Pushing the boundaries — The Standard Model and Beyond at LHC

Theory Outlook

Jakub Scholtz

A JOKE...

Theory: Problems and Motivations

"When life gives you lemons make all kinds of tropical fruit based salads and say you got inspired by life"

- Hierarchy Problem
- Baryogenesis
- Dark Matter
- Flavour
- Neutrino Sector
- H0, Dark Energy
- Just because we can

Hierarchy Problem I

- Scalars pick up the mass-scale (and hence vevs) of whatever they couple to (probably the only accidentally well chosen name)

$$\delta m_H^2 \sim \frac{\lambda}{16\pi}\Lambda_{\rm cut}^2$$

- Say I ignore the Planck corrections (claiming some quantum gravity magic/ ignorance), I am forced into either of three scenarios:

A. There are no particles that couple to Higgs between the weak scale and Planck scale (at any appreciable loop level)

B. I fine-tune the theory: at some UV scale I set the Higgs bare mass as to precisely cancel all the contributions from all the loops.

C. If there any particles that couple to Higgs, they do so in a very peculiar way as to cancel/suppress the contribution to its mass: symmetries

Possibly a reason to believe there are new particles in "our reach".

Hierarchy Problem II

Symmetries:
The Spoon is Special

SUSY

Technicolor

Neutral Naturalness

...

Nothing to Cancel:
There is no Spoon

Extra Dimensions

Randall-Sundrum

...

Cosmological:
Only the Special Spoons Survive

Relaxion

N-naturalness

...

Hierarchy Problem III

Symmetries:
The Spoon is Special

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...

Does not do so well with light Higgs…
Fine-tuned?
Compressed Spectra [1512.05781]
Alignment without decoupling [1805.05754]
See talk by Christina Potter

Hard to hide the higher spin resonances
(techni-rho)/Walking technicolor
Top quark mass is a tough nut to crack

Generally a little hierarchy solution up to 5-10TeV
[hep-ph/0506256], G—> SU(2) x SU(2), v/w ~ 3-5
Contains some amount of light particles
Exciting cosmology
Drives us to understand things like glueballs …

Hierarchy Problem IV

Nothing to Cancel:
There is no Spoon

Extra Dimensions

Randall-Sundrum

…

These have become
standard models
to look for…

[hep-ph/9905221]
[hep-ph/0409309]

Hierarchy Problem V

Dynamically ‘Relaxes’ the Higgs mass [1504.07551]
Has spawned an industry of its own:

- Produces DM [1809.04534,1810.01889]
- Solves/Spoils the Strong CP problem [1708.00010]
- Has Baryogenesis in it [1810.05153]
- Differen Stopping Mechanisms [1607.01786]

The are many ‘Standard Models’
Cosmology picks (reheats) the one that has the lowest value of Higgs vev [1607.06821]

Cosmological: Only the Special Spoons Survive

Relaxion

N-naturalness

…

Hierarchy Problem VI

Symmetries:
The Spoon is Special

SUSY

Technicolor

Neutral Naturalness

...

Nothing to Cancel:
There is no Spoon

Extra Dimensions

Randall-Sundrum

...

Cosmological:
Only the Special Spoons Survive

Relaxion

N-naturalness

...

Hierarchy Problem VII: But what has it done for us?

- It has inspired whole sets of industries of searches (SUSY, KK modes, Techni-particles)

- Since we have found no resonances we started focusing on EFTs (which is a good thing). You will hear a lot more about this on Friday. [One upshot is that we need to get our theory predictions up to speed, since we are not longer bump-hunting].

- It has slowly eroded our tastes (which is good) and taught us humility…

Dark Matter

ADVANTAGES

- Definitely there
- There is so much, we can see it gravitationally
- It is stable
- Points to a whole new sector

DISADVANTAGES

- We can only see it gravitationally
- We mostly know what it is not
- Not even sure it is a particle

Dark Matter II

What do we know?

- The bulk properties are so well known, we now have a Standard Model of Cosmology (LCDM):
  - $\Omega_{\rm CDM} = 0.259$
  - The initial power spectrum is nearly scale invariant
  - Not strongly self-interacting: $\sigma < 1 {\rm cm}^2/{\rm g} \sim {\rm barn}/{\rm GeV}$
  - Not a single type of Primordial Black hole (may be a spectrum, may be a particle)
  - Does not interact with SM much. (Later talks)
  - Many constraints disappear once you consider only a fraction of DM is special…

Dark Matter III

- We get fascinated by the DM-baryon coincidence:

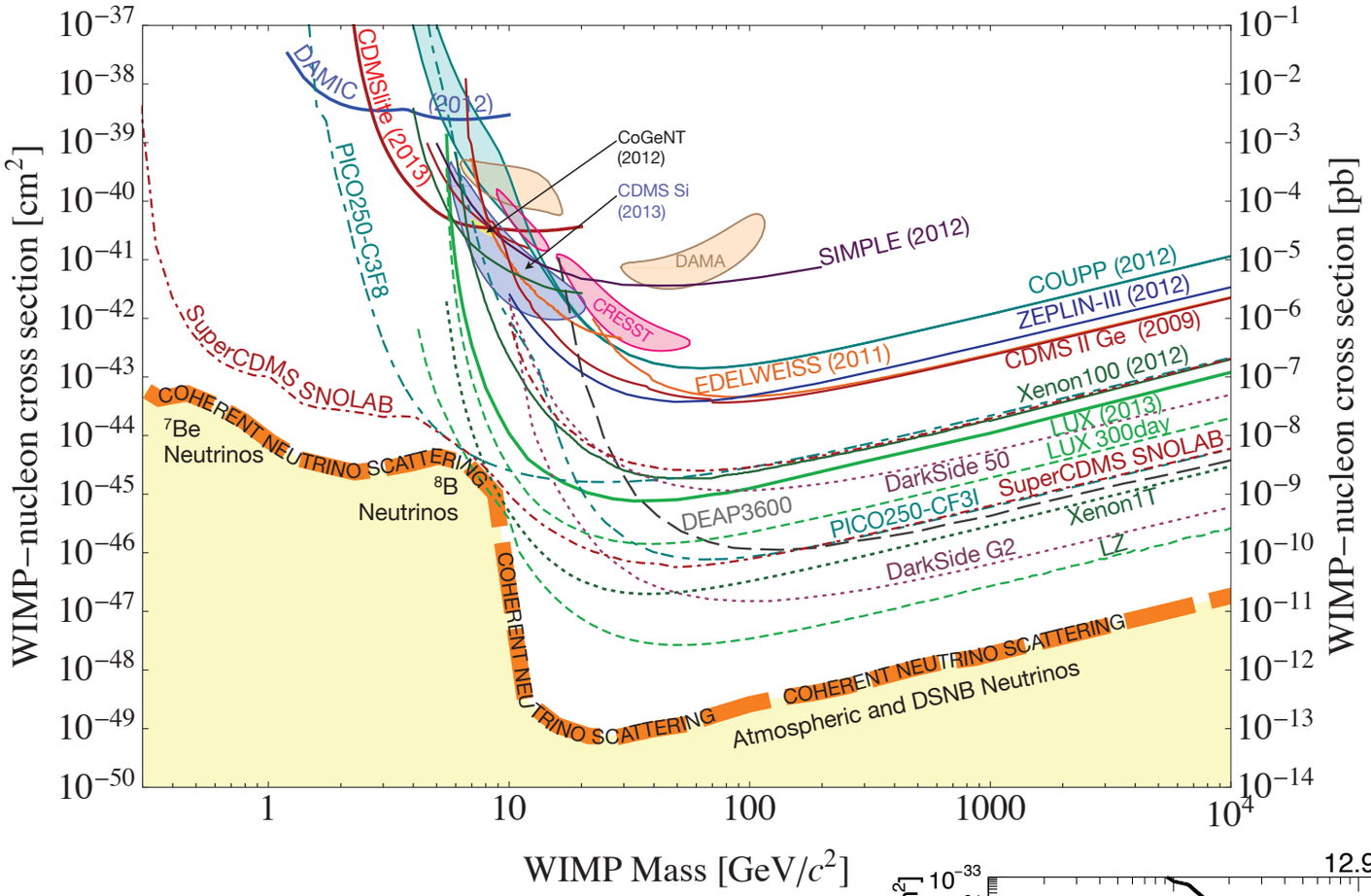
$$\Omega_{\rm DM} \sim \mathcal{O}(1)\Omega_{\rm B}$$

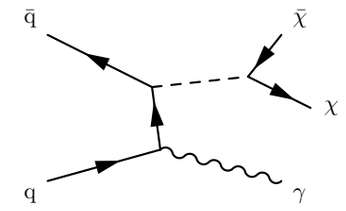
- We often assume this means that DM had to be in thermal equilibrium with the SM. A bit of a red-herring:

$$n_{\rm B} \sim 10^{-10} n_\gamma$$

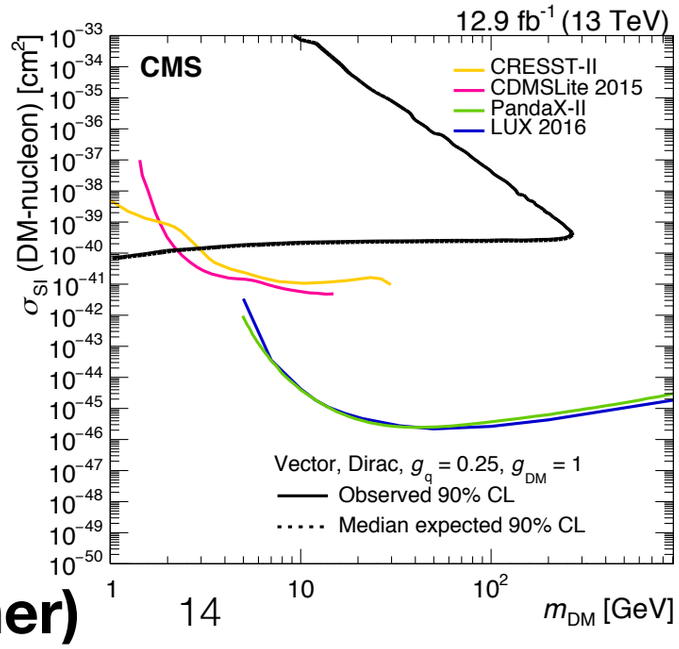
- This makes the WIMP miracle a very accidental miracle.
- Instead asymmetric DM models are more true to this statement (Darkogenesis [1008.1997], Xogenesis [1009.0270], Pangenesis [1105.3730], Asymmetric Freeze-in [1010.0245]
- There are other “coincidences”: SIMP, FIMPs, Axions.
- You can even set the DM abundance by the properties of SM alone (with an inert DM)

