LHC

Tutorial Chat

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LIP Internship Program 2021

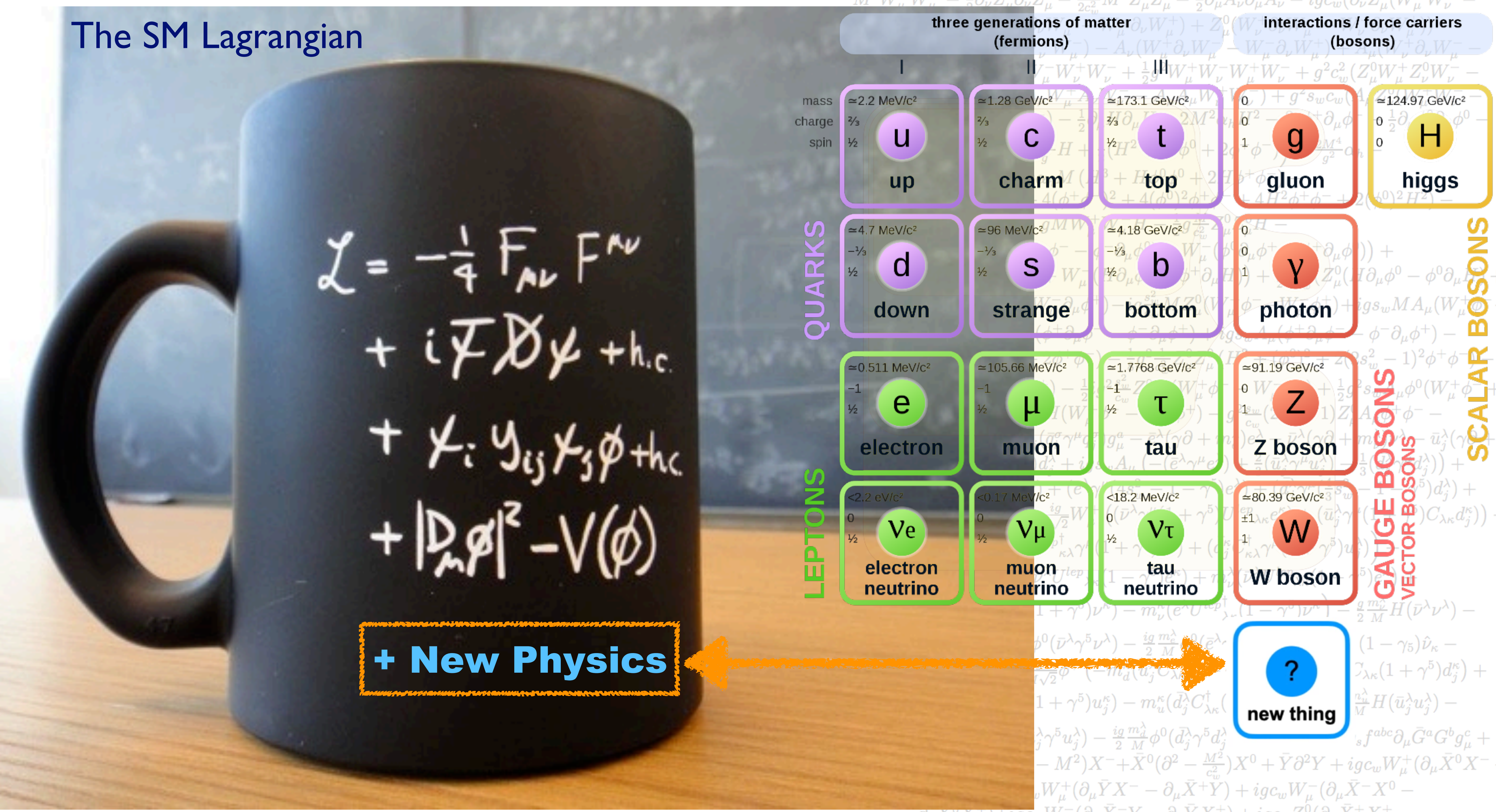
2021 INTERNSHIP PROGRAM
COIMBRA LISBOA MINHO

- Standard Model and New Physics
- Anomalies!
- Detectors → Physics
- Neutrinos@LHC?

LIP

FCT Fundação para a Ciência e a Tecnologia

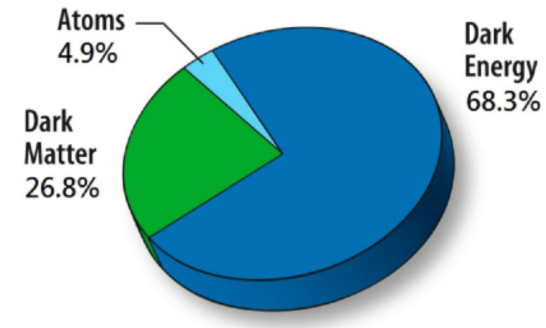
The Standard Model & Beyond

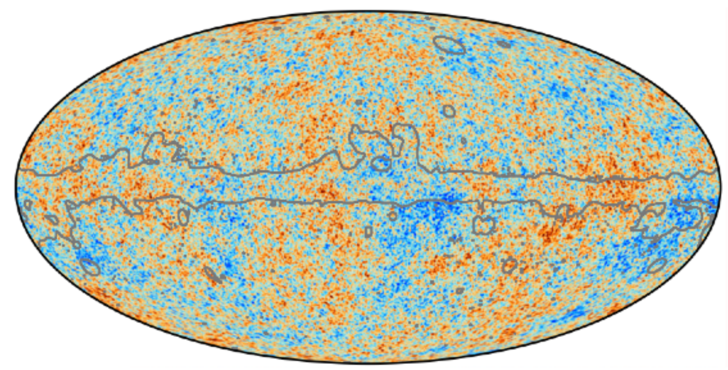


Going Beyond the SM — *New Physics*!

Porque necessitamos Nova Física ?

SM + gravity ≠ cosmos

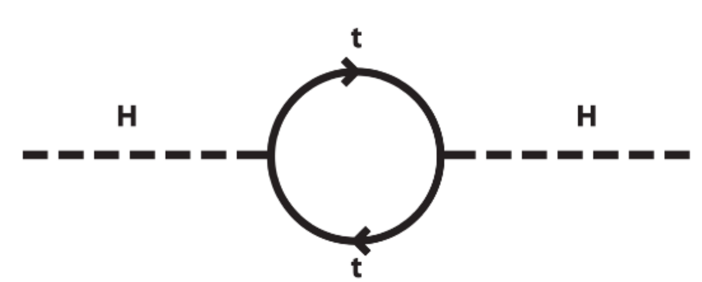




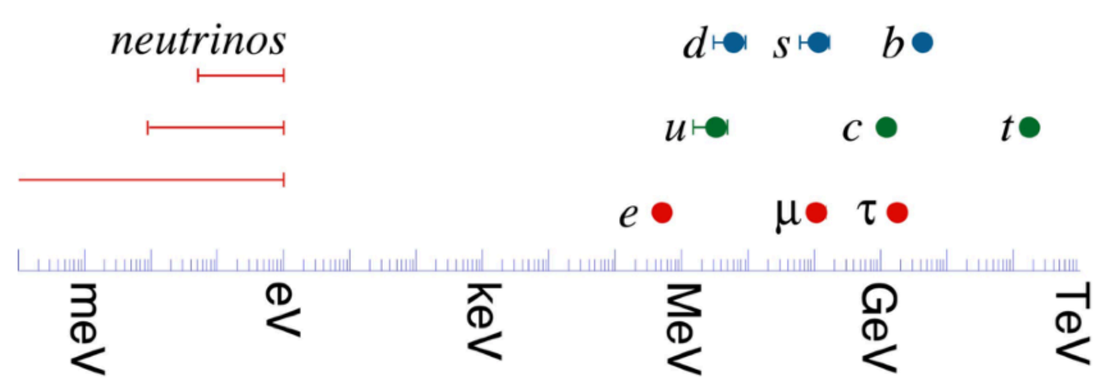
<u>Dados</u> que *decididamente* não conseguimos explicar:

assimetria matéria-antimatéria (CPV?...) — matéria escura (WIMPs, ALPs, ...?) — inflação (inflatão?)

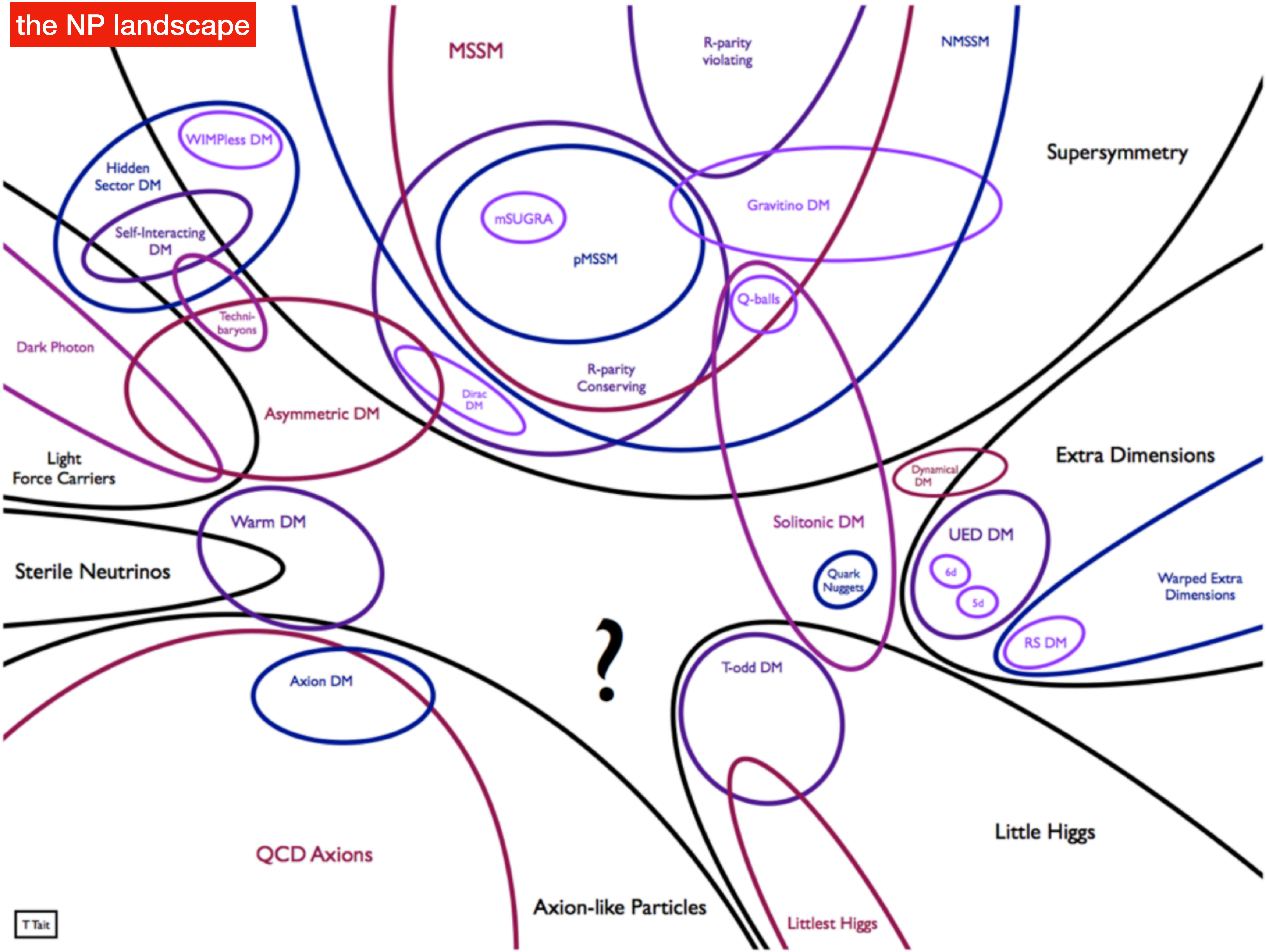
- **Hierarquia electrofraca**
  - Fraca/Gravidade ~10^{24}
  - EWK << Planck (Deserto?)
  - Instabilidade da massa do Higgs
  - Fine tuning
  - Naturalness



- **Hierarquia de sabor**
  - Porquê tantos parâmetros (19+)?
  - Porquê 3 famílias ('Who ordered that?')
  - Porquê $\theta_{QCD} < 10^{-9}$ (Strong CP problem)
  - Porquê hierarquias enormes nas massas e acoplamentos dos fermiões?

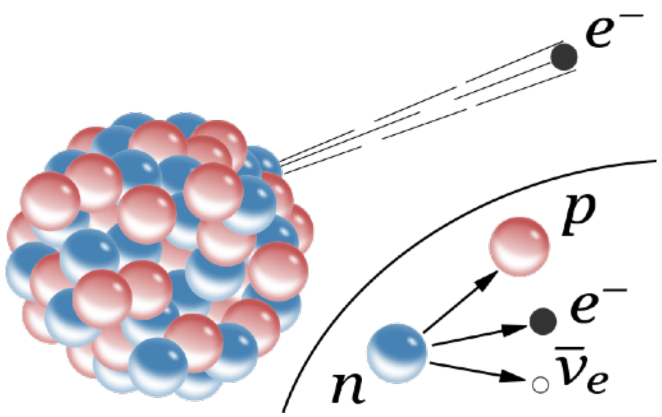


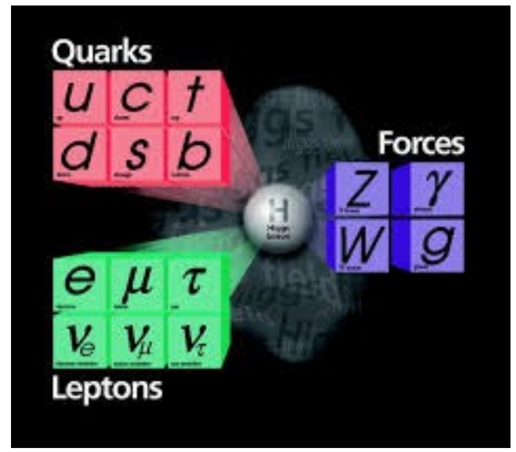
the NP landscape

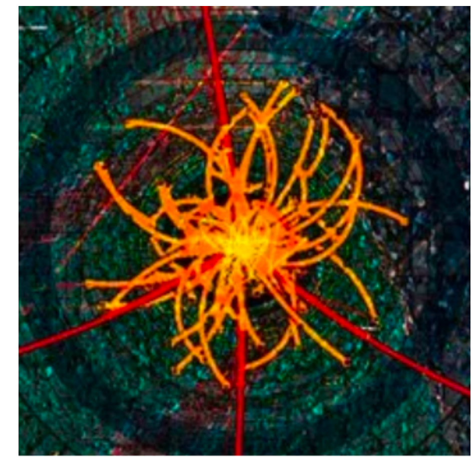


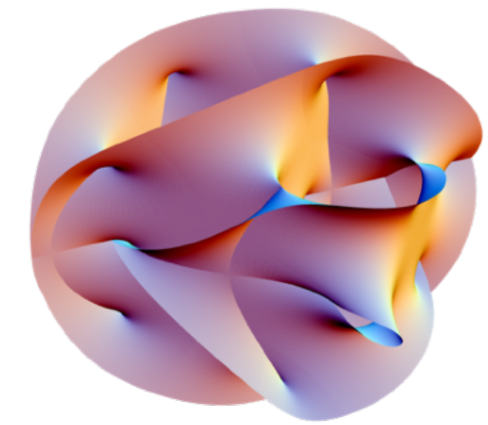
energy scale $m_{Z,W}$ m_H m_t Λ_{NP}

1930 … 1970 2012 2020 … future

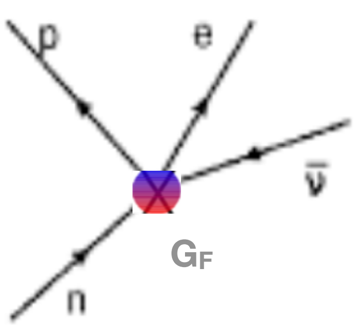


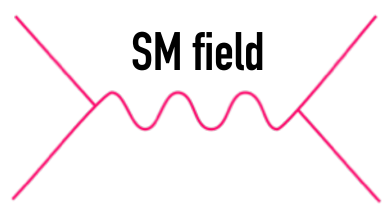


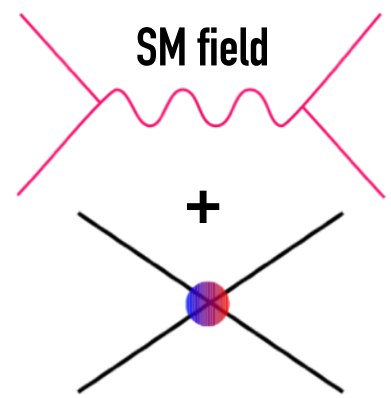


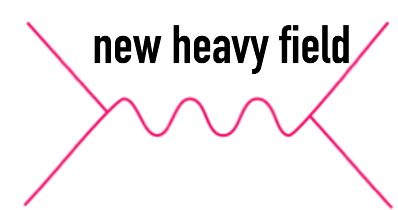


Fermi model	Standard Model	SM-EFT	UV theory









$\mathcal{L}_{\rm Fermi} = -\frac{G_F}{\sqrt{2}} \bar{p}\gamma_\mu n\, \bar{e}\gamma^\mu \nu + {\rm h.c.}$

$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm gauge} + \mathcal{L}_{\rm higgs}$

$\mathcal{L}_{\rm SM\text{-}EFT} = \mathcal{L}_{\rm SM} + \Sigma_i C_i O_i$

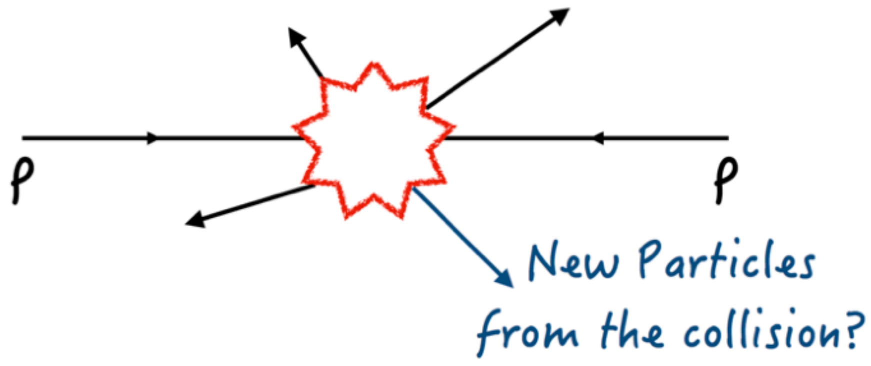
a predecessor of EWK theory

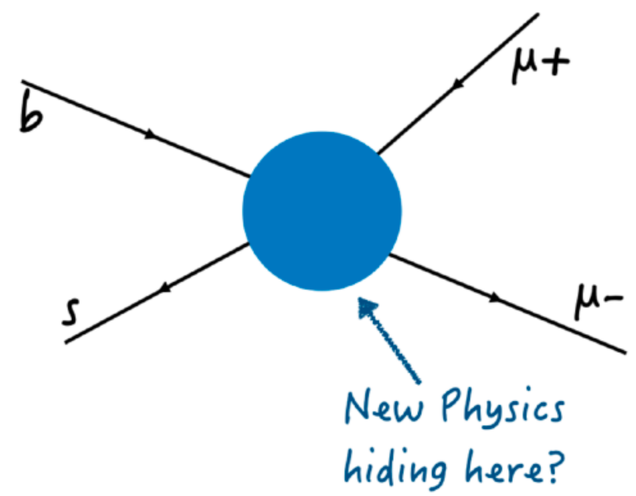
simple and elegant theory describing *almost* all microscopic phenomena

we're here!

