Adam Falkowski

July 2018

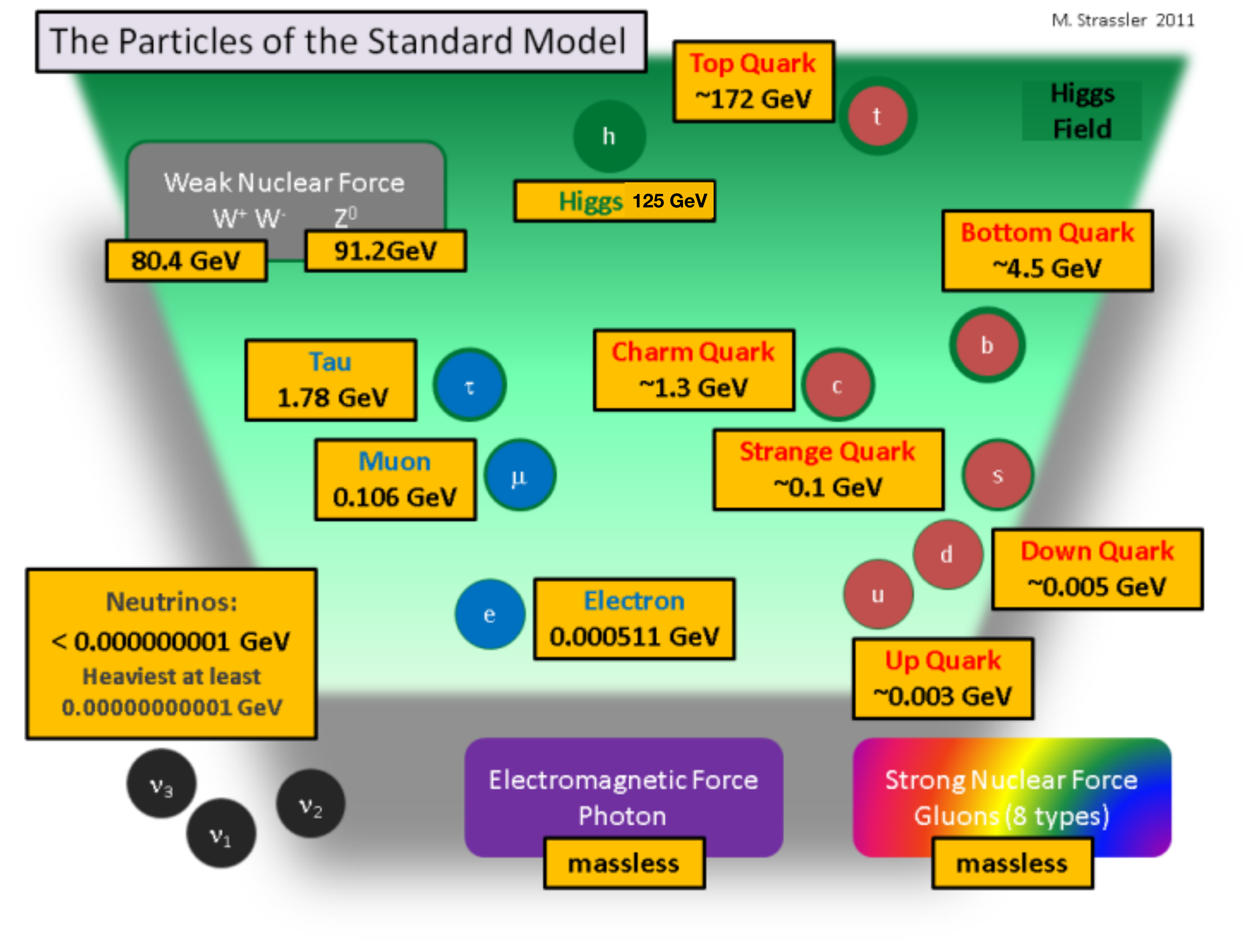
Future of Physics Beyond the Standard Model

Plan

- Part 1: Why must there be something else to discover?
- Part 2: Which theory beyond the Standard Model is the right one?
- Part 3: Future of high-energy colliders
- Part 4: Future of low-energy precision physics
- Part 5: Most promising experimental anomalies

Part 0

The Standard Model

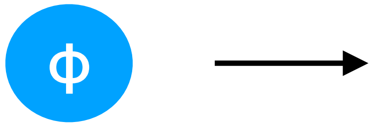


Borrowed from Matt Strassler's blog: http://profmattstrassler.com/

Framework

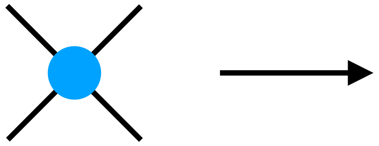
Relativistic quantum field theory (QFT):

- Particles (and their antiparticles) represented by fields with definite transformation properties under Lorentz transformations depending by particle's spin



$\phi(x)$

- Interactions between particles are encoded in a Lagrangian that is a local, hermitian and Lorentz-invariant function of the fields



$\mathscr{L}(\phi)$

- Each spin-1 (vector) particle comes with a corresponding local (gauge) symmetry that is strictly respected by the Lagrangian

$$\partial_\mu \phi \to D_\mu \phi \equiv \partial_\mu \phi - igT^a A^a_\mu \phi$$

Defining principles of Standard Model

	$SU(3)_C$	$SU(2)_W$	$U(1)_Y$
$q = (u_L,d_L)$	3	2	1/6
u_R	3	1	2/3
d_R	3	1	-1/3
$l = (\nu_L,e_L)$	1	2	-1/2
e_R	1	1	-1
H	1	2	1/2

$$Q = T_W^3 + Y$$

- Invariance under local (gauge) symmetry $SU(3)_C{*}SU(2)_L{*}U(1)_Y$ implementing the strong, weak, and electromagnetic forces in nature. Matter content and its transformation under local symmetry deduced from experiment

- Local symmetry spontaneously broken down to $SU(3)_C{*}U(1)_{EM}$ by vacuum expectation value of Higgs field H, implementing short range of the weak force (that is mass of W and Z bosons) and also allowing masses for matter fields

$$\langle H \rangle = \frac{1}{\sqrt{2}} \binom{0}{v}$$

- Renormalizability, postulating that only interaction terms up to mass dimension 4 can appear in Lagrangian, allowing for (in principle) infinite precision of physical predictions

Standard Model Lagrangian

$$\mathscr{L}_{\mathrm{SM}} = -\frac{1}{4}\sum_{V\in B,W^i,G^a} V_{\mu\nu}V^{\mu\nu} + \sum_{f\in q,u,d,l,e} i\bar{f}\gamma^\mu D_\mu f$$

$$-\left(\bar{u}Y_u qH + \bar{d}Y_d H^\dagger q + \bar{e}Y_e H^\dagger l + \mathrm{h.c.}\right)$$

$$+D_\mu H^\dagger D^\mu H + \mu_H^2 H^\dagger H - \lambda(H^\dagger H)^2$$

e.g.

$$\xcancel{V_\mu V_\mu}$$

forbidden
by local symmetry

e.g.

$$\frac{c_6}{\Lambda^2}\xcancel{(H^\dagger H)^3}$$

forbidden
by renormalizability

$$D_\mu f = \partial_\mu f - ig_s G^a_\mu T^a f - ig_L W^i_\mu \frac{\sigma^i}{2} f - ig_Y B_\mu Y f$$

$$V^a_{\mu\nu} = \partial_\mu V^a_\nu - \partial_\nu V^a_\mu + g f^{abc} V^b_\mu V^c_\nu$$

Dimensional analysis crash course

$c = 1 \rightarrow 3 \times 10^8 \text{ m} = 1 \text{ sec}$

$\hbar = 1 \rightarrow 6.6 \times 10^{-16} \text{ sec} = \frac{1}{\text{eV}}$

$$S = \int d^4x \left[\partial_\mu \phi^\dagger \partial_\mu \phi - \frac{1}{4}(\partial_\mu A_\nu - \partial_\nu A_\mu)^2 + i\bar{\psi}\gamma_\mu \partial_\mu \psi + \dots \right]$$

$[S] = \text{mass}^0$ & $[\partial] = \text{mass}^1$

$$[\phi] = \text{mass}^1$$

$$[A_\mu] = \text{mass}^1$$

$$[\psi] = \text{mass}^{3/2}$$

Standard Model success story

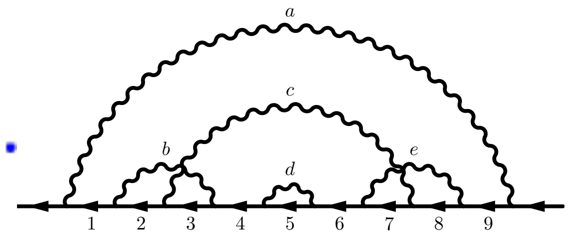
- SM applied to enormous range of experimental observables, from collisions at the LHC (E⩽ few TeV) to atomic physics (E ~ eV)
- Currently, no human-made experiment displays unambiguous deviation from SM prediction
- In some cases, agreement with theory and experiment reaches unbelievable levels, in particular for electron's magnetic moment

Magnetic moment

Fine structure constant

Spin

$$\vec{\mu}_e = g_e \frac{\sqrt{4\pi\alpha}}{2m_e} \vec{S}_e, \quad g_e \equiv 2(1 + a_e), \quad a_e = \frac{\alpha}{2\pi} + \ldots$$



Gyromagnetic factor

Mass

Experiment measures: $a_e = 0.00115965218073(28)$

SM predicts: $a_e = 0.00115965218161(23)$

Agreement up to 13th digit!

Part 1

Why should there be something to discover?

Why BSM?

Standard Model (SM) is a perfectly consistent theories at accessible energies, and it perfectly well describes wide range of phenomena in collider and many other experiments. However, it is certainly not ultimate theory of nature:

- **It will break down as perturbative theory near Planck scale, at $E \approx 10^{19}$ GeV, where gravitational interactions become strong**
- **If decoupled from gravity somehow, U(1) hypercharge group of has Landau pole where its gauge coupling becomes non-perturbative**

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$$\mathscr{L}_{\rm SM}(\eta,\partial) \to \mathscr{L}_{\rm SM+GR} = \sqrt{-g}\left(-\frac{M_{\rm Pl}^2}{2}R + \mathscr{L}_{\rm SM}(g,D)\right) \longleftarrow$$

Quantum theory for SM gravity

$$g_{\mu\nu} = \eta_{\mu\nu} + \frac{1}{M_{\rm Pl}}h_{\mu\nu} \longleftarrow$$

Spin-2 graviton particle as fluctuation of GR metric

$$\mathscr{L}_{\rm SM+GR} \supset \frac{1}{M_{\rm Pl}}h_{\mu\nu}T^{\mu\nu} \longleftarrow$$

Graviton couples to energy-momentum tensor

$$T_{\mu\nu} = F_{\mu\rho}F^{\rho}_{\nu} + \dots$$

$$\mathscr{M}(\gamma\gamma \to h^{(2)}h^{(2)}) \sim \boxed{\frac{E^2}{M_{\rm Pl}^2}} \longleftarrow$$

Amplitudes with graviton grow with energy and become non-perturbative for E > M_{PL}

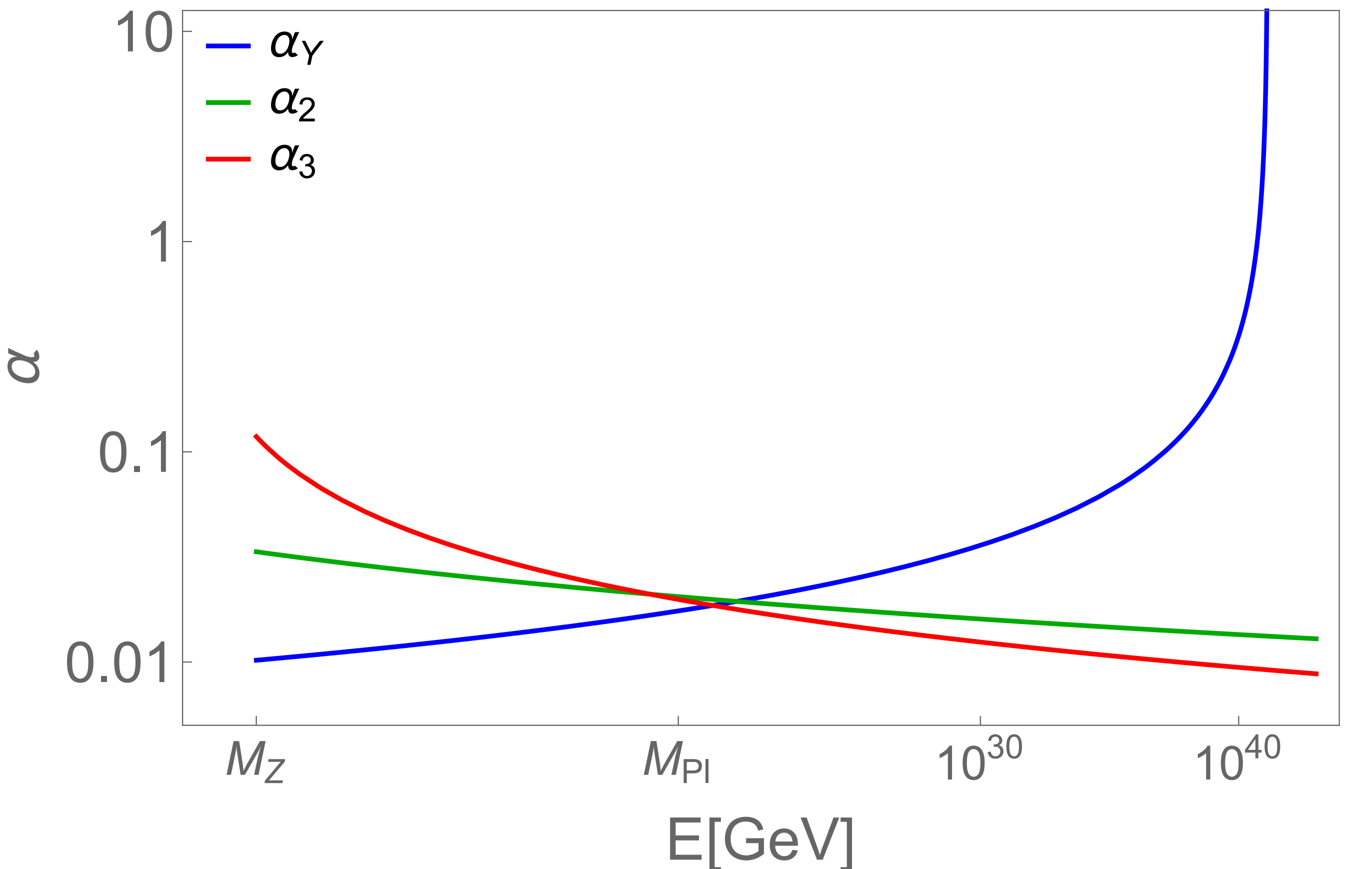
Why BSM?

Standard Model (SM) is a perfectly consistent theories at accessible energies, and it perfectly well describes wide range of phenomena in collider and many other experiments. However, it is certainly not ultimate theory of nature:

- **If decoupled from gravity somehow, U(1) hypercharge group of has Landau pole where its gauge coupling becomes non-perturbative**

$$\frac{1}{\alpha_i(E)} = \frac{1}{\alpha_i(m_Z)} - \frac{b_i}{2\pi} \log\left(\frac{E}{m_Z}\right)$$

$$b_Y = \boxed{\frac{41}{6}}, \quad b_2 = -\frac{19}{6}, \quad b_3 = -7$$



Why BSM?

Standard Model (SM) is a perfectly consistent theories at accessible energies, and it perfectly well describes wide range of phenomena in collider and many other experiments However, it is certainly not ultimate theory of nature:

Yet we have good reasons to think that it becomes invalid well below the Planck scale:

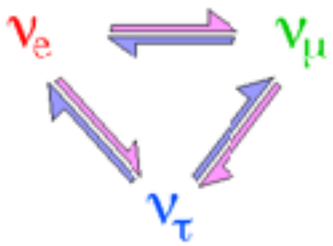
- **Phenomenological Reasons:**
  There exist experimental observations that require new physics below the Planck scale

- **Esthetic Reasons:**
  Certain puzzling aspects of the SM hint at a deeper explanation via new physics

Phenomenological Reasons
For Physics Beyond the Standard Model

A number of experimental observations cannot be explained within the framework of the Standard Model

- Neutrino Oscillations
- Dark Matter
- Baryon Asymmetry
- Inflation



Pheno reasons: neutrino oscillations

- Neutrino physics provides most robust evidence to date for existence of physics beyond SM
- In the SM, there are left-handed but no right-handed neutrinos. Therefore neutrinos are massless once condition of renormalizability is imposed
- It was discovered back in the 90s that neutrinos oscillate = neutrinos of different flavors change into one another. This happens when mass eigenstates are different than flavor eigenstate
- For massless particles, one can always rotate mass eigenstates such that they coincide with flavor eigenstates. Therefore, no doubt that at least 2 neutrinos have masses, which means that SM as originally defined is incomplete
- Trivial to add singlet right-handed neutrino ν^c and write new appropriate Yukawa couplings to make neutrino massive. But neutrinos are so much lighter than other fermions that we suspect different mechanism is in play

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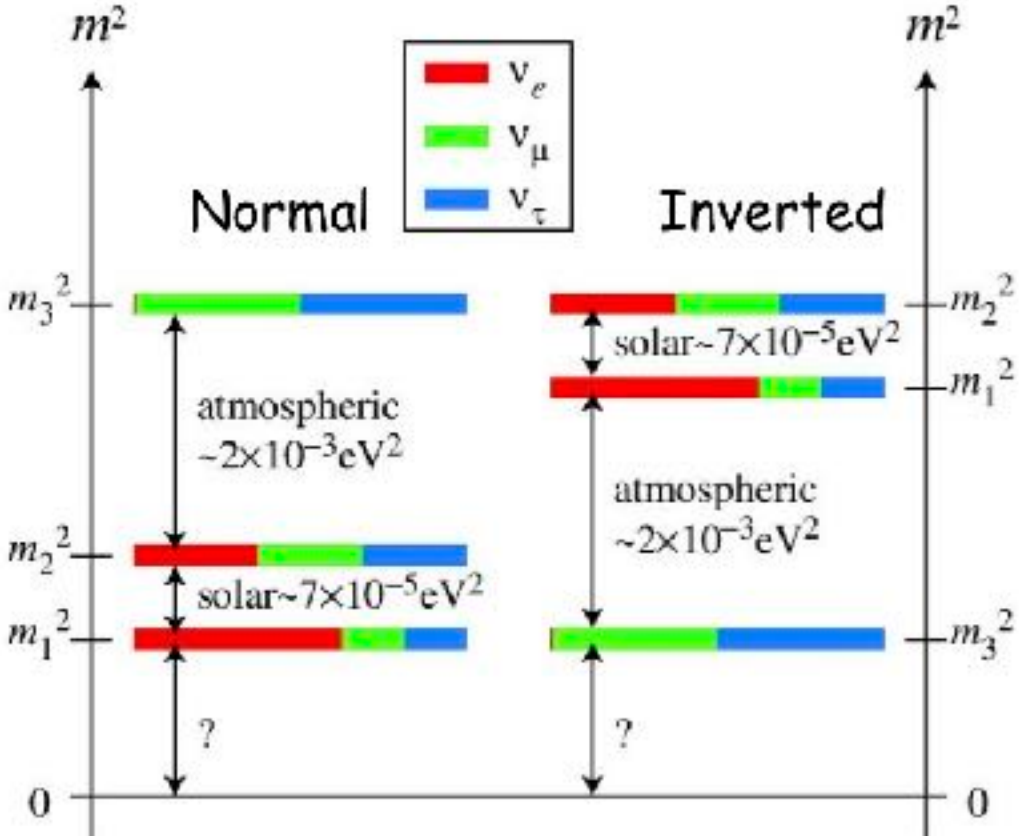
absence of RH neutrino field	**SM local symmetry**	**SM renormalizability**
$\cancel{\bar{\nu}_R \nu_L}$	$\cancel{\nu_L \nu_L}$	$\cancel{(Hl)(Hl)}$



Pheno reasons: dark matter

- Another robust experimental fact requiring physics beyond the Standard Model is the existence of dark matter
- The need for a new matter component that emits little light has been noticed almost 100 years ago by Zwicky from observations of the Coma cluster
- More robust evidence for dark matter emerged in the 1970s from observations of galactic rotation curves by Ford, Rubin, Freeman and others
- Finally, WMAP and Planck satellite observations of the CMB demonstrated unequivocally that dark matter cannot be made of any known particles

For more history see
Bertone Hooper
1605.04909

An ~~The~~ Evidence for DM

1) galaxy rotation curves

$$m\frac{v_c^2(r)}{r} = \frac{G_N m M(r)}{r^2}$$

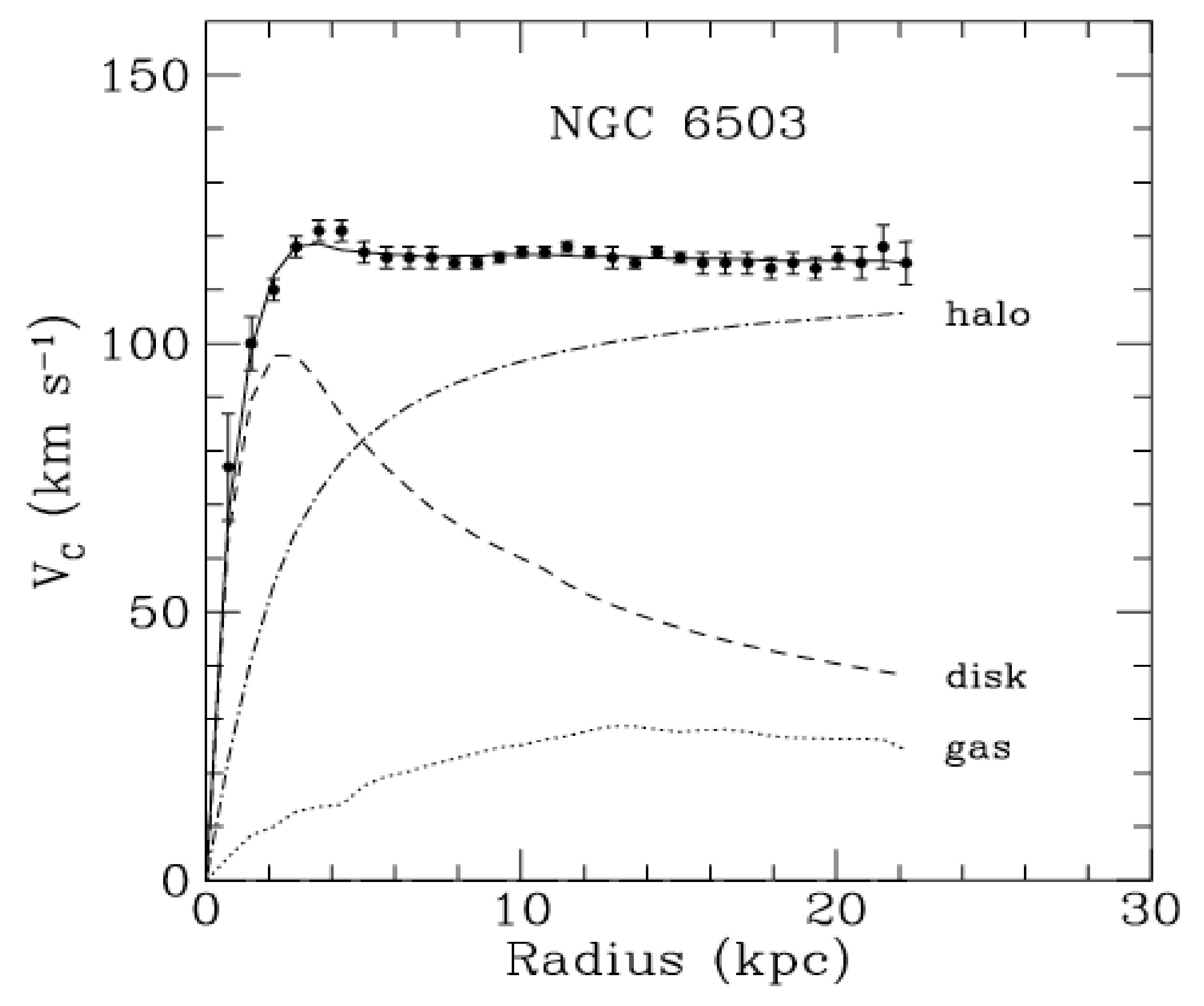
'centrifugal' 'centripetal'

$$v_c(r) = \sqrt{\frac{G_N M(r)}{r}}$$

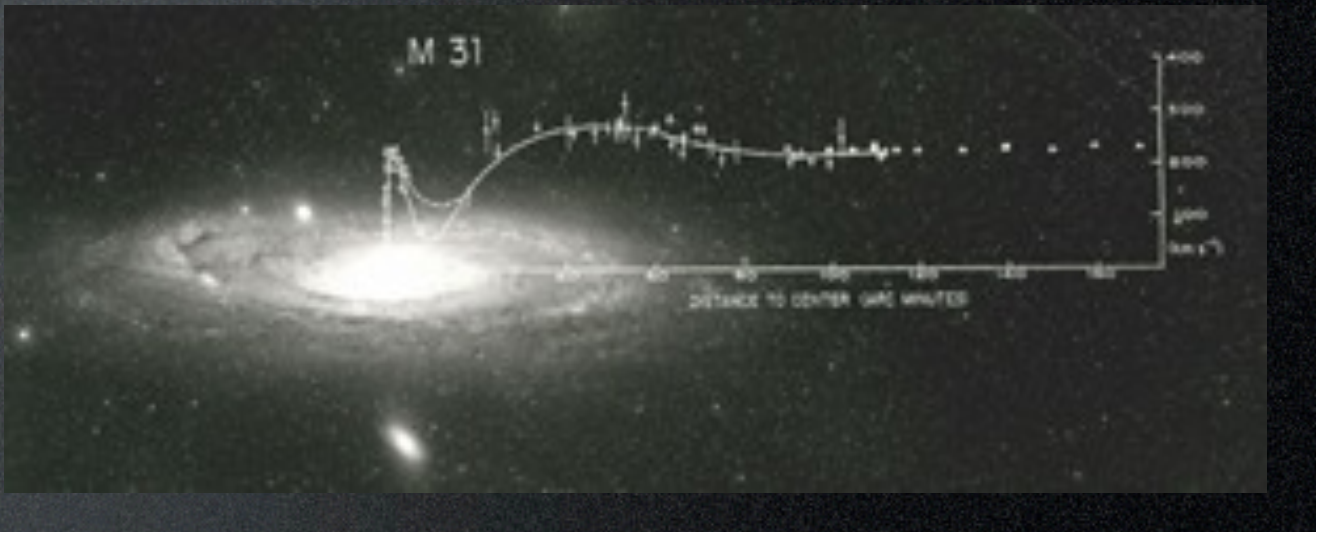
with $M(r) = 4\pi \int \rho(r)\, r^2 dr$

$$v_c(r) \sim \text{const} \Rightarrow \rho_M(r) \sim \frac{1}{r^2}$$

$$\Omega_\text{M} \gtrsim 0.1$$



Begeman et al., MNRAS 249 (1991)



Slide borrowed from M. Cirelli

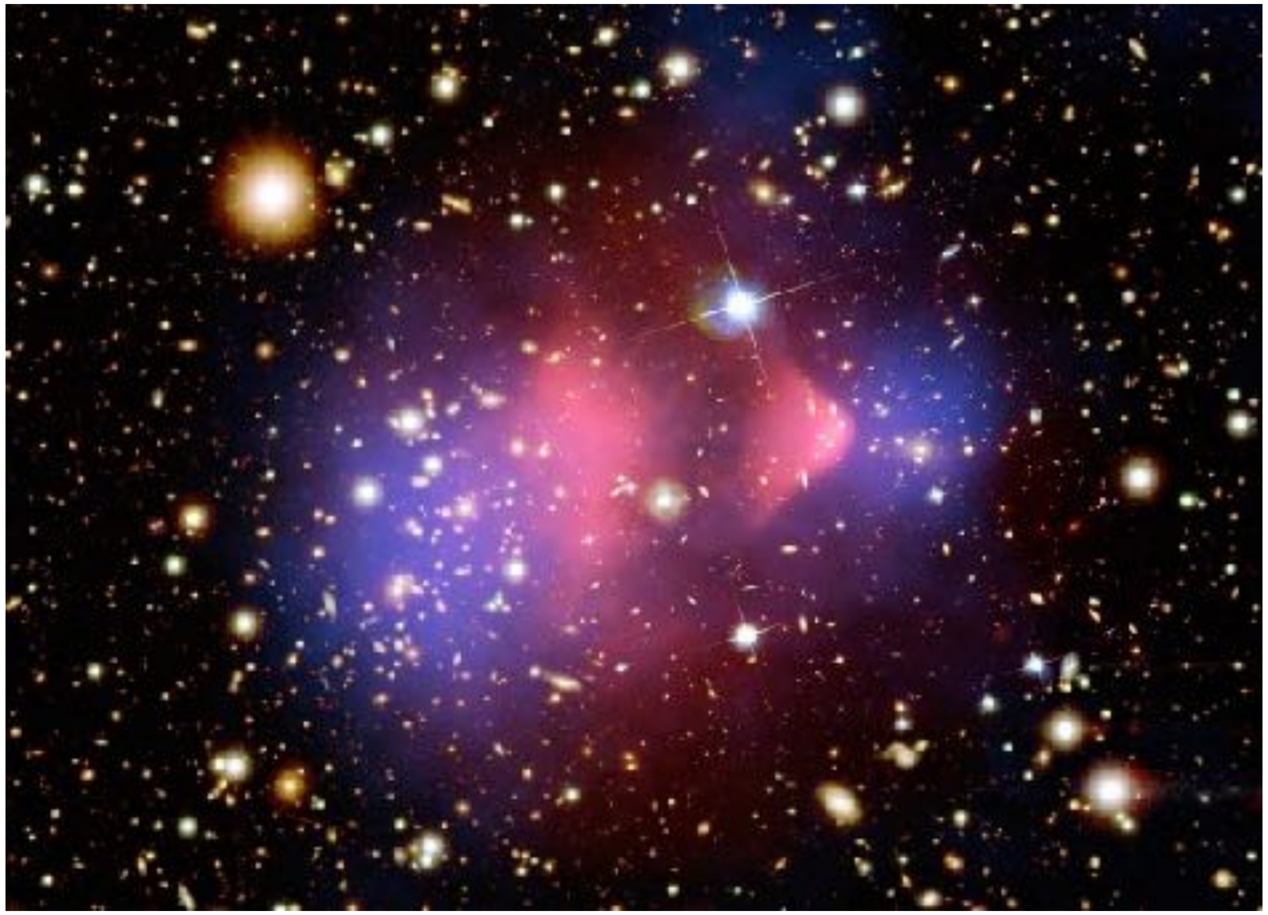
Pheno Reasons - Dark matter

- In several cases of ongoing galactic collisions one can reconstruct gravitational mass distribution using weak lensing (small shape distortions) of visible objects, and combine it with baryonic dust distribution using x-ray images

- Collisions observed in which gravitational potential is clearly not where most of visible dark matter resides

- Spectacular (though not most robust) evidence for collisionless dark matter halos comprising galaxies

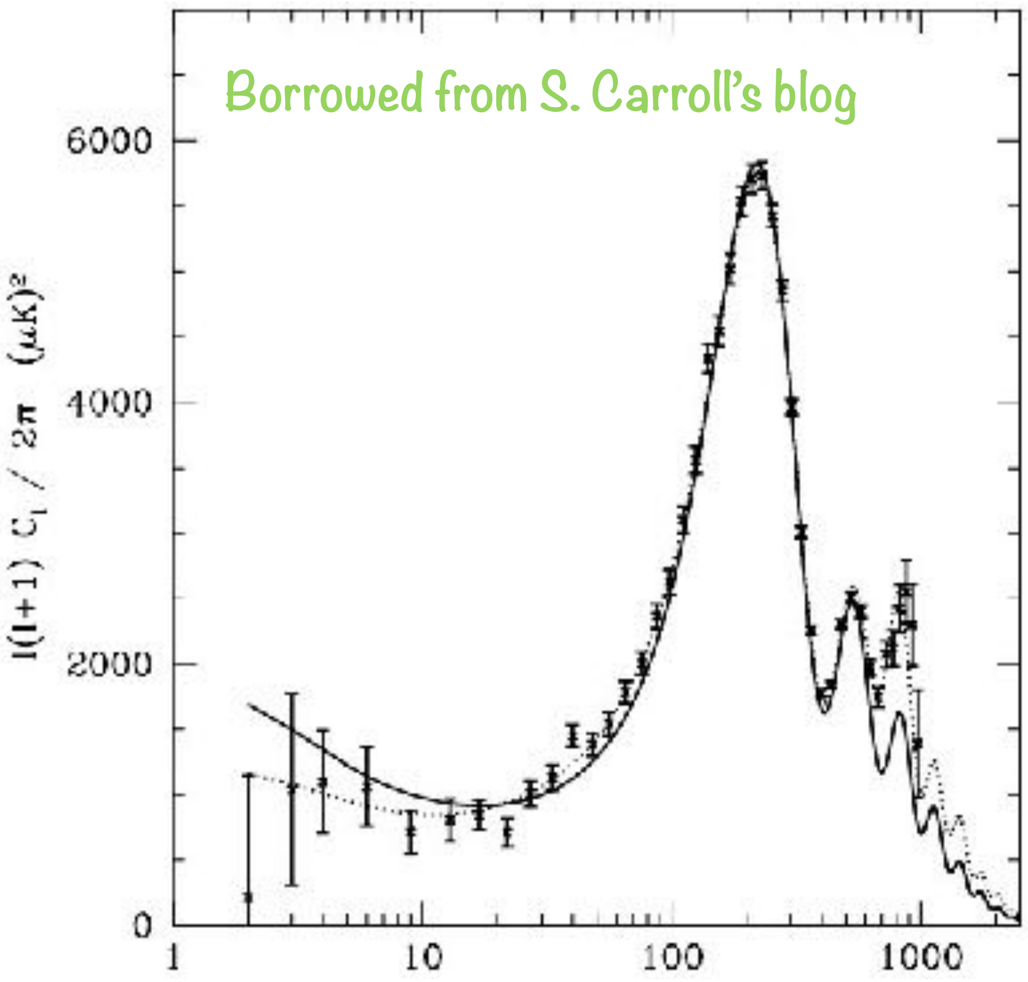
Galactic collisions



Pheno Reasons - Dark matter

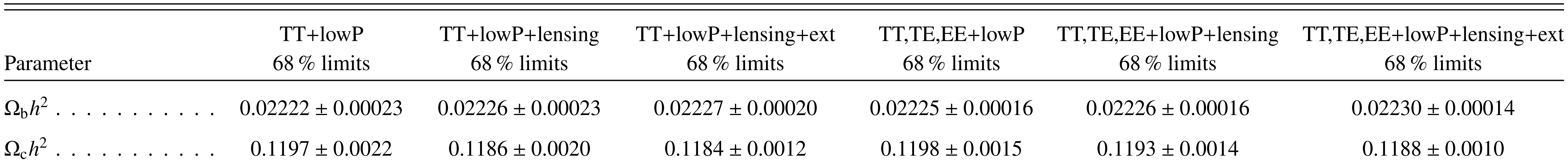
- Dark matter quantitatively predicts shape of CMB acoustic peaks. In particular, it predicts even-numbered peaks are enhanced, and odd-numbered ones are suppressed

- CMB measurements so precise they allow one to determine dark matter abundance with percent level precision!



