

Heavy stable particles, dark corner of modern physics



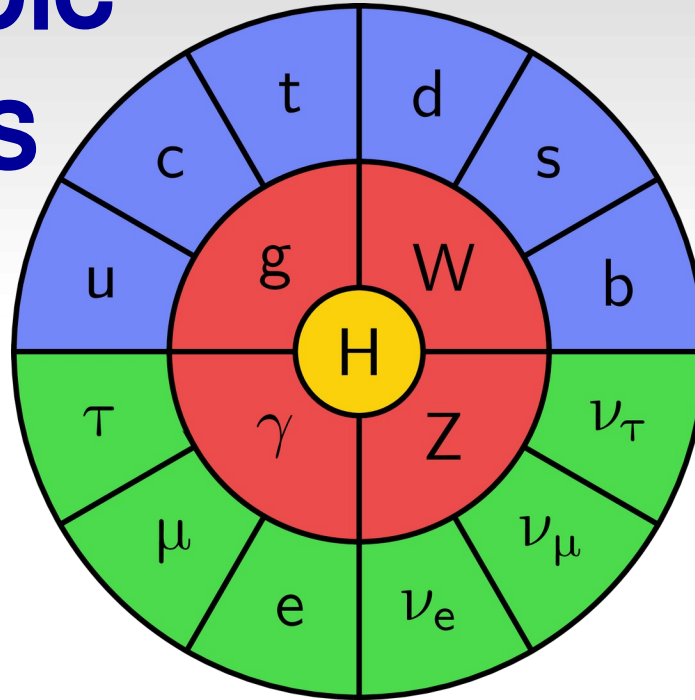
Maxime Gouzevitch

IP2I, Lyon, France

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

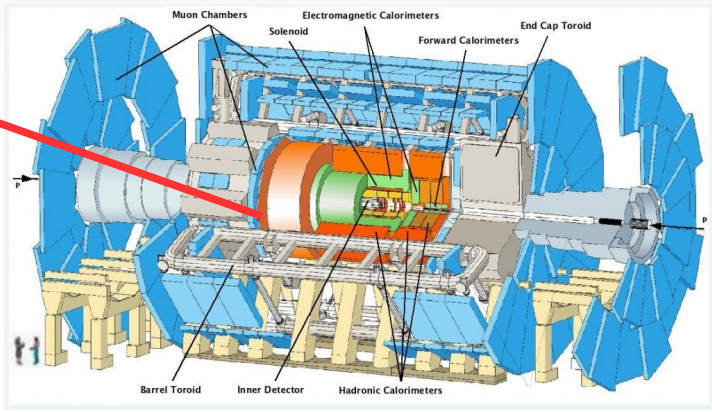
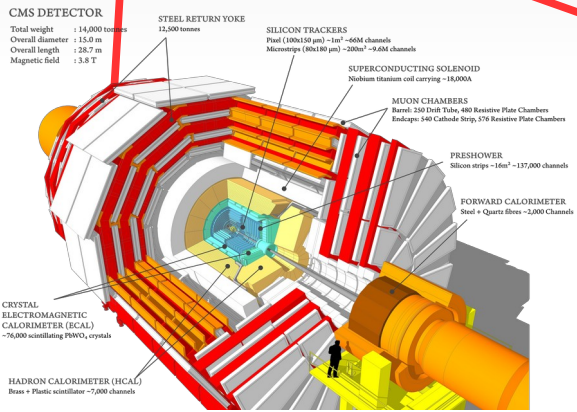
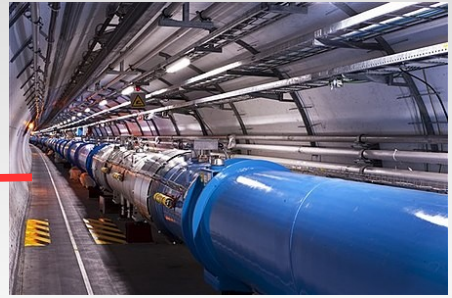
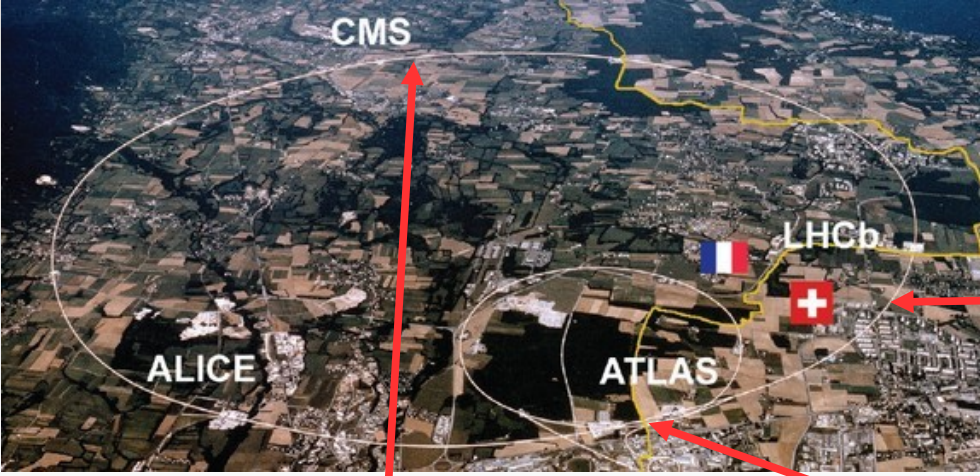


1) How do we look for microscopic physics giant

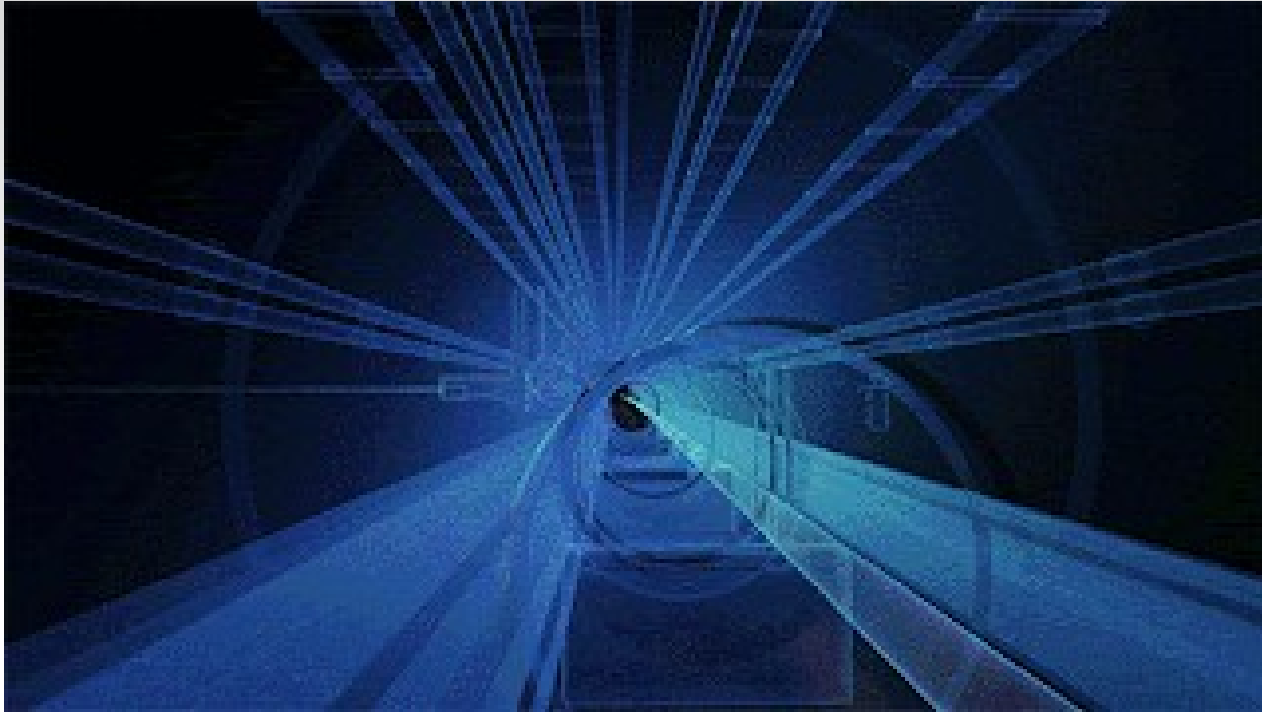


in a collider

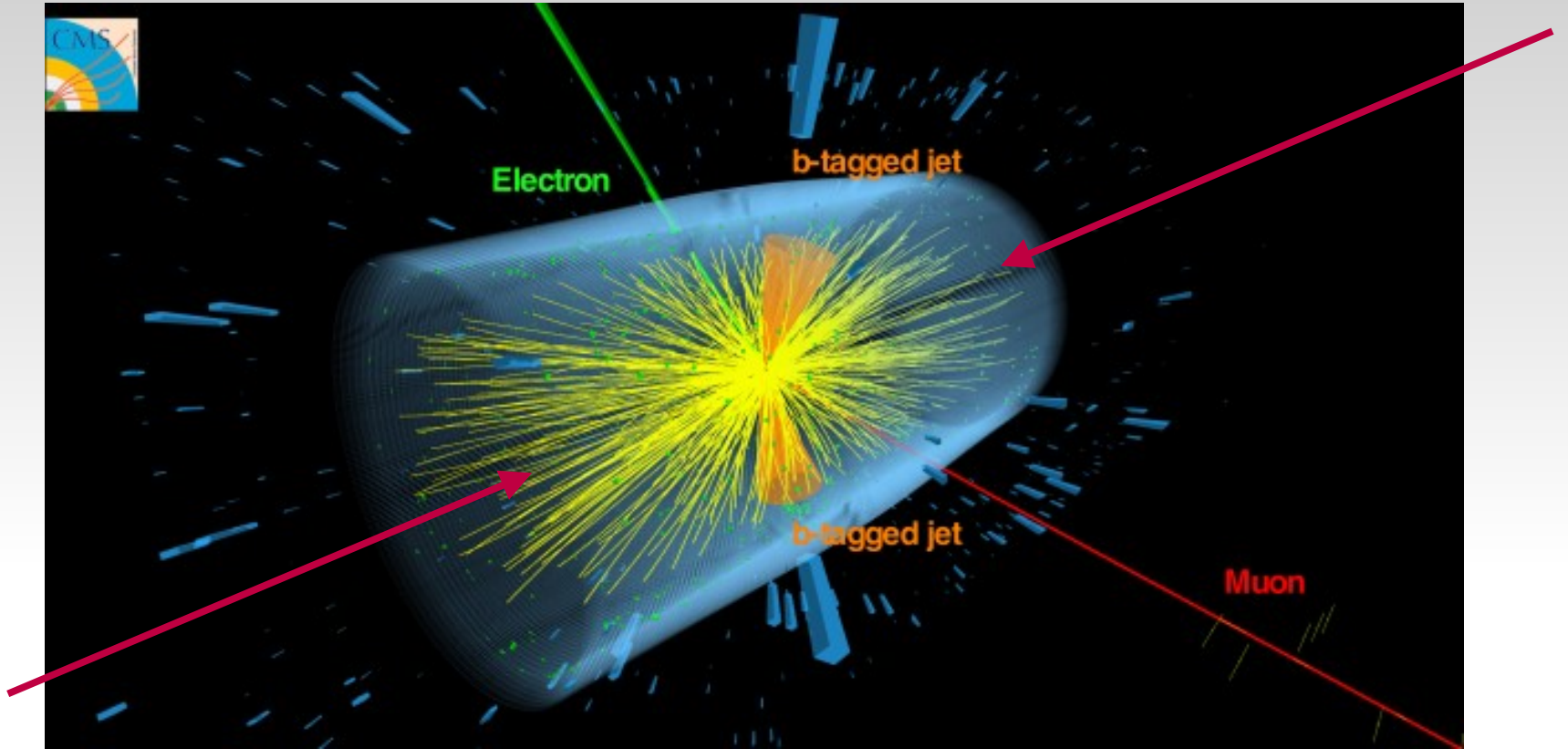
Proton beam parameters	LHC Design	2012 LHC	Early 2015 LHC
# bunches/beam	2808	1374	3 - 458
Bunch spacing [ns]	25	50	25 and 50
Mean bunch length [ns]	1.3	1.2	1.2
Bunch intensity [10^{11} p]	1.15	1.1 - 1.7	1.0 - 1.2
Emittance at injection [μm]	3.5	1.5 - 2.0	1.5 - 3.0
Collision energy/beam [TeV]	7	4	6.5
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

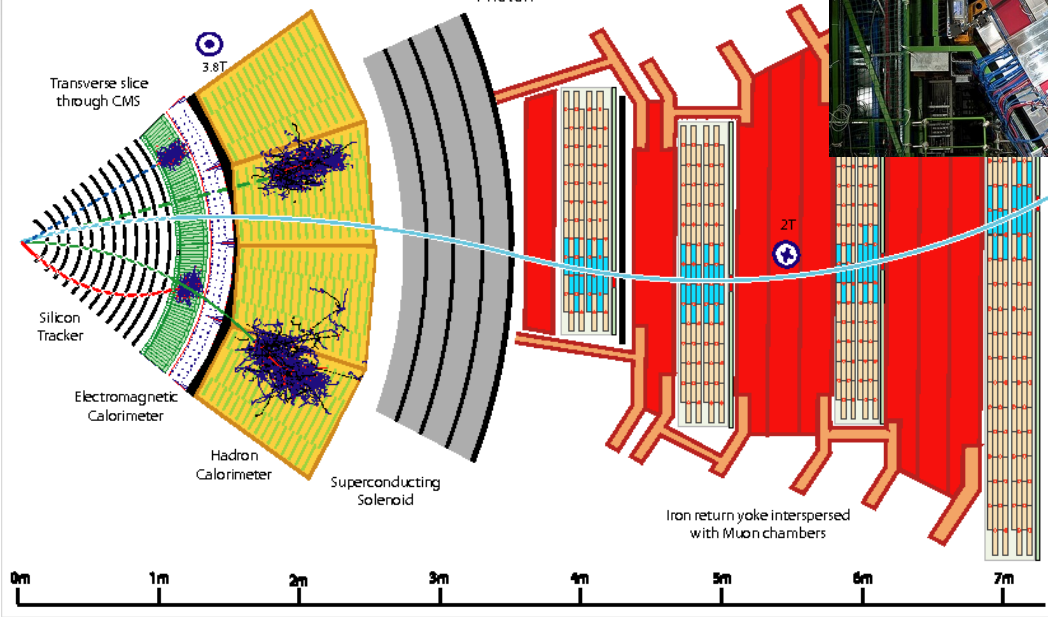


Particles identification

Particle Flow paper



- Key:
- Muon
 - Electron
 - Charged Hadron (e.g. Pion)
 - Neutral Hadron (e.g. Neutron)
 - Photon

