Moriond EW 2017
(TH summary)

Alberto Casas

Instituto de Física Teórica
UAM-CSIC

Summary:

Summary:

No news from BSM

Summary:

No news from BSM

extremely unfair and misleading

We have seen real progress in the search for BSM, both from the experimental and the theoretical sides

and an stimulating positive feedback between Th and Exp

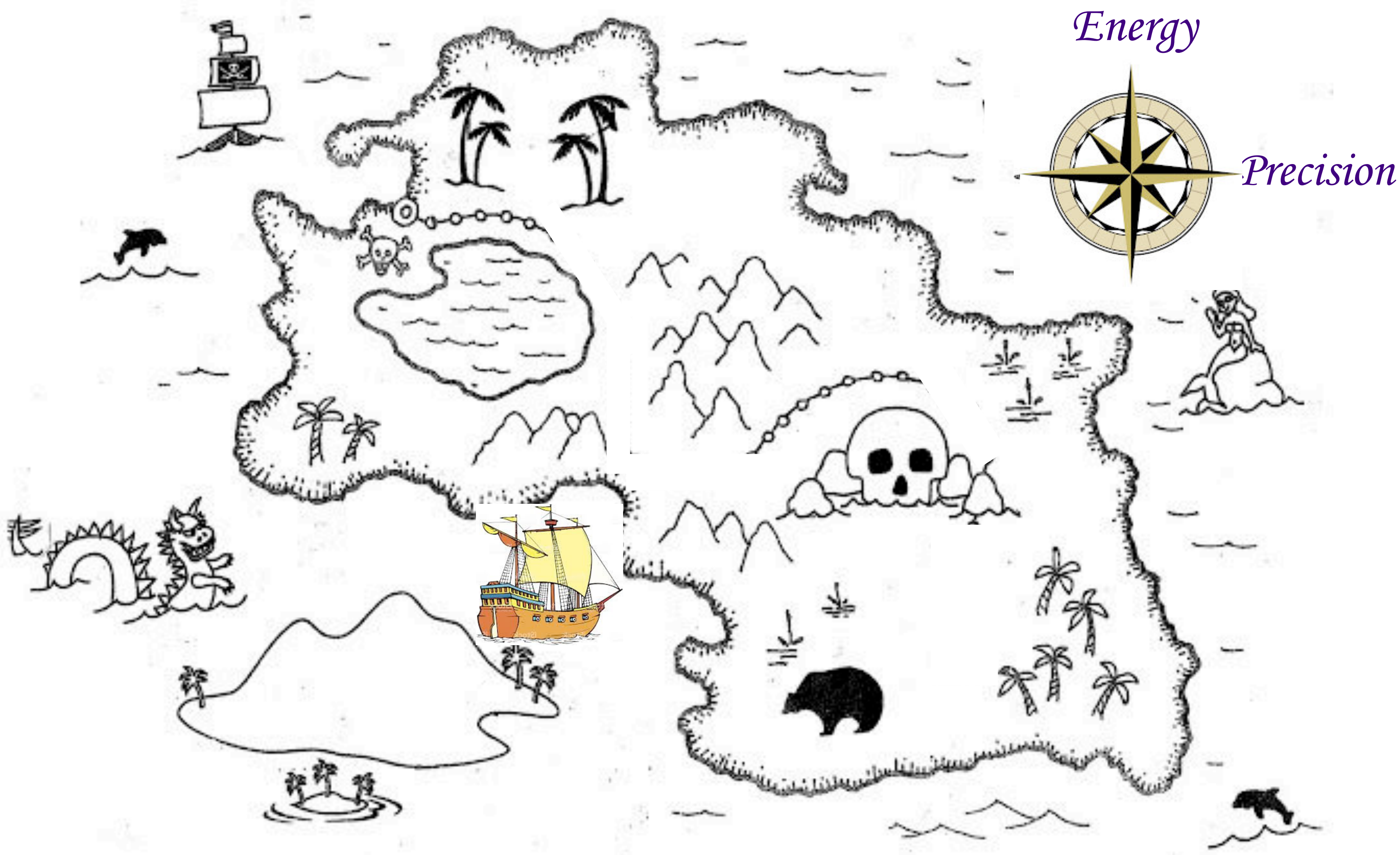
Certainly, the big treasure

has not been discovered yet

TERRA INCOGNITA

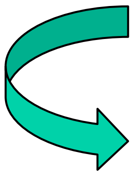
Unexplored territories of nature

TERRA INCOGNITA



TERRA INCOGNITA

Unfortunately, we do not have a cross  in the map to know where the treasure is, as we had for the Higgs boson.



We have to explore the whole territory

Actually, we are not even sure that the BSM treasure is in the territory to be explored, or even if it does exist at all.

Certainly we have very strong indications of BSM physics

- Origin of the EW scale (naturalness)
- Flavour mysteries
- Dark Matter

⋮

... but not necessarily in a scale potencially reachable by current experiments, except the naturalness problem.

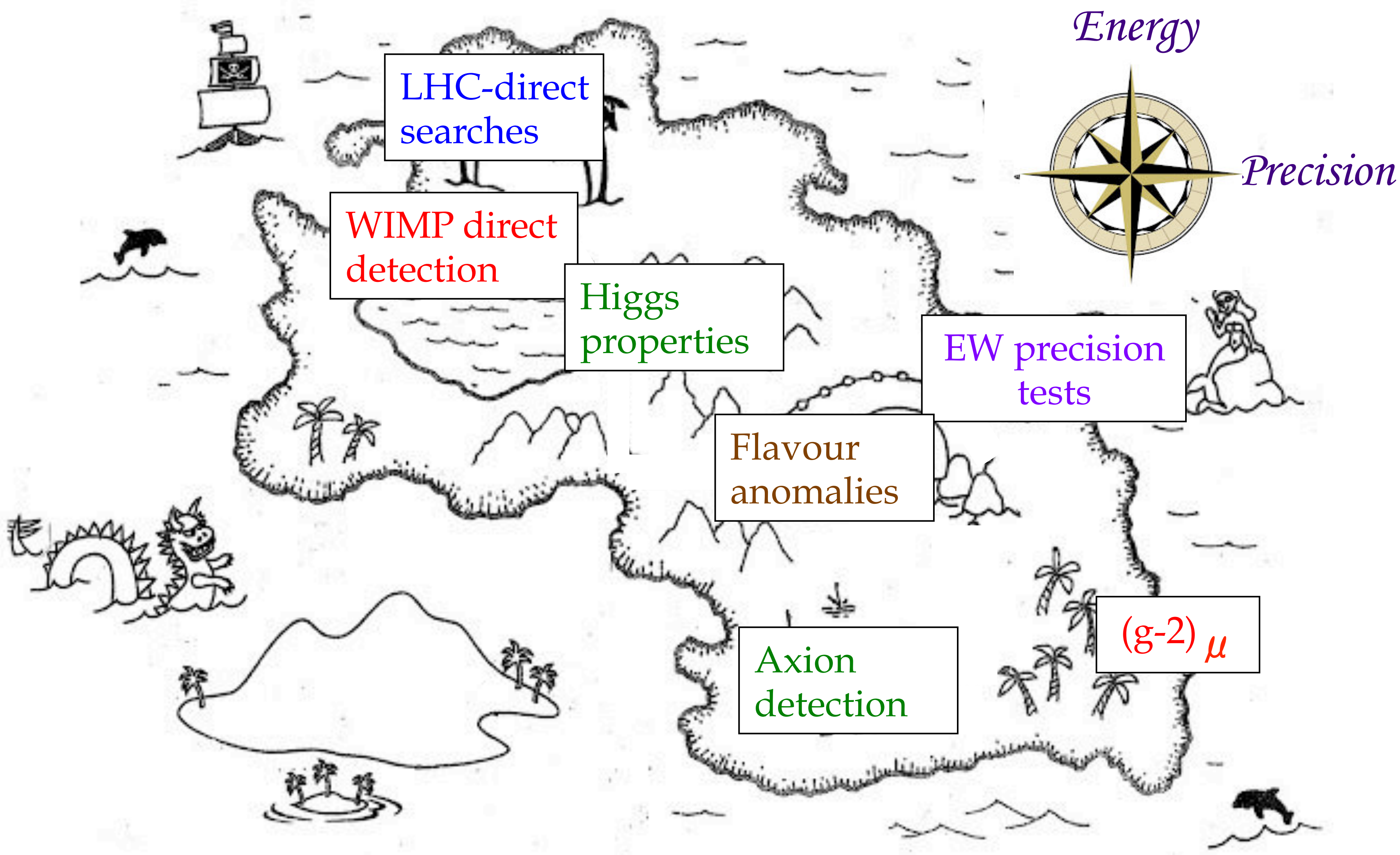
However this is probably the less clear indication for BSM... see later

On the other hand, the reward will be so important, probably a revolution on physics, that it is worth to pursue the search.

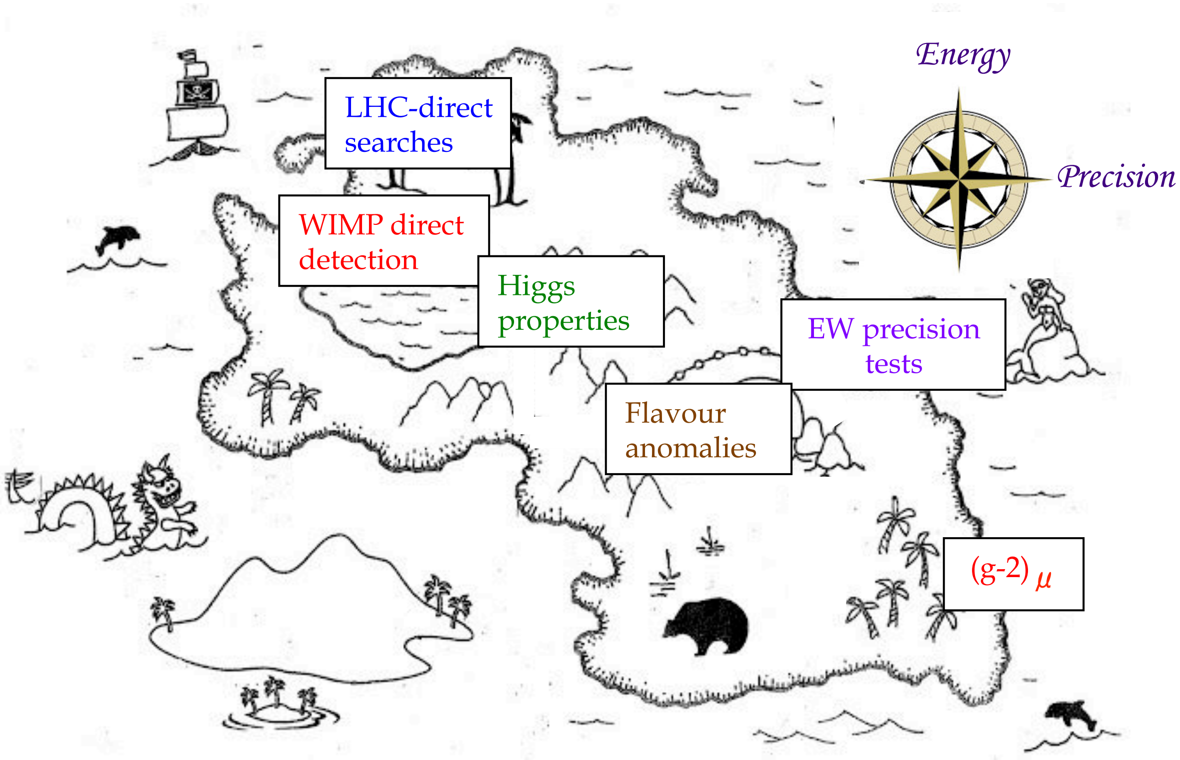
Actually, the content of the BSM treasure is also a mystery:

SUSY, new strong interactions, extra dimensions, origin of flavour, nature of the DM, something unexpected, ... ?