Borrowed from S. Carroll's blog

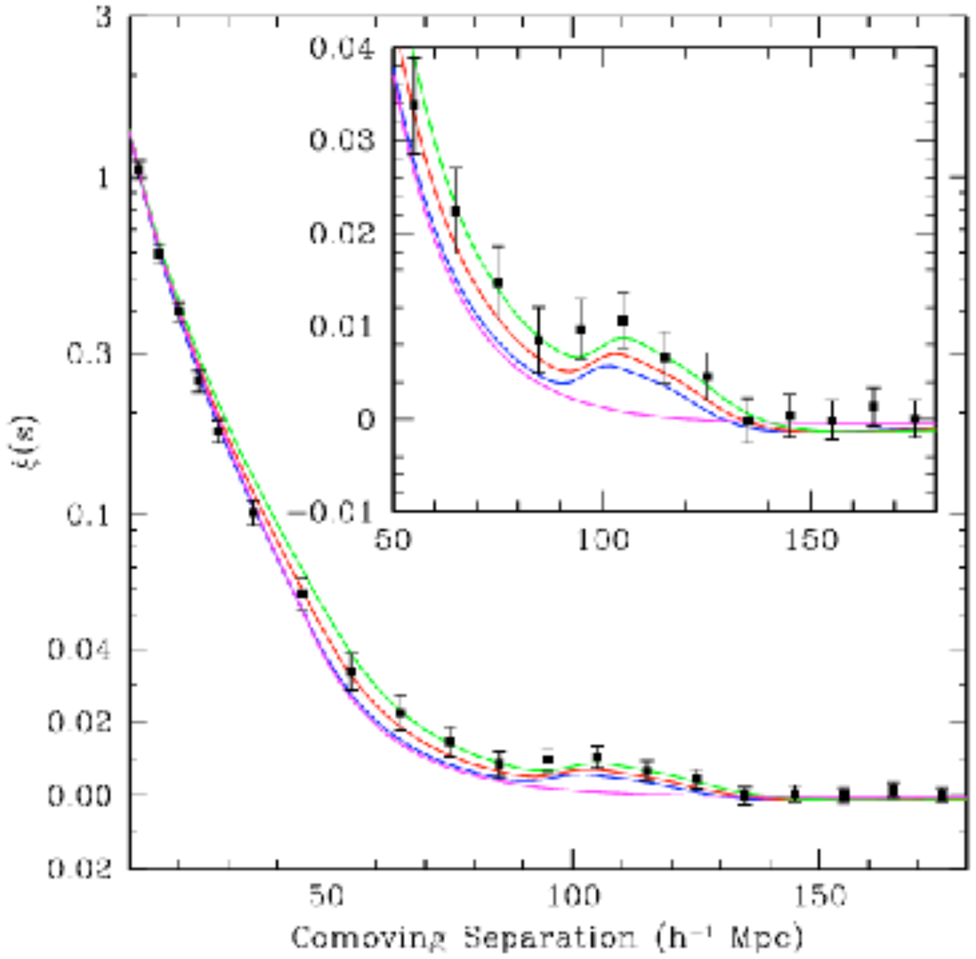
Planck, 1502.01589

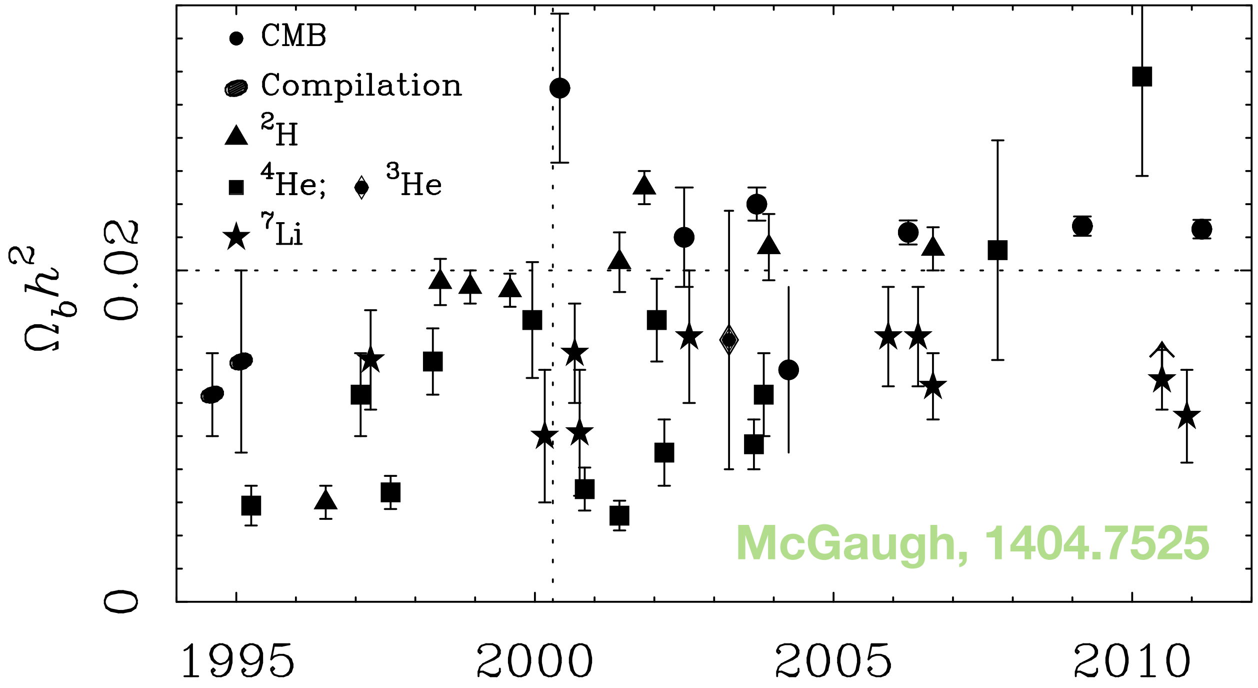


Parameter	TT+lowP 68 % limits	TT+lowP+lensing 68 % limits	TT+lowP+lensing+ext 68 % limits	TT,TE,EE+lowP 68 % limits	TT,TE,EE+lowP+lensing 68 % limits	TT,TE,EE+lowP+lensing+ext 68 % limits
$\Omega_b h^2$	0.02222 ± 0.00023	0.02226 ± 0.00023	0.02227 ± 0.00020	0.02225 ± 0.00016	0.02226 ± 0.00016	0.02230 ± 0.00014
$\Omega_c h^2$	0.1197 ± 0.0022	0.1186 ± 0.0020	0.1184 ± 0.0012	0.1198 ± 0.0015	0.1193 ± 0.0014	0.1188 ± 0.0010

Pheno Reasons - Dark matter

- Dark matter is also necessary to explain the observed dynamics of clusters of galaxies
- Dark Matter is essential to explain how present day large scale structures (galaxies and clusters) are compatible with order 10^{-5} fluctuations at last scattering surface of CMB
- Another quantitative predictions for large scale structure is presence of baryonic acoustic oscillation (BAO) peak in galaxy distribution
- BBN nucleosynthesis is quantitatively successful only assuming most of matter is non-baryonic



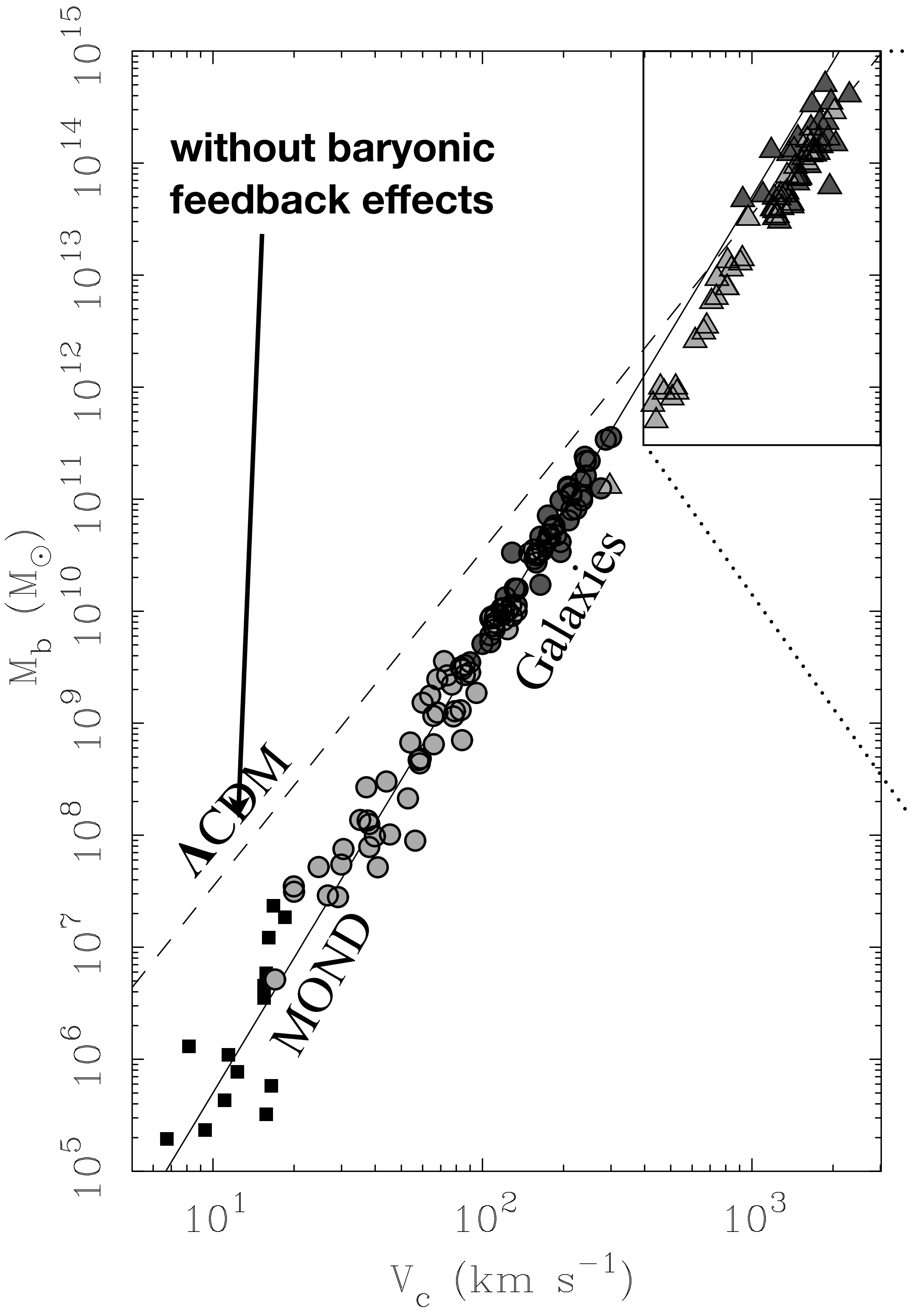


McGaugh, 1404.7525

Pheno Reasons - Dark matter

Modified gravity as alternative to dark matter?

McGaugh, 1404.7525

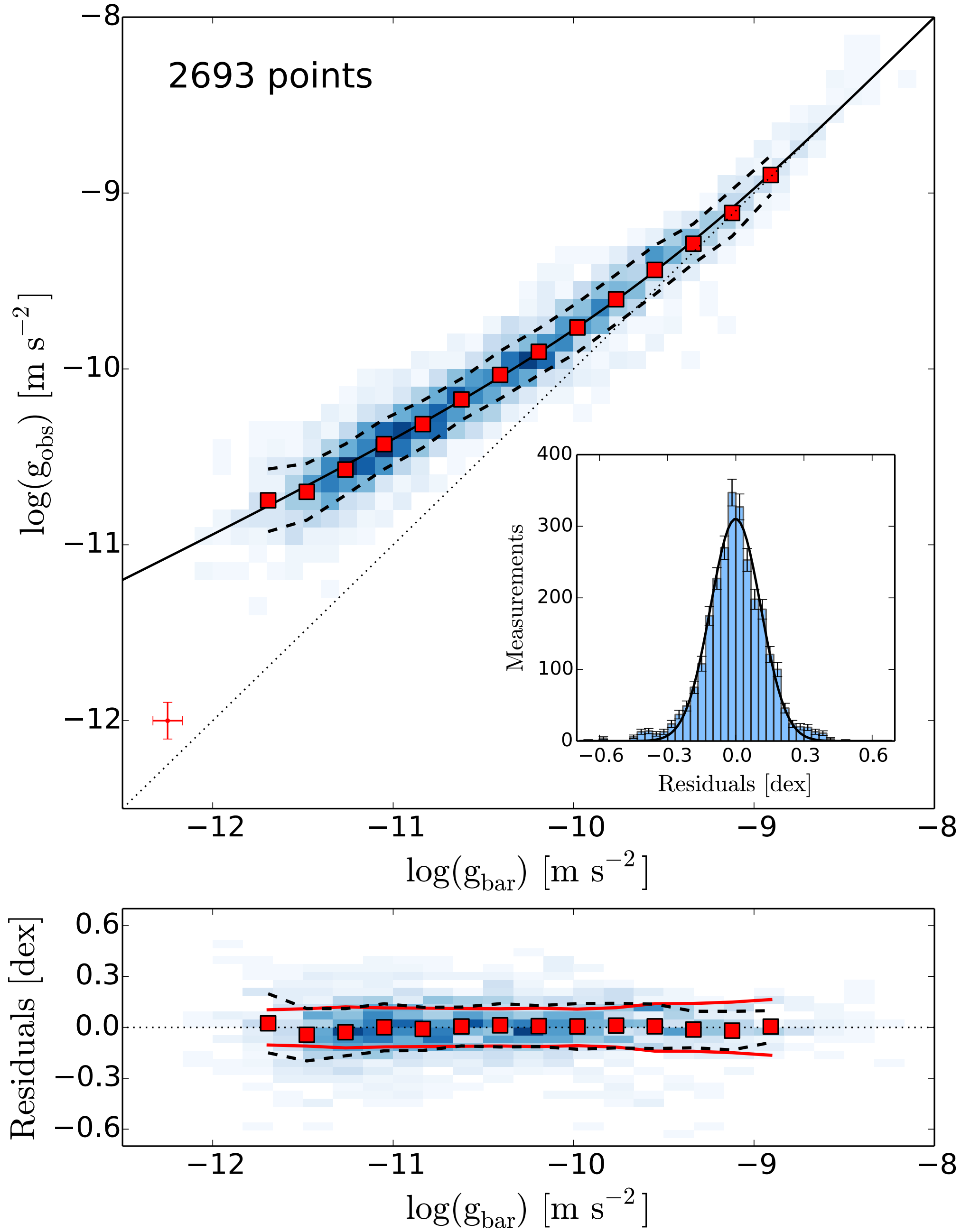


without baryonic feedback effects

- Baryonic Tully-Fisher relation shows that terminal velocity of galactic rotation curves, presumably fixed by galactic dark matter content, correlates very well with baryonic content (stars and gas)
- One can interpret it that galactic rotation curves are determined by baryons, but Newton force law is modified at small accelerations
- It is interesting that simple MOND force laws explains regularities in galactic dynamics over large range of galactic sizes and types

Pheno Reasons - Dark matter

Lelli et al
1609.05917



Sharpened version of previous observation: Mass-Discrepancy Acceleration Relation

$$g_{\rm obs} = \mathcal{F}(g_{\rm bar}) = \frac{g_{\rm bar}}{1 - e^{-\sqrt{g_{\rm bar}/g_\dagger}}}$$

$$g_\dagger \approx 1.2 \times 10^{-10} \mathrm{m/s^2}$$
$$\approx 2.6 \times 10^{-43} \mathrm{GeV}$$

- It is interesting that MOND force laws explains better certain regularities in galactic dynamics over large range of galactic sizes and types

- Given robust evidence for particle dark matter, this may be hint of nature of dark matter interactions, such that this effective force law is reproduced

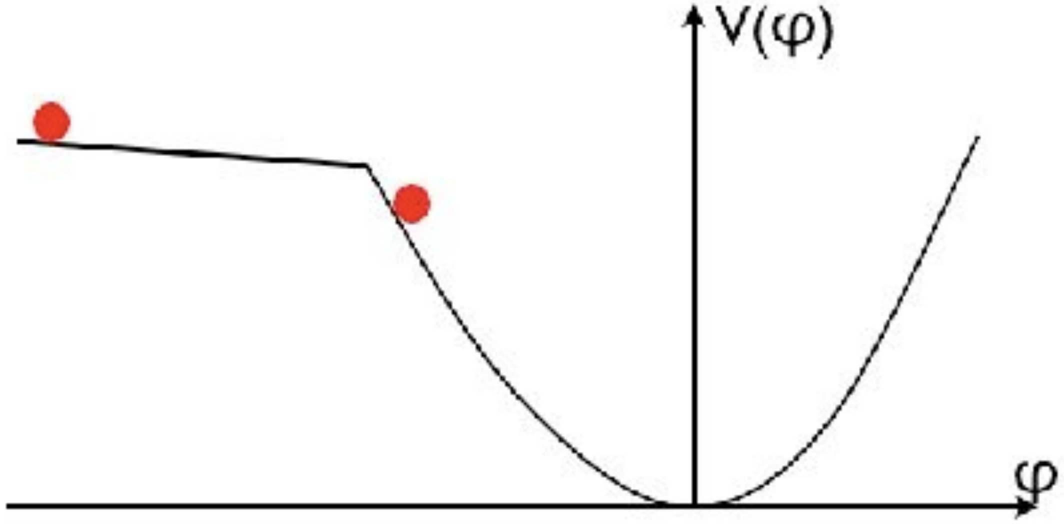
DM vs MOND

	DM	MOND
Galactic rotation curves	✔	✔
Galaxy clusters dynamics	✔	?
CMB/BBN	✔	×
Weak Lensing	✔	?
Large Scale Structure	✔	?
Galactic dynamics	?	✔

Pheno Reasons - Inflation

- Universe is very homogenous, and on average flat
- Temperature of cosmic microwave background at opposite parts of the sky is correlated
- We think these regions of the sky were once causally connected, and then blown apart via superluminal expansion == inflation
- Simplest model is the one with a scalar field slowly rolling down the potential hill

$$\mathcal{L} = \sqrt{-g}\left(-\frac{M_{\text{Pl}}^2}{2}R + \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi)\right)$$

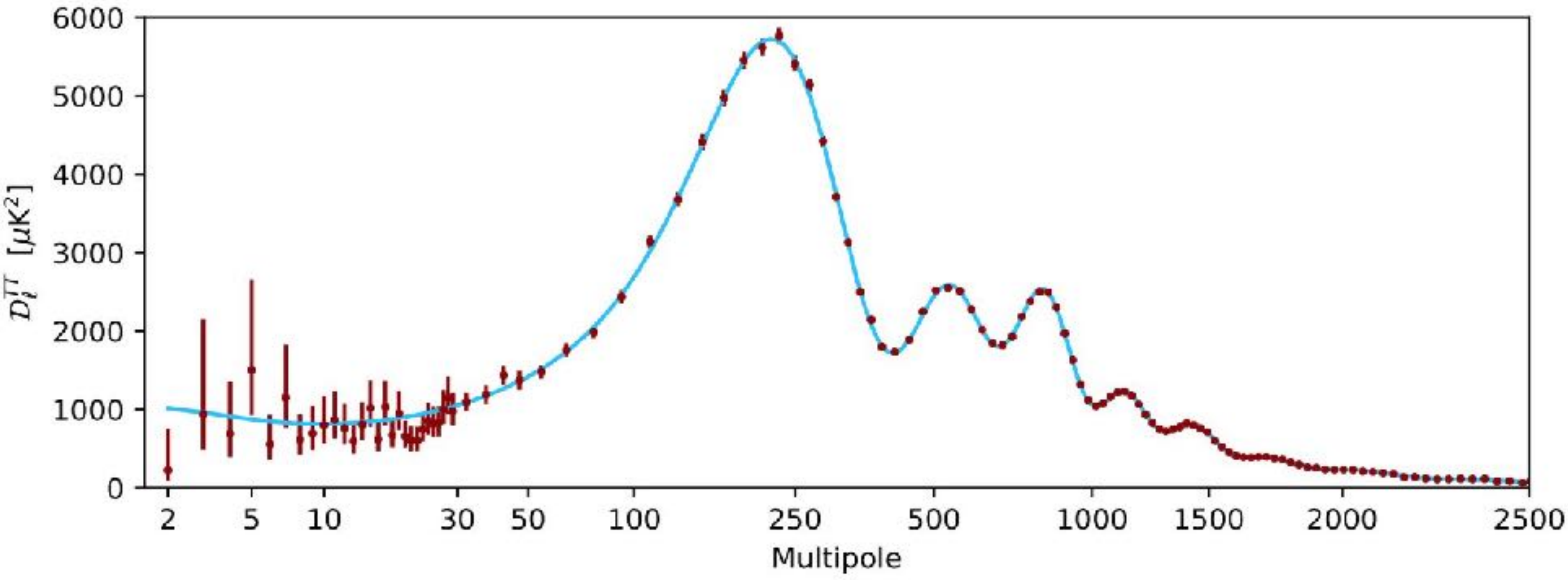


Pheno Reasons - Inflation

Quantum fluctuations of the inflaton field should seed density perturbations in the matter of the universe

WMAP and Planck satellites have observed the sound waves due to these perturbations, proving that the perturbations are coherent on super-horizon scales

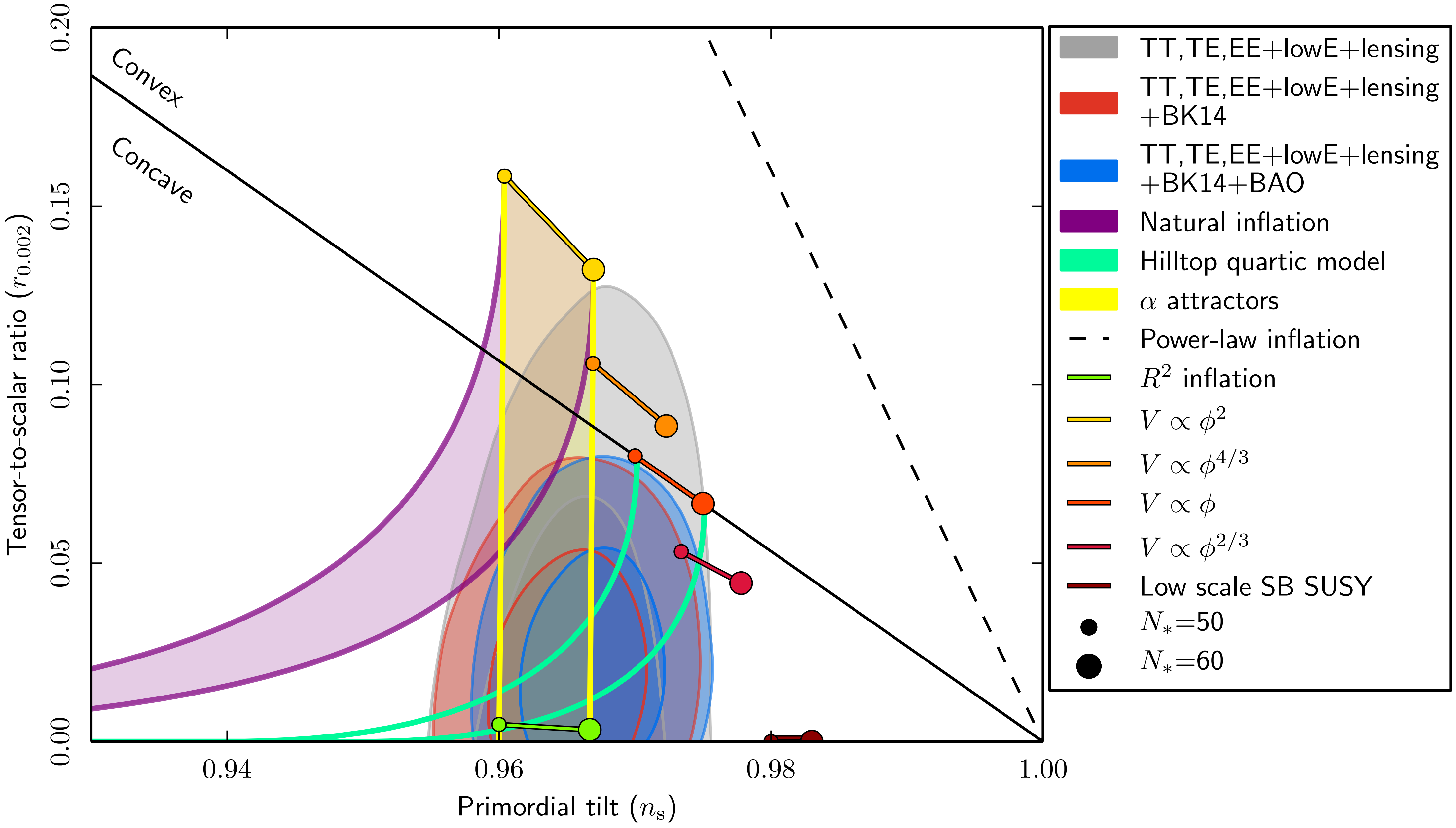
Planck Collaboration: The cosmological legacy of *Planck*



Pheno Reasons - Inflation

Zeroth order prediction is scale-invariant spectrum of perturbation

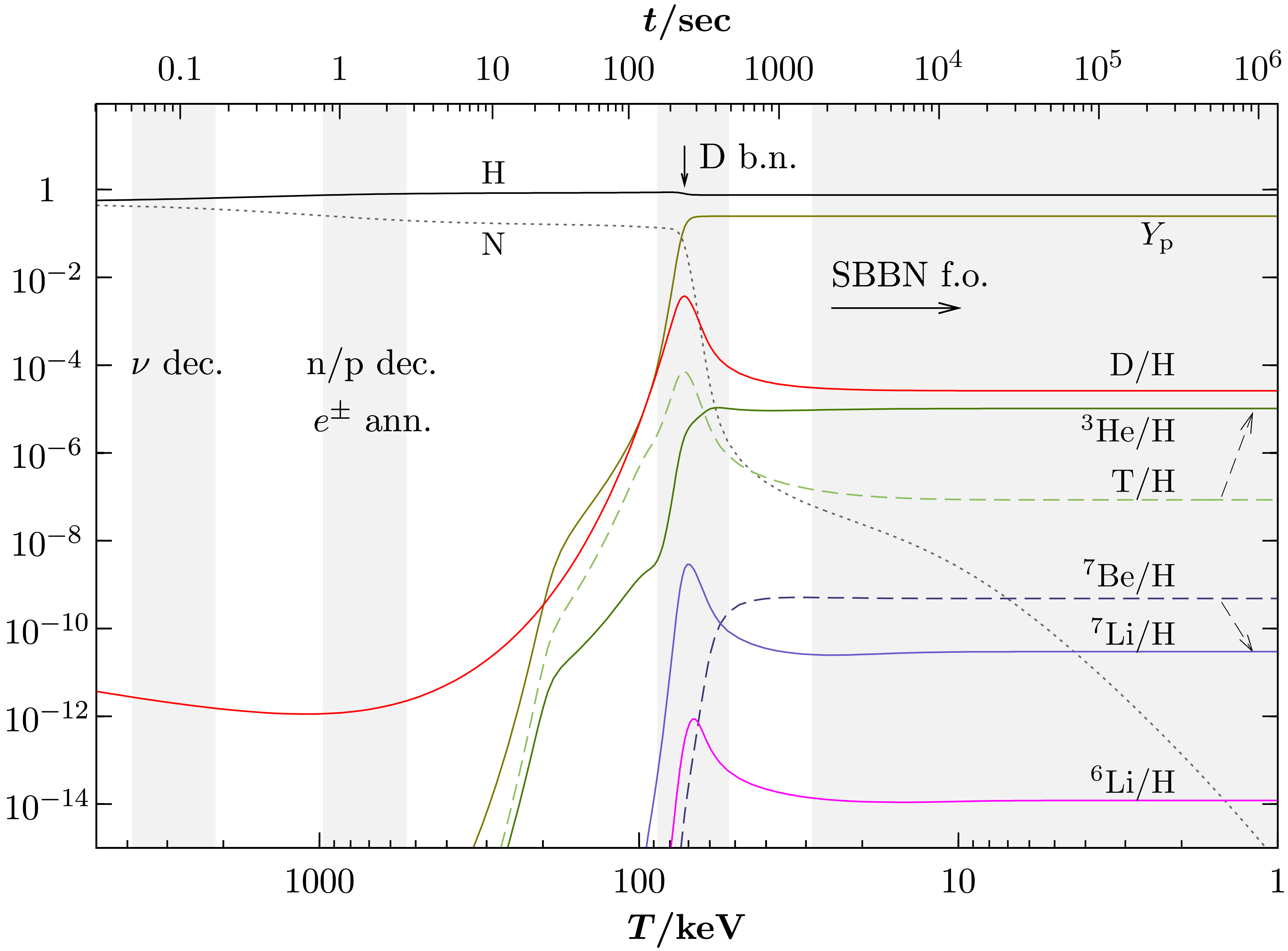
Due to inflaton rolling down the potential hill, there should be small departure from scale invariance, that is spectral index less than 1



Pheno reasons: matter asymmetry

- Today, the universe consists of matter and almost no anti-matter
- Inflation must have wiped out any original baryon asymmetry and make the universe matter-antimatter symmetric
- Some mechanism operating during subsequent evolution must have produced the small baryon asymmetry

Pheno reasons: matter asymmetry



From the abundance of heavier elements in the universe we can precisely deduce the amount of matter and anti-matter

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-10}$$

Pheno reasons: matter asymmetry

- **Sakharov conditions: needs C and CP violation, as well as departure from thermal equilibrium**
- **All these conditions satisfied in the Standard Model**
- **But, CP violation in the CKM matrix is too small to explain the observed asymmetry**
- **There must be another source of CP violation from beyond the Standard Model.**

Summary of Phenomenological Reasons For Physics Beyond the Standard Model

- Neutrino Oscillations
- Dark Matter
- Baryon Asymmetry
- Inflation

All of them experimental facts!

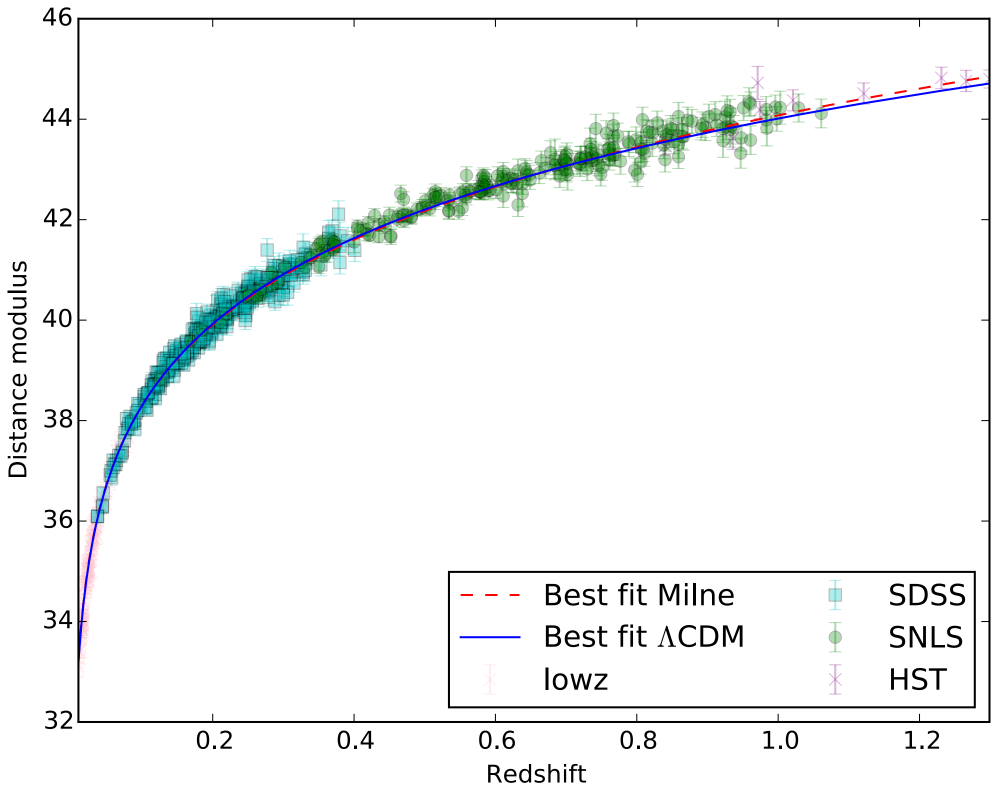
Esthetic Arguments
For Physics Beyond the Standard Model

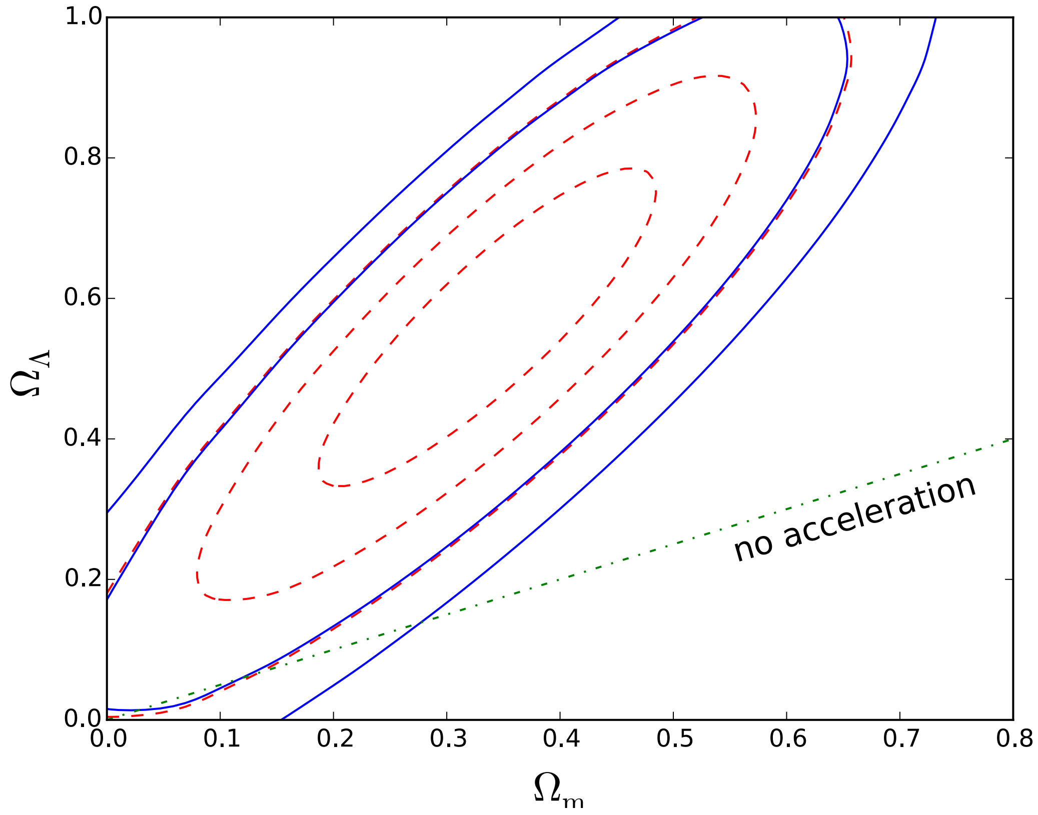
Certain features of the Standard Model appear ad-hoc or fine-tuned and we suspect that they have a deeper explanation

- Small cosmological constant
- Fermion generation structure and mass/mixing hierarchies
- Vacuum metastability
- Gauge coupling unification
- Strong CP problem
- Naturalness problem

Pheno Reasons - Small cosmological constant

Guffanti et al
1506.01354





- Evidence for accelerated expansion from observations of distance to high-redshift supernovae Ia events

- Interpreted as gravitating vacuum energy (or another negative pressure component)

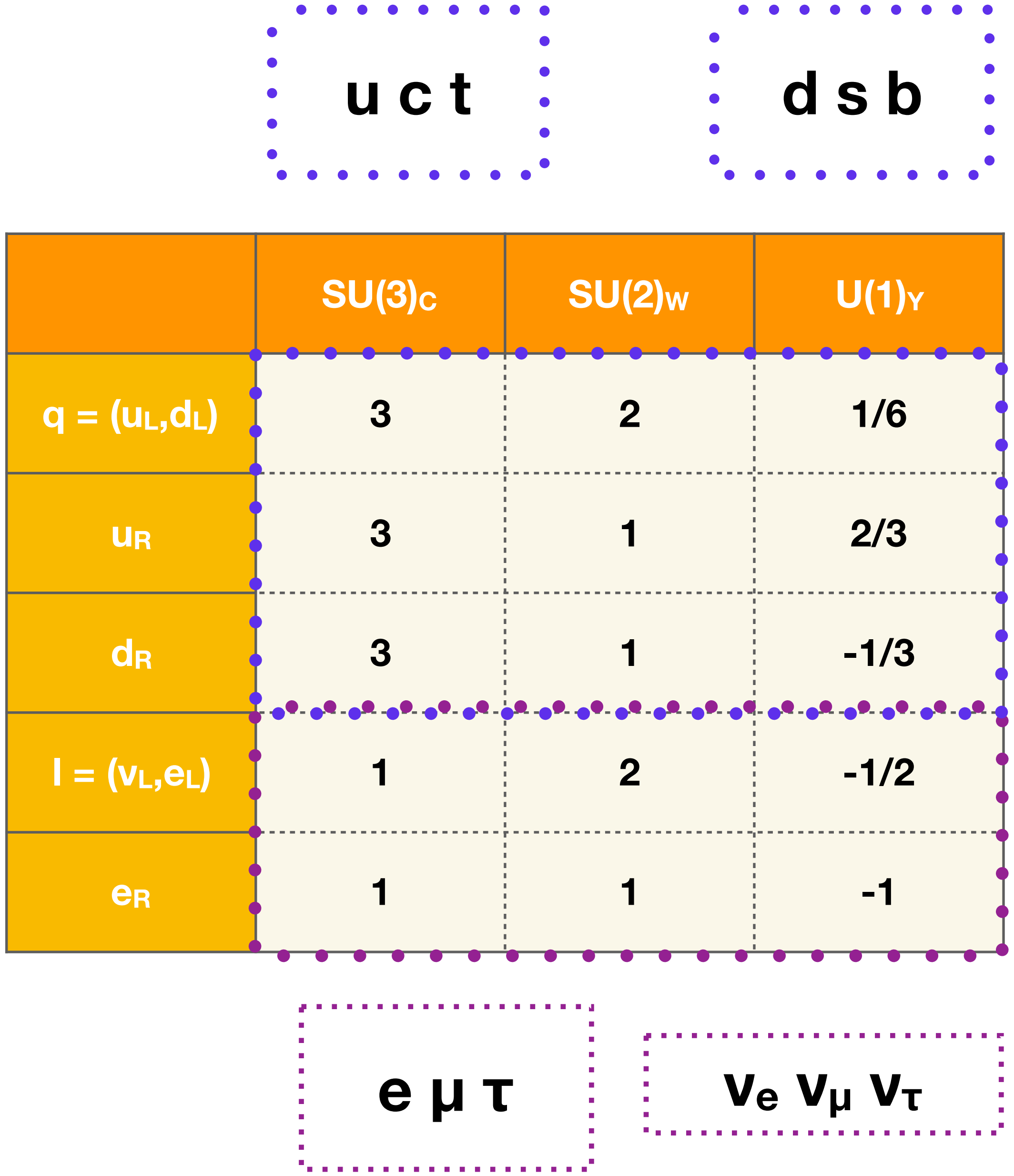
- This is corroborated by CMB pointing to spatial flatness of the universe, which requires additional vacuum energy component in addition to matter

- Simple to implement in GR as cosmological constant
but smallness of Λ may suggest it's more complicated

$$\mathcal{L} = \sqrt{-g} M_{\mathrm{Pl}}^2 \left(-\frac{1}{2} R - \Lambda^2 \right)$$

Fermion generations puzzle
or, who ordered muon?

