IN WAITING FOR NEW DISCOVERIES IN PARTICLE PHYSICS

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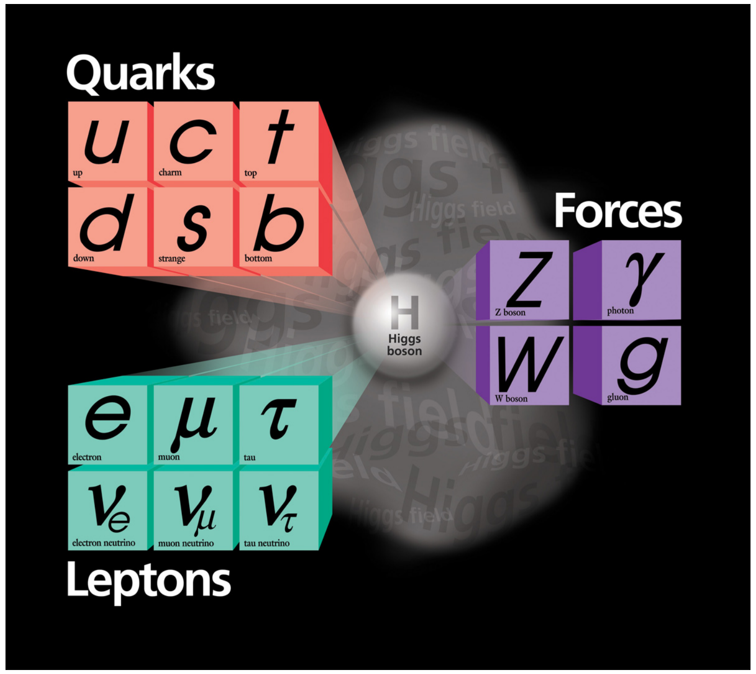
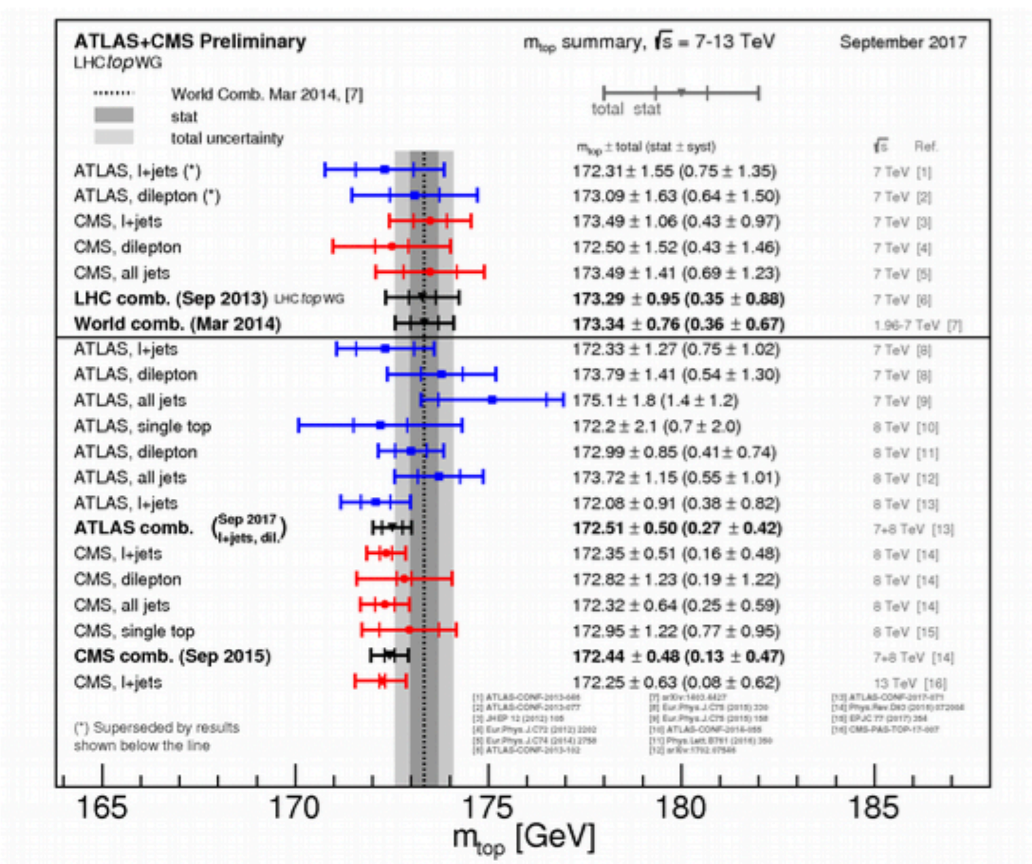
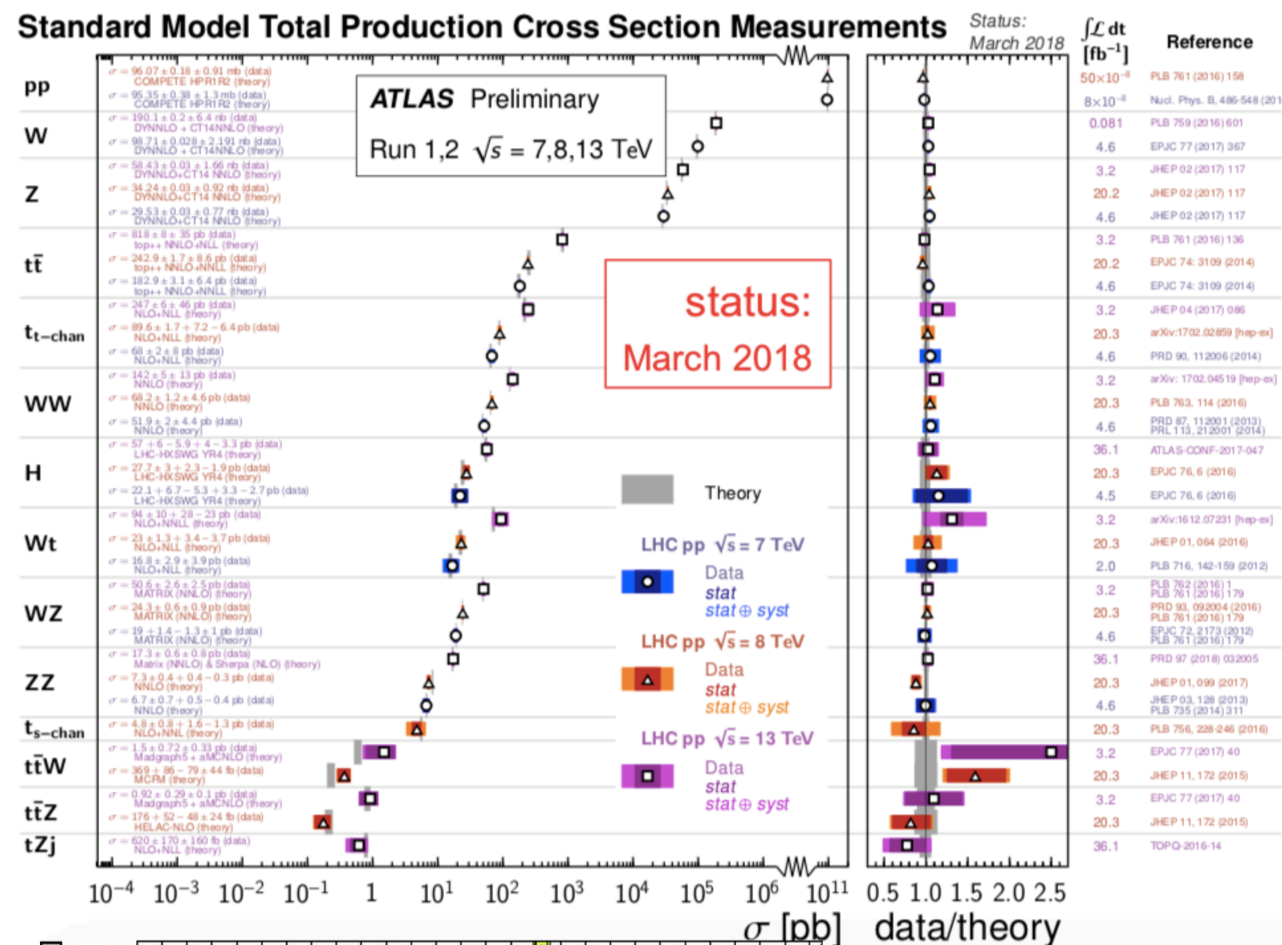
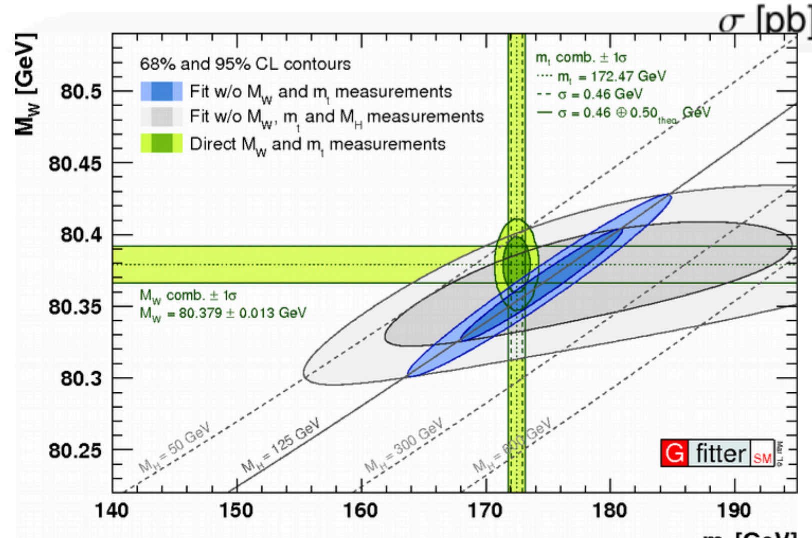
The Standard Model









Extraordinary agreement between measurements and SM predictions

- With the Higgs Boson discovery the Standard Model is completed !
- Why are we not satisfied and think that new physics exists and new discoveries will come?

- There are conceptional problems which require a critical view beyond the SM
- There are small discrepancies which might grow up to become a problem for the SM
- It is hard to believe that the quest for the miracle of Nature is over

THE LAGRANGIAN

$$\mathcal{L} = \mathcal{L}_{gauge} + \mathcal{L}_{Yukawa} + \mathcal{L}_{Higgs},$$

$$\mathcal{L}_{gauge} = -\frac{1}{4}G^a_{\mu\nu}G^a_{\mu\nu} - \frac{1}{4}W^i_{\mu\nu}W^i_{\mu\nu} - \frac{1}{4}B_{\mu\nu}B_{\mu\nu}$$

$$+i\overline{L}_\alpha\gamma^\mu D_\mu L_\alpha + i\overline{Q}_\alpha\gamma^\mu D_\mu Q_\alpha + i\overline{E}_\alpha\gamma^\mu D_\mu E_\alpha$$

$$+i\overline{U}_\alpha\gamma^\mu D_\mu U_\alpha + i\overline{D}_\alpha\gamma^\mu D_\mu D_\alpha + (D_\mu H)^\dagger(D_\mu H),$$

$$+i\overline{N}_\alpha\gamma^\mu\partial_\mu N_\alpha$$

possible right handed neutrino ?

$$\mathcal{L}_{Yukawa} = y^L_{\alpha\beta}\overline{L}_\alpha E_\beta H + y^D_{\alpha\beta}\overline{Q}_\alpha D_\beta H + y^U_{\alpha\beta}\overline{Q}_\alpha U_\beta\tilde{H} + h.c.,$$

$$+y^N_{\alpha\beta}\overline{L}_\alpha N_\beta\tilde{H}$$

$$\mathcal{L}_{Higgs} = -V = m^2 H^\dagger H - \frac{\lambda}{2}(H^\dagger H)^2$$

THE LAGR

$\mathcal{L}$

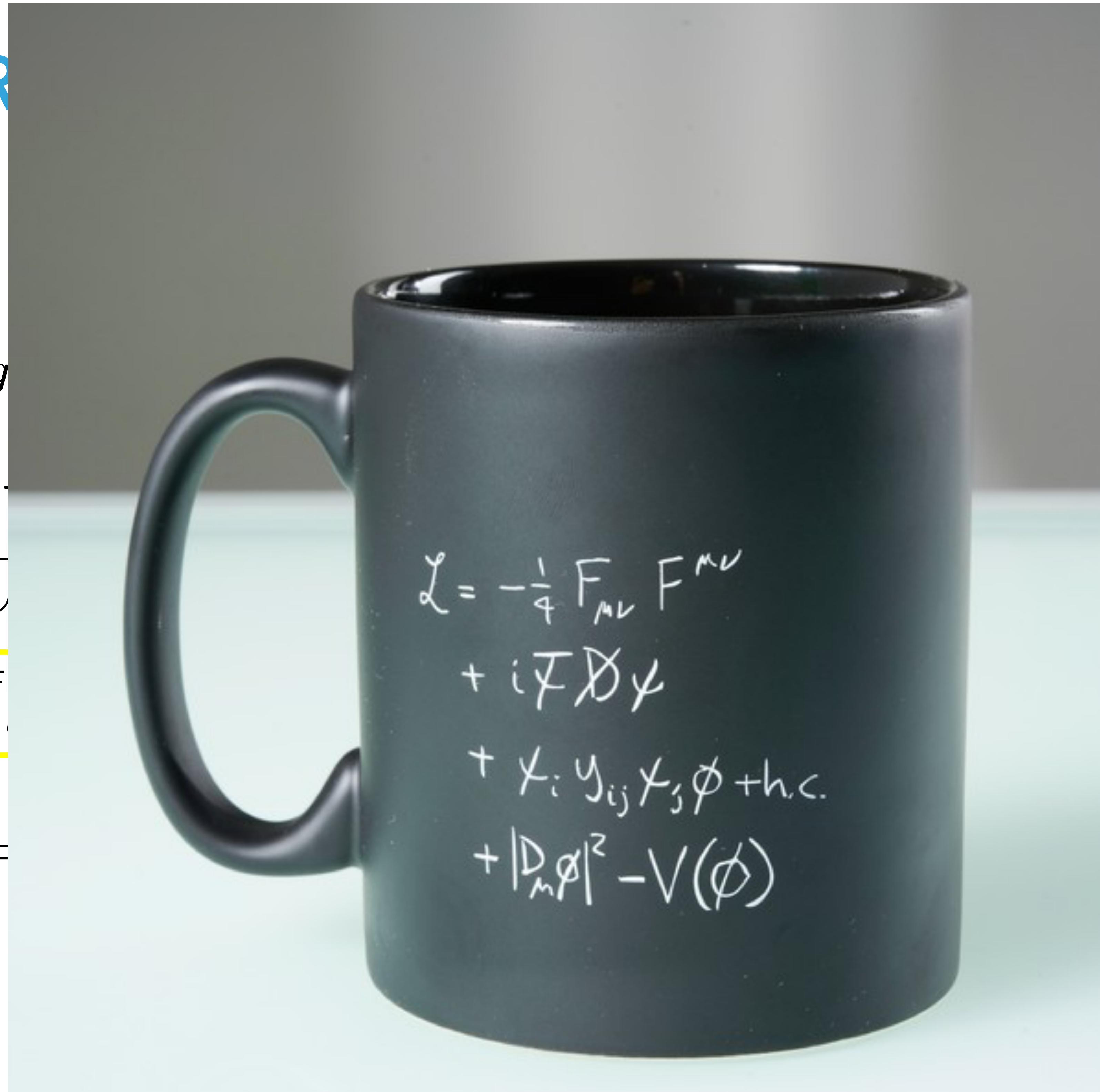
$\mathcal{L}_g$ … $_{\mu\nu}B_{\mu\nu}$

… $D_\mu E_\alpha$

$+i\overline{U}$ … $D_\mu H)$,

$+i\overline{N}$ …

$\mathcal{L}_{Yukawa} =$ … $\tilde{H} + h.c.,$



$$\mathcal{L}_{Higgs} = -V = m^2 H^\dagger H - \frac{\lambda}{2}(H^\dagger H)^2$$

THE LAGRANGIAN

$$\mathcal{L} = \mathcal{L}_{gauge} + \mathcal{L}_{Y}$$

$$\mathcal{L}_{gauge} = -\frac{1}{4}G^{a}_{\mu\nu}$$

$$+i\overline{L}_\alpha\gamma^\mu D_\mu L_\alpha$$

$$+i\overline{U}_\alpha\gamma^\mu D_\mu U_\alpha + i$$

$$+i\overline{N}_\alpha\gamma^\mu\partial_\mu N_\alpha$$

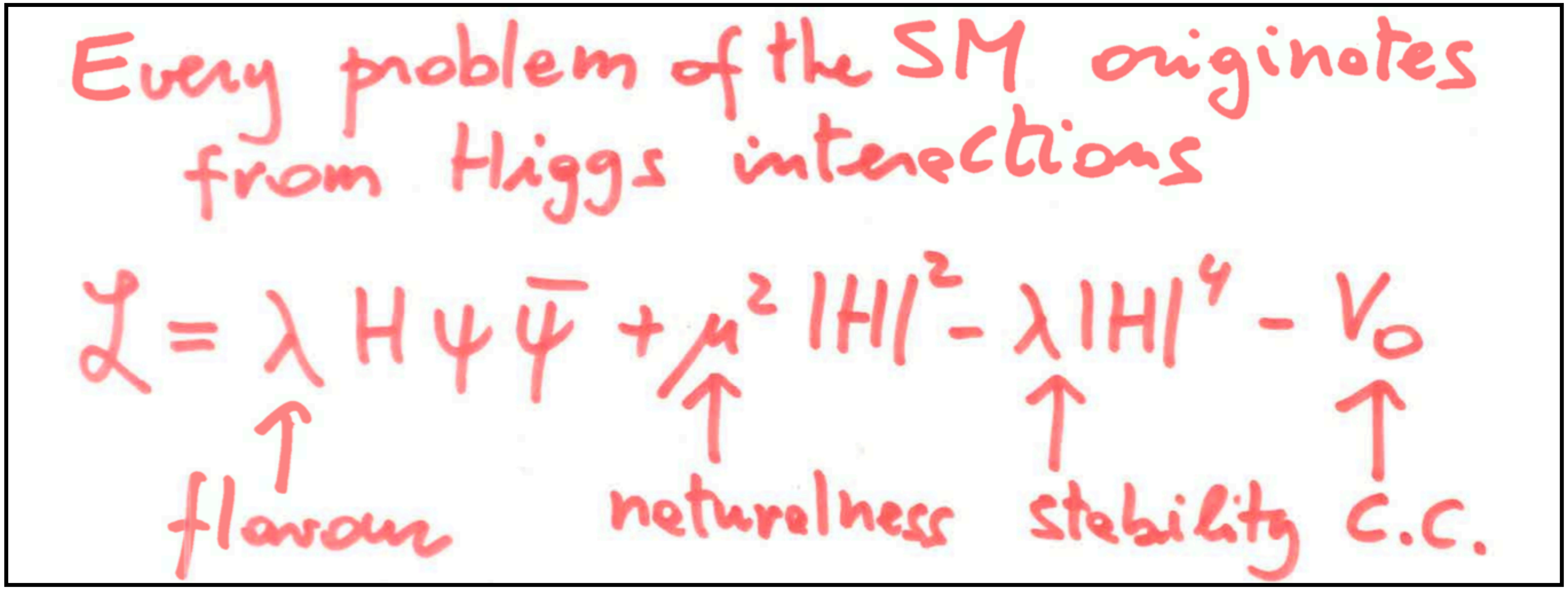
$$\mathcal{L}_{Yukawa} = y^{L}_{\alpha\beta}\overline{L}_\alpha E_\beta H +$$

