Needles in the haystack

or the search for rare physics processes

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LIP
Laboratório de Instrumentação e Física Experimental de Partículas

FCT Fundação para a Ciência e a Tecnologia
Ministério da Ciência, Tecnologia e Ensino Superior

Nuno's introduction

- under-graduate: LEFT/IST (1998)
- graduate: MSc Cambridge, PhD MIT
  - CDF experiment @ Fermilab's Tevatron
    ➠ the most powerful collider then
  - discovery of B_s particle-antiparticle oscillations (doctoral thesis)
- post-graduate/researcher: CERN, Purdue, LIP
  - CMS experiment @ CERN's LHC
    ➠ the most powerful collider now (and next decades')
  - discovery of sequential meson melting in QGP
    discovery of $B_s \rightarrow \mu\mu$ rare decay
  - CMS heavy-quarks' physics group coordinator

rare processes: what

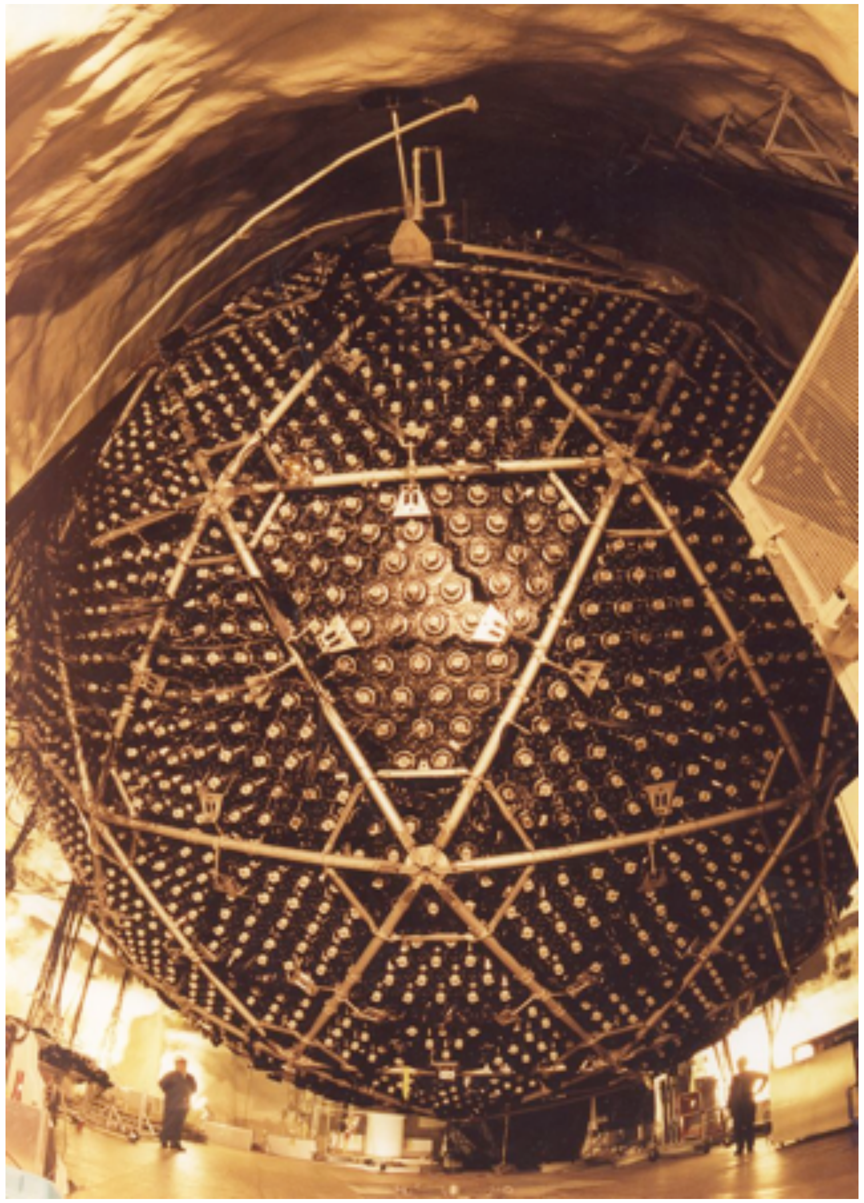
A physics process may be suppressed in different ways and levels:

- **detection**
  - the underlying process itself may not be uncommon but it may escape our detection; e.g. involved objects may have little interaction with matter
  - example: neutrinos, dark matter
- **production**
  - the underlying physics object is scarcely available in nature
  - example: unstable subatomic particles; Higgs, others so-far undetected
- **decay**
  - the underlying object may not be uncommon, but its decay is suppressed
  - rare decays of SM particles (e.g. Higgs, mediator bosons, hadrons, leptons)

rare processes: how

Different strategies are followed:

- low **detection** rates
  - use large-volume, large-area detectors



SNO
(detector target 1000 tonnes of heavy water)

rare processes: how

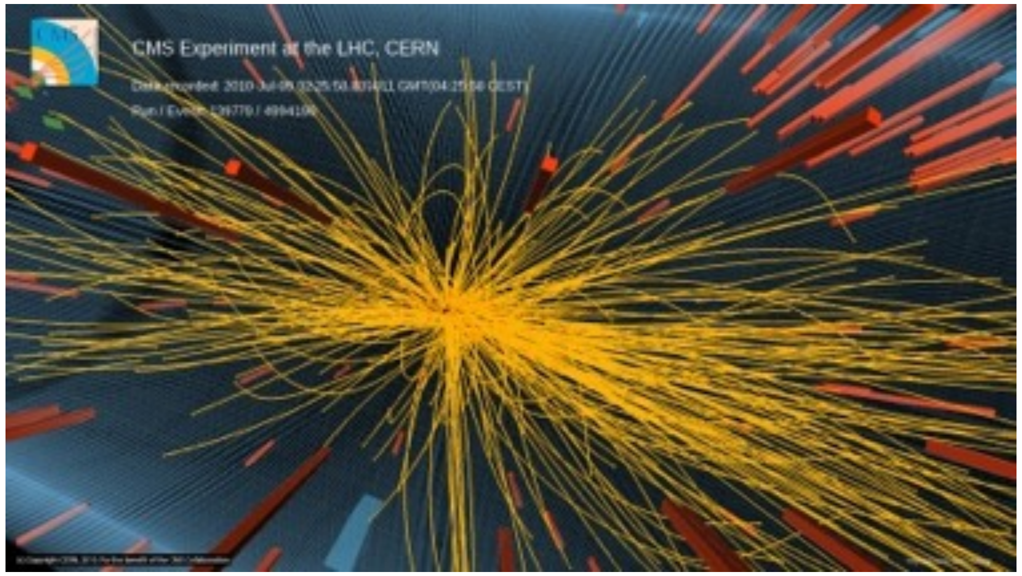
Different strategies are followed:

- low **detection** rates
  - use large-volume, large-area detectors
- low **production** rates
  - eg large-exposure detectors; or
  - carry out particle collisions in the lab, at appropriately high energies, and search for the object of interest from the collision debris

rare processes: how

Different strategies are followed:

- low **detection** rates
  - use large-volume, large-area detectors
- low **production** rates
  - eg large-exposure detectors; or
  - carry out particle collisions in the lab, at appropriately high energies, and search for the object of interest from the collision debris
- low **decay** rates
  - produce large quantities of the particle, and search for its rare decay
  - aka search for needles in the haystack



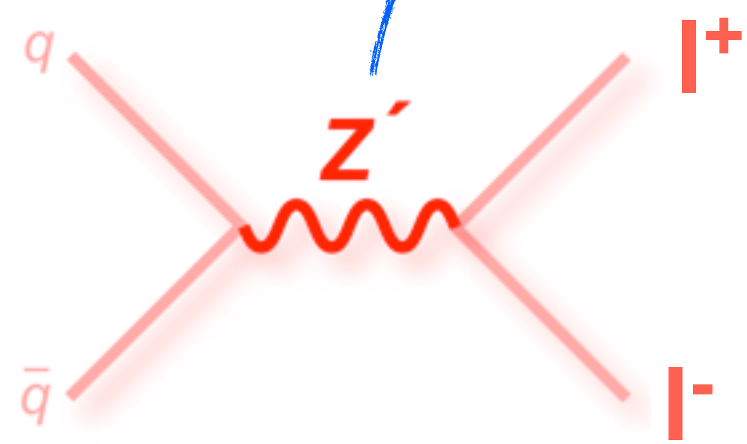
rare processes: why

- the Standard Model (SM) of particle physics is a fantastic theory that summarizes our current knowledge of the subatomic world
  - but it falls short of being the *complete* theory of fundamental interactions
- various competing theoretical ideas have been proposed to extend the SM, that attempt to address some of its shortcomings
  - but experimental guidance is crucial for development
- phase space available for beyond-Standard-Model (BSM) scenarios needs to be systematically probed experimentally, and excluded
  - until evidence for new phenomena (expected or otherwise) is found
- the search and study of rare processes provide a sensitive means to detect physics phenomena beyond the SM

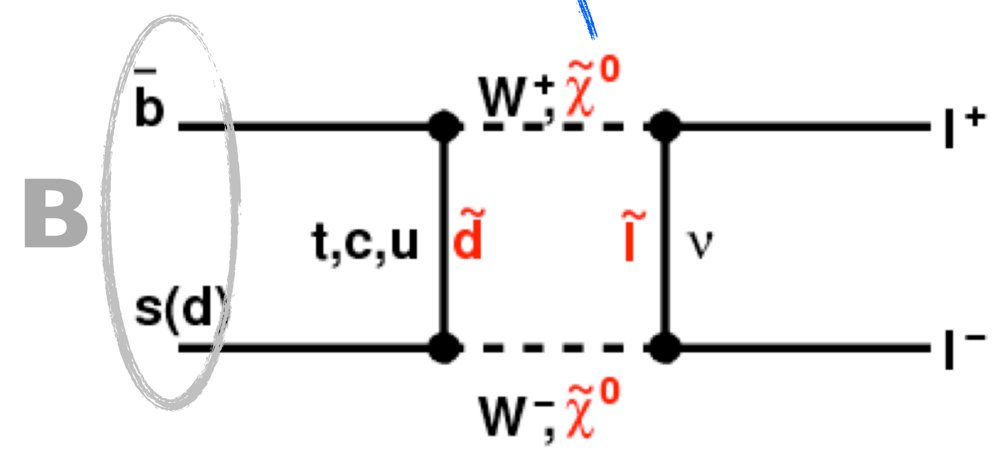
beyond the SM, how?

New Physics

BSM particles may be directly produced in collision



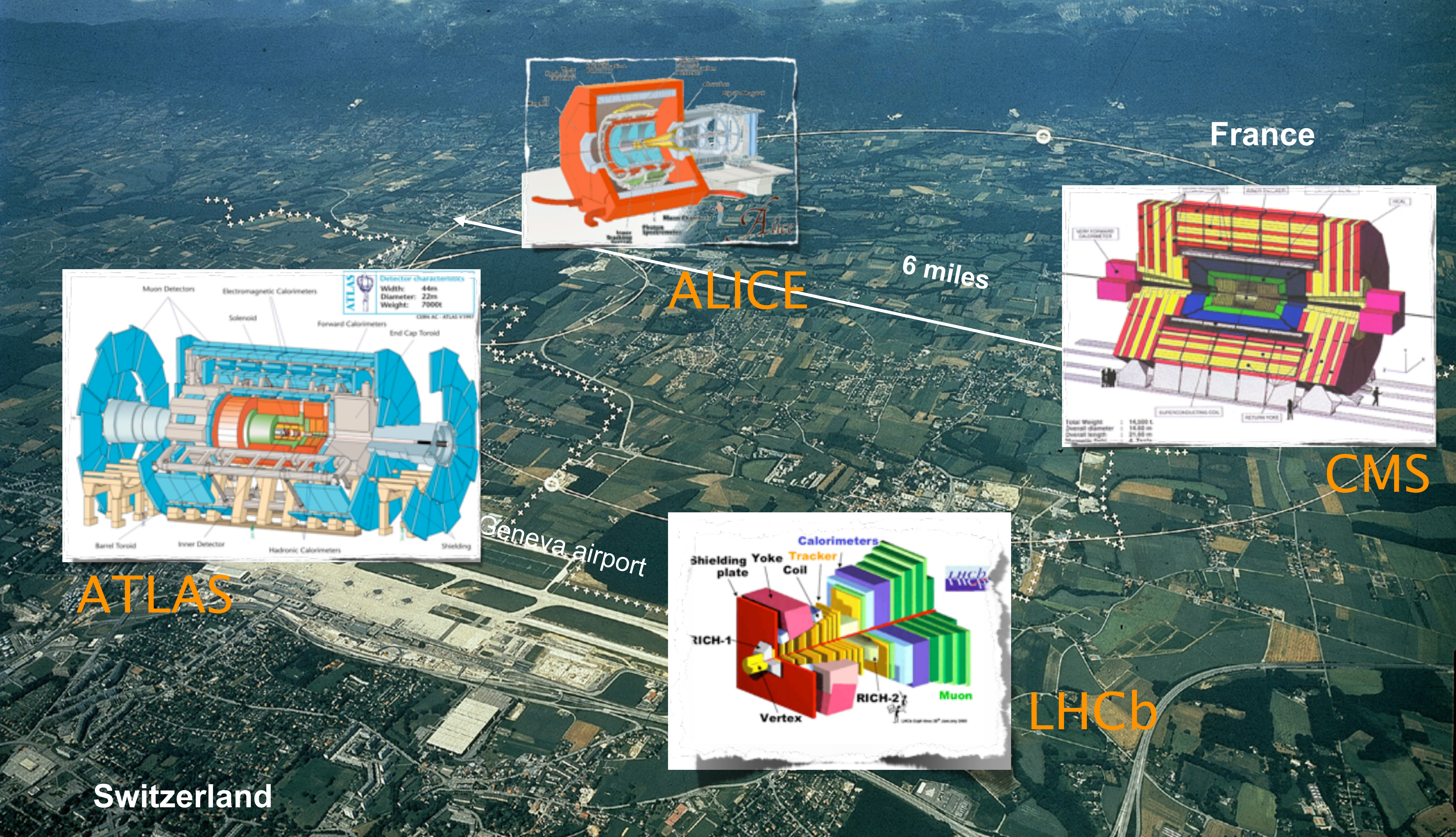
Quantum mechanical effects of BSM particles on SM processes



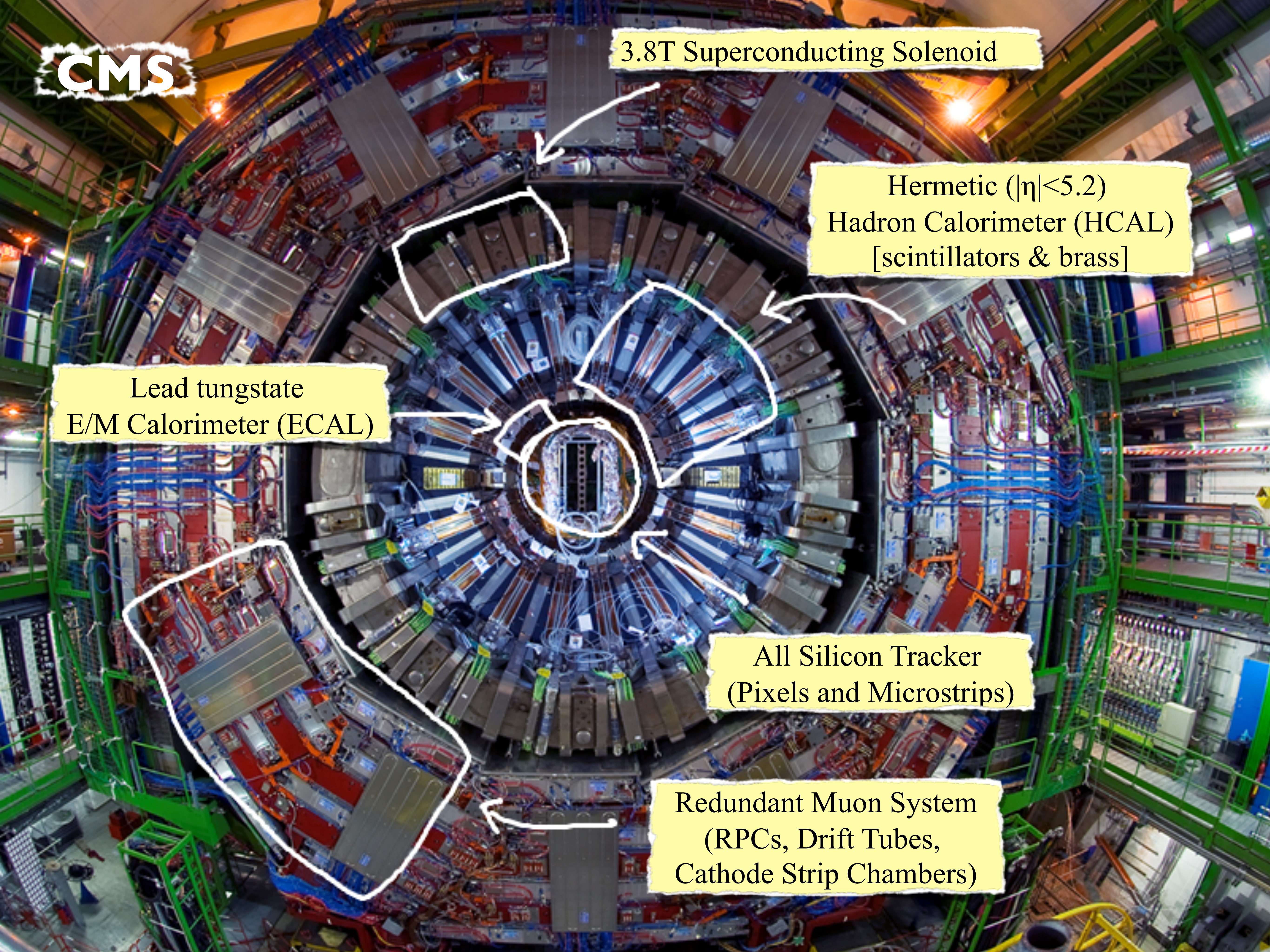
rare production

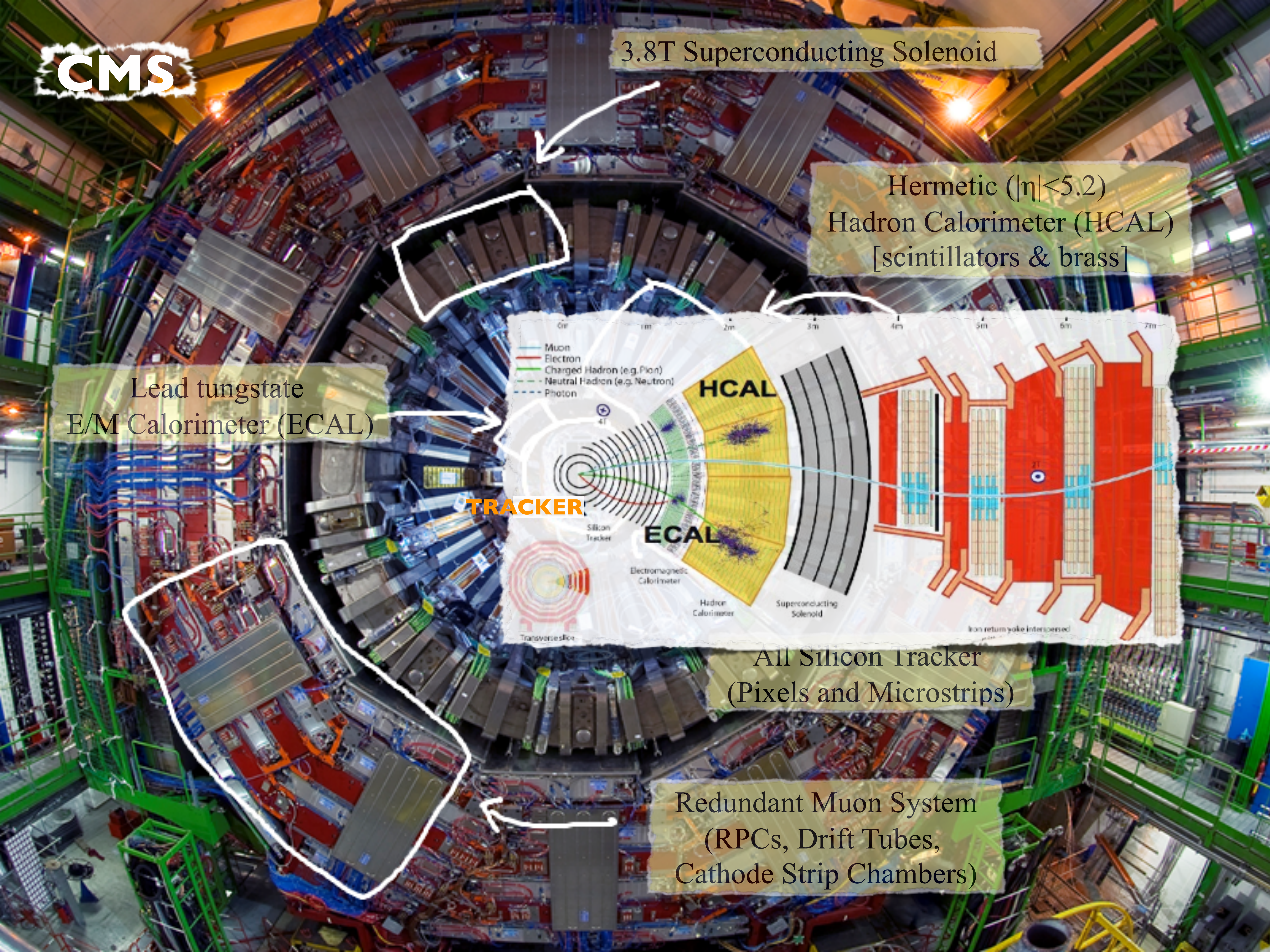
rare decay

the tools



the LHC & its detectors


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
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Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
HCAL
ECAL
TRACKER
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
All Silicon Tracker
(Pixels and Microstrips)
Redundant Muon System
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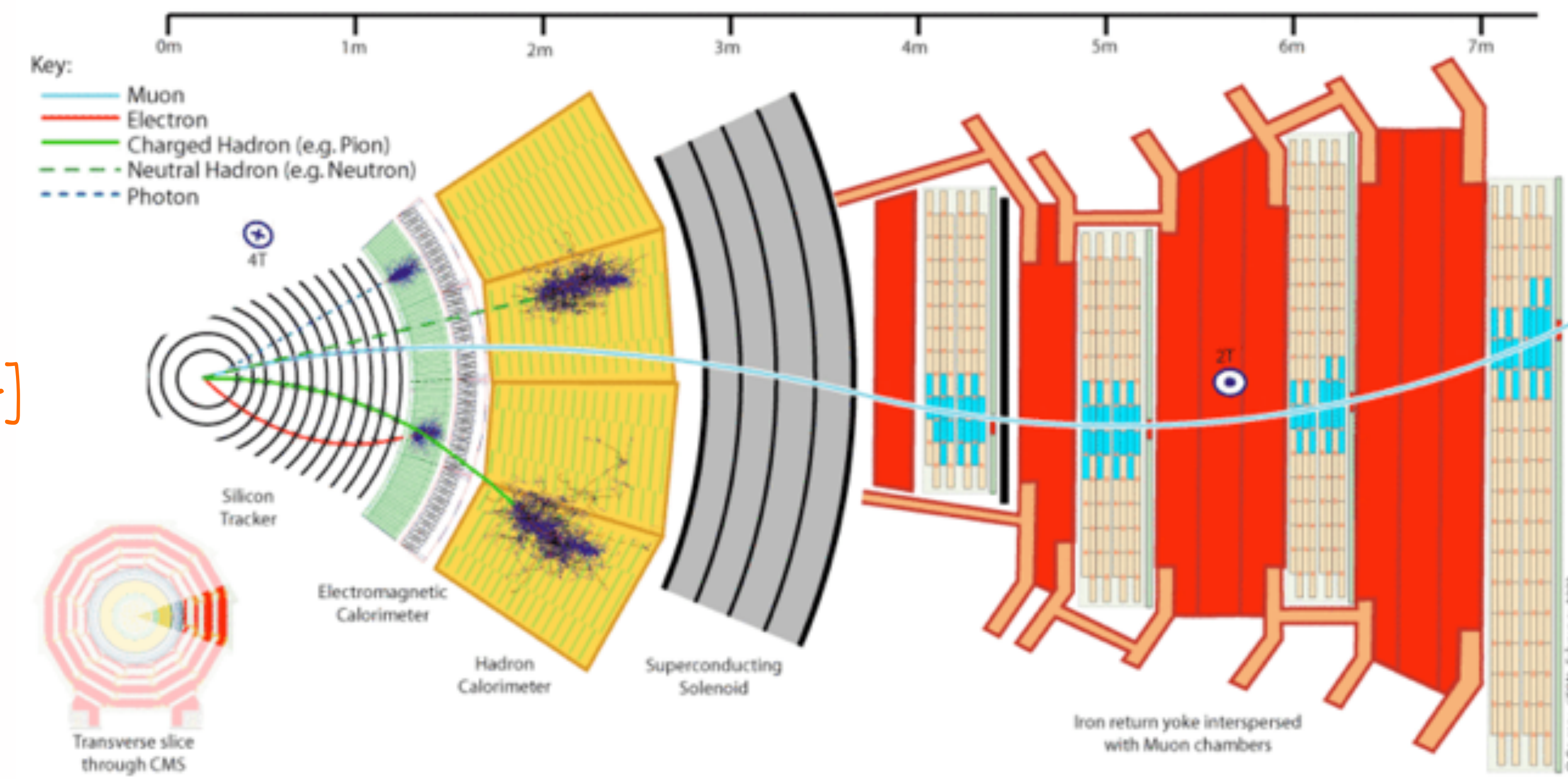
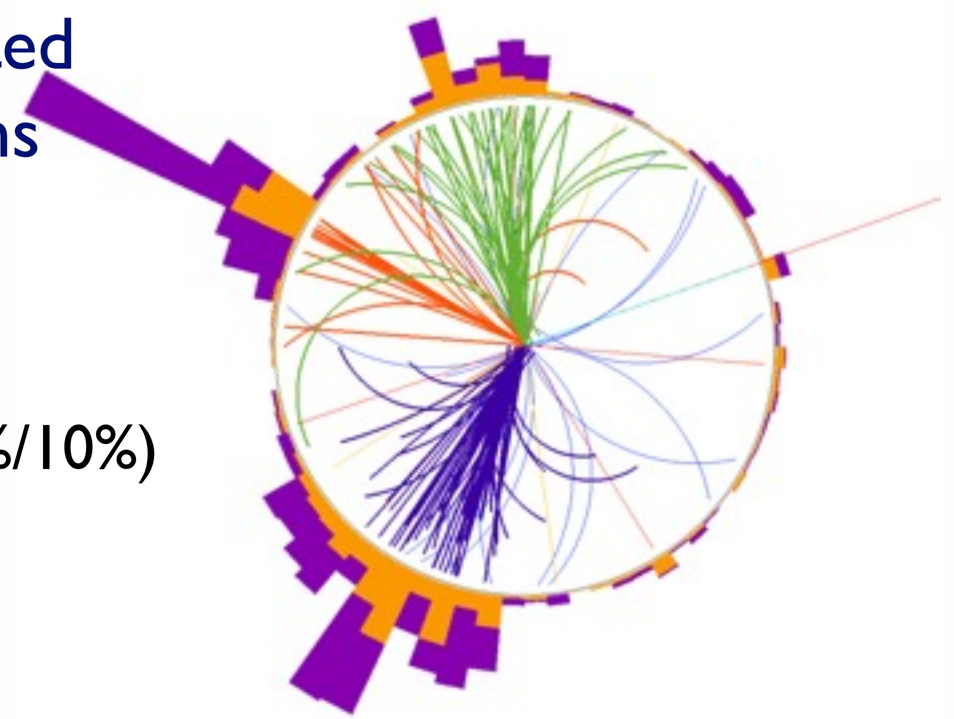
particle identification