- Why 3 generations = carbon copies of particles with the same charges and interactions but different masses
- SM would be perfectly consistent with just one generations, and basic physics and chemistry would be the same (once we readjust couplings due to different RG running)
- The only qualitative effect of 2nd and 3rd generations seems to be the headache of flavor physics and tiny CP violation in certain SM processes



u c t

d s b

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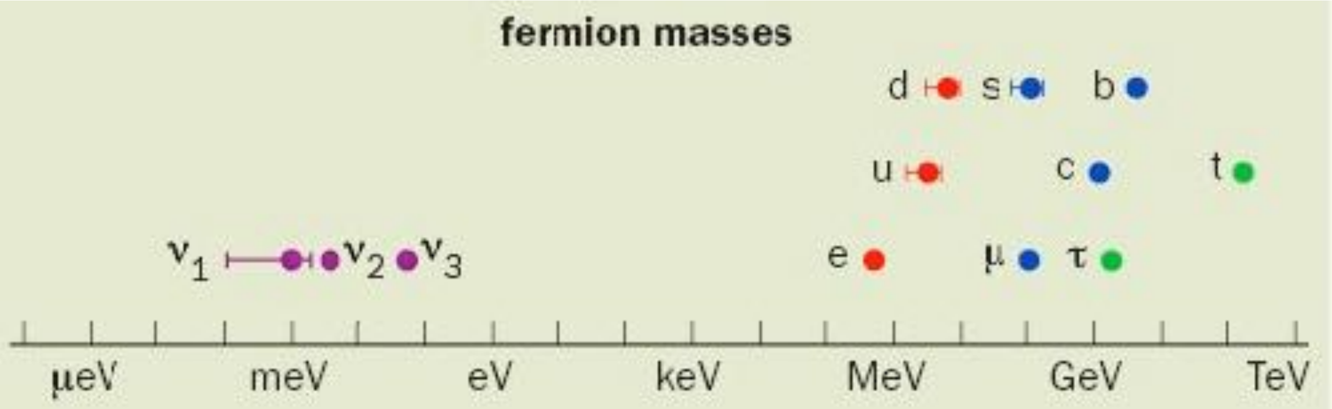
e μ τ

ν_e ν_μ ν_τ

Fermion generation puzzles



Why masses of quarks and leptons from different generations are so different? Is there a pattern?

Why quark mixing matrix is hierarchical? Is there a pattern?

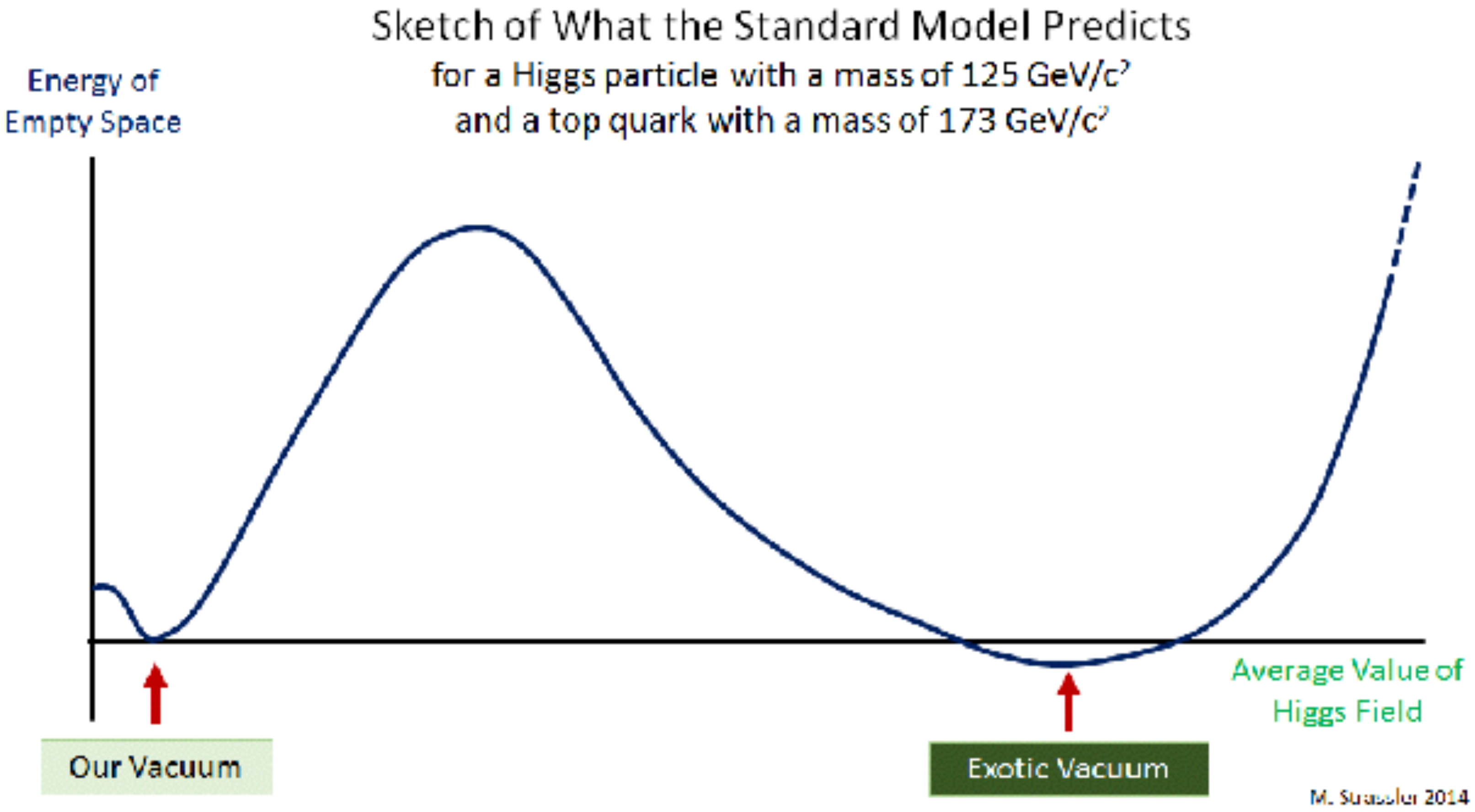
Why quark and neutrino mixing matrices are so different ? Is there some pattern in neutrino mass matrix, or is just anarchic?

$$V_{\mathrm{CKM}} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

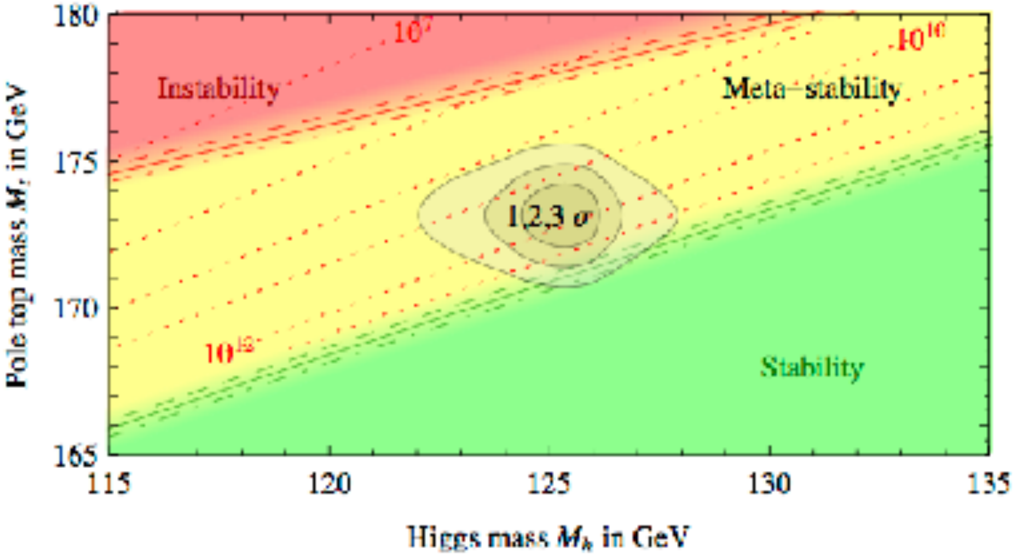
$$\lambda \sim 0.2$$

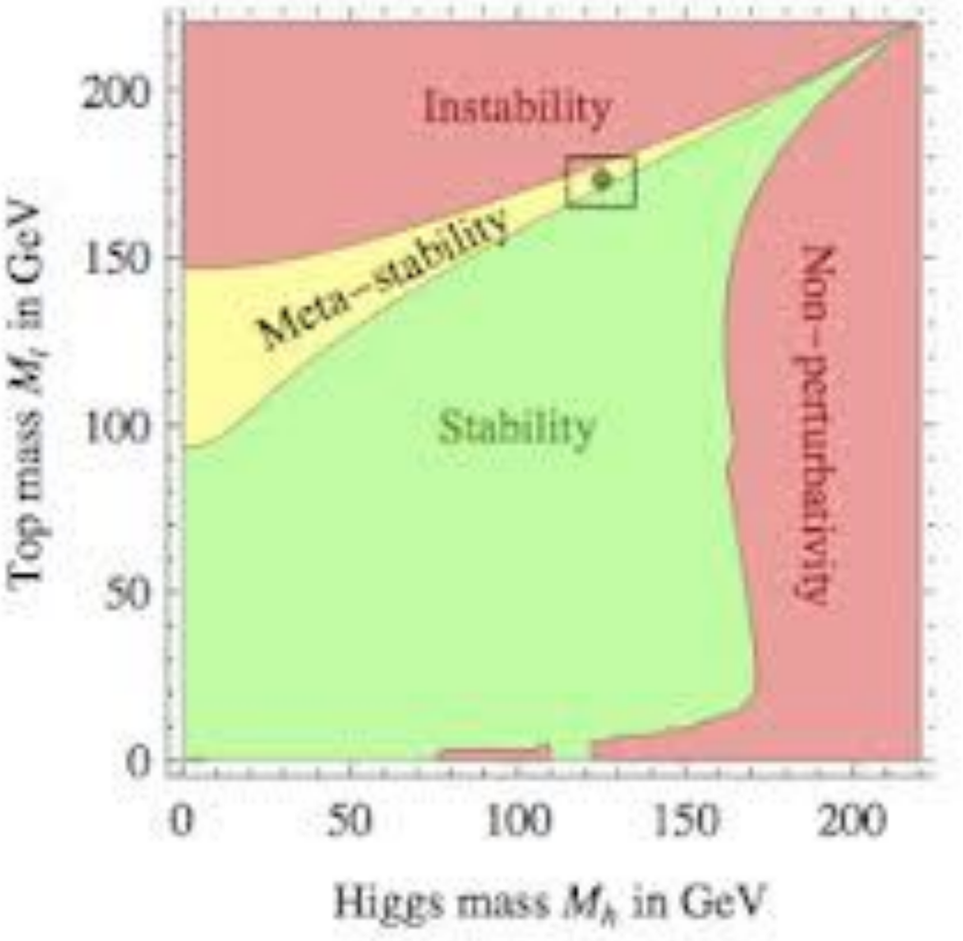
$$V_{\mathrm{PMNS}} \sim \begin{pmatrix} 1 & 1 & 0.1 \\ 1 & 1 & 1 \\ 0.1 & 1 & 1 \end{pmatrix}$$

Esthetic Reasons - Vacuum Metastability



Degrassi et al.
1205.6497





- Given the measured parameters of the SM, the Higgs potential develops another deeper minimum at large field values

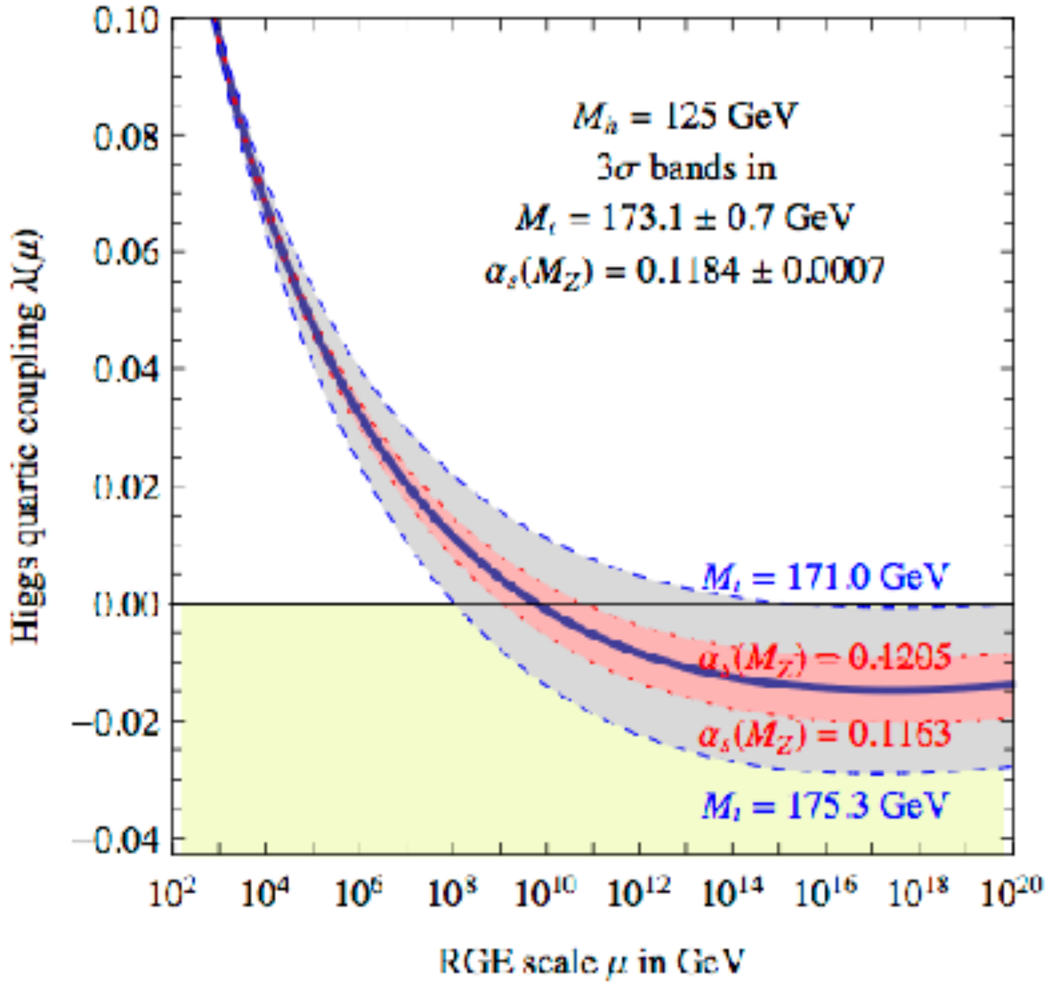
- Our vacuum has a finite lifetime, after which we will all decay

Coincidence or physical law?

Esthetic Reasons - Vacuum Metastability

Degrassi et al.
1205.6497

- Quartic Higgs coupling in the SM decreases with energy, and becomes negative at energies around 10^{10} GeV
- Funny enough, also beta function for quartic almost vanishes just above that scale, so quartic stays small and slightly negative over large range of energies



Coincidence?
Or flatness of Higgs potential at large VEV is required by some physics principle?
Connection to inflation?

Esthetic Reasons - Quantum numbers unification

	$SU(3)_C$	$SU(2)_W$	$U(1)_Y$
$q = (u_L,d_L)$	3	2	1/6
u_R	3	1	2/3
d_R	3	1	-1/3
$l = (\nu_L,e_L)$	1	2	-1/2
e_R	1	1	-1

Charges of SM fermions under hypercharge U(1) are quantized in units of 1/6 (equivalently, electric charge quantized in units of 1/3). However, for U(1) gauge symmetry any real value of charge leads to a consistent theory

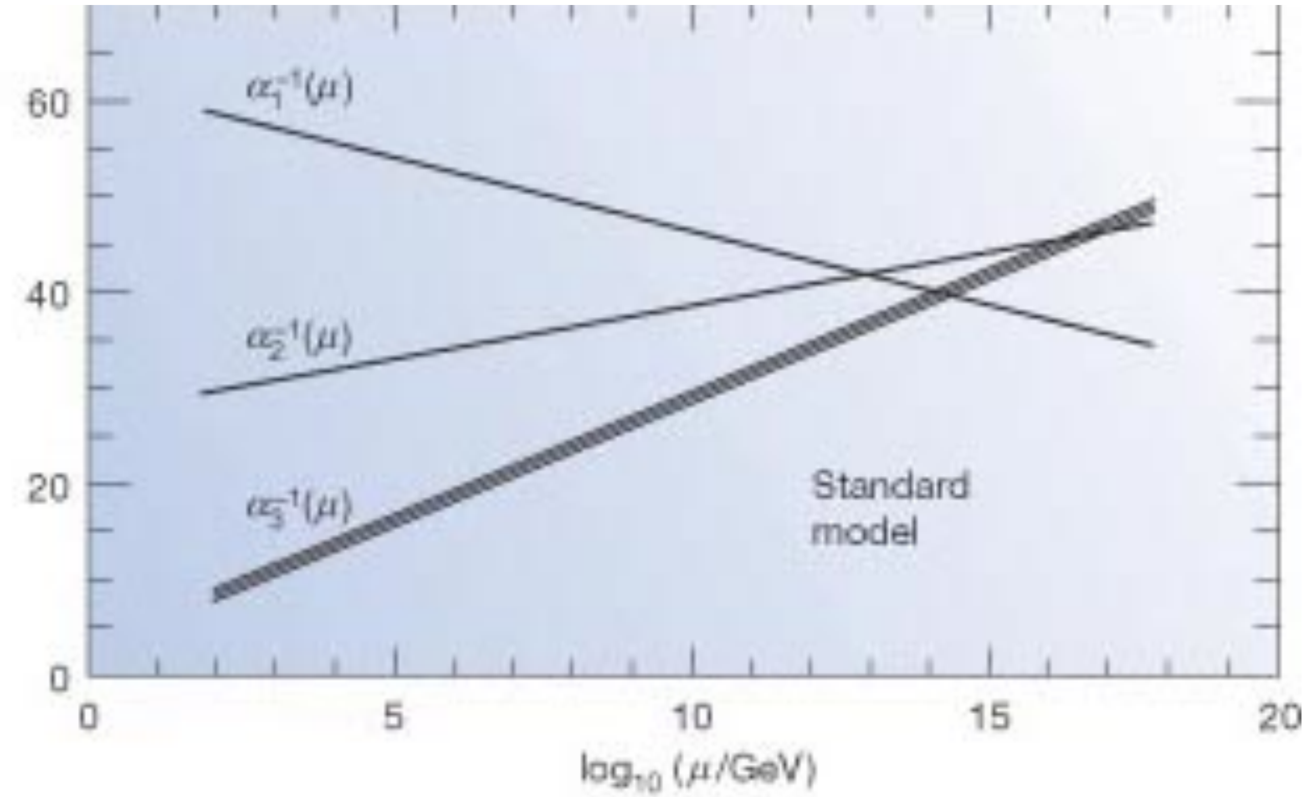
Gauge couplings unification

- 3 coupling constants in the Standard Model evolve with energy scale

- They approximately unify (within 20%) at energies near 10^{14}-10^{16} GeV

- Hint of a larger more fundamental local symmetry?

Borrowed from F.Wilczek's paper



$$\frac{1}{\alpha_i(E)} = \frac{1}{\alpha_i(m_Z)} - \frac{b_i}{2\pi}\log\left(\frac{E}{m_Z}\right)$$

$$b_1 = \frac{41}{10}, \quad b_2 = -\frac{19}{6}, \quad b_3 = -7$$

Esthetic Reasons - Strong CP Problem

$$\mathscr{L}_{\rm SM} = -\frac{1}{4}\sum_{V\in B,W^i,G^a} V_{\mu\nu}V^{\mu\nu} + \sum_{f\in q,u,d,l,e} i\bar{f}\gamma^{\mu}D_{\mu}f$$

$$-\left(\bar{u}Y_u qH + \bar{d}Y_d H^{\dagger}q + \bar{e}Y_e H^{\dagger}l + \mathrm{hc}\,.\right)$$

$$+D_{\mu}H^{\dagger}D^{\mu}H + \mu_H^2 H^{\dagger}H - \lambda(H^{\dagger}H)^2$$

- Given field content, SM Lagrangian contains most general terms consistent with Lorentz symmetry, SU(3)xSU(2)xU(1) local symmetry, and renormalizability

- This leads to 18 free measurable parameters

- Most general... wait a moment

Esthetic Reasons - Strong CP Problem

$$G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu + g_s f^{abc} G^b_\mu G^c_\nu$$

$$\mathcal{L}_{\text{kin}} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu,a}$$

$$\mathcal{L}_\theta = \theta \frac{g_s^2}{64\pi^2} \epsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma}$$

- Symmetries and building principles of SM allow for one more renormalizable term (19th parameter θ)
- It effectively appears via global chiral anomalies when we rephase quark fields so as to render their mass eigenvalues real

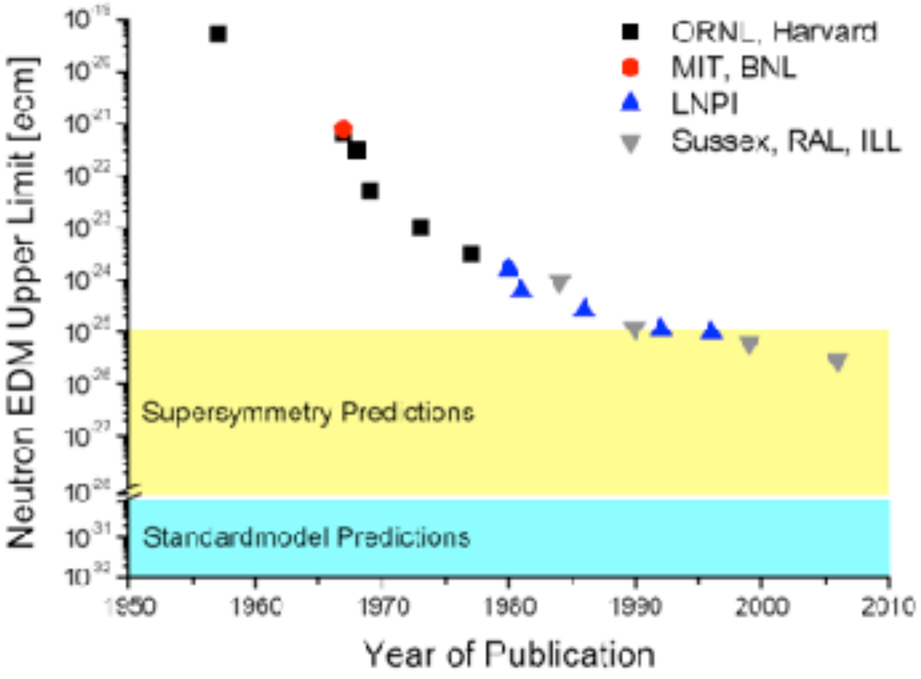
$$\theta \to \theta + \mathrm{ArgDet}(M_u M_d)$$

- This term violates P and CP
- One observable effect would be to produce an electric dipole moment for the neutron

Esthetic Reasons - Strong CP Problem

$$d_n \sim \theta \frac{m_u m_d}{m_u + m_d} \frac{e}{\Lambda^2_{\rm QCD}} \sim \theta \cdot 6 \cdot 10^{-17} e \cdot {\rm cm}$$

- The effect of θ would be to produce an electric dipole moment for the neutron
- Current bounds on neutron EDM imply θ≲10^-9
- Probably hints at existence of new light degree of freedom that effectively makes θ dynamical variable with very small vacuum expectation value



Esthetic Reasons - Naturalness Problem

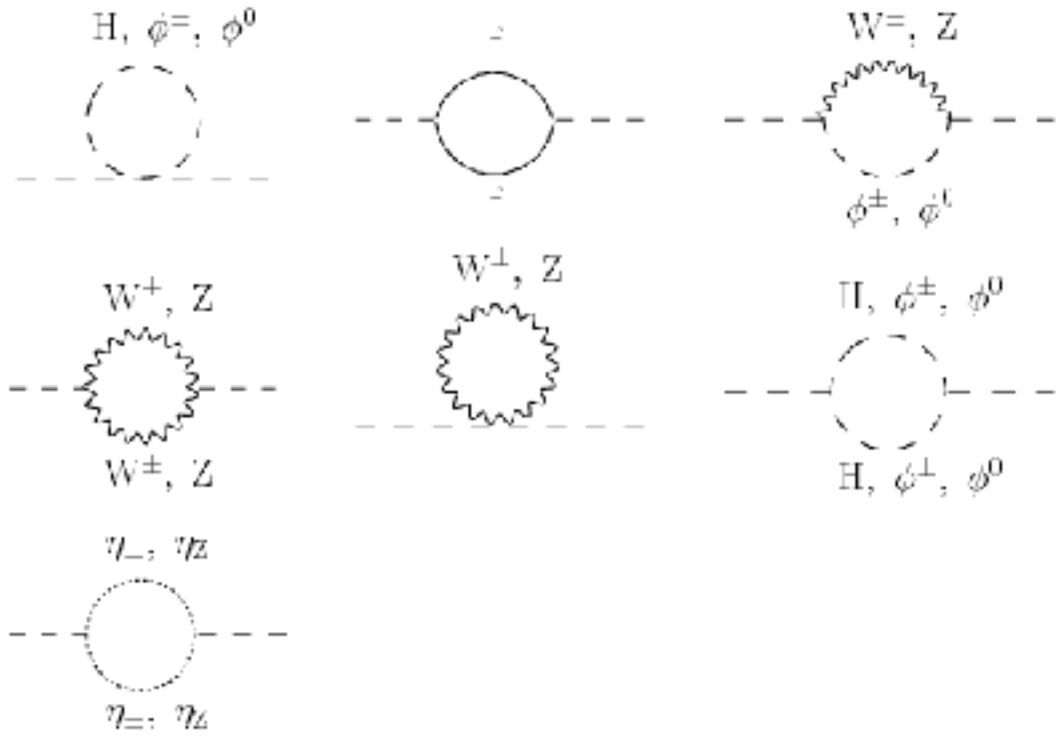
$$\mathscr{L}_{\mathrm{SM}} = -\frac{1}{4}\sum_{V\in B,W^i,G^a} V_{\mu\nu}V^{\mu\nu} + \sum_{f\in q,u,d,l,e} i\bar{f}\gamma^\mu D_\mu f$$

$$-\left(\bar{u}Y_u qH + \bar{d}Y_d H^\dagger q + \bar{e}Y_e H^\dagger l + \mathrm{h.c.}\right)$$

$$+D_\mu H^\dagger D^\mu H + \boxed{\mu_H^2 H^\dagger H} - \lambda(H^\dagger H)^2$$

Standard Model

- Only 1 mass parameter in SM Lagrangian: $\mu_H \approx 88$ GeV
- Secretly, another mass parameter: Λ = max energy where SM is valid
- Typical expectation is that quantum corrections/threshold effects should lead to $\mu_H \sim \Lambda/\pi$, as opposed e.g. to $g \sim \mathrm{Log}[\Lambda/v]/\pi$



Esthetic Reasons - Naturalness Problem

- We expect SM to be part of a more fundamental theory with new particles whose mass is above energy scale $\Lambda > m_Z$
- Generically, mass parameters in low energy theory receive quantum correction proportional to (at least) Λ, unless symmetry in low energy theory forbids that
- This suggests SM should cease to be valid at scale near $\Lambda \sim \pi m_Z \sim 300$ GeV. At this point new theory should emerge with new particles and new symmetries to protect mH

Arguments For Physics Beyond the Standard Model

Experimental facts

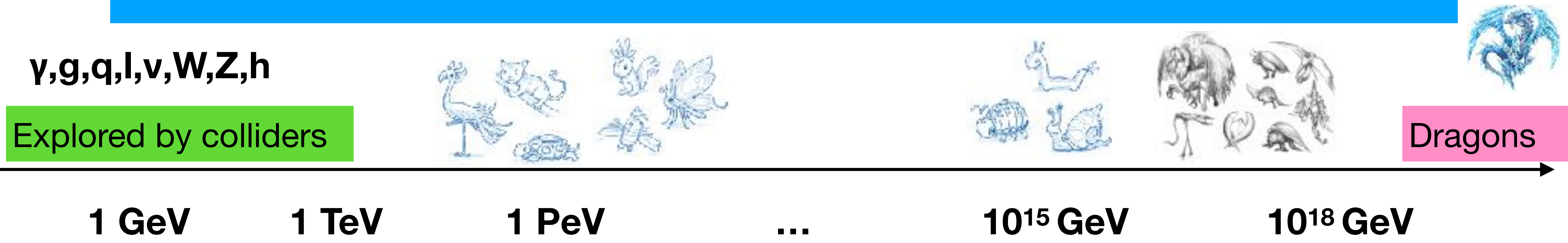
- Neutrino Oscillations
- Dark Matter
- Baryon Asymmetry
- Inflation

Esthetics motivations

- Fermion generation structure and mass/mixing hierarchies
- Vacuum metastability
- Gauge coupling unification
- Strong CP problem
- Naturalness problem

Only argument directly connecting new physics to LHC

Landscape view of physics beyond the Standard Model



γ,g,q,l,ν,W,Z,h

Explored by colliders

Dragons

1 GeV **1 TeV** **1 PeV** **…** **10^{15} GeV** **10^{18} GeV**

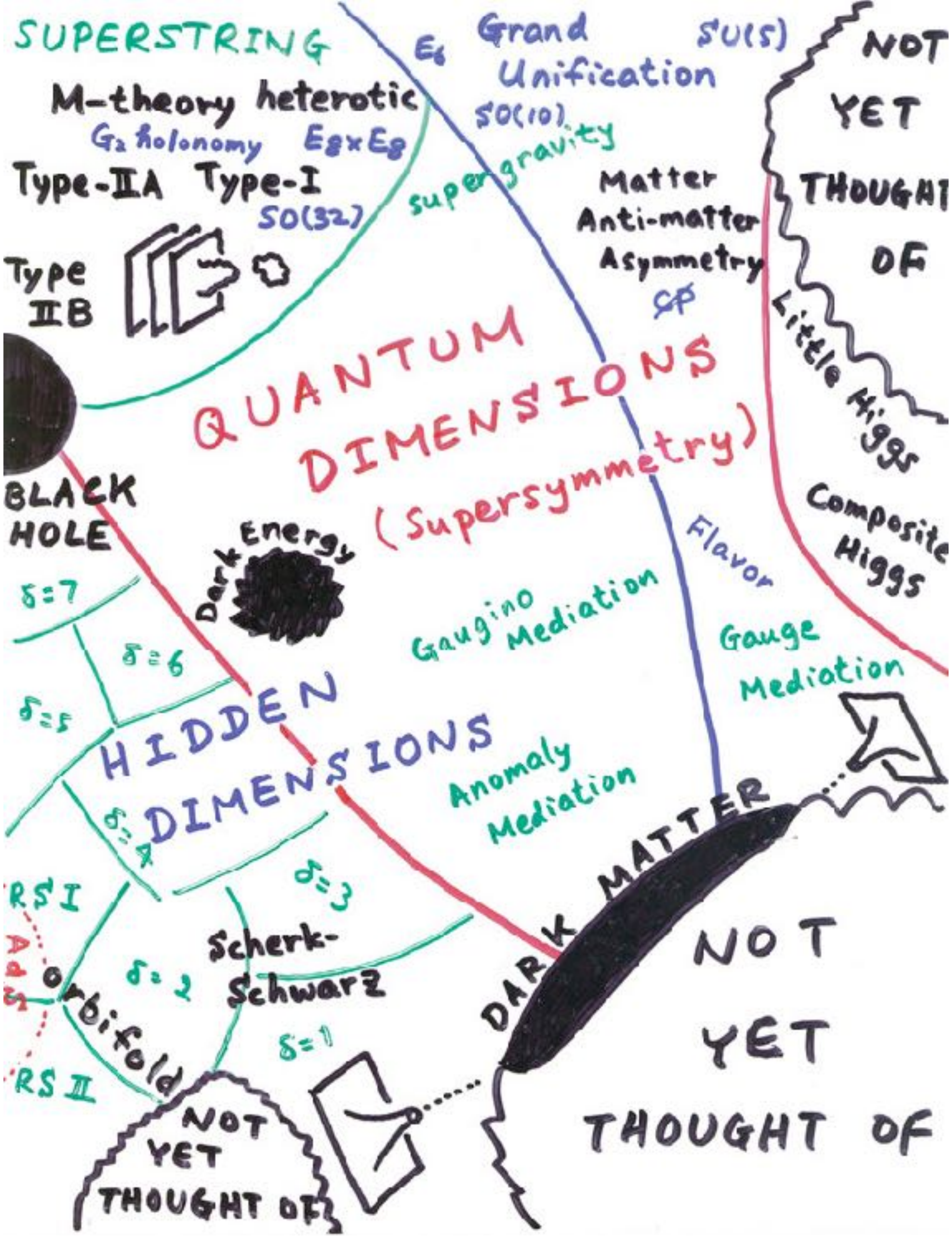
How can we find dark matter/inflaton/heavy neutrino
or other animals addressing the problems of the Standard Model
assuming mass scale of new physics
is between few TeV and Planck scale

?

