
# Heavy stable particles, dark corner of modern physics

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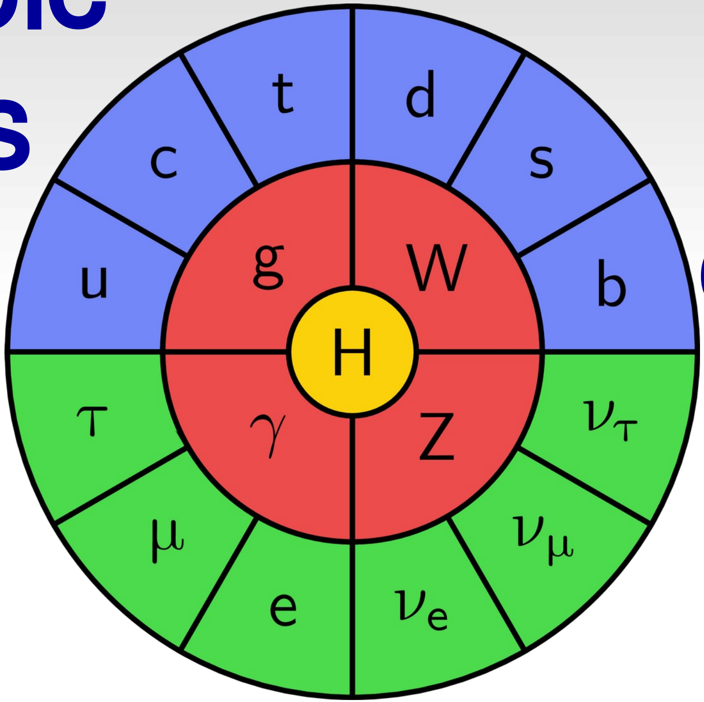
1) How do we look for microscopic physics in GIANT colliders
2) Heavy Stable particles the new frontier

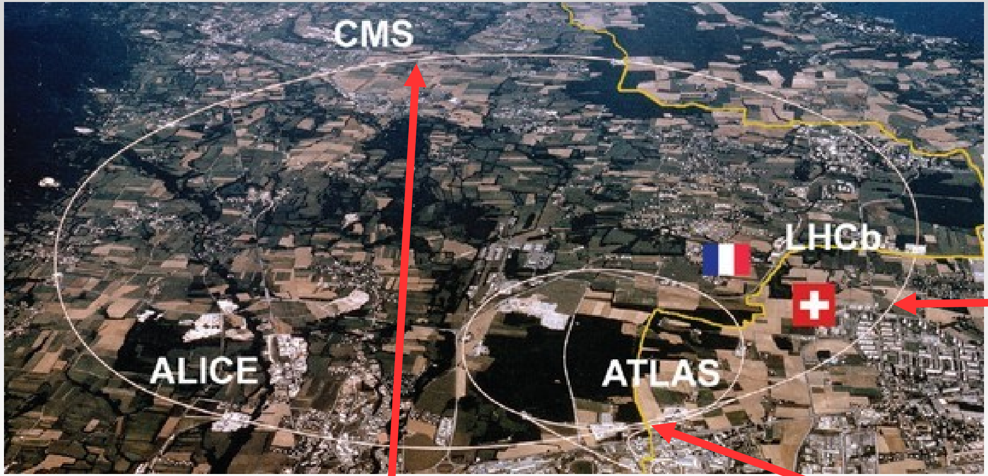
02/10/2024

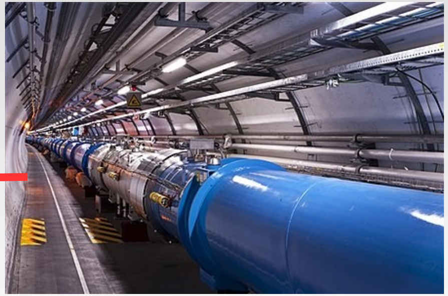
# 1) How do we look for microscopic physics in a giant collider

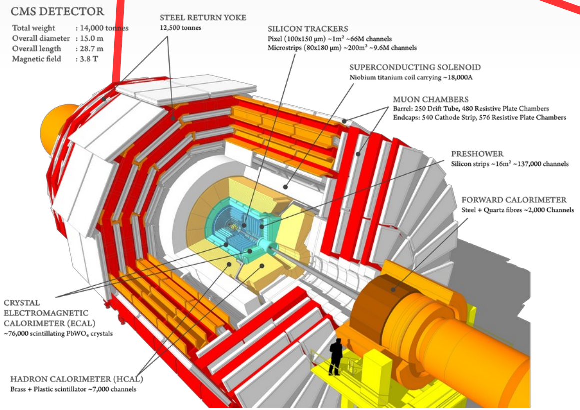


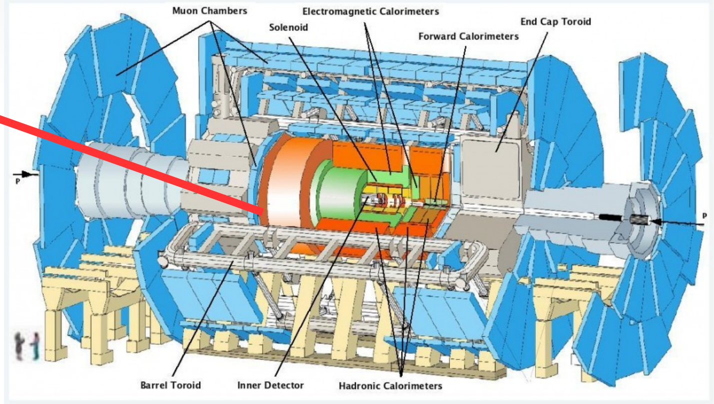
# LHC

| Proton beam parameters | LHC Design | 2012 LHC | Early 2015 LHC |
|---|---|---|---|
| # bunches/beam | 2808 | 1374 | 3 - 458 |
| Bunch spacing [ns] | 25 | 50 | 25 and 50 |
| Mean bunch length [ns] | 1.3 | 1.2 | 1.2 |
| Bunch intensity [$10^{11}$ p] | 1.15 | 1.1 - 1.7 | 1.0 – 1.2 |
| Emittance at injection [μm] | 3.5 | 1.5 – 2.0 | 1.5 – 3.0 |
| Collision energy/beam [TeV] | 7 | 4 | 6.5 |
| Emittance at collision [μm] | 3.75 | 2.4 | 1.5 – 4.0 |
| β* at ATLAS/CMS [m] | 0.55 | 0.6 | 0.8 |