TERRA INCOGNITA



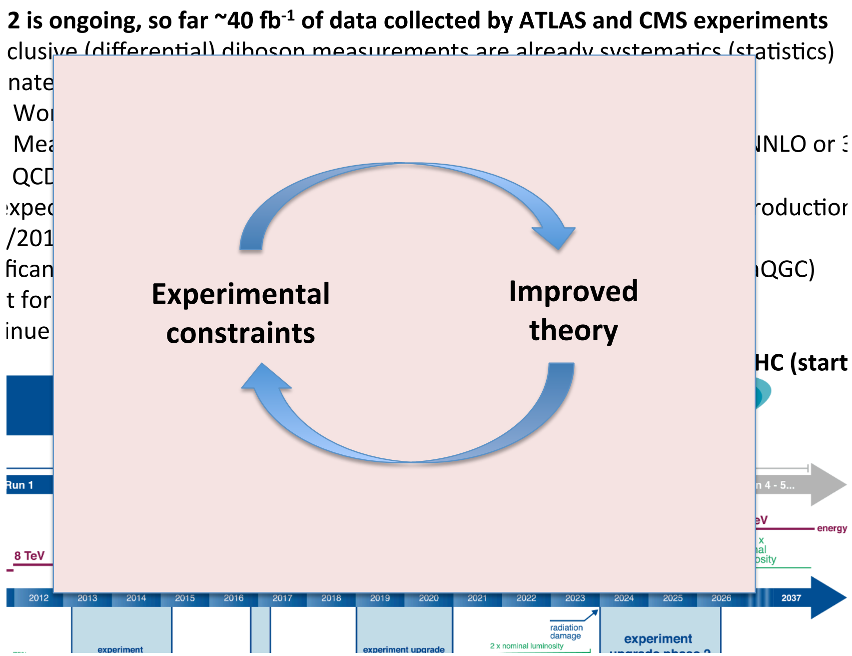
TERRA INCOGNITA



If finally the BSM treasure is found at some place, it would unfair to say that the efforts in other directions were useless. We need to explore all paths.

This conference has shown the impressive efforts of the HEP community to understand and look for new physics in many different ways.

A generic conclusion is that the best way to advance is the feedback between theory and experiment.



from Senka Duric talk

We have seen a lot of progress in both sides !

Important example:

Need for precise determination of PDFs

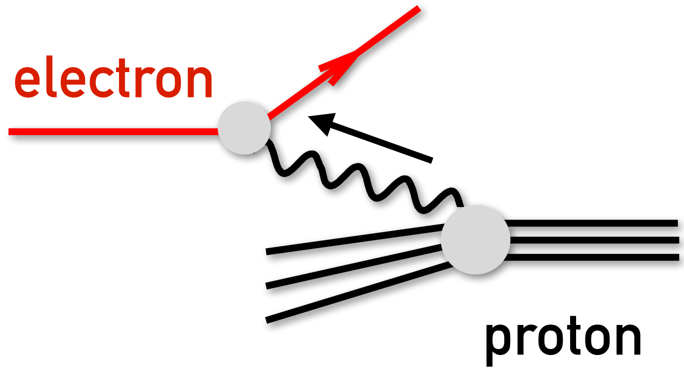
E.g. the PDFs are the main source of uncertainty to improve the determination of M_W.

And this measurement is crucial, as it is "in the heart" of the EW fit, and thus is critical to search for BSM in EW precision tests.

Jens Erler

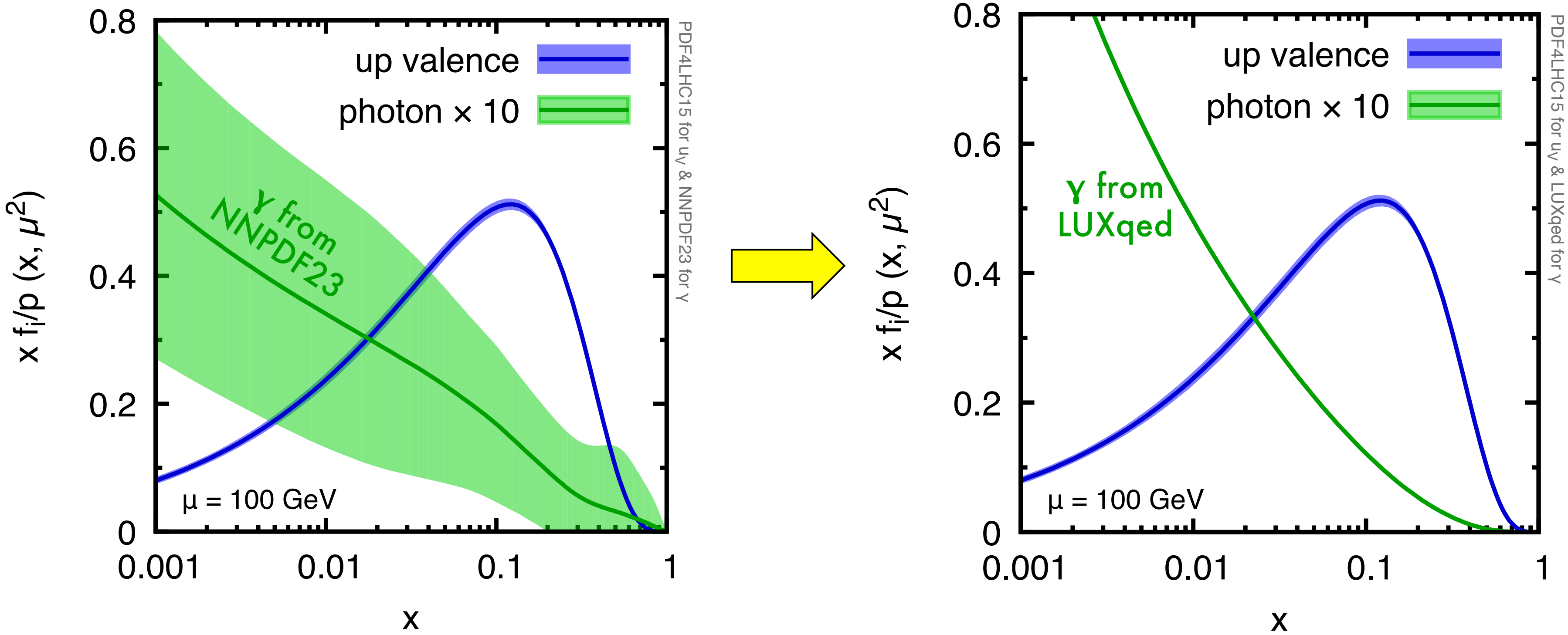
Concerning PDFs, a remarkable result has been presented on the evaluation of the γ - PDF, using an ingenious method.

The idea is to use electron-proton scattering, viewing electrons as probing proton's photonic field (instead of photons from the electron probing proton structure)



$$x f_{\gamma/p}(x,\mu^2) = \frac{1}{2\pi\alpha(\mu^2)} \int_x^1 \frac{dz}{z} \left\{ \int_{\frac{x^2 m_p^2}{1-z}}^{\frac{\mu^2}{1-z}} \frac{dQ^2}{Q^2} \alpha^2(Q^2) \left[\left(z p_{\gamma q}(z) + \frac{2x^2 m_p^2}{Q^2} \right) F_2(x/z, Q^2) - z^2 F_L\left(\frac{x}{z}, Q^2\right) \right] - \alpha^2(\mu^2) z^2 F_2\left(\frac{x}{z}, \mu^2\right) \right\}$$

Gavin Salam



The uncertainty goes from ~ 50 -100 % to ~1% !

Important reduction of uncertainty in relevant processes, as $pp \to HW^+$, $pp \to \ell\ell$

Gavin Salam

Electroweak fit: precise inputs

- One needs 5 input variables to fix the bosonic sector of the SM: $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge couplings and Higgs parameters.
- fine structure constant: α known to $\pm 6.6 \times 10^{-10}$ from Rydberg constant (leaves g_e-2 as new physics constraint)
- Fermi constant: G_F known to $\pm 5.1 \times 10^{-7}$ from muon lifetime
- Z mass: M_Z^2 known to $\pm 4.6 \times 10^{-5}$ from Z-lineshape
  ➡ induces largest input uncertainty
- Higgs mass: M_H^2 known to $\pm 3.8 \times 10^{-3}$ from kinematic reconstruction, but enters only in loops (except total width)
- strong coupling constant: $\alpha_s(M_Z)$ extracted to $\pm 1.4\%$ from EW fit

Jens Erler

crucial quantity, not only for EW precision tests, but to evaluate backgrounds for LHC

Important progress has been reported to evaluate $\alpha_s(M_Z)$ in the lattice

- **Lattice QCD** and **finite size scaling** are a theoretically sound approach to the computation of the fundamental parameters of the SM
- Progress comes from faster computers/better algorithms and also from new ideas in field theory

A particularly appropriate method to compute $\alpha_s(M_Z)$ is the so-called Gradient Flow, based in the addition of an extra "time" coordinate.

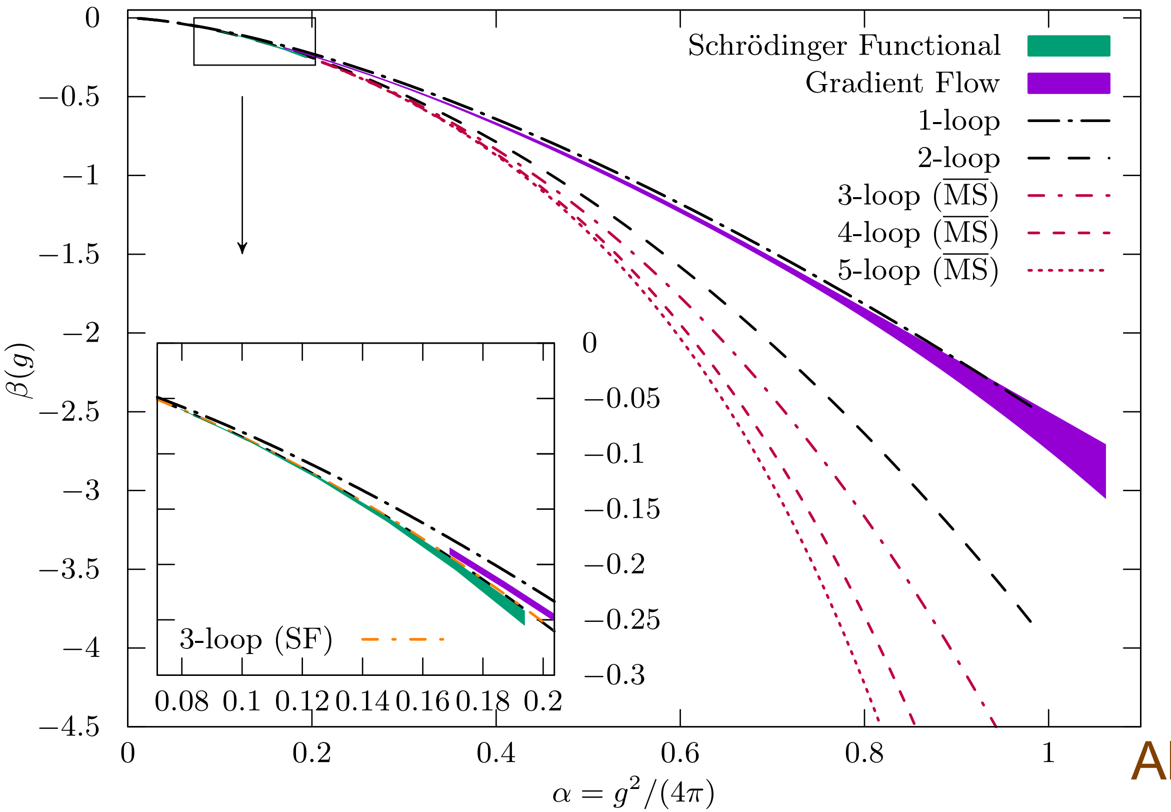
The method allows to save a lot of CPU time and an excellent control of the precision.