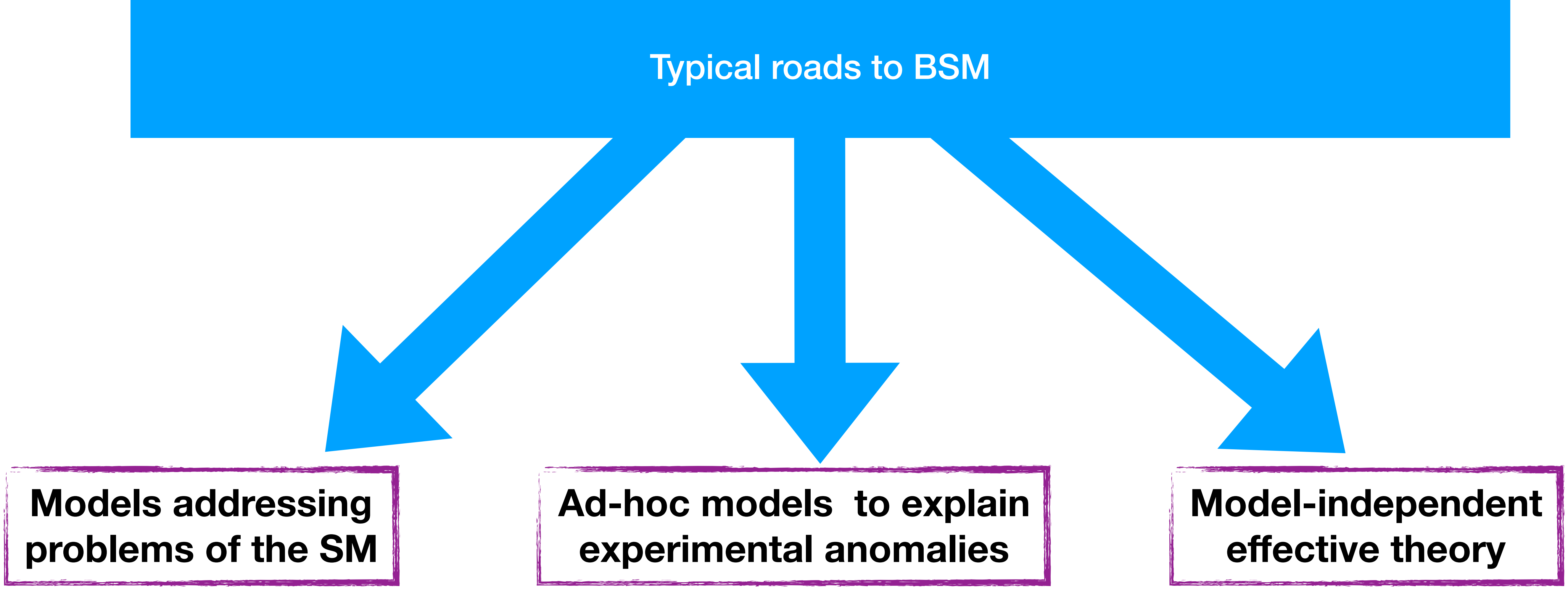
Part 2

Which BSM?

Physics beyond the Standard Model according to H. Murayama



We may be short on discoveries,
but not ideas what could be discovered ;)



Typical roads to BSM

Models addressing problems of the SM

Ad-hoc models to explain experimental anomalies

Model-independent effective theory

e.g supersymmetry to address naturalness, or axions to address theta-problem of QCD

e.g leptoquarks to address B-meson anomalies or milli-charged dark matter to address 21cm absorption signal

e.g. higher-order effective interactions added to the SM

Effective field theory approach to BSM

- It is possible that we already discovered all particles in nature with masses lower than few TeV (or if new light particles exists, it is possible they are so weakly coupled as to be irrelevant)

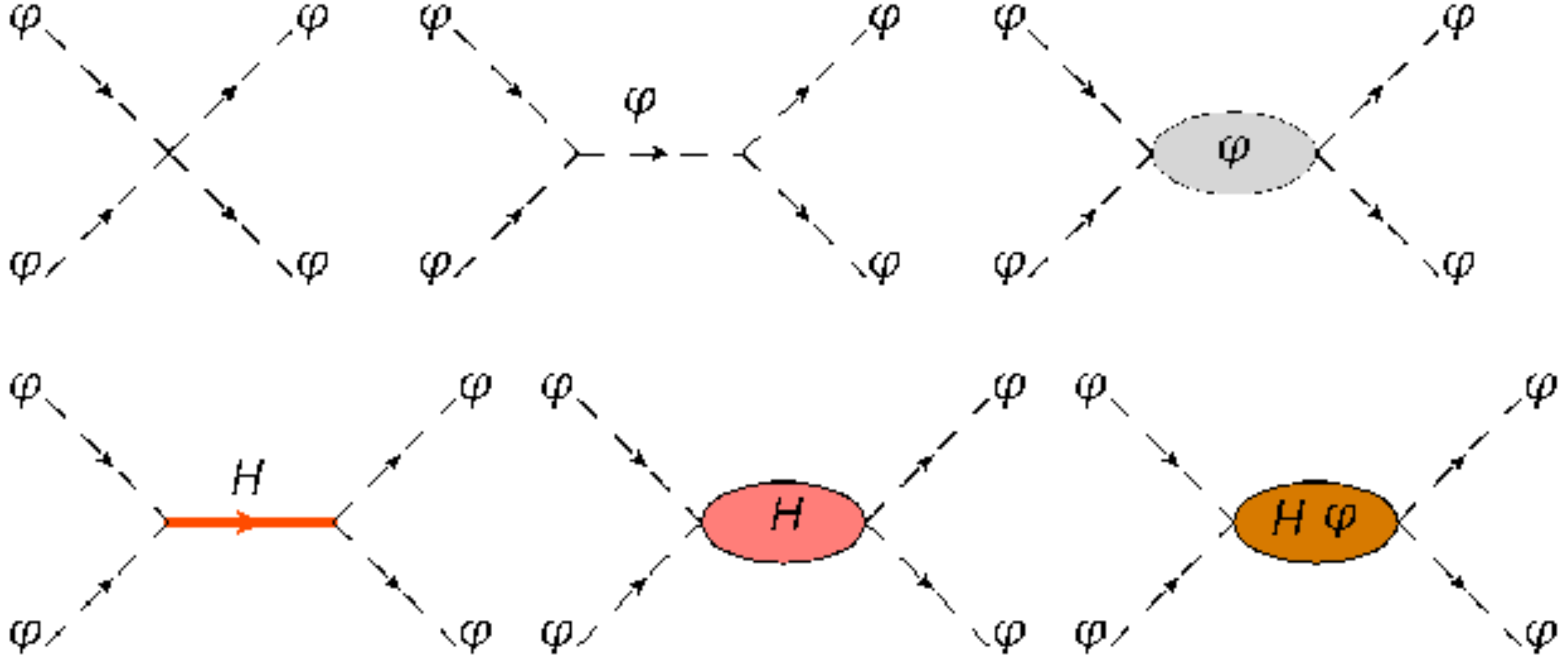
- Particles heavier than few TeV cannot be directly produced in current experiments but, thanks to quantum mechanics, they can be produced *virtually* and still have non-zero impact on low-energy observables

- Irrespectively of what is the more fundamental theory underlying the Standard Model, this situation can be described in a model-independent way using an effective field theory (EFT) approach

Concept of effective Lagrangian

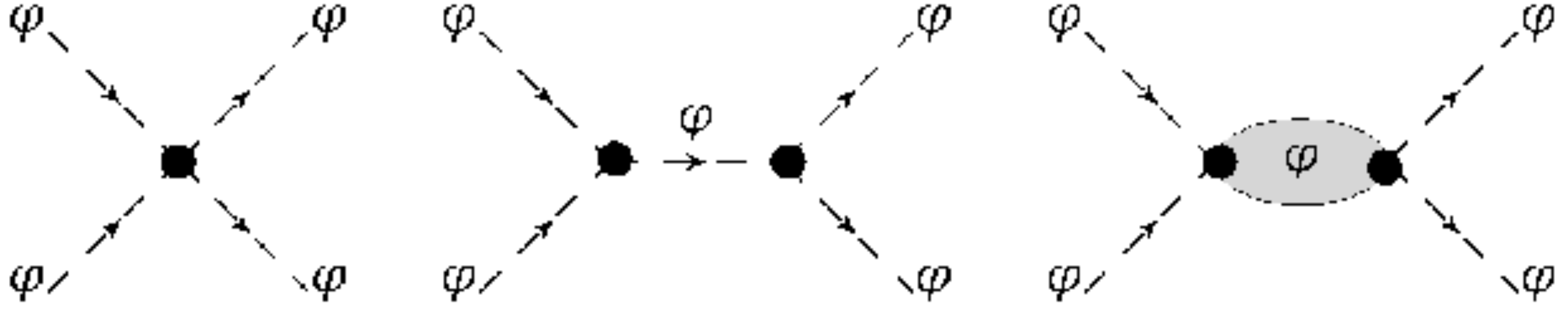
Consider quantum field theory with “light” fields φ and “heavy” fields H $\mathcal{L}(\phi, H)$

We are interested in the scattering amplitudes for “light” fields.
E.g. 2→2 amplitude schematically:



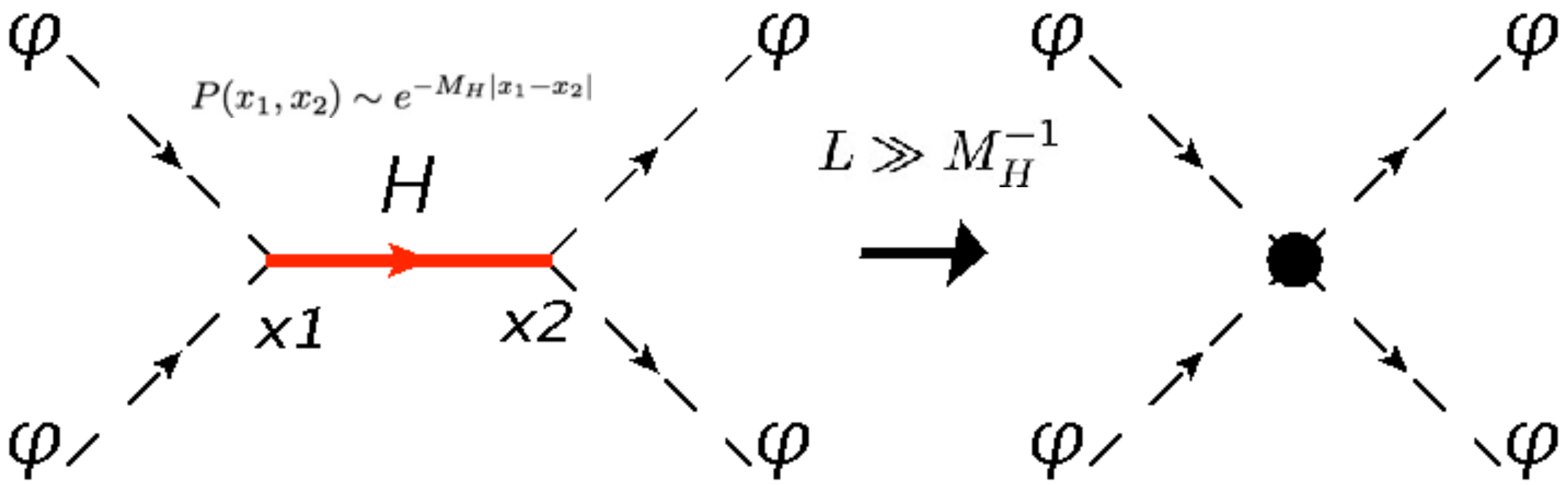
The effective theory is a theory containing only “light” fields φ that reproduces all scattering amplitudes of φ of the full theory containing φ and H. $\mathcal{L}_{\text{eff}}(\phi)$

E.g. 2→2 amplitude schematically:



Note that: ! $\mathcal{L}_{\text{eff}}(\phi) \neq \mathcal{L}(\phi, 0)$!

Local effective Lagrangian



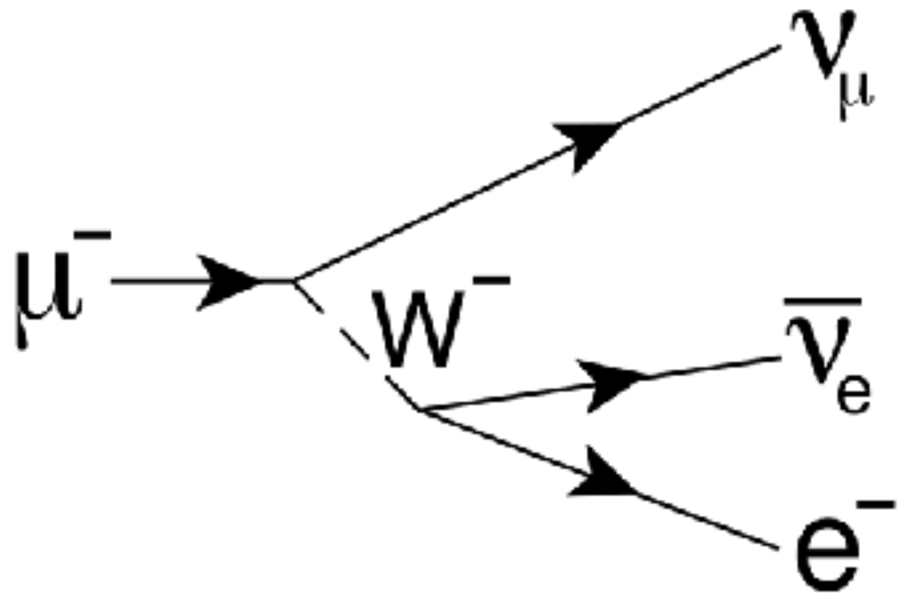
- Propagation of heavy particle H with mass M_H is suppressed at distance scale above its inverse mass

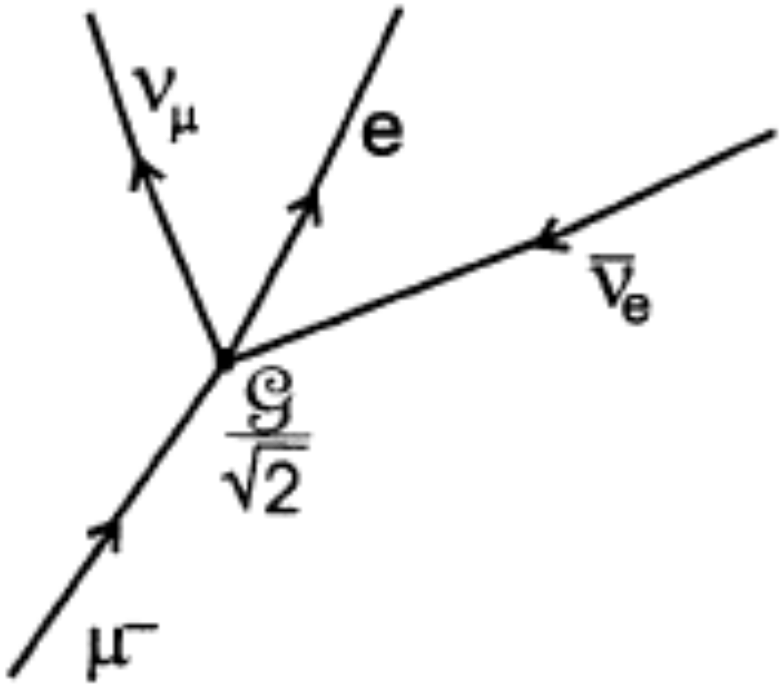
- Processes probing distance scales L >> M_H, equivalently for energy E << M_H, cannot resolve the propagator of H

- Then, intuitively, exchange of heavy particle H between light particles φ should be indistinguishable from a contact interaction of φ

- In other words, the effective Lagrangian describing φ interactions should be well approximated by a local Lagrangian, that is, by a polynomial in φ and its derivatives

Example: Fermi theory

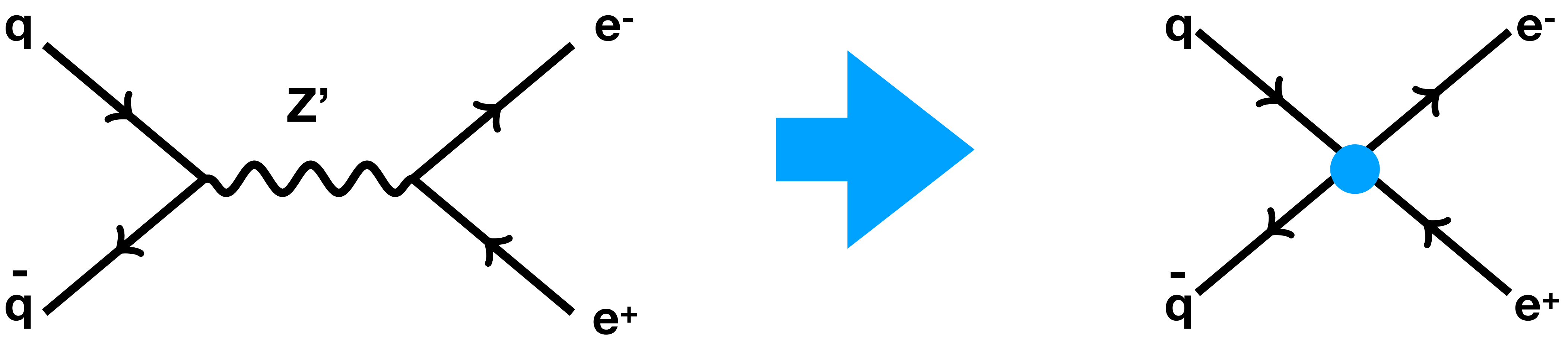




$$\mathscr{L}_{\rm SM} \supset \frac{g_L}{\sqrt{2}}\left[(\bar\nu_\mu\gamma^\alpha\mu_L)+(\bar\nu_e\gamma_\alpha e_L)\right]W^+_\mu + \text{hc}\,.$$

$$\mathscr{L}_{\rm eff} \supset -\frac{g_L^2}{2m_W^2}(\bar\nu_\mu\gamma^\alpha\mu_L)(\bar e_L\gamma_\alpha\nu_e)$$

Example: EFT for BSM



$$\mathscr{L}_{\mathrm{BSM}} \supset g_* \left[(\bar{q}\gamma^{\alpha} q) + (\bar{e}\gamma_{\alpha} e)\right] Z'_{\alpha}$$

$$\mathscr{L}_{\mathrm{eff}} \supset -\frac{g_*^2}{m_{Z'}^2}(\bar{q}\gamma^{\alpha} q)(\bar{e}\gamma_{\alpha} e)$$

Dimensional analysis crash course

$$S = \int d^4x \left[\partial_\mu \phi^\dagger \partial_\mu \phi - \frac{1}{4}(\partial_\mu A_\nu - \partial_\nu A_\mu)^2 + i\bar{\psi}\gamma_\mu \partial_\mu \psi + \dots \right]$$

$$[\partial] = \text{mass}^1$$

$$[\phi] = \text{mass}^1$$

$$[A_\mu] = \text{mass}^1$$

$$[\psi] = \text{mass}^{3/2}$$

Universal language: SMEFT

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \frac{1}{\Lambda}\mathscr{L}_{D=5} + \frac{1}{\Lambda^2}\mathscr{L}_{D=6} + \frac{1}{\Lambda^3}\mathscr{L}_{D=7} + \frac{1}{\Lambda^4}\mathscr{L}_{D=8} + \dots$$

Known SM Lagrangian

Higher-dimensional interactions added to the SM

$$1\ \text{TeV} \lesssim \Lambda \lesssim ?$$

$$\mathscr{M} \sim \mathscr{M}_{\text{SM}} + \frac{E}{\Lambda}c_{D=5} + \frac{E^2}{\Lambda^2}c_{D=6} + \dots$$

Known SM amplitude

Corrections from higher-dimensional interactions

Can be neglected if E/Λ << 1

SMEFT at dimension-5

$$\mathscr{L}_{\rm SMEFT} = \mathscr{L}_{\rm SM} + \frac{1}{\Lambda}\mathscr{L}_{D=5} + \frac{1}{\Lambda^2}\mathscr{L}_{D=6} + \frac{1}{\Lambda^3}\mathscr{L}_{D=7} + \frac{1}{\Lambda^4}\mathscr{L}_{D=8} + \ldots$$

$$\frac{1}{\Lambda}(l_i H) c_{ij} (l_j H) + \text{hc}\,. \to \frac{v^2}{\Lambda} \nu_{L,i} c_{ij} \nu_{L,j} + \text{hc}\,.$$

$$H = \frac{1}{\sqrt{2}}\begin{pmatrix} \cdots \\ v + h + \cdots \end{pmatrix}$$

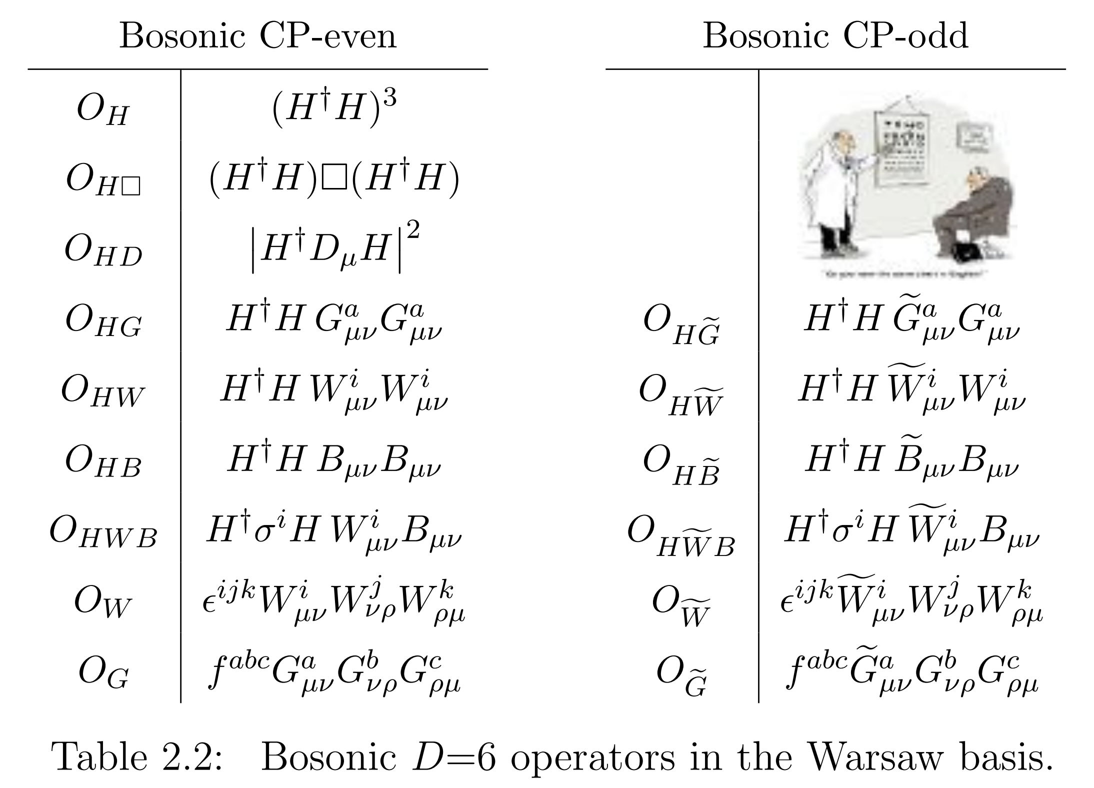
- At dimension 5, the only operators one can construct are so-called Weinberg operators which break lepton number

- After EW breaking they give rise to Majorana mass terms for SM (left-handed) neutrinos

- Neutrino oscillation experiments suggest that these operators are present (unless right-handed neutrinos are light or neutrinos are Dirac).

Dimension-5 interactions are special because they violate lepton number. Therefore, it makes to also consider dimension-6 operators, which have a wider range of physical effects, and are expected to provide dominant observable effects for most model of new physics

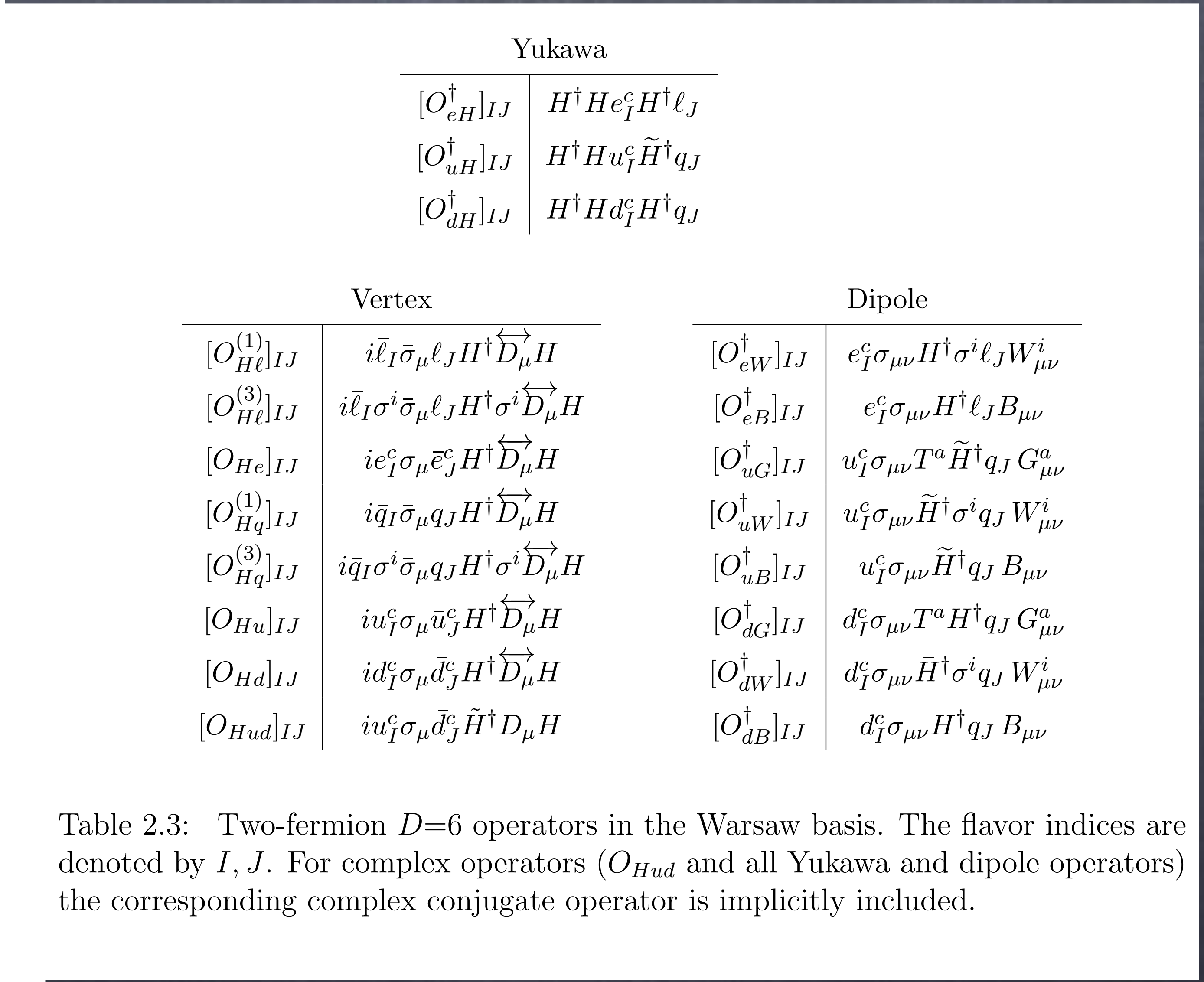
Dimension 6 operators - baryon number conserving



Bosonic CP-even		Bosonic CP-odd	
O_H	$(H^\dagger H)^3$		
$O_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$		
O_{HD}	$\left\|H^\dagger D_\mu H\right\|^2$		
O_{HG}	$H^\dagger H\, G^a_{\mu\nu} G^a_{\mu\nu}$	$O_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^a_{\mu\nu} G^a_{\mu\nu}$
O_{HW}	$H^\dagger H\, W^i_{\mu\nu} W^i_{\mu\nu}$	$O_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}^i_{\mu\nu} W^i_{\mu\nu}$
O_{HB}	$H^\dagger H\, B_{\mu\nu} B_{\mu\nu}$	$O_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B_{\mu\nu}$
O_{HWB}	$H^\dagger \sigma^i H\, W^i_{\mu\nu} B_{\mu\nu}$	$O_{H\widetilde{W}B}$	$H^\dagger \sigma^i H\, \widetilde{W}^i_{\mu\nu} B_{\mu\nu}$
O_W	$\epsilon^{ijk} W^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$	$O_{\widetilde{W}}$	$\epsilon^{ijk} \widetilde{W}^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$
O_G	$f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$	$O_{\widetilde{G}}$	$f^{abc} \widetilde{G}^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$

Table 2.2: Bosonic D=6 operators in the Warsaw basis.

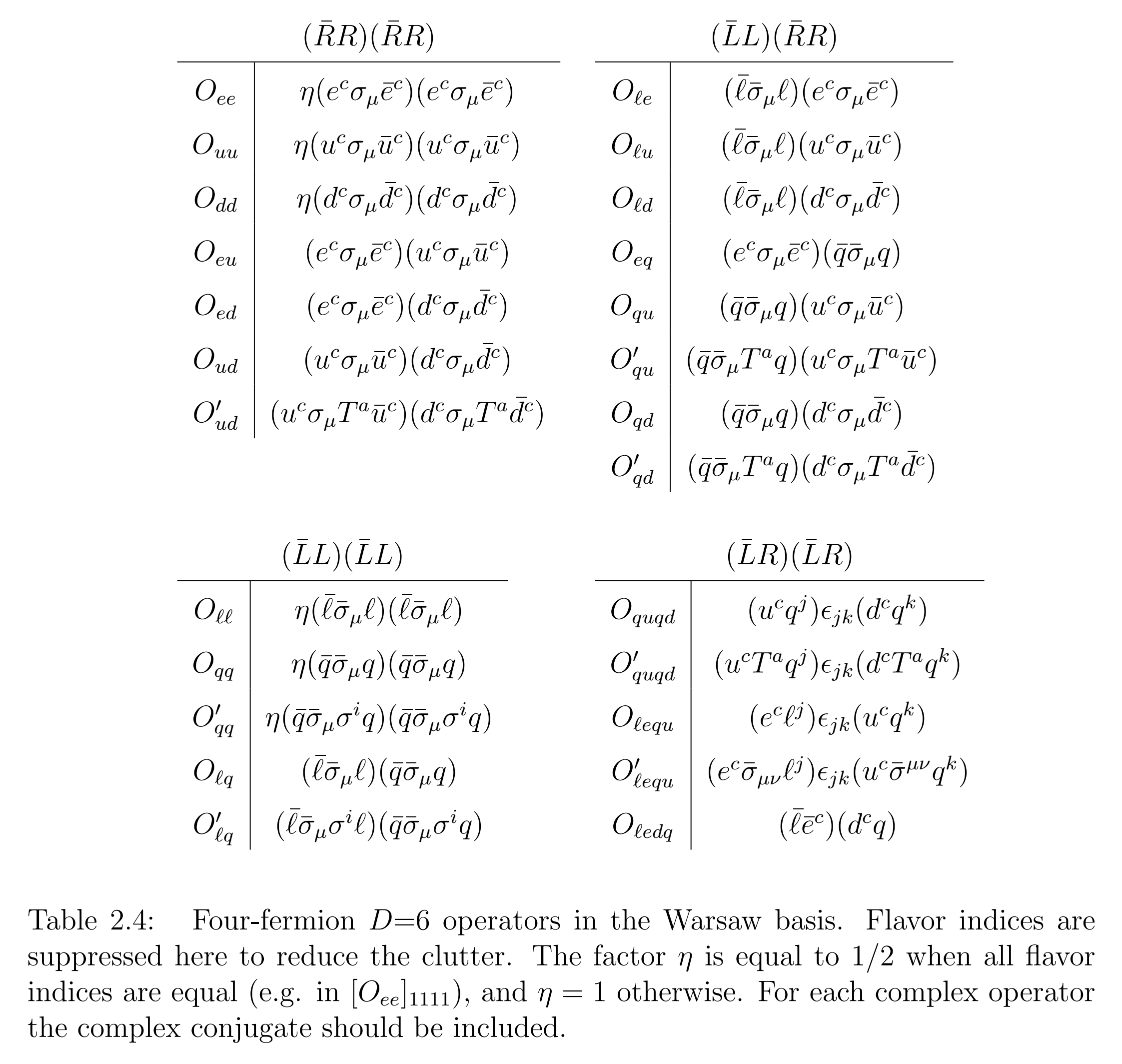
Grządkowski et al.
1008.4884



Yukawa	
$[O^\dagger_{eH}]_{IJ}$	$H^\dagger H e^c_I H^\dagger \ell_J$
$[O^\dagger_{uH}]_{IJ}$	$H^\dagger H u^c_I \widetilde{H}^\dagger q_J$
$[O^\dagger_{dH}]_{IJ}$	$H^\dagger H d^c_I H^\dagger q_J$

Vertex		Dipole	
$[O^{(1)}_{H\ell}]_{IJ}$	$i\bar{\ell}_I \bar{\sigma}_\mu \ell_J H^\dagger \overleftrightarrow{D}_\mu H$	$[O^\dagger_{eW}]_{IJ}$	$e^c_I \sigma_{\mu\nu} H^\dagger \sigma^i \ell_J W^i_{\mu\nu}$
$[O^{(3)}_{H\ell}]_{IJ}$	$i\bar{\ell}_I \sigma^i \bar{\sigma}_\mu \ell_J H^\dagger \sigma^i \overleftrightarrow{D}_\mu H$	$[O^\dagger_{eB}]_{IJ}$	$e^c_I \sigma_{\mu\nu} H^\dagger \ell_J B_{\mu\nu}$
$[O_{He}]_{IJ}$	$i e^c_I \sigma_\mu \bar{e}^c_J H^\dagger \overleftrightarrow{D}_\mu H$	$[O^\dagger_{uG}]_{IJ}$	$u^c_I \sigma_{\mu\nu} T^a \widetilde{H}^\dagger q_J\, G^a_{\mu\nu}$
$[O^{(1)}_{Hq}]_{IJ}$	$i\bar{q}_I \bar{\sigma}_\mu q_J H^\dagger \overleftrightarrow{D}_\mu H$	$[O^\dagger_{uW}]_{IJ}$	$u^c_I \sigma_{\mu\nu} \widetilde{H}^\dagger \sigma^i q_J\, W^i_{\mu\nu}$
$[O^{(3)}_{Hq}]_{IJ}$	$i\bar{q}_I \sigma^i \bar{\sigma}_\mu q_J H^\dagger \sigma^i \overleftrightarrow{D}_\mu H$	$[O^\dagger_{uB}]_{IJ}$	$u^c_I \sigma_{\mu\nu} \widetilde{H}^\dagger q_J\, B_{\mu\nu}$
$[O_{Hu}]_{IJ}$	$i u^c_I \sigma_\mu \bar{u}^c_J H^\dagger \overleftrightarrow{D}_\mu H$	$[O^\dagger_{dG}]_{IJ}$	$d^c_I \sigma_{\mu\nu} T^a H^\dagger q_J\, G^a_{\mu\nu}$
$[O_{Hd}]_{IJ}$	$i d^c_I \sigma_\mu \bar{d}^c_J H^\dagger \overleftrightarrow{D}_\mu H$	$[O^\dagger_{dW}]_{IJ}$	$d^c_I \sigma_{\mu\nu} \bar{H}^\dagger \sigma^i q_J\, W^i_{\mu\nu}$
$[O_{Hud}]_{IJ}$	$i u^c_I \sigma_\mu \bar{d}^c_J \tilde{H}^\dagger D_\mu H$	$[O^\dagger_{dB}]_{IJ}$	$d^c_I \sigma_{\mu\nu} H^\dagger q_J\, B_{\mu\nu}$

Table 2.3: Two-fermion D=6 operators in the Warsaw basis. The flavor indices are denoted by I, J. For complex operators (O_{Hud} and all Yukawa and dipole operators) the corresponding complex conjugate operator is implicitly included.