a more fundamental theory with new degrees of freedom

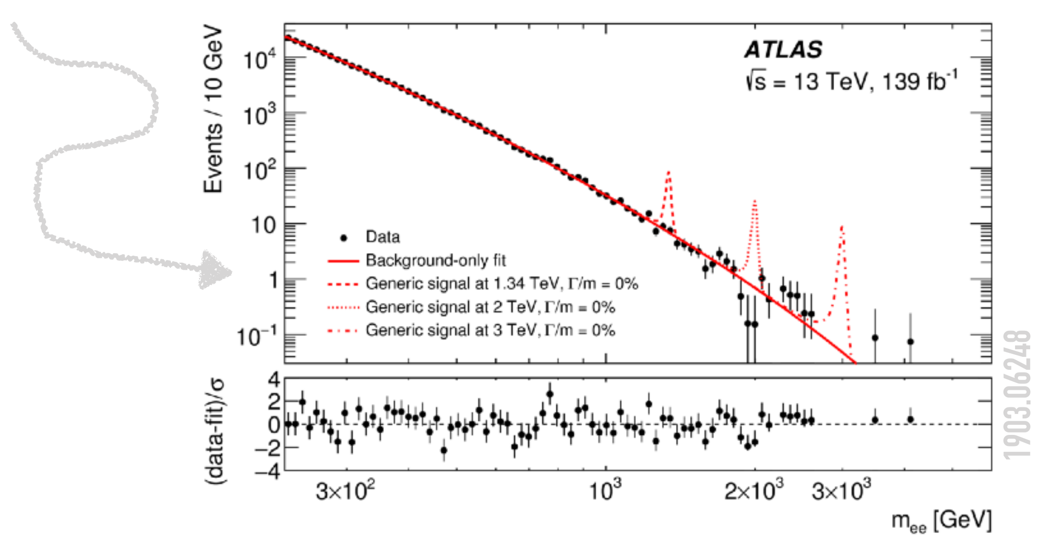
complementary paths to NP @LHC





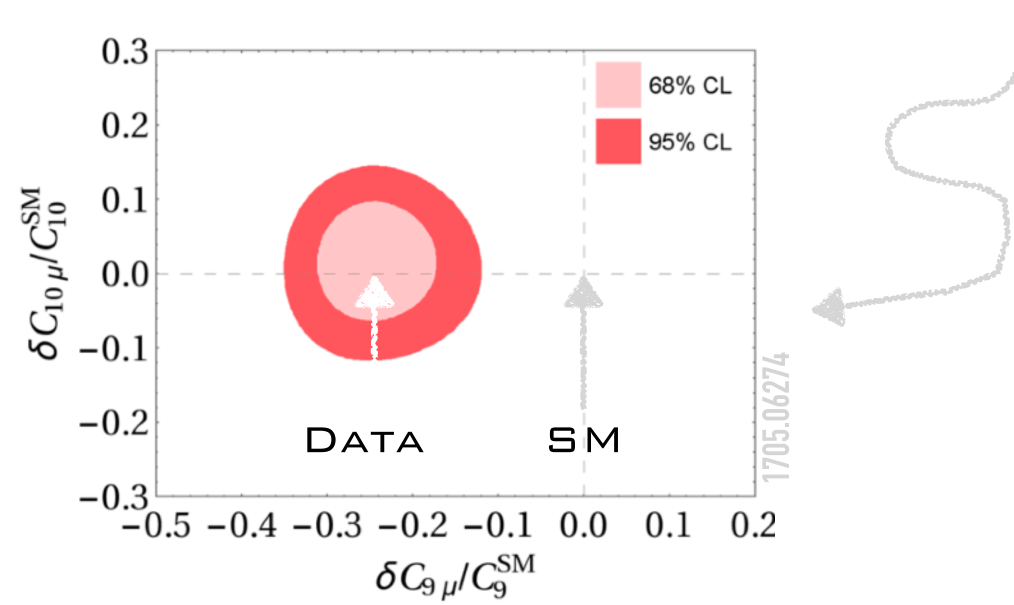
Direct
bump hunting

- searching for the decay products of potentially produced NP particles



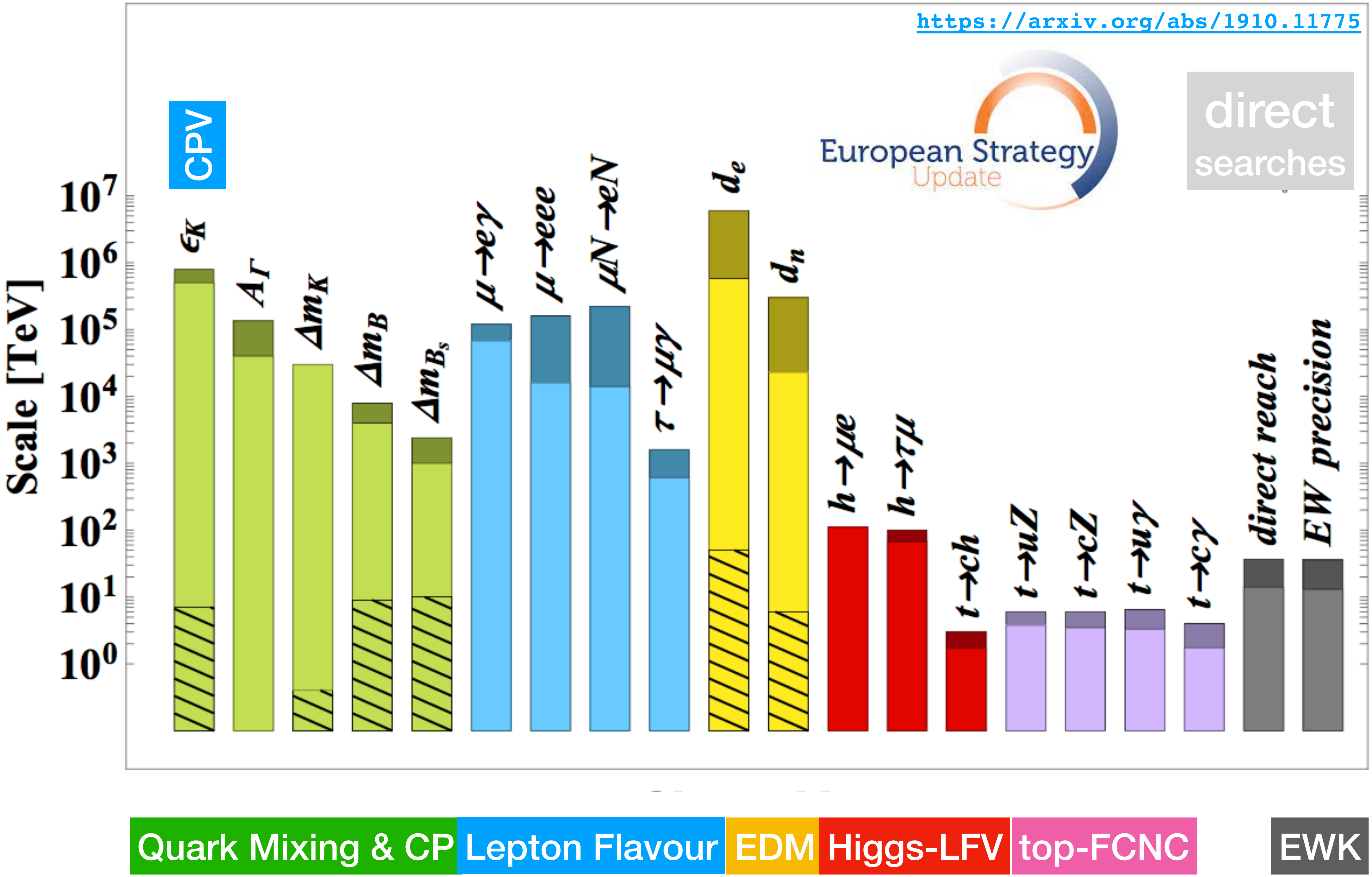
Indirect
precision & rareness

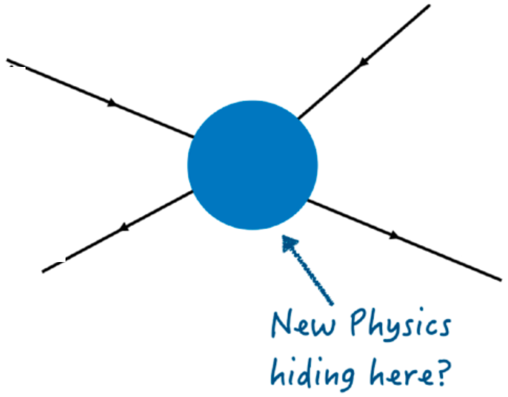
- searching for NP particles running in quantum loops (virtual)



Indirect searches: fuelled by Quantum Mechanics

➡ We can access NP energy scales well beyond the collision energy





Rare Decays

of SM particles, towards NP

beauty
charm
strangeness
top
W,Z
Higgs
leptons (τ,μ)

SUSY
extra dimensions
new bosons Z',W'
leptoquarks
unexpected

?

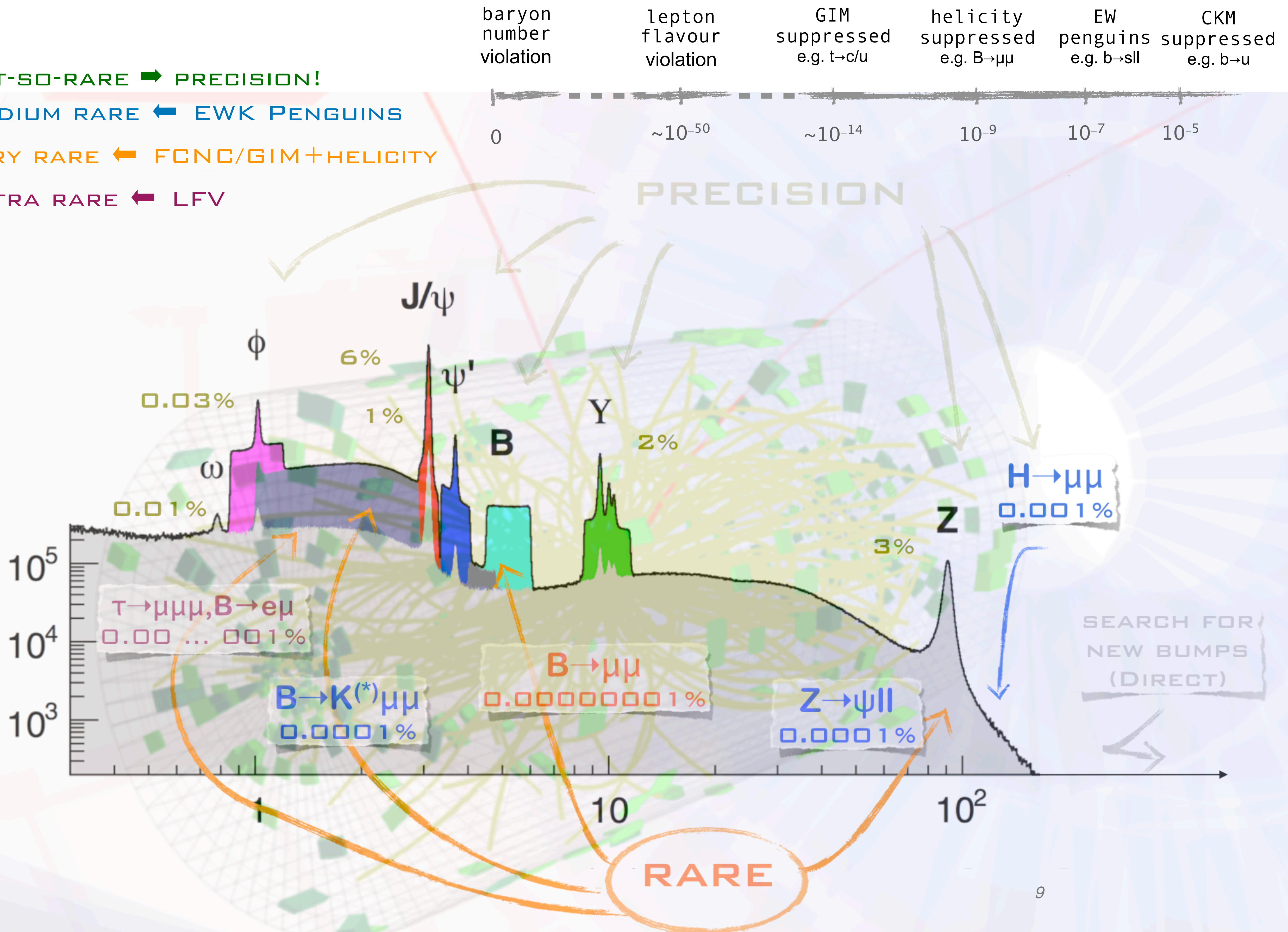
precise & rare

NOT-SO-RARE ➡ PRECISION!

MEDIUM RARE ⬅ EWK PENGUINS

VERY RARE ⬅ FCNC/GIM+HELICITY

ULTRA RARE ⬅ LFV



rare beauty | $B_s \to \mu\mu$

a milestone discovery of the LHC physics program

LETTER

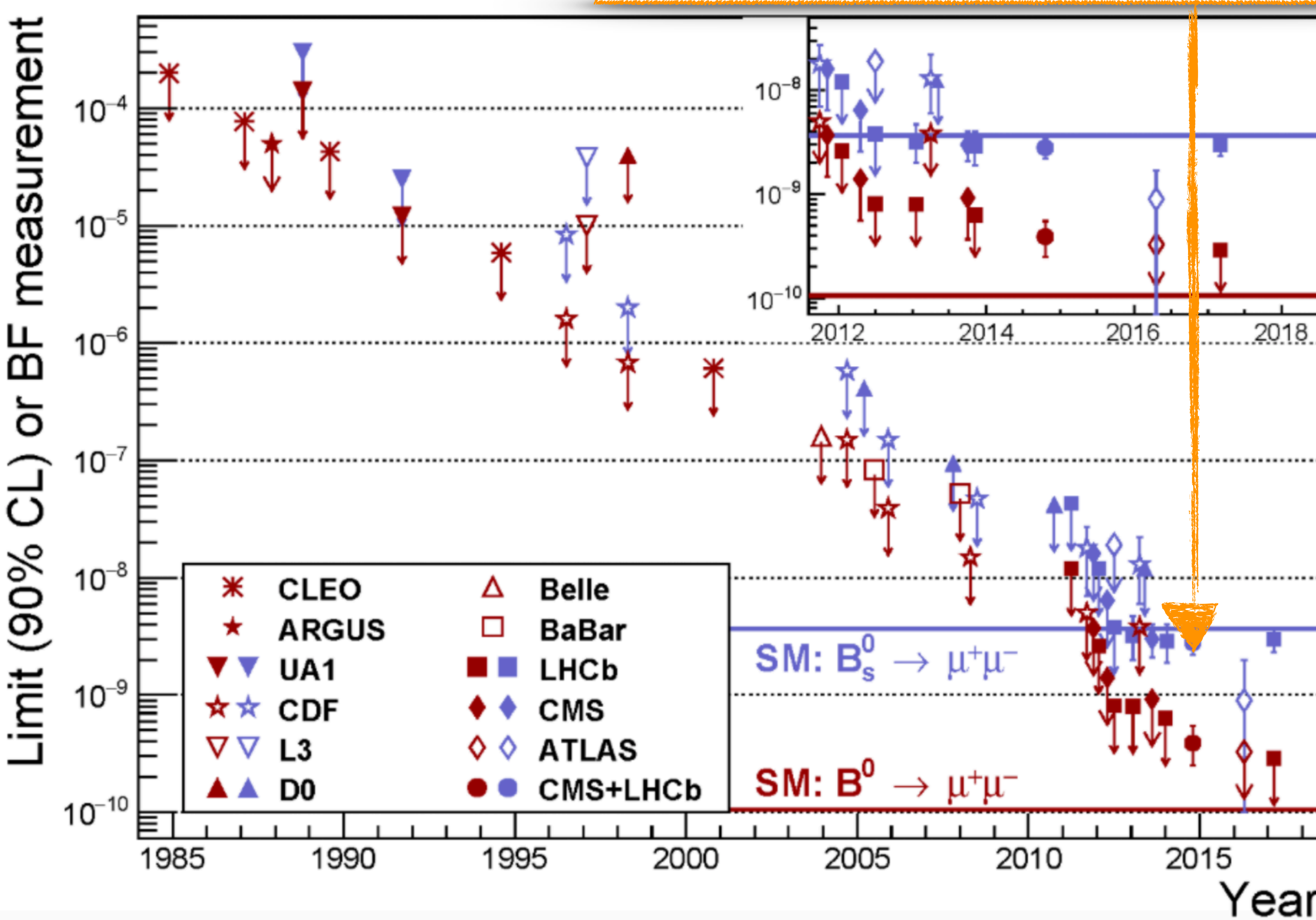
OPEN

doi:10.1038/nature14474

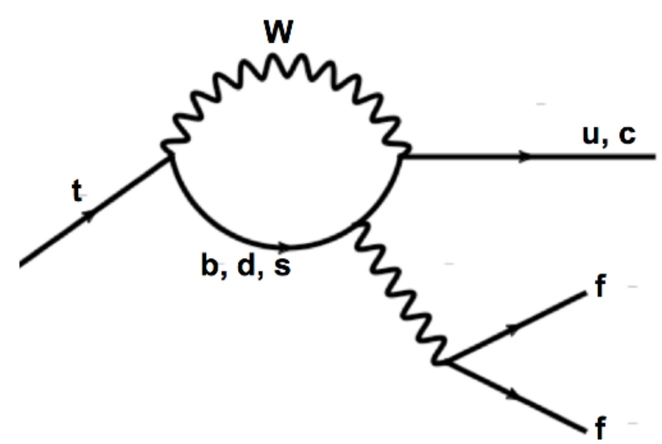
Observation of the rare $B_s^0 \to \mu^+\mu^-$ decay from the combined analysis of CMS and LHCb data

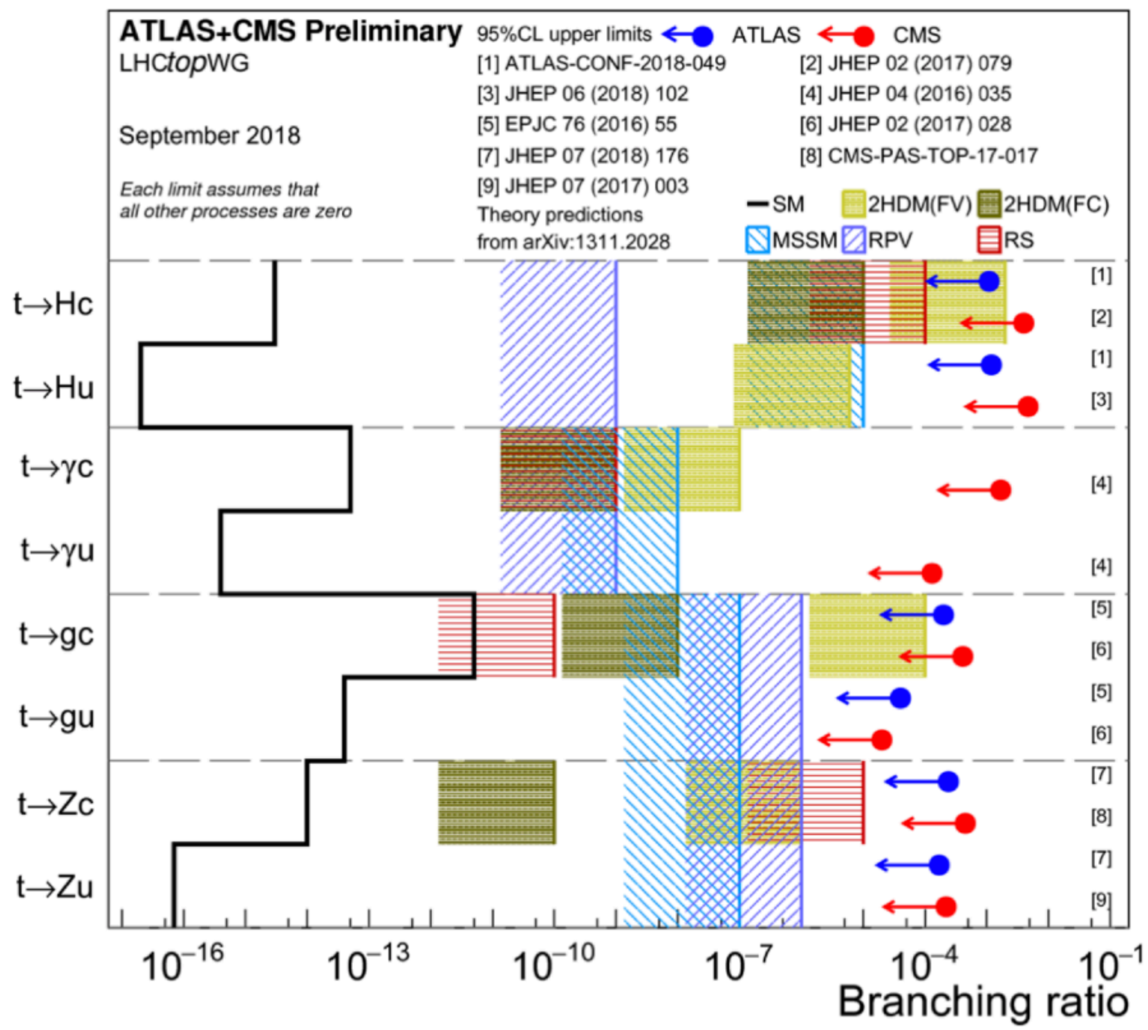
The CMS and LHCb collaborations*

rareness

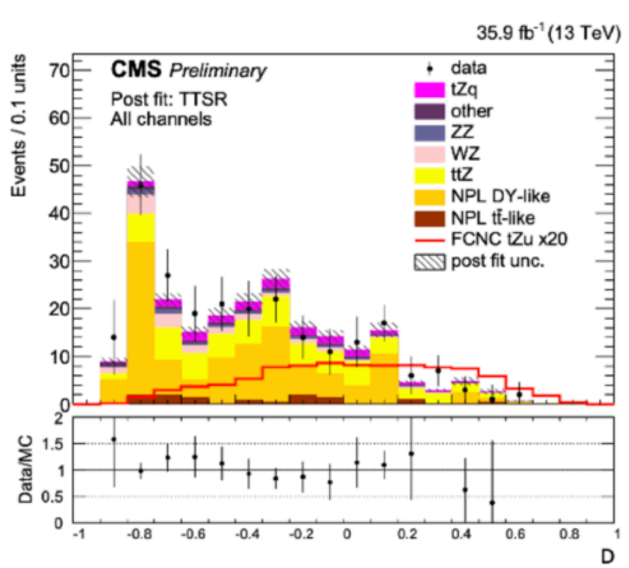


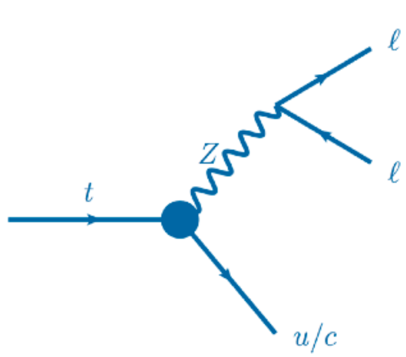
rare top | t→u/c



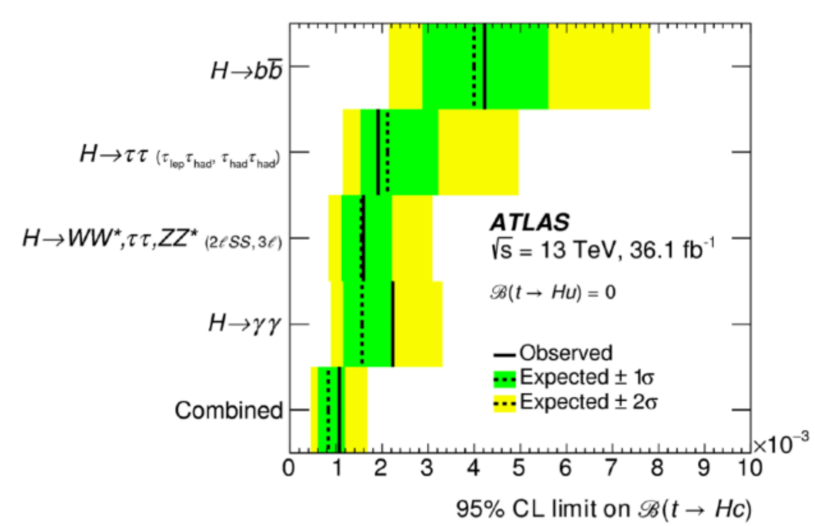


- FCNC/GIM in top sector lead to very rare processes
  - BF~10^{-14}
- rates enhanced in NP models
  - MSSM (10^{-7}), 2HDM (10^{-6}), RS(10^{-5})
- current limits ~10^{-4}