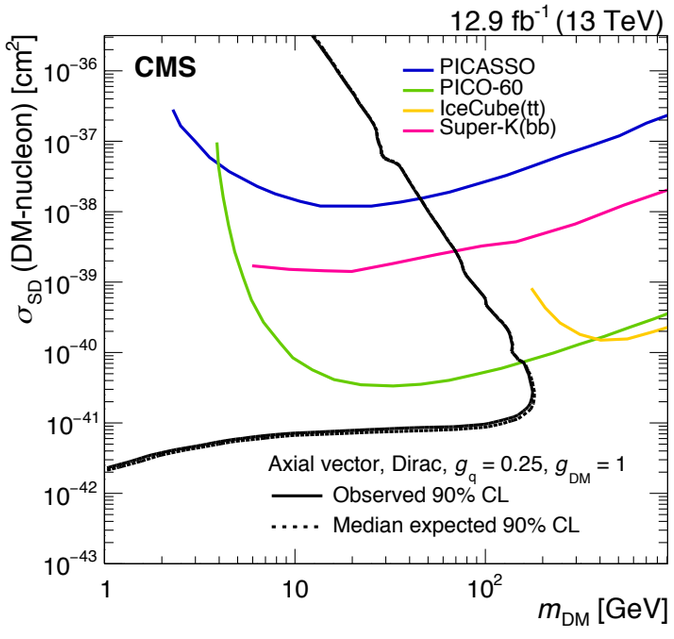
Dark Matter IV





Monophoton

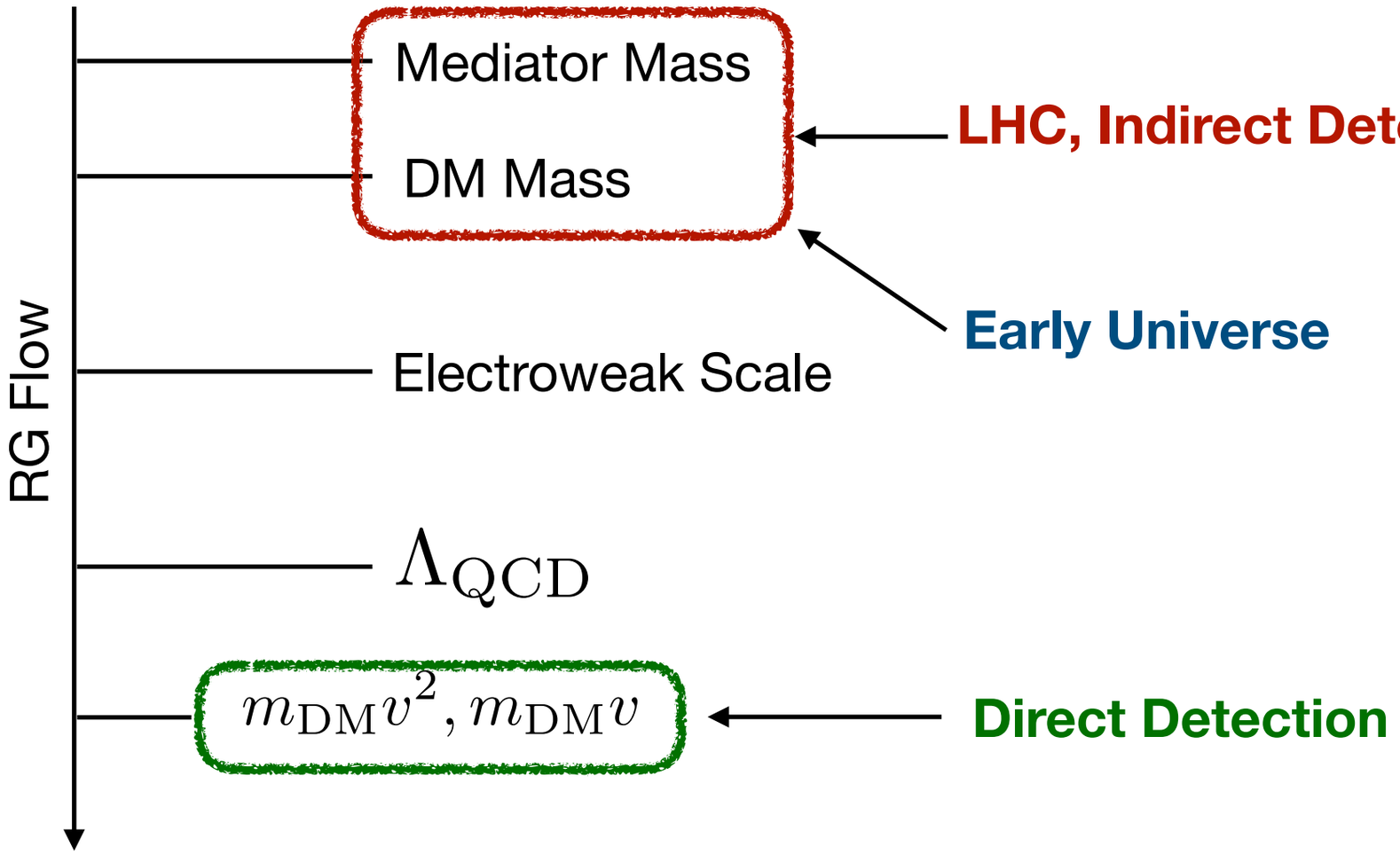




(There will be a talk by Henning Flacher)

Dark Matter V

Collider vs Direct Detection vs Indirect Detection



LHC and Early Universe and Direct Detection may be all probing different scales

—

Without a model, you cannot fairly compare them.

