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# Search for resonances & New Physics at the LHC

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Quantum Field Theory at the Limits: from  
Strong Fields to Heavy Quarks



# overview

the standard model, and beyond  
particle detection at the LHC

resonances

low scale ( $\sim 10$  GeV)

medium scale ( $\sim 100$  GeV)

high scale ( $\sim$ TeV)

(exotica)

summary

# the Standard Model

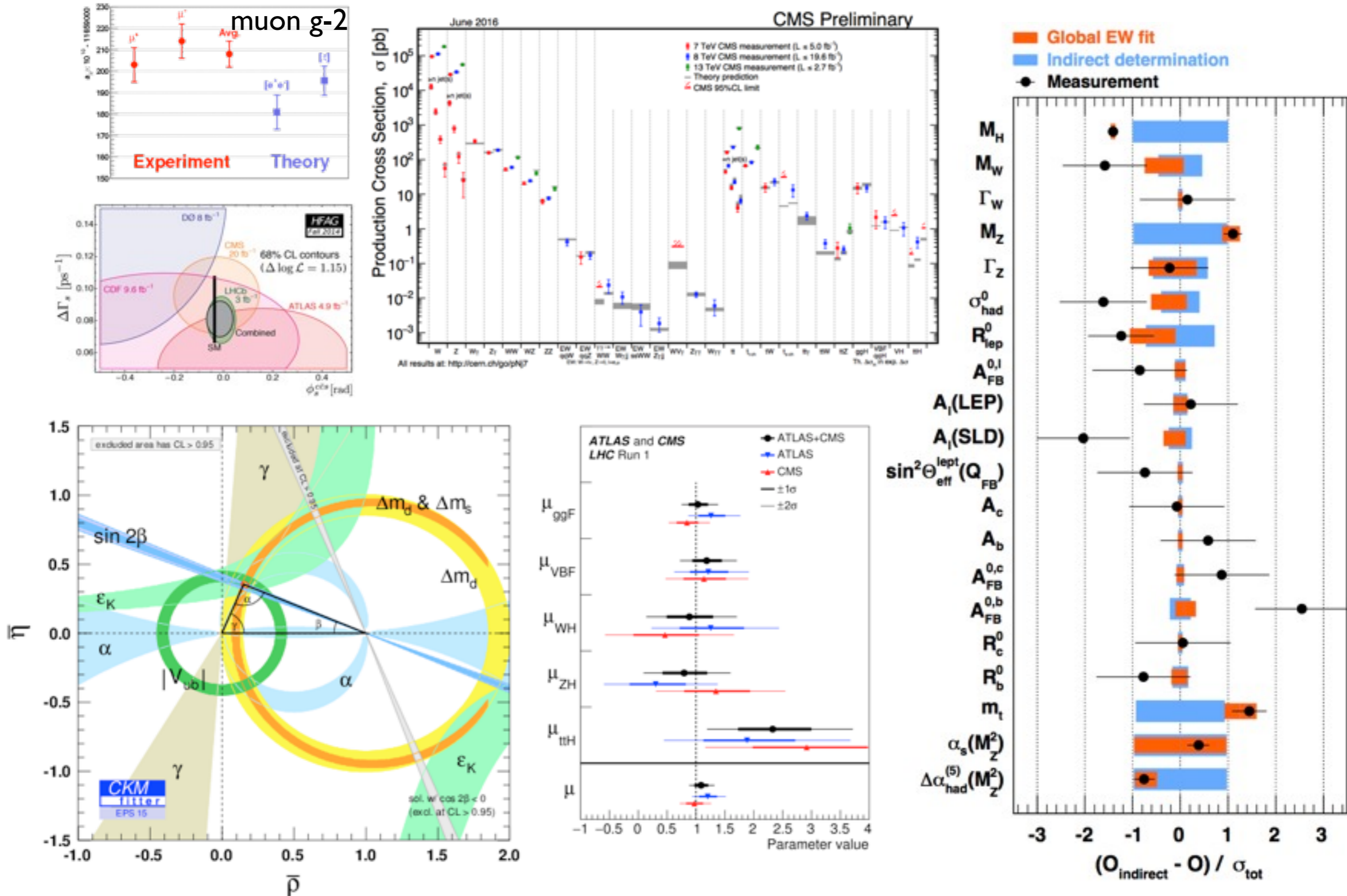
- fully consistent and complete description of the strong, electromagnetic, and weak interactions
- LHC's discovery of the Higgs by ATLAS & CMS completes the SM's elementary particle list
- in short
  - matter built of spin 1/2 particles that exchange 3 kinds of spin 1 particles corresponding to 3 types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

Three Generations of Matter (Fermions)

	I	II	III		
mass→	3 MeV	1.24 GeV	172.5 GeV	0	125.7 GeV
charge→	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
spin→	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
name→	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>γ</b> photon	<b>H</b> Higgs
Quarks	6 MeV $-\frac{1}{3}$	95 MeV $-\frac{1}{3}$	4.2 GeV $-\frac{1}{3}$	0	0
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	0	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	2
			<b>g</b> gluon		<b>G</b> Graviton
Leptons	<2 eV 0	<0.19 MeV 0	<18.2 MeV 0	90.2 GeV 0	
	<b>ν<sub>e</sub></b> electron neutrino	<b>ν<sub>μ</sub></b> muon neutrino	<b>ν<sub>τ</sub></b> tau neutrino	<b>Z<sup>0</sup></b> weak force	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	0.511 MeV -1	106 MeV -1	1.78 GeV -1	80.4 GeV ±1	
	<b>e</b> electron	<b>μ</b> muon	<b>τ</b> tau	<b>W<sup>±</sup></b> weak force	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
					Bosons (Forces)

- 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

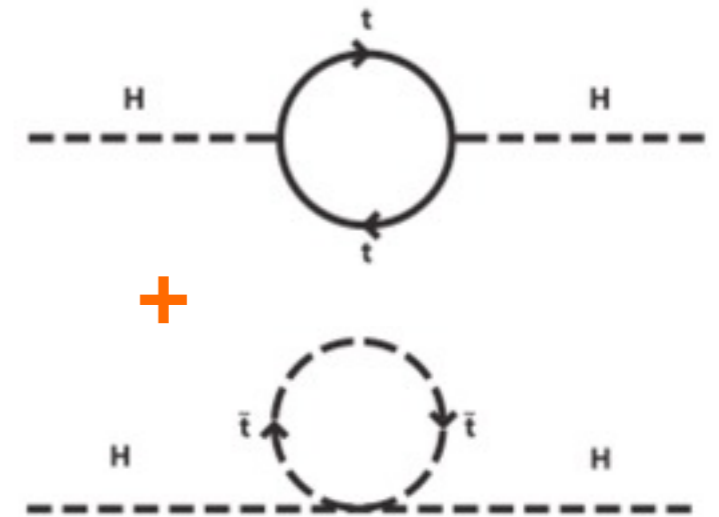


# SM's shortcomings

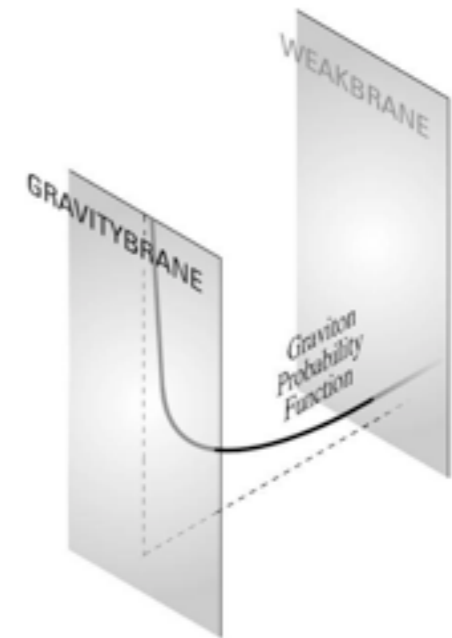
- despite its tremendous success, the SM leaves many open questions
- from the cosmological front
  - dark matter and dark energy (no candidates offered)
  - abundance of matter over antimatter (not enough CPV in quark sector)
  - how can gravity fit into the picture; and btw are there other dimensions of space
- from fermionic sector (and its 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 address the hierarchy problem and other SM shortcomings
- supersymmetry
  - introduce partners to all SM particles, with spin difference 1/2; protects also scalar mass
- Higgsless / composite Higgs
  - H is a bound state (due to some new strong interaction) or dynamically gen. condensate
- little Higgs
  - 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 !**



$\approx 0$



# how ?

- search for phenomena in the data that do not fit in the SM
  - two complementary approaches to discovery:
- look for New Physics in loops (quantum effects): indirect searches
  - carry out precision measurements of the properties of SM particles
  - flavor mixing & CP violation, FCNC, rare decays, LFV, ...
- look for New Physics particles: direct searches
  - exhaustive searches: signature based, generic scope, or model specific
- inspect production rates and decay distributions, look for special kinematic features, such as new **resonances**, or exotic signatures
- the tools: the LHC & its particle detectors
  - ATLAS & **CMS** (general purpose), LHCb (B), ALICE (QGP)

# the Compact Muon Solenoid detector

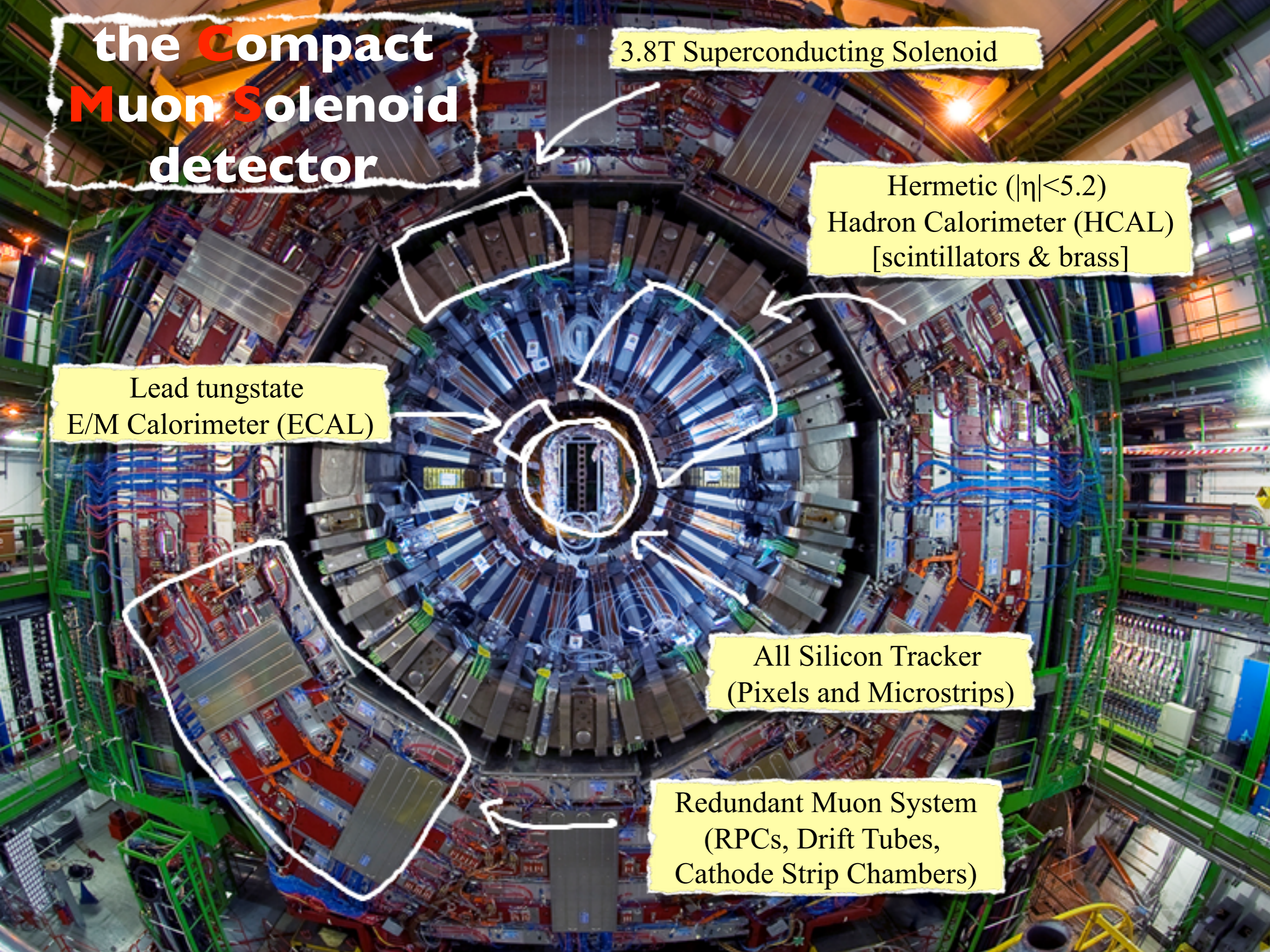
3.8T Superconducting Solenoid

Hermetic ( $|\eta| < 5.2$ )  
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)



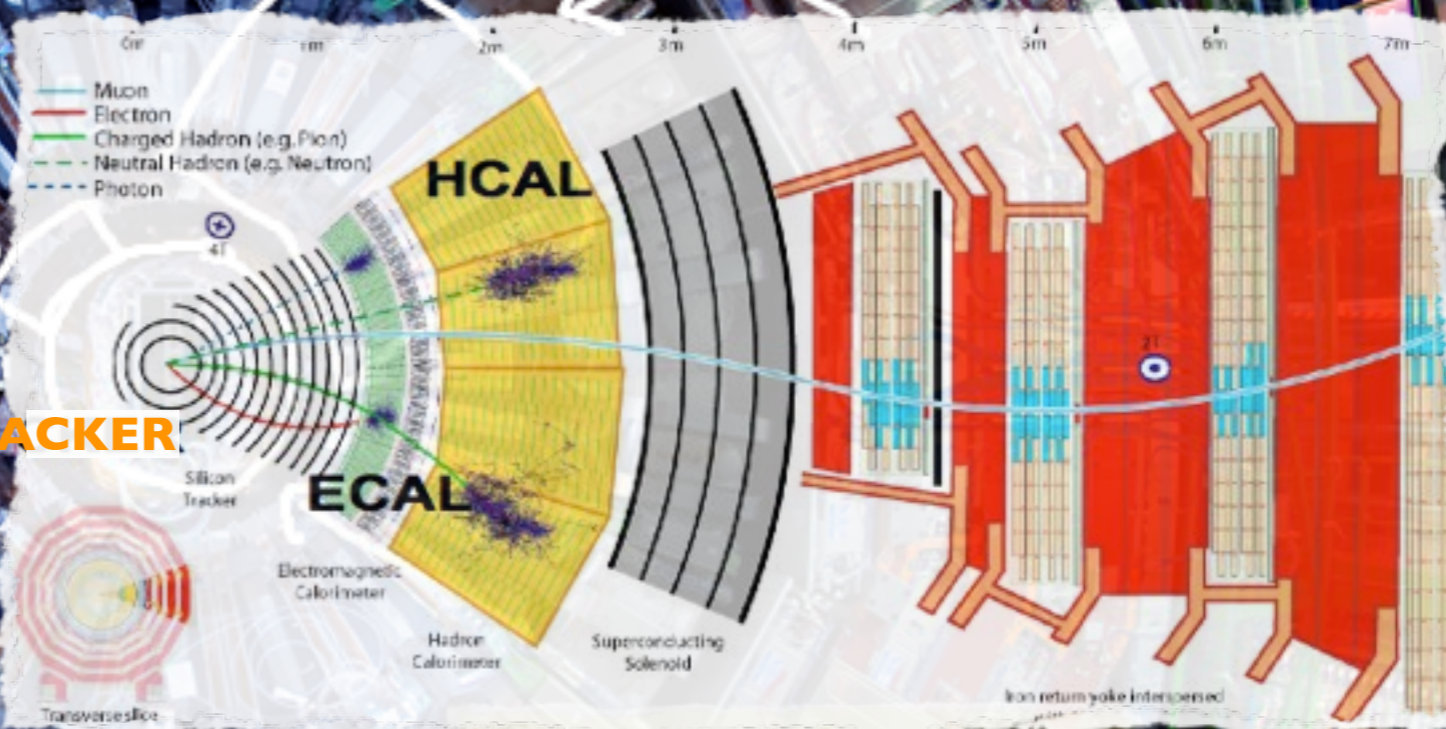


# the Compact Muon Solenoid detector

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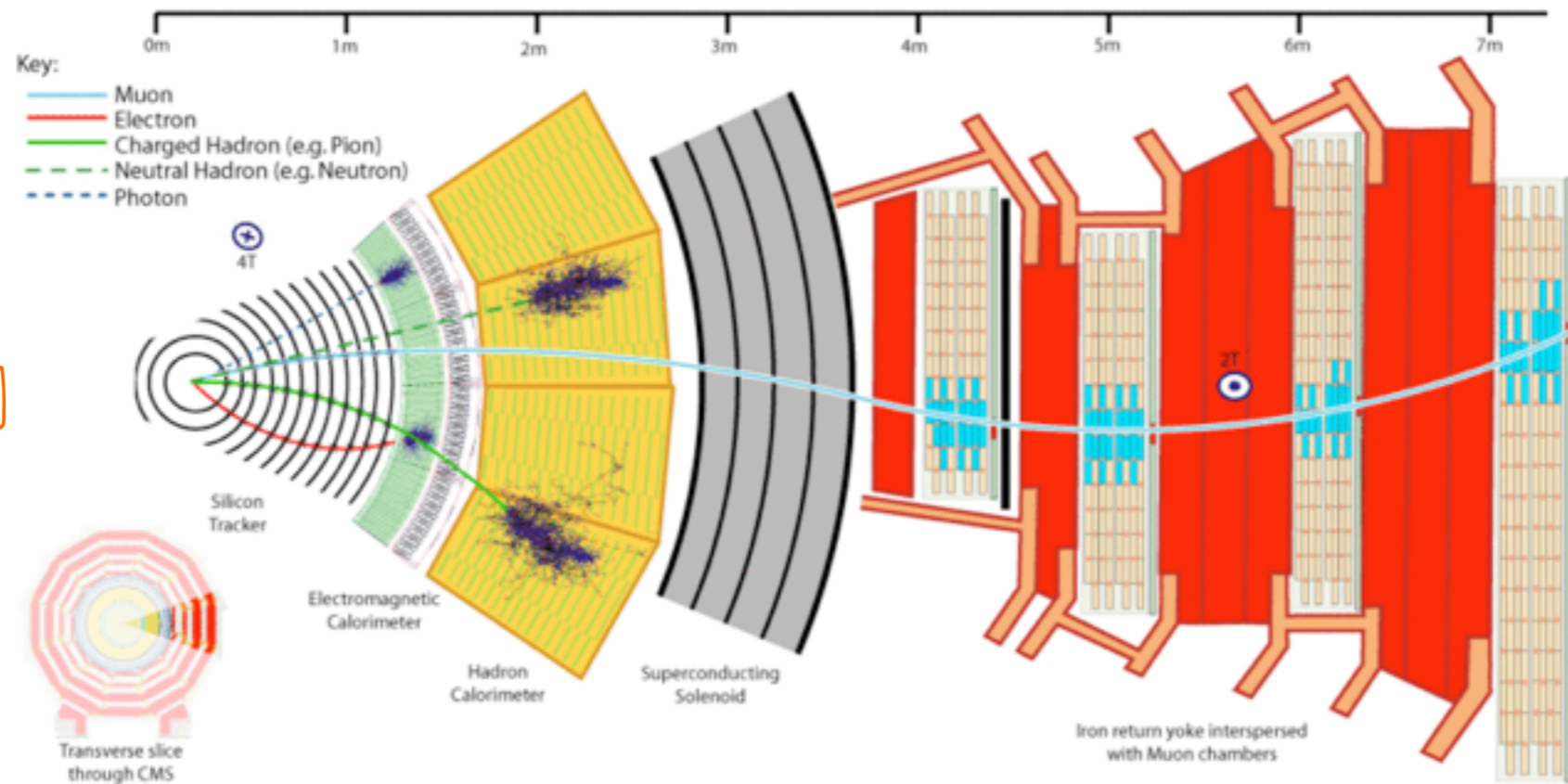


All Silicon Tracker  
(Pixels and Microstrips)

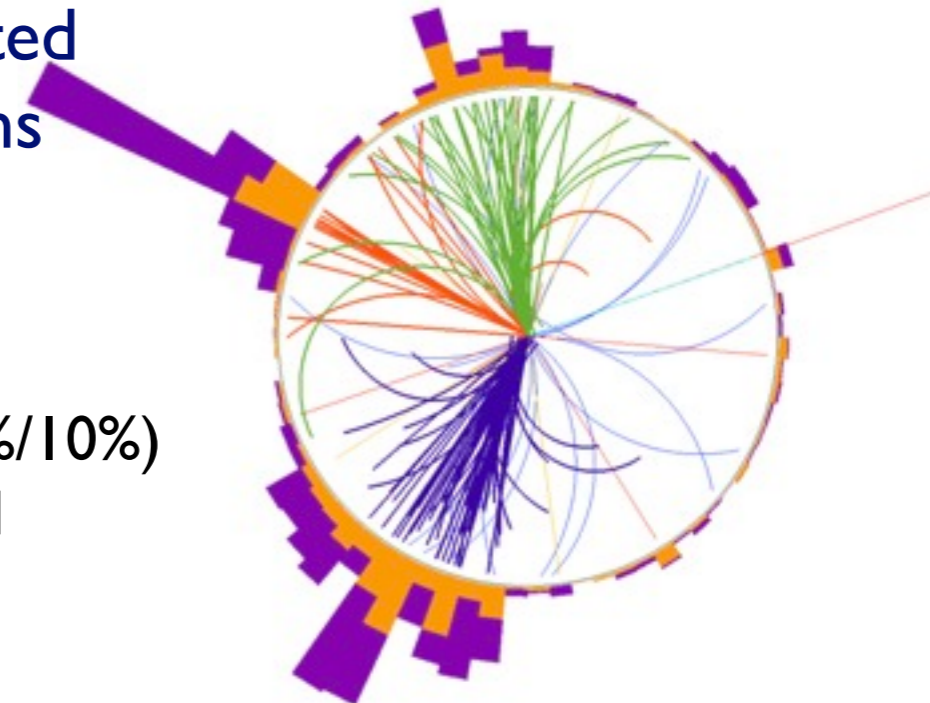
Redundant Muon System  
(RPCs, Drift Tubes,  
Cathode Strip Chambers)

