BSM physics at high energies

– an experimental review

XXI LNF Spring School "Bruno Touschek" in
Nuclear, Subnuclear and Astroparticle Physics

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Content Lecture 2

- dark matter
  - di-invisible → dark matter
  - direct dark matter searches at LHC
  - di-X interplay with dark matter – beyond the LHC
- supersymmetry
  - appeal
  - strong production: jets+MET
  - weak production: leptons+MET
- long-lived particles
  - why long-lived particles?
  - experimental handles
  - backgrounds
  - search status
- looking ahead

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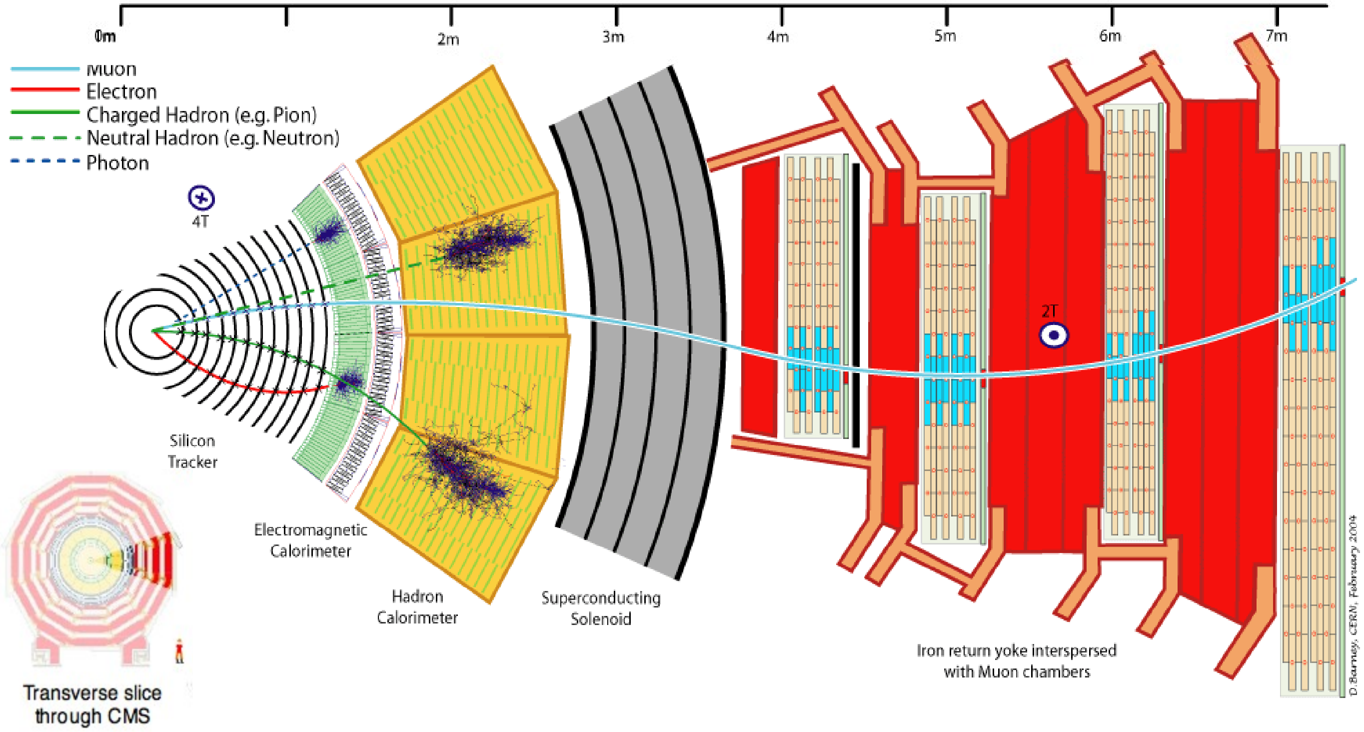
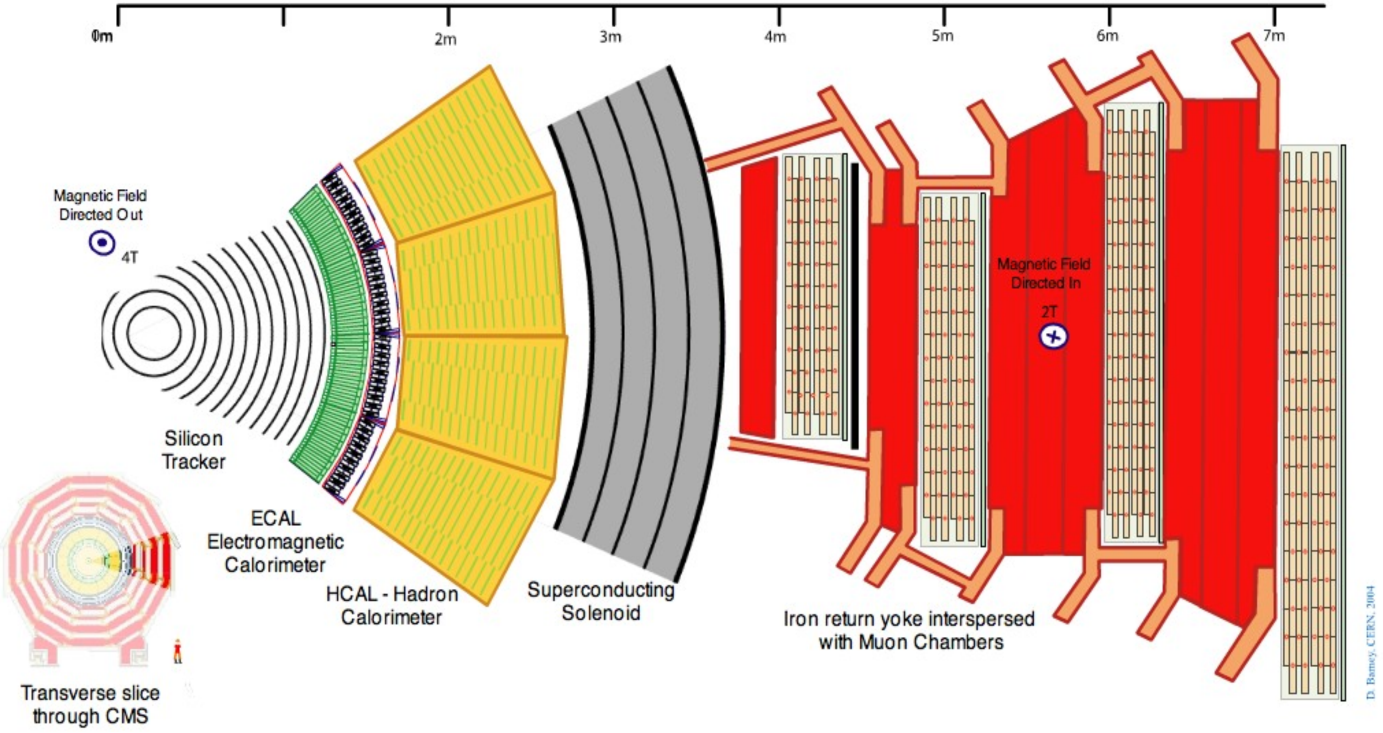
Dark Matter: pairs of ... nothing?

- it's possible we produce particles that don't interact in our detector
  - if very long-lived → dark matter candidate
  - instead of this…:



Dark Matter: pairs of ... nothing?

- it's possible we produce particles that don't interact in our detector
  - if very long-lived → dark matter candidate
  - we see this!   ”missing energy” (MET)



Dark Matter

- production at colliders can happen if
  - kinematically accessible
  - coupling to quarks/gluons
  - production cross section large enough

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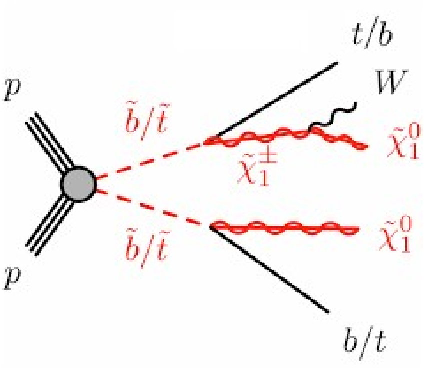
DM from cascade decays

- new particle production
  decay to DM+X
  - typically pair produced
- example: SUSY
  - with R parity always 2 LSP's
    yielding MET



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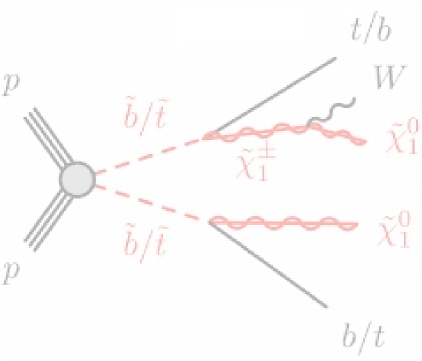
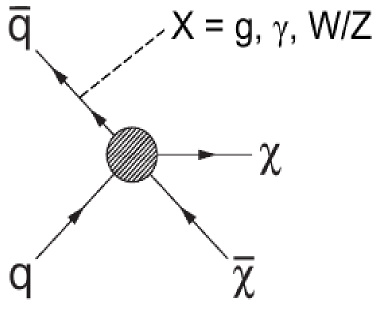
Discussed later



DM produced directly

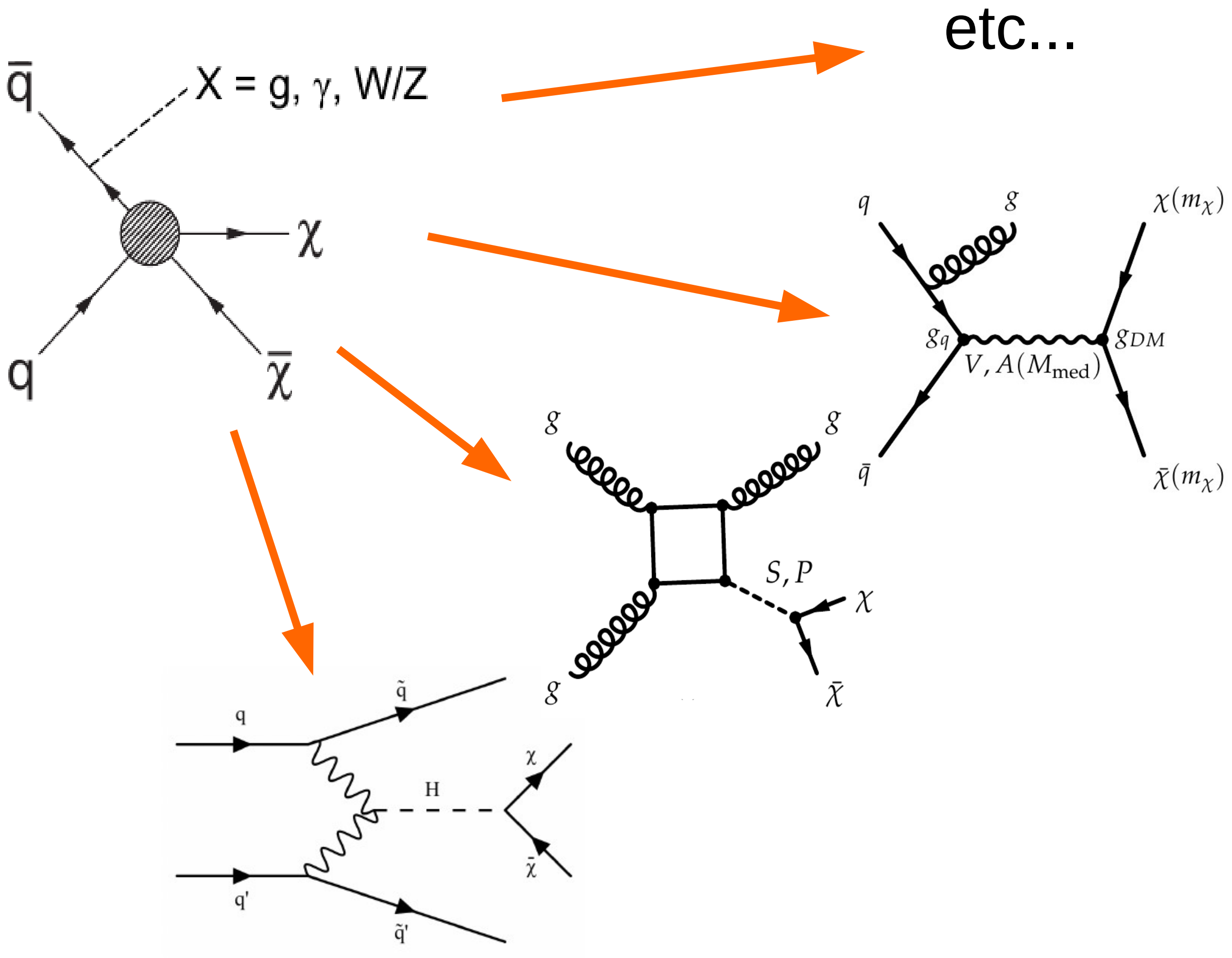
- direct DM pair production through mediator
- but back-to-back DM particles are invisible
  - ISR diagrams provide probe recoiling against DM pair



Direct DM searches

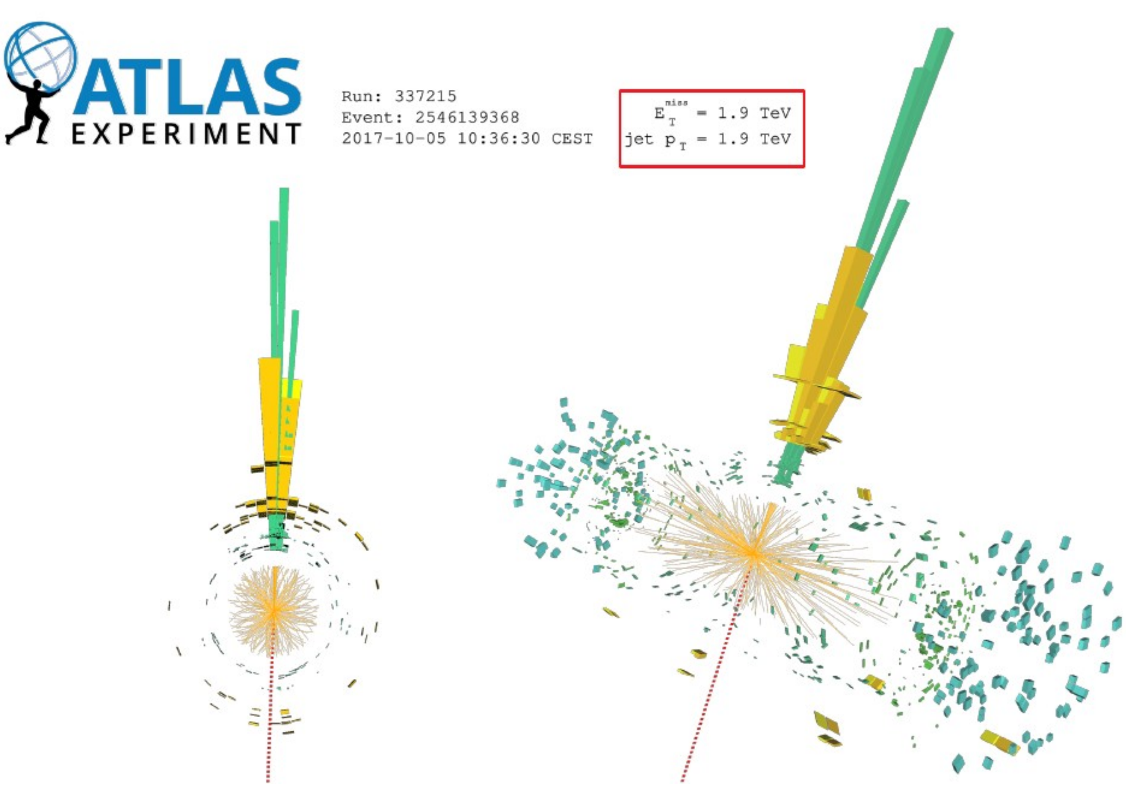
Mediator focus

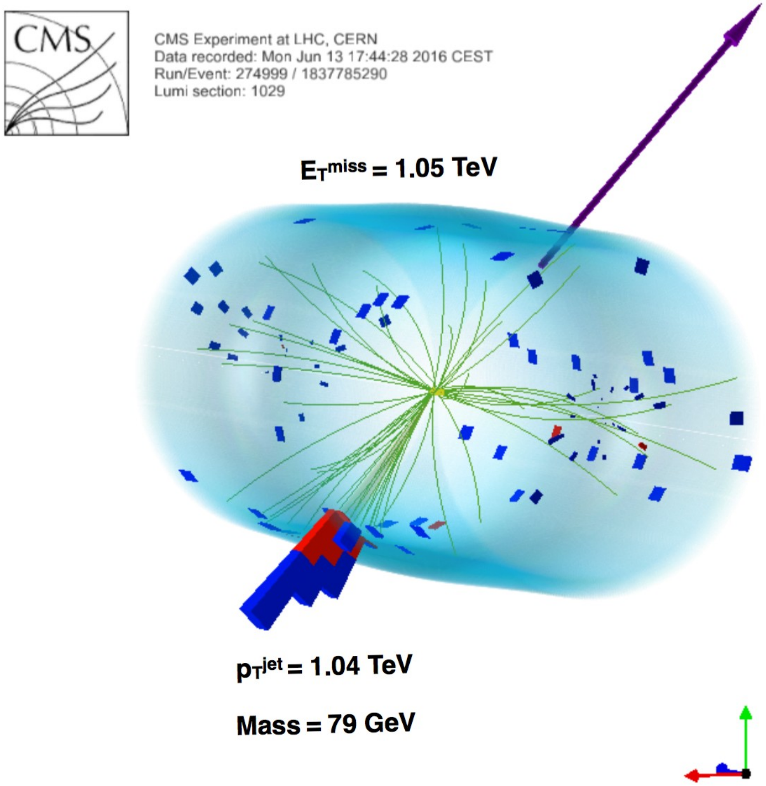
- the LHC's strength is to produce the mediator on-shell
- we must make the mediator explicit
    - an EFT “blob” is not sufficient



- model description
    - mediator type
    - production mode
    - couplings to q and DM
    - mediator and DM mass
    - consider beyond the minimal

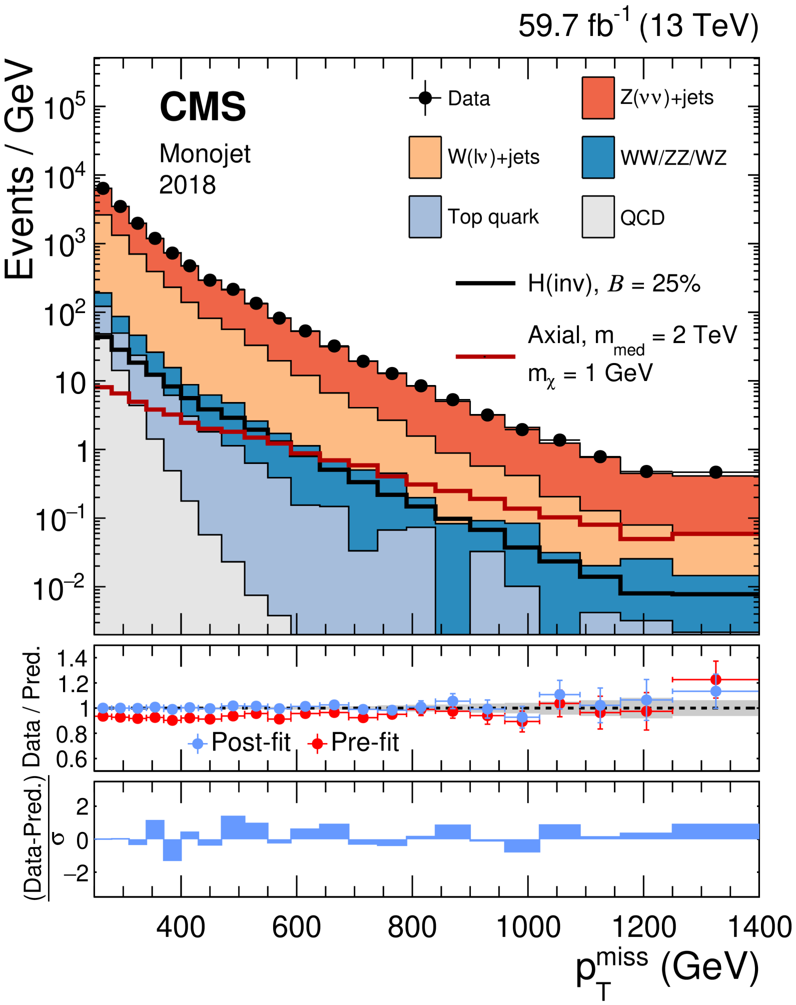
Direct DM searches





Direct DM searches

- Monojet search as the poster child example



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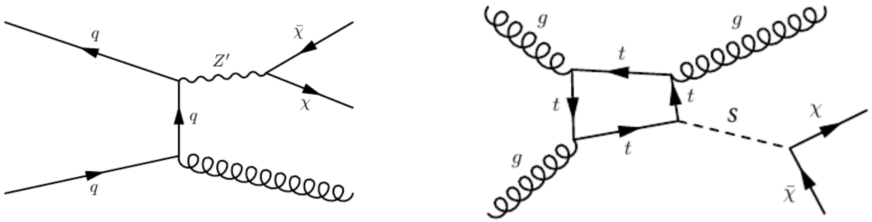
- DM recoils against a jet from QCD ISR



- MET as sensitive observable
  driven by trigger: MET > 250GeV
- irreducible Z→νν dominant BG
- remarkable precision achieved on BG!
  - ~% in bulk, 10% in tails
  - using constraints from Z→μμ, Z→ee, γ+jets, W→μν and W→eν control regions