CMS-TOP-17-017



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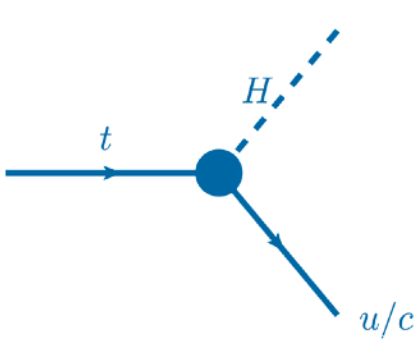
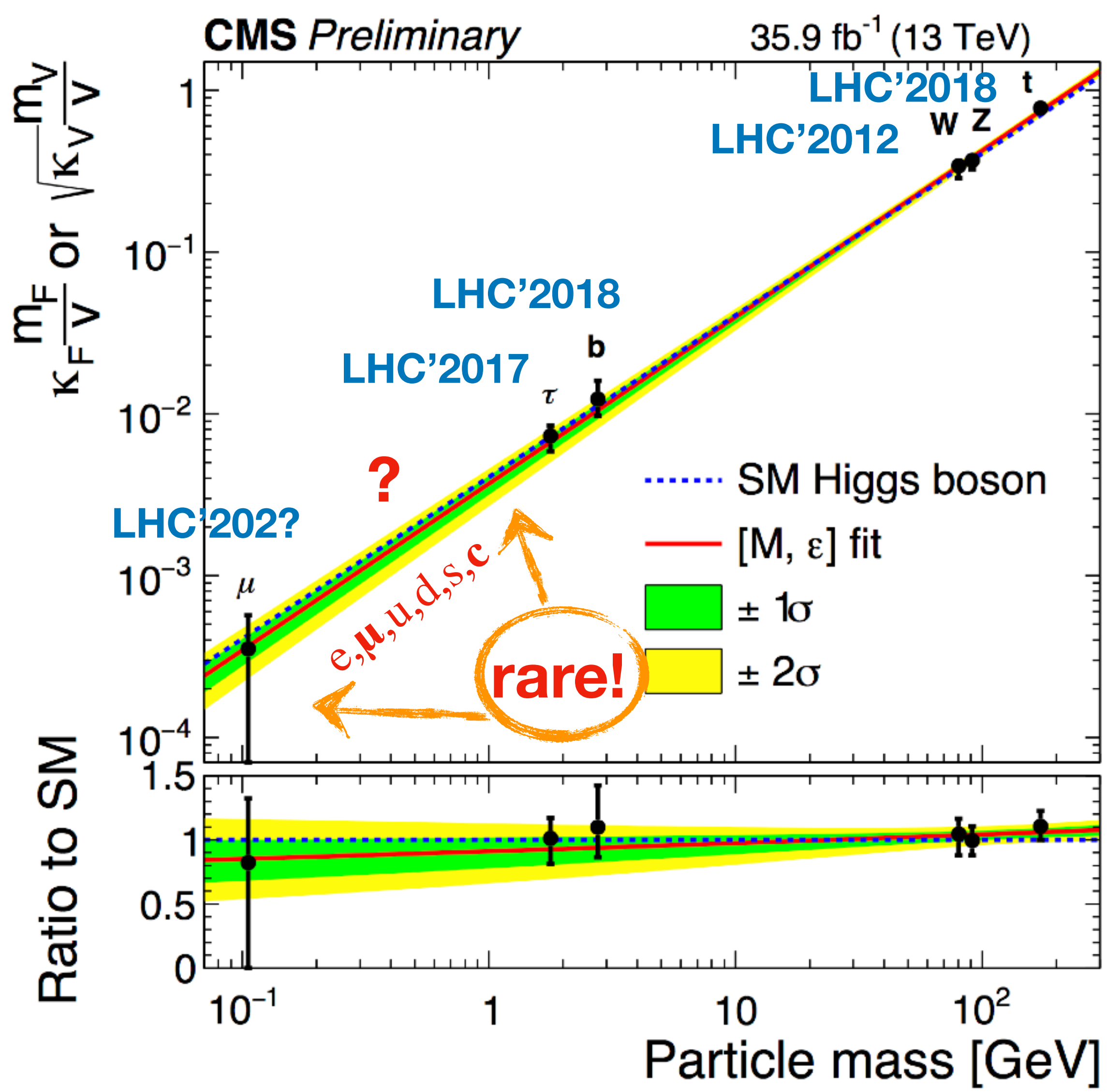
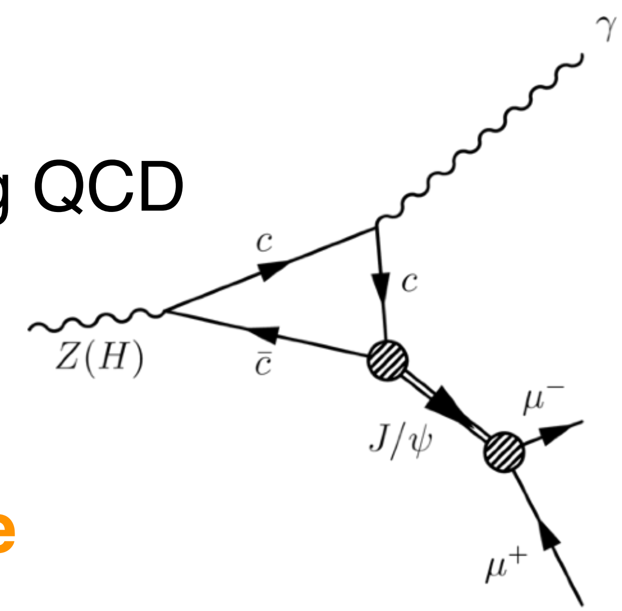
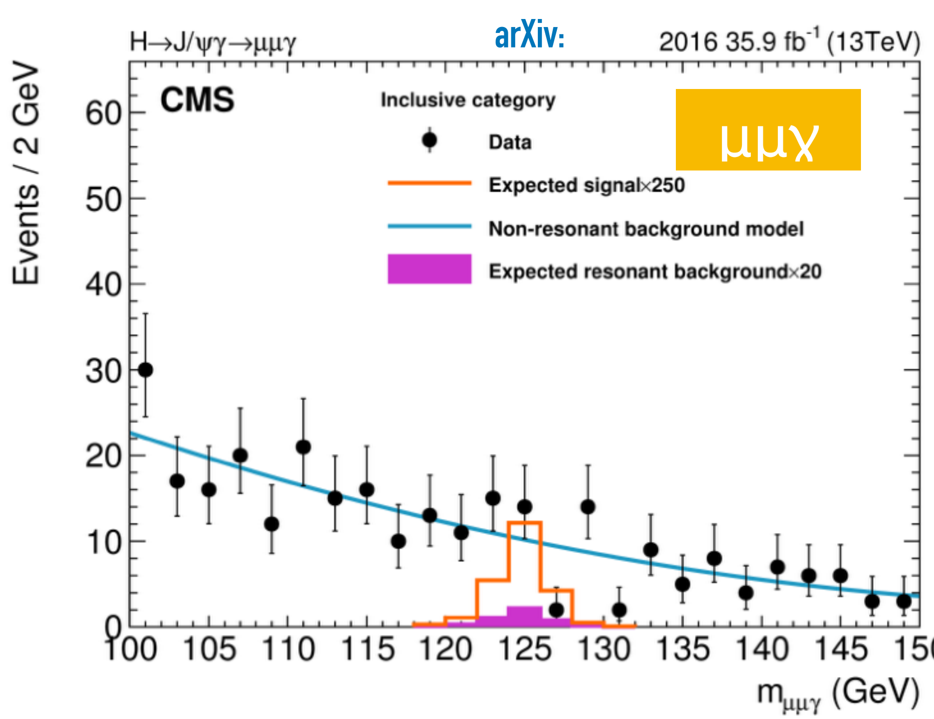


rare Higgs



- $H \to qq$
  - overwhelming QCD background
- $H \to Q\gamma$
  - clean but **rare**
  - $H \to \Upsilon/\psi/\phi/\rho+\gamma$

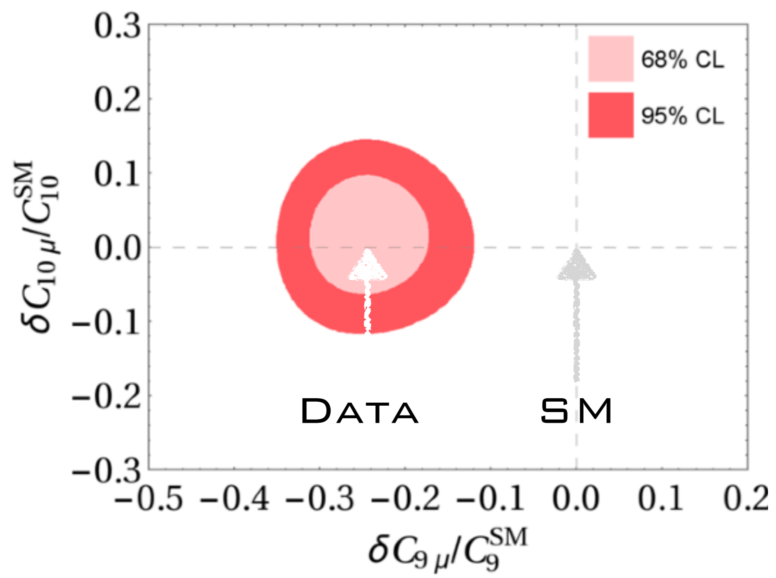




Higgs couplings:

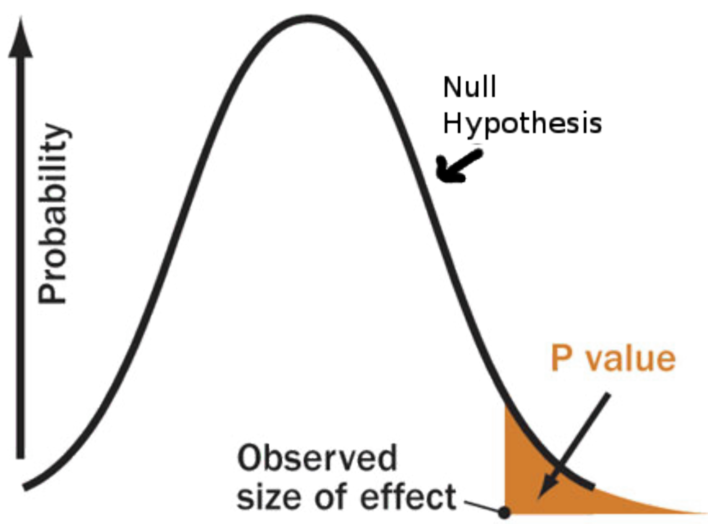
- H to **W,Z,t,b,τ**: done
- H to **γ**: no mass ↠ no coupling
- H to **μ**: clean signature; expect Run2(+Run3)
- H to **c**: challenging, in reach @HL-LHC
- H to **u,d,s,e**: almost hopeless @LHC but NP!

Currently @CMS
$\mu(H \to cc) < 70$ | $\mu(H \to J/\psi\gamma) < 220$



Flavour Anomalies !

statistics! significance of a bump

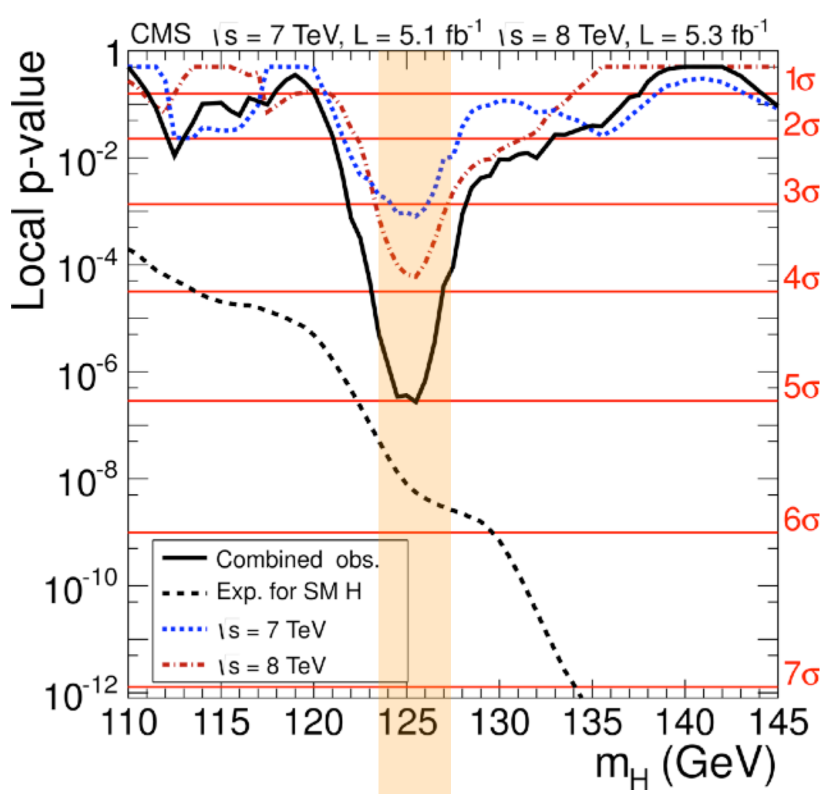


5σ (discovery)
P-VAL: 0.0000003

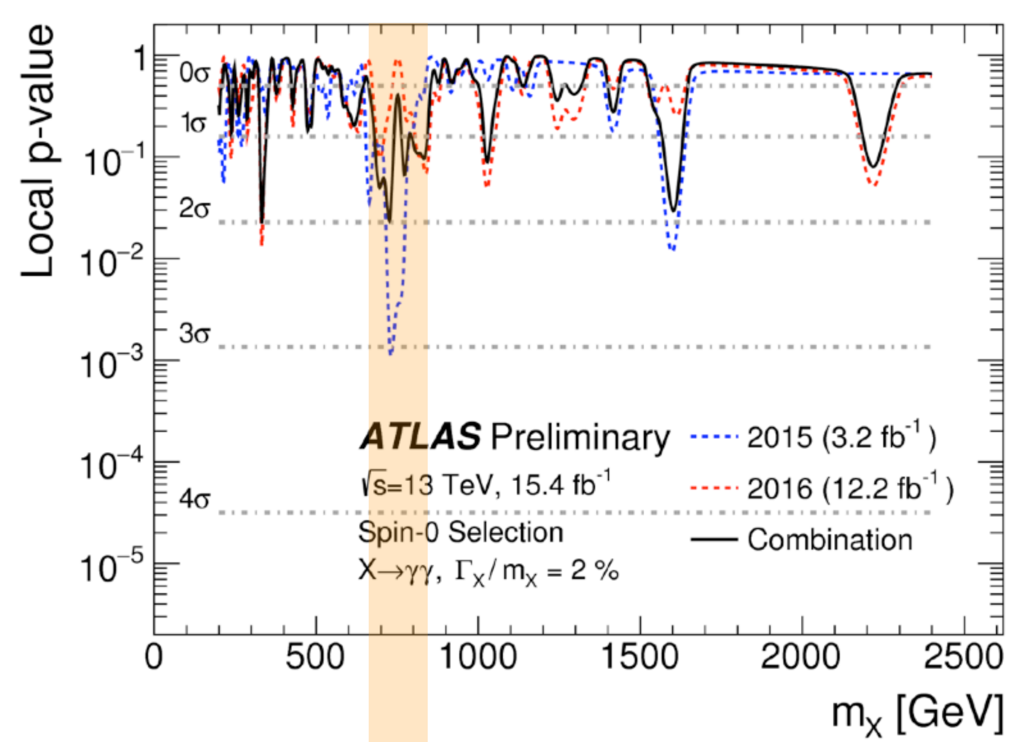
3σ (evidence)
P-VAL: 0.0013

@125GeV: the Higgs!

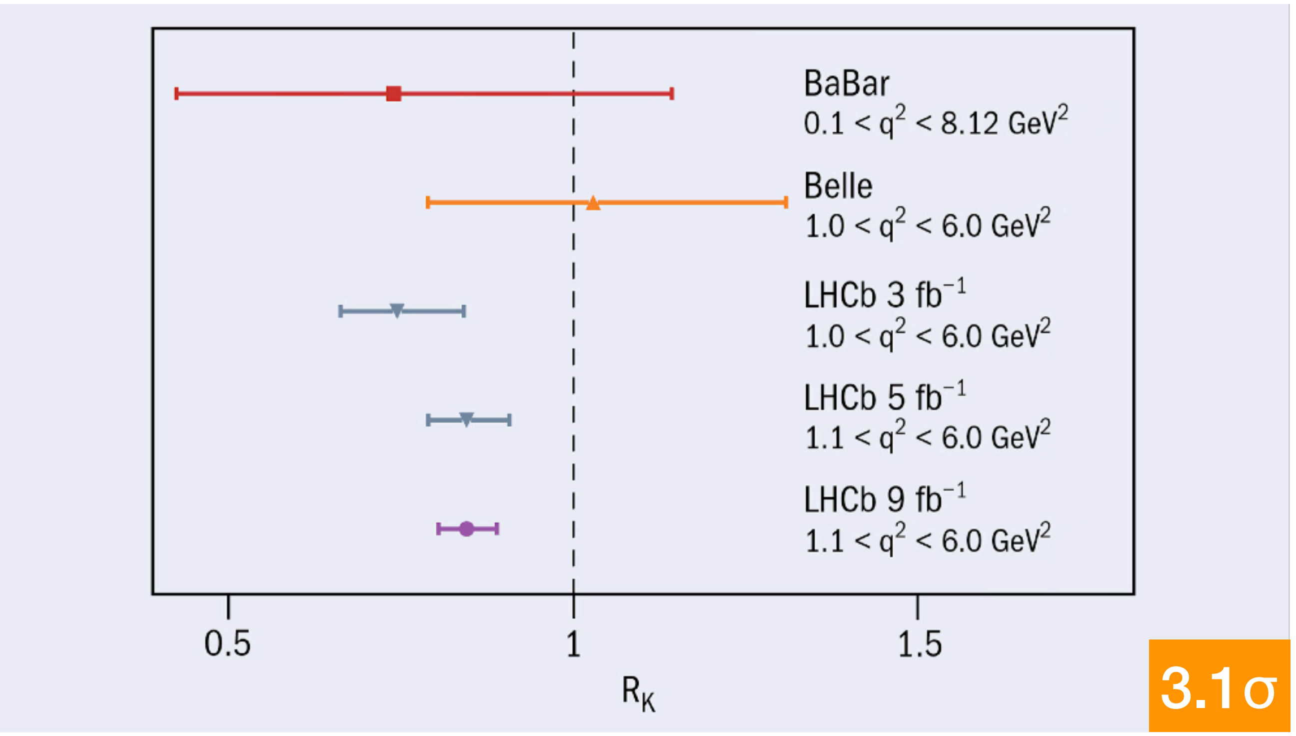
X→γγ



@750GeV: a fluctuation!



Anomalies !

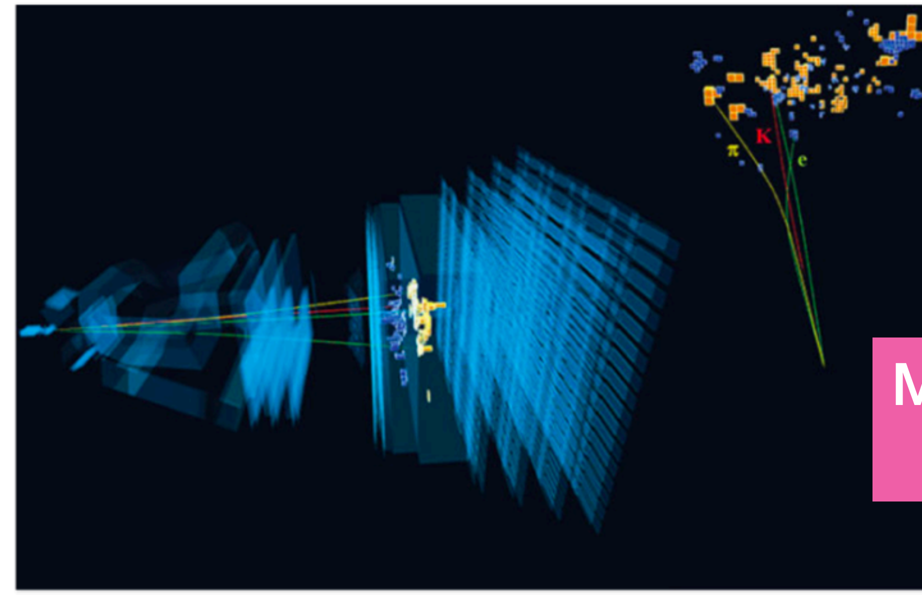


3.1σ

Intriguing new result from the LHCb experiment at CERN

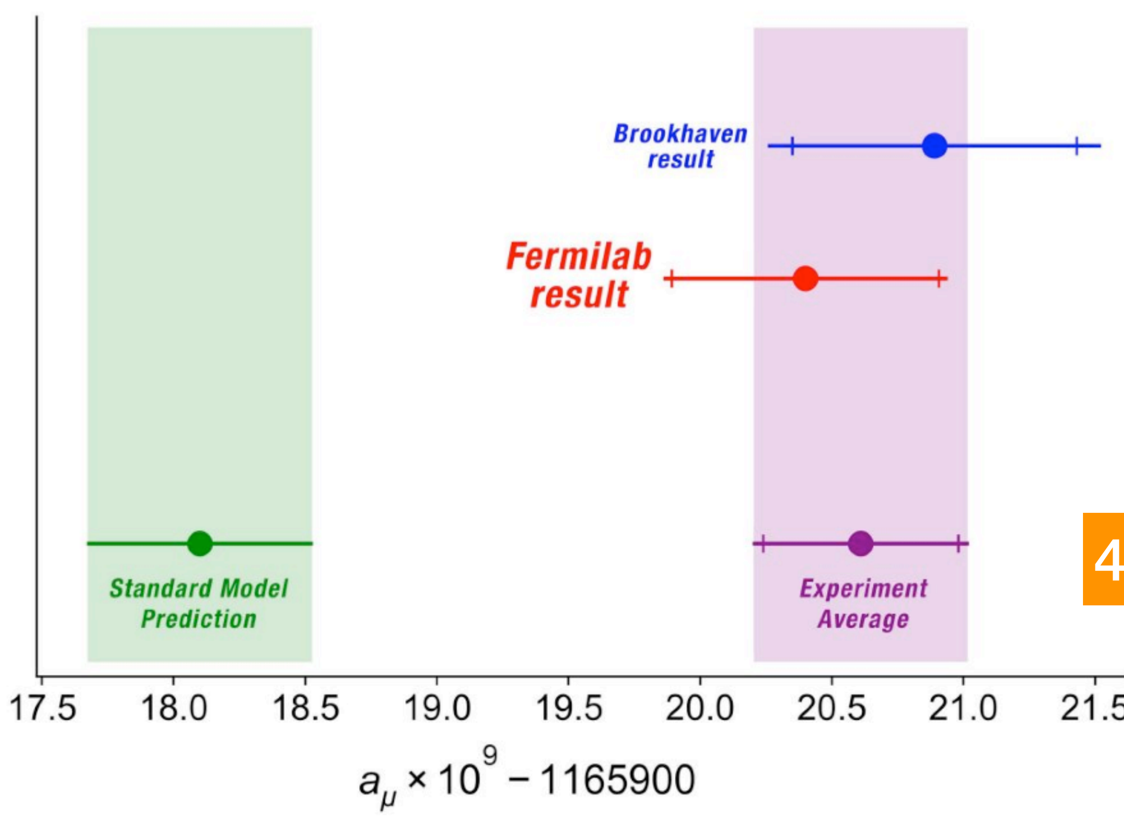
The LHCb results strengthen hints of a violation of lepton flavour universality

23 MARCH, 2021



Very rare decay of a beauty meson involving an electron and positron observed at LHCb (Image: CERN)

March'2021 @CERN



4.2σ

First results from Fermilab's Muon g-2 experiment strengthen evidence of new physics