See e.g. [1402.1173], [1708.02678], [1809.03506]

Dark Matter VI

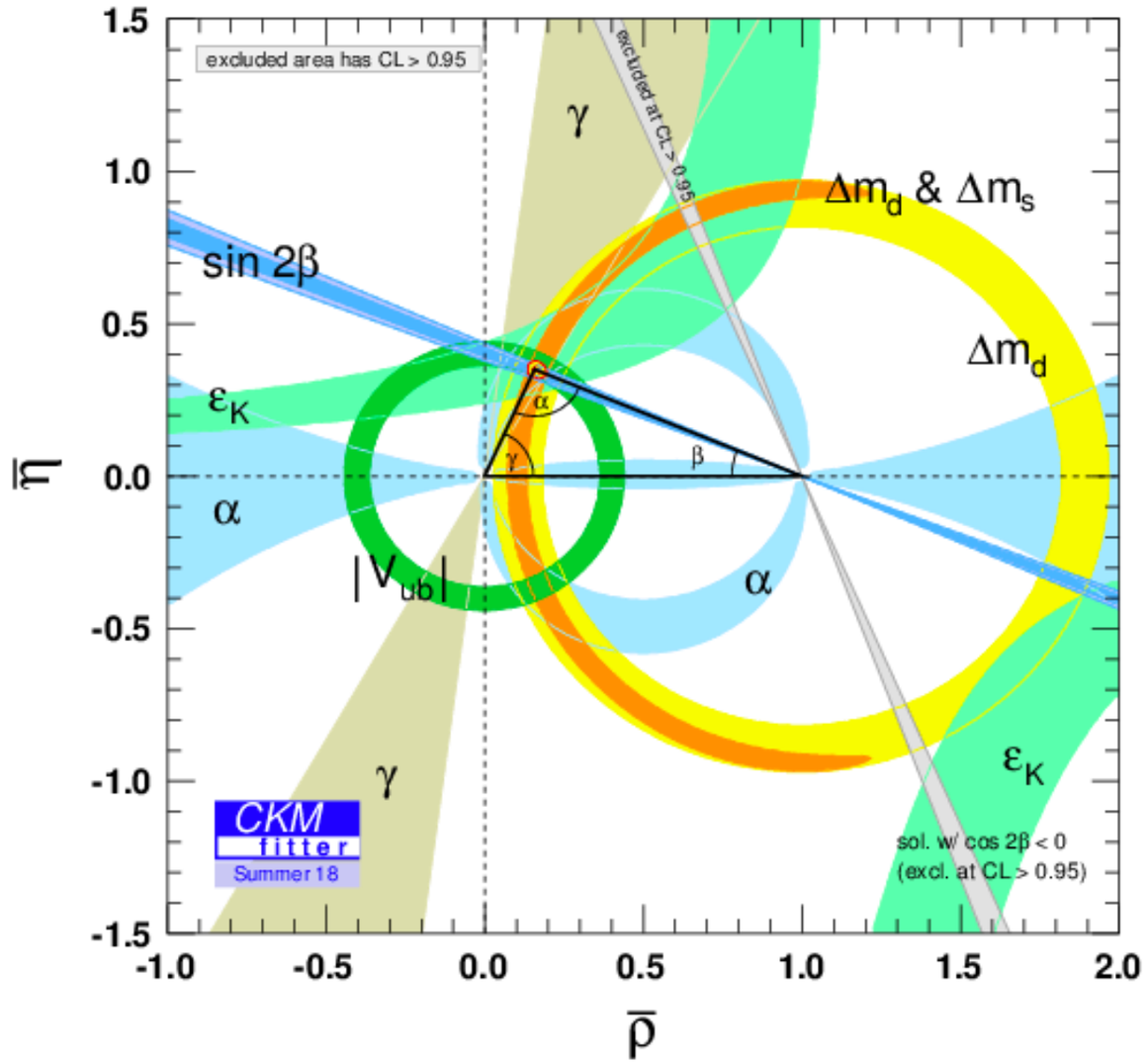
Colliders and Astrophysics are Complimentary

	Coupling to	Assumptions/Uncertainties
Direct Detection	**Nucleons**	**DM velocity profile**
Indirect Detection	**Partons**	**DM density profile, SM backgrounds**
Colliders	**Partons**	**We don’t know if we found a DM state at all**

It’s hard to determine Self-interactions, Temperature, etc. with Collider Data
vs.
Astrophysics is notoriously known for uncertainties (but getting better), but then you already have DM in astrophysical settings (you don’t pay the cost of making it)

Flavour

- The SM flavour structure is hierarchical.
- The CKM appears to be unitary, we don't see clear signs of FCNCs (All the penguins are accounted for…)
- The last statement was meant to be controversial



