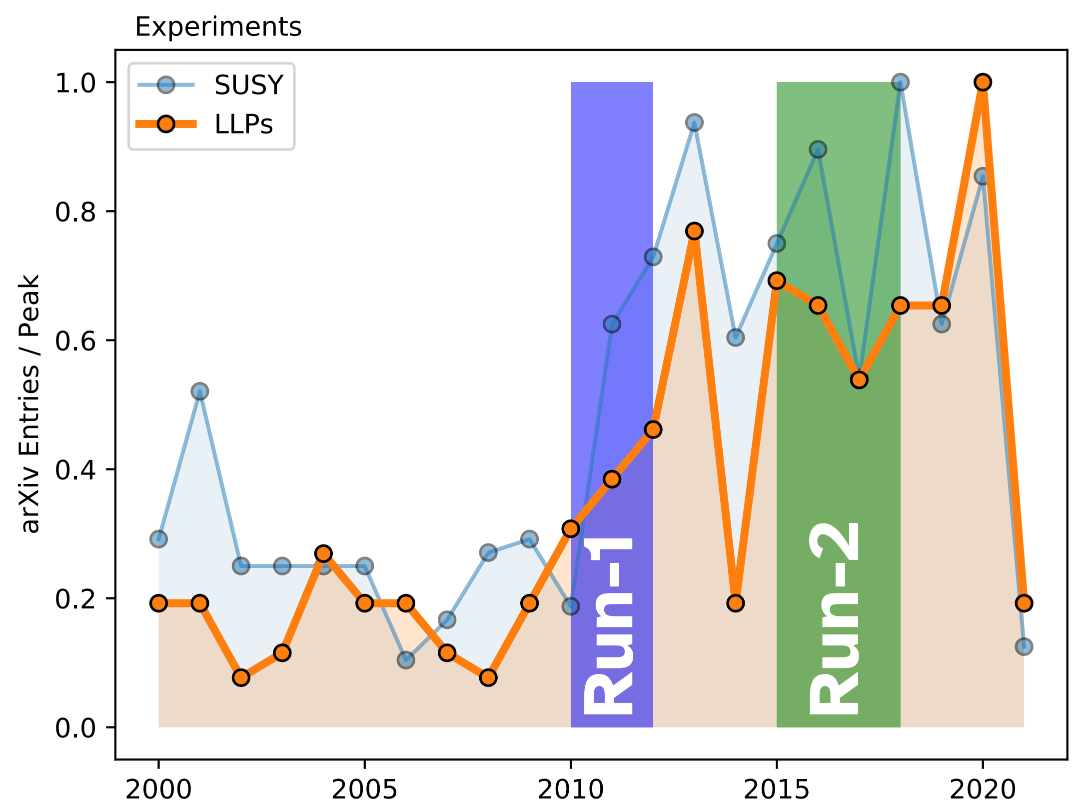
Plots that look like this have become stressful…

But these represent something good:
Excitement from our community!

Pheno

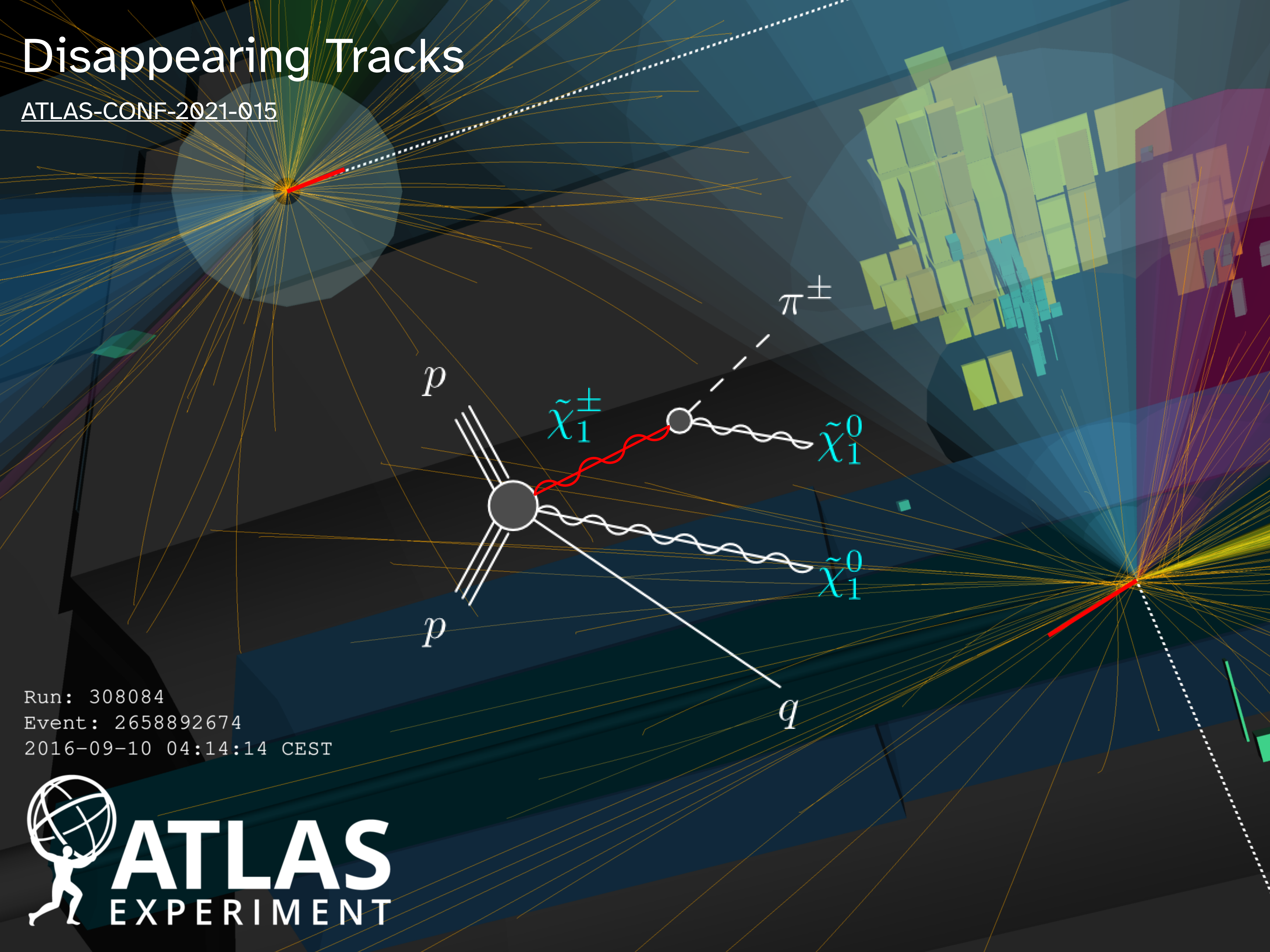
Experiments

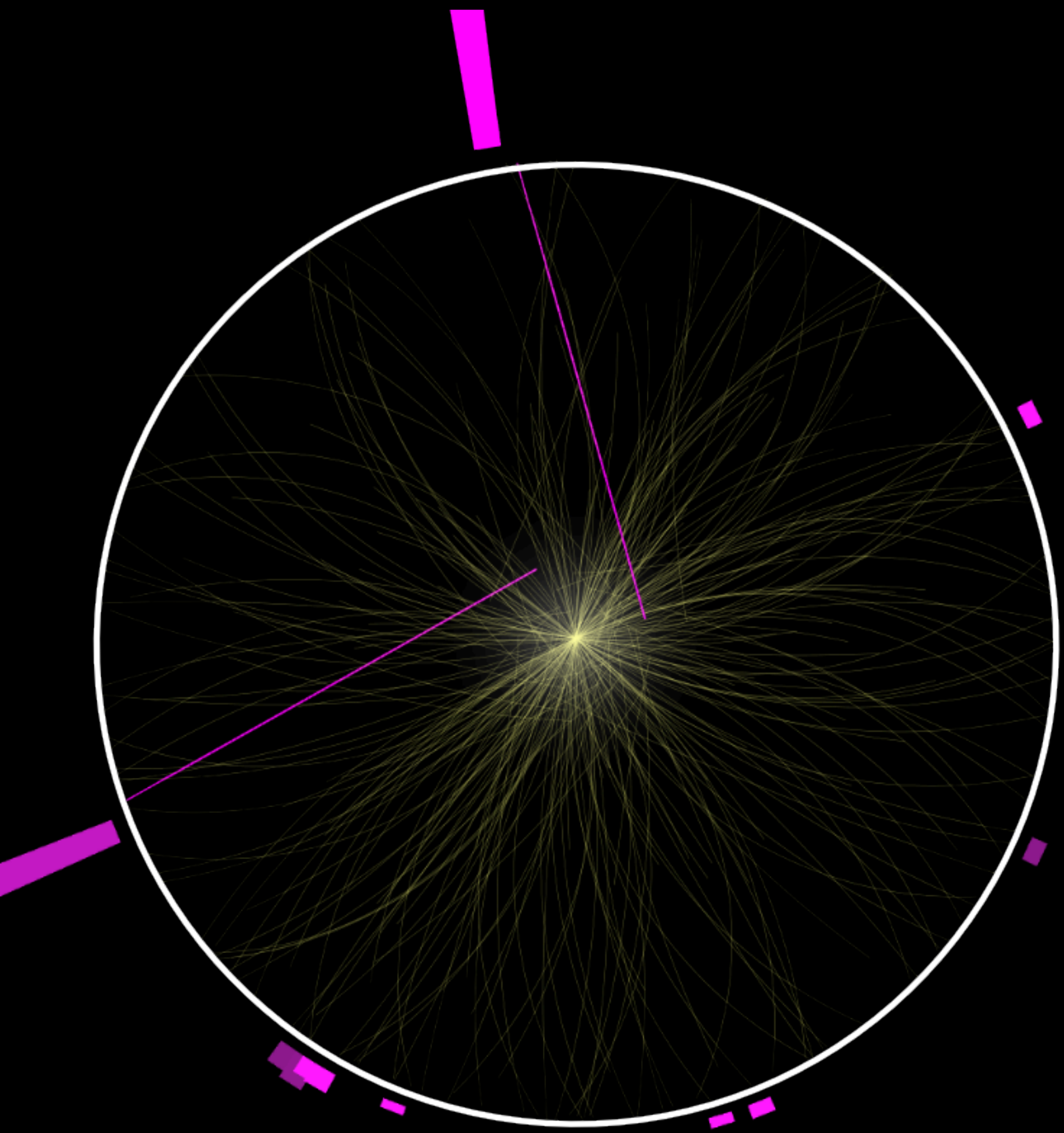


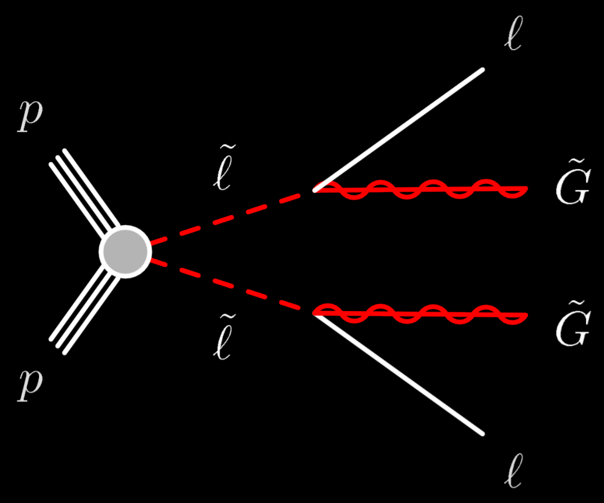


We found a golden ticket!

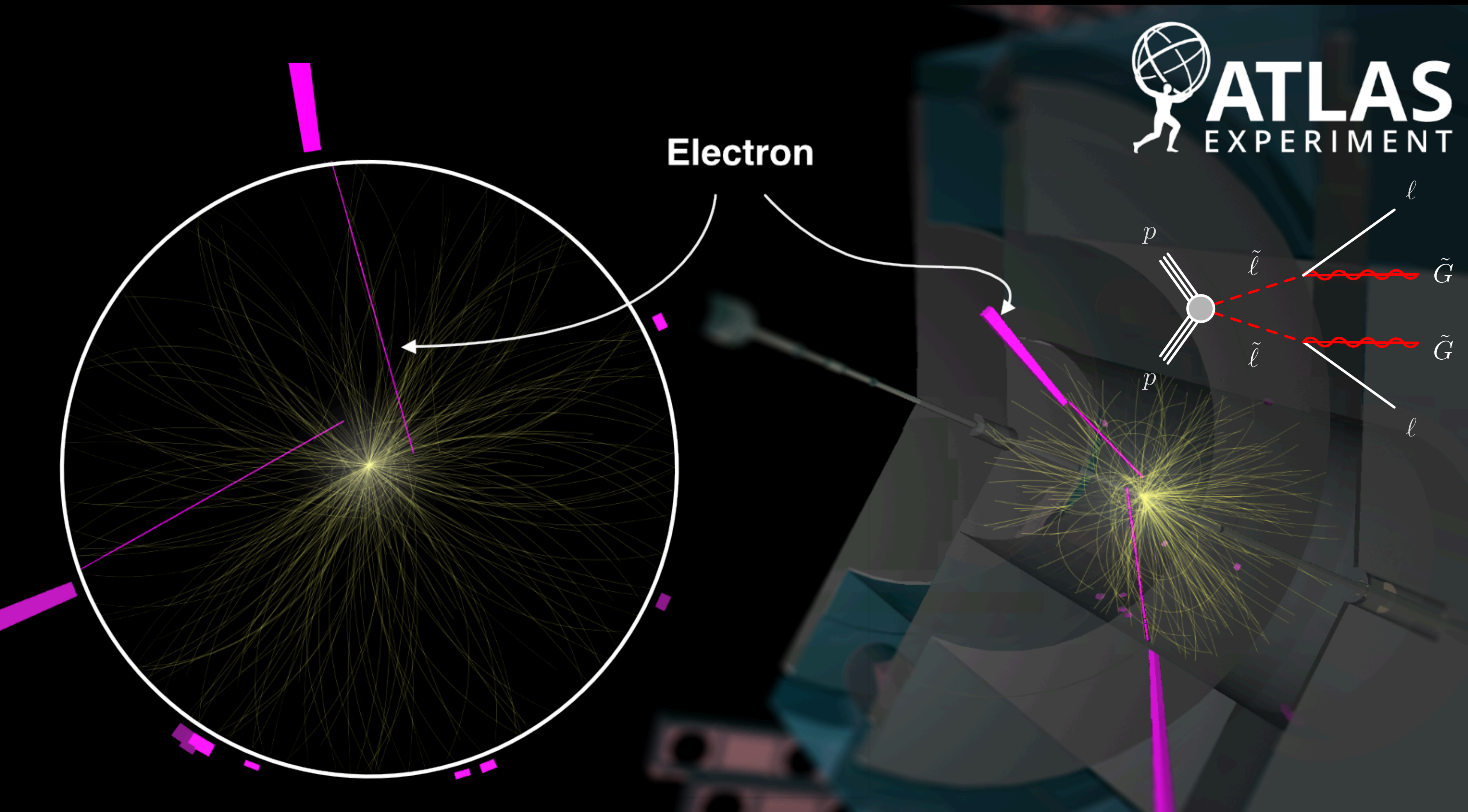
The solution to all our worries!


Disappearing Tracks
ATLAS-CONF-2021-015
p
p
$\tilde{\chi}_1^{\pm}$
$\pi^{\pm}$
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$
q
Run: 308084
Event: 2658892674
2016-09-10 04:14:14 CEST
ATLAS EXPERIMENT





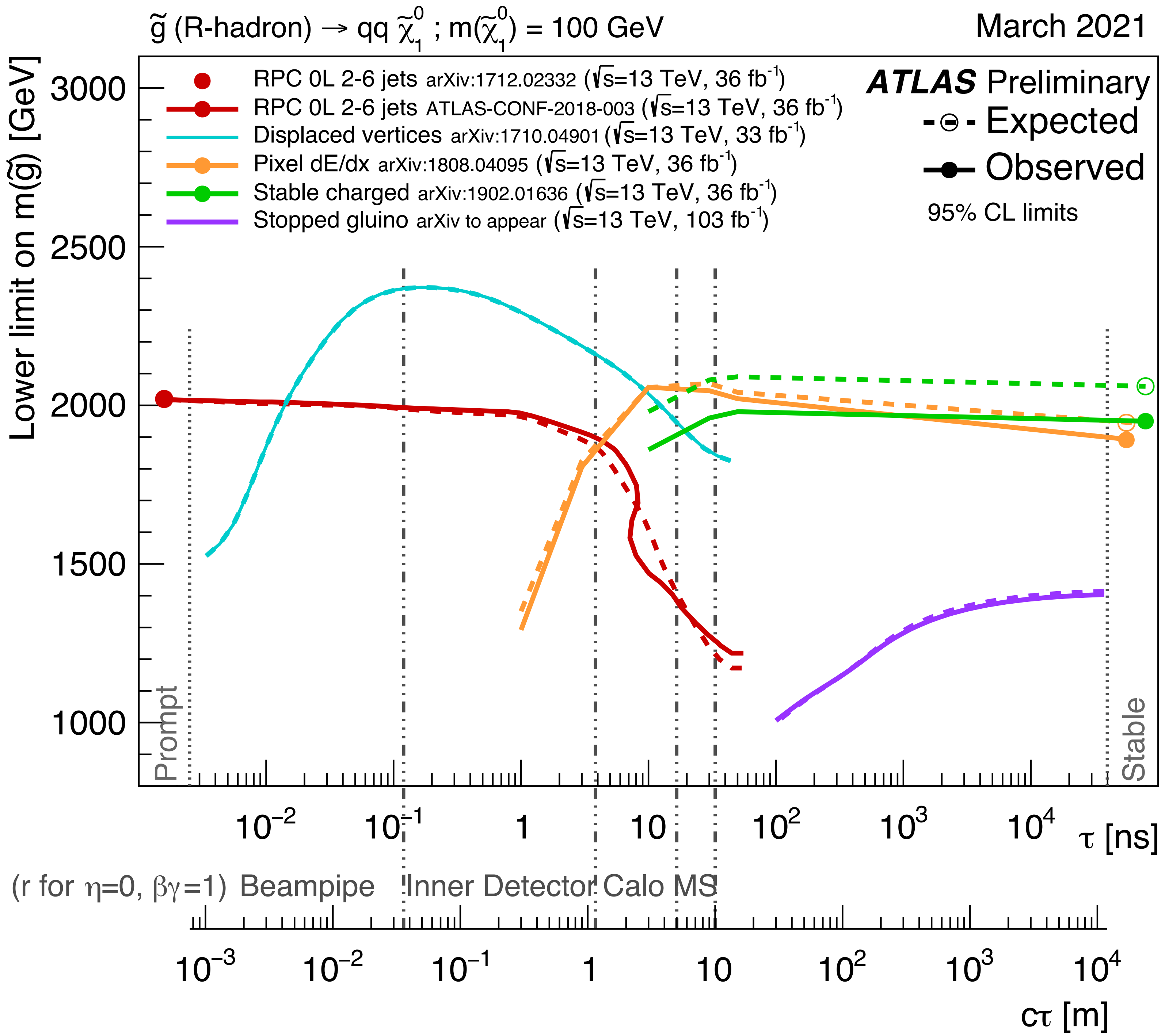
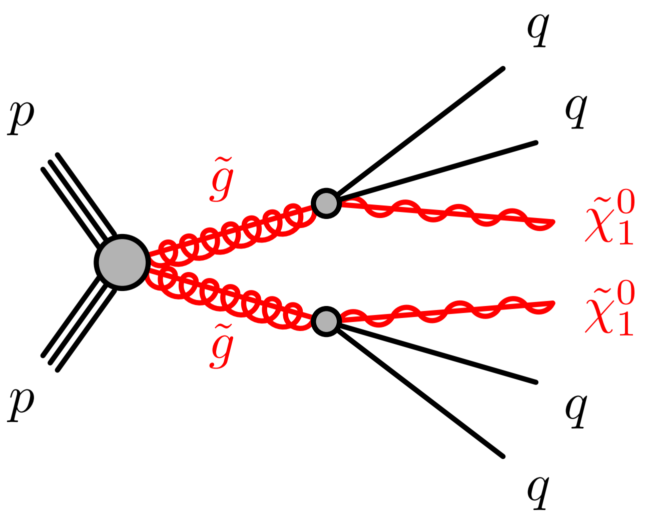
[2011.07812]