April 7, 2021

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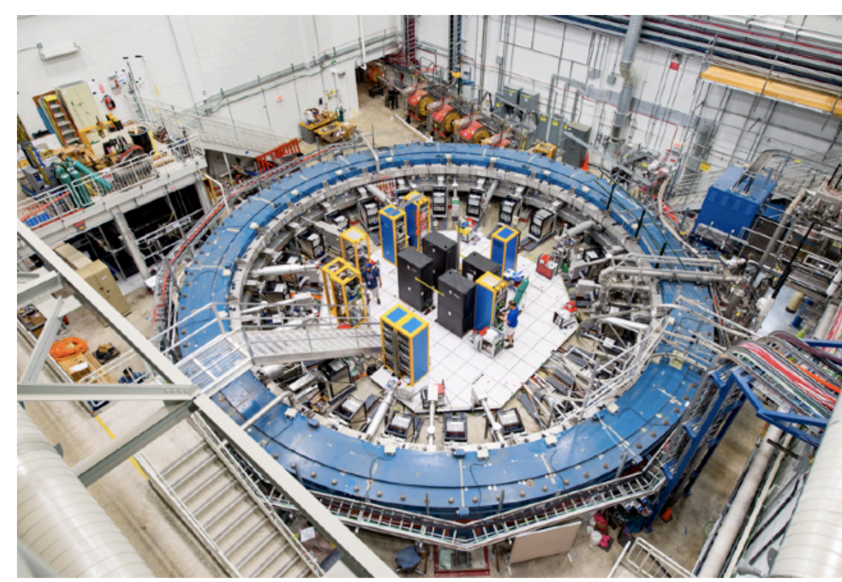
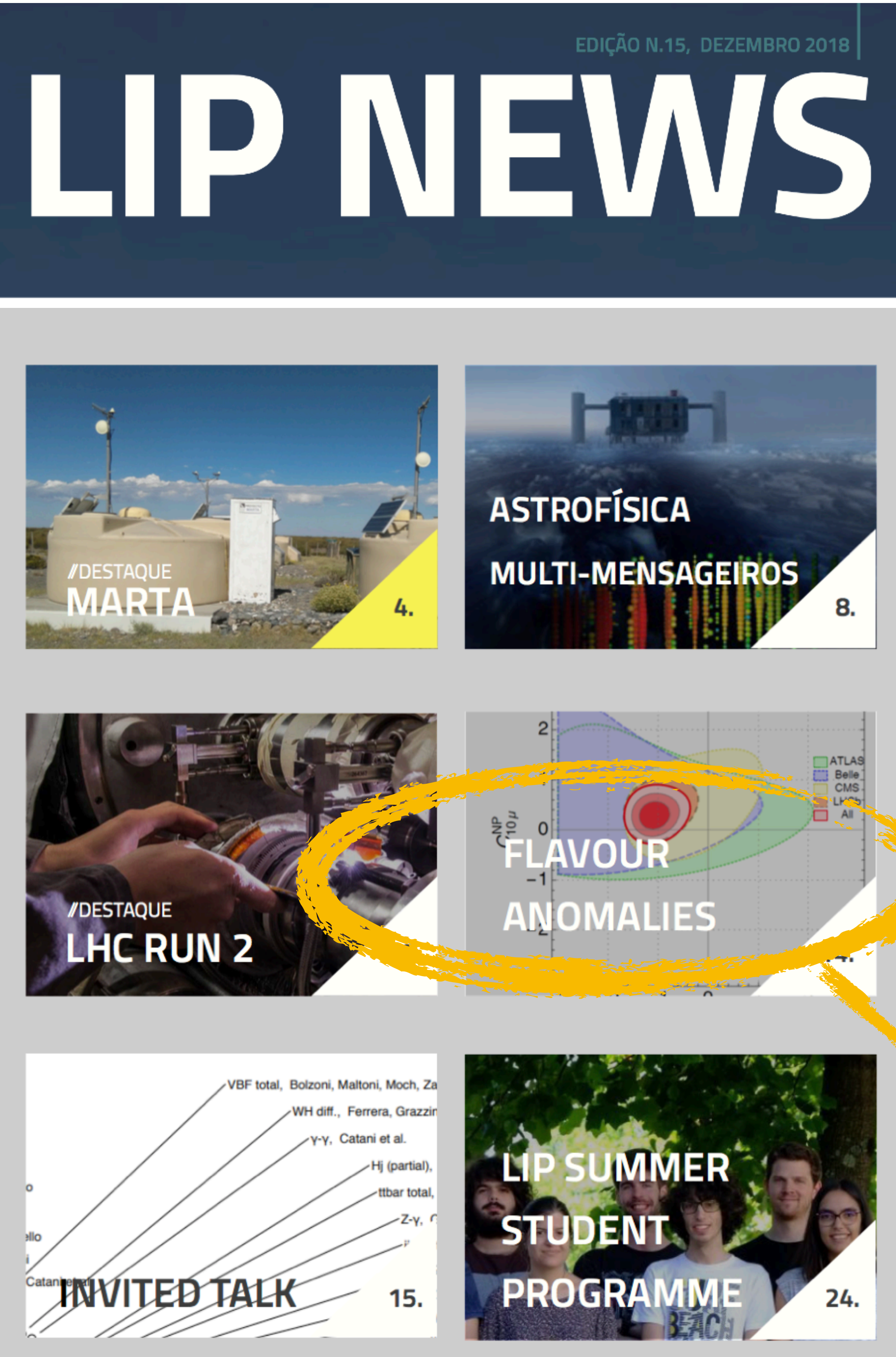


April'2021 @Fermilab

http://www.lip.pt/outreach/lipnews/pdfs/issue15_pt.pdf



Flavour Anomalies

First hints of New Physics at the LHC?

Nuno Leonardo

Over the last few years, a persistent set of deviations from the Standard Model (SM) predictions has emerged from the data. These have been detected in decays of b-quark hadrons. While the deviations are not sufficiently significant if considered individually, when taken together they are. These so-called "flavour anomalies" stand currently as a most exciting indication of New Physics (NP) and a hottest topic in the field of HEP at the moment.

New phenomena beyond the standard theory of particle physics are pursued in a multitude of paths. At the LHC, a main path, which explores the energy frontier, aims at directly detecting new heavy particles, beyond those of the SM. These NP particles may be produced in the collisions, and their presence detected through the products of their decay. Another path, which explores the luminosity frontier, aims at detecting the presence of NP indirectly, through precision measurements. Here, NP particles may virtually contribute to the amplitude of SM-allowed processes, and be revealed through measured deviations relative to the SM expectation, in observable particle properties. The two approaches are complementary and each is actively pursued by exploring a large variety of processes.

Hints of the presence of NP may accordingly be revealed through excesses in distributions (e.g. a bump in the mass spectrum) or measured deviations (e.g. on a particle's decay rate). And as it happens, several such hints, of both kinds, have turned up in the LHC data. However, so far, none of sufficiently high statistical significance, so as to unequivocally exclude possible background fluctuations as their source. Nonetheless, in the case of certain b-hadron decays, several such deviations from theory expectation seem to conspire together — while each individual deviation is still not significant *per se*, the coherent pattern displayed by their ensemble is.

Each deviations is associated to one of two underlying b-quark transitions: (i) b→sll, i.e. bottom to strange quark plus pair of opposite-charge leptons, and (ii) b→clν, i.e. bottom to charm quark plus charged lepton and neutrino. The former can occur only at loop level in the SM (flavor changing neutral current, that is forbidden in SM, at tree level), with high sensitivity to NP (where NP particles can run in the loops). The latter (charged current) occurs at tree level.

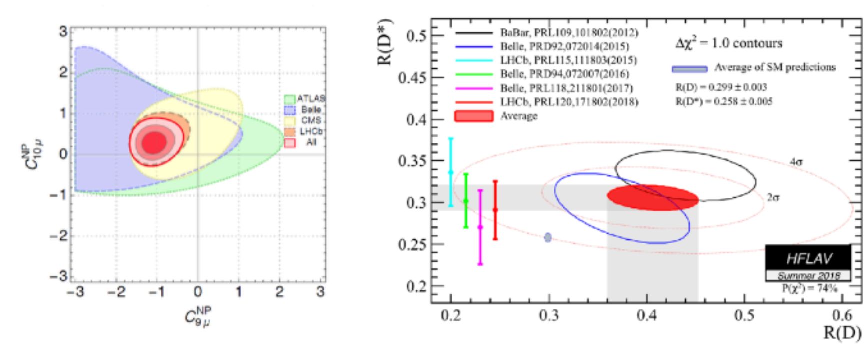
The neutral-current transitions, b→sll, are realised in various rare B decays, both leptonic, e.g. $B_s\to\mu^+\mu^-$, and semileptonic, e.g. $B\to S\mu^+\mu^-$, where S stands for a strange-[illegible] hadron (e.g. K, K*, Φ, Λ). [illegible] addition to [illegible] the latter class o[illegible]s many NP-sensitive [illegible] associa[illegible] to the angular distributions of the de[illegible] products. Deviations are detect[illegible] varying degree in many of th[illegible]. The departure from theory was initially detected by LHCb in one such angular observable, denoted P'_5, in the decay $B^0\to K^{*0}\mu^+\mu^-$. It should be remarked here that for this decay a challenge arises in calculating the theory predictions — specifically, going from the underlying quark-level transition b→sll to the experimentally observed B-meson decay, there are QCD contributions involved whose estimation is non-trivial. And while the P'_5 observable is constructed in such a way as to be more robust in terms of such QCD (B→S) form-factor determinations, some debate persists on the theory front.

There is another major chapter in the saga of flavor anomalies. And this time perhaps even more dramatic: it involves violation of lepton flavor universality (LFU). Apart from the differences in their masses, the SM interactions do not distinguish between the different leptons. This means, for example, that the rates of the decays $B^0\to K^{*0}\mu^+\mu^-$ and $B^0\to K^{*0}e^+e^-$ involving muons and electrons should be comparable.The LHCb data has however revealed that their ratio, R_{K^*}, seems to display a noticeable departure from unit. Important to remark here is that the above-mentioned form-factor uncertainties cancel in the ratios, rendering these observables rather robust theoretically. Indications of LFU violation had actually been also detected earlier at the B factories (BaBar and Belle experiments), between taus and muons, in the decays $B\to D^{(*)}\tau\nu$ and $B\to D^{(*)}\mu\nu$, where the corresponding ratios, R_D and R_{D^*}, exhibit departures from their SM expectations (see figure). These were quite unexpected, with the underlying transitions b→clν occurring at tree level.

Naturally, the anomalies have raised a large excitement amongst both experimentalists and theorists. After all, the ensemble of anomalies when interpreted collectively appear to indicate a departure from the SM, with a significance above the 5σ mark (see figure). Theorists have been actively putting forward classes of models that attempt to explain the anomalies, along with other tensions in the flavor sector, e.g. $(g-2)_\mu$, while simultaneously accommodating other experimental constraints, e.g. from B_s mixing and dilepton mass spectra. Among these, models with extra gauge bosons (Z') or leptoquarks (LQ) appear to be favoured.

From the experimental side, a clarification will be sought by thoroughly exploiting the LHC Run 2 data. Not only will the LHCb measurements be repeated to reach increased precision, contributions from ATLAS and CMS will offer independent input with orthogonal systematics. For example, during 2018 a large, dedicated dataset has been collected by CMS specifically for this purpose. Belle2 is coming online, and within a few years its data will provide decisive input. Dedicated searches for scenarios addressing the anomalies, including Z' and LQ, will be pursued at the LHC.

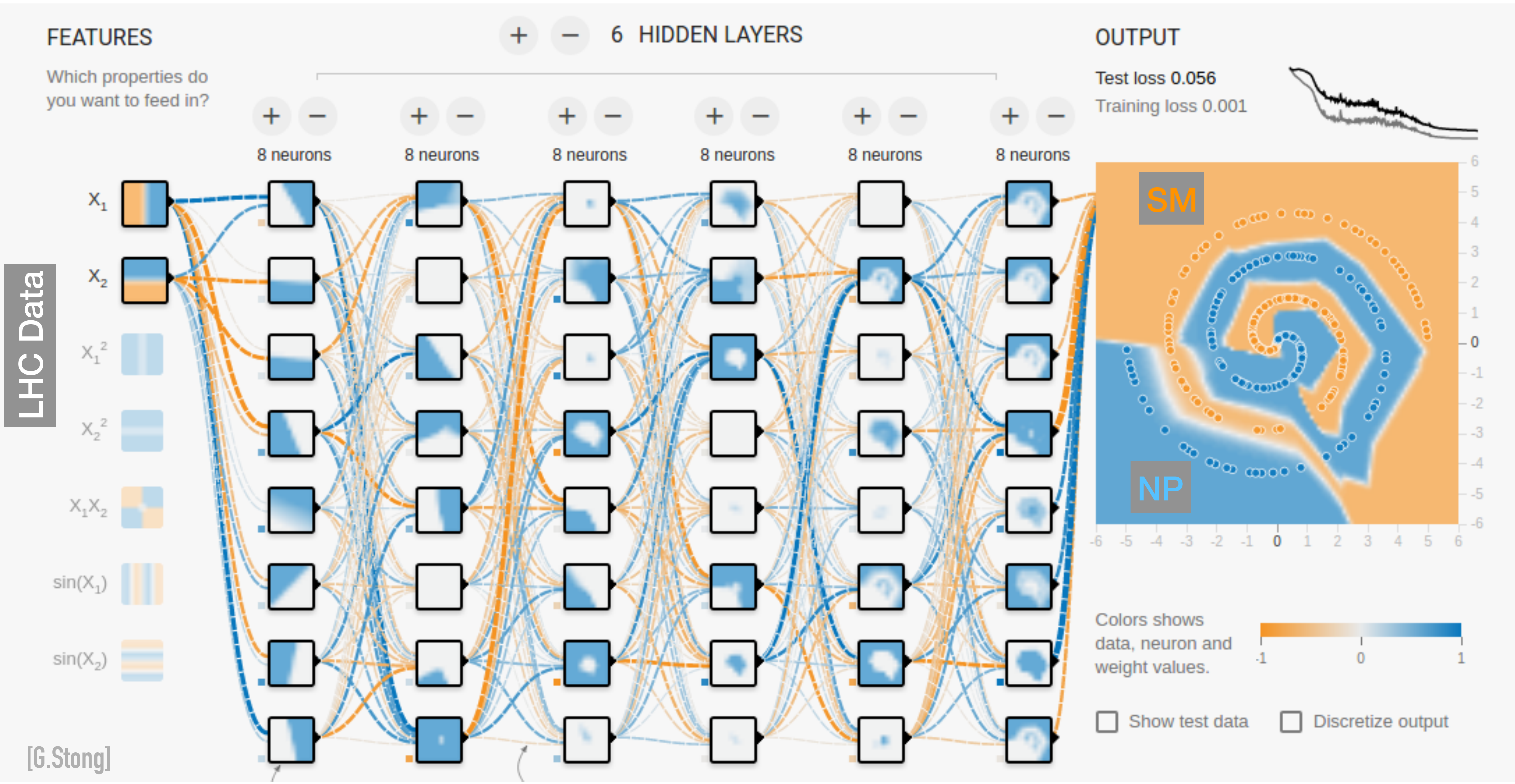
Whether the source of the anomalies turns out to be more mundane statistical fluctuations, underestimations in theory calculations, or genuine NP, it is exciting that a clarification is within reach over the next few years. A confirmation of these flavour anomalies would point to new particles or interactions and have profound implications for our understanding of particle physics.



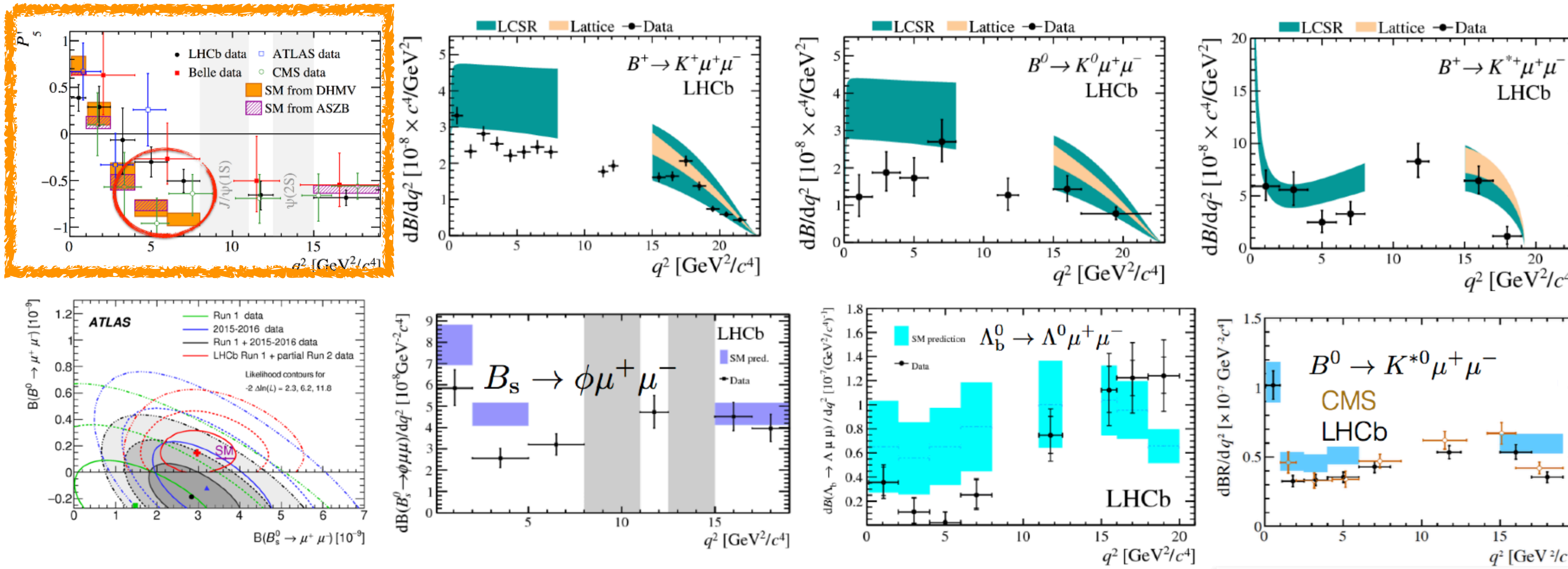
Current status of the flavor anomalies. Left: Global fit to b→sll observables, with results projected on the plane of two EFT coefficients. Right: Fit to b→clν observables. The red elipses represent the regions favoured by the data. The SM lies at the origin (0,0) of the left plot and on the small region at about (0.3,0.25) on the right plot. The tension between data and SM is clearly visible.

multi-variate analysis

a.k.a. multi-messenger … a.k.a. machine learning



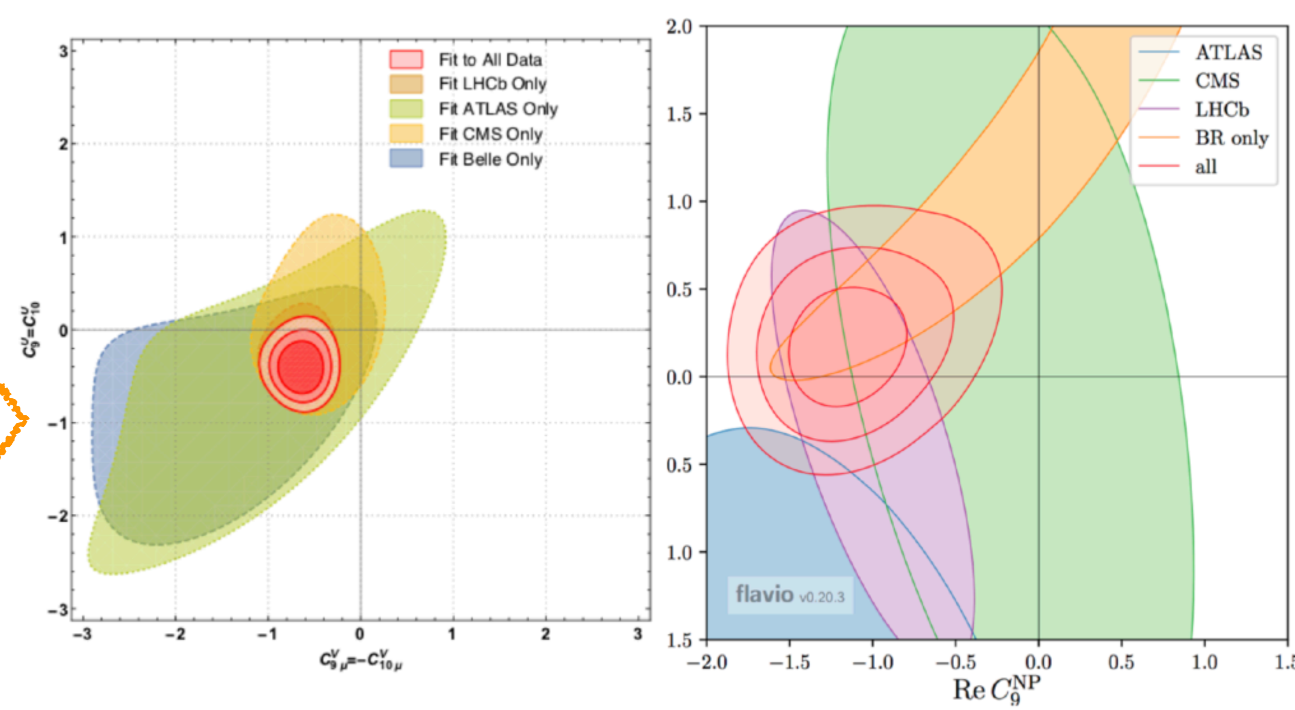
b→sμμ | global fits



Experimental measurements

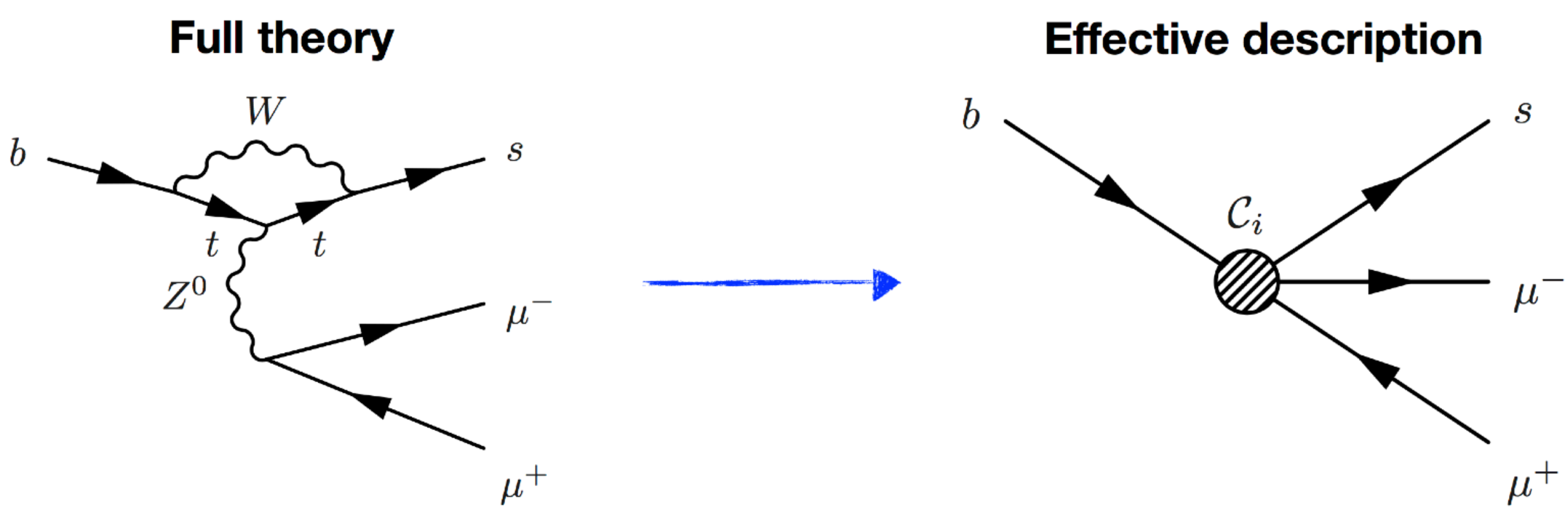
SM - **E**ffective **F**ield **T**heory

$$\mathcal{L}_{\text{SM-EFT}} = \mathcal{L}_{\text{SM}} + \Sigma_i C_i O_i$$



Theory space

b→sμμ | Effective Field Theory



- "point-like interaction" as in the Fermi description of the neutron decay

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} \sum_i V^i_{CKM} C_i(\lambda) \mathcal{O}_i(\lambda)$$