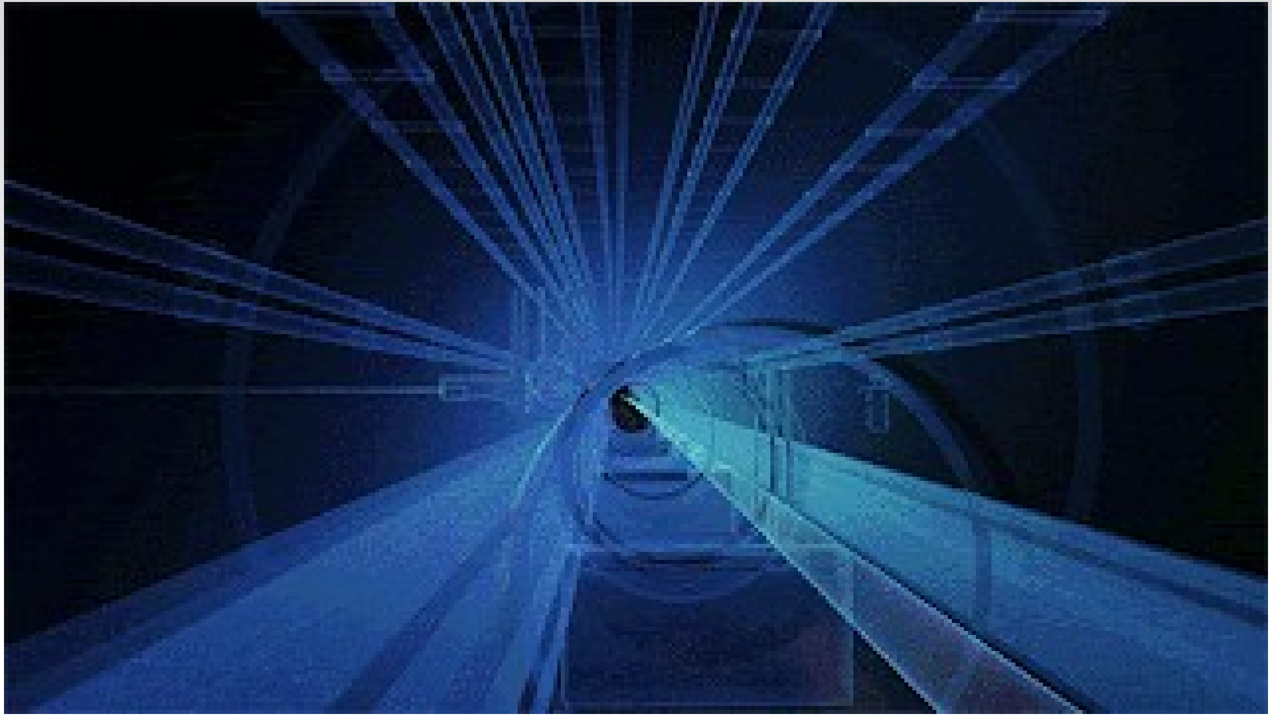


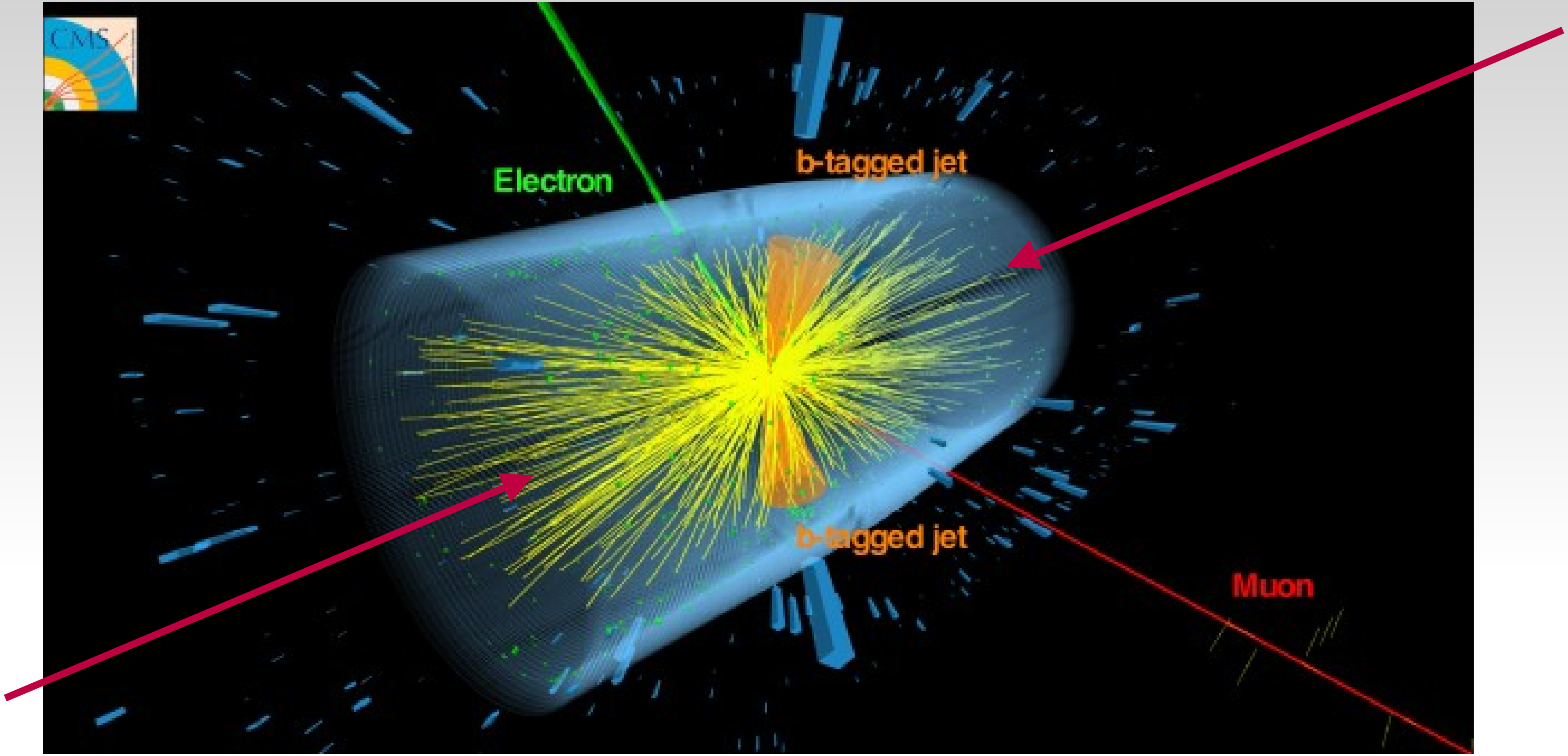


# Collisions

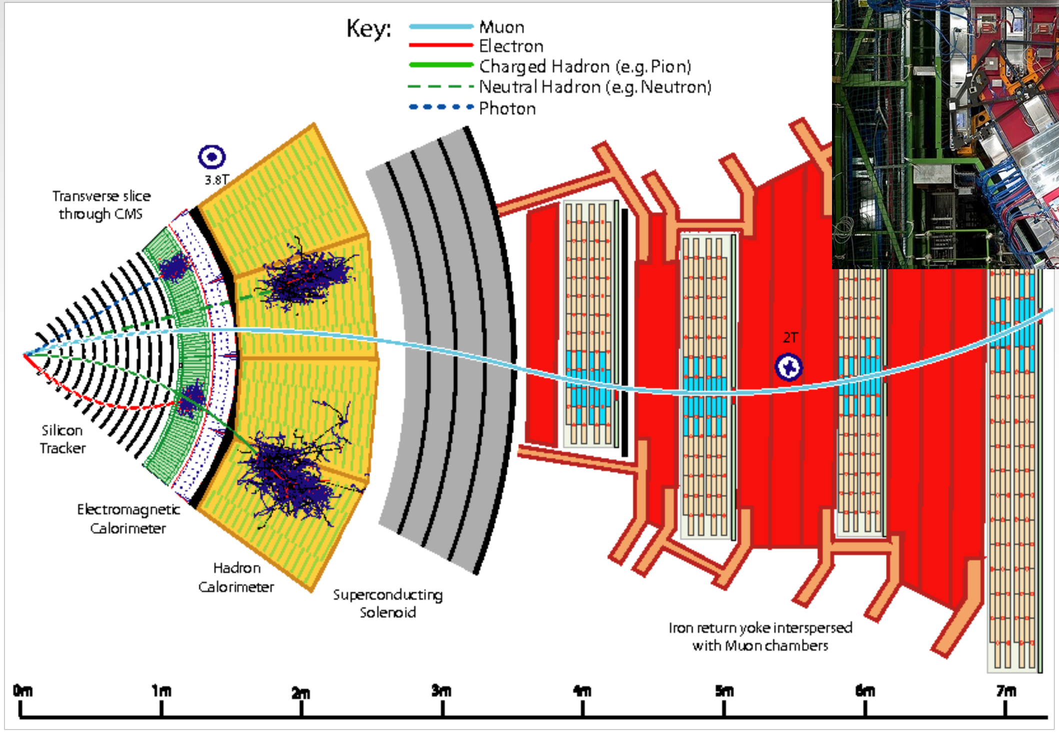


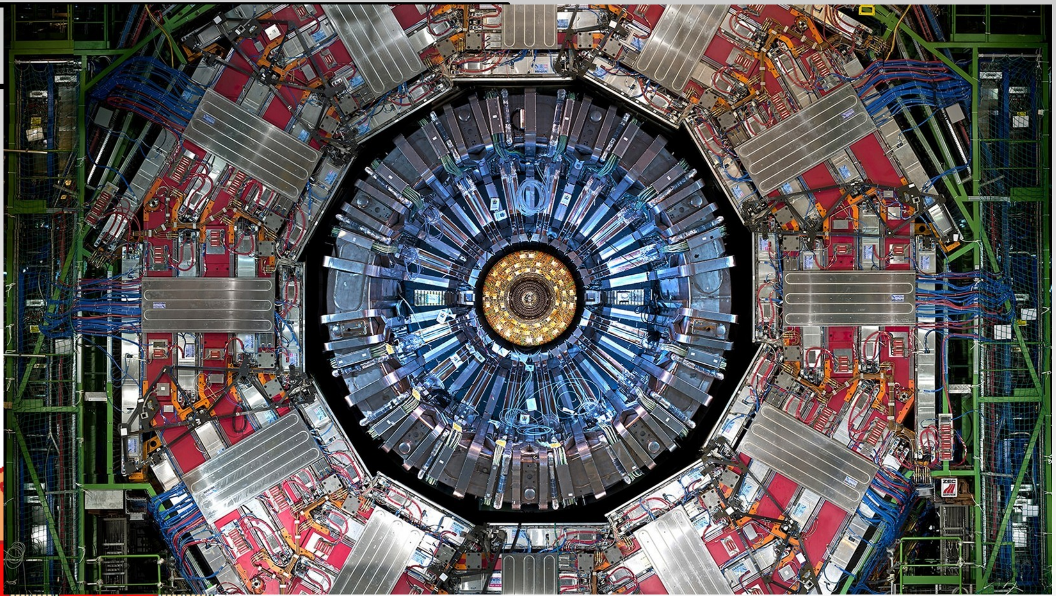
# Collisions again



# Particles identification

## Particle Flow paper

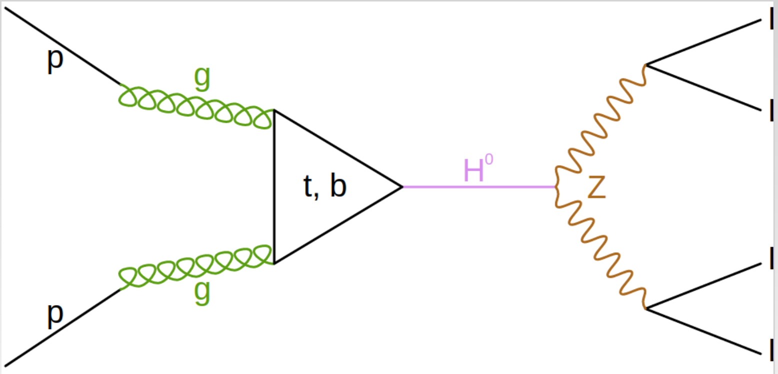


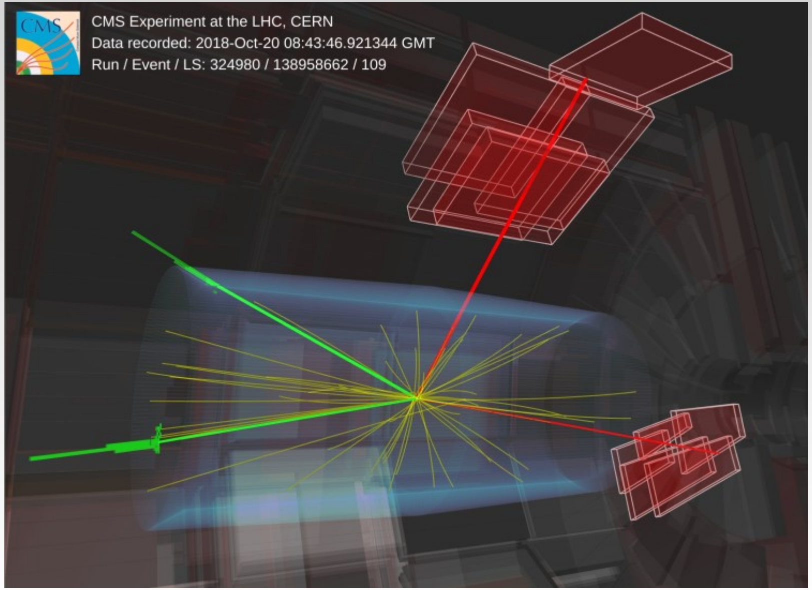



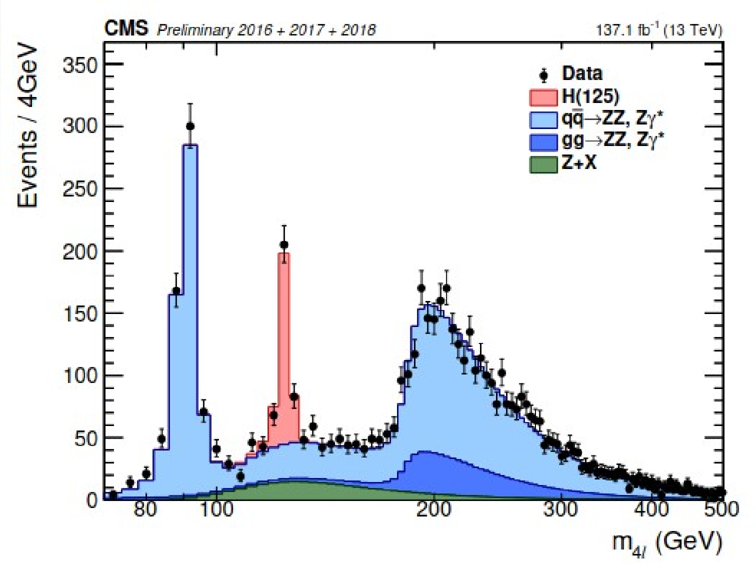
# Higgs boson example

- 4 July 2012: Higgs boson discovery by ATLAS – CMS from LHC
- Nobel prize to theorist who have predicted Higgs mechanism and Higgs boson (Englert-Higgs, Brout died before) in 2013. (Peter Higgs died in 2024)

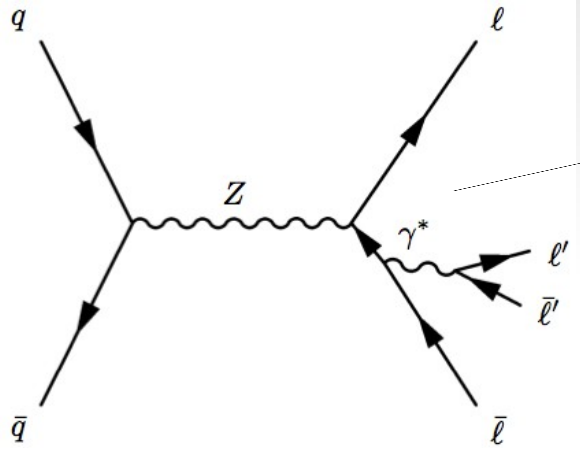
# Higgs boson example

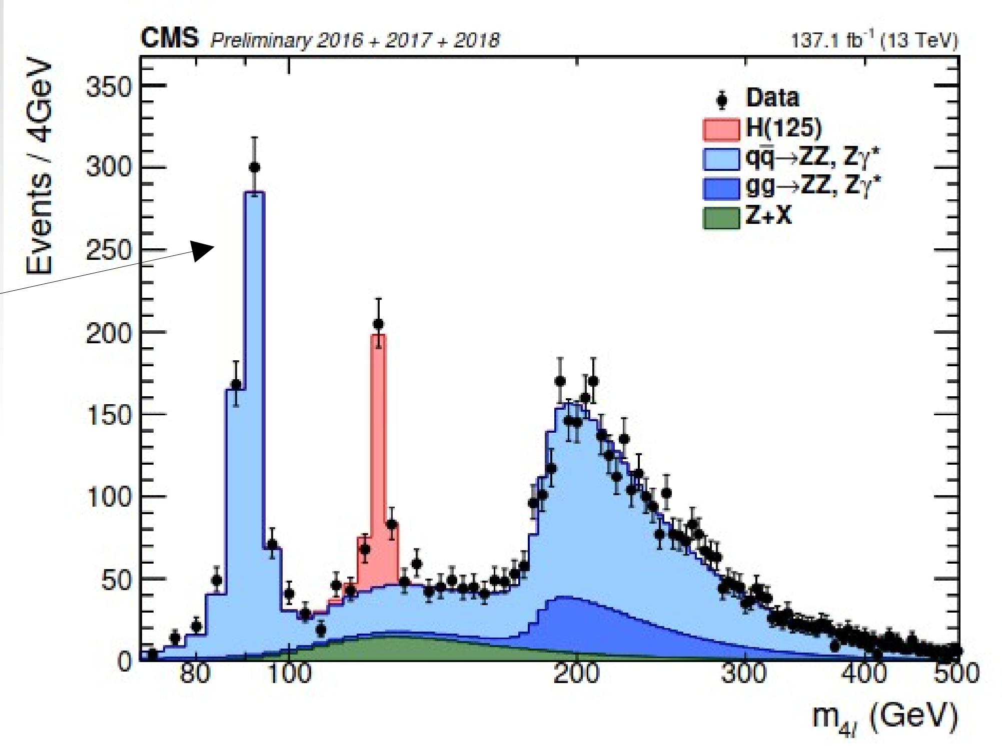


# *Higgs boson example*



# *Homework*

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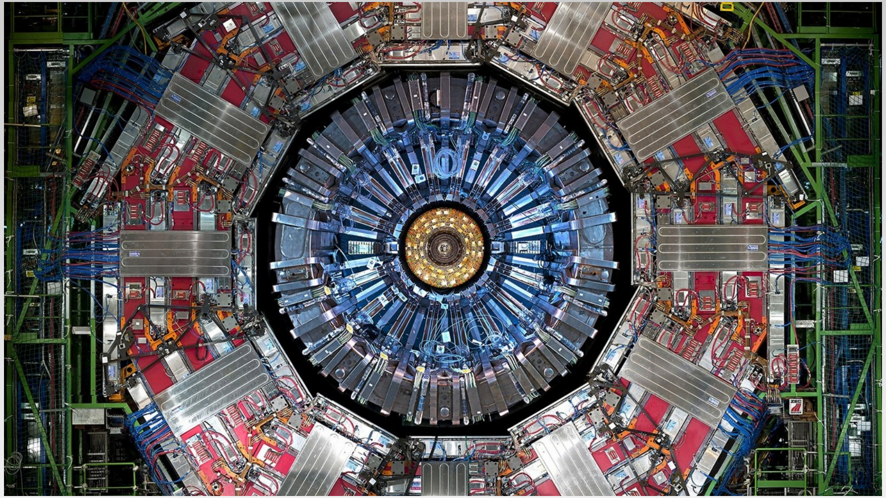
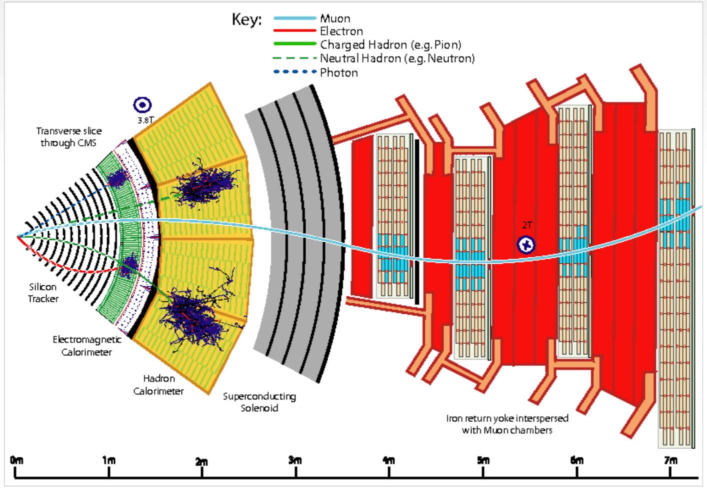
CMS

