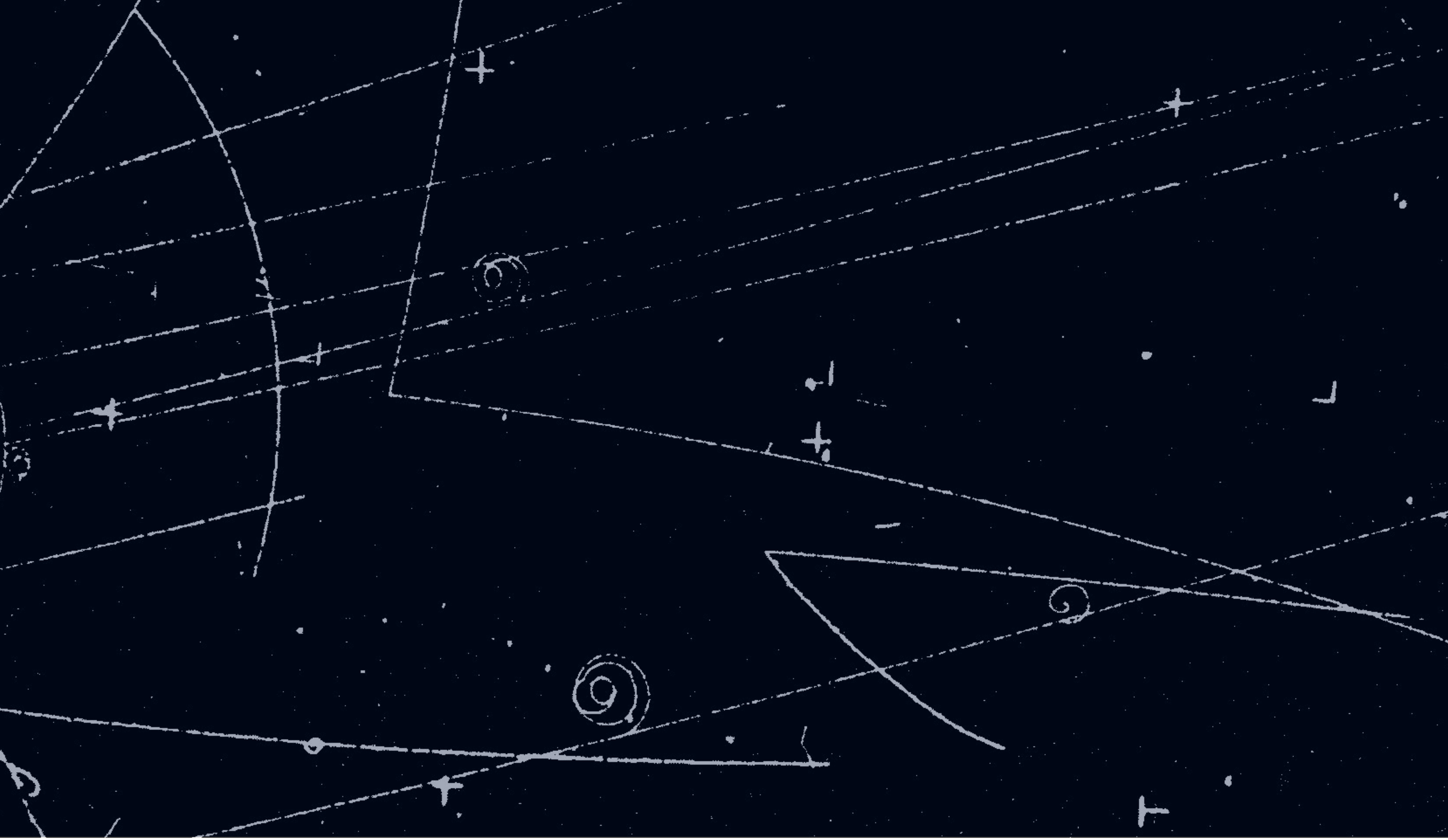

Hunting for new physics using long-lived particles

Kate Pachal
Duke University

Hello to you all

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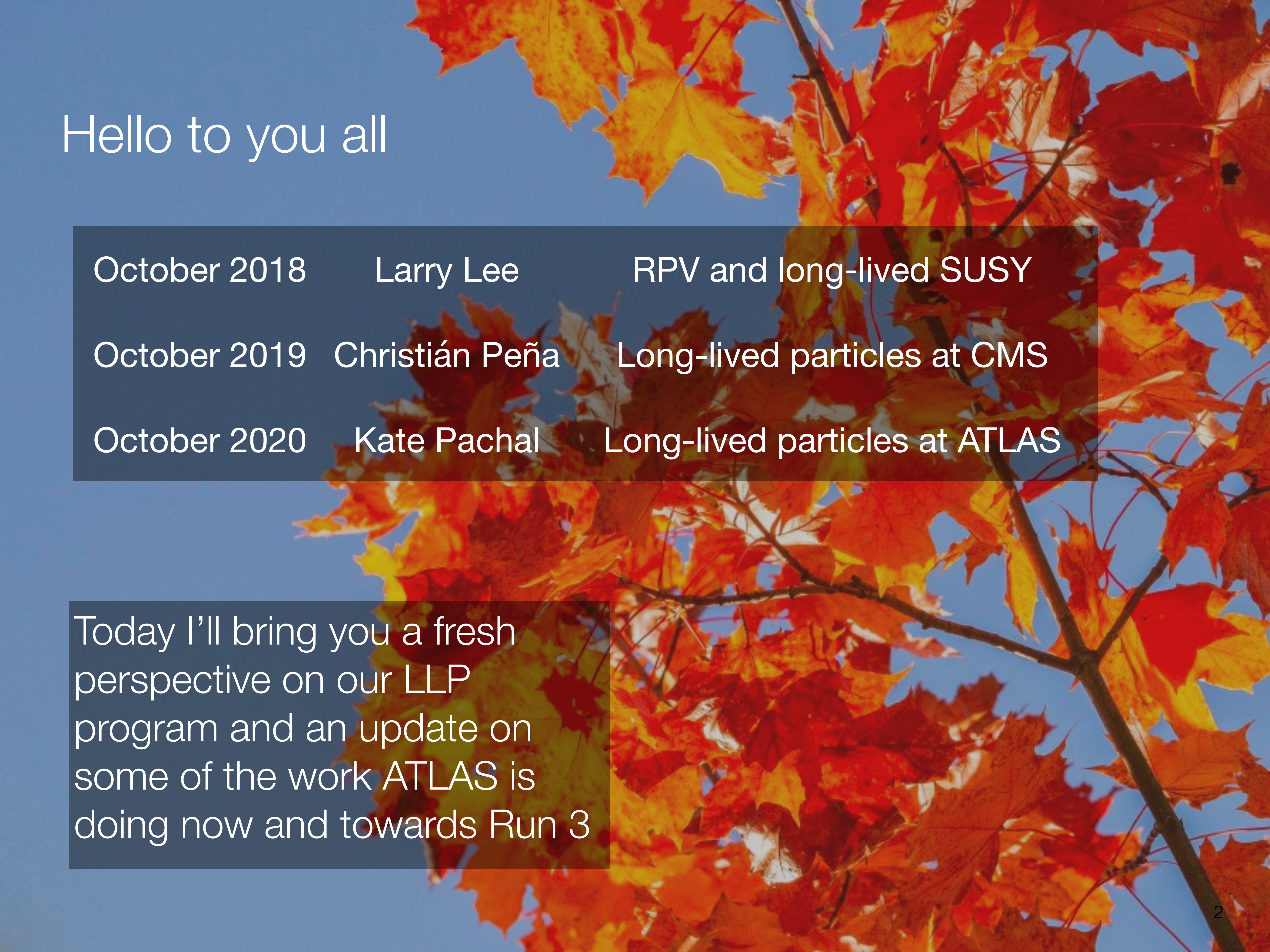
October 2018	Larry Lee	RPV and long-lived SUSY
October 2019	Christián Peña	Long-lived particles at CMS
October 2020	Kate Pachal	Long-lived particles at ATLAS



Hello to you all

October 2018	Larry Lee	RPV and long-lived SUSY
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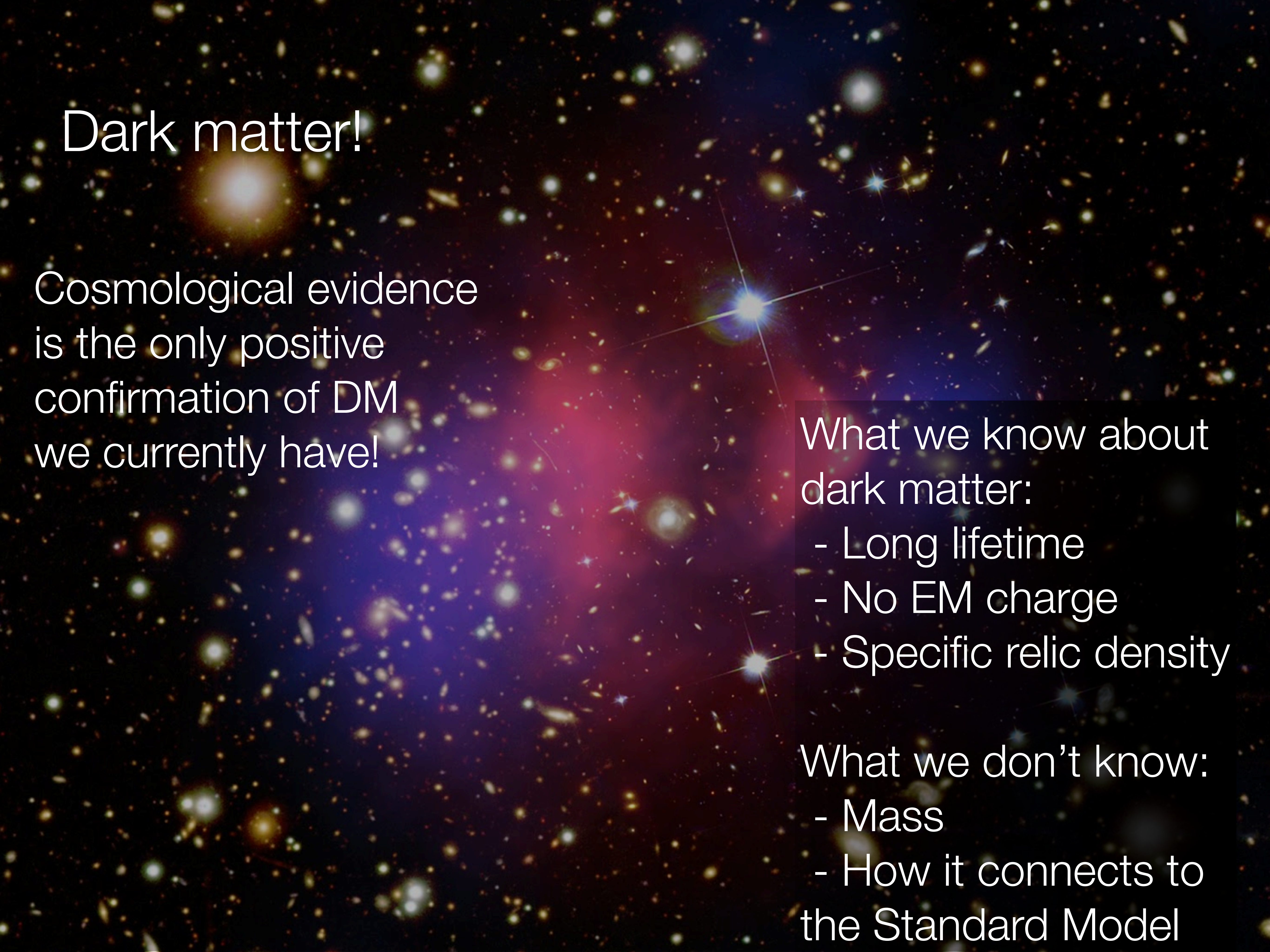
Today I'll bring you a fresh perspective on our LLP program and an update on some of the work ATLAS is doing now and towards Run 3

Dark matter!

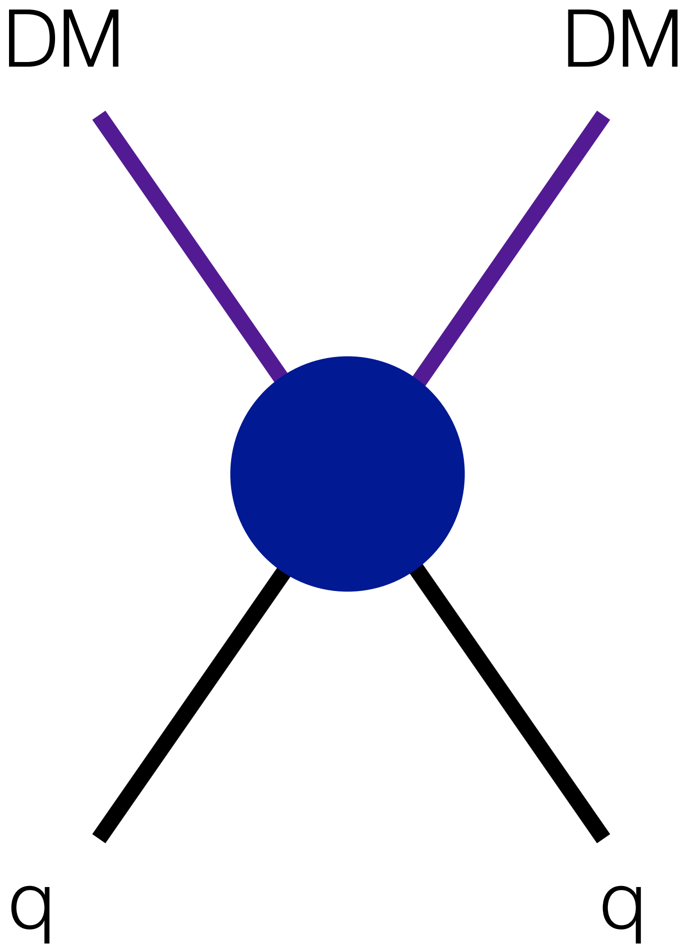


Cosmological evidence is the only positive confirmation of DM we currently have!

What we know about dark matter:
- Long lifetime
- No EM charge
- Specific relic density

What we don't know:
- Mass
- How it connects to the Standard Model

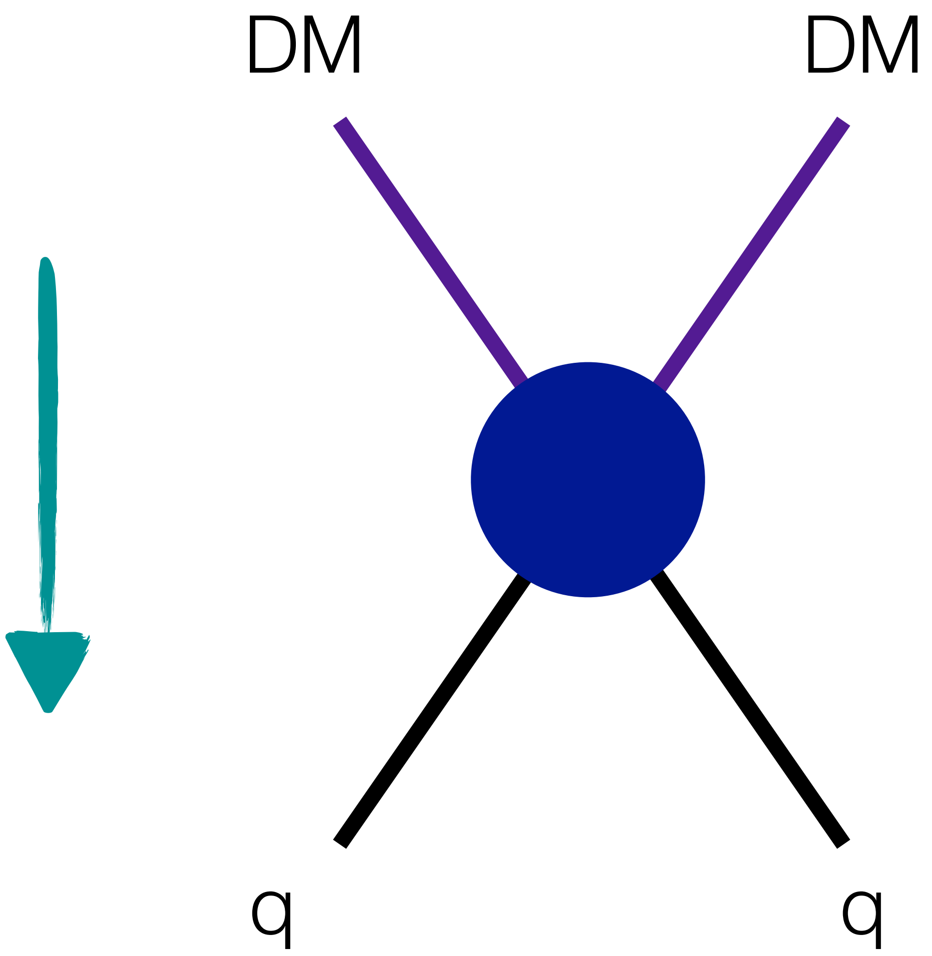
Model-driven: dark matter *at colliders*



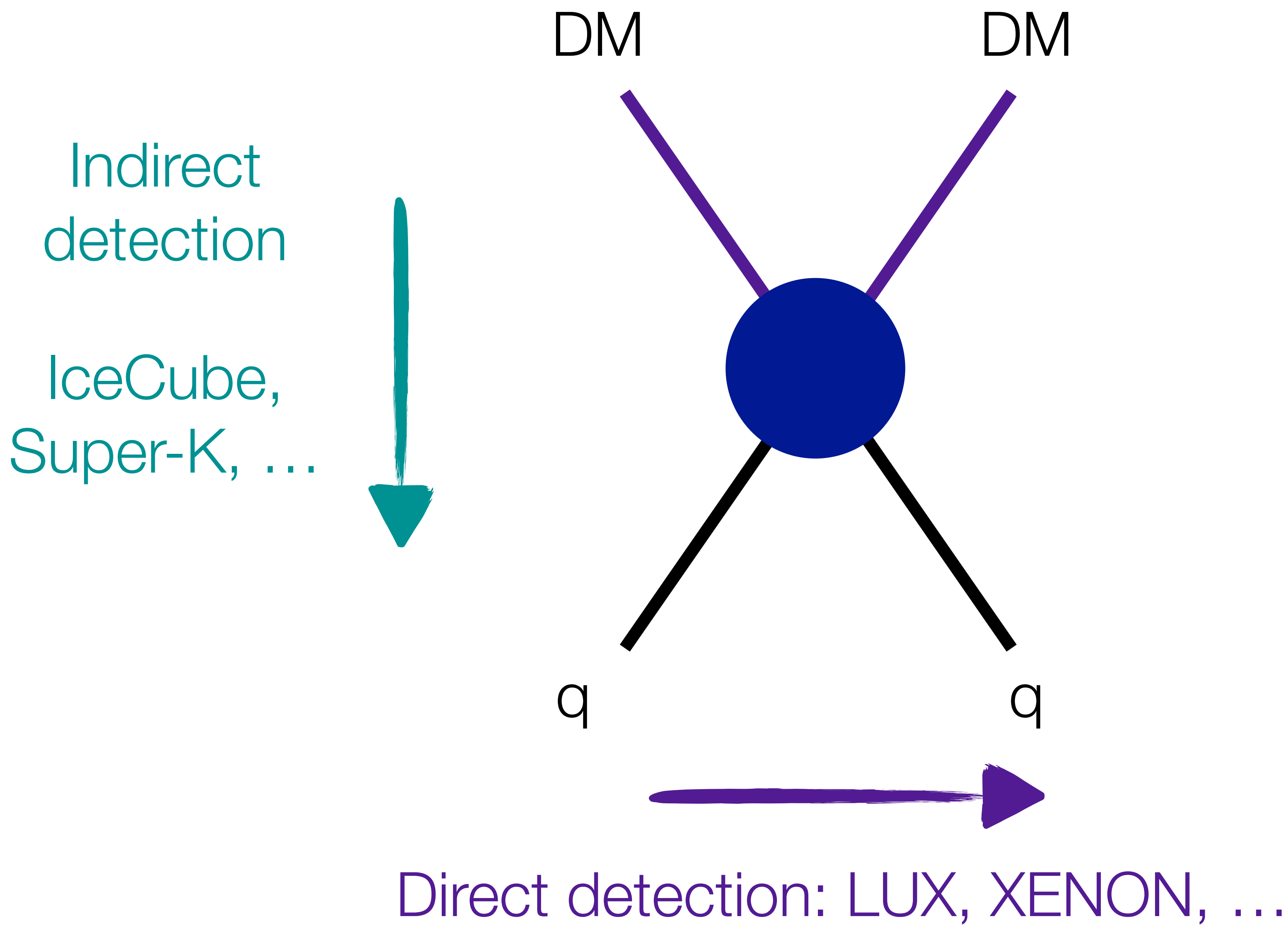
Model-driven: dark matter *at colliders*

Indirect detection

IceCube, Super-K, …



Model-driven: dark matter *at colliders*

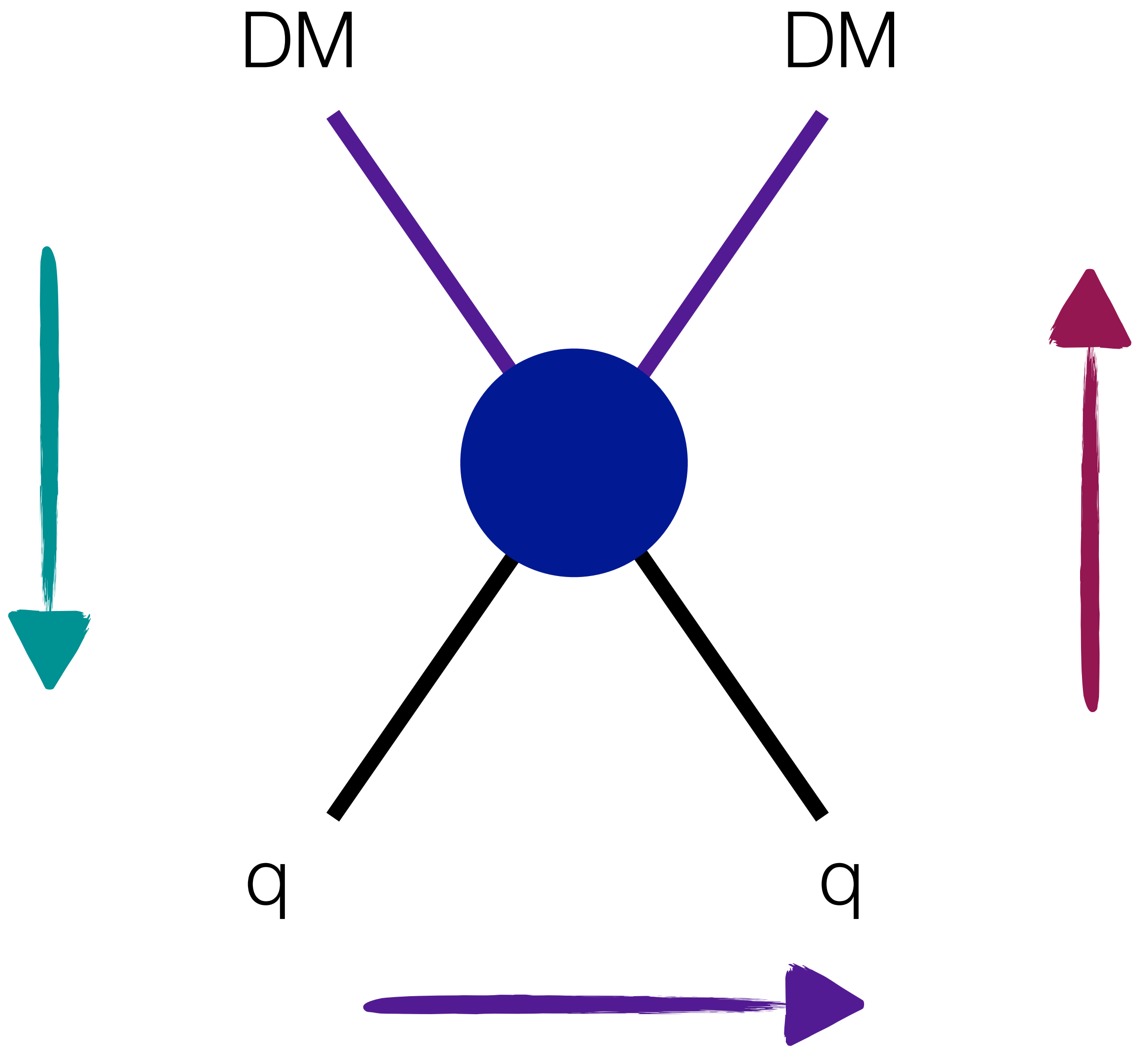


Indirect detection

IceCube, Super-K, …

Direct detection: LUX, XENON, …

Model-driven: dark matter *at colliders*



Indirect detection

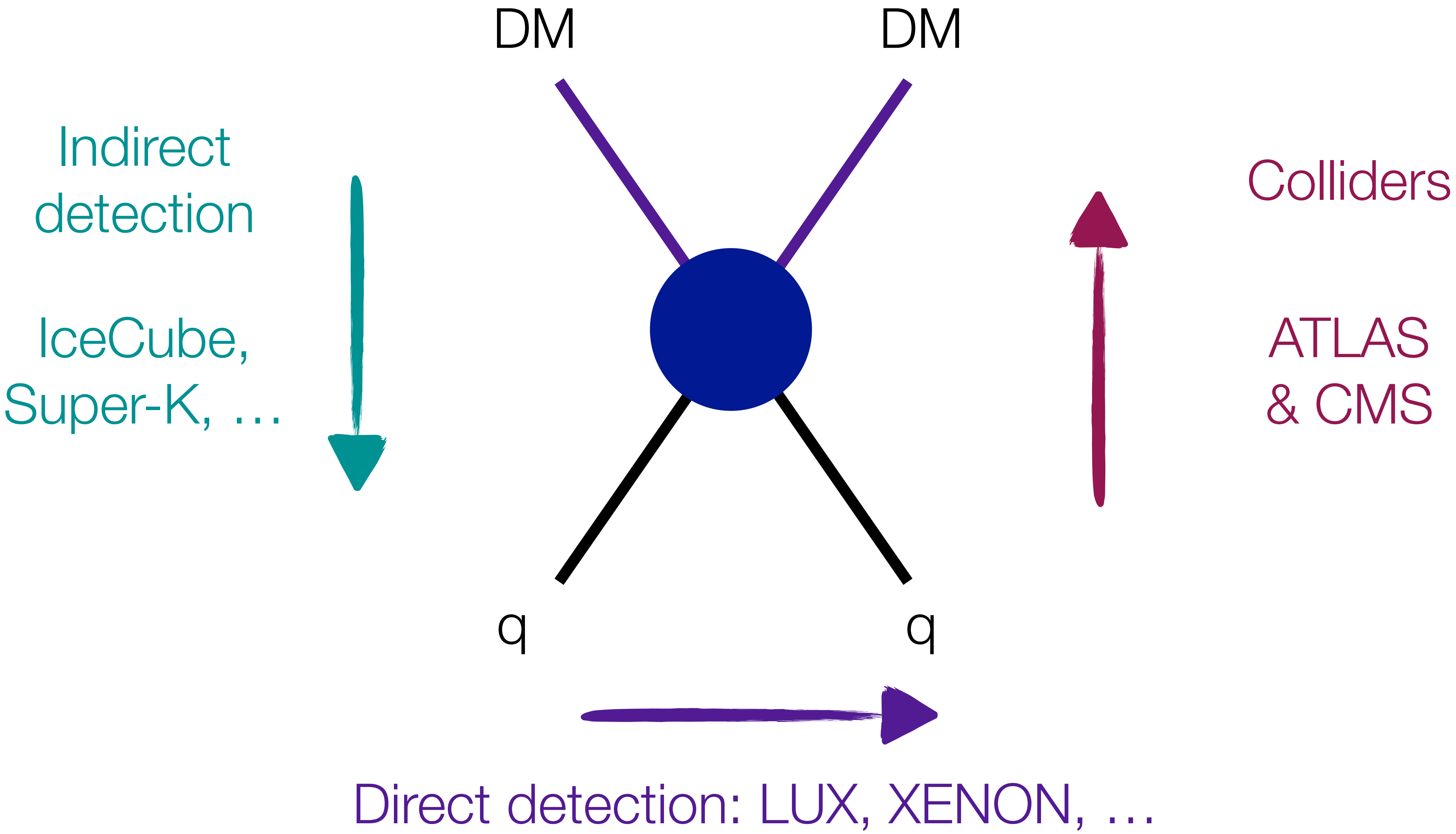
IceCube, Super-K, …

Colliders

ATLAS & CMS

Direct detection: LUX, XENON, …

Model-driven: dark matter *at colliders*



DM

DM

Indirect detection

IceCube, Super-K, …

Colliders

ATLAS & CMS

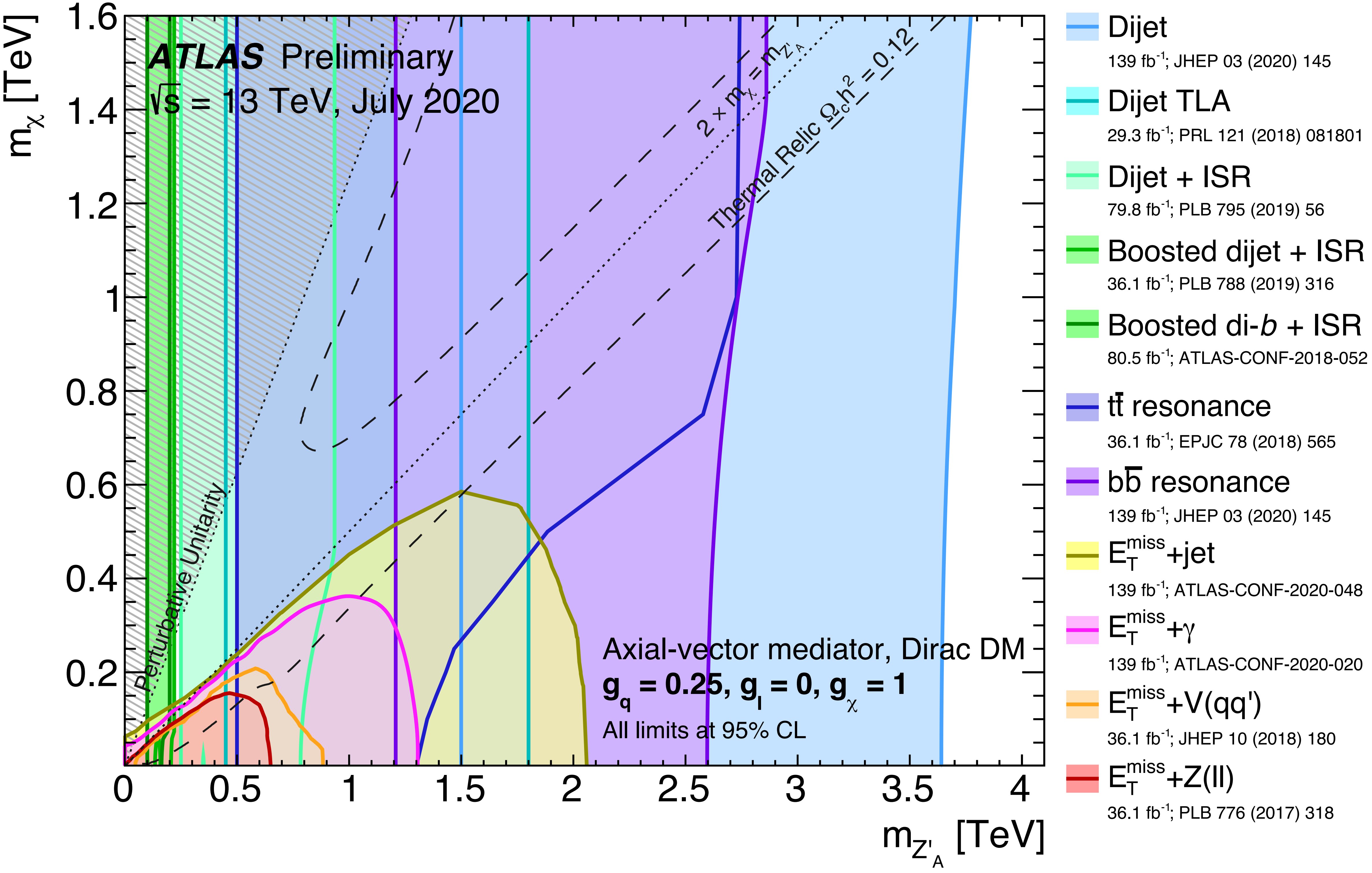
q

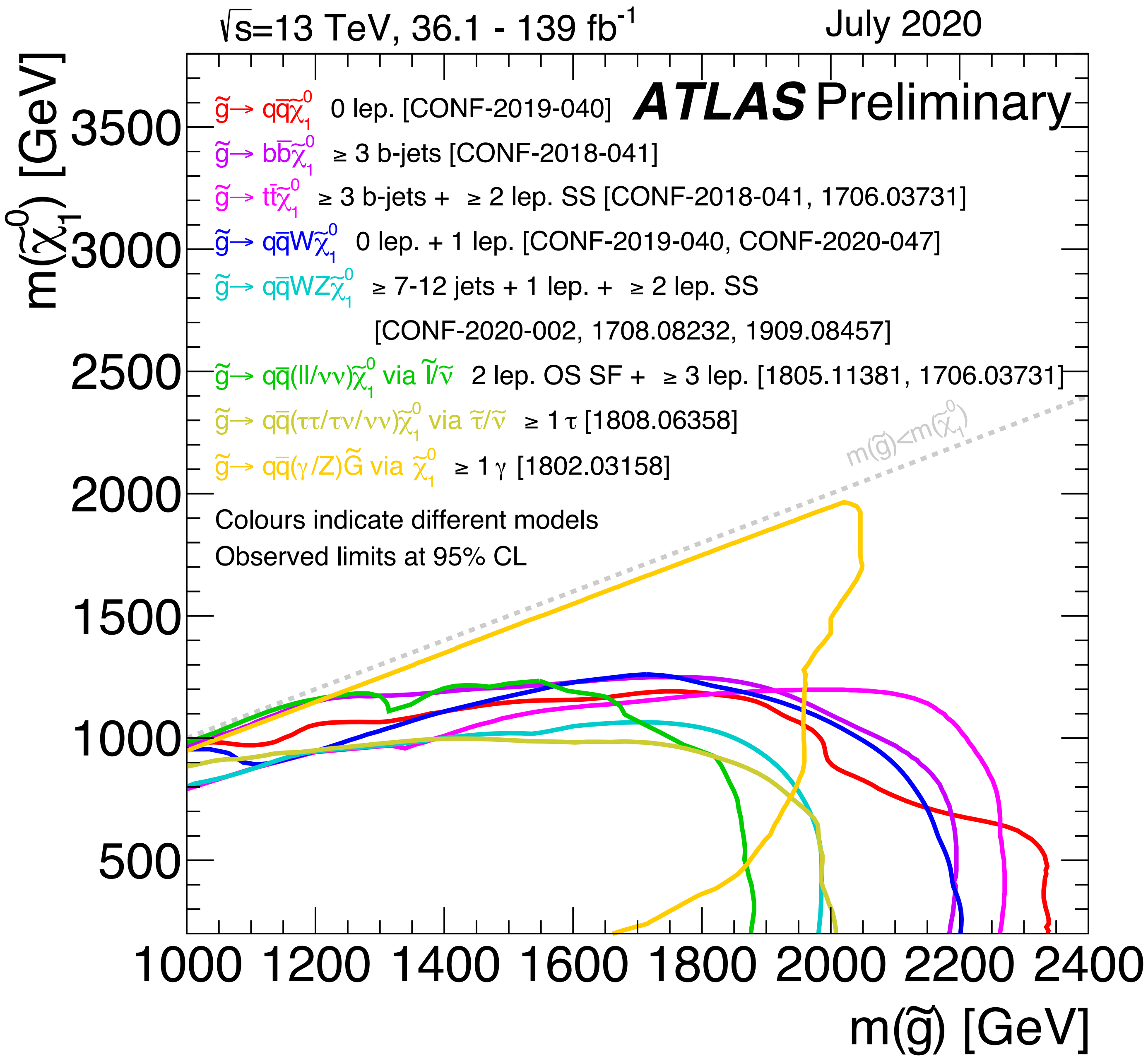
q

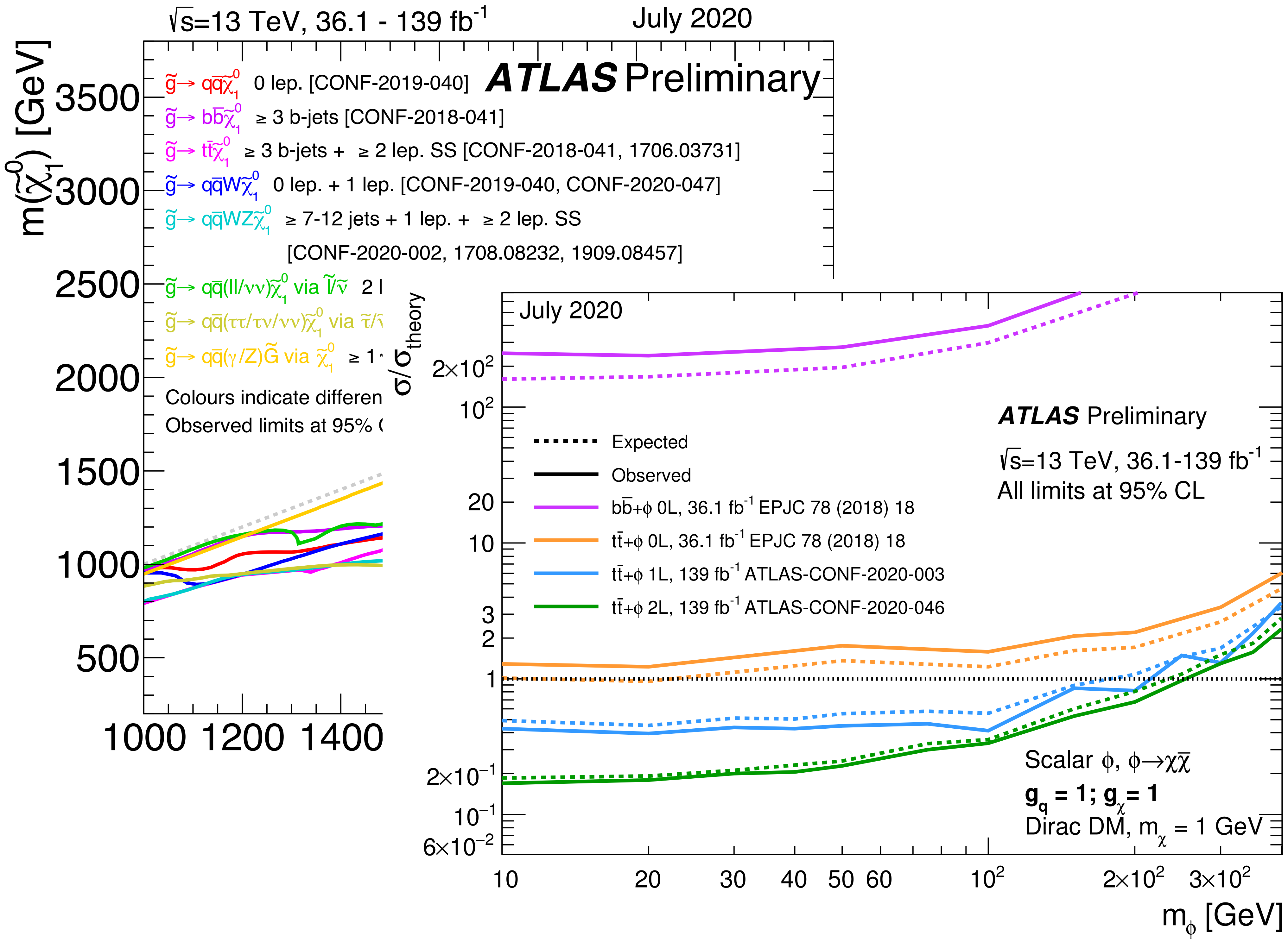
Direct detection: LUX, XENON, …

If there is some interaction with the Standard Model, at a moderate energy scale, → then we should be able to produce DM at the LHC!

LHC dark matter limits today




$\sqrt{s}$=13 TeV, 36.1 - 139 fb^{-1}
July 2020
ATLAS Preliminary
$\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$ 0 lep. [CONF-2019-040]
$\tilde{g} \rightarrow b\bar{b}\tilde{\chi}_1^0$ ≥ 3 b-jets [CONF-2018-041]
$\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ ≥ 3 b-jets + ≥ 2 lep. SS [CONF-2018-041, 1706.03731]
$\tilde{g} \rightarrow q\bar{q}W\tilde{\chi}_1^0$ 0 lep. + 1 lep. [CONF-2019-040, CONF-2020-047]
$\tilde{g} \rightarrow q\bar{q}WZ\tilde{\chi}_1^0$ ≥ 7-12 jets + 1 lep. + ≥ 2 lep. SS [CONF-2020-002, 1708.08232, 1909.08457]
$\tilde{g} \rightarrow q\bar{q}(ll/\nu\nu)\tilde{\chi}_1^0$ via $\tilde{l}/\tilde{\nu}$ 2 lep. OS SF + ≥ 3 lep. [1805.11381, 1706.03731]
$\tilde{g} \rightarrow q\bar{q}(\tau\tau/\tau\nu/\nu\nu)\tilde{\chi}_1^0$ via $\tilde{\tau}/\tilde{\nu}$ ≥ 1 τ [1808.06358]
$\tilde{g} \rightarrow q\bar{q}(\gamma/Z)\tilde{G}$ via $\tilde{\chi}_1^0$ ≥ 1 γ [1802.03158]
Colours indicate different models
Observed limits at 95% CL
$m(\tilde{g})<m(\tilde{\chi}_1^0)$
$m(\tilde{\chi}_1^0)$ [GeV]
3500
3000
2500
2000
1500
1000
500
1000
1200
1400
1600
1800
2000
2200
2400
$m(\tilde{g})$ [GeV]

√s=13 TeV, 36.1 - 139 fb^{-1}
July 2020
ATLAS Preliminary
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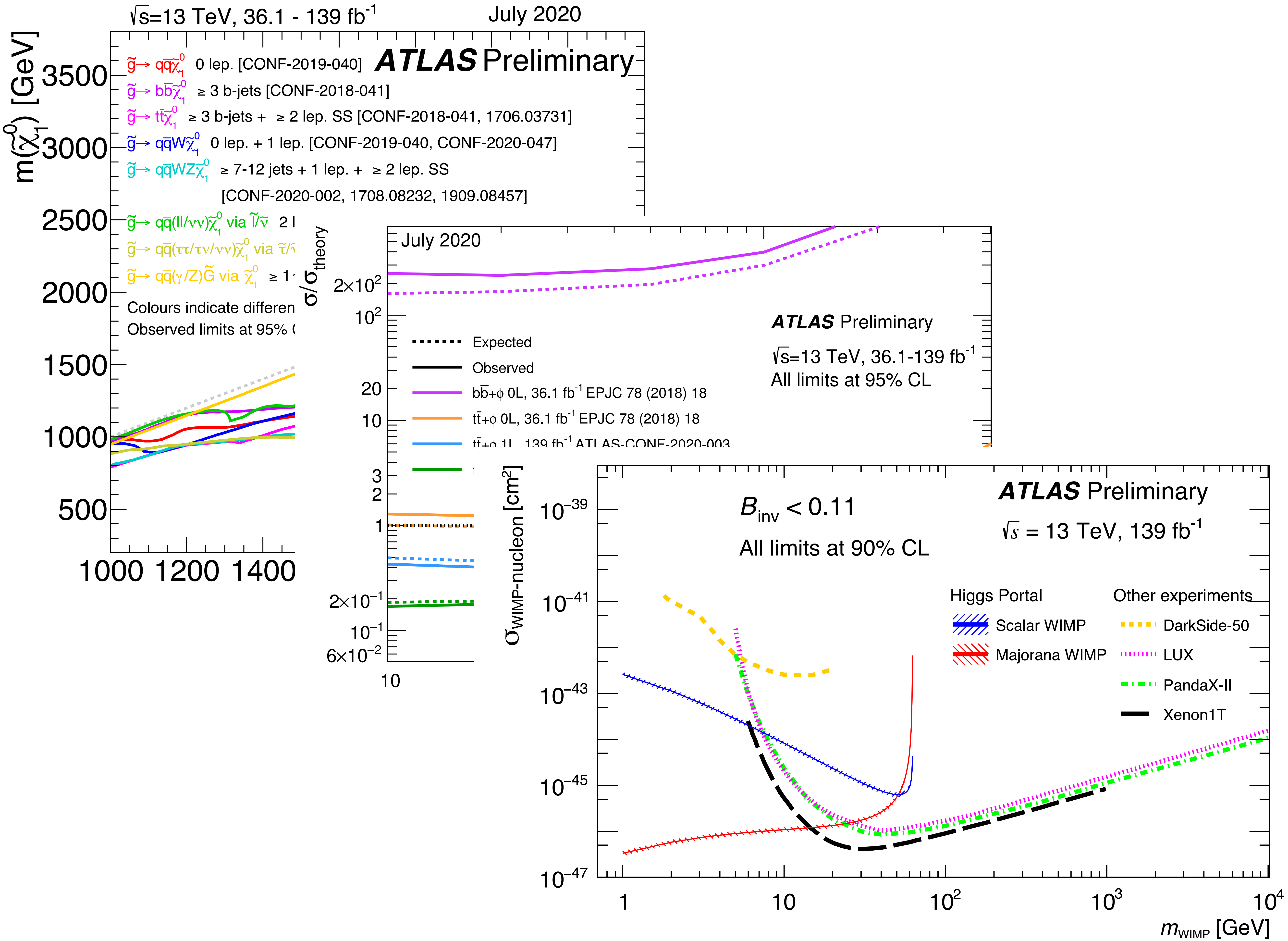
[CONF-2020-002, 1708.08232, 1909.08457]
$\tilde{g}\to q\bar{q}(ll/\nu\nu)\tilde{\chi}_1^0$ via $\tilde{l}/\tilde{\nu}$ 2 l
$\tilde{g}\to q\bar{q}(\tau\tau/\tau\nu/\nu\nu)\tilde{\chi}_1^0$ via $\tilde{\tau}/\tilde{\nu}$
$\tilde{g}\to q\bar{q}(\gamma/Z)\tilde{G}$ via $\tilde{\chi}_1^0$ ≥ 1
Colours indicate differen
Observed limits at 95%
$m(\tilde{\chi}_1^0)$ [GeV]
3500
3000
2500
2000
1500
1000
500
1000
1200
1400
July 2020
σ/σ_{theory}
2×10^2
10^2
20
10
3
2
1
2×10^{-1}
10^{-1}
6×10^{-2}
Expected
Observed
$b\bar{b}+\phi$ 0L, 36.1 fb^{-1} EPJC 78 (2018) 18
$t\bar{t}+\phi$ 0L, 36.1 fb^{-1} EPJC 78 (2018) 18
$t\bar{t}+\phi$ 1L, 139 fb^{-1} ATLAS-CONF-2020-003
$t\bar{t}+\phi$ 2L, 139 fb^{-1} ATLAS-CONF-2020-046
ATLAS Preliminary
√s=13 TeV, 36.1-139 fb^{-1}
All limits at 95% CL
Scalar ϕ, $\phi\to\chi\bar{\chi}$
$g_q = 1; g_\chi = 1$
Dirac DM, m_χ = 1 GeV
10
20
30
40
50
60
10^2
2×10^2
3×10^2
m_ϕ [GeV]



$\sqrt{s}$=13 TeV, 36.1 - 139 fb^{-1}
July 2020
ATLAS Preliminary
$m(\tilde{\chi}_1^0)$ [GeV]
$\tilde{g}\rightarrow q\bar{q}\tilde{\chi}_1^0$ 0 lep. [CONF-2019-040]
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$\tilde{g}\rightarrow q\bar{q}(ll/\nu\nu)\tilde{\chi}_1^0$ via $\tilde{l}/\tilde{\nu}$ 2 l
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$\tilde{g}\rightarrow q\bar{q}(\gamma/Z)\tilde{G}$ via $\tilde{\chi}_1^0$ ≥ 1
Colours indicate differen
Observed limits at 95% (
3500
3000
2500
2000
1500
1000
500
1000
1200
1400
July 2020
σ/σ_{theory}
2×10^2
10^2
20
10
3
2
1
2×10^{-1}
10^{-1}
6×10^{-2}
10
Expected
Observed
$b\bar{b}+\phi$ 0L, 36.1 fb^{-1} EPJC 78 (2018) 18
$t\bar{t}+\phi$ 0L, 36.1 fb^{-1} EPJC 78 (2018) 18
$t\bar{t}+\phi$ 1L, 139 fb^{-1} ATLAS-CONF-2020-003
ATLAS Preliminary
$\sqrt{s}$=13 TeV, 36.1-139 fb^{-1}
All limits at 95% CL
ATLAS Preliminary
$B_{inv} < 0.11$
All limits at 90% CL
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
$\sigma_{WIMP\text{-}nucleon}$ [cm^2]
10^{-39}
10^{-41}
10^{-43}
10^{-45}
10^{-47}
Higgs Portal
Scalar WIMP
Majorana WIMP
Other experiments
DarkSide-50
LUX
PandaX-II
Xenon1T
1
10
10^2
10^3
10^4
m_{WIMP} [GeV]

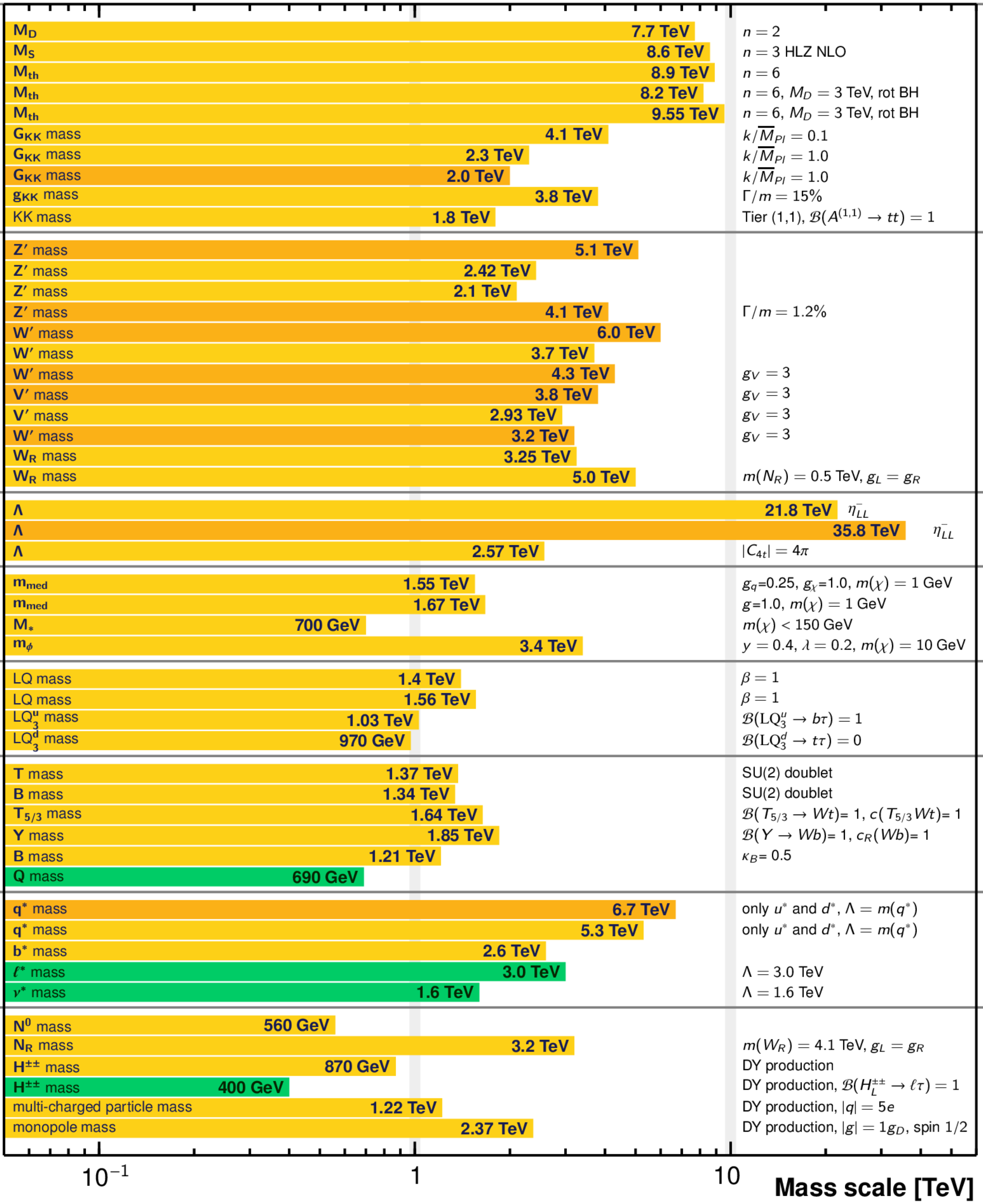
ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2020

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 139)\ \text{fb}^{-1}$

$\sqrt{s} = 8, 13$ TeV



	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt [\text{fb}^{-1}]$	Limit			Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	1 – 4 j	Yes	36.1	🟨 M_D	7.7 TeV	$n = 2$	1711.03301
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	🟨 M_S	8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	🟨 M_{th}	8.9 TeV	$n = 6$	1703.09127
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	🟨 M_{th}	8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	🟨 M_{th}	9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	36.7	🟨 G_{KK} mass	4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	1707.04147
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	🟨 G_{KK} mass	2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	1808.02380
	Bulk RS $G_{KK} \to WV \to \ell\nu qq$	1 e, μ	2 j / 1 J	Yes	139	🟧 G_{KK} mass	2.0 TeV	$k/\overline{M}_{Pl} = 1.0$	2004.14636
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	🟨 g_{KK} mass	3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 3 j	Yes	36.1	🟨 KK mass	1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	139	🟧 Z' mass	5.1 TeV		1903.06248
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	🟨 Z' mass	2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	🟨 Z' mass	2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	0 e, μ	≥ 1 b, ≥ 2 J	Yes	139	🟧 Z' mass	4.1 TeV	$\Gamma/m = 1.2\%$	2005.05138
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	139	🟧 W' mass	6.0 TeV		1906.05609
	SSM $W' \to \tau\nu$	1 τ	–	Yes	36.1	🟨 W' mass	3.7 TeV		1801.06992
	HVT $W' \to WZ \to \ell\nu qq$ model B	1 e, μ	2 j / 1 J	Yes	139	🟧 W' mass	4.3 TeV	$g_V = 3$	2004.14636
	HVT $V' \to WV \to qqqq$ model B	0 e, μ	2 J	–	139	🟧 V' mass	3.8 TeV	$g_V = 3$	1906.08589
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	🟨 V' mass	2.93 TeV	$g_V = 3$	1712.06518
	HVT $W' \to WH$ model B	0 e, μ	≥ 1 b, ≥ 2 J		139	🟧 W' mass	3.2 TeV	$g_V = 3$	CERN-EP-2020-073
	LRSM $W_R \to tb$	multi-channel			36.1	🟨 W_R mass	3.25 TeV		1807.10473
	LRSM $W_R \to \mu N_R$	2 μ	1 J	–	80	🟨 W_R mass	5.0 TeV	$m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679
CI	CI $qqqq$	–	2 j	–	37.0	🟨 Λ	21.8 TeV	η_{LL}^{-}	1703.09127
	CI $\ell\ell qq$	2 e, μ	–	–	139	🟧 Λ	35.8 TeV	η_{LL}^{-}	CERN-EP-2020-066
	CI $tttt$	$\geq$1 e,μ	$\geq$1 b, $\geq$1 j	Yes	36.1	🟨 Λ	2.57 TeV	$\lvert C_{4t} \rvert = 4\pi$	1811.02305
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	🟨 m_{med}	1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi) = 1$ GeV	1711.03301
	Colored scalar mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	🟨 m_{med}	1.67 TeV	g=1.0, $m(\chi) = 1$ GeV	1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	🟨 M_*	700 GeV	$m(\chi) < 150$ GeV	1608.02372
	Scalar reson. $\phi \to t\chi$ (Dirac DM)	0-1 e, μ	1 b, 0-1 J	Yes	36.1	🟨 m_ϕ	3.4 TeV	$y = 0.4$, $\lambda = 0.2$, $m(\chi) = 10$ GeV	1812.09743
LQ	Scalar LQ 1st gen	1,2 e	≥ 2 j	Yes	36.1	🟨 LQ mass	1.4 TeV	$\beta = 1$	1902.00377
	Scalar LQ 2nd gen	1,2 μ	≥ 2 j	Yes	36.1	🟨 LQ mass	1.56 TeV	$\beta = 1$	1902.00377
	Scalar LQ 3rd gen	2 τ	2 b	–	36.1	🟨 LQ_3^u mass	1.03 TeV	$\mathcal{B}(\mathrm{LQ}_3^u \to b\tau) = 1$	1902.08103
	Scalar LQ 3rd gen	0-1 e, μ	2 b	Yes	36.1	🟨 LQ_3^d mass	970 GeV	$\mathcal{B}(\mathrm{LQ}_3^d \to t\tau) = 0$	1902.08103
Heavy quarks	VLQ $TT \to Ht/Zt/Wb + X$	multi-channel			36.1	🟨 T mass	1.37 TeV	SU(2) doublet	1808.02343
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	🟨 B mass	1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3} T_{5/3} \vert T_{5/3} \to Wt + X$	2(SS)/$\geq$3 e,μ	$\geq$1 b, $\geq$1 j	Yes	36.1	🟨 $T_{5/3}$ mass	1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3} Wt)$= 1	1807.11883
	VLQ $Y \to Wb + X$	1 e, μ	≥ 1 b, ≥ 1j	Yes	36.1	🟨 Y mass	1.85 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B \to Hb + X$	0 e,μ, 2 γ	≥ 1 b, ≥ 1j	Yes	79.8	🟨 B mass	1.21 TeV	κ_B= 0.5	ATLAS-CONF-2018-024
	VLQ $QQ \to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	🟩 Q mass	690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	139	🟧 q^* mass	6.7 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1910.08447
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	🟨 q^* mass	5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	36.1	🟨 b^* mass	2.6 TeV		1805.09299
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	🟩 ℓ^* mass	3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	🟩 ν^* mass	1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	1 e, μ	≥ 2 j	Yes	79.8	🟨 N^0 mass	560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	2 μ	2 j	–	36.1	🟨 N_R mass	3.2 TeV	$m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	🟨 $H^{\pm\pm}$ mass	870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	🟩 $H^{\pm\pm}$ mass	400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Multi-charged particles	–	–	–	36.1	🟨 multi-charged particle mass	1.22 TeV	DY production, $\lvert q \rvert = 5e$	1812.03673
	Magnetic monopoles	–	–	–	34.4	🟨 monopole mass	2.37 TeV	DY production, $\lvert g \rvert = 1 g_D$, spin 1/2	1905.10130

🟩 $\sqrt{s}$ = 8 TeV

🟨 $\sqrt{s}$ = 13 TeV partial data

🟧 $\sqrt{s}$ = 13 TeV full data

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*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

Where is the new physics?

- We **know** it’s out there

Where is the new physics?

- We **know** it’s out there

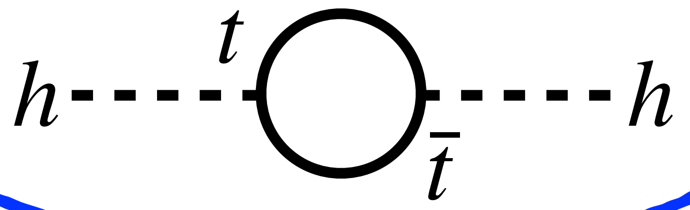
Dark matter?

Where is the new physics?

- We **know** it's out there

Dark matter?

Higgs mass too light?



Where is the new physics?

- We **know** it's out there

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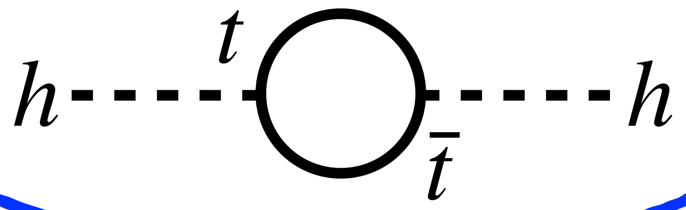
Higgs mass too light?



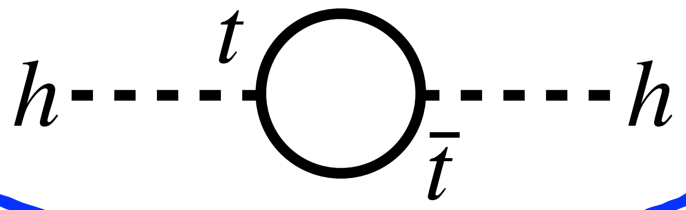
Where is all the antimatter?

Where is the new physics?

- We **know** it's out there

Dark matter?

Higgs mass too light?



Where is all the antimatter?

- So why haven't we seen it yet? A couple possible reasons:

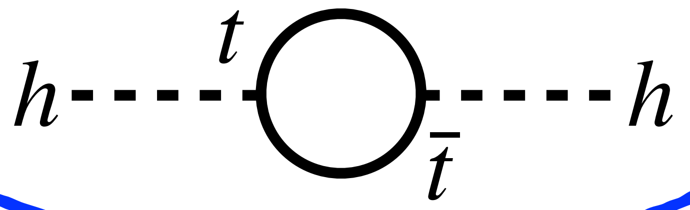
1. It is above the scale accessible by the LHC
2. It isn't where we have been looking

Where is the new physics?

- We **know** it's out there

Dark matter?

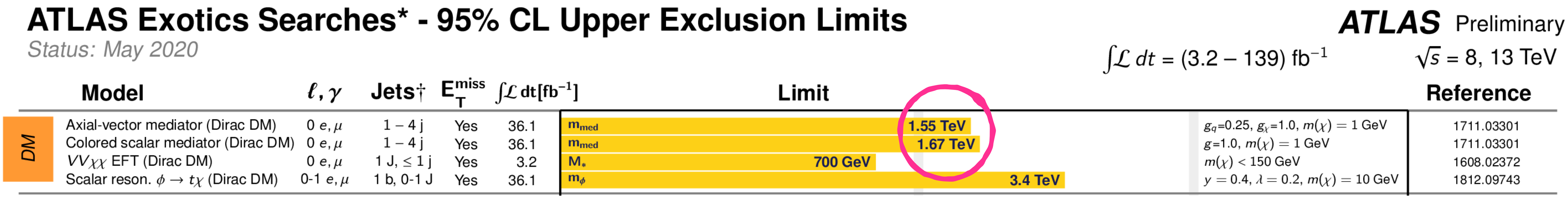
Higgs mass too light?




Where is all the antimatter?

- So why haven't we seen it yet? A couple possible reasons:
  1. It is above the scale accessible by the LHC
  2. It isn't where we have been looking
- In case 1, not much we can do about it. But we have all the power in case 2! Need to understand where else to look.

How we should read our limits



ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2020

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 139)\ \mathrm{fb}^{-1}$

$\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt [\mathrm{fb}^{-1}]$	Limit			Reference
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med}	1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi) = 1$ GeV	1711.03301
	Colored scalar mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med}	1.67 TeV	g=1.0, $m(\chi) = 1$ GeV	1711.03301
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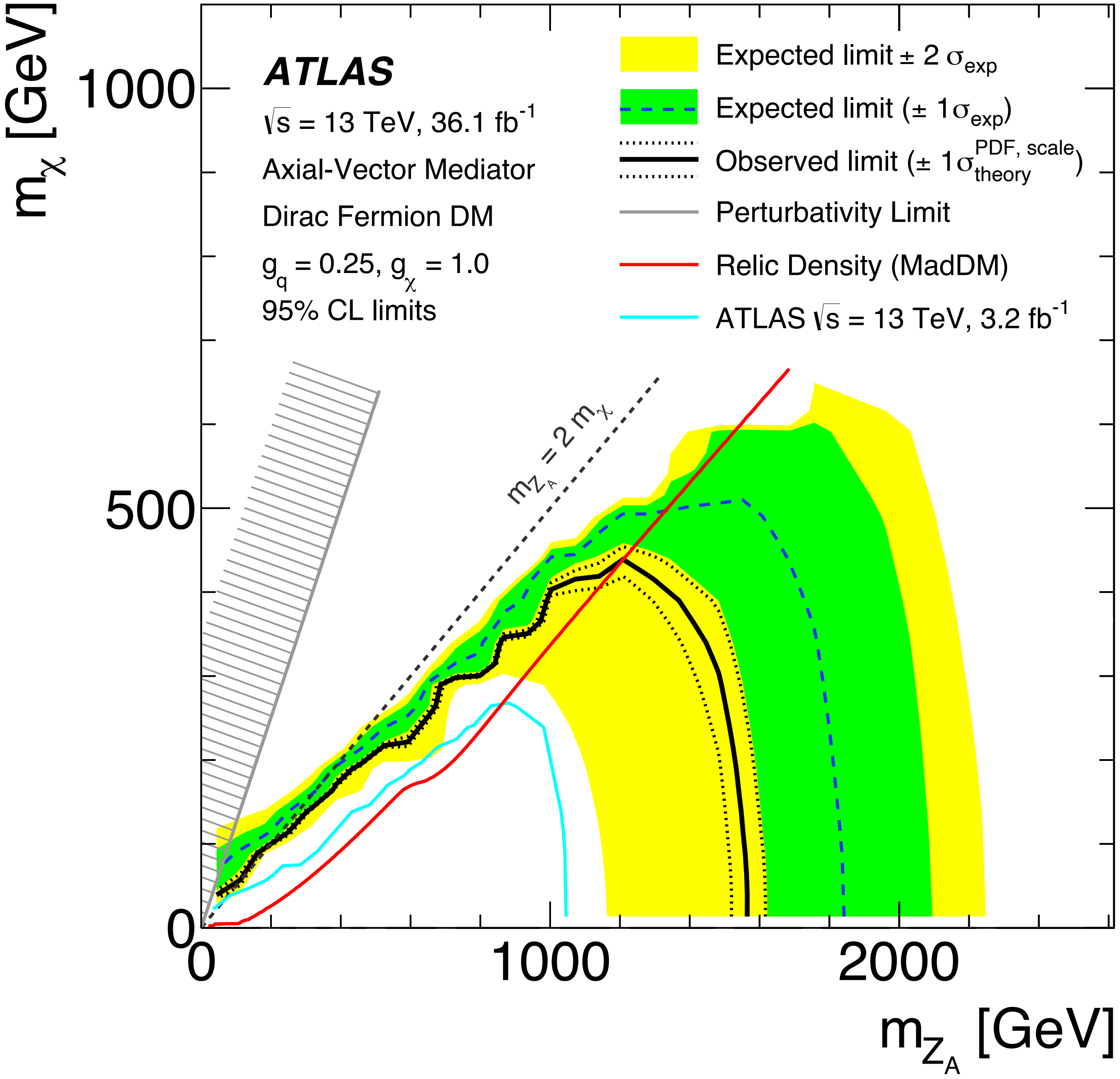

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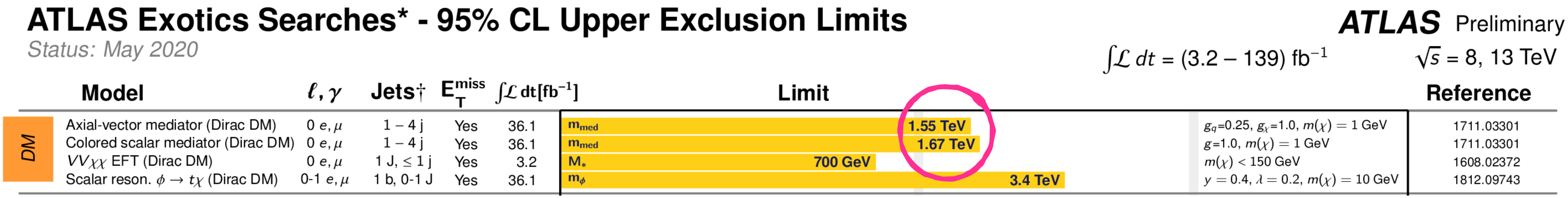

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2020

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 139)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 8,\ 13$ TeV

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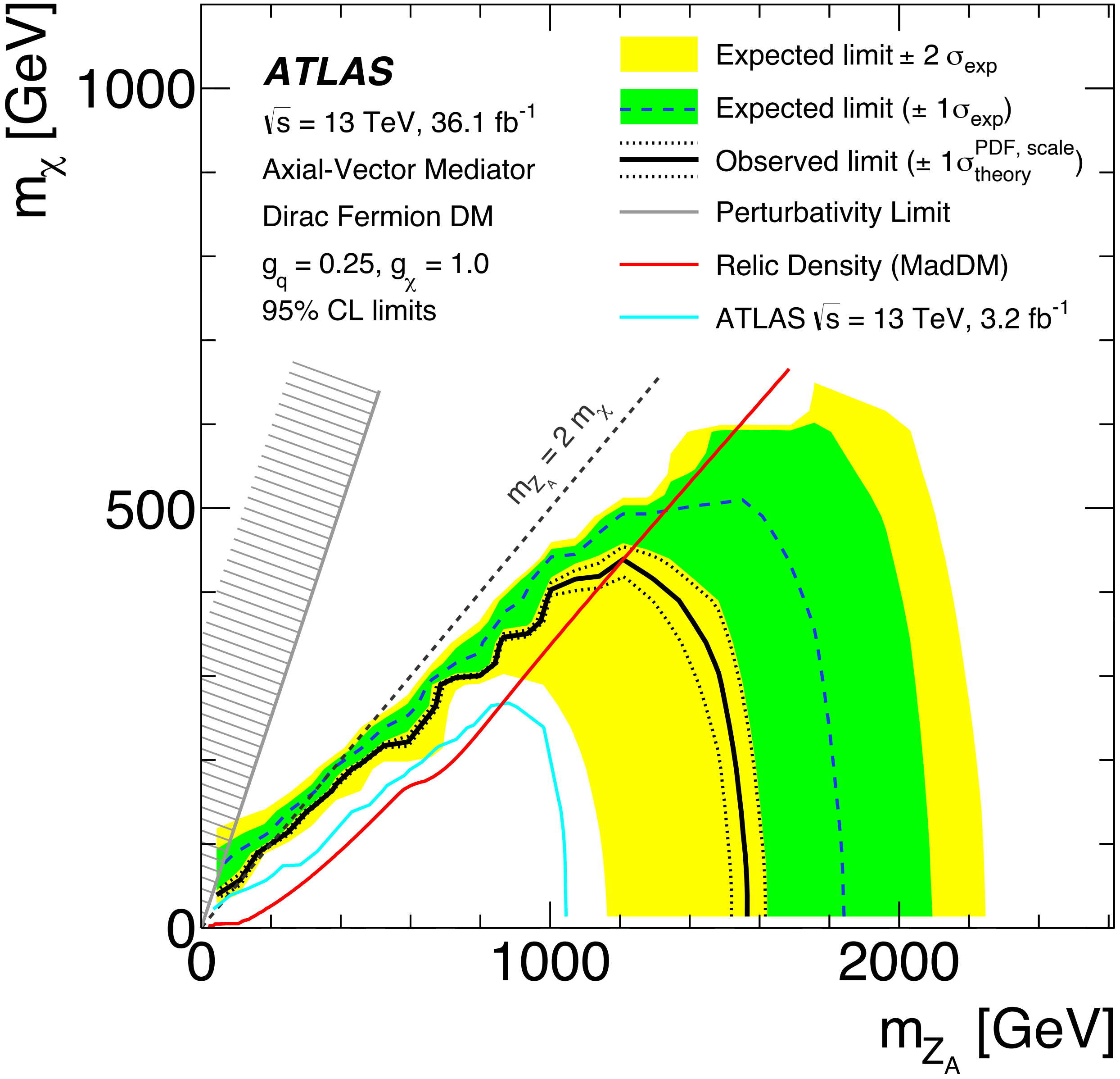

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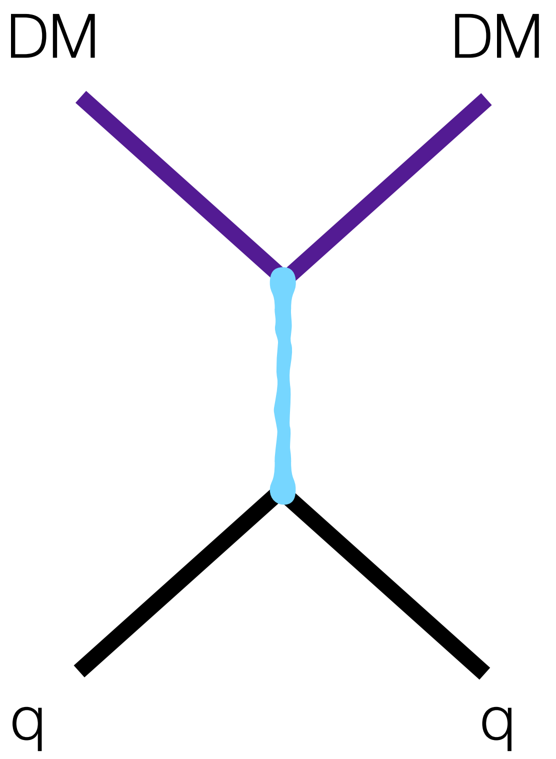

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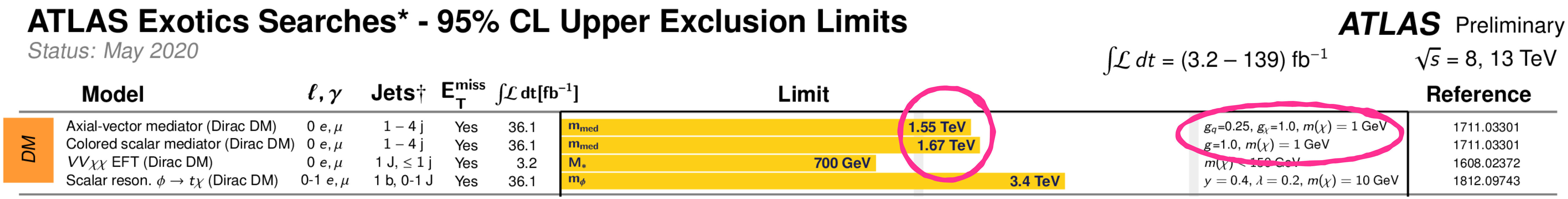

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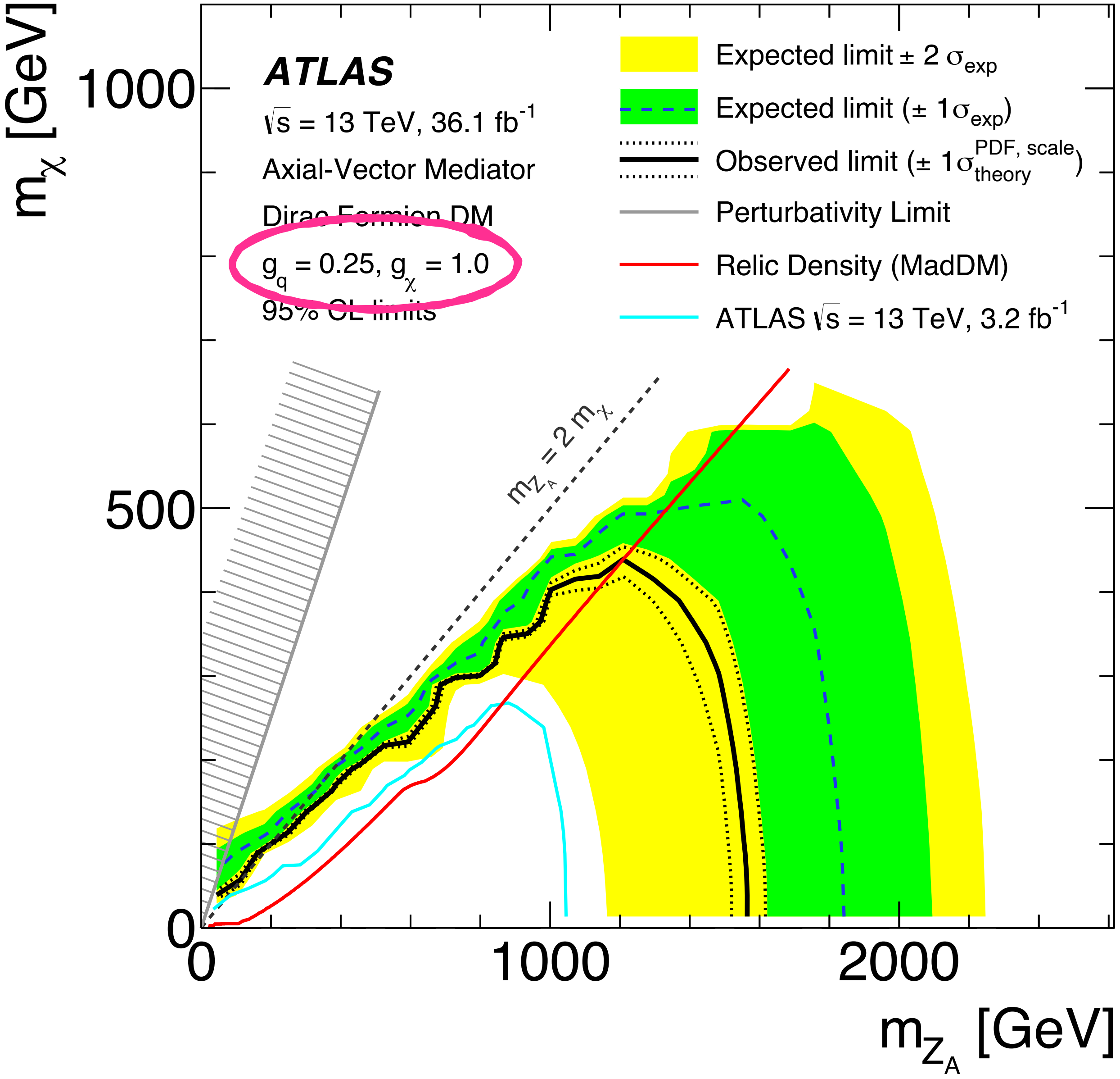

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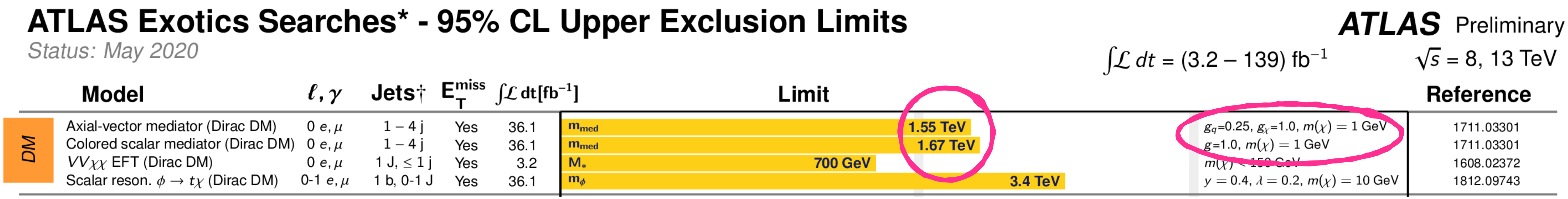

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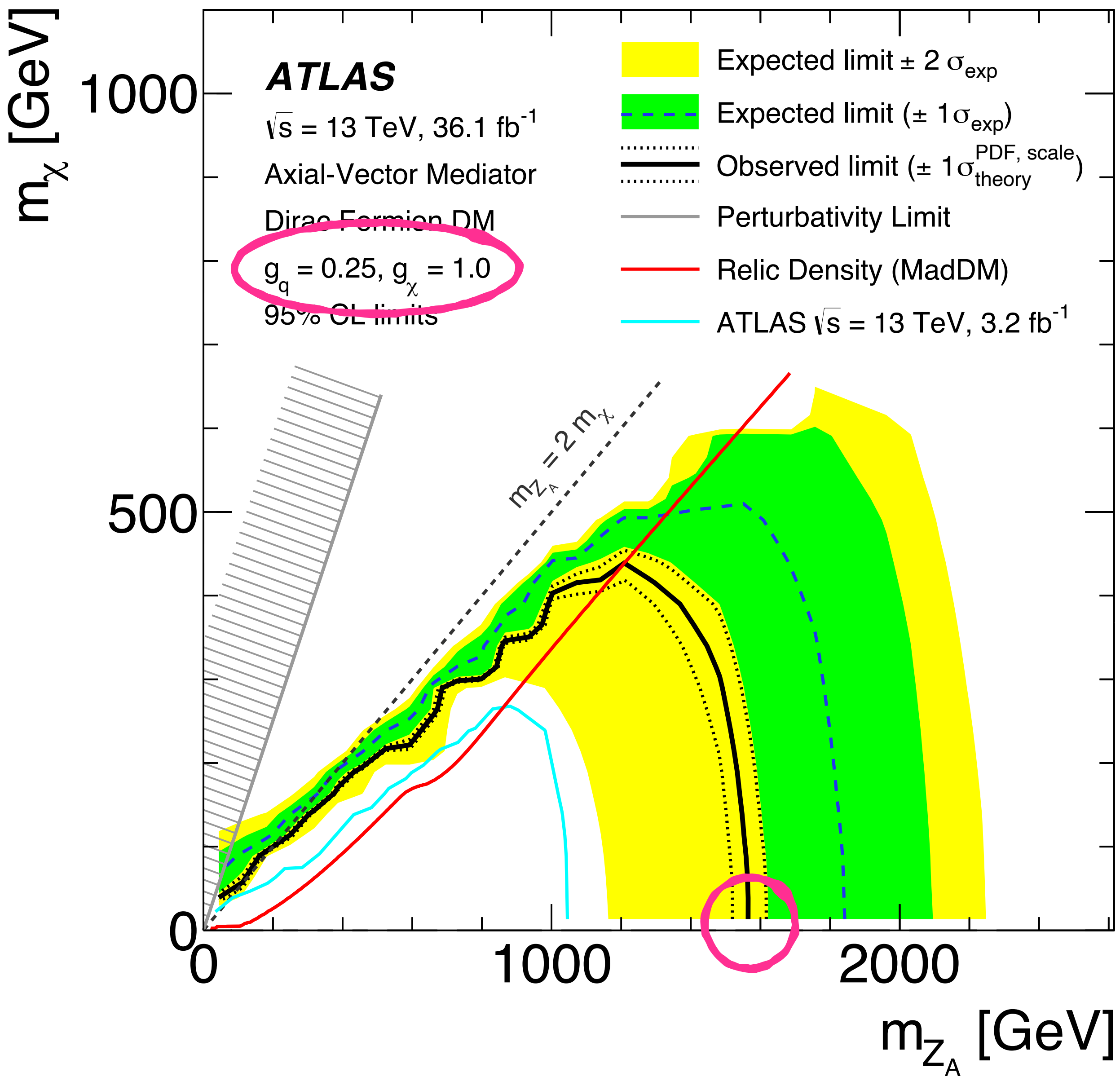

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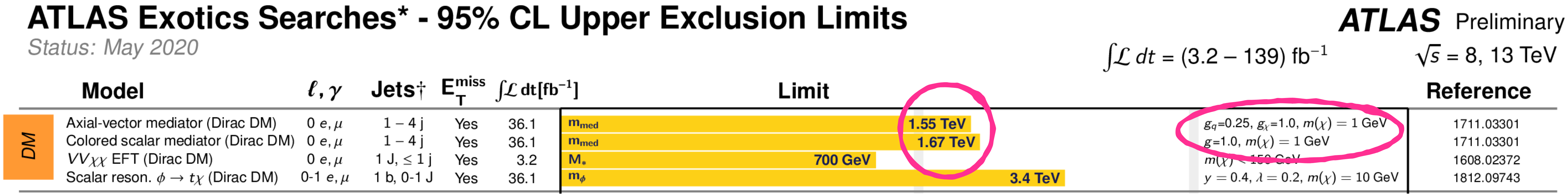

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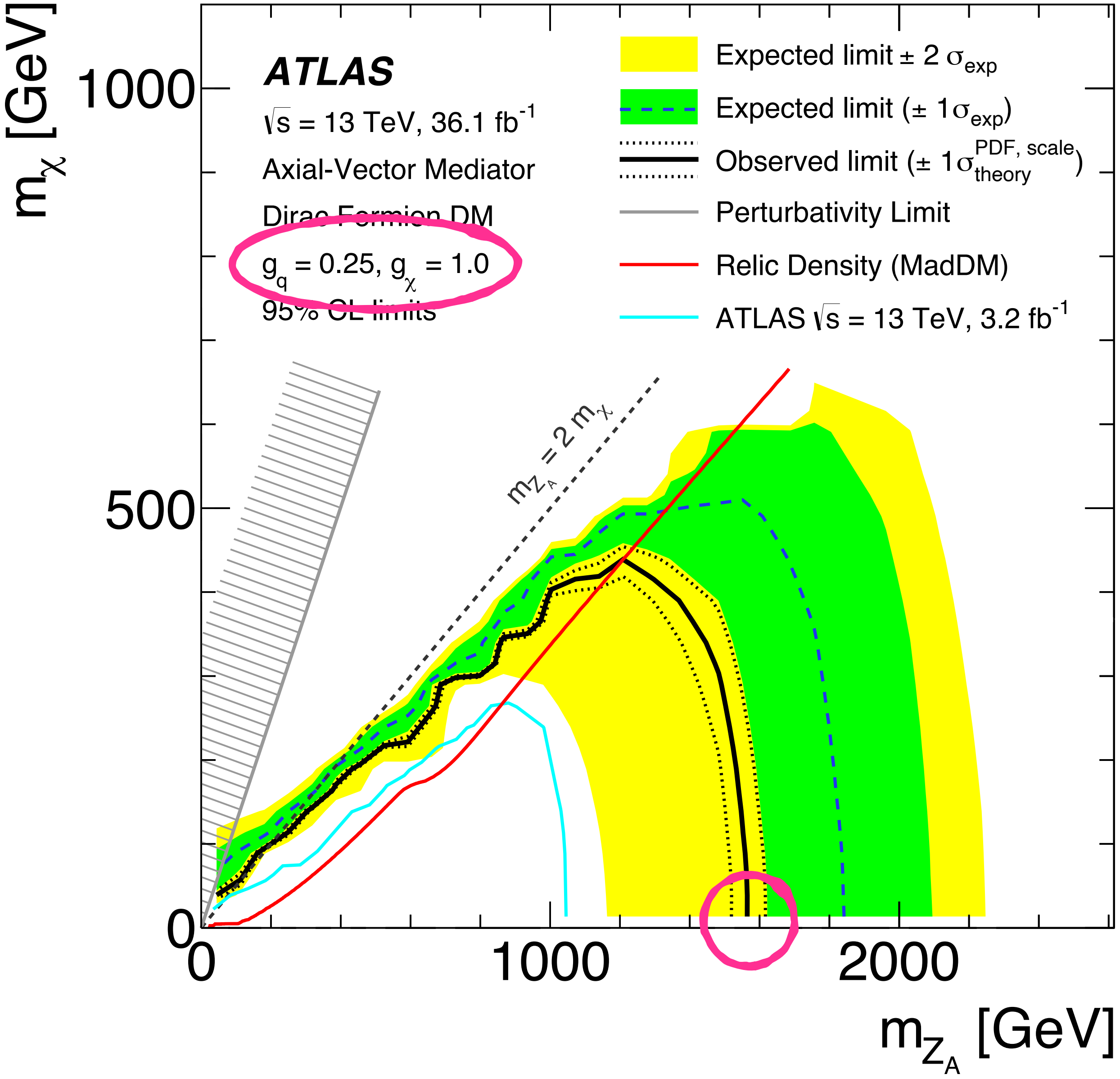

- Remember: we use really simple models and scenarios for these plots
    - Basic t-channel simplified model
    - Only relevant couplings active
    - Best limit at any mass reported
- There is still lots of room for dark matter, just in more complicated scenarios!

