Physics beyond the standard model II

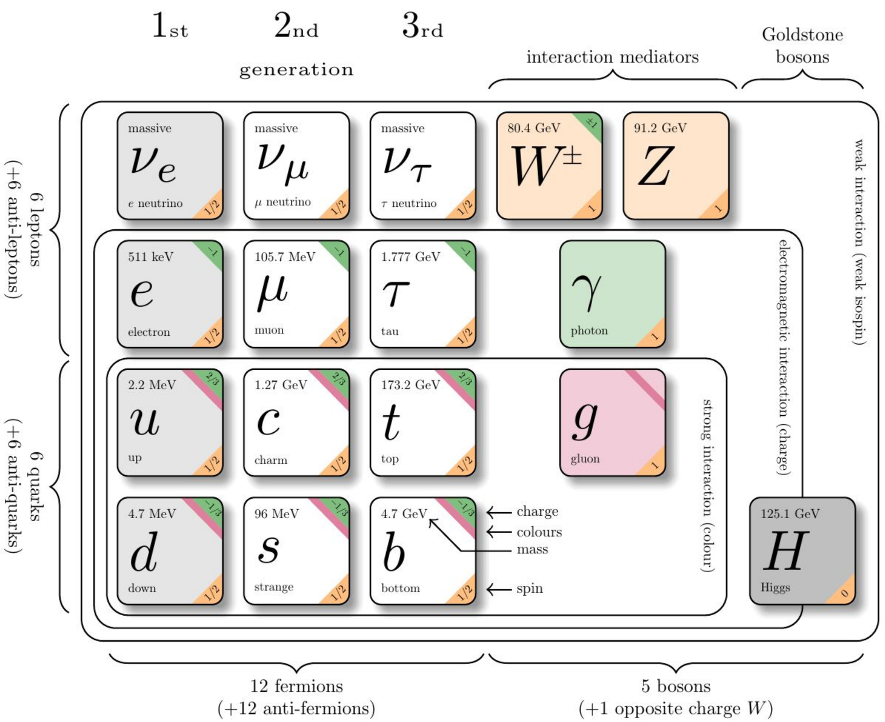
Ben Brüers
DESY Zeuthen, 05.09.2025

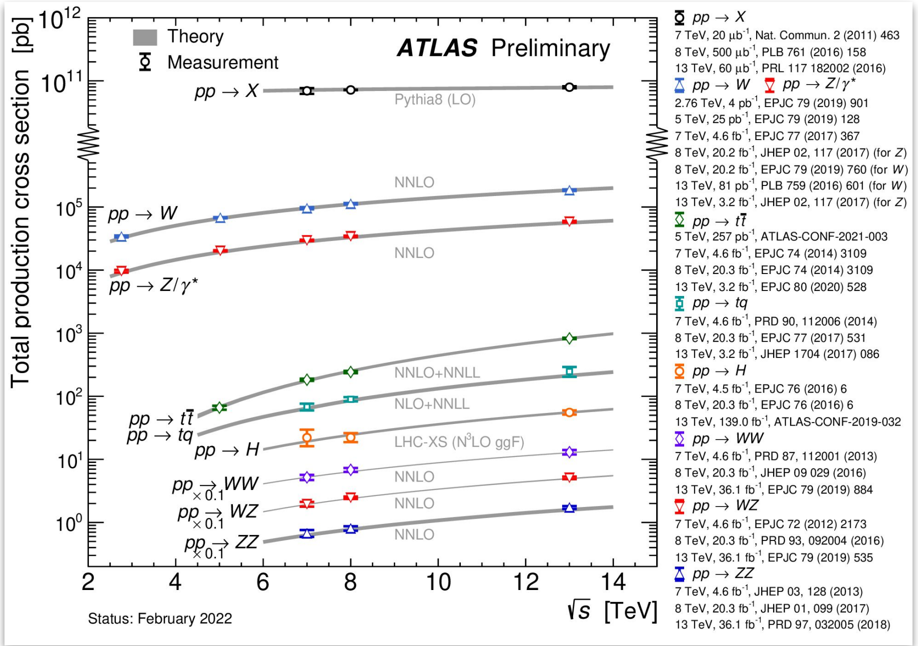
Based on Elisa Pueschel's lecture from 2019

HELMHOLTZ SPITZENFORSCHUNG FÜR GROSSE HERAUSFORDERUNGEN

DESY.

Last time…





http://cds.cern.ch/record/2804061

The Standard model is very precise, but…

Last time (2)...

- …there are a bunch of things it cannot explain:

9 fermion masses (m_u, m_d, m_c, m_s, m_b, m_t; m_e, m_μ, m_τ)

\+ 2 Higgs boson parameters: the mass & VEV (m_H, v)
\+ 3 coupling parameters (g_W, g', g_s)
\+ 4 CKM parameters (3 mixing angles + 1 CP violating phase)
\+ 1 CP violating phase in QCD (see later)

——

19 free parameters

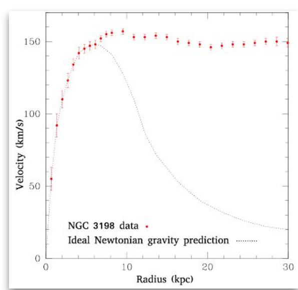
$$\delta M_H^2 = \frac{G_F \Lambda^2}{4\pi^2\sqrt{2}}(6M_W^2 + 3M_Z^2 + M_H^2 - 12m_t^2)$$

$$\delta M_H^2\big|_{t-\mathrm{loop}} \approx -\frac{3G_F}{\pi^2\sqrt{2}} m_t^2 \Lambda^2 \approx -0.075\,\Lambda^2$$

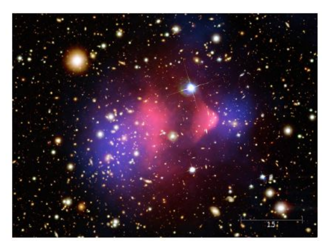
"bare mass" tuned very finely, O(10^{-4})-O(10^{-34}) GeV!

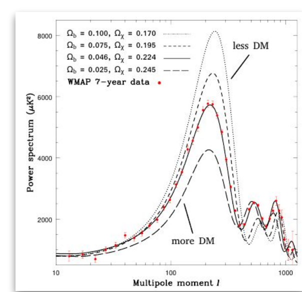
? ? ?

$$\mathcal{L}_{\mathrm{QCD}} = \bar\psi_i(\underbrace{i\gamma^\mu(D_\mu)_{ij}}_{\text{quark dynamics}} - \underbrace{m\delta_{ij}}_{\text{quark mass}})\psi_j - \underbrace{\frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a}_{\text{gluon dynamics}} \cancel{- \underbrace{\bar\Theta\frac{\alpha_s}{8\pi}G^{\mu\nu a}\tilde G^a_{\mu\nu}}_{\text{CP-violating term}}}$$



K. Begeman. Astron. Astrophys. 223 (1989), pp. 47–60

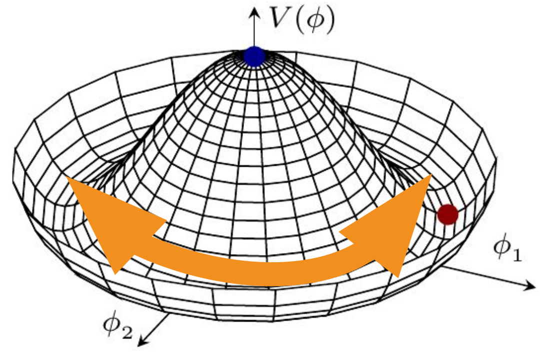

doi:10.1086/381970



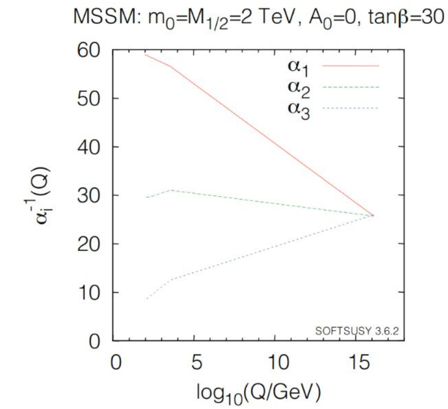
arxiv:1001.4635 arxiv:1006.2483

Last time (3)...

- Discussed multiple SM extension:
  - Axions + ALPs
  - 2HDM(+a)
  - SUSY
  - GUTs
  - Extra dimensions

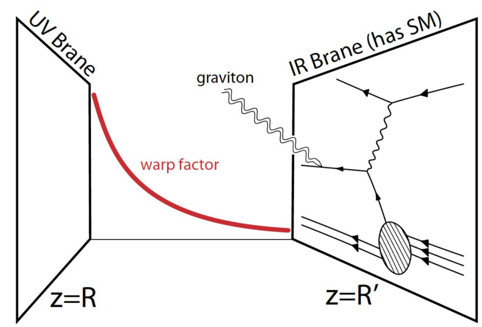


Drawing inspired by
https://indico.scc.kit.edu/event/477/contributions/4854/attachments/2575/3683/KSETA_Durbach_2019_pargner.pdf



Q |fermion> = |boson>

Q |boson> = |fermion>

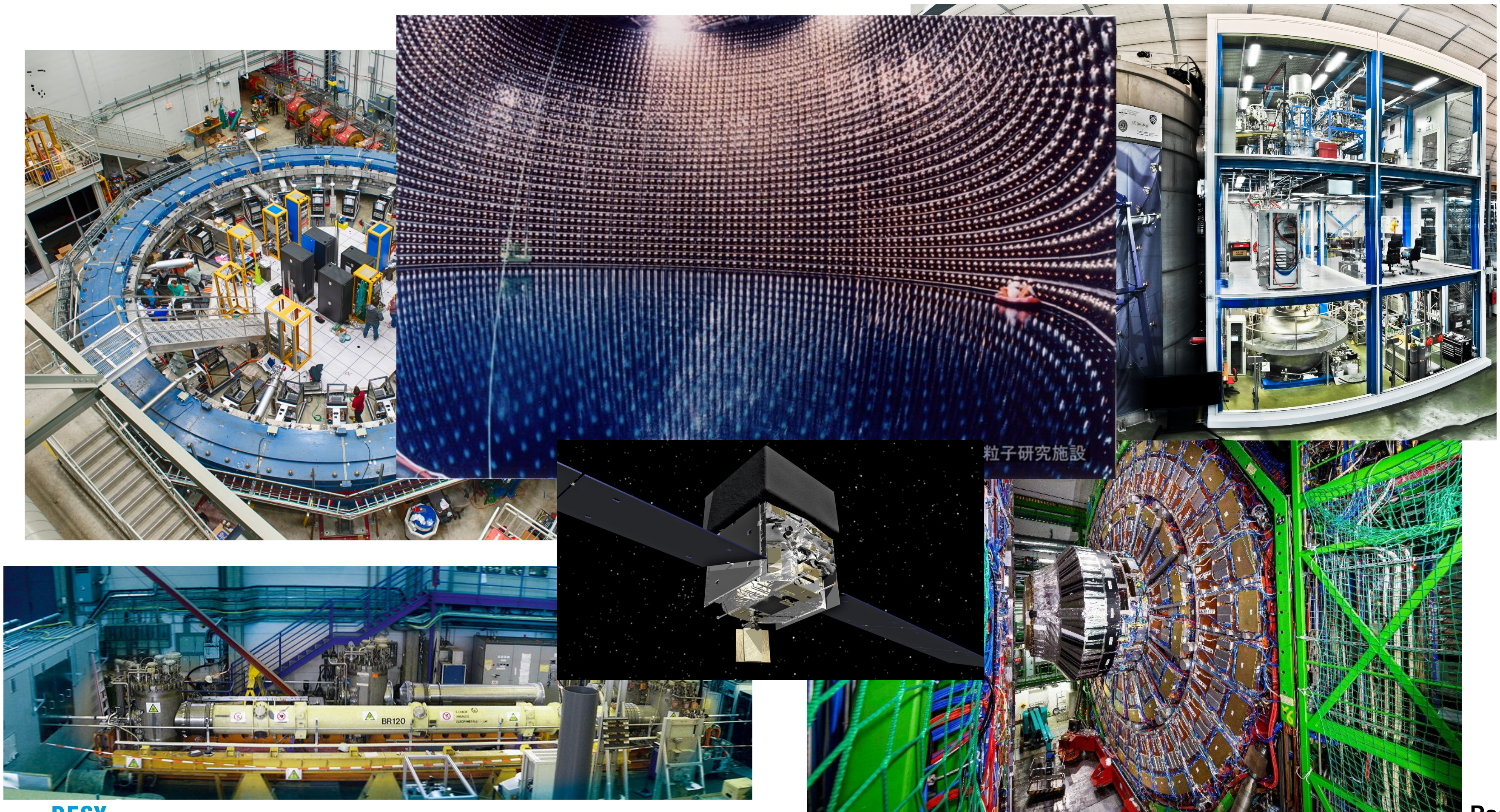


https://www.zeuthen.desy.de/students/2019/Lectures/Pueschel_Lecture1_BeyondSM_2019.pdf

Model	Dark Matter	Hierarchy problem	Strong CP problem	Unification	Gravity
Axions	✅	-	✅	-	-
2HDM	✅	-	-	-	-
SUSY	✅	✅	possible	✅	e.g. mSUGRA
GUTs	-	-	-	✅	-
Extra dims.	✅	✅	-	possible	✅

Today:

- Will discuss experiments searching for physics beyond the Standard Model
- Will cover collider-based experiments and others



The LHC

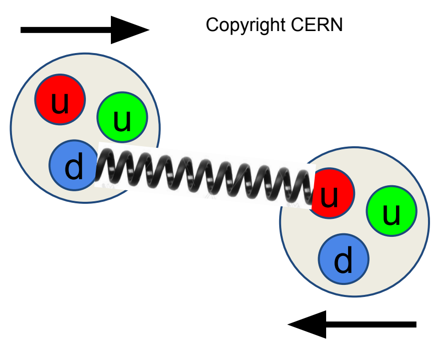
LHC

→circumference 27 km

→proton-proton collisions with a CME of $\sqrt{s}$ = 13 TeV

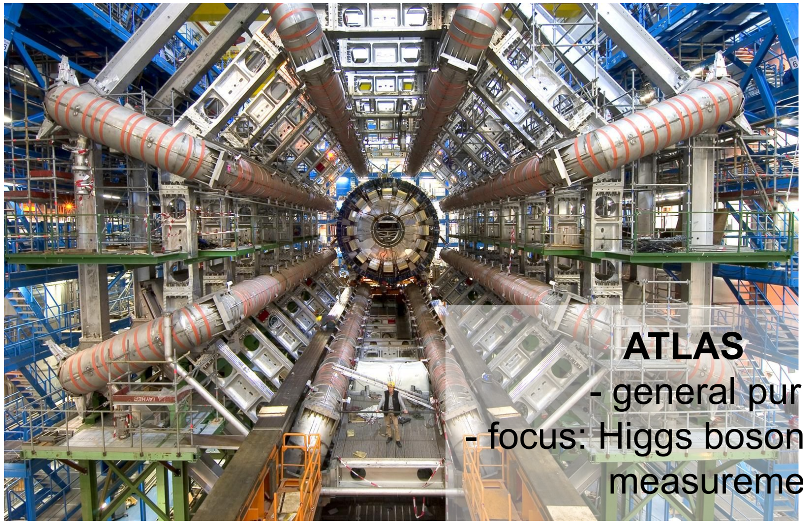
→interacting particles are quarks, so their CME often smaller

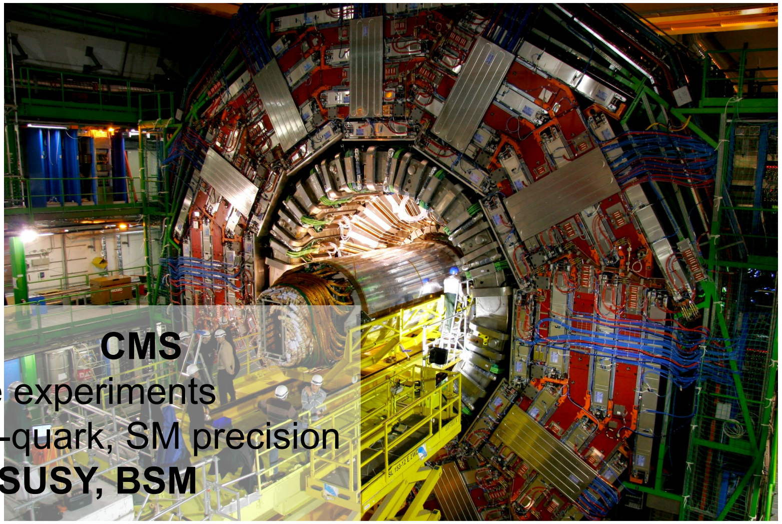
→detectors surround points of collision



https://previews.123rf.com/images/denisnata/denisnata1003/denisnata100300048/6555910-black-spiral-telephone-cable-isolated-on-white-background.jpg

Experiments at the LHC



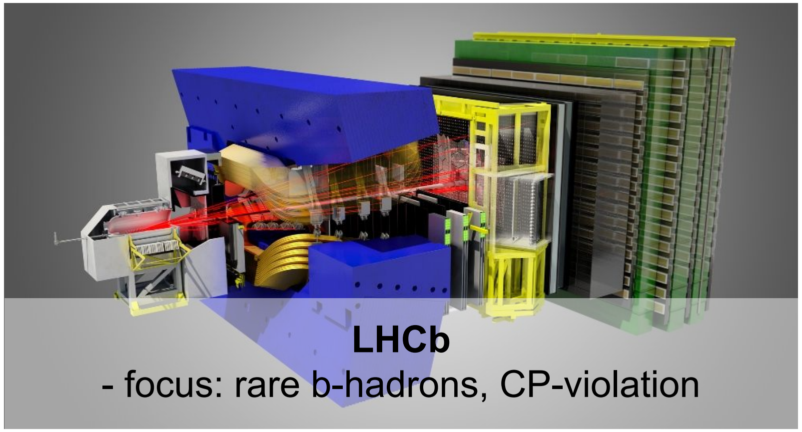


ATLAS & CMS

- general purpose experiments
- focus: Higgs boson, top-quark, SM precision measurements, **SUSY, BSM**

https://www.weltmaschine.de/sites/sites_custom/site_weltmaschine/content/e28861/e36564/e36588/e36608/0511013_01-A4-at-144-dpi.jpg

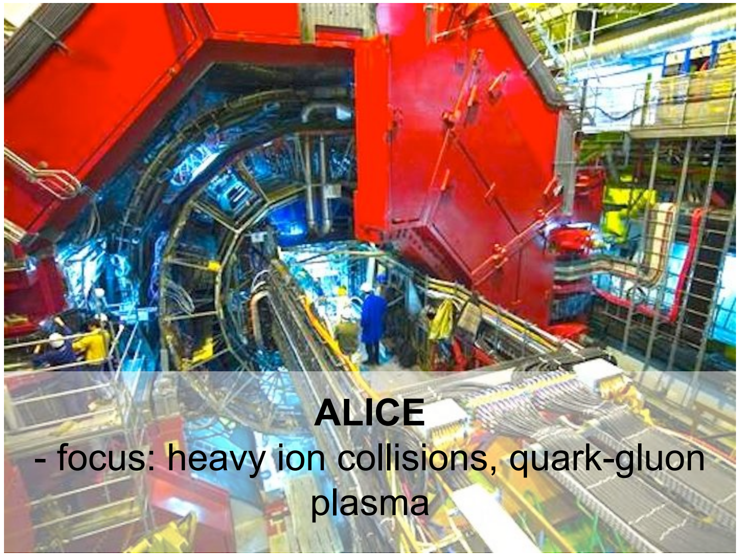
https://cms.cern/sites/default/files/field/image/cds-record-1275108-hoch-20071215_721-nice.jpg



