Moriond EW 2016

Theory Summary

Alex Pomarol CERN & UAB

We like *Moriond EW* (not because the skying, food,…) because we believe that physics around the EW scale can unravel something *fundamental* in particle physics

… exploration of the **energy frontier** has brought a lot of discoveries in the past!

But the situation has changed from the old days (at least for theorists)…

As *Rencontres Moriond*, little by little
particle physics has amazingly evolved from 1966 to 2016

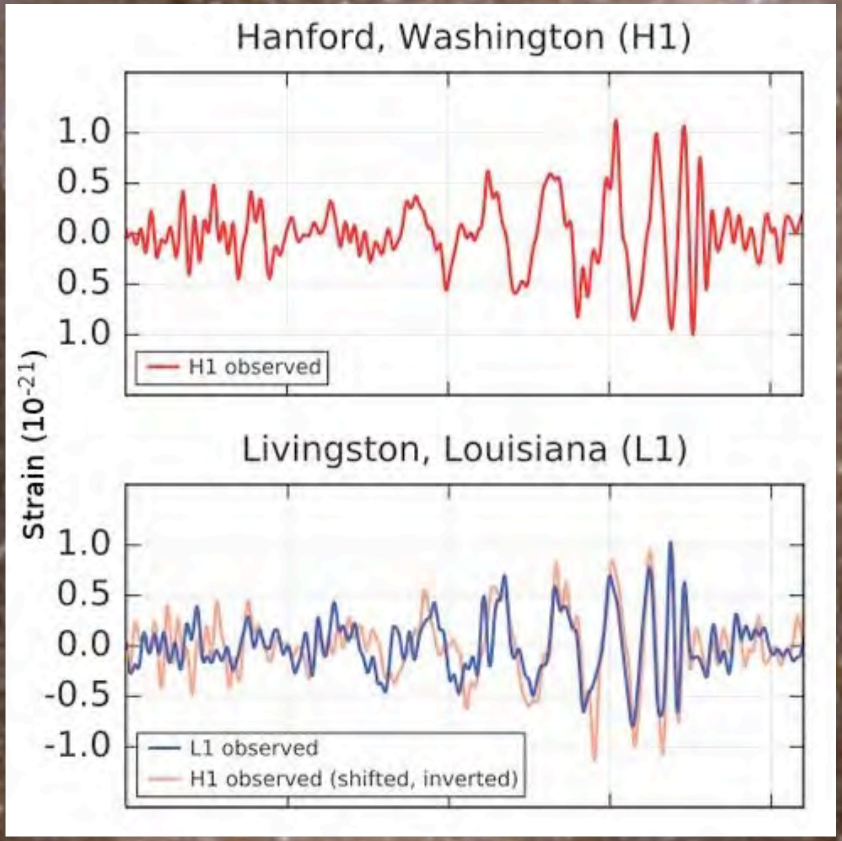
Pre-Higgs era: We were building up the theory
discovery guaranteed:
…, top, Higgs

Post-Higgs era: We now have the theory:

A (quantum field) theory **SM+GR**
that can **consistently** give us the physics up to ~ $\mathbf{M_P}$

Powerful theory that can predict the gravitational waves from a binary BH merger

see Alessandro Nagar's talk



So, why should be new phenomena at the TeV?

Not because the **present** theory is inconsistent!

We have the theory,
but **now** we'd like to understand **why it is like it is**

In particular, we want to understand the origin of the EW scale
(<u>hierarchy problem</u>):

Why $\mathbf{m_W} \ll \mathbf{M_P} \sim 10^{19}$ GeV **?**

↳ **origin of the Higgs potential**

↳ **why the Higgs is so light?**

This is today the **main motivation** to explore the **TeV frontier**

↳ but success not guaranteed… see later

The TeV frontier must be attacked from several fronts

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Role of theorist: Provide the necessary tools & routes to TeV physics

Role of Theorists

Providers (SM)

Better and better predictions of the SM physics

Intending Visionaries (BSM)

Alternative ways to probe physics beyond the SM

Role of Theorists

Providers (SM)

Better and better predictions of the SM physics

8 speakers {

Gudrun Hiller
Lars Hofer
Nicolas Garron
Anna Hayes
Jonathan Engel
Andre Hoang
Giulia Zanderighi
Alessandro Nagar

Intending Visionaries (BSM)

Alternative ways to probe physics beyond the SM

20 speakers {

Nejc Kosnik
Michele Lucente
Boris Kayser
Cedric Delaunay
Aneesh Manohar
Joachim Kopp
Tony Gherghetta
Martin Jung
Felix Brummer
Thomas Rizzo
Aurora Meroni
Elizabeth Jenkins
Aldo DeAndrea
JoAnne Hewett
A. Strumia
Farinaldo Queiroz
Maxim Pospelov
Suzanne Westhoff
J.R. Espinosa
Francesco Sannino

Role of Theorists I

Calculating the SM predictions:

We know the theory (SM+GR),
but we do not know its predictions!

Long ongoing project on how to to deal with **QCD**

From quarks & gluons to hadrons (physical objects):

$\langle \mathbf{K}|(\bar{\mathbf{q}}\gamma^{\mu}\mathbf{q})^{\mathbf{2}}|\pi\pi\rangle$

Non-Perturbative calculations: Lattice

Crucial as now most flavor observables are close to the SM value

In Lattice we trust

we find

$$Re(\varepsilon'/\varepsilon) = 1.38(5.15)(4.43)\times 10^{-4}$$

whereas the experimental value is

$$Re(\varepsilon'/\varepsilon) = 16.6(2.3)\times 10^{-4}$$

$\sim 2.1\sigma$

With this unphysical computation (kinematics, masses) we find

$\Delta I = 1/2$ rule $\quad \frac{\mathrm{Re}A_0}{\mathrm{Re}A_2} = 9.1(2.1)$ for $m_K = 878\ \mathrm{MeV}$ $m_\pi = 422\ \mathrm{MeV}$

$= 12.0(1.7)$ for $m_K = 662\ \mathrm{MeV}$ $m_\pi = 329\ \mathrm{MeV}$

Nicolas Garron

experimentally: 22

↪ in the right direction but not yet there…

Alternative methods:

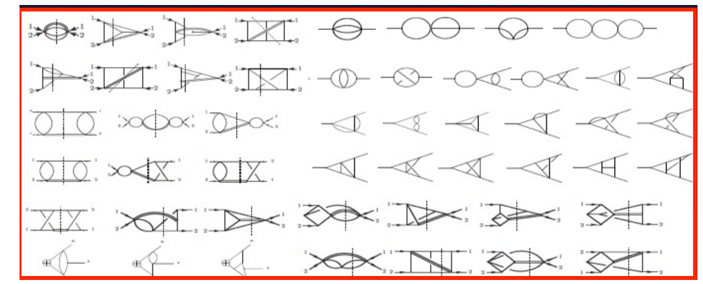
B→K*μμ at high q^2:

– Using a local model against the OPE provides a data-driven method to test the binning and limitations of the OPE.

Gudrun Hiller

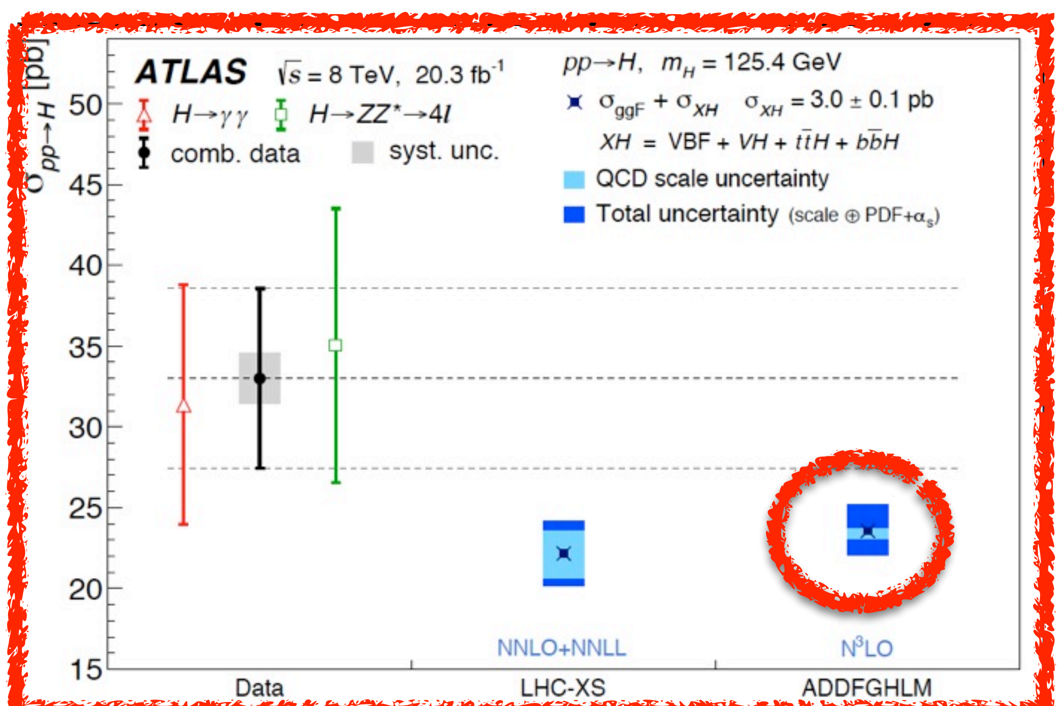
QCD at hadron machines
Perturbative calculations: From LO→…→N³LO

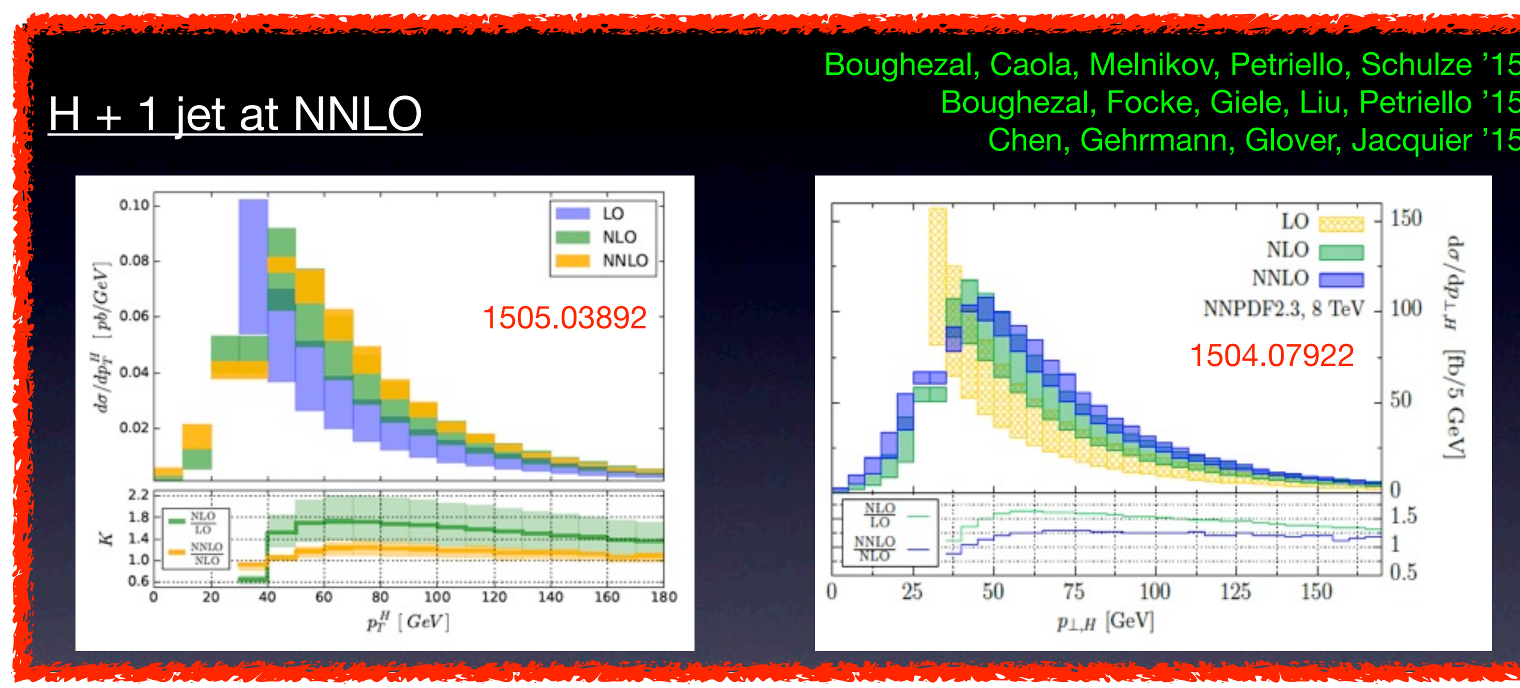
Giulia Zanderighi:



Accept it, they are **the 8th wonder of the world!**

Gave glimpses of these beauties:





from inclusive σ_H at N³LO…

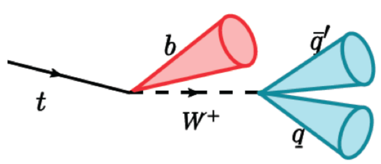
… to H+jet diff. cross-section, crucial to extract more on the Higgs's nature

Extraction of the top mass:

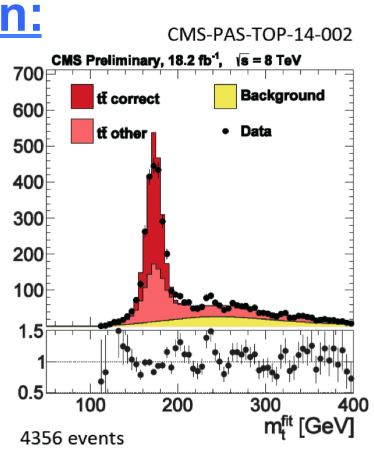
André H. Hoang's proposal:

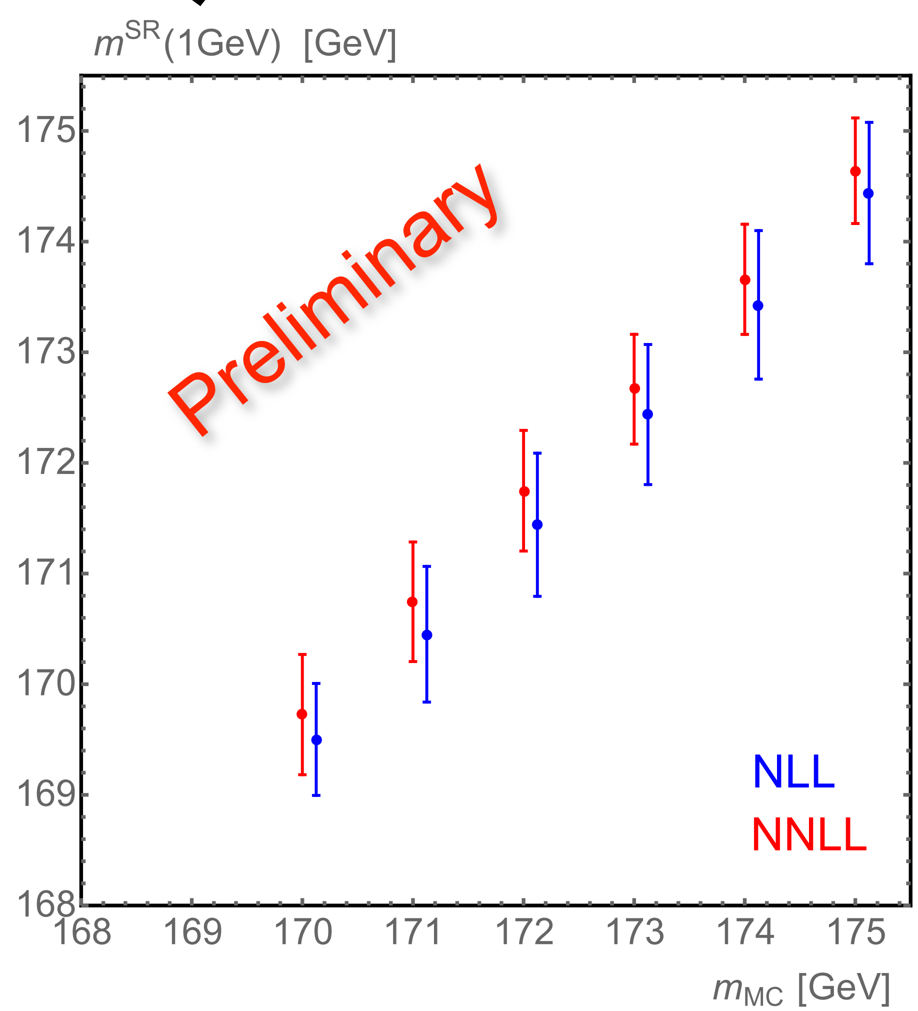
LHC+Tevatron

Direct Reconstruction:



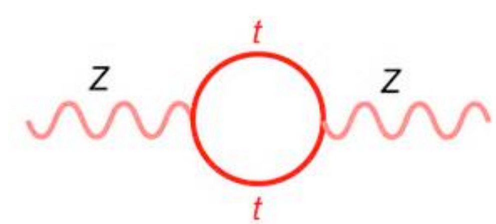
kinematic mass determination





error O(500 MeV)

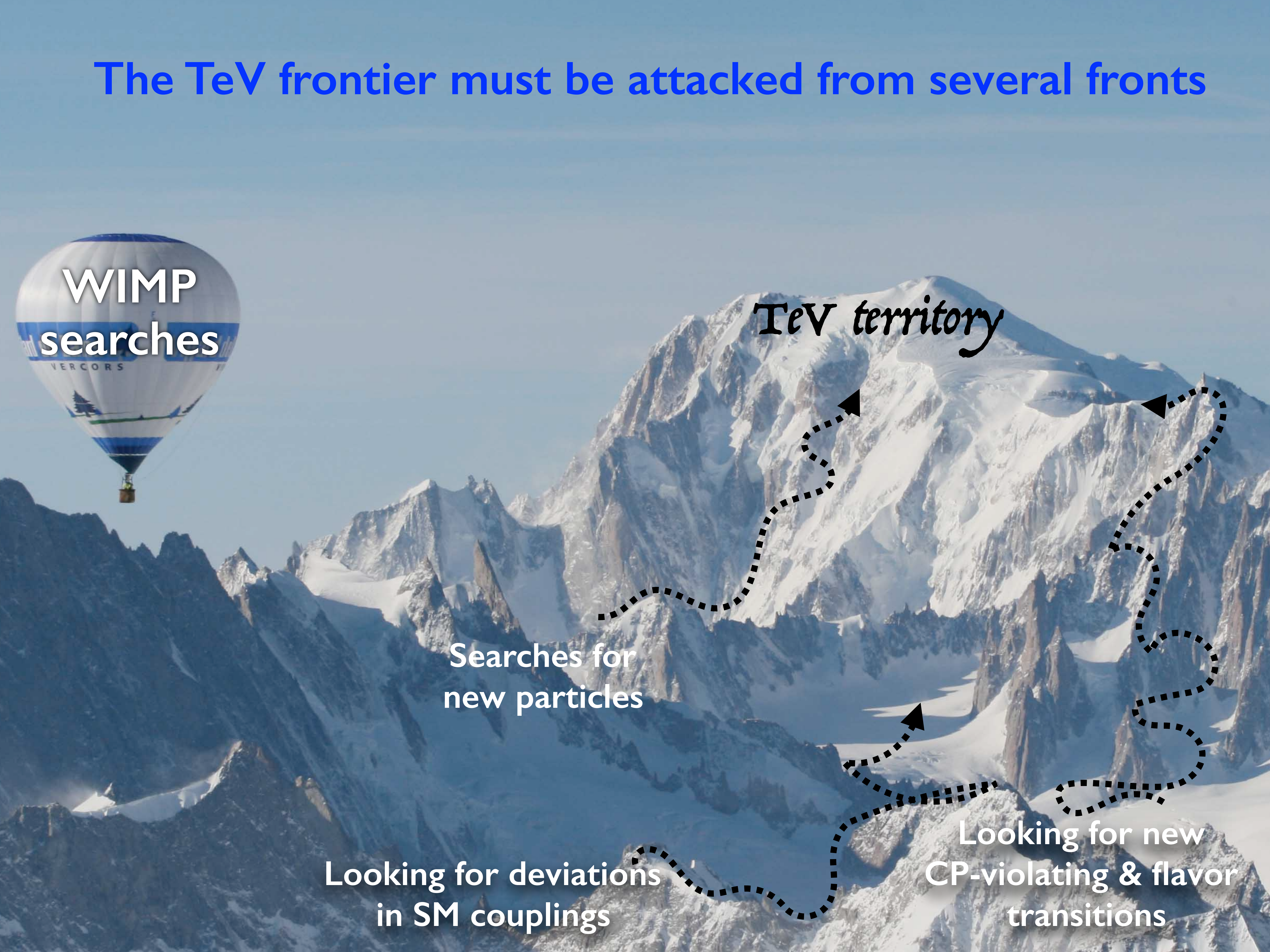
useful for precision tests of the SM!

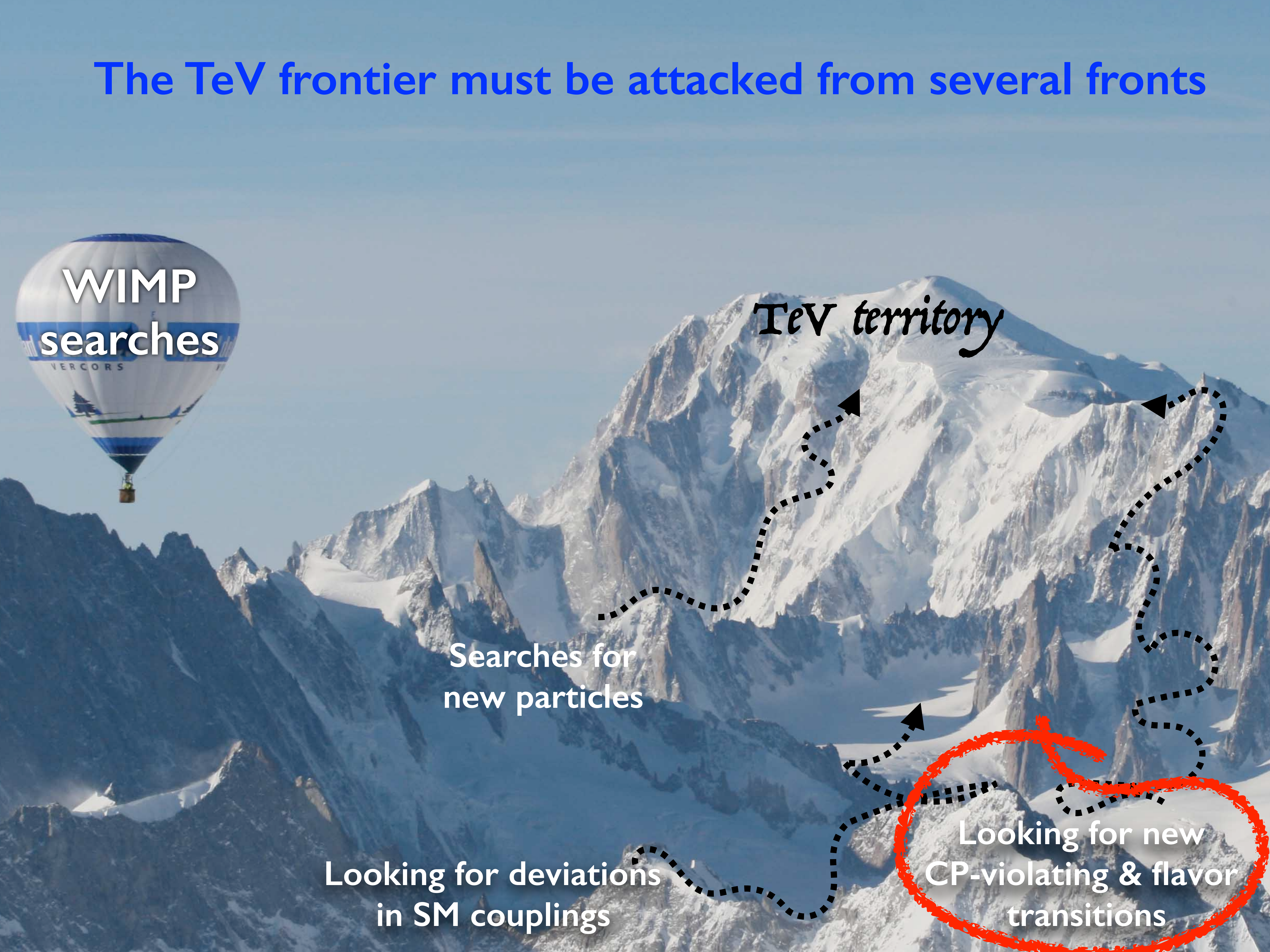


Role of Theorists II

Routes to BSM

The TeV frontier must be attacked from several fronts




The TeV frontier must be attacked from several fronts
WIMP
searches
VERCORS
TeV territory
Searches for
new particles
Looking for deviations
in SM couplings
Looking for new
CP-violating & flavor
transitions

Motivation: Not the **baryon-antibaryon** asymmetry of the universe!