$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
O_{ee}	$\eta(e^c\sigma_\mu\bar{e}^c)(e^c\sigma_\mu\bar{e}^c)$	$O_{\ell e}$	$(\bar{\ell}\bar{\sigma}_\mu\ell)(e^c\sigma_\mu\bar{e}^c)$
O_{uu}	$\eta(u^c\sigma_\mu\bar{u}^c)(u^c\sigma_\mu\bar{u}^c)$	$O_{\ell u}$	$(\bar{\ell}\bar{\sigma}_\mu\ell)(u^c\sigma_\mu\bar{u}^c)$
O_{dd}	$\eta(d^c\sigma_\mu\bar{d}^c)(d^c\sigma_\mu\bar{d}^c)$	$O_{\ell d}$	$(\bar{\ell}\bar{\sigma}_\mu\ell)(d^c\sigma_\mu\bar{d}^c)$
O_{eu}	$(e^c\sigma_\mu\bar{e}^c)(u^c\sigma_\mu\bar{u}^c)$	O_{eq}	$(e^c\sigma_\mu\bar{e}^c)(\bar{q}\bar{\sigma}_\mu q)$
O_{ed}	$(e^c\sigma_\mu\bar{e}^c)(d^c\sigma_\mu\bar{d}^c)$	O_{qu}	$(\bar{q}\bar{\sigma}_\mu q)(u^c\sigma_\mu\bar{u}^c)$
O_{ud}	$(u^c\sigma_\mu\bar{u}^c)(d^c\sigma_\mu\bar{d}^c)$	O'_{qu}	$(\bar{q}\bar{\sigma}_\mu T^a q)(u^c\sigma_\mu T^a\bar{u}^c)$
O'_{ud}	$(u^c\sigma_\mu T^a\bar{u}^c)(d^c\sigma_\mu T^a\bar{d}^c)$	O_{qd}	$(\bar{q}\bar{\sigma}_\mu q)(d^c\sigma_\mu\bar{d}^c)$
		O'_{qd}	$(\bar{q}\bar{\sigma}_\mu T^a q)(d^c\sigma_\mu T^a\bar{d}^c)$

$(\bar{L}L)(\bar{L}L)$		$(\bar{L}R)(\bar{L}R)$	
$O_{\ell\ell}$	$\eta(\bar{\ell}\bar{\sigma}_\mu\ell)(\bar{\ell}\bar{\sigma}_\mu\ell)$	O_{quqd}	$(u^c q^j)\epsilon_{jk}(d^c q^k)$
O_{qq}	$\eta(\bar{q}\bar{\sigma}_\mu q)(\bar{q}\bar{\sigma}_\mu q)$	O'_{quqd}	$(u^c T^a q^j)\epsilon_{jk}(d^c T^a q^k)$
O'_{qq}	$\eta(\bar{q}\bar{\sigma}_\mu\sigma^i q)(\bar{q}\bar{\sigma}_\mu\sigma^i q)$	$O_{\ell equ}$	$(e^c\ell^j)\epsilon_{jk}(u^c q^k)$
$O_{\ell q}$	$(\bar{\ell}\bar{\sigma}_\mu\ell)(\bar{q}\bar{\sigma}_\mu q)$	$O'_{\ell equ}$	$(e^c\bar{\sigma}_{\mu\nu}\ell^j)\epsilon_{jk}(u^c\bar{\sigma}^{\mu\nu} q^k)$
$O'_{\ell q}$	$(\bar{\ell}\bar{\sigma}_\mu\sigma^i\ell)(\bar{q}\bar{\sigma}_\mu\sigma^i q)$	$O_{\ell edq}$	$(\bar{\ell}\bar{e}^c)(d^c q)$

Table 2.4: Four-fermion D=6 operators in the Warsaw basis. Flavor indices are suppressed here to reduce the clutter. The factor η is equal to 1/2 when all flavor indices are equal (e.g. in $[O_{ee}]_{1111}$), and $\eta = 1$ otherwise. For each complex operator the complex conjugate should be included.

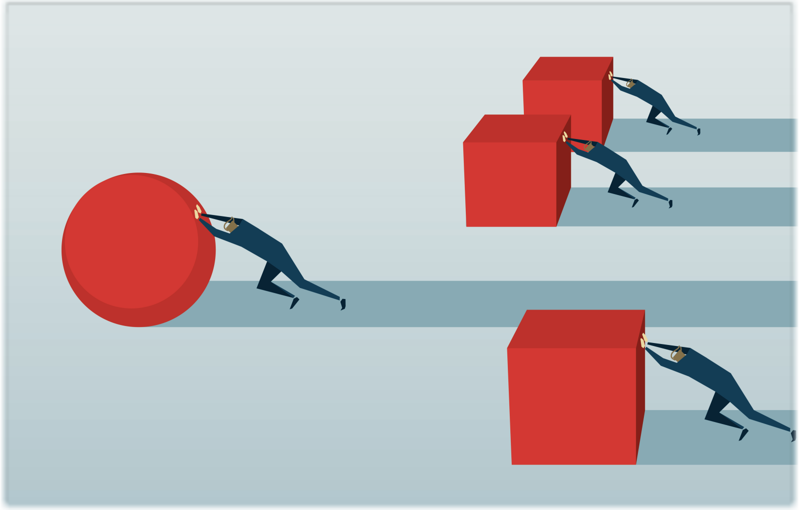
Full set has 2499 distinct operators, including flavor structure and CP conjugates

Alonso et al 1312.2014, Henning et al 1512.03433

Effective theory approach to BSM

- In a sense, the future of particle physics is about determining the Wilson coefficients of all these higher-dimensional operators

- More optimistically, probing an operator suppressed by the scale Λ corresponds to performing an experiment at an experiment at the energy scale Λ. The exciting point is that in many cases Λ >> TeV, thus we are not limited by the LHC reach in exploring high energies!



- EFT language does not describe all possible form of new physics. However it is a very universal language that allows us to systematize our thinking and better plan and design future experiments

Part 3

Future of collider physics

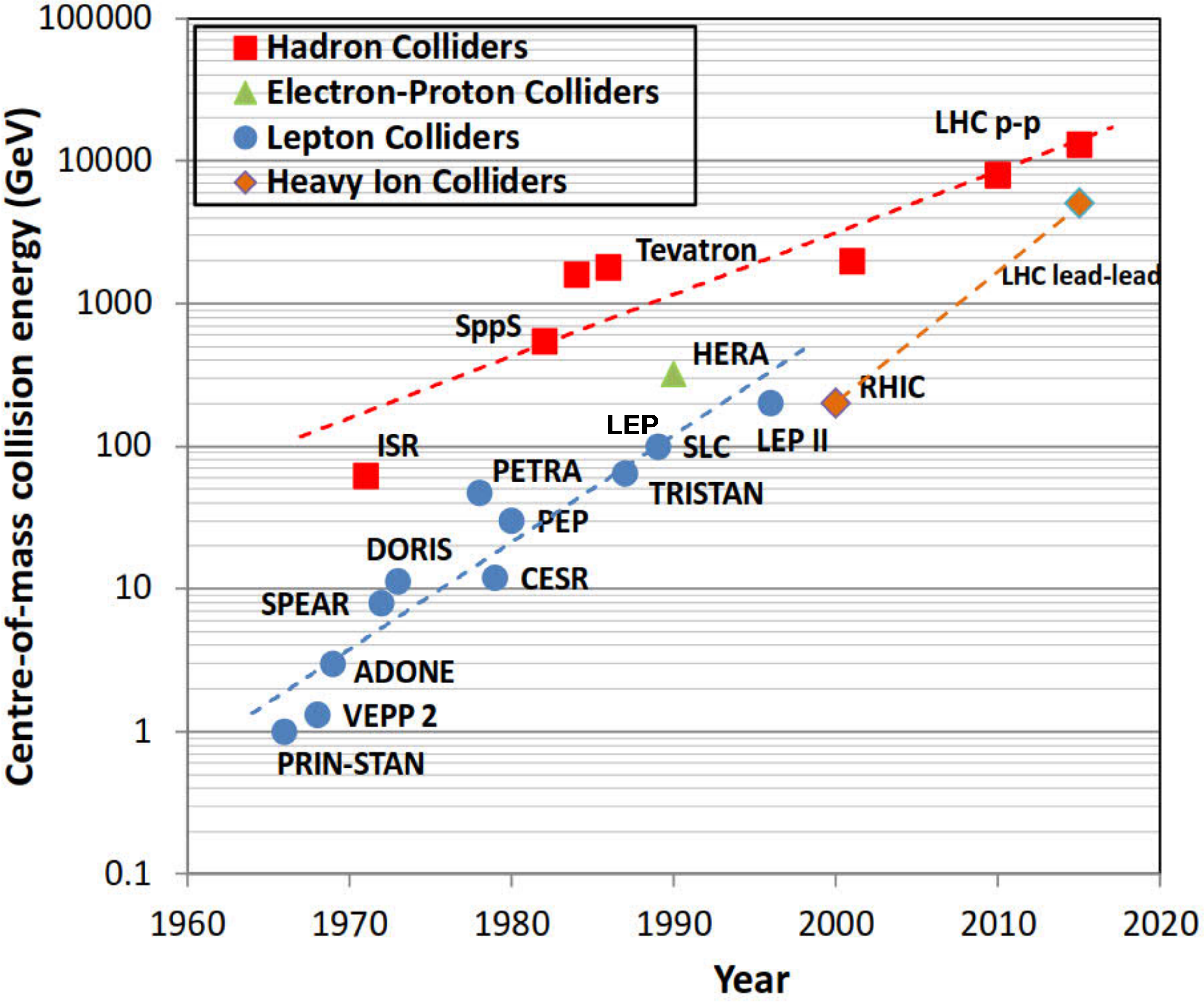
Past of collider physics

- For the last 70 years or so, most of the information about the structure of the fundamental interactions was deduced from observation of particle collisions in high-energy colliders

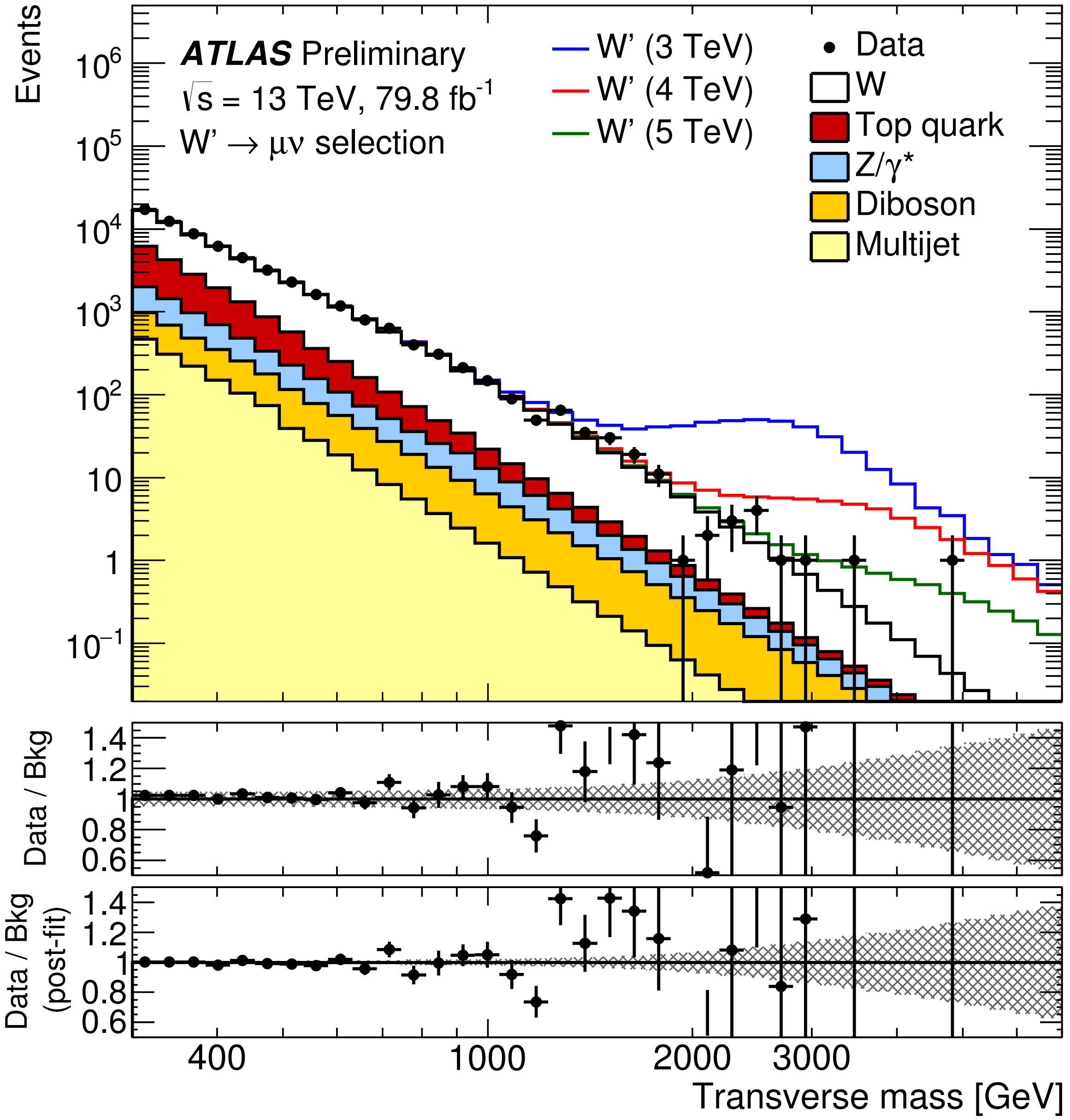
- Collisions with center-of-mass energy E are most robust way to probe degrees of freedom at the distance scale 1/E

Particle	Year	Collider	Energy	Place
Higgs boson	2012	LHC	8 TeV	Europe
Top quark	1995	Tevatron	1.8 TeV	USA
W/Z bosons	1984	SppS	630 GeV	Europe
Gluon	1979	PETRA	38 GeV	Europe
Bottom quark	1977	E288	20 GeV	USA
Tau lepton	1975	SPEAR	3 GeV	USA
Charm quark	1974	SLAC/BNL	3 GeV	USA
…				

Colliders so far

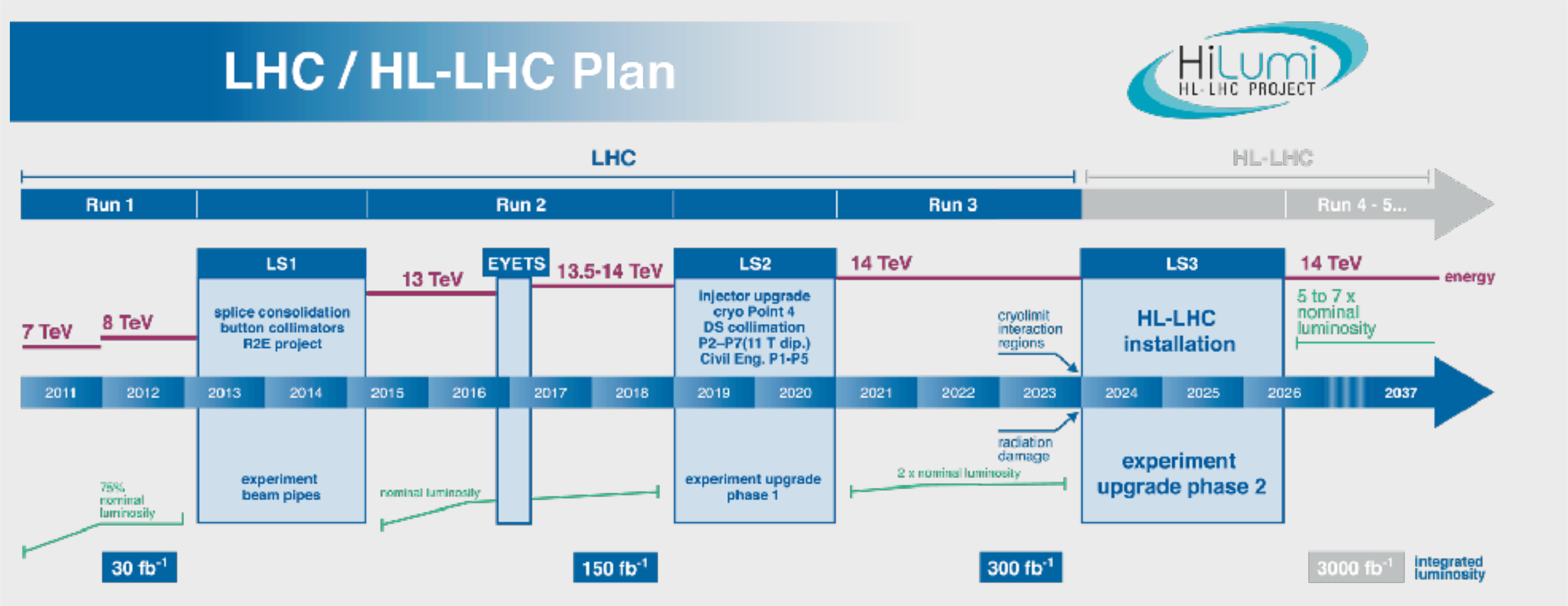


LHC current reach



Current reach for new heavy charged spin-1 bosons: M ~ 5 TeV

Future of the LHC



For the next ~20 years LHC will operate at the same or almost the same energy as today
However, the amount of data will increase tremendously,
about 30 times more than what is available today

Motivation for HL-LHC

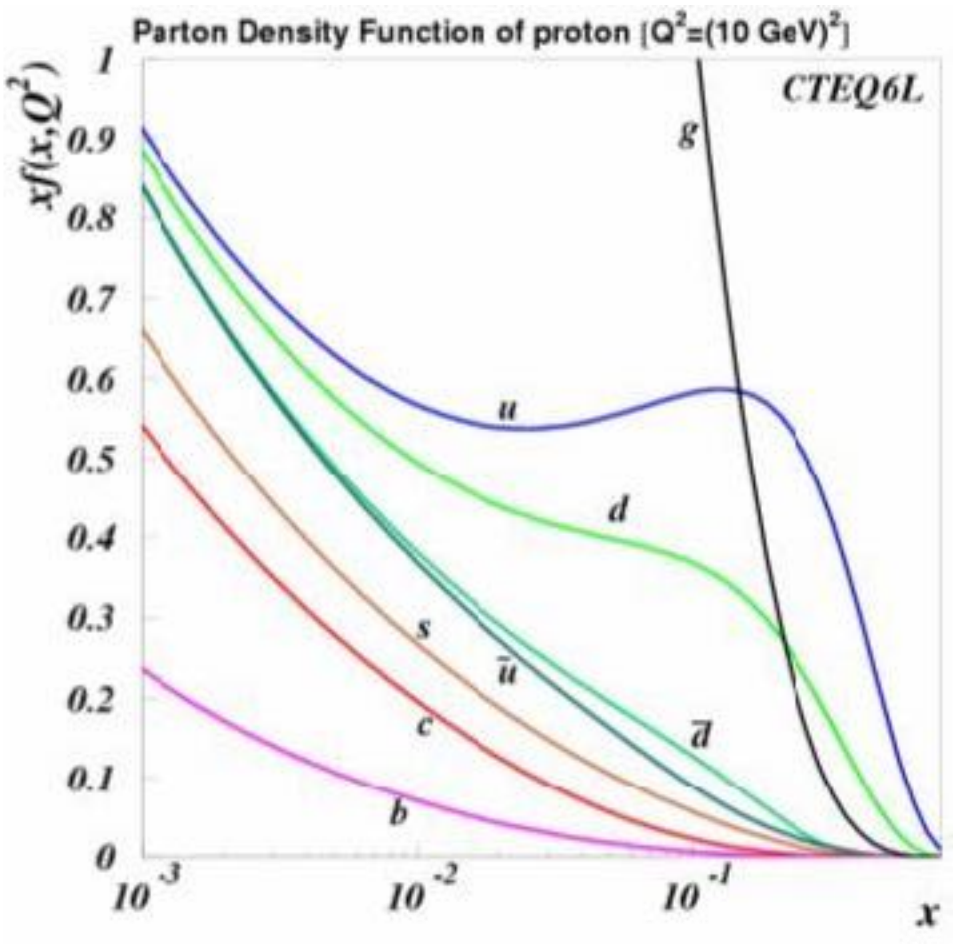
Advantages of more data

- More precise measurements (e.g. of Higgs boson couplings)

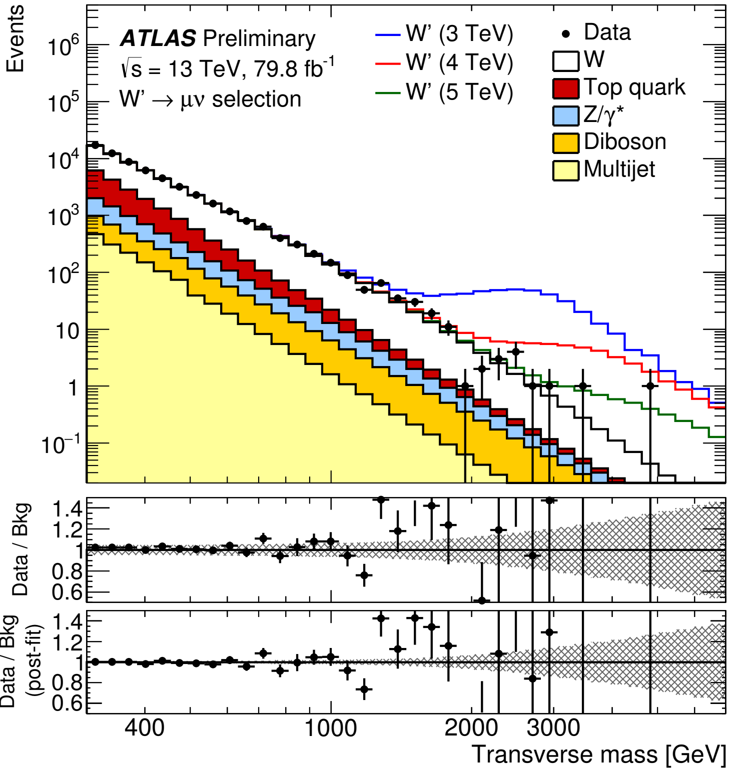
$$\Delta \sim \frac{1}{\sqrt{N}} \rightarrow \frac{\Delta_{\mathrm{HL-LHC}}}{\Delta_{LHC}} \sim \frac{1}{\sqrt{10}} \sim \frac{1}{3}$$

- Better constraints on rate of rare or forbidden processes (e.g. $Z \rightarrow \mu^+ e^-$)

- More events on the high-energy tail, so effectively increased energy reach



HL-LHC constraints from the tail



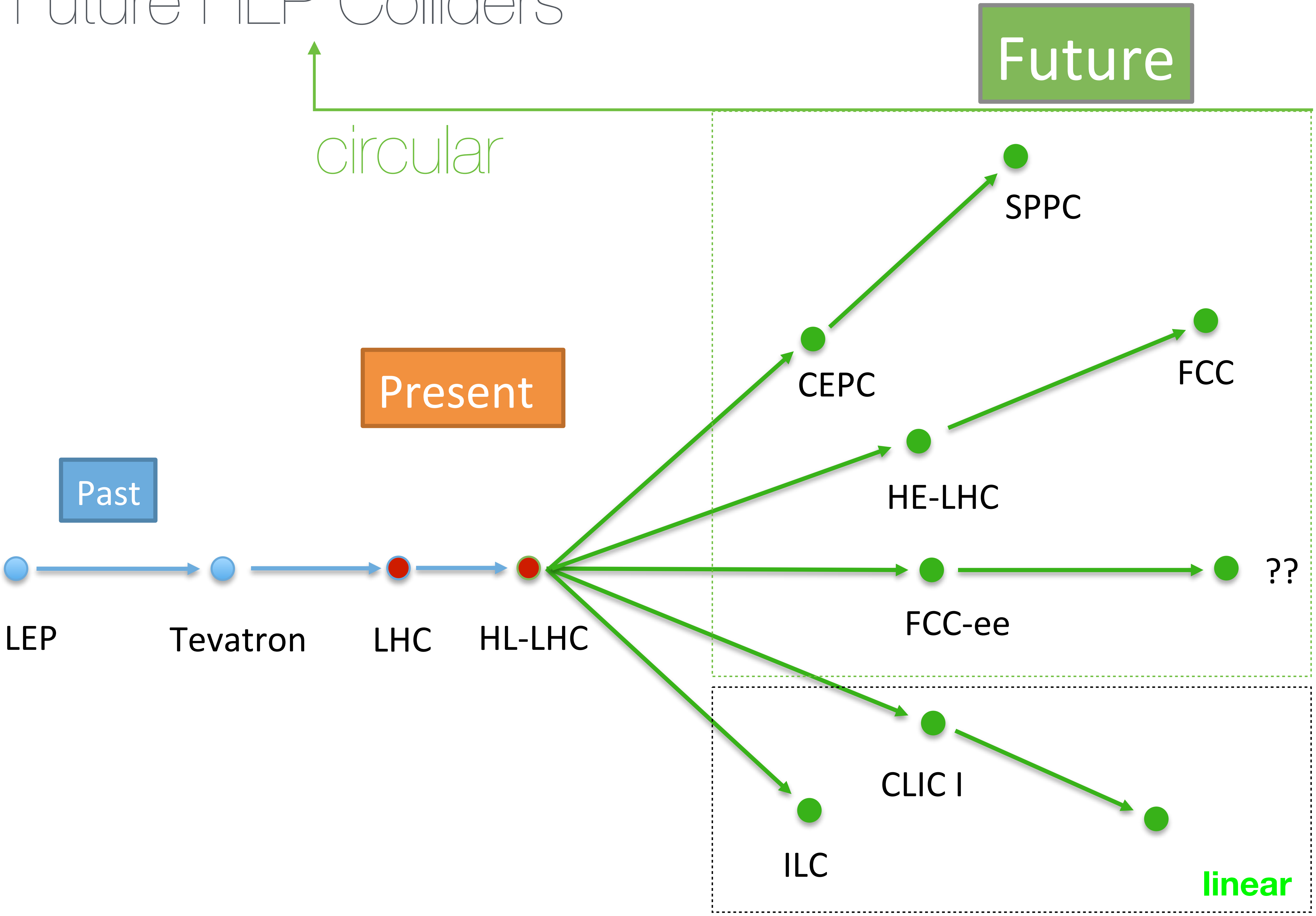
$$N_{\mathrm{LHC}} \approx 1 \times \left(1 + \frac{(5\ \mathrm{TeV})^2}{\Lambda^2}\right)^2$$

$$N_{\mathrm{HL-LHC}} \approx \frac{L_{\mathrm{HL-LHC}}}{L_{\mathrm{LHC}}} \times \left(1 + \frac{(5\ \mathrm{TeV})^2}{\Lambda^2}\right)^2$$

$$2\frac{L_{\mathrm{HL-LHC}}}{L_{\mathrm{LHC}}}\frac{(5\ \mathrm{TeV})^2}{\Lambda^2_{\mathrm{HL-LHC}}} \leq 2\sqrt{\frac{L_{\mathrm{HL-LHC}}}{L_{\mathrm{LHC}}}}$$

$$\Lambda_{\mathrm{HL-LHC}} \geq 5\ \mathrm{TeV}\left(\frac{L_{\mathrm{HL-LHC}}}{L_{\mathrm{LHC}}}\right)^{1/4}$$

Future HEP Colliders



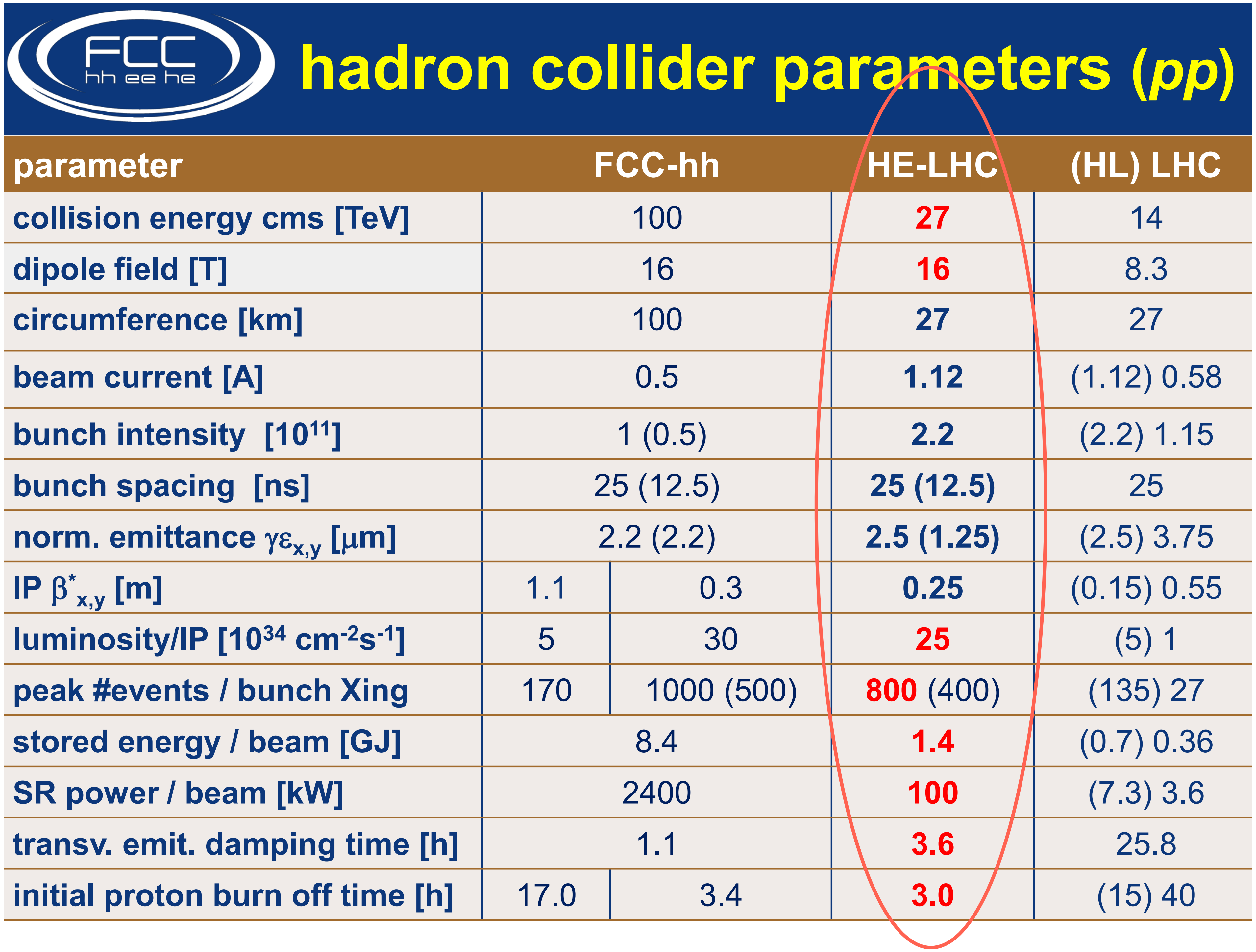
How to increase collision energy

$$\sqrt{S} \sim B \cdot R$$

We need a bigger magnet

We need a bigger collider

HE-LHC



hadron collider parameters (*pp*)

parameter	FCC-hh		HE-LHC	(HL) LHC
collision energy cms [TeV]	100		**27**	14
dipole field [T]	16		**16**	8.3
circumference [km]	100		**27**	27
beam current [A]	0.5		**1.12**	(1.12) 0.58
bunch intensity [10^{11}]	1 (0.5)		**2.2**	(2.2) 1.15
bunch spacing [ns]	25 (12.5)		**25 (12.5)**	25
norm. emittance $\gamma\varepsilon_{x,y}$ [μm]	2.2 (2.2)		**2.5 (1.25)**	(2.5) 3.75
IP $\beta^*_{x,y}$ [m]	1.1	0.3	**0.25**	(0.15) 0.55
luminosity/IP [10^{34} cm^{-2}s^{-1}]	5	30	**25**	(5) 1
peak #events / bunch Xing	170	1000 (500)	**800** (400)	(135) 27
stored energy / beam [GJ]	8.4		**1.4**	(0.7) 0.36
SR power / beam [kW]	2400		**100**	(7.3) 3.6
transv. emit. damping time [h]	1.1		**3.6**	25.8
initial proton burn off time [h]	17.0	3.4	**3.0**	(15) 40

Current technology may allow one to reach magnetic field of 16 T, factor of two larger then that at the LHC, leading to two-fold energy increase

