
IN WAITING FOR NEW DISCOVERIES IN PARTICLE PHYSICS

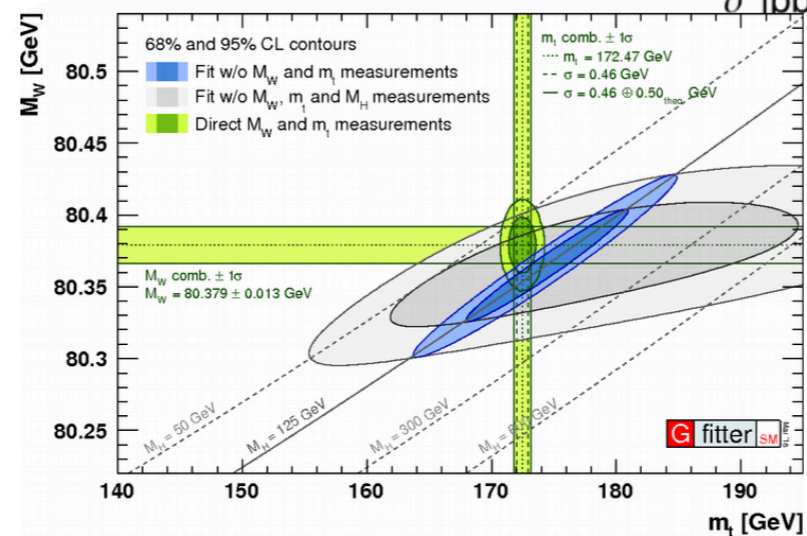
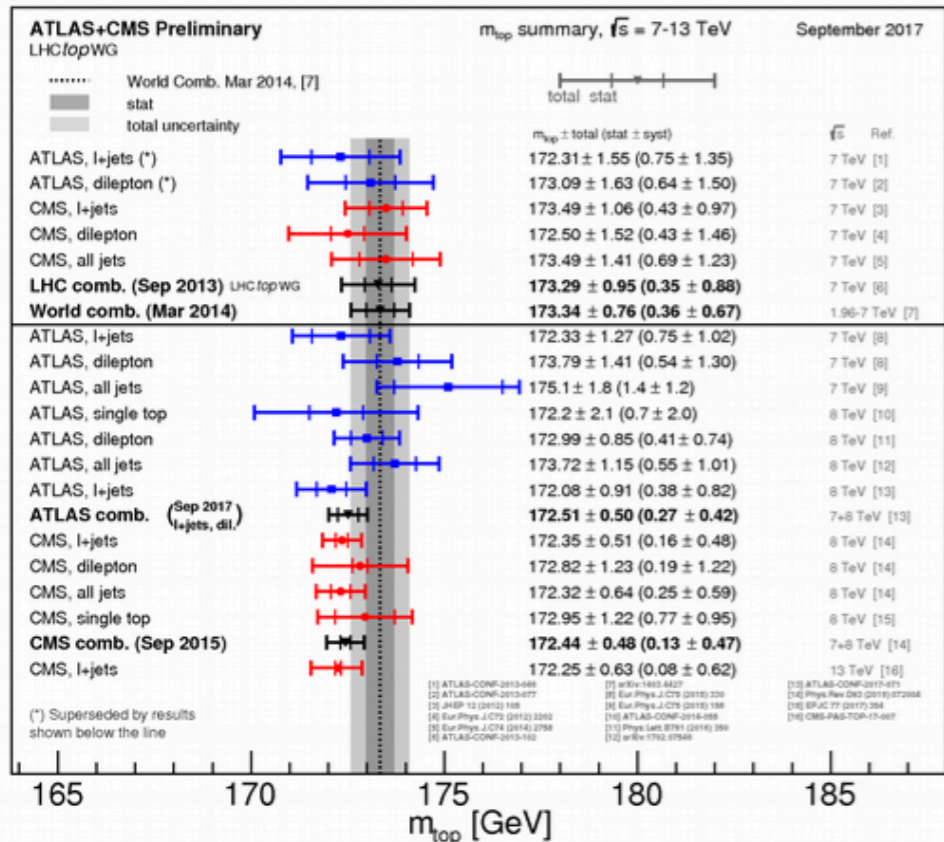
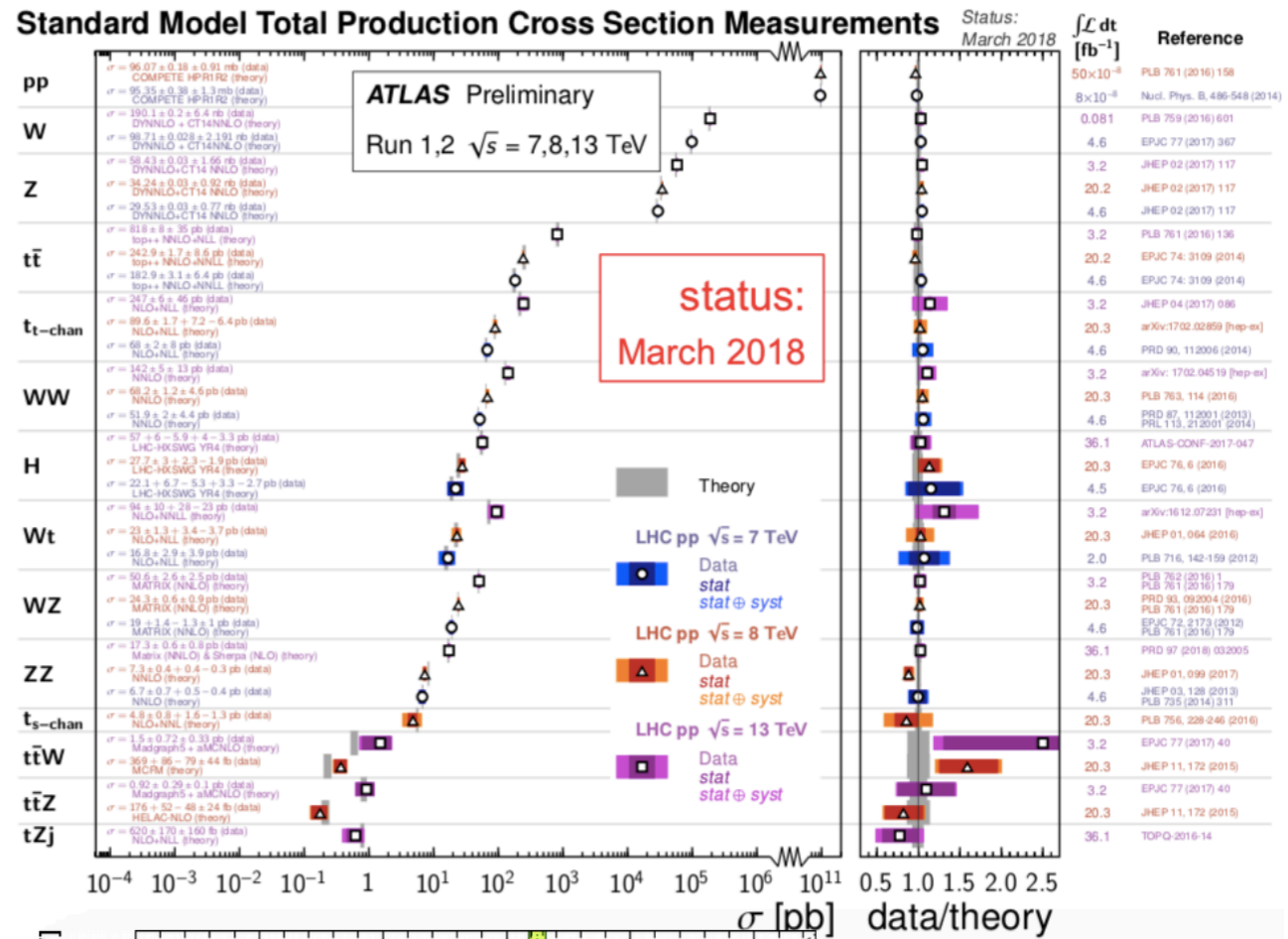
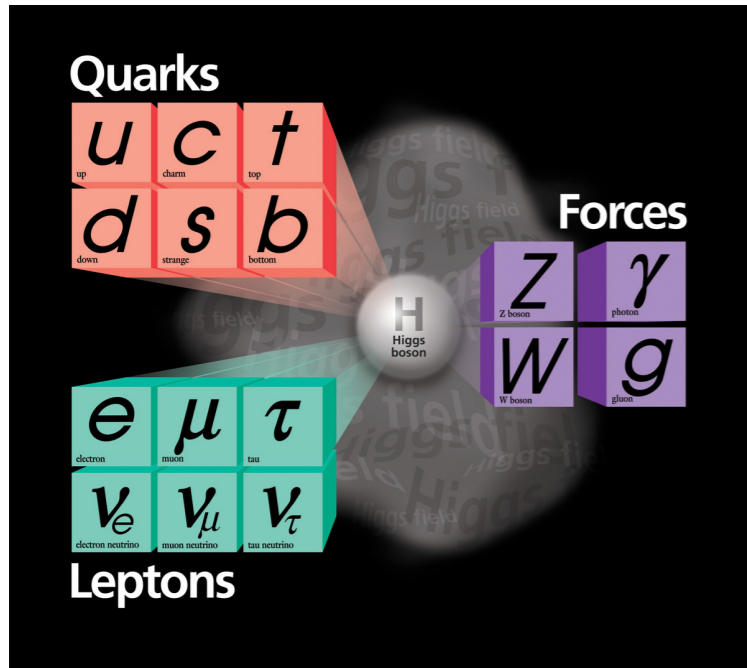


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The Standard Model



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 conceptual 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

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

$$\mathcal{L}_{gauge} = -\frac{1}{4}G_{\mu\nu}^a G_{\mu\nu}^a - \frac{1}{4}W_{\mu\nu}^i W_{\mu\nu}^i - \frac{1}{4}B_{\mu\nu} B_{\mu\nu}$$

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

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

$$+ i\bar{N}_\alpha \gamma^\mu \partial_\mu N_\alpha \quad \leftarrow \text{possible right handed neutrino ?}$$

$$\mathcal{L}_{Yukawa} = y_{\alpha\beta}^L \bar{L}_\alpha E_\beta H + y_{\alpha\beta}^D \bar{Q}_\alpha D_\beta H + y_{\alpha\beta}^U \bar{Q}_\alpha U_\beta \tilde{H} + h.c.,$$

