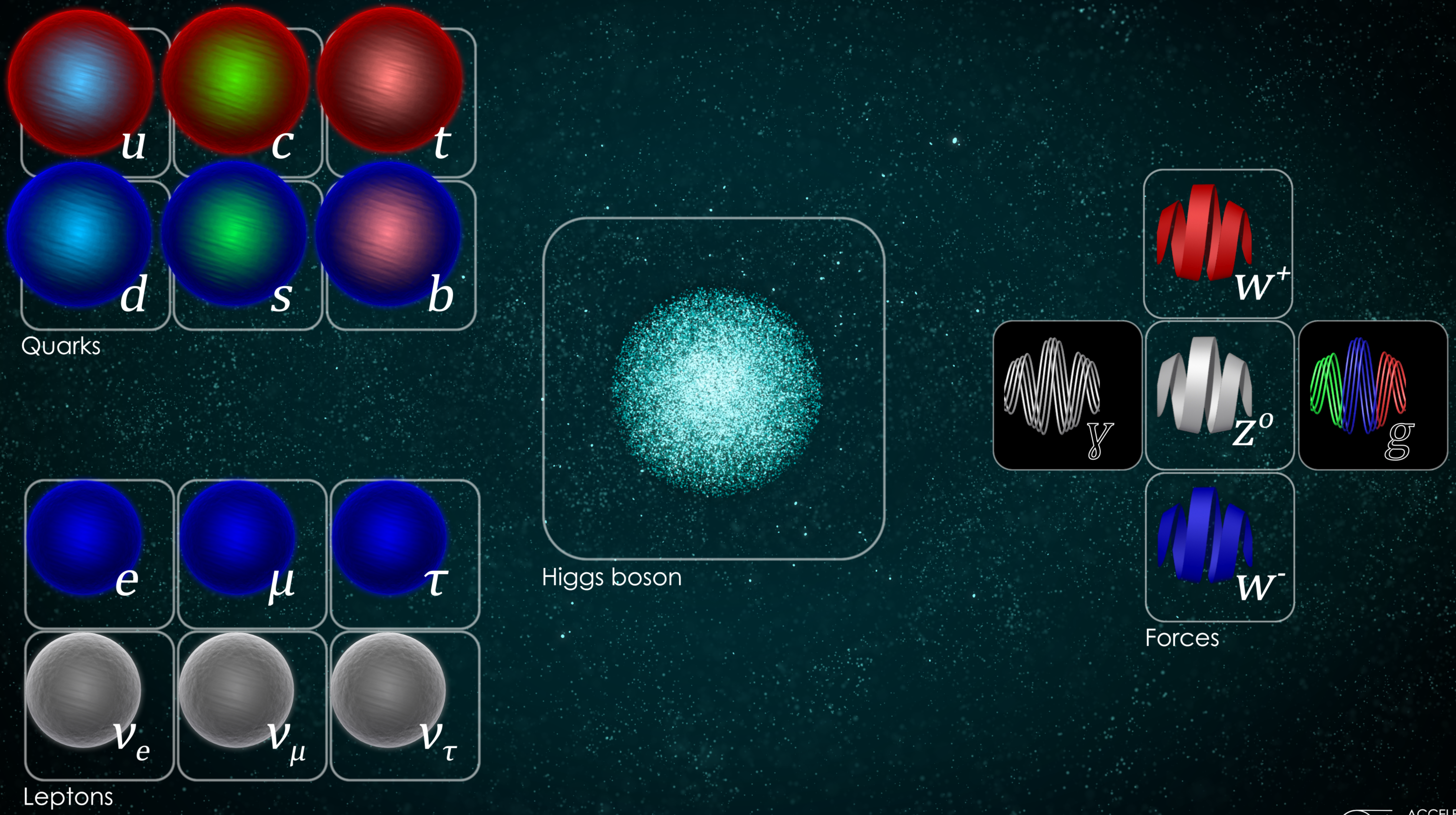
Beyond the Standard Model

of Particle Physics

Alexis Vallier — JRJC 2023

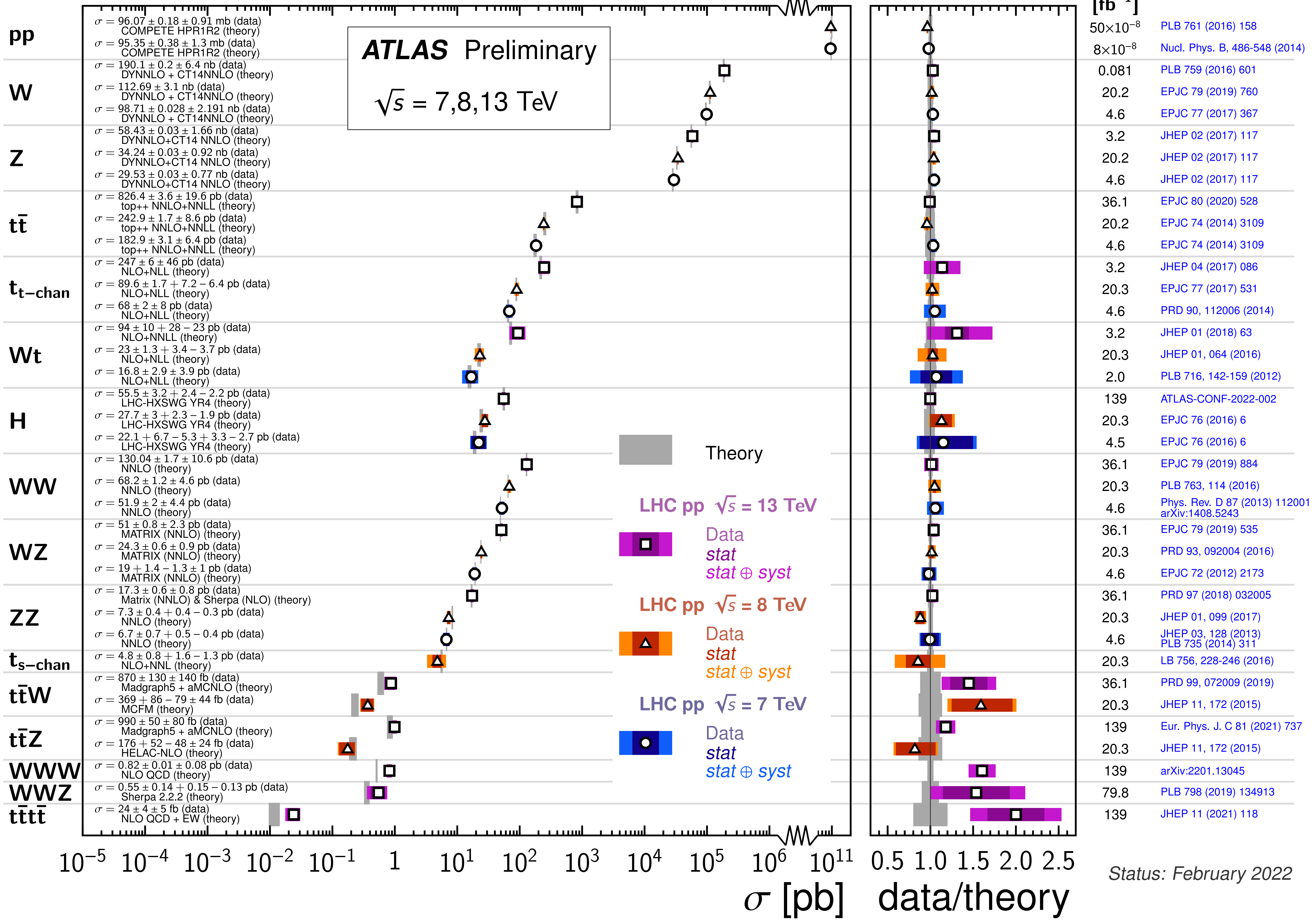
Standard Model Shortcomings

A beautiful $SU(3) \times SU(2) \times U(1)$ theory…



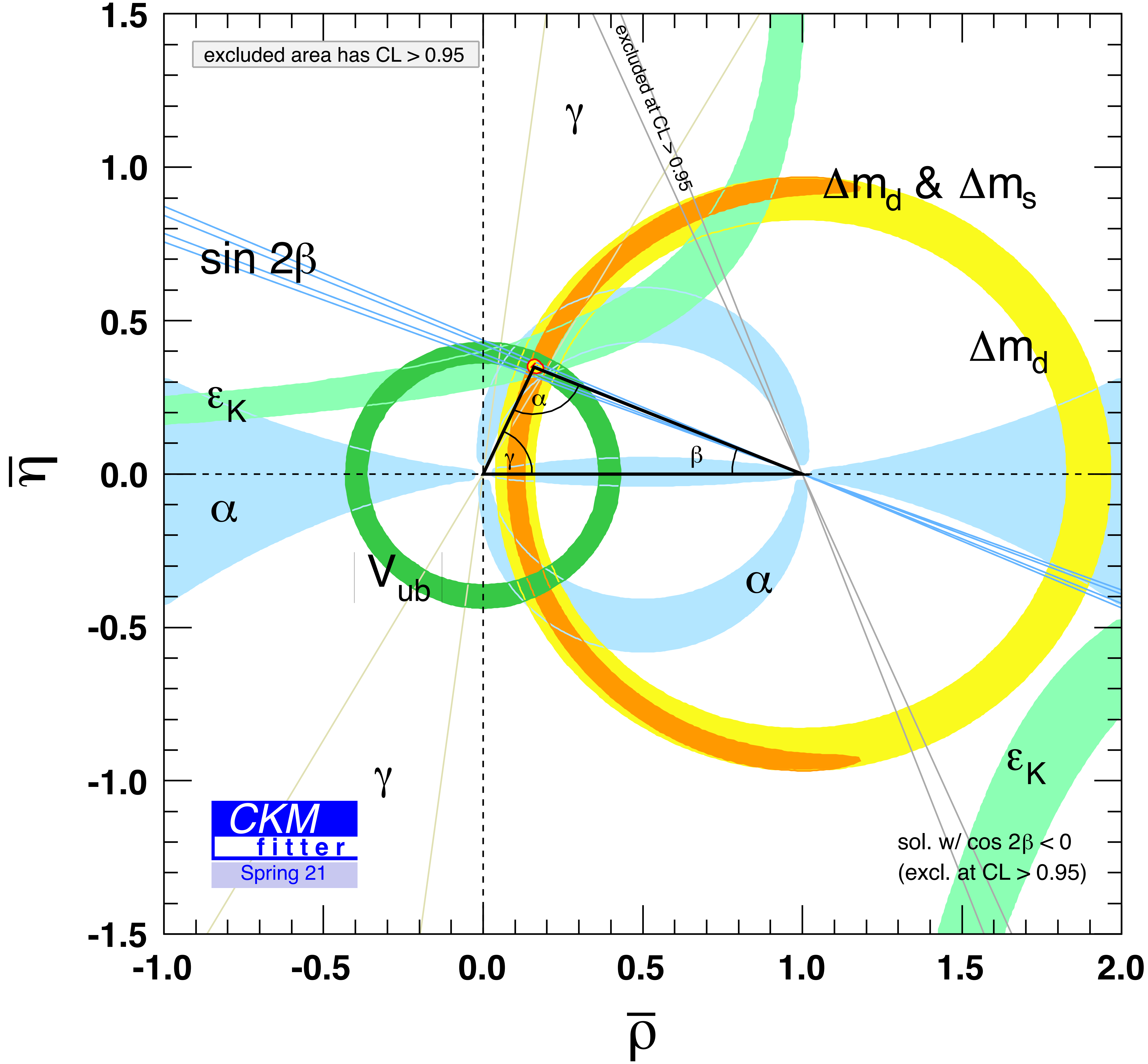
(Image: Daniel Dominguez/CERN)

Standard Model Total Production Cross Section Measurements



			$\int\mathcal{L}\,dt$ [fb^{-1}]	Reference
pp	$\sigma = 96.07 \pm 0.18 \pm 0.91$ mb (data)	COMPETE HPR1R2 (theory)	50×10^{-8}	PLB 761 (2016) 158
	$\sigma = 95.35 \pm 0.38 \pm 1.3$ mb (data)	COMPETE HPR1R2 (theory)	8×10^{-8}	Nucl. Phys. B, 486-548 (2014)
W	$\sigma = 190.1 \pm 0.2 \pm 6.4$ nb (data)	DYNNLO + CT14NNLO (theory)	0.081	PLB 759 (2016) 601
	$\sigma = 112.69 \pm 3.1$ nb (data)	DYNNLO + CT14NNLO (theory)	20.2	EPJC 79 (2019) 760
	$\sigma = 98.71 \pm 0.028 \pm 2.191$ nb (data)	DYNNLO + CT14NNLO (theory)	4.6	EPJC 77 (2017) 367
Z	$\sigma = 58.43 \pm 0.03 \pm 1.66$ nb (data)	DYNNLO+CT14 NNLO (theory)	3.2	JHEP 02 (2017) 117
	$\sigma = 34.24 \pm 0.03 \pm 0.92$ nb (data)	DYNNLO+CT14 NNLO (theory)	20.2	JHEP 02 (2017) 117
	$\sigma = 29.53 \pm 0.03 \pm 0.77$ nb (data)	DYNNLO+CT14 NNLO (theory)	4.6	JHEP 02 (2017) 117
$t\bar{t}$	$\sigma = 826.4 \pm 3.6 \pm 19.6$ pb (data)	top++ NNLO+NNLL (theory)	36.1	EPJC 80 (2020) 528
	$\sigma = 242.9 \pm 1.7 \pm 8.6$ pb (data)	top++ NNLO+NNLL (theory)	20.2	EPJC 74 (2014) 3109
	$\sigma = 182.9 \pm 3.1 \pm 6.4$ pb (data)	top++ NNLO+NNLL (theory)	4.6	EPJC 74 (2014) 3109
$t_{t-\text{chan}}$	$\sigma = 247 \pm 6 \pm 46$ pb (data)	NLO+NLL (theory)	3.2	JHEP 04 (2017) 086
	$\sigma = 89.6 \pm 1.7 + 7.2 - 6.4$ pb (data)	NLO+NLL (theory)	20.3	EPJC 77 (2017) 531
	$\sigma = 68 \pm 2 \pm 8$ pb (data)	NLO+NLL (theory)	4.6	PRD 90, 112006 (2014)
Wt	$\sigma = 94 \pm 10 + 28 - 23$ pb (data)	NLO+NNLL (theory)	3.2	JHEP 01 (2018) 63
	$\sigma = 23 \pm 1.3 + 3.4 - 3.7$ pb (data)	NLO+NLL (theory)	20.3	JHEP 01, 064 (2016)
	$\sigma = 16.8 \pm 2.9 \pm 3.9$ pb (data)	NLO+NLL (theory)	2.0	PLB 716, 142-159 (2012)
H	$\sigma = 55.5 \pm 3.2 + 2.4 - 2.2$ pb (data)	LHC-HXSWG YR4 (theory)	139	ATLAS-CONF-2022-002
	$\sigma = 27.7 \pm 3 + 2.3 - 1.9$ pb (data)	LHC-HXSWG YR4 (theory)	20.3	EPJC 76 (2016) 6
	$\sigma = 22.1 + 6.7 - 5.3 + 3.3 - 2.7$ pb (data)	LHC-HXSWG YR4 (theory)	4.5	EPJC 76 (2016) 6
WW	$\sigma = 130.04 \pm 1.7 \pm 10.6$ pb (data)	NNLO (theory)	36.1	EPJC 79 (2019) 884
	$\sigma = 68.2 \pm 1.2 \pm 4.6$ pb (data)	NNLO (theory)	20.3	PLB 763, 114 (2016)
	$\sigma = 51.9 \pm 2 \pm 4.4$ pb (data)	NNLO (theory)	4.6	Phys. Rev. D 87 (2013) 112001 arXiv:1408.5243
WZ	$\sigma = 51 \pm 0.8 \pm 2.3$ pb (data)	MATRIX (NNLO) (theory)	36.1	EPJC 79 (2019) 535
	$\sigma = 24.3 \pm 0.6 \pm 0.9$ pb (data)	MATRIX (NNLO) (theory)	20.3	PRD 93, 092004 (2016)
	$\sigma = 19 + 1.4 - 1.3 \pm 1$ pb (data)	MATRIX (NNLO) (theory)	4.6	EPJC 72 (2012) 2173
ZZ	$\sigma = 17.3 \pm 0.6 \pm 0.8$ pb (data)	Matrix (NNLO) & Sherpa (NLO) (theory)	36.1	PRD 97 (2018) 032005
	$\sigma = 7.3 \pm 0.4 + 0.4 - 0.3$ pb (data)	NNLO (theory)	20.3	JHEP 01, 099 (2017)
	$\sigma = 6.7 \pm 0.7 + 0.5 - 0.4$ pb (data)	NNLO (theory)	4.6	JHEP 03, 128 (2013) PLB 735 (2014) 311
$t_{s-\text{chan}}$	$\sigma = 4.8 \pm 0.8 + 1.6 - 1.3$ pb (data)	NLO+NNL (theory)	20.3	LB 756, 228-246 (2016)
$t\bar{t}W$	$\sigma = 870 \pm 130 \pm 140$ fb (data)	Madgraph5 + aMCNLO (theory)	36.1	PRD 99, 072009 (2019)
	$\sigma = 369 + 86 - 79 \pm 44$ fb (data)	MCFM (theory)	20.3	JHEP 11, 172 (2015)
$t\bar{t}Z$	$\sigma = 990 \pm 50 \pm 80$ fb (data)	Madgraph5 + aMCNLO (theory)	139	Eur. Phys. J. C 81 (2021) 737
	$\sigma = 176 + 52 - 48 \pm 24$ fb (data)	HELAC-NLO (theory)	20.3	JHEP 11, 172 (2015)
WWW	$\sigma = 0.82 \pm 0.01 \pm 0.08$ pb (data)	NLO QCD (theory)	139	arXiv:2201.13045
WWZ	$\sigma = 0.55 \pm 0.14 + 0.15 - 0.13$ pb (data)	Sherpa 2.2.2 (theory)	79.8	PLB 798 (2019) 134913
$t\bar{t}t\bar{t}$	$\sigma = 24 \pm 4 \pm 5$ fb (data)	NLO QCD + EW (theory)	139	JHEP 11 (2021) 118

Experimentally well verified !



Experimentally well verified !

SM Shortcomings

an overview

- Cosmological/Astrophysical origin
  - Dark matter ?
  - Matter/anti-matter asymmetry ?
  - (Quantum) Gravity ?
  - Inflation ?
  - Cosmological constant problem
    - $\Lambda << $ Zero-point Energy (vacuum energy predicted by QFT), 50 to 120 order of mag.