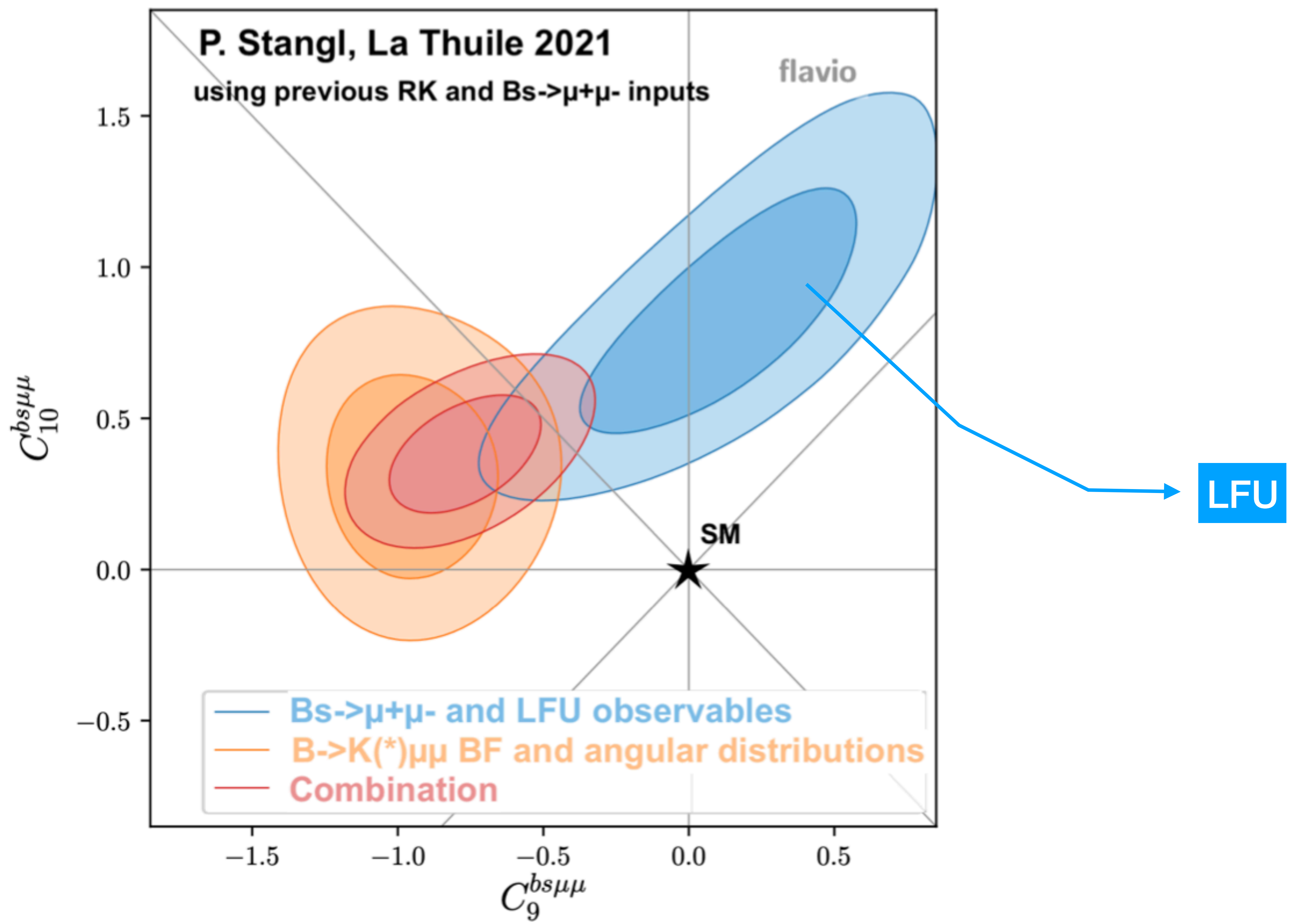
- Wilson coefficients (short-distance): evaluated in perturbation theory
- Local operators (long-distance): the corresponding form factor is computed with, e.g., lattice QCD

- NP can alter $C_i^{(\prime)}$ but also introduce new operators

$$\Delta\mathcal{H}_{\rm NP} = \frac{c_i}{\Lambda^2_{\rm NP}} \mathcal{O}_i$$

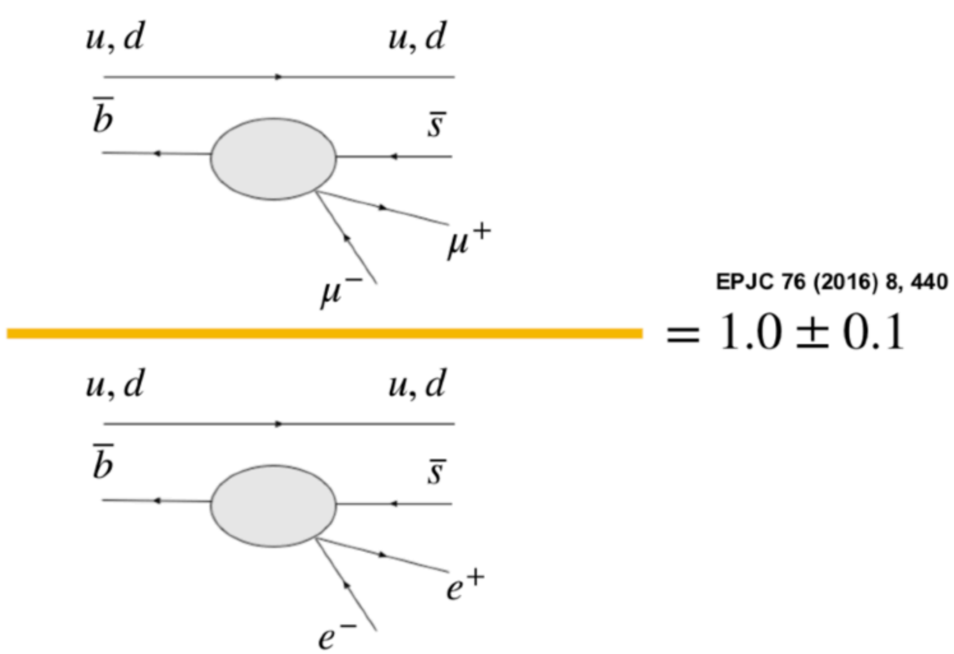
Precision measurements go well beyond collision energies!

b→sμμ | global fit



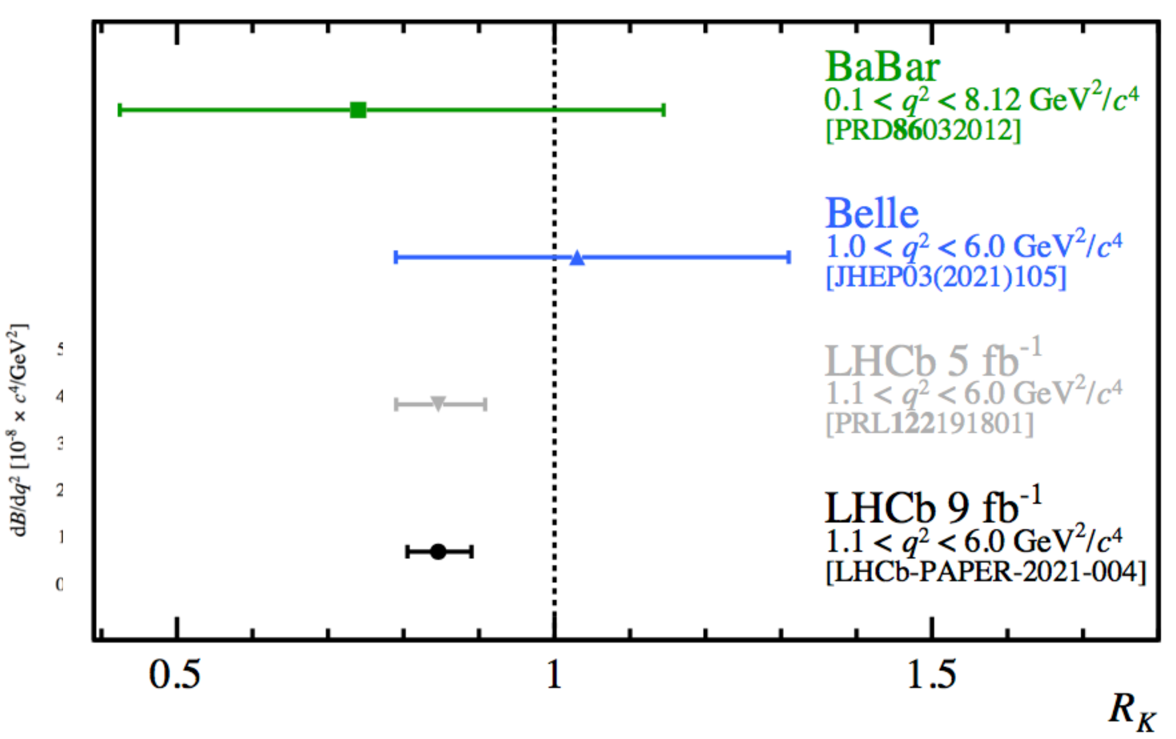
$b \to s ll$ | LFU (e vs μ)

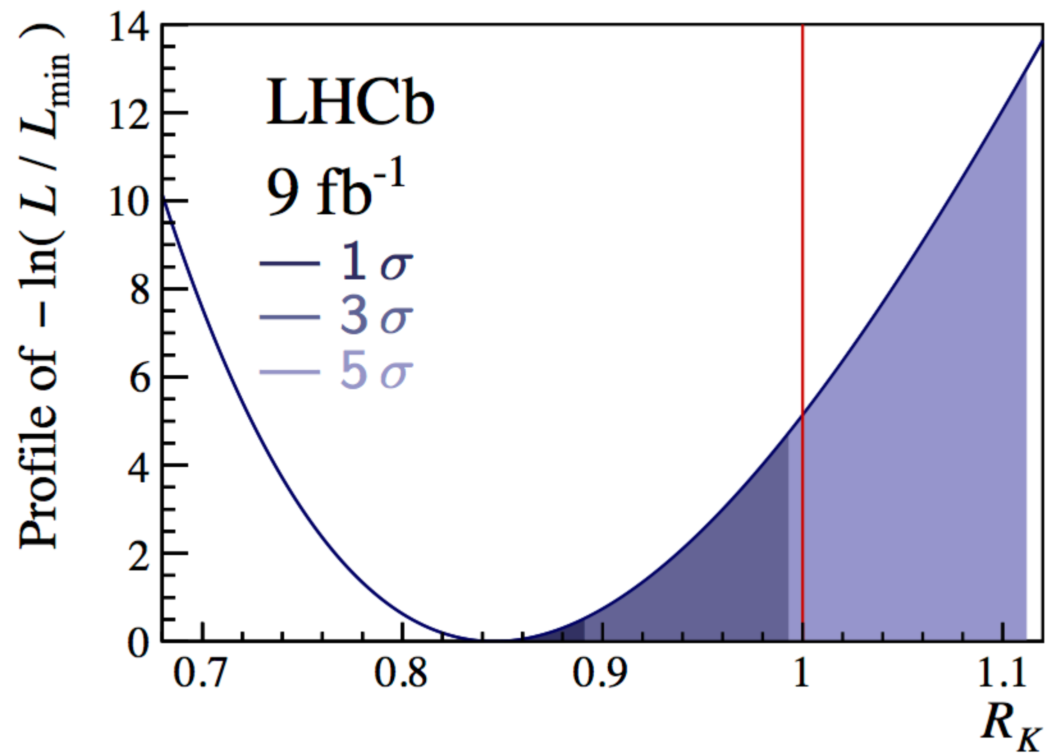
$$R_K = \frac{BR(B^+ \to K^+ \mu^+ \mu^-)}{BR(B^+ \to K^+ e^+ e^-)} \overset{SM}{\cong} 1$$



$$R_K = 0.846 \,^{+0.042}_{-0.039}\,(\text{stat})\,^{+0.013}_{-0.012}\,(\text{syst})$$

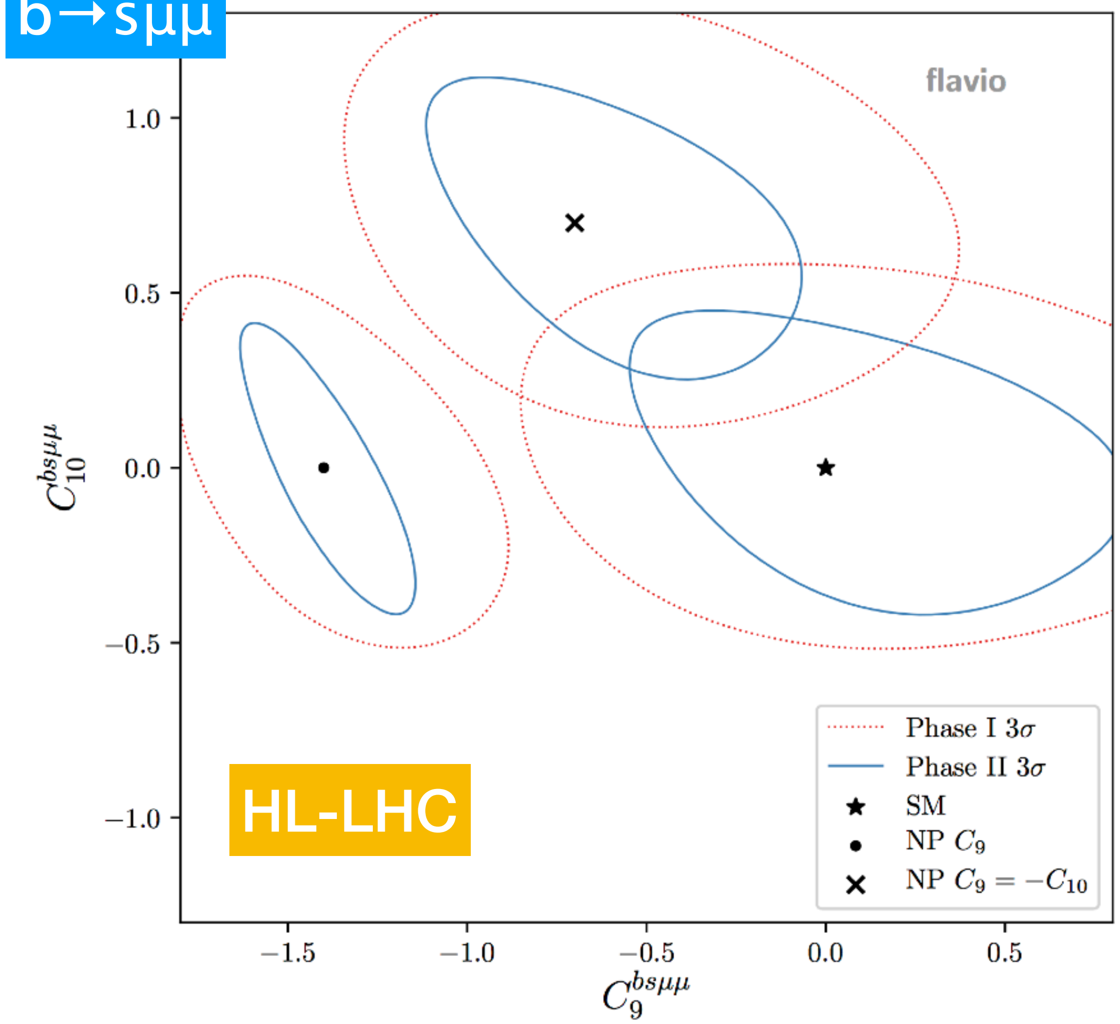
- p-value under SM hypothesis: 0.0010
  → Evidence of LFU violation at 3.1σ





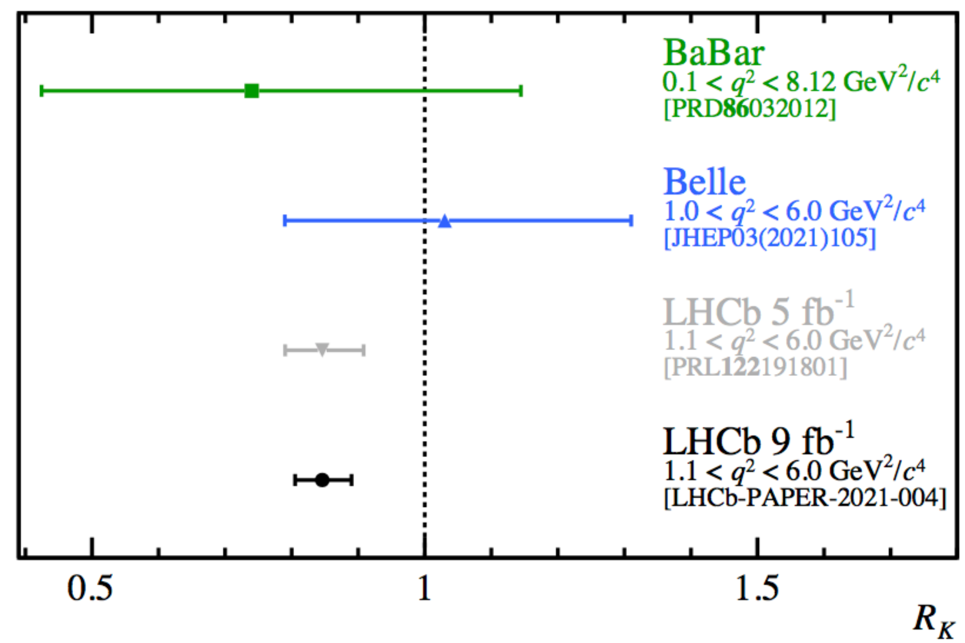
Flavour Anomalies

b→sμμ



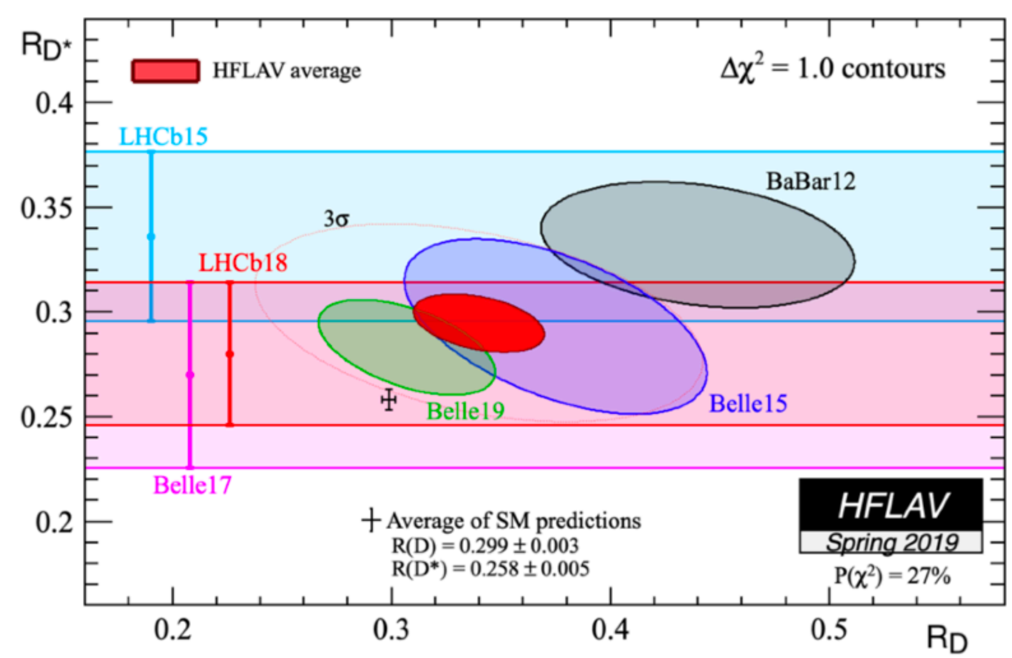
LFUV b→sll

e vs μ



LFUV b→clν

τ vs μ



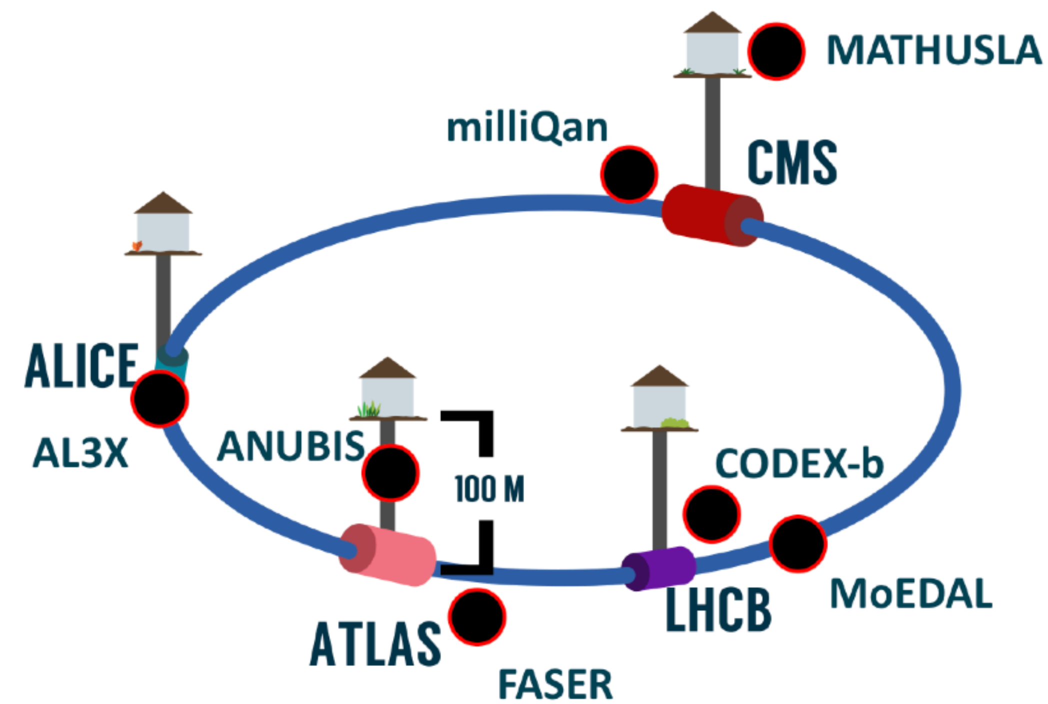
Clarification being actively pursued experimentally by LHCb,CMS,ATLAS and BelleII + theory calculations and model building

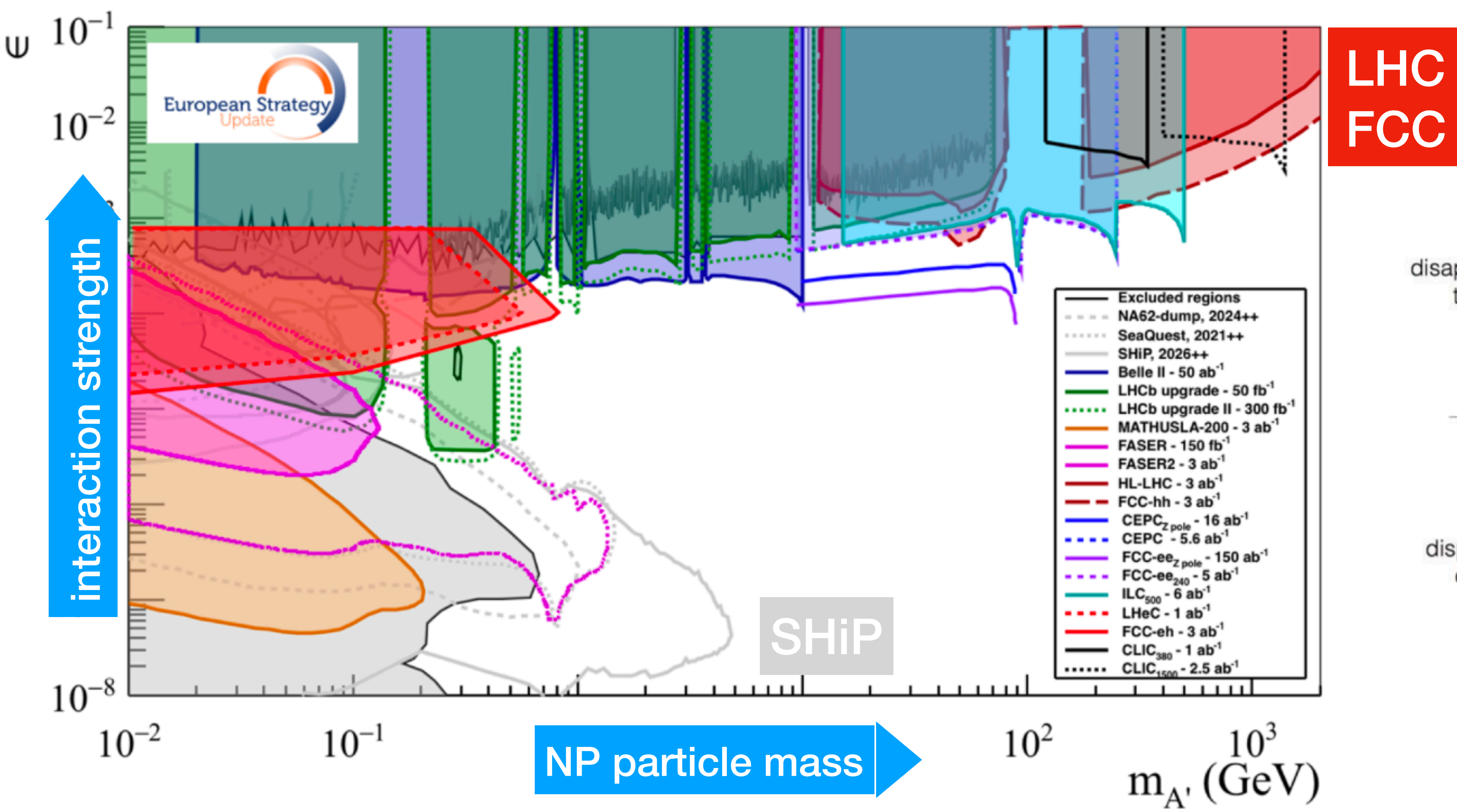
FIPs, neutrinos, dark matter @ LHC !

