

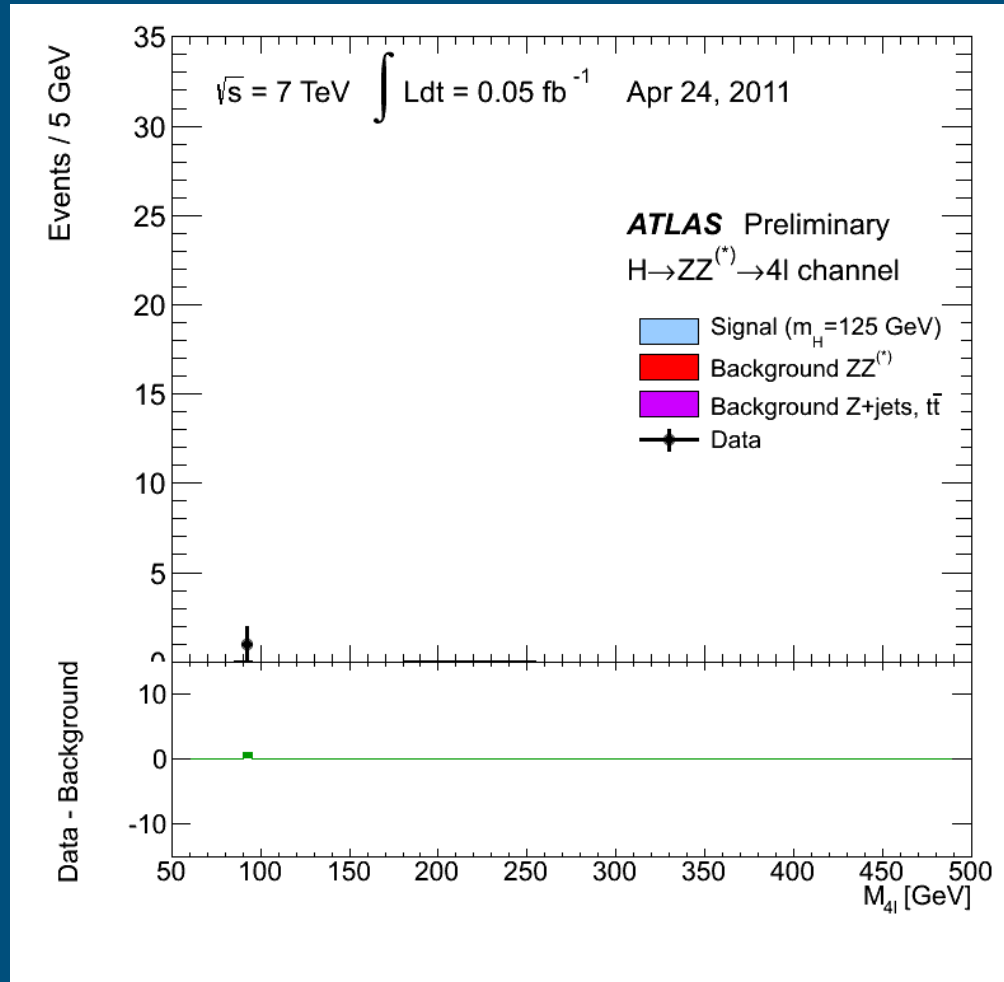
What is beyond the Standard Model?

- *Could it be hiding at the SPS?* -

Richard Jacobsson

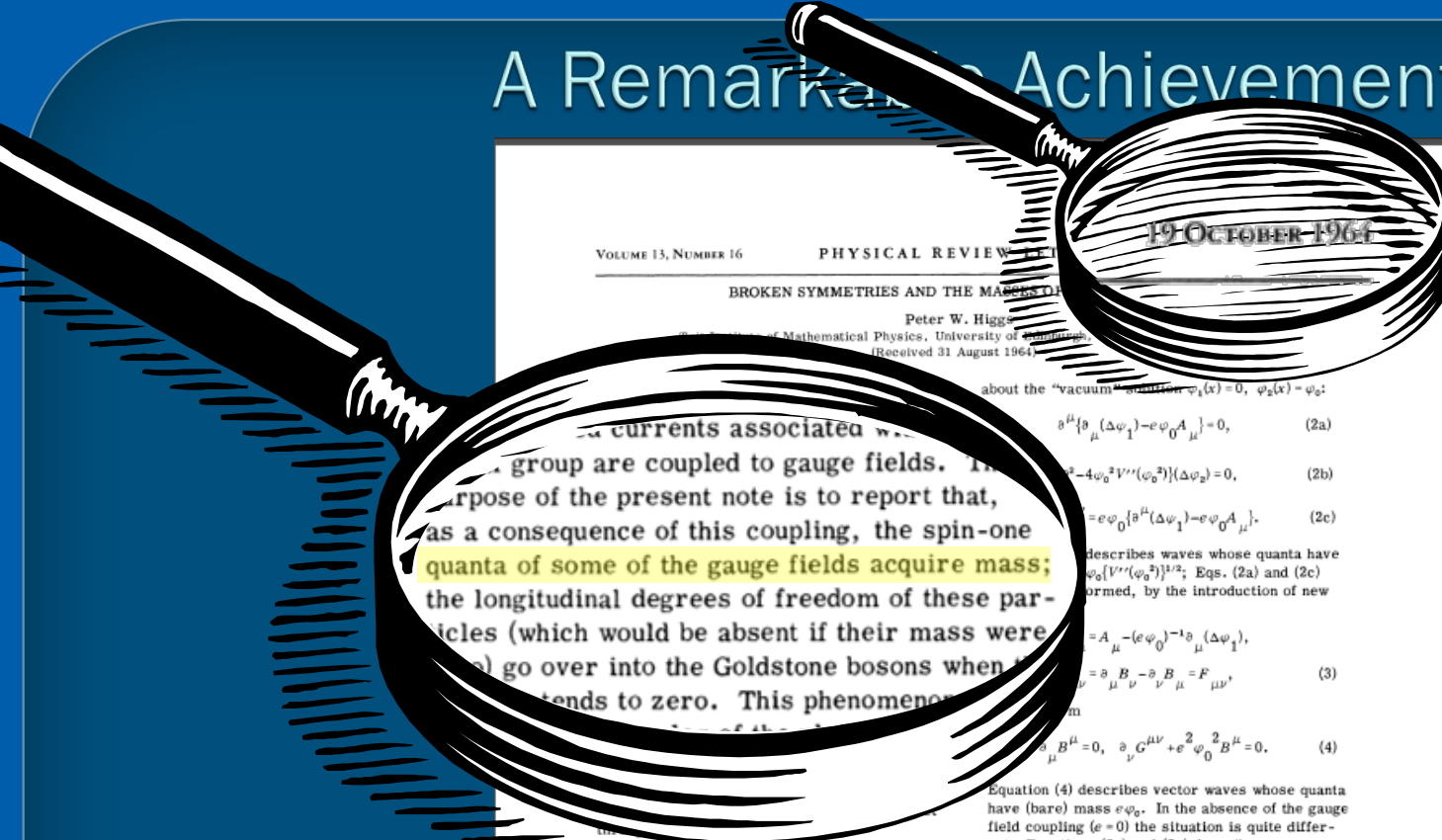
- Recapitulation of the results from LHC Run 1 (apologies to Alice!)
- Validity of the Standard Model
- Fundamental unanswered questions
- Possible solutions

Run 1: What did we find?



- ~1 - 5 Higgs per minute without us knowing!.... O(1 million) at production in total!
 - ATLAS+CMS: 1400 Higgs events after selection cuts
- Mass of the Higgs is equivalent to the total mass of 130 protons!

A Remarkable Achievement



VOLUME 13, NUMBER 16

PHYSICAL REVIEW

19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASS OF PARTICLES

Peter W. Higgs

Department of Mathematical Physics, University of Cambridge,
Cambridge, England
(Received 31 August 1964)

... currents associated with the gauge group are coupled to gauge fields. The purpose of the present note is to report that, as a consequence of this coupling, the spin-one quanta of some of the gauge fields acquire mass; the longitudinal degrees of freedom of these particles (which would be absent if their mass were zero) go over into the Goldstone bosons when the mass tends to zero. This phenomenon is known as the Higgs mechanism.

about the "vacuum" solution $\varphi_1(x)=0, \varphi_2(x)=\varphi_0$:

$$\partial^\mu \{ \partial_\mu (\Delta\varphi_1) - e\varphi_0 A_\mu \} = 0, \quad (2a)$$

$$-4\varphi_0^2 V''(\varphi_0^2) (\Delta\varphi_2) = 0, \quad (2b)$$

$$= e\varphi_0 \{ \partial^\mu (\Delta\varphi_1) - e\varphi_0 A_\mu \}, \quad (2c)$$

describes waves whose quanta have mass $m = \varphi_0 [V''(\varphi_0^2)]^{1/2}$; Eqs. (2a) and (2c) are transformed, by the introduction of new fields B_μ and $F_{\mu\nu}$, into

$$= A_\mu - (e\varphi_0)^{-1} \partial_\mu (\Delta\varphi_1),$$

$$= \partial_\mu B_\nu - \partial_\nu B_\mu = F_{\mu\nu}, \quad (3)$$

$$\partial_\nu B^\mu = 0, \quad \partial_\nu G^{\mu\nu} + e^2 \varphi_0^2 B^\mu = 0. \quad (4)$$

Equation (4) describes vector waves whose quanta have (bare) mass $e\varphi_0$. In the absence of the gauge field coupling ($e=0$) the situation is quite different: Equations (2a) and (2c) describe zero-mass scalar and vector bosons, respectively. In passing, we note that the right-hand side of (2c) is just the linear approximation to the conserved current: it is linear in the vector potential, gauge invariance being maintained by the presence of the gradient term.⁵

When one considers theoretical models in which spontaneous breakdown of symmetry under

$$L = -\frac{1}{2}(\nabla\varphi_1)^2 - \frac{1}{2}(\nabla\varphi_2)^2 - V(\varphi_1^2 + \varphi_2^2) - \frac{1}{2}F_{\mu\nu}F^{\mu\nu}, \quad (1)$$

where

$$\nabla_\mu \varphi_1 = \partial_\mu \varphi_1 - eA_\mu \varphi_2,$$

$$\nabla_\mu \varphi_2 = \partial_\mu \varphi_2 + eA_\mu \varphi_1,$$

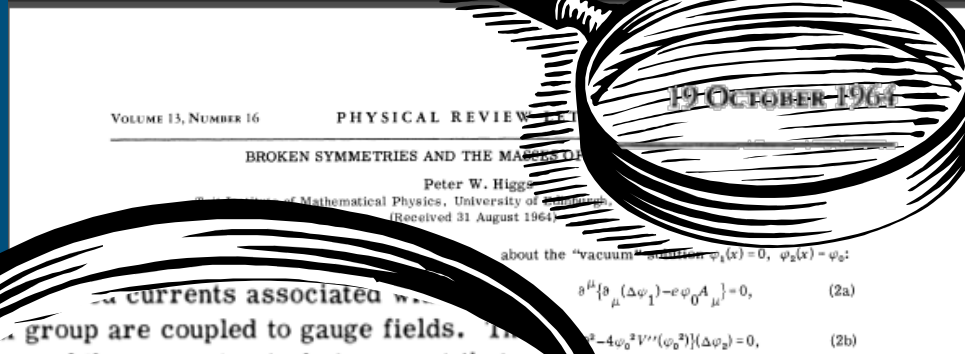
$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

e is a dimensionless coupling constant. L is invariant under simultaneous gauge transformations of the kind $\varphi_1 \pm i\varphi_2$ and of the second kind $A_\mu \pm \partial_\mu \alpha$. Let us suppose that $V'(\varphi_0^2) = 0$, that there is a spontaneous breakdown of $U(1)$ symmetry. Consider the equations [derived from (1)] governing the propagation of small