$$+ y_{\alpha\beta}^N \bar{L}_\alpha N_\beta \tilde{H} \quad \leftarrow$$

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

THE LAGR

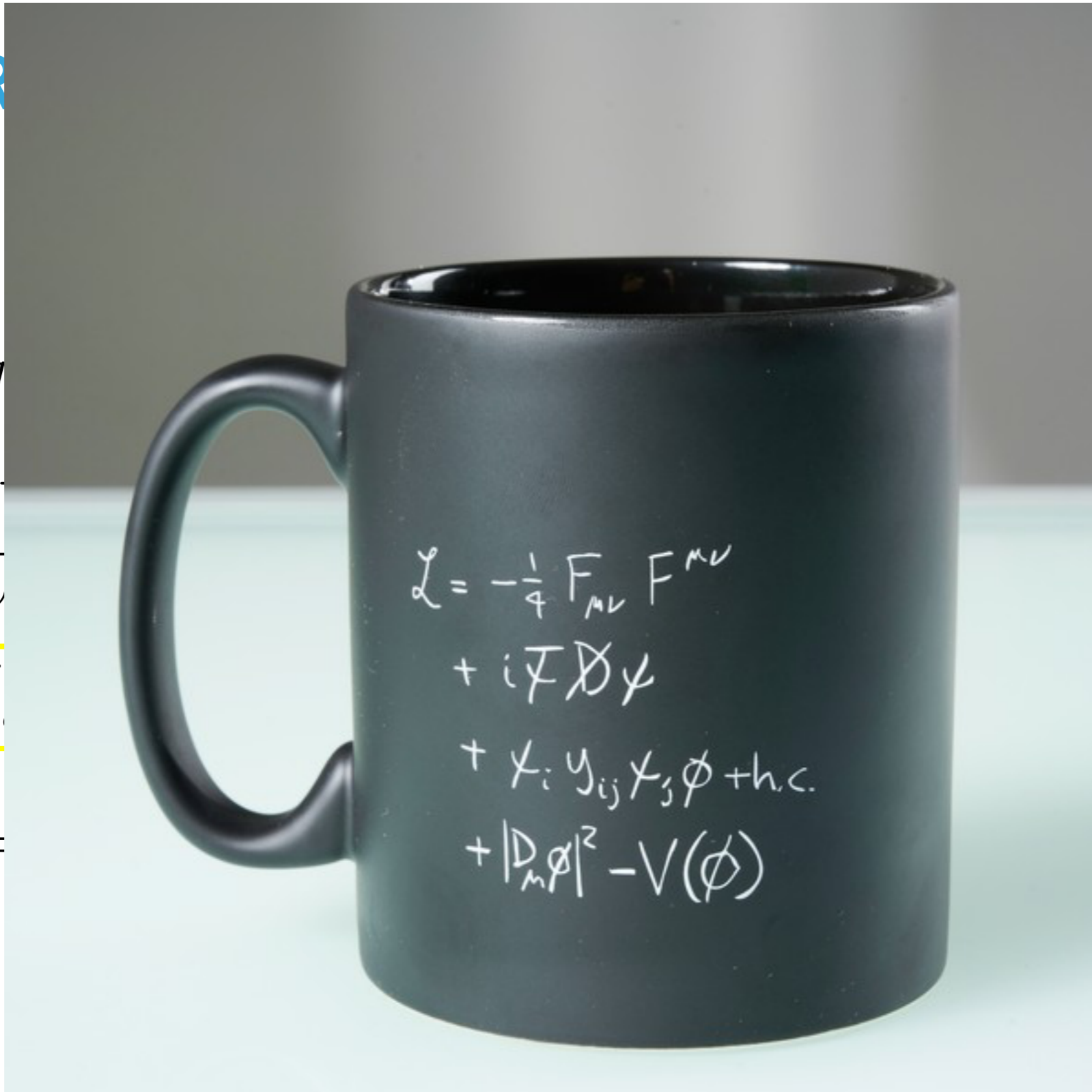
$$\mathcal{L}$$

$$\mathcal{L}_g$$

$$+i\bar{U}$$

$$+i\bar{N}$$

$$\mathcal{L}_{Yukawa} =$$



$${}_{\mu\nu}B_{\mu\nu}$$

$$D_{\mu}E_{\alpha}$$

$$D_{\mu}H),$$

$$\tilde{H} + h.c.,$$

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

THE LAGRANGIAN

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

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

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

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

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

$$\mathcal{L}_{Yukawa} = y_{\alpha\beta}^L\bar{L}_\alpha E_\beta H +$$

$$+y_{\alpha\beta}^N\bar{L}_\alpha N_\beta$$

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

$$\begin{aligned} \mathcal{L}_{SM} = & -\frac{1}{2}\partial_\nu g_\mu^a\partial_\nu g_\mu^a - g_s f^{abc}\partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc}f^{ade}g_\mu^b g_\nu^c g_\mu^d g_\nu^e - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - \\ & M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2}M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z_\mu^0(W_\mu^+ W_\nu^- - \\ & W_\nu^+ W_\mu^-) - Z_\nu^0(W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0(W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+)) - \\ & ig s_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^+)) - \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + g^2 c_w^2(Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - \\ & Z_\mu^0 Z_\nu^0 W_\mu^+ W_\nu^-) + g^2 s_w^2(A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\nu W_\mu^+ W_\nu^-) + g^2 s_w c_w(A_\mu Z_\nu^0(W_\mu^+ W_\nu^- - \\ & W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-) - \frac{1}{2}\partial_\mu H \partial_\mu H - 2M^2 \alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\ & \beta_h \left(\frac{2M^2}{g^2} + \frac{2M}{g}H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right) + \frac{2M^4}{g^2} \alpha_h - \\ & g\alpha_h M(H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^-) - \\ & \frac{1}{8}g^2 \alpha_h(H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2) - \\ & gMW_\mu^+ W_\mu^- H - \frac{1}{2}g\frac{M}{c_w^2}Z_\mu^0 Z_\mu^0 H - \\ & \frac{1}{2}ig(W_\mu^+(\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W_\mu^-(\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)) + \\ & \frac{1}{2}g(W_\mu^+(H\partial_\mu \phi^- - \phi^- \partial_\mu H) + W_\mu^-(H\partial_\mu \phi^+ - \phi^+ \partial_\mu H)) + \frac{1}{2}g\frac{1}{c_w}(Z_\mu^0(H\partial_\mu \phi^0 - \phi^0 \partial_\mu H) + \\ & M(\frac{1}{c_w}Z_\mu^0 \partial_\mu \phi^0 + W_\mu^+ \partial_\mu \phi^- + W_\mu^- \partial_\mu \phi^+)) - ig\frac{s_w^2}{c_w}MZ_\mu^0(W_\mu^+ \phi^- - W_\mu^- \phi^+) + ig s_w M A_\mu(W_\mu^+ \phi^- - \\ & W_\mu^- \phi^+) - ig\frac{1-2c_w^2}{2c_w}Z_\mu^0(\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + ig s_w A_\mu(\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\ & \frac{1}{4}g^2 W_\mu^+ W_\mu^- (H^2 + (\phi^0)^2 + 2\phi^+ \phi^-) - \frac{1}{8}g^2 \frac{1}{c_w^2}Z_\mu^0 Z_\mu^0 (H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-) - \\ & \frac{1}{2}g^2 \frac{s_w^2}{c_w}Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_w^2}{c_w}Z_\mu^0 H(W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + \\ & W_\mu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H(W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 \frac{s_w}{c_w}(2c_w^2 - 1)Z_\mu^0 A_\mu \phi^+ \phi^- - \\ & g^2 s_w^2 A_\mu A_\mu \phi^+ \phi^- + \frac{1}{2}ig_s \lambda_{ij}^a (\bar{q}_i^\alpha \gamma^\mu q_j^\alpha) g_\mu^a - \bar{e}^\lambda (\gamma^\mu \partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda (\gamma^\mu \partial + m_\nu^\lambda) \nu^\lambda - \bar{u}_j^\lambda (\gamma^\mu \partial + \\ & m_u^\lambda) u_j^\lambda - \bar{d}_j^\lambda (\gamma^\mu \partial + m_d^\lambda) d_j^\lambda + ig s_w A_\mu (-\bar{e}^\lambda \gamma^\mu e^\lambda + \frac{2}{3}(\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda \gamma^\mu d_j^\lambda)) + \\ & \frac{ig}{4c_w}Z_\mu^0 \{(\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}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - 1 - \gamma^5) d_j^\lambda) + \\ & (\bar{u}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 + \gamma^5) u_j^\lambda)\} + \frac{ig}{2\sqrt{2}}W_\mu^+ ((\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) U^{lep}{}_{\lambda\kappa} e^\kappa) + (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa)) + \\ & \frac{ig}{2\sqrt{2}}W_\mu^- ((\bar{e}^\kappa U^{lep}{}_{\kappa\lambda}^\dagger \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^\kappa C_{\kappa\lambda}^\dagger \gamma^\mu (1 + \gamma^5) u_j^\lambda)) + \\ & \frac{ig}{2M\sqrt{2}}\phi^+ (-m_e^\kappa (\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa} (1 - \gamma^5) e^\kappa) + m_\nu^\lambda (\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa} (1 + \gamma^5) e^\kappa) + \\ & \frac{ig}{2M\sqrt{2}}\phi^- (m_e^\lambda (\bar{e}^\lambda U^{lep}{}_{\lambda\kappa}^\dagger (1 + \gamma^5) \nu^\kappa) - m_\nu^\kappa (\bar{e}^\lambda U^{lep}{}_{\lambda\kappa}^\dagger (1 - \gamma^5) \nu^\kappa) - \frac{g}{2} \frac{m_\nu^\lambda}{M} H(\bar{\nu}^\lambda \nu^\lambda) - \\ & \frac{g}{2} \frac{m_\nu^\lambda}{M} H(\bar{e}^\lambda e^\lambda) + \frac{ig}{2} \frac{m_\nu^\lambda}{M} \phi^0 (\bar{\nu}^\lambda \gamma^5 \nu^\lambda) - \frac{ig}{2} \frac{m_\nu^\lambda}{M} \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda) - \frac{1}{4} \bar{\nu}_\lambda M_{\lambda\kappa}^R (1 - \gamma_5) \hat{\nu}_\kappa - \\ & \frac{1}{4} \bar{\nu}_\lambda M_{\lambda\kappa}^R (1 - \gamma_5) \hat{\nu}_\kappa + \frac{ig}{2M\sqrt{2}}\phi^+ (-m_d^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa) + \\ & \frac{ig}{2M\sqrt{2}}\phi^- (m_d^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - m_u^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \gamma^5) u_j^\kappa) - \frac{g}{2} \frac{m_u^\lambda}{M} H(\bar{u}_j^\lambda u_j^\lambda) - \\ & \frac{g}{2} \frac{m_d^\lambda}{M} H(\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_u^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2} \frac{m_d^\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c + \\ & \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + igc_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \\ & \partial_\mu \bar{X}^+ X^0) + ig s_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + igc_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \\ & \partial_\mu \bar{X}^0 X^+) + ig s_w W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + igc_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \\ & \partial_\mu \bar{X}^- X^-) + ig s_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \\ & \partial_\mu \bar{X}^- X^-) - \frac{1}{2}gM(\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H) + \frac{1-2c_w^2}{2c_w} igM(\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-) + \\ & \frac{1}{2c_w} igM(\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + igMs_w(\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + \\ & \frac{1}{2}igM(\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0) . \end{aligned}$$

THE LAGRANGIAN

Every problem of the SM originates from Higgs interactions

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

↑
↑
↑
↑

flavour
naturalness
stability
C.C.

