Beyond the Standard Model (SM) of Particle Physics

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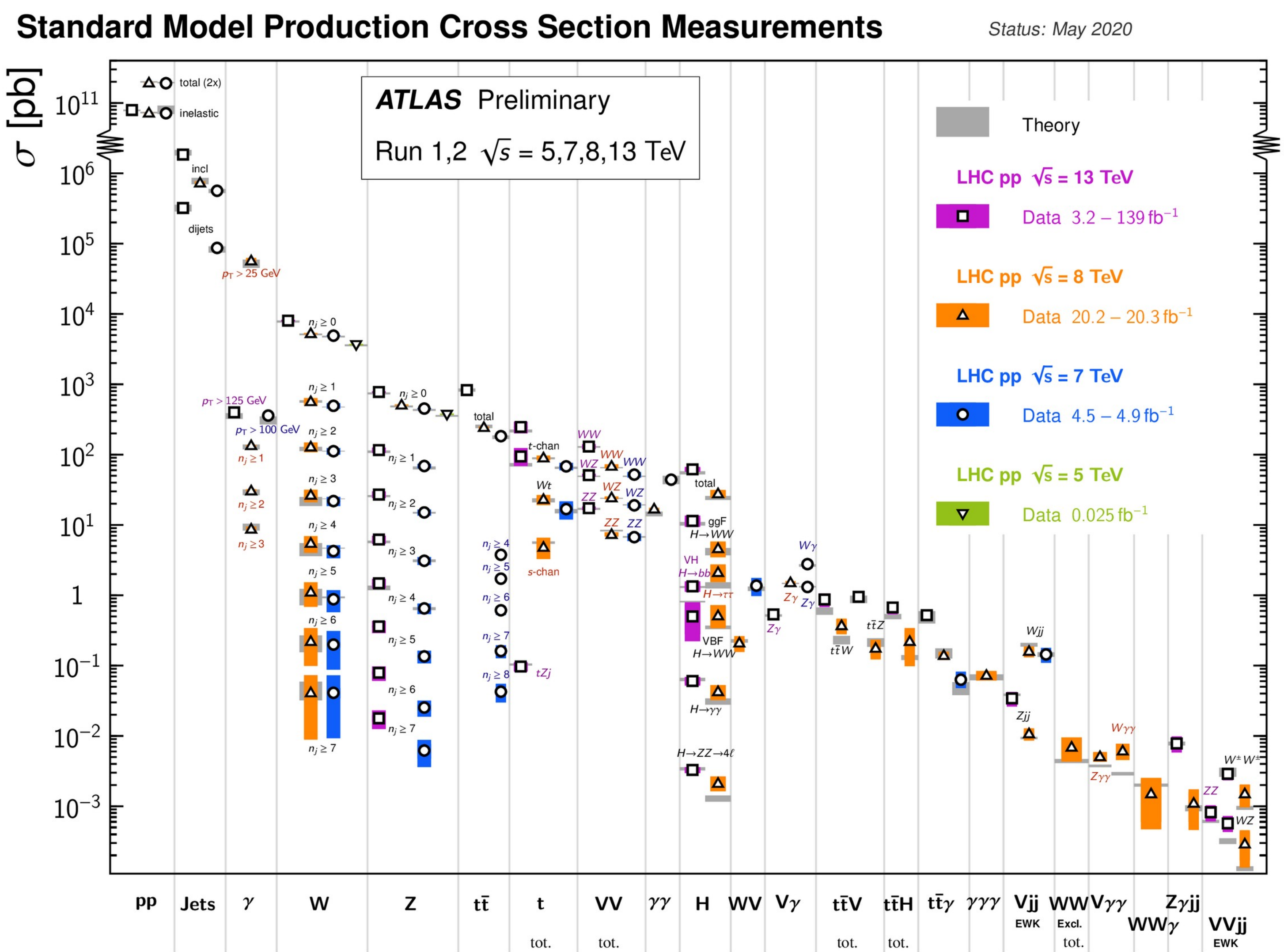
The SM works (too) well ...



- **Measurements in agreement with predictions**
- **Including the Higgs the SM is self-consistent**

No need for new physics

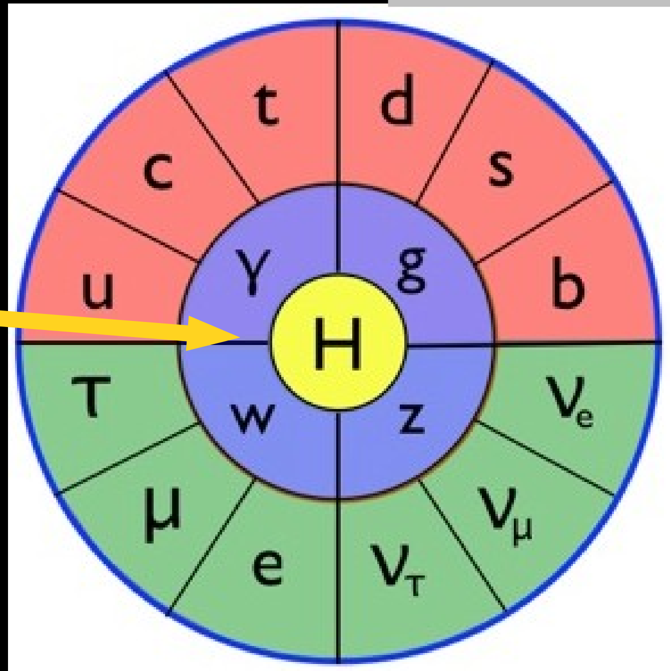
Why do we need new physics?

CERN
main auditorium

CERN, July 2012
Centre piece of the Standard Model cake has been found: the Higgs boson!

We know everything!

Symmetry Magazine



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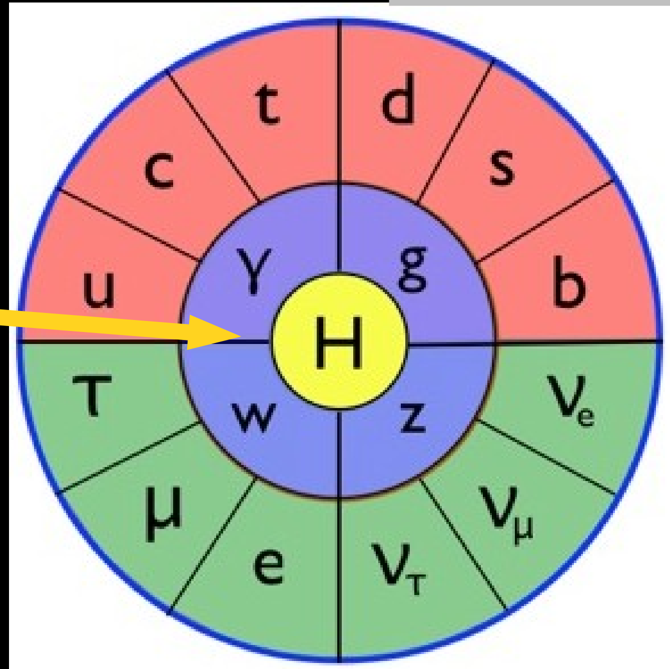

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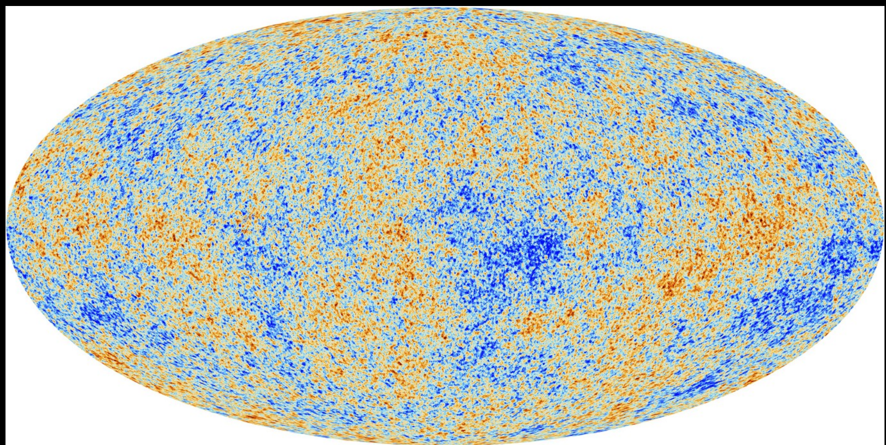
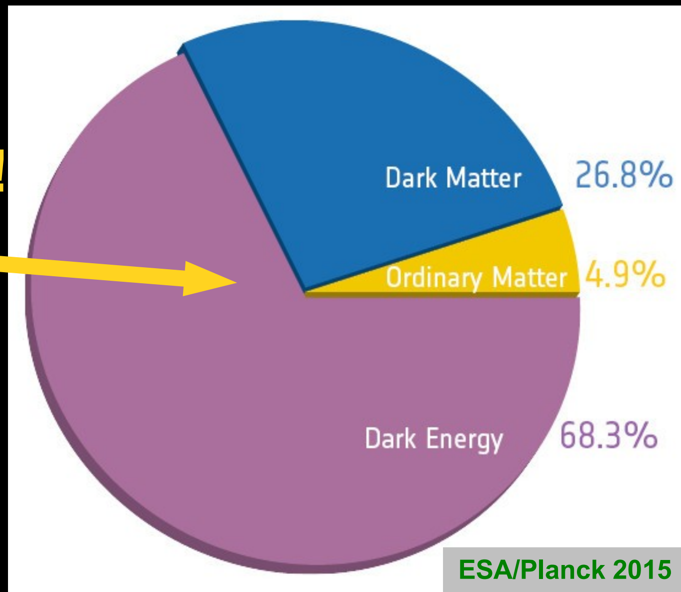


Universe
cosmic microwave background

ESA 2015
Only 4.9 % ordinary matter in the universe!



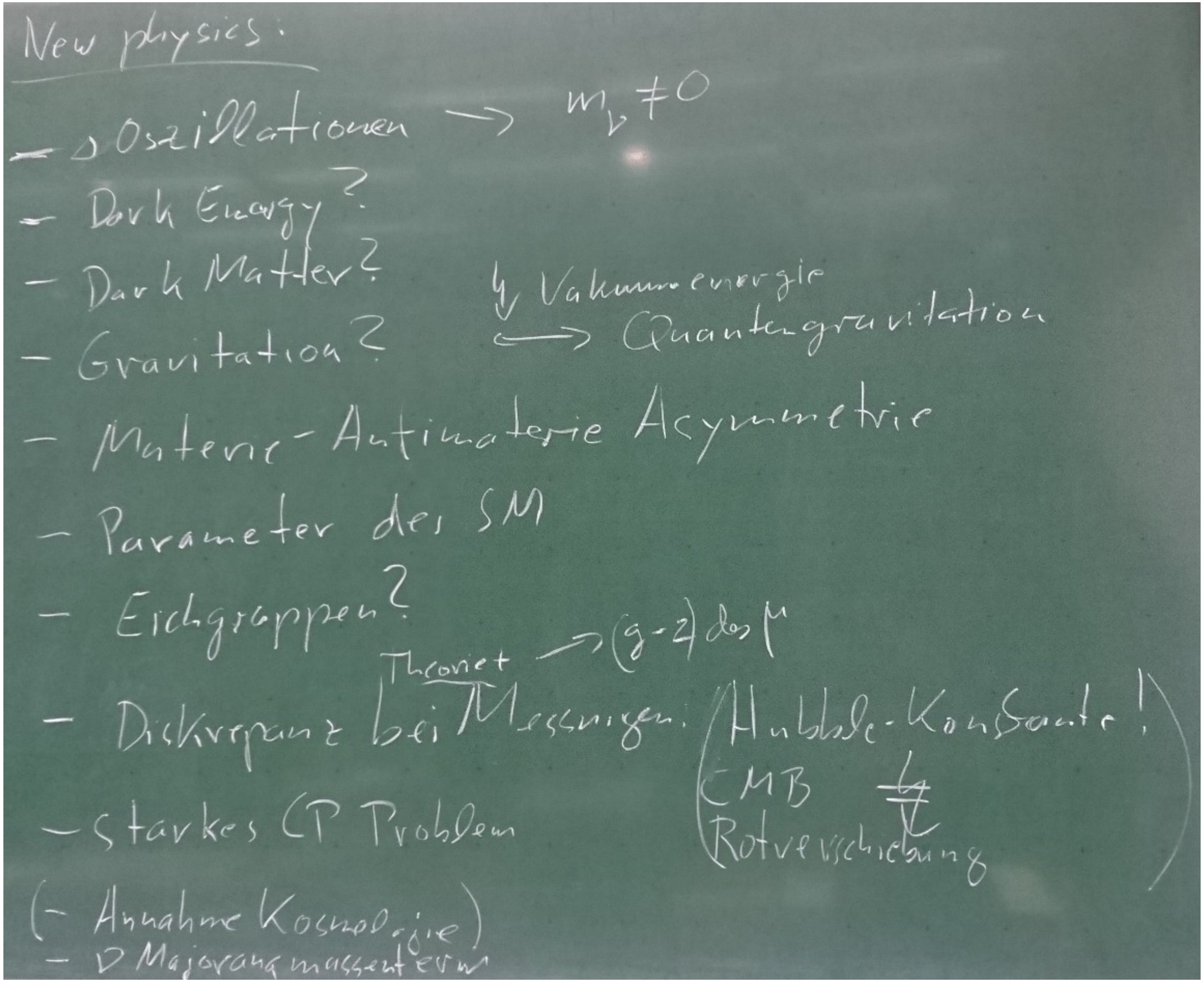
ESA/Planck 2015

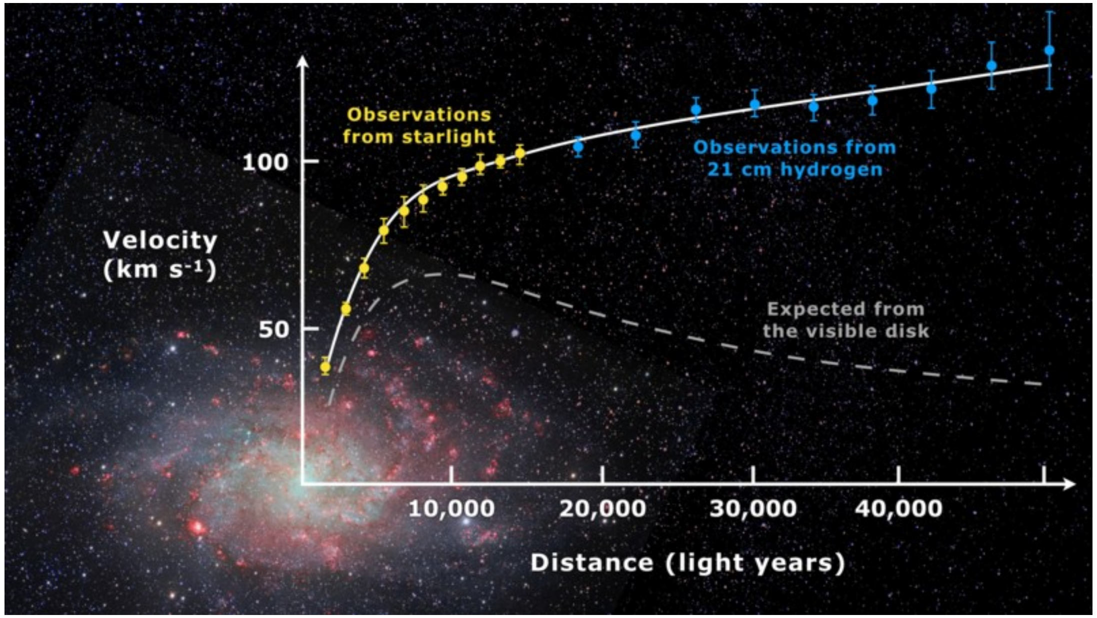
We still know nothing!

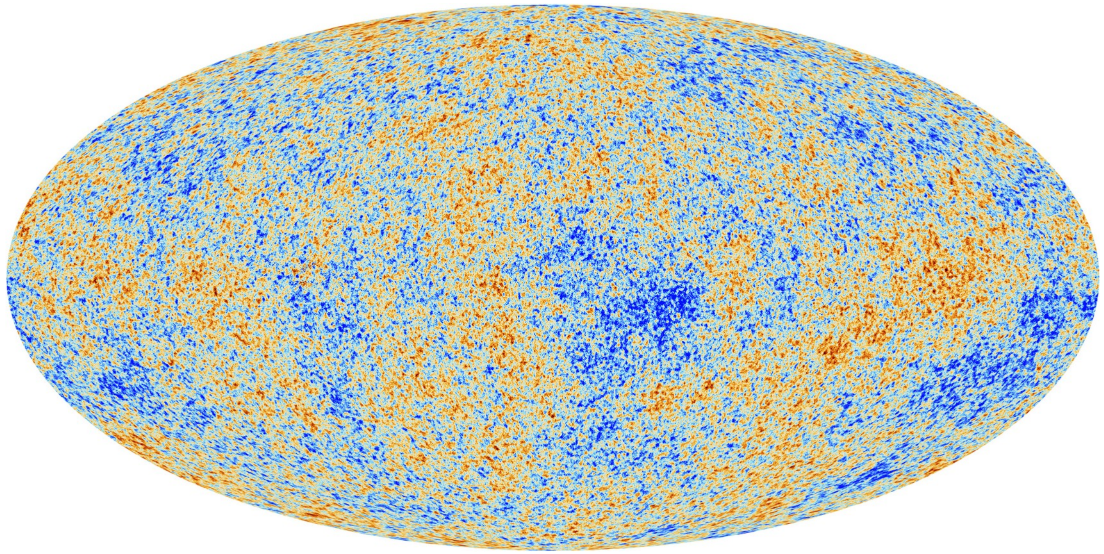
Let's collect some arguments

Your collected arguments

- Matter-antimatter-asymmetry
- Neutrino masses nonzero, but unknown
- Complicated gauge symmetry groups; something simpler should exist
- Large number of SM parameters
- Only one Higgs boson; why not more?
- Why four forces? No gravity in SM.
- Unification of electroweak and strong forces
- No CP violation in strong interaction although possible
- P, CP, and T symmetries violated; why not CPT?
- Cosmology: Can matter distribution in universe be explained?