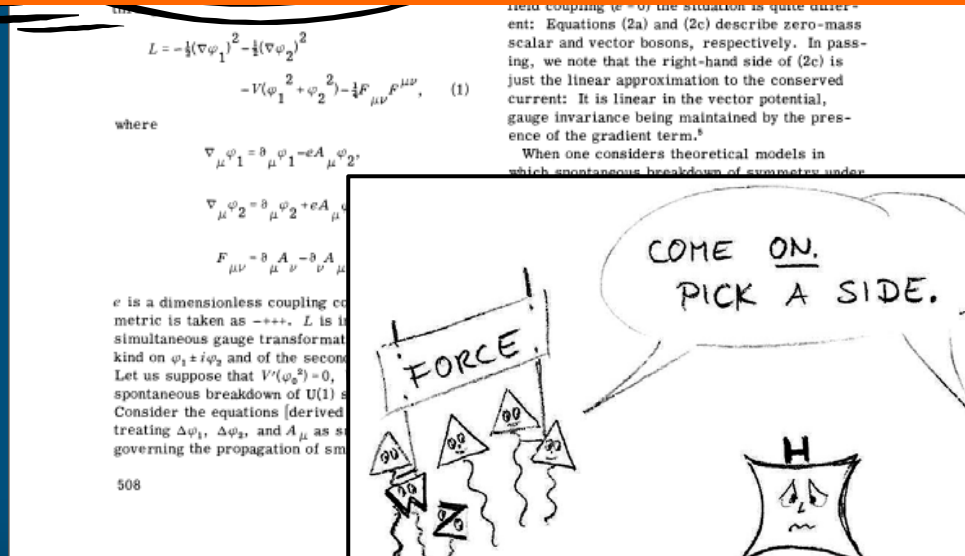
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A Remarkable Achievement



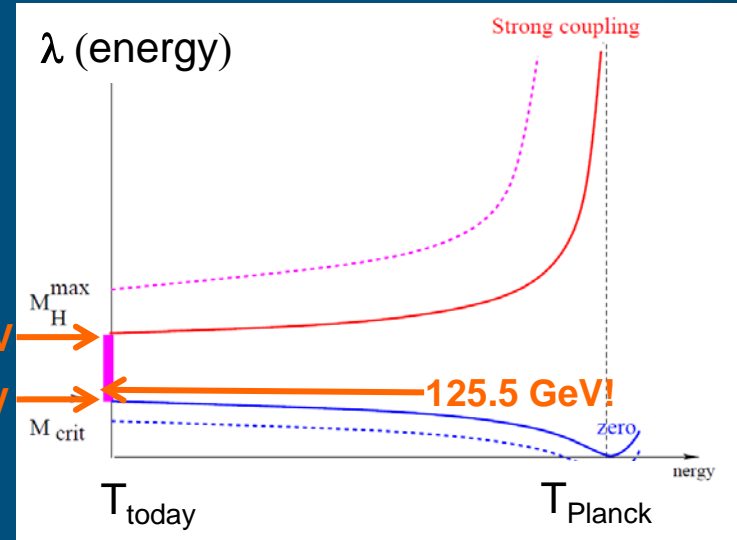
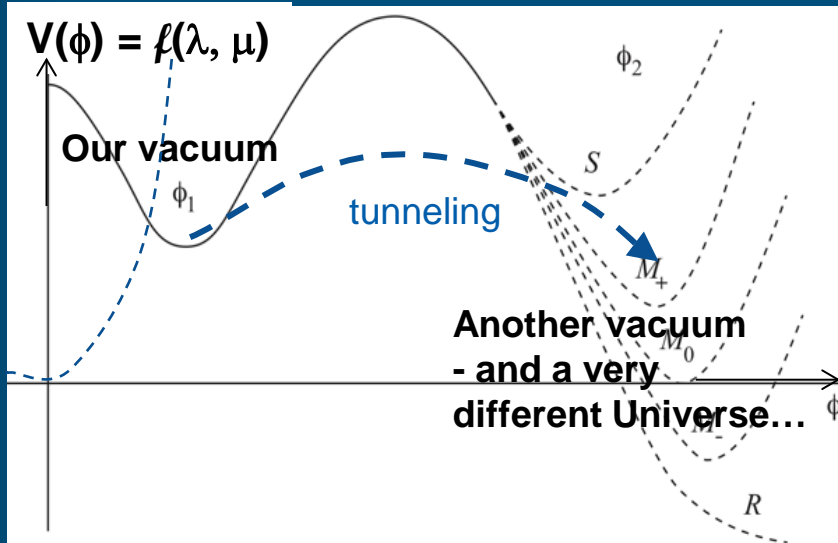
The most fundamental aspect of the appearance of the Higgs field is *not* just the generation of mass of particles but it is the breaking of the confinement to travel at the speed of light and allowing formation of complex structures!



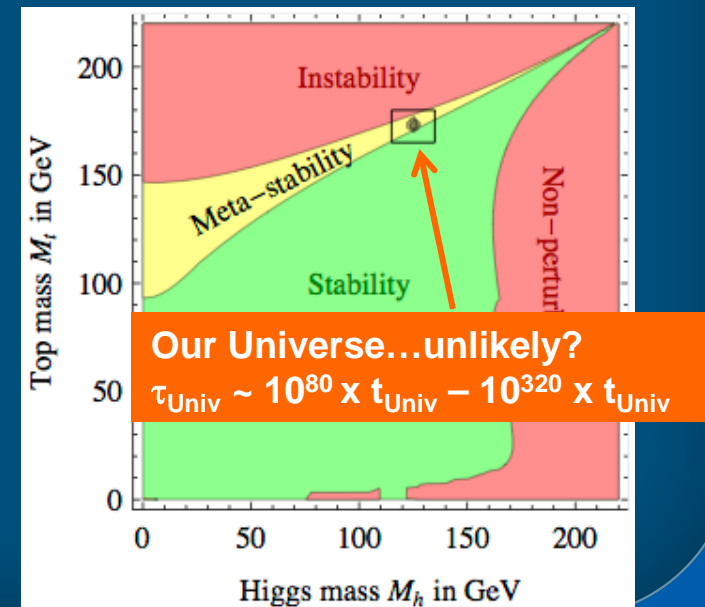
Is our vacuum – the Universe - stable?



- Probably, but just with a hair fine margin!
 - At least up to now as we are here to talk about it!



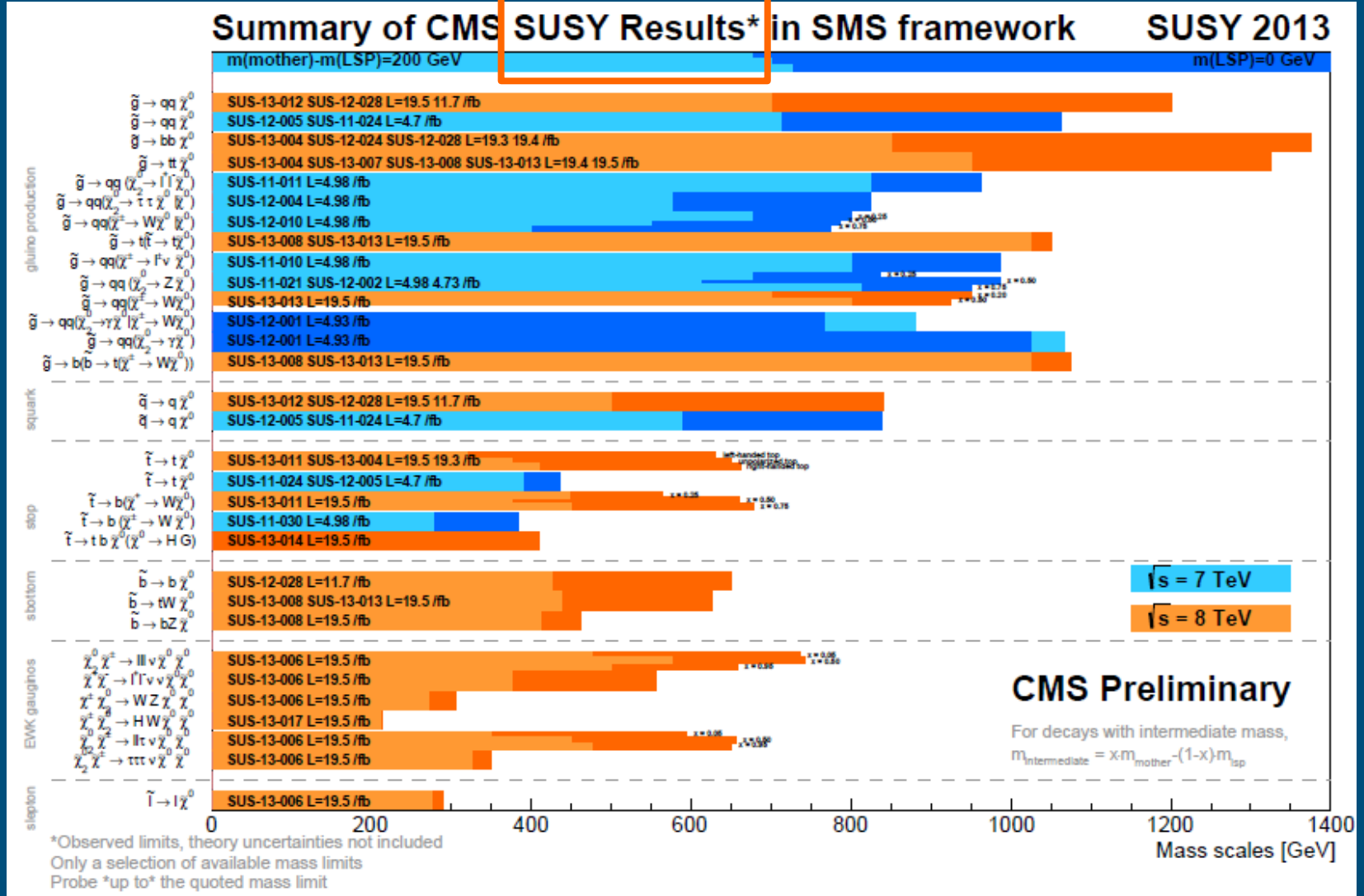
- If not:
 - A true vacuum could seed anywhere like a bubble and expand....
 - The current laws of physics would be lost and replaced for another version of the same fields....



Run 1 Searches: What did we not find....?



- LHC : A theory killer!



Run 1 Searches: What did we not find...?