$$+y^{N}_{\alpha\beta}\overline{L}_\alpha N_\beta$$

$$\mathcal{L}_{Higgs} = -V =$$

$$\begin{gathered}
\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g^a_\mu\partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu\partial_\nu W^-_\mu - \\
M^2W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu\partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)) - \\
igs_w(\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - \\
W^-_\nu\partial_\nu W^+_\mu)) - \tfrac{1}{2}g^2W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2s_wc_w(A_\mu Z^0_\nu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H\partial_\mu H - 2M^2\alpha_h H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - \tfrac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \\
\beta_h\left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right) + \tfrac{2M^4}{g^2}\alpha_h - \\
g\alpha_h M\left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) - \\
\tfrac{1}{8}g^2\alpha_h\left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2\right) - \\
gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \\
\tfrac{1}{2}ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) + \\
\tfrac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) + \\
M\left(\tfrac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+\right) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_wMA_\mu(W^+_\mu\phi^- - \\
W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \\
\tfrac{1}{4}g^2W^+_\mu W^-_\mu\left(H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right) - \tfrac{1}{8}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu\left(H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-\right) - \\
\tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2s_wA_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \tfrac{1}{2}ig^2s_wA_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - \\
g^2s_w^2A_\mu A_\mu\phi^+\phi^- + \tfrac{1}{2}ig_s\lambda^a_{ij}(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda(\gamma\partial + m^\lambda_\nu)\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + \\
m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_wA_\mu\left(-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)\right) + \\
\tfrac{ig}{4c_w}Z^0_\mu\{(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{d}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - 1 - \gamma^5)d^\lambda_j) + \\
(\bar{u}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 + \gamma^5)u^\lambda_j)\} + \tfrac{ig}{2\sqrt{2}}W^+_\mu\left((\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) + \\
\tfrac{ig}{2\sqrt{2}}W^-_\mu\left((\bar{e}^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_e(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_e(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa\right) - \tfrac{g}{2}\tfrac{m^\lambda_\nu}{M}H(\bar{\nu}^\lambda\nu^\lambda) - \\
\tfrac{g}{2}\tfrac{m^\lambda_e}{M}H(\bar{e}^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{m^\lambda_\nu}{M}\phi^0(\bar{\nu}^\lambda\gamma^5\nu^\lambda) - \tfrac{ig}{2}\tfrac{m^\lambda_e}{M}\phi^0(\bar{e}^\lambda\gamma^5e^\lambda) - \tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa - \\
\tfrac{1}{4}\overline{\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa} + \tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_d(\bar{u}^\lambda_jC_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_jC_{\lambda\kappa}(1+\gamma^5)d^\kappa_j\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_d(\bar{d}^\lambda_jC^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_jC^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j\right) - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar{u}^\lambda_ju^\lambda_j) - \\
\tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar{d}^\lambda_jd^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5d^\lambda_j) + \bar{G}^a\partial^2G^a + g_sf^{abc}\partial_\mu\bar{G}^aG^bg^c_\mu + \\
\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2Y + igc_wW^+_\mu(\partial_\mu\bar{X}^0X^- - \\
\partial_\mu\bar{X}^+X^0) + igs_wW^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+Y) + igc_wW^-_\mu(\partial_\mu\bar{X}^-X^0 - \\
\partial_\mu\bar{X}^0X^+) + igs_wW^-_\mu(\partial_\mu\bar{X}^-Y - \partial_\mu\bar{Y}X^+) + igc_wZ^0_\mu(\partial_\mu\bar{X}^+X^+ - \\
\partial_\mu\bar{X}^-X^-) + igs_wA_\mu(\partial_\mu\bar{X}^+X^+ - \\
\partial_\mu\bar{X}^-X^-) - \tfrac{1}{2}gM\left(\bar{X}^+X^+H + \bar{X}^-X^-H + \tfrac{1}{c_w^2}\bar{X}^0X^0H\right) + \tfrac{1-2c_w^2}{2c_w}igM\left(\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-\right) + \\
\tfrac{1}{2c_w}igM\left(\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-\right) + igMs_w\left(\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-\right) + \\
\tfrac{1}{2}igM\left(\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0\right).
\end{gathered}$$

THE LAGRANGIAN

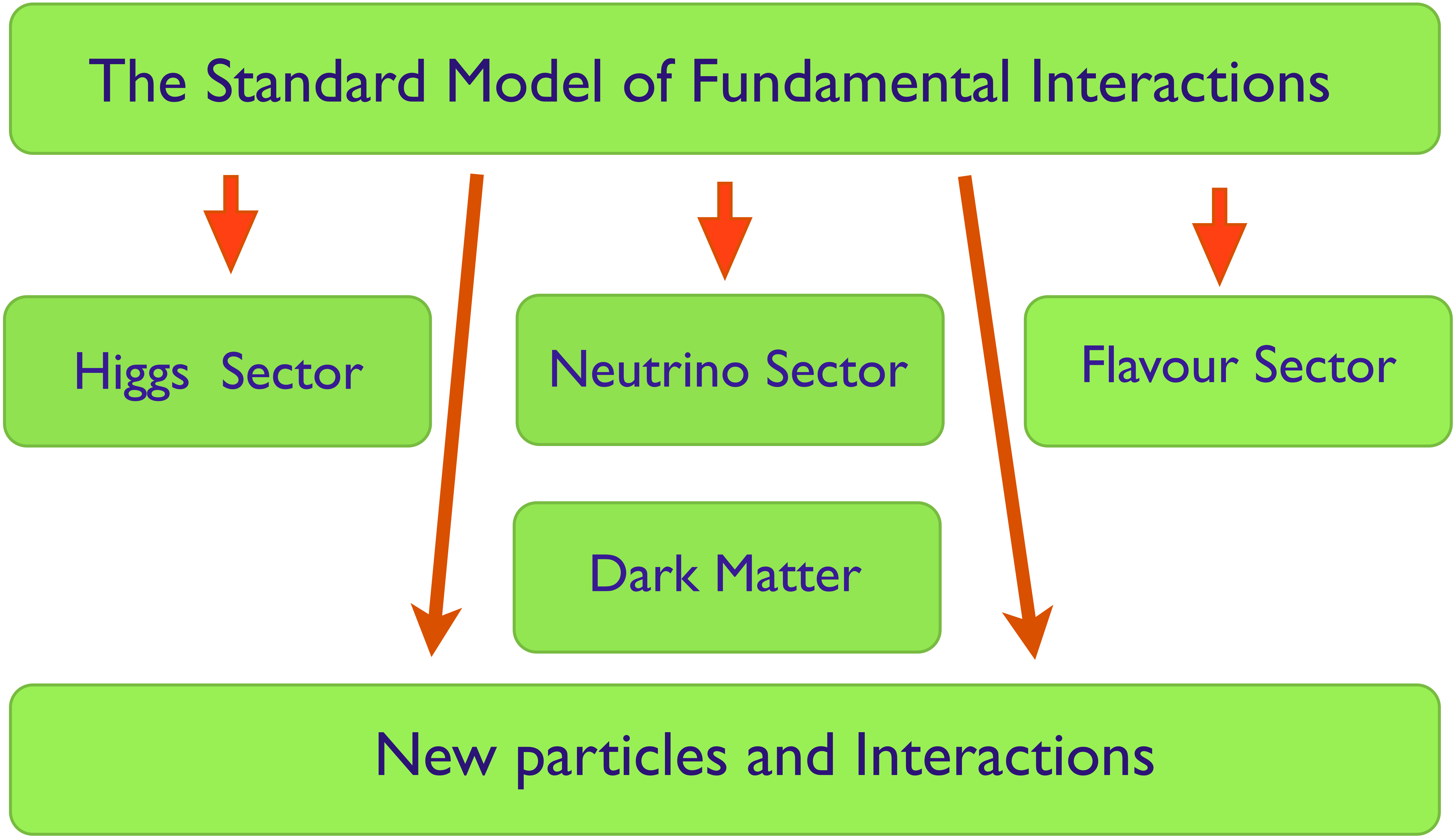


G.F. Giudice

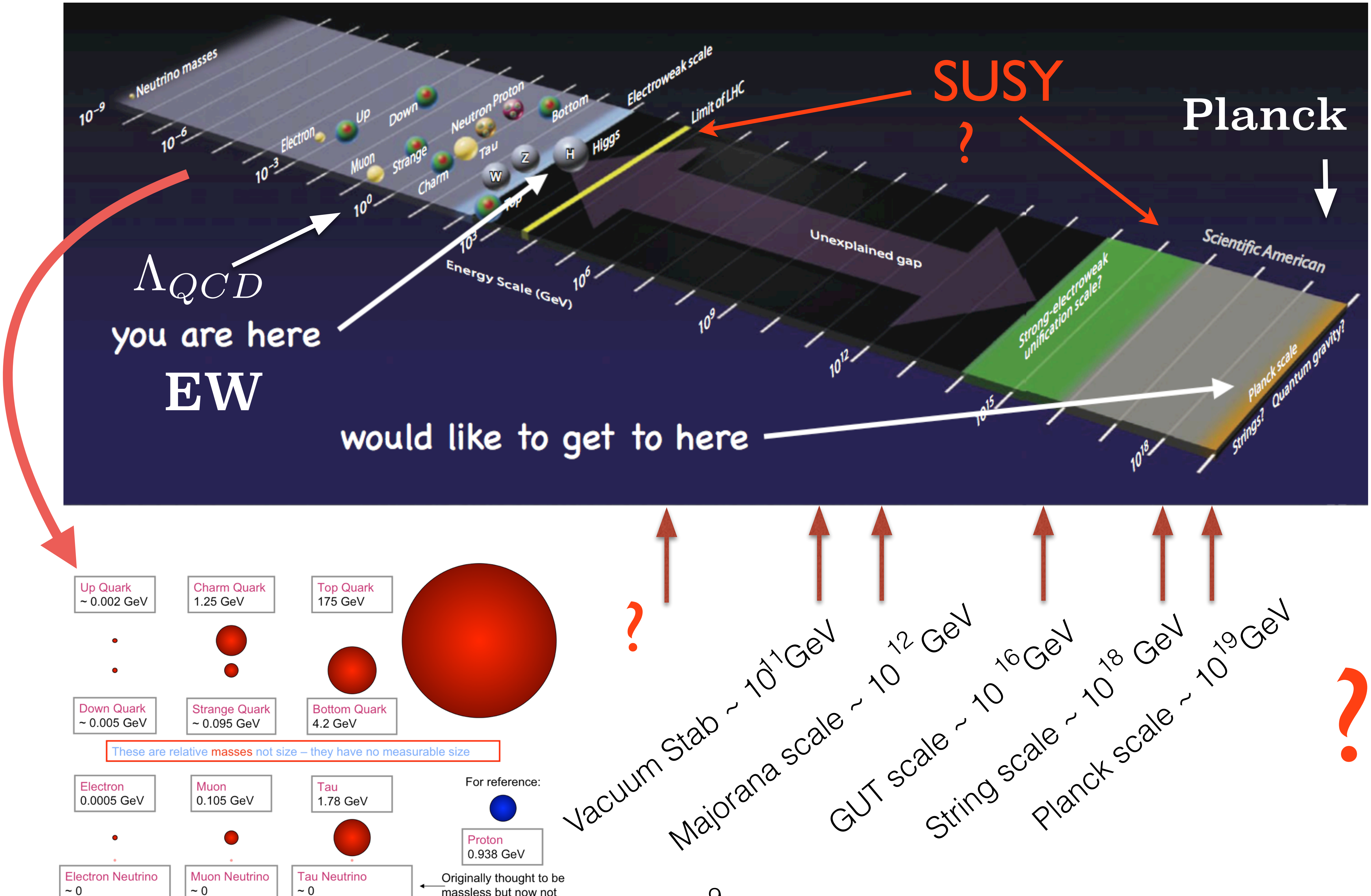
The H boson is not just … "another particle":

- ❑ Profoundly different from all elementary particles discovered previously
- ❑ It got almost no properties; brings a different type of "force"
- ❑ Related to the most obscure sector of Standard Model
- ❑ Linked to some of the deepest structural questions (flavour, naturalness, vacuum, ...)
- → Its discovery opens new paths of exploration, provides a unique door into new physics, and calls for a very broad and challenging experimental programme which will extend for decades

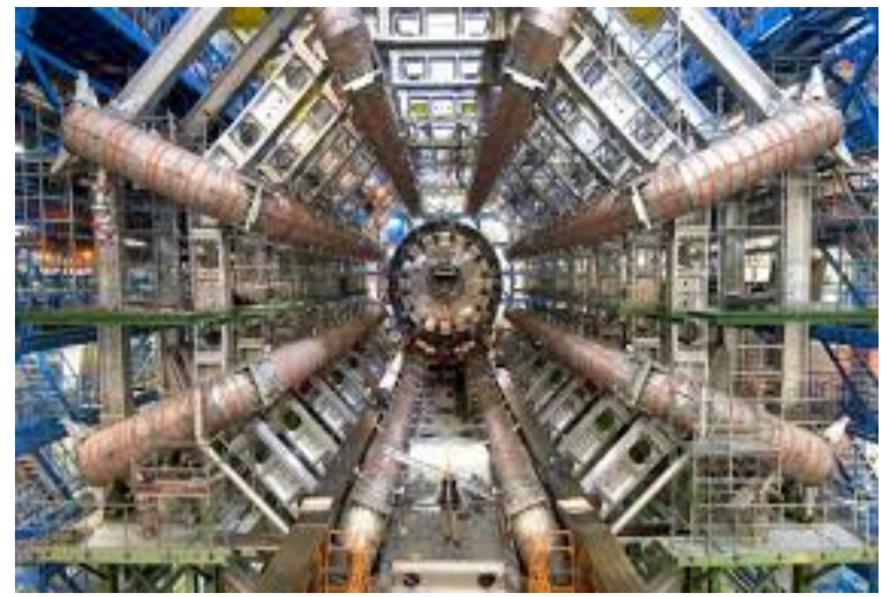
THE STANDARD MODEL: THE WAYS BEYOND

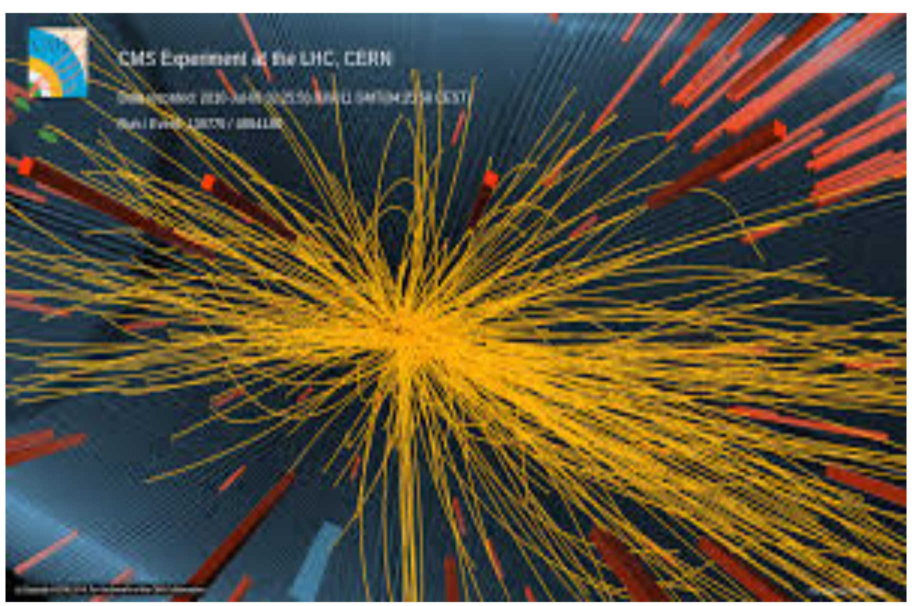


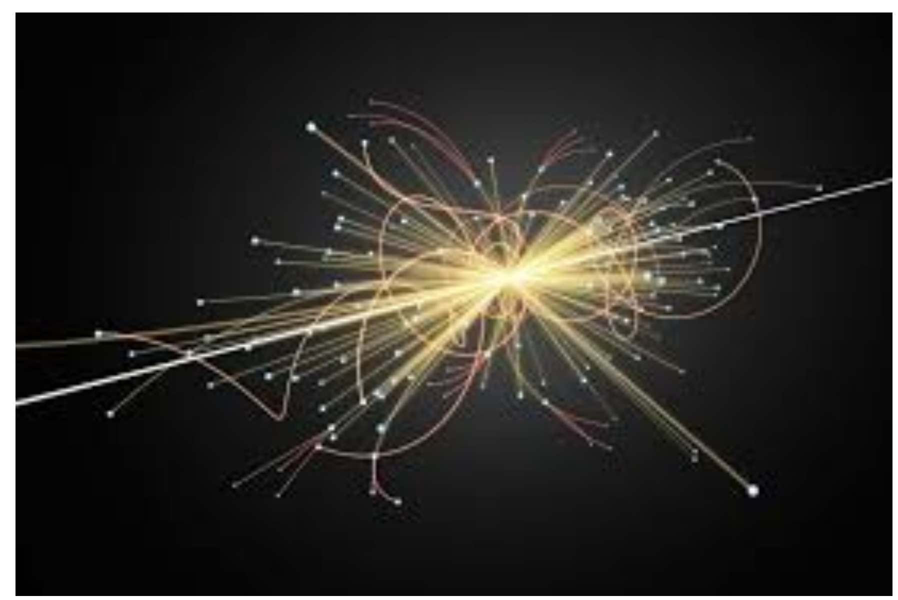
Is there another scale except for EW and Planck?