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 of Fundamental Interactions

```
graph TD; A[The Standard Model of Fundamental Interactions] --> B[Higgs Sector]; A --> C[Neutrino Sector]; A --> D[Flavour Sector]; B --> E[New particles and Interactions]; C --> E; D --> E; C --> F[Dark Matter];
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Higgs Sector

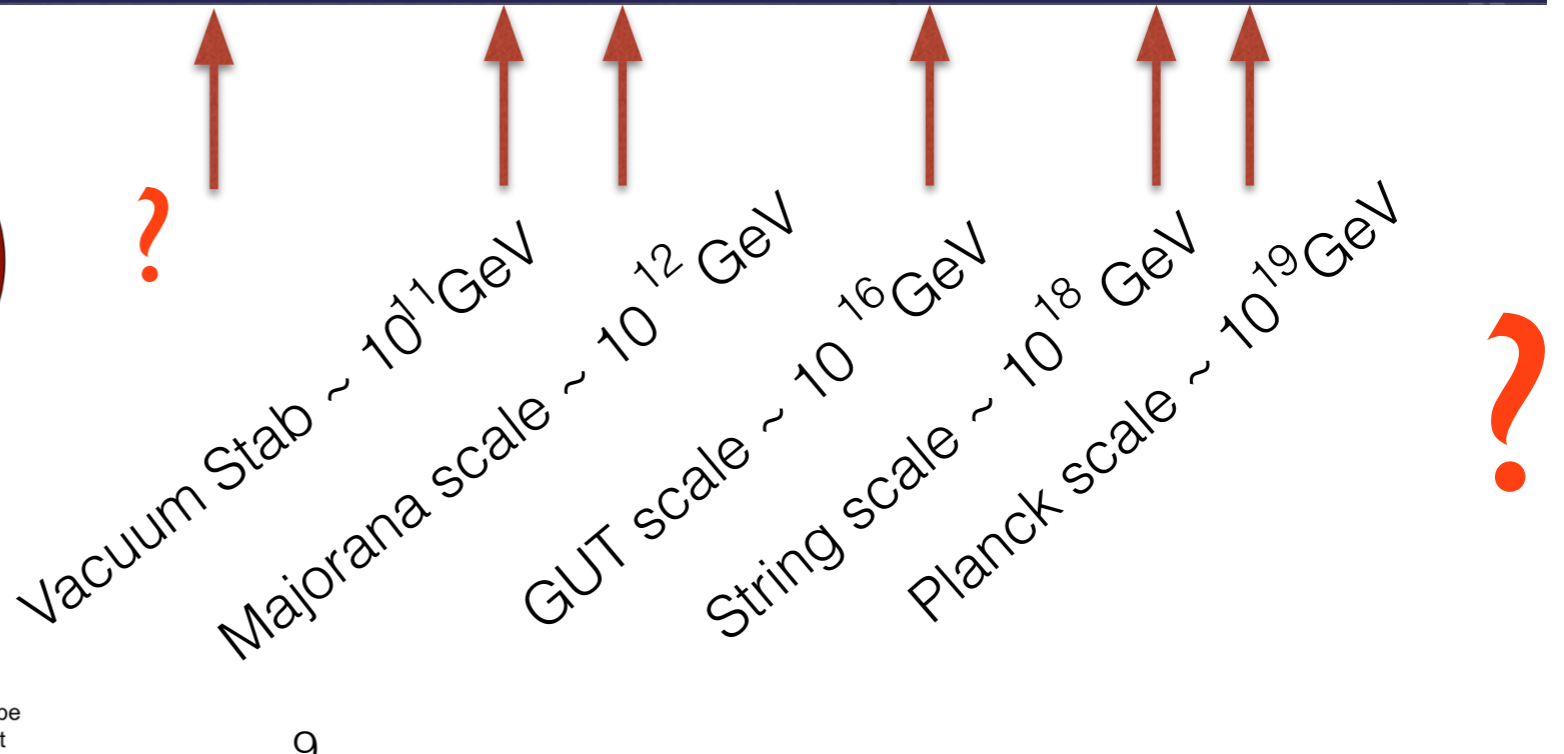
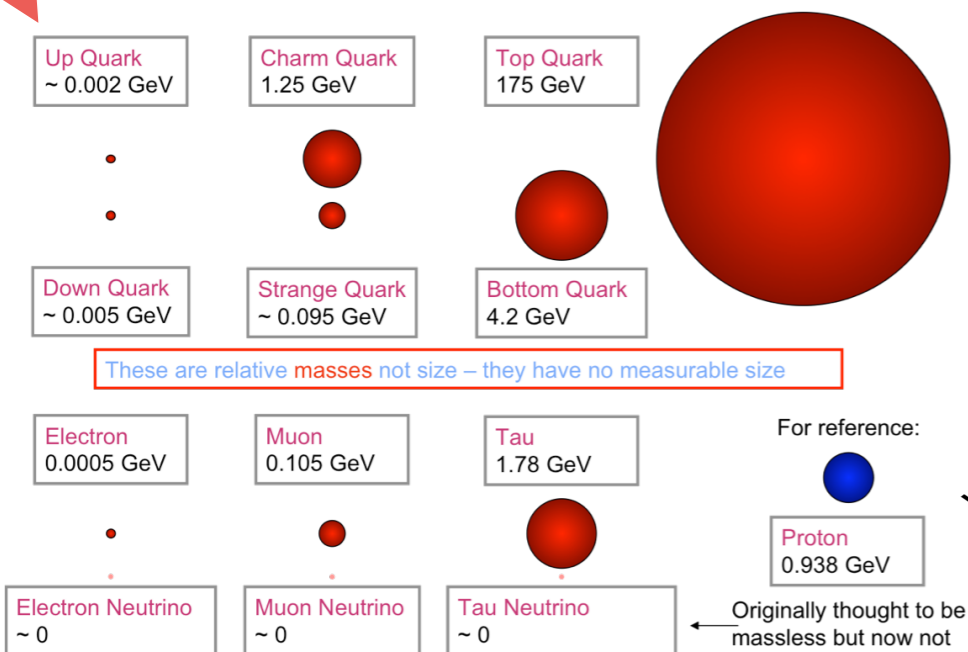
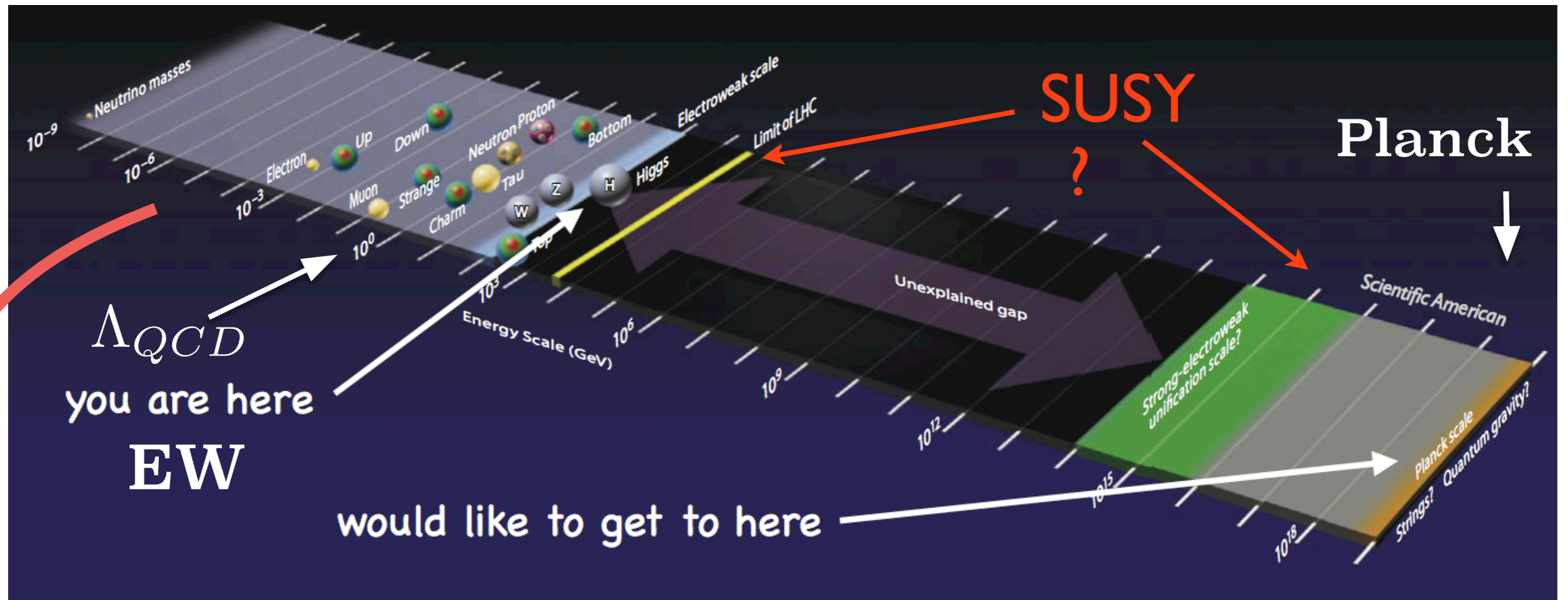
Neutrino Sector

Flavour Sector

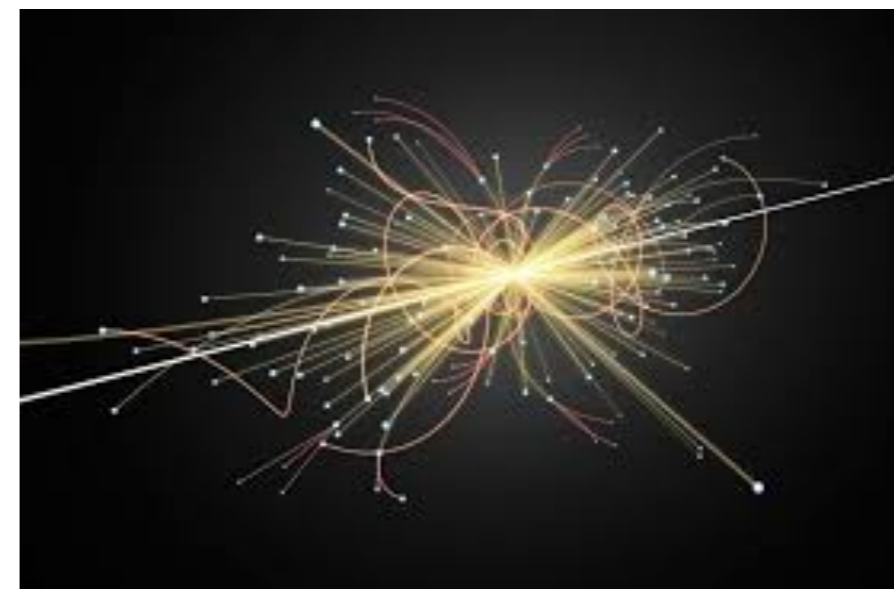
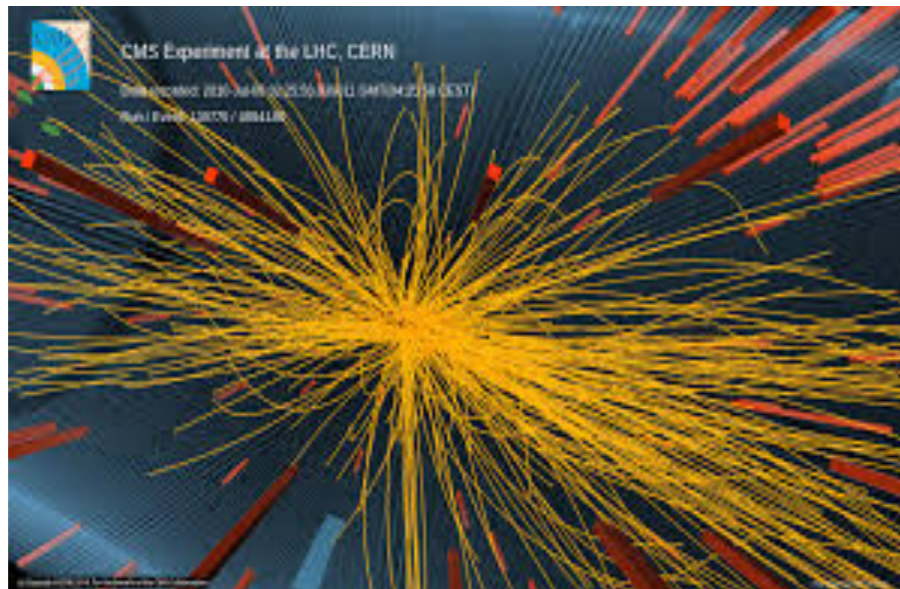
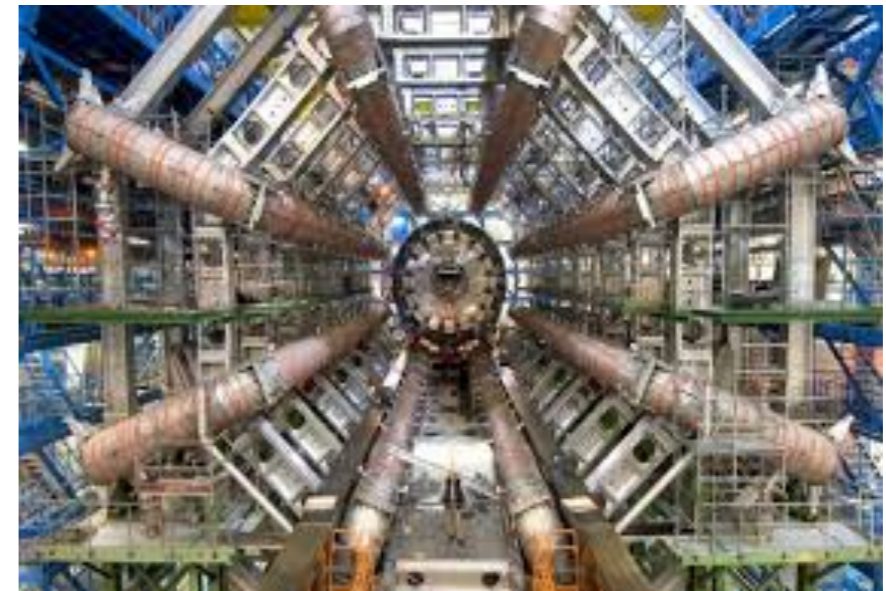
Dark Matter

New particles and Interactions

Is there another scale except for EW and Planck?

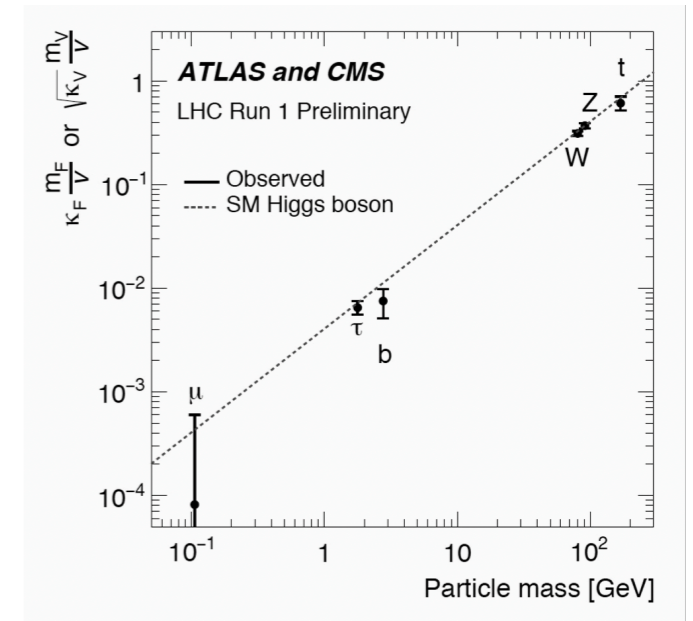
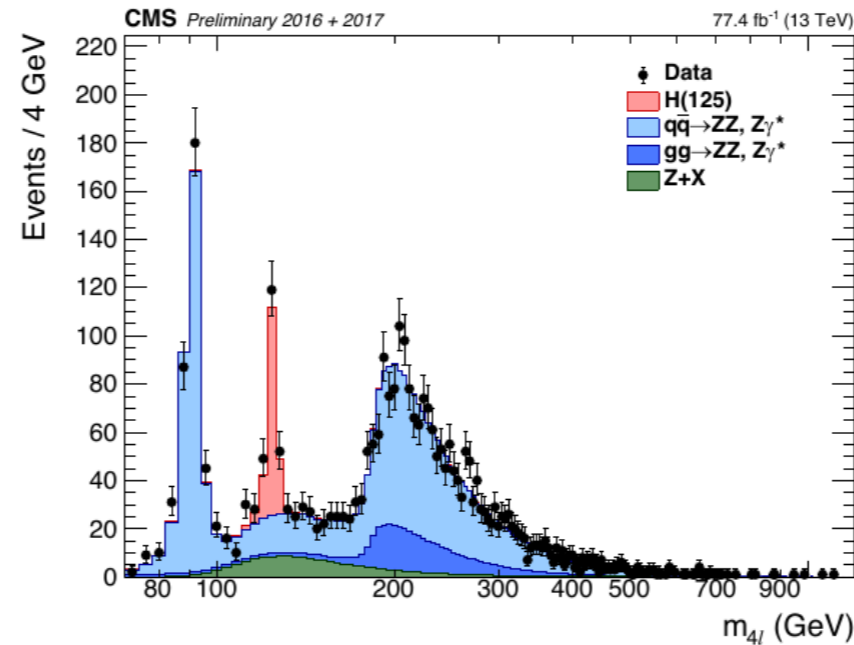
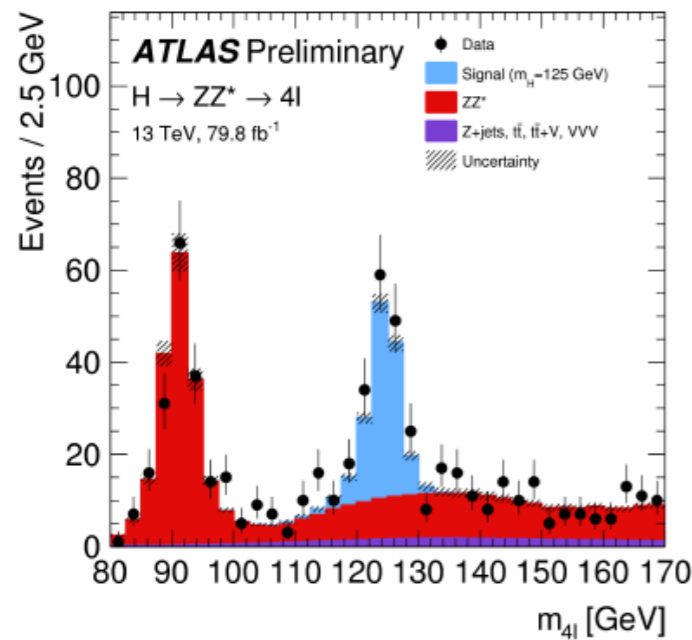


Accelerator Physics

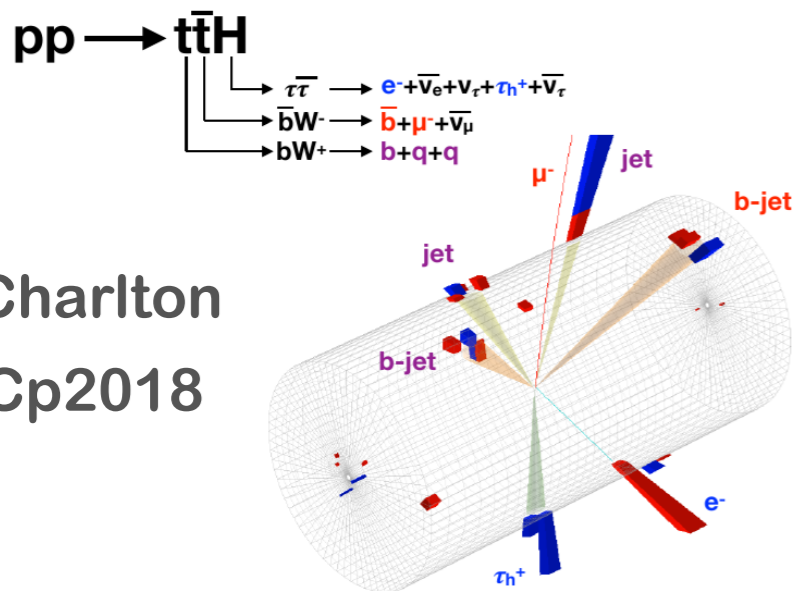


Higgs bosons - entering precision era

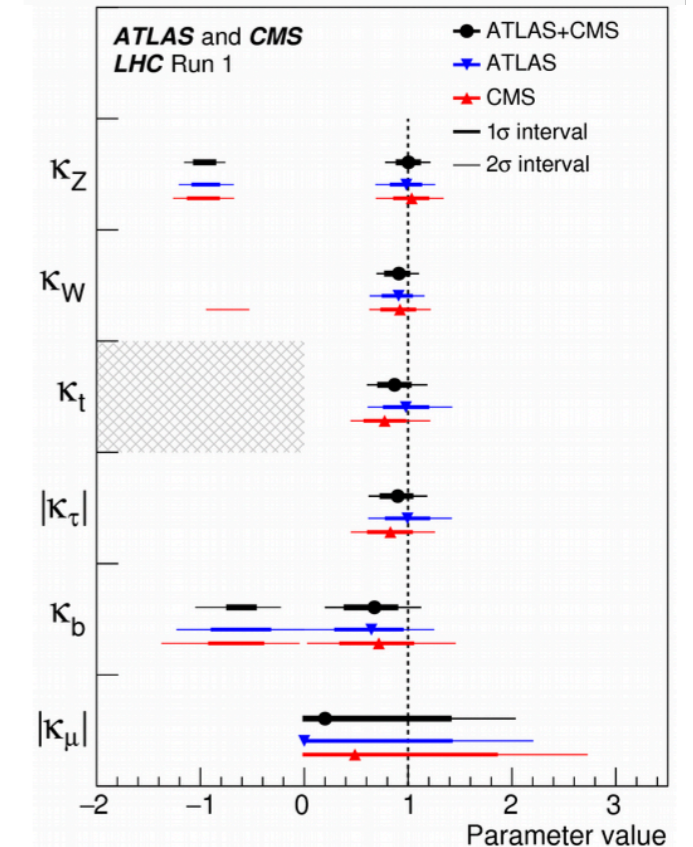
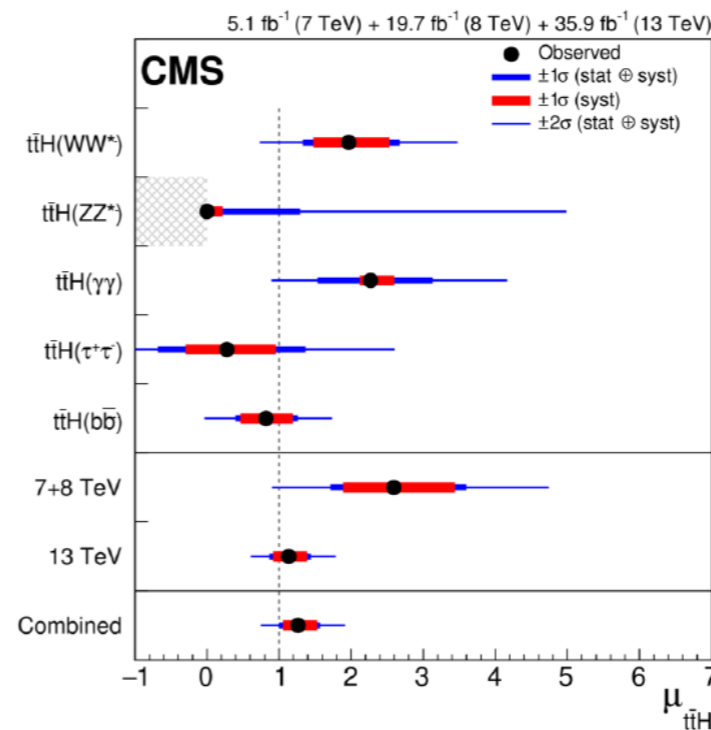
Run-2 analyses with 80 fb^{-1} for the first time – higher precision is coming!



ttH observation



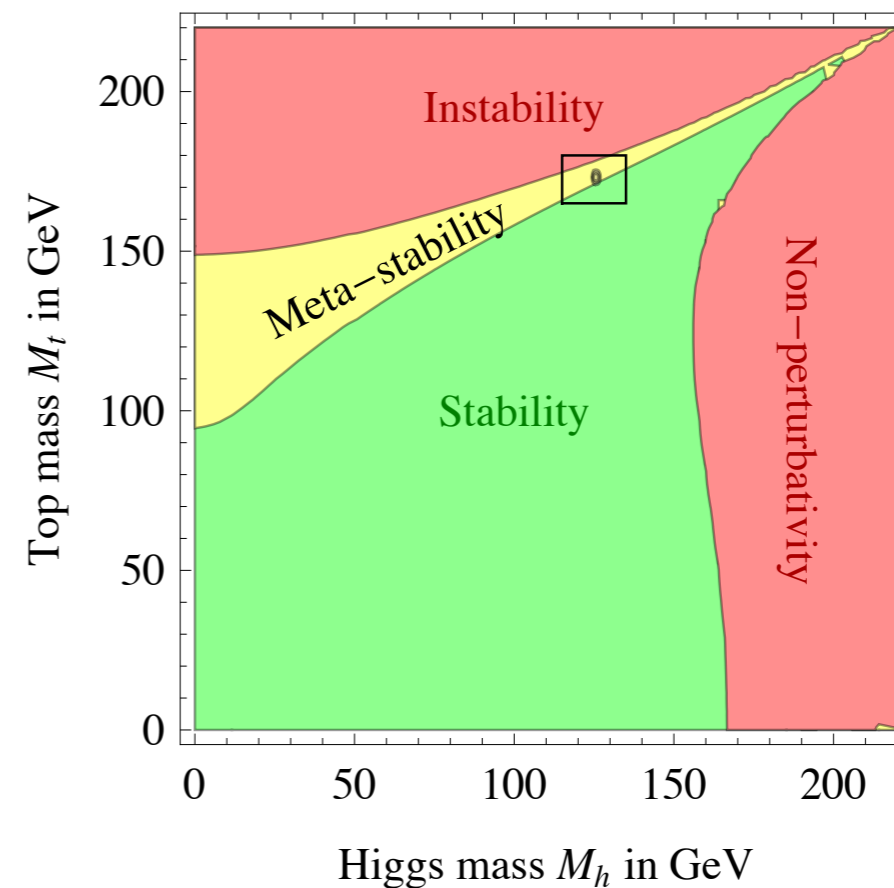
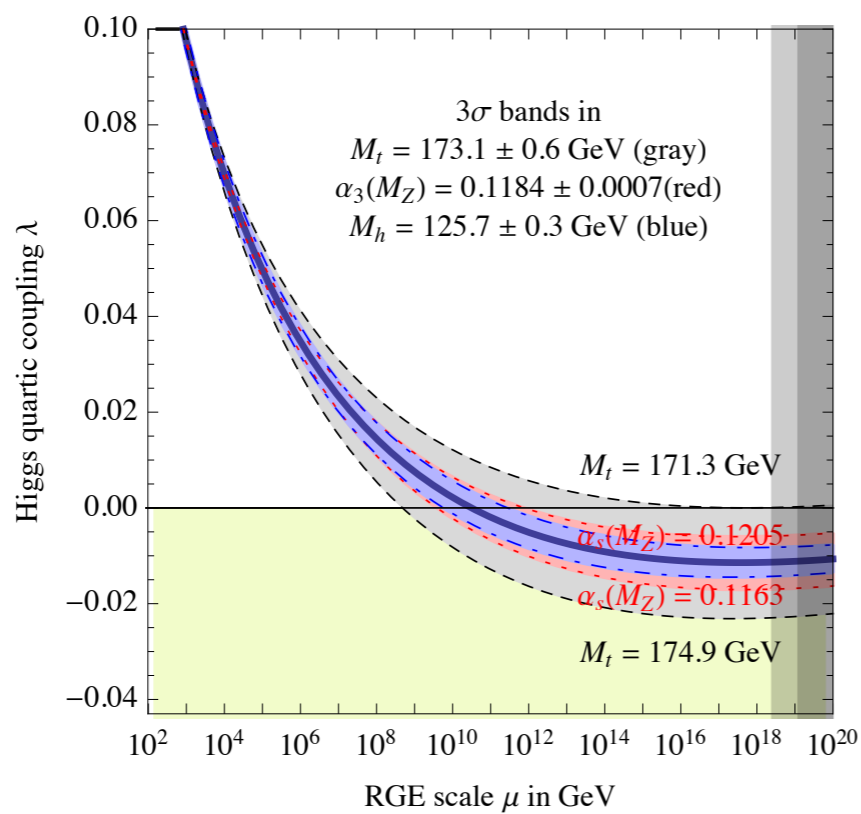
D. Charlton
 LHCp2018



THE STANDARD MODEL: THE STATUS REPORT AND OPEN QUESTIONS

📌 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)

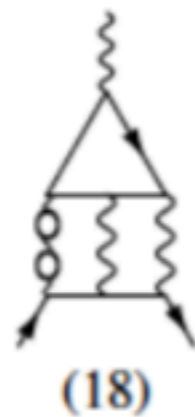
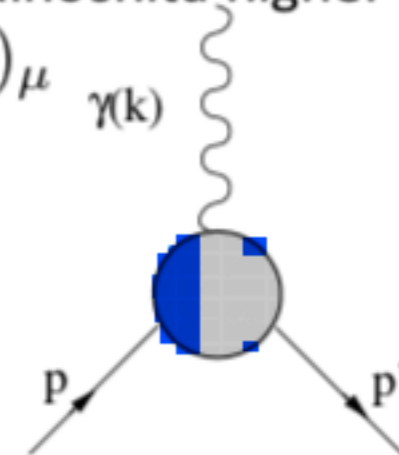
Muon anomalous magnetic moment

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

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

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

For electron a_e theory and experiment agrees!



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

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).

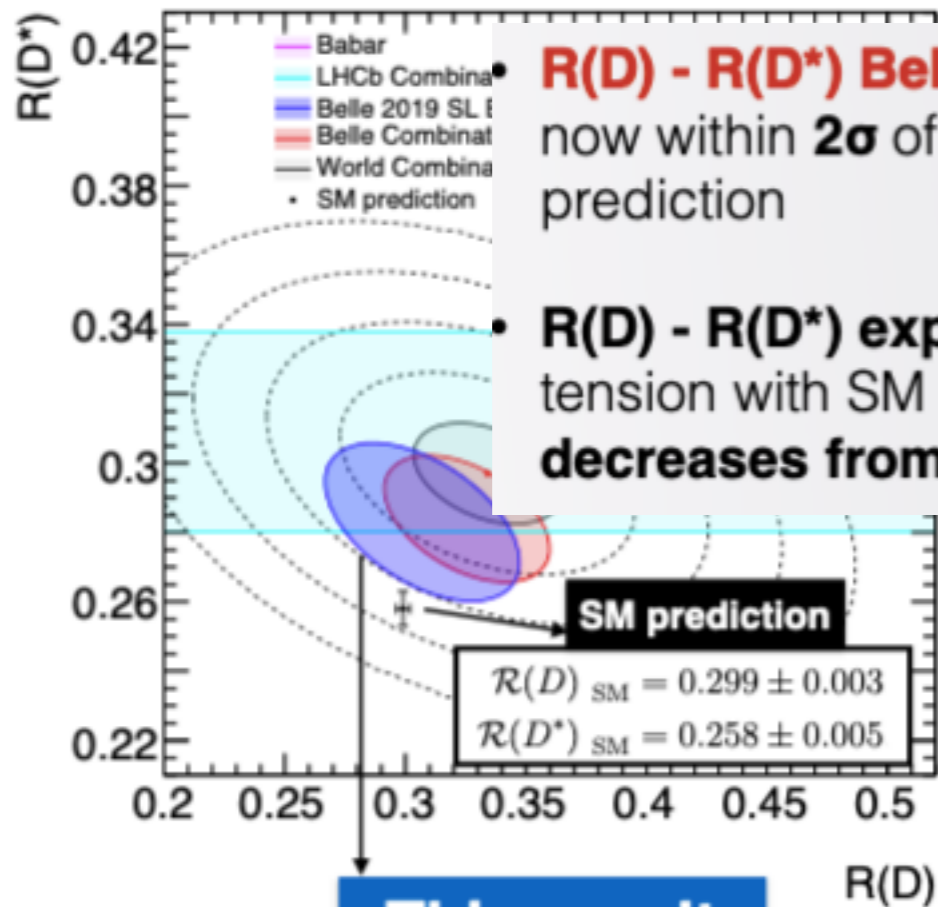
Fermilab and J-Park experiments are expected to clarify existing discrepancy!

THE STANDARD MODEL: THE STATUS REPORT AND OPEN QUESTIONS

B physics anomalies: experimental results \neq SM predictions!

charged current (SM tree level)

$$R_{D^{(*)}} = \frac{BR(B \rightarrow D^{(*)} \tau \nu_\tau)}{BR(B \rightarrow D^{(*)} \mu \nu_\mu)} \quad 3.8\sigma$$



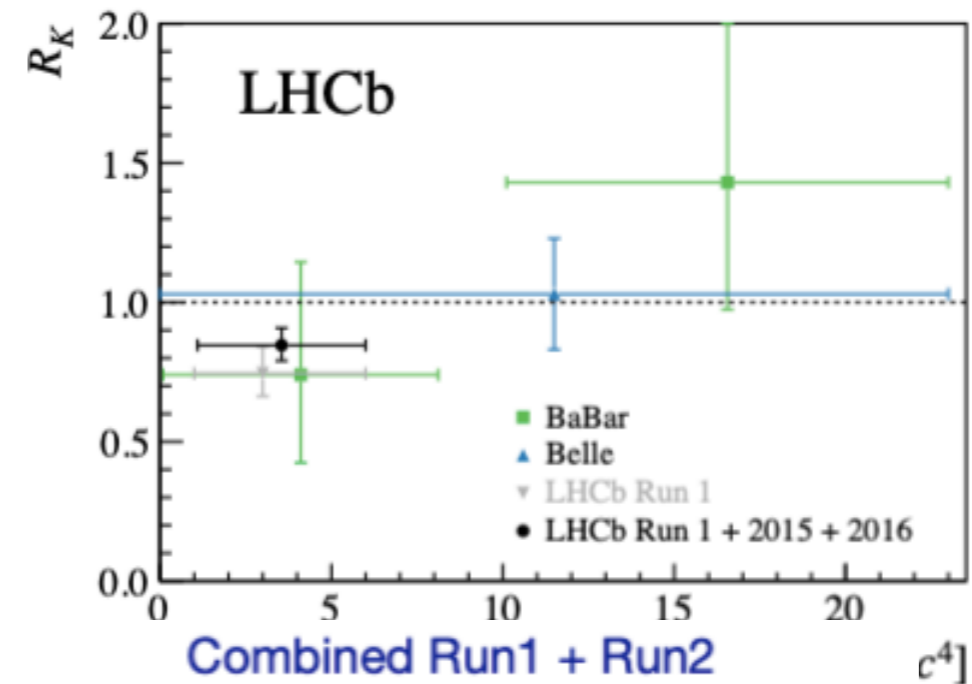
This result