# particle identification

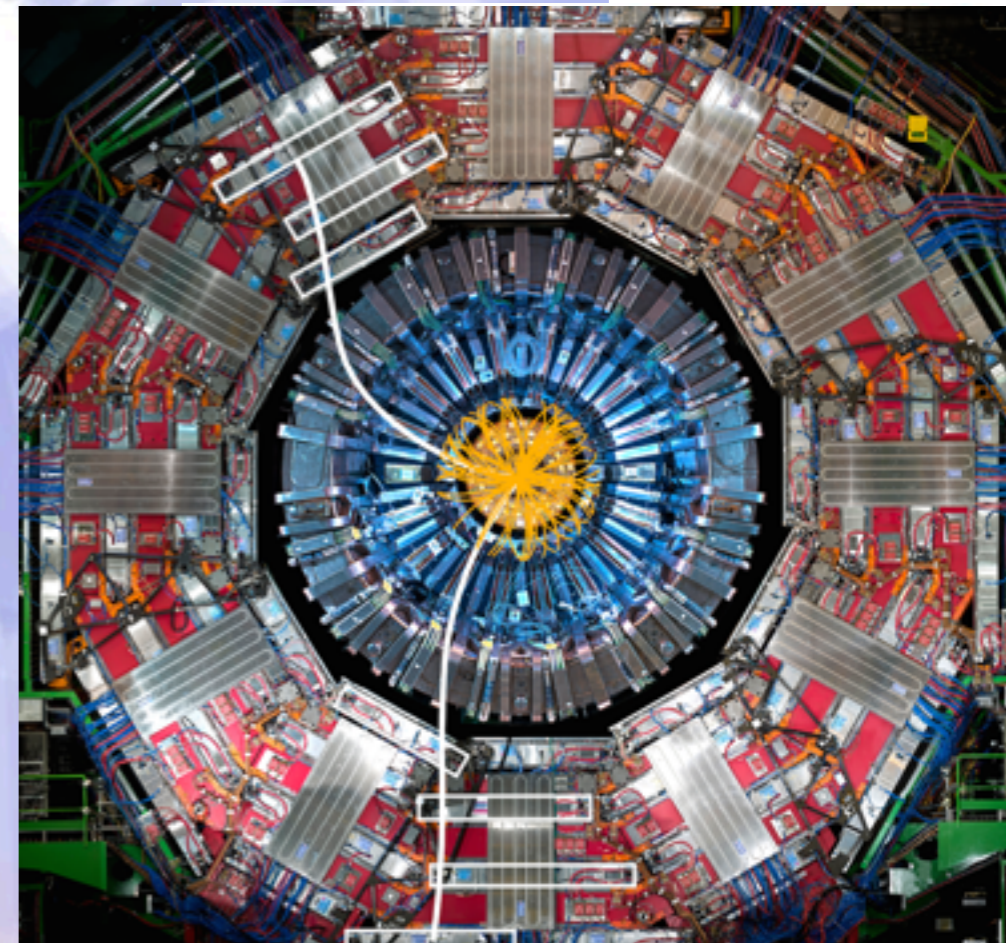
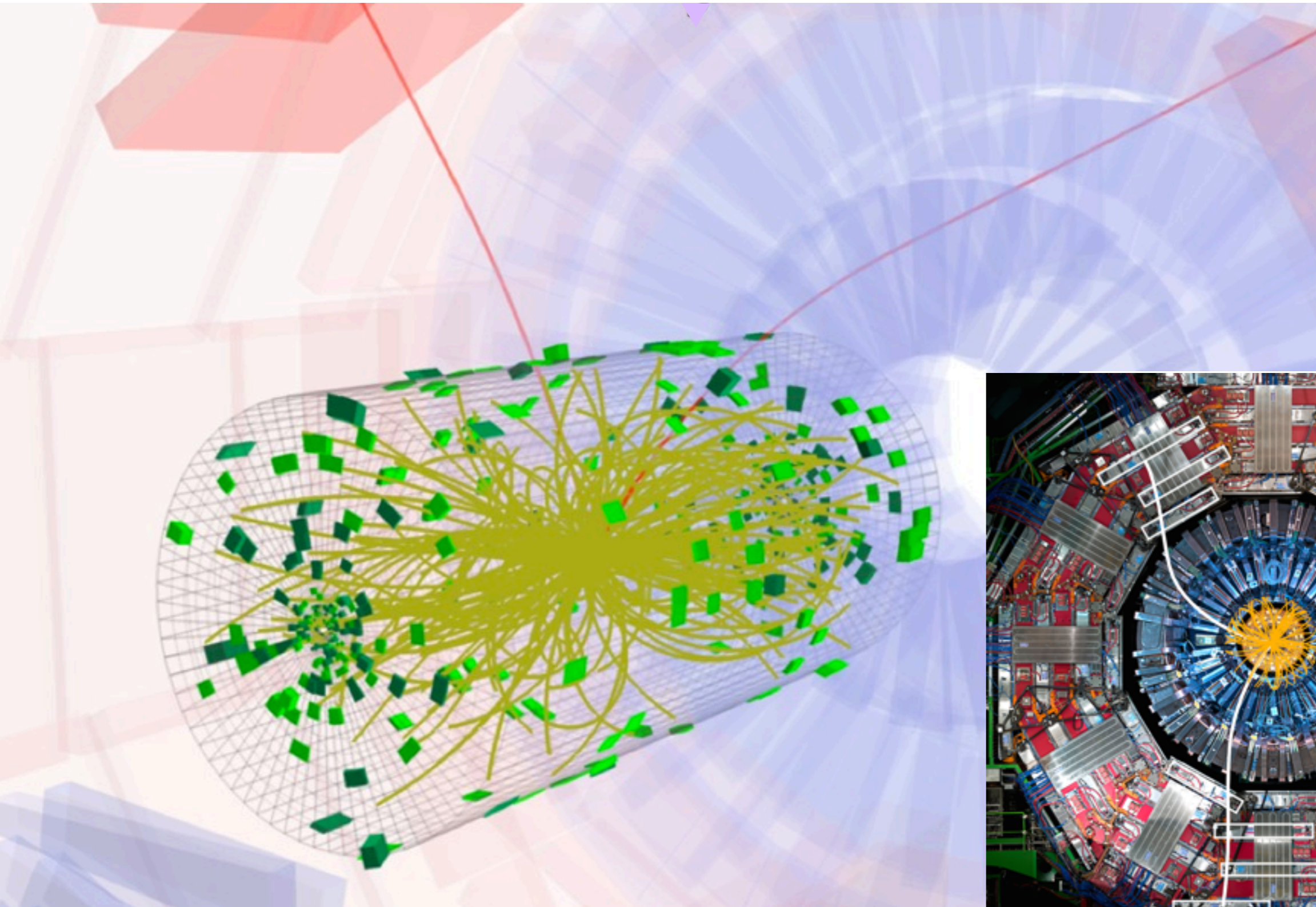
[leading order]



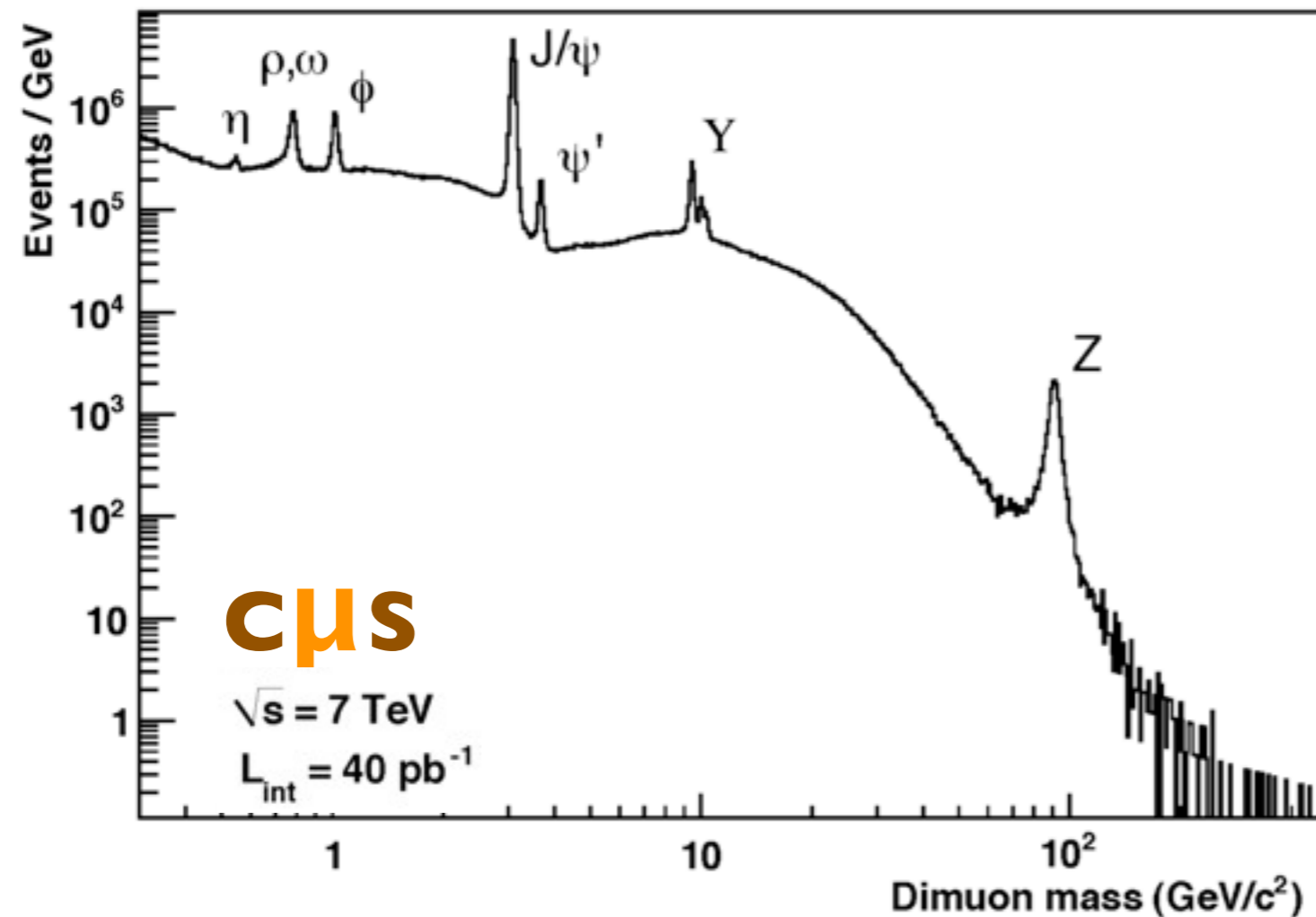
- [higher order corrections] objects are finally reconstructed using information from different detector subsystems combined in a **particle flow** algorithm
  - electrons radiate via bremsstrahlung
  - photons may convert to  $e^+e^-$  pairs in the tracker
  - **jet** (q,g) energy is formed of charged/neutral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



# a di-muon event

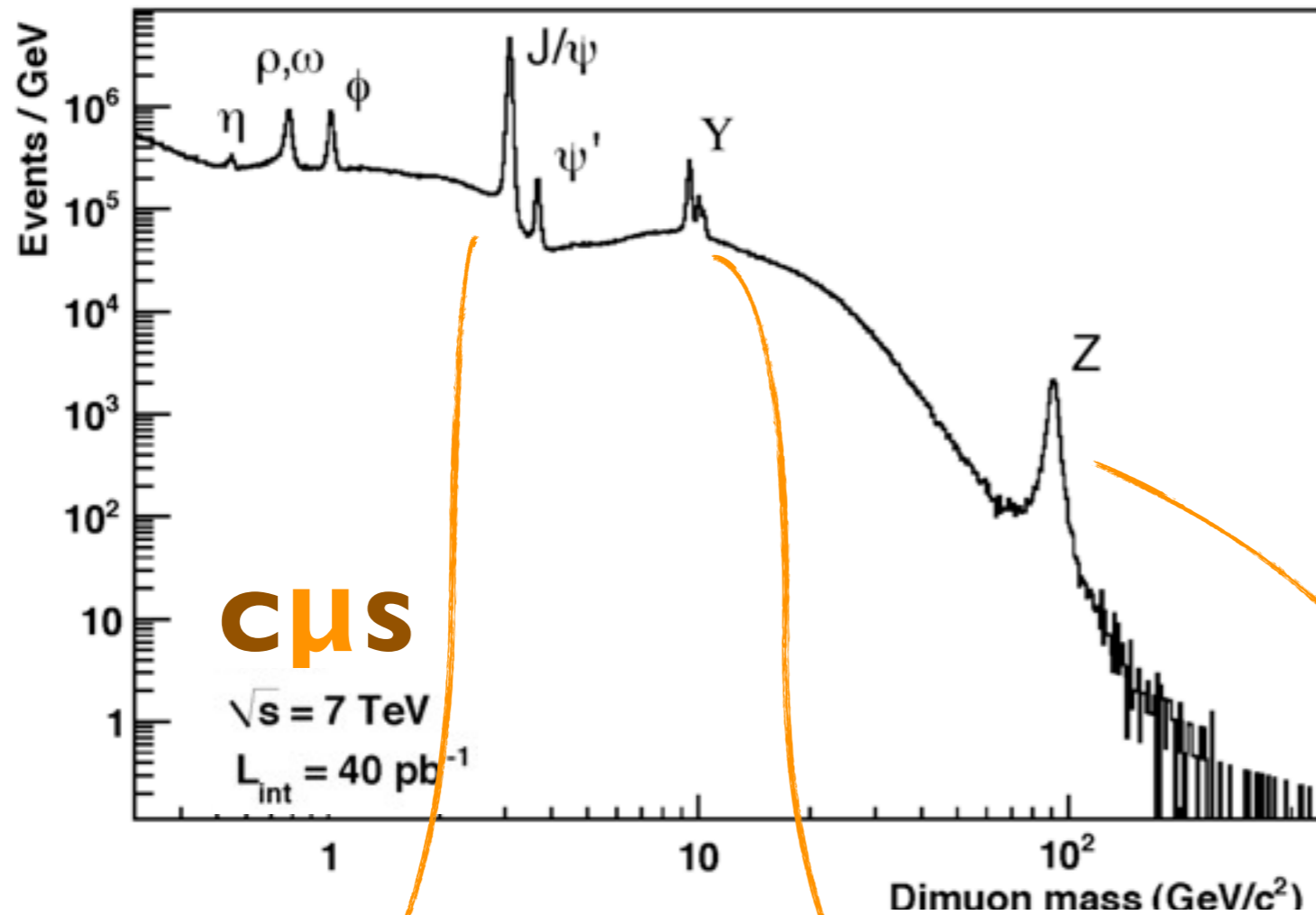


# the di-muon resonance spectrum

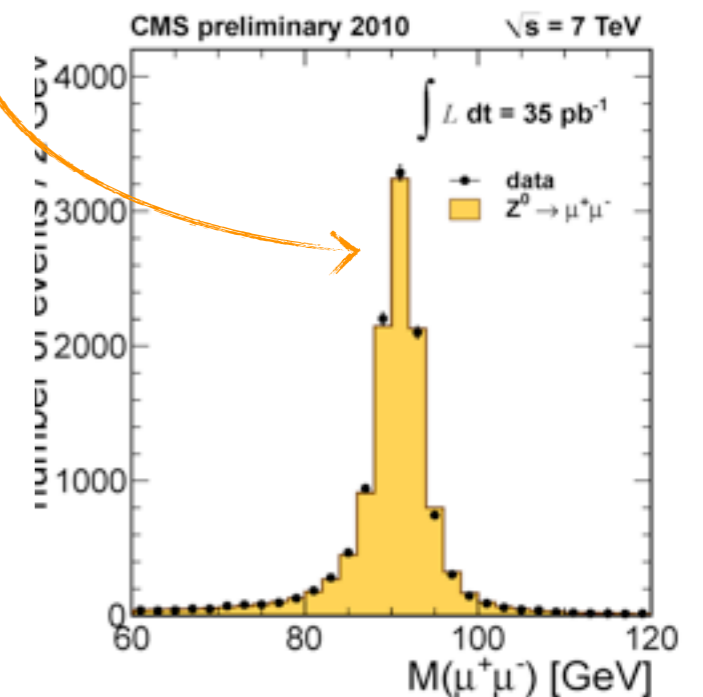
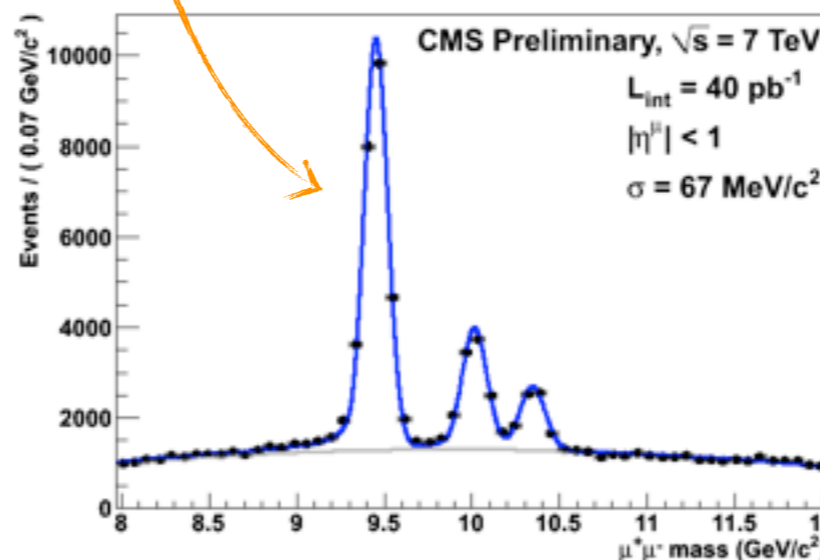
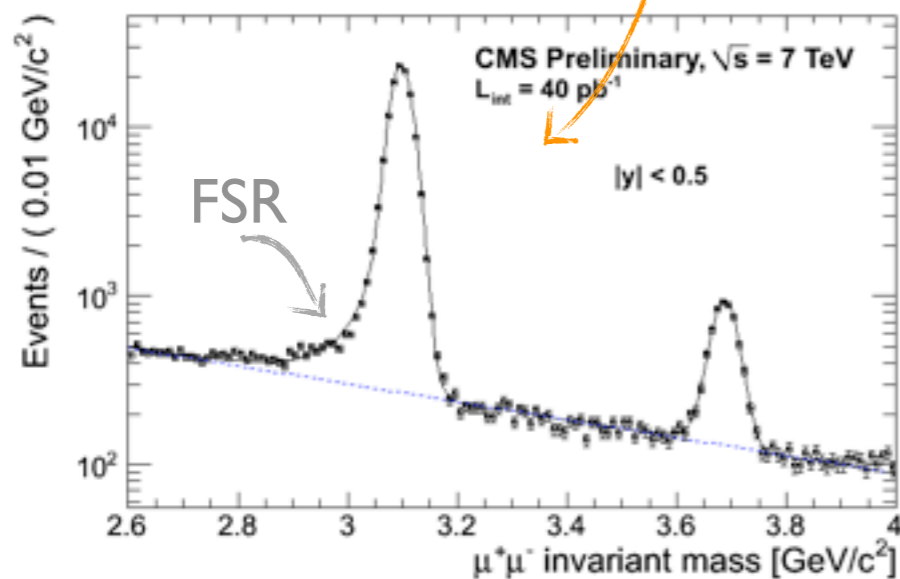


aka  
Standard Model's re-discovery  
@ LHC Run I

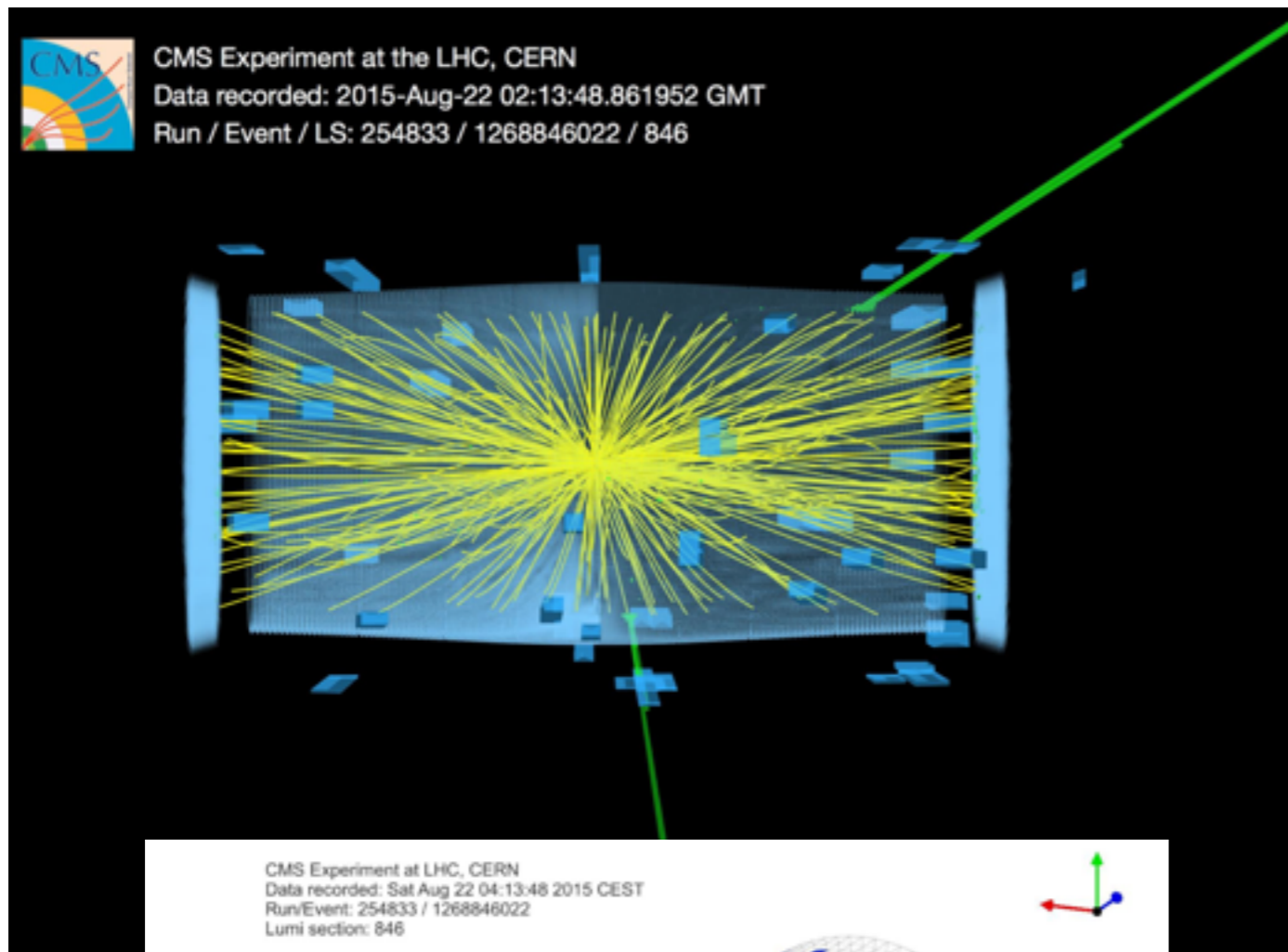
# the di-muon resonance spectrum



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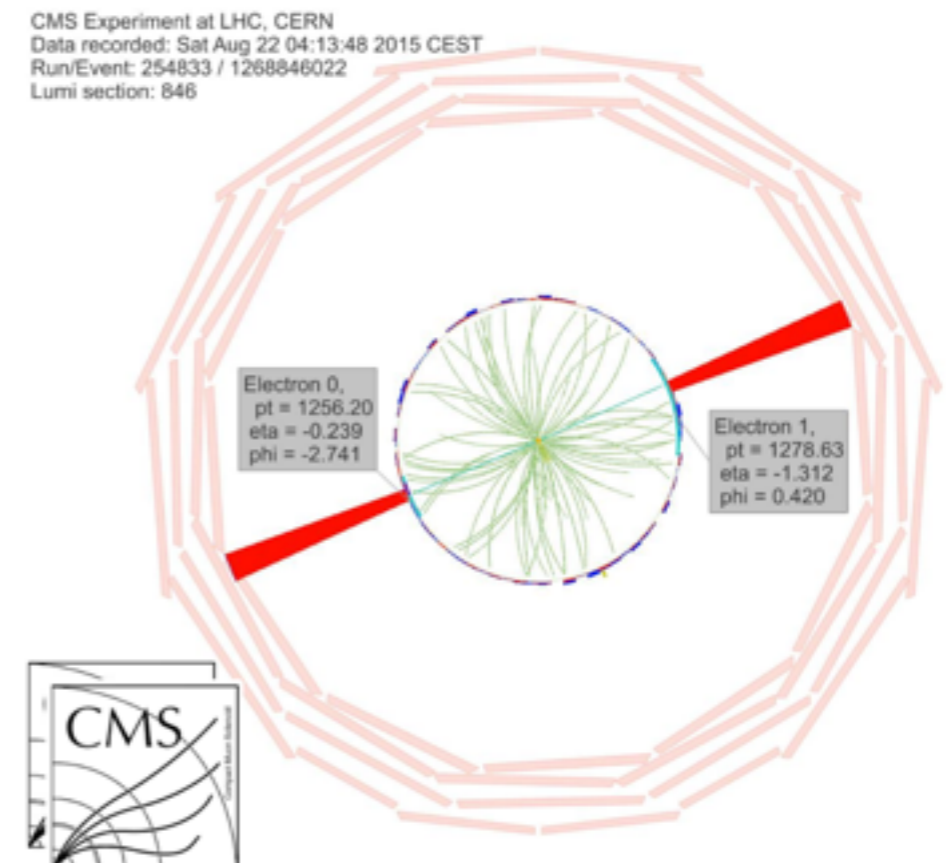
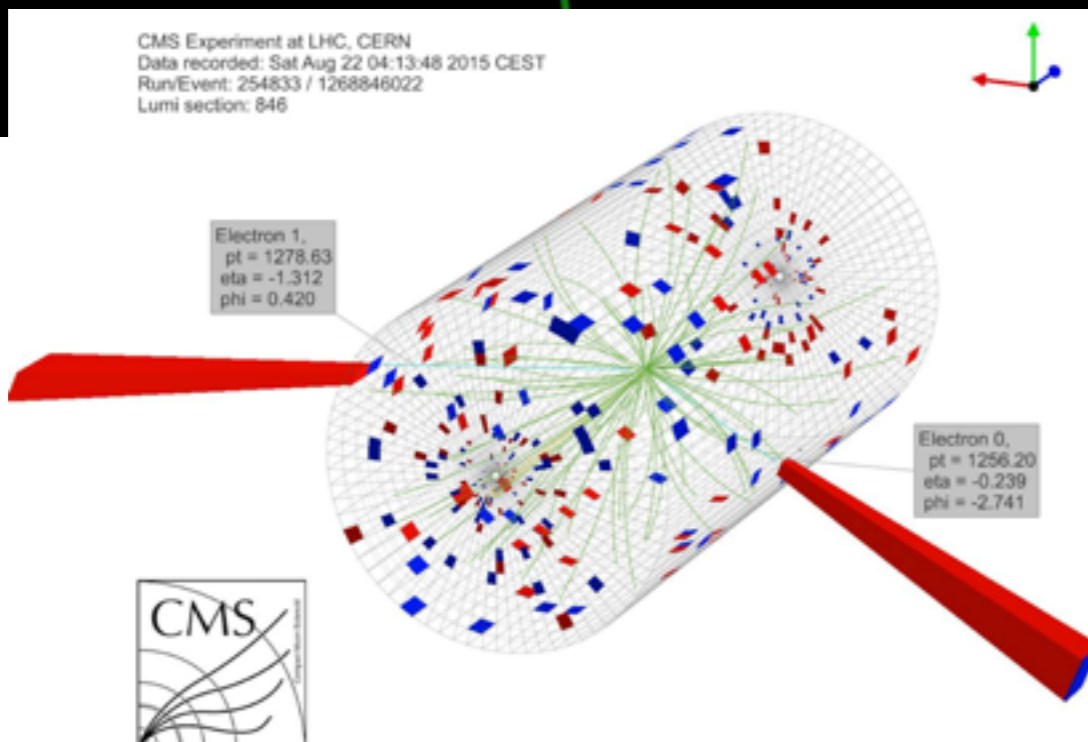