Accelerator Physics

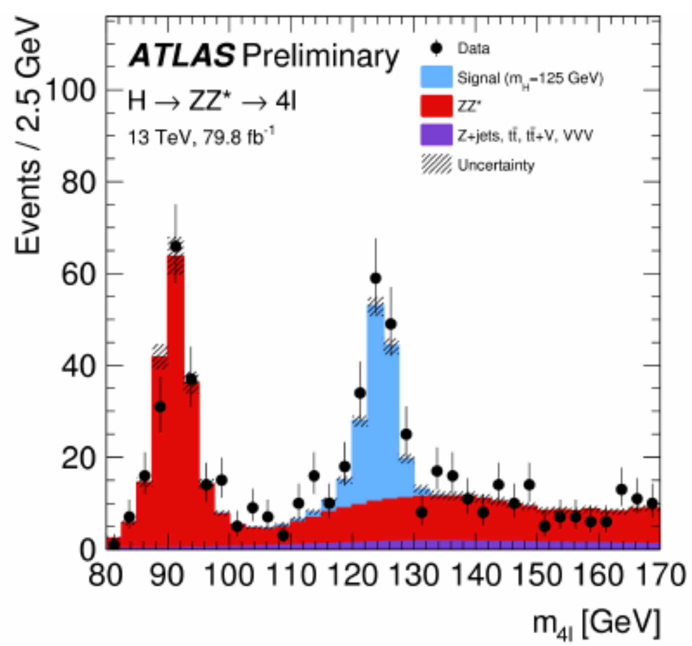


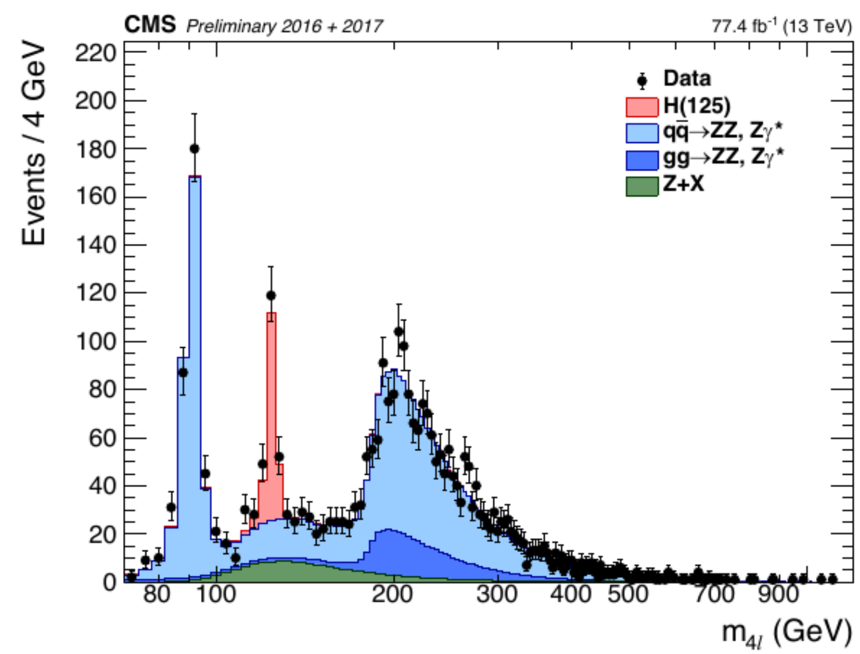


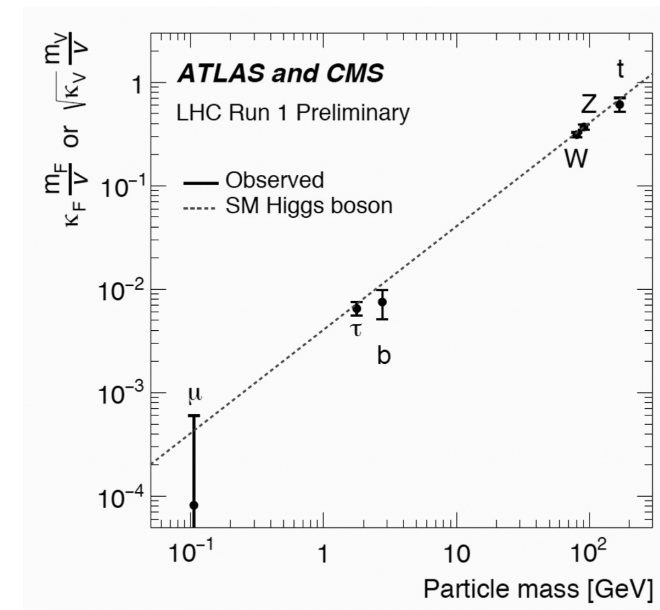


Higgs bosons - entering precision era

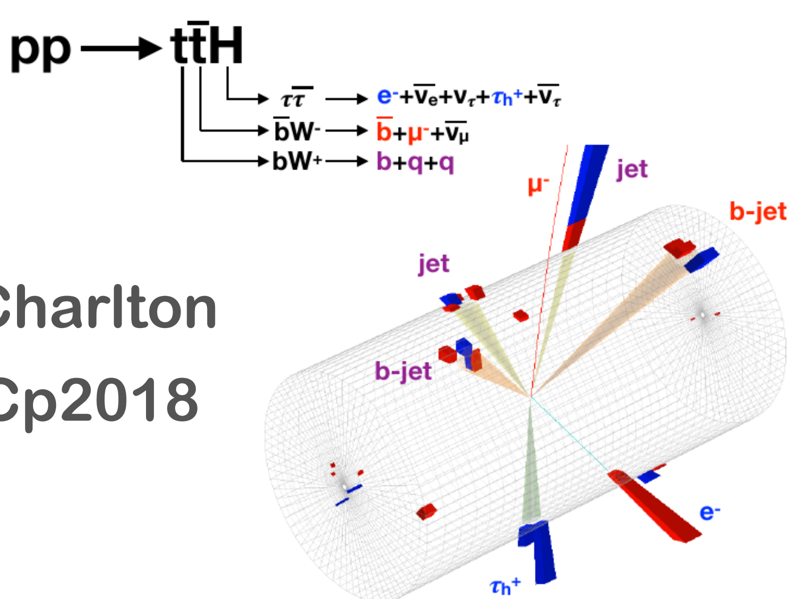
Run-2 analyses with 80 fb^{-1} for the first time – higher precision is coming!

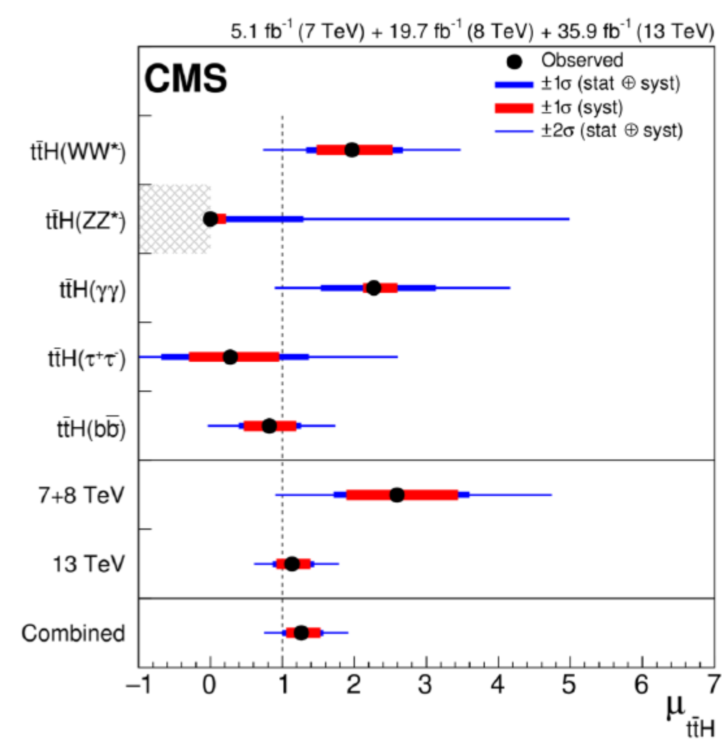


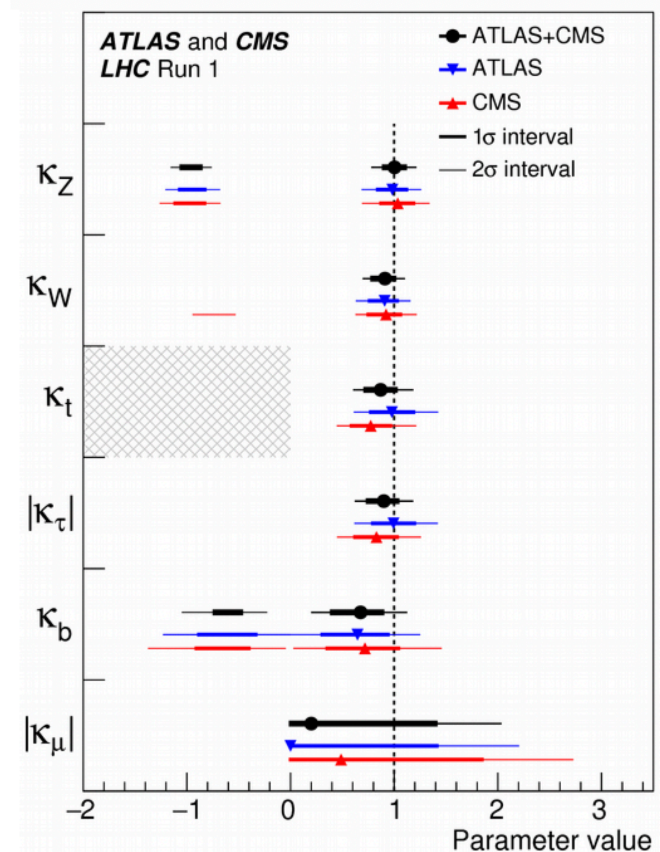




ttH observation

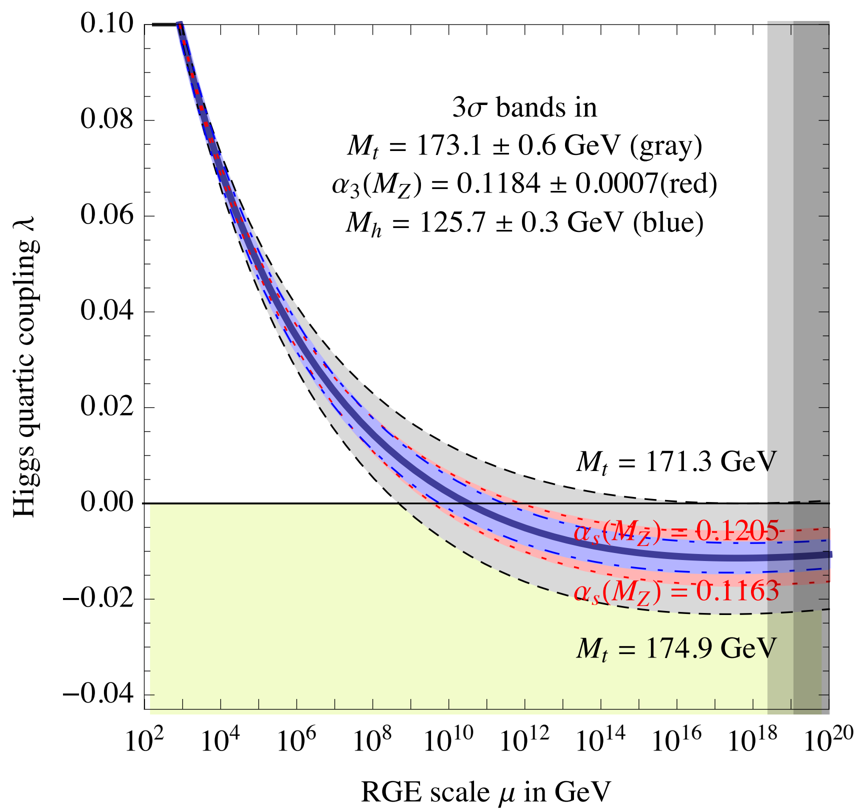


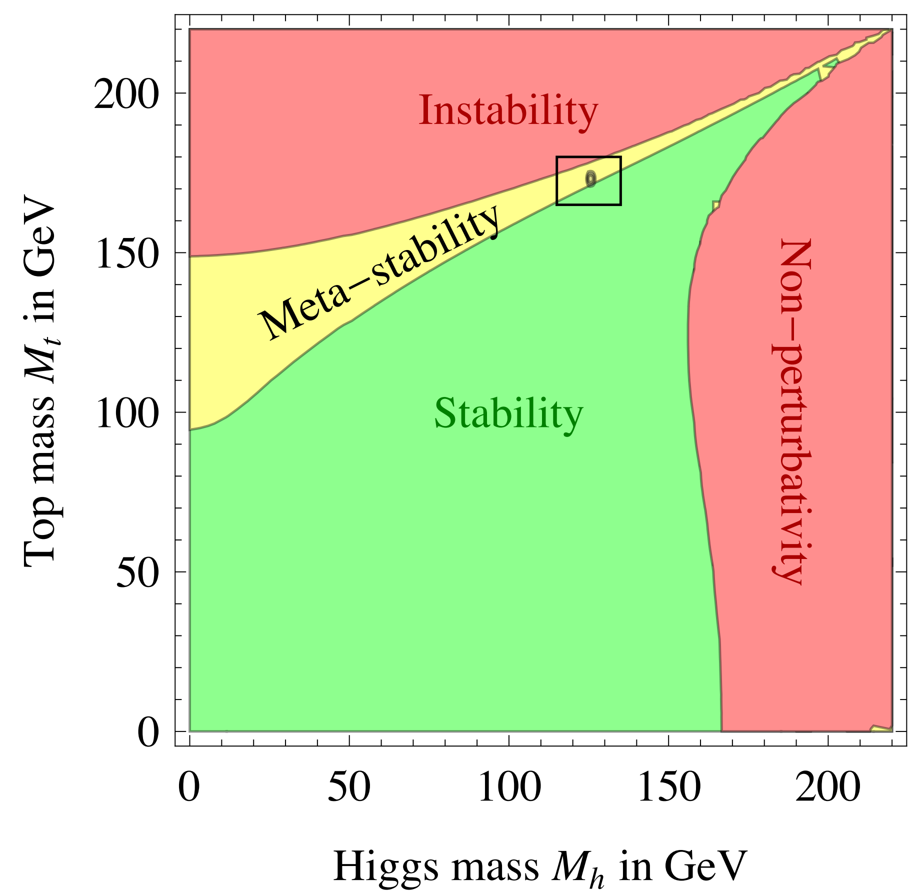




D. Charlton
LHCp2018

- The electroweak vacuum is unstable under radiative corrections
- The whole construction of the SM may be in trouble being metastable or even unstable



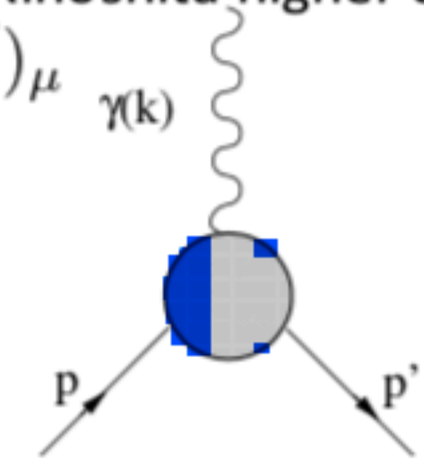


- the situation crucially depends on the top and Higgs mass values and requires severe fine-tuning and high accuracy of calculations (3 loops)

Muon anomalous magnetic moment

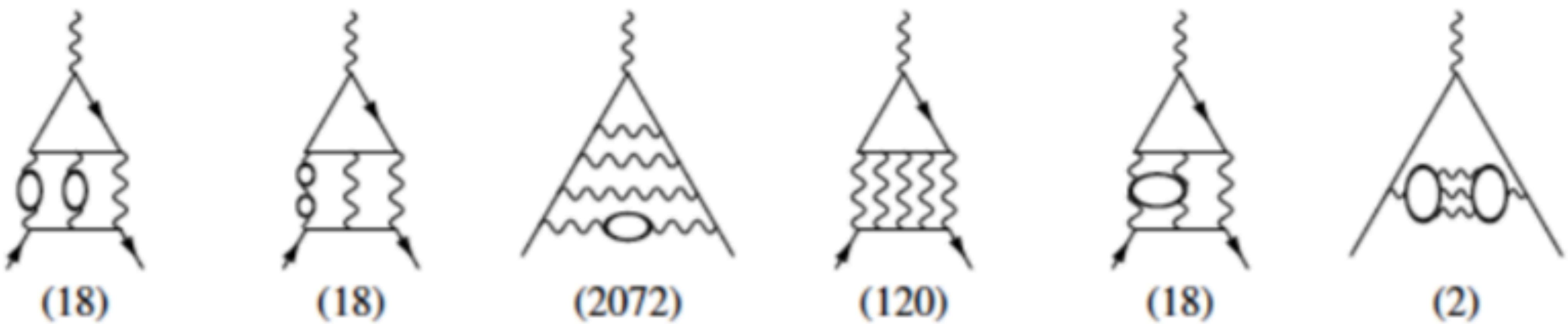
(Schwinger α/π, Kinoshita higher orders in α)

$$ie\bar{u}_\ell(p')\left[\gamma^\mu - \frac{a_\ell}{2m_\ell} i\sigma^{\mu\nu} q_\nu\right] u_\ell(p)\epsilon^*_\mu, \qquad q_\mu = (p-p')_\mu$$



Dirac equation predicts g=2 $a = (g-2)/2$

For electron a_e theory and experiment agrees!



$$a_\mu^{th} - a_\mu^{exp} = -(3.06 \pm 0.76) \times 10^{-8}$$ 4 σ

Theory: uncertainty in hadronic contributions to the muon g – 2, (Jägerlehner, 1802.08019).
Lattice QCD great progress light-by-light study (RBC & UKQCD, 1801.07224).

Fermilab and J-Park experiments are expected to clarify existing discrepancy!

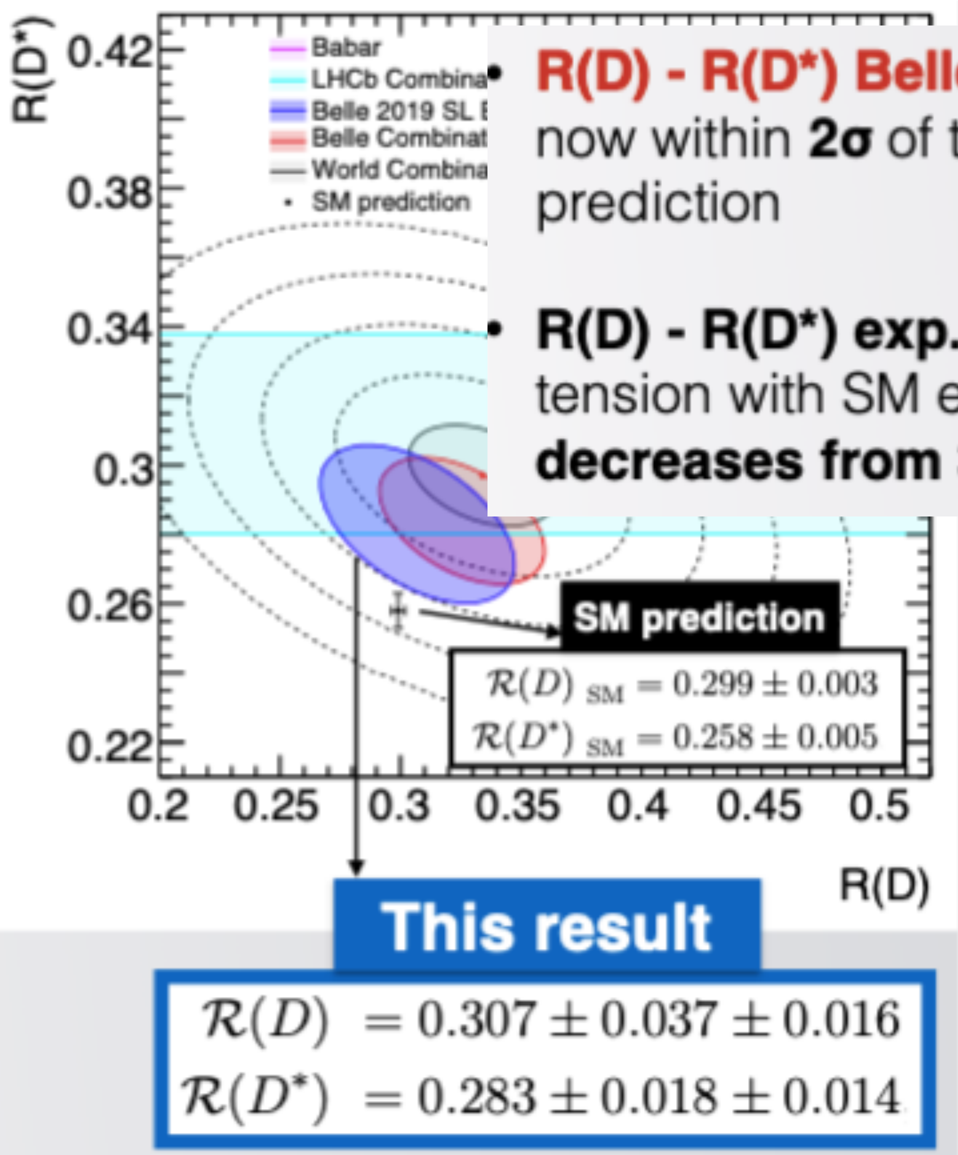
B physics anomalies: experimental results ≠ SM predictions!

charged current (SM tree level)

$$R_{D^{(*)}} = \frac{BR(B \to D^{(*)}\tau\nu_\tau)}{BR(B \to D^{(*)}\mu\nu_\mu)}$$

3.8σ

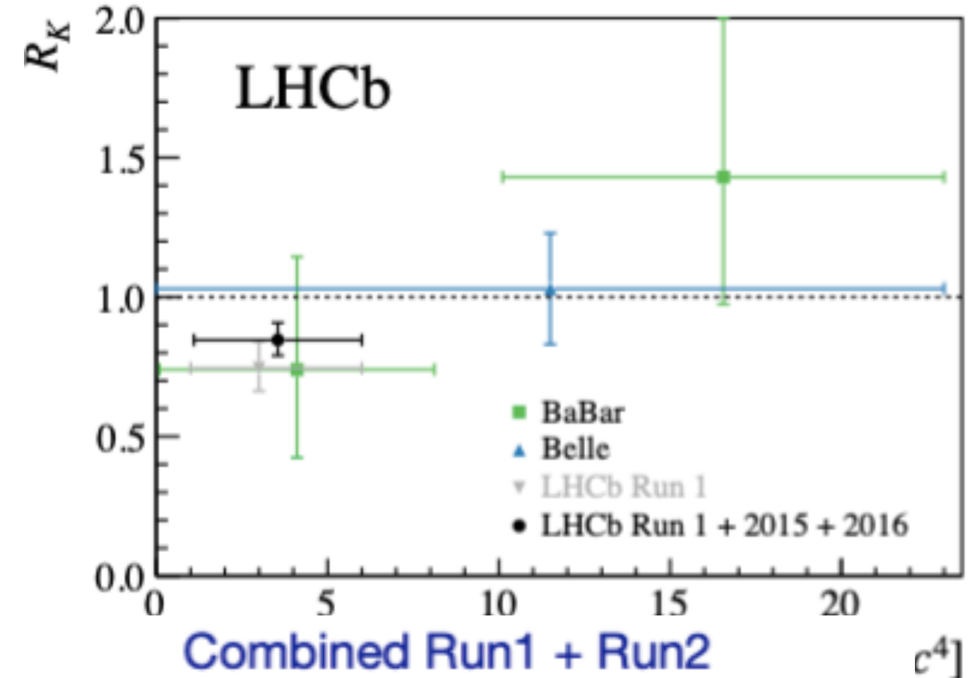
- **R(D) - R(D*) Belle average** is now within **2σ** of the SM prediction
- **R(D) - R(D*) exp. world average** tension with SM expectation **decreases from 3.8σ to 3.1σ**