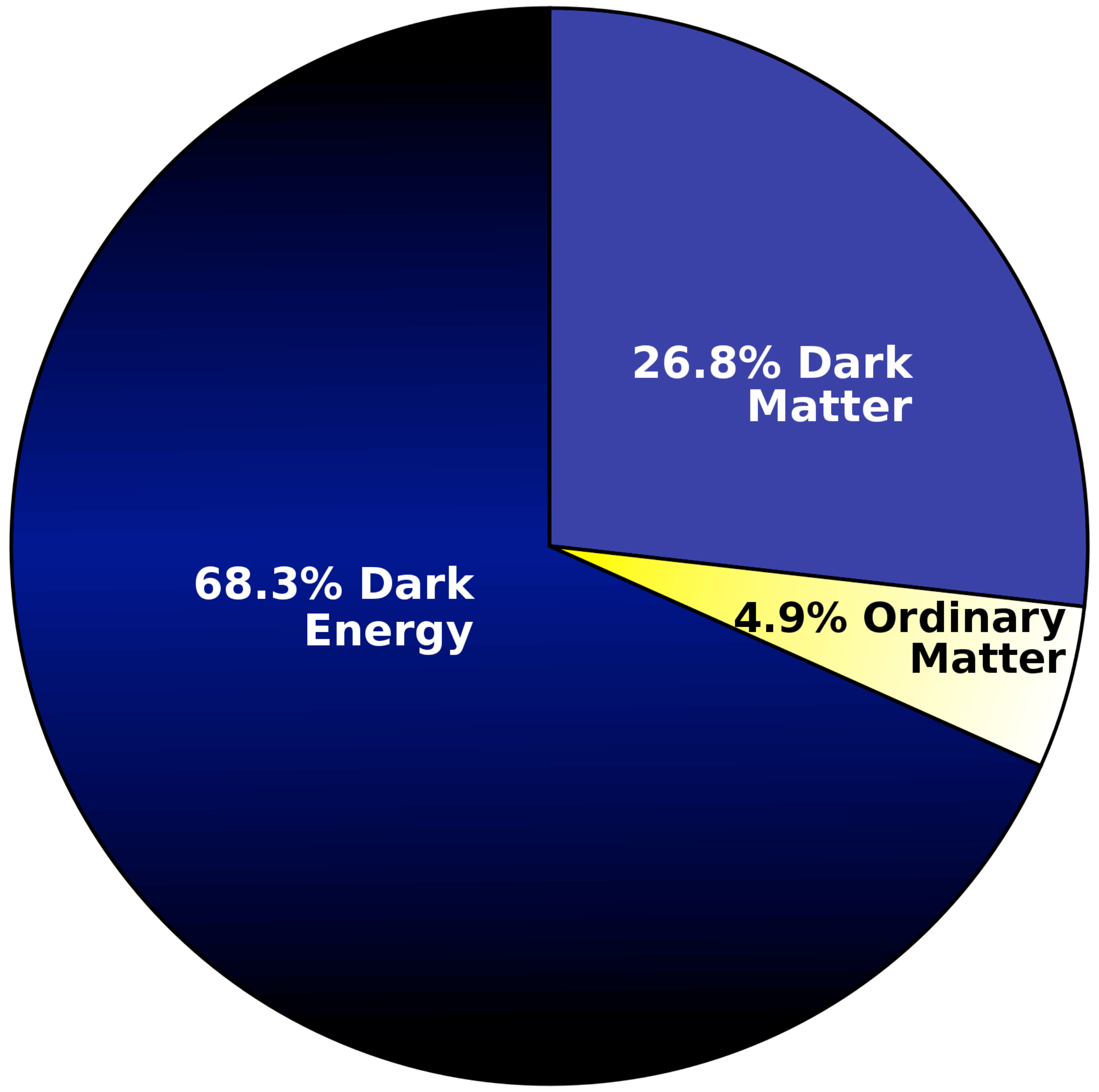
- Theoretical origin
  - Hierarchy problem
  - Why 3 families/flavours ?
  - Neutrino masses ?
  - Vacuum stability

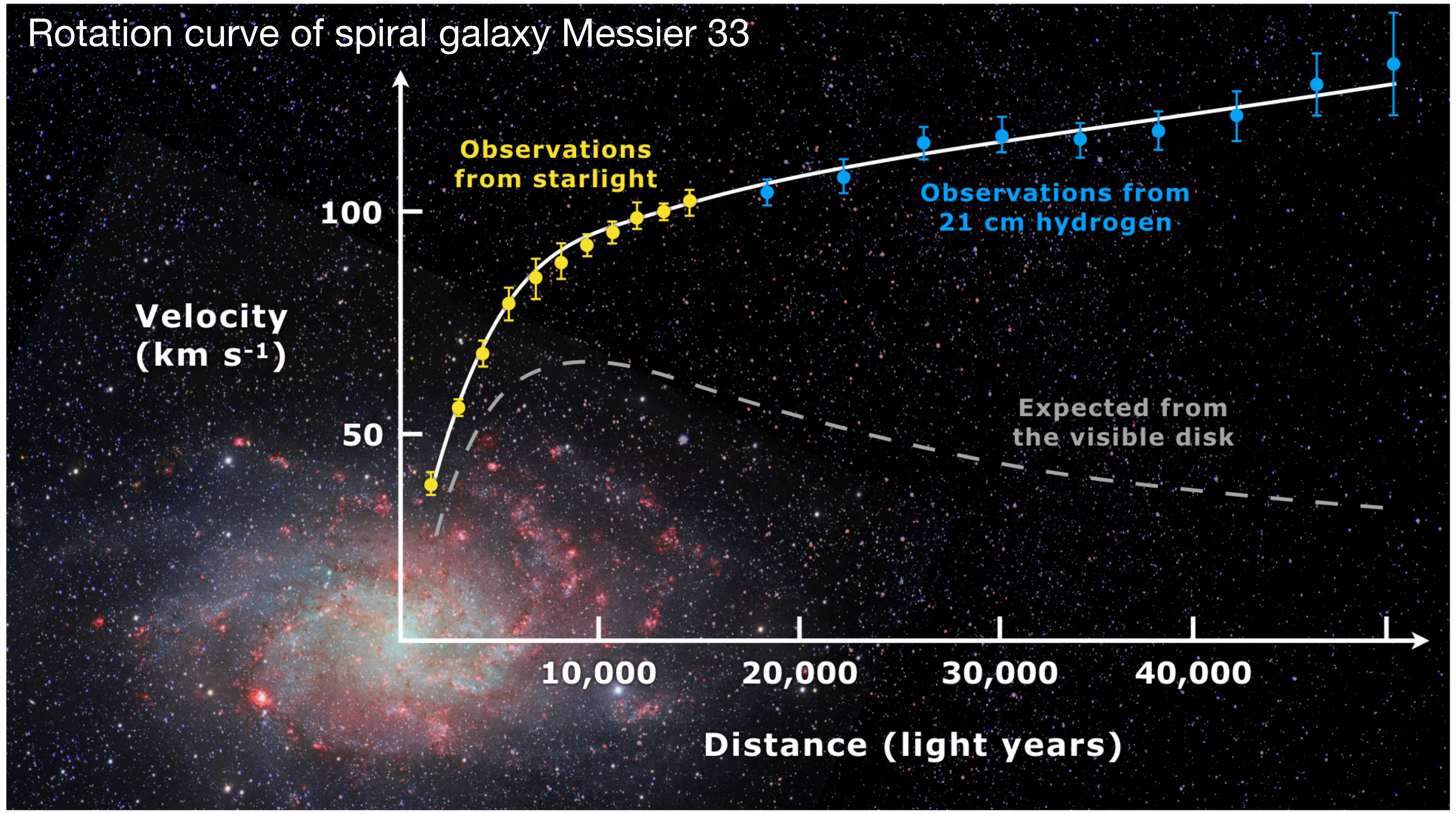
SM cannot explain our universe and has some internal lacks

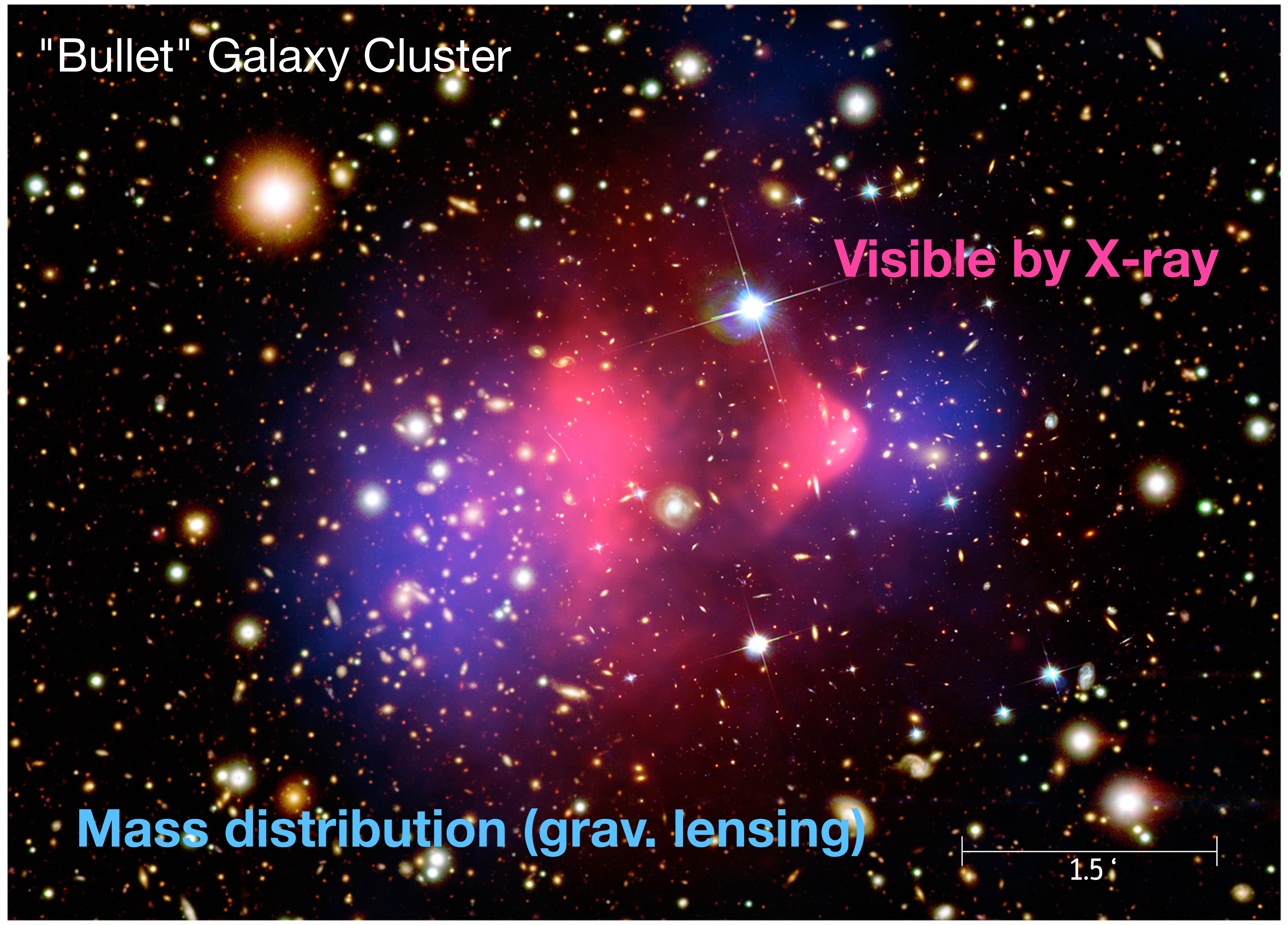
→ We need Physics Beyond the Standard Model

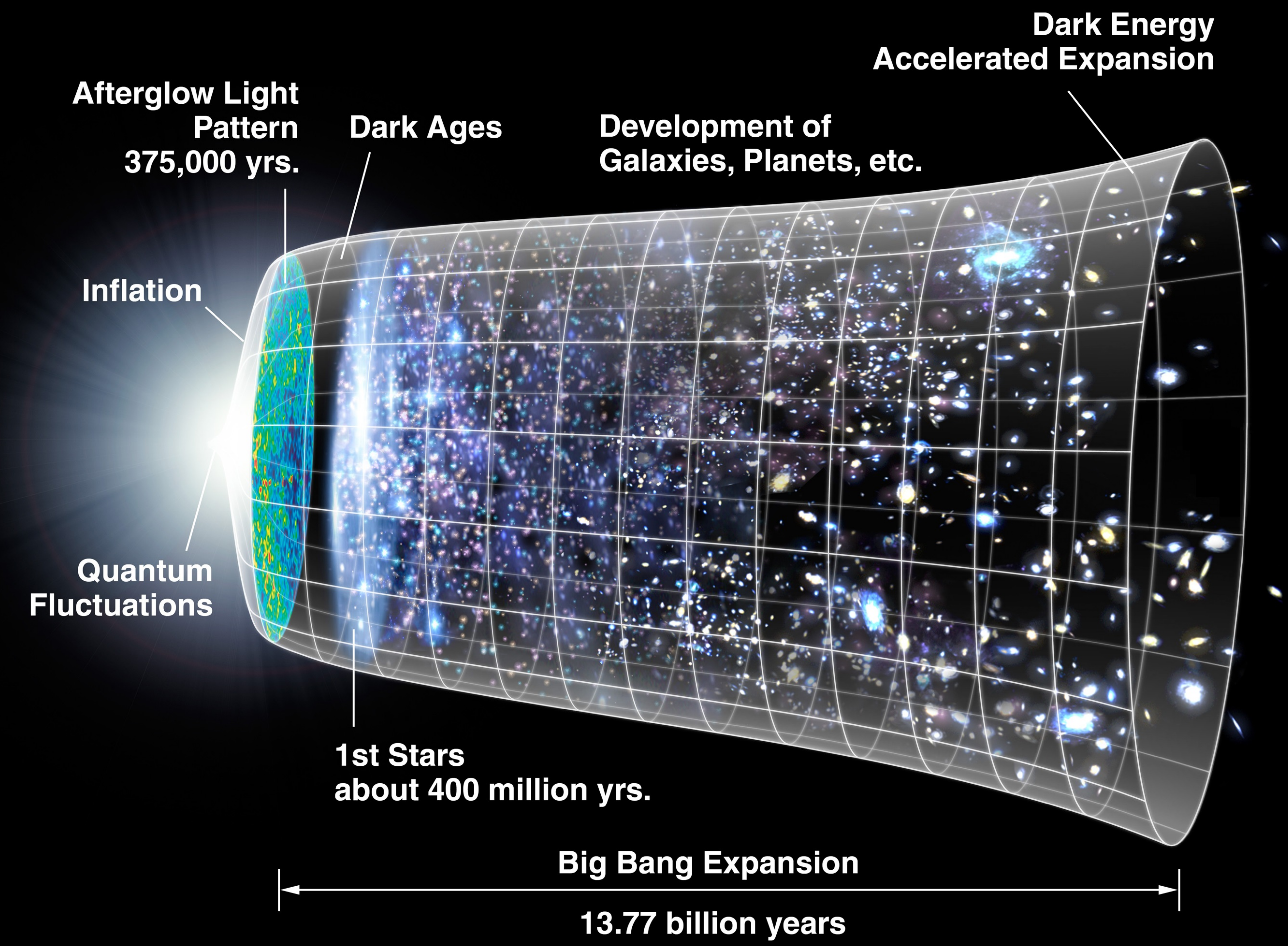
Dark Matter

- DM clear evidences in astrophysics
  - Gravitational observations cannot be explained with known visible matter
- SM provides no DM candidate !
- DM = 85% of the universe matter content









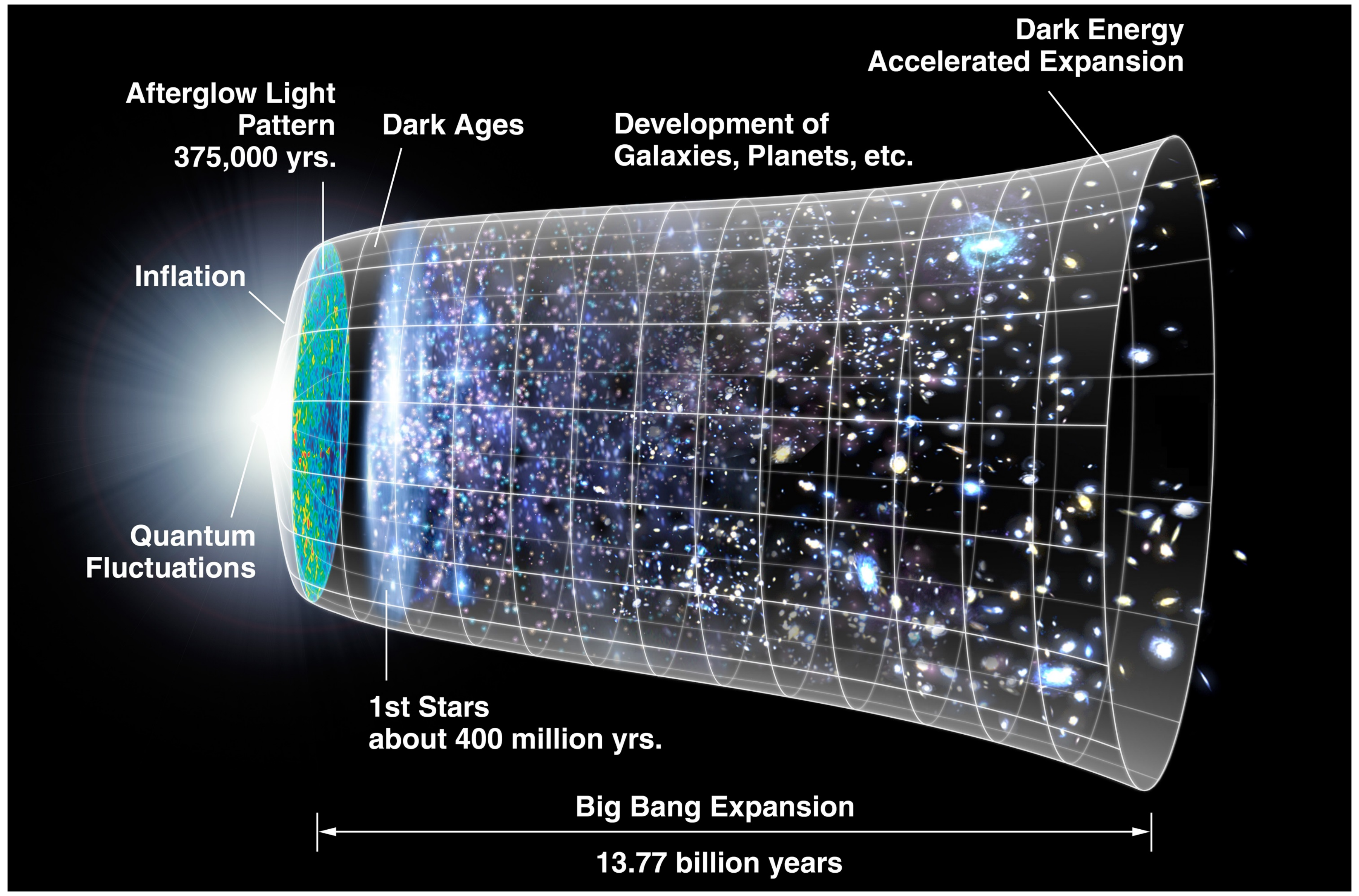
Where does inflation comes from?