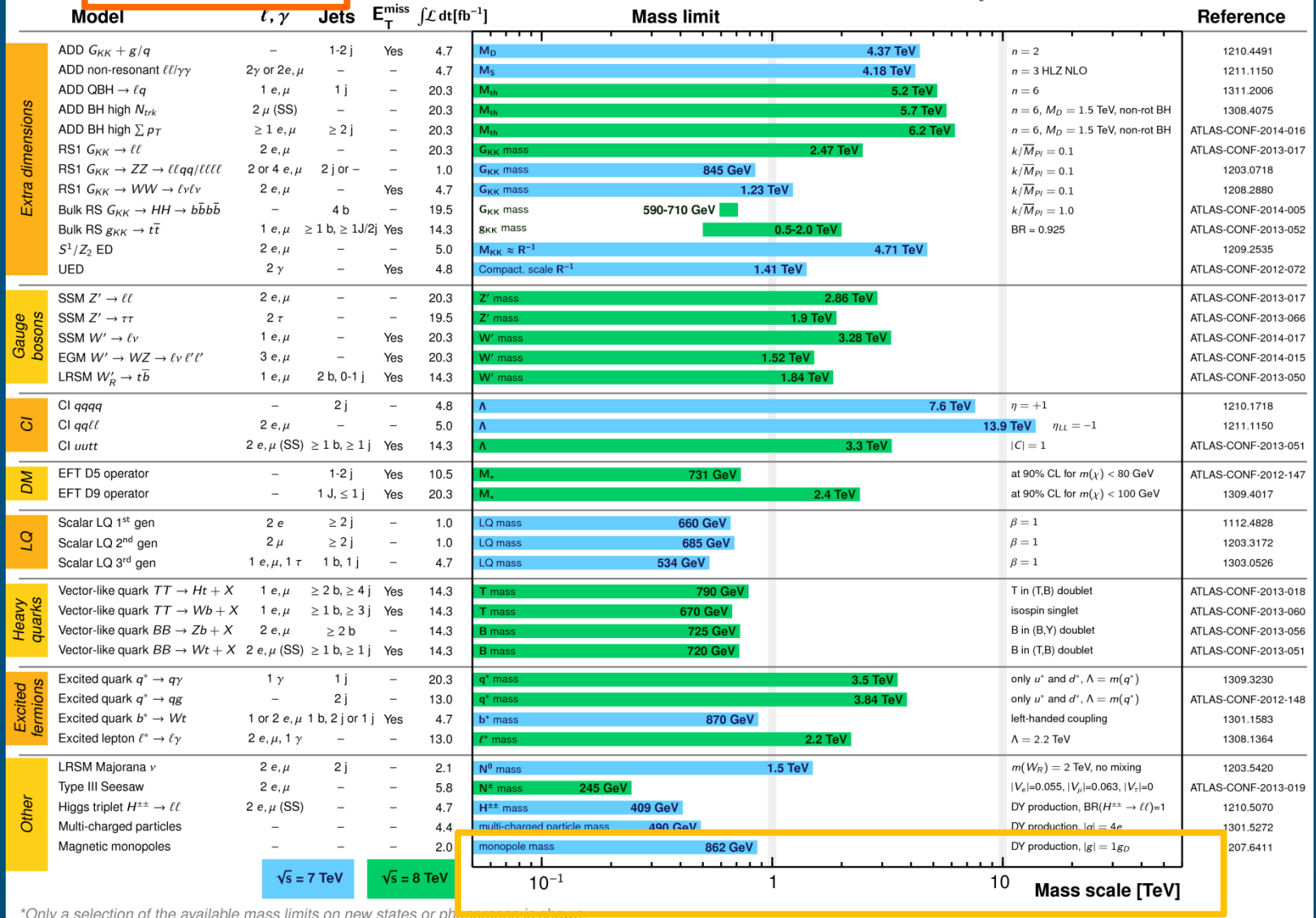


ATLAS Exotics Searches* - 95% CL Exclusion

Status: April 2014

ATLAS Preliminary

$$\int \mathcal{L} dt = (1.0 - 20.3) \text{ fb}^{-1} \quad \sqrt{s} = 7, 8 \text{ TeV}$$



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

Run 1: Precision measurements?

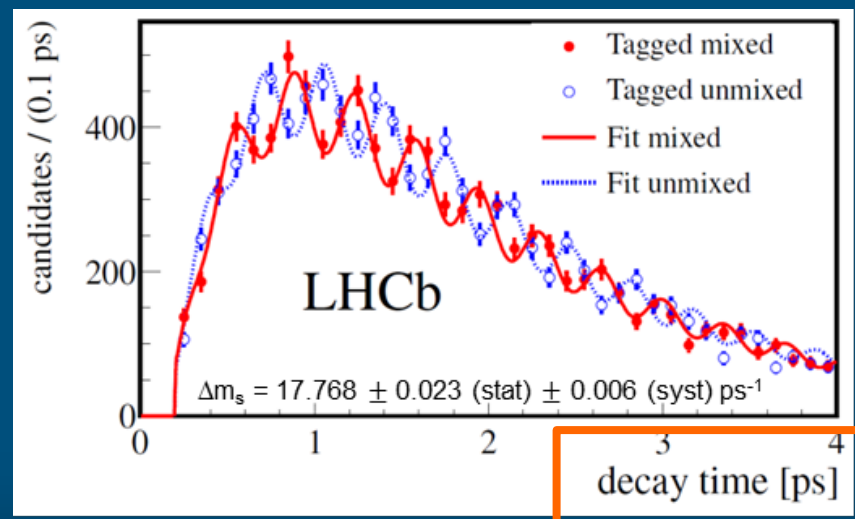
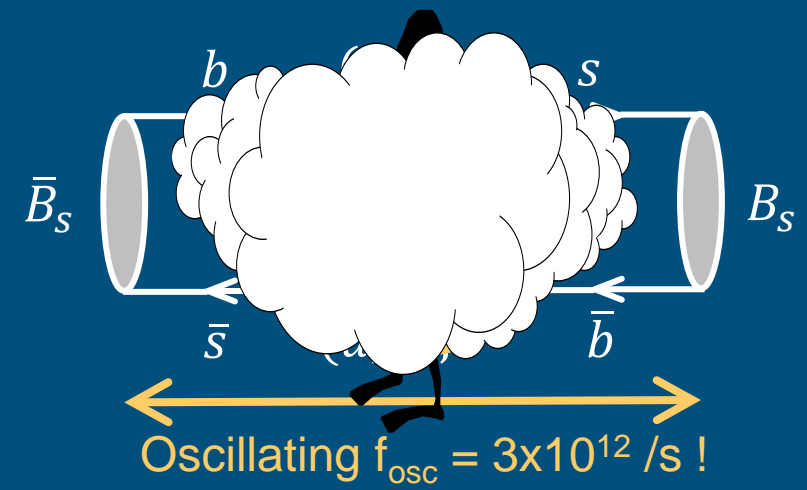
Recipe:

- Choose processes which are rare and calculable to high precision in SM
 - Indirectly find evidence for New Physics as discrepancy from SM prediction!
 - Virtual effects allow probing energies much higher than the E_{cms} of the LHC

Ex. B_s meson "adolescent identity problem"

$$\Phi_S^{exp} = \Phi_S^{SM} + \Phi_S^{NP}$$

Φ_S^{NP} contribution from New Physics



LHCb-PAPER-2012-006

Run 1: Precision measurements?

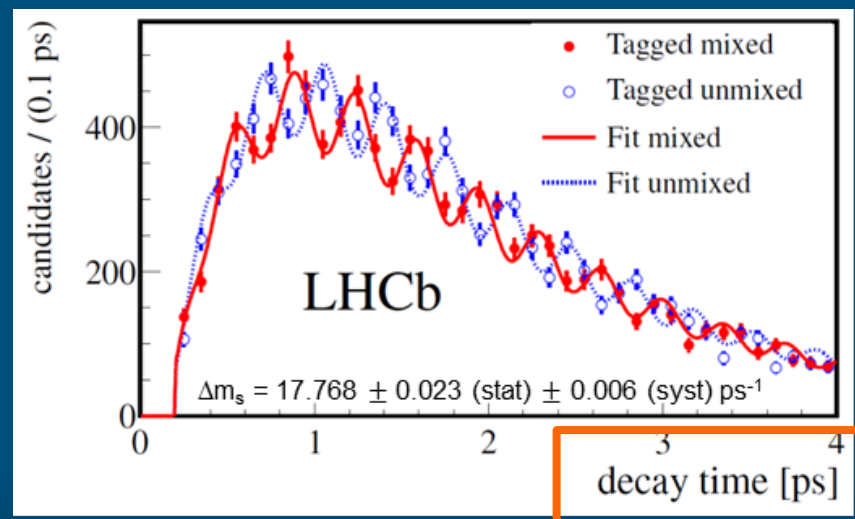
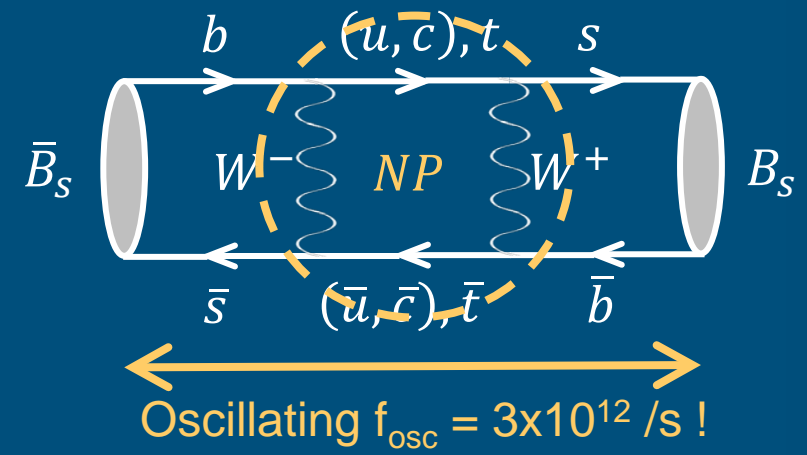
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Ex. B_s meson "adolescent identity problem"

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Φ_S^{NP} contribution from New Physics

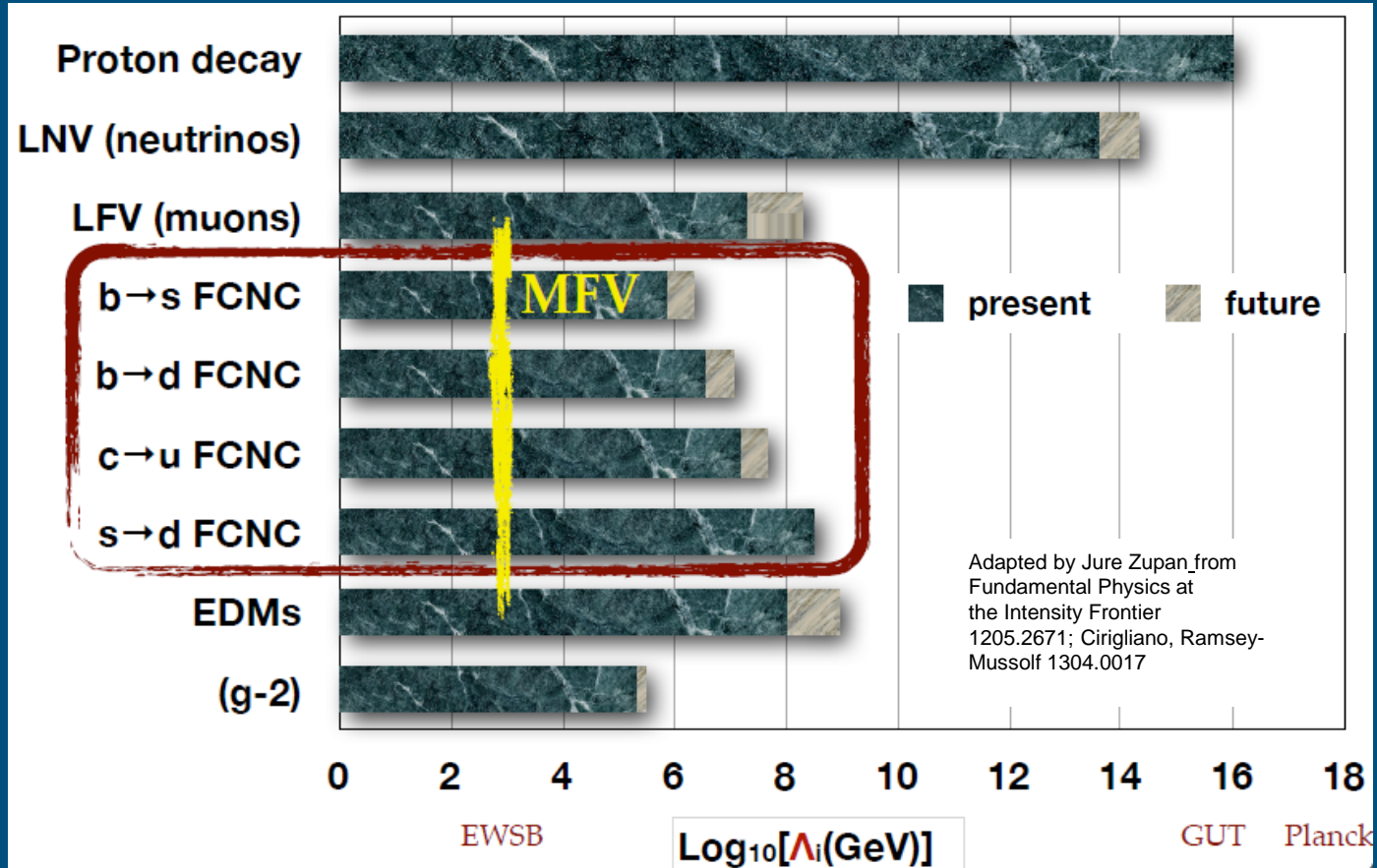


Run 1 Precision – What did we not find?