What if we've been thinking too simplistically?

How to get the right amount of dark matter in the universe

SM ↔ Some mediator ↔ DM

Freeze-out scenarios:
lots of DM in the early
universe, decouples once
temperature drops
enough

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Freeze-in scenarios: no DM in early universe, mediator and SM in equilibrium. DM sector slowly populated via **very small coupling** to mediator.

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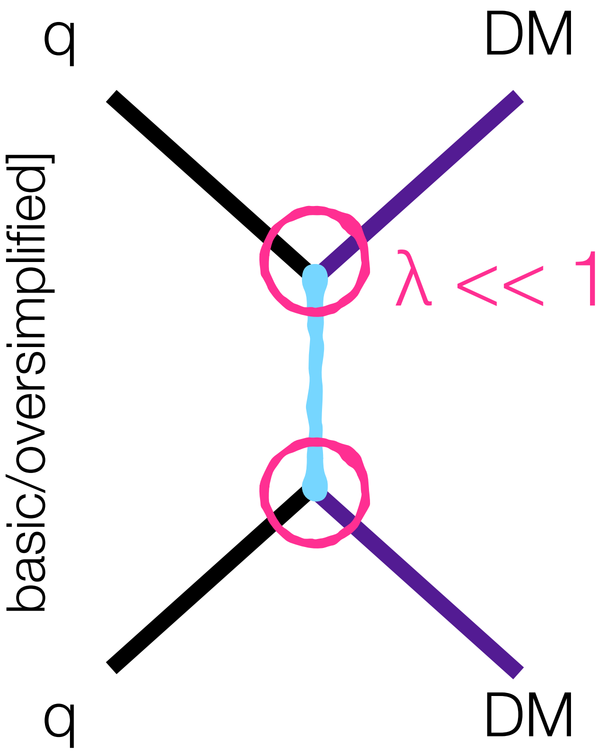
Still gets you the right relic density

arXiv:2001.05024
& Jan Heisig

Suppressed decays in dark matter models

[Warning - still super basic/oversimplified]



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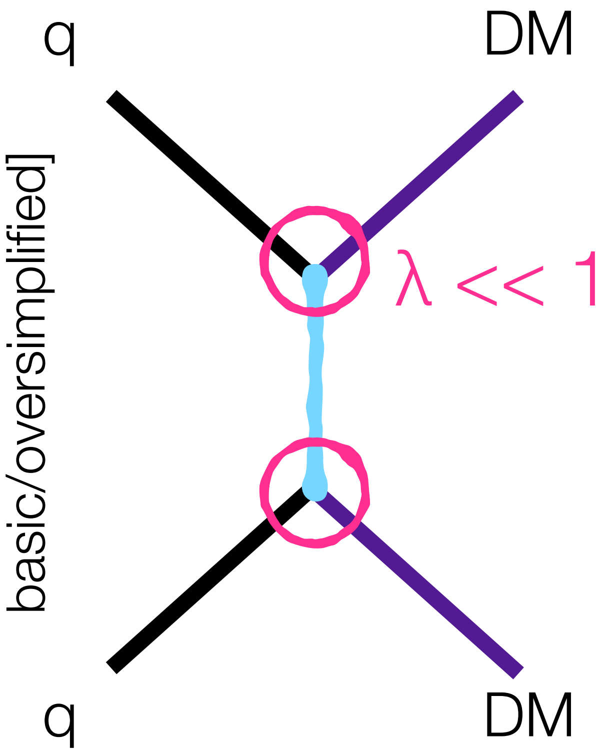

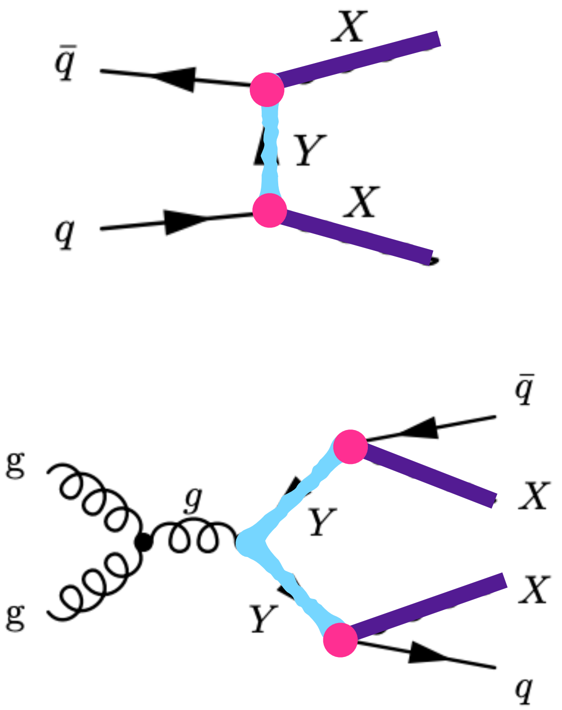

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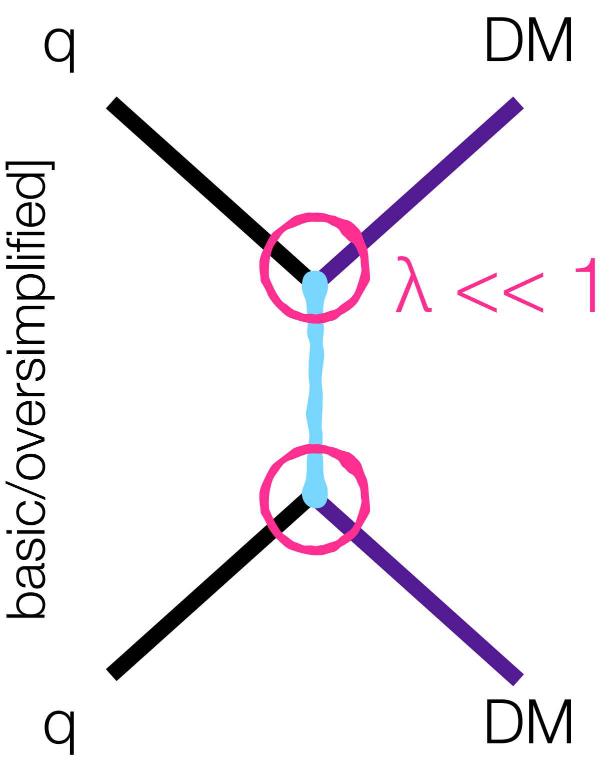

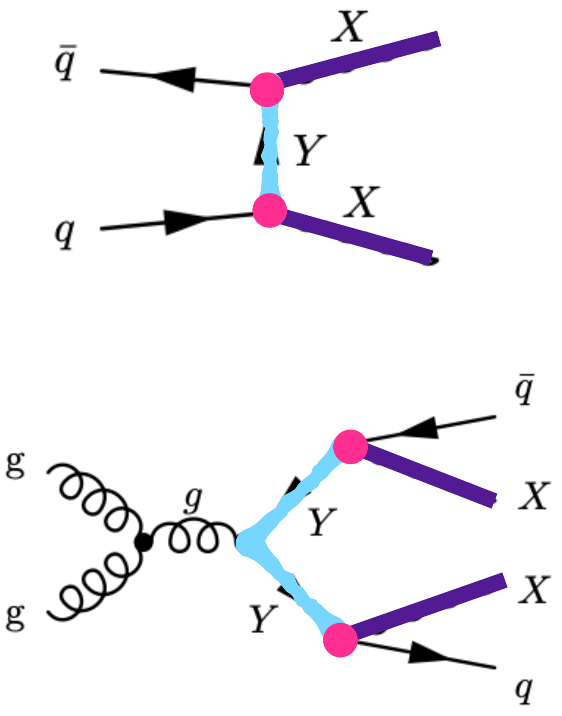

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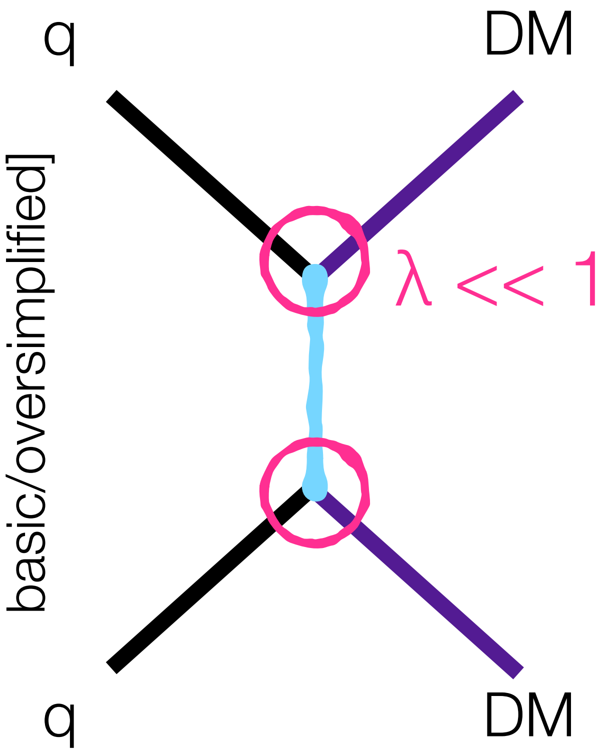

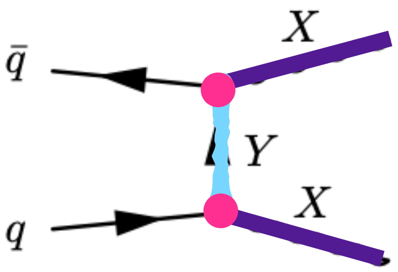

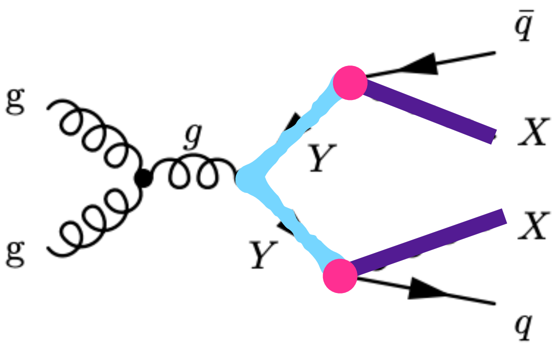

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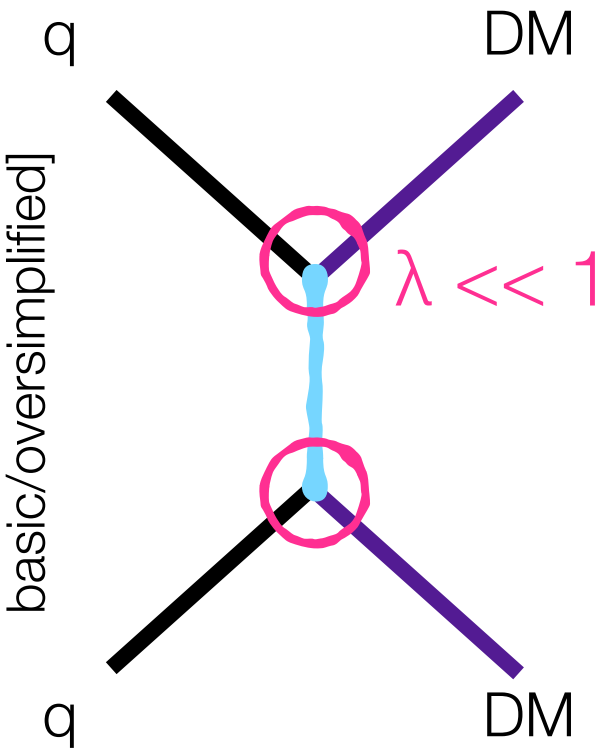

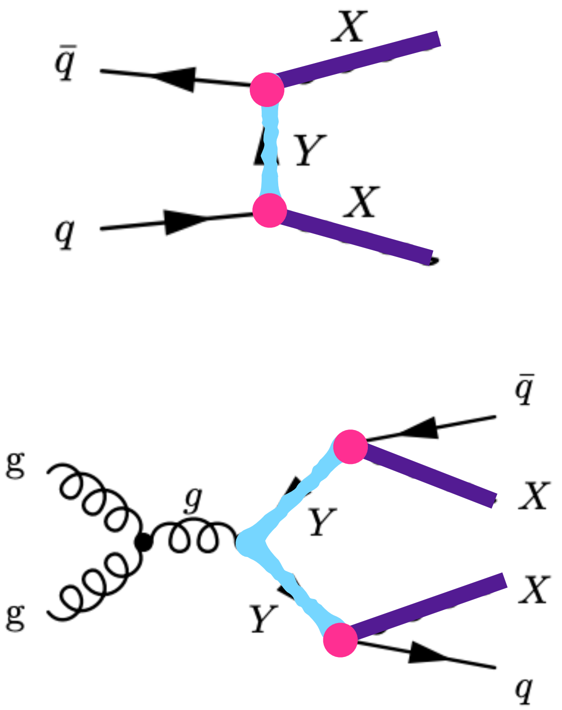

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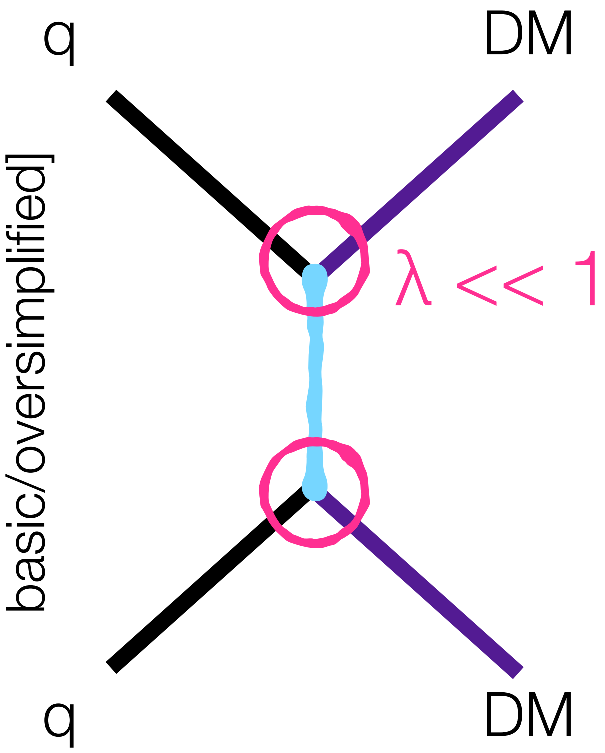

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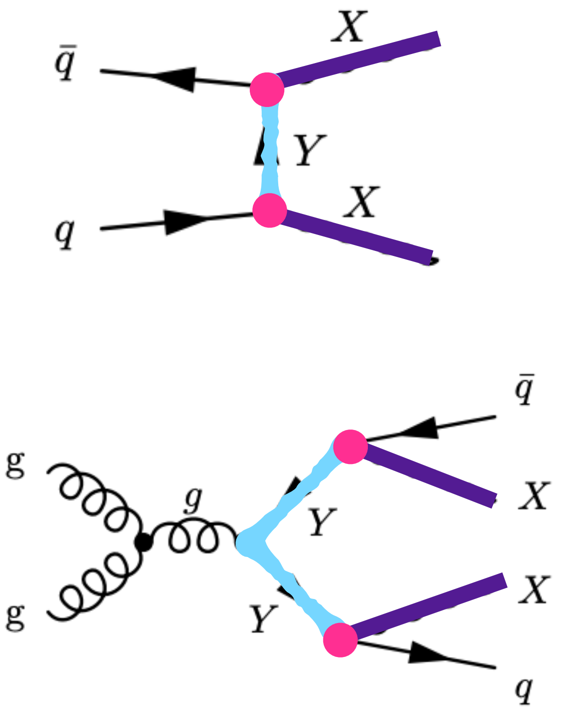

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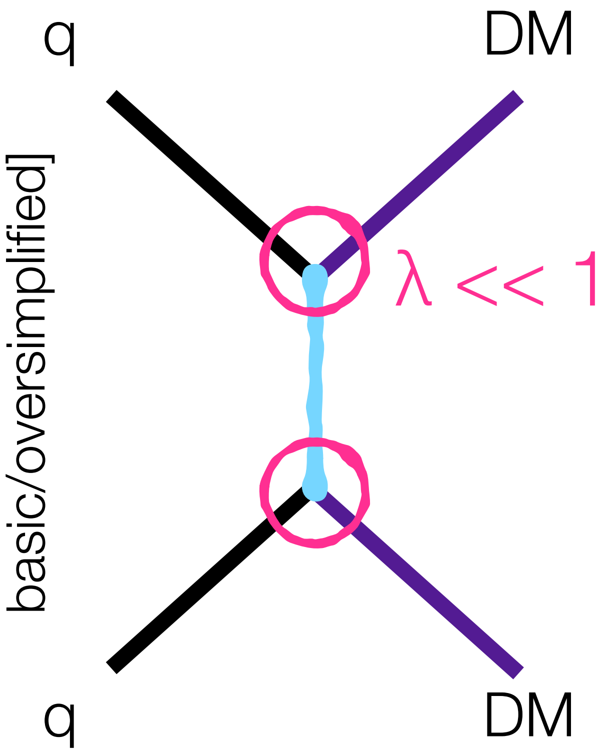

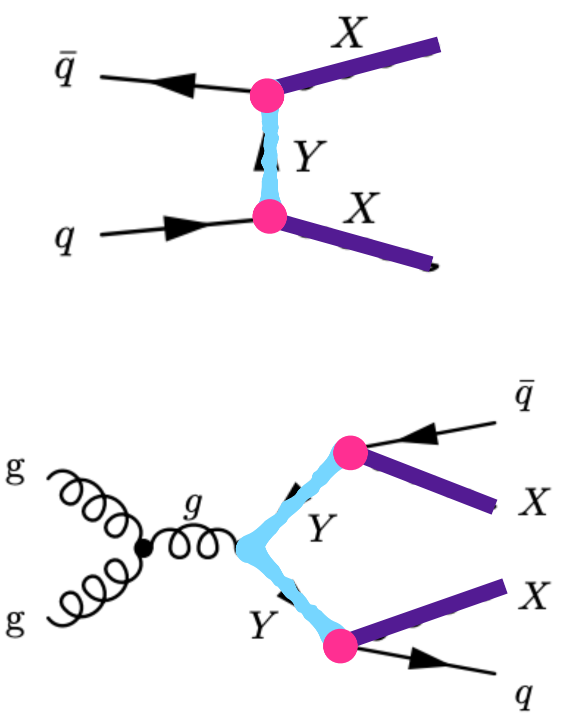

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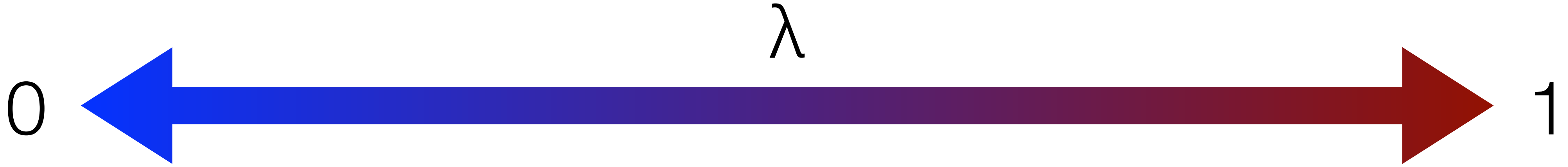

Freeze-in

Conversion-driven freeze-out

Co-annihiliation

Vanilla WIMPs

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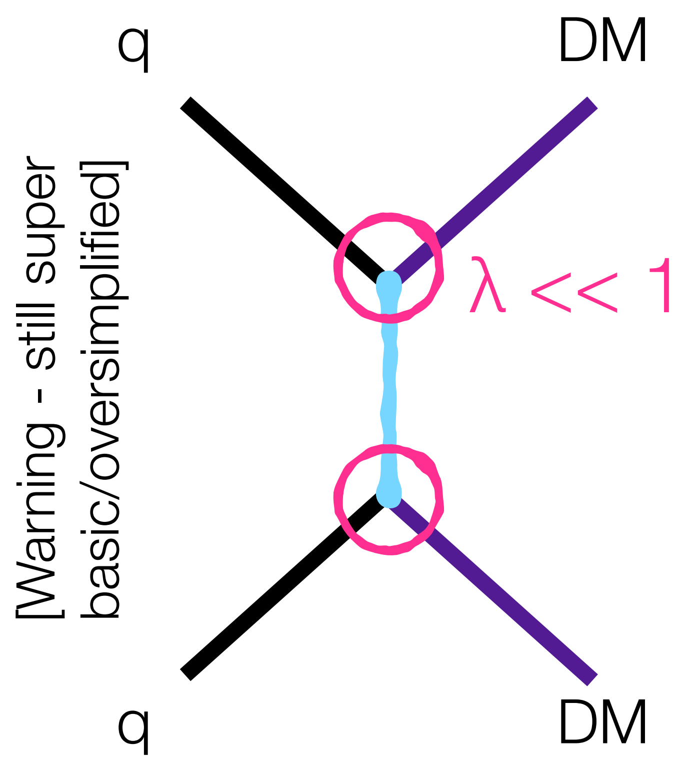

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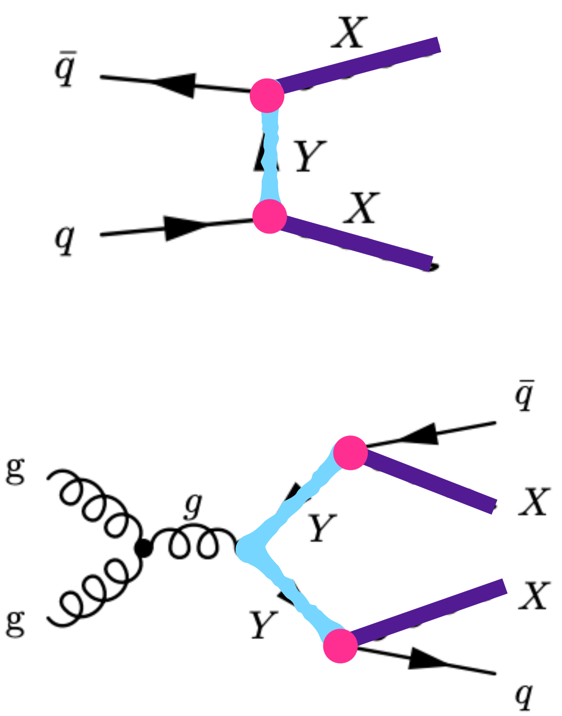

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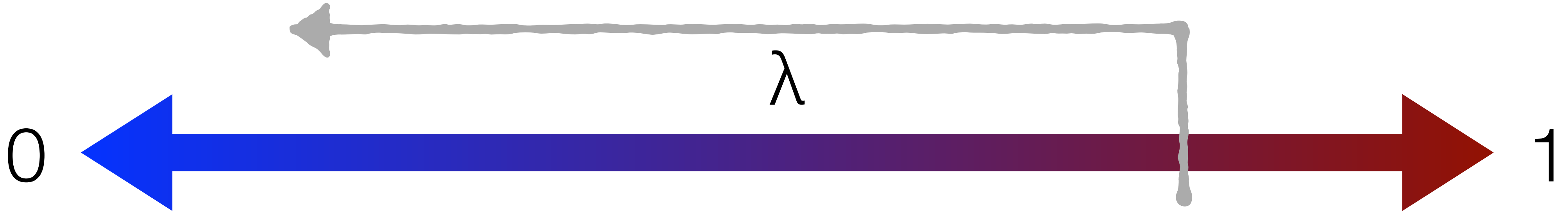

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Long lifetimes and where to find them

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e.g. SM lepton flavour violation

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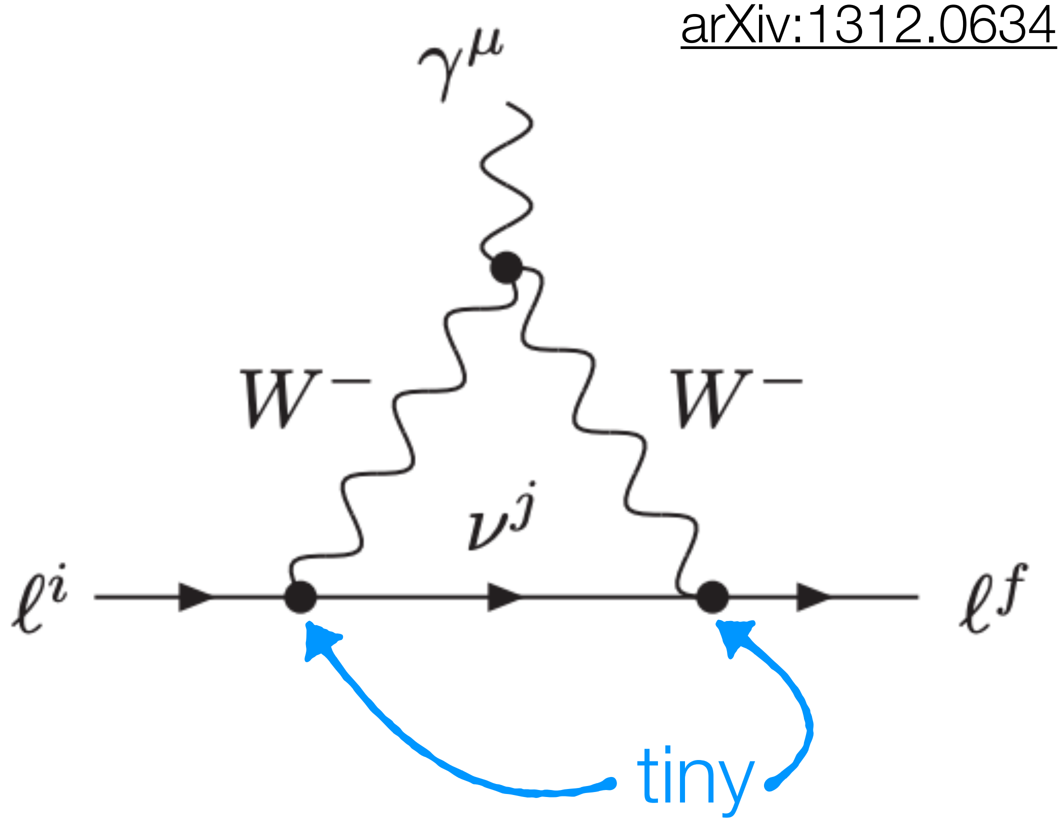
arXiv:1312.0634



$\mu \to e\gamma$ BR < 1e-13

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Limited phase space

e.g. K_{short} vs K_{long} lifetimes

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$K^0_S \to \pi\pi$

$K^0_L \to \pi\pi\pi$

Mass of K^0 just a bit larger than mass of three pions

Lifetime 9e-11 s versus 5e-8 s

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e.g. K_{short} vs K_{long} lifetimes

Decays via heavy particle

e.g. μ to e via off-shell W

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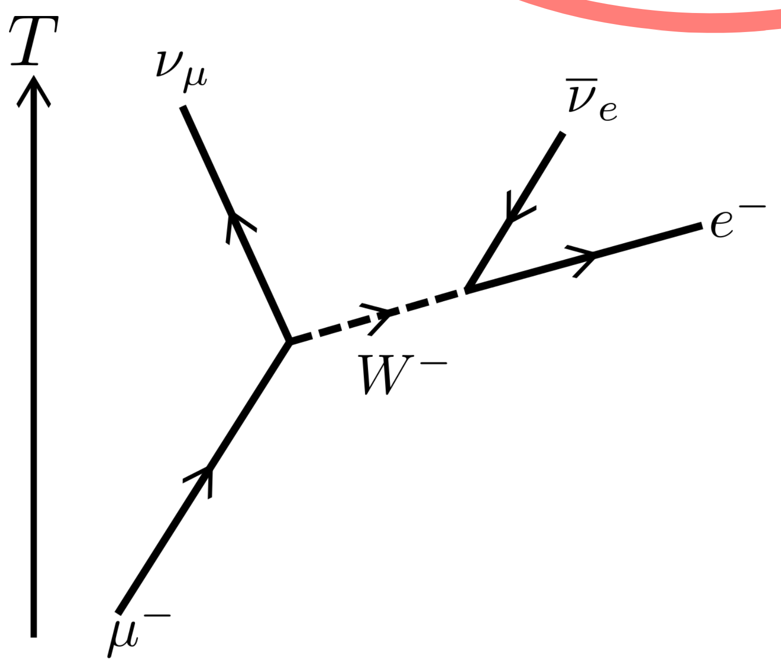

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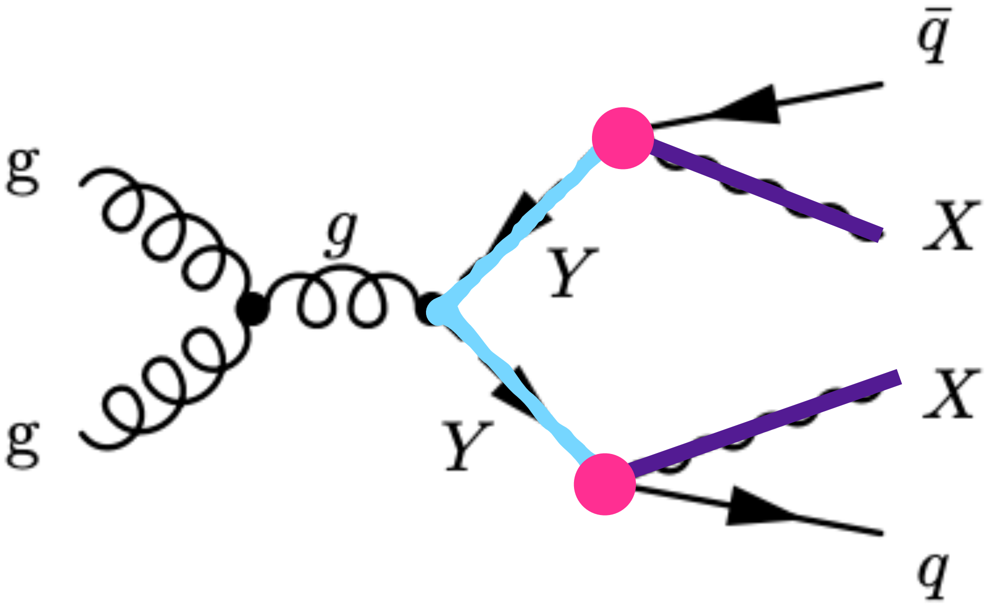

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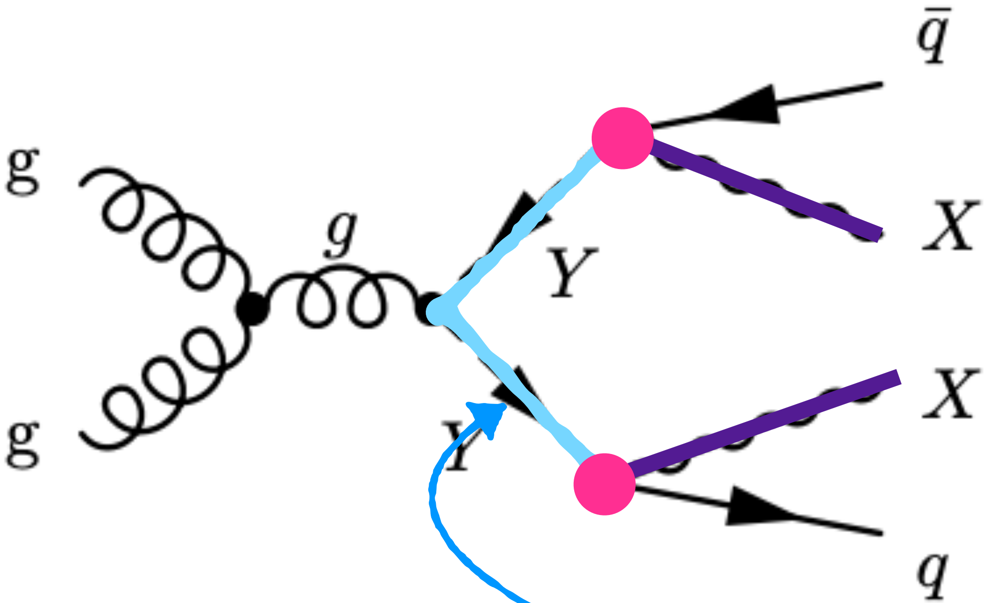

Becomes long-lived when λ” is very small

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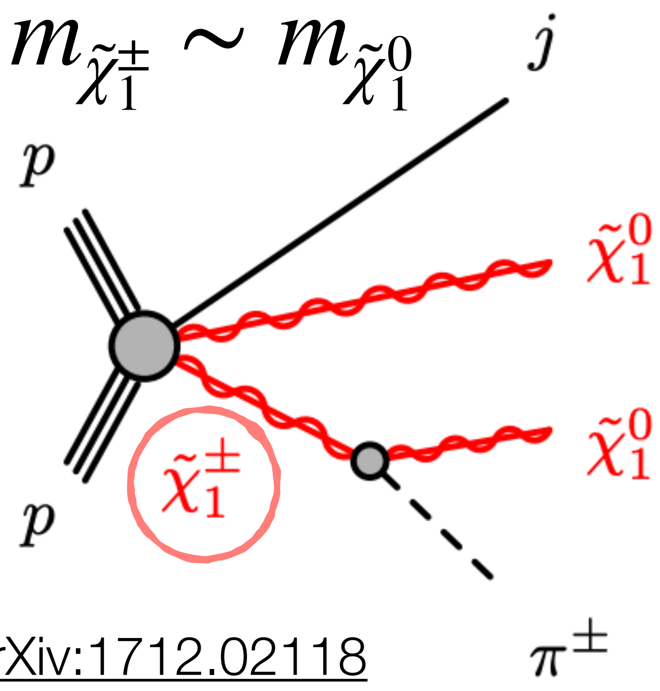

$$m_{\tilde{\chi}_1^\pm} \sim m_{\tilde{\chi}_1^0}$$

arXiv:1712.02118

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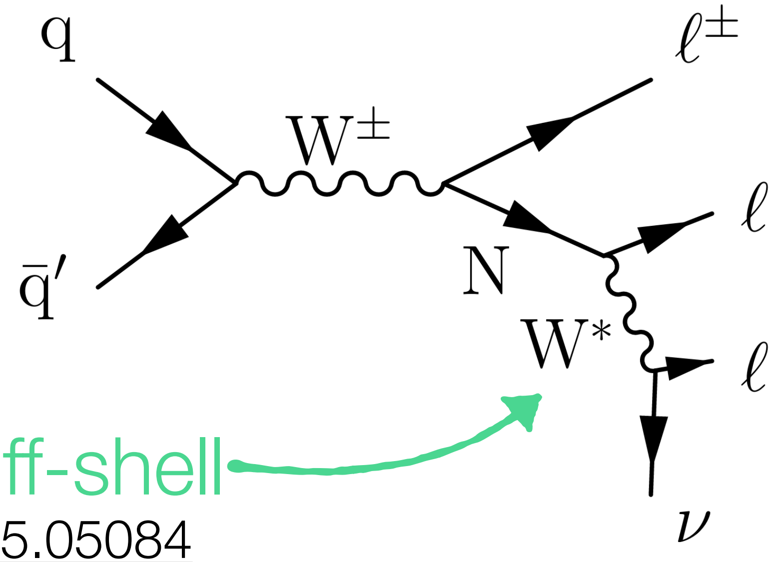

super off-shell

arXiv:1805.05084

BSM with long lived particles

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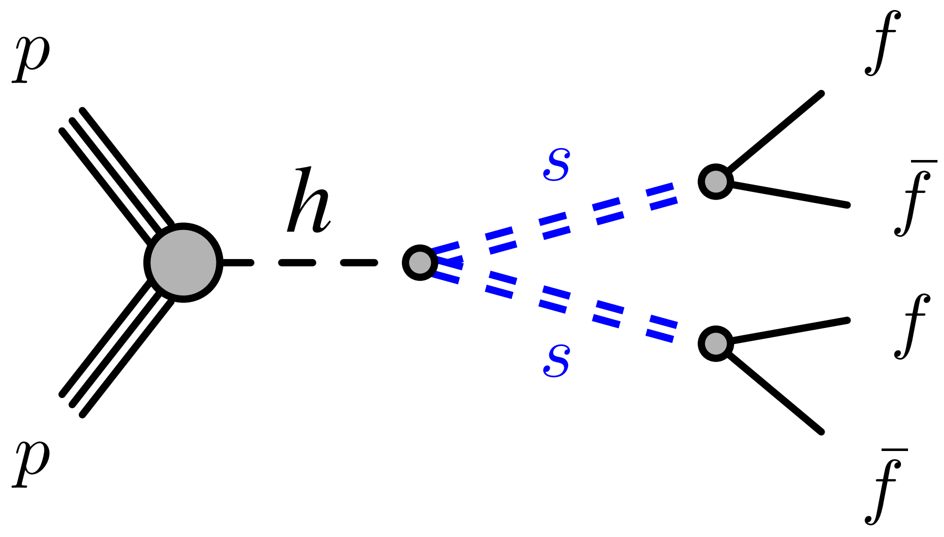

EXOT-2018-61

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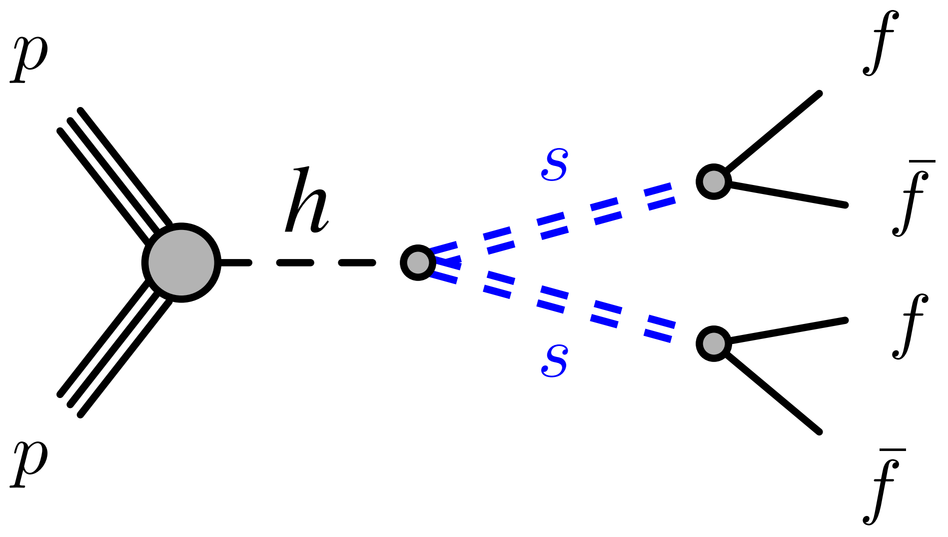

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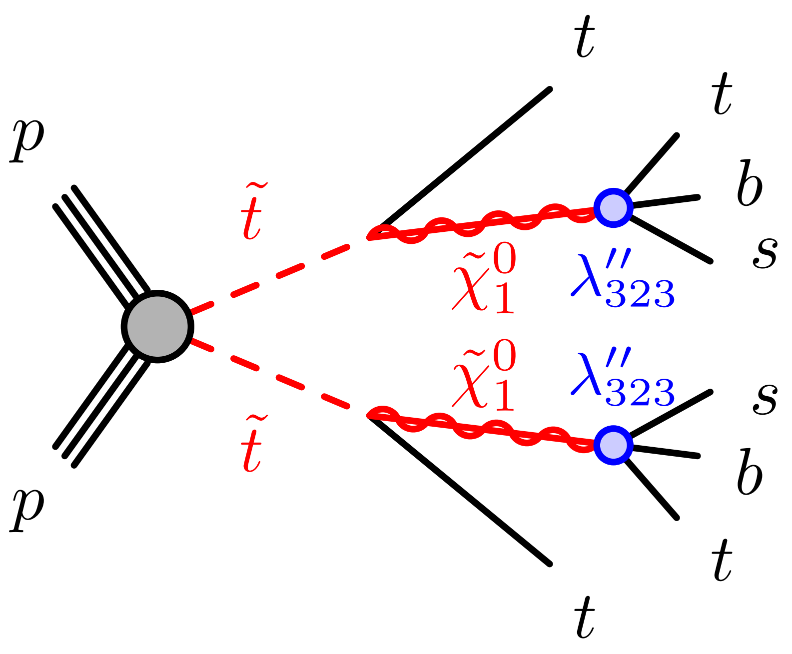
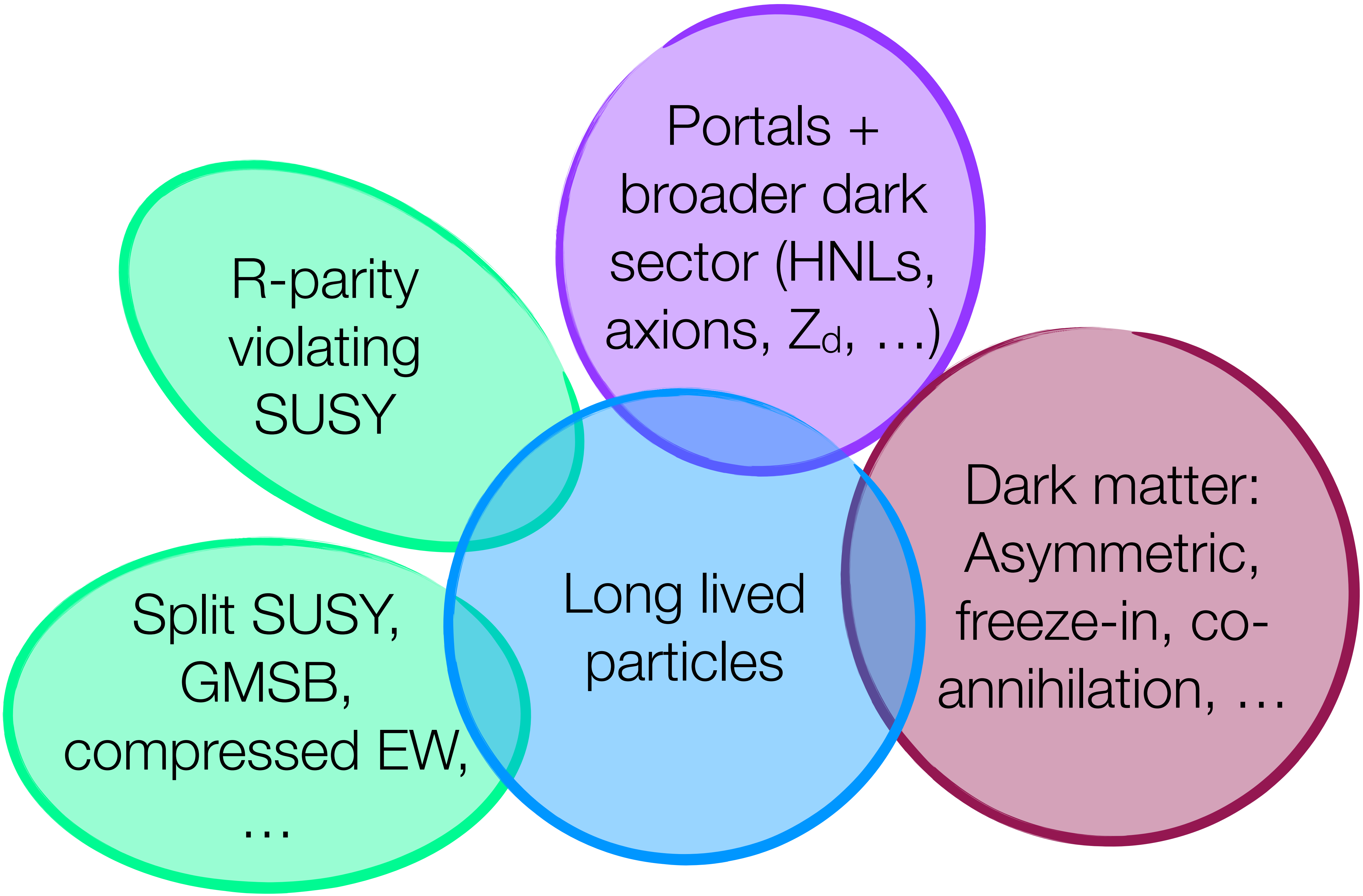
SUSY!

Example: R-parity violation



(Parts of) the LLP world



Portals + broader dark sector (HNLs, axions, Z_d, …)

R-parity violating SUSY

Long lived particles

Dark matter: Asymmetric, freeze-in, co-annihilation, …

Split SUSY, GMSB, compressed EW, …

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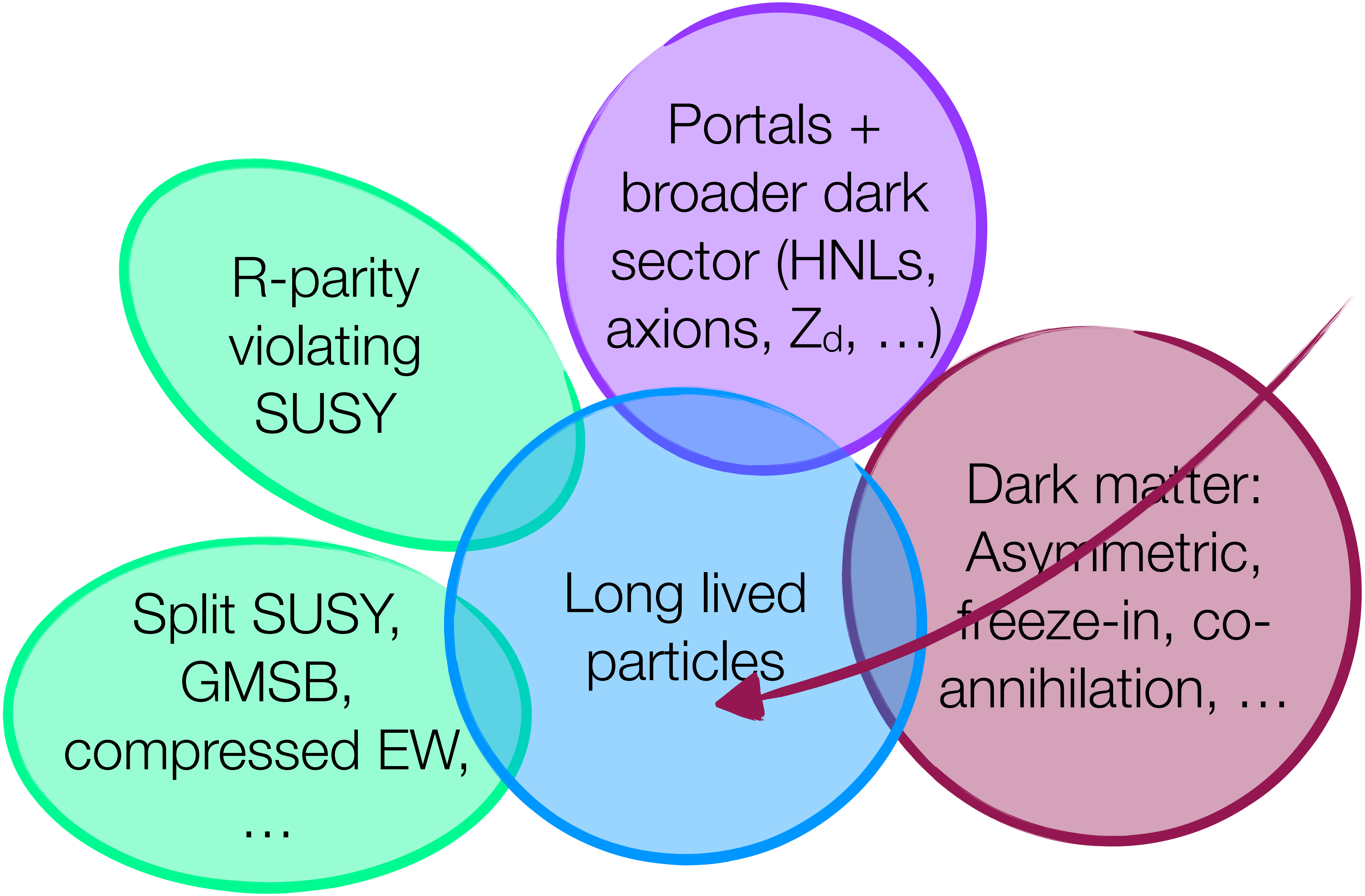

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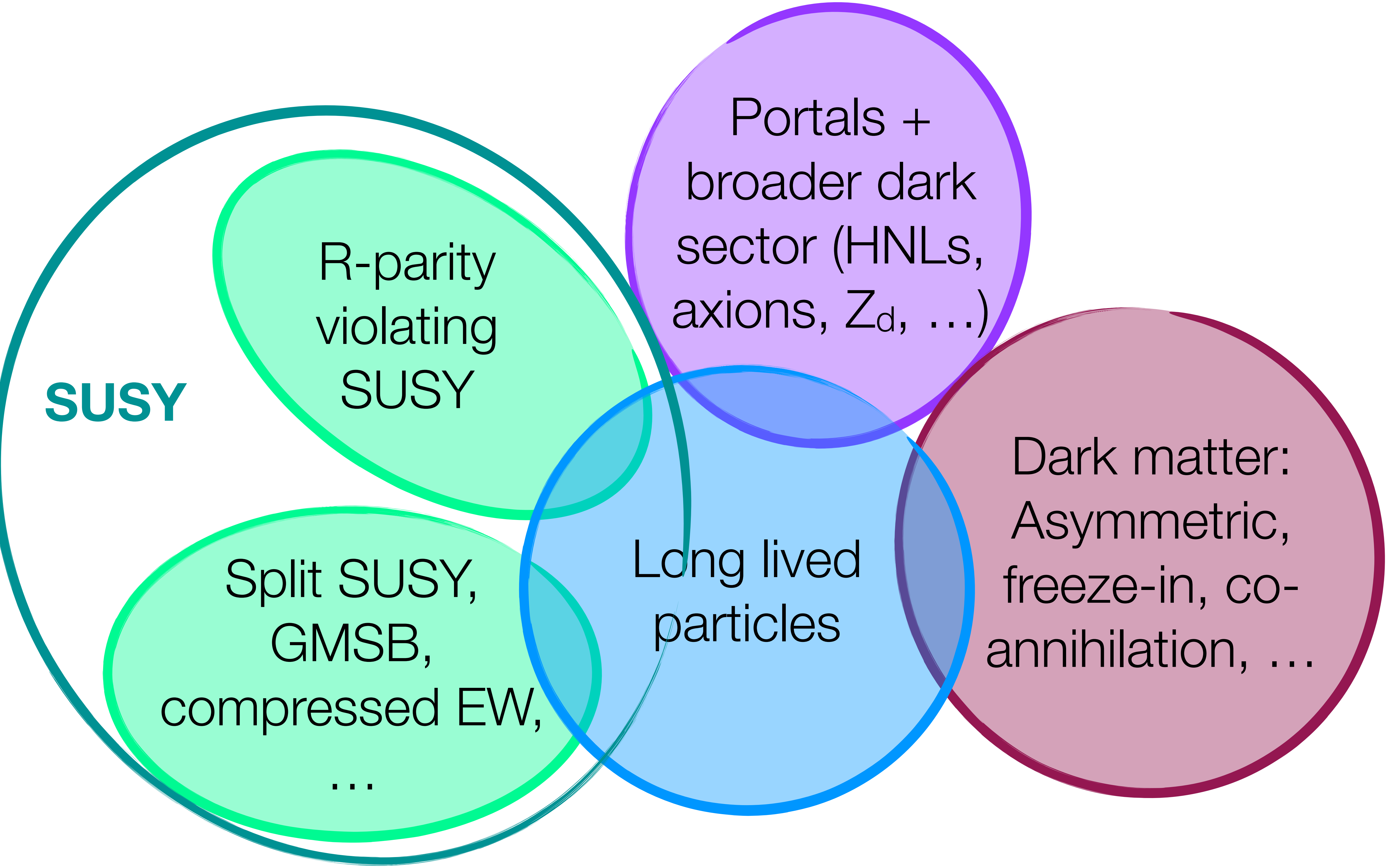

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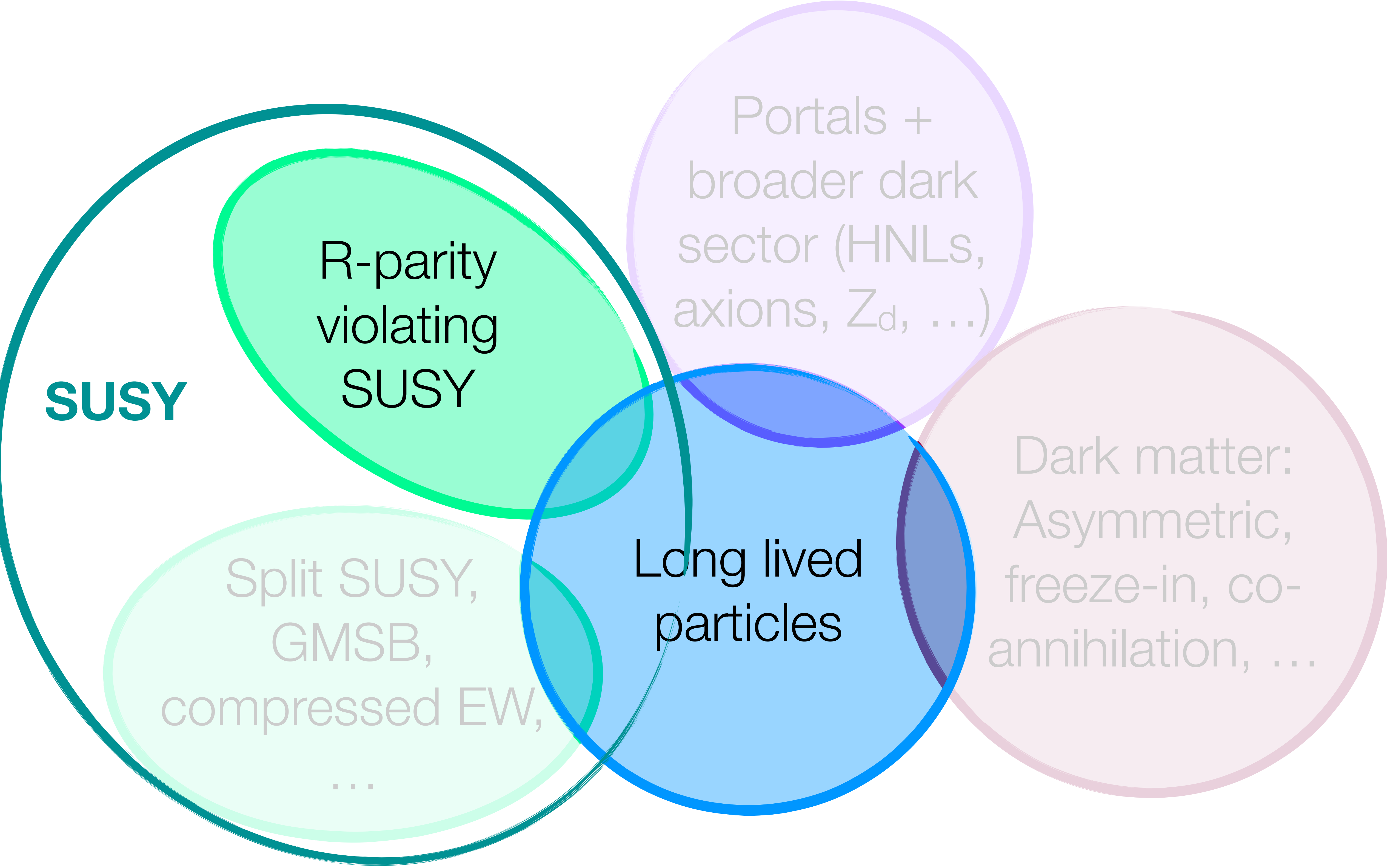
(Parts of) the LLP world



SUSY

R-parity violating SUSY

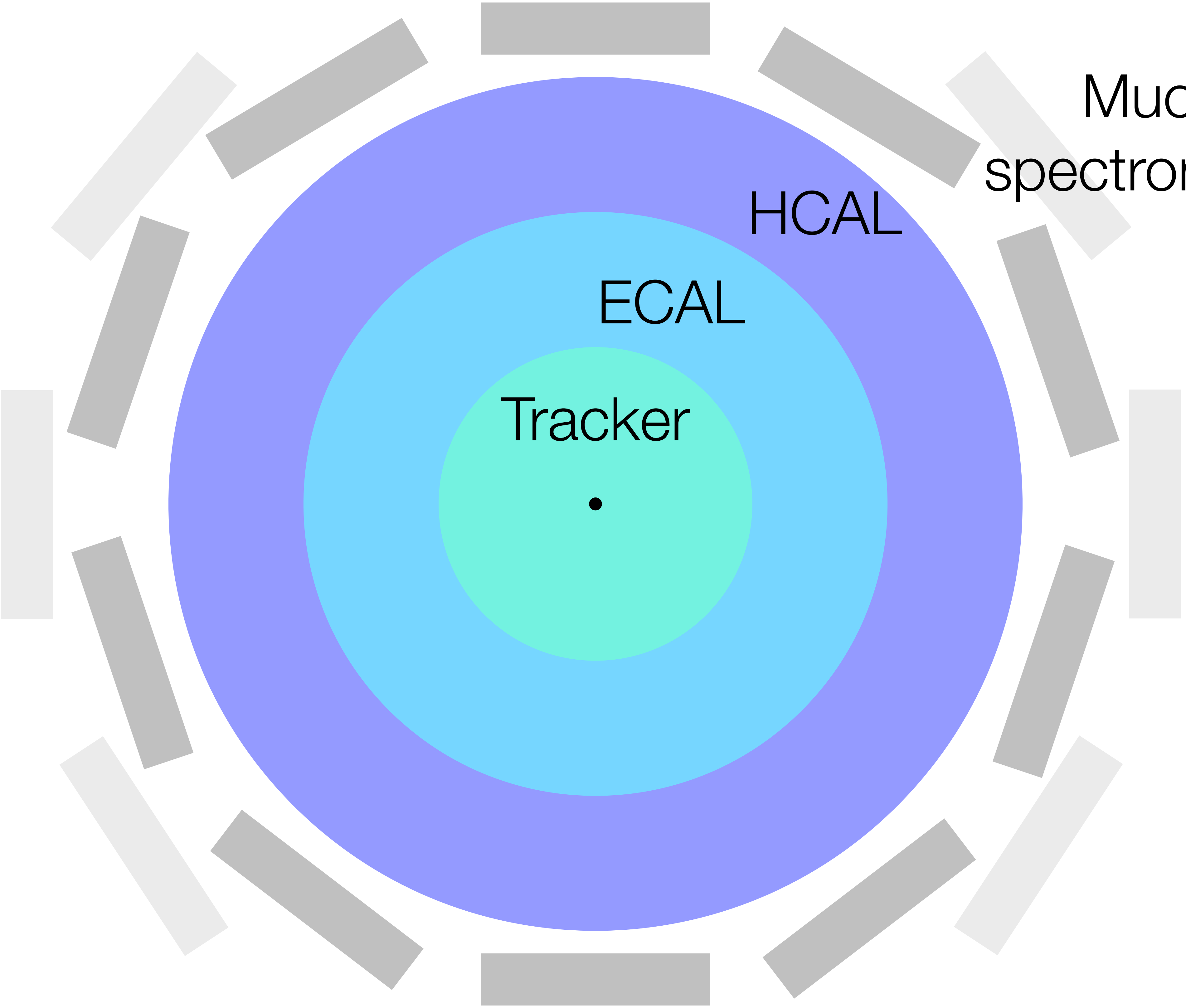
Split SUSY, GMSB, compressed EW, …

Long lived particles

Portals + broader dark sector (HNLs, axions, Z_d, …)

Dark matter: Asymmetric, freeze-in, co-annihilation, …

ATLAS detector and missing energy



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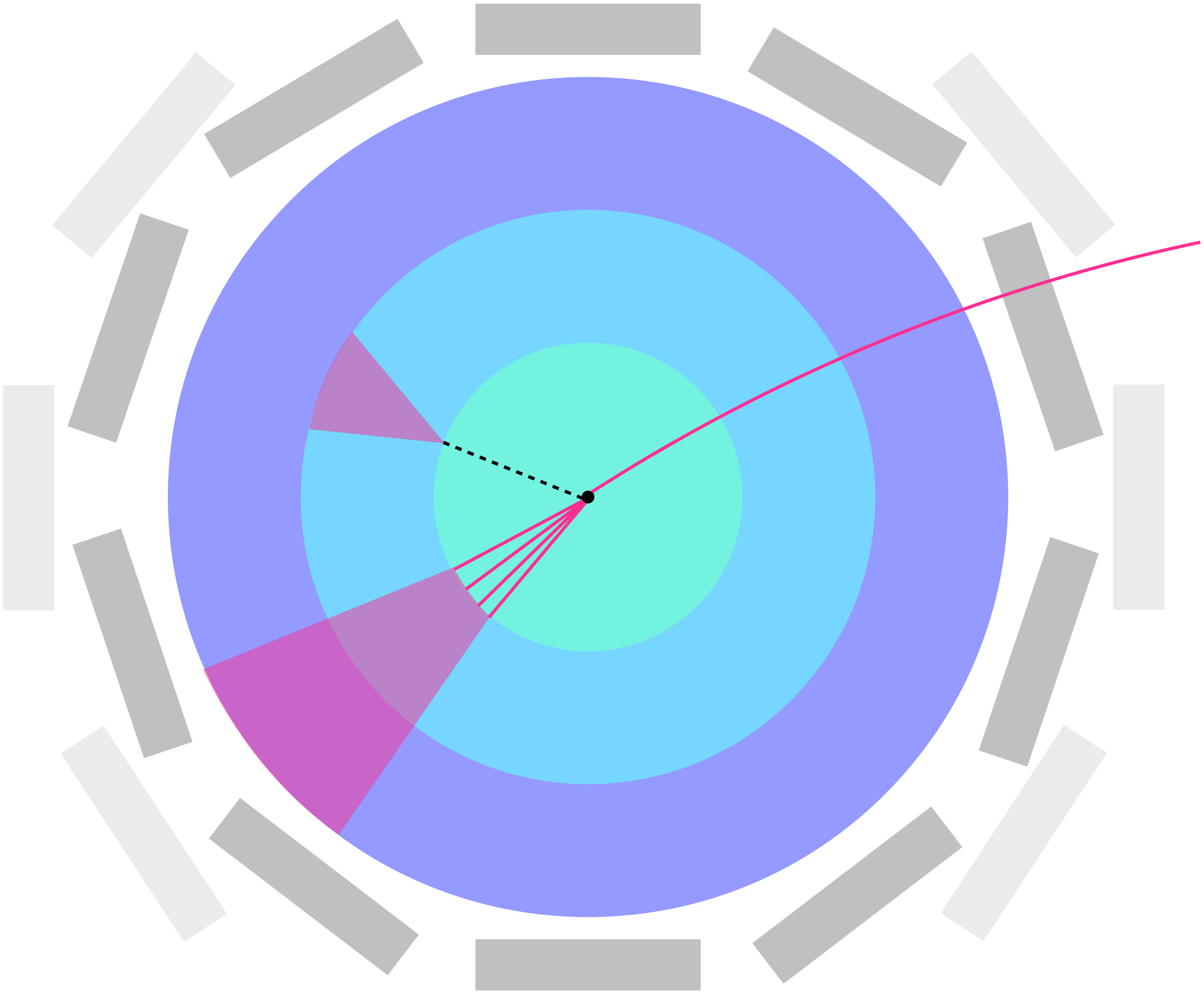

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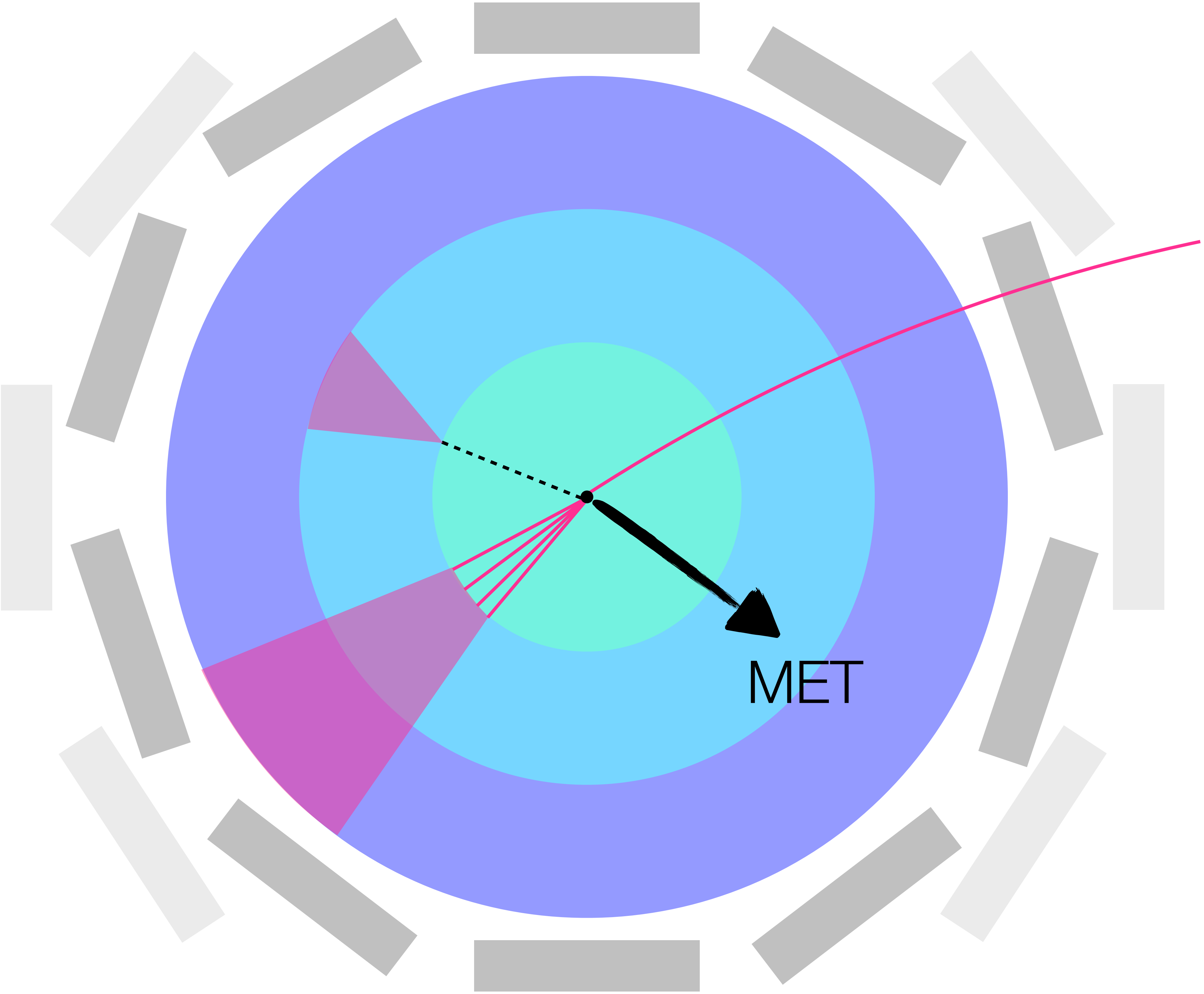

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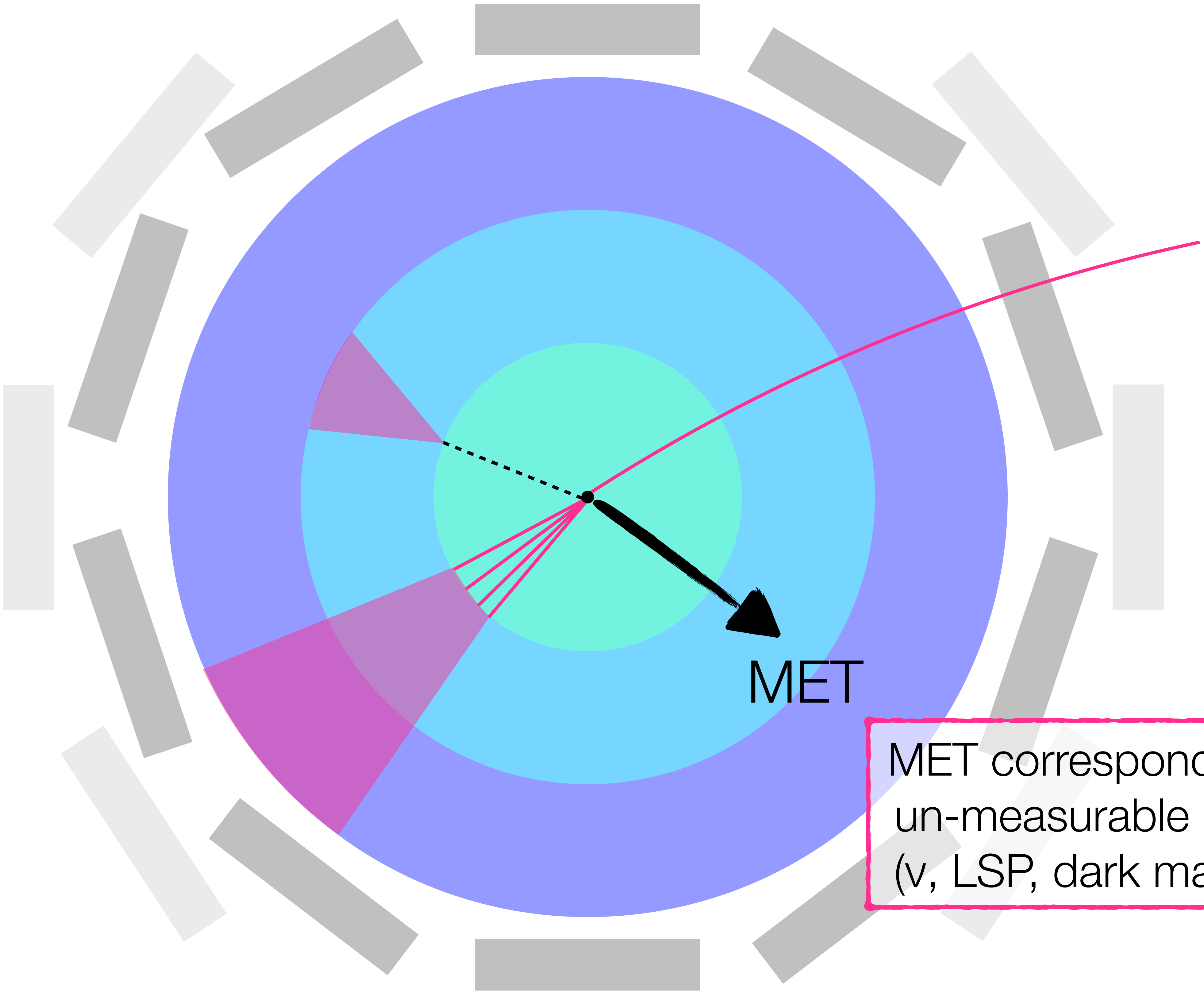

MET corresponds to an un-measurable particle (ν, LSP, dark matter,…)

* corrected compared to recording - I missed a decimal place

Connecting lifetime to location

Mean distance travelled = $\beta\gamma c\tau$

- $c\tau$ = simple distance metric. Order 30cm* for τ = 1 nanosecond
- Lorentz boost $\beta\gamma = p/M$. Ranges from ~ 0.8 or 0.9 for really heavy particles to ~30 for really light ones.

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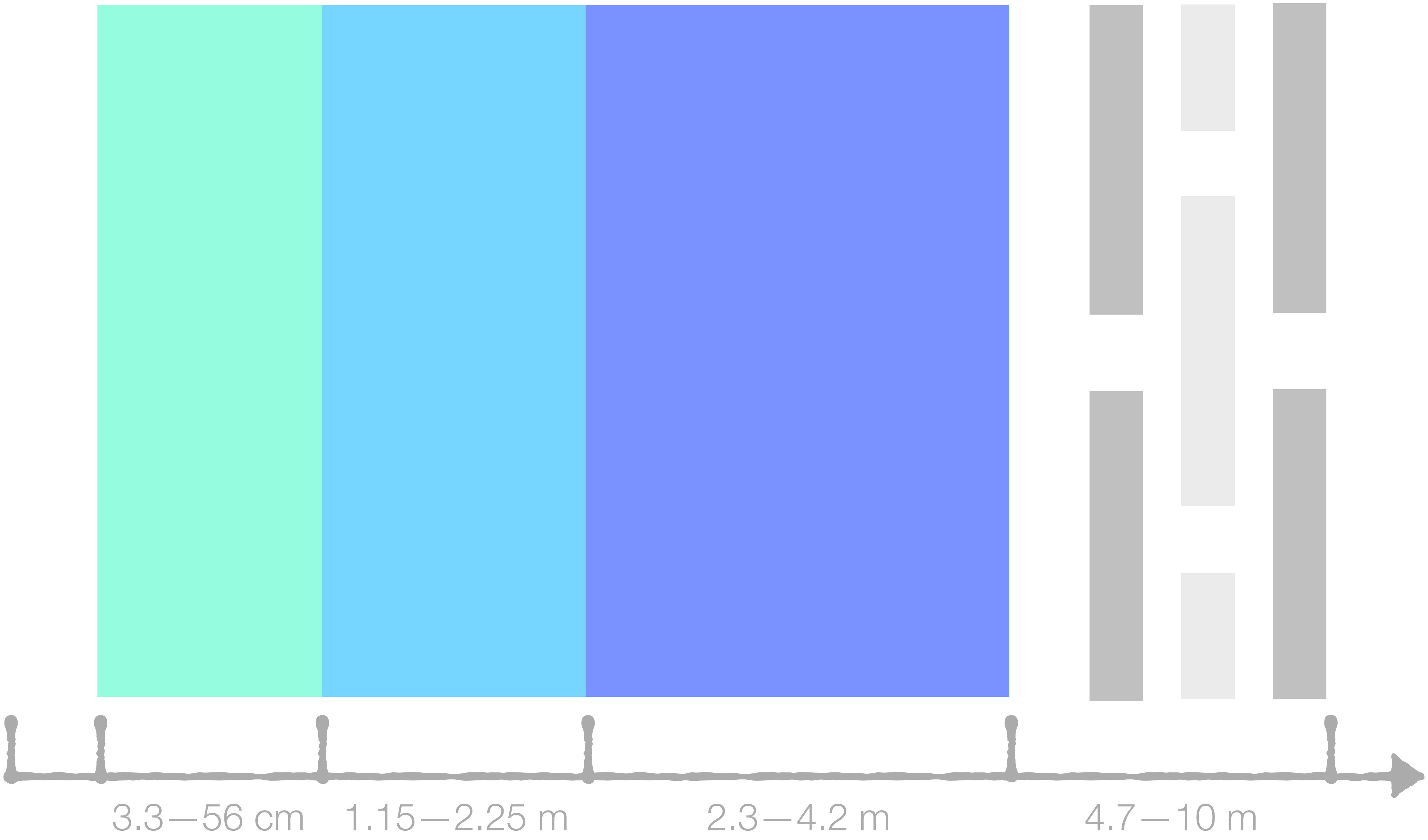
Values of τ ~ 10^{-13} to 10^{-7} seconds are “long-lived particles”

Where should we look for particle decays?