Flavour II

However, we do see anomalies:

$$r_D^{(*)} \equiv \frac{B \to D^{(*)} \tau \nu_\tau}{B \to D^{(*)} \mu \nu_\mu}$$

$$\Delta a_{CP} = a_{K^+K^-} - a_{\pi^+\pi^-}$$

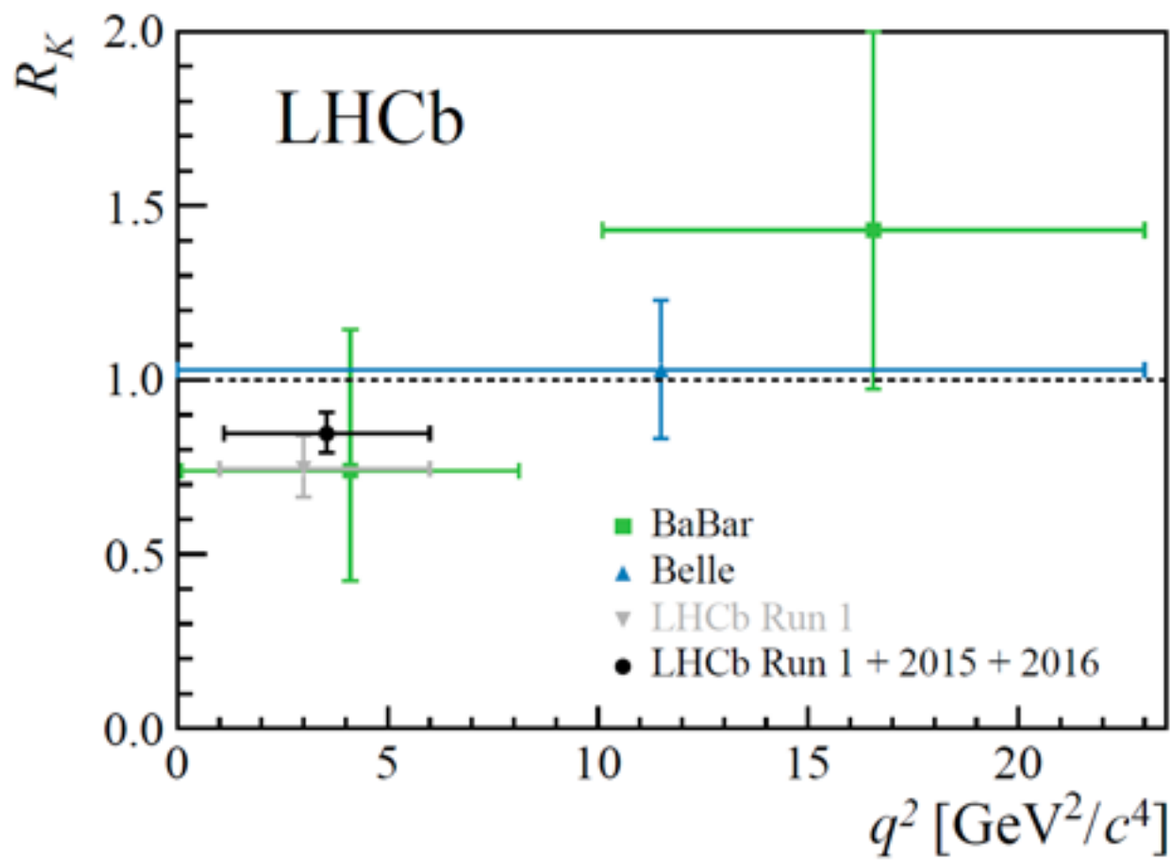
$$r_K^{(*)} \equiv \frac{B \to K^{(*)} \mu^+ \mu^-}{B \to K^{(*)} e^+ e^-}$$

$$(g-2)_e \text{ vs.} (g-2)_\mu$$

a_e	$(1.1596521816 \pm 0.0000000002) \times 10^{-3}$	$(1.1596521809 \pm 0.0000000003) \times 10^{-3}$	[95]	1.9σ
a_μ	$(1.1659182 \pm 0.0000004) \times 10^{-3}$	$(1.1659209 \pm 0.0000006) \times 10^{-3}$	[95]	3.4σ
a_τ	$(1.17721 \pm 0.00005) \times 10^{-3}$	$(-1.8 \pm 1.7) \times 10^{-2}$	[95]	1.1σ

Flavour III

- LHCb measurement. But consistent with previous results.
- The significance of the anomaly has gone down.
- This measurement is now 2.5 sigma away from SM.
- A sign of FCNC?
- Points to a scale of 3-30TeV… Exciting!!!



$$R_K = 0.864^{+0.060+0.016}_{-0.054-0.014}$$

Flavour IV: Charm Sector

$$A_{CP}(f,t) = \frac{\Gamma(D^0(t)\to f) - \Gamma(\overline{D}^0(t)\to f)}{\Gamma(D^0(t)\to f) + \Gamma(\overline{D}^0(t)\to f)}$$

$$\Delta A_{CP} = A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)$$

$$\Delta A_{CP}^{\text{Exp.}} = (-15.6 \pm 2.9)\times 10^{-4}$$

Measurement

$$|\Delta A_{CP}| \leq (2.0 \pm 1.0)\times 10^{-4}\,.$$

Prediction

Whooping 5.3 sigma!!!