Direct DM searches

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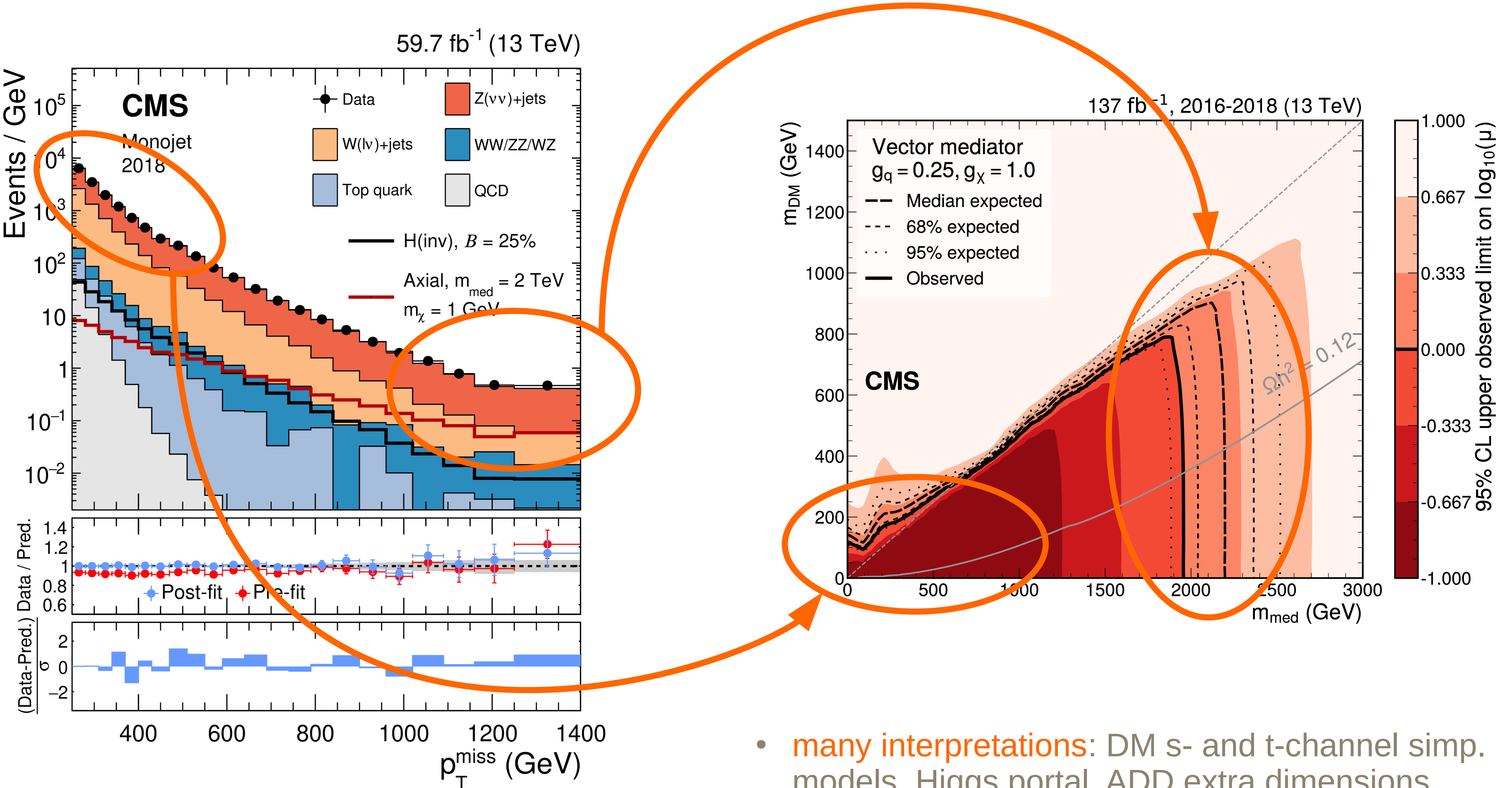

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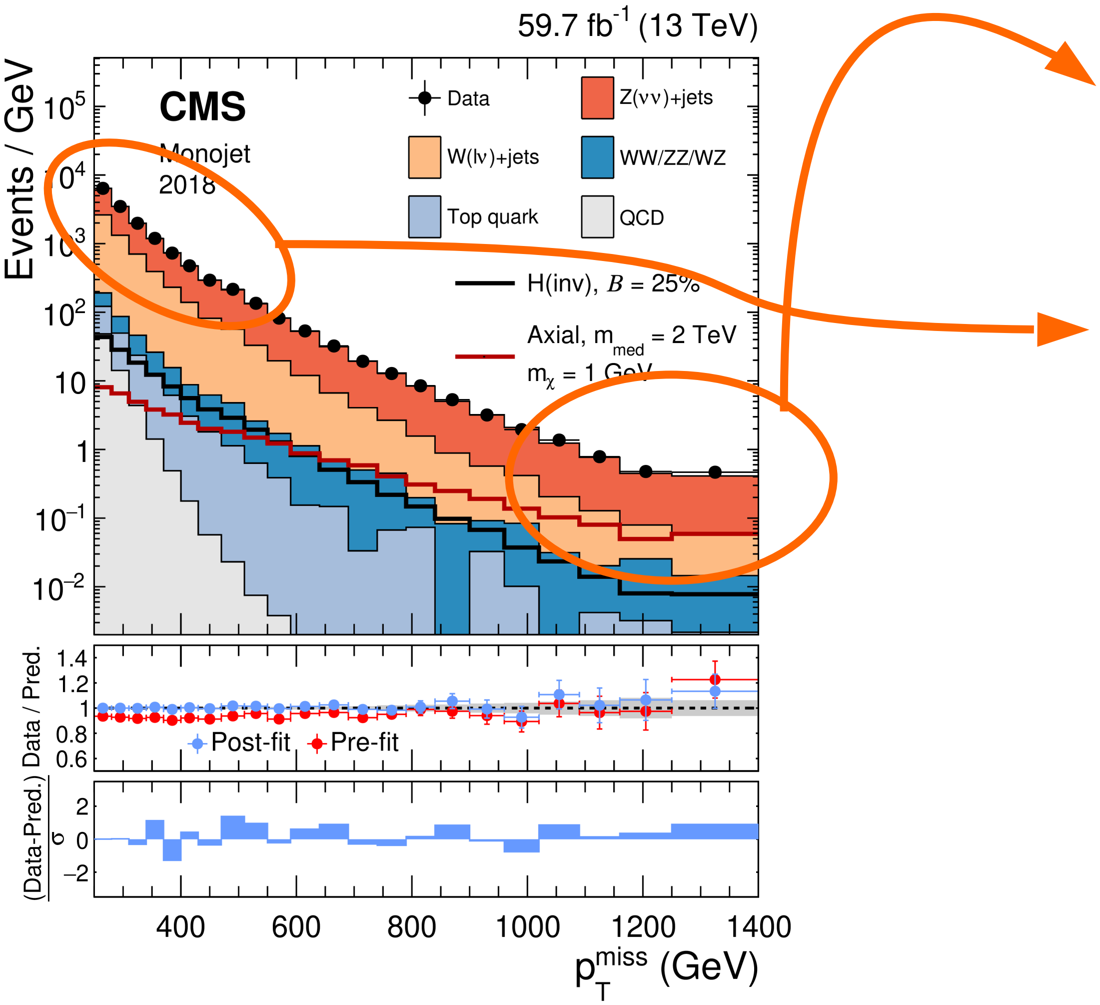
- many interpretations: DM s- and t-channel simp. models, Higgs portal, ADD extra dimensions, LeptoQuarks,...

Direct DM searches

- Monojet search as the poster child example



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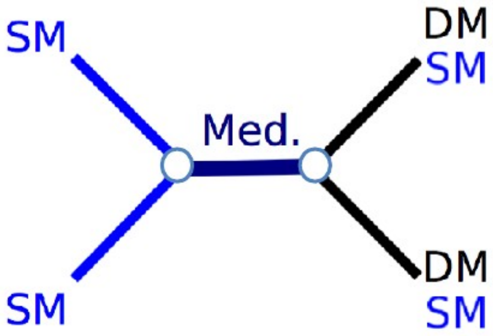
- statistically limited
    - improve slowly with luminosity
- systematically limited
    - no low-hanging fruits left
    - improve with hard work
    - challenges and opportunities at higher lumi
- theoretical uncertainties already very well controlled
    - NLO QCD+EWK
    - arXiv:1705.04664

Di-X search interplay with DM

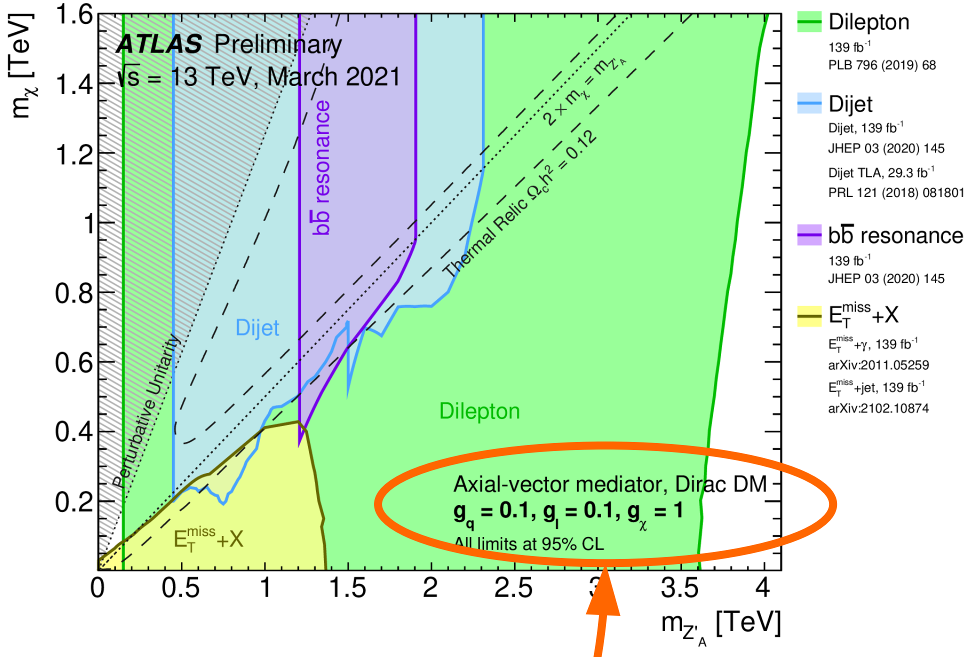
beyond the invisible: link to visible

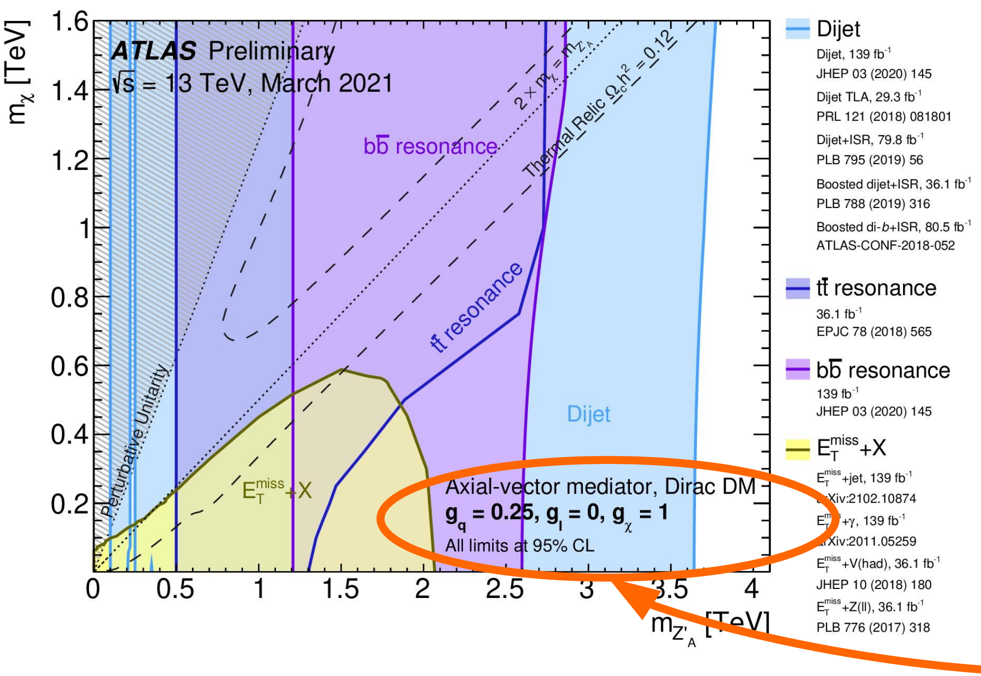
- LHC sensitivity to DM strongest when producing mediator on-shell
- new mediator may still be probed event if dark matter inaccessible (eg. kinematically) at LHC
  - quark (jet) final states guaranteed
  - muon and electron pairs possibly too
- thus we can indirectly constrain dark matter models
  - constraints on couplings
  - from searches in dijet and dilepton final states
  - model dependency!
    → always specify all parameters/assumptions



Di-X search interplay with DM

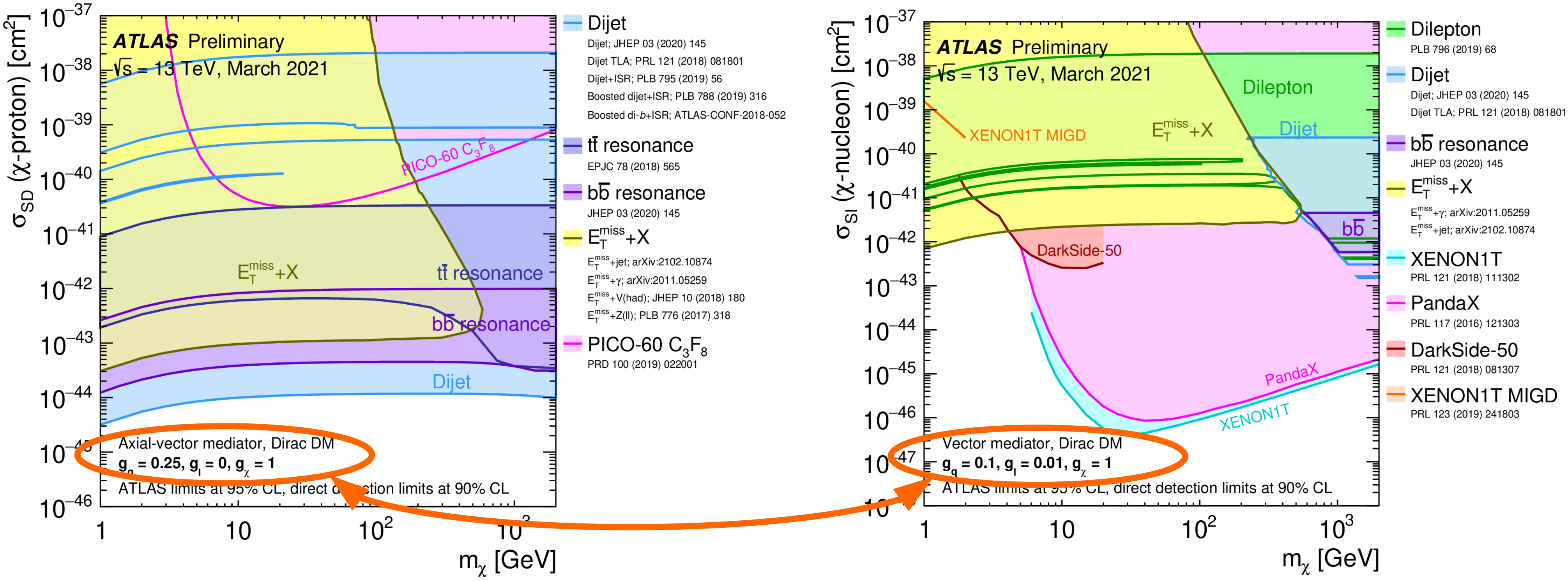
- interpretation in LHC phase space
  - probing mediators to several TeV
  - strong complementarity of invisible and visible channels
- exclusions crucially depend on couplings to SM and DM!





Dark Matter beyond LHC

- translate interpretation in phase space of direct DM detection searches
- take-home message: complementarity
    - best LHC results for low-mass DM, with mediator produced on-shell
- model dependency!



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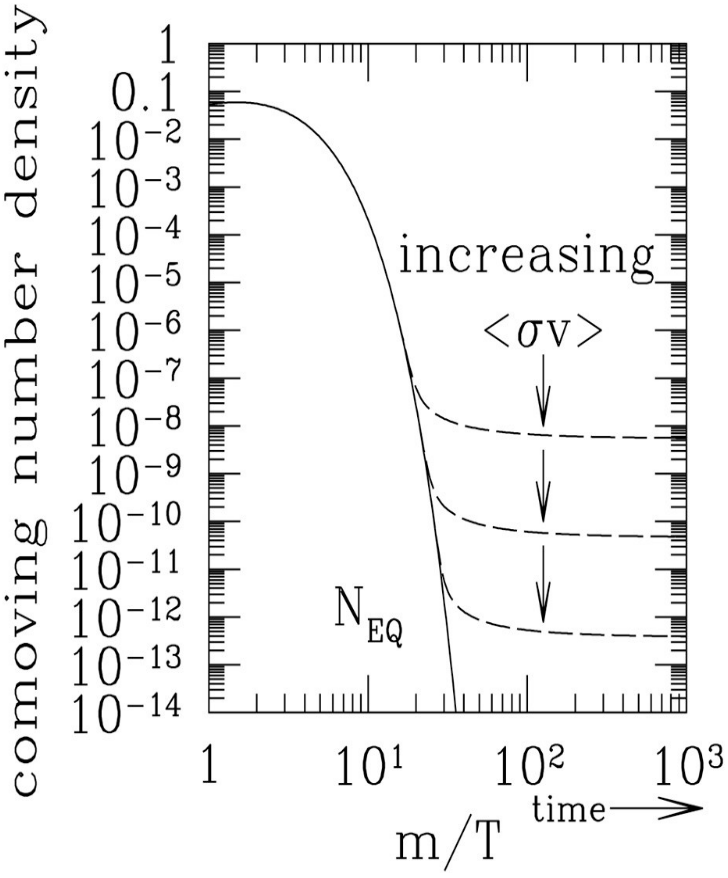
The WIMP miracle

- ...assuming thermal dark matter production...
- ...assuming cold dark matter...
- ...assuming DM to be 1 particle...

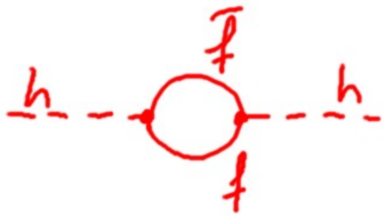
- relic dark matter density is inversely proportional to the DM annihilation cross section
  - correct relic density at

    $\langle\sigma v\rangle \sim 3 \times 10^{-26}$ cm^3 / s
  - this is the cross section of a 100 GeV particle with a coupling like the weak interaction
- so cosmology and particle physics points us independently to a special mass scale, the weak scale
  - special role for the Higgs boson?
  - the superesymmetry neutralino?



Supersymmetry

- hierarchy problem: scalar mass sensitive to all scales

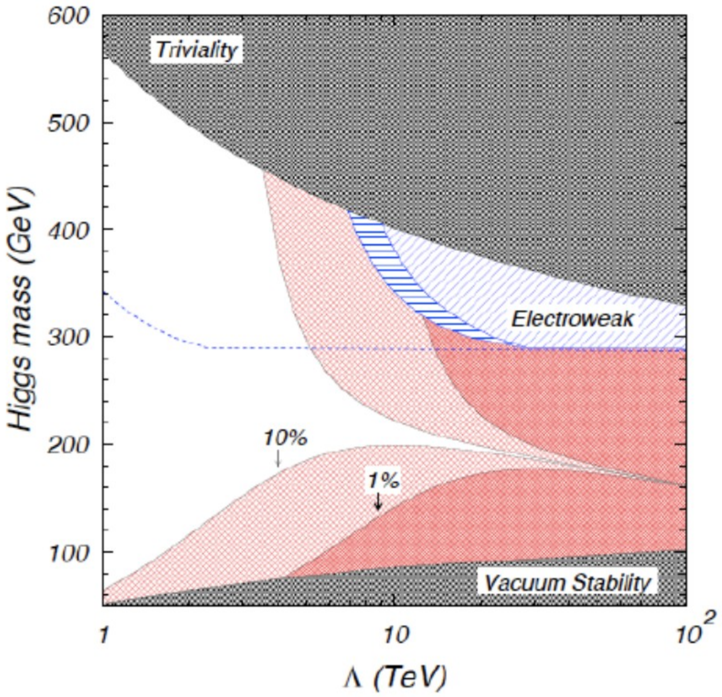


  - the integral can be cut off at a momentum scale Λ

$$m_h^2 = (m_h^0)^2 + \frac{3\Lambda^2}{8\pi^2 v^2}\left(m_h^2 + 2m_W^2 + m_Z^2 - 4m_t^2\right)$$

  - to cancel this radiative correction up to the Planck scale…

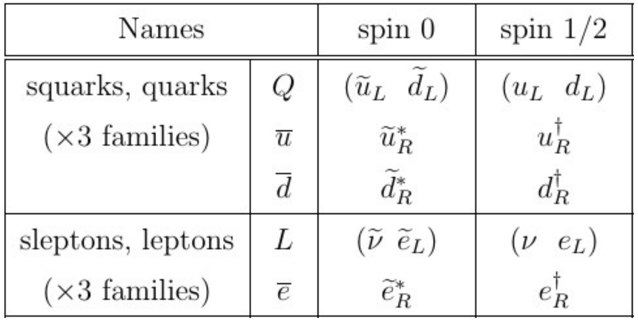
    we need to cancel 32 orders of magnitude
    → fine tuning



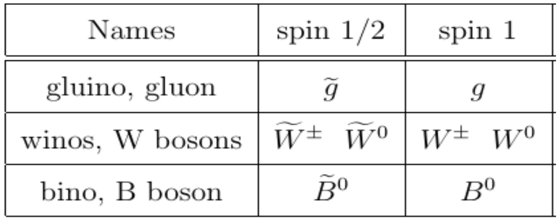
Supersymmetry

- possible solution: supersymmetry (SUSY):

  add a boson for each fermion, and vice versa
  - scalar quarks and leptons



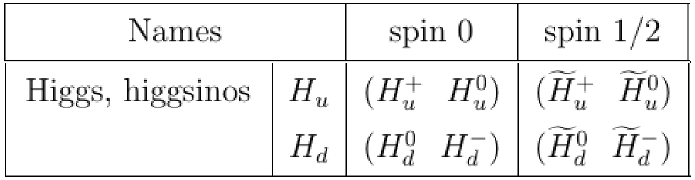
Names		spin 0	spin 1/2
squarks, quarks	Q	$(\tilde{u}_L \ \ \tilde{d}_L)$	$(u_L \ \ d_L)$
(×3 families)	$\overline{u}$	$\tilde{u}^*_R$	$u^\dagger_R$
	$\overline{d}$	$\tilde{d}^*_R$	$d^\dagger_R$
sleptons, leptons	L	$(\tilde{\nu} \ \ \tilde{e}_L)$	$(\nu \ \ e_L)$
(×3 families)	$\overline{e}$	$\tilde{e}^*_R$	$e^\dagger_R$