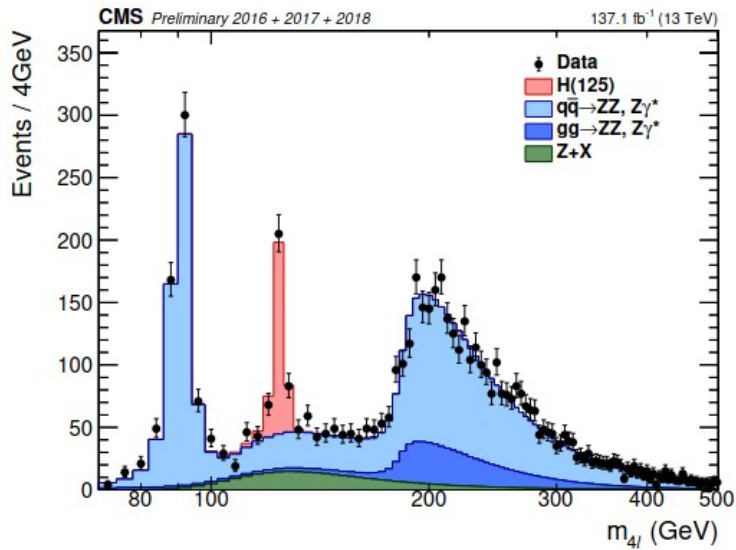
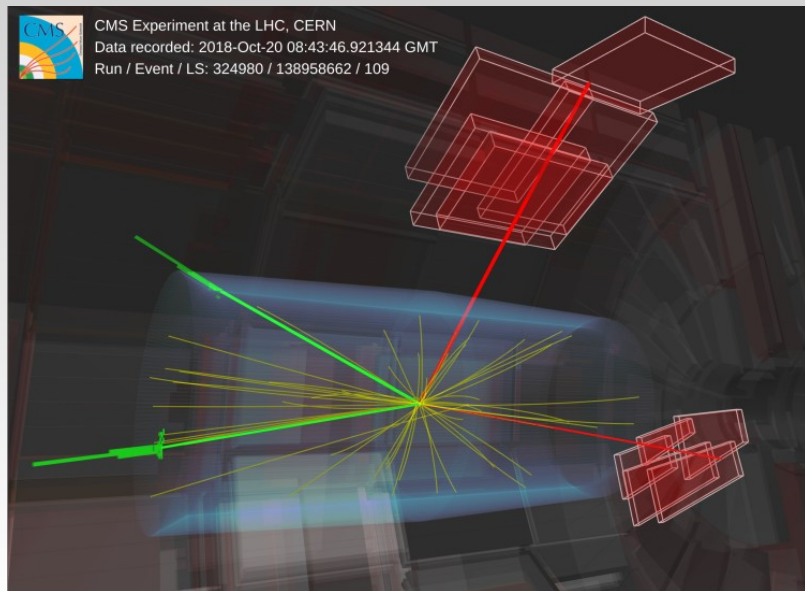
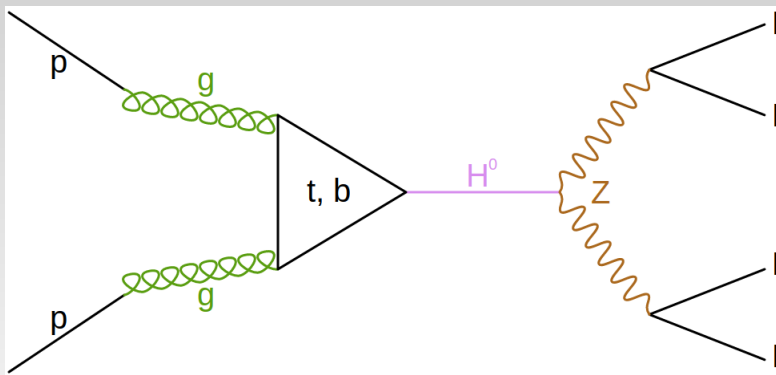


Higgs boson example

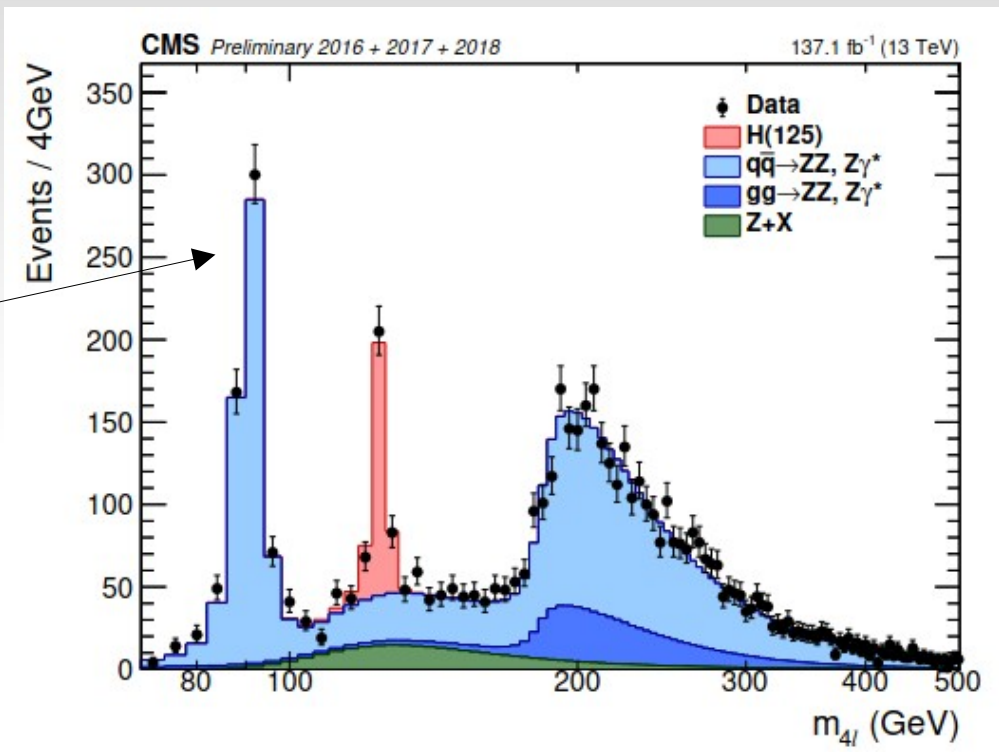
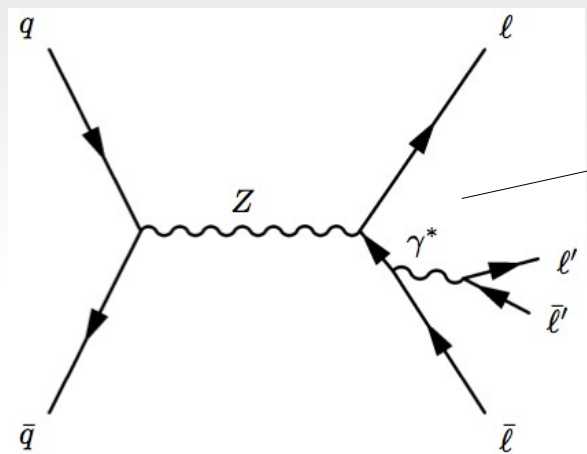
- 4 July 2012: Higgs boson discovery by ATLAS – CMS from LHC
- Nobel prize to theorist who have predicted Higgs mechanism and Higgs boson (Englert-Higgs, Brout died before) in 2013. (Peter Higgs died in 2024)



Higgs boson example



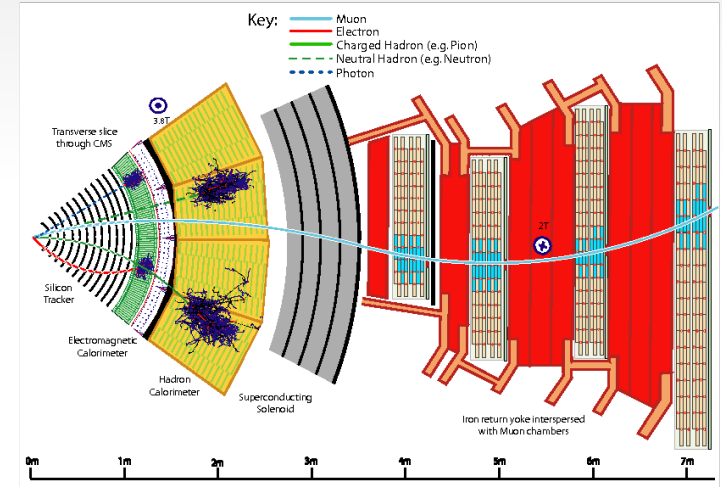
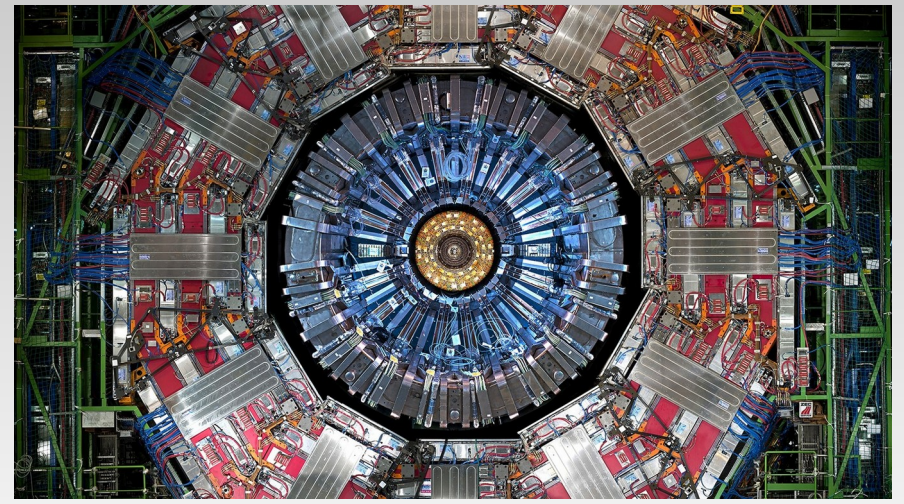
Higgs boson example



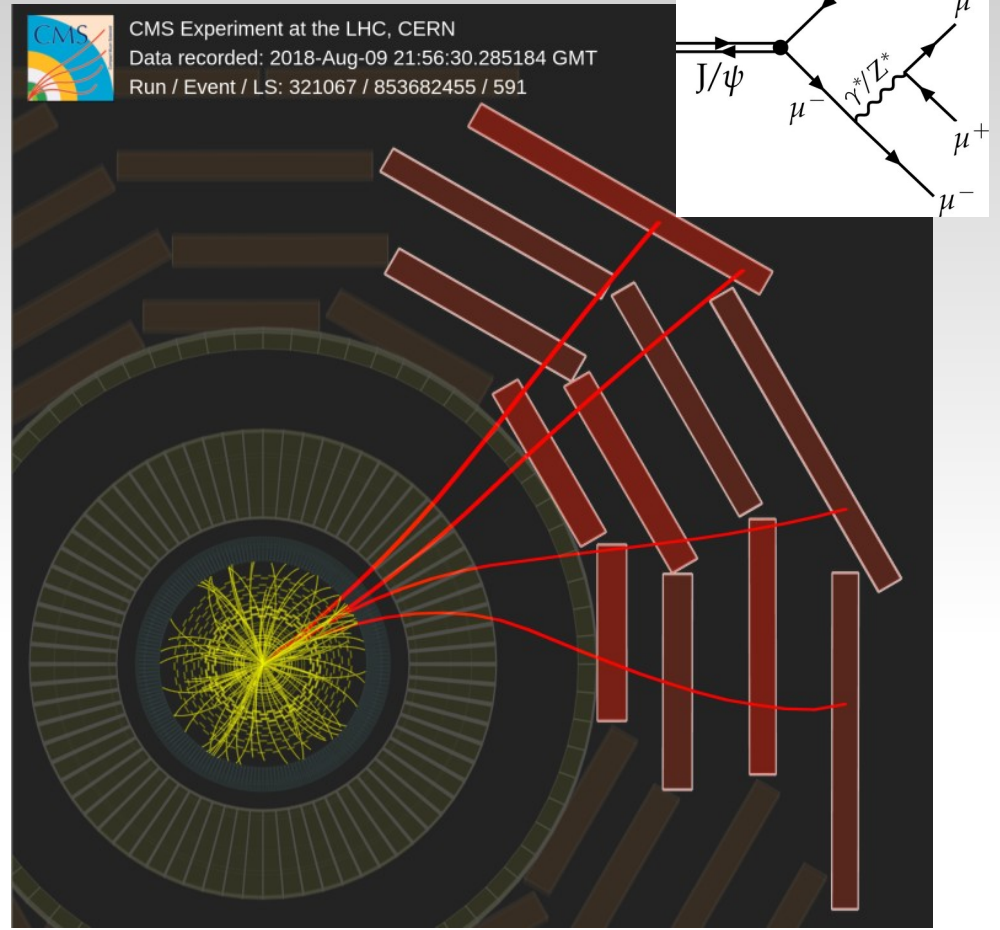
Homework



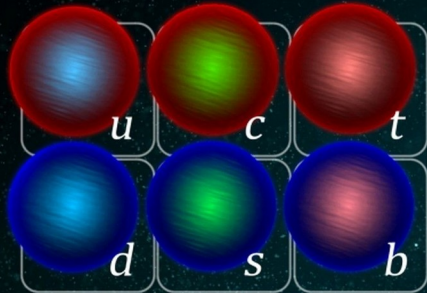
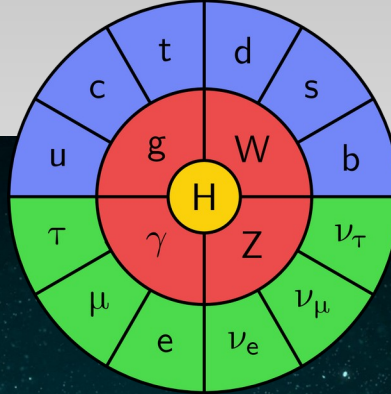
Homework



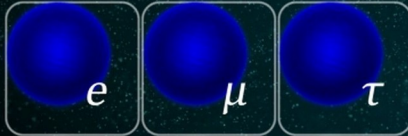
Homework



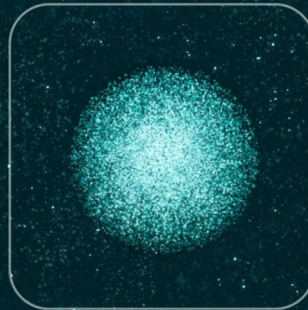
What do we have now?