FCNC - SM loop process: $R_{K^{(*)}}$ anomaly

$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu\mu)}{BR(B \to K^{(*)}ee)}$$

2.5σ

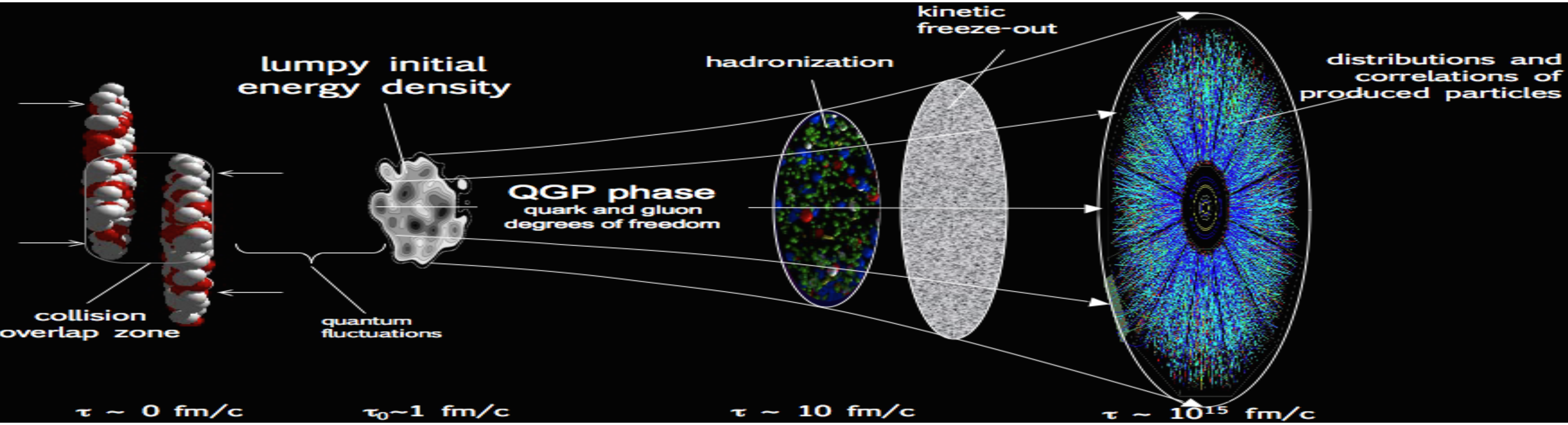


$$R_K = 0.846\ ^{+0.060}_{-0.054}\,(\text{stat.})\ ^{+0.016}_{-0.014}\,(\text{syst.})$$

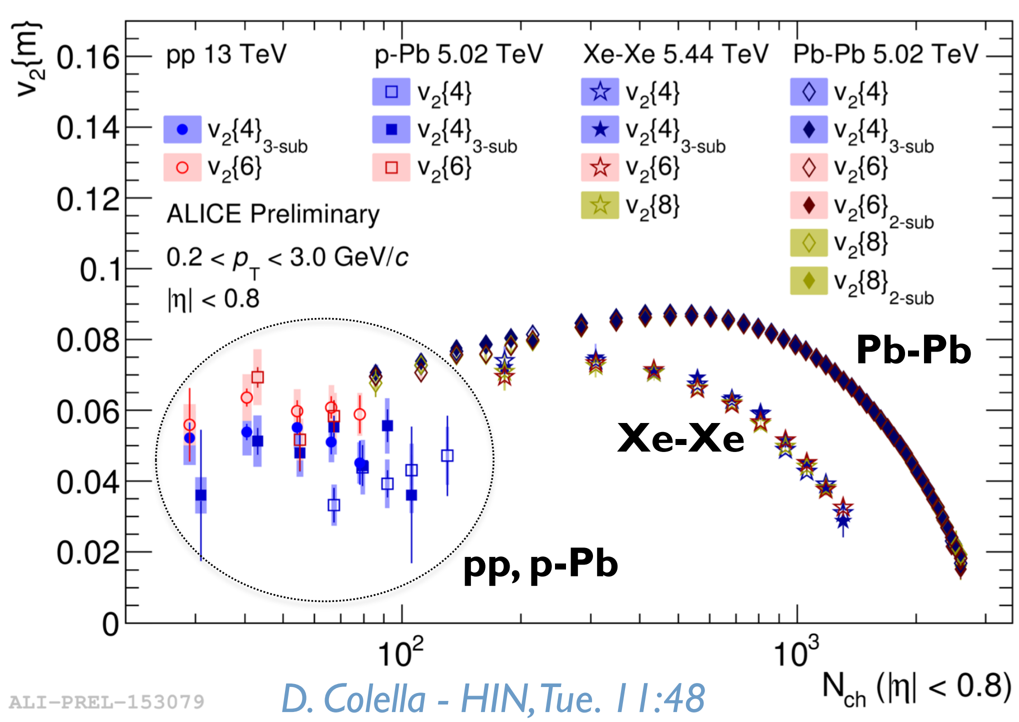
LHCb: the discrepancy present in $B_s \to \phi\mu\mu$ and $\Lambda_b \to \Lambda\mu\mu$

Discrepancy might dissolve and might as well grow up

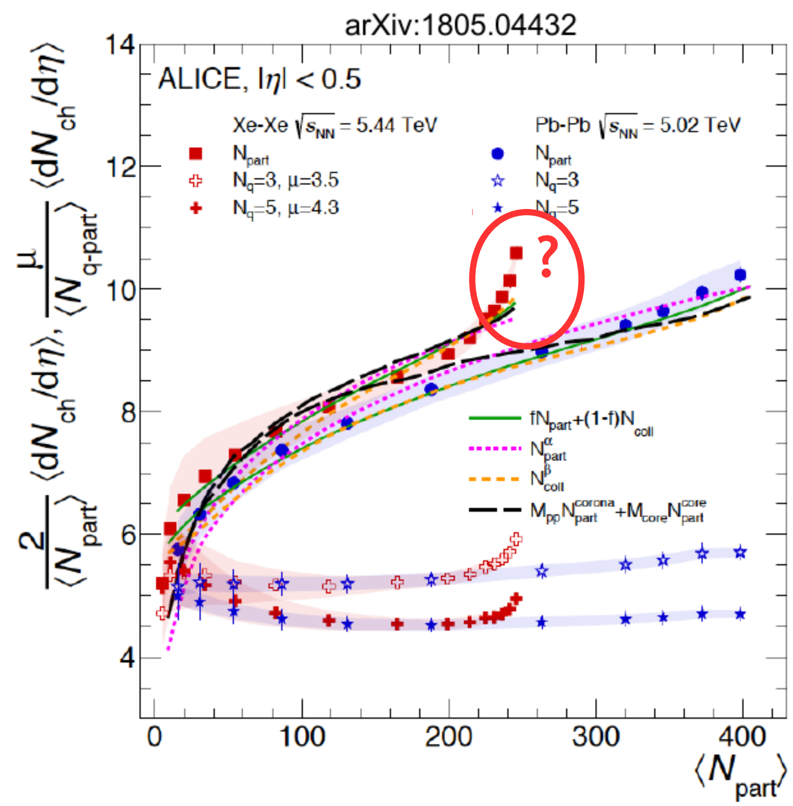
Heavy Ion Collisions: new State of Matter and new Phenomena at Density Frontier



Collectivity in small systems

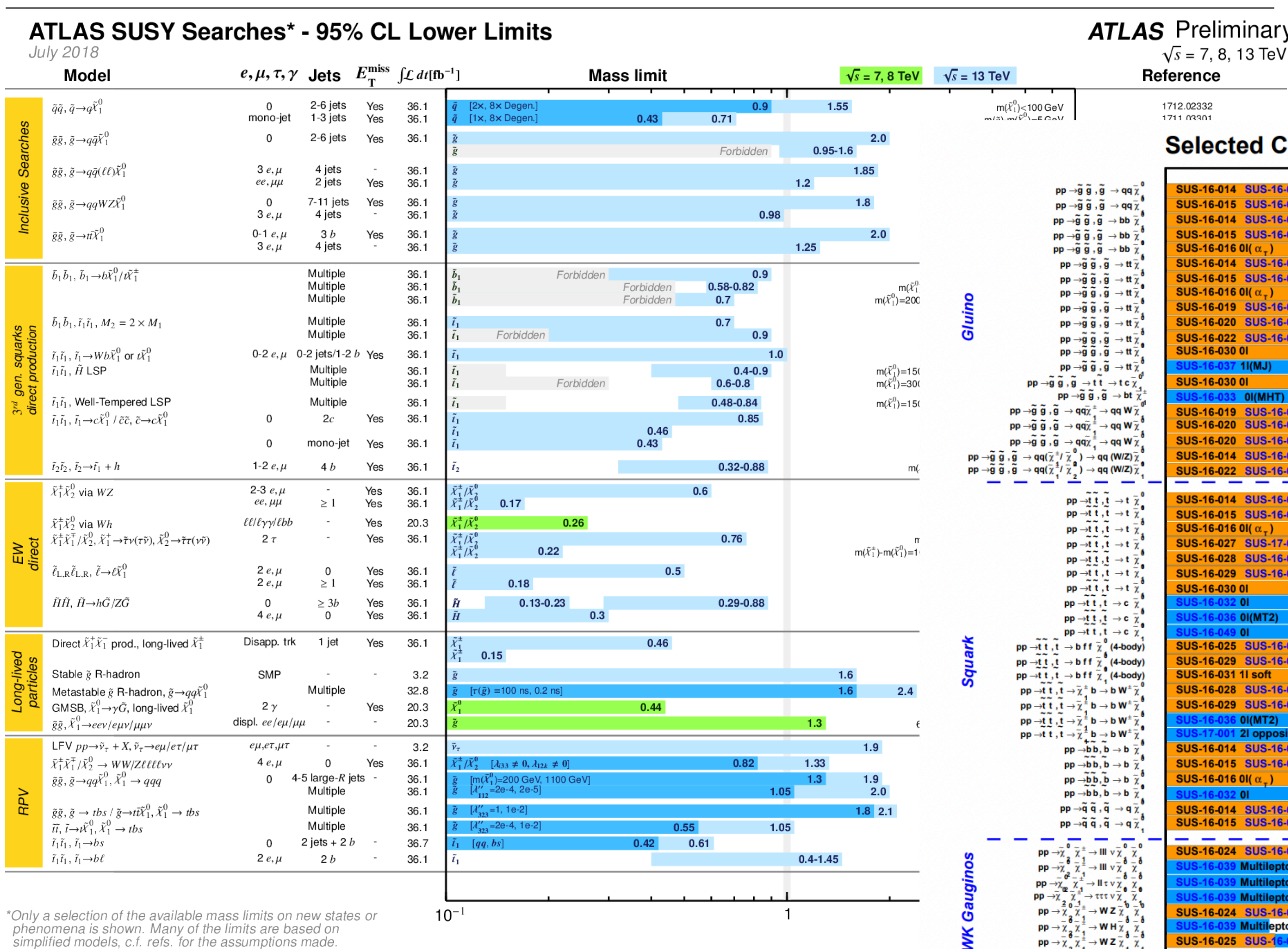


D. Colella - HIN, Tue. 11:48

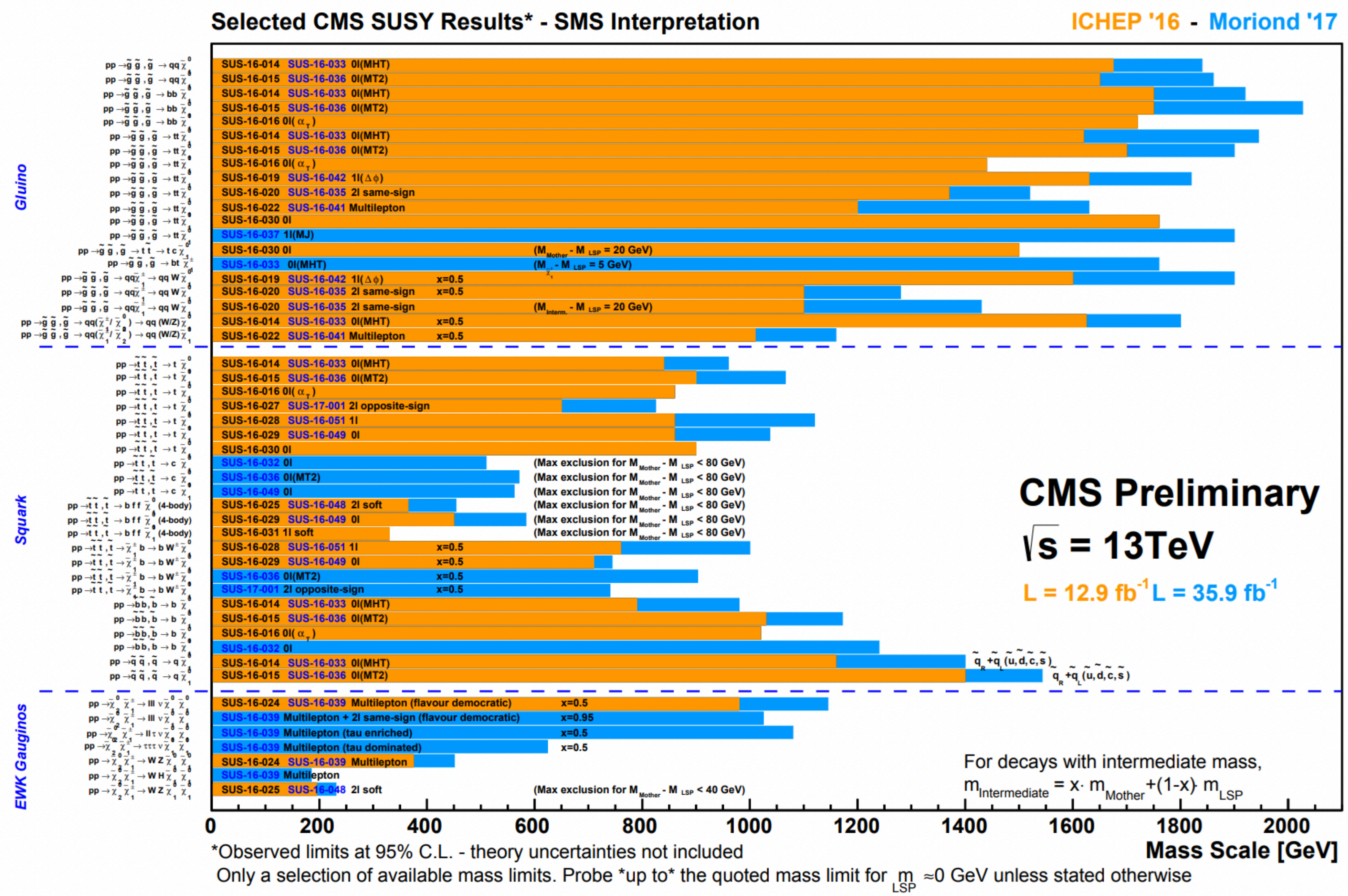


Sharp increase in multiplicity at high centrality in XeXe – not seen in PbPb

BEYOND THE STANDARD MODEL: SEARCH FOR NEW PARTICLES



SUSY or not SUSY?



- No evidence for SUSY yet → strong message from the LHC.

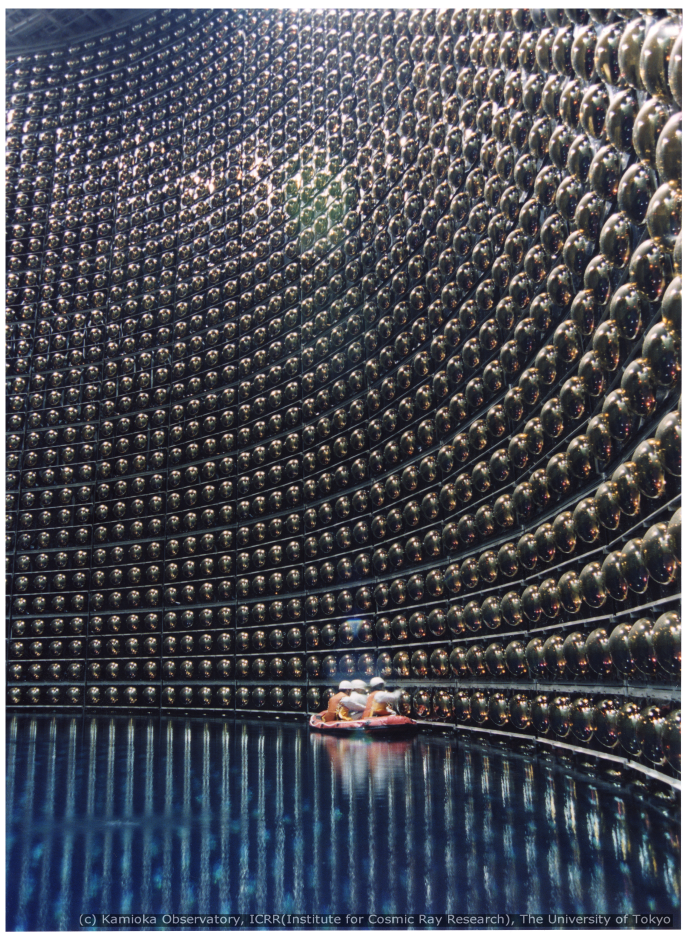
- In most favourable / challenging scenarios we exclude
gluinos up to O(2) / O(1) TeV.
squarks up to O(1.5) / O(0.5) TeV.
stops and sbottoms up to O(1) / O(0.7) TeV.
EW produced sparticles up to O(0.5-1) / O(0.1) TeV.

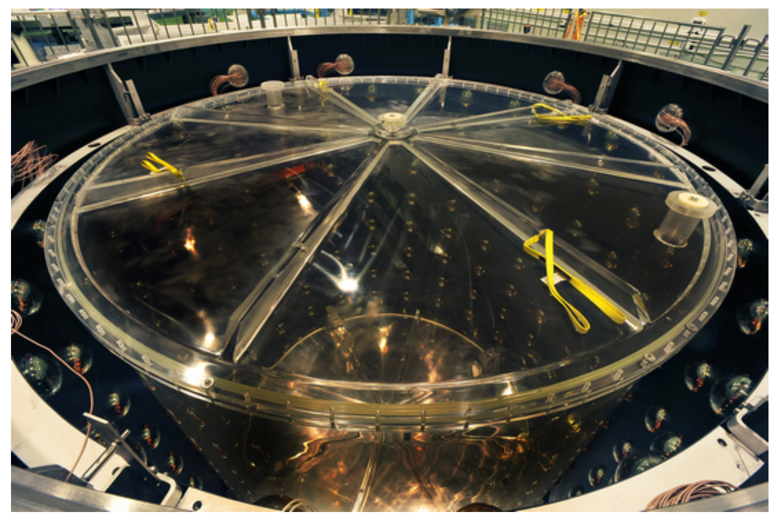
- Regions of parameter space still not well covered.