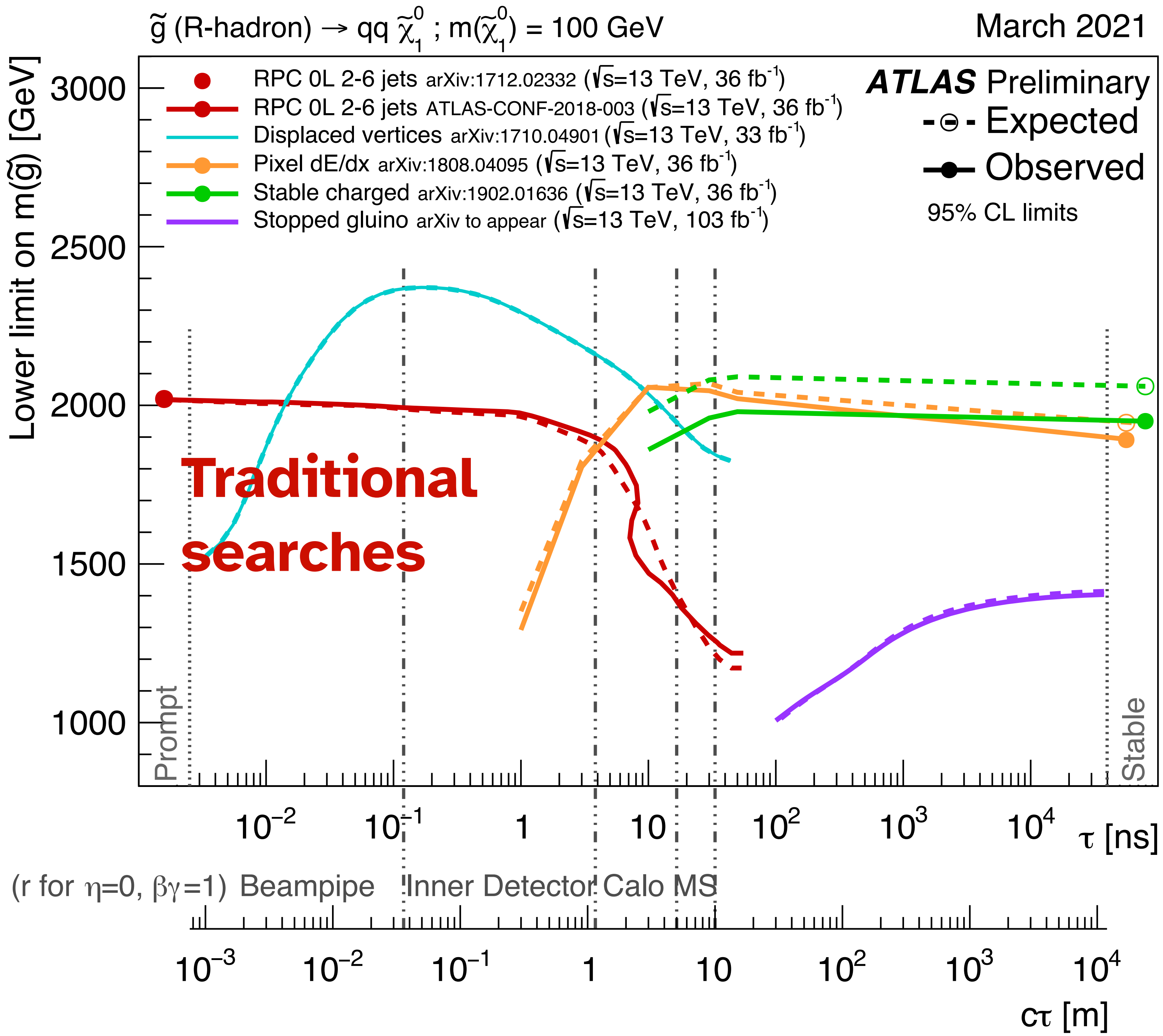


Simulated Signal Event
Selectron Pair Production $\tilde{e} \rightarrow e\tilde{G}$

$m(\tilde{e}) = 500$ GeV, $\tau(\tilde{e}) = 1$ ns

[2011.07812]


g̃ (R-hadron) → qq χ̃₁⁰ ; m(χ̃₁⁰) = 100 GeV
March 2021
ATLAS Preliminary
Expected
Observed
95% CL limits
RPC 0L 2-6 jets arXiv:1712.02332 (√s=13 TeV, 36 fb⁻¹)
RPC 0L 2-6 jets ATLAS-CONF-2018-003 (√s=13 TeV, 36 fb⁻¹)
Displaced vertices arXiv:1710.04901 (√s=13 TeV, 33 fb⁻¹)
Pixel dE/dx arXiv:1808.04095 (√s=13 TeV, 36 fb⁻¹)
Stable charged arXiv:1902.01636 (√s=13 TeV, 36 fb⁻¹)
Stopped gluino arXiv to appear (√s=13 TeV, 103 fb⁻¹)
Lower limit on m(g̃) [GeV]
Prompt
Stable
τ [ns]
(r for η=0, βγ=1) Beampipe
Inner Detector
Calo
MS
cτ [m]



g̃ (R-hadron) → qq $\tilde{\chi}_1^0$; m($\tilde{\chi}_1^0$) = 100 GeV
March 2021
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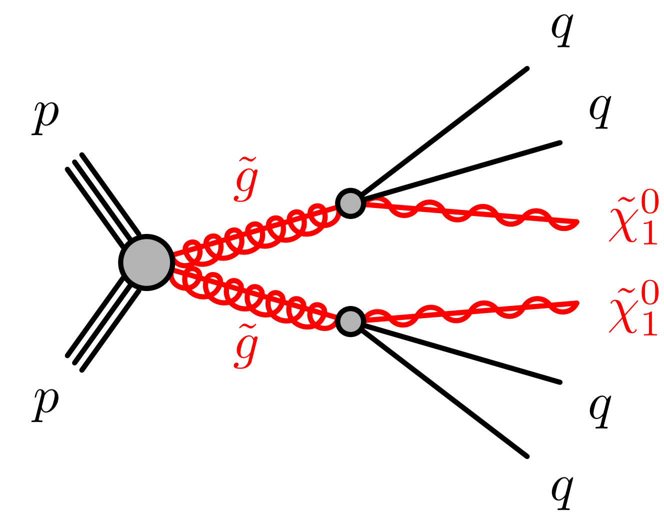
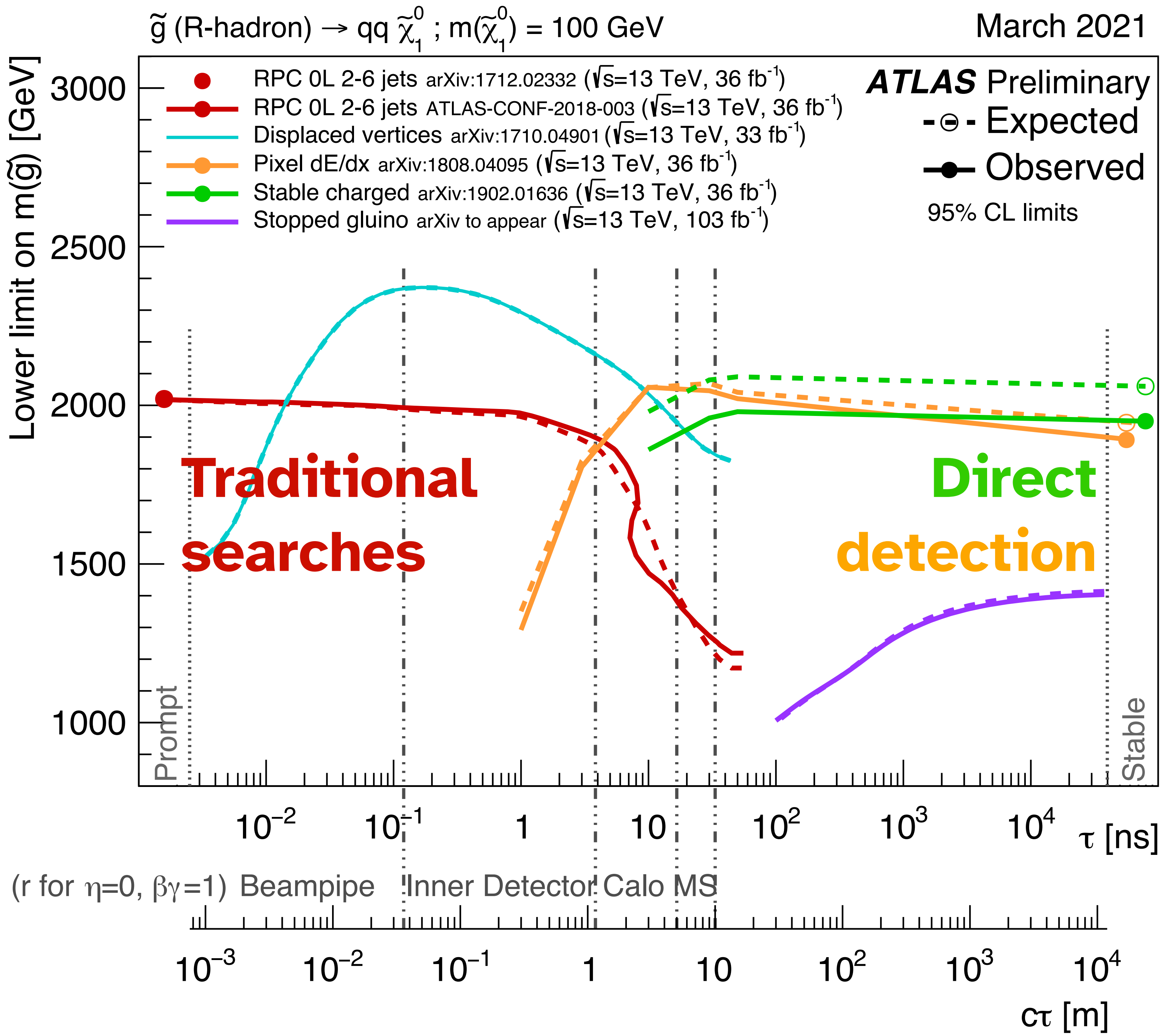
Stopped gluino arXiv to appear ($\sqrt{s}$=13 TeV, 103 fb^{-1})
ATLAS Preliminary
Expected
Observed
95% CL limits
Lower limit on m(g̃) [GeV]
3000
2500
2000
1500
1000
Traditional
searches
Prompt
Stable
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
10^{4}
τ [ns]
(r for η=0, βγ=1) Beampipe
Inner Detector
Calo
MS
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
10^{4}
cτ [m]


p
p
$\tilde{g}$
$\tilde{g}$
q
q
q
q
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$



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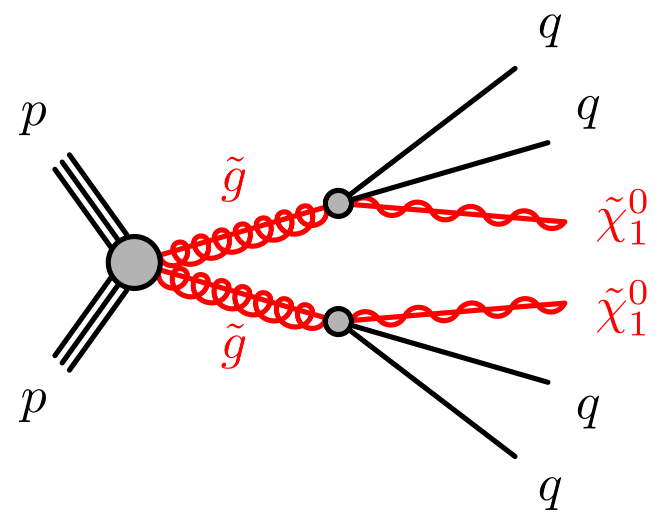
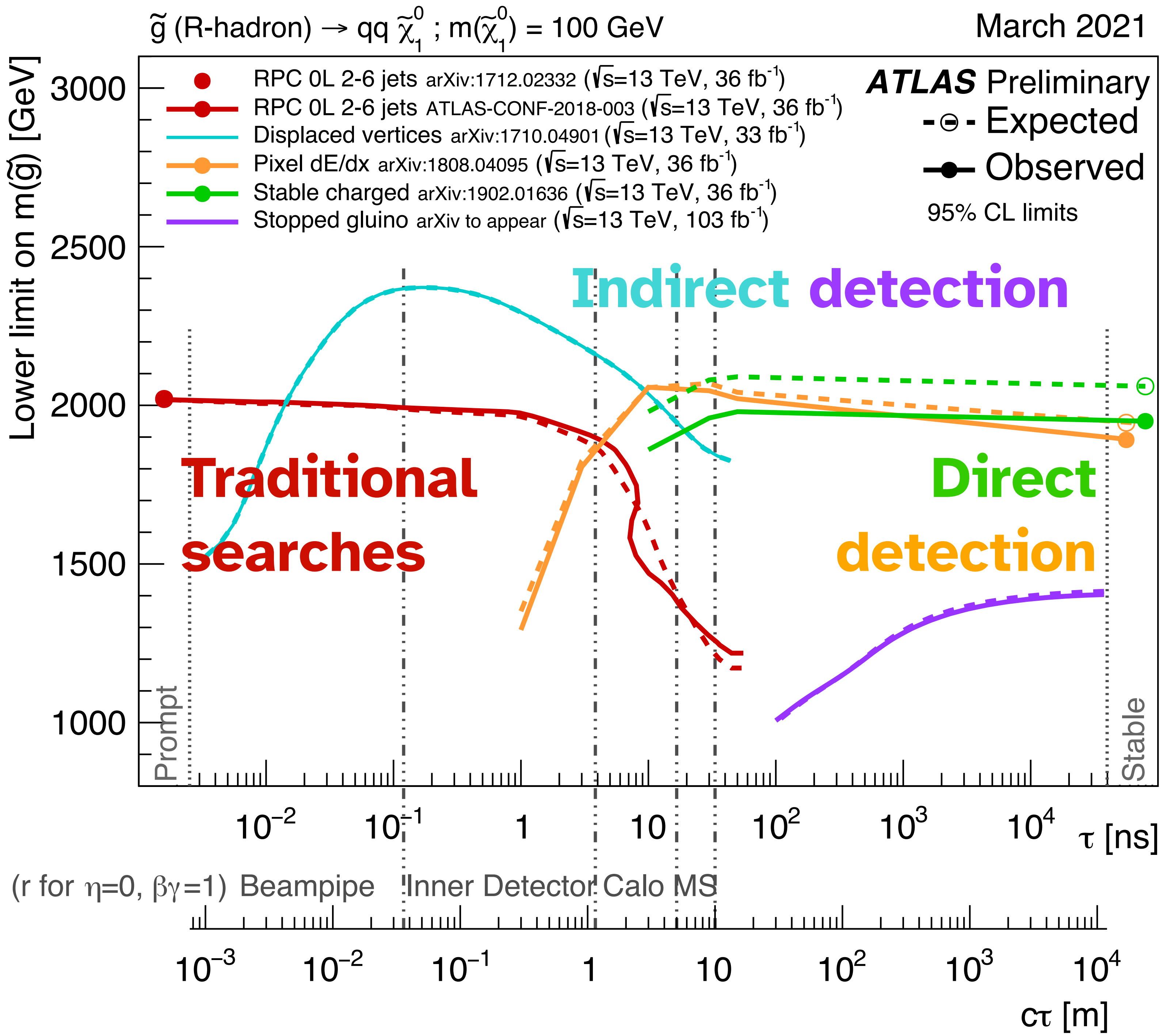
Lower limit on m(g̃) [GeV]
Traditional searches
Direct detection
Prompt
Stable
τ [ns]
(r for η=0, βγ=1) Beampipe Inner Detector Calo MS
cτ [m]



p
p
q
q
q
q
$\tilde{g}$
$\tilde{g}$
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$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Indirect detection
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Prompt
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τ [ns]
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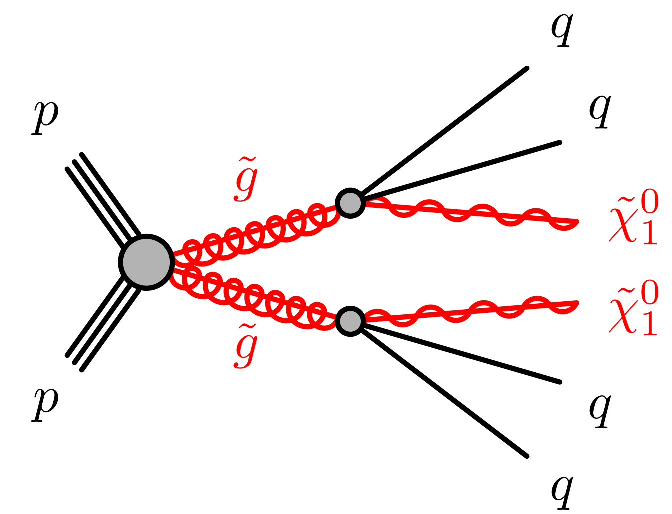
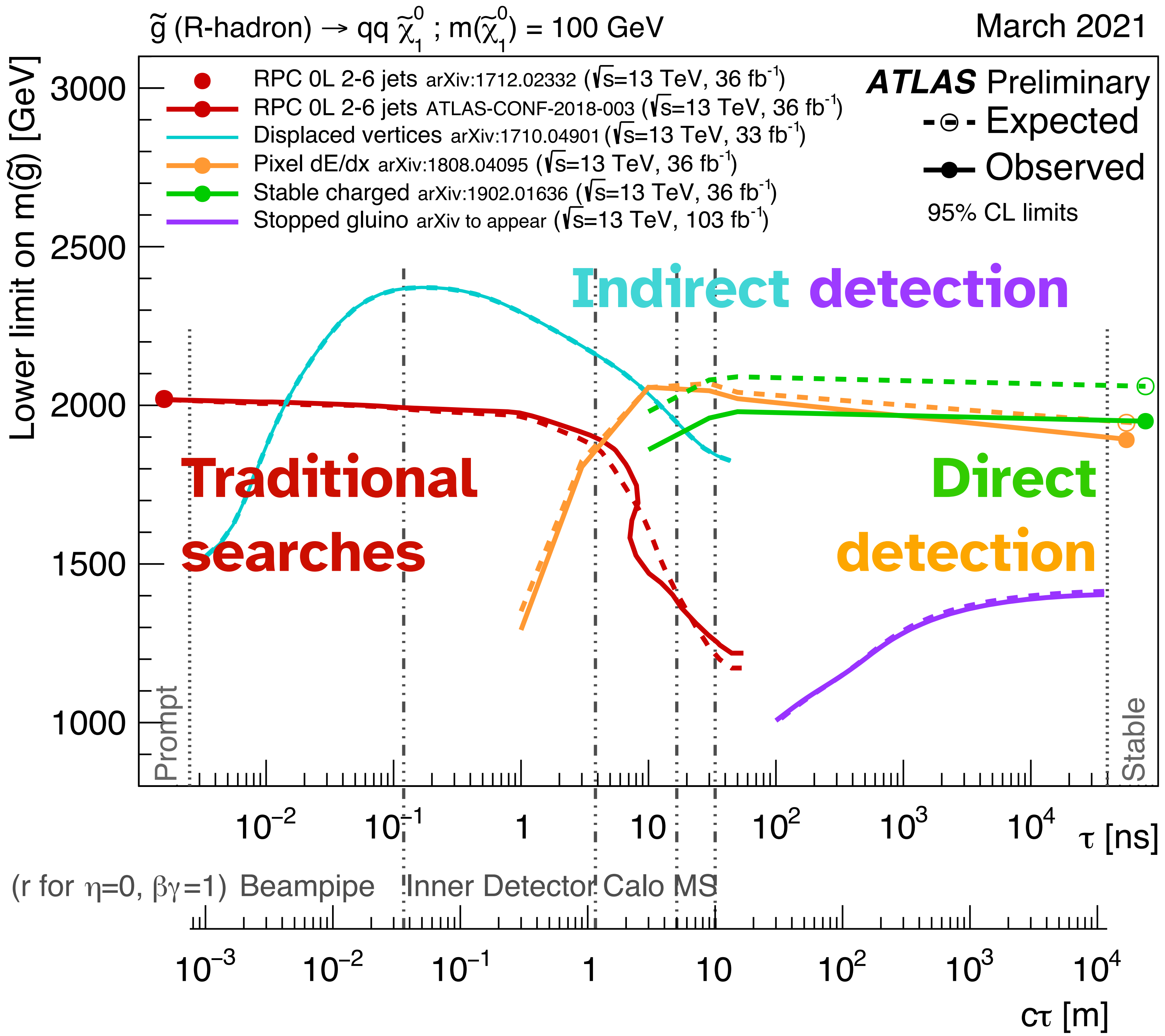
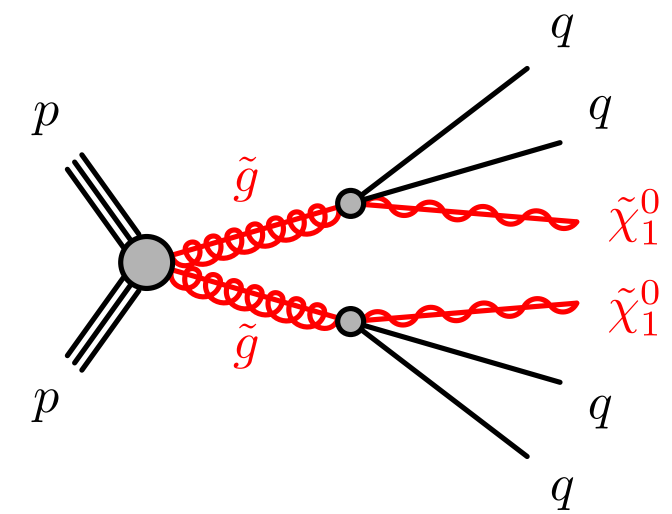
cτ [m]


p
p
g̃
g̃
q
q
q
q
χ̃⁰₁
χ̃⁰₁





Robust 2 TeV gluino limits!