Quarks



Leptons

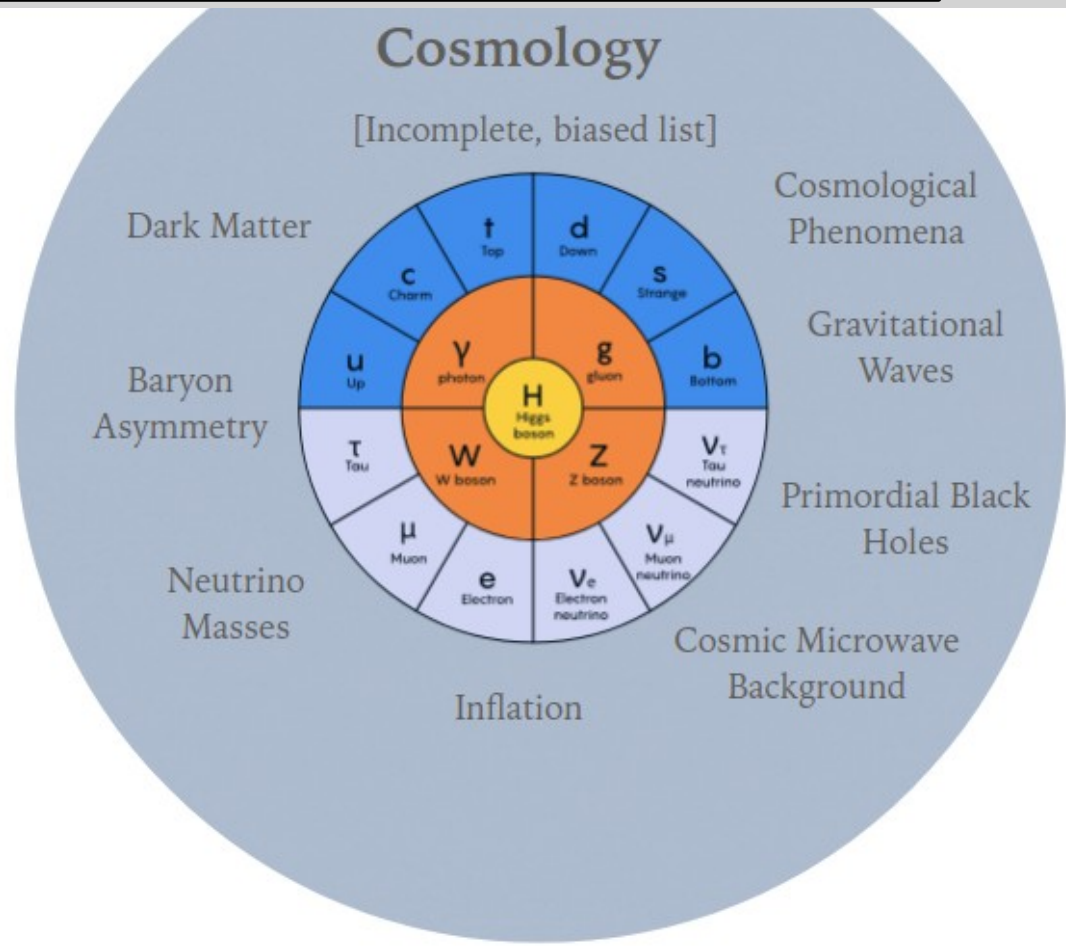


Higgs boson

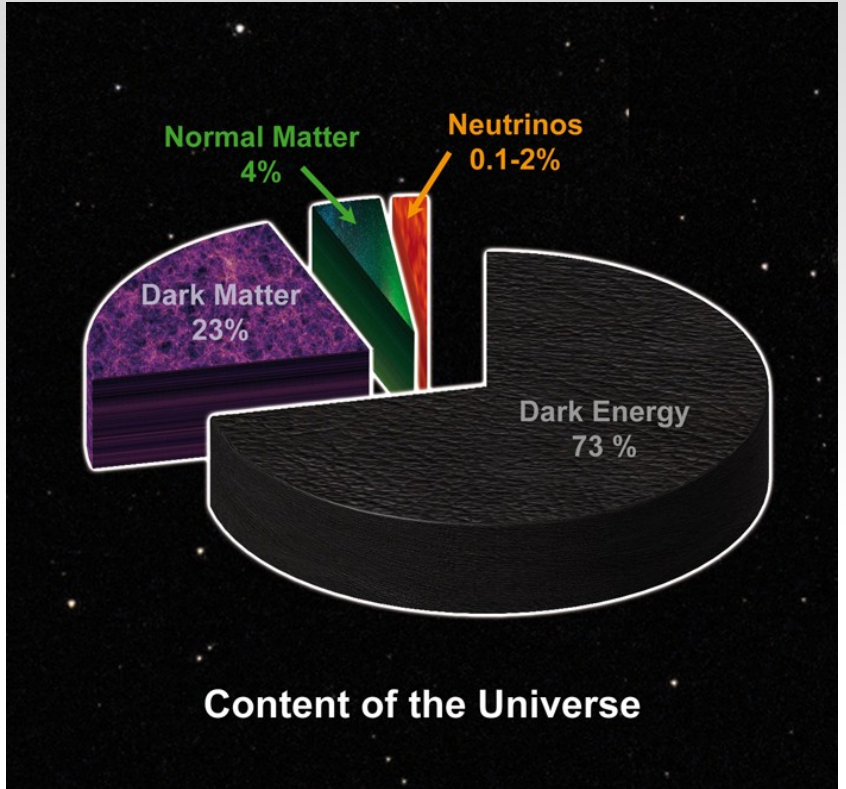
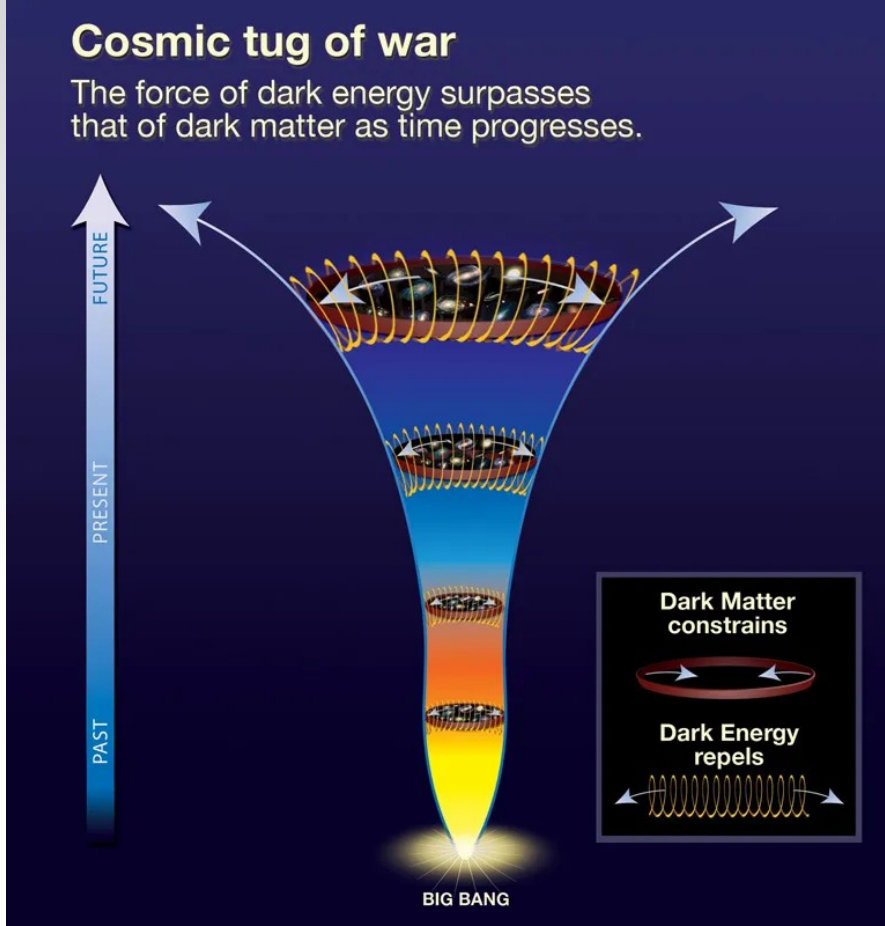


Forces

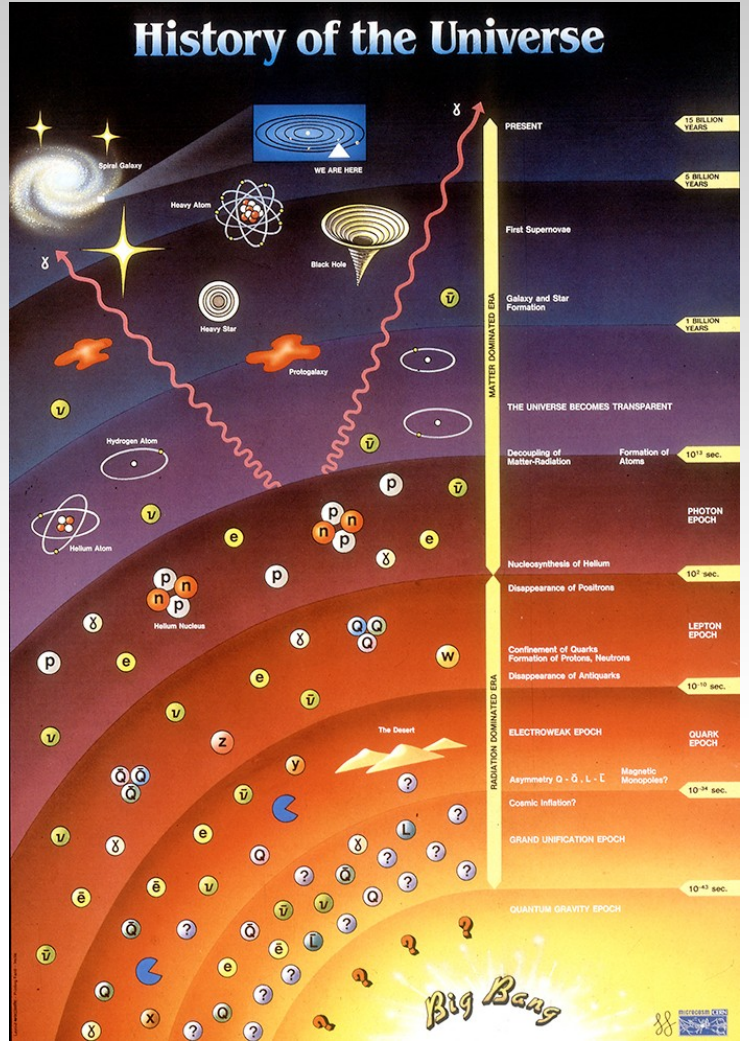
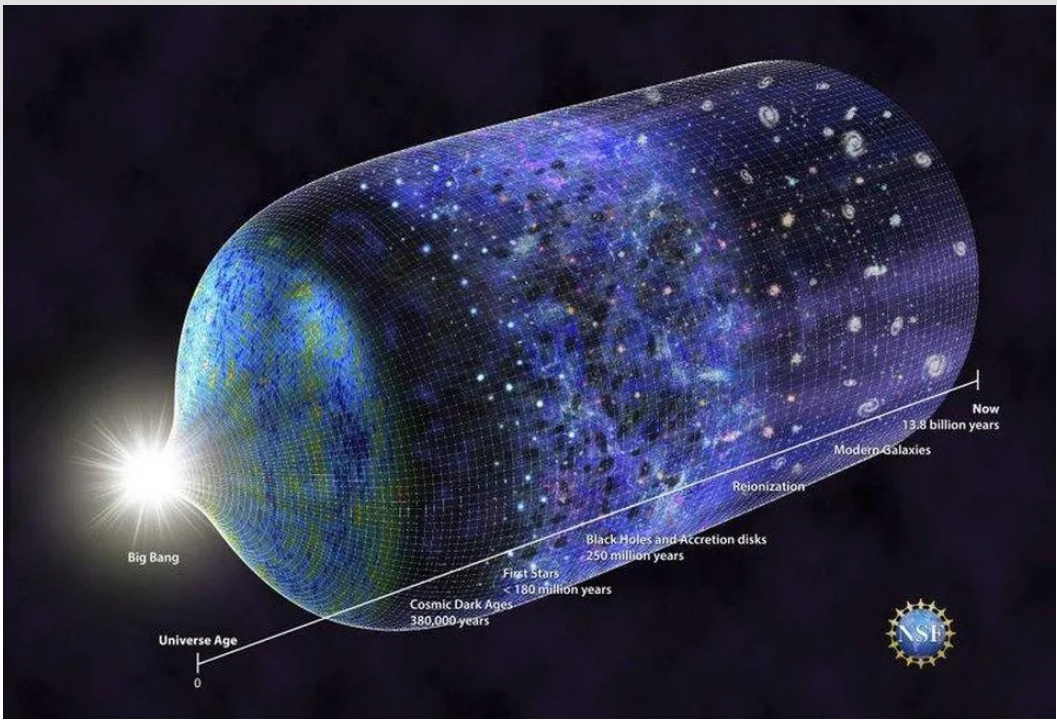
What do we don't know?