New physics:
- ν Oszillationen → m_ν ≠ 0
- Dark Energy ?
- Dark Matter ?
- Gravitation ?
Vakuumenergie
→ Quantengravitation
- Materie-Antimaterie Asymmetrie
- Parameter des SM
- Eichgruppen ?
Theoriet
→ (g-2) des μ
- Diskrepanz bei Messungen.
Hubble-Konstante !
CMB ≠ Rotverschiebung
- starkes CP Problem
(- Annahme Kosmologie)
- ν Majorana massenterm

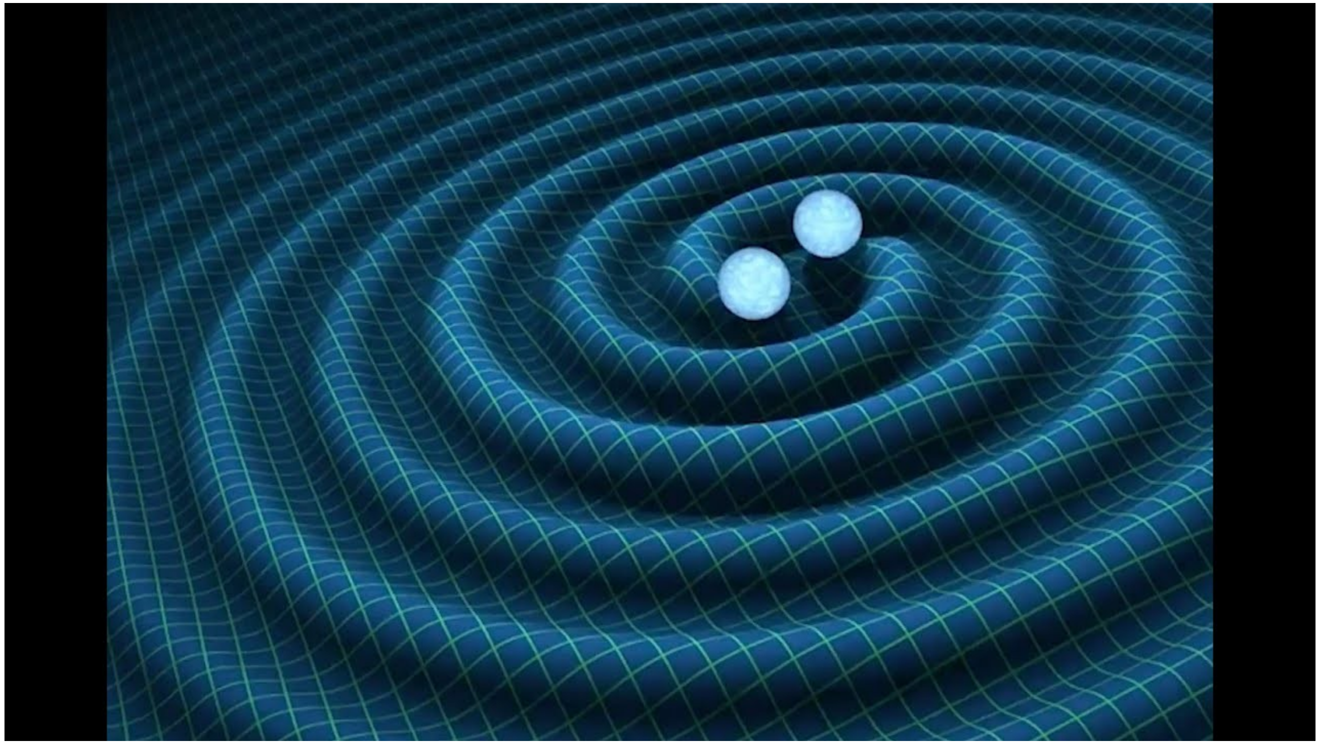




- Rotational speed of stars in galaxies
  - Too little visible matter
  - Dark Matter
- Cosmic microwave background
  - Accelerated expansion of universe
  - SM of Cosmology: ΛCDM
  - Dark Energy

Gravitational waves

Nobel prize 2017



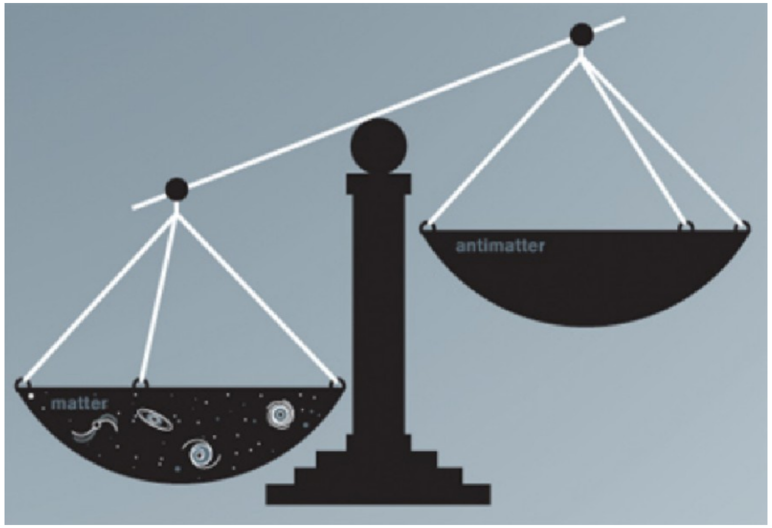
LIGO

- **But gravity is not included in the Standard Model of Particle Physics**
  - **SM: Gauge quantum field theory in flat 4d spacetime**
  - **GR: Nonquantised geometric field theory**
- **No quantum field theory of gravity so far …**

Matter-antimatter asymmetry

CKM

0.97434	0.22506	0.00357
0.22492	0.97351	0.0411
0.00875	0.0403	0.99915

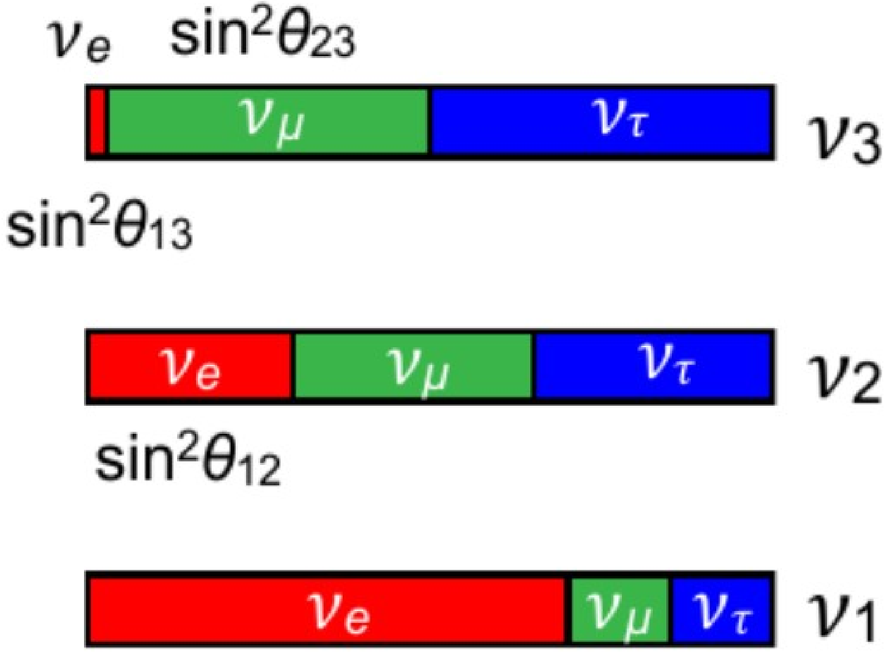


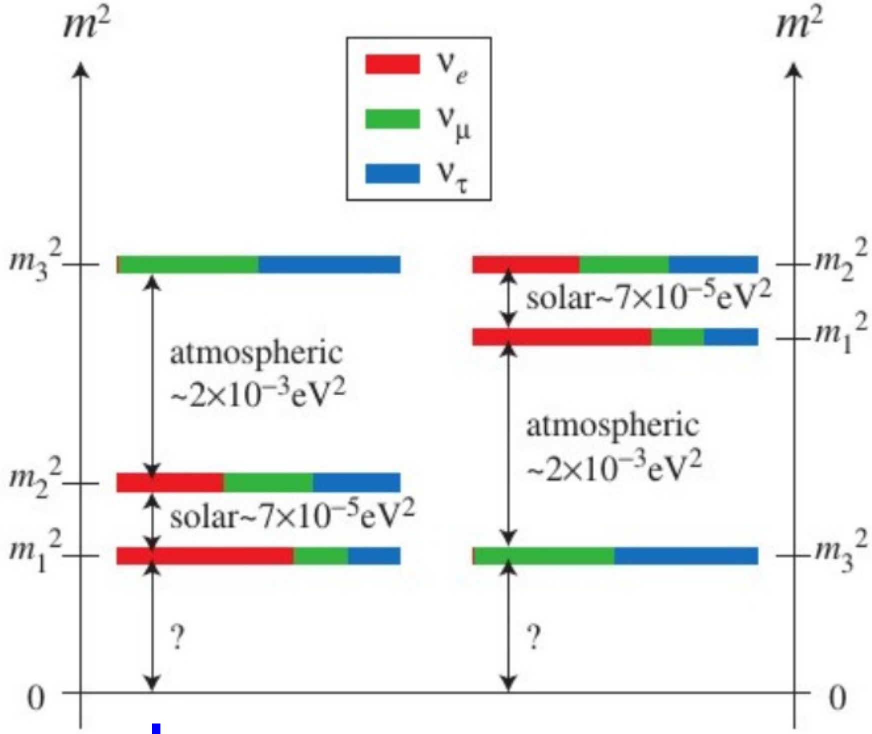
Quantum diaries

- **Baryon asymmtry in the universe**
  - **Requires CP violation (Sakharov 1967)**
  - **Only known source in SM, CKM matrix, not sufficient!**

Neutrino properties

PMNS matrix





Rept.Prog.Phys. 76 (2013) 056201

- **Neutrinos in SM of particle physics are massless**
- **Observation of neutrino oscillations well estabishled**
  - **Neutrinos must have some very small masses!**
  - **Analog to CKM matrix exists: PMNS**
- **Is there CP violation in PMNS?**
- **Are neutrinos their own antiparticles (Majorana instead of Dirac)?**

Muon anomalous magnetic moment

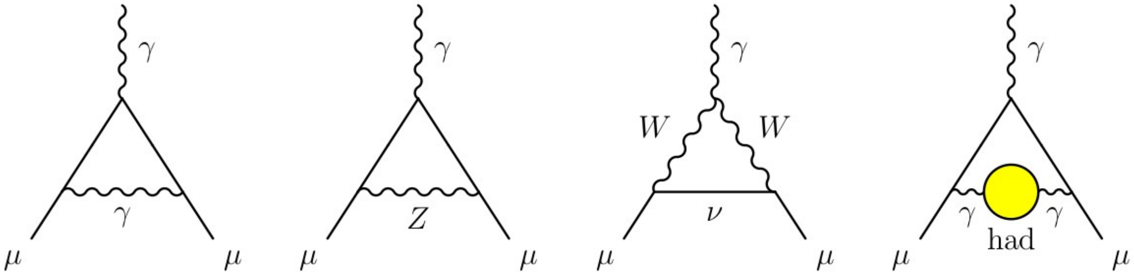
- **Interaction of particle with spin S in magnetic field B**

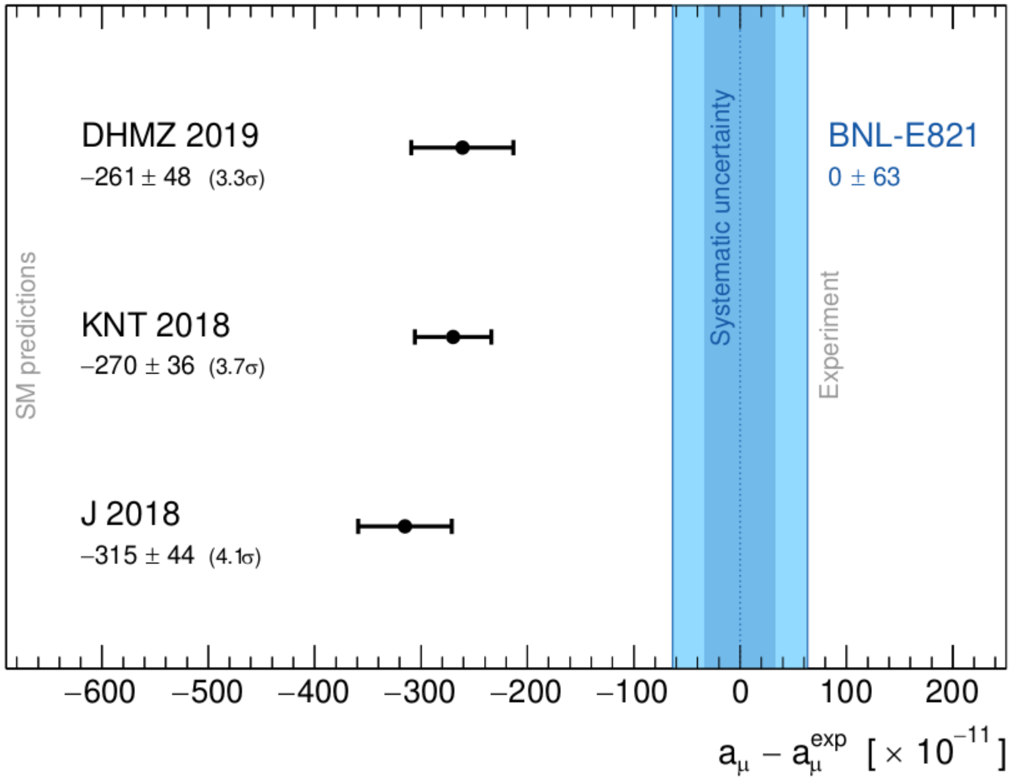
$$E = -\vec{\mu}_m \cdot \vec{B}$$

  - **Dirac: $g_\mu = 2$**

$$\vec{\mu}_m = g\frac{q}{2m}\vec{S}$$

- **Radiative corrections allow deviation**
  - **Anomalous magnetic moment (g - 2)**





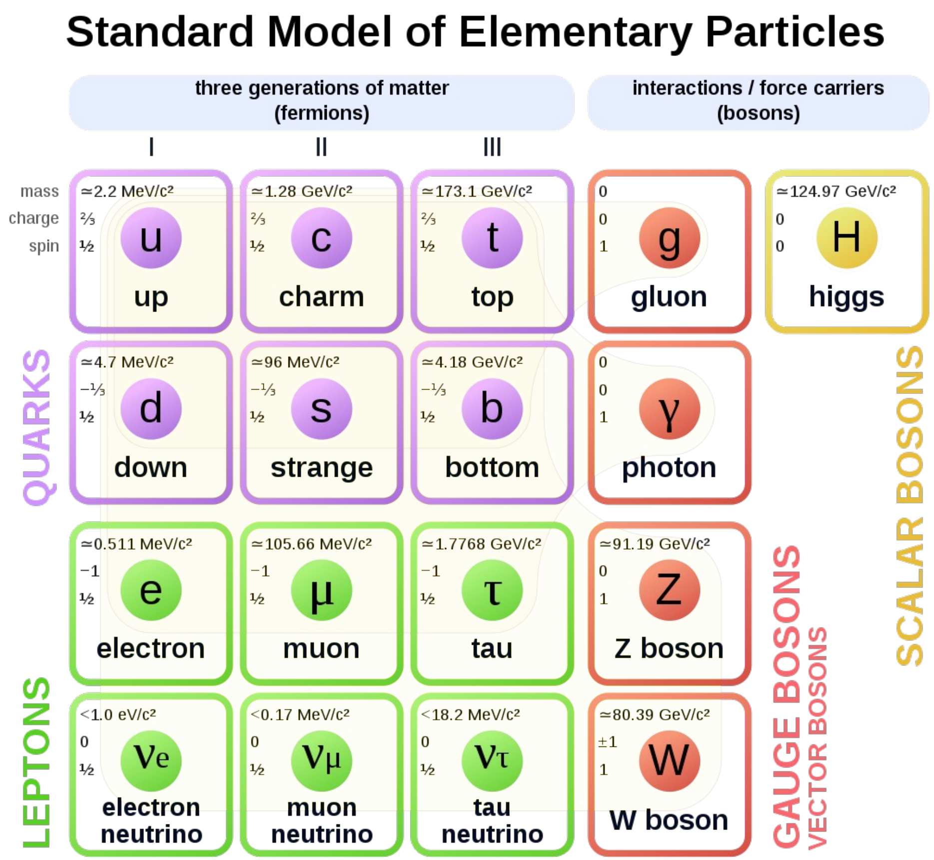
P.A.Zyla et al., PDG, Prog.Theor.Exp.Phys. (2020) 083C01.