LHCb

- focus: rare b-hadrons, CP-violation

https://hep.syr.edu/wp-content/uploads/2021/04/LHCbDetectorlight1.jpg



ALICE

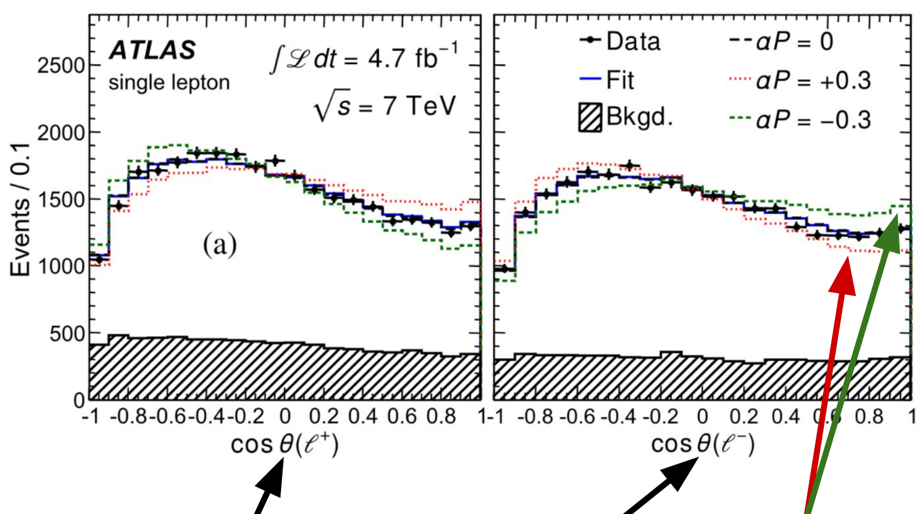
- focus: heavy ion collisions, quark-gluon plasma

https://www.phy.ornl.gov/images/heavy_ions/ALICE_gen_BIG.html

How to search for BSM physics at colliders

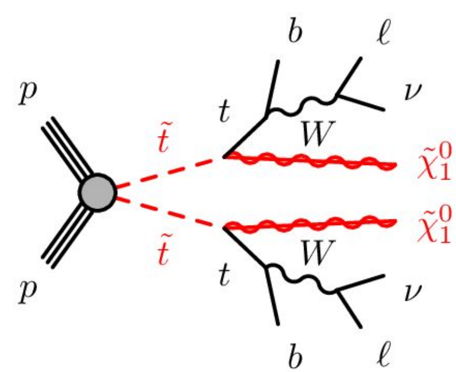
- BSM physics must be rare and/or involve heavy particles (else discovered)
- Two search principles:
  - BSM physics slightly modifies masses, couplings, etc.
    → investigate these effects in precision measurements
  - **BSM physics particles produced in proton collisions**
    → search for the particles / reconstruct their decays, etc.
    → ideally investigate signatures that are rare in the SM

doi:10.1103/PhysRevLett.111.232002

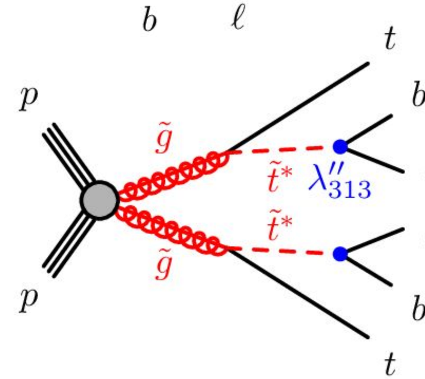


polar angle of lepton w.r.t. beam axis

with BSM physics



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2018-08/fig_01d.png

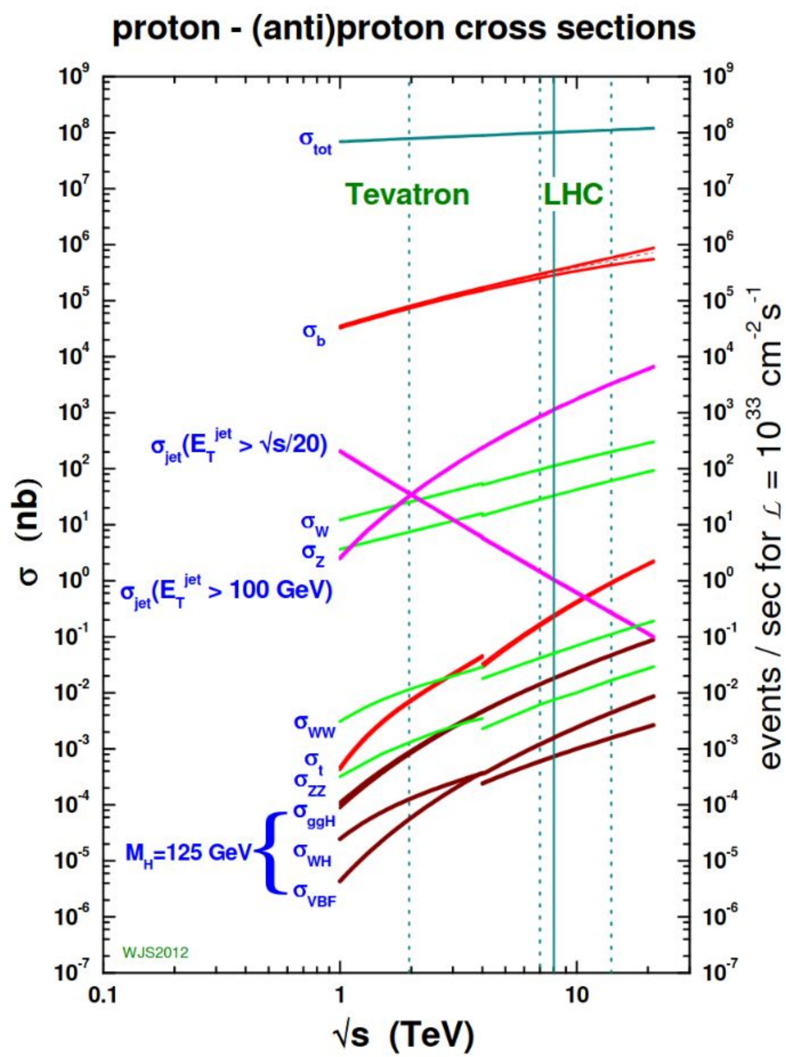


https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2020-27/fig_01f.png

Metrics to keep in mind

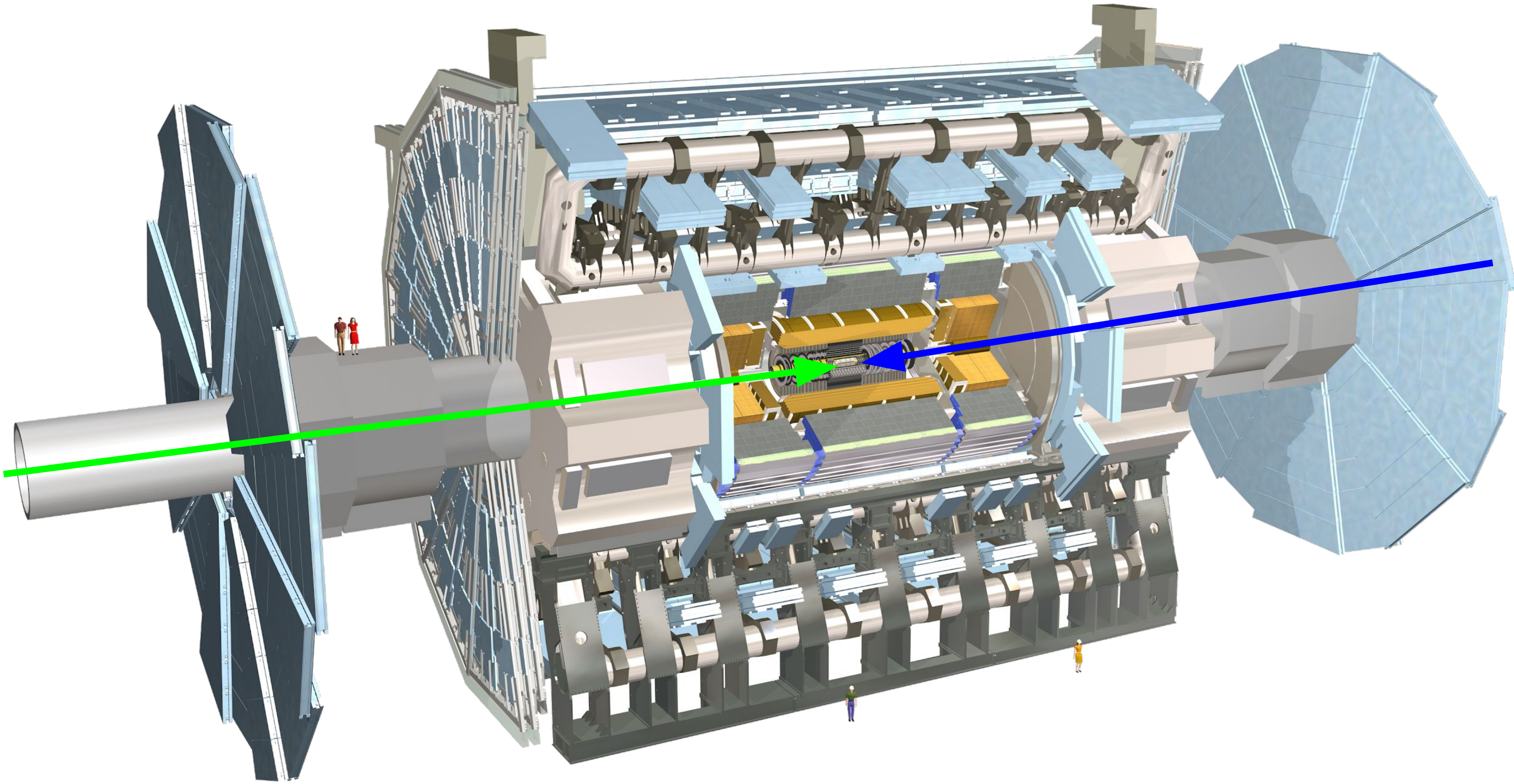
$$N_{obs} = \int \mathcal{L}(t)\, \sigma\, \varepsilon\, A\, dt$$

- BSM physics must be rare and/or involve heavy particles (else discovered)
- Cross-section must not be too low, else will not be able to discover anything
  → **important model metric**
- Too investigate very rare signatures need many collision events
- The mass of the particles must not be heavier than CME, else not produced
- Can only detect particles produced in area of detector (detector not infinite) and if detector sufficiently efficient
  → **important collider metrics: CME, luminosity, detector efficiency**



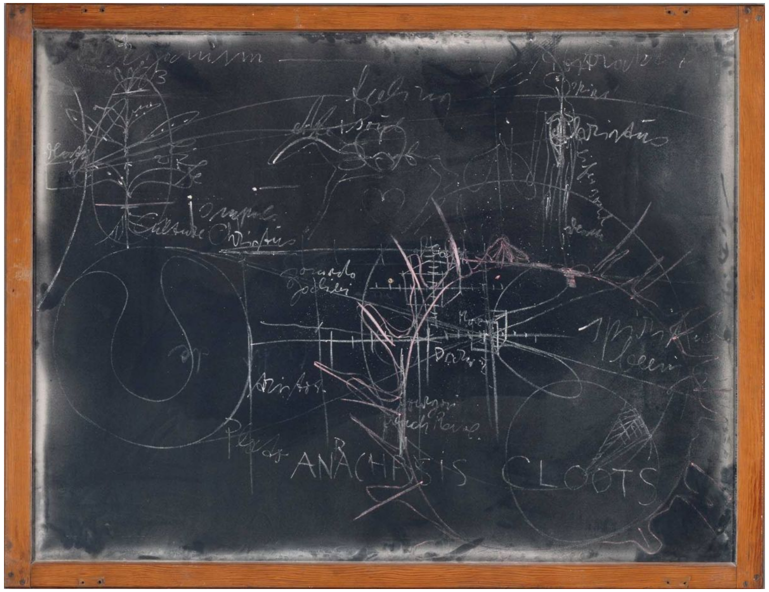
http://www.hep.ph.ic.ac.uk/~wstirlin/plots/crosssections2012_v5.pdf

The ATLAS detector



How do we measure particles with the ATLAS detector?

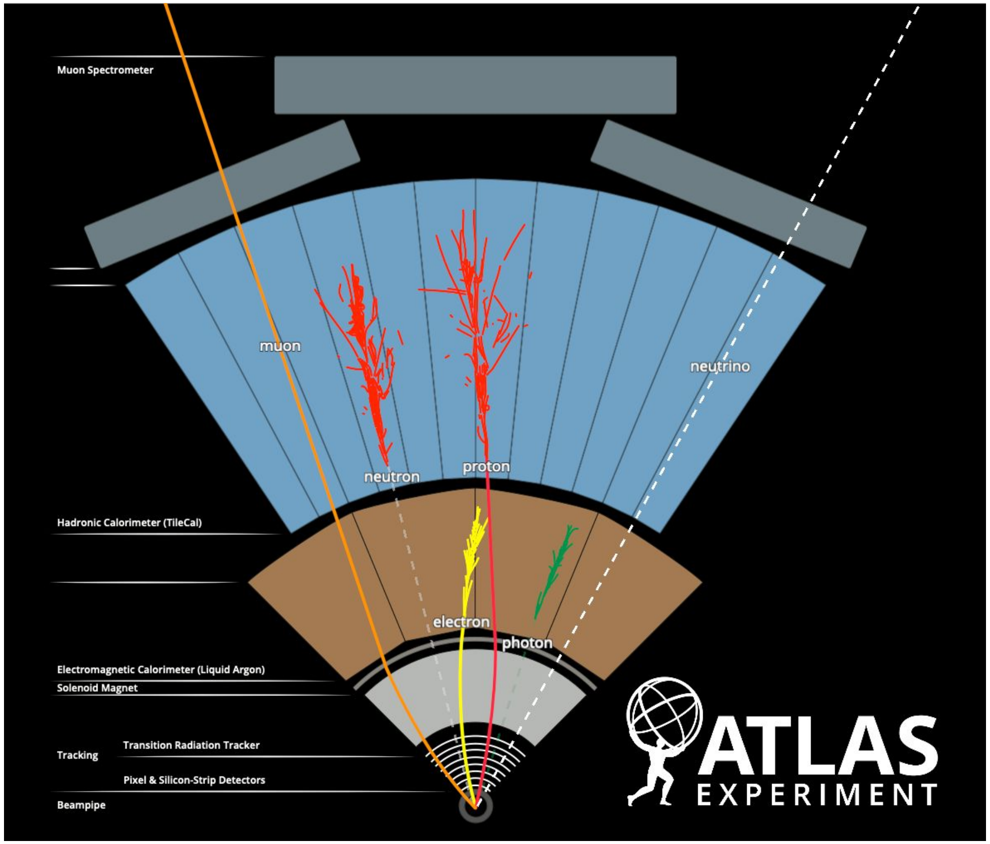
It's blackboard time!



https://cameo.mfa.org/images/b/ba/2000.979-CR9834-d1.jpg

(summary on the next slide)

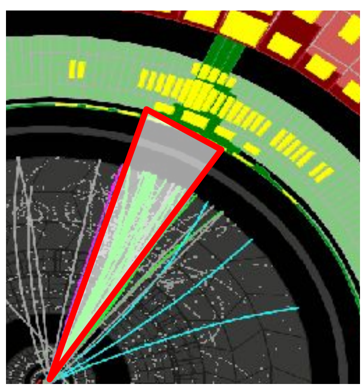
Particle reconstruction: ATLAS detector



- Multi-layer detector, measure particles via their interaction with the detector
- Inner-most detector: measure tracks of charged particles (electron, muon, charged hadron)
- ECAL / HCAL: measure energy of EM-interacting / hadronically interacting particle
  → concept: make particles lose all their energy and measure the loss
- Muon chambers for high precision muon momentum measurements
- NB: due to quark confinement, quarks cannot exist alone
  → form collimated hadron sprays, we call these “jets”

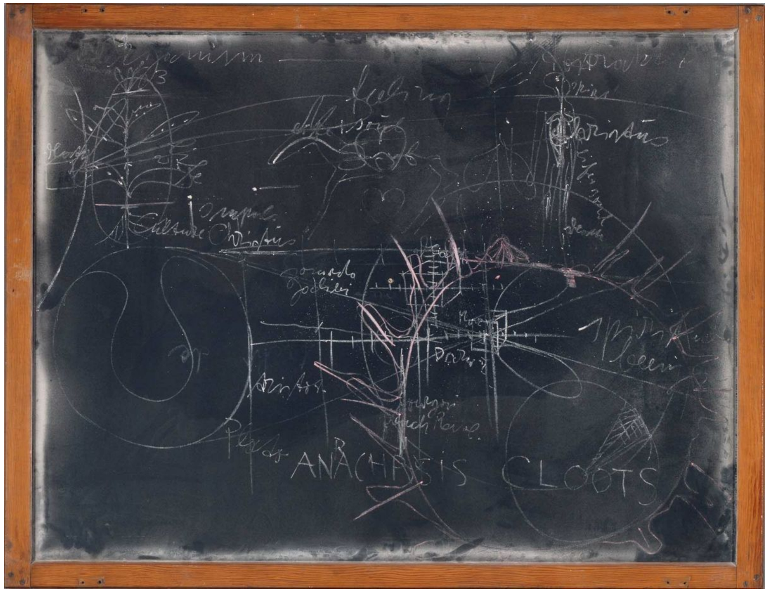
q ⟶ had. 1, had. 2, had. 3, …, had. n

confinement



What about invisible particles?

It’s blackboard time!



https://cameo.mfa.org/images/b/ba/2000.979-CR9834-d1.jpg

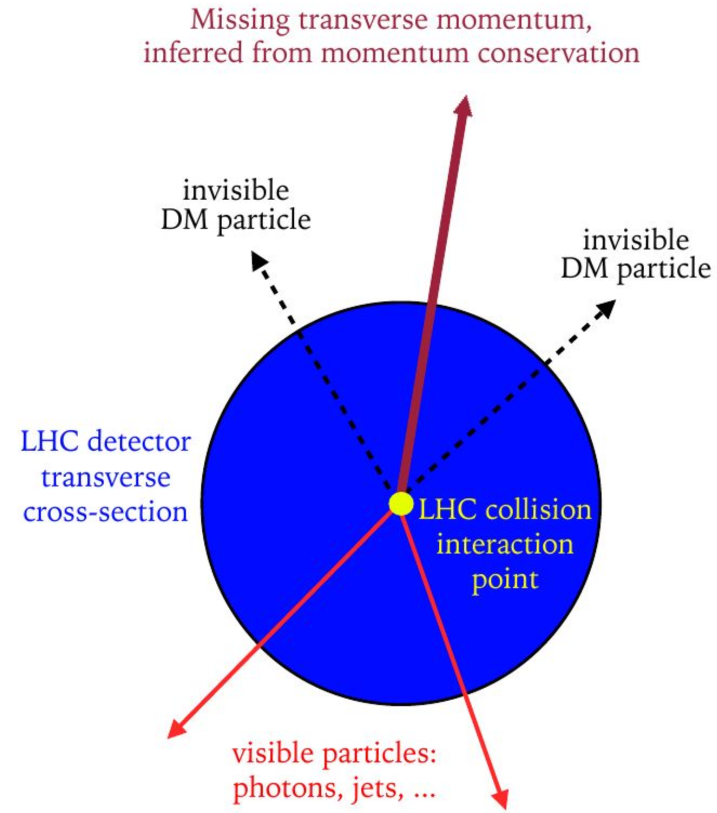
(summary on the next slide)

How do we measure invisible particles?

- Neutrinos and potential BSM particles interact weakly with detector→no signal
- But: if produced with particles that produce a signal: can use **momentum conservation** to **infer** on them
- Protons collide heads on: momentum of interacting particles in direction orthogonal to the beam axis is ~0
- Momentum is conserved → momenta of all particles in the plane transverse to the beam axis must sum to zero → can infer on the total momentum of the particles escaping detection and the direction of it in the transverse plane → **this is called Missing Transverse Momentum** and the magnitude **Missing Transverse Energy (MET)**

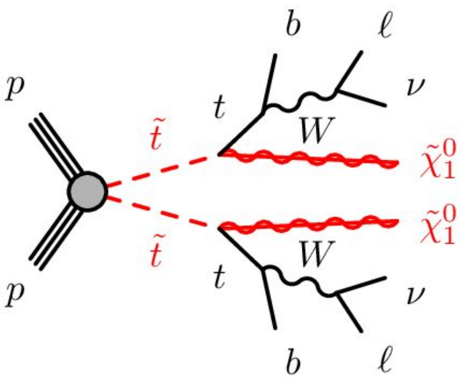
$$0 = \sum_{\text{all}} \vec{p}_{T,i} = \sum_{\text{visible}} \vec{p}_{T,i} + \sum_{\text{in-visible}} \vec{p}_{T,j}$$

Missing transverse momentum



How do we search for the BSM particles?