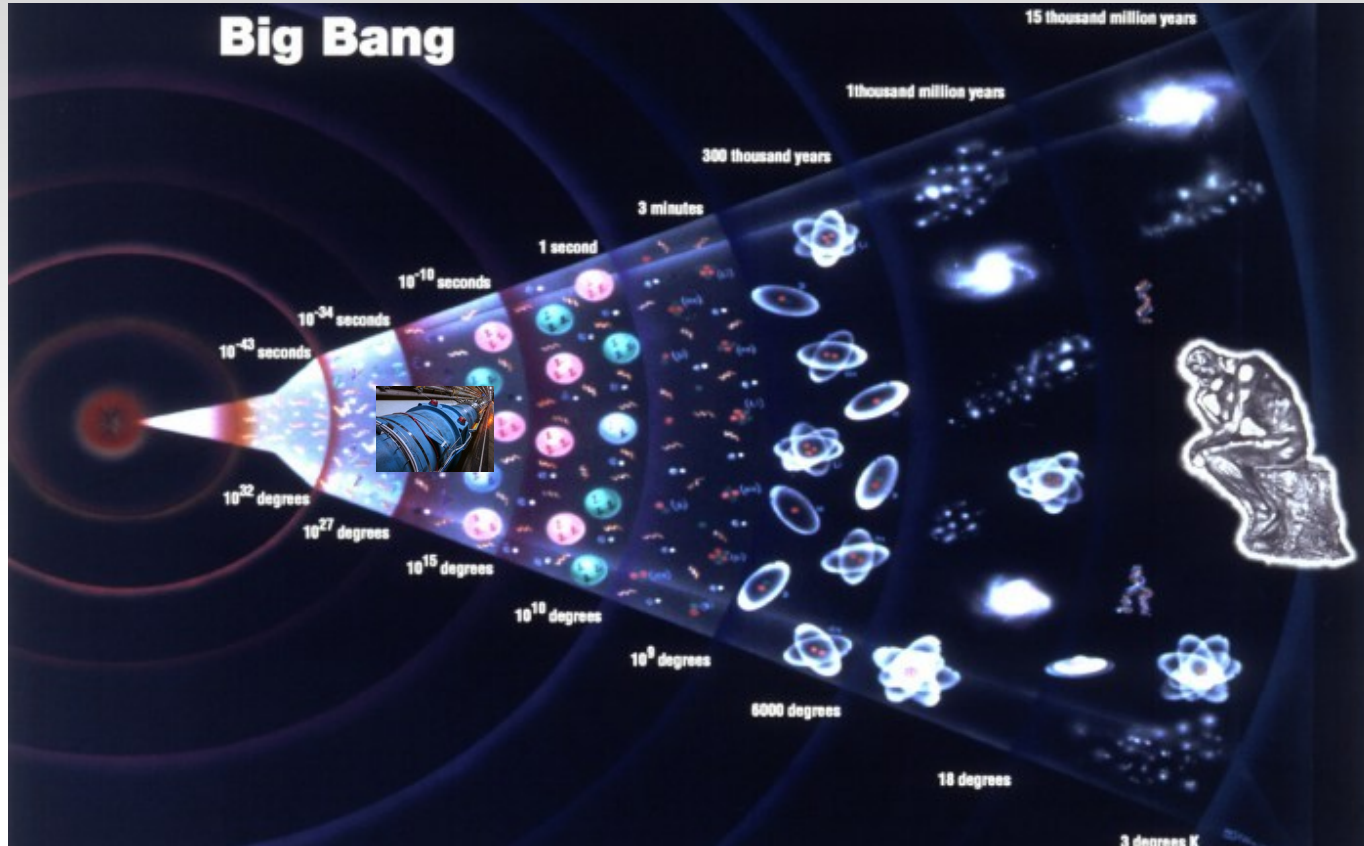
What do we don't know: dark matter – dark energy



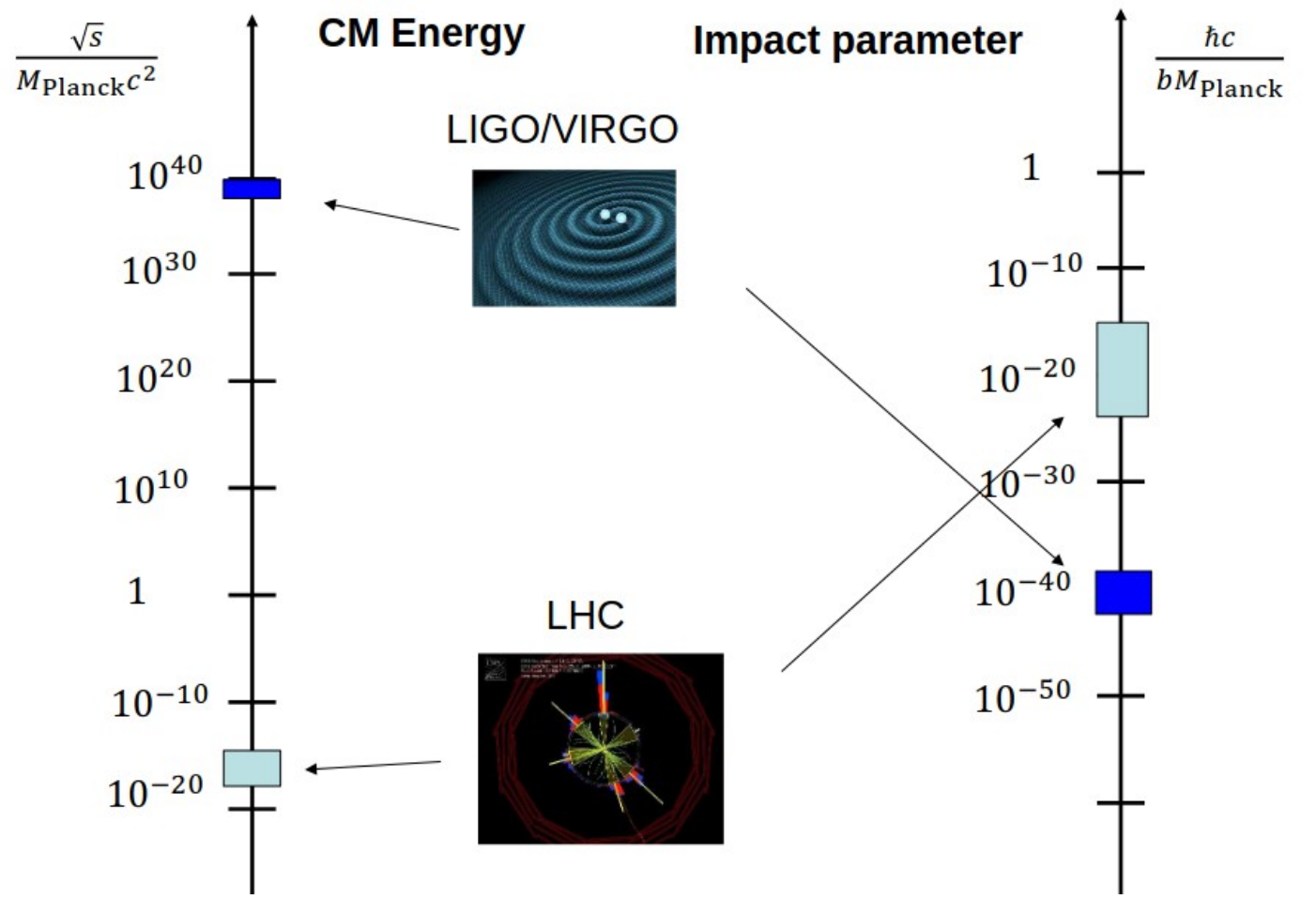
What do we don't know: inflation, matter antimatter asymmetry



LHC time travel machine



LHC energy domain



ATLAS / CMS looks at high energy phenomena



Dijet Pair 1:
 $pt = 3.49 \text{ TeV}$
 $Mass = 1.88 \text{ TeV}$

PF Jet 1,
 $pt = 2.218 \text{ TeV}$
 $eta = 0.27$
 $phi = 1.47$

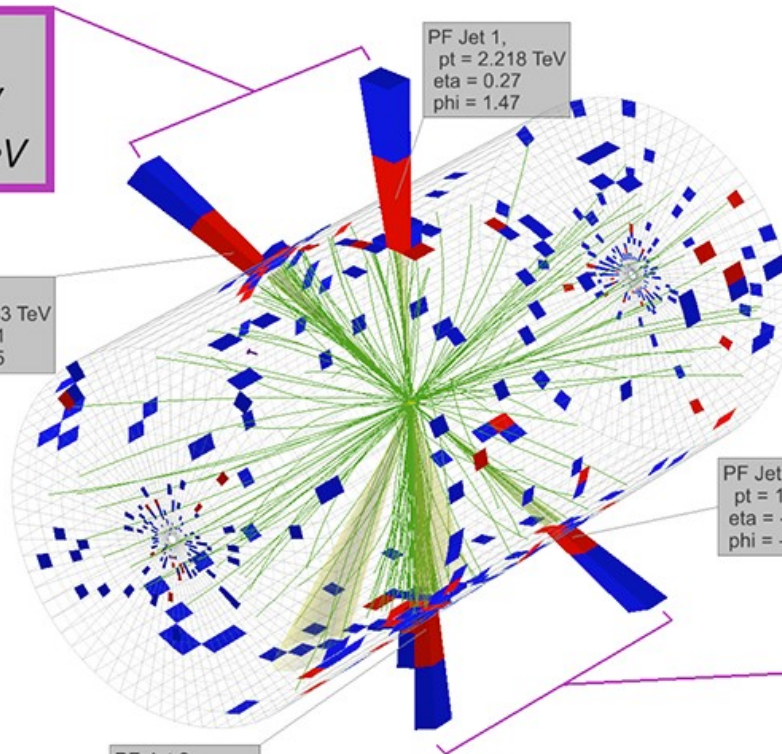
PF Jet 3,
 $pt = 1.733 \text{ TeV}$
 $eta = 0.21$
 $phi = 2.45$

PF Jet 4,
 $pt = 1.408 \text{ TeV}$
 $eta = -0.74$
 $phi = -1.17$

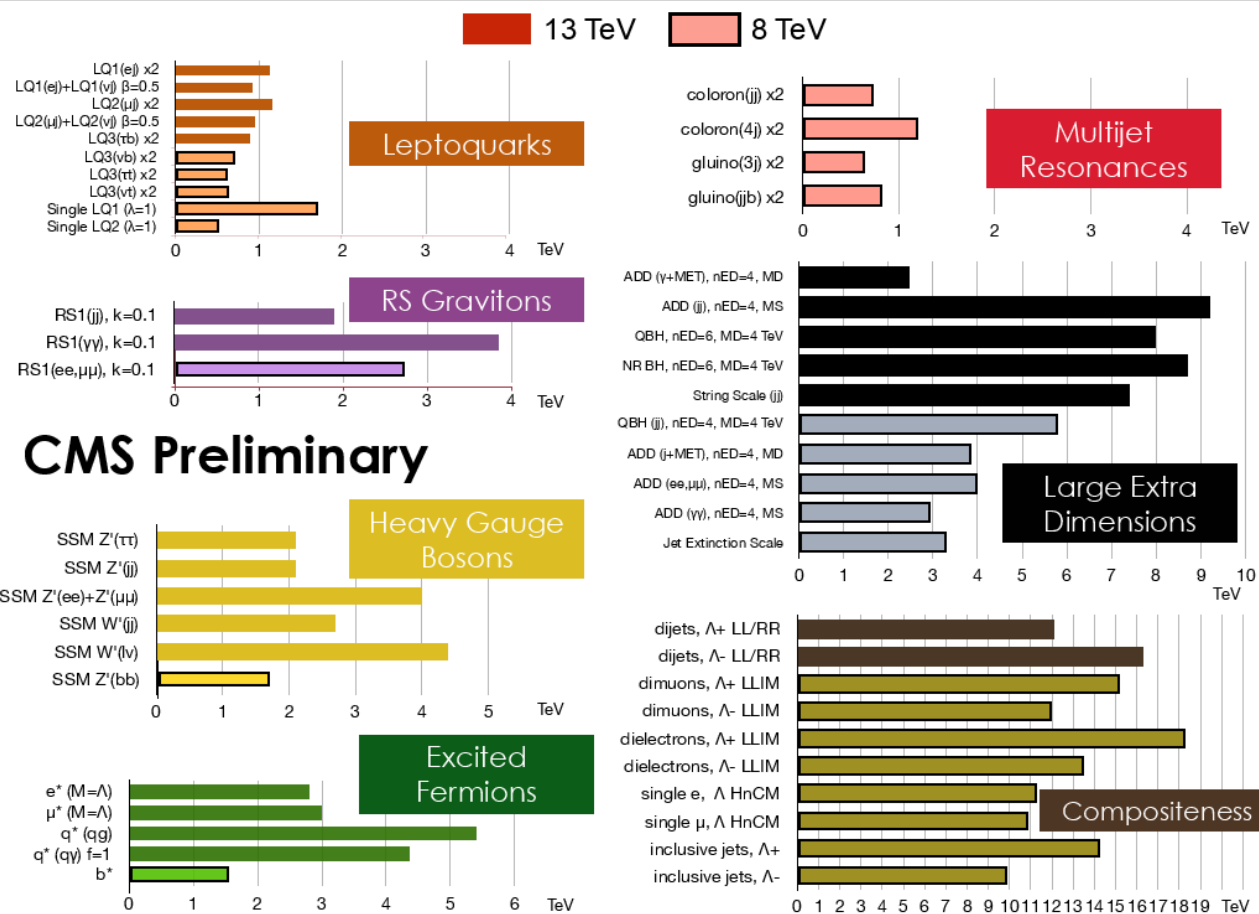
PF Jet 2,
 $pt = 2.042 \text{ TeV}$
 $eta = 0.29$
 $phi = -1.27$

Dijet Pair 2:
 $pt = 3.45 \text{ TeV}$
 $Mass = 1.86 \text{ TeV}$

CMS Experiment at LHC, CERN
Data recorded: Sat Oct 28 12:41:12 2017 EEST
Run/Event: 305814 / 971086788
Lumi section: 610



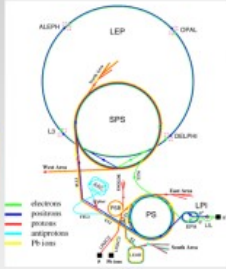
ATLAS / CMS looks at high energy phenomena



CMS Preliminary

2) Heavy and stable :
quest of next 15 years

**RECENT
PAST**

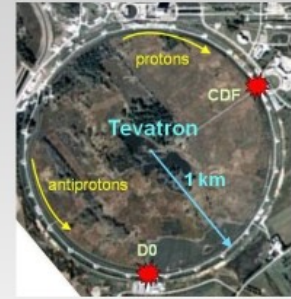


**LEP e+e-
209 GeV (CERN)**

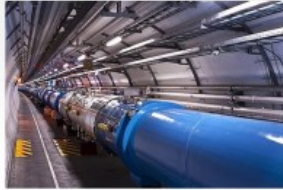
- Z factory
- $m_H > 114$ GeV

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

- W, Z factory
- $M \sim 175$ GeV
- $M_H \neq 2 M_W$



PRESENT



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

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

**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

**HYPOTHETICAL
AFTER
TOMORROW
2035 → 2050**

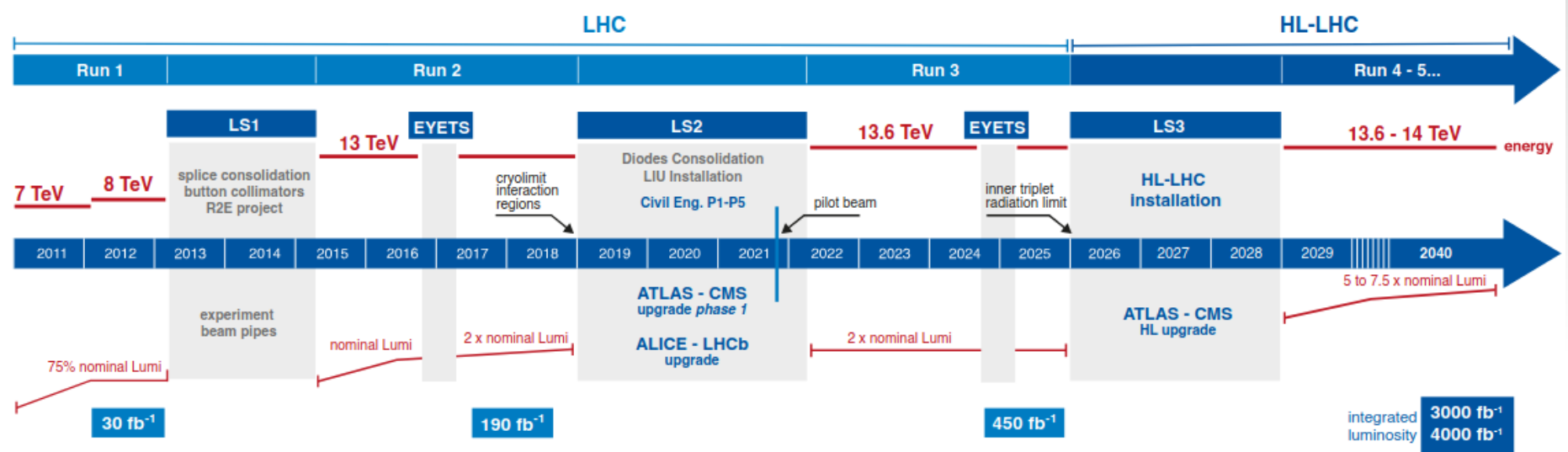
e+e- linear
ILC 350, 500 GeV (JAPAN)
CLIC 380-3000 GeV (CERN)
e+e- circular
CEPC 240 GeV (CHINE)
FCC-ee 90-350 GeV (CERN)

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?