FCC

FCC

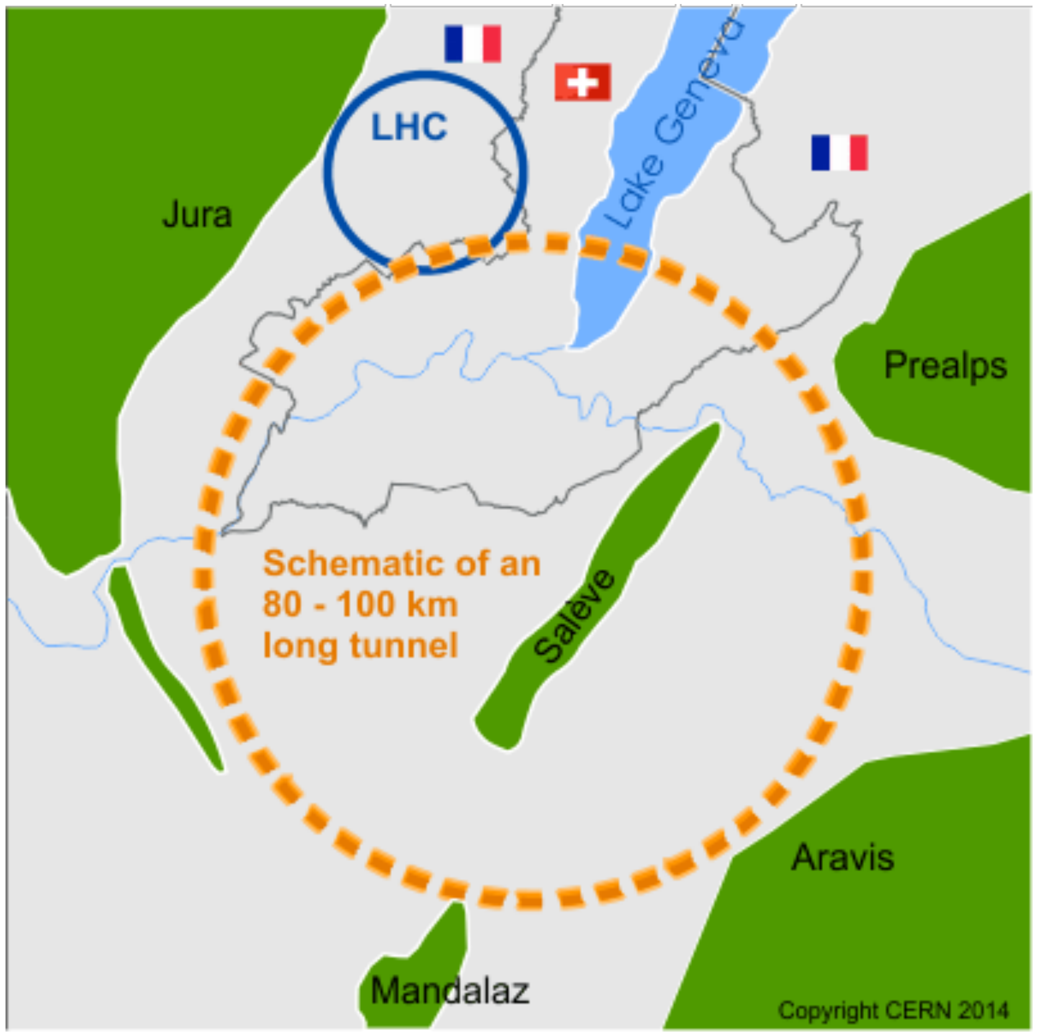
Future Circular Collider

FCC-ee: e^+e^- with $\sqrt{s}$ = 90 - 350 GeV

FCC-hh: pp with $\sqrt{s}$ ~ 100 TeV

Circumference: 80-100 km

schematic at CERN location



CepC

Circular Electron Positron Collider

CepC: e^+e^- with $\sqrt{s}$ = 240 - 250 GeV

SppC: pp with $\sqrt{s}$ = 70 - 100 TeV

Circumference/Length: 54-100 km

investigated site in China

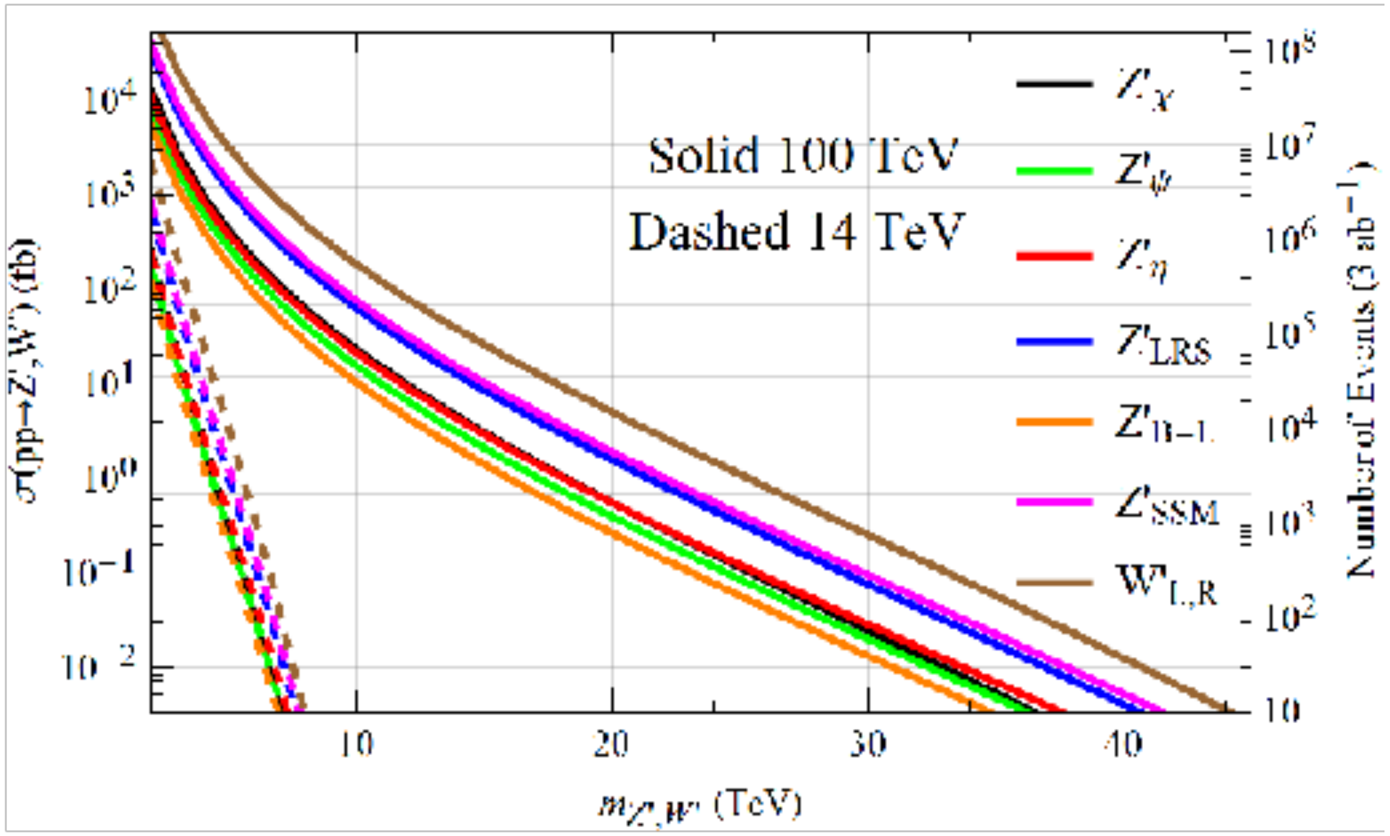
Motivation for higher energy colliders

Advantages of more energy

- Directly exploring new energy range in search for new particles

- Energy = accuracy, for processes whose cross section grows with energy

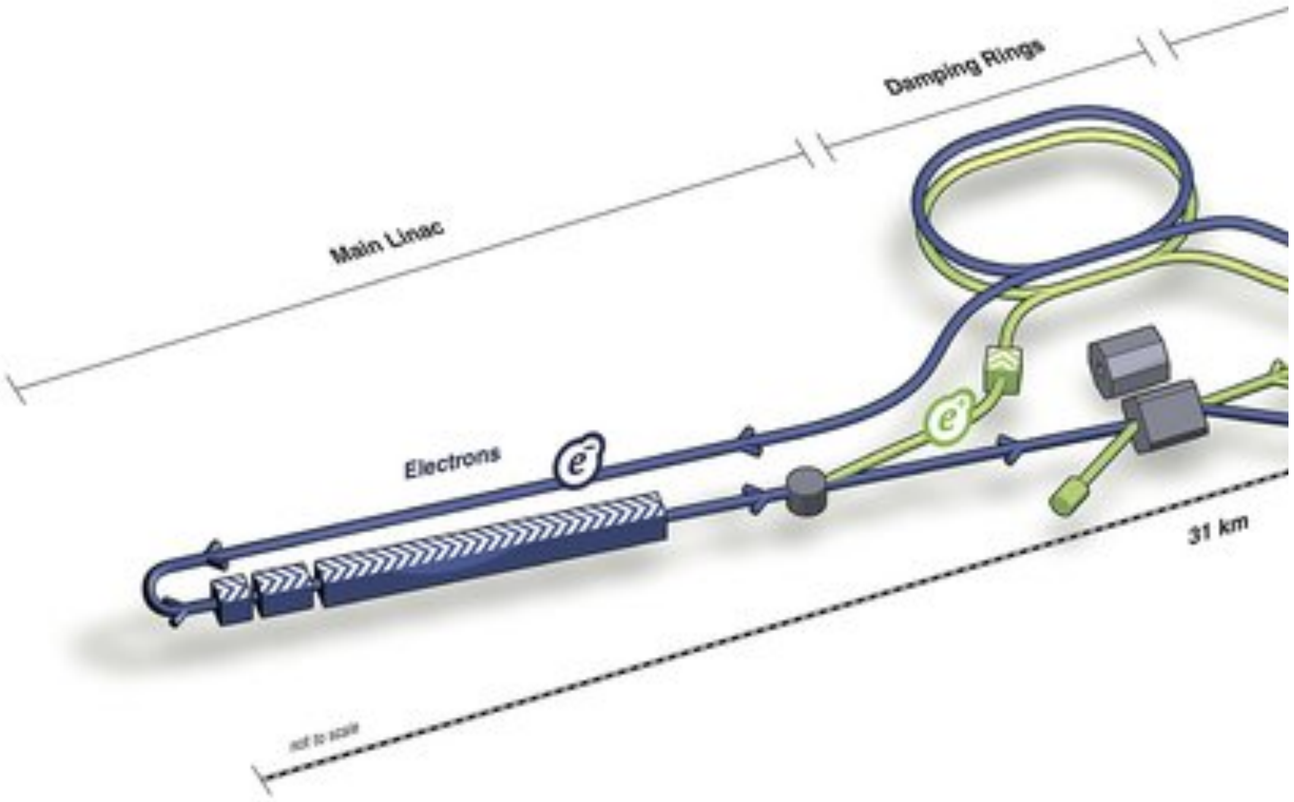
- Access to Standard Model processes whose cross section at the LHC is too small to be observable



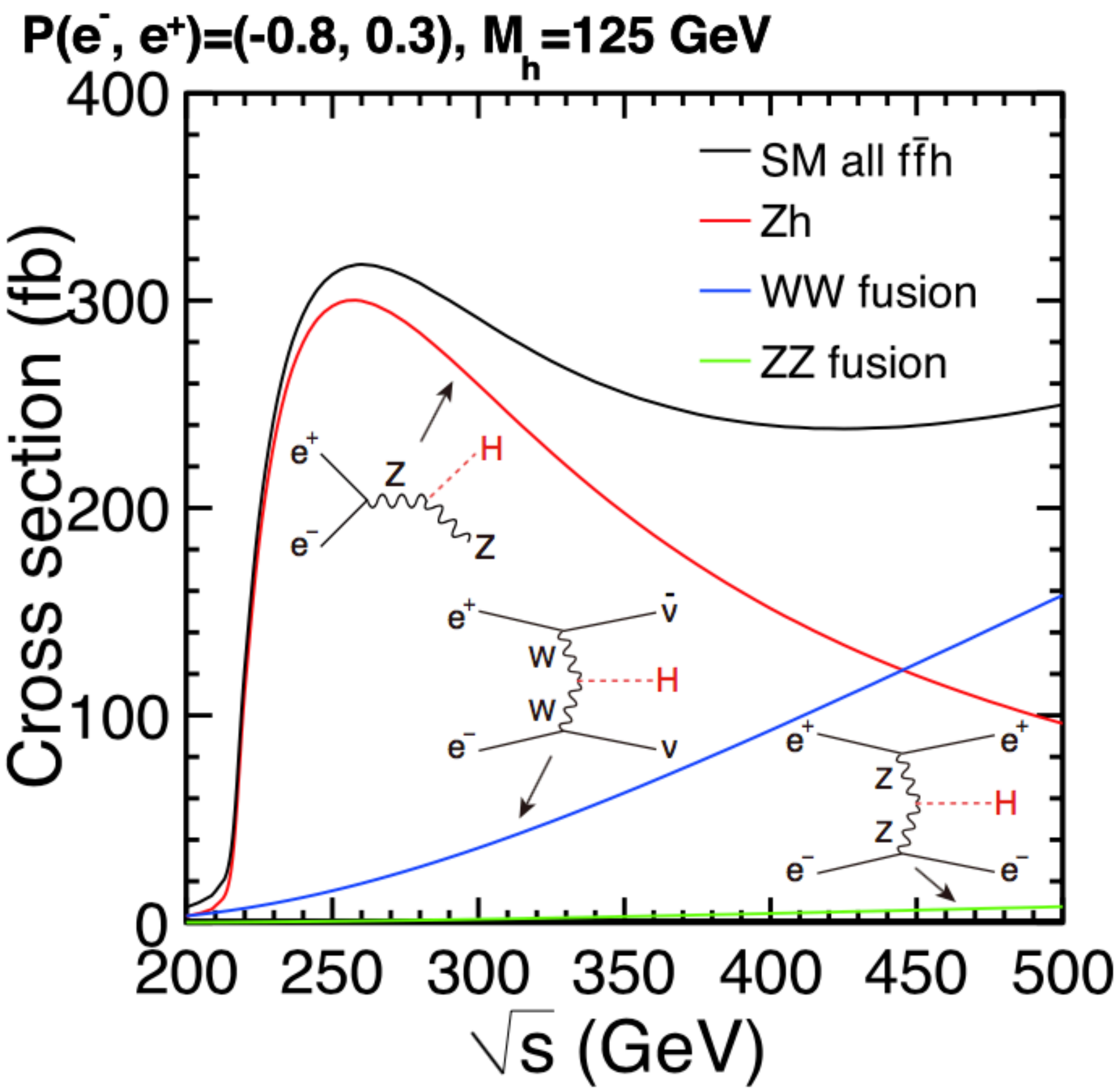
Other collider ideas

- Use 100km collider (in the first stage) as ~250 GeV e^+e^- collider, to serve as a Higgs factory
- Muon collider to lower synchrotron emission
- Linear e^+e^- collider to avoid synchrotron emission completely
- Wake field plasma acceleration
- …

ILC



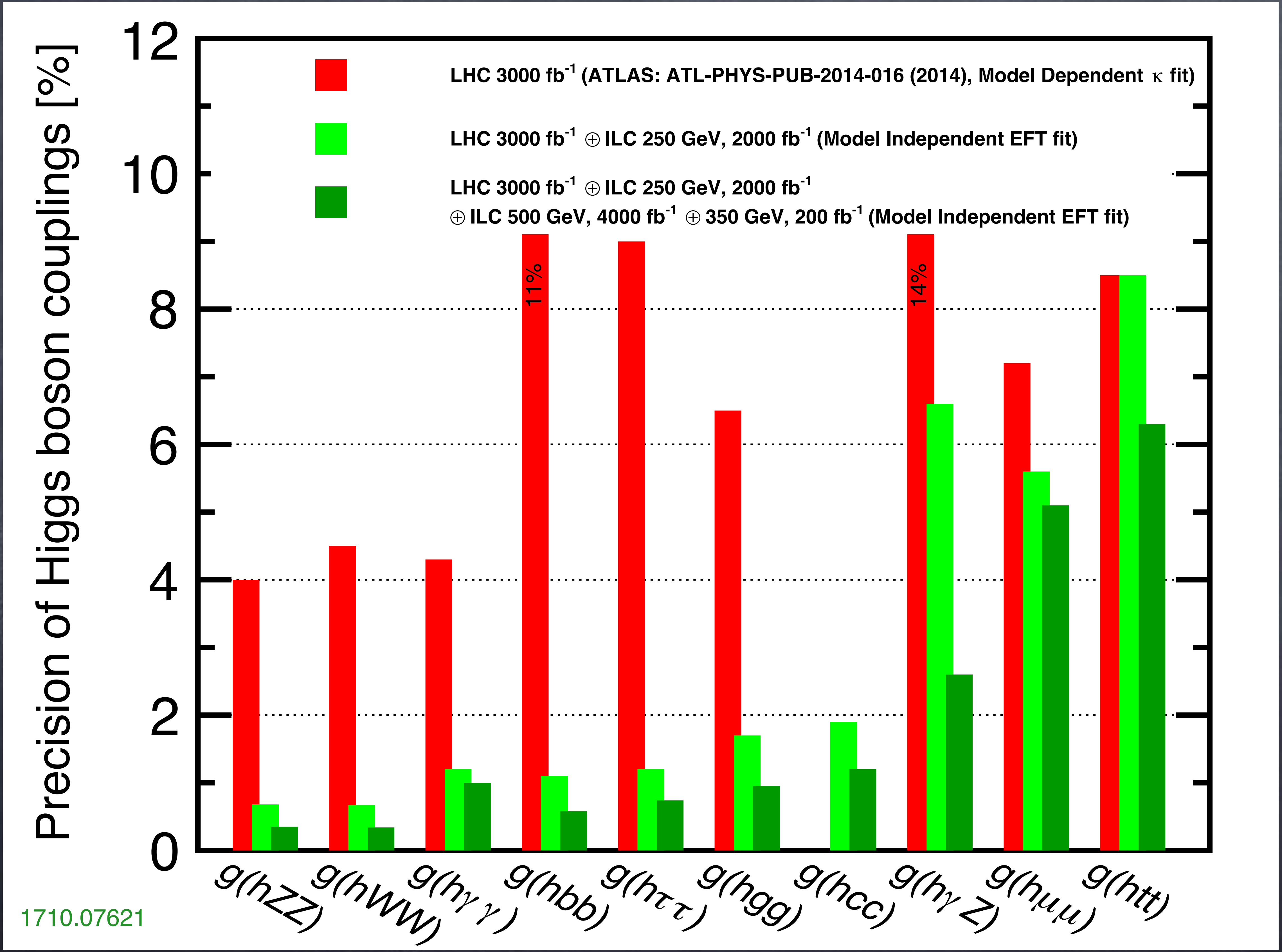
for the latest news see 1710.07621 and 1711.00568



Initially ~20km machine colliding electrons and positrons in Kitakami/Japan, with c.o.m energy of 250 GeV. Upgradable to ~30km and 500 GeV

Clean environment of e+e- collisions together with high luminosity will allow for per-mille level precision studies of Higgs boson interactions

Higgs couplings precision measurements



1710.07621

Motivation for lepton colliders

Advantages of lepton colliders

- Cleaner environment of lepton colliders allows for very precise measurements of cross sections and branching fractions

- Precision measurements effectively allow one to probe physics at energies much larger than the direct energy reach of the machine

Operators to Observables to Constraints

$$\mathcal{L} \supset -\frac{c_{H\Box}}{\Lambda^2}\partial_\mu(H^\dagger H)\partial_\mu(H^\dagger H) \quad \Longrightarrow \quad h \to h\left(1+\frac{c_{H\Box}v^2}{2\Lambda^2}\right)$$

But then *all* Higgs boson couplings present in SM are universally rescaled

$$\frac{h}{v}\left[2m_W^2 W_\mu^+ W_\mu^- + m_Z^2 Z_\mu Z_\mu\right]$$
$$\to \frac{h}{v}\left(1+\frac{c_{H\Box}v^2}{2\Lambda^2}\right)\left[2m_W^2 W_\mu^+ W_\mu^- + m_Z^2 Z_\mu Z_\mu\right]$$

$$\frac{h}{v}\sum_f m_f \bar{f} f$$
$$\to \frac{h}{v}\left(1+\frac{c_{H\Box}v^2}{2\Lambda^2}\right)\sum_f m_f \bar{f} f$$

Bound on Wilson coefficient $c_{H\Box}$ from Higgs signal strength measurements at LHC

$$\mu = 1.09 \pm 0.11$$

$$-0.13 < \frac{v^2 c_{H\Box}}{\Lambda^2} < 0.31 \qquad @\ 95\%\ \mathrm{CL}$$

Run-1 ATLAS+CMS
1606.02266

For the negative-sign bound

$$\frac{\Lambda}{g_*} \gtrsim 0.7\ \mathrm{TeV}. \qquad \Lambda \gtrsim \begin{cases} 9\ \mathrm{TeV} & g_* \sim 4\pi \\ 700\ \mathrm{GeV} & g_* \sim 1 \end{cases}$$

weakly coupled

strongly coupled

Operators to Observables to Constraints

$$\mathcal{L} \supset -\frac{c_{H\Box}}{\Lambda^2}\partial_\mu(H^\dagger H)\partial_\mu(H^\dagger H) \quad \Longrightarrow \quad h \to h\left(1+\frac{c_{H\Box}v^2}{2\Lambda^2}\right)$$

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$$\frac{h}{v}\sum_f m_f \bar{f} f$$
$$\to \frac{h}{v}\left(1+\frac{c_{H\Box}v^2}{2\Lambda^2}\right)\sum_f m_f \bar{f} f$$

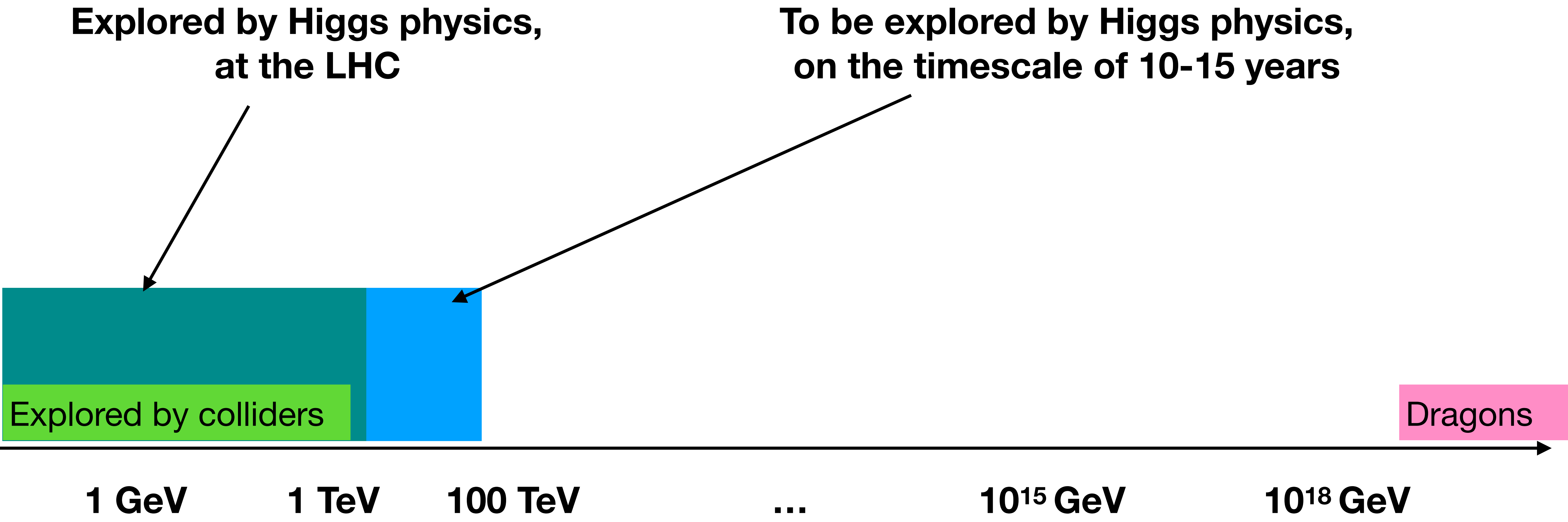
Bound on Wilson coefficient $c_{H\Box}$ from Higgs signal strength measurements at LHC

$$\mu = 1.000 \pm 0.001 \qquad -0.002 < \frac{c_{H\Box}v^2}{\Lambda^2} < 0.002 \qquad @95\%\mathrm{CL}$$

ILC
3606.02266

$$\frac{\Lambda}{g_*} \gtrsim 5.5\ \mathrm{TeV} \quad . \qquad \Lambda \gtrsim \begin{cases} 70\ \mathrm{TeV} & g_* \sim 4\pi \\ 5.5\ \mathrm{TeV} & g_* \sim 1 \end{cases}$$

strongly coupled
weakly coupled



Explored by Higgs physics,
at the LHC

To be explored by Higgs physics,
on the timescale of 10-15 years

Explored by colliders

Dragons

1 GeV **1 TeV** **100 TeV** **…** **10^{15} GeV** **10^{18} GeV**

Part 4

Future of low-energy precision physics

Landscape view of physics beyond the Standard Model

Explored by colliders

Dragons

1 GeV **1 TeV** **1 PeV** **…** **10^{15} GeV** **10^{18} GeV**

How can we find dark matter/inflaton/heavy neutrino or other physics addressing problems of the Standard Model assuming mass scale of new physics is between few TeV and Planck scale?

Example: Grand unification

SM gauge interactions

GUT gauge interactions

$$\sum_f \bar{f}\gamma^\mu \left(g_s G^a_\mu T^a + g_L W^i_\mu \frac{\sigma^i}{2} + g_Y B_\mu Y \right) f \subset g_{\mathrm{GUT}} \bar{\psi}\gamma^\mu V^\alpha_\mu T^\alpha \psi$$

	$SU(3)_C$	$SU(2)_W$	$U(1)_Y$
$q = (u_L,d_L)$	3	2	1/6
u_R	3	1	2/3
d_R	3	1	-1/3
$l = (\nu_L,e_L)$	1	2	-1/2
e_R	1	1	-1

unified coupling constant

Gauge field of larger group G containing SM gauge fields

Generators of larger group G containing $SU(3)_C$*$SU(2)_L$*$U(1)_Y$

Representation of G containing all SM fermions

SU(5) grand unification

	$SU(3)_C$	$SU(2)_W$	$U(1)_Y$
$q = (u_L, d_L)$	3	2	1/6
u_R	3	1	2/3
e_R	1	1	-1
d_R	3	1	-1/3
$l = (\nu_L, e_L)$	1	2	-1/2

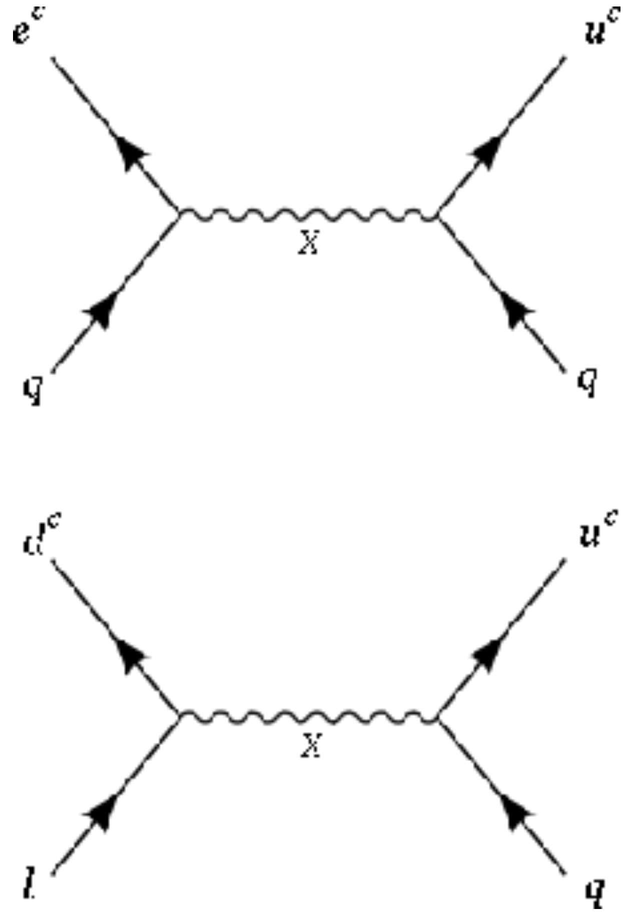
SU(5)

$$\mathbf{5} = \begin{pmatrix} \nu_L \\ e_L \\ \bar{d}_R(\times 3) \end{pmatrix} \qquad \mathbf{10} = \begin{pmatrix} u_L(\times 3) \\ d_L(\times 3) \\ \bar{u}_R(\times 3) \\ \bar{e}_R \end{pmatrix}$$

$$V_\mu^\alpha T^\alpha = \begin{pmatrix} W_\mu^i \frac{\sigma^i}{2} & X \\ X^\dagger & G_\mu^a \frac{\lambda^a}{2} \end{pmatrix} + \dots$$

SU(5) grand unification

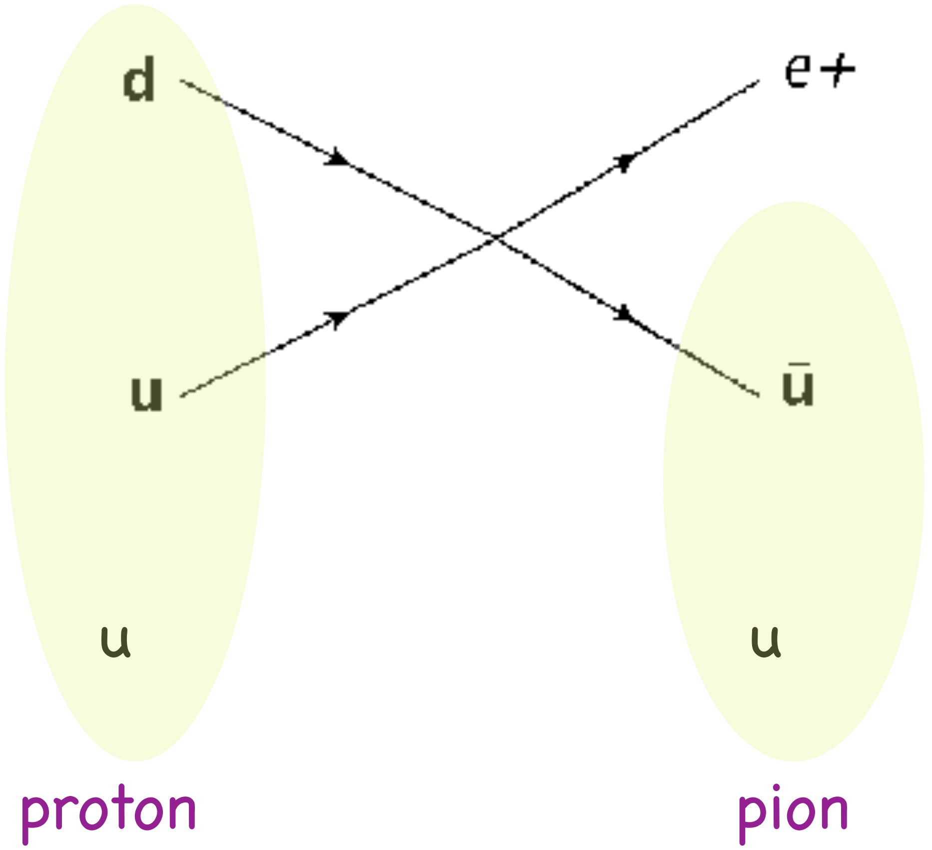
$$\begin{pmatrix} l \\ \bar{d}_R \end{pmatrix}^{\dagger} \gamma^{\mu} \begin{pmatrix} W^i_\mu \frac{\sigma^i}{2} & X \\ X & G^a_\mu \frac{\lambda^a}{2} \end{pmatrix} \begin{pmatrix} l \\ \bar{d}_R \end{pmatrix}$$



“Off-diagonal” gauge boson mediate new interactions between quarks and leptons which can lead to proton decay, e.g.

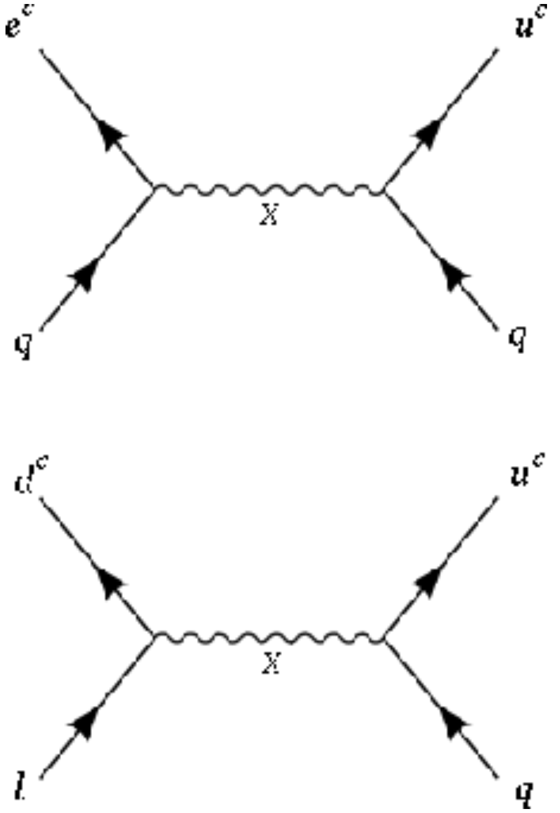
$$p \to e^+ \pi^0$$

$$\tau(p \to e^+ \pi^0) \geq 1.6 \times 10^{34} \text{ years}$$



SU(5) grand unification

$$\begin{pmatrix} l \\ \bar{d}_R \end{pmatrix}^{\dagger} \gamma^{\mu} \begin{pmatrix} W^i_\mu \frac{\sigma^i}{2} & X \\ X & G^a_\mu \frac{\lambda^a}{2} \end{pmatrix} \begin{pmatrix} l \\ \bar{d}_R \end{pmatrix} + \dots$$



“Off-diagonal” gauge boson mediate new interactions between quarks and leptons which can lead to proton decay, e.g.