Mean distance travelled = βγcτ



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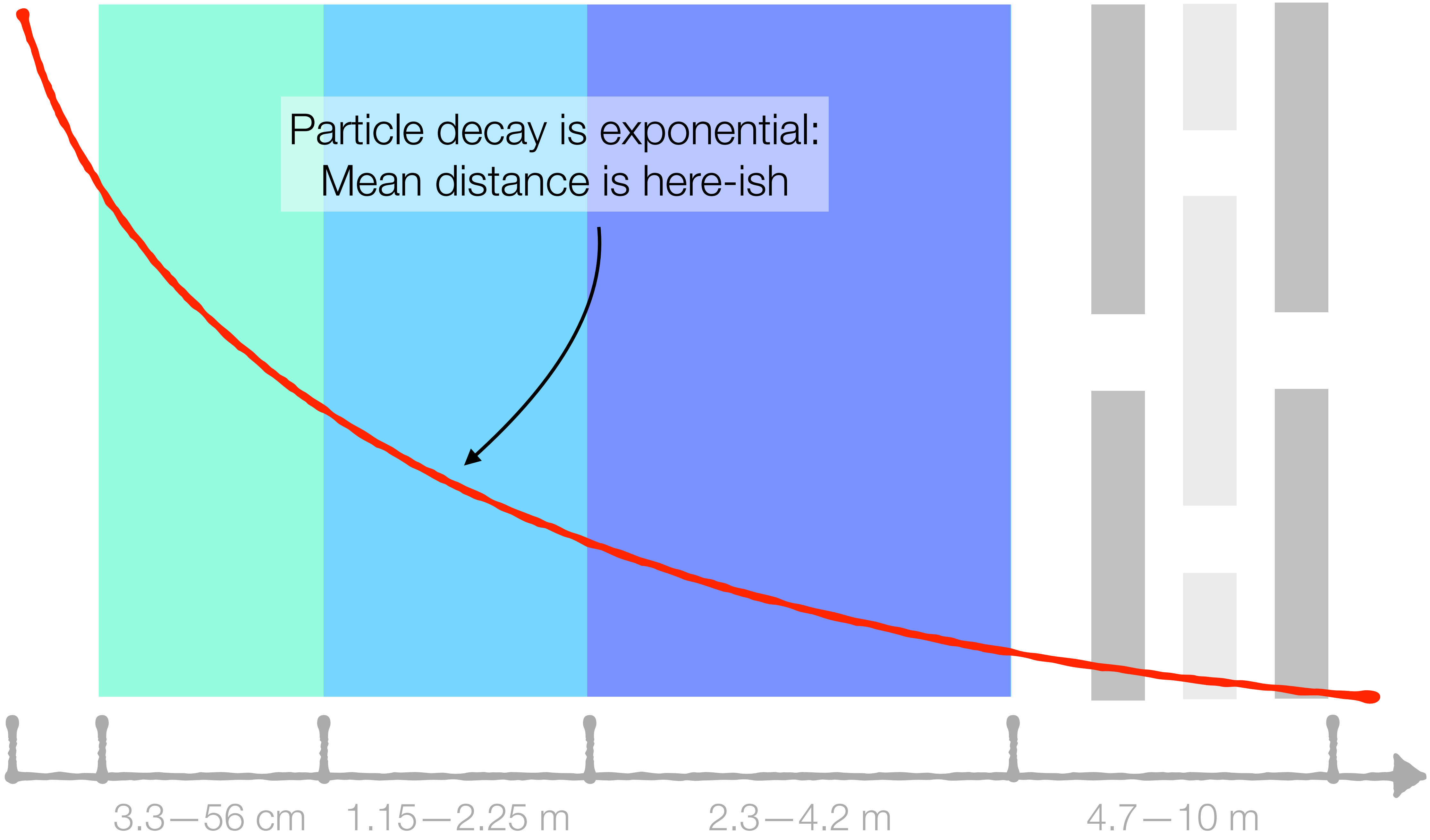

Particle decay is exponential: Mean distance is here-ish

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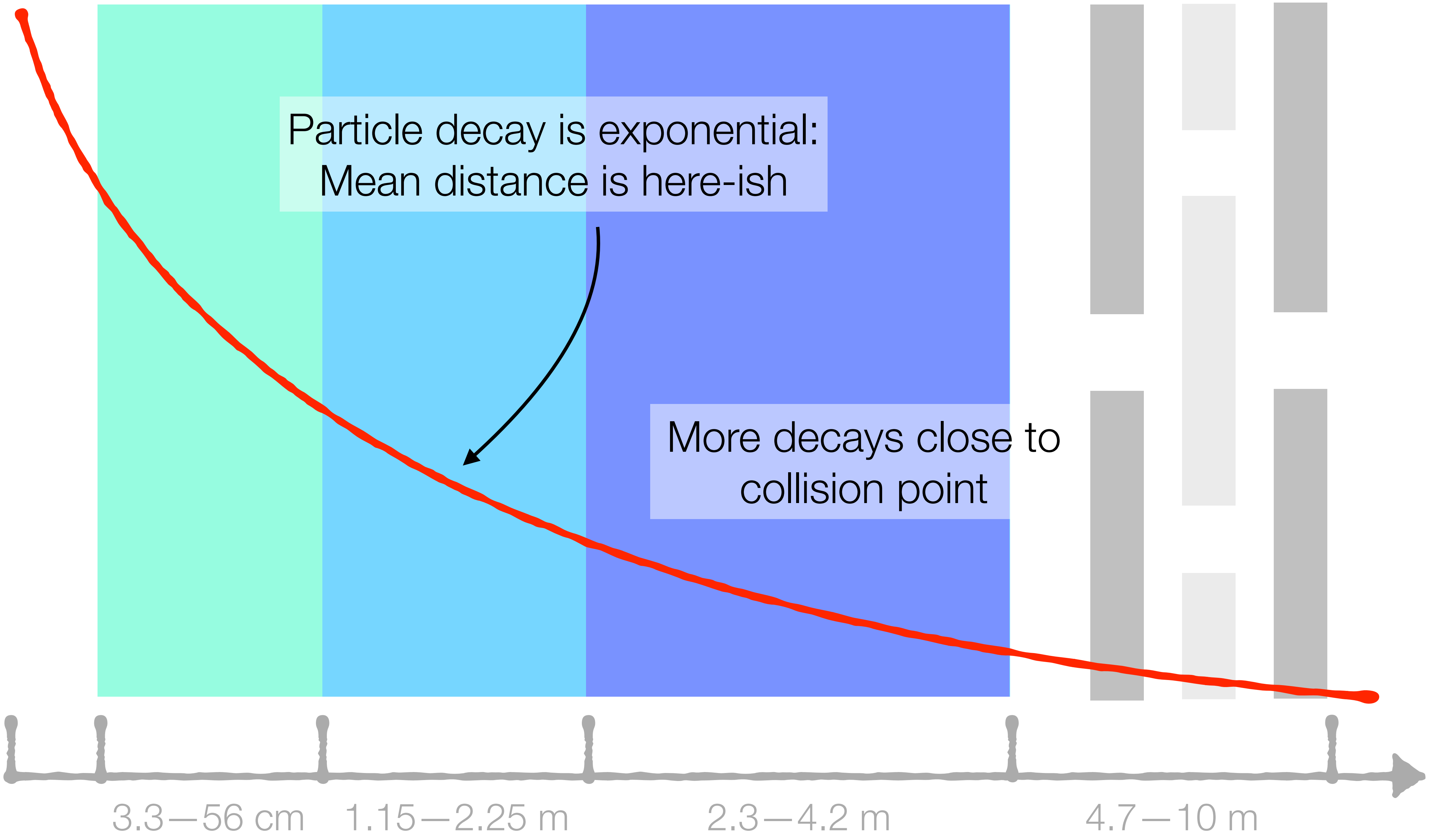

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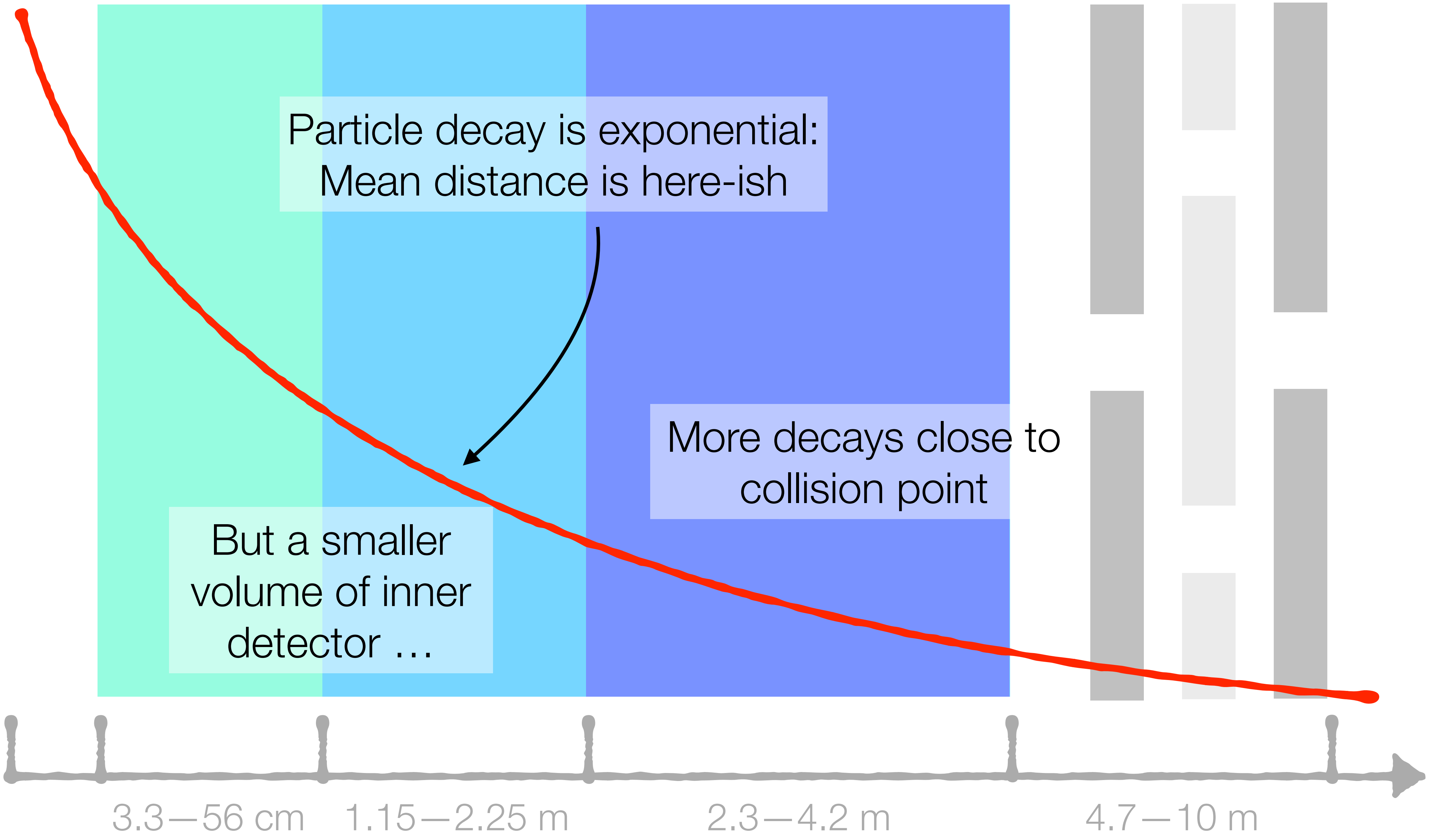

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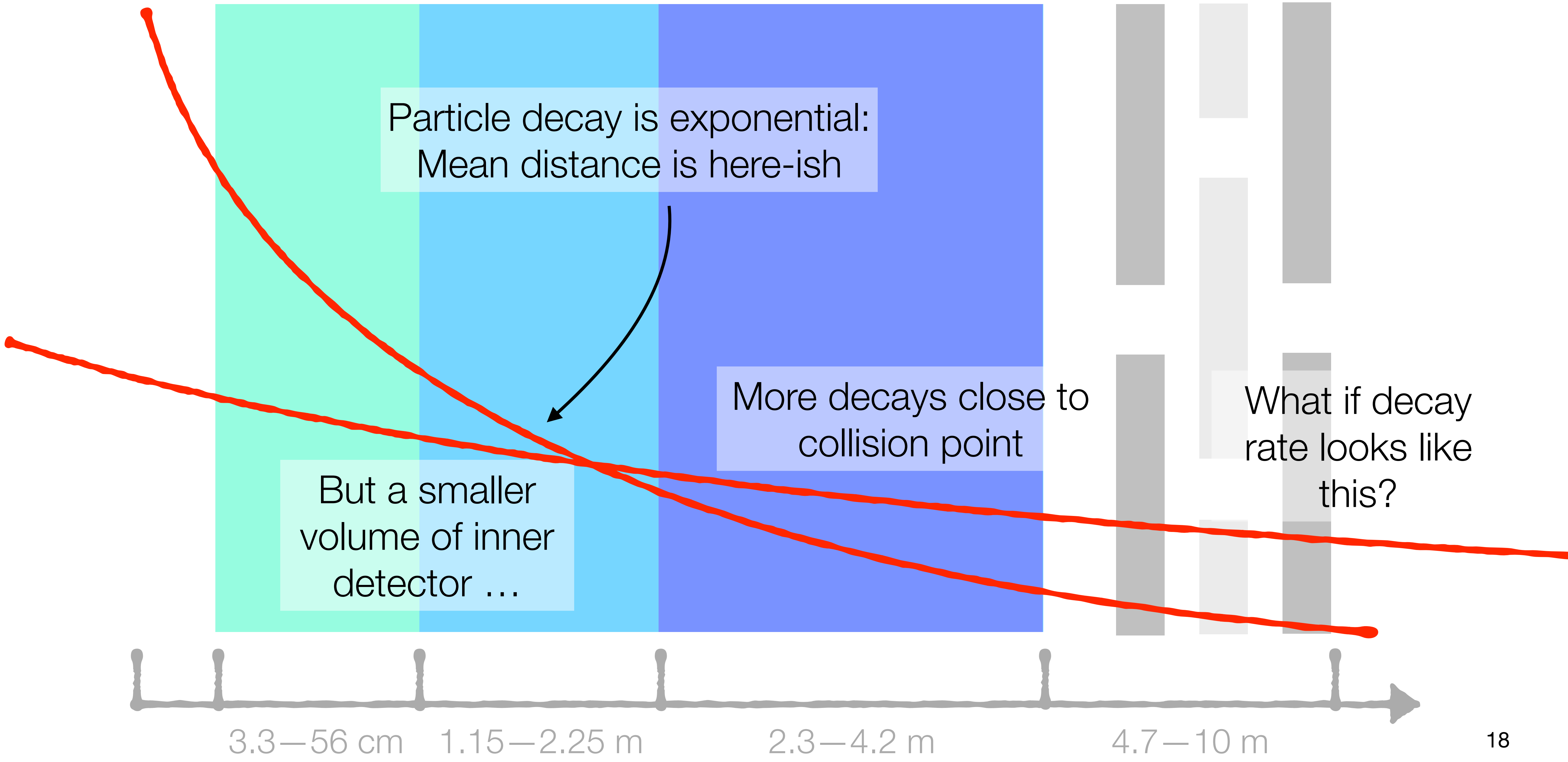

Particle decay is exponential: Mean distance is here-ish

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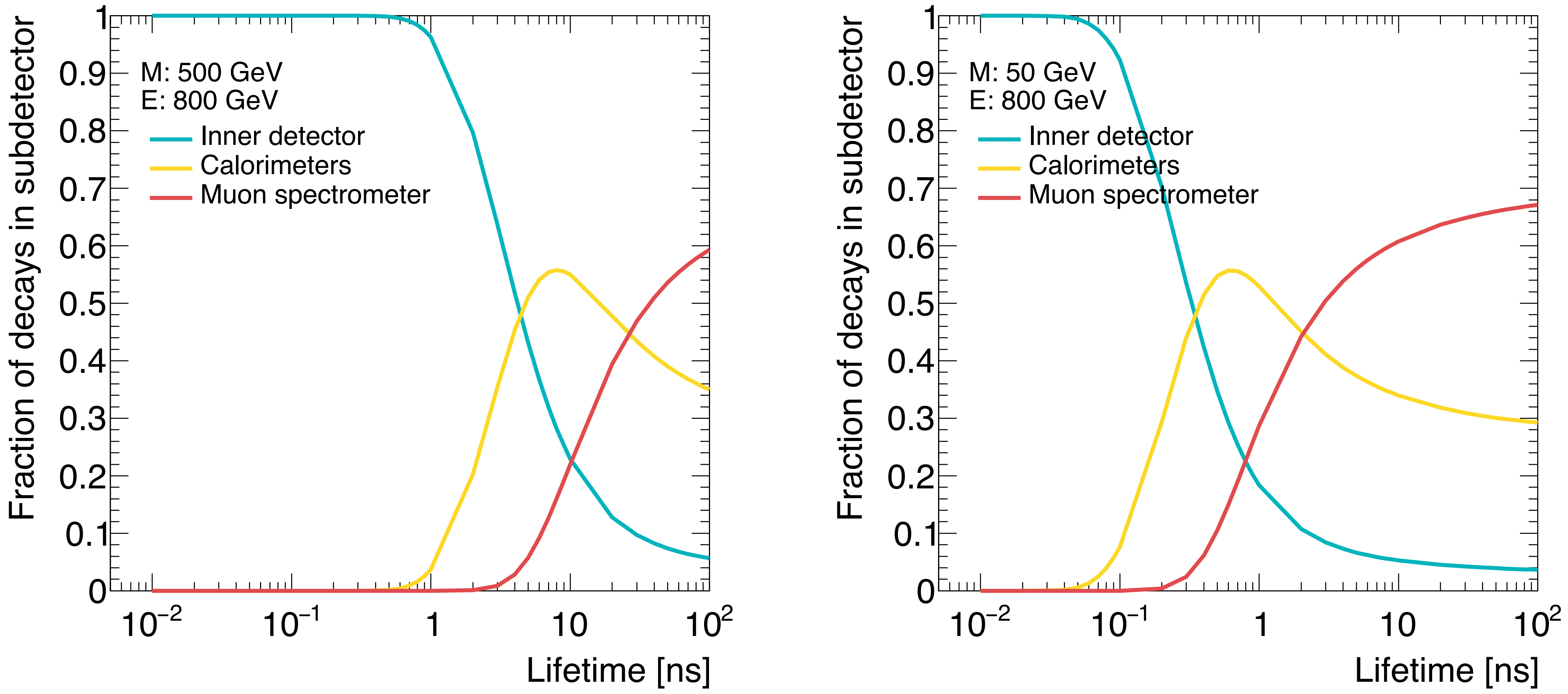
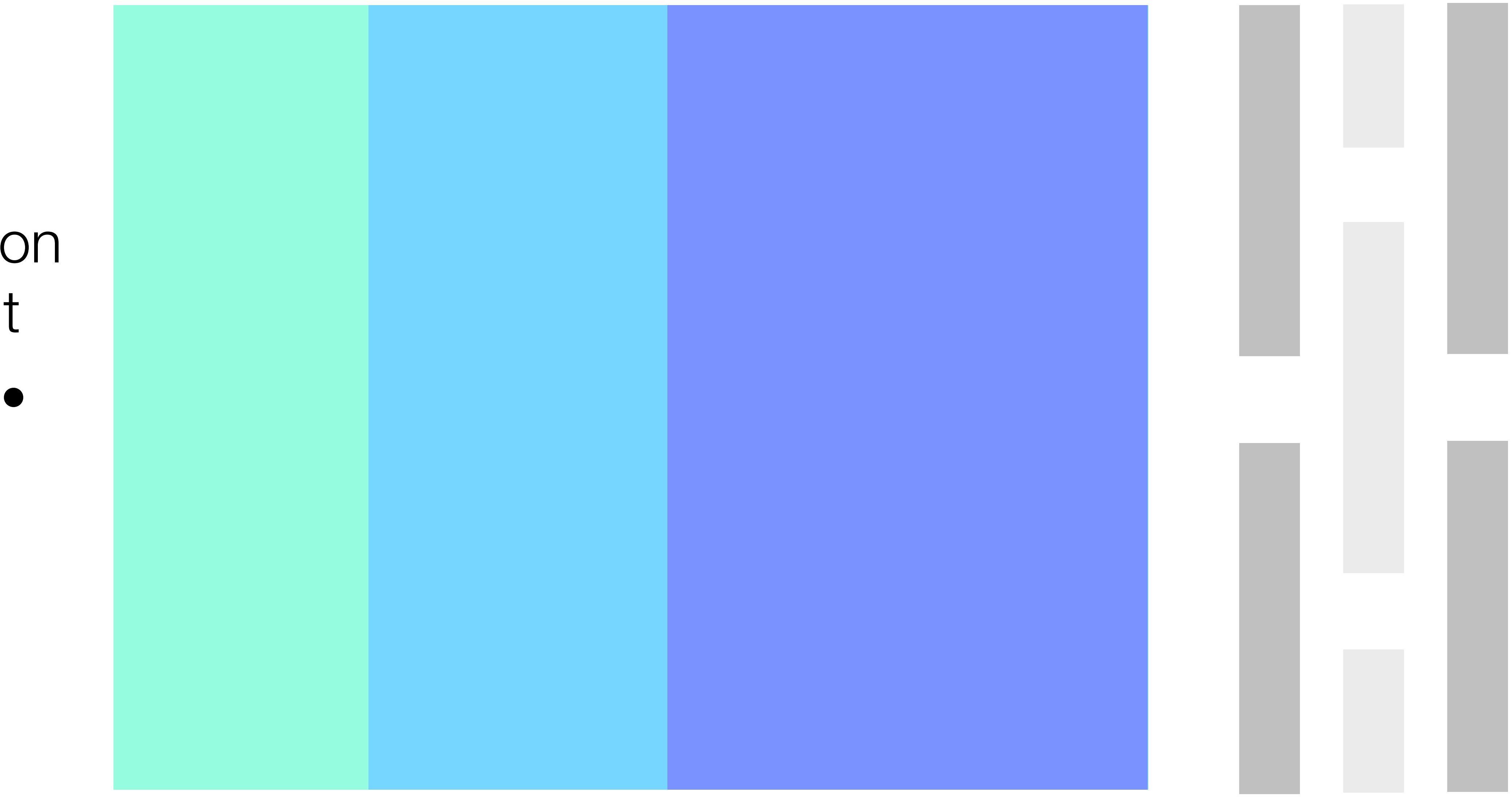
What if decay rate looks like this?

Different detector systems for different targets



- Lighter particles have higher βγ and so travel farther for the same lifetime
- Muon spectrometer becomes useful for Higgs-portal-style signatures
- For target masses > order 100 GeV (i.e. EW SUSY), **inner detector is critical**

How do we use our detectors for these searches?



Tracking

EM showers

Hadronic showers

Stable charged particles (muons)

Collision point

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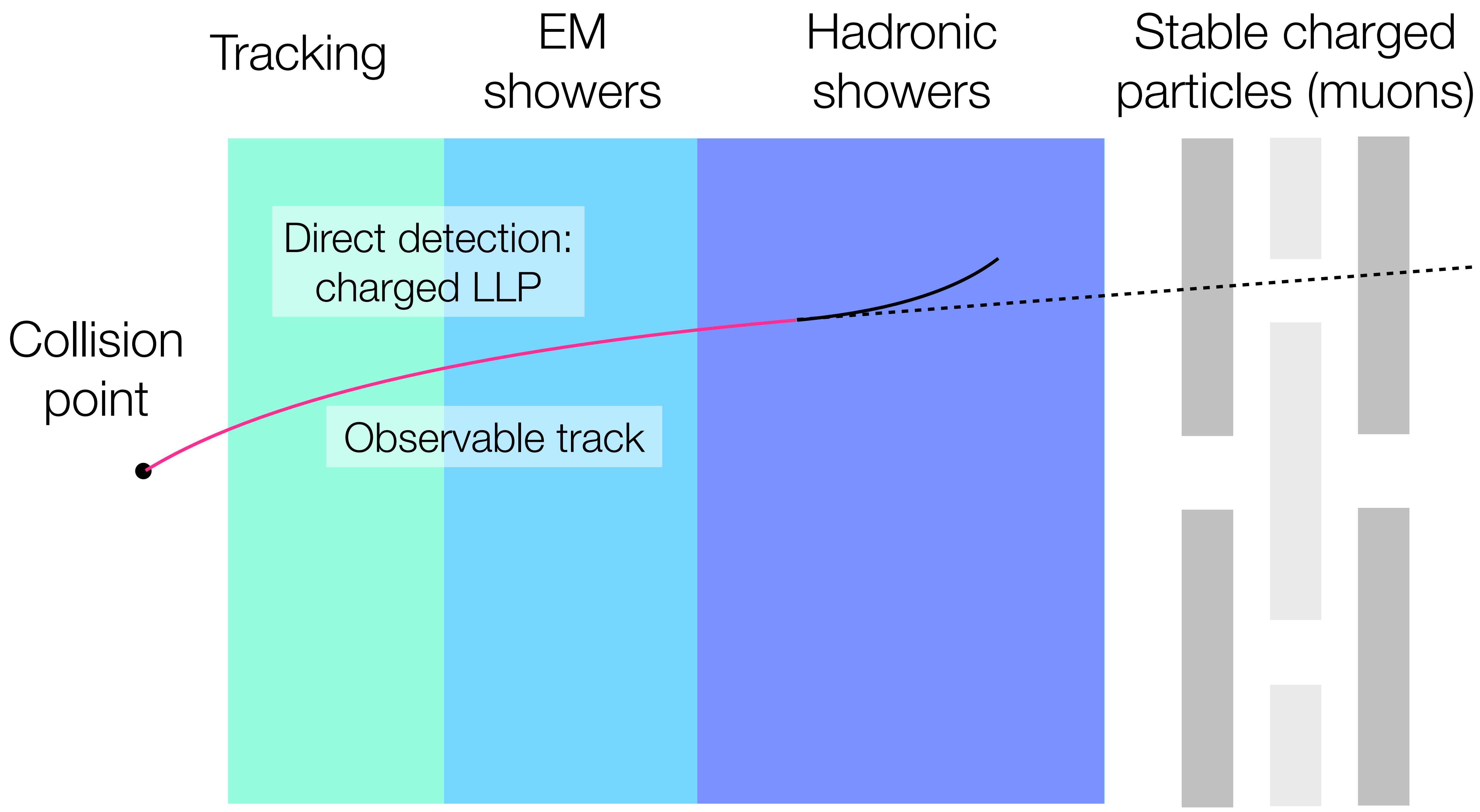

Direct detection: charged LLP

Observable track

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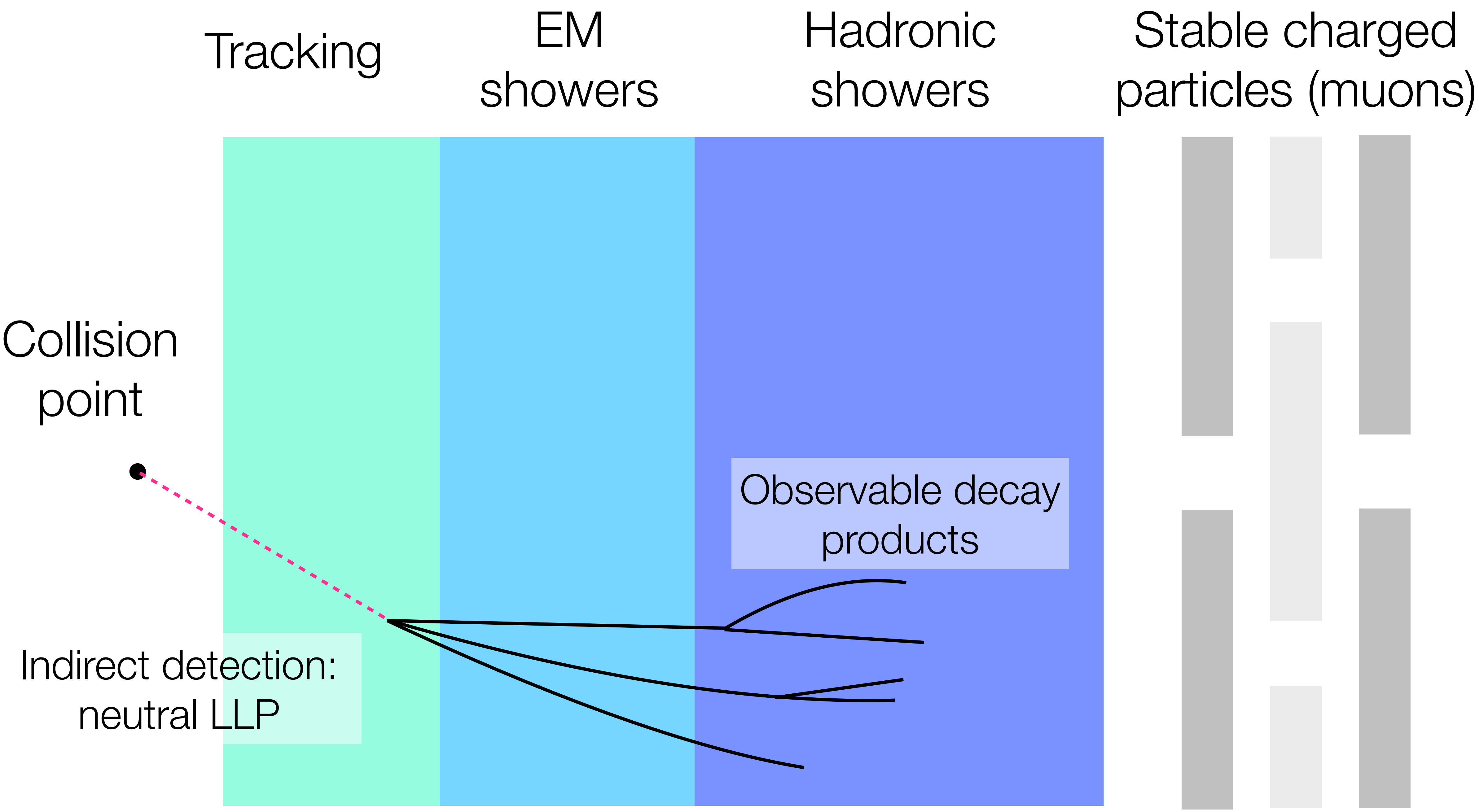

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Stable charged particles (muons)

Collision point

Observable decay products

Indirect detection: neutral LLP

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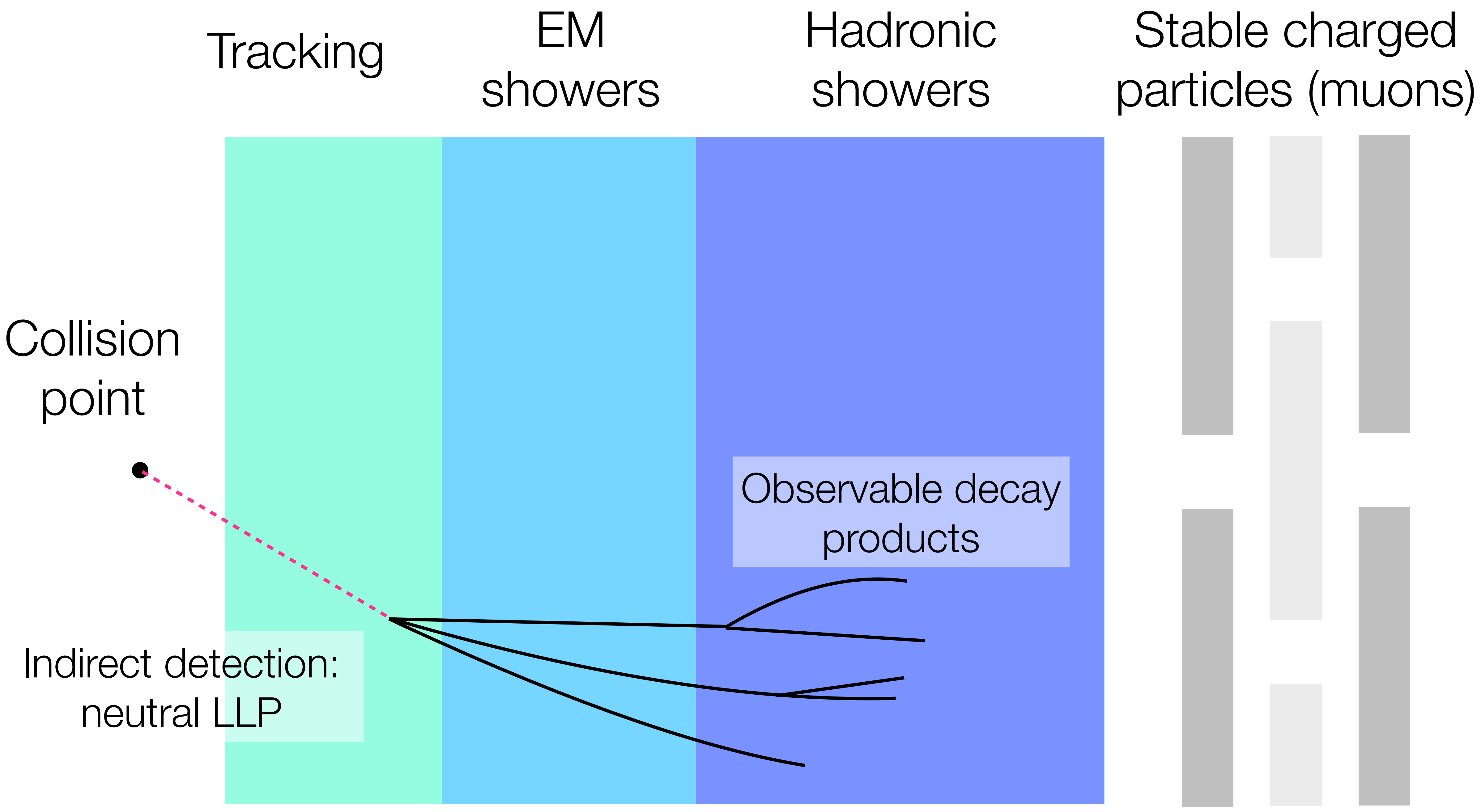
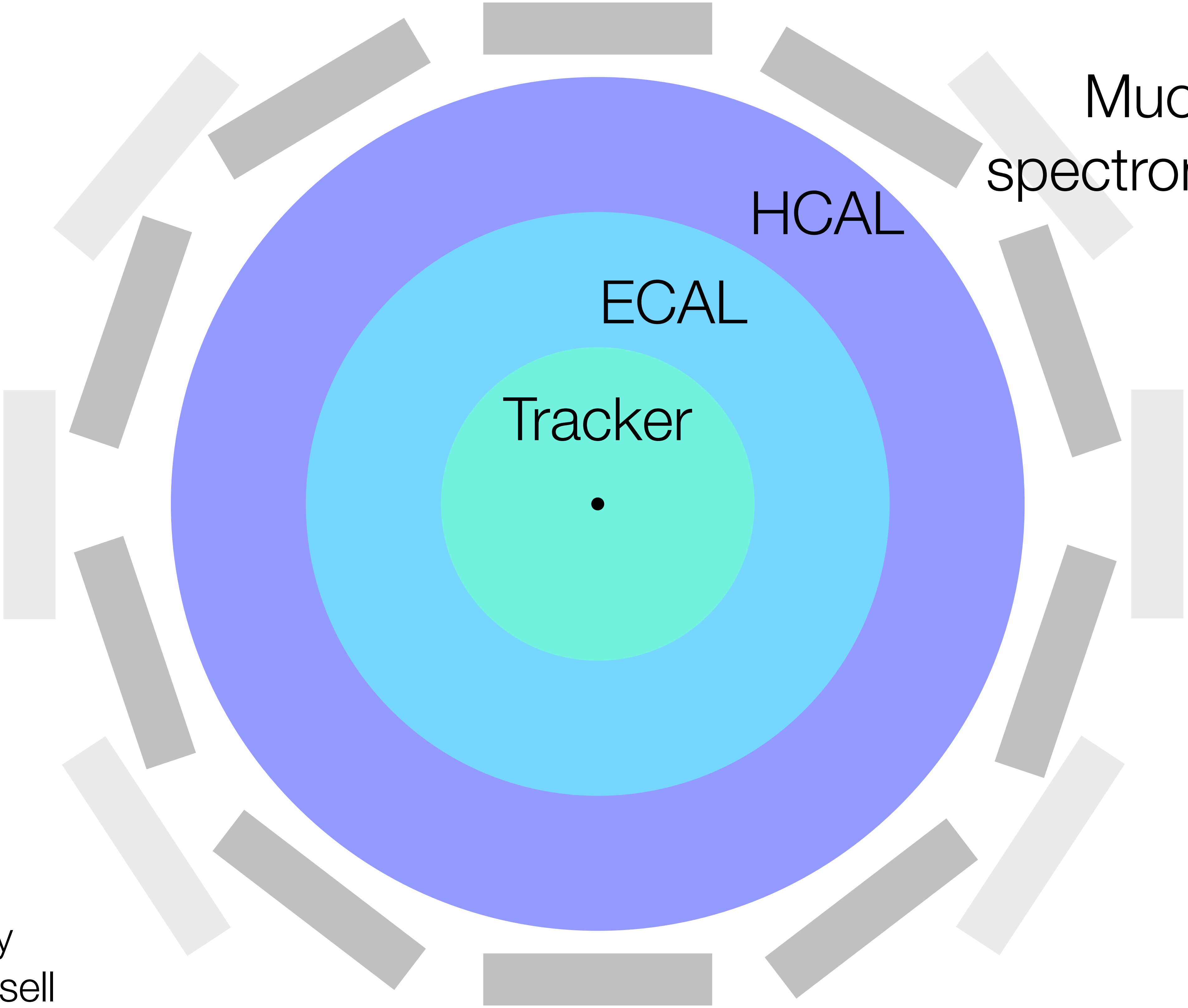


For heavy LLPs, can use timing as well

What would new long-lived physics look like?



Inspired by
Heather Russell

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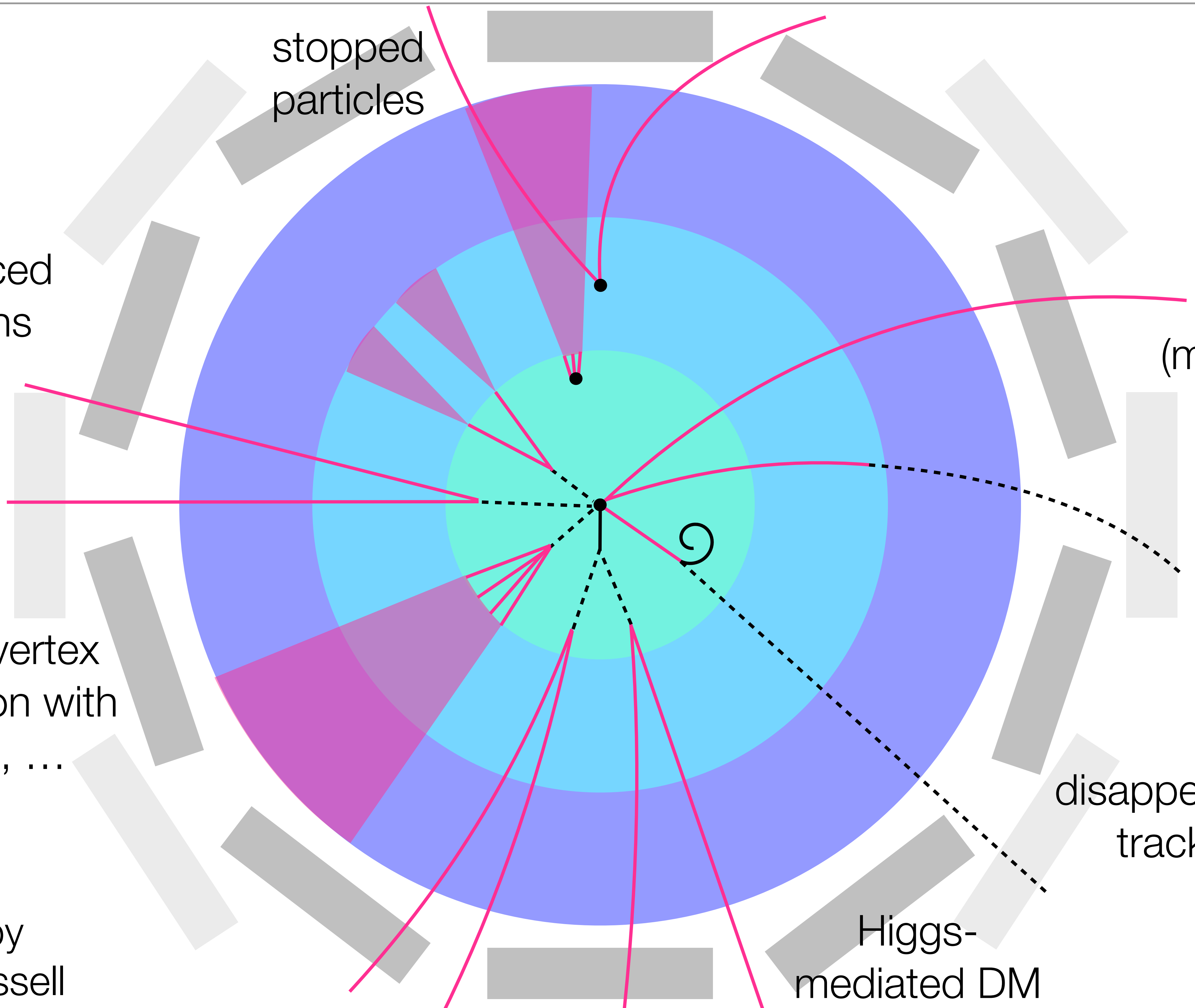

stopped particles

displaced leptons

(meta-)stable charged particles

displaced vertex in association with MET, jets, …

disappearing tracks

Higgs-mediated DM

Inspired by Heather Russell

What makes LLPs so hard?

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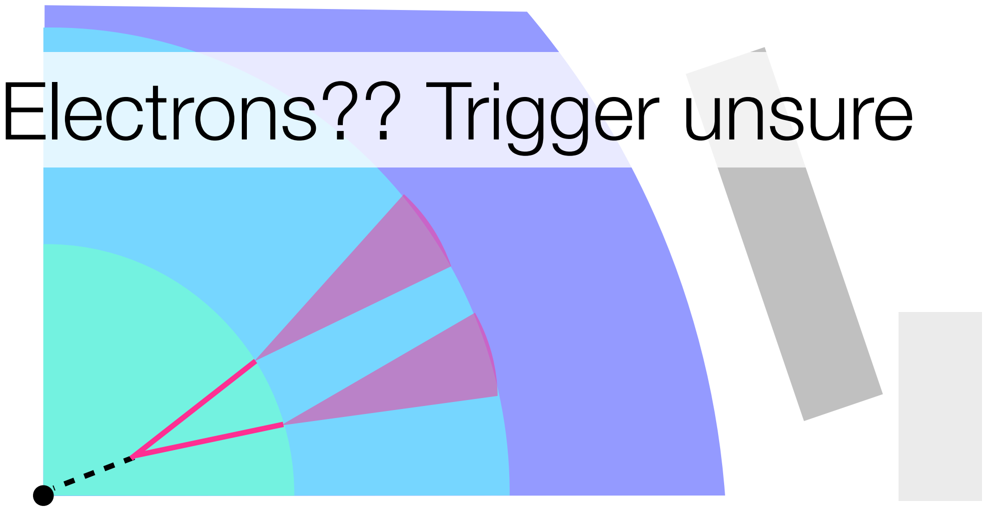
Triggering



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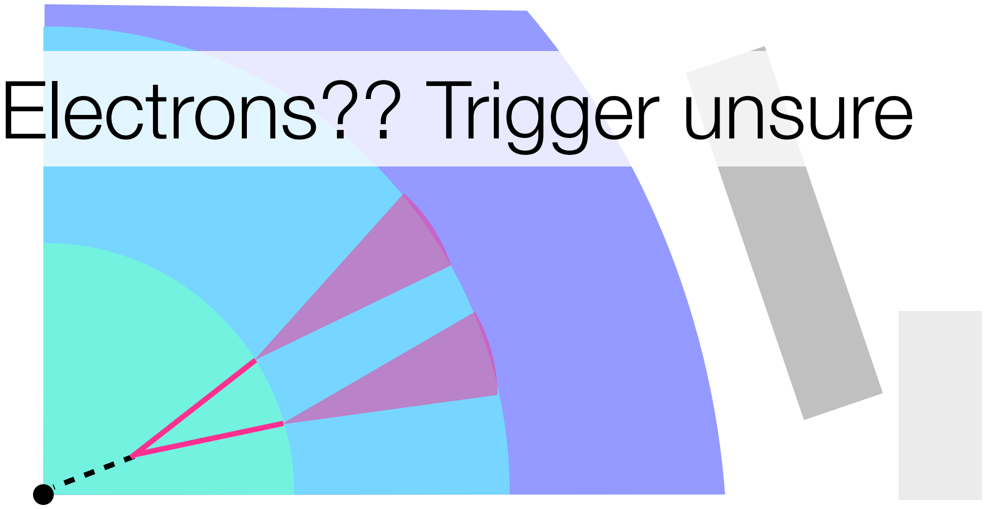

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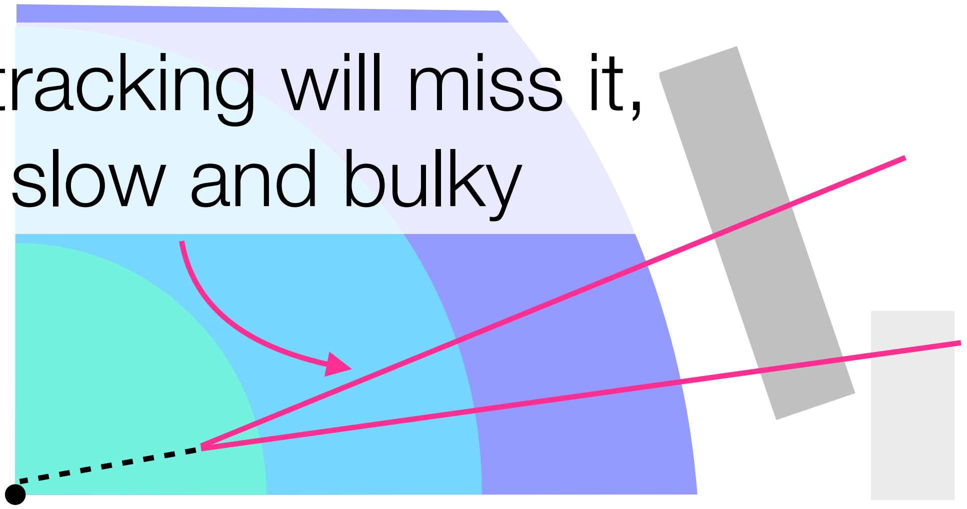
Large-radius tracking



Standard tracking will miss it,
LRT is slow and bulky

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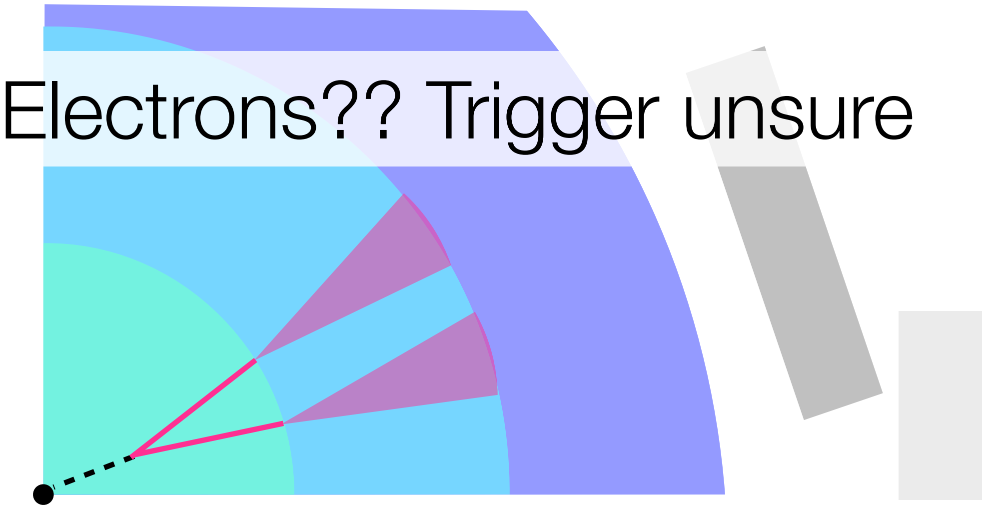

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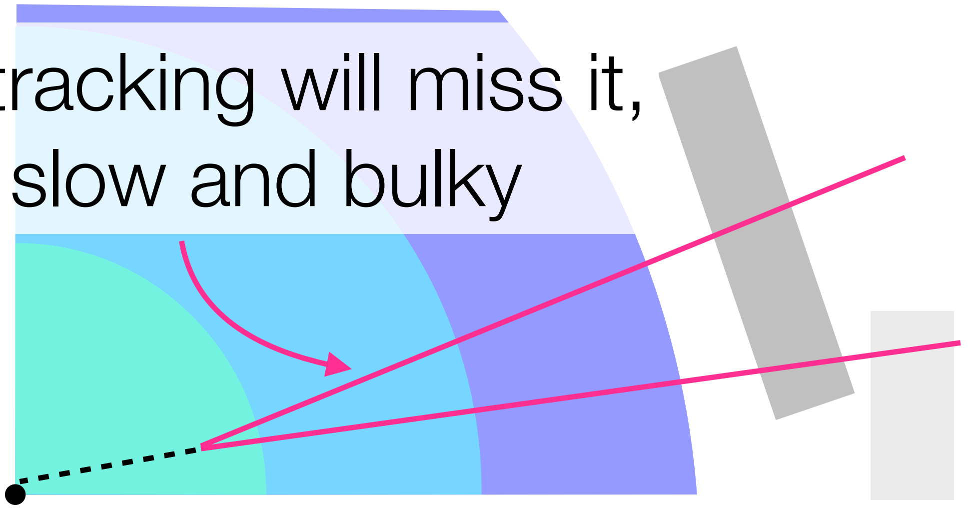

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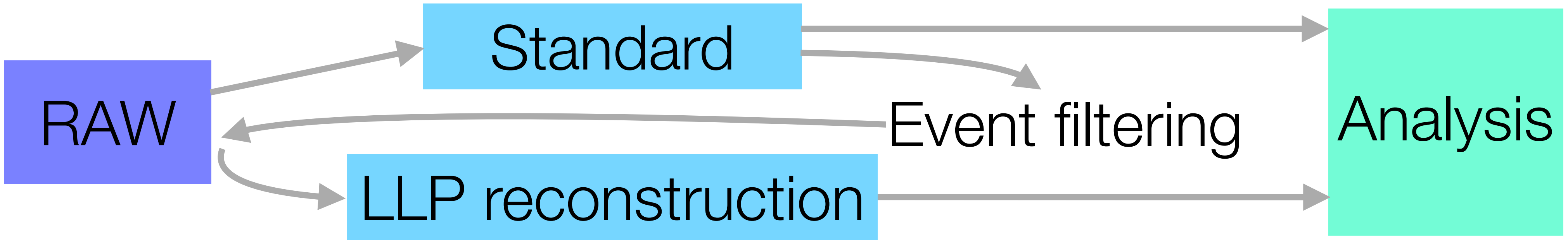
Data flow



RAW

Standard

LLP reconstruction

Event filtering

Analysis

Understanding backgrounds

- Long-lived particle searches often have small and/or unusual backgrounds due to ~no simple Standard Model processes imitating signatures
- Sources of remaining backgrounds LLP searches include:

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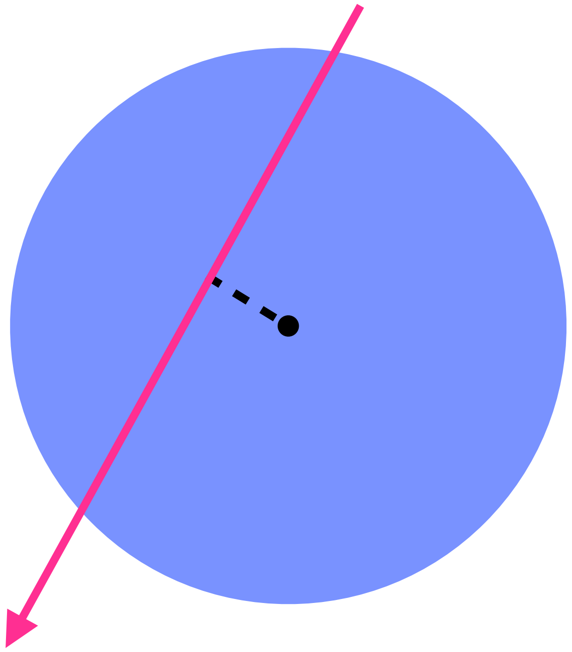

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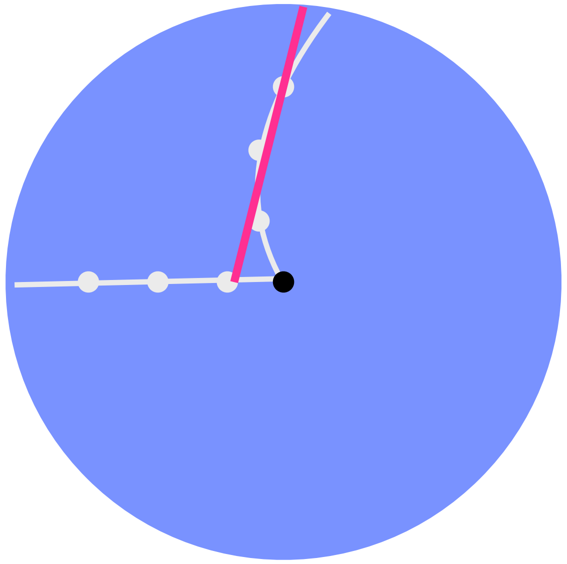

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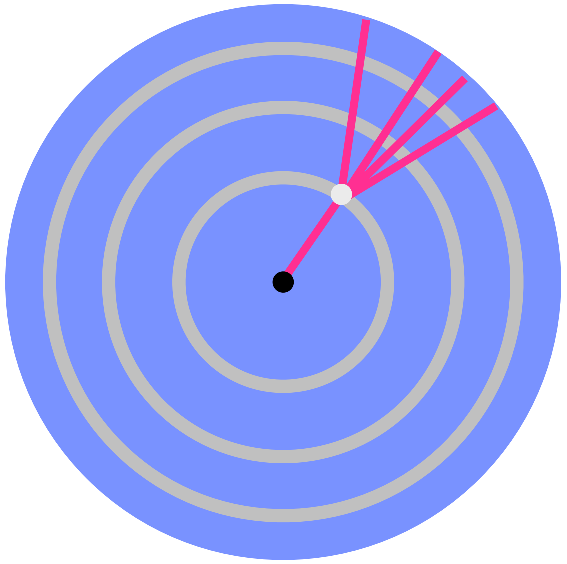

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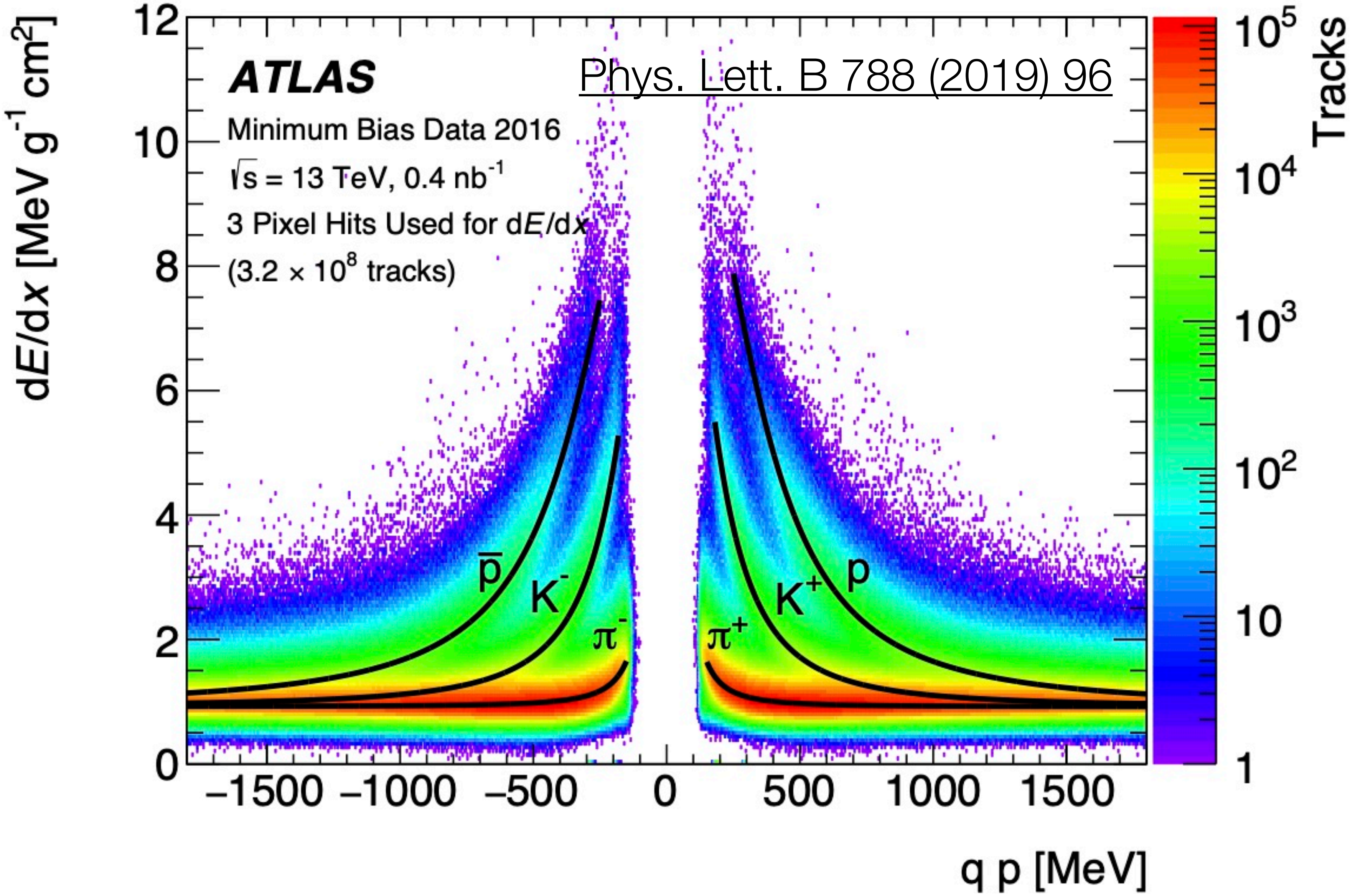
  - Occasionally, even beam-induced backgrounds and cavern backgrounds
- For almost all background contributions, no possibility of simulating them well
- So you will see fully data-driven background estimates for ~all LLP searches!

A direct detection example: pixel dEdx analysis

For a relativistic particle, $\beta = v/c$, $\gamma = E/m$, $\beta\gamma = p/M$



Phys. Lett. B 788 (2019) 96

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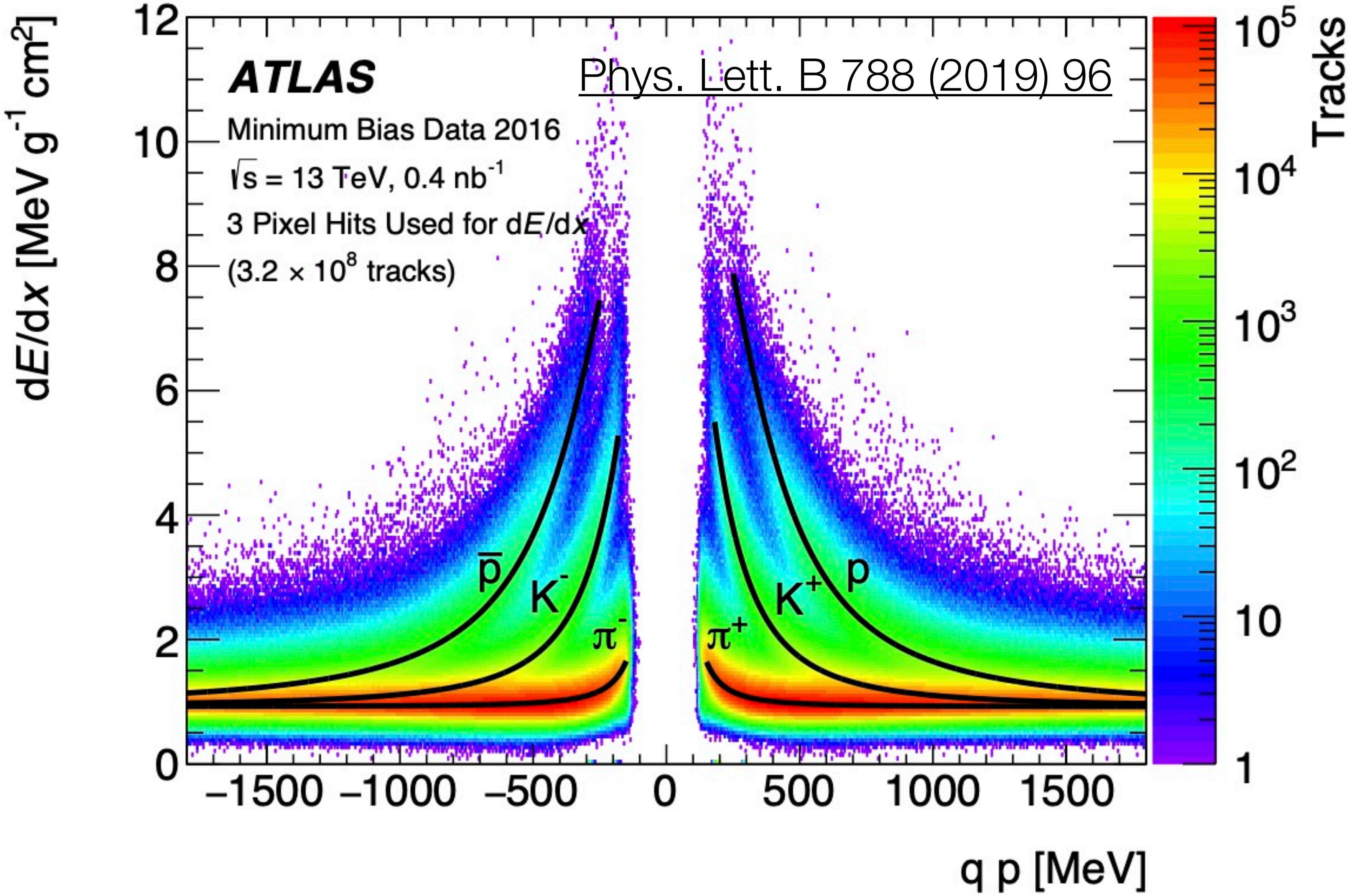

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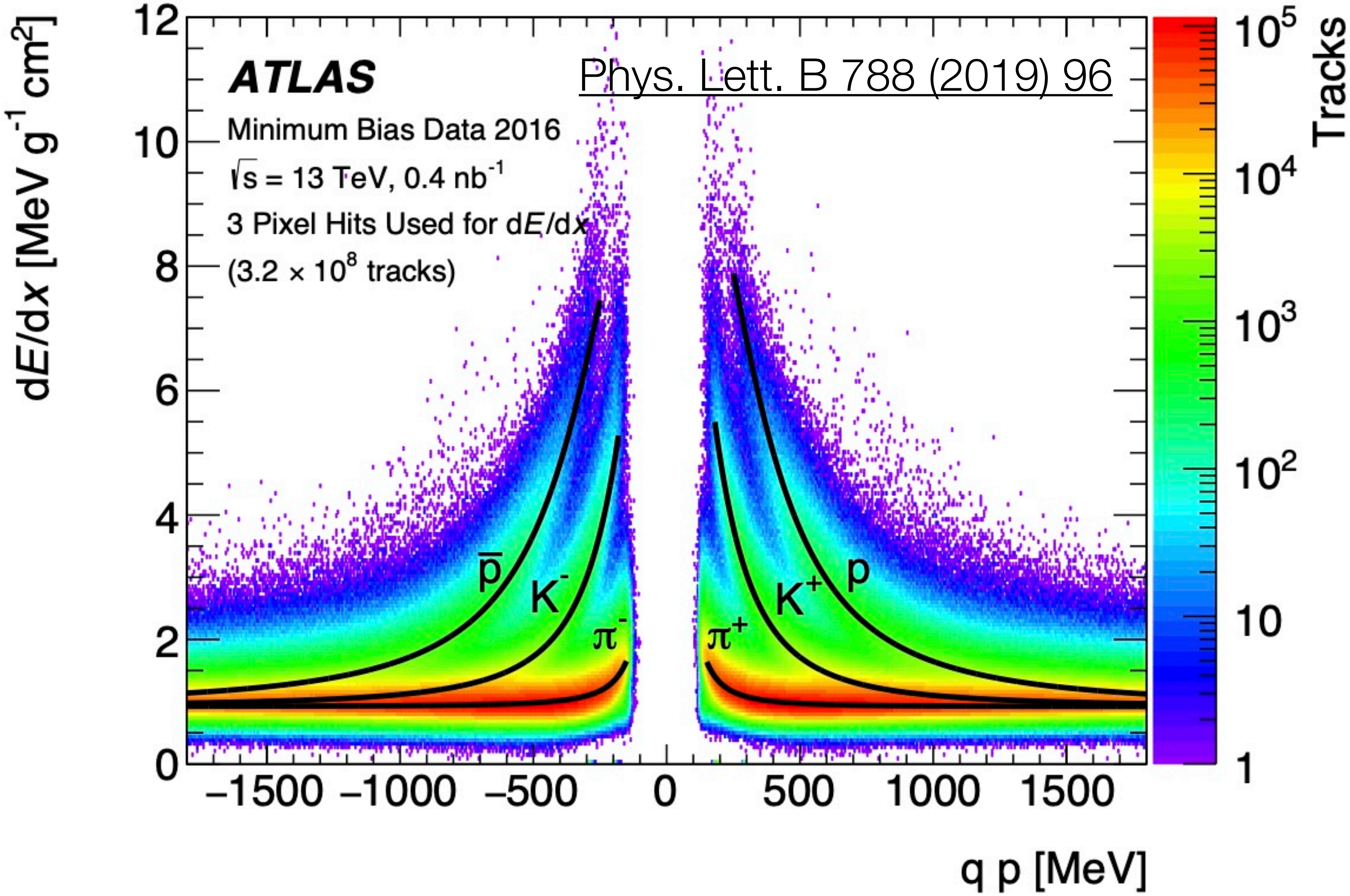

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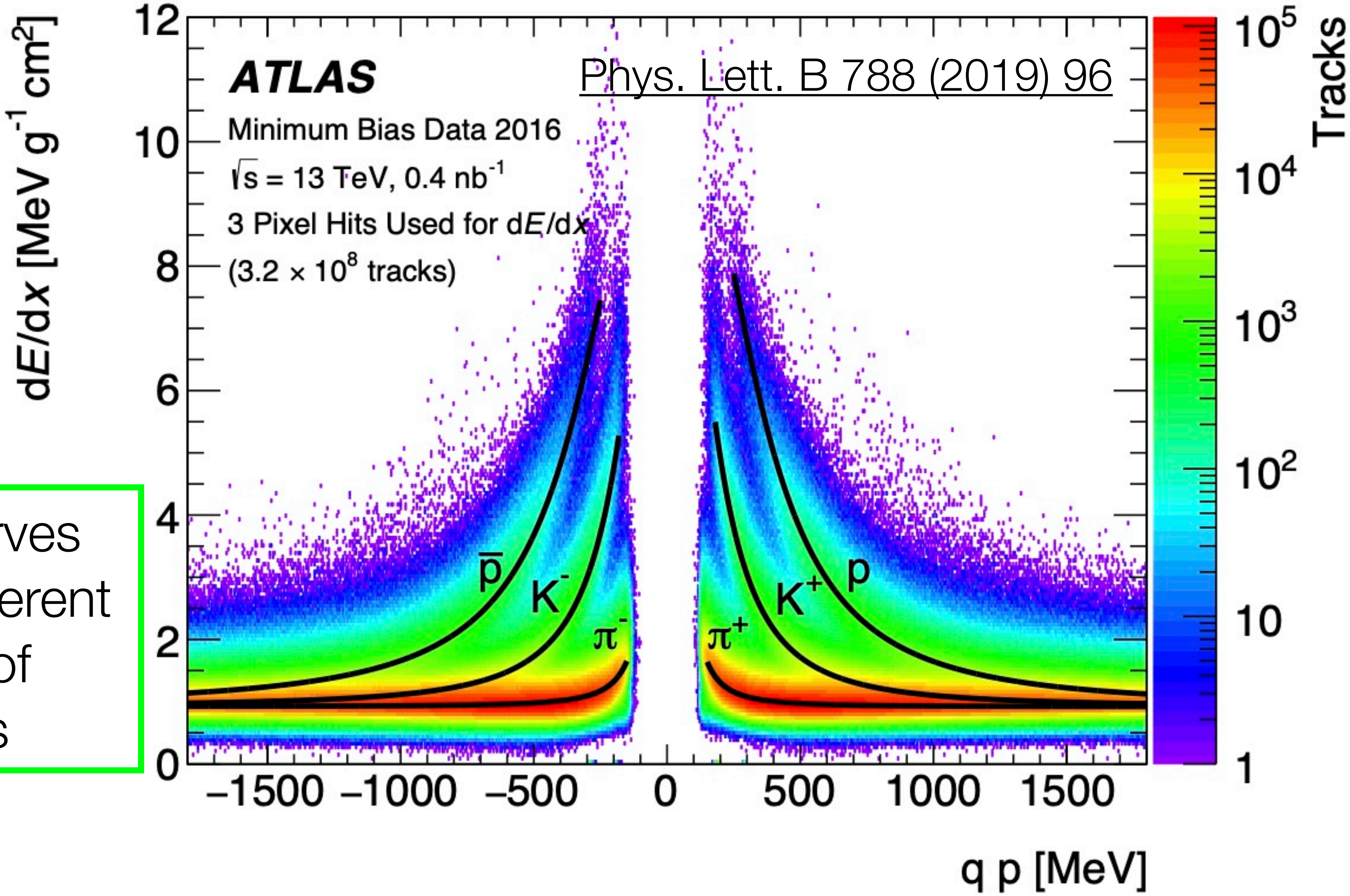

Distinct curves separate different masses of particles

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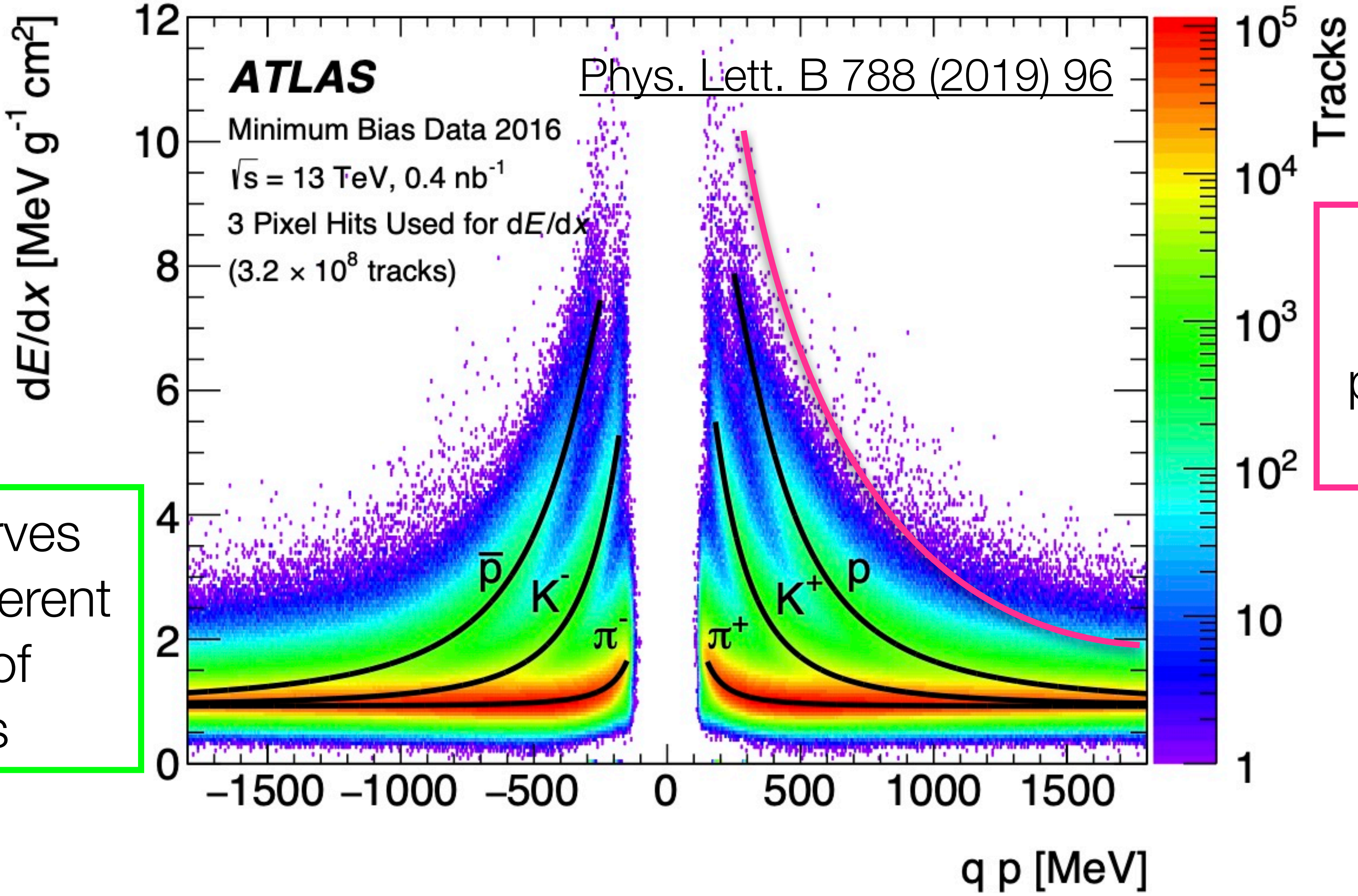

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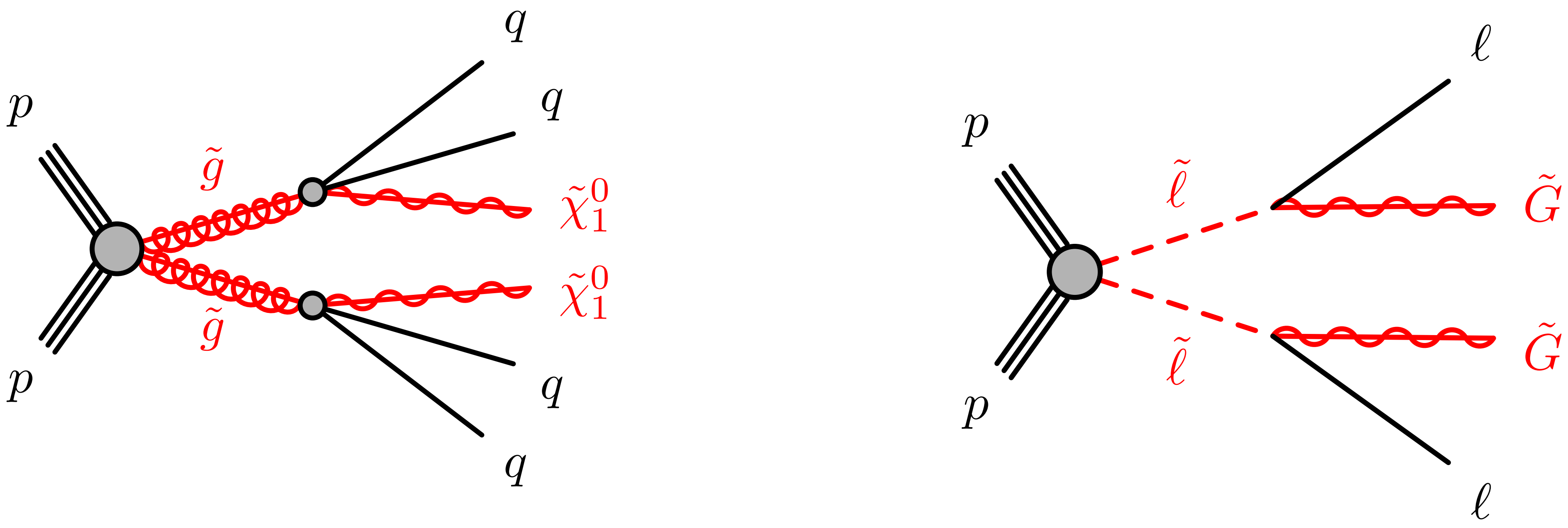
Distinct curves separate different masses of particles

New heavy charged particle could be out here!