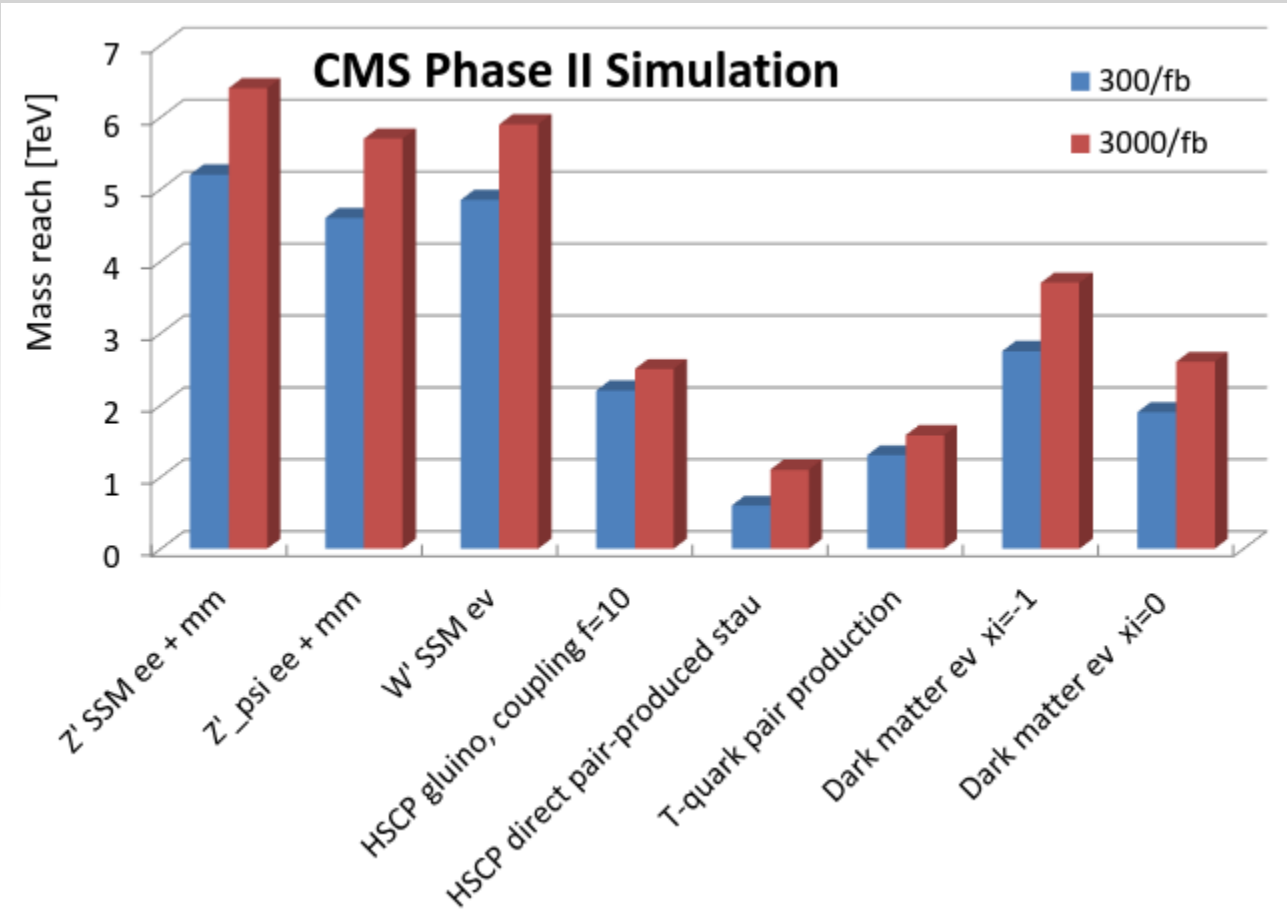


LHC / HL-LHC Plan



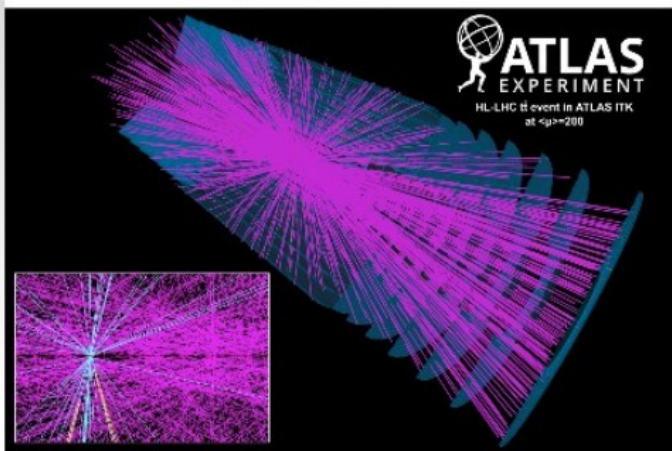
Nearly no energy increases at HL-LHC

What are the next 15 years at LHC?

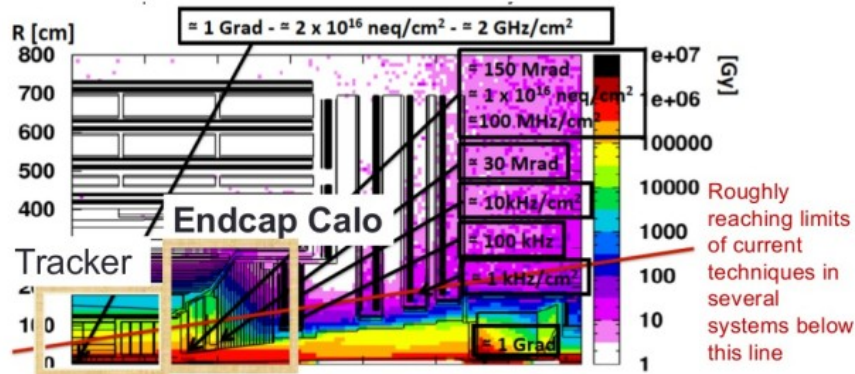


What would be an HL-LHC detector

Very high pileup



- 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

CMS HL-LHC Upgrade: Scope



Technical proposal CERN-LHCC-2015-010 <https://cds.cern.ch/record/2020886>
Scope Document CERN-LHCC-2015-019 <https://cds.cern.ch/record/2055167/files/LHCC-G-165.pdf>

Complete replacement**

L1-Trigger/HLT/DAQ**

<https://cds.cern.ch/record/2283192>
<https://cds.cern.ch/record/2283193>

- Tracks in L1-Trigger at 40 MHz
- PFlow-like selection 750 kHz output
- HLT output 7.5 kHz

Calorimeter Endcap**

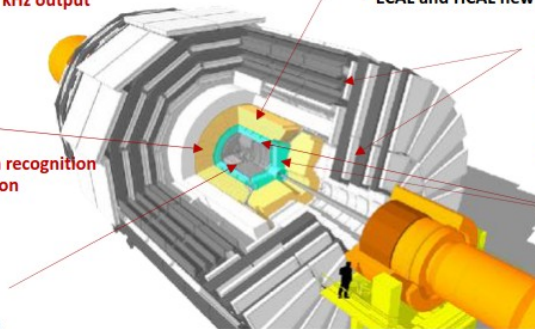
<https://cds.cern.ch/record/2293646>

- 3D showers imaging for pattern recognition
- Precision timing for PU mitigation
- Si, Scint+SiPM in Pb/W-SS

Tracker**

<https://cds.cern.ch/record/2272264>

- P_r module design for tracking in L1-Trigger
- Extended coverage to $\eta \approx 3.8$
- Much reduced material budget
- Si-Strip and Pixels increased granularity



Barrel Calorimeters*

<https://cds.cern.ch/record/2283187>

- ECAL crystal granularity readout at 40 MHz
- Precision timing for e/ γ at 30 GeV, for vertex localization ($H \rightarrow \gamma\gamma$)
- ECAL and HCAL new Back-End boards

Muon systems* ***

<https://cds.cern.ch/record/2283189>

- Extended GEM coverage to $\eta \approx 3$
- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$

MIP Timing Detector***

<https://cds.cern.ch/record/2296612>

- Precision timing for PU mitigation
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

Major Electronics Upgrade/ Consolidation *

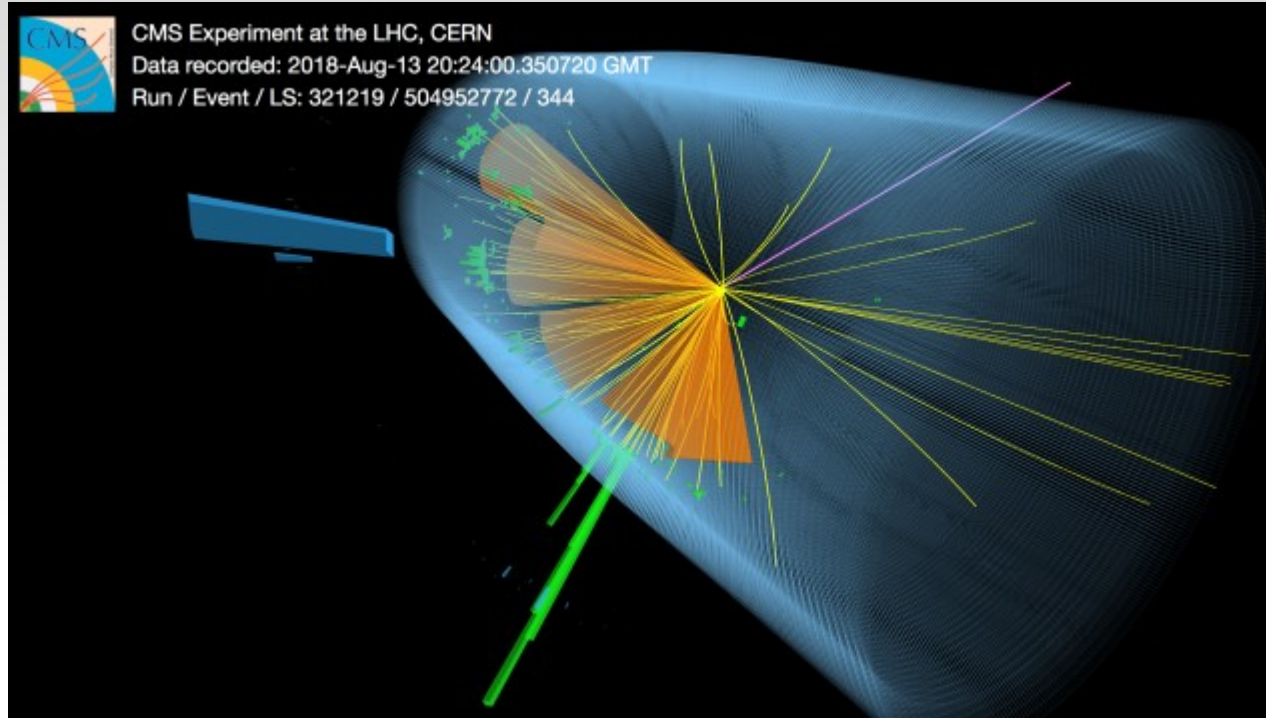
New Detector System***

Beam Radiation Instr. and Luminosity
Common Systems and Infrastructure
<https://cds.cern.ch/record/2020886>

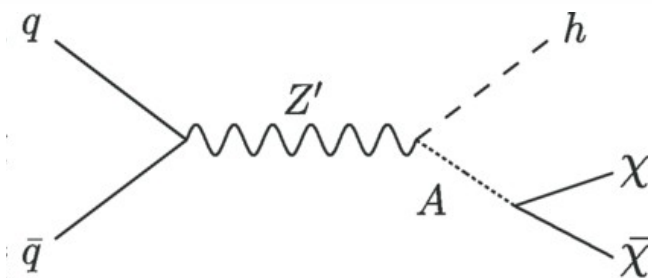
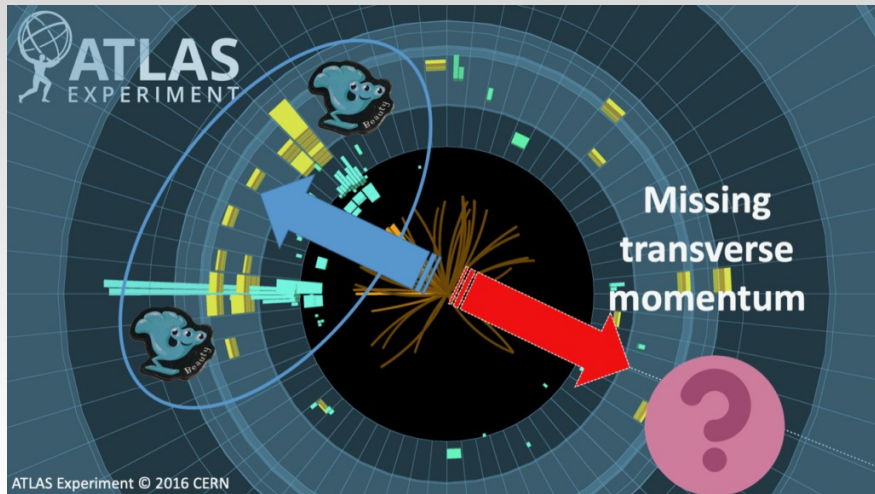
New paradigms for a HEP experiment to meet the unprecedented challenges
and fully exploit the HL-LHC luminosity and physics potential