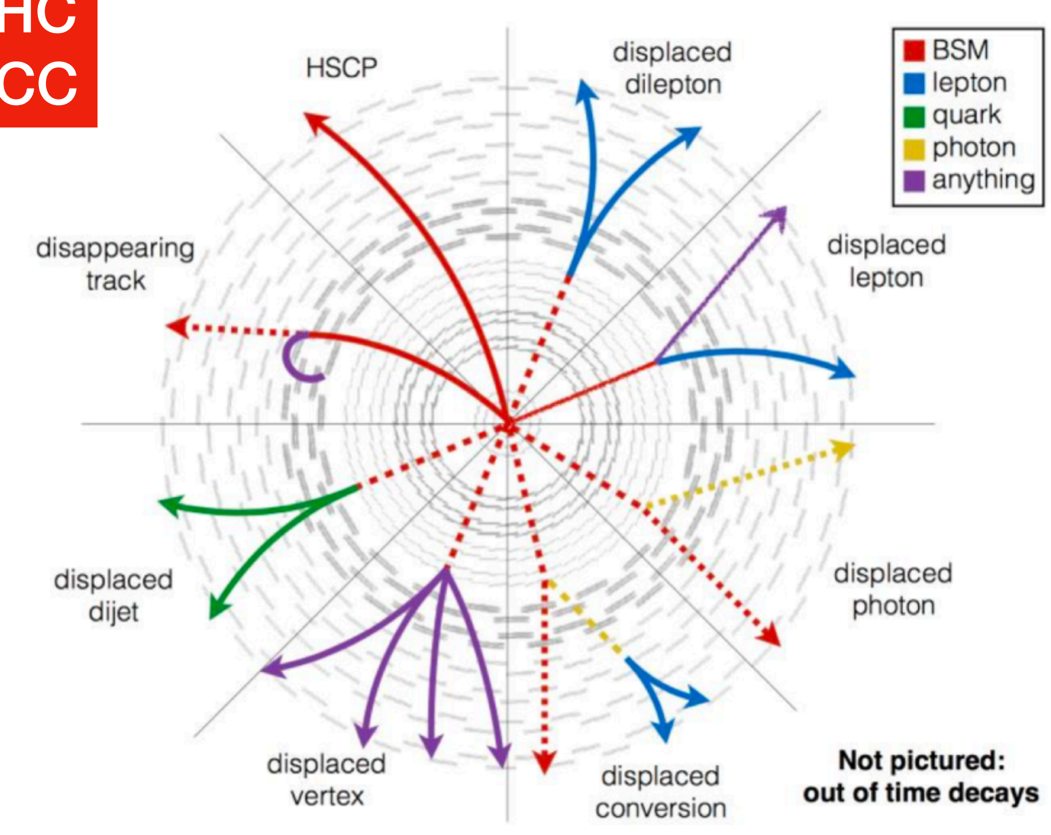
Feebly Interacting Particles

Explore the exotic & unconventional

- New trigger strategies
- New experimental signatures
- New dedicated detectors
- At LHC and beyond





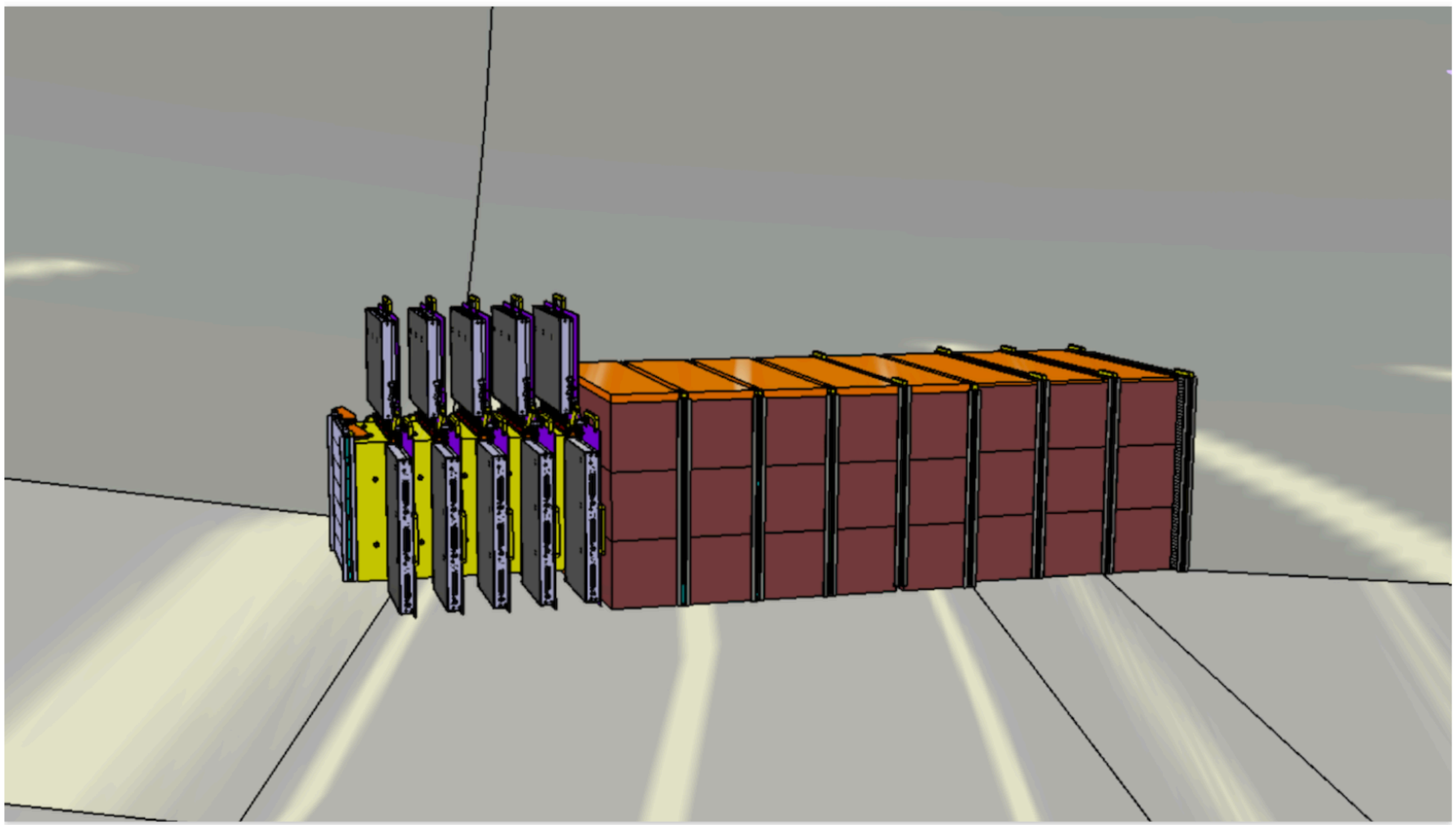


https://home.cern/fr/news/news/experiments/cern-approves-new-lhc-experiment

CERN approves new LHC experiment

SND@LHC, or Scattering and Neutrino Detector at the LHC, will be the facility's ninth experiment

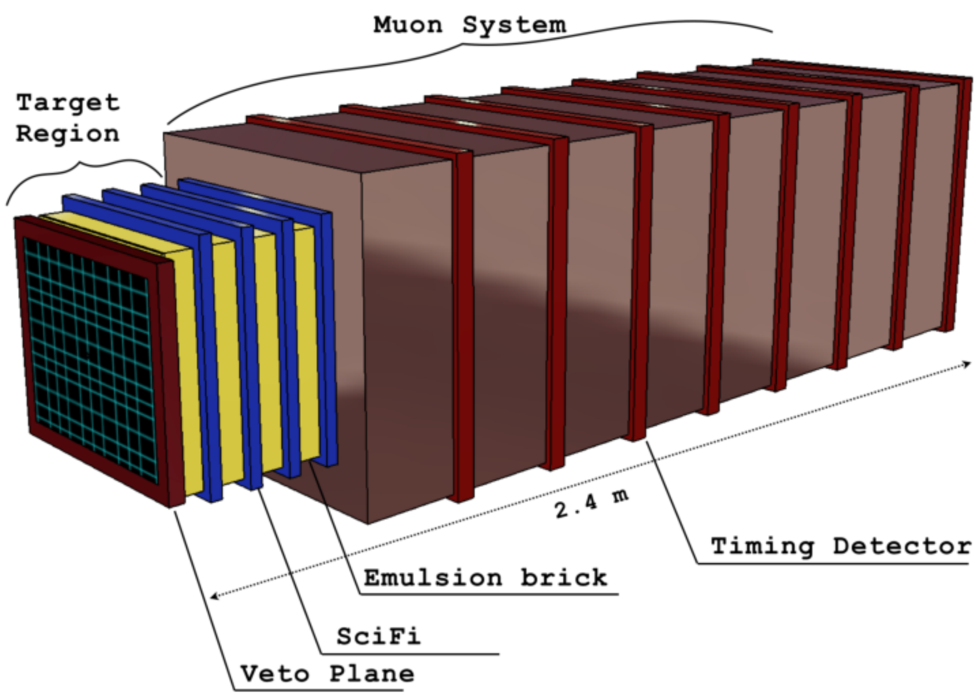
27 AVRIL, 2021 | Par Ana Lopes

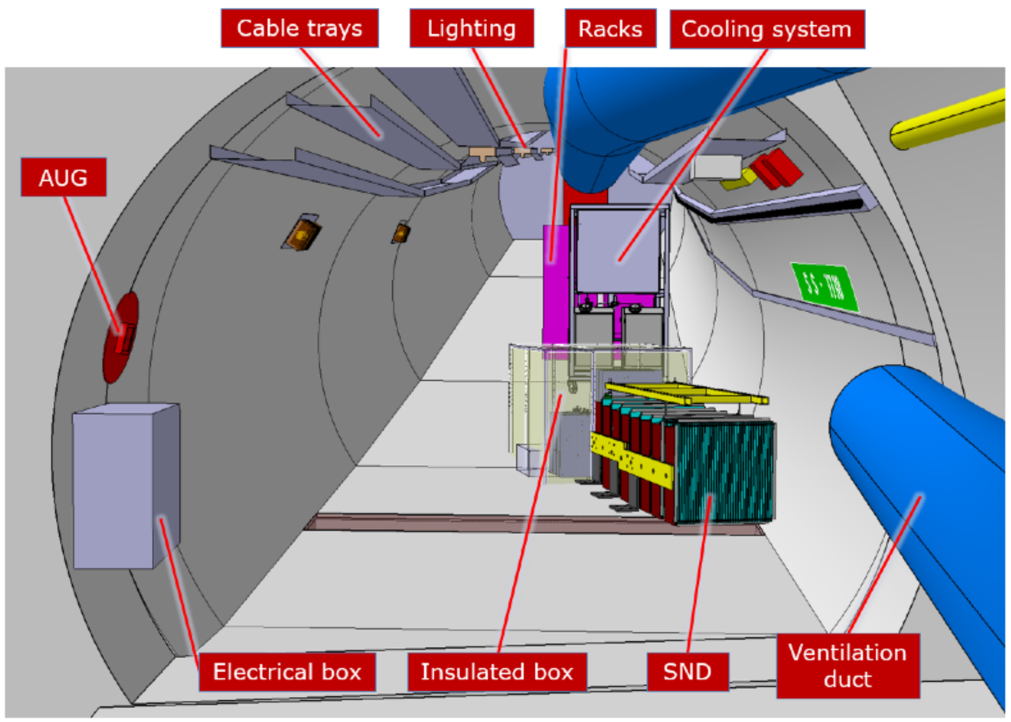


The SND@LHC experiment consists of an emulsion/tungsten target for neutrinos (yellow) interleaved with electronic tracking devices (grey), followed downstream by a detector (brown) to identify muons and measure the energy of the neutrinos. (Image: Antonio Crupano/SND@LHC)

Neutrinos @ LHC !

SND@LHC





The 9th LHC experiment just approved!
Getting ready to take data at start of Run3!

<u>**SND@LHC Physics goals**</u>

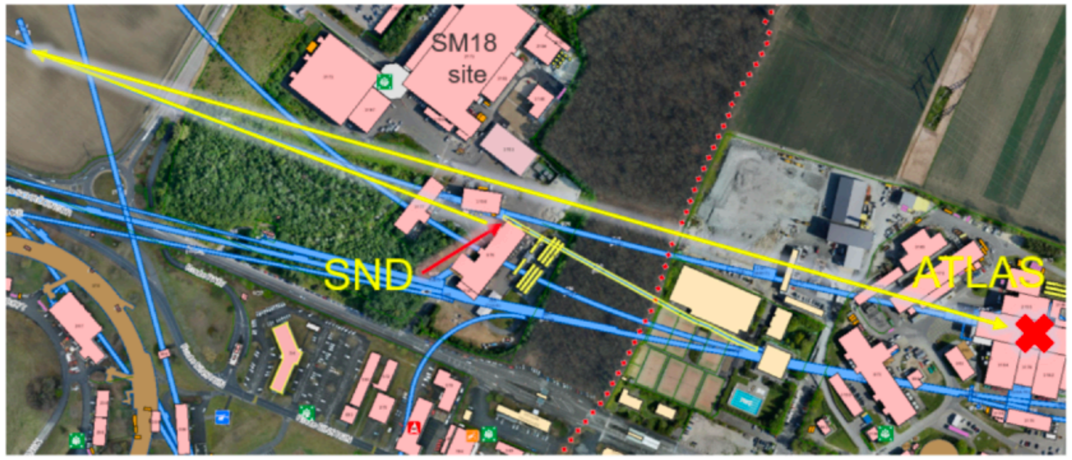
Detect collider neutrinos for first time

Energy range so far unexplored (350GeV-10TeV)

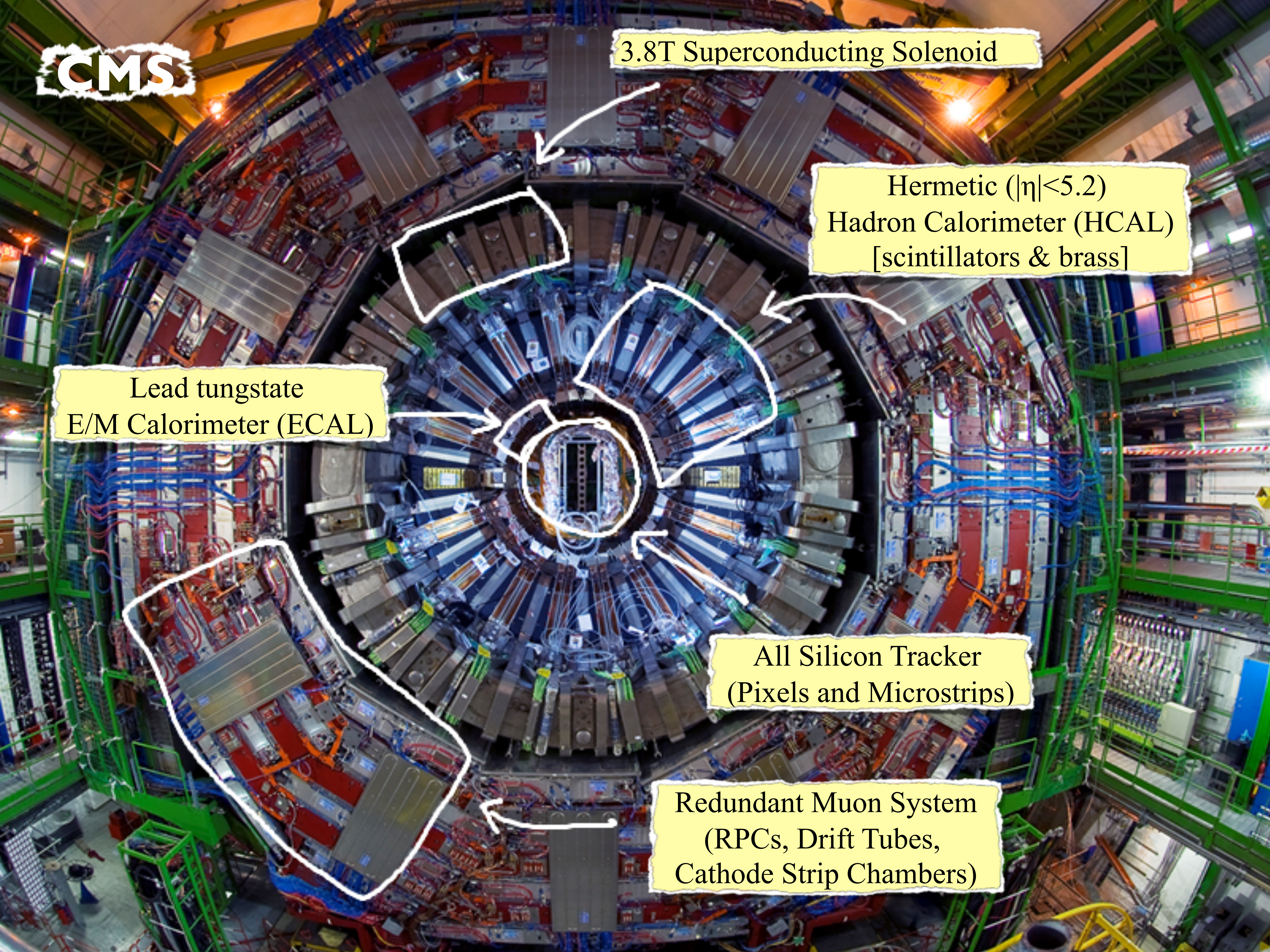
Measure HF production in so-far unexplored region (not covered by any other LHC experiment)