Names	spin 1/2	spin 1
gluino, gluon	$\tilde{g}$	g
winos, W bosons	$\widetilde{W}^\pm \ \ \widetilde{W}^0$	$W^\pm \ \ W^0$
bino, B boson	$\widetilde{B}^0$	B^0

majorana fermions as
gauge boson partners (“-inos”)

extended Higgs sector and
fermionic superpartners



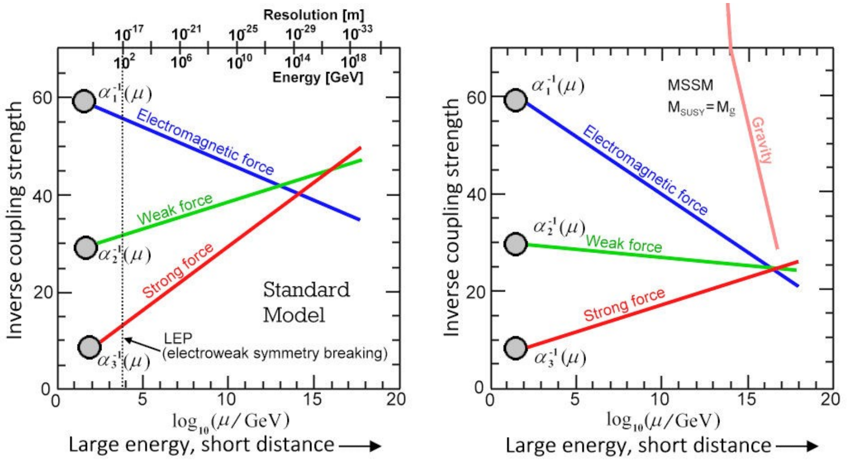
Names		spin 0	spin 1/2
Higgs, higgsinos	H_u	$(H^+_u \ \ H^0_u)$	$(\widetilde{H}^+_u \ \ \widetilde{H}^0_u)$
	H_d	$(H^0_d \ \ H^-_d)$	$(\widetilde{H}^0_d \ \ \widetilde{H}^-_d)$

- mixing between bino, winos and Higgsinos → charginos and neutralinos

- no SUSY at same masses observed → no perfect cancellation
  - to save naturalneess and avoid new fine tuning:
    higgsino ~ 100 GeV
    stop ~ 400 GeV
    gluino ~ 2000 GeV

Supersymmetry appeal

- hierarchy problem
- unification of the forces



- EW symmetry breaking can be a natural consequence of SUSY breaking
  - under certain conditions in the Higgs sector
- dark matter
  - gravitational evidence is overwhelming
  - SUSY can provide an ideal WIMP
  - note: dark matter is not a requirement put on SUSY models

    it's the reverse: require proton stability through conservation of R parity
    → SUSY particles must come in pairs
    → the lightest SUSY particle is stable

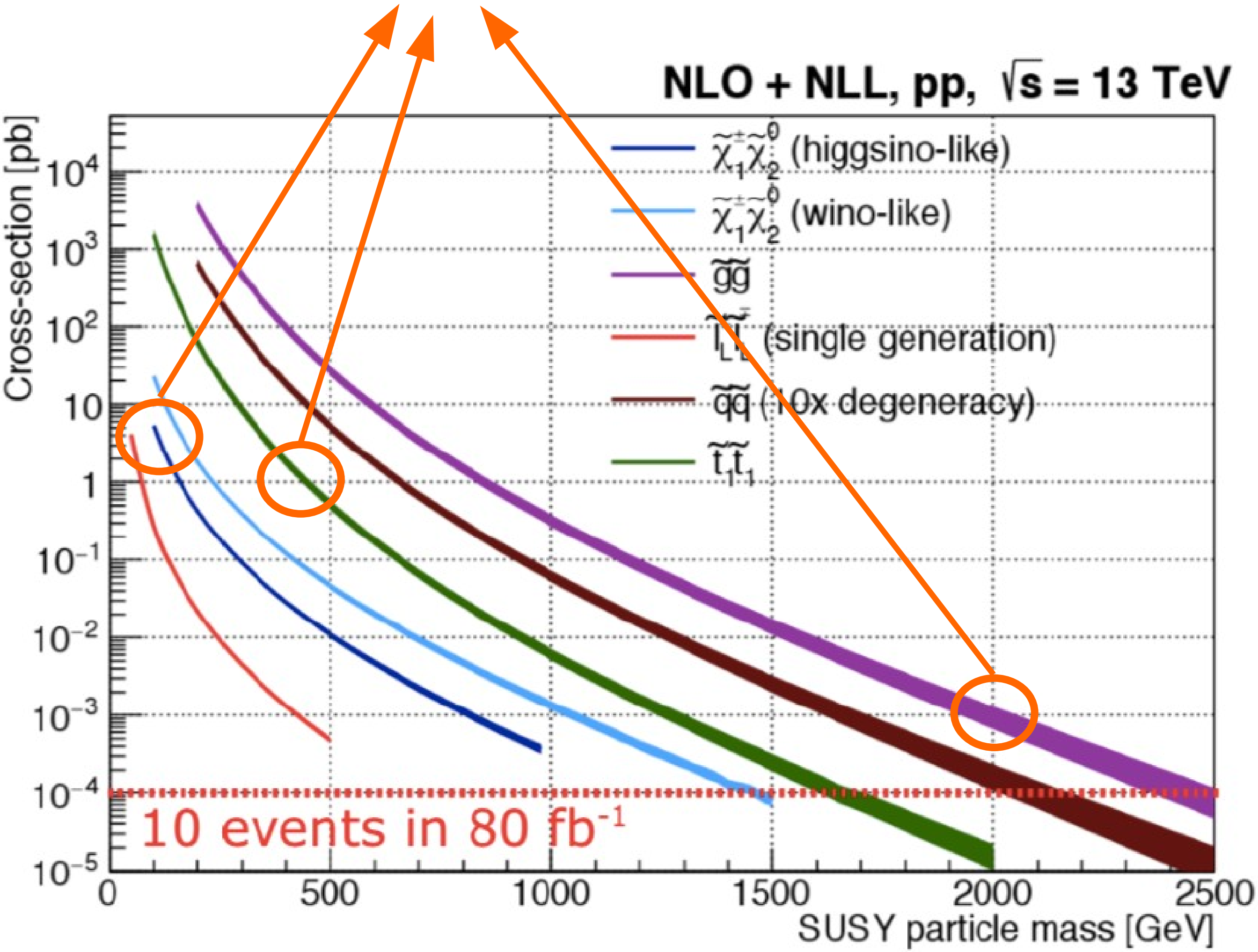
$$P_R = (-1)^{2s+3B+L}$$

- string theory requires SUSY
  - but no indication at what energy scale

Supersymmetry at LHC

- collider cross sections can be quite large
- current LHC energy and luminosity probes natural SUSY directly

- SUSY can still hide in experimentally difficult decays



Supersymmetry at LHC

- high cross sections for strong production of heavy squarks and gluinos
  - the squarks and gluinos then decay depending on the SUSY spectrum of lighter sparticles
  - but since they are coloured, they will always produce quarks or gluons (jets)
  - and the LSP will always give rise to undetected momentum in the detector
  - generic feature: missing energy + jets + possible leptons/photons/...

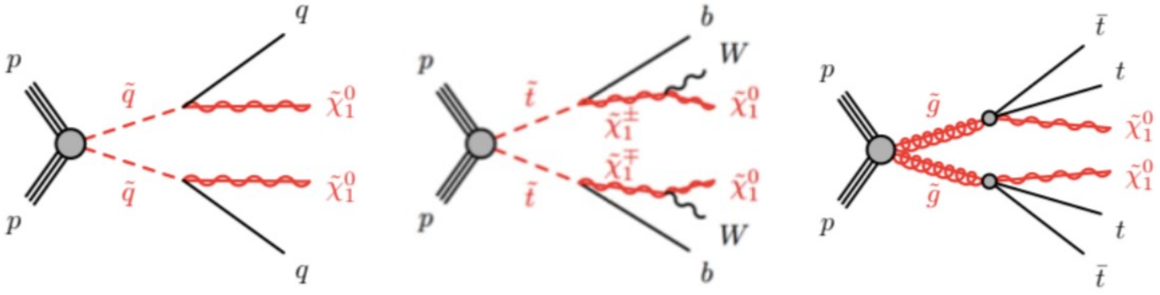
    a particularly SUSY-like signature are same-charge lepton pairs

- small cross sections for electroweak production of charginos, neutralinos, and sleptons
  - Z's and W's appear in the decays, or leptons directly from the sleptons → can be used to suppress backgrounds
  - depending on spectrum configurations, final states arise with 2, 3, 4 leptons, with or without Z resonances, same charge or not, same flavour or not
  - generic feature: leptons + MET, but absence of jets

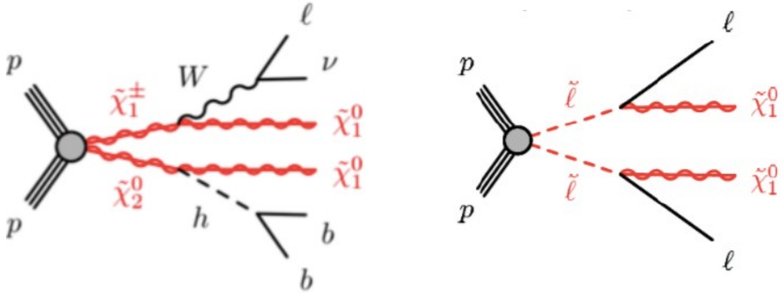
- also Higgs bosons can appear in the decays!

Supersymmetry at LHC

some example diagrams



- classic hadronic SUSY signatures
  - jets + MET
  - lepton + jets + MET
  - SS dileptons + jets + MET
  - …

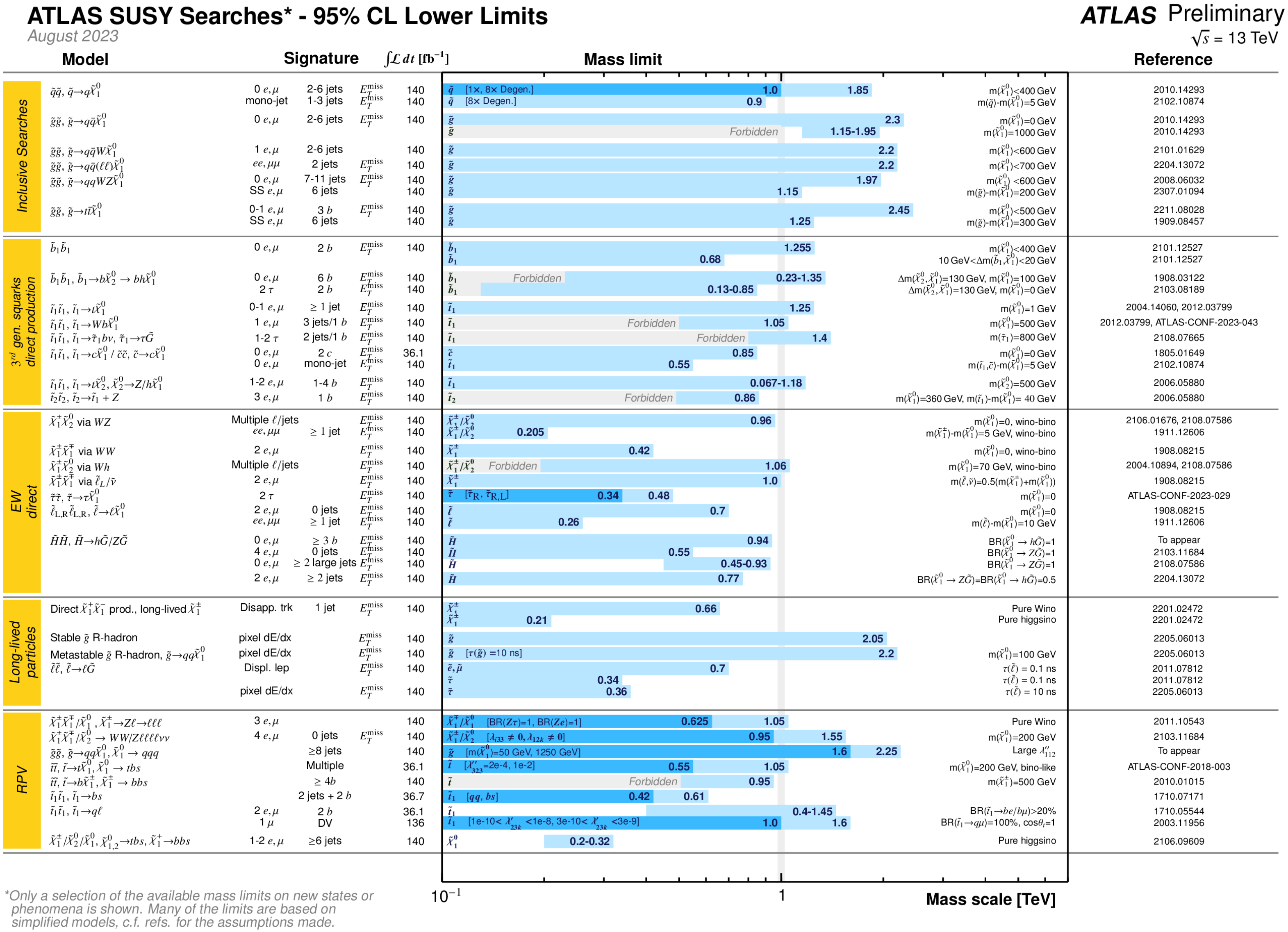


- classic electroweak SUSY signatures
  - Z/W/H + MET
  - dileptons + MET
  - ...

- many 10's of searches, years of work, no hints of SUSY
  - maybe nature chose something else than these classic signatures?

Supersymmetry at LHC

- current experimental situation



ATLAS SUSY Searches* - 95% CL Lower Limits
August 2023

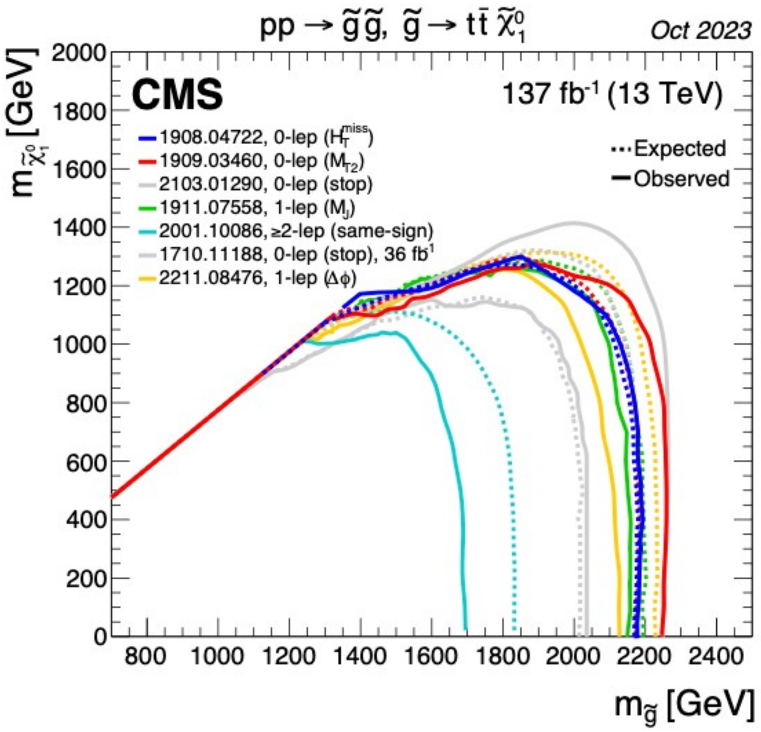
ATLAS Preliminary
$\sqrt{s}$ = 13 TeV

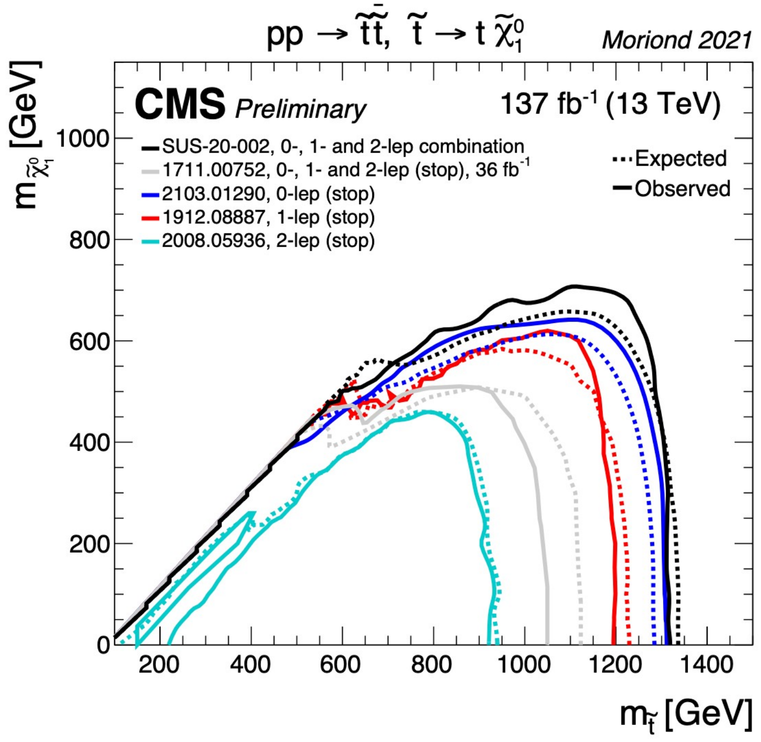
	Model	Signature			$\int\mathcal{L}\,dt$ [fb^{-1}]	Mass limit			Reference
Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$	0 e,μ	2-6 jets	E_T^{miss}	140	$\tilde{q}$ [1×, 8× Degen.]	1.0 1.85	m($\tilde{\chi}^0_1$)<400 GeV	2010.14293
		mono-jet	1-3 jets	E_T^{miss}	140	$\tilde{q}$ [8× Degen.]	0.9	m($\tilde{q}$)-m($\tilde{\chi}^0_1$)=5 GeV	2102.10874
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0 e,μ	2-6 jets	E_T^{miss}	140	$\tilde{g}$	2.3	m($\tilde{\chi}^0_1$)=0 GeV	2010.14293
						$\tilde{g}$	Forbidden 1.15-1.95	m($\tilde{\chi}^0_1$)=1000 GeV	2010.14293
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}W\tilde{\chi}^0_1$	1 e,μ	2-6 jets		140	$\tilde{g}$	2.2	m($\tilde{\chi}^0_1$)<600 GeV	2101.01629
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}^0_1$	$ee,\mu\mu$	2 jets	E_T^{miss}	140	$\tilde{g}$	2.2	m($\tilde{\chi}^0_1$)<700 GeV	2204.13072
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}^0_1$	0 e,μ	7-11 jets	E_T^{miss}	140	$\tilde{g}$	1.97	m($\tilde{\chi}^0_1$) <600 GeV	2008.06032
		SS e,μ	6 jets		140	$\tilde{g}$	1.15	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=200 GeV	2307.01094
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	E_T^{miss}	140	$\tilde{g}$	2.45	m($\tilde{\chi}^0_1$)<500 GeV	2211.08028
		SS e,μ	6 jets		140	$\tilde{g}$	1.25	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=300 GeV	1909.08457
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$	0 e,μ	2 b	E_T^{miss}	140	$\tilde{b}_1$	1.255	m($\tilde{\chi}^0_1$)<400 GeV	2101.12527
						$\tilde{b}_1$	0.68	10 GeV<Δm($\tilde{b}_1$,$\tilde{\chi}^0_1$)<20 GeV	2101.12527
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}^0_2\to bh\tilde{\chi}^0_1$	0 e,μ	6 b	E_T^{miss}	140	$\tilde{b}_1$	Forbidden 0.23-1.35	Δm($\tilde{\chi}^0_2$,$\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=100 GeV	1908.03122
		2 τ	2 b	E_T^{miss}	140	$\tilde{b}_1$	0.13-0.85	Δm($\tilde{\chi}^0_2$,$\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=0 GeV	2103.08189
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}^0_1$	0-1 e,μ	$\geq$ 1 jet	E_T^{miss}	140	$\tilde{t}_1$	1.25	m($\tilde{\chi}^0_1$)=1 GeV	2004.14060, 2012.03799
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}^0_1$	1 e,μ	3 jets/1 b	E_T^{miss}	140	$\tilde{t}_1$	Forbidden 1.05	m($\tilde{\chi}^0_1$)=500 GeV	2012.03799, ATLAS-CONF-2023-043
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to\tilde{\tau}_1 b\nu$, $\tilde{\tau}_1\to\tau\tilde{G}$	1-2 τ	2 jets/1 b	E_T^{miss}	140	$\tilde{t}_1$	Forbidden 1.4	m($\tilde{\tau}_1$)=800 GeV	2108.07665
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}^0_1$ / $\tilde{c}\tilde{c}$, $\tilde{c}\to c\tilde{\chi}^0_1$	0 e,μ	2 c	E_T^{miss}	36.1	$\tilde{c}$	0.85	m($\tilde{\chi}^0_1$)=0 GeV	1805.01649
		0 e,μ	mono-jet	E_T^{miss}	140	$\tilde{t}_1$	0.55	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}^0_1$)=5 GeV	2102.10874
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}^0_2$, $\tilde{\chi}^0_2\to Z/h\tilde{\chi}^0_1$	1-2 e,μ	1-4 b	E_T^{miss}	140	$\tilde{t}_1$	0.067-1.18	m($\tilde{\chi}^0_2$)=500 GeV	2006.05880
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ	1 b	E_T^{miss}	140	$\tilde{t}_2$	Forbidden 0.86	m($\tilde{\chi}^0_1$)=360 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}^0_1$)= 40 GeV	2006.05880
EW direct	$\tilde{\chi}^{\pm}_1\tilde{\chi}^0_2$ via WZ	Multiple ℓ/jets		E_T^{miss}	140	$\tilde{\chi}^{\pm}_1/\tilde{\chi}^0_2$	0.96	m($\tilde{\chi}^0_1$)=0, wino-bino	2106.01676, 2108.07586
		$ee,\mu\mu$	$\geq$ 1 jet	E_T^{miss}	140	$\tilde{\chi}^{\pm}_1/\tilde{\chi}^0_2$	0.205	m($\tilde{\chi}^{\pm}_1$)-m($\tilde{\chi}^0_1$)=5 GeV, wino-bino	1911.12606
	$\tilde{\chi}^{\pm}_1\tilde{\chi}^{\mp}_1$ via WW	2 e,μ		E_T^{miss}	140	$\tilde{\chi}^{\pm}_1$	0.42	m($\tilde{\chi}^0_1$)=0, wino-bino	1908.08215
	$\tilde{\chi}^{\pm}_1\tilde{\chi}^0_2$ via Wh	Multiple ℓ/jets		E_T^{miss}	140	$\tilde{\chi}^{\pm}_1/\tilde{\chi}^0_2$	Forbidden 1.06	m($\tilde{\chi}^0_1$)=70 GeV, wino-bino	2004.10894, 2108.07586
	$\tilde{\chi}^{\pm}_1\tilde{\chi}^{\mp}_1$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e,μ		E_T^{miss}	140	$\tilde{\chi}^{\pm}_1$	1.0	m($\tilde{\ell}$,$\tilde{\nu}$)=0.5(m($\tilde{\chi}^{\pm}_1$)+m($\tilde{\chi}^0_1$))	1908.08215
	$\tilde{\tau}\tilde{\tau}$, $\tilde{\tau}\to\tau\tilde{\chi}^0_1$	2 τ		E_T^{miss}	140	$\tilde{\tau}$ [$\tilde{\tau}_{\mathrm{R}}$, $\tilde{\tau}_{\mathrm{R,L}}$]	0.34 0.48	m($\tilde{\chi}^0_1$)=0	ATLAS-CONF-2023-029
	$\tilde{\ell}_{\mathrm{L,R}}\tilde{\ell}_{\mathrm{L,R}}$, $\tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e,μ	0 jets	E_T^{miss}	140	$\tilde{\ell}$	0.7	m($\tilde{\chi}^0_1$)=0	1908.08215
		$ee,\mu\mu$	$\geq$ 1 jet	E_T^{miss}	140	$\tilde{\ell}$	0.26	m($\tilde{\ell}$)-m($\tilde{\chi}^0_1$)=10 GeV	1911.12606
	$\tilde{H}\tilde{H}$, $\tilde{H}\to h\tilde{G}/Z\tilde{G}$	0 e,μ	$\geq$ 3 b	E_T^{miss}	140	$\tilde{H}$	0.94	BR($\tilde{\chi}^0_1\to h\tilde{G}$)=1	To appear
		4 e,μ	0 jets	E_T^{miss}	140	$\tilde{H}$	0.55	BR($\tilde{\chi}^0_1\to Z\tilde{G}$)=1	2103.11684
		0 e,μ	$\geq$ 2 large jets	E_T^{miss}	140	$\tilde{H}$	0.45-0.93	BR($\tilde{\chi}^0_1\to Z\tilde{G}$)=1	2108.07586
		2 e,μ	$\geq$ 2 jets	E_T^{miss}	140	$\tilde{H}$	0.77	BR($\tilde{\chi}^0_1\to Z\tilde{G}$)=BR($\tilde{\chi}^0_1\to h\tilde{G}$)=0.5	2204.13072
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^{\pm}_1$	Disapp. trk	1 jet	E_T^{miss}	140	$\tilde{\chi}^{\pm}_1$	0.66	Pure Wino	2201.02472
						$\tilde{\chi}^{\pm}_1$	0.21	Pure higgsino	2201.02472
	Stable $\tilde{g}$ R-hadron	pixel dE/dx		E_T^{miss}	140	$\tilde{g}$	2.05		2205.06013
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}^0_1$	pixel dE/dx		E_T^{miss}	140	$\tilde{g}$ [$\tau(\tilde{g})$ =10 ns]	2.2	m($\tilde{\chi}^0_1$)=100 GeV	2205.06013
	$\tilde{\ell}\tilde{\ell}$, $\tilde{\ell}\to\ell\tilde{G}$	Displ. lep		E_T^{miss}	140	$\tilde{e},\tilde{\mu}$	0.7	$\tau(\tilde{\ell})$ = 0.1 ns	2011.07812
						$\tilde{\tau}$	0.34	$\tau(\tilde{\ell})$ = 0.1 ns	2011.07812
		pixel dE/dx		E_T^{miss}	140	$\tilde{\tau}$	0.36	$\tau(\tilde{\ell})$ = 10 ns	2205.06013
RPV	$\tilde{\chi}^{\pm}_1\tilde{\chi}^{\mp}_1/\tilde{\chi}^0_1$, $\tilde{\chi}^{\pm}_1\to Z\ell\to\ell\ell\ell$	3 e,μ			140	$\tilde{\chi}^{\mp}_1/\tilde{\chi}^0_1$ [BR($Z\tau$)=1, BR(Ze)=1]	0.625 1.05	Pure Wino	2011.10543
	$\tilde{\chi}^{\pm}_1\tilde{\chi}^{\mp}_1/\tilde{\chi}^0_2\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets	E_T^{miss}	140	$\tilde{\chi}^{\pm}_1/\tilde{\chi}^0_2$ [$\lambda_{i33}\neq 0,\lambda_{12k}\neq 0$]	0.95 1.55	m($\tilde{\chi}^0_1$)=200 GeV	2103.11684
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to qqq$		$\geq$8 jets		140	$\tilde{g}$ [m($\tilde{\chi}^0_1$)=50 GeV, 1250 GeV]	1.6 2.25	Large λ''_{112}	To appear
	$\tilde{t}\tilde{t}$, $\tilde{t}\to t\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to tbs$		Multiple		36.1	$\tilde{t}$ [λ''_{323}=2e-4, 1e-2]	0.55 1.05	m($\tilde{\chi}^0_1$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}$, $\tilde{t}\to b\tilde{\chi}^{\pm}_1$, $\tilde{\chi}^{\pm}_1\to bbs$		$\geq$ 4b		140	$\tilde{t}$	Forbidden 0.95	m($\tilde{\chi}^{\pm}_1$)=500 GeV	2010.01015
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$		2 jets + 2 b		36.7	$\tilde{t}_1$ [qq, bs]	0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to q\ell$	2 e,μ	2 b		36.1	$\tilde{t}_1$	0.4-1.45	BR($\tilde{t}_1\to be/b\mu$)>20%	1710.05544
		1 μ	DV		136	$\tilde{t}_1$ [1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9]	1.0 1.6	BR($\tilde{t}_1\to q\mu$)=100%, cosθ_t=1	2003.11956
	$\tilde{\chi}^{\pm}_1/\tilde{\chi}^0_2/\tilde{\chi}^0_1$, $\tilde{\chi}^0_{1,2}\to tbs$, $\tilde{\chi}^+_1\to bbs$	1-2 e,μ	$\geq$6 jets		140	$\tilde{\chi}^0_1$	0.2-0.32	Pure higgsino	2106.09609