- **Extremely precise prediction from theory (at level of 5 10^{-7})**
  - **In disagreement with measurements!**
  - **Corrections (loops) sensitive to new physics (particles)**

$$a_\mu = \frac{g_\mu - 2}{2} \neq 0$$

Large number of parameters

- "Standard Model" **18**
  - Nine fermion masses
  - Three coupling constants
  - Higgs mass and vacuum expectation value
  - Three CKM mixing angles + one phase
- Including neutrino masses
  - Three more fermion masses
  - Three PMNS angles + one phase **25**
- Including strong CP phase parameter
  - No CP violation in QCD **26**
- Two more for Majorana neutrinos?

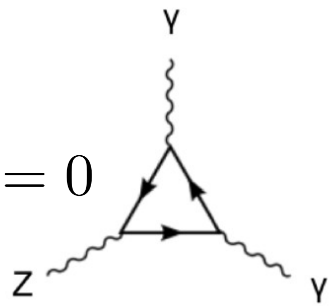


Attribution of most parameters

- Gauge interactions (couplings): 3
- Higgs sector (masses): 14 !
- Flavour sector (CP): 8 !

Theory deficits

- **Complicated gauge structure of three interactions** $\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$
  - Reason for gauge groups?
  - Is there some unification to one elemental force?
- **CP violating term in QCD Lagrangian → 0** $\theta \frac{g_s^2}{32\pi^2} \mathcal{G}^A_{\mu\nu} \tilde{\mathcal{G}}^{\mu\nu}_A$
  - Why so small?
- **Minimal Higgs sector added "ad hoc"**
  - Twelve hugely different Yukawa couplings to give the observed fermion masses
- **"Conspiracy" between electroweak and strong parameters**
  - Atoms are electrically neutral, electron and quark charges compensate
  - No chiral anomaly, chiral current is conserved $Q_e + N_C \cdot (Q_u + Q_d) = 0$



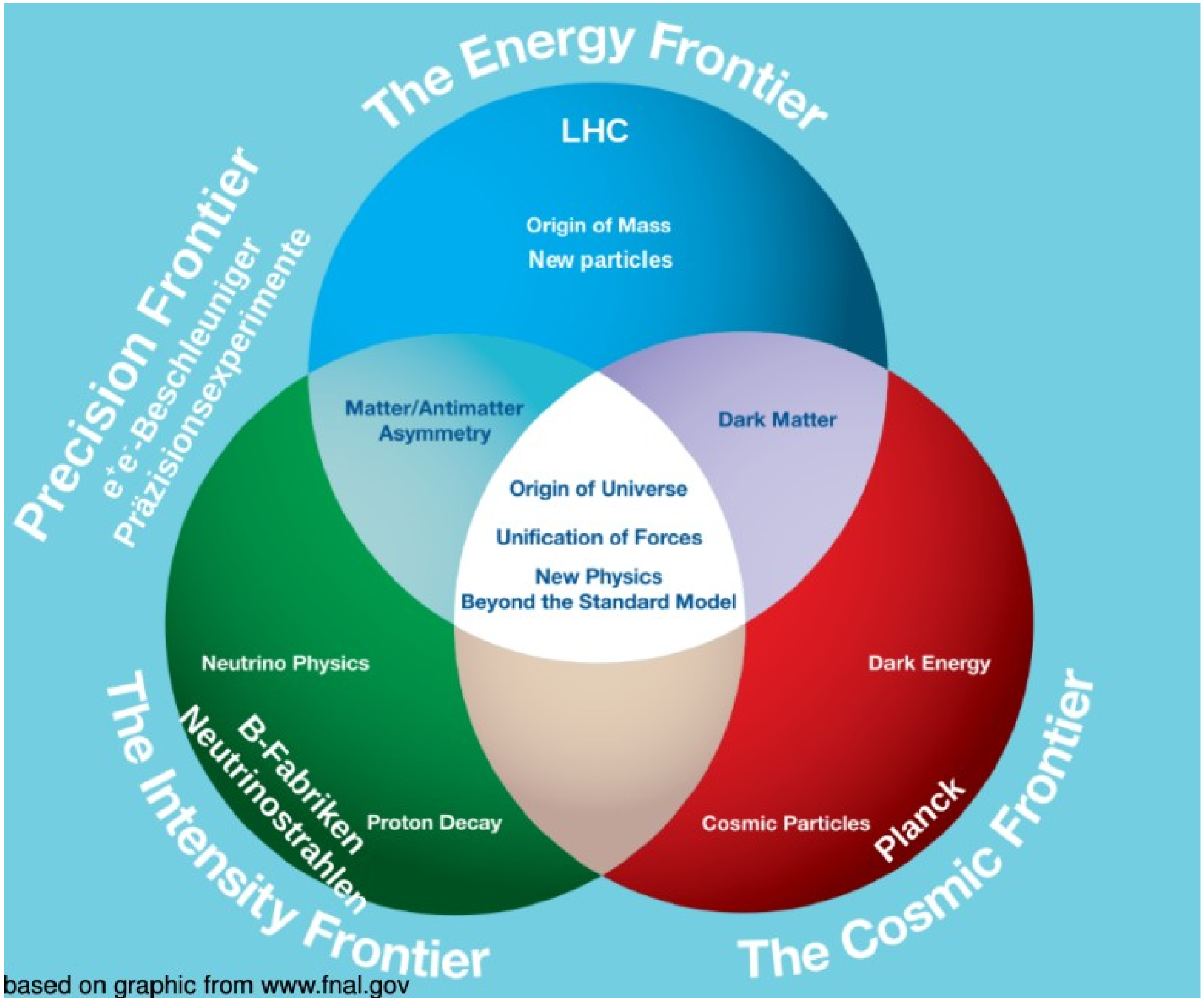
- **Hierarchy problem**
  - SM as effective theory valid from $\Lambda_{\mathrm{ewk}} \approx 10^2 \mathrm{GeV}$ up to some scale
  - Gravity not included so could be $\Lambda_{\mathrm{Planck}} \approx 10^{19} \mathrm{GeV}$
  - New physics needed, but nothing for 17 orders of magnitude?

Summary of open points

- **Evidence from cosmology**
  - **No particle candidate for dark matter or energy**
  - **Gravity not included in the "Standard Model of Particle Physics"**
  - **Matter-antimatter asymmetry not explained**
- **Evidence from lab experiments**
  - **Neutrino oscillations require neutrino masses (not in SM)**
  - **Deviations in precision experiments (g-2)**
- **Theoretical deficits**
  - **Large number of free parameters – are there any relations?**
  - **Complicated gauge structure – is there a simpler more unified one?**
  - **Is there enough CP violation?**
  - **Ad hoc Higgs sector: What explains the hugely different particle masses?**
  - **Relation between QCD and EWK parameters – is there a deeper reason?**
  - **Is there nothing between the electroweak and Planck (gravity) scale?**

Wishlist to SM extensions

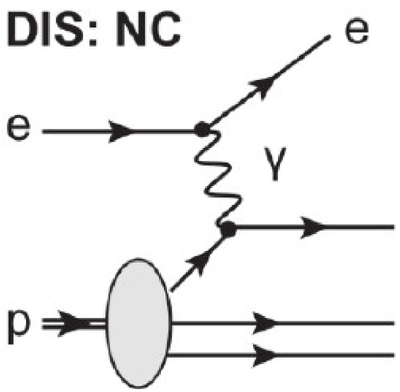
- **Wishlist to BSM physics**
  - Containment:
    SM as low-energy approximation
  - Predictive power:
    Explains new phenomena
  - Simplicity:
    Simpler structure
  - Deductibility:
    Less ad hoc assumptions and/or free parameters
  - Completeness:
    Inherent reasons for nonexistence of otherwise possible effects

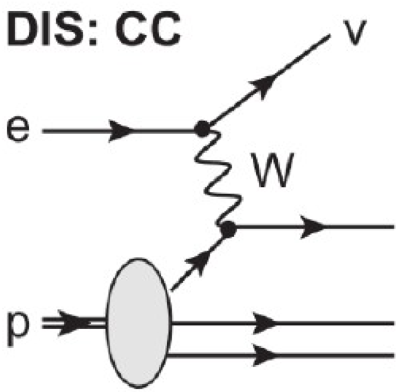


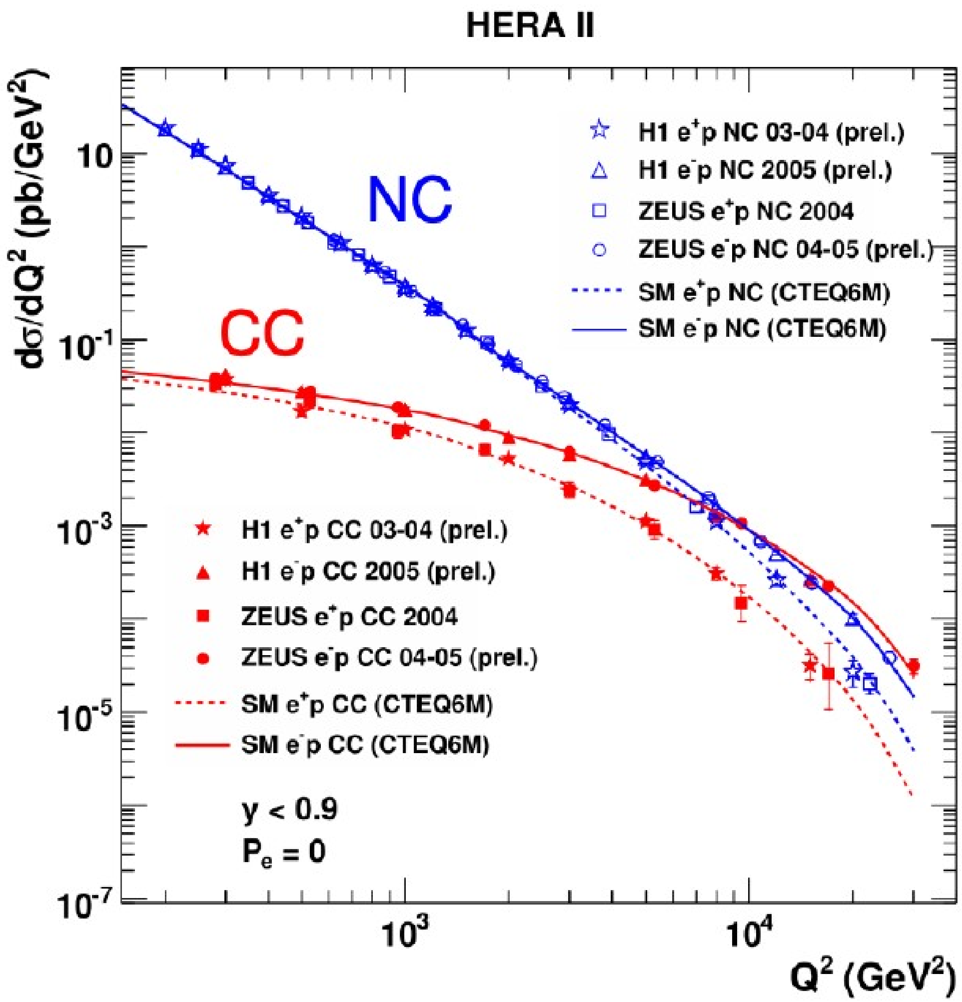
Possible SM extensions

- **New symmetries**
  - Grand Unified Theories (GUT): Unification of SM gauge interactions into one
  - Supersymmetry (SUSY): Symmetry between fermions and bosons
  - Further gauge groups, e.g. U(1) or new right-handed gauge bosons
- **New substructures**
  - Compositeness: Quarks and leptons not elementary
  - Technicolor: Higgs (and W/Z) bosons not elementary
    - Bound states of massless particles: Mass = binding energy
- **New concepts**
  - Further spacetime dimensions
  - Strings instead of particles

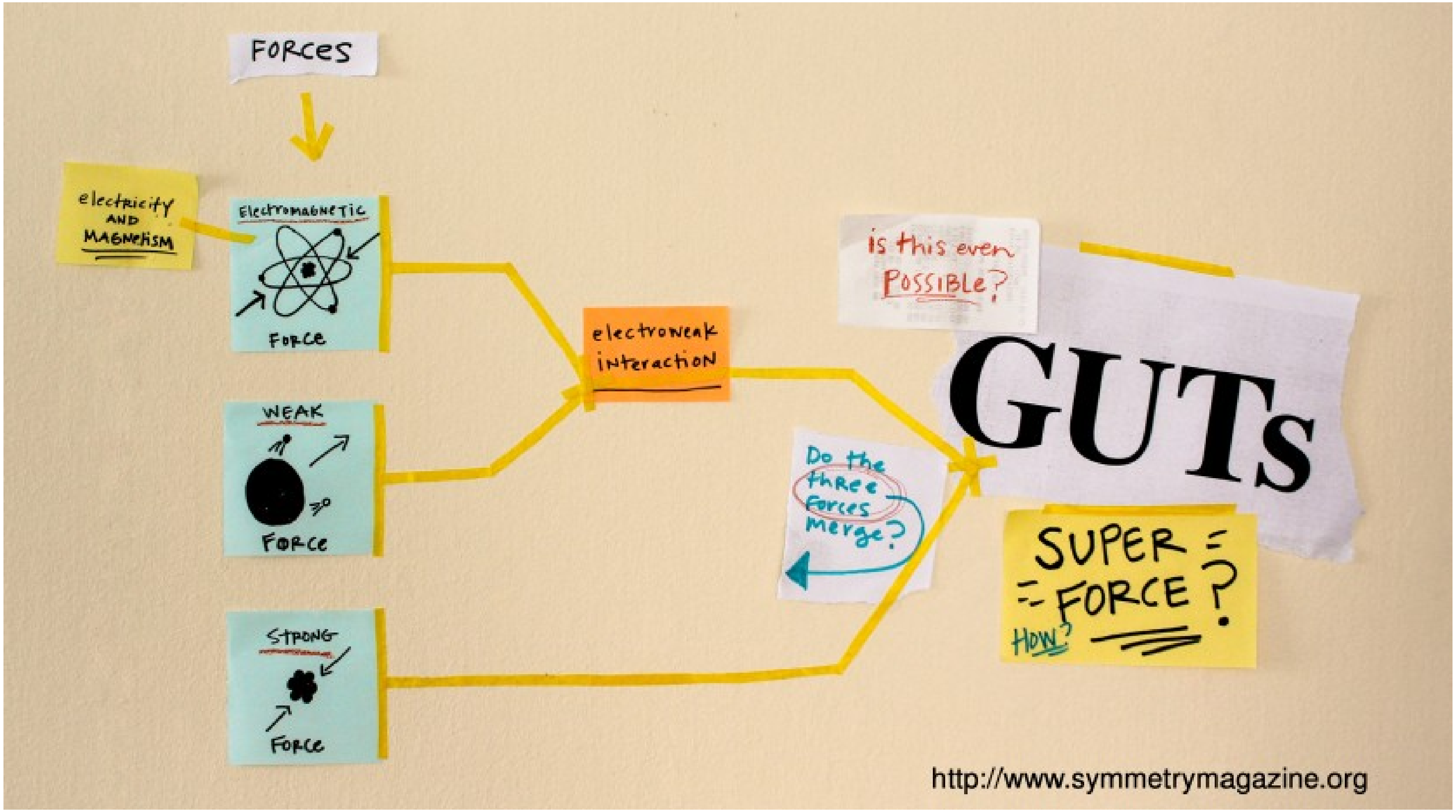
- **Electroweak unification:**
  - Electromagnetic and weak interaction as same force
  - Same strength for $Q^2 \gg M_{W,Z}^2$
  - Low-energy differences due to boson masses (propagators)







GUT: Historical successes



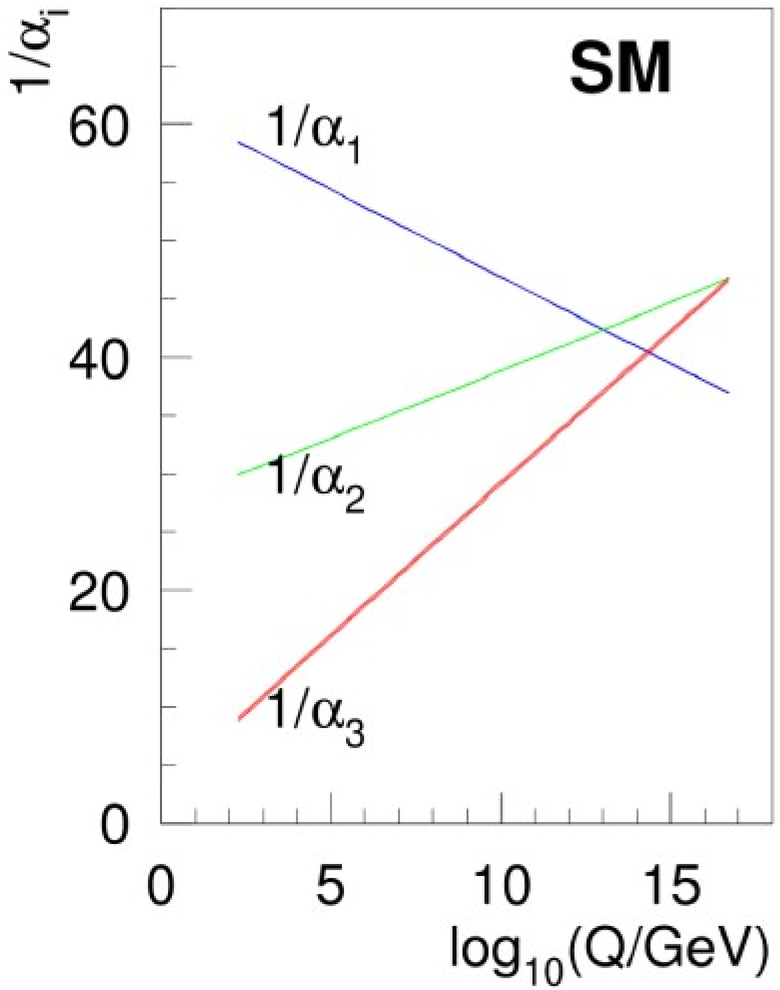
GUT: Example SU(5)

SU(5) simplest group to embed SM:

- New bosons X with weak isospin and color (leptoquarks)
- Predicts unification of gauge coupling strengths
  - Running couplings α_{em}, α_W, α_s almost meet at

$$\Lambda_{\rm GUT} \approx 10^{15}{\rm GeV} \approx \Lambda_{\rm Planck}$$

  - Hint towards unification with gravity?



arXiv:hep-ph/0012288

Big desert:

- No new physics inbetween
- Unification not exact; something else in addition?