$$R(D) = 0.307 \pm 0.037 \pm 0.016$$

$$R(D^*) = 0.283 \pm 0.018 \pm 0.014$$

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

$$R_{K^{(*)}} = \frac{BR(B \rightarrow K^{(*)} \mu \mu)}{BR(B \rightarrow K^{(*)} e e)} \quad 2.5\sigma$$

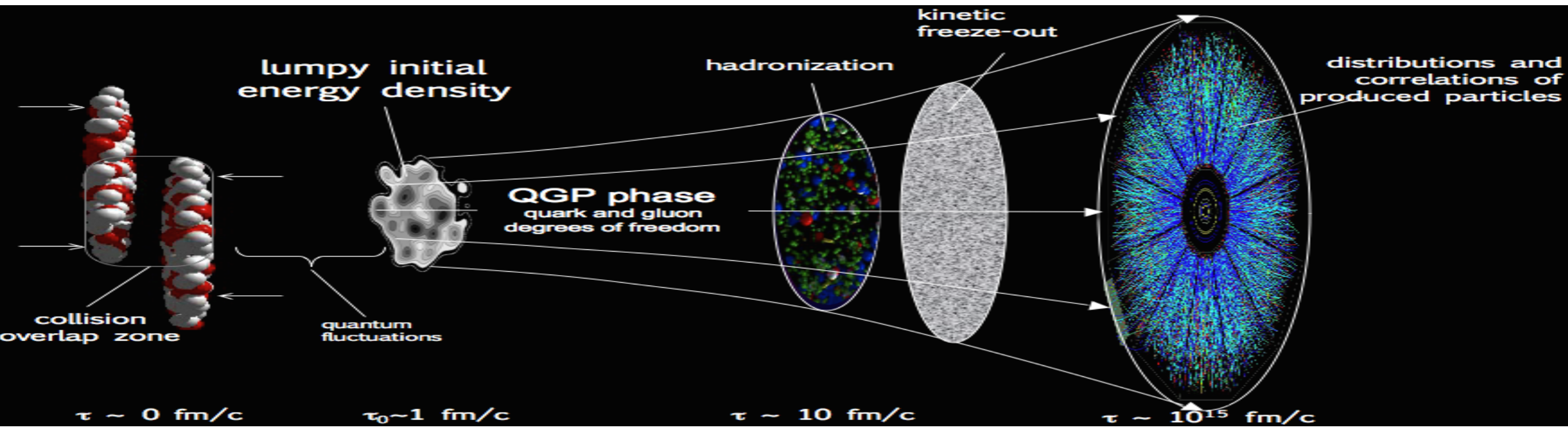


$$R_K = 0.846^{+0.060}_{-0.054}(\text{stat.})^{+0.016}_{-0.014}(\text{syst.})$$

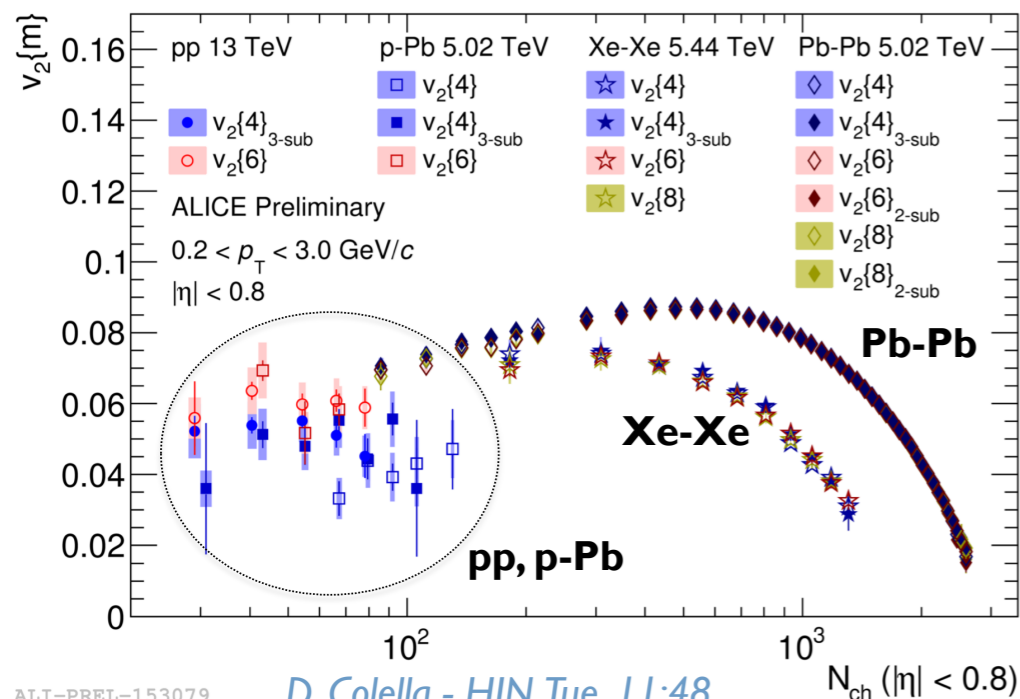
LHCb: the discrepancy present in $B_s \rightarrow \phi \mu \mu$ and $\Lambda_b \rightarrow \Lambda \mu \mu$

Discrepancy might dissolve and might as well grow up

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

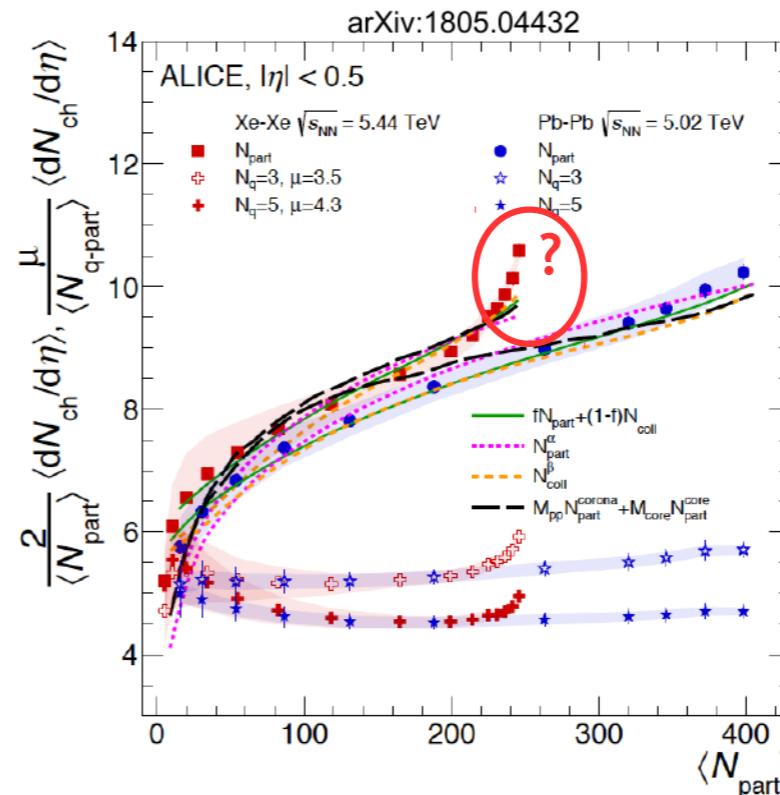


Collectivity in small systems



ALI-PREL-153079

D. Coella - 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

ATLAS SUSY Searches* - 95% CL Lower Limits July 2018

Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit	$\sqrt{s} = 7, 8 \text{ TeV}$	$\sqrt{s} = 13 \text{ TeV}$	Reference	
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\nu}^0$	0	2-6 jets	Yes	36.1	\tilde{q} [2x, 8x Degen.]	0.9	1.55	
	mono-jet	1-3 jets	Yes	36.1	\tilde{q} [1x, 8x Degen.]	0.43	0.71	1712.02332	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\nu}^0$	0	2-6 jets	Yes	36.1	\tilde{g}	Forbidden	0.95-1.6	1711.09390
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\ell\ell\tilde{\nu}^0$	3 e, μ	4 jets	-	36.1	\tilde{g}	Forbidden	1.85	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}WZ\tilde{\nu}^0$	0	7-11 jets	Yes	36.1	\tilde{g}	0.98	1.8	
3 rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\nu}^0/\tilde{\nu}^+$	Multiple	Multiple	Yes	36.1	\tilde{b}_1	Forbidden	0.9	$m(\tilde{\nu}^0) < 100 \text{ GeV}$
	$\tilde{b}_1\tilde{b}_1, \tilde{t}_1\tilde{t}_1, M_2 = 2 \times M_1$	Multiple	Multiple	Yes	36.1	\tilde{b}_1	Forbidden	0.58-0.82	$m(\tilde{\nu}^0) = 200$
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\nu}^0$ or $t\tilde{\nu}^0$	0-2 e, μ	0-2 jets/1-2 b	Yes	36.1	\tilde{t}_1	Forbidden	0.7	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow W\tilde{\nu}^0$	Multiple	Multiple	Yes	36.1	\tilde{t}_1	Forbidden	0.9	$m(\tilde{\nu}^0) = 150$
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\nu}^0/\tilde{\nu}^+$	Multiple	Multiple	Yes	36.1	\tilde{t}_1	Forbidden	0.4-0.9	$m(\tilde{\nu}^0) = 300$