What is the dark energy?

Do they come from new scalar fields?

Matter / Antimatter

Where has all antimatter disappeared?



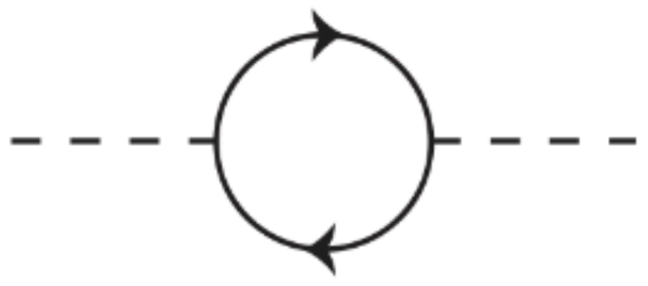
- Big Bang: **equal amounts of Matter & Antimatter**
- But we lived in a **universe entirely made of matter**
- One common explanation of Baryon asymmetry: Sakharov conditions
    1. Baryon Number Violation (generate an excess of Baryons)
    2. **C and CP violations (process producing more B won’t be counter balance by anti-process)**
    3. Interactions out of thermal equilibrium (otherwise produce excess will vanish by CPT invariance)
- But **observed CP violation** in CKM matrix **much too small**!

Hierarchy problem

Why the Higgs boson mass is so small?

$$m_H^2 = \boxed{m_0^2} + \boxed{\Delta m_H^2}$$

Bare mass Radiative corrections



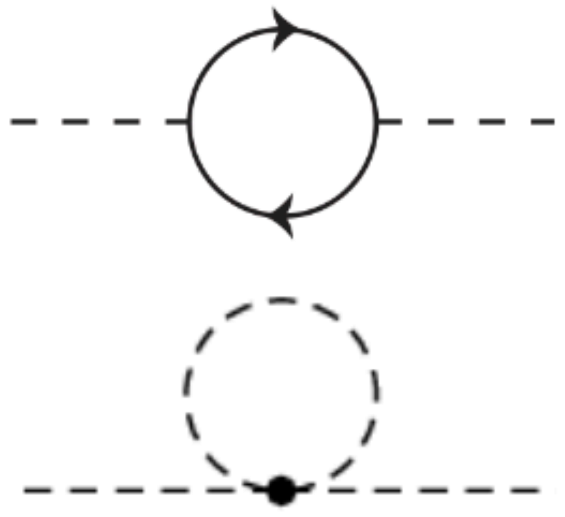
$$\Delta m_H^2 = -\frac{{y_f}^2}{16\pi^2}\left[\boxed{2\Lambda^2} + 6m_f^2\ln(\Lambda/m_f) + ...\right]$$

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}\left[\boxed{\Lambda^2} - 2m_S^2\ln(\Lambda/m_S) + ...\right]$$

- Loop corrections to Higgs boson mass are divergent (quadratic)
  - Because it is a scalar (fermions masses are protected)
- Fine-tuning: very accurate cancellation to keep m_H close to the EW scale
  - Very unatural

How to solve these Standard Model shortcomings?

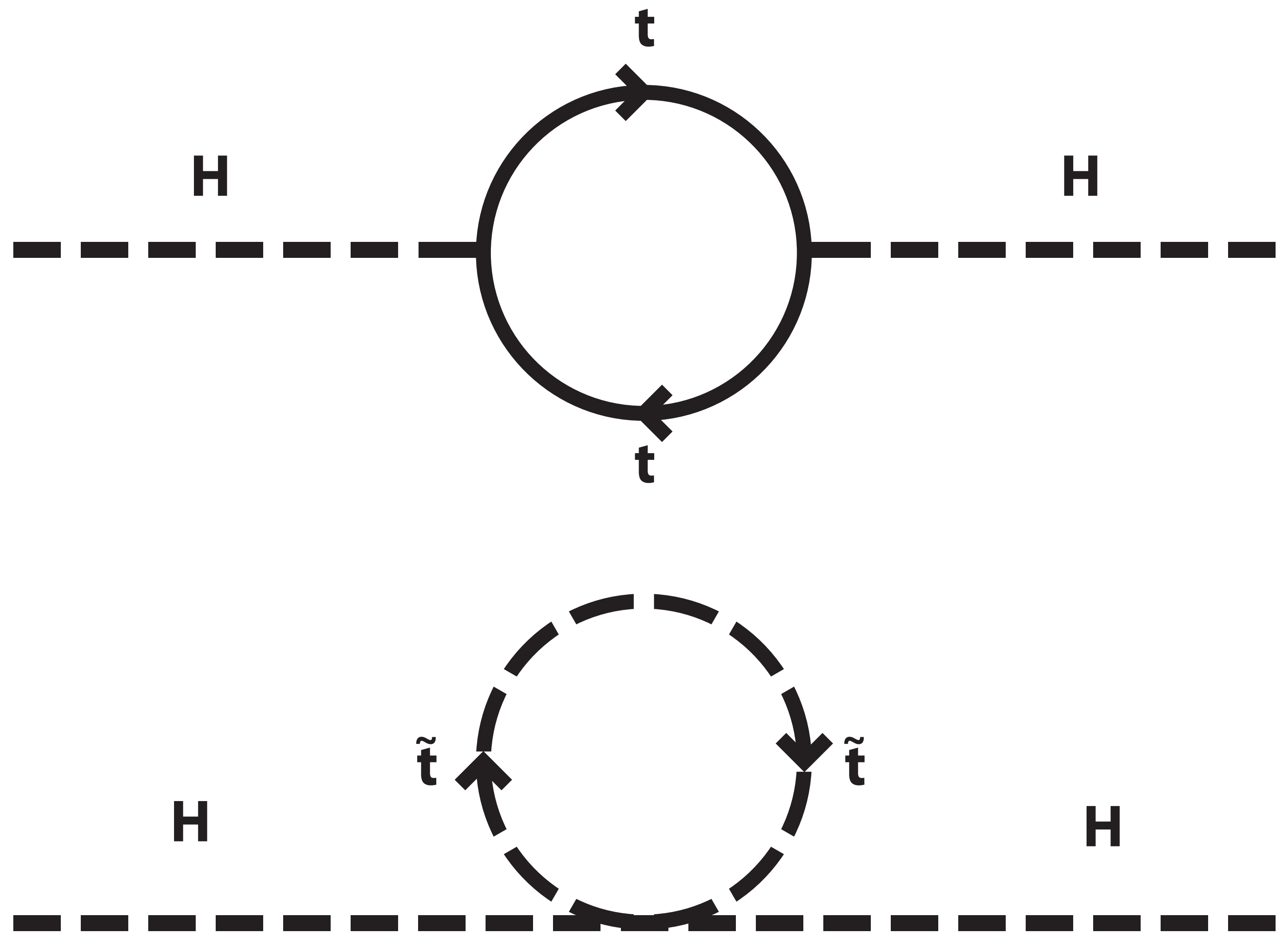
Super Symmetry



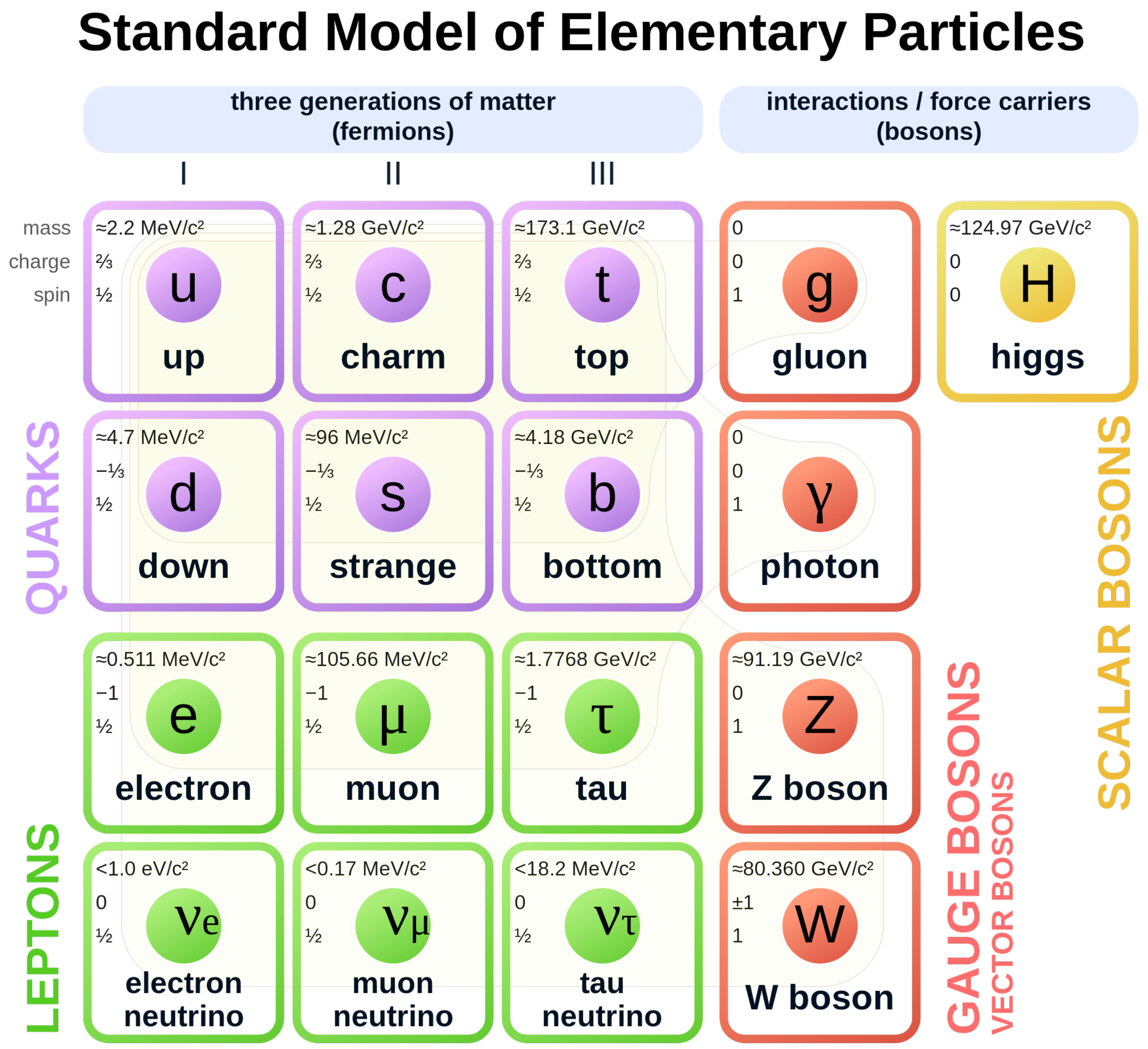
$$\Delta m_H^2 = -\frac{{y_f}^2}{16\pi^2}[2\Lambda^2 + 6m_f^2 \ln(\Lambda/m_f) + ...]$$

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}[\Lambda^2 - 2m_S^2 \ln(\Lambda/m_S) + ...]$$

- Impose space-time symmetry between bosons and fermions
  - Each boson (fermion) has its supersymmetric fermion (boson) partner
- Automatic cancellation of divergences
- Provide interesting candidates for new particles
  - Dark matter candidates?

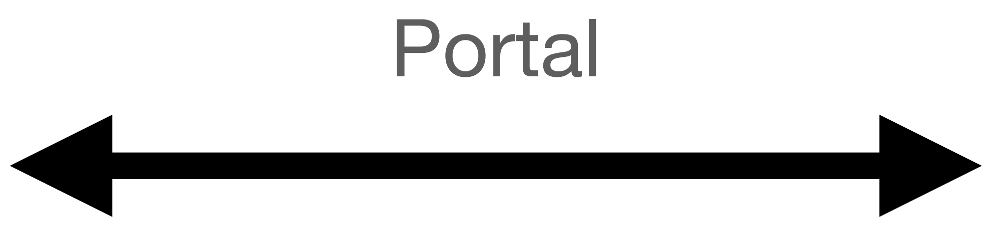


Dark sector



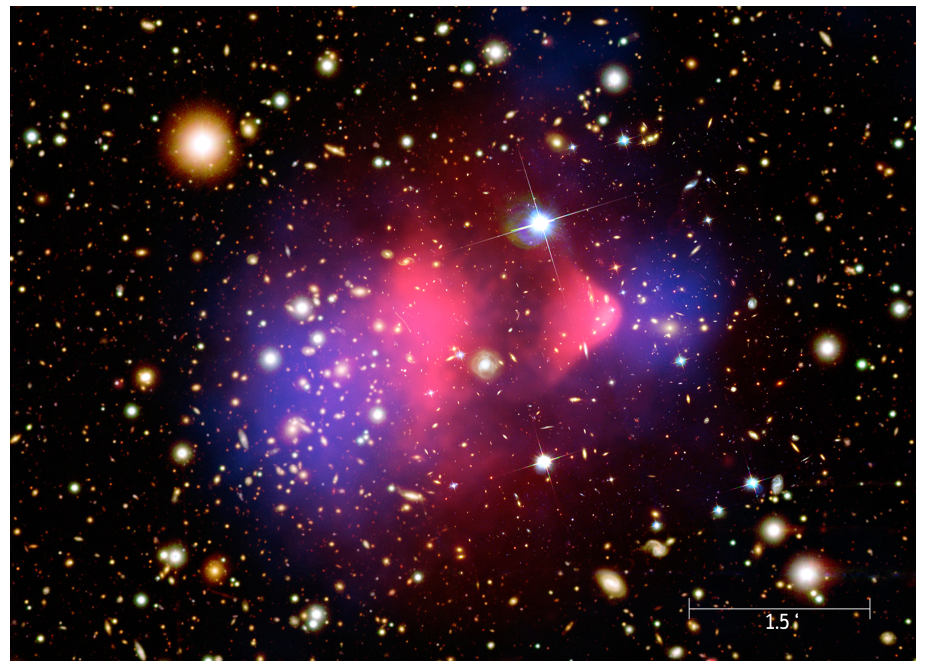
Standard Model of Elementary Particles

	three generations of matter (fermions) I	II	III	interactions / force carriers (bosons)	
mass charge spin					
QUARKS	≈2.2 MeV/c² ⅔ ½ u up	≈1.28 GeV/c² ⅔ ½ c charm	≈173.1 GeV/c² ⅔ ½ t top	0 0 1 g gluon	≈124.97 GeV/c² 0 0 H higgs
QUARKS	≈4.7 MeV/c² −⅓ ½ d down	≈96 MeV/c² −⅓ ½ s strange	≈4.18 GeV/c² −⅓ ½ b bottom	0 0 1 γ photon	SCALAR BOSONS
LEPTONS	≈0.511 MeV/c² −1 ½ e electron	≈105.66 MeV/c² −1 ½ μ muon	≈1.7768 GeV/c² −1 ½ τ tau	≈91.19 GeV/c² 0 1 Z Z boson	
LEPTONS	<1.0 eV/c² 0 ½ ν_e electron neutrino	<0.17 MeV/c² 0 ½ ν_μ muon neutrino	<18.2 MeV/c² 0 ½ ν_τ tau neutrino	≈80.360 GeV/c² ±1 1 W W boson	GAUGE BOSONS VECTOR BOSONS



Portal

Dark or Hidden Sector

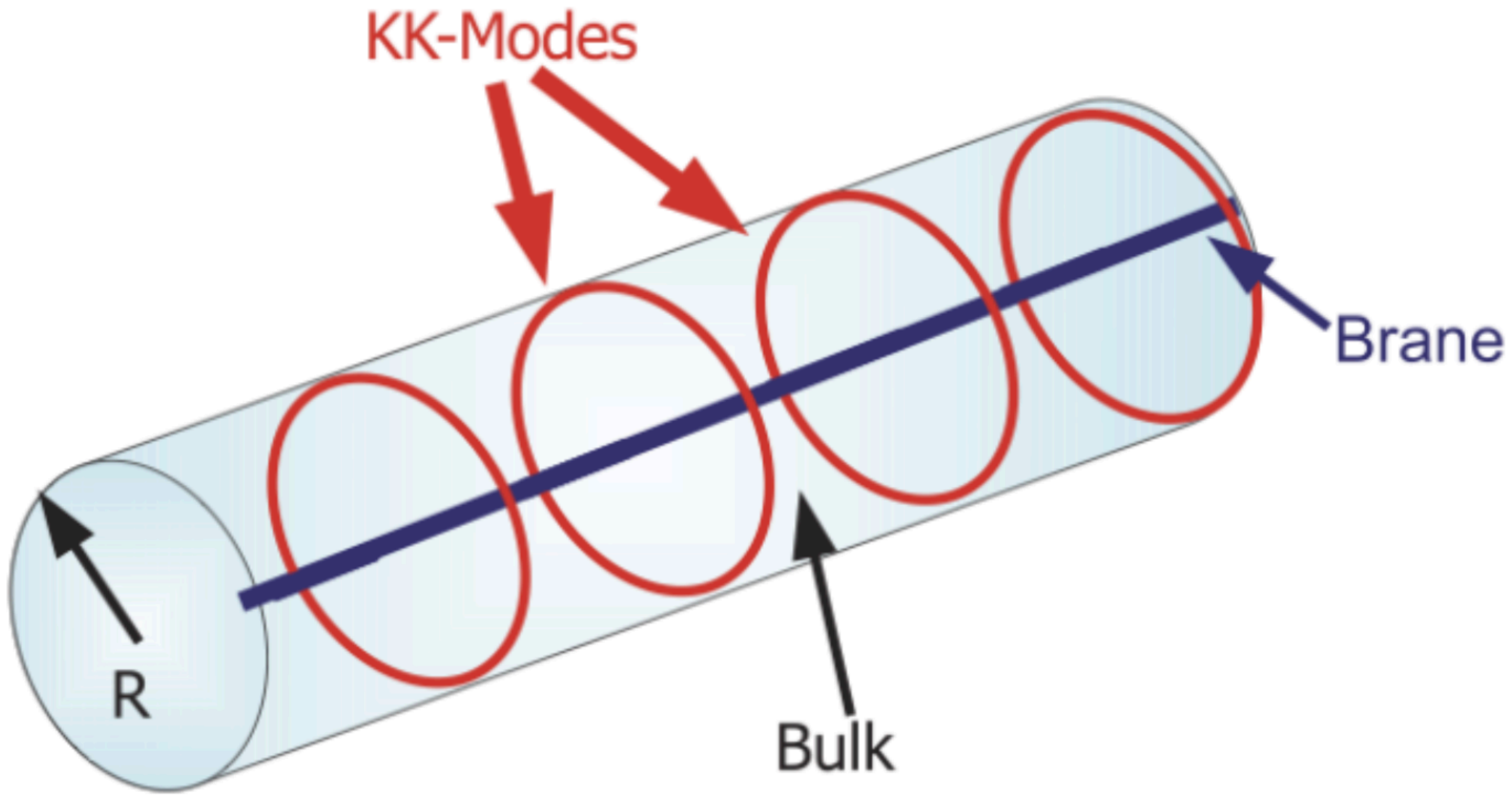


New Gauge group with particles interacting weakly with SM

- DM candidates in independent Gauge Group
- Interact weakly to SM, indirectly or via gravity
    - Eg: Dark photon, sterile neutrinos, Axions, 2HDM…
- Usually at LHC search for simplified models: one DM particle and one mediator (or a few)
- If Dark sector weakly coupled to SM: can be long-lived (unconventional signatures)

