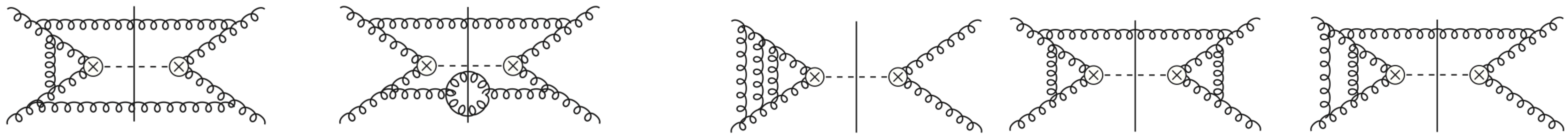
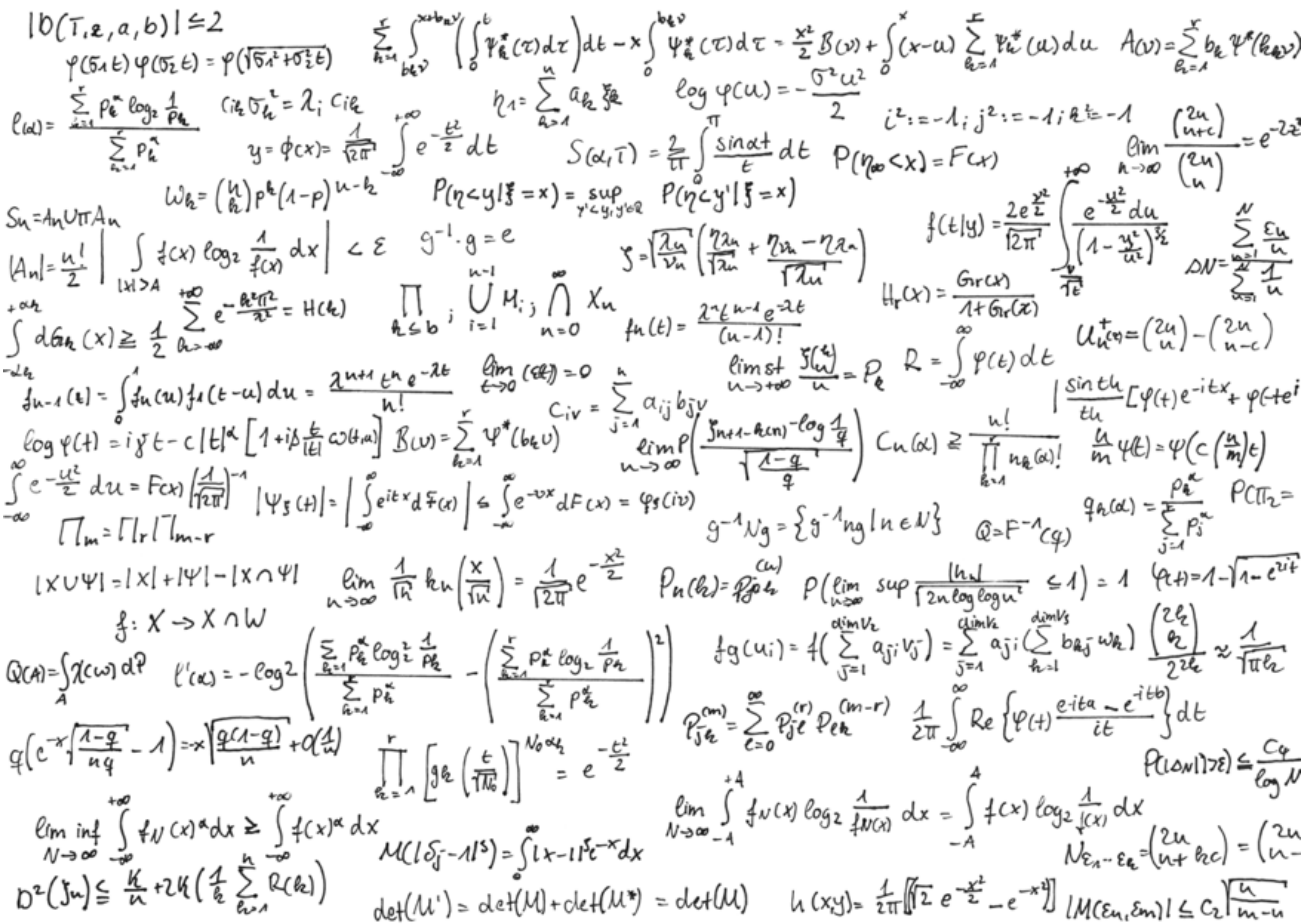
Physics at the LHC after the Higgs discovery: what’s next?

Michelangelo L. Mangano
Theory Group
PH Department
CERN

michelangelo.mangano@cern.ch





A “real” story from the past ...

Barcelona, 15 March 1493 .....

Columbus:

Your Majesty, the fleet needs an **upgrade**, we need to go back to the Indies with **10 times** more ships

King Ferdinand and Queen Isabellagnieszka:

You discovered the Indies, your theory is right, why do you need more?