- In the data, select those collision events with:
  - 2 jets compatible with a bottom-quark
  - 2 leptons
  - MET compatible with 2x χ^0_1 and 2x ν
  - Maybe an invariant mass requirement on the system of b-W-χ^0_1



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2018-08/fig_01d.png

- **Caveat: we might not have saved these events in ATLAS!!**
  - Protons collide every 25 ns in ATLAS
    → 1 Mb of data / event or 40 Tb of data per second!!
    → cannot store this!! & most not of interest (low energy)
  - Solution: coarsely analyse all collision event as they happen
  - Only store events fulfilling certain criteria, e.g. 6 jets, 2 leps →"triggering"
  - **So: the BSM physics you can find depends on your trigger criteria!**

Triggering criteria in ATLAS (in 2018)

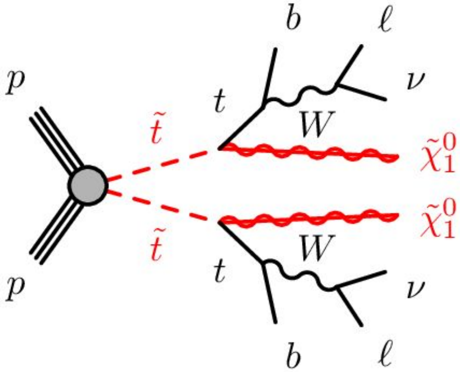
- Lots of triggers there! But sometimes need to add one… ATL-DAQ-PUB-2019-001/

Trigger	**Typical offline selection**	**Trigger Selection**		**L1 Peak Rate [kHz]**	**HLT Peak Rate [Hz]**
		L1 [GeV]	HLT [GeV]	$L=2.0\times10^{34}\ cm^{-2}s^{-1}$	
Single leptons	Single isolated μ, $p_T > 27$ GeV	20	26 (i)	16	218
	Single isolated tight e, $p_T > 27$ GeV	22 (i)	26 (i)	31	195
	Single μ, $p_T > 52$ GeV	20	50	16	70
	Single e, $p_T > 61$ GeV	22 (i)	60	28	20
	Single τ, $p_T > 170$ GeV	100	160	1.4	42
Two leptons	Two μ, each $p_T > 15$ GeV	2×10	2×14	2.2	30
	Two μ, $p_T > 23, 9$ GeV	20	22, 8	16	47
	Two very loose e, each $p_T > 18$ GeV	2×15 (i)	2×17	2.0	13
	One e & one μ, $p_T > 8, 25$ GeV	20 (μ)	7, 24	16	6
	One loose e & one μ, $p_T > 18, 15$ GeV	15, 10	17, 14	2.6	5
	One e & one μ, $p_T > 27, 9$ GeV	22 (e, i)	26, 8	21	4
	Two τ, $p_T > 40, 30$ GeV	20 (i), 12 (i) (+jets, topo)	35, 25	5.7	93
	One τ & one isolated μ, $p_T > 30, 15$ GeV	12 (i), 10 (+jets)	25, 14 (i)	2.4	17
	One τ & one isolated e, $p_T > 30, 18$ GeV	12 (i), 15 (i) (+jets)	25, 17 (i)	4.6	19
Three leptons	Three very loose e, $p_T > 25, 13, 13$ GeV	20, 2×10	24, 2×12	1.6	0.1
	Three μ, each $p_T > 7$ GeV	3×6	3×6	0.2	7
	Three μ, $p_T > 21, 2\times5$ GeV	20	20, 2×4	16	9
	Two μ & one loose e, $p_T > 2\times11, 13$ GeV	2×10 (μ)	2×10, 12	2.2	0.5
	Two loose e & one μ, $p_T > 2\times13, 11$ GeV	2×8, 10	2×12, 10	2.3	0.1
Signle photon	One loose γ, $p_T > 145$ GeV	24 (i)	140	24	47
Two photons	Two loose γ, each $p_T > 55$ GeV	2×20	2×50	3.0	7
	Two γ, $p_T > 40, 30$ GeV	2×20	35, 25	3.0	21
	Two isolated tight γ, each $p_T > 25$ GeV	2×15 (i)	2×20 (i)	2.0	15
Single jet	Jet ($R = 0.4$), $p_T > 435$ GeV	100	420	3.7	35
	Jet ($R = 1.0$), $p_T > 480$ GeV	111 (topo: $R = 1.0$)	460	2.6	42
	Jet ($R = 1.0$), $p_T > 450$ GeV, $m_{jet} > 45$ GeV	111 (topo: $R = 1.0$)	420, $m_{jet} > 35$	2.6	36
b−jets	One b ($\epsilon = 60\%$), $p_T > 285$ GeV	100	275	3.6	15
	Two b ($\epsilon = 60\%$), $p_T > 185, 70$ GeV	100	175, 60	3.6	11
	One b ($\epsilon = 40\%$) & three jets, each $p_T > 85$ GeV	4×15	4×75	1.5	14
	Two b ($\epsilon = 70\%$) & one jet, $p_T > 65, 65, 160$ GeV	2×30, 85	2×55, 150	1.3	17
	Two b ($\epsilon = 60\%$) & two jets, each $p_T > 65$ GeV	4×15, $\lvert\eta\rvert < 2.5$	4×55	3.2	15
Multijets	Four jets, each $p_T > 125$ GeV	3×50	4×115	0.5	16
	Five jets, each $p_T > 95$ GeV	4×15	5×85	4.8	10
	Six jets, each $p_T > 80$ GeV	4×15	6×70	4.8	4

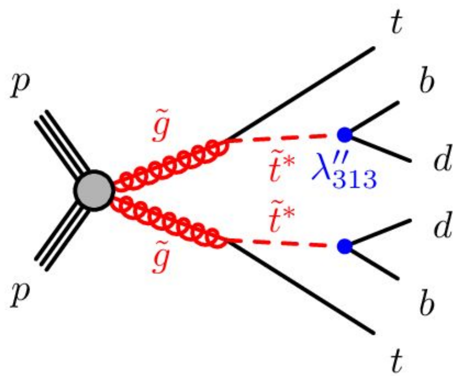
Model dependence of collider searches

- **Disadvantage of triggering: need to know what you are looking for…**
- **Need to select a model to design your search!**
  → BSM searches at collider depend on the model you are investigating!!!!

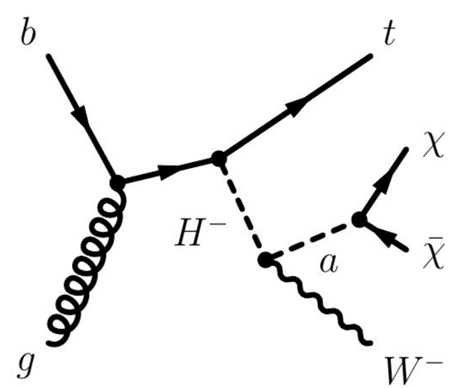
https://www.ataxia.org/wp-content/uploads/2022/07/needle-in-a-haystack-1752846_960_720.jpg



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2018-08/fig_01d.png

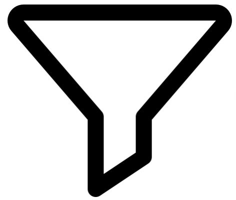


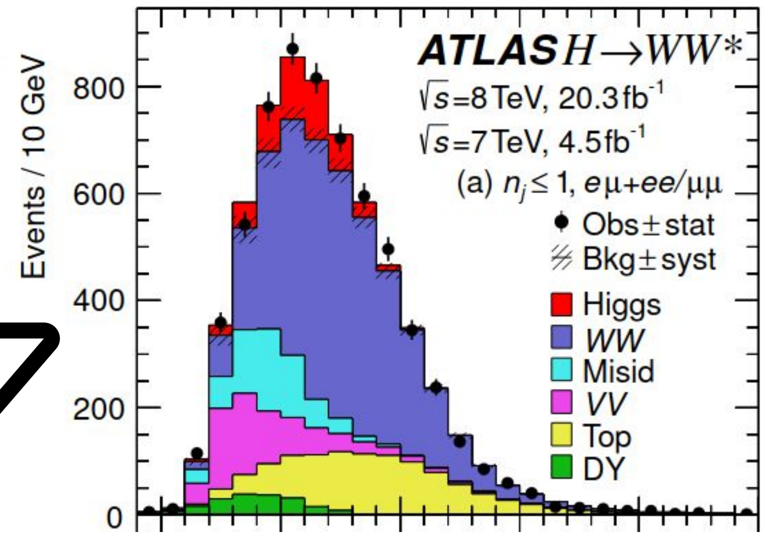
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2020-27/fig_01f.png



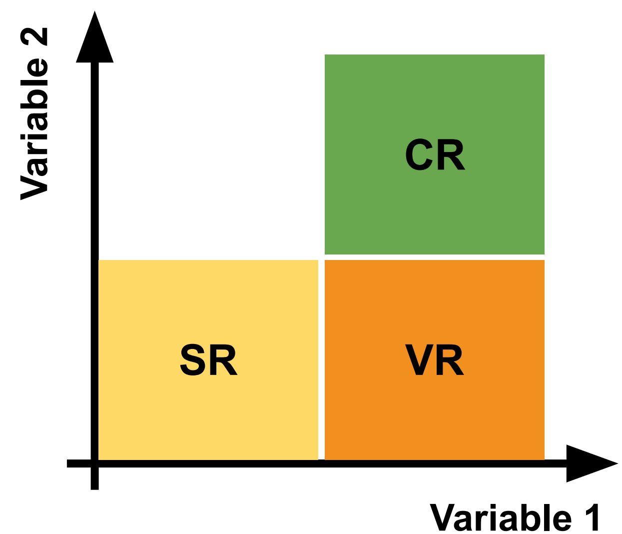
Ok fine, we triggered, we reconstructed our particles, what’s next?

- The entire dataset still contains very many collision events
- BSM physics is rare→ need to filter data to “see” our BSM physics
- Use e.g. number of reconstructed electrons, jet momenta, etc.
- Filtered data comprised of our signal & Standard Model background
- Define multiple “filters” = “regions”
    - **Signal regions:** much signal, little bkg.
    - **Control regions:** estimate bkg.
    - **Validation regions:** verify bkg. estimate





HIGG-2012-27

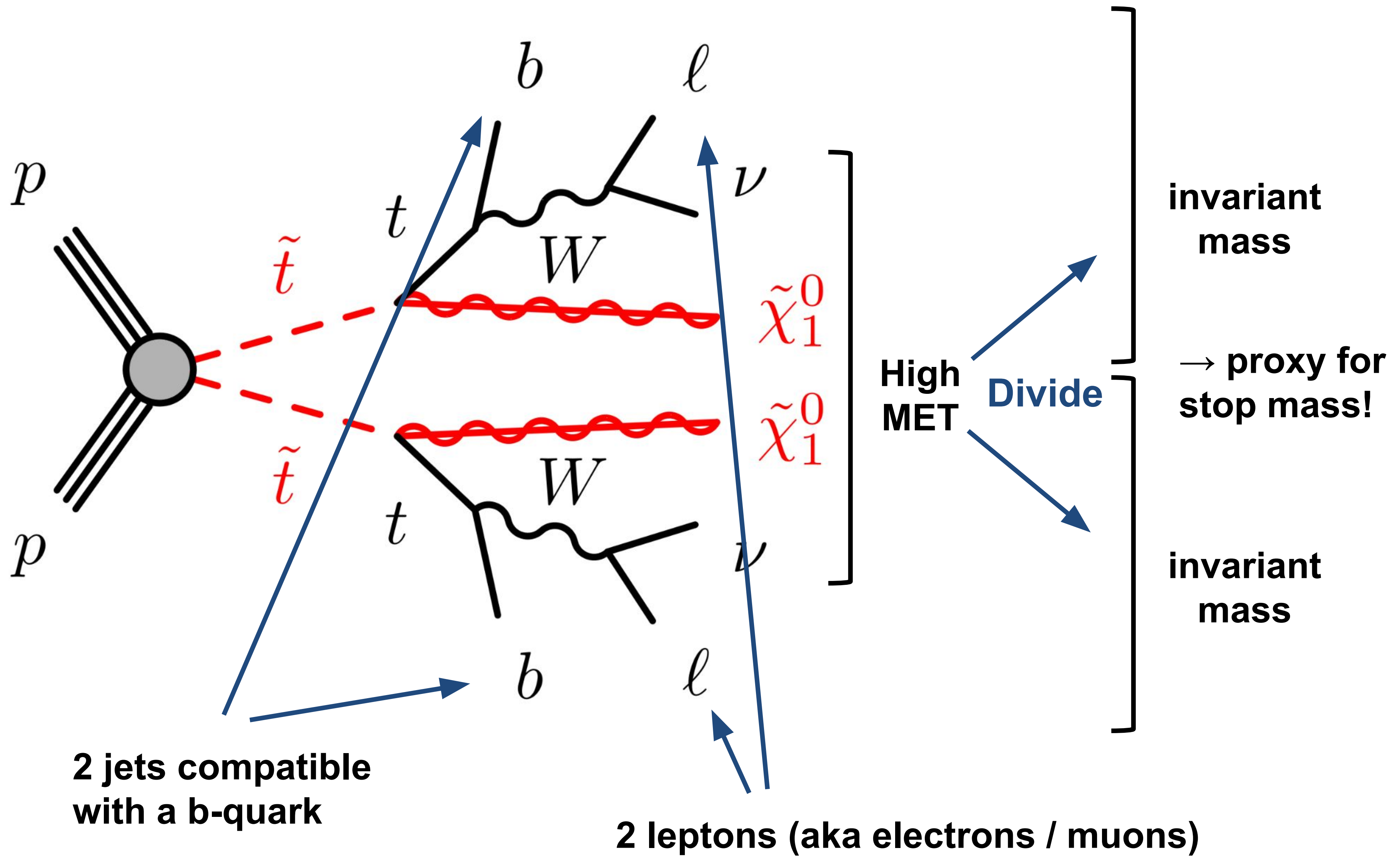


Searching for SUSY

- Recall: there are many SUSY models, e.g. MSSM, pMSSM, CMSSM, etc.
- In practise: study simplified versions of these models to reduce number of parameters to study (MSSM has 124 free parameters)
- Often also reduce number of production channels / decay channels
- Result give an **indication** for what would happen in the full model

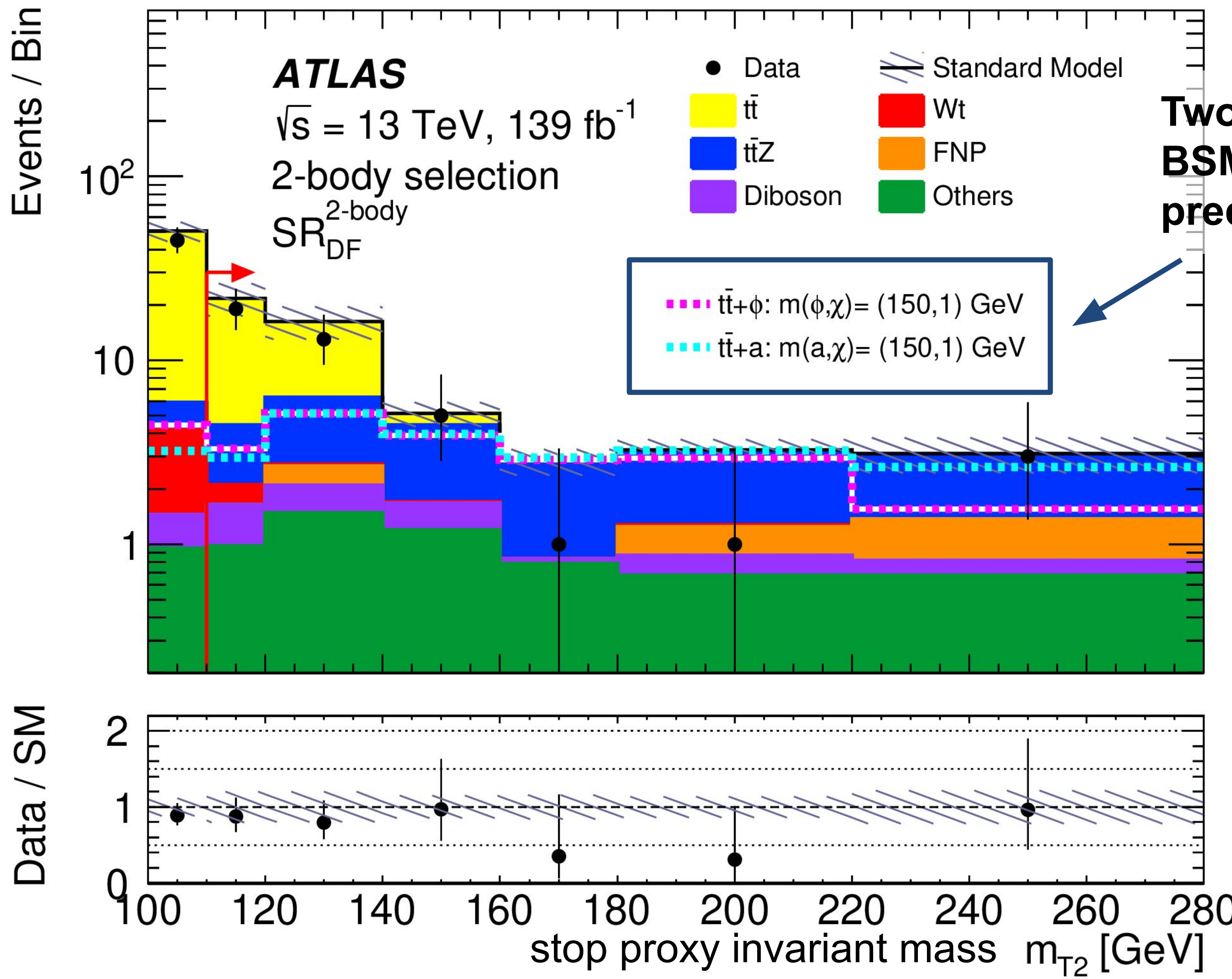
SUSY example: stop-2L

SUSY-2018-08



Stop-2L: final distribution

SUSY-2018-08

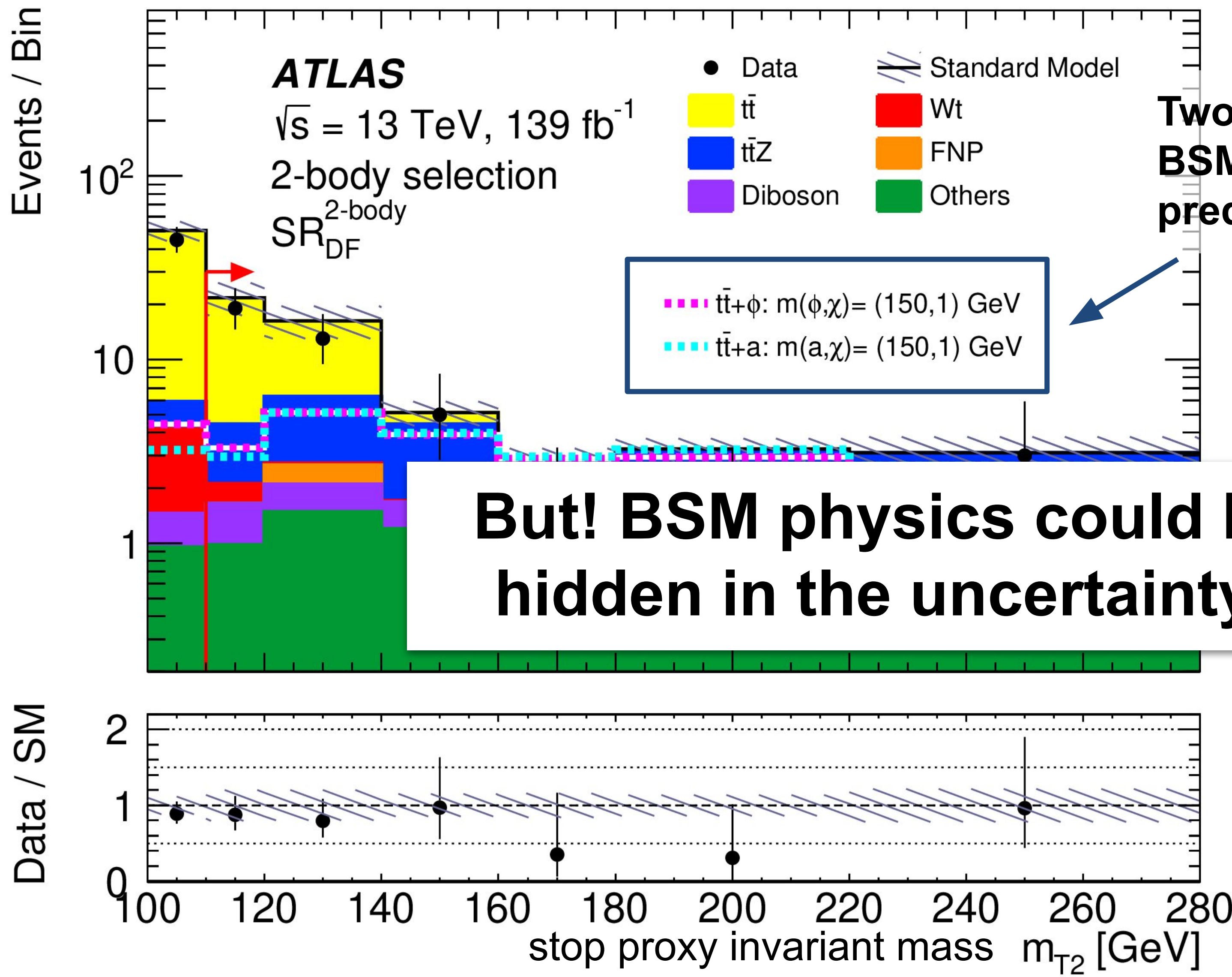


Two example BSM predictions!