Event selection in the dEdx analysis



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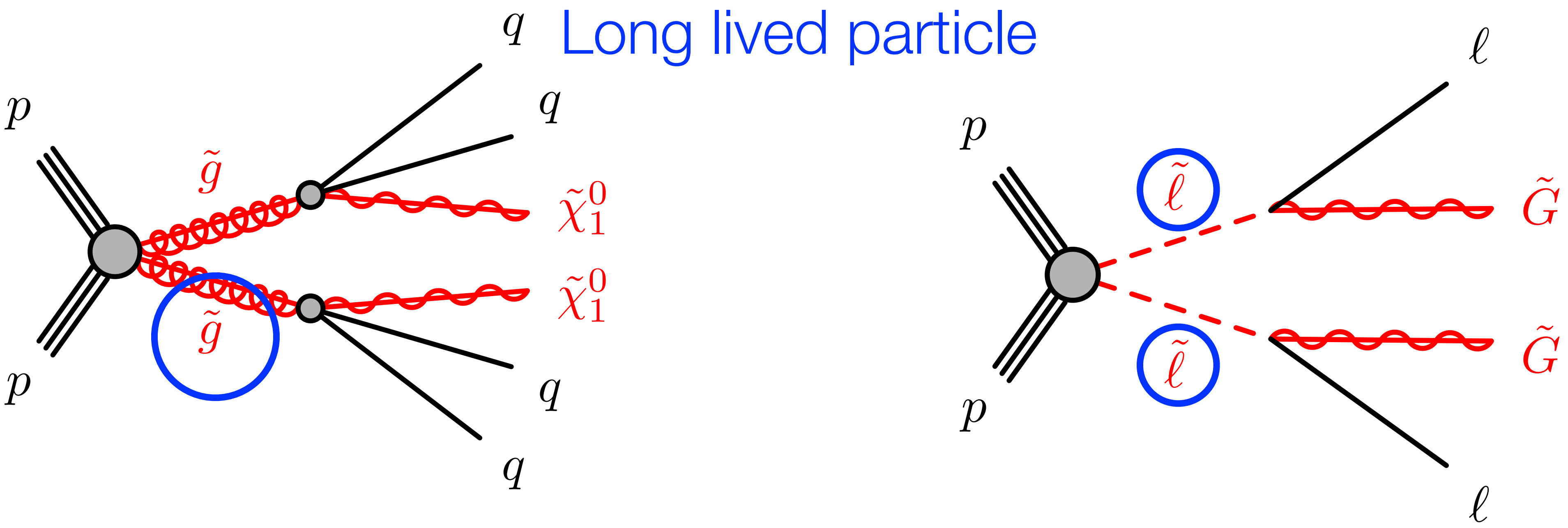

Long lived particle

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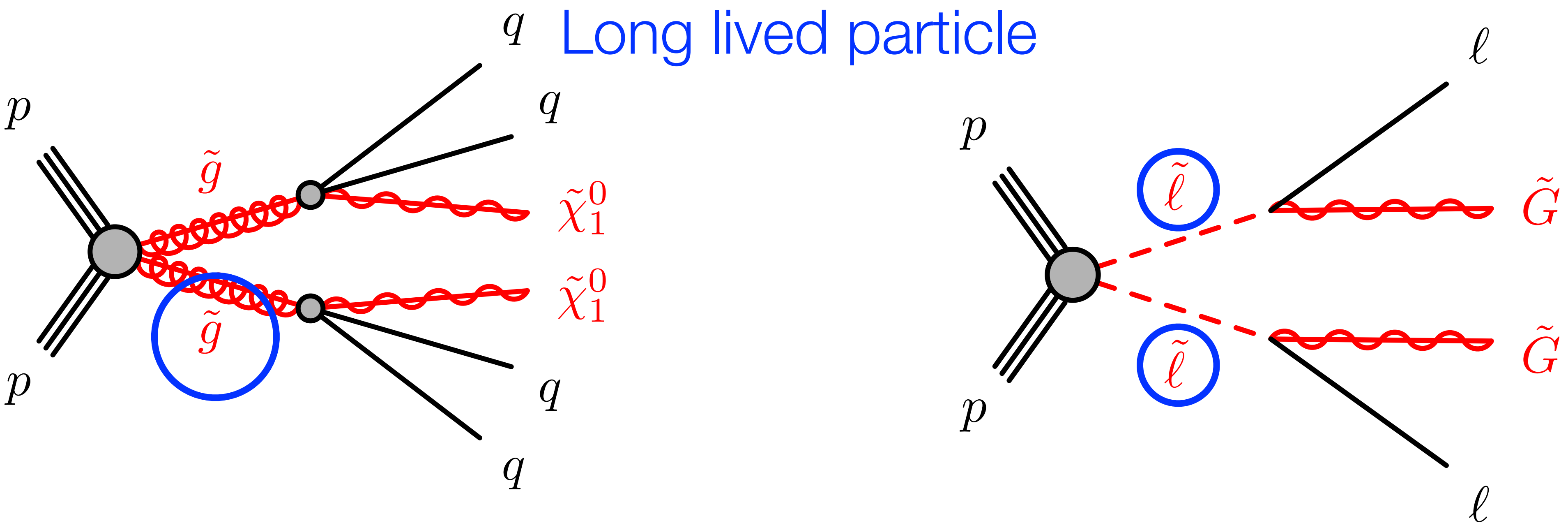

Long lived particle

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- **High momentum** compared to SM backgrounds

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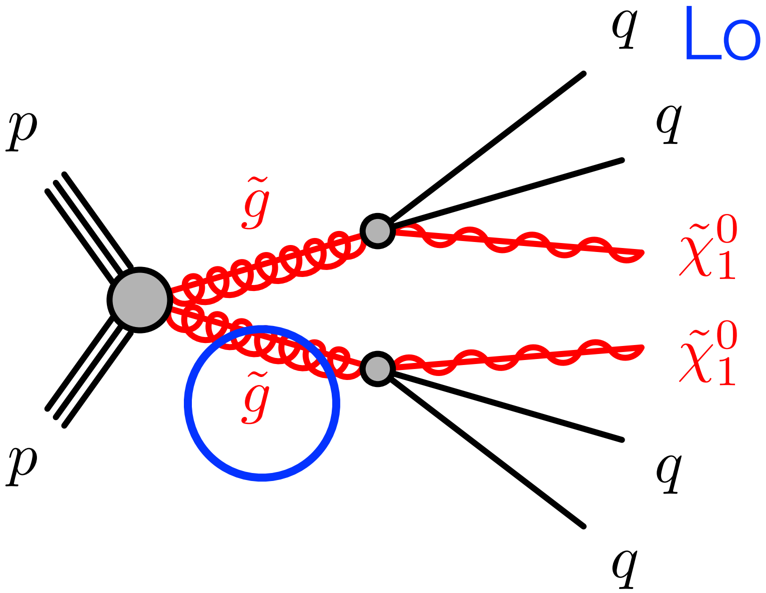

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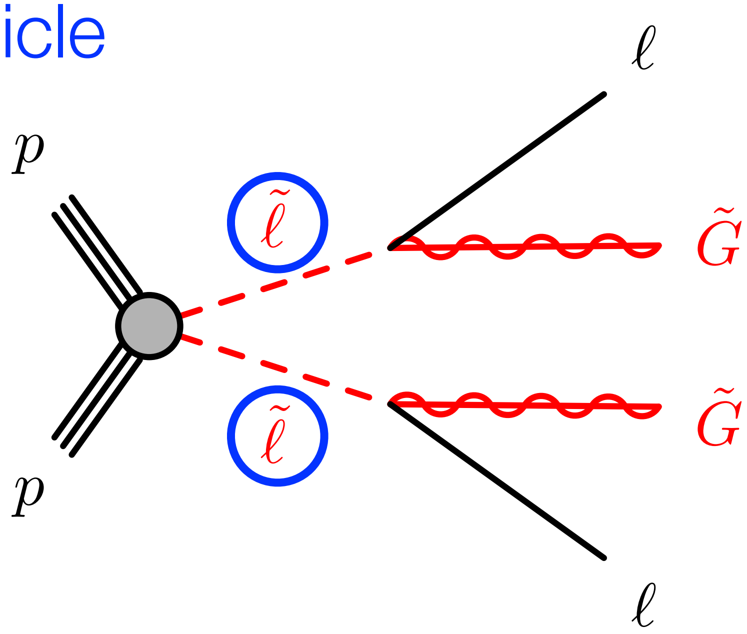

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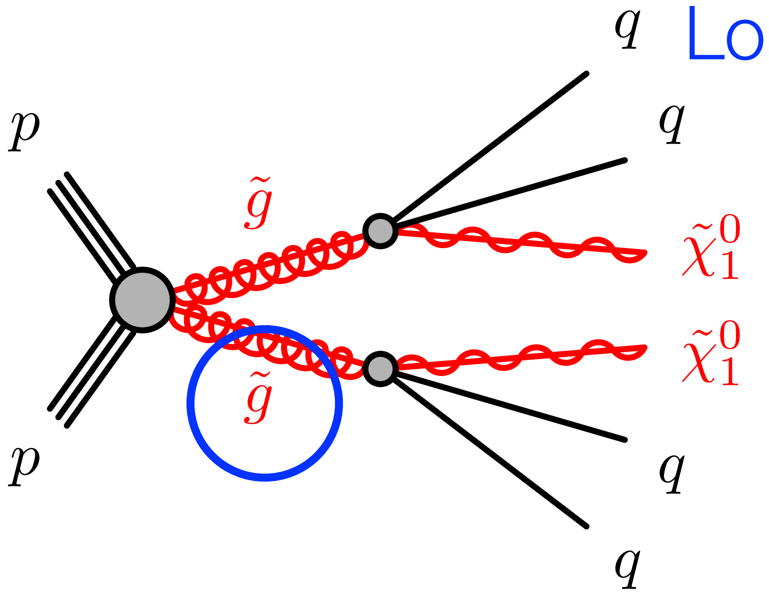

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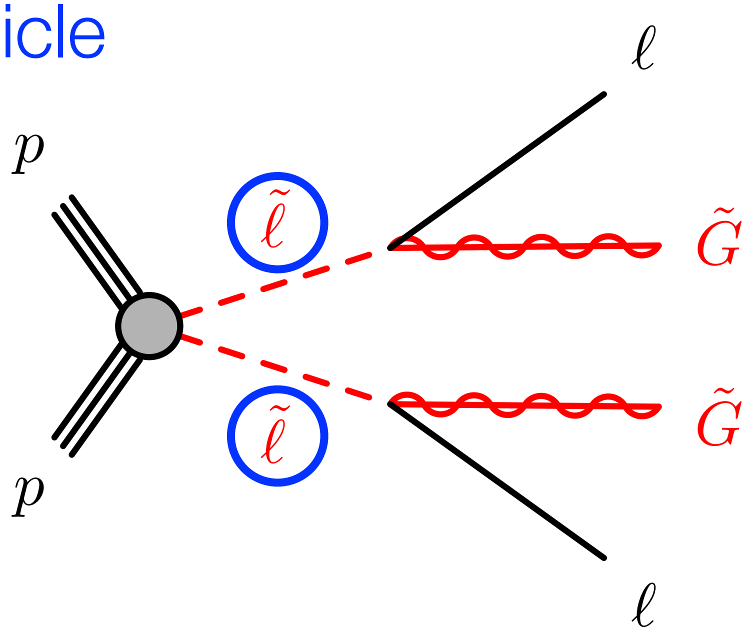

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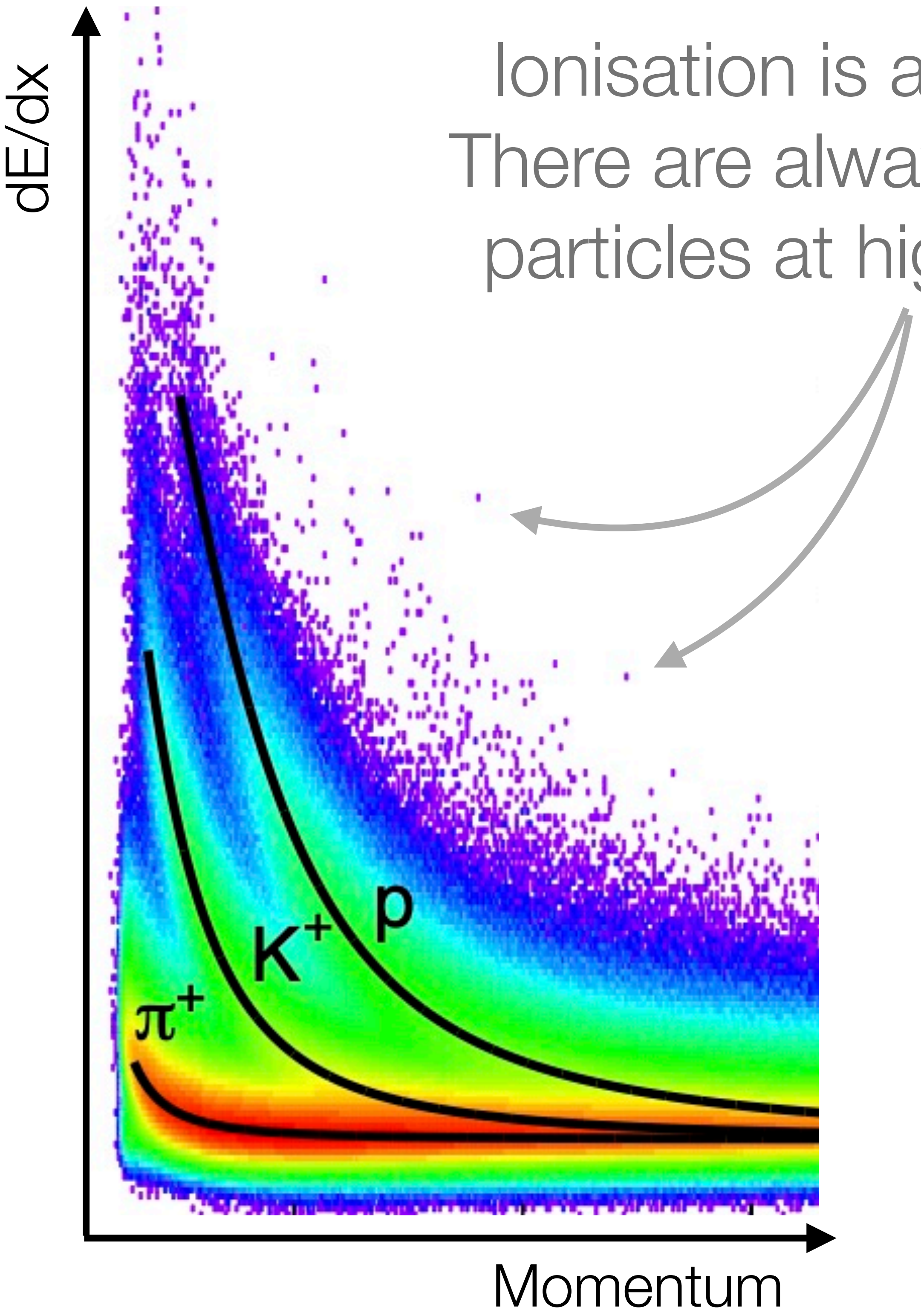
Selection: missing momentum in event, high momentum track with large dE/dx

Backgrounds in the dEdx search



Ionisation is a **distribution**:
There are always tails with SM
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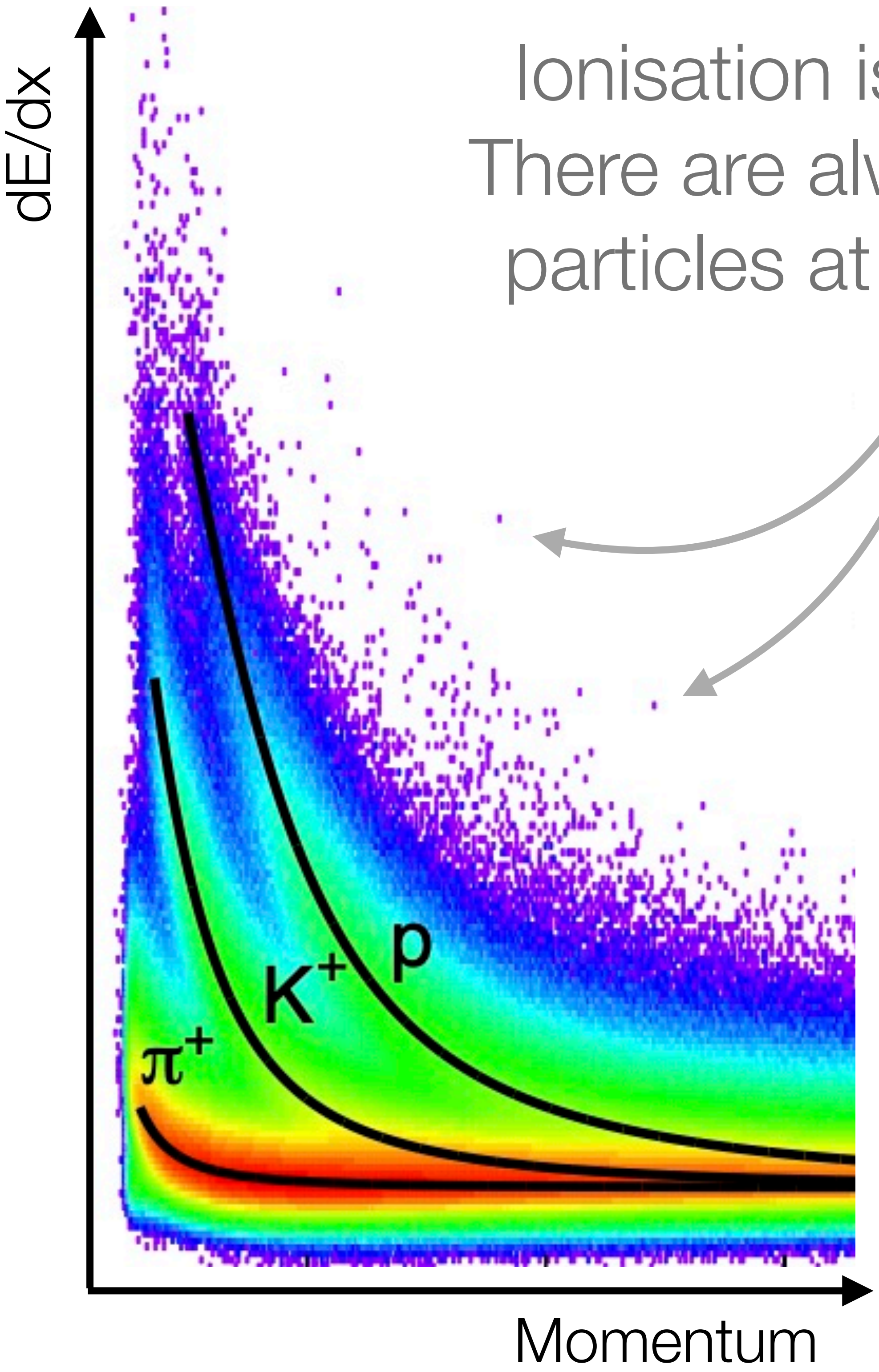

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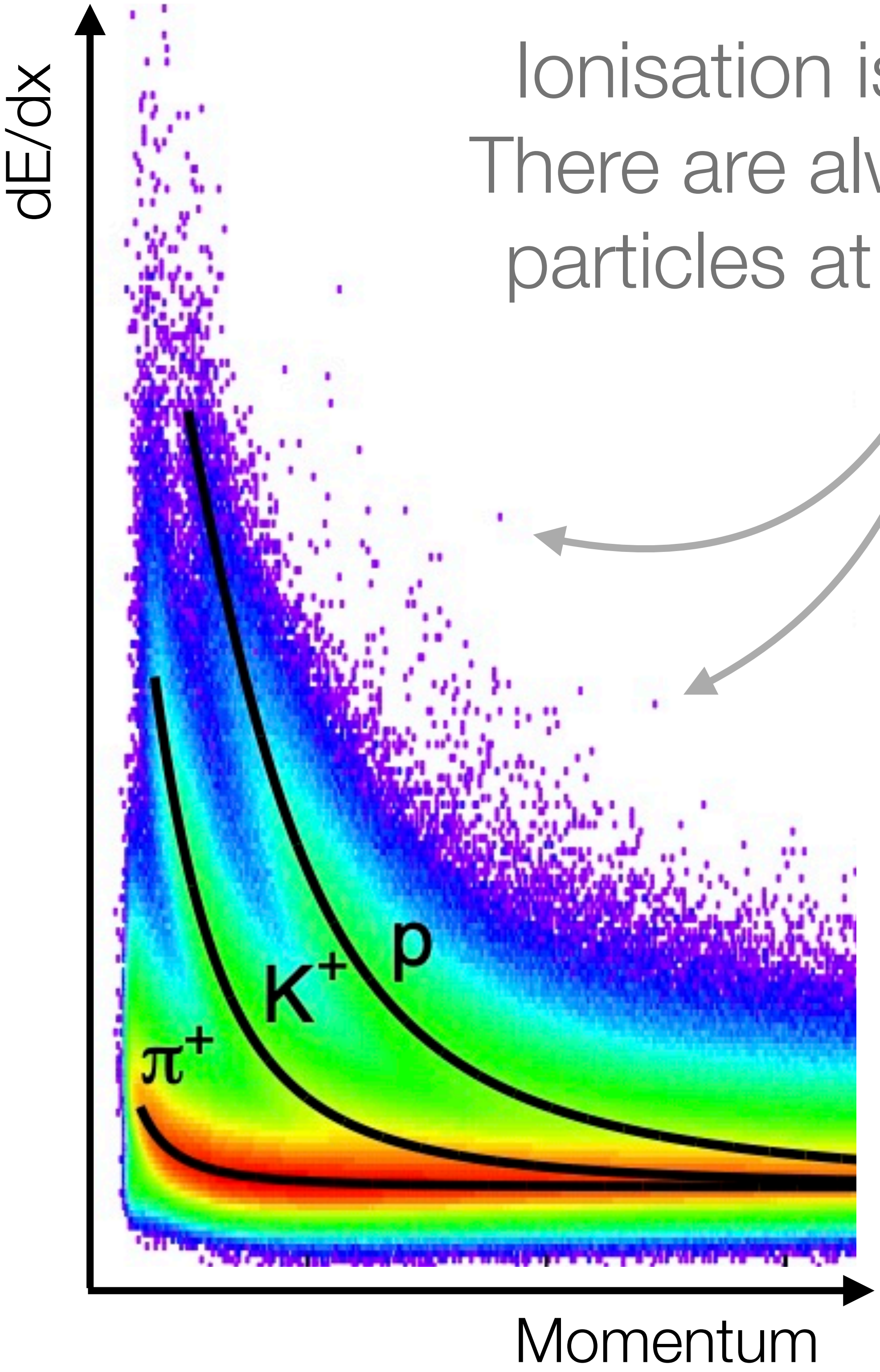

Ionisation is a **distribution**:
There are always tails with SM
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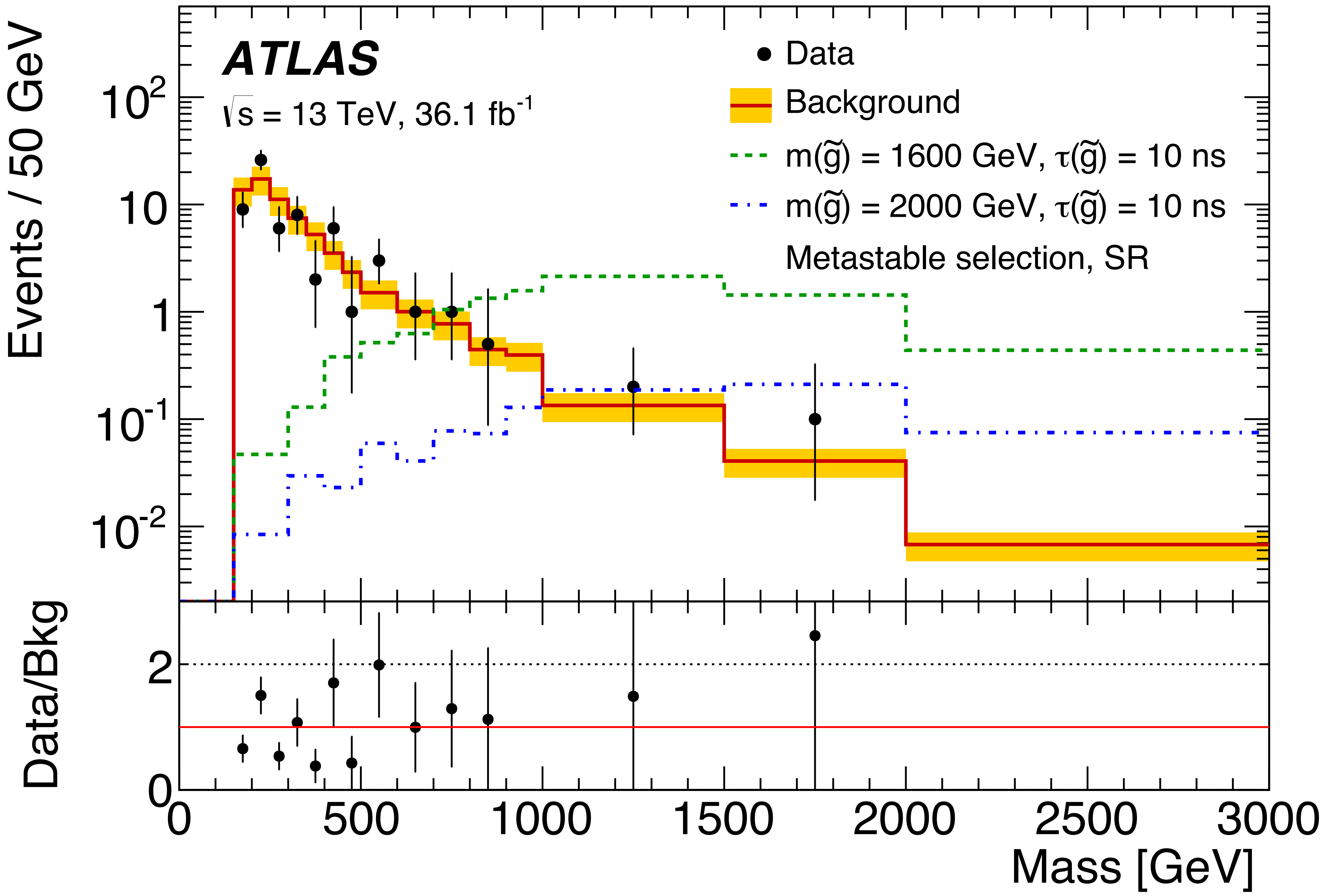
How do we predict tails?

- Missing momentum is **independent** of track dEdx
- Use **control regions** with low missing momentum to predict SM backgrounds
- Convert prediction from p and dEdx to most likely particle mass

dEdx latest results and current status

Optimised for lower lifetimes



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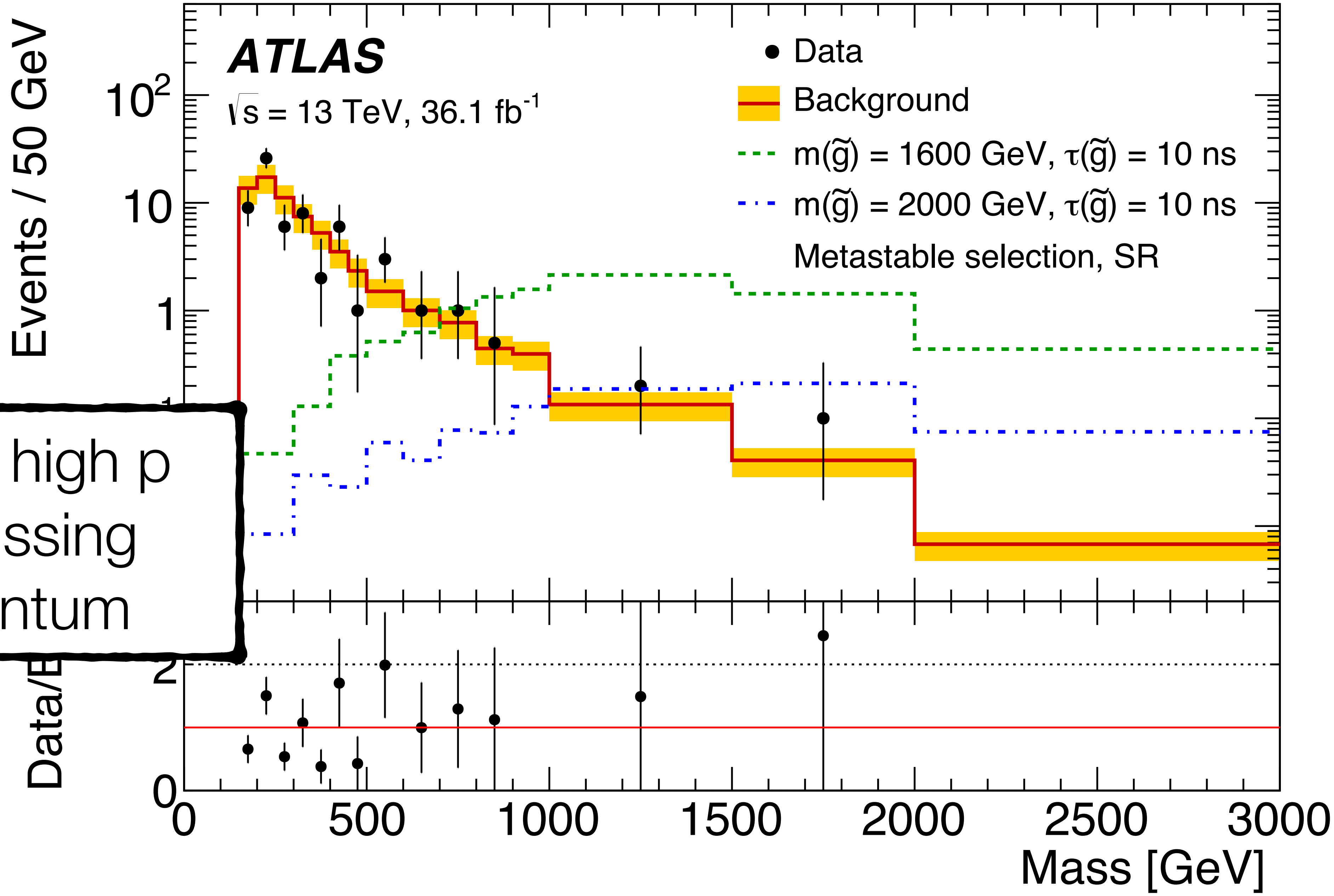

Data at high p and missing momentum

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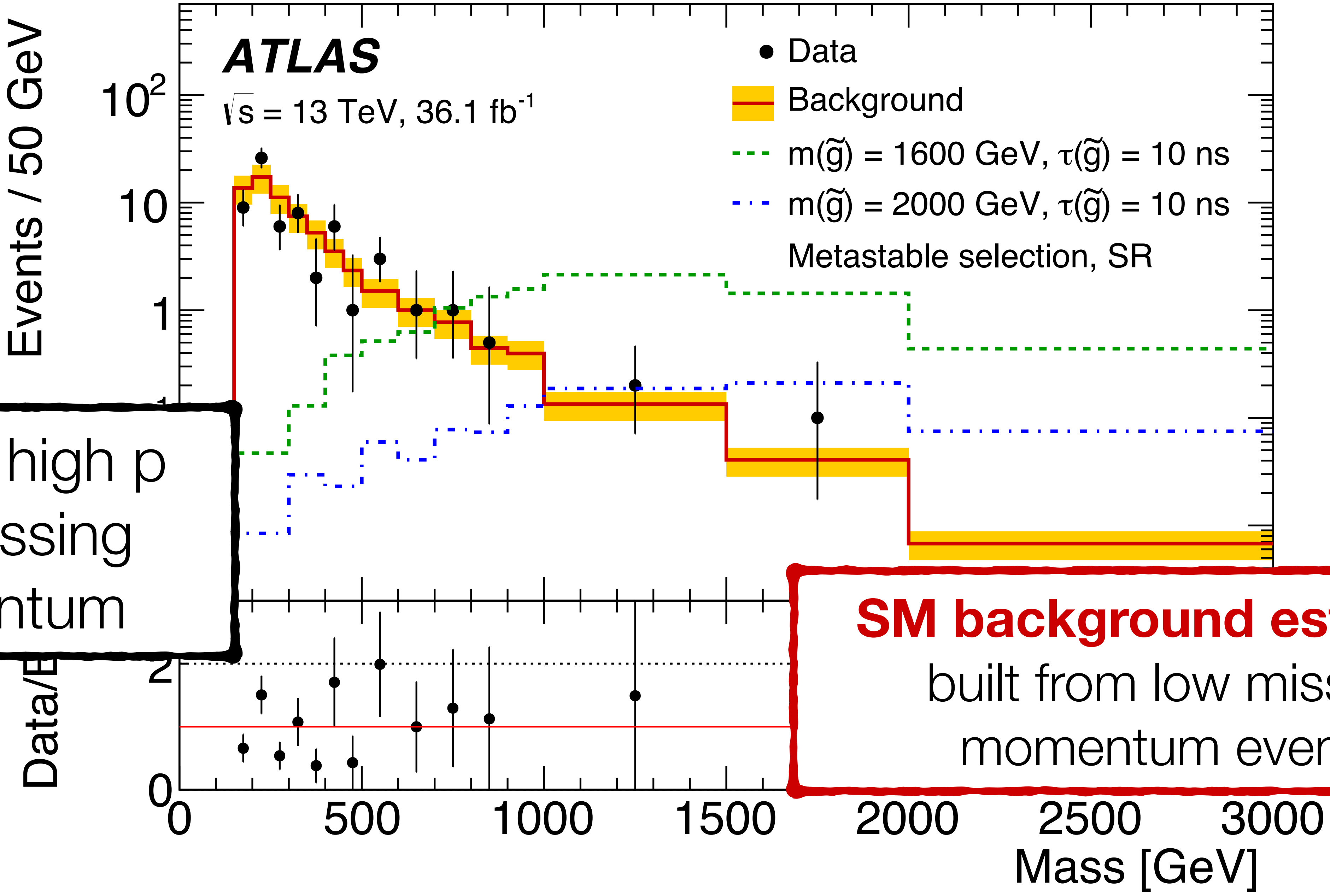

Data at high p and missing momentum

SM background estimate built from low missing momentum events

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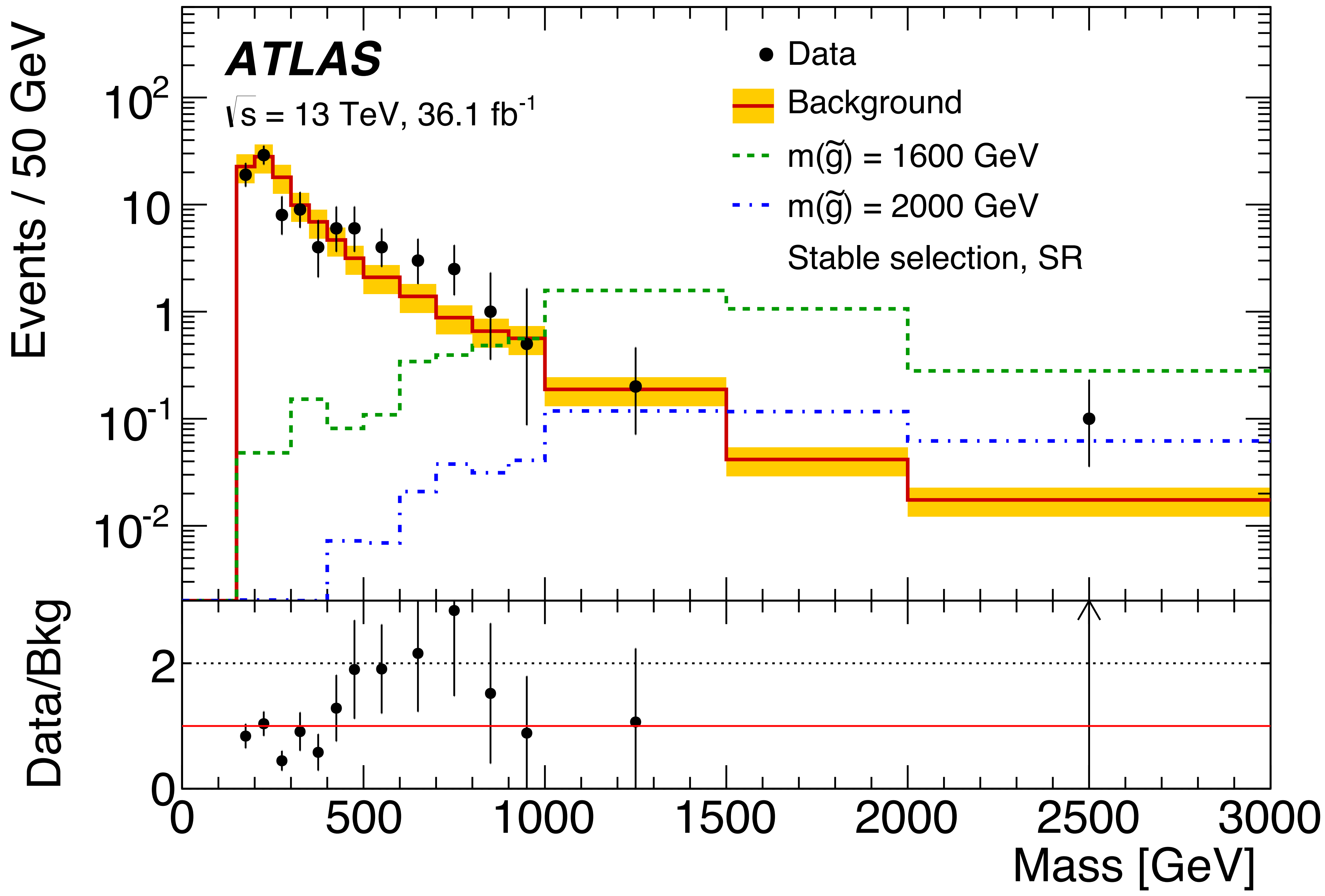
Optimised for higher lifetimes



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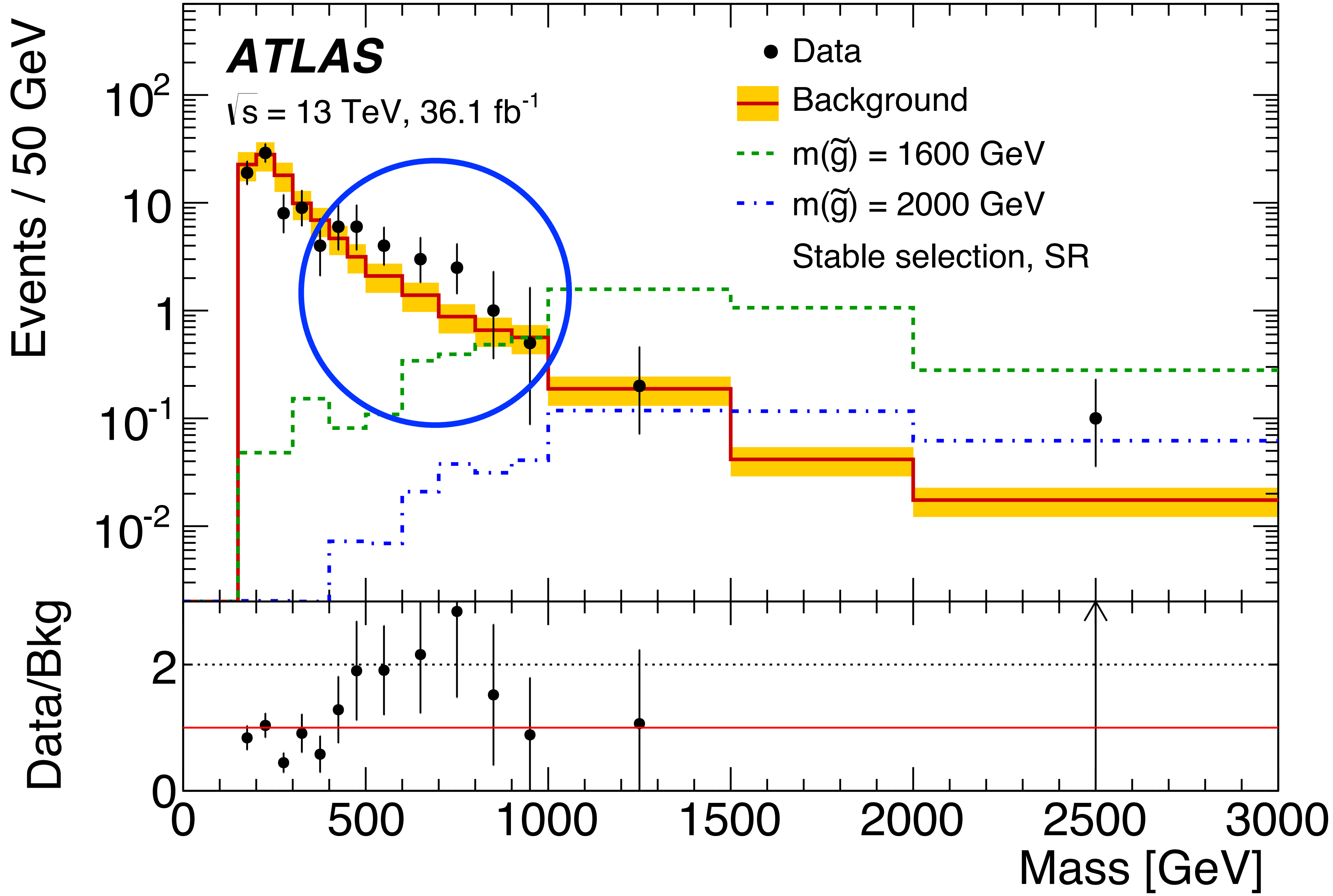

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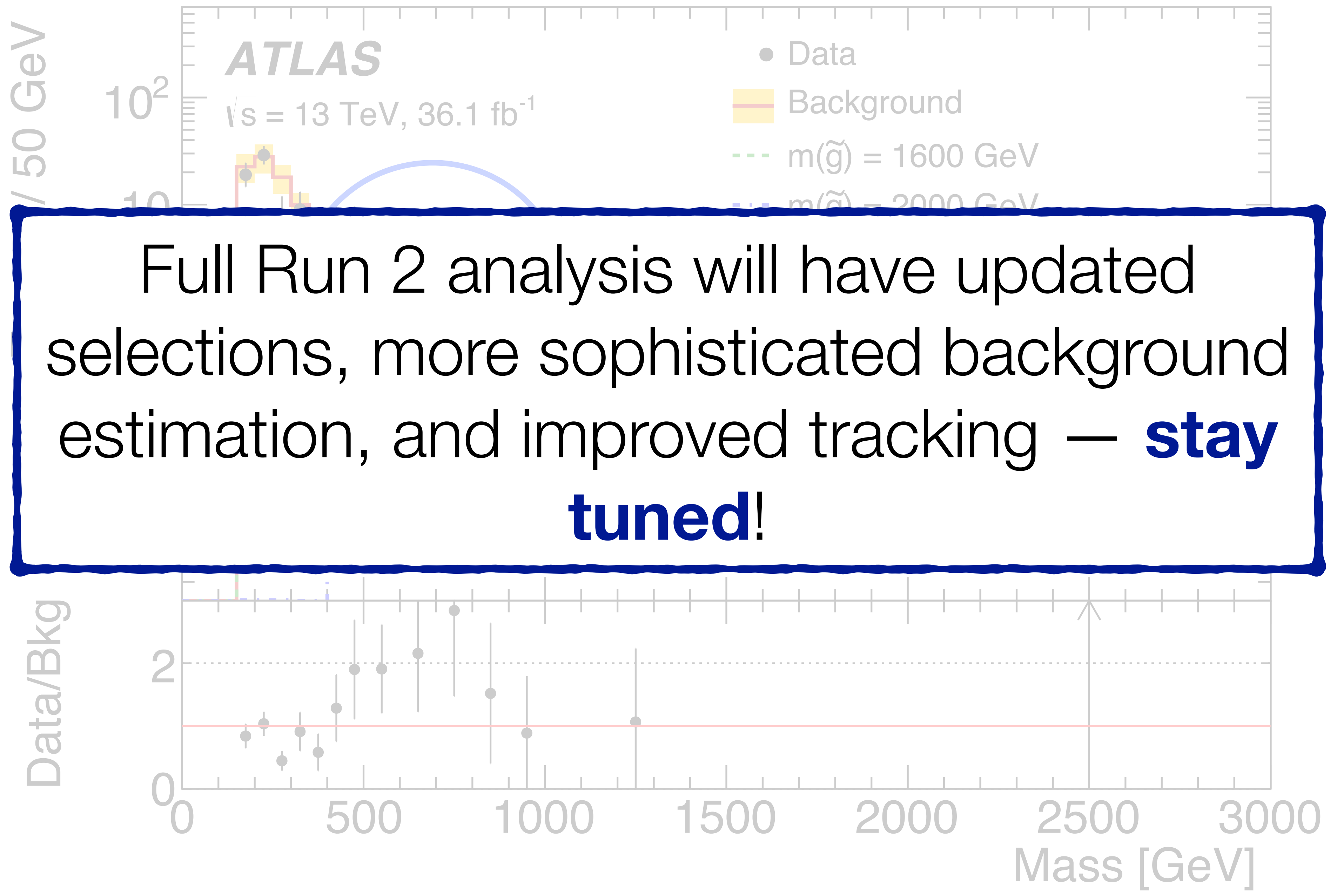
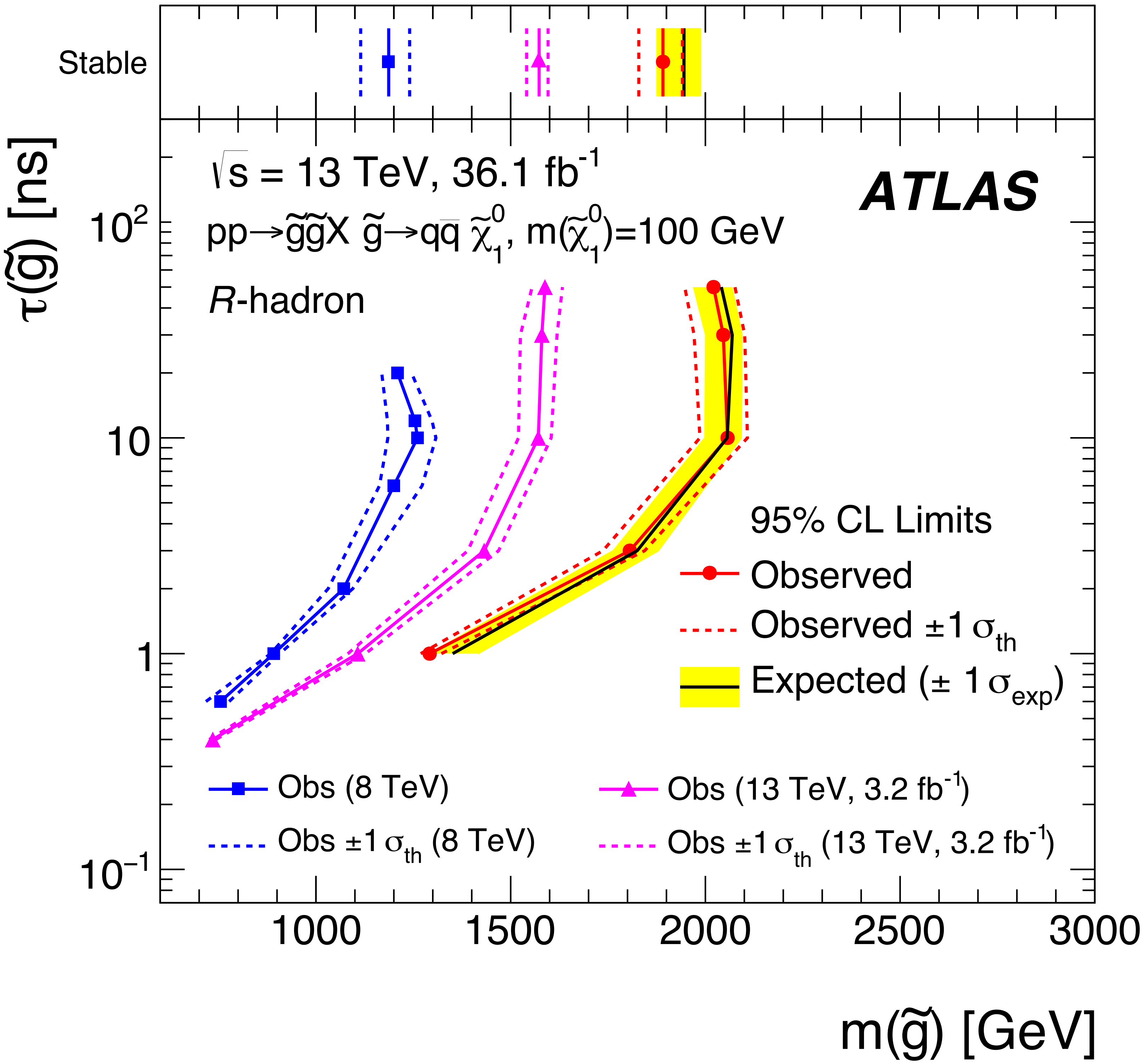


Full Run 2 analysis will have updated selections, more sophisticated background estimation, and improved tracking — **stay tuned**!

Phys. Lett. B 788 (2019) 96

Setting limits with dEdx

TODO



- Above: recent reinterpretation

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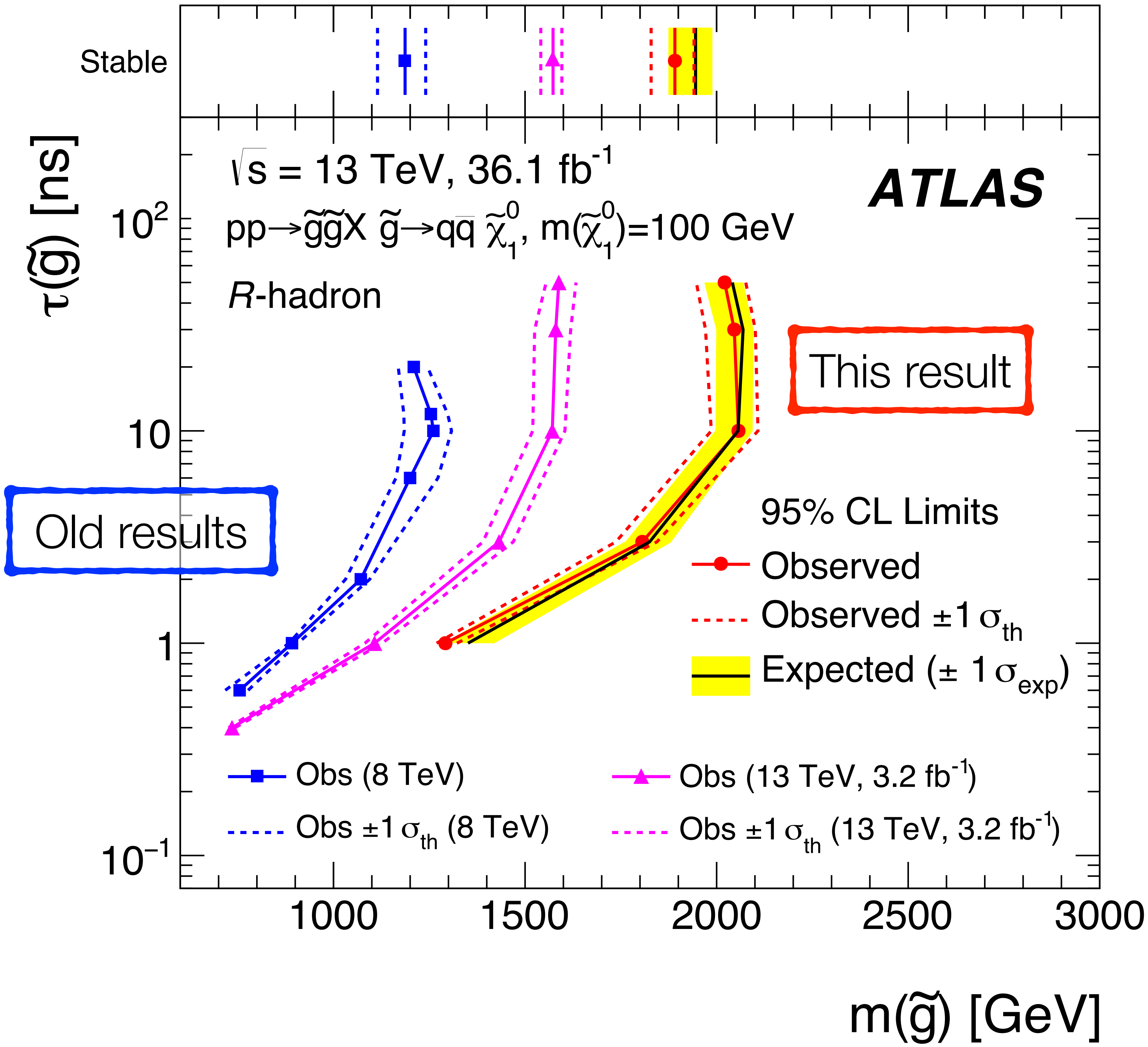
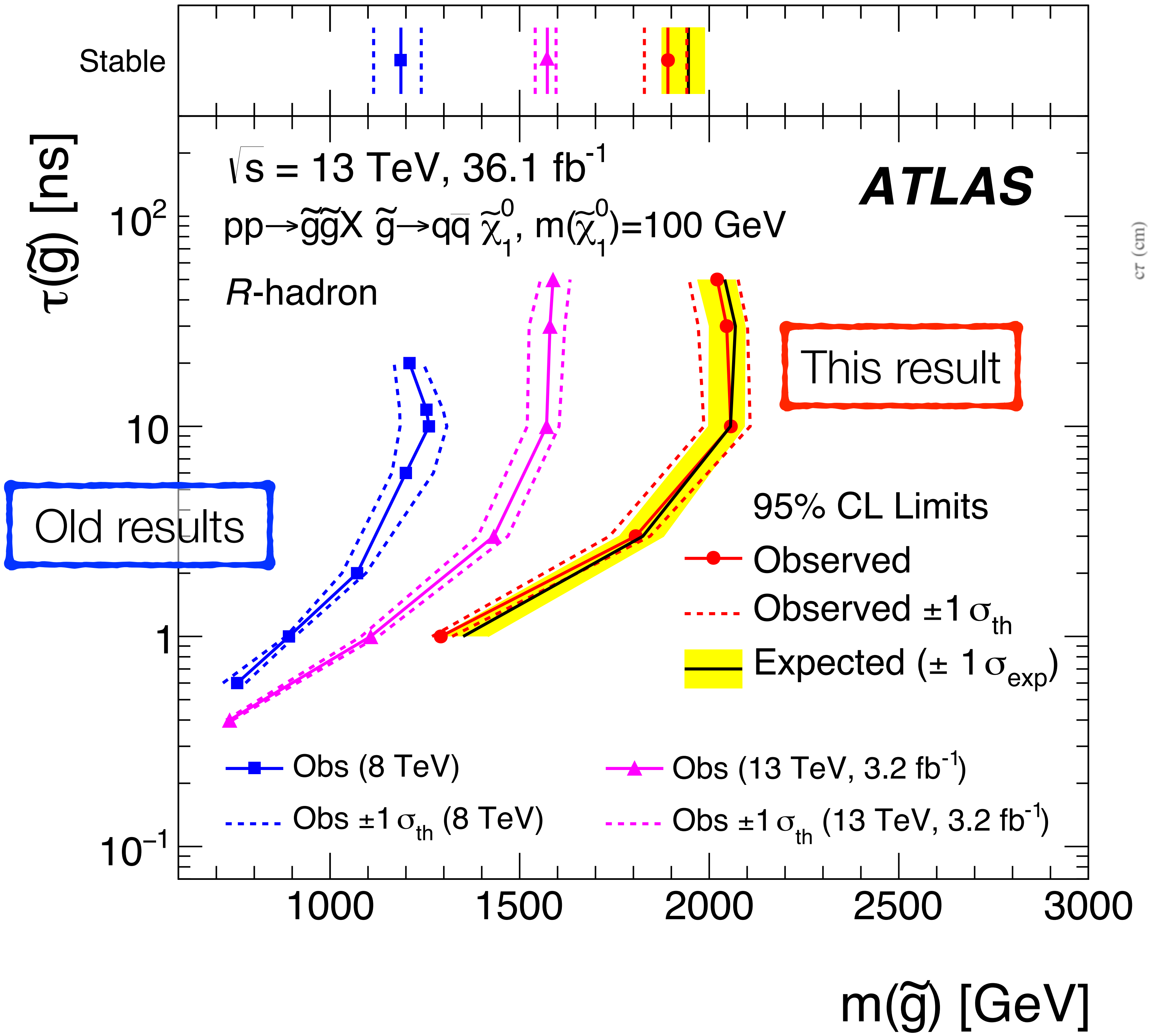
TODO



- Above: recent reinterpretation

Setting limits with dEdx

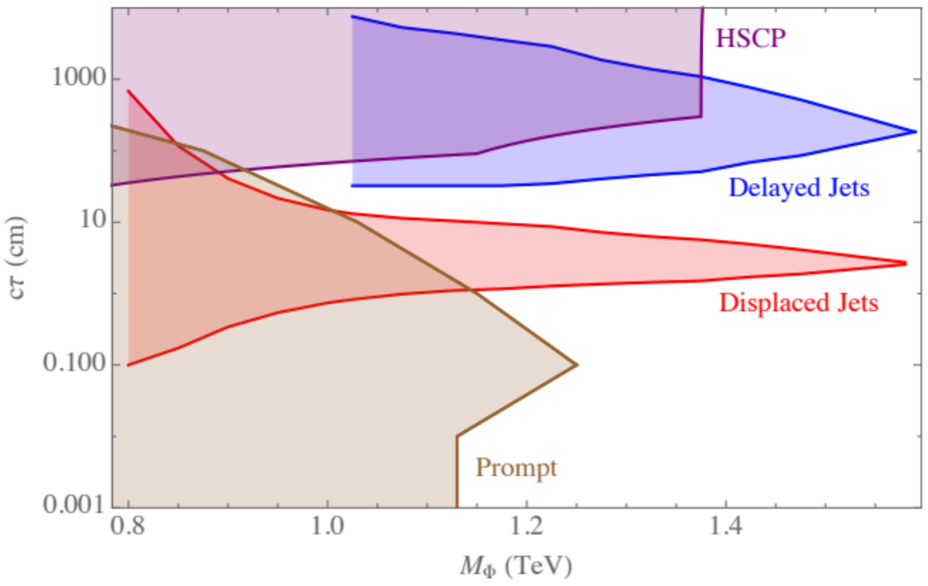
TODO



This result

Old results

arXiv:2004.00636



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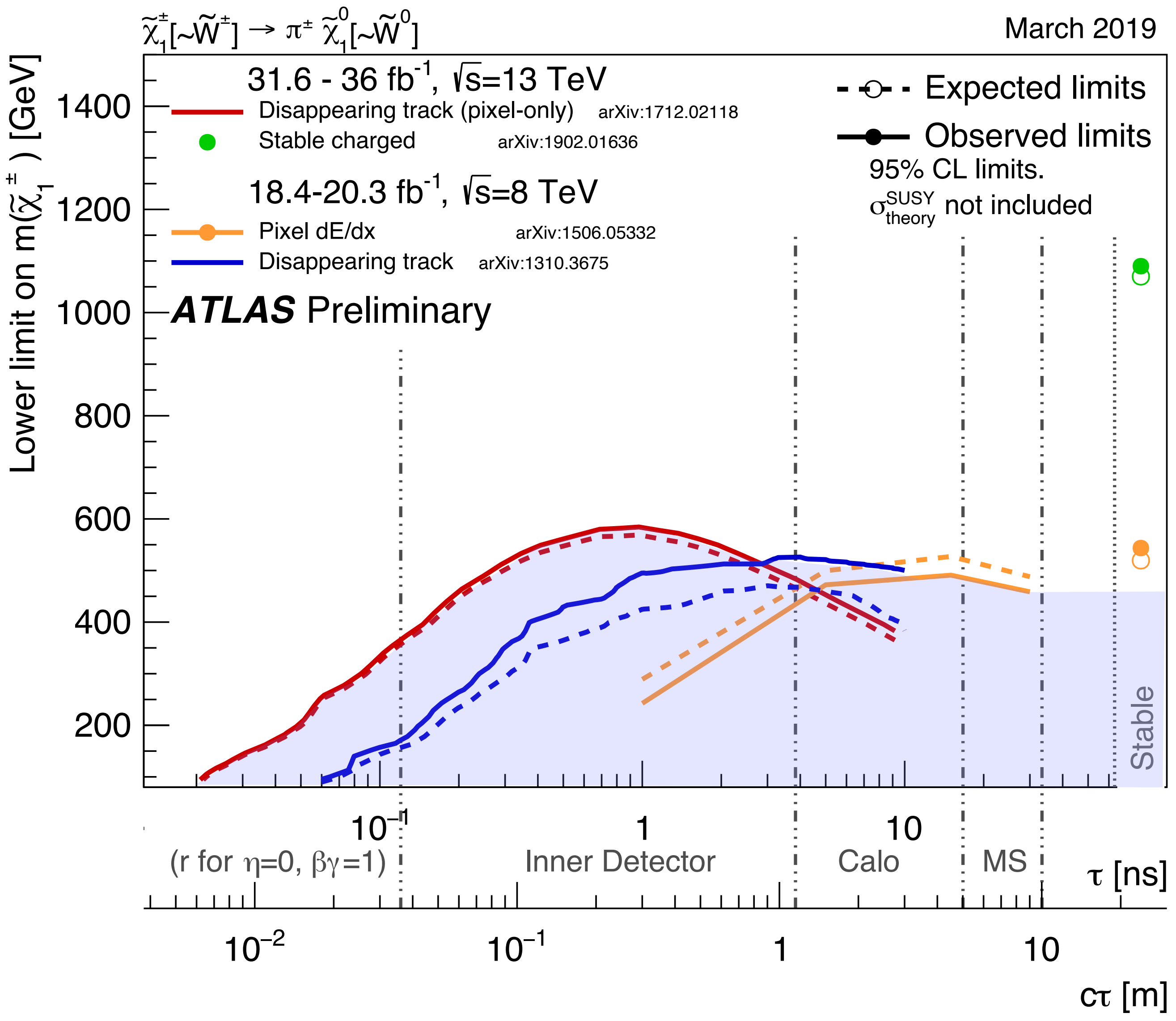
Disappearing tracks

arXiv:1712.02118



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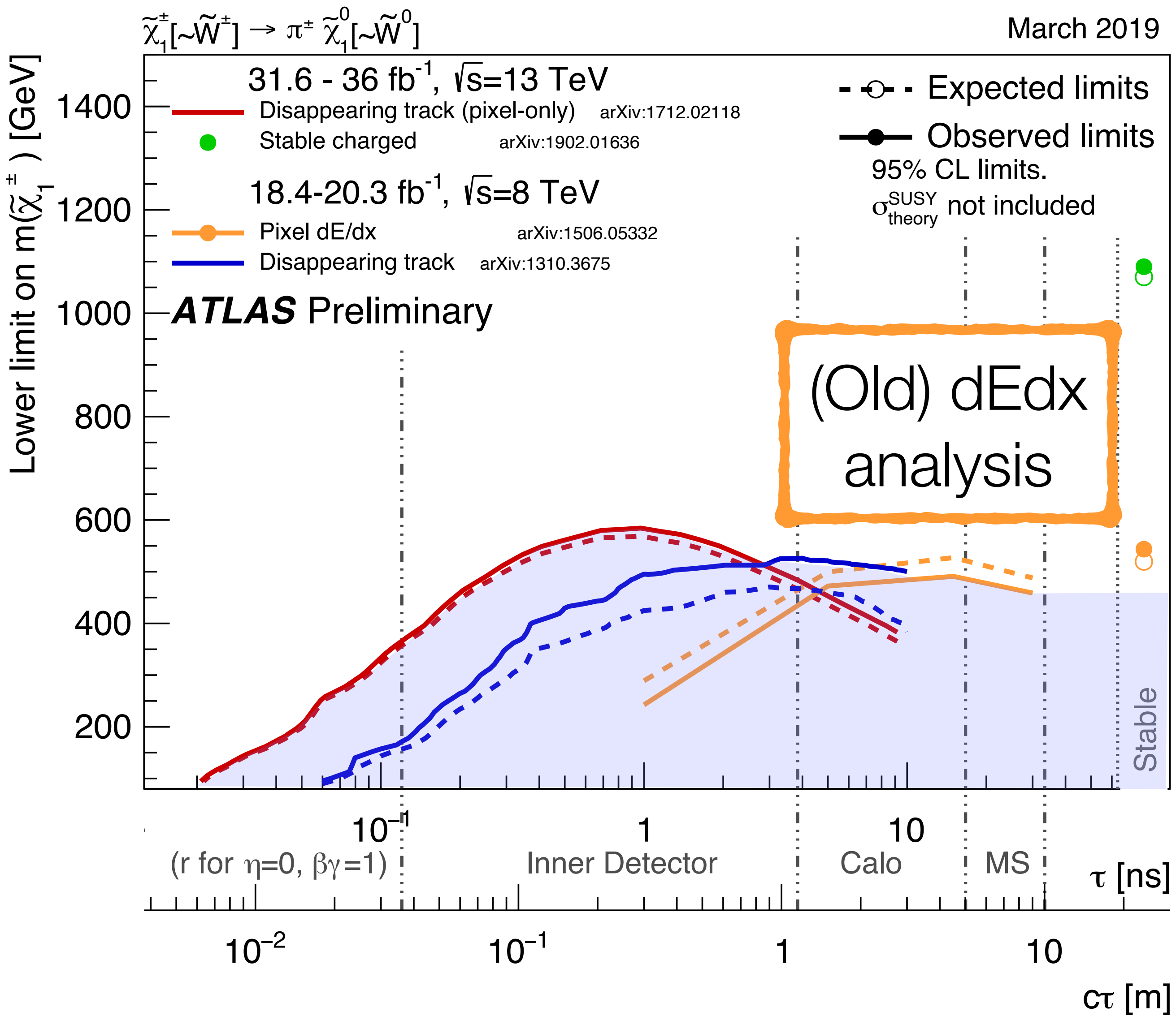

(Old) dEdx analysis

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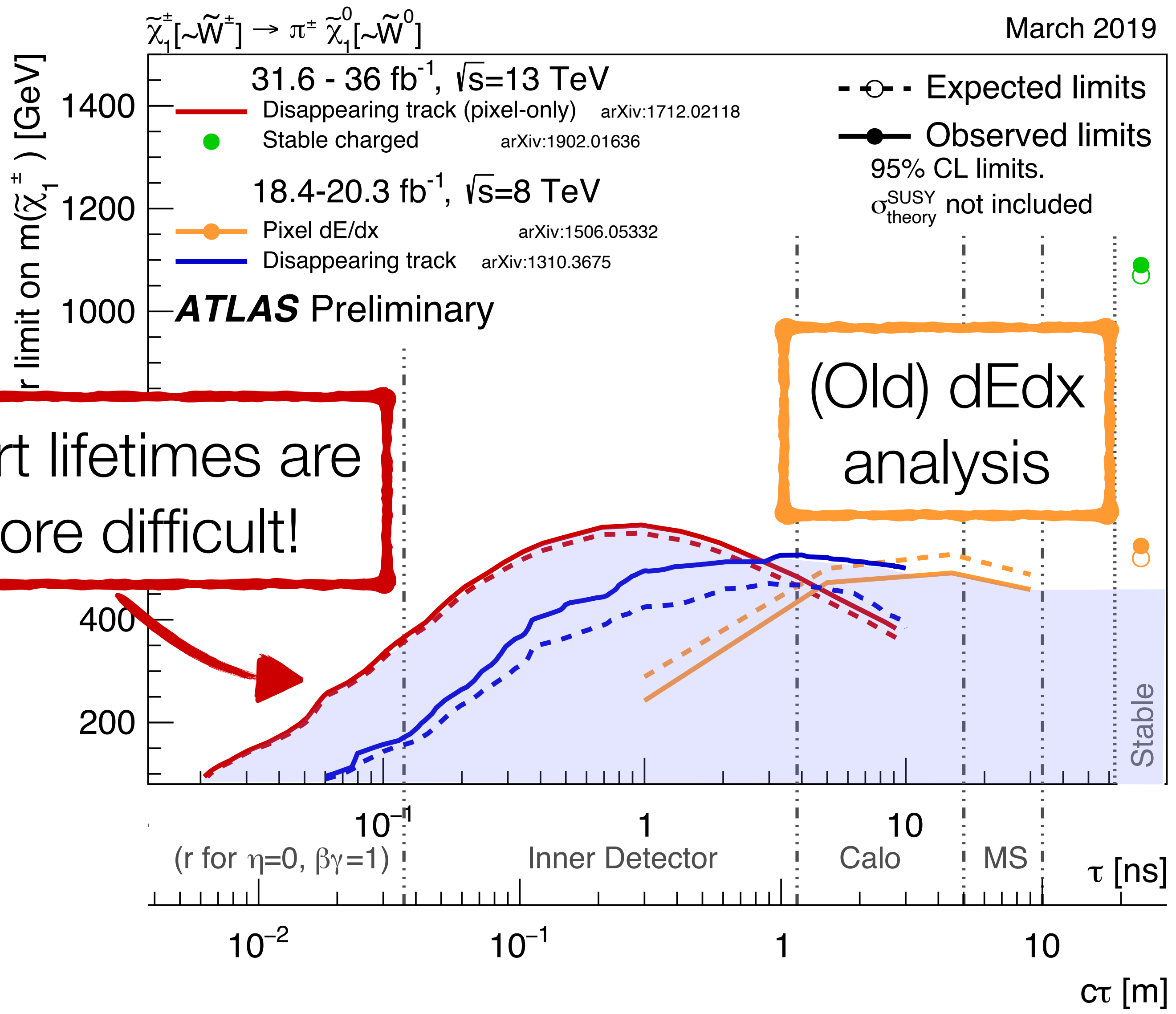
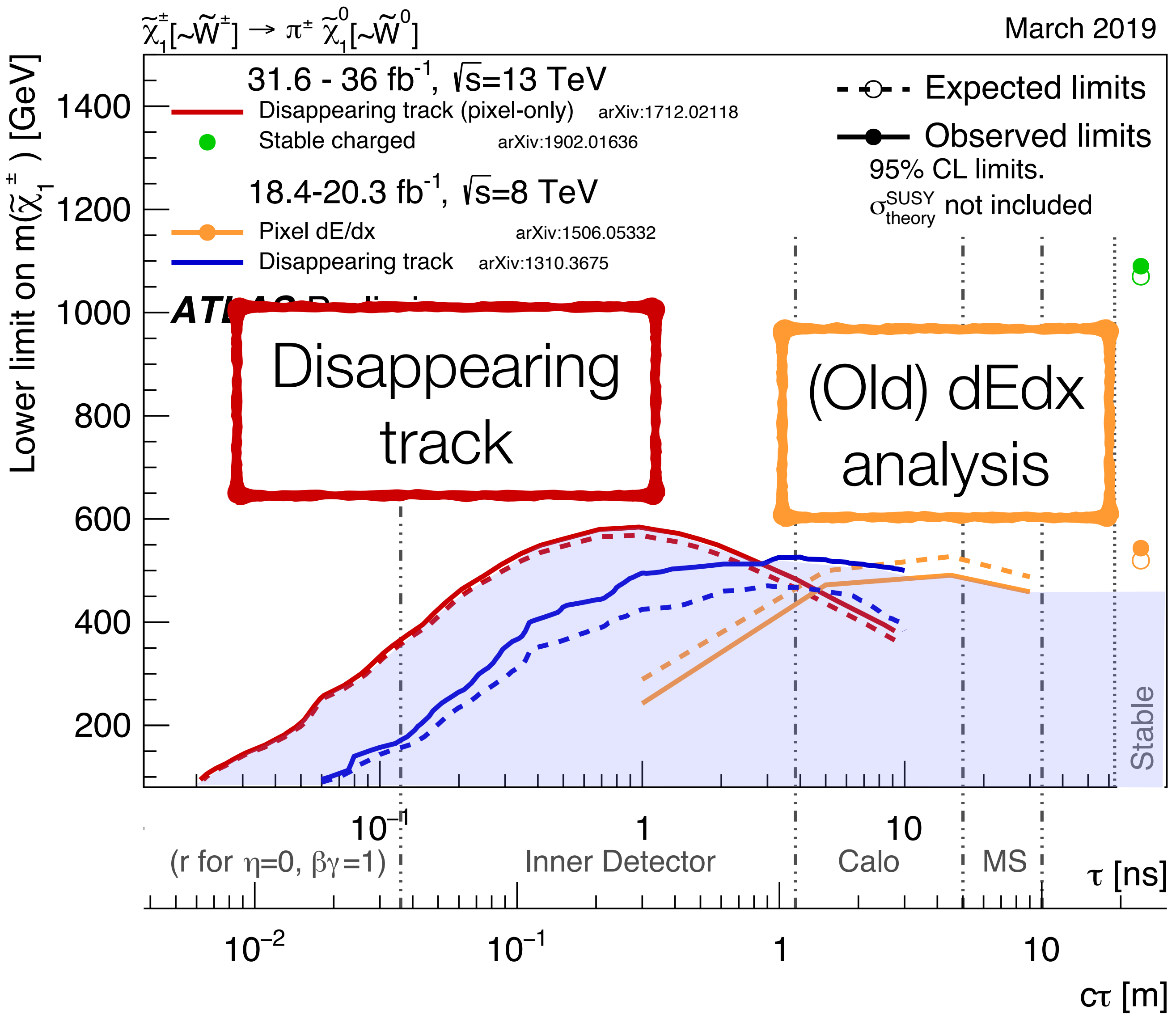


Short lifetimes are more difficult!

(Old) dEdx analysis

Disappearing tracks

arXiv:1712.02118



Disappearing track

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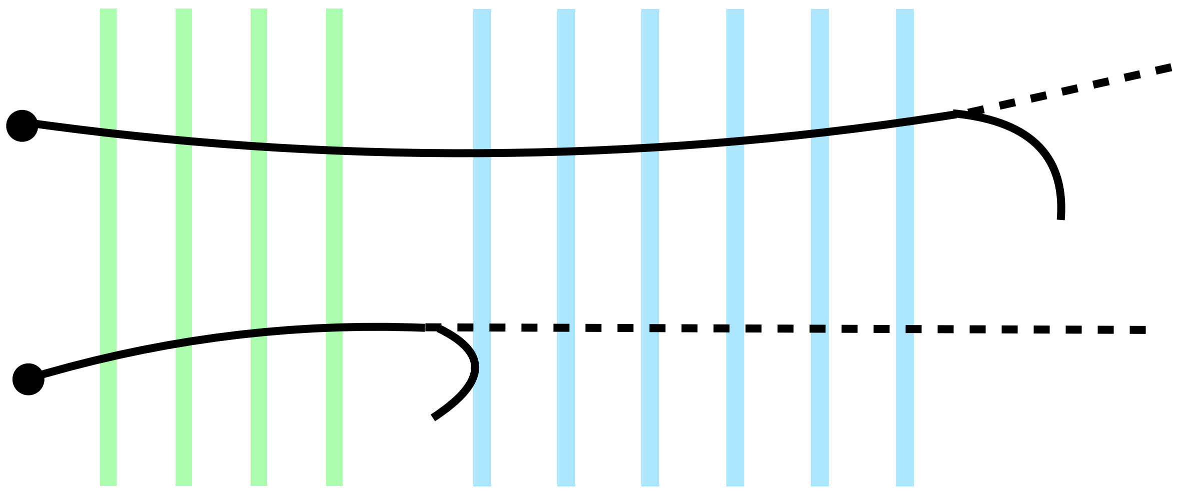

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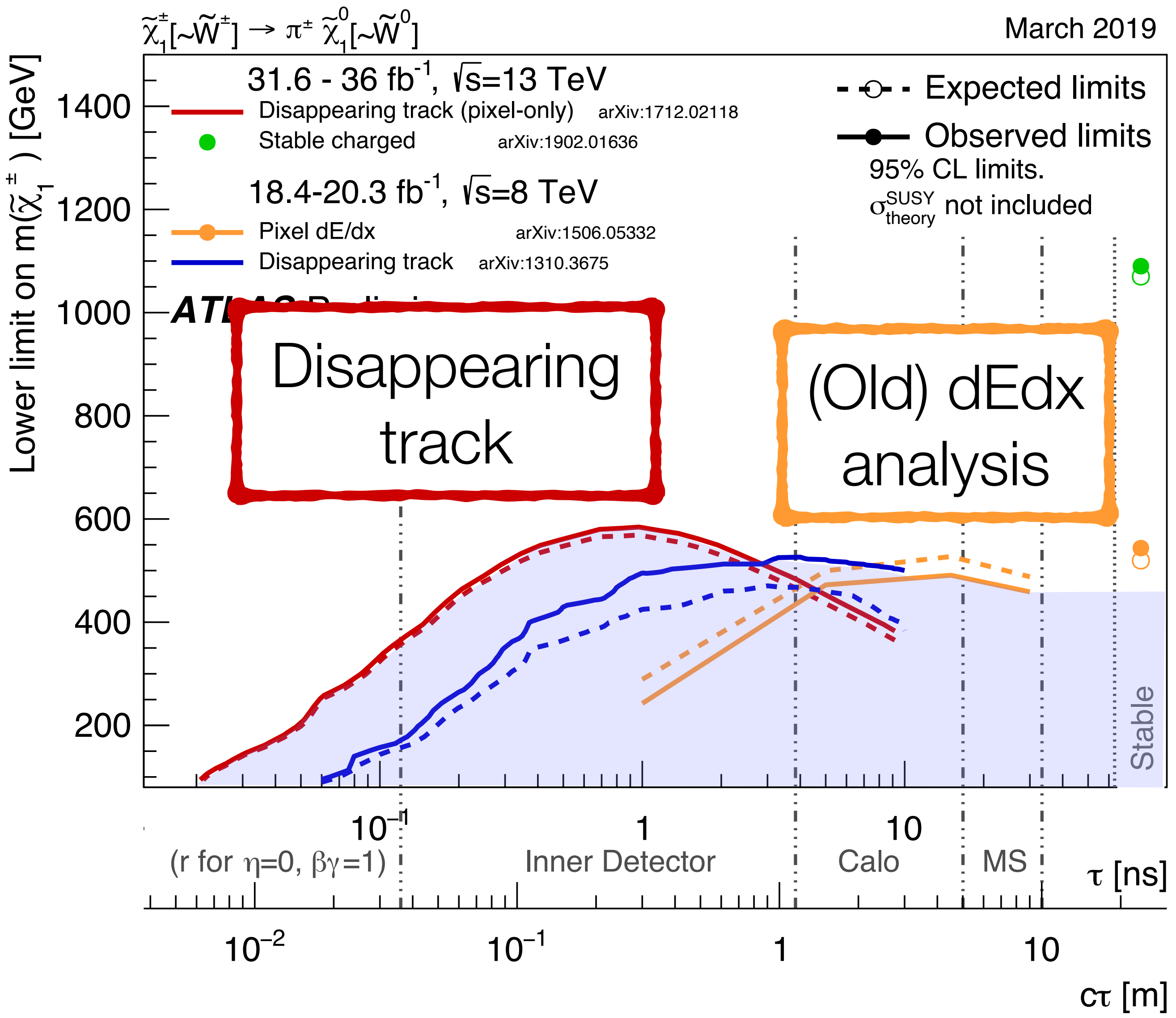

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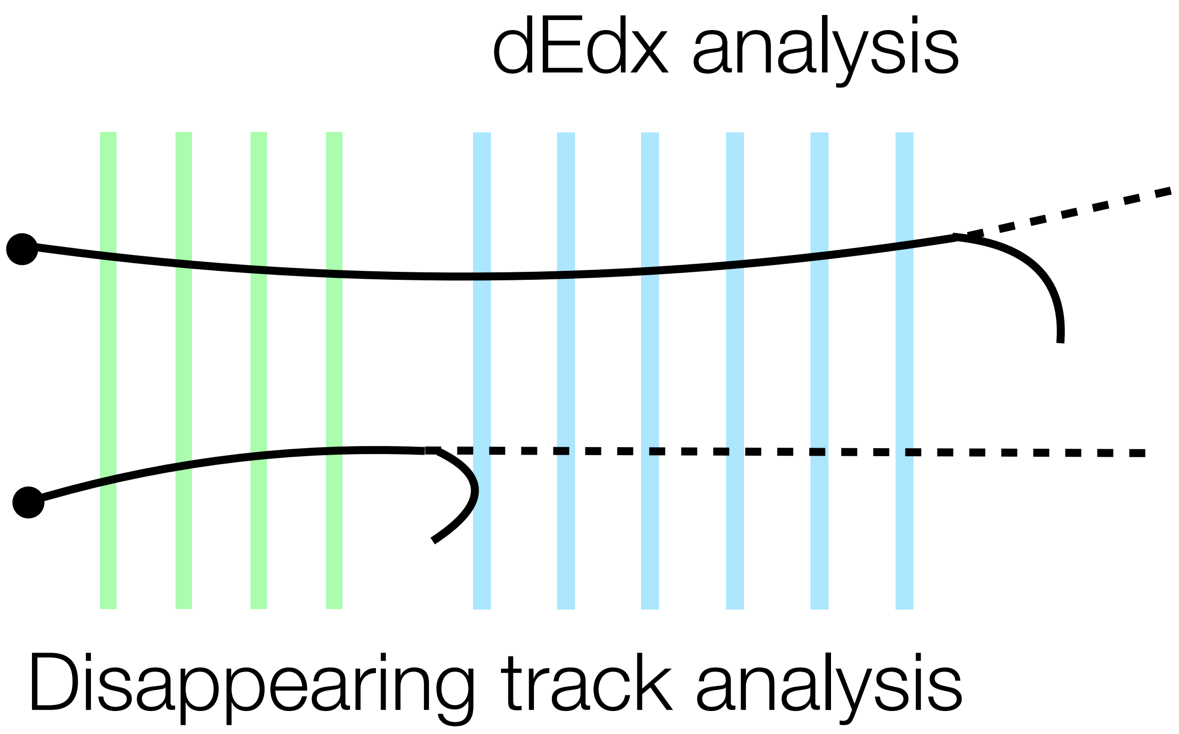
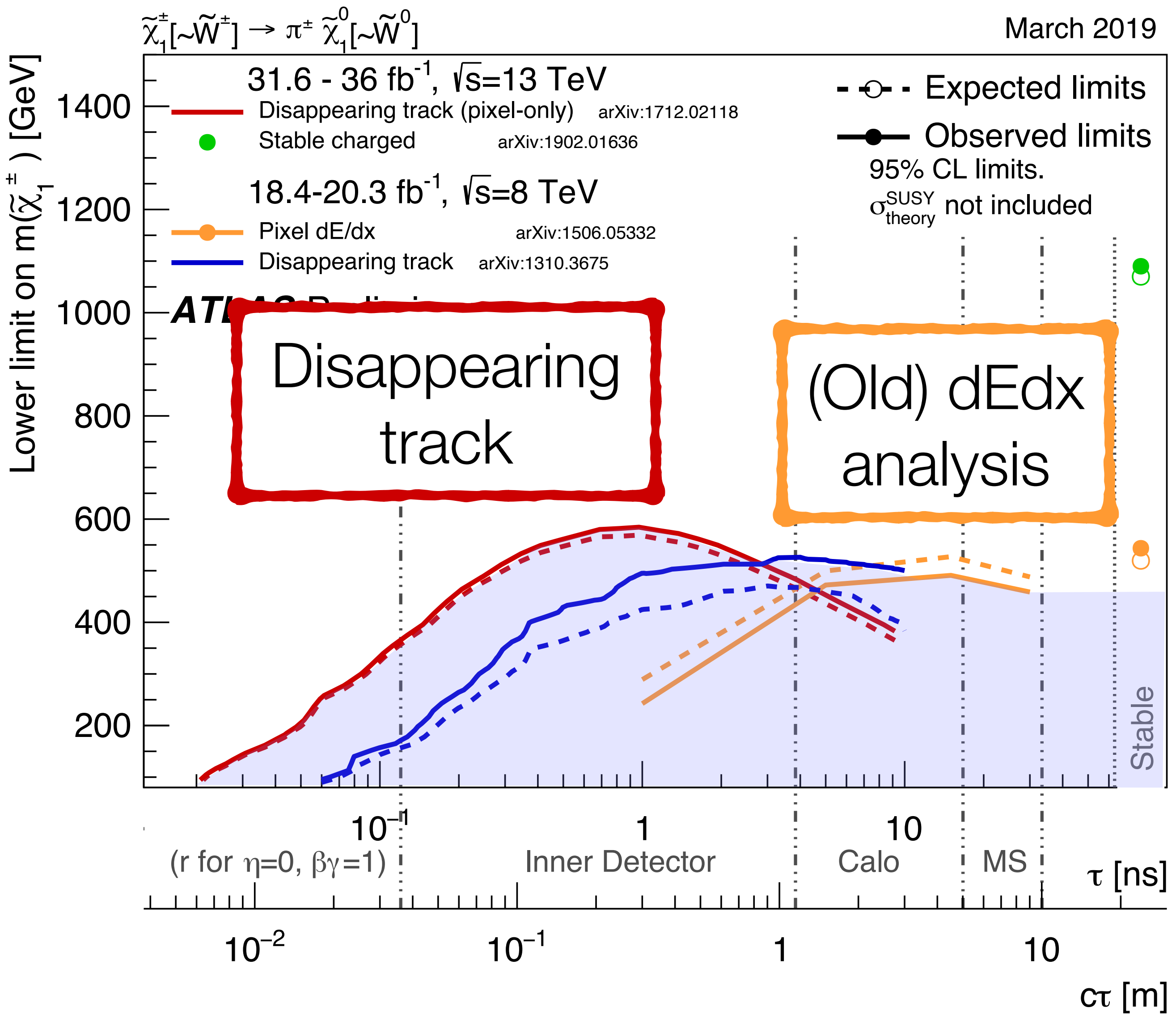


dEdx analysis

Disappearing track analysis



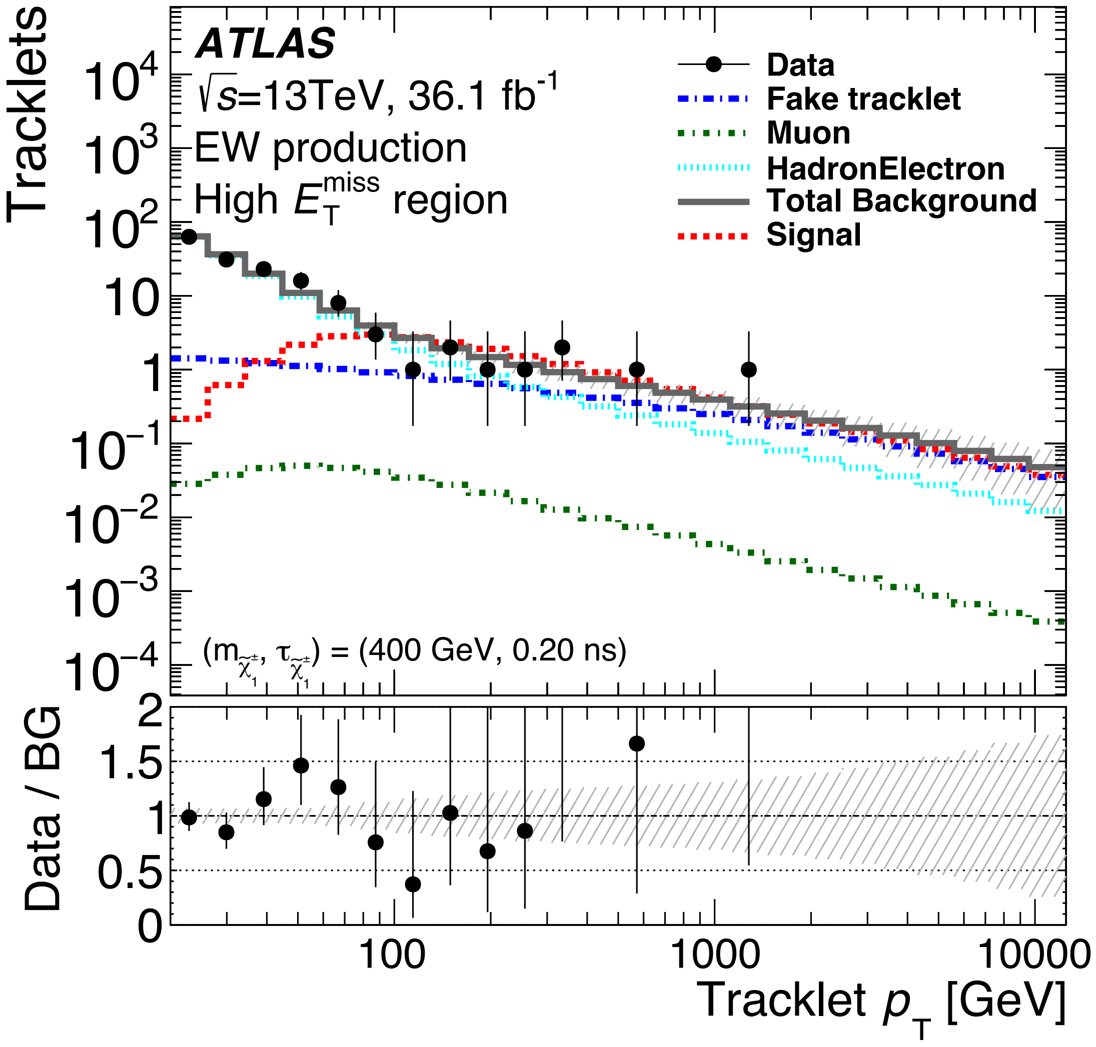
Disappearing track

(Old) dEdx analysis

- Pure wino LSP scenarios naturally predicts a $\tilde{\chi}_1^\pm$ lifetime around 0.2 ns
- Signature: track that vanishes midway through inner detector
- Similar to dEdx, commonly reinterpreted (including covering key range in pure-Higgsino LSP)

Disappearing tracks

- Trigger: missing energy
- Backgrounds:
    - Real hadrons & leptons that dramatically change direction (bremsstrahlung, material interactions, multiple scattering)
    - Fake tracklets made from mis-associated hits
- Extract templates in control regions and perform fit in signal regions to get normalisations



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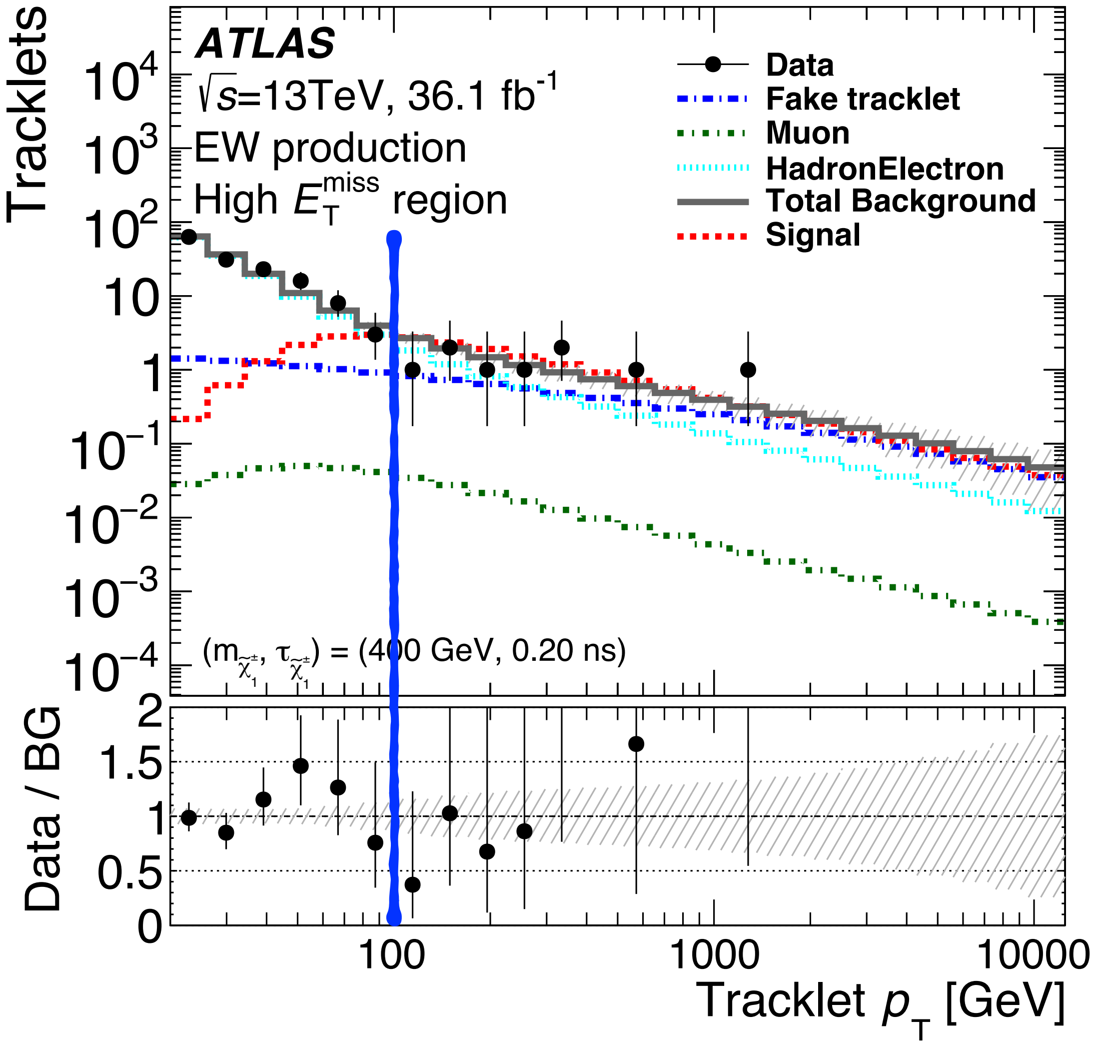

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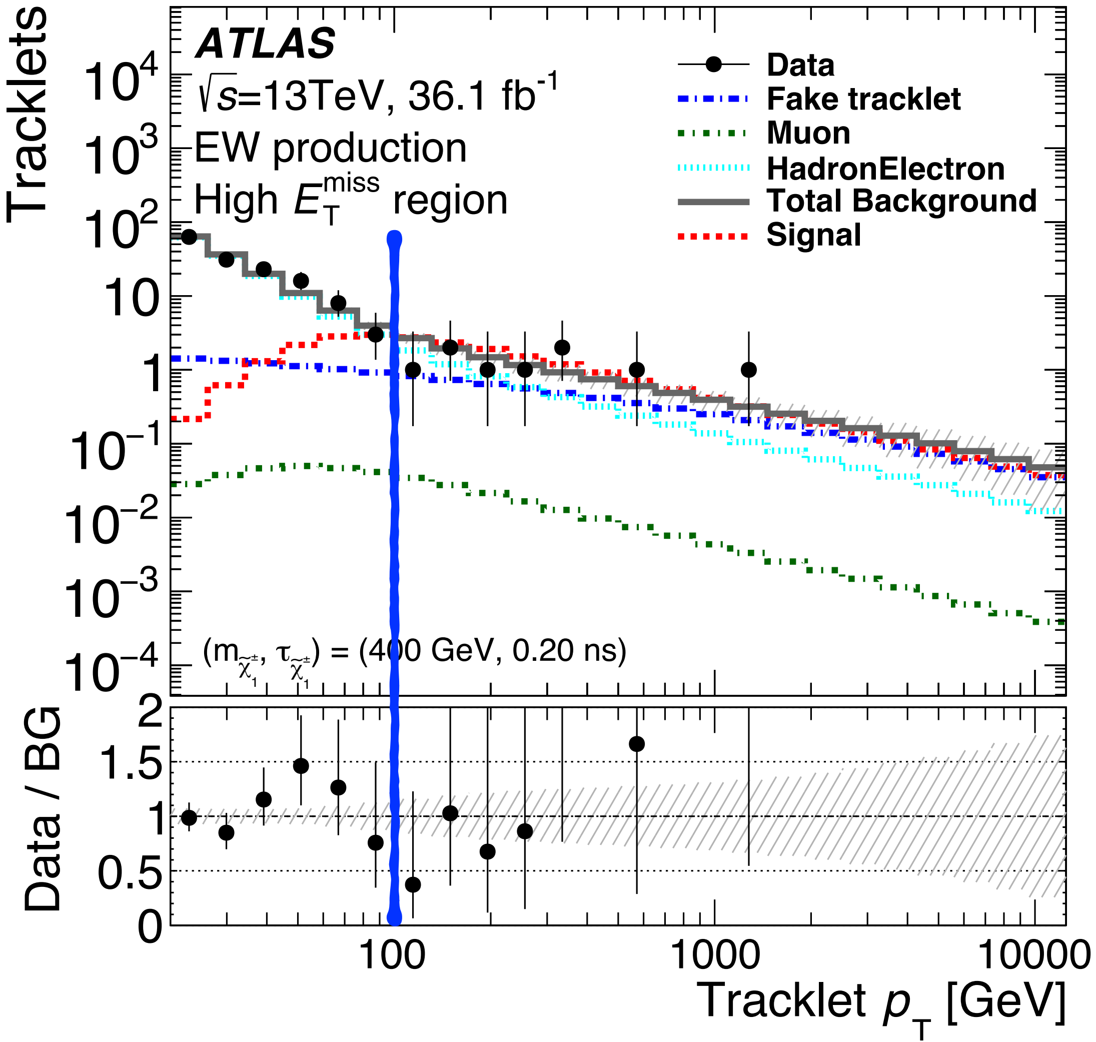