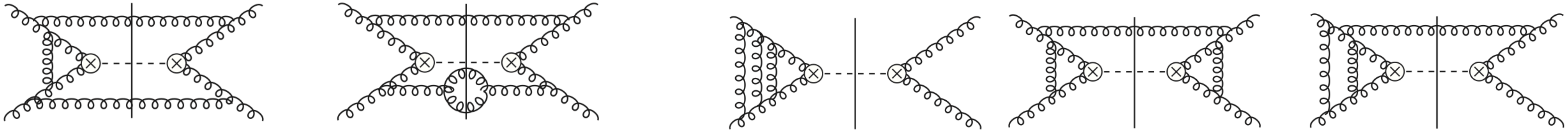
Columbus:

Theorists* say these may not be the **standard Indies**. They calculated the Earth radius, and the standard Indies cannot be so close: these are likely to be ***beyond* the standard Indies** (*moving eastward ...*)

** If the King had listened to theorists to start with, he would have never authorized the mission: everyone one would have died of starvation well before reaching the “standard” Indies ...*

The explorer’s checklist

- Confirm you’ve landed in the right place
- Explore surroundings
  - look for what you expect
  - search for new “commodities”
- Push further the boundary of unchartered territories



$|D(T,z,a,b)| \leq 2$

$\varphi(\sigma_1 t)\varphi(\sigma_2 t) = \varphi(\sqrt{\sigma_1^2+\sigma_2^2}\, t)$

$\sum_{k=1}^{r} \int_{b_k v}^{x+b_k v} \left(\int_0^t \Psi_k^*(\tau) d\tau \right) dt - x \int_0^{b_k v} \Psi_k^*(\tau) d\tau = \frac{x^2}{2} B(v) + \int_0^x (x-u) \sum_{k=1}^{r} \Psi_k^*(u) du$

$A(v) = \sum_{k=1}^{r} b_k \Psi^*(b_k v)$

$\ell(\alpha) = \frac{\sum_{k=1}^{r} p_k^\alpha \log_2 \frac{1}{p_k}}{\sum_{k=1}^{r} p_k^\alpha}$

$c_{ik} \sigma_k^2 = \lambda_i c_{ik}$

$\eta_1 = \sum_{k=1}^{n} a_k \xi_k$

$\log \varphi(u) = -\frac{\sigma^2 u^2}{2}$

$i^2 := -1;\ j^2 := -1;\ k^2 := -1$

$y = \phi(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} e^{-\frac{t^2}{2}} dt$

$S(\alpha, T) = \frac{2}{\pi} \int_0^T \frac{\sin \alpha t}{t} dt$

$P(\eta_\infty < x) = F(x)$

$\lim_{n\to\infty} \frac{\binom{2n}{n+c}}{\binom{2n}{n}} = e^{-2z^2}$

$W_k = \binom{n}{k} p^k (1-p)^{n-k}$

$P(\eta < y \mid \xi = x) = \sup_{y' < y,\, y' \in Q} P(\eta < y' \mid \xi = x)$

$S_n = A_n \cup \pi A_n$

$f(t|y) = \frac{2e^{\frac{y^2}{2}}}{\sqrt{2\pi}} \int_{\frac{y}{\sqrt{t}}}^{+\infty} \frac{e^{-\frac{u^2}{2}} du}{\left(1 - \frac{y^2}{u^2}\right)^{3/2}}$

$|A_n| = \frac{n!}{2}$

$\left| \int_{|x|>A} f(x) \log_2 \frac{1}{f(x)} dx \right| < \varepsilon$

$g^{-1} \cdot g = e$

$\zeta = \sqrt{\frac{\lambda_n}{\nu_n}} \left(\frac{\eta_{\lambda_n}}{\sqrt{\lambda_n}} + \frac{\eta_{\nu_n} - \eta_{\lambda_n}}{\sqrt{\lambda_n}} \right)$

$\Delta N = \frac{\sum_{n=1}^{N} \frac{\varepsilon_n}{n}}{\sum_{n=1}^{N} \frac{1}{n}}$

$H_r(x) = \frac{G_r(x)}{1 + G_r(x)}$

$\sum_{h=-\infty}^{+\infty} e^{-\frac{k^2\pi^2}{x^2}} = H(k)$

$\prod_{k \leq b};\ \bigcup_{i=1}^{n-1} M_i;\ \bigcap_{n=0}^{\infty} X_n$

$f_n(t) = \frac{\lambda^n t^{n-1} e^{-\lambda t}}{(n-1)!}$

$U_n^+(c) = \binom{2n}{n} - \binom{2n}{n-c}$

$\int_{-\alpha_k}^{+\alpha_k} dG_k(x) \geq \frac{1}{2}$

$R = \int_{-\infty}^{\infty} \varphi(t) dt$

$\lim_{n\to+\infty} st \frac{\xi_n^{(k)}}{n} = P_k$

$f_{n-1}(t) = \int_0^t f_n(u) f_1(t-u) du = \frac{\lambda^{n+1} t^n e^{-\lambda t}}{n!}$

$\lim_{t\to 0} (\varepsilon t) = 0$

$c_{iv} = \sum_{j=1}^{n} a_{ij} b_{jv}$

$\left| \frac{\sin th}{th} [\varphi(t) e^{-itx} + \varphi(-t) e^{i}\right.$

$\log \varphi(t) = i\gamma t - c|t|^\alpha \left[1 + i\beta \frac{t}{|t|} \omega(t,\alpha)\right]$

$B(v) = \sum_{k=1}^{r} \Psi^*(b_k v)$

$\lim_{n\to\infty} P\left(\frac{\xi_{n+1} - h(n) - \log \frac{1}{q}}{\sqrt{\frac{1-q}{q}}} \right)$