Good agreement of data & SM prediction → didn't find BSM physics **within precision** (i.e. cyan / pink models excluded)

Stop-2L: final distribution

SUSY-2018-08



Two example BSM predictions!

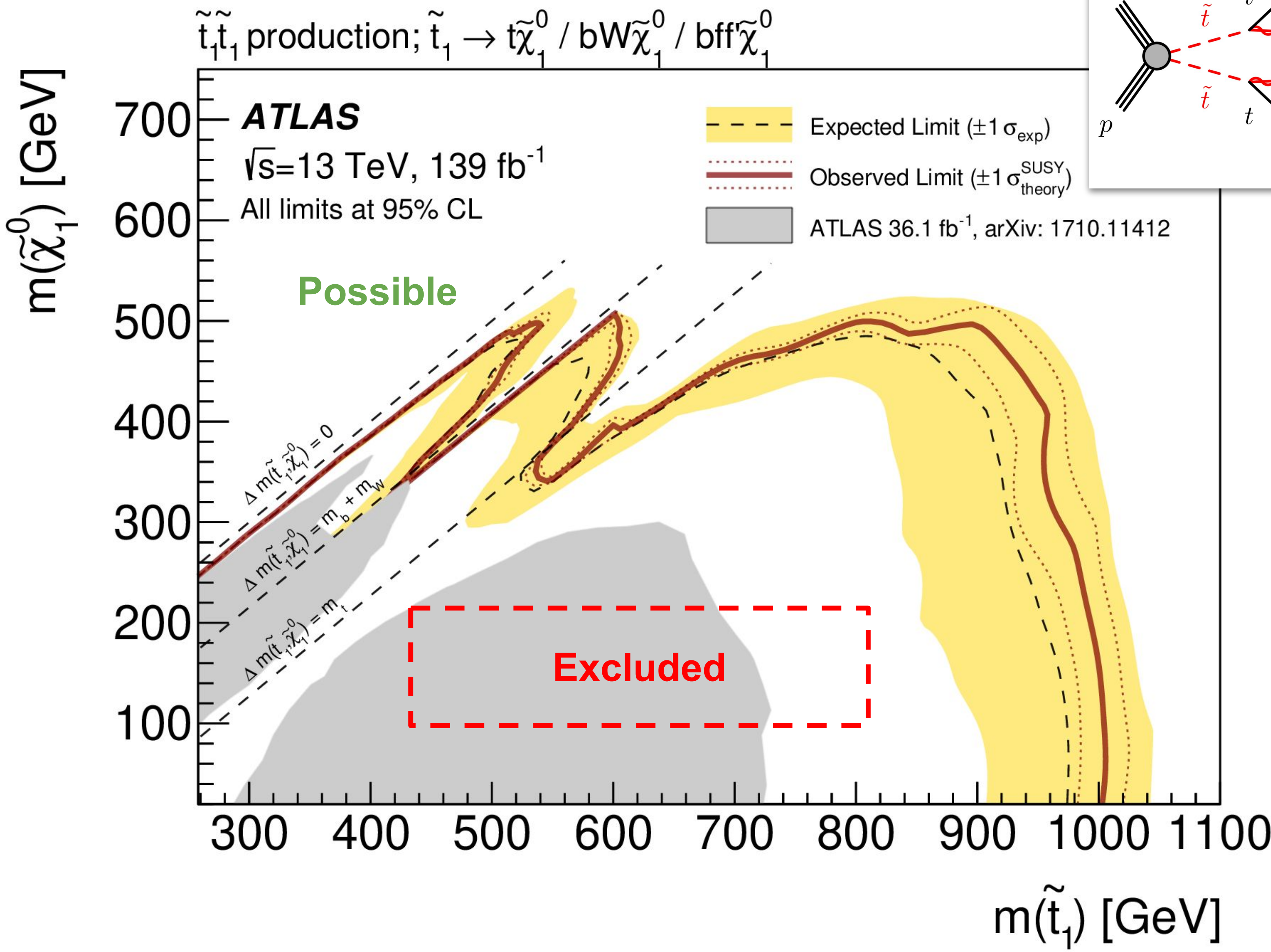
But! BSM physics could be hidden in the uncertainty!

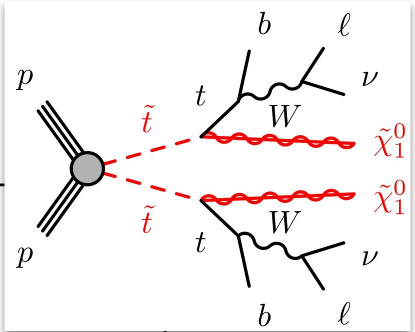
… agreement … data & SM prediction
→ didn't find BSM physics **within precision** (i.e. cyan / move models excluded)

Stop-2L: results

SUSY-2018-08

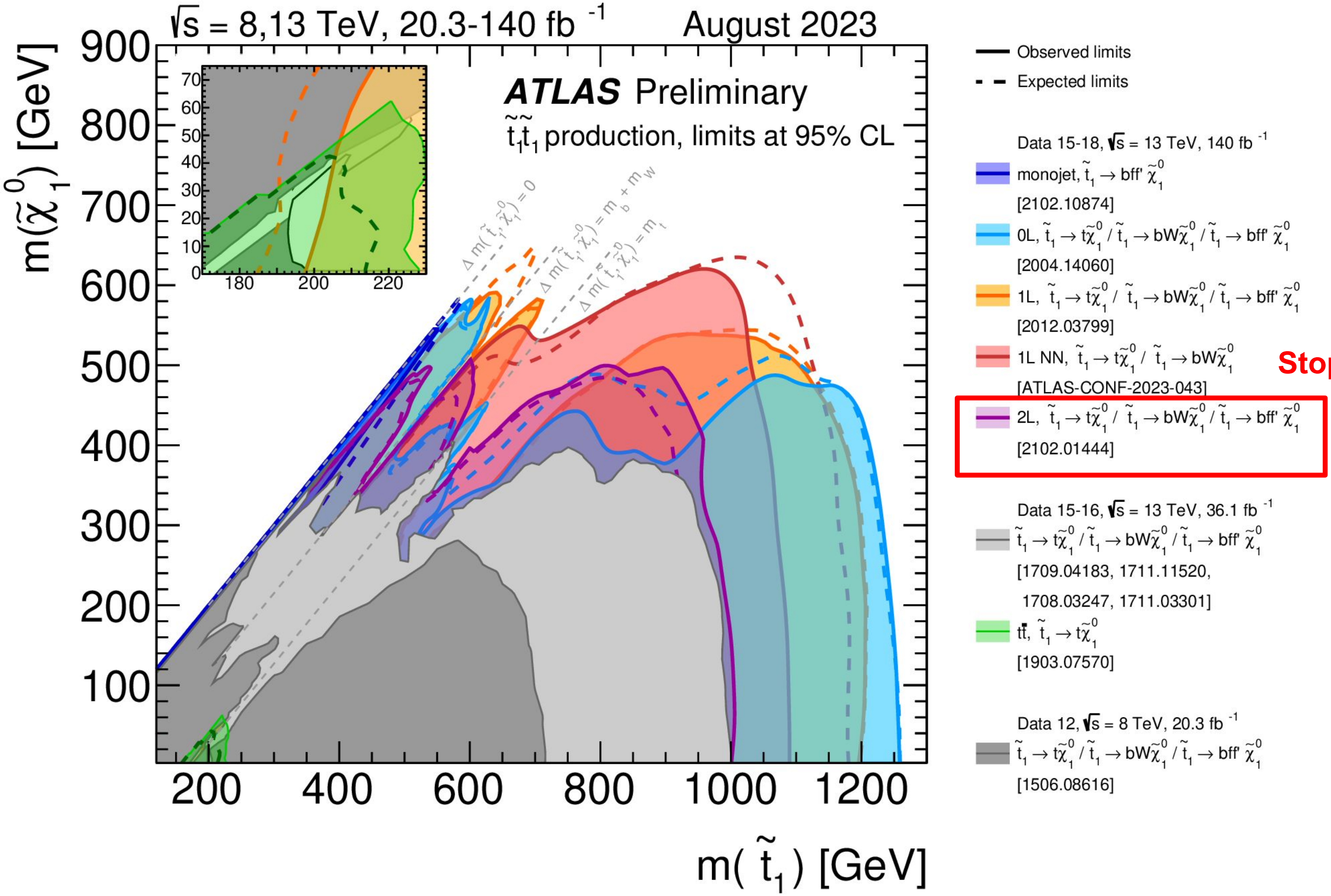
Cannot exclude a model if it is hidden in the uncertainty* → exclusion limits





*this is all very qualitatively/hand-wavy/visual speaking. For the technically correct way consult the Data Analysis Lectures.

There are many SUSY searches out there

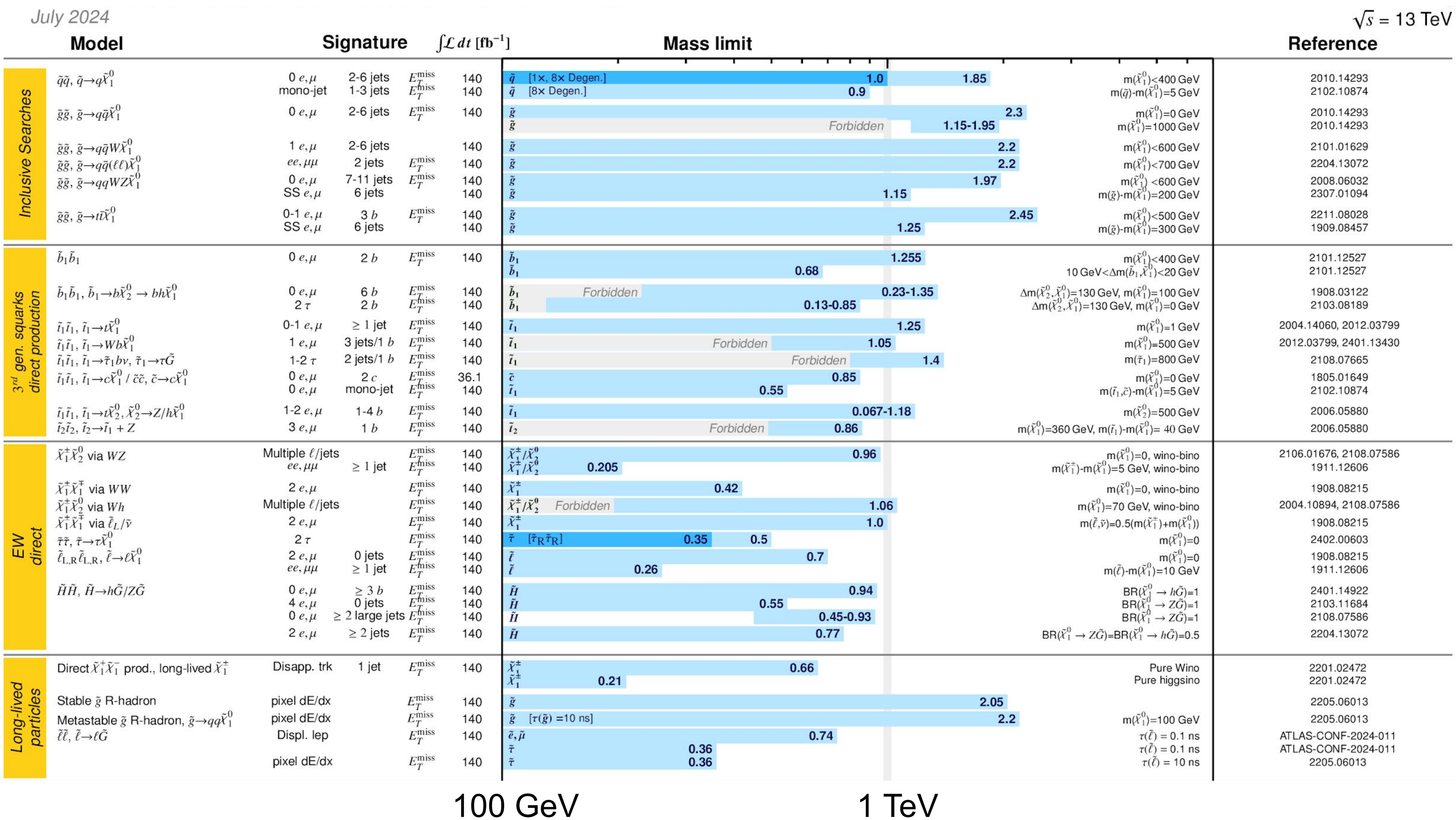


Stop-2L

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2023-025/fig_06.png

There are many SUSY searches out there

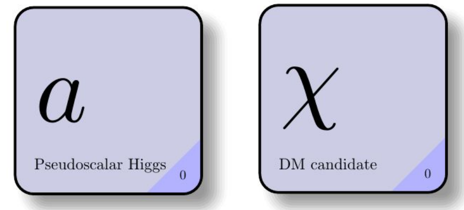
- SUSY particle masses between 100 GeV and 1 TeV largely excluded
- Some models under pressure; hierarchy problem only solved if masses “light”

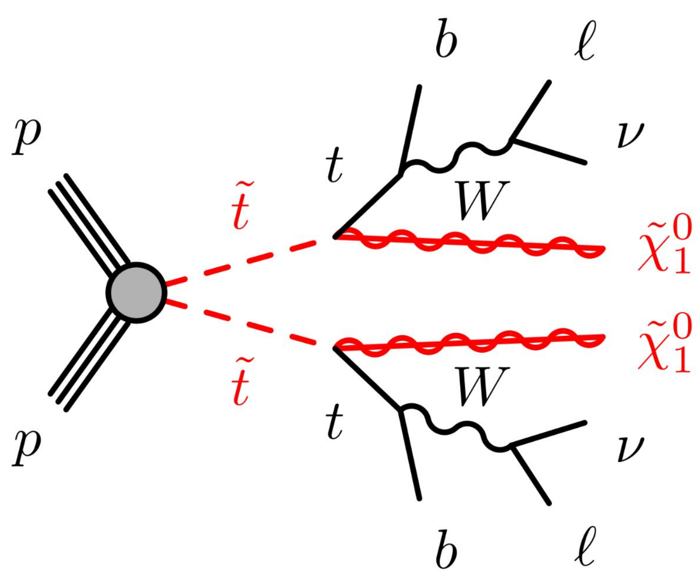


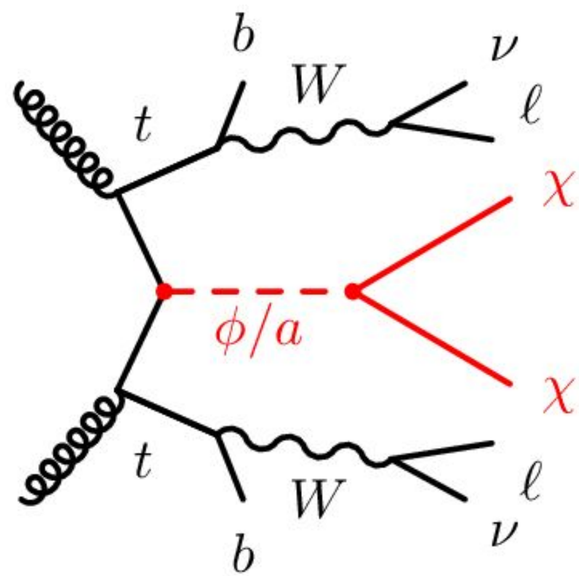
Searching form Dark Matter with Stop-2L

- In a simplified Dark Matter model, can produce Dark Matter from a mediator radiating off an inner top-quark line
- This mediator decays into 2x DM particle
- Final state the same as in Stop-2L!!!
- Simultaneously search for SUSY and DM!!!