Alberto Ramos

A precise determination of

$$\alpha_{\mathrm{GF}}(L) \in [0.2, 1]\ (\sim 4 - 0.2\ \mathrm{GeV})$$

has been performed from 3-flavour QCD, and then matched to $\alpha_s(M_Z)$



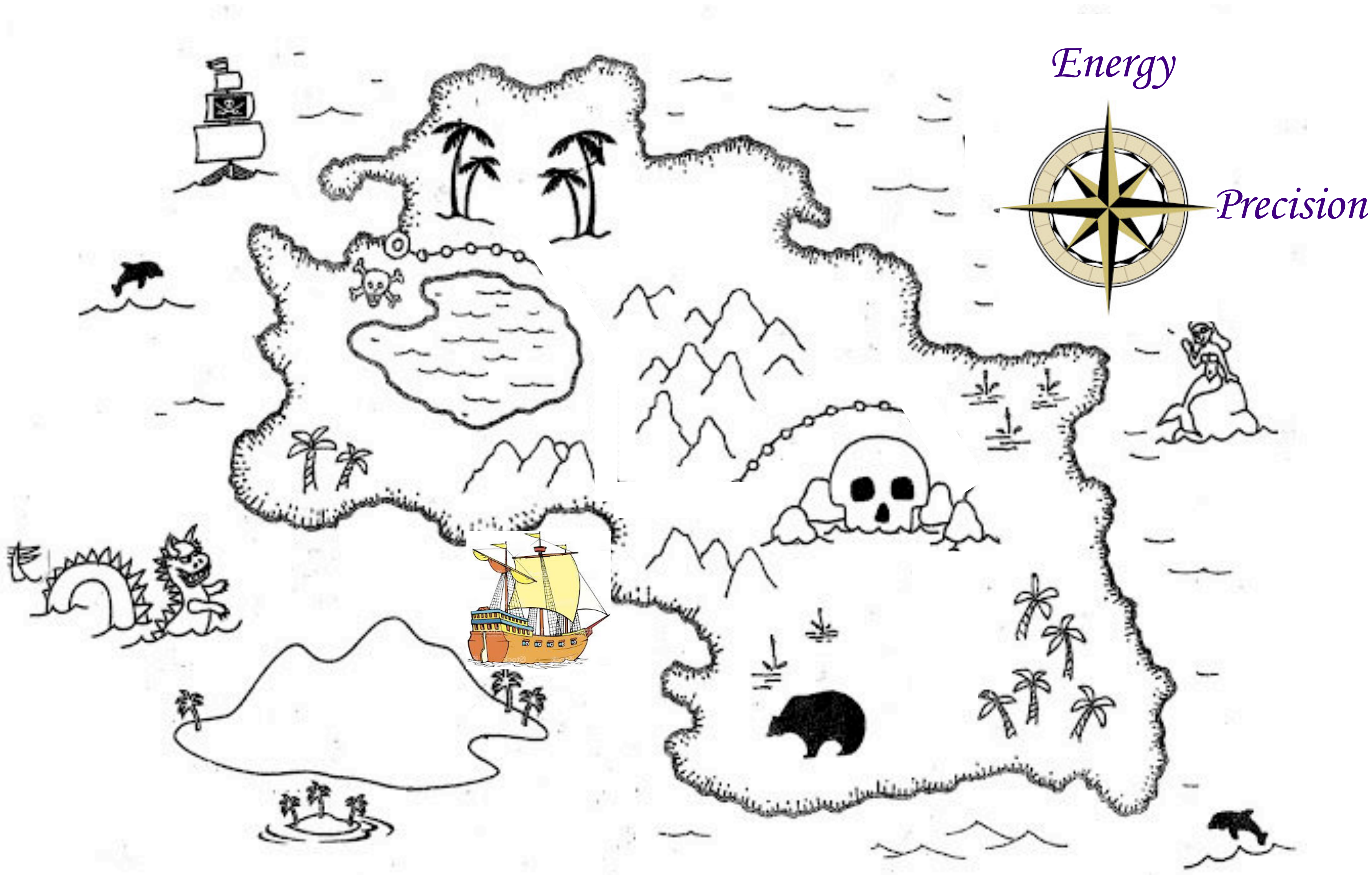
Alberto Ramos

The preliminary result has already a % accuracy

$$\alpha_s(M_Z) = 0.1179(10)(2)$$

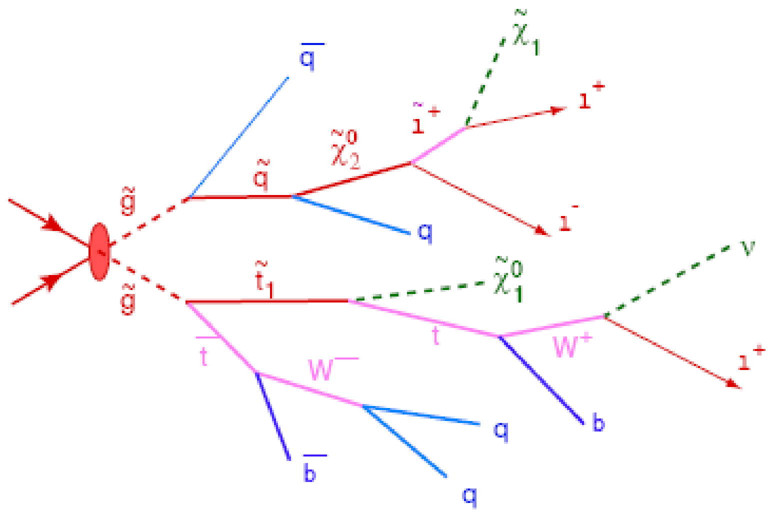
In the future can become the most precise determination of $\alpha_s(M_Z)$

TERRA INCOGNITA



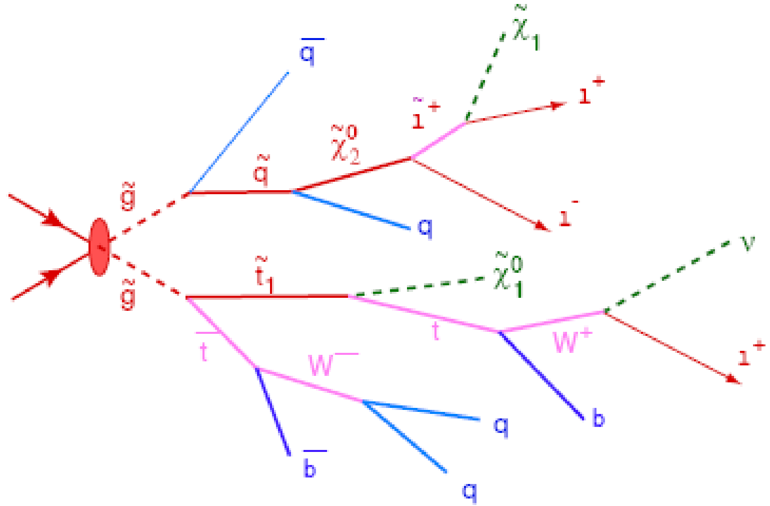
Two main strategies to search for BSM

- Direct searches (typically, production of BSM particles)



Two main strategies to search for BSM

- Direct searches (typically, production of BSM particles)



- Fingerprints in the effective theory

$$\mathscr{L}_{\mathrm{EFT}} = \mathscr{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^{n_i}} \, \mathcal{O}_i$$

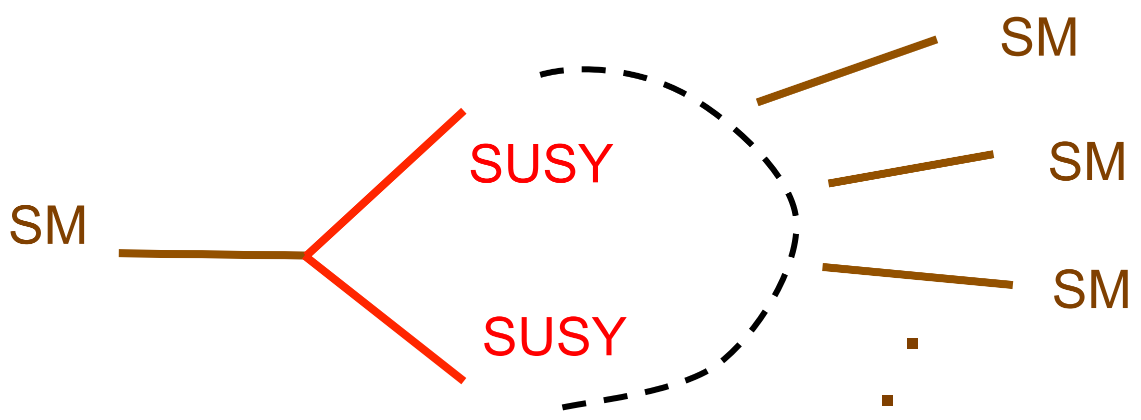
Two main strategies to search for BSM

Which approach is potentially more efficient depends on the type of BSM scenario

The most reasonable thing is to explore both avenues

E.g. for SUSY, typically direct searches are more efficient than looking for fingerprints in the EFT

Due to R-parity, SUSY-induced diagrams in the SM- EFT are loop-supressed



$$\Rightarrow \quad \mathcal{L}_{\rm eff} \sim \underbrace{\frac{g^6}{(4\pi)^2}}_{\text{additional suppression}} \frac{1}{\Lambda^2} |H|^6 \; + \; \cdots$$

On the other hand, BSM theories which violate some (exact or approximate) SM symmetry, are much more likely to be discovered by indirect searches, thanks to their impact in the EFT.

E.g. this happens for BSM physics which is not flavour-blind

Indirect Searches of BSM

Low-En observables (possibly showing deviations from SM predictions)

Indirect Searches of BSM

Map them into an EFT (derive c_i or put limits on them)

$$\mathscr{L}_{\rm EFT} = \mathscr{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^{n_i}}\, \mathcal{O}_i$$

↗

Low-En observables (possibly showing deviations from SM predictions)

Indirect Searches of BSM

Look for an UV theory that could reproduce the EFT

$$\mathscr{L}_{\rm NP} = \mathscr{L}_{\rm SM} + \cdots$$

Map them into an EFT (derive c_i or put limits on them)

$$\mathscr{L}_{\rm EFT} = \mathscr{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^{n_i}} \mathcal{O}_i$$

Low-En observables (possibly showing deviations from SM predictions)

Indirect Searches of BSM

Look for an UV theory that could reproduce the EFT

$$\mathscr{L}_{\rm NP} = \mathscr{L}_{\rm SM} + \cdots$$

Jose Santiago

Map them into an EFT (derive c_i or put limits on them)

$$\mathscr{L}_{\rm EFT} = \mathscr{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^{n_i}}\, \mathcal{O}_i$$

Michael Trott

Low-En observables (possibly showing deviations from SM predictions)

Using measurements in the SMEFT in a global constraint program needs to check if the measurement is precise and accurate enough that it is necessary to include one loop (SMEFT) corrections.

E.g. at one loop the number of SMEFT parameters contributing to the precise LEPI pseudo-observables exceeds the number of measurements. As a result the SMEFT parameters contributing to LEP data are formally unbounded when the size of loop corrections are reached until other data is considered in a global analysis.

The size of these loop effects is generically a correction of order ~% to leading effects in the SMEFT.

Fortunately, one-loop results in the SMEFT are becoming increasingly available in well defined formalisms.

Michael Trott

Indirect Searches of BSM

Look for an UV theory that could reproduce the EFT

$$\mathscr{L}_{\rm NP} = \mathscr{L}_{\rm SM} + \cdots$$

Jose Santiago

Map them into an EFT (derive c_i or put limits on them)

$$\mathscr{L}_{\rm EFT} = \mathscr{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^{n_i}} \mathcal{O}_i$$

Michael Trott

Low-En observables (possibly showing deviations from SM predictions)

MatchMaker:

Automated tool to perform tree-level and one-loop matching of arbitrary theories into arbitrary effective Lagrangians

- Features of current version:
  - Matching to SMEFT fully automated
  - Basis-independent results: generate all redundant and evanescent operators. A specific basis is chosen by the user via external file (default Warsaw basis)

Jose Santiago

great news for model-building !