$C_n(\alpha) \geq \frac{n!}{\prod_{k=1}^{r} n_k(\alpha)!}$

$\frac{n}{m} \psi(t) = \psi\left(c\left(\frac{n}{m}\right) t\right)$

$\int_{-\infty}^{\infty} e^{-\frac{u^2}{2}} du = F(x) \left(\frac{1}{\sqrt{2\pi}}\right)^{-1}$

$|\Psi_\xi(t)| = \left| \int_{-\infty}^{\infty} e^{itx} dF(x) \right| \leq \int_{-\infty}^{\infty} e^{-vx} dF(x) = \varphi_\xi(iv)$

$q_k(\alpha) = \frac{p_k^\alpha}{\sum_{j=1}^{r} p_j^\alpha}$

$P(\Pi_2 =$

$\Pi_m = \Pi_r \Pi_{m-r}$

$g^{-1} N g = \{ g^{-1} n g \mid n \in N \}$

$Q = F^{-1}(q)$

$|X \cup \Psi| = |X| + |\Psi| - |X \cap \Psi|$

$\lim_{n\to\infty} \frac{1}{\sqrt{h}} k_n\left(\frac{x}{\sqrt{n}}\right) = \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}}$

$P_n(k) = P_{jk}^{(n)}$

$P\left(\lim_{n\to\infty} \sup \frac{|h_n|}{\sqrt{2n \log \log n}} \leq 1 \right) = 1$

$\varphi(t) = 1 - \sqrt{1 - e^{2it}}$

$f: X \to X \cap W$

$fg(u_i) = f\left(\sum_{j=1}^{\dim V_2} a_{ji} v_j \right) = \sum_{j=1}^{\dim V_2} a_{ji} \left(\sum_{k=1}^{\dim V_3} b_{kj} w_k \right)$

$\frac{\binom{2k}{k}}{2^{2k}} \approx \frac{1}{\sqrt{\pi k}}$

$Q(A) = \int_A \chi(\omega) dP$

$\ell'(\alpha) = -\log 2 \left(\frac{\sum_{k=1}^{r} p_k^\alpha \log_2^2 \frac{1}{p_k}}{\sum_{k=1}^{r} p_k^\alpha} - \left(\frac{\sum_{k=1}^{r} p_k^\alpha \log_2 \frac{1}{p_k}}{\sum_{k=1}^{r} p_k^\alpha} \right)^2 \right)$

$P_{jk}^{(m)} = \sum_{\ell=0}^{\infty} P_{j\ell}^{(r)} P_{\ell k}^{(m-r)}$

$\frac{1}{2\pi} \int_{-\infty}^{\infty} \mathrm{Re} \left\{ \varphi(t) \frac{e^{ita} - e^{-itb}}{it} \right\} dt$

$q\left(e^{-x\sqrt{\frac{1-q}{nq}}} - 1\right) = -x \sqrt{\frac{q(1-q)}{n}} + o\left(\frac{1}{n}\right)$

$\prod_{k=1}^{r} \left[g_k\left(\frac{t}{\sqrt{N_0}} \right) \right]^{N_0 \alpha_k} = e^{-\frac{t^2}{2}}$

$P(|\Delta N| > \varepsilon) \leq \frac{C_q}{\log N}$

$\lim_{N\to\infty} \int_{-A}^{+A} f_N(x) \log_2 \frac{1}{f_N(x)} dx = \int_{-A}^{A} f(x) \log_2 \frac{1}{f(x)} dx$

$\lim \inf_{N\to\infty} \int_{-\infty}^{+\infty} f_N(x)^\alpha dx \geq \int_{-\infty}^{+\infty} f(x)^\alpha dx$

$M(|\delta_j - 1|^s) = \int_0^\infty |x-1|^s e^{-x} dx$

$N_{\varepsilon_n \cdots \varepsilon_k} = \binom{2n}{n+kc} = \binom{2n}{n-}$

$D^2(\xi_n) \leq \frac{K}{n} + 2K\left(\frac{1}{k} \sum_{k=1}^{n} R(k) \right)$

$\det(M') = \det(M) + \det(M^*) = \det(M)$

$h(x,y) = \frac{1}{2\pi} \left[\sqrt{2}\, e^{-\frac{x^2}{2}} - e^{-x^2} \right]$

$|M(\varepsilon_n \varepsilon_m)| \leq C_2 \sqrt{\frac{n}{m-n}}$

The LHC checklist

- **Confirm you've landed in the right place**
  - *is the new particle at 125 GeV the Higgs of the Standard Model?*