Provide <u>observables</u> that receive small SM contributions due to the "accidental" symmetries of the SM:

Lepton number, flavor-symmetries up to small Yukawas, CP-conservation unless 3 family concurrence

We do not expect that BSM will share these "accidents" as these are theories with more structure, so we expect them to give large effects to these observables

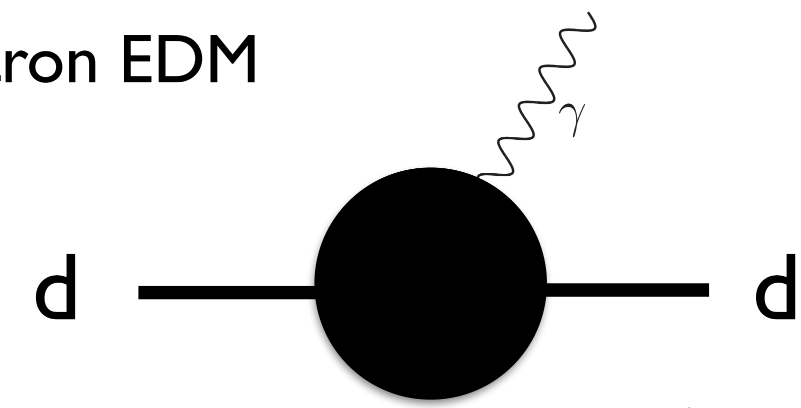
e.g. supersymmetry, composite Higgs

Clean paths to BSM…

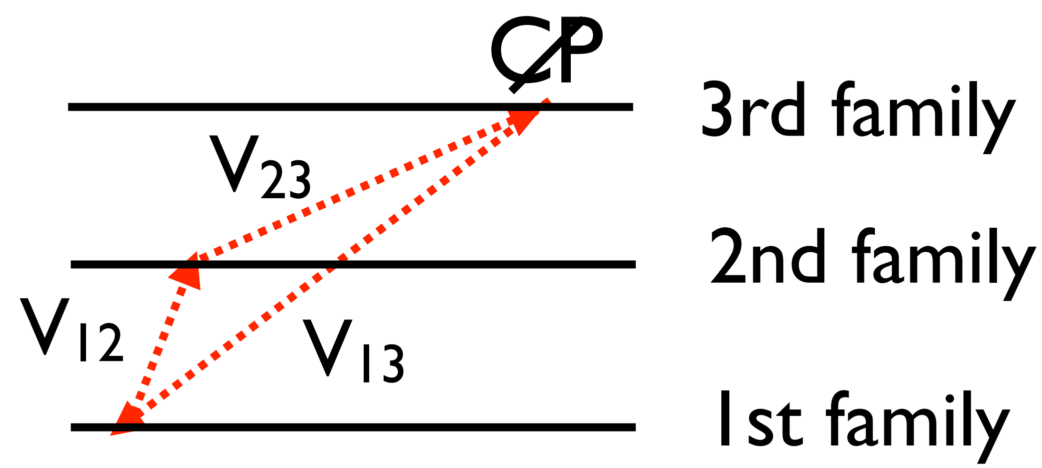
Best example:

Electric Dipole Moments (EDM)

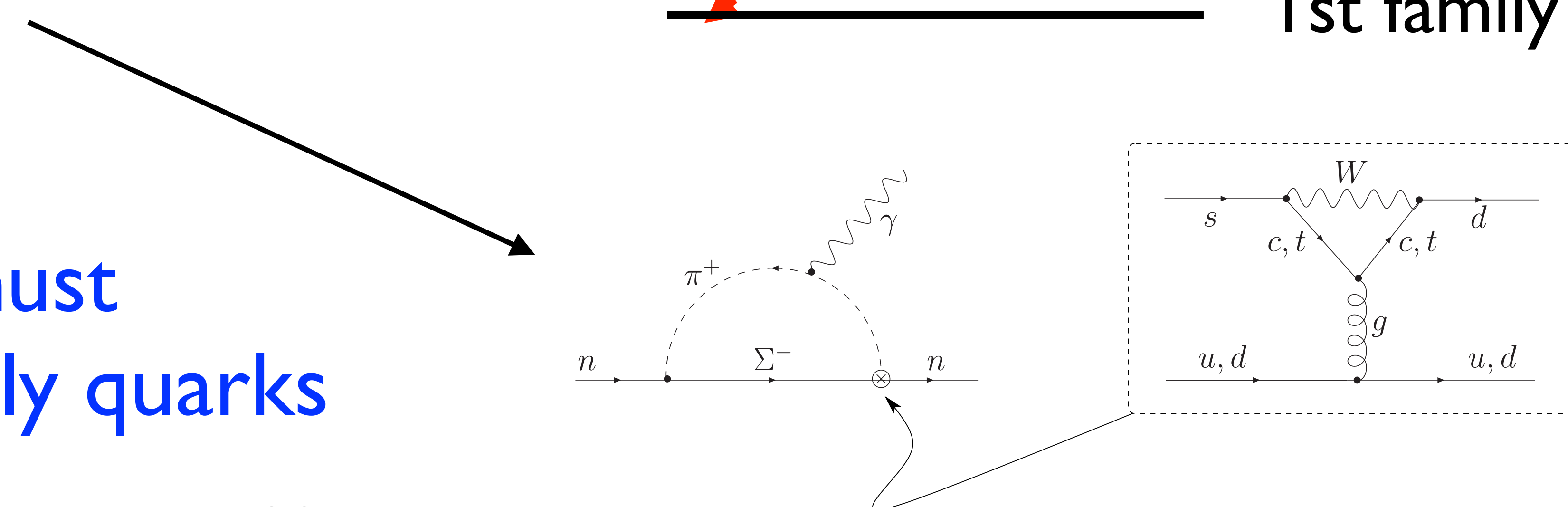
e.g. neutron EDM



"Selection rules"



In the SM must
involve the 3 family quarks



d_n extremely small ~ 10^{-32} e·cm

assuming θ=0
from an axion!

experimentally: **$d_n < 2.9\times10^{-26}$ e·cm**

CP-violating phases in BSM are **ubiquitous** ☛ larger contributions

Relatively "cheap" experiment, but as competitive as the LHC!!

Flavor Physics

	b→s ($\lvert V_{tb}V_{ts}\rvert \alpha \lambda^2$)	b→d ($\lvert V_{tb}V_{td}\rvert \alpha \lambda^3$)	s→d ($\lvert V_{ts}V_{td}\rvert \alpha \lambda^5$)	c→u ($\lvert V_{cb}V_{ub}\rvert \alpha \lambda^5$)
ΔF=2 box	ΔM_{Bs}, $A_{CP}(B_s \to J/\Psi \Phi)$	ΔM_B, $A_{CP}(B \to J/\Psi K)$	ΔM_K, ε_K	x,y, q/p, Φ
QCD Penguin	$A_{CP}(B \to hhh)$, $B \to X_s \gamma$	$A_{CP}(B \to hhh)$, $B \to X \gamma$	$K \to \pi^0 ll$, ε'/ε	$\Delta a_{CP}(D \to hh)$
EW Penguin	$B \to K^{(*)} ll$, $B \to X_s \gamma$	$B \to \pi ll$, $B \to X \gamma$	$K \to \pi^0 ll$, $K^\pm \to \pi^\pm \nu \nu$	$D \to X_u ll$
Higgs Penguin	$B_s \to \mu \mu$	$B \to \mu \mu$	$K \to \mu \mu$	$D \to \mu \mu$

F. Teubert Brookhaven15

Flavor Physics

	b→s ($|V_{tb}V_{ts}| \propto \lambda^2$)	b→d ($|V_{tb}V_{td}| \propto \lambda^3$)	s→d ($|V_{ts}V_{td}| \propto \lambda^5$)	c→u ($|V_{cb}V_{ub}| \propto \lambda^5$)
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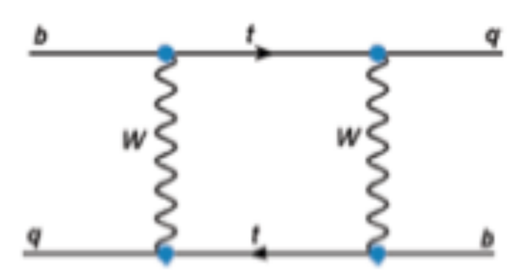
Higgs Penguin	$B_s \to \mu \mu$	$B \to \mu \mu$	$K \to \mu \mu$	$D \to \mu \mu$

F. Teubert Brookhaven15

central in the past for searching BSM effects



Flavor Physics

	b→s ($|V_{tb}V_{ts}| \propto \lambda^2$)	b→d ($|V_{tb}V_{td}| \propto \lambda^3$)	s→d ($|V_{ts}V_{td}| \propto \lambda^5$)	c→u ($|V_{cb}V_{ub}| \propto \lambda^5$)
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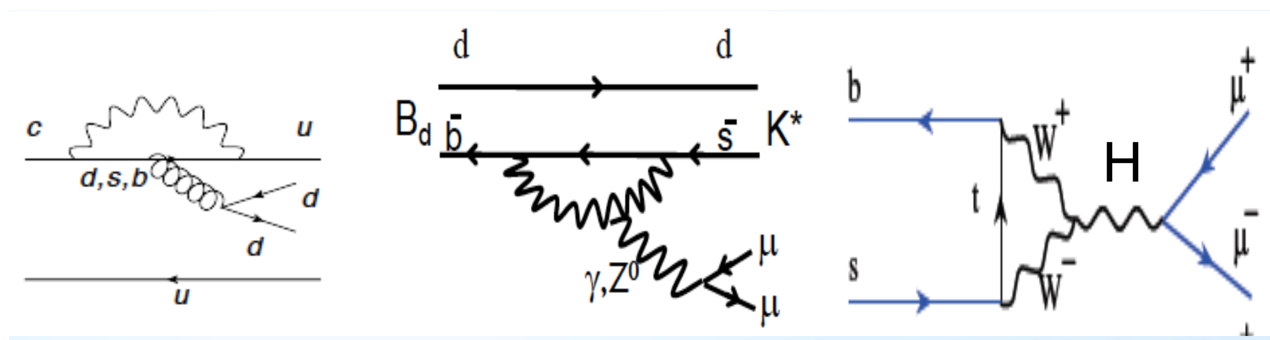
QCD Penguin	$A_{CP}(B \to hhh)$, $B \to X_s \gamma$	$A_{CP}(B \to hhh)$, $B \to X \gamma$	$K \to \pi^0 ll$, ε'/ε	$\Delta a_{CP}(D \to hh)$
EW Penguin	$B \to K^{(*)} ll$, $B \to X_s \gamma$	$B \to \pi ll$, $B \to X \gamma$	$K \to \pi^0 ll$, $K^{\pm} \to \pi^{\pm} \nu \nu$	$D \to X_u ll$
Higgs Penguin	$B_s \to \mu \mu$	$B \to \mu \mu$	$K \to \mu \mu$	$D \to \mu \mu$

F. Teubert Brookhaven15

ΔF=1



QCD Penguin EW Penguin Higgs Penguin

becoming a mature field
with plenty of new observables
constraining different BSM physics

Flavor Physics

	b→s ($\lvert V_{tb}V_{ts}\rvert\ \alpha\ \lambda^2$)	b→d ($\lvert V_{tb}V_{td}\rvert\ \alpha\ \lambda^3$)	s→d ($\lvert V_{ts}V_{td}\rvert\ \alpha\ \lambda^5$)	c→u ($\lvert V_{cb}V_{ub}\rvert\ \alpha\ \lambda^5$)
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Higgs Penguin	$B_s \to \mu\ \mu$	$B \to \mu\ \mu$	$K \to \mu\ \mu$	$D \to \mu\ \mu$

F. Teubert Brookhaven15

Lost opportunities: Observables with small SM contributions (expected large BSM effects!) are measured at the level of the SM predictions

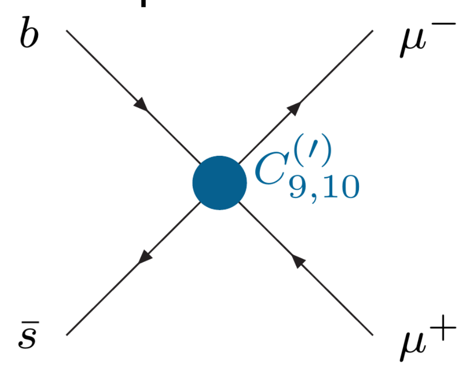
We have now to dig into the details of the SM contributions