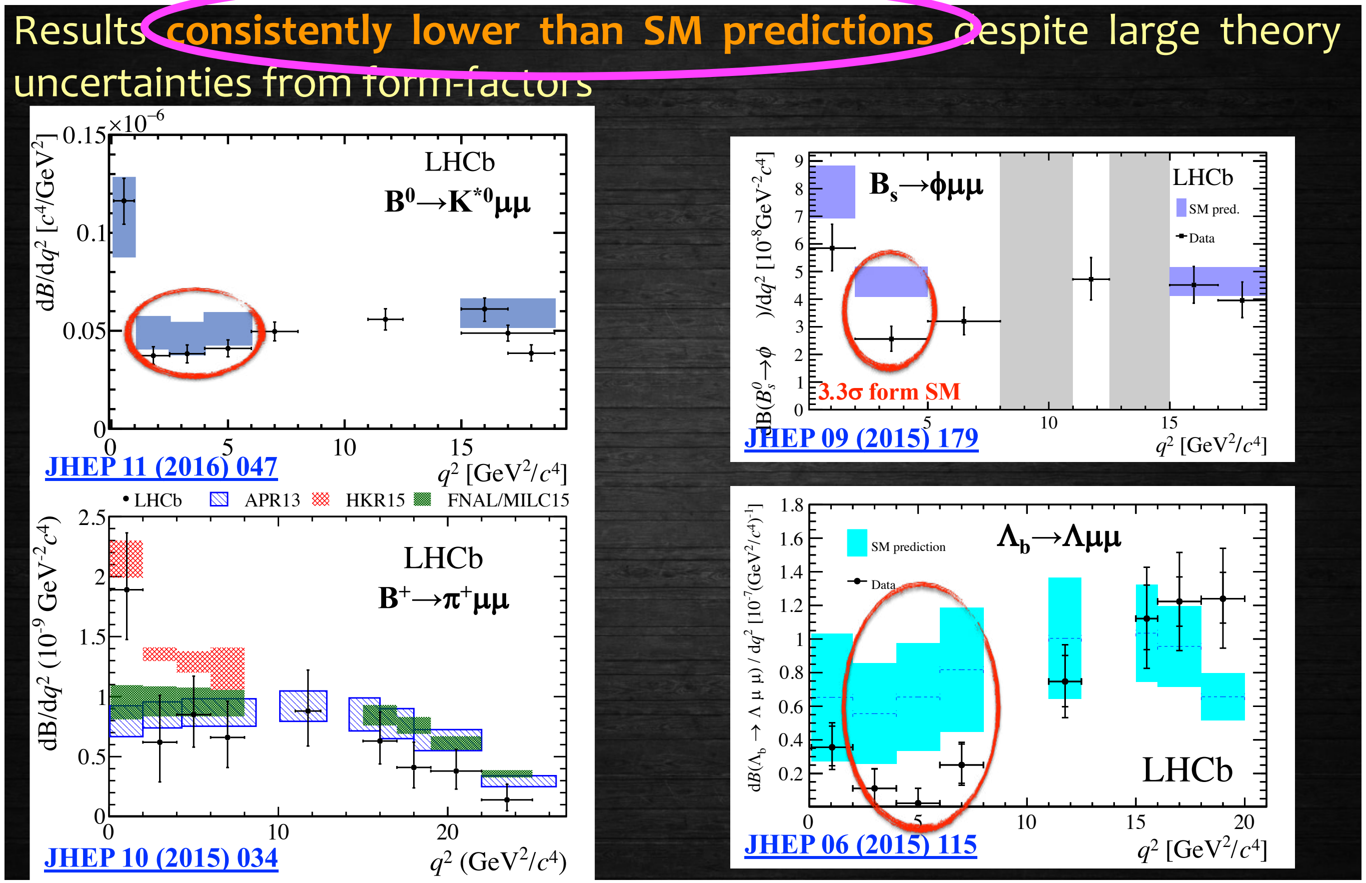
Going to specific examples....

The most vivid discussions in the conference were about the *flavour anomalies* of B-decays and their interpretation in terms of NP.

In particular, $b \to s\ \mu\mu$ anomalies:

$$B \to K^* \mu\mu, \;\; B_s \to \phi\mu\mu, \;\; B^+ \to K^+ \mu\mu, \;\; \text{etc.}$$

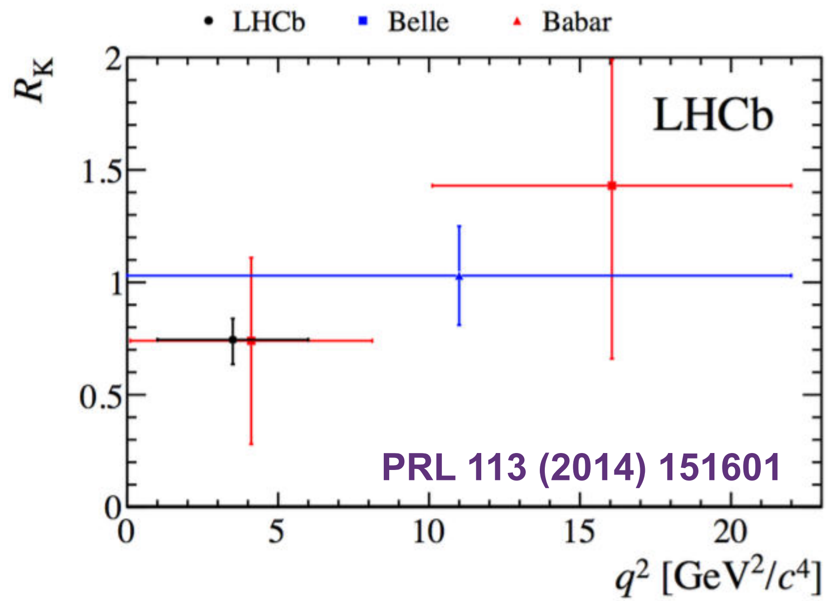
(Branching ratios typically below the SM prediction, so far)



from Bifani's talk (LHCb), based on results from 2015

$$\mathcal{R}(K) \equiv \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}$$

shows 2.6 **σ** discrepancy with SM



Similarly other observables, as

$$P_5' = \sqrt{2}\,\frac{\mathrm{Re}(A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*})}{\sqrt{|A_0|^2(|A_\perp|^2 + |A_{||}|^2)}}$$

globally, ~ O(>4**σ**) discrepancy with SM

Joaquim Matias

These results can be interpreted in terms of an EFT with

Coefficient	Best fit	1σ	Pull_{SM} (σ)
$\mathcal{C}_9^{\text{NP}}$	-1.05	$[-1.25, -0.85]$	4.7
$\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{10}^{\text{NP}}$	-0.59	$[-0.74, -0.44]$	4.3

Joaquim Matias

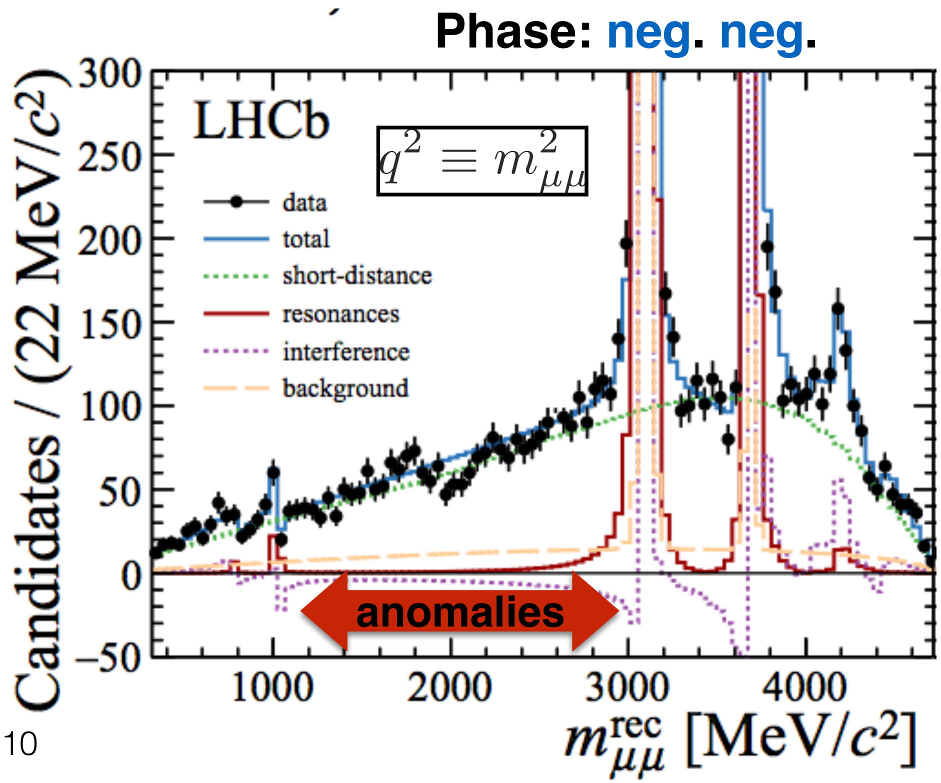
where

- $\mathcal{O}_9 = \frac{e^2}{16\pi^2}\bar{s}\gamma_\mu(1-\gamma_5)b\,\bar{\ell}\gamma^\mu\ell$
- $\mathcal{O}_{10} = \frac{e^2}{16\pi^2}\bar{s}\gamma_\mu(1-\gamma_5)b\,\bar{\ell}\gamma^\mu\gamma_5\ell$

These conclusions would be mitigated if there were other sizeable SM contributions, e.g. from charm loops.

Quim Matias has argued against this possibility

Another possibility, SM resonance effects on C_9 , has been almost discarded by the LHCb analysis



Siim Tolk's talk

To settle the question we need more experimental data

- ★ First results from ATLAS (still with sizeable error bars)

  Bevan

- ★ First results from CMS (going in the SM direction)

  Dinardo

- ★ Experimental update from LHCb, especially for R(K) (in the way)

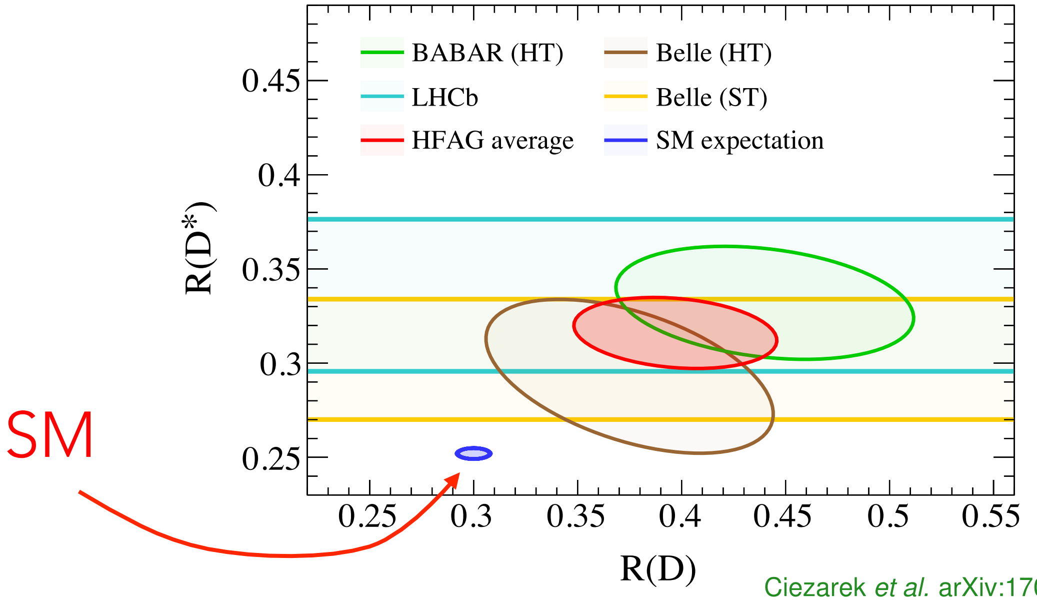
Bifani

Certainly we are impatient, but also admit that it is a very difficult experimental analysis.

For the moment we can dream of BSM physics associated to these flavour anomalies.

A similar tension occurs for $R_{D(*)}$:

$$R_{D^{(*)}} = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu})}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu})} \quad \text{where} \quad \ell = e, \mu$$



Ciezarek *et al.* arXiv:1703.01766

The $R_{D^{(*)}}$ tension can be also interpreted in terms of NP:

$$\mathcal{L}_{\rm eff}^{\ell} = -\frac{G_F V_{cb}}{\sqrt{2}} [(1+\epsilon_L^{\ell})\bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{c}\gamma^\mu(1-\gamma_5)b + \cdots$$

with

$$\epsilon_L = 0.13$$

Martin Camalich

What new physics?