[leading order]

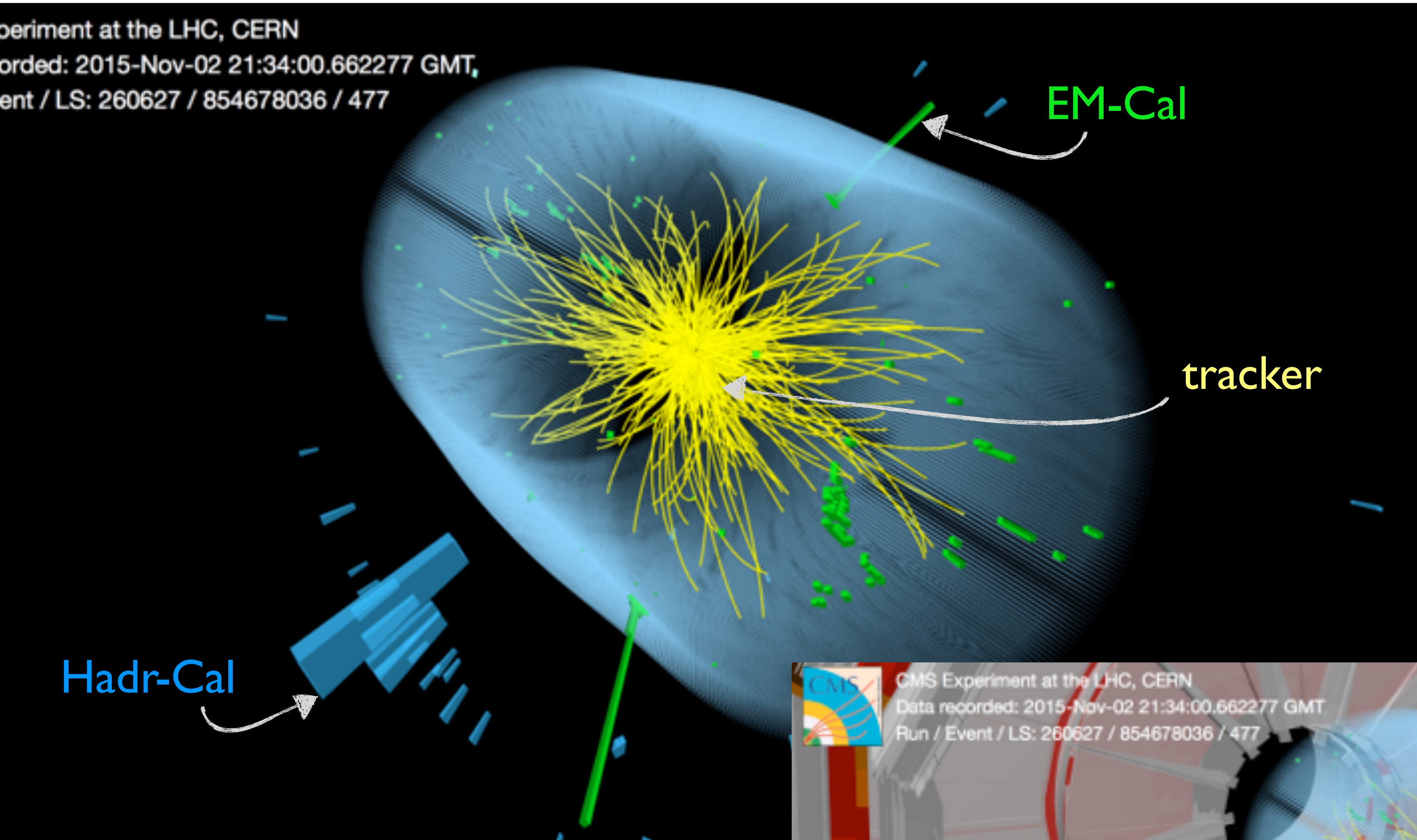


- [higher order corrections] objects are finally reconstructed using information from different detector subsystems combined in a particle flow algorithm
  - electrons radiate via bremsstrahlung
  - photons may convert to e^+e^- pairs in the tracker
  - jet (q,g) energy is formed of charged/neutral hadrons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



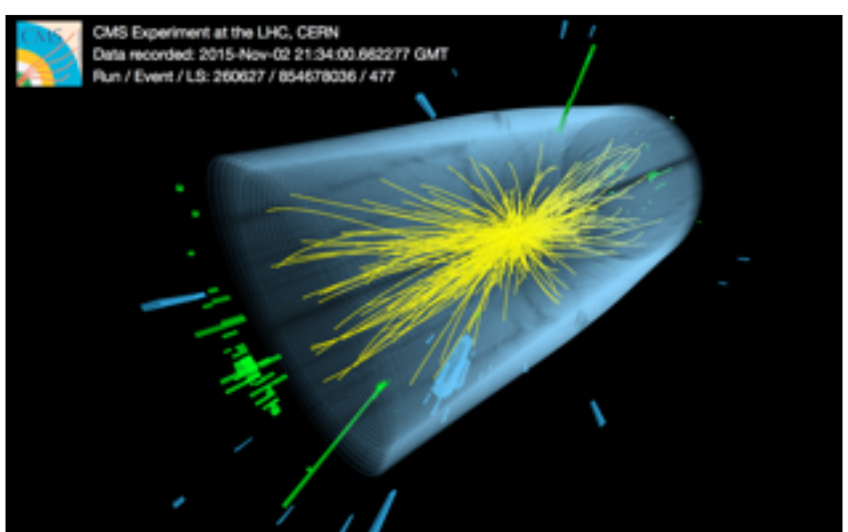
di–photons

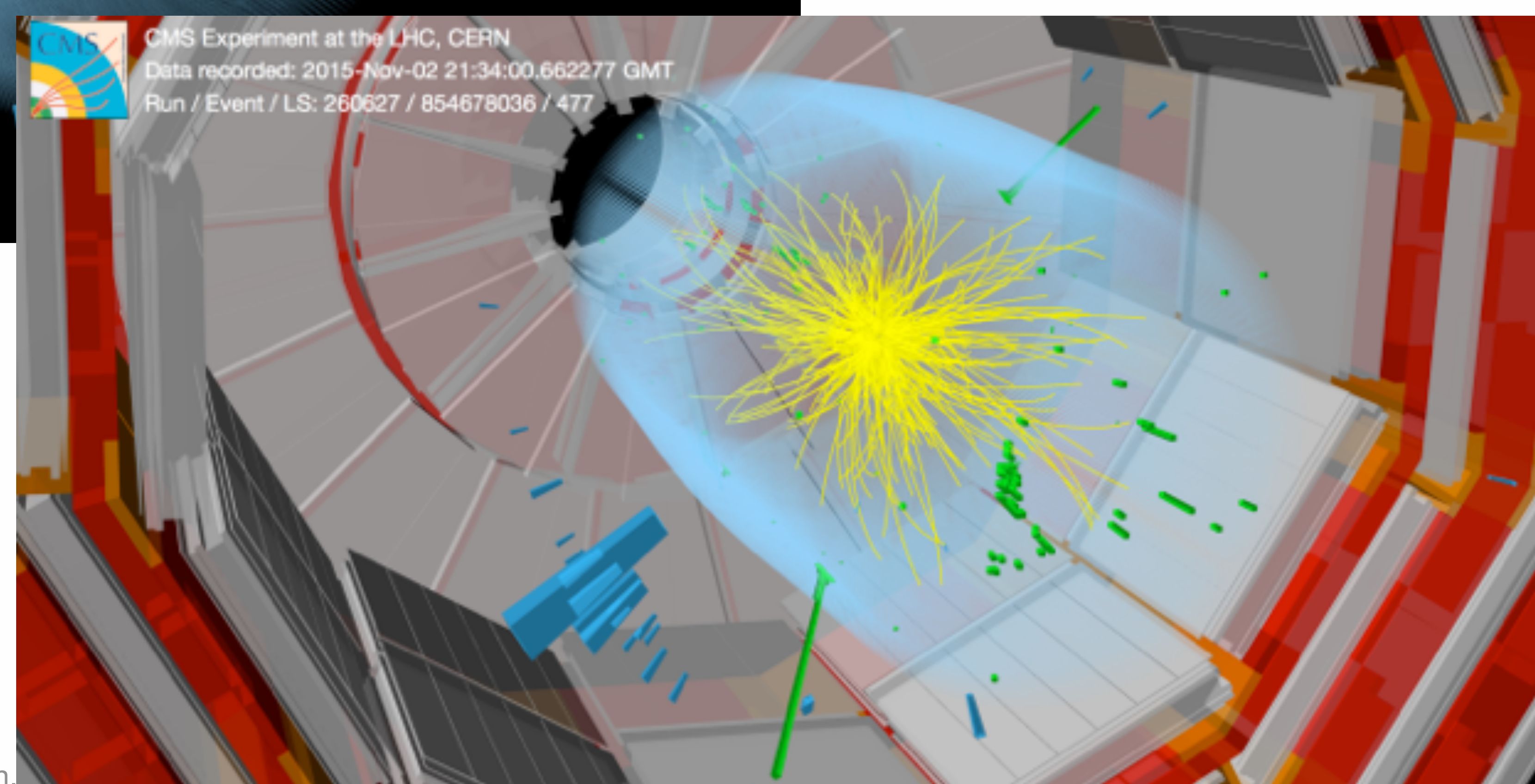
$\chi \rightarrow \gamma\gamma$



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

CMS-PHO-EVENTS-2015-007





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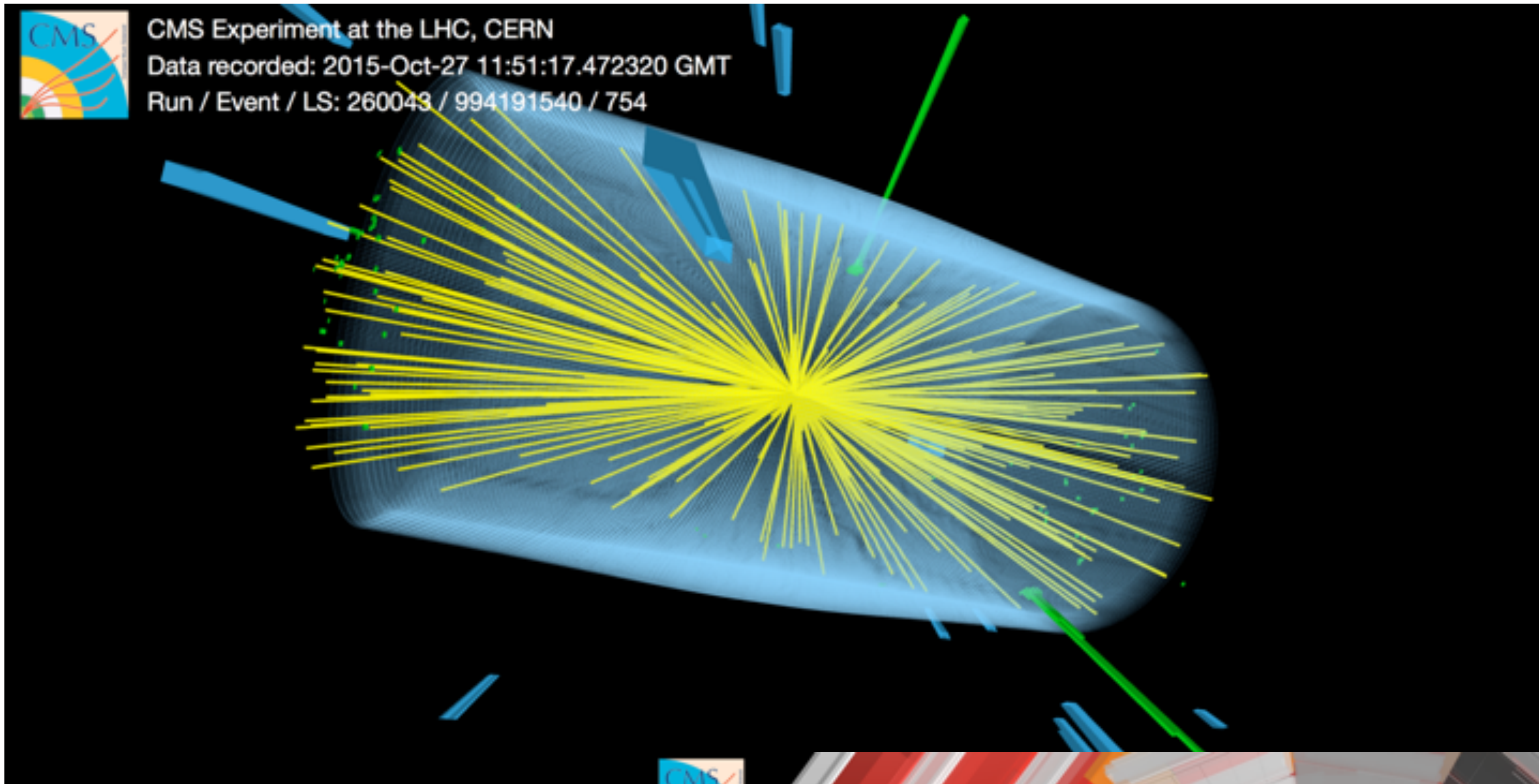
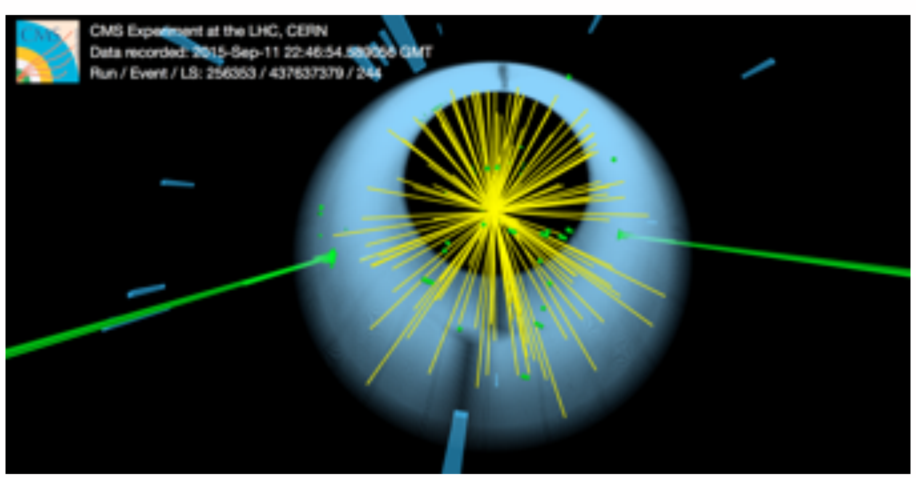
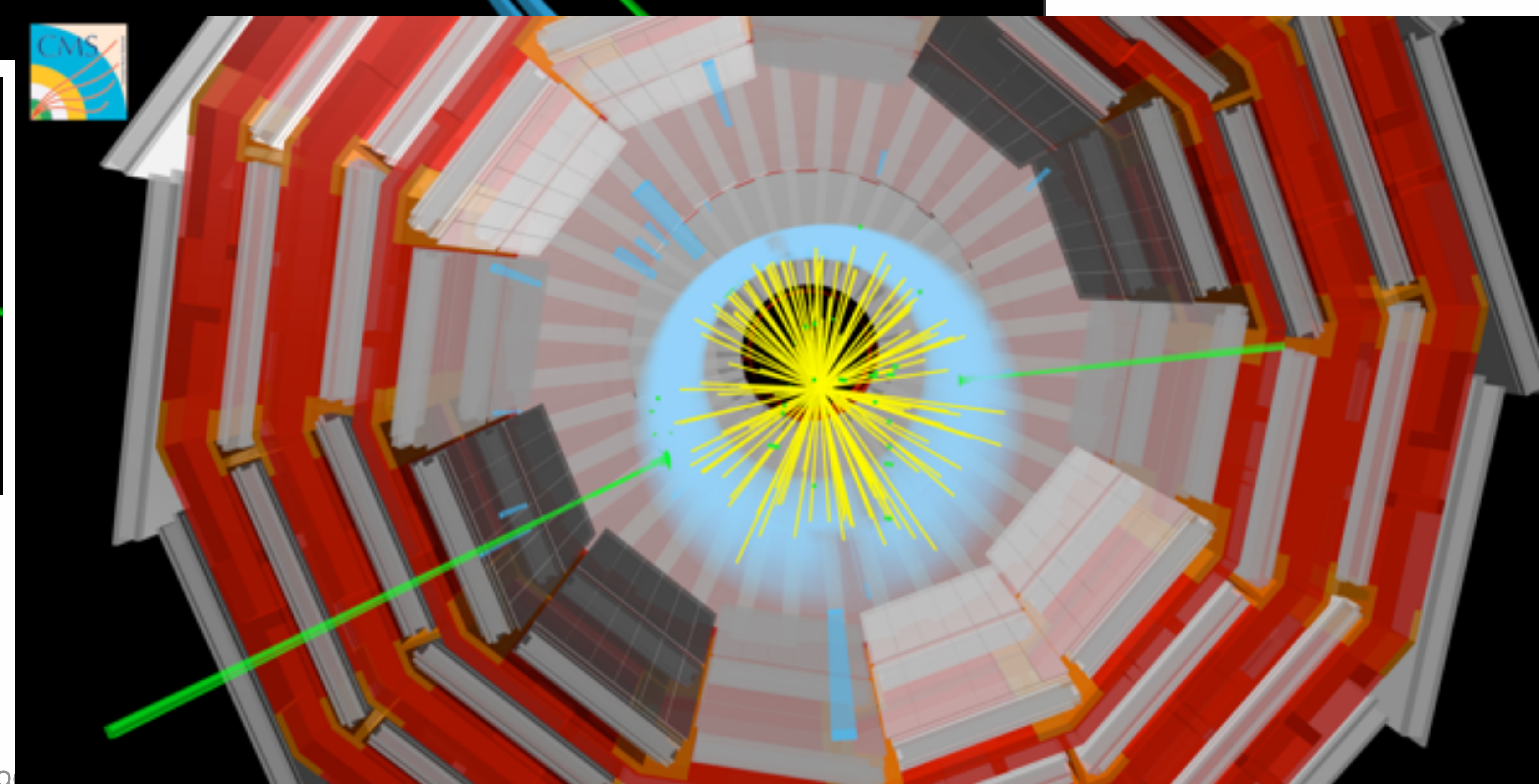


?