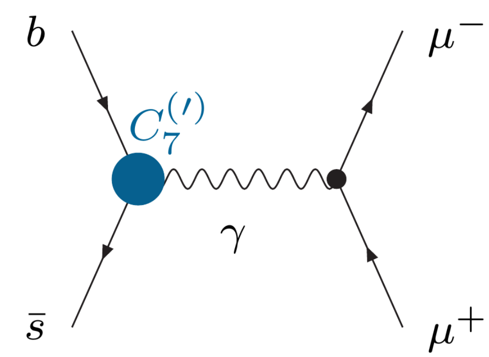
BSM model builders must now be sure to satisfy constraints from $\Delta F=1$ observables (to be added to the $\Delta F=2$):

Lars Hofer

New physics in $b \to s\ell\ell$

SM and NP particles induce an effective $b\bar{s}\mu^+\mu^-$ coupling





$$\mathcal{O}_9^{(\prime)} = \frac{\alpha}{4\pi}[\bar{s}\gamma^\mu P_{L(R)}b][\bar{\mu}\gamma_\mu\mu]$$

$$\mathcal{O}_{10}^{(\prime)} = \frac{\alpha}{4\pi}[\bar{s}\gamma^\mu P_{L(R)}b][\bar{\mu}\gamma_\mu\gamma_5\mu]$$

$$\mathcal{O}_7^{(\prime)} = \frac{\alpha}{4\pi}m_b[\bar{s}\sigma_{\mu\nu}P_{R(L)}b]F^{\mu\nu}$$

+ scalar operators
(not relevant for this talk)

processes	$\mathcal{C}_7^{(\prime)}$	$\mathcal{C}_9^{(\prime)}$	$\mathcal{C}_{10}^{(\prime)}$
$B \to X_s\gamma$, $B \to K^*\gamma$	✓		
$B \to X_s\mu^+\mu^-$	✓	✓	✓
$B_s \to \mu^+\mu^-$			✓
$B \to K^{(*)}\mu^+\mu^-$, $B_s \to \phi\mu^+\mu^-$	✓	✓	✓

Even the SM seems to show some tension with the experimental values… see later

The TeV frontier must be attacked from several fronts

The expected most sensitive SM particle to BSM:

The Higgs ≡ BEH

it must be *blamed* for the hierarchy problem!

Higgs EFT (quite develop in the last years) useful for parametrizing deformations form the SM Higgs

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda^{d-4}} \sum_i C_i O_i^{(d)}$$

Elizabeth Jenkins

↳ Higgs ~ coordinates of a d=4 space

Aneesh Manohar

deformations can have a simple geometrical interpretation

HEFT: risk of democratizing the BSM effects (not all are equally important):

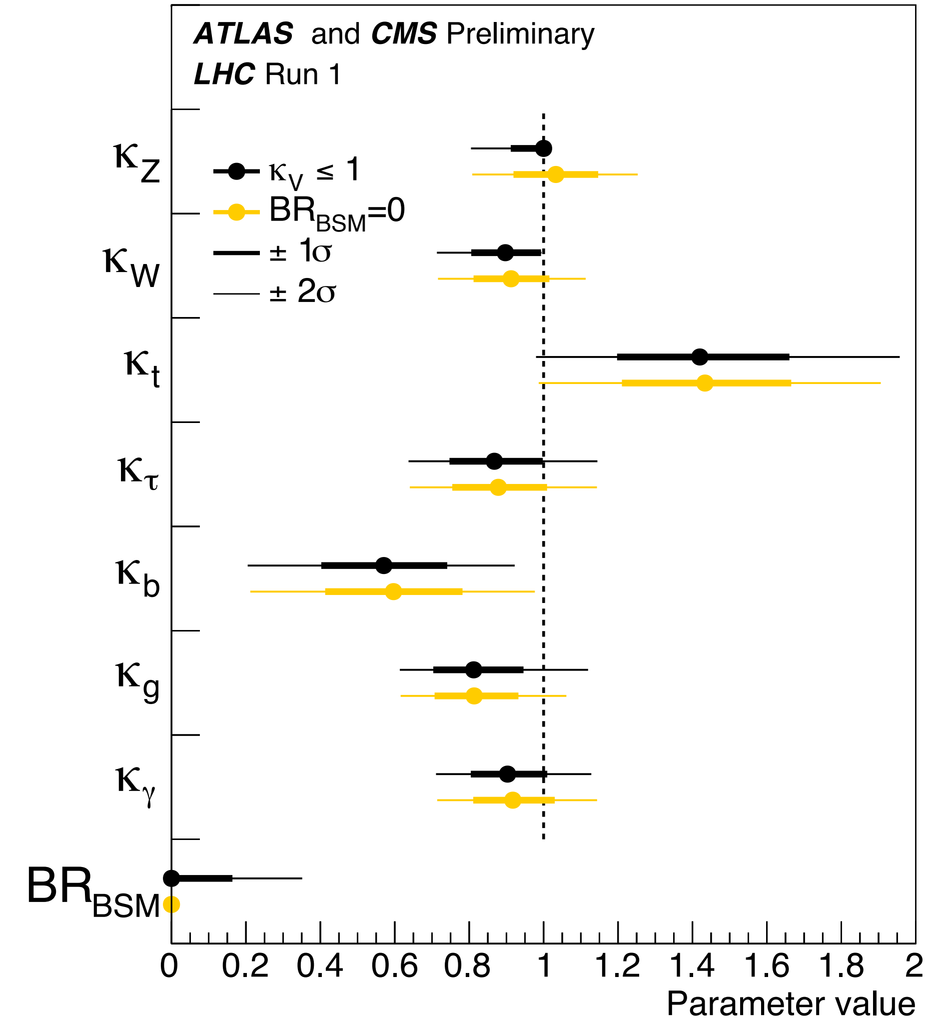
pseudoNGB Higgs: **hff , hVV , h^3**

shown in a weakly-coupled calculable model

Aurora Meroni

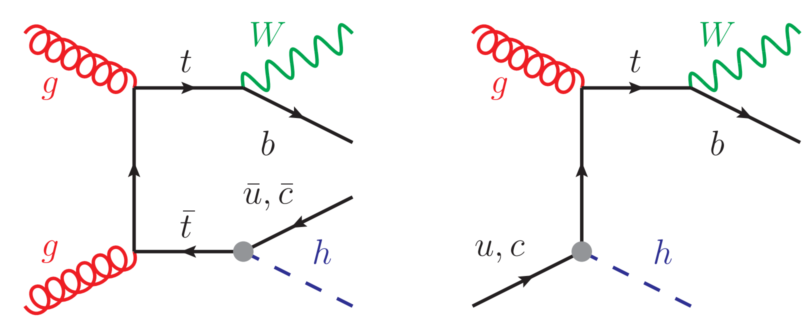
Higgs physics is maturing:

Most important couplings have been measured, showing reasonable agreement with the SM



Still few interesting Higgs couplings to be measured:

1) h^3 , hZγ
2) Flavor-violating couplings
3) Couplings to light fermions:



Joachim Kopp

hee coupling: too small for the LHC

proposal for looking at **atomic physics:**
Higgs-Yukawa int. shift atomic freq.: $g_{hee} \lesssim 0.1$

Cedric Delaunay

The TeV frontier must be attacked from several fronts

Motivation for WIMPs:

TeV new physics
for the hierarchy problem

stable remnant

Realistic candidate for DM
WIMP "miracle"!

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TeV new physics
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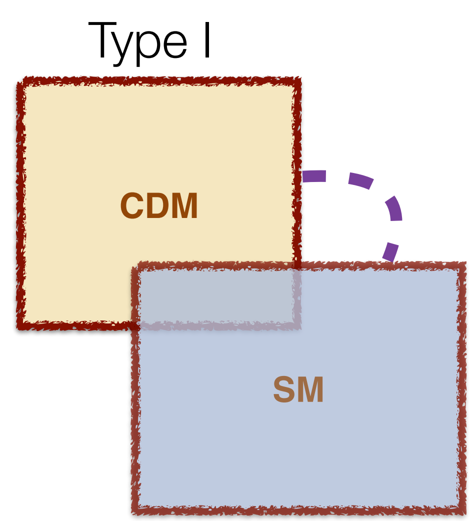
Realistic candidate for DM
WIMP "miracle"!

Not only in **susy** (neutralino),
but also in **strongly-coupled solutions** to the hierarchy problem

CDM Type I



- TC Baryon[1]
- TC Meson[2]
- Millicharged Comp. DM[3]
- Stealth DM[4]
- Solitons/Little Higgs[5]
- ....

[1]Nussinov 85 & Barr, Chivukula, Farhi 90
[2]Gudnason, Kouvaris, Sannino ph-0603014, 0608055
[3]Kouvaris 1304.7476
[4]Appelquist et al. 1503.04203
[5]Gillioz, 1103.5990

Francesco Sannino

Motivation for WIMPs:

TeV new physics
for the hierarchy problem

stable remnant

Realistic candidate for DM
WIMP "miracle"!

Finding a WIMP will reinforce the whole TeV-collider program!

Motivation for WIMPs:

TeV new physics
for the hierarchy problem

stable remnant

Realistic candidate for DM
WIMP "miracle"!

If no TeV physics explaining the origin of EW

Motivation for WIMPs:

~~TeV new physics for the hierarchy problem~~

stable remnant →

~~Realistic candidate for DM WIMP "miracle"!~~

If no TeV physics explaining the origin of EW

The motivation for WIMPs falls

Motivation for WIMPs:

~~TeV new physics for the hierarchy problem~~

stable remnant →

~~Realistic candidate for DM~~
~~WIMP "miracle"!~~

If no TeV physics explaining the origin of EW

The motivation for WIMPs falls

Many other possibilites for DM beyond WIMPs are there:

DM classification

At some early cosmological epoch of hot Universe, with temperature T >> DM mass, the abundance of these particles relative to a species of SM (e.g. photons) was

Normal: Sizable interaction rates ensure thermal equilibrium, $N_{DM}/N_{\gamma}=1$. Stability of particles on the scale $t_{Universe}$ is required. *Freeze-out* calculation gives the required annihilation cross section for DM --> SM of order ~ 1 pbn, which points towards weak scale. These are **WIMPs**. Asymmetric DM is also in this category.

Very small: Very tiny interaction rates (e.g. 10^{-10} couplings from WIMPs). Never in thermal equilibrium. Populated by thermal leakage of SM fields with sub-Hubble rate (*freeze-in*) or by decays of parent WIMPs. [Gravitinos, sterile neutrinos, and other "feeble" creatures – call them **super-WIMPs**]