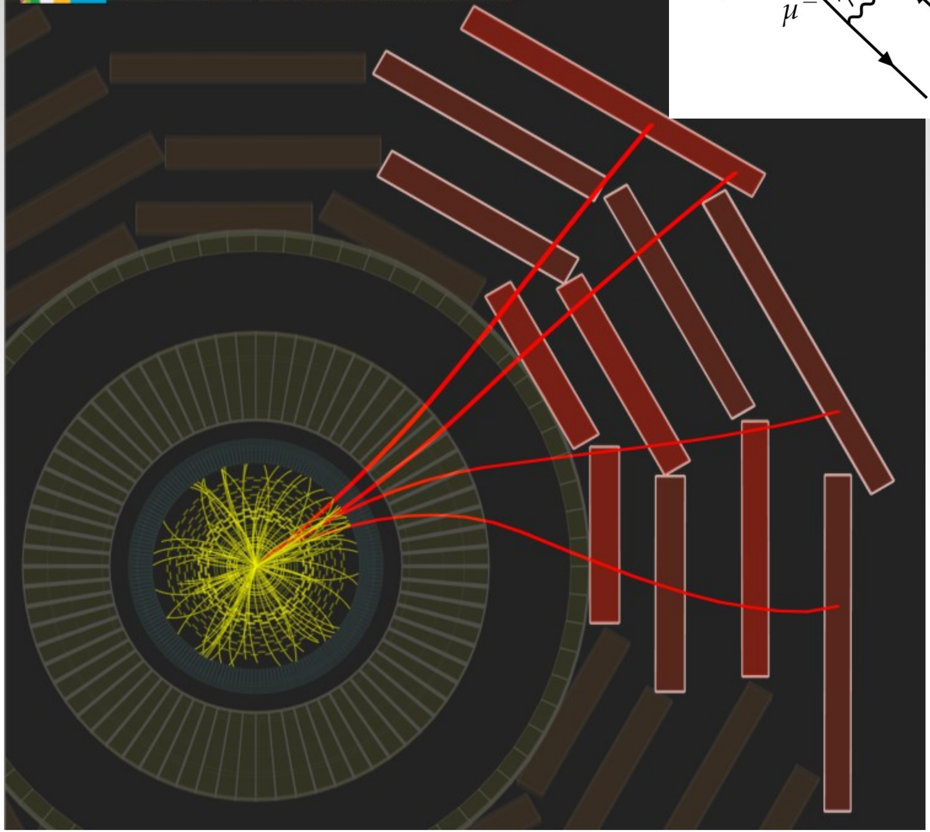
Compact Muon Solenoid

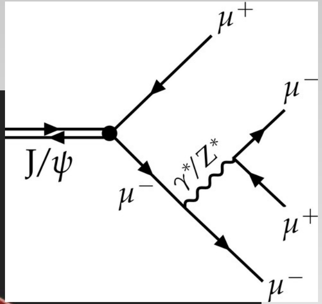




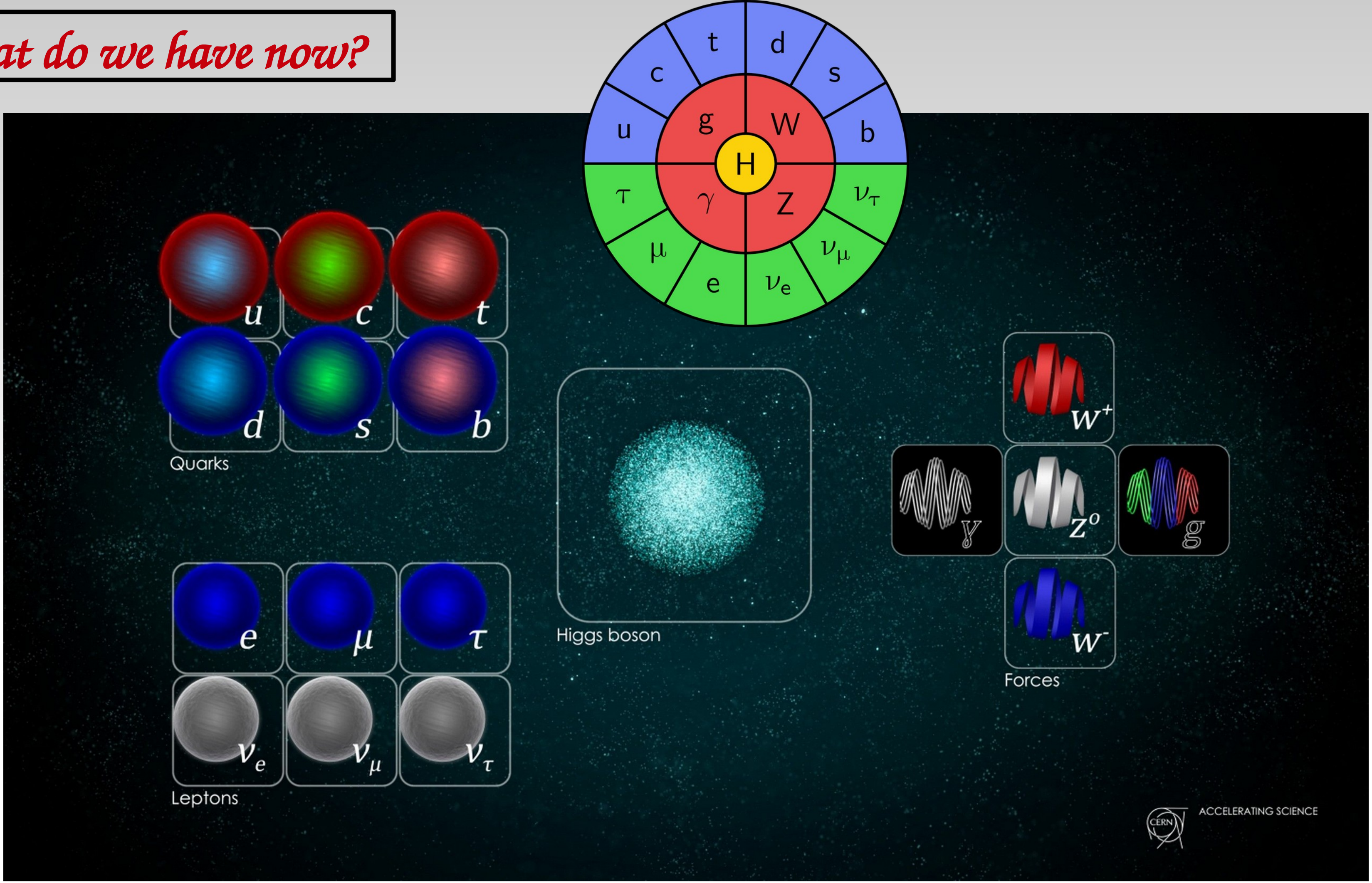
# Homework

CMS Compact Muon Solenoid

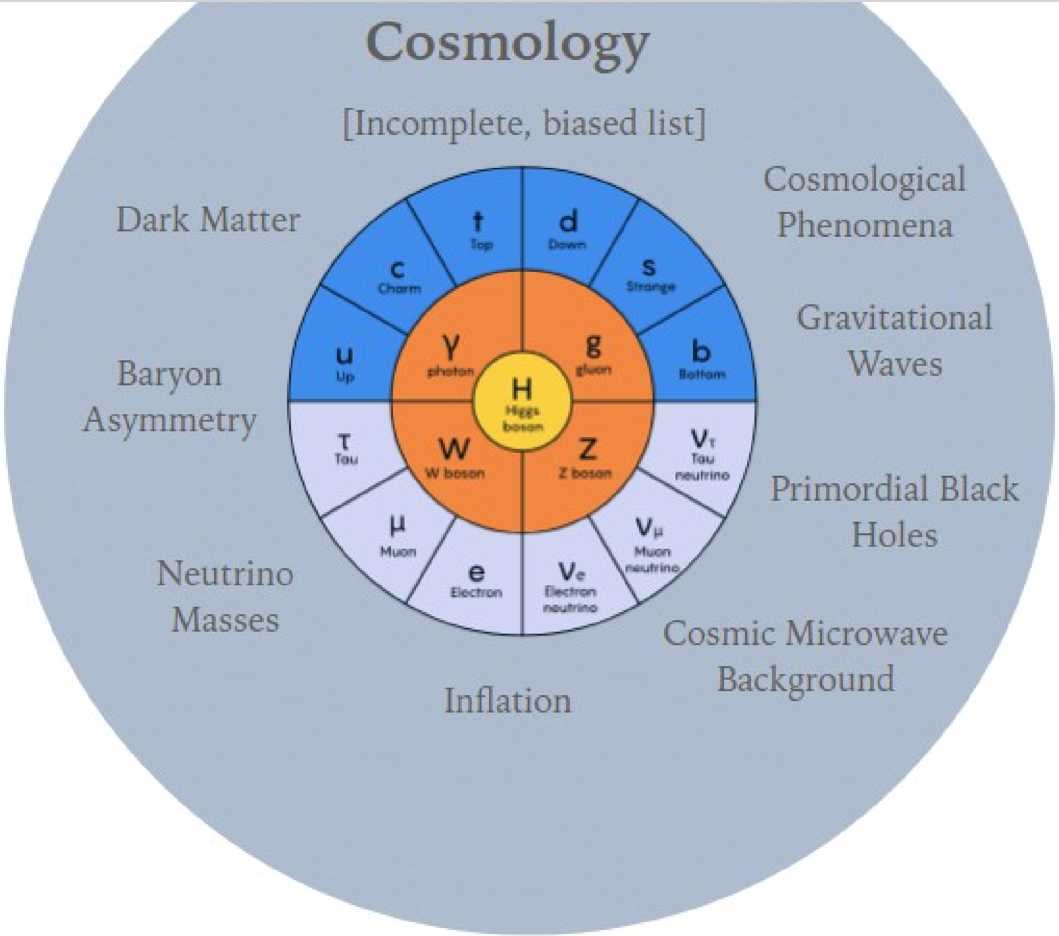


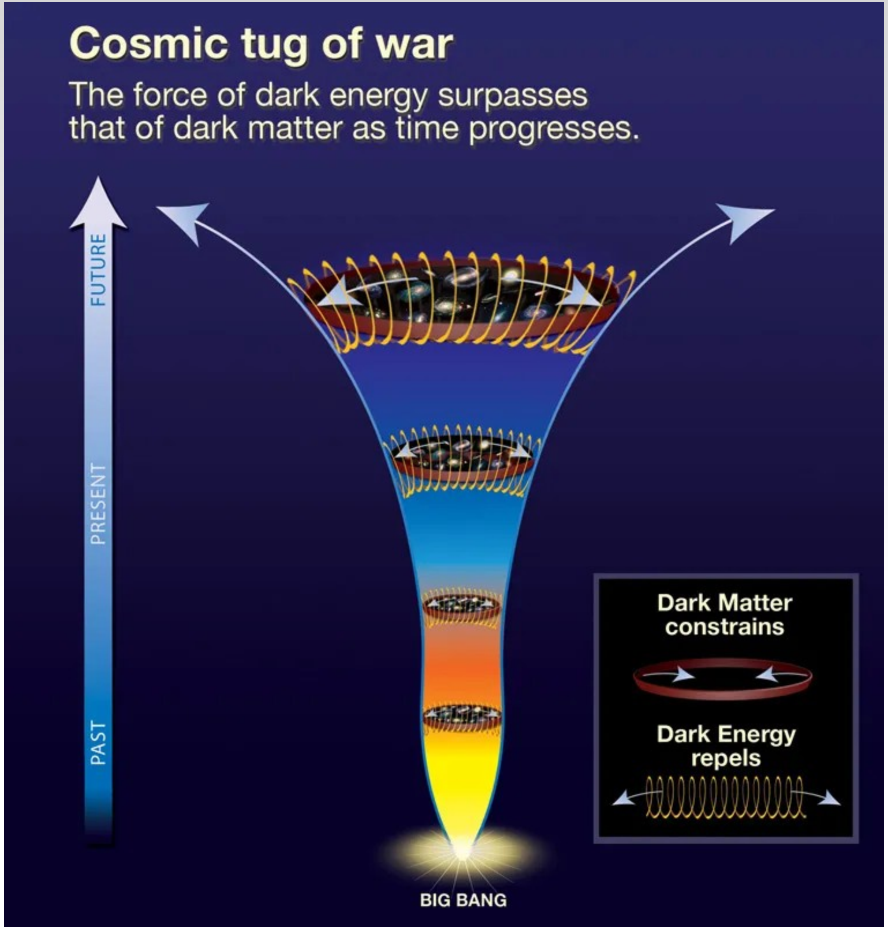
# What do we have now?

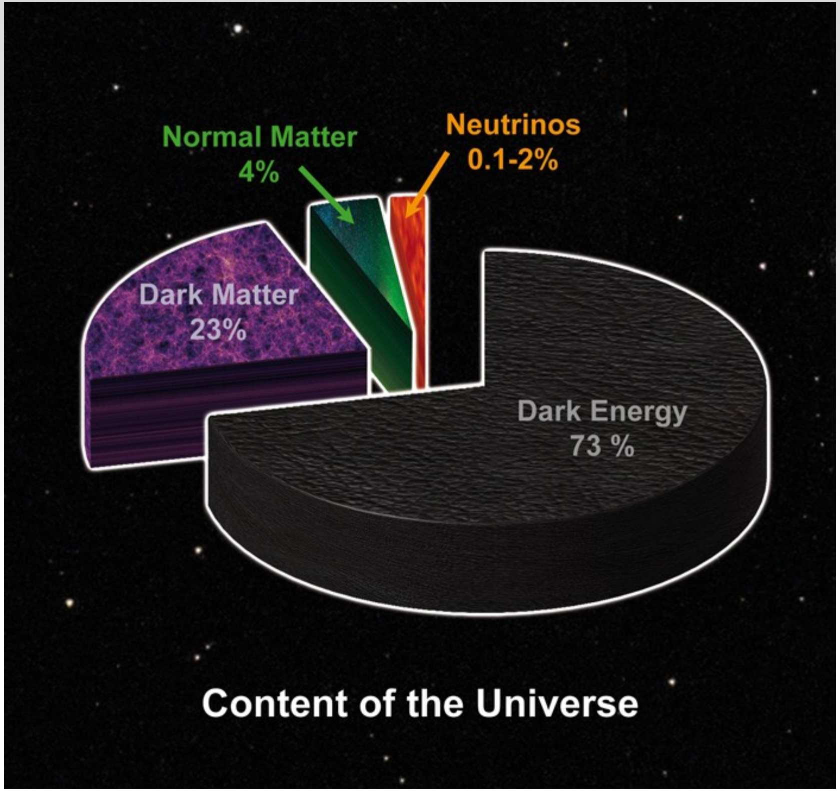


# *What do we don't know?*

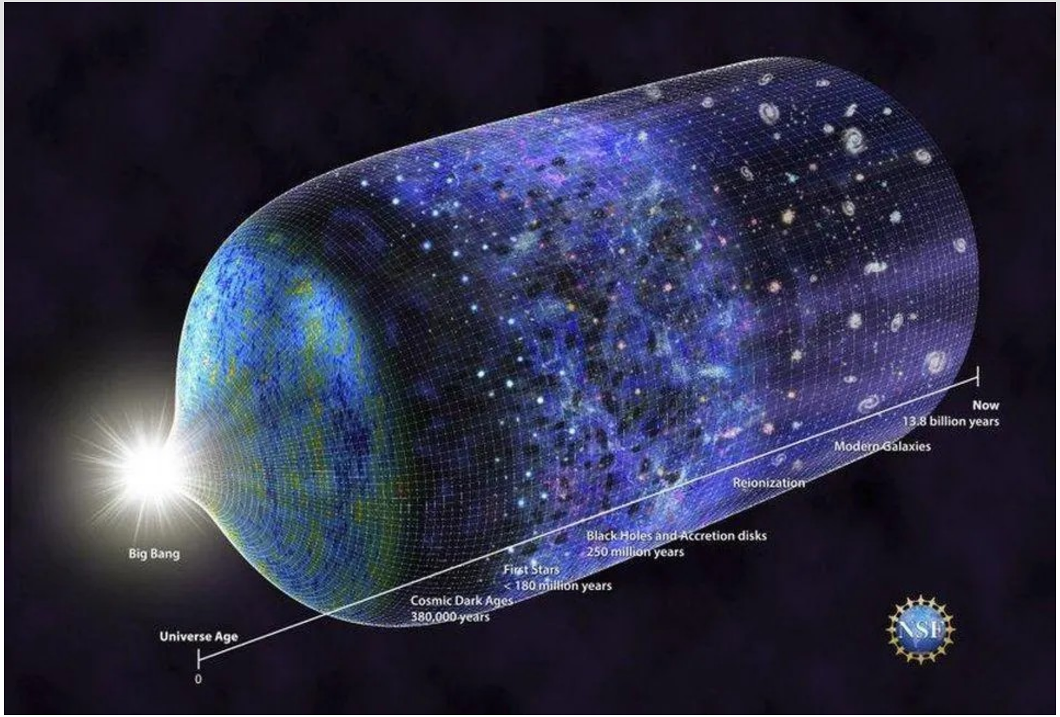


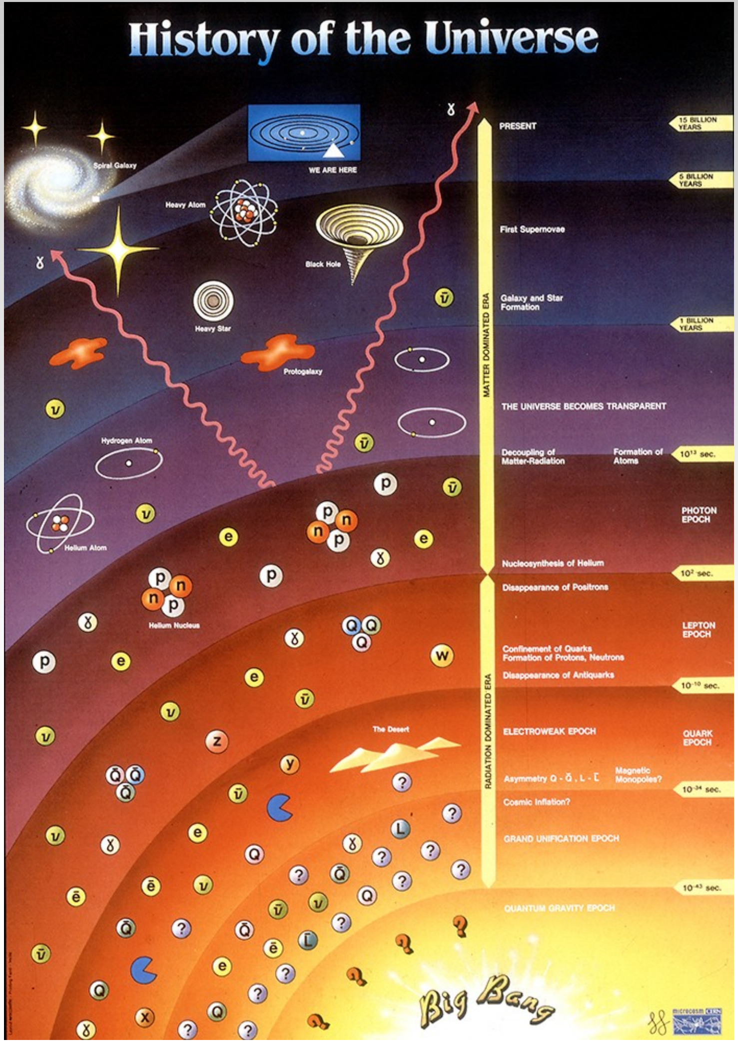
# What do we don't know: dark matter – dark energy