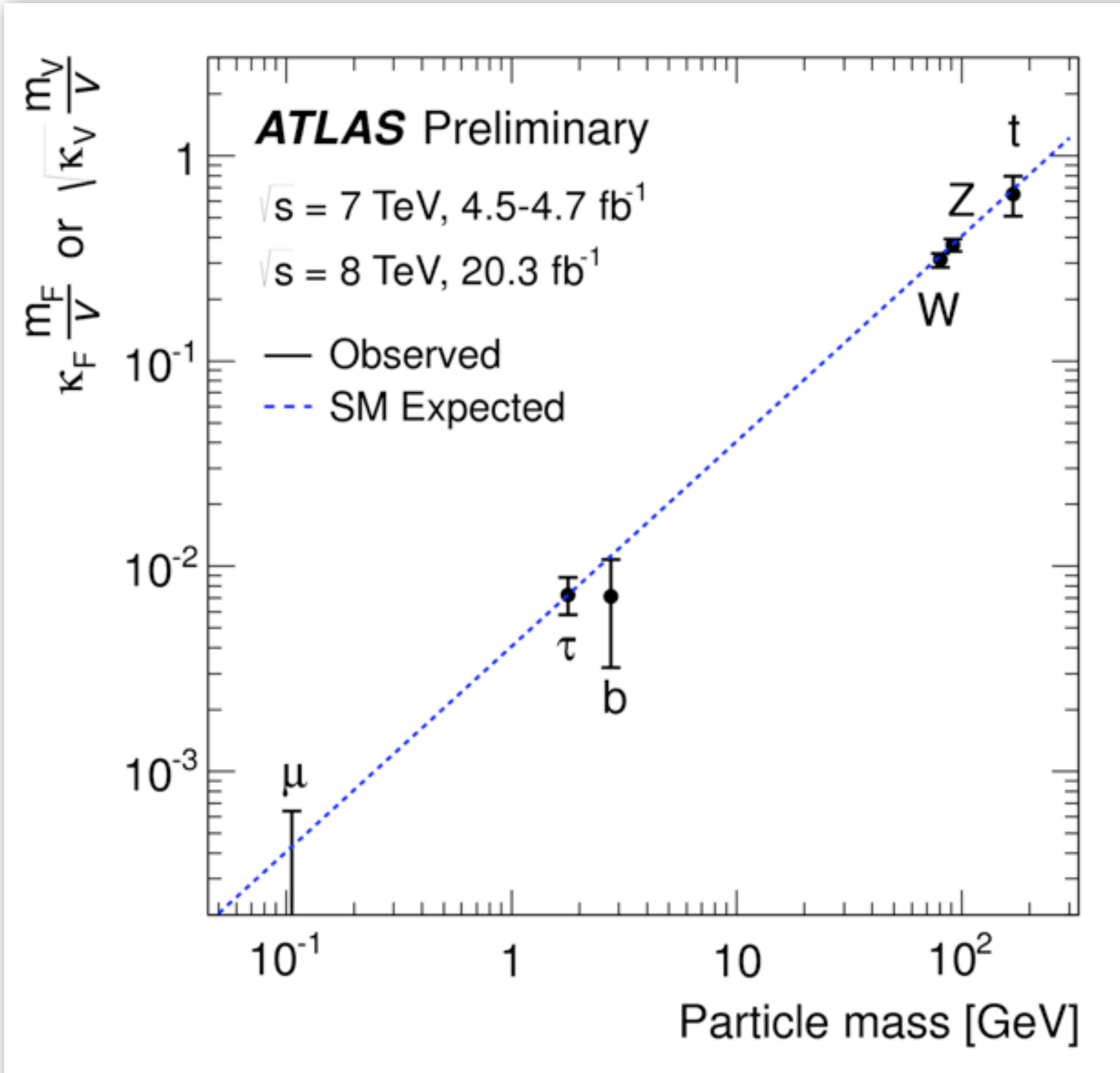
- **Explore surroundings**
  - look for what you expect: the *guaranteed deliverables*
    - *systematically study and measure with ever-growing precision the interactions of the Higgs boson, and of the other SM particles*
  - search for new "commodities" - the *known unknowns, follow a path ...*
    - *dark matter, origin of neutrino masses, baryon asymmetry of the universe*

- **Push further the boundary of unchartered territories** - *search the Eldorado*
  - *supersymmetry, new forces, extra dimensions, ...*

The Higgs discovery goal provided in the 90's the reference target for the design of the LHC accelerator and experiments.

But the physics goals and ambitions of the LHC always went beyond the Higgs discovery .....

Run 1 of the LHC determined, with a precision of ±20%, that the Higgs boson gives a mass to SM particles



Open Higgs issues for run 2 and beyond

1. *This limited precision,* due to low statistics, *is not sufficient to probe most possible scenarios alternative to the SM:* ***will the SM withstand more accurate tests?***

   Example: BR[$H \to \mu\tau$] = (0.89 ± 0.40)% reported by CMS, needs more statistics to confirm (In the SM should be 0)

2. *The Higgs mechanism has only been tested on a fraction of the SM particles,* due to low statistics: ***do the other particles (e.g. muon, charm, etc) interact with the Higgs as predicted by the SM?***

   Example: more than 300 fb^{-1} required to establish $H \to \mu\mu$ at 5σ

3. *Neutrino masses are not a SM ingredient:* ***how do neutrinos acquire their mass?***