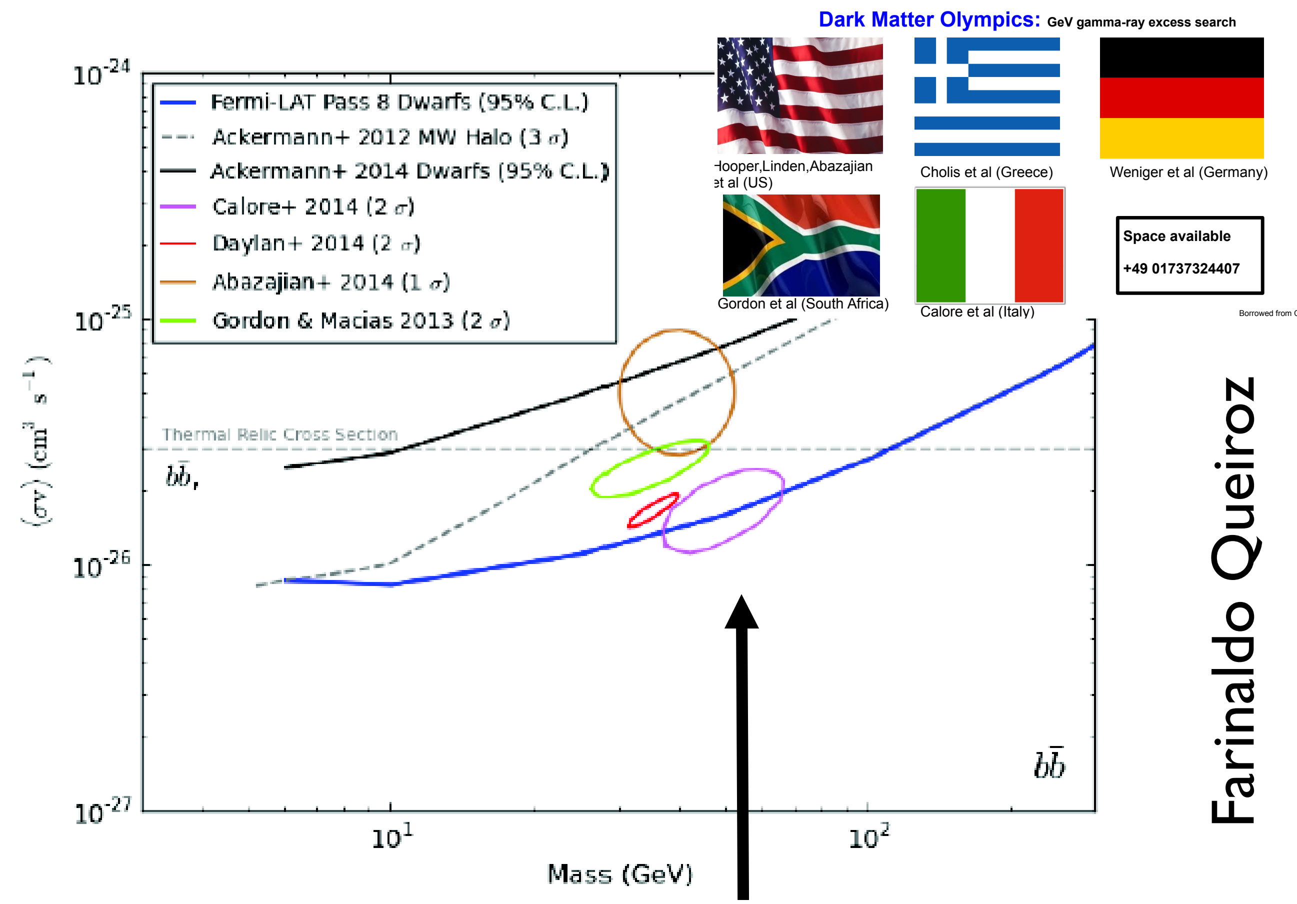
Huge: Almost non-interacting light, m< eV, particles with huge occupation numbers of lowest momentum states, e.g. $N_{DM}/N_{\gamma}\sim 10^{10}$. "Super-cool DM". Must be bosonic. Axions, or other very light scalar fields – call them **super-cold DM**.

Maxim Pospelov

- WIMPs searches a mature field → see experimental summary

- Theorists prepare to interpret any excess (in one day!)

1st Olympic Games:
Best fit to the GeV γ-ray excess



Farinaldo Queiroz

- Also quite developed are LHC searches for DM:

Missing E_T vs Direct Mediator searches

example: neutralino-like models Susanne Westhoff

The TeV frontier must be attacked from several fronts

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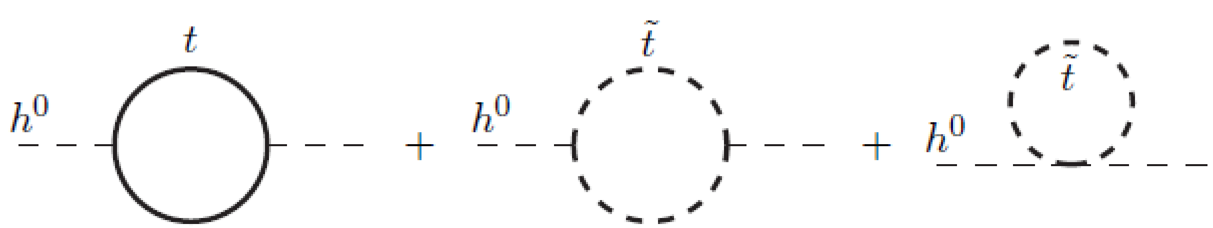
↳ no new ideas in collider physics?

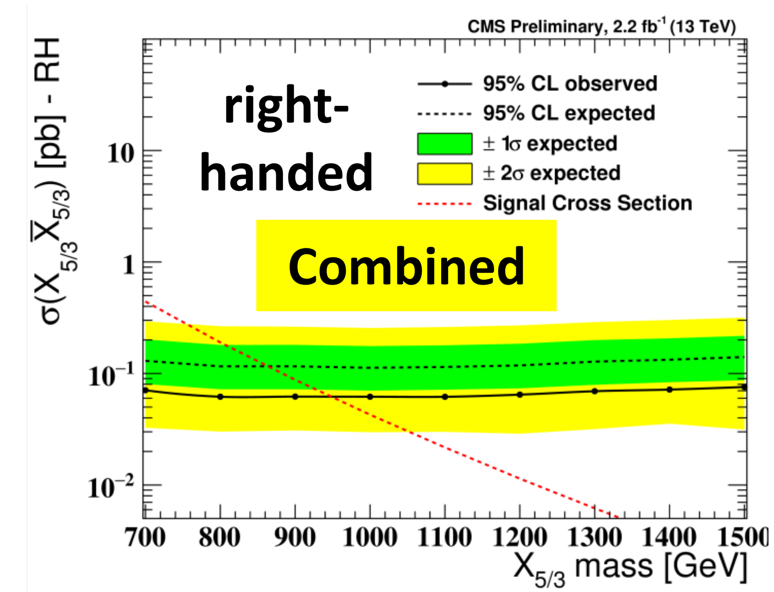
all moved to anomaly chasing?

Some remark:

7-8 TeV → 13 TeV

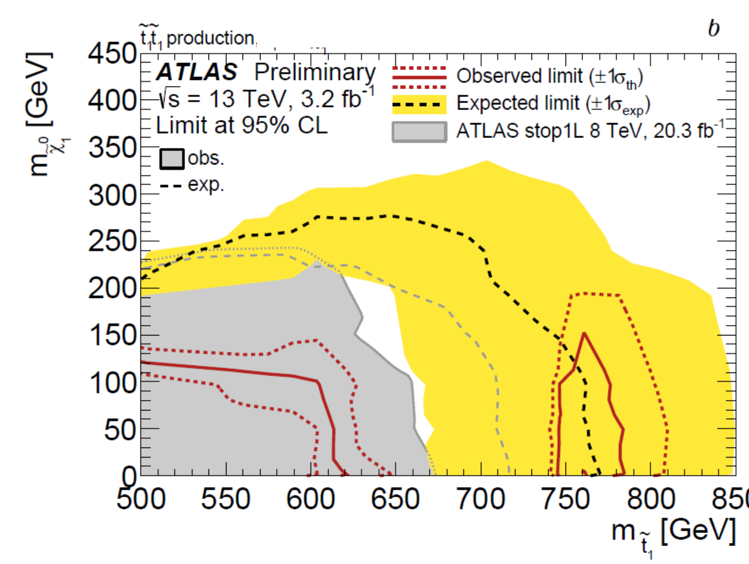
Not yet sign of the partners of the top (*Golden* BSM modes):





$$\mathbf{m(X_{5/3}) > 960\ GeV}$$

$$\mathbf{m(\tilde{t},\tilde{b}) \gtrsim 700 - 800\ GeV}$$



➡ Who is keeping the Higgs light?

(

NEUTRINOS:

Neutrino mass origin **probably**
has to do with physics at scales much larger than TeV:

$$\mathbf{m_\nu \sim \frac{y^2}{g^2}\frac{m_W^2}{M}}$$

10^{15} GeV?

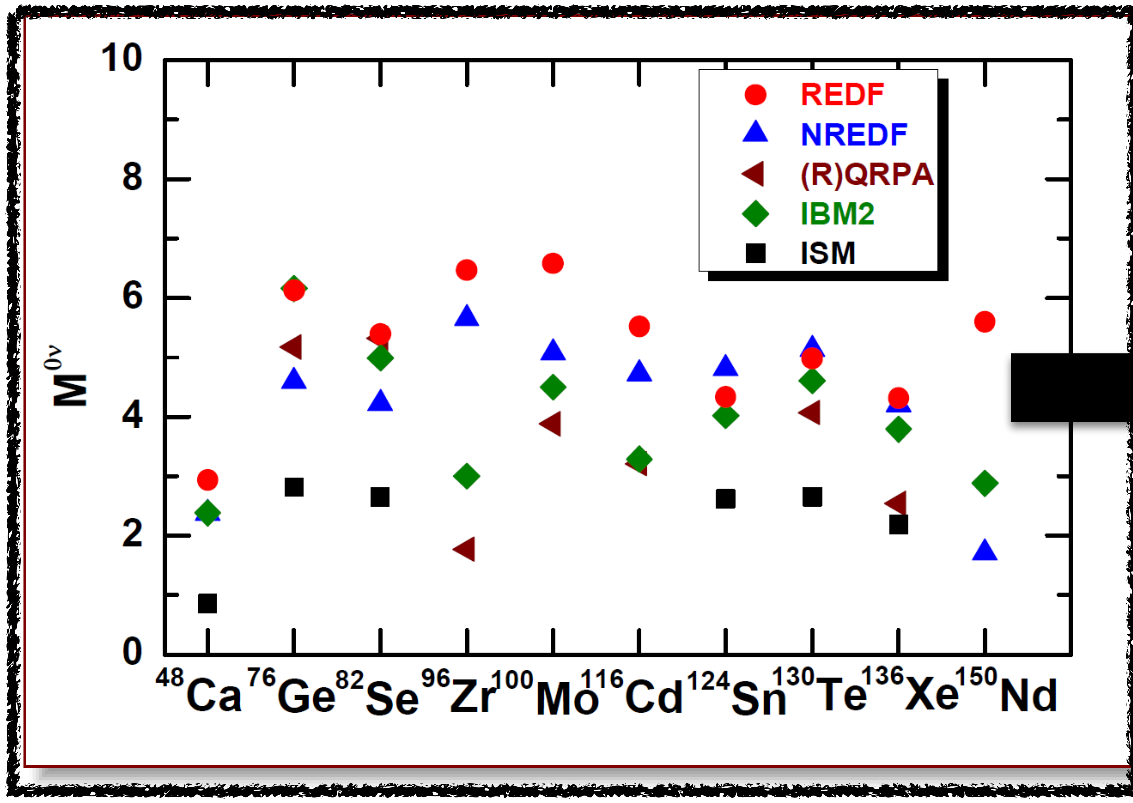
The Majorana (see-saw) idea fits nicely and explains
why neutrinos are much much lighter
than the other SM fermions

Not a necessity: Possible origin could also be at the TeV (if y≪1)

- Left-Right models proposal for neutrinos — JoAnne Hewett
- Possible scenarios with testable baryogengesis — Michele Lucente

ν0 ββ decay ☛ crucial future experiment

Crucial the ν-exchange nuclear matrix element: $M^{0\nu}$



New approach:

Jonathan Engel

- **Ab Initio Calculations:** Start from a well justified two-nucleon + three-nucleon Hamiltonian, then solve full many-body Schrödinger equation to good accuracy in space large enough to include all important correlations. At present, works pretty well in systems near closed shells up to $A \approx 50$.
- Inter… (as boson…

New

Has potential to combine and ground virtues of shell model and density functional theory.

Goal is accurate matrix elements with quantified uncertainty by end of collaboration (5 years from now).

Presence of ν-sterile?

If true, real breakthrough, although its origin will not likely have a connection with the EW scale

reason for the 5% reduction of the reactor antineutrino observed flux? Probably nuclear?