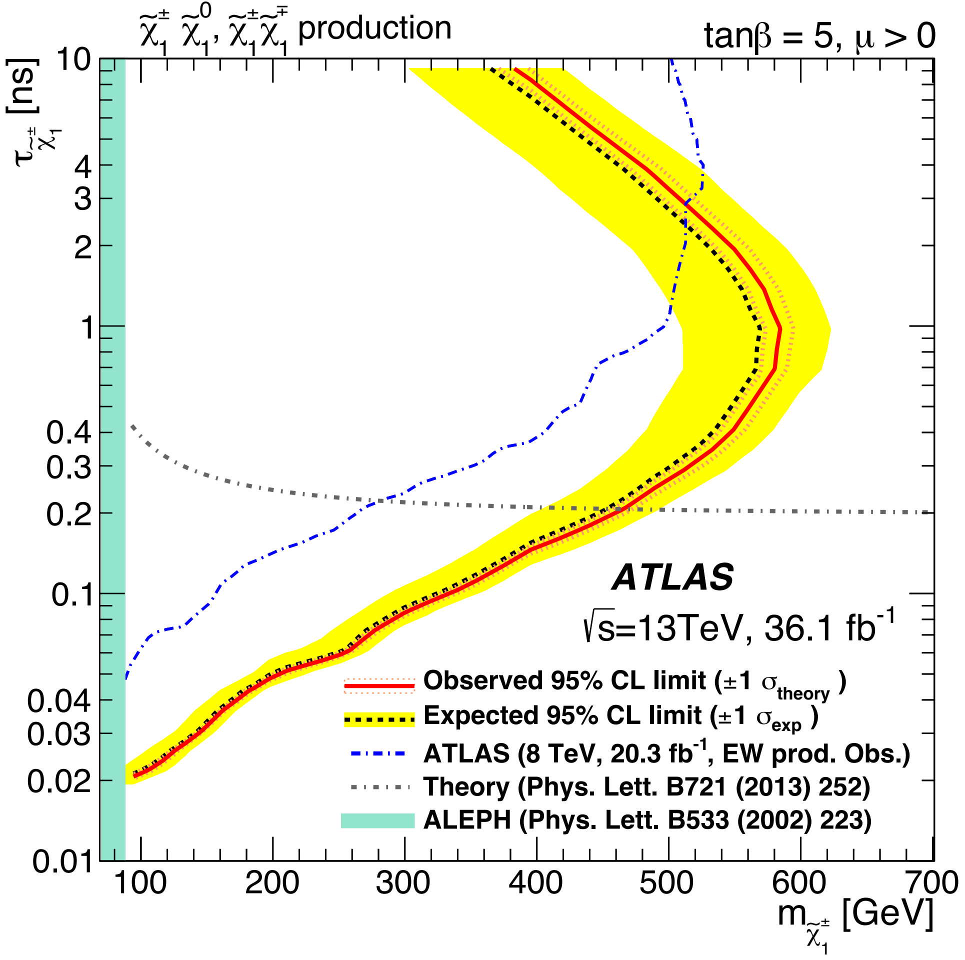

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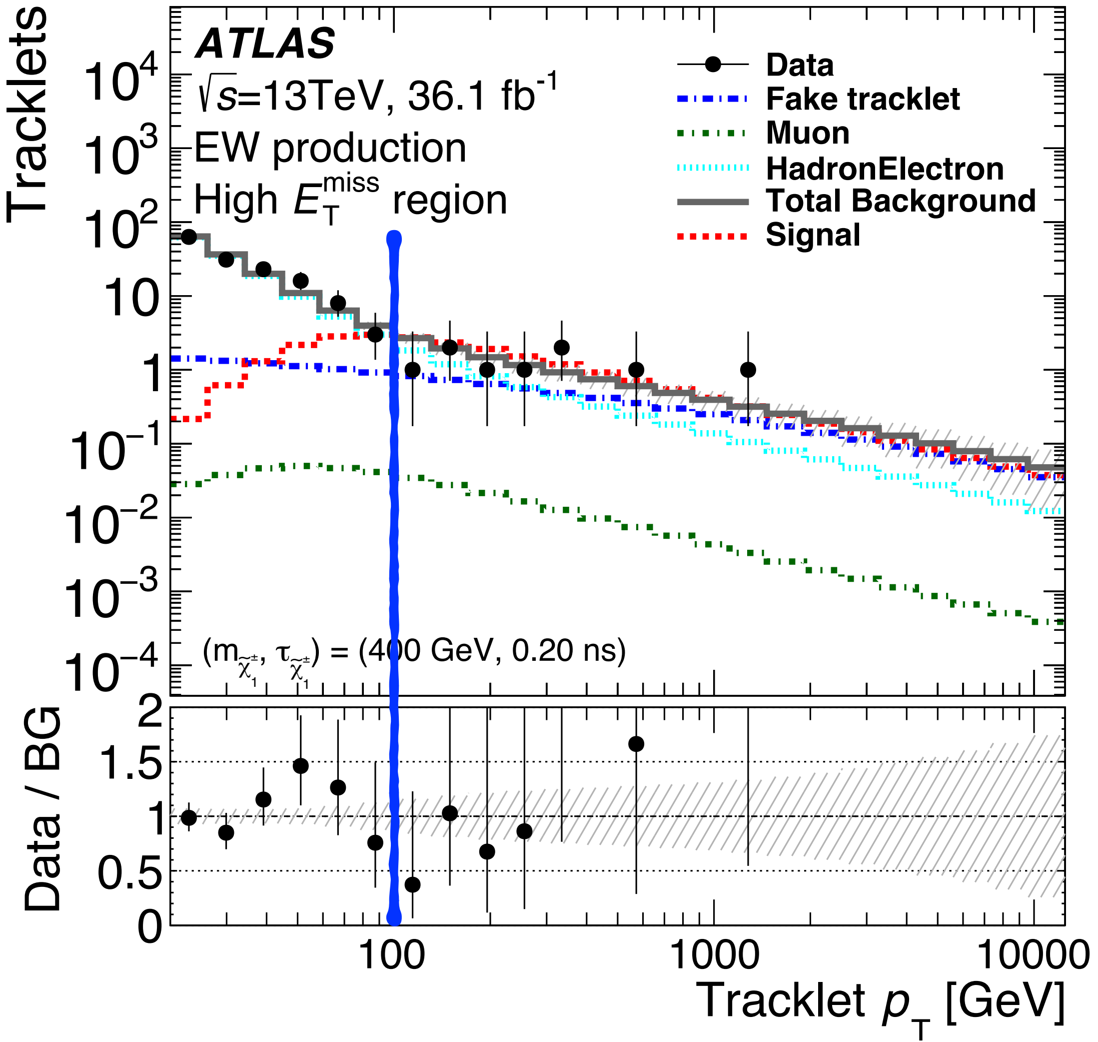
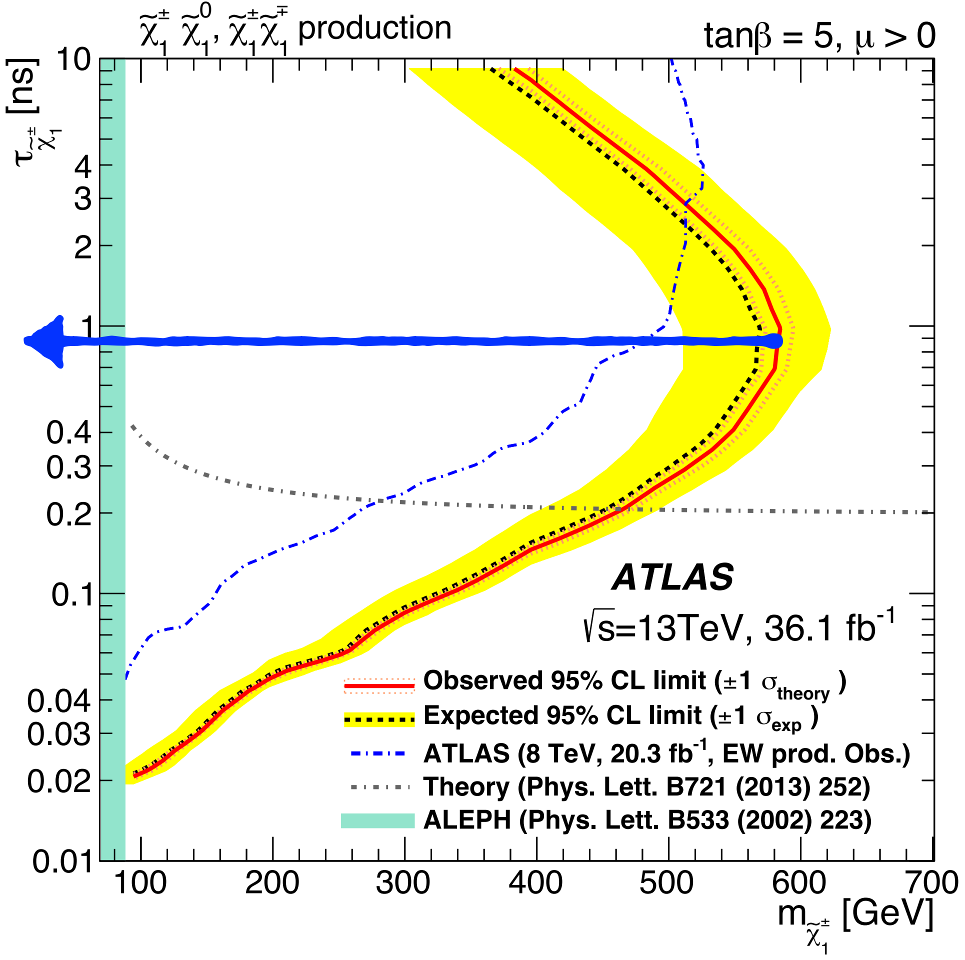
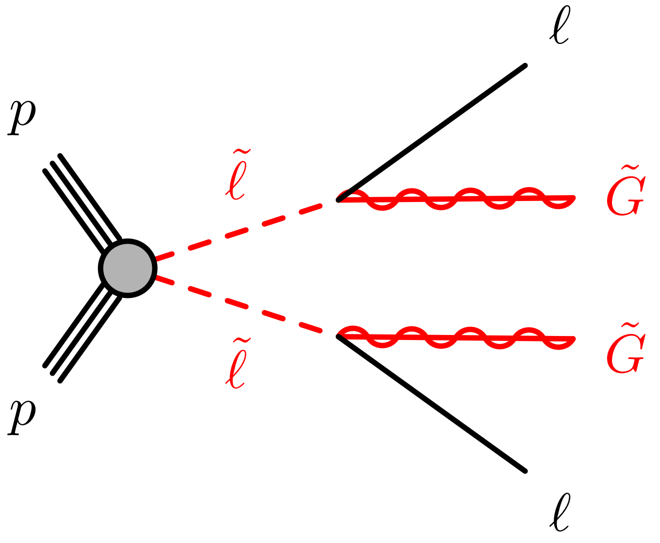


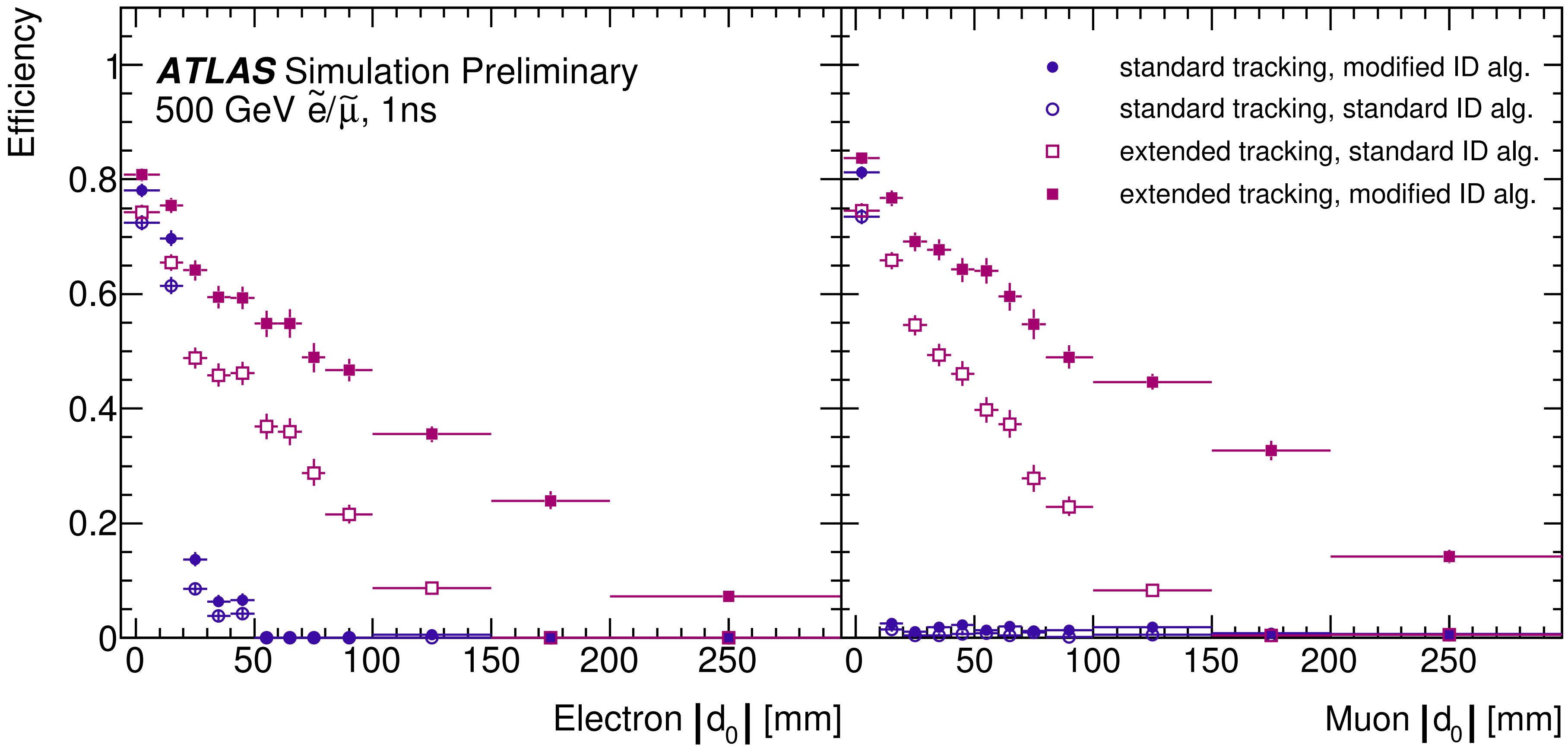


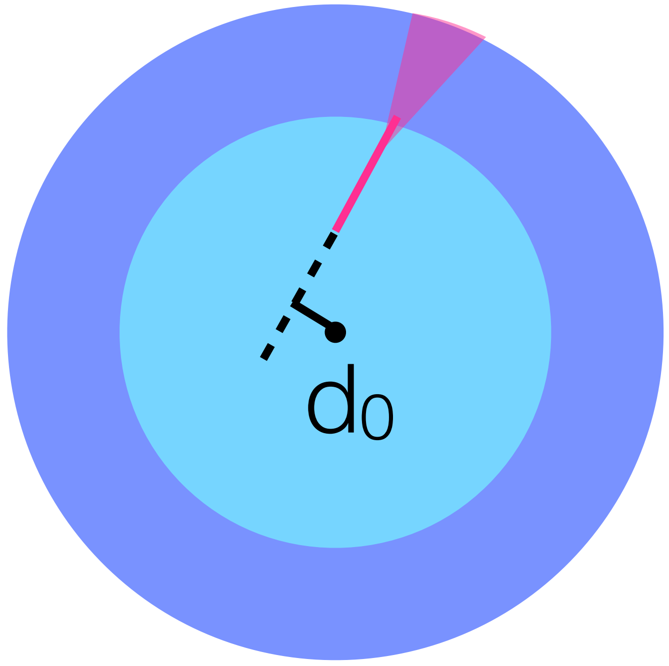
Indirect detection example: displaced leptons

New!
Public last
week for ICPPA

- Search for two light leptons (3 SRs: ee, μμ, eμ) not originating from the collision point
- Requires special “large radius” tracking for displaced objects, customised electron and muon identification



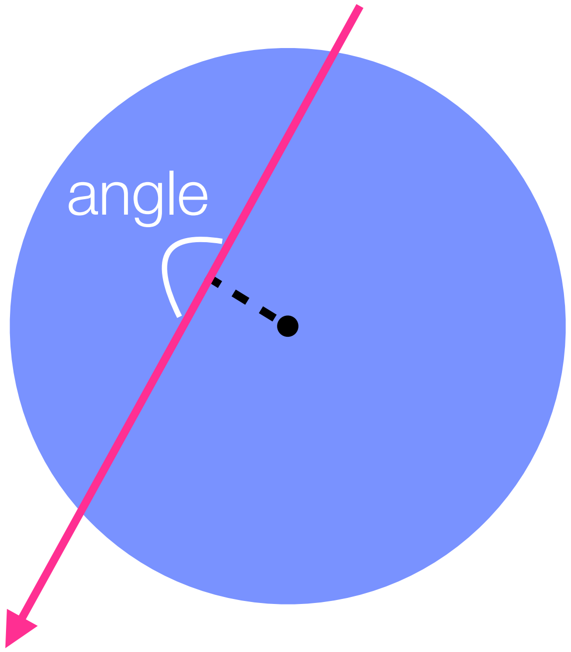




Backgrounds to displaced leptons

Main backgrounds

- Cosmic ray muons



1) Remove:

Any muon back-to-back with another muon/muon spectrometer hits

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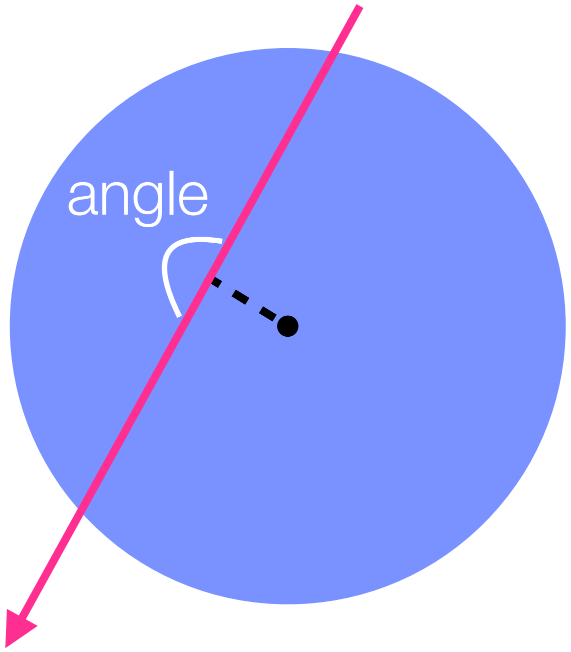

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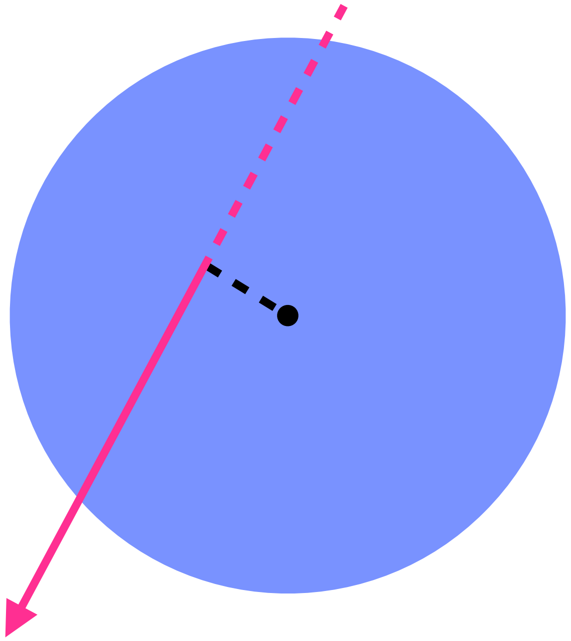
Any muon back-to-back with another muon/muon spectrometer hits

Background estimation

- μμ: extrapolate from cases where cosmic muons correctly tagged

Measure probability of tagging each half of cosmic muon

Apply to 1-tagged control sample to estimate SR events



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- Cosmic ray muons
- “Fake” electrons: track mis-associated to calorimeter energy deposit
- Heavy-flavour decays

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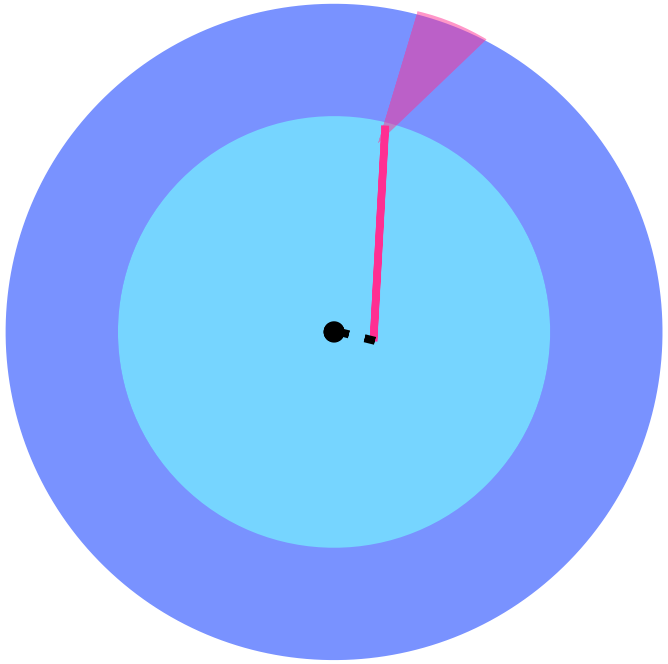
All leptons must be isolated and of good quality (track/calo agreement, good track, …)



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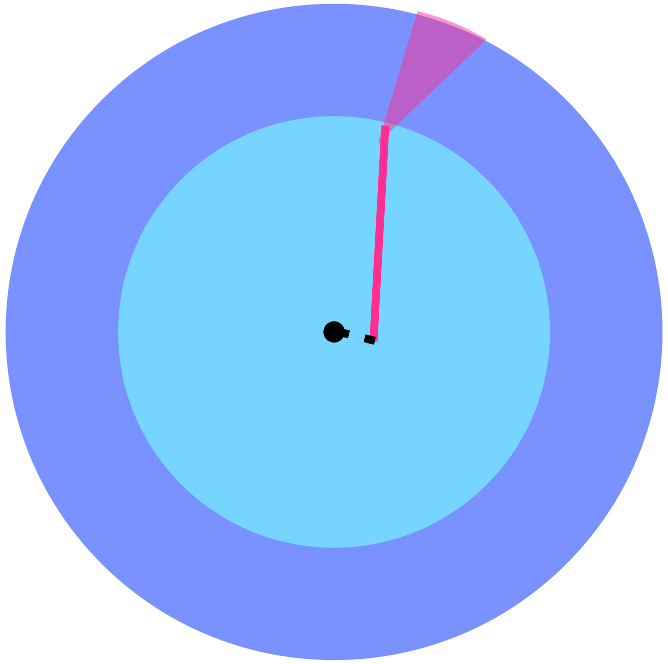

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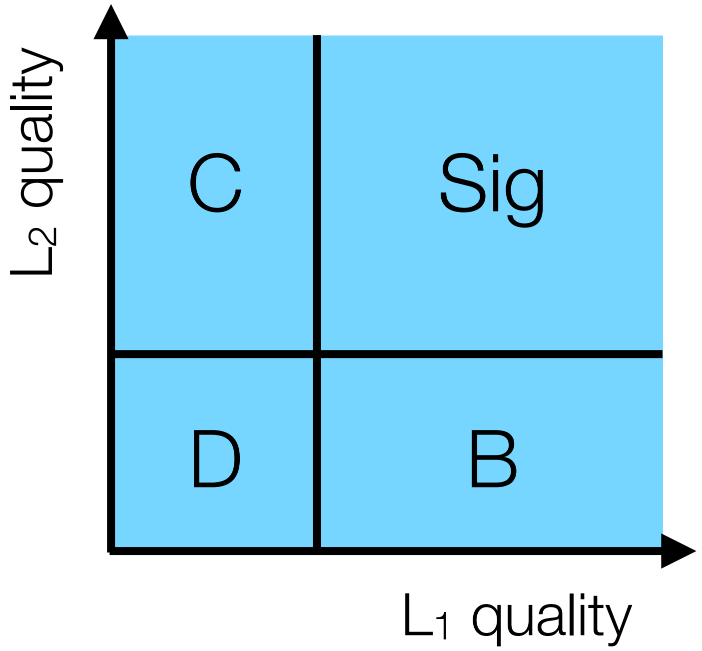
- ee, eμ: extrapolate from low to high lepton quality



2) Estimate:

Quality of two leptons independent.

$N_{sig} = N_B * N_C / N_D$

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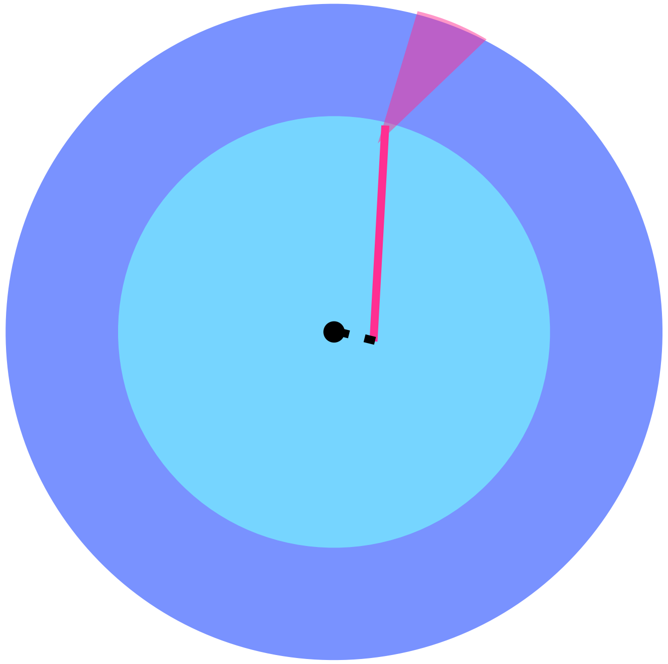

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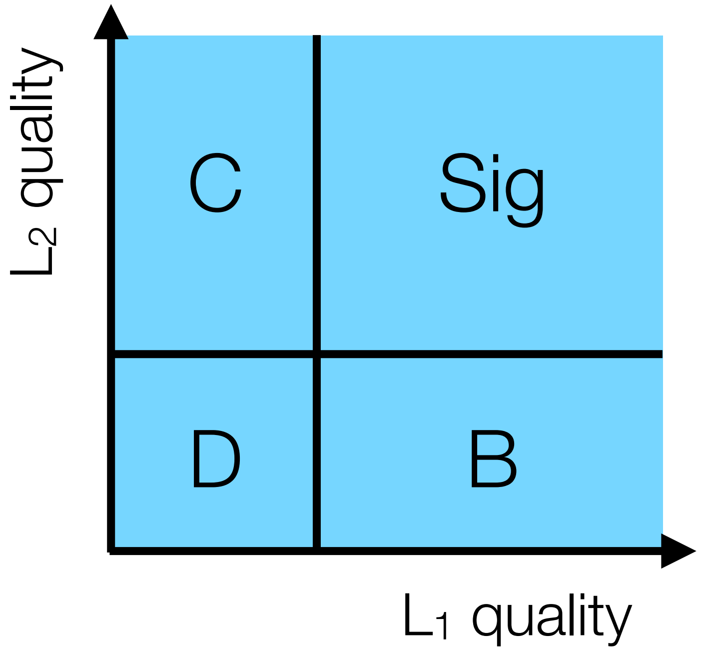

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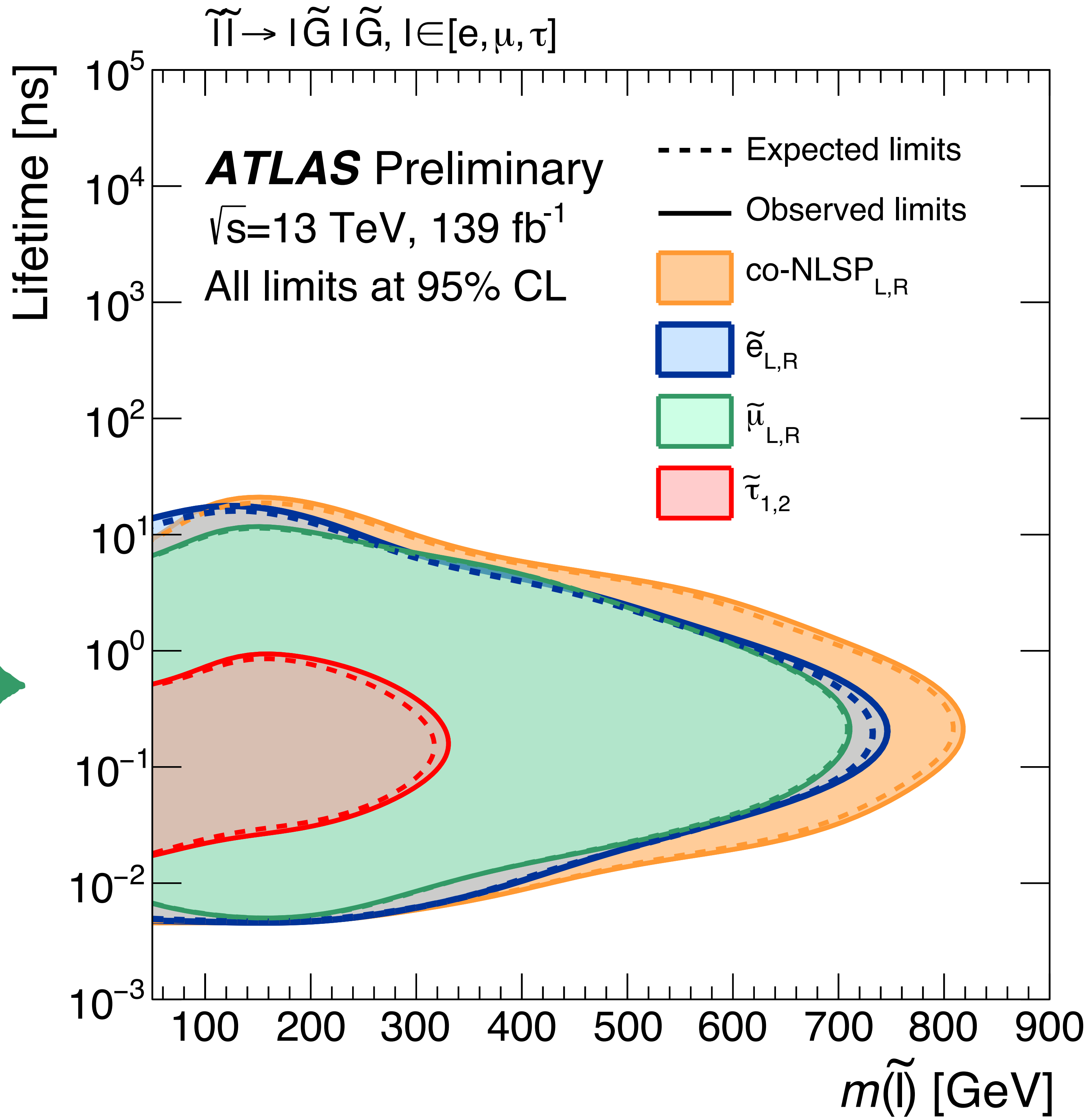
Results from displaced lepton search

Region	SR-ee	SR-$\mu\mu$	SR-$e\mu$
Fake + Heavy-Flavor	0.46 ± 0.10	–	$0.007^{+0.019}_{-0.007}$
Cosmics	–	$0.11^{+0.20}_{-0.11}$	–
Expected Background	0.46 ± 0.10	$0.11^{+0.20}_{-0.11}$	$0.007^{+0.019}_{-0.007}$
Observed events	0	0	0

Model-independent upper limits: ~3 events

Model-dependent limits: staus and co-NLSP sleptons

LEP limits (previous best) are up to ~ 65-90 GeV



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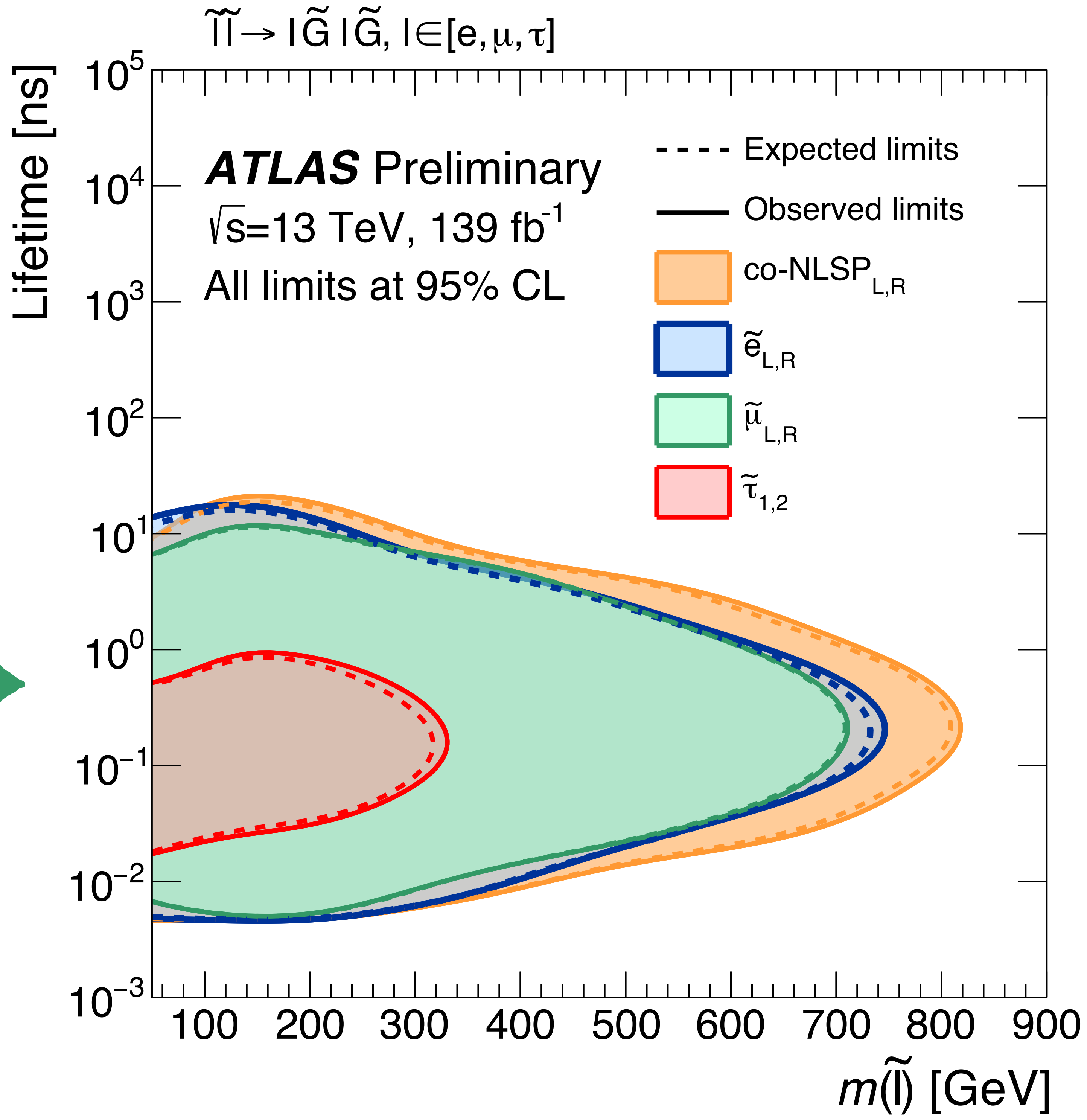

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For more details, ask your new postdoc Lesya Horyn!

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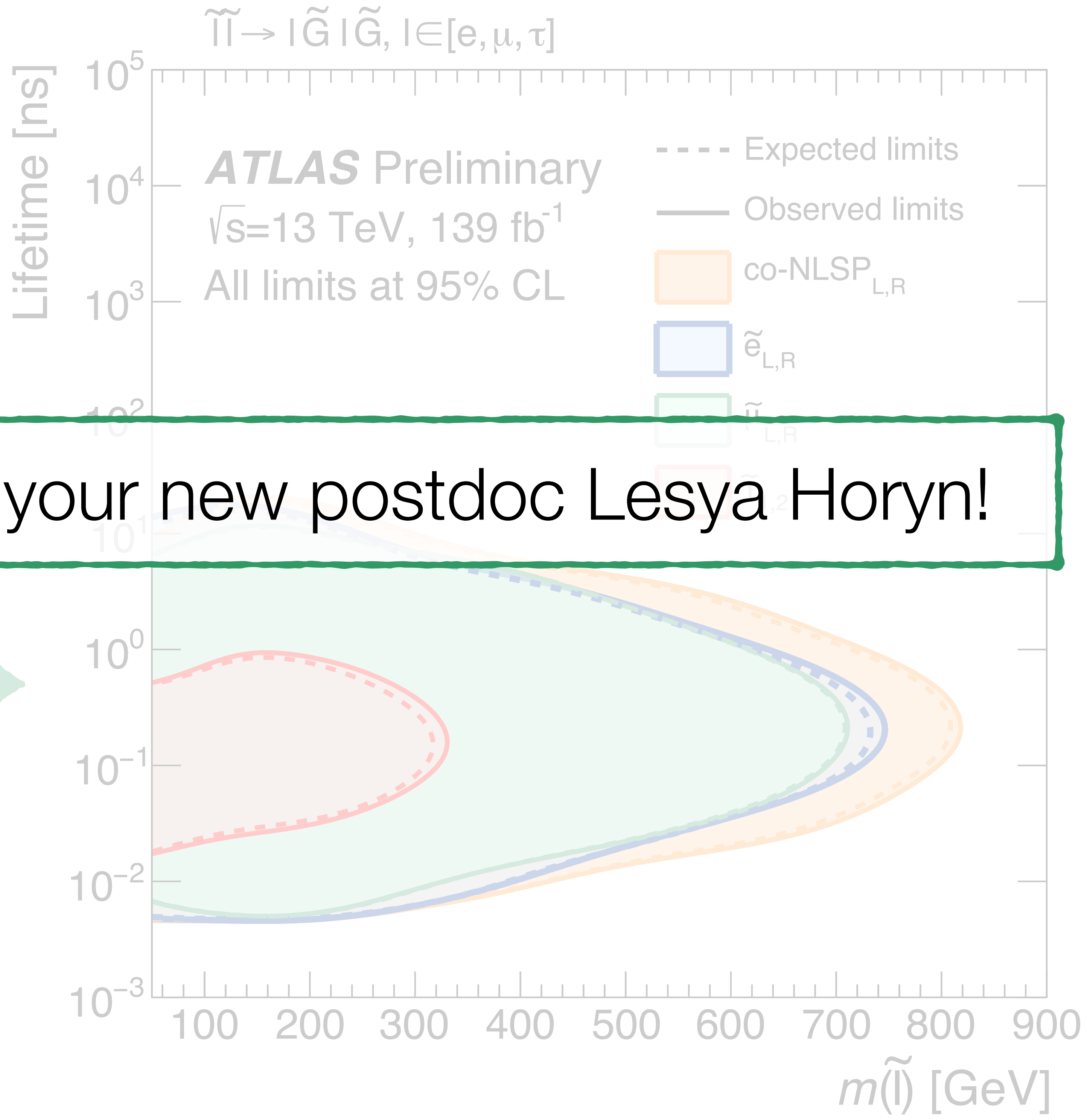


LEP limits (previous best) are up to ~ 65-90 GeV

All new at the LHC!

Why LLP searches are the right target for Run 3

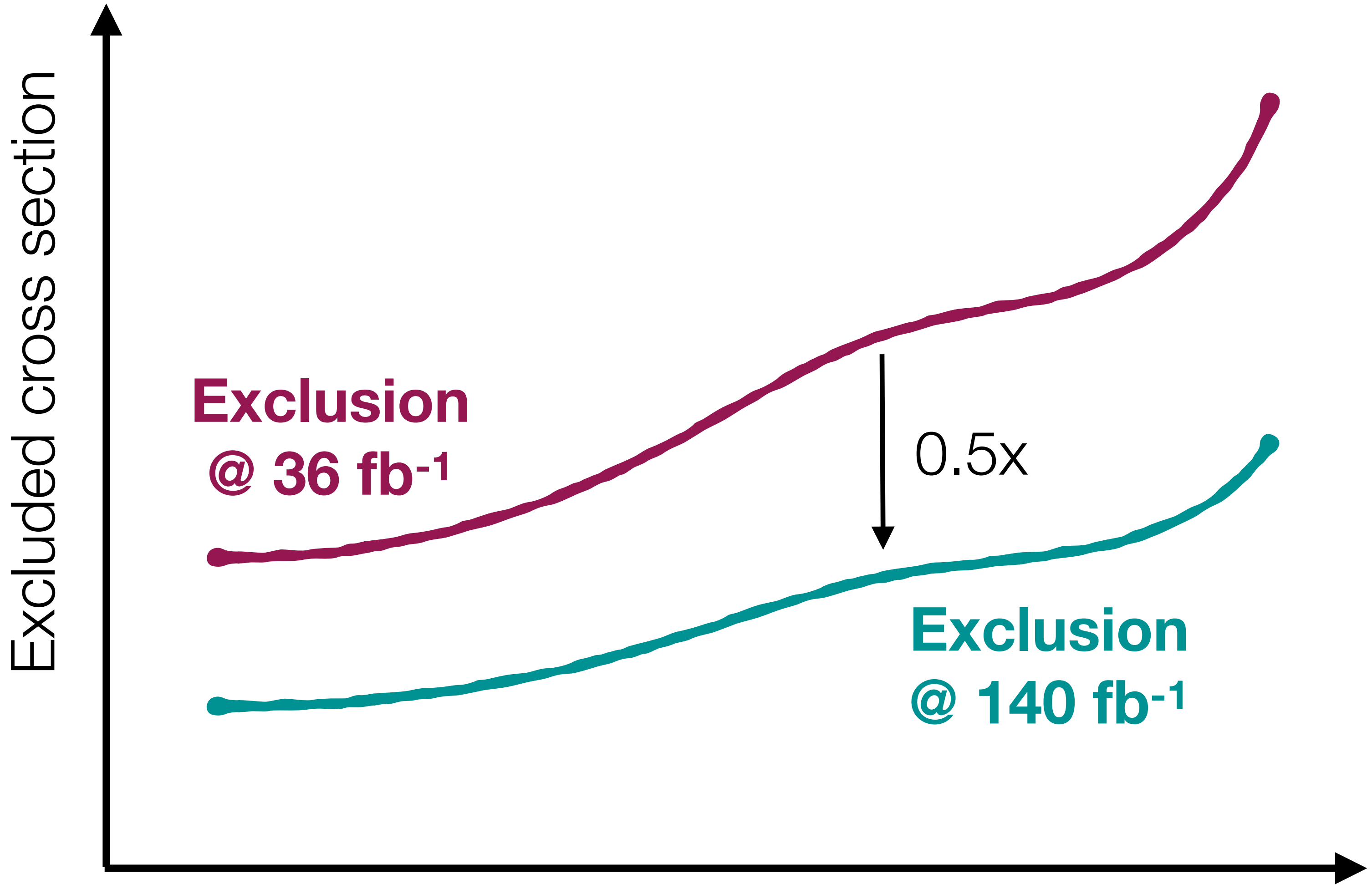
- When we decide to do any search, must consider a couple factors:
- We should look **somewhere important**
  - **Motivated by theory**: we already know LLPs are strongly motivated in many BSM models
- We should look **somewhere effective**
  - Look for targets which will benefit most from **increasing datasets**
  - Find **opportunities** where the LHC dataset and our technical abilities give us the most power, so work invested will yield better results
  - Prioritise “**discovery potential**”!
  - LLPs are a great candidate for effectiveness as well

LLPs and increasing datasets

Rule of thumb: with **high backgrounds**, sensitivity $\mathcal{S} \approx s/\sqrt{b}$

$s, b \propto \mathcal{L}$, therefore $\mathcal{S} \propto \sqrt{\mathcal{L}}$

Need 4x the data to double the analysis reach!



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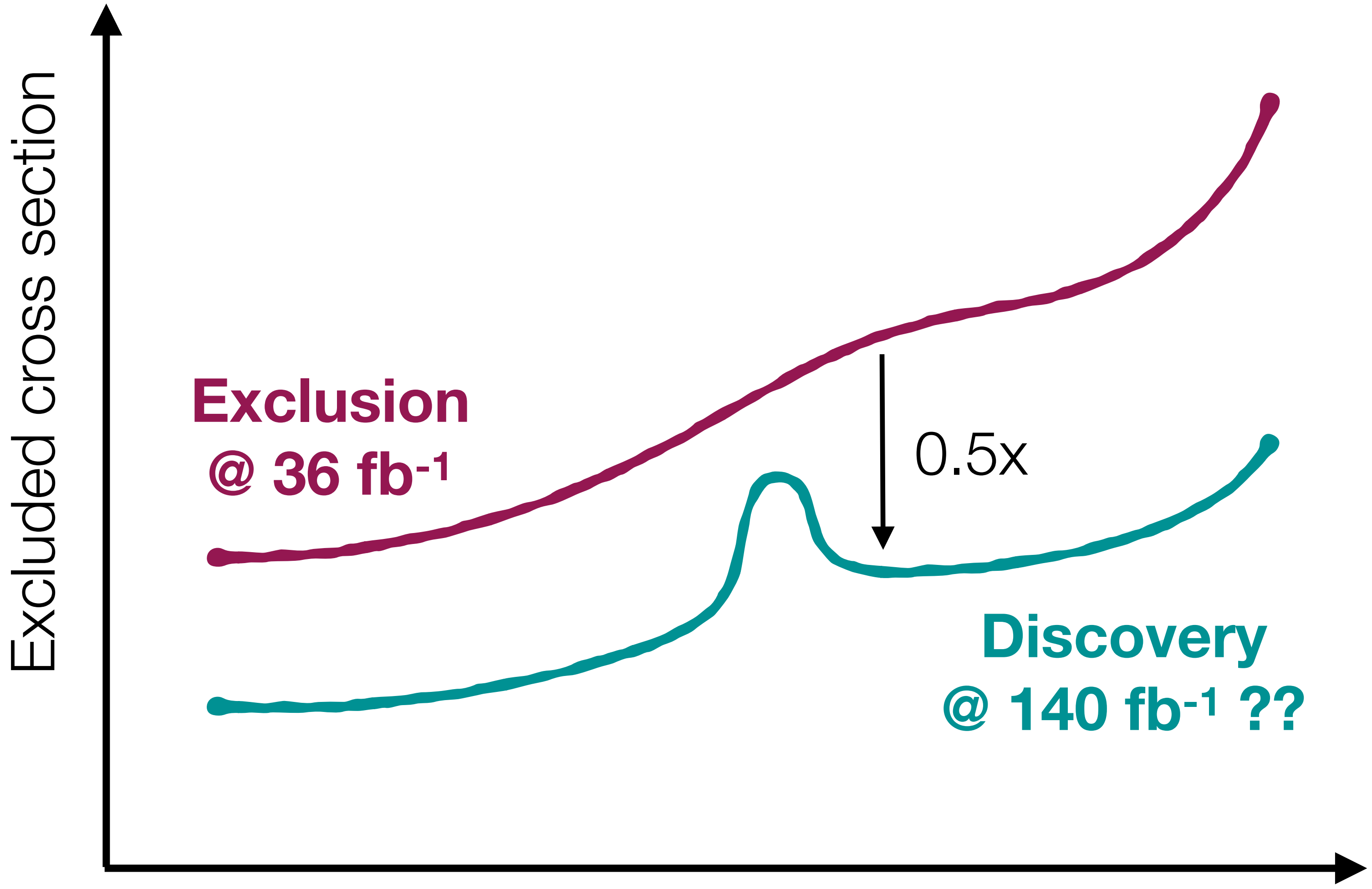

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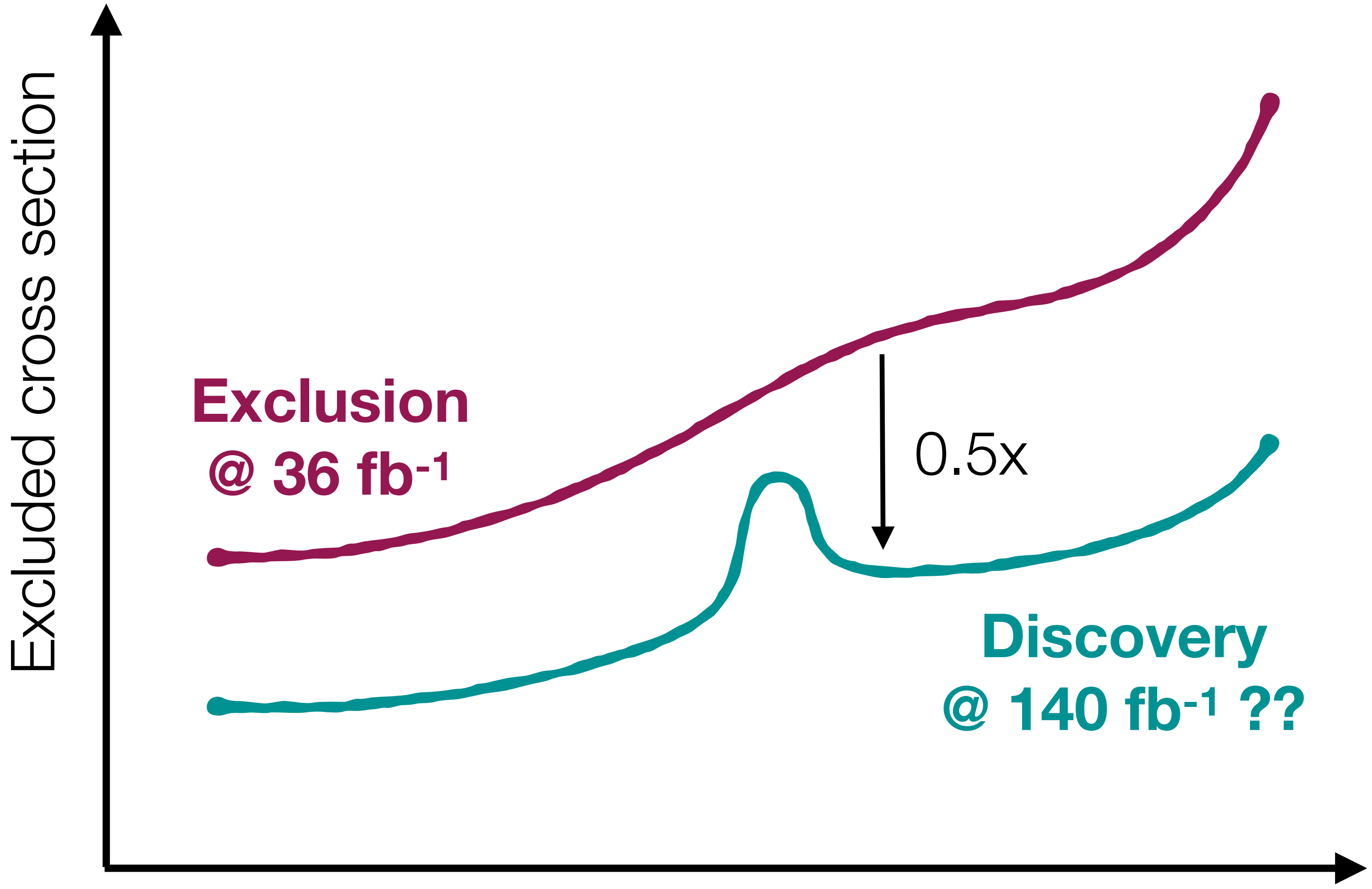


With < 2σ excess at 36 fb^{-1}

→ need 270 fb^{-1} for discovery potential

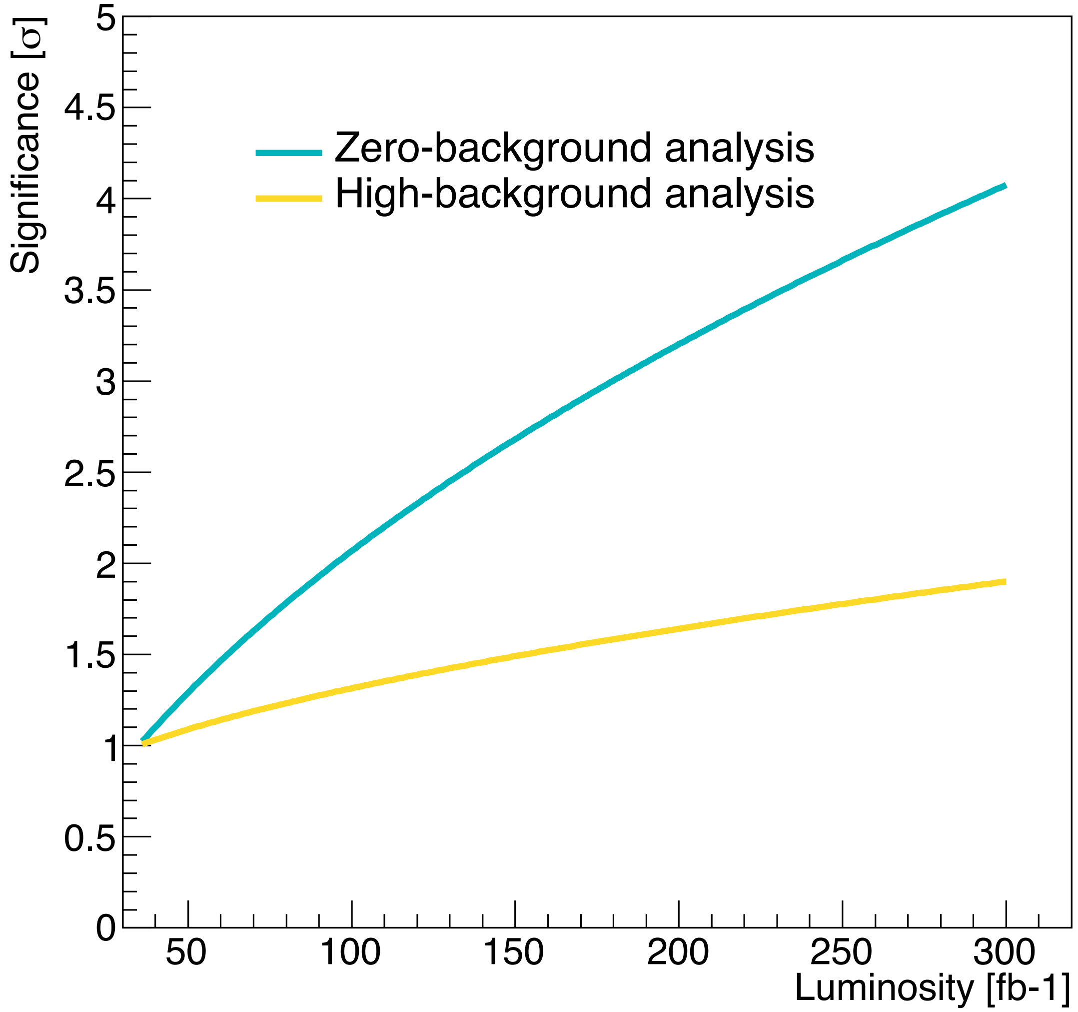
LLPs and increasing datasets

For LLP analyses, cuts can always be tuned to keep ~zero background events while keeping some signal acceptance

Upper limit on 0 events is ~3

Cross section limit is ~3/$\mathscr{L}$, therefore $\mathscr{S} \propto \mathscr{L}$

b = 0.1
δb = 0.2
s = 1



b = 100
δb = $\sqrt{b}$
s = 8

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LLP analyses **benefit most** from increasing luminosity!

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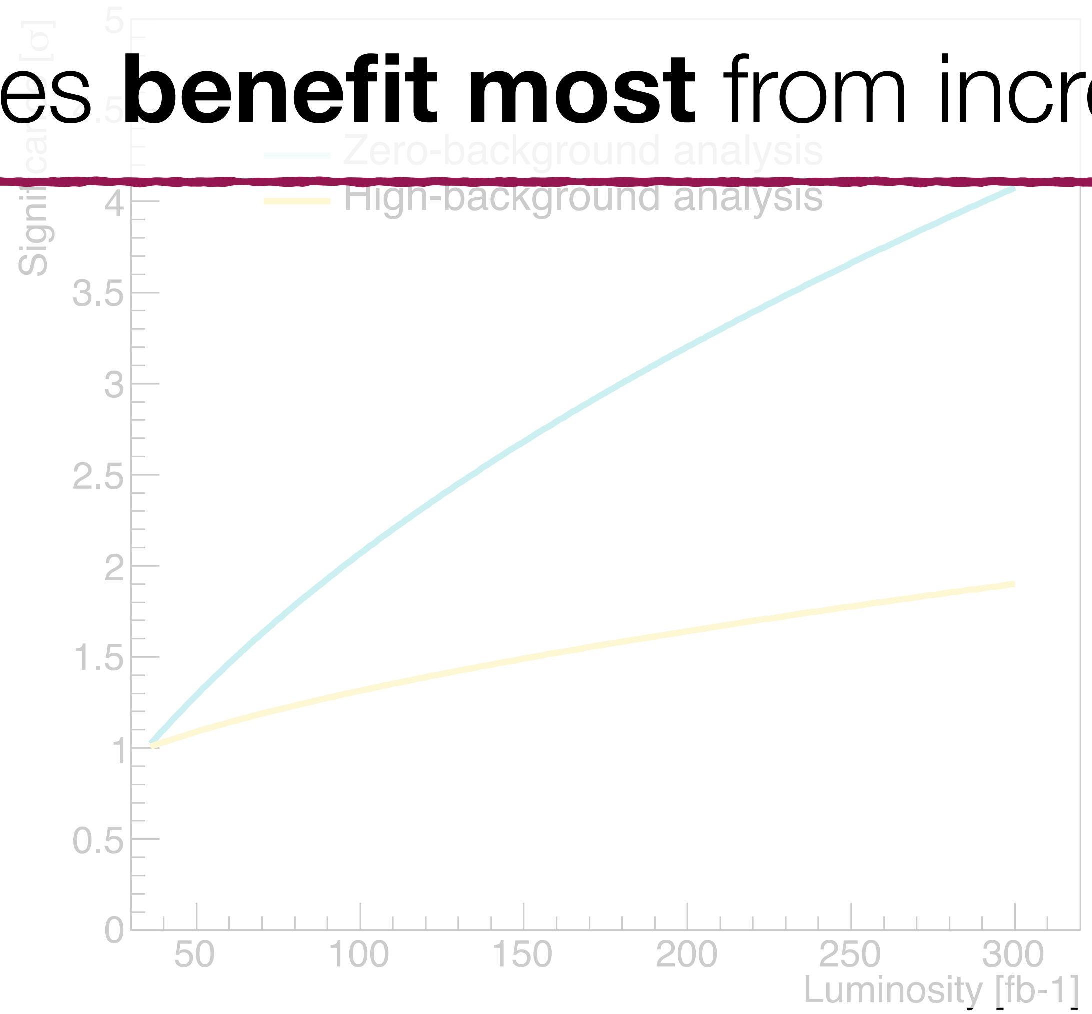

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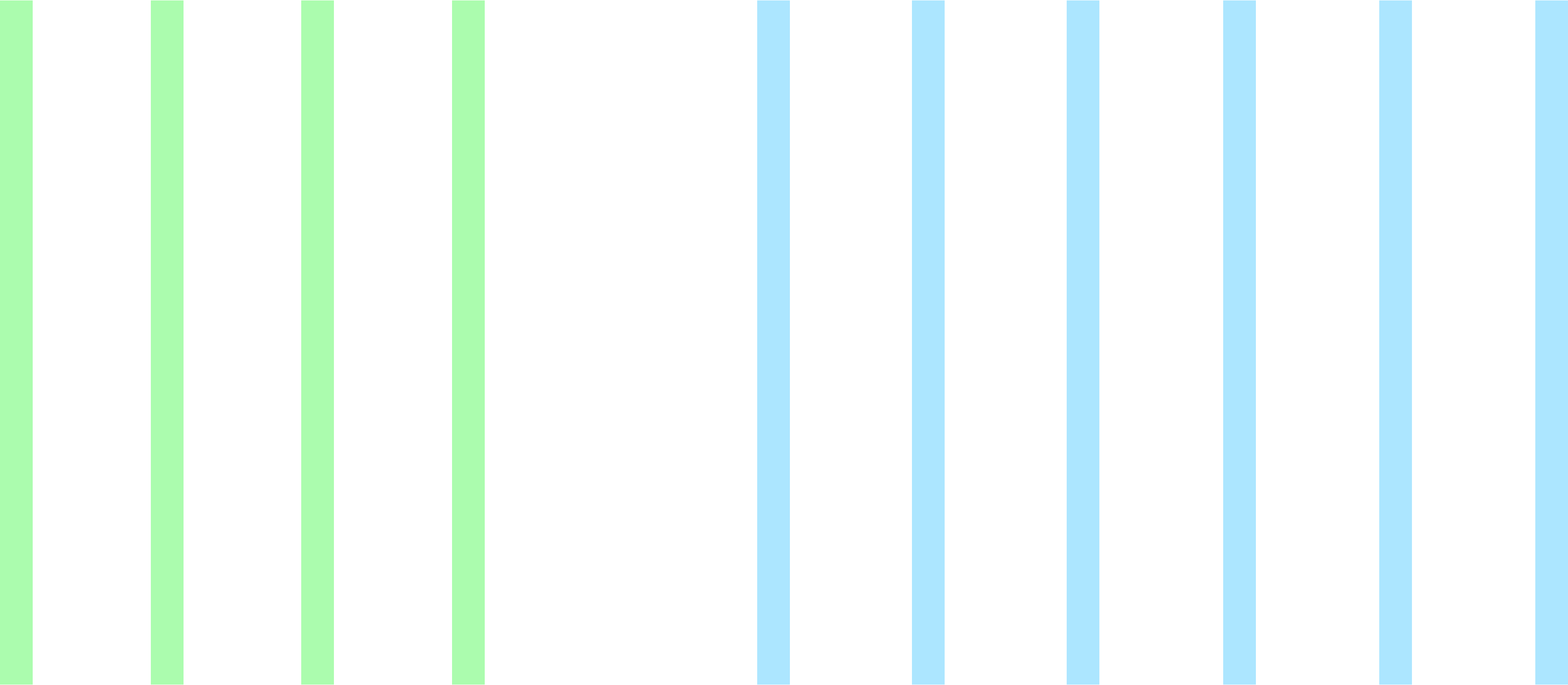
New triggers to extend ATLAS LLP search reach

Run 2

- Tracking at high-level trigger only for “standard” tracks and in regions of interest

Run 3

- Extending HLT tracking to full event in all jet and MET signatures
- Introducing large-radius tracking in specific regions of interest (in progress)



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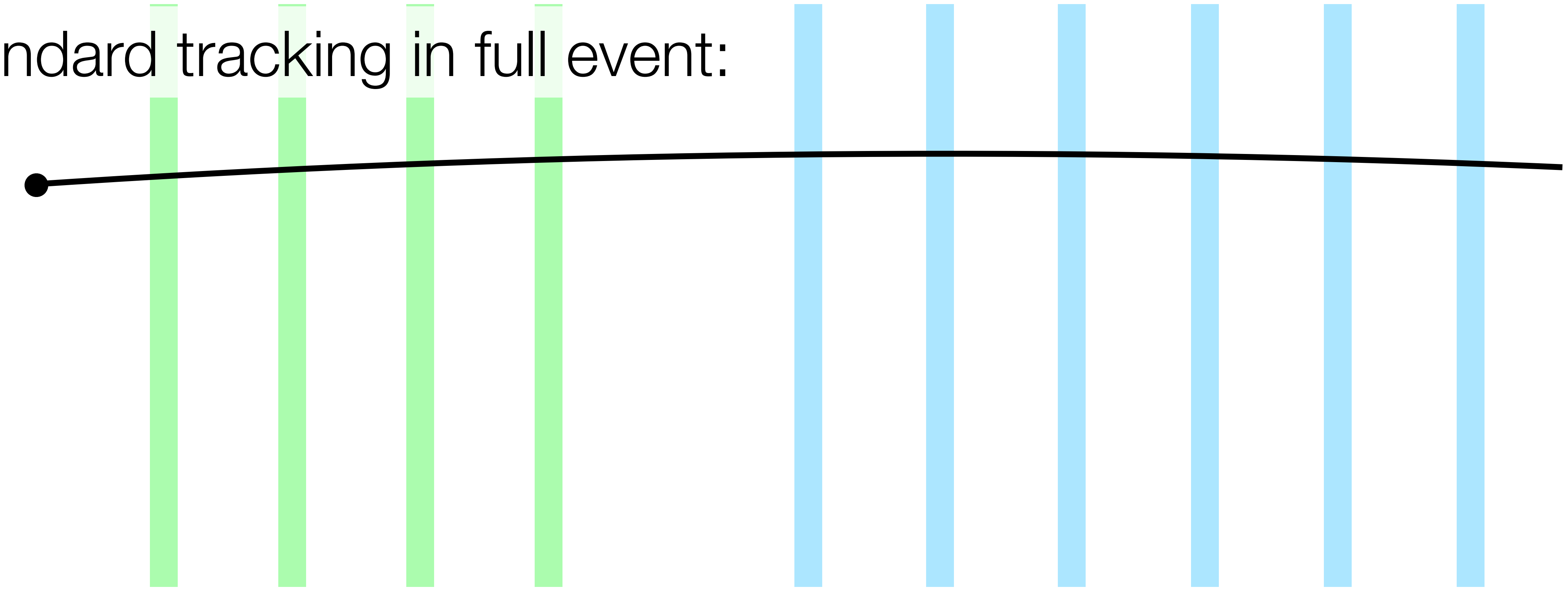

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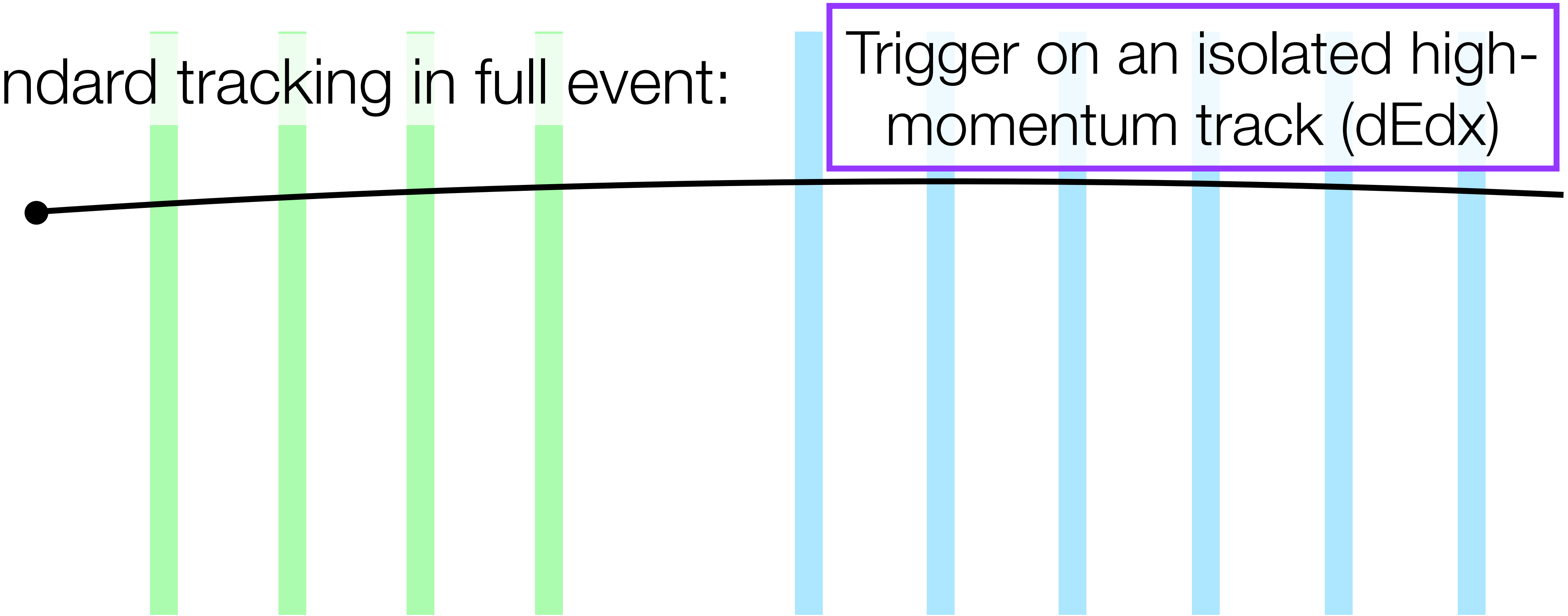

With standard tracking in full event:

Trigger on an isolated high-momentum track (dEdx)

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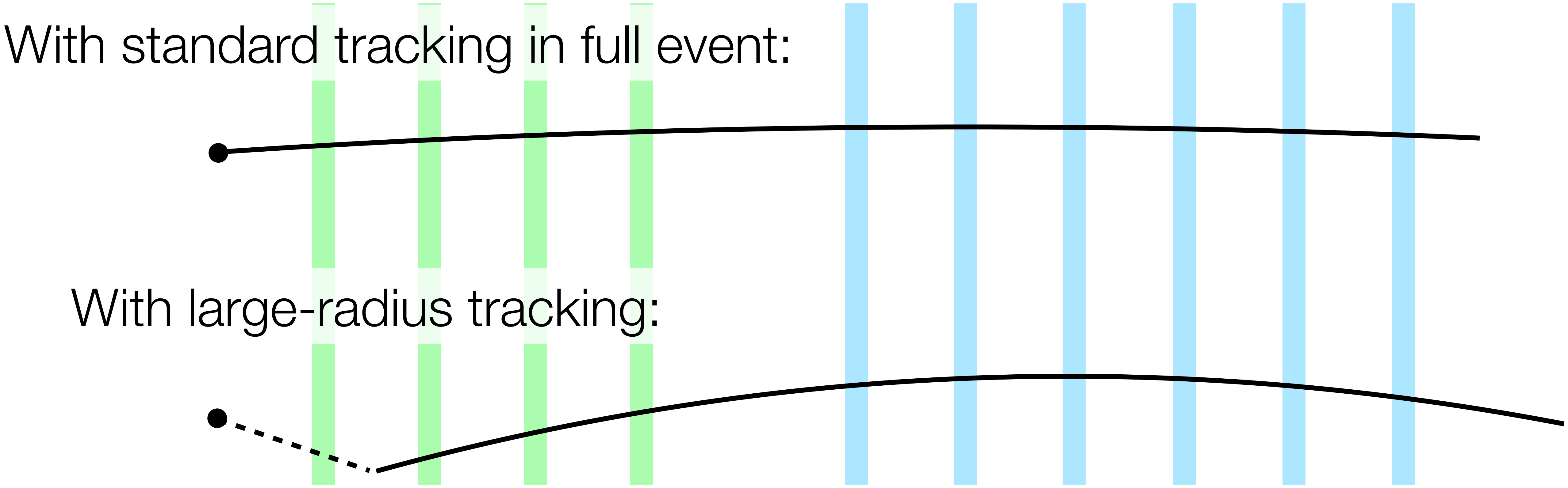

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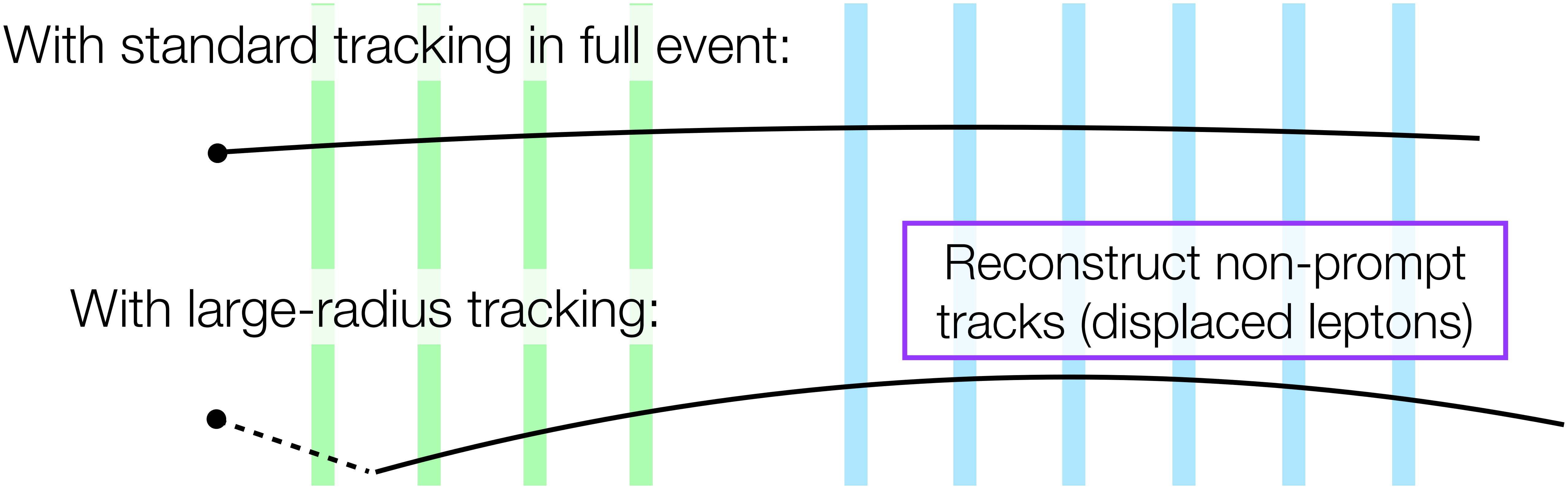

With standard tracking in full event:

With large-radius tracking:

Reconstruct non-prompt tracks (displaced leptons)

New triggers to extend ATLAS LLP search reach

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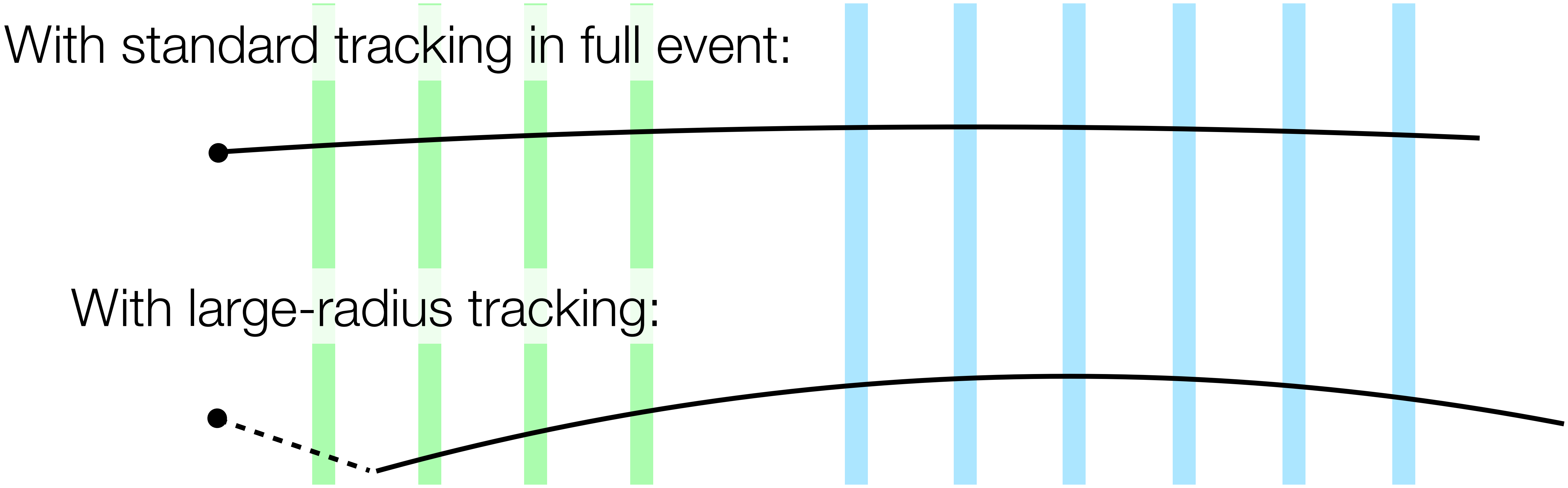
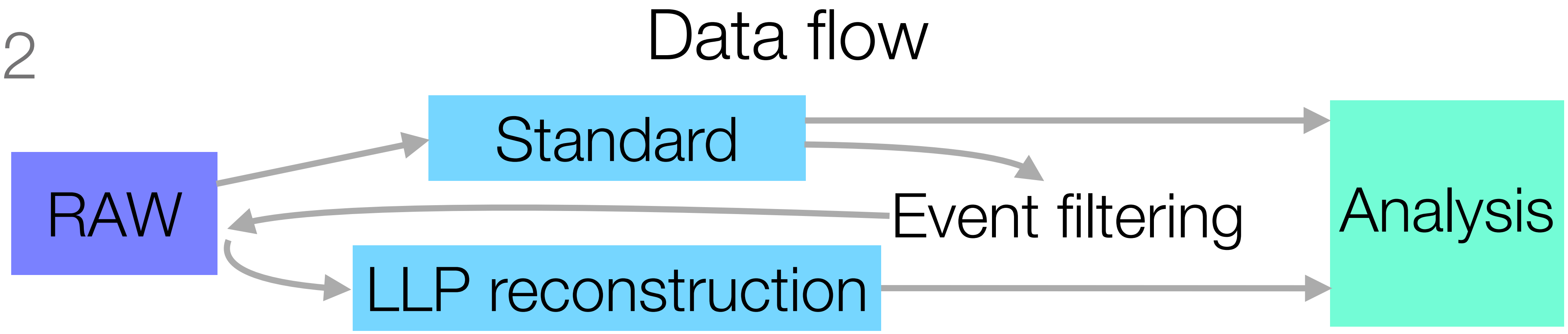


With standard tracking in full event:

With large-radius tracking:

Better data flow

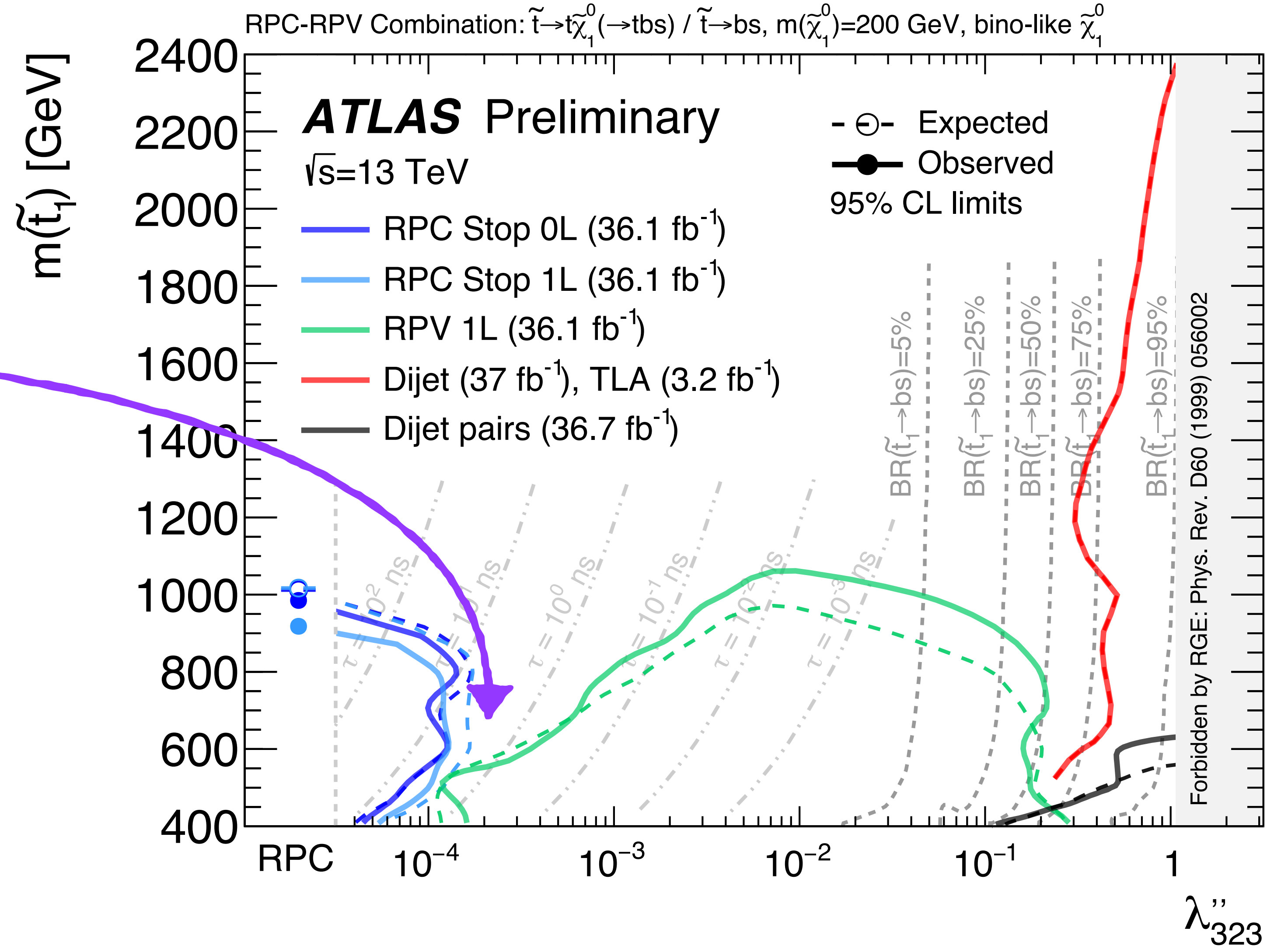
Run 2



- Due to size of large-radius tracking output, was impossible to run on all events
- Filtering step used information in standard reconstruction to pick events which would be processed with LRT - essentially acts as a second trigger with signal efficiency < 1
- Ongoing work has reduced LRT output size so that no filters needed in Run 3
- Result: **increased acceptance for every analysis** using large-radius tracking; corresponding sensitivity increase

Reinterpretations

This should be
covered by displaced
vertex+jets analysis



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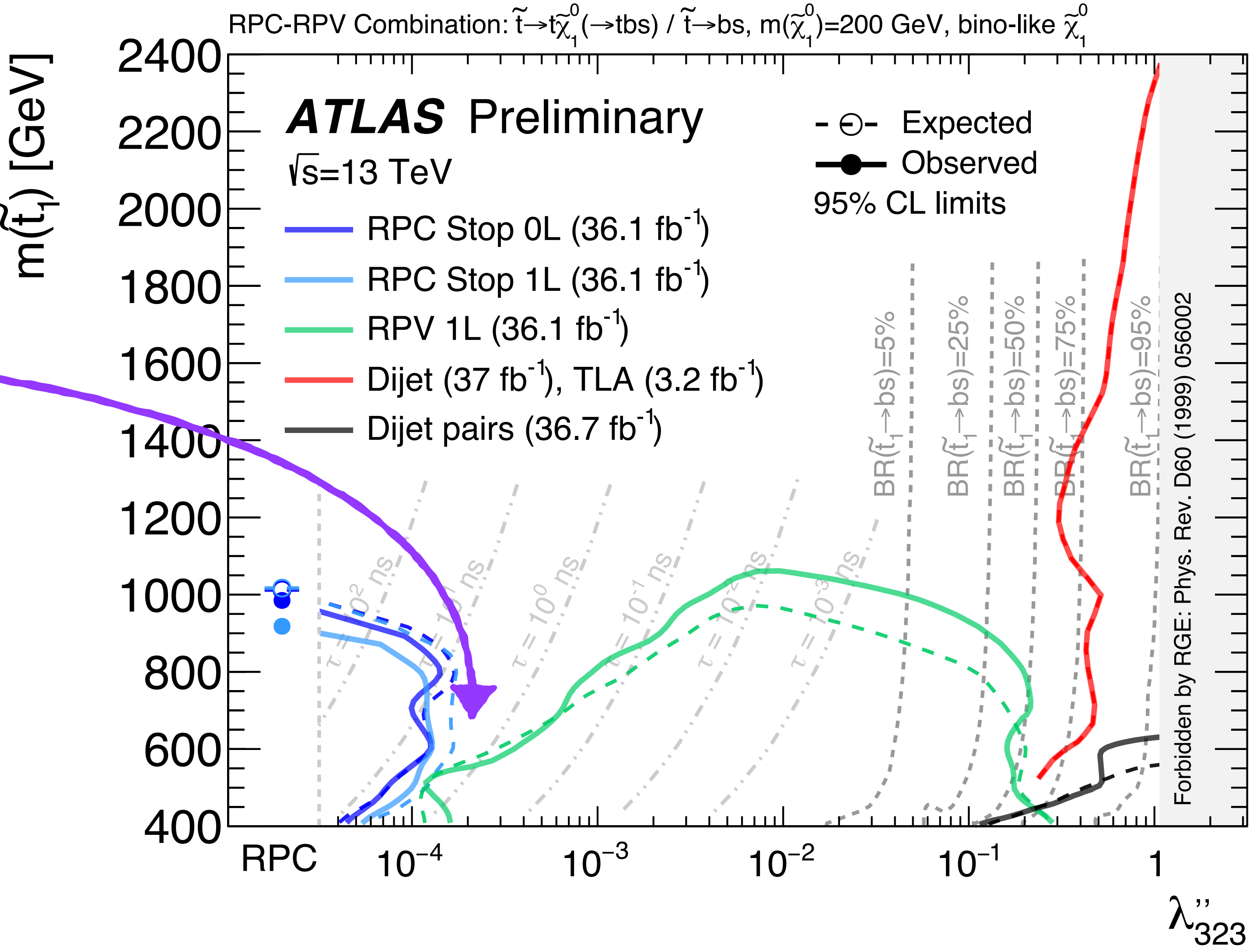

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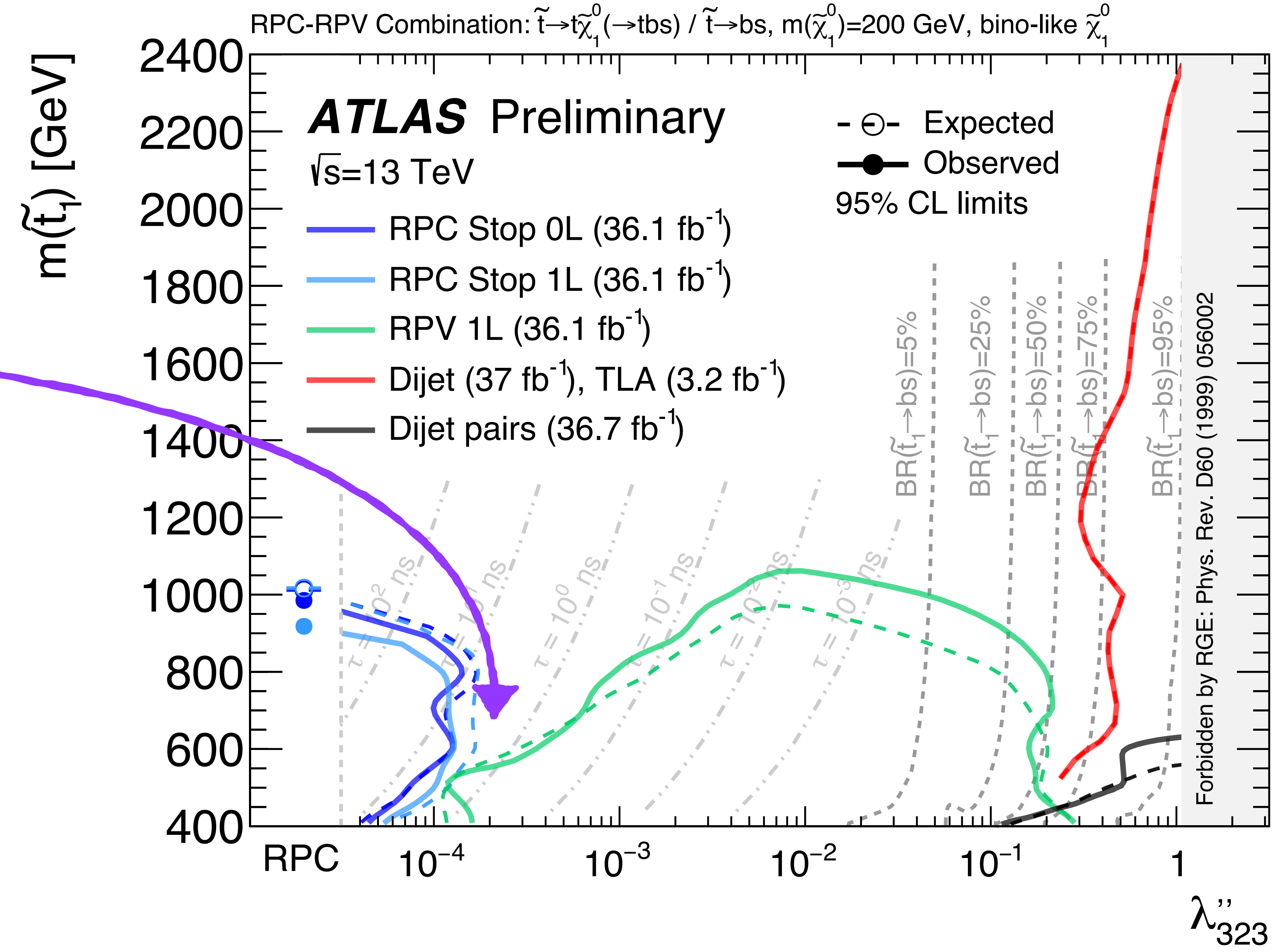


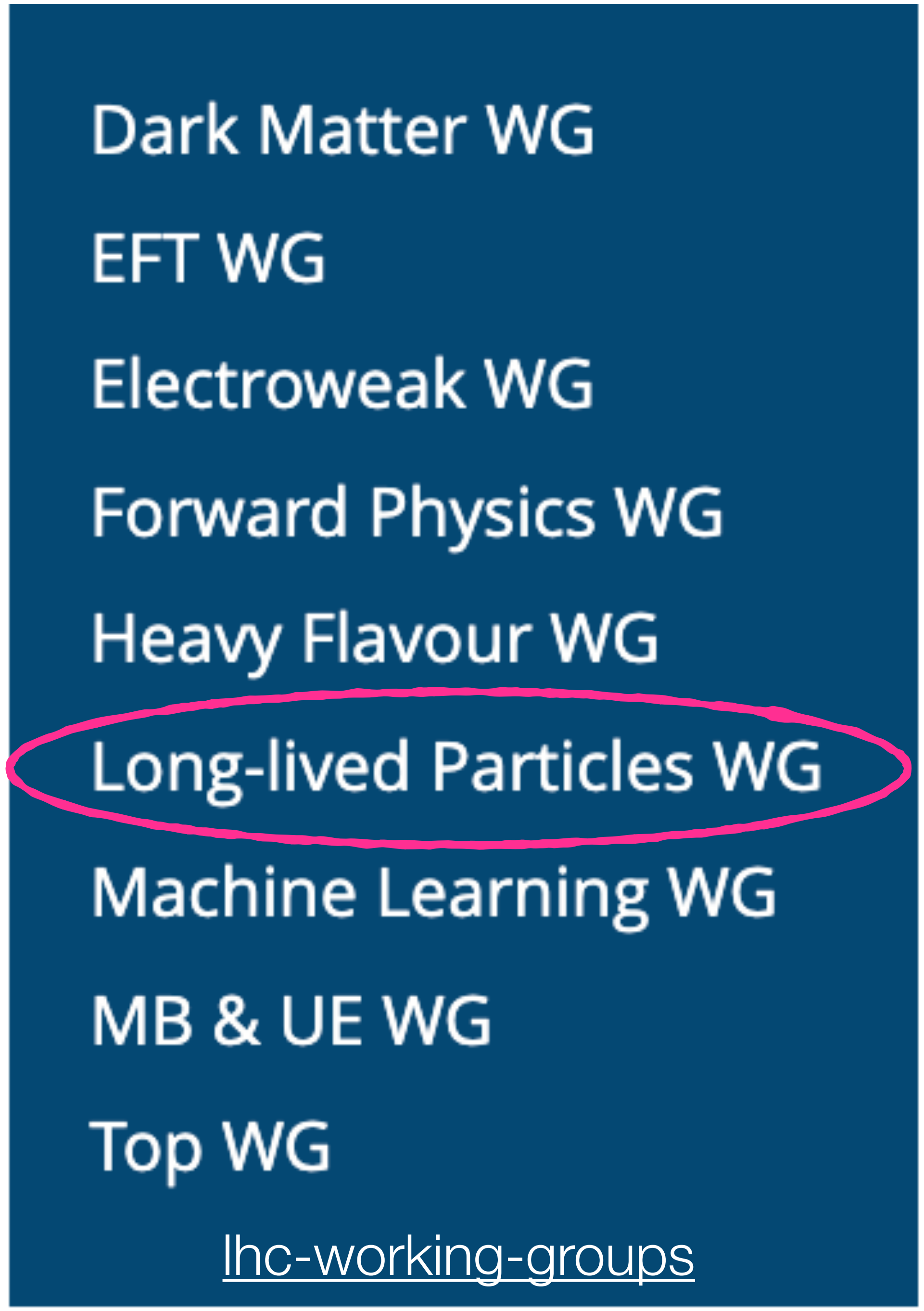
- Testing new interpretations for LLP searches can be tricky after the fact!