- 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

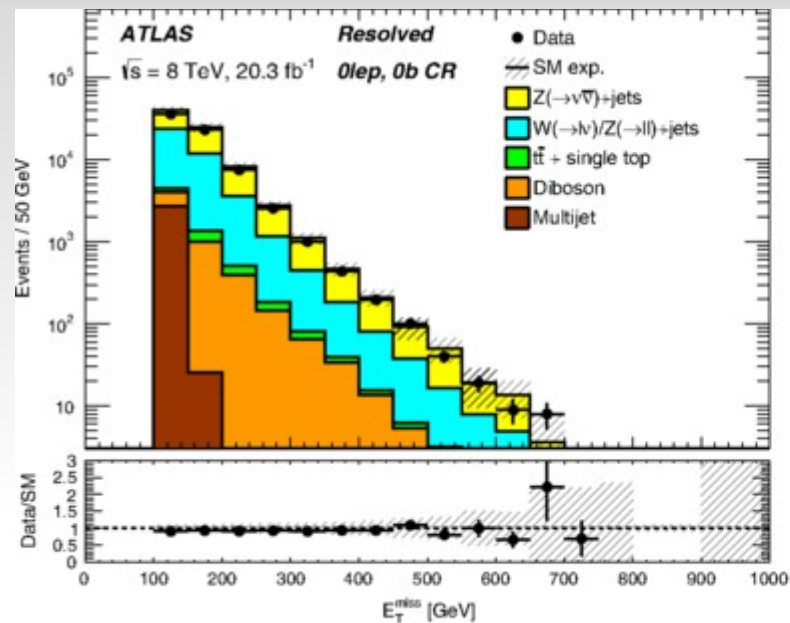
ATLAS / CMS actual dark matter search: missing energy



ATLAS / CMS actual dark matter search



(b) Z' -2HDM

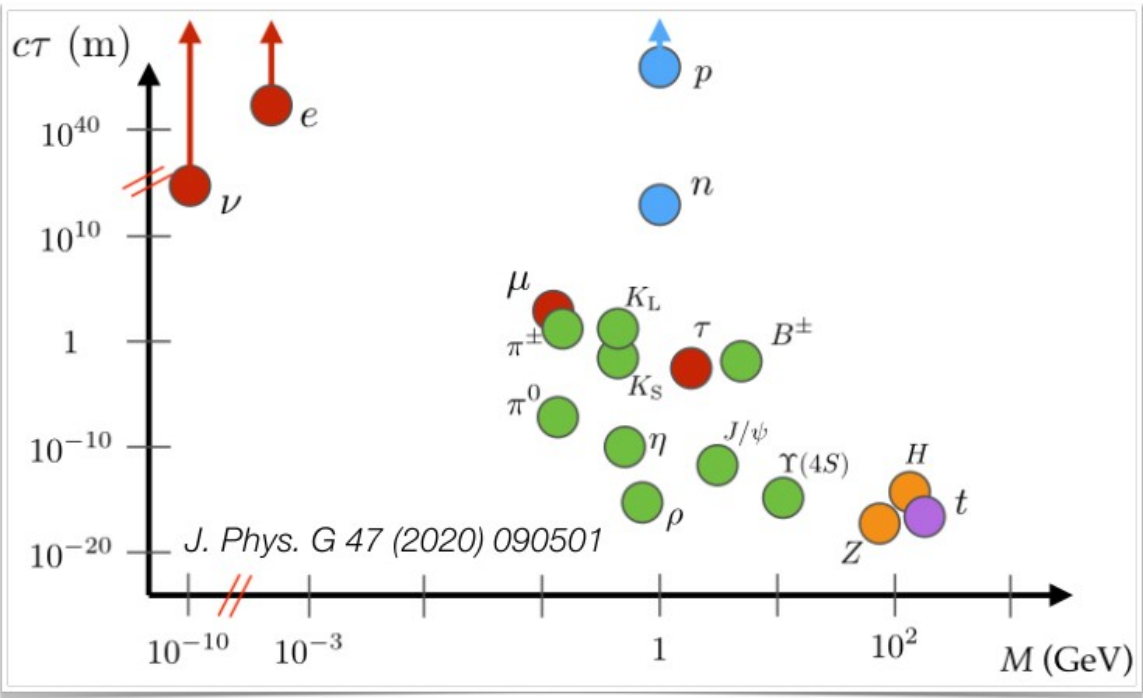


(a) Resolved channel

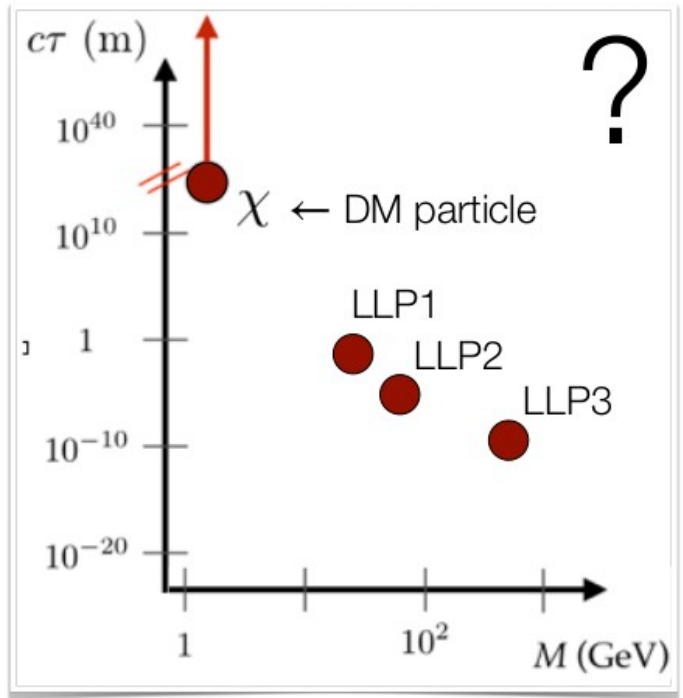
Can we do better

What if the Dark Sector is non-trivial?

SM sector

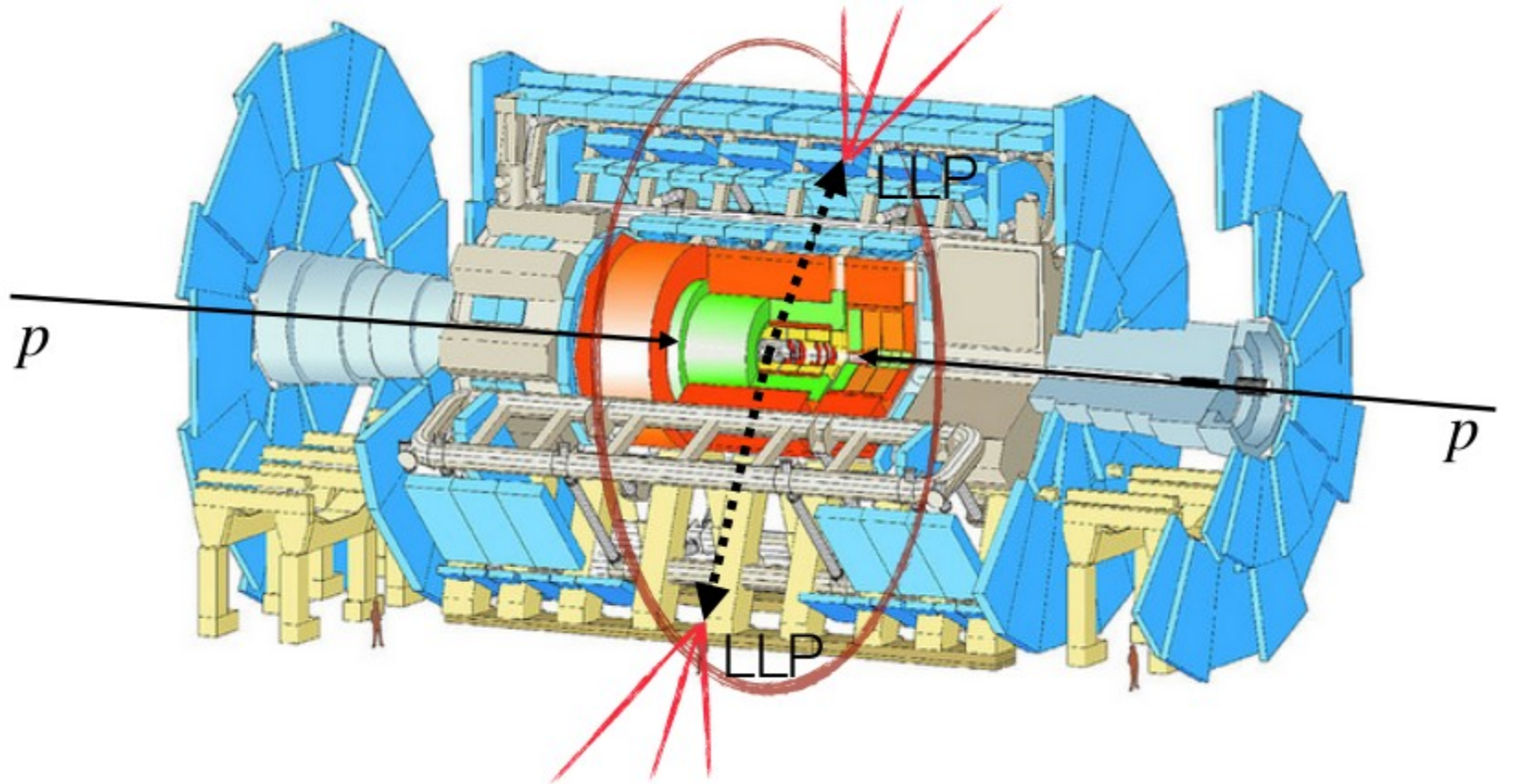


Dark Sector

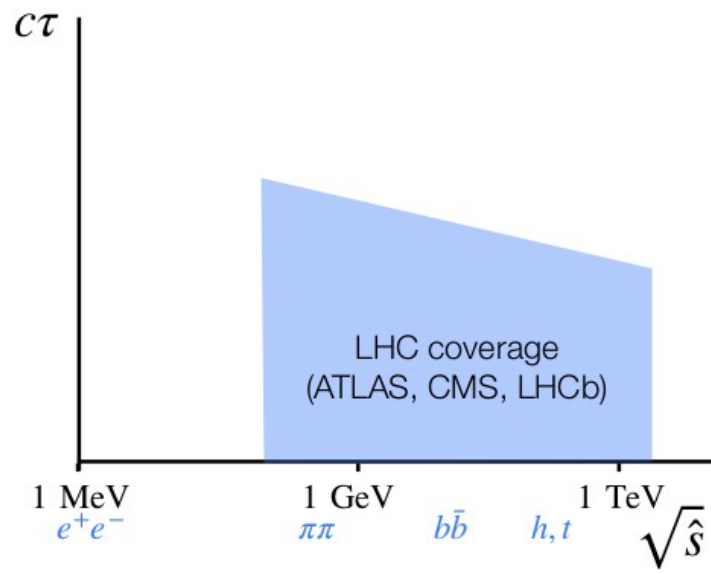
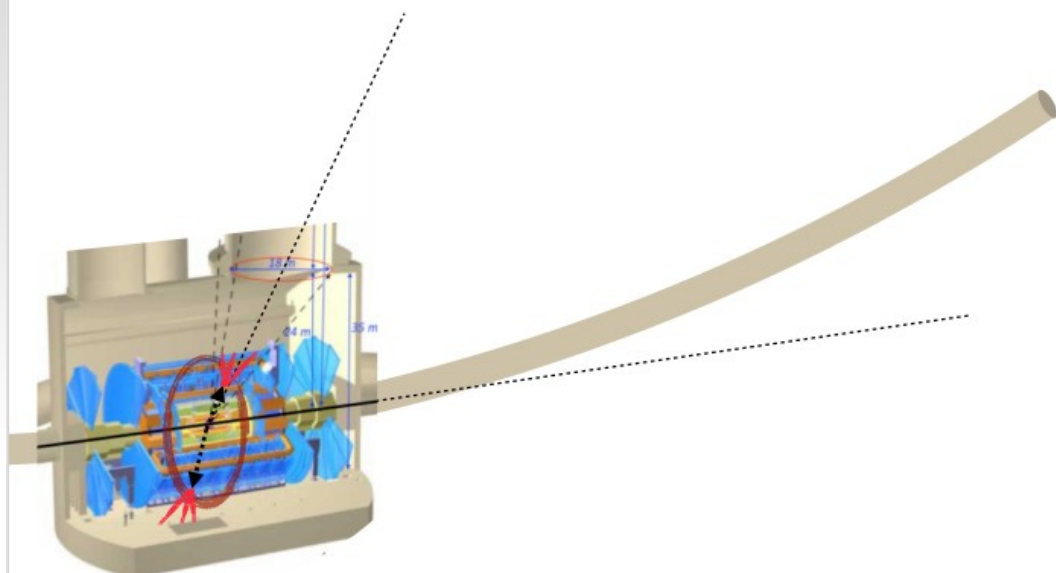


[Long-lived particle (LLP) signatures ubiquitous in many other BSM scenarios like e.g. baryogenesis]