Anna Hayes

"Background" for determining CP-violating phases

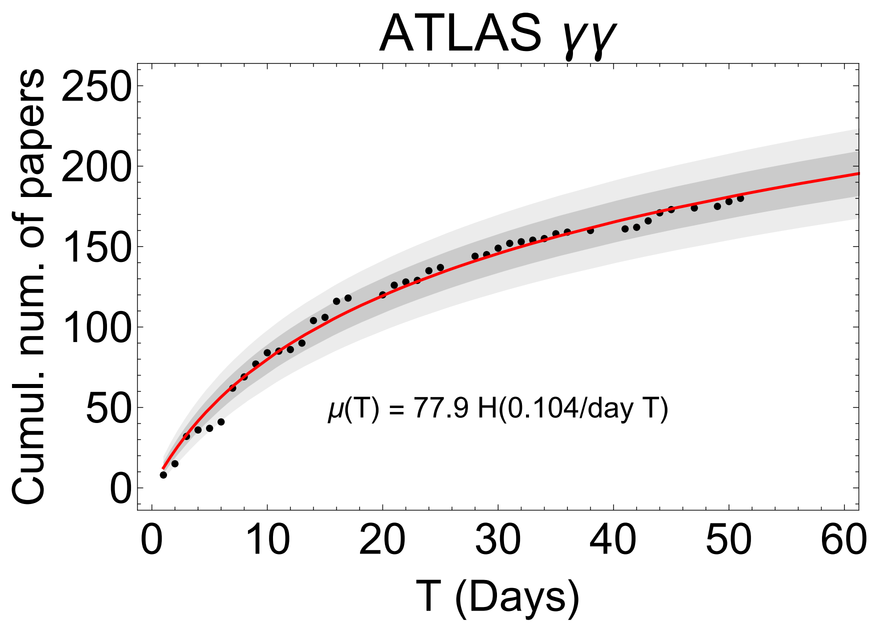
Boris Kayser

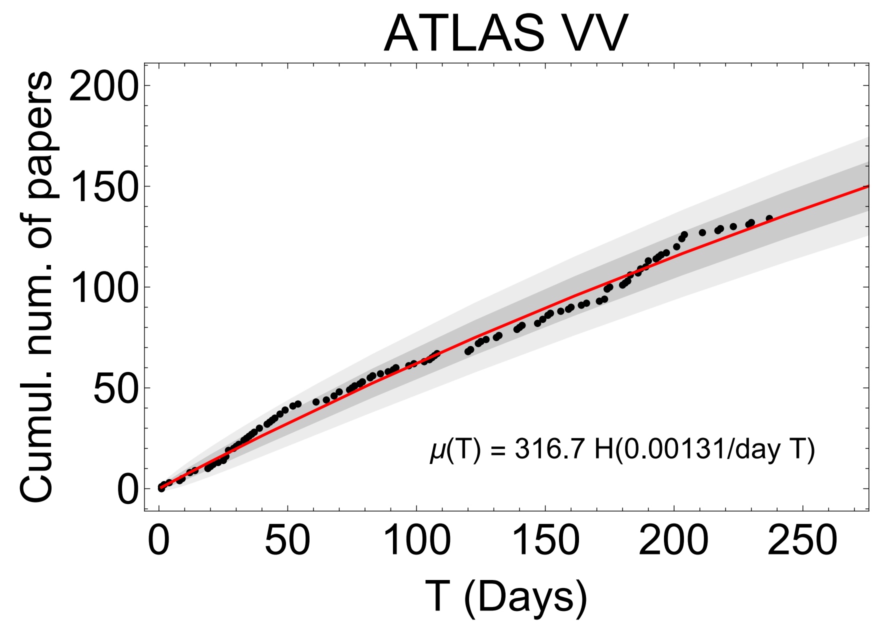
)

ANOMALIES

ANOMALIES

8 th talks out of 28!





arXiv:1603.0204

ANOMALIES

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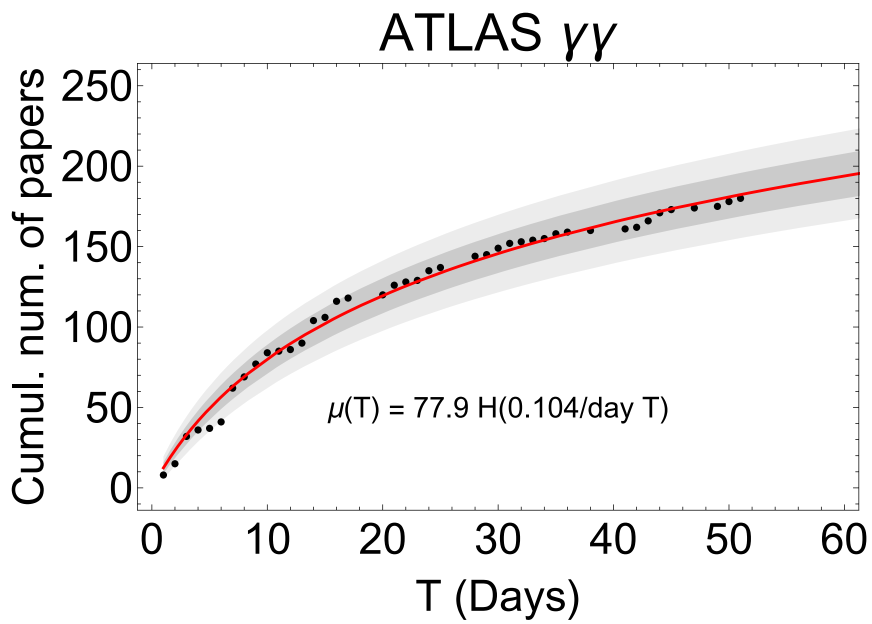

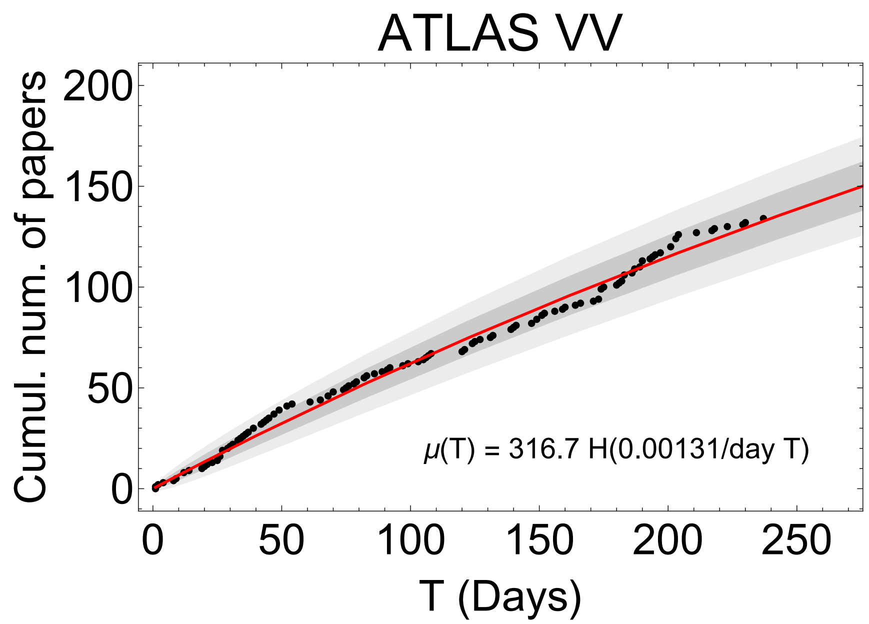

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Understandable: Little BSM experimental data, for too many theorists

Anomalies can even *captivate* very good people

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↳ Anomalies: Are a very passional thing!

Rational approach to anomalies:

- Experimental error?
- Statistical fluctuation?
- SM contributions under control?
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↳ yes, theory bias (or theory nose)

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No clear connection with any BSM explaining the EW scale !

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FERMI: γ-ray line at 130 GeV (3.2 σ)

OPERA: υ faster than light (~6 σ)

CDF: W+2*j* (3.2 σ)

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Not a crazy signal: expected from susy:

$$\tilde{q} \rightarrow \tilde{B} \rightarrow \tilde{H}$$

↳ jet ↳ Z ↘ LSP: missing E_T

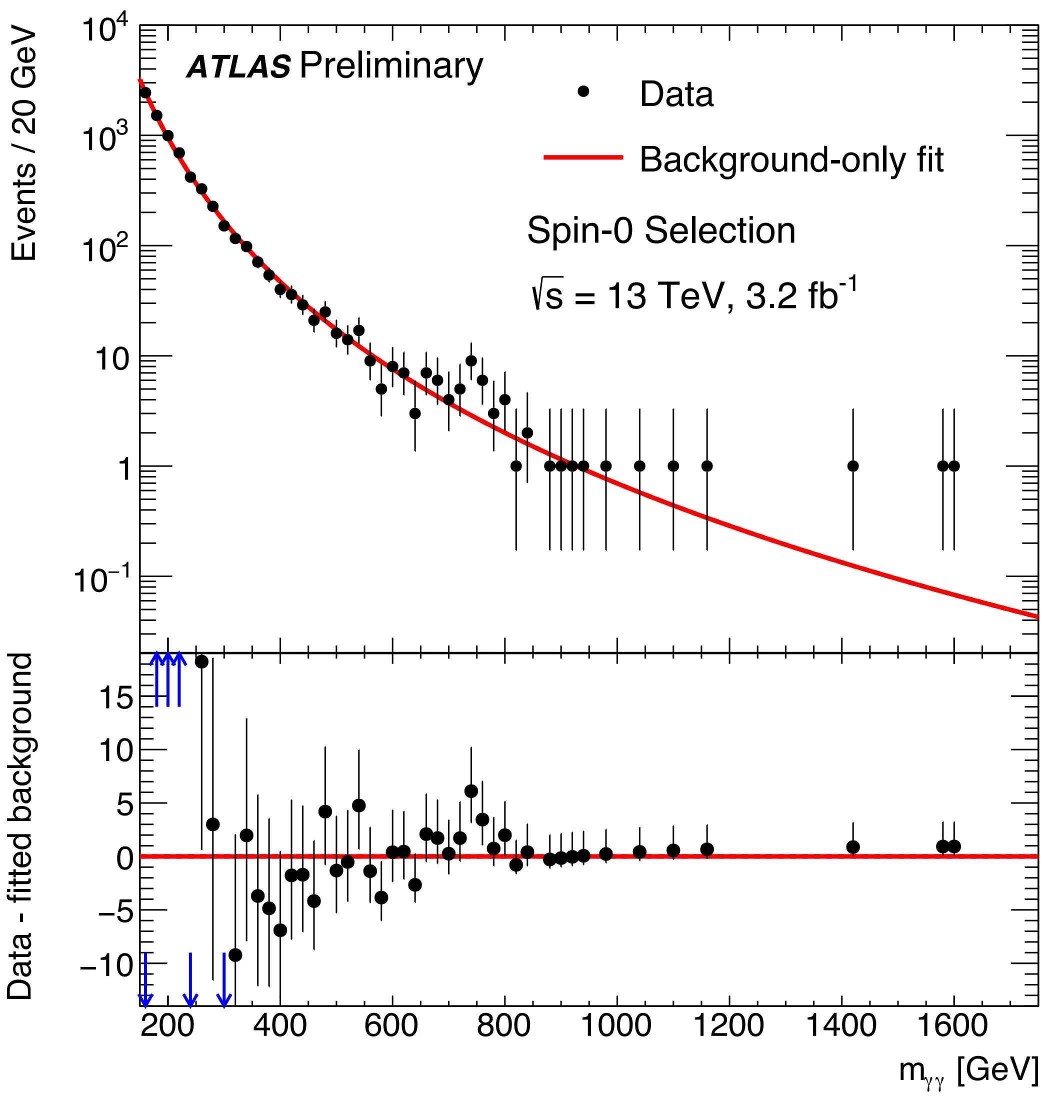
Thomas Rizzo

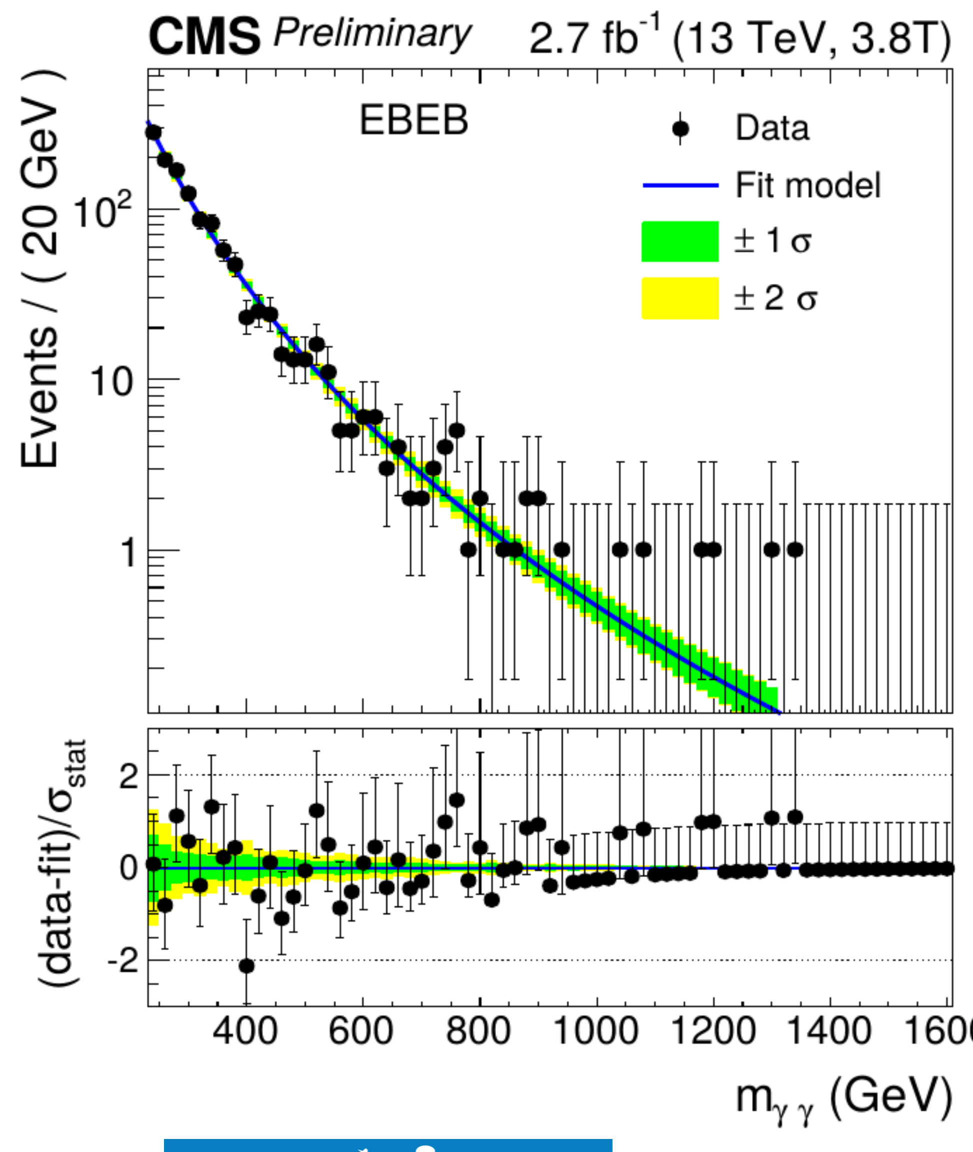
III) Di-photon excess:

Bumps are in principle clean observables

SPIN-0 ANALYSIS

background-only fit

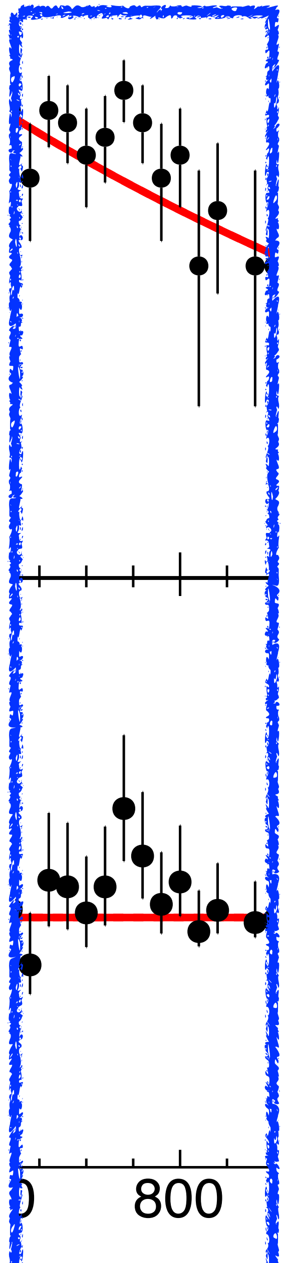


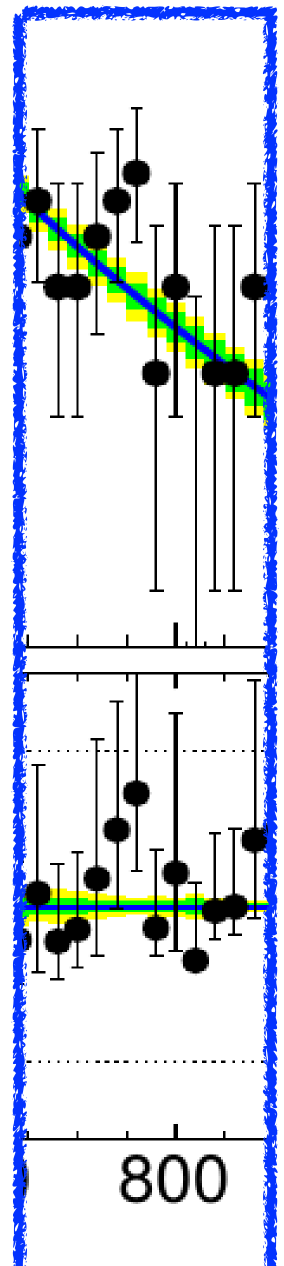


suggested to

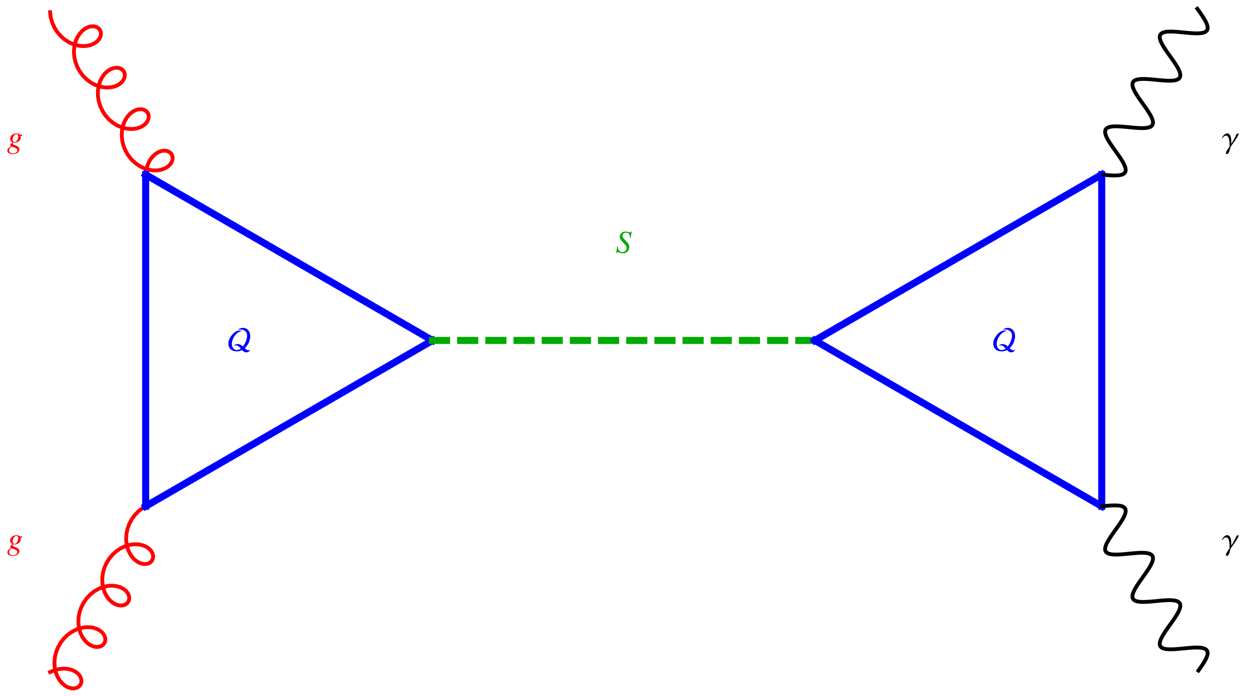
III) Di-photon excess:

Data in the eyes of a theorist





Simple theory interpretation:

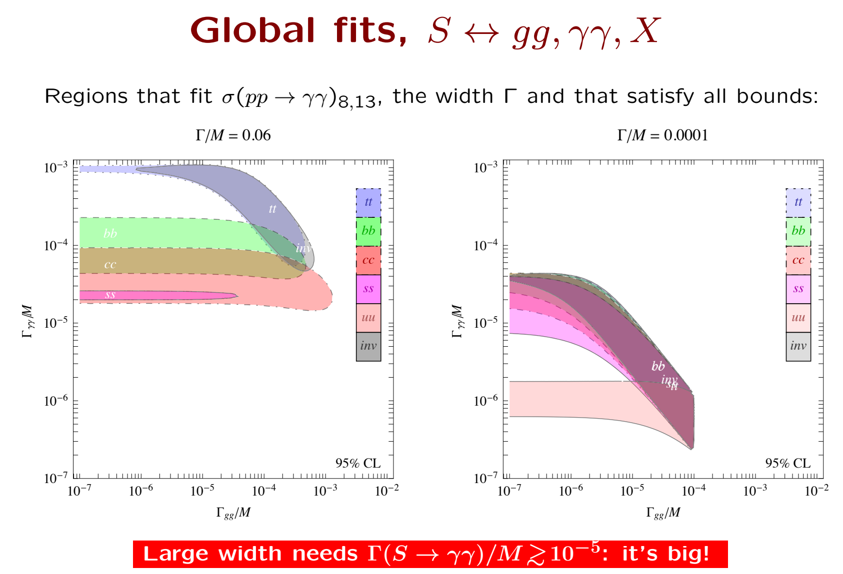


A. Strumia

Extra fermions Q or scalars $\tilde{Q}$ needed

Strumia's "modus operandi":

1) Fit it !



2) Add the minimal extension to the SM that explain it !

VolksModell

But this does not answer any fundamental question:

Why is this around the EW scale? What points to?

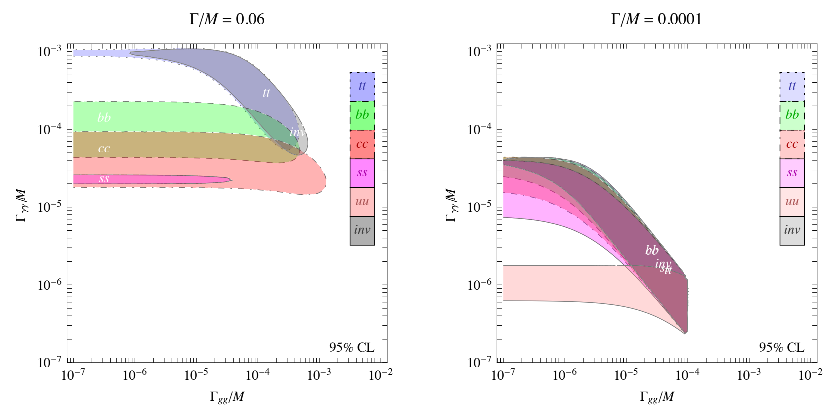
Was expected? What else we can expect?

Global fits, $S \leftrightarrow gg, \gamma\gamma, X$

Strumia's "modus operandi":

1) Fit it !

Regions that fit $\sigma(pp \to \gamma\gamma)_{8,13}$, the width Γ and that satisfy all bounds:



Large width needs $\Gamma(S \to \gamma\gamma)/M \gtrsim 10^{-5}$: it's big!

2) Add the minimal extension to the SM that explain it !

VolksModell

The width of S is crucial:

If large ☛ **strong dynamics**

A possibility already proposed to explain the EW scale

Was predicted? Not… but yes.

Not essential, but present in QCD-like theories: η, η'

If small ☛ **even susy could accommodate it**

But why so much extra matter there? Not expected!

Two possible scenarios we can imagine in the future

In August is confirmed…

New Revolution in particle physics!

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Theory colleagues

… avalanche of theory papers

In August is not confirmed…

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New-Physics at the TeV

Pros

Origin of the EW scale

Cons

No new particles seen,
no new flavor-violations seen,
no deviations on Higgs couplings seen,
no deviations on Z/W couplings seen,
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Null results from **well-motivated** experiments
(as Michelson-Morley experiment) give a motivation for
a change of **paradigm!**

1) Relaxion:

P.W. Graham, D.E. Kaplan, S.Rajendran
arXiv:1504.07551

Can explain why $m_W \ll M_P$ without new-physics at the TeV

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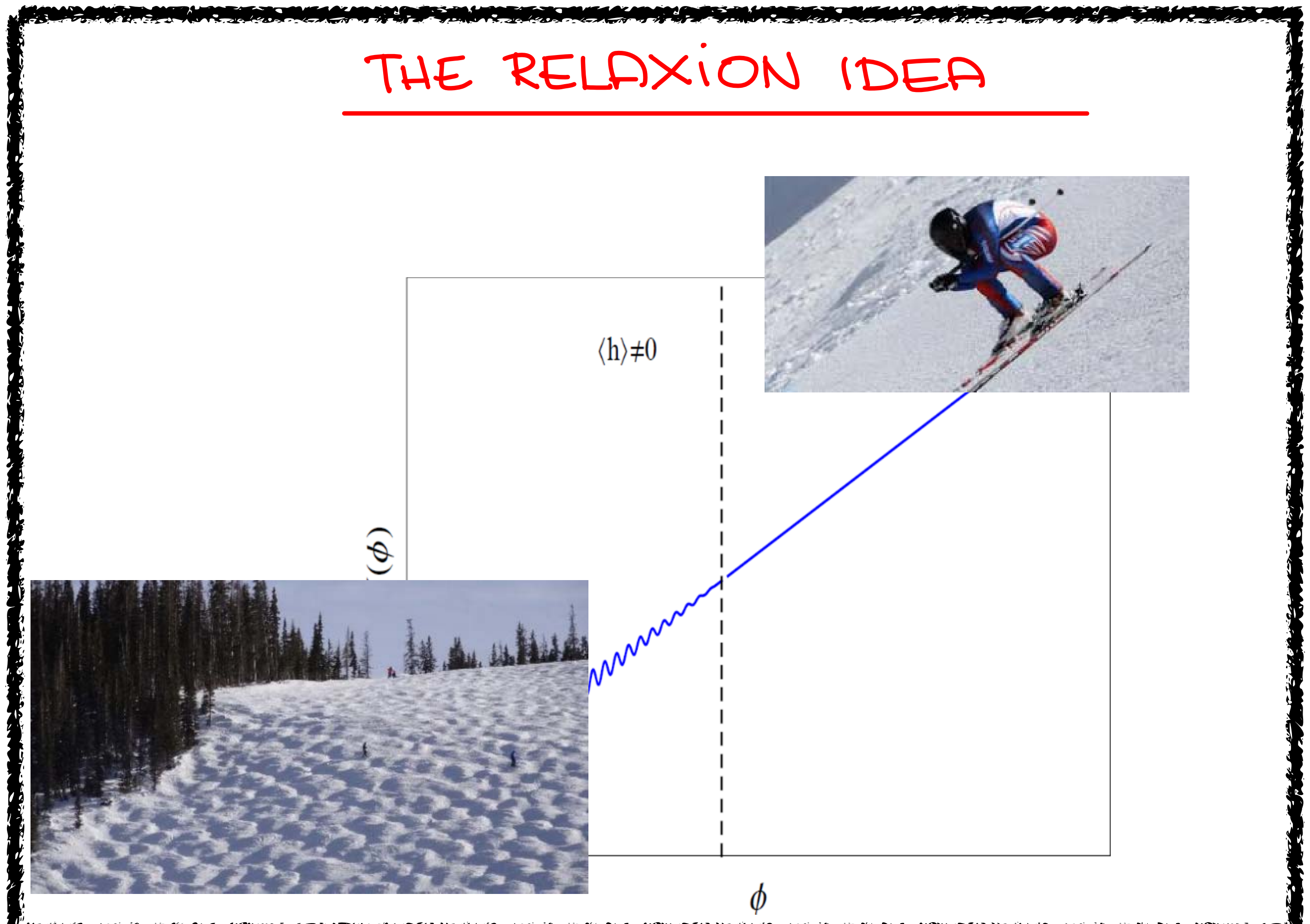
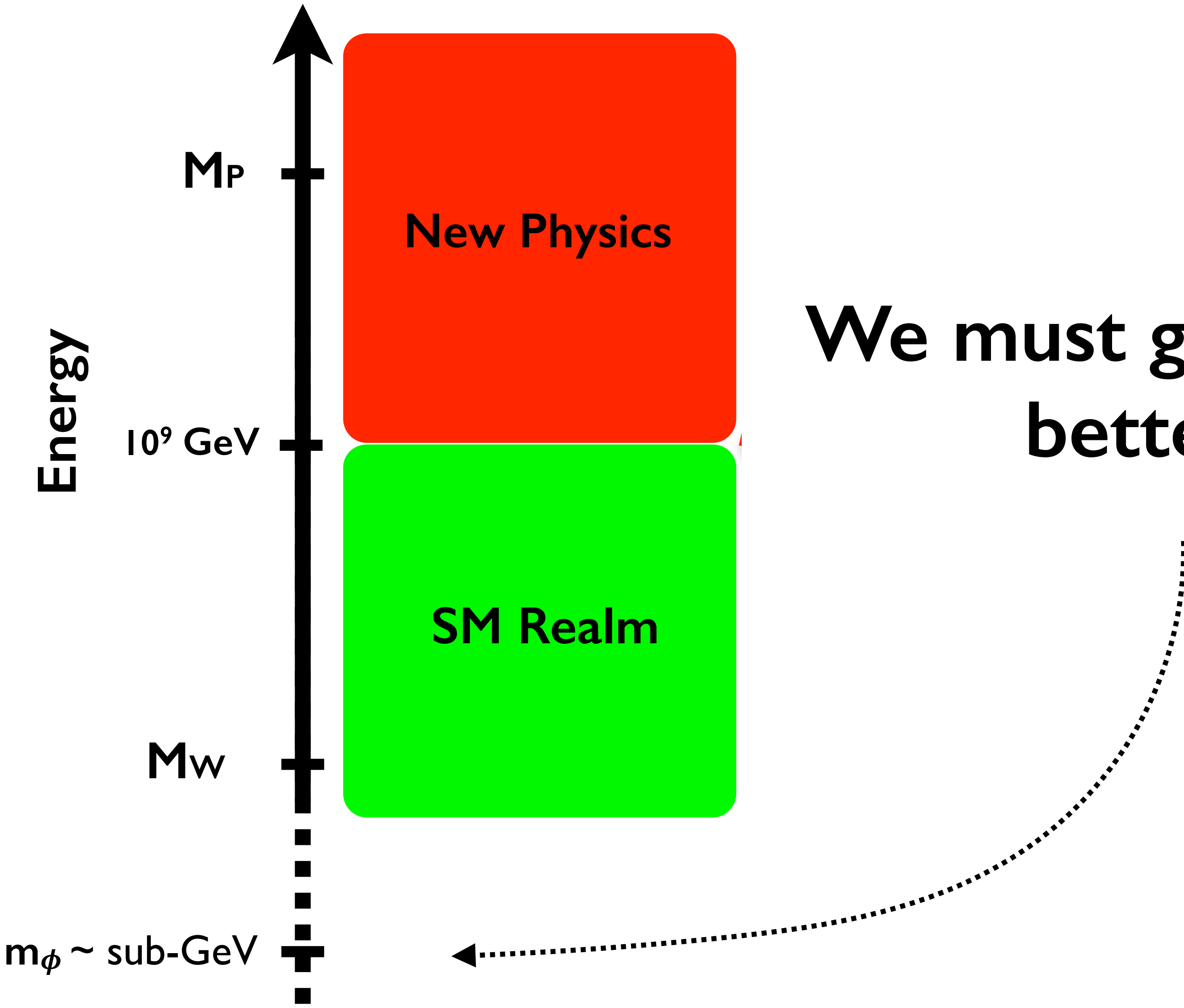
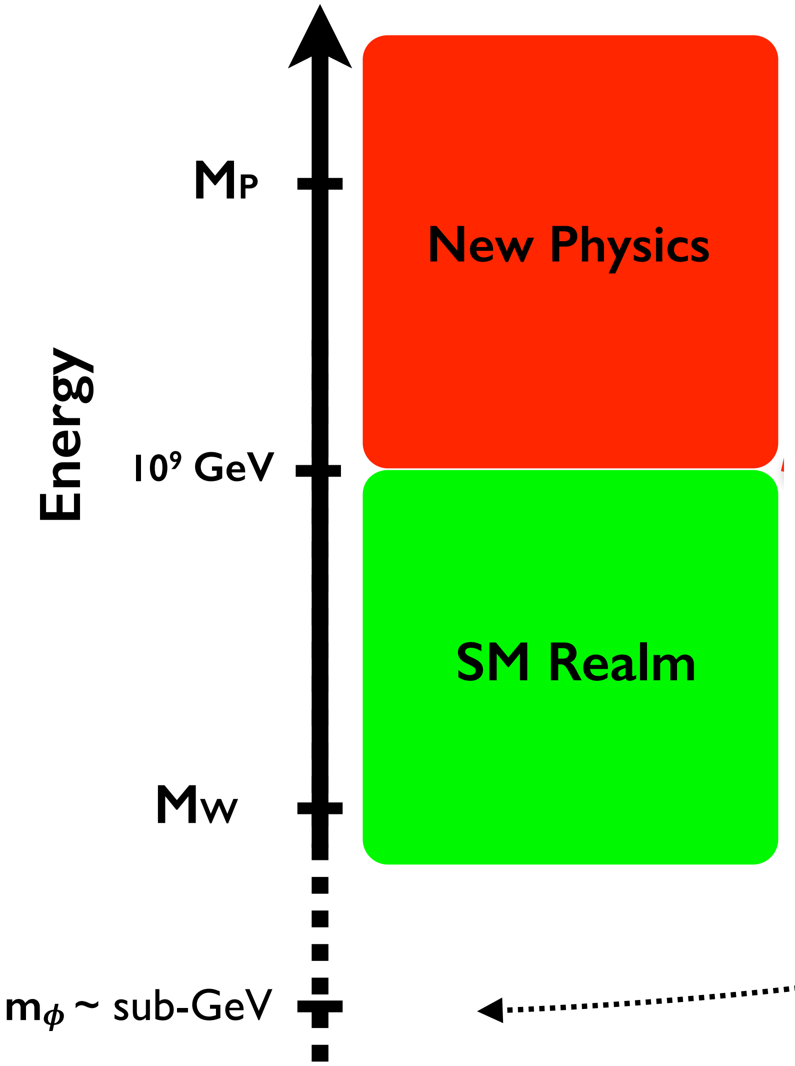
History is important!
$\boldsymbol{\phi}$ was stabilized long ago at very small values !



J.R.Espinosa



We must go back to the low-energy & explore better the weakly-coupled regime



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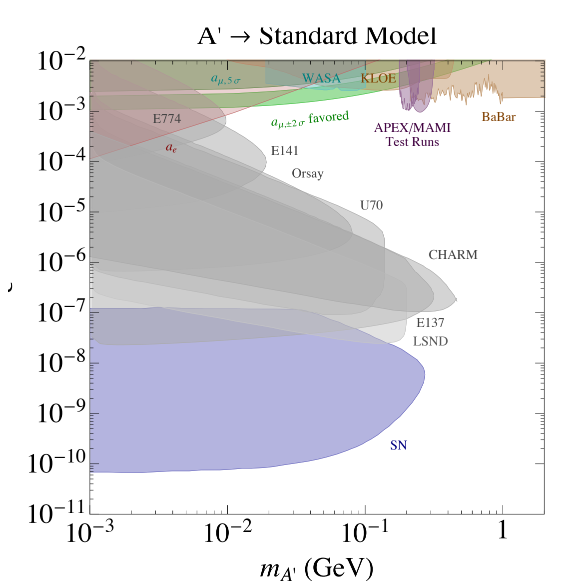
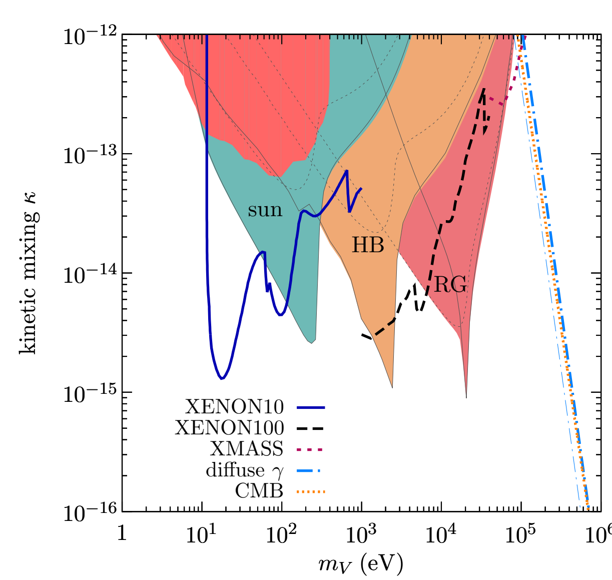
Very important motivation to connect with already ongoing searches:





Maxim Pospelov

2) Forget to explain the EW scale!

Accept it is tuned: $m_W \ll M_P$

and look for another reasons for the smallness of the EW scale:

DM, gauge-coupling unification, **"Anthropic" (Multiverse)**

Split-MSSM: Part of the spectrum heavy, other light:
2 Higgs doublet model?

Brummer Felix

Split-Composite Higgs:
Most of the spectrum is heavy
Signal: Long-lived triplet scalar:

f > 10 TeV = long-lived decay

$$T \to tbSS \Rightarrow c\tau \approx 0.2\,\mathrm{mm} \left(\frac{1}{c_3^T}\right)^2 \left(\frac{8}{g_\rho}\right)^3 \left(\frac{3\ \mathrm{TeV}}{m_T}\right)^5 \left(\frac{f}{10\ \mathrm{TeV}}\right)^4$$

can produce a displaced vertex!

Tony Gherghetta

Epilogue

It was the best of times,
It was the worst of times,
…
It was the spring of hope,
It was the winter of despair
A Tale of Two Cities

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  We could discover plenty,
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Thank you!

and to all that made possible another successful Moriond!