Graviton

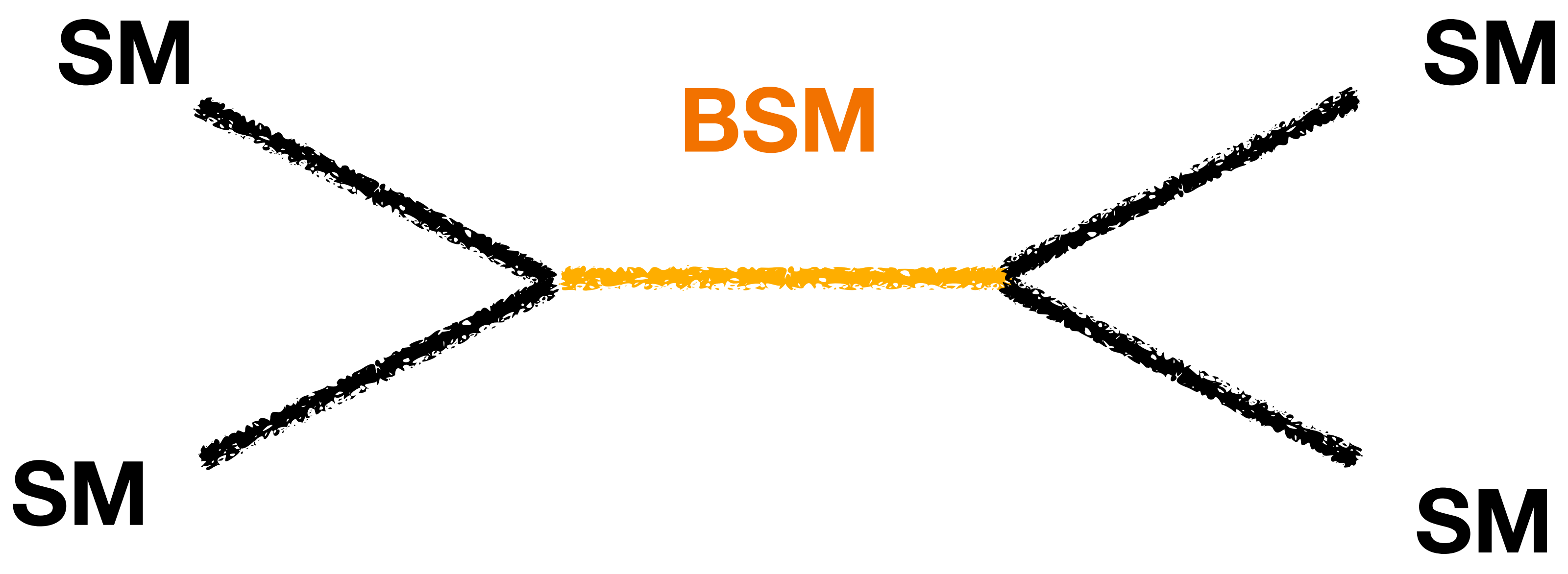
- Several models try to include gravity with extra dimensions
  - Based on Kaluza-Klein Tower
  - SM in (3+1)D, gravitation in all dimensions
  - Could explain why EW scale << M_{planck}



How to search for BSM physics?

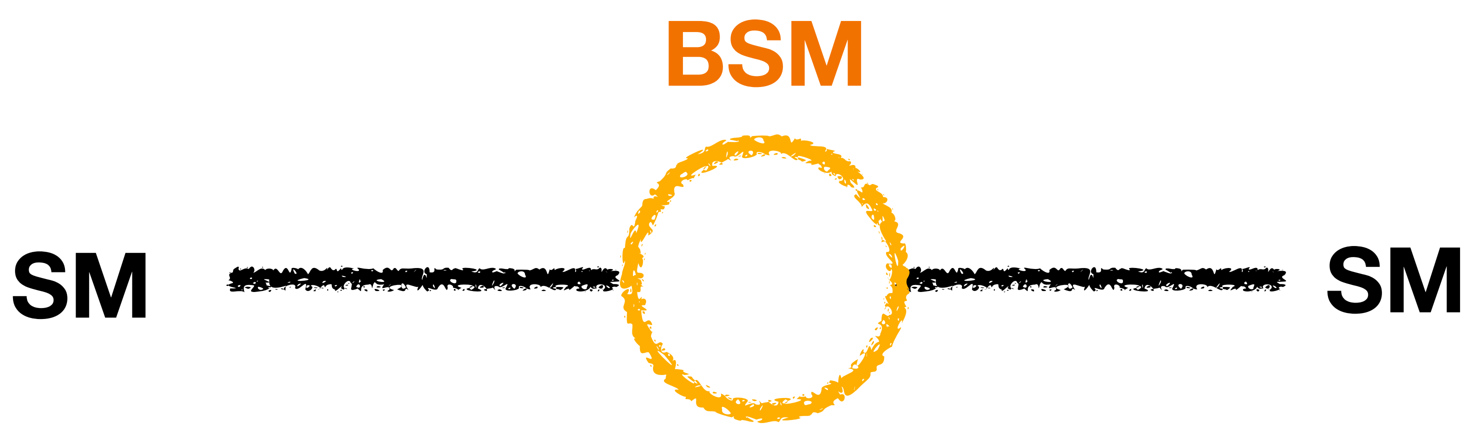
Direct vs Indirect searches

Relativistic Path



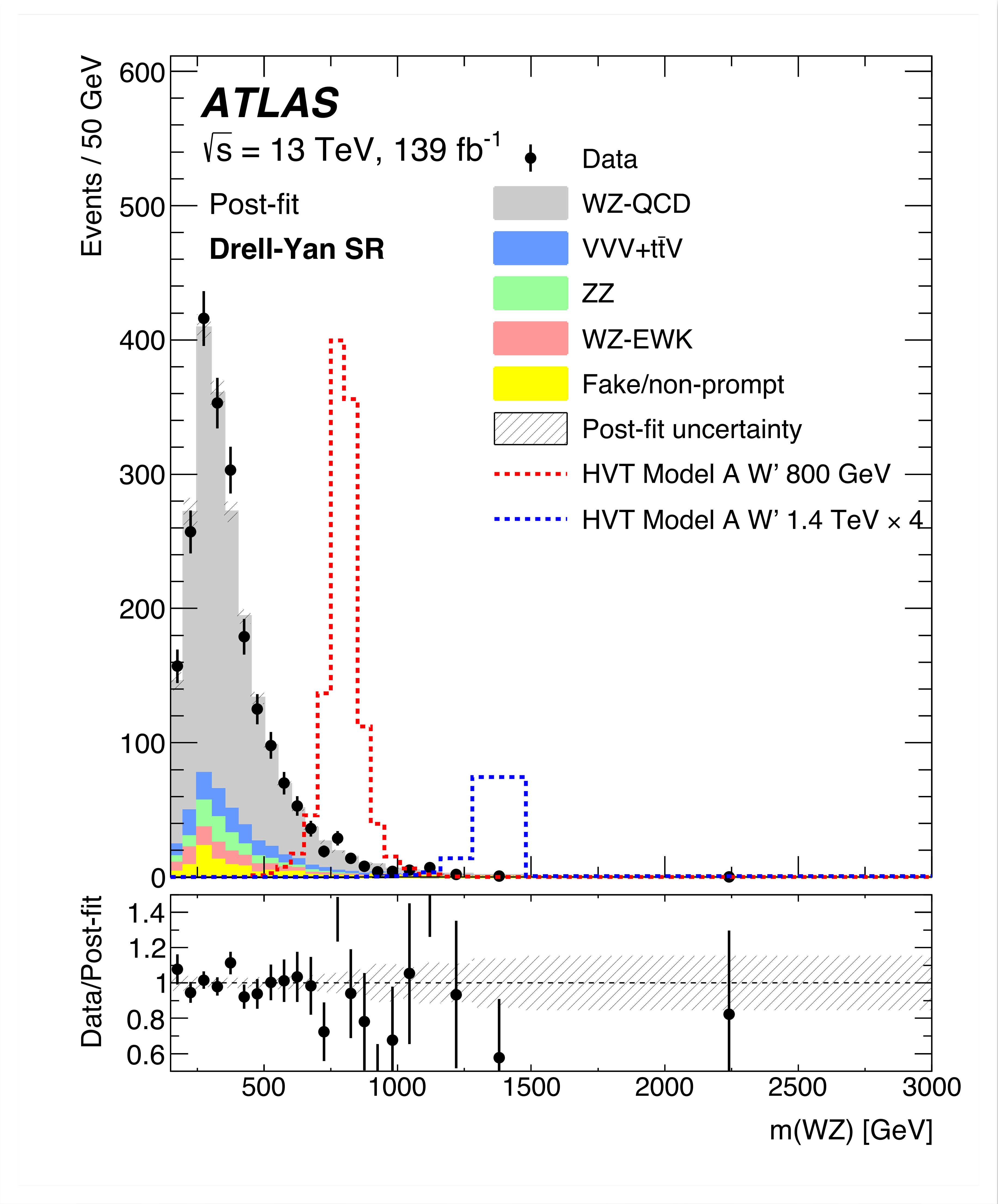
- Direct detection of new resonances or particles
- Need enough energy to produce it

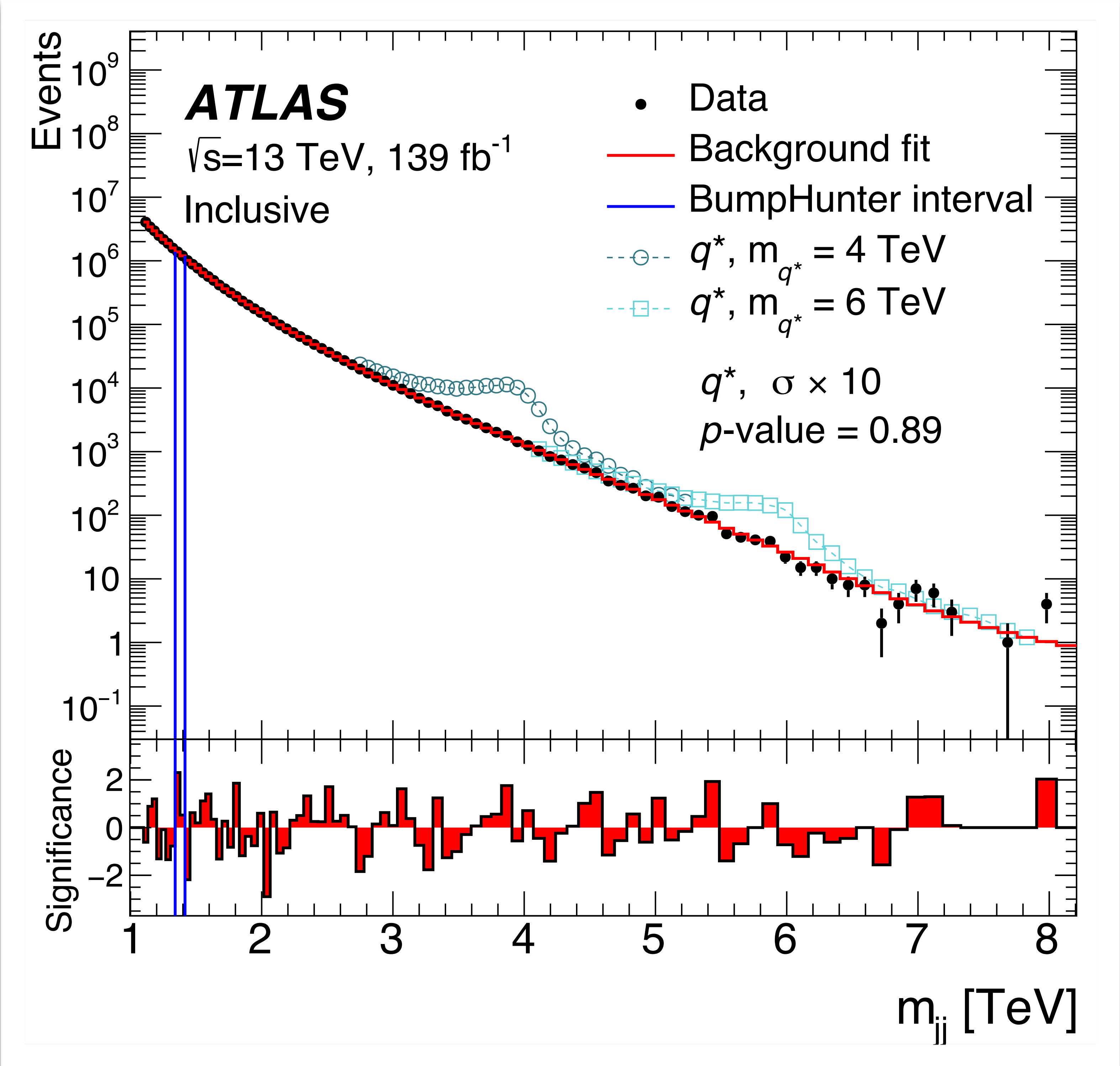
Quantum Path



- Search for small deviation from SM predictions
- Reach energy scales higher than colliding energy
- Need enough statistics to have high precision (and precise SM predictions)

Search for resonances





- Look for new states decaying to SM particles:
  - dijets, dileptons, dibosons
- Usually look a excess over SM predictions
  - « Bump » in Mass spectrum
  - Data driven-bkg prediction or Monte-Carlo based

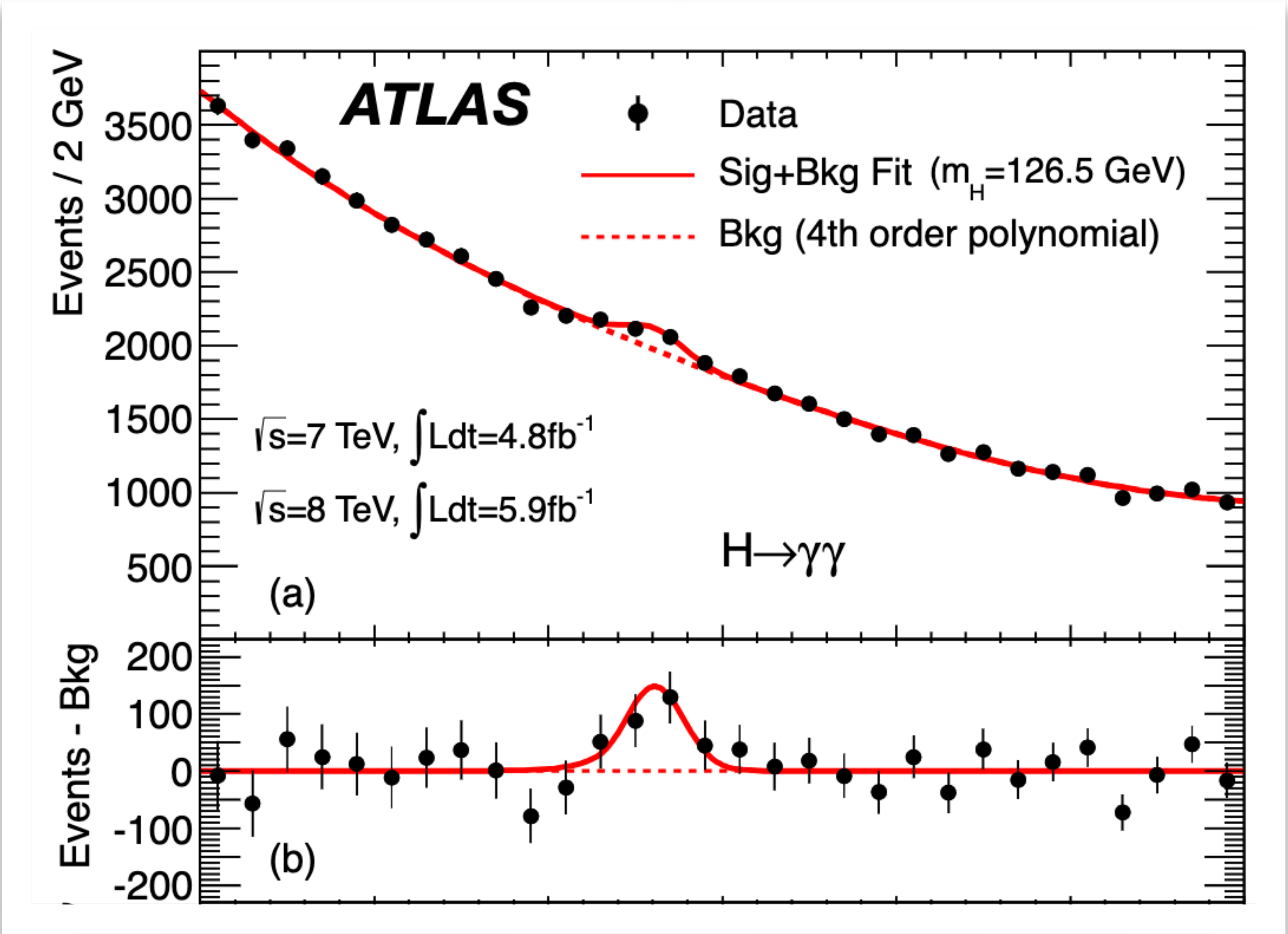
Significance

- Likelihood ratio:

$$\lambda(\mu_0) = -2\log\frac{\boxed{\mathcal{L}(\mu_0,\hat{\hat{\theta}}_{\mu_0})}}{\boxed{\mathcal{L}(\hat{\mu},\hat{\theta})}}.$$