EW direct	$\tilde{\chi}_1^0\tilde{\chi}_2^0$ via WZ	2-3 e, μ	≥ 1	Yes	36.1	$\tilde{\chi}_1^0/\tilde{\chi}_2^0$	0.17	0.6	$m(\tilde{\chi}_1^0) = 1$
	$\tilde{\chi}_1^0\tilde{\chi}_2^0$ via Wh	$\ell\ell\gamma\gamma/\ell b\bar{b}$	≥ 1	Yes	20.3	$\tilde{\chi}_1^0/\tilde{\chi}_2^0$	0.26	0.76	
	$\tilde{\chi}_1^0\tilde{\chi}_1^0/\tilde{\chi}_2^0, \tilde{\chi}_1^0 \rightarrow \tilde{\nu}\nu(\tilde{\nu}\bar{\nu}), \tilde{\chi}_2^0 \rightarrow \tilde{\nu}\tau(\tilde{\nu}\bar{\nu})$	2 τ	-	Yes	36.1	$\tilde{\chi}_1^0/\tilde{\chi}_2^0$	0.22	0.5	
	$\tilde{\chi}_1^0\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \tilde{\nu}\tilde{\nu}$	2 e, μ	0	Yes	36.1	$\tilde{\chi}_1^0$	0.18	0.5	
	$\tilde{h}_1, \tilde{h}_2, \tilde{h}_3 \rightarrow \tilde{\nu}\tilde{\nu}$	2 e, μ	≥ 1	Yes	36.1	\tilde{h}_1	0.13-0.23	0.29-0.88	
Long-lived particles	Direct $\tilde{\chi}_1^0\tilde{\chi}_1^0$ prod., long-lived $\tilde{\chi}_1^0$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}_1^0$	0.15	0.46	
	Stable \tilde{g} R-hadron	SMP	-	-	3.2	\tilde{g}	-	1.6	
	Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow q\tilde{q}\tilde{\nu}^0$	Multiple	-	-	32.8	\tilde{g} [$\tau(\tilde{g}) = 100 \text{ ns}, 0.2 \text{ ns}$]	-	1.6	2.4
RPV	GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma G$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$	0.44	-	
	$\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \rightarrow c\tilde{\nu}/e\tilde{\nu}/\mu\tilde{\nu}$	displ. $e\tilde{\nu}/e\mu/\mu\tilde{\nu}$	-	-	20.3	\tilde{g}	-	1.3	
	LFV $pp \rightarrow \tilde{\nu}_i + X, \tilde{\nu}_i \rightarrow e\mu/\tau\mu/\mu\tau$	$e\mu, \tau\mu, \mu\tau$	-	-	3.2	$\tilde{\nu}_i$	-	1.9	
	$\tilde{\chi}_1^0\tilde{\chi}_1^0/\tilde{\chi}_2^0 \rightarrow WWZZ\ell\ell\nu\nu$	4 e, μ	0	Yes	36.1	$\tilde{\chi}_1^0/\tilde{\chi}_2^0$ [$A_{333} \neq 0, A_{322} \neq 0$]	0.82	1.33	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\nu}^0, \tilde{\chi}_1^0 \rightarrow q\tilde{q}\tilde{\nu}^0$	0	4-5 large-R jets	-	36.1	\tilde{g} [$M_{323} = 200 \text{ GeV}, 1100 \text{ GeV}$] $\tilde{\chi}_1^0$ [$M_{323} = 20-4, 20-5$]	-	1.05	1.3

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

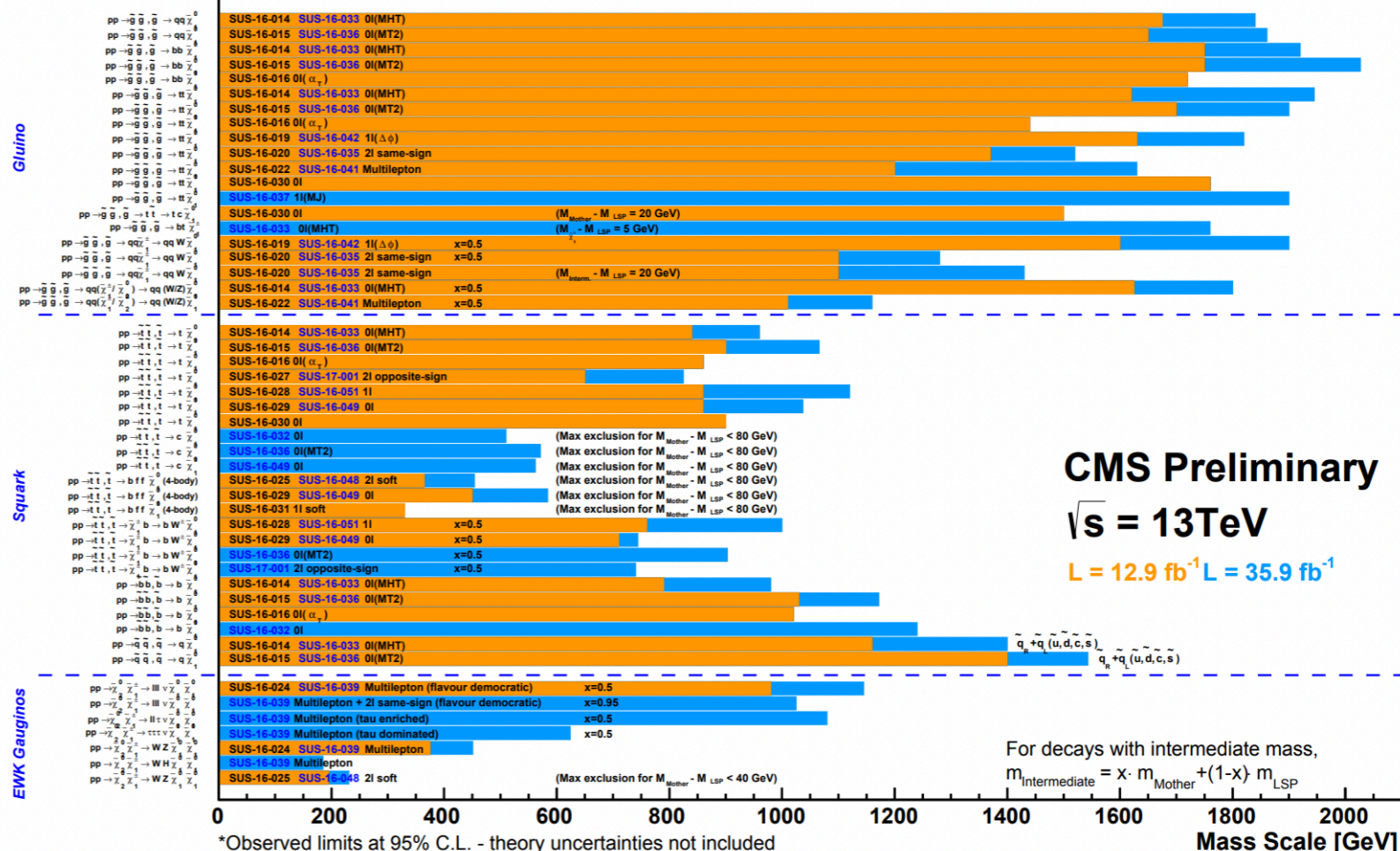
ATLAS Preliminary $\sqrt{s} = 7, 8, 13 \text{ TeV}$

SUSY or not SUSY?

Gluino