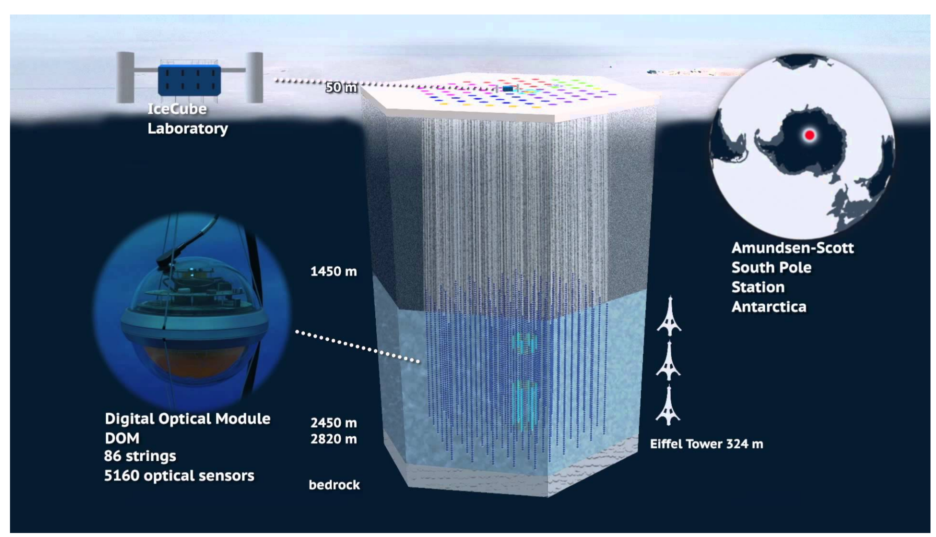
- Next step is to complete the program with the full Run 2 dataset (150 fb^{-1} expected).

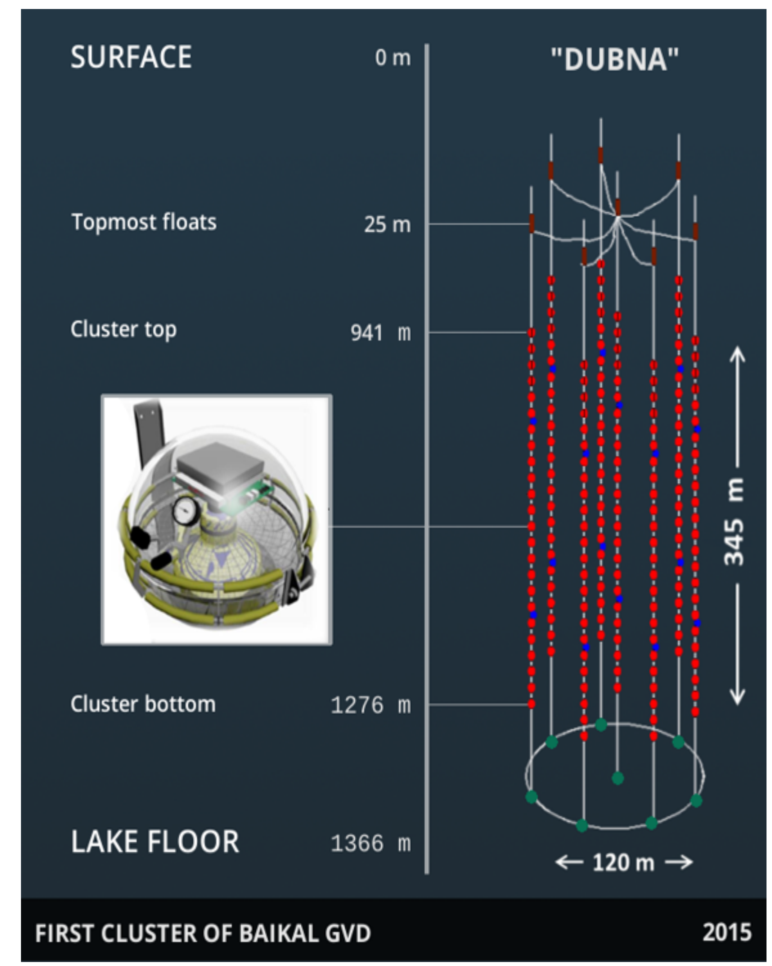
- Ensure we cover all signatures within our reach.

Neutrino Physics

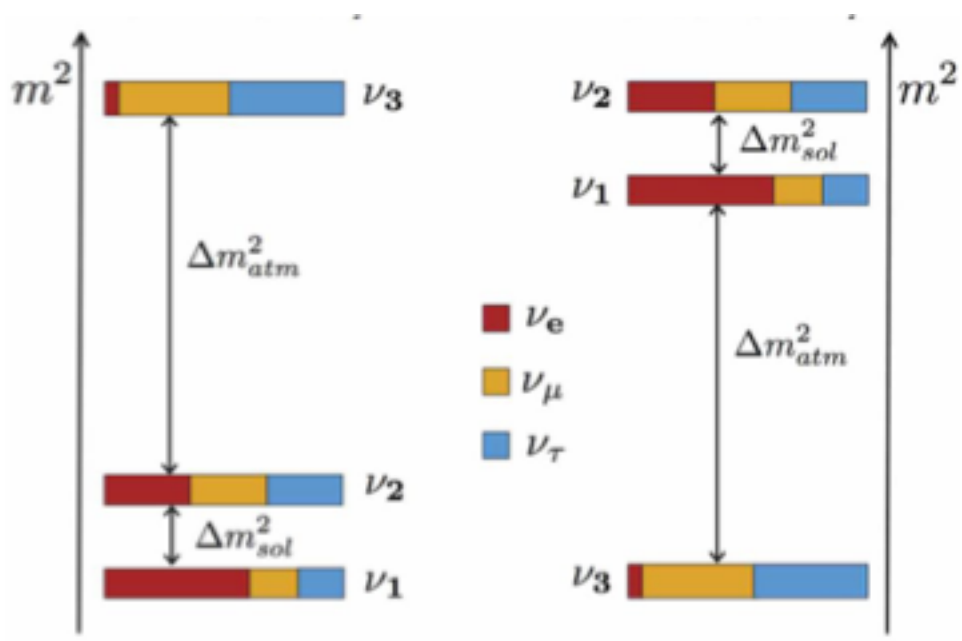








Neutrino Physics



parameter	best fit ± 1σ	3σ range
Δm^2_{21} [10^{-5}eV^2]	$7.55^{+0.20}_{-0.16}$	7.05–8.14
$\lvert\Delta m^2_{31}\rvert$ [10^{-3}eV^2] (NO)	2.50±0.03	2.41–2.60
$\lvert\Delta m^2_{31}\rvert$ [10^{-3}eV^2] (IO)	$2.42^{+0.03}_{-0.04}$	2.31-2.51
$\sin^2\theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.73–3.79
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.45–5.99
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.53–5.98
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	1.96–2.41
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	1.99–2.44
δ/π (NO)	$1.32^{+0.21}_{-0.15}$	0.87–1.94
δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.12–1.94

de Salas et al, 1708.01186

- Absolute value of neutrino masses ?
- Mass hierarchy?
- Dirac or Majorana?
- Fourth sterile neutrino?
- Neutrino dark matter?

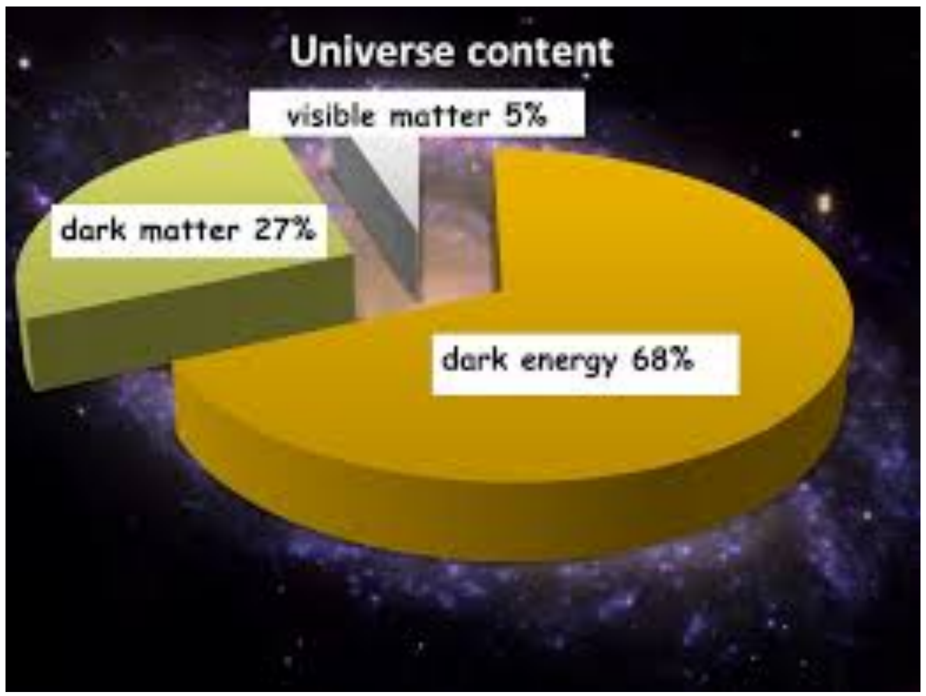
$$0.06\ eV < \sum m_\nu < 0.12\ eV$$

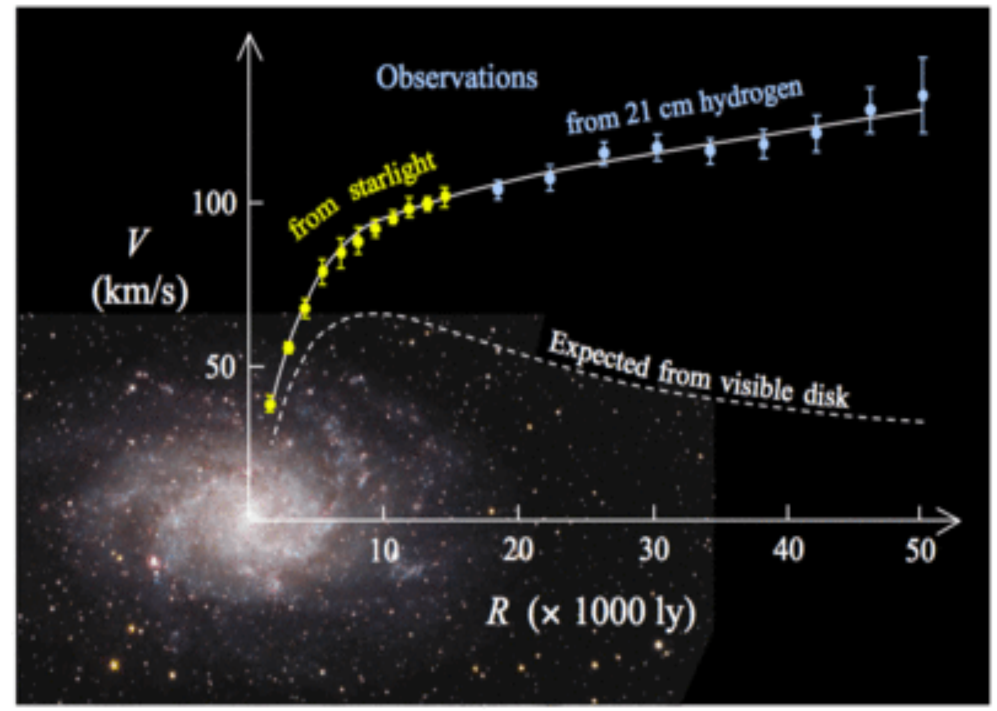
ν-osc CMB

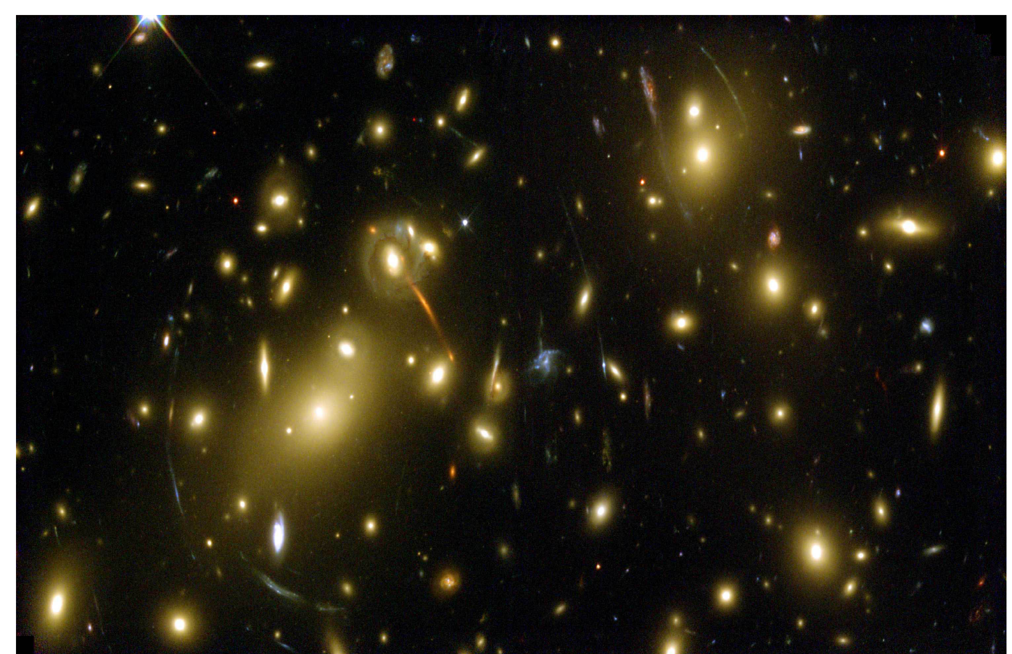
PMNS-matrix parameters are measured with high accuracy of few %

- Normal hierarchy favoured at 3.1 σ
- Nonzero CP phase favoured
- Upper octant favoured

Dark Matter


Universe content
visible matter 5%
dark matter 27%
dark energy 68%


Observations
from 21 cm hydrogen
from starlight
Expected from visible disk
V
(km/s)
100
50
10
20
30
40
50
R (× 1000 ly)

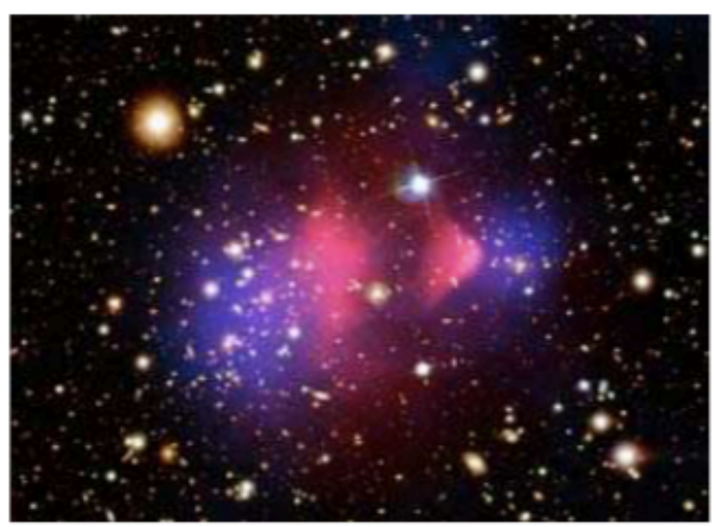


Major problem: 85% of matter is dark and remains invisible!

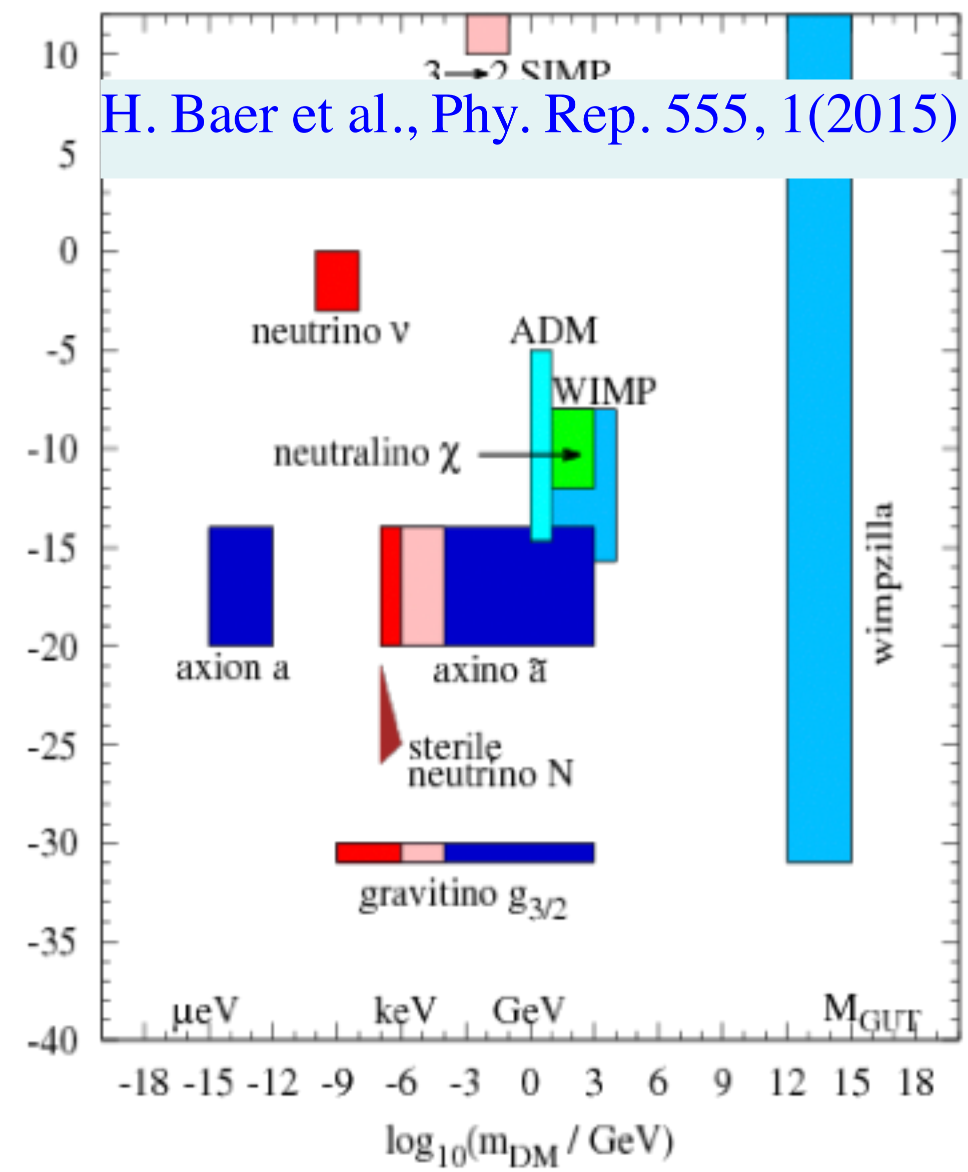
Is this compatible with the SM?

Does it requires modification of the SM or addition of gravity?