[1903.10490]

Flavour V: Charm Sector

$$A(D^0 \to \pi^+\pi^-) = V_{cd}V_{ud}^*\left(A_{Tree} + A^d_{Peng.}\right) + V_{cs}V_{us}^* A^s_{Peng.} + V_{cb}V_{ub}^* A^b_{Peng.}$$

$$A \equiv \frac{G_F}{\sqrt{2}}\lambda_d\, T\left[1 + \frac{\lambda_b}{\lambda_d}\frac{P}{T}\right] \text{ where } \lambda_q = V_{cq}^* V_{uq}$$

$$\begin{aligned}
\text{Br} &\propto \frac{G_F^2}{2}|\lambda_d|^2|T|^2\left|1 + \frac{\lambda_b}{\lambda_d}\frac{P}{T}\right|^2, \qquad \textbf{From experiment} \\
a_{CP}^{\text{dir}} &= \frac{-2\left|\frac{\lambda_b}{\lambda_d}\right|\sin\gamma\left|\frac{P}{T}\right|\sin\phi}{1 - 2\left|\frac{\lambda_b}{\lambda_d}\right|\cos\gamma\left|\frac{P}{T}\right|\cos\phi + \left|\frac{\lambda_b}{\lambda_d}\right|^2\left|\frac{P}{T}\right|^2} \approx -13\times10^{-4}\left|\frac{P}{T}\right|\sin\phi
\end{aligned}$$

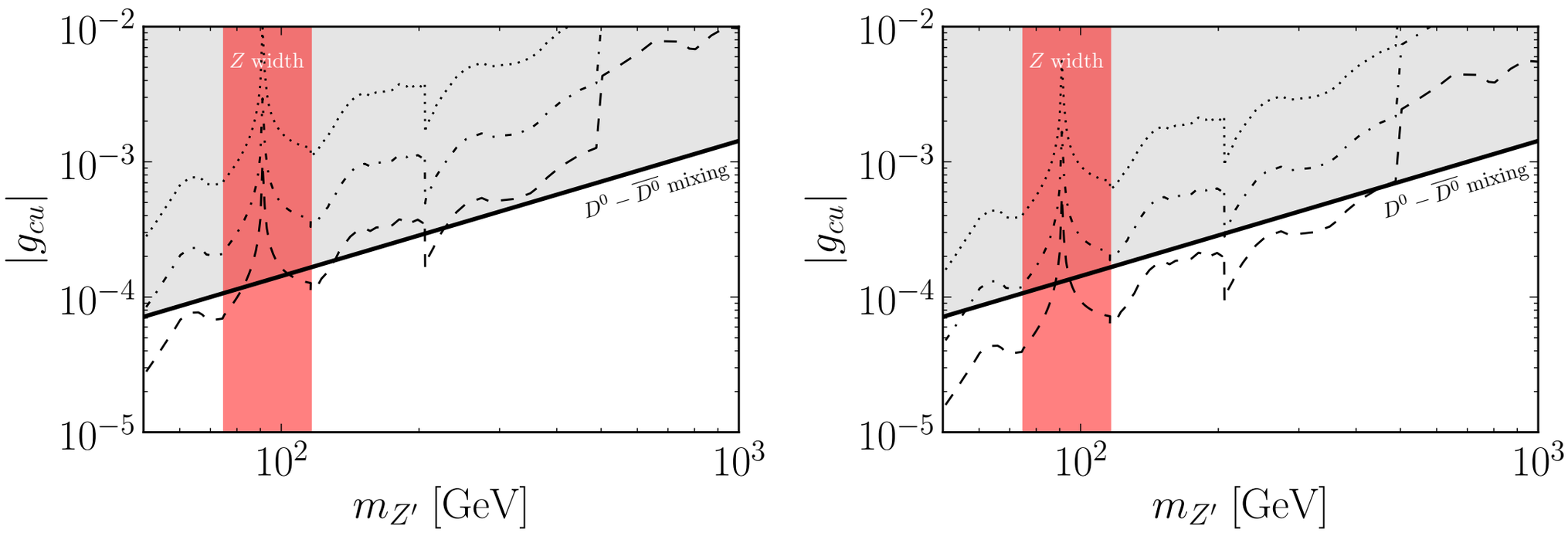
$$\begin{aligned}
\left|a_{CP}^{\text{dir}}\right| &\leq 1.3\times10^{-4}, \\
|\Delta A_{CP}| &\approx 13\times10^{-4}\left|\left|\frac{P}{T}\right|_{K^+K^-}\sin\phi_{K^+K^-} + \left|\frac{P}{T}\right|_{\pi^+\pi^-}\sin\phi_{\pi^+\pi^-}\right| \leq 2.6\times10^{-4}
\end{aligned}$$

$$\begin{aligned}
\left|\frac{P}{T}\right|_{\pi^+\pi^-} &= 0.093 \pm 0.011 \\
\left|\frac{P}{T}\right|_{K^+K^-} &= 0.075 \pm 0.015
\end{aligned}$$

LCSR

Flavour VI: Charm Sector

- Is this BSM? We think it may be: [1903.10490]
- Heavy gluon does not work, since 2013 the monojet searches have improved.
- But a light Z' does
- How about the I=1/2 rule?



Baryogenesis

$$\eta \equiv \frac{n_b}{s} = 10^{-10}$$

Sakharov Conditions imply out of equilibrium stage during Cosmology:

- Phase transitions: Gravitational Waves, Deformed Power Spectrum, Change of scalar sector

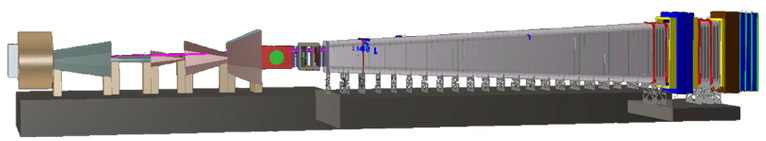
- Long lived particles: Recent LHC efforts on improving tracking, MATHUSLA etc.