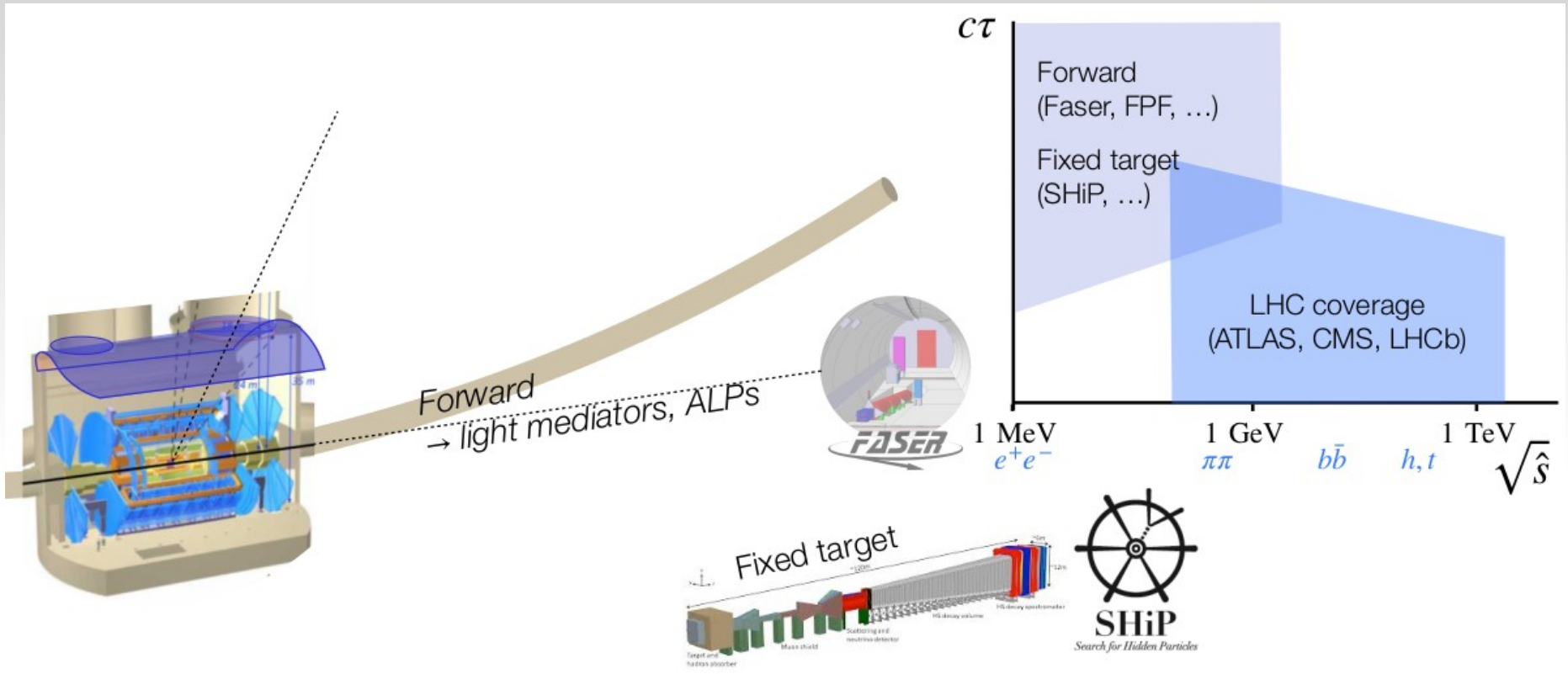
Timing and distance is the new frontier



Timing and distance is the new frontier



Timing and distance is the new frontier

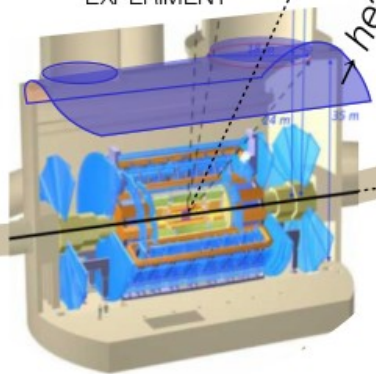


Timing and distance is the new frontier

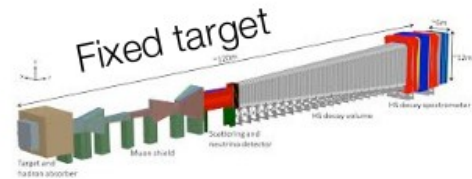
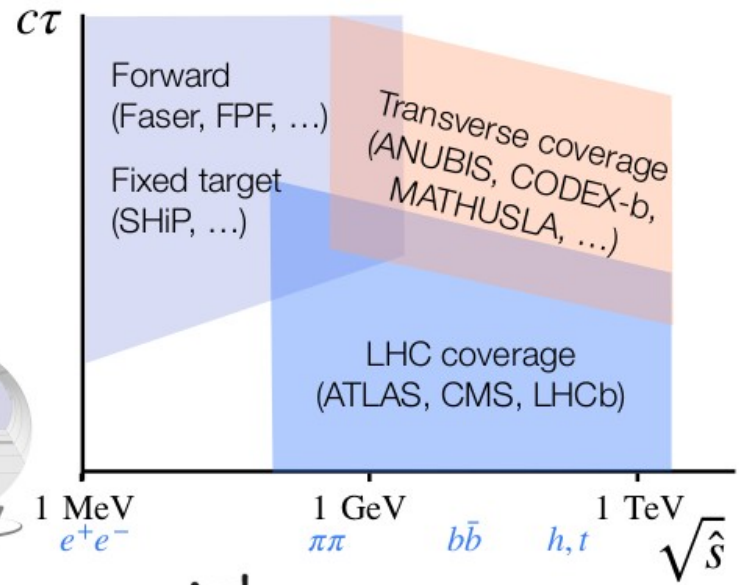
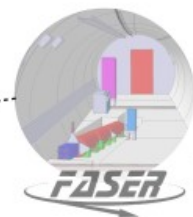
+ Other transverse proposals:
MATHUSLA, CODEX, ...



Transverse
heavy mediators
e.g. Higgs

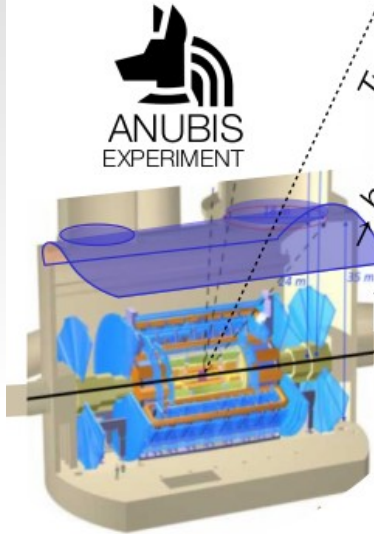


Forward
→ light mediators, ALPs



Timing and distance is the new frontier

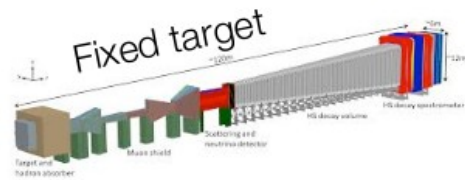
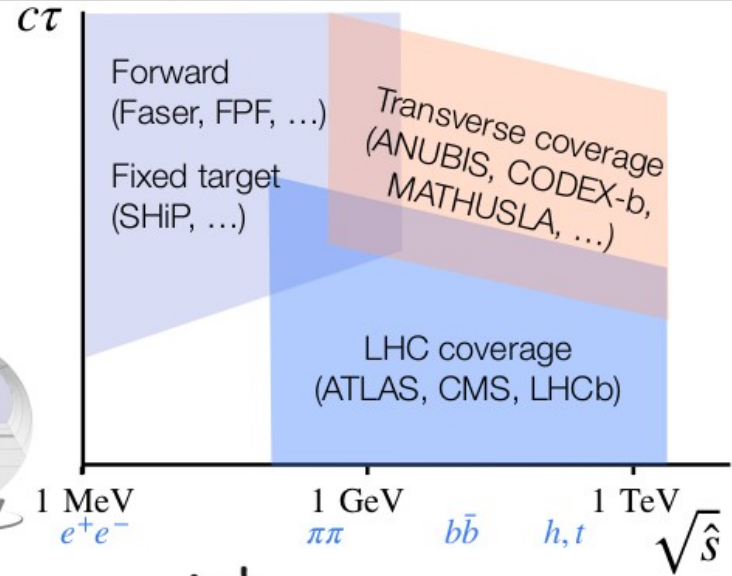
+ Other transverse proposals:
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Transverse
heavy mediators
e.g. Higgs

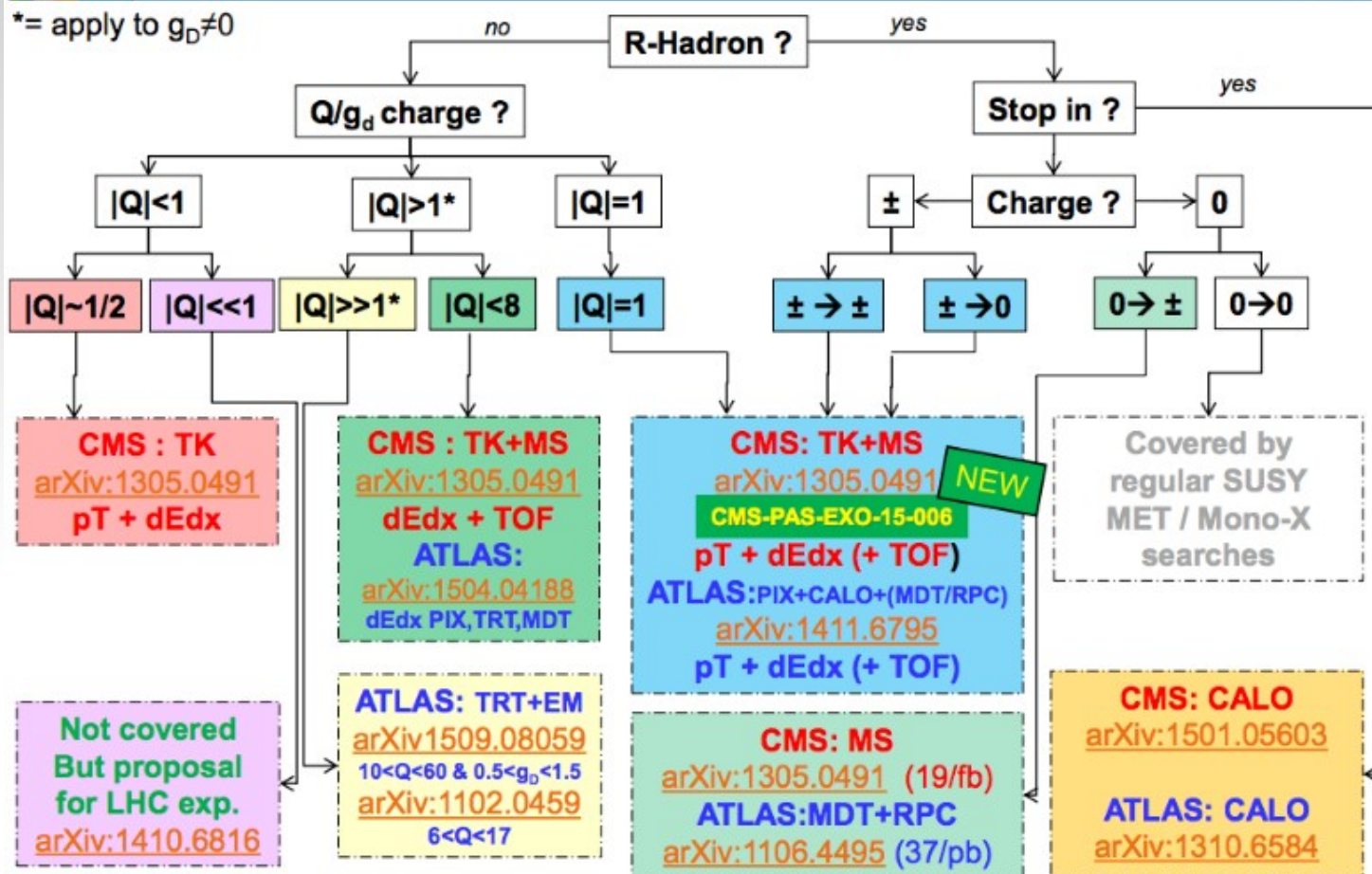
Complementarity!

Forward
→ light mediators, ALPs



How can you look for long living particle at LHC

*= apply to $g_D \neq 0$



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 $m_{\tilde{\tau}_{L,R}}^2$, μ , $\tan\beta$, and A_τ) close to $\tilde{\chi}_1^0$ mass.
	\tilde{G}	GMSB	Large N , small M , and/or large $\tan\beta$.
	\tilde{g} MSB	SUGRA	No detailed phenomenology studies, see [23]. 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_τ .	
	AMSB	Small m_0 , large $\tan\beta$.	
	\tilde{g} MSB	Generic in minimal models.	
$\tilde{\tau}_{\pm 1}$	\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 μ .
	\tilde{g} MSB		\tilde{e}_1 and $\tilde{\mu}_1$ co-LSP and also SMP when stau mixing small.
$\tilde{\chi}_1^\pm$	$\tilde{\chi}_1^0$	MSSM	$m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} \lesssim m_{\pi^\pm}$. Very large $M_{1,2} \gtrsim 2$ TeV $\gg \mu $ (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 \mu $. 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
\tilde{G}		GMSB	SUSY GUT extensions [25–27].
\tilde{g}		MSSM	Very small $M_3 \ll M_{1,2}$, O-II models near $\delta_{GS} = -3$.
$\tilde{\tau}_1$	GMSB		SUSY GUT extensions [25–29].
	$\tilde{\chi}_1^0$	MSSM	Non-universal squark and gaugino masses. Small $m_{\tilde{g}}^2$ and M_3 , small $\tan\beta$, large A_t .
\tilde{b}_1			Small $m_{\tilde{g}}^2$ 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.

- **Heavy:** Implies slow particles, $\beta < 1.0$
- **Stable:** Lives long enough so it can reach tracker 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)
± 1	1	$\frac{1}{2}$	Universal Extra Dimensions (KK lepton) Fat Higgs with a fat top (ψ fermions) 4th generation (chiral) fermions Mirror and/or vector-like fermions
$\pm \frac{2}{3}$	3	$\frac{1}{2}$	Fat Higgs with a fat top (ψ scalars)
0		$\frac{1}{2}$	Warped Extra Dimensions with GUT parity (XY gaugino)
0		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
$\epsilon < 1$	1	$\frac{1}{2}$	Warped Extra Dimensions with GUT parity (XY gaugino) GUT with $U(1) - U(1)'$ mixing Extra singlets with hypercharge $Y = 2\epsilon$ Millicharged neutrinos
?	?	$0/1/1$	“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 C_{QCD} , spin S , and scenario.