$m_{??}$ ~ 800 GeV

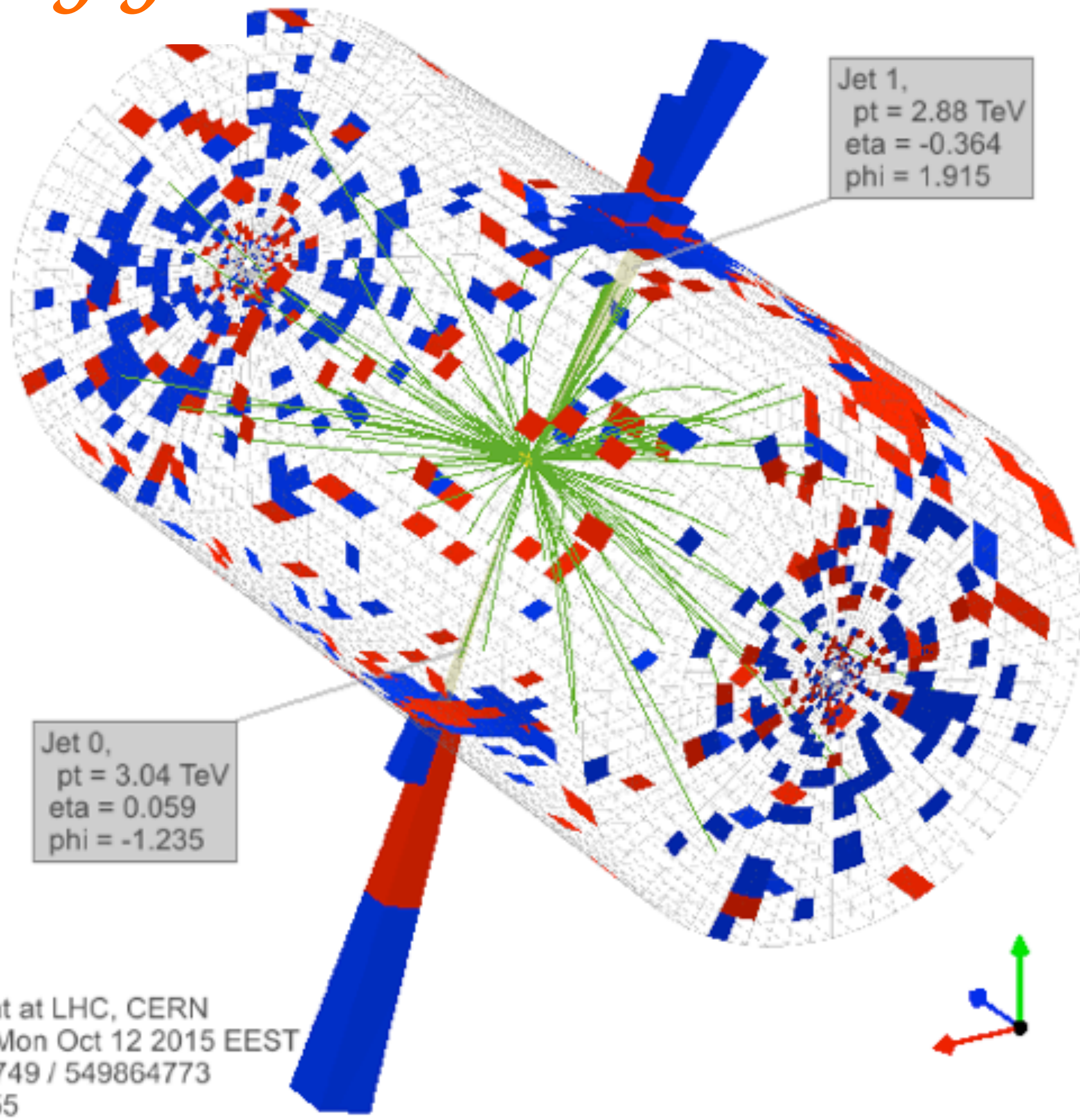




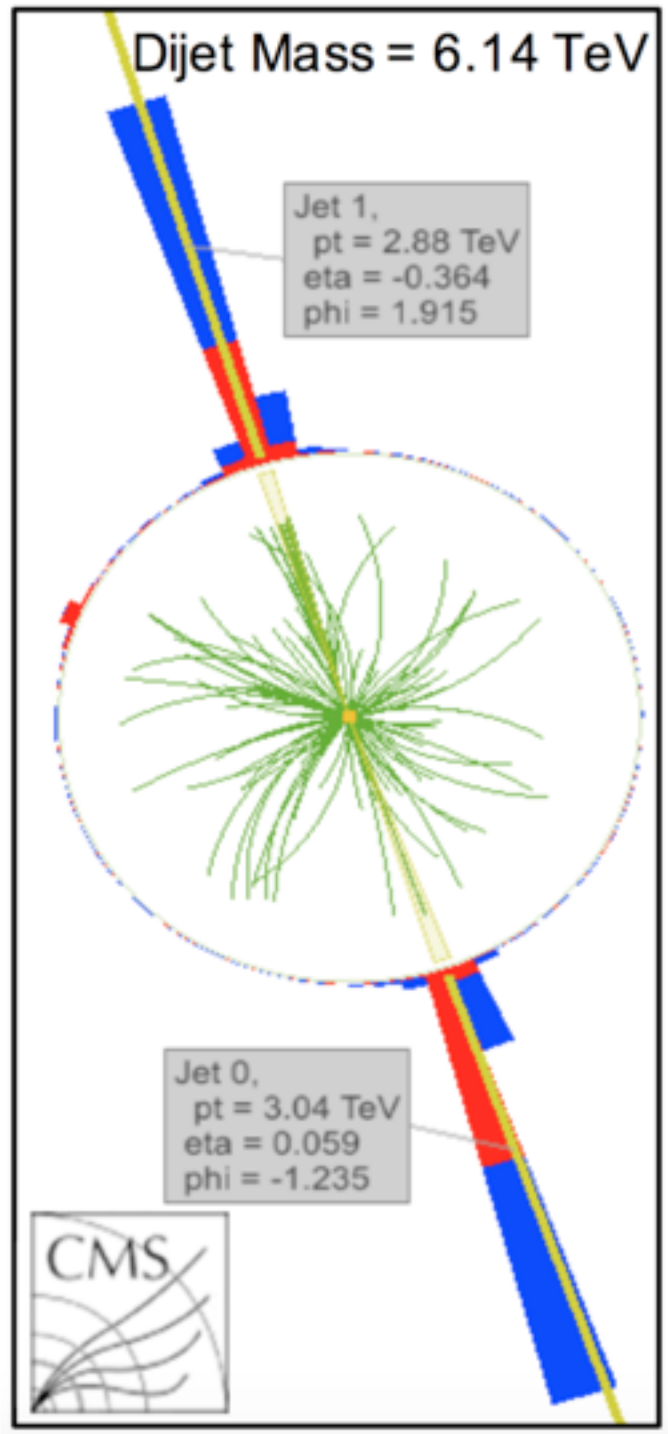
$$\rho = \frac{p}{ZeB}$$

di-jets

$X \rightarrow jj$

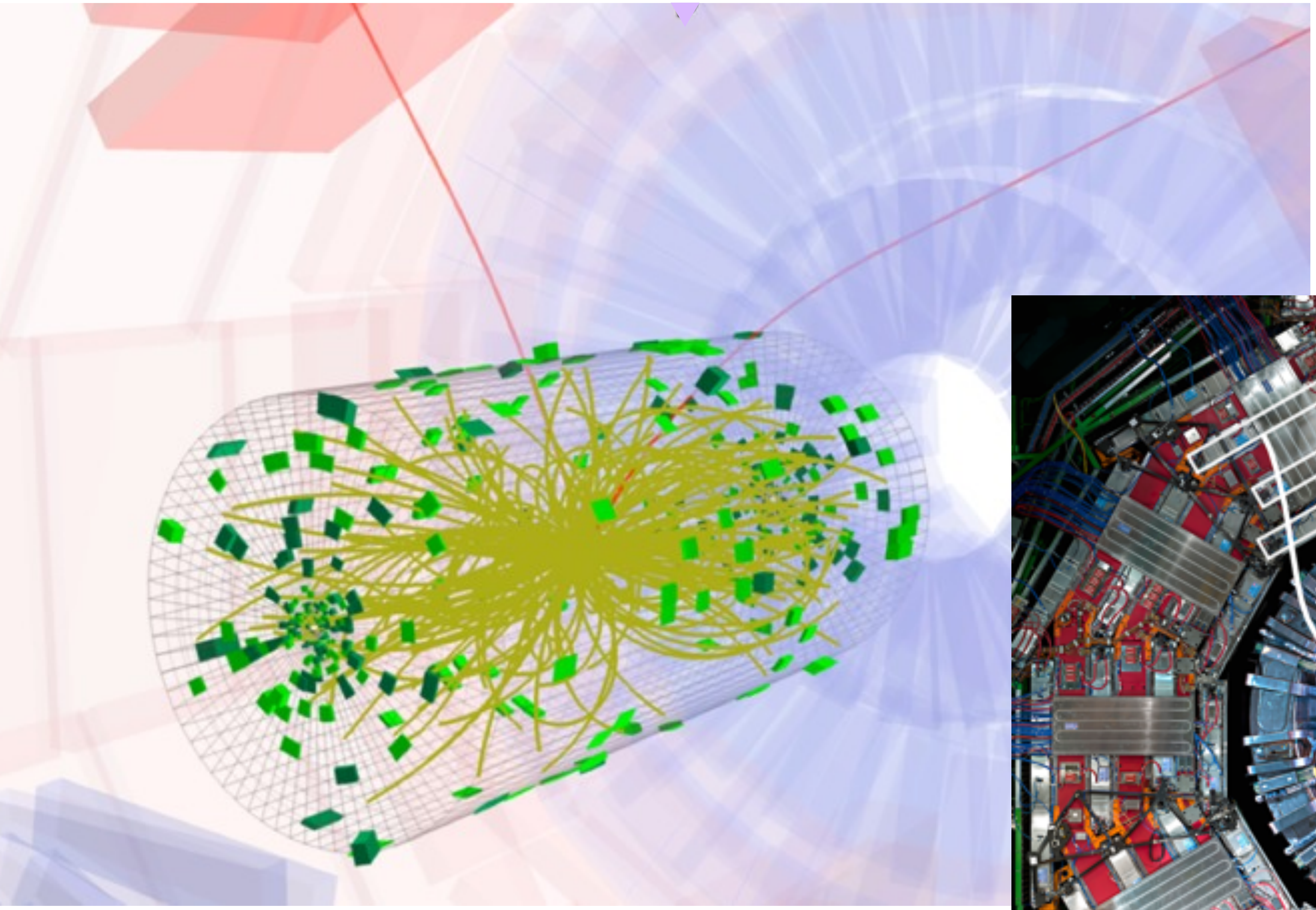


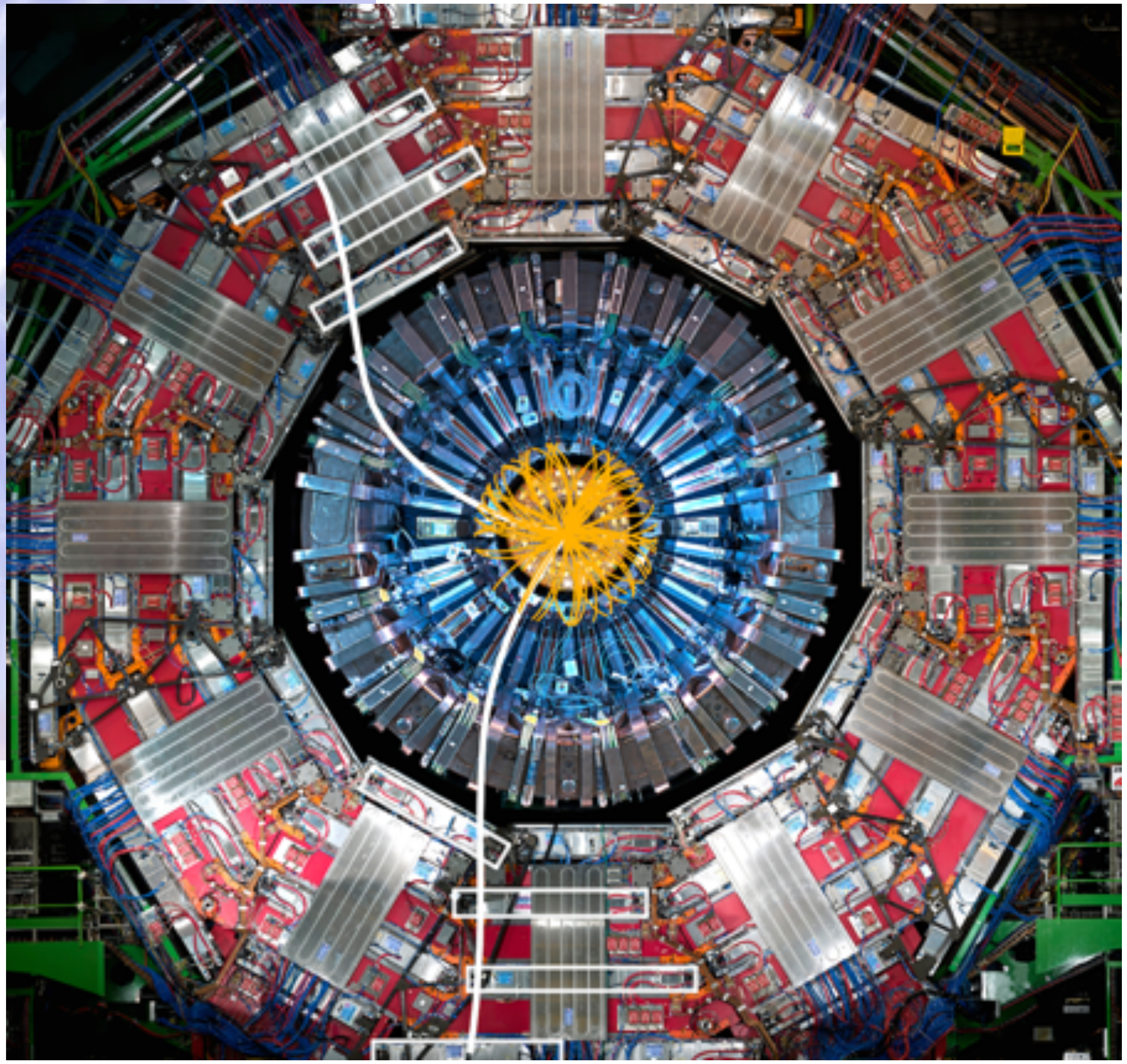
CMS Experiment at LHC, CERN
Data recorded: Mon Oct 12 2015 EEST
Run/Event: 258749 / 549864773
Lumi section: 355
Dijet Mass: 6.14 TeV



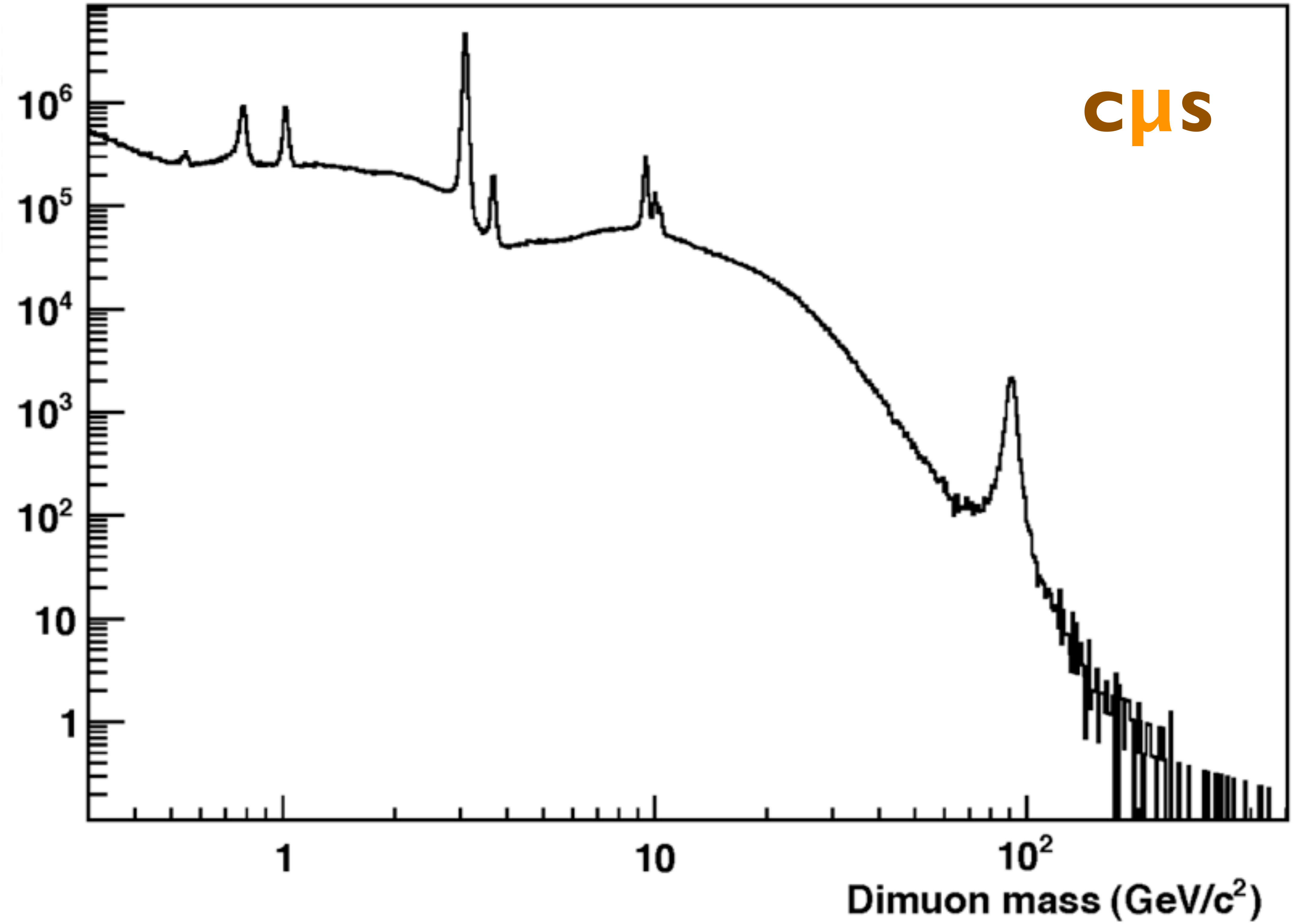
di-muons

$X \rightarrow \mu\mu$

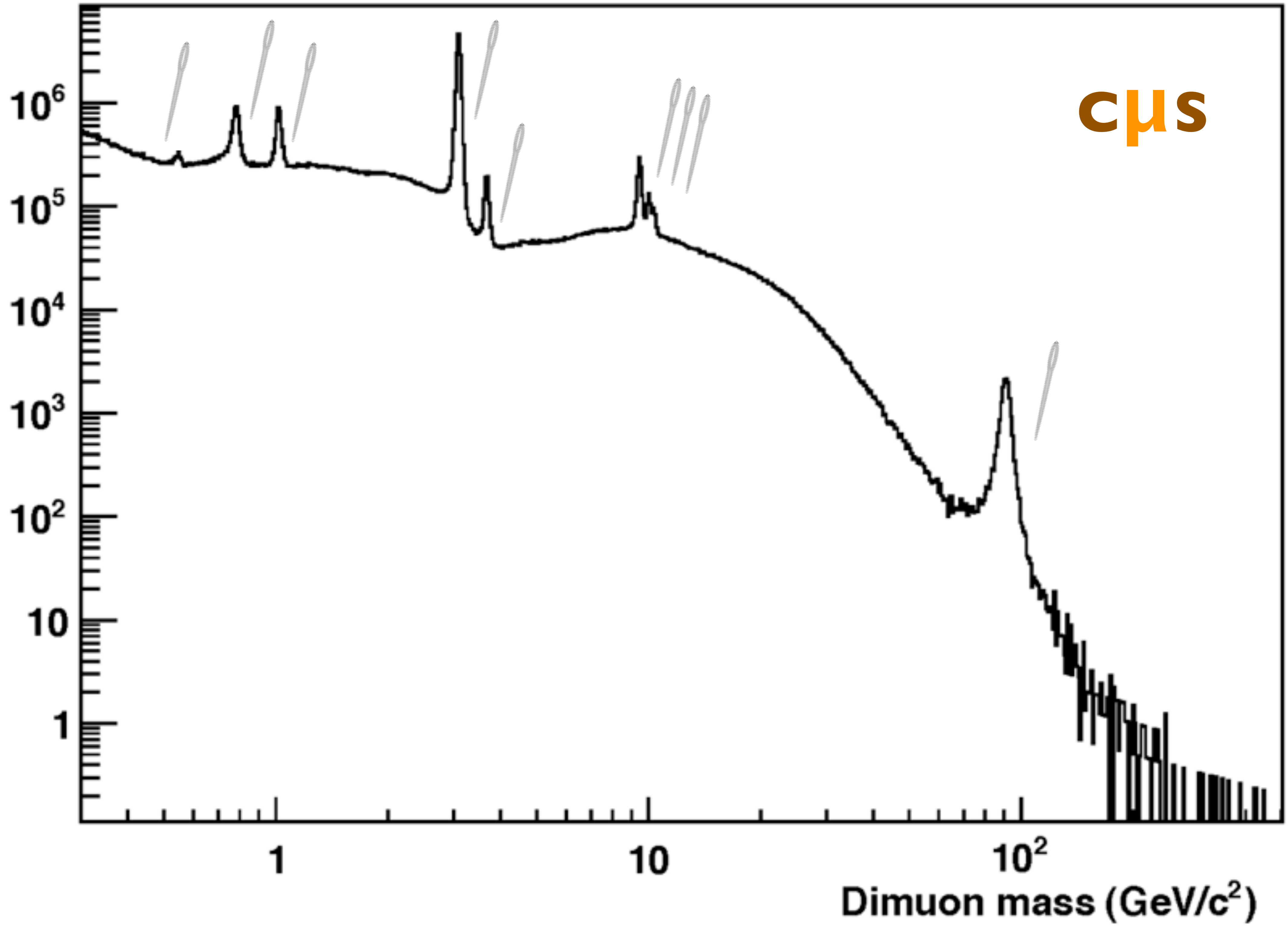




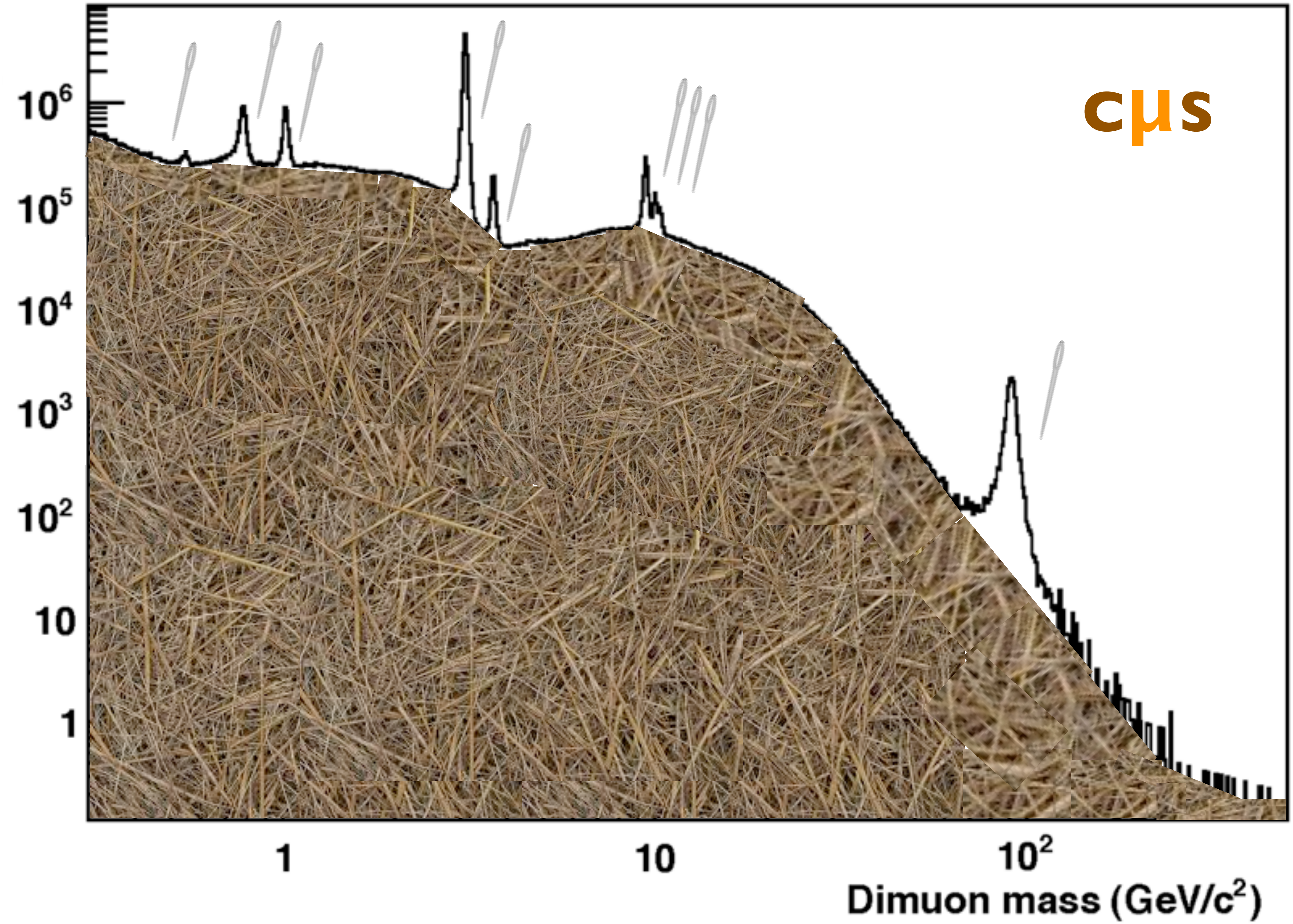
the di-muon spectrum (X →μμ)