- This is one of our **key points for improvement**. Internally, new framework for code preservation allowing easy re-running within the collaboration

- What about for **external users**? Continually looking for improved ways to make our results useful - let us know any suggestions!

ATLAS + CMS (+ Dark matter + …)

- Newly established **LHC LLP working group** could give us a chance to solve problems together
    - Establish joint benchmarks and directions?
    - Sharing software/simulation/etc work?
    - Common guidelines for reinterpretation materials?



Dark Matter WG

EFT WG

Electroweak WG

Forward Physics WG

Heavy Flavour WG

Long-lived Particles WG

Machine Learning WG

MB & UE WG

Top WG

lhc-working-groups

ATLAS + CMS (+ Dark matter + …)

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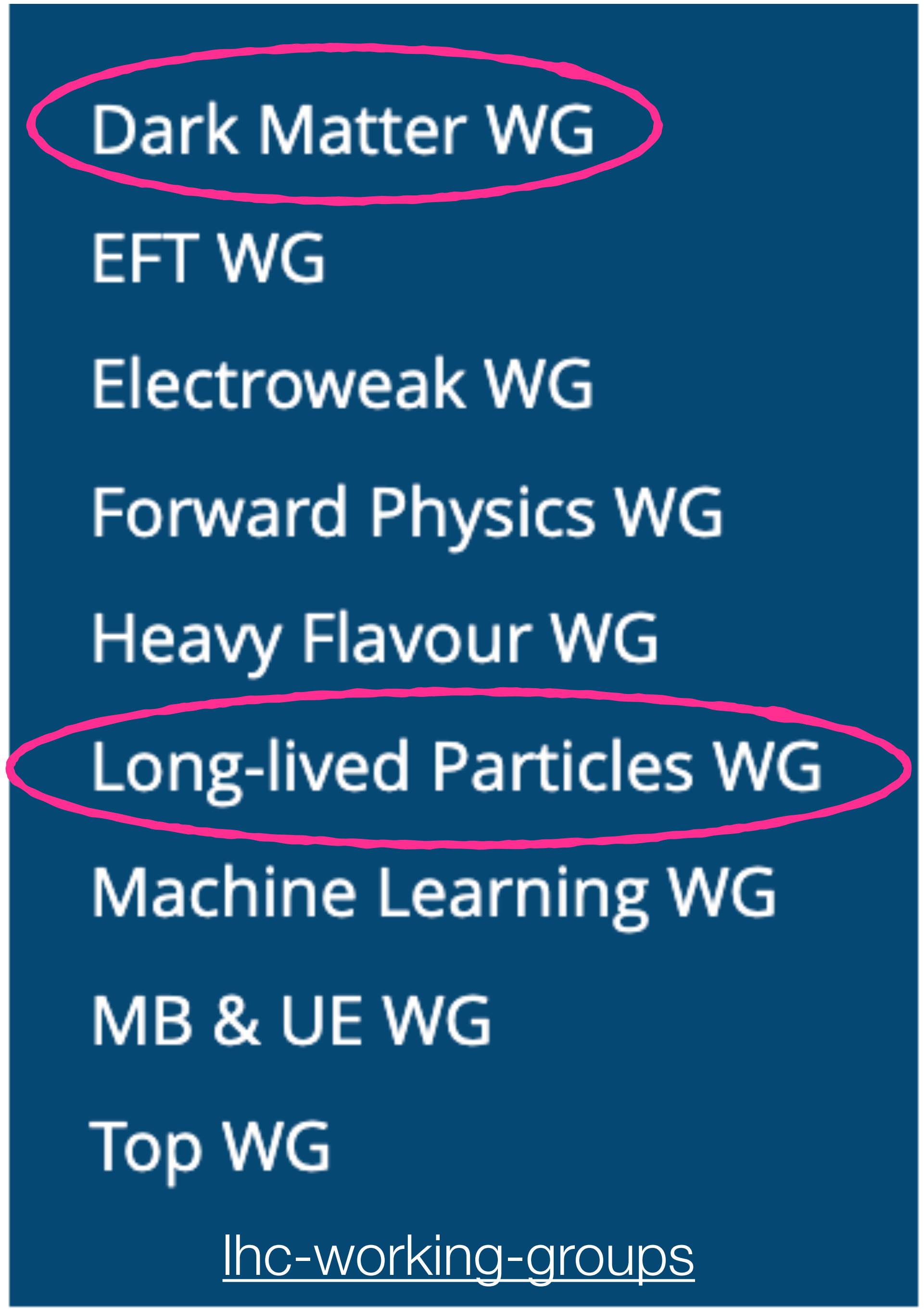

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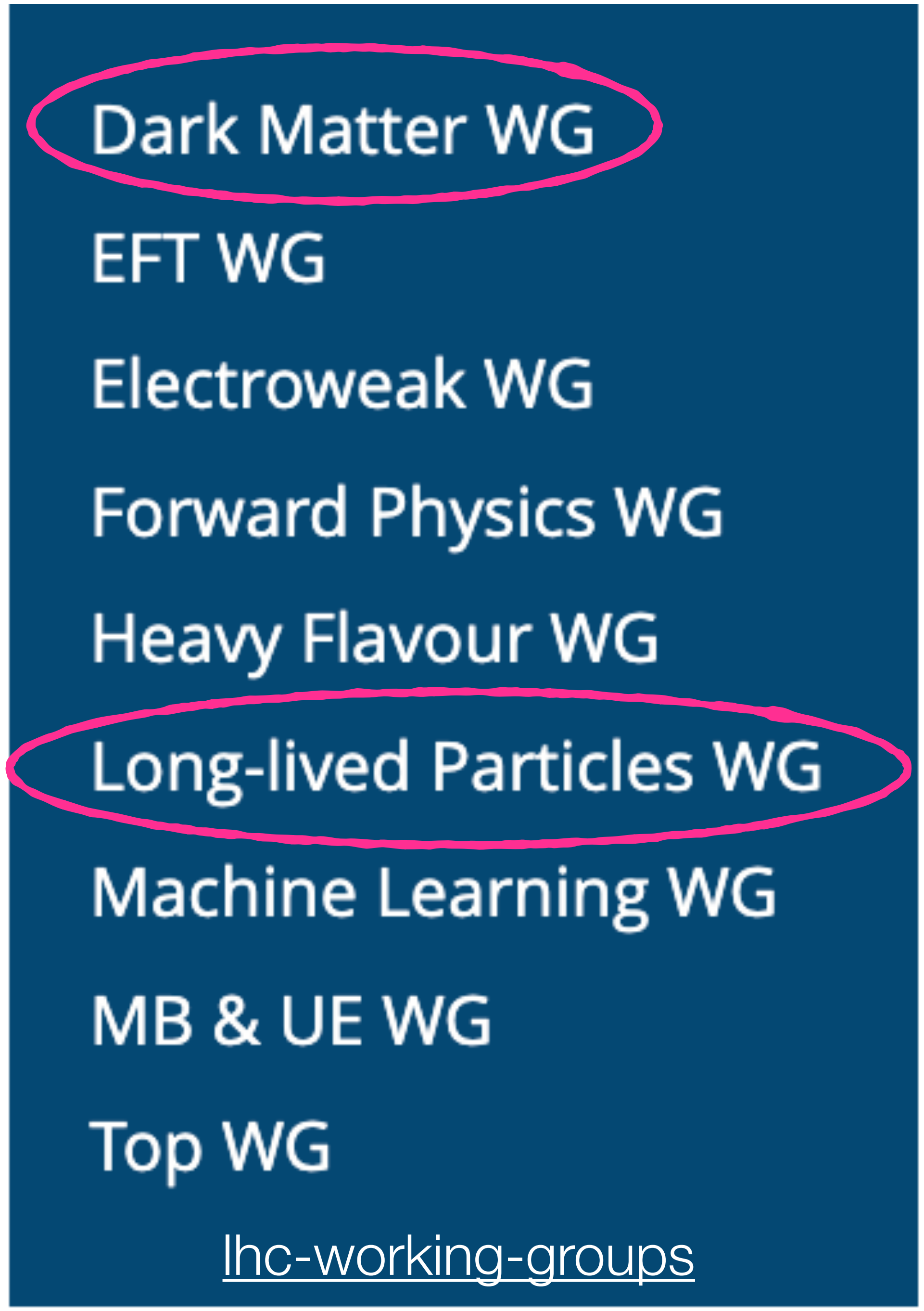
Reach out - let’s work together!



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Long lived particles …

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→ belong naturally in tons of BSM models

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→ provide fun, exciting opportunities to work outside the box

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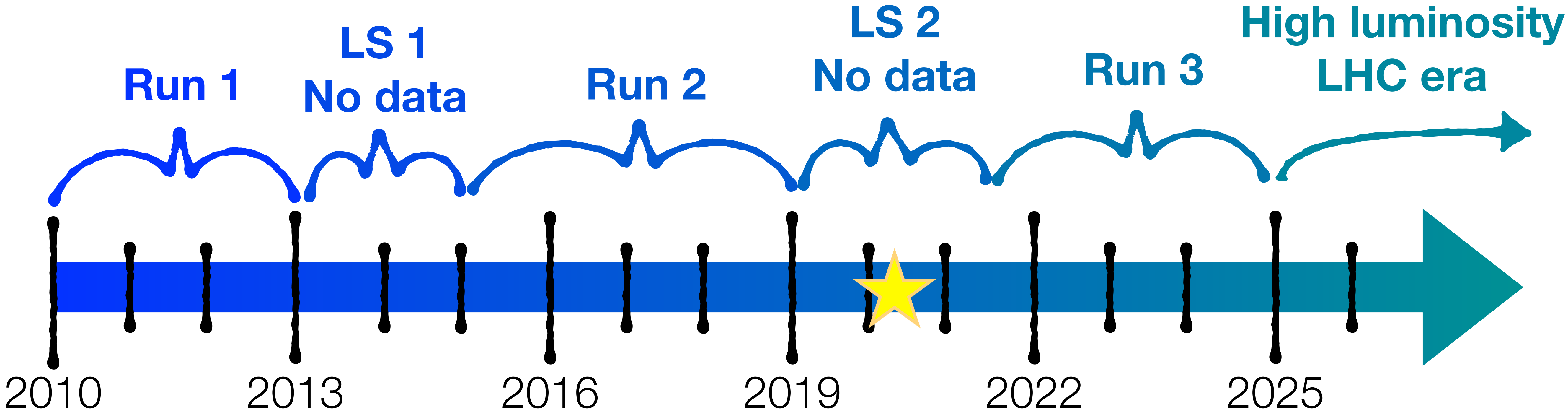
They could be your topic of the week *every* week!

Backup

LHC: energies and datasets

Two **key factors**: amount of data collected and collision centre of mass energy



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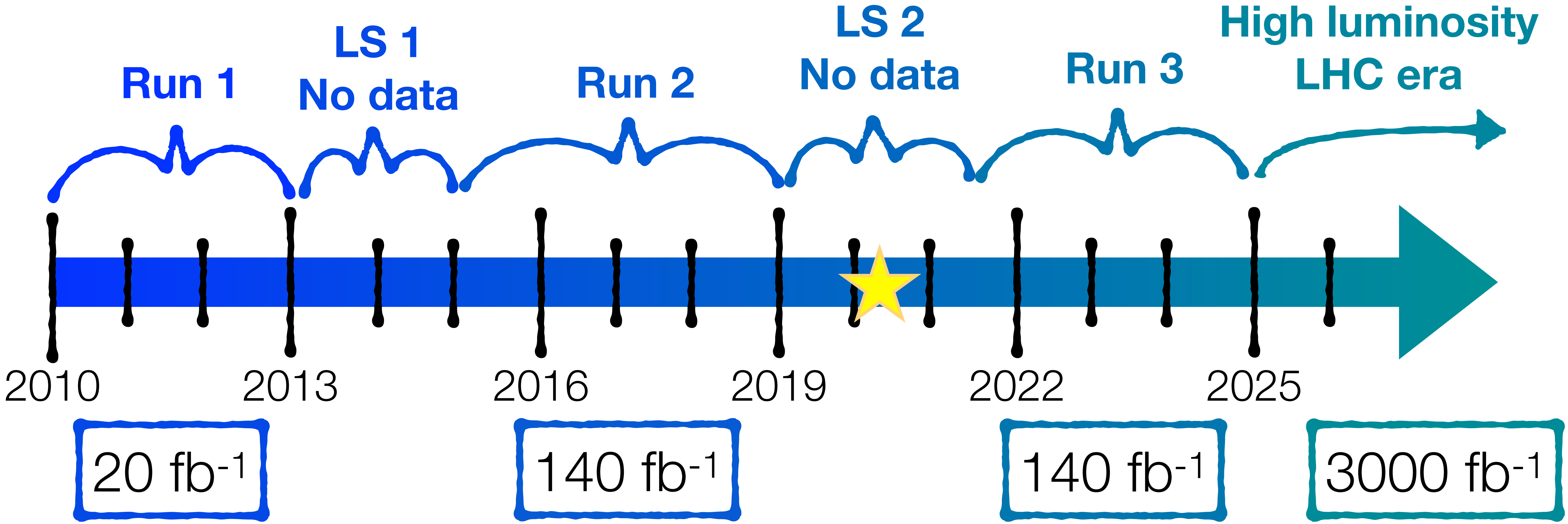

Run 1

LS 1
No data

Run 2

LS 2
No data

Run 3

High luminosity
LHC era

2010 2013 2016 2019 2022 2025

$20\ \text{fb}^{-1}$

$140\ \text{fb}^{-1}$

$140\ \text{fb}^{-1}$

$3000\ \text{fb}^{-1}$

- Amount of data collected: “luminosity”
- Measure in “inverse femtobarns”: more fb^{-1} = more data

LHC: energies and datasets

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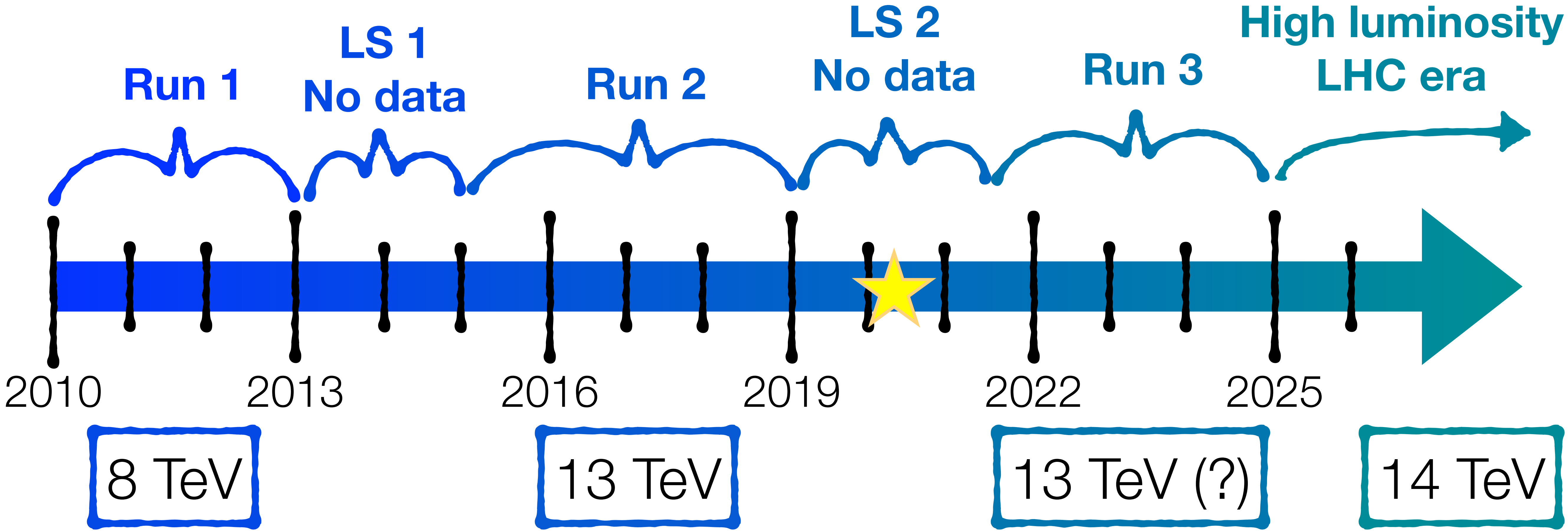


Run 1

LS 1
No data

Run 2

LS 2
No data

Run 3

High luminosity
LHC era

8 TeV

13 TeV

13 TeV (?)

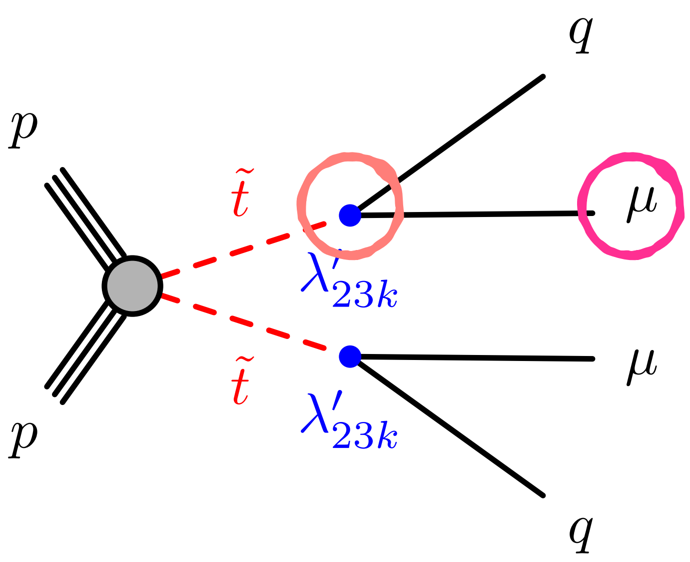
14 TeV

- Center of mass energy: “TeV”
- Higher energy = higher rate of interesting processes

Indirect detection example: Displaced vertices + a muon

arXiv:2003.11956

Vertex far away from collision point



High p_T muon and MET used for triggering

μ not required to come from DV, but must not point to collision

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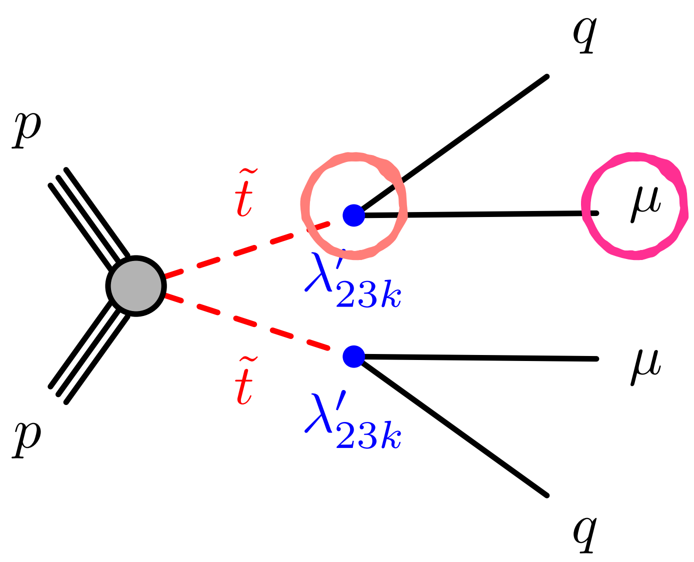
High-mass vertex excludes K_{long}



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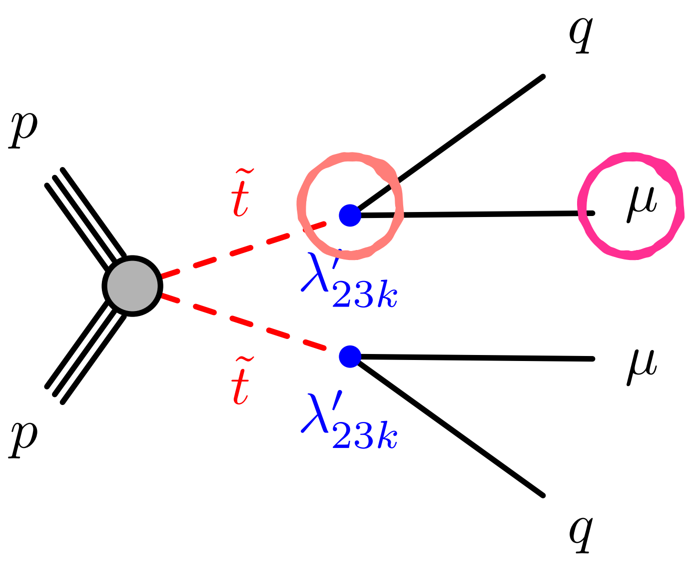

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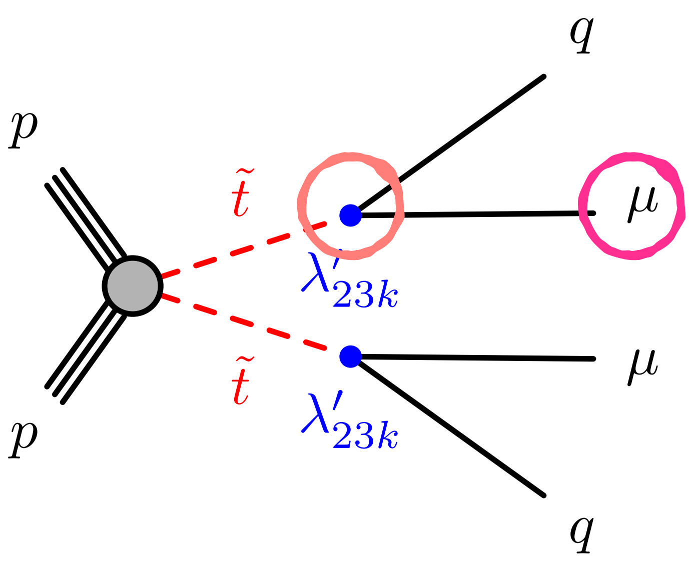

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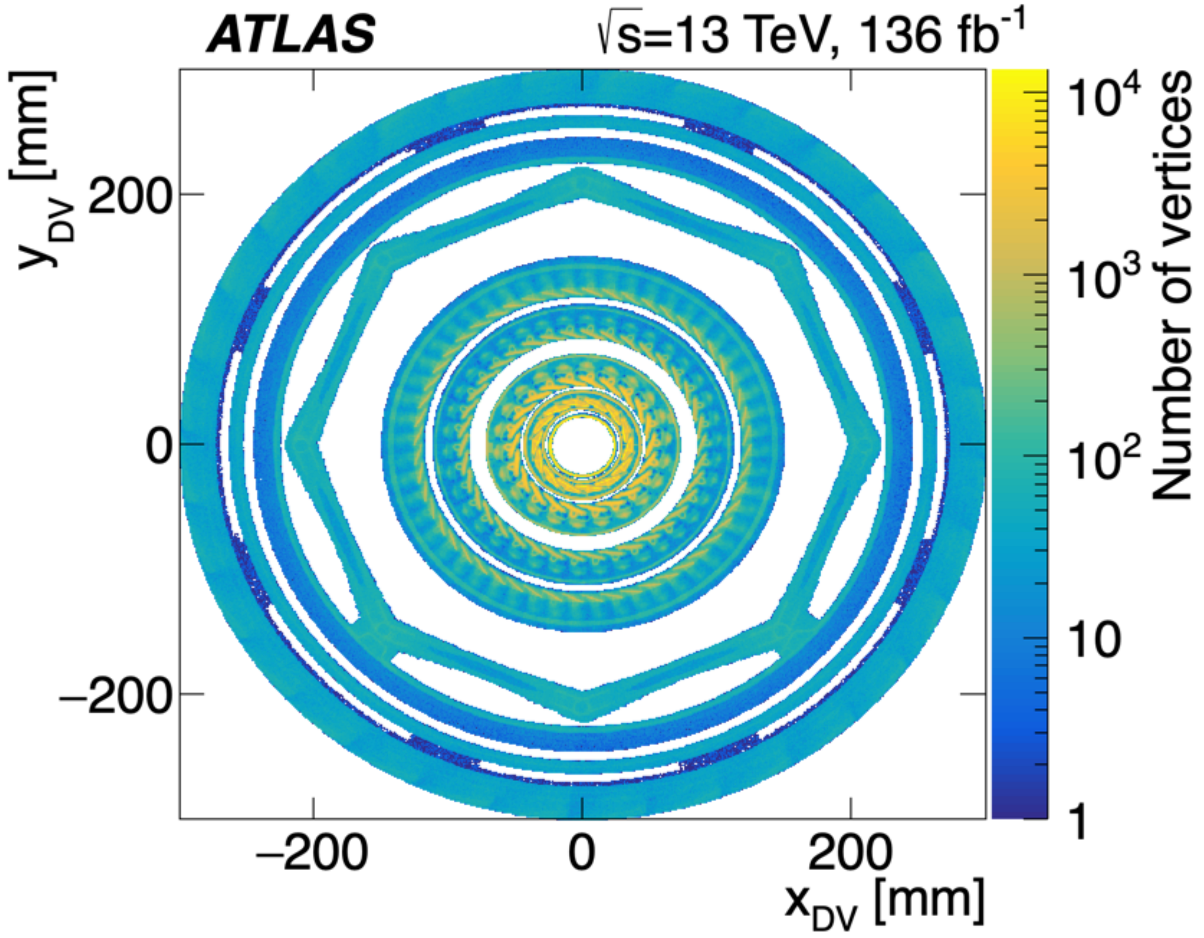
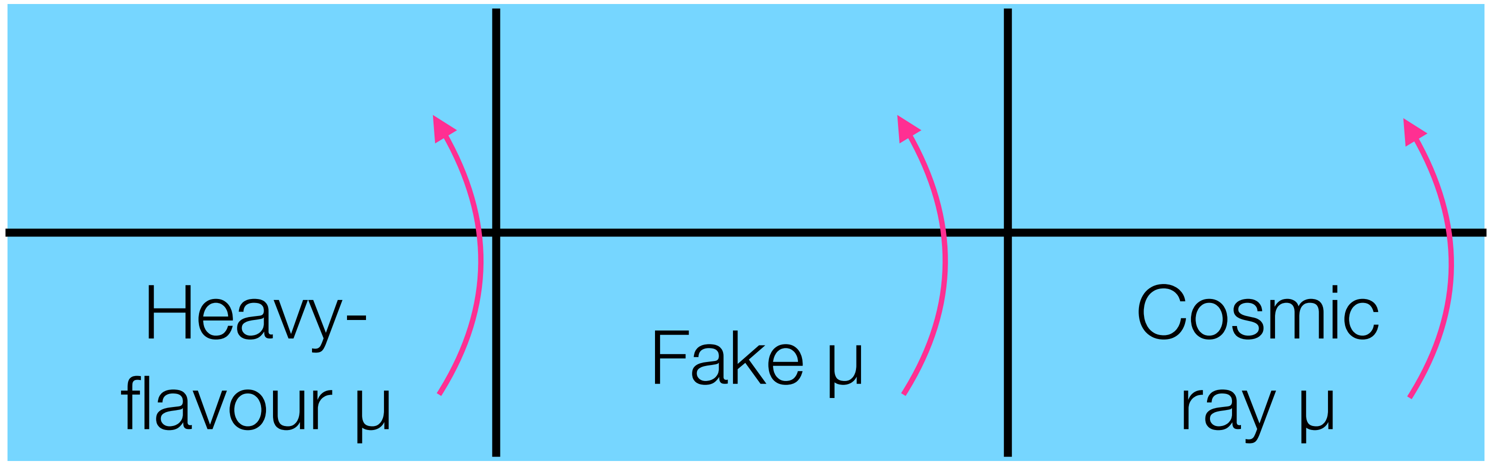


Results of DV + muon

Control region with background-like DVs

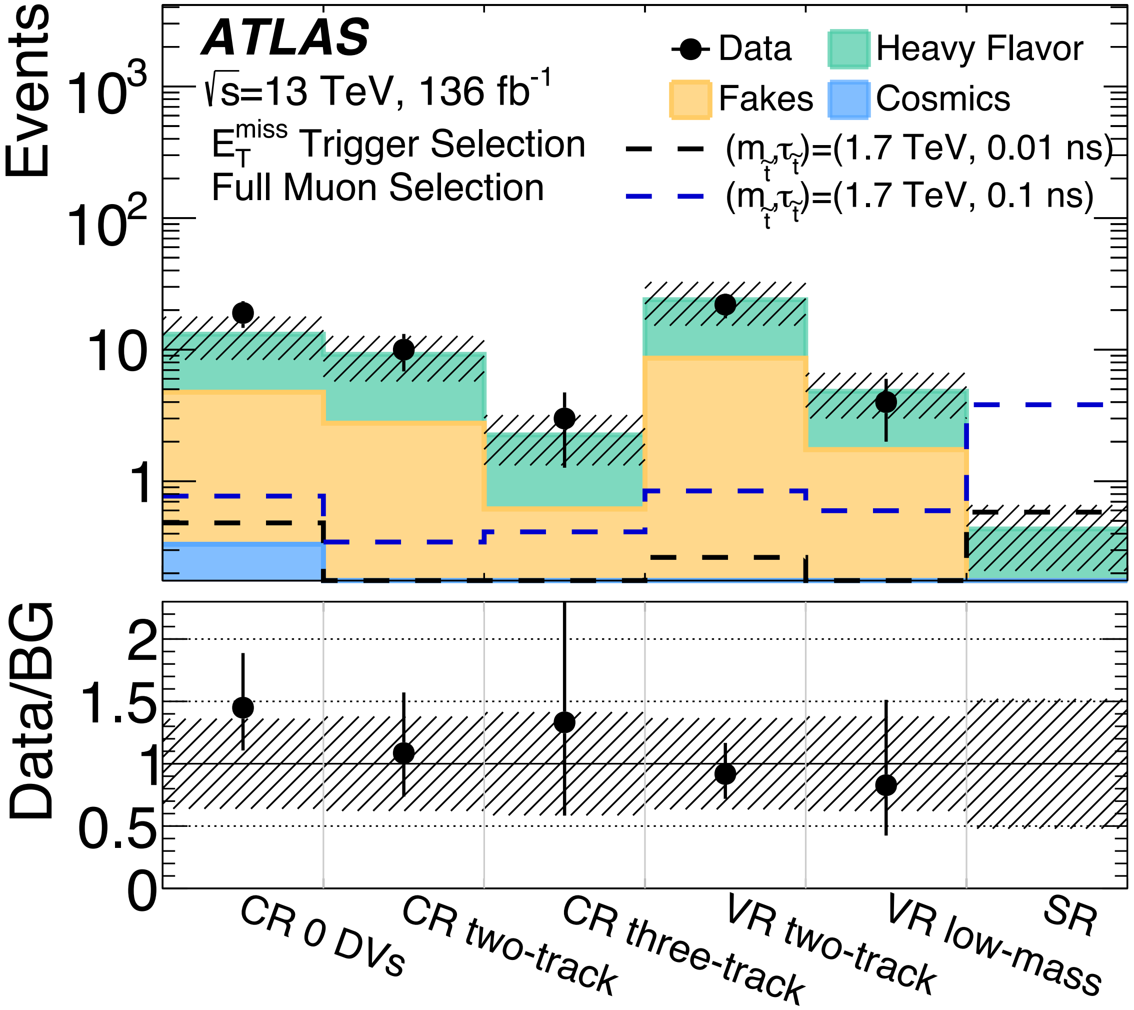


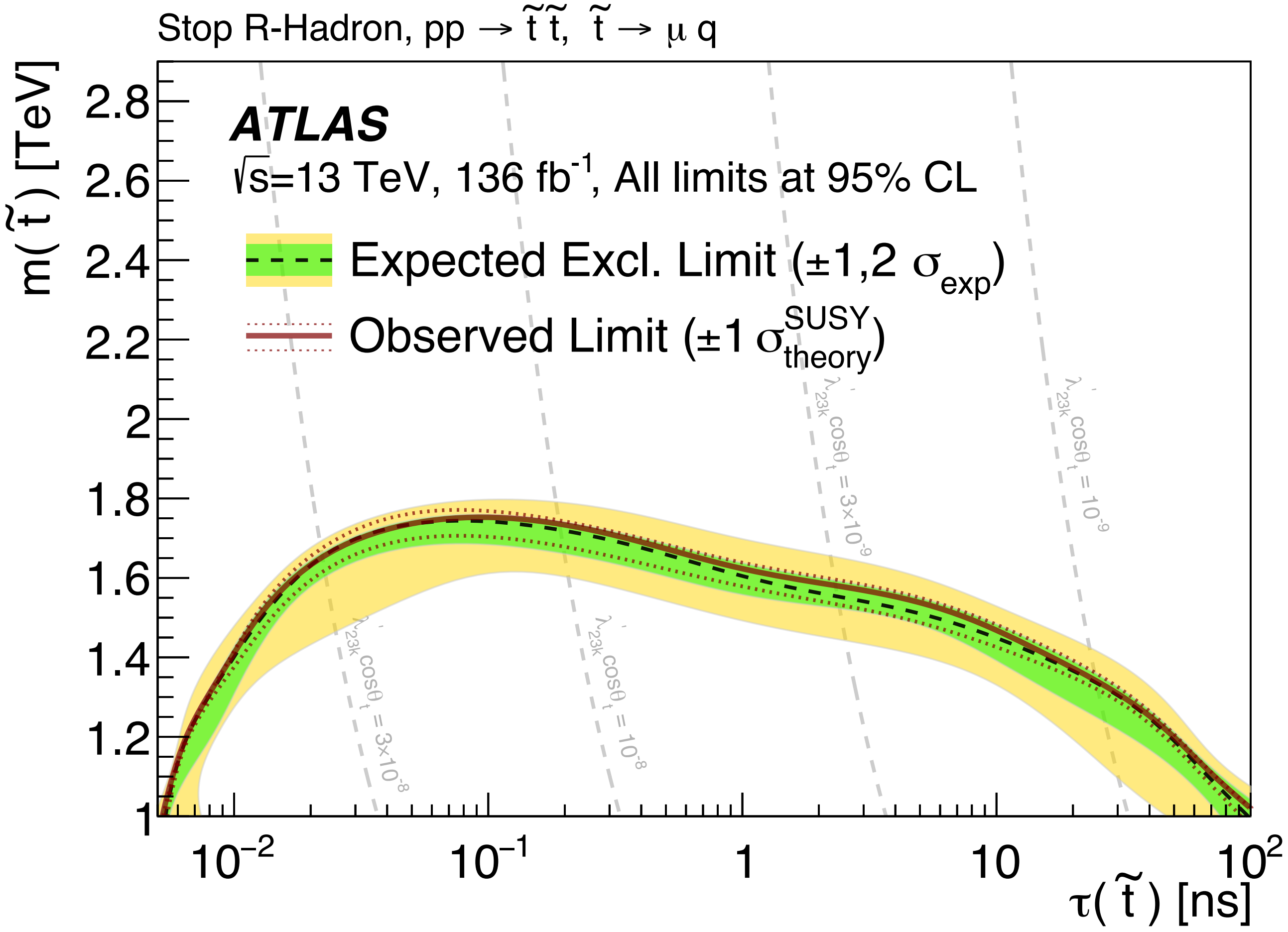
Heavy-flavour μ

Fake μ

Cosmic ray μ

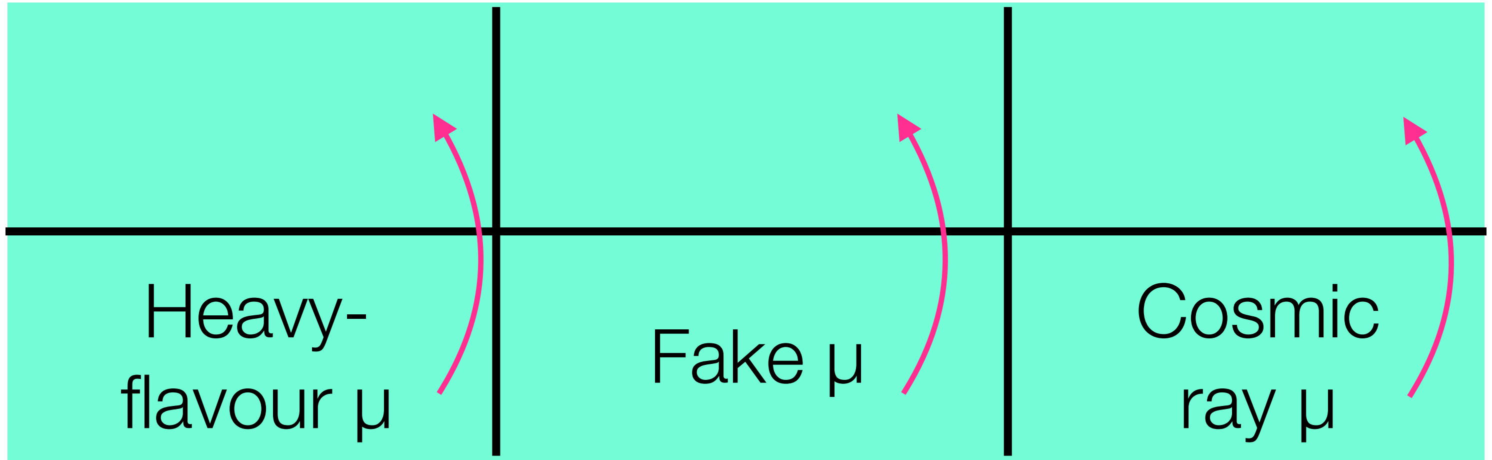
Derive transfer factors from ratios





Results of DV + muon

Apply transfer factors in regions with signal like DVs



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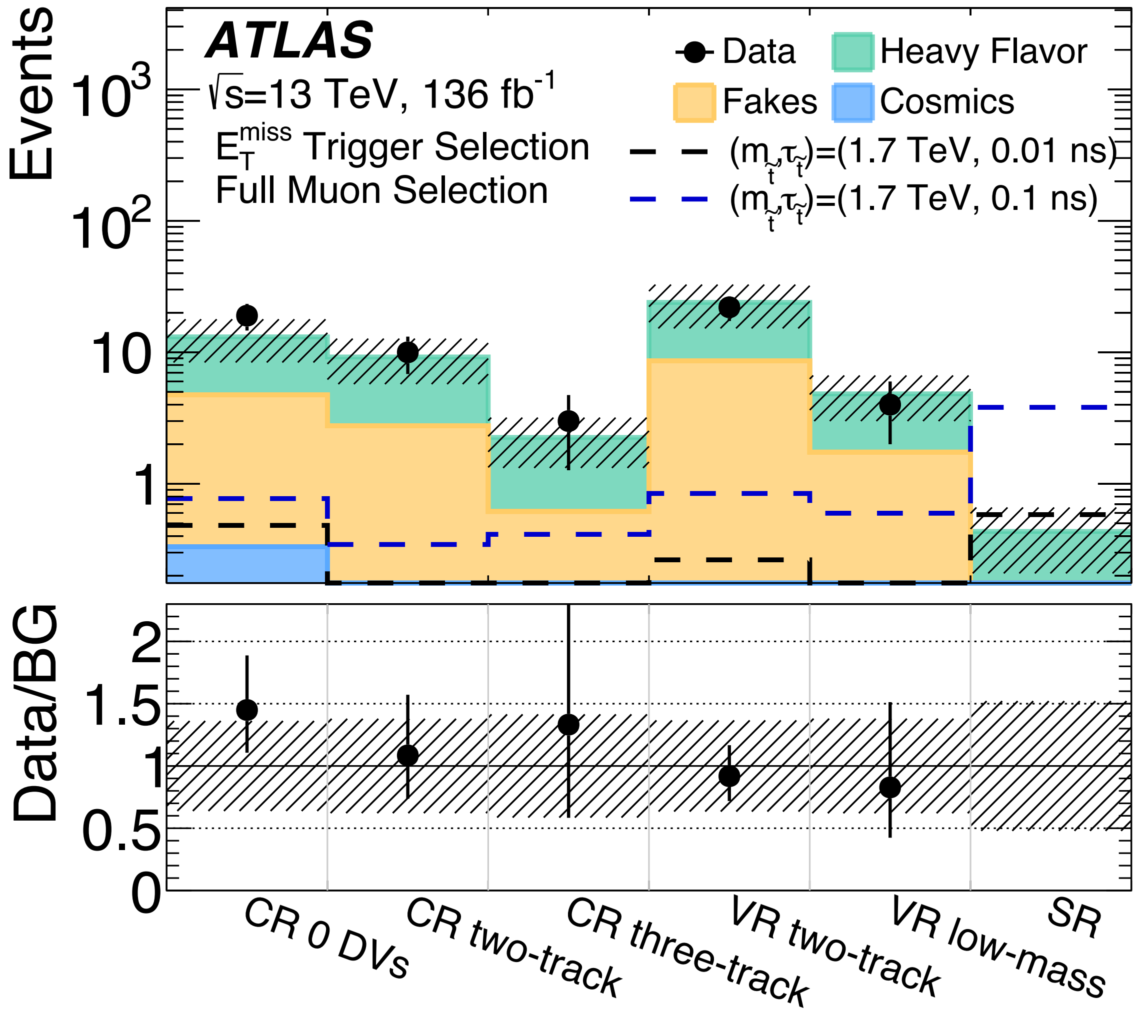
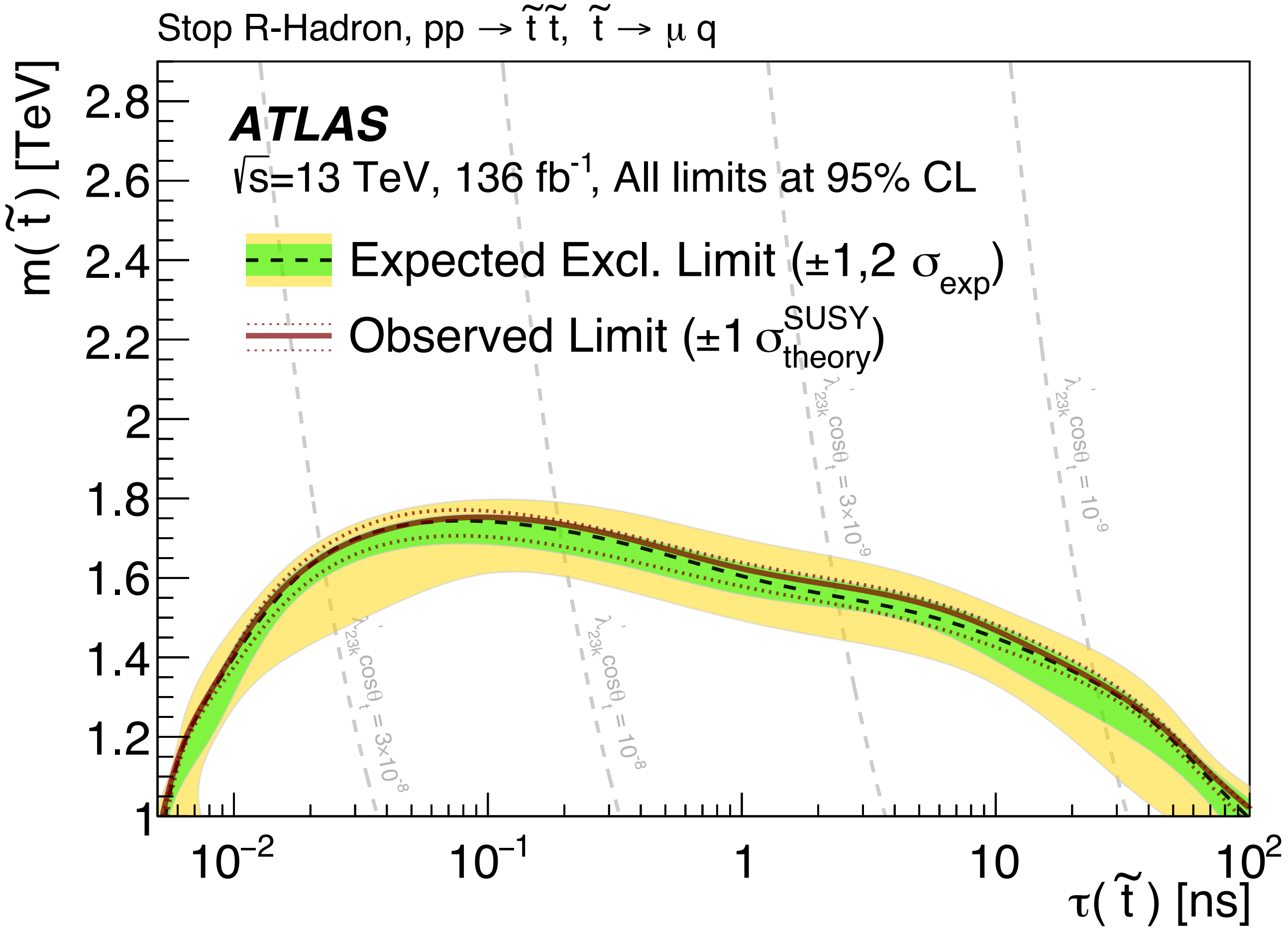
Cosmic ray μ





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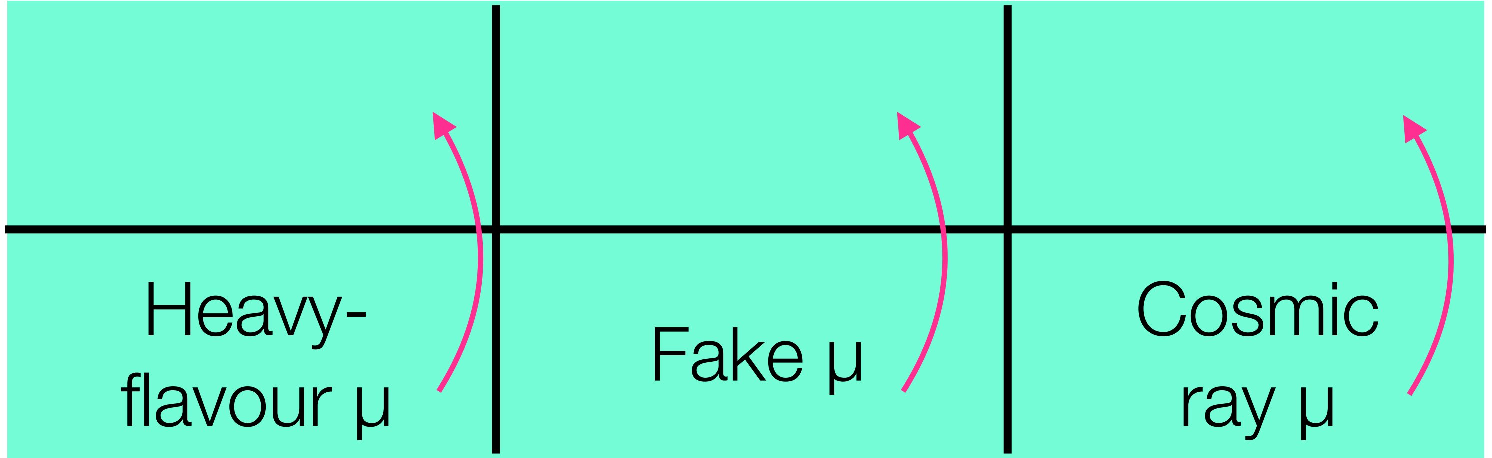
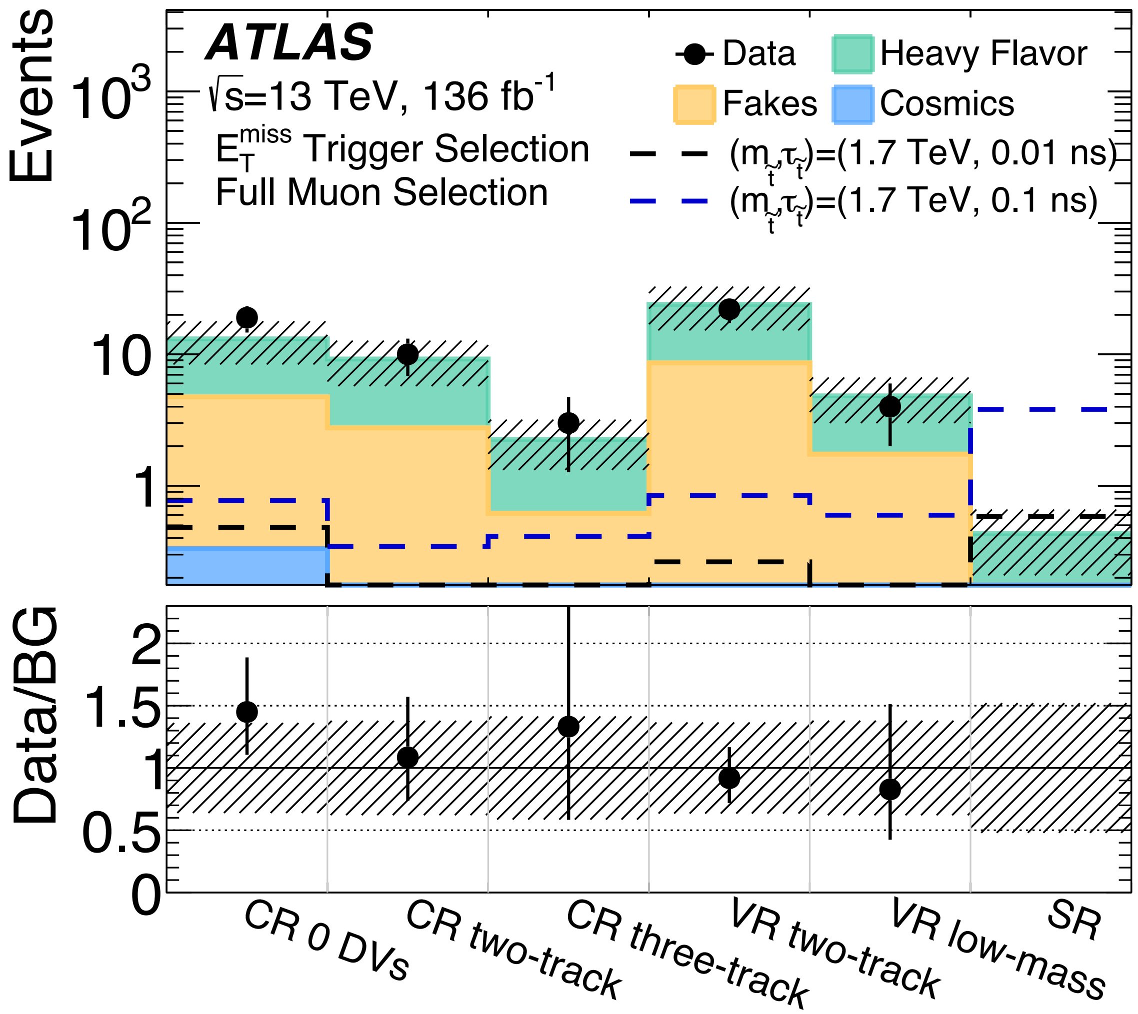
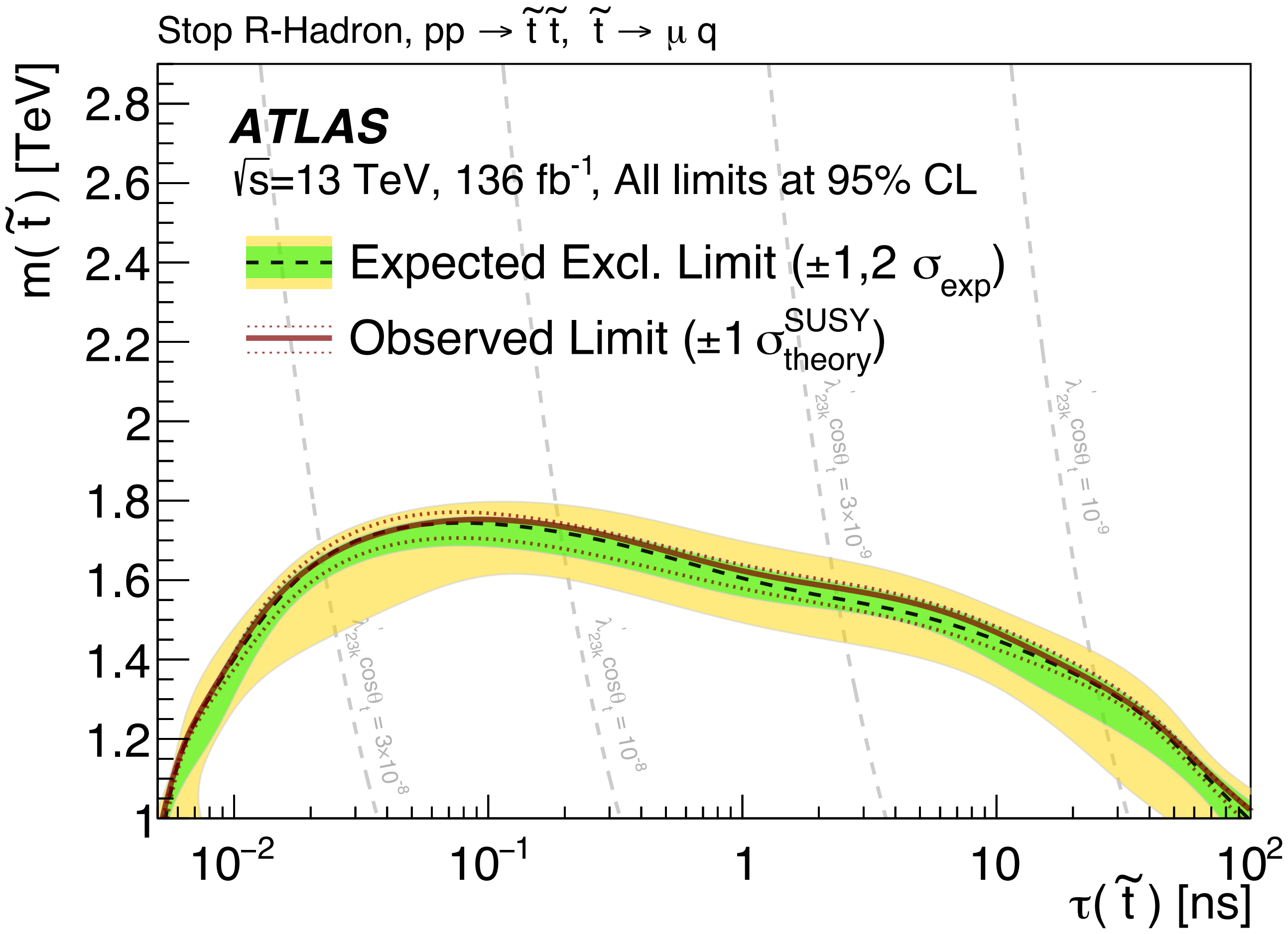


Background estimate!





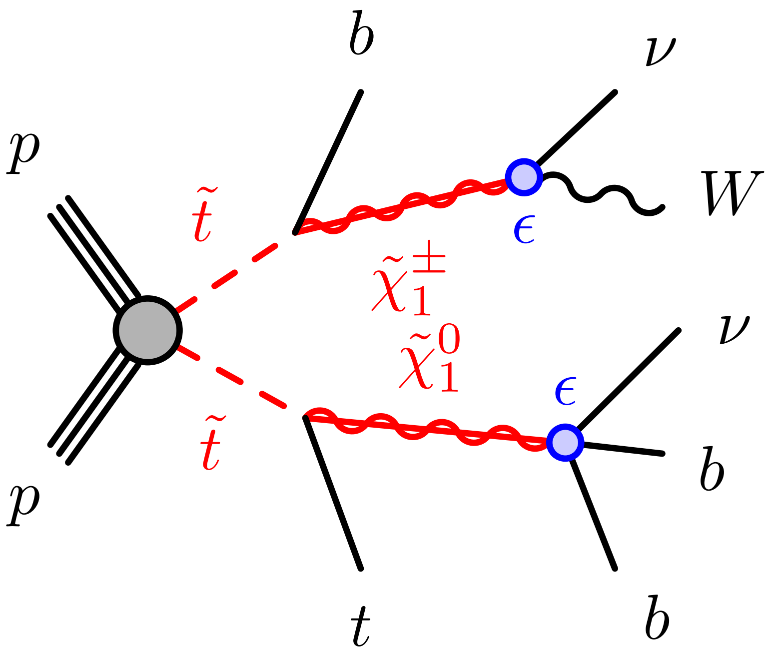
Improving analysis targeting

- LLP analyses fairly simple at this point and target signals not necessarily most important for Run 3
- **dEdx**: optimise for lighter signals; add two-track signal region to improve targeting of SUSY-specific models
- **Disappearing track**: attempting to target even shorter lifetimes
- **Displaced leptons**: optimise directly for staus, focusing on lowering lepton p_T threshold, add 1 displaced lepton + 1 tau SR
- **In general**: move away from long-lived squarks/gluinos and target direct EWK production instead

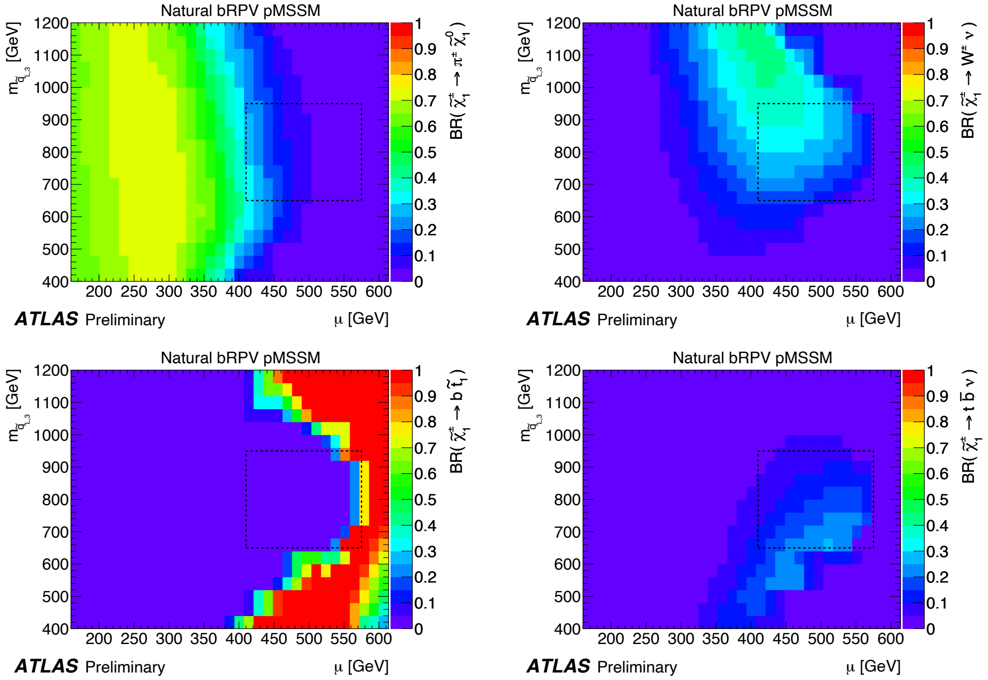
L-violating bilinear coupling

$$\mu'^{i} L_i H_u$$

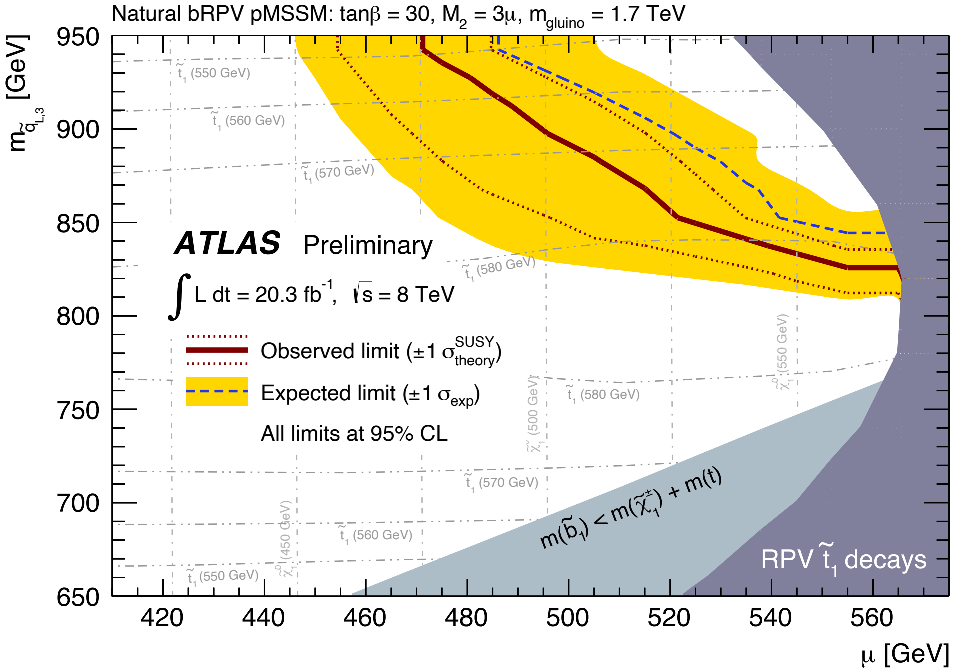
- Representative interactions between Higgsinos/leptons and Higgses/sleptons
  - $\tilde{\chi}^0 \rightarrow \ell^{\pm} W^{\mp},\ \nu Z$
  - $\tilde{\chi}^{\pm} \rightarrow \ell^{\pm} Z,\ W^{\pm}\nu$



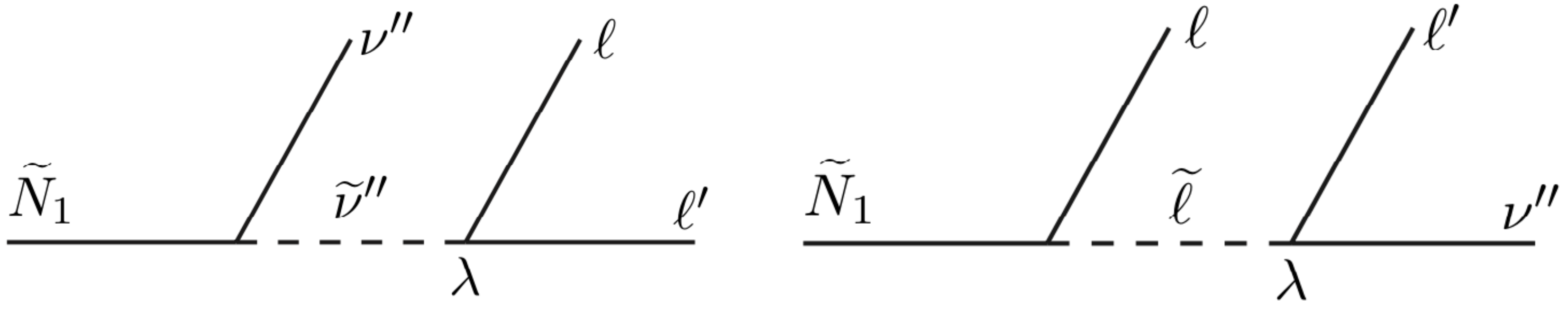
- Get neutrino masses automatically
- Can convert terms between bilinear and trilinear depending on basis, so other analyses have implications here and vice-versa



Run 1 summary: huge variations in final states and kinematics with small changes in model parameters!



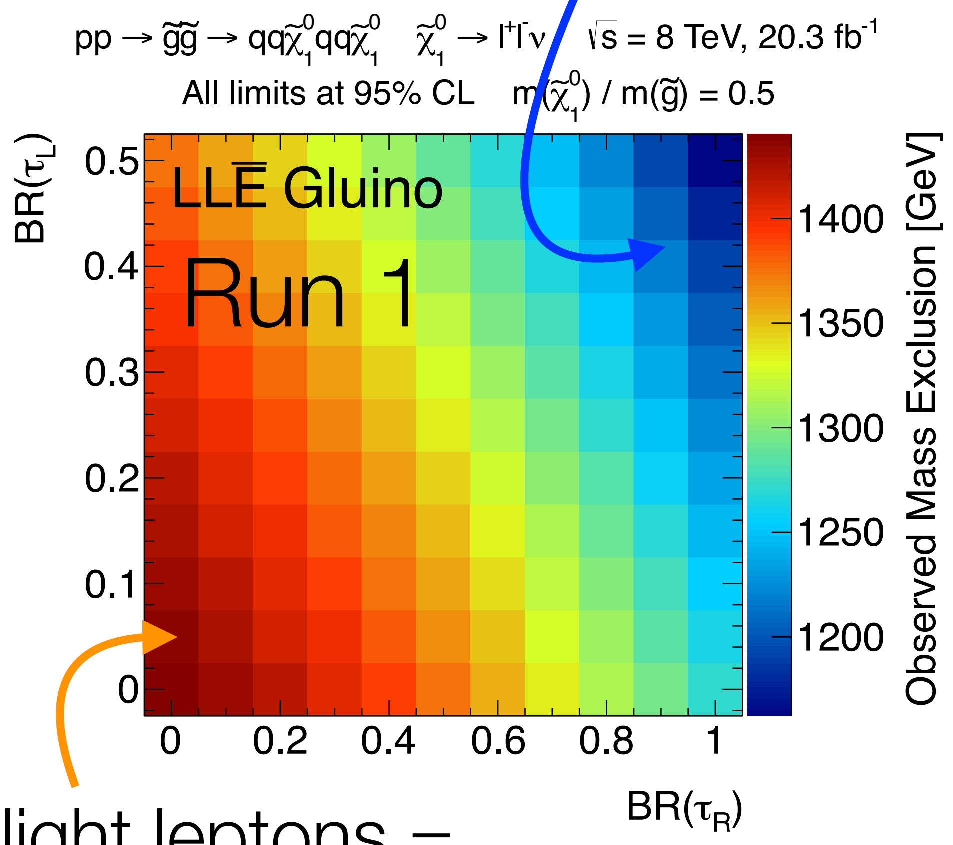
Lepton coupling, L-violating LLE: λ



Primes indicate flavour indices: determine different combinations of leptons

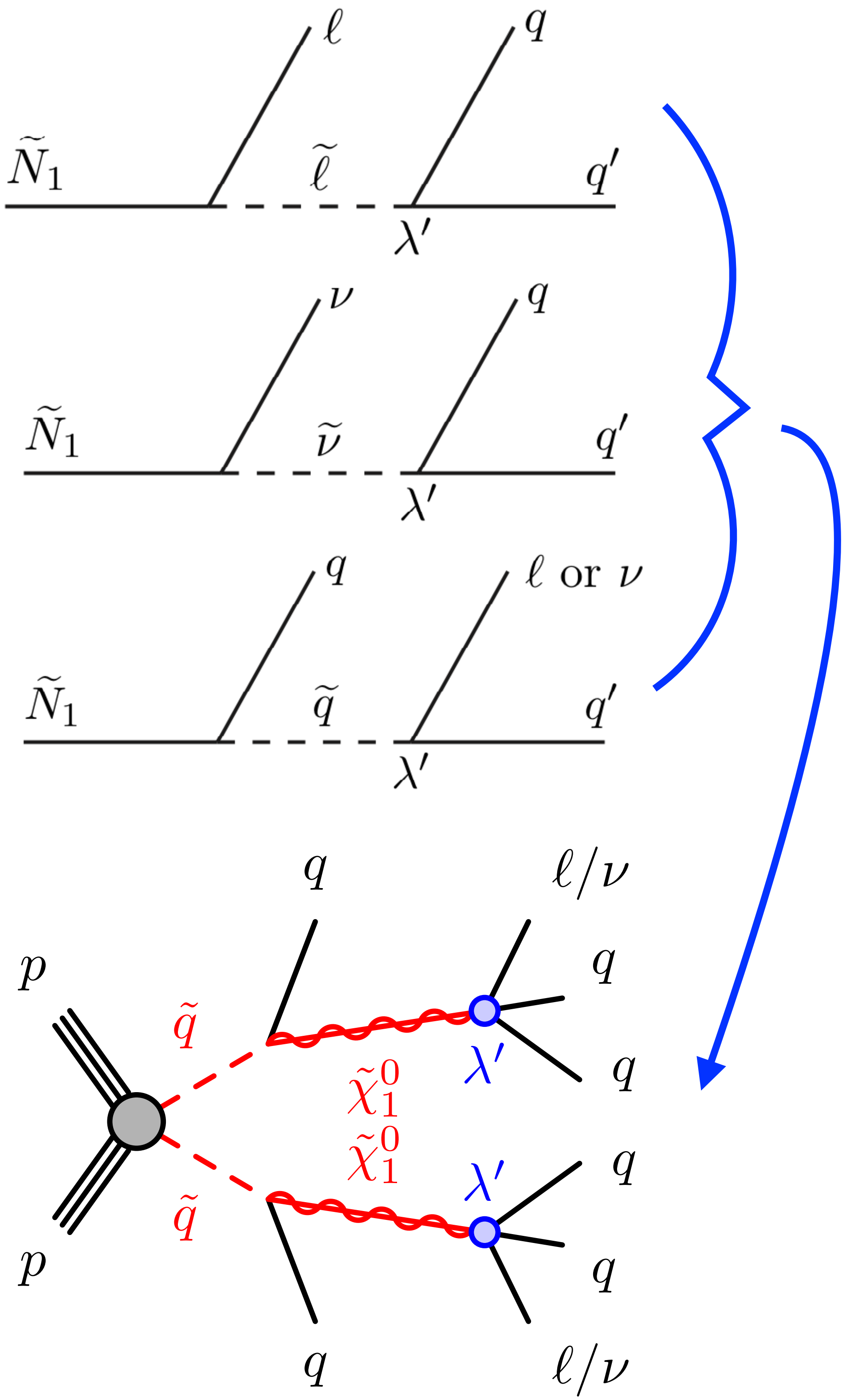
- LSP decays to leptons via sneutrino/slepton
- Very small λ: get nonzero lifetime for intermediate particle and we'll see displaced lepton pairs (covered by dilepton DV) or one displaced, one prompt (should be some coverage from exotics HNL? Displaced leptons?)
- Medium λ: lots of prompt leptons in the final state. Constraints from electroweak 3L and 4L analyses

taus = weaker limits



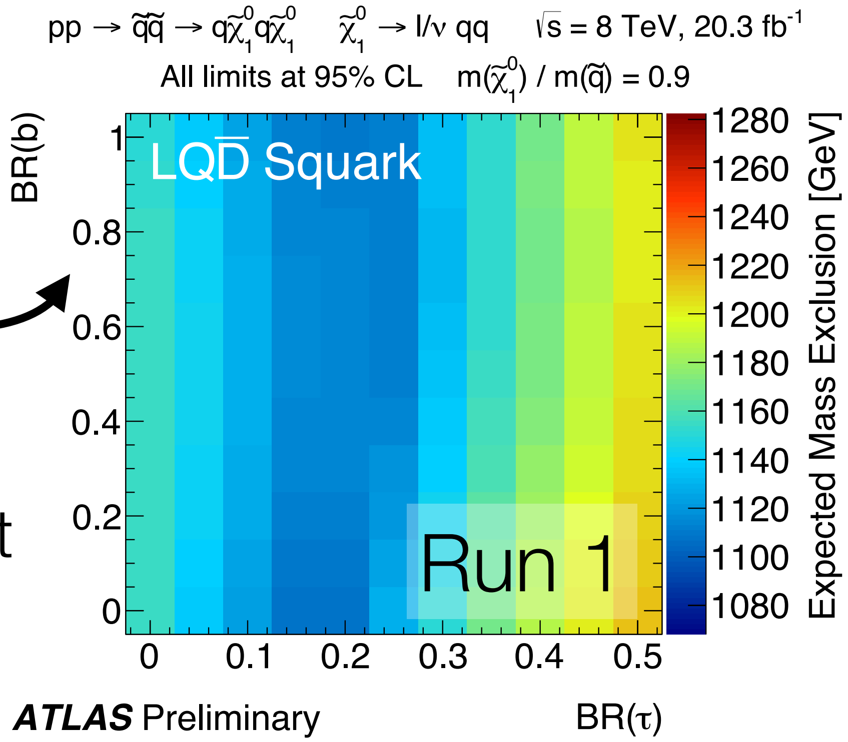
light leptons = stronger limits

Leptons and jets, L-violating LQD: λ’



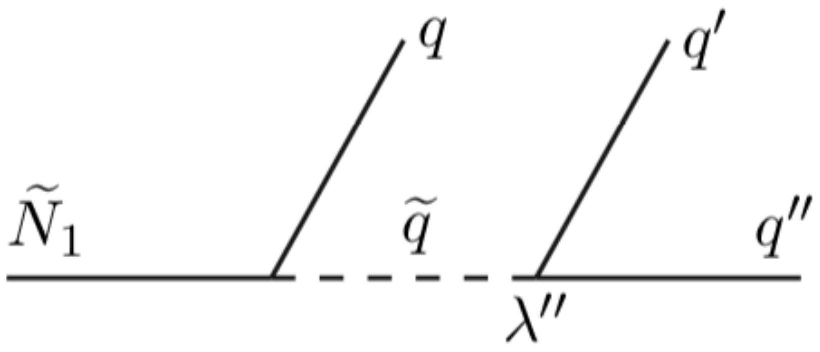
Analysis reach varies with final state flavours…

… and mass splittings: no Run 1 exclusions for largest splittings

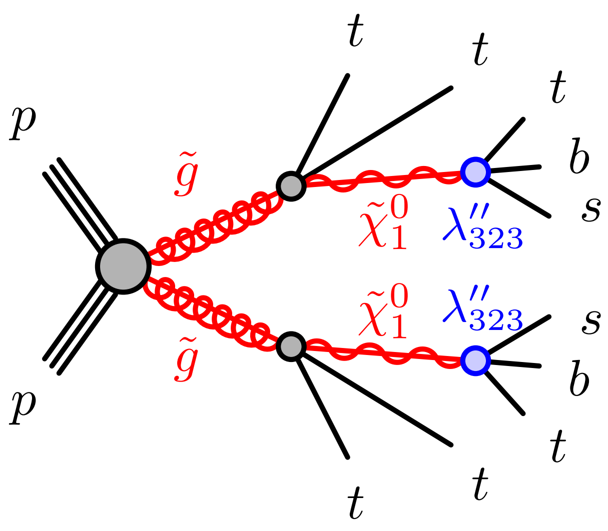


- Couple quarks to leptons and neutrinos: get LSP decay to jets and l/ν
- Small λ’: long-lived N1 leads to displaced jets; coverage from DV analyses
- Medium λ’: multijets and lepton or significant MET. Constraints from multijet 0L, EW 3L (not shown today), stop B-L (discussed already), multijet 1L (see next section) at present

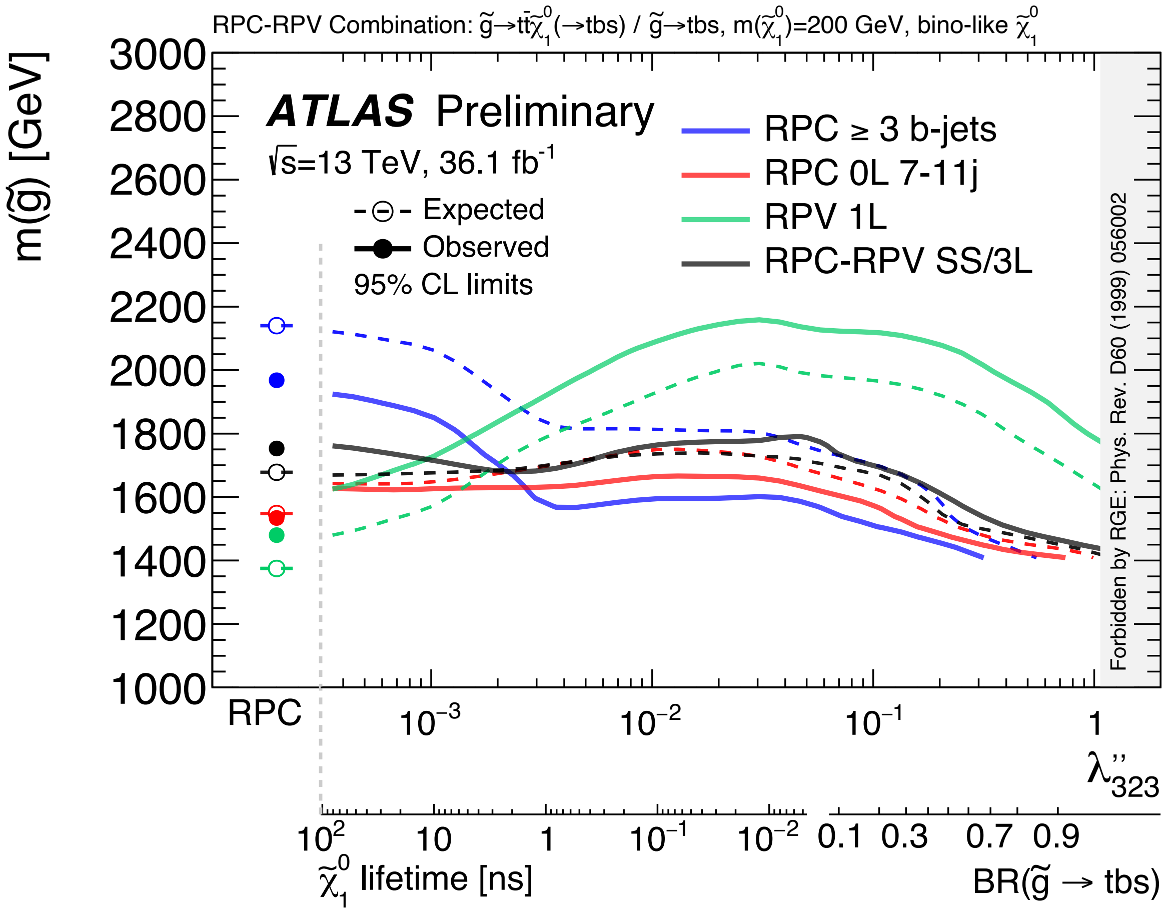
B-violation with tons of quarks, UDD: λ”

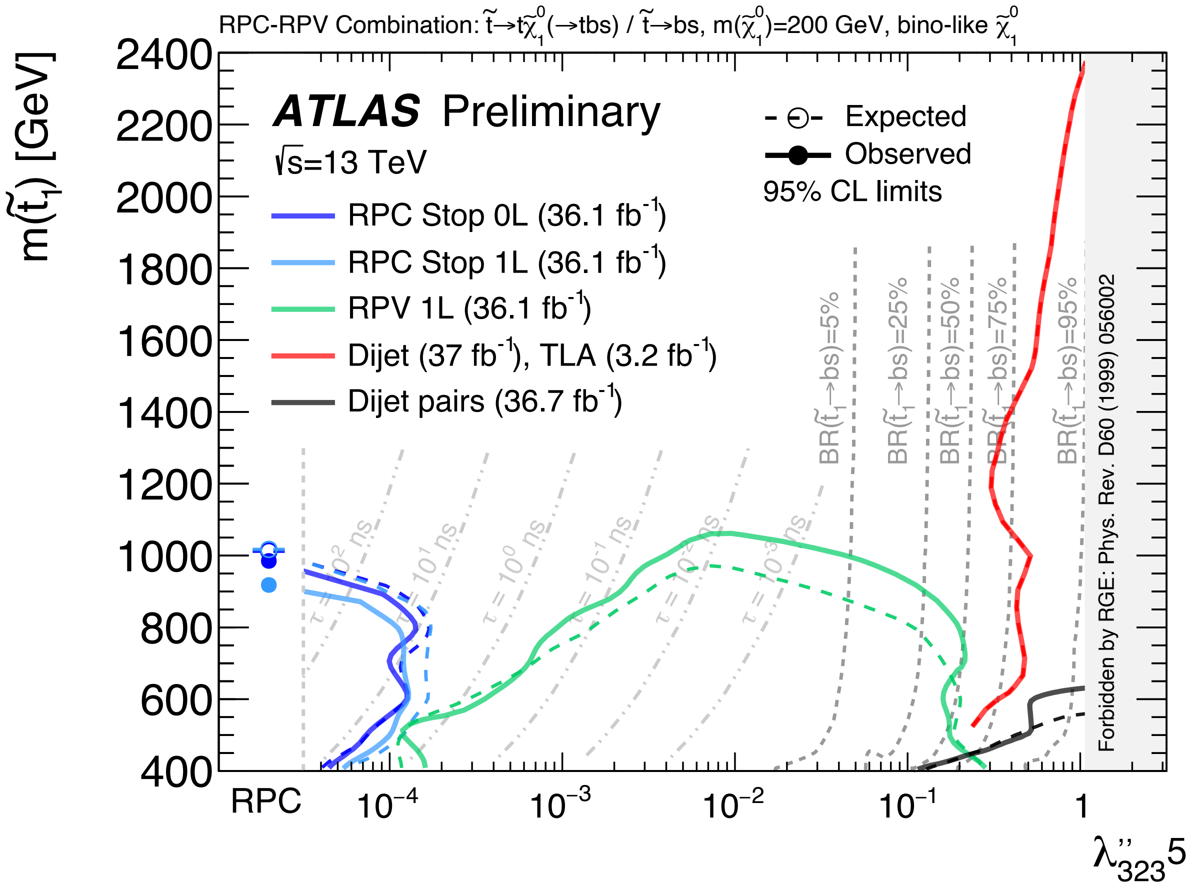


Note different indices will result in different quark flavours!