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Supersymmetry at LHC

- zooming in on gluino and stop searches
  - drivers of the fine-tuning tests





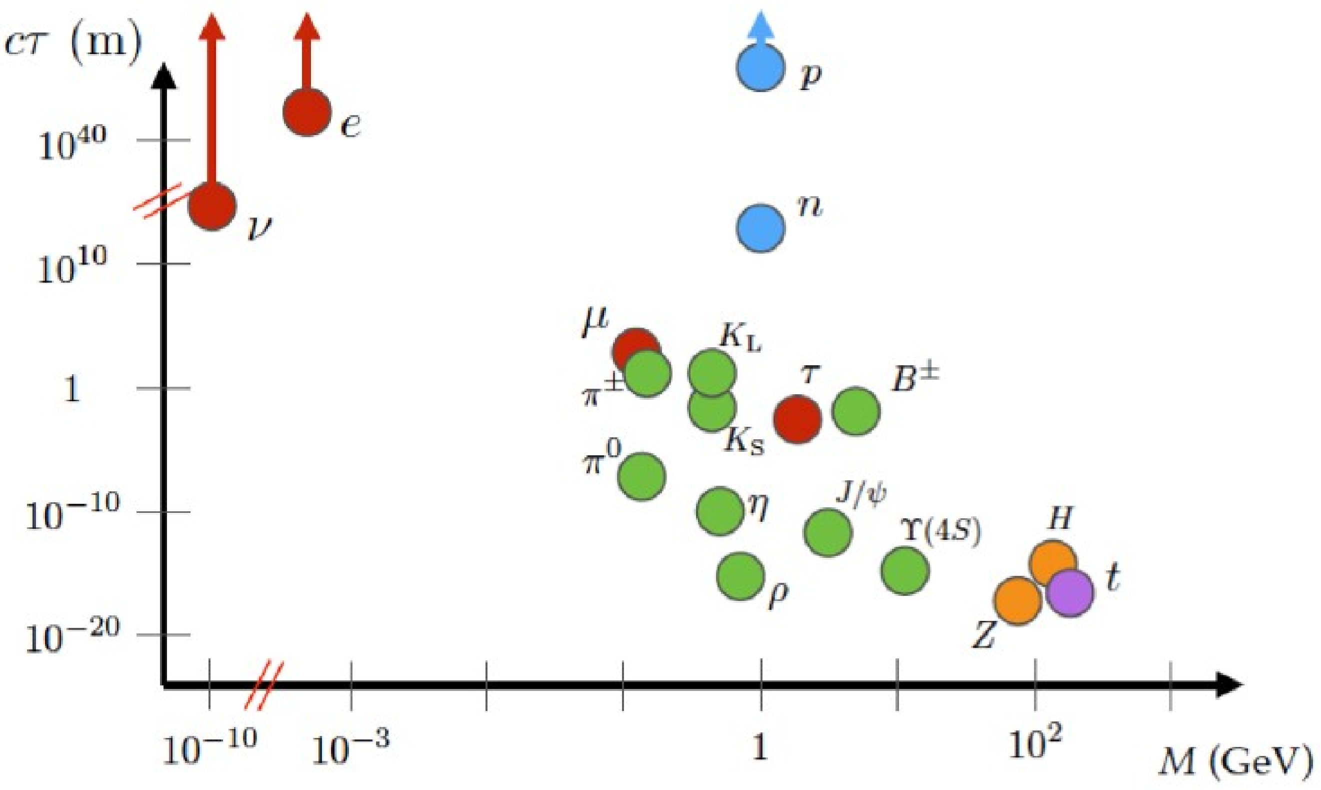
- limits from direct searches are now very stringent
  - fine tuning seems inevitable
  - simple low-mass SUSY solutions losing traction

Content Lecture 2

- dark matter
    - di-invisible → dark matter
    - direct dark matter searches at LHC
    - di-X interplay with dark matter – beyond the LHC
- supersymmetry
    - appeal
    - strong production: jets+MET
    - weak production: leptons+MET
- long-lived particles
    - why long-lived particles?
    - experimental handles
    - backgrounds
    - search status
- looking ahead

Long-Lived Particles in the SM

- the SM has a large diversity of long-lived particles



- why is this picture the way it is?

Phase space

- Fermi's golden rule states

$$\boxed{W = \frac{2\pi}{\hbar}\left|\mathcal{M}_{fi}\right|^2 \cdot \rho(E')}$$

with W the reaction probability, M_{fi} the matrix element, and ρ(E') the density of possible states in the final state, also called the phase space factor

- from this, one can calculate the partial decay width of a 2-body decay

$$\frac{1}{\tau} = \Gamma = \frac{|\vec{p}^*|}{32\pi^2 m_i^2} \int |M_{fi}|^2 d\Omega$$

with

$$p^* = \frac{1}{2m_i}\sqrt{\left[(m_i^2 - (m_1+m_2)^2\right]\left[m_i^2 - (m_1-m_2)^2\right]}$$

- so the smaller the mass difference between initial and final state, the smaller the partial width, and the larger the lifetime

Phase space

- example 1: the neutron lifetime
- dimensional rough calculation:
  - weak decay: $\Gamma \propto G_F^2$
  - mass dimension for partial width → multiply with a mass scale: $\Gamma \propto G_F^2 \Delta^5$
  - the mass scale in the neutron decay phase space is: $\Delta = m_n - m_p \approx 10^{-3}\,\mathrm{GeV}$
  - add in some factors pi from the phase space:

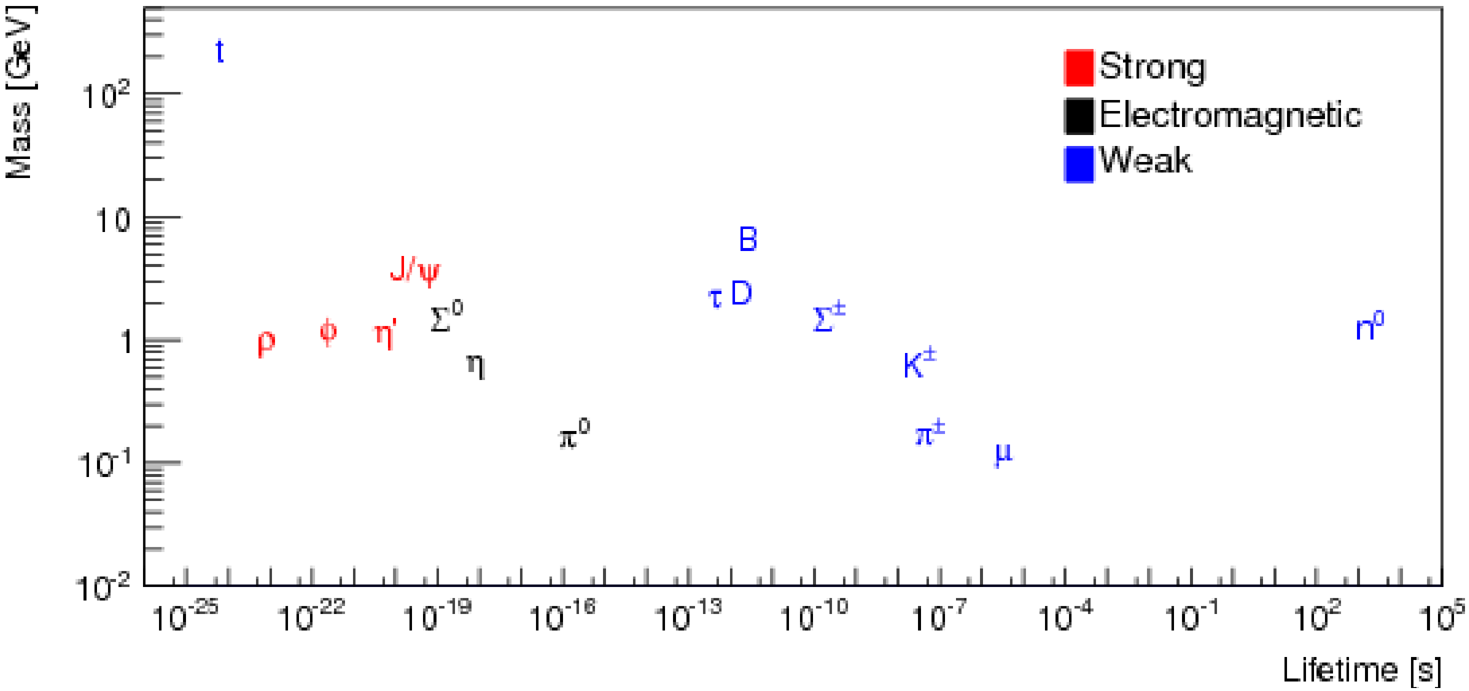
$$\Gamma \propto \frac{1}{\pi^3} G_F^2 (m_n - m_p)^5$$

- this gives ~31s ; the real value is 882s
  - not super accurate, but not bad
  - the importance of the phase space factor jumps out

- example 2: the neutral kaon
  - 2 (near) CP eigenstates from superposition of K^0 and anti-K^0
  - K_S → ππ: $m_K - 2m_\pi \approx 220\,\mathrm{MeV}$ $\boxed{\tau(K_S) = 0.9 \times 10^{-10}\,\mathrm{s}}$
  - K_L → πππ: $m_K - 3m_\pi \approx 80\,\mathrm{MeV}$ $\boxed{\tau(K_L) = 0.5 \times 10^{-7}\,\mathrm{s}}$

Coupling strength

- the matrix element calculation will involve a coupling strength



- we know 3 forces in nature
  - strong decays: $\tau \sim 10^{-22}$ s → $c\tau$ ~ 10 fm
  - EM decays: $\tau \sim 10^{-18}$ s → $c\tau$ ~ .1 nm
  - weak decays: $\tau \sim 10^{-10}$ s → $c\tau$ ~ cm

experimentally
not observable

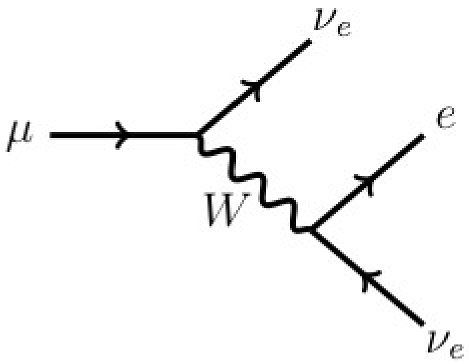
great for experiment!

Coupling strength

- from experiment:
  - strong decays: $\tau \sim 10^{-22}$ s → $c\tau \sim 10$ fm
  - EM decays: $\tau \sim 10^{-18}$ s → $c\tau \sim .1$ nm
  - weak decays: $\tau \sim 10^{-10}$ s → $c\tau \sim$ cm
- but from the Standard Model in our energy range
  - $\alpha_S \sim 1$
  - $\alpha_W \sim 1/30$
  - $\alpha_{EM} \sim 1/137$
- lifetime ~ 1 / coupling^2
  - $(\alpha_S / \alpha_{EM})^2$ → factor 10^4 - makes sense
  - $(\alpha_W / \alpha_{EM})^2$ → way off; something else going on too...

Mass barrier

- when the decay must proceed through an off-shell heavy mediator, we pick up another lifetime effect
- example from the muon decay
  - no color charge, so no strong decay
  - no EM decay possible without violating lepton number conservation (μ → eγ, μ → eee)
  - so only weak decay possible



- the weak decay involves an intermediate W boson
  - the W boson propagator: $-\frac{i(g_{\mu\nu} - p_\mu p_\nu)}{p^2 - M_W^2}$
  - the W is very heavy wrt the muon, so it simplifies: $\frac{ig_{\mu\nu}}{M_W^2}$
- so we pick up a $1/M_W^4 \sim G_F^2$ dependence in the decay probability
- this is why the weak decays are so much weaker than the EM ones
  - luckily leading to experimentally observable long-lived processes

Recap: why such diversity in lifetime?

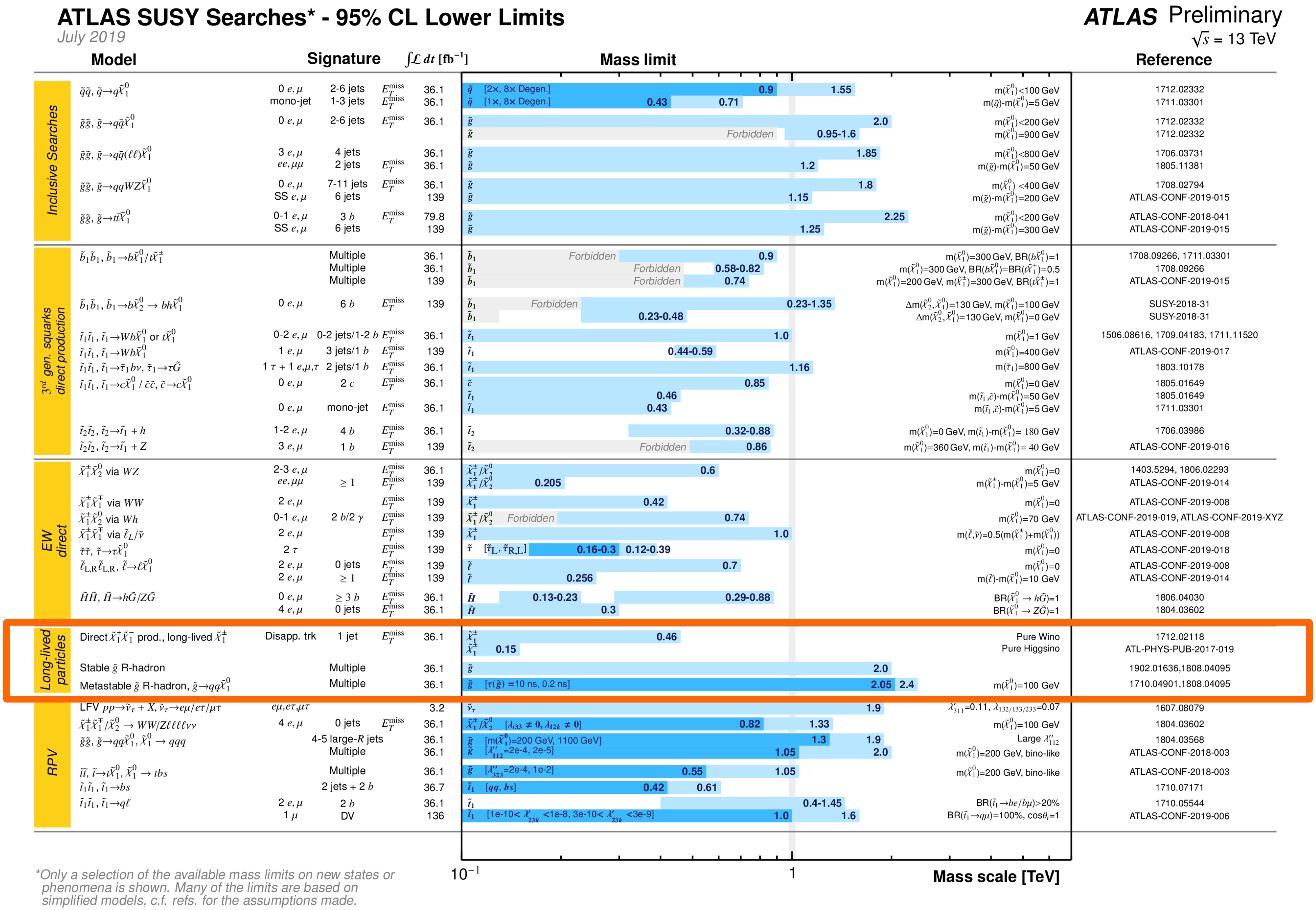
- main reasons for decay lifetime differences:
  - coupling of the interaction
  - mass barrier for decays with heavy mediator
  - phase space small if mass difference in and out small
- all these effects come in with some exponent, so effects are large

- other things playing
  - decaying particle's mass
  - Lorentz structure and potential mixing factors (eg. CKM)
  - number of decay channels

    including eg. colour factors
  - suppression if only loop-level decay allowed
  - decay through mixing
- these other effects usually don't play in the standard model
- but they may be very relevant in BSM scenarios

Back to SUSY at LHC

- current experimental situation



*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Examples of long-lived SUSY