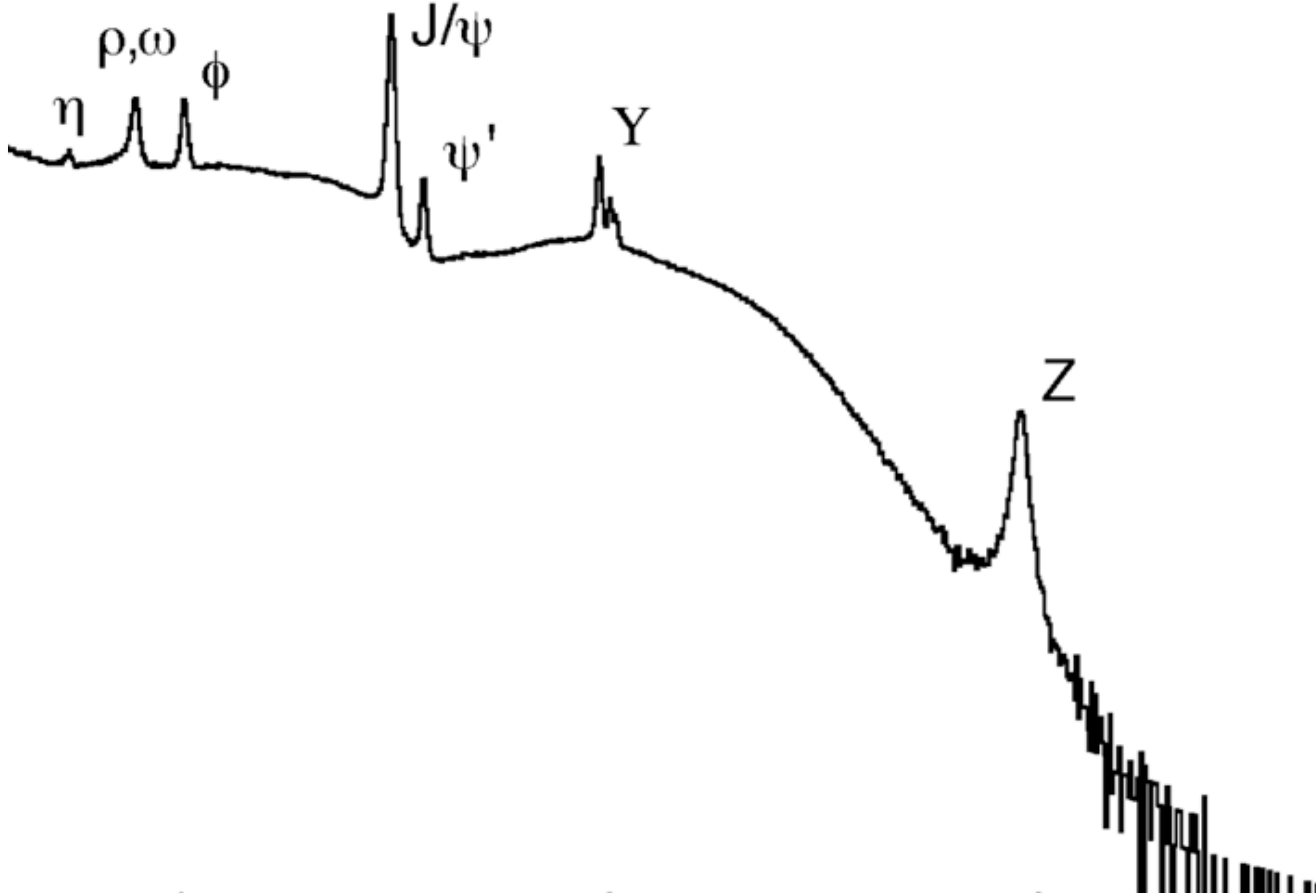
needles



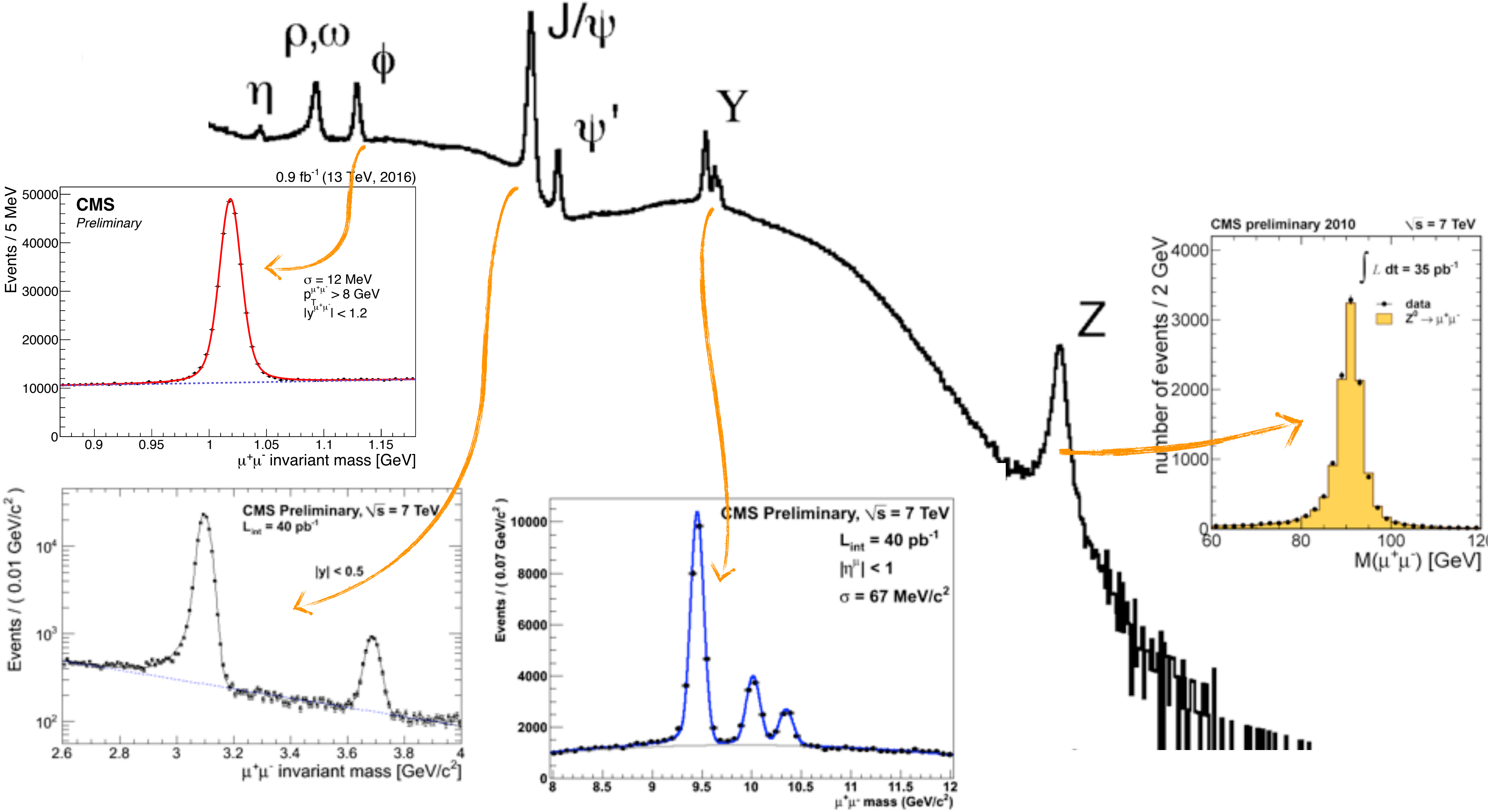
needles on top of the haystack



naming the needles

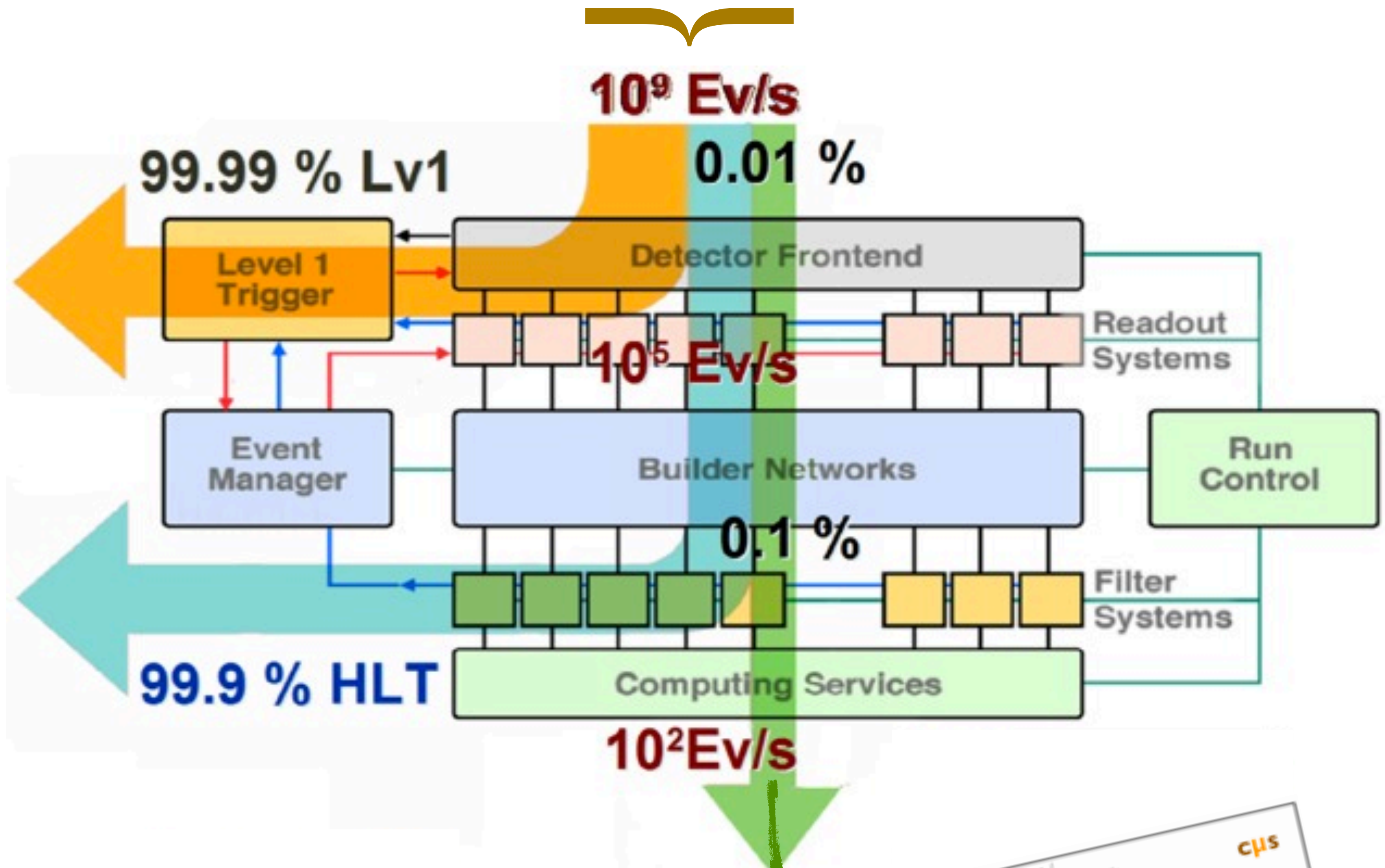


how we *see* particles



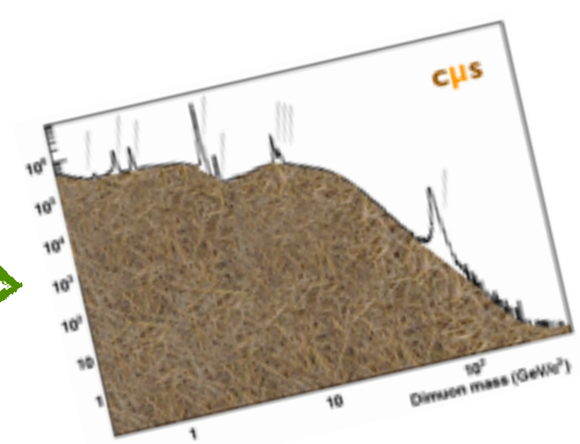
trigger
= real-time event filtering

DETECTOR



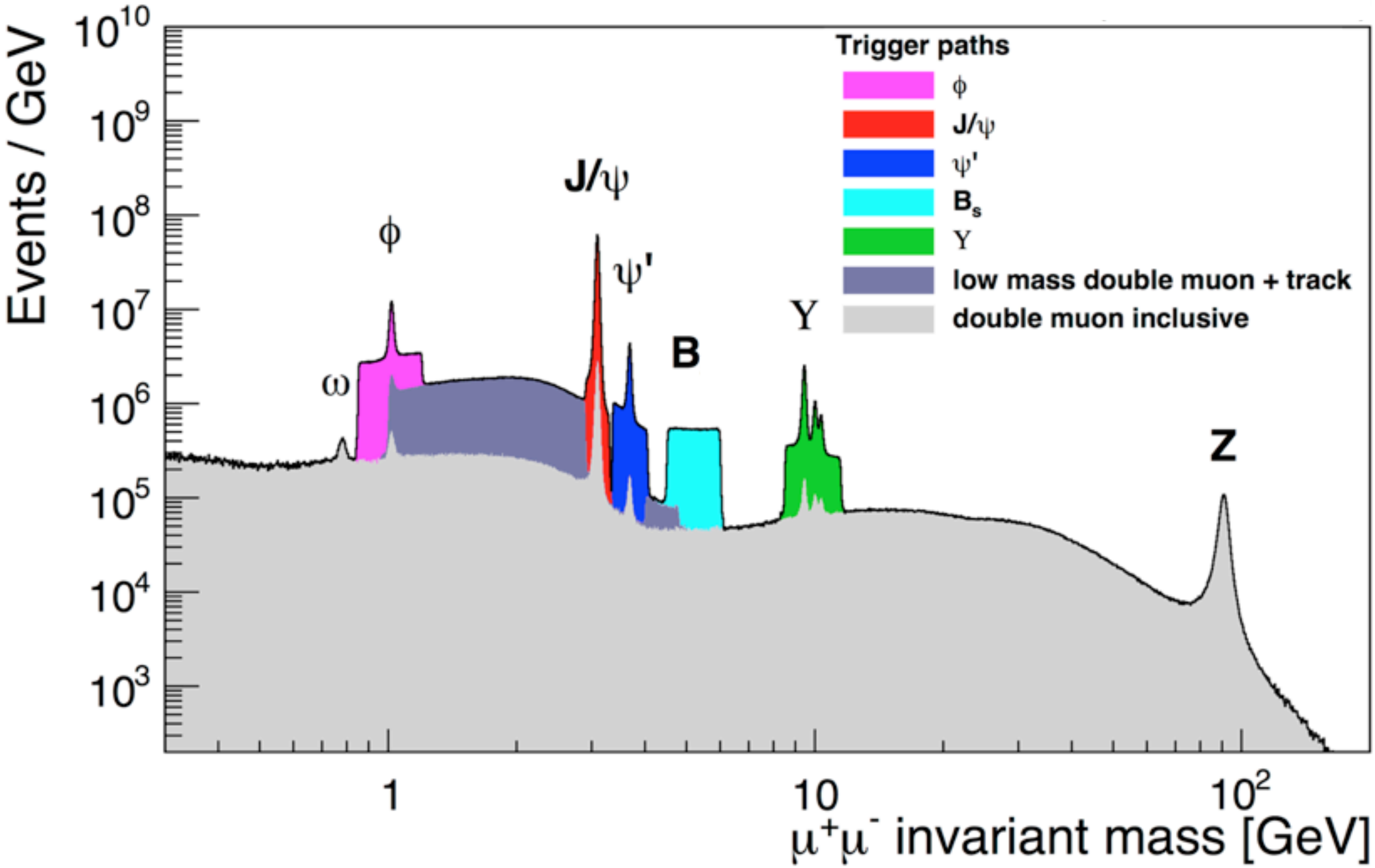
TRIGGER SYSTEM

- majority of collisions **(hay)** is rejected in real-time
- only small fraction is saved for offline analysis
- most interesting phenomena are rare **(needles)**



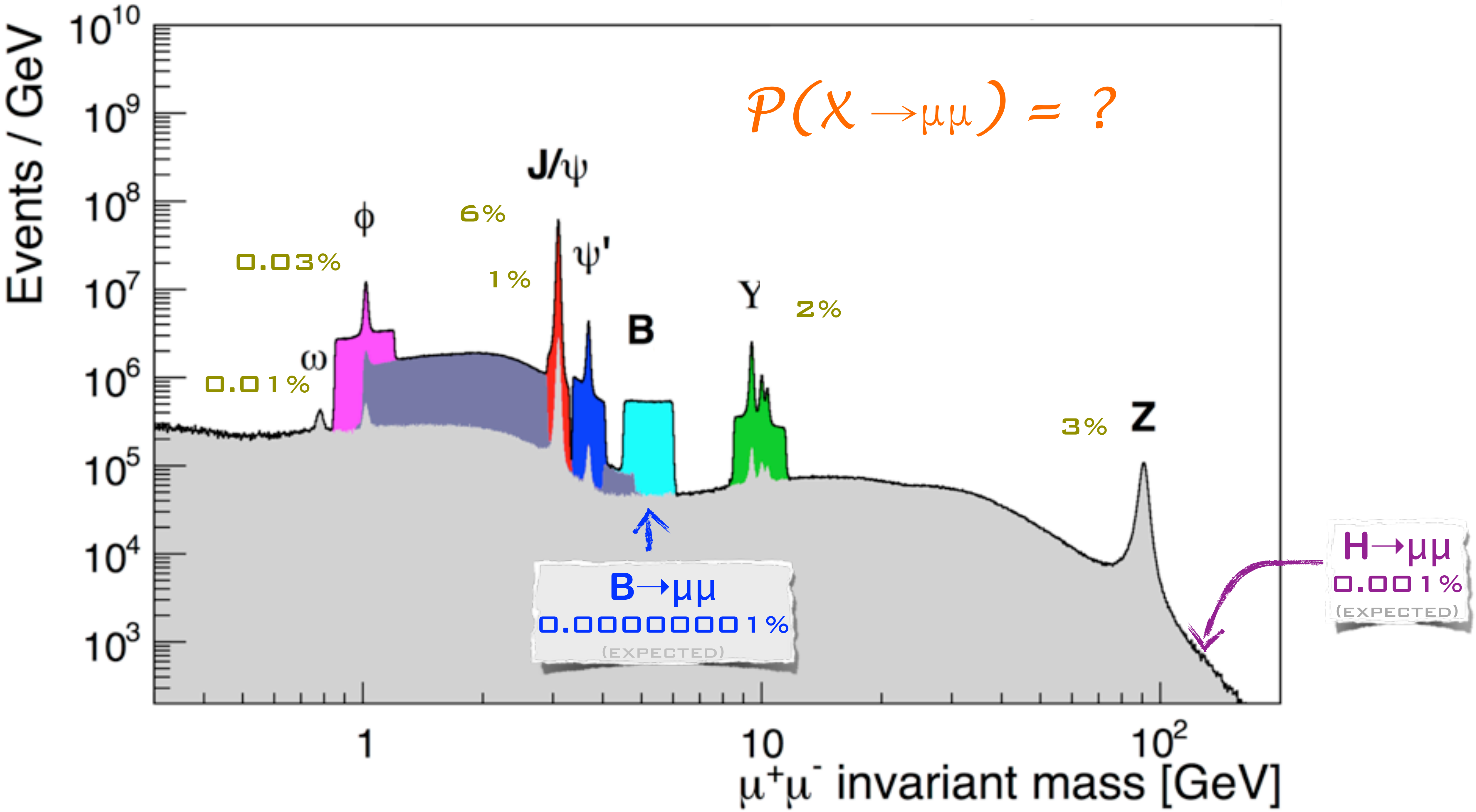
PHYSICS

di-muon trigger



- the **trigger** is the most **critical** stage in the search for **rare** phenomena
- the deployed algorithms determine a search's sensitivity and success

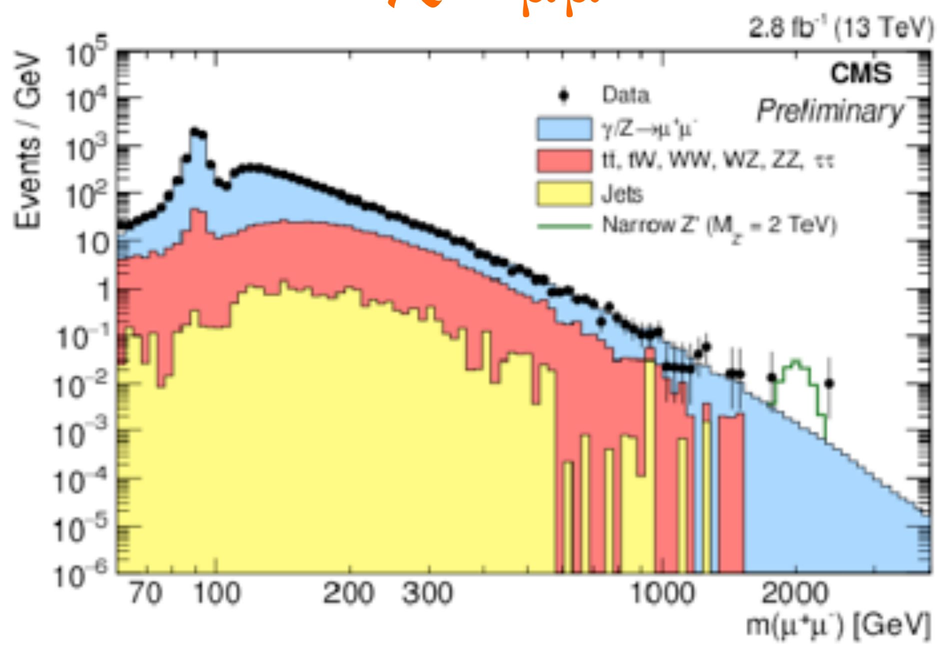
X →μμ decays: not-so-rare, rare, ultra-rare



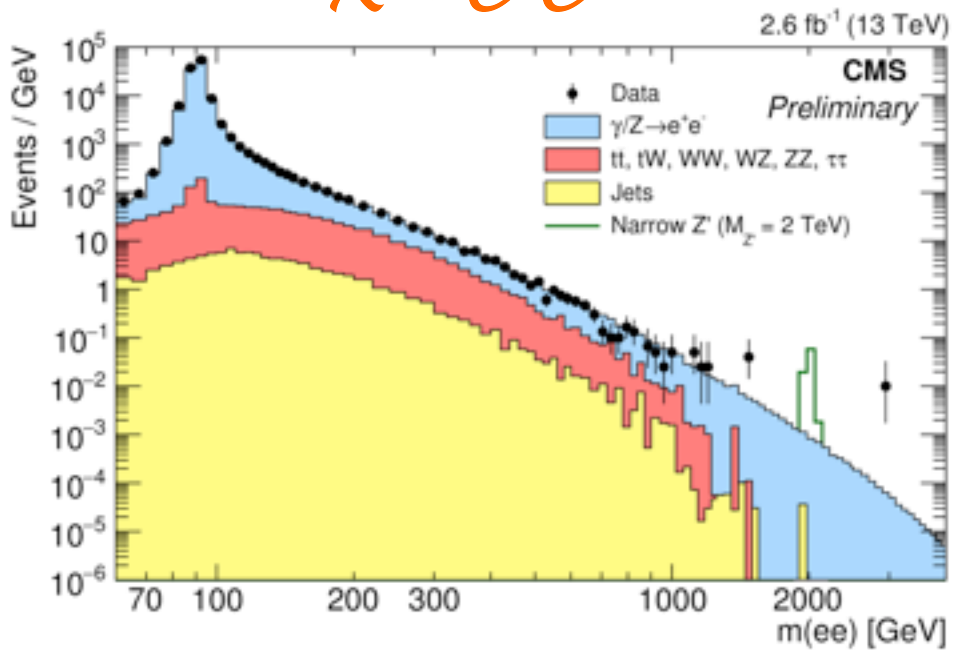
Note B→μμ and H→μμ are similarly rare processes when accounting for both *production* and *decay* rates

search for bumps at higher masses

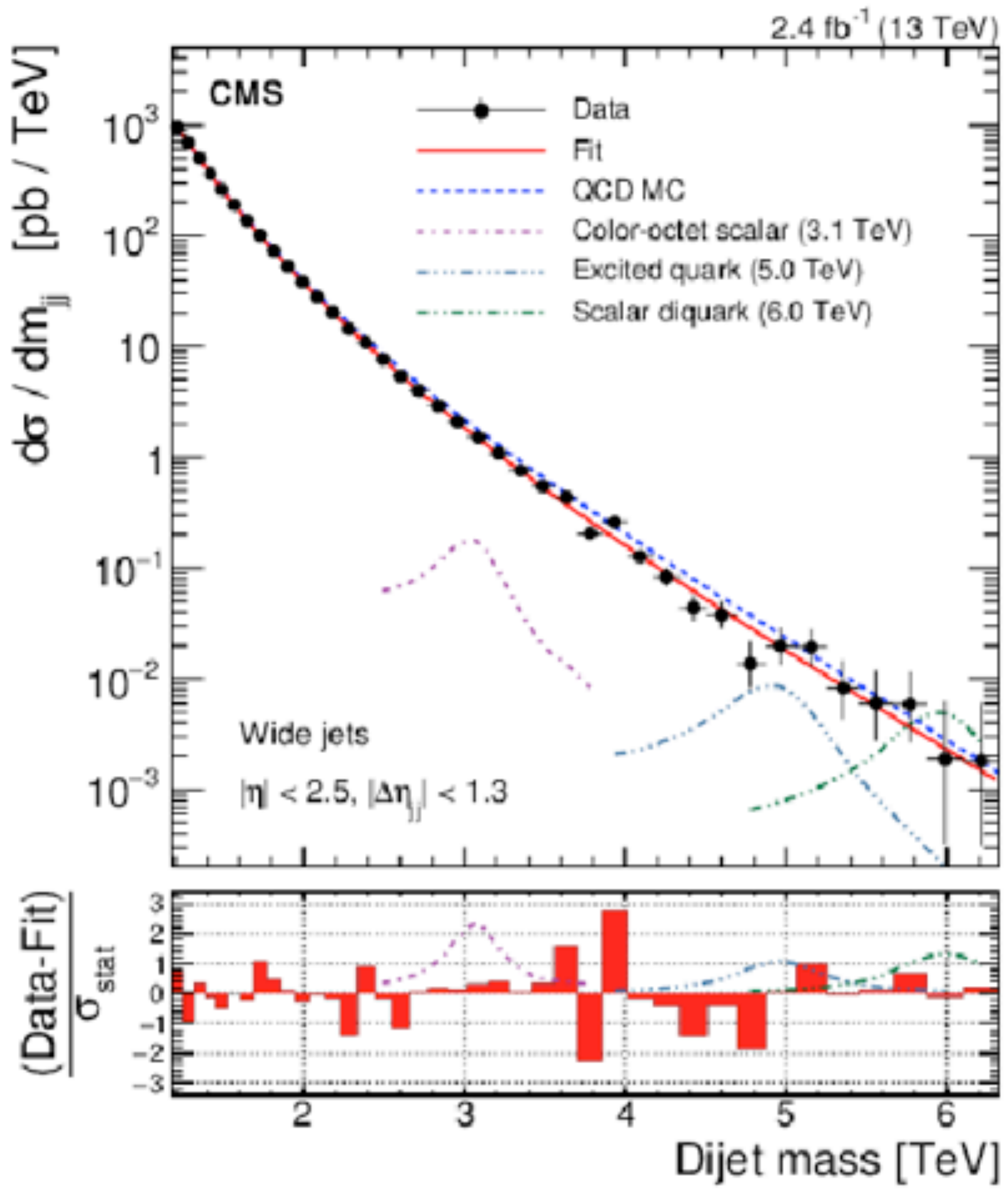
$X \to \mu\mu$



$X \to e\,e$

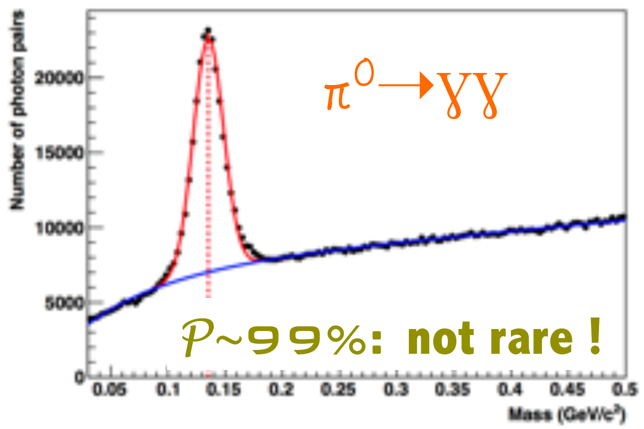


$X \to j\,j$



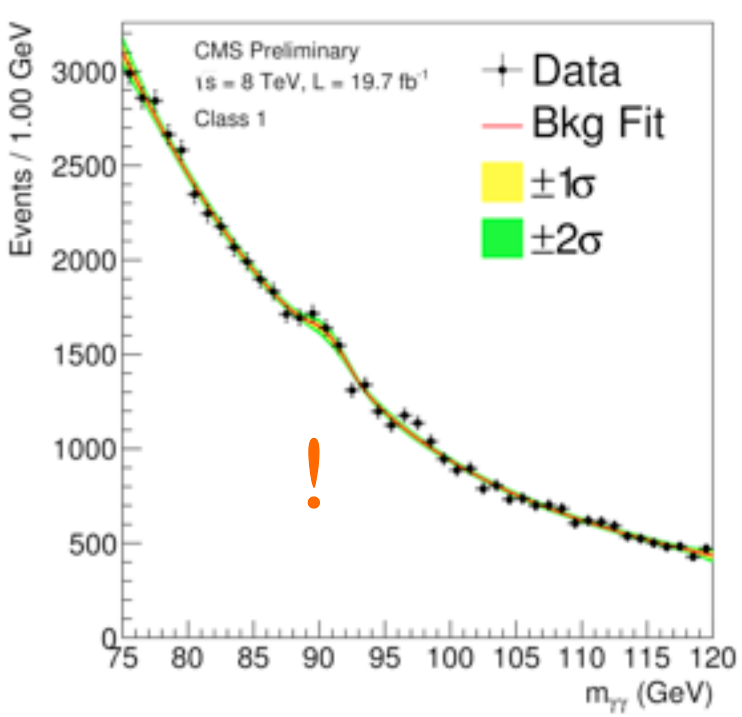
di–photon spectrum $(X \to \gamma\gamma)$