Jet-filled final states, but with t’s present you can have lepton(s) and MET as well





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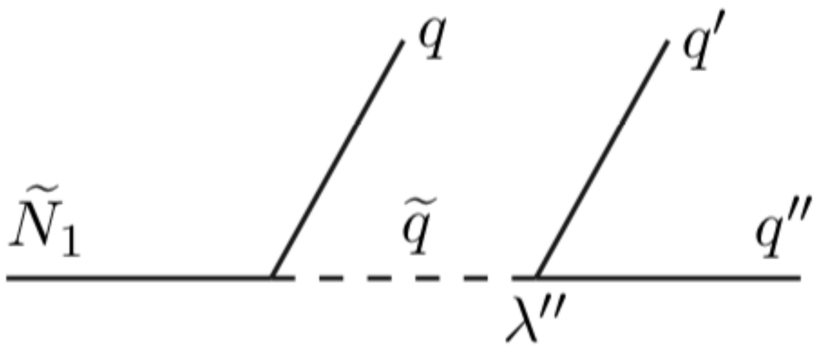

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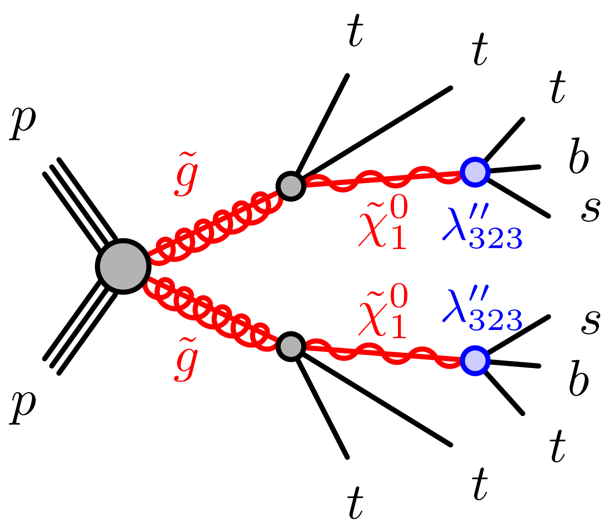

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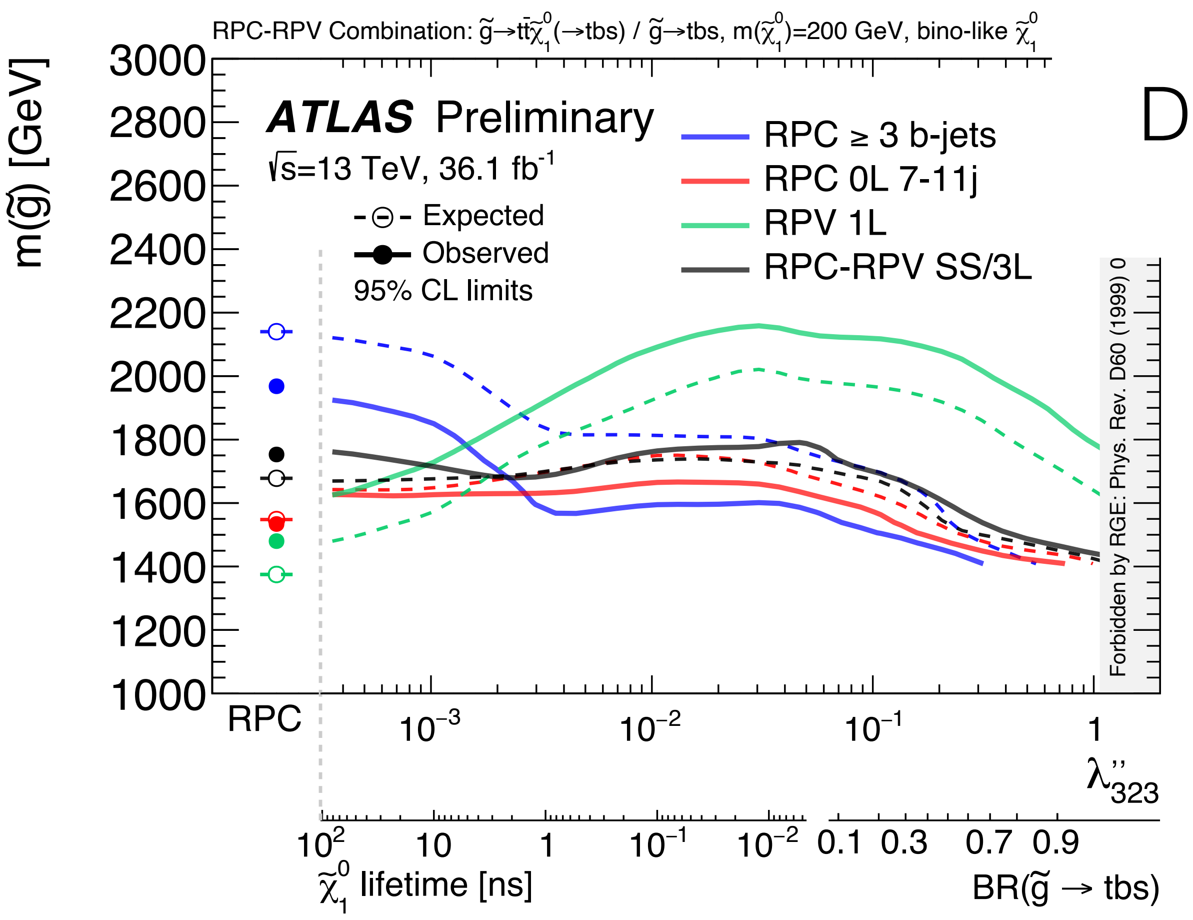
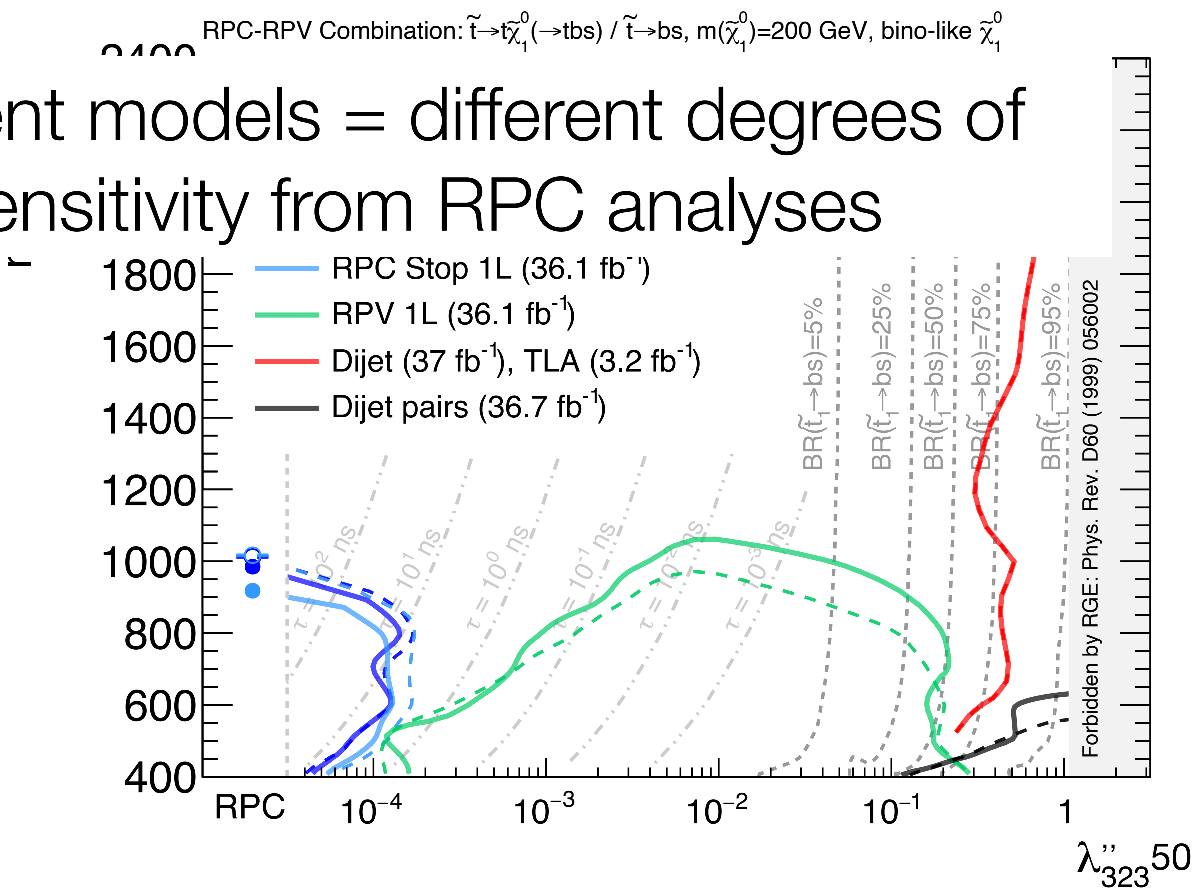
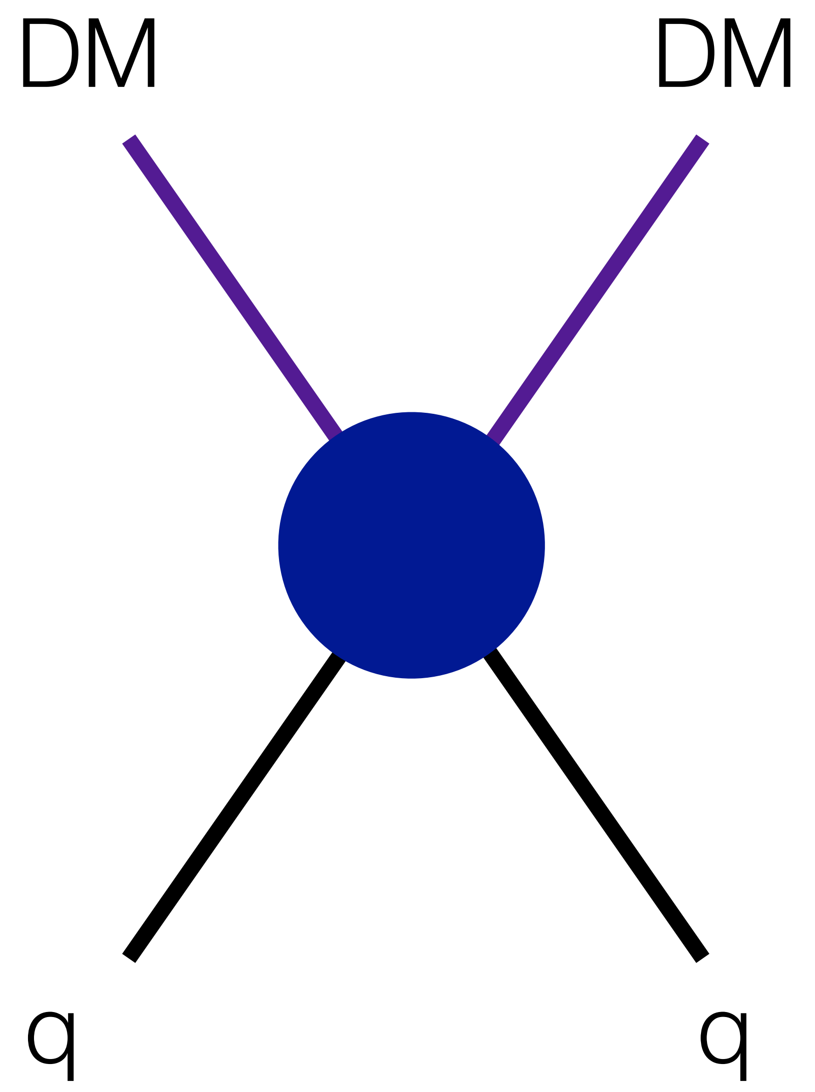




Different models = different degrees of sensitivity from RPC analyses

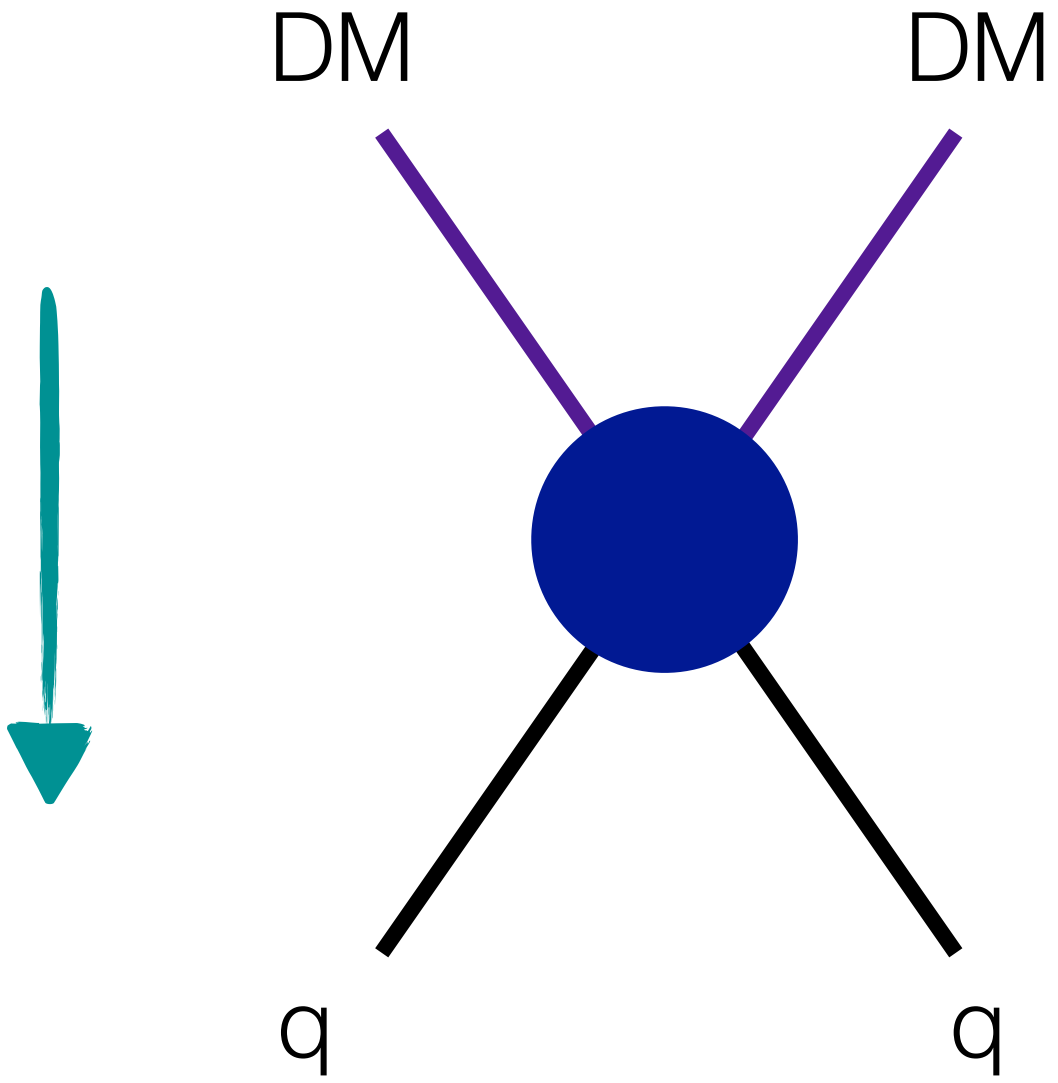
Dark matter at colliders



Dark matter at colliders

Indirect detection

IceCube, Super-K, …



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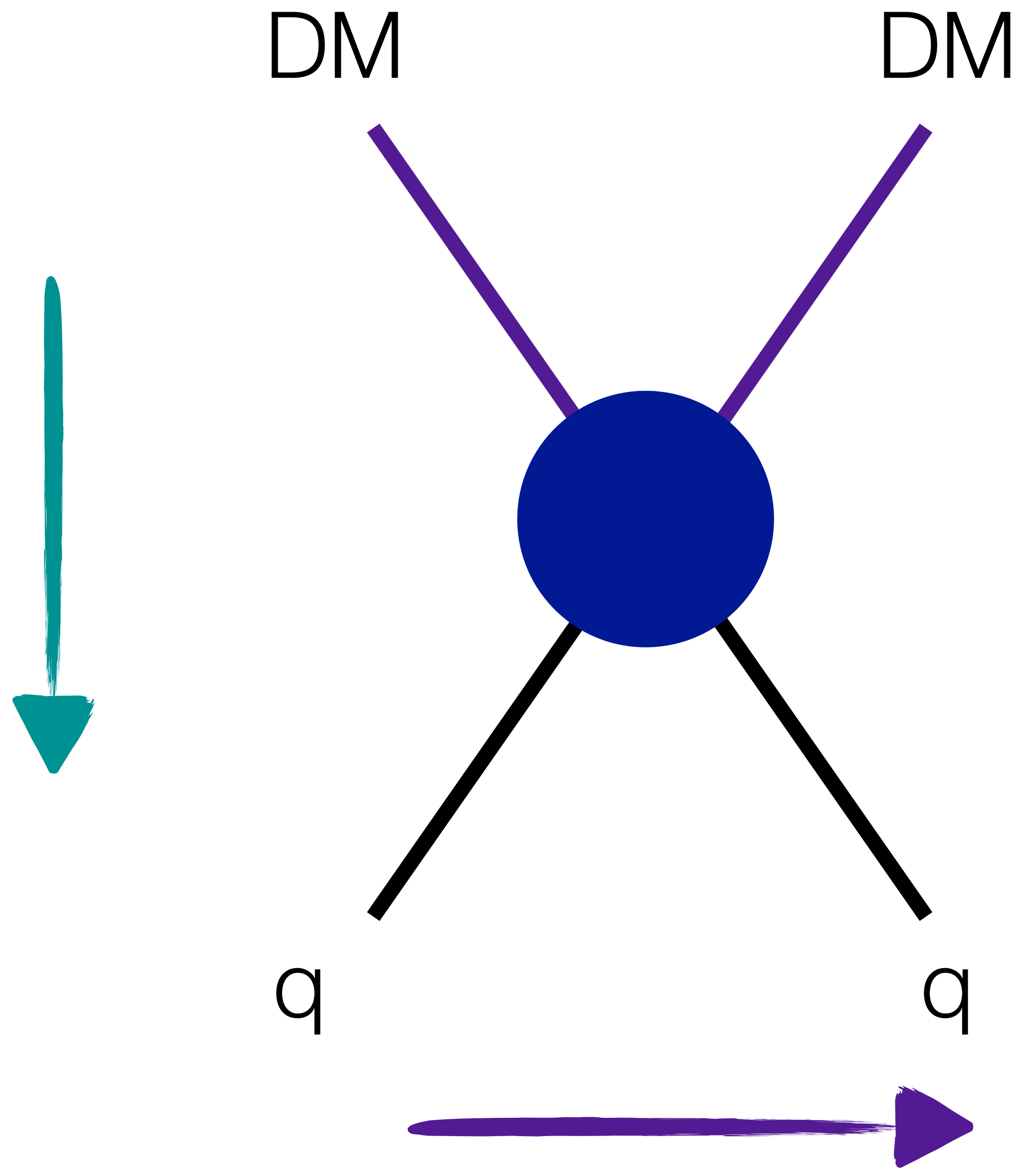
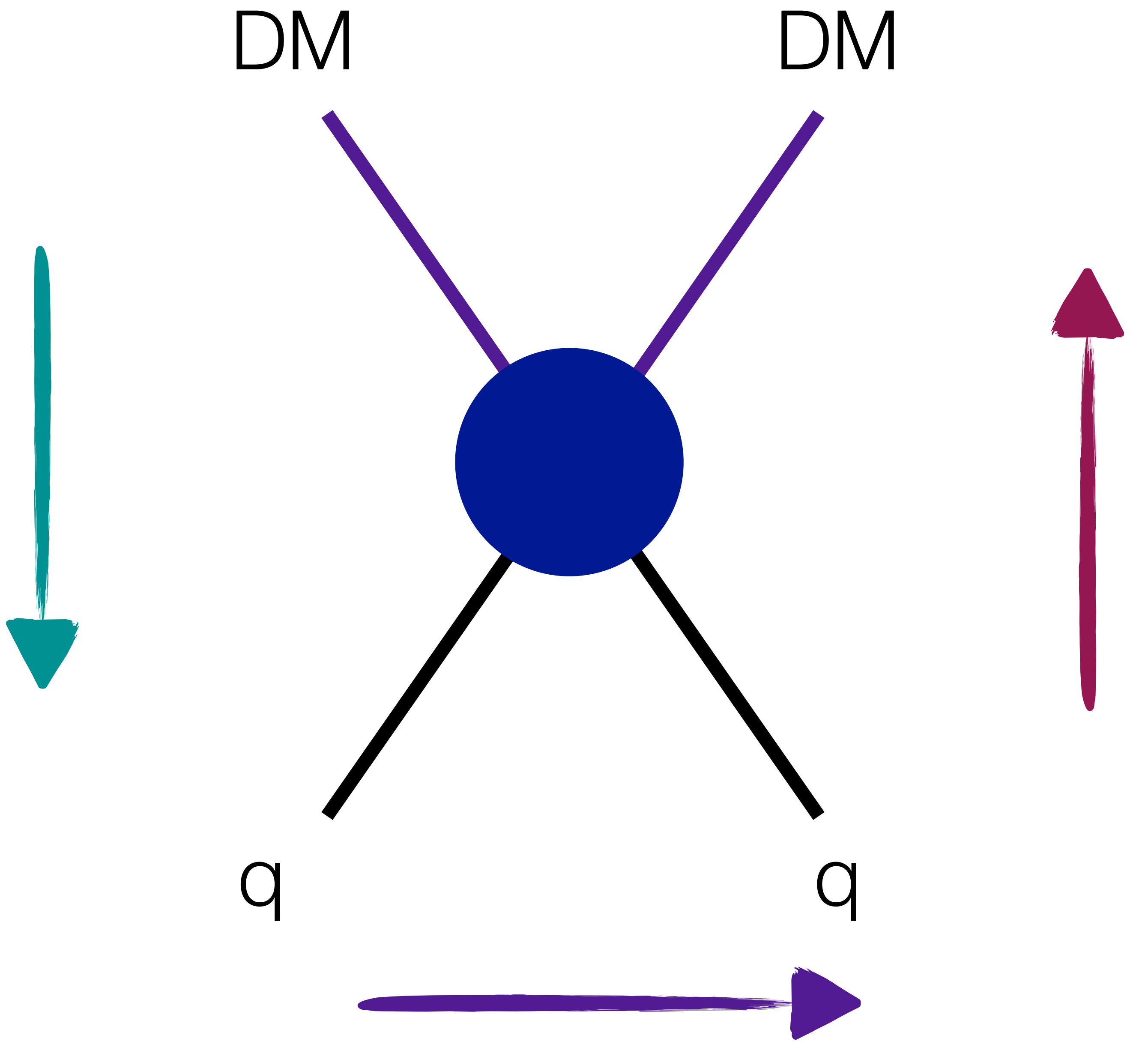


Indirect detection

IceCube, Super-K, …

Direct detection: LUX, XENON, …

Dark matter at colliders



Indirect detection

IceCube, Super-K, …

Colliders

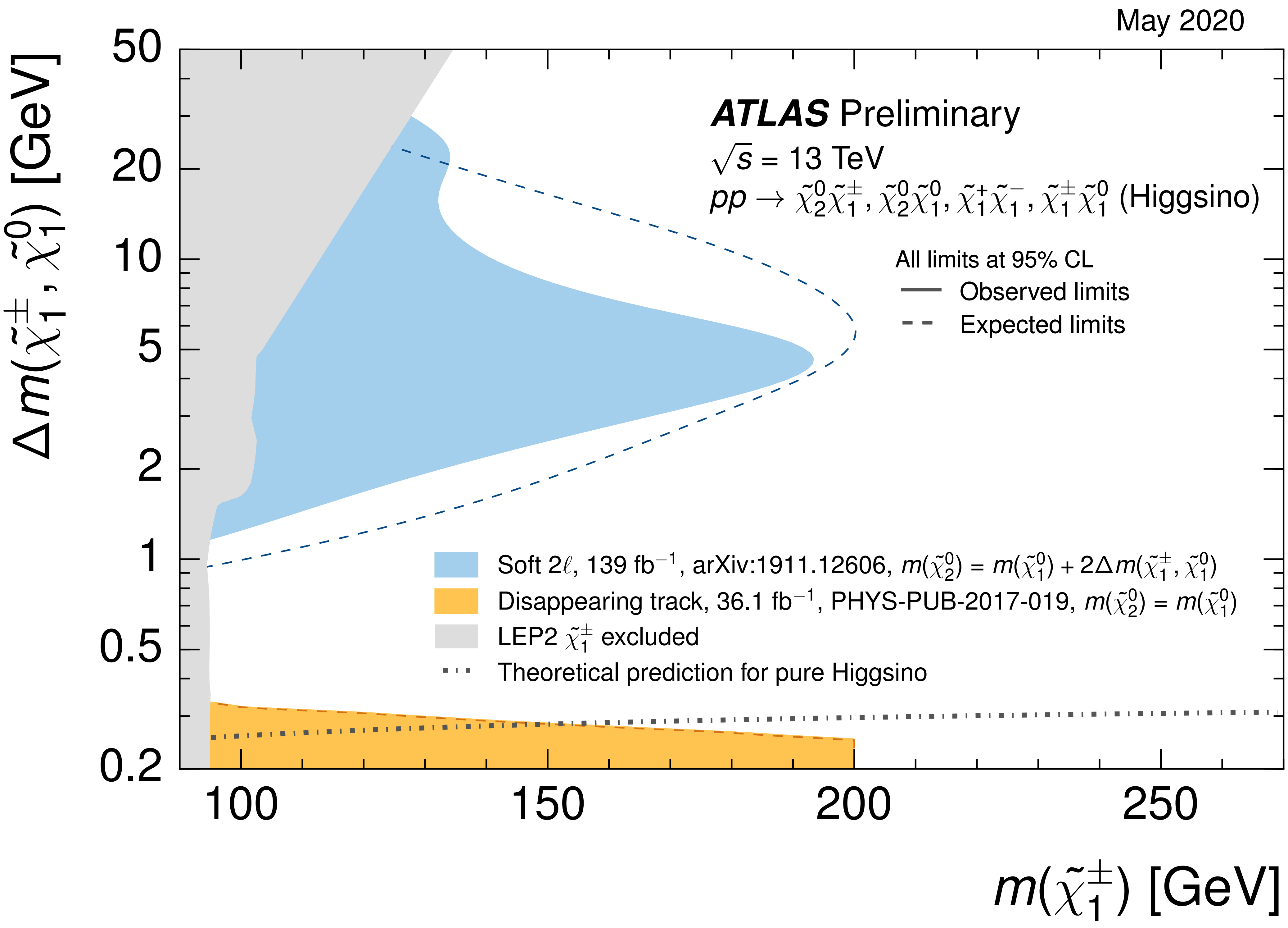
ATLAS & CMS

Direct detection: LUX, XENON, …

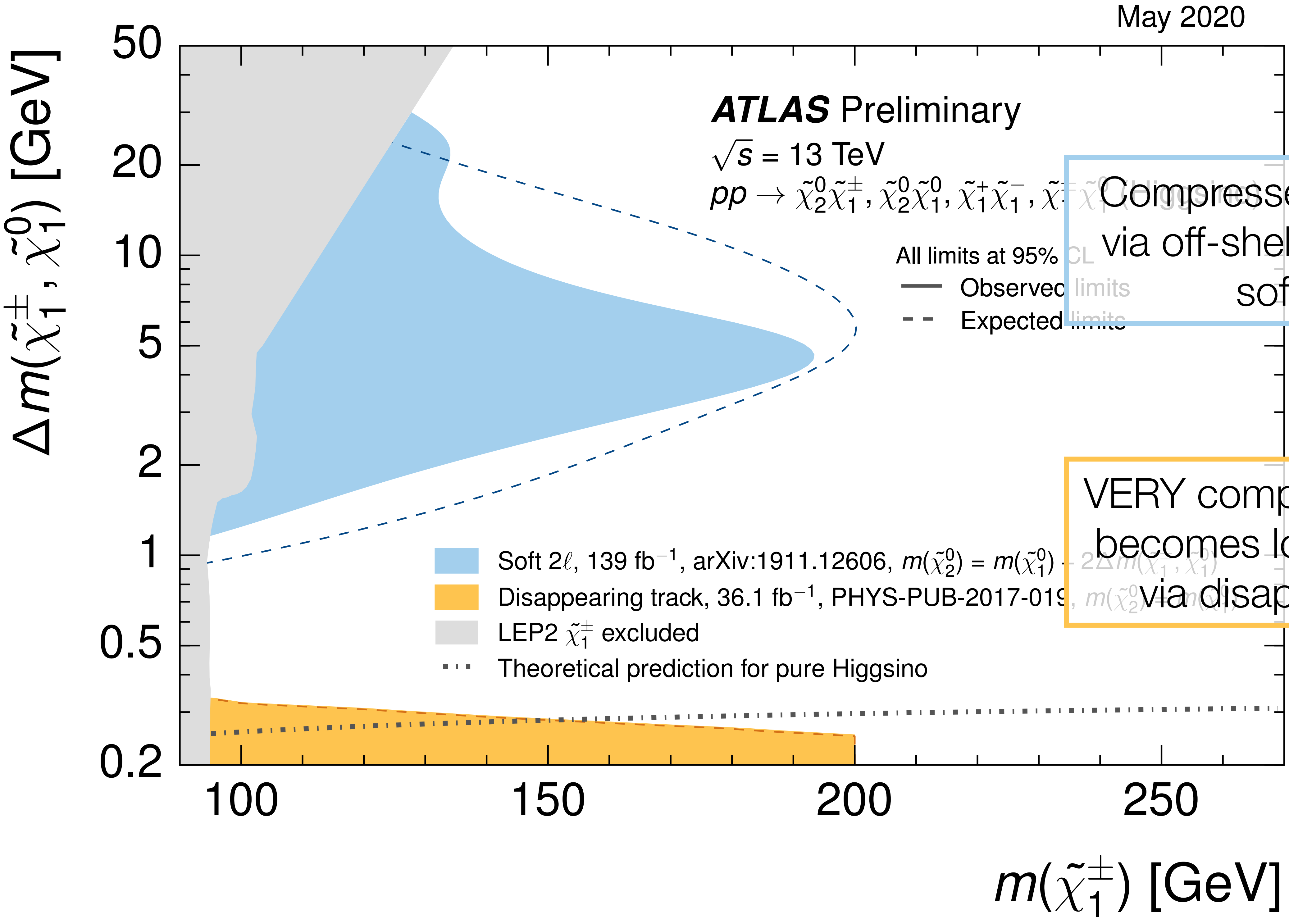
What about dark matter in RPV?

- Gravitino takes over as most likely dark matter candidate
- RPV would allow its decay, but proportionally to gravitational coupling, and thus the lifetime is really really long
-

LLP searches
and the Higgsino mass gap



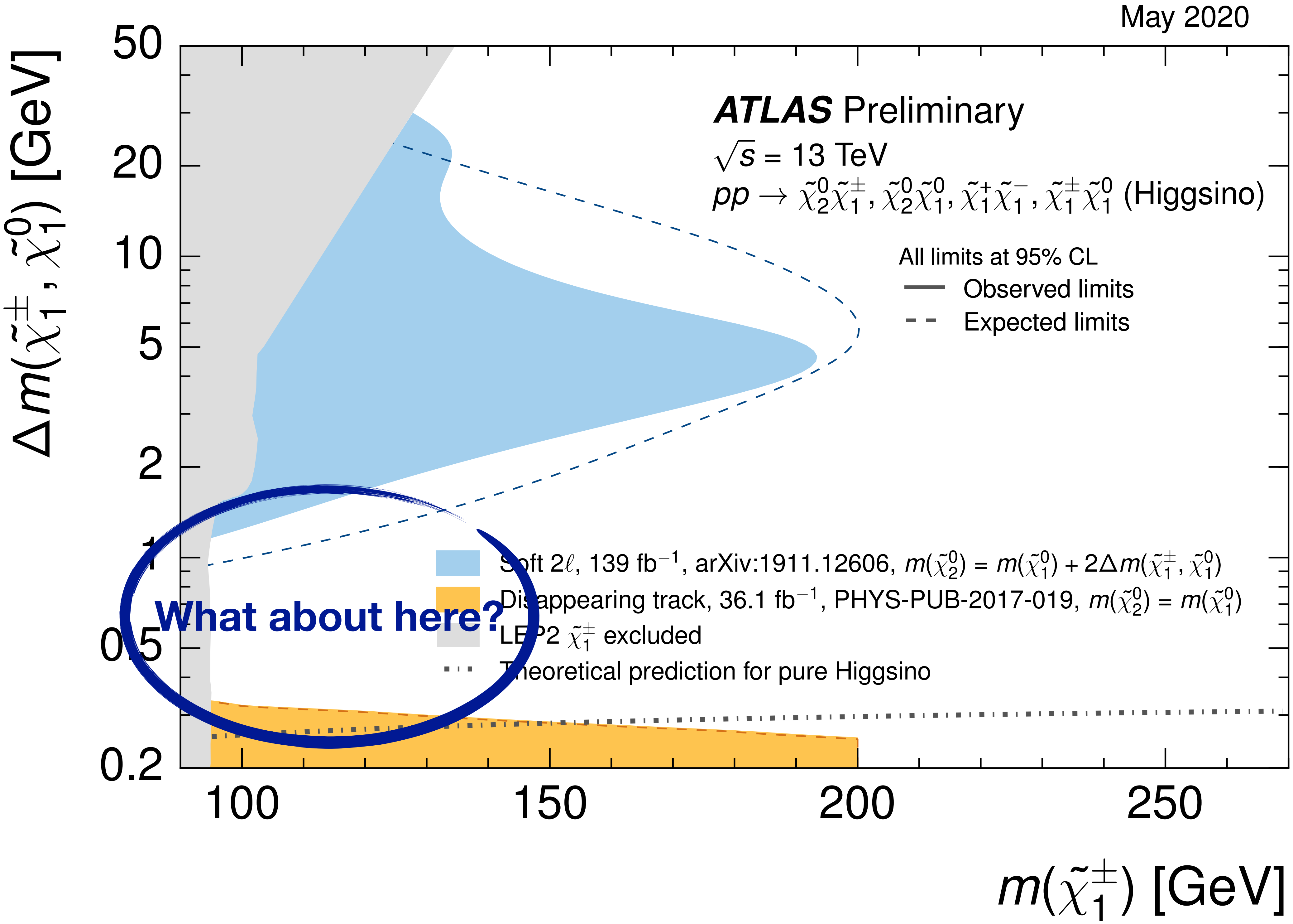
LLP searches and the Higgsino mass gap



Compressed region: decay via off-shell W, identify very soft leptons

VERY compressed: chargino becomes long-lived, search via disappearing track:

LLP searches
and the Higgsino mass gap



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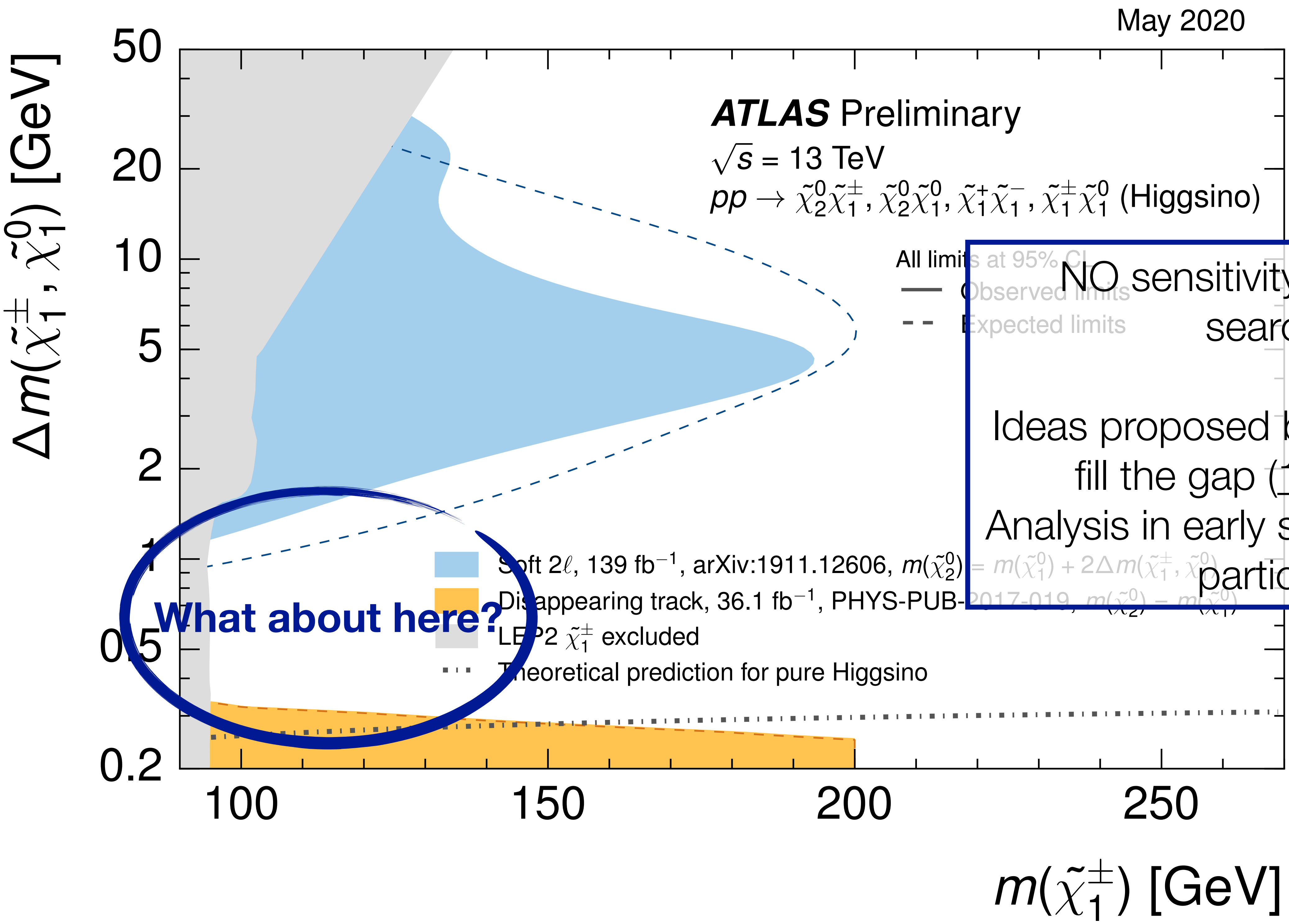
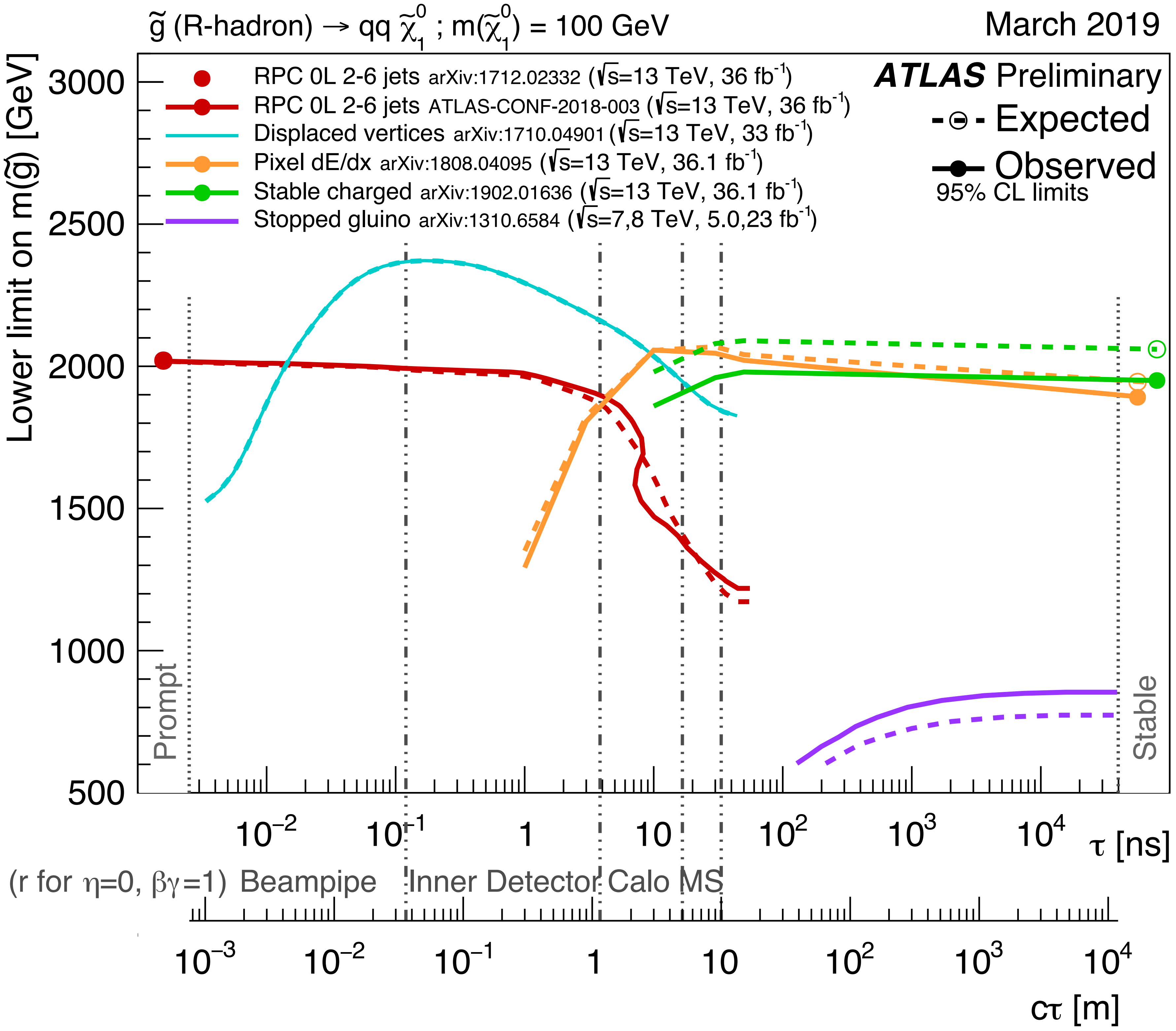


What about here?

NO sensitivity with current searches!

Ideas proposed by Tokyo team to fill the gap (1910.08065)
Analysis in early stages; I intend to participate

Why standard searches don’t suffice



What is a trigger?

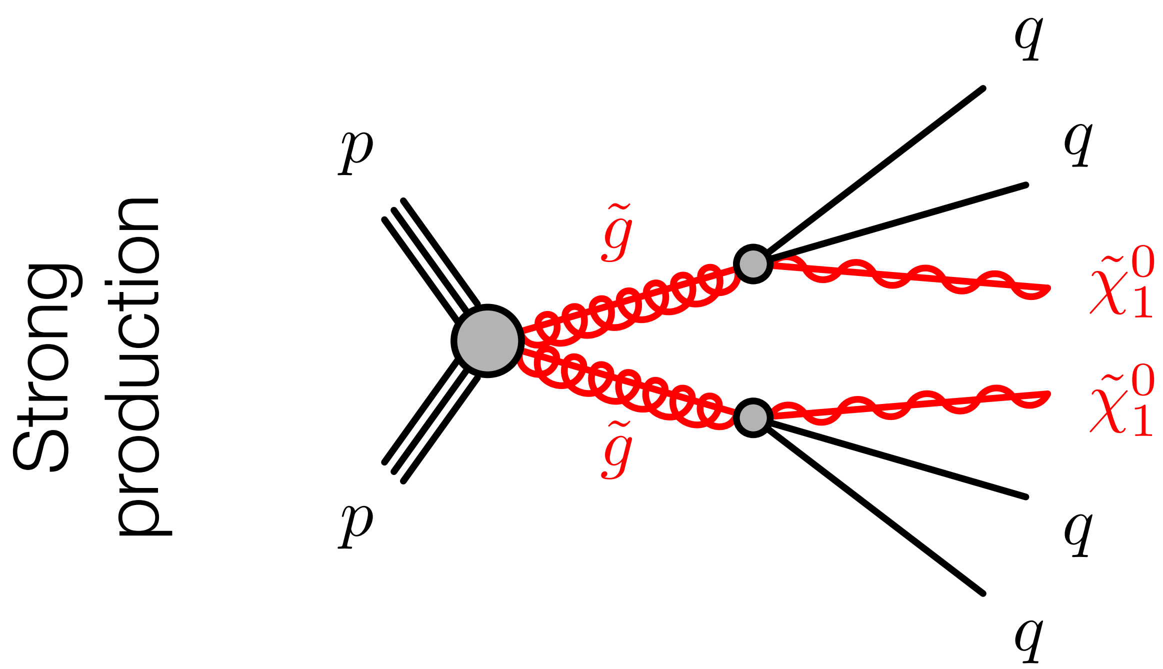
Data leaves detector at 40 MHz: way more than we can process and store!

Hardware L1 trigger reduces flow to 100 kHz

Software HLT passes ~1 kHz: 40,000 x less

A perfect drop of physics!

More dEdx: R-hadrons

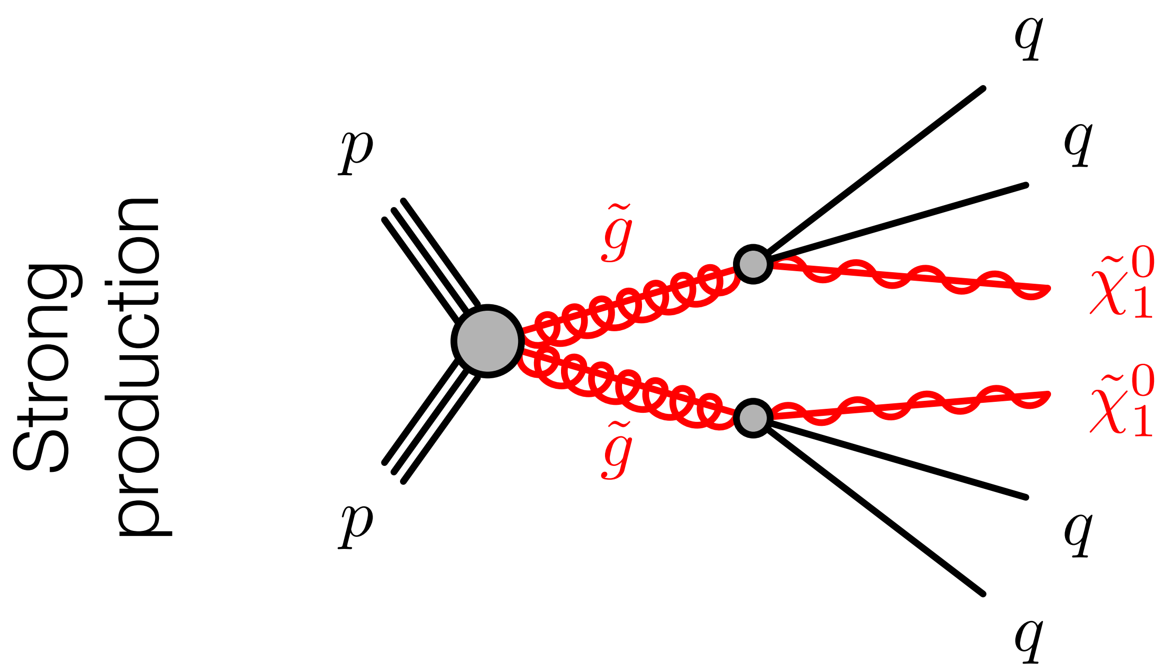


~20% of these hadrons are charged

$\tilde{g}u\bar{d}$ $\tilde{g}s\bar{d}$ $\tilde{g}s\bar{u}$

- Long lived squark or gluino results in R-hadron. Charged fraction hypothesized ~20%
- R-hadron interacts minimally with calorimeter (think very high pT pion) - missing energy signature
- Case where stable charged particle not necessarily going to do better at long lifetimes: charge flipping can occur as R-hadron collects & deposits quarks in calorimeter. Can have ID track and nothing in the MS

More dEdx: R-hadrons



Our gluino isn't charged… but all strongly charged particles must hadronise

~20% of these hadrons are charged

$\tilde{g}u\bar{d}$ $\tilde{g}s\bar{d}$ $\tilde{g}s\bar{u}$

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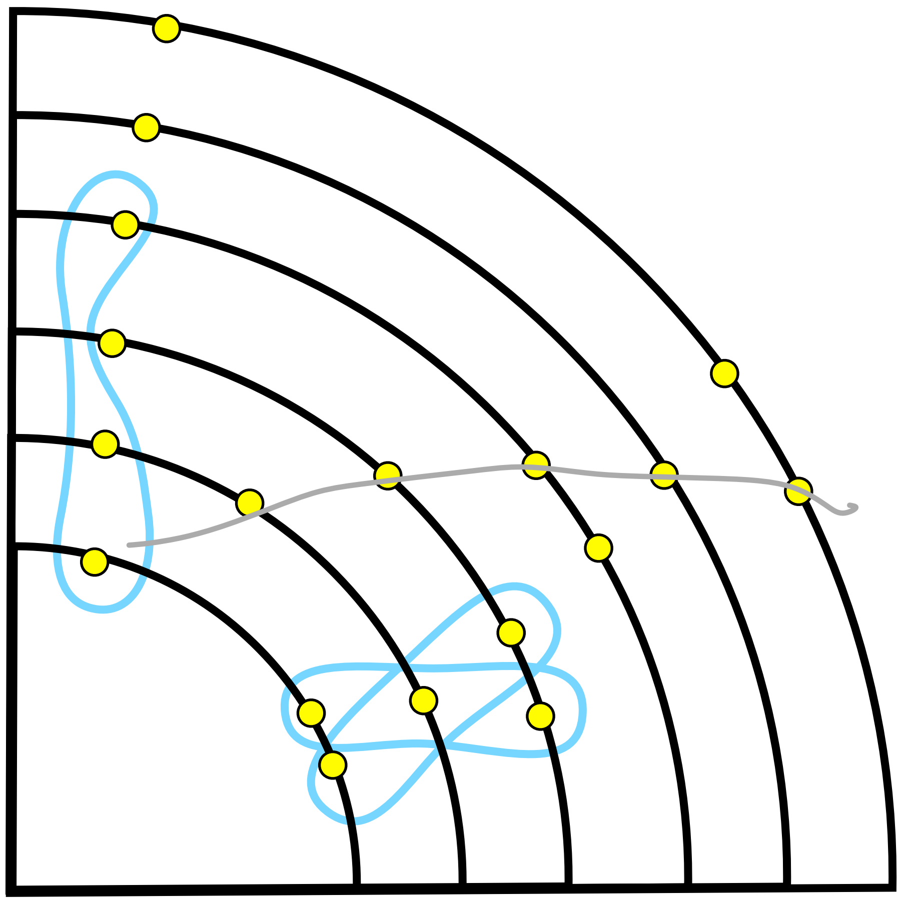
Cosmic ray vetos

- ~70% of cosmic events in ATLAS reconstructed as two muons. Remainder are missing top half (timing identified as backward-going).
- In these cases, use muon spectrometer hits to check opposite a reconstructed muon
  - Use direction from spectrometer hits to do matching, rather than η/ϕ w.r.t. origin
- Additional veto for cases where incoming muon would have passed through non-instrumented slice at $\eta=0$
- Efficiency for eliminating cosmics = 99.7% as tested in cosmic run

How does track reconstruction work? ATLAS



Pierfrancesco Butti

Next: outside-in starts from TRT seeds and extrapolates backwards. Both restrict candidates to near PV.

- Inside-out tracking (ATLAS primary)
  - Find **seeds** (pixel detector only) using 3-hit groups.
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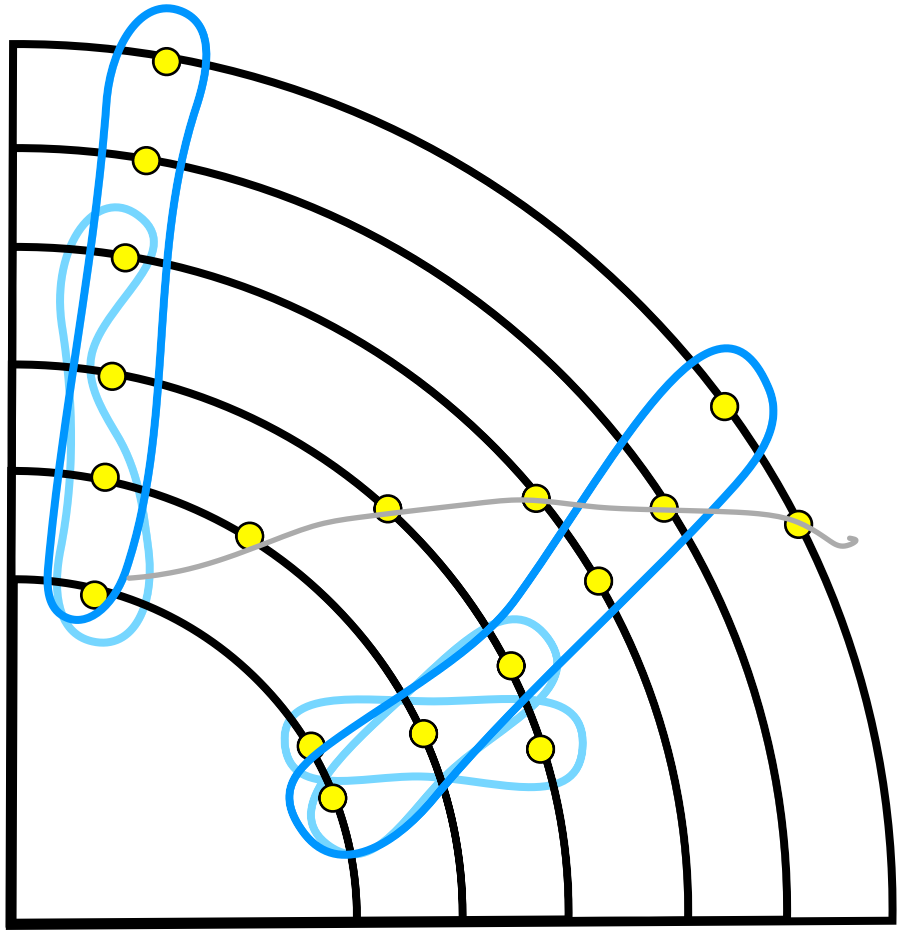
How does track reconstruction work? ATLAS



Pierfrancesco Butti

Next: outside-in starts from TRT seeds and extrapolates backwards. Both restrict candidates to near PV.

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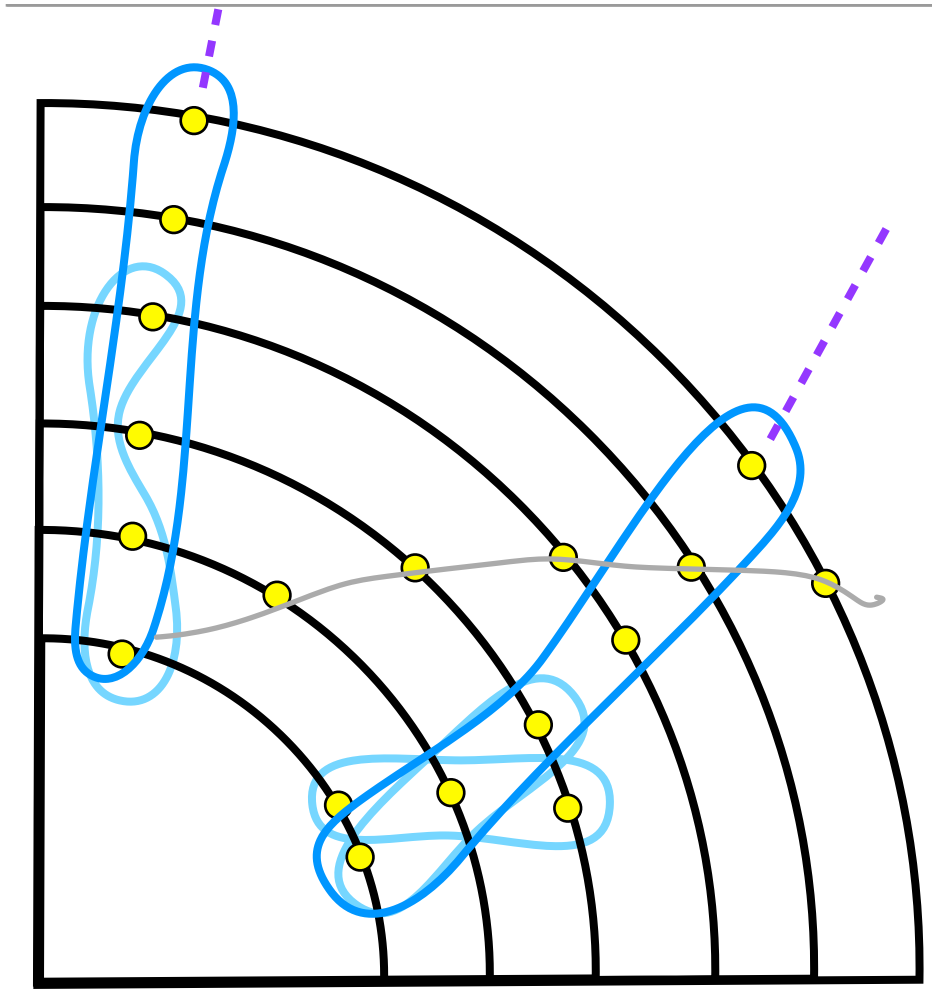

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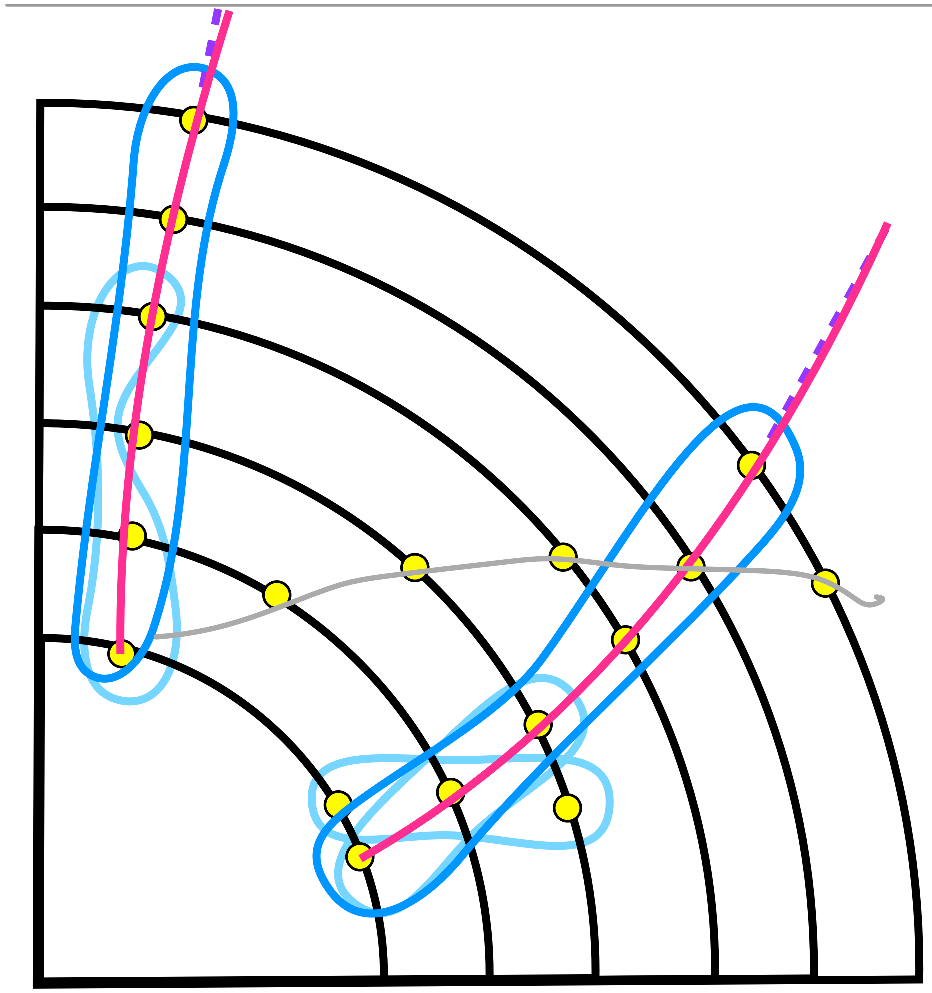

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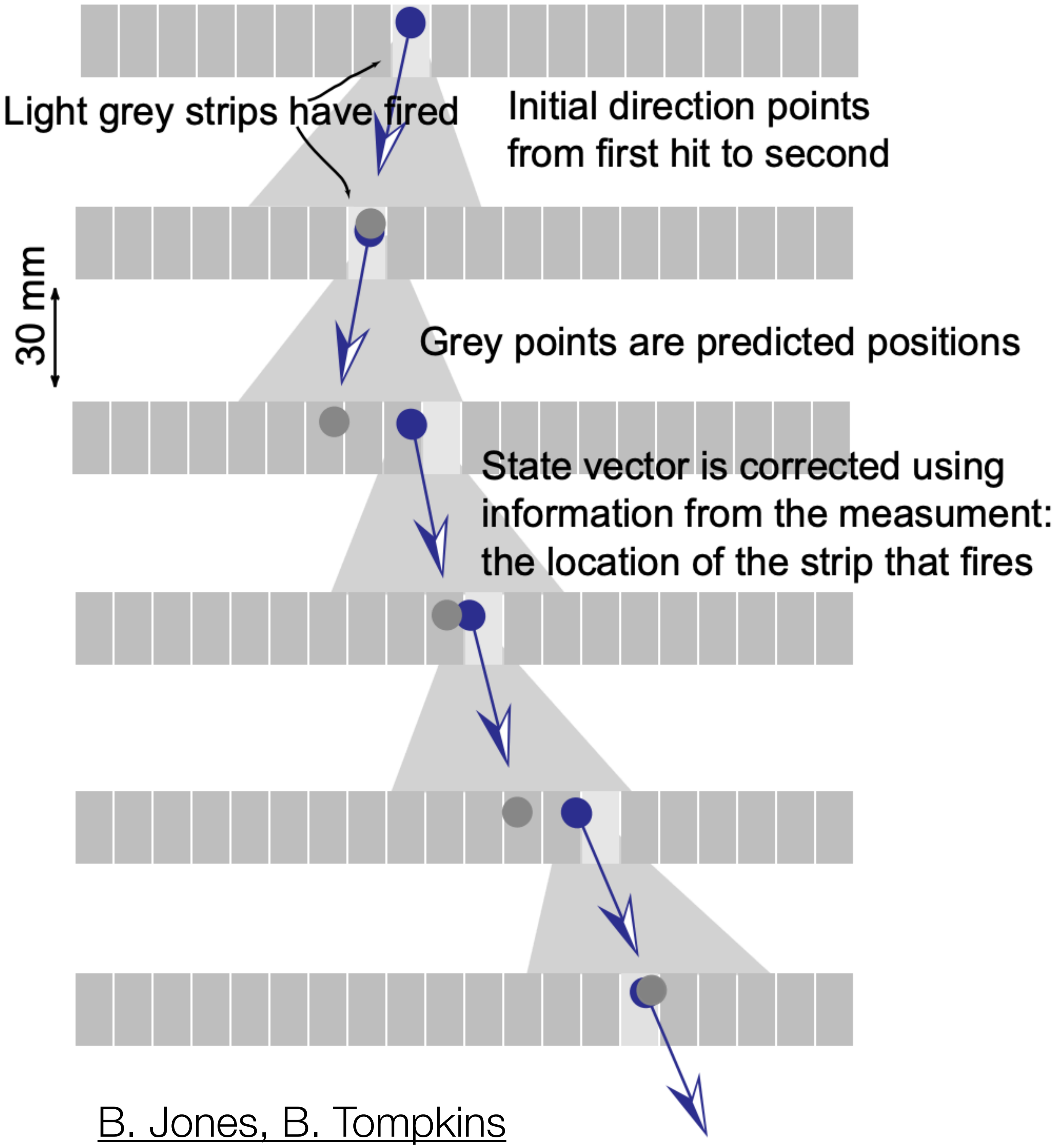
What’s a Kalman filter?

- “Linear quadratic estimation”. Algorithm which uses set of points to predict next point in the set using joint probability distribution of those already observed.

- Prediction step, then once next point is added, taken into account and probability distribution adjusted.



Light grey strips have fired

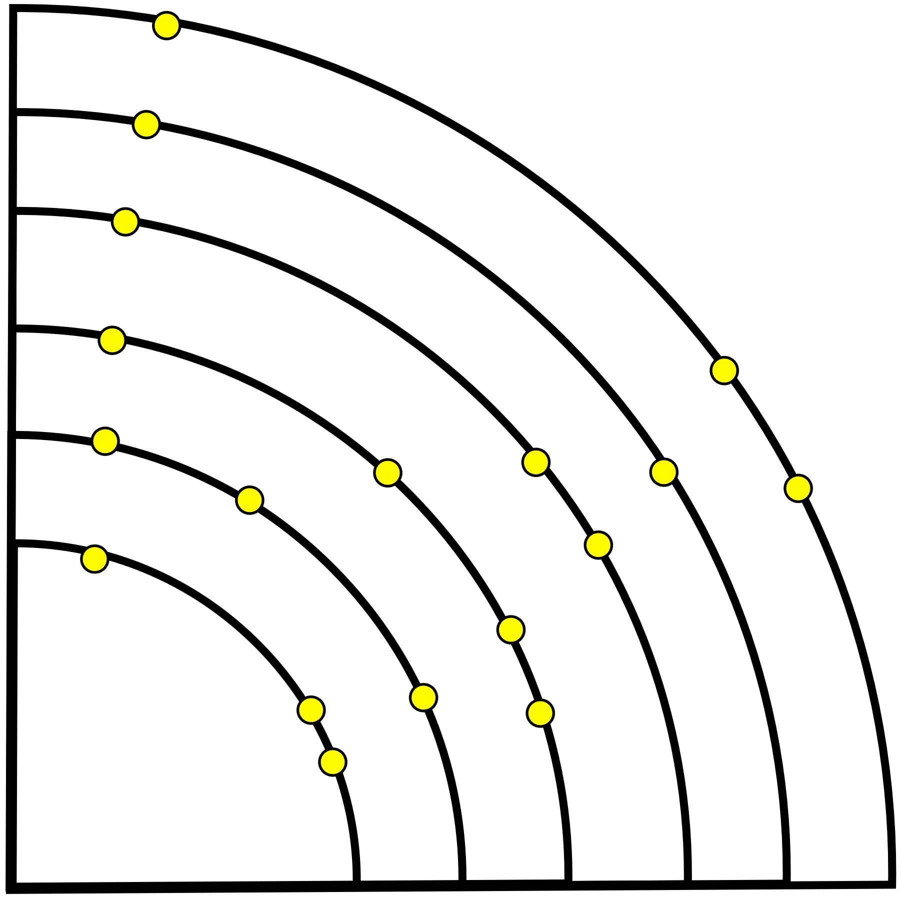
Initial direction points from first hit to second

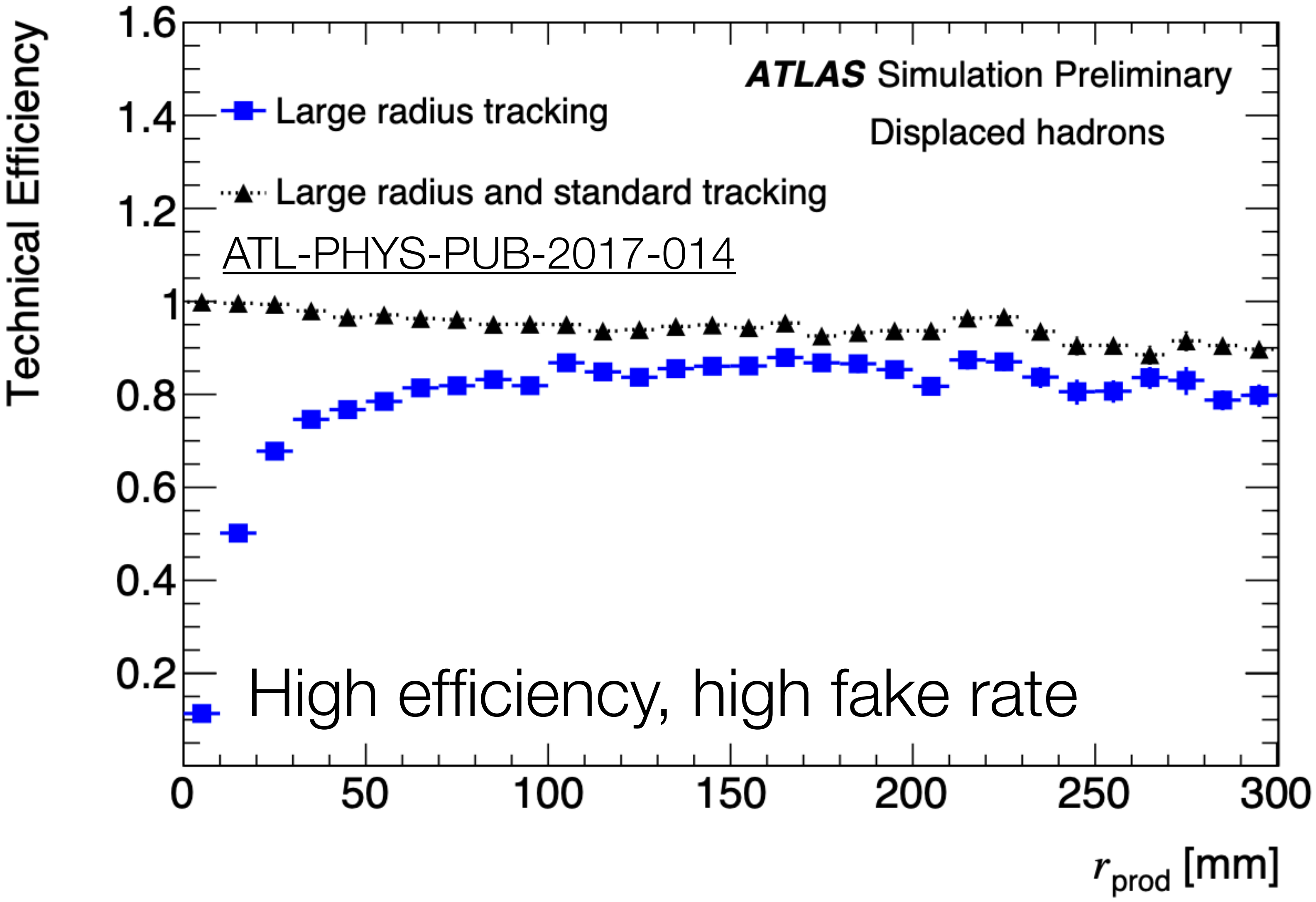
Grey points are predicted positions

State vector is corrected using information from the measument: the location of the strip that fires

B. Jones, B. Tompkins

Large-radius tracking in ATLAS





ATL-PHYS-PUB-2017-014

High efficiency, high fake rate

- After inside-out and outside-in standard tracking, leftover points can now be used for second-pass tracking
- Sequential Kalman filter. Otherwise much the same as standard tracking but with loosened z0 and d0 requirements

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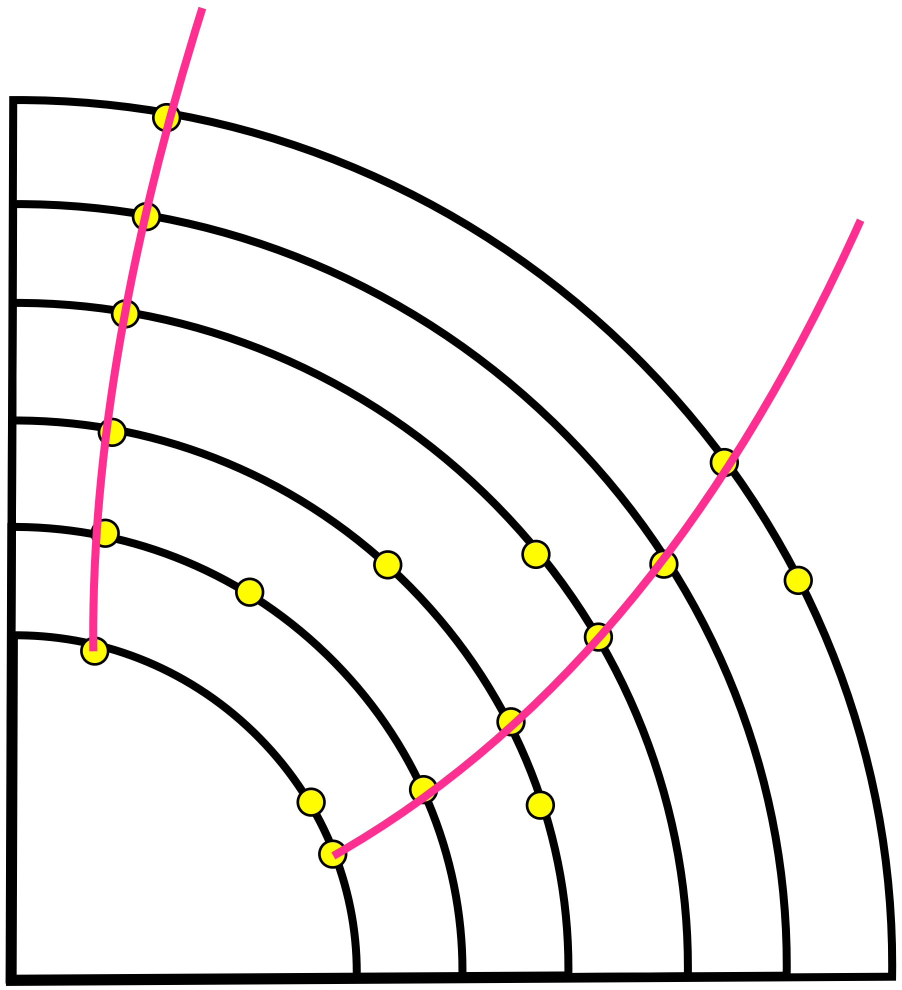

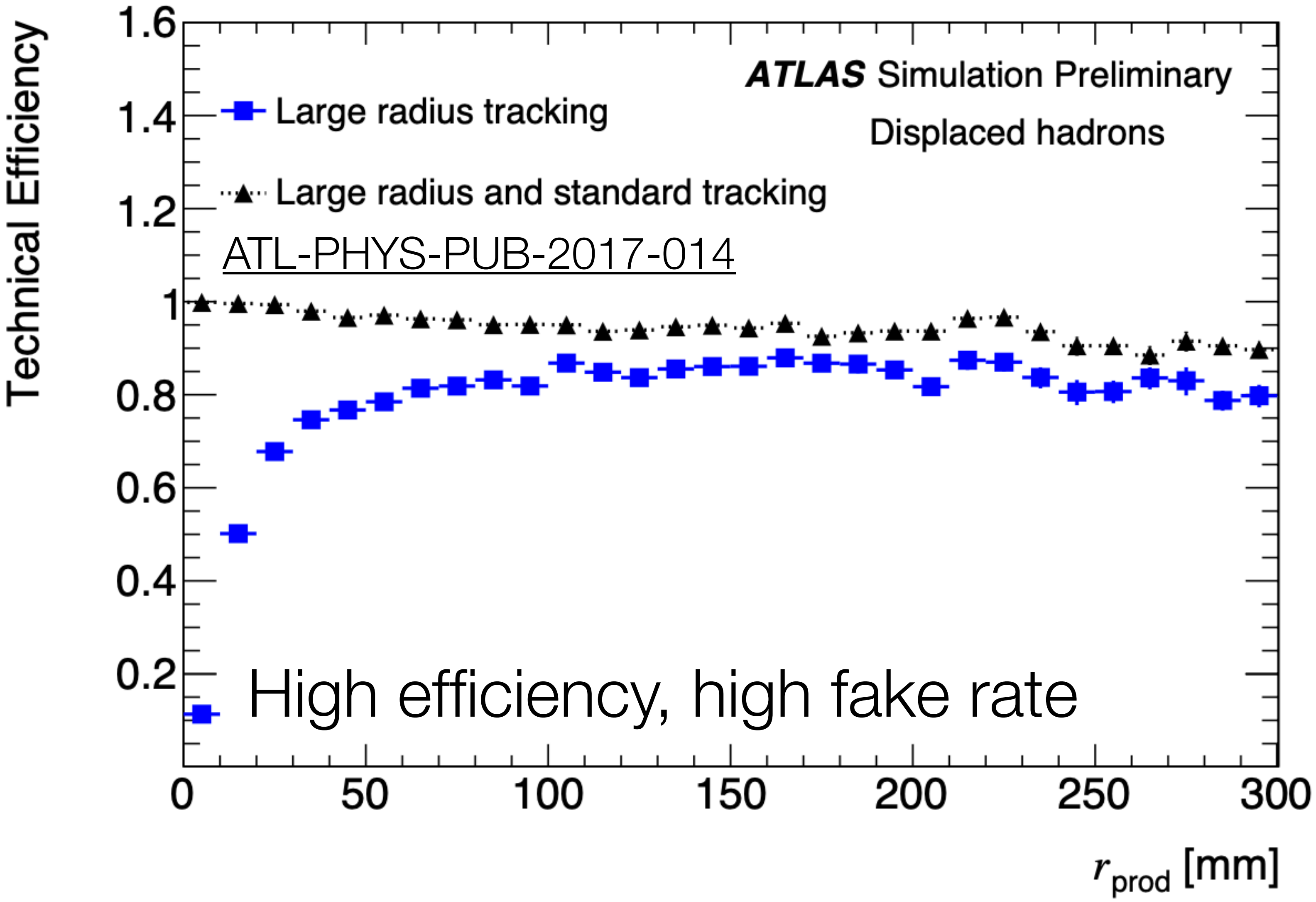

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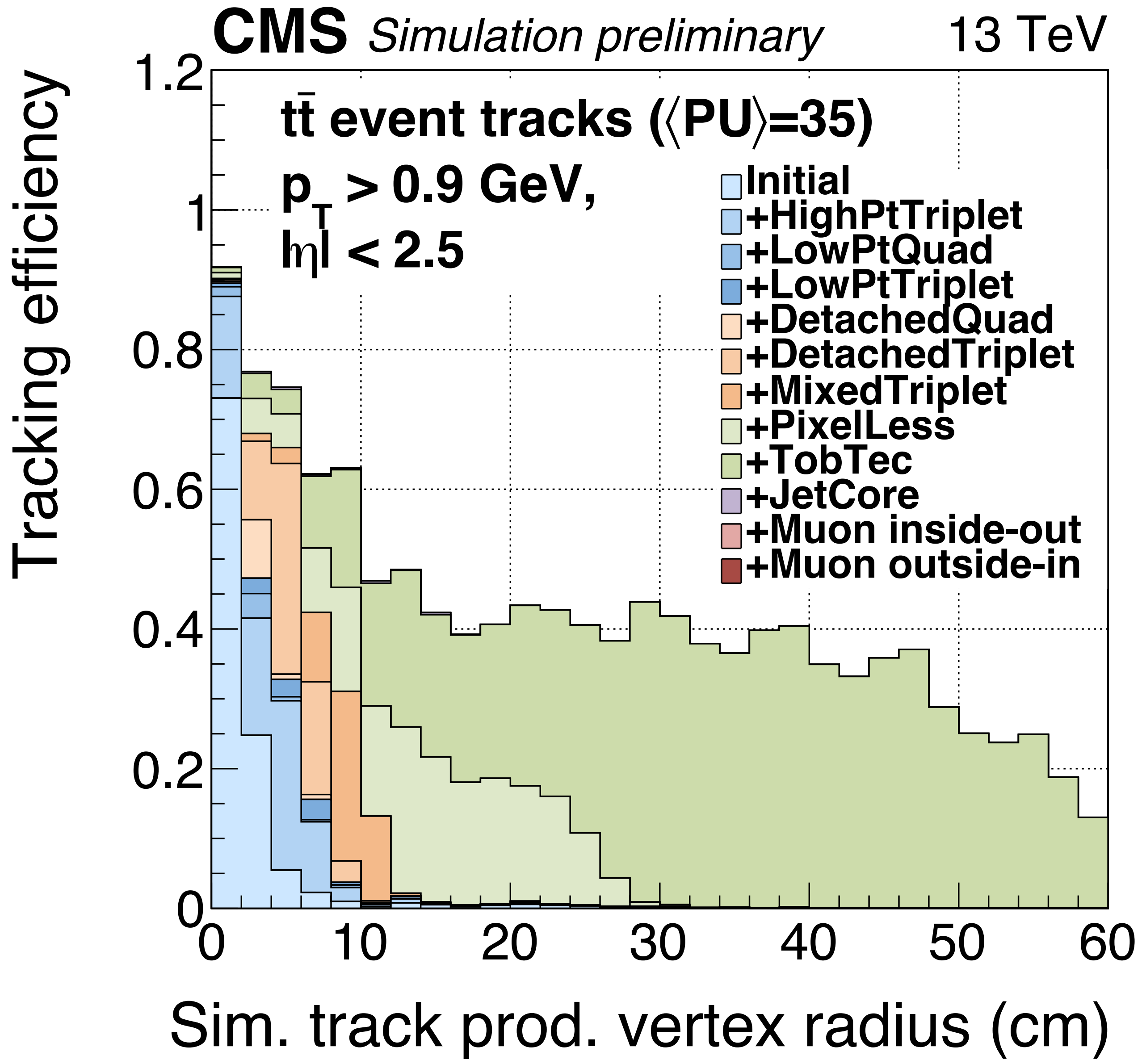
Large radius tracking and ATLAS data flow

- LRT is slow and has a high fake rate: can not run in default reconstruction
- Instead, define filters based on standard reconstruction to identify some fraction of events (currently ~10%)
- These events are separately reconstructed from RAW with all machinery of interest to long lived particle searches
- Get to keep all tracks selected by LRT, but need to sacrifice some events to keep rates low. Adds a trigger-like layer of inefficiency to analyses requiring LRT

Large-radius tracking in CMS



Lower efficiency, lower fake rate
Efficiency sacrifice worth it to
get to run in all data!