# a di-electron event

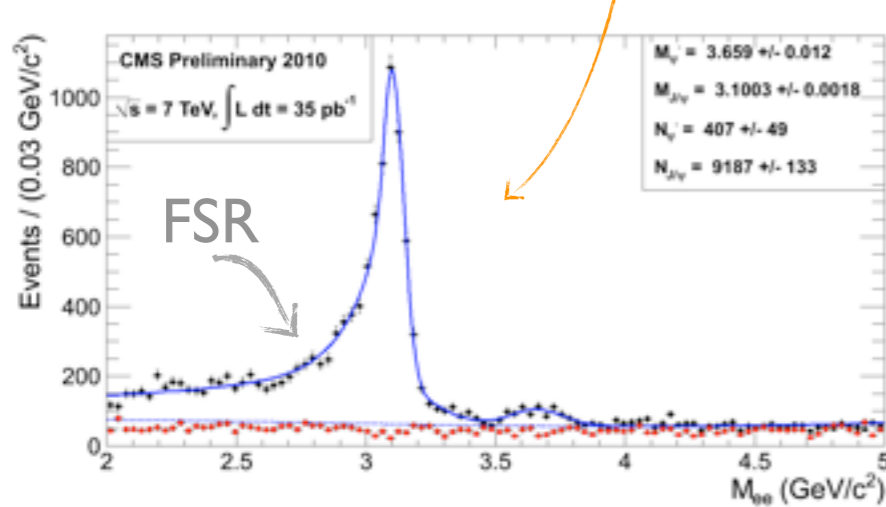
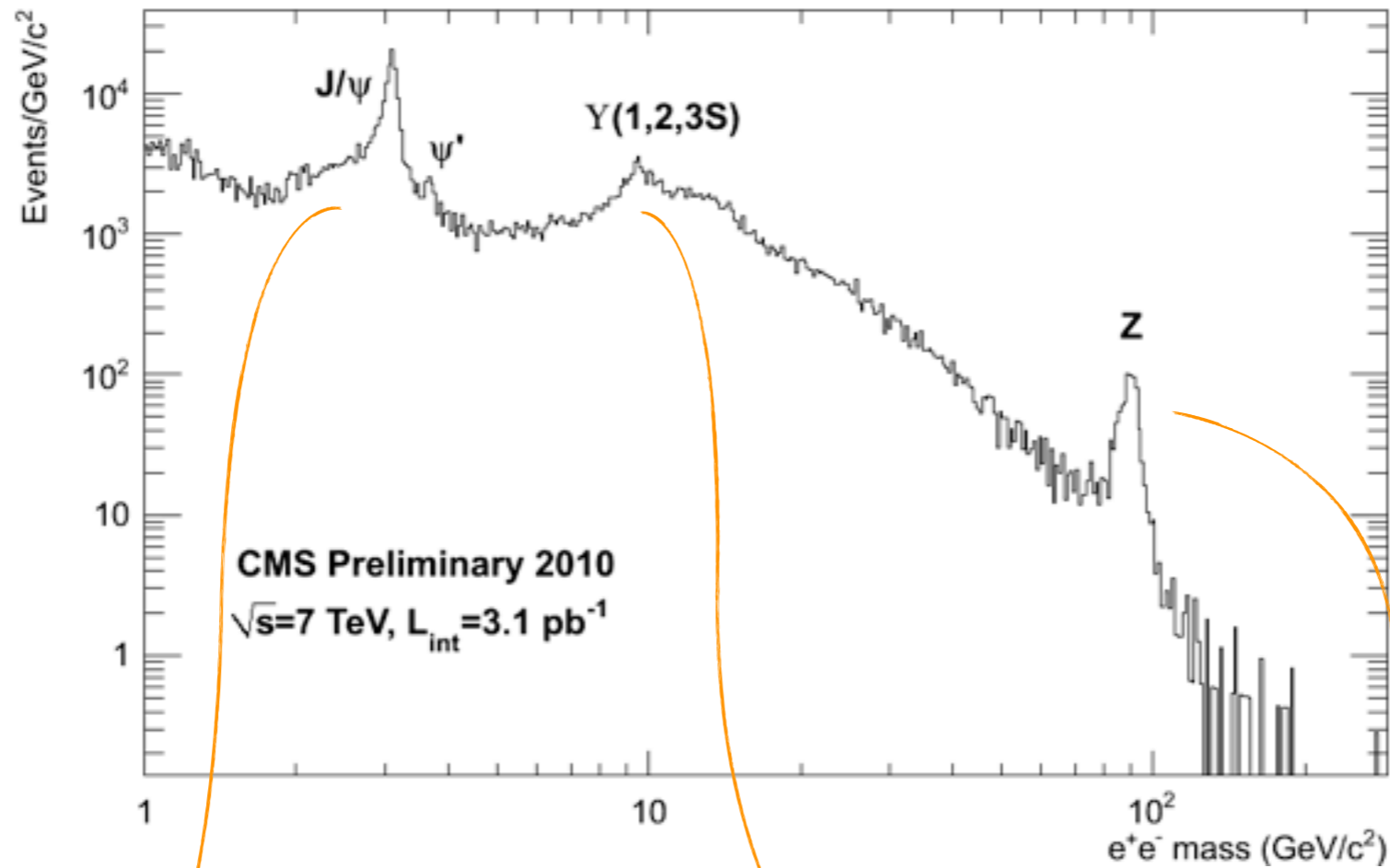


CMS-DP-2015-039

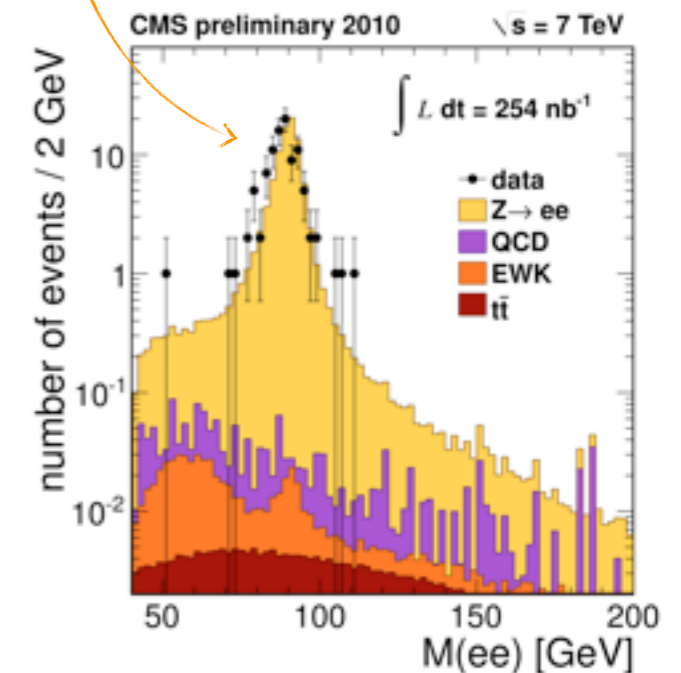
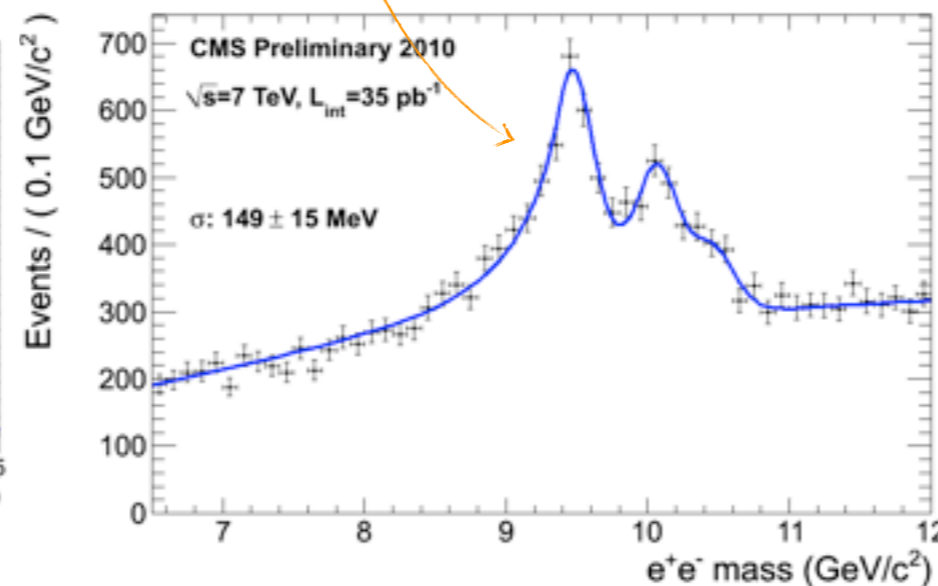
Candidate Electron-Positron pair with an invariant mass of 2.9 TeV in pp collision at  $\sqrt{s} = 13\text{TeV}$



# the di-electron resonance spectrum

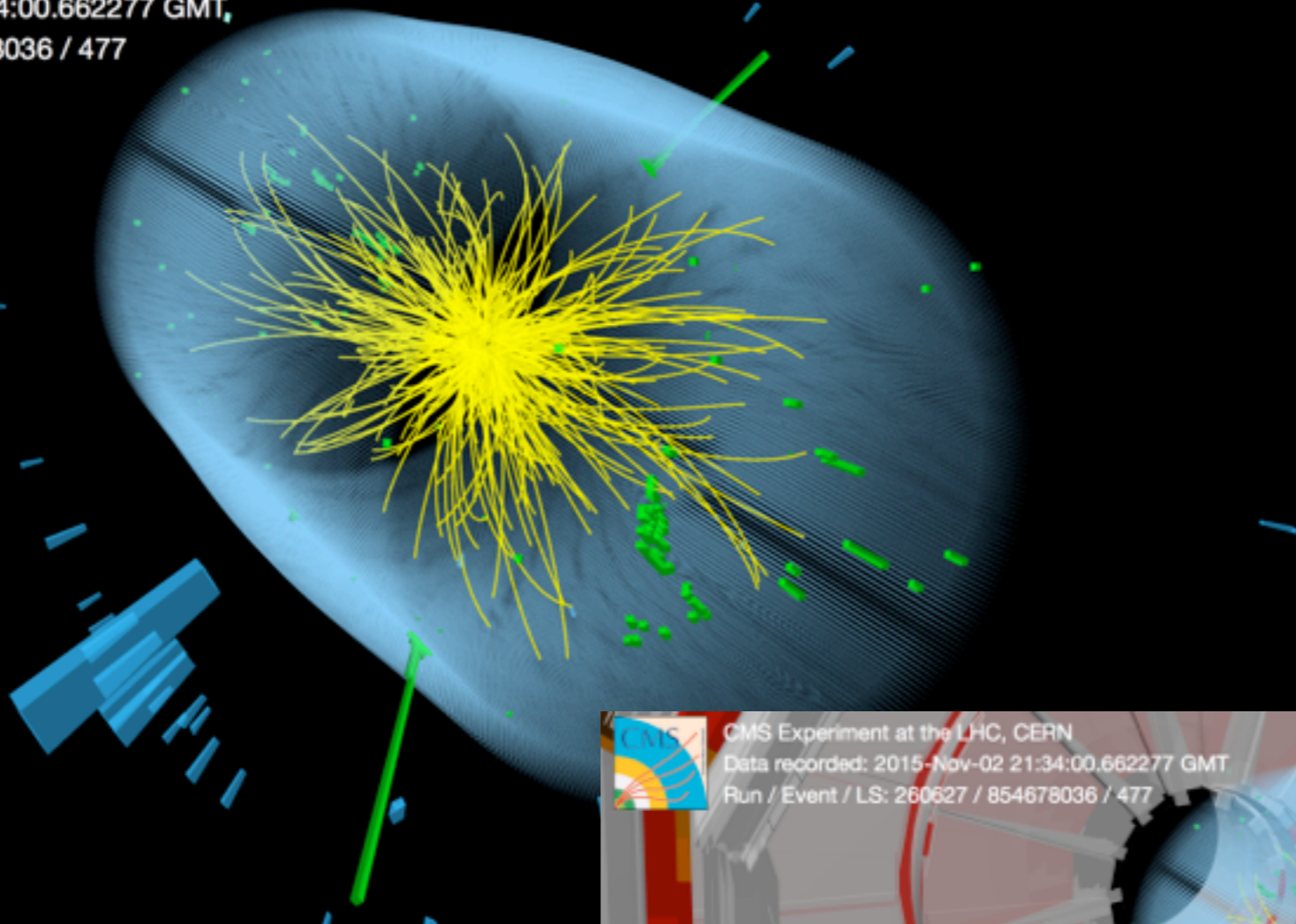


$M_{J/\psi} = 3.659 \pm 0.012$   
 $M_{\psi^*} = 3.1003 \pm 0.0018$   
 $N_{J/\psi} = 407 \pm 49$   
 $N_{\psi^*} = 9187 \pm 133$



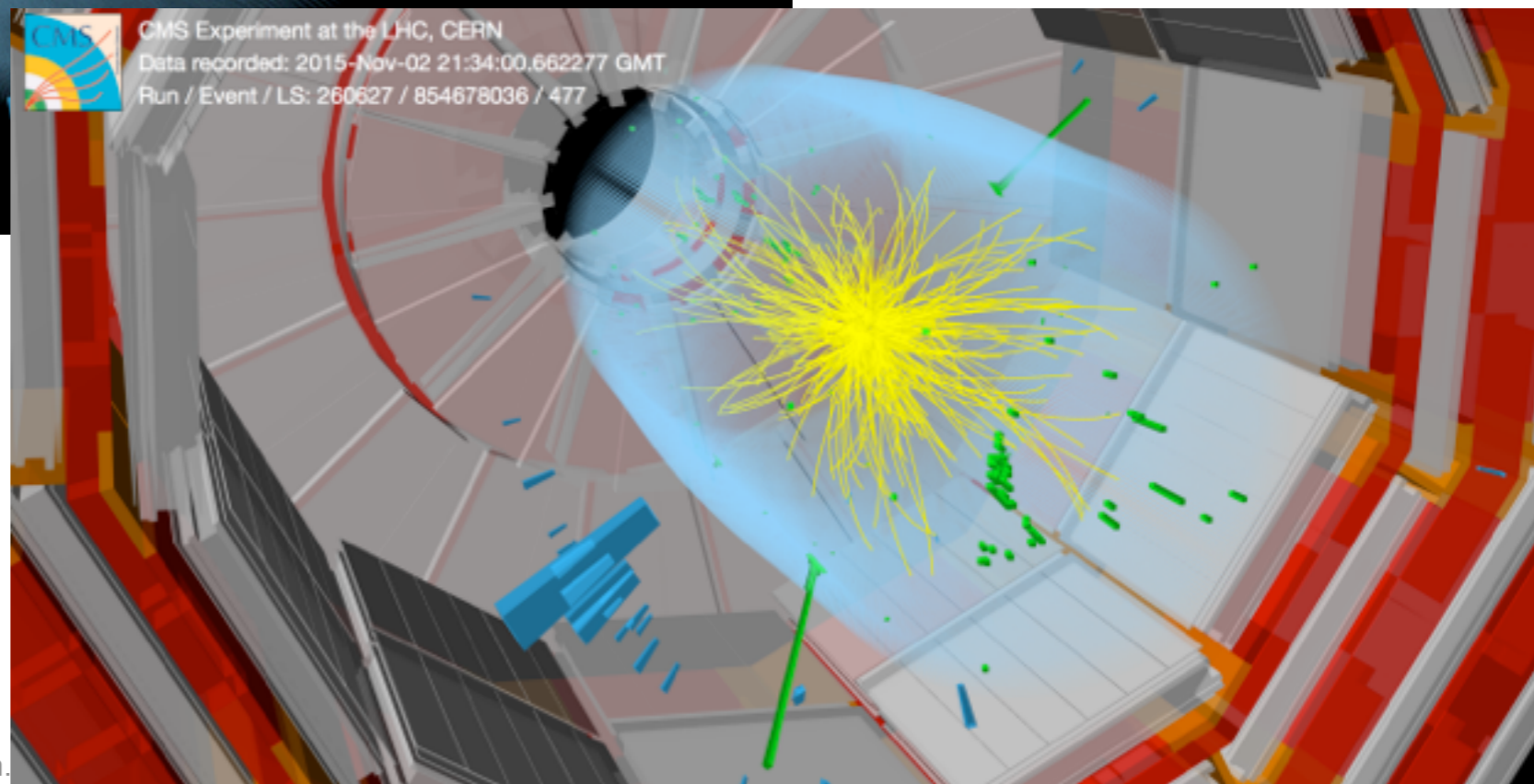
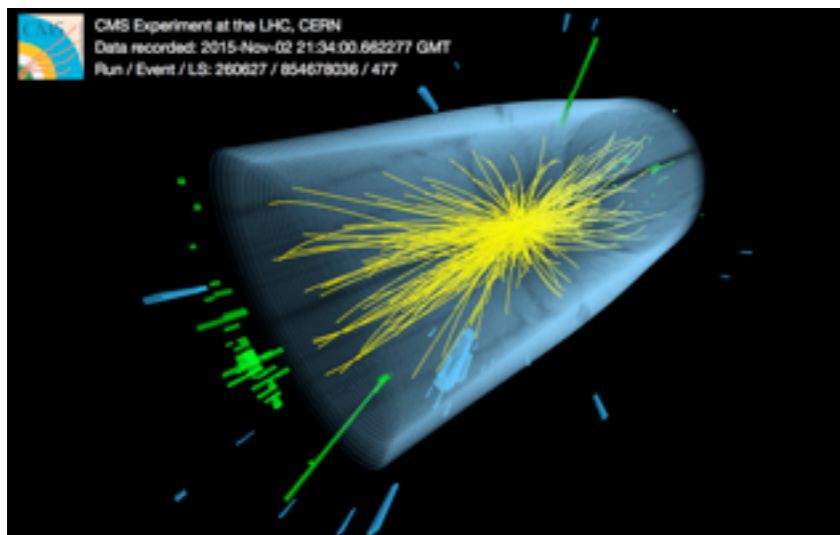
# a di-photon event

Experiment at the LHC, CERN  
Data recorded: 2015-Nov-02 21:34:00.662277 GMT,  
Run / Event / LS: 260627 / 854678036 / 477



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

CMS-PHO-EVENTS-2015-007

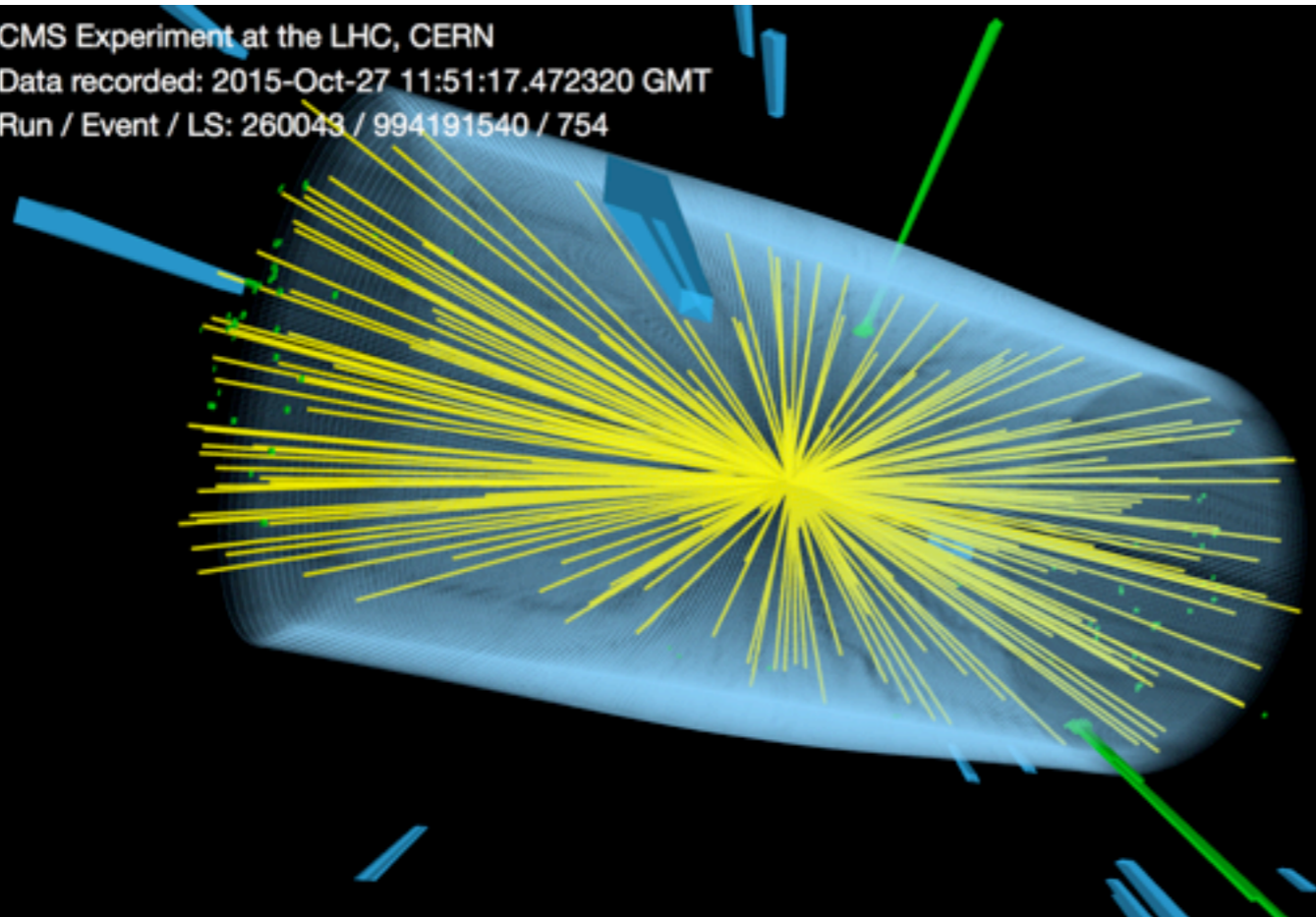


nuno@cern.



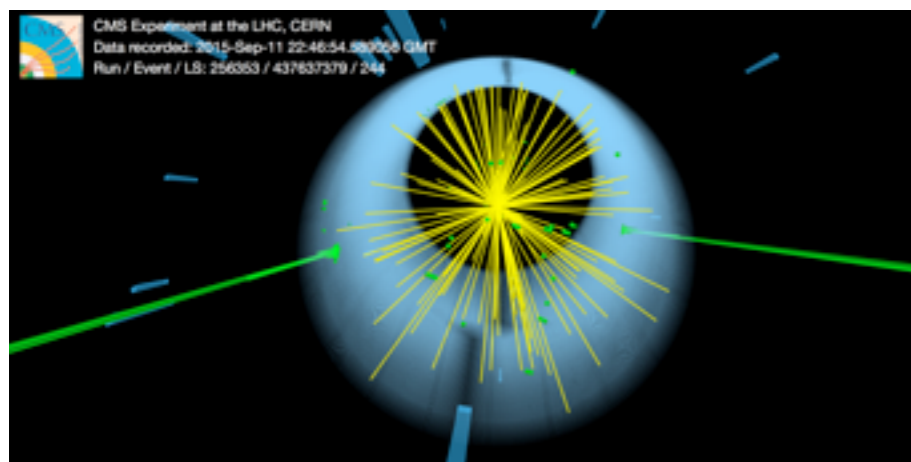


CMS Experiment at the LHC, CERN  
 Data recorded: 2015-Oct-27 11:51:17.472320 GMT  
 Run / Event / LS: 260043 / 994191540 / 754

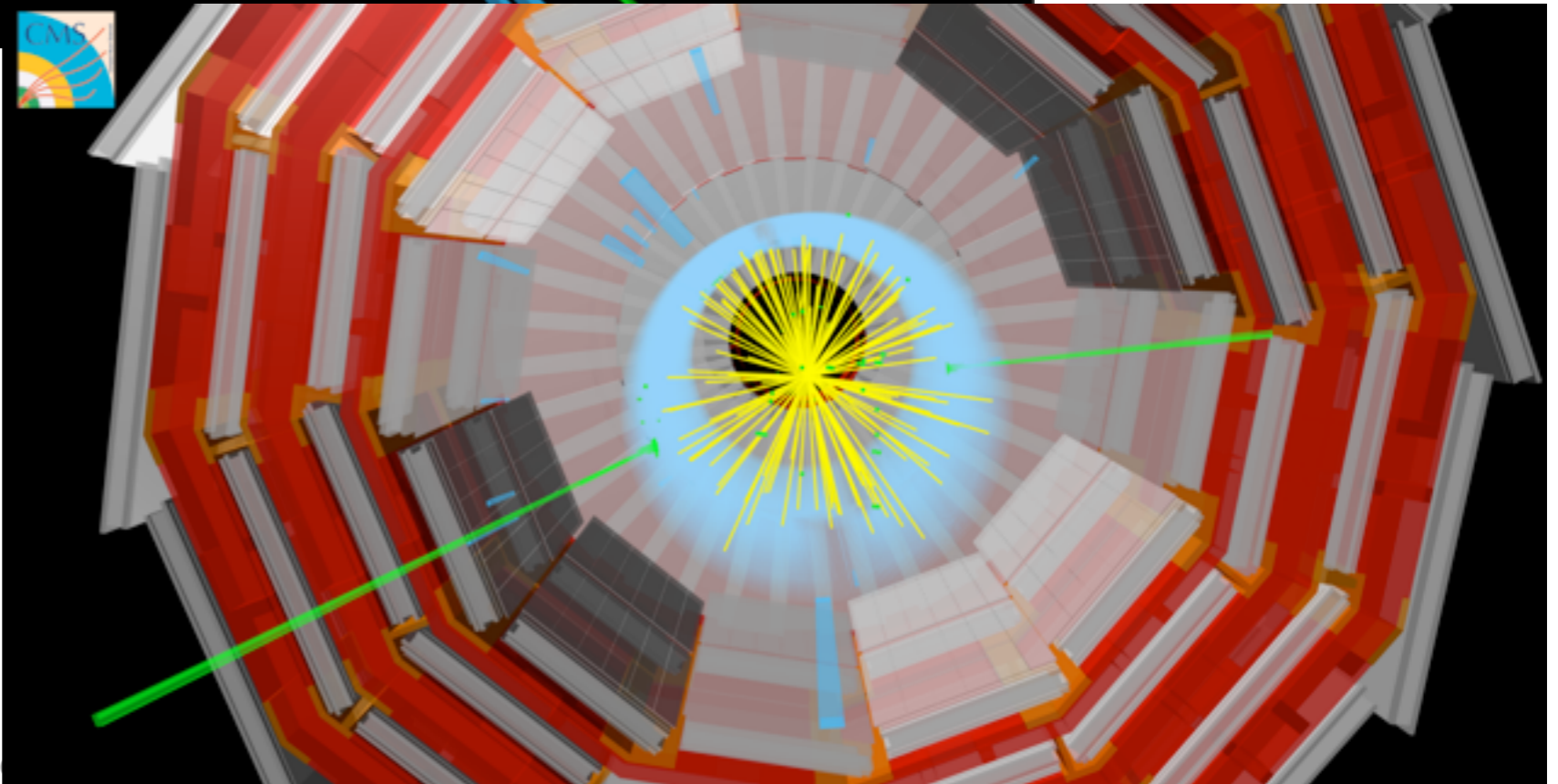


?