Squark
EWK Gauginos

Selected CMS SUSY Results* - SMS Interpretation

ICHEP '16 - Moriond '17

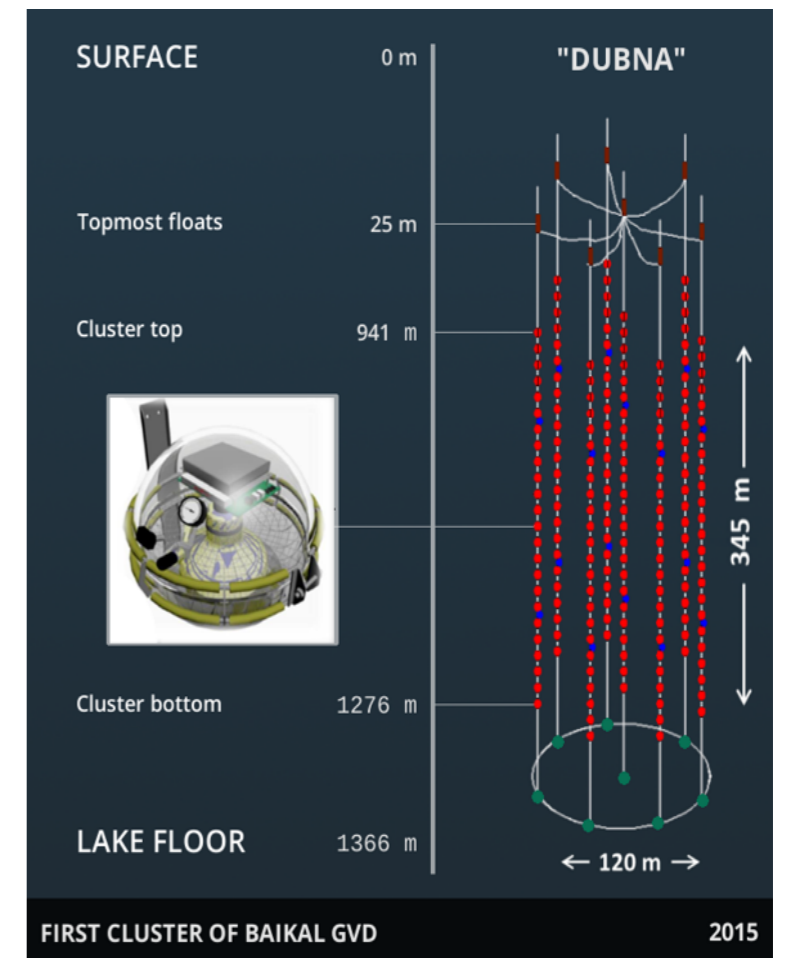
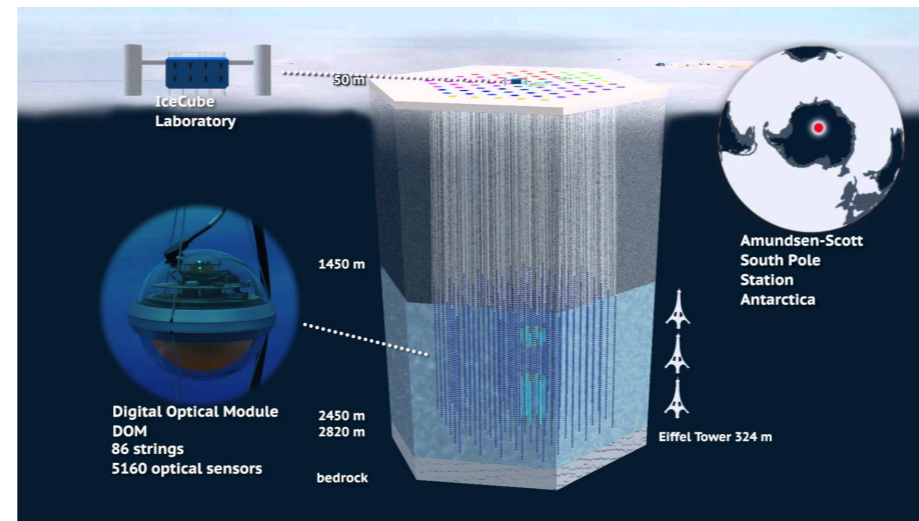
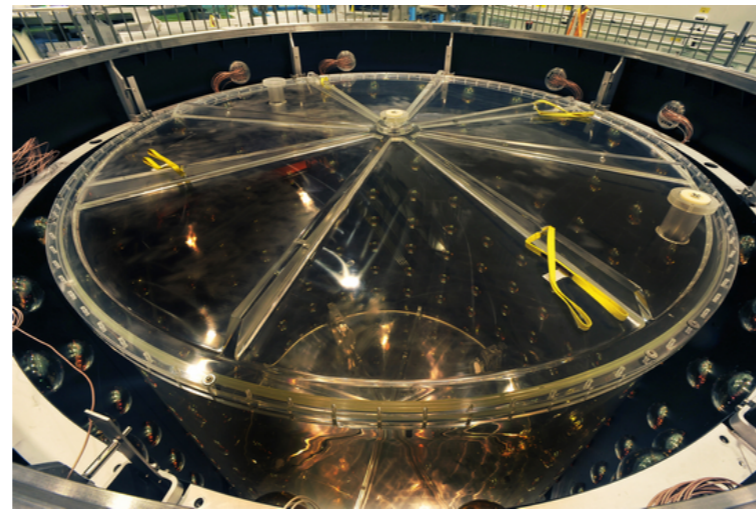
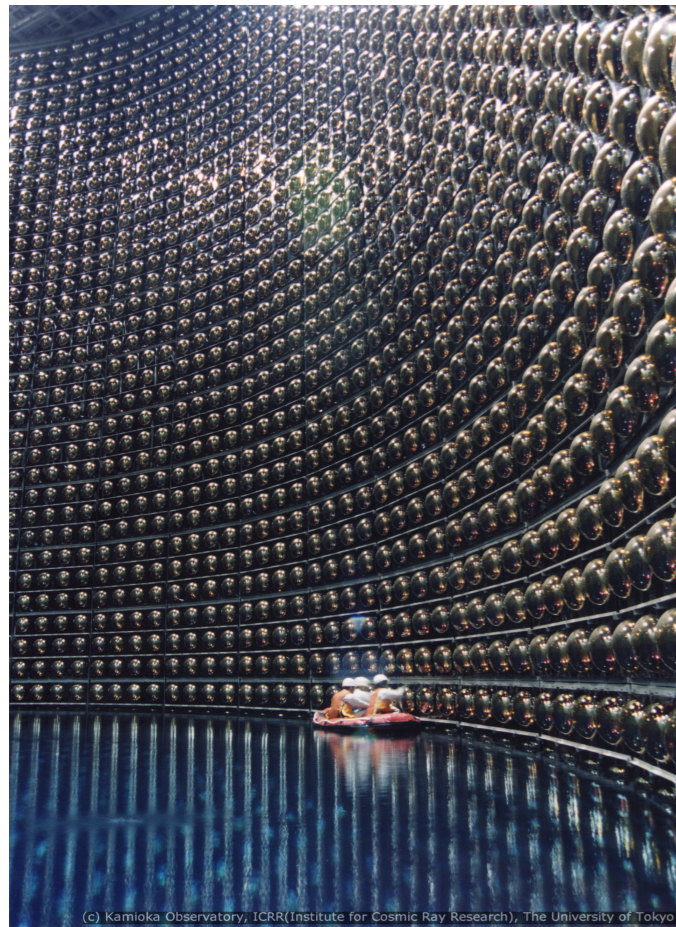


CMS Preliminary
 $\sqrt{s} = 13 \text{ TeV}$
 $L = 12.9 \text{ fb}^{-1} \quad L = 35.9 \text{ fb}^{-1}$

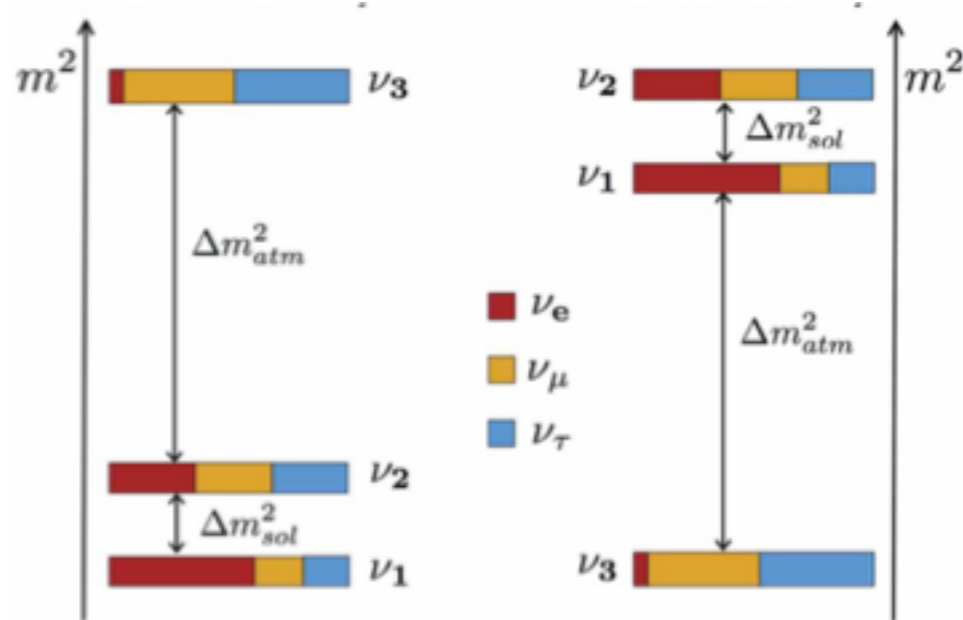
*Observed limits at 95% C.L. - theory uncertainties not included
Only a selection of available mass limits. Probe *up to* the quoted mass limit for $m_{\text{LSP}} \approx 0 \text{ GeV}$ unless stated otherwise

- No evidence for SUSY yet \rightarrow strong message from the LHC.
- In most favourable / challenging scenarios we excluded
 - 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



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

$$0.06 \text{ eV} < \sum m_\nu < 0.12 \text{ eV}$$

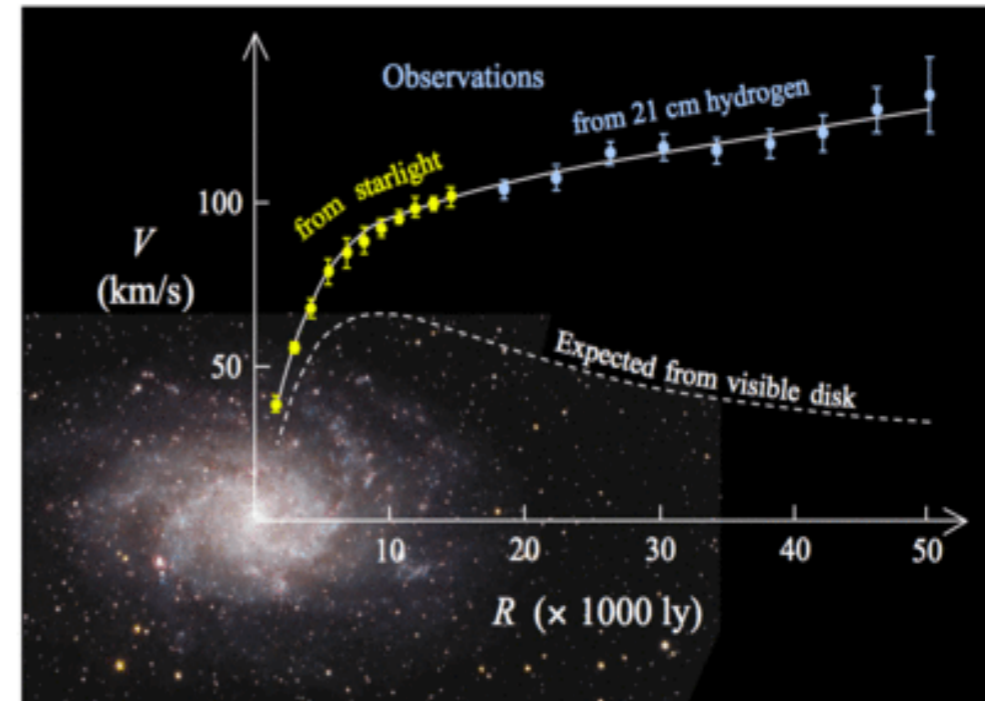
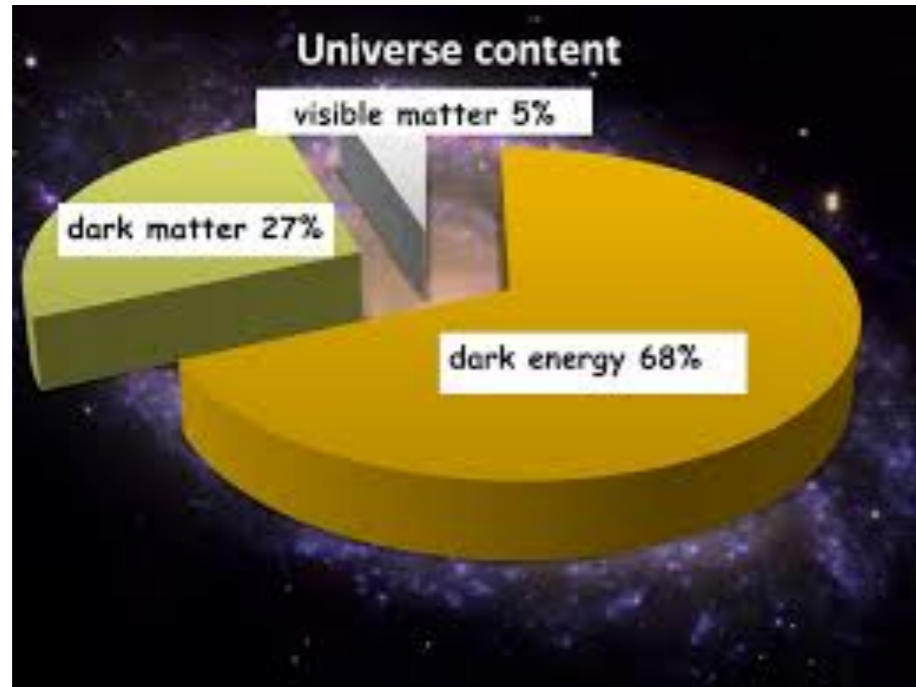
↑
↑
ν-OSC
CMB

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

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

parameter	best fit $\pm 1\sigma$	3σ range
Δm_{21}^2 [10^{-5}eV^2]	$7.55^{+0.20}_{-0.16}$	7.05–8.14
$ \Delta m_{31}^2 $ [10^{-3}eV^2] (NO)	2.50 ± 0.03	2.41–2.60
$ \Delta m_{31}^2 $ [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

Dark Matter



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?

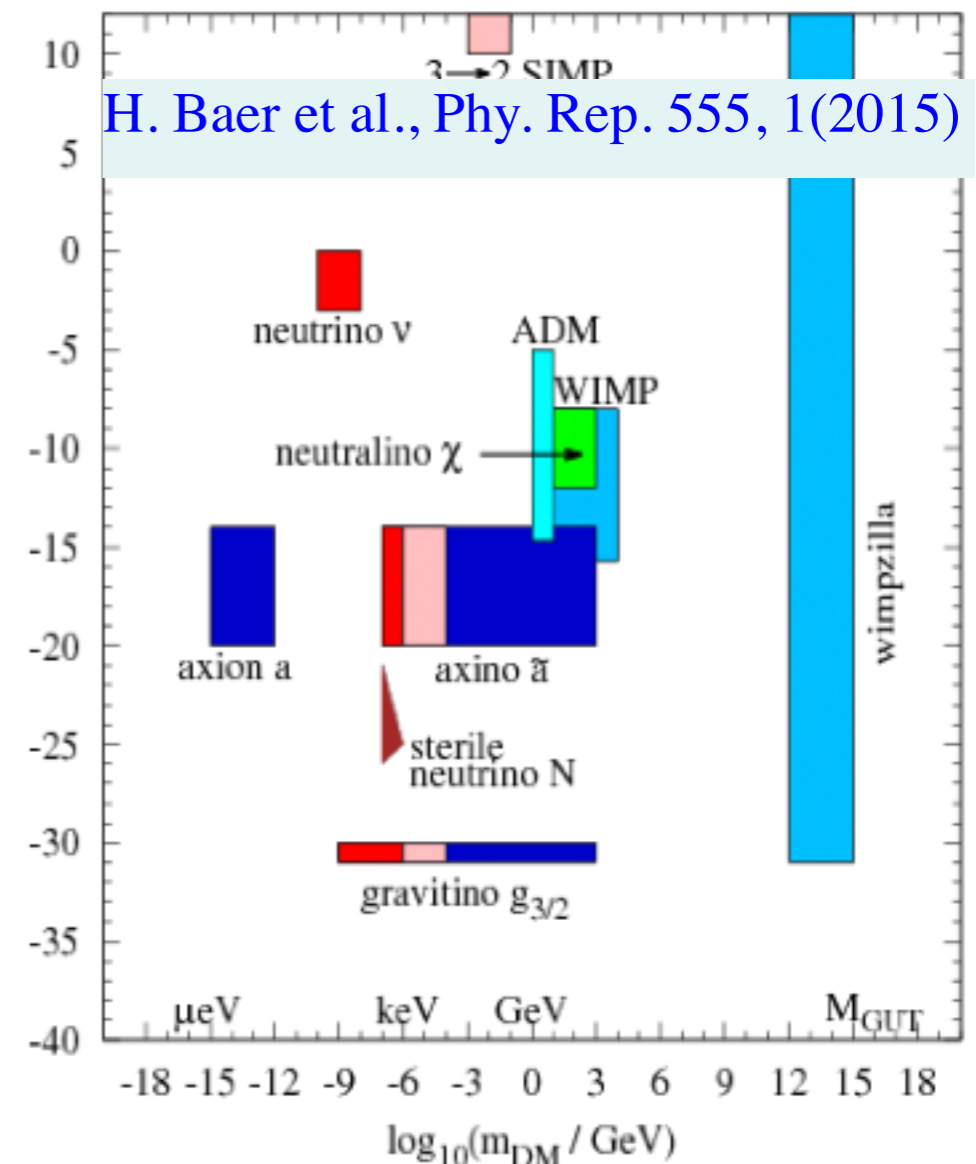
- Many candidates in many orders of magnitude of mass:

- **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**



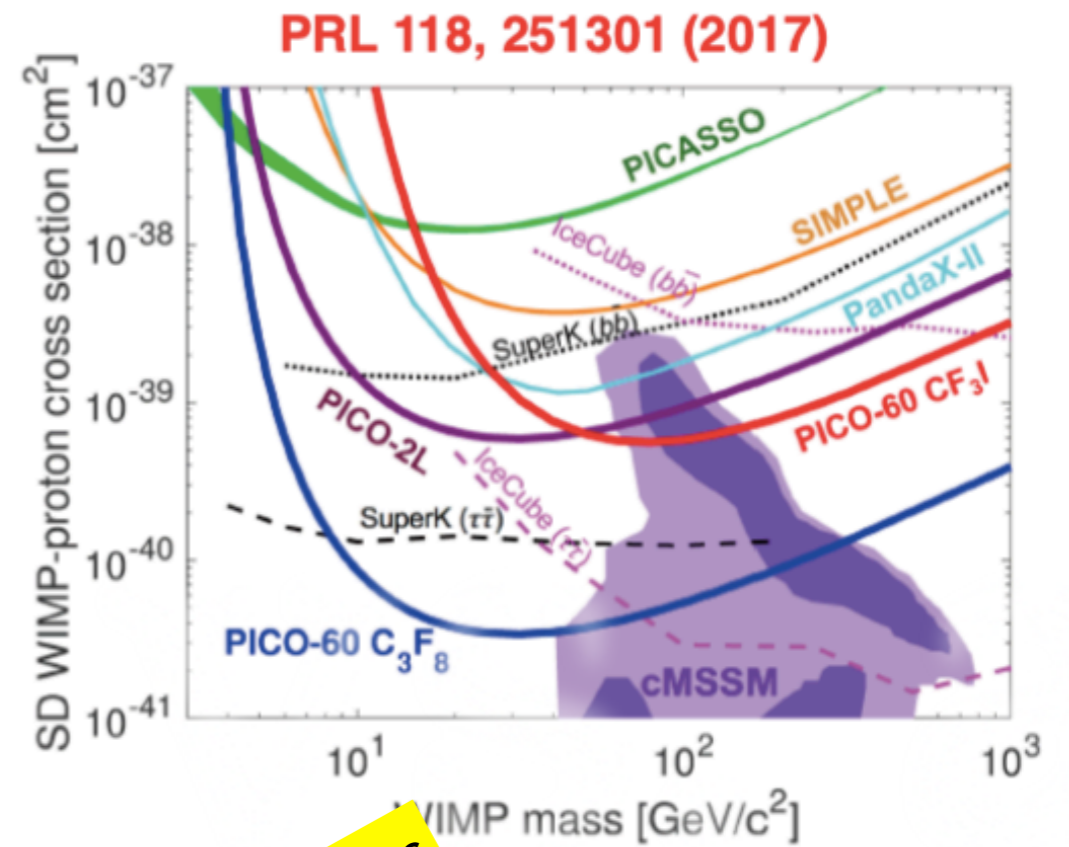
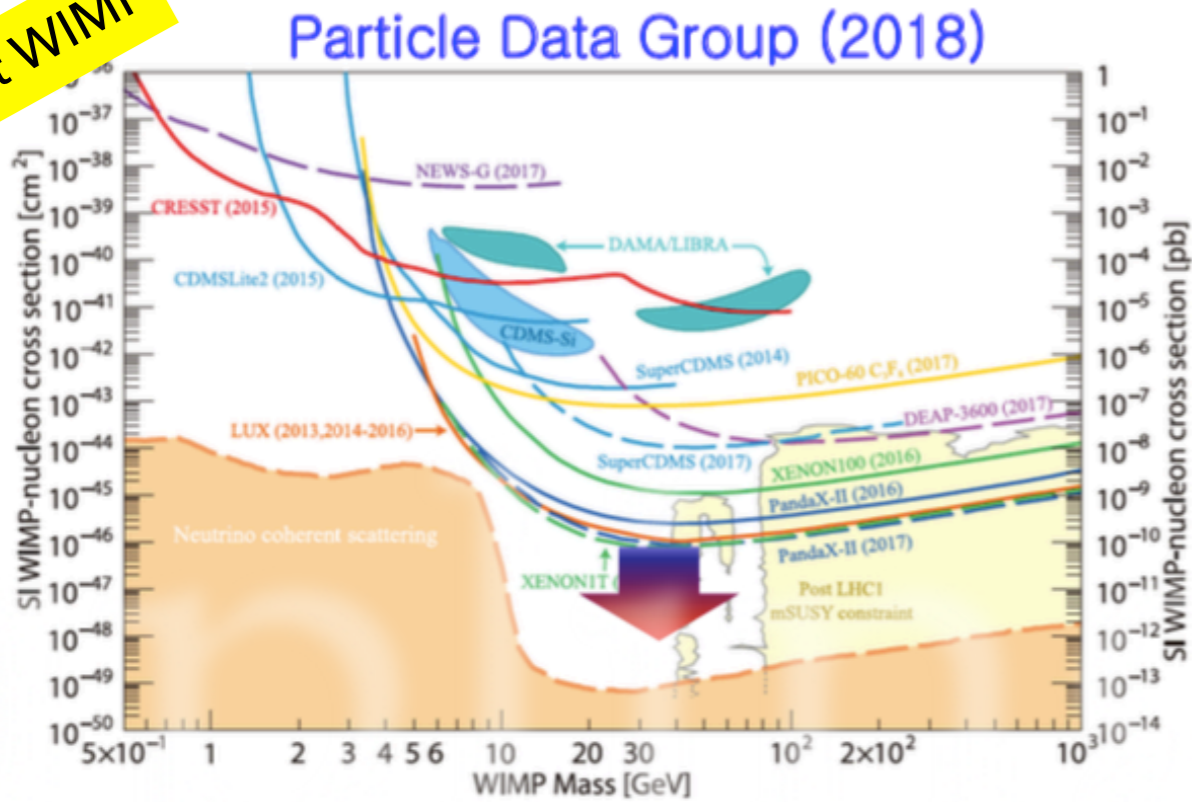
M. Drees

- Direct, indirect, collider

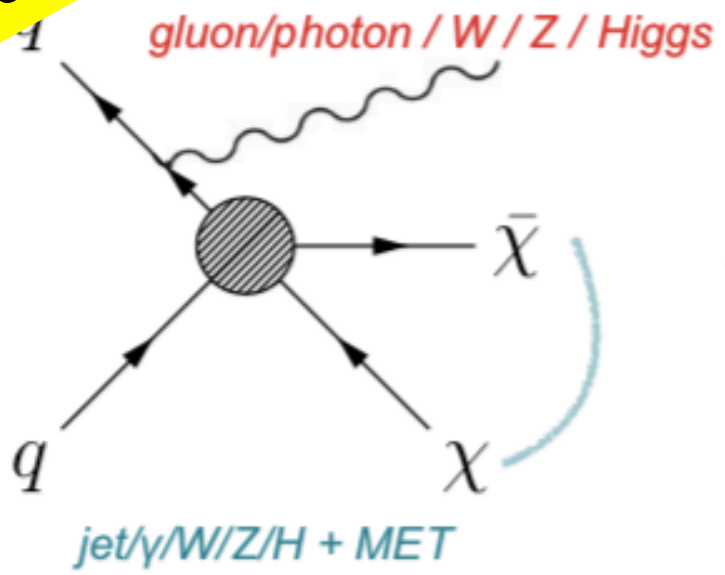


BEYOND THE STANDARD MODEL: DARK MATTER SEARCHES

Direct WIMP



Colliders WIMP

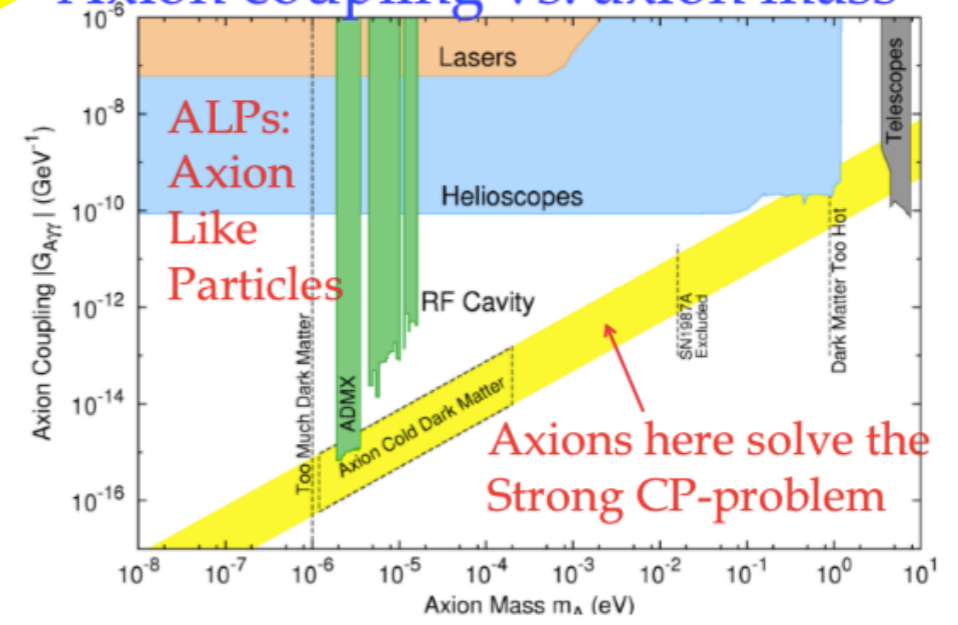


- **mono-jet**
 - most general signature, constraints on many models
- **mono-photon**
 - more challenging for background estimation
 - less powerful: EW vs. strong interaction
- **mono-W/Z leptonic**
 - clean signature and simple trigger
 - penalized by W/Z branching fraction
- **mono-W/Z hadronic**
 - 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

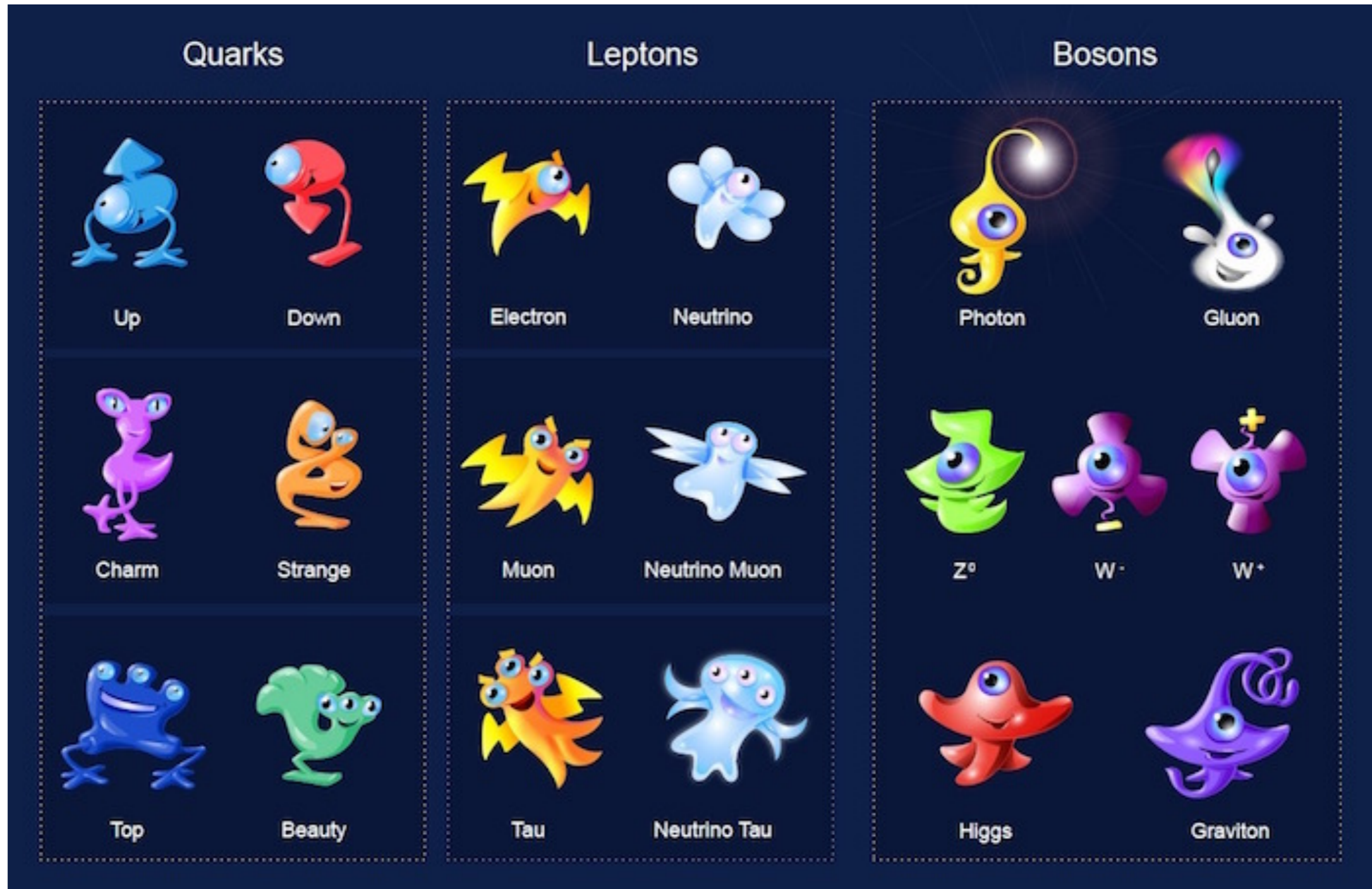