   The LHC plays a role in exploring possible answers

4. ***Are there more Higgs bosons?***

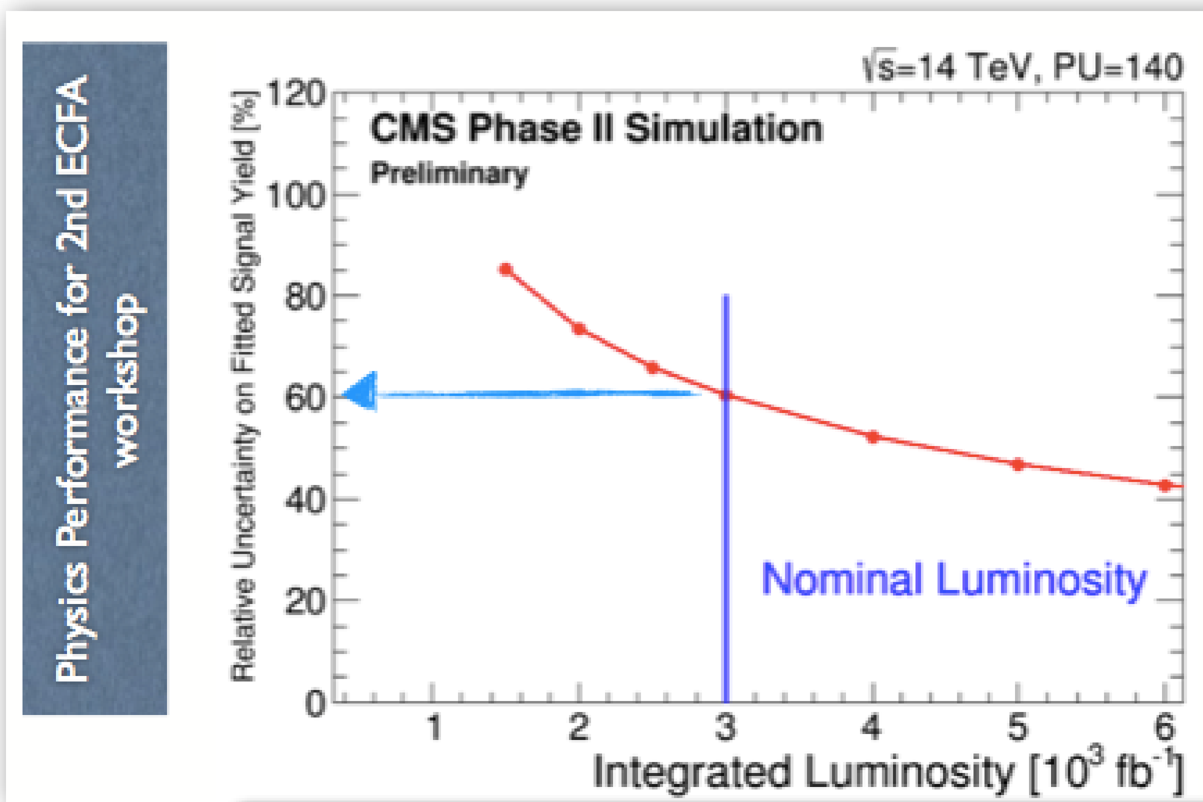
   Most theories beyond the SM have more Higgs bosons

5. What gives mass to the Higgs ??

Obvious question, with a trivial answer in the SM: the Higgs gives mass to itself!

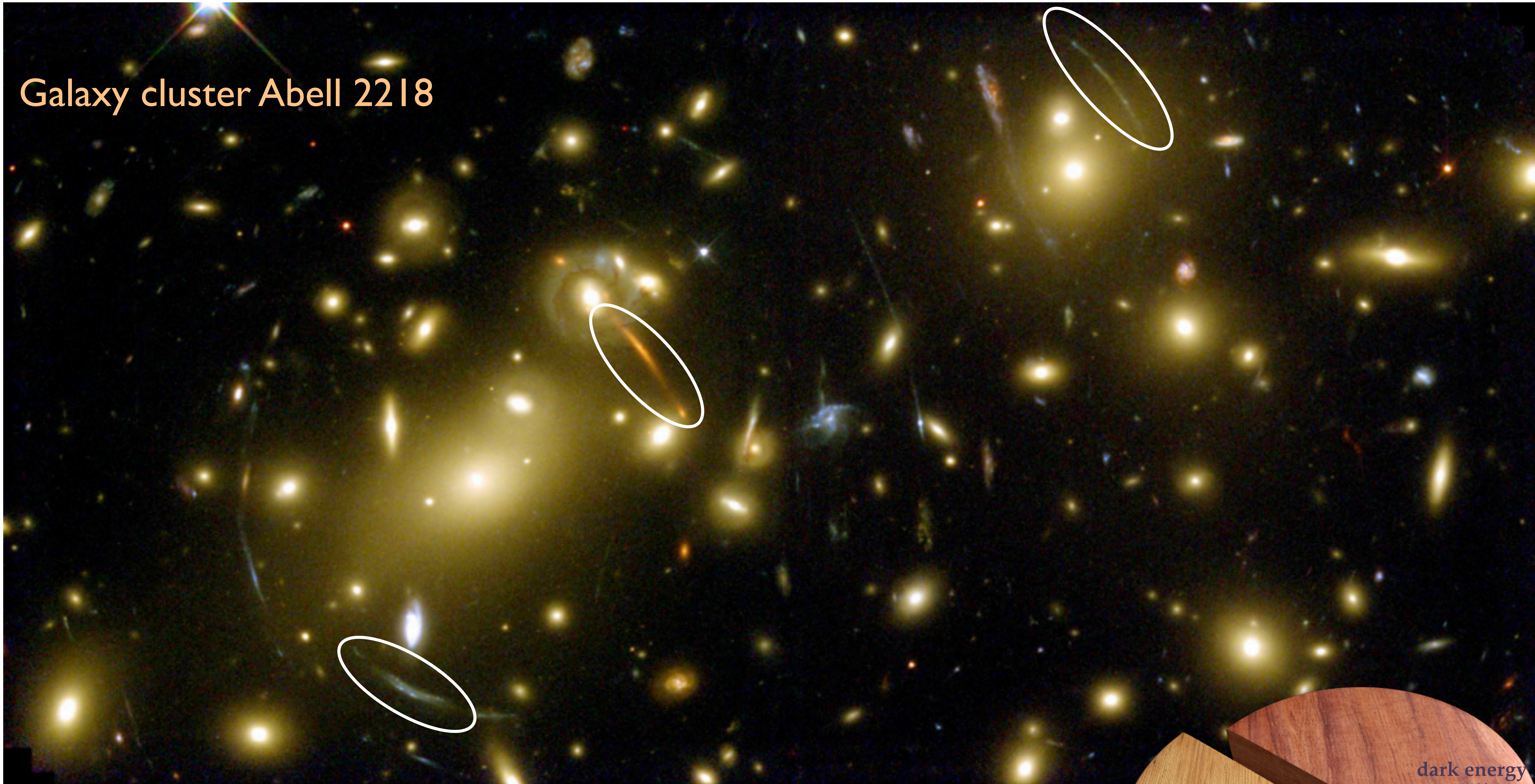
But less trivial answers can arise in beyond-the-SM scenarios