- Large radius tracking run as part of *standard reconstruction* in CMS
- Tracking in 4 steps (seeding, track finding, fitting, selecting good tracks) repeated many times with loosening restrictions. Each pass, used points are removed
- This reduces combinatorics for next pass. Large-radius tracks allowed as late iterations.

ATLAS track triggers in Run 3

- Cancellation of FTK project means need to find an alternative form of pileup suppression in Run 3
- Proposal: full-scan tracking above some p_T threshold (TBD) for events passing jet or MET L1 trigger
- This allows rejection of pileup jet triggered events and more accurate MET
- Tracking in trigger runs within ROIs: even full scan. Identify ROI, use modified fast tracking (different seed finding, fast Kalman filter) to get initial candidates. Offline ambiguity solver produces precision tracks. Probably sacrifice precision tracks in Run 3.
- Tracking in trigger is an opportunity for LLPs - can use MET or jet L1 to seed custom trigger - but it is also a hazard: rejection of jets with tracks not associated to PV could kill displaced signals. Studies ongoing.

ATLAS track trigger in Runs 4-5

- HTT (hardware track trigger) current plan but up in the air: details will depend on readout speed of ITk components.
  - Pattern matching in AM chips
  - First and second stage tracking done by FPGAs
- L1Track: 4 MHz rate, can fit tracks with pT > 4 GeV. First stage fit only, happens in ROI. Can be done on ~10% of detector.
- Global HTT: Second stage (HLT) tracking to be done in full detector using similar associative memory pattern matching. Can run on ~10% of events as requested by Event Filter
- Option to replace global HTT with CPUs if performance and computing budget seem comparable

CMS track trigger in Runs 4-5

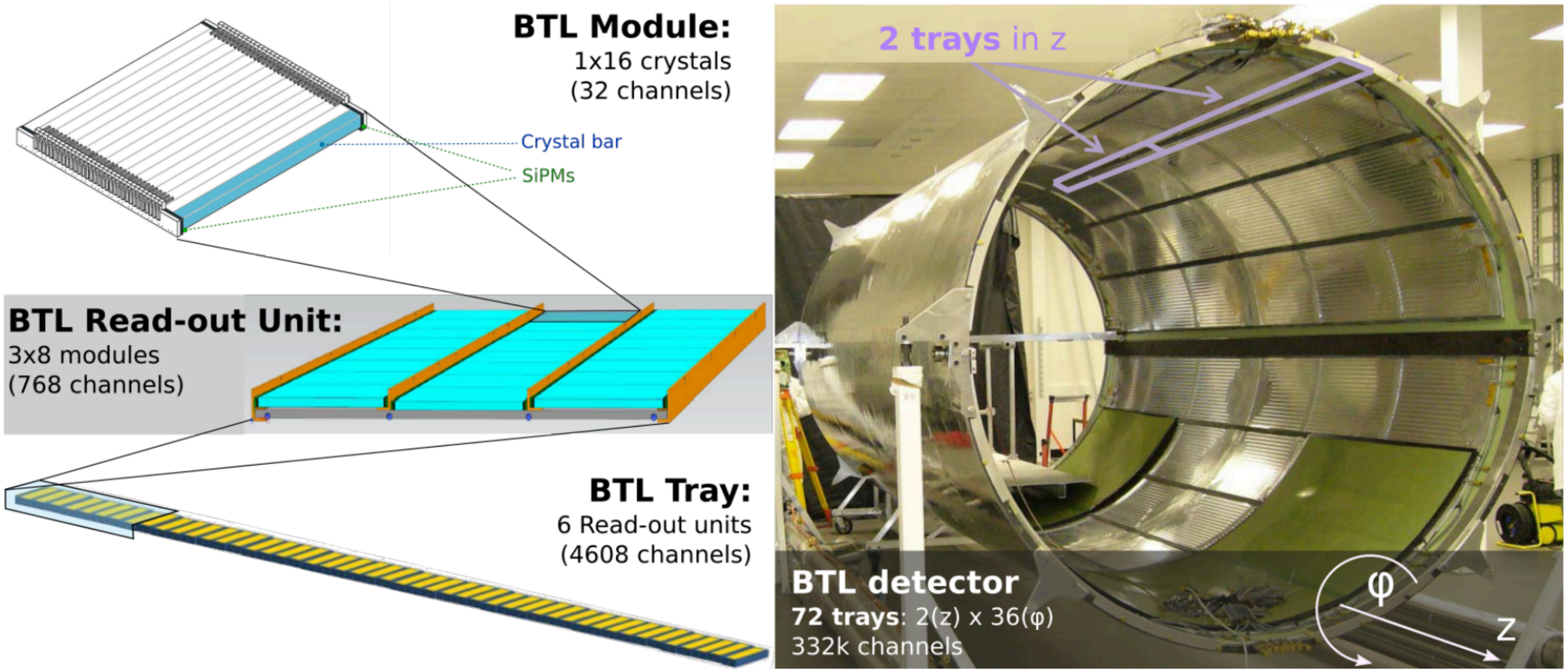
- Hardware level at run 1: “stubs” in outer tracker
    - Assume we have a track originating from beam and passing through two closely spaced tracking layers. Pass if two hits + beamline compatible with high pT track
    - FPGA-based second stage will extend stubs into track candidates. Two algorithms being tested, so far similar performance: extending stubs geometrically into tracklets, or Hough transforms + Kalman filters.
- Software at HLT
    - Moving to GPUs allows many-thread processing
    - New algorithms plus smart data formatting/accessing tunes for GPUs make most efficient use of it

CERN-LHCC-2015-010

CERN-LHCC-2017-027

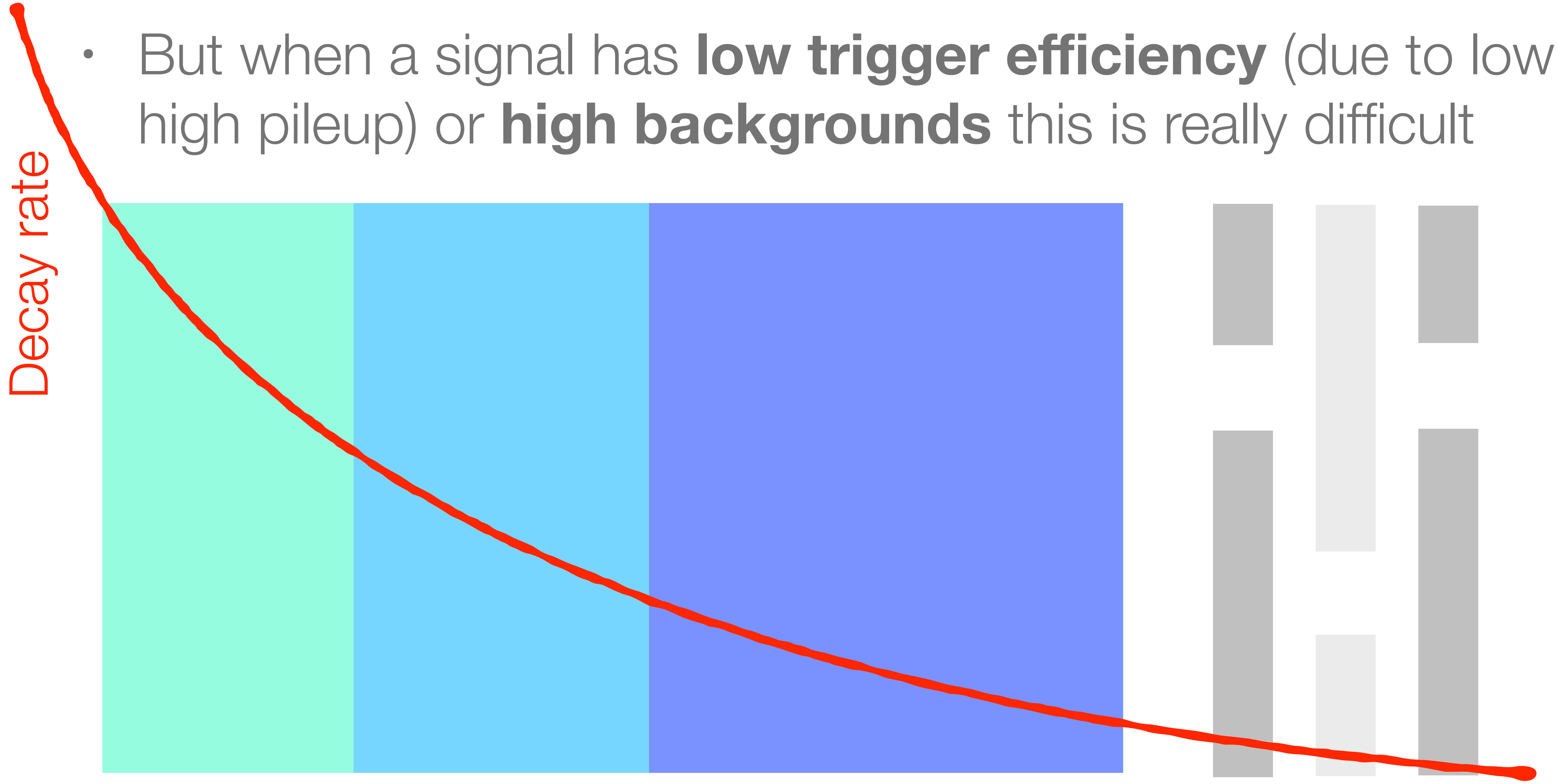
MIP timing detector

- Resolution ~30 ps in timing and ~3mm in z direction
- Barrel coverage (ATLAS only has forward coverage with HGTD): therefore can use for centrally produced LLPs
- Lutetium-yttrium orthosilicate crystals (LYSO) + silicon photomultipliers



Beyond CMS and ATLAS

- Long lived neutral particle can **only** be seen via decay products
- As long as we can get **full efficiency** and **zero background** with our detector, always better to search closer to collision point
- But when a signal has **low trigger efficiency** (due to low mass or high pileup) or **high backgrounds** this is really difficult



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If the lifetime is long enough…

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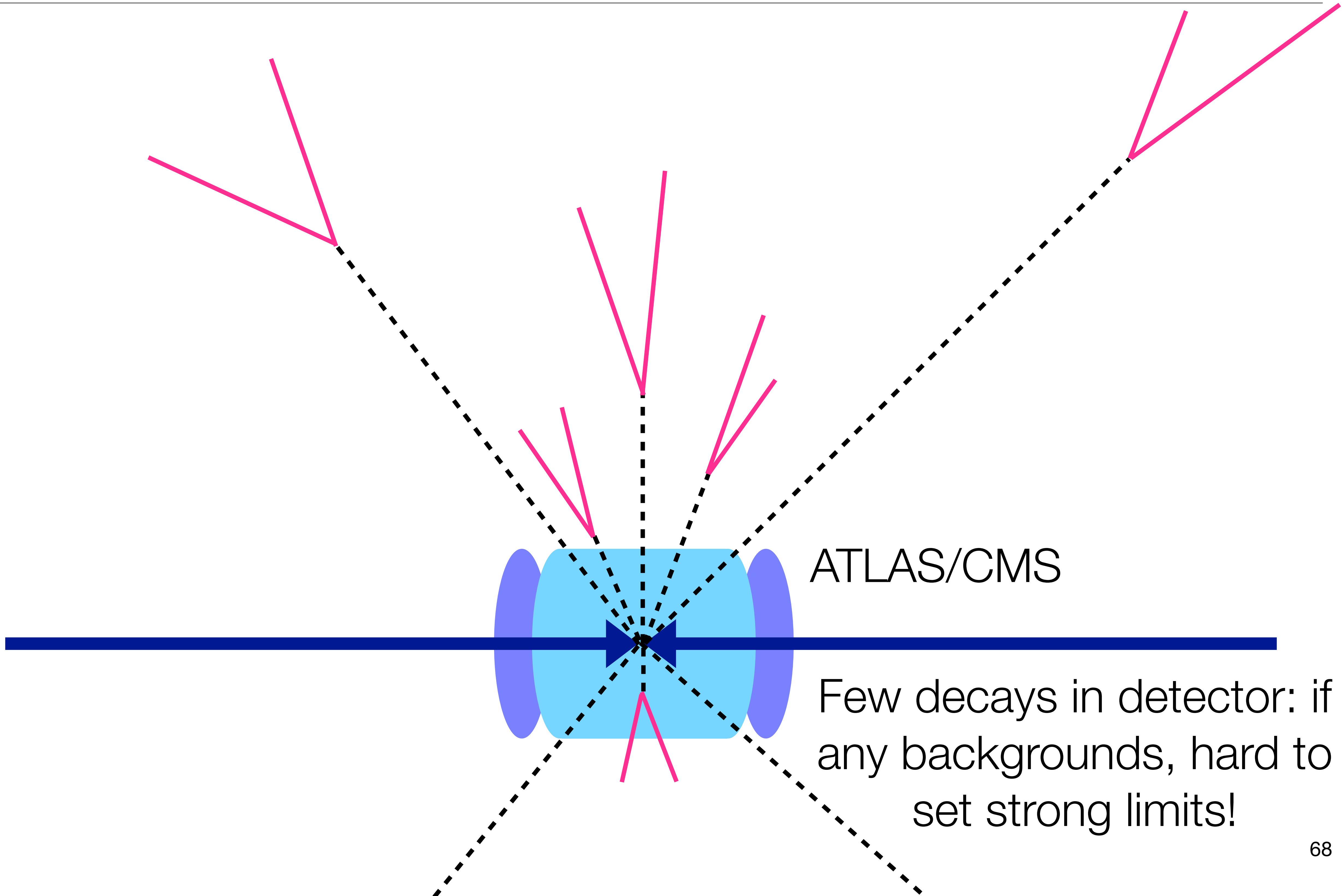
If the lifetime is long enough…

…we do much better by looking out here

Why we need a dedicated LLP experiment



ATLAS/CMS

Few decays in detector: if any backgrounds, hard to set strong limits!

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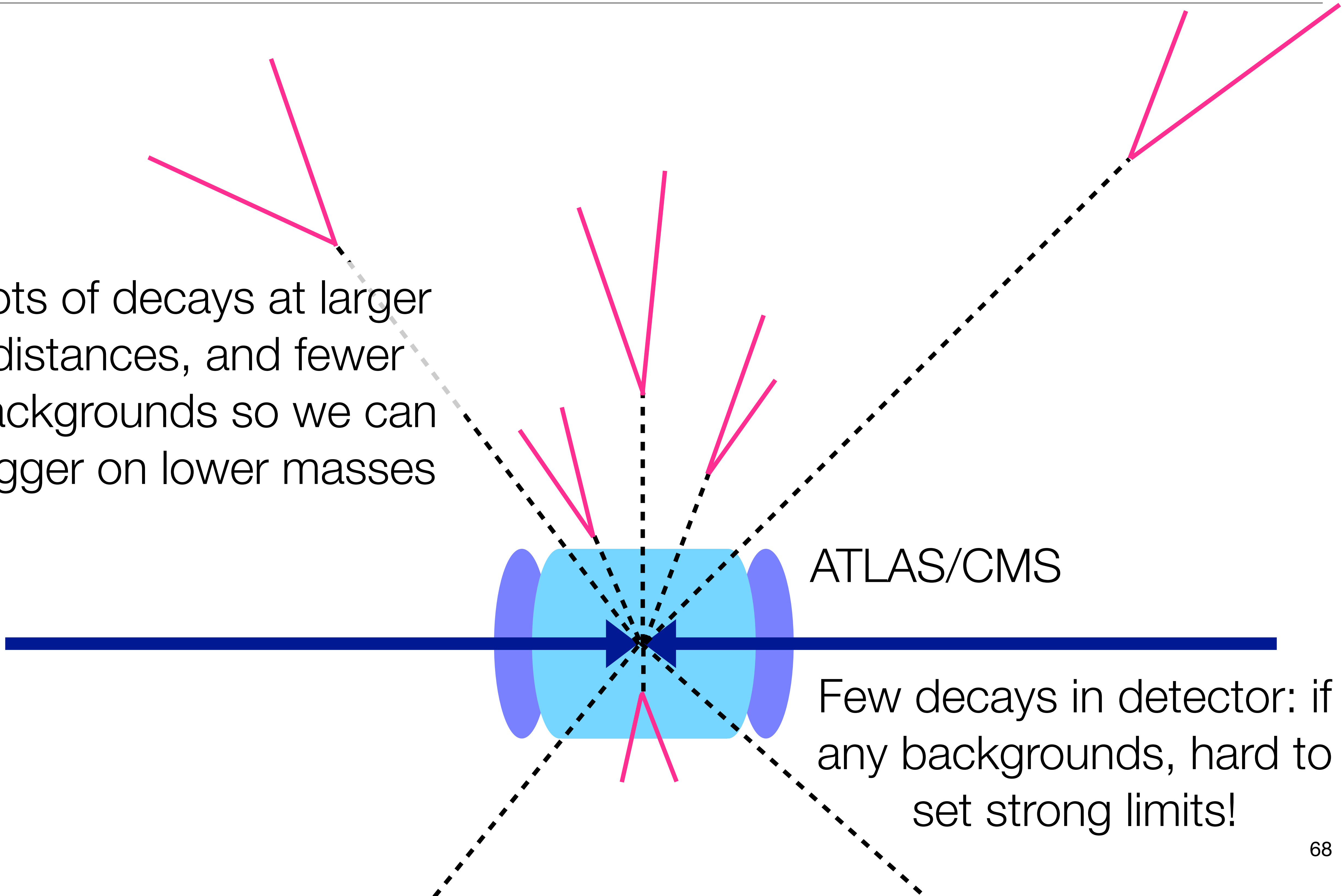

Lots of decays at larger distances, and fewer backgrounds so we can trigger on lower masses

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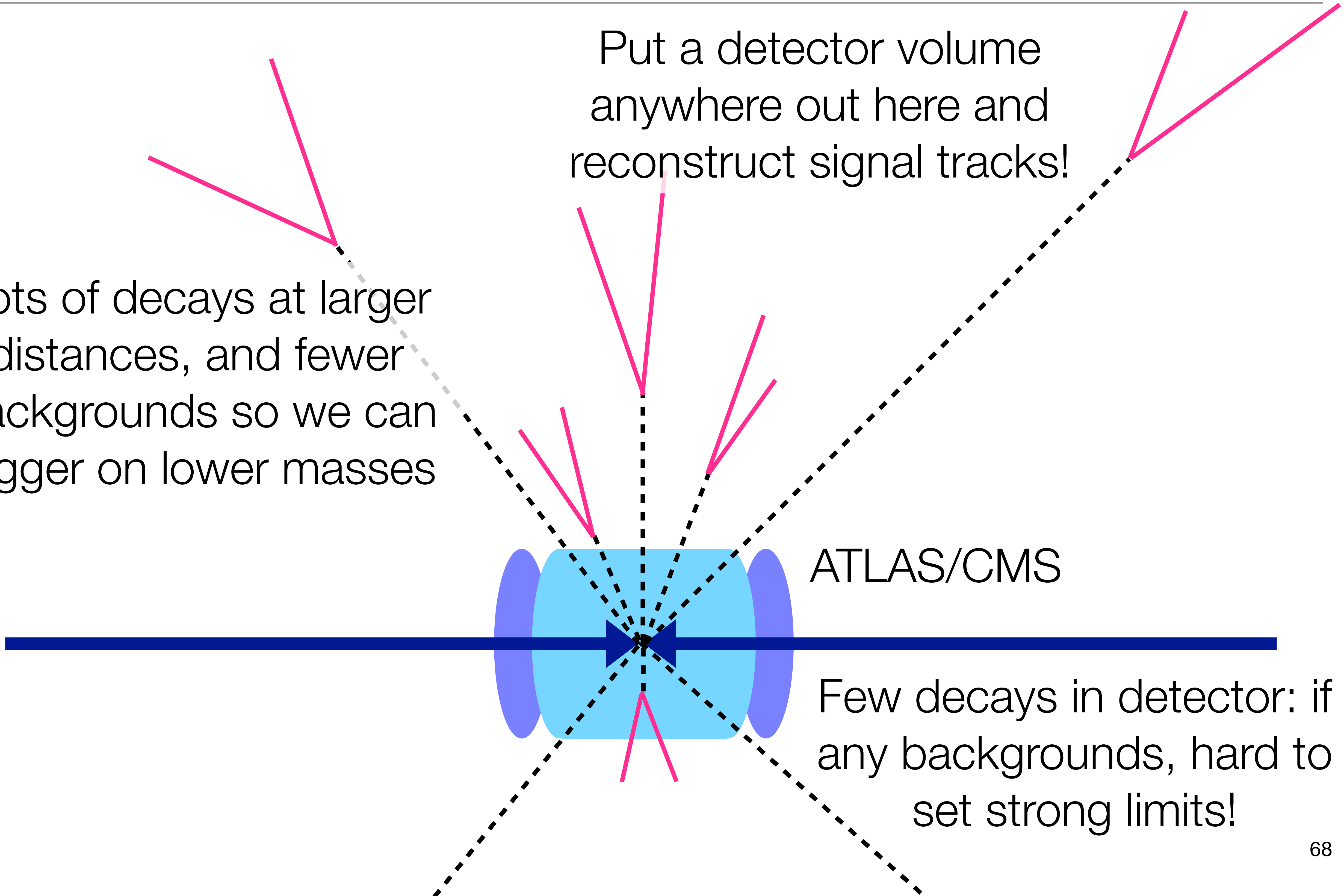

Put a detector volume anywhere out here and reconstruct signal tracks!

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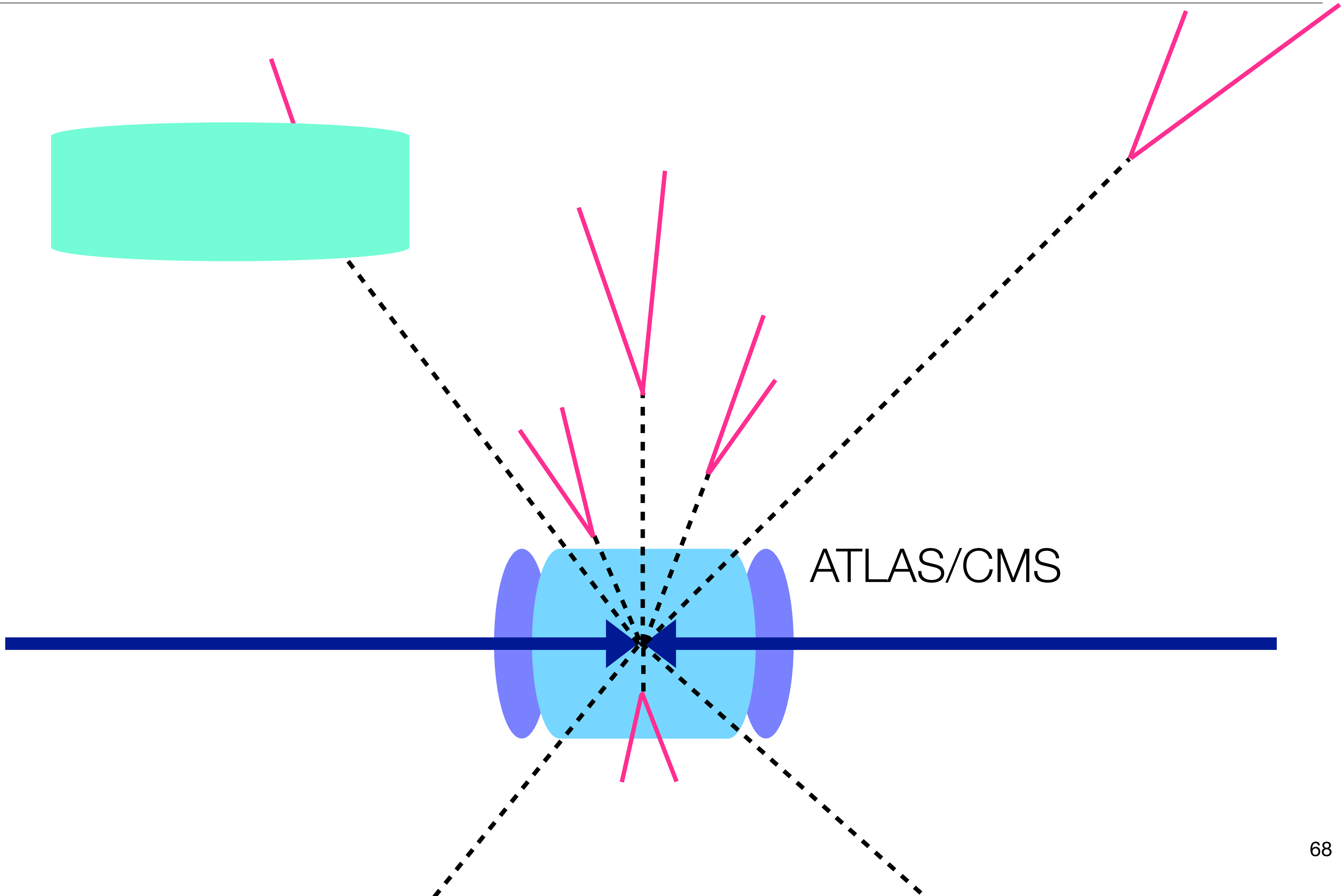

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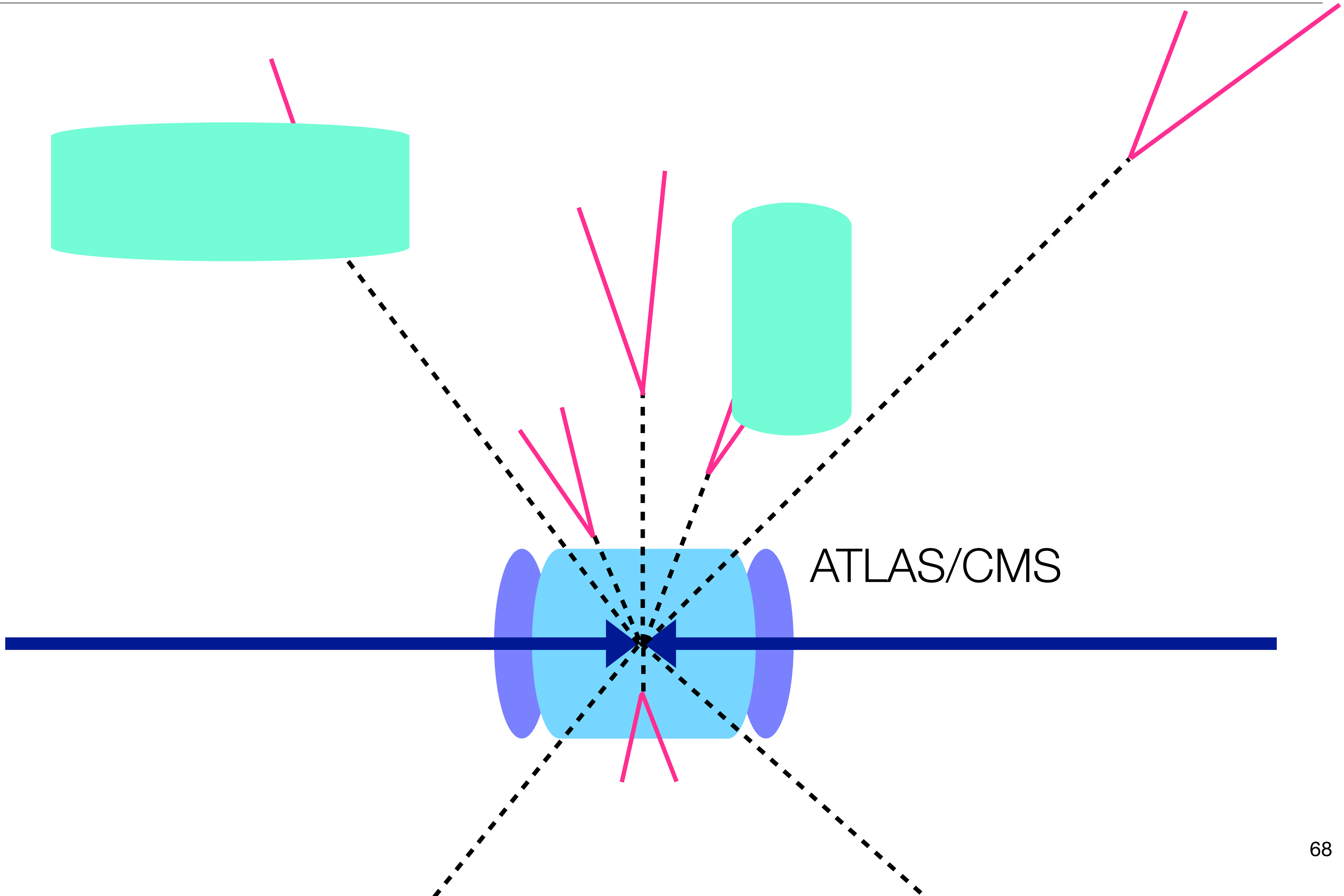

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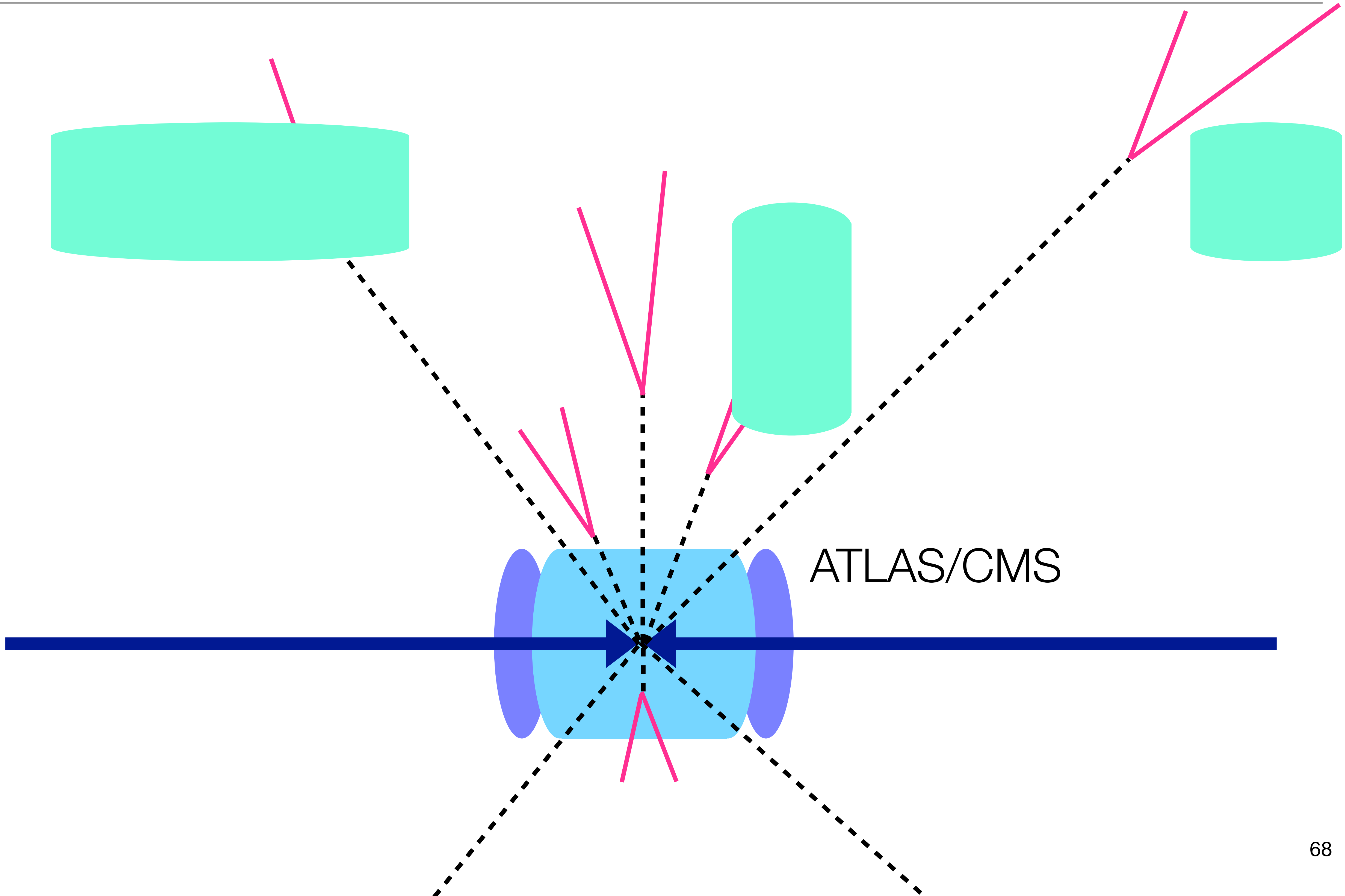

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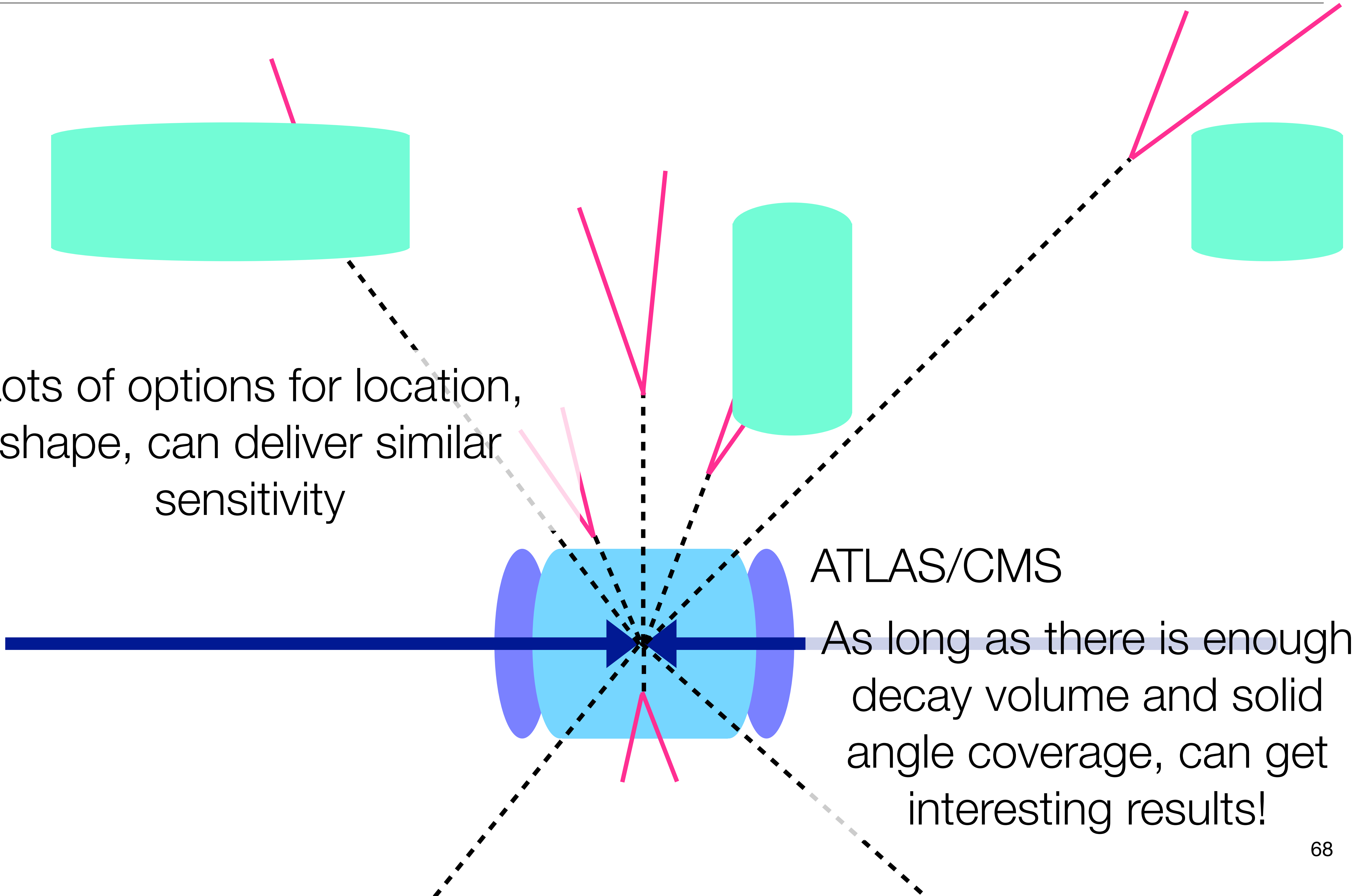


Lots of options for location, shape, can deliver similar sensitivity

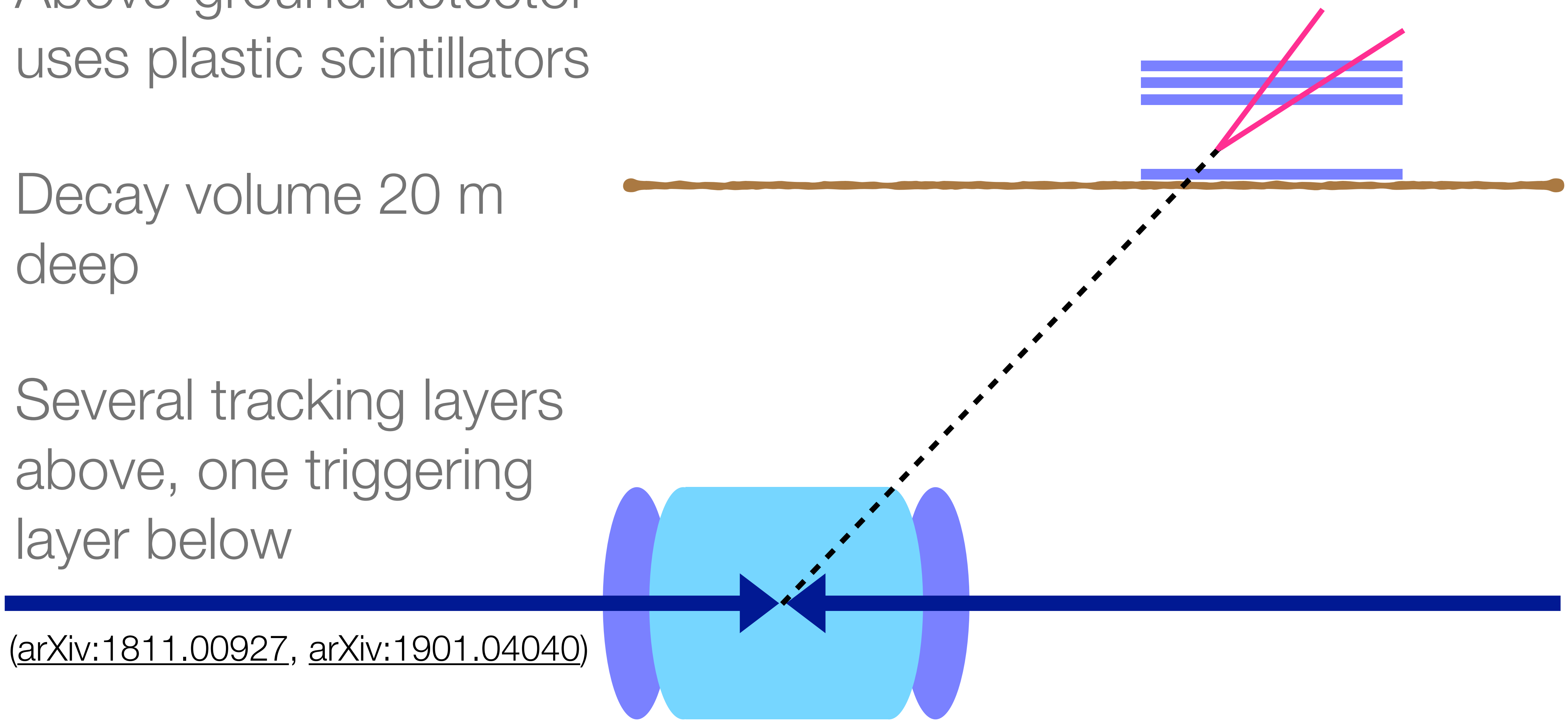
As long as there is enough decay volume and solid angle coverage, can get interesting results!

Example: MATHUSLA

- Above-ground detector uses plastic scintillators

- Decay volume 20 m deep

- Several tracking layers above, one triggering layer below



(arXiv:1811.00927, arXiv:1901.04040)

MATHUSLA is a leading proposal today, with **long lifetime reach** and the bonus opportunity to study **cosmic ray showers**

J. Feng, I. Galon, F. Kling, S. Trojanowski

P. Agrawal et al

M. Raggi, V. Kozhuharov

FASER

- FASER experiment now approved by LHCC and moving forward! Only approved dedicated LLP search at LHC.
- Downstream 480m from ATLAS, specialises in sub-GeV signals (e.g. dark photons)
  - Very light signals are produced along the beamline, as opposed to heavier particles which are produced centrally
- Can have a tiny experiment: just 10cm diameter by 5 m long
- Triggering/veto layer, empty decay volume, then 3 tracking layers and an EM calorimeter

Note on dark photons: generic term for neutral vector particle which has some interaction with SM fermions (e.g. kinetic mixing). Considered to have a nonzero but very small mass (viable DM candidate)

MATHUSLA @ European Strategy
MATHUSLA LOI

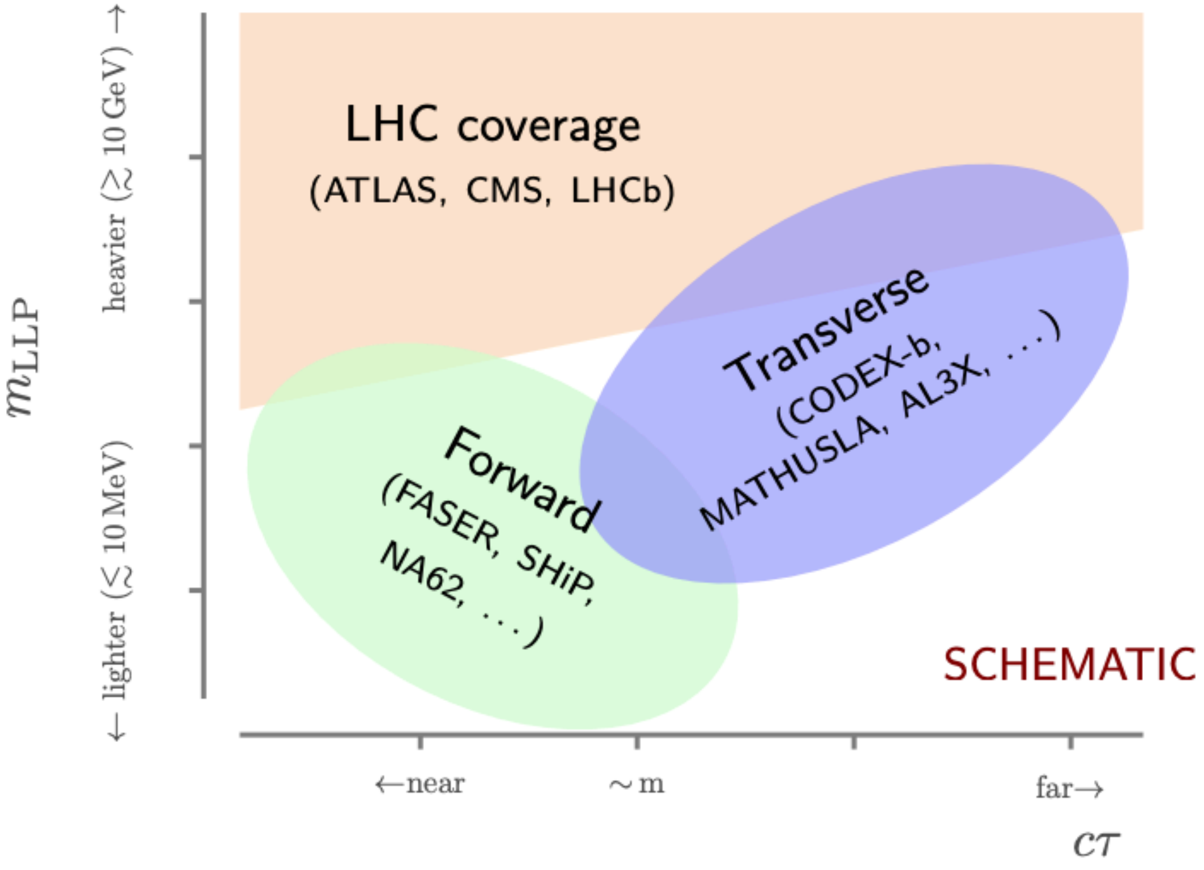
MATHUSLA

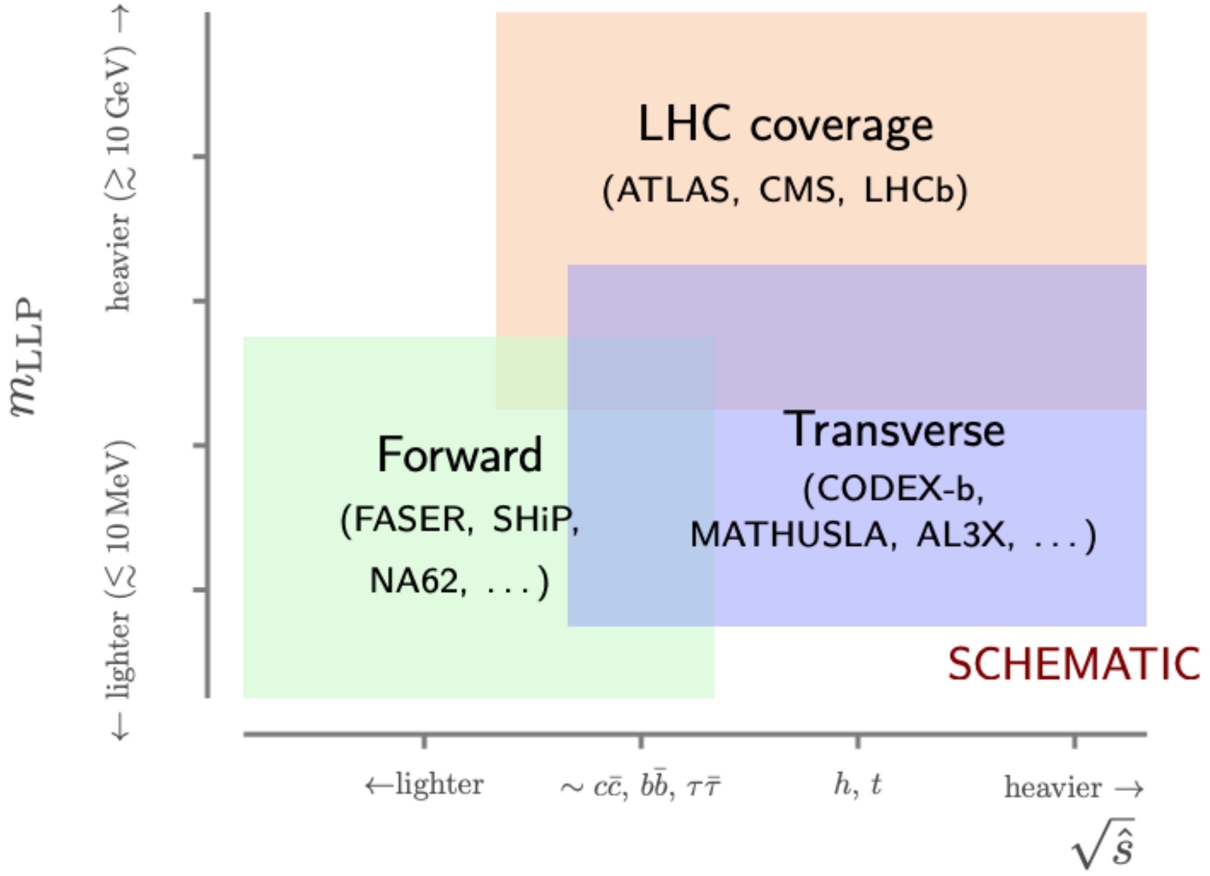
- Design: nominally 100x100x20 m
  - Modular; can easily scale up or down as needed to fit budget
- Location near CMS site, already discussed
- Technology likely plastic scintillator + SiPM: RPCs considered but gas + high voltage too inconvenient/dangerous
- Cosmic ray backgrounds challenging: down-going easy to veto, but splash back (albedo) requires more work
- However, opportunity for measuring with fine granularity incoming cosmic ray showers also. Physics case document in progress for this.

MATHUSLA, FASER, SHiP, etc

- So many models one could compare in that any specific interpretation would appear biased
- However, can roughly group proposals by type: forward/light and off-axis/heavier. One of each is complementary but more than one per category is not necessary

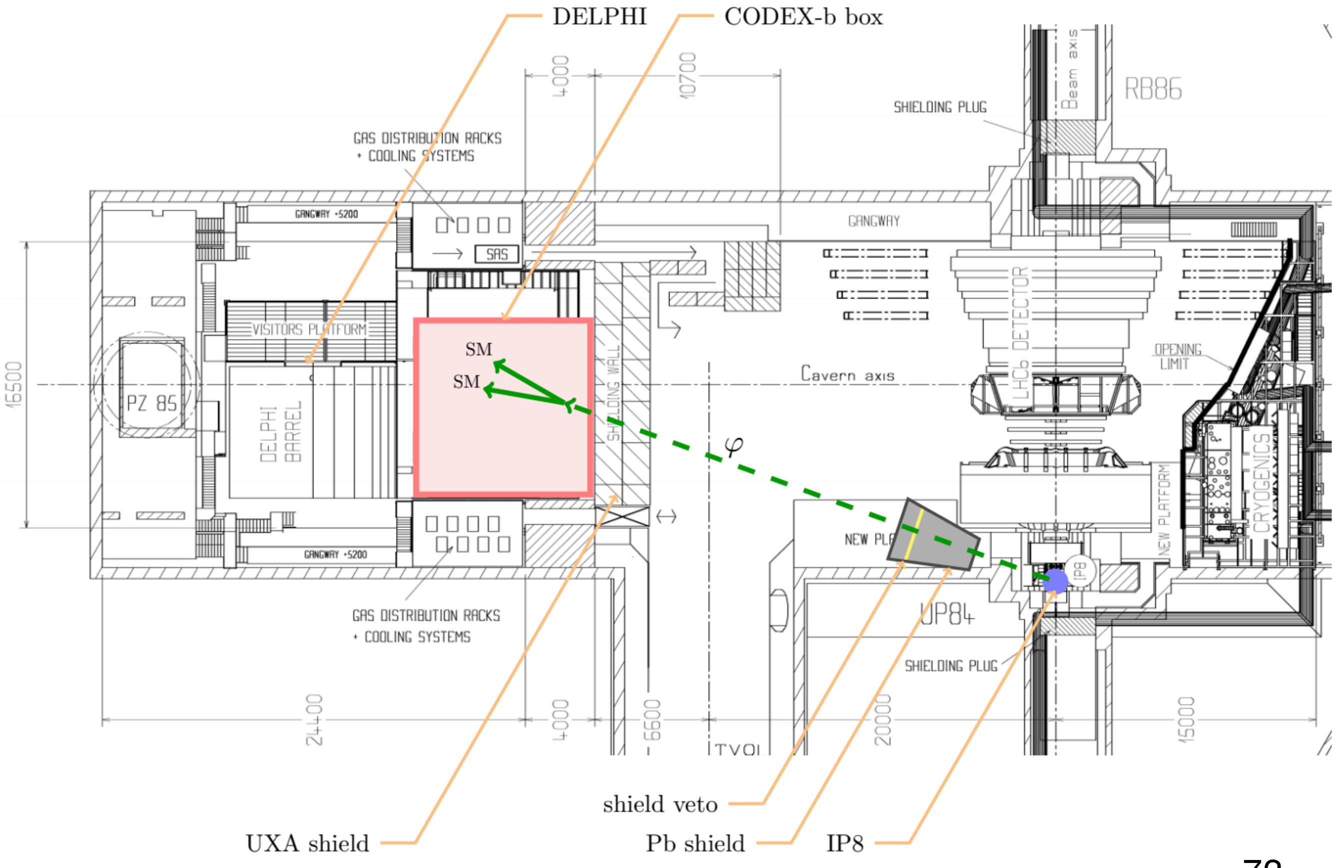
CODEX-b EOI





CODEX-b

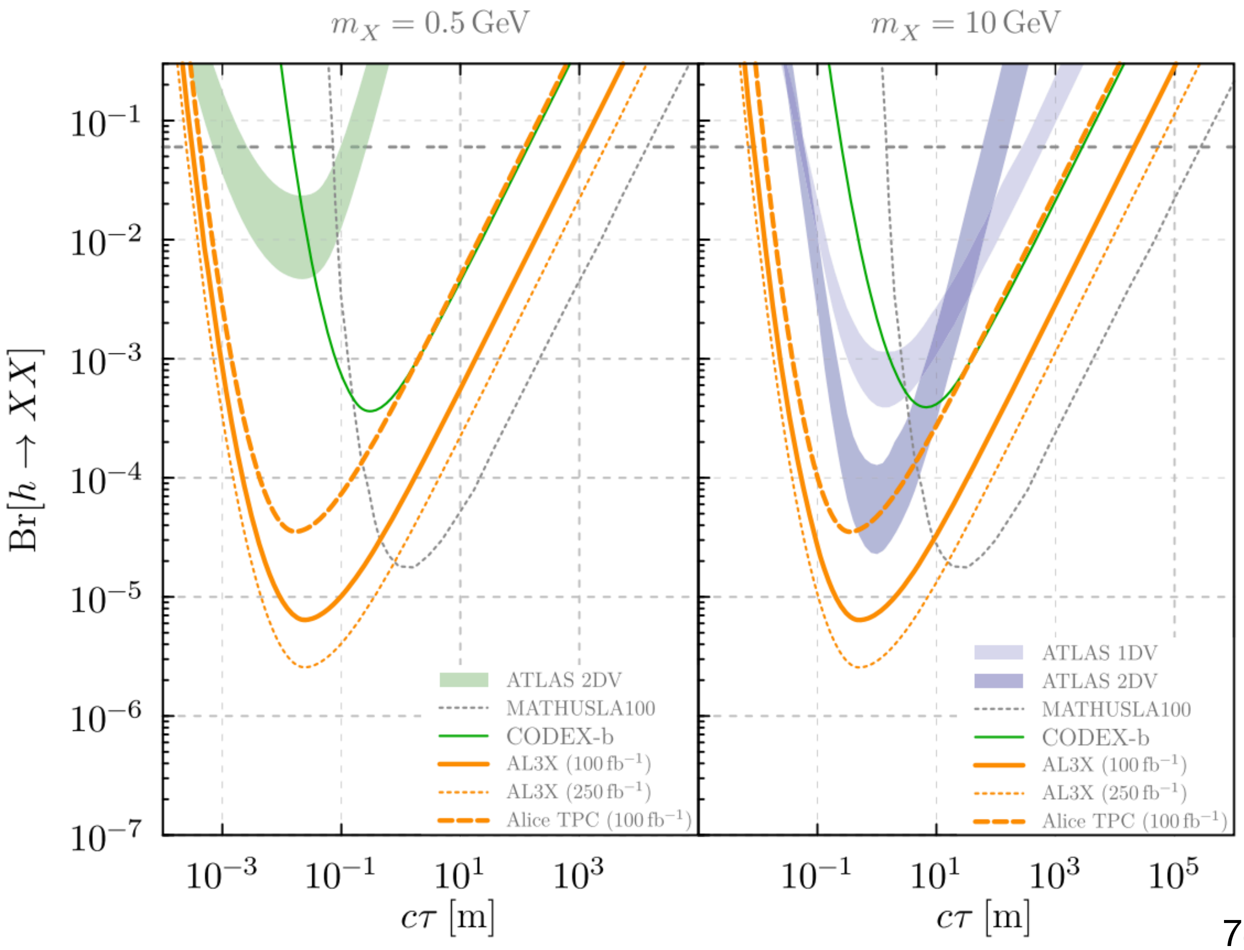
- Off-axis experiment 25m from LHCb interaction point, volume ~ 10x10x10 m
  - Existing chamber near LHCb where remains of DELPHI currently sit: old detector could be removed for extra space
- Detector design options: 6 layers of RPCs, option for scintillator-based calorimetry.
- Add shielding between LHCb and experiment
- Initial tests of detector tech already completed



V. Gligorov, S. Knapen, B. Nachman, M. Papucci, D. Robinson

AL3X

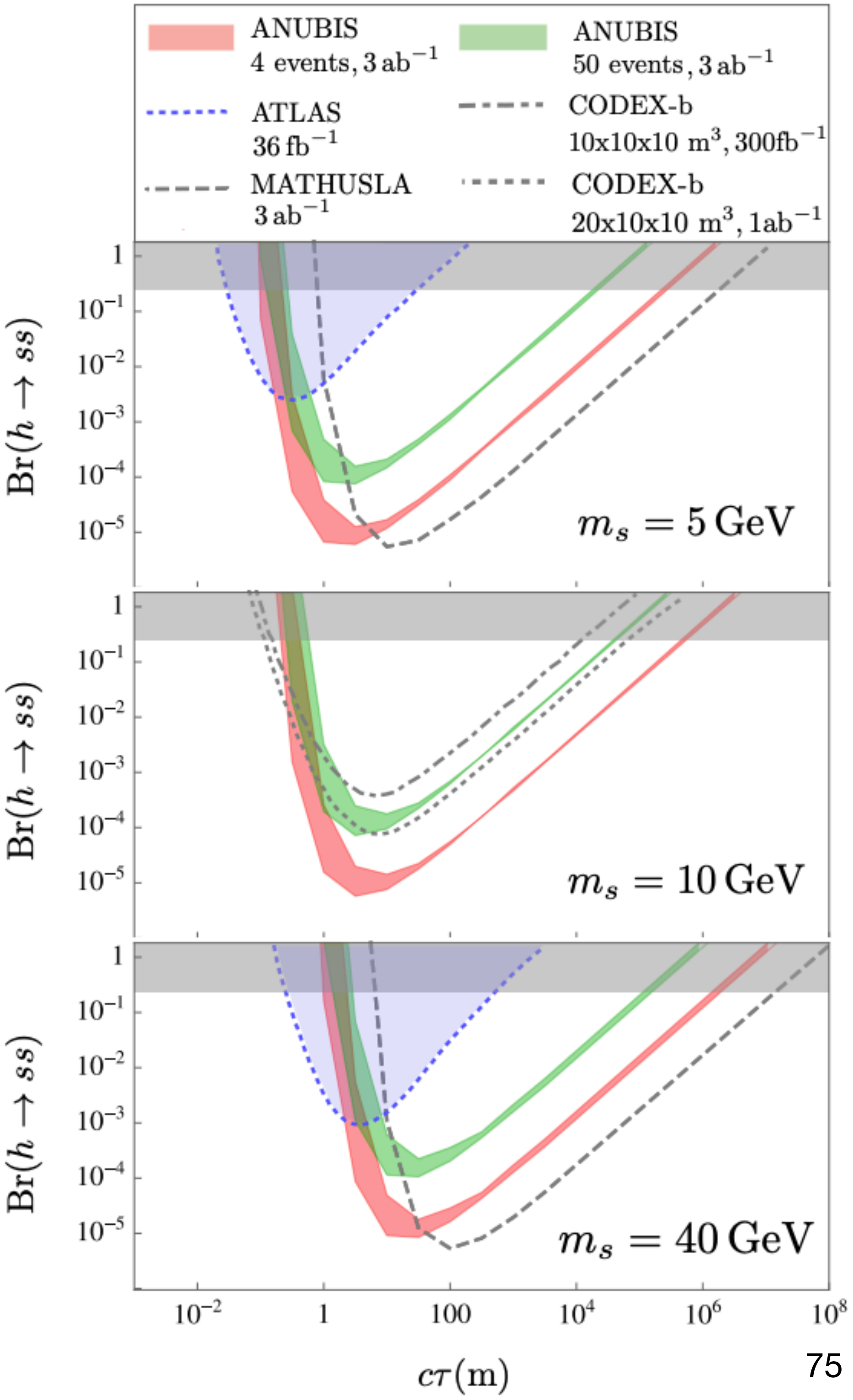
- ALICE has no current plans for Run 5, when LHC heavy ion program likely finished
- AL3X would reuse portions of ALICE detector (particularly time projection chamber and L3 magnet) for a LLP search program during Run 5
- Requires modified IP: move it downstream by ~11 m and deliver higher luminosity (100 fb^{-1}). Add additional shielding between IP and experiment
- Experiment affordable; cost of moving IP to be determined



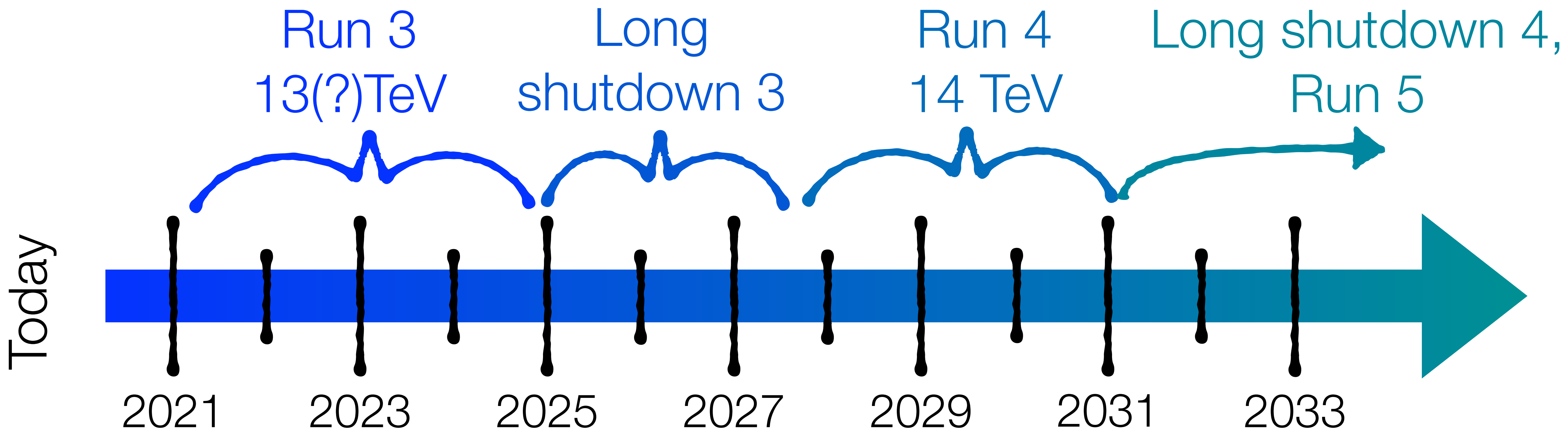
M. Bauer, O. Brandt, L. Lee, C. Ohm

ANUBIS

- Instrument ATLAS access shaft with removable layers of tracking detector (RPCs) in order to use shaft as decay volume
- Close enough to integrate with ATLAS beam crossing information
- 18m vertical depth and 18m diameter. Four equally spaced tracking stations
- Coverage comparable to CODEX-b in lifetime and depth
- Budget ~ 10M euros



LHC + LLP timeline



Run 3
13(?)TeV

Long
shutdown 3

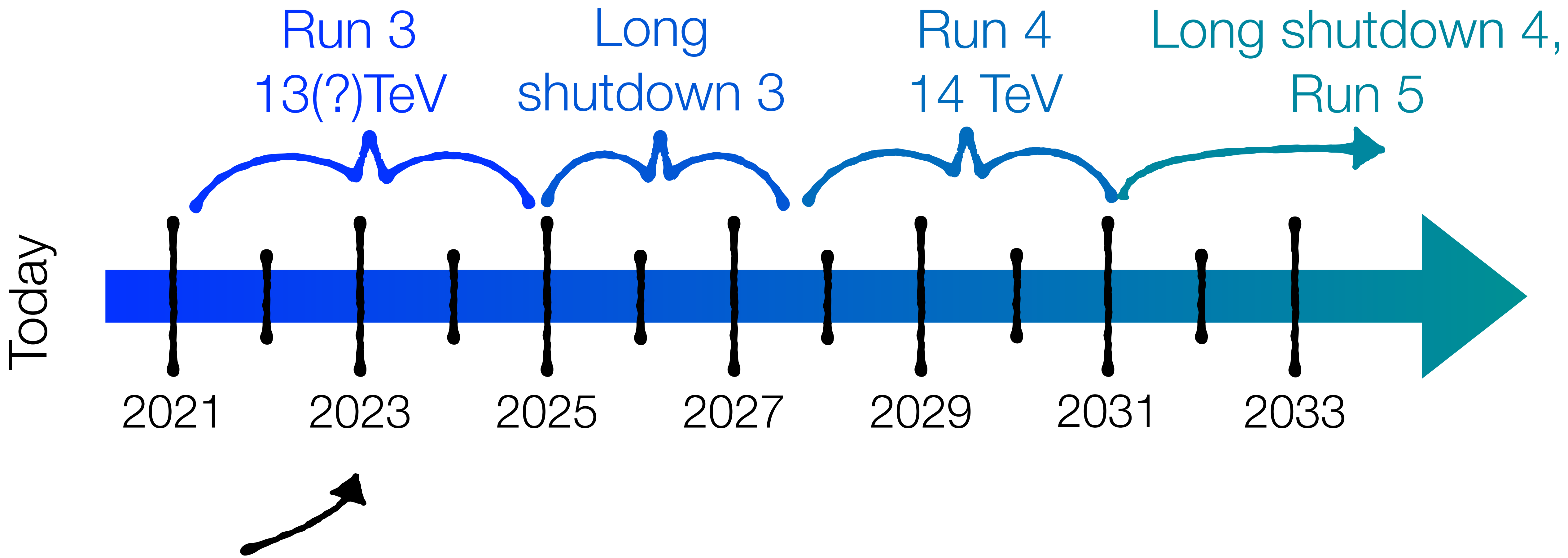
Run 4
14 TeV

Long shutdown 4,
Run 5

Today

2021 2023 2025 2027 2029 2031 2033

LHC + LLP timeline



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ATLAS & CMS
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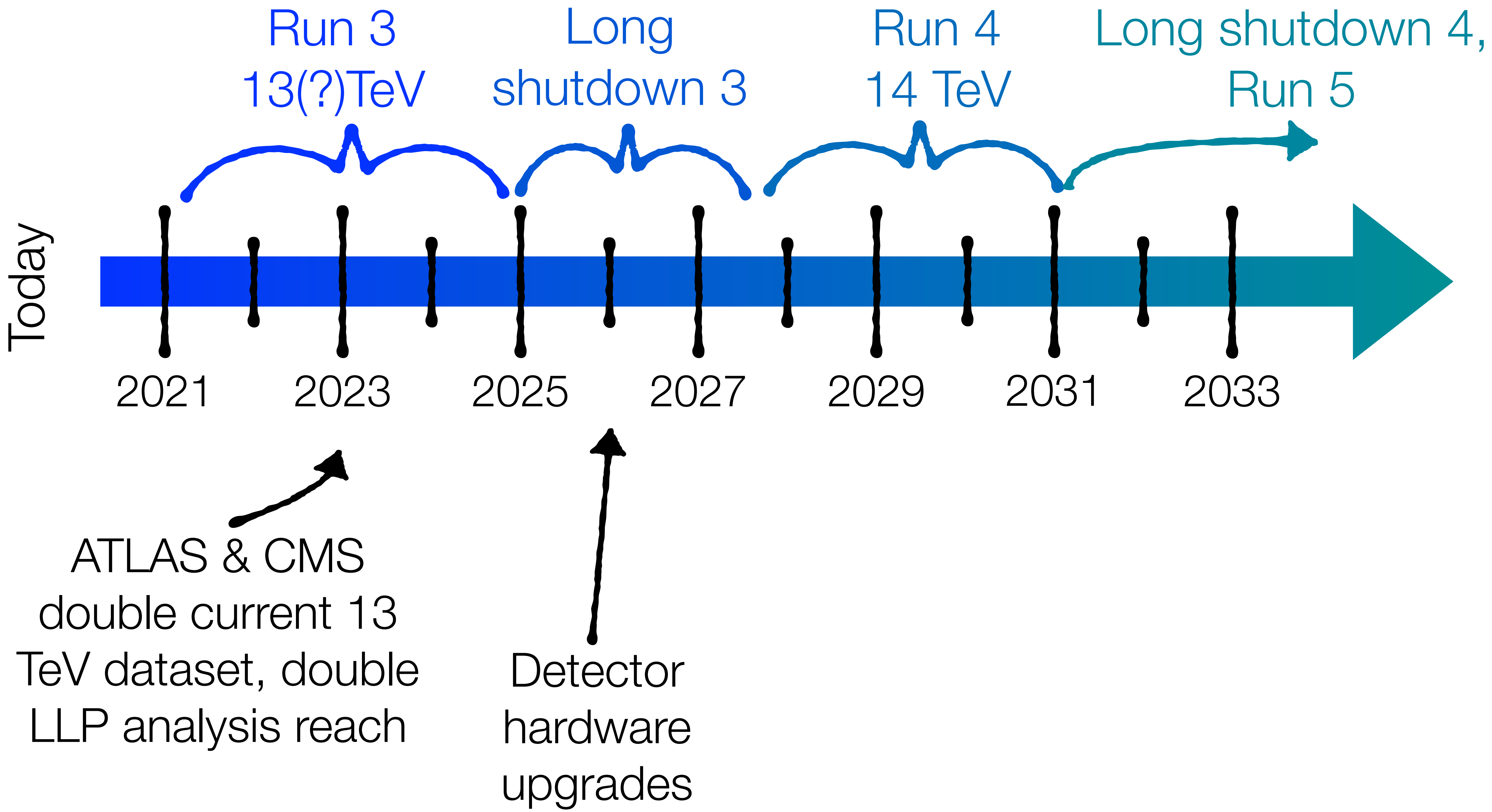
LHC + LLP timeline



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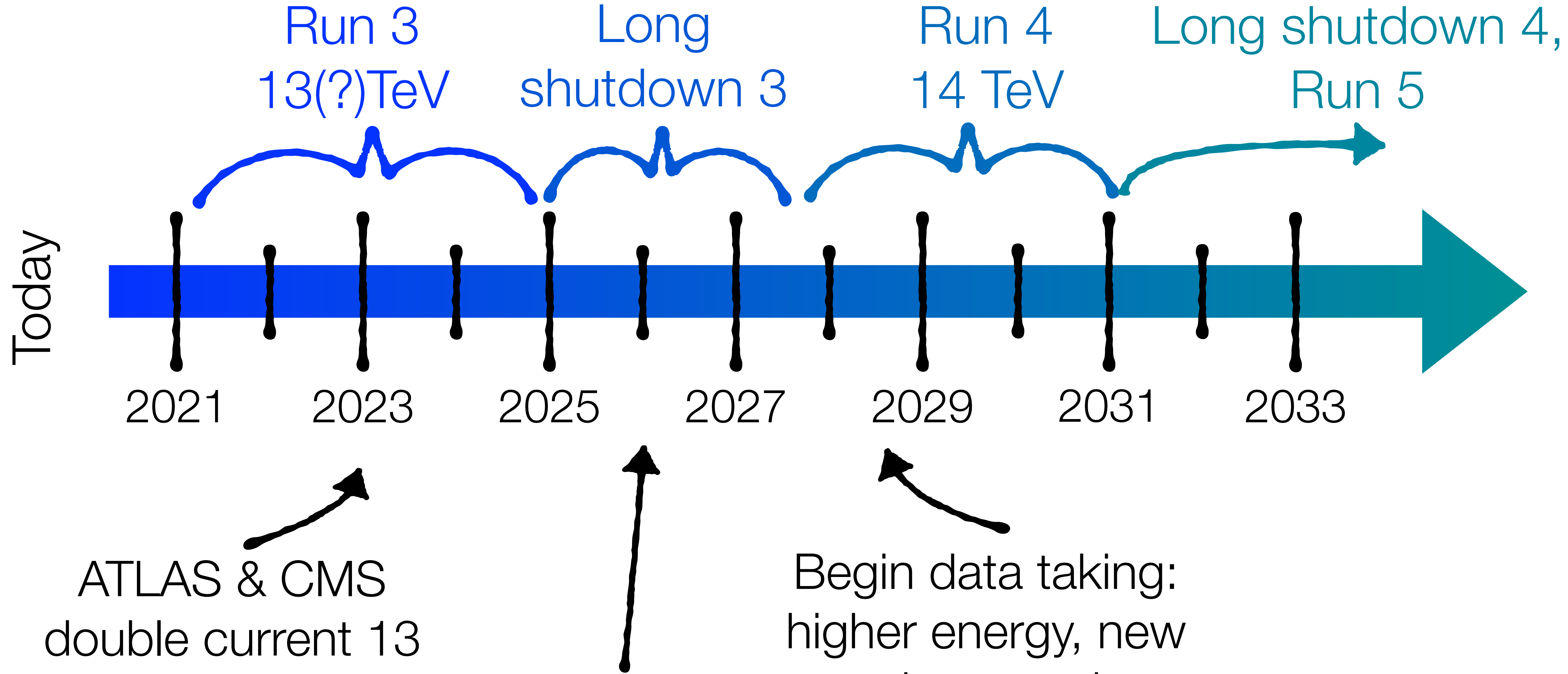
Detector hardware upgrades

LHC + LLP timeline



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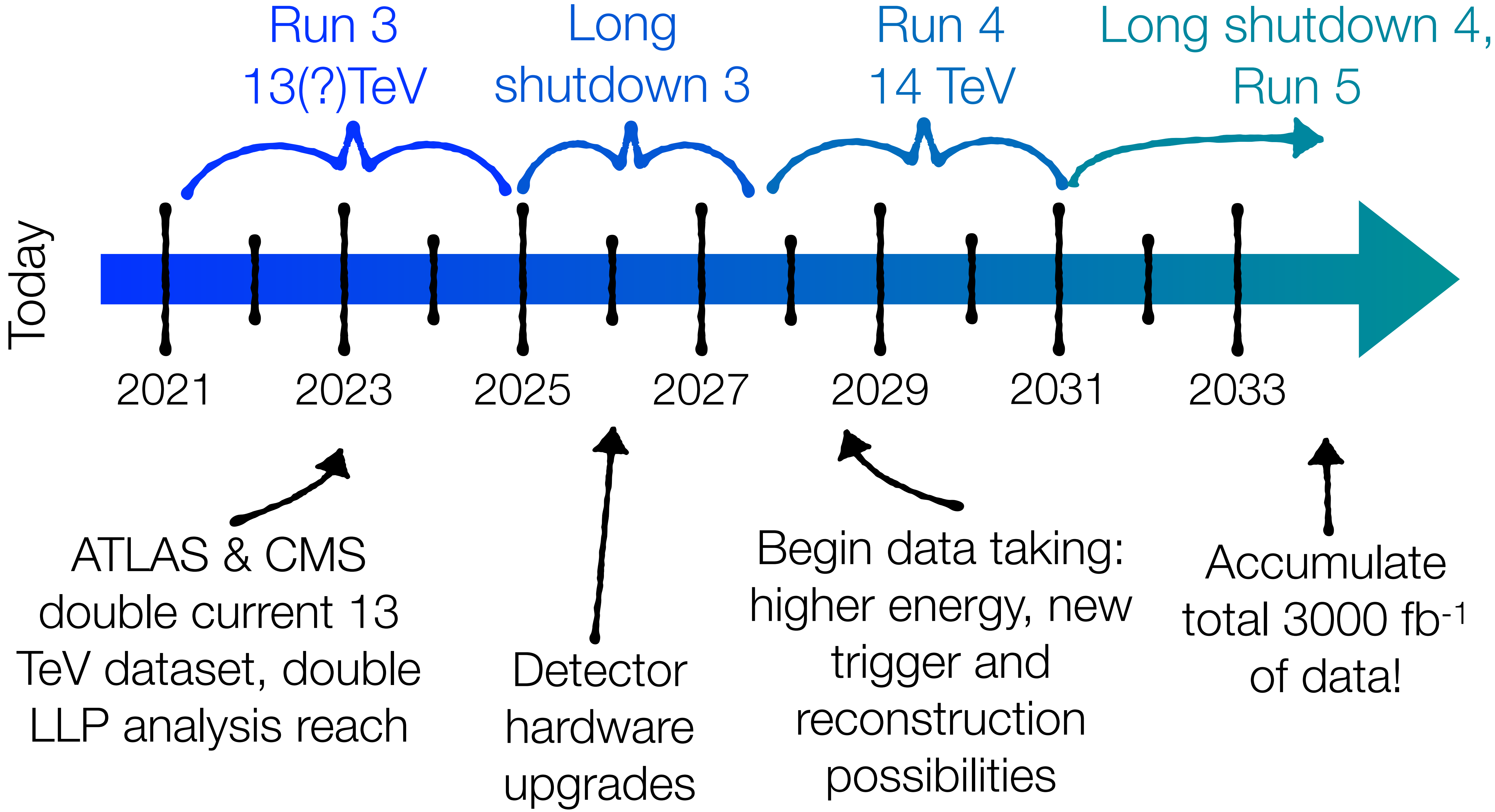

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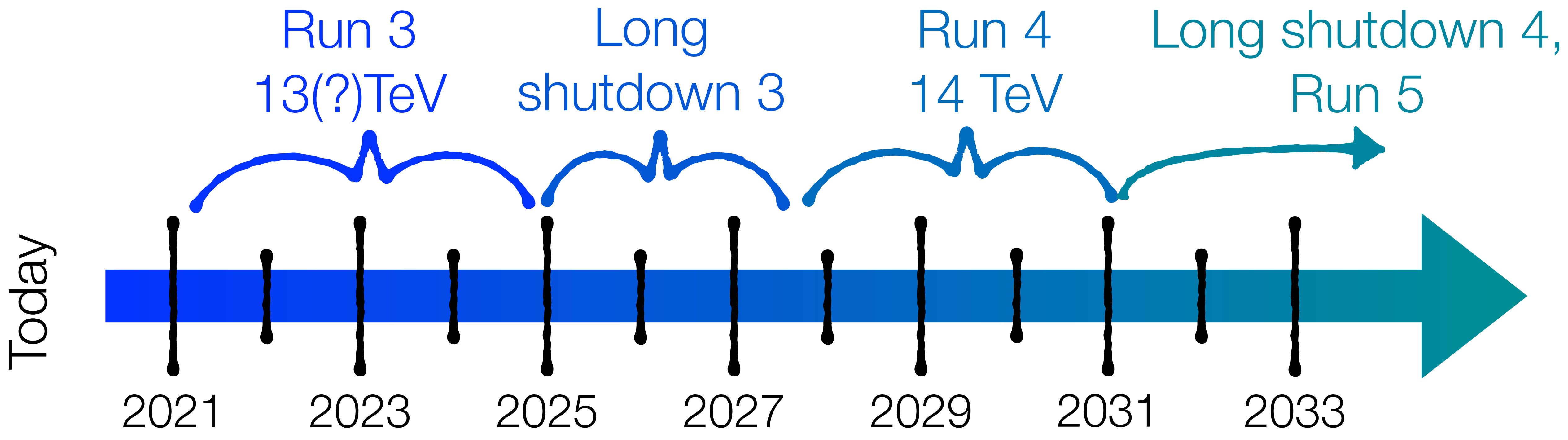
Accumulate total 3000 fb^{-1} of data!

LHC + LLP timeline



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Today

2021 2023 2025 2027 2029 2031 2033

New LLP detector design
finalisation, tests, building,
installation, commissioning

New experiment taking data!