A bit of homework: what is Beta

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

$$x' = \gamma (x - vt)$$

$$y' = y$$

$$z' = z$$

	Boost	Centre Masse
t'	E	M
x'	P_x	0
y'	P_y	0
z'	P_z	0

A bit of homework: what is Beta

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$\beta = \frac{v}{c}$$

$$E = \gamma M$$

$$E^2 = \gamma^2 M^2$$

$$E^2 = \frac{M^2}{1 - \beta^2} \Rightarrow E^2 - \beta E^2 = M^2$$

$$p = \beta \gamma M$$

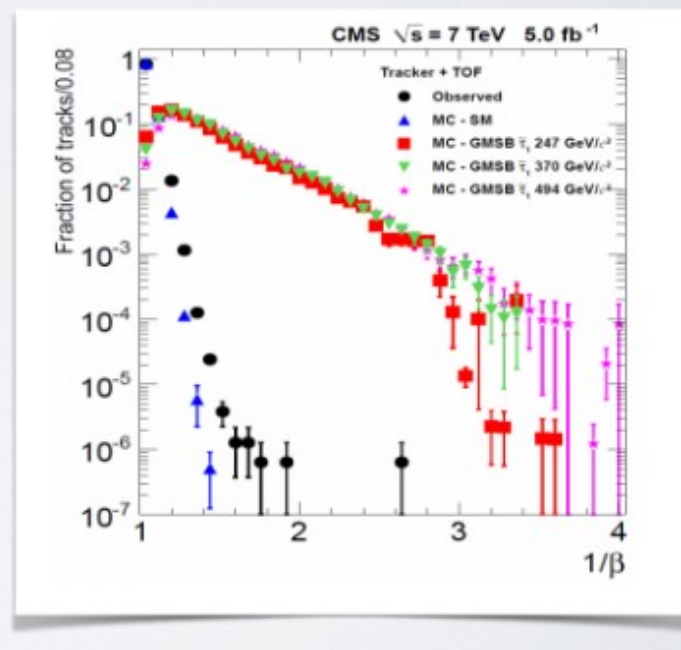
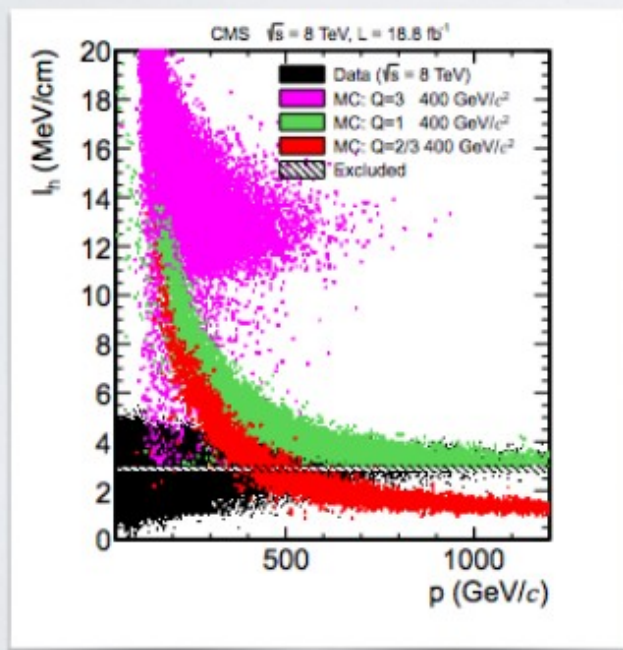
How can you look for HSCP

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

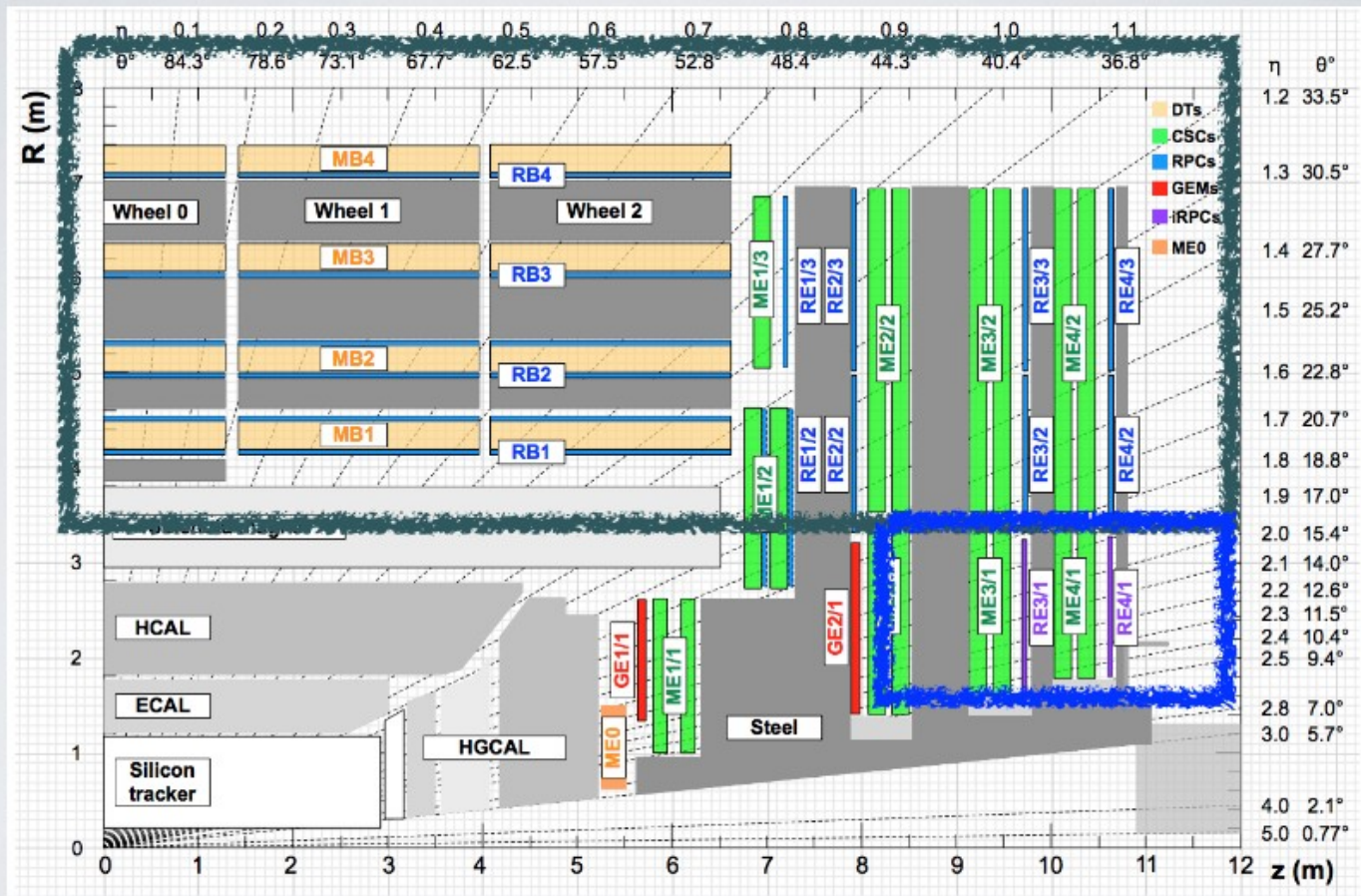
$$\frac{dE}{dx} \approx Q^2 \left[\frac{A}{\beta^2} + B \right] \text{ for } \beta \ll 1$$

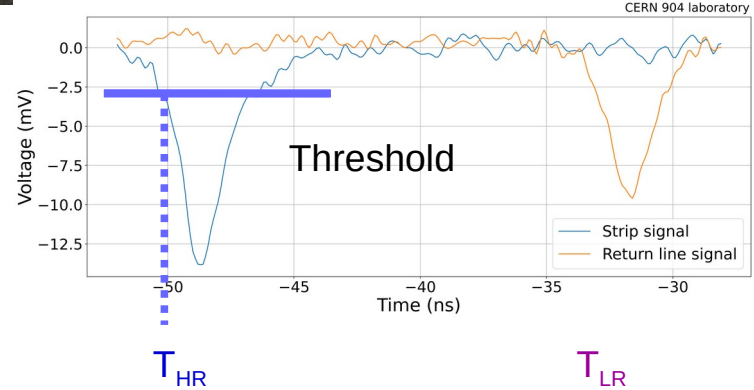
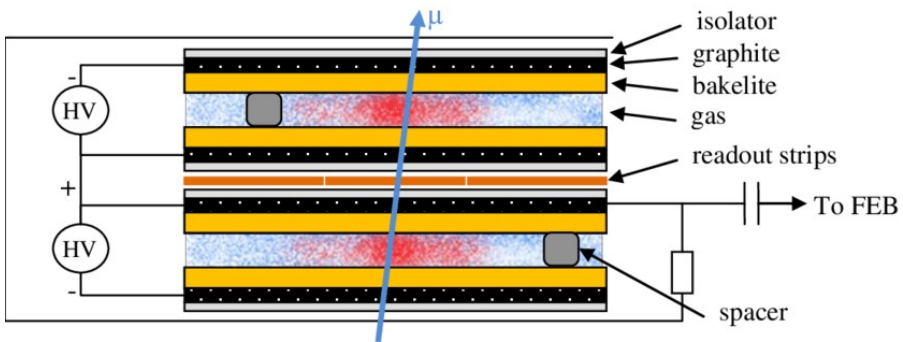
- **TOF:** Time of flight

$$\frac{1}{\beta} = 1 + \frac{c\delta t}{L}$$

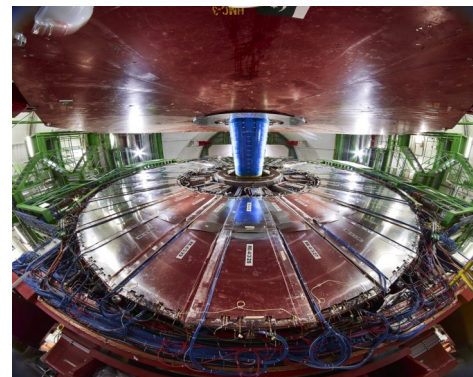


RPC chambers: high precision timing at HL-LHC for TOF

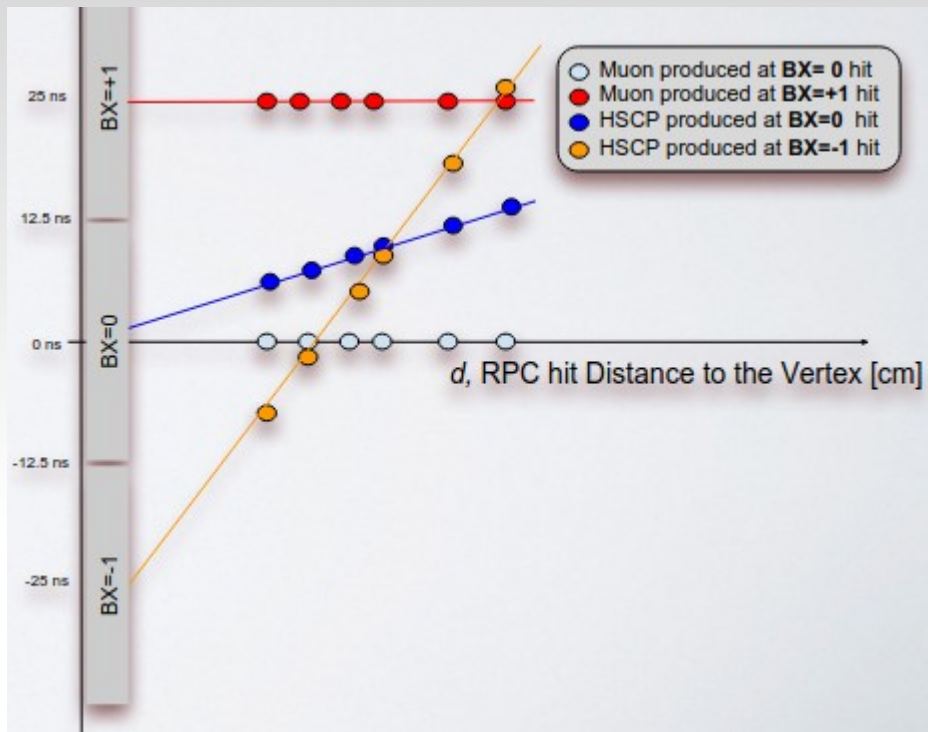




- Very fast detector : time resolution 0.5 – 1.5 ns depending on the type



How can we see slow HSCP



CMS trigger system today

- LHC collisions : every 25 ns (bunch crossing - BX)
- 40 MHz collisions
- L1 super-fast 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

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:

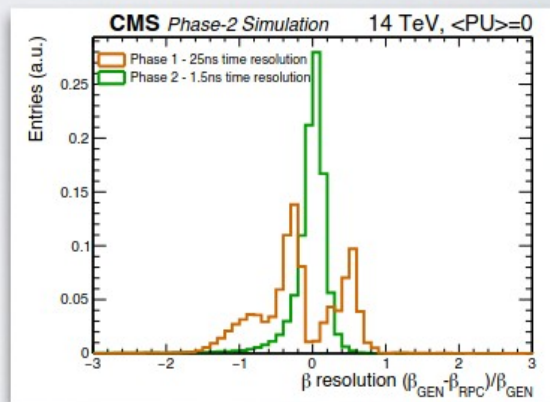
$$t_{delay} = t_0 + \frac{d}{c}(\beta^{-1} - 1)$$

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:

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



A bit of homework: t_{delay}

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

A bit of homework: t_{delay}

$$\begin{aligned} t_0 + \cancel{t_0} - t_{\mu} &= t_0 + \frac{d}{v} - \frac{d}{c} \\ &= t_0 + \frac{d}{c} \frac{c}{v} - \frac{d}{c} = t_0 + \frac{d}{c} \left(\frac{1}{\beta} - 1 \right) \end{aligned}$$

(5)

$$t_{\text{delay}} = t_0 + \frac{6\text{m}}{308\text{m/s}} (2-1)$$
$$\begin{aligned} \beta=0.5 \quad t_{\text{delay}} - t_0 &= 2e-8\text{s} \\ &= 20\text{ns} \left(\frac{1}{\beta} - 1 \right) \end{aligned}$$
$$\begin{aligned} \beta=0.9 : \quad &= 20\text{ns} \times \left(\frac{1}{0.9} - 1 \right) \\ &= 2\text{ns} \end{aligned}$$

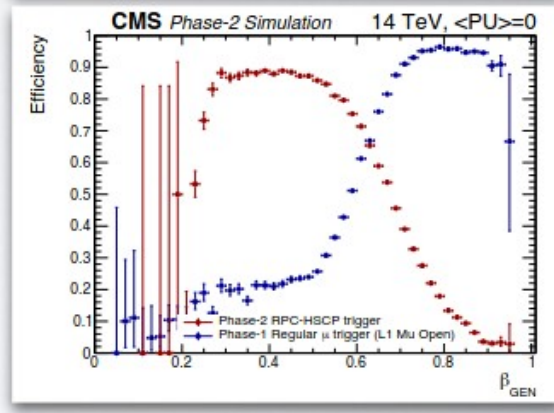
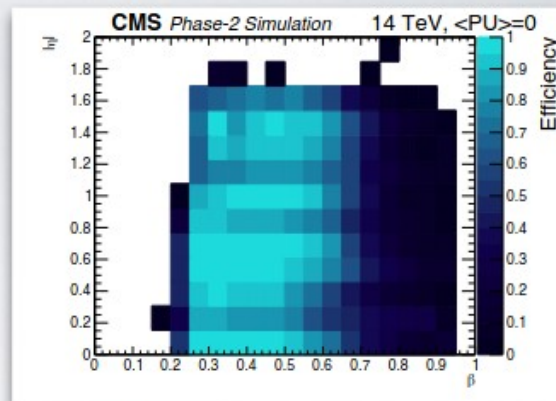
Trigger Algorithm proposal

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 $\beta < 0.6$



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...