- Neutrinos: chance to connect different problems

But there are Baryogenesis scenarios that avoid the Sakharov conditions — so don’t get your hopes up (Spontaneous Baryogenesis)

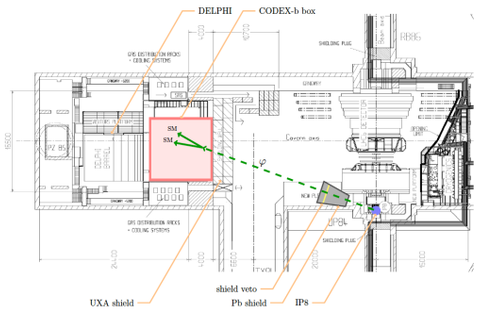
Baryogenesis: Long Lived Particles

SHIP



Alekhin et al. (2015)

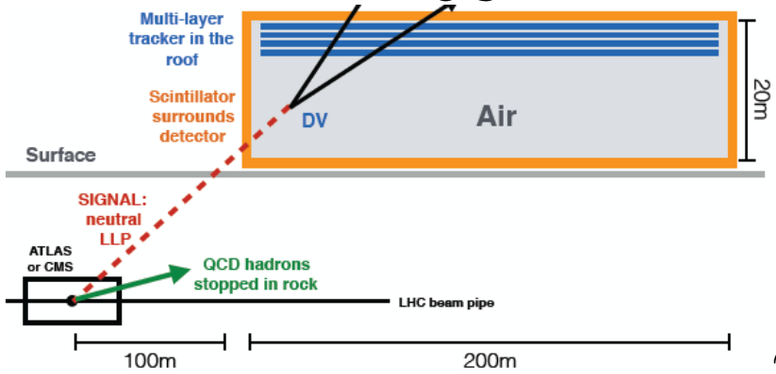
CODEX-b



$\sim 1000\ \mathrm{m}^3$

Gligorov, Knapen, Papucci, Robinson (2016)

MATHUSLA



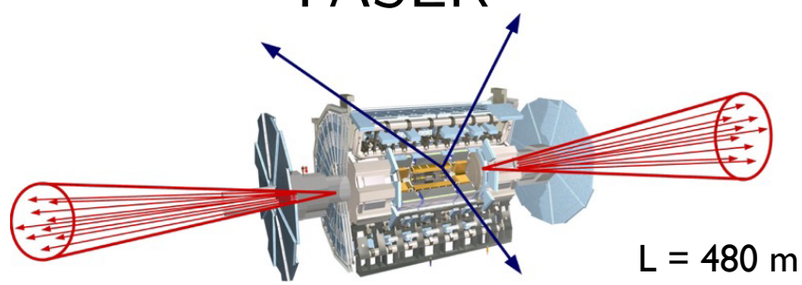
$\sim$

$2 \times 10^5\ \mathrm{m}^3 \sim$1 IKEA

Chou, Curtin & Lubatti (2016)

Curtin & Peskin (2017)

FASER



L = 480 m downstream from ATLAS/CMS IP

$\sim 1\ \mathrm{m}^3 \sim 5\mu$IKEAs

Feng, Galon, Kling & Trojanowski (2017)

Credits: I. Galon at FNAL workshop on HL/HE-LHC (4-6 April 2018)

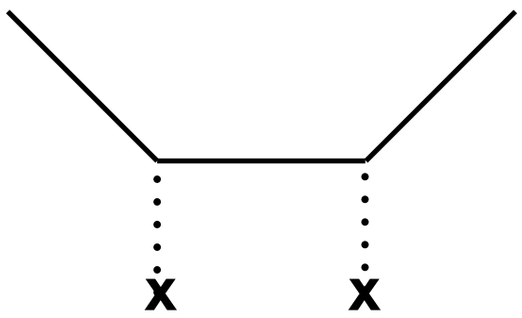
Target complementary life-time and kinematic regions (forward and central, short and long)
Note: CepC and FCC could incorporate the basic of these experiments from the beginning

[Stolen from Monica D'Onofrio]

Neutrino Sector

Too many options with many scale choices: Consider Seesaw mechanisms

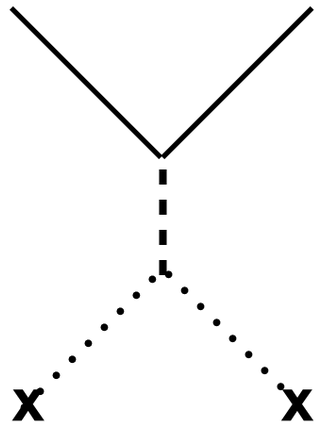
Type I



Fermionic Singlet

$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$

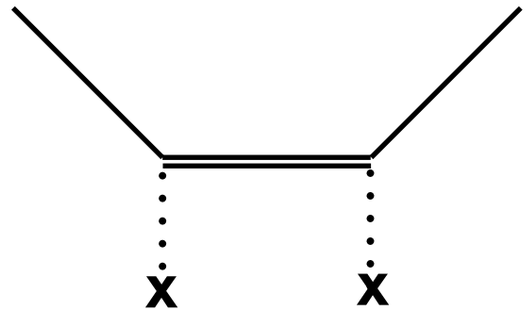
Type II



Scalar Singlet

$$m_\nu = Y_\Delta \frac{\mu}{M_\Delta^2} v^2$$

Type III



Fermionic Triplet

$$m_\nu = Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma v^2$$

$$\frac{1}{\Lambda}(LH)^c(LH)$$

Neutrino Sector: musings

- We will learn about the light neutrino mass from Cosmology (for caveat see the next talk) and from Katrin.

- Unfortunately, knowing LH masses, does not teach us much.