Push precisions!

$$\sigma_{stat+sys+th} < \Phi_s^{NP}$$

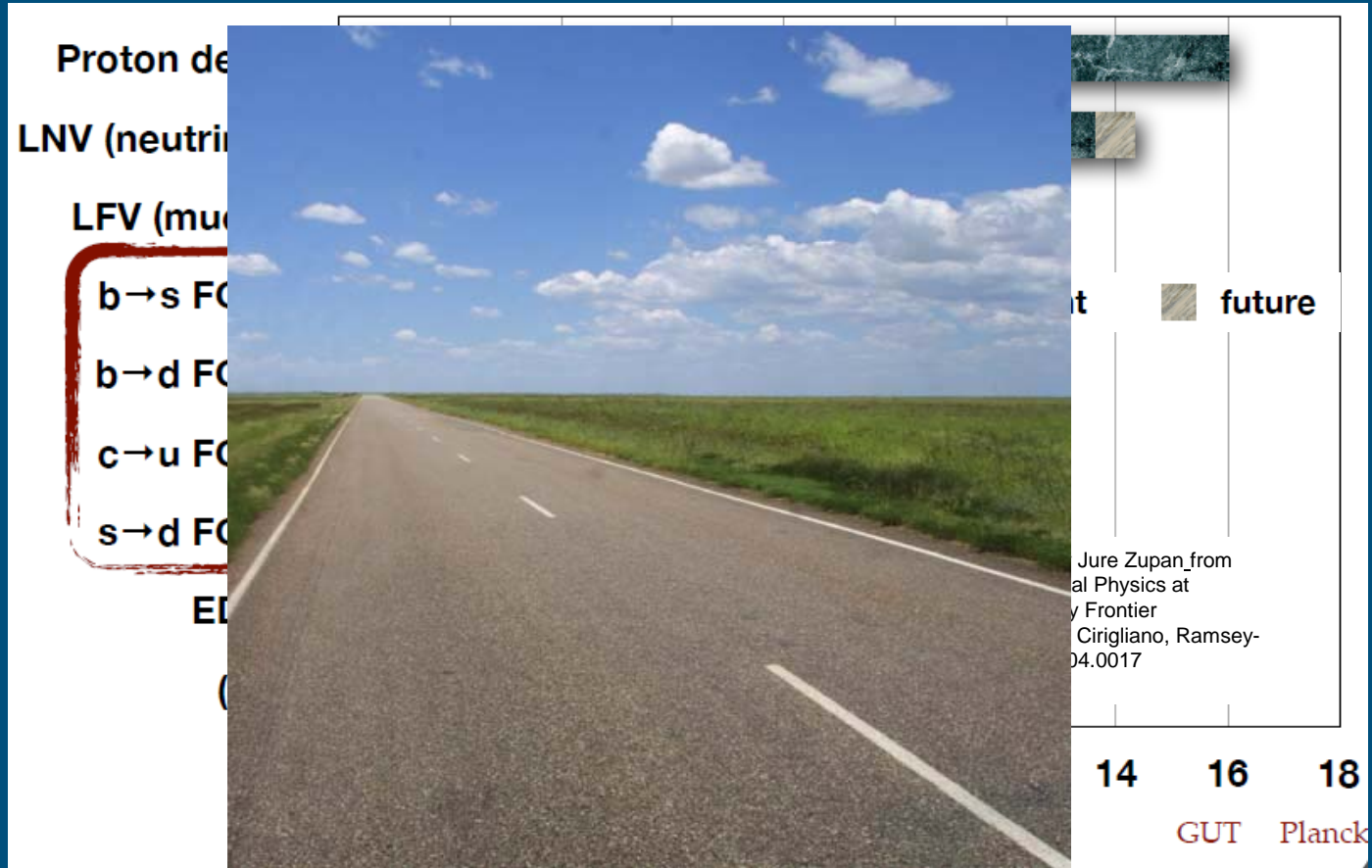


No new particles in sight up to 10⁴ TeV with coupling to flavour!! = 10 000 x direct reach of LHC!

Run 1 Precision – What did we not find?



Push precisions! $\sigma_{stat+sys+th} < \Phi_s^{NP}$

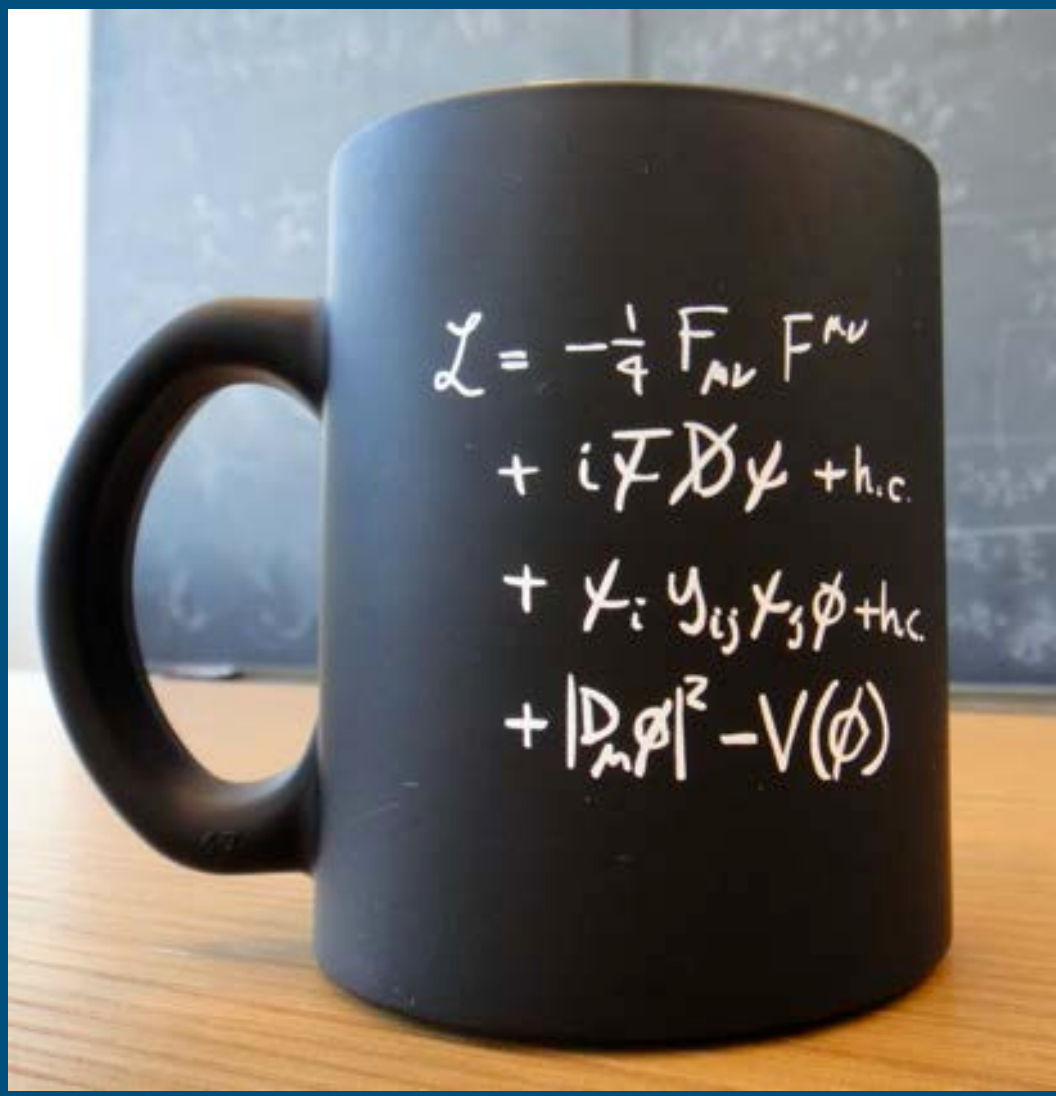


No new particles in sight up to 10^4 TeV with coupling to flavour!! = 10 000 x direct reach of LHC!

Universe 0 K - 10¹⁶K++ in one formula?



- So, is it just this simple...??



	I	II	III	
Quarks	2.4 MeV u	1.3 GeV c	170 GeV t	0 γ
	4.8 MeV d	104 MeV s	4.2 GeV b	0 g
	<2.2 eV ν _e	<0.2 MeV ν _μ	<16 MeV ν _τ	91 GeV Z
Leptons	0.5 MeV e	16 MeV μ	1.8 GeV τ	80 GeV W
				126 GeV H
				Bosons

Validity of SM

Planck scale

GUT scale

10^{27} K

10^{16} K

10^{13} K

10^8 K

10^4 K

10^3 K

2.7 K

New

Physics

(SUSY, extra dimensions, GUT, ...)

Standard

Model

What we thought, or *hoped*....
And still do...

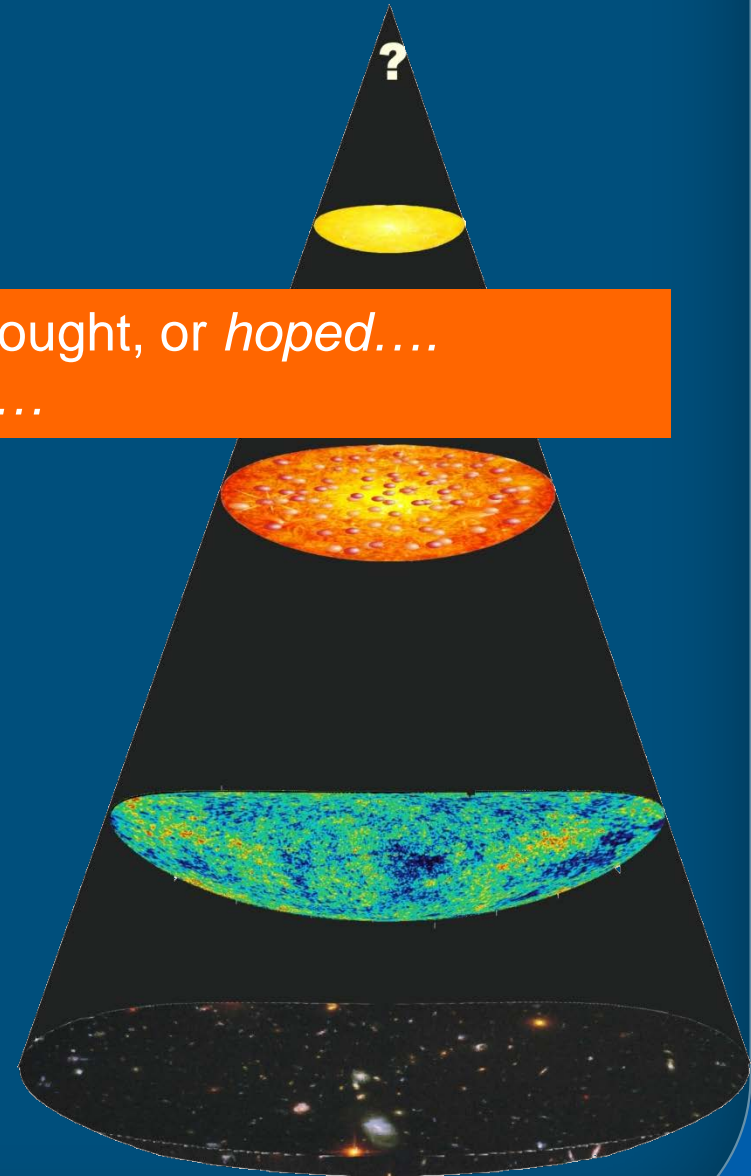
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0.000001 sec