Indirect Searches of BSM

Look for an UV theory that could reproduce the EFT

$$\mathscr{L}_{\rm NP} = \mathscr{L}_{\rm SM} + \cdots$$

Map them into an EFT (derive c_i or put limits on them)

$$\mathscr{L}_{\rm EFT} = \mathscr{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^{n_i}}\,\mathcal{O}_i$$

Low-En observables (possibly showing deviations from SM predictions)

Several solutions to the various flavour anomalies have been presented in the meeting

- ★ New scalar and fermions
- ★ Leptoquarks
- ★ Z′ s
- ★ Extra-Dimensions

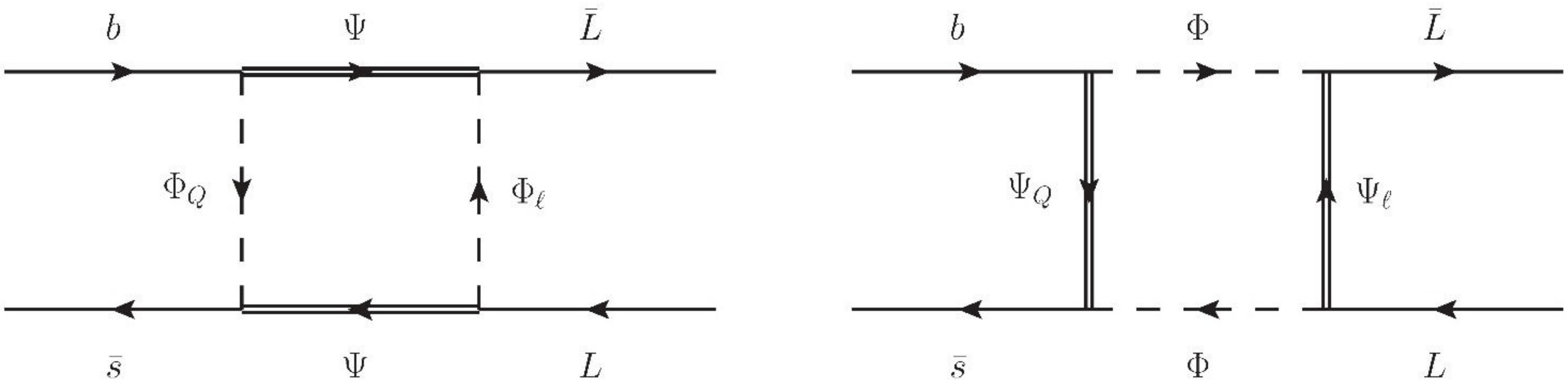
Crivellin

Sumensari

Panico

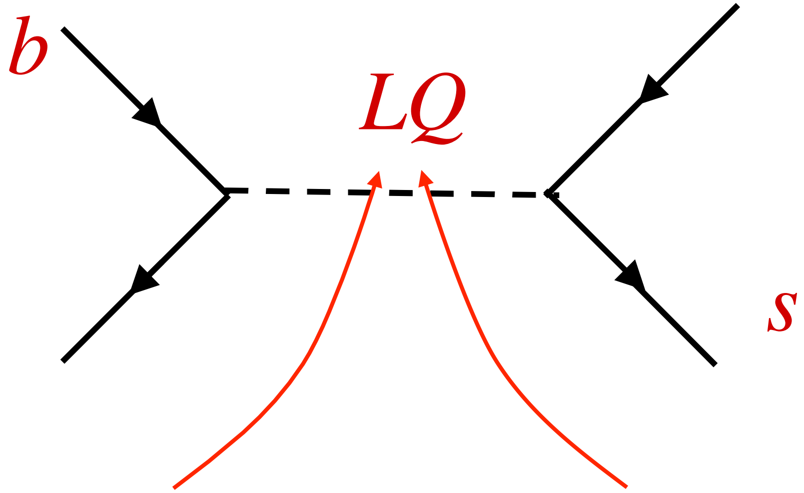
Fuentes

New Scalars and Fermions in $b \to s\mu\mu$



Andreas Crivellin

R(D$^{(*)}$) and b→sμμ with Leptoquarks



(for $b \to s \ \mu\mu$)

Scalar leptoquark (triplet)
with Y=-2/3

Scalar leptoquark (doublet)
with Y=1/6

Andreas Crivellin

Olcyr Sumensari

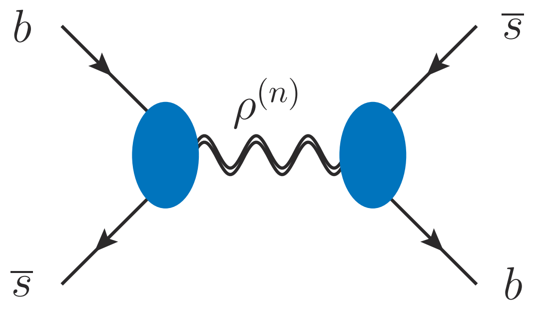
An extra-dimensional (RS) origin for LHCb anomalies

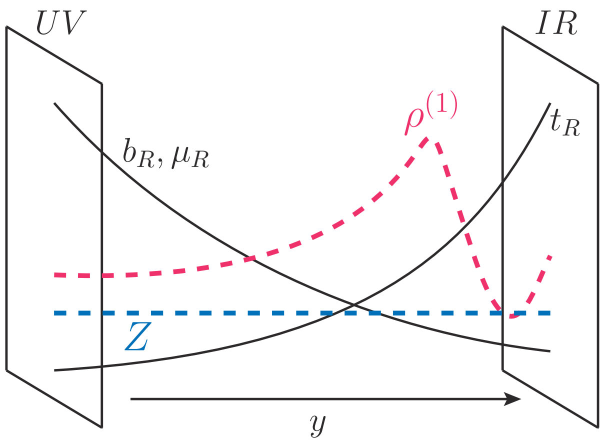
Giuliano Panico

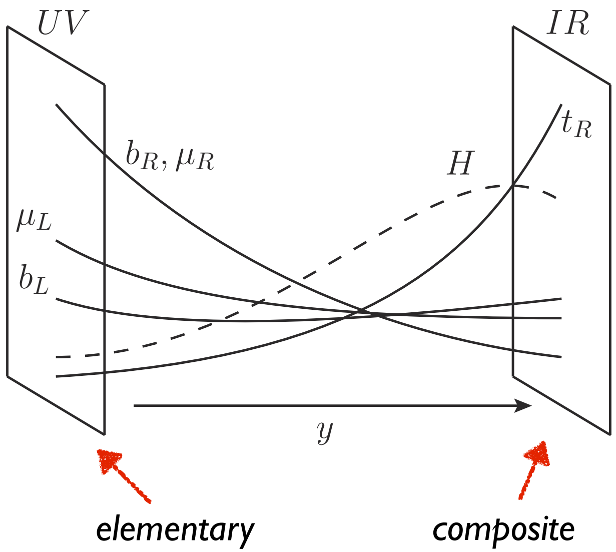
Massive KK modes have a non-trivial profile

⇓

Universality violation







Another important flavour/CP observable: $\frac{\epsilon'_K}{\epsilon_K}$

$$\mathrm{Re}\,\frac{\epsilon'}{\epsilon_K} = \mathrm{Re}\left(\frac{i e^{i(\delta_2-\delta_0)}}{\sqrt{2}\epsilon_K}\right)\left[\mathrm{Im}\,A_2 - \frac{\mathrm{Re}\,A_2}{\mathrm{Re}\,A_0}\mathrm{Im}\,A_0\right]$$

ε': a possible gem in search of new phenomena

Amarjit Soni

$$\mathrm{Re}\,\frac{\epsilon'_K}{\epsilon_K}\bigg|_{\mathrm{EXP}} = (16.6 \pm 2.3)\times 10^{-4}$$

[PDG, 2016]

2.8σ ⟷

$$\frac{\epsilon'_K}{\epsilon_K}\bigg|_{\mathrm{SM}} = (1.06 \pm 5.07)\times 10^{-4}$$

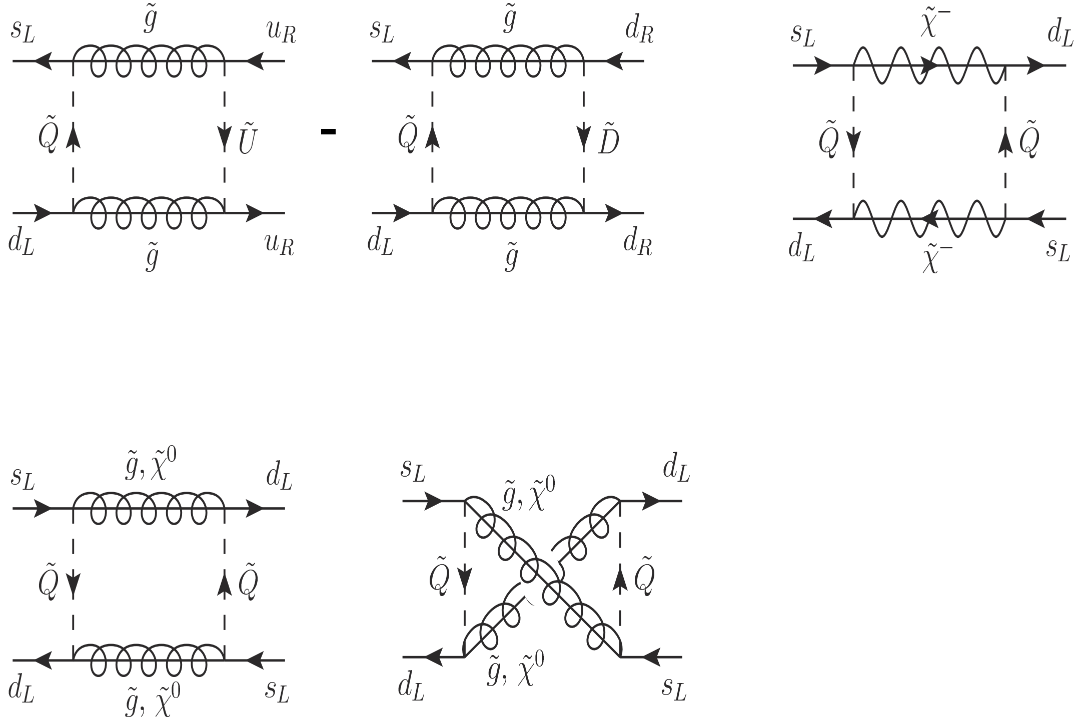
tension

[RBC-UKQCD, 2015]
[Buras, Gorbahn, Jager, Jamin, 2015]
[**TK**, Nierste, Tremper, 2016]

Soni's talk reported the impressive progress made in lattice calculations necessary for **ε'/ε** calculations in the SM during the past years

Some presentations proposed BSM solutions to the discrepancy if it is finally confirmed.

★ SUSY



In the MSSM one can simultaneously enhance ϵ'_K and suppress the new-physics contributions to ϵ_K. This requires flavour mixing among left-handed squarks, masses of right-handed up-type squarks different from those of the down-type squarks, and a gluino mass above 1.5 times the mass of the left-handed squarks.