- Many candidates in many orders of magnitude of mass:
  - MOND (Problems: large scales, Bullet cluster)
  - Primordial black holes (LIGO, but constraints)
  - Fuzzy (very light bosons)
  - Warm (KeV sterile)
  - WIMP
  - Axions/ALPs
  - Dark sector
  - Gravitinos
  - Moduli
  - Wimpzillas



M. Drees

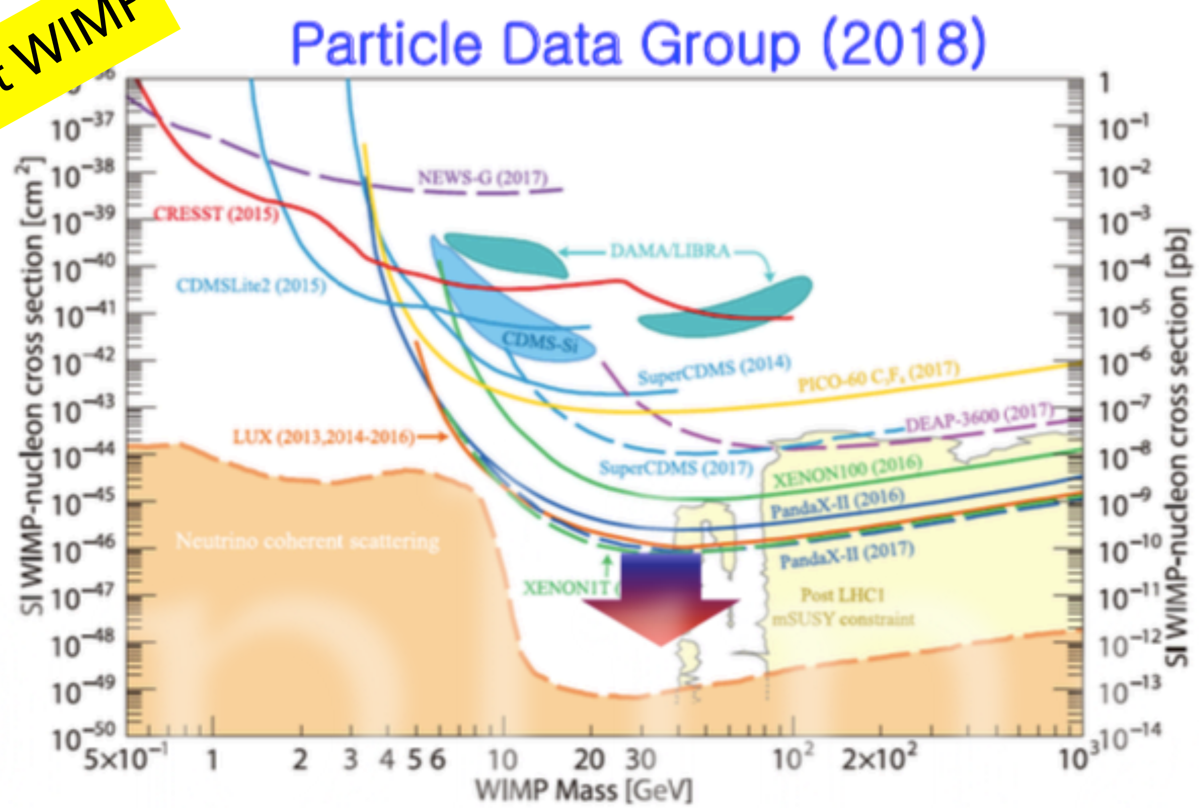


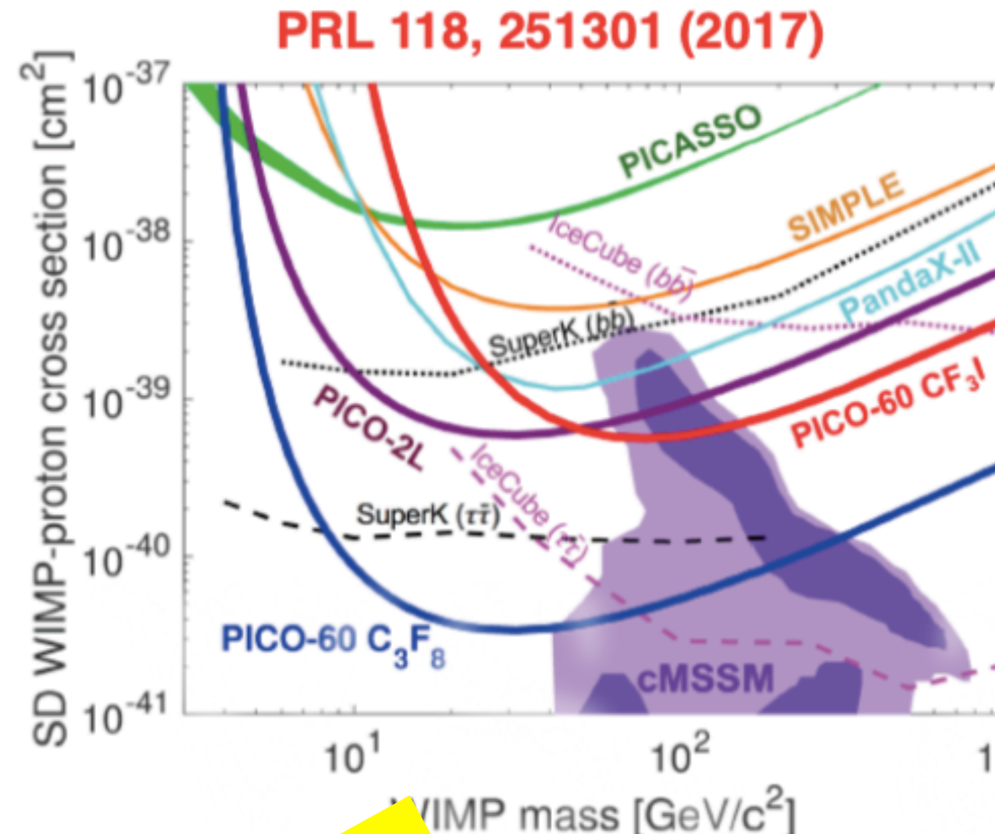
H. Baer et al., Phy. Rep. 555, 1(2015)

- Direct, indirect, collider

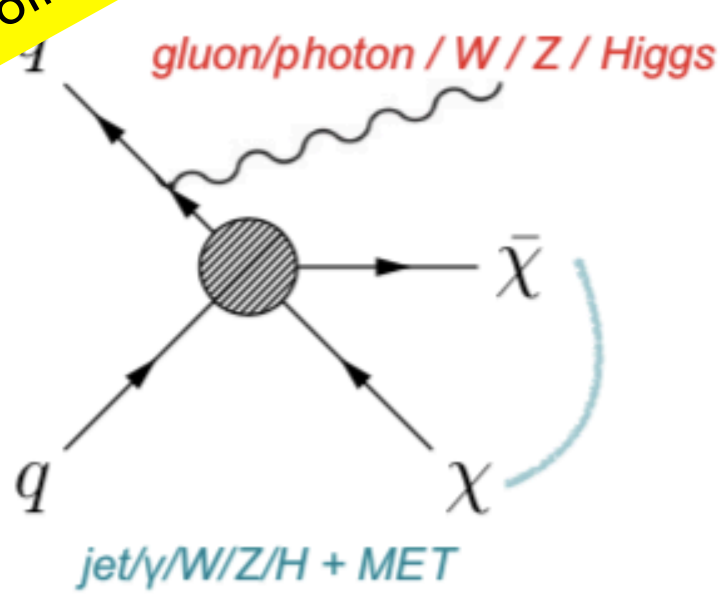
BEYOND THE STANDARD MODEL: DARK MATTER SEARCHES

Direct WIMP





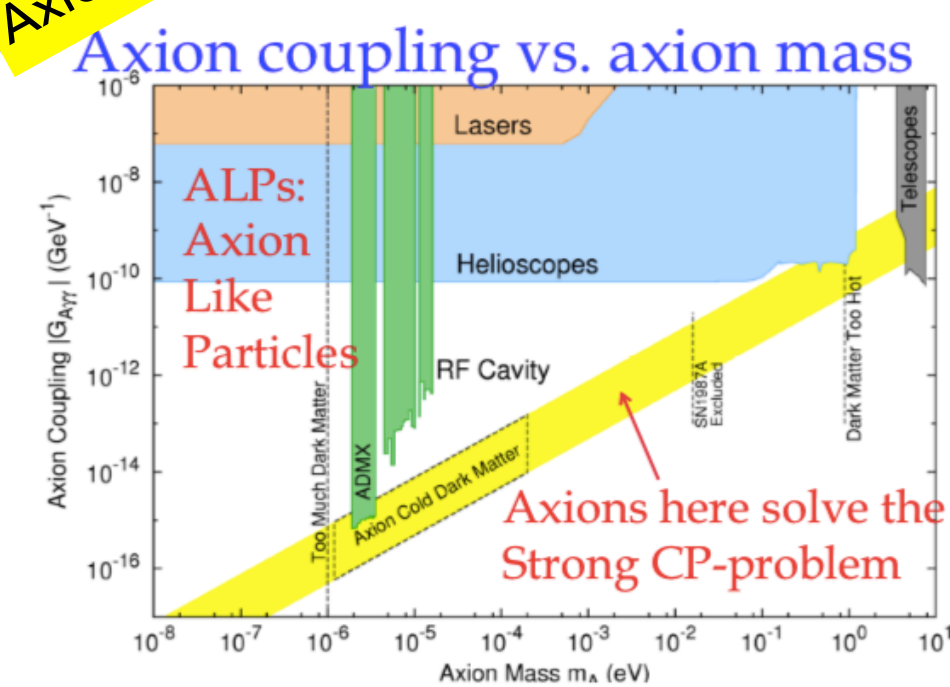
Colliders WIMP



- mono-jet
  - most general signature, constraints on many models
- mono-photon
  - more challenging for background estimation
  - less powerful: EW vs. strong interaction
- mono-W/Z leptonic
  - clean signature and simple trigger
  - penalized by W/Z branching fraction
- mono-W/Z hadronic
  - larger statistics with larger background
- tt+MET/bb+MET and mono-top
  - more complicated experimentally
  - powerful in some scenarios
- mono-Higgs
  - powerful in some scenarios

D. del Re

Axion-likes



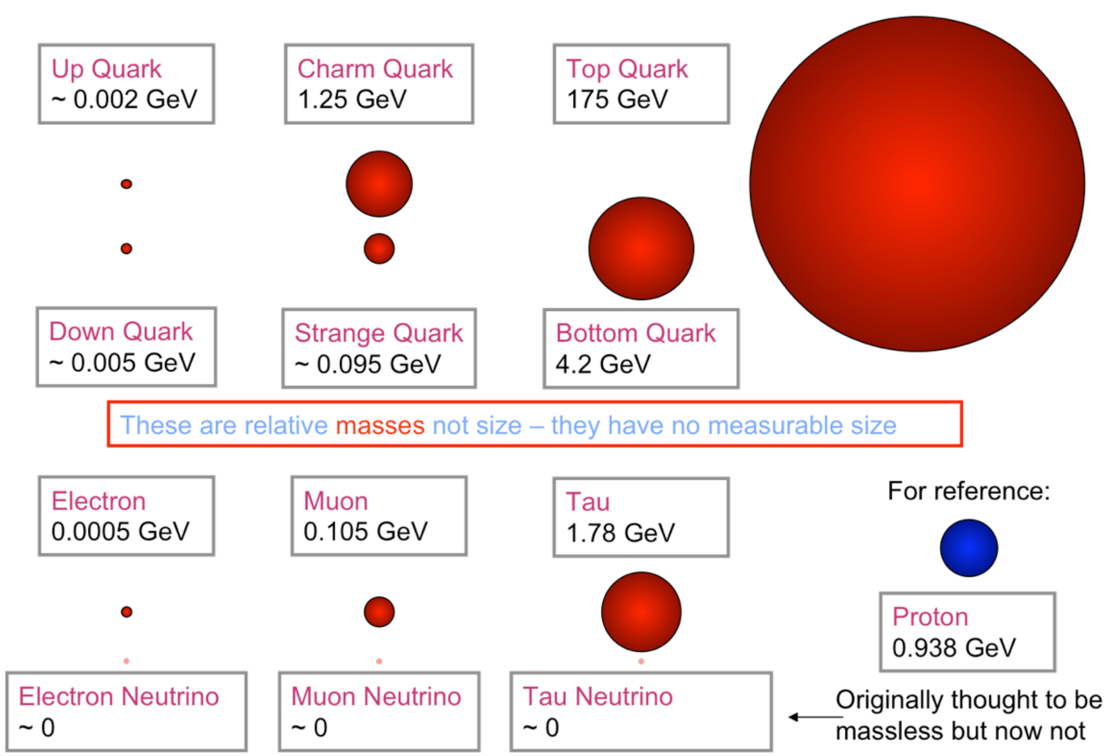
Y. Semertzidis

Flavour Sector

- Mass spectrum?

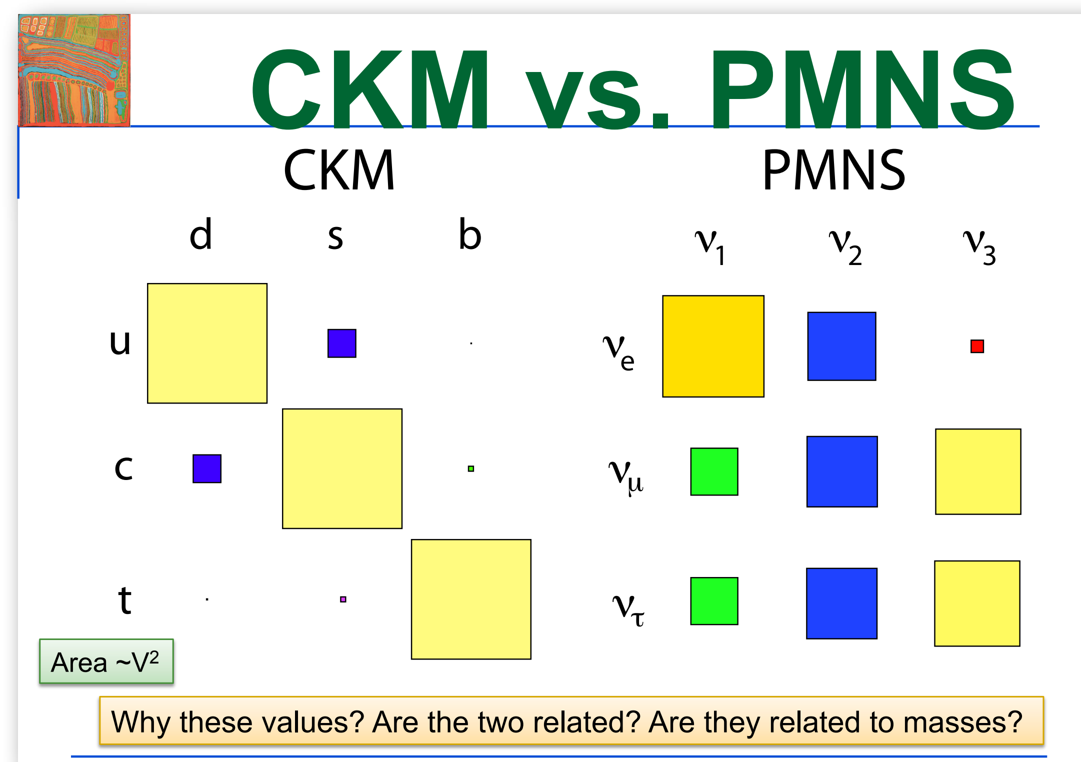
$$m_{quark} = y_{quark} \cdot v$$
$$m_{lepton} = y_{lepton} \cdot v$$
$$m_W = g/\sqrt{2} \cdot v$$
$$m_Z = \sqrt{g^2 + g'^2}/\sqrt{2} \cdot v$$
$$m_H = \sqrt{\lambda} \cdot v$$
$$m_\gamma = 0$$
$$m_{gluon} = 0$$

SM



- Mixing Matrices?

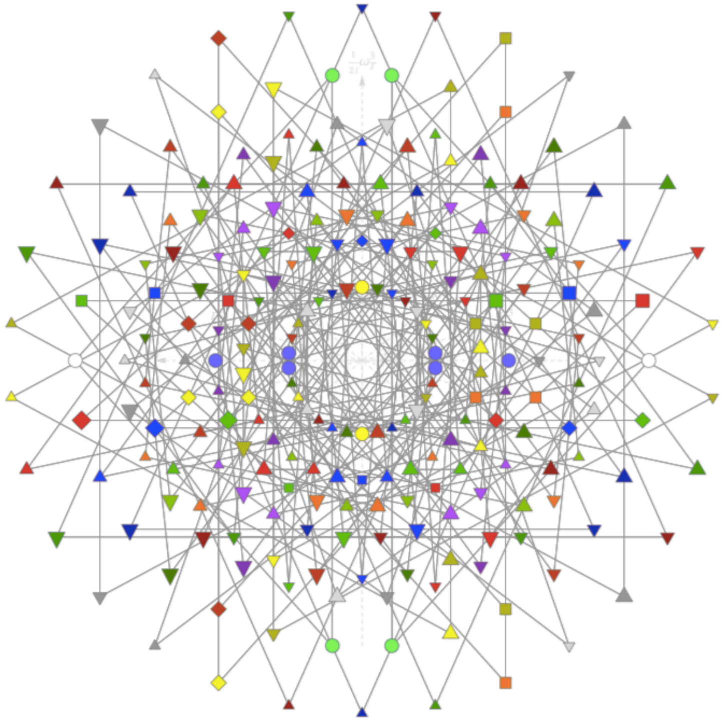
- Quark-Lepton Symmetry
- Strong difference in parameters



- What are the CKM and PMNS phases?
- Where lies the source of CP violation: in quark or lepton sector?

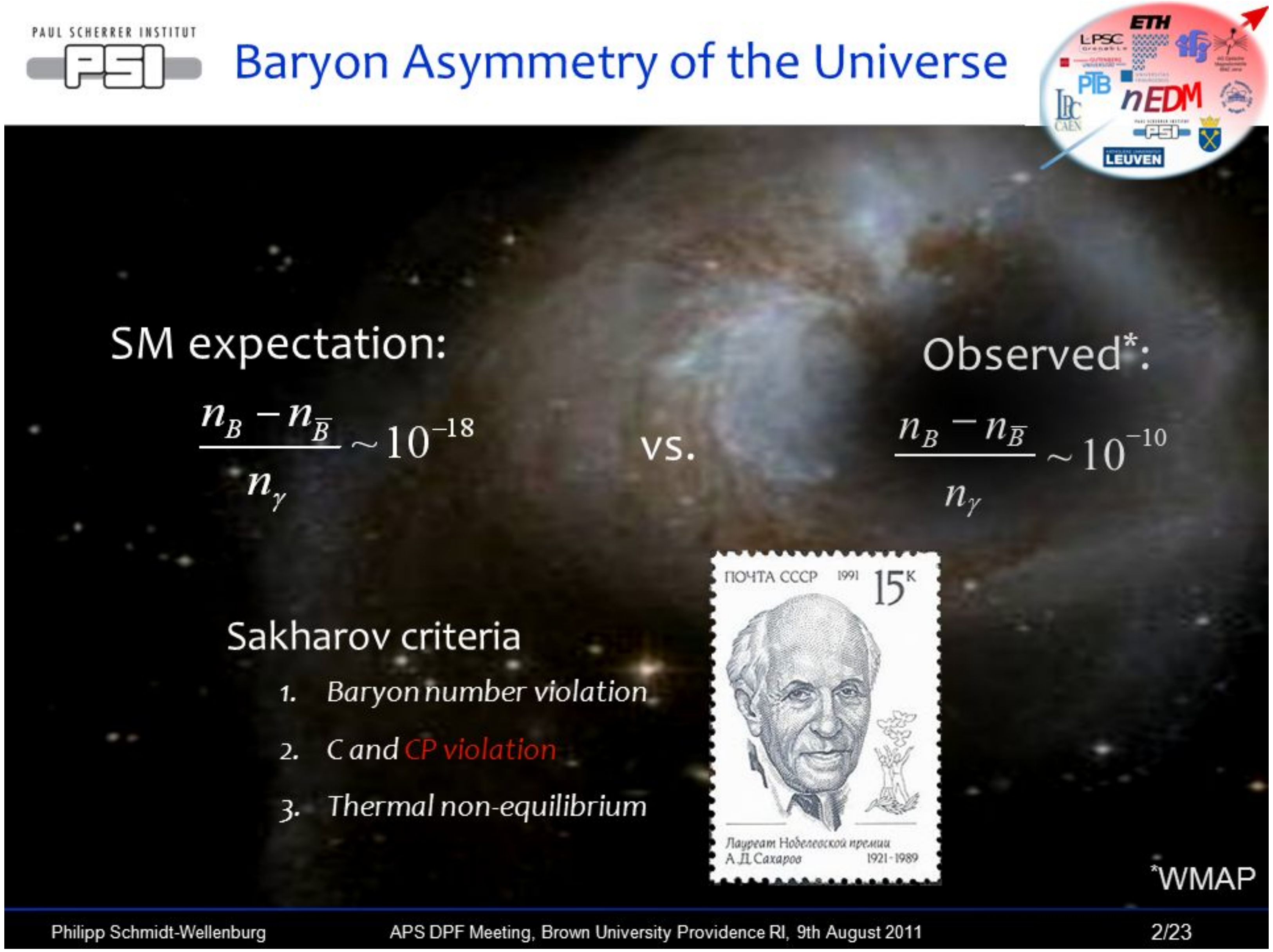
$$J_{CP} = \frac{1}{8} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos \theta_{13} \sin \delta$$

Looking for new physics we are looking for new Symmetry of Nature!