$m_{\gamma\gamma}$ <1 GeV



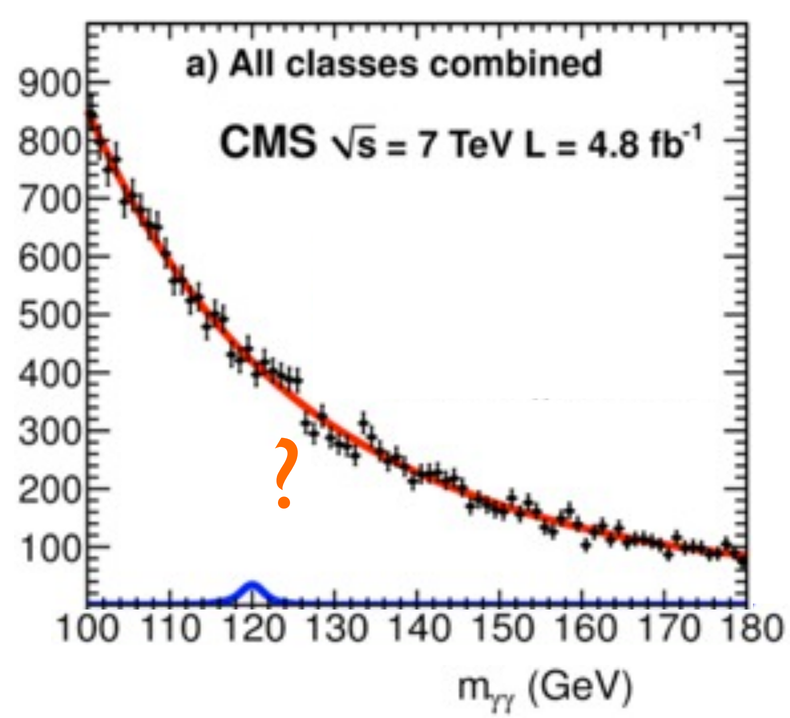
Search for bumps in the di-photon spectrum

80< $m_{\gamma\gamma}$ <110 GeV



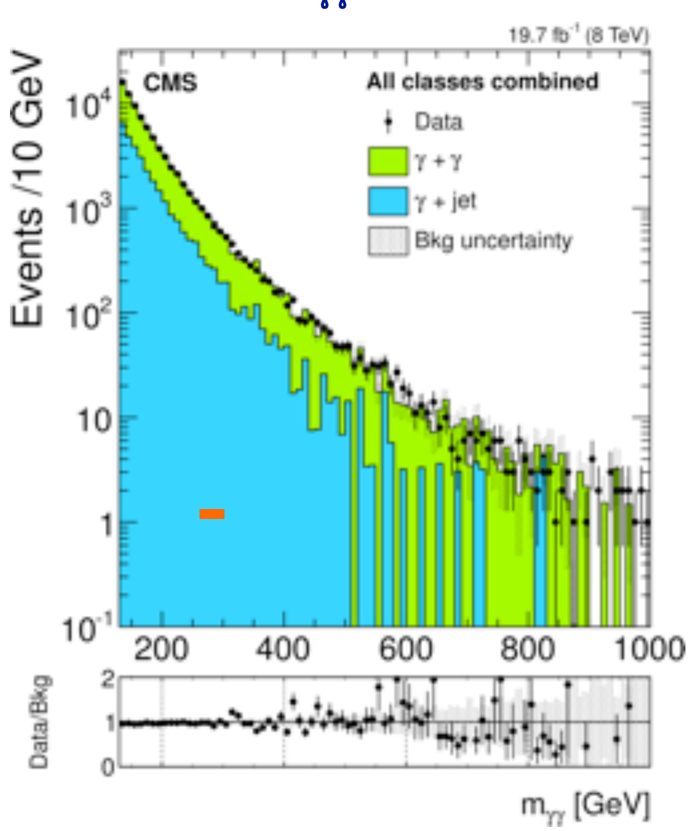
note 'double-fake' from Z→ee

110< $m_{\gamma\gamma}$ <150 GeV



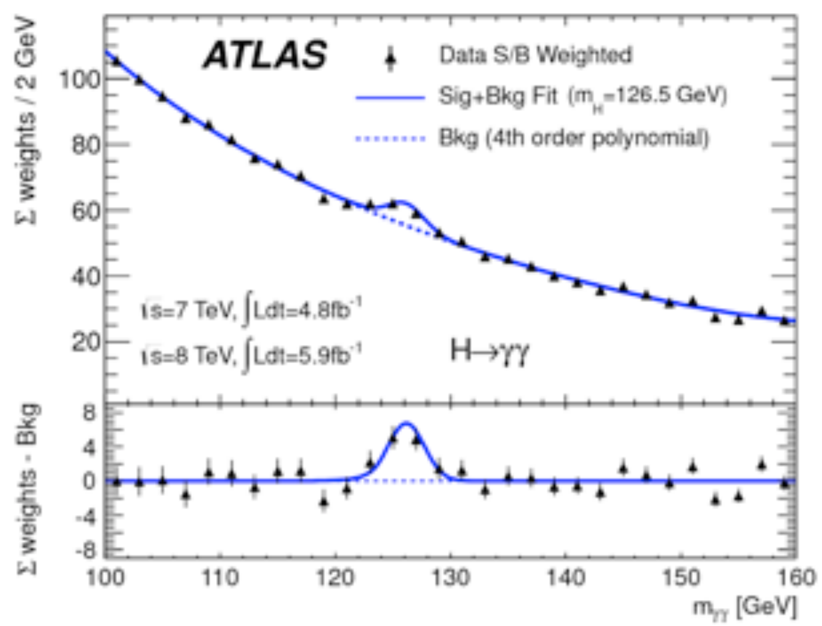
hint of a bump at m~124GeV?
significance 3.1σ(1.8σ) local (global)

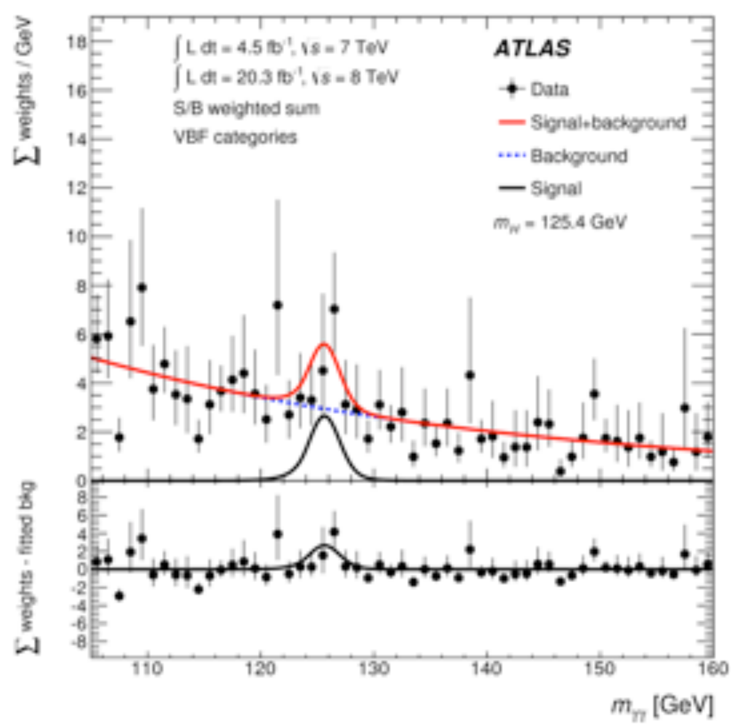
150< $m_{\gamma\gamma}$ <850 GeV

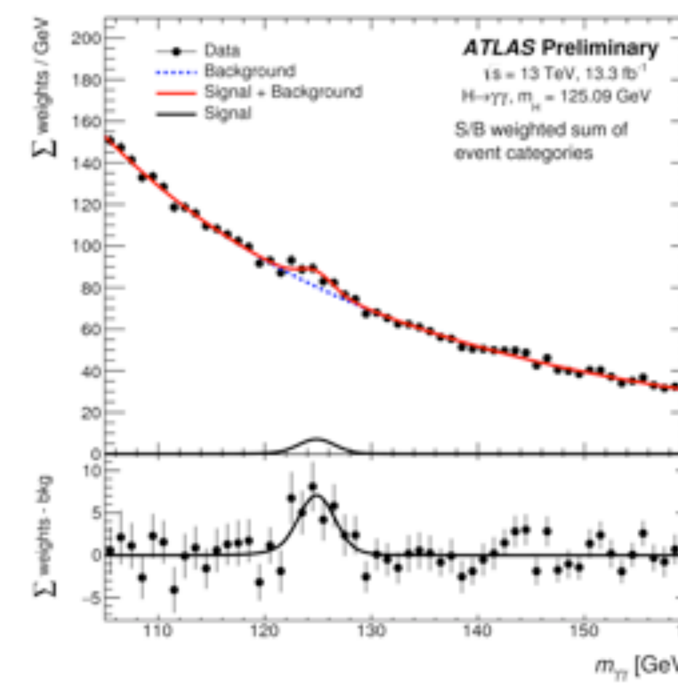


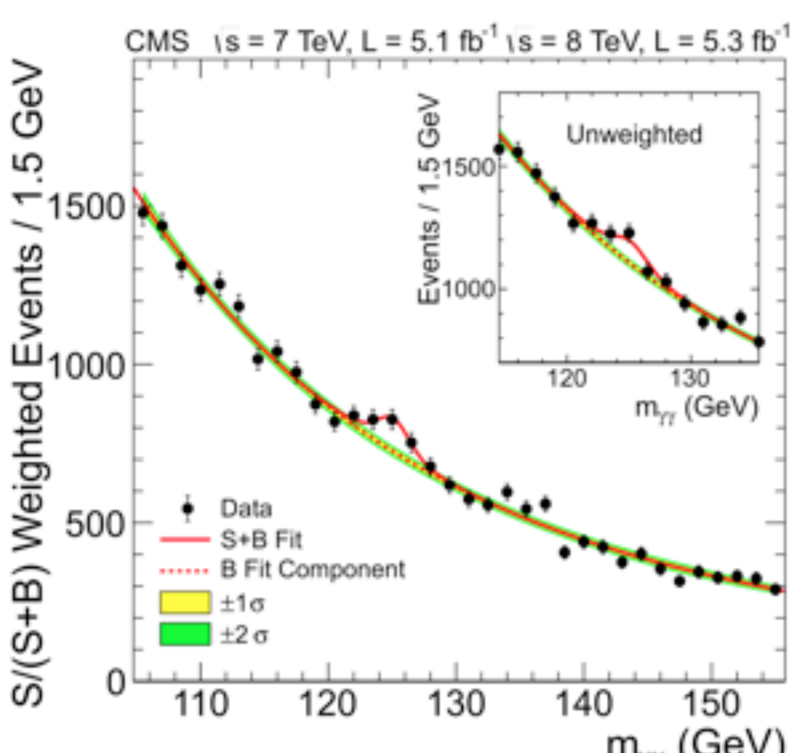
the bump at 125GeV, aka Higgs boson

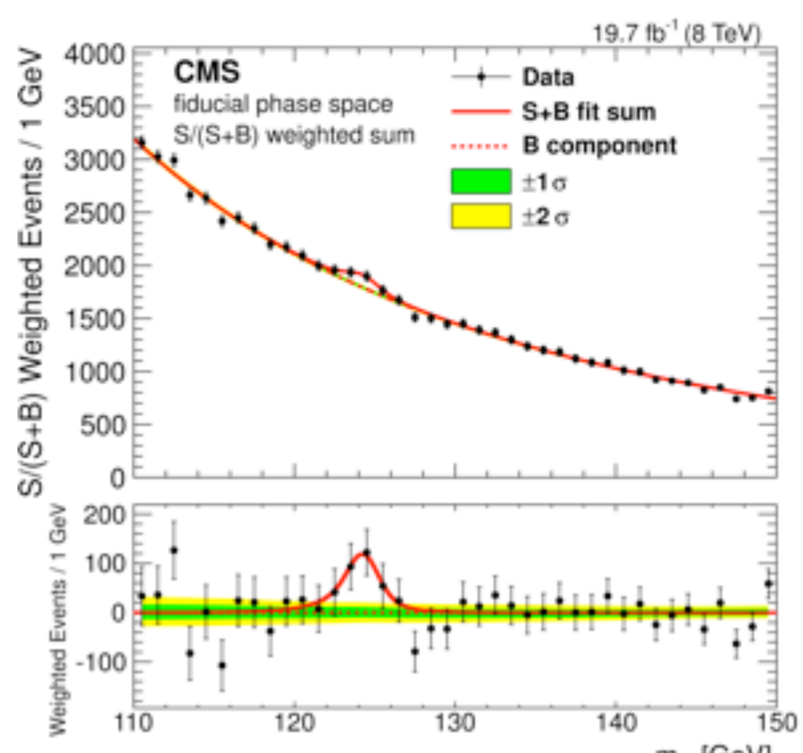
10 fb^{-1} (7/8TeV) | 20 fb^{-1} (8TeV) | 13 fb^{-1} (13TeV)

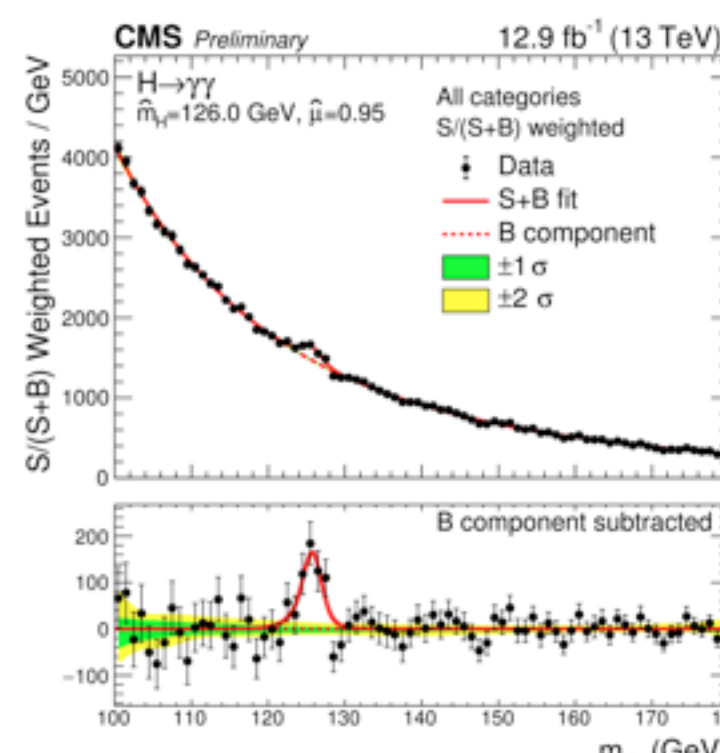






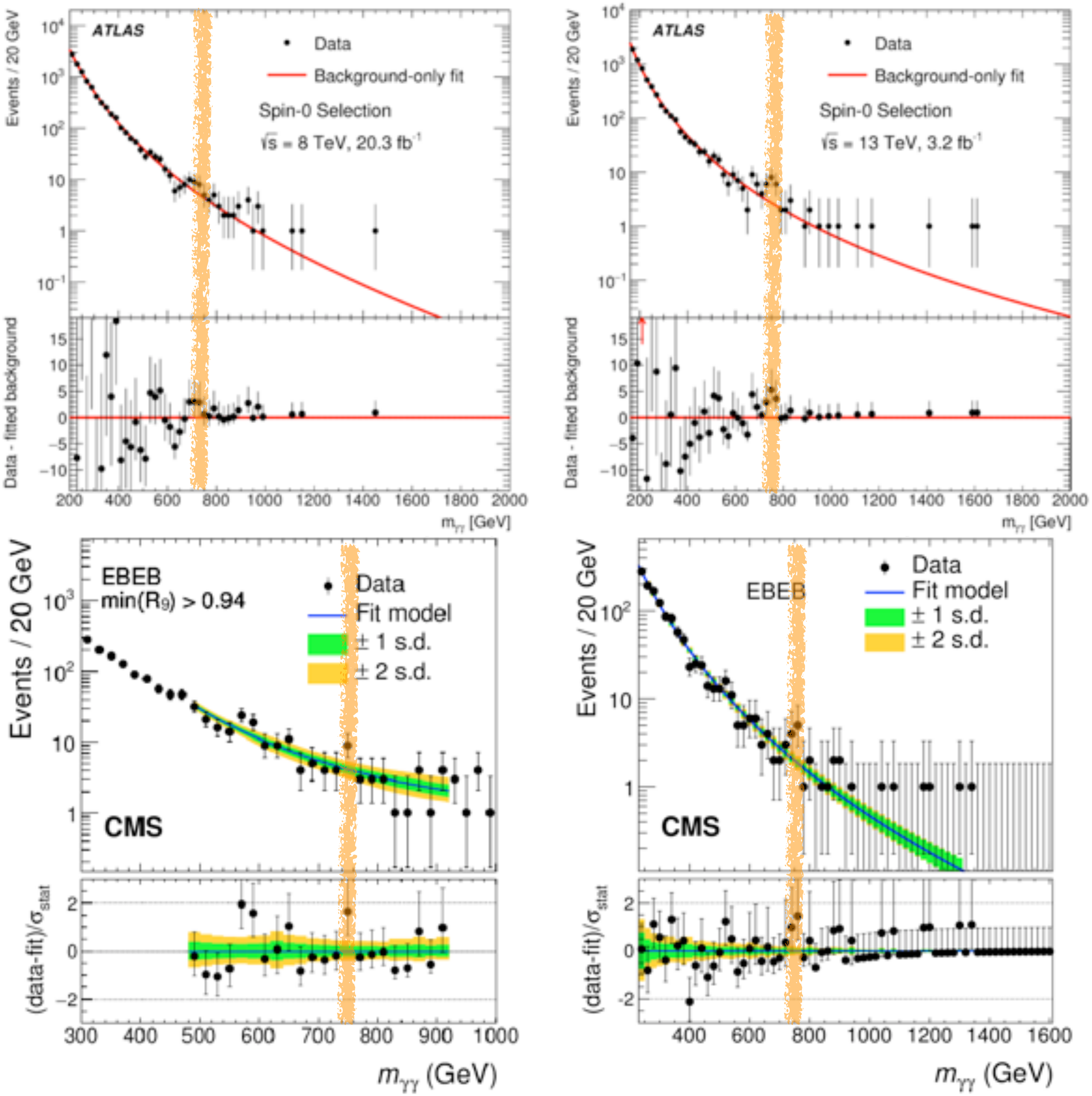






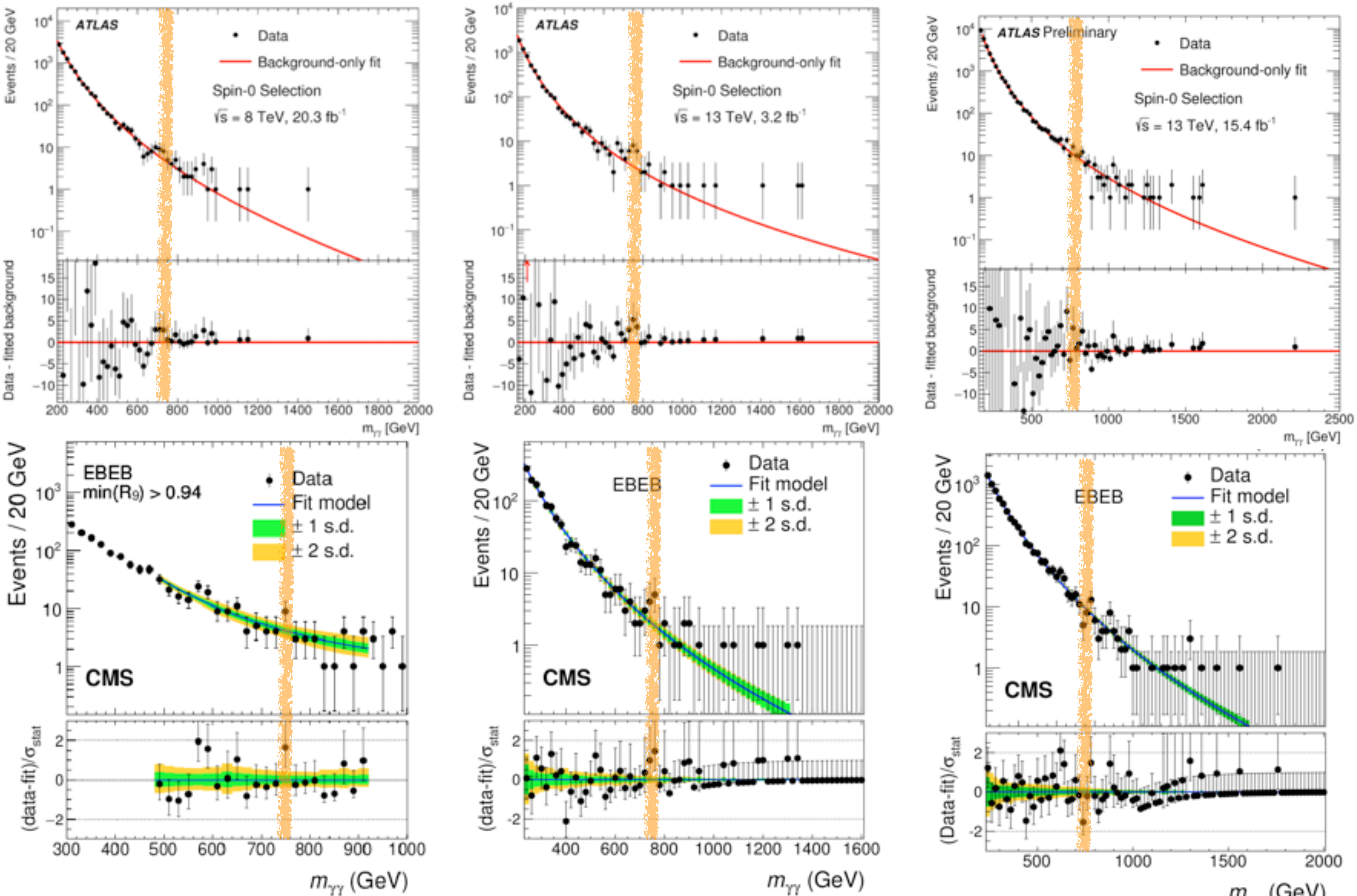
the bump at 750GeV

20 fb^{-1} (8TeV)   3 fb^{-1} (13TeV)



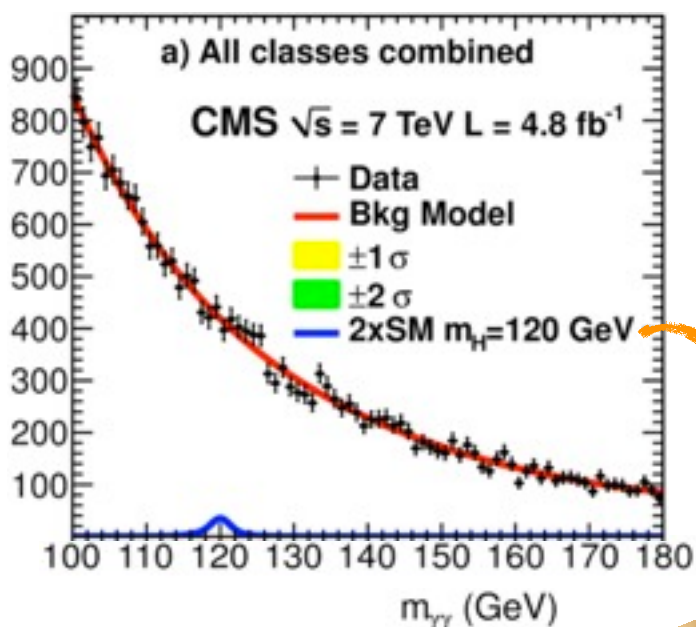
the non–bump at 750GeV

20 fb^{-1} (8TeV) 3 fb^{-1} (13TeV) 15 fb^{-1} (13TeV)



significance of a bump

@125GeV

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2016 Review of Particle Physics.
C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016).