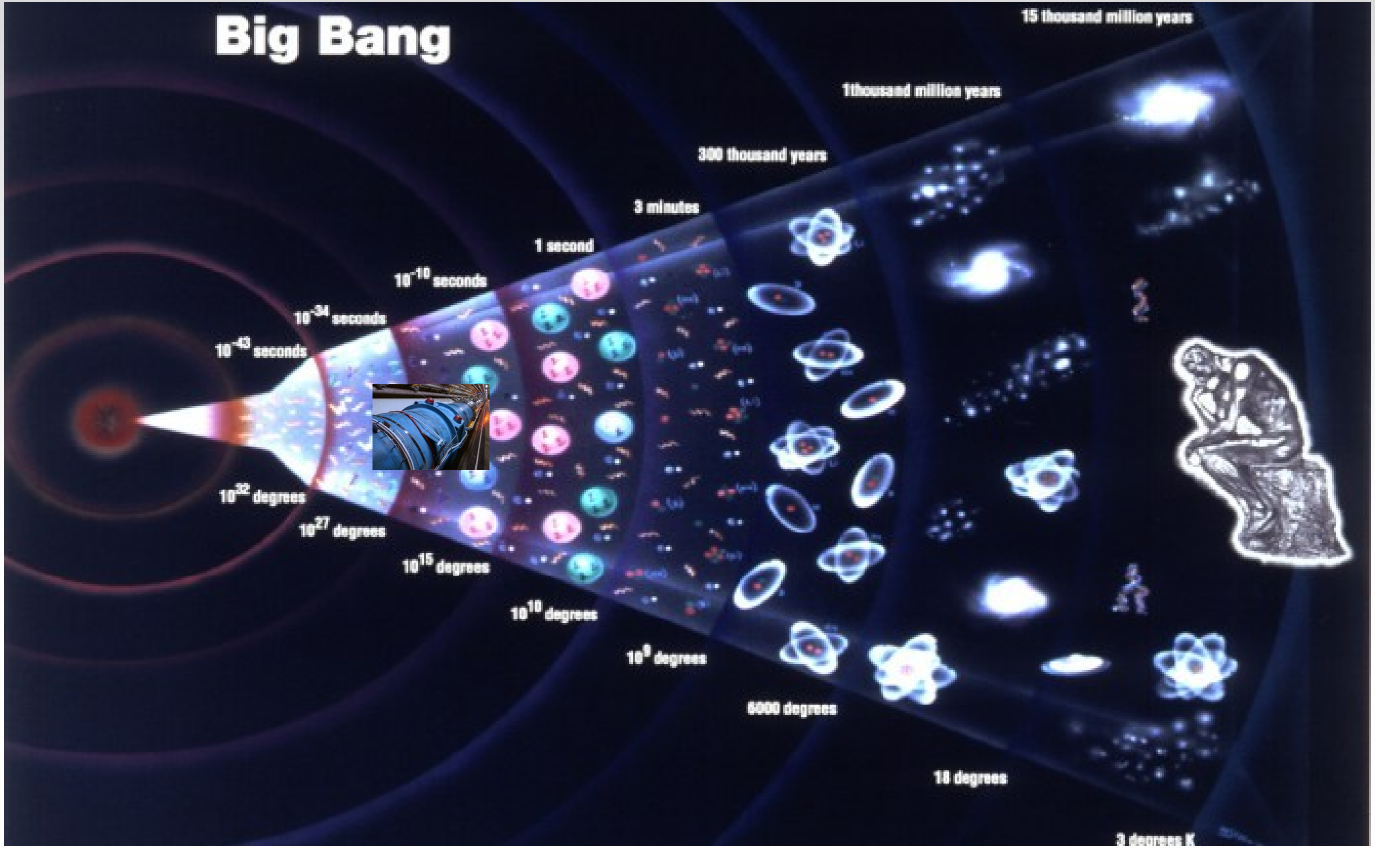



# *What do we don't know: inflation, matter antimatter asymmetry*

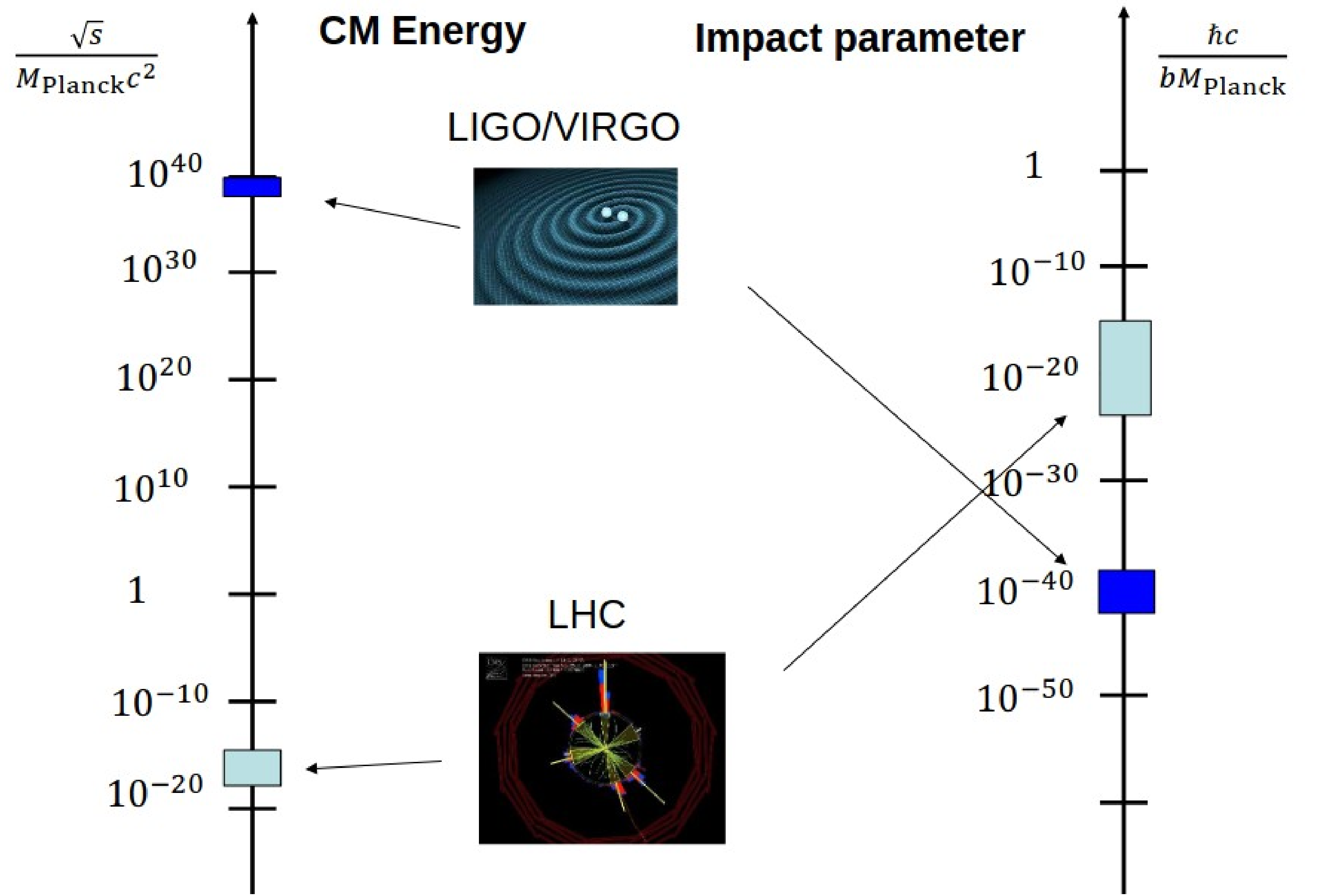


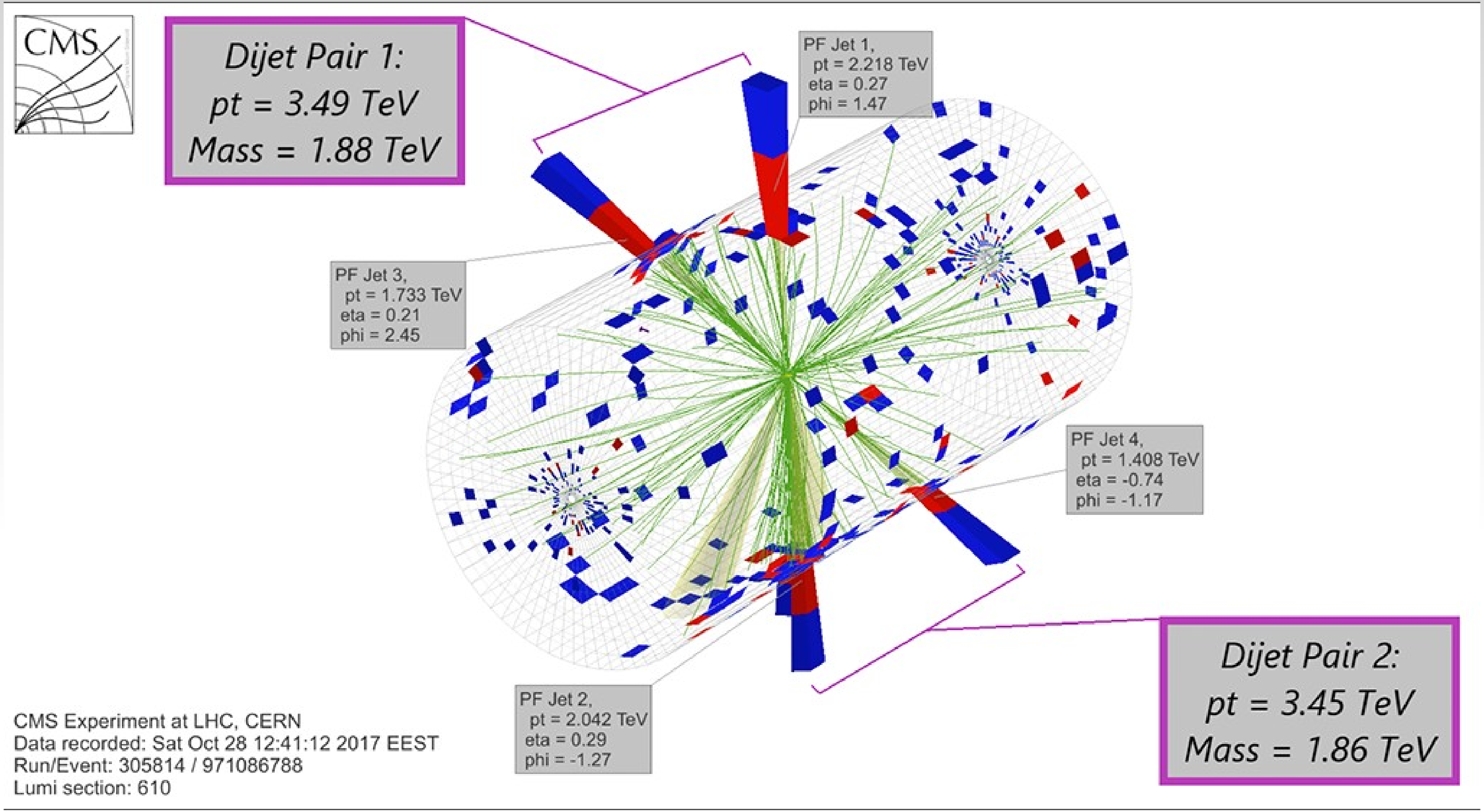
# *LHC time travel machine*



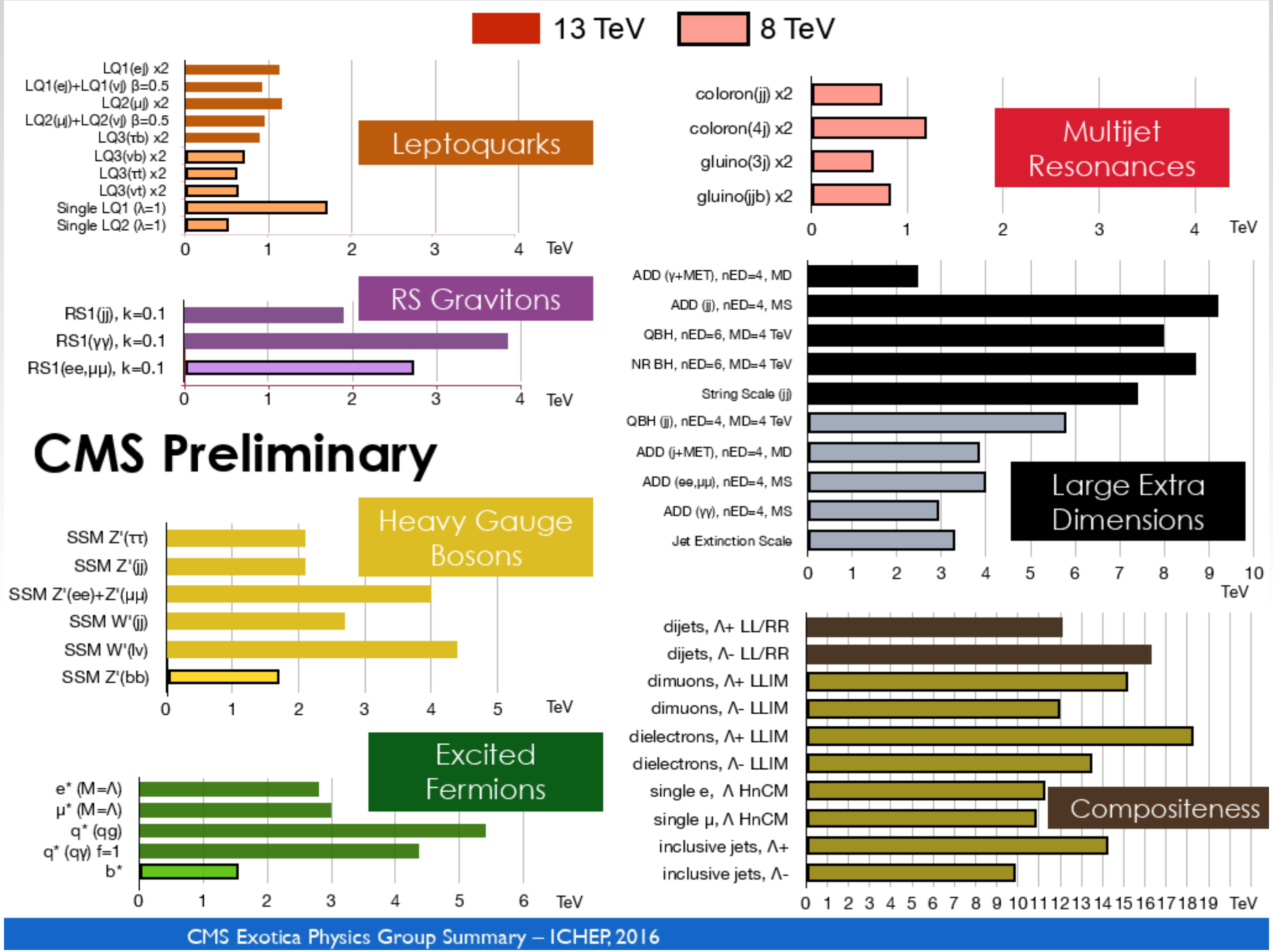
# *LHC energy domain*

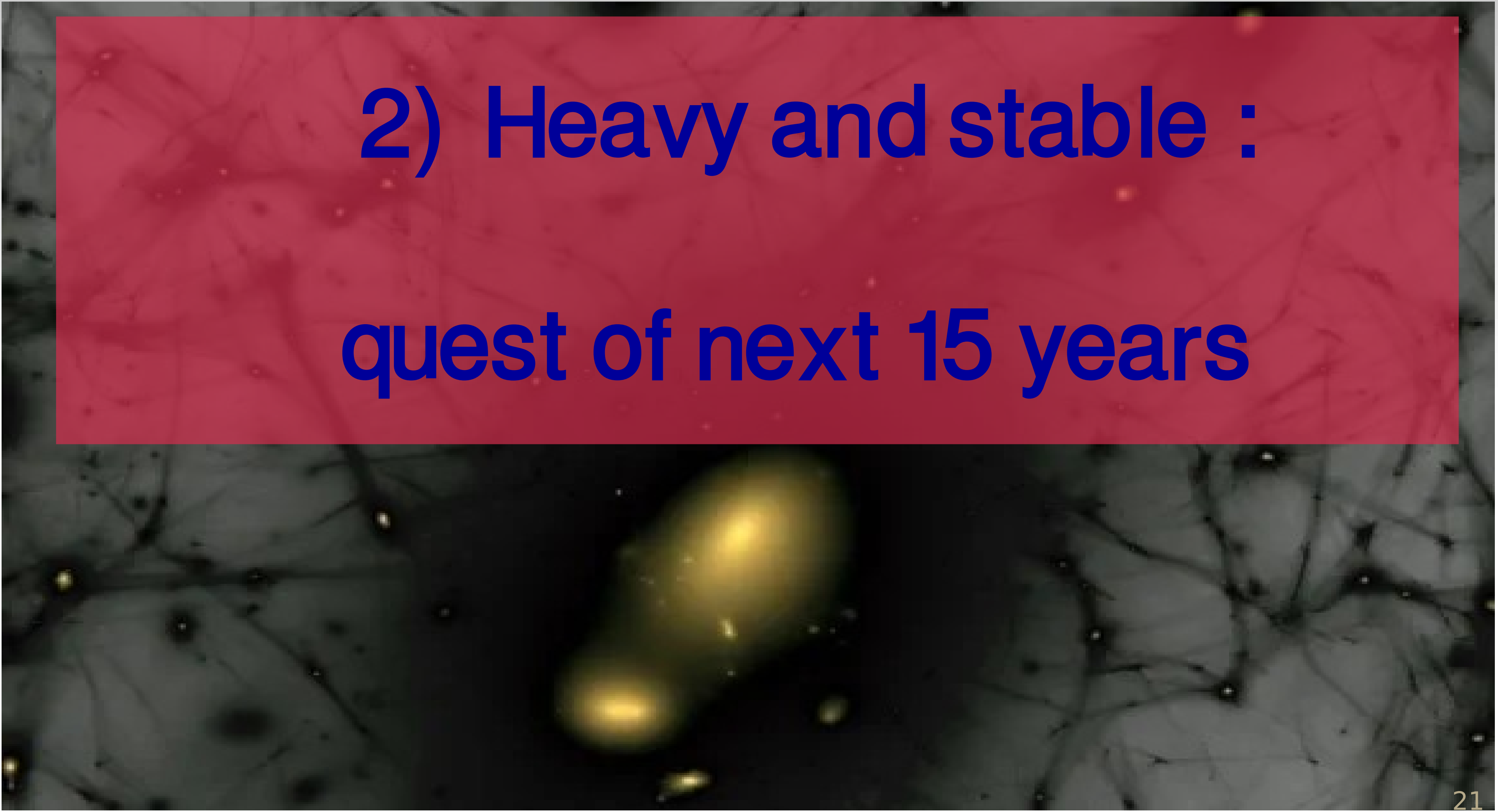


# ATLAS / CMS looks at high energy phenomena

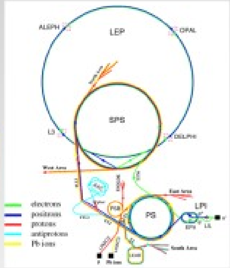


# ATLAS / CMS looks at high energy phenomena




2) Heavy and stable :
quest of next 15 years

**RECENT PAST**

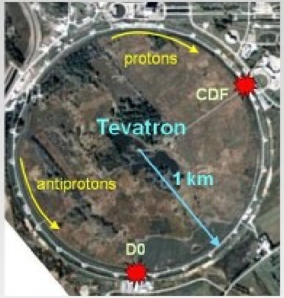



**LEP e+e-**
**209 GeV (CERN)**

- Z factory
- $m_H > 114$ GeV

**TEVATRON p+p-**
**1.96 TeV (USA)**

- W, Z factory
- M ~ 175 GeV
- $M_H$ != 2 $M_W$

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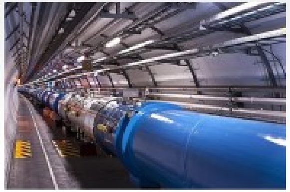
**PRESENT**



**LHC p+p+**
**14 TeV**
**(CERN)**

- W, Z, Top factory
- $M_H$ = 125 GeV

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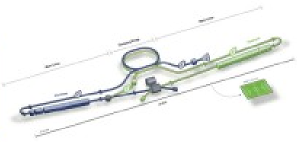
**TOMORROW?**
**2023-2035**



**ILC e+e- ???**
**250 GeV (JAPAN)**

- Z, H factory
(Very disfavoured)

**HL-LHC p+p+**
**14 TeV**
**(CERN)**

- H factory: 10 Lumi LHC

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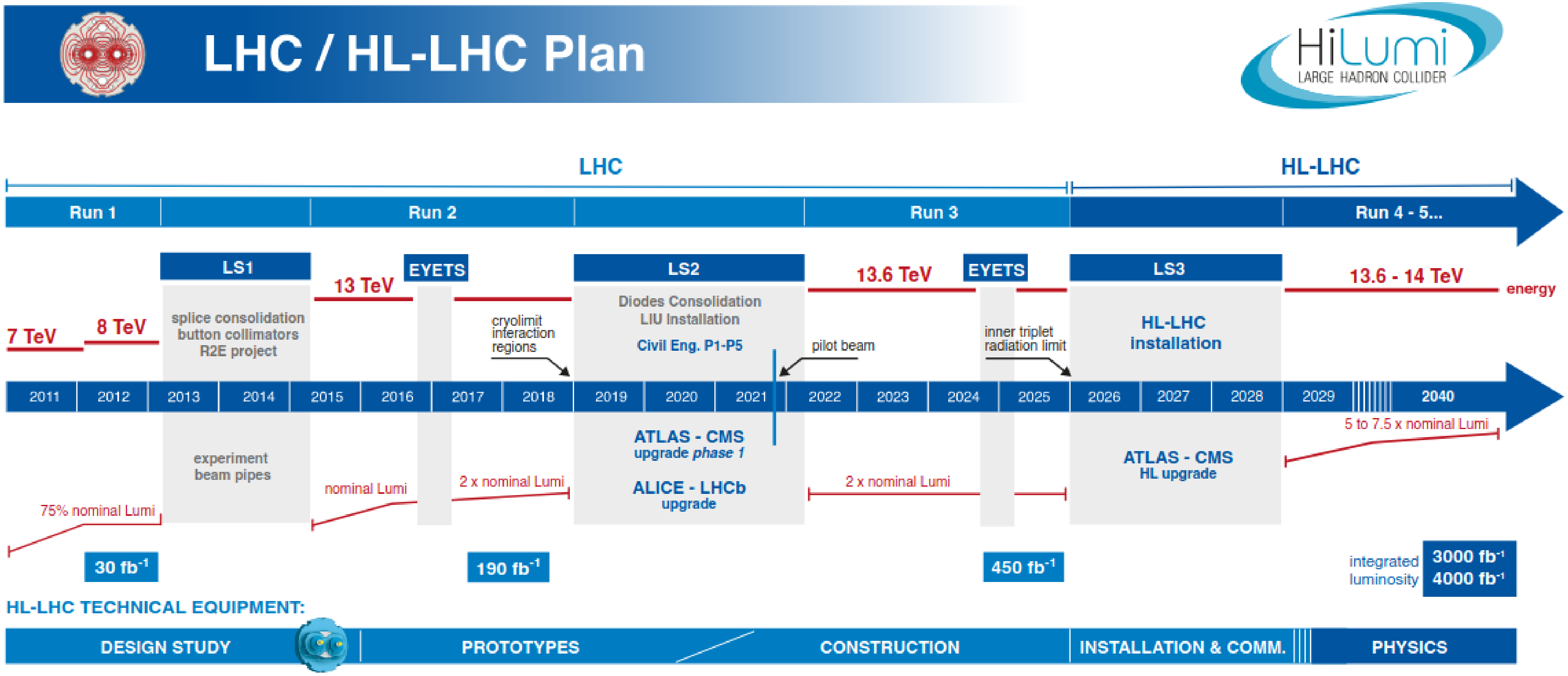
**HYPOTHETICAL AFTER TOMORROW**
**2035→ 2050**