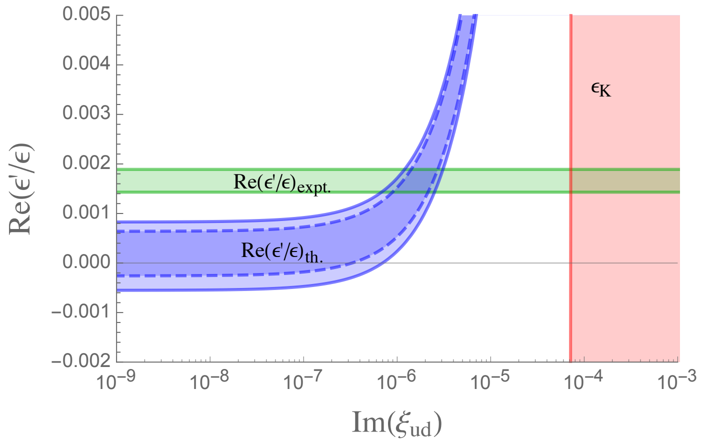
Ulrich Nierste

★ Right-handed charged currents

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{2}{v^2}\tilde{\varphi} i D_\mu \varphi \, \bar{u}_R \gamma^\mu \xi \, d_R$$

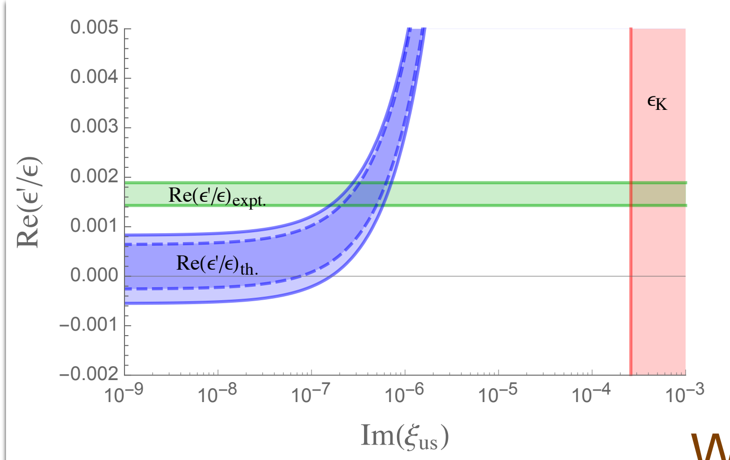
- ξ generally a 3x3 matrix
  - Right-handed analogue of the CKM matrix

ξ_{ud}



Effective scale $\Lambda \sim 100\,\mathrm{TeV}$

ξ_{us}

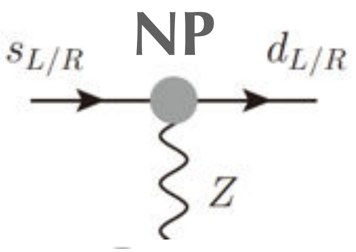
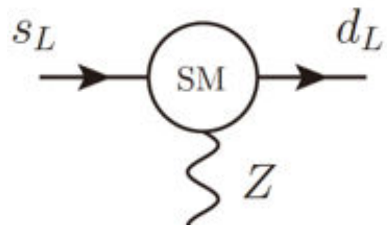


Effective scale $\Lambda \sim 300\,\mathrm{TeV}$

Wouter Dekens

★ Modified Z-couplings

NP contributions to s-d-Z coupling which has the same magnitude as the SM Z-penguin can explain ϵ'_K discrepancy

Im  $\simeq -$ Im 

→ ϵ'_K can be solved

O(1) contribution to $\mathcal{B}(K \to \pi\nu\bar{\nu})$

Teppei Kitahara

Apart from flavour/CP anomalies, no important tensions with the SM have been reported. But we do not lose hope...

A promising territory for that is Higgs physics:

- ★ Last sector of SM discovered: new opportunities to find BSM

- ★ Still large uncertainties and many important SM predictions to be tested: $y_{\mu\mu},\ \lambda_3,\ \lambda_4, \cdots$

- ★ Directly related to the naturalness problem

This connects with the fact that the big questions continue to excite the imagination of theorists, driving them to new and suggestive scenarios of NP.

TERRA INCOGNITA

This may illuminate the path to the BSM treasure.

We have seen proposals inspired by:

- ★ Naturalness problem
- ★ Strong CP problem
- ★ Baryon asymmetry
- ★ Flavour puzzles
- ★ Origin of the dark matter

We have seen proposals inspired by:

- ★ Naturalness problem
- ★ Strong CP problem
- ★ Baryon asymmetry
- ★ Flavour puzzles
- ★ Origin of the dark matter

Naturalness problem

Simple (maybe naive) arguments, related to the size of the EW scale, suggest that

$$\Lambda_{\mathrm{NP}} \lesssim \mathcal{O}(\mathrm{TeV})$$

↳ we can expect BSM physics at LHC

...but the NP does not appear

SM in remarkable health: making us theorists sick

Jens Erler

(naive) Naturalness doesn't apply

- Misconceptions about H.P.
- Alternatives: Relaxion, Clockwork,..
- Landscape?

(naive) Naturalness applies

- New Physics at the ~ TeV scale
- Possibly at the LHC reach
- SUSY, Technicolor, Extra Dim. ...

(naive) Naturalness doesn't apply

- Misconceptions about H.P.
- Alternatives: Relaxion, Clockwork,..
- Landscape?

(naive) Naturalness applies

- New Physics at the ~ TeV scale
- Possibly at the LHC reach
- SUSY, Technicolor, Extra Dim. ...

We still don't know which way has been chosen by NATURE

So, it is sensible to consider and explore all possibilities

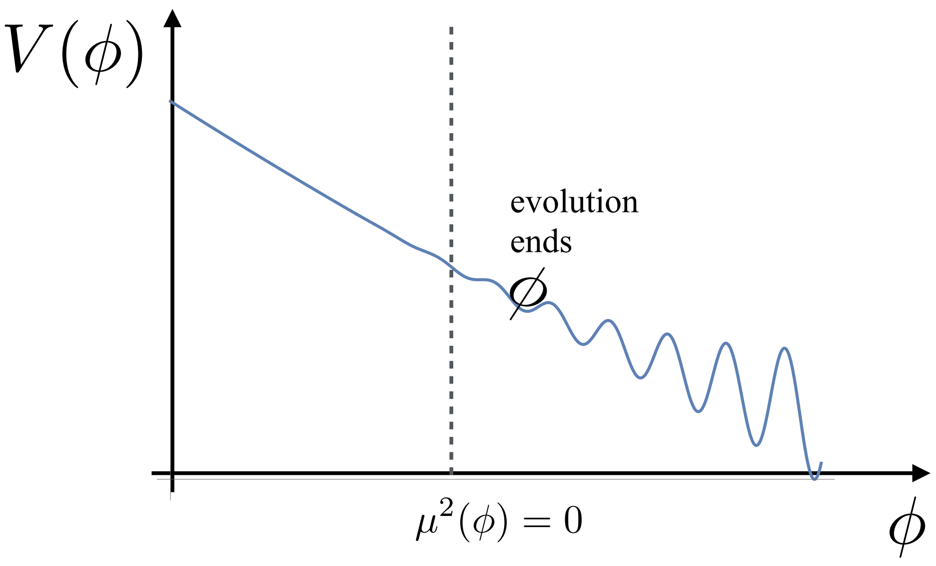
Relaxion

- A dynamical solution/amelioration of the Higgs fine-tuning problem:

(i) Add a scalar (relaxion) Higgs dependent mass: $\overbrace{(\Lambda^2 - g^2\phi^2)}^{\mu^2(\phi)}\, H^\dagger H$.

(ii) ϕ roles till μ^2 changes sign $\Rightarrow \langle H \rangle \neq 0 \Rightarrow$ stops rolling.

Gilad Perez



Typically, for this mechanism to work, a (back reaction) potential, mixing h and ϕ is needed

$$\Delta V_{br}(h,\phi) = -\tilde{M}^{4-j}\hat{h}^j \cos\left(\frac{\phi}{f}\right)$$

⟹ The relaxion and the Higgs mix

$$\sin\theta \sim \frac{\tilde{M}^2 v}{m_h^2 f} \quad , \quad m_\phi \sim \frac{\tilde{M} v}{f}$$

Gilad Perez

The sizes of these two parameters determine to a large extent the phenomenology, e.g. h–physics, K–physics, etc.

Clockwork

The idea is to start with the EW scale and generate M_P thanks to an extremely small coupling

Take N+1 copies of gravity, giving N+1 gravitons, coupled as

$$\mathcal{L} = -\frac{m^2}{2}\sum_{j=0}^{N-1}\left(\left[h_j^{\mu\nu} - q h_{j+1}^{\mu\nu}\right]^2 - \left[\eta_{\mu\nu}(h_j^{\mu\nu} - q h_{j+1}^{\mu\nu})\right]^2\right)$$

This includes a massless graviton.

Imagine SM fields only "charged" under last diffeomorphism invariance, couple to last graviton.

$$-\frac{1}{M_N} h_N^{\mu\nu} T_{\mu\nu} \to -\frac{1}{M_P}\tilde{h}_0^{\mu\nu} T_{\mu\nu} \longrightarrow M_P = q^N M_N$$

Matthew McCullogh

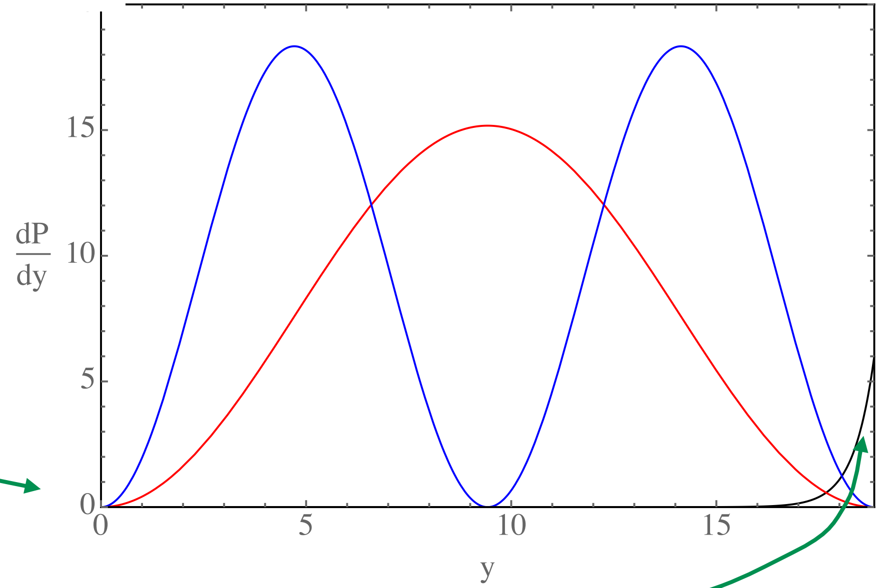
Clockwork

This theory can come from 4+1 dimension, with metric

$$ds^2 = e^{\frac{4k|y|}{3}}(dx^2 + dy^2)$$

(Somehow similar to RS but different)

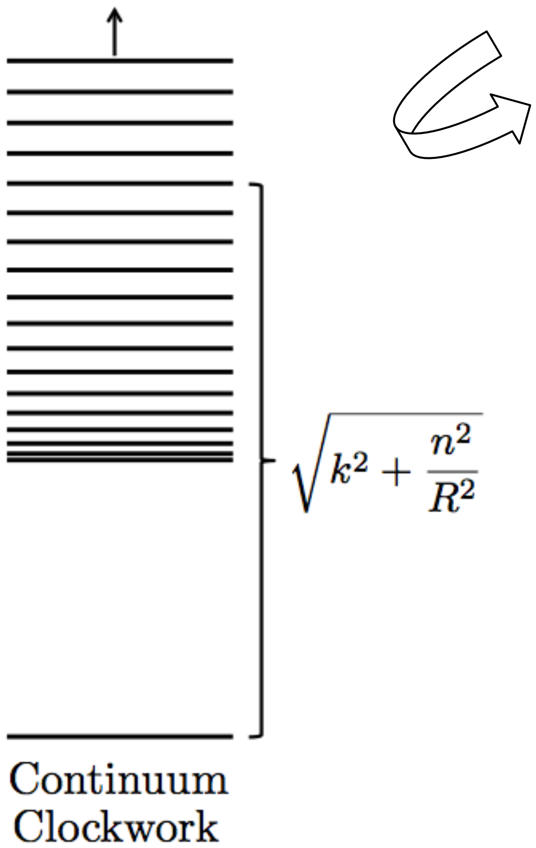
$$dP = e^{2k|y|}\,\psi_n^2(y)\,d(y/\pi R)$$



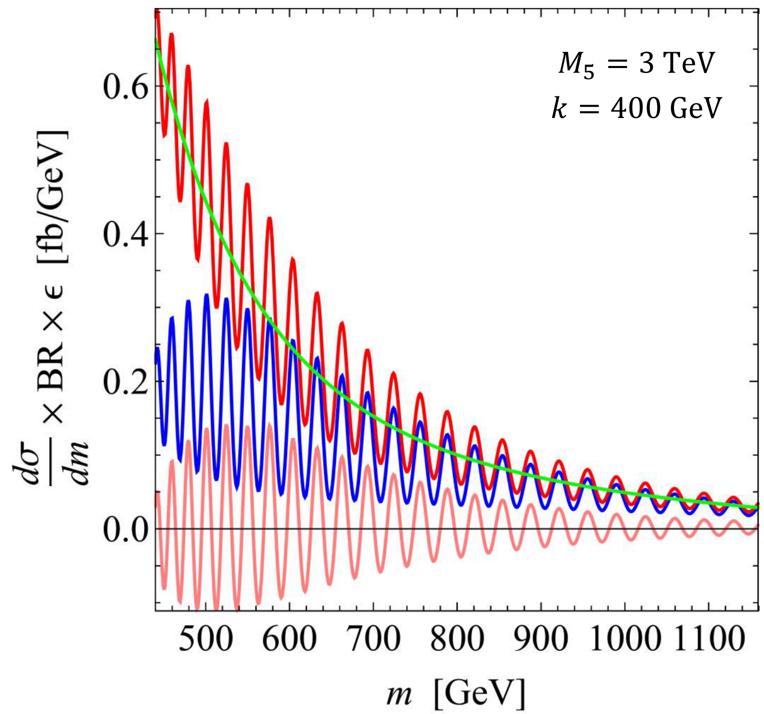
If the SM fields are located at y=0, then they coupled very little with the first (massless) KK-mode, i.e. the usual graviton.