Conditional fit: fix μ=μ0

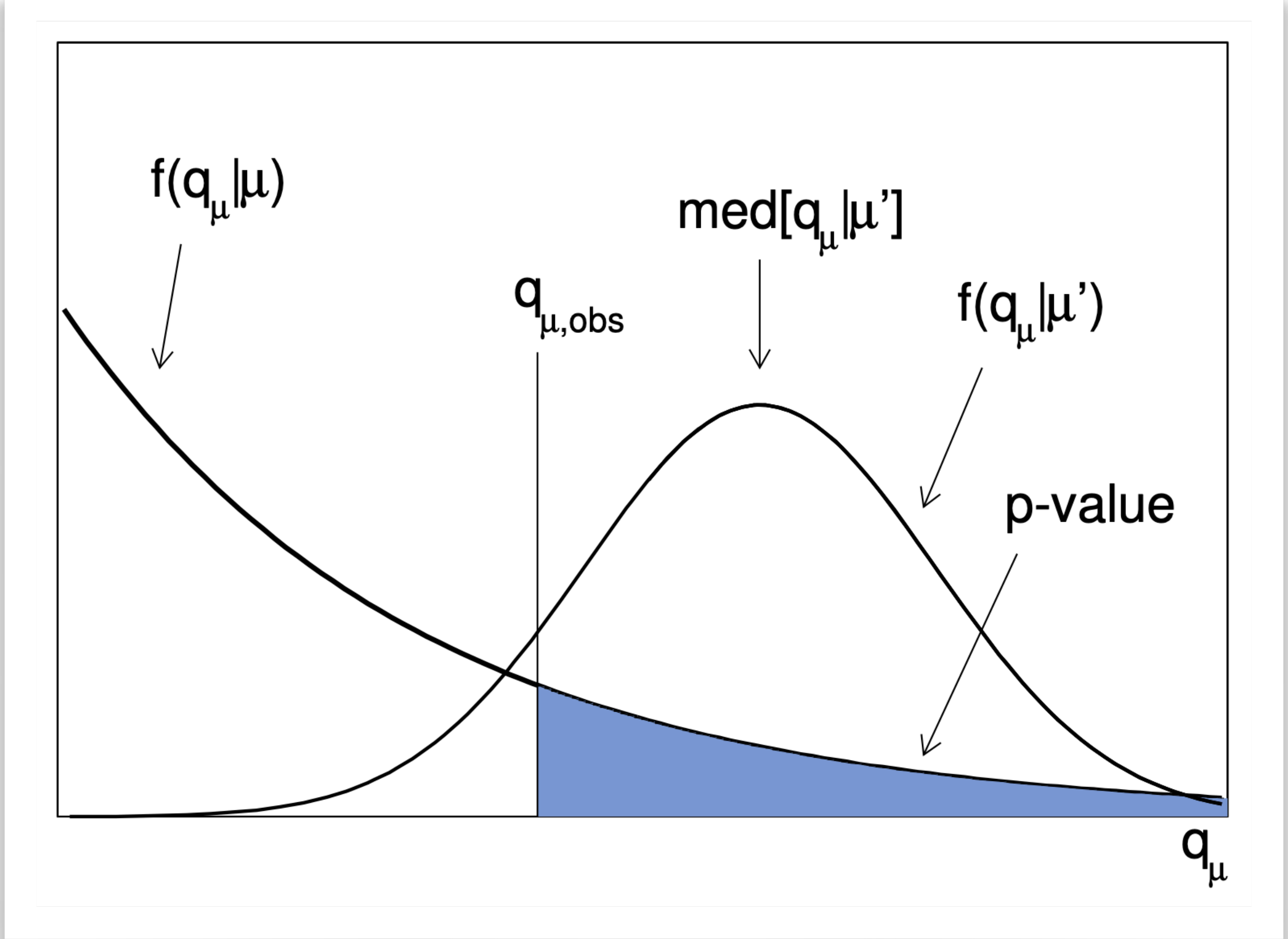
Best Fit

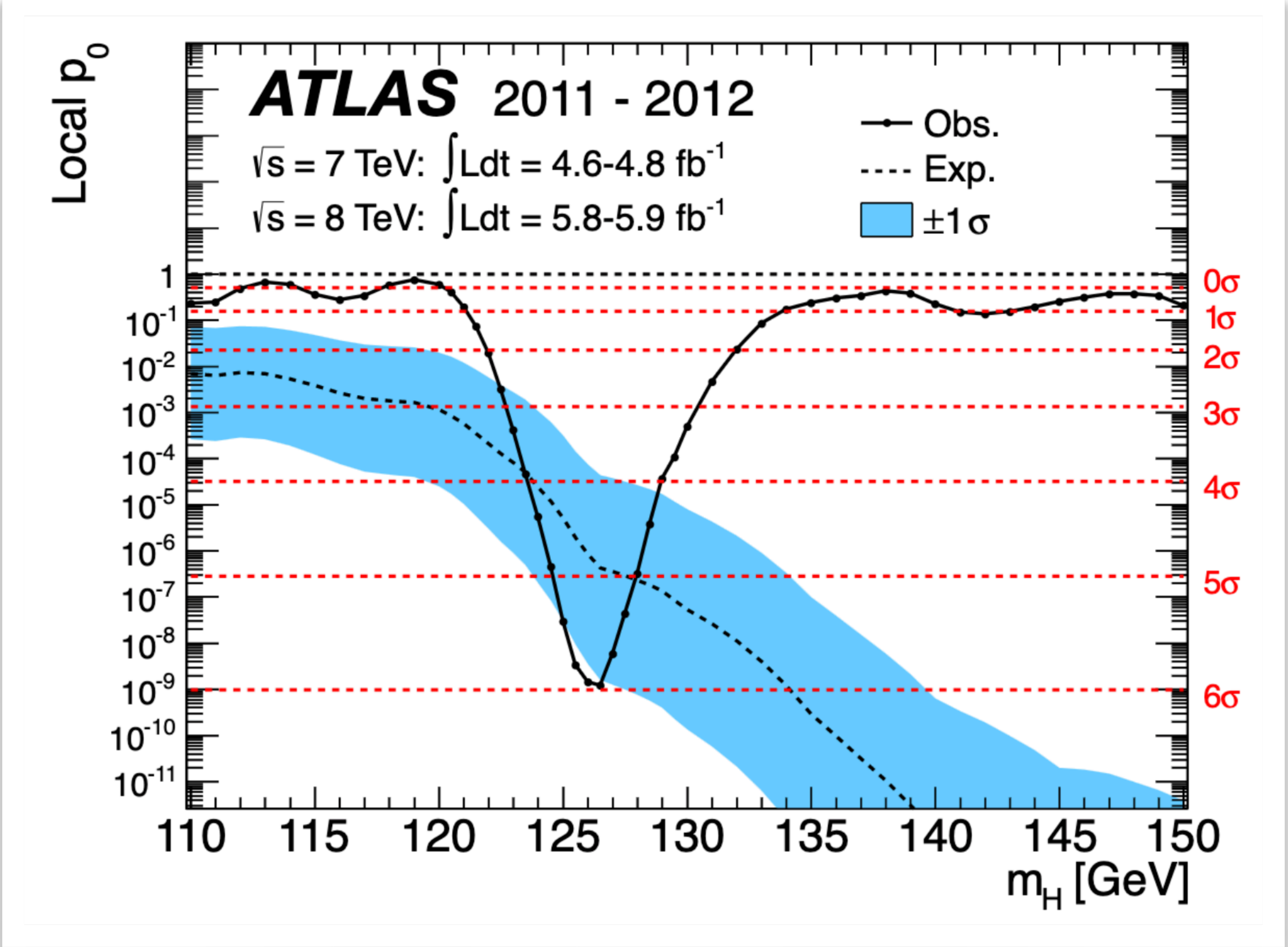


- Test compatibility of data with Background only (B-only) hypothesis (μ0=0) :

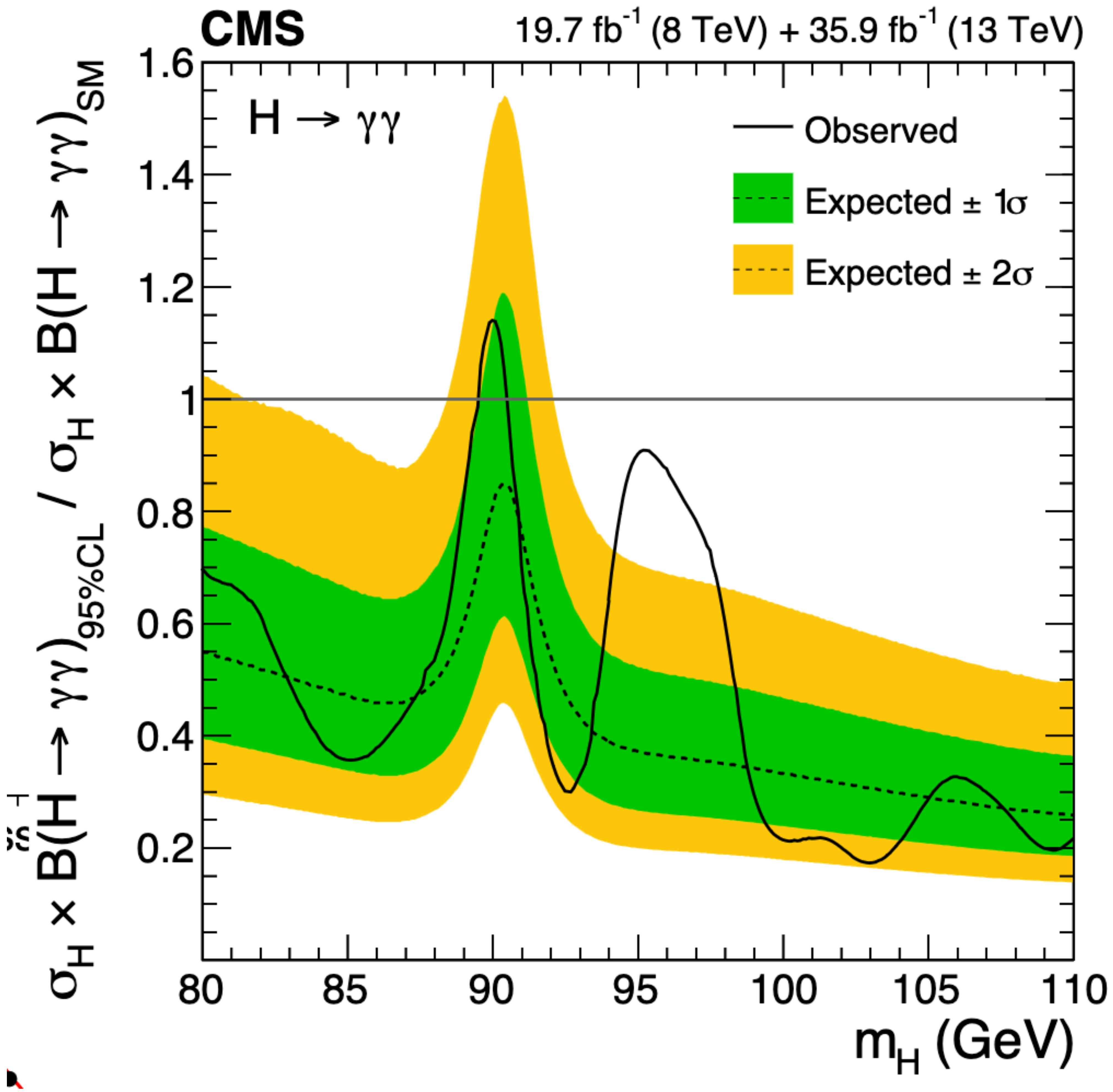
$$t_0^{\text{uncap}} = \begin{cases} +\lambda(0) & \hat{\mu} \geq 0 \\ -\lambda(0) & \hat{\mu} < 0. \end{cases}$$

- Compute p-value and convert it in significance





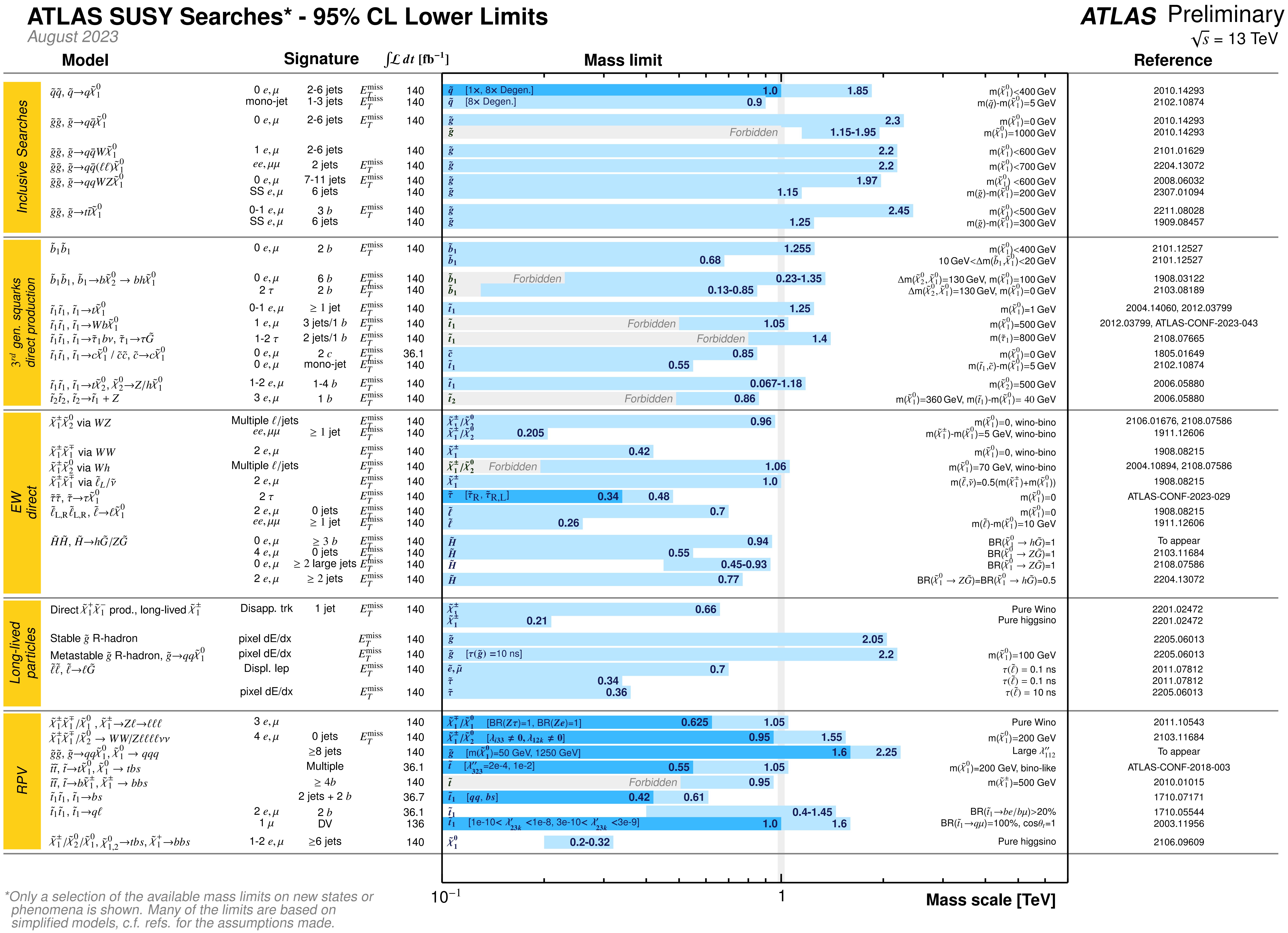
Cross-section upper limit



- If no excess observed, set upper limits on cross-section:
  - If the signal exist in nature, its cross-section should be lower
- Look for μ_0 for which p-value=5%

$$\tilde{q}_{\mu_0} = \begin{cases} \lambda(\mu_0) & 0 \leq \hat{\mu} \leq \mu_0 \\ -2\log \frac{L(\mu=\mu_0,\hat{\theta}_{\mu=\mu_0})}{L(\mu=0,\hat{\theta}_{\mu=0})} & \hat{\mu} < 0 \\ 0 & \hat{\mu} > \mu_0 \end{cases}$$

- Expected = B-only hypothesis average (and +/- 1 or 2 sigma deviation from average expectation)


ATLAS SUSY Searches* - 95% CL Lower Limits

August 2023

ATLAS Preliminary

$\sqrt{s}$ = 13 TeV

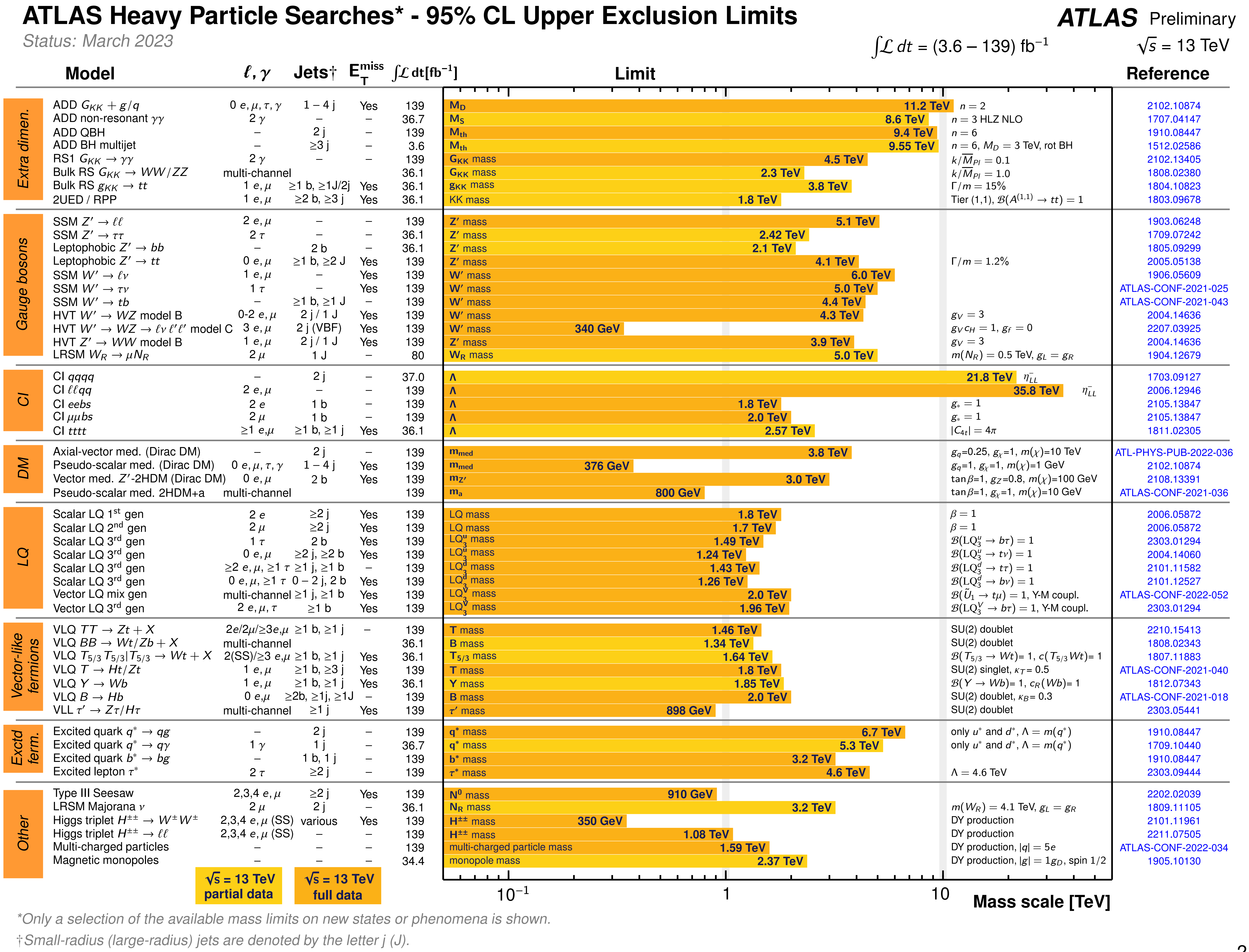
	Model	Signature			$\int\mathcal{L}\,dt$ [fb^{-1}]	Mass limit			Reference
Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0 e,μ	2-6 jets	$E_T^{\rm miss}$	140	$\tilde{q}$ [1×, 8× Degen.]	1.0 / 1.85	m($\tilde{\chi}_1^0$)<400 GeV	2010.14293
		mono-jet	1-3 jets	$E_T^{\rm miss}$	140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

Up to now, no sign of SUSY!