GAUGE AND HIGGS BOSONS

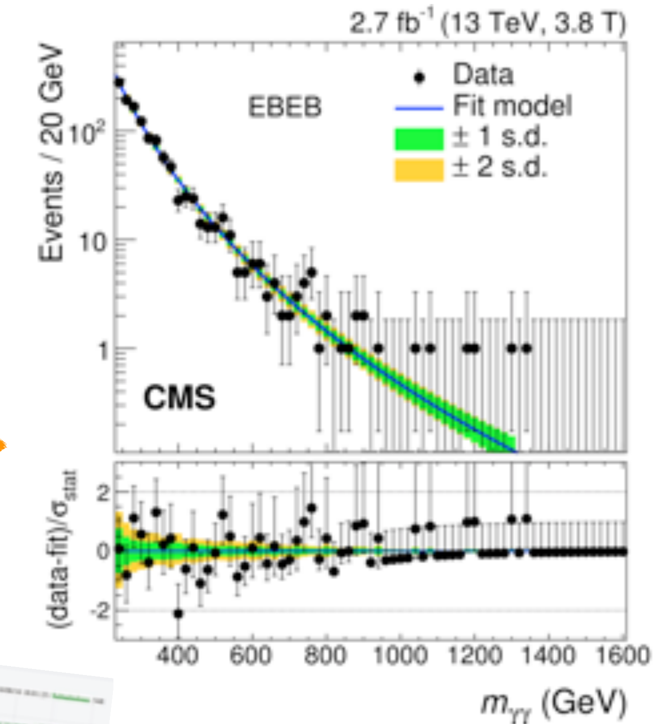
H^0 $J = 0$ INSPIRE search

In the following H^0 refers to the signal that has been discovered in the Higgs searches. Whereas the observed signal is labeled as a spin 0 particle and is called a Higgs Boson, the detailed properties of H^0 and its role in the context of electroweak symmetry breaking need to be further clarified. These issues are addressed by the measurements listed below. Concerning mass limits and cross section limits that have been obtained in the searches for neutral and charged Higgs bosons, see the sections "Searches for Neutral Higgs Bosons" and "Searches for Charged Higgs Bosons ($H^\pm$ and $H^{\pm\pm}$)", respectively.

H^0 MASS	125.09 ± 0.24 GeV
H^0 SPIN AND CP PROPERTIES	
H^0 DECAY WIDTH	< 1.7 GeV CL=95.0%

@750GeV

Hint: the next bump
(that will stay with us…)
will be revolutionary!

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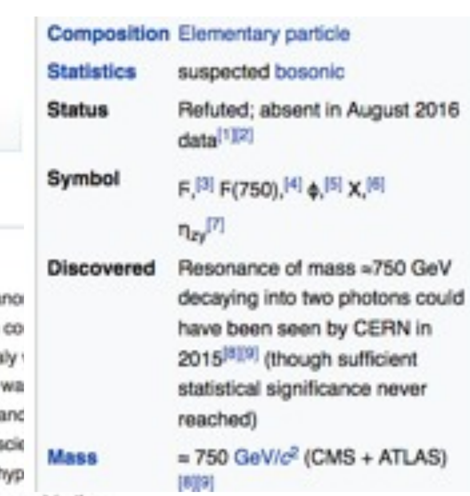
750 GeV diphoton excess

From Wikipedia, the free encyclopedia

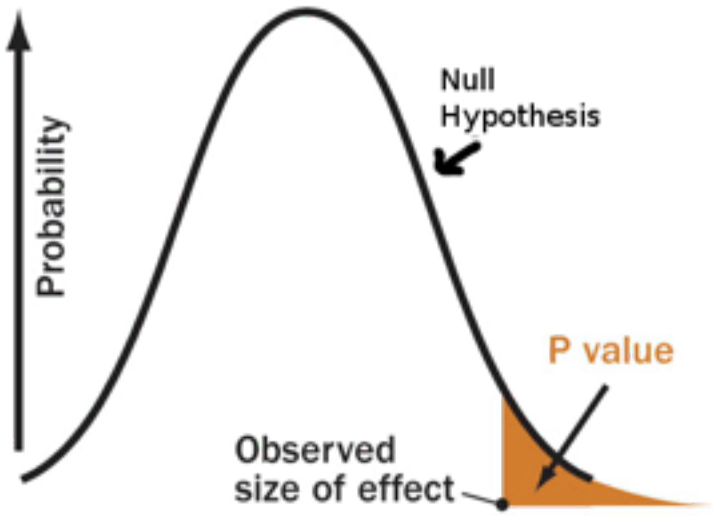
The **750 GeV diphoton excess** in particle physics was an ano[…] collected at the Large Hadron Collider (LHC) in 2015, which co[…] an indication of a new particle or resonance.[8][9] The anomaly […] data collected in 2016, suggesting that the diphoton excess wa[…] fluctuation.[1][2] In the interval between the December 2015 and […] results, the anomaly generated considerable interest in the scie[…] community, including about 500 theoretical studies.[10] The hyp[…] particle was denoted by the Greek letter Ϝ (pronounced digamma) in the scientific literature, owing to the decay channel in which the anomaly occurred.[3] The data, however, were always less than five standard deviations (sigma) different from that expected if there was no new particle, and, as such, the anomaly never reached the accepted level of statistical significance required to announce a discovery in particle physics.[11] After the August 2016 results, interest in the anomaly sank as it was considered a statistical fluctuation.[12]



Composition	Elementary particle
Statistics	suspected bosonic
Status	Refuted; absent in August 2016 data[1][2]
Symbol	Ϝ,[3] F(750),[4] ϕ,[5] X,[6] $\eta_{\gamma\gamma}$[7]
Discovered	Resonance of mass ≈750 GeV decaying into two photons could have been seen by CERN in 2015[8][9] (though sufficient statistical significance never reached)
Mass	≈ 750 GeV/c² (CMS + ATLAS)[8][9]

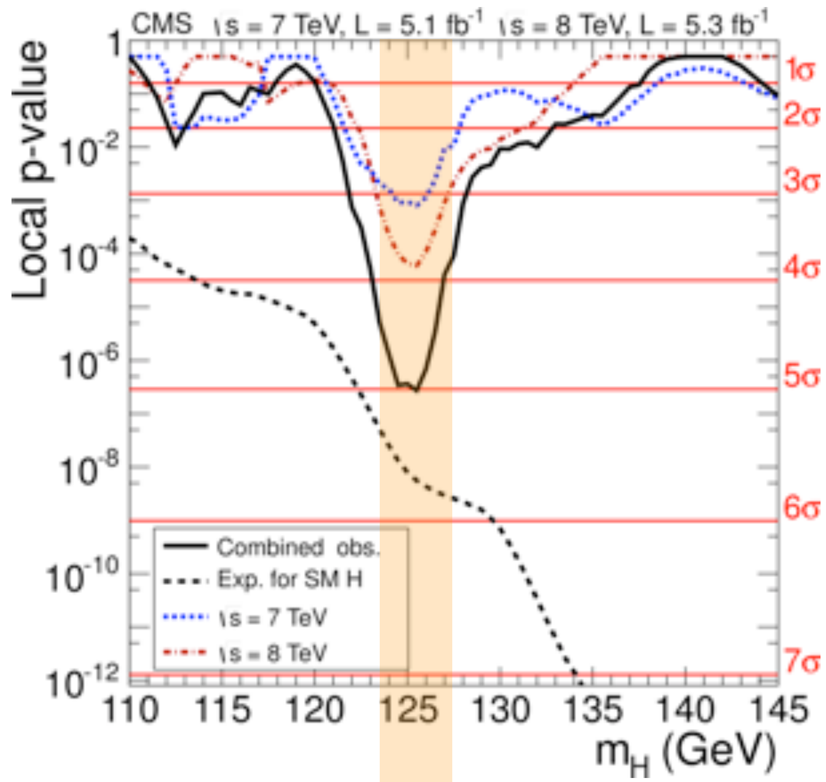
statistical significance of a bump

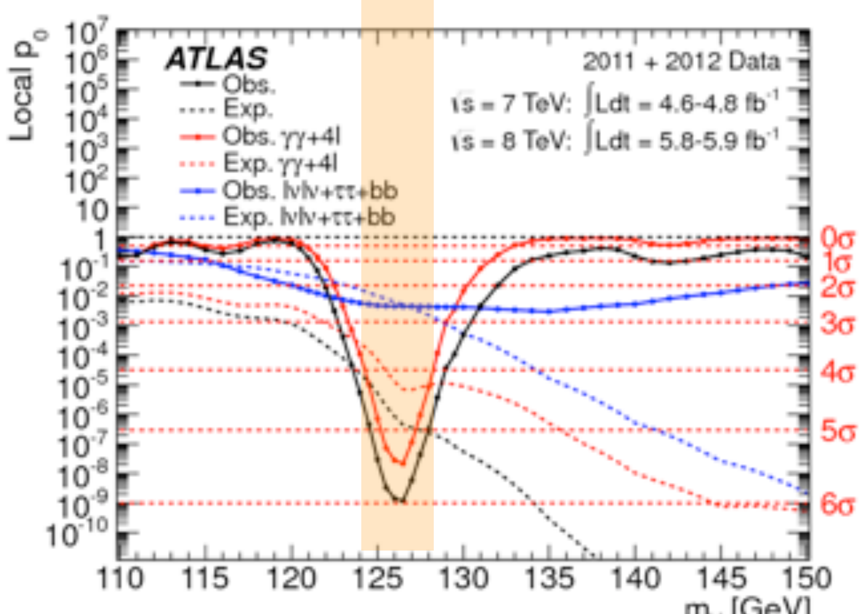
- say we have found an excess in the data
- then need to estimate likelihood that excess is due to a statistical fluctuation of the data as opposed to a genuine new physics signal
- p-value: probability of obtaining at least as extreme a result as observed in data assuming the null hypothesis is true
  - ie probability of background fluctuation to mimic the observed excess in data
- p-value is normally expressed in number of standard deviations of a normal distribution
  - 5σ ⇔ p-value: 0.0000003
  - 3σ ⇔ p-value: 0.0013



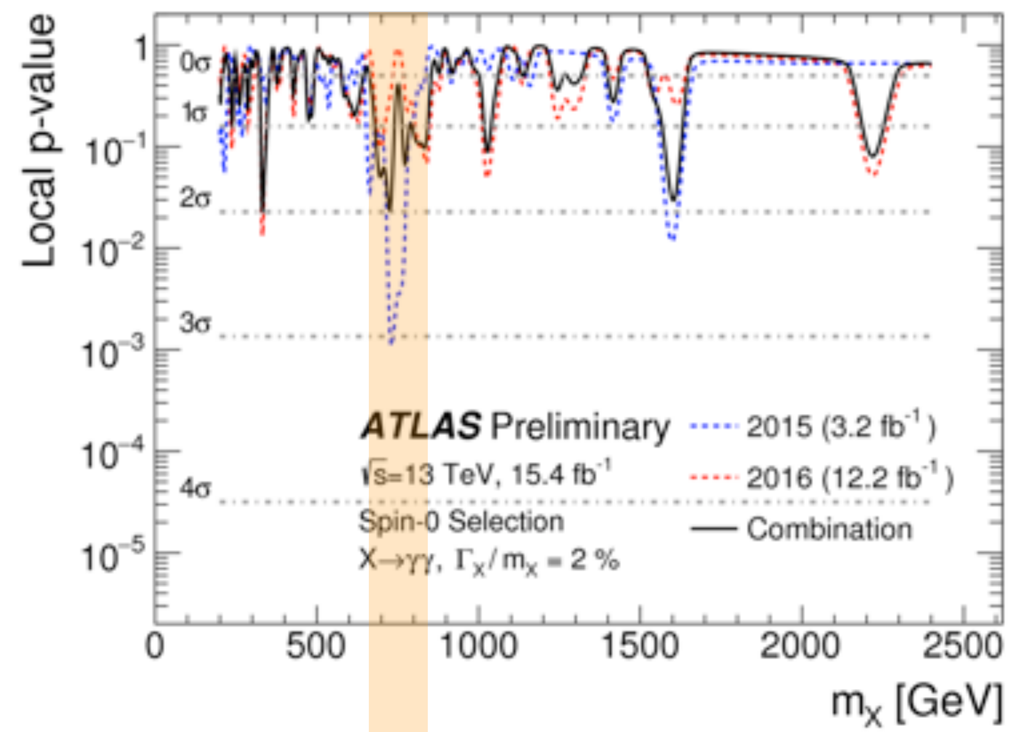
bumps' p-values

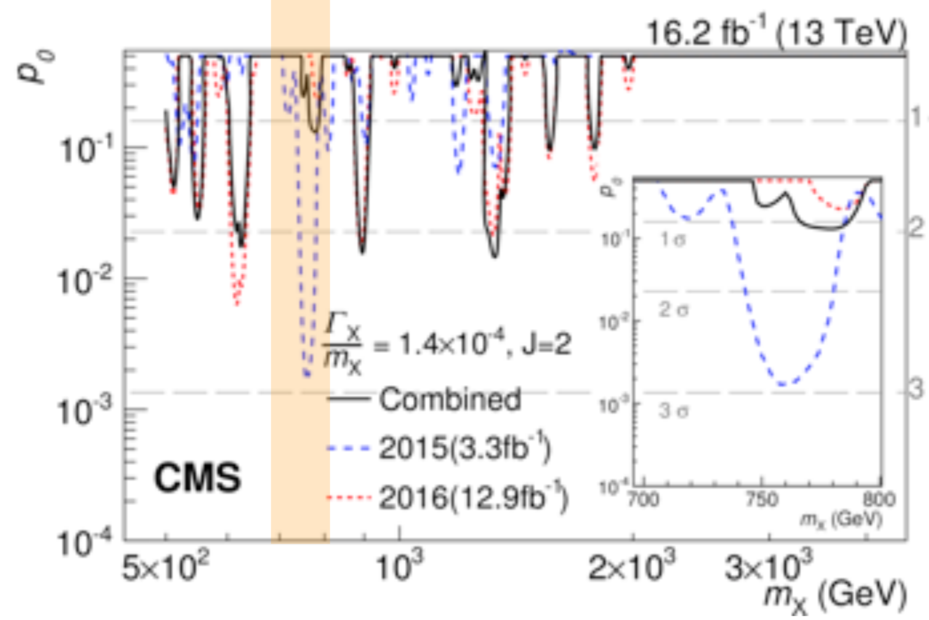
@125GeV





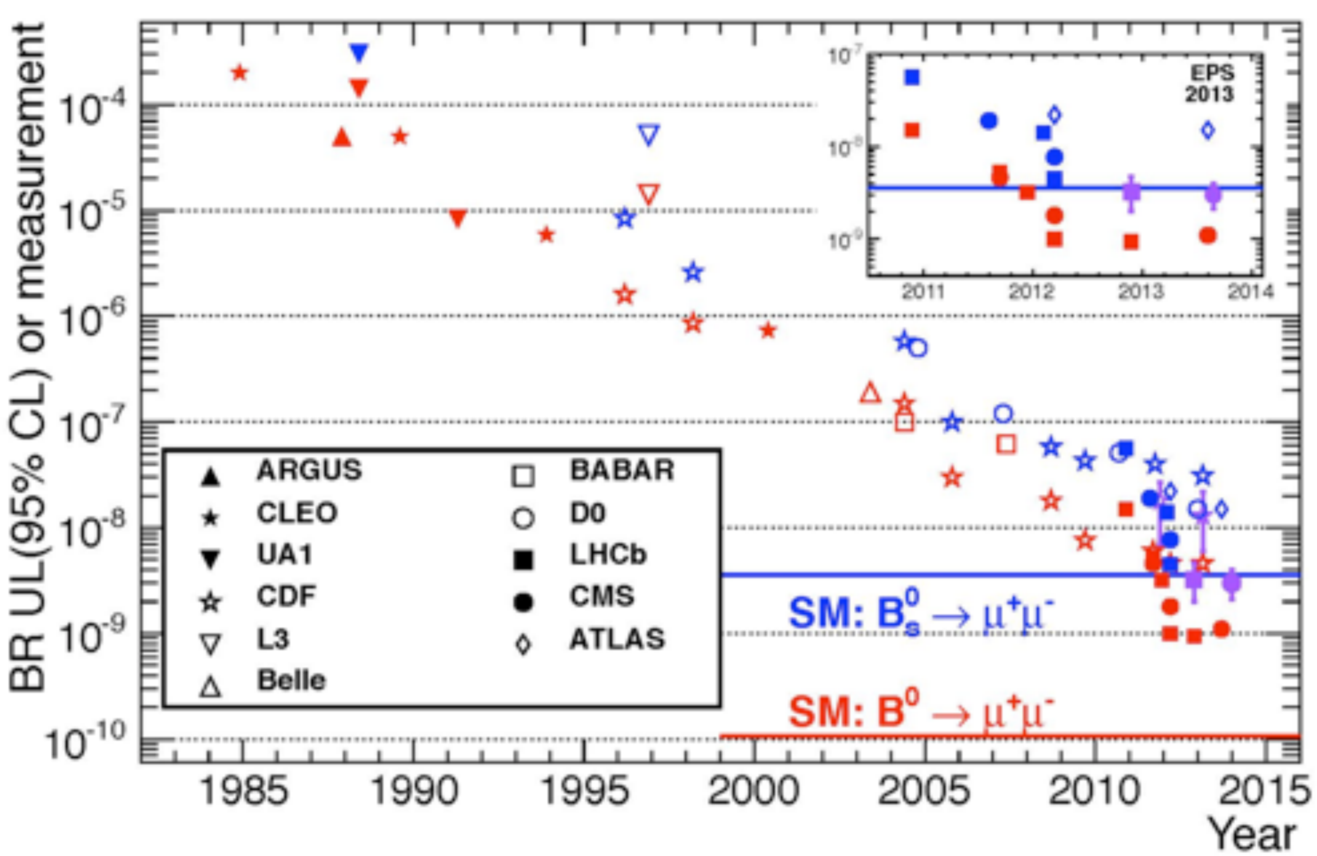
@750GeV

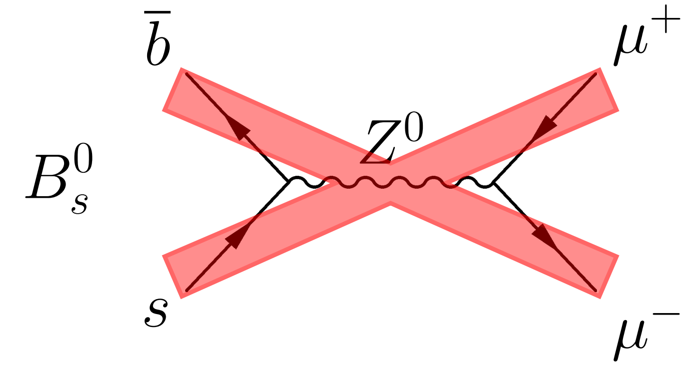


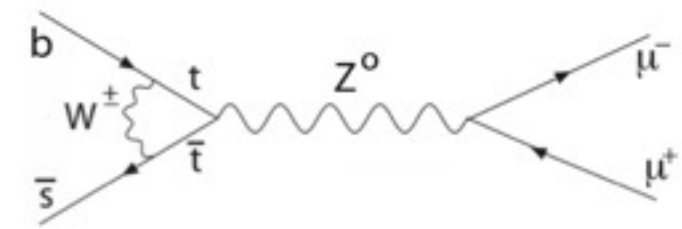


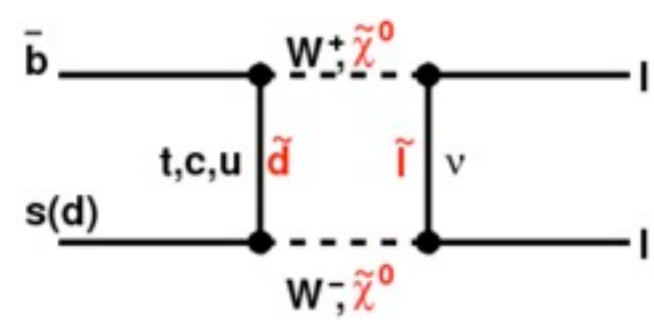
searching for an *ultra-rare* decay: B→μμ

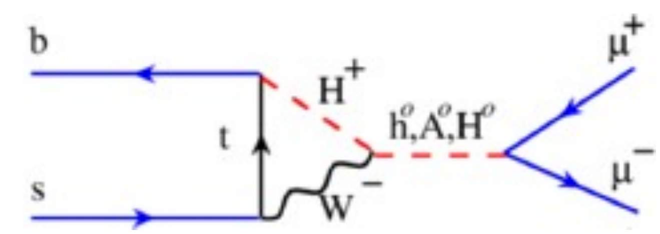
- the decay $B_s \to \mu\mu$ is very suppressed in SM, O (10^{-9})
- it can be sizably enhanced by various BSM models
- search has been pursued for 3 decades

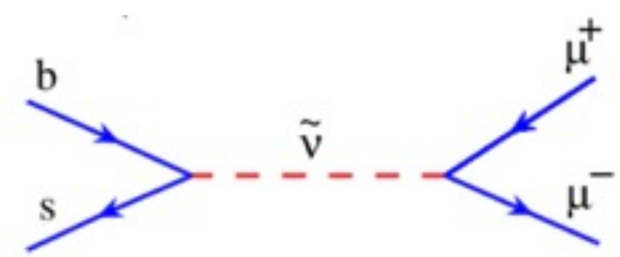






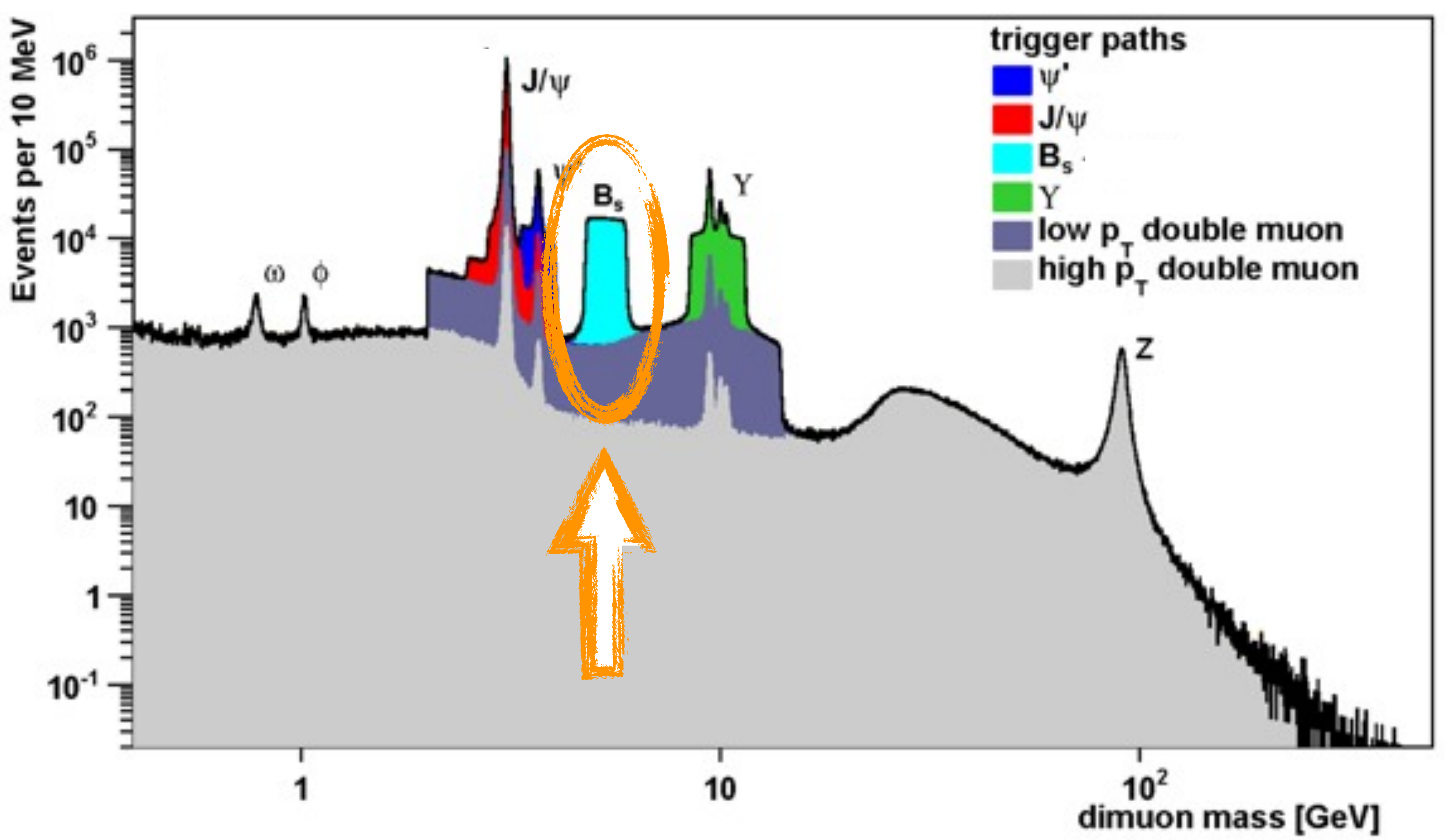






searching for an *ultra-rare* decay: B→μμ

1. ONLINE SELECTION (TRIGGER)



Dimuon Trigger

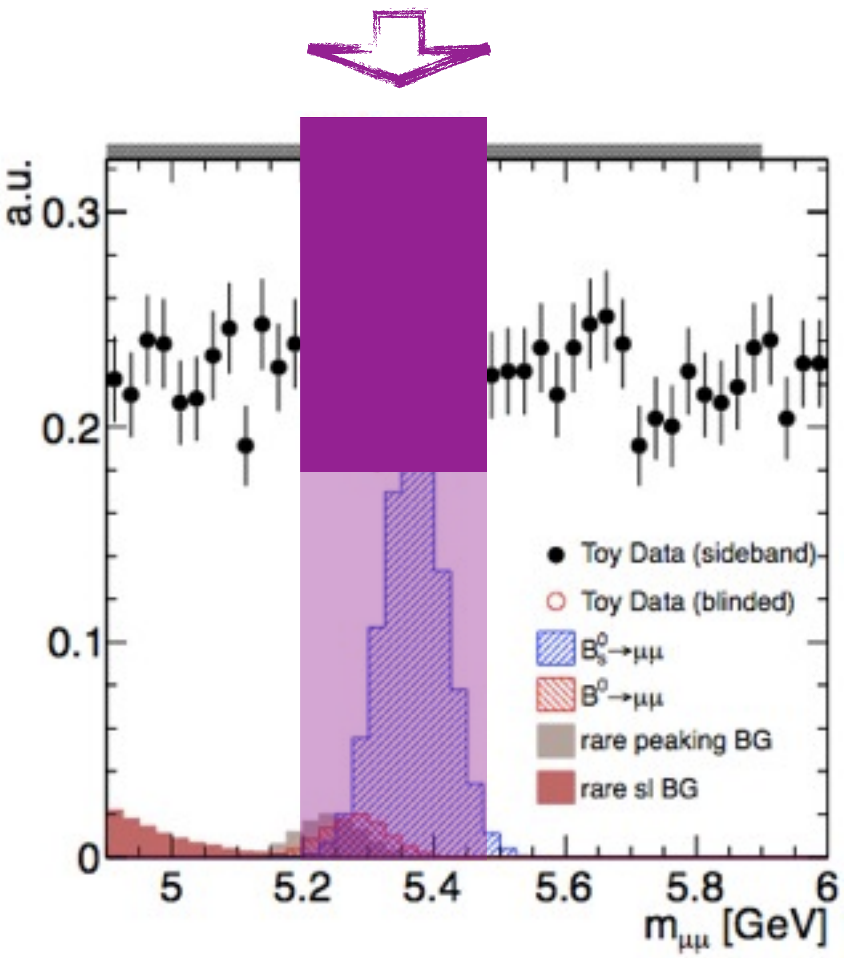
- L1 Hardware Trigger
  - p_T>3 GeV (few kHz)
- HLT Full tracking and vertexing
- HLT $B_s \to \mu\mu$
  - Leading and sub-leading μ p_T>3,4 (4,4) GeV $|\eta_{\mu\mu}|$<1.8 (1.8<$|\eta_{\mu\mu}|$<2.2)
  - p_T (μμ)>5 (4.8-6) GeV
  - 4.8 <m(μμ)< 6.0 GeV
  - $P(\chi^2/dof)$ >0.5%