**e+e- linear**
ILC 350, 500 GeV (JAPAN)
CLIC 380-3000 GeV (CERN)
**e+e- circular**
CEPC 240 GeV (CHINE)
FCC-ee 90-350 GeV (CERN)

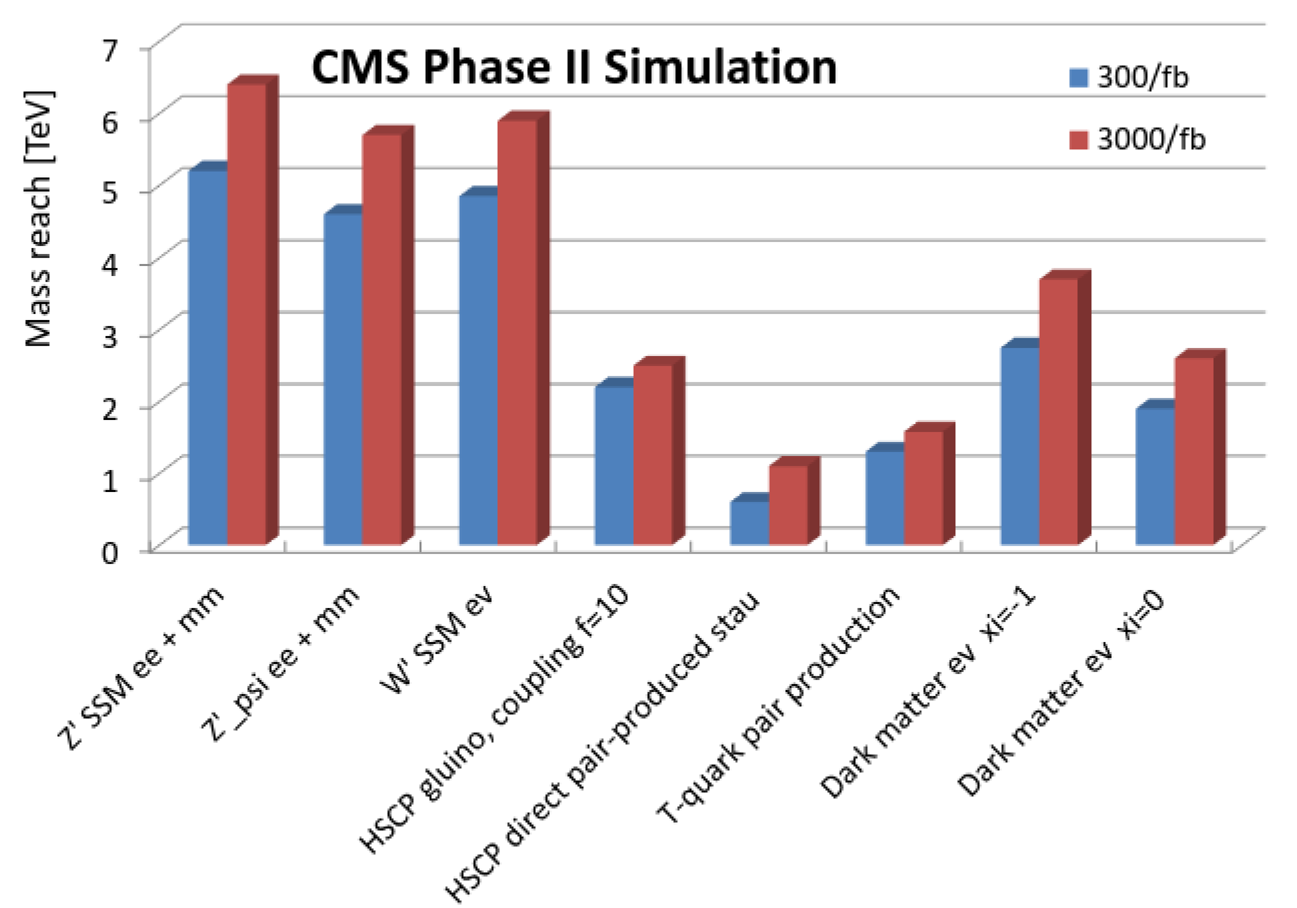
**p+p+**
CEPC ~ 50-70 TeV (CHINE)
HE-LHC ~ 30 TeV (CERN)
FCC-pp ~ 100 TeV (CERN)

# *What are the next 15 years at LHC?*

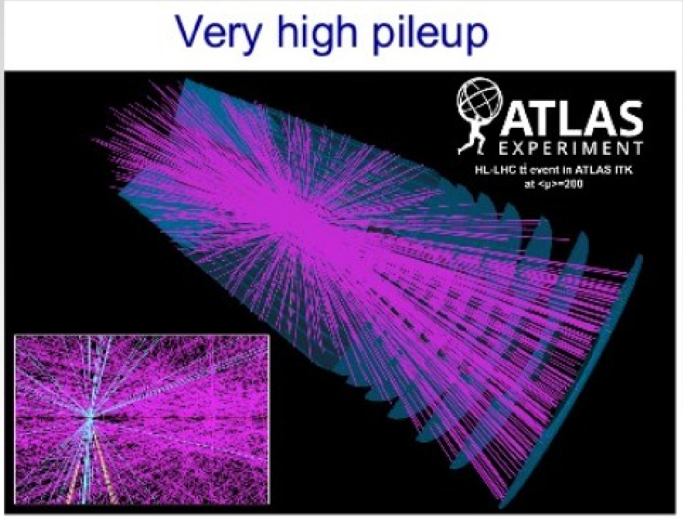



Nearly no energy increas at HL-LHC

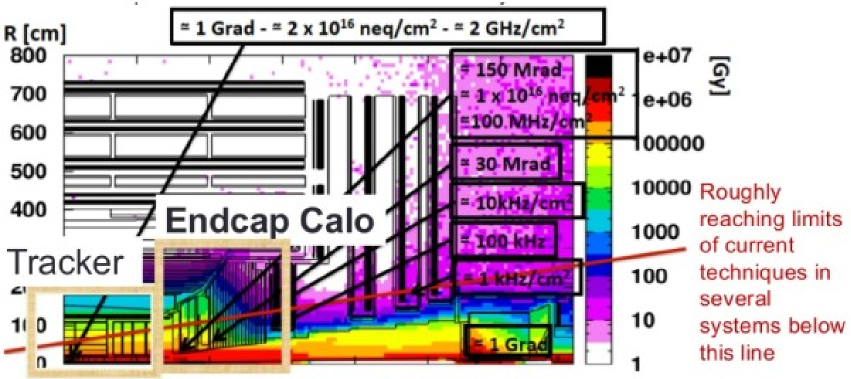
# What are the next 15 years at LHC?



# What would be an HL-LHC detector

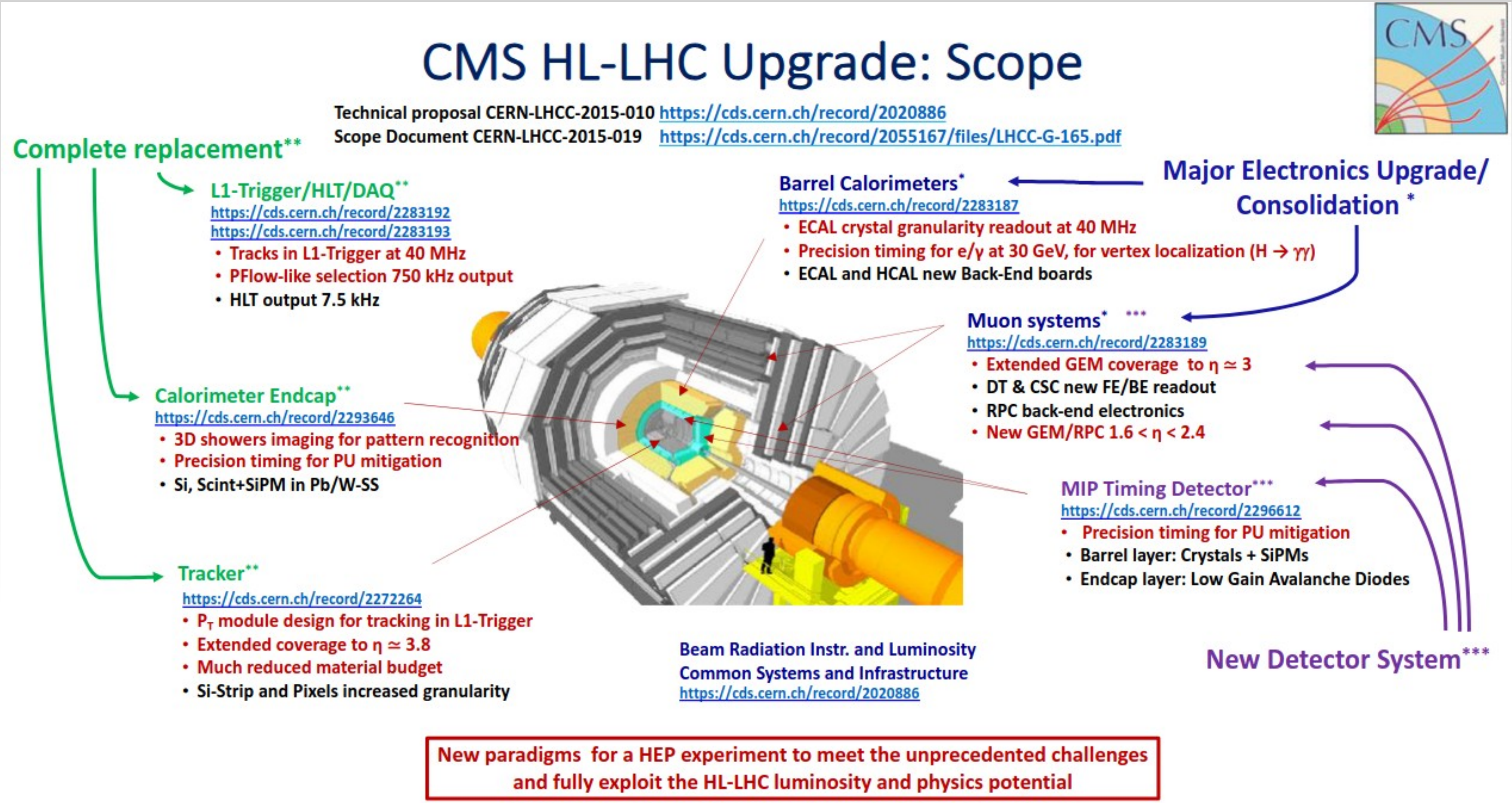



- In-time PU = 140 – 200
  - For example for a jet with R = 0.5 PU energy within the catchment area can be up to 100 GeV.
- Out-of-time PU:
  - collisions every 25 ns (since 2015)



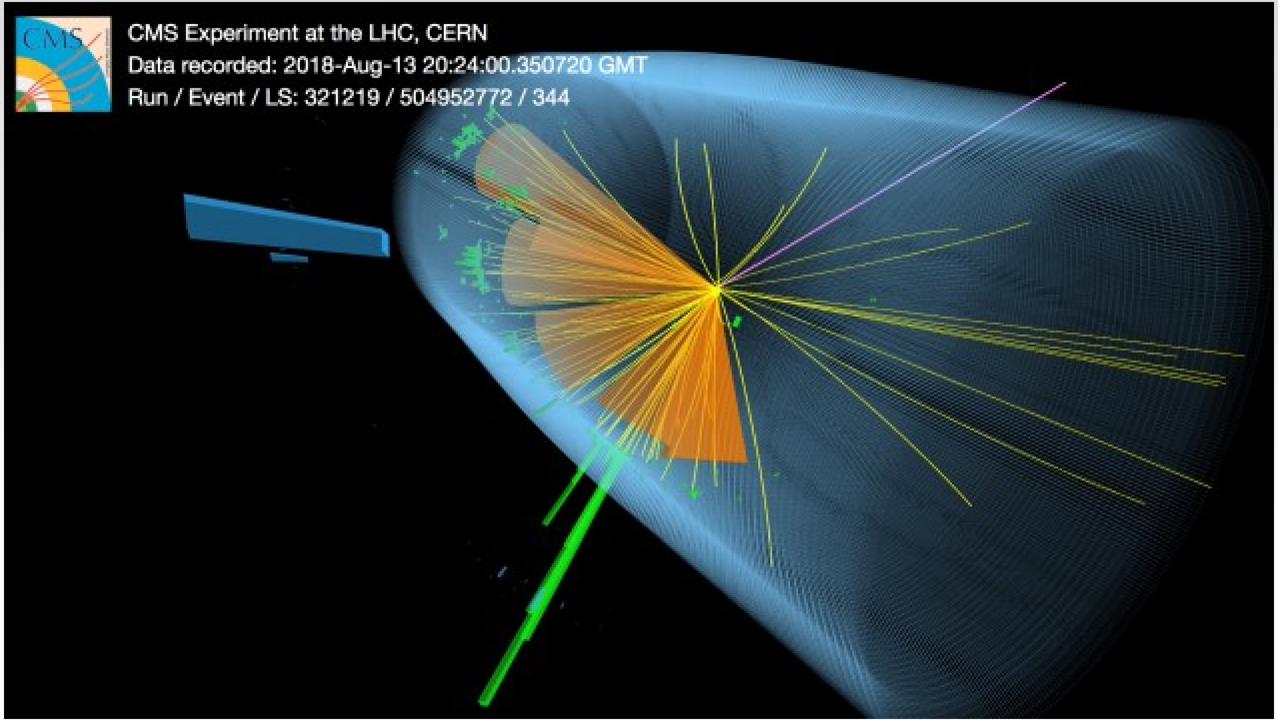

- The present system already suffered aging → Many Phase I upgrades considered.
- Aging during HL-LHC would be much more severe.

# What would be an HL-LHC detector

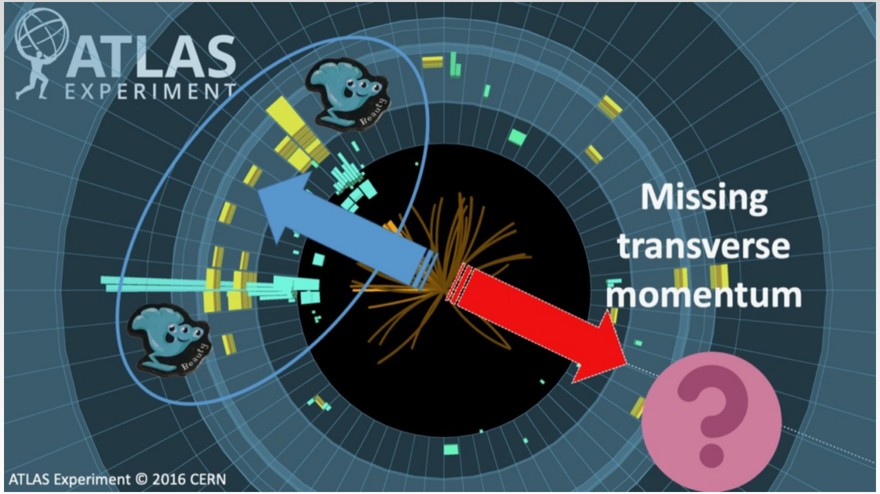


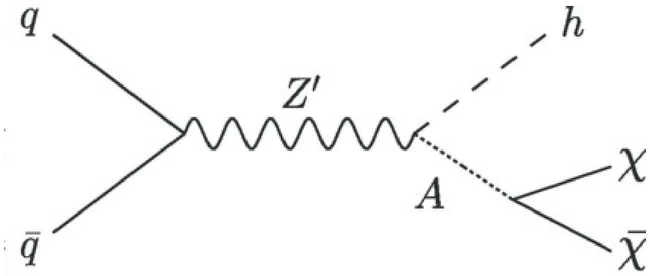

- High precision timing detectors : Timing layer between tracker and calorimeter
- High precision timing for Muon chambers : 1.5 – 0.5 ns time resolution
- New tracker with high rate fast transmission

