# The Future of Particle Physics

*"…the direct method may be used…but indirect methods will be needed in order to secure victory…."*

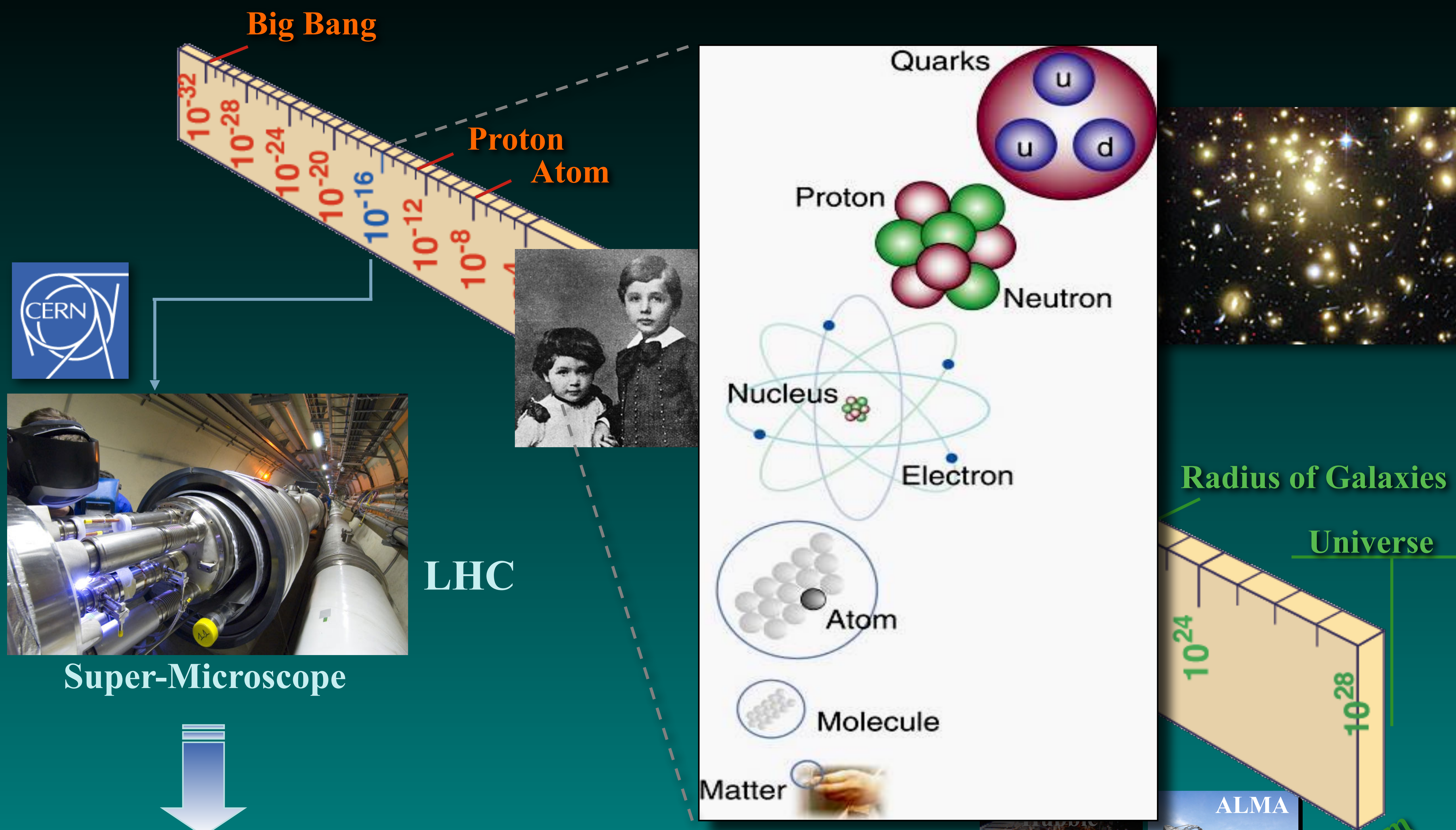
*"The direct and the indirect lead on to each other in turn. It is like moving in a circle…."*

*Who can exhaust the possibilities of their combination?"*

**Sun Tzu, *The Art of War***


*ohn Ellis*

KING'S College LONDON

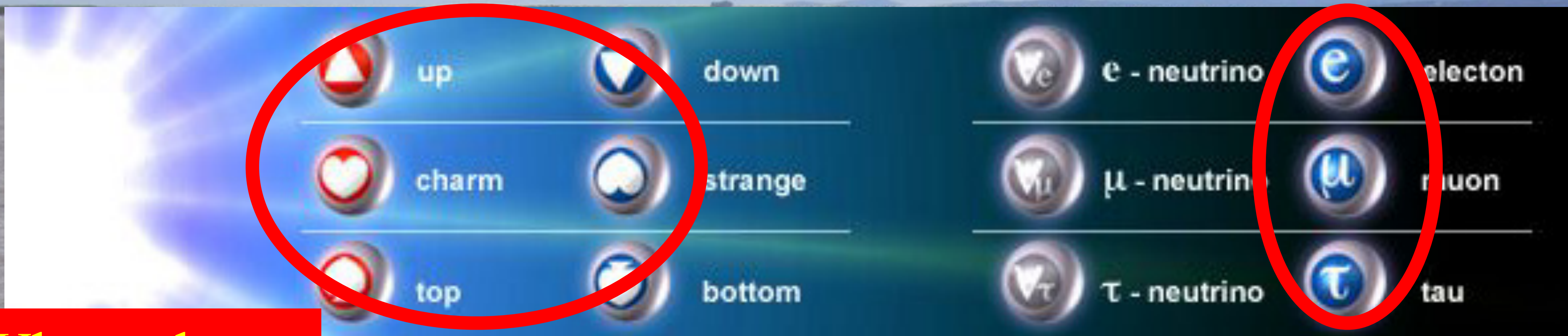




Study physics laws of first moments after Big Bang increasing Symbiosis between Particle Physics, Astrophysics and Cosmology

# The ‘Standard Model’

## The matter particles




Where does mass come from?

## The fundamental interactions

Gravitation electromagnetism weak nuclear force strong nuclear force

# Why do Things Weigh?

Newton:

Weight proportional to Mass

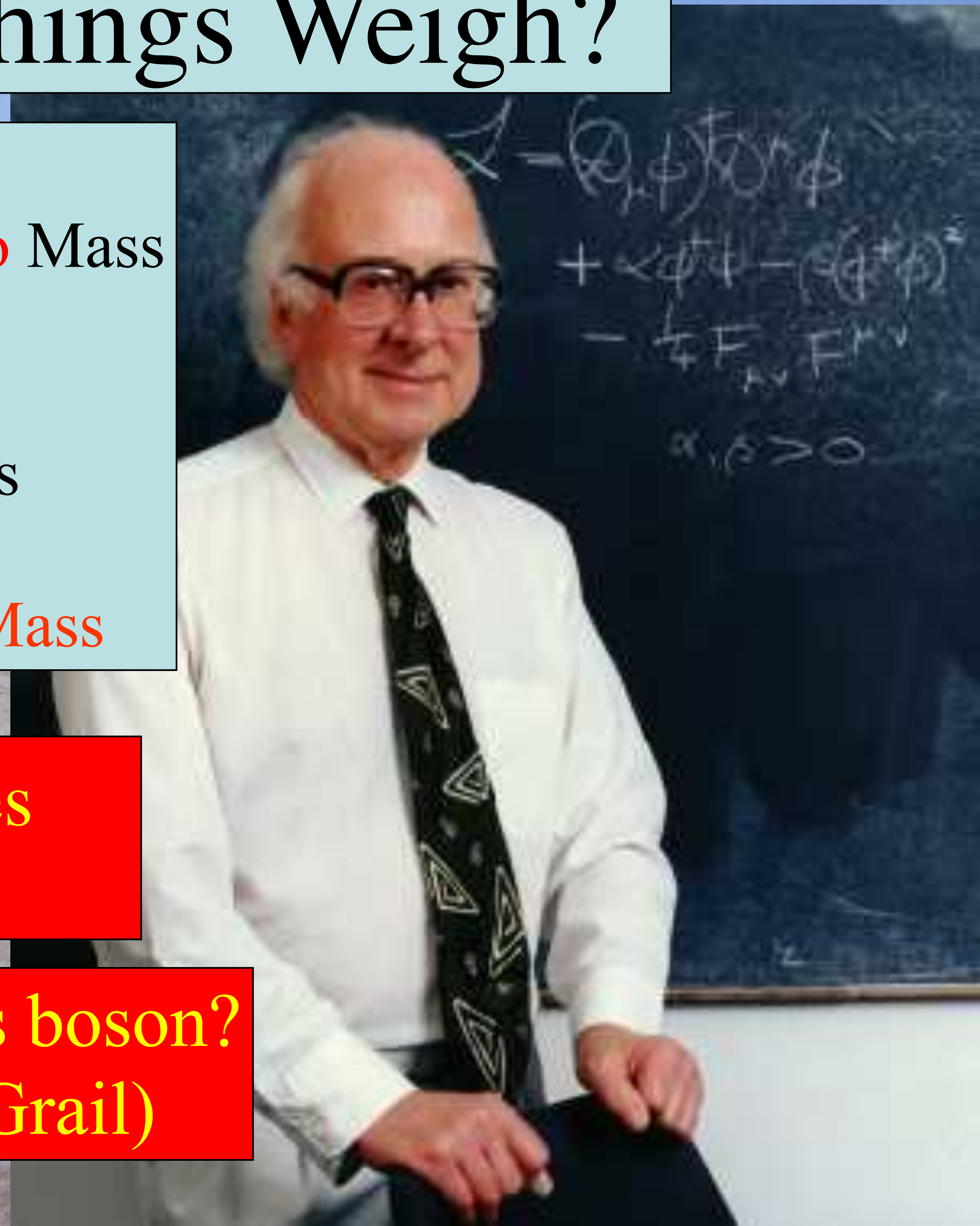
Einstein:

Energy related to Mass

Neither explained origin of Mass

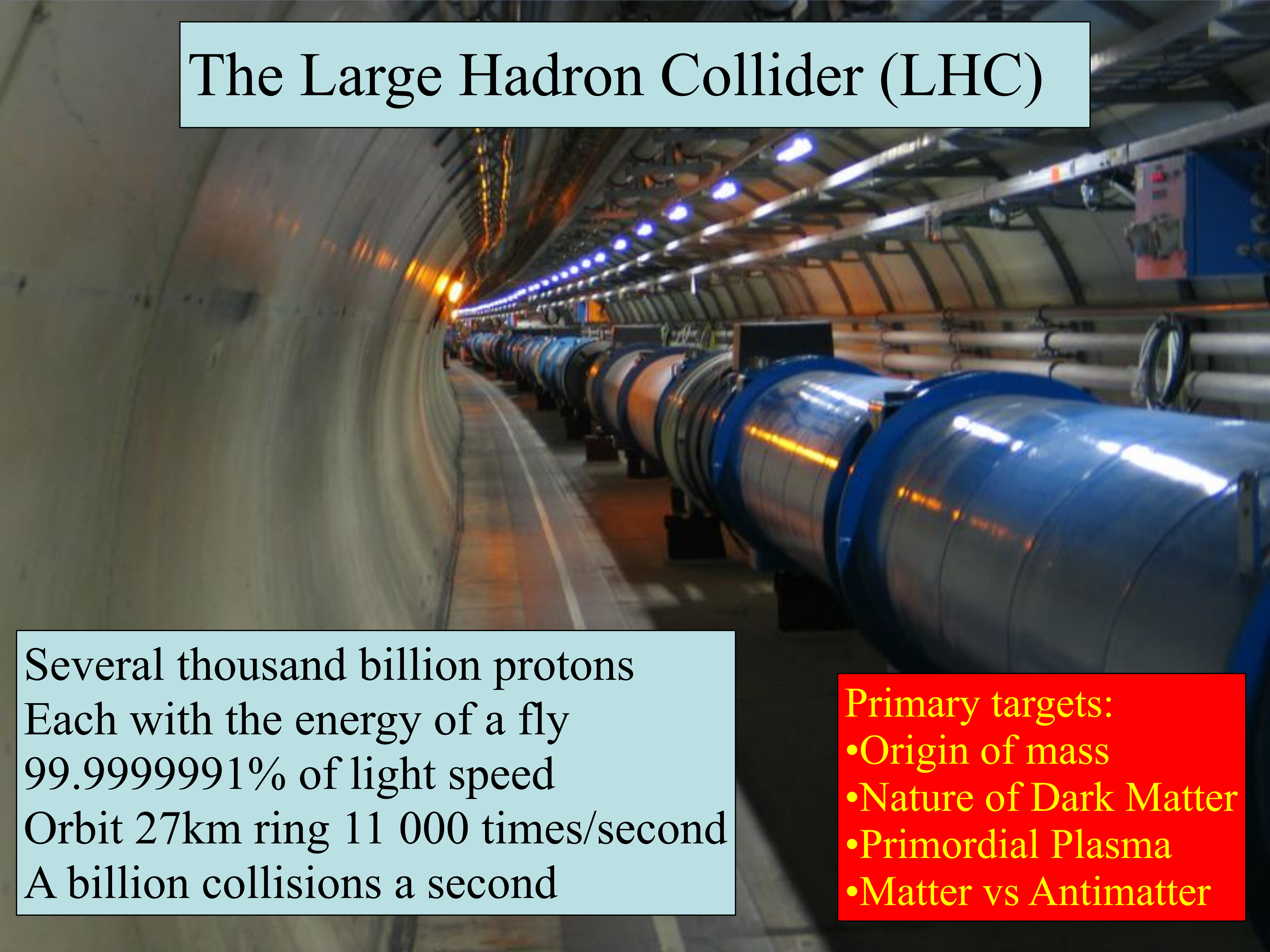
Where do the masses come from ?

Are masses due to Higgs boson?
(the physicists' Holy Grail)



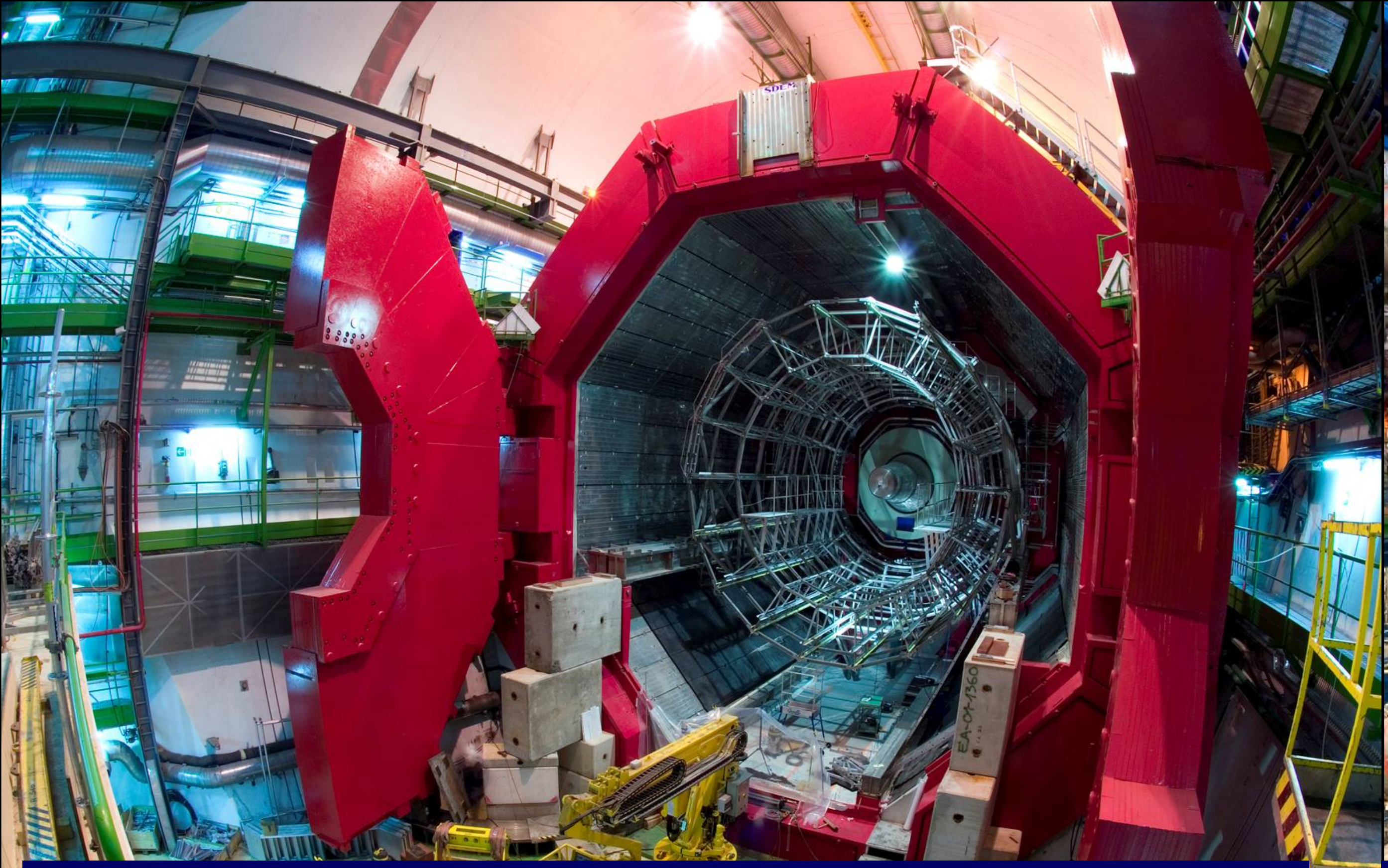
# The Large Hadron Collider at CERN

# The Large Hadron Collider (LHC)

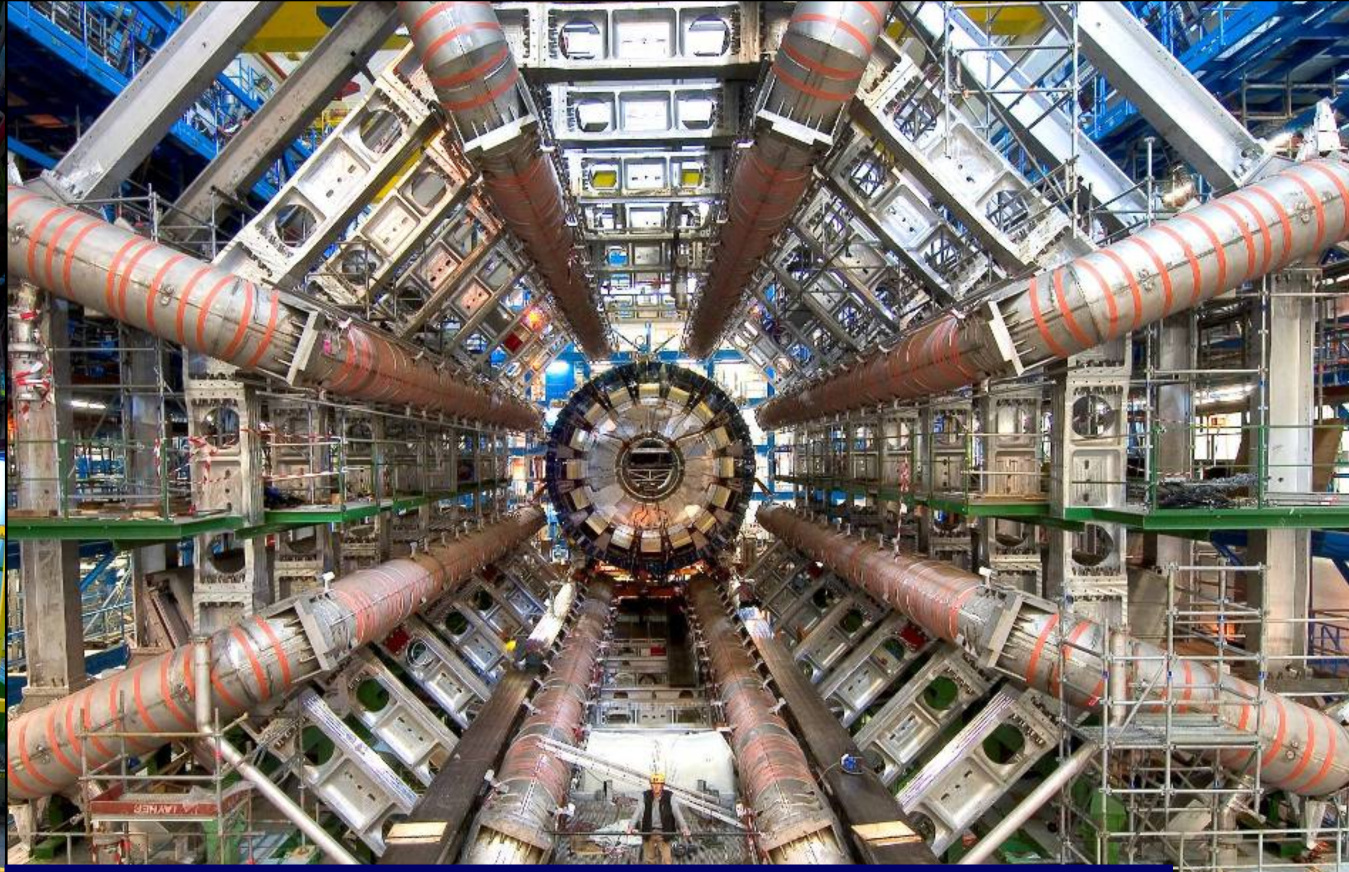


Several thousand billion protons
Each with the energy of a fly
99.9999991% of light speed
Orbit 27km ring 11 000 times/second
A billion collisions a second

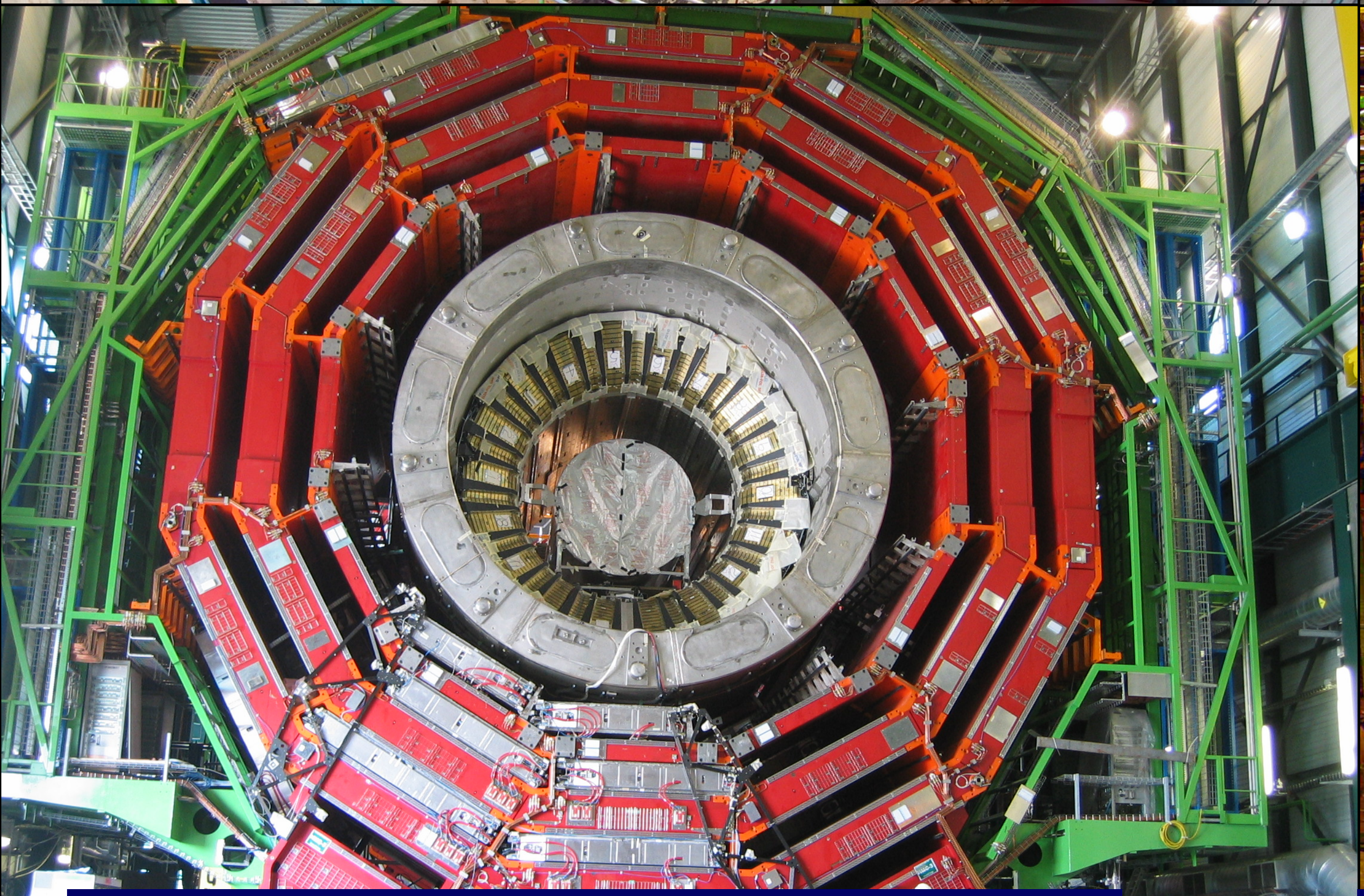
Primary targets:
- Origin of mass
- Nature of Dark Matter
- Primordial Plasma
- Matter vs Antimatter