1 min

380 000 yrs

13.7 billion yrs



Validity of SM

Planck scale
GUT scale



0.0000000000000001 sec
0.00001 sec

1 min

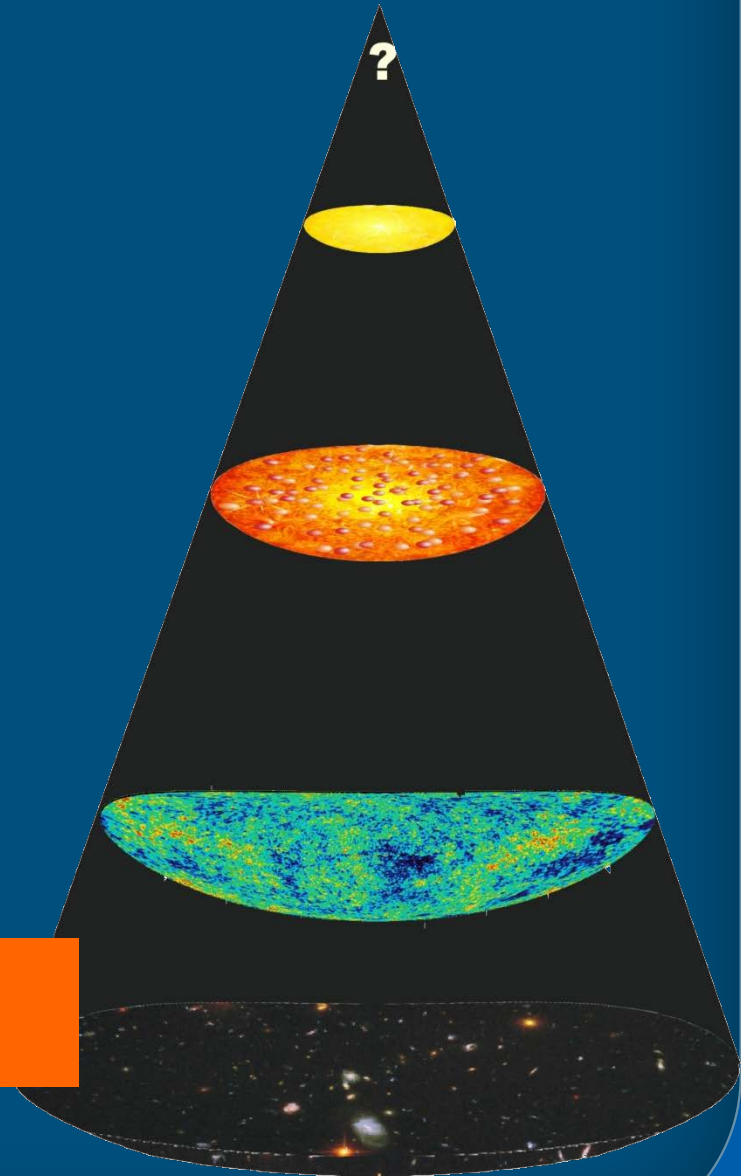
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New Physics

Standard Model

Standard Model works perfectly well
on everything it attempts to explain



Validity of SM

Planck scale
GUT scale

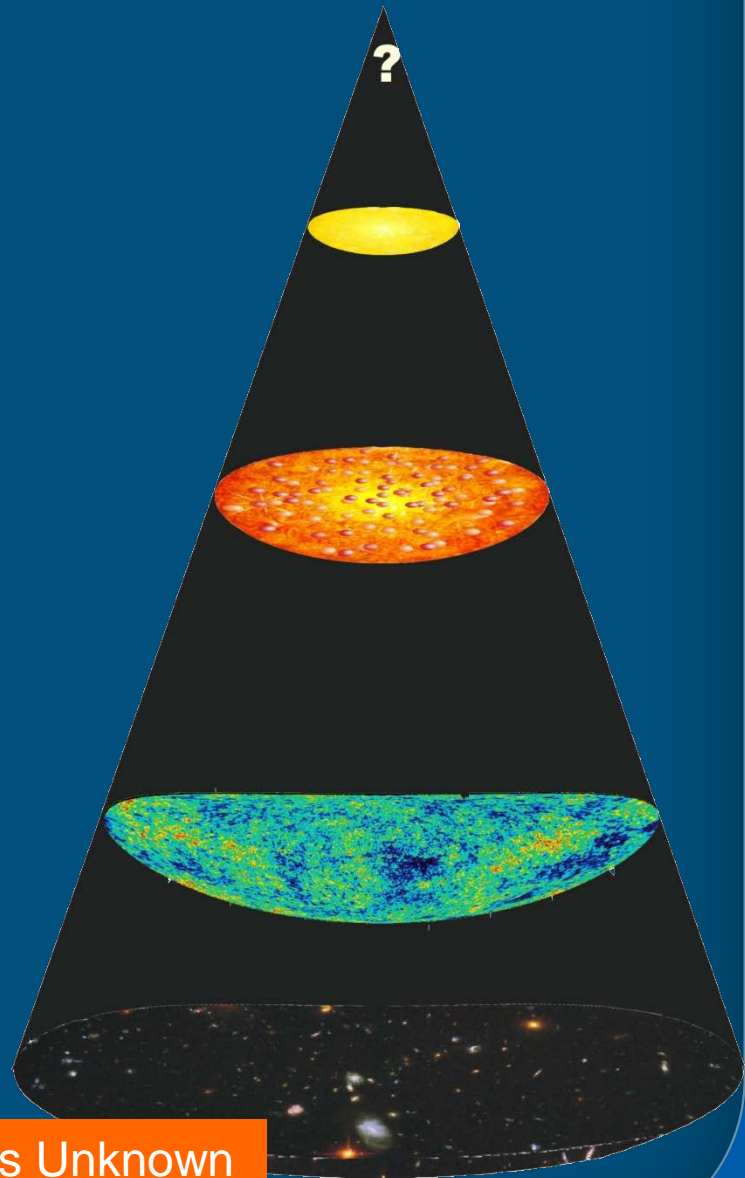
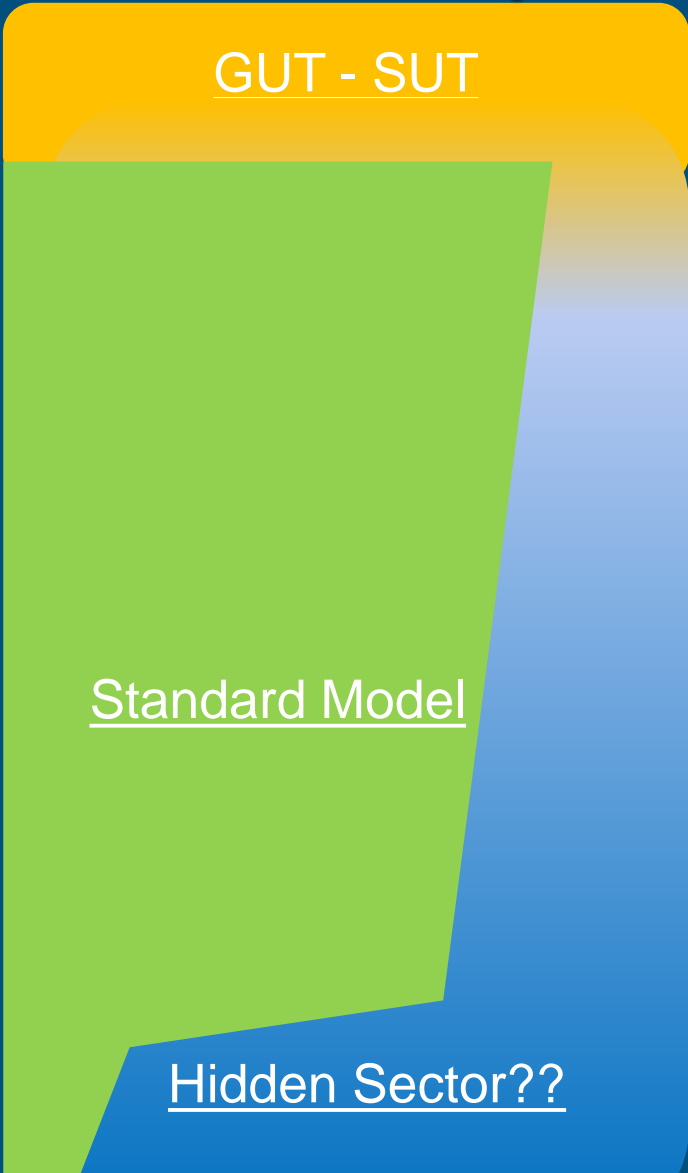


0.0000000000000001 sec
0.000001 sec

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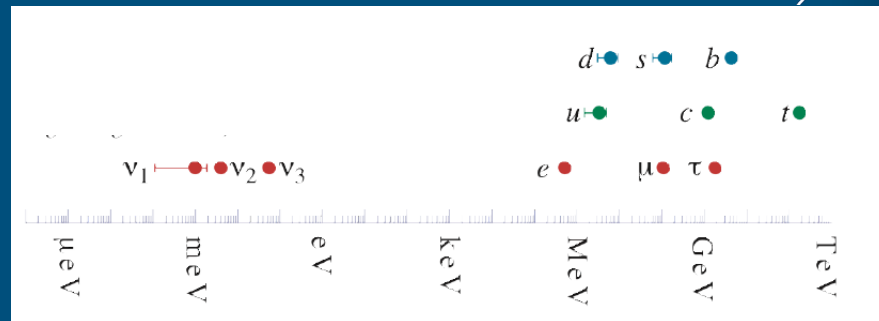


96% of energy content in Universe today is Unknown

Unresolved Experimental Evidence beyond SM

- Neutrino oscillations

→ *Tiny* masses and flavour mixing



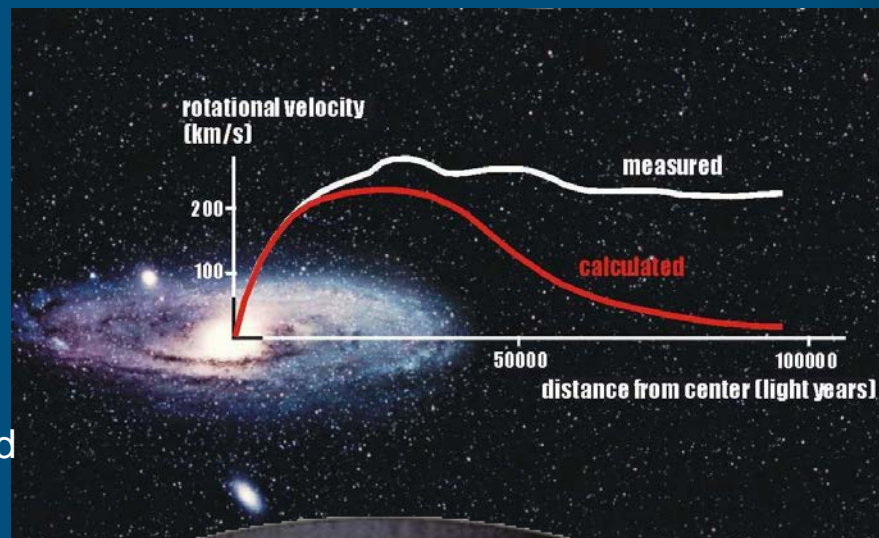
- Baryon asymmetry of the Universe

→ BBN and CMB $\eta = \left\langle \frac{n_B}{n_\gamma} \right\rangle_{T=3K} \sim 6 \times 10^{-10}$

→ CP violation in quark sector $\rightarrow \eta \sim 10^{-20} !!$

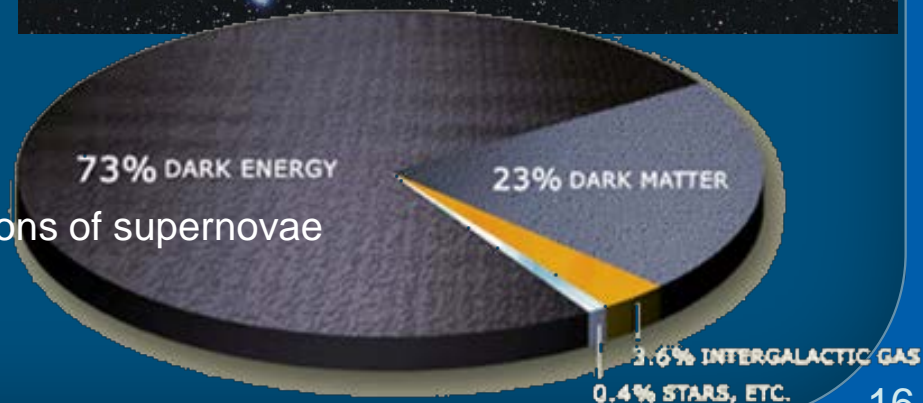
- Dark Matter

→ Non-baryonic, neutral and stable or long-lived



- Dark Energy

→ From apparent luminosity-distance observations of supernovae

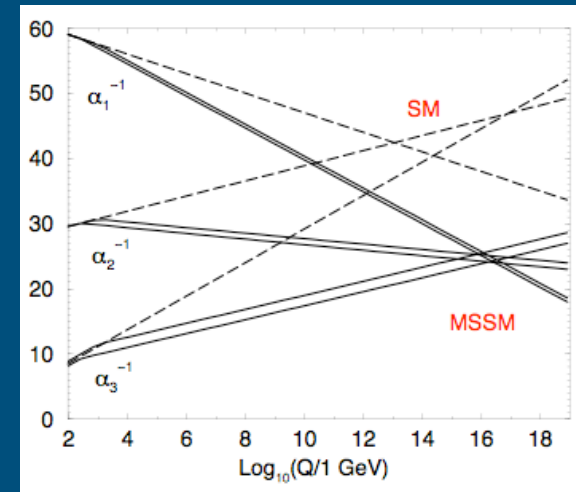
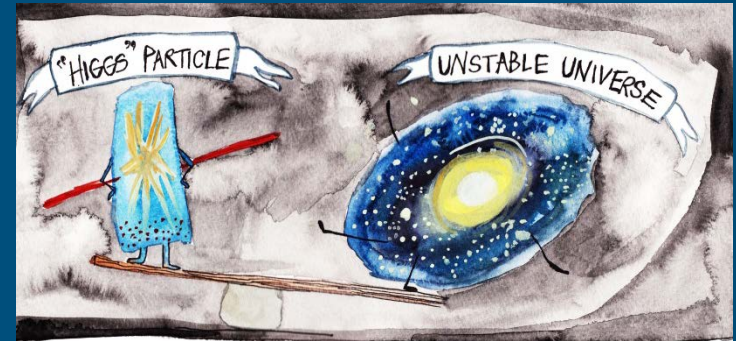
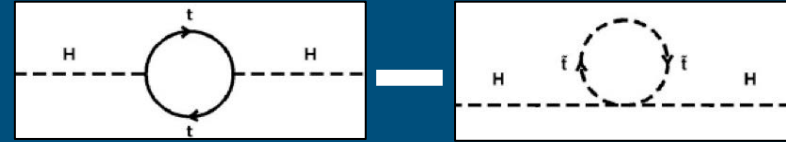