Tested with a multitude of signatures

No sign of new & heavy particles…



ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

Status: March 2023

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.6 - 139)\ \mathrm{fb}^{-1}$

$\sqrt{s} = 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimen.	ADD $G_{KK} + g/q$	0 e, μ, τ, γ	1 – 4 j	Yes	139	M_D 11.2 TeV	$n = 2$	2102.10874
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	139	M_{th} 9.4 TeV	$n = 6$	1910.08447
	ADD BH multijet	–	≥3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2 γ	–	–	139	G_{KK} mass 4.5 TeV	$k/\overline{M}_{Pl} = 0.1$	2102.13405
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel			36.1	G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	1808.02380
	Bulk RS $g_{KK} \rightarrow tt$	1 e, μ	≥1 b, ≥1J/2j	Yes	36.1	g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	1 e, μ	≥2 b, ≥3 j	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \rightarrow tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	2 e, μ	–	–	139	Z' mass 5.1 TeV		1903.06248
	SSM $Z' \rightarrow \tau\tau$	2 τ	–	–	36.1	Z' mass 2.42 TeV		1709.07242
	Leptophobic $Z' \rightarrow bb$	–	2 b	–	36.1	Z' mass 2.1 TeV		1805.09299
	Leptophobic $Z' \rightarrow tt$	0 e, μ	≥1 b, ≥2 J	Yes	139	Z' mass 4.1 TeV	$\Gamma/m = 1.2\%$	2005.05138
	SSM $W' \rightarrow \ell\nu$	1 e, μ	–	Yes	139	W' mass 6.0 TeV		1906.05609
	SSM $W' \rightarrow \tau\nu$	1 τ	–	Yes	139	W' mass 5.0 TeV		ATLAS-CONF-2021-025
	SSM $W' \rightarrow tb$	–	≥1 b, ≥1 J	–	139	W' mass 4.4 TeV		ATLAS-CONF-2021-043
	HVT $W' \rightarrow WZ$ model B	0-2 e, μ	2 j / 1 J	Yes	139	W' mass 4.3 TeV	$g_V = 3$	2004.14636
	HVT $W' \rightarrow WZ \rightarrow \ell\nu\, \ell'\ell'$ model C	3 e, μ	2 j (VBF)	Yes	139	W' mass 340 GeV	$g_V c_H = 1$, $g_f = 0$	2207.03925
	HVT $Z' \rightarrow WW$ model B	1 e, μ	2 j / 1 J	Yes	139	Z' mass 3.9 TeV	$g_V = 3$	2004.14636
	LRSM $W_R \rightarrow \mu N_R$	2 μ	1 J	–	80	W_R mass 5.0 TeV	$m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV	η_{LL}^-	1703.09127
	CI $\ell\ell qq$	2 e, μ	–	–	139	Λ 35.8 TeV	η_{LL}^-	2006.12946
	CI $eebs$	2 e	1 b	–	139	Λ 1.8 TeV	$g_* = 1$	2105.13847
	CI $\mu\mu bs$	2 μ	1 b	–	139	Λ 2.0 TeV	$g_* = 1$	2105.13847
	CI $tttt$	≥1 e,μ	≥1 b, ≥1 j	Yes	36.1	Λ 2.57 TeV	$\|C_{4t}\| = 4\pi$	1811.02305
DM	Axial-vector med. (Dirac DM)	–	2 j	–	139	m_{med} 3.8 TeV	g_q=0.25, g_χ=1, $m(\chi)$=10 TeV	ATL-PHYS-PUB-2022-036
	Pseudo-scalar med. (Dirac DM)	0 e, μ, τ, γ	1 – 4 j	Yes	139	m_{med} 376 GeV	g_q=1, g_χ=1, $m(\chi)$=1 GeV	2102.10874
	Vector med. Z'-2HDM (Dirac DM)	0 e, μ	2 b	Yes	139	$m_{Z'}$ 3.0 TeV	$\tan\beta$=1, g_Z=0.8, $m(\chi)$=100 GeV	2108.13391
	Pseudo-scalar med. 2HDM+a	multi-channel			139	m_a 800 GeV	$\tan\beta$=1, g_χ=1, $m(\chi)$=10 GeV	ATLAS-CONF-2021-036
LQ	Scalar LQ 1st gen	2 e	≥2 j	Yes	139	LQ mass 1.8 TeV	$\beta = 1$	2006.05872
	Scalar LQ 2nd gen	2 μ	≥2 j	Yes	139	LQ mass 1.7 TeV	$\beta = 1$	2006.05872
	Scalar LQ 3rd gen	1 τ	2 b	Yes	139	LQ_3^u mass 1.49 TeV	$\mathcal{B}(\mathrm{LQ}_3^u \rightarrow b\tau) = 1$	2303.01294
	Scalar LQ 3rd gen	0 e, μ	≥2 j, ≥2 b	Yes	139	LQ_3^u mass 1.24 TeV	$\mathcal{B}(\mathrm{LQ}_3^u \rightarrow t\nu) = 1$	2004.14060
	Scalar LQ 3rd gen	≥2 e, μ, ≥1 τ	≥1 j, ≥1 b	–	139	LQ_3^d mass 1.43 TeV	$\mathcal{B}(\mathrm{LQ}_3^d \rightarrow t\tau) = 1$	2101.11582
	Scalar LQ 3rd gen	0 e, μ, ≥1 τ	0 – 2 j, 2 b	Yes	139	LQ_3^d mass 1.26 TeV	$\mathcal{B}(\mathrm{LQ}_3^d \rightarrow b\nu) = 1$	2101.12527
	Vector LQ mix gen	multi-channel	≥1 j, ≥1 b	Yes	139	LQ_3^V mass 2.0 TeV	$\mathcal{B}(\tilde{U}_1 \rightarrow t\mu) = 1$, Y-M coupl.	ATLAS-CONF-2022-052
	Vector LQ 3rd gen	2 e, μ, τ	≥1 b	Yes	139	LQ_3^V mass 1.96 TeV	$\mathcal{B}(\mathrm{LQ}_3^V \rightarrow b\tau) = 1$, Y-M coupl.	2303.01294
Vector-like fermions	VLQ $TT \rightarrow Zt + X$	2e/2μ/≥3e,μ	≥1 b, ≥1 j	–	139	T mass 1.46 TeV	SU(2) doublet	2210.15413
	VLQ $BB \rightarrow Wt/Zb + X$	multi-channel			36.1	B mass 1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3}T_{5/3}\|T_{5/3} \rightarrow Wt + X$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \rightarrow Wt)$= 1, $c(T_{5/3}Wt)$= 1	1807.11883
	VLQ $T \rightarrow Ht/Zt$	1 e, μ	≥1 b, ≥3 j	Yes	139	T mass 1.8 TeV	SU(2) singlet, κ_T= 0.5	ATLAS-CONF-2021-040
	VLQ $Y \rightarrow Wb$	1 e, μ	≥1 b, ≥1 j	Yes	36.1	Y mass 1.85 TeV	$\mathcal{B}(Y \rightarrow Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B \rightarrow Hb$	0 e,μ	≥2b, ≥1j, ≥1J	–	139	B mass 2.0 TeV	SU(2) doublet, κ_B= 0.3	ATLAS-CONF-2021-018
	VLL $\tau' \rightarrow Z\tau/H\tau$	multi-channel	≥1 j	Yes	139	τ' mass 898 GeV	SU(2) doublet	2303.05441
Exctd ferm.	Excited quark $q^* \rightarrow qg$	–	2 j	–	139	q^* mass 6.7 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1910.08447
	Excited quark $q^* \rightarrow q\gamma$	1 γ	1 j	–	36.7	q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \rightarrow bg$	–	1 b, 1 j	–	139	b^* mass 3.2 TeV		1910.08447
	Excited lepton τ^*	2 τ	≥2 j	–	139	τ^* mass 4.6 TeV	$\Lambda = 4.6$ TeV	2303.09444
Other	Type III Seesaw	2,3,4 e, μ	≥2 j	Yes	139	N^0 mass 910 GeV		2202.02039
	LRSM Majorana ν	2 μ	2 j	–	36.1	N_R mass 3.2 TeV	$m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
	Higgs triplet $H^{\pm\pm} \rightarrow W^\pm W^\pm$	2,3,4 e, μ (SS)	various	Yes	139	$H^{\pm\pm}$ mass 350 GeV	DY production	2101.11961
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	2,3,4 e, μ (SS)	–	–	139	$H^{\pm\pm}$ mass 1.08 TeV	DY production	2211.07505
	Multi-charged particles	–	–	–	139	multi-charged particle mass 1.59 TeV	DY production, $\|q\| = 5e$	ATLAS-CONF-2022-034
	Magnetic monopoles	–	–	–	34.4	monopole mass 2.37 TeV	DY production, $\|g\| = 1g_D$, spin 1/2	1905.10130

$\sqrt{s} = 13$ TeV partial data

$\sqrt{s} = 13$ TeV full data

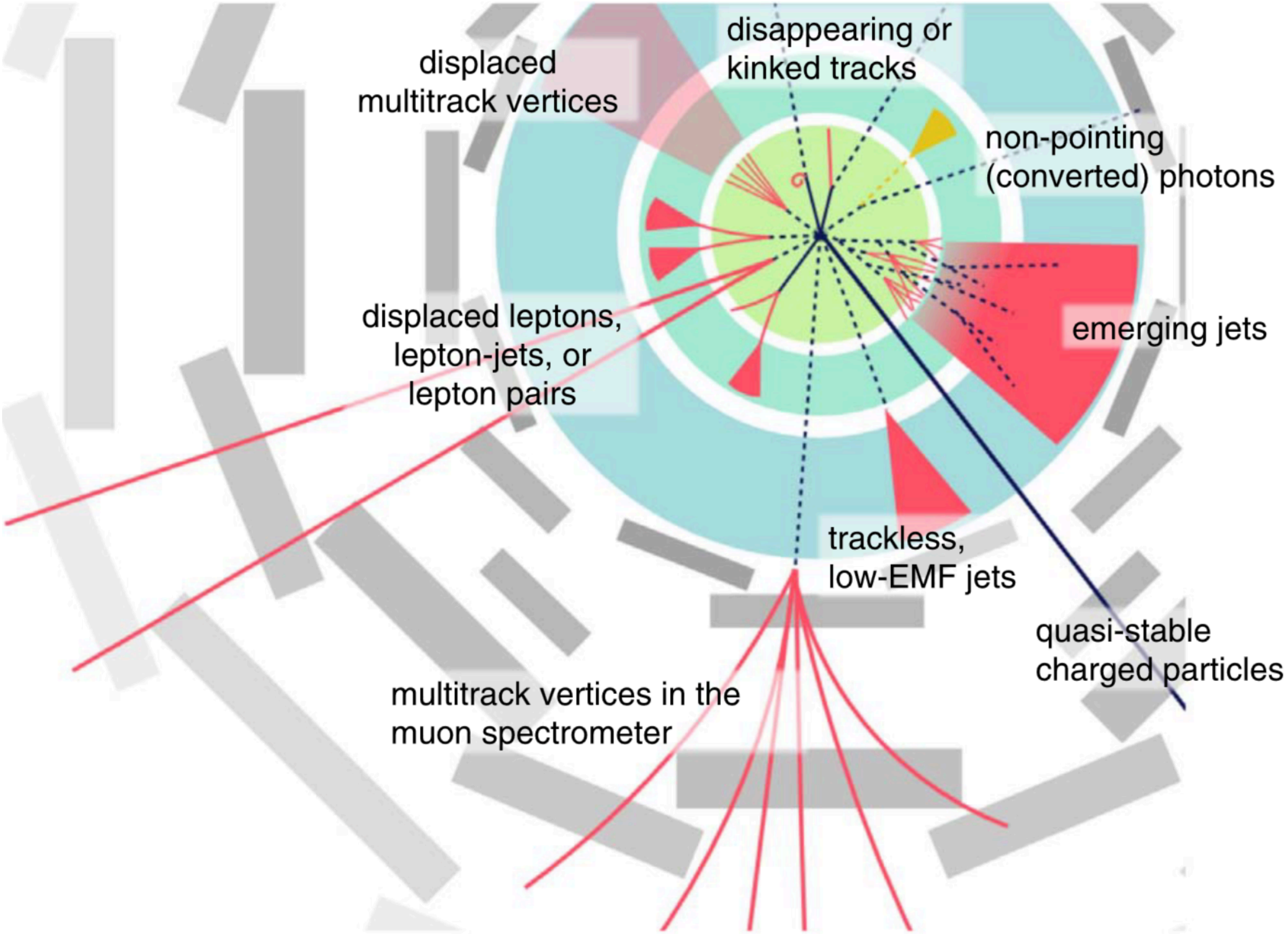
*Only a selection of the available mass limits on new states or phenomena is shown.

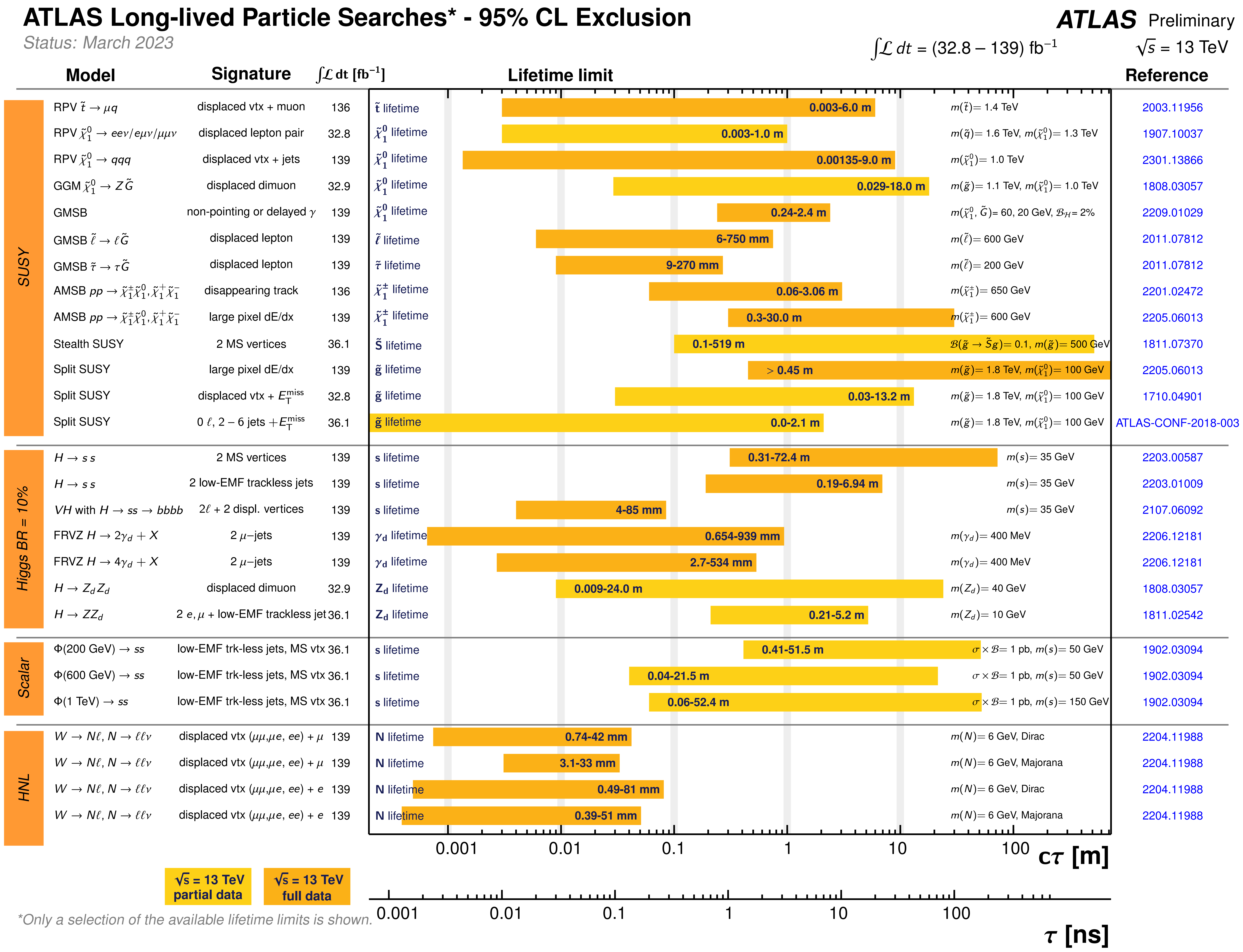
†Small-radius (large-radius) jets are denoted by the letter j (J).

Unconventional signatures

Of Long Lived Particles

- BSM can be long lived
  - Weak interaction (weak decay)
  - Compressed spectra
- Results in uncommon signatures
  - Highly displaced tracks/jets
  - Disappearing tracks
- Experimental challenge!