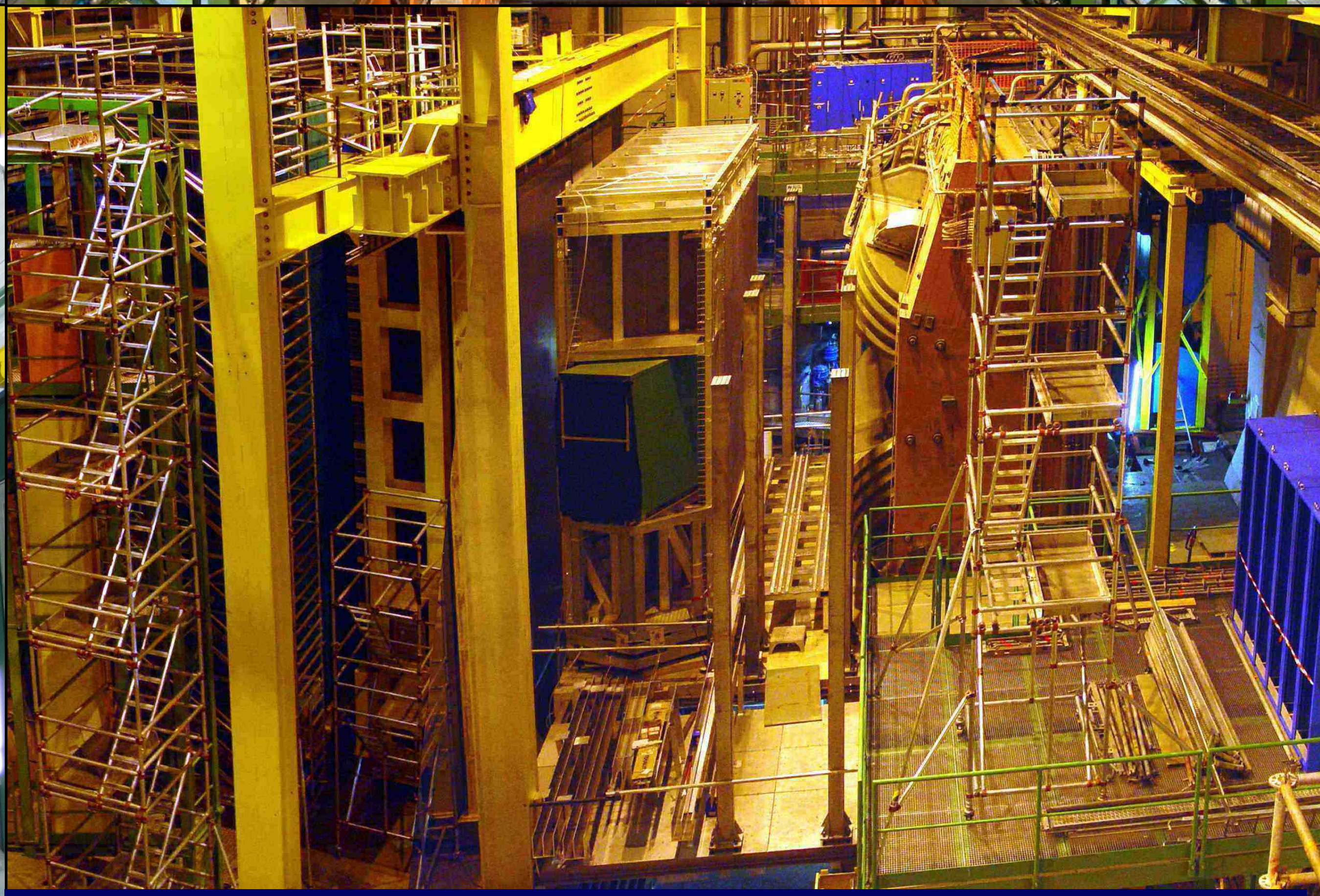
ALICE: Primordial cosmic plasma



ATLAS: Higgs and dark matter

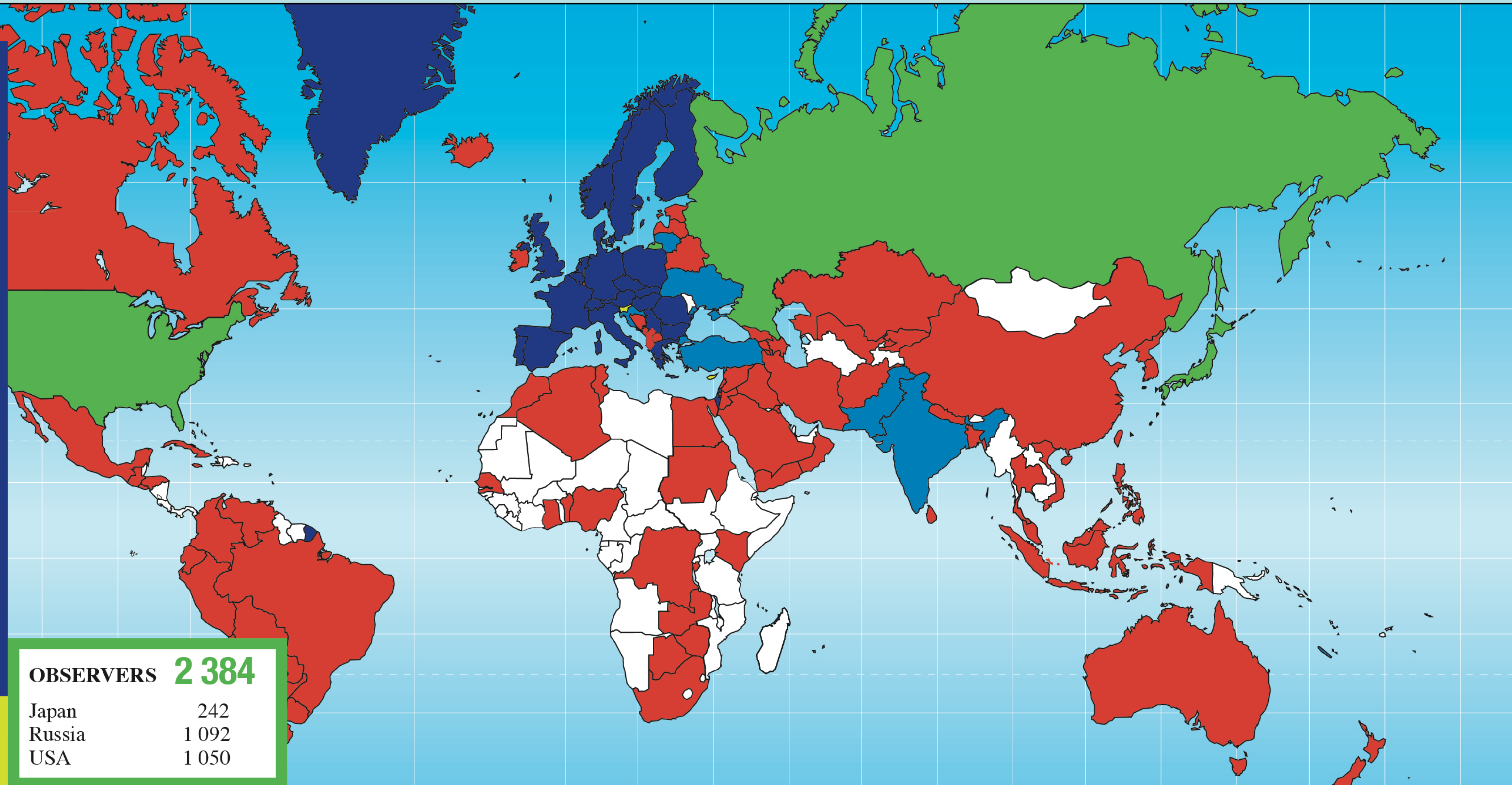


CMS: Higgs and dark matter



LHCb: Matter-antimatter difference

# Scientists from around the World



| MEMBER STATES | 6 951 |
|---|---|
| Austria | 95 |
| Belgium | 108 |
| Bulgaria | 68 |
| Czech Republic | 207 |
| Denmark | 43 |
| Finland | 76 |
| France | 772 |
| Germany | 1 [illegible] |
| Greece | 212 |
| Hungary | [illegible] |
| Israel | 54 |
| Italy | 1 806 |
| Netherlands | 157 |
| Norway | 56 |
| Poland | 303 |
| Portugal | 90 |
| Romania | 135 |
| Serbia | 46 |
| Slovakia | 119 |
| Spain | 403 |
| Sweden | 70 |
| Switzerland | 204 |
| United Kingdom | 703 |

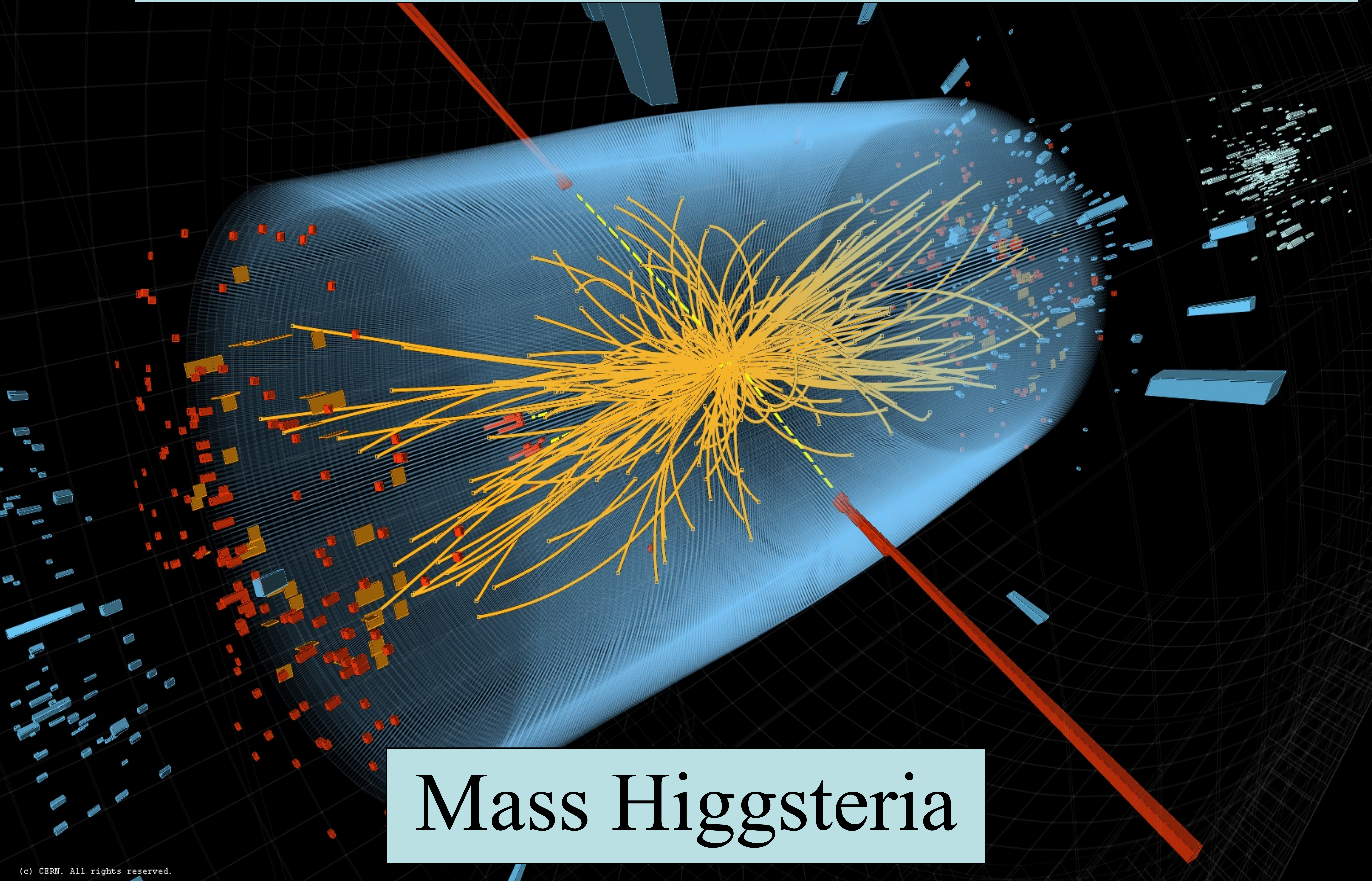
| ASSOCIATE MEMBERS IN THE PRE-STAGE TO MEMBERSHIP | 52 |
|---|---|
| Cyprus | 19 |
| Slovenia | 33 |

| ASSOCIATE MEMBERS | 728 |
|---|---|
| Croatia | 44 |
| India | 351 |
| Lithuania | 24 |
| Pakistan | 60 |
| Turkey | 161 |
| Ukraine | 88 |

| OBSERVERS | 2 384 |
|---|---|
| Japan | 242 |
| Russia | 1 092 |
| USA | 1 050 |

| OTHERS | 1 750 |
|---|---|
| Albania | 2 |
| Algeria | 9 |
| Argentina | 21 |
| Armenia | 14 |
| Australia | 28 |
| Azerbaijan | 6 |
| Bahrain | 2 |
| Bangladesh | 6 |
| Belarus | 50 |
| Benin | 1 |
| Bolivia | 2 |
| Bosnia & Herzegovina | 3 |
| Bostwana | 1 |
| Brazil | 117 |
| Burundi | 1 |
| Canada | 147 |
| Chile | 22 |
| China | 548 |
| Colombia | 34 |
| Congo | 1 |
| Cuba | 15 |
| Ecuador | 9 |
| Egypt | 24 |
| El Salvador | 1 |
| Estonia | 14 |
| Georgia | 53 |
| Ghana | 1 |
| Gibraltar | 1 |
| Guatemala | 2 |
| Hong Kong | 2 |
| Honduras | 1 |
| Iceland | 5 |
| Indonesia | 10 |
| Iran | 50 |
| Iraq | 1 |
| Ireland | 16 |
| Jamaica | 1 |
| Jordan | 3 |
| Kazakhstan | 10 |
| Kenya | 1 |
| Korea | 148 |
| Kosovo | 1 |
| Kyrgyzstan | 1 |
| Latvia | 7 |
| Lebanon | 23 |
| Luxembourg | 3 |
| Malaysia | 16 |
| Malta | 5 |
| Mexico | 77 |
| Montenegro | 8 |
| Morocco | 27 |
| Nepal | 8 |
| New Zealand | 6 |
| Nigeria | 2 |
| North Korea | 3 |
| North Macedonia | 2 |
| Oman | 1 |
| Palestine | 7 |
| Paraguay | 1 |
| Peru | 7 |
| Philippines | 4 |
| Saint Kitts and Nevis | 1 |
| Saudi Arabia | 2 |
| Senegal | 1 |
| Singapore | 4 |
| South Africa | 45 |
| Sri Lanka | 6 |
| Sudan | 1 |
| Syria | 3 |
| Taiwan | 41 |
| Thailand | 22 |
| Tunisia | 6 |
| Uruguay | 1 |
| Uzbekistan | 3 |
| Venezuela | 9 |
| Viet Nam | 9 |
| Yemen | 1 |
| Zambia | 1 |
| Zimbabwe | 2 |

# 2012: The Discovery of the Higgs Boson





# Mass Higgsteria

# Higgsdependence Day!

*…to make an end is to make a beginning.*

*The end is where we start from.*

T.S. Eliot, *Little Gidding*

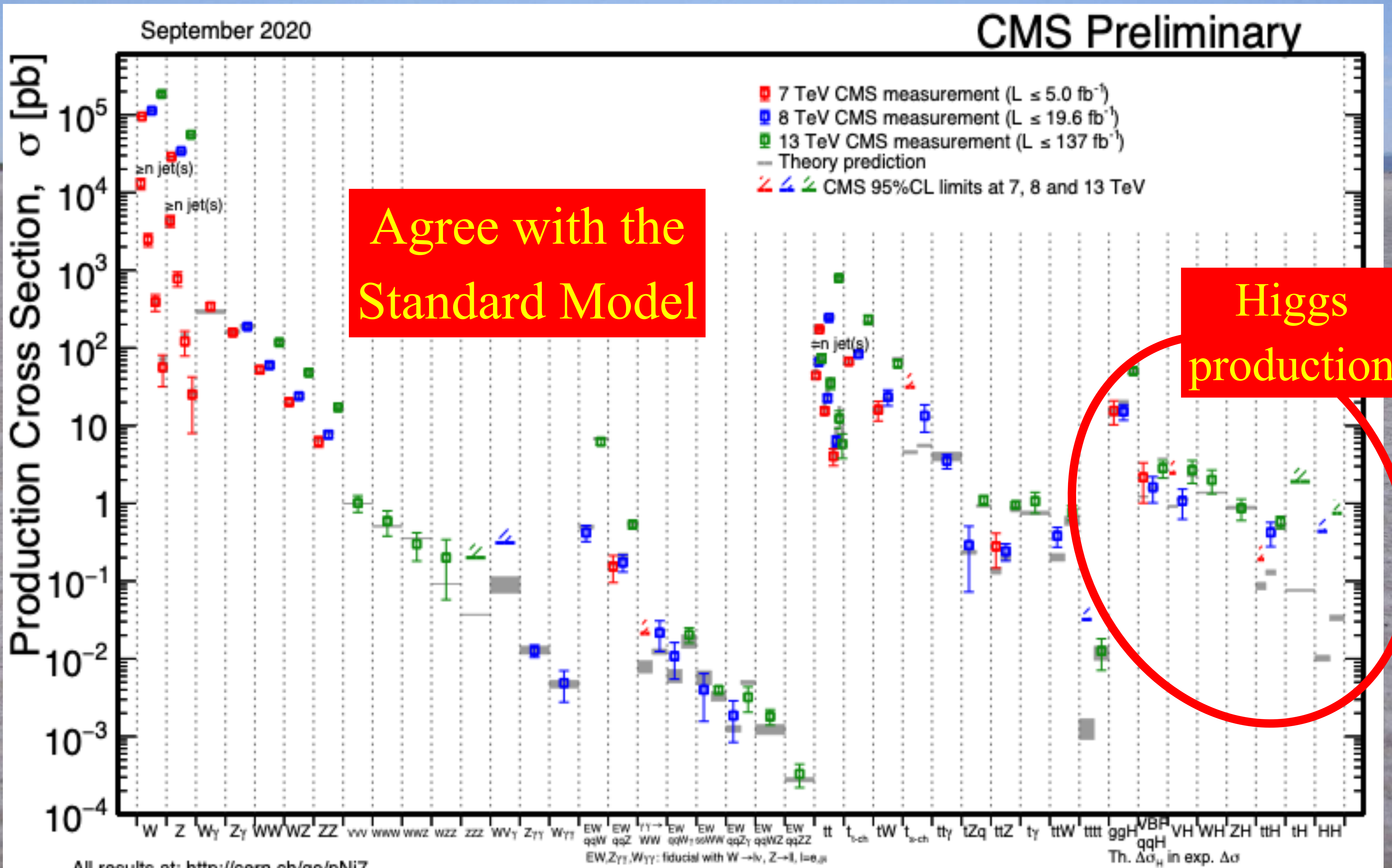
# The Particle Higgsaw Puzzle

Has LHC found the missing piece?

Is it the right shape?

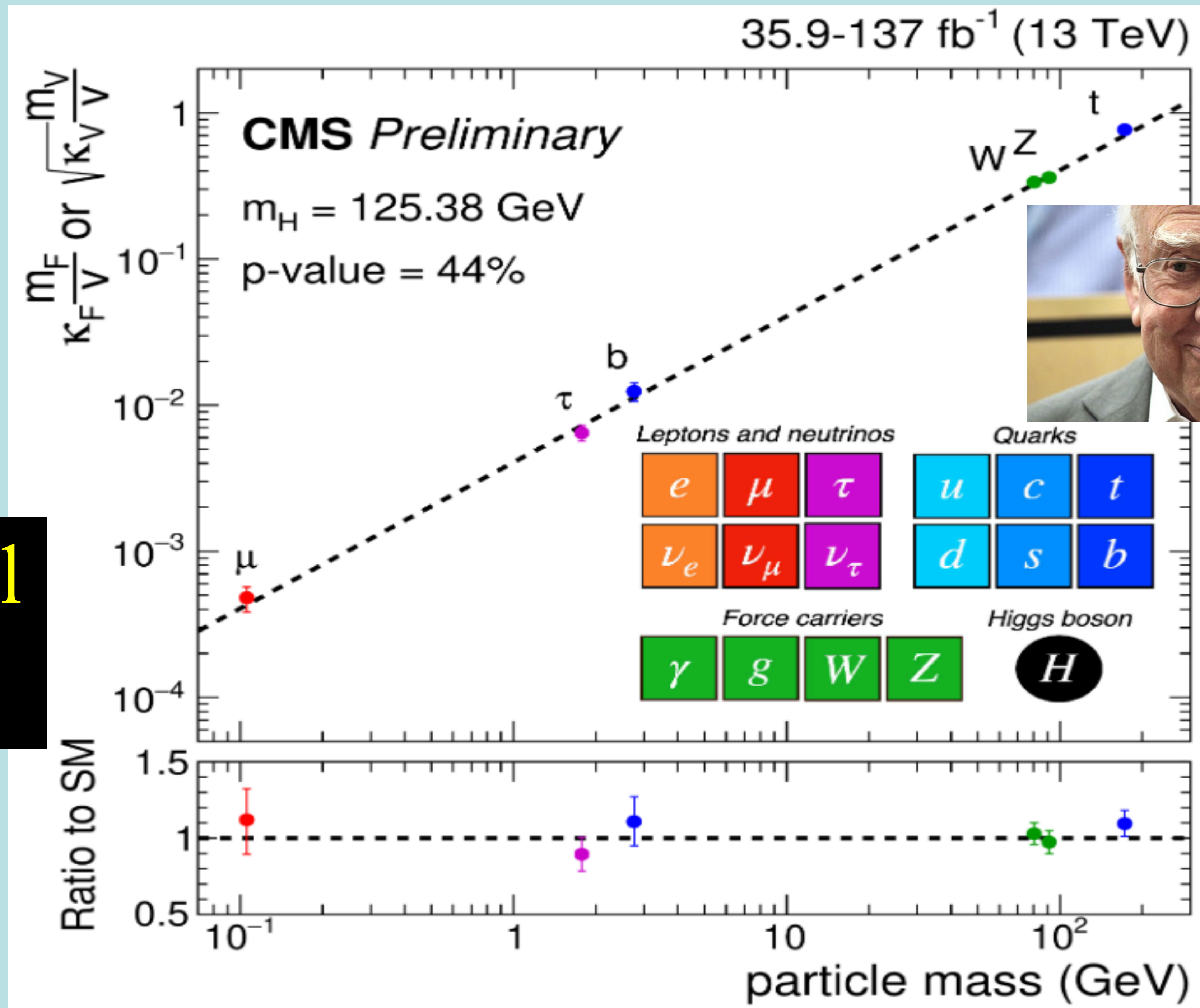
Is it the right size?

# LHC Measurements



# It Walks and Quacks like a Higgs

- Do couplings scale ~ mass? With scale = v?




Global fit

BUT

# Everything about Higgs is Puzzling

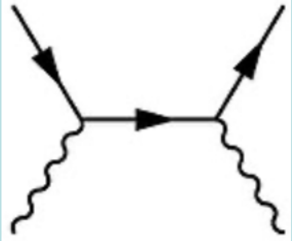
$$\mathcal{L} = yH\psi\overline{\psi} + \mu^2|H|^2 - \lambda|H|^4 - V_0$$ + …

- Pattern of Yukawa couplings y:
  - **Flavour problem**
- Magnitude of mass term μ:
  - **Naturalness/hierarchy problem**
- Magnitude of quartic coupling λ:
  - **Stability of electroweak vacuum**
- Cosmological constant term $V_0$:
  - **Dark energy**

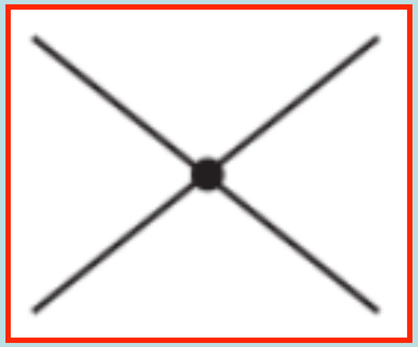
Higher-dimensional interactions?

# Effective Field Theories (EFTs)
## a long and glorious History

- 1930's: "Standard Model" of QED had d=4

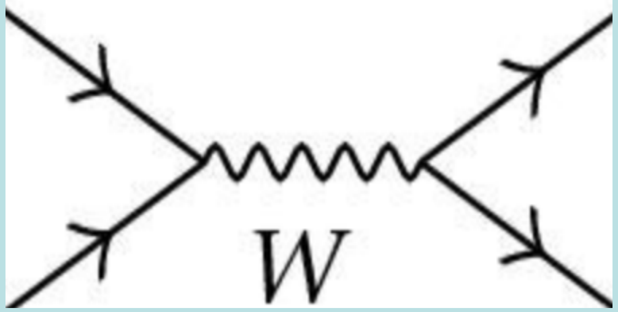


- **Fermi's four-fermion theory of the weak force**

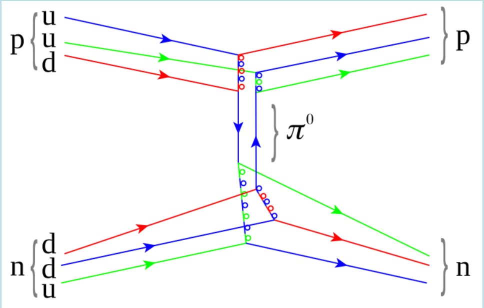


- Dimension-6 operators: form = S, P, V, A, T?
  - Due to exchanges of massive particles?