Axion-likes

Axion coupling vs. axion mass



Y. Semertzidis

Flavour Sector



BEYOND THE STANDARD MODEL: THE MASS SPECTRUM AND MIXINGS

- Mass spectrum?

$$m_{quark} = y_{quark} \cdot v$$

$$m_{lepton} = y_{lepton} \cdot v$$

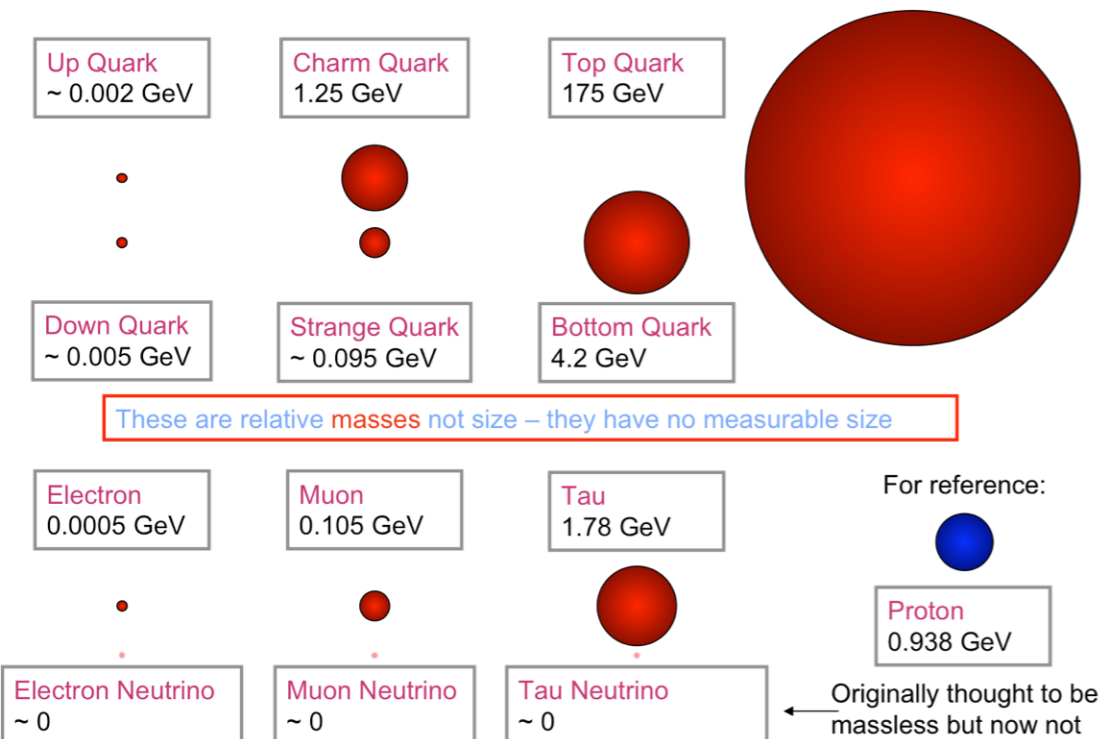
$$m_W = g/\sqrt{2} \cdot v$$

$$m_Z = \sqrt{g^2 + g'^2}/\sqrt{2} \cdot v$$

$$m_H = \sqrt{\lambda} \cdot v$$

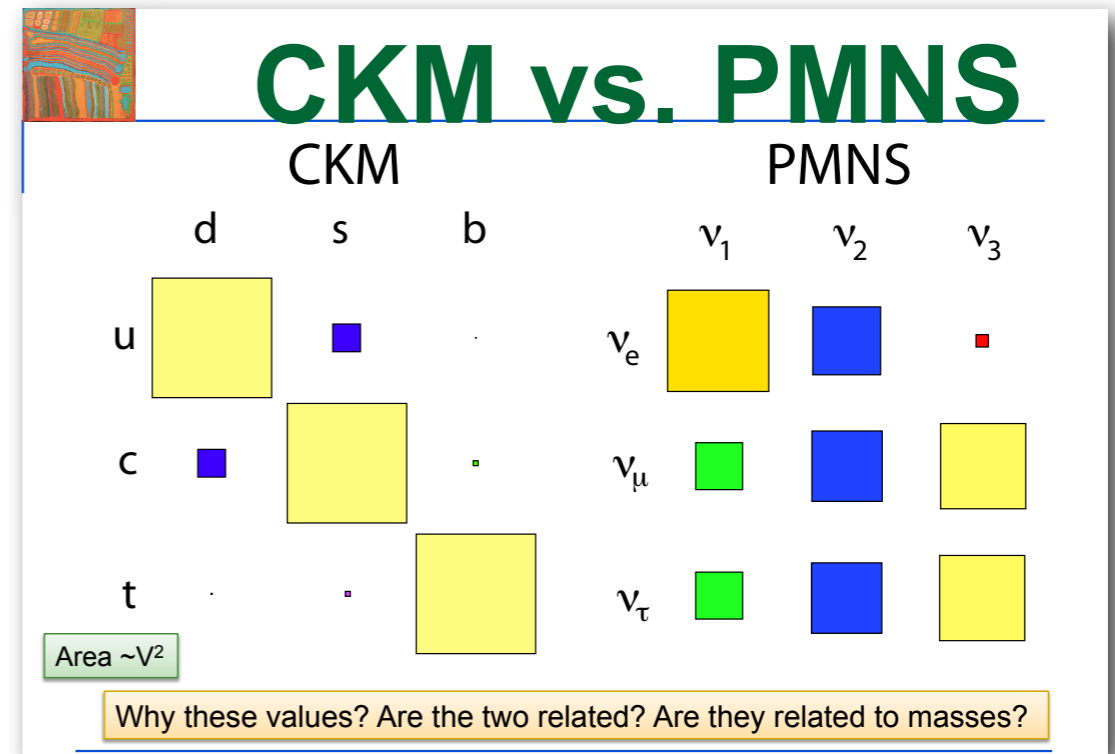
SM $m_\gamma = 0$

$$m_{gluon} = 0$$



- Mixing Matrices?

- Quark-Lepton Symmetry
- Strong difference in parameters

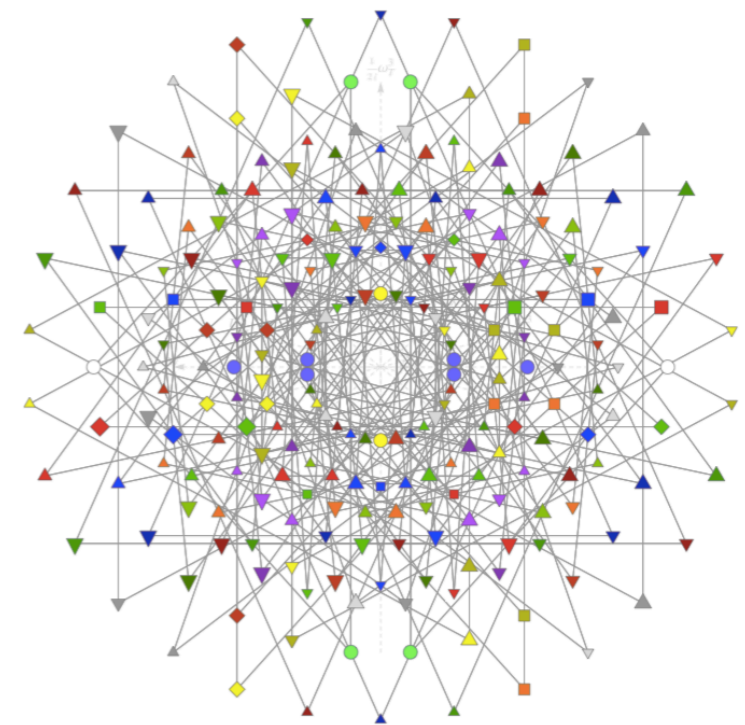


- What are the CKM and PMNS phases?
- Where lies the source of CP violation: in quark or lepton sector?

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

BEYOND THE STANDARD MODEL: QUEST FOR SYMMETRY

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



E8 roots

Symmetry might be tricky

THE STANDARD MODEL: CONCEPTUAL PROBLEMS



Baryon Asymmetry of the Universe



SM expectation:

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-18}$$

vs.

Observed*:

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

Sakharov criteria

1. Baryon number violation
2. C and CP violation
3. Thermal non-equilibrium



WMAP

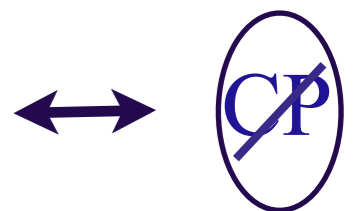
- Baryon number is conserved in the SM with exponential accuracy
- Violation of baryon number occurs in Grand Unified Theories and in Lepton=fourth color models (Pati-Salam model)

New particles = Leptoquarks, Extended Higgs sector

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



- Violation of CP invariance in the SM achieved via phase factors in the CKM and PMNS mixing matrices



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, unnaturalness, 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 ?



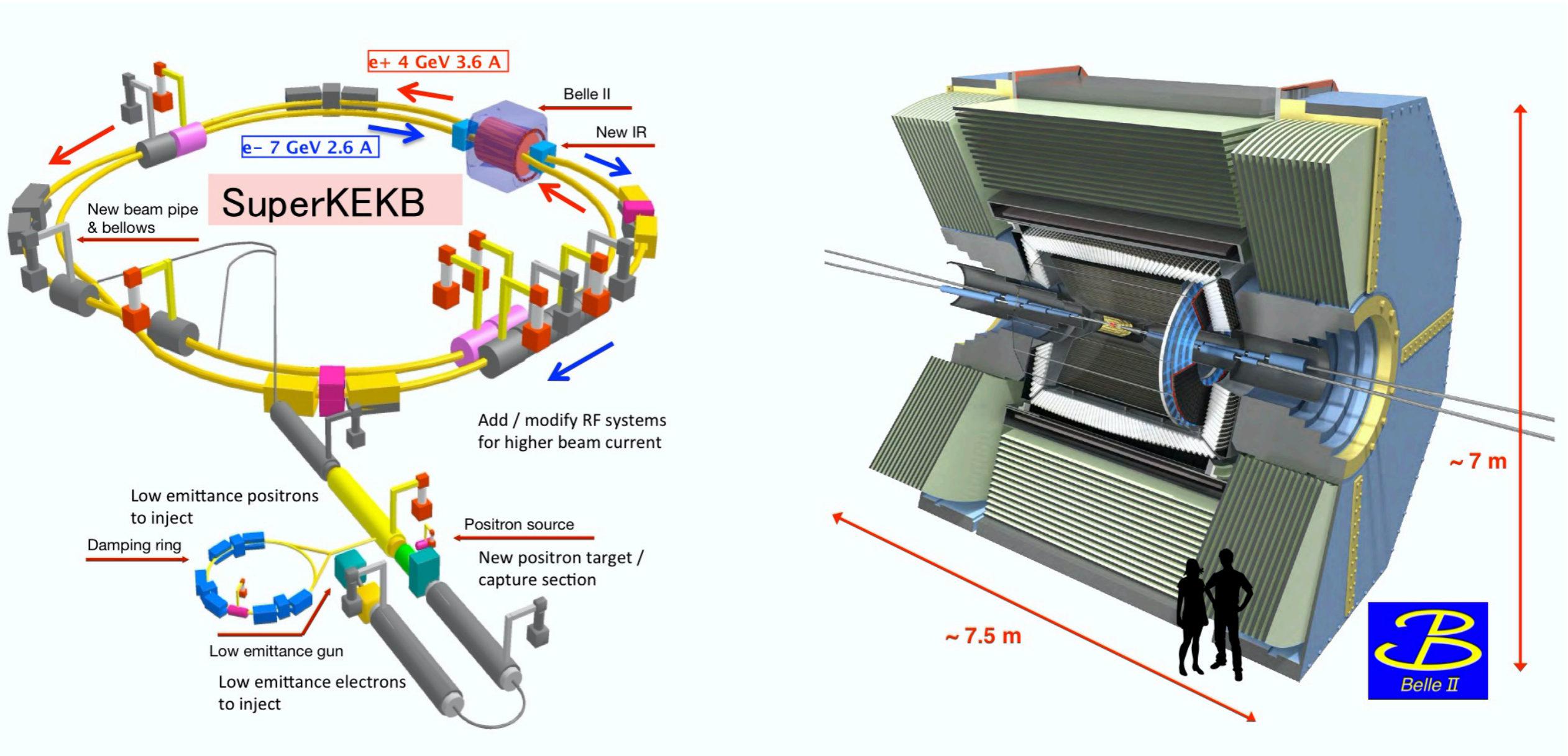
How Will We Make Progress?

- 🌐 **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

Relativistic Heavy Ion Collider at Brookhaven National Laboratory (BNL), USA

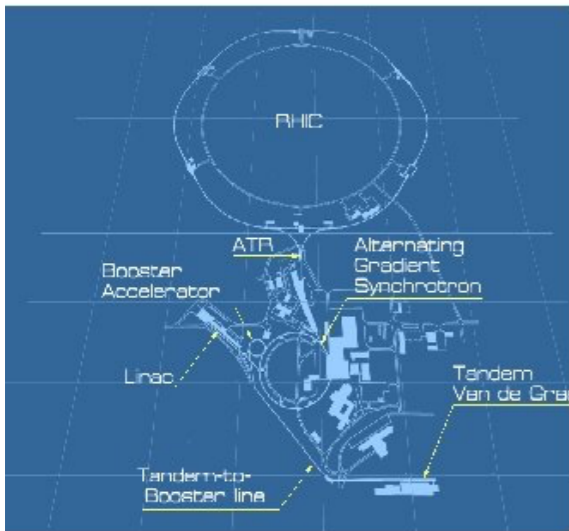
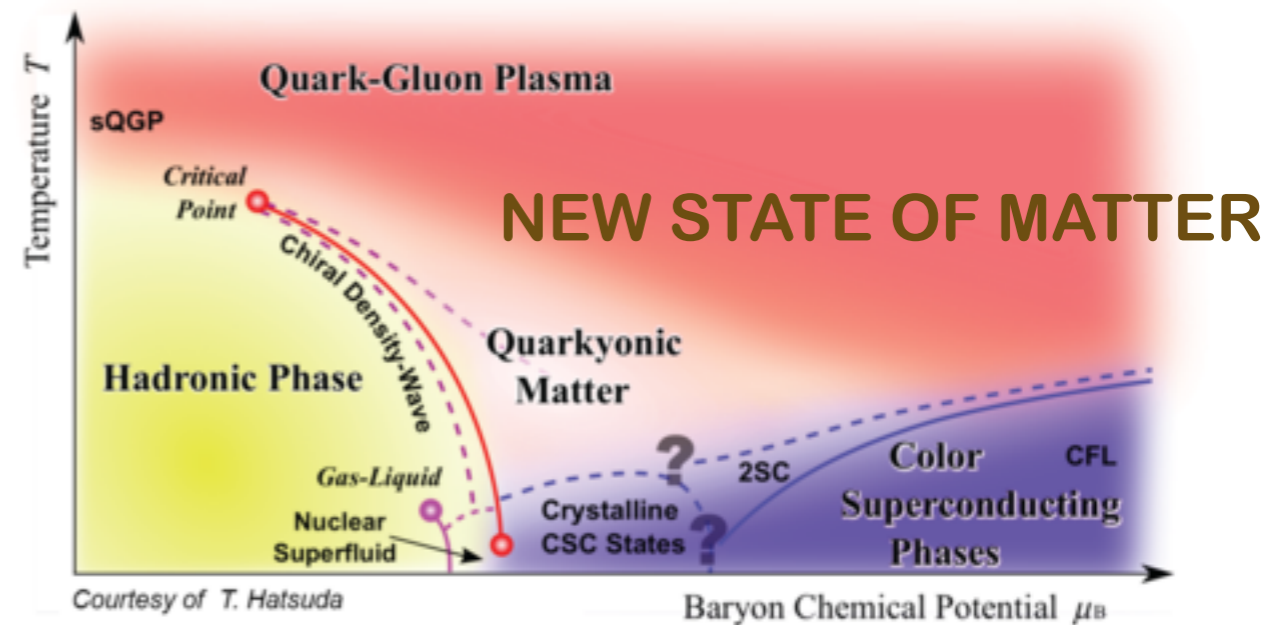
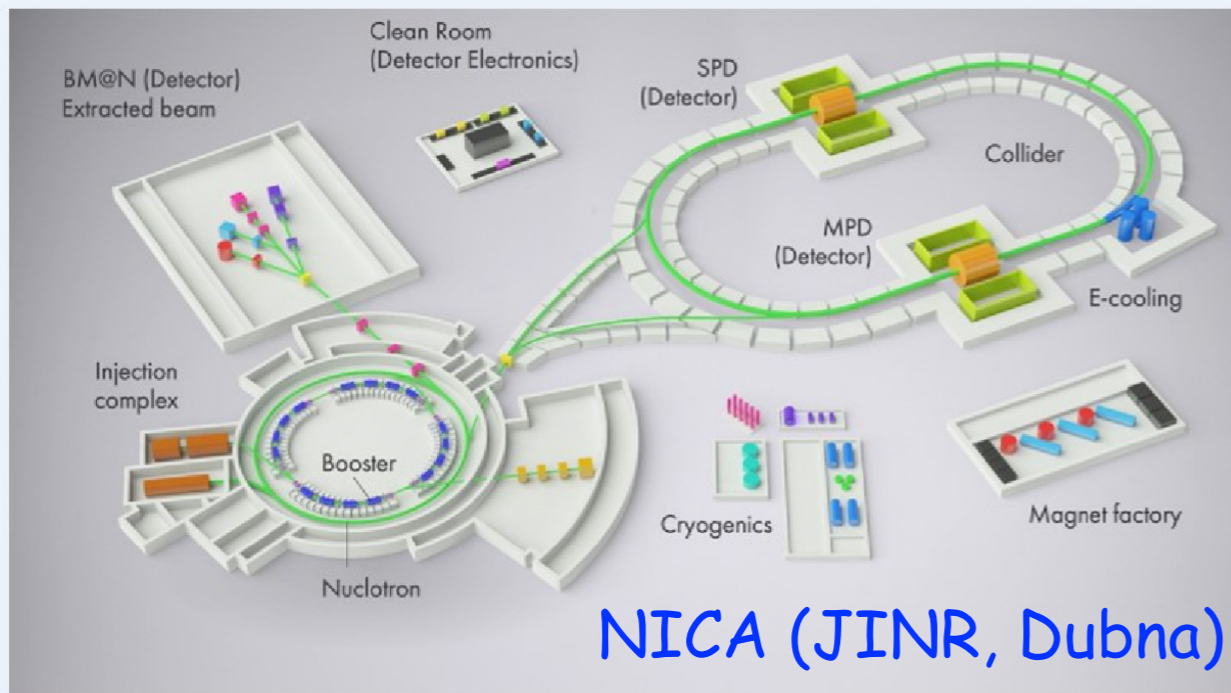
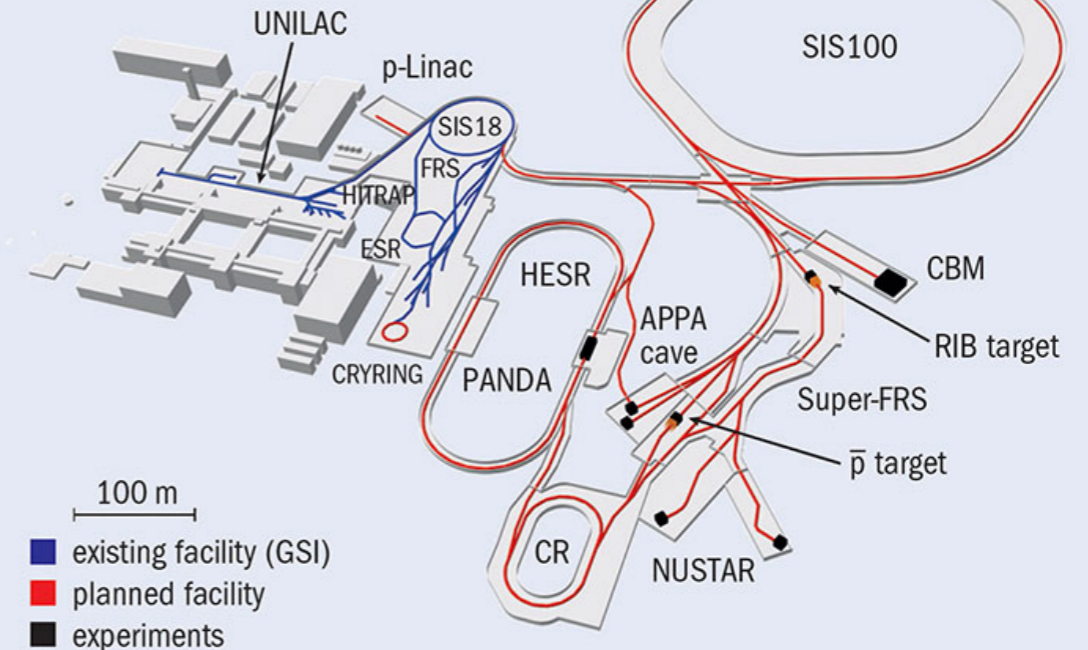


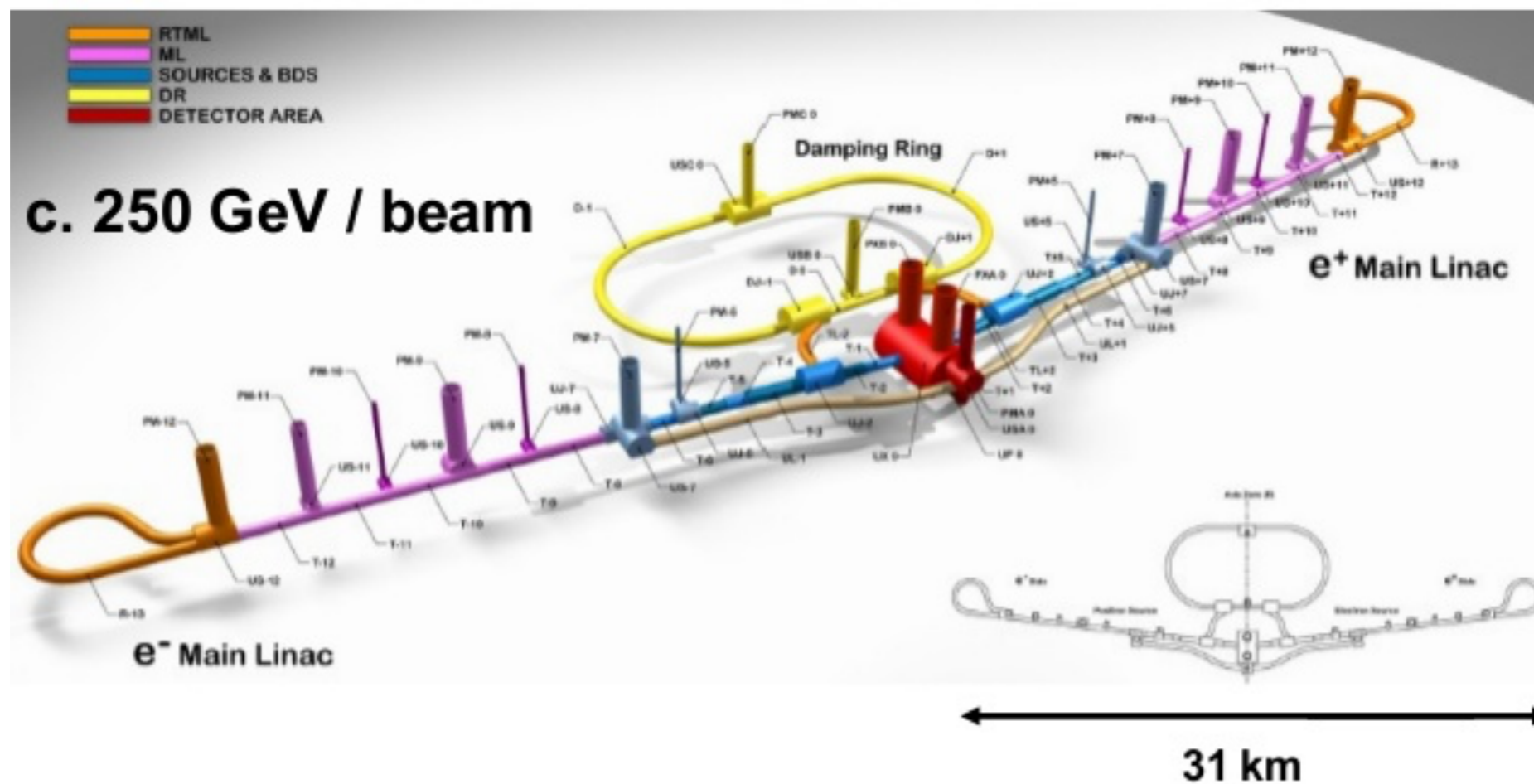