Predicts:

- ~ Value of weak mixing angle
- No anomaly → neutral atoms
- No B or L conservation; proton decay
- Magnetic monopoles

Remark: In SU(5) $\alpha \rightarrow \alpha_1 = \dfrac{5\alpha}{3\cos^2\theta_W}$

Supersymmetry (SUSY)

- **Supersymmetry SUSY**
  - Symmetry between fermions and bosons
  - Postulate: Lagrangian invariant under supersymmtry transformations
  - Original motivation: Extension of Poincare-Group
  - First prototype: Wess-Zumino model at Uni Karlsruhe
- **Minimal Supersymmetric Standard Model (MSSM)**
  - Superpartners to existing particles with spin different by ± ½
  - Other properties identical between normal and SUSY particles
  - Contains dark matter candidates, e.g. neutralinos
  - Unification of coupling strengths
  - Solution of Hierarchy problem in Higgs sector
  - Dynamic generation of electroweak symmetry breaking
  - No superpartners with identical properties (mass) found → must be broken symmetry with SUSY particle masses LARGER

MSSM: Particle content

Particle content:

- **Spin-½ fermions and spin-0 sfermions**
- **Spin-1 gauge bosons and spin-½ gauginos**
- **More complex Higgs sector required (two Higgs doublets → five Higgs'ses)**

Leptons	$\frac{1}{2}$	$\begin{pmatrix}\nu_{e,L}\\ e_L\end{pmatrix}, e_R \quad \begin{pmatrix}\nu_{\mu,L}\\ \mu_L\end{pmatrix}, \mu_R \quad \begin{pmatrix}\nu_{\tau,L}\\ \tau_L\end{pmatrix}, \tau_R$
Sleptons	0	$\begin{pmatrix}\tilde\nu_{e,L}\\ \tilde e_L\end{pmatrix}, \tilde e_R \quad \begin{pmatrix}\tilde\nu_{\mu,L}\\ \tilde\mu_L\end{pmatrix}, \tilde\mu_R \quad \begin{pmatrix}\tilde\nu_{\tau,L}\\ \tilde\tau_L\end{pmatrix}, \tilde\tau_R$
Quarks	$\frac{1}{2}$	$\begin{pmatrix}u_L\\ d_L\end{pmatrix}, u_R, d_R \quad \begin{pmatrix}s_L\\ c_L\end{pmatrix}, s_R, c_R \quad \begin{pmatrix}t_L\\ b_L\end{pmatrix}, t_R, b_R$
Squarks	0	$\begin{pmatrix}\tilde u_L\\ \tilde d_L\end{pmatrix}, \tilde u_R, \tilde d_R \quad \begin{pmatrix}\tilde s_L\\ \tilde c_L\end{pmatrix}, \tilde s_R, \tilde c_R \quad \begin{pmatrix}\tilde t_L\\ \tilde b_L\end{pmatrix}, \tilde t_R, \tilde b_R \leftrightarrow \tilde t_{1,2}, \tilde b_{1,2}, \ldots$
Gauge bosons	1	$W^\pm, Z^0, \gamma, g$
Gauginos	$\frac{1}{2}$	$\tilde W^\pm, \tilde Z^0, \tilde\gamma, \tilde g$
Higgsinos	$\frac{1}{2}$	$\tilde H^0_{1,2}, \tilde H^\pm$
Higgs bosons	0	$h, H, A, H^\pm$

Gauginos and Higgsinos: $\tilde\gamma, \tilde Z^0, \tilde H^0_{1,2} \leftrightarrow \underbrace{\tilde\chi^0_{1,2,3,4}}_{\text{Neutralinos}}; \quad \tilde W^\pm, \tilde H^\pm \leftrightarrow \underbrace{\tilde\chi^\pm_{1,2}}_{\text{Charginos}}$

MSSM at LHC

Unification of couplings actually works

Ideal scale for superpartners: 1 TeV

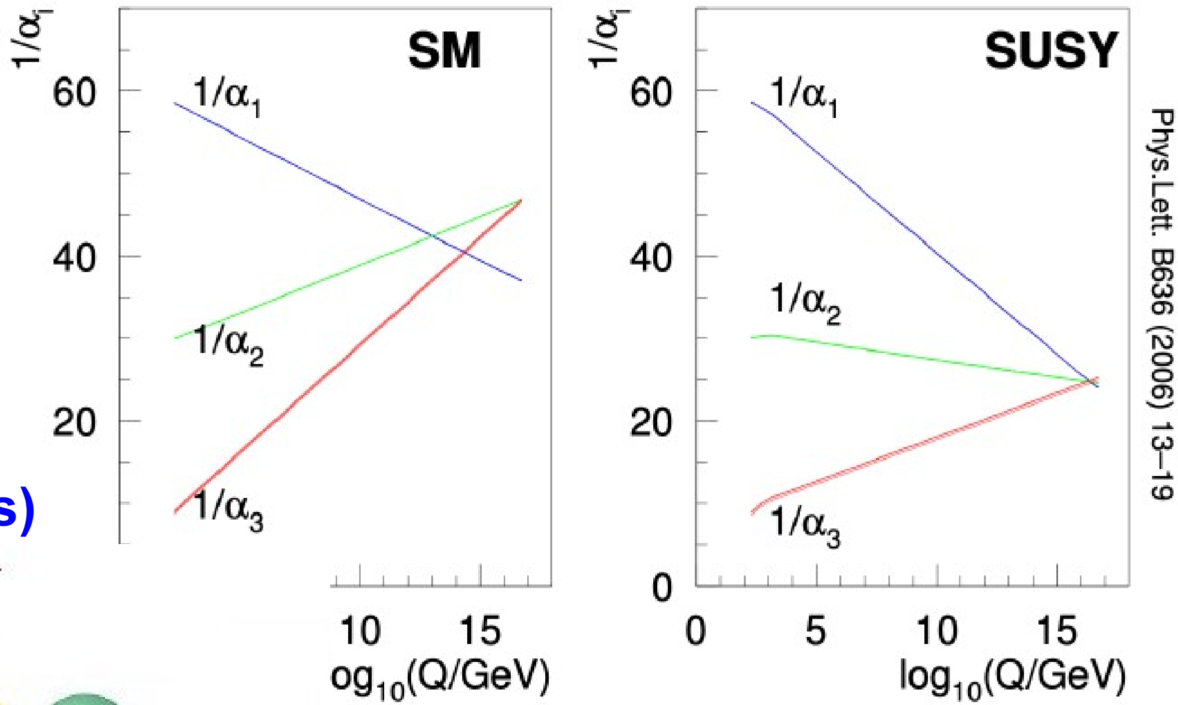
→ perfect for discovery at the LHC

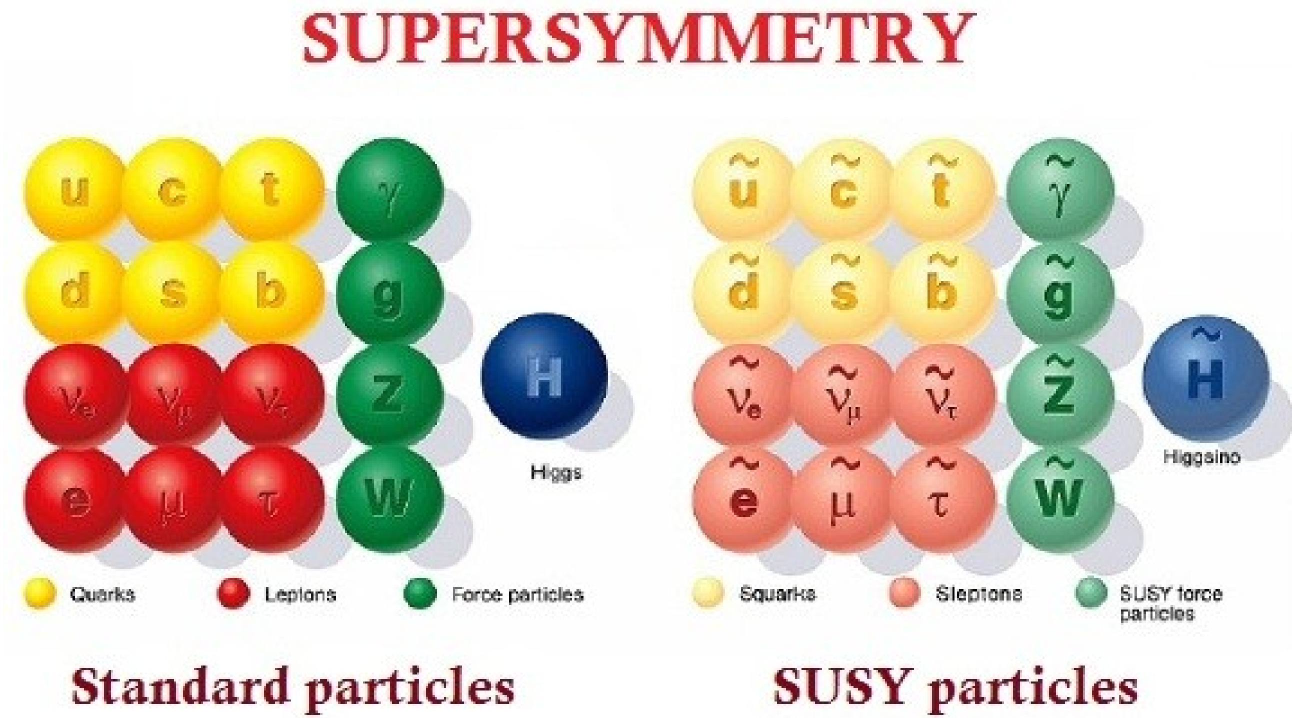
Lighest SUSY particle (LSP) candidate

for Cold Dark Matter (CDM)!

→ WIMP searches, also elsewhere

(Weakly Interacting Massive Particles)





Not the slighest glimpse found of something SUSY at the LHC

– no massive superpartners

– no missing E_T signatures of CDM candidates

→ No WIMPs found

Maybe try ALPs

QCD and C, P, T Invariance

Lorentz-scalar in QED $$-\frac{1}{4}\mathcal{F}_{\mu\nu}\mathcal{F}^{\mu\nu} = \frac{1}{2}\left(\vec{E}^2 - \vec{B}^2\right)$$ OK

No effect, since surface term with QED fields → 0 at ∞ $$-\frac{1}{4}\mathcal{F}_{\mu\nu}\tilde{\mathcal{F}}^{\mu\nu} = \left(\vec{E}\cdot\vec{B}\right)$$ ~~P~~, ~~T~~

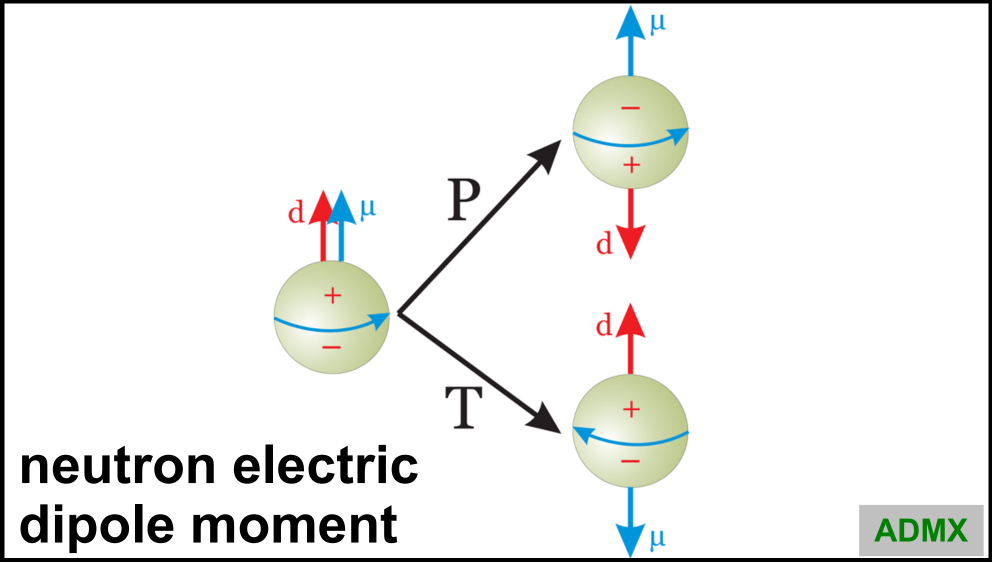
The case of QCD

Dual tensor: $$\tilde{\mathcal{F}}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}\mathcal{F}_{\rho\sigma}$$

If all m_q > 0, possible term of

$$\theta\,\frac{g_s^2}{32\pi^2}\mathcal{G}^A_{\mu\nu}\tilde{\mathcal{G}}^{\mu\nu}_A$$ →

should have effect, because of degenerate nonperturbative QCD vacuum with phase 0 ≤ θ ≤ 2π.



Neutron EDM

Including weak CP violating effects → $\bar{\theta}\frac{g_s^2}{32\pi^2}\mathcal{G}^A_{\mu\nu}\tilde{\mathcal{G}}^{\mu\nu}_A$

where $0 \leq \bar{\theta} \leq 2\pi$

NMR measurement with spin-polarised, trapped (t ≈ 150s), ultracold neutrons (v < 7 m/s → total reflection)
B ≈ 1 µT, E ≈ 10 kV/cm

$$h\nu_{\uparrow\uparrow} = |2\mu_n B + 2d_n E|$$

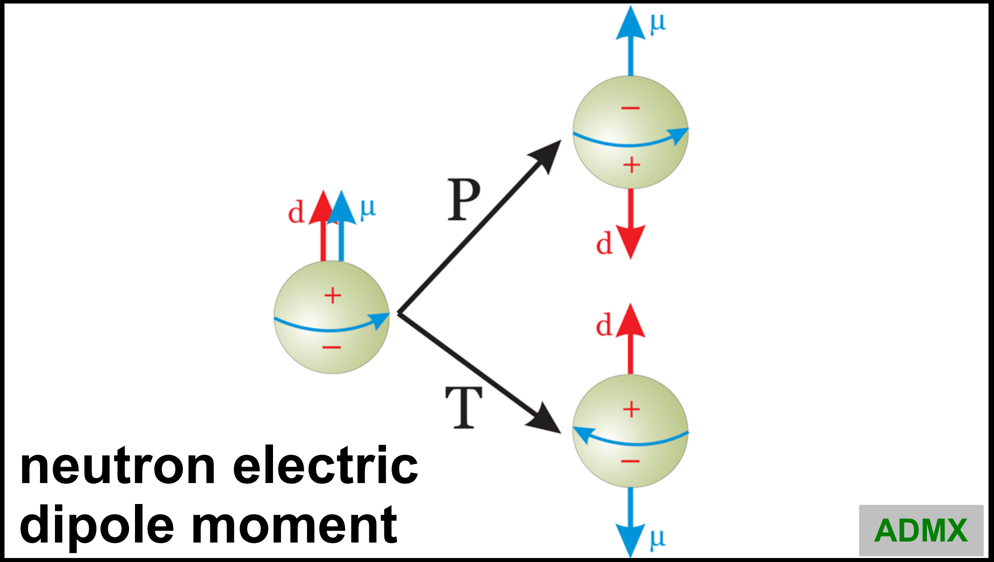
$$h\nu_{\uparrow\downarrow} = |2\mu_n B - 2d_n E|$$

Measure change in spin precession frequency between E parallel and anti-par.