- V-A ➔ massive vector bosons ➔ gauge theory



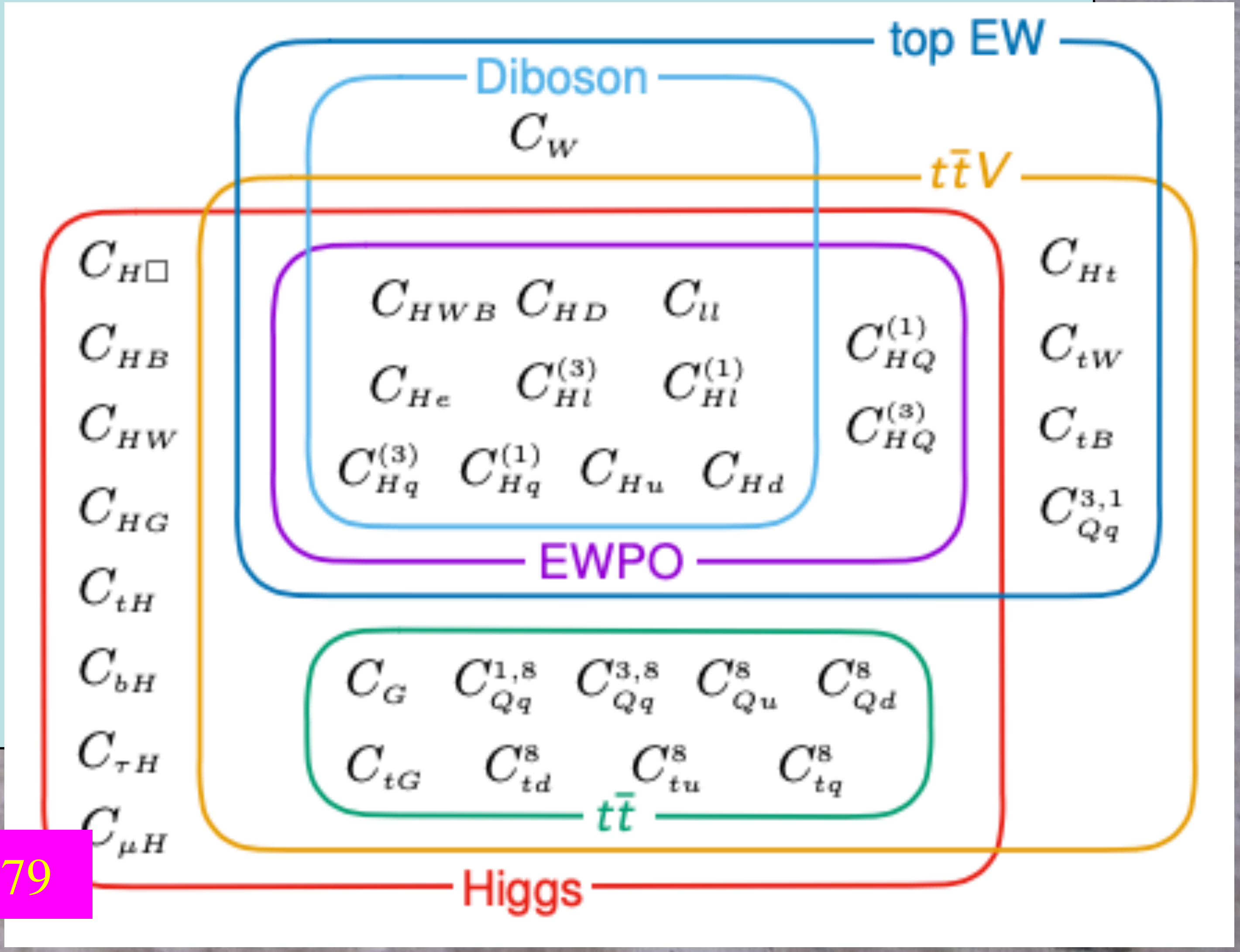

- Yukawa's meson theory of the strong N-N force
  - Due to exchanges of mesons? ➔ pions




- Chiral dynamics of pions: $(\partial\pi\partial\pi)\pi\pi$ clue ➔ QCD

# Global SMEFT Fit
## to Top, Higgs, Diboson, Electroweak Data

- Global fit to dimension-6 operators using precision electroweak data, $W^+W^-$ at LEP, top, Higgs and diboson data from LHC Runs 1 and 2
- Search for BSM
- Constraints on BSM
  - At tree level
  - At loop level




JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

# Data included in Global Fit

| EW precision observables | | Ref. |
|---|---|---|
| Precision electroweak measurem… | | |
| $\Gamma_Z$, $\sigma^0_{\mathrm{had.}}$, $R^0_\ell$, $A^\ell_{FB}$, $A_\ell$(SLD), A… | | |
| Combination of CDF and D0 W… | | |
| LHC run 1 W boson mass meas… | | |

| Diboson LEP & LHC |
|---|
| $W^+W^-$ angular distribution me… |
| $W^+W^-$ total cross section meas… final states for 8 energies |
| $W^+W^-$ total cross section meas… $qqqq$ final states for 7 energies |
| $W^+W^-$ total cross section mea… & $qqqq$ final states for 8 energies |
| ATLAS $W^+W^-$ differential cr… $p_T > 120$ GeV overflow bin |
| ATLAS $W^+W^-$ fiducial differe… $\frac{d\sigma}{dp^T_{\ell_1}}$ |
| ATLAS $W^\pm Z$ fiducial differential cross section in the $\ell^+$… $\frac{d\sigma}{dp^T_Z}$ |
| CMS $W^\pm Z$ normalised fiducial differential cross section… channel, $\frac{1}{\sigma}\frac{d\sigma}{dp^T_Z}$ |
| ATLAS $Zjj$ fiducial differential cross section in the $\ell^+\ell^-$… |

| LHC Run 1 Higgs |
|---|
| ATLAS and CMS LHC Run 1 combination of Higgs sig… Production: $ggF$, $VBF$, $ZH$, $WH$ & $ttH$ Decay: $\gamma\gamma$, $ZZ$, $W^+W^-$, $\tau^+\tau^-$ & $b\bar{b}$ |
| ATLAS inclusive $Z\gamma$ signal strength measurement |

| LHC Run 2 Higgs … |
|---|
| ATLAS combination … including ratios of bra… |
| Signal strengths\|coars… |
| CMS LHC combinatio… Production: $ggF$, $VB$… Decay: $\gamma\gamma$, $ZZ$, $W^+W$… |
| CMS stage 1.0 STXS … 13 parameter fit \| 7 pa… |
| CMS stage 1.0 STXS… |
| CMS stage 1.1 STXS… |
| CMS differential cross… tion in the $WW^* \to \ell$… $\frac{d\sigma}{dn_{\mathrm{jet}}}$ \| $\frac{d\sigma}{dp^T_H}$ |
| ATLAS $H \to Z\gamma$ sign… |
| ATLAS $H \to \mu^+\mu^-$ si… |

| Tevatron & Run 1 top | $n_{\mathrm{obs}}$ | Ref. |
|---|---|---|
| Tevatron combination of differential $t\bar{t}$ forward-backward asymmetry, $A_{FB}(m_{t\bar{t}})$. | 4 | [7] |
| ATLA… $\frac{d\sigma}{dm_{t\bar{t}}}$ | | |
| ATLA… $\frac{d\sigma}{dm_{t\bar{t}}}$ | | |
| CMS… $\frac{d\sigma}{dm_{t\bar{t}}}$ | | |
| CMS… dilept… | | |
| ATLA… dilept… | | |
| ATLA… $A_C(m$… | | |
| CMS… $\frac{d\sigma}{dm_{t\bar{t}}dy}$ | | |
| ATLA… decay. | | |
| ATLA… $f_0$, $f_L$ | | |
| CMS… $f_0$, $f_L$ | | |
| ATLA… | | |
| CMS… | | |
| ATLA… $\frac{d\sigma}{dp^T_t}$ | | |
| CMS… | | |
| CMS… $\frac{d\sigma}{dp^T_{t+\bar{t}}}$ | | |
| CMS… $\sigma_t \| \sigma_{\bar{t}} \| \sigma_{t+\bar{t}} \| R_t$. | | |
| ATLAS $s$-channel single-top cross section measurement. | | |
| CMS $tW$ cross section measurement. | 1 | [33] |
| ATLAS $tW$ cross section measurement in the single lepton channel | 1 | [34] |
| ATLAS $tW$ cross section measuremen… | | |

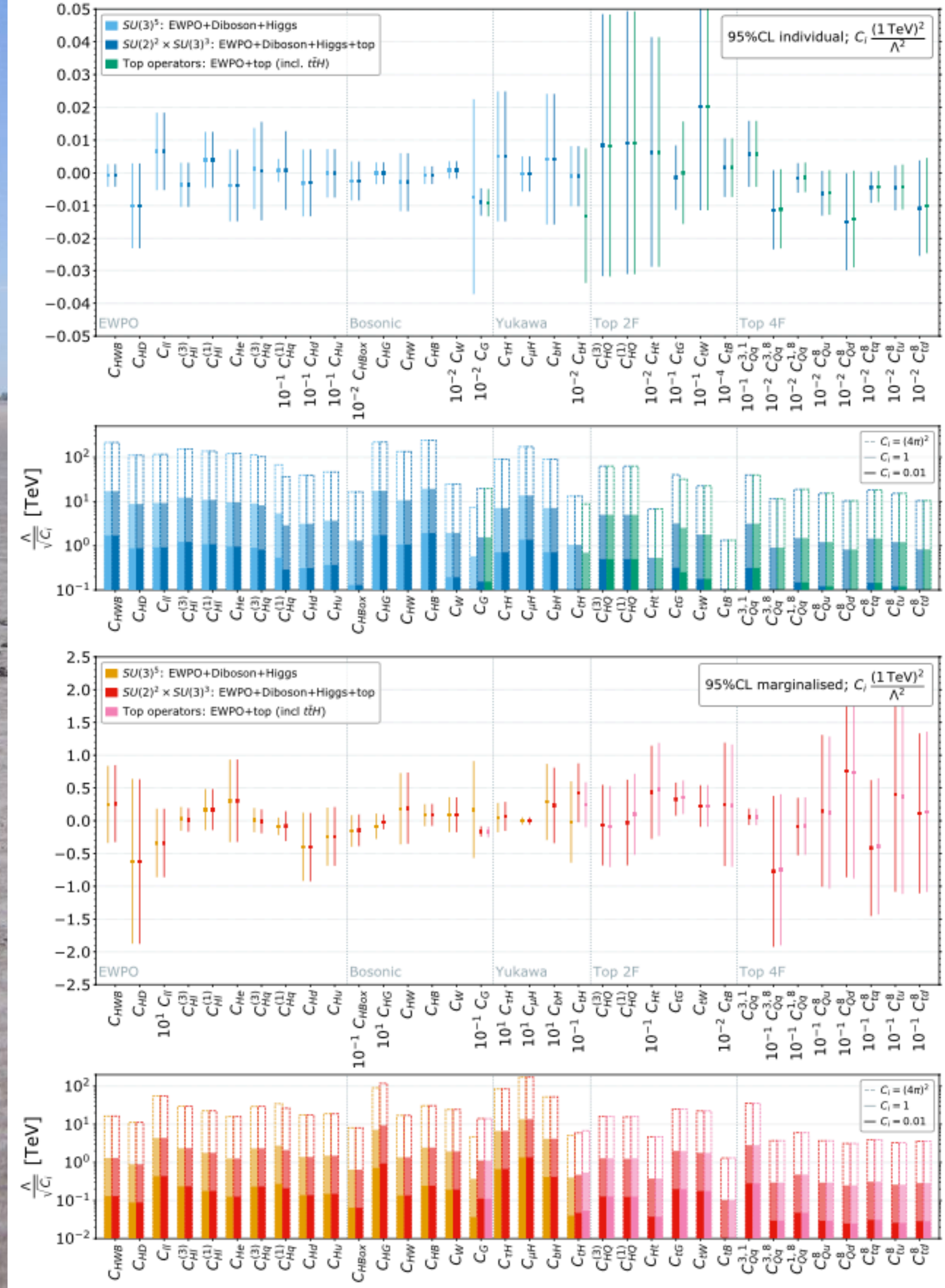
| Run 2 top | $n_{\mathrm{obs}}$ | Ref. |
|---|---|---|
| CMS $t\bar{t}$ differential distributions in the dilepton channel. $\frac{d\sigma}{dm_{t\bar{t}}}$ | 6 | [36, 231] |
| CMS $t\bar{t}$ differential distributions in the $\ell$+jets channel. $\frac{d\sigma}{dm_{t\bar{t}}}$ | 10 | [37] |
| ATLAS measurement of differential $t\bar{t}$ charge asymmetry, $A_C(m_{t\bar{t}})$. | 5 | [38] |
| ATLAS $t\bar{t}W$ & $t\bar{t}Z$ cross section measurements. $\sigma_{t\bar{t}W} \| \sigma_{t\bar{t}Z}$ | 2 | [39] |
| CMS $t\bar{t}W$ & $t\bar{t}Z$ cross section measurements. $\sigma_{t\bar{t}W} \| \sigma_{t\bar{t}Z}$ | 1\|1 | [40] |
| CMS $t\bar{t}Z$ differential distributions. $\frac{d\sigma}{dp^T_Z}$ \| $\frac{d\sigma}{d\cos\theta^*}$ | 4\|4 | [41] |
| CMS measurement of differential cross sections and charge ratios for $t$-channel single-top quark production. $\frac{d\sigma}{dp^T_{t+\bar{t}}}$ \| $R_t\,(p^T_{t+\bar{t}})$ | 5\|5 | [42] |
| CMS measurement of $t$-channel single-top and anti-top cross sections. $\sigma_t$, $\sigma_{\bar{t}}$, $\sigma_{t+\bar{t}}$ & $R_t$. | 4 | [43] |
| CMS measurement of the $t$-channel single-top and anti-top cross sections. $\sigma_t \| \sigma_{\bar{t}} \| \sigma_{t+\bar{t}} \| R_t$. | 1\|1\|1\|1 | [44] |
| CMS $t$-channel single-top differential distributions. $\frac{d\sigma}{dp^T_{t+\bar{t}}}$ \| $\frac{d\sigma}{d\|y_{t+\bar{t}}\|}$ | 4\|4 | [45] |
| ATLAS $tW$ cross section measurement. | | |
| CMS $tZ$ cross section measurement. | | |
| CMS $tW$ cross section measurement. | | |
| ATLAS $tZ$ cross section measurement. | | |
| CMS $tZ$ ($Z \to \ell^+\ell^-$) cross section measurement | | |

**328 measurements included in global analysis**

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

# Dimension-6 Constraints with Top-Specific $SU(2)^2 \times SU(3)^3$

- **Individual operator coefficients**
- **Marginalised over all other operator coefficients**
- **New Physics $\gtrsim$ TeV scale**

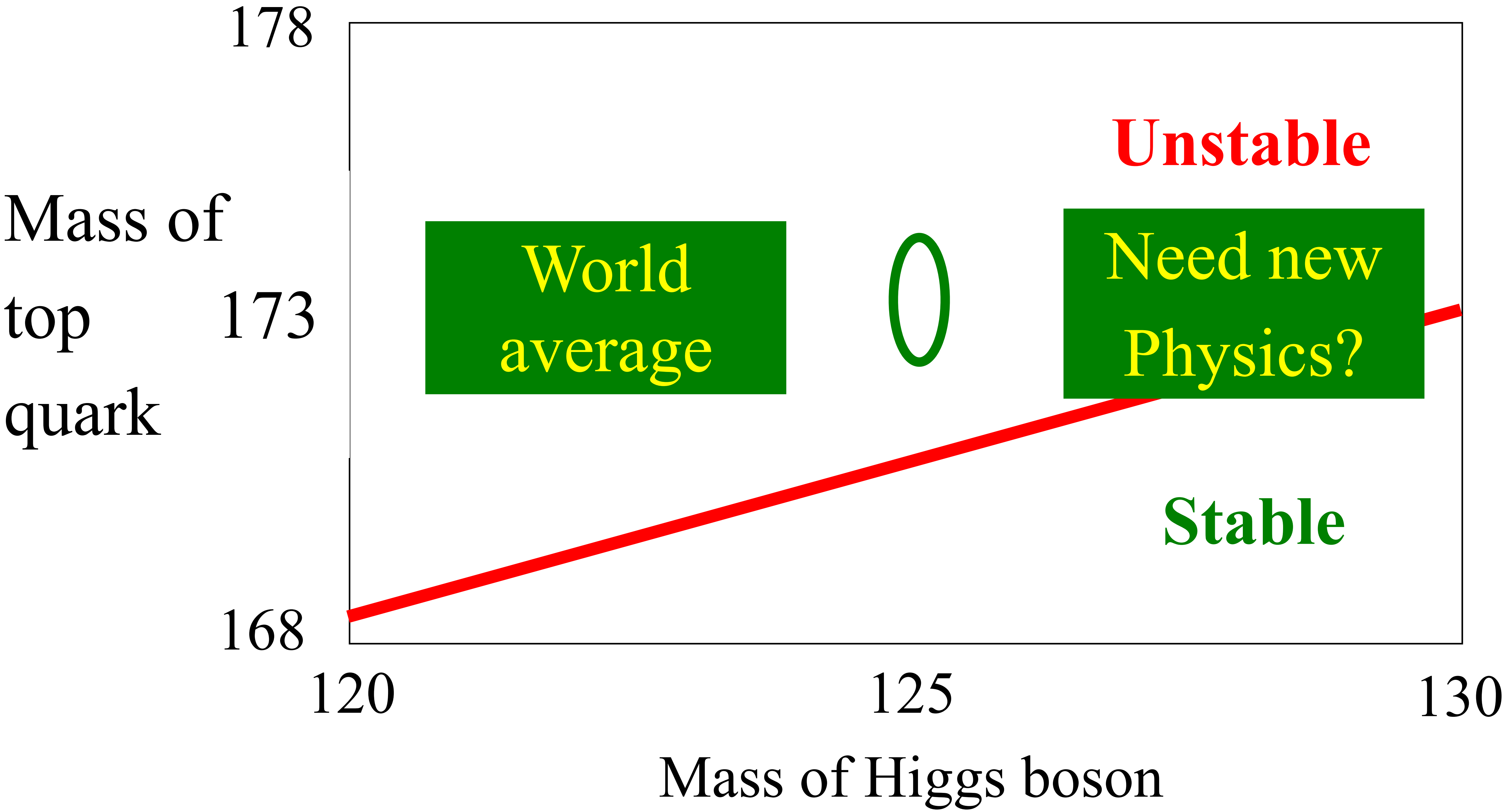



JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

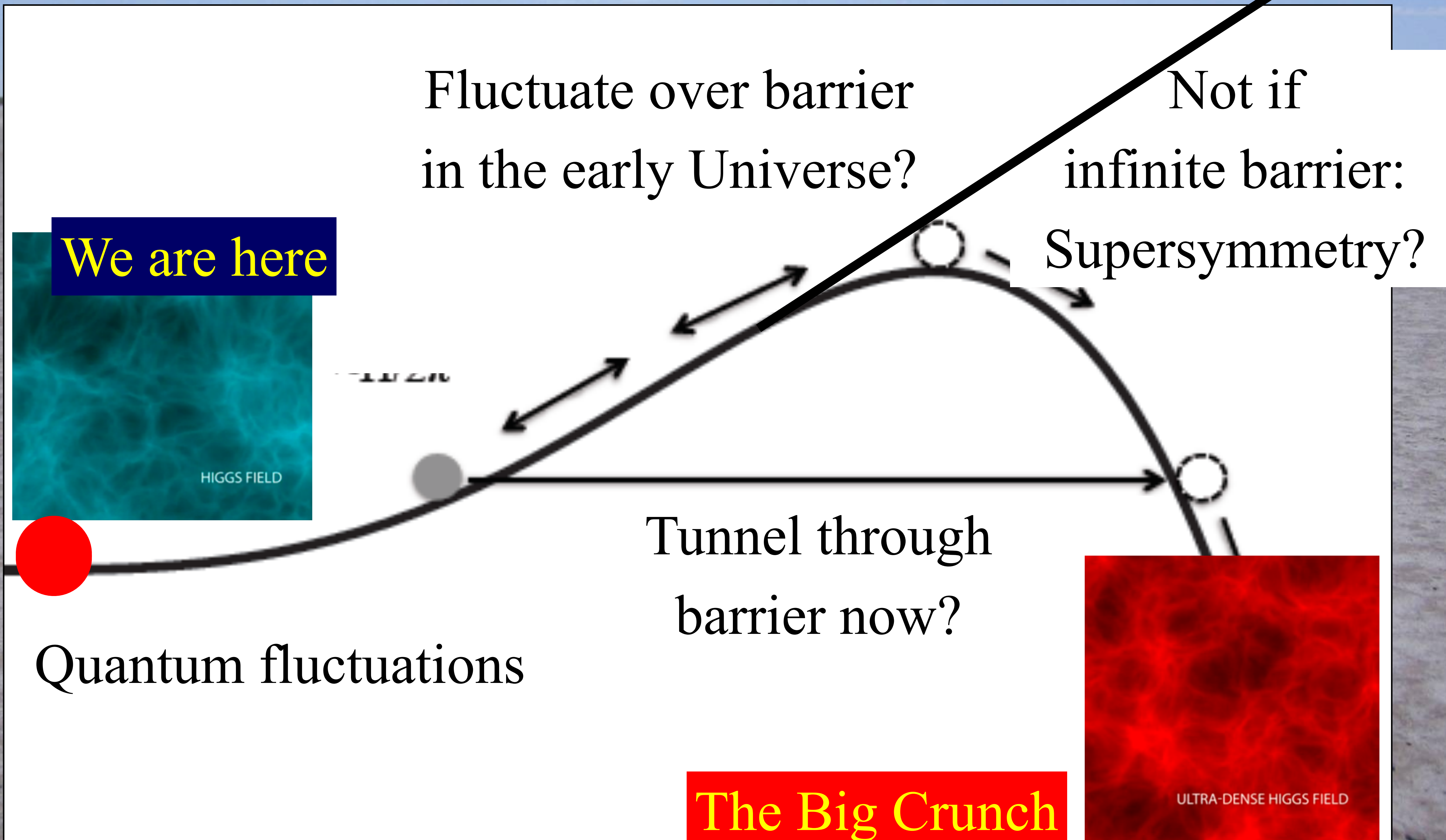
- **«Empty» space is unstabl** Run 3 SUSY
- **Dark matter** Run 3 SUSY
- **Flavour & origin of matte** Run 3 SUSY
- Masses of neutrinos
- Hierarchy problem Run 3 SUSY
- Inflation SUSY
- Quantum gravity SUSY
- …

# Is “Empty Space” Unstable?

Depends on masses of Higgs boson and top quark



# Should it have Collapsed already?



# Beyond the Stars: Dark Matter

- Proposed by Fritz Zwicky, based on observations of the Coma galaxy cluster
- The galaxies move too quickly
- The observations require a stronger gravitational field than provided by the visible matter
- **Dark matter?**
- Particles we can discover at the LHC?

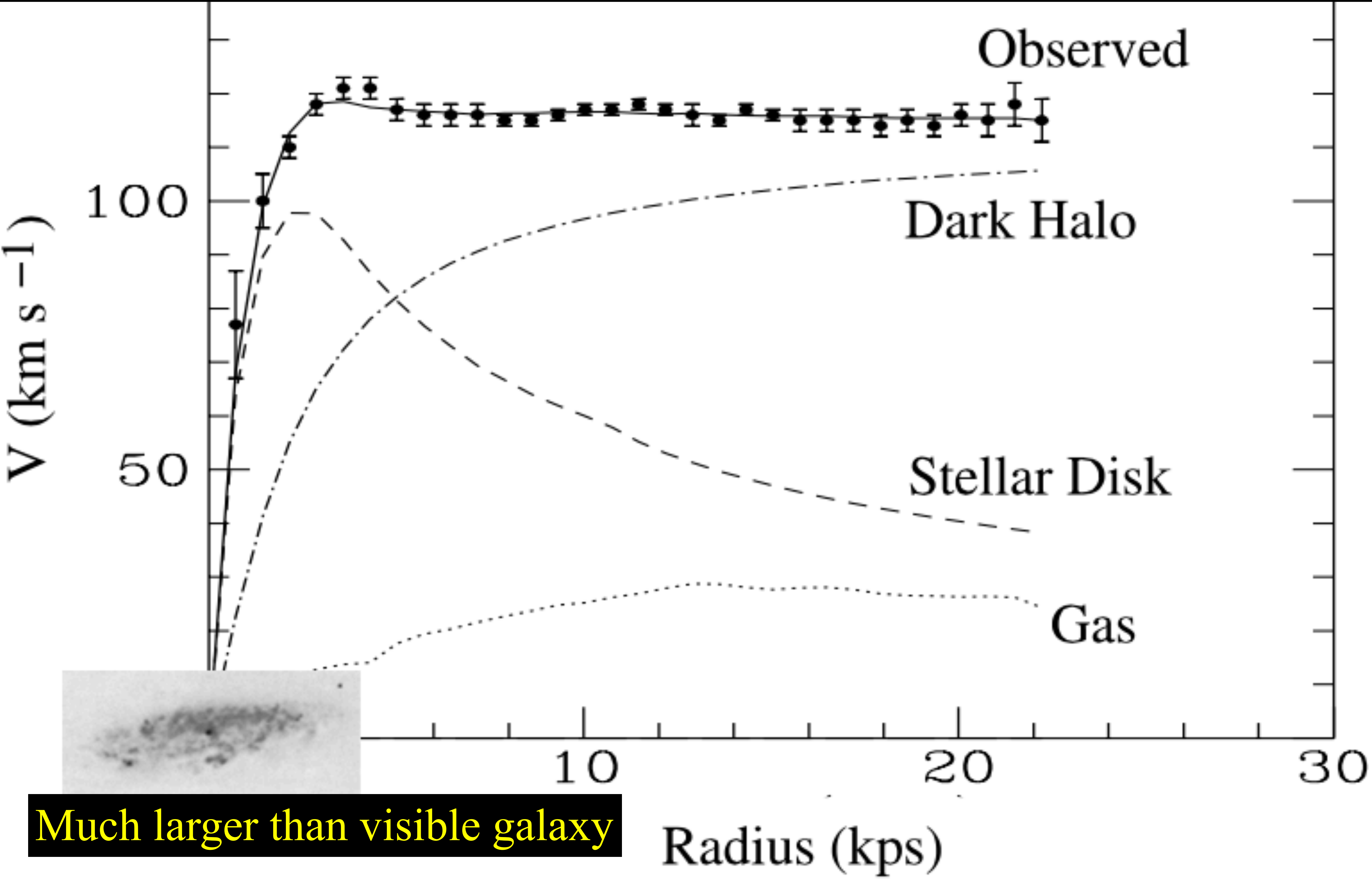
# The Rotation Curves of Galaxies

- Measured by Vera Rubin
- The stars also orbit ‘too quickly’
- Her observations also required a stronger gravitational field than provided by the visible matter

Scanned at the American Institute of Physics

- **Further strong evidence for dark matter**
- Also:
  - Formation of galaxies, cosmic microwave background, …

# Sample Rotation Curve: NGC 6503




Much larger than visible galaxy

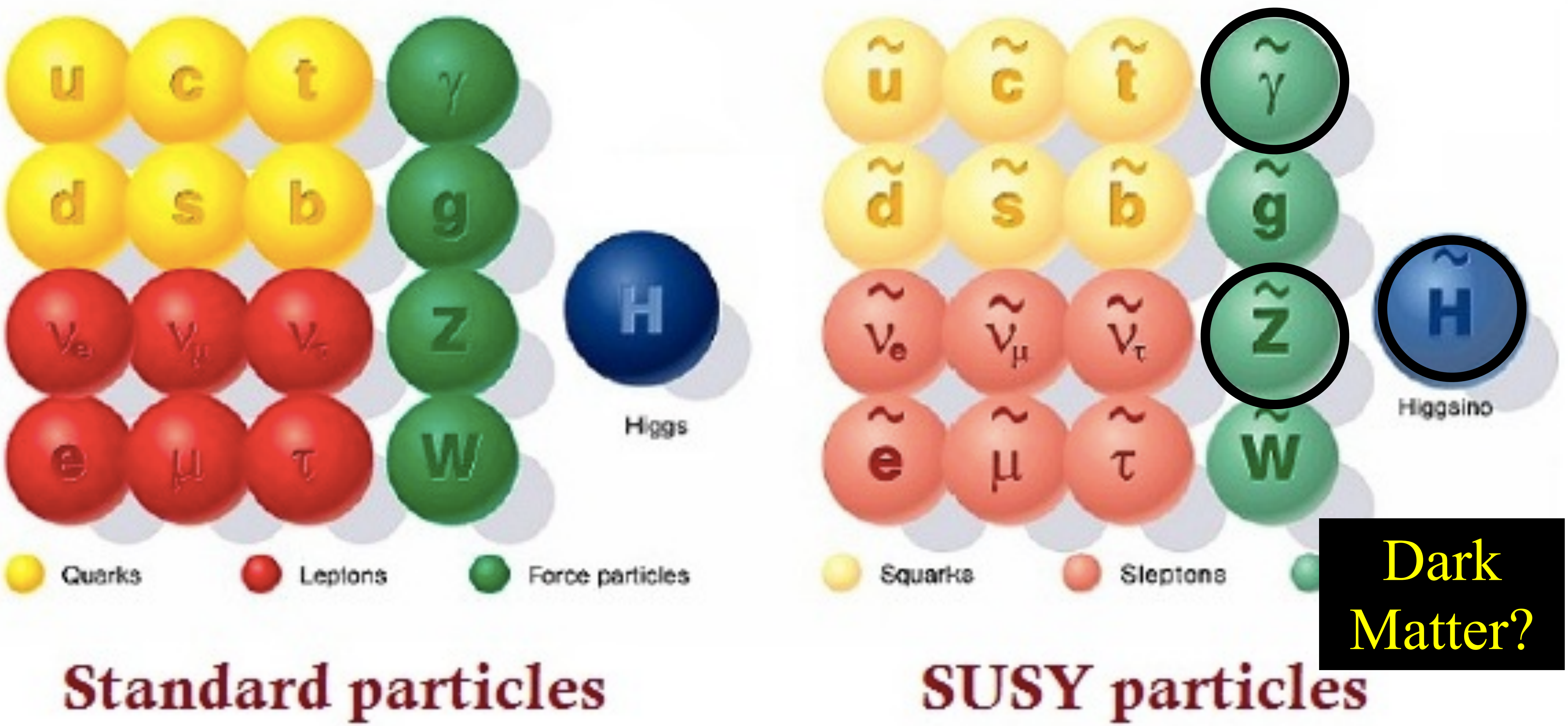
What lies beyond the Standard Model?