# ATLAS / CMS actual dark matter search: missing energy

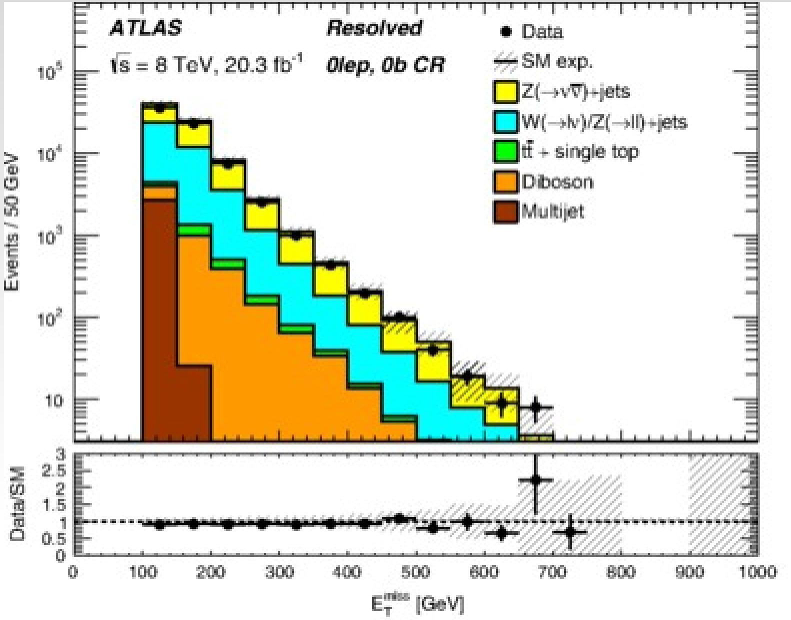


# ATLAS / CMS actual dark matter search




(b) $Z'$-2HDM

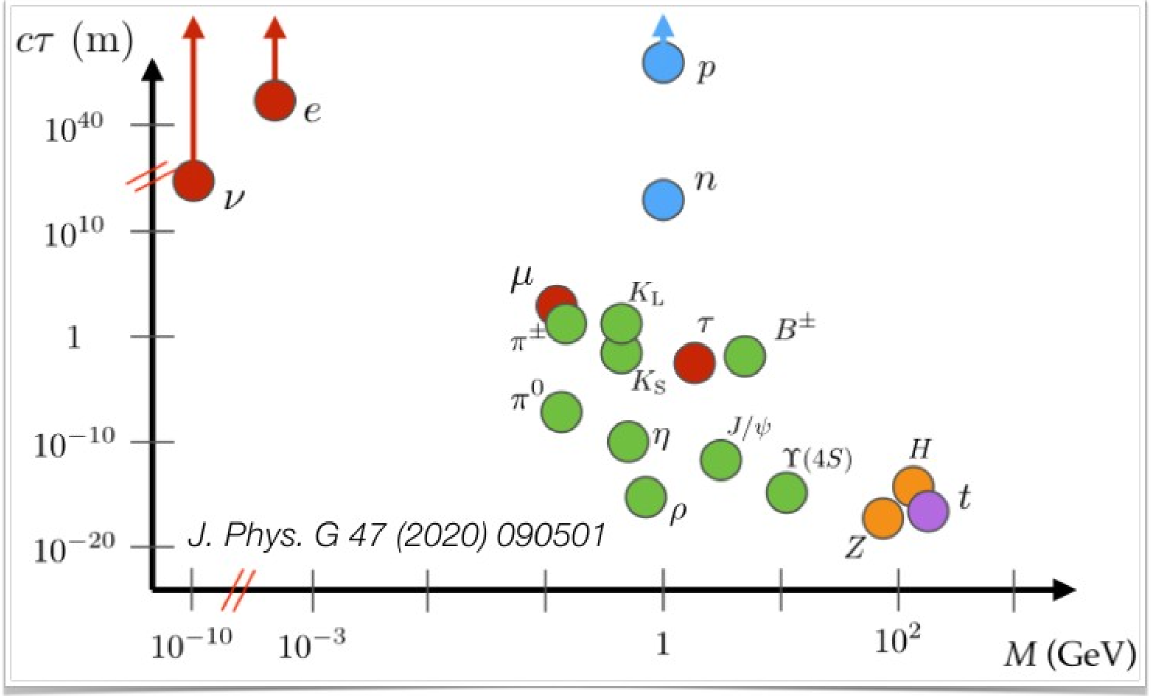



(a) Resolved channel

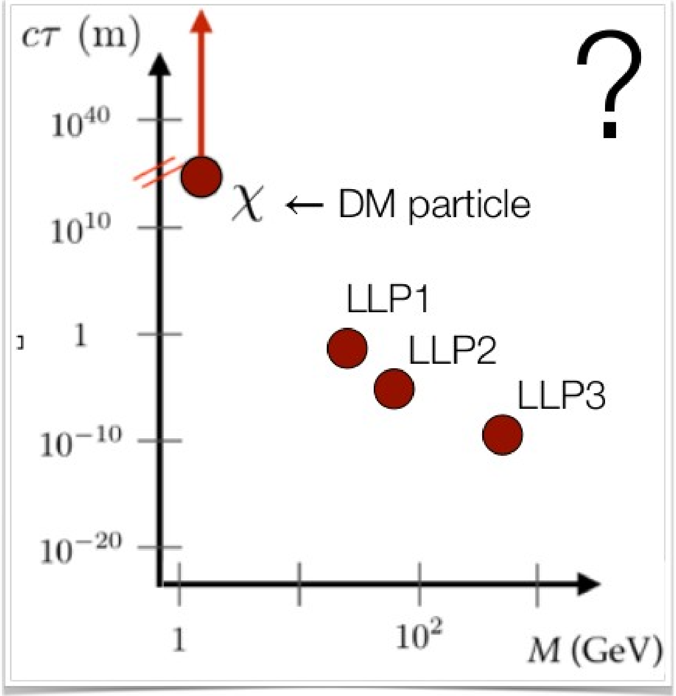
# Can we do better

What if the Dark Sector is non-trivial?

SM sector

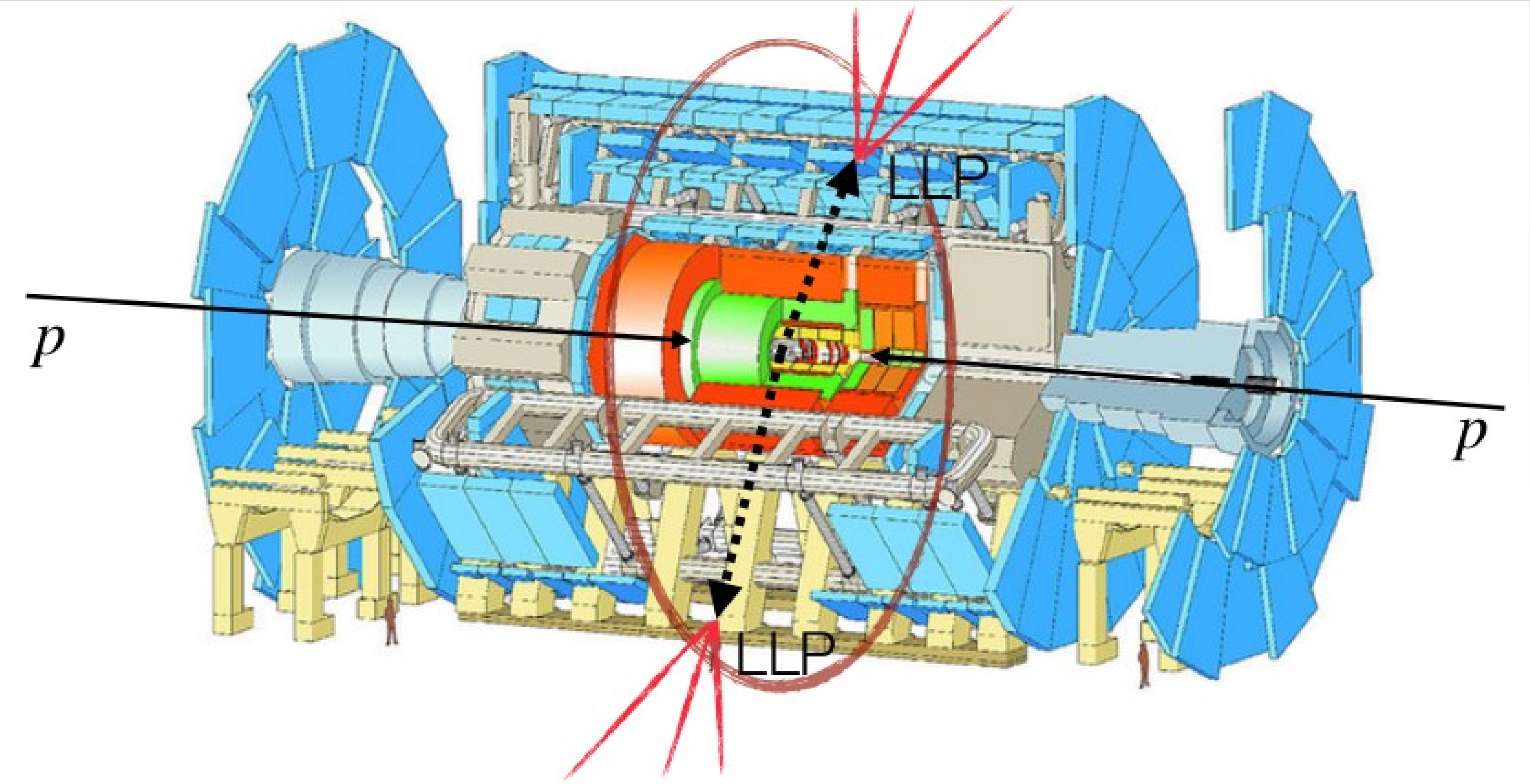



Dark Sector




[ Long-lived particle (LLP) signatures ubiquitous in many other BSM scenarios like e.g. baryogengesis ]

# *Timing and distance is the new frontier*



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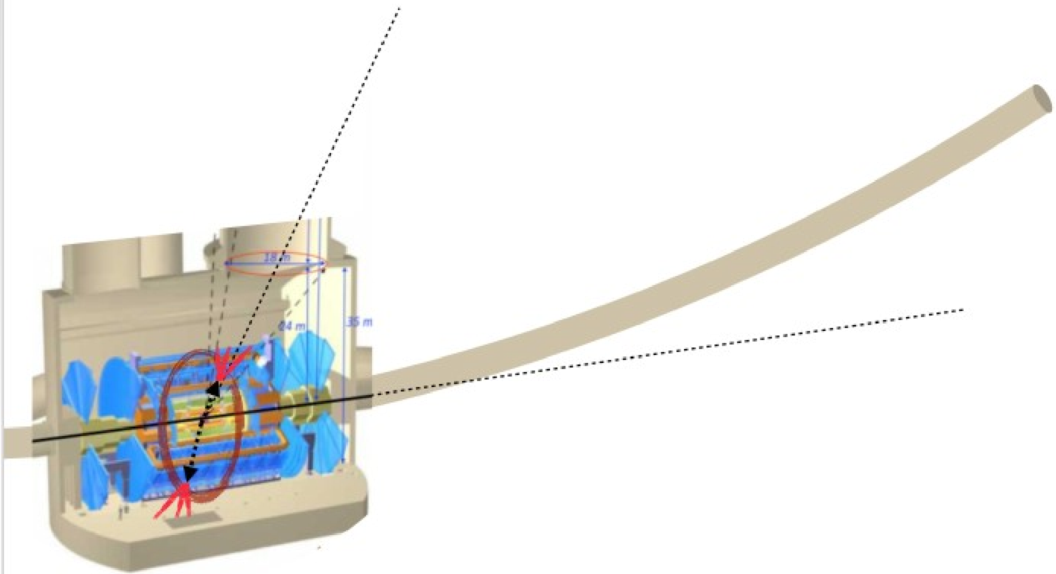


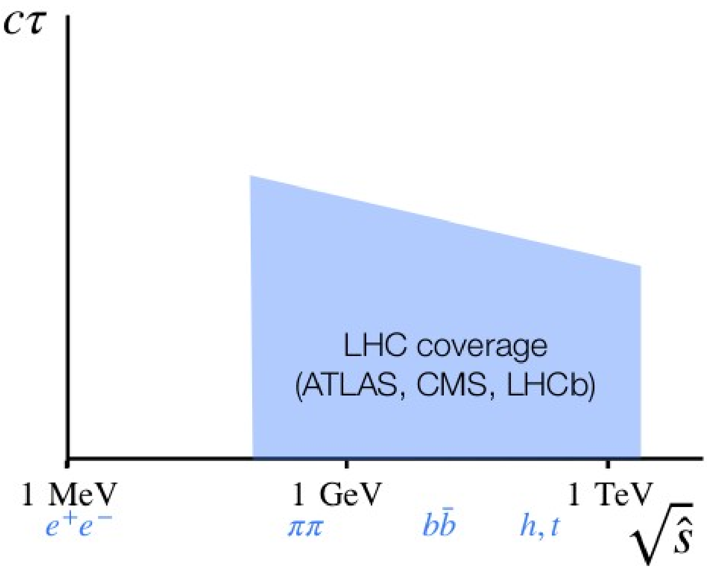

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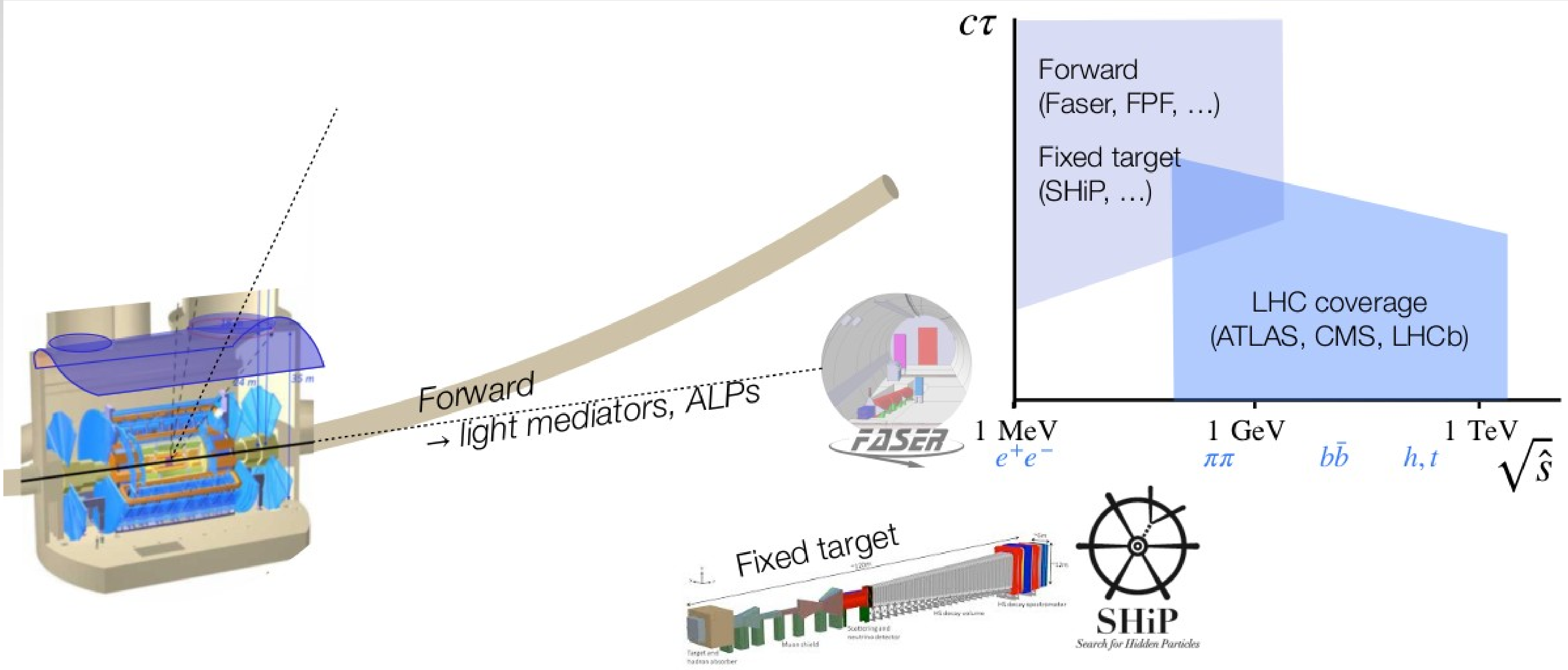

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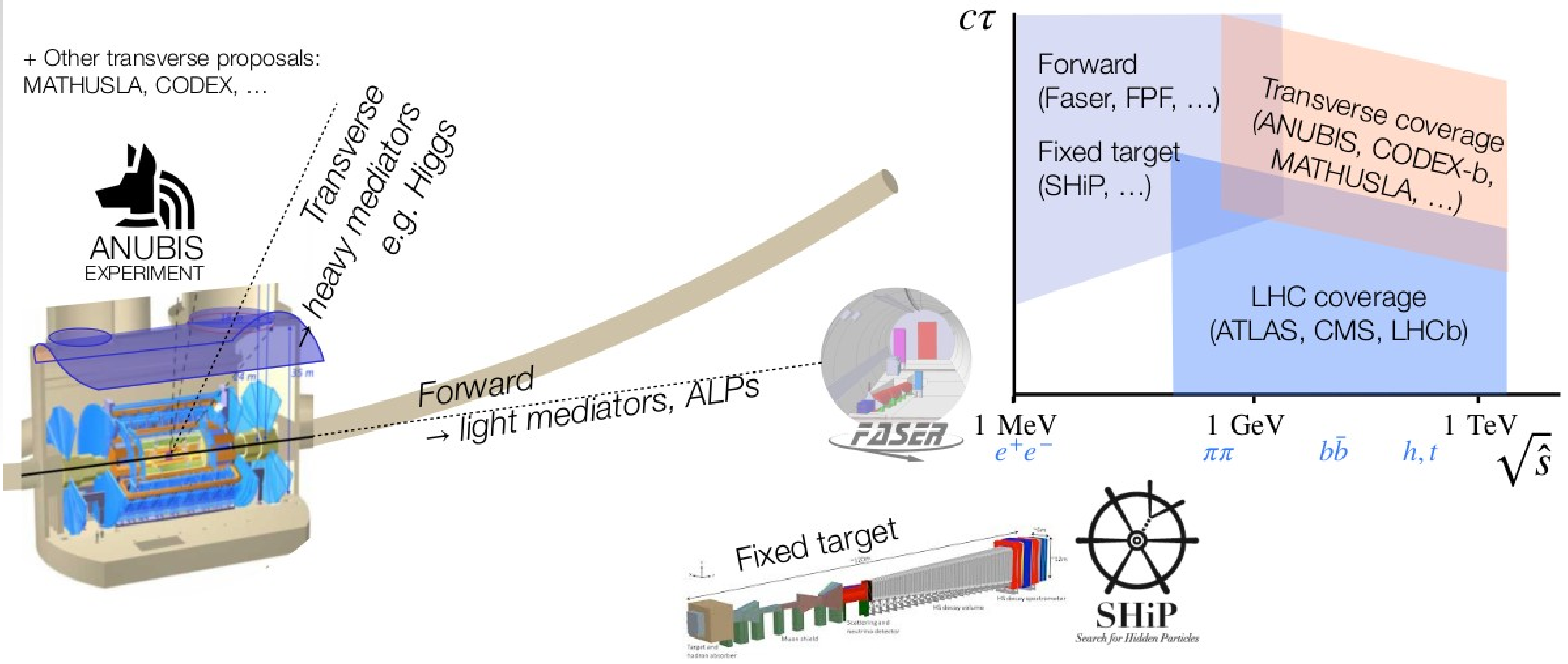