Figure 1. Schematic layout of ENL complex for polarized proton operations. Courtesy of MacKay (private communication) and BNL Collider Accelerator Department.

FAIR (GSI, Germany)



ELECTRON-POSITRON LINEAR COLLIDER (JAPAN)

International Linear Collider (ILC)



TECHNOLOGY EXISTS, CONSTRUCTION DID NOT START YET

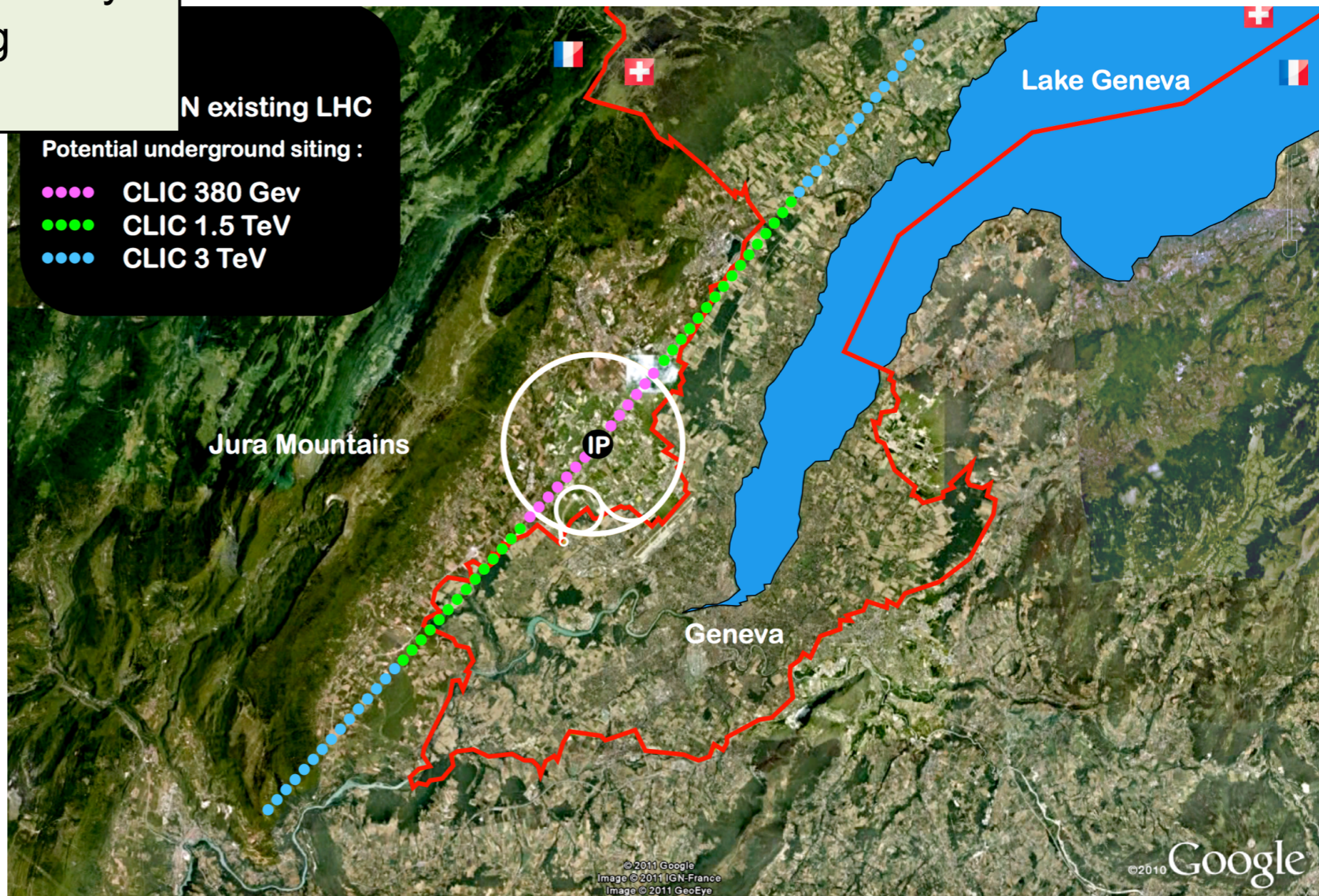
Linear e^+e^- collider with \sqrt{s} up to 3 TeV

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
 $\sqrt{s} \sim 100 \text{ TeV}$, $L \sim 2 \times 10^{35}$; 4 IP, $\sim 20 \text{ ab}^{-1}/\text{expt}$
- ❑ **e⁺e⁻ collider (FCC-ee):** possible first step
 $\sqrt{s} = 90\text{-}350 \text{ GeV}$, $L \sim 200\text{-}2 \times 10^{34}$; 2 IP
- ❑ **pe collider (FCC-he):** option $\sqrt{s} \sim 3.5 \text{ TeV}$, $L \sim 10^{34}$

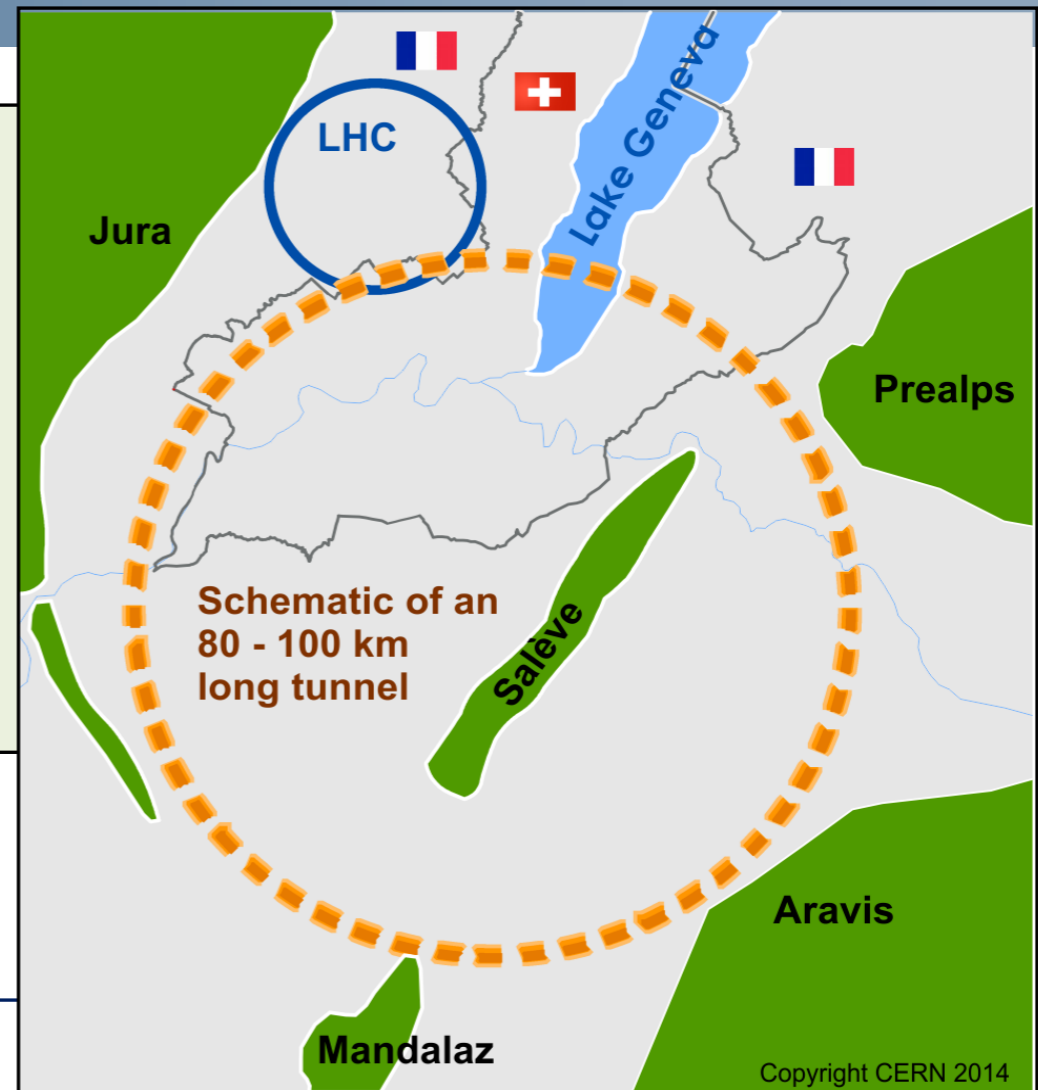
Main technology challenge: ~ 16 T magnets

FCC-hh: a ~100 TeV pp collider is expected to:

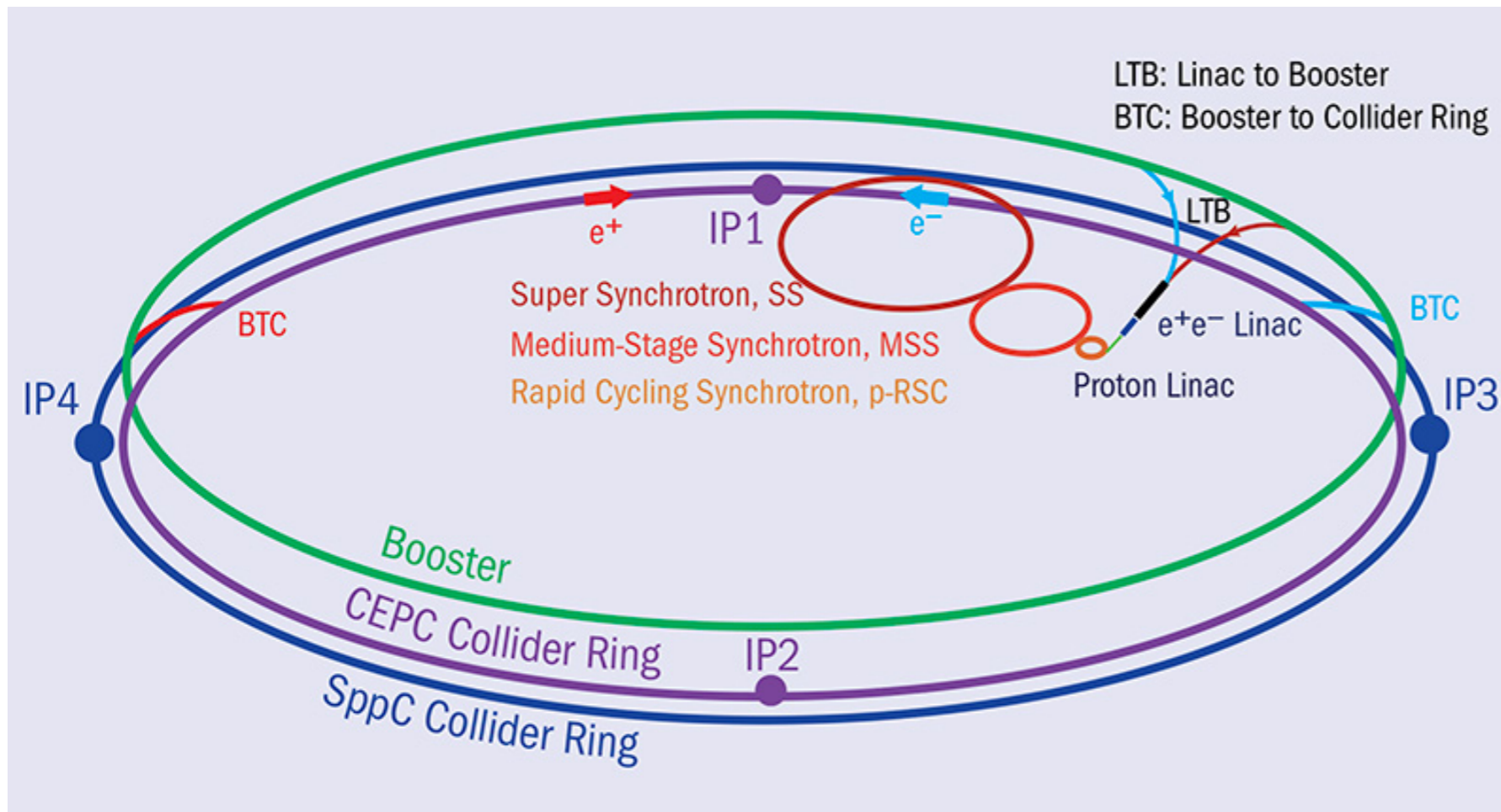
- ❑ explore directly the 10-50 TeV E-scale
- ❑ conclusive exploration of EWSB dynamics
- ❑ say the final word about heavy WIMP dark matter

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, $\Delta M_W < 1 \text{ MeV}$, $\Delta m_{\text{top}} \sim 10 \text{ MeV}$




CIRCULAR EP COLLIDER (CHINA)



WORLD OF COLLIDERS

Physicists around the world are designing a range of particle colliders that are much bigger than the Large Hadron Collider at CERN, Europe's particle-physics laboratory.


- Proton collider
- Electron-positron collider

 **CERN-HOSTED LARGE HADRON COLLIDER**
2009–35
Circumference: 27 km
Energy: 14 teraelectronvolts (TeV)

 Length: 31 km
JAPAN-HOSTED INTERNATIONAL LINEAR COLLIDER
Proposed: 2030
Energy: ≤ 1 TeV

 50 or 100 km
CHINA-HOSTED ELECTRON-POSITRON COLLIDER
Proposed: 2028
Energy: 0.24 or ≤ 0.35 TeV

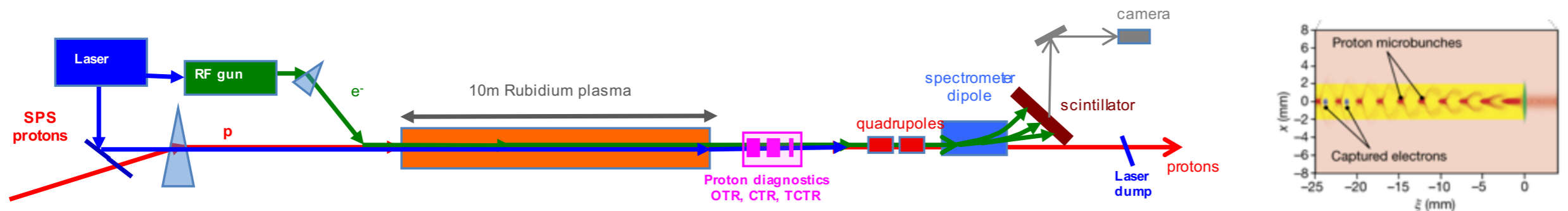
 50 or 100 km
CHINA-HOSTED PROTON COLLIDER
Proposed: 2030s
Energy: 70–100 TeV or 100–140 TeV

 100 km
CERN-HOSTED SUPER PROTON COLLIDER
Proposed: 2035–40
Energy: 100 TeV

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 \rightarrow injected e^- beam accelerated in the wake of the p beam
 $\sim 3 \times 10^{11}$ p/bunch at 400 GeV \rightarrow 20 kJ (cfr ~ 40 J for laser/ e^- driving pulses)



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

NEW TECHNOLOGY, HIGHT GRADIENT, COMPACT ACCELERATOR