# Supersymmetry

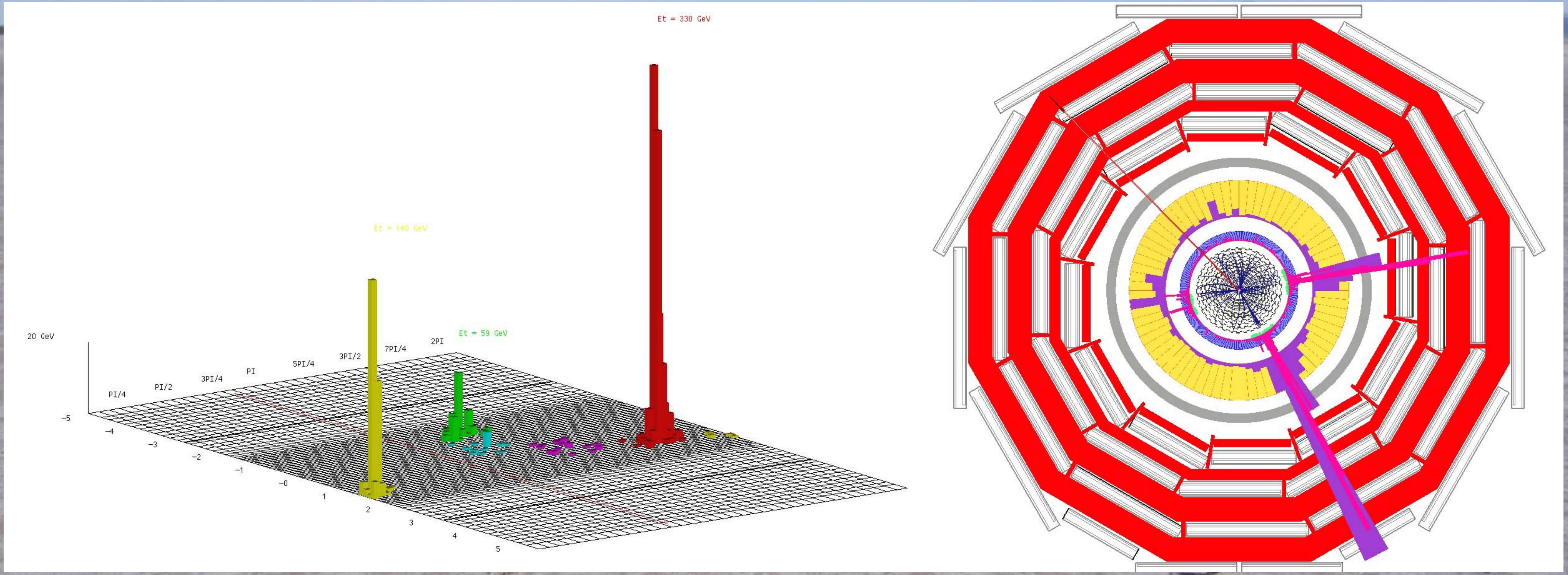
New motivations
From LHC Run 1

- **Stabilize electroweak vacuum**
- **Successful prediction for Higgs mass**
  - **Should be < 130 GeV in simple models**
- **Successful predictions for couplings**
  - **Should be within few % of SM values**
- Naturalness, GUTs, string, …, **dark matter**

# Minimal Supersymmetric Extension of the Standard Model



# Classic LHC Dark Matter Signature

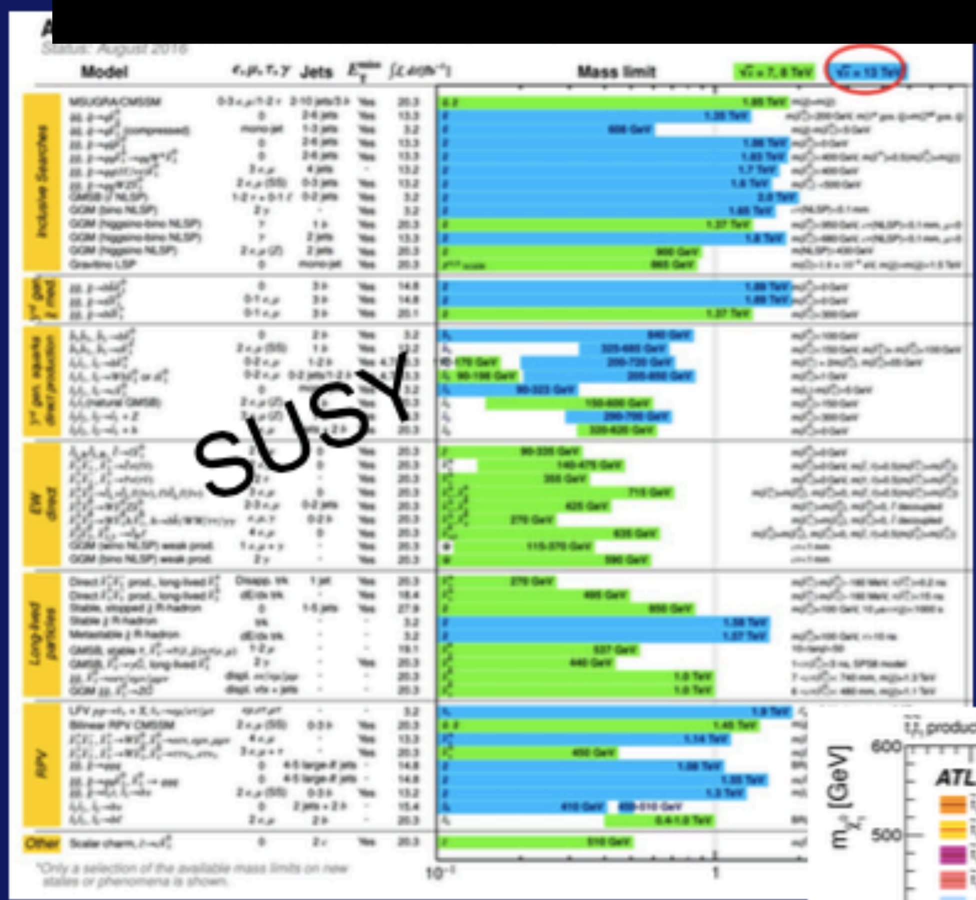


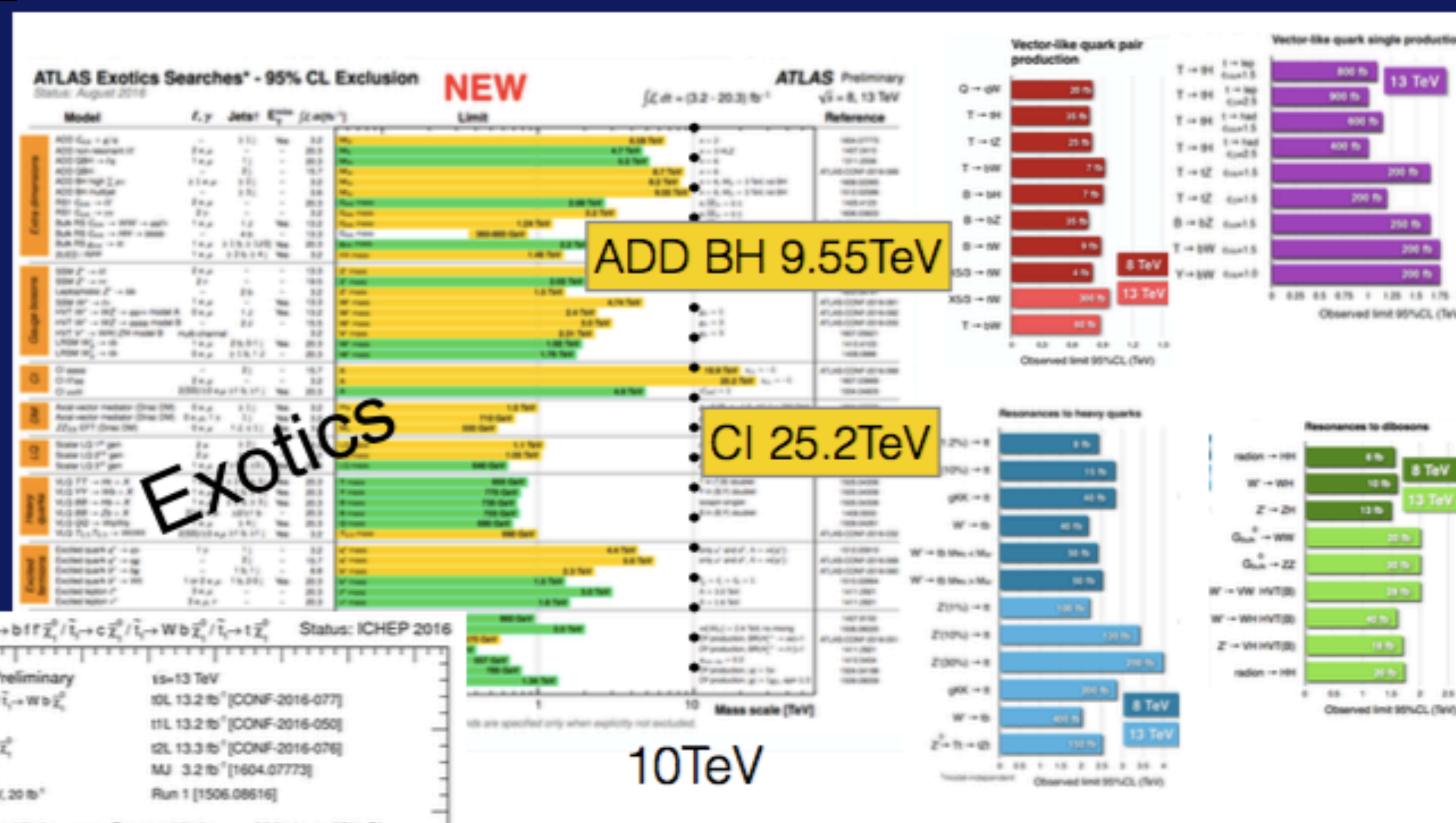

Missing transverse energy
carried away by dark matter particles

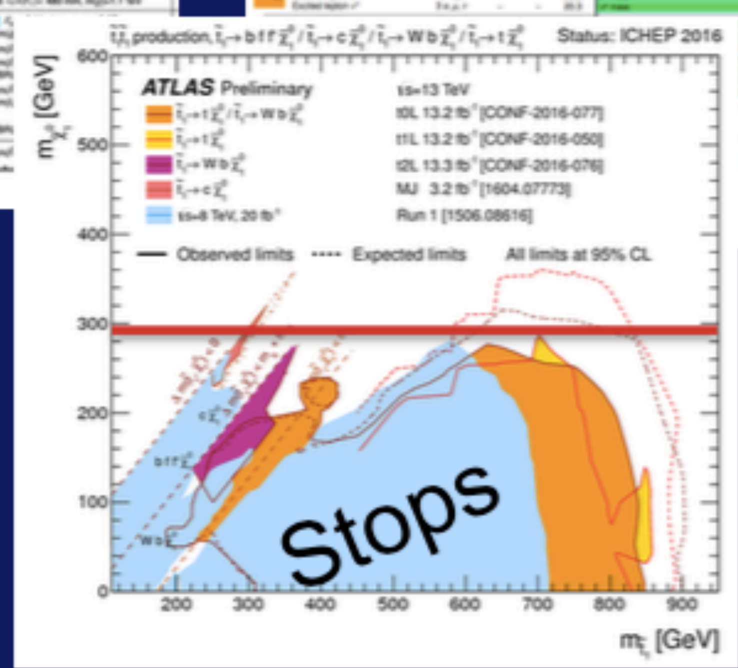
# Nothing (yet) at the LHC

No supersymmetry

Nothing else, either



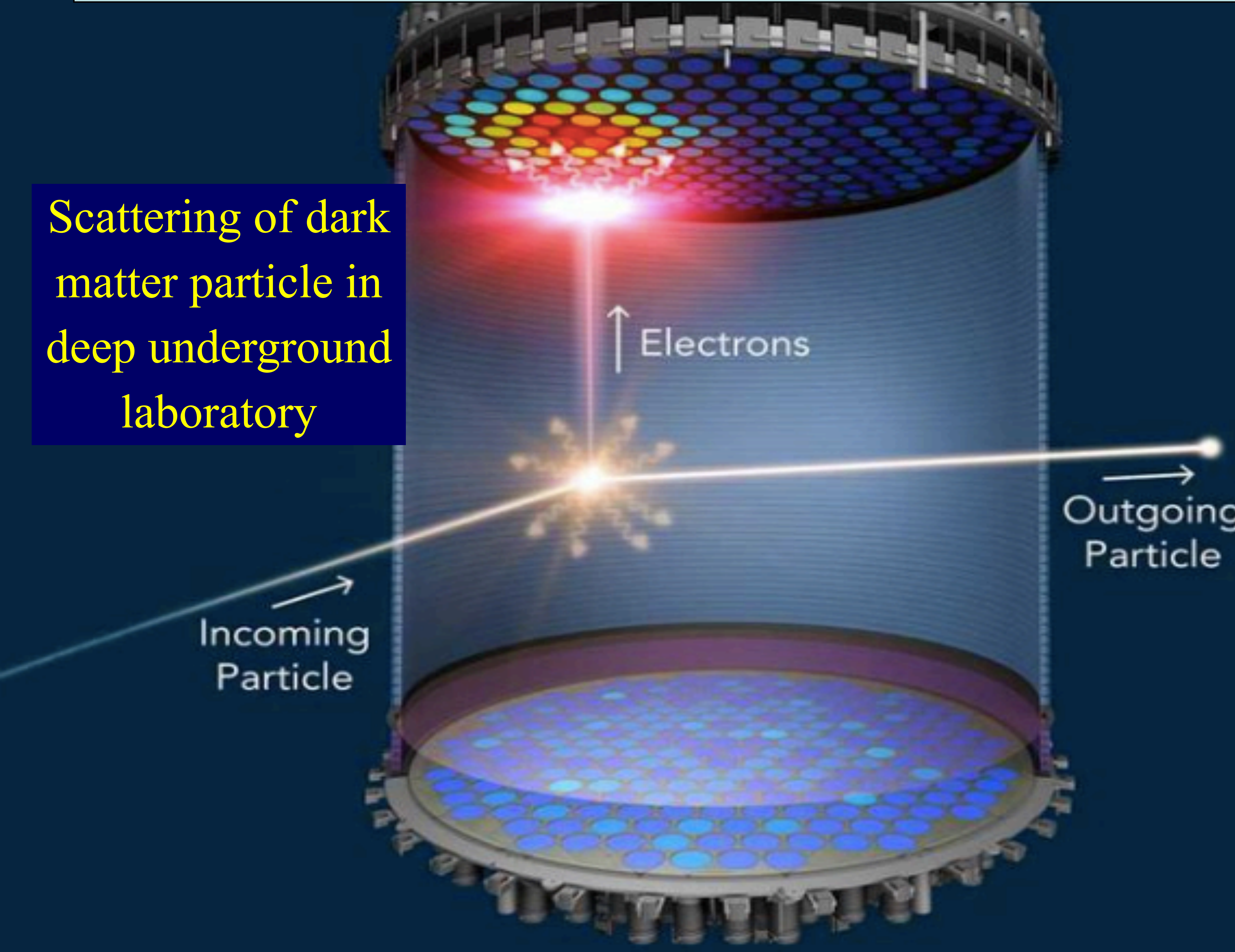

More of same?

Unexplored nooks?

Novel signatures?

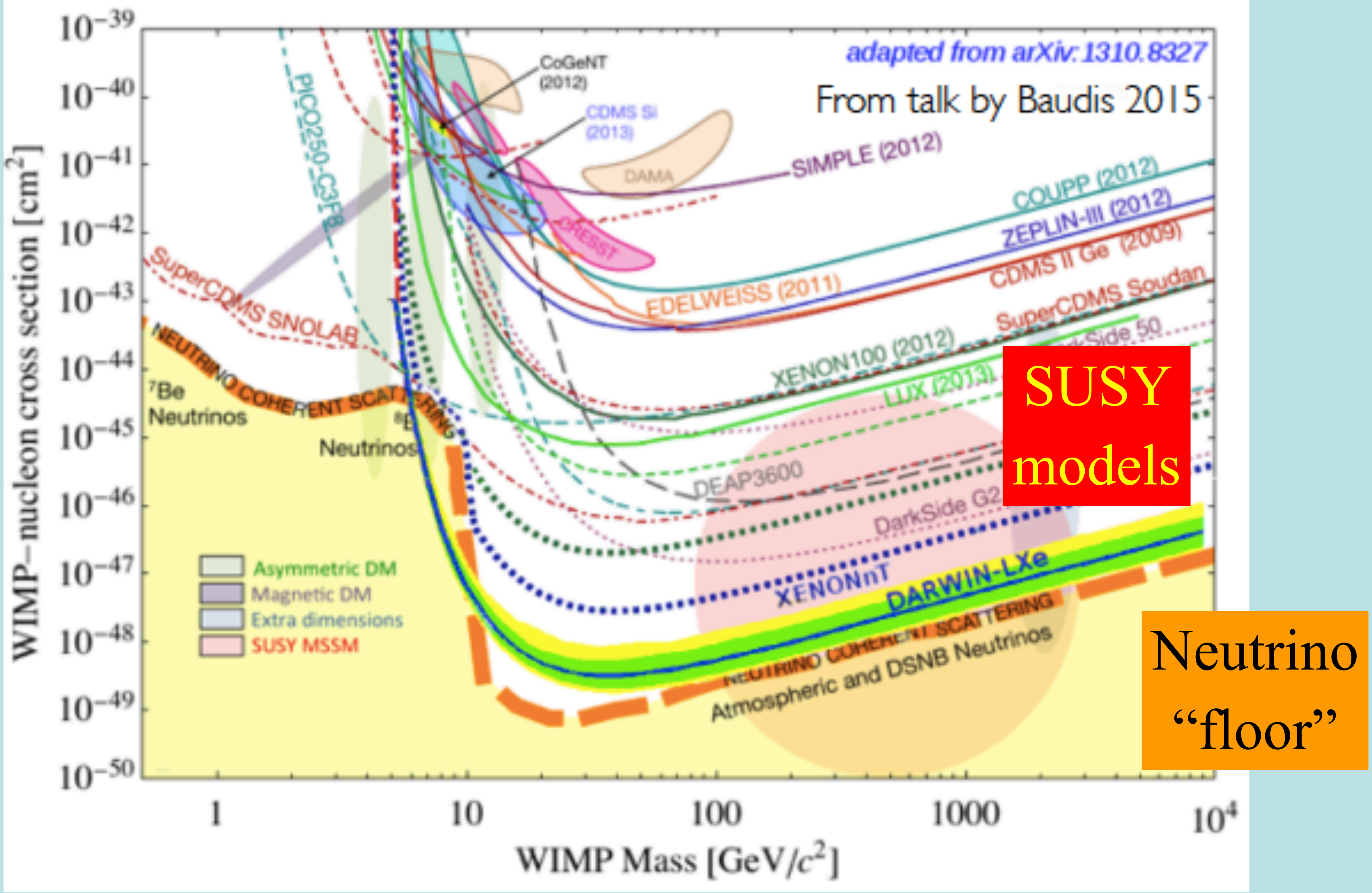
# Direct Dark Matter Detection

Scattering of dark matter particle in deep underground laboratory

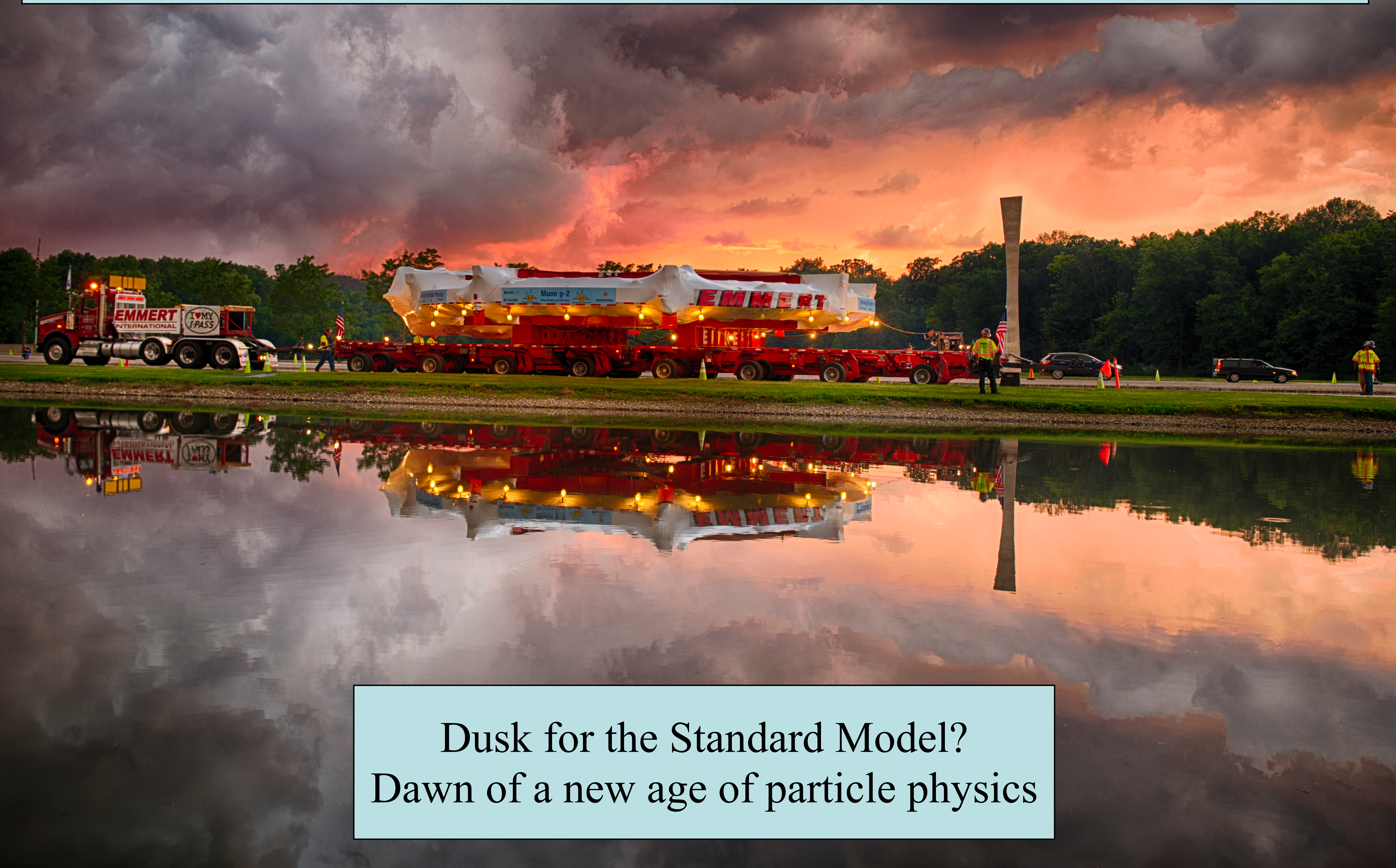


# Direct Dark Matter Searches

- Compilation of present and future sensitivities



# The Anomalous Magnetic Moment of the Muon




Dusk for the Standard Model?
Dawn of a new age of particle physics

# It began with Dirac …

- Two fundamental papers:
  - "The quantum theory of the electron" (1928)

    The Dirac equation: $(i\gamma_\mu \partial^\mu - m)\psi = 0$ predicts that the electron's magnetic moment $g = 2$

    *"That was really an unexpected bonus for me, completely unexpected"*

  - "The Quantum Theory of the Emission and Absorption of Radiation" (1927)

    The basis for QED (and all of quantum field theory) enables the calculations of the anomaly: $g \neq 2$

# … and then Schwinger

- First calculation of leading-order contribution to $g - 2$ in QED: $\frac{\alpha}{2\pi}$ (1947)
- Inscribed on his tombstone




[1] Walke, Thompson, and Holt, Phys. Rev. **57**, 171 (1940).
[2] Solomon, Gould, and Anfinsen, Phys. Rev. **72**, 1097 (1947).
[3] Feather, Proc. Camb. Phil. Soc. **35**, 599 (1938).
[4] Glendenin, Nucleonics, in press for January, 1948.
[5] Marshall and Ward, Can. J. Research **15**, 29 (1939).
[6] This result is in good agreement with a value of 250 kev, given in *Radioisotopes, Catalog and Price List No. 2*, revised September, 1947, distributed by Isotopes Branch, United States Atomic Energy Commission. Unfortunately, the Atomic Energy Commission's result is not supported by any published experimental evidence.