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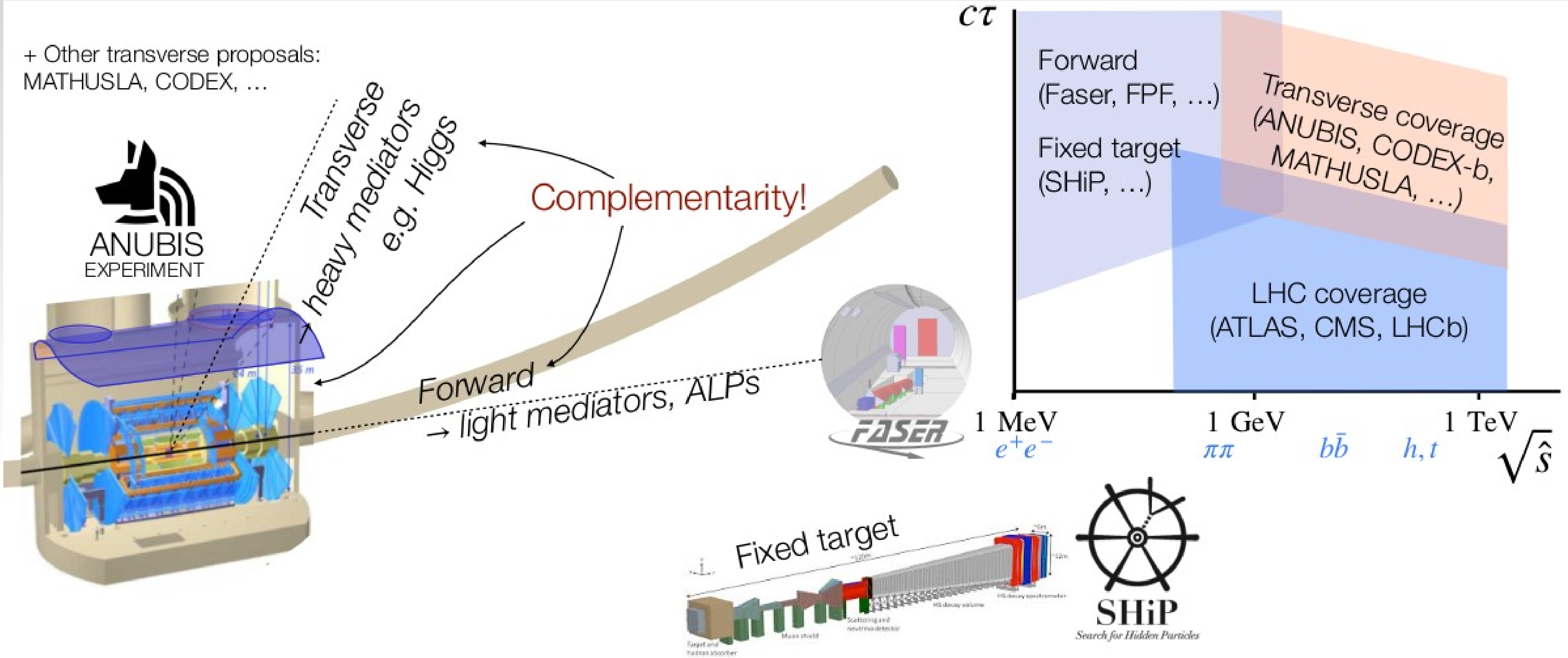
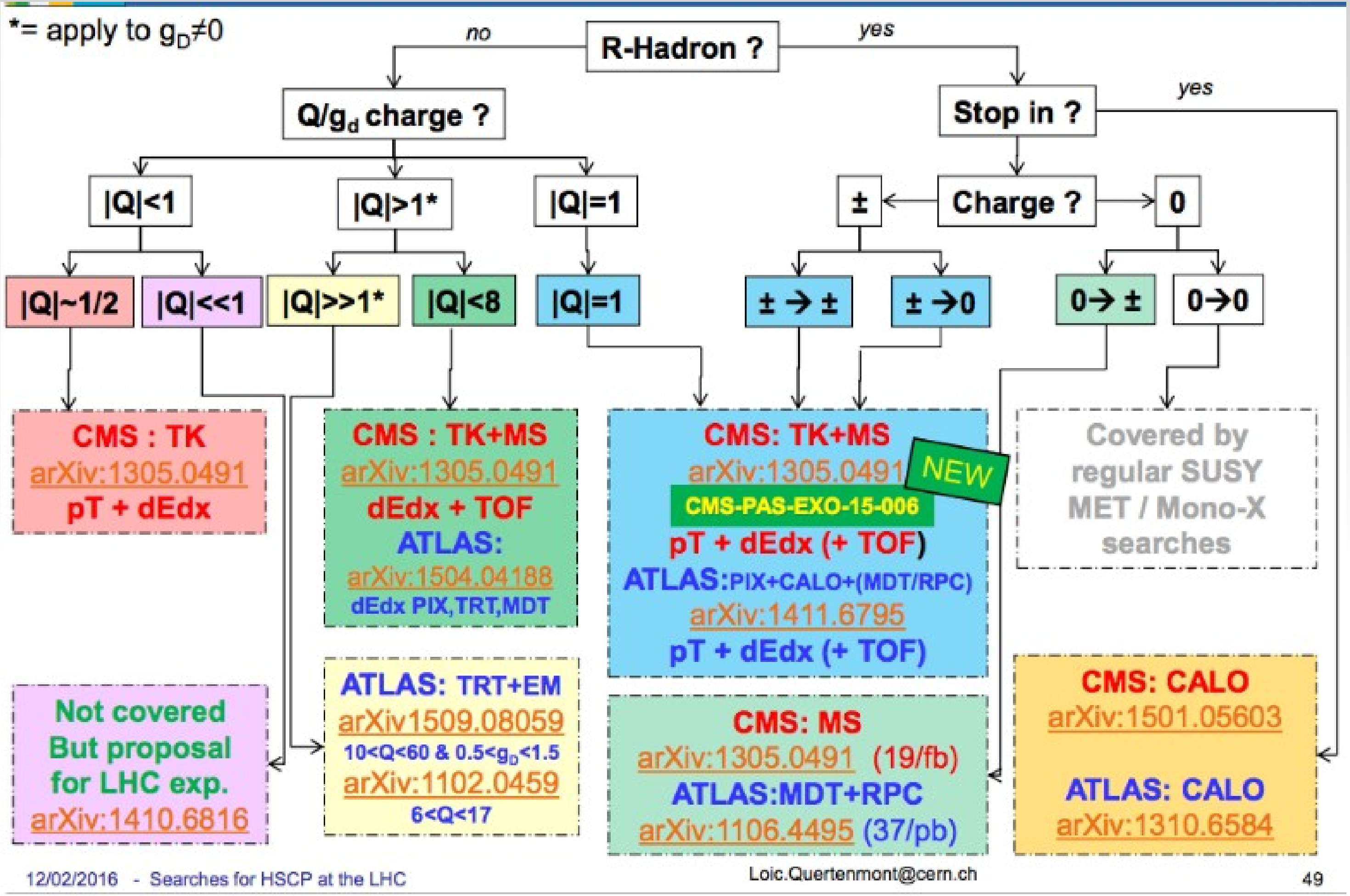


# How can you look for long living particle at LHC




R-hadron : Have a colored charge

# Heavy Stable Charged Particles

| SMP | LSP | Scenario | Conditions |
|---|---|---|---|
| $\tilde{\tau}_1$ | $\tilde{\chi}_1^0$ | MSSM | $\tilde{\tau}_1$ mass (determined by $m^2_{\tilde{\tau}_{L,R}}$, $\mu$, $\tan\beta$, and $A_\tau$) close to $\tilde{\chi}_1^0$ mass. |
| | $\tilde{G}$ | GMSB | Large $N$, small $M$, and/or large $\tan\beta$. |
| | | $\tilde{g}$MSB | No detailed phenomenology studies, see [23]. |
| | | SUGRA | Supergravity with a gravitino LSP, see [24]. |
| | $\tilde{\tau}_1$ | MSSM | Small $m_{\tilde{\tau}_{L,R}}$ and/or large $\tan\beta$ and/or very large $A_\tau$. |
| | | AMSB | Small $m_0$, large $\tan\beta$. |
| | | $\tilde{g}$MSB | Generic in minimal models. |
| $\tilde{\ell}_{i1}$ | $\tilde{G}$ | GMSB | $\tilde{\tau}_1$ NLSP (see above). $\tilde{e}_1$ and $\tilde{\mu}_1$ co-NLSP and also SMP for small $\tan\beta$ and $\mu$. |
| | $\tilde{\tau}_1$ | $\tilde{g}$MSB | $\tilde{e}_1$ and $\tilde{\mu}_1$ co-LSP and also SMP when stau mixing small. |
| $\tilde{\chi}_1^+$ | $\tilde{\chi}_1^0$ | MSSM | $m_{\tilde{\chi}_1^+} - m_{\tilde{\chi}_1^0} \lesssim m_{\pi^+}$. Very large $M_{1,2} \gtrsim 2$ TeV $\gg \lvert\mu\rvert$ (Higgsino region) or non-universal gaugino masses $M_1 \gtrsim 4M_2$, with the latter condition relaxed to $M_1 \gtrsim M_2$ for $M_2 \ll \lvert\mu\rvert$. Natural in O-II models, where simultaneously also the $\tilde{g}$ can be long-lived near $\delta_{GS} = -3$. |
| | | AMSB | $M_1 > M_2$ natural. $m_0$ not too small. See MSSM above. |
| $\tilde{g}$ | $\tilde{\chi}_1^0$ | MSSM | Very large $m^2_{\tilde{q}} \gg M_3$, e.g. split SUSY. |
| | $\tilde{G}$ | GMSB | SUSY GUT extensions [25–27]. |
| | $\tilde{g}$ | MSSM | Very small $M_3 \ll M_{1,2}$, O-II models near $\delta_{GS} = -3$. |
| | | GMSB | SUSY GUT extensions [25–29]. |
| $\tilde{t}_1$ | $\tilde{\chi}_1^0$ | MSSM | Non-universal squark and gaugino masses. Small $m^2_{\tilde{q}}$ and $M_3$, small $\tan\beta$, large $A_t$. |
| $\tilde{b}_1$ | | | Small $m^2_{\tilde{q}}$ and $M_3$, large $\tan\beta$ and/or large $A_b \gg A_t$. |

Table 1
Brief overview of possible SUSY SMP states considered in the literature. Classified by SMP, LSP, scenario, and typical conditions for this case to materialise in the given scenario. See text for details.

**arxiv:hep-ph/0611040**

- **Heavy**: Implies slow particles, $\beta < 1.0$
- **Stable**: Lives long enough so it can reach tracke and/or muon detectors or even get past them.
- **Charged**: Can be detected by the muon detectors.

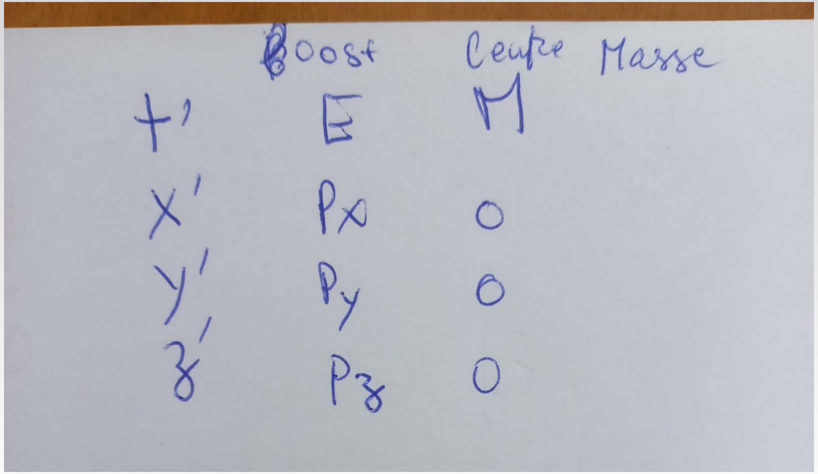
HSCP are predicted in many theoretical models beyond Standard Model (BSM).

| $Q_{em}$ | $C_{QCD}$ | $S$ | Model(s) |
|---|---|---|---|
| 0 | **8** | 1 | Universal Extra Dimensions (KK gluon) |
| $\pm 1$ | **1** | $\frac{1}{2}$ | Universal Extra Dimensions (KK lepton) |
| | | | Fat Higgs with a fat top ($\psi$ fermions) |
| | | | 4th generation (chiral) fermions |
| | | | Mirror and/or vector-like fermions |
| | | 0 | Fat Higgs with a fat top ($\psi$ scalars) |
| $\pm\frac{4}{3}$ | **3** | $\frac{1}{2}$ | Warped Extra Dimensions with GUT parity (XY gaugino) |
| | | 0 | 5D Dynamical SUSY-breaking (xyon) |
| $-\frac{1}{3},\frac{2}{3}$ | **3** | $\frac{1}{2}$ | Universal Extra Dimensions (KK down, KK up) |
| | | | 4th generation (chiral) fermions |
| | | | Mirror and/or vector-like fermions |
| | | | Warped Extra Dimensions with GUT parity (XY gaugino) |
| $\epsilon < 1$ | **1** | $\frac{1}{2}$ | GUT with $U(1) - U(1)'$ mixing |
| | | | Extra singlets with hypercharge $Y = 2\epsilon$ |
| | | | Millicharged neutrinos |
| ? | ? | $0/\frac{1}{2}/1$ | "Technibaryons" |

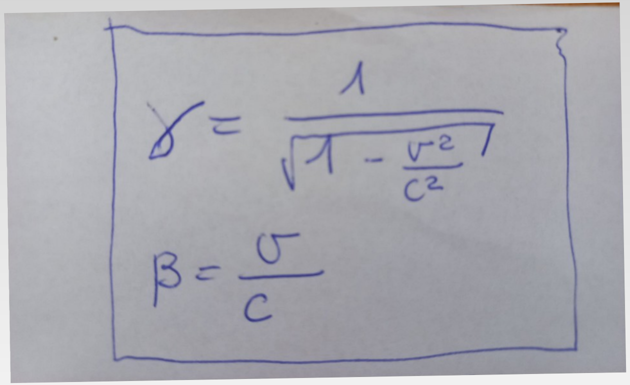
Table 2
Examples of possible SMP states in a variety of models beyond the MSSM (for MSSM SMPs, see Tab. 1). Classified by electric charge $Q$, colour representation $CQCD$, spin $S$, and scenario.

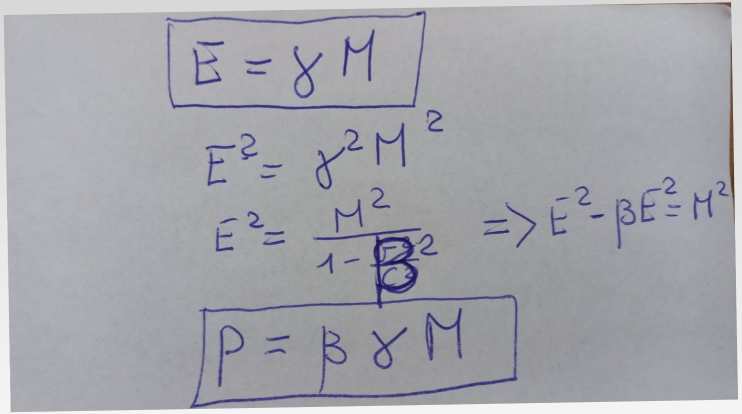
# A bit of homework: what is Beta

$$t' = \gamma\left(t - \frac{vx}{c^2}\right)$$
$$x' = \gamma\left(x - vt\right)$$
$$y' = y$$
$$z' = z$$



# A bit of homework: what is Beta

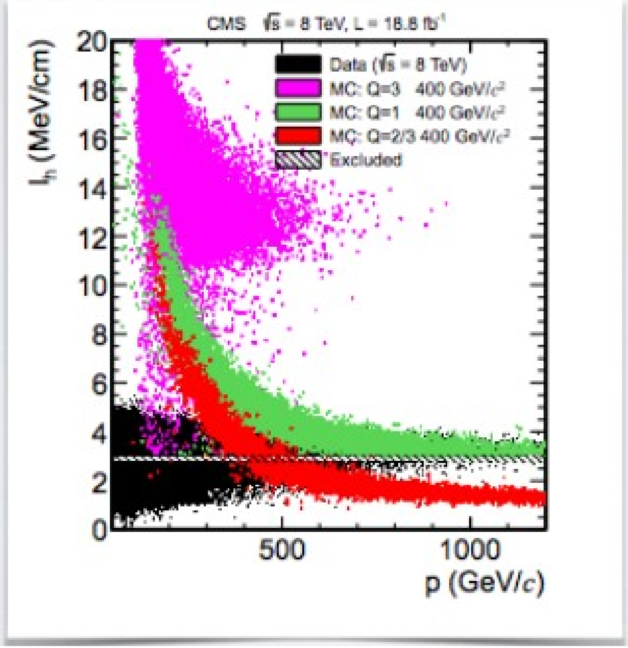


# *How can you look for HSCP*

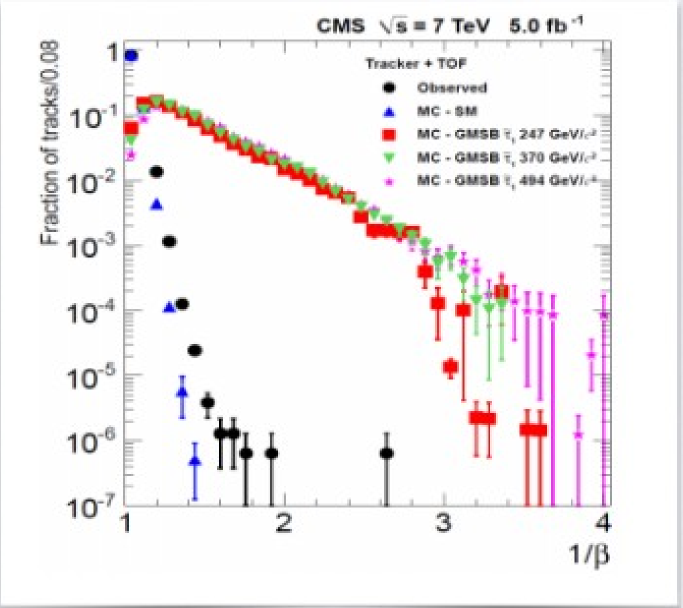
- **dE/dx:** Ionization energy lost.