[1903.04497] - J Alimena, et al

Neutral

Production \ Decay	$\gamma\gamma(+\text{inv.})$	$\gamma+\text{inv.}$	$jj(+\text{inv.})$	$jj\ell$	$\ell^+\ell^-(+\text{inv.})$	$\ell^+_\alpha\ell^-_{\beta\neq\alpha}(+\text{inv.})$
DPP: sneutrino pair or neutralino pair	†	SUSY	SUSY	SUSY	SUSY	SUSY
HP: squark pair, $\tilde{q}\to jX$ or gluino pair $\tilde{g}\to jjX$	†	SUSY	SUSY	SUSY	SUSY	SUSY
HP: slepton pair, $\tilde{\ell}\to\ell X$ or chargino pair, $\tilde{\chi}\to WX$	†	SUSY	SUSY	SUSY	SUSY	SUSY
HIG: $h\to XX$ or $\to XX+\text{inv.}$	Higgs, DM*	†	Higgs, DM*	RHν	Higgs, DM* RHν*	RHν*
HIG: $h\to X+\text{inv.}$	DM*, RHν	†	DM*	RHν	DM*	†
RES: $Z(Z')\to XX$ or $\to XX+\text{inv.}$	Z', DM*	†	Z', DM*	RHν	Z', DM*	†
RES: $Z(Z')\to X+\text{inv.}$	DM	†	DM	RHν	DM	†
CC: $W(W')\to\ell X$	†	†	RHν*	RHν	RHν*	RHν*

EM Charged

Production \ Decay	$\ell+\text{inv.}$	$jj(+\text{inv.})$	$jj\ell$	$\ell\gamma$
DPP: chargino pair or slepton pair	SUSY DM*	SUSY DM*	SUSY	†
HP: $\tilde{q}\to jX$	SUSY DM*	SUSY DM*	SUSY	†
RES: $Z'\to XX$	Z', DM*	Z', DM*	Z'	†
CC: $W'\to X+\text{inv.}$	DM*	DM*	RHν	†

QCD Charged

Production \ Decay	$j+\text{inv.}$	$jj(+\text{inv.})$	$j\ell$	$j\gamma$
DPP: squark pair or gluino pair	SUSY	SUSY	SUSY	†

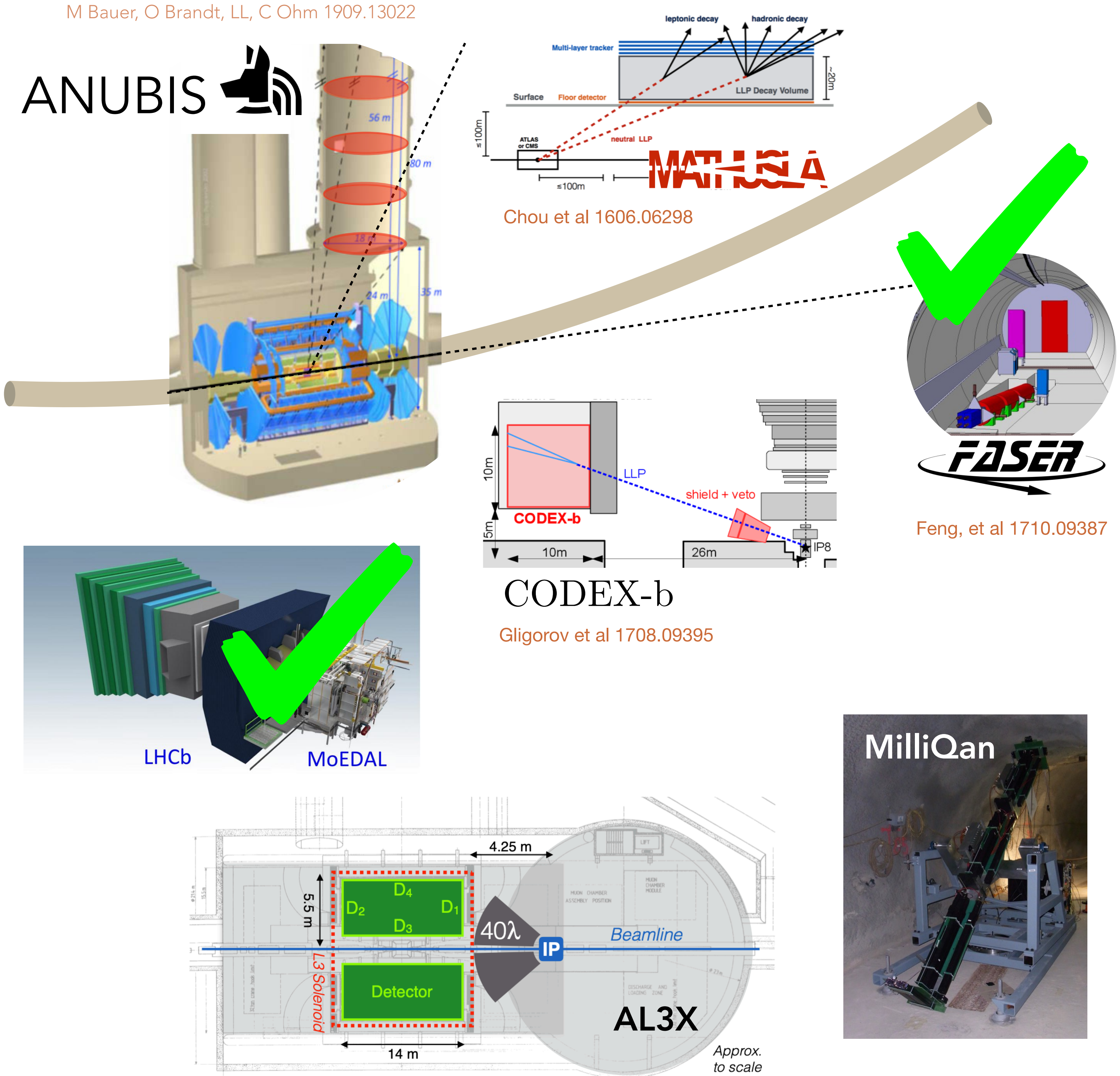
Especially since the beginning of the LLP boom, **wide signature coverage**

We've looked in most of these places now and see nothing.

n.b. Slide definitely over-selling exclusions…

LHC Run-3, Run-4+

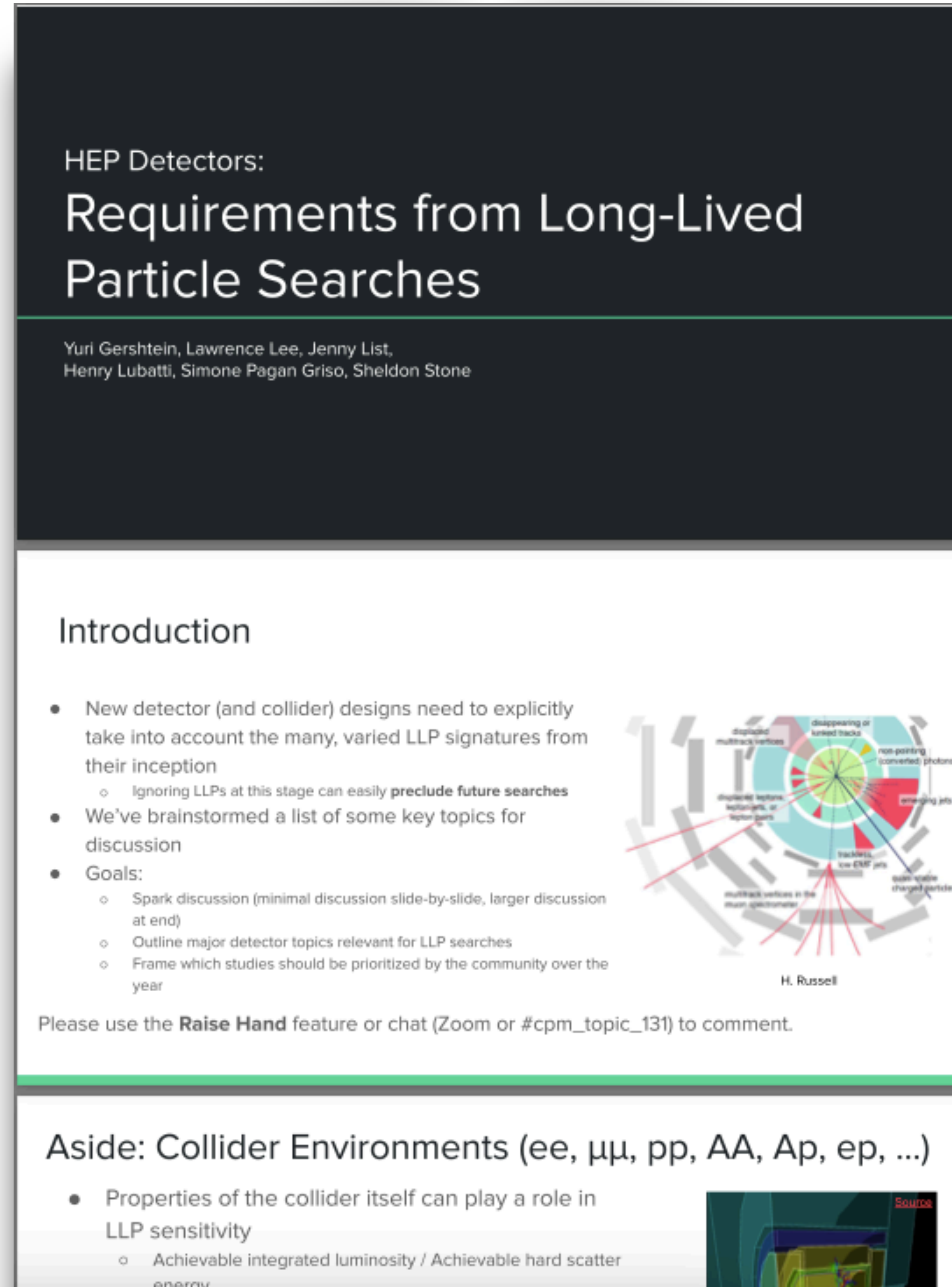
- LLP searches continue into the HL-LHC era
- Also dedicated LLP detector ideas!
- FASER is funded and under construction!
- Going to push the HL-LHC program heavily in the direction of LLPs



Slide borrowed from O. Brandt

Future colliders

- Building new detectors -> Opportunity to not preclude LLPs in detector designs
- Starting to see lots of LLP projections for future
- Session at Snowmass community planning meeting in Oct
    - We outlined important considerations for next generation of experiments
    - Detector readout constraints, timing resolution, detector granularity
- Now that the Higgs is found, the **primary** goal of any future collider is BSM
    - So LLPs can carry real monetary priority



- **LLPs are no longer the golden ticket they once were!**

- Yes, let's not preclude them in the future…

- But there's no long-lived zoo that was waiting to be found at ~O(100 GeV)

- Can **not** sacrifice finding a 2 TeV stop or a 500 GeV Higgsino WIMP to increase one LLP signature

- When it comes to building experiments, it's sometimes a zero-sum game…

τ_{LLP}

LLPs will start
to wane a bit…

But only because
we've done our
job!

Wanted to stretch the limits of our lamp post

But let's be careful before we move the lamppost entirely

It was there for a reason

$^{\tau}$LLP

LLPs will start
to wane a bit…

WANTED
TO STRETCH
THE LIMITS
OF OUR

WE'RE DOING EXACTLY OUR JOB
AND PROBING EVERY LAST THING WE CAN!

IT WAS THERE FOR A
REASON

Backup

Search for Stopped Gluinos in pp Collisions at √s = 7 TeV	1011.5861 (hep-ex)	10/pb	10.1103/PhysRevLett.106.011801	EXO10003
Search for Quark Compositeness with the Dijet Centrality Ratio in pp Collisions at √s = 7 TeV	1010.4439 (hep-ex)	2.9/pb	10.1103/PhysRevLett.105.262001	
Search for Dijet Resonances in 7 TeV pp Collisions at CMS	[illegible] (hep-ex)	2.9/pb	10.1103/PhysRevLett.105.[illegible]	

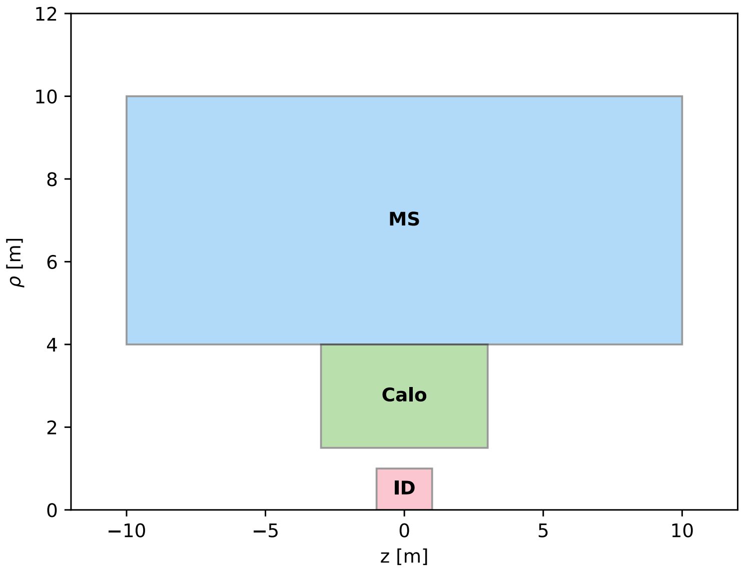
3rd ever Paper from CMS Exotica!

Gluino pair, squark pair, R-hadron; pixel ionisation, calorimeter timing	Phys.Lett. B701 (2011) 1-19	10-MAR-11	7	34 pb^{-1}	Documents | 1103.1984 | Inspire HepData | Internal
Gluino pair, squark pair, gluino-squark; 0 lepton	Phys.Lett. B701 (2011) 186-203	25-FEB-11	7	35 pb^{-1}	Documents | 1102.5290 | Inspire HepData | Internal
Gluino pair, squark pair, gluino-squark; 1 lepton	Phys.Rev.Lett. 106 (2011) 131802	11-FEB-11	7	35 pb^{-1}	Documents | 1102.2357 | Inspire HepData | Internal

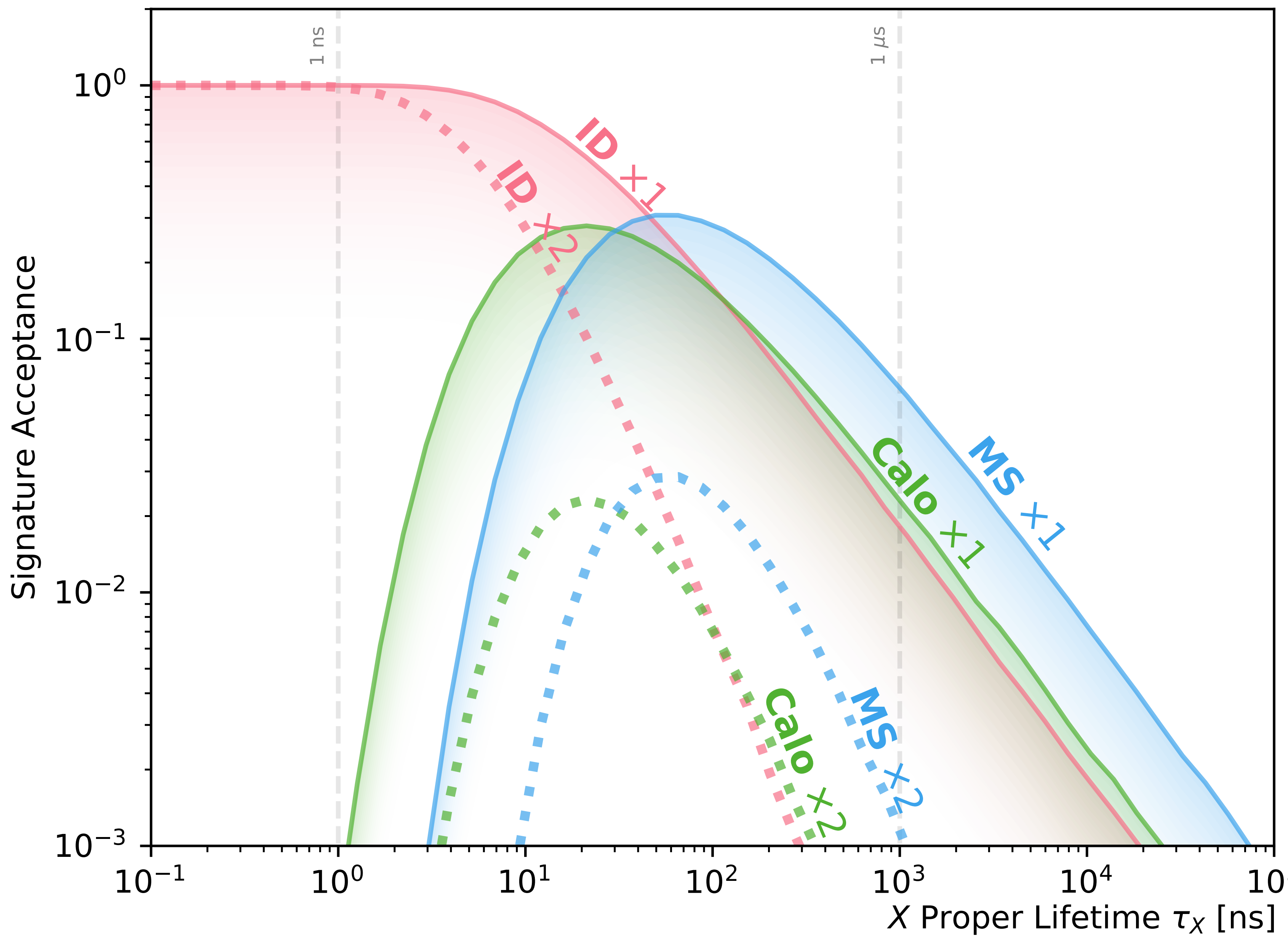
3rd ever Paper from ATLAS SUSY!

Highly ionizing particle search 7 TeV 2010	Phys.Lett. B698 (2011) 353-370	02-FEB-11	7	3.1 pb^{-1}	Documents | 1102.0459 | Inspire Internal
Di-photons plus MET search 7 TeV 2010	Phys.Rev.Lett. 106 (2011) 121803	02-JAN-11	7	3.1 pb^{-1}	Documents | 1012.4272 | Inspire Internal
Dijet angular search 7 TeV 2010	Phys.Lett. [illegible] (2011) 327-345	26-SEP-10	7	3.1 pb^{-1}	Documents | [illegible] | Inspire Internal
Dijet resonance search 7 TeV 2010	Phys. Rev. Lett. 105 (2010) 161801	13-AUG-10	7	315 nb^{-1}	Documents | 1008.2461 | Inspire Internal

4th ever Paper from ATLAS Exotics!



[1810.12602] - LL, C. Ohm, A. Soffer, T. Yu



Because the time of decay is exponential (in rest frame), getting the largest, closest detector is important.