## On Quantum-Electrodynamics and the Magnetic Moment of the Electron

JULIAN SCHWINGER
*Harvard University, Cambridge, Massachusetts*
December 30, 1947

ATTEMPTS to evaluate radiative corrections to electron phenomena have heretofore been beset by divergence difficulties, attributable to self-energy and vacuum polarization effects. Electrodynamics unquestionably requires revision at ultra-relativistic energies, but is presumably accurate at moderate relativistic energies. It would be desirable, therefore, to isolate those aspects of the current theory that essentially involve high energies, and are subject to modification by a more satisfactory theory, from aspects that involve only moderate energies and are thus relatively trustworthy. This goal has been achieved by transforming the Hamiltonian of current hole theory electrodynamics to exhibit explicitly the logarithmically divergent self-energy of a free electron, which arises from the virtual emission and absorption of light quanta. The electromagnetic self-energy of a free electron can be ascribed to an electromagnetic mass, which must be added to the mechanical mass of the electron. Indeed, the only meaningful statements of the theory involve this combination of masses, which is the experimental mass of a free electron. It might appear, from this point of view, that the divergence of the electromagnetic mass is unobjectionable, since the individual contributions to the experimental mass are unobservable. However, the transformation of the Hamiltonian is based on the assumption of a weak interaction between matter and radiation, which requires that the electromagnetic mass be a small correction ($\sim(e^2/\hbar c)m_0$) to the mechanical mass $m_0$.

The new Hamiltonian is superior to the original one in essentially three ways: it involves the experimental electron mass, rather than the unobservable mechanical mass; an electron now interacts with the radiation field only in the presence of an external field, that is, only an accelerated electron can emit or absorb a light quantum;* the interaction energy of an electron with an external field is now subject to a *finite* radiative correction. In connection with the last point, it is important to note that the inclusion of the electromagnetic mass with the mechanical mass does not avoid all divergences; the polarization of the vacuum produces a logarithmically divergent term proportional to the interaction energy of the electron in an external field. However, it has long been recognized that such a term is equivalent to altering the value of the electron charge by a constant factor, only the final value being properly identified with the experimental charge. Thus the interaction between matter and radiation produces a renormalization of the electron charge and mass, all divergences being contained in the renormalization factors.

The simplest example of a radiative correction is that for the energy of an electron in an external magnetic field. The detailed application of the theory shows that the radiative correction to the magnetic interaction energy corresponds to an additional magnetic moment associated with the electron spin, of magnitude $\delta\mu/\mu = (\frac{1}{2}\pi)e^2/\hbar c = 0.001162$. It is indeed gratifying that recently acquired experimental data confirm this prediction. Measurements on the hyperfine splitting of the ground states of atomic hydrogen and deuterium[1] have yielded values that are definitely larger than those to be expected from the directly measured nuclear moments and an electron moment of one Bohr magneton. These discrepancies can be accounted for by a small additional electron spin magnetic moment.[2] Recalling that the nuclear moments have been calibrated in terms of the electron moment, we find the additional moment necessary to account for the measured hydrogen and deuterium hyperfine structures to be $\delta\mu/\mu = 0.00126 \pm 0.00019$ and $\delta\mu/\mu = 0.00131 \pm 0.00025$, respectively. These values are not in disagreement with the theoretical prediction. More precise conformation is provided by measurement of the $g$ values for the $^2S_{\frac{1}{2}}$, $^2P_{\frac{1}{2}}$, and $^2P_{3/2}$ states of sodium and gallium.[3] To account for these results, it is necessary to ascribe the following additional spin magnetic moment to the electron, $\delta\mu/\mu = 0.00118 \pm 0.00003$.

# $\mathcal{O}(\frac{\alpha}{\pi})^5$ Calculations in QED

**Complete Tenth-Order QED Contribution to the Muon $g-2$**

Tatsumi Aoyama,[1,2] Masashi Hayakawa,[3,2] Toichiro Kinoshita,[4,2] and Makiko Nio[2]

[1] *Kobayashi-Maskawa Institute for the Origin of Particles and the Universe (KMI), Nagoya University, Nagoya, 464-8602, Japan*
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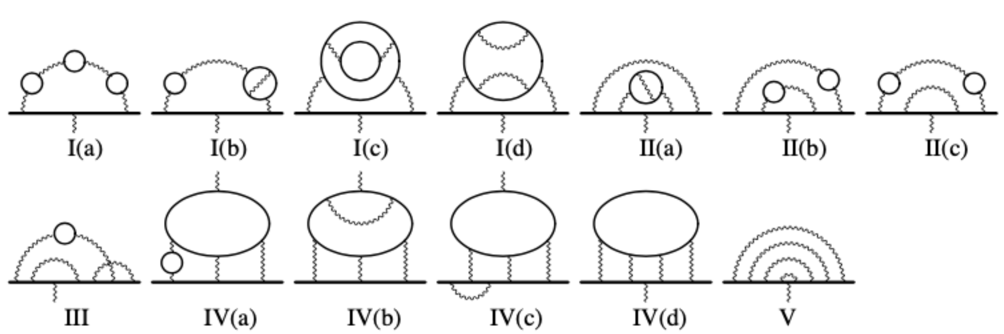
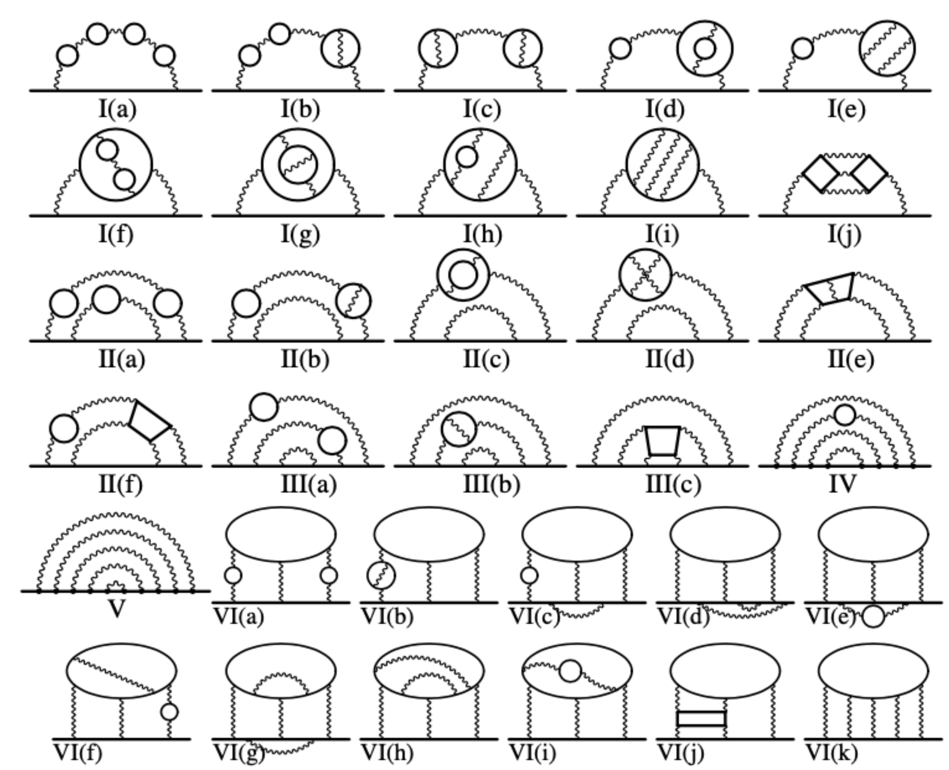
(Dated: August 21, 2012)

We report the result of our calculation of the complete tenth-order QED terms of the muon $g-2$. Our result is $a_\mu^{(10)} = 753.29\ (1.04)$ in units of $(\alpha/\pi)^5$, which is about 4.5 s.d. larger than the leading-logarithmic estimate 663 (20). We also improved the precision of the eighth-order QED term of $a_\mu$, obtaining $a_\mu^{(8)} = 130.8794\ (63)$ in units of $(\alpha/\pi)^4$. The new QED contribution is $a_\mu(\text{QED}) = 116\ 584\ 718\ 951\ (80) \times 10^{-14}$, which does not resolve the existing discrepancy between the standard-model prediction and measurement of $a_\mu$.

PACS numbers: 13.40.Em,14.60.Ef,12.20.Ds

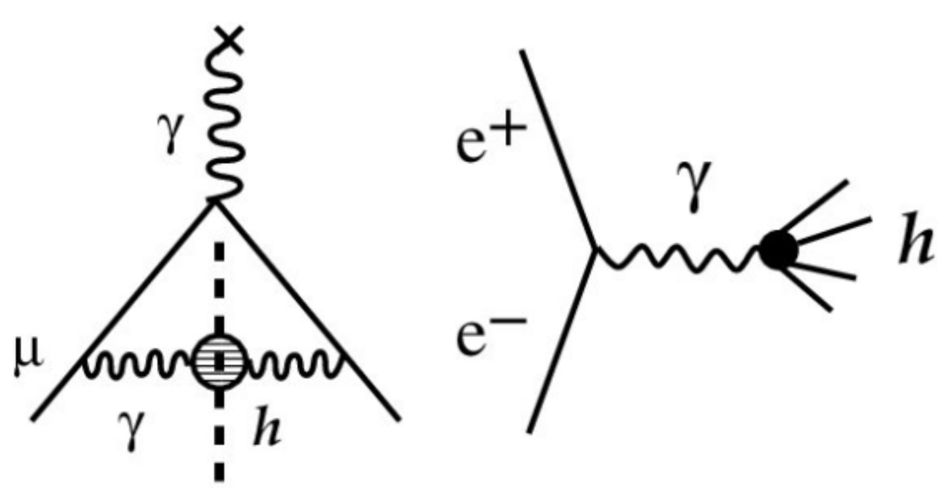



(2012)

# Theory Initiative

- Comprehensive review of calculations of the Standard Model contributions to $g_\mu - 2$
- Including discussion of the uncertainties
- Particularly in calculation of leading-order vacuum polarisation




Aoyama et al, arXiv:2006.04822


Physics Reports 887 (2020) 1–166

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## The anomalous magnetic moment of the muon in the Standard Model


T. Aoyama [1,2,3], N. Asmussen [4], M. Benayoun [5], J. Bijnens [6], T. Blum [7,8], M. Bruno [9], I. Caprini [10], C.M. Carloni Calame [11], M. Cè [9,12,13], G. Colangelo [14,*], F. Curciarello [15,16], H. Czyż [17], I. Danilkin [12], M. Davier [18,*], C.T.H. Davies [19], M. Della Morte [20], S.I. Eidelman [21,22,*], A.X. El-Khadra [23,24,*], A. Gérardin [25], D. Giusti [26,27], M. Golterman [28], Steven Gottlieb [29], V. Gülpers [30], F. Hagelstein [14], M. Hayakawa [31,2], G. Herdoíza [32], D.W. Hertzog [33], A. Hoecker [34], M. Hoferichter [14,35,*], B.-L. Hoid [36], R.J. Hudspith [12,13], F. Ignatov [21], T. Izubuchi [37,8], F. Jegerlehner [38], L. Jin [7,8], A. Keshavarzi [39], T. Kinoshita [40,41], B. Kubis [36], A. Kupich [21], A. Kupść [42,43], L. Laub [14], C. Lehner [26,37,*], L. Lellouch [25], I. Logashenko [21], B. Malaescu [5], K. Maltman [44,45], M.K. Marinković [46,47], P. Masjuan [48,49], A.S. Meyer [37], H.B. Meyer [12,13], T. Mibe [1,*], K. Miura [12,13,3], S.E. Müller [50], M. Nio [2,51], D. Nomura [52,53], A. Nyffeler [12,*], V. Pascalutsa [12], M. Passera [54], E. Perez del Rio [55], S. Peris [48,49], A. Portelli [30], M. Procura [56], C.F. Redmer [12], B.L. Roberts [57,*], P. Sánchez-Puertas [49], S. Serednyakov [21], B. Shwartz [21], S. Simula [27], D. Stöckinger [58], H. Stöckinger-Kim [58], P. Stoffer [59], T. Teubner [60,*], R. Van de Water [24], M. Vanderhaeghen [12,13], G. Venanzoni [61], G. von Hippel [12], H. Wittig [12,13], Z. Zhang [18], M.N. Achasov [21], A. Bashir [62], N. Cardoso [47], B. Chakraborty [63], E.-H. Chao [12], J. Charles [25], A. Crivellin [64,65], O. Deineka [12], A. Denig [12,13], C. DeTar [66], C.A. Dominguez [67], A.E. Dorokhov [68], V.P. Druzhinin [21], G. Eichmann [69,47], M. Fael [70], C.S. Fischer [71], E. Gámiz [72], Z. Gelzer [23], J.R. Green [9], S. Guellati-Khelifa [73], D. Hatton [19], N. Hermansson-Truedsson [14], S. Holz [36], B. Hörz [74], M. Knecht [25], J. Koponen [1], A.S. Kronfeld [24], J. Laiho [75], S. Leupold [42], P.B. Mackenzie [24], W.J. Marciano [37], C. McNeile [76], D. Mohler [12,13], J. Monnard [14], E.T. Neil [77], A.V. Nesterenko [68], K. Ottnad [12], V. Pauk [12], A.E. Radzhabov [78], E. de Rafael [25], K. Raya [79], A. Risch [12], A. Rodríguez-Sánchez [6], P. Roig [80], T. San José [12,13], E.P. Solodov [21], R. Sugar [81], K. Yu. Todyshev [21], A. Vainshtein [82], A. Vaquero Avilés-Casco [66], E. Weil [71], J. Wilhelm [12], R. Williams [71], A.S. Zhevlakov [78]

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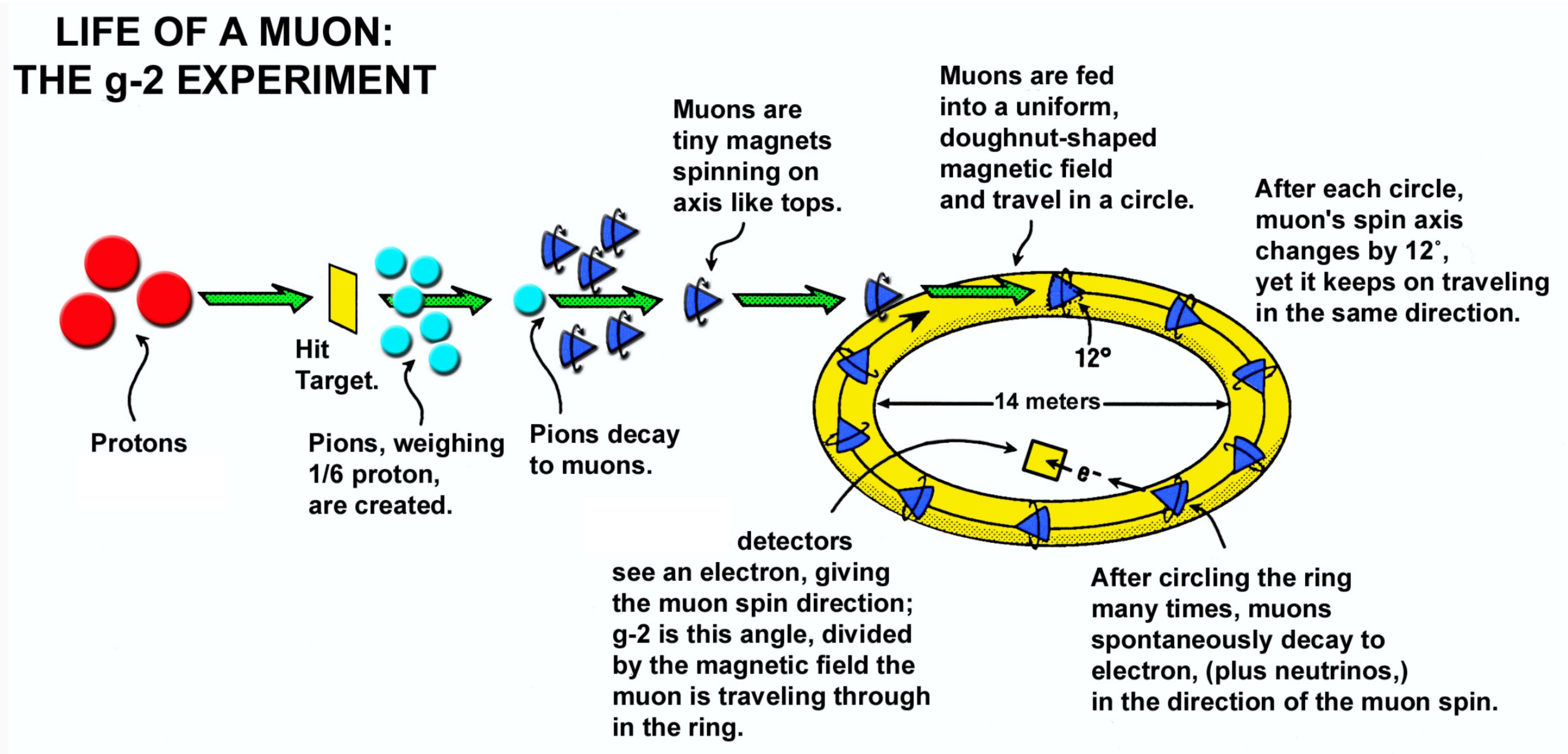
E-mail address: MUON-GM2-THEORY-SC@fnal.gov (G. Colangelo, M. Davier, S.I. Eidelman, A.X. El-Khadra, M. Hoferichter, C. Lehner, T. Mibe, A. Nyffeler, B.L. Roberts, T. Teubner).



https://doi.org/10.1016/j.physrep.2020.07.006

# Experimental Principle of Storage Ring Experiments

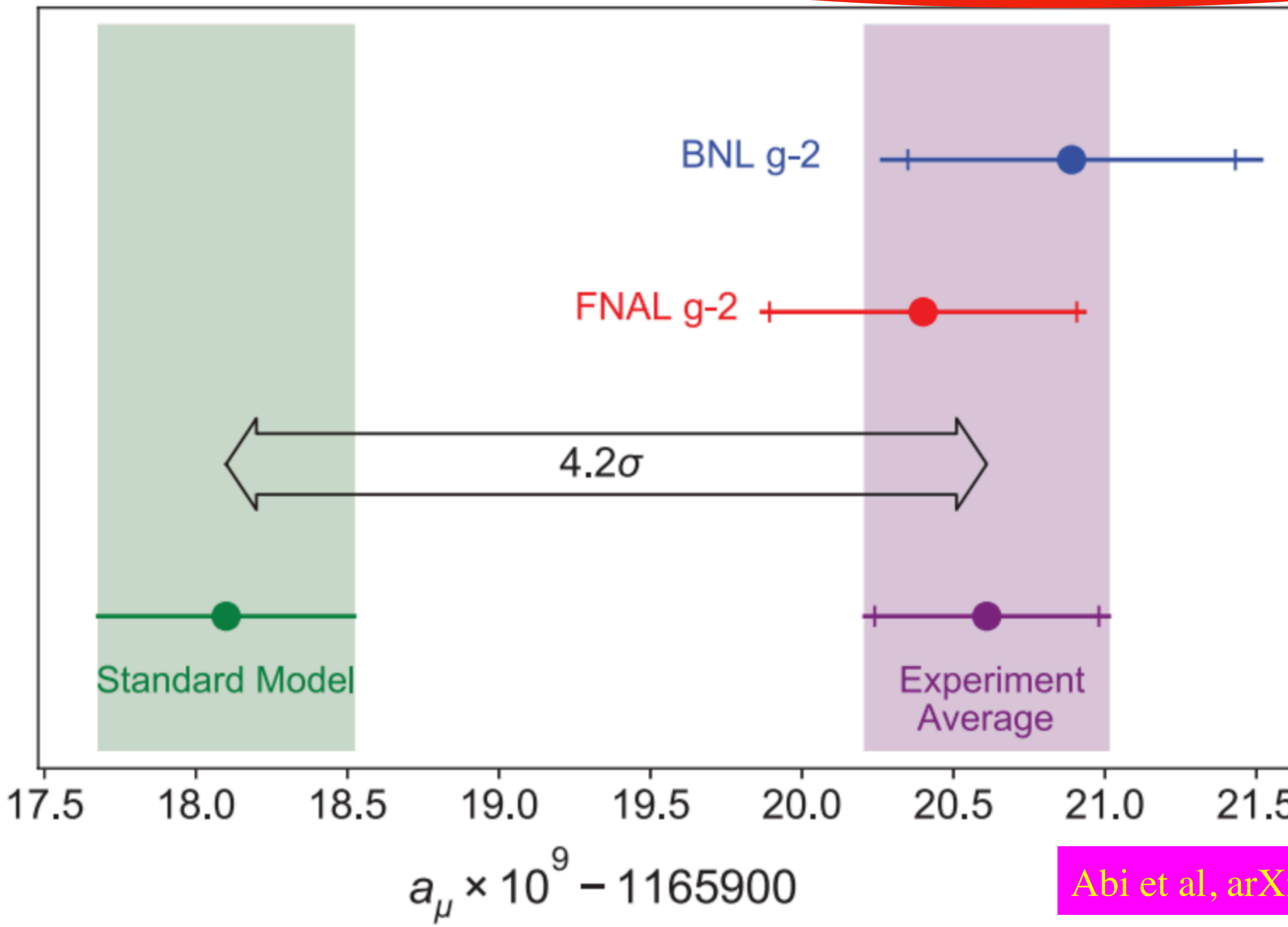


# Fermilab Measurement

FNAL result $a_\mu(\mathrm{FNAL}) = 116\,592\,040(54) \times 10^{-11} \quad (0.46\,\mathrm{ppm})$

Combined result: $a_\mu(\mathrm{Exp}) = 116\,592\,061(41) \times 10^{-11} \quad (0.35\,\mathrm{ppm})$

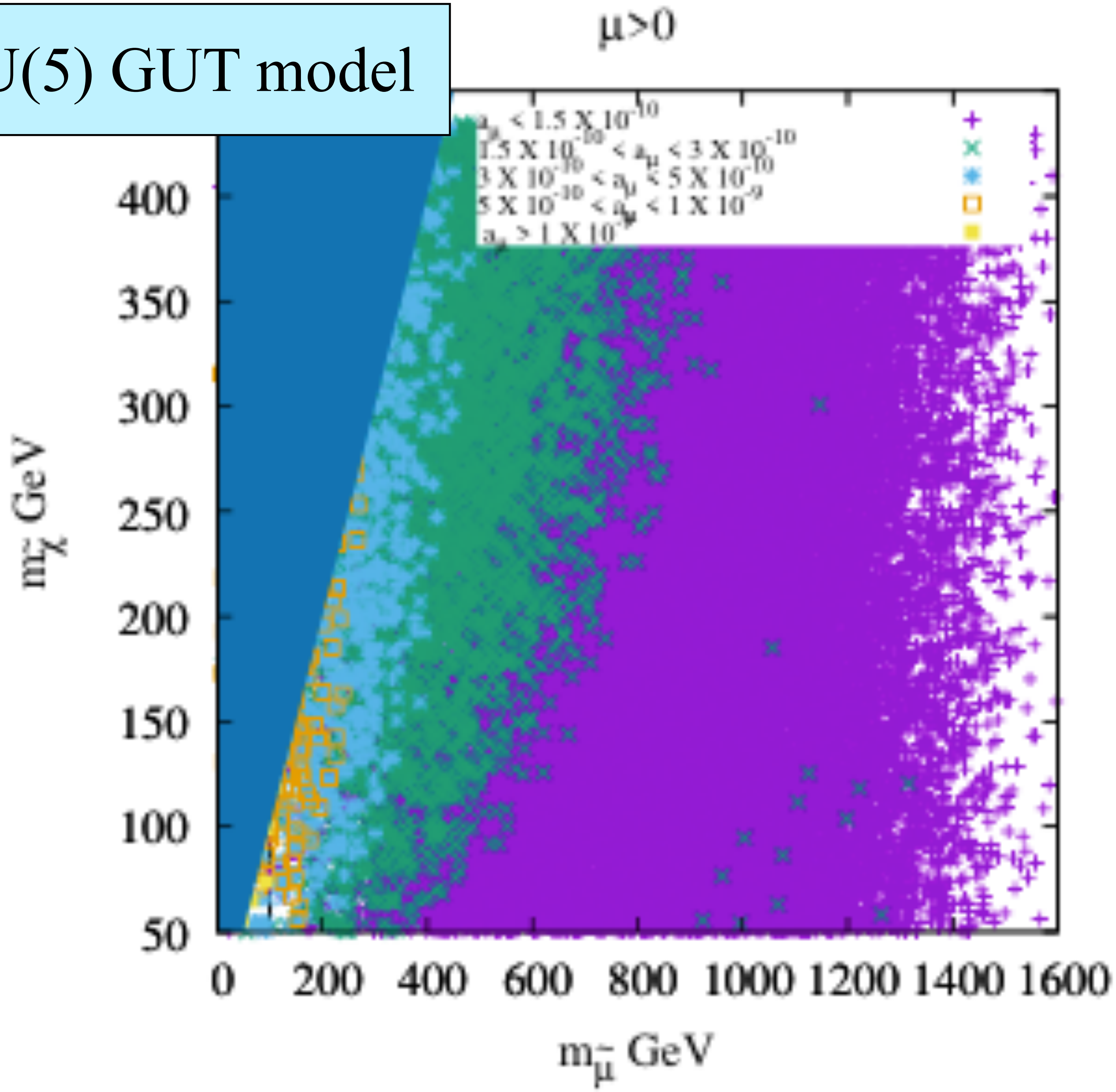
Difference from Standard Model: $a_\mu(\mathrm{Exp}) - a_\mu(\mathrm{SM}) = (251 \pm 59) \times 10^{-11}$