Simplified DM model







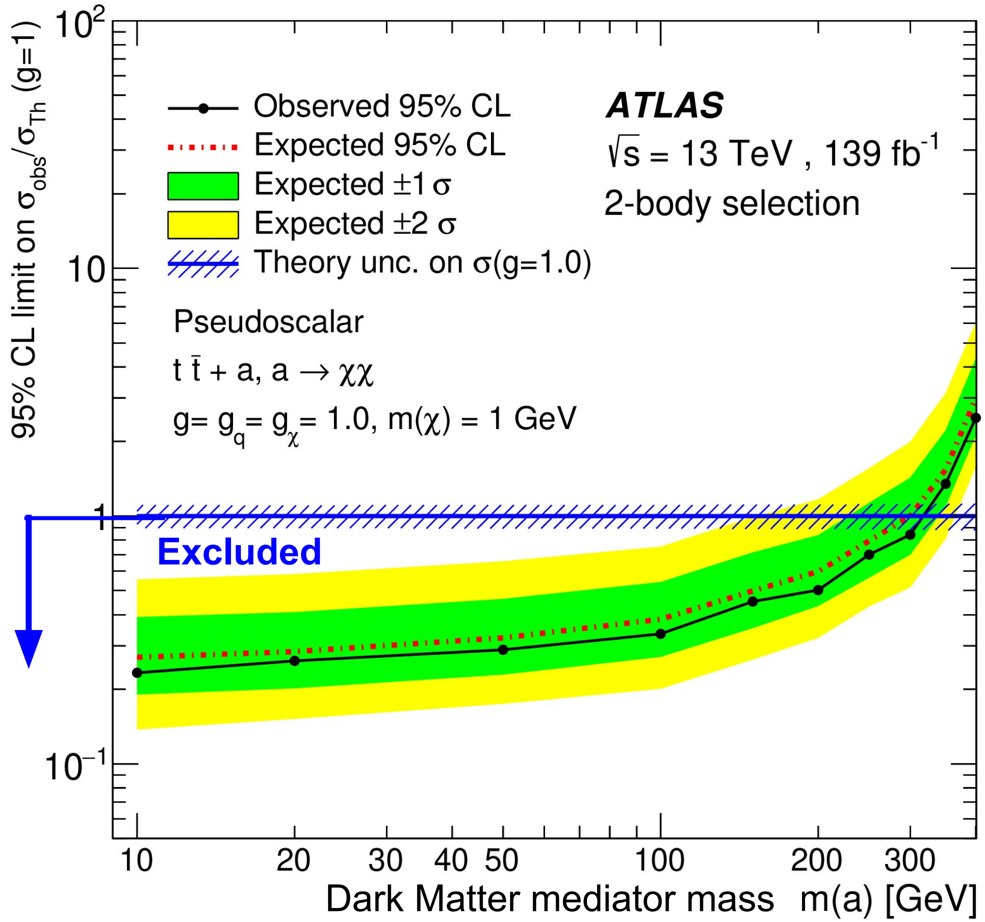
SUSY-2018-08

Stop-2L Dark Matter results

- Exclude DM mediator masses up to 300 GeV

= "maximum factor with which I can multiply the BSM prediction so it is hidden in the uncertainty"*

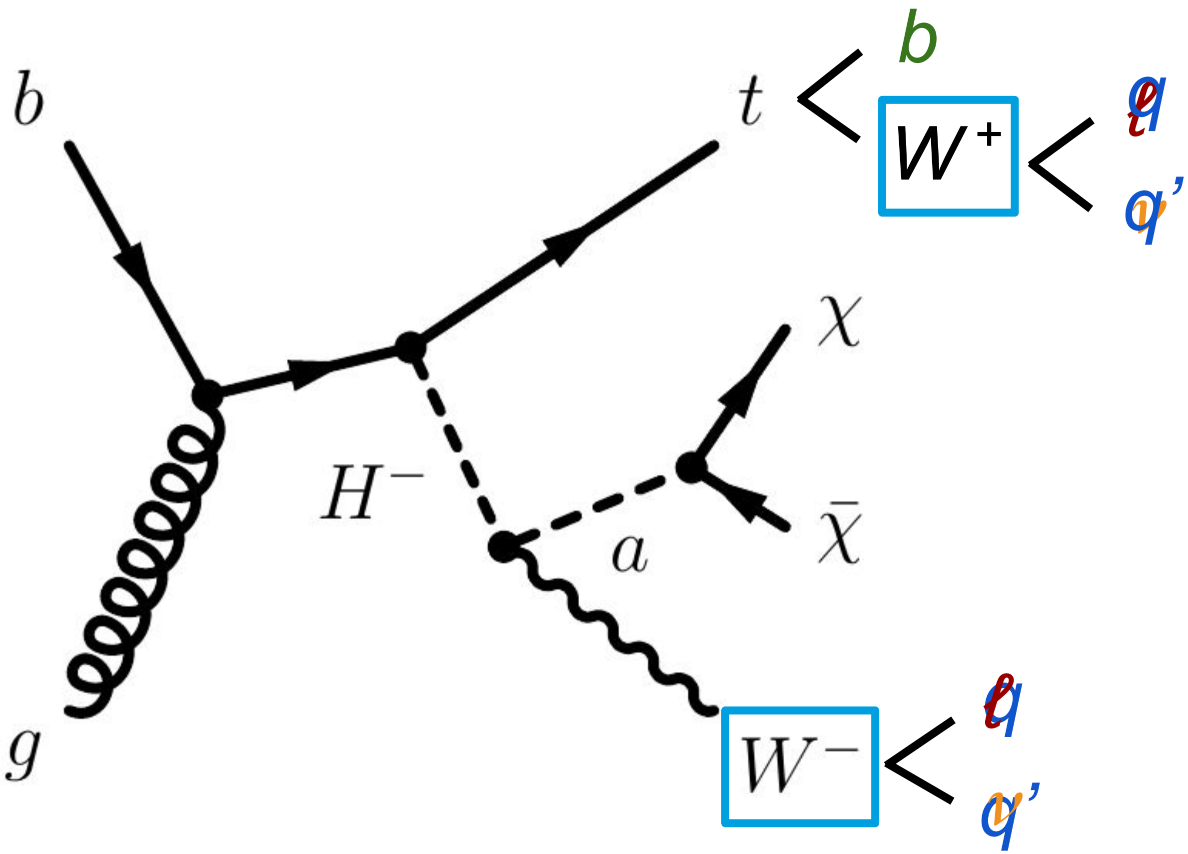
If below 1: not hidden in uncertainty! So excluded!

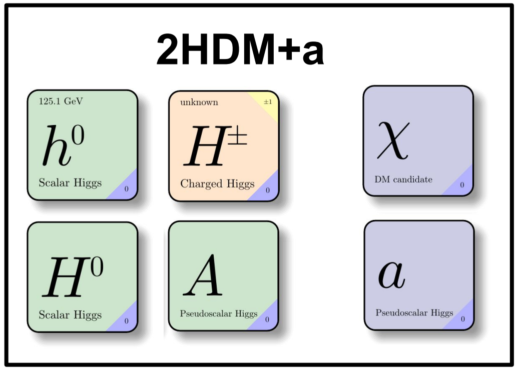


SUSY-2018-08

*again: not entirely / technically correct.

Searching for Dark Matter in tW+DM

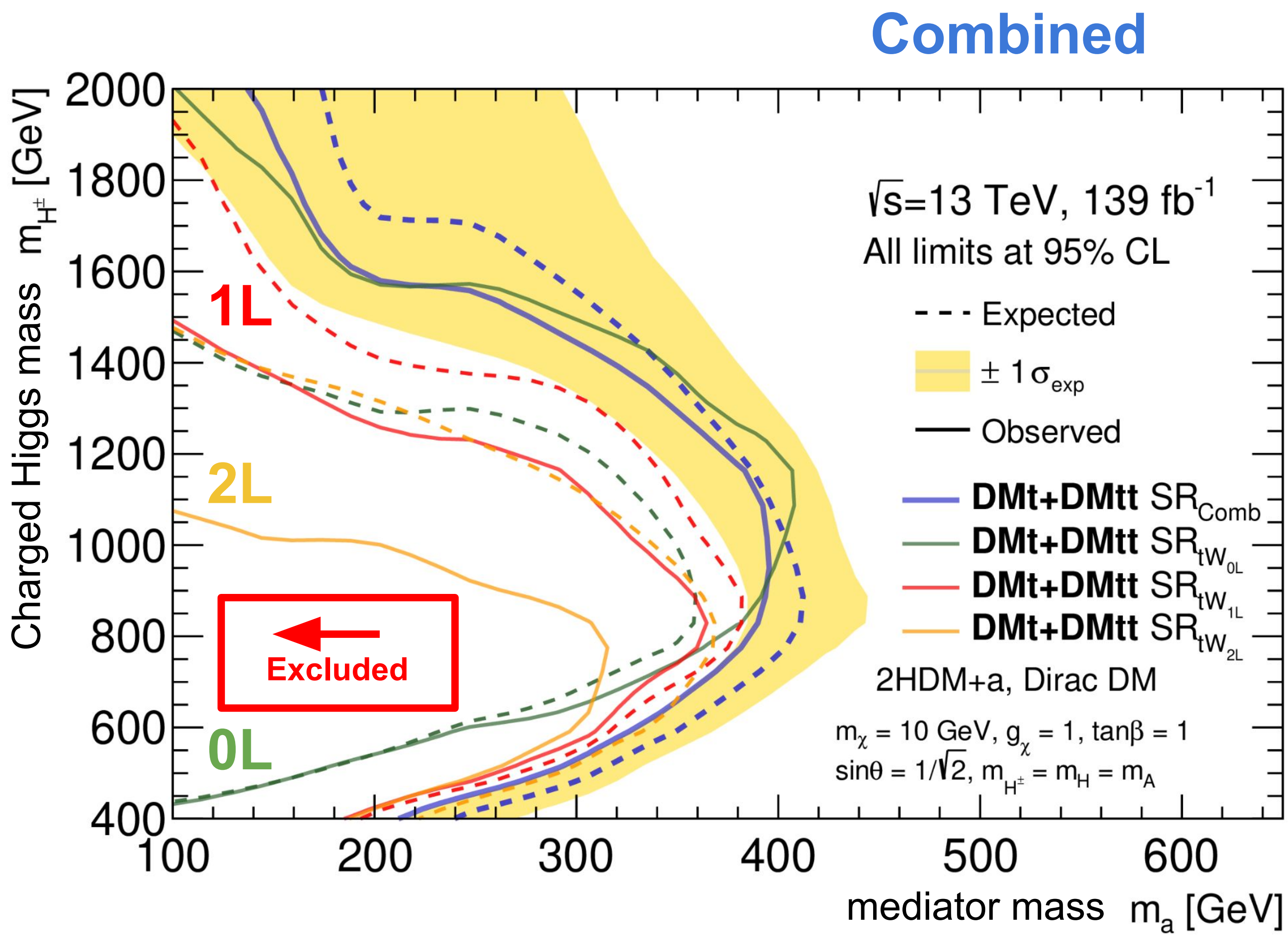




- tW+DM high x-sec
- Two **W-bosons**:
  zero, one or two visible leptons (e,μ)
- **0L, 1L, 2L channel**
  → basically 3 separate searches
- To get maximum sensitivity
  → combine the three searches

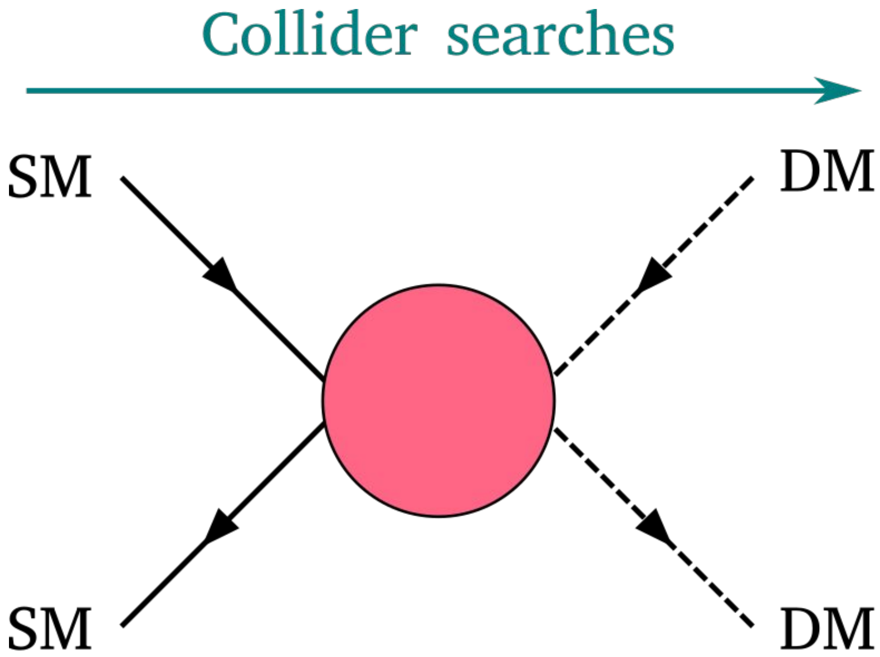
tW+DM: results

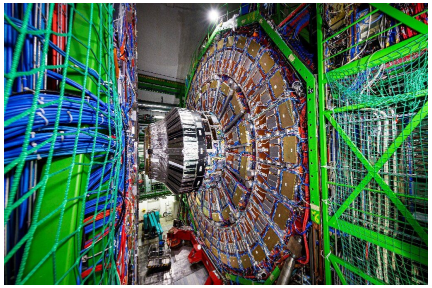
- Exclude DM mediator masses up to 300 GeV

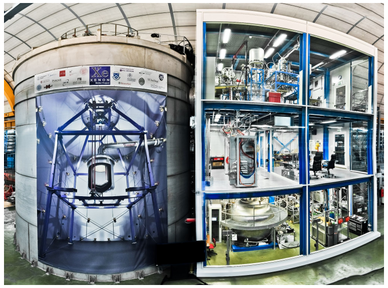


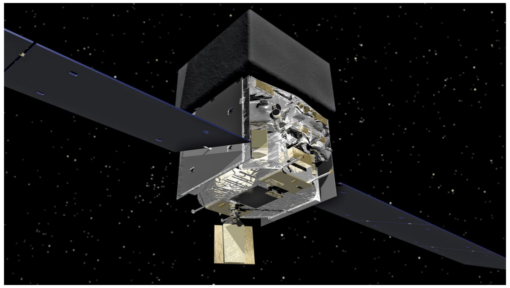
BREAK
(5-10 mins)

Other ways to search for Dark Matter





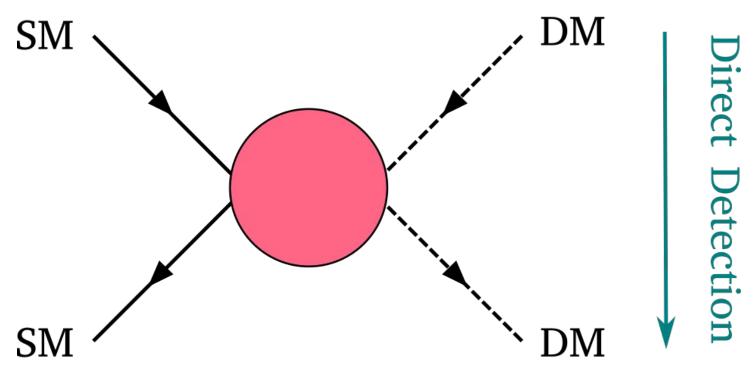




Direct detection Dark Matter searches

arxiv:1903.03026

- Assume: permanent flow of DM particles through planet earth
- **DM scatters with nuclei** (as no EM interaction) → **measurable**
- Number of scattered DM particles depends on:
  - Density of DM, ρ_0=0.3 GeV/c^2/cm^3
  - DM velocity w.r.t. earth ~220 km/s
  - DM-nuclei cross-section
  - Mass of DM & interacting nucleus
  - Mass of detector → **higher better**
  - Spin of DM particle and spin sensitivity of target material
  - Minimum recoil energy sensitivity of detector → **lower better**



total detector mass

velocity distribution

DM density

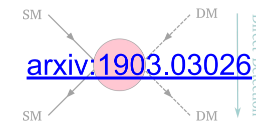
$$\frac{dR}{dE_{\mathrm{nr}}} = \frac{\rho_0 M}{m_N m_\chi} \int_{v_{\mathrm{min}}}^{v_{\mathrm{esc}}} v f(v) \frac{d\sigma}{dE_{\mathrm{nr}}} \, dv$$

Events per recoil energy

mass of nucleus/DM

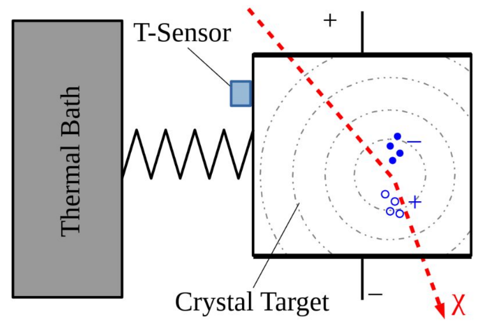
differential interaction cross-section, $\propto m_N$

Experimental setups of DD experiments

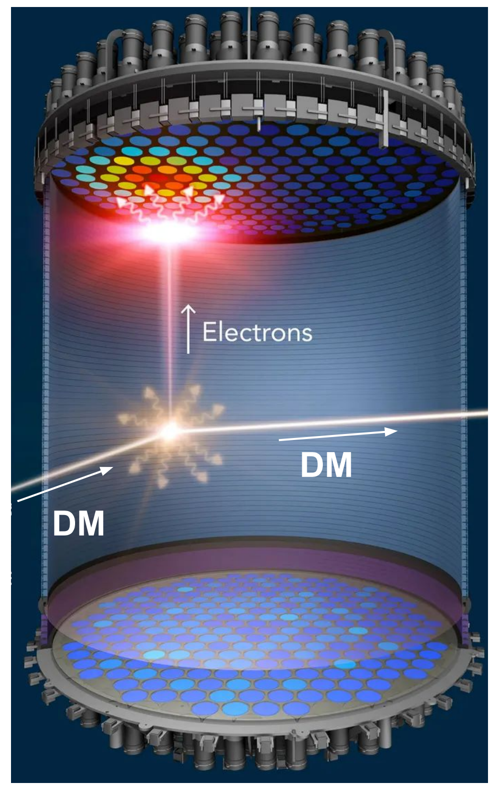


- Measure recoil of nuclei by DM → phonons/heat
- Backgrounds:
  - cosmic muons, neutrons (from nuclear decays, cosmic μ)
  - γ, $\beta^{\pm}$ from radioactive decays → often interact via EM
- Use very pure, non-activated, well-selected materials & shielding
- Measure two signals: one from EM recoil (e.g. charge; higher for bkg.); one from nuclear recoil (e.g. heat)

Image credit bottom:
https://th-thumbnailer.cdn-si-edu.com/3Qxw0k7nJ0cC7BUwbFSP5zHO6w8=/fit-in/1600x0/https%3A%2F%2Ftf-cmsv2-smithsonianmag-media.s3.amazonaws.com%2Ffiler%2F42%2Fd5%2F42d5a303-b006-4972-9efa-92797a25ba9c%2F31667821088_f762d2c200_o.jpg



Cryogenic detectors:
- At very low T (mK)
- Scattering DM increases T
- Bkg. ionises material → separate signal
- Materials: Ge, Si



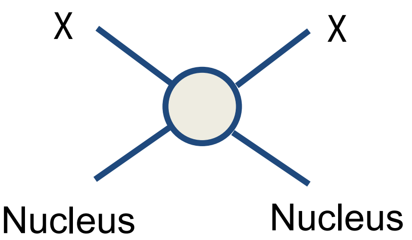
Noble liquid detectors:
- E.g. liquid Ar, Xe
- Phonons from DM→ photons + ionisation

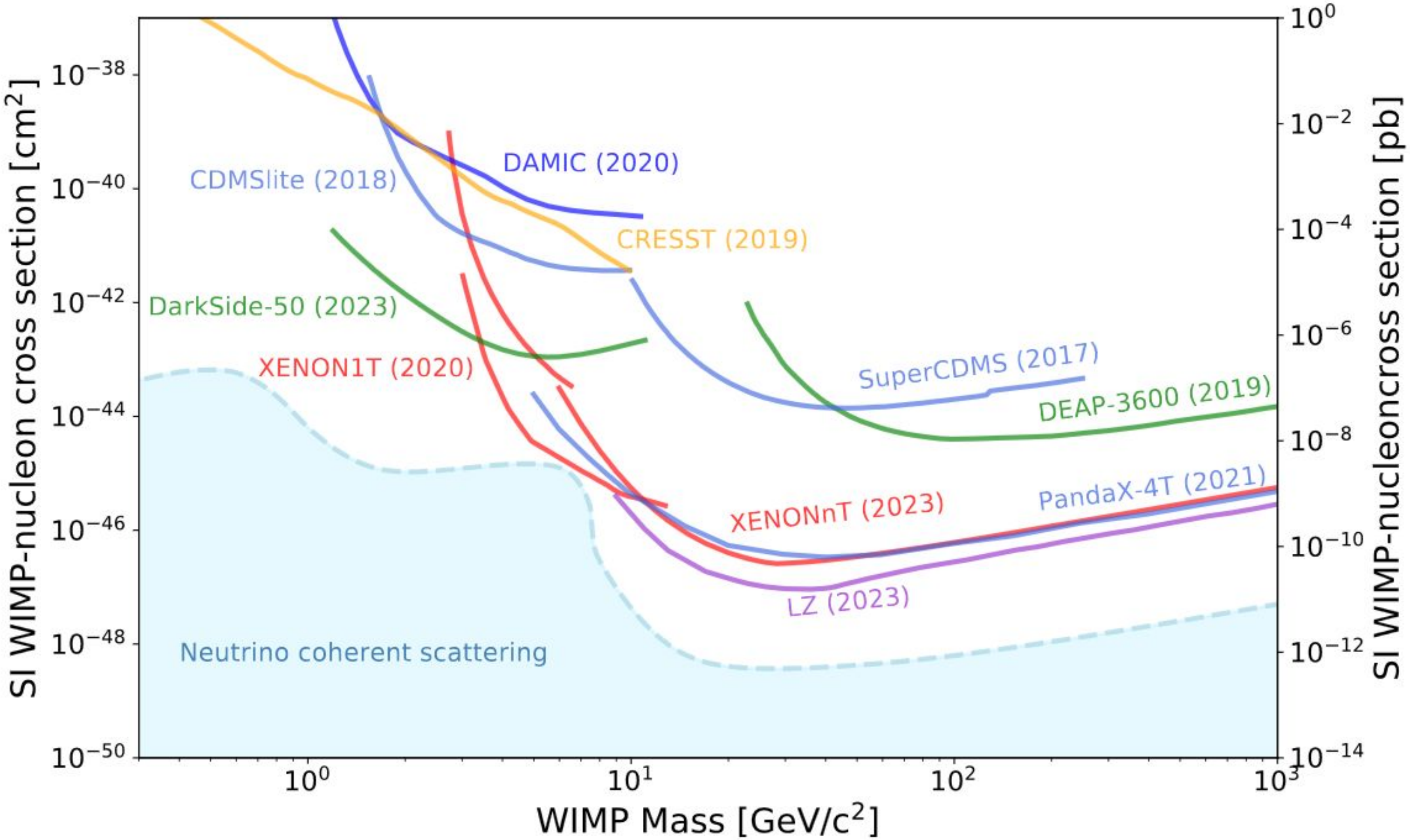
- Example XENON experiment
- Detect photons with PMTs at the side
- Detect ionisation by E-field + scintillation signal at the top
- Ratio of photons/ionisation different for DM / bkg.