$$\frac{dE}{dx} \approx Q^2 \left[\frac{A}{\beta^2} + B\right] \text{ for } \beta << 1$$

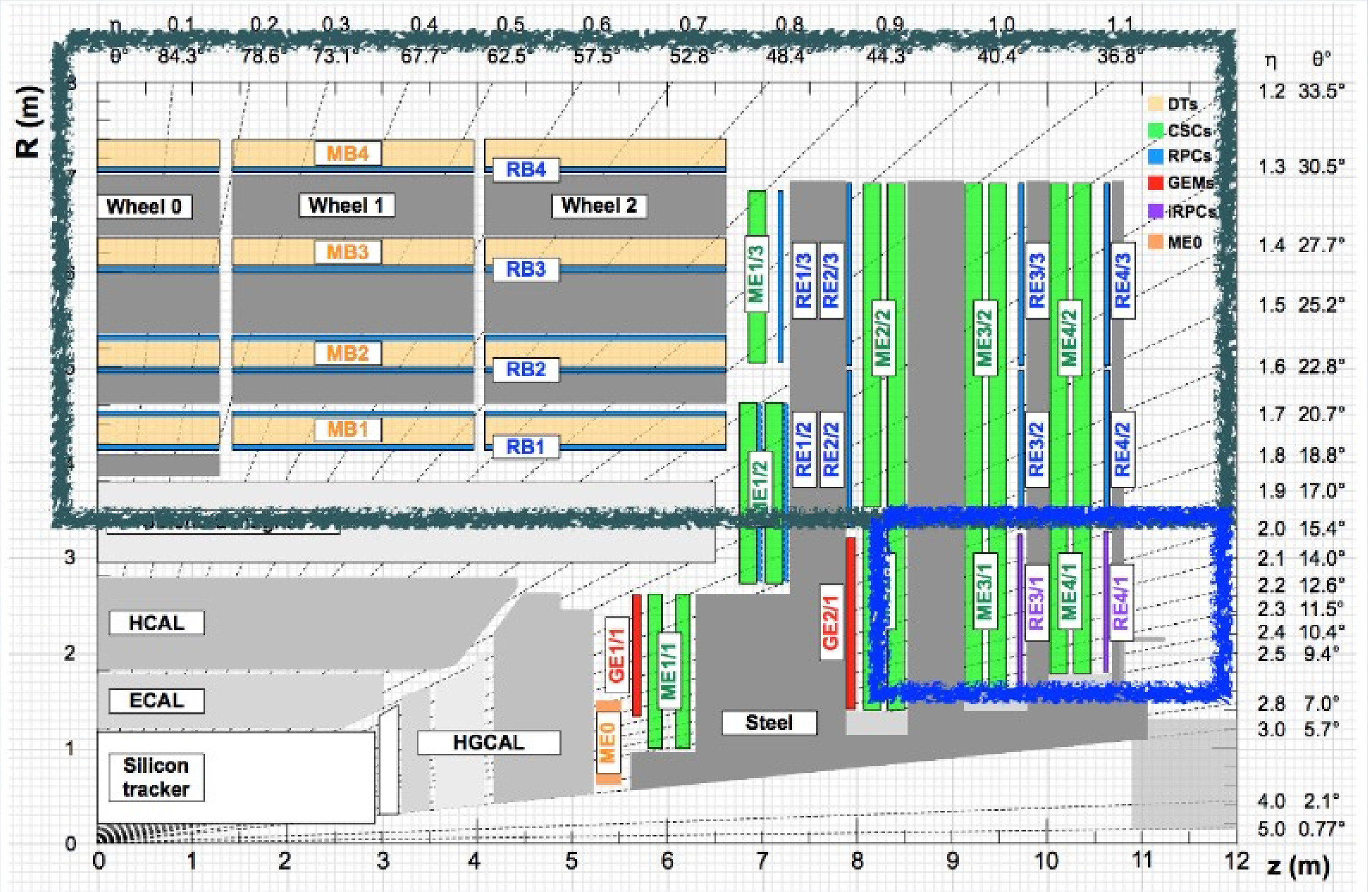


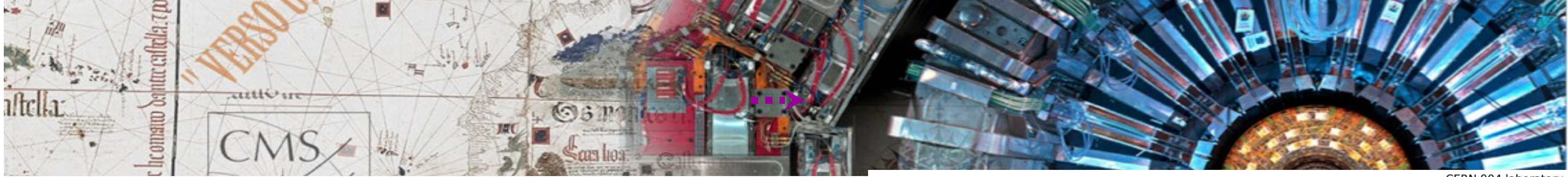

- **TOF:** Time of flight

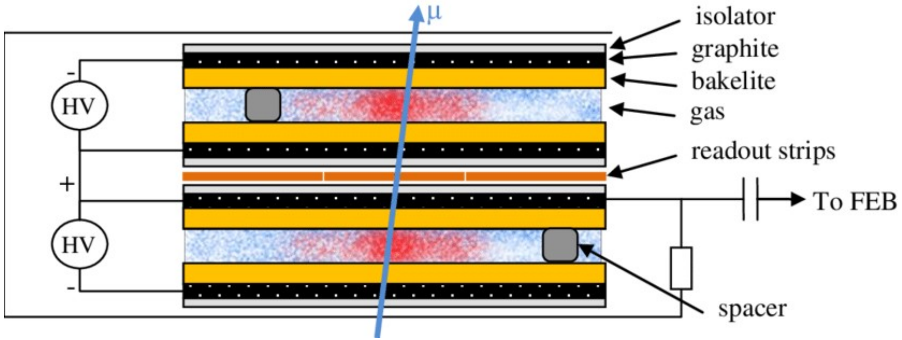
$$\frac{1}{\beta} = 1 + \frac{c\delta_t}{L}$$

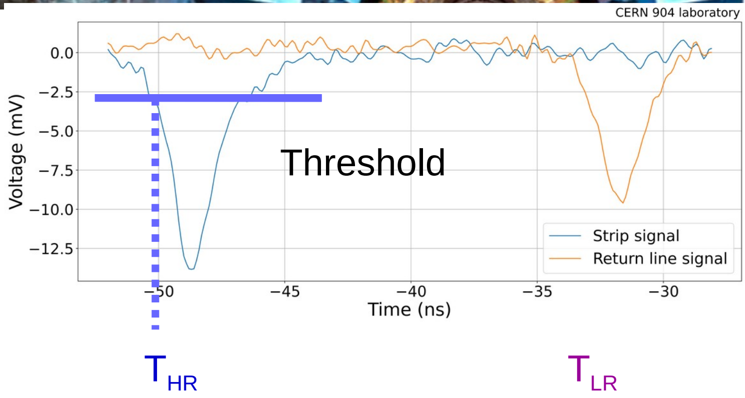


# RPC chambers: high precision timing at HL-LHC for TOF

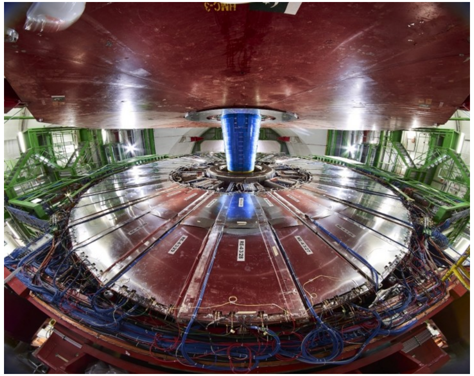




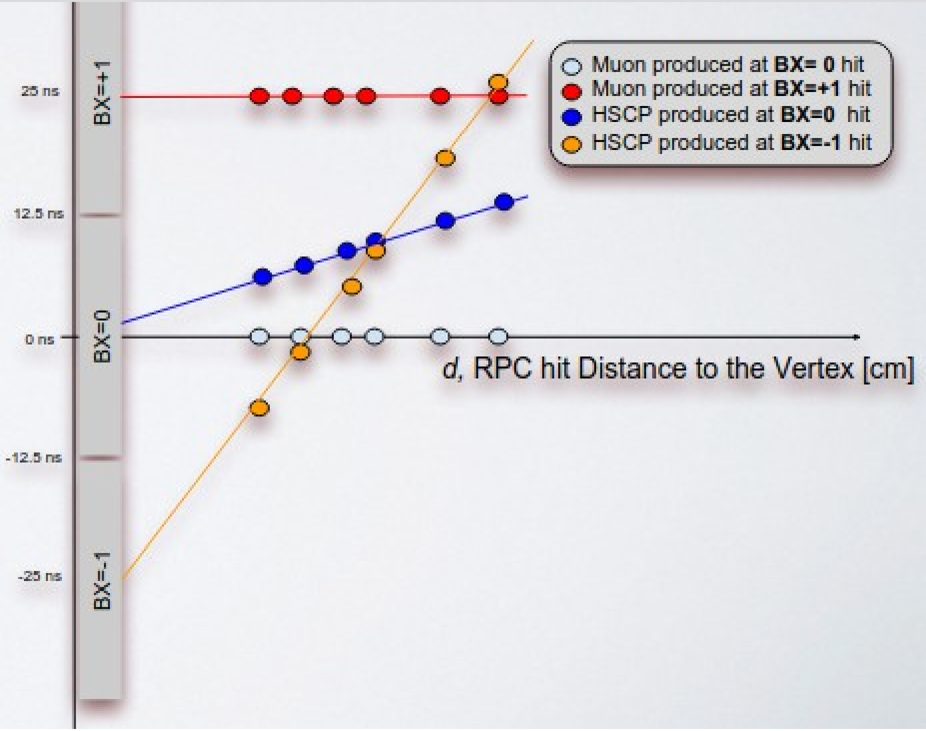



- Very fast detector : time resolution 0.5 – 1.5 ns depending on the type



# How can we see slow HSCP




CMS trigger system today

- LHC collisions : every 25 ns (bunch crossing - BX)
- 40 MHz collisions
- L1 super-fact trigger : 100 kHz can be selected to be analysed by computer (High Level Trigger)
- 1000 events can be written on tape

HSCP : breaks this paradigm. We need to identify Multi-BX events

# How can we see slow HSCP

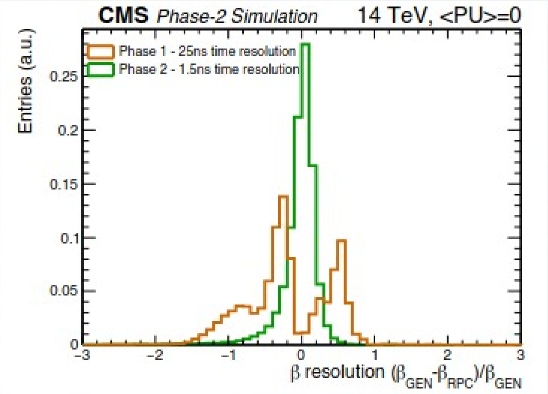
## Time and Speed measurement

Starting from the simple equation:

$$v_{layer} = \frac{|\overrightarrow{RPCHit}|}{ToF}$$

After some algebra we have that β and $t_0$ are related by the following expression:

$$t_{delay} = t_0 + \frac{d}{c}(\beta^{-1} - 1)$$




where $t_{delay}$ is the time measured with respect to a particle moving at speed of light, d is the distance from the interaction point to the impact point and c is the speed of light. For the muon the second term in Eq. 2 vanishes. For the HSCPs we performed a Least Squares Fit, using the linear form:

$$y = a + bx$$

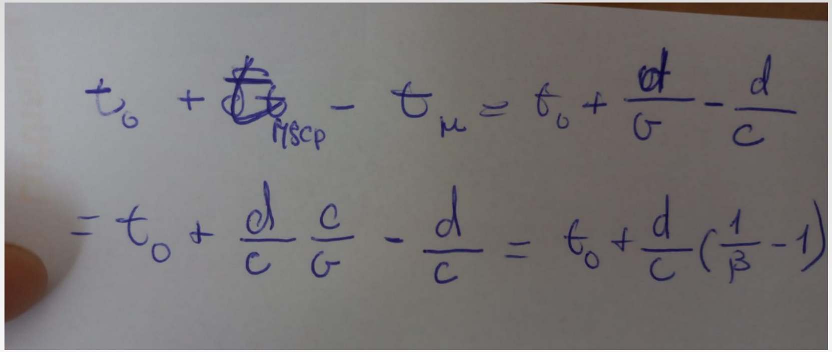
where:

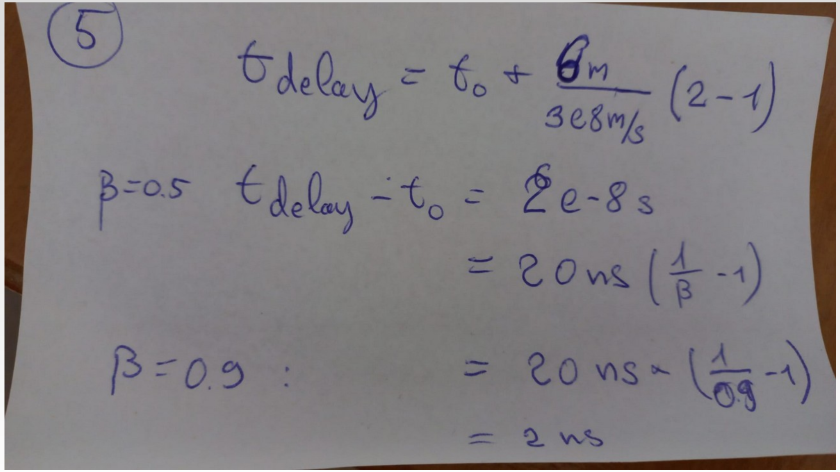
$$\mathrm{a} = t_0 \text{ and } \mathrm{b} = \frac{\beta^{-1} - 1}{c}$$

# A bit of homework: tdelay

$$t_{delay} = t_0 + t_{MSCP} - t_{\mu}$$

# A bit of homework: tdelay



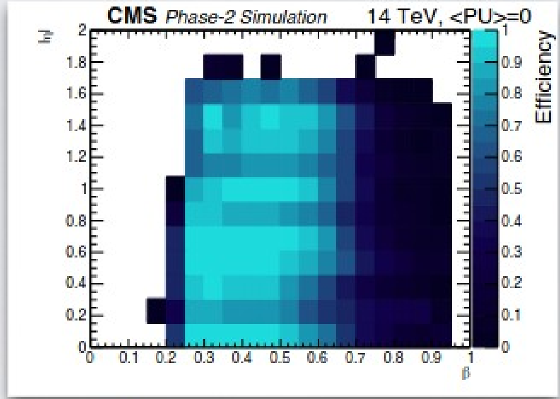



# How can we see slow HSCP

## Trigger Algorithm proposal

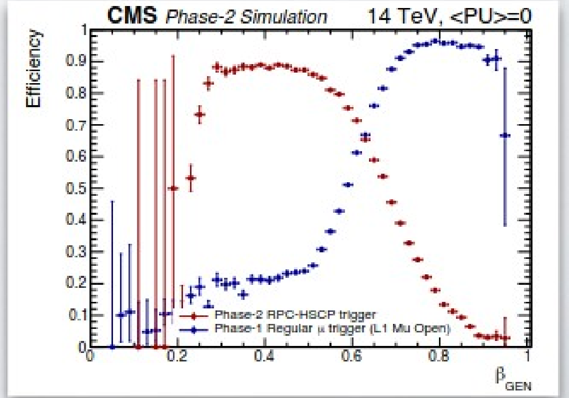
The trigger algorithm is:

1. at least 3 hits correlated in space.
2. error in beta < 30% (to assure good quality of the fit)
3. slope > 0 (to exclude muons and identify slow moving particles)




### EFFICIENCIES.

The new trigger proposal will be complement for the present muon trigger whose efficiency sharply drops for particles with β < 0.6



# In Conclusion

Timing upgrade of the LHC detectors for HL-LHC phase opens a new Era in search for Long Lived particle which were in the blind spot till now.

You can join CMS collaboration and in particular RPC/Muon detector and contribute as senior scientist, PhD or Master to this adventure and may be discover the dark side of the Universe that we failed to tackle till now...