Unresolved Theoretical “Evidence” beyond SM

Prejudice...: “Universe is fine-tuned by chance or *driven* by obligation?”

Below GUT scale:

- Hierarchy problem
→ Stability of Higgs mass
- SM flavour structure
- Strong CP problem
 - In principle, strong interaction comes with a naturally large CP violation, why suppressed?
- Unification of coupling constants
- Gravity



Above GUT scale (next time!)

- Event horizon problem, flatness, density variation which lead to structure formation,

While we had bounds for the Higgs, no hard evidence for the next scale....

??

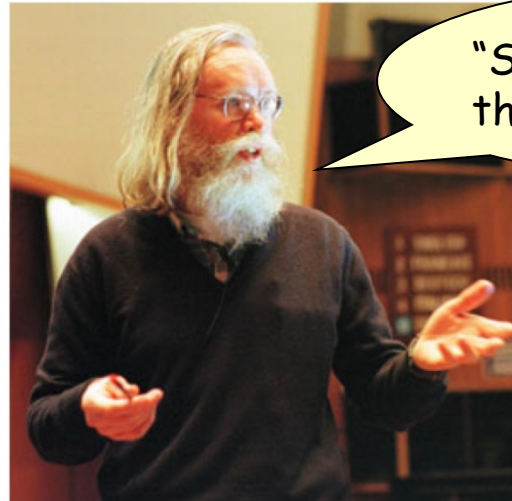


But Where Is Everybody?

Nima

Why still SUSY searches
in 2040++ ?

Indeed, even if fine-tuned,
it makes our universe more likely



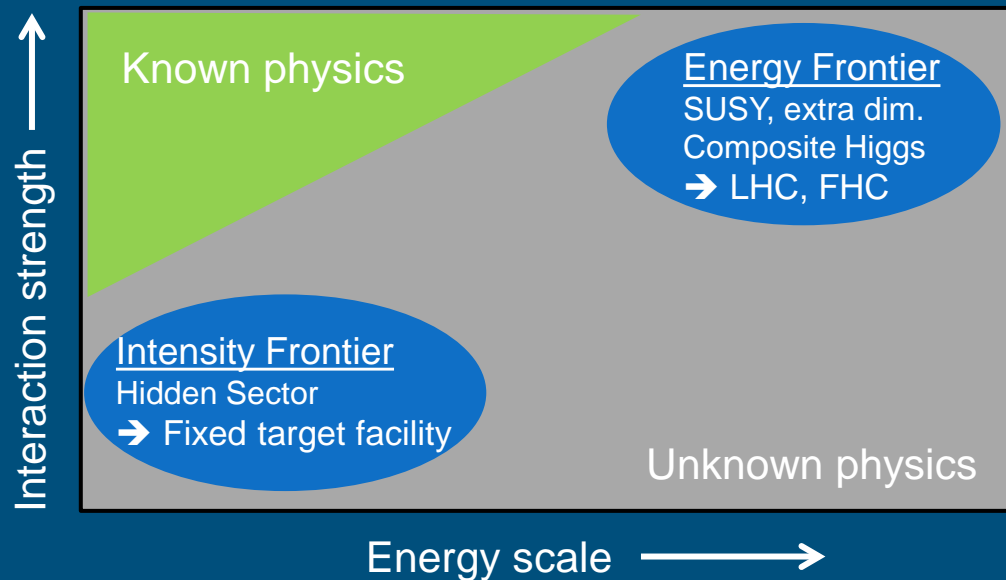
"SUSY anywhere is better
than SUSY nowhere"

Ellis

On the contrary - What if...?



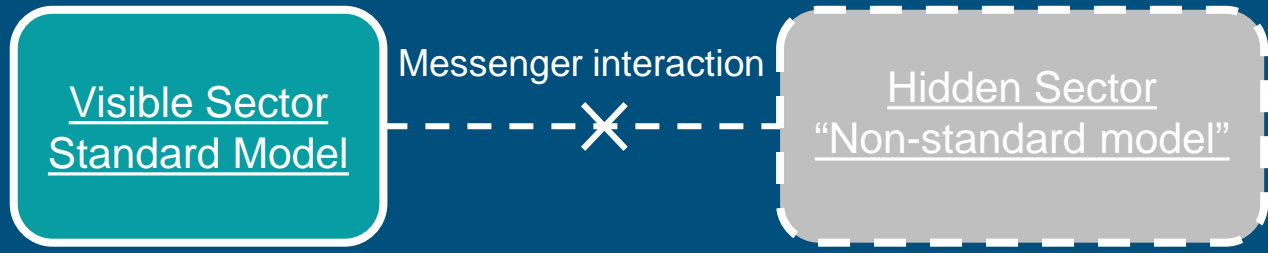
What about solutions to (some) these questions *below* the mass of the W boson?



→ Must have very weak couplings → Hidden Sector

Hidden Sector?

$$\mathcal{L}_{World} = \mathcal{L}_{SM} + \mathcal{L}_{mediation} + \mathcal{L}_{HS}$$



- Most Hidden Sector particles have none of the charges of SM, only make up mass!
 - Hidden Sector may have their own charges and dynamics! → Mirror World

- Some may have both SM and HS charges!

$$\mathcal{L}_{mediation} = \sum_{k,l,n}^{k+l=n+4} \frac{\mathcal{O}_{HS}^{(k)} \mathcal{O}_{SM}^{(l)}}{\Lambda^n}$$

- “Portals” to the Hidden Sector !
- Dynamics of Hidden Sector may drive dynamics of Visible Sector!
 - Dark Matter
 - Higgs mass
 - Neutrino oscillations
 - Baryon asymmetry
 - Dark Energy
 - Inflaton
 -

Examples of Portals to Hidden Sector



Standard Model portals:

D = 2: Vector portal

- Kinetic mixing with massive dark/secluded/paraphoton $V : \frac{1}{2} \epsilon F_{\mu\nu}^{SM} F_{HS}^{\mu\nu}$

→ Interaction with 'mirror world' constituting dark matter

D = 2: Higgs portal

- Mixing with dark scalar $\chi : (\mu\chi + \lambda\chi^2)H^\dagger H$

→ Mass to Higgs boson and right-handed neutrino, and function as inflaton in accordance with Planck and BICEP measurements

D = 5/2: Neutrino portal

- Mixing with right-handed neutrino N (Heavy Neutral Lepton): $YH^\dagger \bar{N}L$

→ Neutrino oscillation, baryon asymmetry, dark matter

D = 4: Axion portal

- Mixing with axion like particles, pseudo-scalars, axial vectors : $\frac{a}{F} G_{\mu\nu} \tilde{G}^{\mu\nu}, \frac{\partial_\mu a}{F} \bar{\psi} \gamma_\mu \gamma_5 \psi$, etc

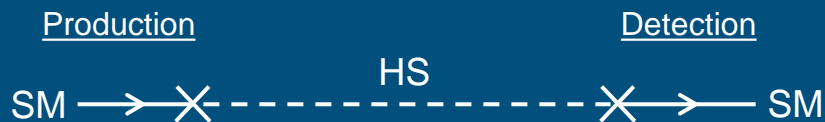
→ Solve strong CP problem

- And higher dimensional operator portals and supersymmetric portals (light sgoldstino, light neutralino,...)

Common features of ‘Portals’ to Hidden Sector



“Direct detection” through both portals in and out:



- ◉ Cosmologically interesting and accessible $m_{HS} \sim \mathcal{O}(MeV - GeV)$
 - Production through meson decays (π , K, D, B)
 - Decay to l^+l^- , $\pi^+\pi^-$, $l\pi$, $l\rho$, $\gamma\gamma$, etc
 - ◉ Production and decay rates are very suppressed relative to SM.
 - Production branching ratios $\mathcal{O}(10^{-10})$
 - Long-lived objects
 - Travel unperturbed through *ordinary* matter
 - Fixed-target experiment
 - Large number of protons on target and large decay volume!
- Experimental challenge → Intensity Frontier**
- Complementary physics program to searches for new physics by LHC!

Ex. Right-handed Majorana neutrinos



Three Generations of Matter (Fermions) spin 1/2

	I	II	III	
mass	2.4 MeV	1.27 GeV	173.2 GeV	0
charge	2/3	2/3	2/3	0
name	Left up Right u	Left charm Right c	Left top Right t	g gluon
Quarks	Left down Right d	Left strange Right s	Left bottom Right b	0 0 0 γ photon
	Left electron neutrino Right ν _e	Left muon neutrino Right ν _μ	Left tau neutrino Right ν _τ	91.2 GeV 0 0 Z weak force
Leptons	Left electron Right e	Left muon Right μ	Left tau Right τ	126 GeV 0 0 H Higgs boson
	0.511 MeV	105.7 MeV	1.777 GeV	80.4 GeV ±1 W [±] weak force
				spin 0



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Ex. νMSM with Heavy Neutral Leptons by Asaka and Shaposhnikov

Role of N_1 with a mass of $\mathcal{O}(\text{keV})$
 → Dark Matter

Role of N_2 and N_3 with a mass of $\mathcal{O}(m_q/m_{l\pm})$ (100 MeV – GeV):
 → Neutrino oscillations and mass, and matter-antimatter asymmetry