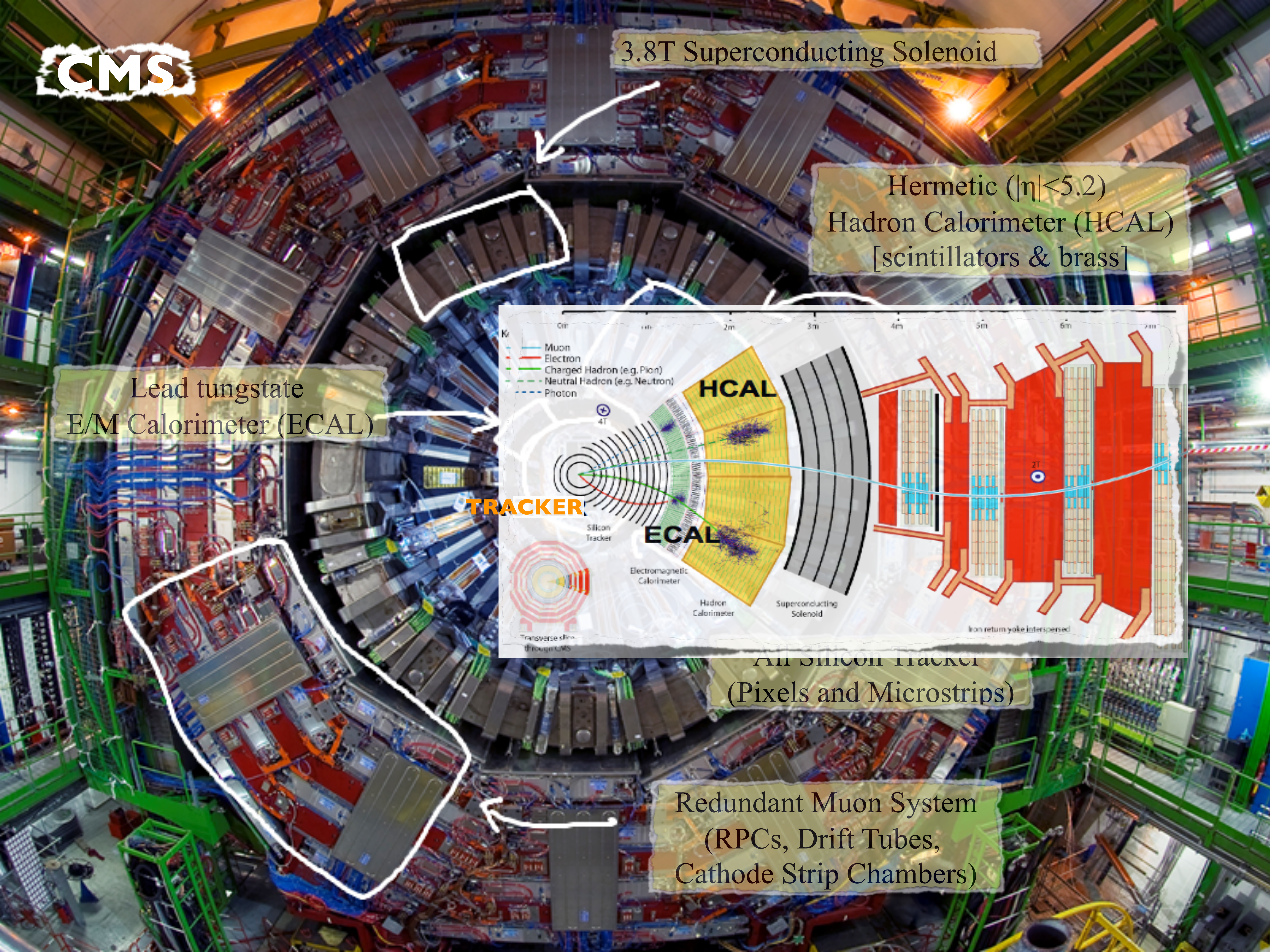
LFU tests

Search for FIPs and Light Dark Matter



Detector & Event Reconstruction

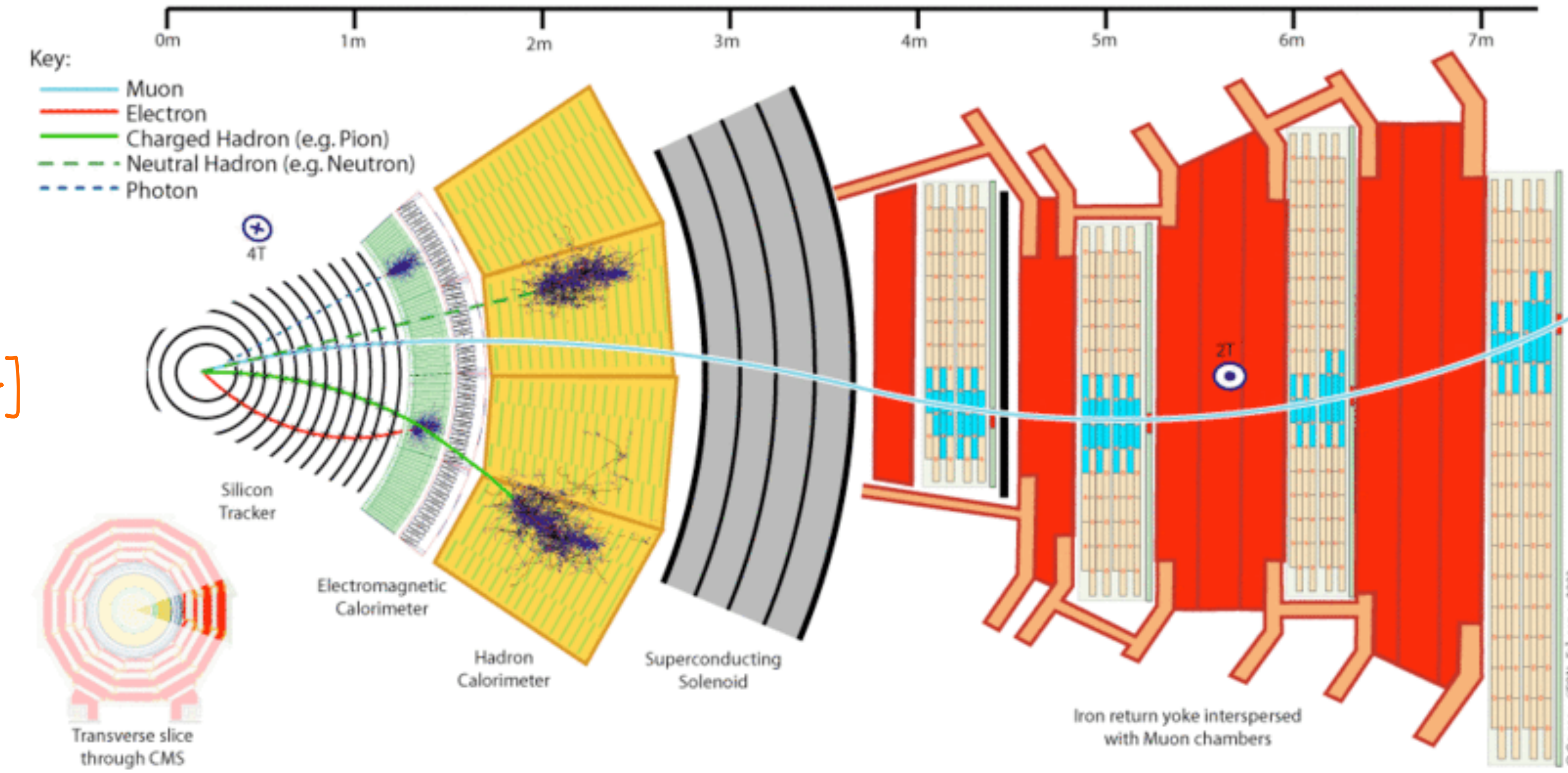

CMS
3.8T Superconducting Solenoid
Hermetic (|η|<5.2)
Hadron Calorimeter (HCAL)
[scintillators & brass]
Lead tungstate
E/M Calorimeter (ECAL)
All Silicon Tracker
(Pixels and Microstrips)
Redundant Muon System
(RPCs, Drift Tubes,
Cathode Strip Chambers)



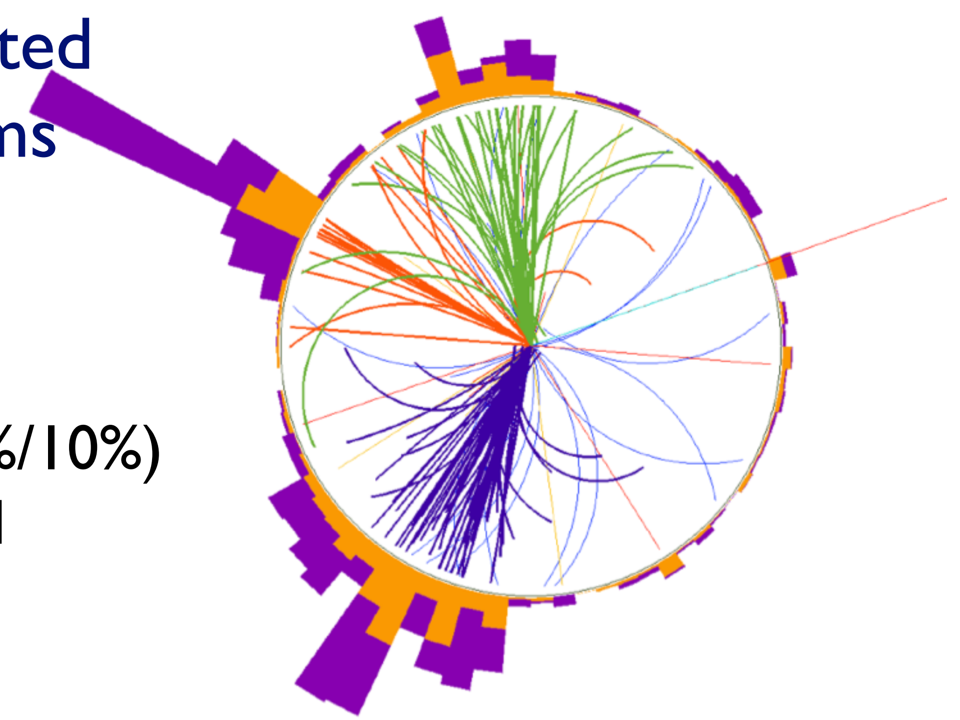
CMS
3.8T Superconducting Solenoid
Hermetic (|η|<5.2)
Hadron Calorimeter (HCAL)
[scintillators & brass]
Lead tungstate
E/M Calorimeter (ECAL)
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
0m
2m
3m
4m
5m
6m
4T
2T
HCAL
ECAL
TRACKER
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed
(Pixels and Microstrips)
Redundant Muon System
(RPCs, Drift Tubes,
Cathode Strip Chambers)

particle identification

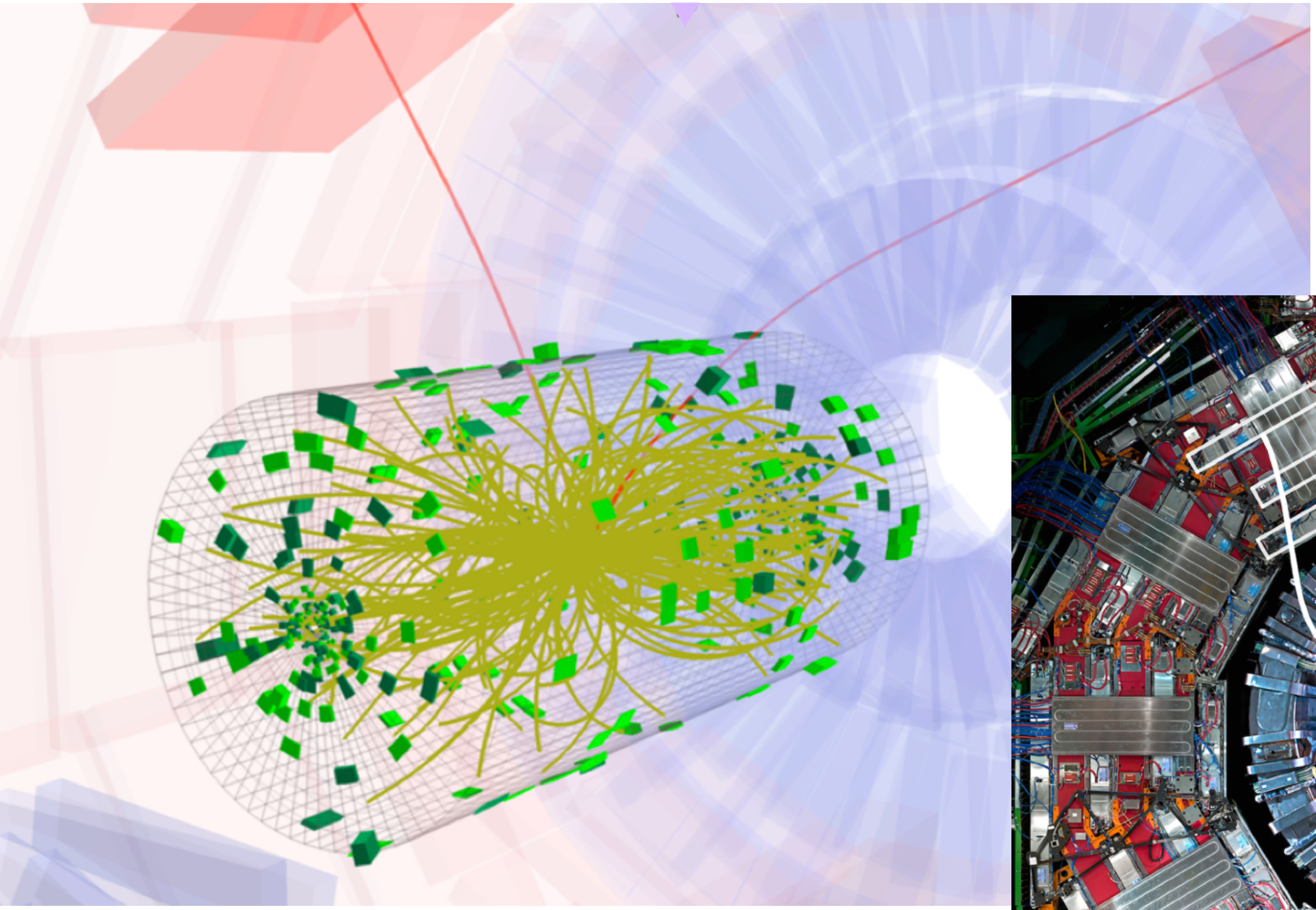
[leading order]



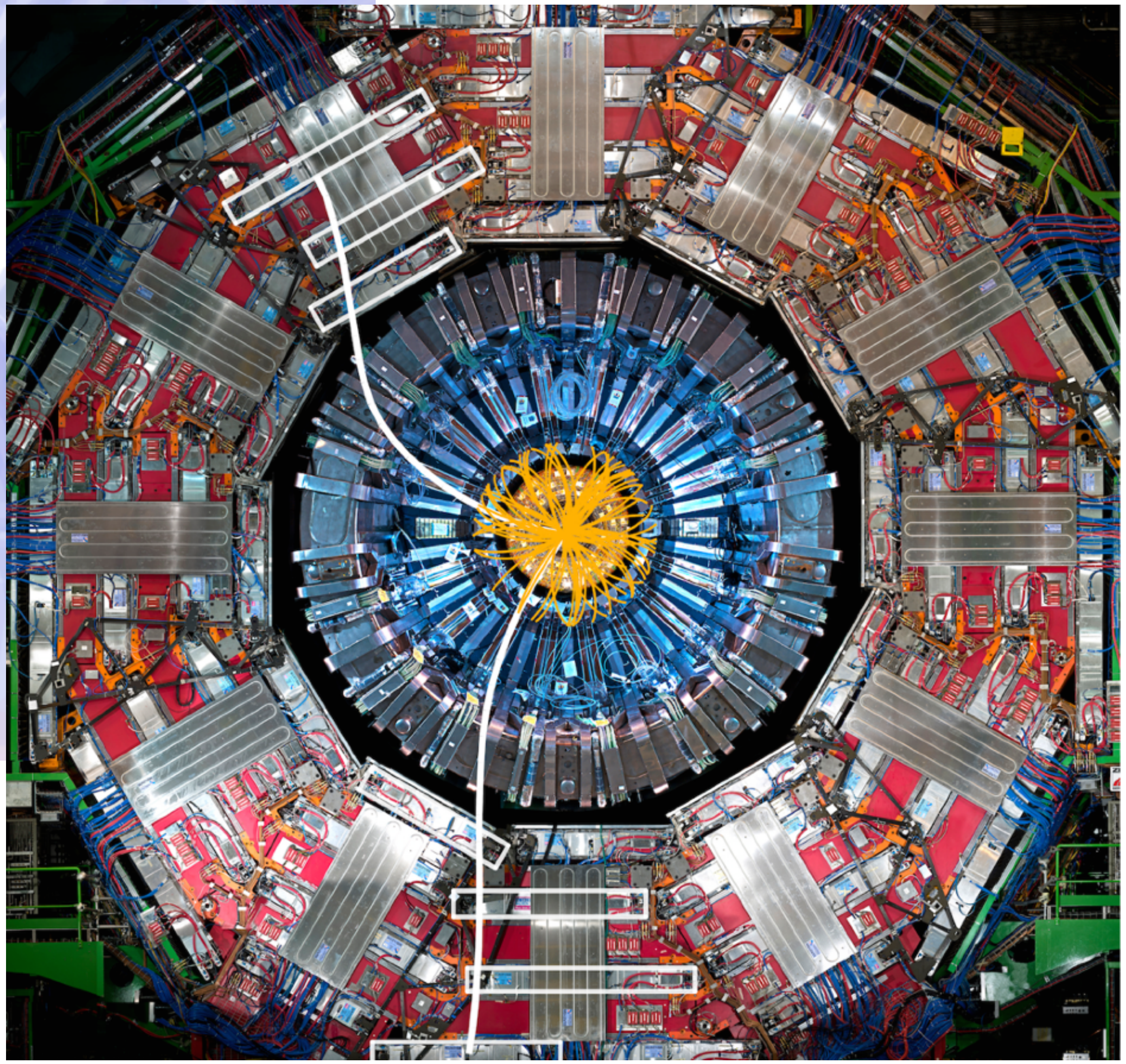
- [higher order corrections] objects are finally reconstructed using information from different detector subsystems combined in a particle flow algorithm
  - electrons radiate via bremsstrahlung
  - photons may convert to e^+e^- pairs in the tracker
  - jet (q,g) energy is formed of charged/neutral hadrons (65%/10%) and photons (25%): calorimeter and tracker info exploited
  - missing E_T requires 'full event' reconstruction



a di-muon event

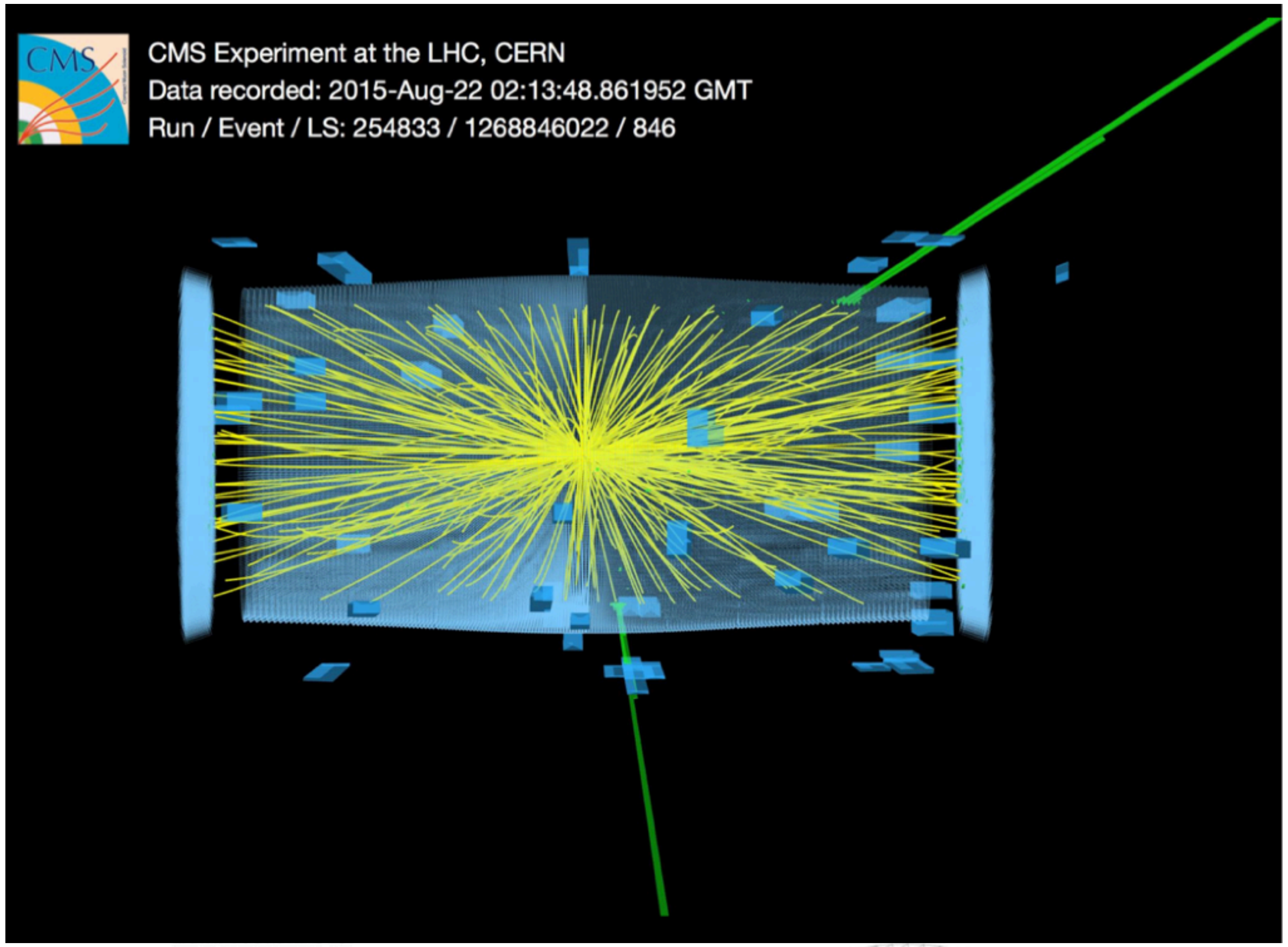


$X \rightarrow \mu\mu$



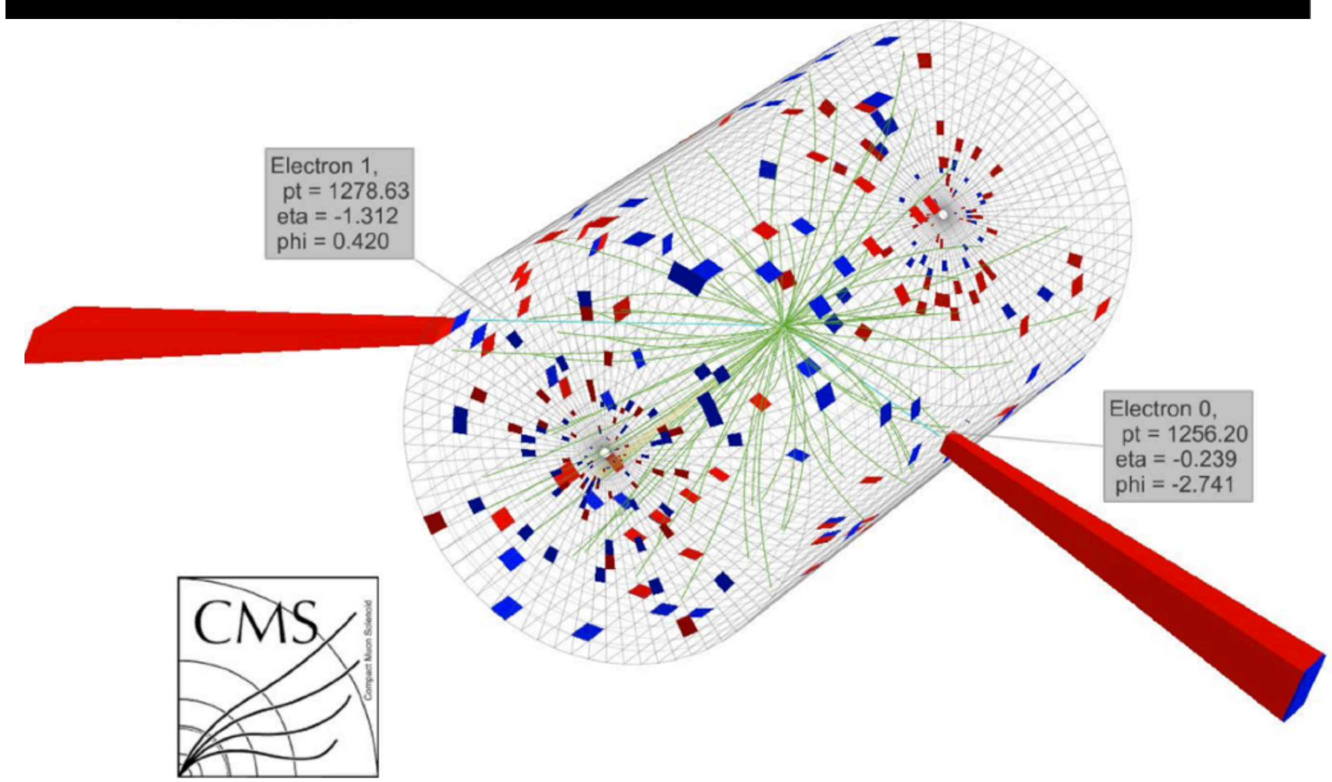
More on this on the Thursday tutorial!