DD experiments – results

rpp2024-rev-dark-matter

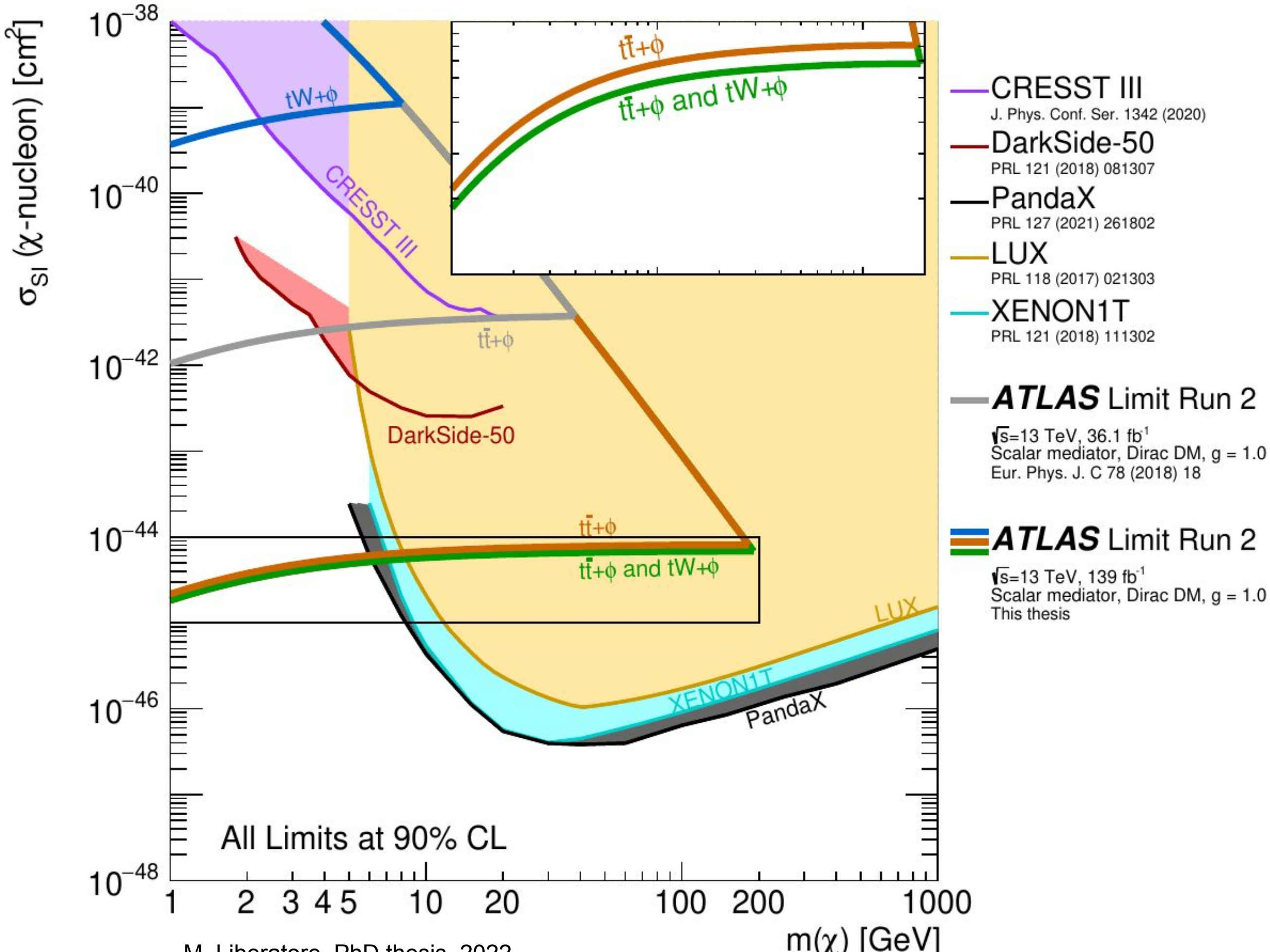
- Direct detection experiment results interpreted in terms of Effective Field Theories, no assumption on interaction mechanism of DM and nucleus
- The neutrino floor is not that far!

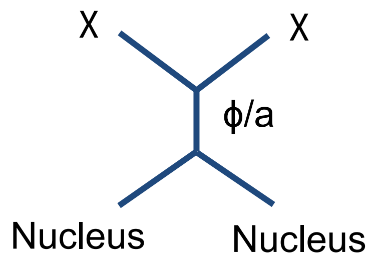




DD experiments – comparison to collider

- Comparing to collider: need to use a “simplified DM model” → additional modiator ϕ/a
- Collider searches dominate at low masses!



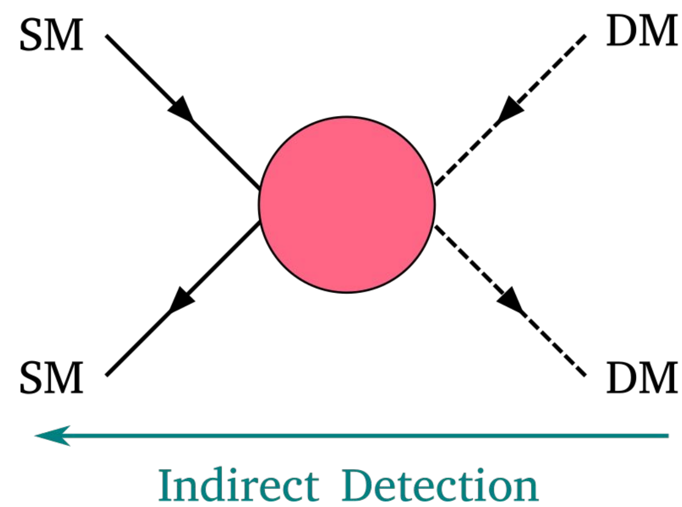


M. Liberatore, PhD thesis, 2022

Indirect detection Dark Matter searches

rpp2022-rev-dark-matter

- In areas of high mass density: Dark Matter will annihilate → indirect detection
- Annihilation yields signals such as photon pairs, neutrinos, baryons
- High mass density areas: sun, galaxy centers, …



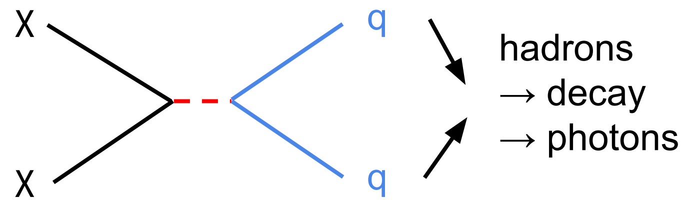
- Production rate of IDD events depends on:
  - Annihilation rate / cross-section
  - Dark Matter density
  - The number of final state particles

$$\Gamma_f^A = c\frac{\rho_{\rm DM}^2}{m_{\rm DM}^2}\langle\sigma v\rangle N_f^A$$

https://www.youcanseethemilkyway.com/wp-content/uploads/2023/01/Massive_Black_Hole_at_the_Center_of_the_Milky_Way.jpg

Experimental techniques of indirect detection

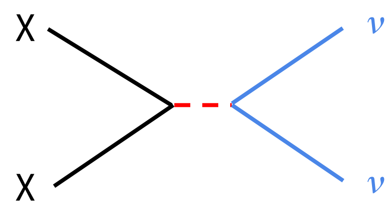
- **Photons**
  - produced e.g. when DM + DM → quarks
  - search for high energy photons (“gamma rays”) e.g. from the galactic center
  - experiments: e.g. FERMI-LAT

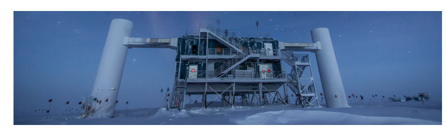


https://www.symmetrymagazine.org/sites/default/files/legacy/images/200912/article05_image01.jpg

---

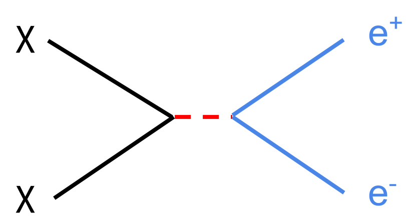
- **Neutrinos**
  - produced e.g. in the sun
  - search for high energy neutrinos from sun
  - experiments: e.g. IceCube, Kamiokande

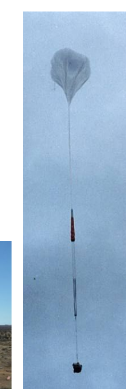




https://cdn.mos.cms.futurecdn.net/CJ4pxsggF4VwYdRXPvT3tK.jpg

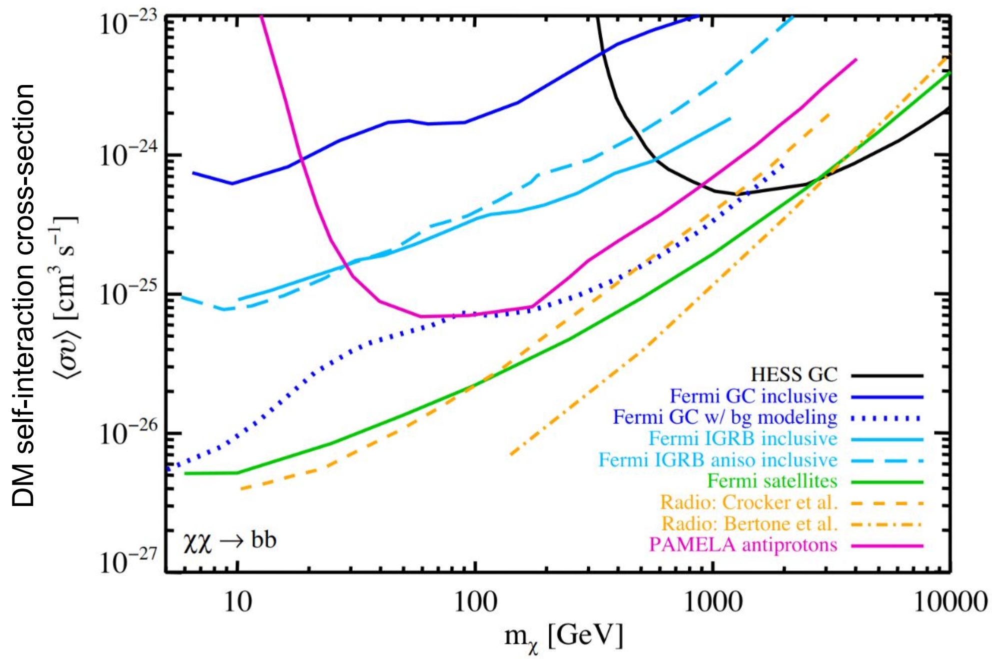
- **Antiparticles**
  - produced e.g. if DM + DM → e^+e^-
  - charged particles deflected in universe → generally search for antiparticles
  - experiments: e.g. HEAT, AMS, HESS





Indirect detection: results

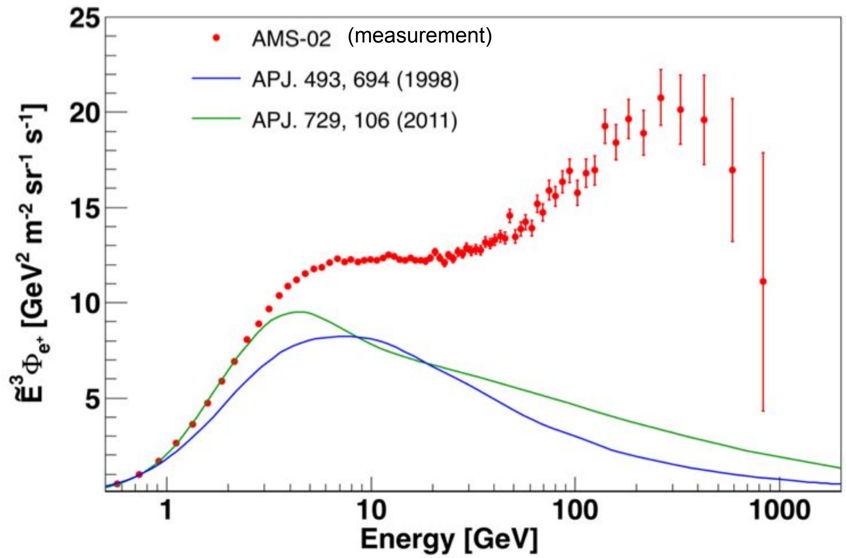
arxiv:1604.00014



- Covered mass range comparable to DD

- Exciting result: excess of positrons observed by multiple experiments (AMS, FERMI, PAMELA)

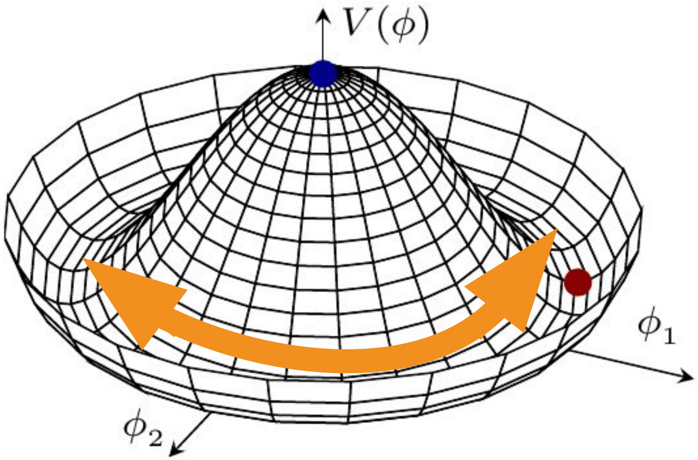
- Yet unclear if it is due to Dark Matter, astrophysical origin investigated



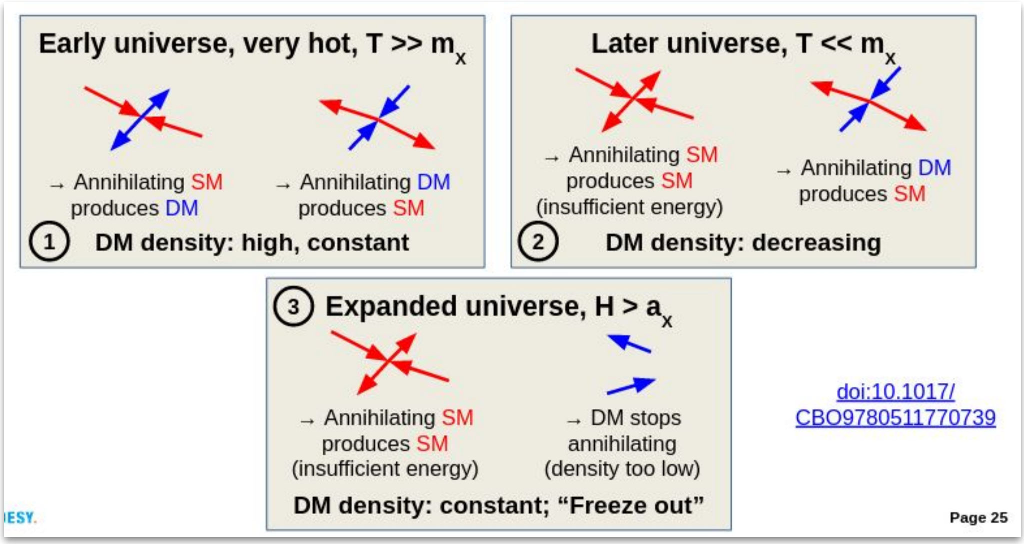
https://ams02.space/sites/default/files/inline-images/%20PhysRevLett.122.041102.Fig5_.png

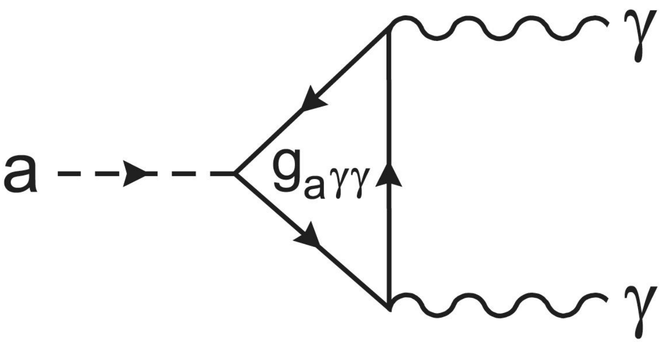
Axions

(Lecture 1)



- Searches so far considered WIMP DM
  → mass & x-sec. similar to weak bosons
- Also covered Axion Dark Matter last time
  → much lighter DM candidates
  → origin from solution of strong CP probl.
- Interact with SM matter by 2-photon vertex

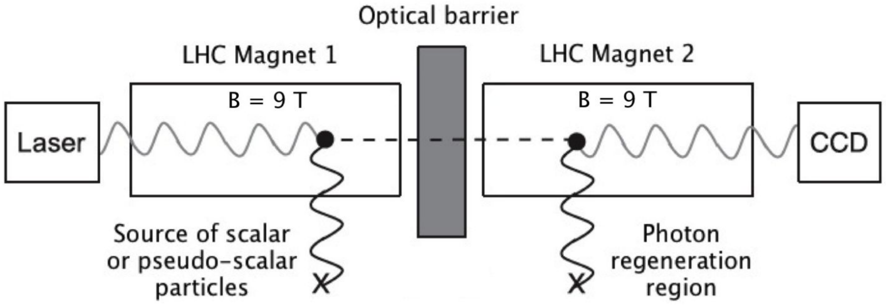




Axions search experiments

- Idea of Axion experiments:
    - can interact with Axions by exposing them to strong magnetic fields (=high photon flux)
    - can produce Axions by using strong lasers and strong magnetic fields
- ALPs experiment: shine laser into a strong magnetic field
    - photons converted to Axions
    - photons stopped by wall, Axions pass through
    - on the other side: another strong magnet→ Axions converted to photons

https://particle-physics.desy.de/sites/site_particle-physics/content/e221990/e222445/e228223/e228225/e228229/ALPS_ger.jpg

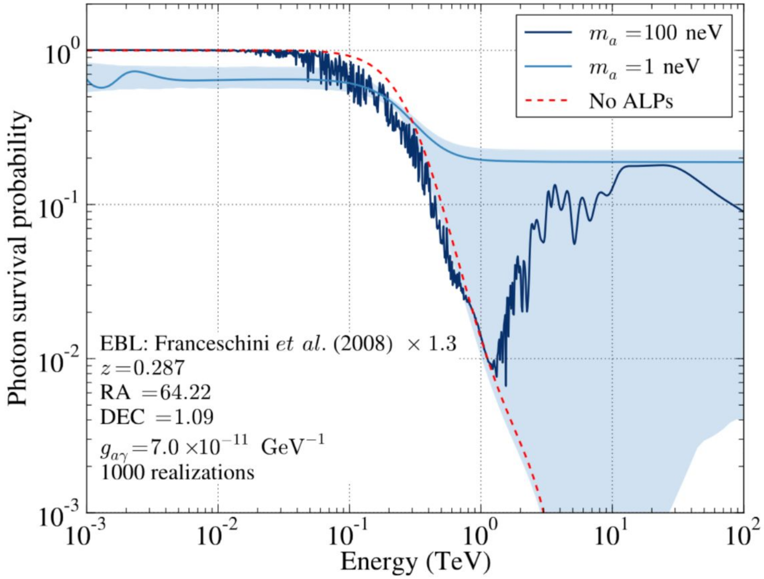


arxiv:1410.2566

Searching for Axions from & in the universe

- CAST / (Baby-)IAXO experiments: search for Axions produced in sun
  - use a large magnet to point at the sun: Axions converted to photons
  - measure these photons
- The magnetic fields converting (photons → Axions) & (Axions → photons) can also be of astrophysical origin
  - expect to measure more high energy photons if there are Axions