$$-\delta\nu = 4d_n E/h$$

$$d_n < 2.9 \cdot 10^{-26} e\text{cm}$$

Best limit → $\bar{\theta} < 10^{-10}$ **!!**



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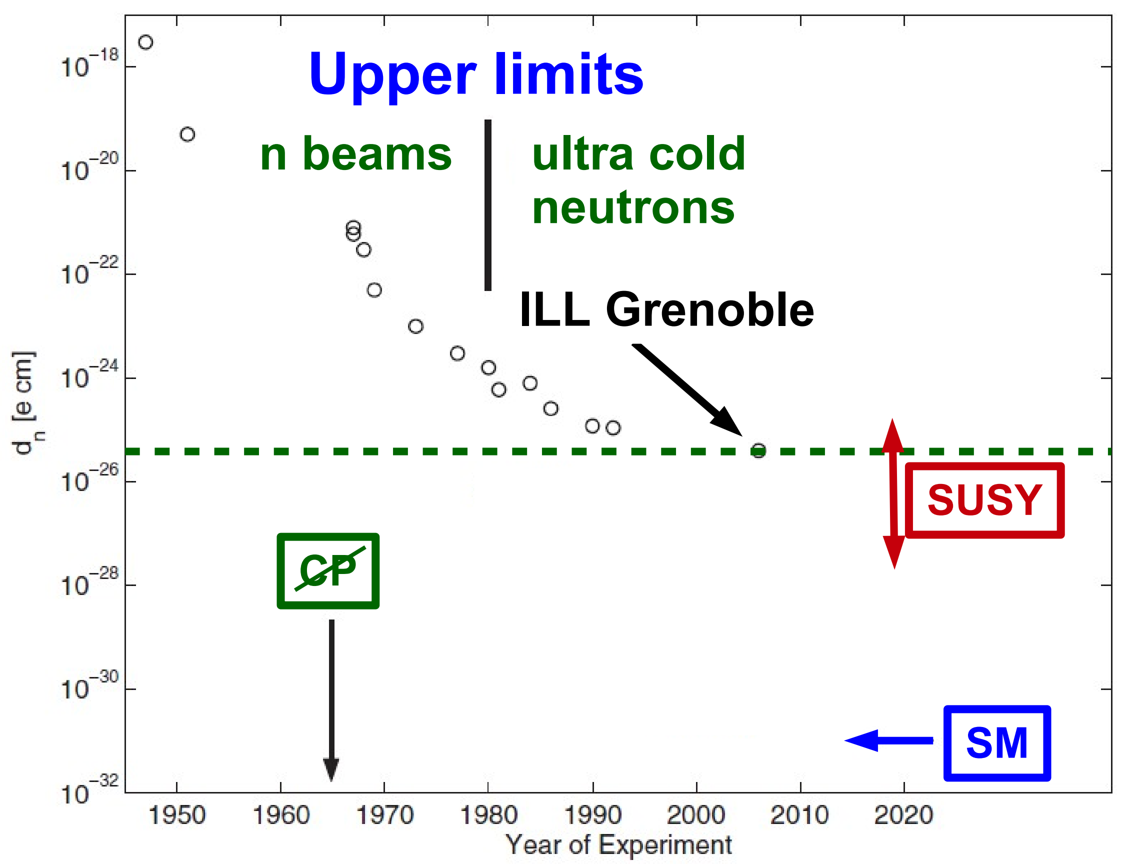

J. Phys. G, 2009, 36, 104002

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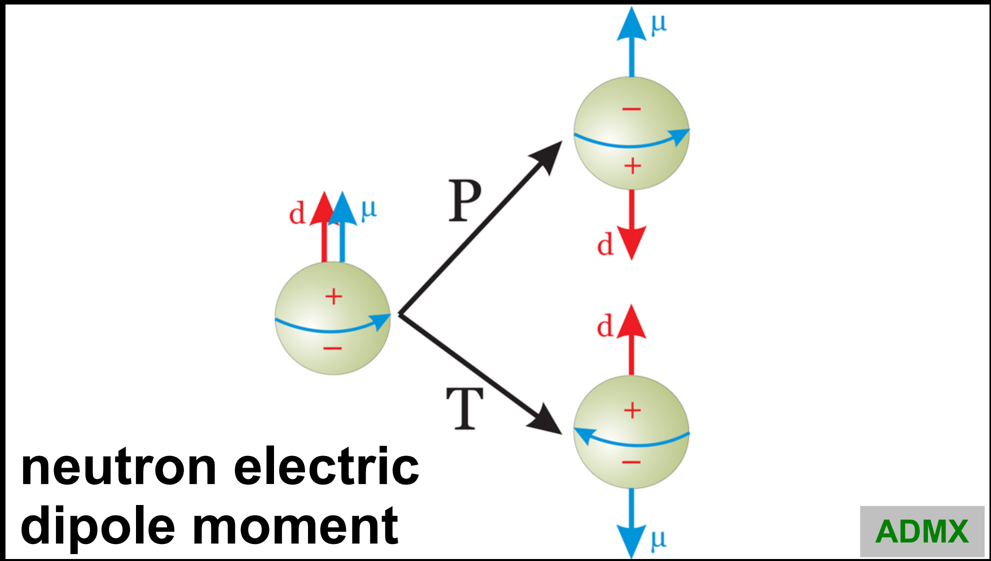
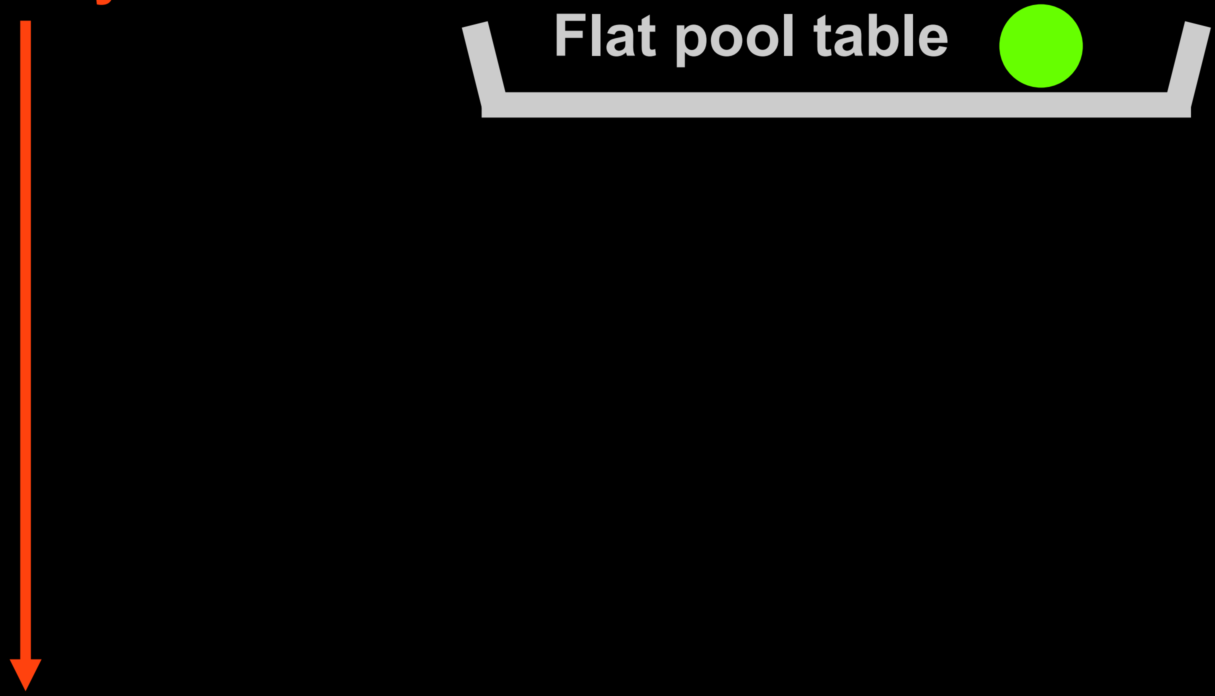


Pool Table Analogy

QCD conserves CP invariance

Gravity



Perfectly symmetric

P. Sikivie, Physics Today, 12/1996;
arXiv:hep-ph/9506229

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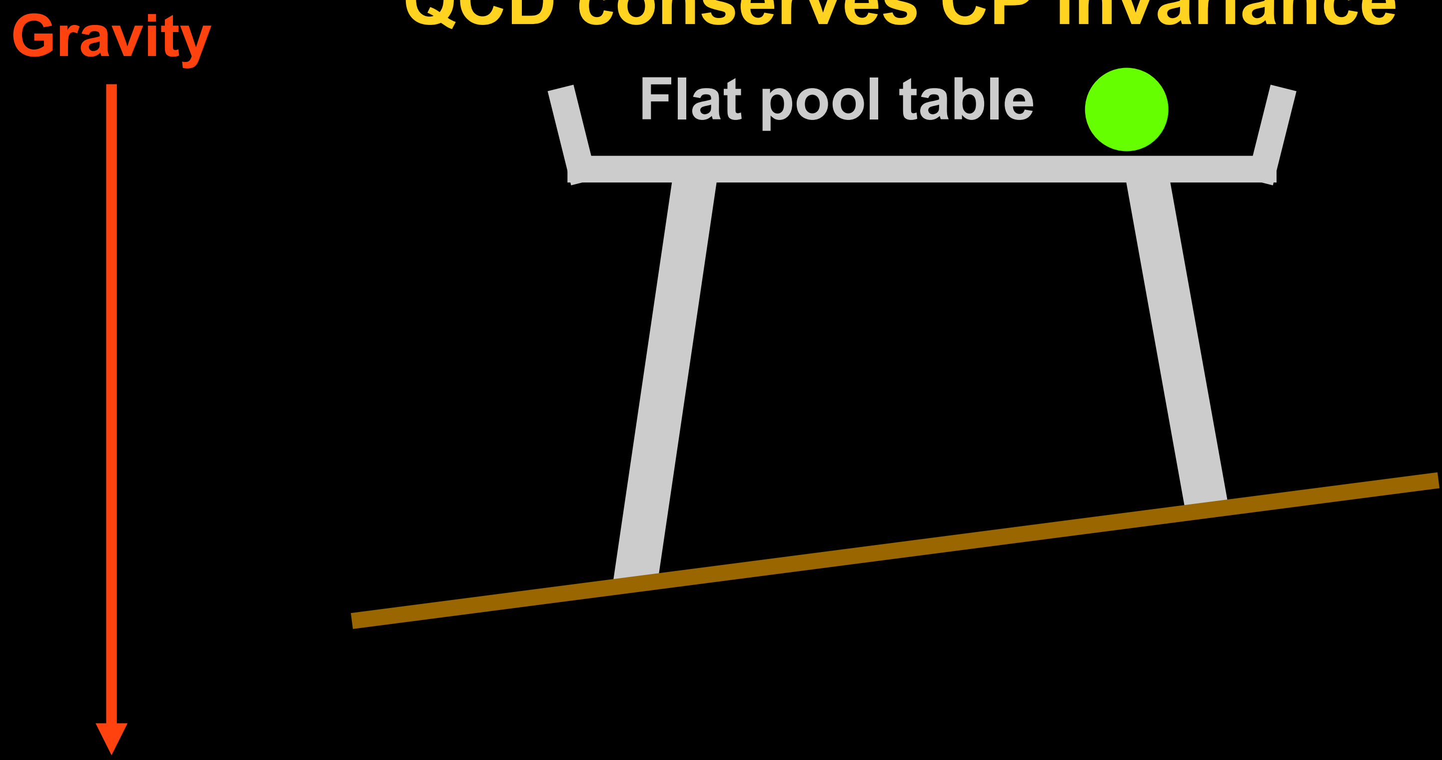

Perfectly symmetric relative to gravity

But why ...?

Floor inclined → broken symmetry

By accident?
Everywhere?
→ perfect tuning ...

P. Sikivie, Physics Today, 12/1996; arXiv:hep-ph/9506229

Pool Table Analogy

QCD conserves CP invariance

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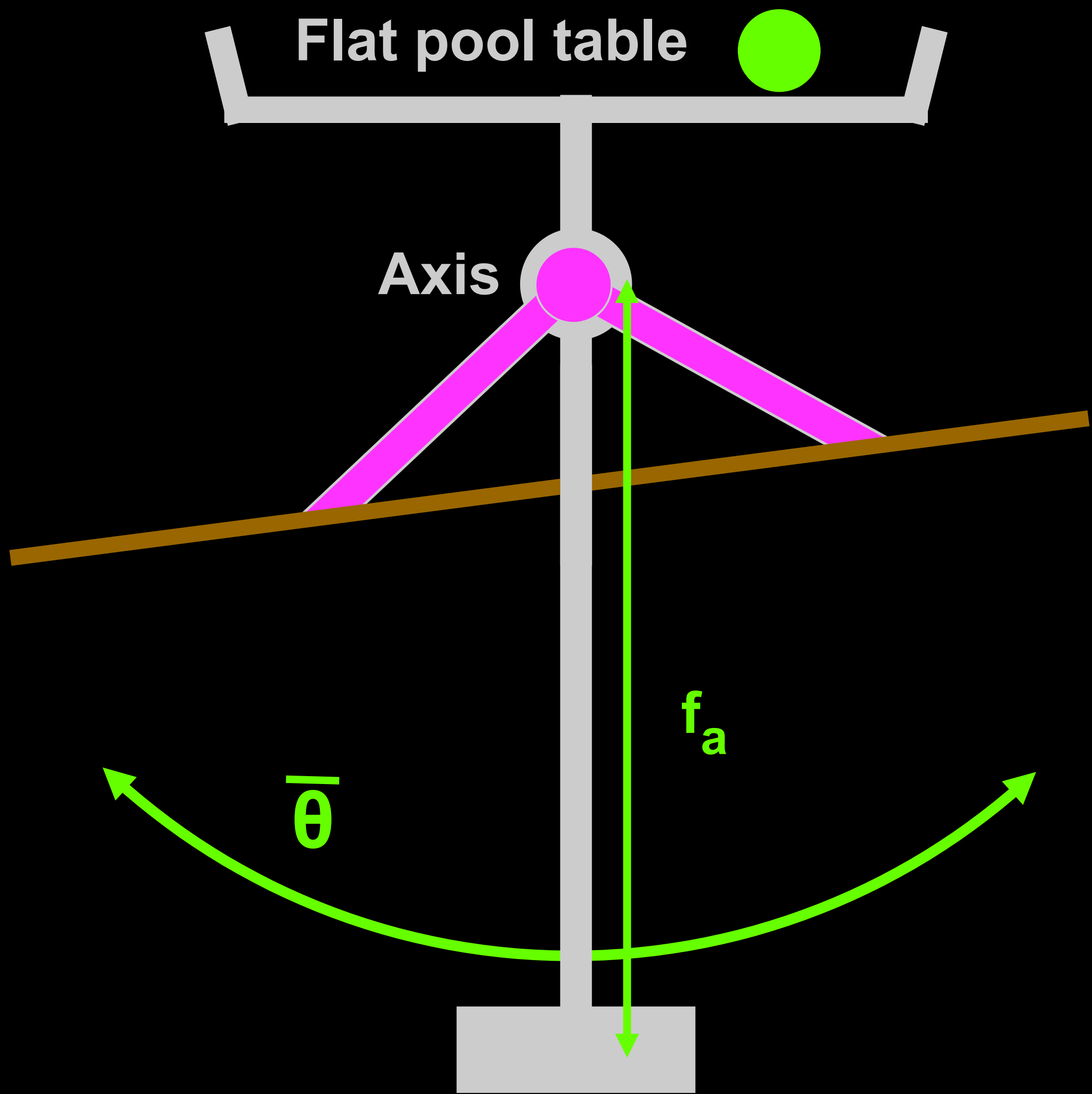


Perfectly symmetric relative to gravity

Floor inclined → broken symmetry

Symmetry restored dynamically … at the cost of potential oscillations

New degree of freedom → Axion

P. Sikivie, Physics Today, 12/1996; arXiv:hep-ph/9506229

Peccei-Quinn Mechanism (1977)

Institut für Experimentelle Teilchenphysik

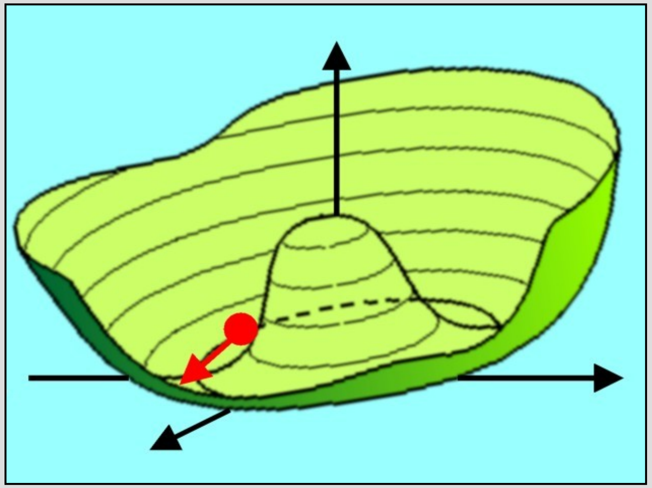
Repeat successful recipes →
Similar to Brout-Englert-Higgs mechanism!

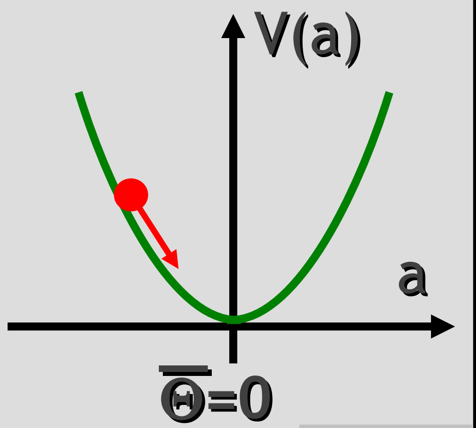
Postulate global $U(1)_{PQ}$ chiral symmetry, spontaneously broken at scale f_a

- **Dynamically generated CP violating term restores QCD CP invariance**
- **Axions as resulting pseudoscalar bosons (Wilczek, Weinberg, 1978)**

$E \approx \Lambda_{QCD} \approx f_\pi \ll f_a$

- $U_{PQ}(1)$ explicitly broken by QCD vacuum effects
- Mexican hat tilts
- Axions acquire a mass





G. Raffelt

Mexican-hat potential → minimum at θ = 0

Axion Properties

Reinterpretation $\bar{\theta} \rightarrow \frac{a(x)}{f_a}$

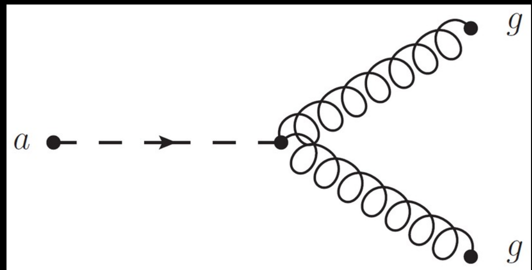
$\rightarrow$ pseudo-scalar axion field

$\rightarrow$ PQ scale, axion decay constant

Original PQWW axion suggestion quickly excluded by experiment ...

$$f_a \sim (\sqrt{2}G_F)^{-1/2} \approx 247\,\mathrm{GeV}$$

Axions effectively couple to gluons



$\rightarrow$ axions mix with π^0

$\rightarrow$ properties scale

$$m_a f_a \sim m_\pi f_\pi$$

$$\approx 140\,\mathrm{MeV} \cdot 100\,\mathrm{MeV}$$

Peccei, Quinn, PRL 1977, 38, 1440; PRD 1977, 16, 1791;
Wilczek, PRL 1978, 40, 279; Weinberg, PRL 1978, 40, 223.