Testing how the Higgs interacts with itself (*this is how we probe the origin of the Higgs mass*) will require the full High Luminosity programme, and possibly more



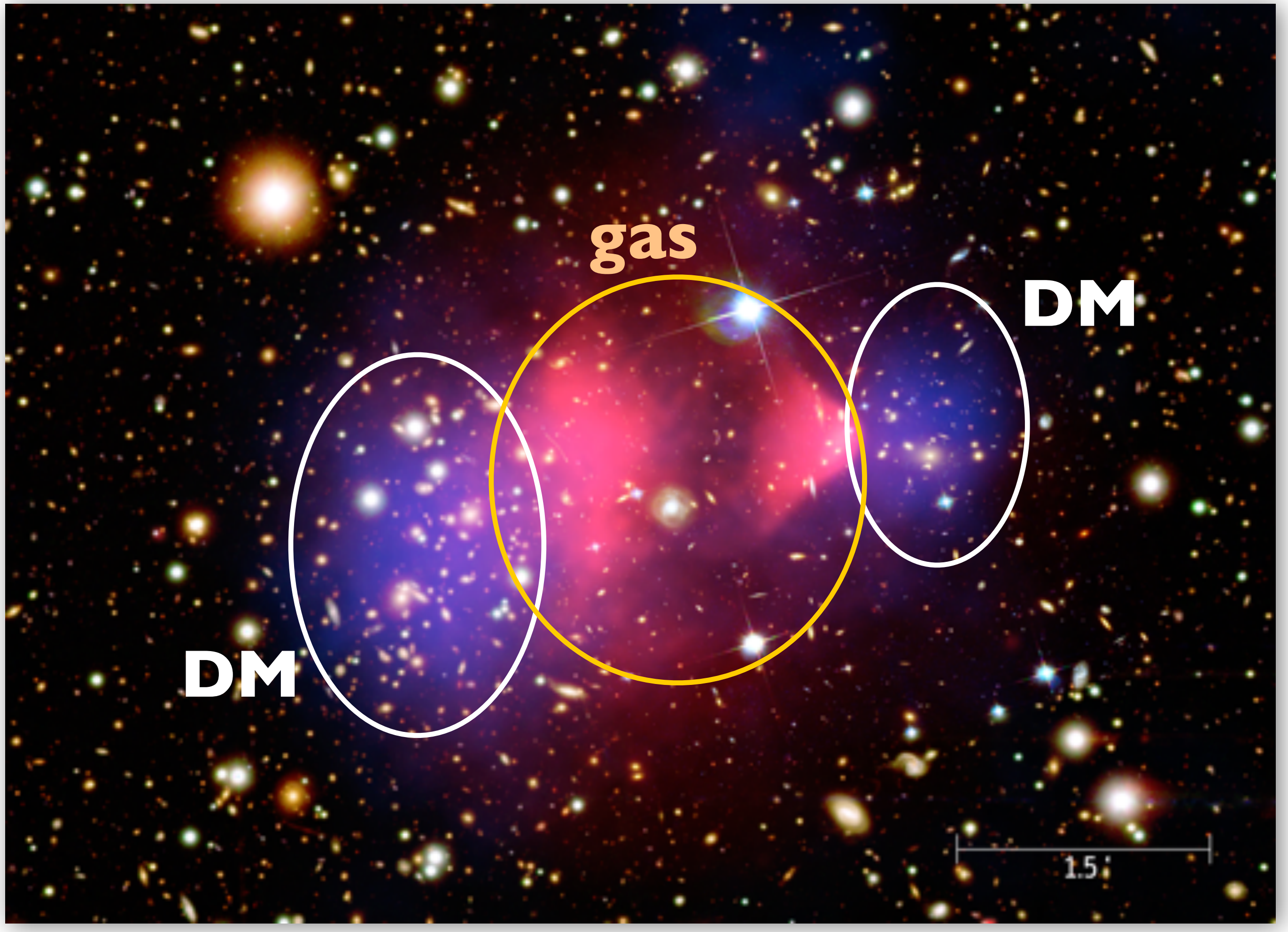
The measurement of Higgs self-interactions has broad implications on issues such as the nature of the EW phase transition during the Big Bang