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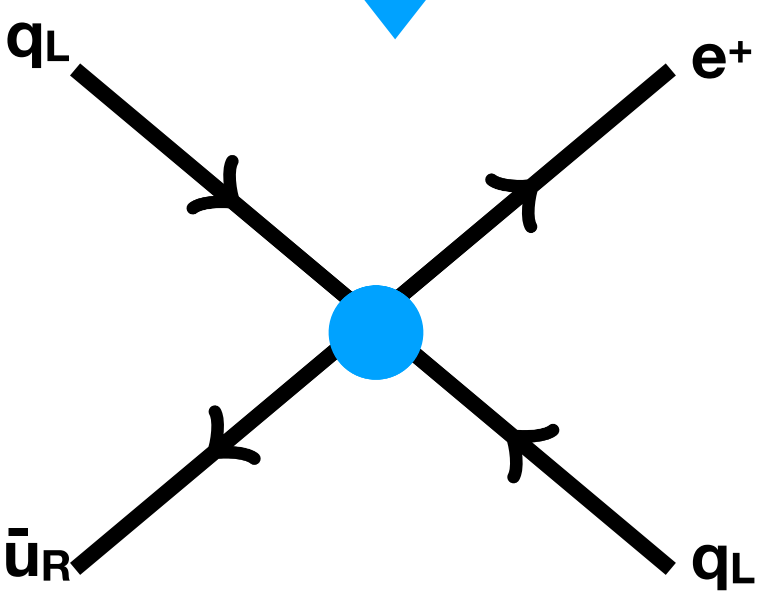
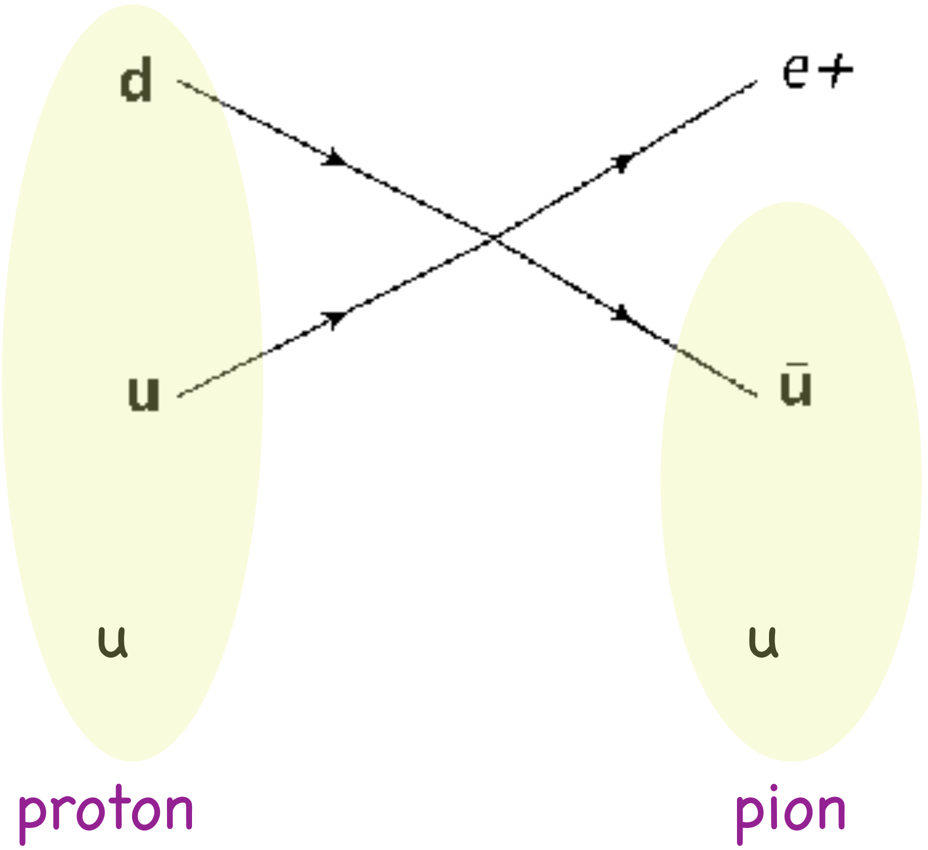


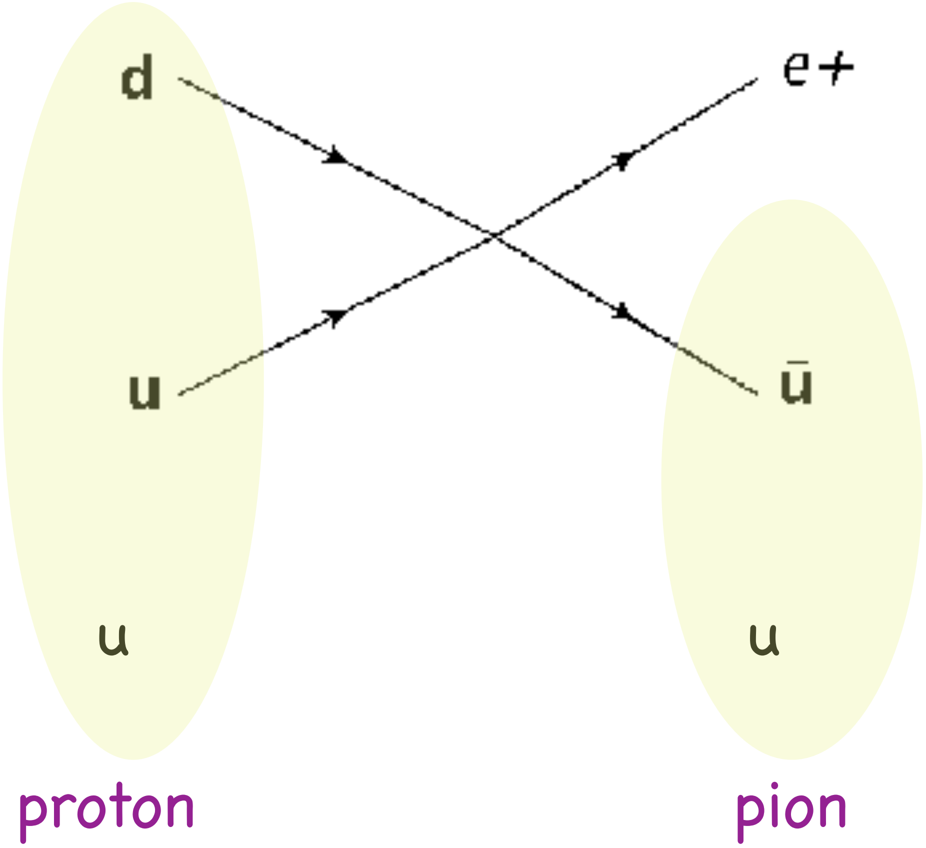


Proton decay: model independent analysis

- Special subclass of dimension-6 operators violating baryon and lepton numbers (but preserving B-L)

$$\mathscr{L}_{\text{SMEFT}} \supset \frac{1}{\Lambda_B^2}(q_L q_L)(\bar{u}_R \bar{e}_R)$$

- They lead to baryon number violating transitions which in particular enable proton decay, e.g. via p → π_0 e^+



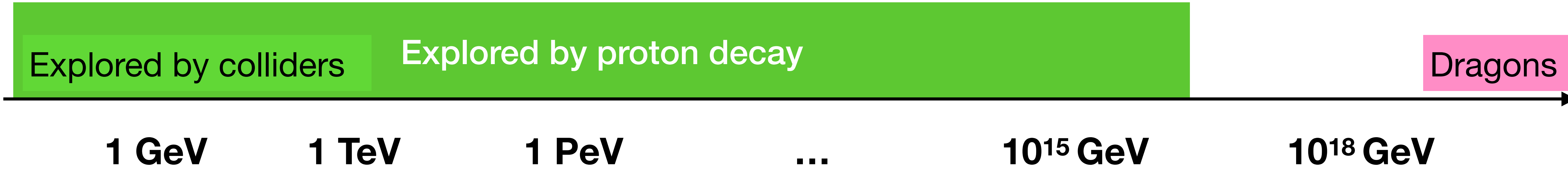
- Scale Λ_B suppressing these operators must be of order 10^{16} GeV

$$\mathcal{M}(p \to e^+\pi^0) \sim \frac{1}{\Lambda_B^2}$$

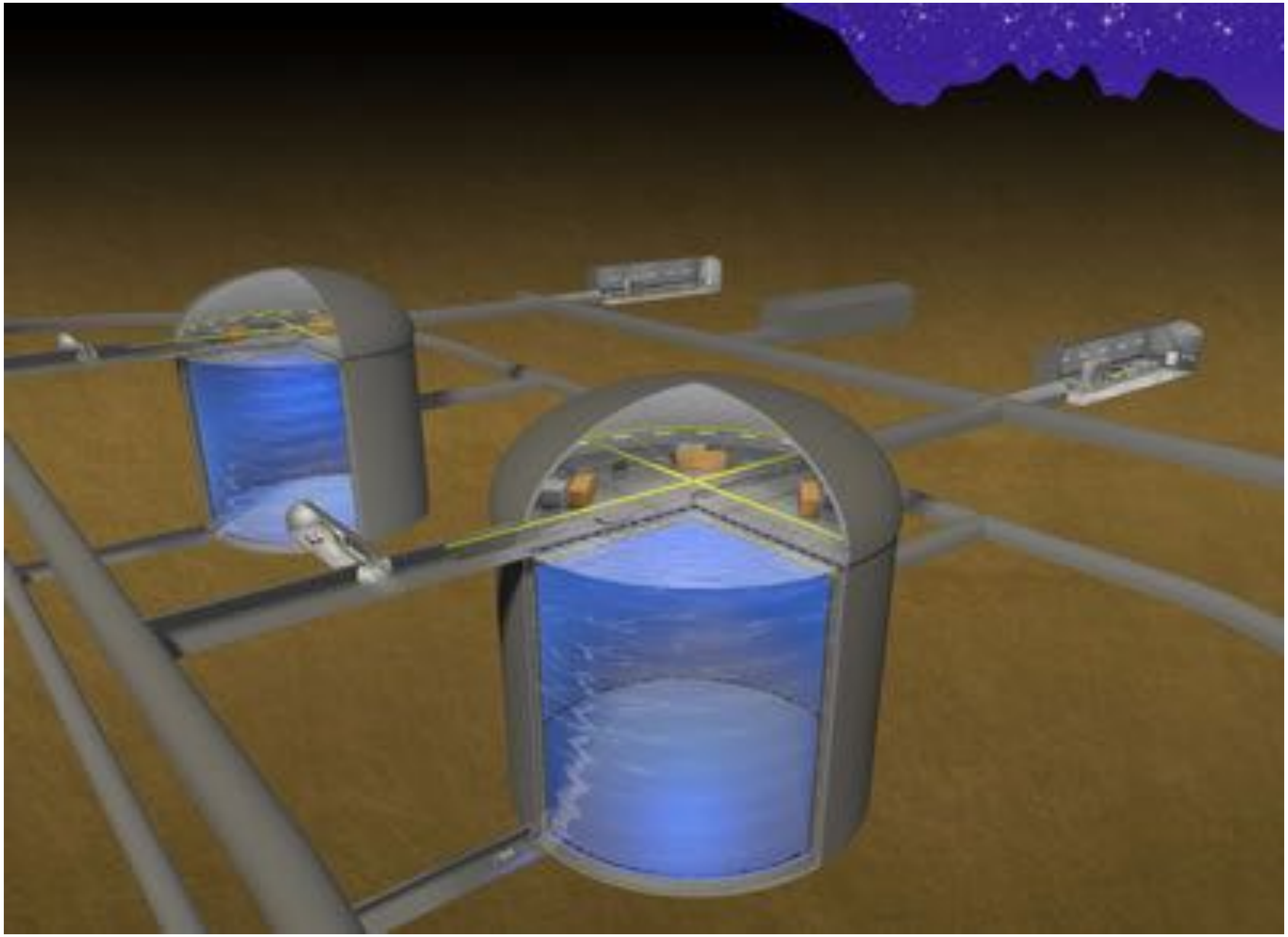
$$\Gamma(p \to e^+\pi^0) \sim \frac{m_p^5}{8\pi\Lambda_B^4}$$

$$\tau(p \to e^+\pi^0) \sim \frac{8\pi\Lambda_B^4}{m_p^5}$$

$$\hbar = 1 \to 1 \text{ sec} = \frac{1.5\times 10^{24}}{\text{GeV}} \qquad \sim 10^{34}\text{years}\left(\frac{\Lambda_B}{10^{16}\text{GeV}}\right)^4$$

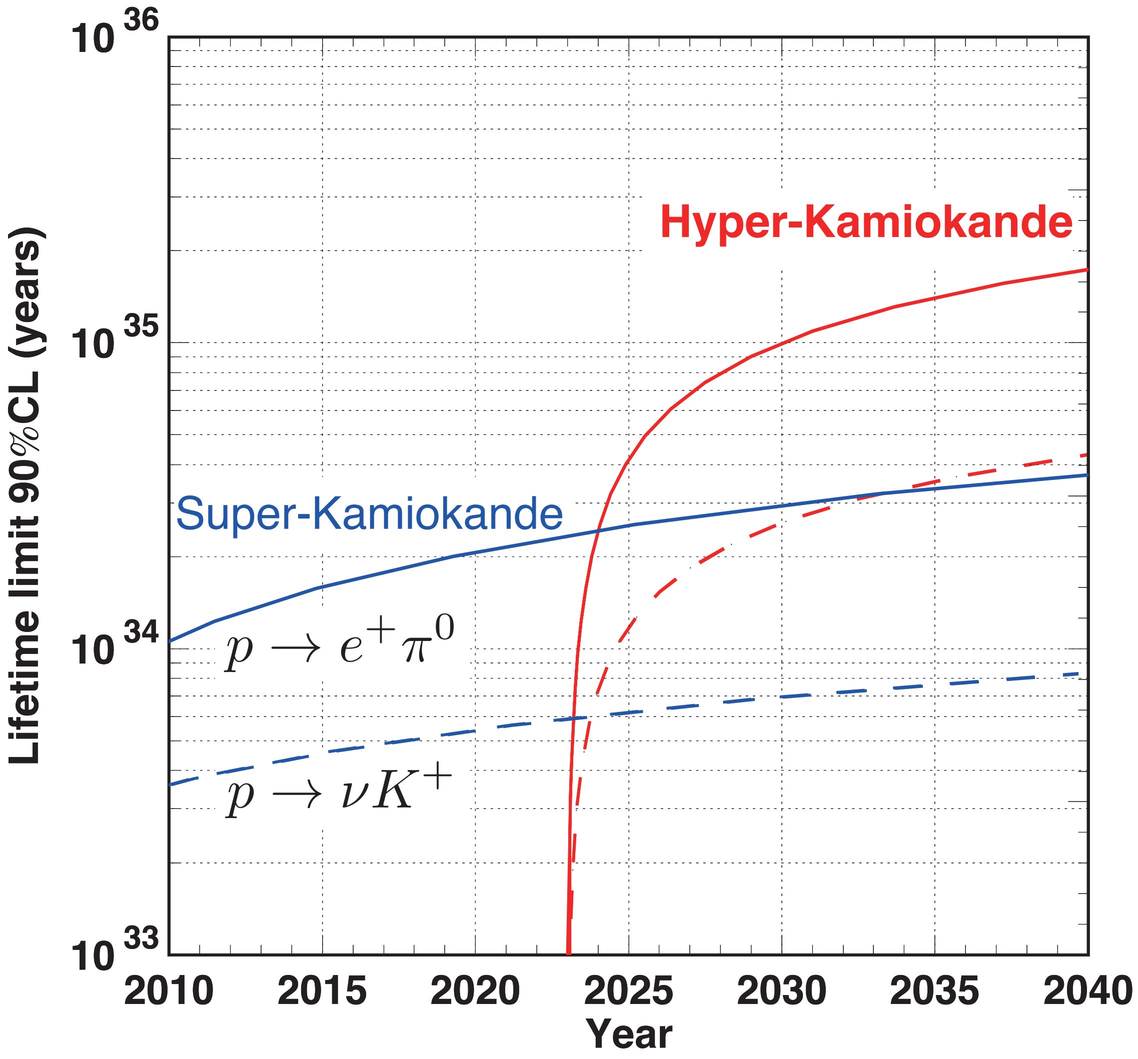


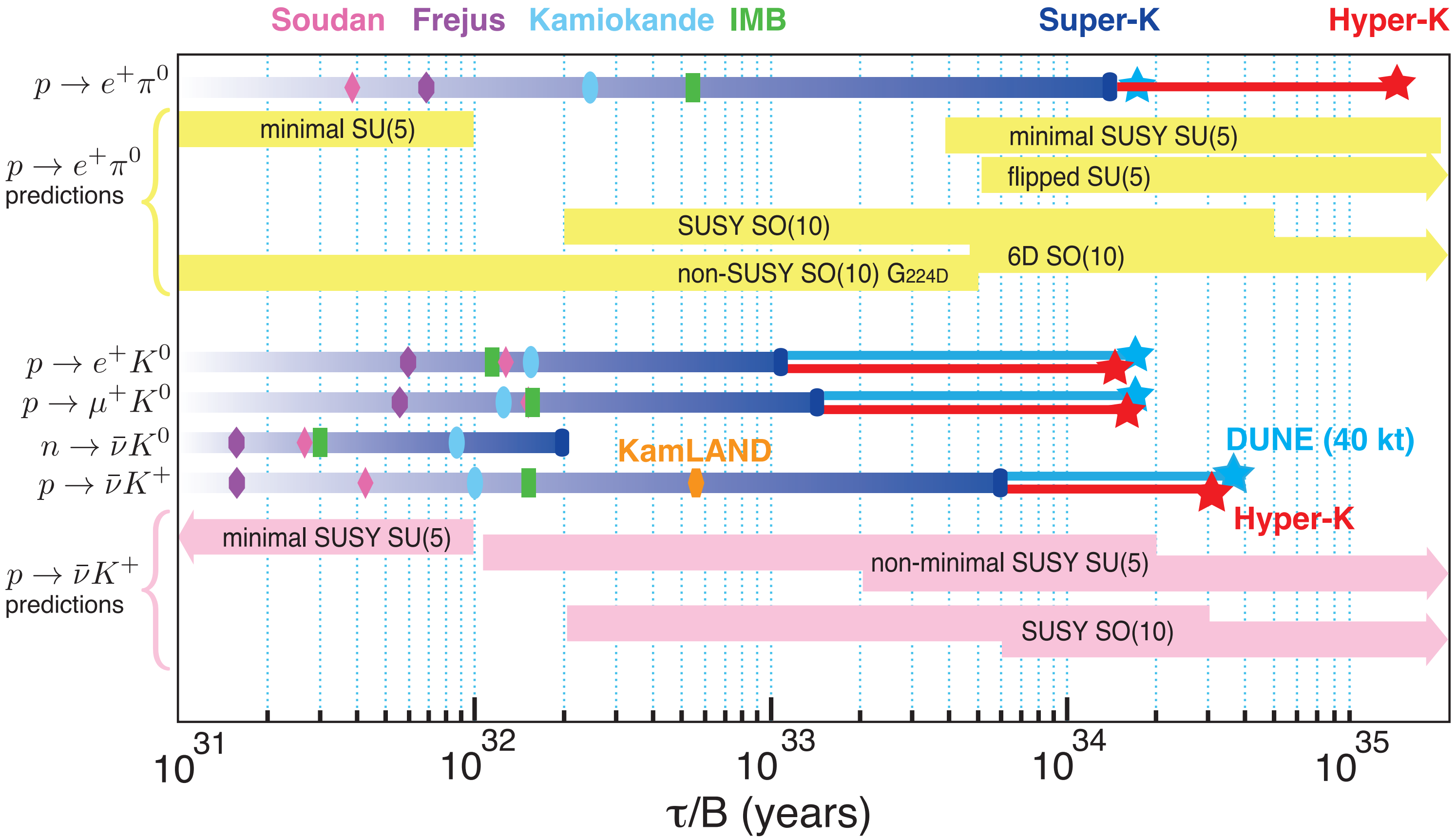
Hyperkamiokande project



Basically, a huge 74x60m water tank equipped with photomultipliers
To start operation in 2026 near Kamioka in Japan

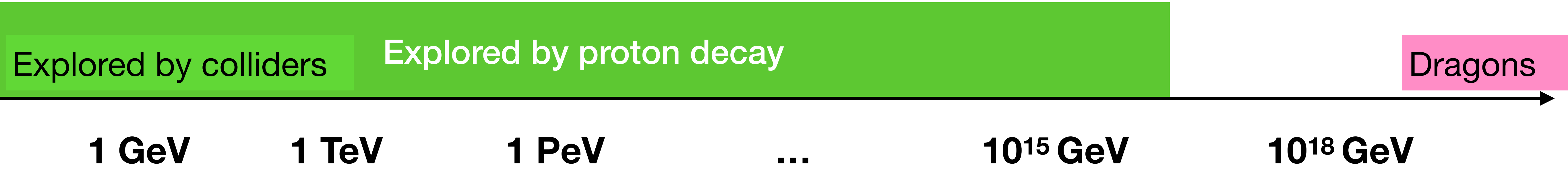
Hyperkamiokande project





- Current limit on proton lifetime probe new physics up to Λ_B of order 10^{16} GeV !
- Baryon violating dimension-6 operators are best probed of all
- Limits on scale Λ_B will get improved by factor of 2 in coming decades

Proton decay summary



General lessons

- Reach for new physics can be largely superior compared to what we can directly explore using colliders
- Observables where the Standard Model predicts zero signal, or its prediction is extremely suppressed, are most favorable in terms on the new physics reach
- This is the case when new physics violates (exact or approximate) global symmetries of the Standard Model

Interlude: global symmetries of the Standard Model

Exact

- Baryon number conservation
- Lepton number conservation
- Lepton flavor number conservation

Approximate

- Flavor symmetry
- CP
- Parity

PMNS matrix

$$\ell = \begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix} \qquad \nu = \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

$$\mathscr{L} \supset \frac{g_L}{\sqrt{2}} \bar{\nu}_L \gamma^\mu [\mathbf{1}] \ell_L W_\mu^+ + \bar{\ell}_R [M_e] \ell_L + \nu_L^T [M_\nu] \nu_L + \mathrm{hc}\,.$$

$$M_e = V_e^\dagger M_e^{\mathrm{diag}} U_e \qquad M_\nu = U_\nu^T M_e^{\mathrm{diag}} U_\nu$$

$$\ell_L \to U_e \ell_L, \quad \ell_R \to V_e \ell_R, \quad \nu_L \to U_\nu \nu_L,$$

$$\mathscr{L} \supset \frac{g_L}{\sqrt{2}} \bar{\nu}_L \gamma^\mu [U_\nu^\dagger U_e] \ell_L W_\mu^+ + \bar{\ell}_R [M_e^{\mathrm{diag}}] \ell_L + \nu_L^T [M_\nu^{\mathrm{diag}}] \nu_L + \mathrm{hc}\,.$$

PMNS matrix: $\boxed{V_{\mathrm{P}} = U_\nu^\dagger U_e}$

Equivalently, rotate: $\nu_L \to V_P \nu_L,$

$$\mathscr{L} \supset \frac{g_L}{\sqrt{2}} \bar{\nu}_L \gamma^\mu [\mathbf{1}] \ell_L W_\mu^+ + \bar{\ell}_R [M_e^{\mathrm{diag}}] \ell_L + \nu_L^T V_{\mathrm{P}}^\dagger [M_\nu^{\mathrm{diag}}] V_{\mathrm{P}} \nu_L + \mathrm{hc}\,.$$

PMNS matrix

$$\mathbf{V_P} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Elements of the PMNS matrix and neutrino mass difference squared measured with good precision by a host of neutrino oscillation experiments

$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right) + 2\sum_{i>j} \mathrm{Im}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin\left(\frac{\Delta m^2_{ij}L}{2E}\right),$$

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 0.83$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$	$0.271 \to 0.345$
$\theta_{12}/^\circ$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$	$31.38 \to 35.99$
$\sin^2\theta_{23}$	$0.441^{+0.027}_{-0.021}$	$0.385 \to 0.635$	$0.587^{+0.020}_{-0.024}$	$0.393 \to 0.640$	$0.385 \to 0.638$
$\theta_{23}/^\circ$	$41.6^{+1.5}_{-1.2}$	$38.4 \to 52.8$	$50.0^{+1.1}_{-1.4}$	$38.8 \to 53.1$	$38.4 \to 53.0$
$\sin^2\theta_{13}$	$0.02166^{+0.00075}_{-0.00075}$	$0.01934 \to 0.02392$	$0.02179^{+0.00076}_{-0.00076}$	$0.01953 \to 0.02408$	$0.01934 \to 0.02397$
$\theta_{13}/^\circ$	$8.46^{+0.15}_{-0.15}$	$7.99 \to 8.90$	$8.49^{+0.15}_{-0.15}$	$8.03 \to 8.93$	$7.99 \to 8.91$
$\delta_{\mathrm{CP}}/^\circ$	261^{+51}_{-59}	$0 \to 360$	277^{+40}_{-46}	$145 \to 391$	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.03 \to 8.09$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.524^{+0.039}_{-0.040}$	$+2.407 \to +2.643$	$-2.514^{+0.038}_{-0.041}$	$-2.635 \to -2.399$	$\begin{bmatrix} +2.407 \to +2.643 \\ -2.629 \to -2.405 \end{bmatrix}$

Esteban et al
1611.01514

PMNS matrix and new physics

- Neutrino masses and mixing can be interpreted as evidence for new physical scale Λ, which shows up as mass parameter suppressing dimension-5 operator in SMEFT Lagrangian

$$\mathscr{L}_{\text{SMEFT}} \supset -\frac{1}{\Lambda}(Hl)^T[C_\nu](Hl)$$
$$\to -\frac{v^2}{2\Lambda}\nu^T[C_\nu]\nu$$

- With C~1, new scale is of order Λ~10^{15} GeV

$$[V_P^T M_\nu^{\text{diag}} V_P] = \frac{v^2}{2\Lambda}[C_\nu]$$

- Simplest UV completion of that EFT: 2 or more singlet neutrinos with large Majorana mass terms and Yukawa couplings to SM doublets

$$C_\nu \sim 1 \Rightarrow m_\nu \sim 0.06 \text{ eV}\left(\frac{10^{15}\text{ GeV}}{\Lambda}\right)$$

- Heavy neutrinos could be anywhere between keV and Planck scale. However large scale appearing in effective Lagrangian suggests their mass scale is >> TeV

$$\Delta\mathscr{L}_{\text{SM}} \supset -NY_\nu' Hl - \frac{1}{2}NMN + \text{h.c.}$$

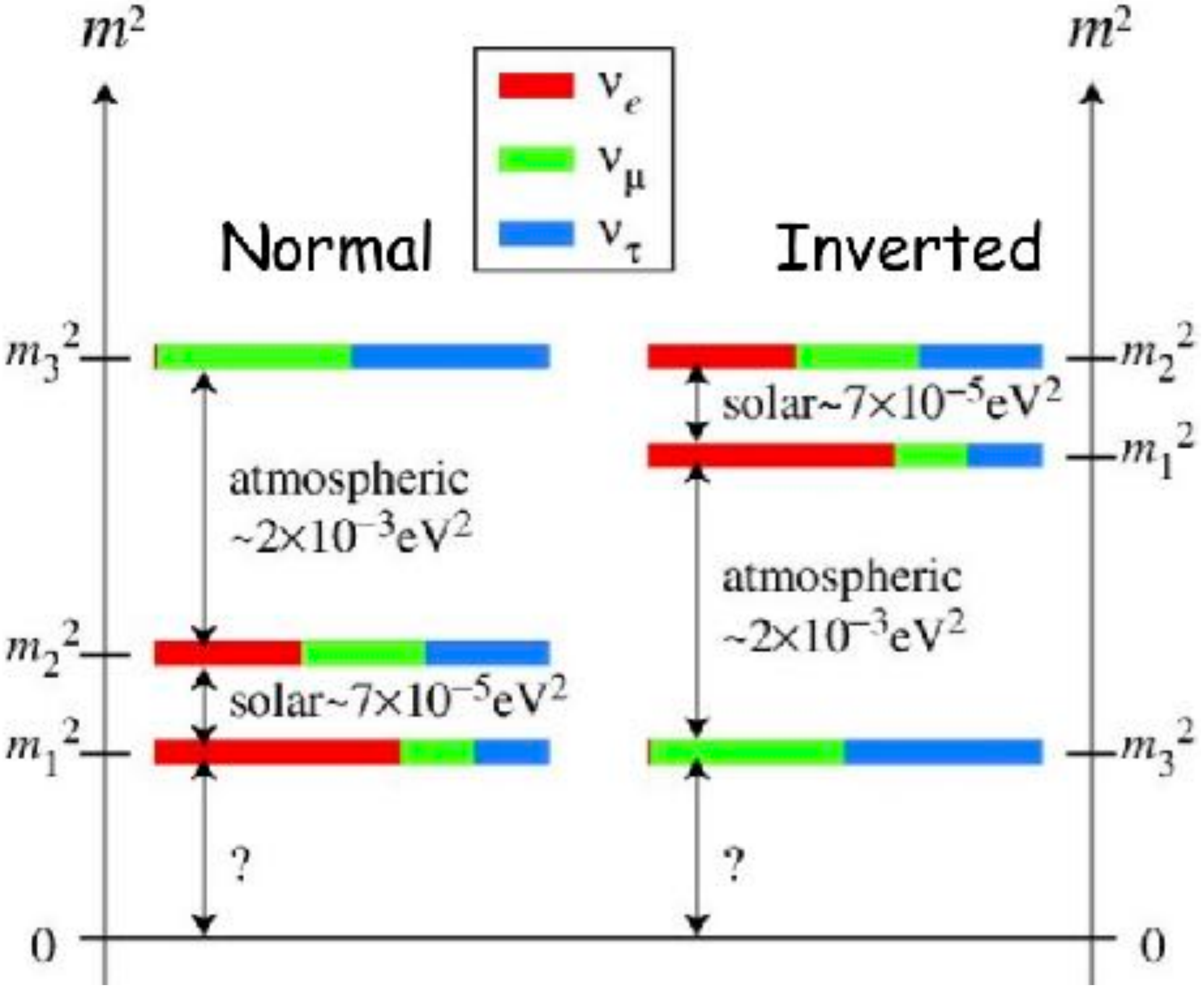
$$\frac{Y_\nu}{\Lambda} = -\frac{1}{2}(Y_\nu' Hl)^T M^{-1} Y_\nu' Hl$$

Neutrino remaining challenges

$$\mathbf{V_P} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

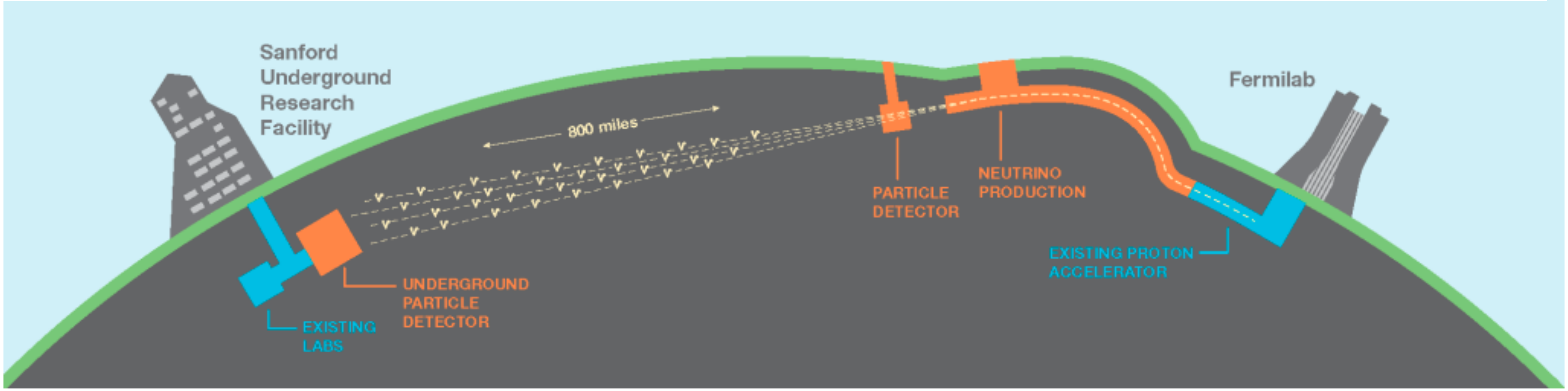
Outstanding questions

- Normal vs Inverted ordering
- Absolute mass scale of neutrino
- Measurement of CP-violating phase in PMNS matrix



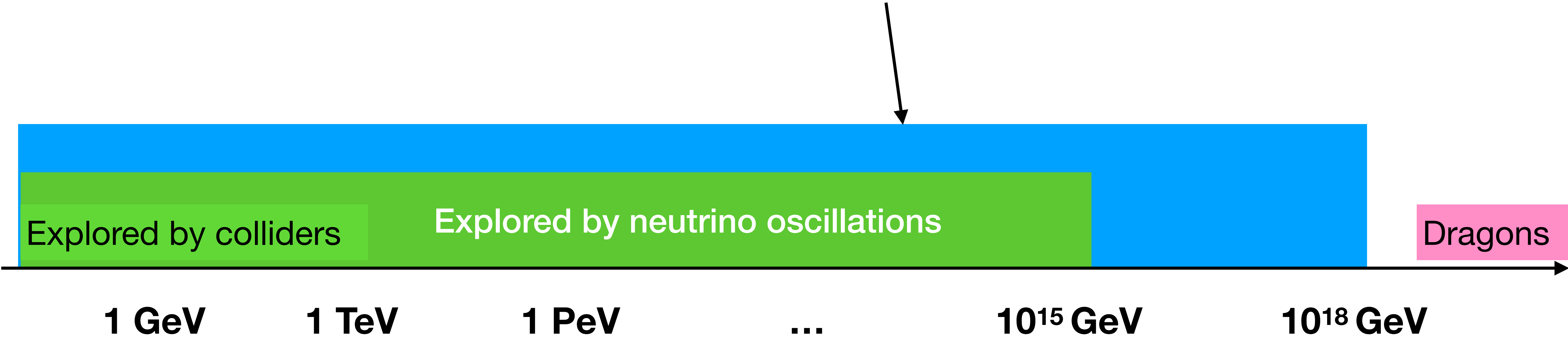
Future of neutrino oscillations

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \simeq\; & \boxed{\sin^2\theta_{23}}\boxed{\sin^2 2\theta_{13}}\frac{\sin^2(\Delta_{31}-\boxed{aL})}{(\Delta_{31}-\boxed{aL})^2}\Delta_{31}^2 \\
& + \boxed{\sin 2\theta_{23}}\boxed{\sin 2\theta_{13}}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-\boxed{aL})}{(\Delta_{31}-\boxed{aL})}\Delta_{31}\frac{\sin(\boxed{aL})}{(\boxed{aL})}\Delta_{21}\cos(\Delta_{31}+\delta_{CP}) \\
& + \boxed{\cos^2\theta_{23}}\sin^2 2\theta_{12}\frac{\sin^2(\boxed{aL})}{(\boxed{aL})^2}\Delta_{21}^2,
\end{aligned}
$$



- New neutrino beam facility at Fermilab
- A highly capable Near Detector at Fermilab to measure the unoscillated neutrino spectrum and flux constraints
- A large LArTPC deep underground at SURF (Lead (SD) 1300 km baseline) to measure oscillations and non-beam physics
- Exposure of ~10 years to ν / $\bar{\nu}$ modes (50% / 50%)

Neutrino landscape



Possibly explored by future neutrino oscillations experiments

Explored by colliders

Explored by neutrino oscillations

Dragons

1 GeV

1 TeV

1 PeV

…

10^{15} GeV

10^{18} GeV

Lepton-flavor violation

- In the Standard Model, individual lepton number for each generation is conserved