Axion Parameter Space

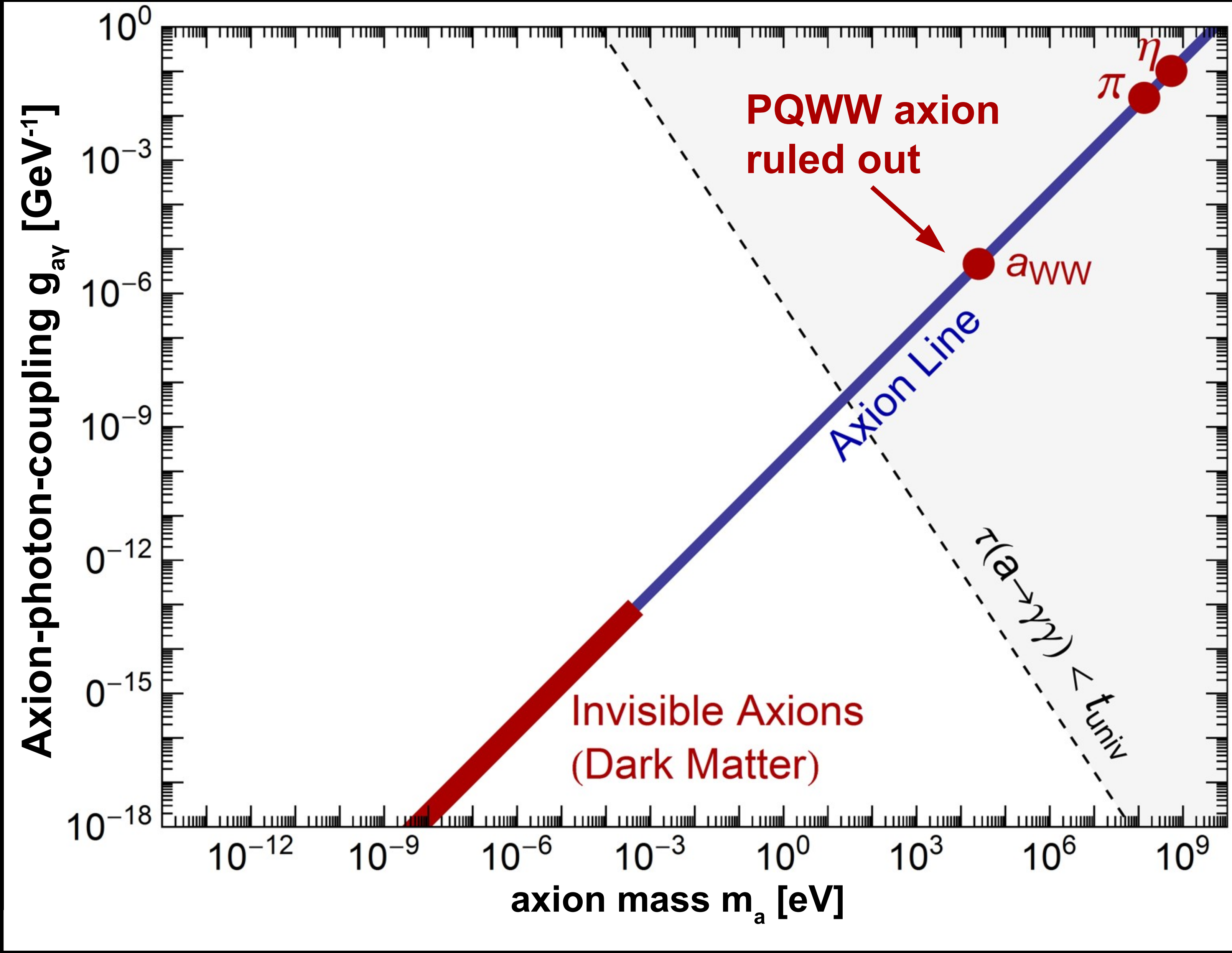
How can we find/ exclude axions In this plane?

Two parameters:
axion mass m_a

axion-γ-coupling

$$g_{a\gamma} \sim 1/f_a$$

$$m_a f_a \sim m_\pi f_\pi$$



Axion Properties

Reinterpretation $\bar{\theta} \to \frac{a(x)}{f_a}$ → pseudo-scalar axion field

→ PQ scale, axion decay constant

Original PQWW axion suggestion quickly excluded by experiment ...

$$f_a \sim (\sqrt{2}G_F)^{-1/2} \approx 247\,\mathrm{GeV}$$

Two alternatives not in contradiction with experiment:

KSVZ (Kim-Shifman-Vainshtein-Zakharov)

DFSZ (Dine-Fischler-Srednicki-Zhitnitskii)

KSVZ Axion, PRL 1979, 43,103; NPB 1980, 166, 493.
DFSZ Axion, SJNP 1980, 31, 260; PLB 1981, 104, 199.

$$m_a \lesssim 10\,\mathrm{meV}$$

A. Vainshtein
Julius-Wess-Award 2014

→ Low Energy Physics!

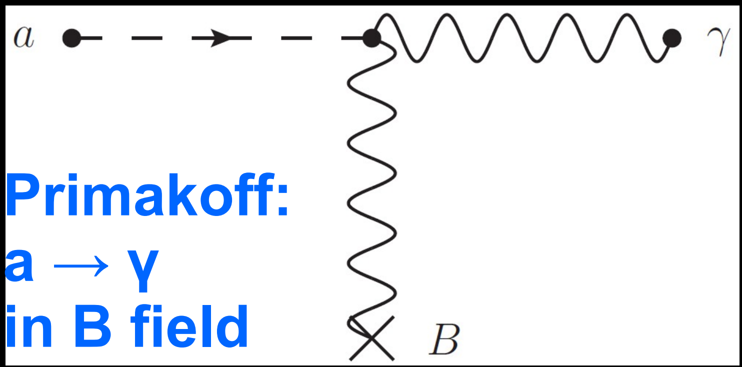
ALPs: axion-like particles:

WEAKLY INTERACTING AND LIGHT!

Cosmic Axions – Haloscopes

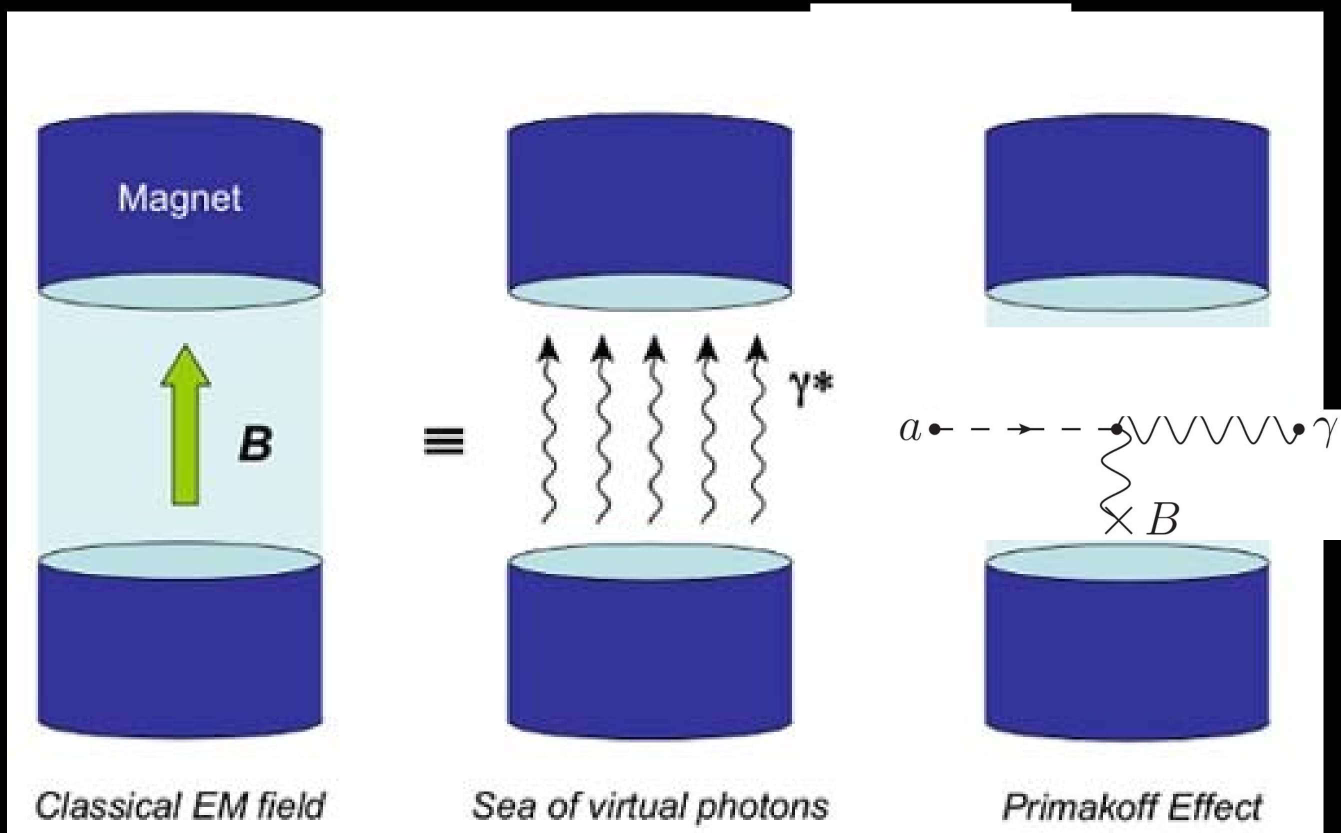
Cosmic mass window

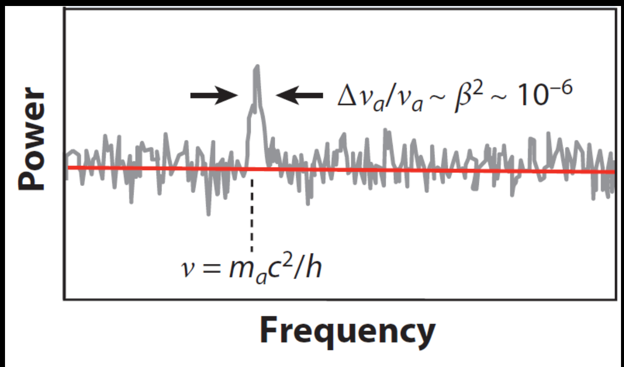
$m_a \approx 1$ µeV - 10meV
$v_a \approx 300$ km/s
$\rightarrow E_a \approx (1 \pm 10^{-6})\, m_a$
$P_{sig} \approx 10^{-22}$ W



Primakoff:
$a \rightarrow \gamma$
in B field

Microwave resonators (Sikivie 1983) of very high quality $Q \sim 10^5$





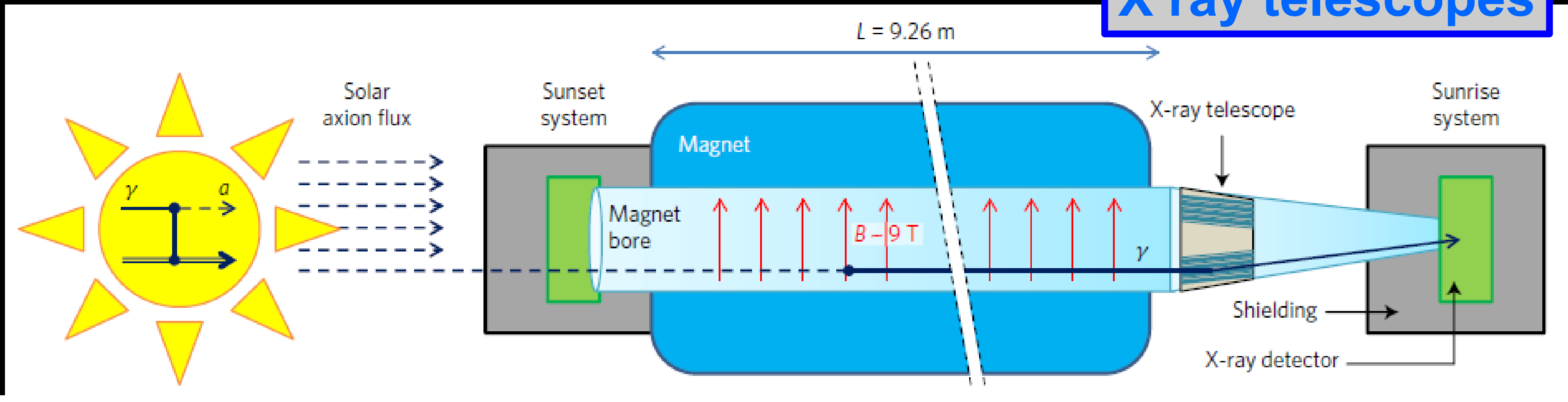
FFT

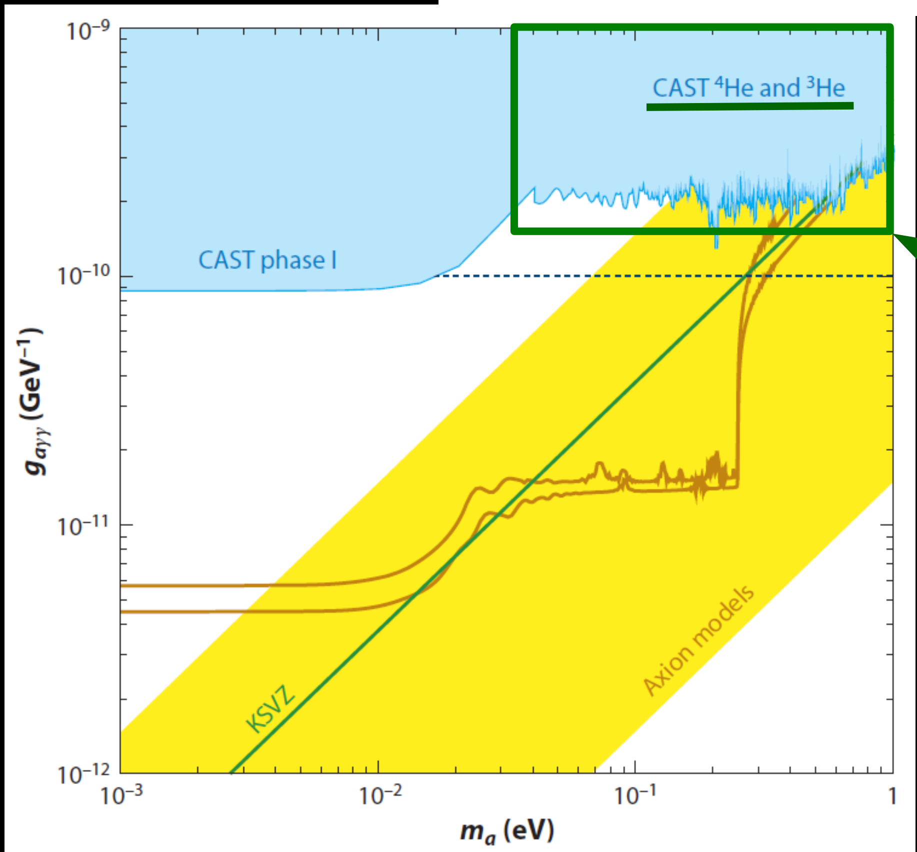
Tune cavity to resonant frequency $\omega \sim m_a$ (bandpass)

Adapted from ADMX
Graham et al., ARNPS 2015, 65, 485.

E_a, keV's

X ray telescopes





Transition depends on coherence length

$$P_{a\to\gamma} = \left(g_{a\gamma} B \frac{\sin(qL/2)}{q}\right)^2$$

$$q = m_a^2/2E$$

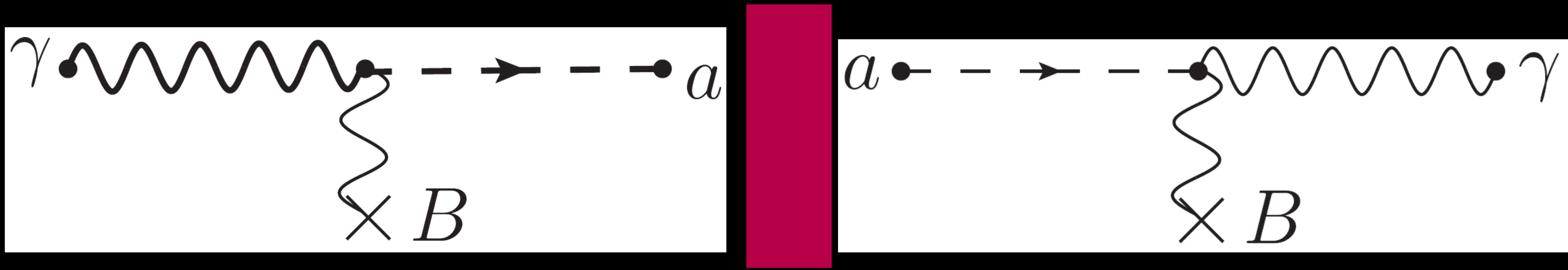
In vacuum: $m_a \lesssim 0.02\,\mathrm{eV}$

Filling vacuum with ^{4}He and ^{3}He to extend to higher masses
→ reaches yellow QCD axion band!