searching for an ultra-rare decay: B→μμ

1. ONLINE SELECTION (TRIGGER)

2. BLIND THE DATA (AVOID BIAS)

SIGNAL REGION BLINDED



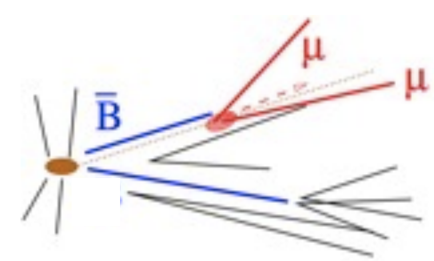
analysis procedure and event selection developed without inspecting the data in region where signal is expected

"box opening" only later, at final analysis stages

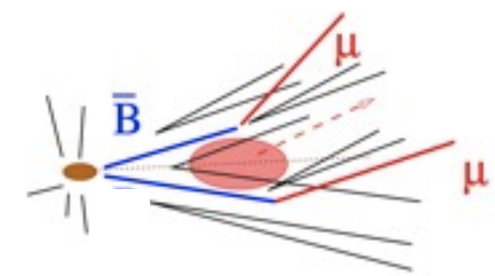
searching for an *ultra-rare* decay: B→μμ

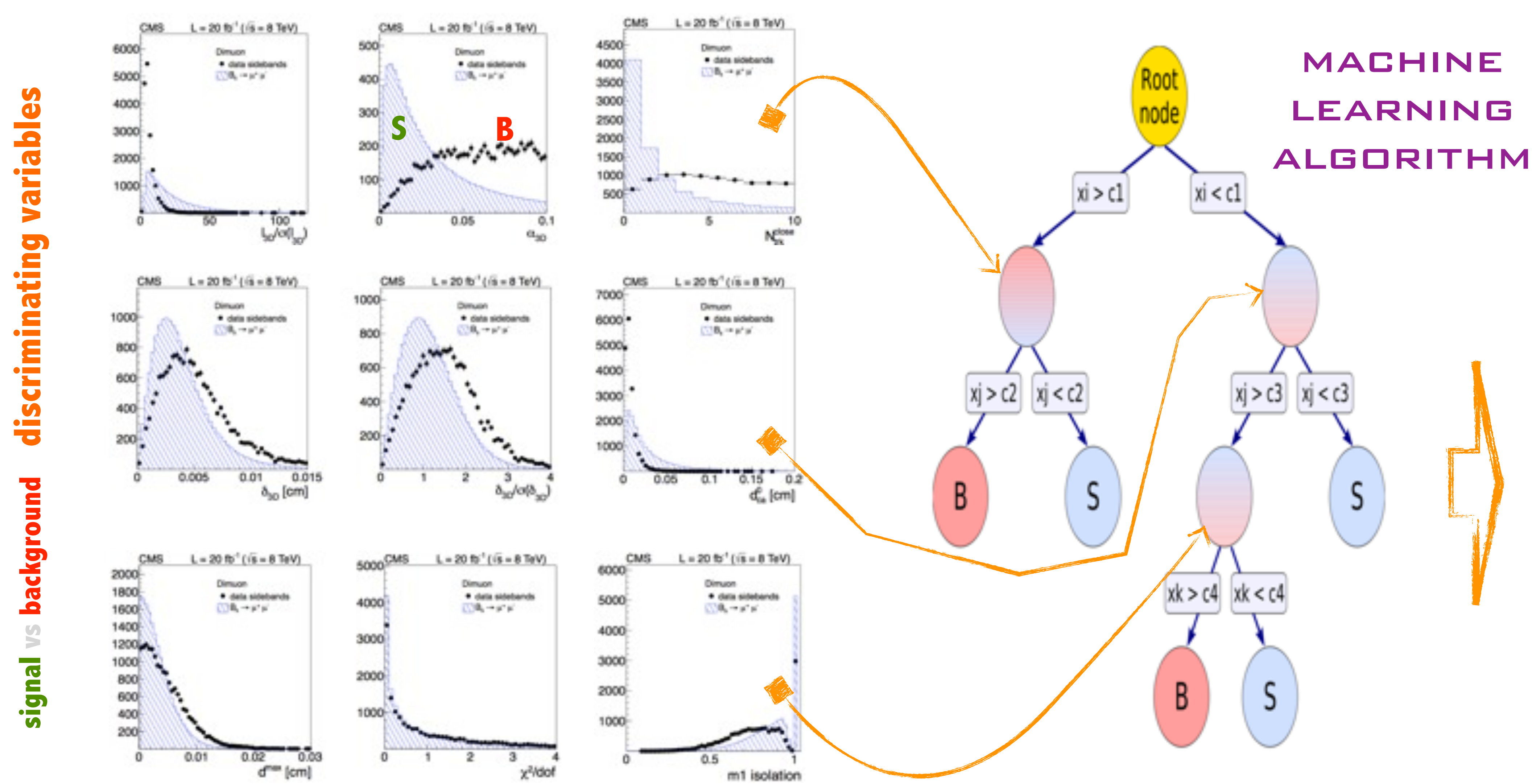
1. ONLINE SELECTION (TRIGGER)
2. BLIND THE DATA (AVOID BIAS)
3. MULTIVARIATE SELECTION

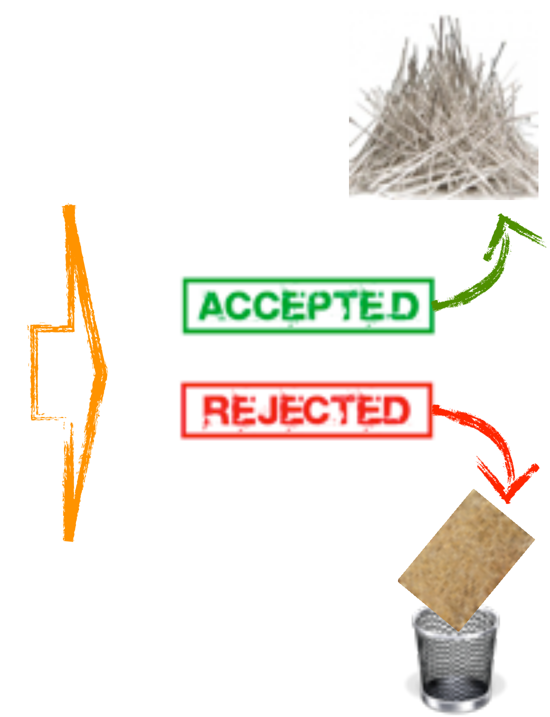
signal



background



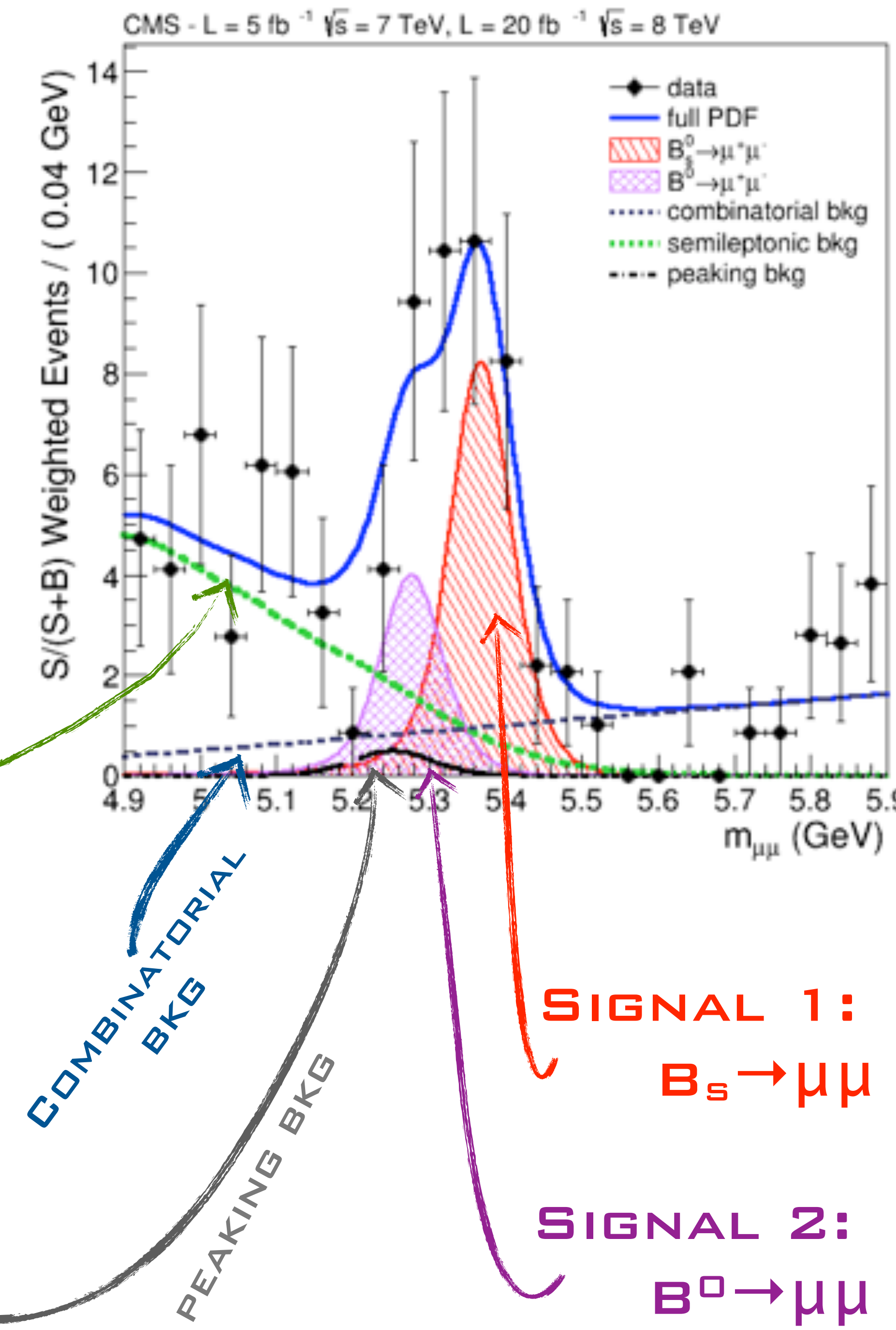


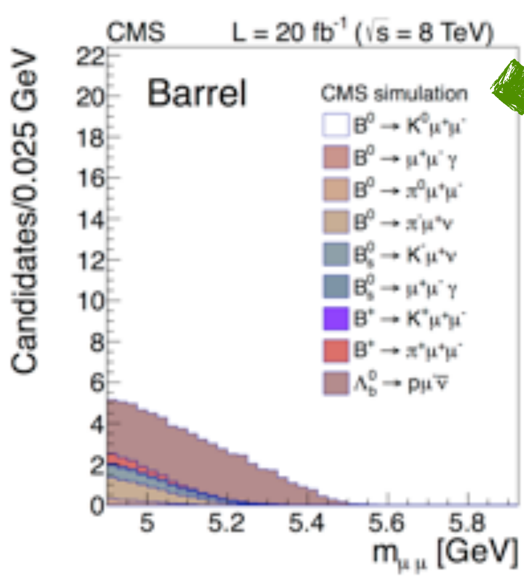


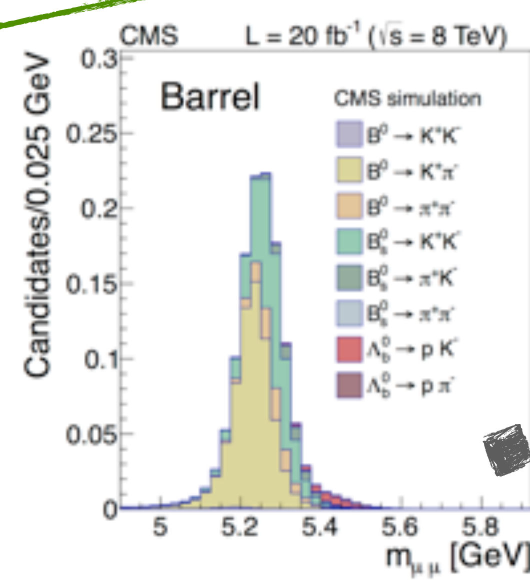
searching for an ultra-rare decay: B→μμ

1. ONLINE SELECTION (TRIGGER)
2. BLIND THE DATA (AVOID BIAS)
3. MULTIVARIATE SELECTION
4. **FIT THE DATA (LIKELIHOOD)**

Fit the data accounting for the various signal and background components ⇨

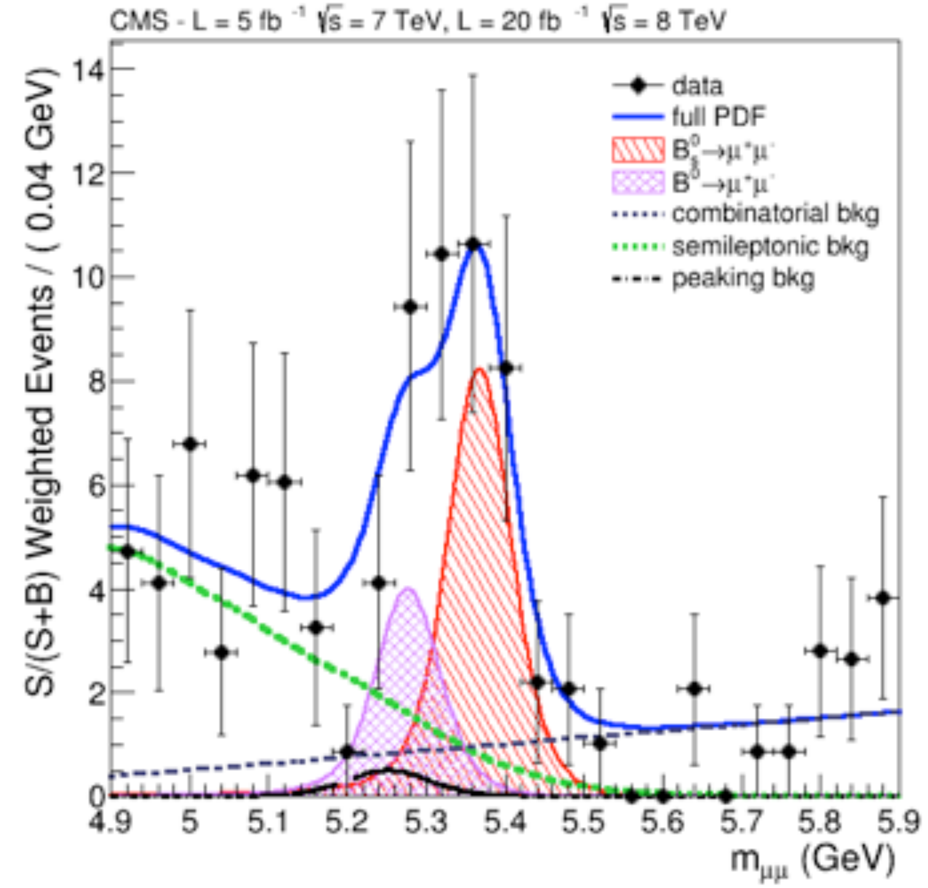




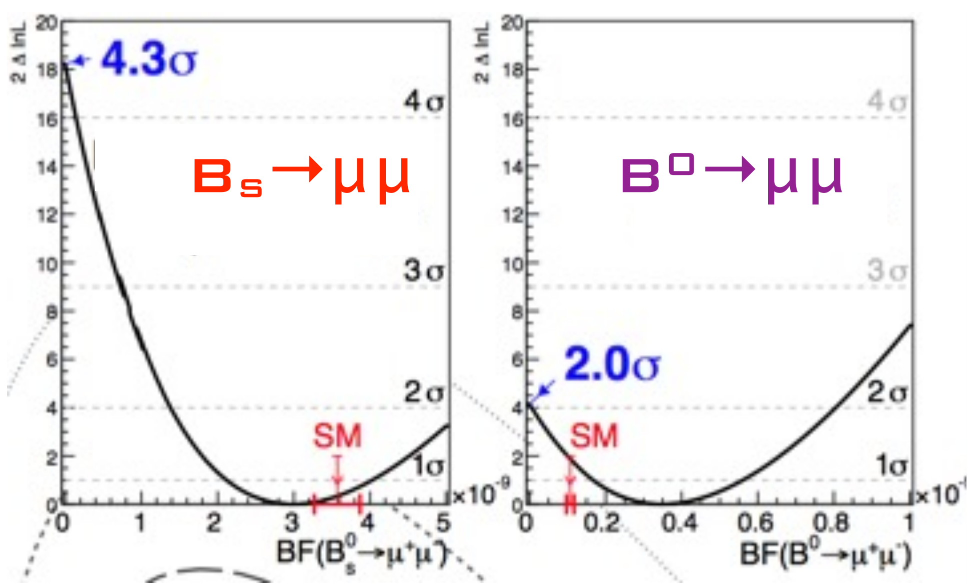


searching for an *ultra-rare* decay: $B \to \mu\mu$

1. ONLINE SELECTION (TRIGGER)
2. BLIND THE DATA (AVOID BIAS)
3. MULTIVARIATE SELECTION
4. FIT THE DATA (LIKELIHOOD)
5. **STATISTICAL SIGNIFICANCE**

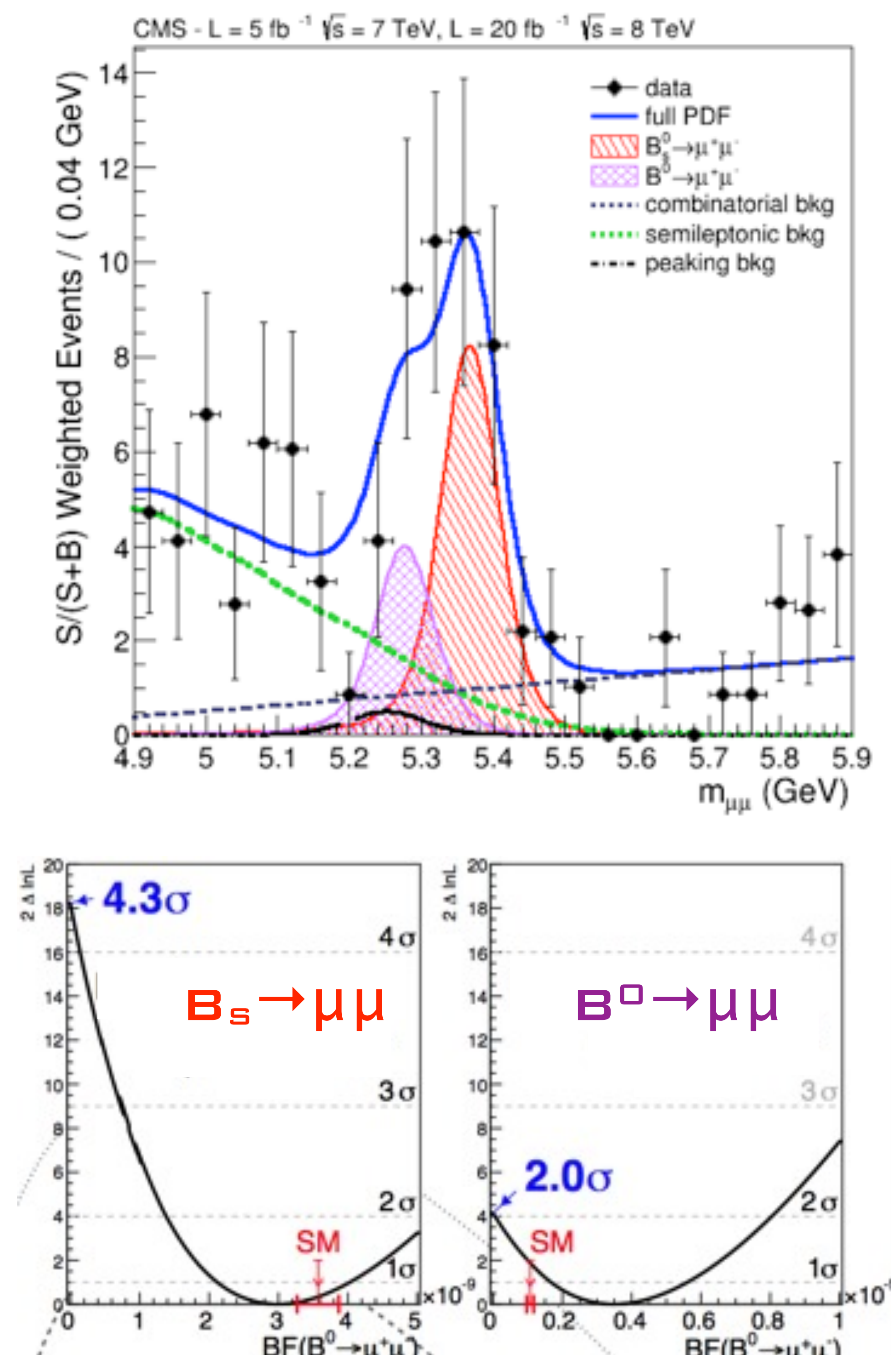


is the observed excess a genuine signal,
or just a fluctuation of the background?