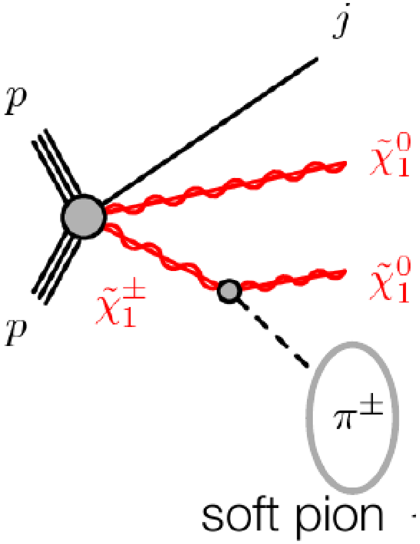
…from compressed spectrum

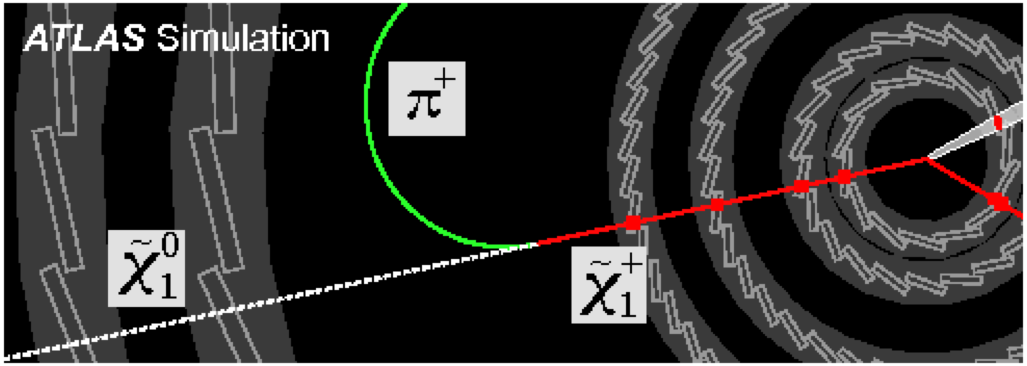
- eg. AMSB scenario
  - chargino and neutralino nearly mass degenerate

    ~300 MeV mass splitting → phase space suppression
  - just enough room for a soft pion to be emitted

    weak decay with off-shell "hadronic W"
  - chargino becomes long-lived
- phenomenology of long-lived chargino
  - disappearing track if decay within tracker

    soft pion almost impossible to reconstruct
  - strong ionization from mass (see later)
- note: often the disappearing track is not there or usable in online event selection (trigger)



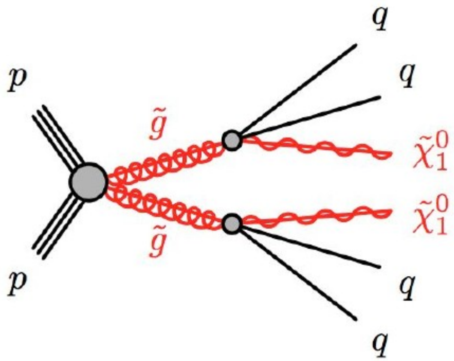


Examples of long-lived SUSY

… from mass barrier

- imagine the gluino much lighter than the squarks
  - gluino carries double colour charge
    → needs to decay to 2 quarks and LSP
  - such 3-body decay must happen
    through intermediate squark (R parity...)
  - if squarks heavy enough, gluino becomes long-lived

$$c\tau \simeq 2 \times 10^{-1} \left(\frac{2\ \mathrm{TeV}}{M_3}\right)^5 \left(\frac{\tilde{m}}{10^6\ \mathrm{GeV}}\right)^4 \mathrm{mm}$$



example from
Nucl.Phys. B726 (2005) 35-52

- long-lived gluinos → R hadrons
  - long-lived gluino carries color charge
  - QCD confinement implies the gluino must hadronize → R hadron

    R-meson, R-baryon, R-gluinoball

Examples of long-lived SUSY

- R hadrons bring unexpected phenomenology
  - can be very massive thus non-relativistic
    - out-of-time signals in various subdetectors
  - can be charged or neutral (gluino dressed with quarks or gluons)
    - if charged, heavy particle ionization in detector (see later)
  - can have nuclear interactions with material
  - interaction with material can lead to charge change
    - disappearing track, appearing track, kinked track
  - can get stopped in material to decay at later time
    - preferentially trapped in dense material
    - decay time could be very large
- such features are useful to search for the signal
  - but also difficult to simulate, control, predict,...

Examples of long-lived SUSY

… from coupling

- if R parity is not conserved
  - vertices are possible that violate B or L conservation
  - proton lifetime must stay sufficiently long (~10^{34})
  - hence the “couplings” of the new vertices must be sufficiently small

- easy to obtain long-lived particles in an R parity violating model
  - example: long-lived neutralino

    3-body decay through off-shell fermion

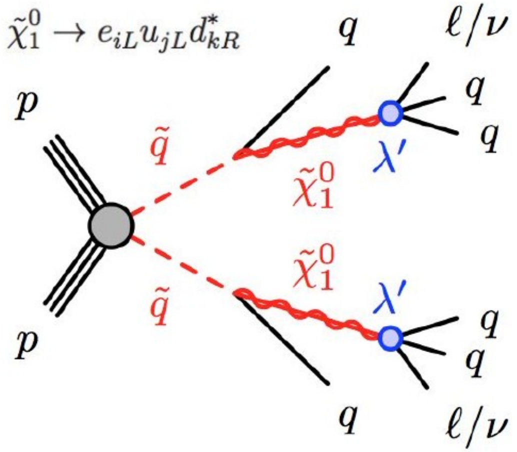
$$c\tau \simeq \frac{3}{\lambda'^2_{ijk}} \left(\frac{m_{\tilde{f}}}{100\ \mathrm{GeV}} \right)^4 \left(\frac{1\ \mathrm{GeV}}{m_{\tilde{\chi}_1^0}} \right)^5 \mathrm{mm}$$

    (see: Phys.Rept.420:1-202,2005)

  - relevant phenomenology

    displaced jets, displaced leptons

    typically no missing momentum

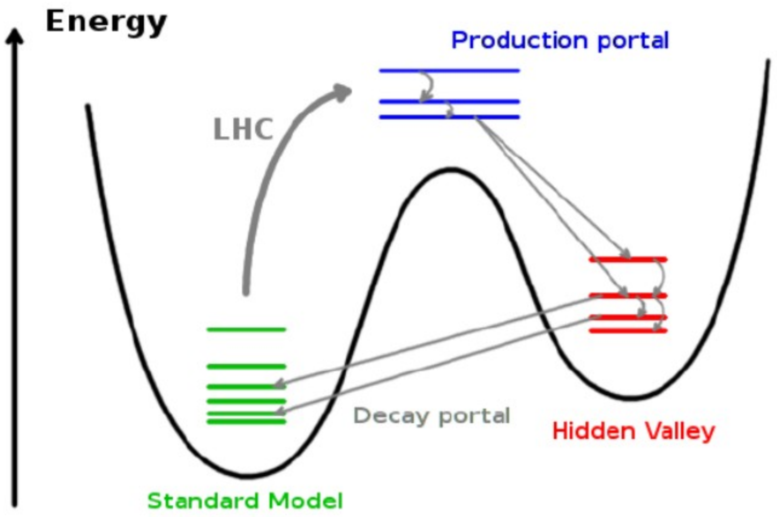


Portals

- imagine a dark sector
  - new particles that do not carry Standard Model charges

    may contain dark matter particles (mass couples to gravity)
  - a connection may arise from heavy particles charged under both SM and DS

- or it may arise through SM portals
  - Higgs portal
  - hypercharge portal
  - neutrino portal
- these are the only ways a dark sector may be directly coupled to the SM through a renormalizable operator



- new states with long lifetimes are generic features of dark sector models
  - dark sector may be rich, eg. with dark QCD, bound states, etc
  - portal couplings can be small

Portals example: kinetic mixing

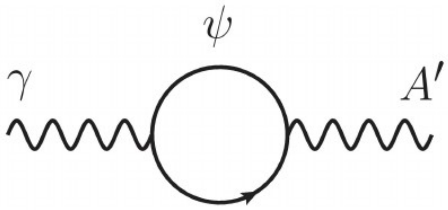
- suppose we add a U(1)' boson to the SM

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} - \frac{1}{4} B'_{\mu\nu} B^{\mu\nu\prime} - \frac{\kappa}{2} B'_{\mu\nu} B^{\mu\nu}$$

kinetic mixing
[Holdom '86]

we call this a dark photon

- the kinetic mixing term can be generated through new heavy particles that couple both to hypercharge and to the new U(1)'



$$\sim \frac{e\, g_D}{16\pi^2} \log \frac{m_\psi}{M_*}$$

  - generates coupling 10^{-3} for m_ψ ~ EW scale
- but a priori, the coupling can be anything

Portals example: kinetic mixing

- let's now add a new fermion only charged under U(1)'

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}B'_{\mu\nu}B^{\mu\nu\prime} - \frac{\kappa}{2}B'_{\mu\nu}B^{\mu\nu} + i\bar{\psi}(\partial\!\!\!/ + ie'B' + iM_{\rm mCP})\psi$$

- and redefine the field

$$B' \to B' + \kappa B$$

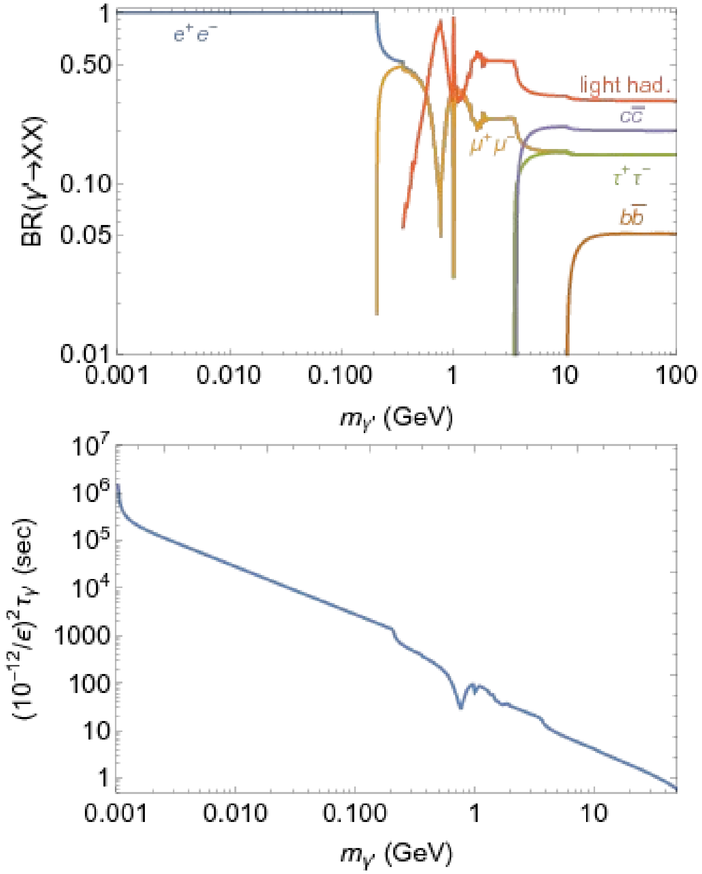
- mixing term disappears and new fermion gets hypercharge

- for a massless dark photon
  - after EWSB arbitrary apparent electric charge:

$$Q = \kappa e' \cos\theta_W$$

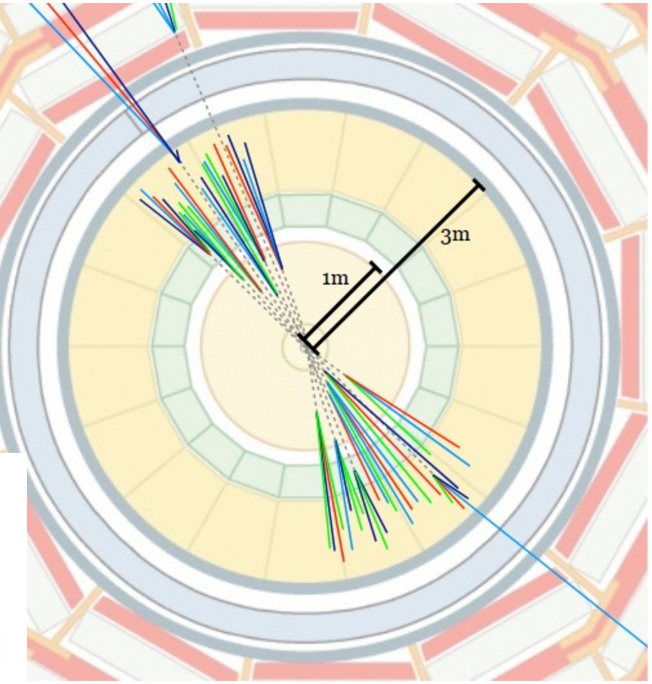
  - new fermions are "millicharged" particles
- for massive dark photon
  - coupling goes through off-shell photon/Z
  - rich phenomenology: decays to electron, muon, hadron, quark pairs
  - at low mass, charged particles can further radiate dark photons → lepton jets
  - lifetime proportional to 1 / ($m_{A'}$ ε^2)

relevant at low masses and couplings

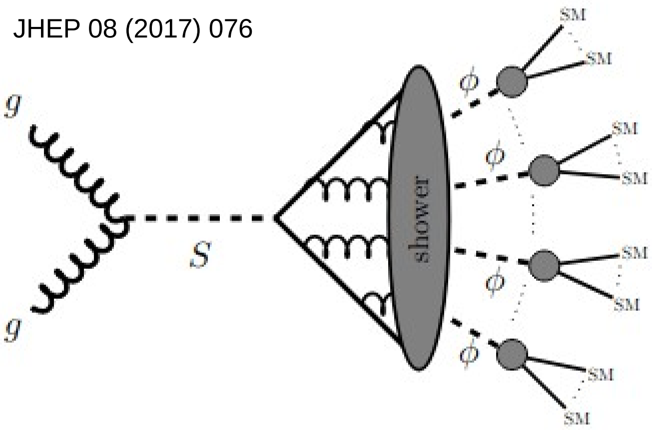


Portals example: dark QCD

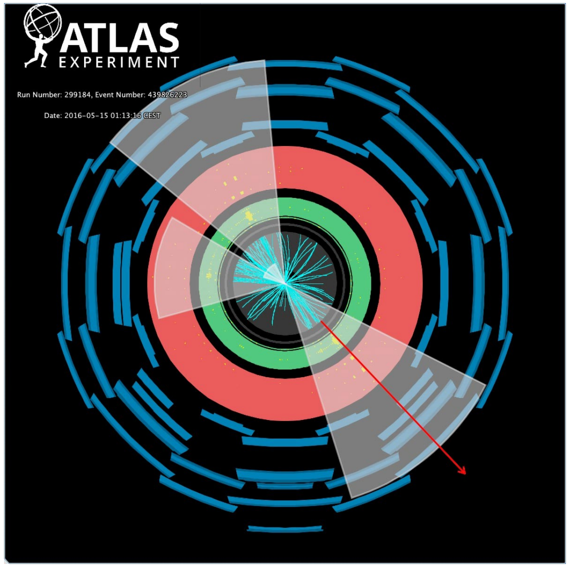
- assume a dark QCD: particles decoupled from SM, but with an SU(3) force
  - produce through a heavy mediator carrying SM and dark charge
  - decaying back to SM through hypercharge portal
- very unusual final states
  - emerging jets
  - semi-visible jets
  - Soft Unclustered Energy Patterns



arXiv:2403.01556
JHEP 05 (2015) 059



arXiv:2403.05311
JHEP 08 (2017) 076



Phys.Rev.Lett. 115 (2015) 17, 171804
Phys.Lett.B 848 (2024) 138324

Heavy Neutral Leptons

- neutrinos have mass, but right-handed neutrinos were not observed, so we cannot put them in the usual SU(2) doublet
  - no Dirac mass terms $m_D \bar{\nu} \nu = m_D (\bar{\nu}_L \nu_R + \bar{\nu}_R \nu_L)$
- one way out is to add right-handed Majorana neutrino, but a sterile one
  - no SM gauge couplings
- seesaw mechanism generates the neutrino masses
  - righthanded neutrino mixes in mass eigenstates

$$-\frac{1}{2}\begin{pmatrix}\bar{\nu}_L & \bar{\nu}_R\end{pmatrix}\begin{pmatrix}0 & m_D \\ m_D & m_{M,R}\end{pmatrix}\begin{pmatrix}\nu_L \\ \nu_R\end{pmatrix}$$

- several flavours of seesaw models exist

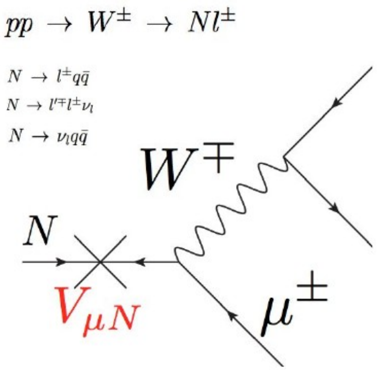
- if the righthanded neutrino is light, it can become long-lived

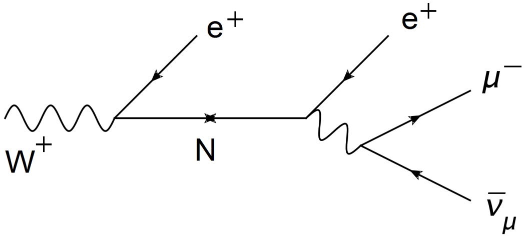
$$c\tau_N \sim 3.7\left(\frac{1\,\mathrm{GeV}}{m_N}\right)^5\left(\frac{0.1}{|V_{\ell N}|^2}\right)\ [\mathrm{mm}]$$

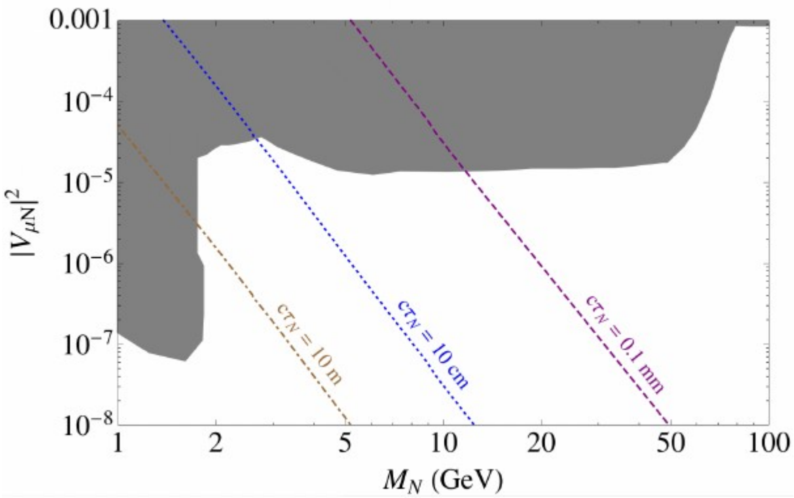
  - this is a combination of a mass (phase space) and a mixing effect

Heavy Neutral Leptons

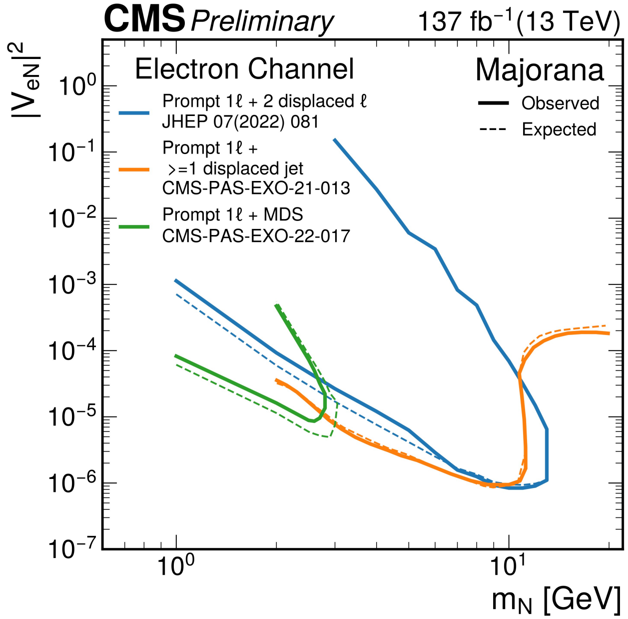
- rich right-handed neutrino phenomenology at LHC (eg. Phys. Rev. D 91, 093010)







- long-lived effect only at very low sterile neutrino mass
  - strong dependence from m^5
- experimentally difficult phase space
  - soft decay products
  - collimated objects
  - hadron resonances
- at lower mass, also production in B/D meson decays



Long-lived particle pheno wrap up

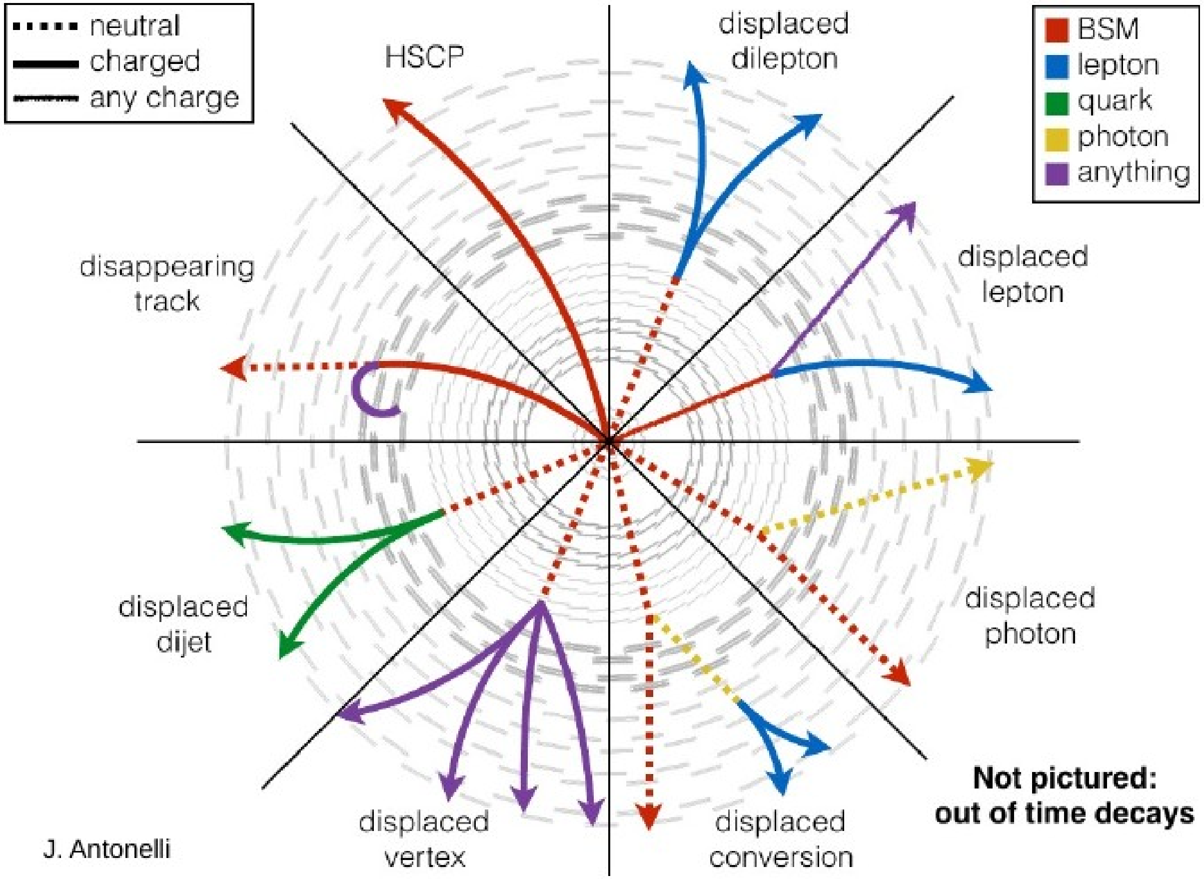
- particles can be long-lived due to variety of effects
  - narrow phase space, small coupling, and mass barrier as main lifetime drivers
  - weak force gives us many observable long-lived particles already