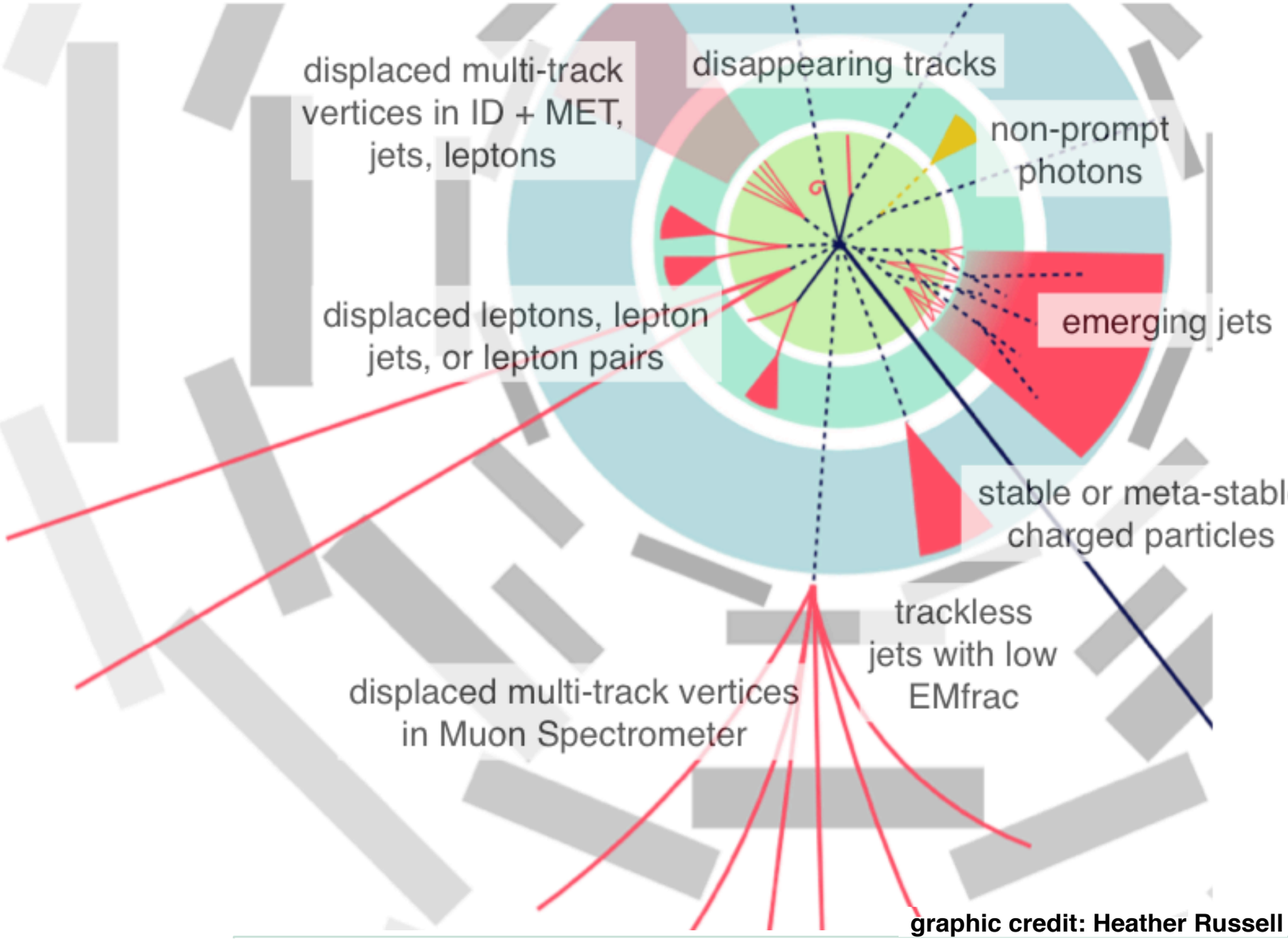
- The seesaw scales have a range from 100GeV — 10^15 GeV.

- There are ways to connect Leptogenesis to the RH Neutrino (around 10^10 GeV).

- There are great new ways to generate the Lepton Flavour structures [1812.02158]

- Sometimes, the best constraints on Neutrino mass generation comes from indirect effects in the scalar sector [1710.09683]

Just because we can?
We should!!!



graphic credit: Heather Russell

List Again

Hierarchy Problem: Why there should be new physics close

Baryogenesis: Definitely there, interesting parameter space

Dark Matter: Definitely there, complementarity

Flavour: Hints of anomalies. New scales that are close.

Neutrino Sector: Definitely there, but where?

H0 tension, Dark Energy: For another day…

Just because we can: Because we should

Conclusions:

This is where I am going to be excessively positive

- On one hand, it is sad that low scale SUSY was not the answer. But then again, imagine that all we were doing now was classifying which SUSY scenario we are in…
- On the other hand, we have learned something: Nature is cheeky, clever and mischievous and we will have to be much more clever to figure out what is happening.
- This leads to several things:
  - We have to be even more clever, systematic and imaginative
  - We have to abandon some silly ideas about beauty (which was always in the eye of the beholder)
  - With a much larger class of models available (reduced symmetry), we need to start using different principles to decide what is worth pursuing and what is not (experimental feasibility comes to mind)
  - If you can't bump hunt, you need to learn to calculate tails
- Machine learning will be useful to deal with the chaos, but only if we use it intelligently.
- More than ever, we need to consult Astro and Cosmo people: less symmetry means we need more measurements.