E8 roots

Symmetry might be tricky



- Baryon number is conserved in the SM with exponential accuracy

- Violation of baryon number occur in Grand Unified Theories and in Lepton=fourth color models (Pati-Salam model)

New particles = Leptoquarks, Extended Highs sector

$$B = \frac{N_q - N_{\bar{q}}}{3}$$

$\not{B}$

- Violation of CP invariance in the SM achieved via phase factors in the CKM and PMNS mixing matrices ⟷ $\not{CP}$

BAU requires larger CP than in the SM

Possible Baryogeneses via Leptogeneses

The presence of new phase factors in extended models (2HDM, SUSY, etc)

WHAT MAKES US THINK THAT THERE IS PHYSICS BEYOND THE STANDARD MODEL?

- Small discrepancy with experimental data
- Possible new ingredients in neutrino sector (majorana neutrino)
- Instability of electroweak vacuum
- Inability to describe the Dark matter (unless it has pure gravitational nature)
- Baryon asymmetry of the Universe is a fundamental problem (Baryon and Lepton genesis might require new ingredients)
- Lack of understanding of flavor structure of the SM calls for explanation at higher level
- New era in gravity due to discovery of gravitational waves and black holes might change the landscape

Ideas (conventional and not)

- Symmetries
  - Supersymmetry, family, ...
- Compositeness
  - Higgs, fermions, ...
- Extra dimensions
  - large, warped, ...
- Dark or hidden sectors
  - Dark, SUSY-breaking, random, ...
- Unification
  - GUT, string, ...
- New dynamical ideas
  - Relaxion, nnaturalness, clockwork, string instantons, ...
- Random or environmental
  - multiverse
- String remnants
  (need not solve SM problem)
  - *Z'*, vector fermions, extended Higgs, dark, moduli, axions, ...

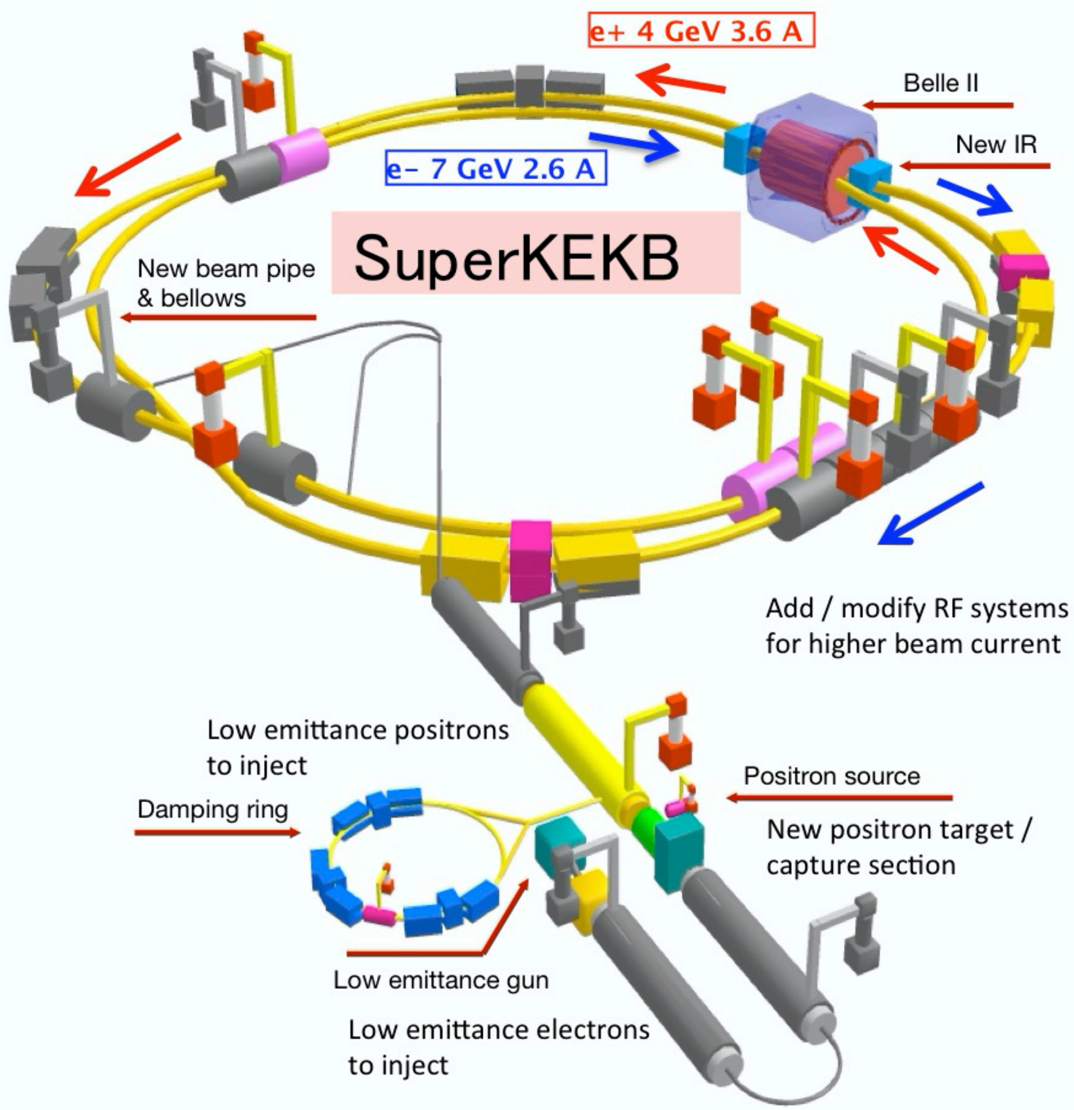
Which way to go ?

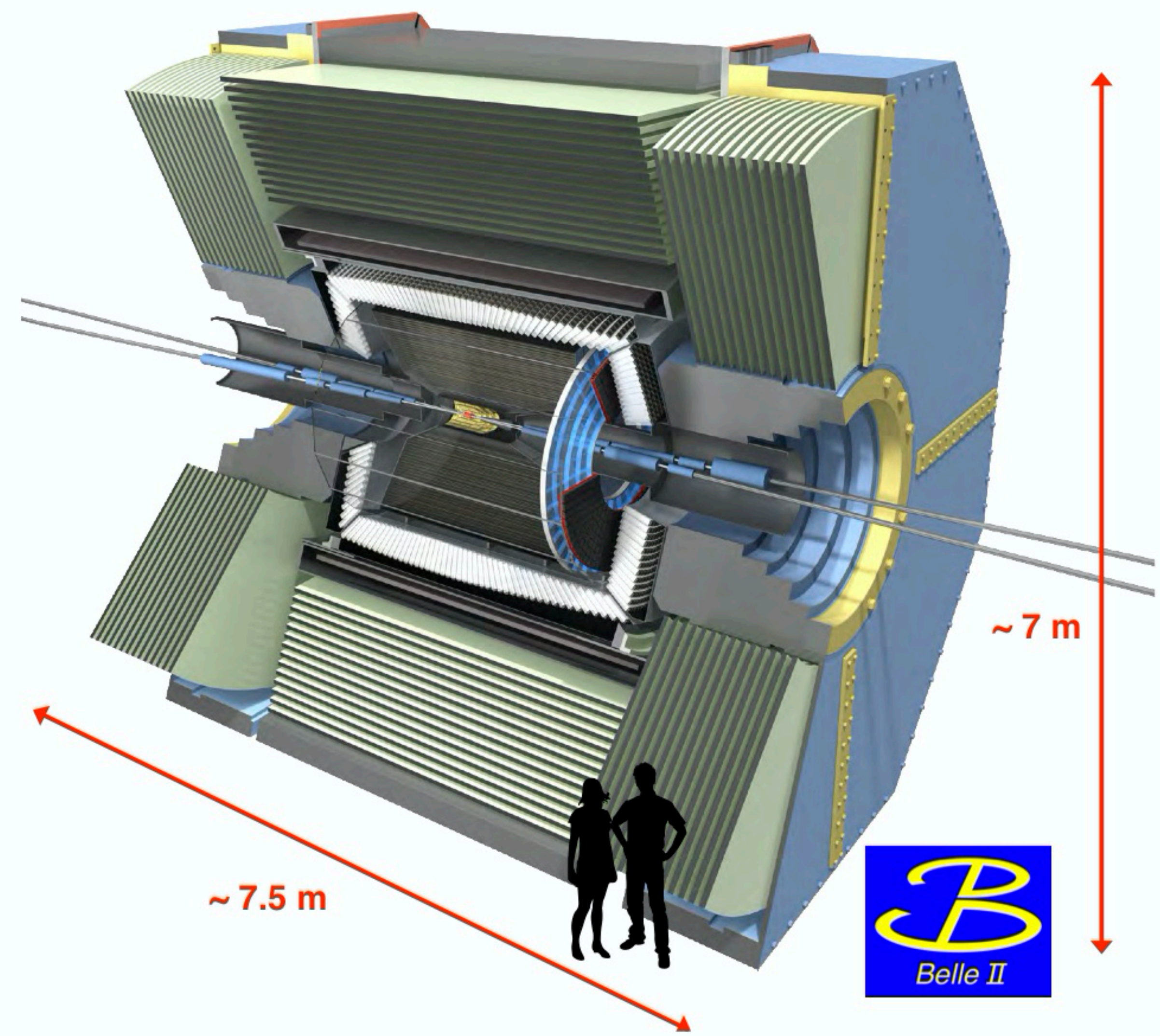
How Will We Make Progress?

- The energy frontier
- The precision frontier and neutrinos
- Cosmology and astrophysics

Preparation for the future

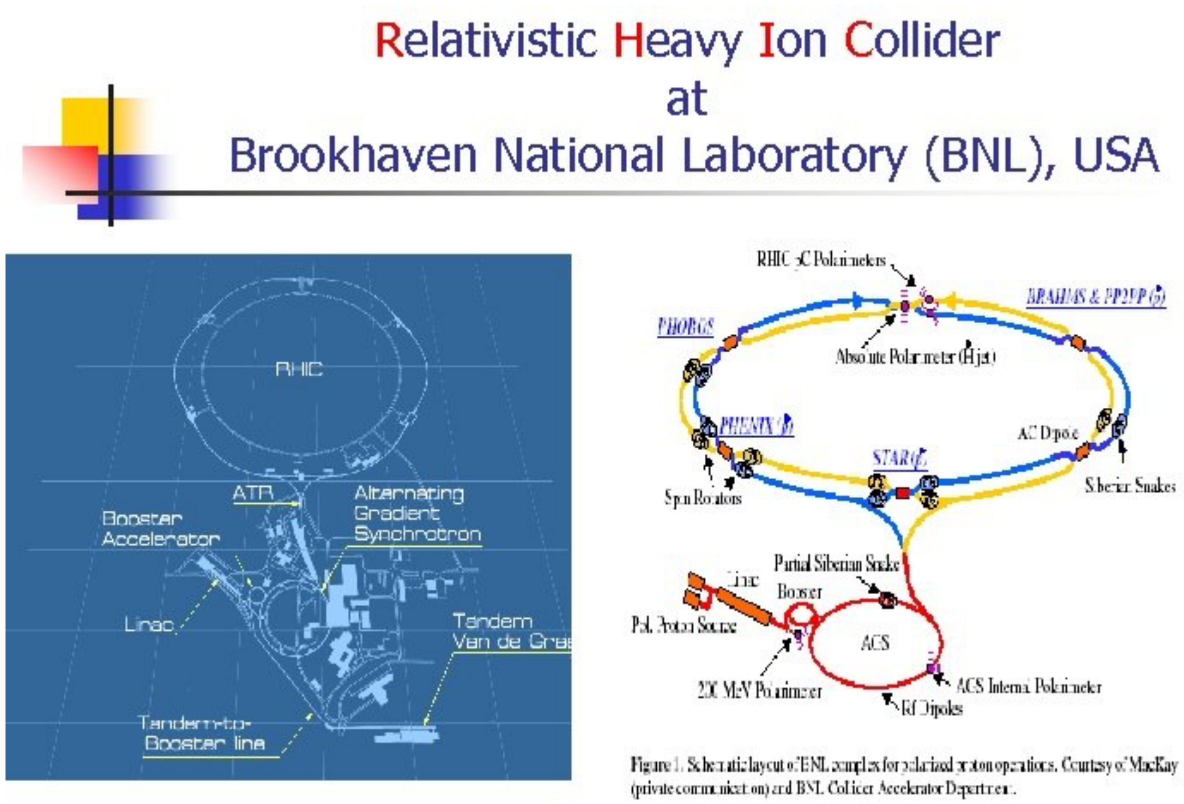
SUPER BEAUTY FACTORY IN JAPAN (KEK)

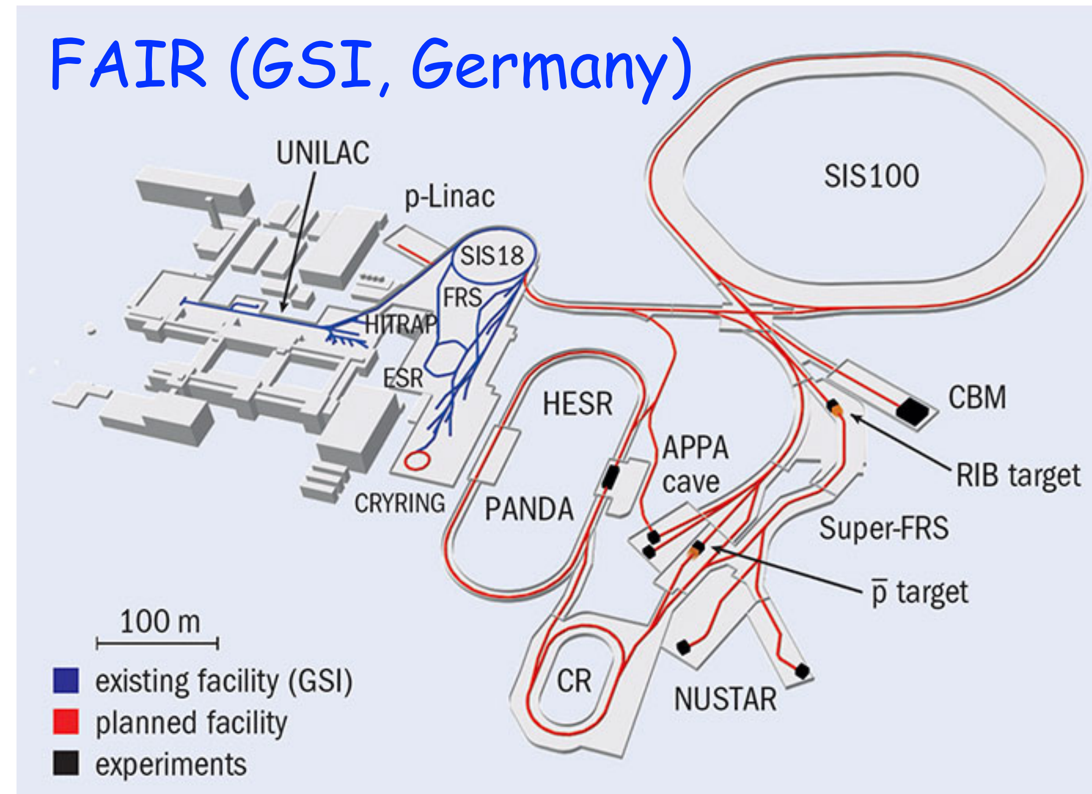


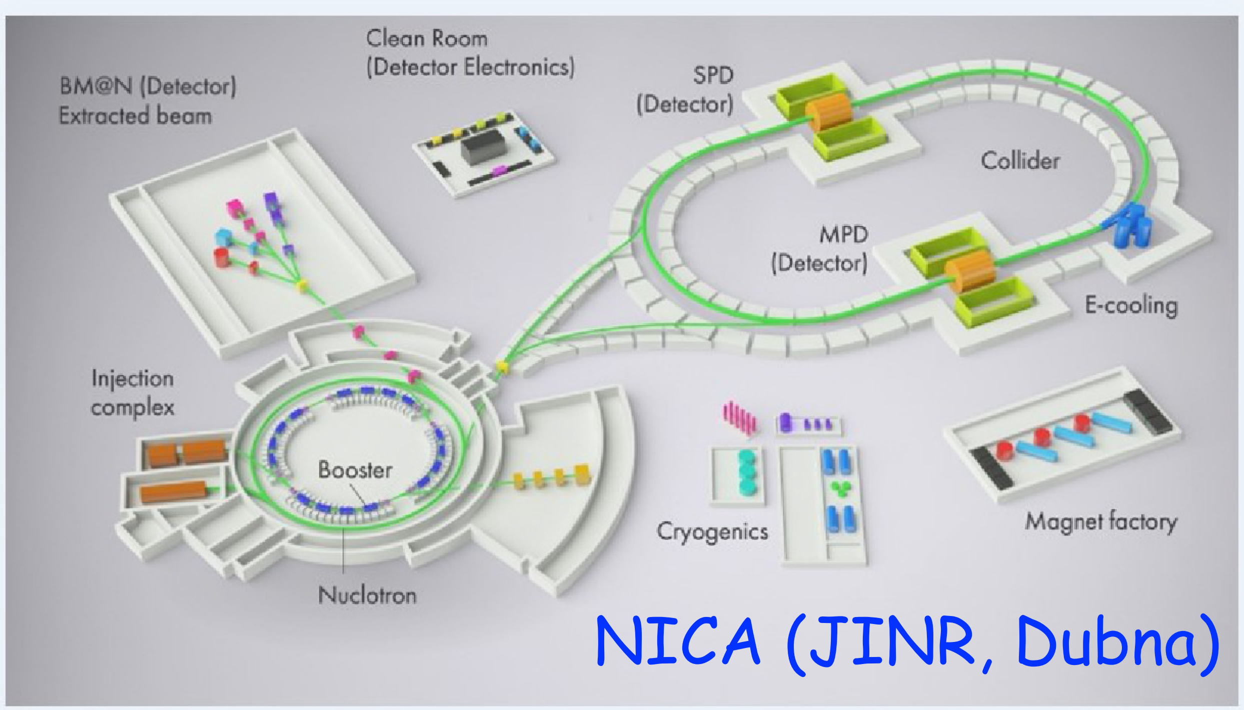


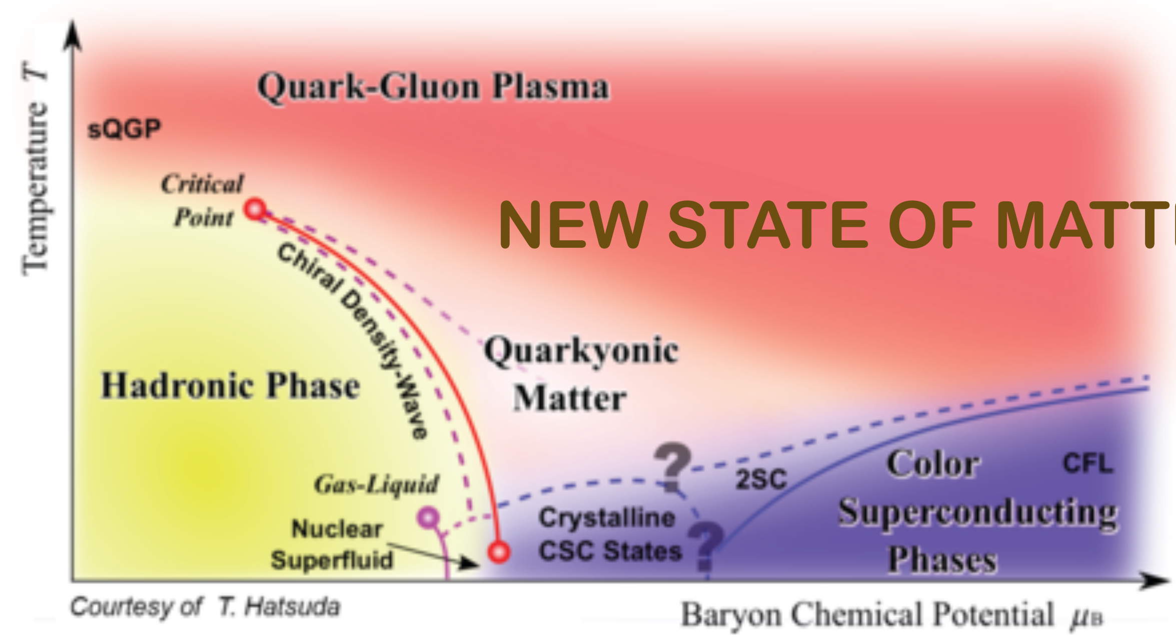
STYDY OF B-PHYSICS, EXOTIC HADRONS, CP VIOLATION, ETC