Matthew McCullogh

Typical spectrum



Very distinctive signals at colliders



Matthew McCullogh

Clockwork

Using a discretized 5th dimension (with N sites) gives the Clockwork Lagrangian in 4d

A version of this, with chains of fermionic and scalar fields has been used to build a Clockwork WIMP:

$$\mathbf{R_0} \;\overset{S_1}{\text{———}}\; L_1 \;\overset{C_1}{\text{———}}\; R_1 \;\overset{S_2}{\text{———}}\; L_2 \;\overset{C_2}{\text{———}}\; \ldots \;\overset{C_N}{\text{———}}\; R_N \;\text{———}\; \mathbf{L_{SM}}$$

fermions

scalars

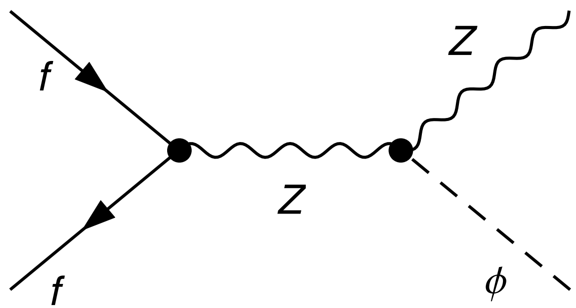
tiny couplings DM-SM ⇒ metastable dark matter

Daniele Teresi

Radion

In a similar context, RS constructions, a method has been proposed to detect the radion field at the ILC

The radion field corresponds to the fluctuations of the size of the 5th dimension. Typically mixes with the Higgs and thus couples to the Z



This can be used to detect it at the ILC

Andrei Angelescu

SUSY

We have not seen many proposals in the context of SUSY (neither in composite Higgs or extra-dimensions).

There has been however a very interesting proposal in NMGSB

NMGSM (Next to Minimal Gauge-Mediated Susy-Breaking) is a nice SUSY construction, since it has the advantages of GM (simplicity and predictivity) and can naturally reproduce m_h. Then

LSP is gravitino, NLSP is dominantly singlino.

Long-lived singlino

Ben Allanach

At the end of decay chains, $\tilde{N}_1 \to a_1 \tilde{G} \to b\bar{b}\tilde{G}$.

$$c\tau_{\tilde{N}_1} \approx 2.5\,\mathrm{cm} \left(\frac{100\,\mathrm{GeV}}{M_{\tilde{N}_1}}\right)^5 \left(\frac{M}{10^6\,\mathrm{GeV}}\right)^2 \left(\frac{\tilde{m}}{\mathrm{TeV}}\right)^2 .$$

Hence, we have displaced decays, but for $M > 10^{10}$ GeV, it decays outside of the detector.

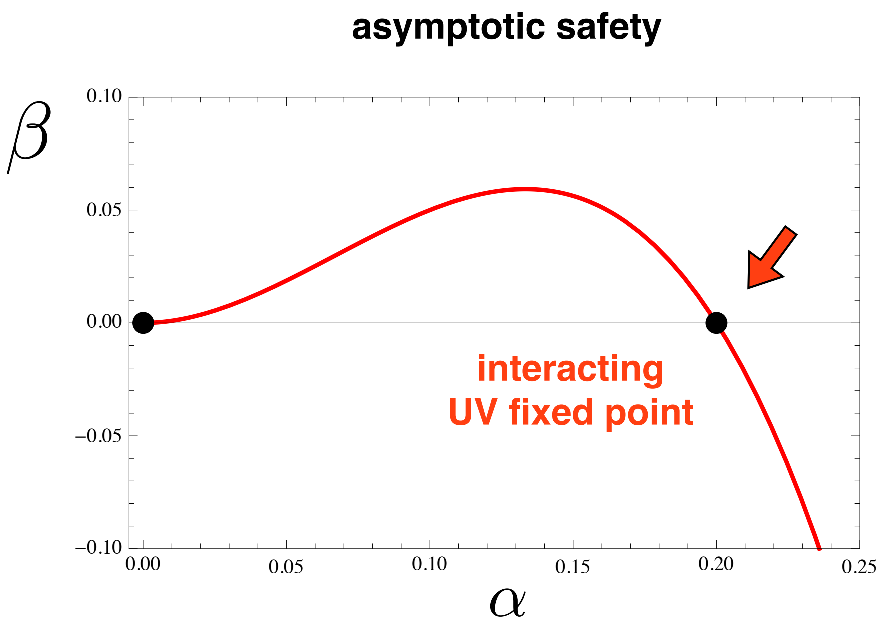
Ben Allanach

Incidentally, there have been many (exp and th) presentations discussing displaced vertices. This is a difficult but promising subject, as it has little background.

Asymptotic safety of the SM

Somehow related to the naturalness problem is the question of the behaviour of the (pure) SM at arbitrary high scales

From the QFT point of view, asymptotic (UV) safety requires an UV fixed point



Daniel Litim

Asymptotic safety of the SM

This requires new SM representations and appropriate Yukawa couplings

These possibilities have been completely classified. Not all of them match with the SM gauge couplings.

In some cases. the scale at which the new states enter is fully determined. In some cases it is at TeV-scales

The scenario could be tested at colliders

Daniel Litim

We have seen proposals inspired by:

- ★ Naturalness problem
- ★ Strong CP problem
- ★ Baryon asymmetry
- ★ Flavour puzzles
- ★ Origin of the dark matter

ALPs (Axion-Like-Particles)

The PQ solution to the strong CP problem predicts a pNBGB, with derivative couplings and mass

$$m_a^2 f_a^2 = m_\pi^2 f_\pi^2$$

But

Models enlarging the strong SM gauge sector, with scale **Λ'**

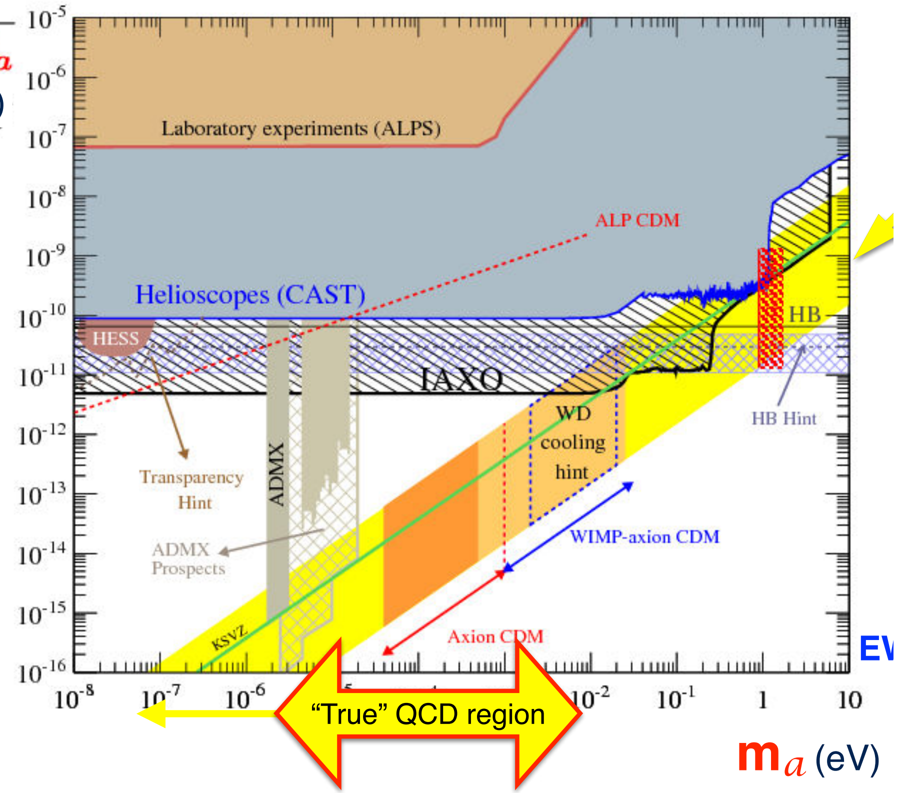
$$m_a^2 f_a^2 = m_\pi^2 f_\pi^2 + \Lambda'^4 \quad , \quad \Lambda' \gg \Lambda_{\rm QCD}$$

relax the parameter space

Belén Gavela

$g_{a\gamma} \sim \frac{\alpha}{8\pi f_a}$ (GeV^{-1})

rich phenomenology



Inspired by this, one can look for general axion-like particles with derivative couplings

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{\partial_\mu a}{f_a} \times {\rm SM}^\mu$$

general effective couplings

Belén Gavela

⇨ write the ALP eff Lagrangian from linear (SMEFT) and non-linar EWSB. E.g.

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm SM} + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) + \sum_i^{\rm bosonic} c_i \mathbf{O}_i^{d=5}$$

$$\mathbf{O}_{\tilde{B}} = -B_{\mu\nu}\tilde{B}^{\mu\nu}\frac{a}{f_a} \qquad \mathbf{O}_{\tilde{G}} = -G^a_{\mu\nu}\tilde{G}^{a\mu\nu}\frac{a}{f_a}$$

$$\mathbf{O}_{\tilde{W}} = -W^a_{\mu\nu}\tilde{W}^{a\mu\nu}\frac{a}{f_a} \qquad \mathbf{O}_{a\Phi} = i(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)\frac{\partial^\mu a}{f_a}$$

⇨ Distinctive signals, including dispaced vertices and “flattish” MET

Belén Gavela

We have seen proposals inspired by:

- ★ Naturalness problem
- ★ Strong CP problem
- ★ Baryon asymmetry
- ★ Flavour puzzles
- ★ Origin of the dark matter

EW Baryogenesis from a dark sector

Adding a scalar, S, to the SM, the phase transition at finite T can be much stronger

However, the Higgs-S coupling, $\lambda_m h^2 S^2$, must be quite strong:

→ S only only constitutes a small fraction of the relic density

Jim Cline

EW Baryogenesis from a dark sector

A better model can be constructed by adding a Majorana fermion

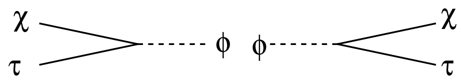
$$\frac{1}{2}\,\bar{\chi}\,[m_\chi + S(\eta\,P_L + \eta^* P_R)]\,\chi$$

with $\mathrm{Im}(m_\chi\,\eta) \neq 0$. Creates CP asymmetry between χ helicities at bubble wall. Bonus: χ is a dark matter candidate

To transfer CP asymmetry to SM leptons, need an inert Higgs doublet ϕ and coupling ("CP portal interaction")

$$y\,\bar{\chi}\phi L_\tau$$

Asymmetry is transferred by (inverse) decays,



$$\chi\bar{L}_\tau \to \phi, \qquad \phi \to \bar{L}_\tau\chi,$$

The model is safe for DD and can give signals at LHC

Jim Cline

We have seen proposals inspired by:

- ★ Naturalness problem
- ★ Strong CP problem
- ★ Baryon asymmetry
- ★ Flavour puzzles
- ★ Origin of the dark matter

Dynamical Yukawa couplings

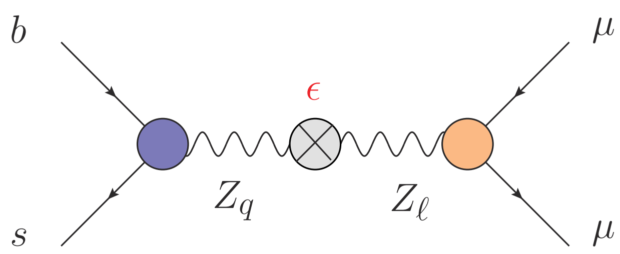
In the limit $Y_{u,d,e,\nu} \to 0$ (and 3 right-handed Majorana neutrinos):

$$\mathcal{G} = \mathbf{SU(3)}_Q \times \mathbf{SU(3)}_D \times \mathbf{SU(3)}_U \times \mathbf{SU(3)}_\ell \times \mathbf{SU(3)}_E \times \mathcal{O}\mathbf{(3)}_{\nu_R}$$

- Promote this symmetry to a local symmetry of nature
- Yukawas arise from dynamical fields:

★ An application:

$\mathbf{U(1)}_q \times \mathbf{U(1)}_{\mu-\tau}$ **couplings**



Javier Fuentes

may explain the b → s ll anomalies if the two Z's mix.