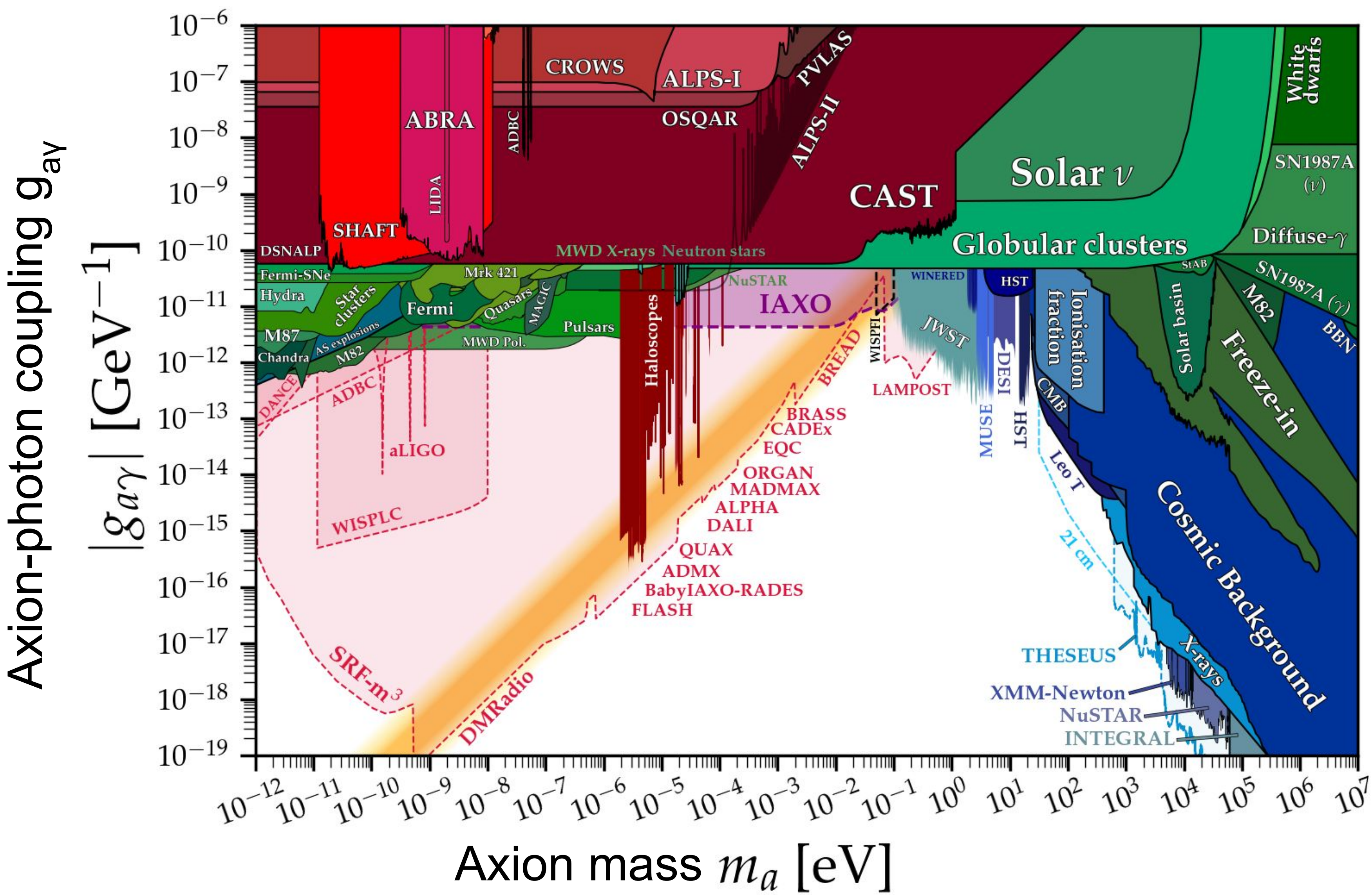
https://mediastream.cern.ch/MediaArchive/Photo/Public/2002/0209017/0209017_01/0209017_01-A4-at-144-dpi.jpg



M. Meyer, The Opacity of the Universe for High and Very High Energy γ-Rays, https://inspirehep.net/literature/1254304

Axions: exclusion limits

Ciaran O'Hare, AxionLimits, doi:10.5281/zenodo.3932430, Link



The magnetic moment of the muon

rpp2022-rev-g-2-muon-anom-mag-moment

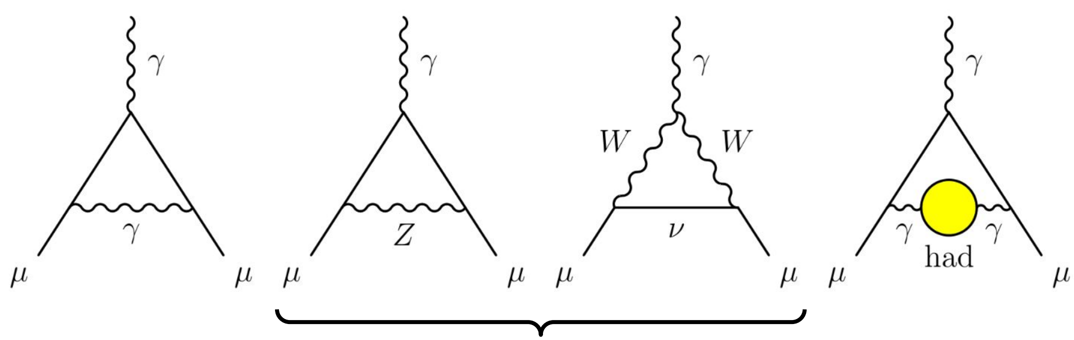
- Recall: circular current = magnetic field → magnetic dipole moment
- Similarly: charged particles on circular orbits & spinning around themselves exhibit magnetic dipole moment
- Magnetic dipole moment basically indicates how strongly a particle is affected by a magnetic field

?? spin-vector

$$\mathbf{m}_{\mathrm{S}} = -\frac{g_{\mathrm{S}}\,\mu_{\mathrm{B}}\,\mathbf{S}}{\hbar}, \qquad \mu_{\mathrm{B}} = \frac{e\hbar}{2m_{\mathrm{e}}}$$

constant

- For the muon: g_μ = 2 (SM LO), loop effects → g_μ > 2
- Measure the difference: $a_\mu = (g_\mu - 2) / 2$ → **stress-test Standard Model (the loops it predicts)**



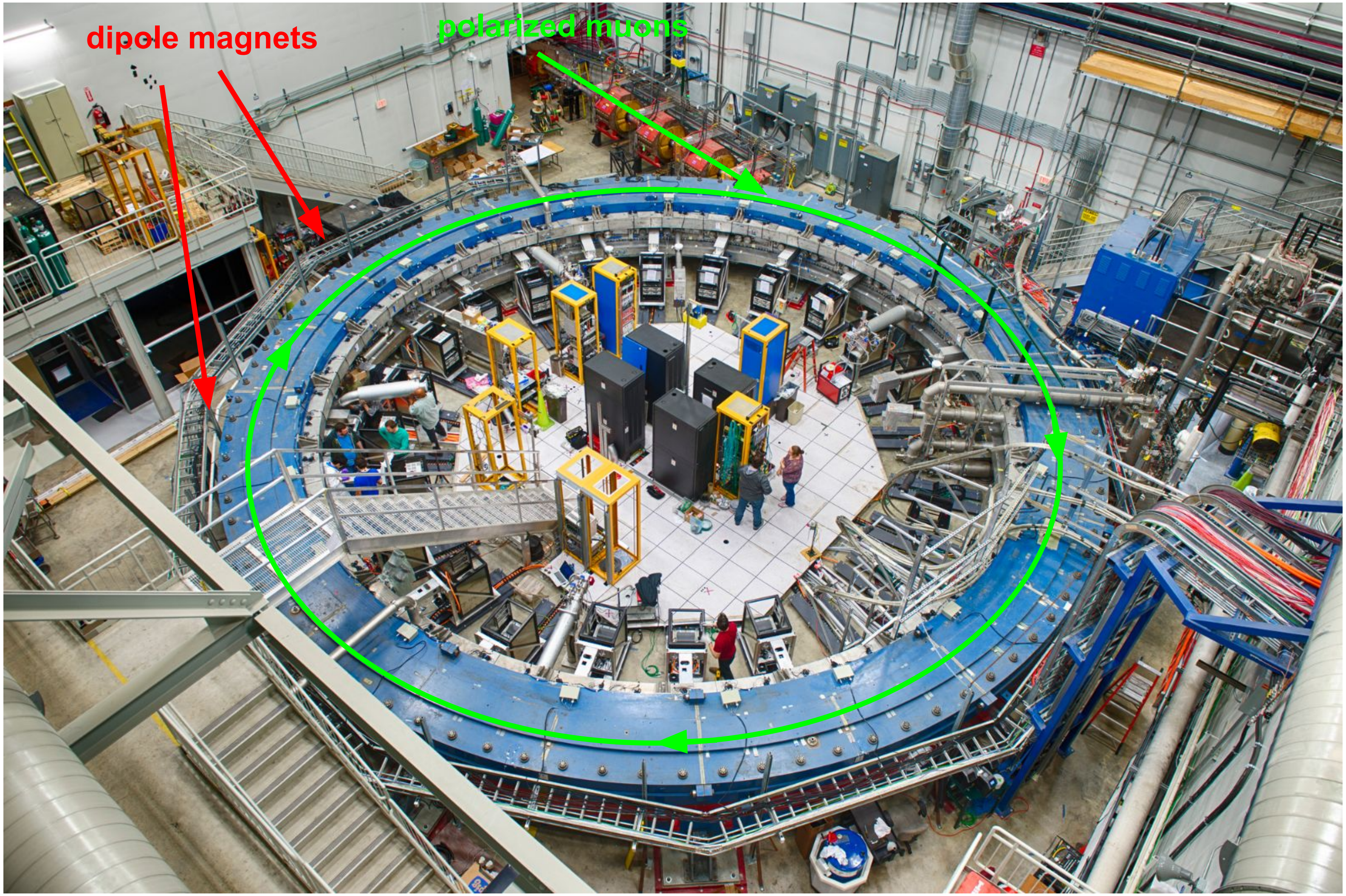
QED	weak	QCD
→ uncert.: 0.1 ($\times 10^{-11}$)	→ uncert.: 1.0 ($\times 10^{-11}$)	→ uncert.: 40 ($\times 10^{-11}$)

https://www.particlebites.com/?p=8972

How to measure g-2

$$\mathbf{F} = q\,\mathbf{v} \times \mathbf{B}$$

- Produce muons, store ring via dipole magnets



https://upload.wikimedia.org/wikipedia/commons/7/7c/Fermilab_g-2_%28E989%29_ring.jpg

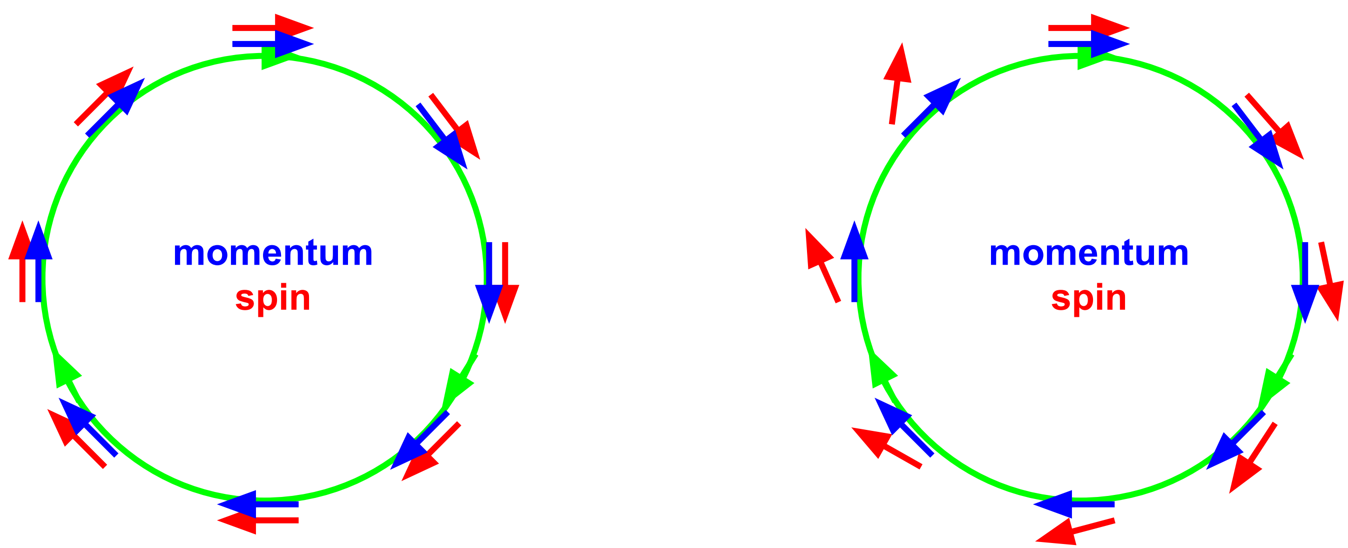
How to measure g-2 (2)

Sweigart, PhD thesis

- Two frequencies:
  - rotation frequency of muons (cyclotron frequency) ω_c
  - precision frequency due to spin ω_s
- Their difference depends on g-2!!!
  → measure ω_a & **B** → g-2 (*)!!

$$\omega_a \equiv \omega_s - \omega_c = -a_\mu \frac{eB}{m_\mu}$$

*in reality you measure ωP - the Lamor frequency of the free proton - instead of **B**



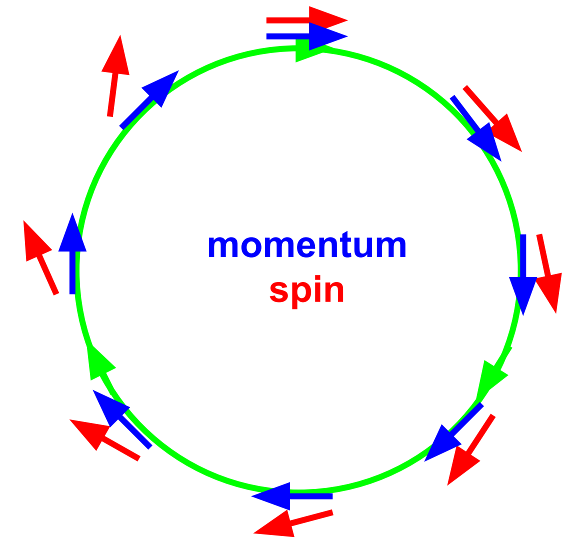
g = 2

https://muse.lnf.infn.it/wp-content/uploads/2019/09/lusiani-patras-may19-v2.pdf

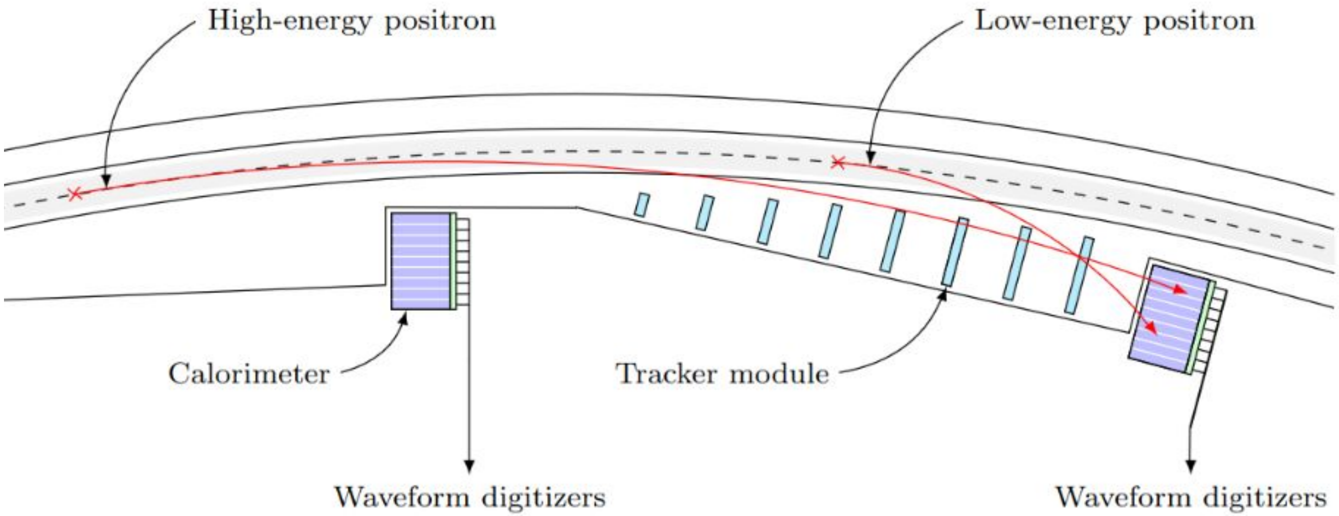
g != 2

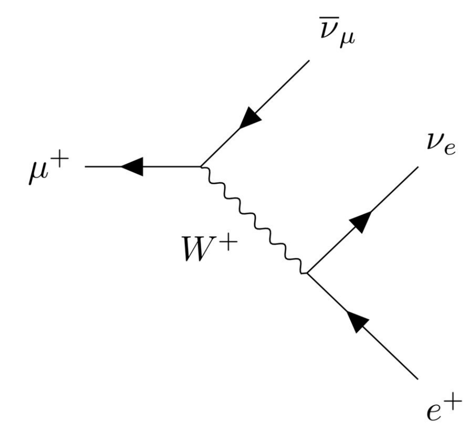
How to measure g-2 (3)

- Muon is not stable and decays
- Measure energy of decay positrons
  → Most energetic if muon momentum & spin align!
- **If filter out most energetic positrons, see modulation with frequency ω_a!!!**



g != 2

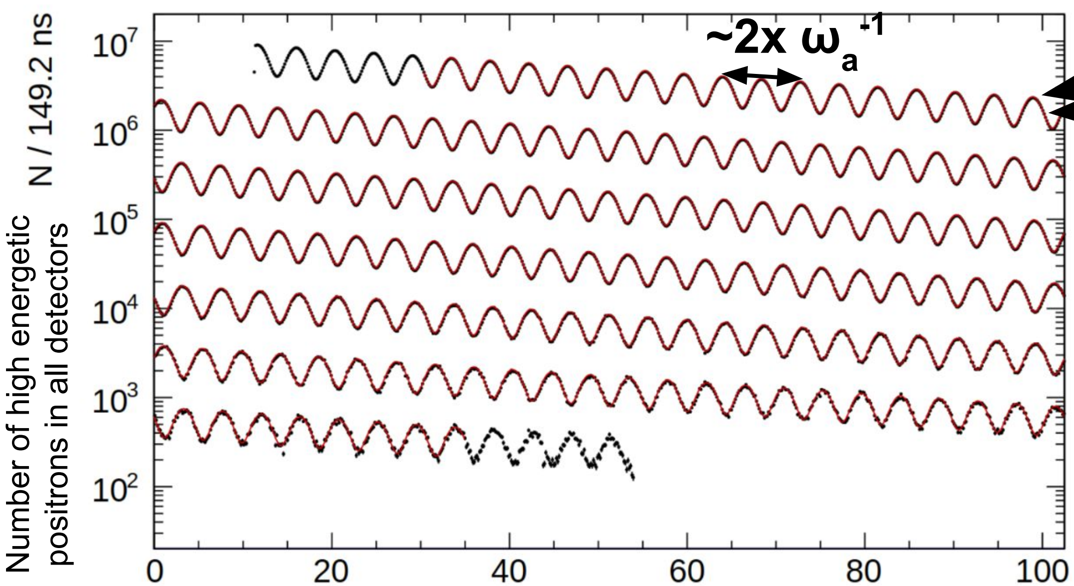




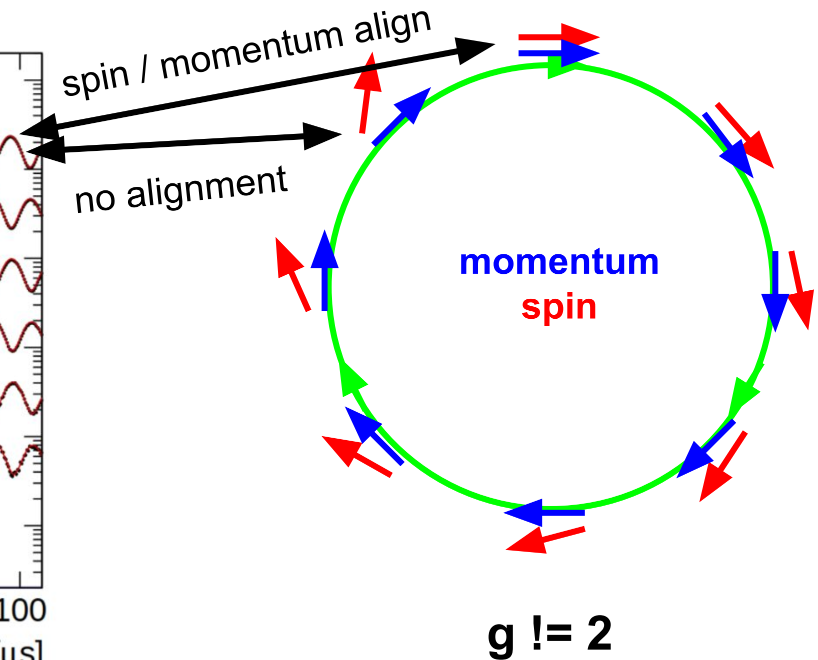
[Sweigart, PhD thesis]