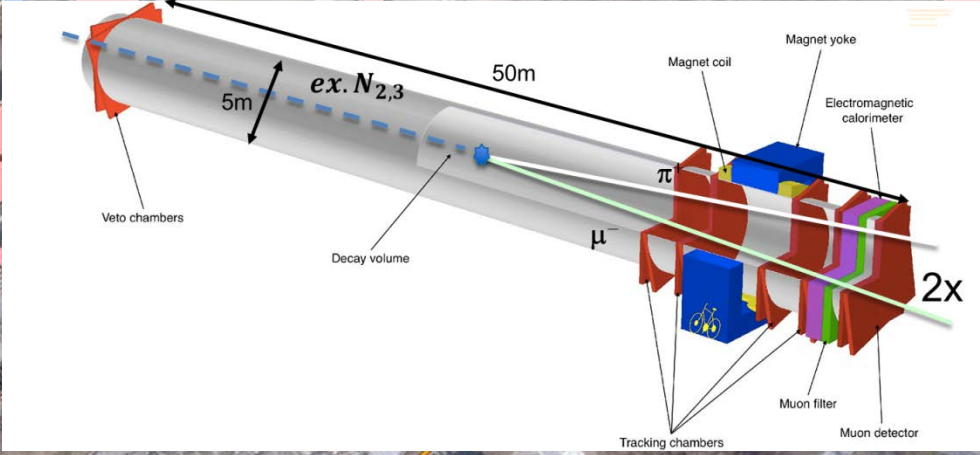
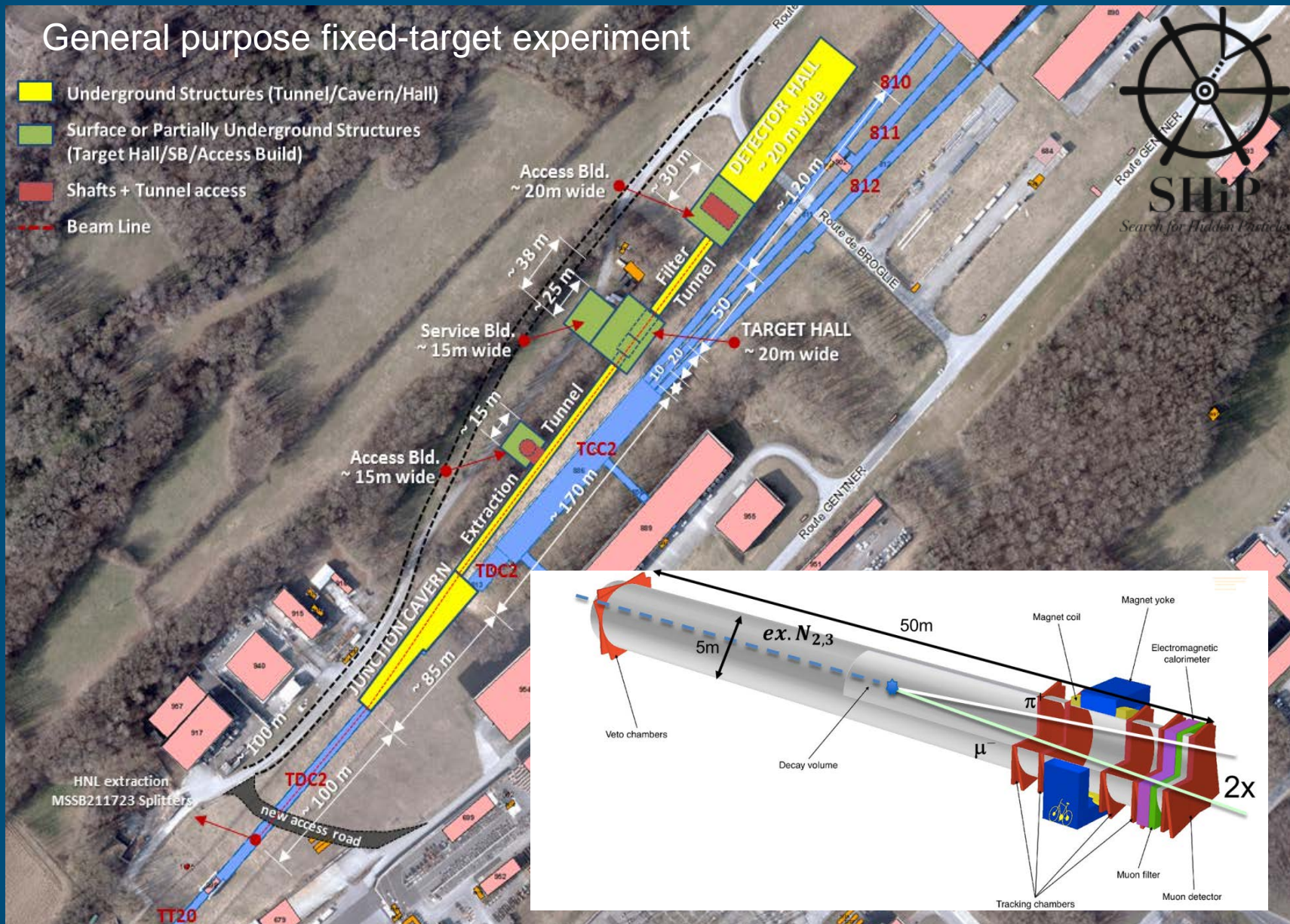
Simple extension and no new energy scale!

Proposal: Search for Hidden Particles



General purpose fixed-target experiment

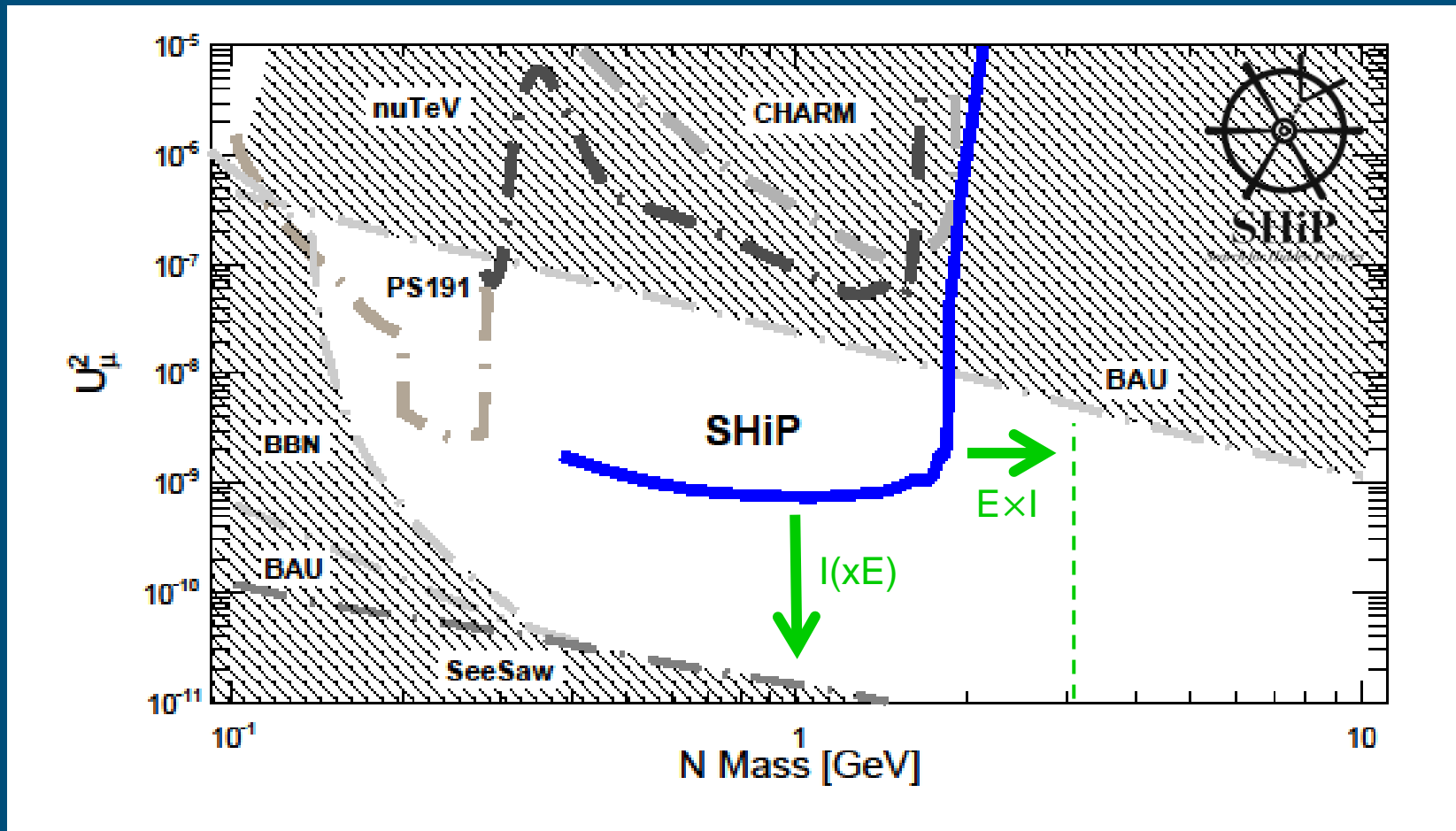
- Underground Structures (Tunnel/Cavern/Hall)
- Surface or Partially Underground Structures (Target Hall/SB/Access Build)
- Shafts + Tunnel access
- Beam Line



Ex. Expected Sensitivity to $N_{2,3} \rightarrow \mu\pi$



Sensitivity based on current SPS with 2×10^{20} p.o.t in ~ 5 years of CNGS-like operation





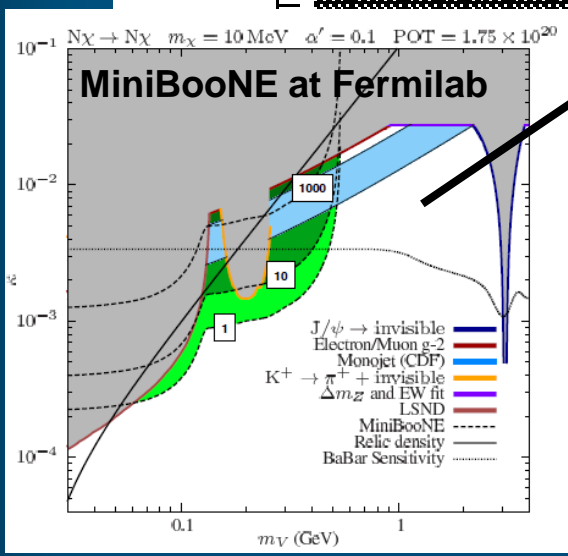
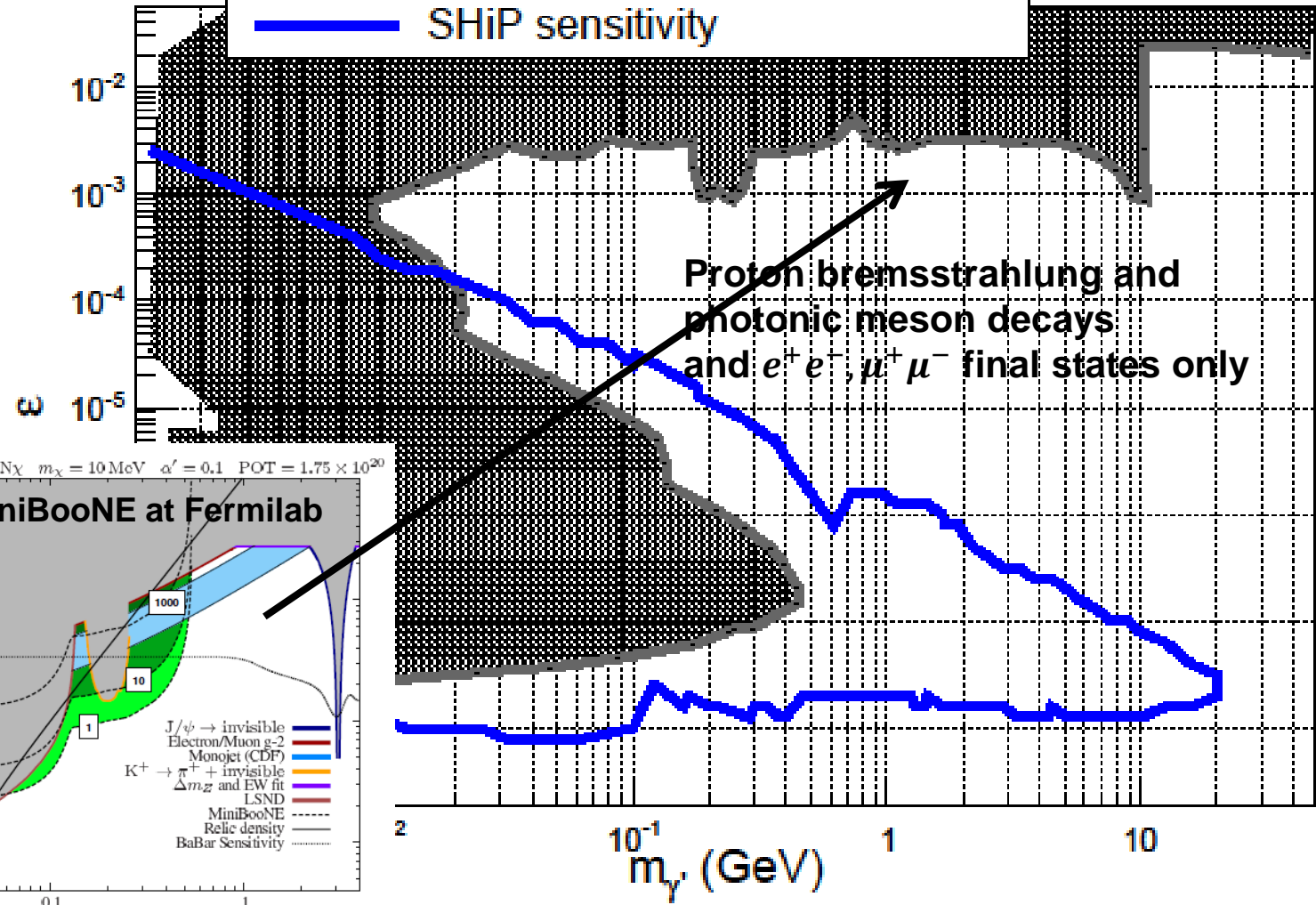
→ Colliders out of luck