Here: CERN Axion Solar Telescope (CAST)
Uses LHC magnet prototype!

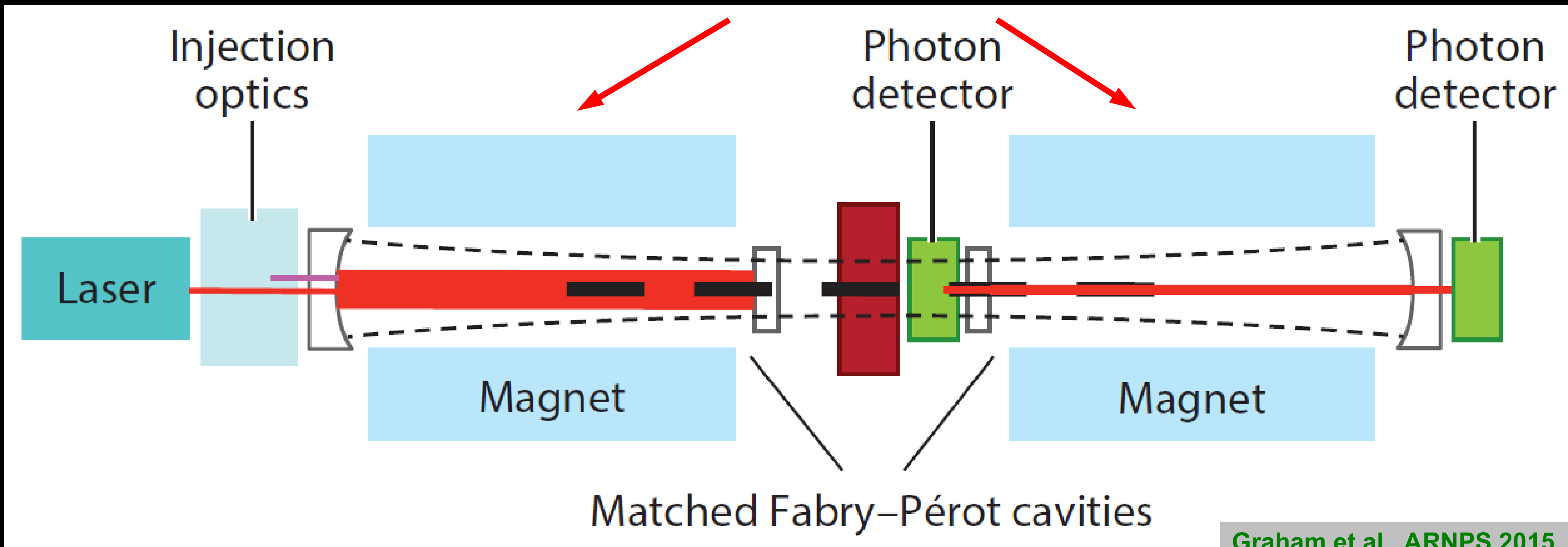
CAST, Nat. Phys. 2017.
Graham et al., ARNPS 2015, 65, 485.

Light shines through walls (LSW)



Aligned?
Same tune?

Injection side **Detection side**



Graham et al., ARNPS 2015, 65, 485.

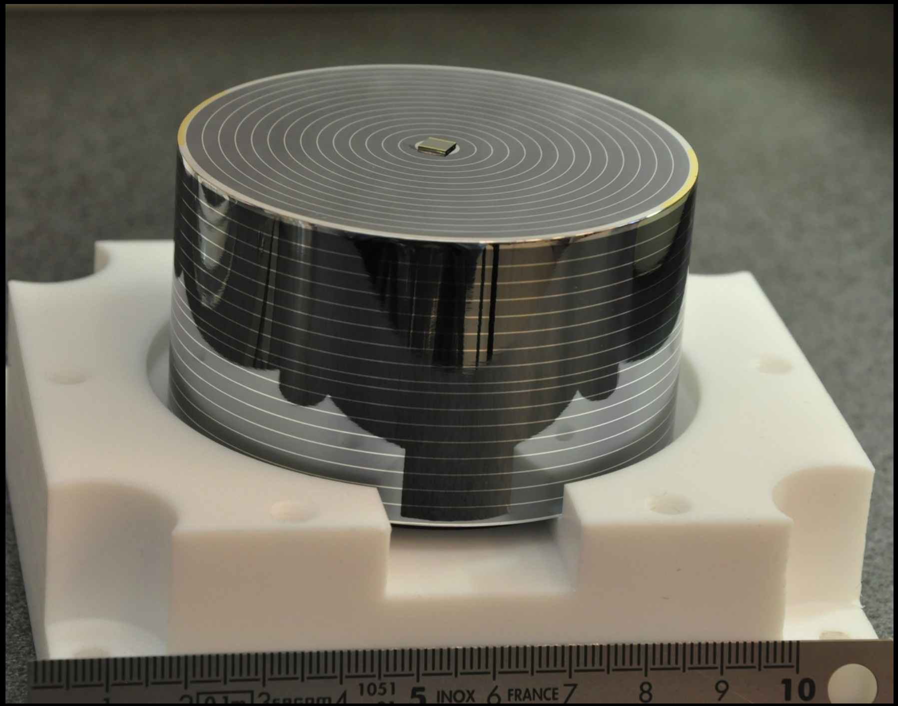
Edelweiss

$m_a \approx 10^0 - 10^3$ eV

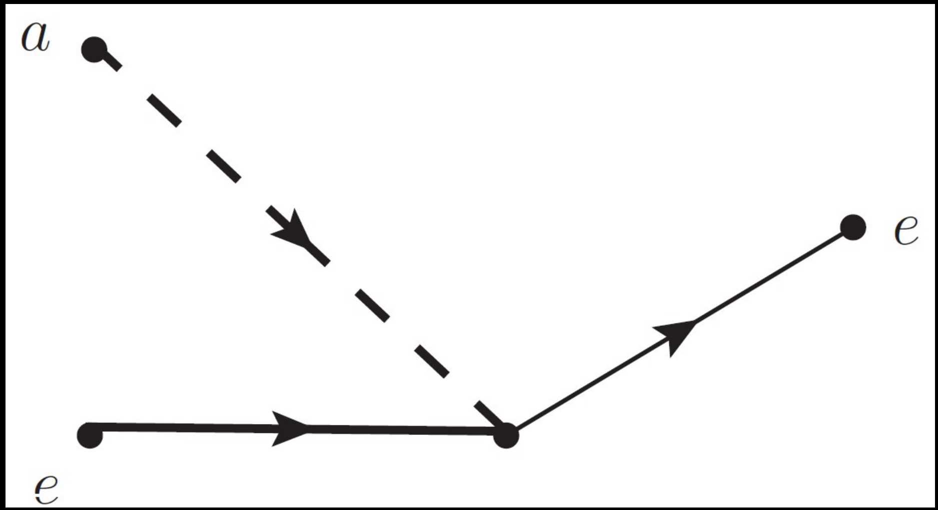
Designed for WIMPs to detect N recoils (Weakly Interacting Massive Particles)

Situated in underground lab of Modane

Uses Germanium monocrystals in radiation-poor environment at 18 mK



Can detect Primakoff and axioelectric effect



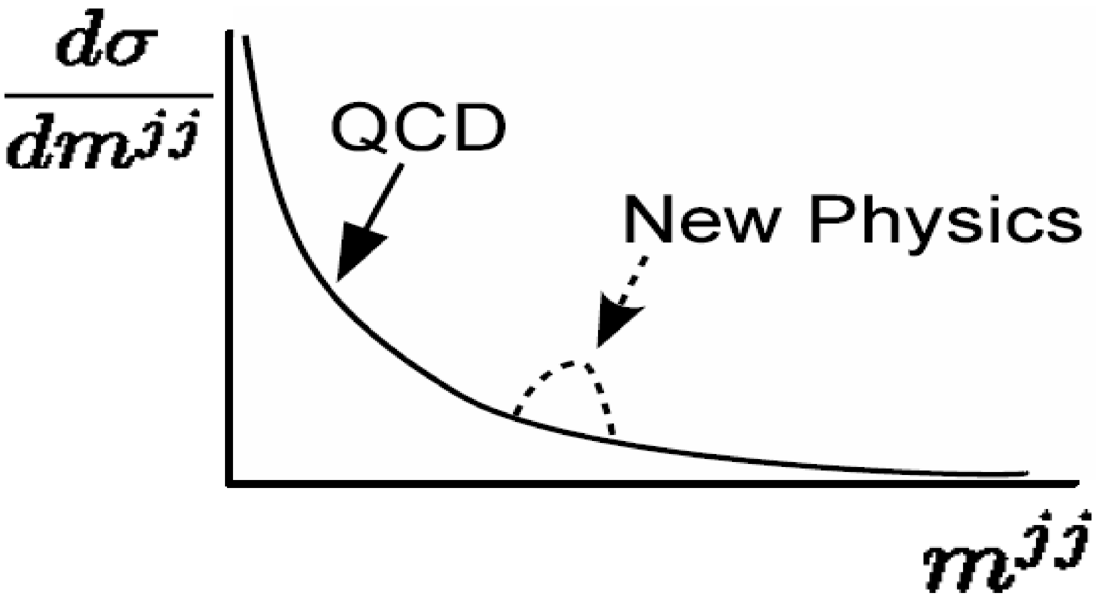
Measure electron recoils
→ searched also for DM and solar axions.

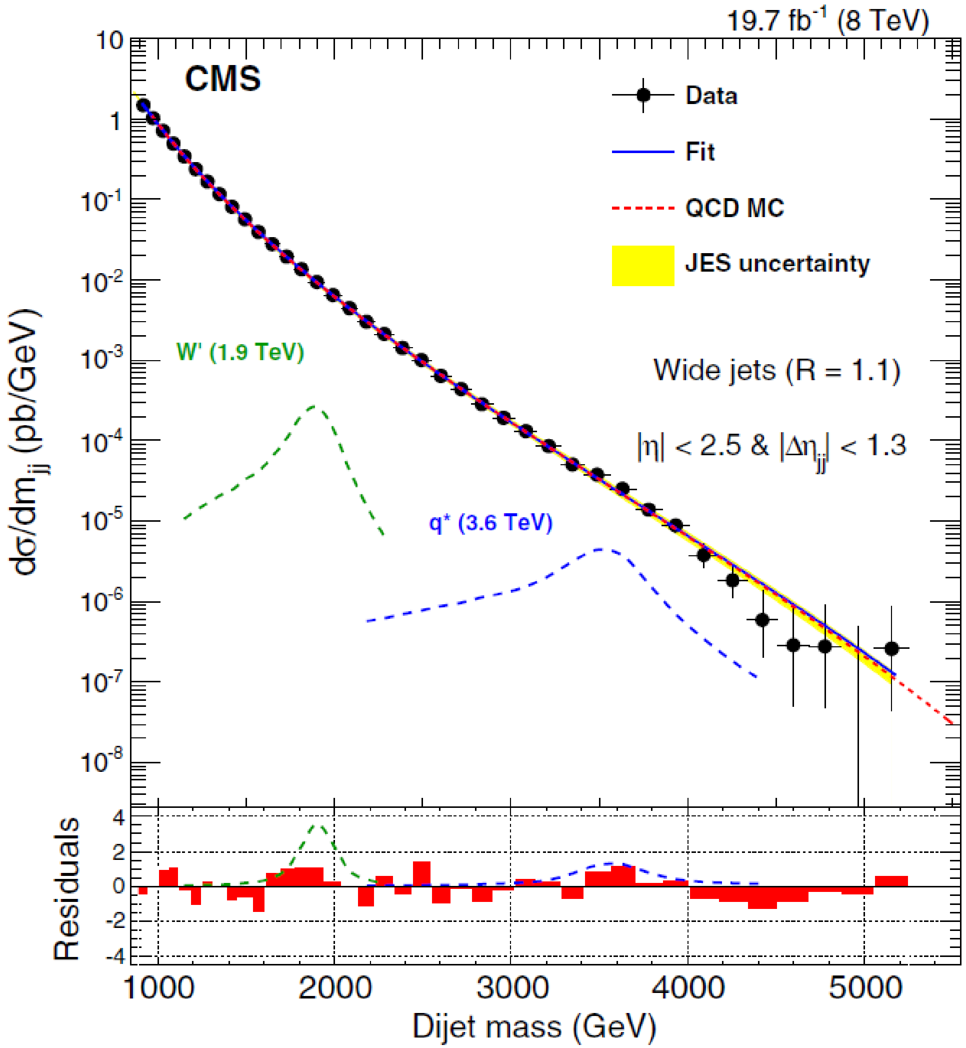
Edelweiss, JCAP 2013, 1311, 067.

Example for direct search for new phenomena: Dijet resonance

Absolute prediction of QCD not required,
only shape of distribution needed
→ perform a "bump hunt"

Nothing found so far! Not in Run 1 or 2, neither with ATLAS nor CMS.



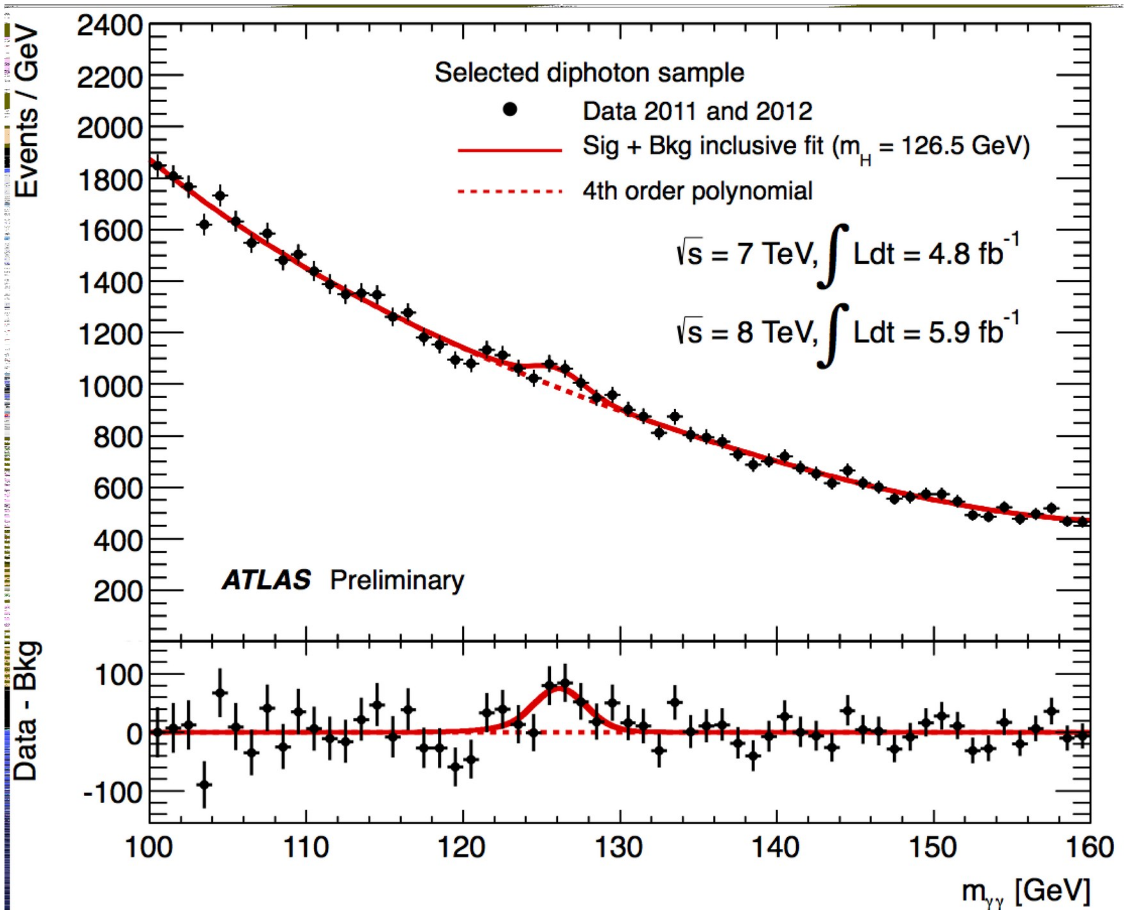


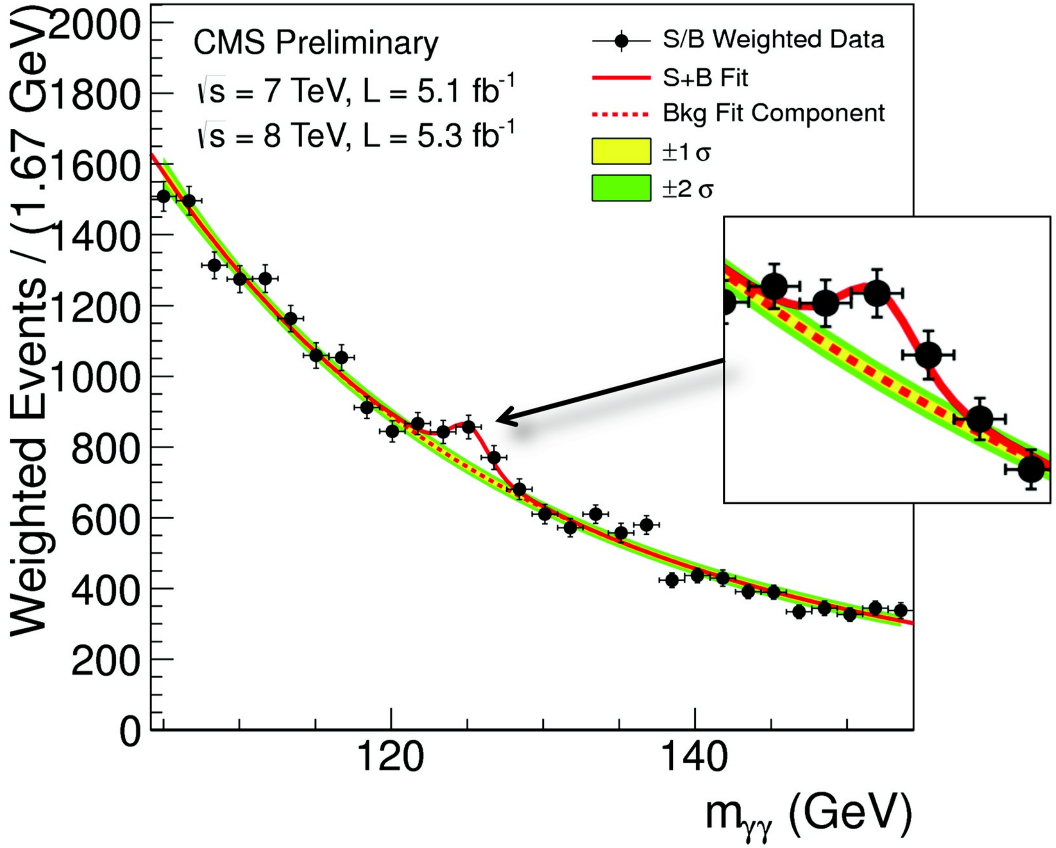
CMS, PR, 2015, D91, 052009.