$m_{??} \sim 700 - 800 \text{ GeV}$



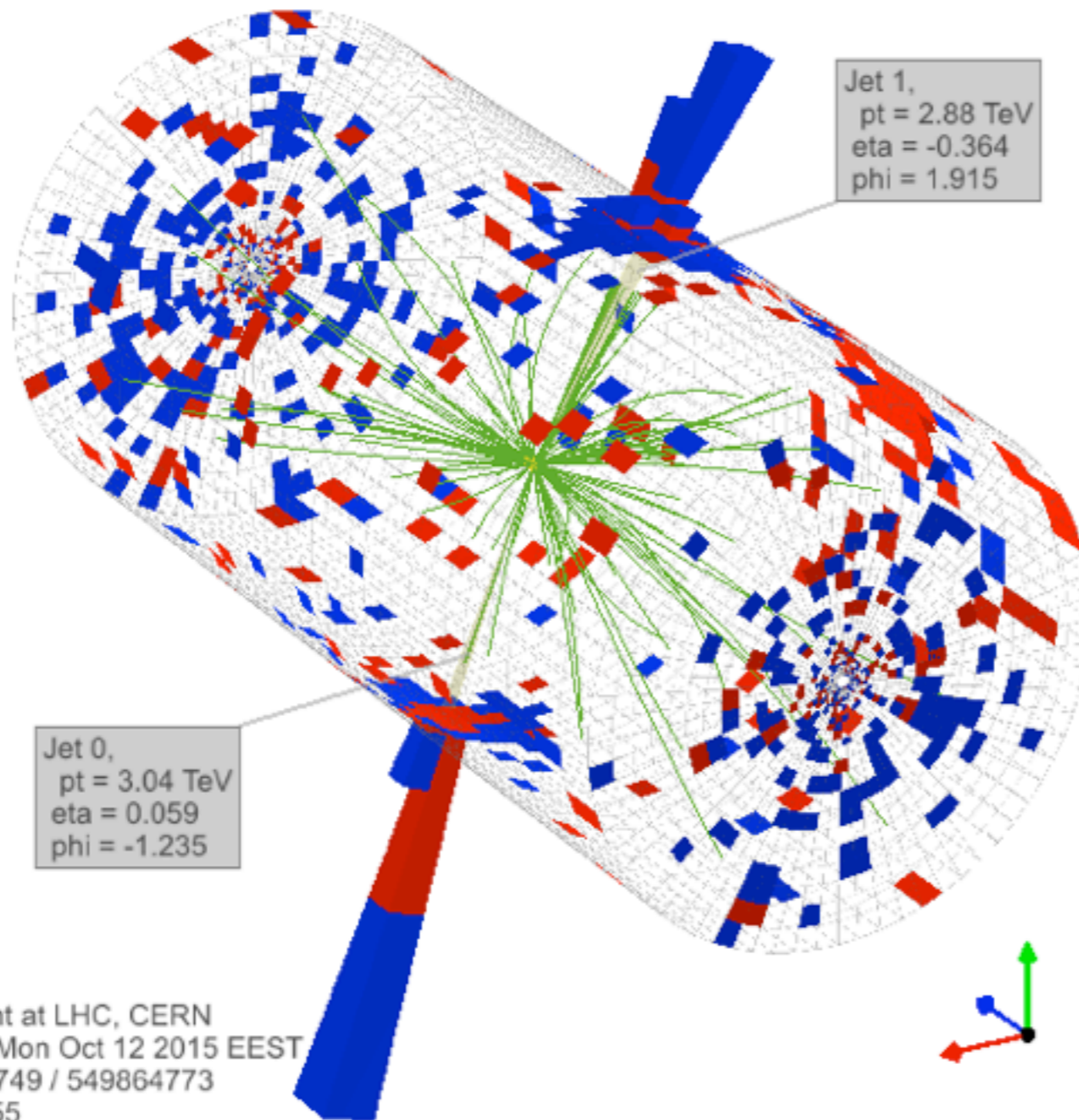
CMS Experiment at the LHC, CERN  
 Data recorded: 2015-Sep-11 22:46:54.987656 GMT  
 Run / Event / LS: 256353 / 437637379 / 244



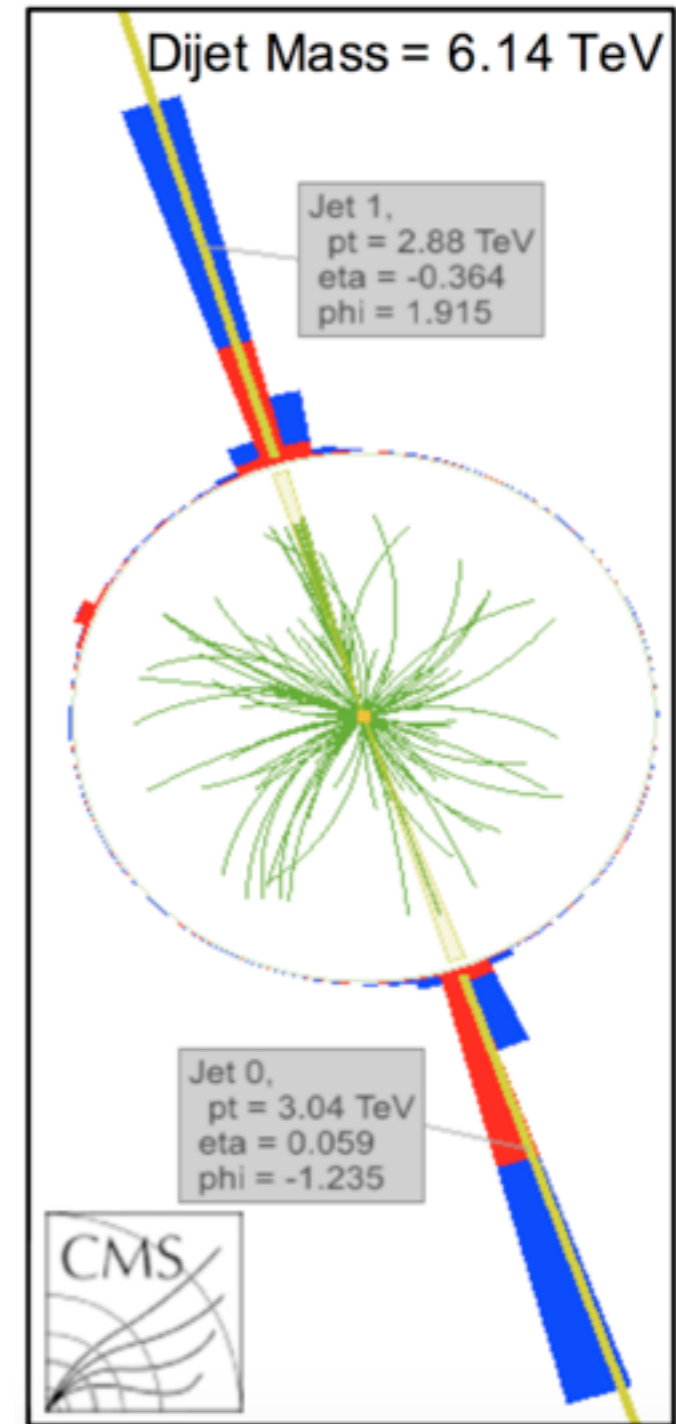
$$\rho = \frac{p}{ZeB}$$

nuno

# a di-jet event



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



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



Run 251244 Event 204117665

$\sqrt{s} = 13 \text{ TeV}$

$\mu_1$   
 $p_T = 58.7 \text{ GeV}$   
 $\eta = 1.8$

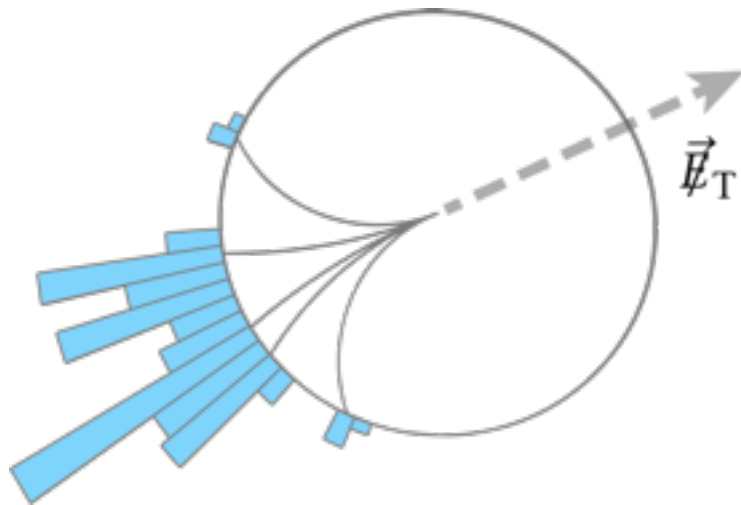
$pp \rightarrow ZZ \rightarrow 2e2\mu$   
 $m_{\mu\mu} = 91.1 \text{ GeV}$   
 $m_{ee} = 88.2 \text{ GeV}$   
 $m_{4\ell} = 208.9 \text{ GeV}$

$e_1$   
 $p_T = 63.3 \text{ GeV}$   
 $\eta = 1.2$

$\mu_2$   
 $p_T = 36.1 \text{ GeV}$   
 $\eta = 0.98$

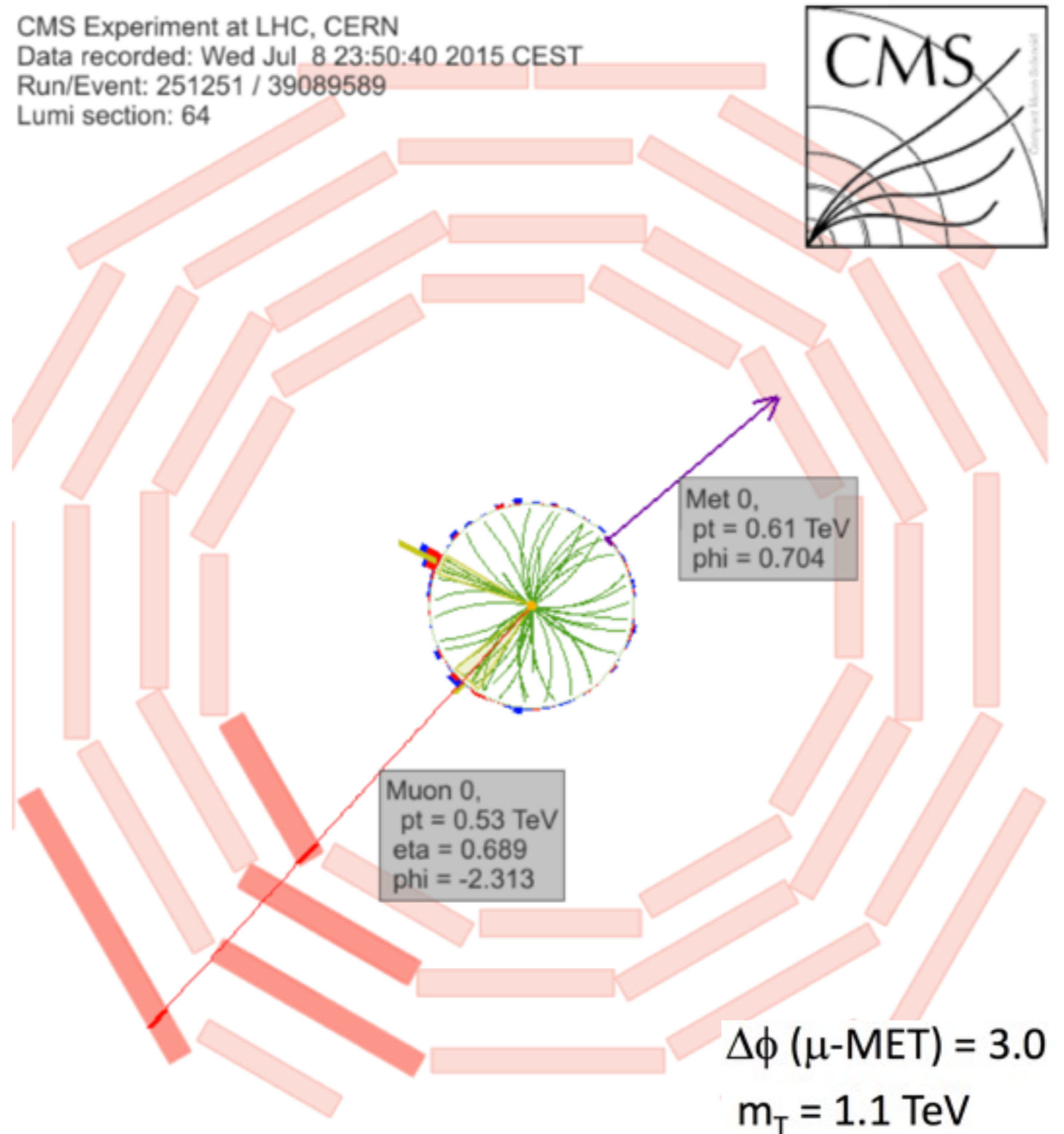
$e_2$   
 $p_T = 25.5 \text{ GeV}$   
 $\eta = 0.20$

# a muon + missing $E_T$ event



- missing transverse momentum (**MET**)
  - momentum imbalance in the plane perpendicular to the beam direction
  - sources: the neutrinos; other undetectable particles (LSP, graviton, DM, ... other?)

CMS Experiment at LHC, CERN  
Data recorded: Wed Jul 8 23:50:40 2015 CEST  
Run/Event: 251251 / 39089589  
Lumi section: 64



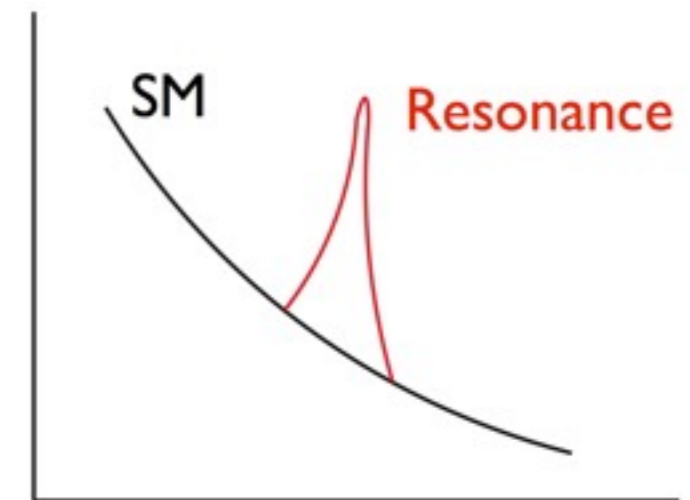
# resonances

- a particle resonance is mathematically described by a relativistic Breit-Wigner distribution

- may be derived from propagator form

$$\left| \frac{1}{s - m^2 + im\Gamma} \right|^2 = \frac{1}{(s - m^2)^2 + m^2\Gamma^2} \quad \begin{array}{l} \text{mass, } \mathbf{m} \\ \text{width, } \mathbf{\Gamma=1/\tau} \end{array}$$

- **narrow** resonances appear in reconstructed mass spectra as peaks whose width is determined by (Gaussian) detector resolution

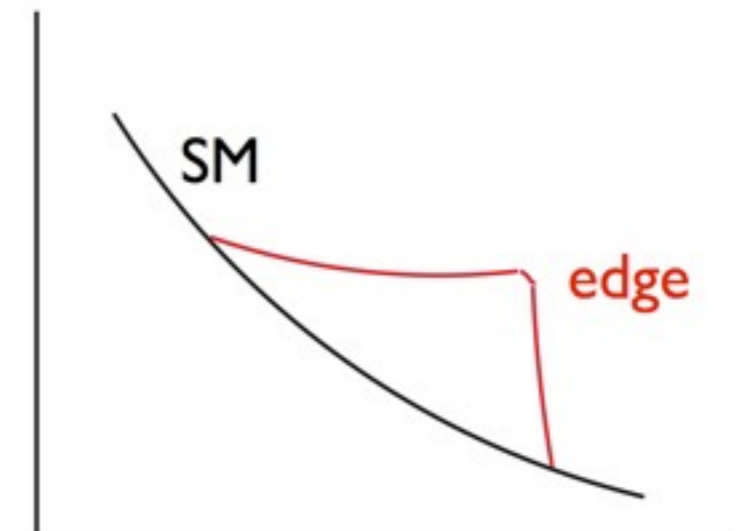


- search for new resonance  $\implies$  “bump hunting”

- if not all final state particles are detected

- **transverse mass** has **endpoint** at true mass:  $M_T \lesssim M$

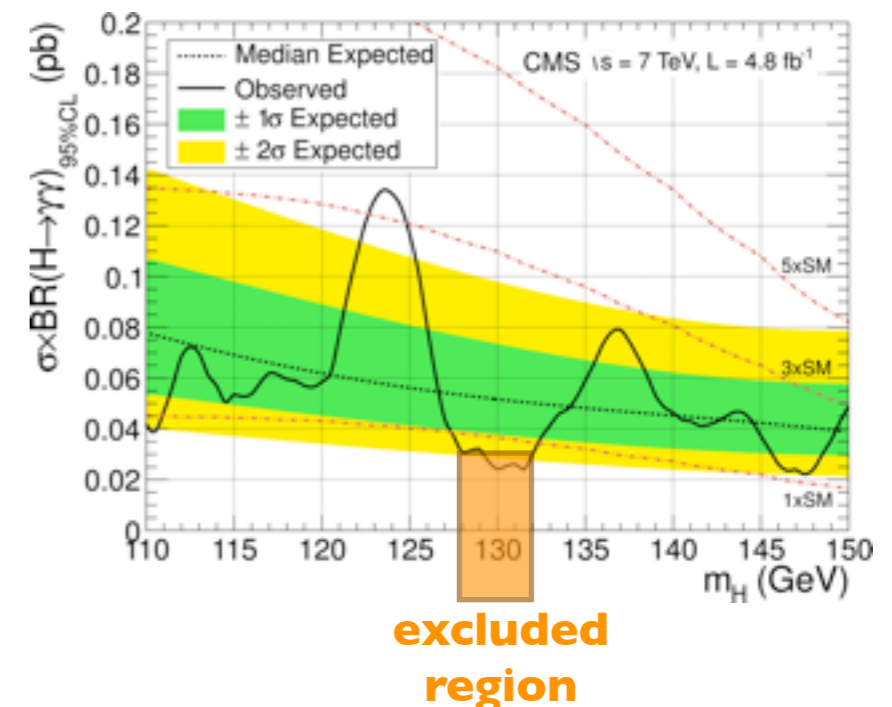
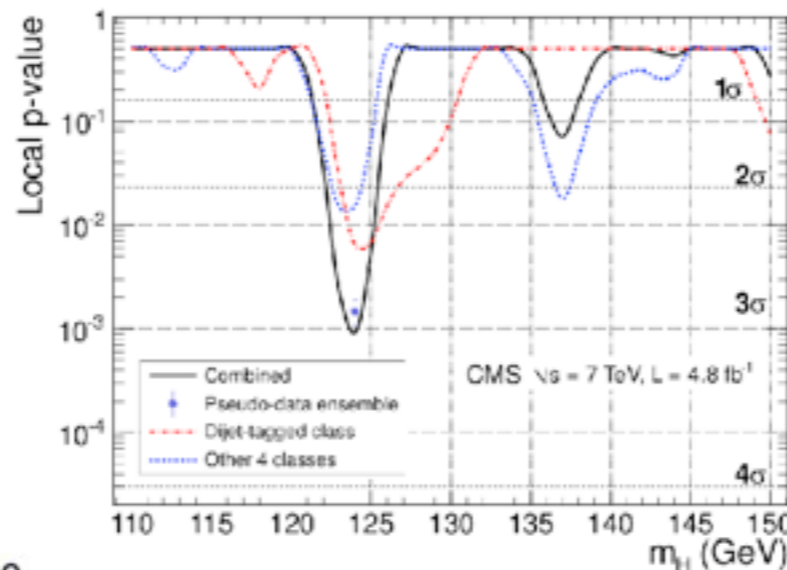
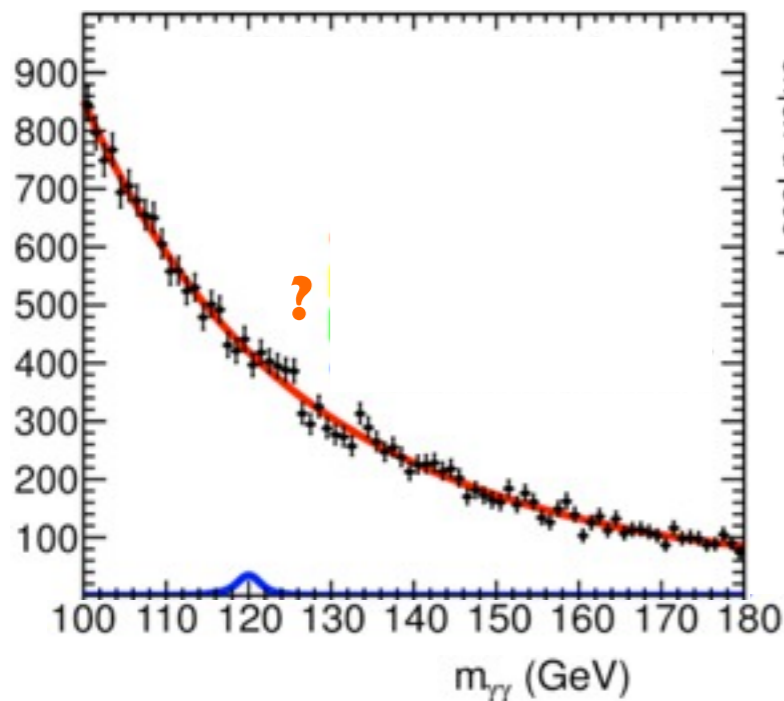
- eg  $W' \rightarrow l \nu \implies M_T = \sqrt{2 \cdot p_T^\ell \cdot E_T^{\text{miss}} \cdot (1 - \cos \Delta\phi_{\ell, \nu})}$