- long-lived particles arise in multitude of contexts
  - many proposals for problems of the SM model have versions that involve longlived particles
  - also generic portal models for dark sectors often involve long-lived particles when decays back to SM happen
  - regularly very exotic proposals appear
  - often similar signatures arise in different contexts ← models are not easy guidelines

- take-away message
  - long-lived particle phenomenology is very rich
  - lifetimes are very sensitive to model parameters
- also: long-lived particles were not invented because we observed no BSM physics yet at the LHC
  - they have always been there, but have become more visible now that mainstream searches have only been placing limit

Building an experimental story

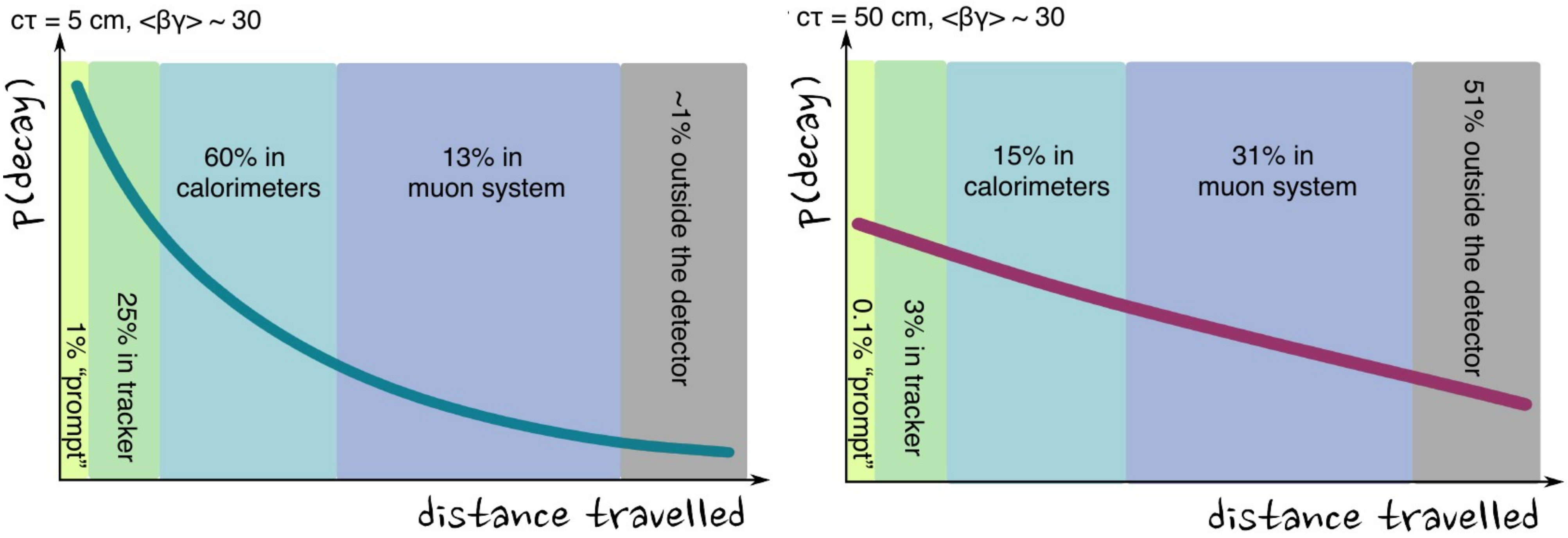
- so the question then is: how to approach this richness experimentally
- signatures are very diverse...



Not pictured: out of time decays

Building an experimental story

- and interplay between very different subdetectors



- No one-size-fits-all approach – decay products, lifetime, mass, boost: all dramatically affect the detector signature
    - ...and sometimes all subdetectors must be combined for optimal results

Experimental strategy

- lacking a clear top-down driving paradigm, we must work bottom-up
- we need to take an as experimental position as possible
  - pheno models identify a final state as interesting
  - then a search for this final state is built around the experimental signature rather than the model details
    - use the detector's capabilities as the basic driver of the analysis
    - keep the pheno model as an inspiration
- using the fact that SM long-lived particles give typically very different features than the signal sought, long-lived particle searches often manage to suppress the background to a negligible level
  - being statistically limited is great for discovery
  - good for analysis robustness
- the challenges are numerous though...

Experimental challenges

- non-standard simulation
  - sometimes special care in event generation
  - GEANT challenges for R hadrons, SIMPs, quirks,...
- non-standard reconstruction
  - timing info
  - secondary vertices
  - displaced jets and leptons
  - dE/dx
  - veto on material interactions
  - ...
- non-standard triggers
  - analysis specific, but common challenges
  - opportunities in scouting and parking
- non-standard backgrounds
  - cosmics, beam halo, spikes, noise,...
  - missing hits from dynamic inefficiency, broken modules,...
  - rare hadron decays and/or resolution tails

Know your detector

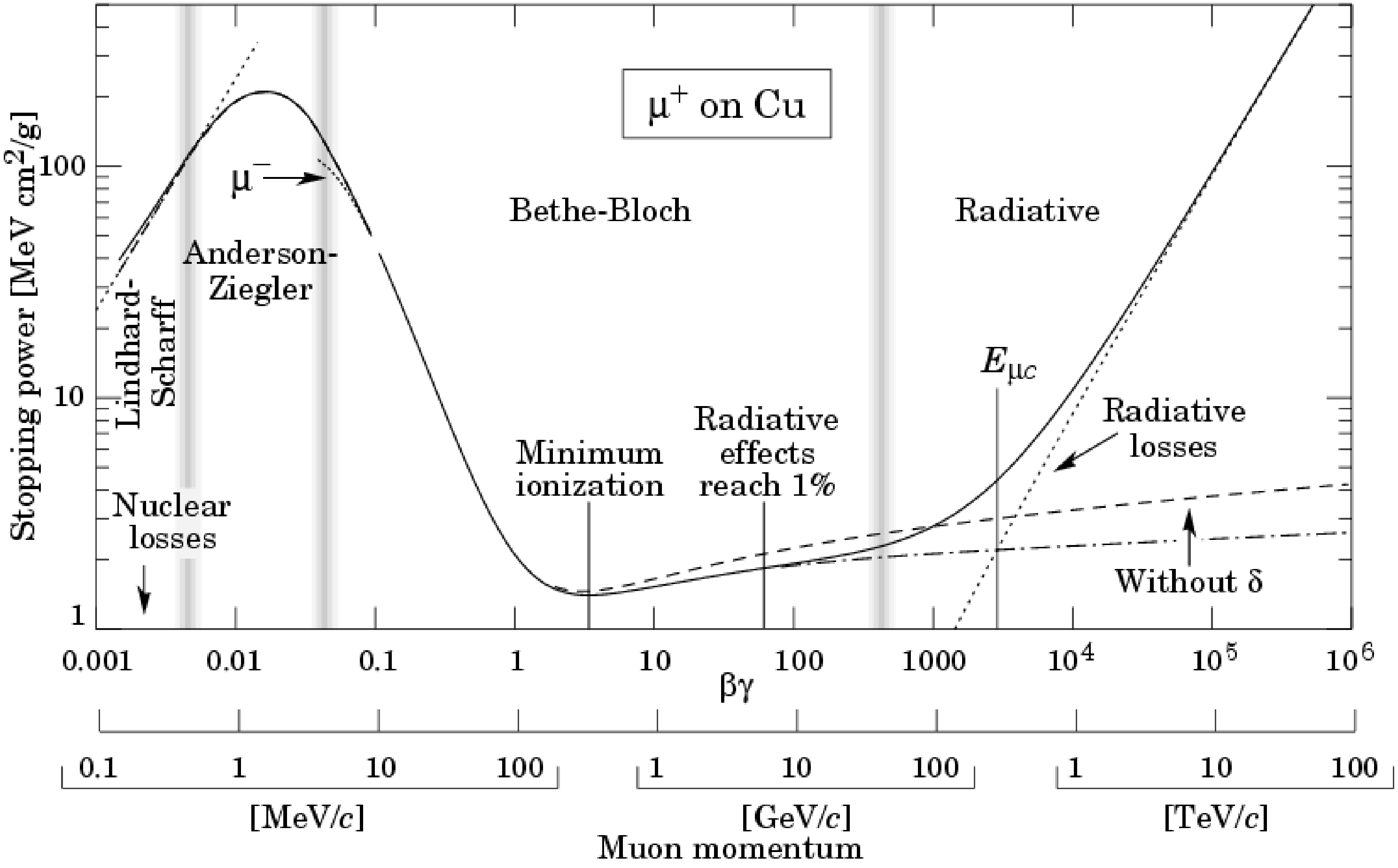
- to keep it focused, I will not discuss special simulation or trigger pecularities
  - very technical and very analysis specific

- I'll focus on a few low-level detector aspects
  - to demonstrate the potential power of rarely used techniques
  - to show one of the fun things of long-lived searches:
    detector knowledge is power
- then I'll demonstrate some of the unusual backgrounds
  - detector related
  - accelerator related
  - algorithmic

- this is heavily CMS (and own experience) biased, but it applies broadly
  - each analysis will have its own challenges

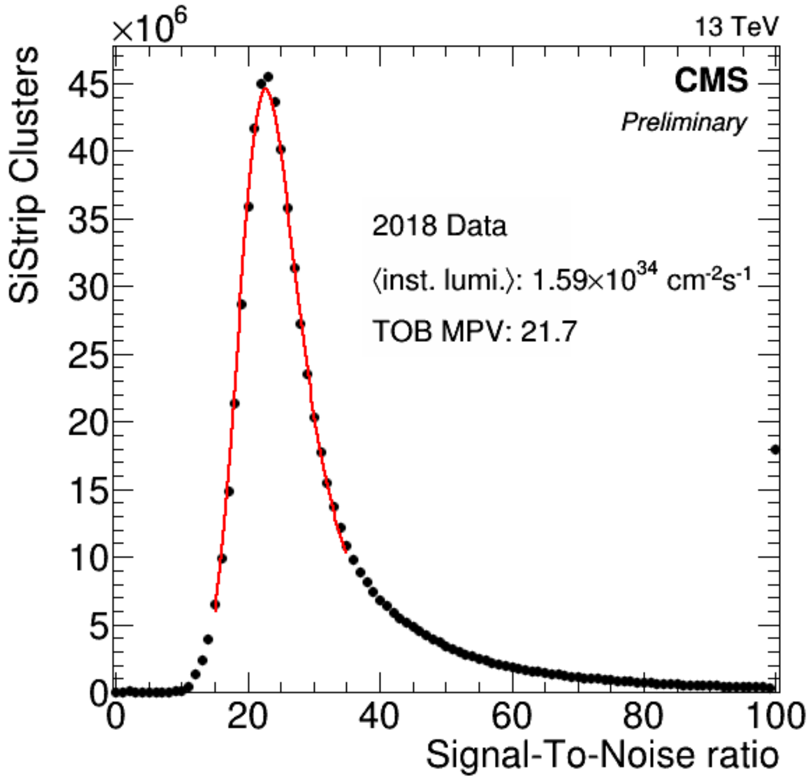
Using ionization energy

- ionization energy loss is decribed by the Bethe-Bloch relation



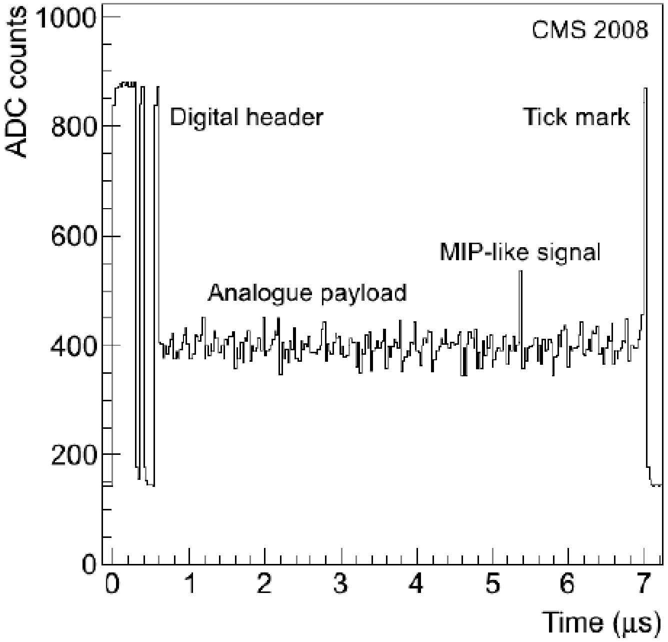
Using ionization energy

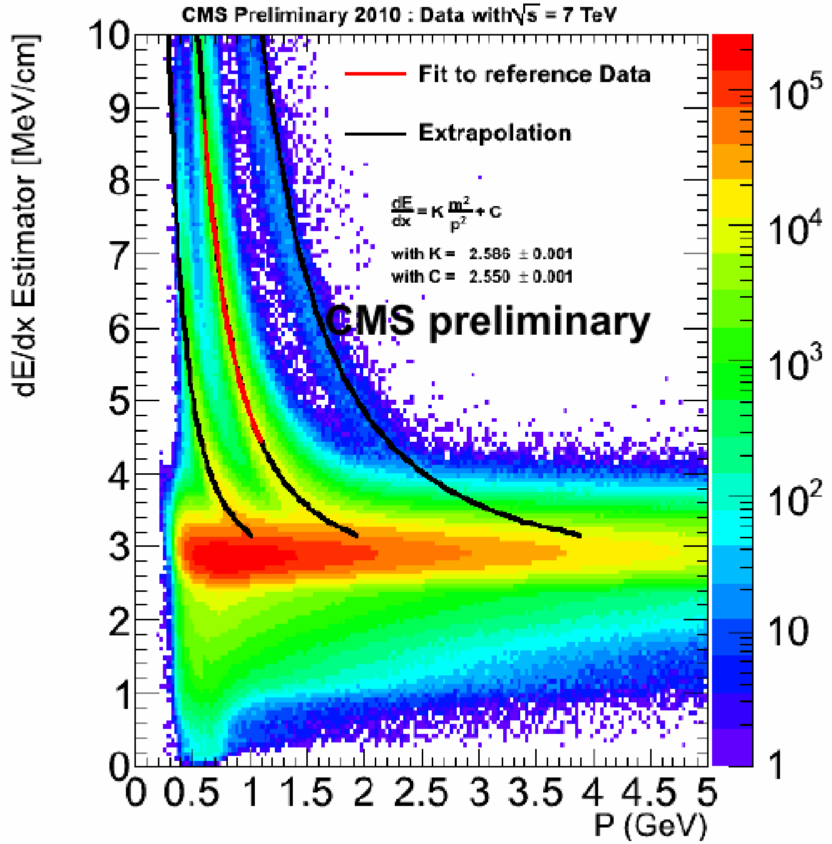
- our tracking detectors measure energy deposits from MIPs with a very good signal-over-noise
  - usually we just use the information that a hit occurred at a certain position to seed the tracking algo



Using ionization energy

- but we have more:
  we measure the ionization energy
  - within a certain dynamic range
  - current CMS tracker has an analogue readout



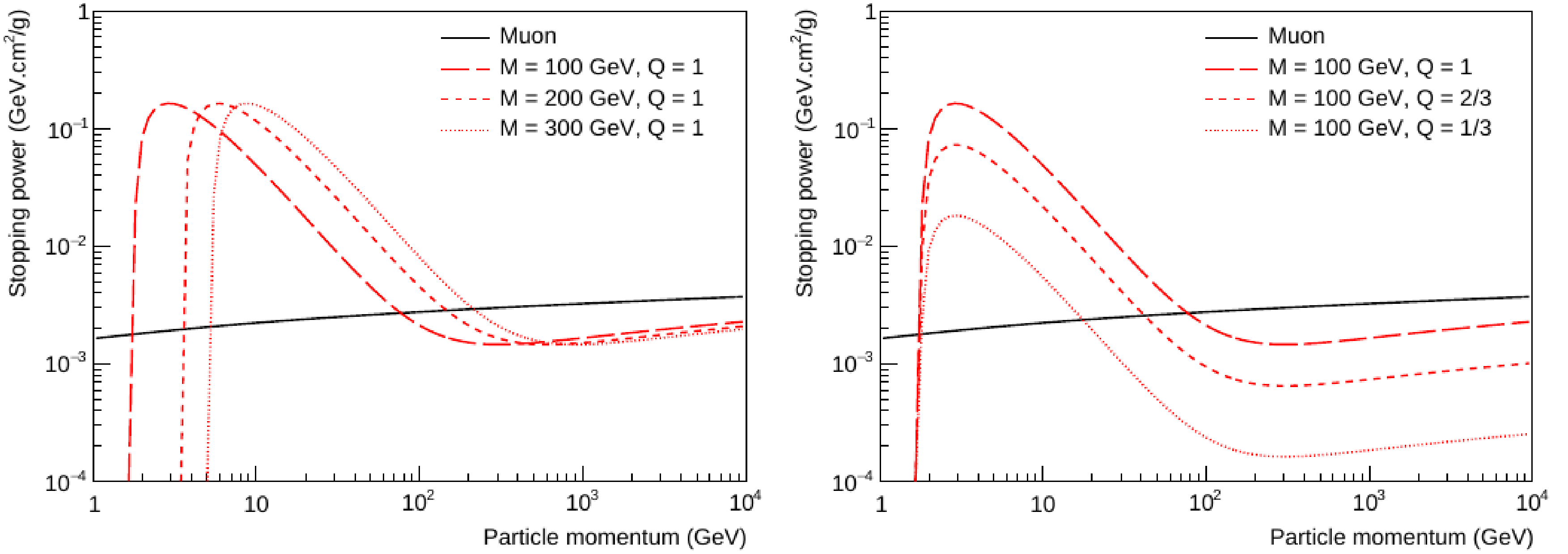


dE/dx can be estimated also taking into account track inclination

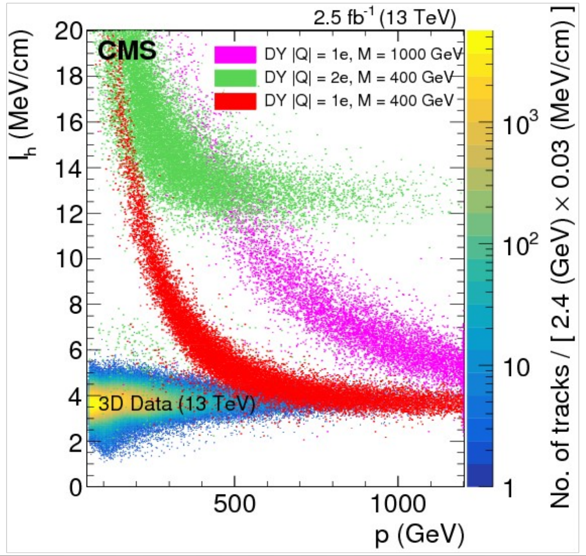
at low momentum we can estimate the mass

Using ionization energy

- effect of mass – effect of charge

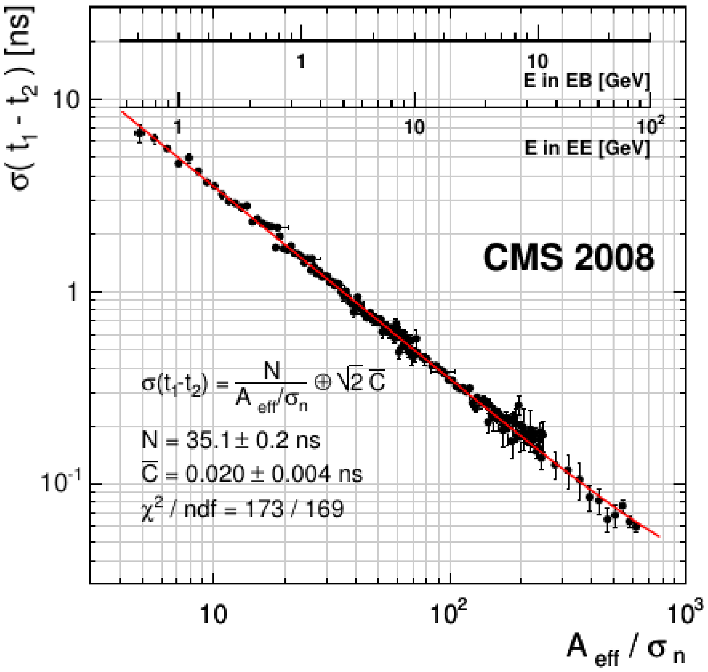


- dE/dx can be used to
  - select massive charged particles ionizing the detector
  - select both high-charge or low-charge particles

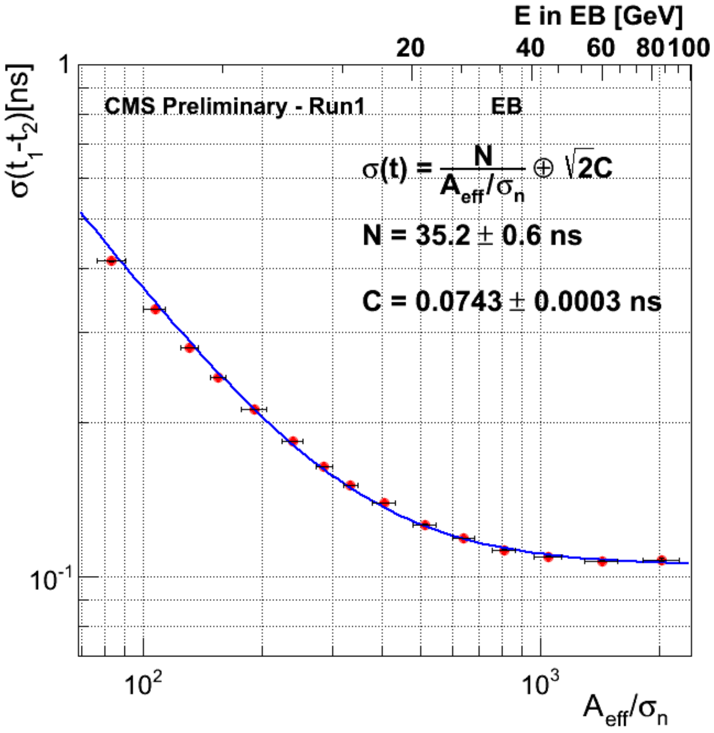


Using timing

- excellent timing of ECAL signals
- 200ps (300ps) timing resolution in barrel (endcap) for typical Z energies
  - applications in delayed photons and jets