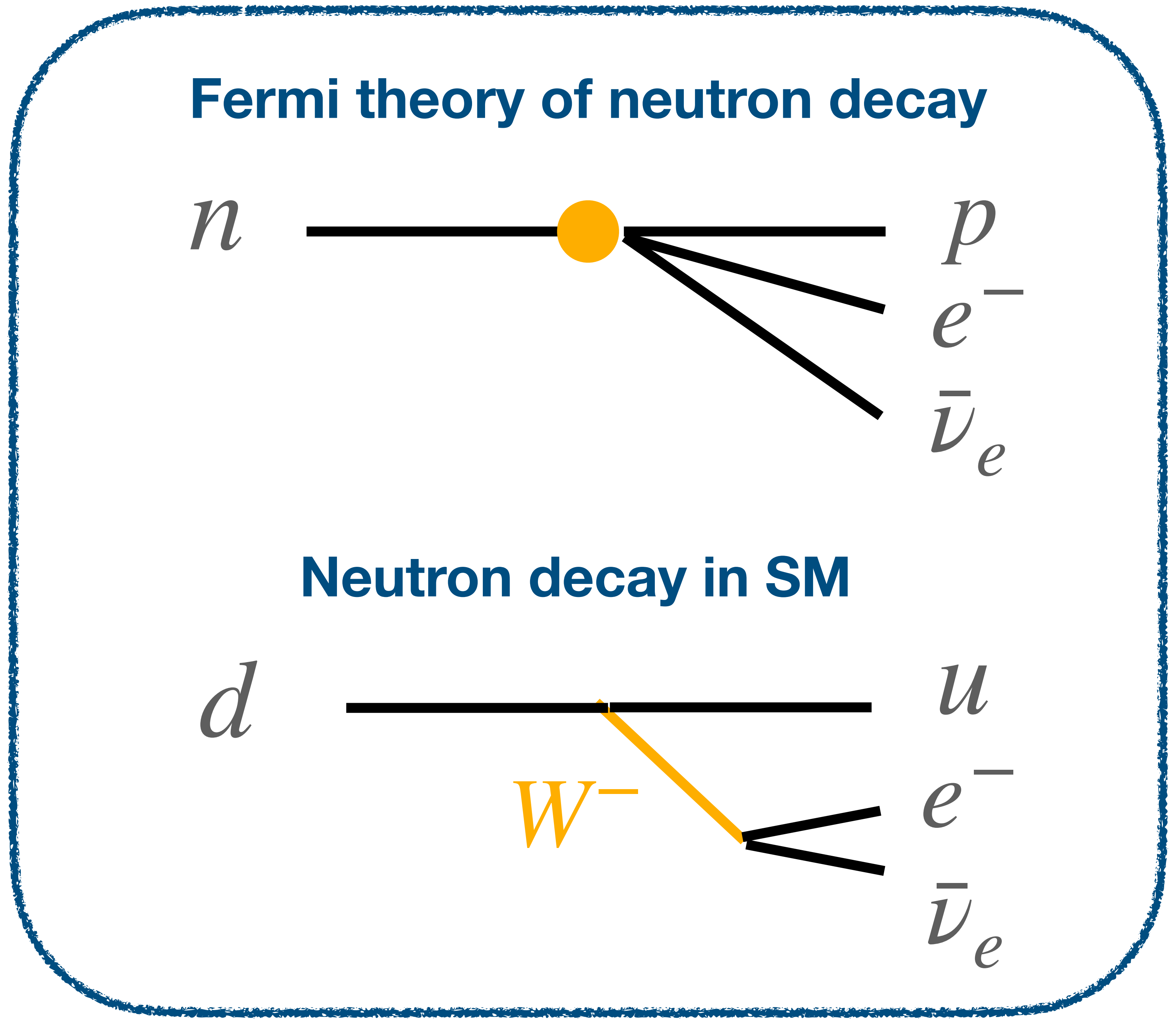
No sign of new Long-lived particles…

Indirect Searches

With Effective Field Theory

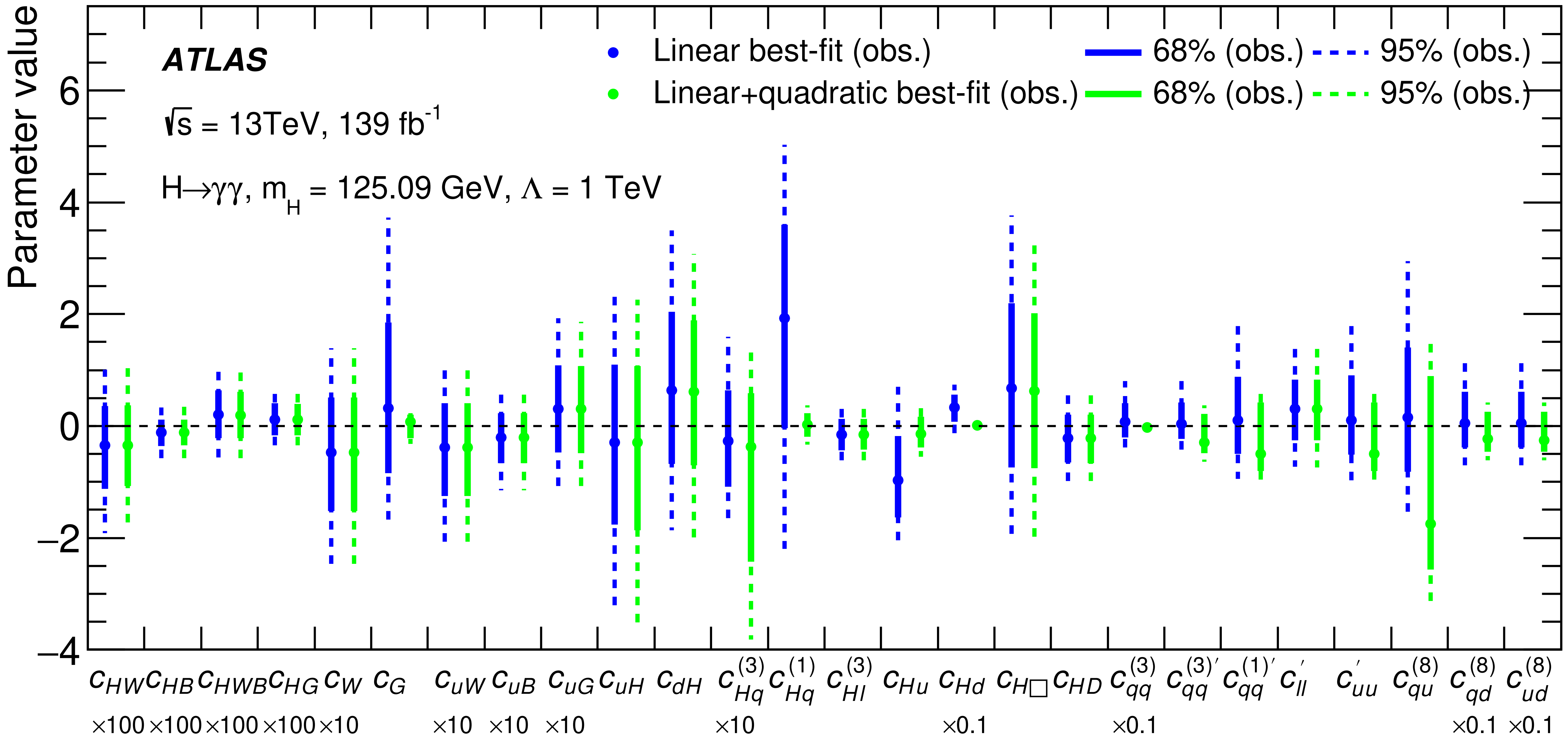
$$\mathcal{L}_{\rm SMEFT} \;=\; \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\sum_i c_i^{(5)}\mathcal{O}_i^{D=5} + \frac{1}{\Lambda^2}\sum_i c_i^{(6)}\mathcal{O}^{D=6} \;+\; \dots$$

- No sign of BSM yet, SM+BSM could be treated with an effective theory:
  - Not a renormalizable theory: predictions breaks when E~ Λ (new physics scale)
- Great tool to collect coherently informations of different sector (Higgs, top, EW)



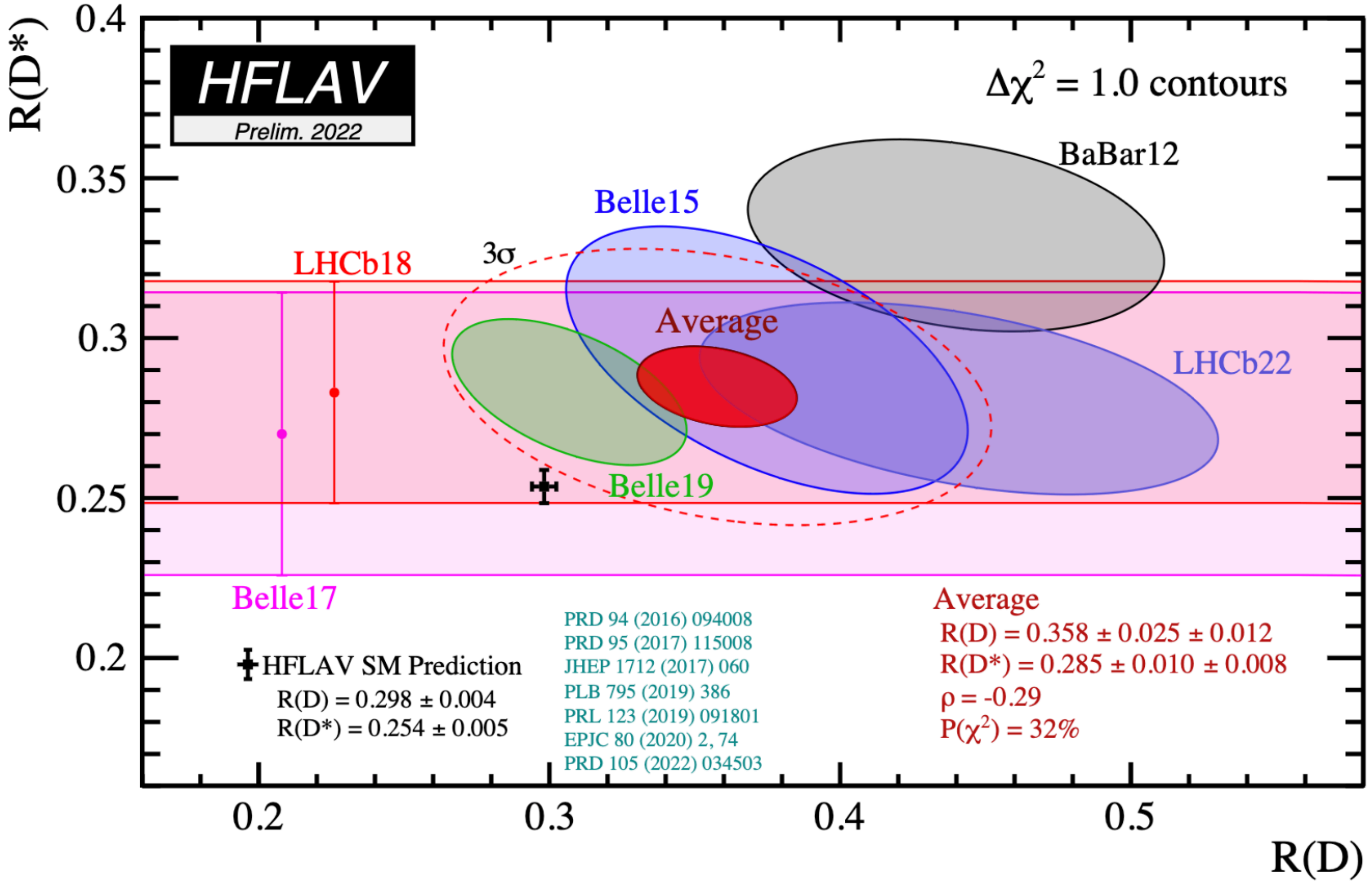
Fermi theory of neutron decay

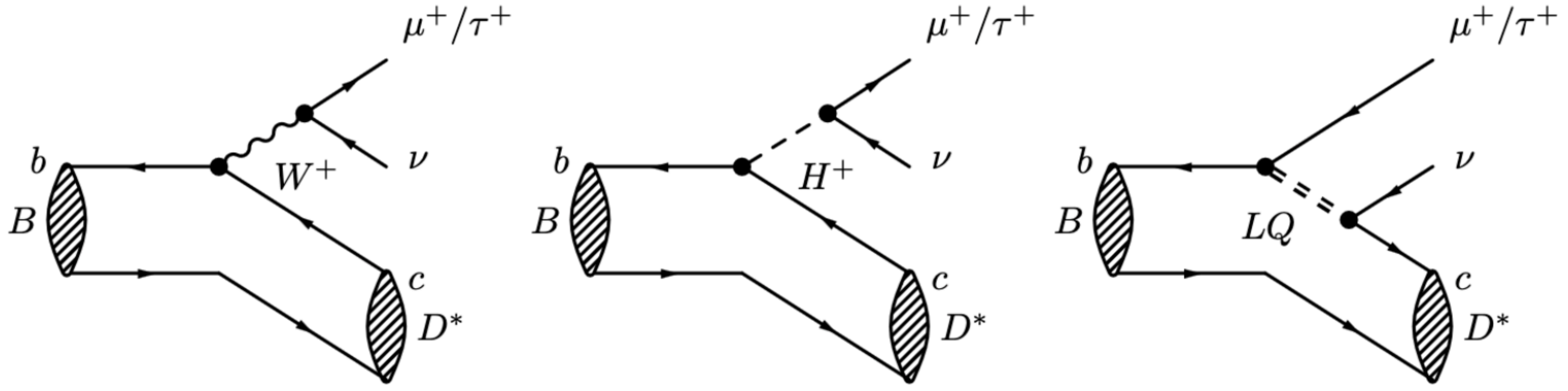
Neutron decay in SM



Indirect Searches in Heavy Flavour

Test of lepton universality

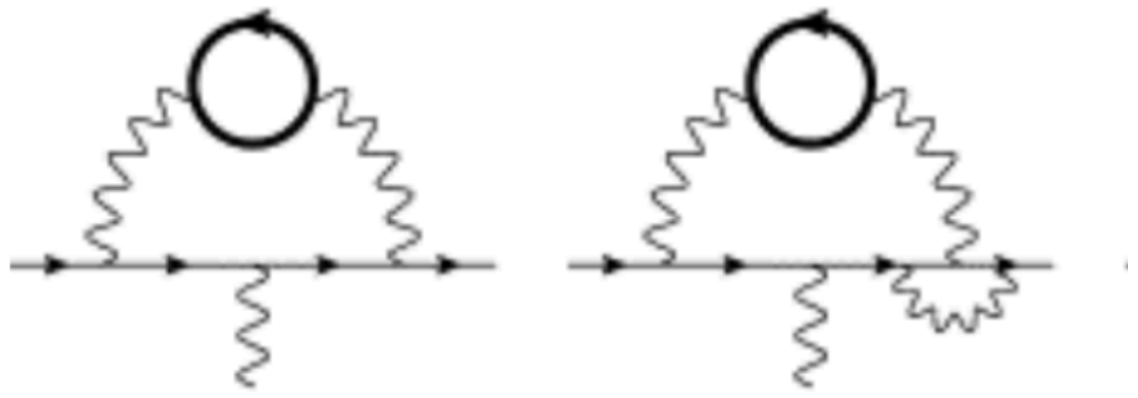




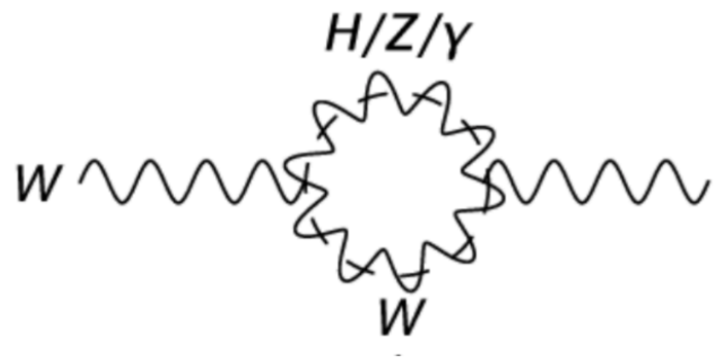
$$R\left(D^{(*)}\right) = \frac{\mathscr{B}\left(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau\right)}{\mathscr{B}\left(\bar{B} \to D^{(*)}\mu^-\bar{\nu}_\mu\right)}$$

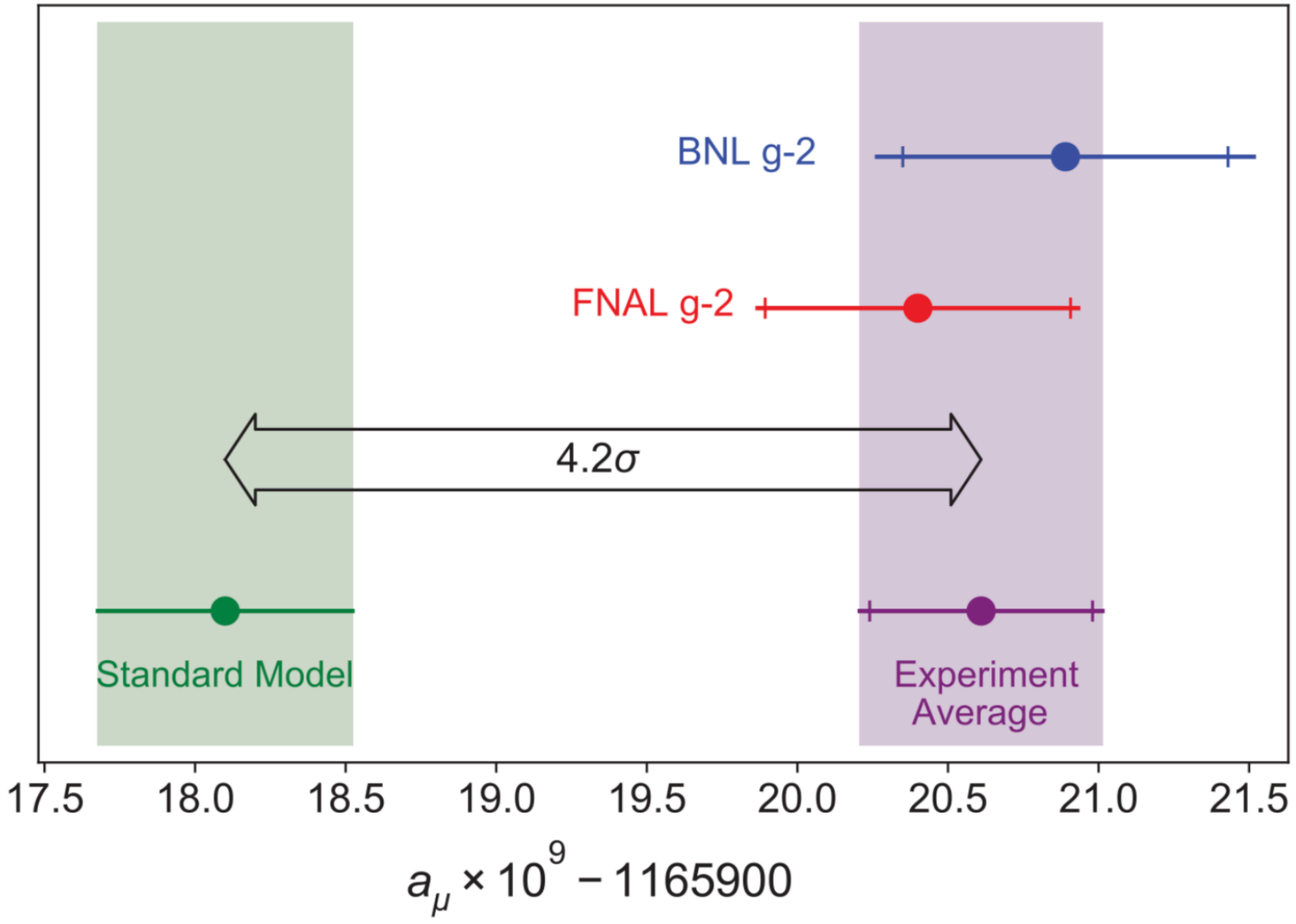
- In SM, difference comes only from lepton masses difference (phase-space)
- BSM can have dynamics different amoung quark generation (e.g. Charged Higgs, Lepto-quark)