Abi et al, arXiv:2104.03281

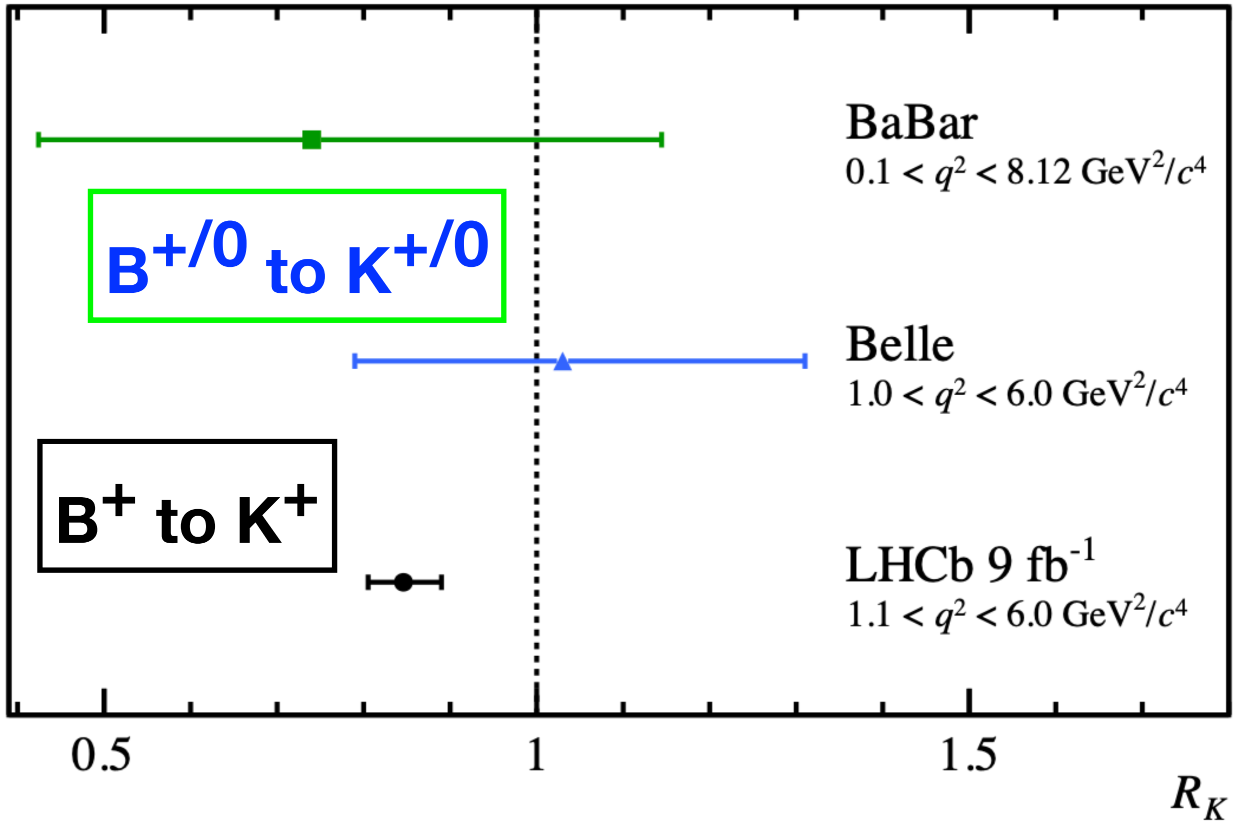
# Supersymmetric Interpretation

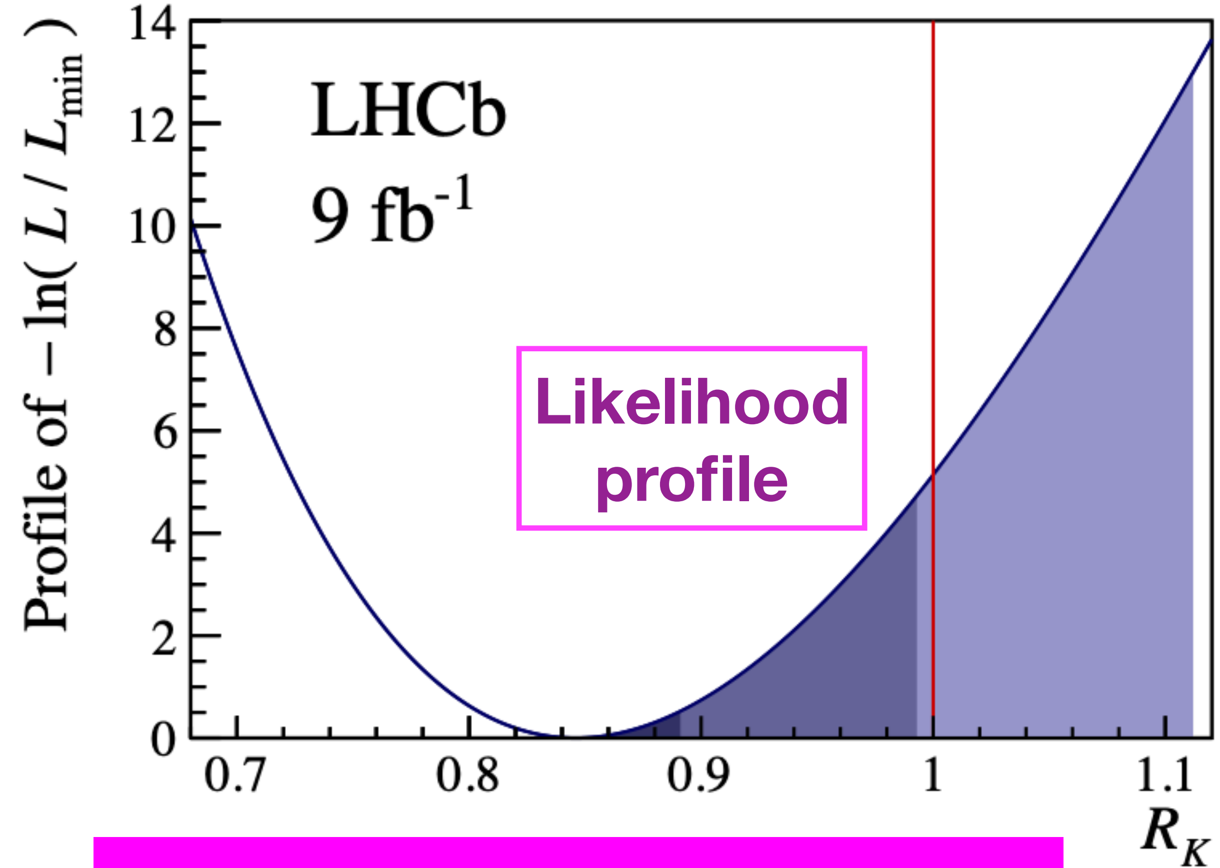
In Flipped SU(5) GUT model

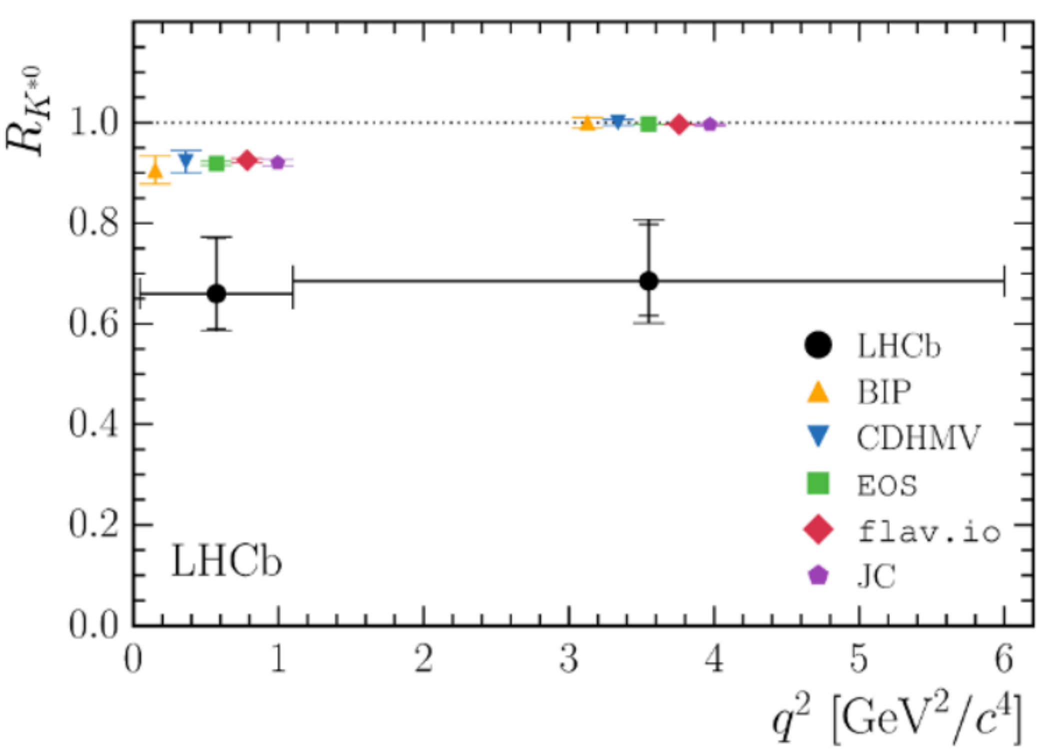



JE, Evans, Nagata, Nanopoulos & Olive, to appear

# Anomalies in B Decays



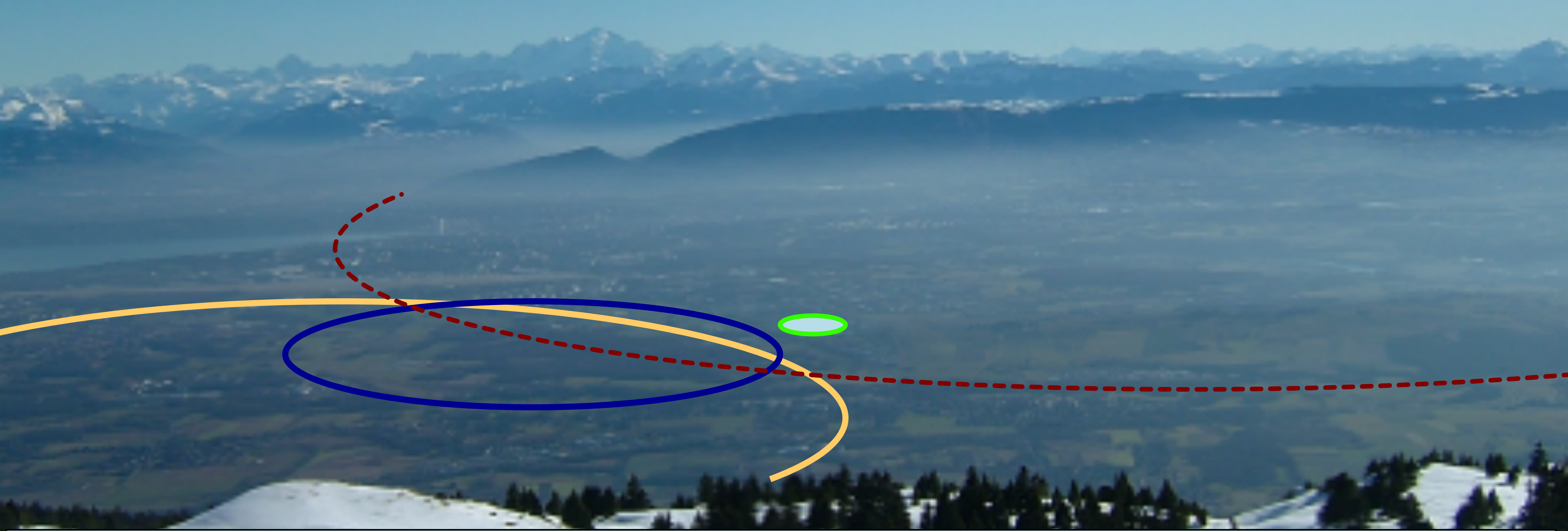

LHCb Collaboration, arXiv:2103.11769

- Seen in several B to K (*) transitions
- Also deviations from Standard Model predictions in kinematic distributions
- Also in decays of other B particles

**CEPC-SPPC**

*Preliminary Conceptual Design Report*

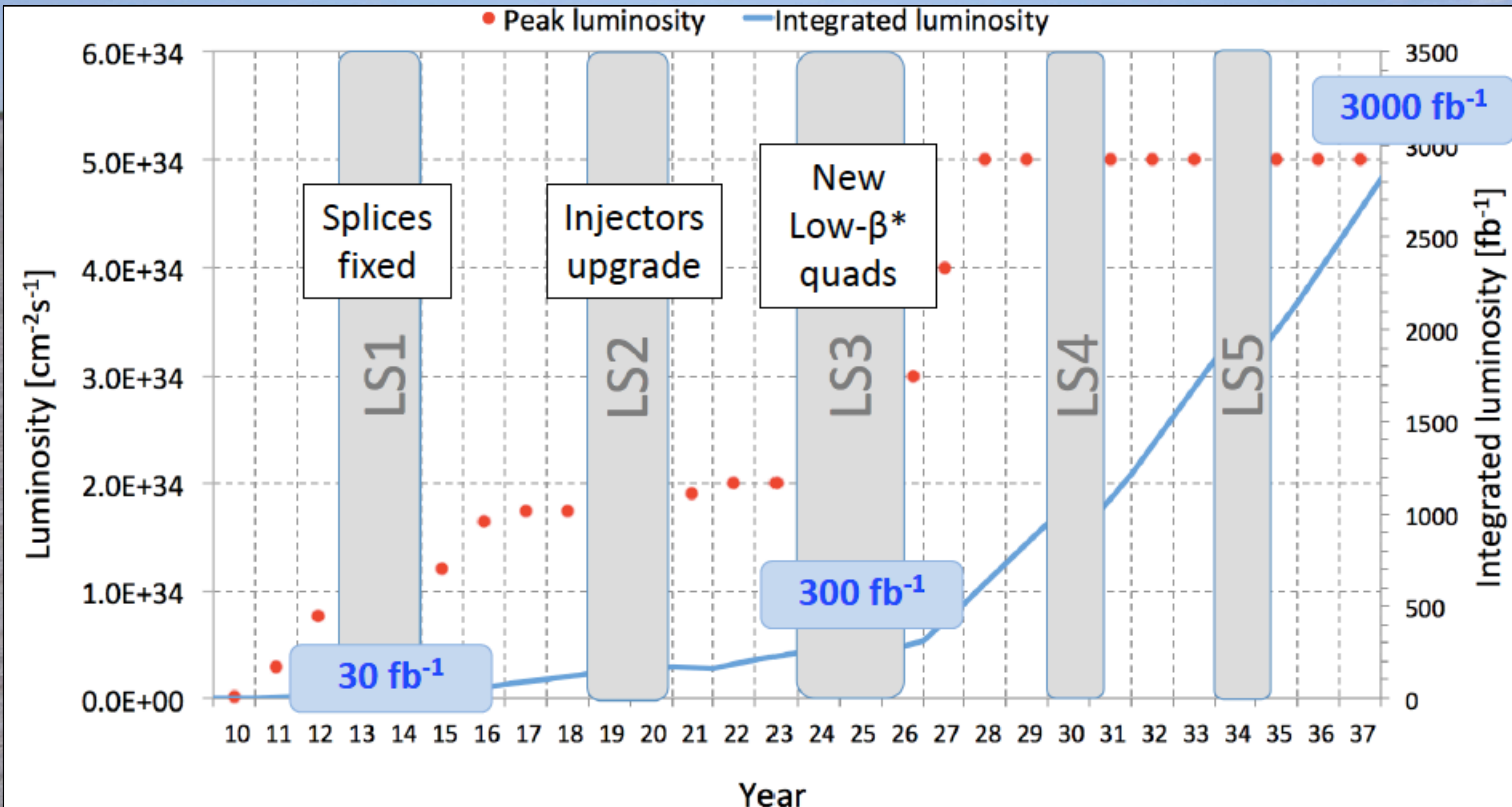
# Future Circular Colliders



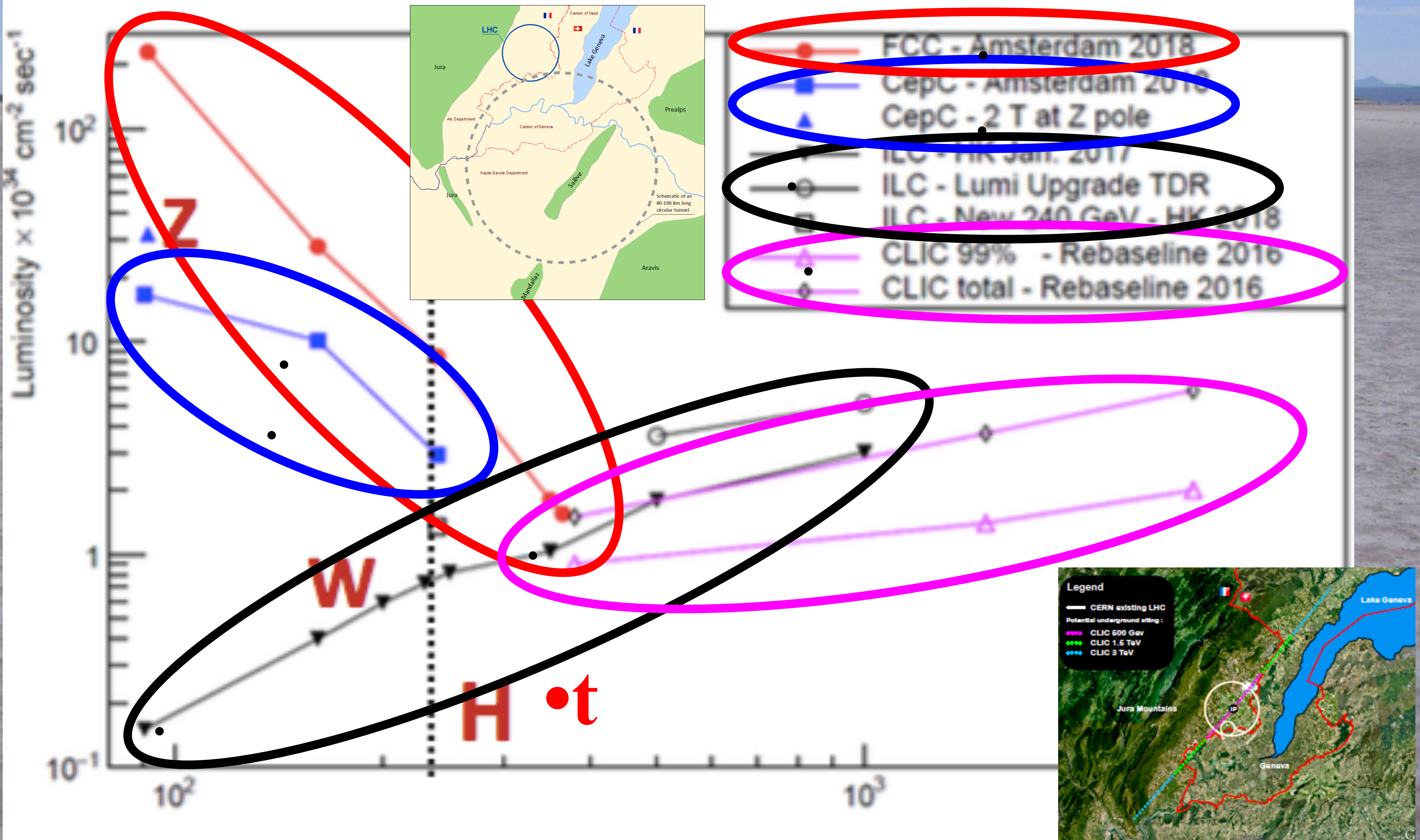
## The vision:

explore 10 TeV scale directly (100 TeV pp) + indirectly ($e^+e^-$)

# The LHC in Future Years

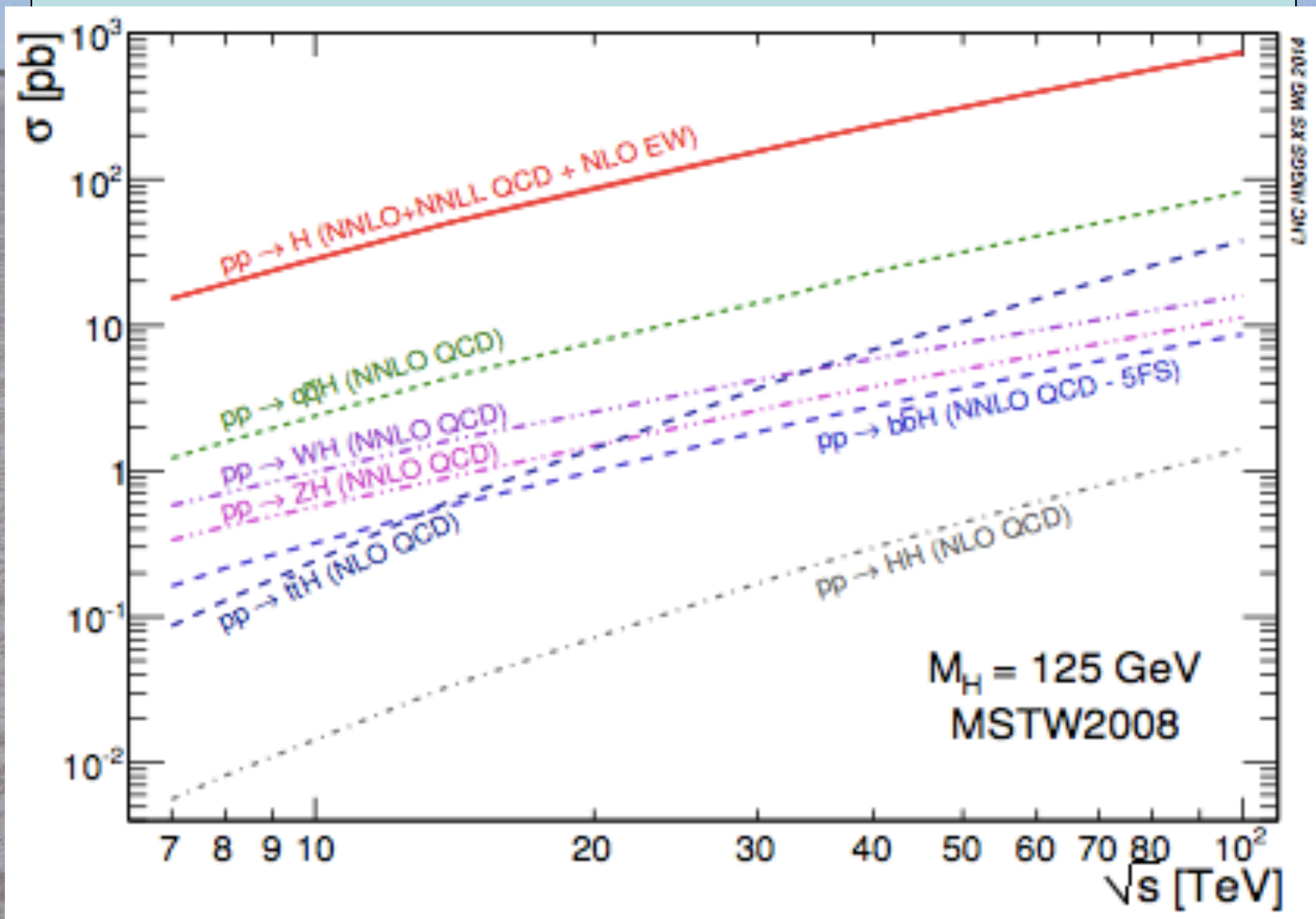


# Possible Future $e^+e^-$ Colliders: Luminosity vs Energy



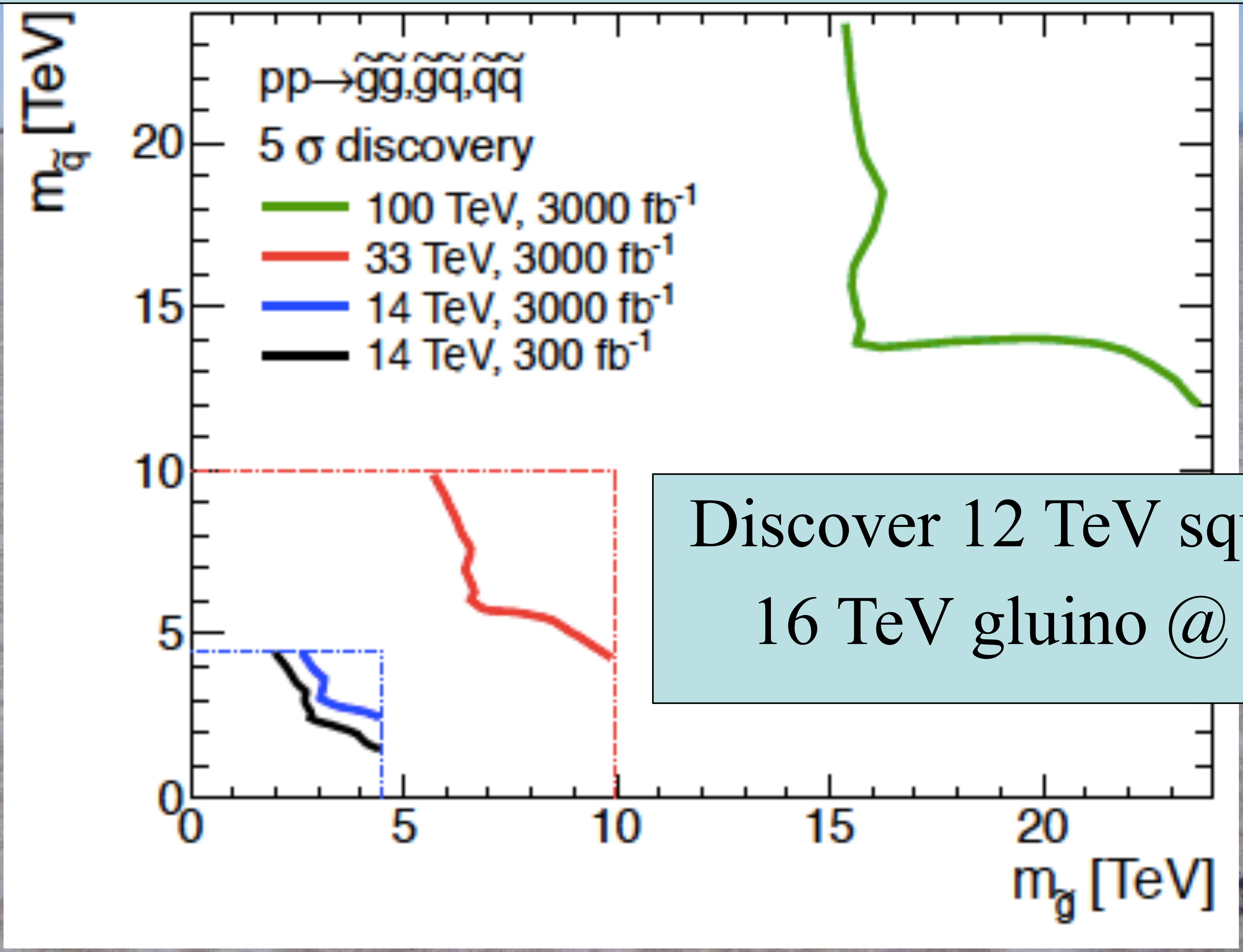
# Higgs Cross Sections

- At the LHC and beyond:



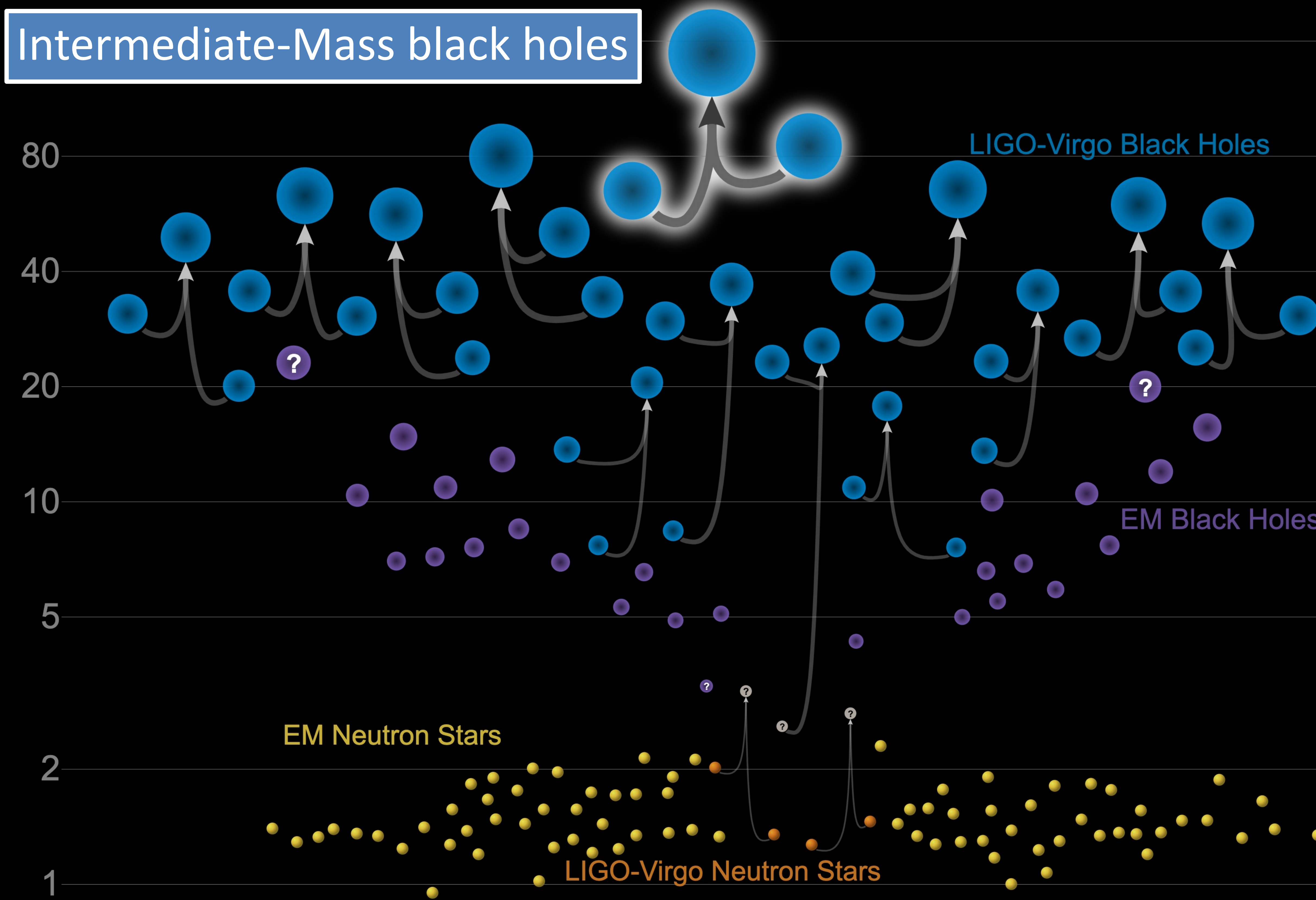

We still believe in supersymmetry
You must be joking!

# Squark-Gluino Plane




Discover 12 TeV squark,
16 TeV gluino @ 5σ

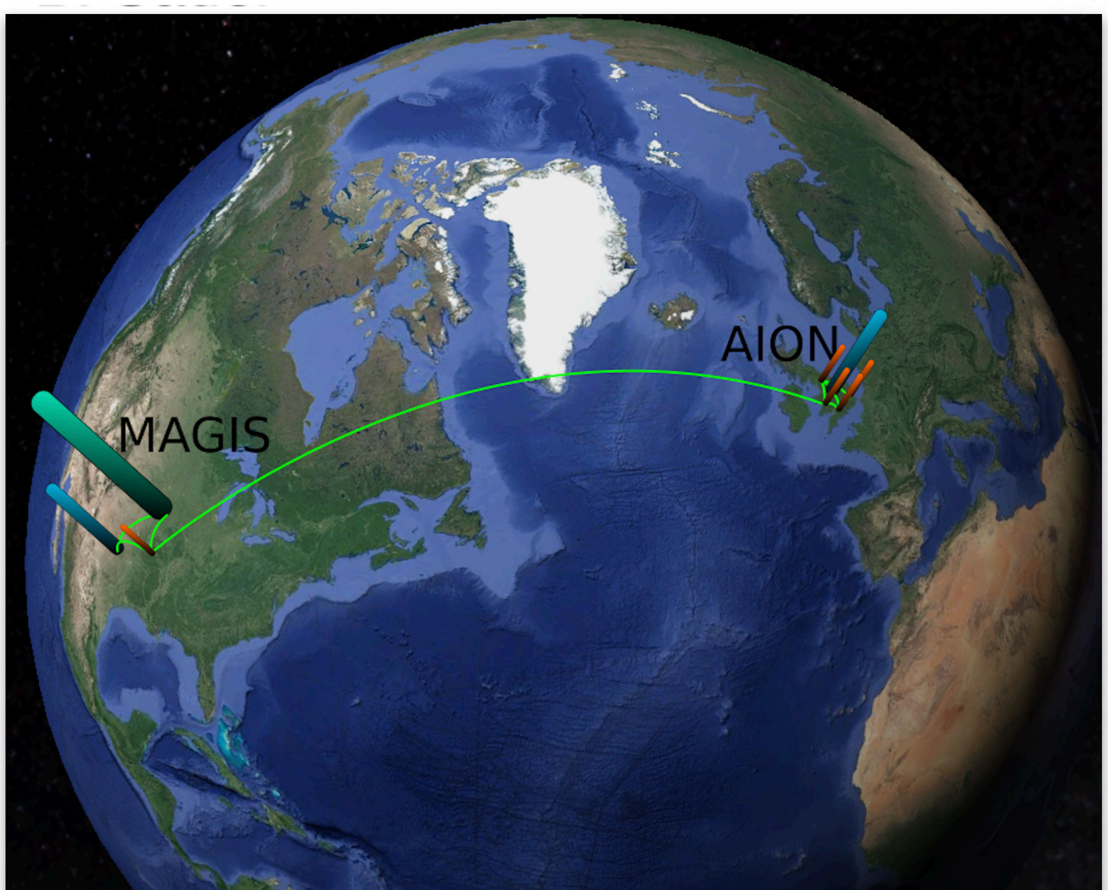
# LIGO-Virgo Black Hole & Neutron Star Masses

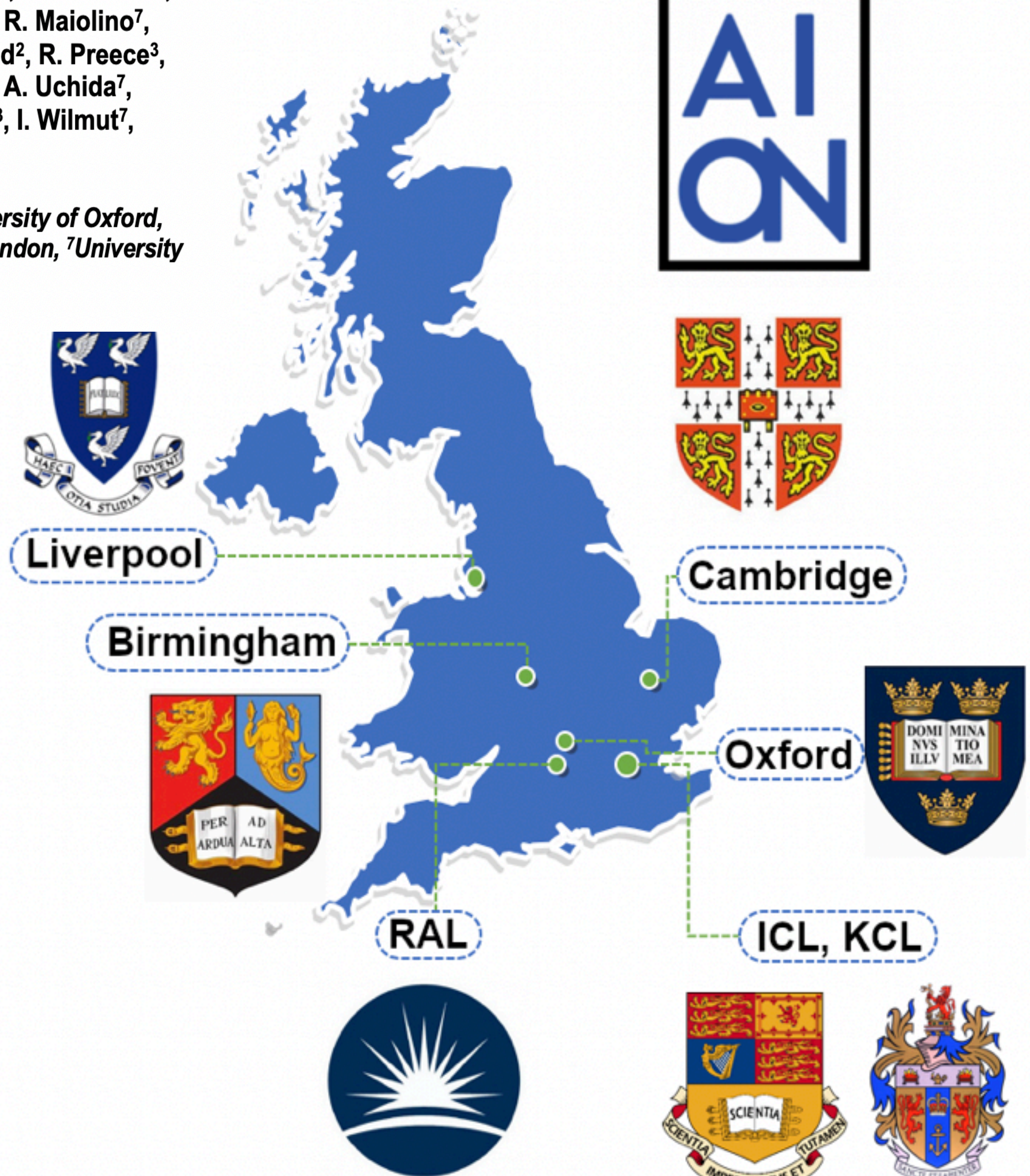


# AION Collaboration

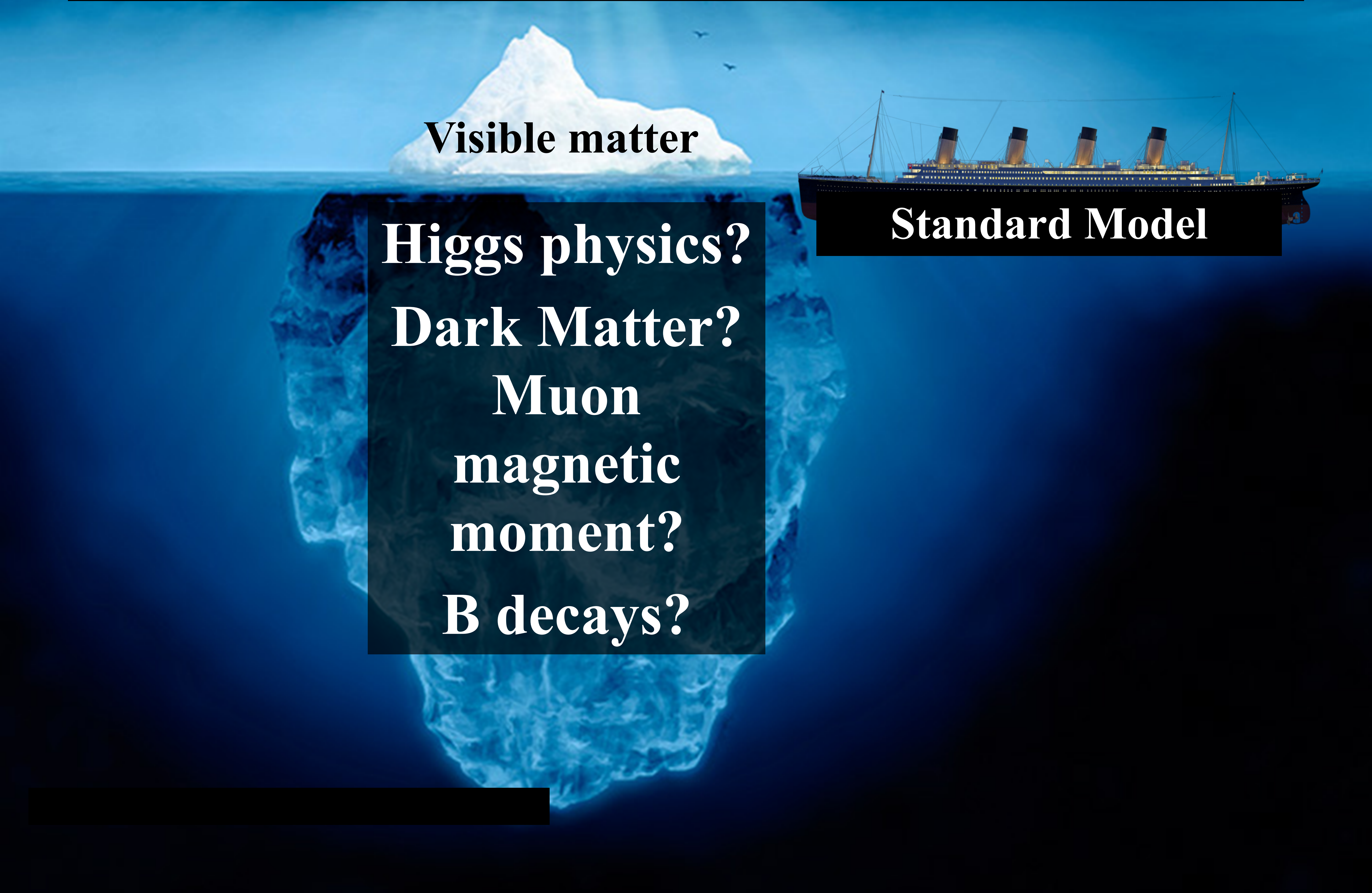

L. Badurina[1], S. Balashov[2], E. Bentine[3], D. Blas[1], J. Boehm[2], K. Bongs[4], D. Bortoletto[3], T. Bowcock[5], W. Bowden[6,*], C. Brew[2], O. Buchmueller[6], J. Coleman[5], G. Elertas[5], J. Ellis[1,&], C. Foot[3], V. Gibson[7], M. Haehnelt[7], T. Harte[7], R. Hobson[6,*], M. Holynski[4], A. Khazov[2], M. Langlois[4], S. Lellouch[4], Y.H. Lien[4], R. Maiolino[7], P. Majewski[2], S. Malik[6], J. March-Russell[3], C. McCabe[1], D. Newbold[2], R. Preece[3], B. Sauer[6], U. Schneider[7], I. Shipsey[3], Y. Singh[4], M. Tarbutt[6], M. A. Uchida[7], T. V-Salazar[2], M. van der Grinten[2], J. Vossebeld[4], D. Weatherill[3], I. Wilmut[7], J. Zielinska[6]

*[1]Kings College London, [2]STFC Rutherford Appleton Laboratory, [3]University of Oxford, [4]University of Birmingham, [5]University of Liverpool, [6]Imperial College London, [7]University of Cambridge*

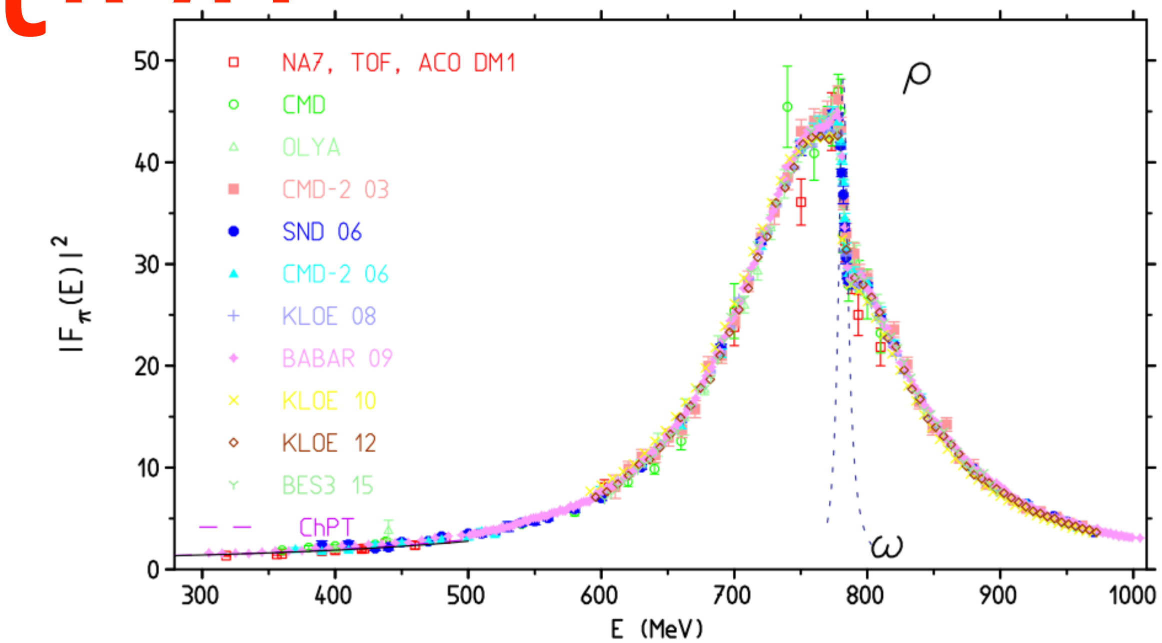



# Summary

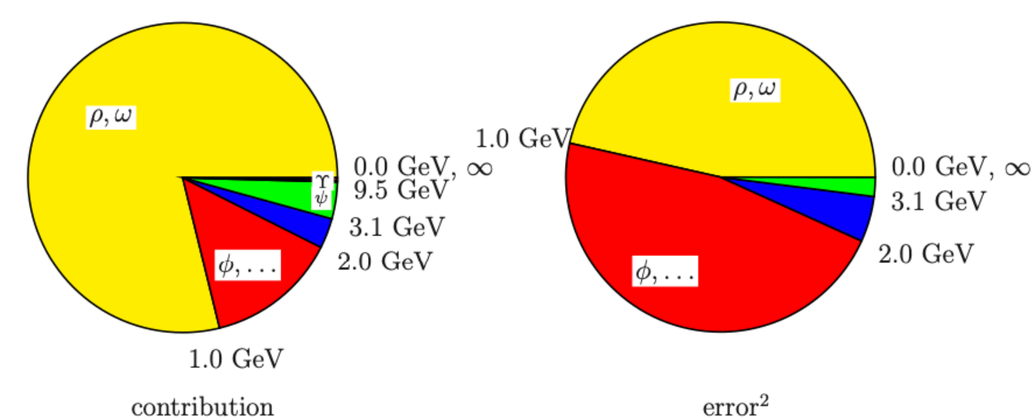

Visible matter
Higgs physics?
Dark Matter?
Muon magnetic moment?
B decays?
Standard Model
[redacted]

# Hadronic Vacuum Polarization

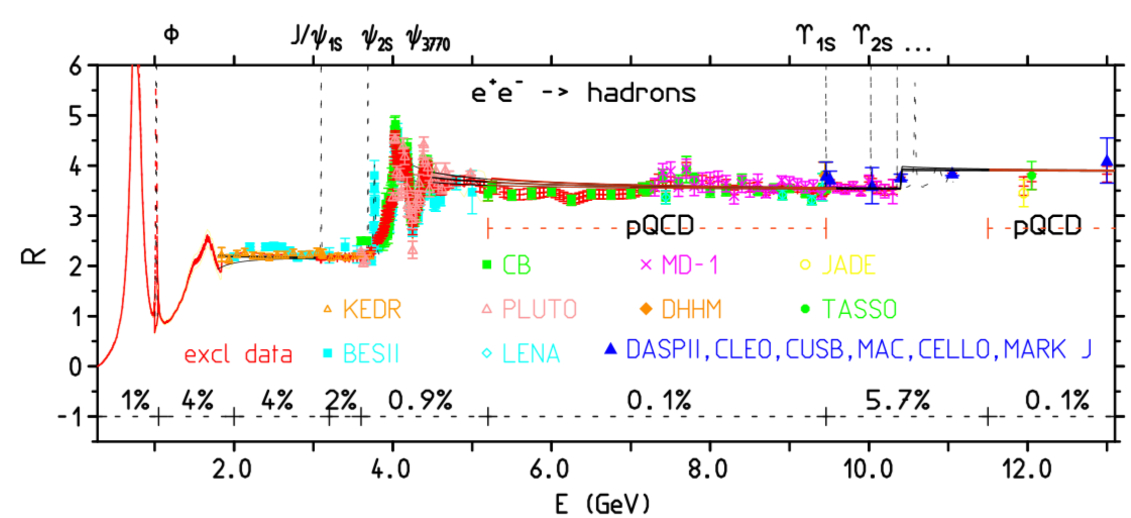
- Most important contribution is from low energies $\lesssim 1$ GeV, dominated by $\rho$ and $\omega$ peaks, taking account of interference effects




- Uncertainties dominated by $\rho$ and $\omega$ region, and by region between 1 and 2 GeV ($\phi$, etc.)




- High energies under good control from perturbative QCD




$$a_\mu^{\mathrm{HVP,\,LO}} = 693.1(2.8)_{\mathrm{exp}}(2.8)_{\mathrm{sys}}(0.7)_{\mathrm{DV+QCD}} \times 10^{-10}$$
$$= 693.1(4.0) \times 10^{-10}\,.$$

Aoyama et al, arXiv:2006.04822

Where are we?