How to measure g-2 (4)

https://www.particlebites.com/?p=8999

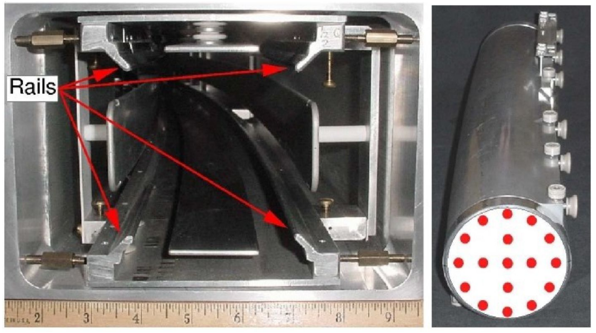


Sweigart, PhD thesis



- **If filter out most energetic positrons, see modulation with frequency ω_a!!!**

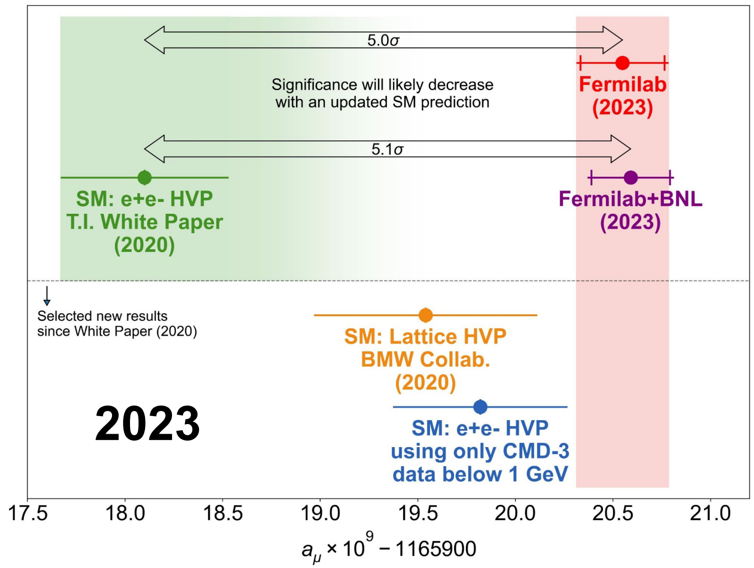
- Besides ω_a, must measure **B**!
- Measure magnetic field with special "trolley" measuring the field very precisely every three days & many other tools



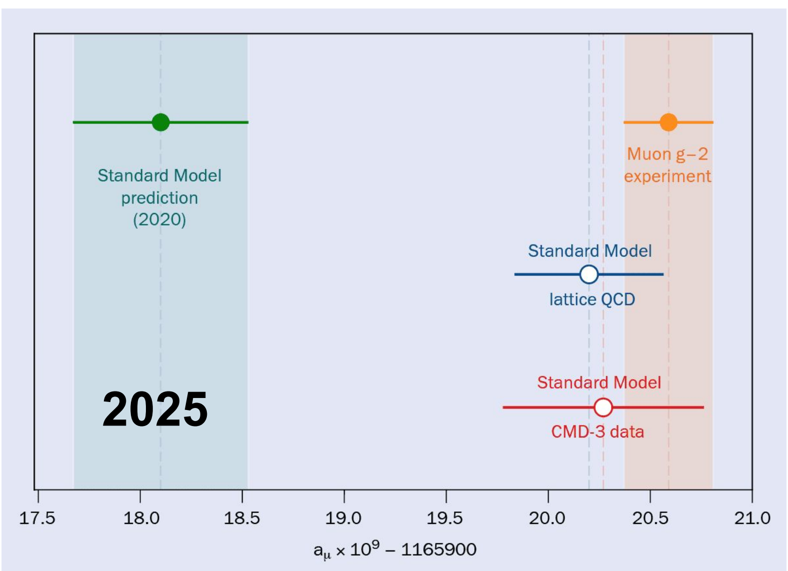
https://conference.ippp.dur.ac.uk/event/999/contributions/5220/attachments/4218/4977/Schreckenberger_Planck2021.pdf

Results of g-2

https://pbs.twimg.com/media/F3LmADjWcAAlAxb?format=jpg&name=4096x4096



https://physicsworld.com/a/the-muons-magnetic-moment-exposes-a-huge-hole-in-the-standard-model-unless-it-doesnt/



- g-2 measured extremely precisely to ~10 digits!
- In 2023: 5.1σ discrepancy of theory pred. and meas.
  - theory pred. use data-driven approach
  - less discrepancy from lattice QCD
- In 2025: new measurement as input to theory pred.
  → good agreement in g-2
  → but meas. very different from previous ones (!?)
  - lattice result reproduced

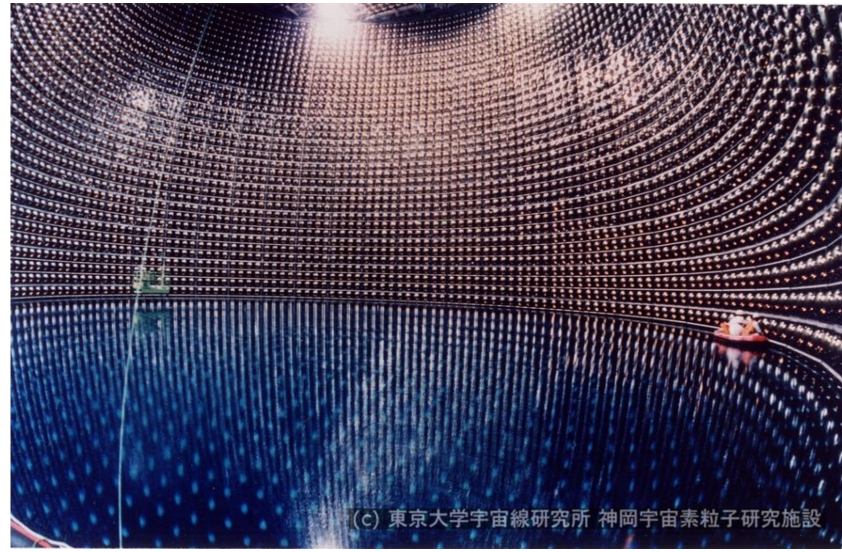
g-2 seems resolved for now.

https://cerncourier.com/a/do-muons-wobble-faster-than-expected/

Proton stability

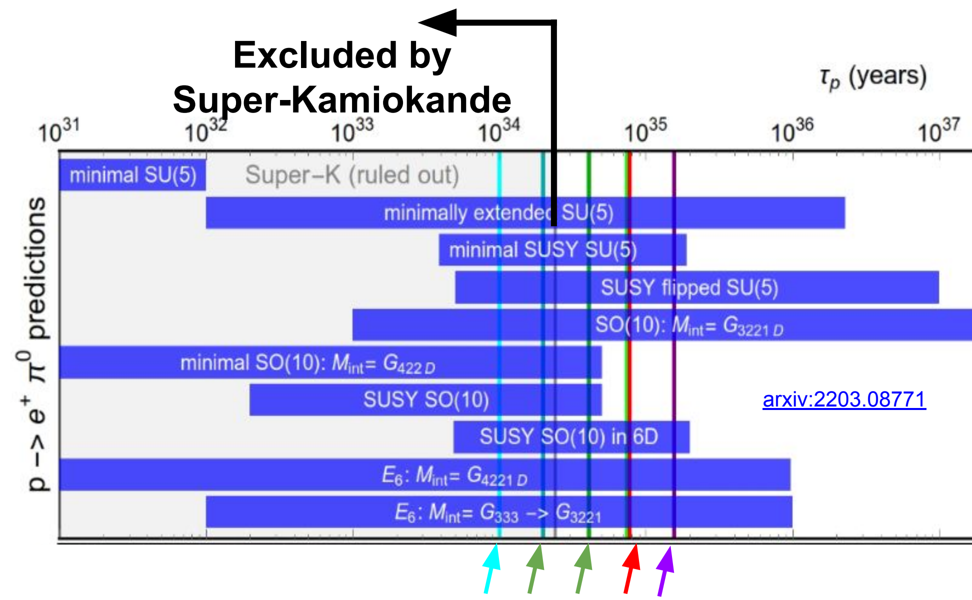
arxiv:2010.16098

- Proton is stable in SM (Baryon number conservation)
- Grand Unified Theories can predict that the proton is not stable
- “Not stable” → lifetimes >10^{30} y



https://wechseljetzt.de/uploads/Super-K2-7d5e2bccc48802c113419e3c24de77c03662e919.jpg

- Search for proton decay e.g. with Super-Kamiokande
  - 27.5 T of Water → many protons
  - Search for p → $\ell^+ \pi^0$
  - Proton lifetime > 10^{34} y
- Multiple models excluded, but still room for SUSY ;)



colored lines → future experiments

Summary

- Many, many searches / experiments targeting BSM physics
- Constraints on many model parameters, yet not clear what BSM physics is
- Many exciting experiments/results coming up investigating BSM physics further, e.g.
  - XENON n-ton → in operation
  - ALPS II → in operation
  - Hyper Kamiokande
  - HL-LHC
  - BabyIAXO
  - …and many more!
- **What will we find?**

https://thumbs.dreamstime.com/b/llama-closeup-funny-expression-face-mouth-open-appears-to-be-talking-humorous-96704071.jpg

Thank you

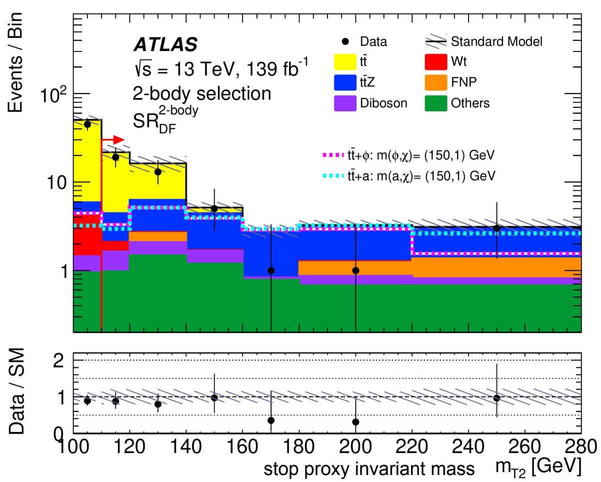
Backup slides

Stop-2L: statistical analysis

[SUSY-2018-08]

1. Triggering

2. Event selection & background estimation



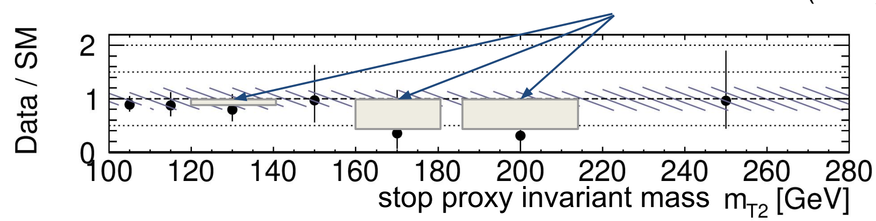
3. Statistical analysis

How compatible is the data with the Standard Model prediction? (Data Analysis lecture)

$$\ell = -2\ln\left(\frac{\mathcal{L}(\text{data}, H_1)}{\mathcal{L}(\text{data}, H_0)}\right)$$

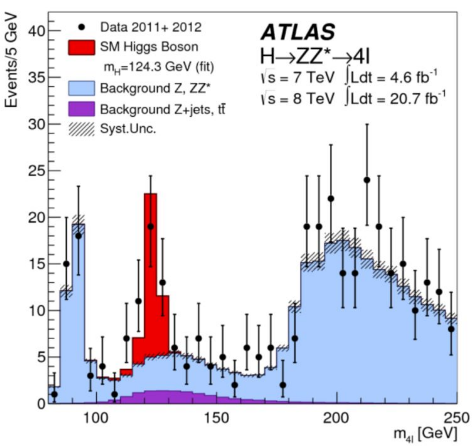
3a) If very compatible → up to which x-sec. can I exclude BSM physics? → *exclusion limits*

How much BSM could fit here? (none)



3b) If not compatible
→ check 10^{35}x for mistakes
→ **CELEBRATE!!!**

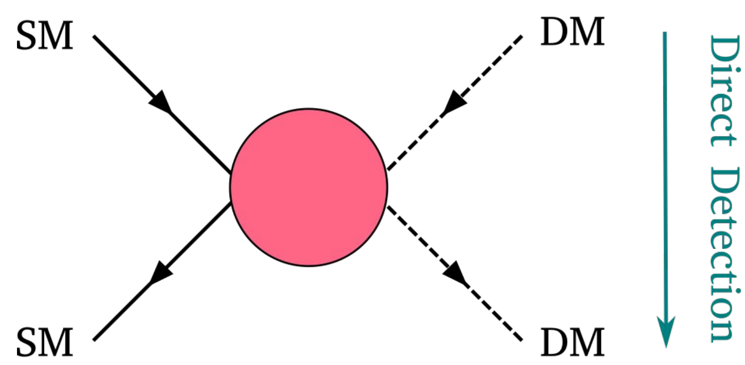
https://media.istockphoto.com/id/133838482/de/foto/champaign.jpg?s=170667a&w=0&k=20&c=e7OMItD6AU5BnKQqnhD4GV70YpIZ_0QiCGJVJhyP6Z8=



Direct detection Dark Matter searches

1903.03026

- Assume: permanent flow of DM particles through planet earth
- DM scatters with SM particles → **measurable!**
- DM scatters with nuclei as no EM int.
- No. scattered DM particles depends:
  - Density of DM → from rotation curve: ρ_0=0.3 GeV/c^2/cm^3 (±50%)
  - DM velocity w.r.t. planet earth, ~220 km/s with some variation
  - DM-nuclei cross-section
  - Mass of DM & interacting nuclei
  - Spin of DM particle and sensitivity of target material



There is an ideal ratio of m_X / m_N!

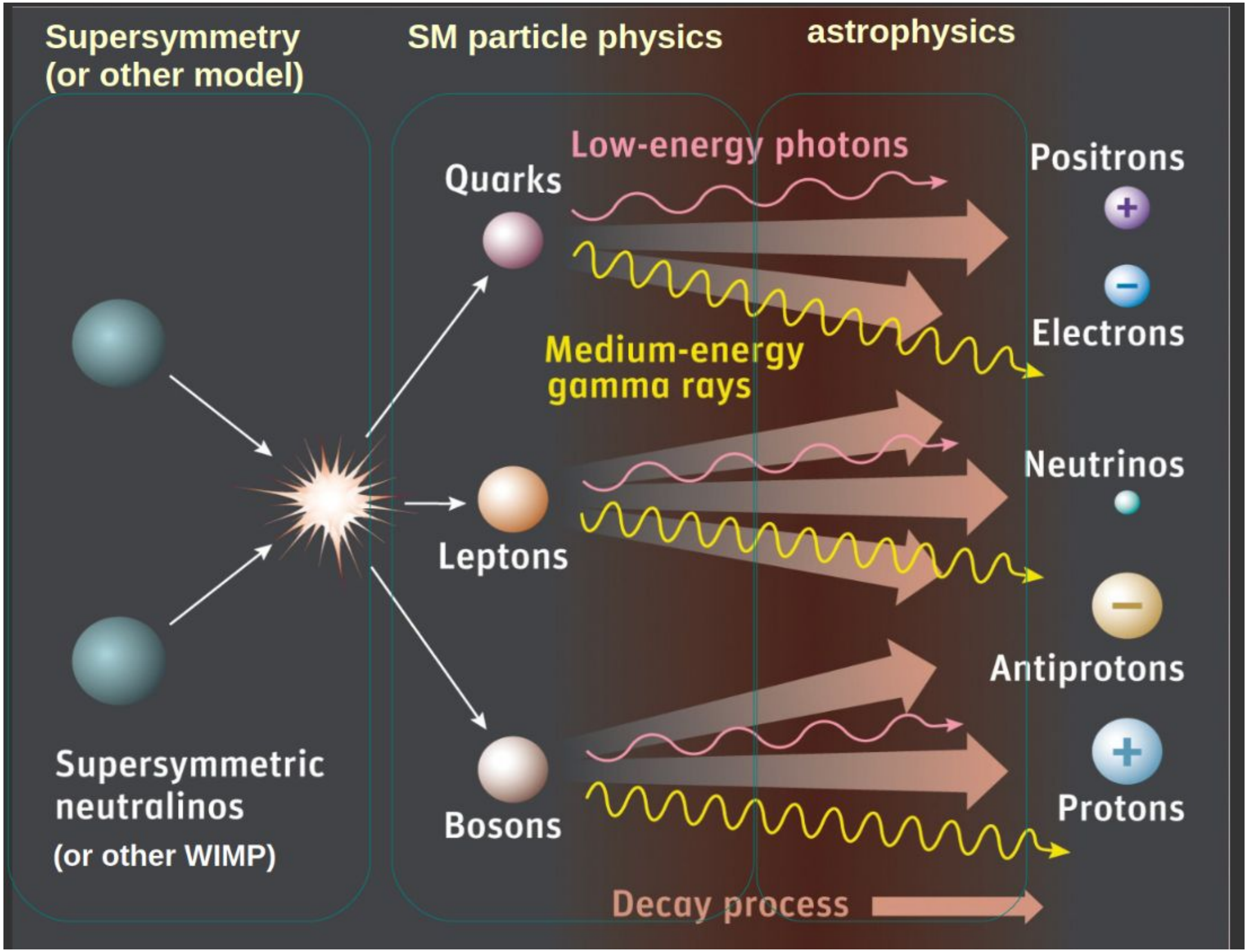
Recoil energy → **higher = less**

$$\frac{dR}{dE_{\rm nr}} \propto \exp\left(-\frac{E_{\rm nr}}{E_0}\frac{4m_\chi m_N}{(m_\chi+m_N)^2}\right)$$

Events per recoil energy

Most probably kinetic energy of DM (depends on velocity) → **higher = more**

Indirect detection all in one slide



https://www.mpi-hd.mpg.de/lin/events/isapp2011/pages/lectures/de_los_Heros.pdf

Contact

DESY.

Deutsches Elektronen-Synchrotron

www.desy.de

Ben Brüers
ATLAS group (Zeuthen)
ben.brueers@desy.de
+49 33762 7-7640