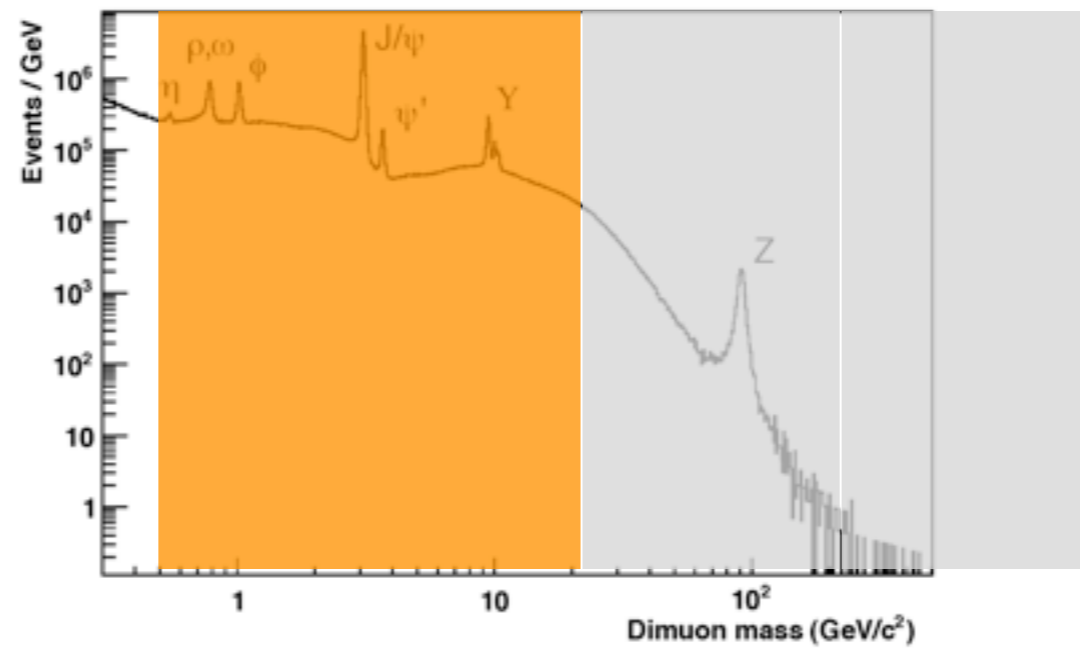


$$M_T^2 = (E_{T,1} + E_{T,2})^2 - (\vec{p}_{T,1} + \vec{p}_{T,2})^2 \xrightarrow{m_1 \sim m_2 \rightarrow 0} 2E_{T,1}E_{T,2}(1 - \cos \phi)$$

# signal significance

- once an hint of a resonance is detected in a mass spectrum, one needs to quantify its statistical significance, namely probability that excess is due to a statistical fluctuation of background as opposed to genuine new physics signal
- p-value: probability of obtaining at least as extreme results as observed in data assuming the null hypothesis is true (tested with pseudo experiments)
- p-value is expressed in number of standard deviations of normal distribution:
  - eg discovery  $\Leftrightarrow 5\sigma \Leftrightarrow$  p-value: 1 part in 3.5 million
- a realistic example:





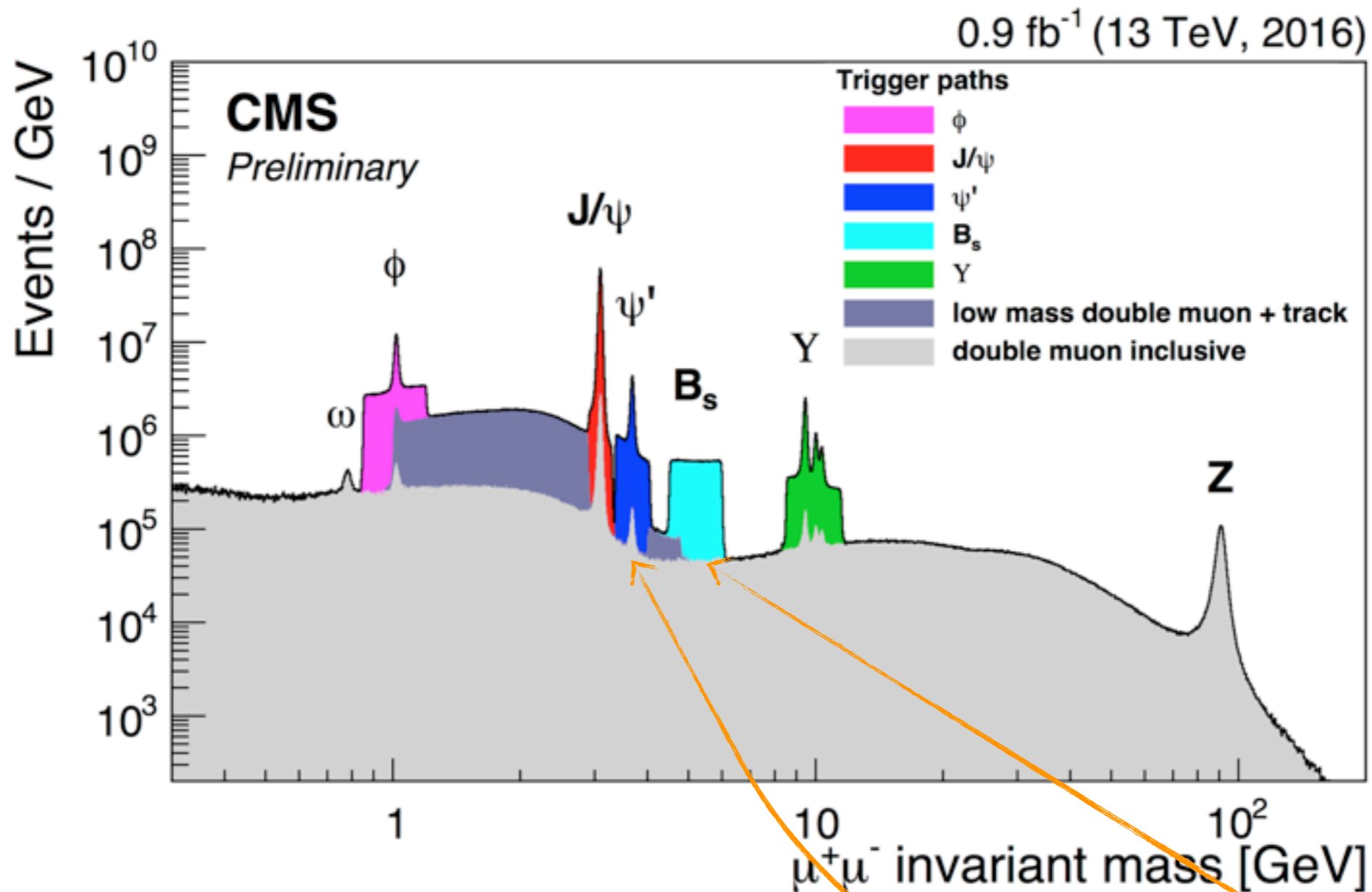
resonances: low mass

# low-mass resonances

- realm of QCD
  - hadrons, heavy flavor, quarkonia and B physics
  - exotic hadron states
- New Physics via
  - precision measurement of particle properties
  - rare (heavy flavor) decays
  - possible new light states
- Disclaimer
  - focus on hadron production, not their properties



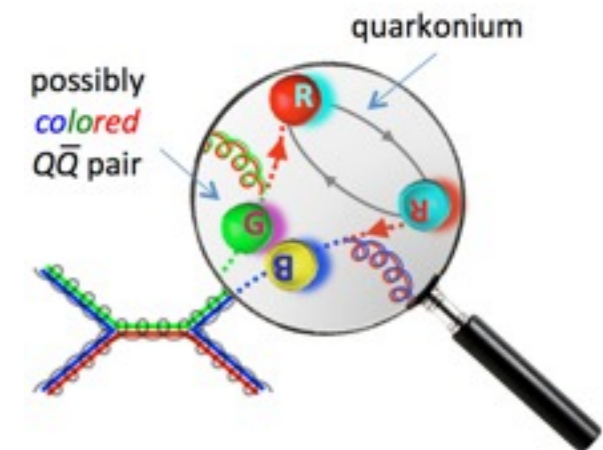
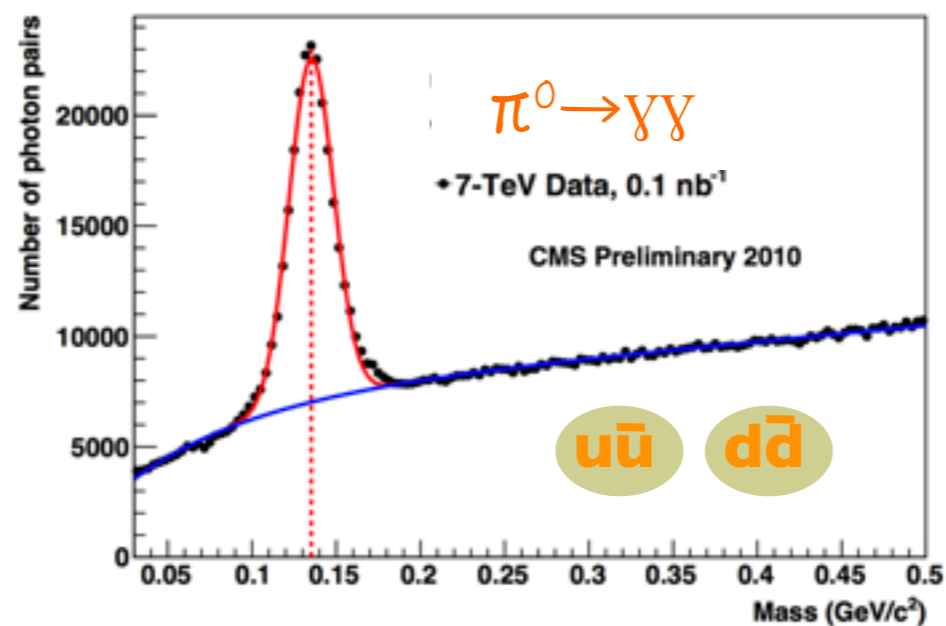
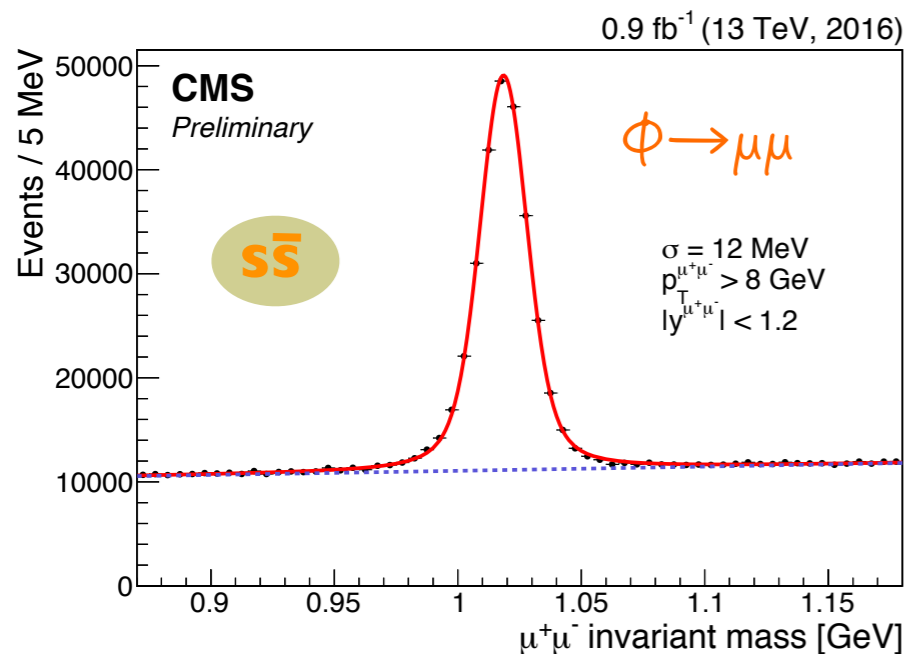
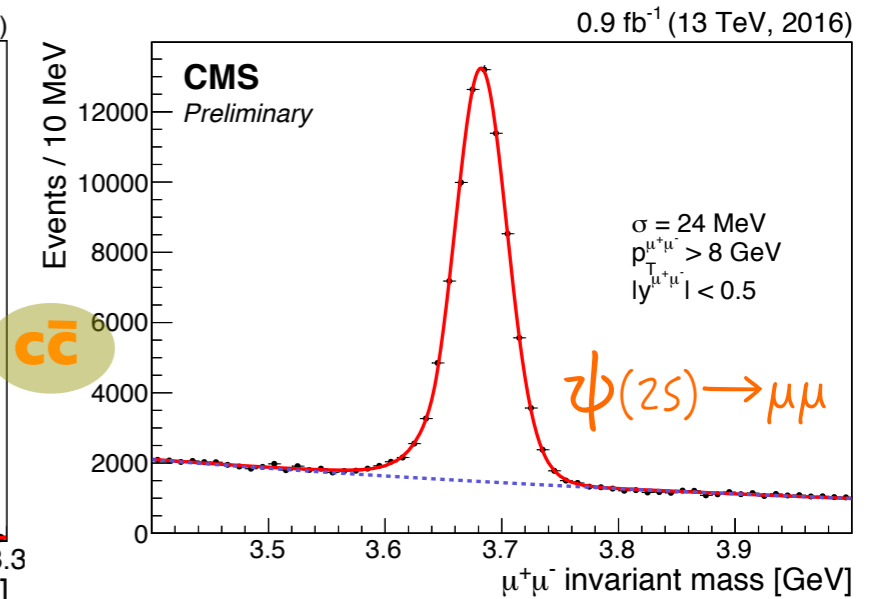
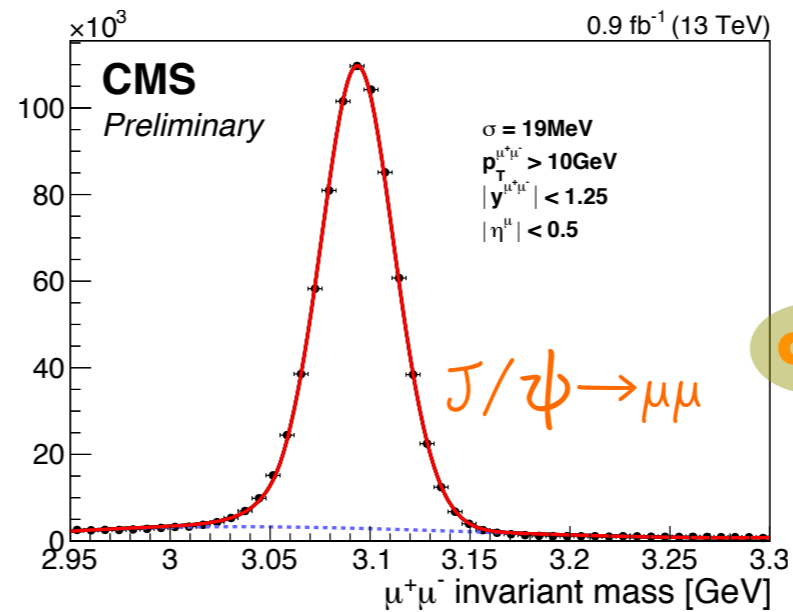
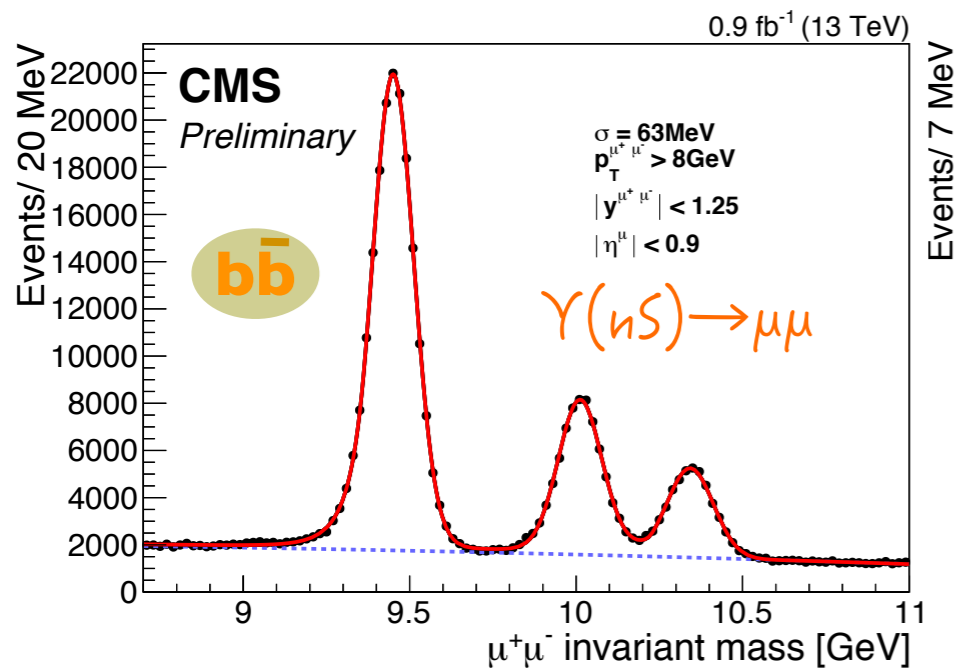
# resonances to di-muons



- **Trigger**

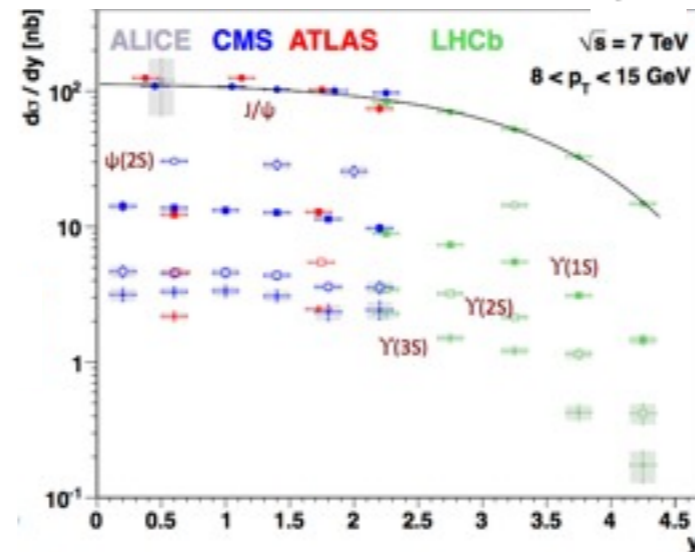
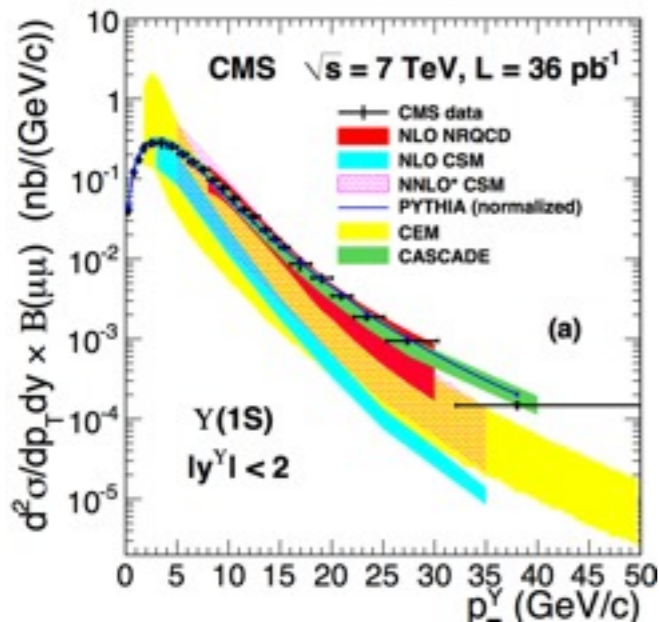
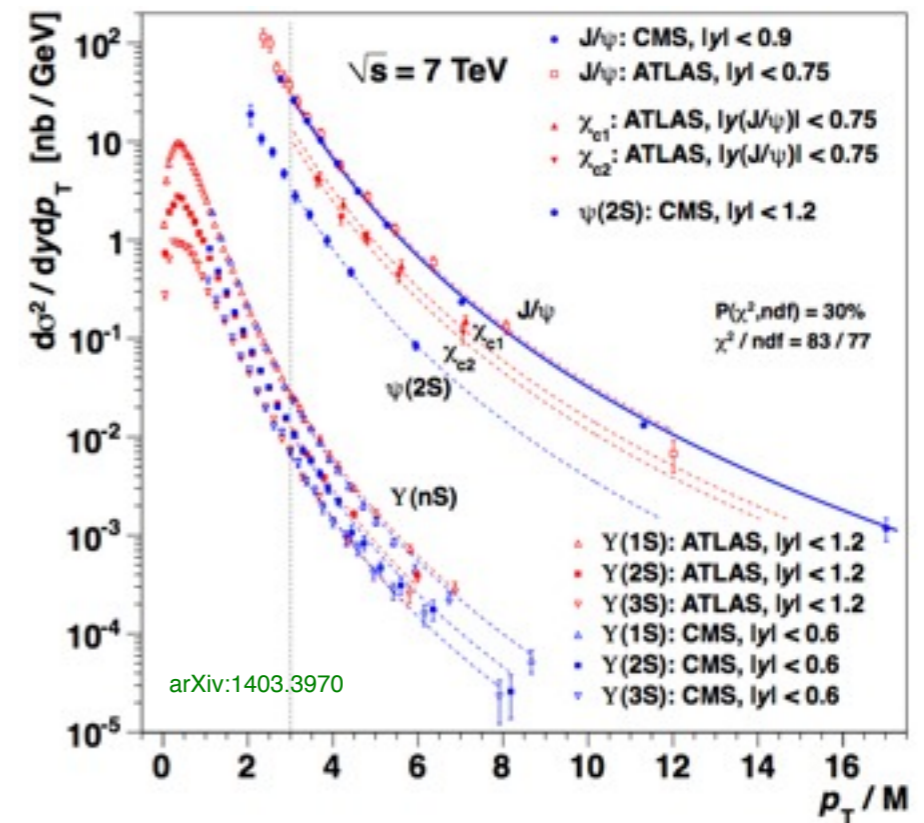
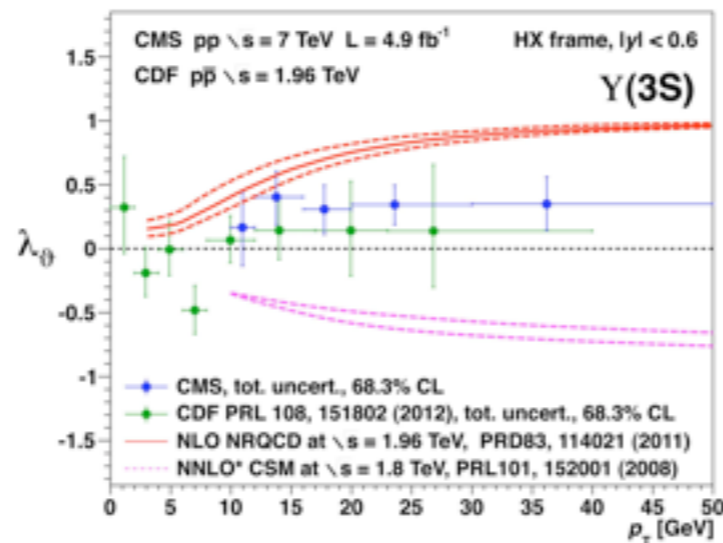
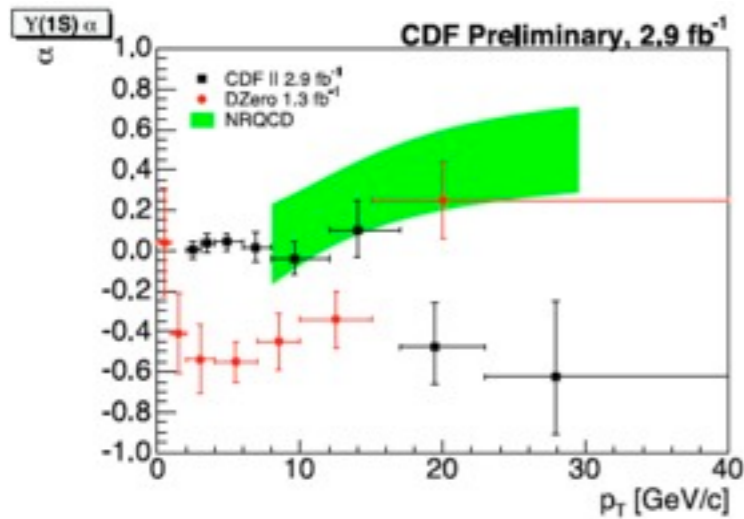
- the first, critical ingredient of any LHC analysis
- plot highlights dedicated triggers for heavy-flavor **measurements** and **searches**

# quarkonium resonances



# [extra: quarkonia and hadron production mechanisms]

- heavy quarkonia (discovered 40 years ago!) is an ideal laboratory in which to study QCD