Requiring pair-produced LLPs to both decay in far away detectors doesn't make sense…

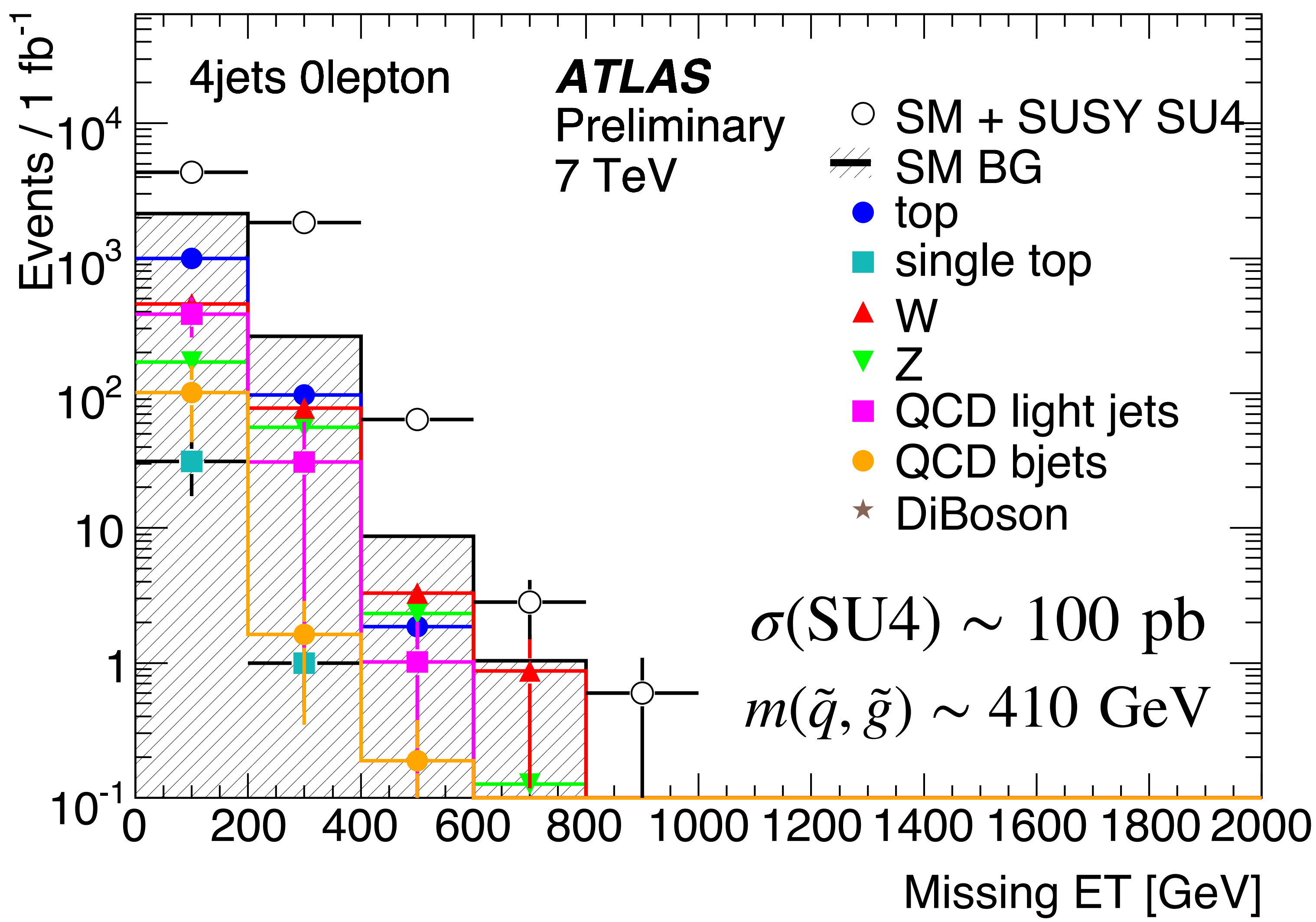
WE WERE A BIT OPTIMISTIC…

ATLAS NOTE

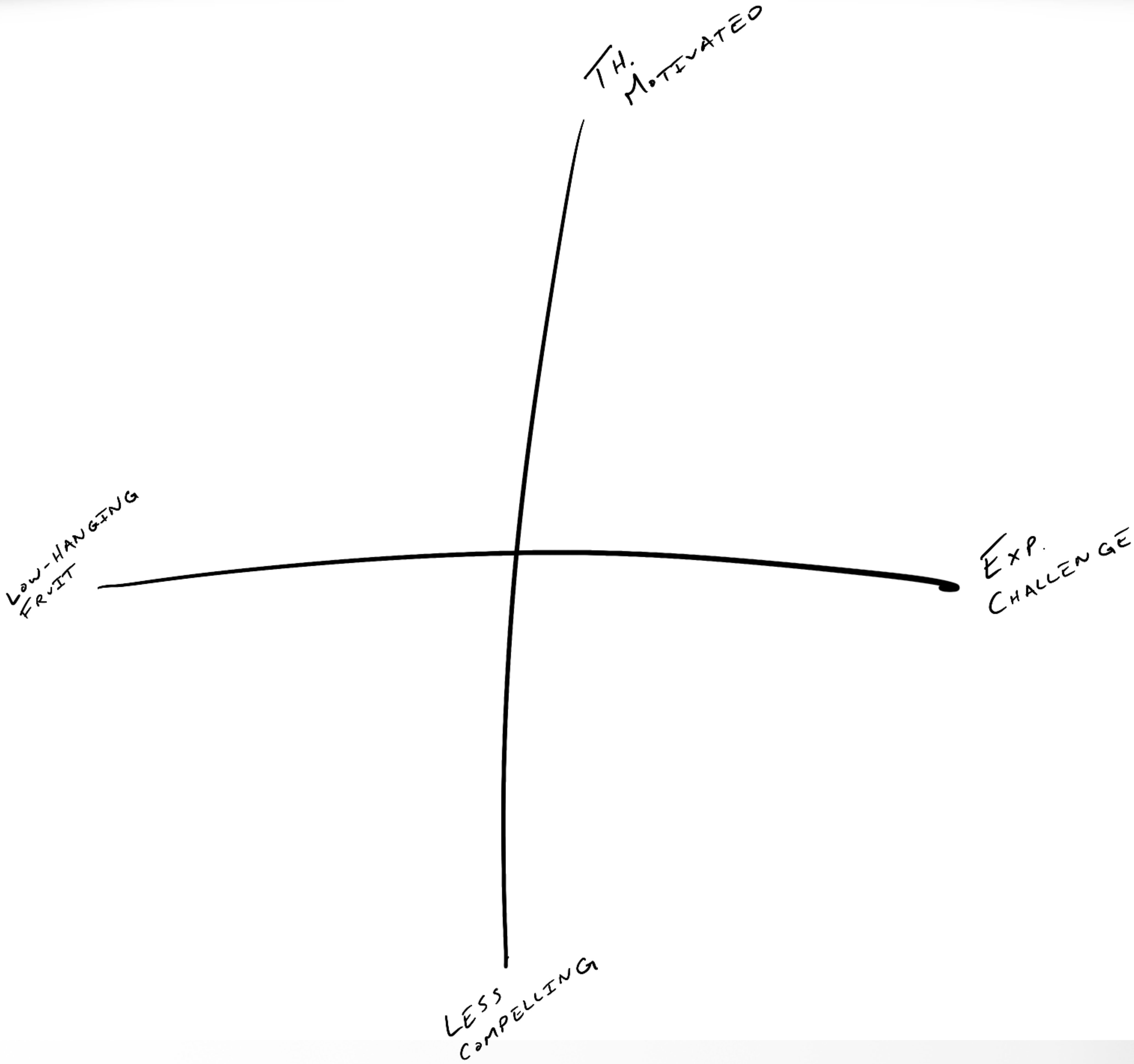
July 23, 2010

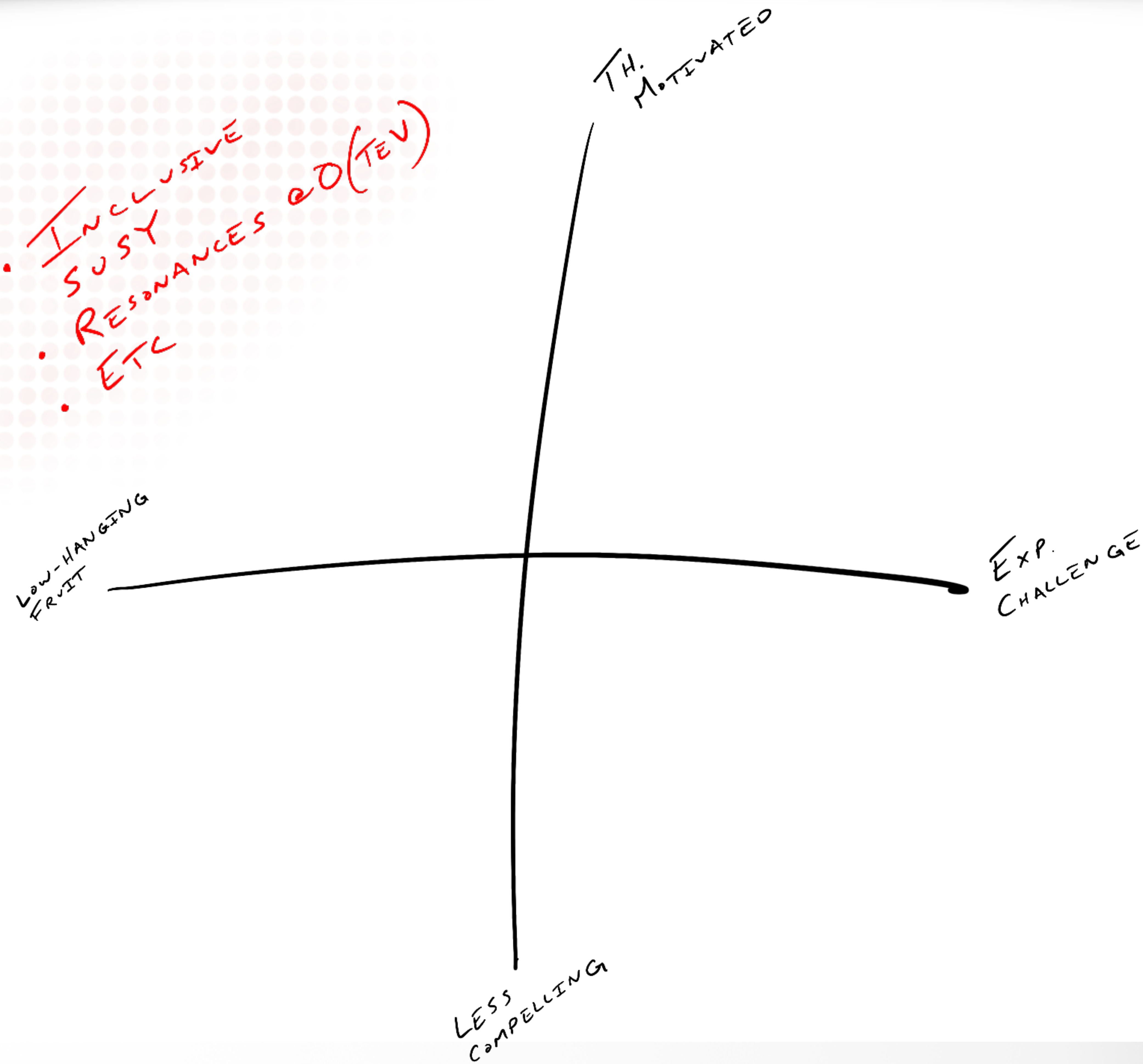
Prospects for Supersymmetry discovery based on inclusive searches at a 7 TeV centre-of-mass energy with the ATLAS detector