searching for an *ultra-rare* decay: B→μμ

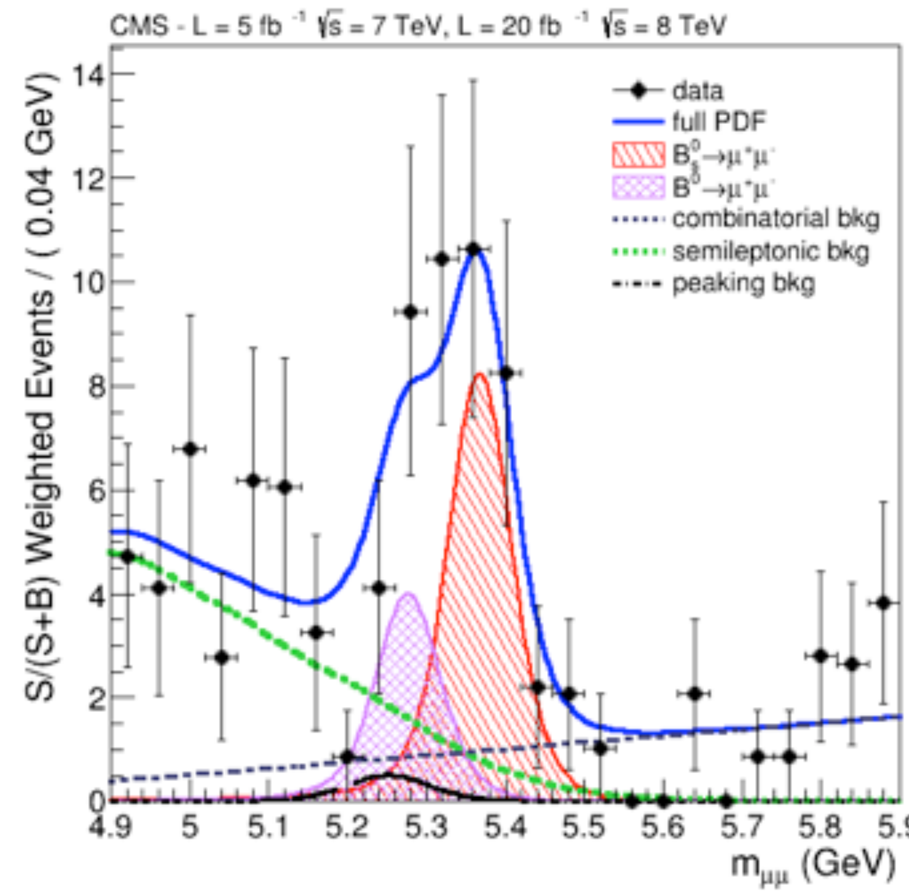
1. ONLINE SELECTION (TRIGGER)
2. BLIND THE DATA (AVOID BIAS)
3. MULTIVARIATE SELECTION
4. FIT THE DATA (LIKELIHOOD)
5. STATISTICAL SIGNIFICANCE
6. **EXTRACT MEASUREMENT**



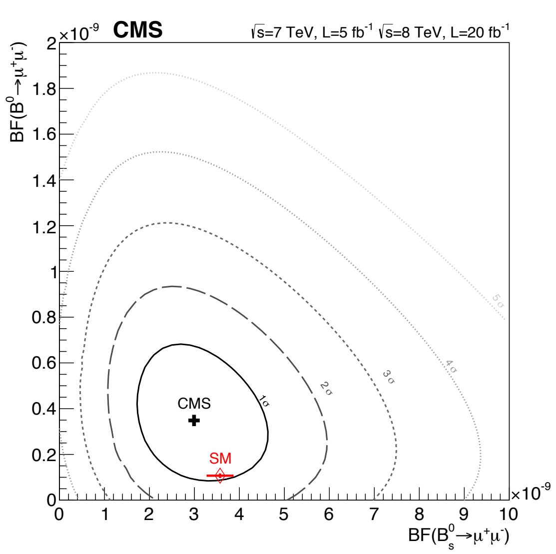
$$BR(B_s \to \mu\mu) = \left(3.0^{+0.9}_{-0.8}\ (\text{stat})^{+0.6}_{-0.4}\ (\text{syst})\right) \times 10^{-9}$$

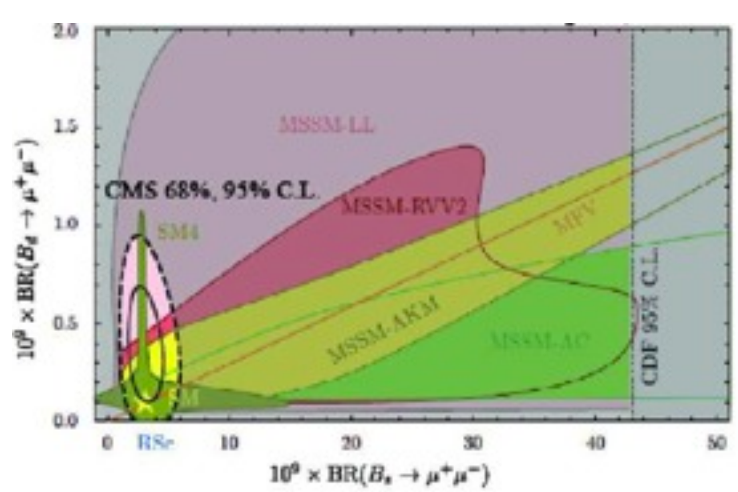
searching for an ultra-rare decay: B→μμ

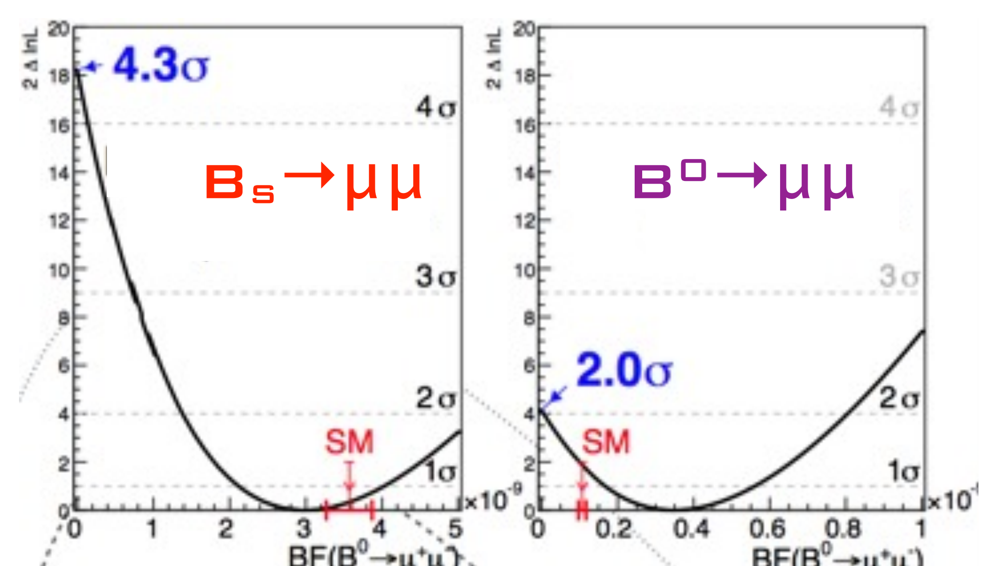
1. Online selection (trigger)
2. Blind the data (avoid bias)
3. Multivariate selection
4. Fit the data (likelihood)
5. Statistical significance
6. Extract measurement
7. **Compare to theory**



the SM... and Beyond







$$BR(B_s\to\mu\mu)=\left(3.0^{+0.9}_{-0.8}\ (\text{stat})^{+0.6}_{-0.4}\ (\text{syst})\right)\times10^{-9}$$

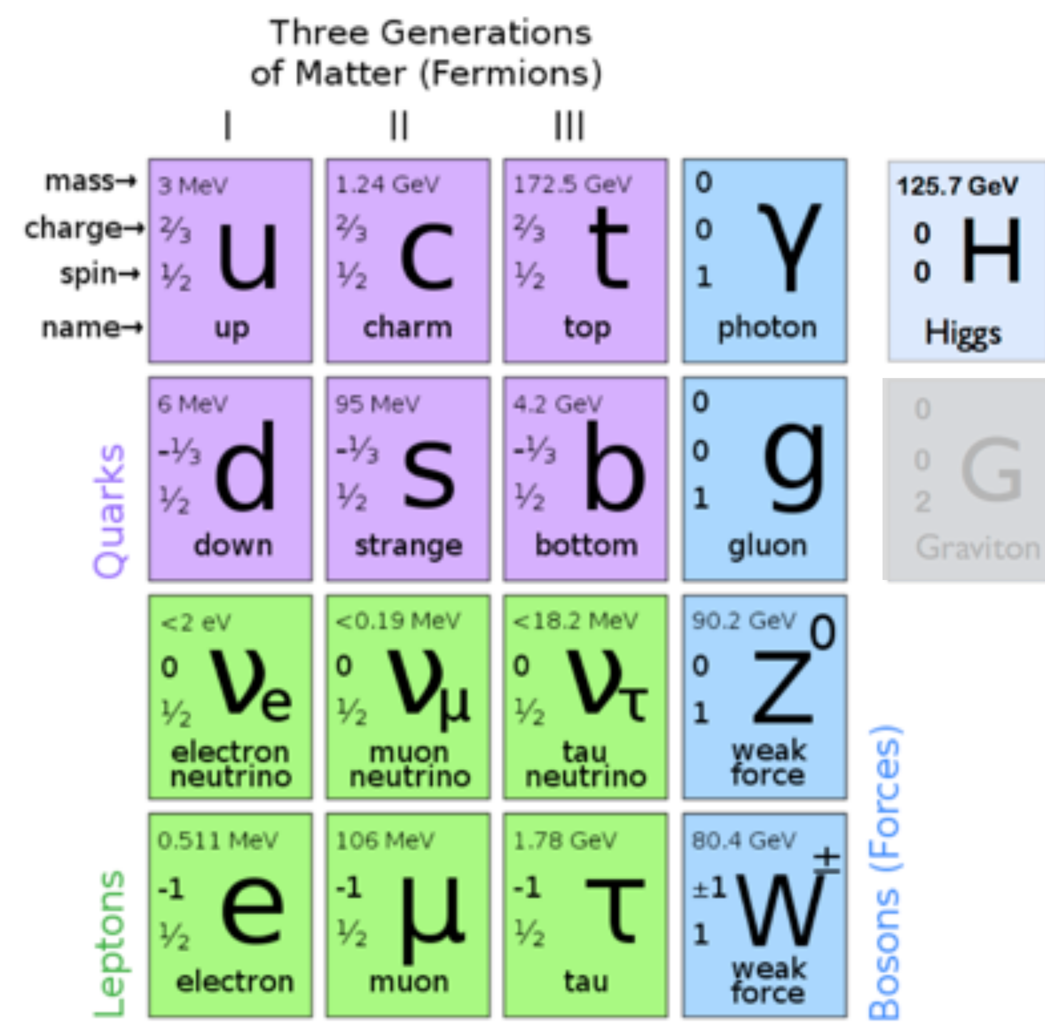
summary

- LHC is and will continue to be the world's frontier accelerator
- many outstanding results during Run1, incl. two major discoveries
  - observation of the Higgs boson and of the $B_s \to \mu\mu$ rare decay
  - LIP had direct involvement in both
- rare processes provide a portal to New Physics, beyond the SM
- the search is ongoing! You're very much welcome to join!

Thank You

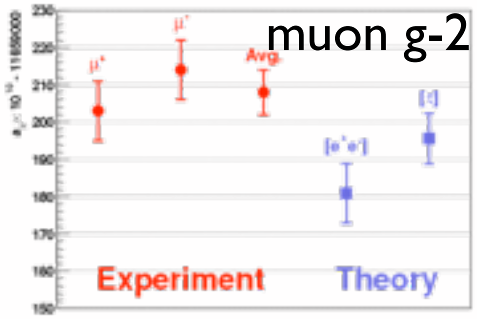
the Standard Model

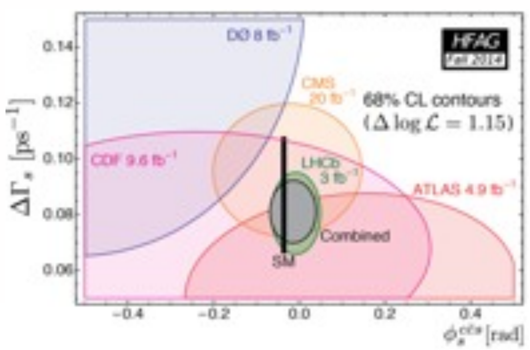
- fully consistent and complete description of the strong, electromagnetic, and weak interactions
- LHC's discovery of the Higgs by ATLAS & CMS completes the SM's elementary particle list
- in short
  - matter built of spin 1/2 particles that exchange 3 kinds of spin 1 particles corresponding to 3 types of (gauge) interactions
  - matter fermions and weak bosons have mass (via Higgs mechanism)

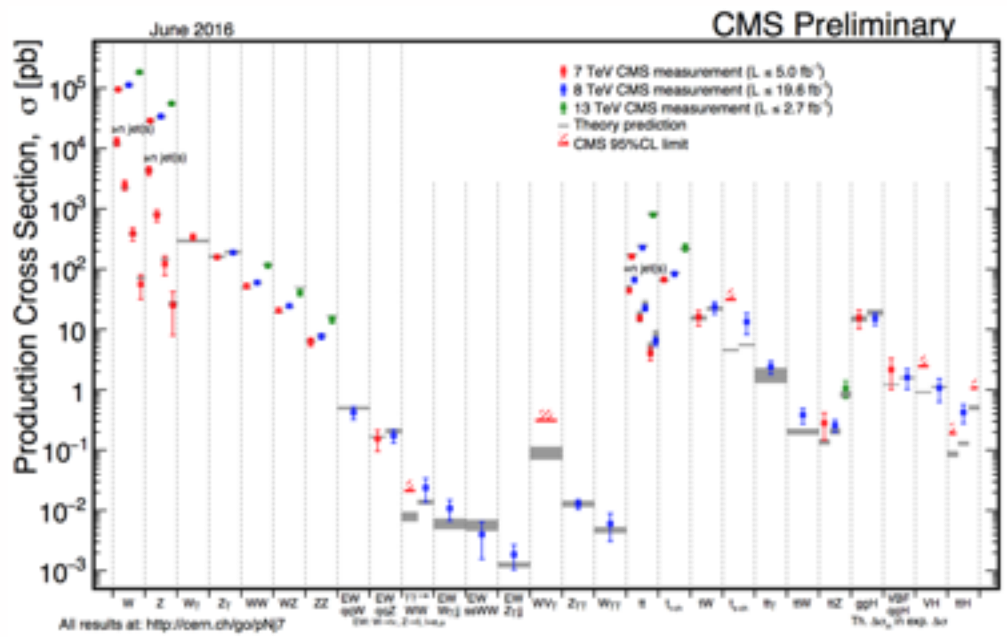


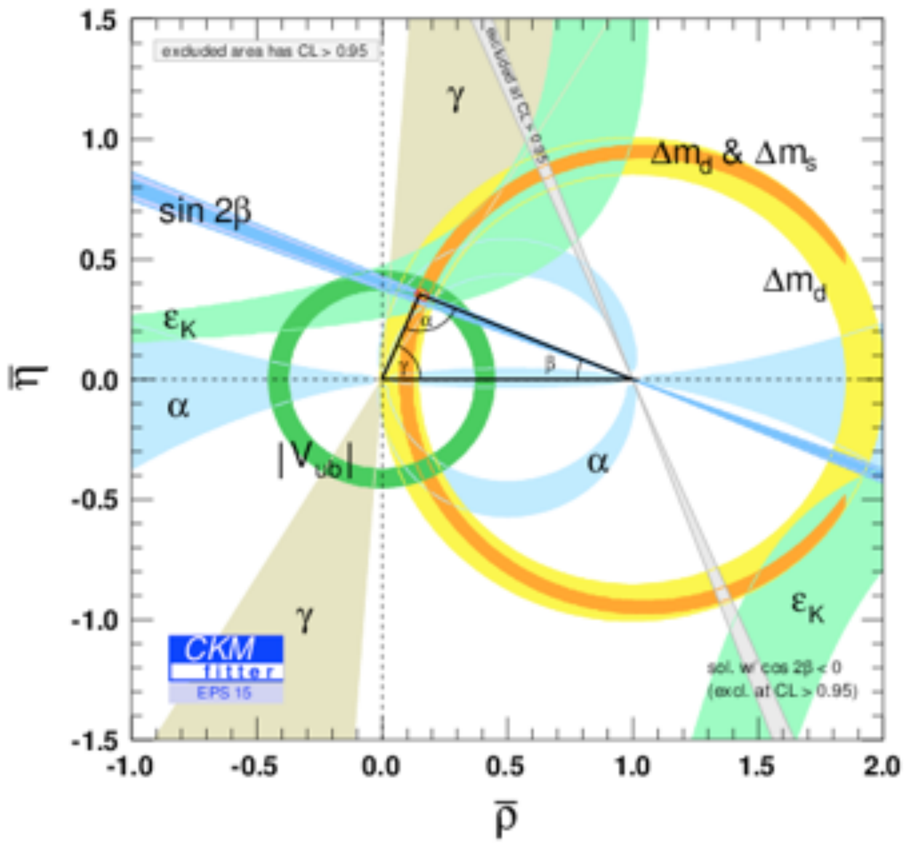
- there appears to be 3 generations of matter particles; there appears to be 3 macroscopic space dimensions
- (extra) gravitation presumably mediated by spin 2 gravitons, and extremely weak

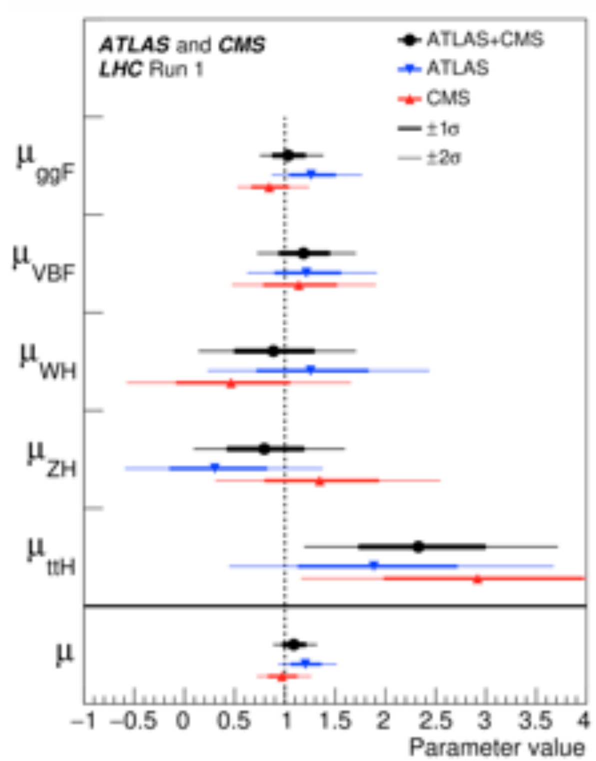
SM's experimental scrutiny

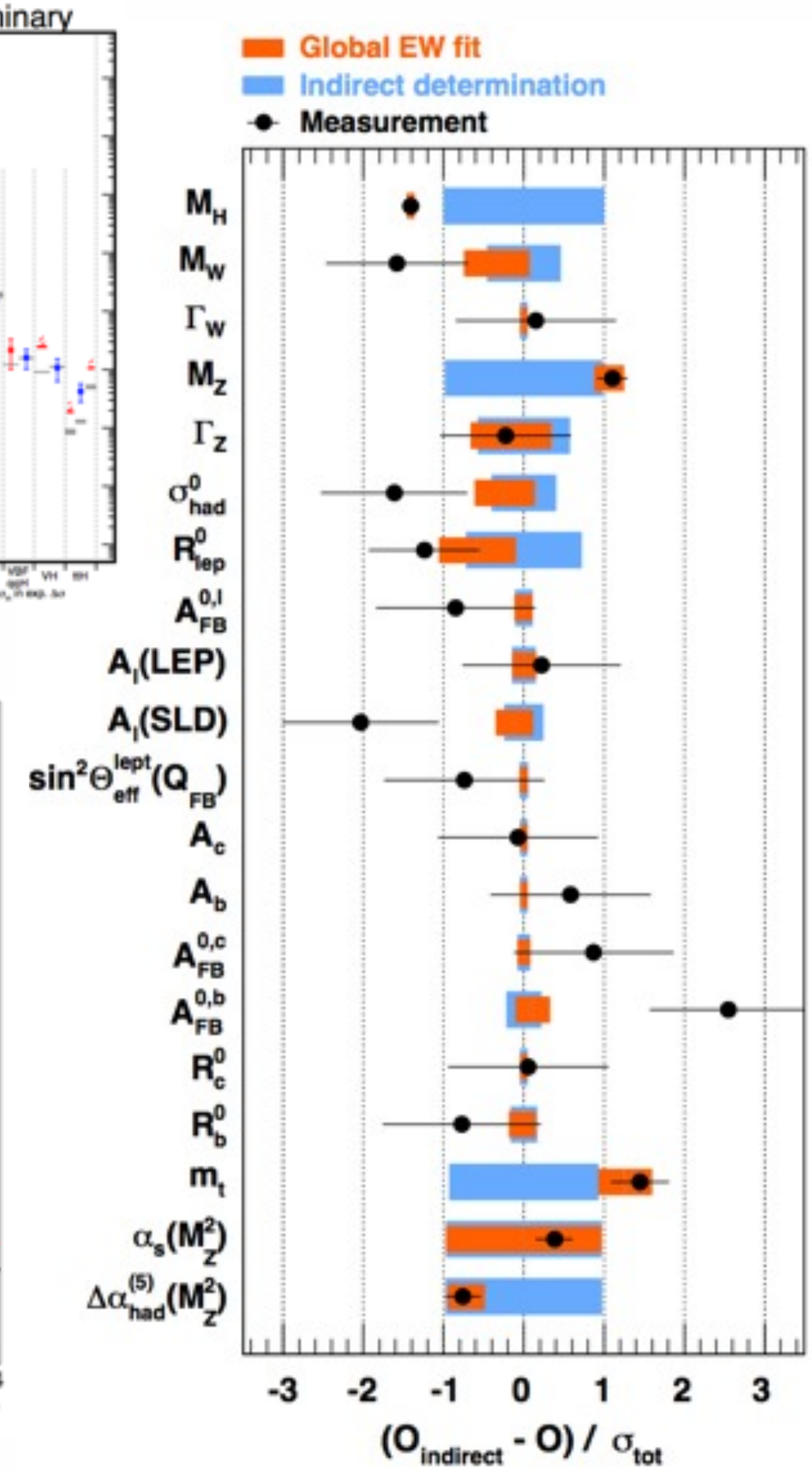










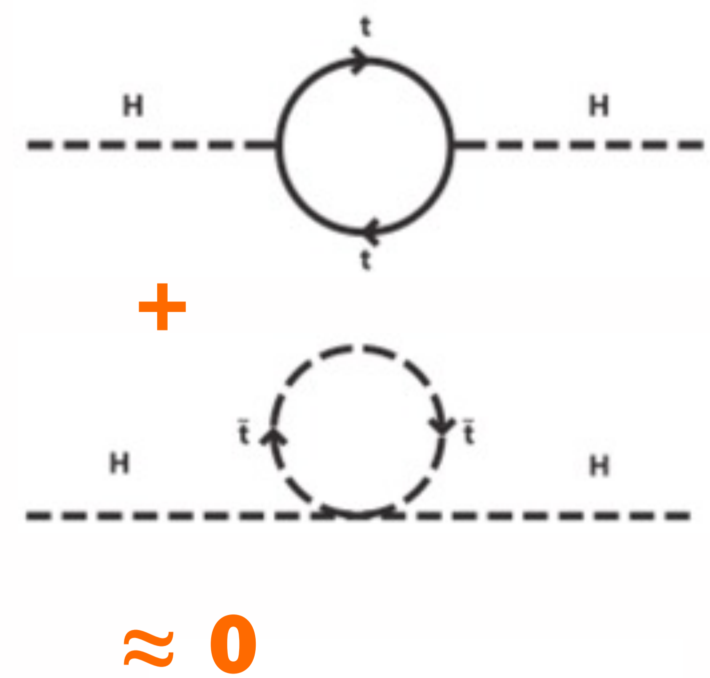


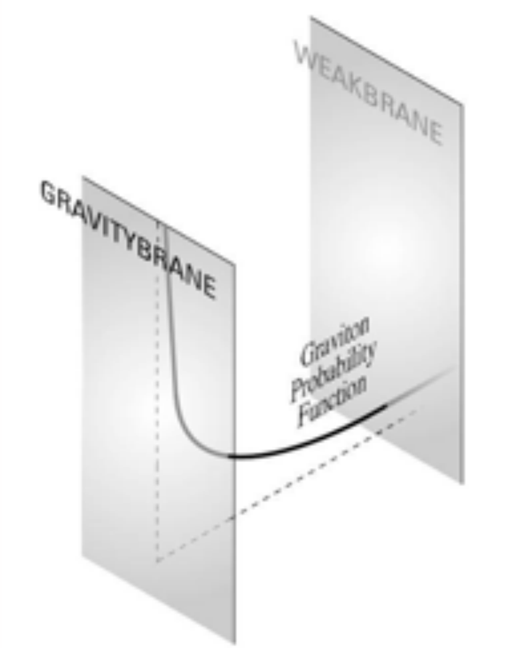
SM's shortcomings

- despite its tremendous success, the SM leaves many open questions
- from the cosmological front
  - dark matter and dark energy (no candidates offered)
  - abundance of matter over antimatter (not enough CPV in quark sector)
  - how can gravity fit into the picture; and btw are there other dimensions of space
- from fermionic sector (and it's structure)
  - why 3 generations; are there additional quarks or do they have substructure
  - why not neutral colored fermions; spin, color charge, why are they quantized
  - why so large hierarchies of fermion masses, and of coupling constants
- from the scalar sector
  - what stabilizes the Higgs mass -- aka the 'hierarchy problem'

going beyond the SM?

- various New Physics scenarios exist that attempt to extend the SM and address some of its short comings
- supersymmetry
  - introduce partners to all SM particles, with spin difference 1/2; protects scalar mass
- higgsless / composite higgs / little higgs
  - H is a bound state (due to some new strong interaction) or dynamically gen. condensate
  - H is pseudo-Goldstone boson of a spontaneously broken symmetry
- extra dimensions
  - N-dim space; gravity propagates in more dims, SM only in “our” brane; eg warped extra dimensions can explain weakness of G





- many other scenarios possible ‣ including some we did not think about !