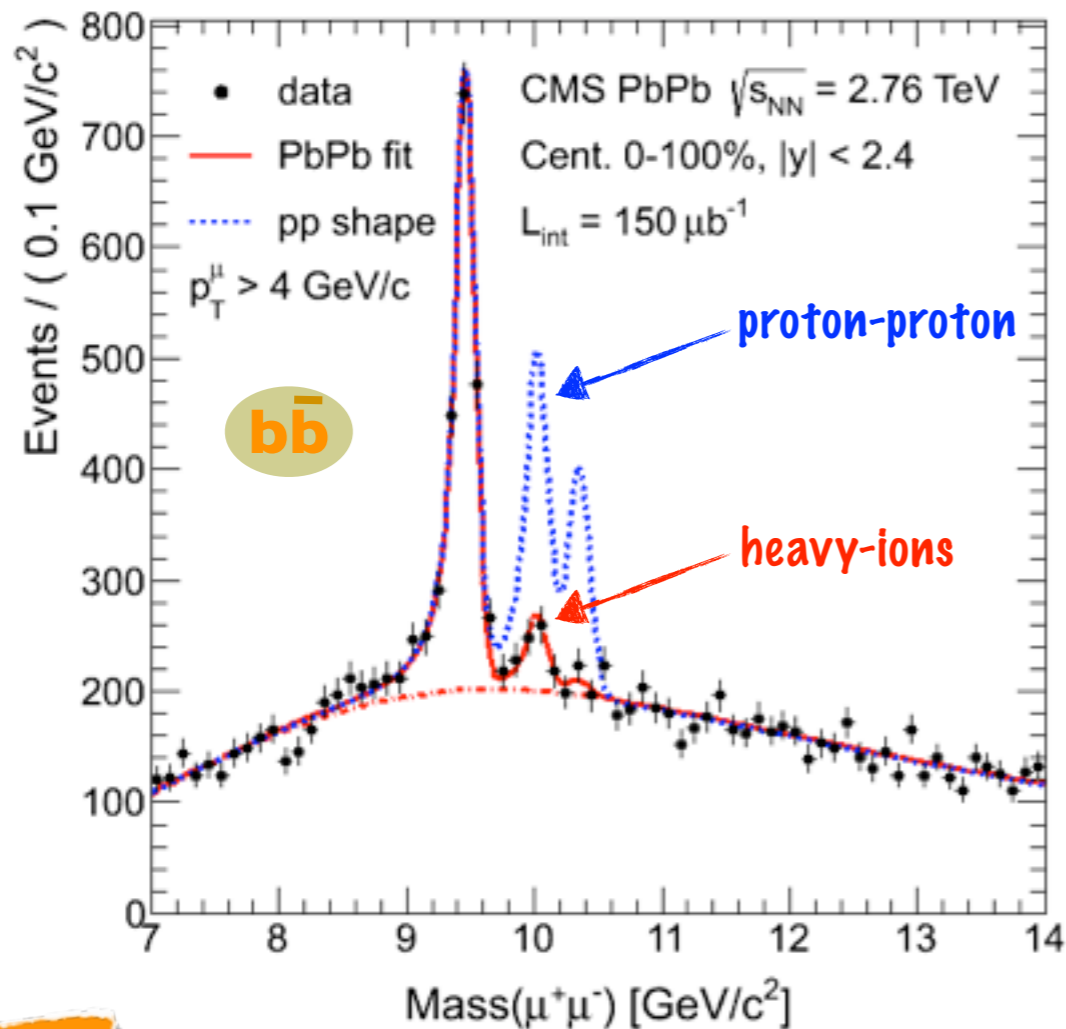


note:  $p_T$  is mass-rescaled to equalize kinematic effects of different average parton momenta and phase spaces

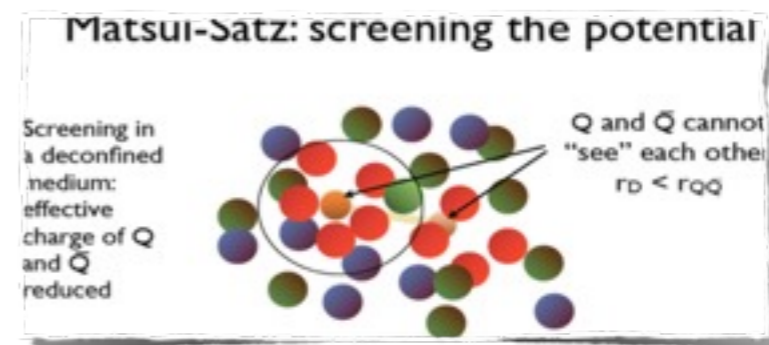
- cross sections for 7 quarkonia have similar  $p_T/M$  shapes (for  $p_T/M > 3$ )
- polarizations for 5 quarkonia tend (similarly) to unpolarized limit
  - Ockham hints: all quarkonia dominantly produced by a single mechanism...
- ➡ LHC Run2 will allow to explore the higher  $p_T$  regime (which is the most sensitive)

# resonance *disappearance*

- nominally we search for the appearance of unknown new resonances
- sometimes we search for the **disappearance** of known old resonances



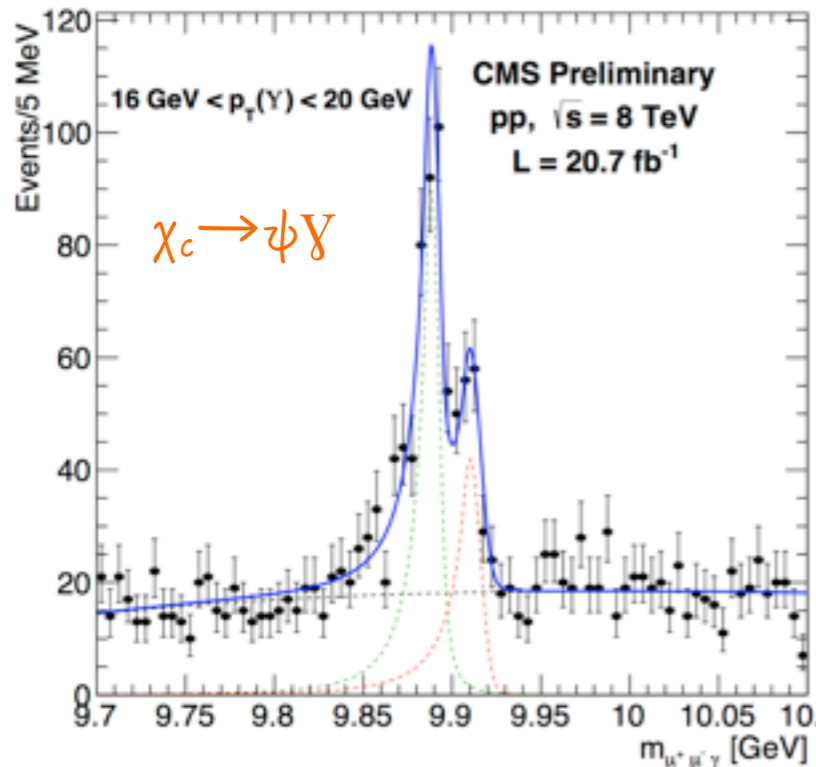
- the three  $Y(nS)$  states are reconstructed for the first time in heavy ion collisions
- excited states more suppressed than ground state ( $>5\sigma$  observation)
- discovered and established pattern of quarkonium sequential melting
  - less tightly bound states more suppressed
- spectacular indication of **QGP** @ LHC



found  
@LHC

“text book” result  
in heavy ion collisions

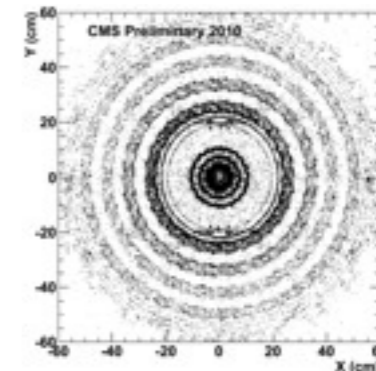
# di-muons + photons



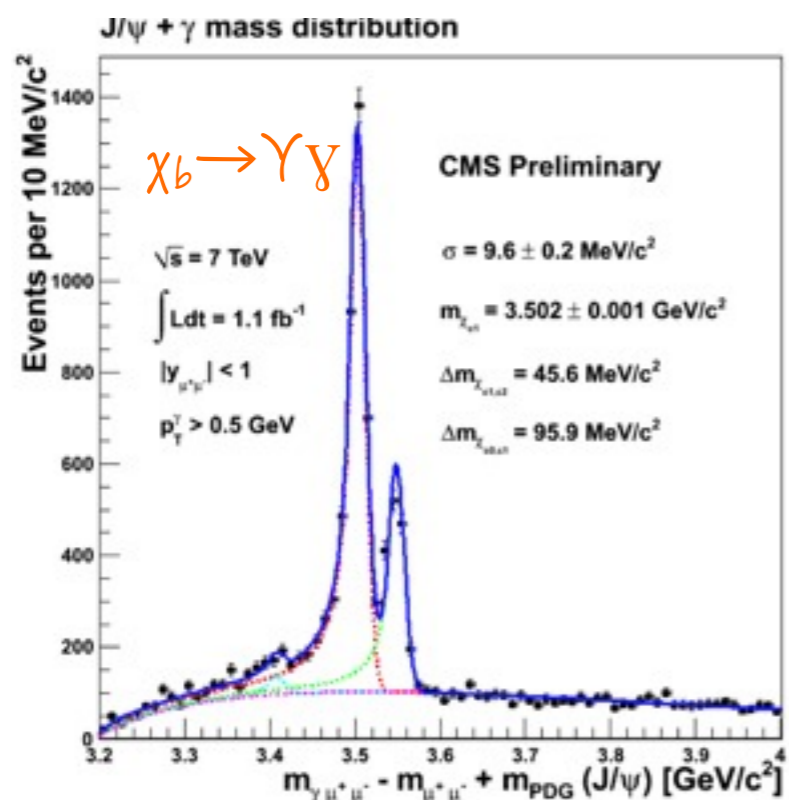
$c\bar{c}$

- excited (p-wave) quarkonia states
- reconstruct soft photon via conversions

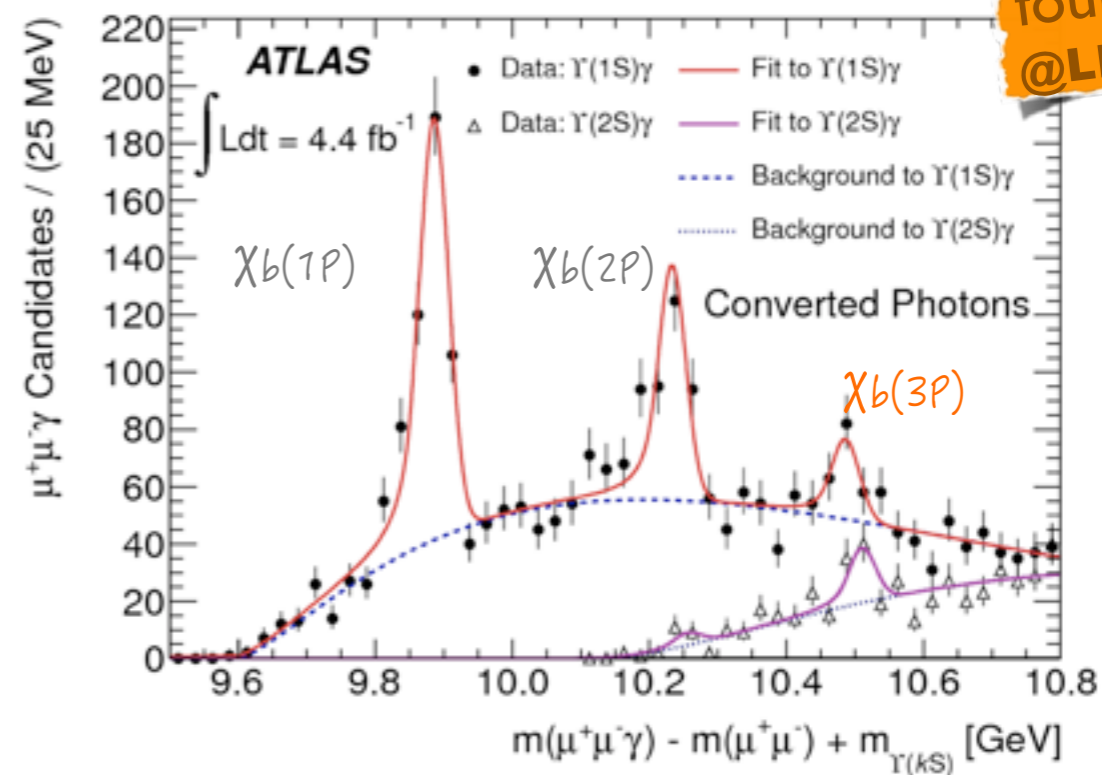
$$\chi_b \rightarrow \Upsilon \gamma \begin{cases} \rightarrow e^+e^- \\ \rightarrow \mu^+\mu^- \end{cases}$$



- $\chi_b(3P)$ : first new meson observed at LHC



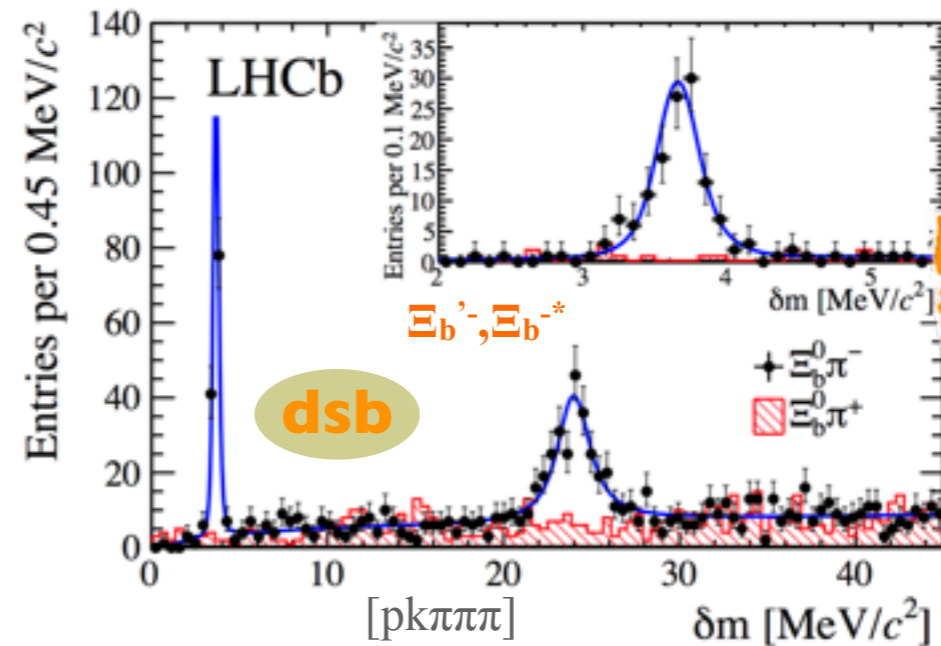
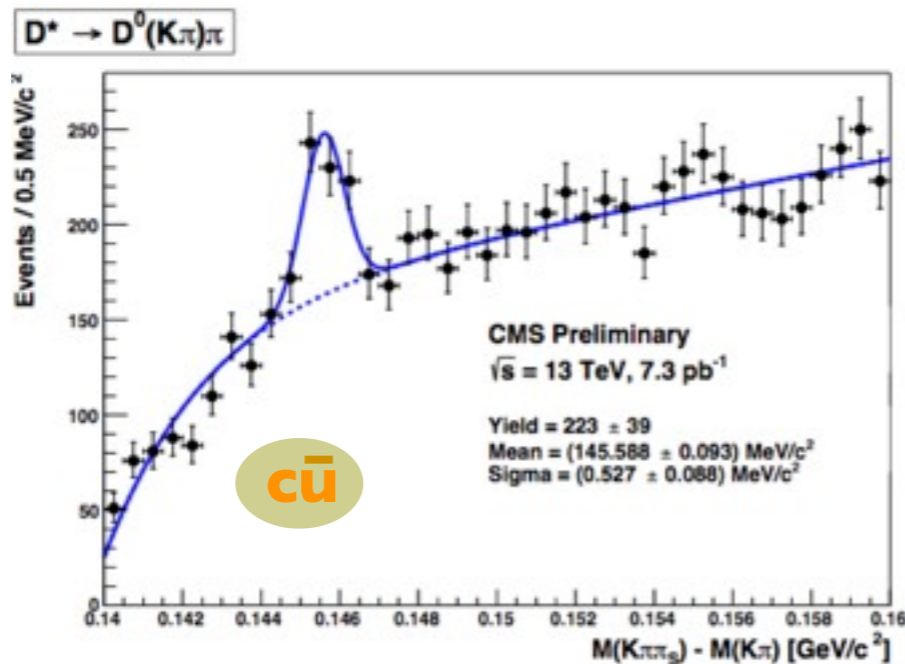
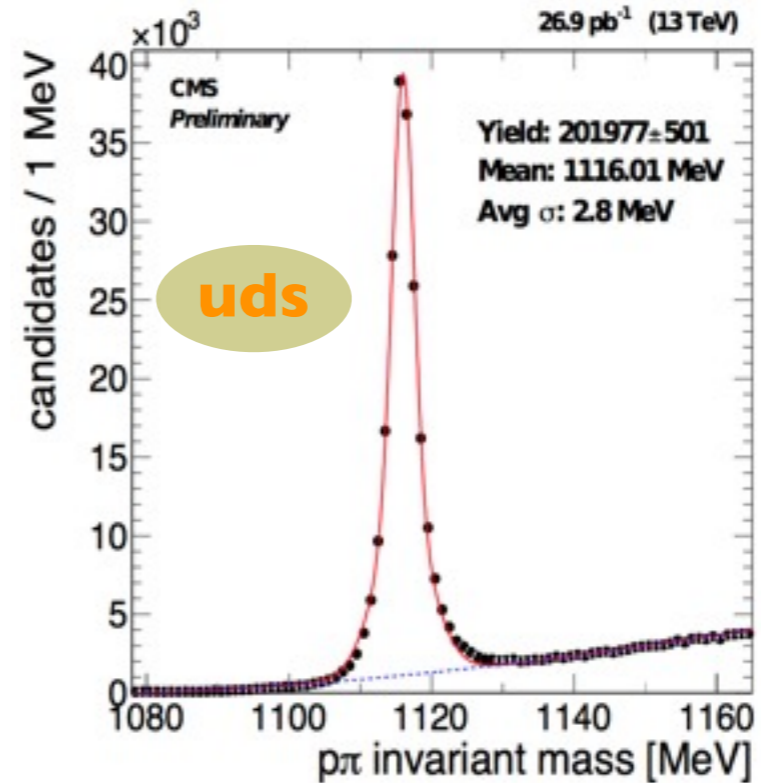
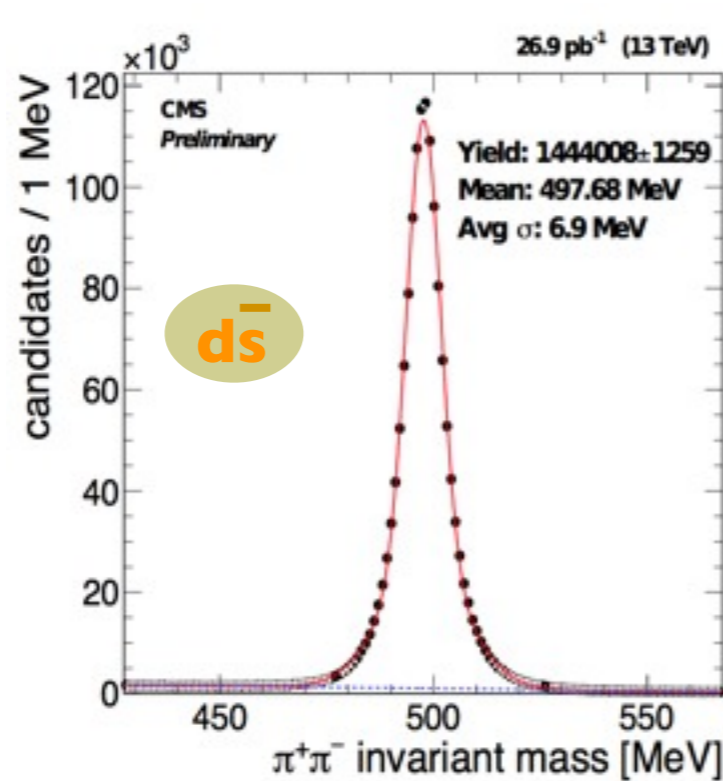
$b\bar{b}$



found @LHC

# charged 'tracks'

- low momentum charged, stable hadrons are reconstructed in the tracker, and are used in turn to reconstruct other, unstable hadronic resonances

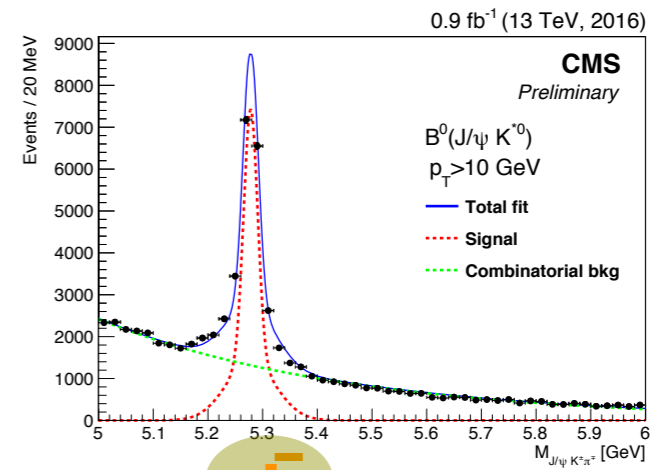
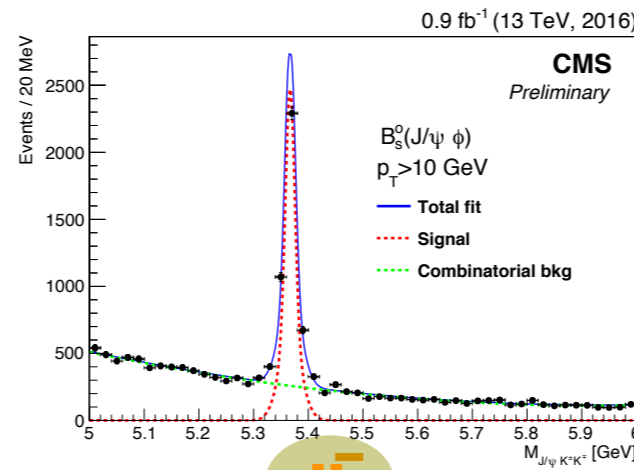
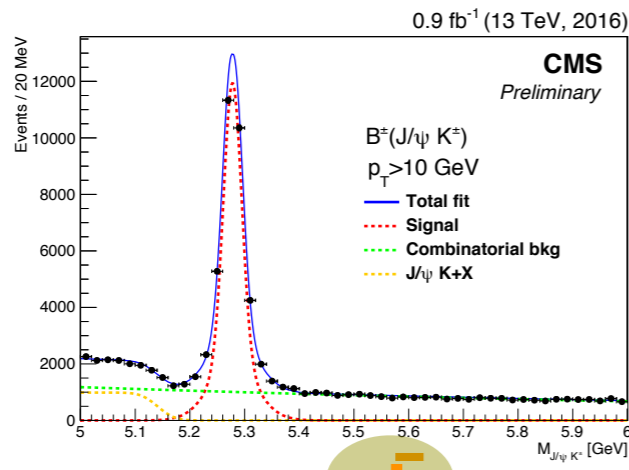


found @LHC

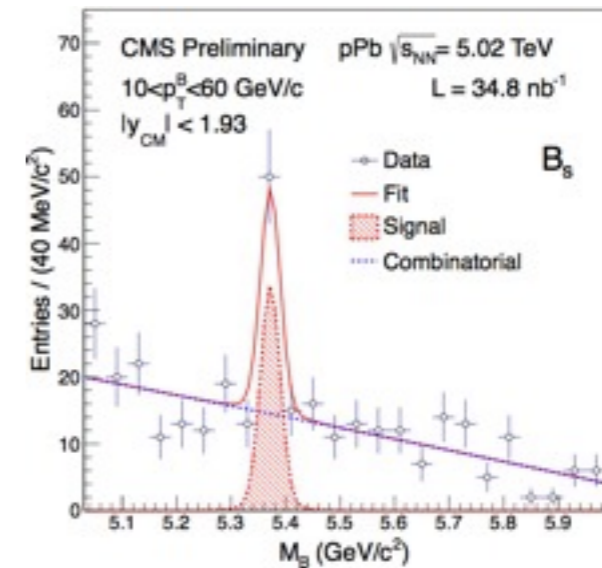
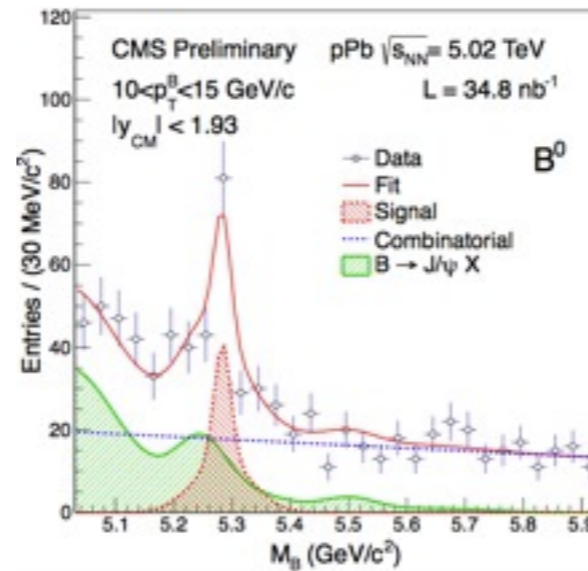
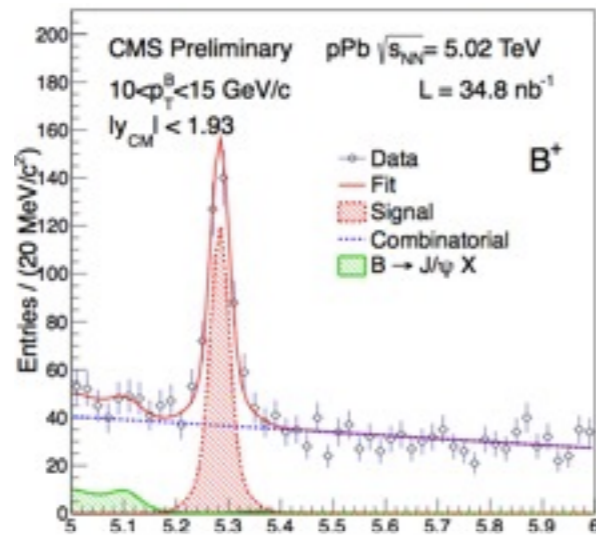
# muons + tracks