HEAVY-ION COLLIDERS



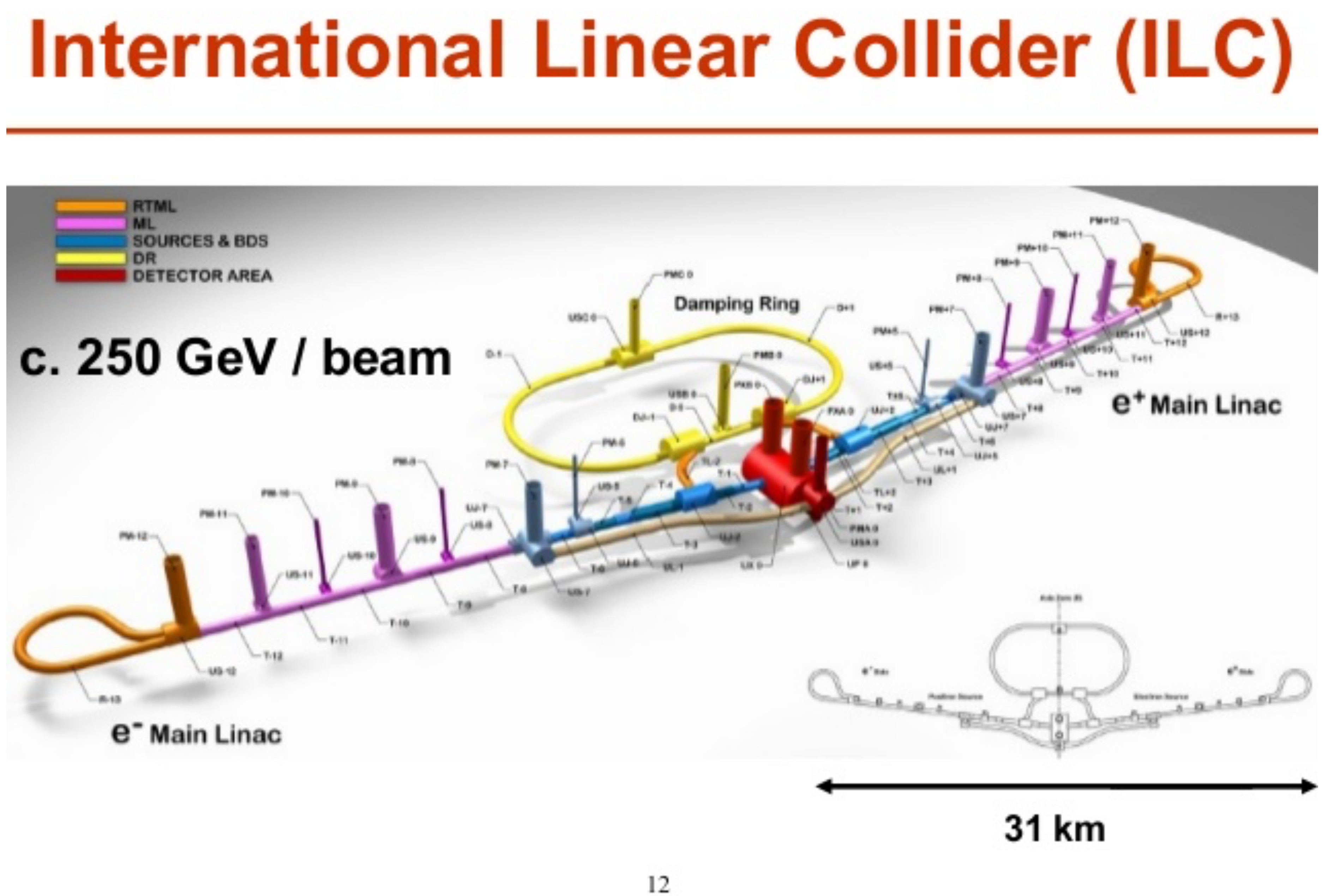






NEW STATE OF MATTER

ELECTRON-POSITRON LINEAR COLLIDER (JAPAN)

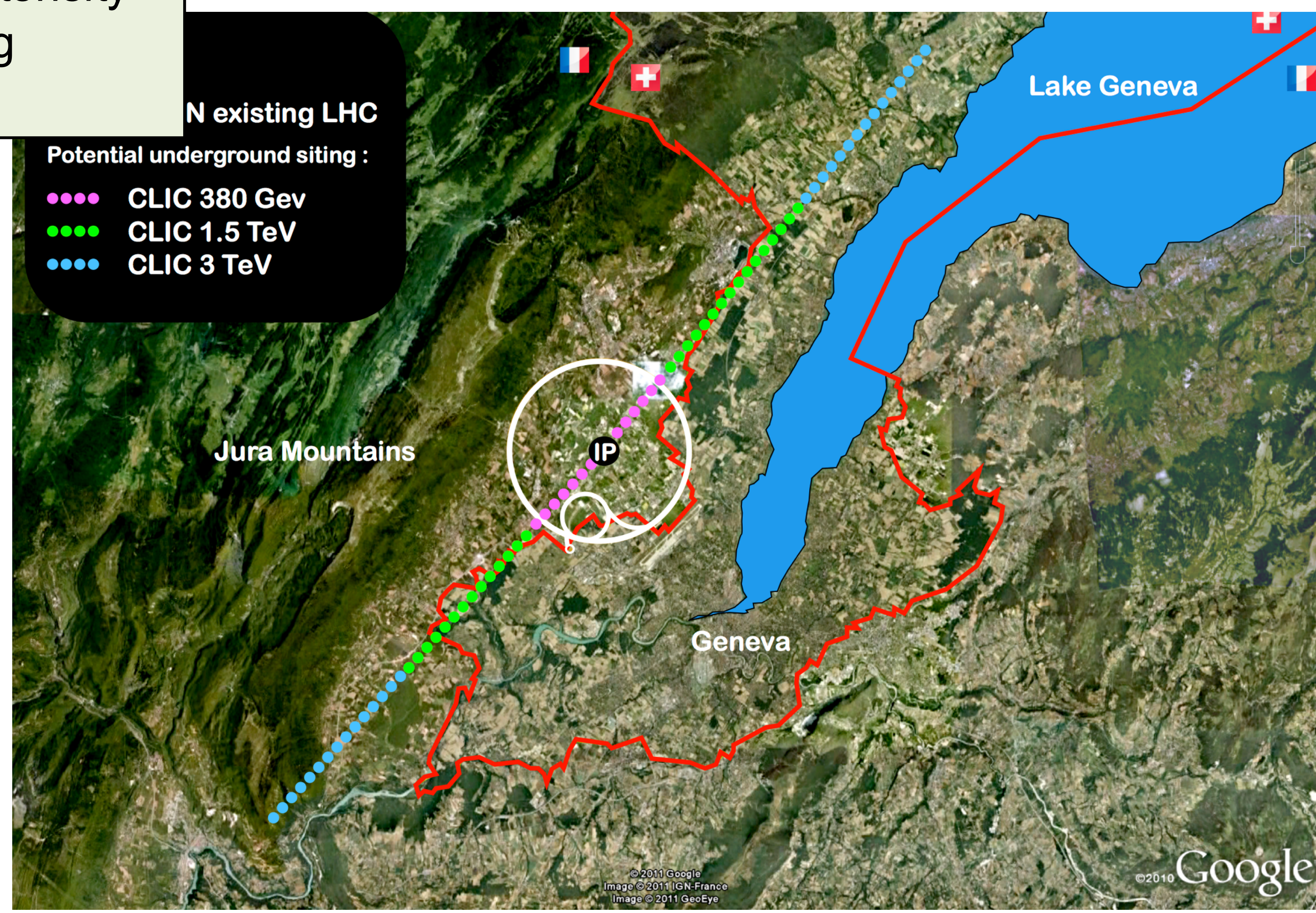


TECHNOLOGY EXISTS, CONSTRUCTION DID NOT START YET

Linear e^+e^- collider with $\sqrt{s}$ up to 3 TeV

100 MV/m accelerating gradient needed for compact (~50 km) machine
→ based on normal-conducting accelerating structures and a two-beam acceleration scheme: power transfer from low-E high-intensity drive beam to (warm) accelerating structures of main beam

Compact Linear Collider (CLIC)



TECHNOLOGY IS TESTED

Future Circular Colliders (FCC)

Conceptual design study of a ~100 km ring:

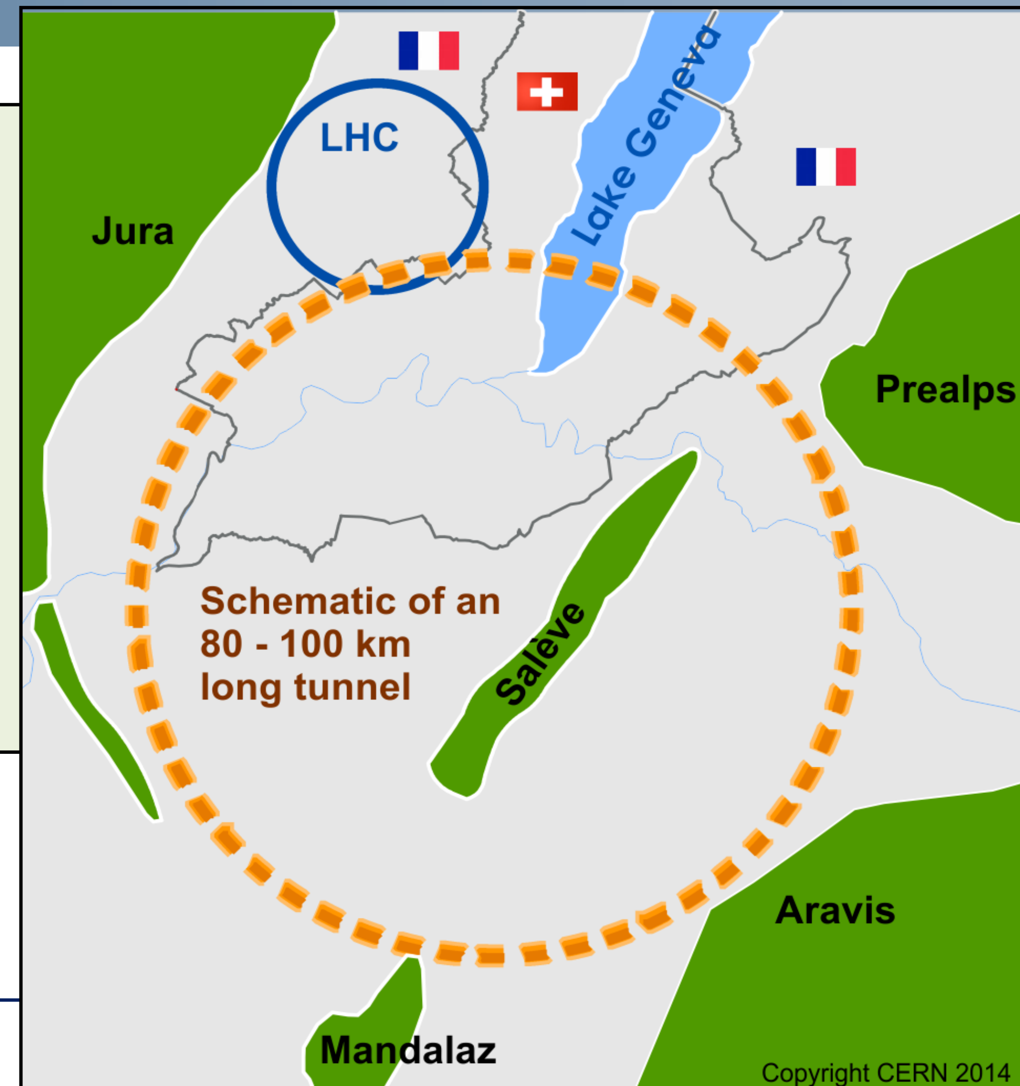
- **pp collider (FCC-hh):** ultimate goal

  $\sqrt{s}$ ~ 100 TeV, L~2x10^{35}; 4 IP, ~20 ab^{-1}/expt

- **e^+e^- collider (FCC-ee):** possible first step

  $\sqrt{s}$ = 90-350 GeV, L~200-2 x 10^{34}; 2 IP

- **pe collider (FCC-he):** option $\sqrt{s}$ ~ 3.5 TeV, L~10^{34}



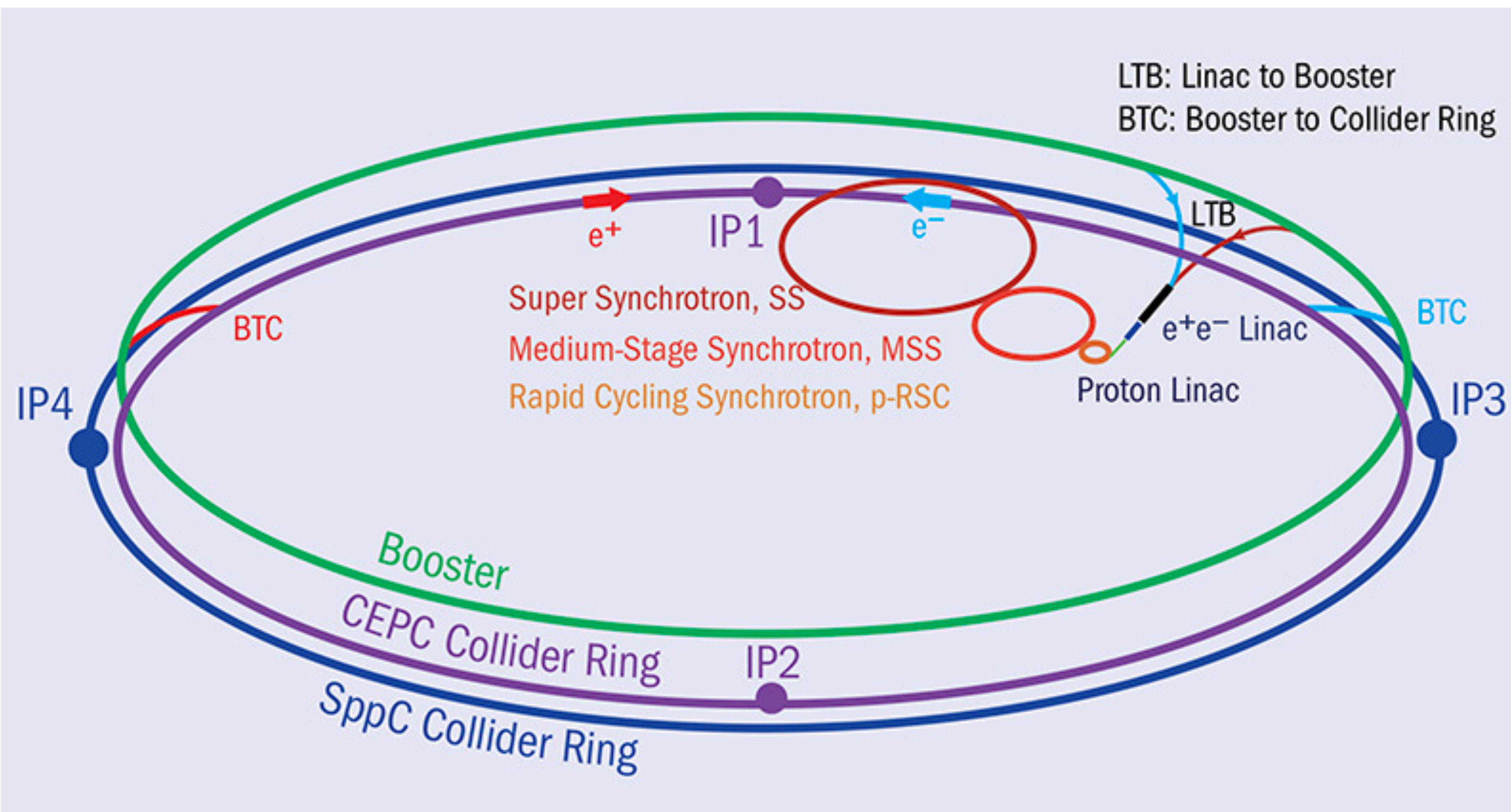
Main technology challenge: ~ 16 T magnets

FCC-hh: a ~100 TeV pp collider is expected to:
- explore directly the 10-50 TeV E-scale
- conclusive exploration of EWSB dynamics
- say the final word about heavy WIMP dark matter

FCC-ee: 90-350 GeV
- measure many Higgs couplings to few permill
- indirect sensitivity to E-scale up to O(100 TeV) by improving by ~20-200 times the precision of EW parameters measurements, ΔM_W < 1 MeV, Δm_{top} ~ 10 MeV

FUTURE ACCELERATORS

CIRCULAR EP COLLIDER (CHINA)

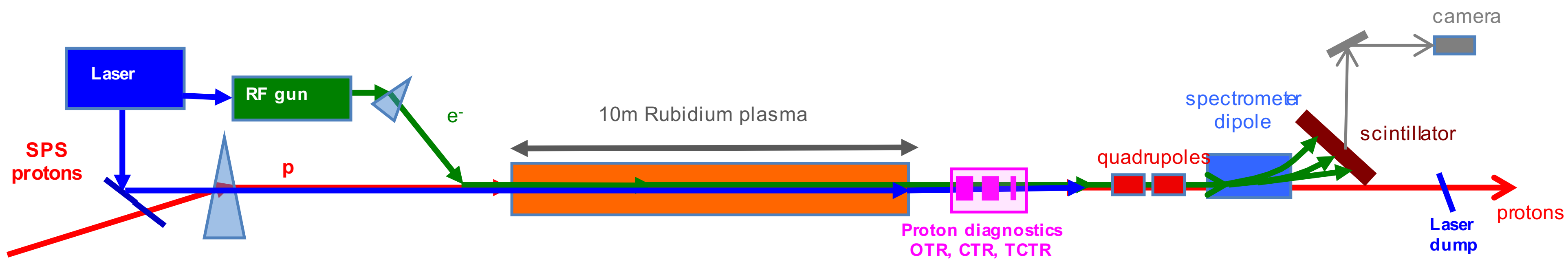


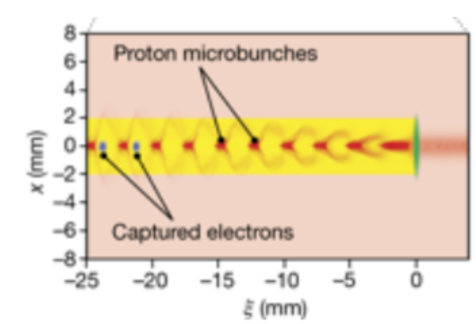
AWAKE

Advanced Proton Driven Plasma Wakefield Acceleration Experiment

Proof-of-concept demonstrated: 400 GeV protons from SPS generate strong EM fields in a 10 m plasma cell → injected e^- beam accelerated in the wake of the p beam

~ 3×10^{11} p/bunch at 400 GeV → 20 kJ (cfr ~ 40 J for laser/e^- driving pulses)





2018: **first demonstration of p-driven e^- acceleration** (paper published in *Nature*):
20 MeV → 2 GeV over 10 m: corresponds to **gradient of 200 MV/m**

NEW TECHNOLOGY, HIGHT GRADIENT, COMPACT ACCELERATOR