Dynamical Yukawa couplings

One can go further and makes these symmetries local.

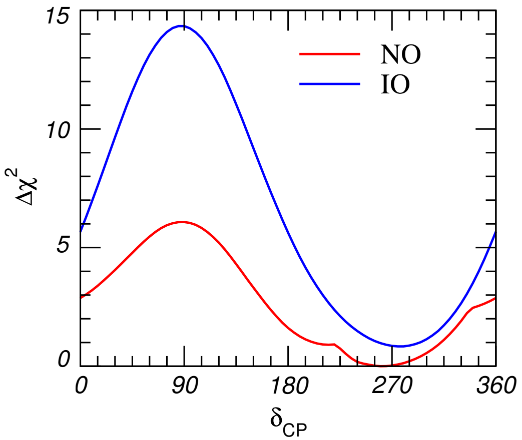
- ★ Extra states (to cancel anomalies):
- ★ Flavour gauge bosons (massive) $\neq$ MFV
- ★ All leptons acquire masses by see-saw

Pablo Quílez

Open questions in the ν-sector

Global 3-neutrino fits have been presented.

★ CP phase



CP conservation allowed at 70% CL

★ Slight preference for Normal ordering of masses. This result is strengthened by cosmological observations (like CMB), but is not yet concusive

★ Non-standard 4-fermion interactions would introduce degeneracy that makes determination of mass ordering impossible

Thomas Schwetz

Open questions in the ν-sector

Extended ν-sector

The presence of e.g. a 4th (sterile) neutrino modifies the U-matrix:

$$U_{3\times 4} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \end{pmatrix}$$

Lepton flavour/number violating decays mediated by heavy neutrinos:
$K \to \pi e \mu$, $K^+ \to \pi^- \ell^+ \ell^+$

Non-trivial constraints on the scenario

Cédric Weiland

Open questions in the ν-sector

Possible neutrino emission from BBH mergers

According to the stellar evolution models, matter disappears long before the BBH merging → no particle emission expected

This picture can be tested.

Consider possible **neutrino** emission from BBH merger

$$f^{\nu}_{\mathrm{BBH}} = \frac{E_\nu}{E_{\mathrm{GW}}}$$

Assumption:

$E_\nu \propto E_{\mathrm{GW}}$

$\Rightarrow$ universal

Matthias Vereecken

Open questions in the ν-sector

Possible neutrino emission from BBH mergers

The parameter f^{ν}_{BBH} can be constrained from

- ★ Direct searches (ν coincident with LIGO events)
- ★ Difusse ν-flux

The bounds are still above conventional models

Matthias Vereecken

DM issues

WIMPS

The non-observation of new physics at the LHC and null results in direct DM searches put significant pressure on the WIMP idea. Many simple models have been ruled out, but still interesting simple models are alive, e.g. spin ½ DM with axial coupling to Z (like Higgsinos).

Scalar singlets also viable

For WIMPS with Z' portal, there is also a significant experimental pressure on the heavy mediator

Felix Kahlhoefer

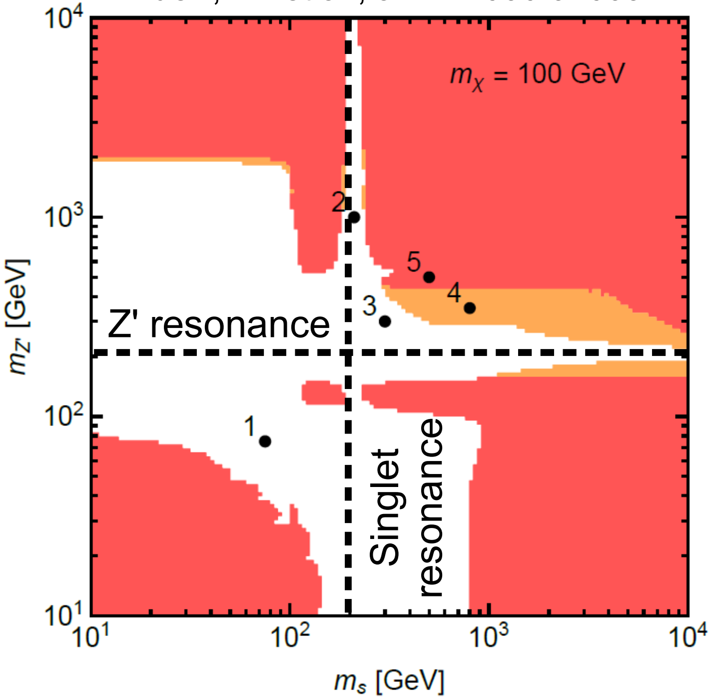
DM issues

WIMPS

Things change for better if the dark sector has additional structure

E.g. an additional light singlet for U(1)′ models (testable at LHC)

Duerr, FK et al., arXiv:1606.07609



Red: All coupling combinations are excluded by at least one constraint.

White: At least one coupling combination is compatible with all constraints.

Orange: Large values of g_q cannot reliably be excluded due to the mediator width becoming large ($\Gamma/m_{Z'}$ > 0.3).

Felix Kahlhoefer

DM issues

Ultralight axion DM

Concrete realization: an angular field of periodicity $2\pi F$ i.e. an axion-like field with a potential from non-perturbative effects (not QCD axion).

$$\mathcal{L} \sim -\frac{1}{2}(\partial\phi)^2 - \underbrace{\Lambda^4(1 - \cos[\phi/F])}_{V(\phi)}$$

$$m \sim \Lambda^2/F$$

Perturbations supressed at small scales; could help to avoid some small scale problems of standard CDM

Lam Hui

DM issues

Self-interacting DM

Usual CDM simulations predict a cusp at the center of dwarf galaxies, instead of a core, as observed.

Astrophysical possible solutions:

- Including baryons on the simulations
- Supernova feedback
- Tidal effects
- Low star-formation rates

Particle physics solution:

- postulate dark matter interactions that become relevant at small scales, without modifying the physics at large scales.

DM self-interactions

In order to preserve the usual freeze-out mechansm to obtain the relic density, one has to play with heavy mediators, e.g. Z's

Camilo Garcia-Cely

DM issues

Scotogenic DM

- The scotogenic model is a minimal model of the dark matter (DM) and neutrino mass. Deshpande and Ma, PRD, 18, 2574 (1978),Ma, PRD, 73, 077301 (2006)
- It contains

$$D = \begin{pmatrix} C^+ \\ \frac{1}{\sqrt{2}}(S + iA) \end{pmatrix}_{J=\frac{1}{2}, Y=\frac{1}{2}}, \quad N_{R_{J=0,Y=0}}$$

charged under Z_2 symmetry (stabilizing DM). Here either S or N can be considered as DM (depending on parameter space).

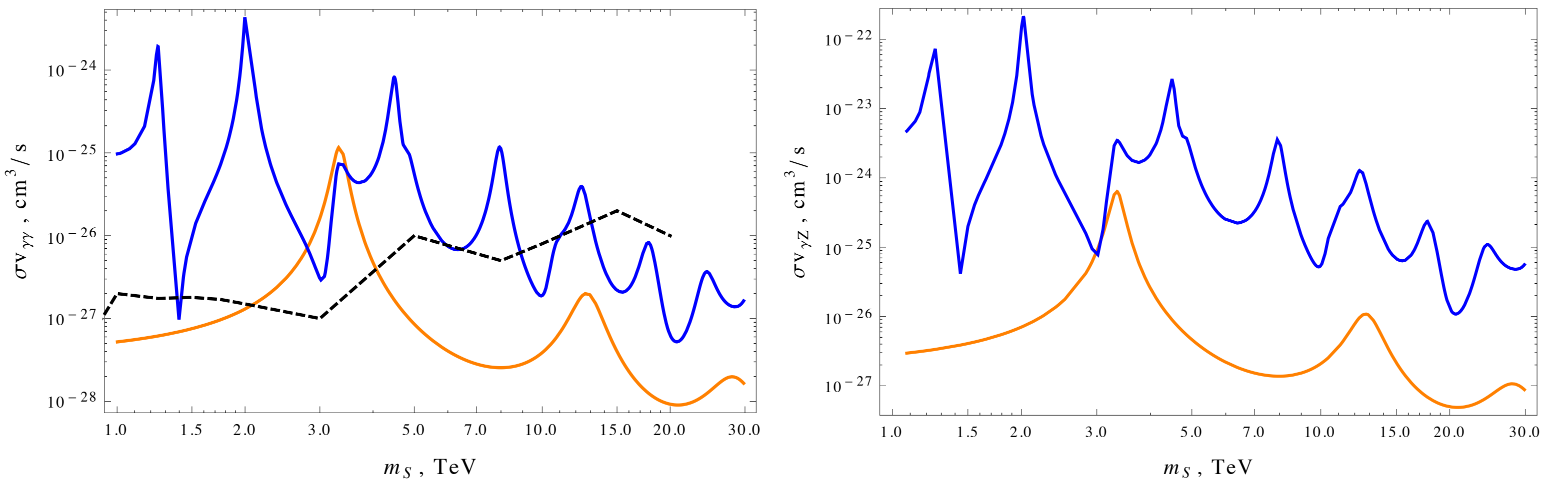
The Sommerfeld enhancement is important in this model.

Ahmed Chowdhury

DM issues

Scotogenic DM

$SS \to \gamma\gamma$ and $SS \to \gamma Z$:



★ HESS has sensitivity to probe the 1-30 TeV DM mass range

★ CTA will improve the limits in a O(10) factor

Ahmed Chowdhury

SMASH

We have seen many presentations where more than one problem was addressed at the same time. E.g.

- ★ Strong CP problem + DM
- ★ Baryon Asymmetry + DM
- ★ Flavour anomalies and naturalness
- ★ ....

But, in this line, the prize is for Carlos Tamarit presentation, where 5 problems are addressed at the same time!

SMASH

$$\mathcal{L} = \mathcal{L}^{SM}_{\text{kin}} + \mathcal{L}^{SM}_{\text{yuk}}$$

$$- \left[\frac{M^2}{2} + \xi_H \, H^\dagger H + \xi_\sigma \, |\sigma|^2 \right] R$$

$$-\lambda_H \left(H^\dagger H - \frac{v^2}{2} \right)^2 - 2\lambda_{H\sigma} \left(H^\dagger H - \frac{v^2}{2} \right) \left(|\sigma|^2 - \frac{v_\sigma^2}{2} \right)$$

STABILITY

INFLATION

$$-\lambda_\sigma \left(|\sigma|^2 - \frac{v_\sigma^2}{2} \right)^2 - [y\sigma\tilde{Q}Q + y_{Q_{d\,i}}\sigma Q d_i + c.c]$$

CP PROBLEM

$$-[F_{ij} L_i \epsilon H N_j + \frac{1}{2} Y_{ij} \sigma N_i N_j + c.c.]$$

SEESAW AND LEPTOGENESIS

Carlos Tamarit

SMASH

All the mechanisms were already known, but put them together produces adicional constraints/predictions. E.g.

Axion mass and coupling to photons in reach of upcoming experiments (MADMAX, CULTASK)

$$50\,\mu\text{eV} \lesssim m_A \lesssim 200\,\mu\text{eV}\,, |C_{A\gamma}| = 1.25(4)$$

Precise predictions for cosmological observables n_s, r, $\alpha \lesssim 10^{-3}$, Δn_{eff}=0.02-0.03 can be probed by experiments (LiteBird, CORE, 21cm measurements)

QCD axion window could be probed by microlensing data (EROS, Subaru)

Carlos Tamarit

Summary:

An impressive amount of good, useful and imaginative work

TERRA INCOGNITA

Good luck with the search!