The ATLAS Collaboration

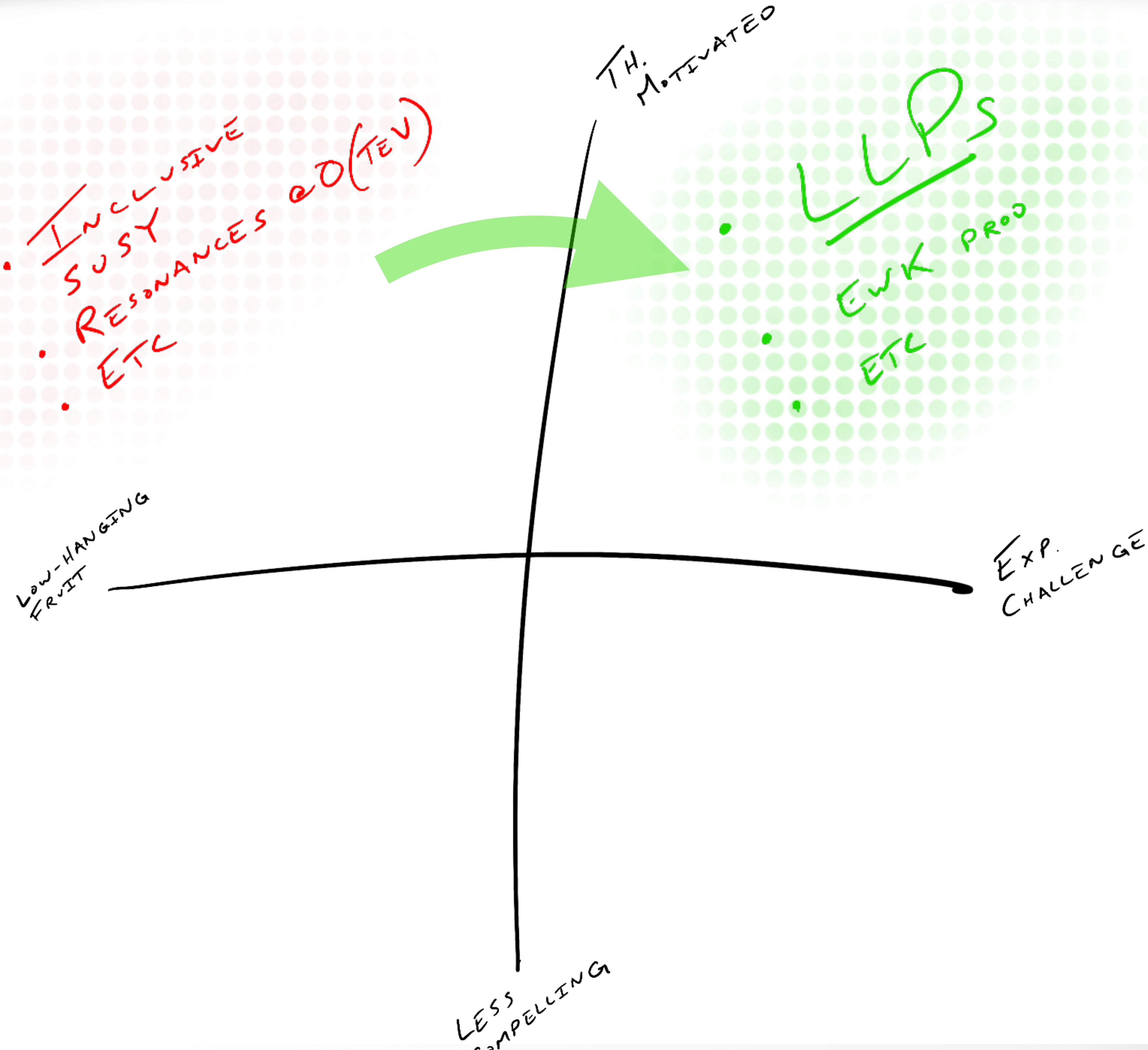


ATL-PHYS-PUB-2010-010

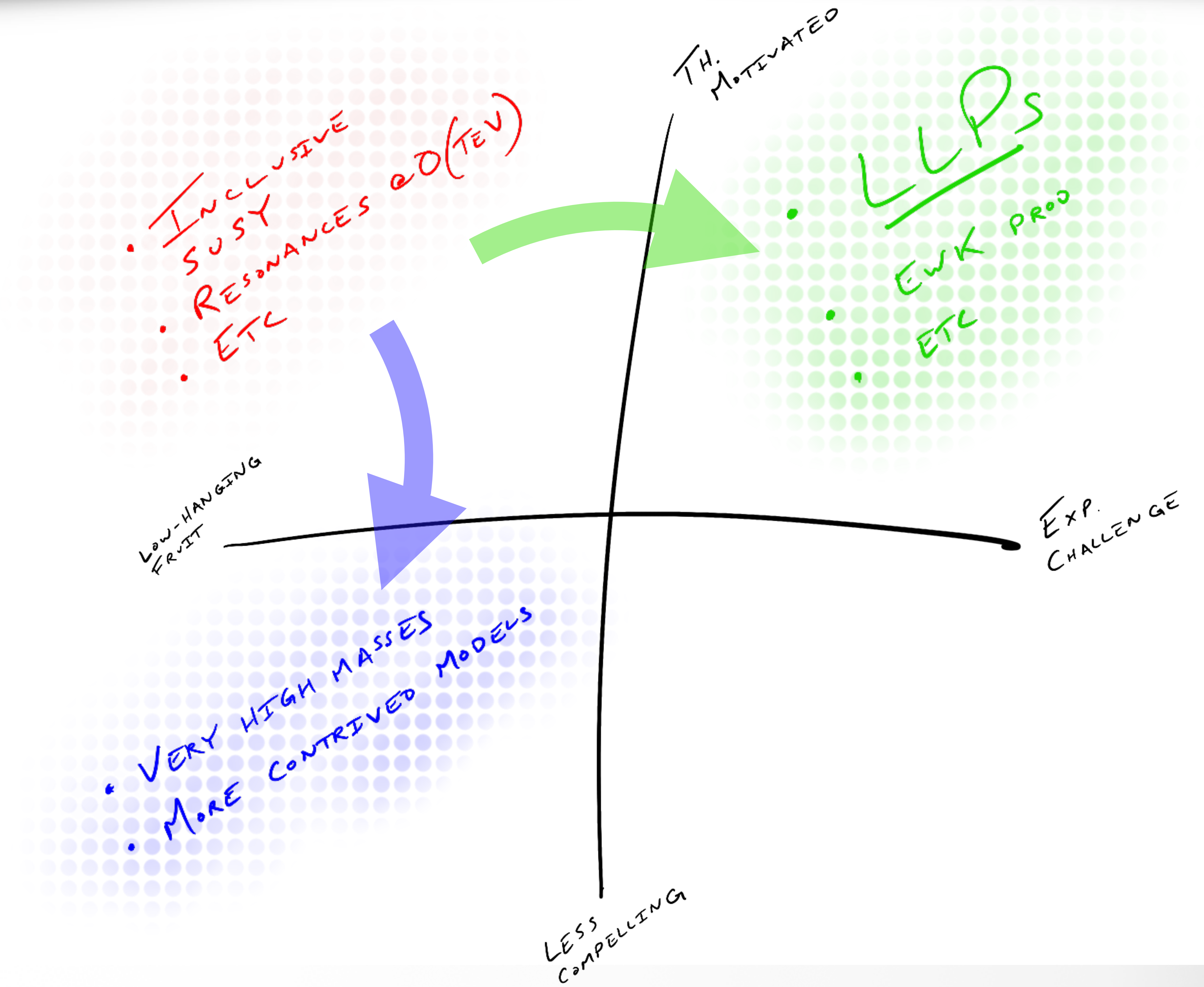

TH. MOTIVATED
LOW-HANGING FRUIT
EXP. CHALLENGE
LESS COMPELLING

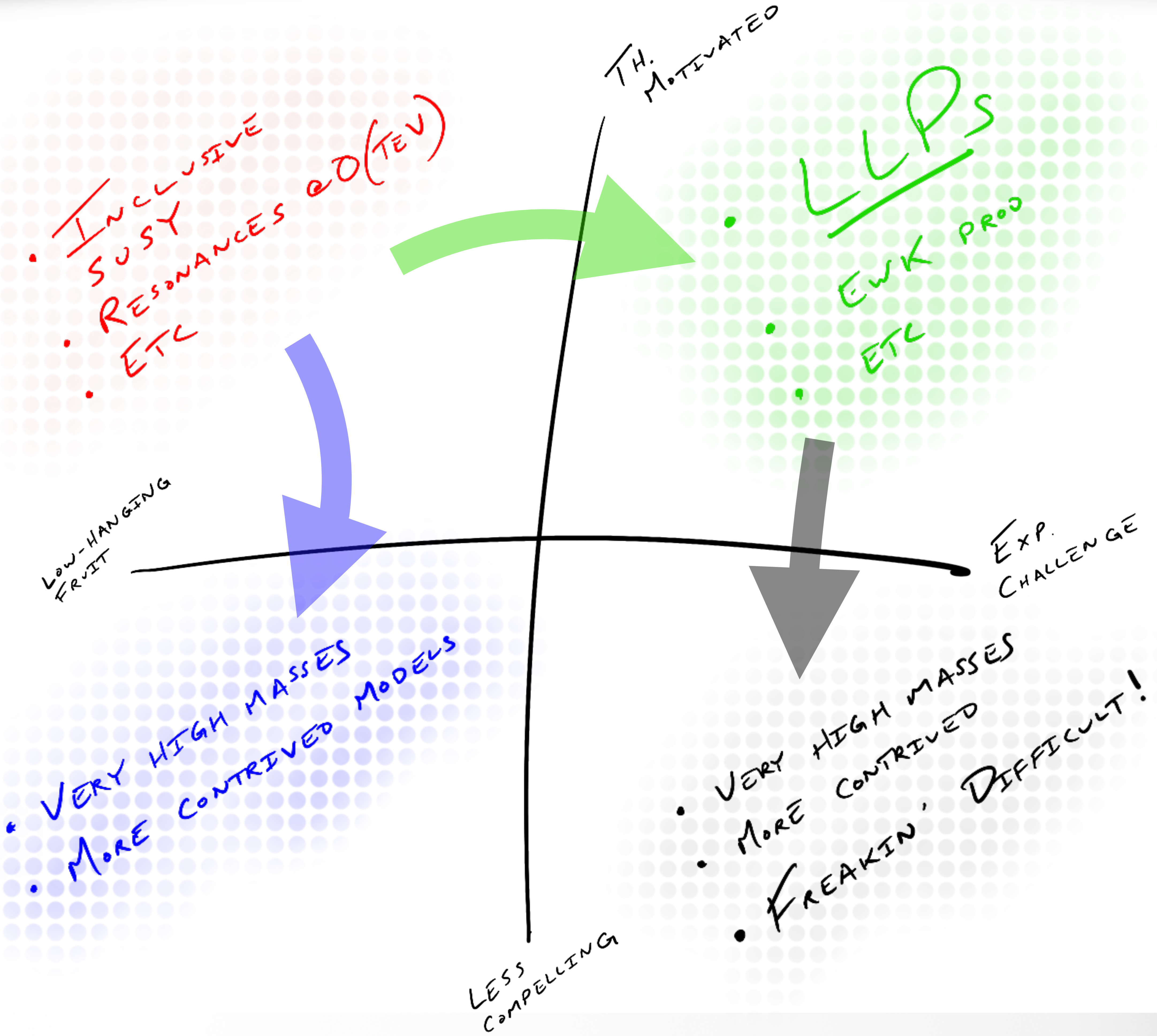


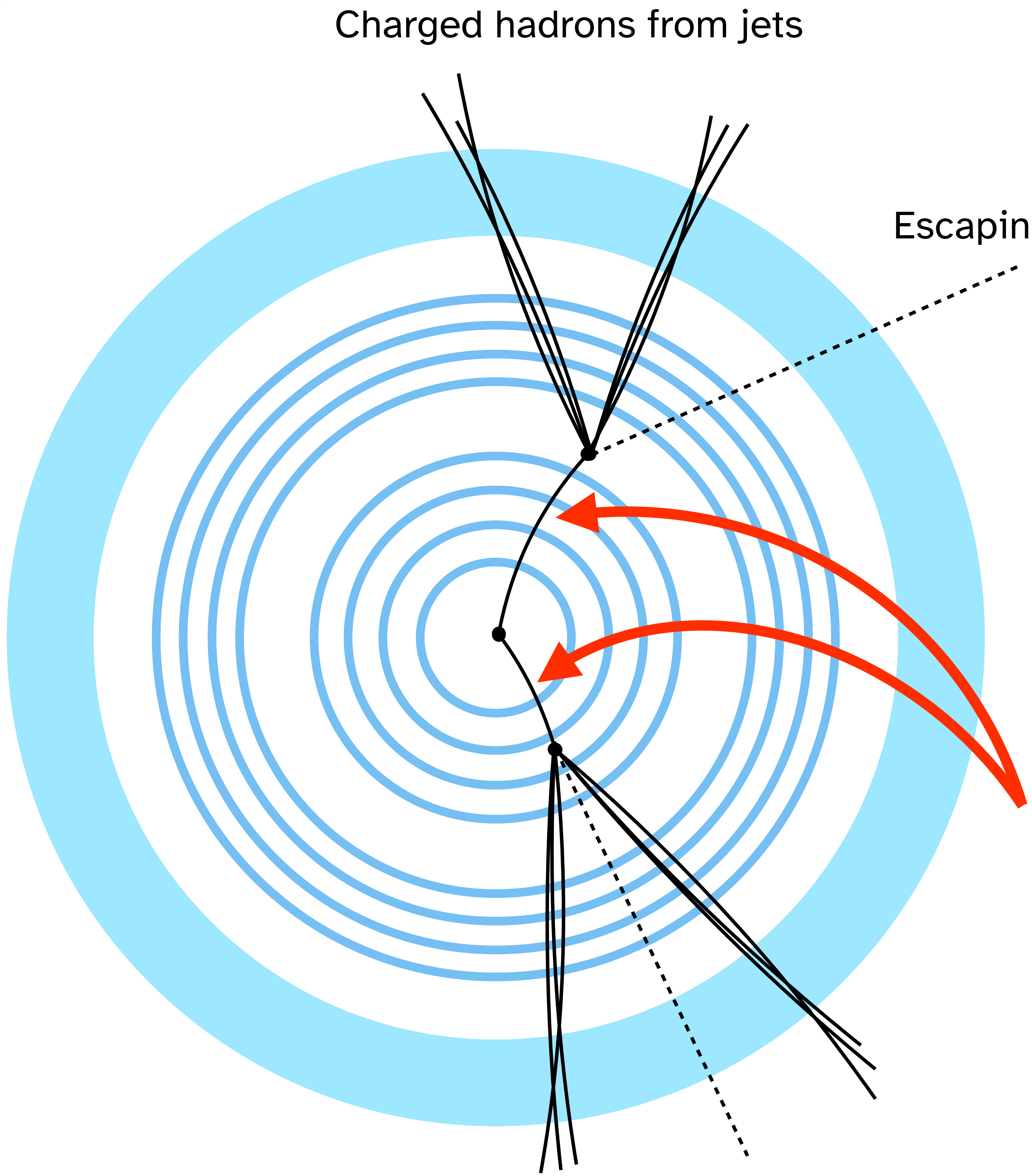
TH. MOTIVATED
• INCLUSIVE SUSY
• RESONANCES @O(TEV)
• ETC
LOW-HANGING FRUIT
EXP. CHALLENGE
LESS COMPELLING

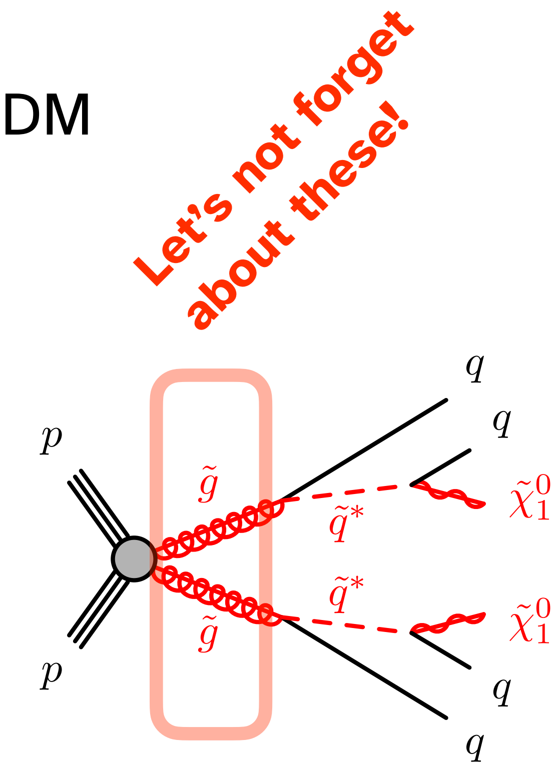


Th. Motivated
Inclusive SUSY
Resonances @O(TeV)
Etc
LLPs
EWK prod
Etc
Low-Hanging Fruit
Exp. Challenge
Less Compelling


TH. MOTIVATED
LESS COMPELLING
LOW-HANGING FRUIT
EXP. CHALLENGE
• INCLUSIVE SUSY
• RESONANCES @O(TEV)
• ETC
• LLPS
• EWK PROD
• ETC
• VERY HIGH MASSES
• MORE CONTRIVED MODELS


Th. Motivated
Low-Hanging Fruit
Exp. Challenge
Less Compelling
• Inclusive SUSY
• Resonances @O(TeV)
• Etc
LLPs
• EWK Prod
• Etc
• Very High Masses
• More Contrived Models
• Very High Masses
• More Contrived
• Freakin' Difficult!



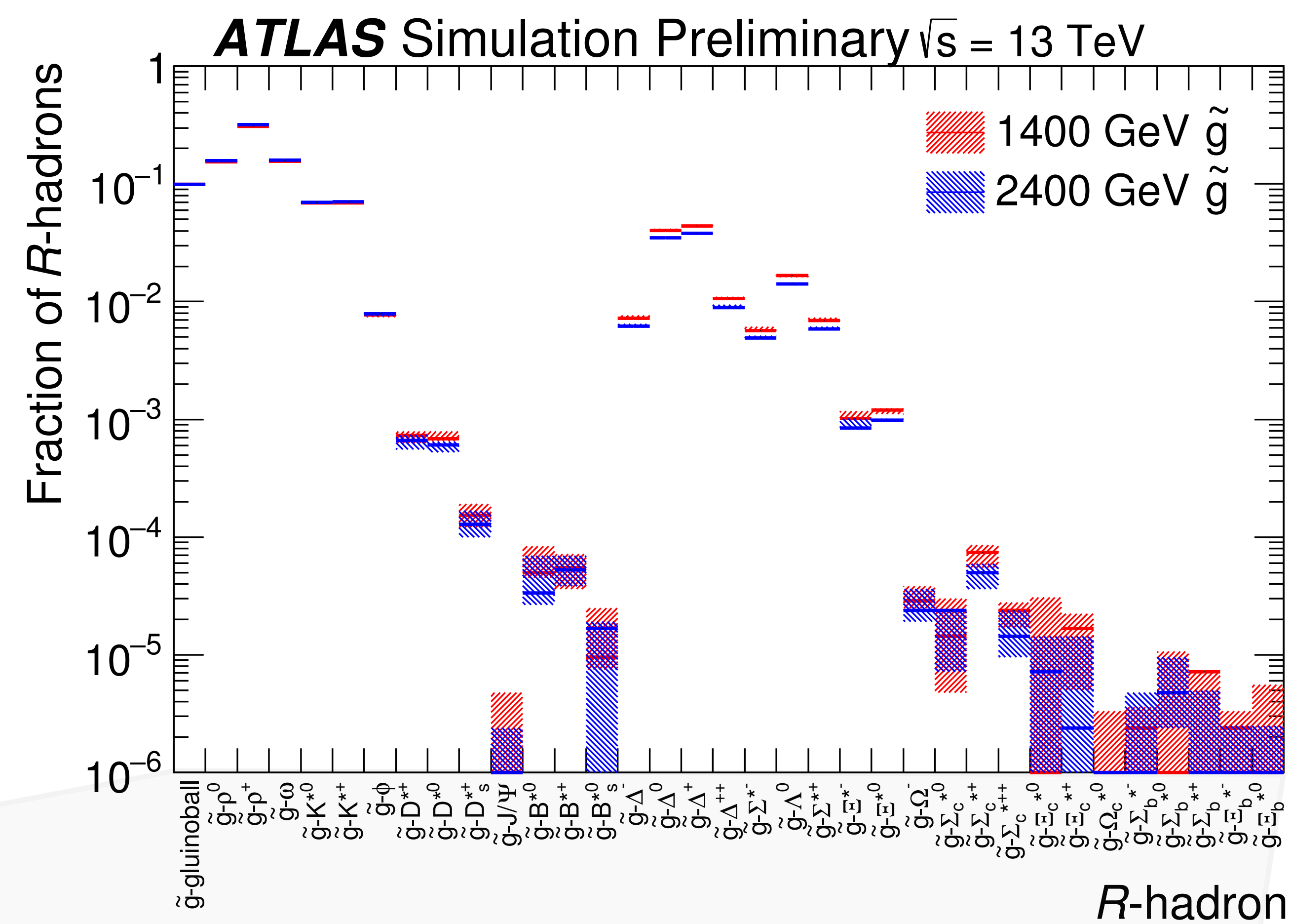


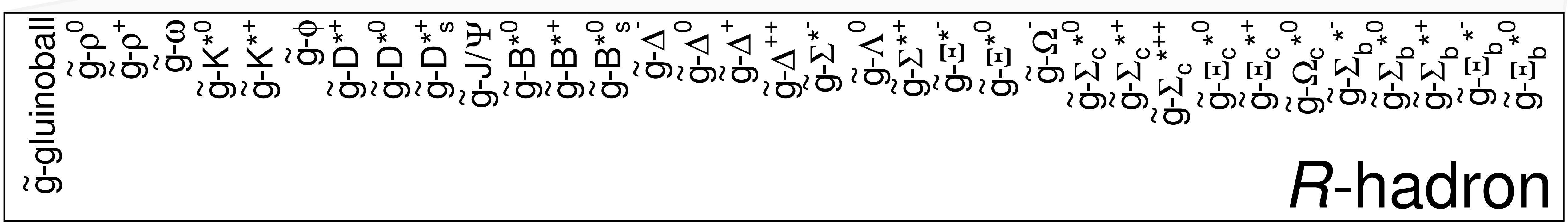
But R-Hadrons carry SM charge!

R-Hadron Spectrum

- SUSY Gluino is a color octet (like a gluon)
  - Hadronization process is just SM-dynamics 🙂
  - (Unfortunately it's QCD 😬)
- Gluino picks up SM spectator partons to form a color-singlet
- Population of R-Hadrons can vary w/ model
  - Using different constituent quark mass assumptions, we assemble space of RH spectra
  - Giving their frequency and mass spectrum
  - The properties of the lightest R-Hadron are particularly important

ATL-PHYS-PUB-2019-019

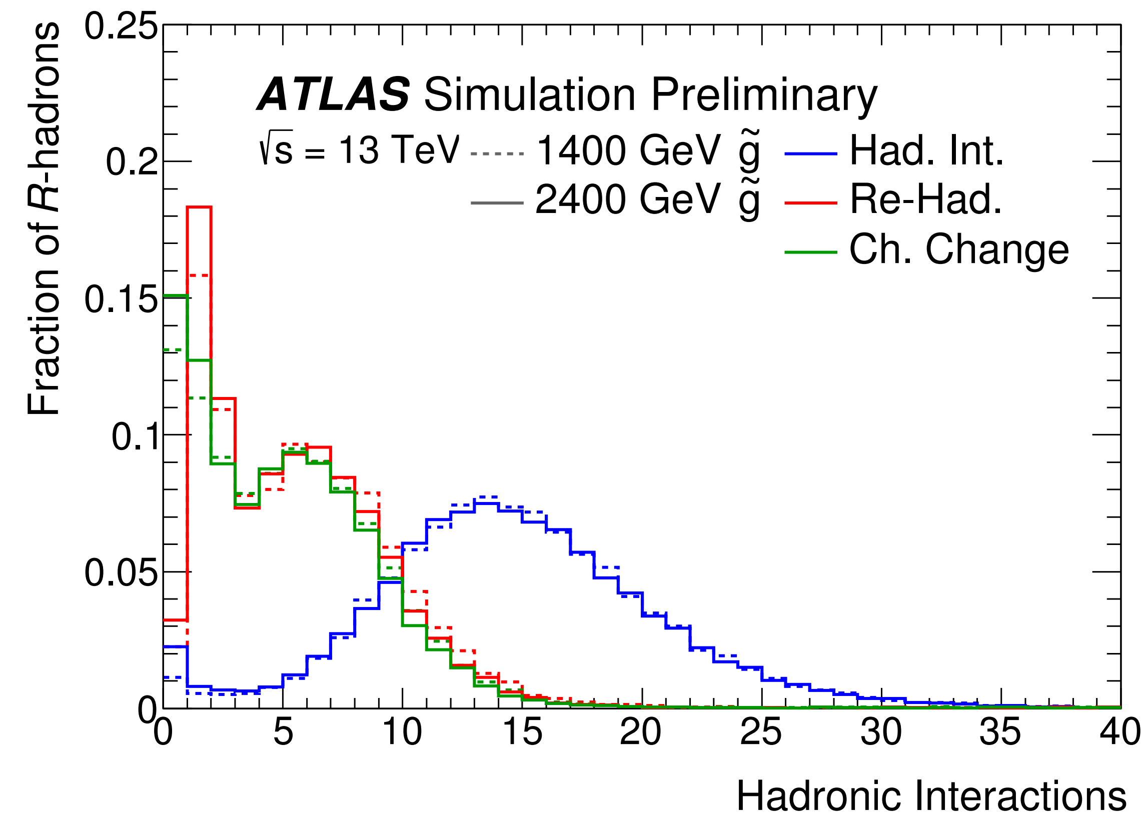




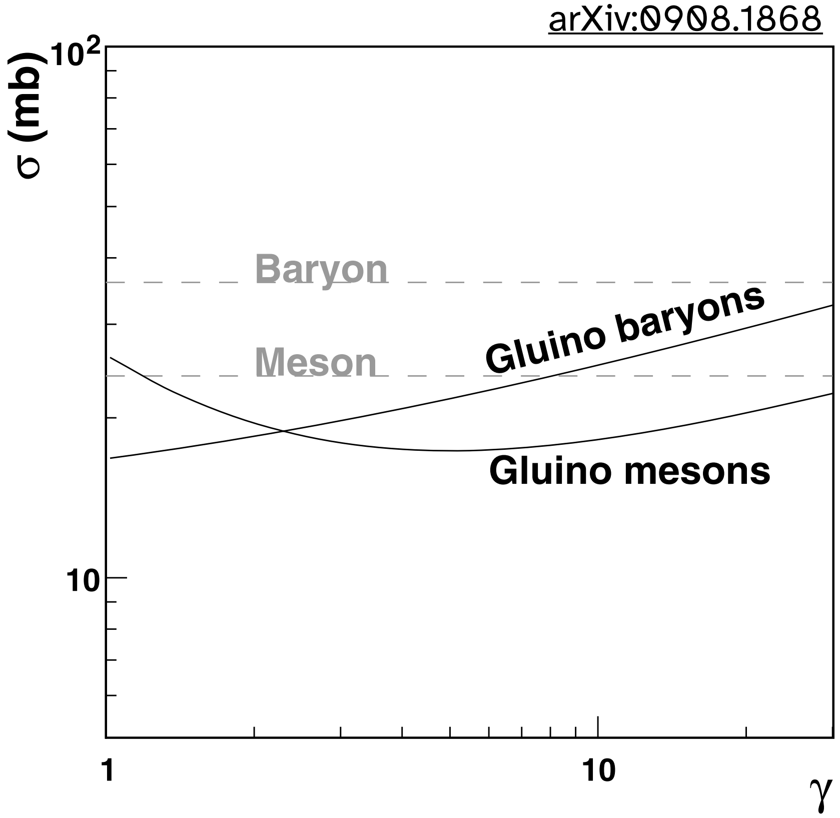
INTERACTIONS

- As R-Hadron travels through material, lots of hadronic interactions
- Many interactions will change species, and many will even change electric charge!
- R-Hadron-to-nucleon interaction cross section using "Triple Regge" model