# Summary of the Standard Model

- Particles and SU(3) × SU(2) × U(1) quantum numbers:

| | | |
|---|---|---|
| $L_L$<br>$E_R$ | $\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L , \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L , \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$<br>$e^-_R , \mu^-_R , \tau^-_R$ | ($\mathbf{1}$,$\mathbf{2}$,-1)<br>($\mathbf{1}$,$\mathbf{1}$,-2) |
| $Q_L$<br>$U_R$<br>$D_R$ | $\begin{pmatrix} u \\ d \end{pmatrix}_L , \begin{pmatrix} c \\ s \end{pmatrix}_L , \begin{pmatrix} t \\ b \end{pmatrix}_L$<br>$u_R , c_R , t_R$<br>$d_R , s_R , b_R$ | ($\mathbf{3}$,$\mathbf{2}$,+1/3)<br>($\mathbf{3}$,$\mathbf{1}$,+4/3)<br>($\mathbf{3}$,$\mathbf{1}$,-2/3) |

- Lagrangian:

$$\begin{aligned} \mathcal{L} &= -\frac{1}{4} F^a_{\mu\nu} F^{a\,\mu\nu} \\ &+ i\bar{\psi}\, \not{D} \psi + h.c. \\ &+ \psi_i y_{ij} \psi_j \phi + h.c. \\ &+ |D_\mu \phi|^2 - V(\phi) \end{aligned}$$

gauge interactions
matter fermions
Yukawa interactions
Higgs potential

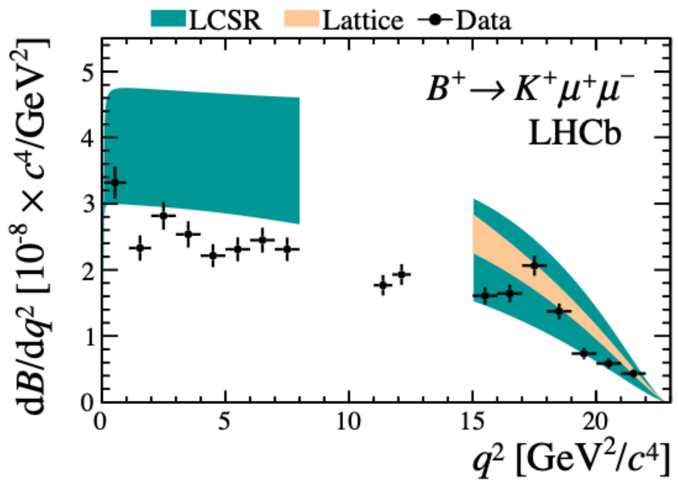
Tested < 0.1% before LHC

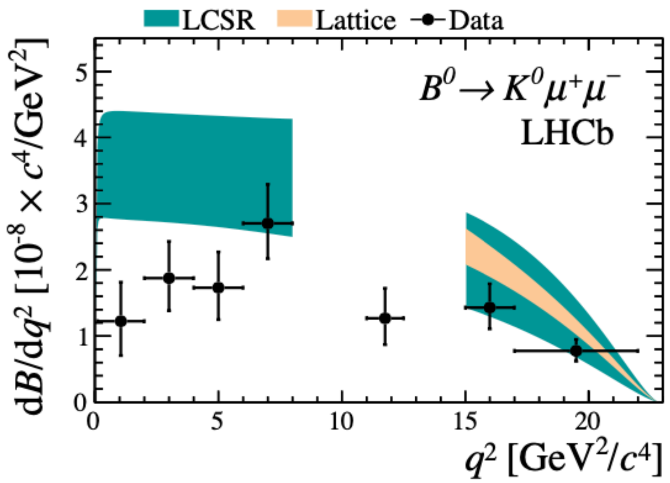
Testing now in progress

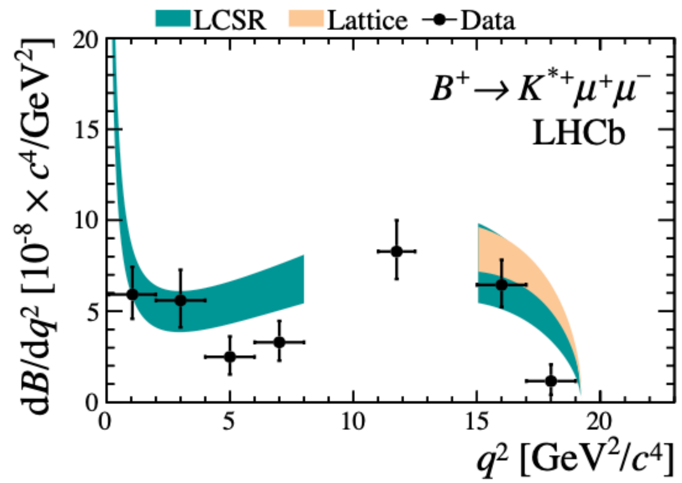
# Other Measurements

[JHEP06(2014)133]

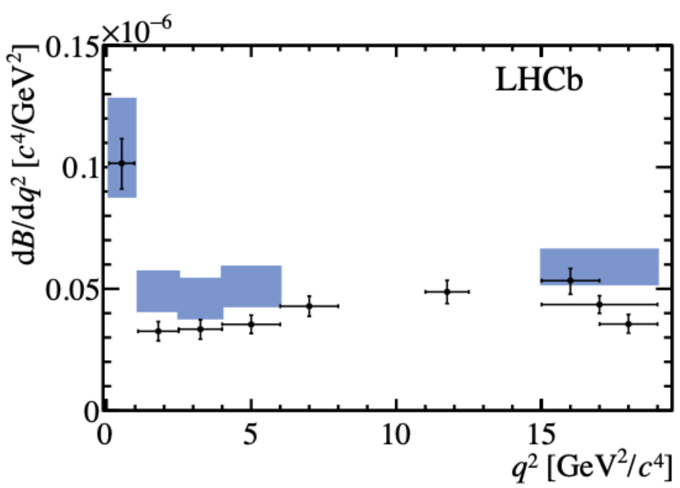
**Rates**

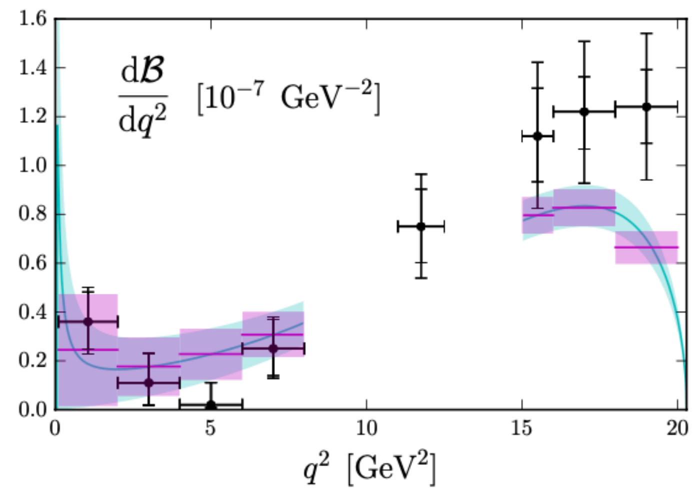


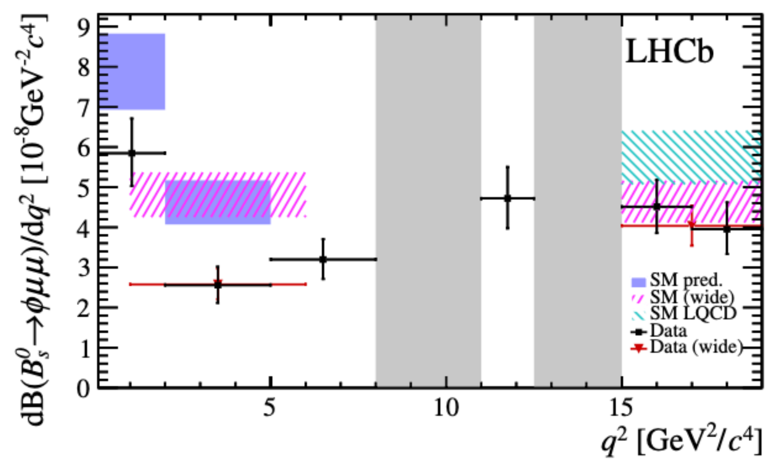




$B^0 \to K^{*0}\mu^+\mu^-$ [JHEP11(2016)047], $\Lambda_b \to \Lambda\mu^+\mu^-$ [JHEP06(2015)115] $B_s \to \phi\mu^+\mu^-$ [JHEP09(2015)179]



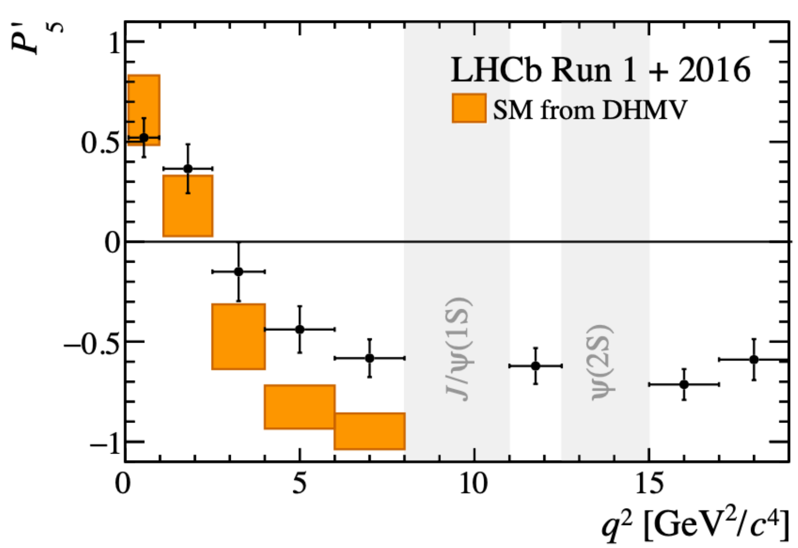



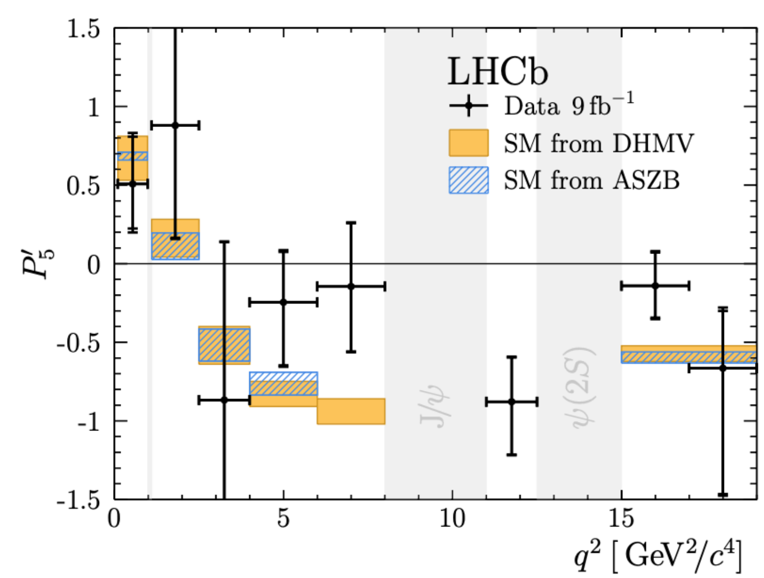




- SM predictions suffer from large hadronic uncertainties

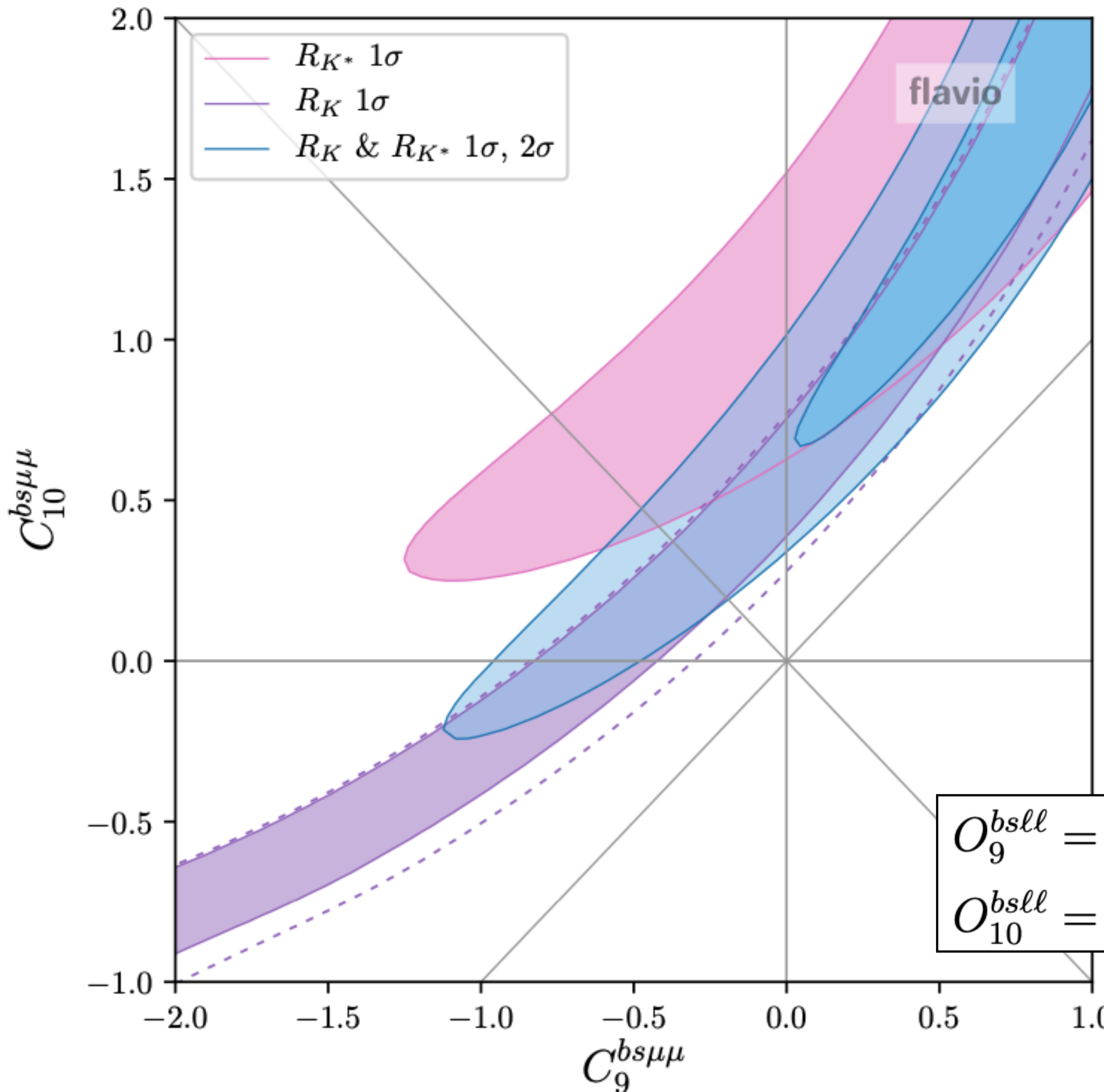
Left: $B^0 \to K^{*0}\mu^+\mu^-$ [PRL125011802(2020)], Right: $B^+ \to K^{*+}\mu^+\mu^-$ [arXiv:2012.13241]

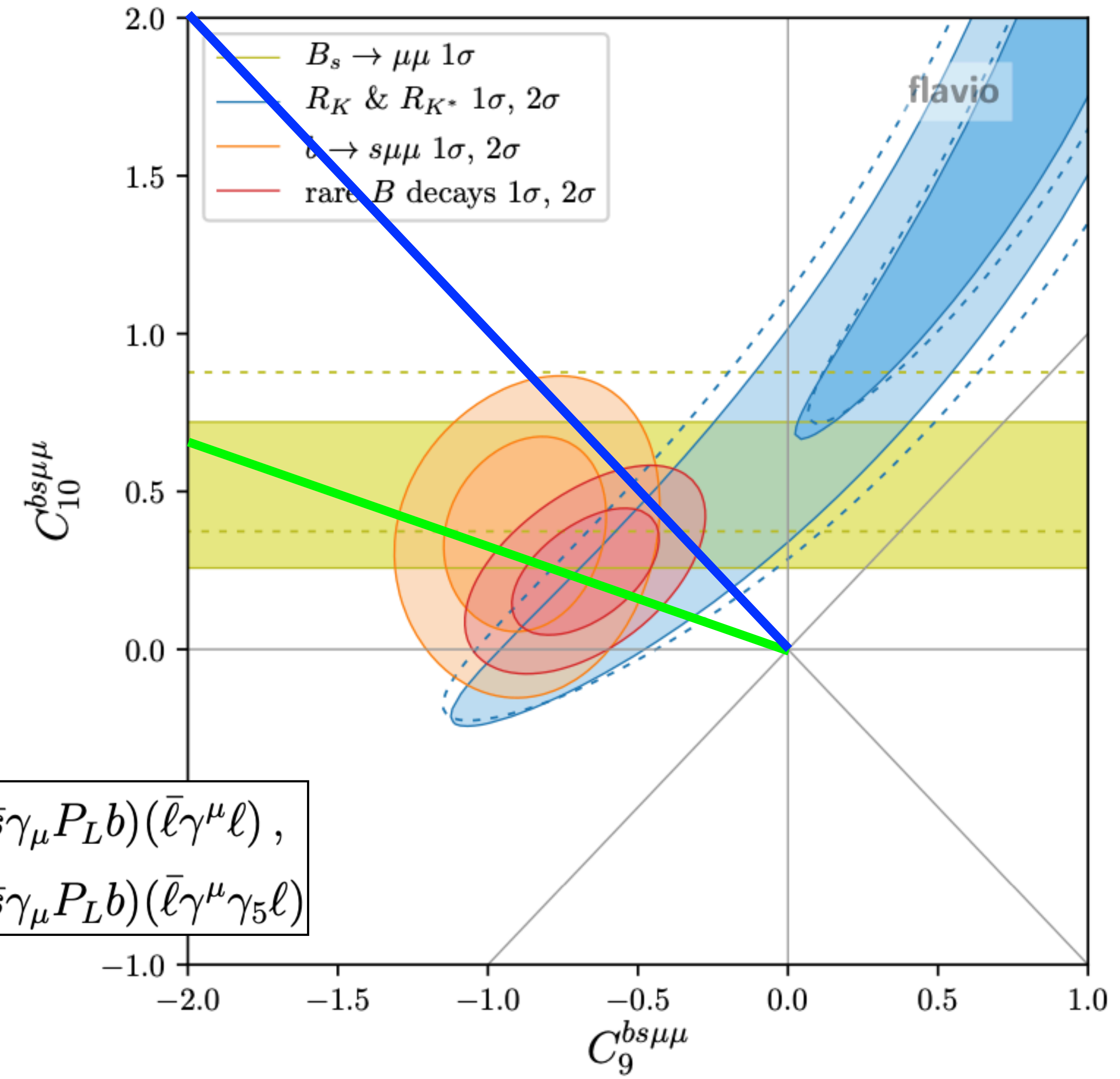
**Angular distributions**



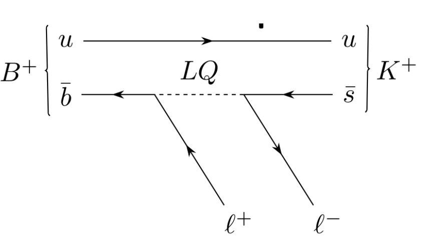



# Altmannshofer+Stangl, arXiv:2103.13370




$$O_9^{bs\ell\ell} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,,$$
$$O_{10}^{bs\ell\ell} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$




**Many interpretations invoke leptoquarks (arXiv:2103.12504, 12724, 13991), but**

## U(1)' models of flavour anomalies + dark matter

**JE+Malcolm+Tunney, arXiv:1705.03447**

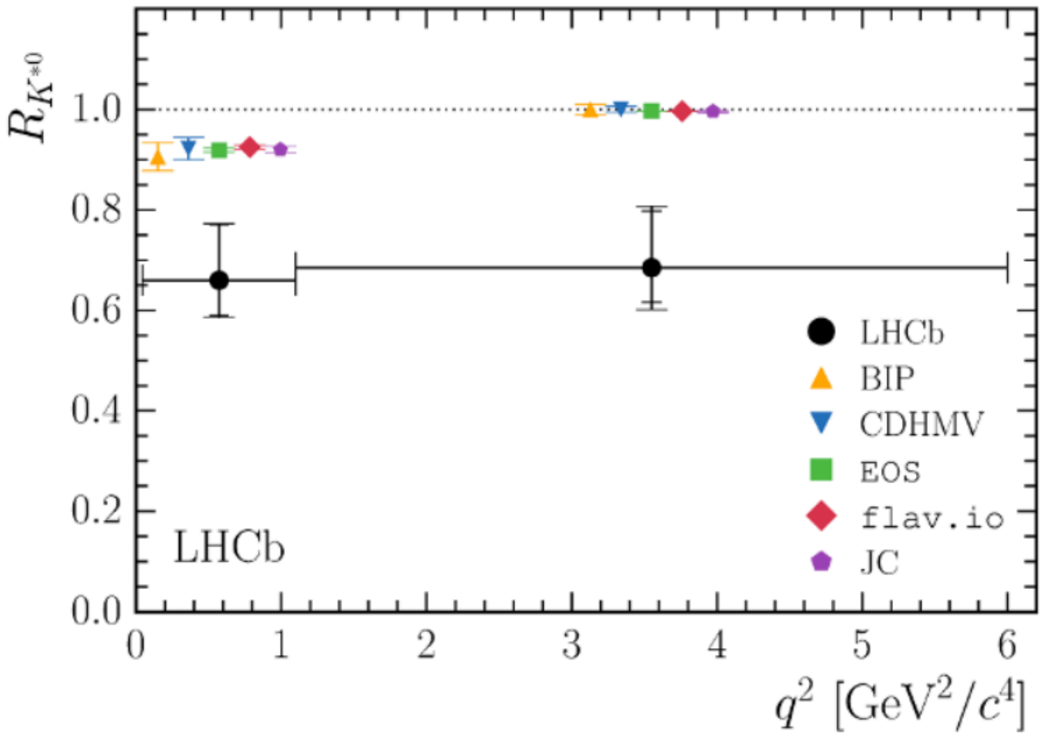
Models with only left-handed quark couplings and two dark fermions

| $Y'_{q_L}$ | $Y'_{t_L}$ | $Y'_{\mu_L}$ | $Y'_{\mu_R}$ | $Y'_{\tau_L}$ | $Y'_{\tau_R}$ | $Y'_{A_L}$ | $Y'_{A_R}$ | $Y'_{B_L}$ | $Y'_{B_R}$ |
|---|---|---|---|---|---|---|---|---|---|
| 1/3 | -2/3 | 2/3 | 1/3 | -2/3 | -1/3 | 0 | 1 | -1/3 | -4/3 |

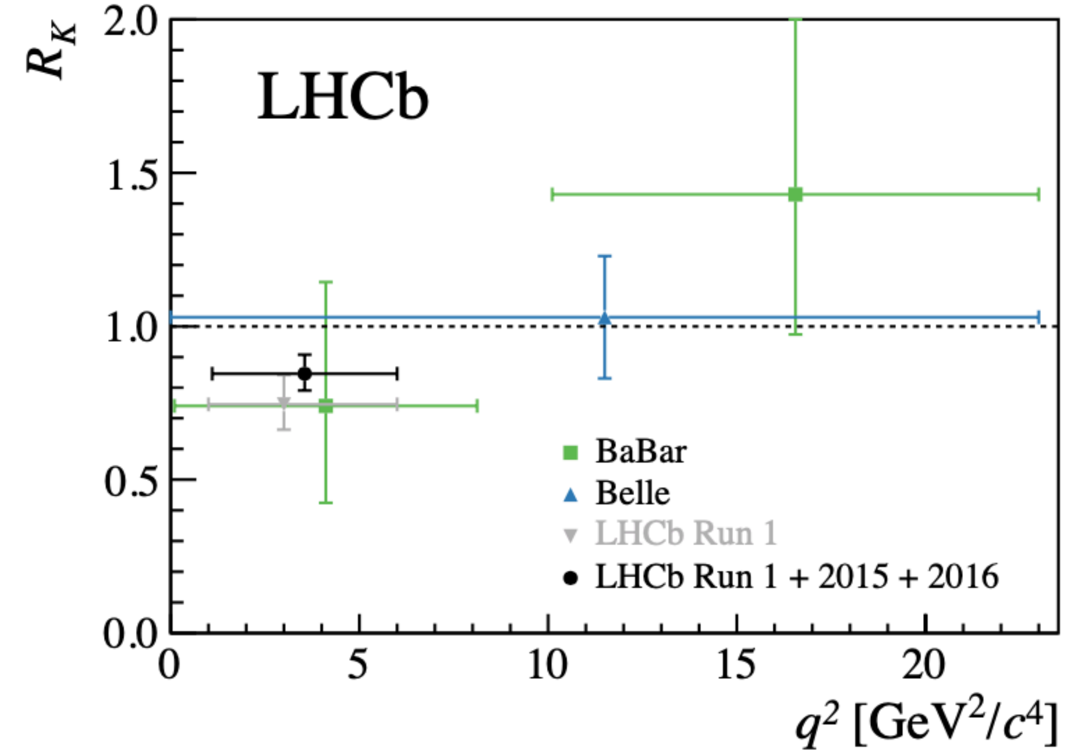
Models with right-handed charge 2/3 quark couplings and one DM fermion

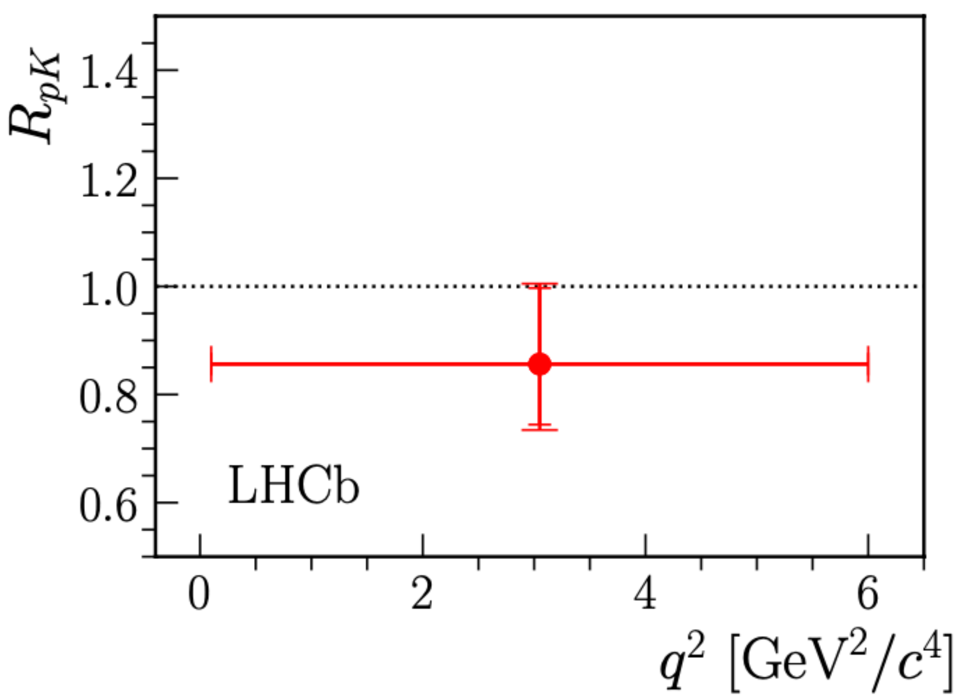
| | $Y'_{q_L}$ | $Y'_{q_R}$ | $Y'_{t_L}$ | $Y'_{t_R}$ | $Y'_{\mu_L}$ | $Y'_{\mu_R}$ | $Y'_{\tau_L}$ | $Y'_{\tau_R}$ | $Y'_{\chi_L}$ | $Y'_{\chi_R}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Vector-like $\mu$ coupling and axial DM coupling | | | | | | | | | | |
| (A) | 0 | 1 | 1 | 0 | -2 | -2 | -1 | -2 | 1 | -1 |
| Vector-like $\mu$ couplings | | | | | | | | | | |
| (B) | 1/3 | 1/3 | -1/3 | 0 | -1 | -1 | 0 | -1/3 | 1 | 1/3 |
| (C) | 1/2 | 0 | -1/2 | 1 | -1/2 | -1/2 | -1 | -3/2 | 1 | 0 |
| No first- and second-generation couplings | | | | | | | | | | |
| (D) | 0 | 0 | 1/2 | 1 | -3/2 | -2 | 0 | 0 | 1 | 0 |
| (E) | 0 | 0 | 1/2 | 1 | -3/2 | 0 | 0 | -2 | 1 | 0 |

# Previous LHCb Measurements




BaBar:[PRD86(2012)032012],Belle:[PRL103(2009)171801]




Left: $B^0 \to K^{*0}\ell^+\ell^-$ $R_{K^*}$ $3\mathrm{fb}^{-1}$
[JHEP08(2017)055]

Right: $B^+ \to K^+\ell^+\ell^-$ $R_K$ $5\mathrm{fb}^{-1}$
[PRL122(2019)191801]

Bottom: $\Lambda_b \to pK\ell^+\ell^-$ $R_{pK}$ $4.7\mathrm{fb}^{-1}$
[JHEP05(2020)040]