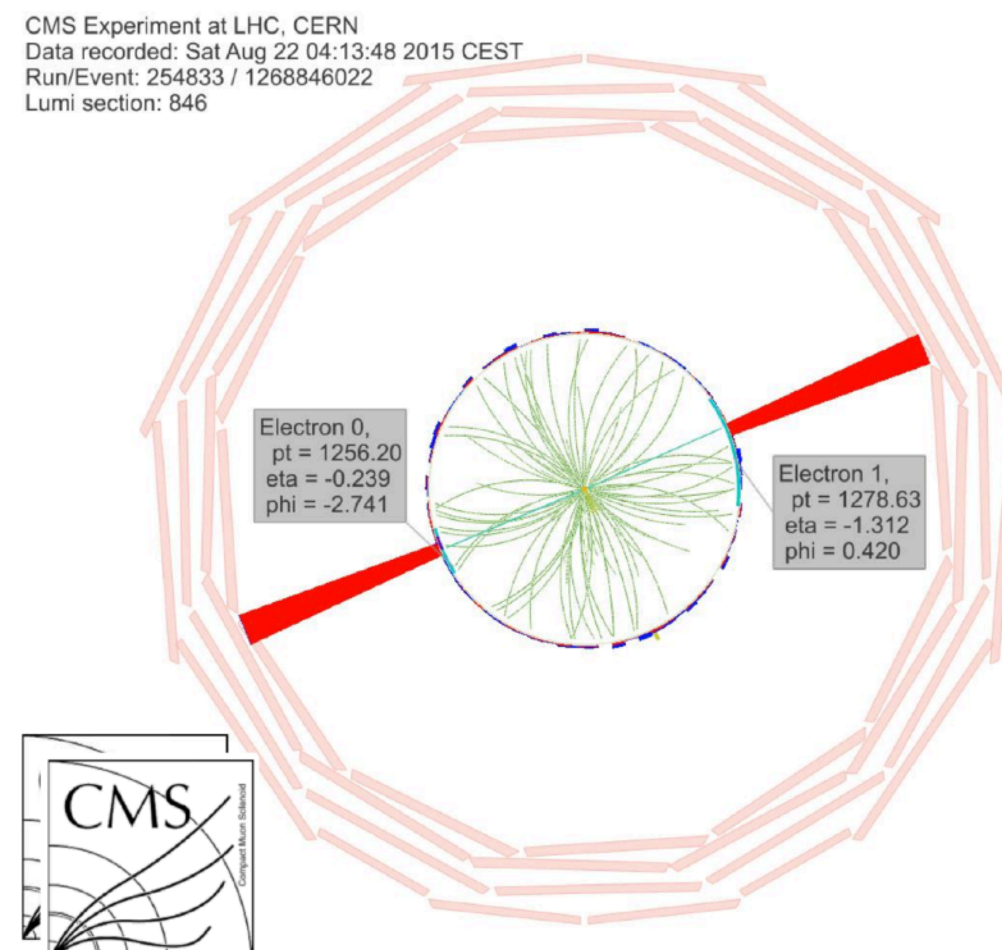
a di-electron event



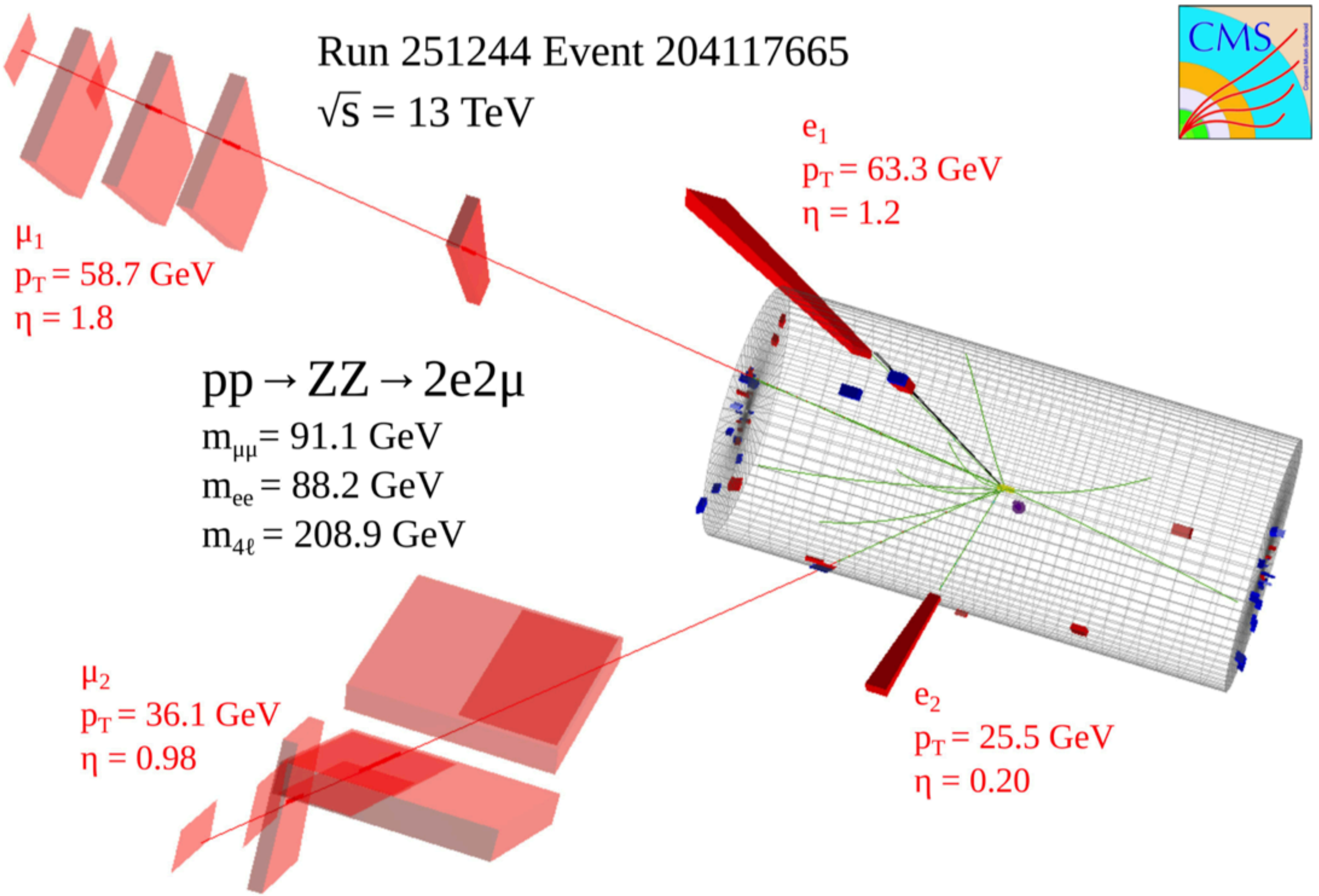
CMS-DP-2015-039

Event Display of a Candidate Electron-Positron Pair with an Invariant Mass of 2.9 TeV

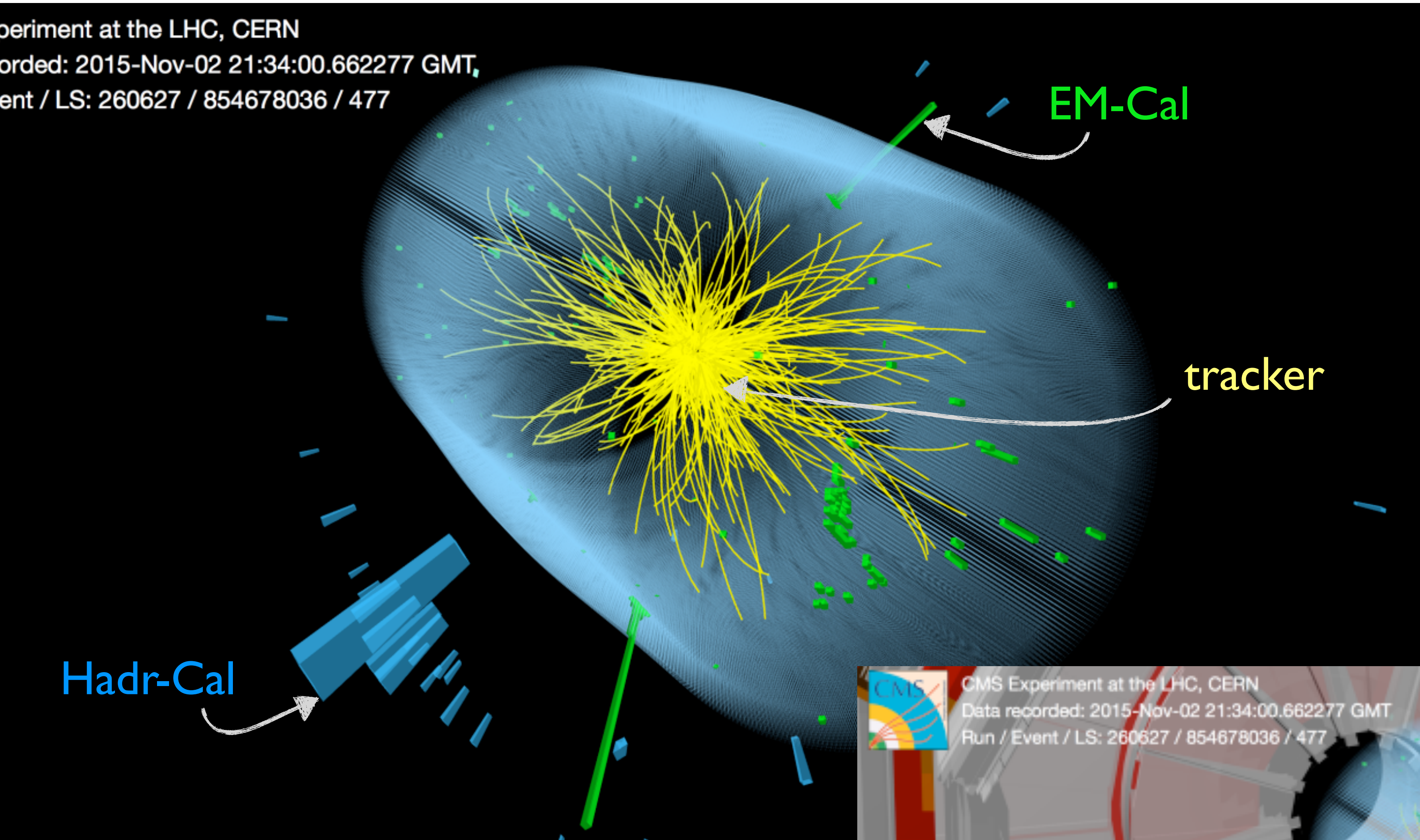




a $\mu^+\mu^-e^+e^-$ event



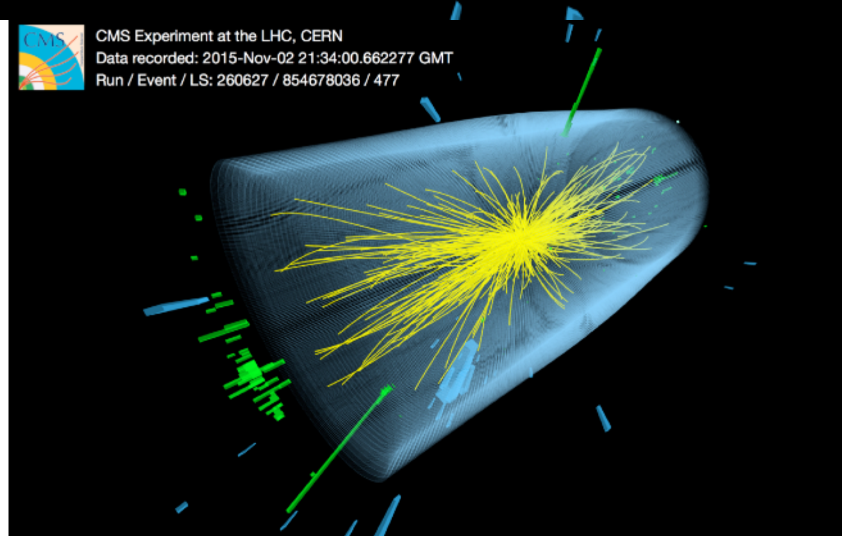
di-photons

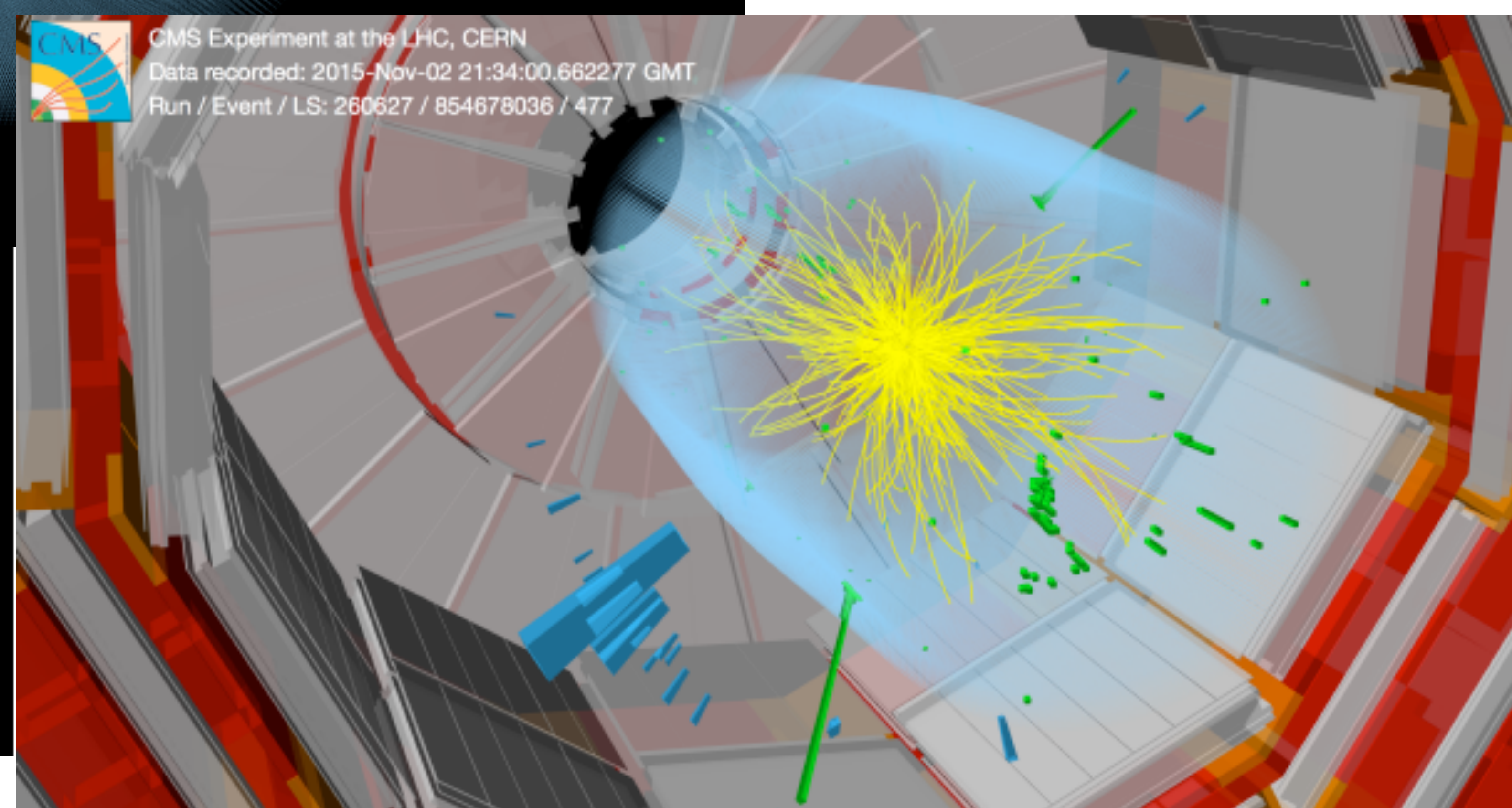


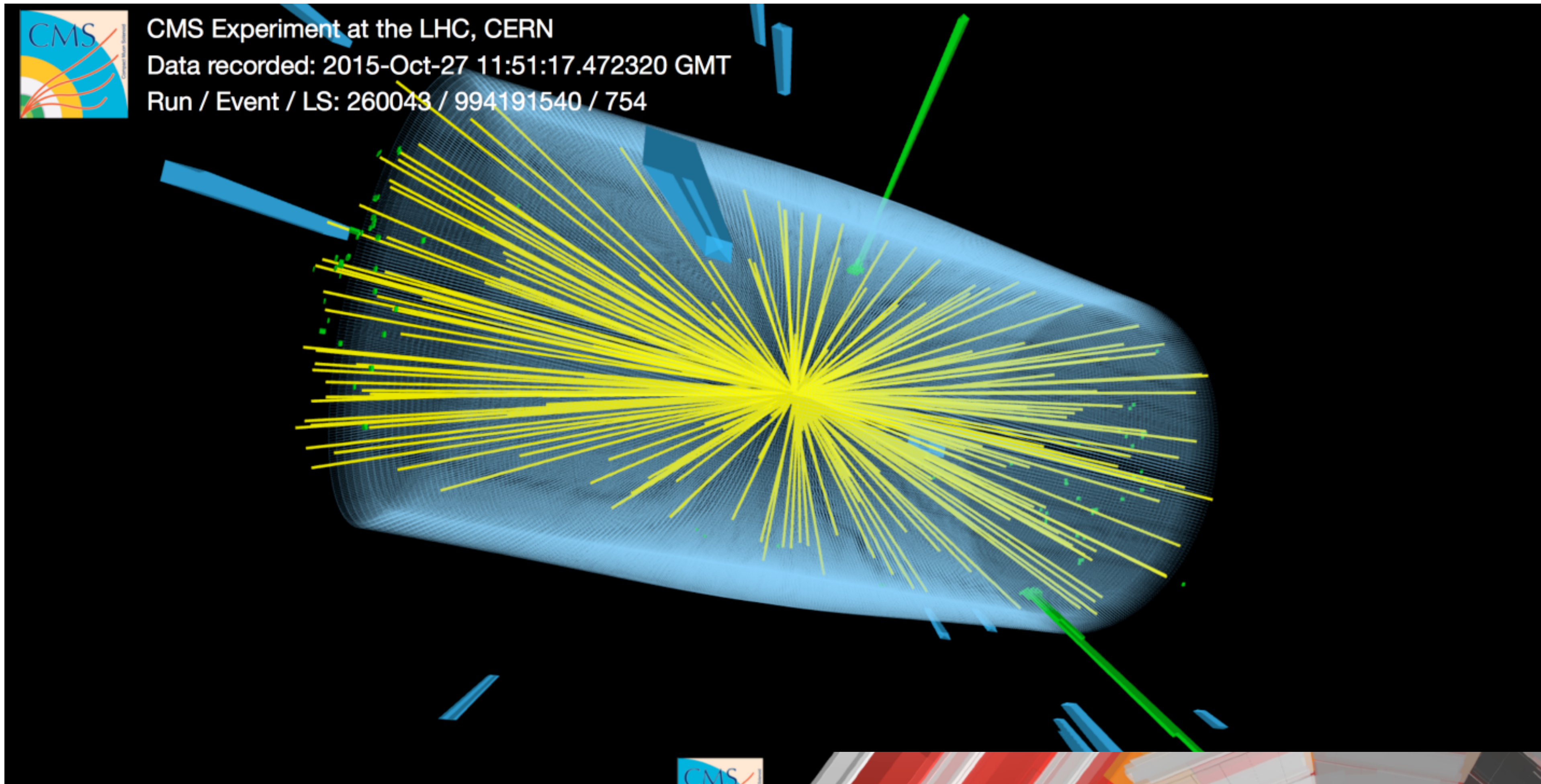
$X \to \gamma\gamma$

$m_{\gamma\gamma}$ ~ 750 GeV

CMS-PHO-EVENTS-2015-007

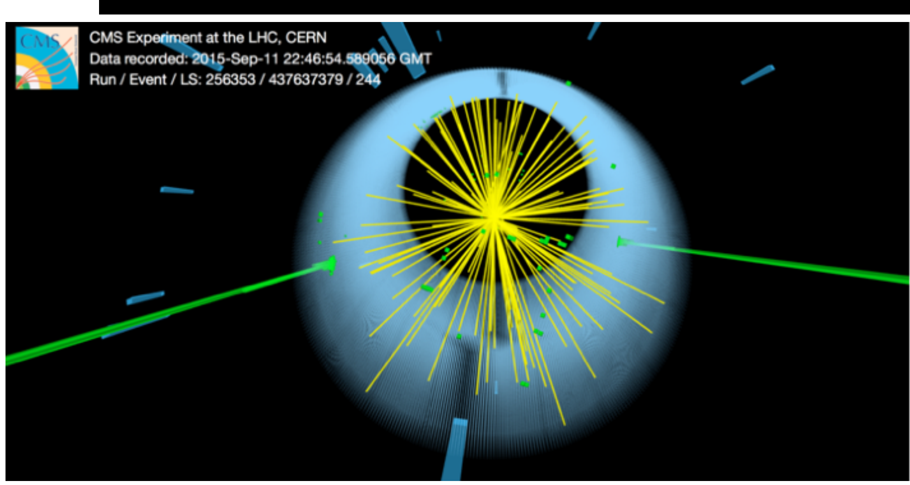


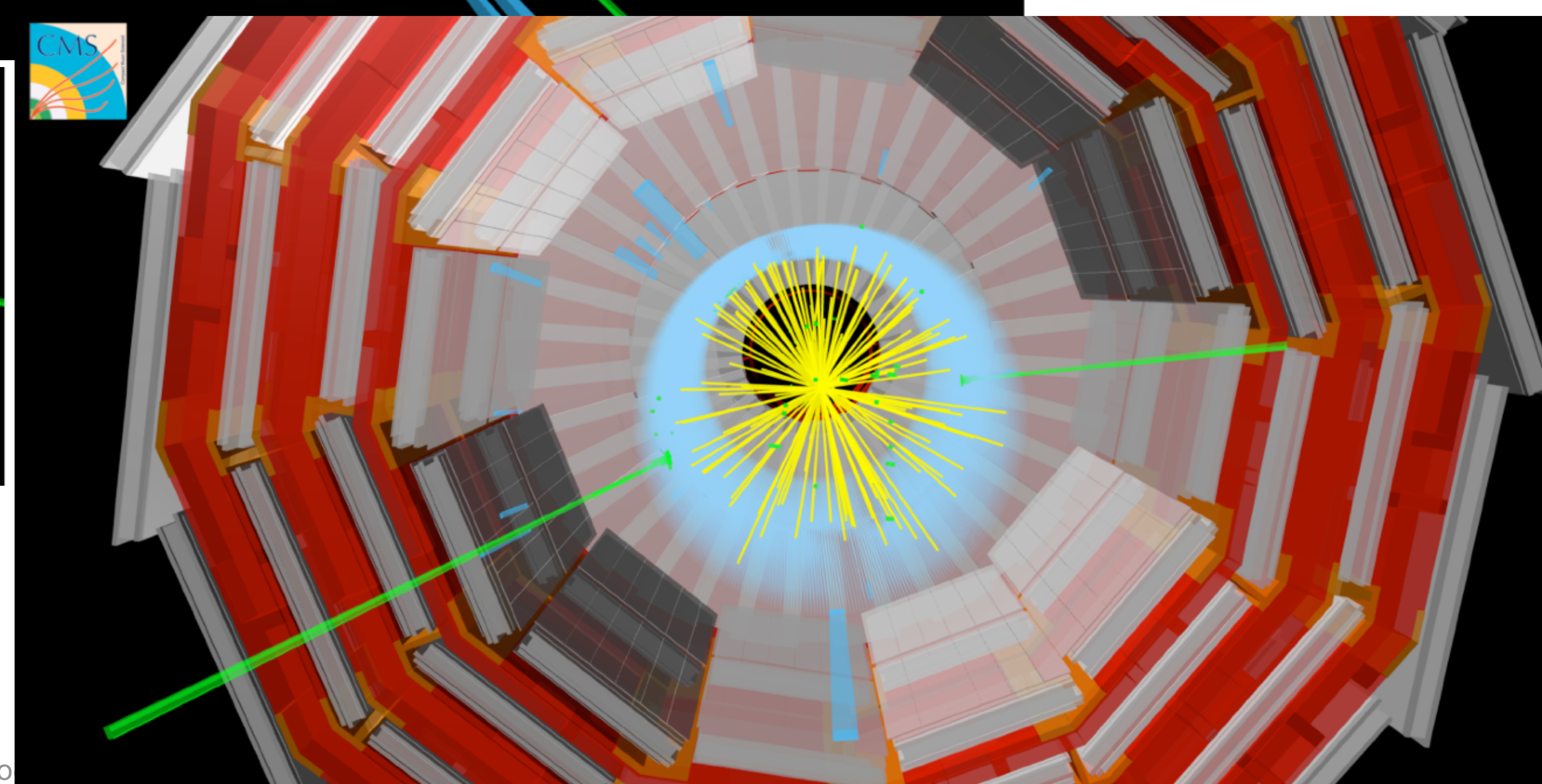


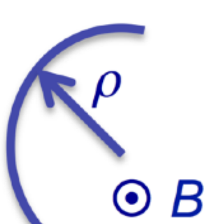


?

m?? ~ 800 GeV







$$\rho = \frac{p}{ZeB}$$

a di-jet event

X → j j