ATL-PHYS-PUB-2019-019

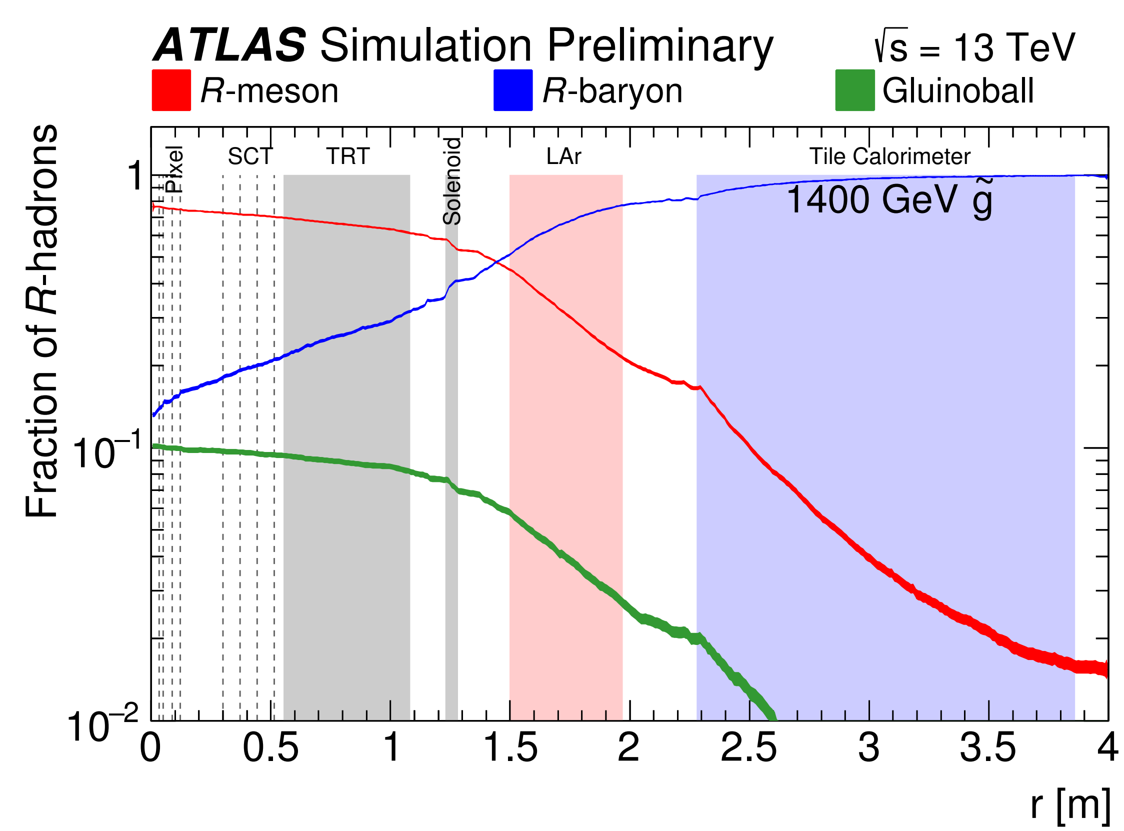


arXiv:0908.1868



Generic model

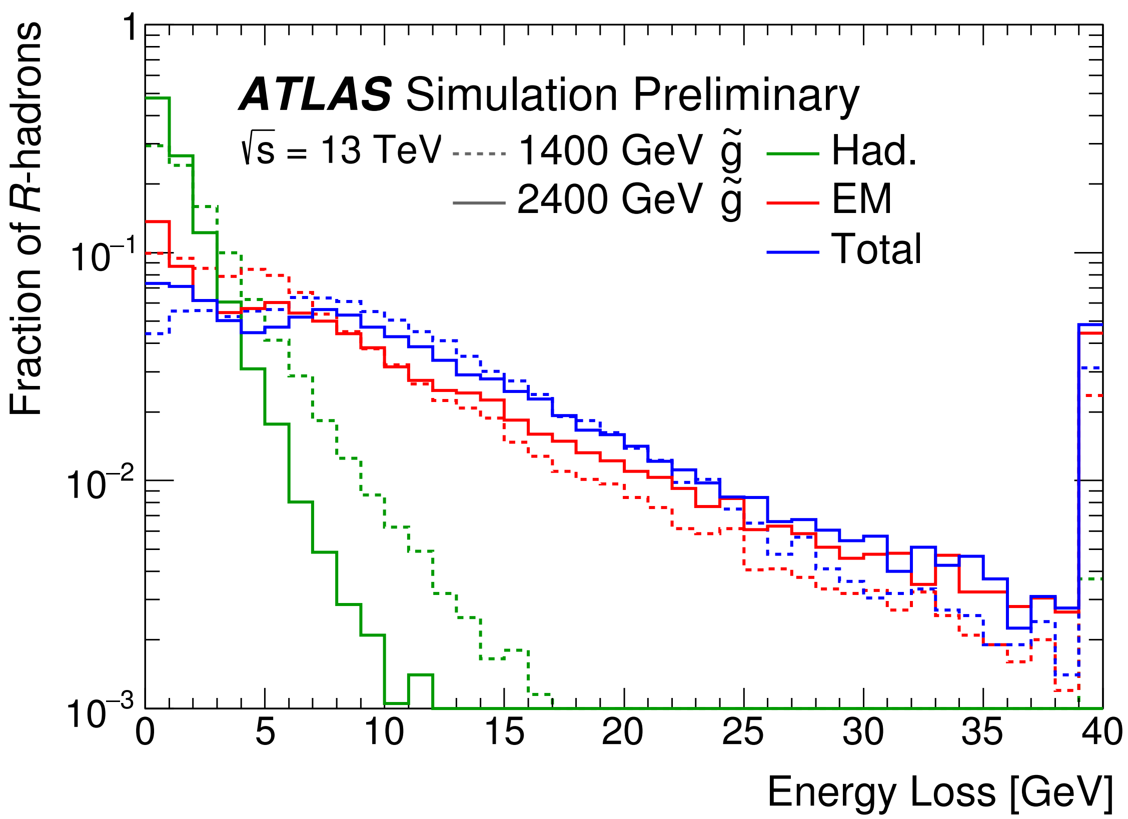
Triple Regge model

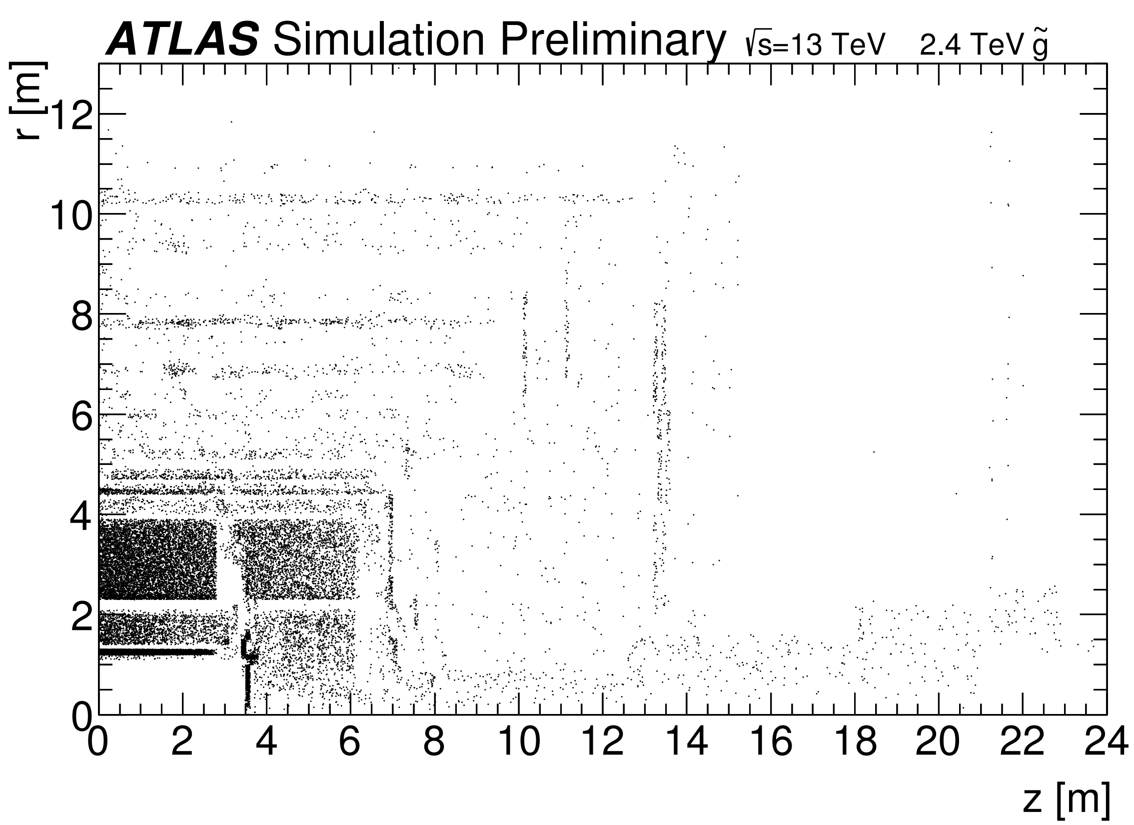


Energy Loss

- R-Hadrons will lose energy as they traverse the detector
    - Both EM and hadronic effects contribute
- Interacting LLPs could lose *all* momentum and come to **rest** in detector material
    - Depending on τ, could decay much later
    - (Keep an eye out for an updated ATLAS search…)

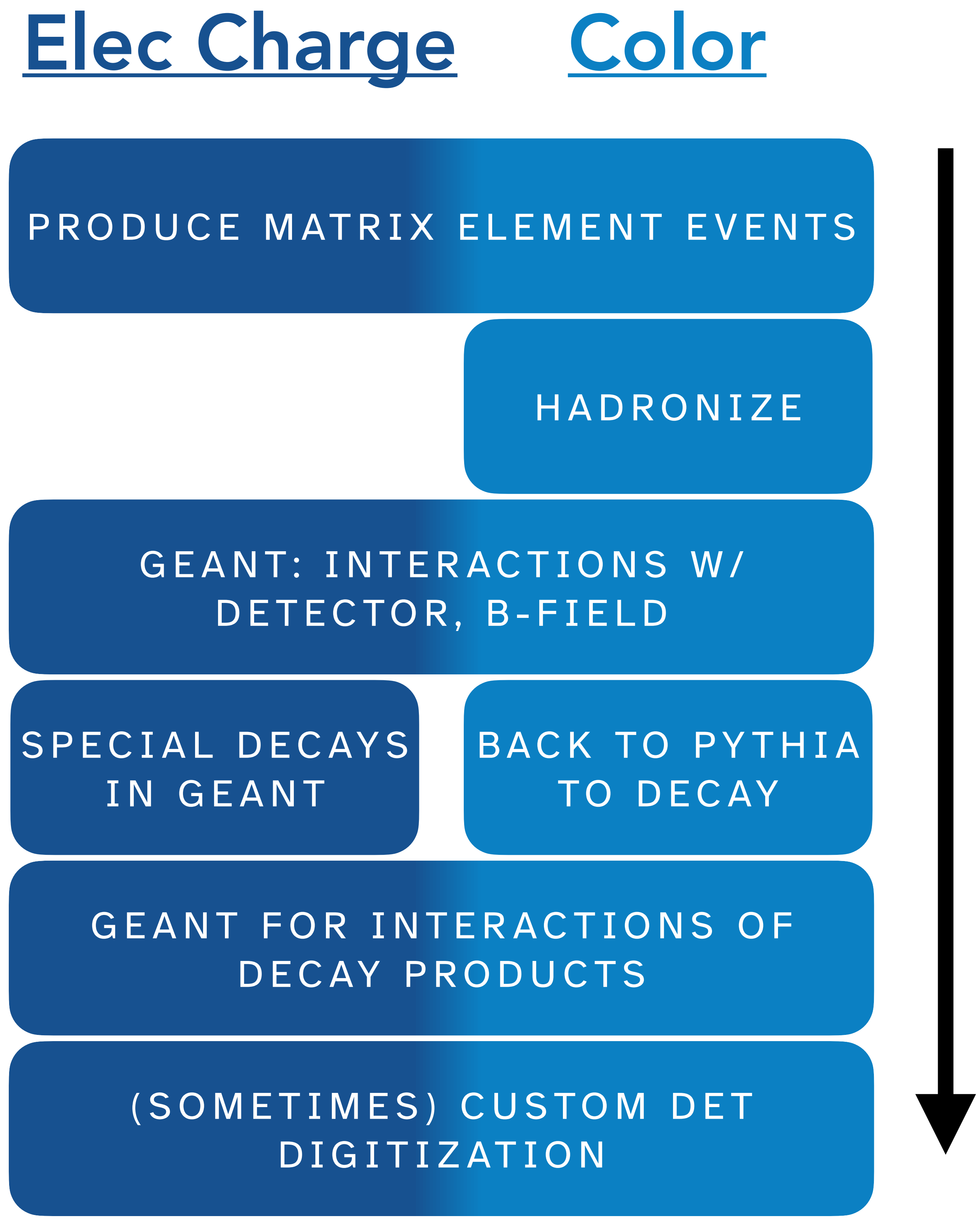
ATL-PHYS-PUB-2019-019





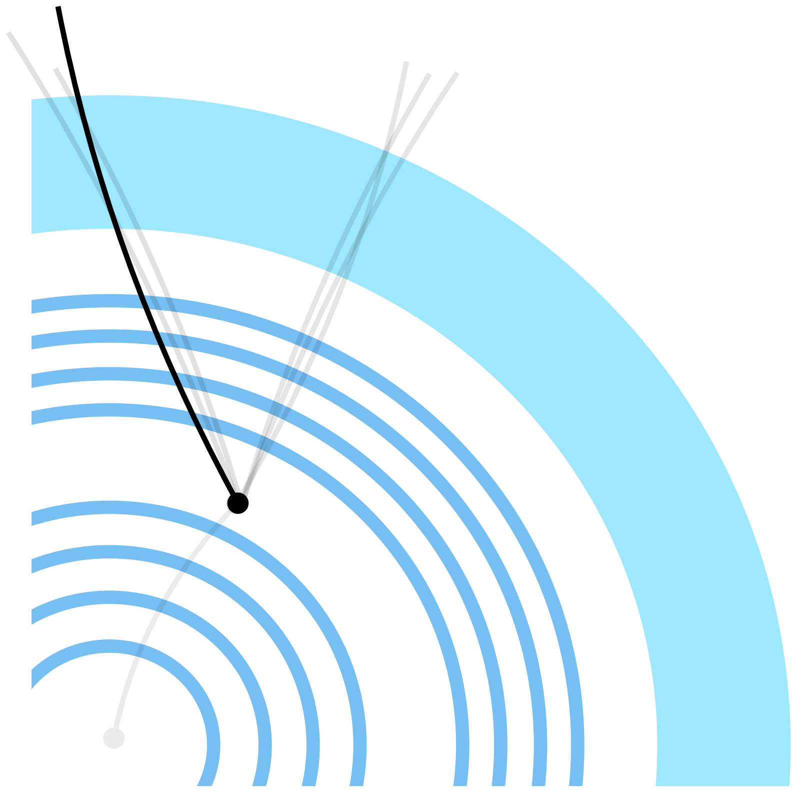
IMPLEMENTATION

- **Simulating any charged LLP is a technical challenge!**
    - Complex dance between GEANT and Pythia
    - Breaks default MC data flow paradigm
- **Every ATLAS search** for a EM/ strongly charged LLP has used this setup

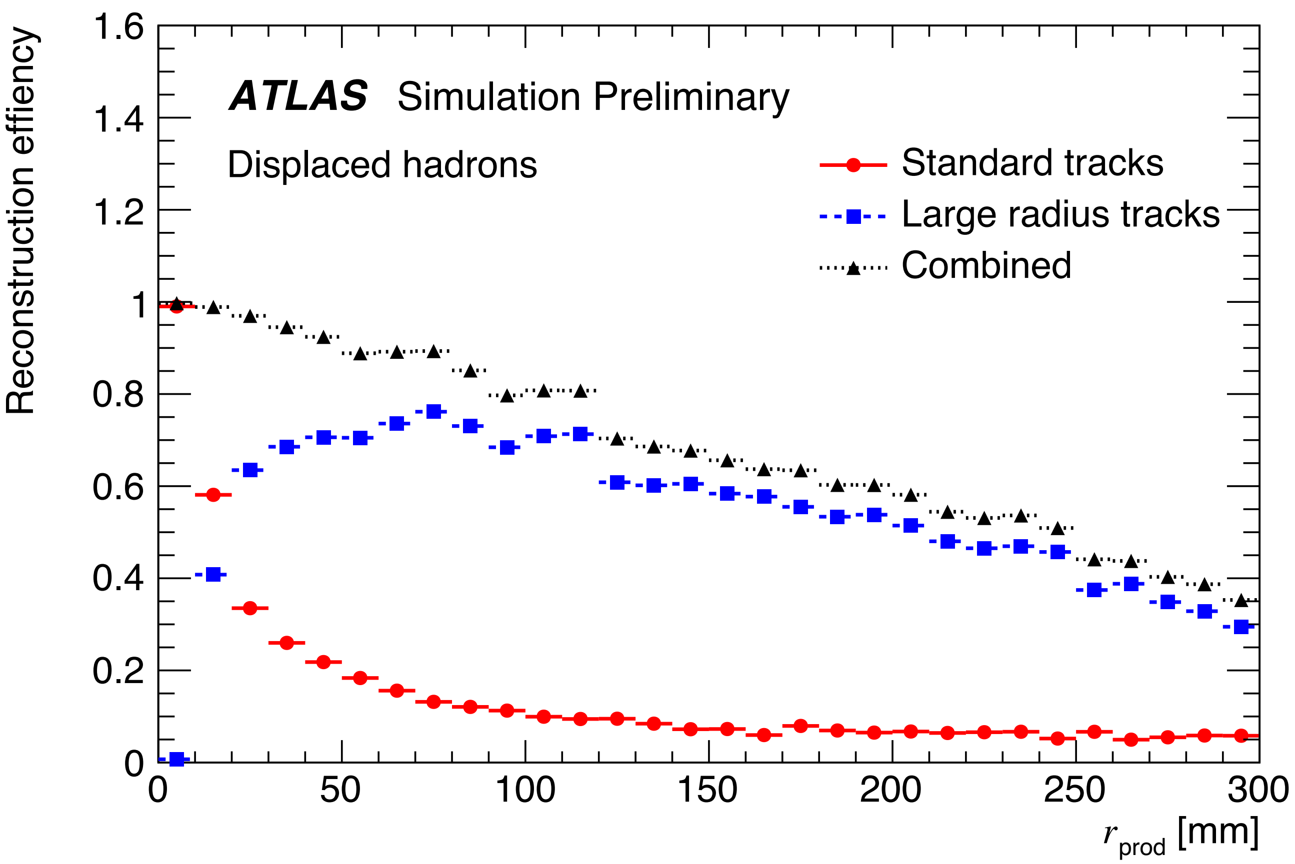


Large Radius Tracking

ATL-PHYS-PUB-2017-014

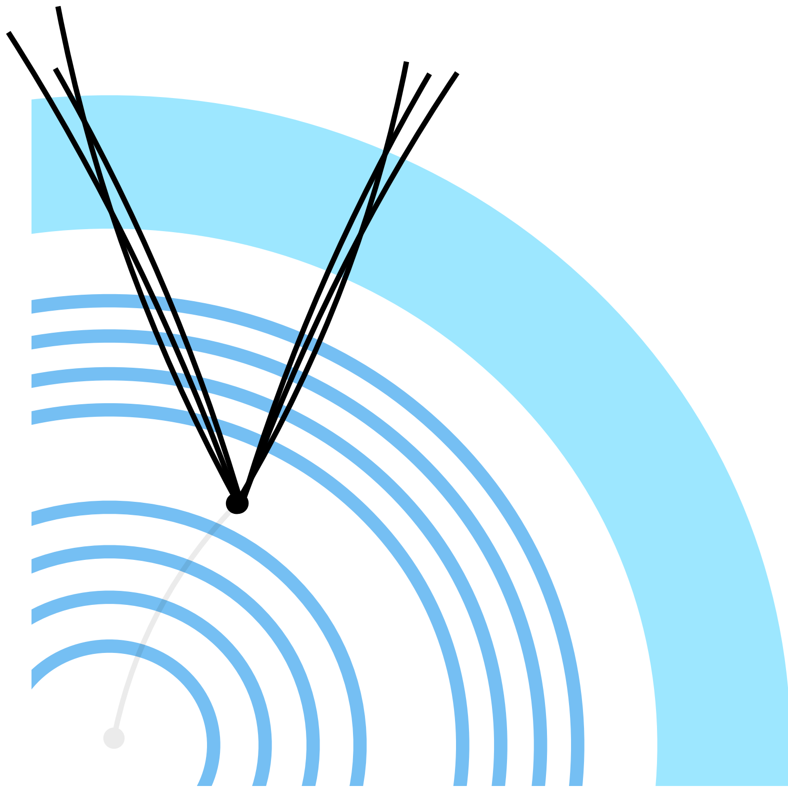


- Default tracking on ATLAS turns off at $d_0 > 10$mm
- **In order to retain reco efficiency at larger d_0, additional tracking step run**
  - Uses unused hits from nominal tracking
- Even reasonably modeled in simulation
- **Computationally expensive, so run on a subset of events from special Raw data stream written out at Tier0**