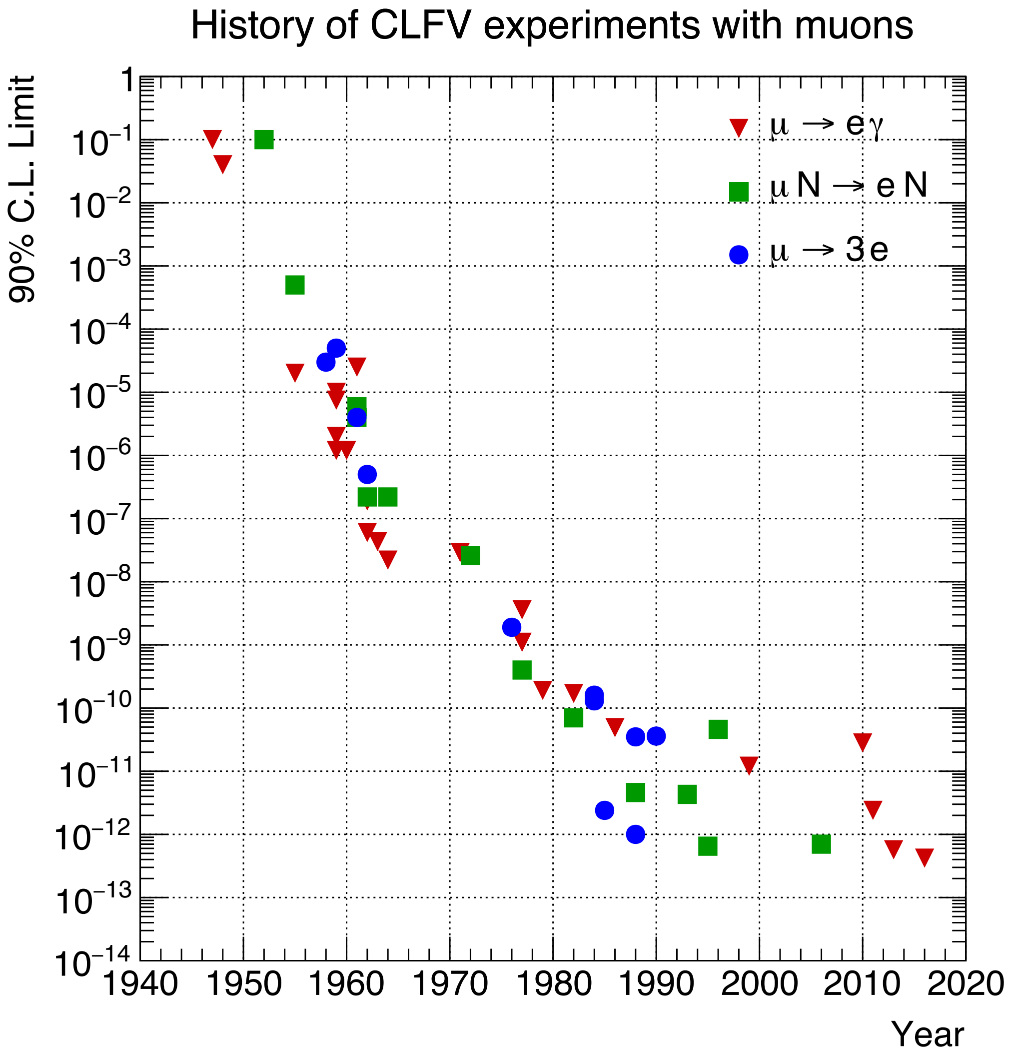
- Neutrino masses violate lepton number, but their effects are tiny due to small neutrino masses, and do not lead to observable effects outside of neutrino oscillation

- However, there might be other new physics at a lower mass scale that gives larger, observable effect

$$\mu^- \to e^-\nu_\mu\bar{\nu}_e$$ **OK**

$$\mu^- \to \xcancel{e^-\gamma} \quad \mathrm{Br}(\mu \to e\gamma) < 4 \times 10^{-13}$$

$$\mu^- \to \xcancel{e^-e^-}e^+ \quad \mathrm{Br}(\mu \to 3e) < 10^{-12}$$



Lepton-flavor violation

$$\mathscr{L}_{\text{SMEFT}} \supset \frac{1}{\Lambda^2} B_{\mu\nu} \bar{e}_R \gamma_\mu \gamma_\nu l_2 H + \text{hc}\,.$$

$$\to \frac{v \cos\theta_W}{\sqrt{2}\Lambda^2} A_{\mu\nu} \bar{e}_R \gamma_\mu \gamma_\nu \mu_L + \text{hc}\,.$$

$$\mathscr{M}(\mu \to e\gamma) \sim \frac{v}{\Lambda^2} \qquad \Gamma(\mu \to e\gamma) \sim \frac{v^2 m_\mu^3}{\Lambda^4}$$

$$\text{Br}(\mu \to e\gamma) \sim \frac{v^2 m_\mu^3}{\Lambda^4 \Gamma_\mu} \sim 10^{-12} \left(\frac{10^5\ \text{TeV}}{\Lambda} \right)^4$$

$\Gamma_\mu = 3 \times 10^{-10}\ \text{eV}$

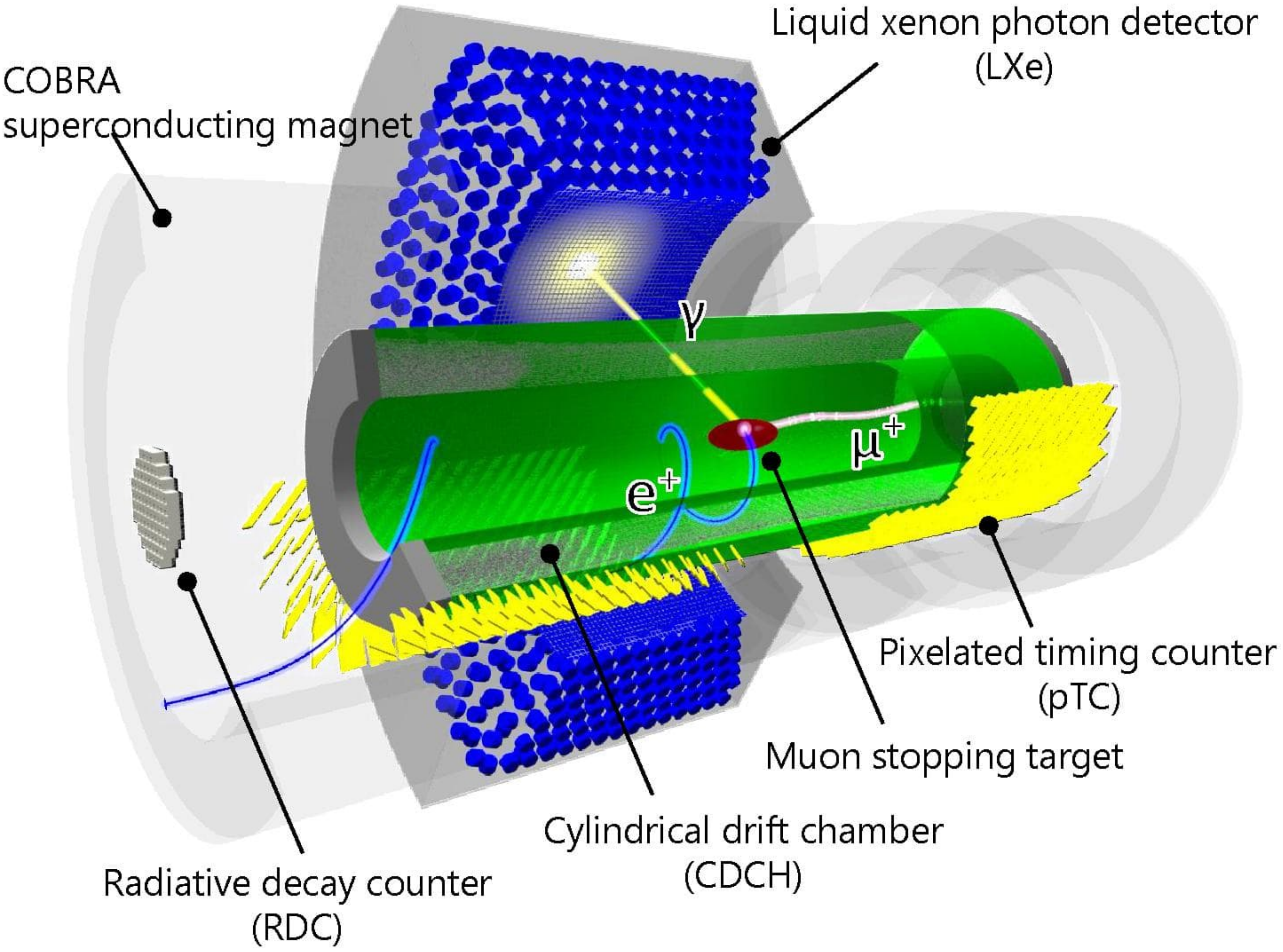
Future of lepton-flavor violation

LFV Process	Present Bound	Future Sensitivity	
$\mu \to e\gamma$	4.2×10^{-13} [26]	$4 \cdot 10^{-14}$ [27]	MEG-2
$\tau \to e\gamma$	3.3×10^{-8} [30]	$\sim 10^{-8} - 10^{-9}$ [29]	Belle-2
$\tau \to \mu\gamma$	4.4×10^{-8} [30]	$\sim 10^{-8} - 10^{-9}$ [29]	
$\mu \to 3e$	1.0×10^{-12} [31]	$\sim 10^{-16}$ [32]	
$\tau \to 3e$	2.7×10^{-8} [33]	$\sim 10^{-9} - 10^{-10}$ [29]	
$\tau \to 3\mu$	2.1×10^{-8} [33]	$\sim 10^{-9} - 10^{-10}$ [29]	
$\mu^-, \mathrm{Au} \to e^-, \mathrm{Au}$	7.0×10^{-13} [34]		
$\mu^-, \mathrm{Ti} \to e^-, \mathrm{Ti}$	4.3×10^{-12} [35]	$\sim 10^{-18}$ [36]	Comet

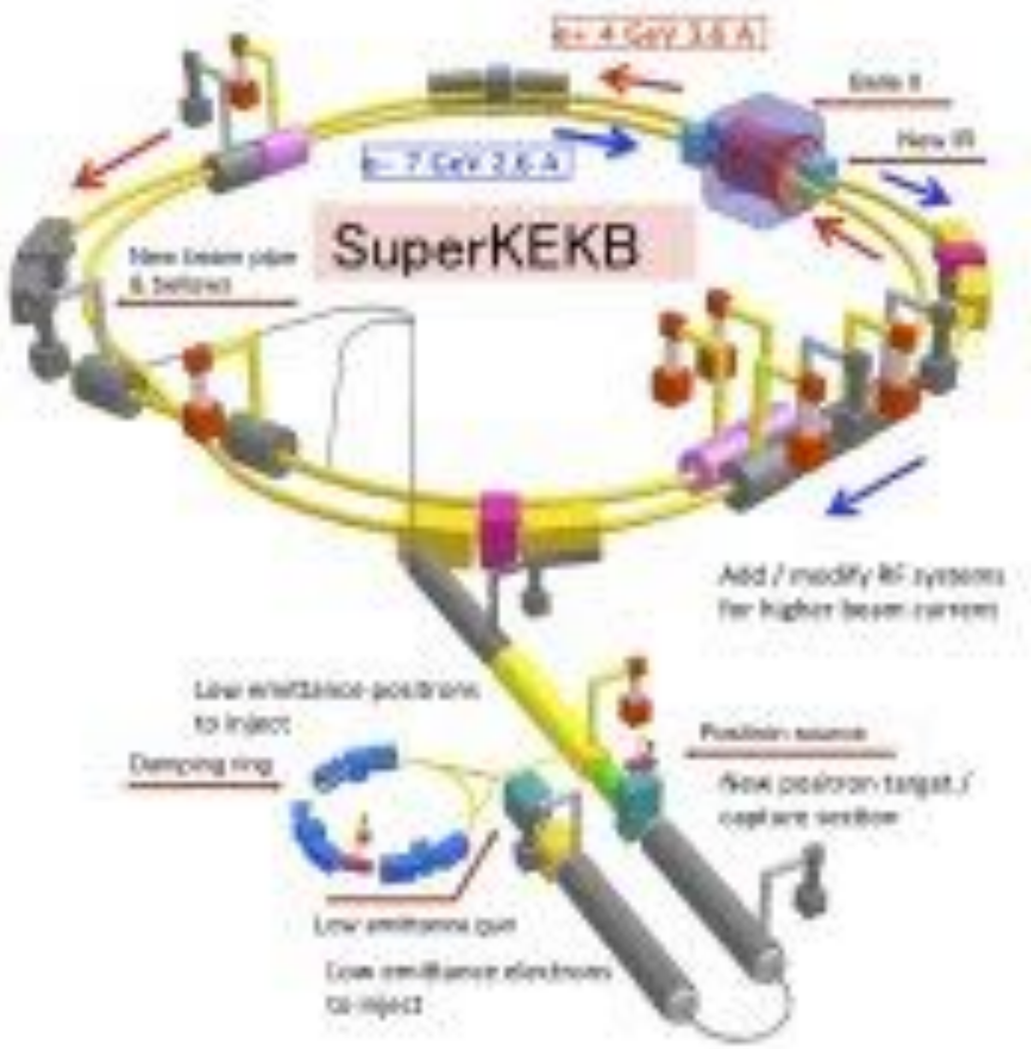
- Moderate progress expected in coming years for most decay channels, coming from upgrade of Belle and MEG experiments

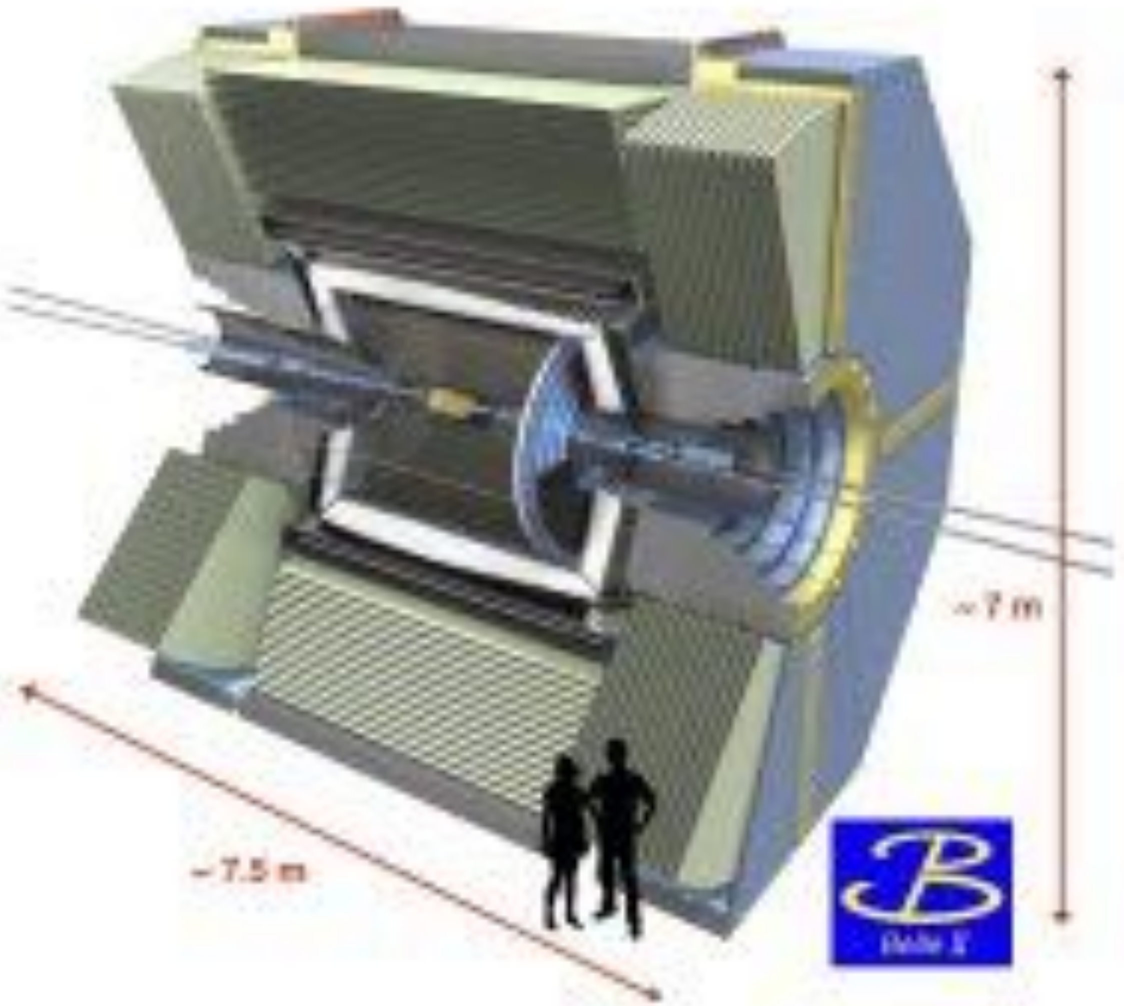
- Huge progress in muon conversion on atoms

MEG-2 experiment

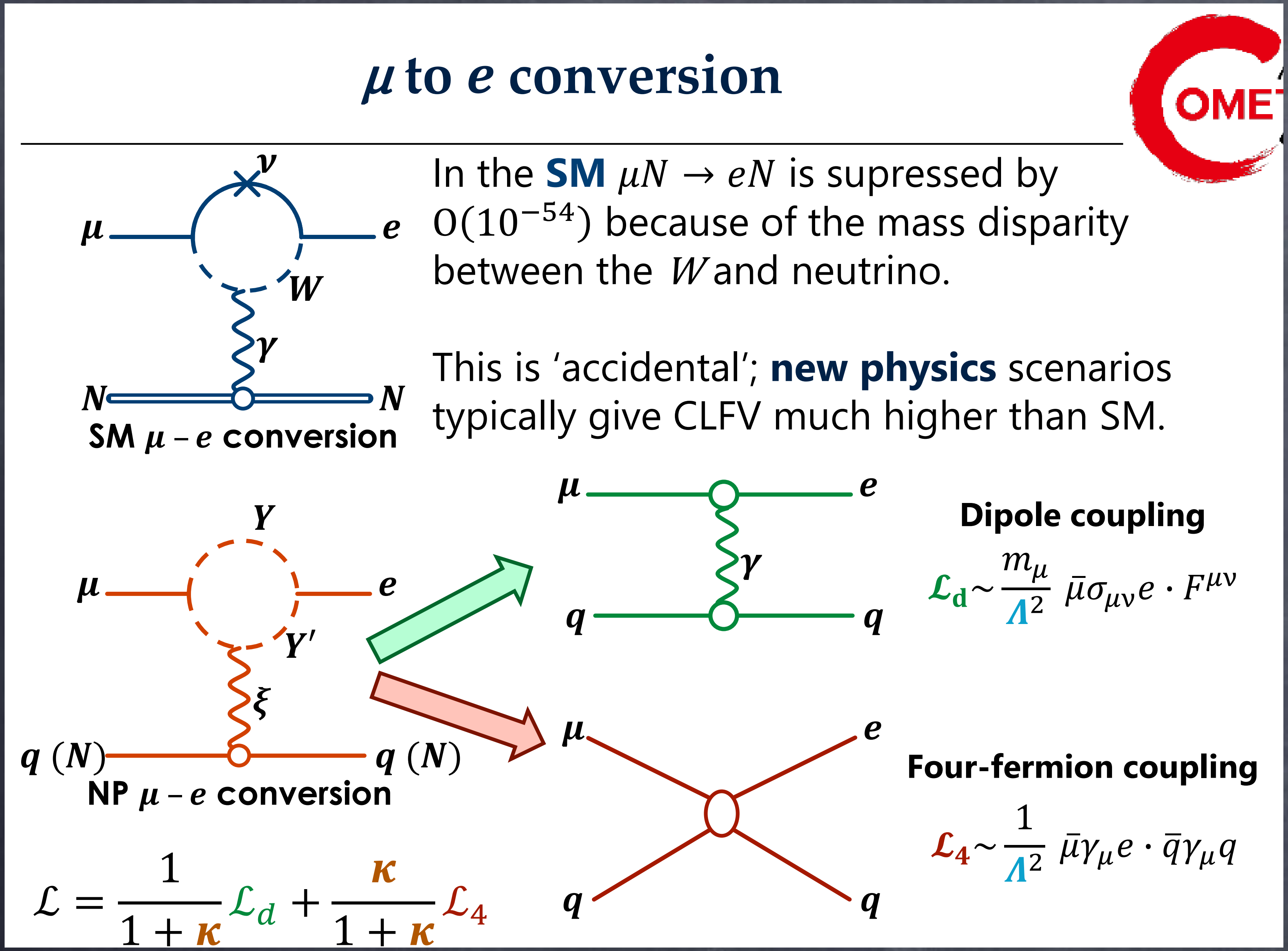


Belle-2 experiment





Lepton-flavor violation



μ to e conversion

In the **SM** $\mu N \to eN$ is supressed by $O(10^{-54})$ because of the mass disparity between the W and neutrino.

This is 'accidental'; **new physics** scenarios typically give CLFV much higher than SM.

SM $\mu - e$ conversion

NP $\mu - e$ conversion

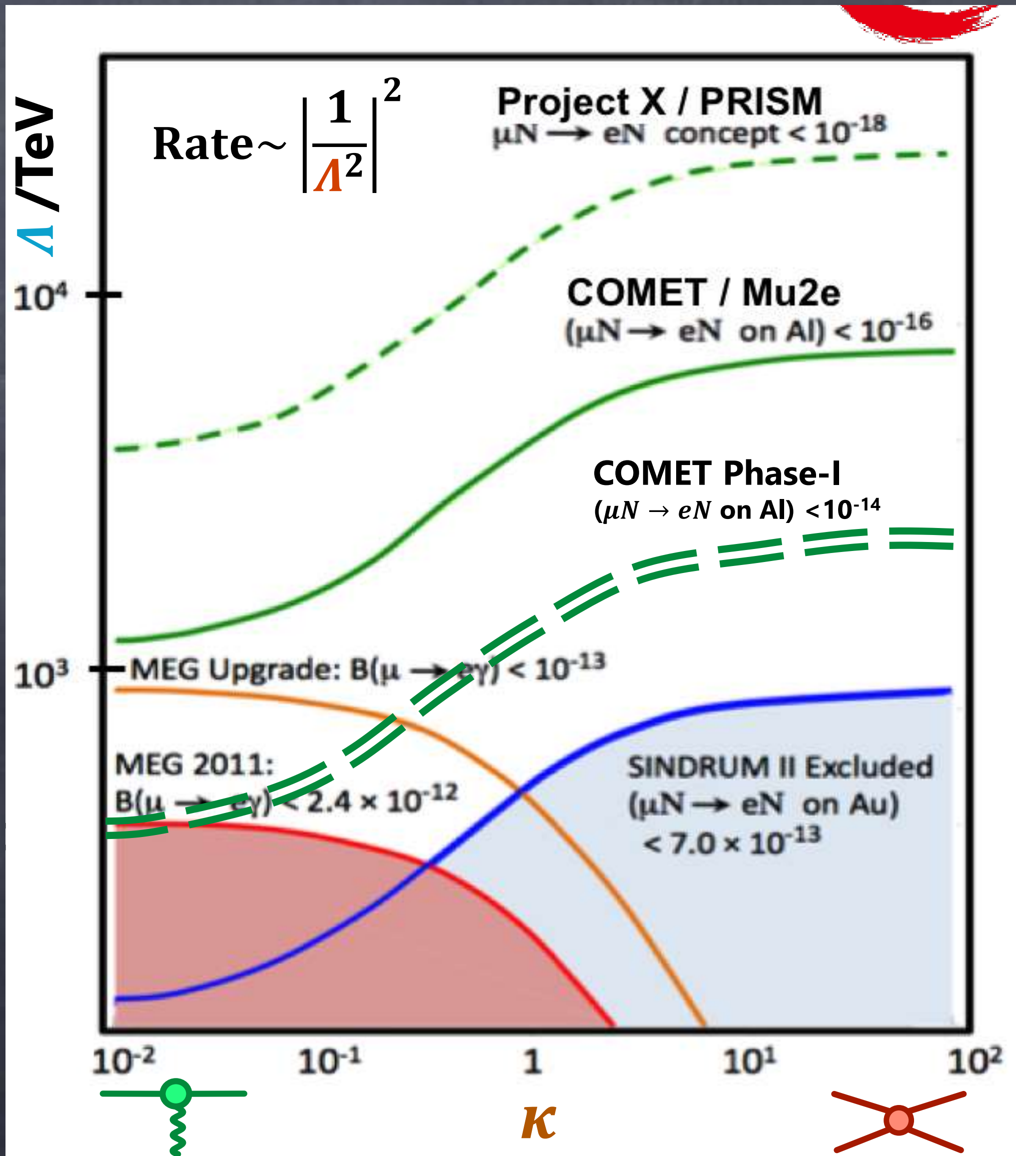
Dipole coupling

$$\mathcal{L}_d \sim \frac{m_\mu}{\Lambda^2}\,\bar{\mu}\sigma_{\mu\nu}e \cdot F^{\mu\nu}$$

Four-fermion coupling

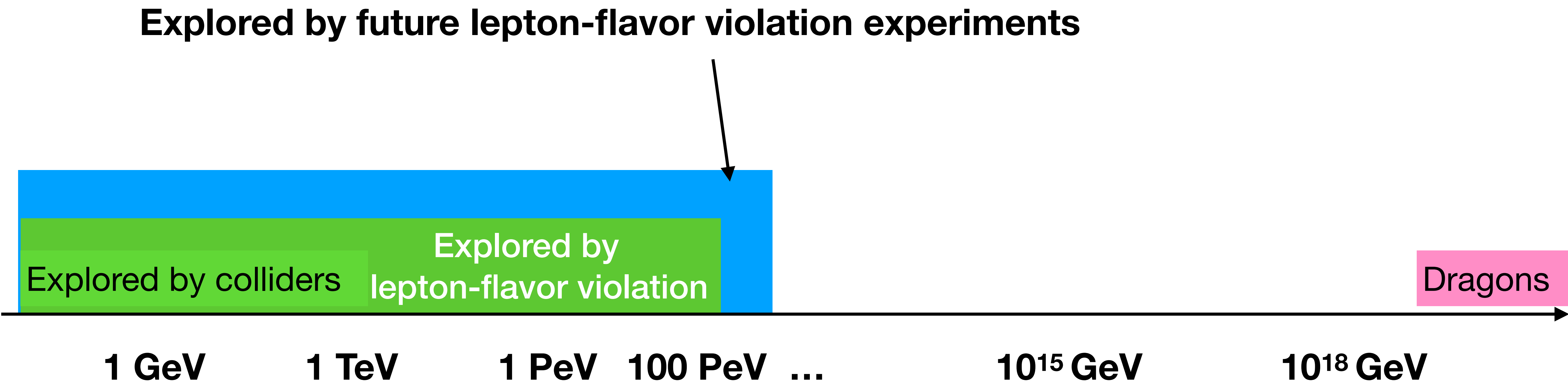
$$\mathcal{L}_4 \sim \frac{1}{\Lambda^2}\,\bar{\mu}\gamma_\mu e \cdot \bar{q}\gamma_\mu q$$

$$\mathcal{L} = \frac{1}{1+\kappa}\mathcal{L}_d + \frac{\kappa}{1+\kappa}\mathcal{L}_4$$



Borrowed from
P. Litchfield's talk
at PASCOS'16

Lepton flavor violation landscape



Explored by future lepton-flavor violation experiments

Explored by colliders

Explored by lepton-flavor violation

Dragons

1 GeV

1 TeV

1 PeV

100 PeV

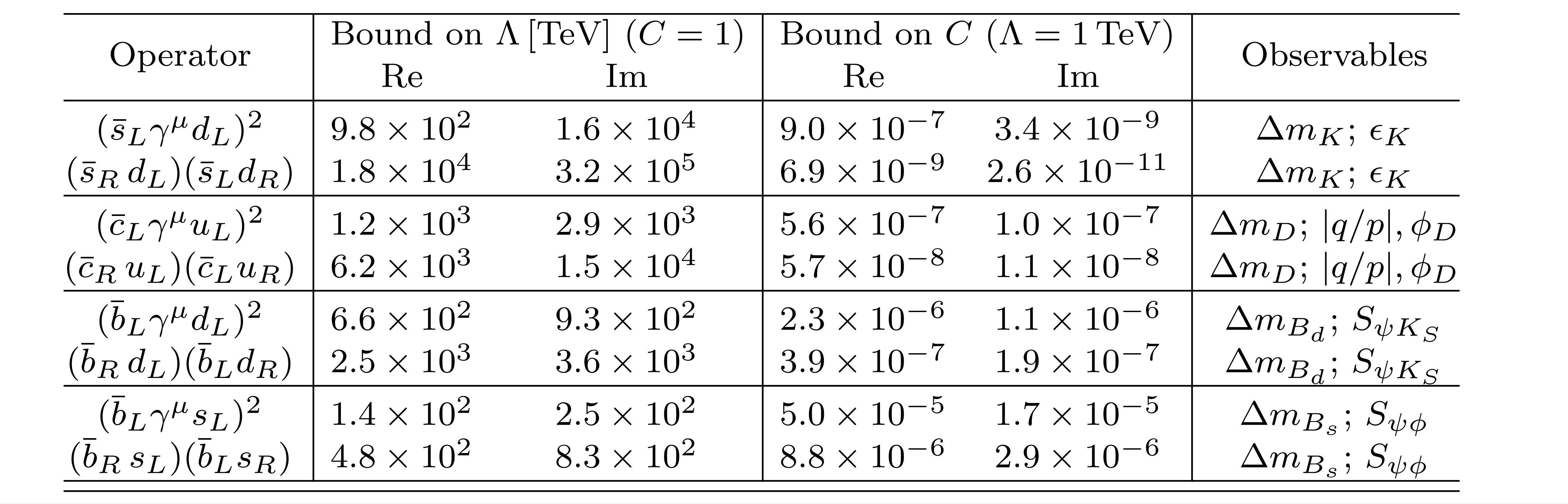
…

10^{15} GeV

10^{18} GeV

Flavor physics

- Flavor number violating transitions are extremely sensitive probes of new physics
- E.g. ΔS=2 kaon mixing processes probe CP-violating new physics up to 10^6 TeV!
- Soon Belle-2 B-factory will multiply amount of data by factor of 100, and LHCb will make many new analyses. Unfortunately, further progress not straightforward because of uncertainties in SM calculations

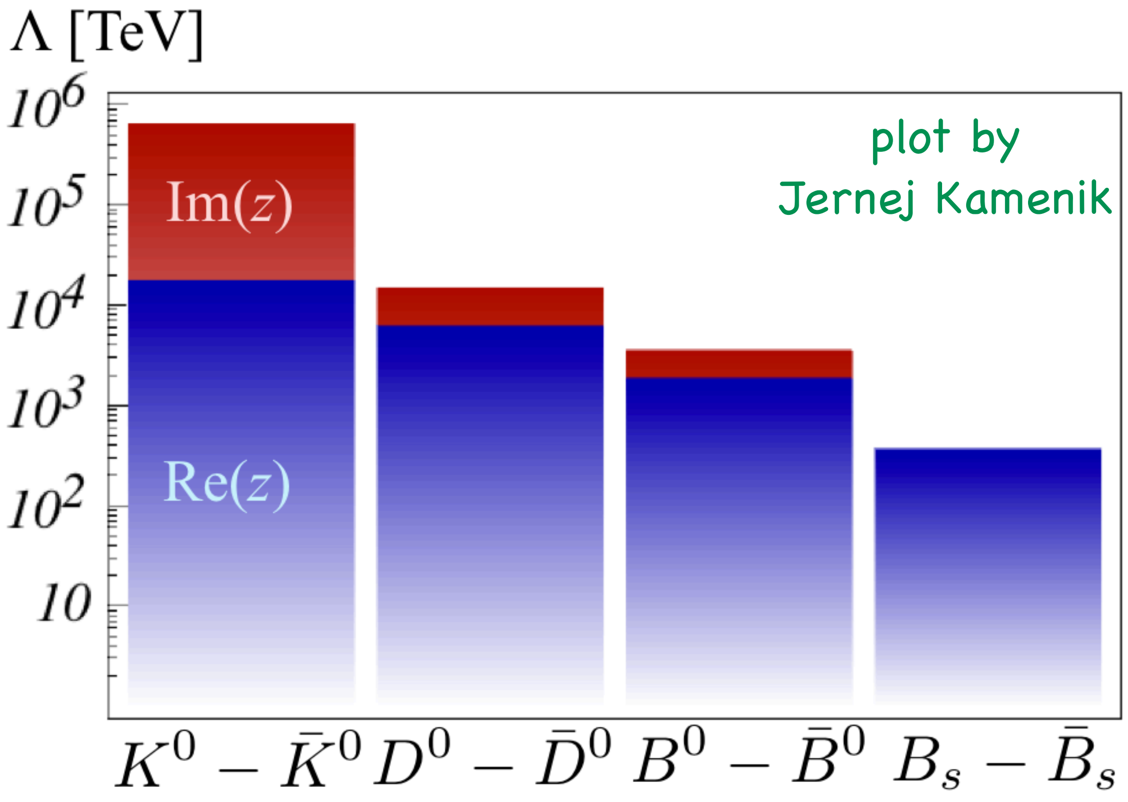


Operator	Bound on Λ [TeV] $(C=1)$		Bound on C $(\Lambda = 1\,\text{TeV})$		Observables
	Re	Im	Re	Im	
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	$\Delta m_K;\ \epsilon_K$
$(\bar{s}_R\,d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	$\Delta m_K;\ \epsilon_K$
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{c}_R\,u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2	2.3×10^{-6}	1.1×10^{-6}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_R\,d_L)(\bar{b}_L d_R)$	2.5×10^3	3.6×10^3	3.9×10^{-7}	1.9×10^{-7}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.4×10^2	2.5×10^2	5.0×10^{-5}	1.7×10^{-5}	$\Delta m_{B_s};\ S_{\psi\phi}$
$(\bar{b}_R\,s_L)(\bar{b}_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	$\Delta m_{B_s};\ S_{\psi\phi}$

Isidori
1302.0661

Flavor changing neutral currents

- Flavor number violating transitions are extremely sensitive probes of new physics
- E.g. ΔS=2 kaon mixing processes probe CP-violating new physics up to 10^6 TeV!
- Soon Belle-2 B-factory will multiply amount of data by factor of 100, and LHCb will make many new analyses. Unfortunately, further progress not straightforward because of uncertainties in SM calculations



plot by Jernej Kamenik

Operator	Bound on Λ [TeV] $(C=1)$		Bound on C $(\Lambda = 1\,\text{TeV})$		Observables
	Re	Im	Re	Im	
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	$\Delta m_K;\ \epsilon_K$
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$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D;\ \lvert q/p\rvert,\phi_D$
$(\bar{c}_R\,u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D;\ \lvert q/p\rvert,\phi_D$
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$(\bar{b}_R\,s_L)(\bar{b}_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	$\Delta m_{B_s};\ S_{\psi\phi}$

Isidori 1302.0661

Other precision experiment

- Parity violation in electron scattering on nuclei (P2) or on electrons (MOLLER), or in atomic transitions (Ra). Reach of order 100 TeV.
- Electric dipole moments of electron (Cesium atomic traps) and neutron (PSI, ILL, …). Reach of order 100 TeV.
- Muon (g-2 experiment) and electron magnetic moments. Reach of order 100 TeV.
- W boson mass. Reach of order 30 TeV.
- Neutrino scattering on electrons and nuclei. Reach of order 10 TeV
- Trident neutrino production. Reach of order 10 TeV.

Part 5

Hints of new particles?

Hints of new particles?

- Globally, the SM explains very well the available data from existing collider and precision experiments

- However, there are a few anomalies here and there

- Most of them are probably statistical fluctuations, or underestimated systematic errors, or theoretical errors…

- Nevertheless, it is possible that at least one of them is a harbinger of new physics beyond the Standard Model

Most interesting anomalies

- Magnetic moment of muon (and electron)
- Lepton-flavor-universality violation in certain B-meson decays
- Strong absorption signal of 21cm radiation from the cosmic dawn
- Appearance of electron neutrinos in LSND and mini-Boone
- Disappearance of electron neutrinos in short-baseline reactor experiments

Future of new physics beyond the Standard Model