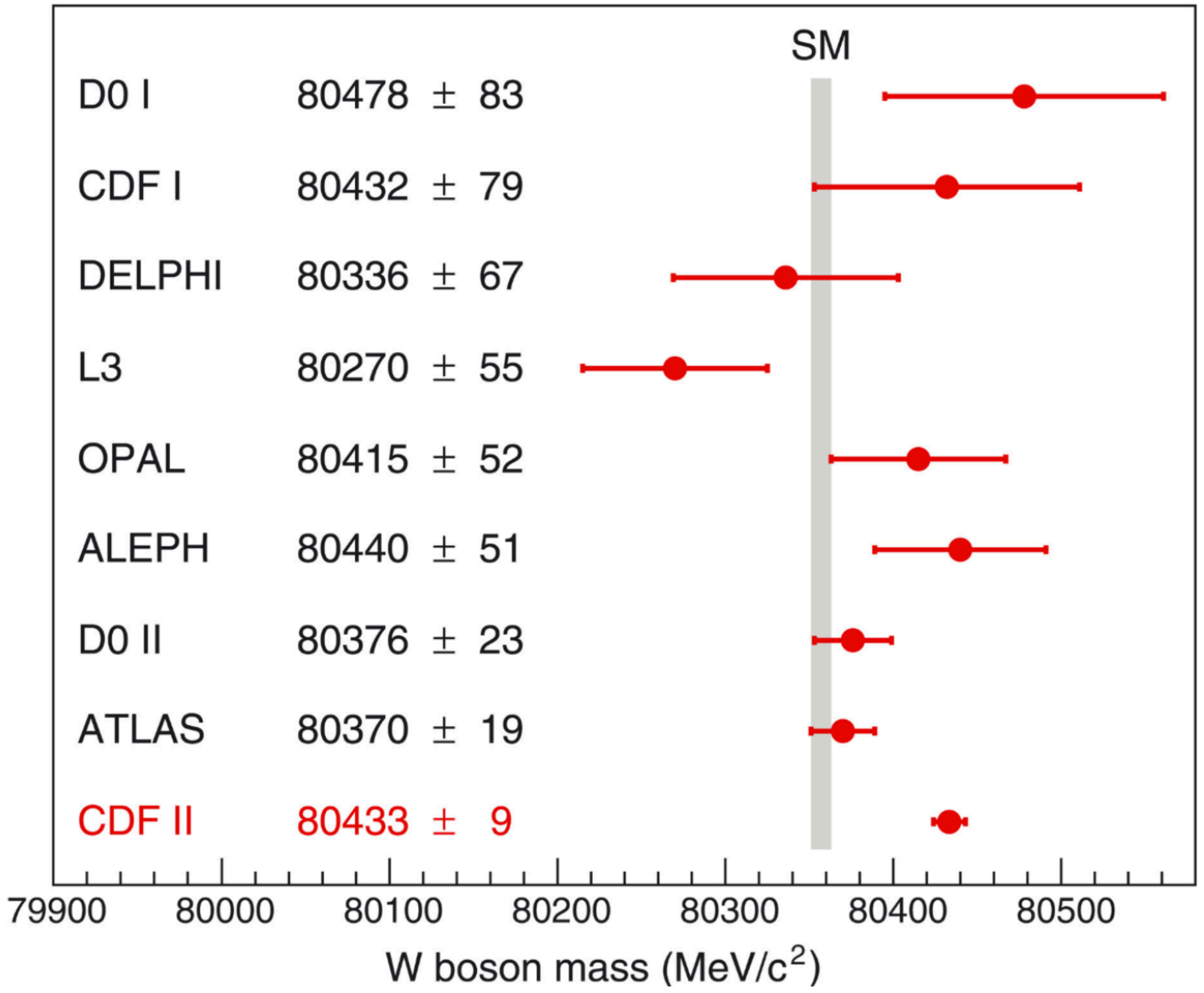
$g_\mu - 2$



m_W





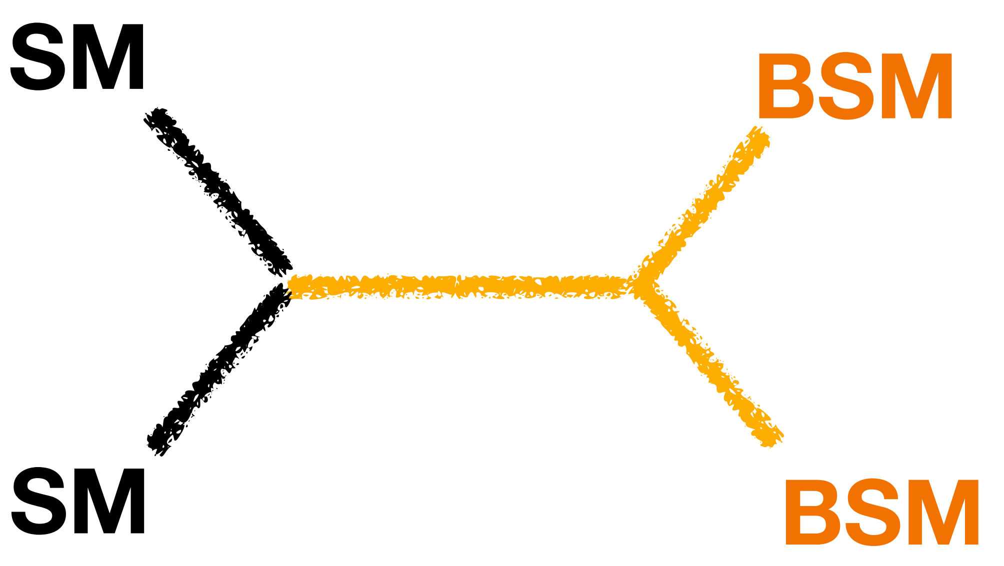


- Tremendous efforts to control both experimental and theoretical uncertainties

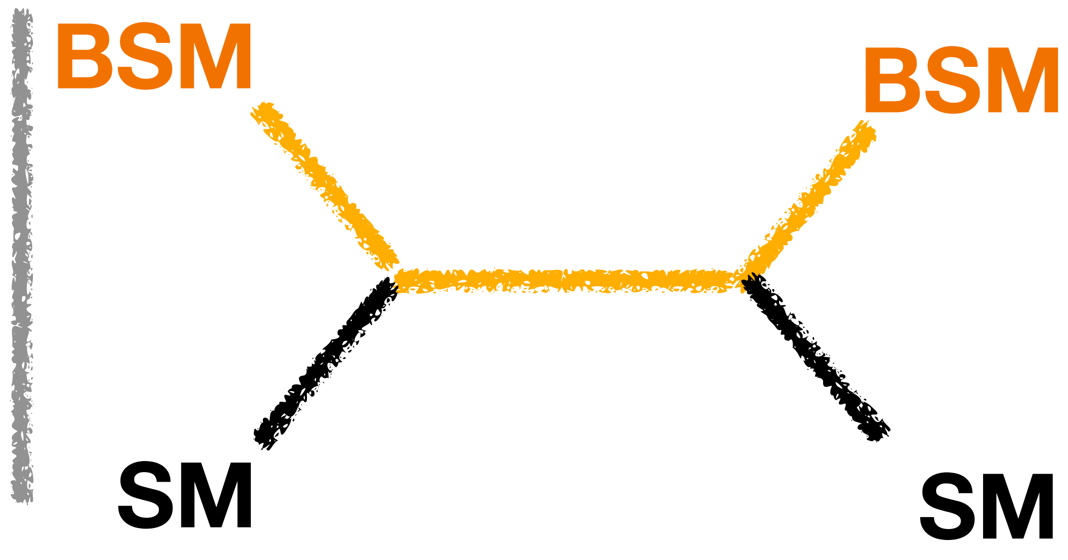
It's not all about LHC!

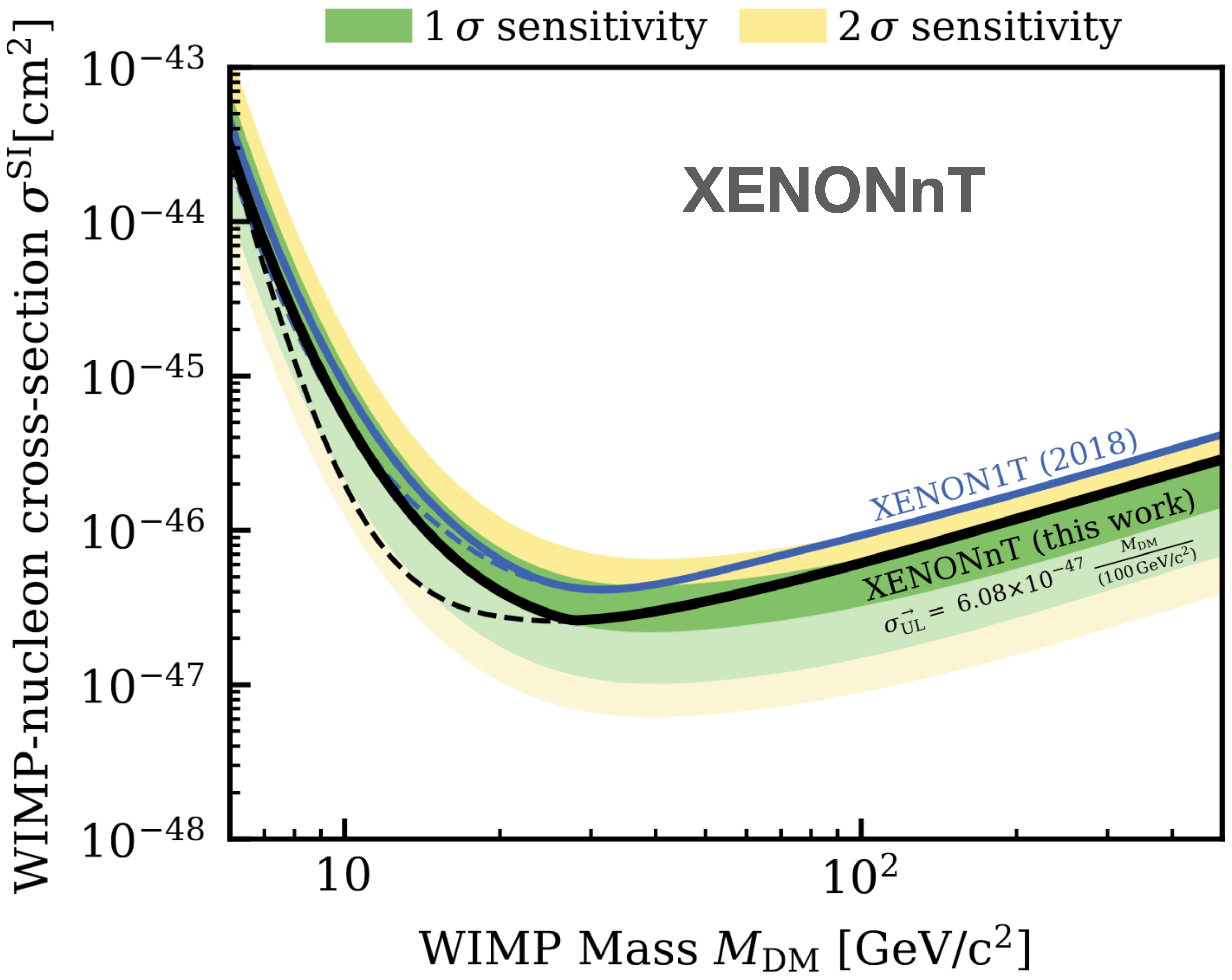
Non-collider searches

Production



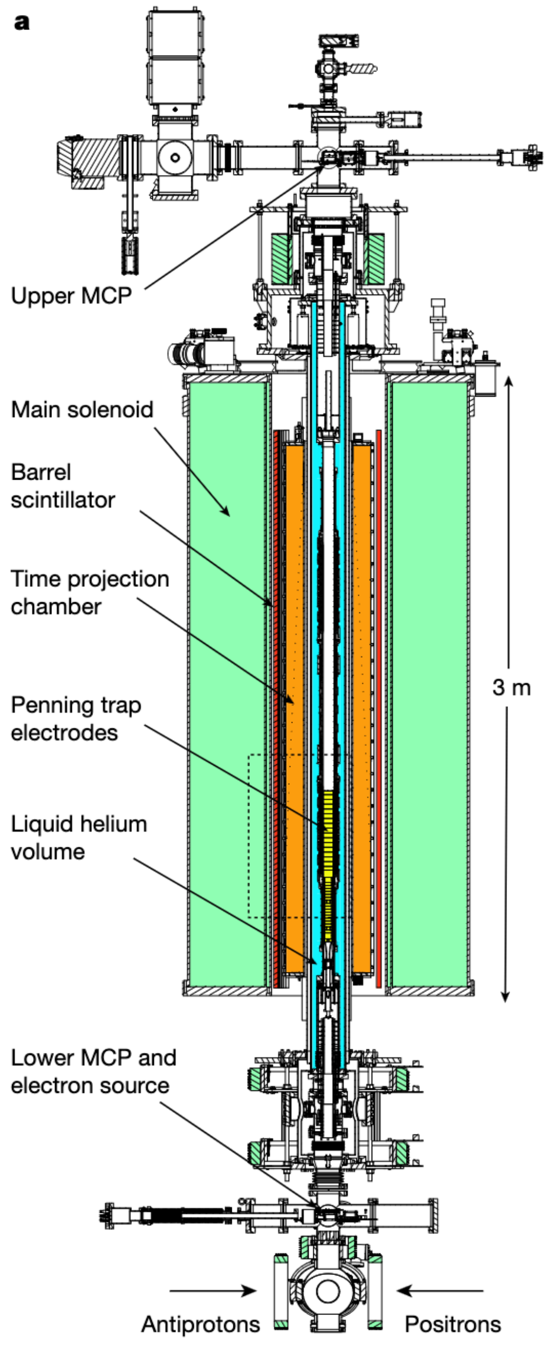
Scaterring

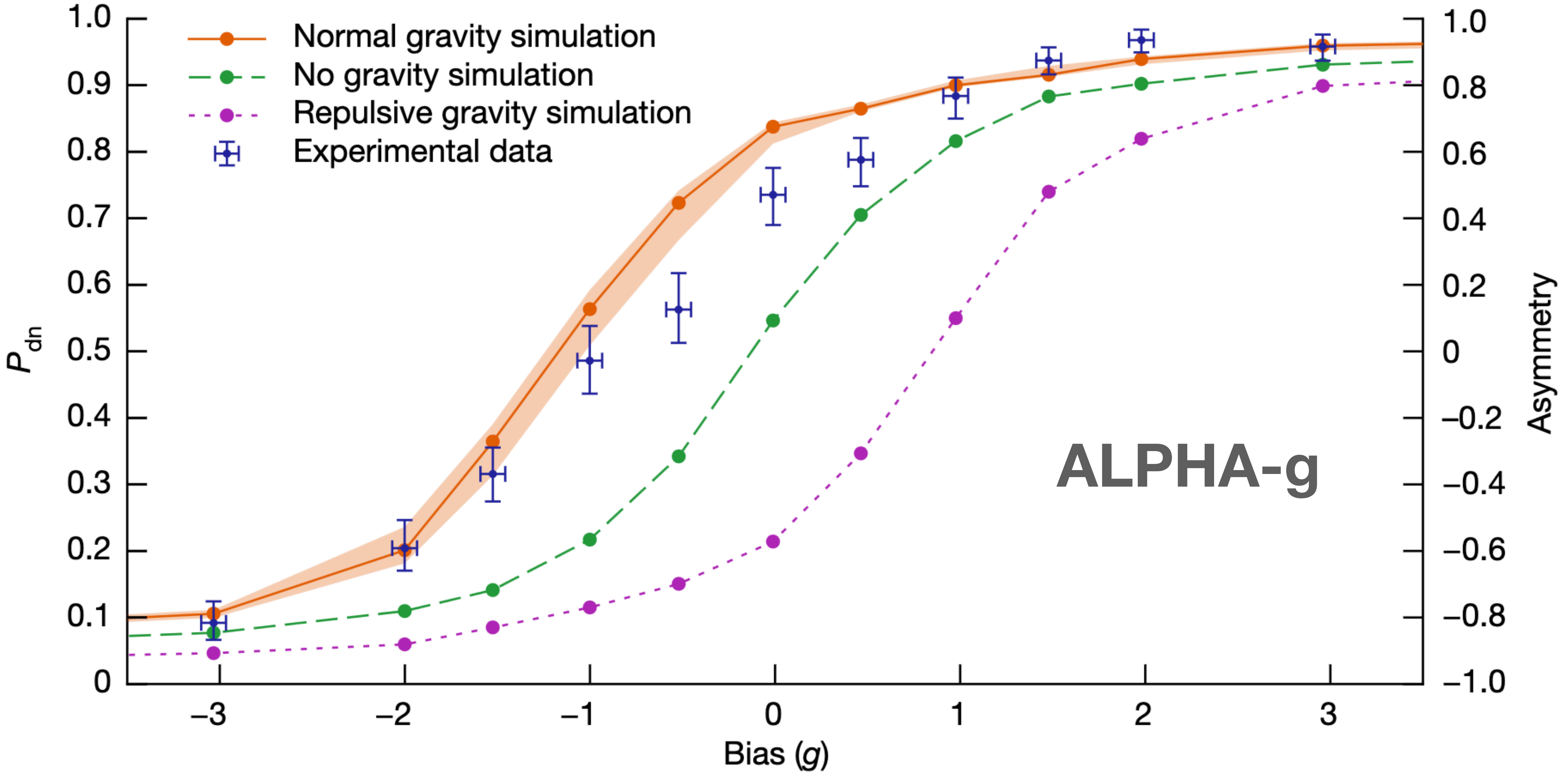




Antimatter precise measurements

- Do the antimatter falls like matter?
- Repulsive gravity?





Conclusion

~~Rock~~ Particle Physics is not dead

- We know that Standard Model is not a complete description of Nature
- We need a better description with a Beyond Standard Model theory
- We want to find experimental evidence of BSM
  - We are searching in and more and more diverse signatures

> *We can't always get what we want,*
>
> *but if we try sometimes we just might find…*
>
> *…and get what we need!*

See how the BSM session speakers rocks :-)