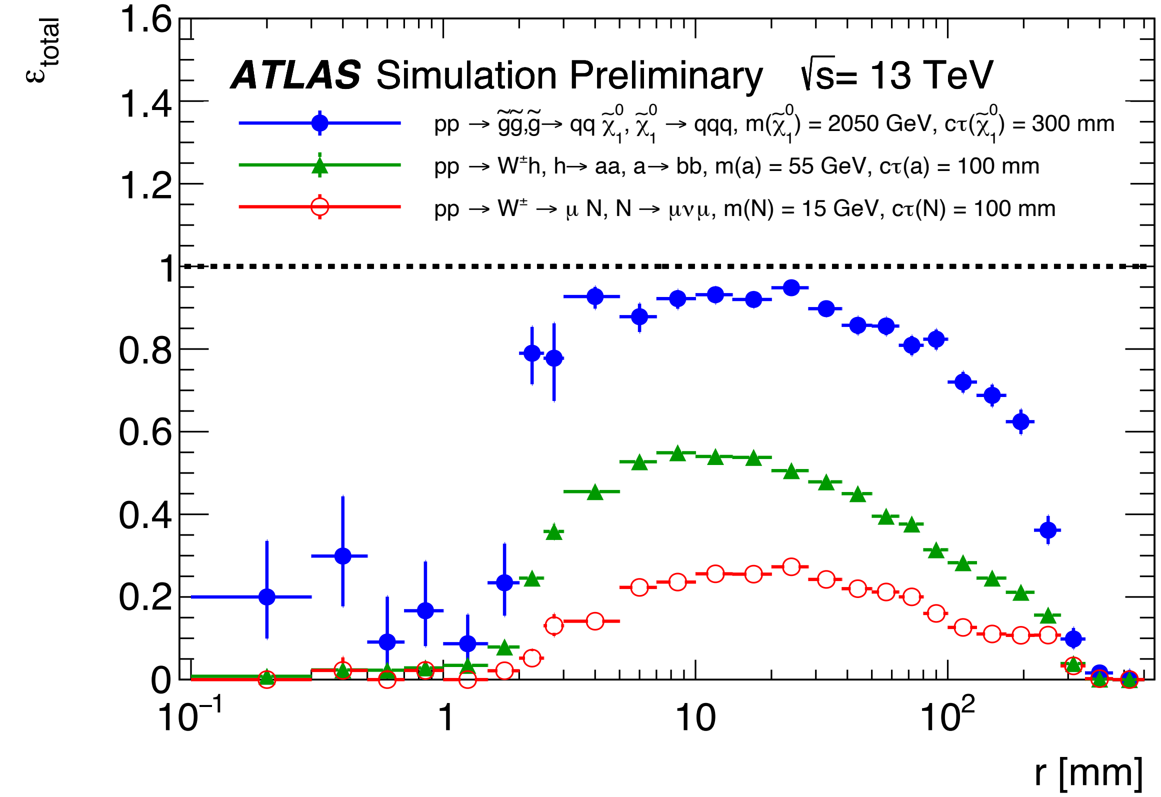


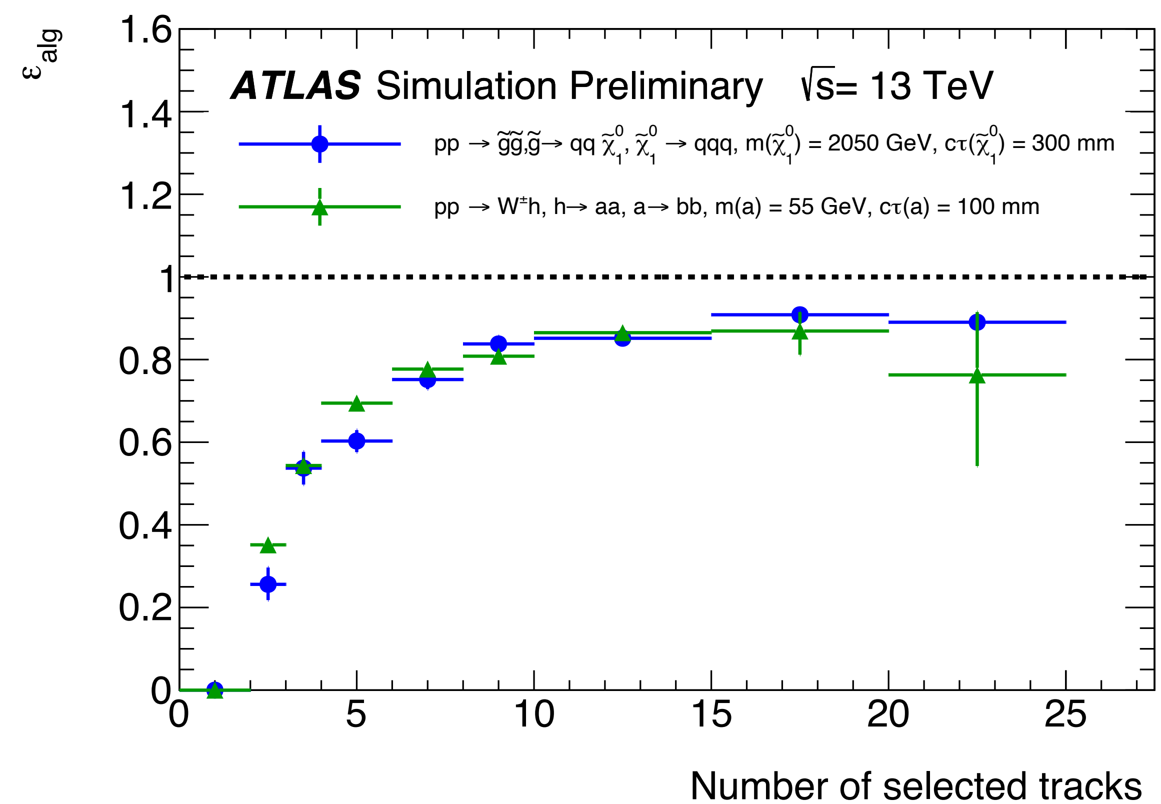
DISPLACED VERTEXING

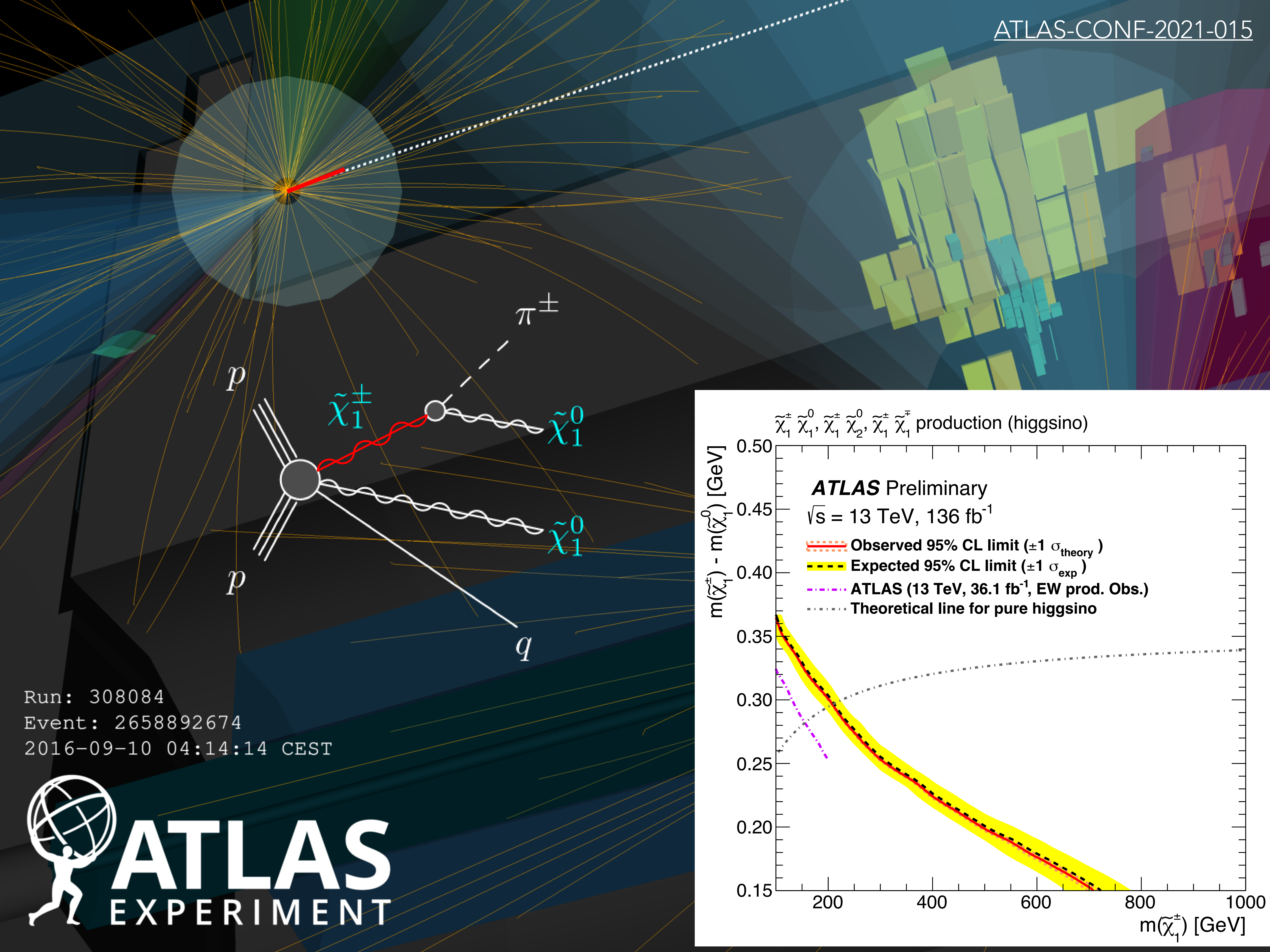
ATL-PHYS-PUB-2019-013

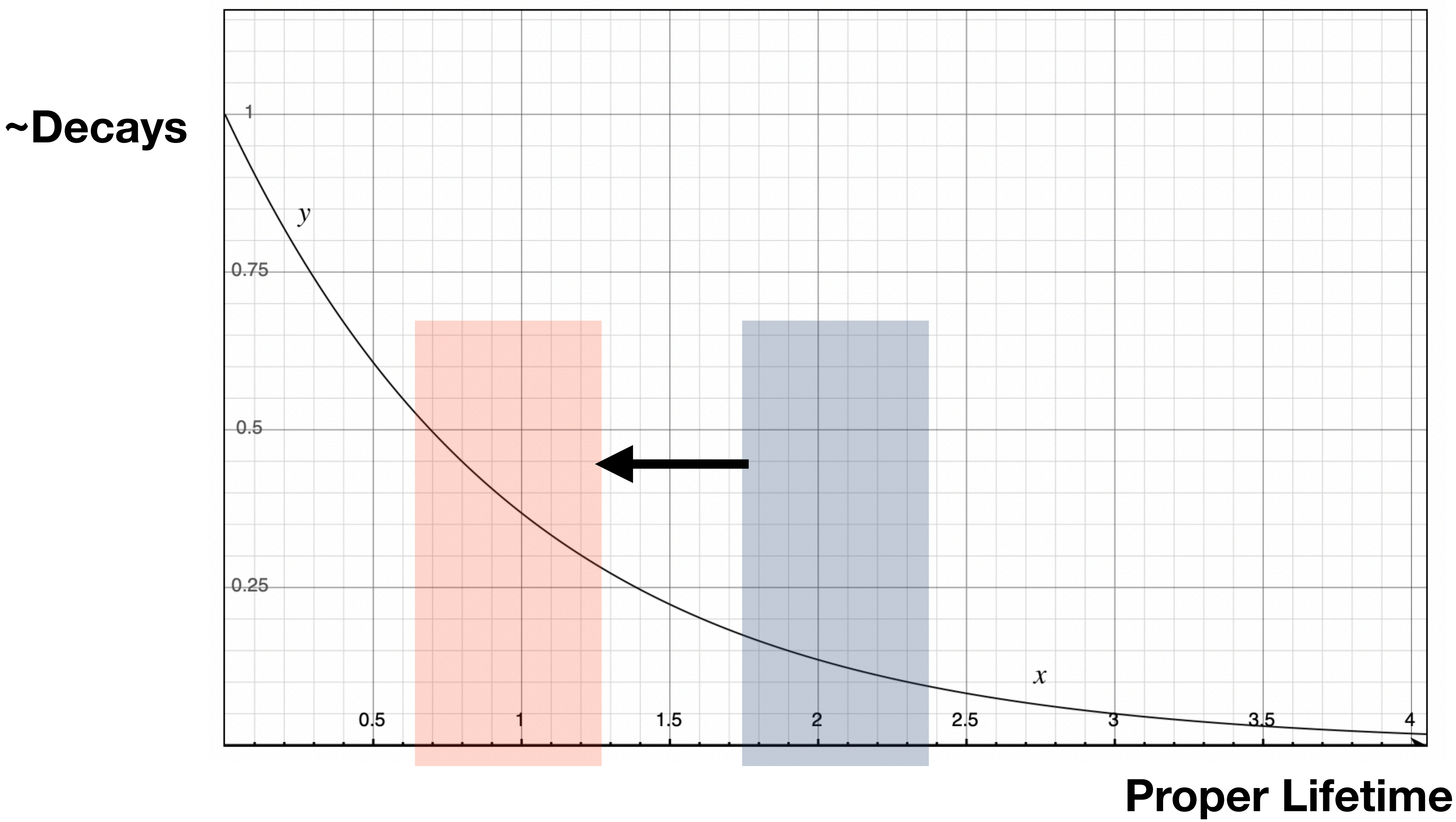


- We use these tracks (and standard tracks) to form displaced vertices
  - Retains efficiency at large radius
- Finds 2-track seed vertices
- Merges them into multitrack vertices
- Merges compatible vertices and attaches compatible tracks






ATLAS-CONF-2021-015
p
p
$\tilde{\chi}_1^{\pm}$
$\pi^{\pm}$
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$
q
Run: 308084
Event: 2658892674
2016-09-10 04:14:14 CEST
ATLAS
EXPERIMENT
$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^0$, $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$, $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ production (higgsino)
ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 136 fb^{-1}
Observed 95% CL limit (±1 σ_{theory})
Expected 95% CL limit (±1 σ_{exp})
ATLAS (13 TeV, 36.1 fb^{-1}, EW prod. Obs.)
Theoretical line for pure higgsino
$m(\tilde{\chi}_1^{\pm}) - m(\tilde{\chi}_1^0)$ [GeV]
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
200
400
600
800
1000
$m(\tilde{\chi}_1^{\pm})$ [GeV]

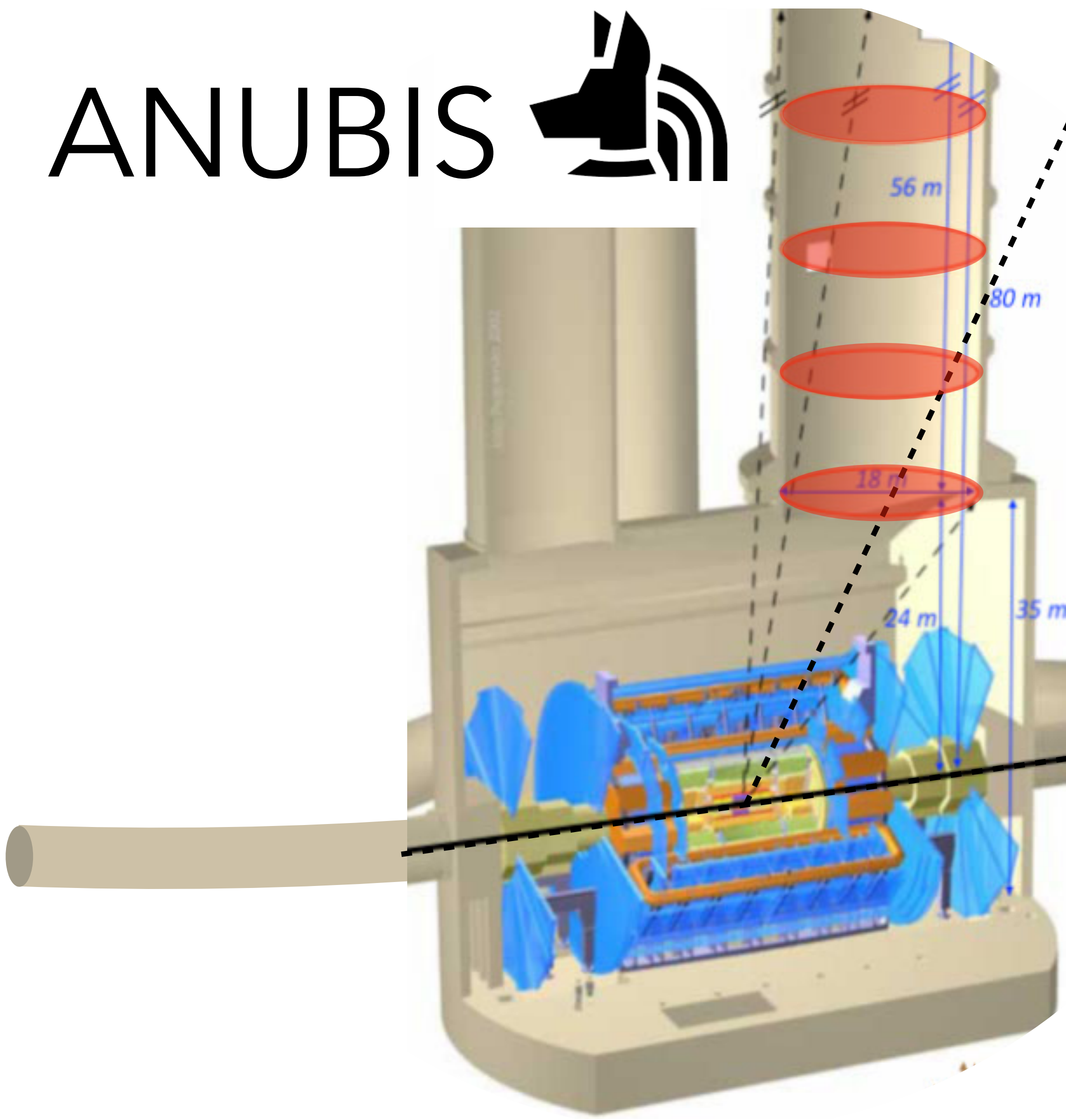


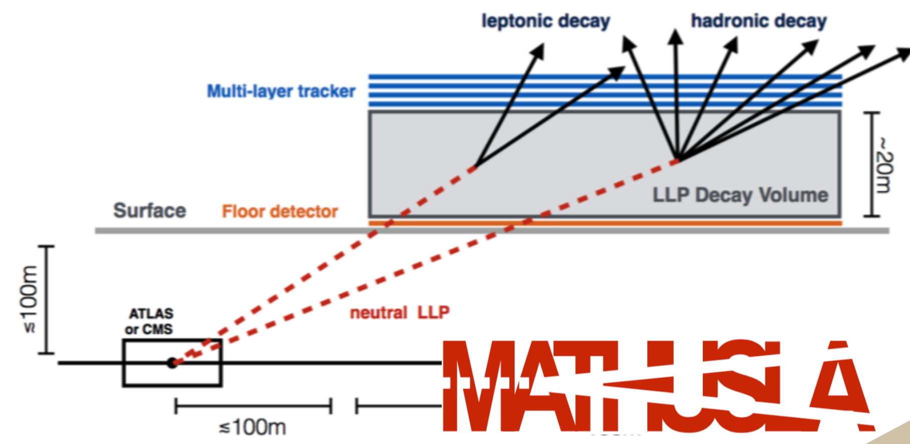
Remember: The proper time of decay **always** sampled from an exponential

Getting the largest, closest detector is important.

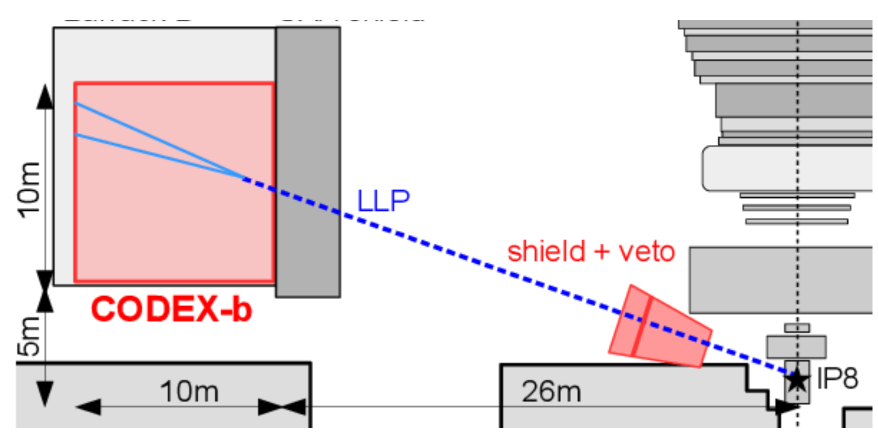
Where to look for long-lived particles?