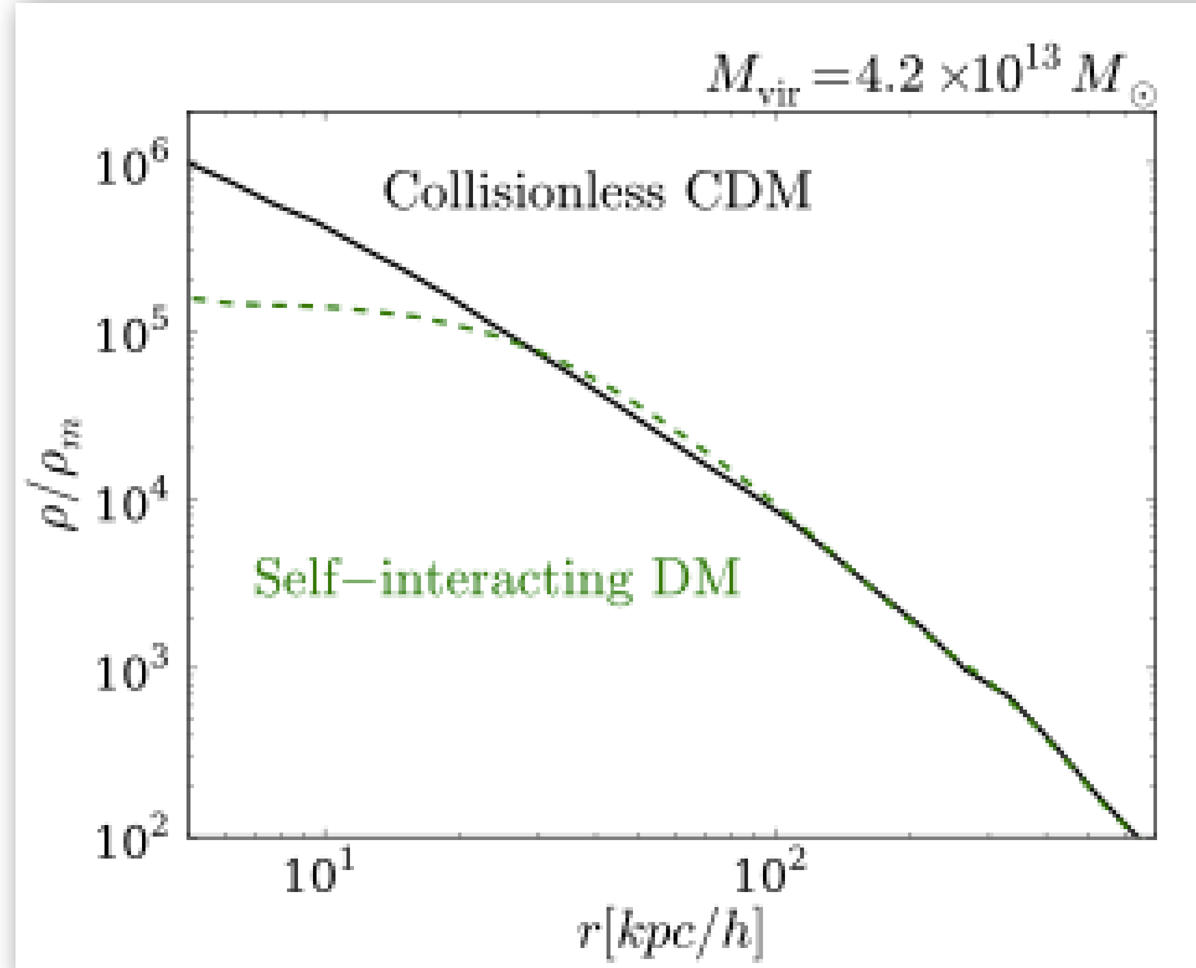
What is Dark Matter?



The modeling of Dark Matter has become more and more articulate. From a single source (WIMP, axion, neutrino, ...) to the possibility of dark hidden worlds

Evidence building up for self-interacting DM





σ~ 1cm² (m$_\chi$/g)~2×10^{-24} cm² (m$_\chi$/GeV)

For a WIMP: σ~10^{-38} cm² (m$_\chi$/100 GeV)

Growing interest in models with rich sectors of "dark" particles, coupled to the SM ones via weakly interacting "portals"

6. Can the Higgs be the portal between the visible and the hidden world?

Plausible BSM theories of this type exist. They may also

- solve the hierarchy problem in a *natural* way
- connect the mechanisms that create the matter-over-antimatter asymmetry in the Universe, with those generating Dark Matter
- explain why there are similar amounts of visible and dark matter in the Universe

The opportunities for testing and discovering such scenarios at the LHC are being studied

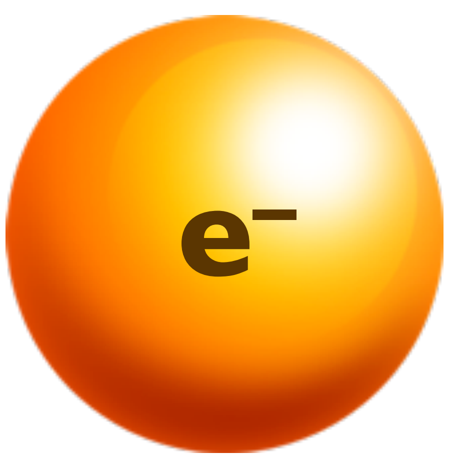
The search for Dark Matter particles at the LHC continues, independently of these scenarios, and remains one of the key goals of future runs ....