- LHC ($\sqrt{s} = 14$ TeV): with 1 ab^{-1} , i.e. 3-4 years: $\sim 2 \times 10^{16}$ in 4π
- SPS@400 ($\sqrt{s} = 27$ GeV) with 2×10^{20} pot, i.e. ~ 5 years: $\sim 2 \times 10^{17}$

Ex. Expected sensitivity to Dark Photons





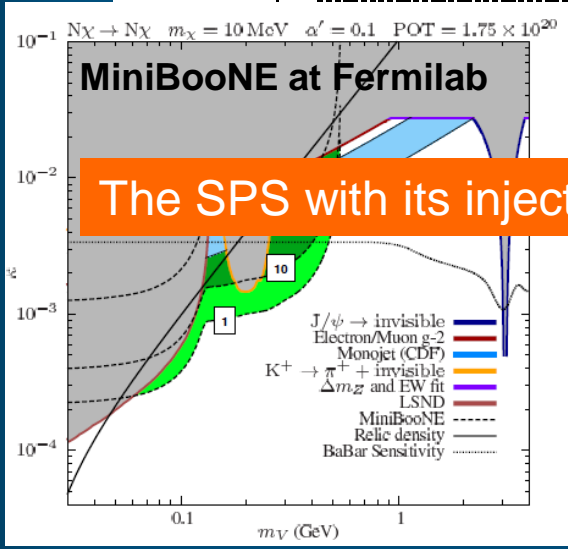
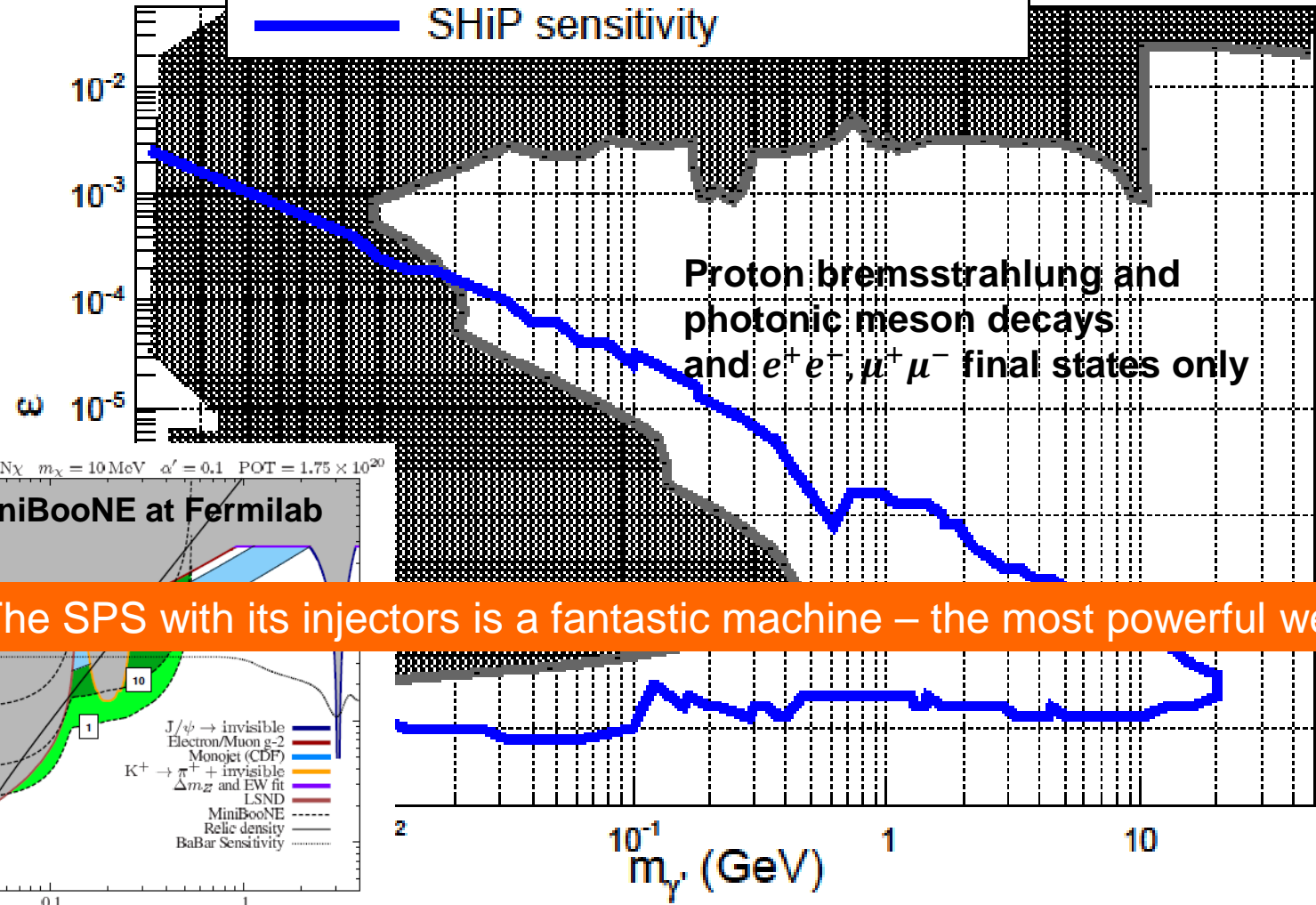
 Current limits on dark photons
 SHiP sensitivity



Ex. Expected sensitivity to Dark Photons



 Current limits on dark photons
 SHiP sensitivity



The SPS with its injectors is a fantastic machine – the most powerful we have!

Conclusions



We worried about finding just a Standard Model Higgs....



Conclusions



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...but taking all experimental results together with the remarkable progress in cosmological observations and theory makes the situation even more intriguing!

Conclusions



We worried about finding just a Standard Model Higgs....



...but taking all experimental results together with the remarkable progress in cosmological observations and theory makes the situation even more intriguing!

- The future requires a very open strategy and multiple points of attack!
 - Continued searches with the opening of a new energy domain at ~ 13 TeV
 - Precision measurements of Higgs and the top quark
 - Precision measurements in flavour physics
 - ...and...
 - Searches for a Hidden Sector!
- SPS is the most powerful machine there is around
- However, it remains clear, whatever is found or not found will require
 - Future colliders
 - ...and...
 - Future (fast cycling!) injectors for fixed target experiments!

Conclusions

We worried about finding just a Standard Model Higgs....



...but taking all experimental results together with the remarkable progress in cosmological observations and theory makes the situation even more intriguing!



Let's not run out of fuel!

- The future requires
 - Continued search for new particles
 - Precision measurements
 - Precision measurements
 - ...and...
 - Searches for a dark sector
- SPS with its injector
- However, it remains a challenge
 - Future colliders
 - ...and...
 - Future (fast cycling!) injectors for fixed target experiments!

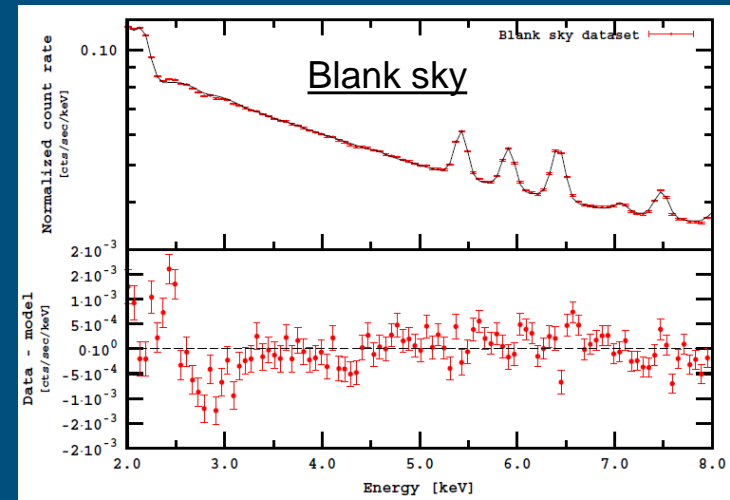
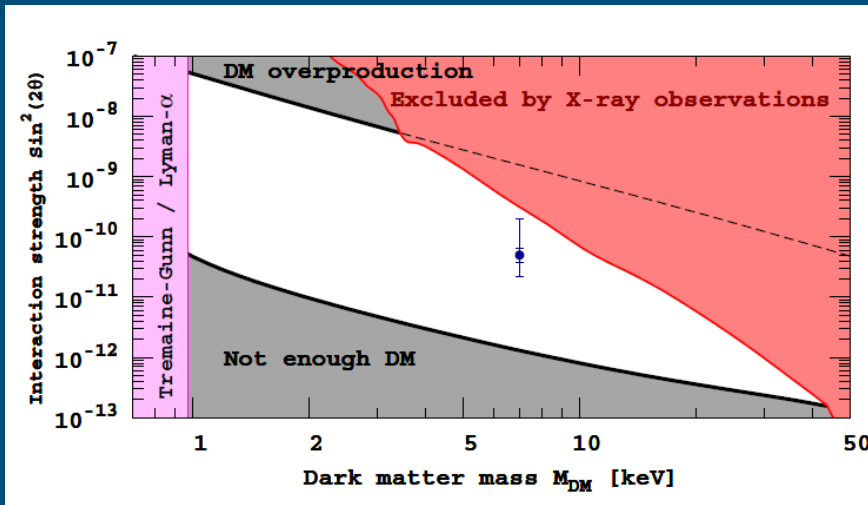
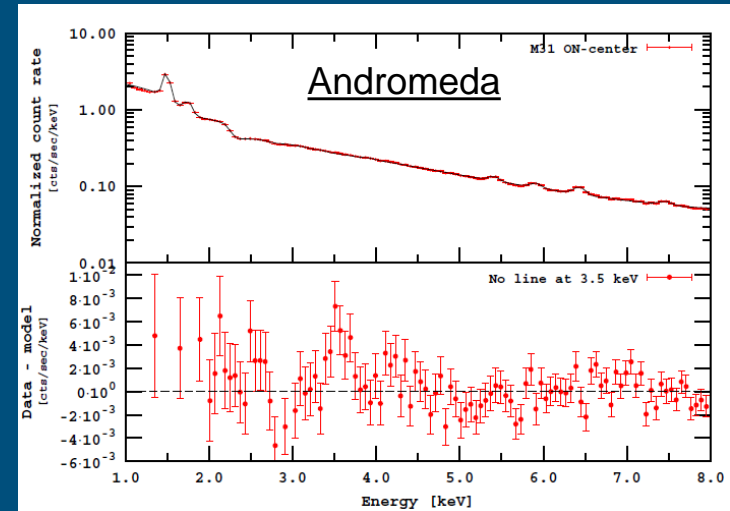
of attack!
 ~13 TeV
 ground
 require

Reserve

Intriguing hints from galaxy spectrum?

○ Two recent publications:

- ➔ arXiv:1402.2301 : Detection of an unidentified emission line in the stacked XMM-Newton X-ray spectra of Galaxy Clusters at $E_\gamma \sim (3.55 - 3.57) \pm 0.03 \text{ keV}$
- ➔ arXiv:1402.4119 : An unidentified line in the X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster at $E_\gamma \sim 3.5 \text{ keV}$



Confirmation by Astro-H with better energy resolution required