type of collisions:

pp



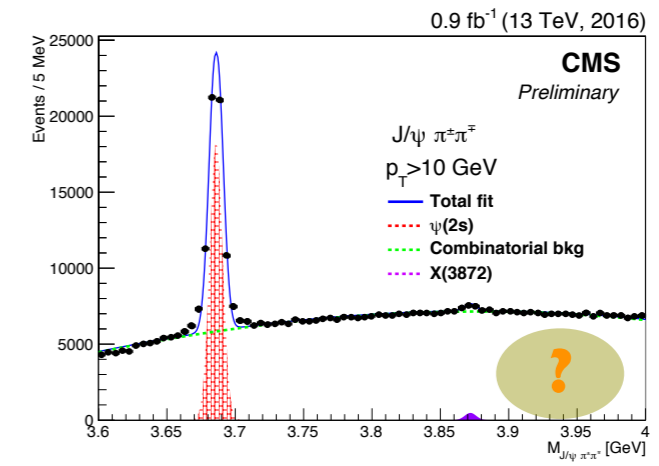
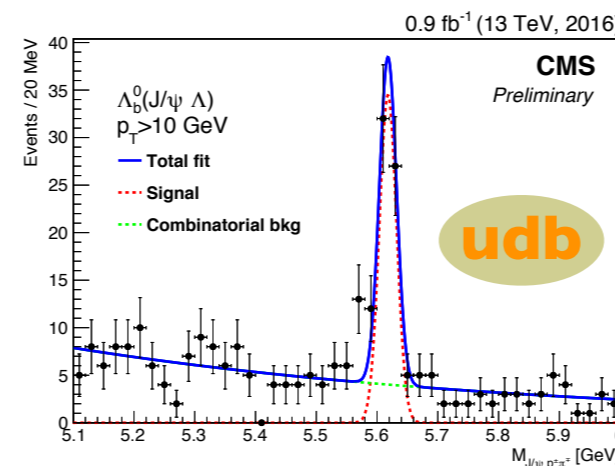
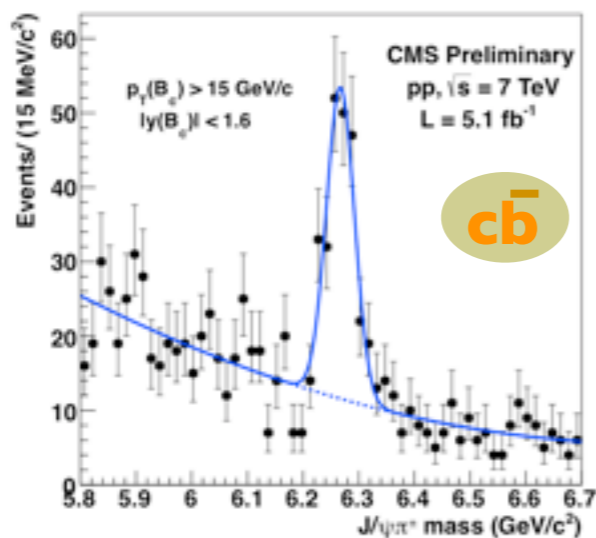
p+Pb (!)



found @LHC

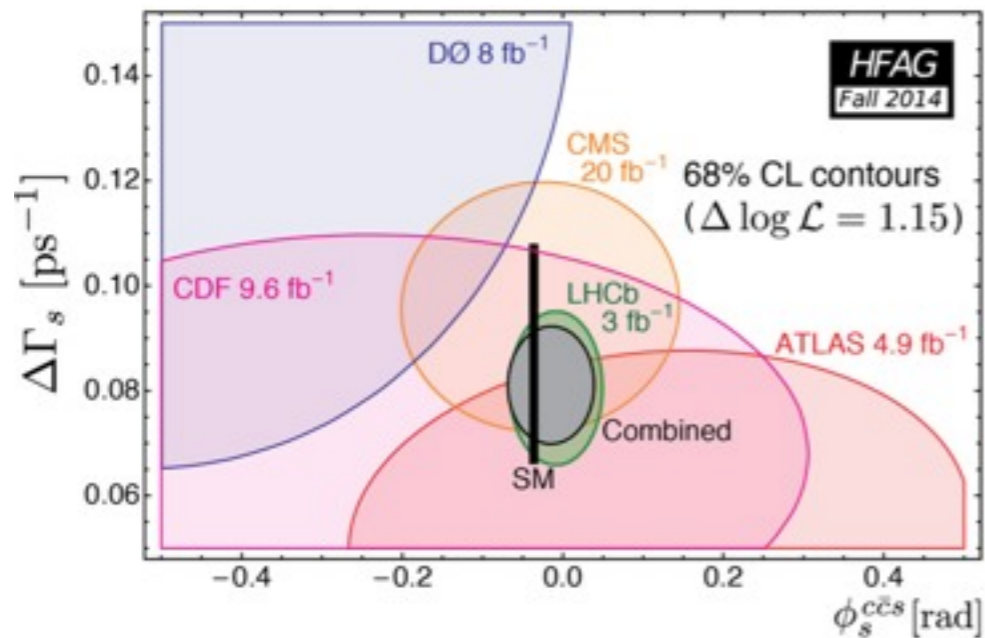
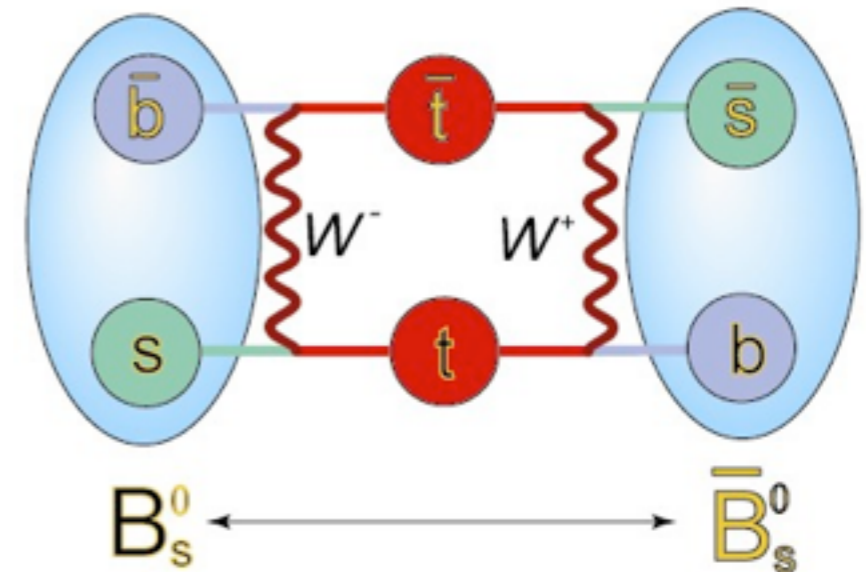
for first time in ion collisions

pp

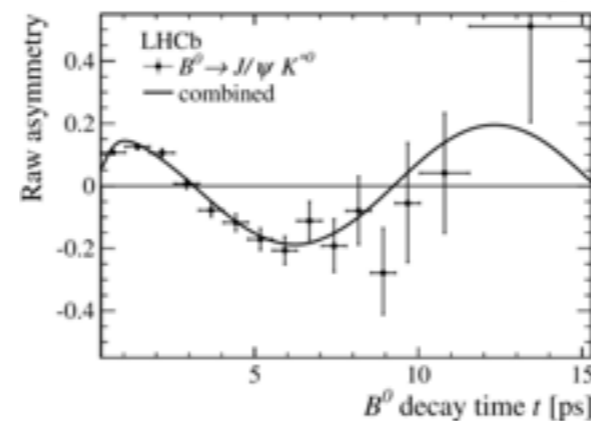
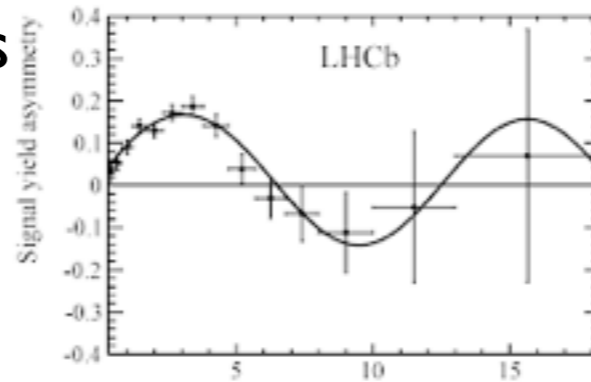


# [extra: resonance oscillations]

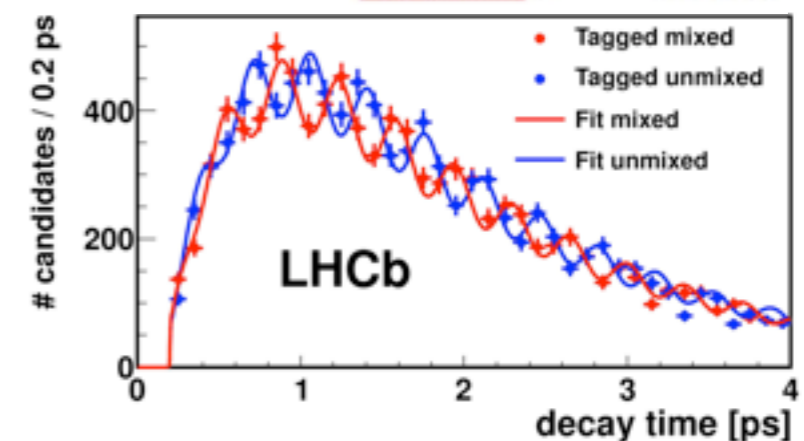
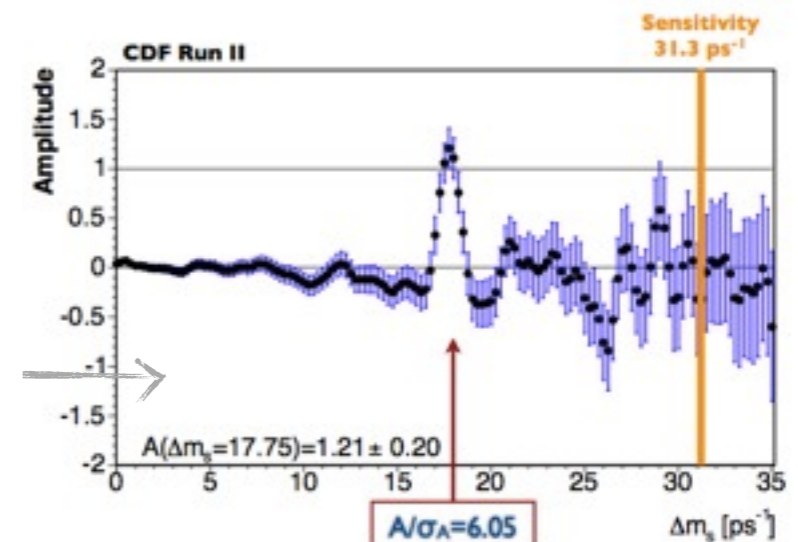
- neutral mesons undergo spontaneous, rapid particle-antiparticle transitions
  - a purely quantum mechanical phenomenon
- contributions of new heavy particles in the loop may modify the oscillation frequency ( $\Delta m$ ) or CPV phase ( $\Phi$ )
  - sensitive to New Physics



nuno@cern.ch



Resonances & NP



22



# [extra: quantum mechanics of particle oscillations]

- allowing for a flavor-changing perturbation ( $\Delta F$ ) in the hamiltonian

$$\mathcal{H} = \mathcal{H}_0 + \mathcal{H}_{\Delta F} \quad i \frac{d}{dt} \psi = \mathcal{H} \psi \quad i \frac{d}{dt} \begin{pmatrix} a \\ b \end{pmatrix} = \begin{pmatrix} m - \frac{i}{2}\Gamma & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{12}^* - \frac{i}{2}\Gamma_{12}^* & m - \frac{i}{2}\Gamma \end{pmatrix} \begin{pmatrix} a \\ b \end{pmatrix}$$

$$|\psi\rangle = a |P^0\rangle + b |\bar{P}^0\rangle$$

- a pure flavor eigenstate at  $t=0$  will evolve to an admixture
  - non-diagonal elements in  $H \Rightarrow$  flavor eigenstates differ from mass eigenstates

$$\begin{aligned} |P_L\rangle &= p |P^0\rangle + q |\bar{P}^0\rangle \\ |P_H\rangle &= p |P^0\rangle - q |\bar{P}^0\rangle \end{aligned} \quad \text{with } |p|^2 + |q|^2 = 1$$

- time evolution of flavor eigenstates (after finding  $H$  eigenvalues  $\lambda_{H,L}$ )

$$|P_{L,H}\rangle_t = e^{-i\lambda_{L,H}t} |P_{L,H}\rangle = e^{-im_{L,H}t - \frac{1}{2}\Gamma_{L,H}t} |P_{L,H}\rangle$$

- probability for particle-antiparticle transition

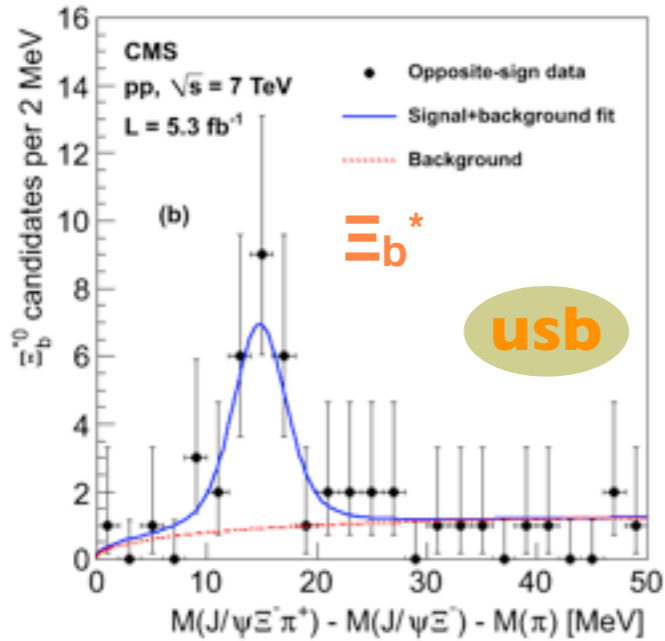
$$|\langle P^0 | \mathcal{H} | \bar{P}^0 \rangle|^2 = \left| \frac{p}{q} \right|^4 |\langle \bar{P}^0 | \mathcal{H} | P^0 \rangle|^2 = \left| \frac{p}{q} \right|^2 \frac{1}{2} e^{-\Gamma t} \left[ \cosh \left( \frac{\Delta\Gamma}{2} t \right) - \cos(\Delta m t) \right]$$

with  $\Delta\Gamma \equiv \Gamma_L - \Gamma_H$  and  $\Delta m \equiv m_H - m_L$

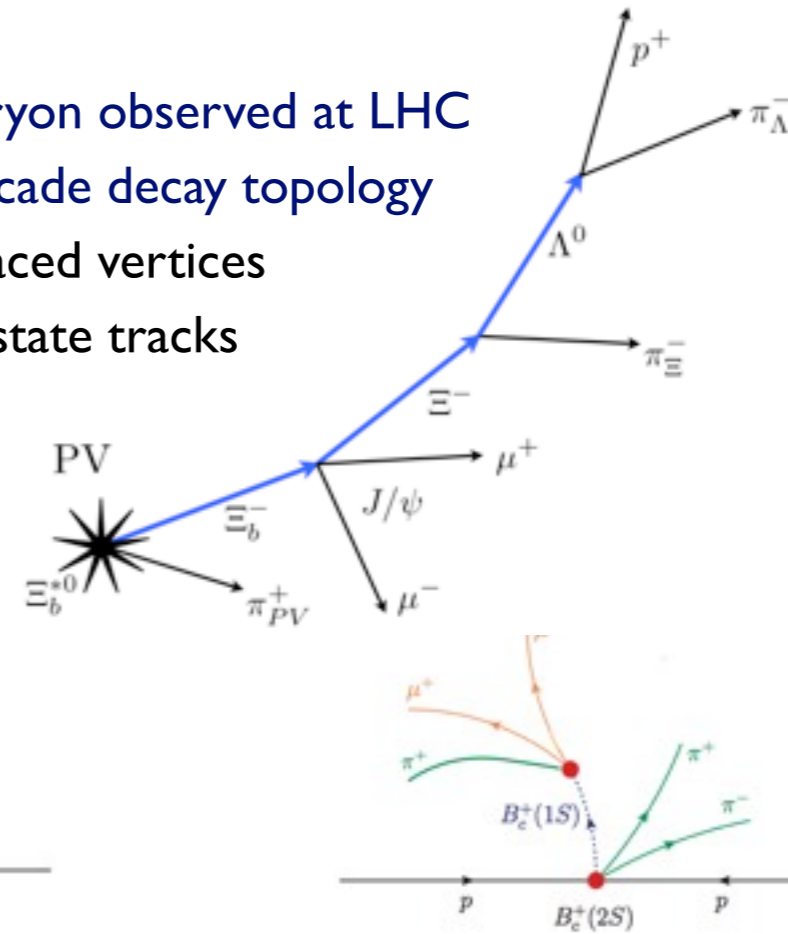
- neglecting CPV in mixing (i.e.  $p/q=1$ ) and  $\Delta\Gamma$ , the mixing probability is:

$$\mathcal{P}_{B_q^0 \rightarrow \bar{B}_q^0}(t) = \mathcal{P}_{\bar{B}_q^0 \rightarrow B_q^0}(t) = \frac{\Gamma}{2} e^{-\Gamma t} [1 - \cos(\Delta m t)]$$

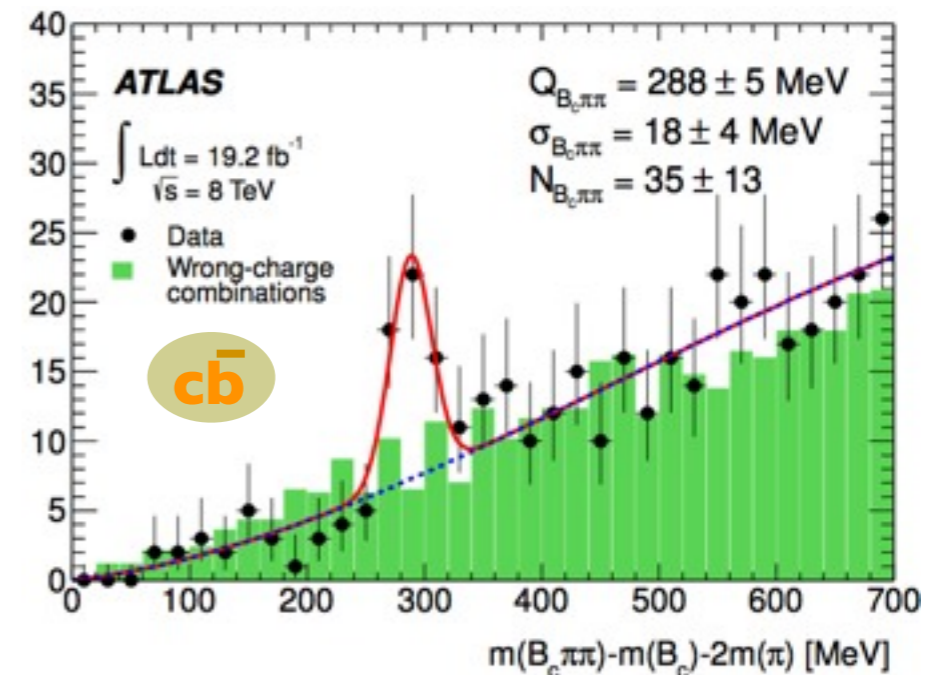
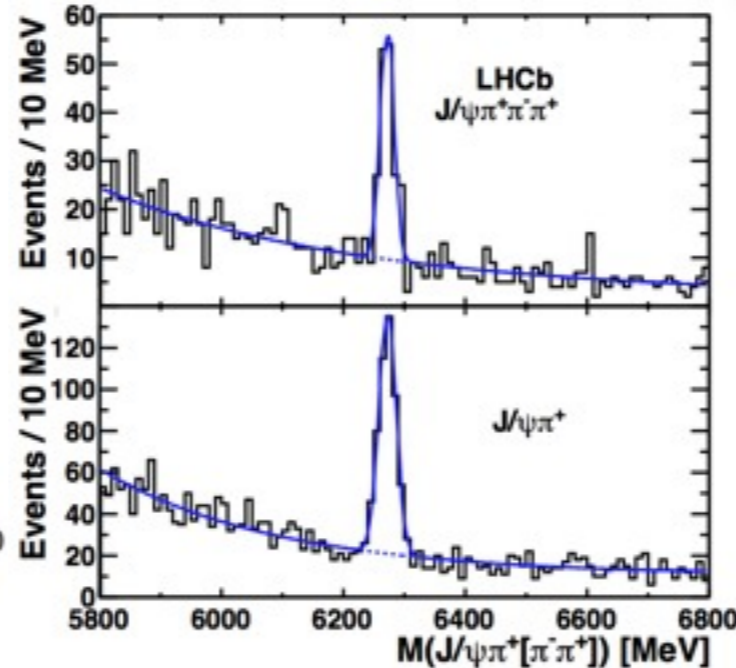
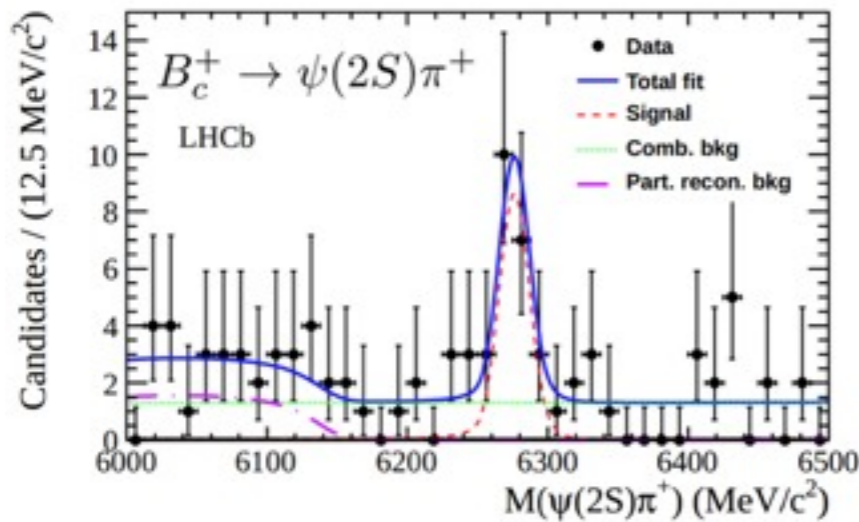
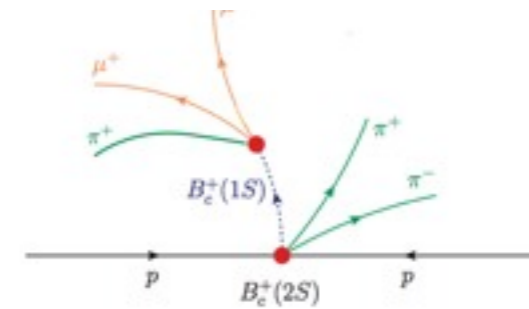
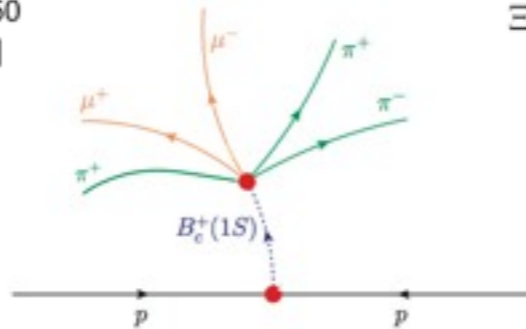
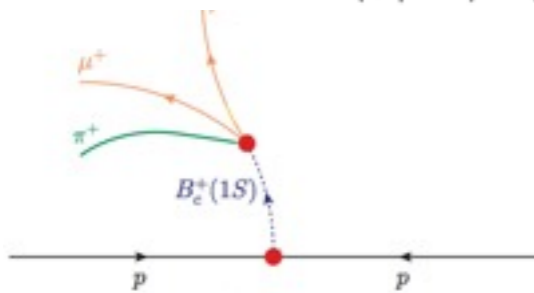
# new hadron resonances with $J/\psi$ + tracks



- first new baryon observed at LHC
- complex cascade decay topology
  - 4 displaced vertices
  - 6 final state tracks