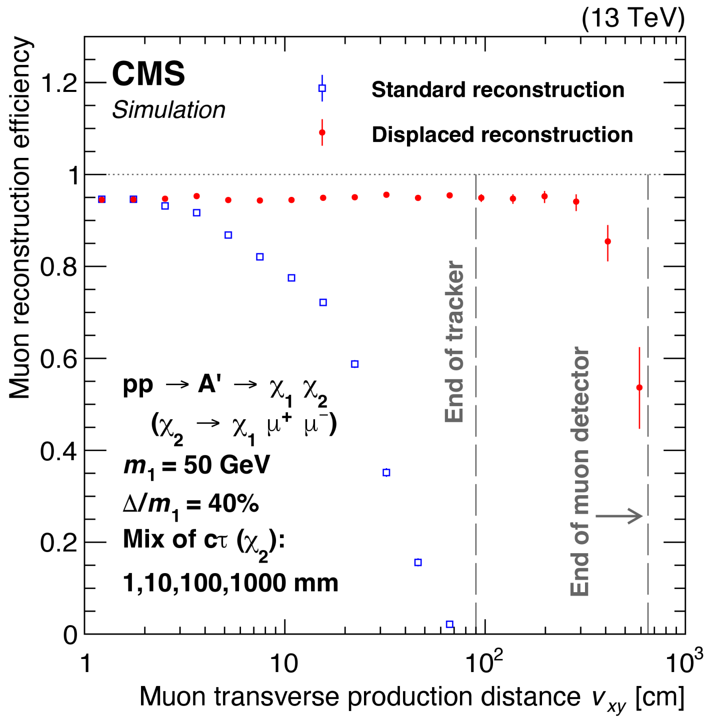
JINST 5 (2010) T03011



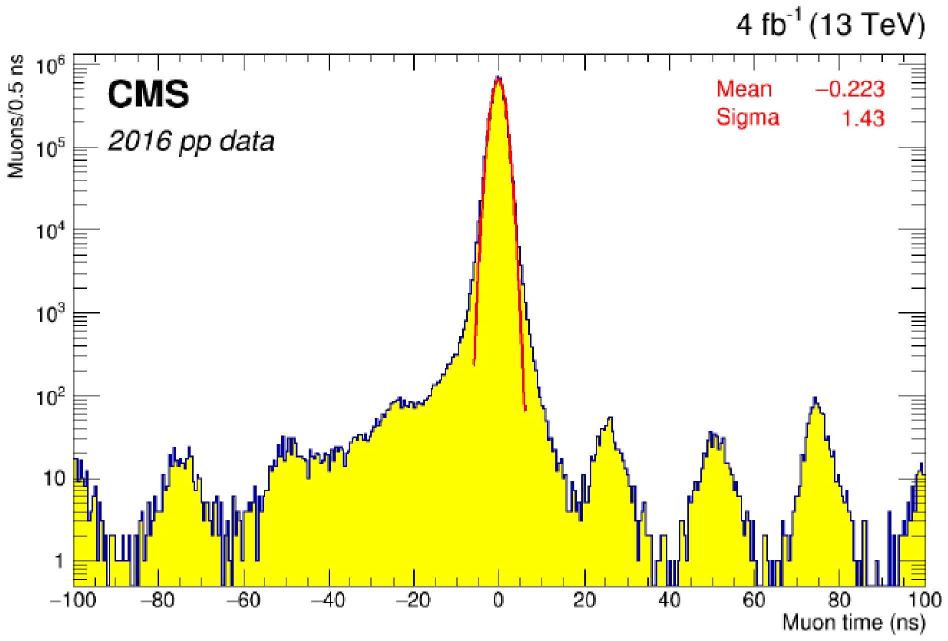
CMS-DP-2014/011

Using timing

- also muon systems typically have good timing capabilities
  - muon algorithms often use that in their ID variables
- long-lived particles may need reconstructions that take into account out-of-time signals



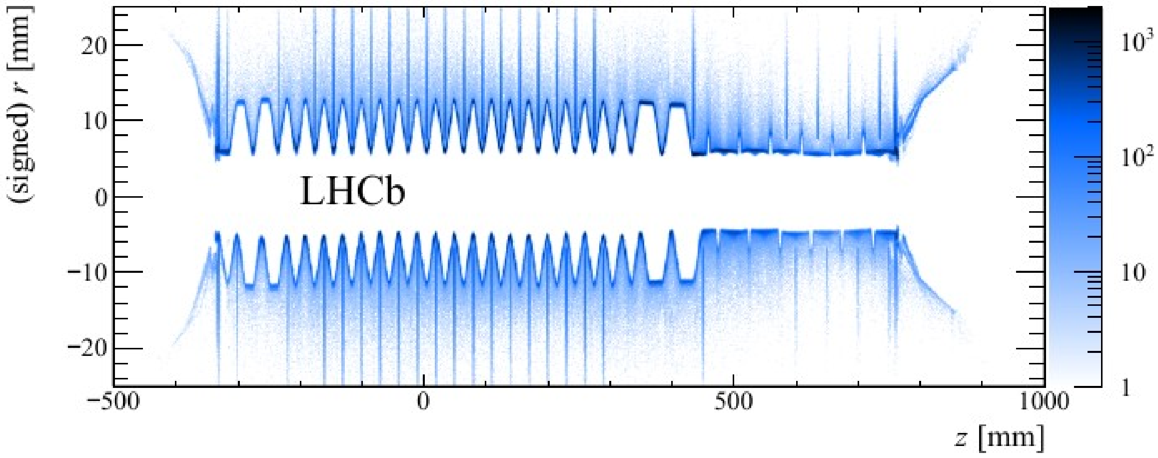
Phys. Rev. Lett. 132 (2024) 041802

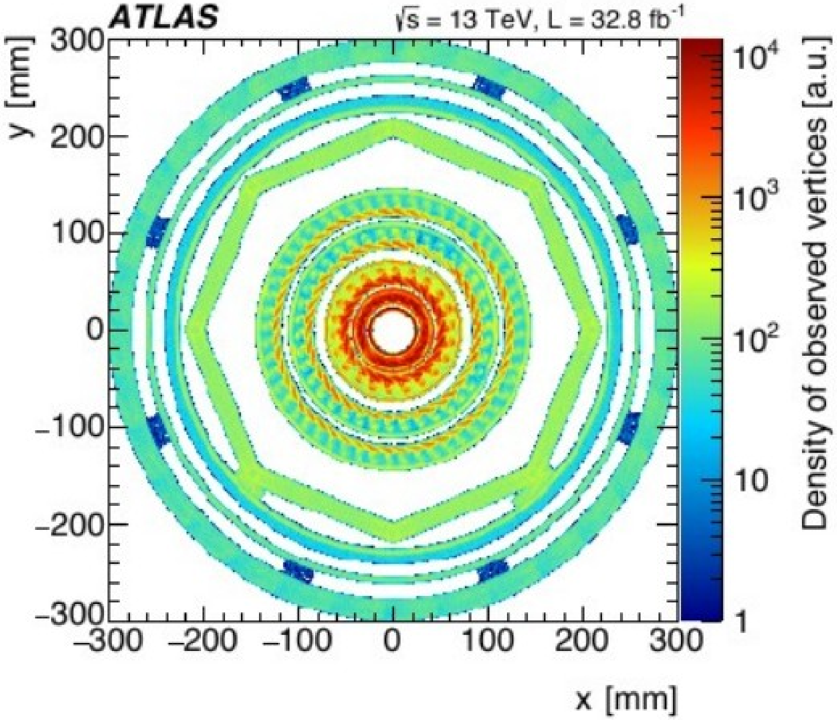


JINST 13 (2018) 06, P06015

Using material veto

- background from photon conversions and nuclear interactions in tracker layers can profit strongly from a material veto
    - veto secondary vertices that coincide with material location
- must do a dedicated data measurement
    - using nuclear interactions
    - using conversions to muons: lower statistics but cleaner
    - mostly useful in inner regions



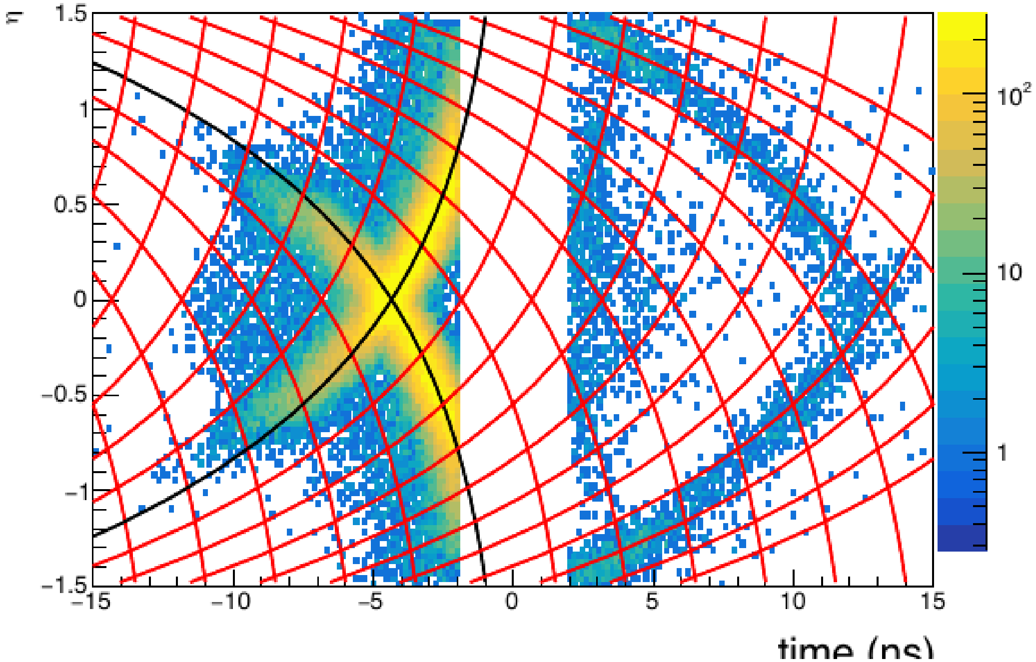


Background from beam halo

- beam halo are muons travelling along with the LHC beam
  - but parallel, at potentially large radius
  - created on the LHC collimators
- since they are in sync with the beam, their timing is off in reconstruction

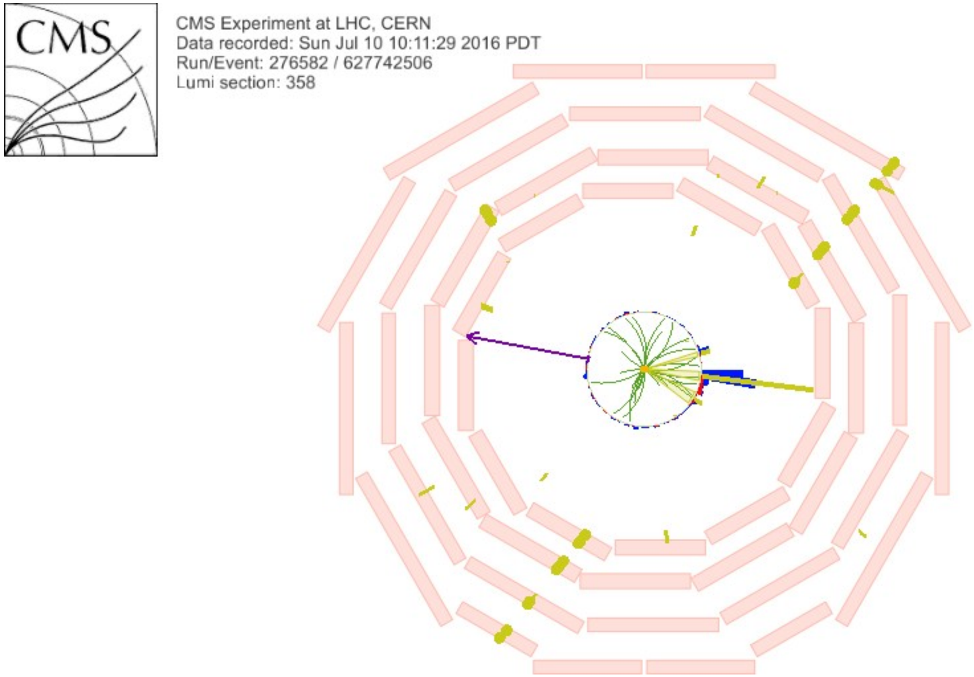
$$t^{\text{halo}} = -\frac{\pm z + \sqrt{z^2 + R^2}}{c} = -\frac{R}{2c}e^{\pm\eta}$$

- example time distribution for energy deposits in the CMS ECAL



Background from cosmic muons

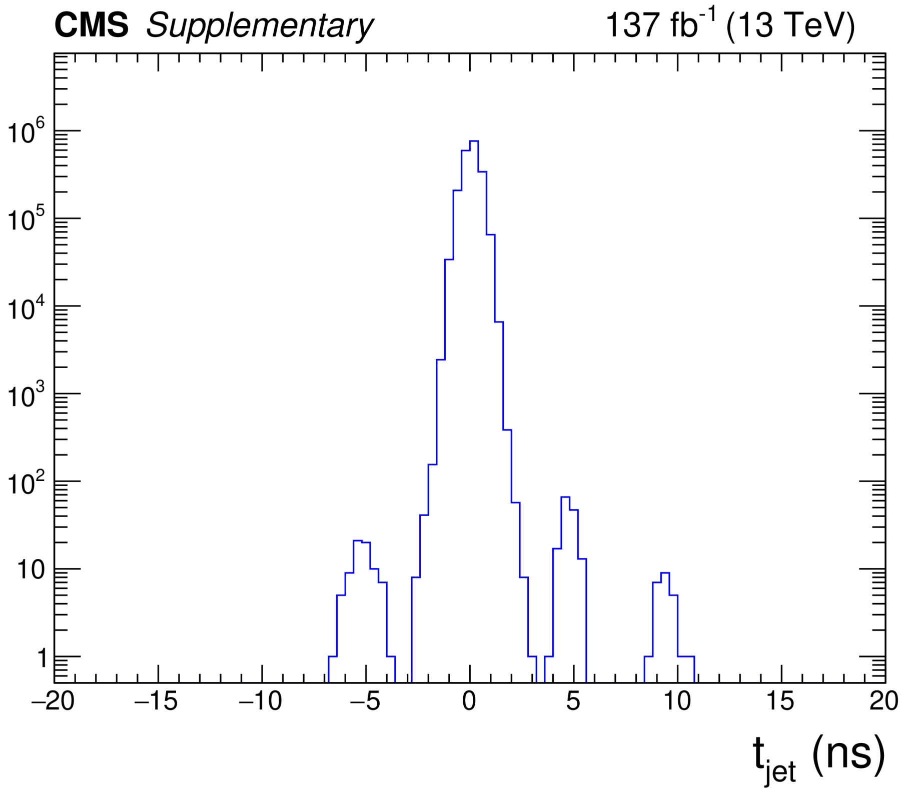
- cosmic muons come in continuously, so their timing is random
- when severely out of time, some hits may be lost
  - could lead to missing tracker track, while muon or calo deposit is there
- typically angular variables are used to suppress this background
  - using the fact that you see two muons/tracks that belong to the same track really
- one of the few backgrounds for which larger luminosity helps
  - only integrated data-taking time counts



Background from sattelite bunches

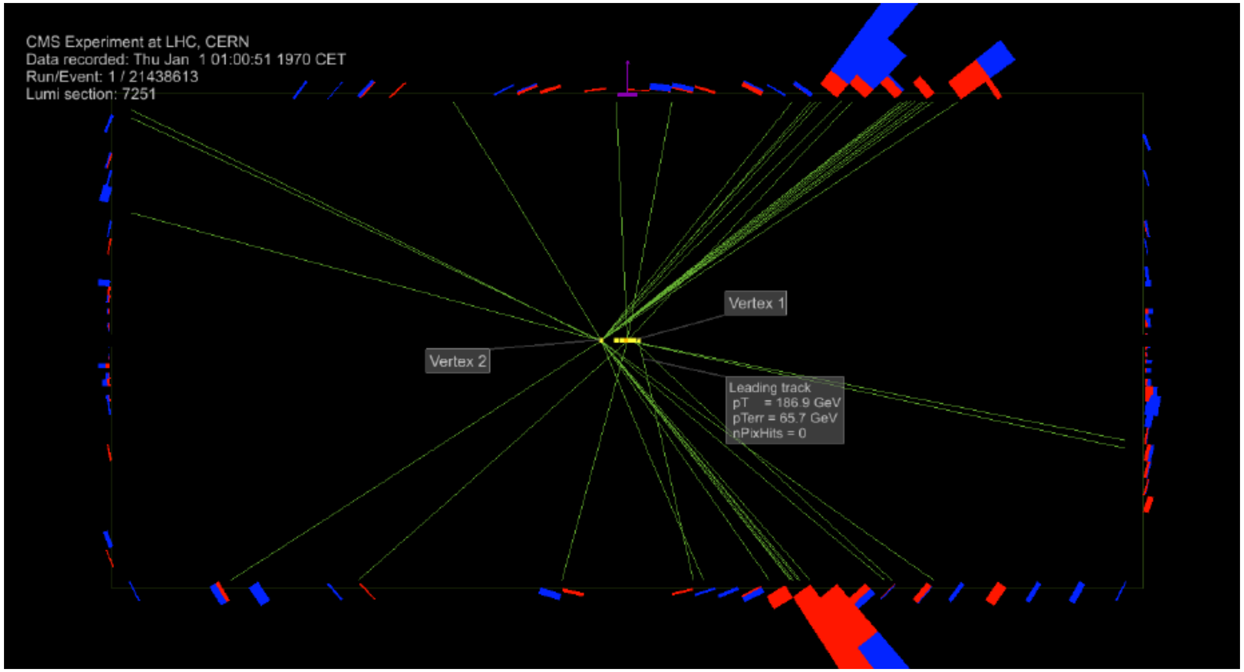
- LHC bunching each 25ns is not perfect
  - RF has 2.5ns buckets
- by selecting out-of-time ECAL hits, you may pick up real physics from nearby RF buckets
  - very small effect, but important for a few analyses
  - suppression is analysis dependent

Phys. Lett. B 797 (2019) 134876



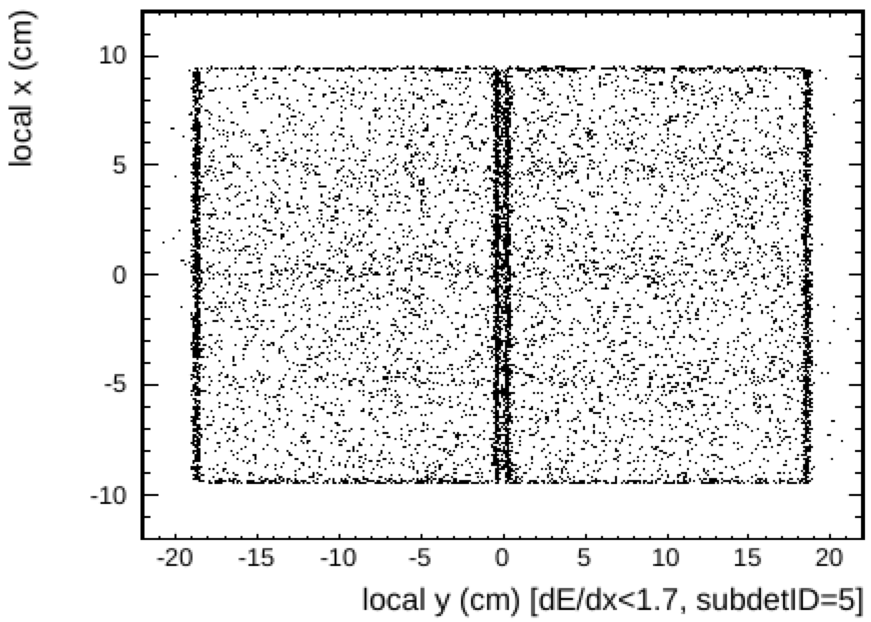
Background from wrong vertex

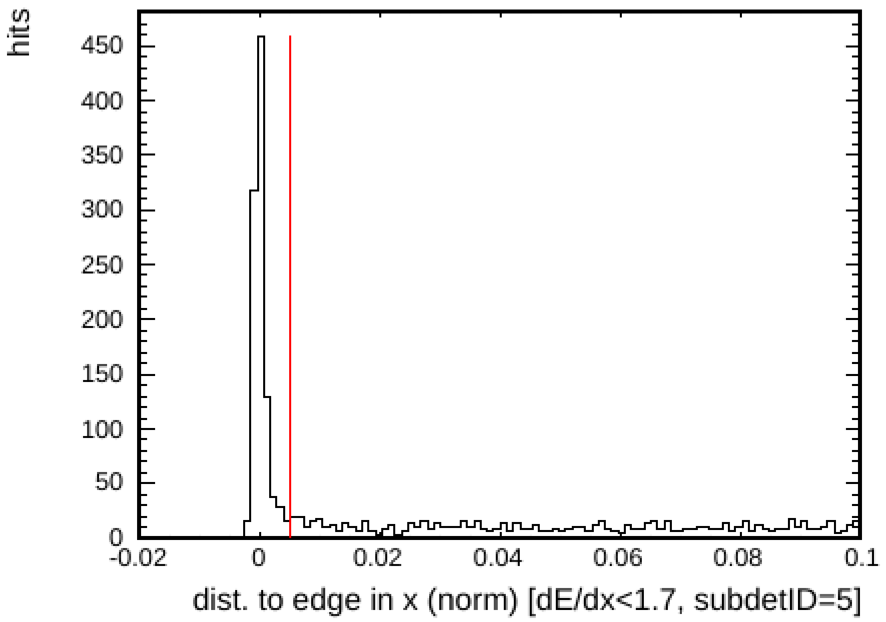
- in standard CMS jets, we remove all charged hadrons not associated to the primary vertex
  - this helps significantly in reducing pileup effects
- suppose you are looking for neutral jets as a signal
  - if you choose a wrong primary vertex, then tracks from real QCD jets will be removed, making them neutral
  - such a wrong choice has only a very small probability
  - but the QCD cross section is huge
- must use non-standard reconstruction to suppress this