Milestones of the XX century

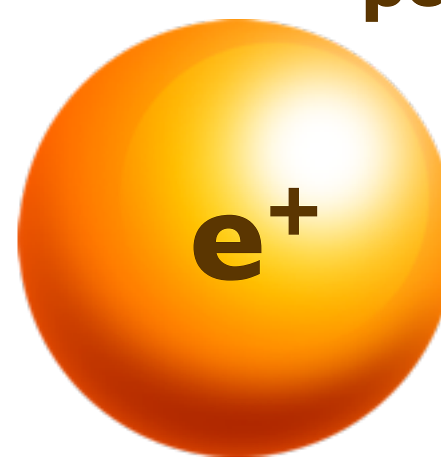
Special relativity from space-time symmetry
+
quantum mechanics

foremost consequence of the two:

the electron is not alone !



positron

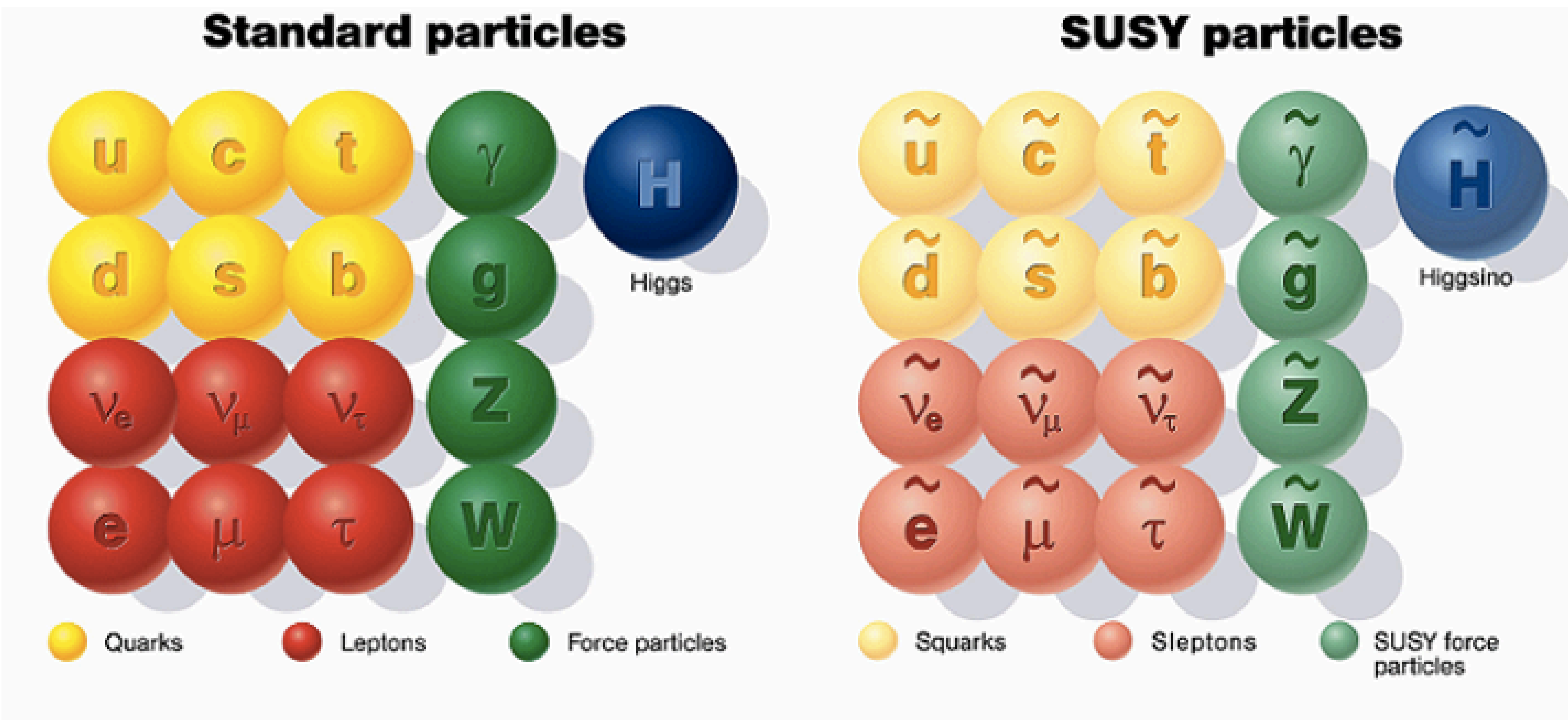


this is generalized to all other fundamental particles: *(except the photon and the Z)* ***they all have an antiparticle !!***

Supersymmetry: an additional possible symmetry of the space-time

... in fact, the largest possible symmetry of the space-time as we know it ....

foremost consequence: each SM particle has a "supersymmetric partner"



Is Supersymmetry (*SUSY*) really an underlying symmetry of our world ?

Fundamental implications:

- the discovery of a single Susy particle implies the existence of all others!!
- several SUSY particles and interactions directly address, and could solve, open issues of particle physics:
  - breaking of EW symmetry, triggering the Higgs mechanism
  - origin of DM
  - origin of matter/antimatter asymmetry
  - “hierarchy problem”
  - relation between gravity and the “other” forces (strong and electroweak)
  - unification of all forces (GUT), and a framework to understand neutrino masses

Most other BSM theories address one or more of these issues.

None has the same intrinsic “simplicity” (builds on the basic concept of space-time symmetries), with the most extensive range of conceptual and practical implications