This direct search was successful ...

Resonance at about 125 GeV ...

In this case in the diphoton mass spectrum ...



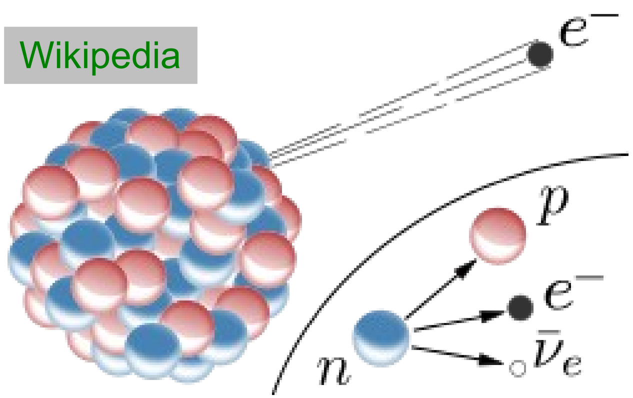


CERN Seminar, 04.07.2012

Recall lecture: Four-fermion coupling

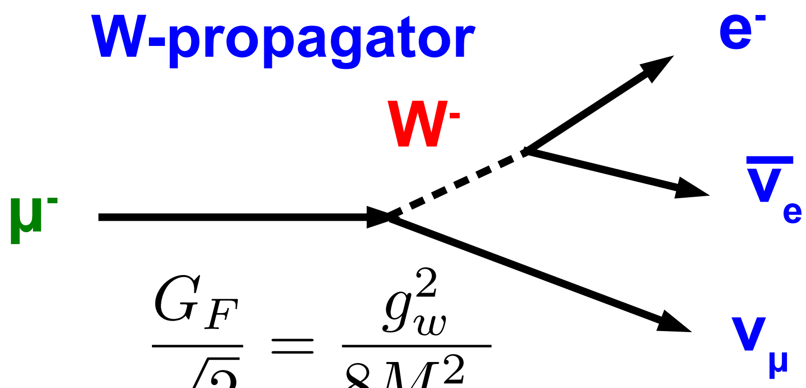
β-decay

Wikipedia



μ-decay

W-propagator



$$\frac{G_F}{\sqrt{2}} = \frac{g_w^2}{8M_W^2}$$

Versuch einer Theorie der β-Strahlen. I[1]).

Von **E. Fermi** in Rom.

Mit 3 Abbildungen. (Eingegangen am 16. Januar 1934.)

Eine quantitative Theorie des β-Zerfalls wird vorgeschlagen, in welcher man die Existenz des Neutrinos annimmt, und die Emission der Elektronen und Neutrinos aus einem Kern beim β-Zerfall mit einer ähnlichen Methode behandelt, wie die Emission eines Lichtquants aus einem angeregten Atom in der Strahlungstheorie. Formeln für die Lebensdauer und für die Form des emittierten kontinuierlichen β-Strahlenspektrums werden abgeleitet und mit der Erfahrung verglichen.

Fermi, Z. Phys., 1934, 88, 16; Nuovo Cim., 1934, 11, 1

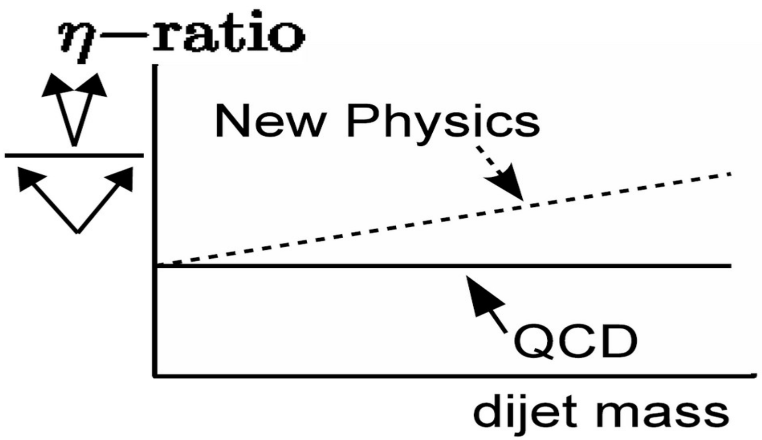
Contact interactions (CI)

Models considering elementary particles as composite:
“Compositeness”, ...

Terazawa, Phys. Rev. D, 1980, 22, 184.
Eichten, Lane, Peskin, Phys. Rev. Lett., 1983, 50, 811,
Baur, Hinchcliffe, Zeppenfeld, Int. J. Mod. Phys. A, 1987, 2, 1285.
Hewett, Rizzo, Phys. Rept., 1989, 183, 193.
Frampton, Glashow, Phys. Lett. B, 1987, 190, 157.
Simmons, Phys. Rev. D, 1997, 55, 1678.
Randall, Sundrum, Phys. Rev. Lett., 1999, 83, 3370.

Approximate low-energy phenomena as contact interaction:

QCD: t-channel scattering ~ Rutherford
New physics: More isotropic!

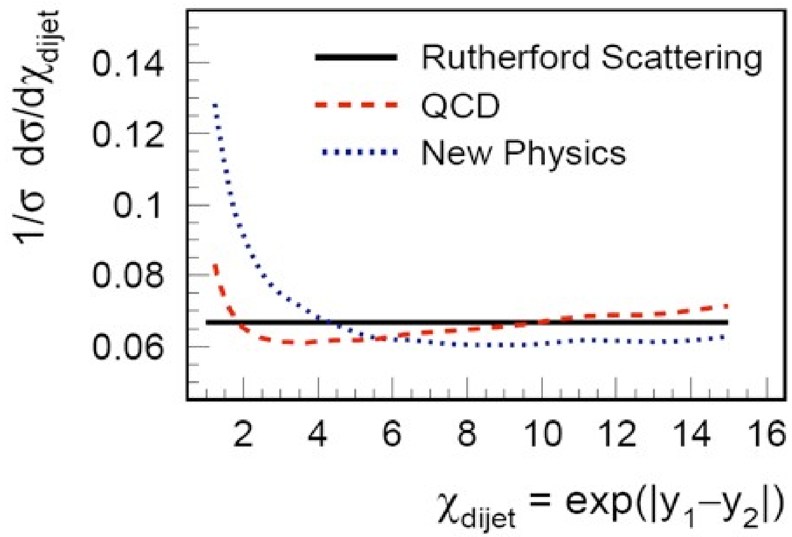


CI addition to SM Lagrangian
(flavour-diagonal, avoids FCNC)

$$\mathcal{L}_{qq} = \frac{g^2}{2\Lambda^2}\left\{\eta_{LL}\left(\bar{q}_L\gamma^\mu q_L\right)\left(\bar{q}_L\gamma_\mu q_L\right) + 2\eta_{LR}\left(\bar{q}_L\gamma^\mu q_L\right)\left(\bar{q}_R\gamma_\mu q_R\right) + \eta_{RR}\left(\bar{q}_R\gamma^\mu q_R\right)\left(\bar{q}_R\gamma_\mu q_R\right)\right\}$$

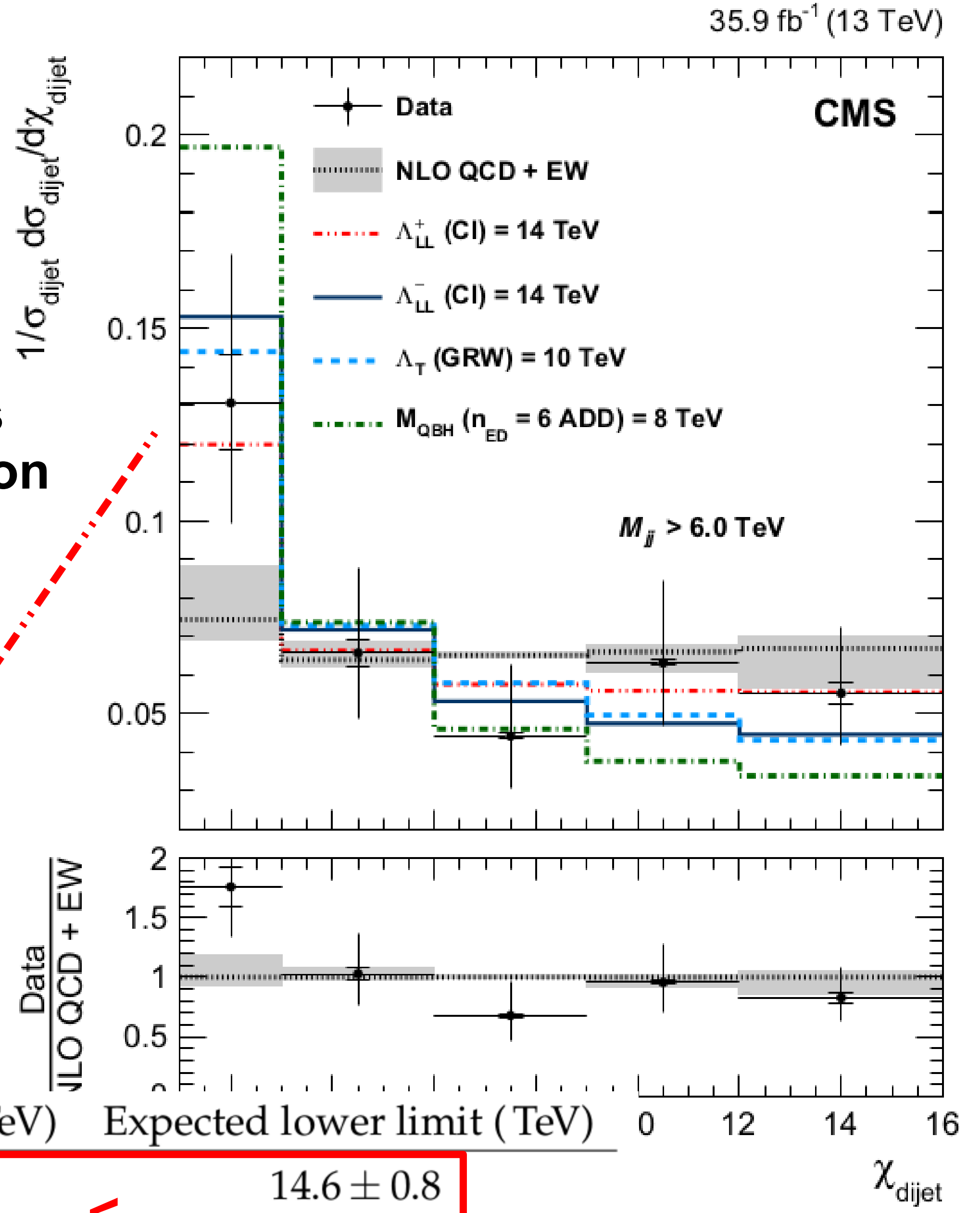
Eichten, Hinchcliffe, Lane, Quigg, Rev. Mod. Phys., 1984, 56, 579.

Indirect search in dijet system



$$\chi = \exp(|\eta_1 - \eta_2|) = \frac{1+|\cos(\hat{\theta})|}{1-|\cos(\hat{\theta})|}$$

Upwards fluctuation



CMS Result 2018:
Compatible with SM only :-(
NLO (QCD + EW) + NLO CI

Observed smaller than expected limits

Model		Observed lower limit (TeV)		Expected lower limit (TeV)
CI	$\Lambda^{+}_{LL/RR}$	12.8	<	14.6 ± 0.8
	$\Lambda^{-}_{LL/RR}$	17.5		23.5 ± 3.0

CMS, EPJC 78 (2018) 789.

To be continued ... SS2021

Teilchenphysik II: Top-Quarks und Jets am LHC

Sommersemester 2021 (4022171)

Institut für Experimentelle Teilchenphysik

Link zur Webseite

- **Teilchenphysik II:**
  - **Top-Quarks und Jets am LHC (N. Jafari, K. Rabbertz)**
  - **W, Z und Higgs an Collidern (R. Wolf)**
- **Moderne Methoden der Datenanalyse (P. Goldenzweig, G. Quast, R. Wolf)**
- **Sowie ggf. Theorie, Astroteilchenphysik, Beschleunigerphysik, ...**

To be continued … SS2021

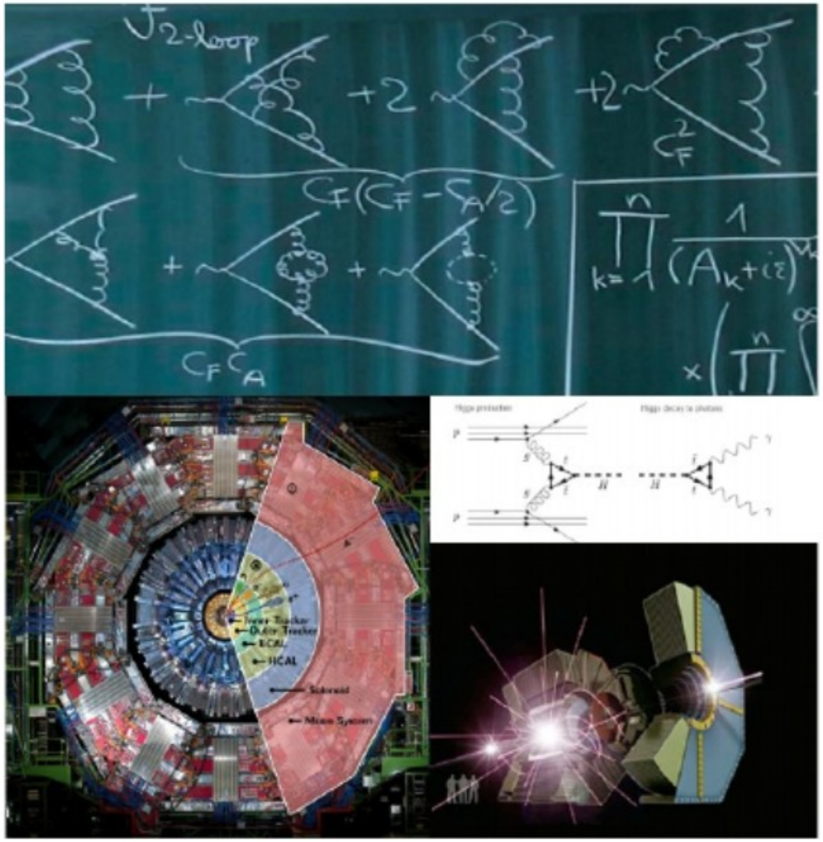
Hauptseminar

„Experimentelle und Theoretische Methoden der Teilchenphysik "

Prof. Dr. G. Heinrich, Prof. Dr. G. Quast, Dr. S. Gieseke

Mi. 16:00-17:30, Geb. 30.23, Raum 12-1

als Blockseminar am Ende des Semesters



- **Themengebiete:**
  - **Beschleuniger & Teilchendetektoren**
  - **Monte-Carlo-Simulation und Statistische Datenanalyse**
  - **Eichtheorien und Higgs-Mechanismus**
  - **Neue Ergebnisse vom Large-Hadron-Collider am CERN**
  - **Suche nach Physik jenseits des Standardmodells**
- **Vorbesprechung: Mi, 14.04.2021**
- **Anmeldung über ILIAS erforderlich**

Collider-Physik am ETP

- **CMS: Collider-Physik bei den höchsten Energien am LHC**
  - **Physikanalyse:**
    - **Präzisionsmessungen zu QCD, Top, W/Z**
    - **Higgs-Eigenschaften**
    - **Suche nach Abweichungen und neuer Physik (DM, ...)**
  - **Siliziumdetektoren**
  - **Grid-Computing**
- **Belle/Belle II: B-Physik and der Y(4S)-Resonanz**
  - **Analyse der Belle-Daten: CP-Verletzung im B-System**
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