Background from geometry

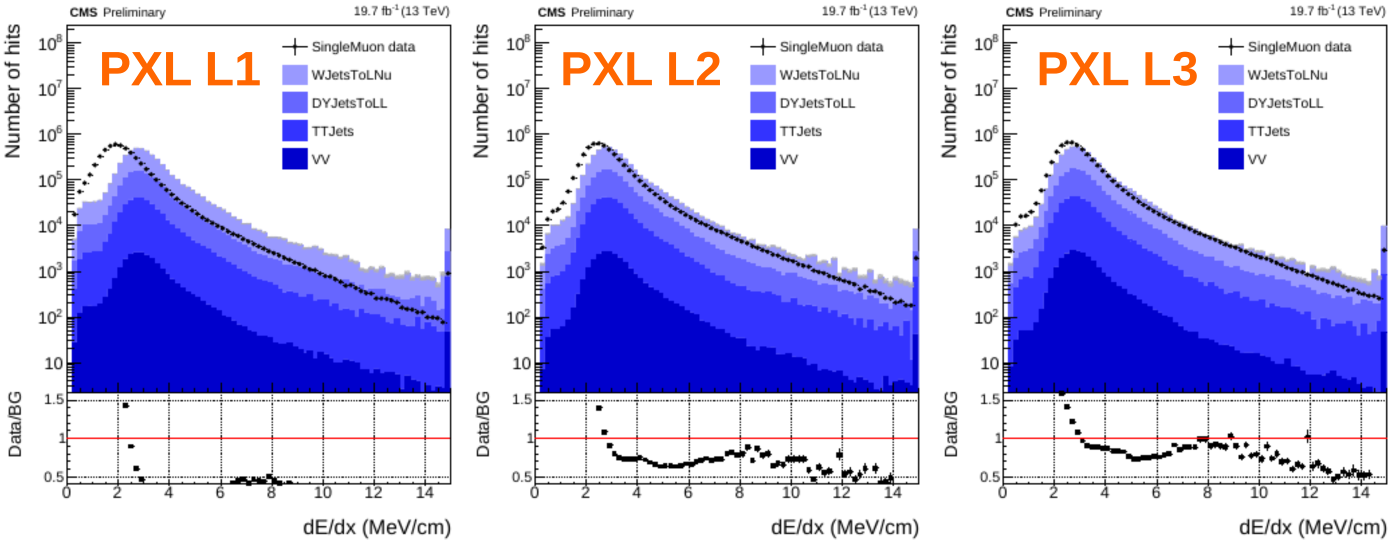
- for fractionally charged particles, one selects tracks with many low dE/dx hits
- edges of silicon sensors don't collect all charge → low dE/dx
- tracker geometry such that presence of edge hit implies increased probability of additional edge hit(s)
    - this leads to increased background
    - suppress by rejecting tracks with hits on edges



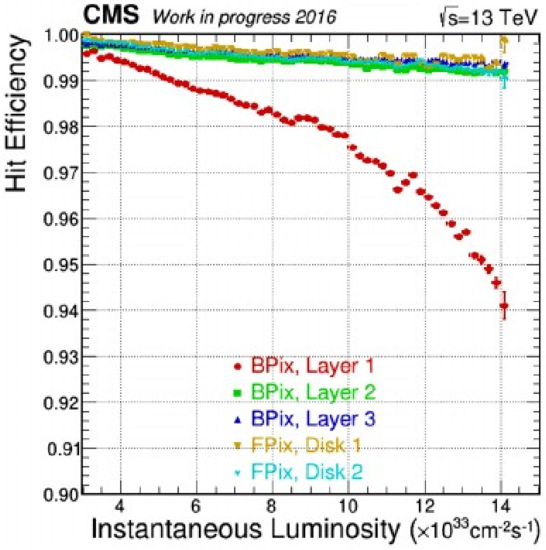


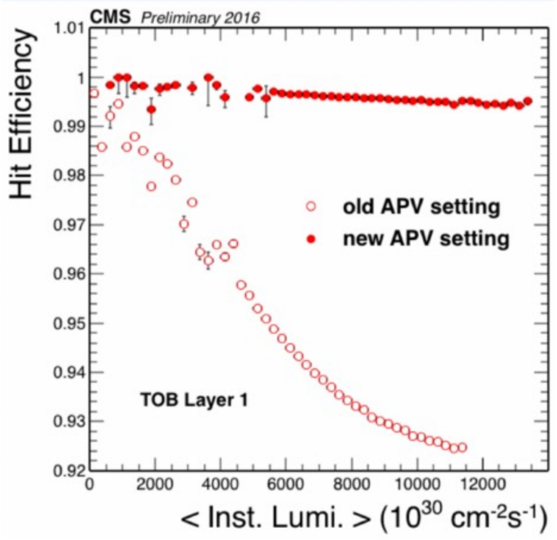
Background from radiation

- dE/dx very sensitive to radiation damage
- fake low dE/dx



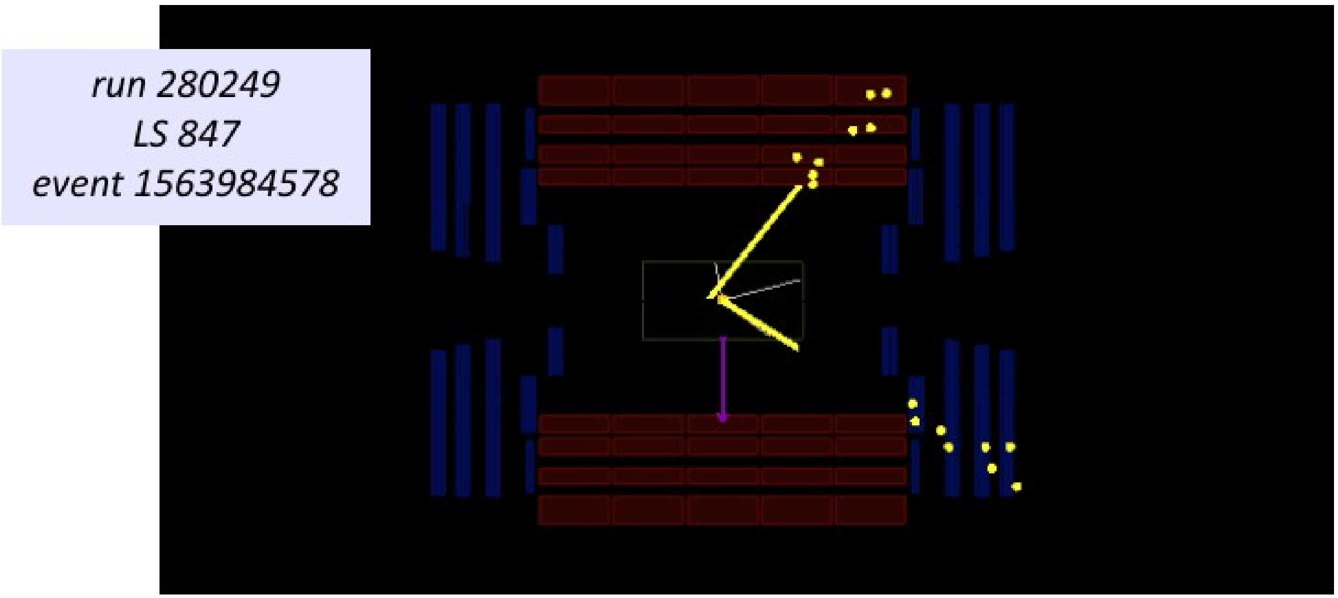
- high particle fluxes also induce dynamic inefficiencies
  - some expected
  - some problematic
  - mitigation not always possible





Background from trigger misfiring

- when timing of a L1 trigger object (“primitive”) is not sufficiently accurate, it may be associated to a wrong bunch crossing
- the trigger system may then read out the wrong bunch crossing
- tracking detectors read out in a very narrow timing window
  - while muon integrates in broad window
- so the event read out in the adjacent bunch crossing will look to have muons, but no tracks in the tracker
  - a fake long-lived event!



run 280249
LS 847
event 1563984578

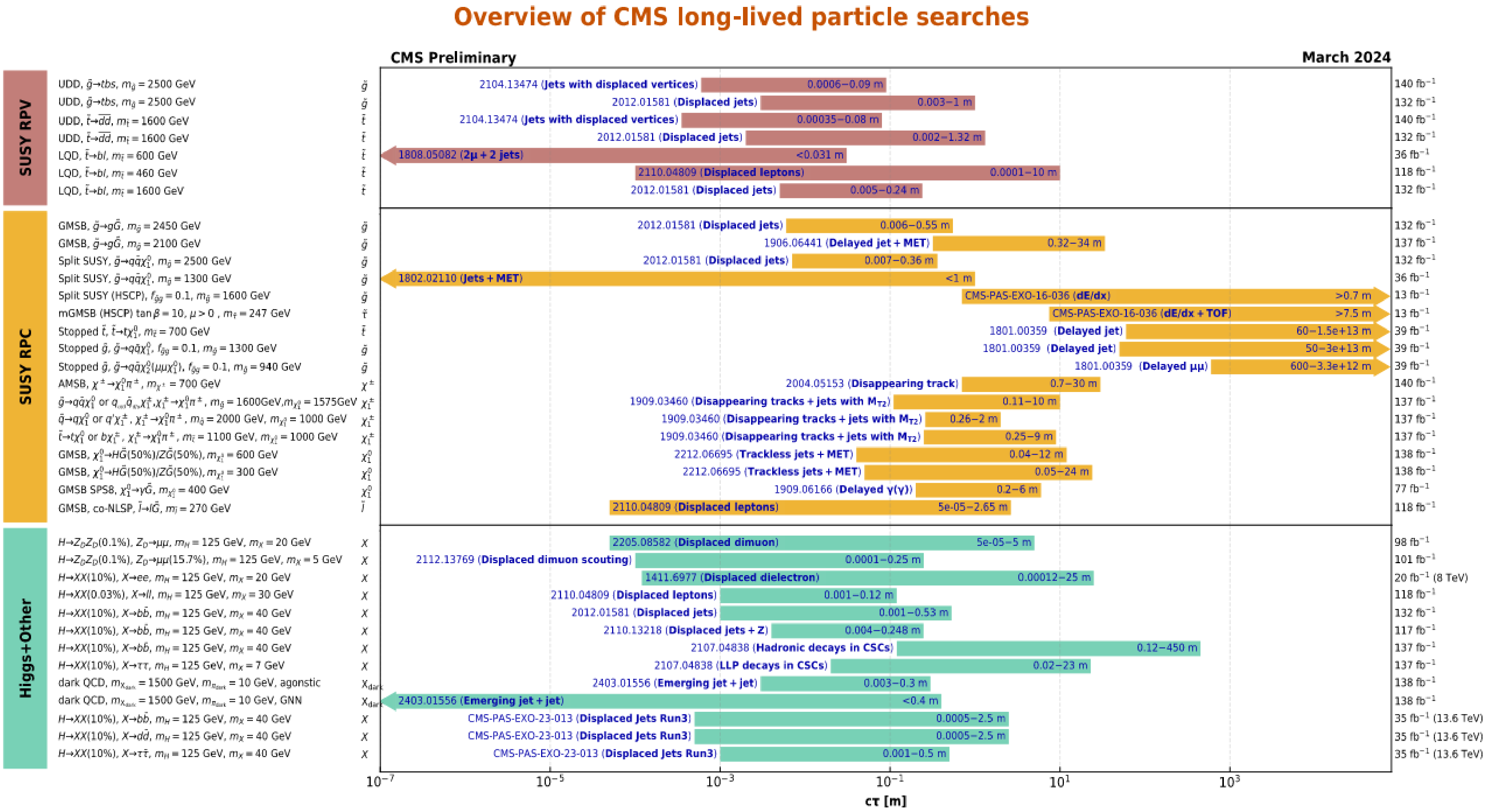
Backgrounds...

- I showed you several examples, but for sure this is not an exhaustive list
- none of these are regular physics backgrounds
- none of these can be modeled reliably in simulation
    - must be estimated from data
- all of these force you to take a step back from usual objects and usual tools
    - often they touch upon low-level detector or algorithm details

- hard, but fun!

Search status

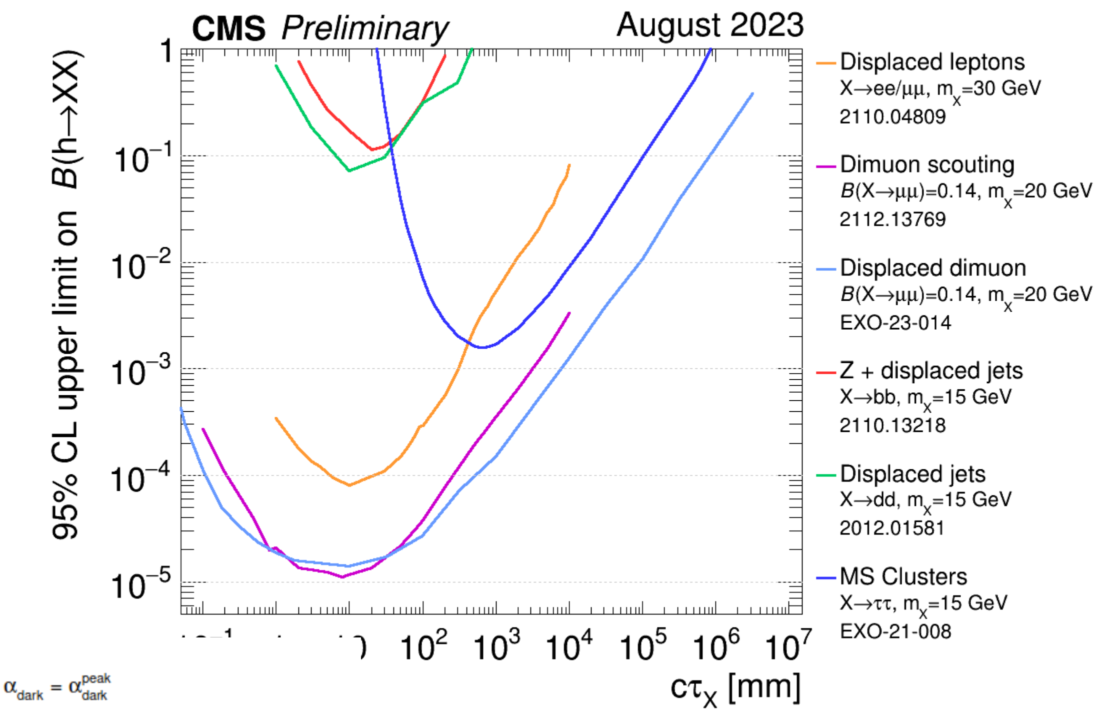
- many many results

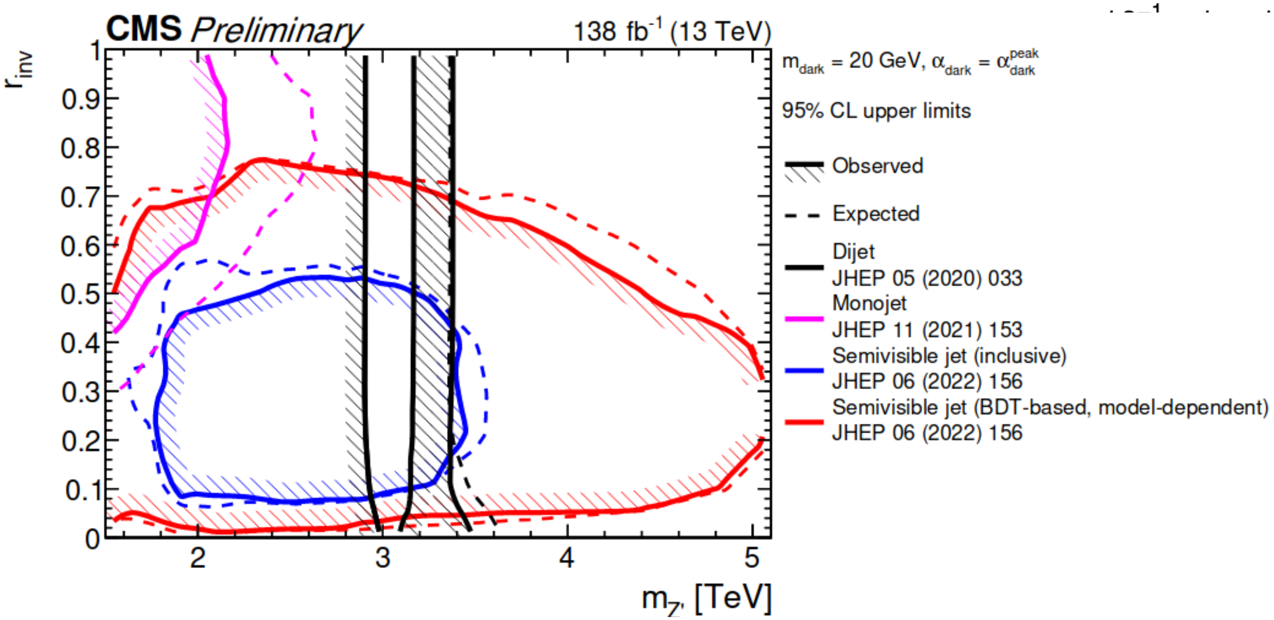


Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

Search status

- just a few highlights
- to demonstrate the complementarity of our searches





Content Lecture 2

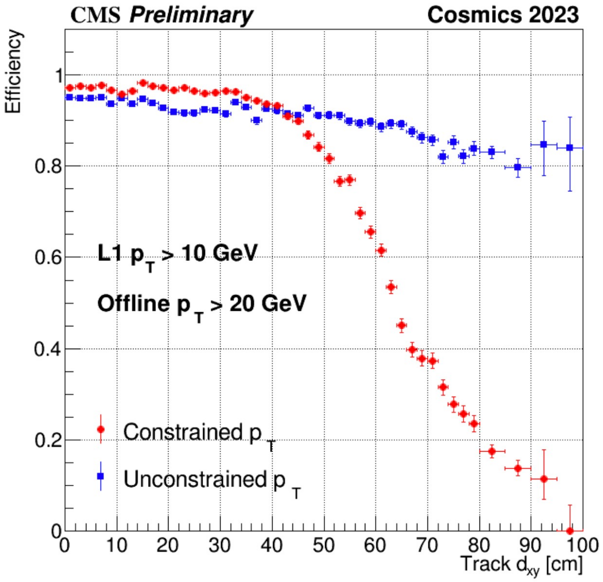
- dark matter
    - di-invisible → dark matter
    - direct dark matter searches at LHC
    - di-X interplay with dark matter – beyond the LHC
- supersymmetry
    - appeal
    - strong production: jets+MET
    - weak production: leptons+MET
- long-lived particles
    - why long-lived particles?
    - experimental handles
    - backgrounds
    - search status
- looking ahead

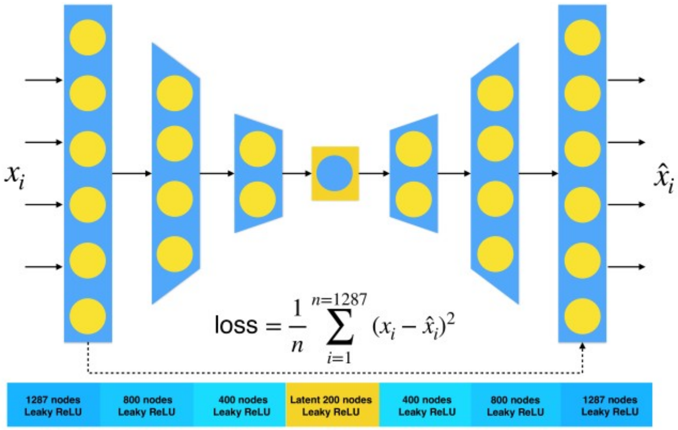
Looking ahead

- LHC Run-3 brings many new opportunities
  - new low-threshold triggers
    - increased bandwidth, scouting, parking
  - new displaced triggers
  - new algorithms and new analysis techniques
    - a lot of machine learning

- HL-LHC will be another big step
  - tracking at L1 trigger
  - increased timing precision
  - flavour tagging in forward region
  - improved VBF signature tagging
  - shower reconstruction in calorimeter
  - …

- new ideas for searches keep emerging
  - eg. unsupervised searches → anomaly detection
  - eg. weird signatures





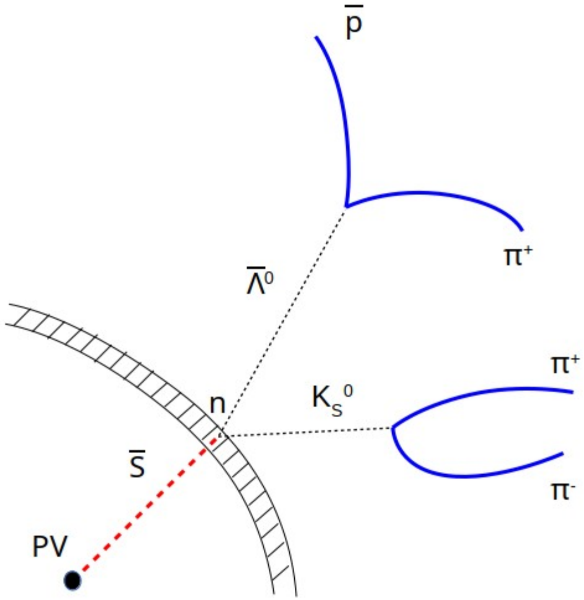
$$\text{loss} = \frac{1}{n}\sum_{i=1}^{n=1287}(x_i - \hat{x}_i)^2$$

The SM strikes back: sexaquarks

- proposal for a bound state S(uuddss)
  - absolutely stable if $m_S \leq 2\,(m_p + m_e) = 1877.6\ \mathrm{MeV}$
- S is special
  - spin-0, flavour singlet, CP even, Q=0, B=2, S=-2
  - very compact object, almost De Broglie wavelength
- phenomenology
  - relatively abundant production in collisions
  - expected interaction rate with material very small
  - it will look like a soft nuclear interaction
  - can look inclusively for events with |ΔB|=2, |ΔS|=2

    eg. in upsilon decays with lambda's
    or in low-momentum pp collisions
  - can attempt to reconstruct the S

    interaction on neutron gives K_S and Λ^0
    pointing to material
  - very soft signature, no trigger



$\bar{\Lambda}^0$: m = 1116 MeV, cτ = 7.9 cm
K^0: m = 498 MeV, cτ = 2.7 cm

Thank you!