ANUBIS



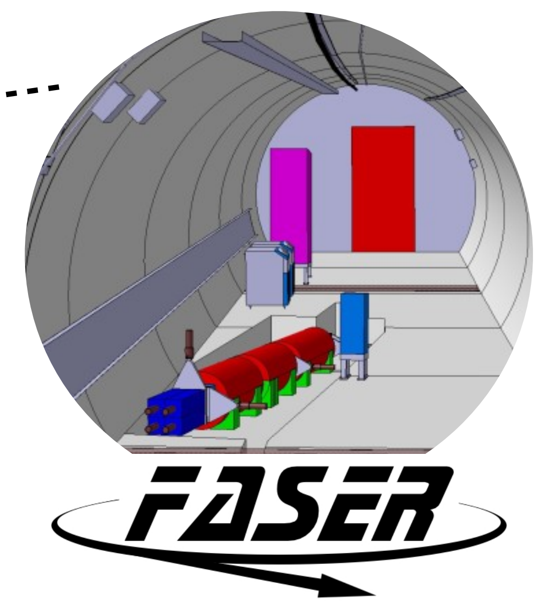


Chou et al 1606.06298



CODEX-b

Gligorov et al 1708.09395



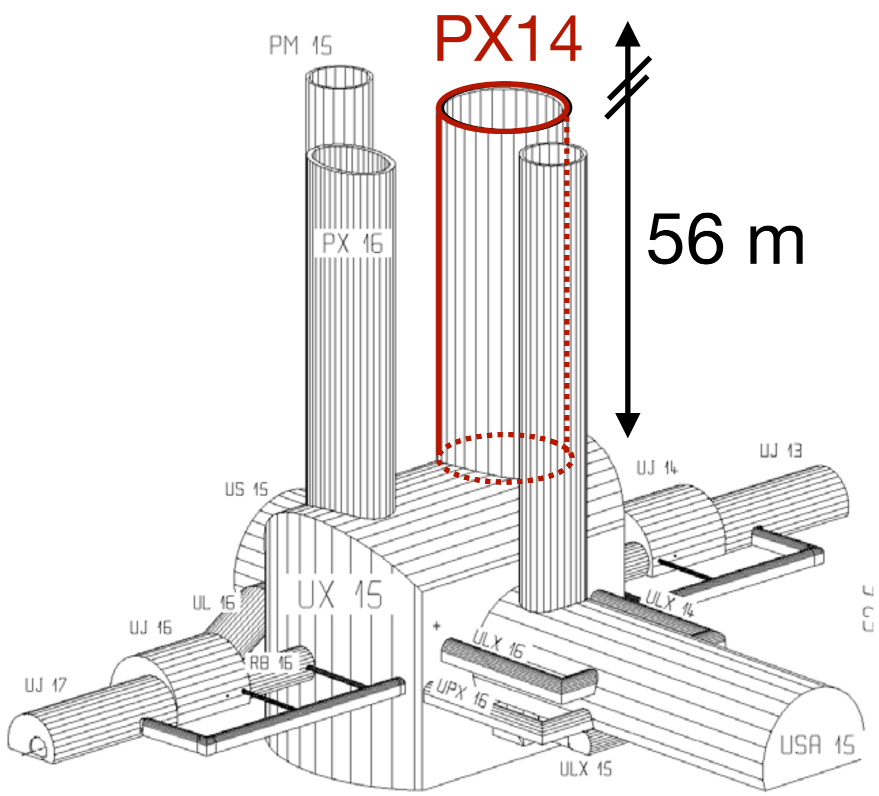
Feng, et al 1710.09387

We propose to instrument the ATLAS service shaft

Bauer, OB, Lee, Ohm 1909.13022

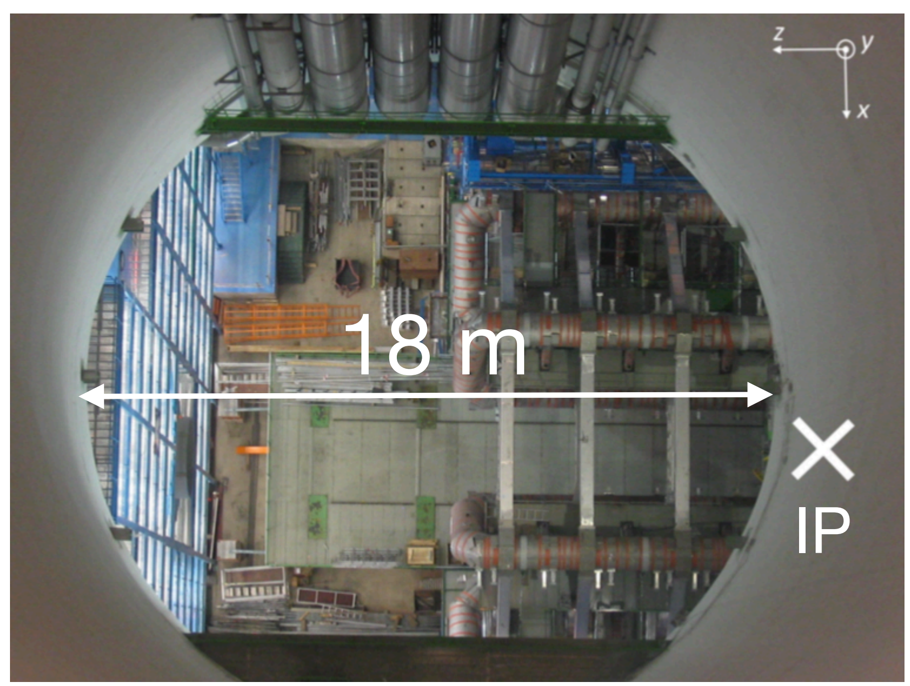
From OB

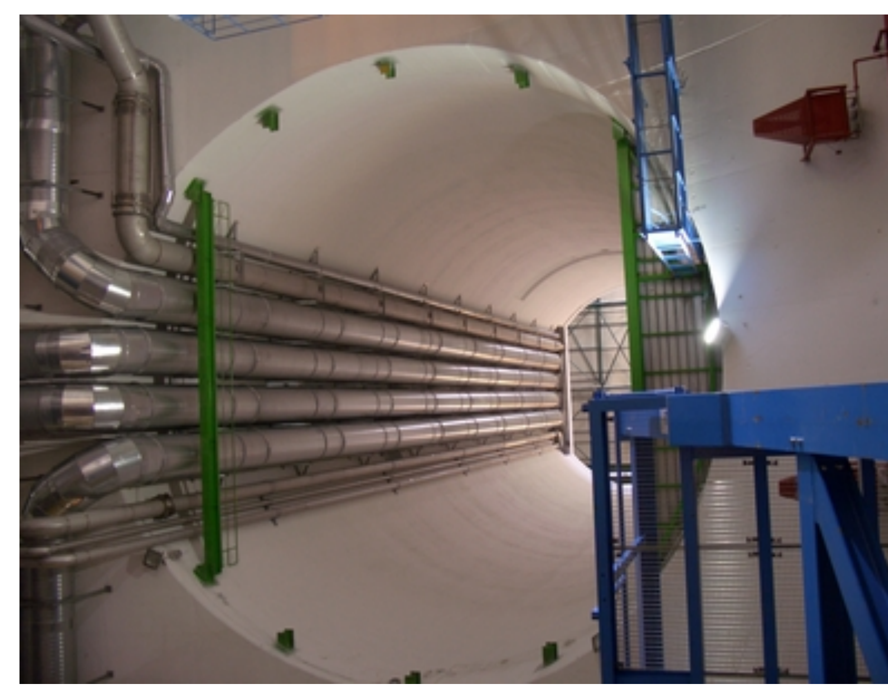
ANUBIS



- Existing geometry allows for minimal civil engineering costs

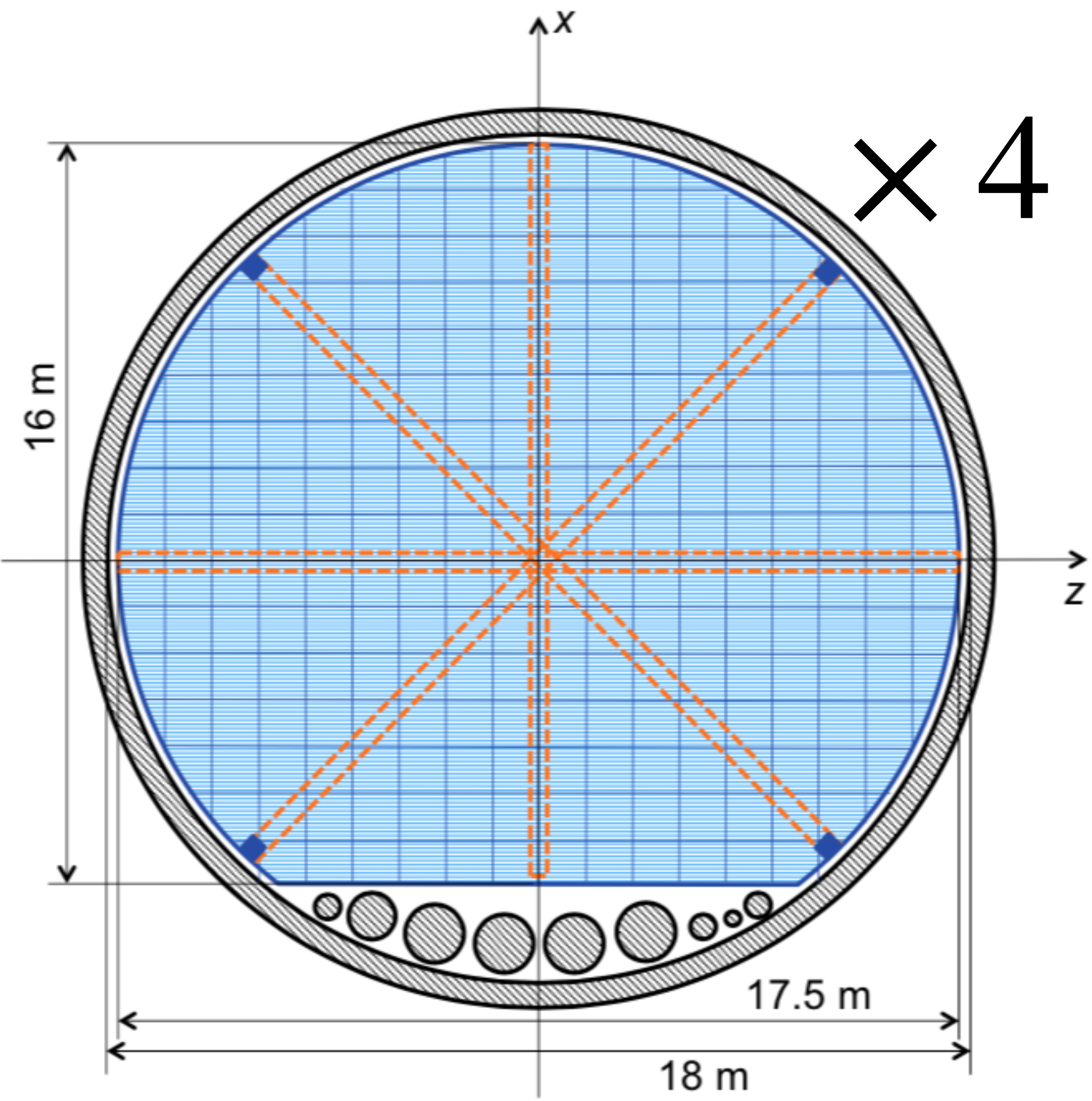
- Projective decay volume optimises acceptance for different lifetimes

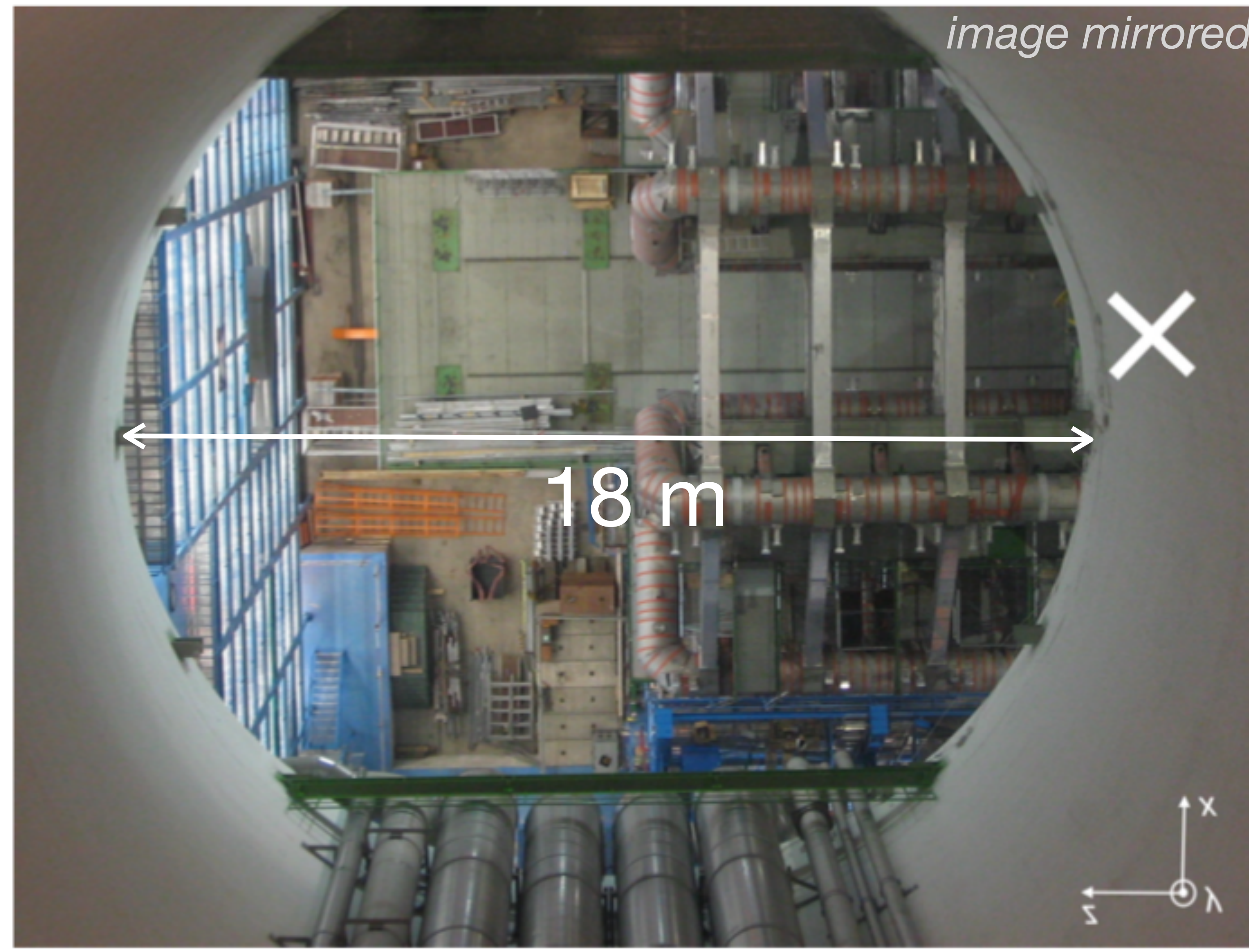




From OB

ANUBIS

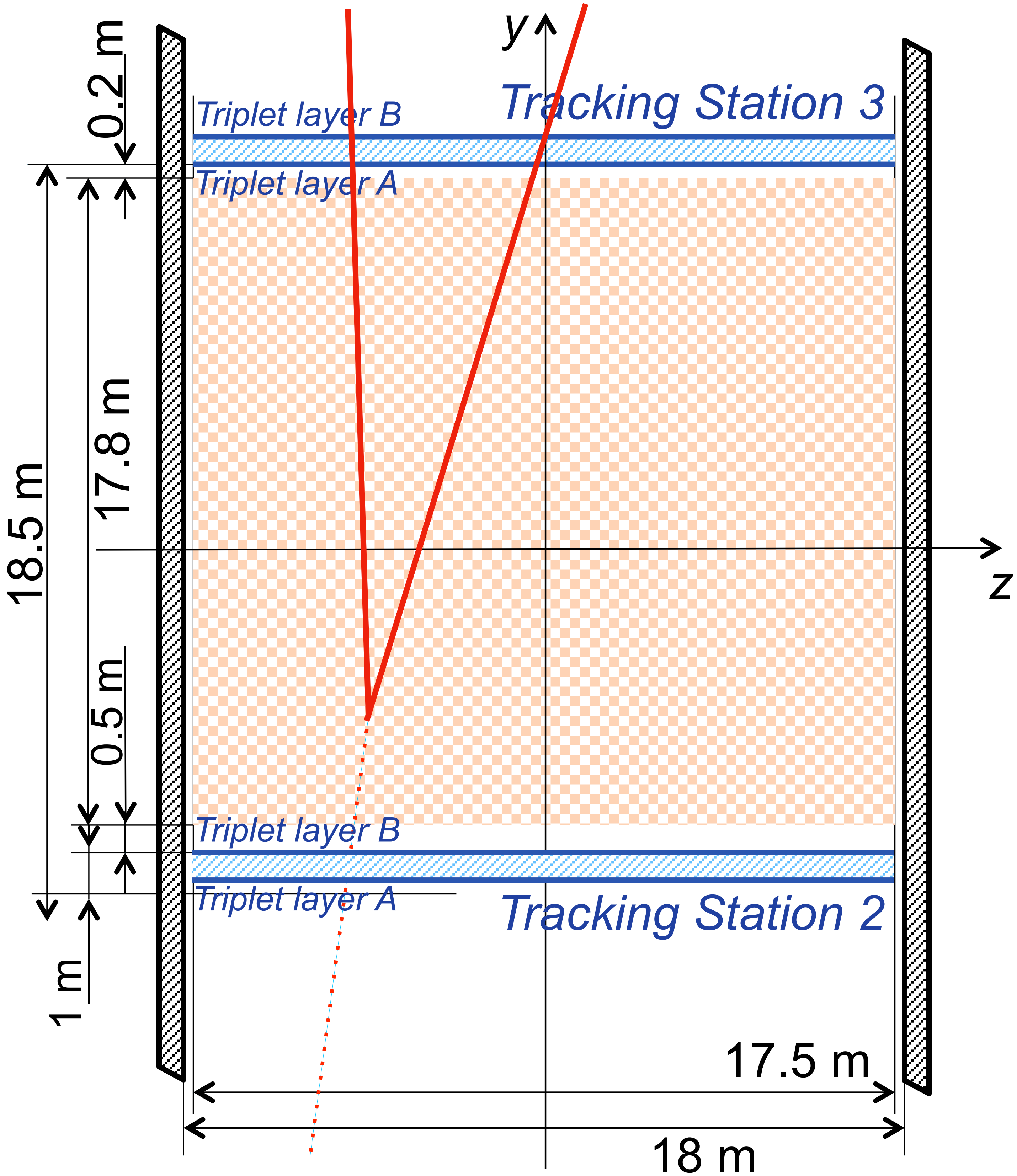




Current proposal:
Four evenly spaced tracking stations with a cross-sectional area of 230 m^2 each

From OB

ANUBIS



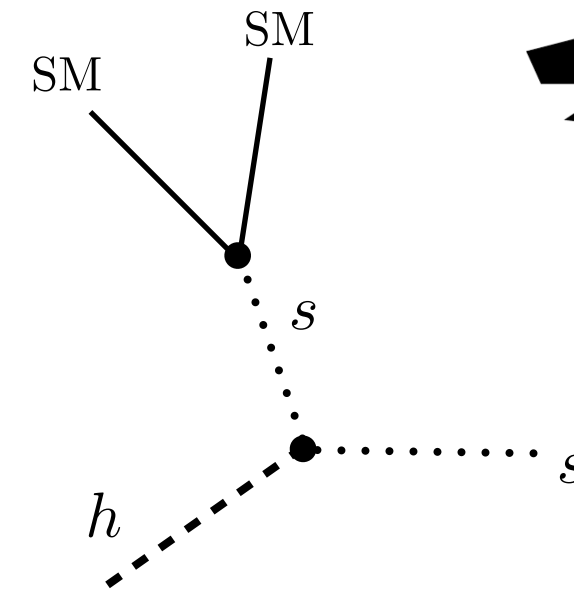
Parameter	Specification
Time resolution	$\delta t \lesssim 0.5$ ns
Angular resolution	$\delta\alpha \lesssim 0.01$ rad
Spatial resolution	$\delta x, \delta z \lesssim 0.5$ cm
Per-layer hit efficiency	$\varepsilon \gtrsim 98\%$

Angular & spatial resolution:

- Reconstruct displaced vertices: reach $m_{\text{LLP}} \gtrsim K_L$ for $m_{\text{mediator}} \approx 100$ GeV
- Fiducialise volume

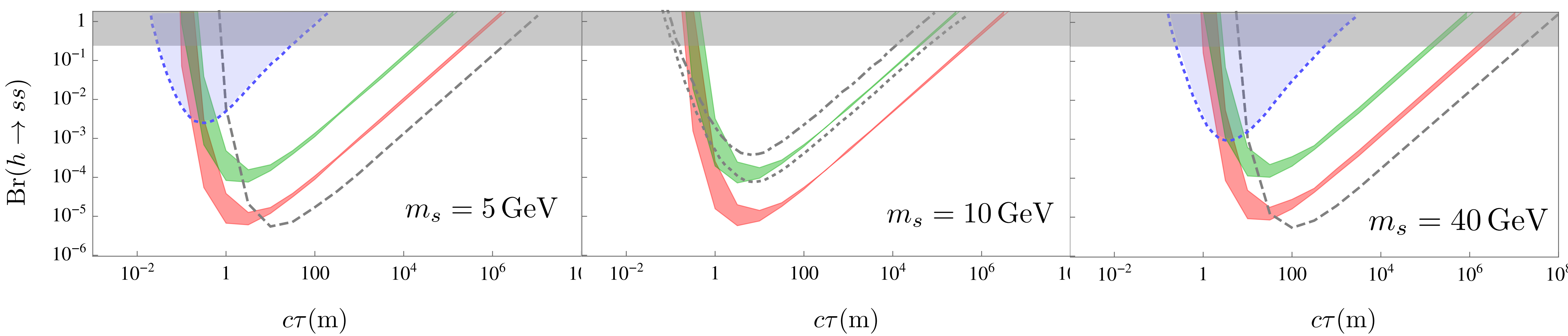
From OB

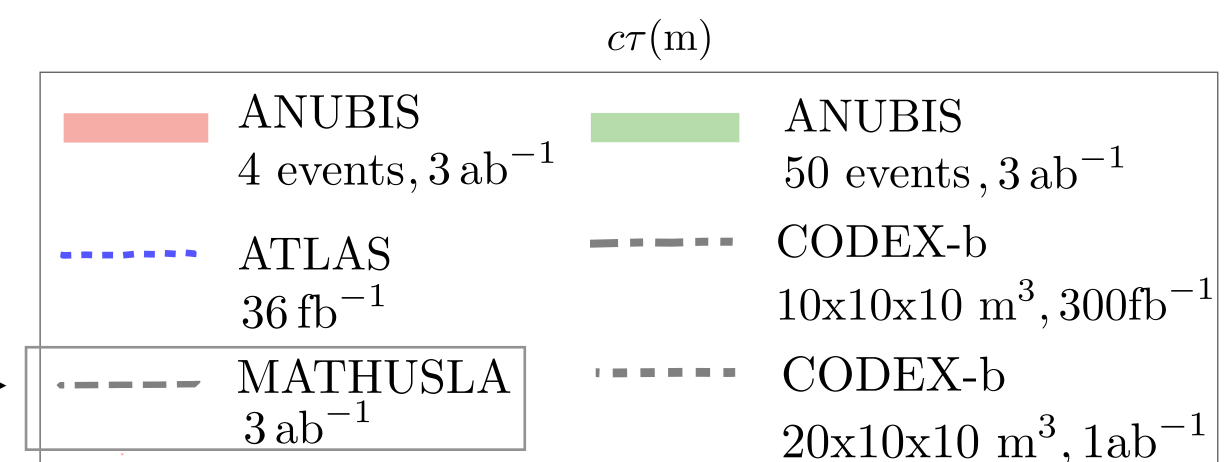
ANUBIS



Sensitivity study for exotic Higgs decays

$$\mathcal{L} = \lambda s^2 H^\dagger H \qquad h \to ss,\, s \to \mathrm{SM\,SM}$$





200 x 200 x 20 m^3 decay volume →