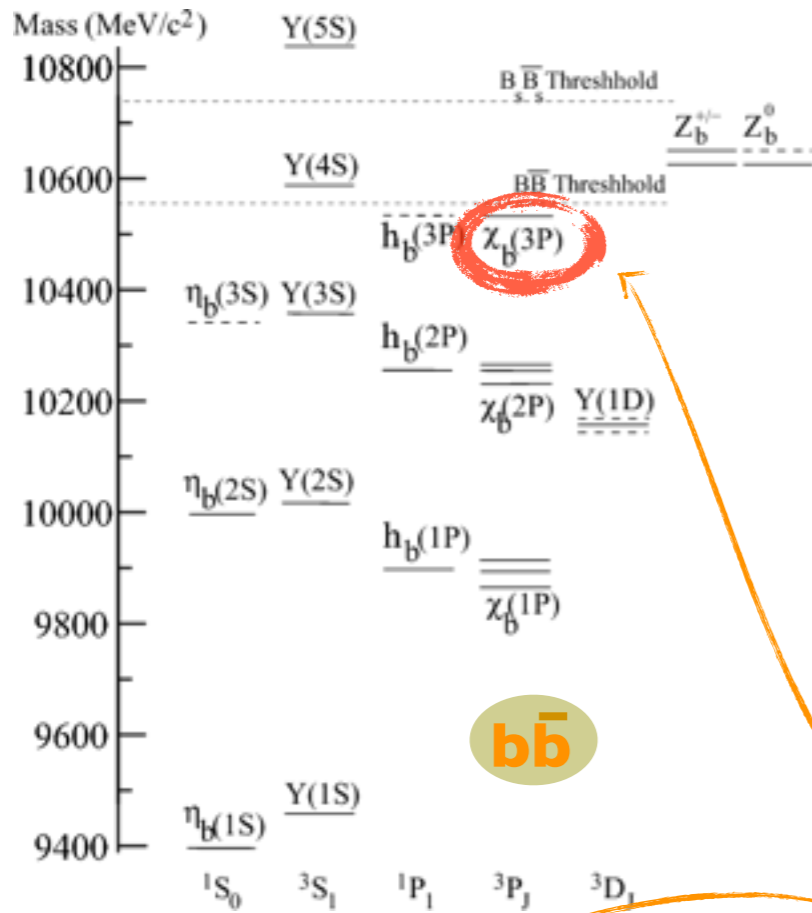


found @LHC



# [extra: beauty spectroscopy]

## mesons



A decade ago, only one b baryon had been seen:  $\Lambda_b$

CDF and D0 contributed several such discoveries:

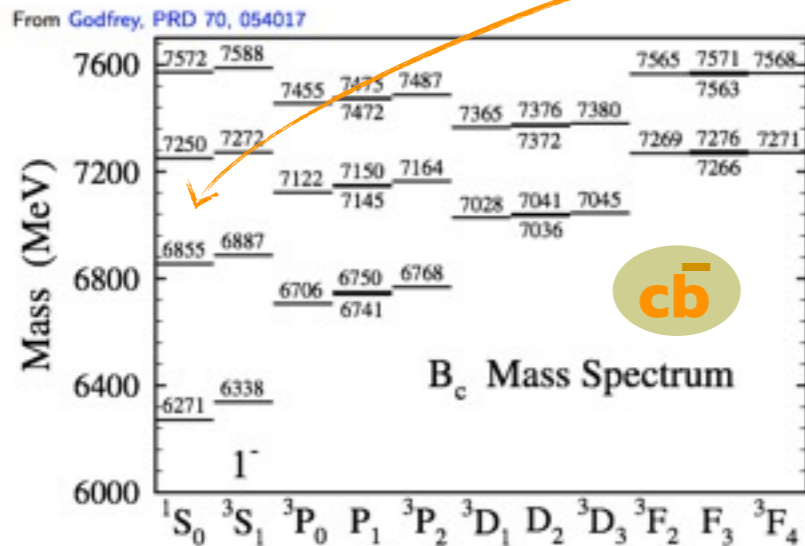
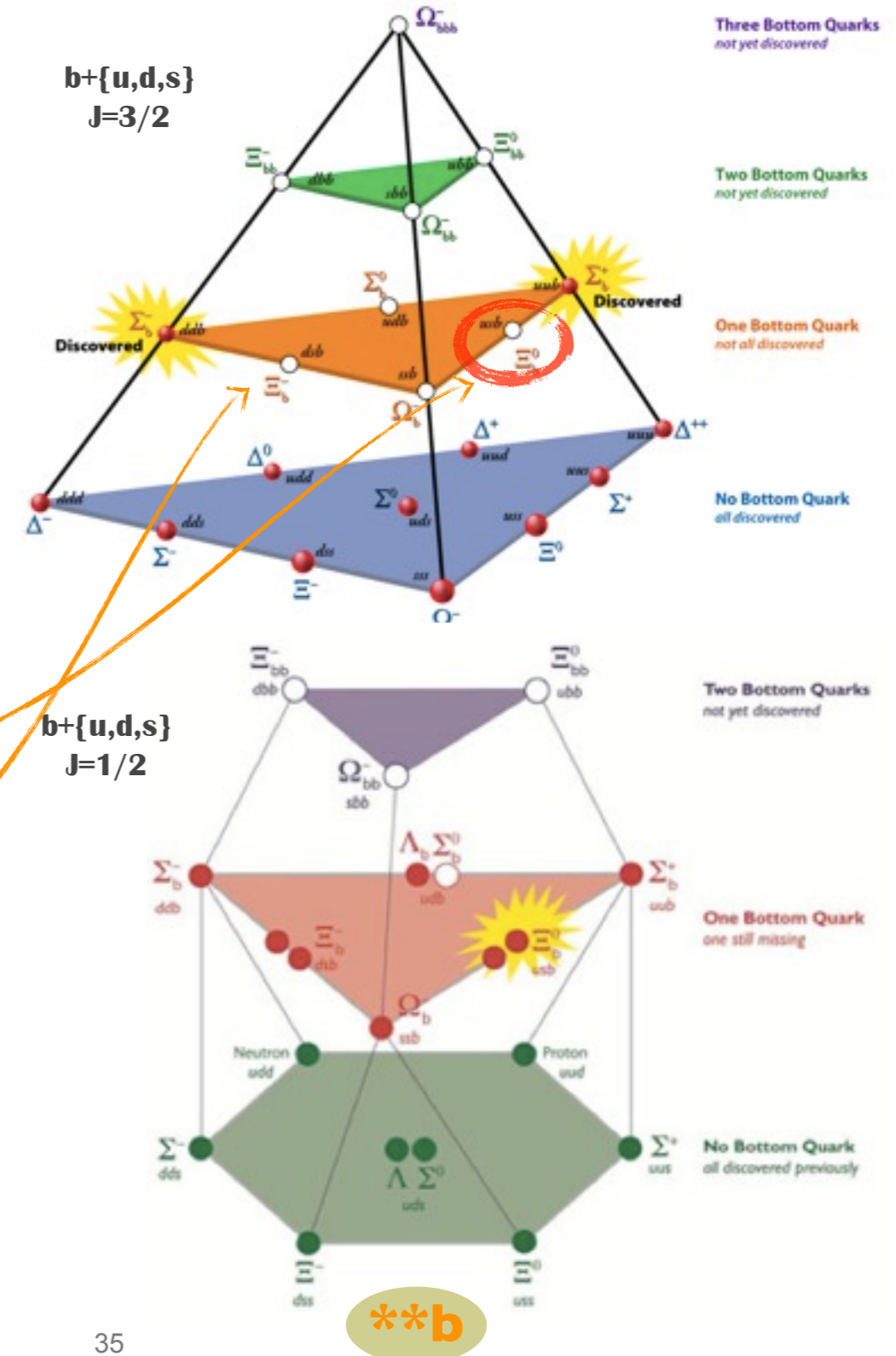
- ▶  $\Sigma_b^-$  (2006)
- ▶  $\Xi_b^-$  (2007)
- ▶  $\Omega_b$  (2008)

LHC:

- ▶  $\chi_b(3P)$  (ATLAS' 2011)
- ▶  $\Xi_b^{*0}$  (CMS'2012)
- ▶  $B_c(2S)$  (ATLAS'2014)
- ▶  $\Xi_b^{*-}$ ,  $\Xi_b'^-$  (LHCb'2014)

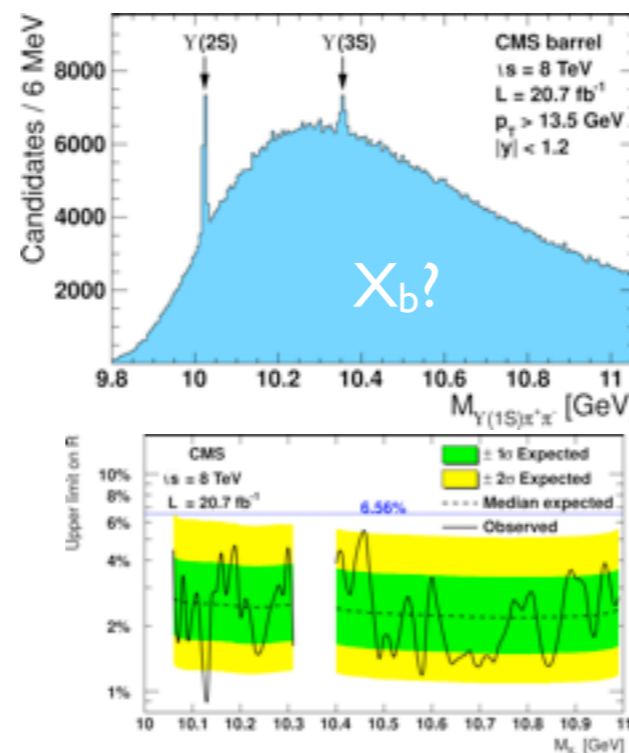
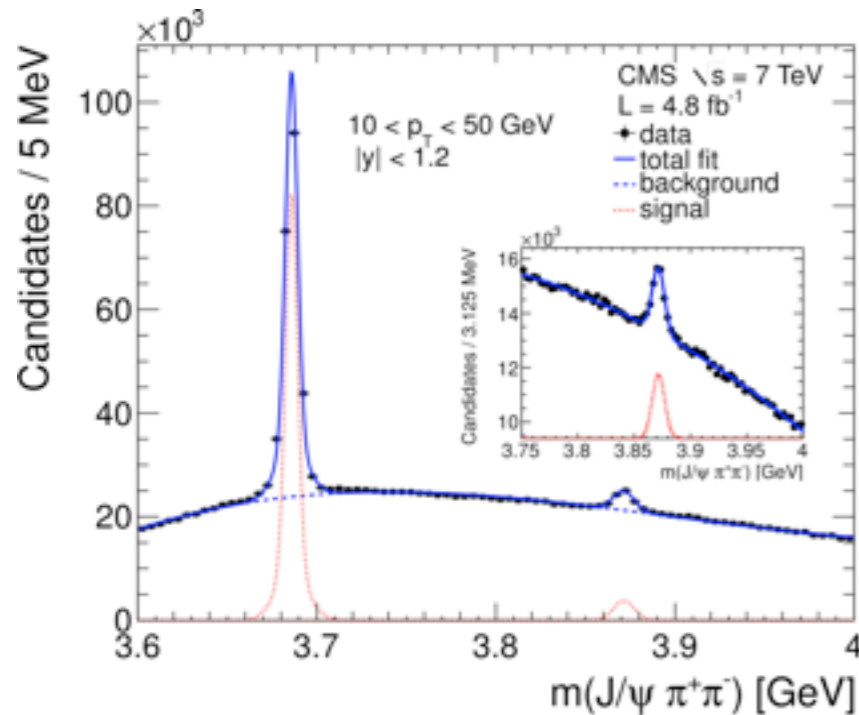
Several other expected resonances **awaiting to be discovered!**

## baryons

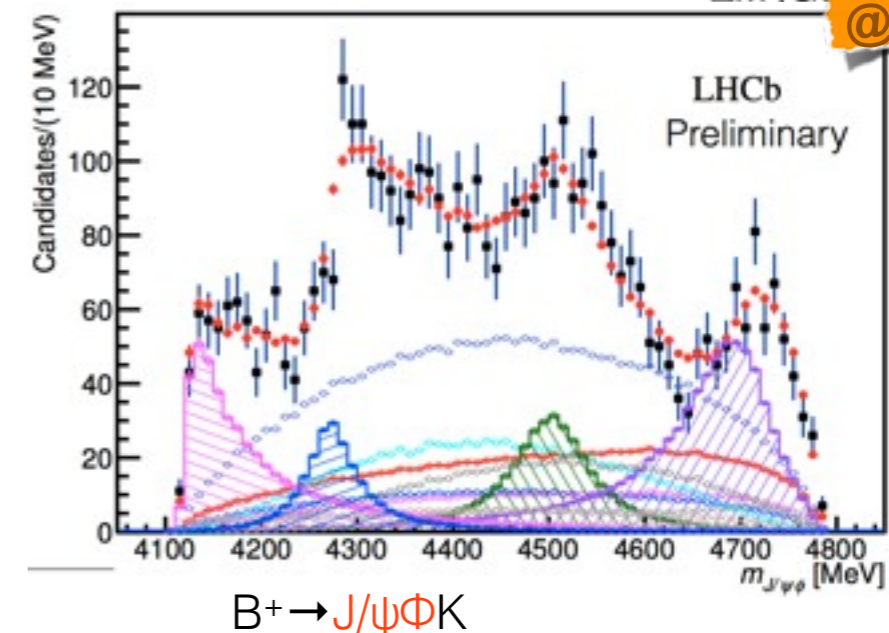
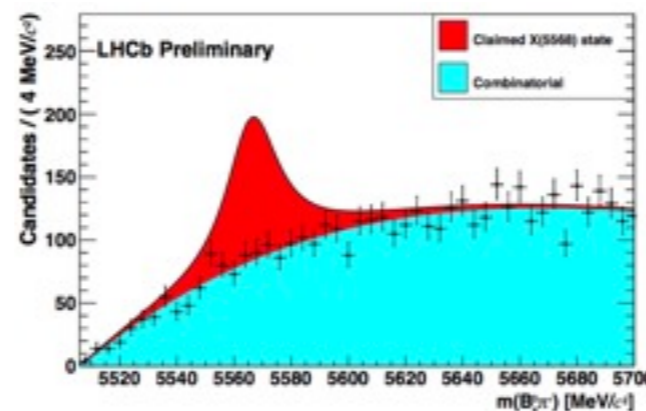
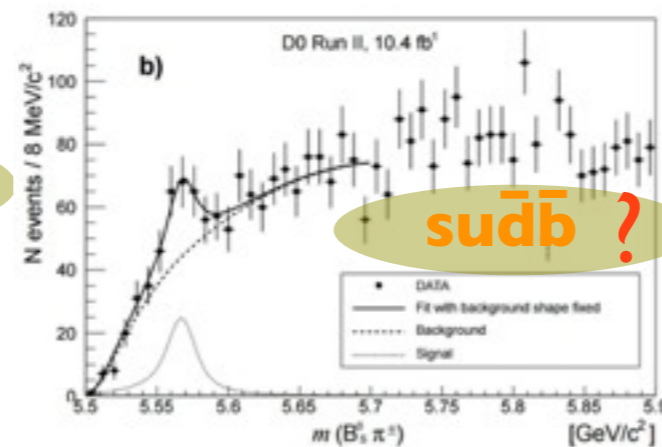
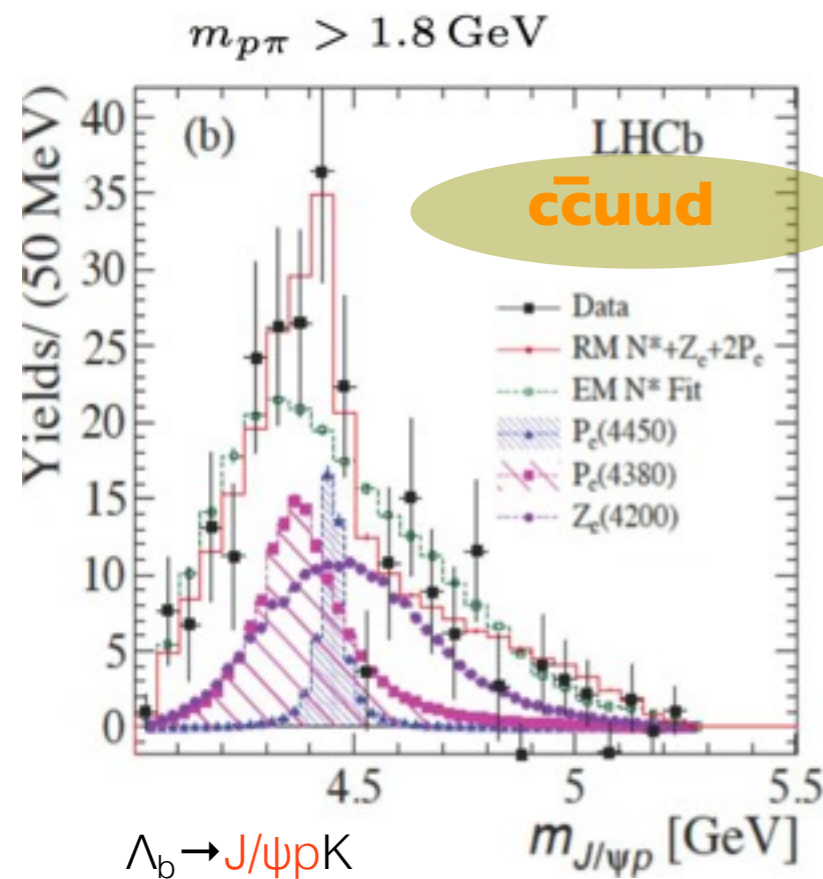
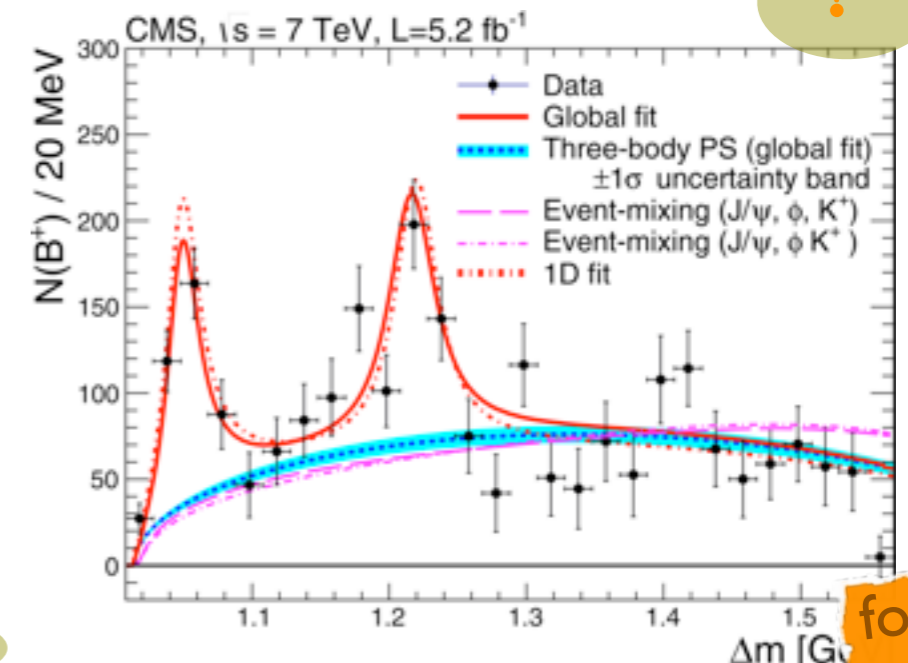


\*\*b

# tertraquarks, pentaquarks,... and all that



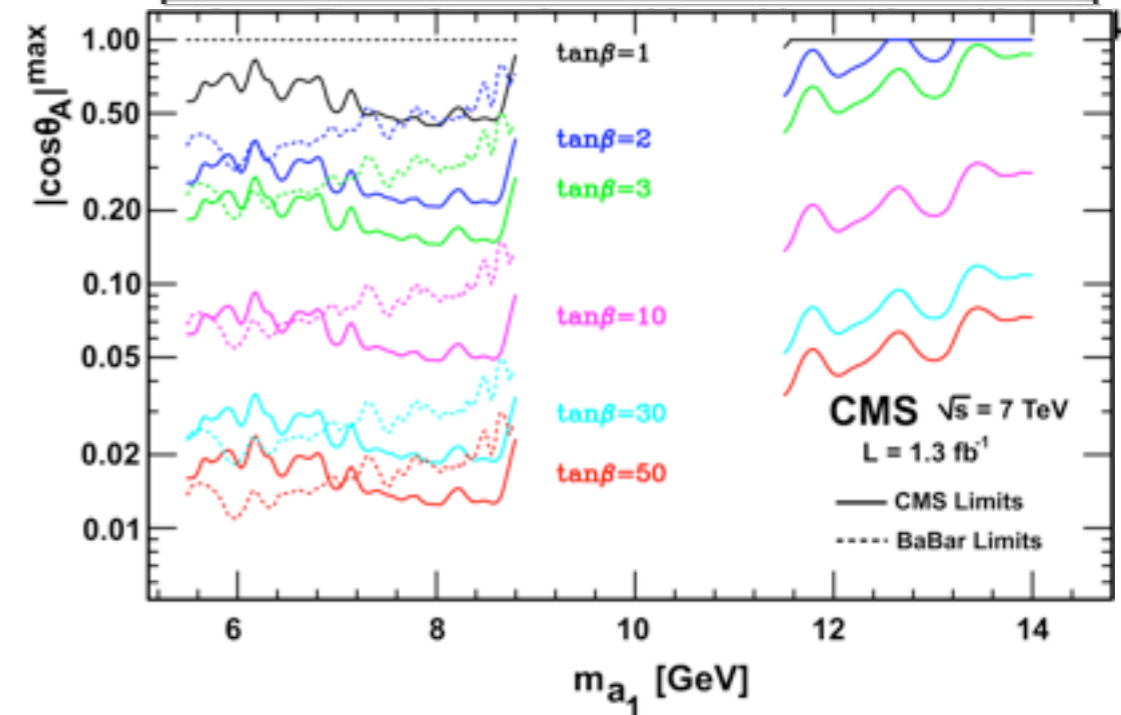
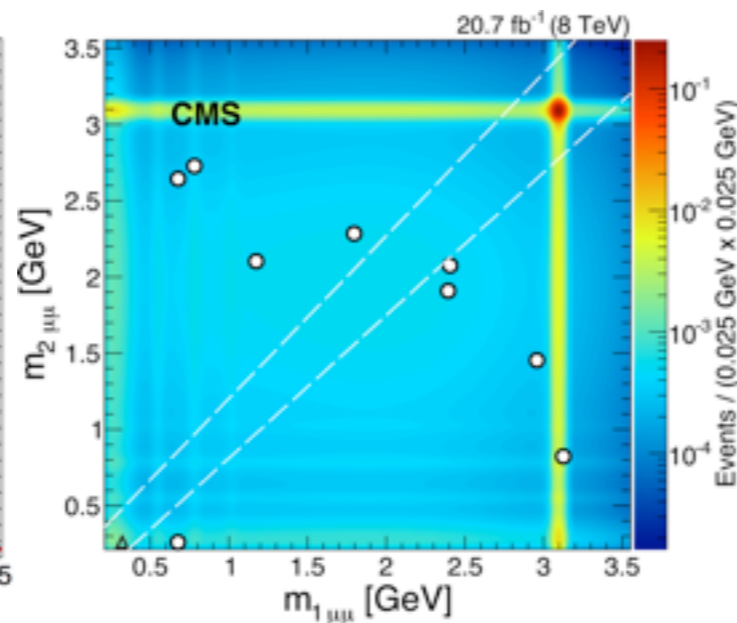
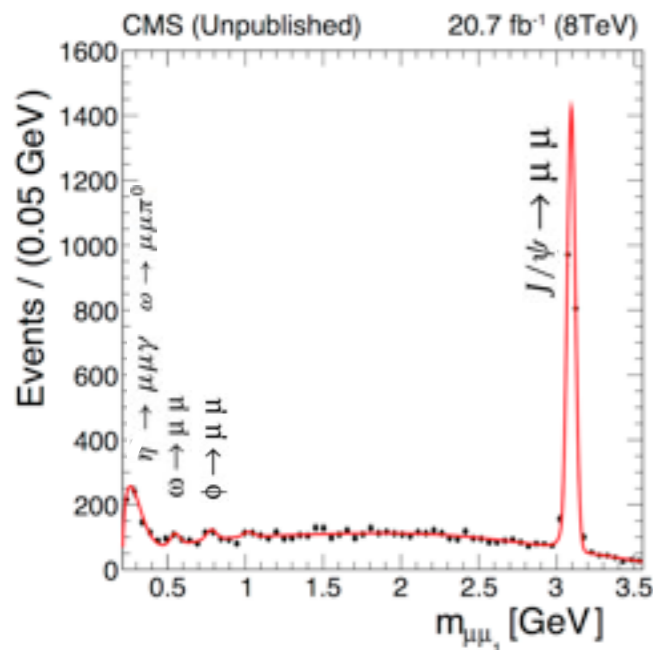
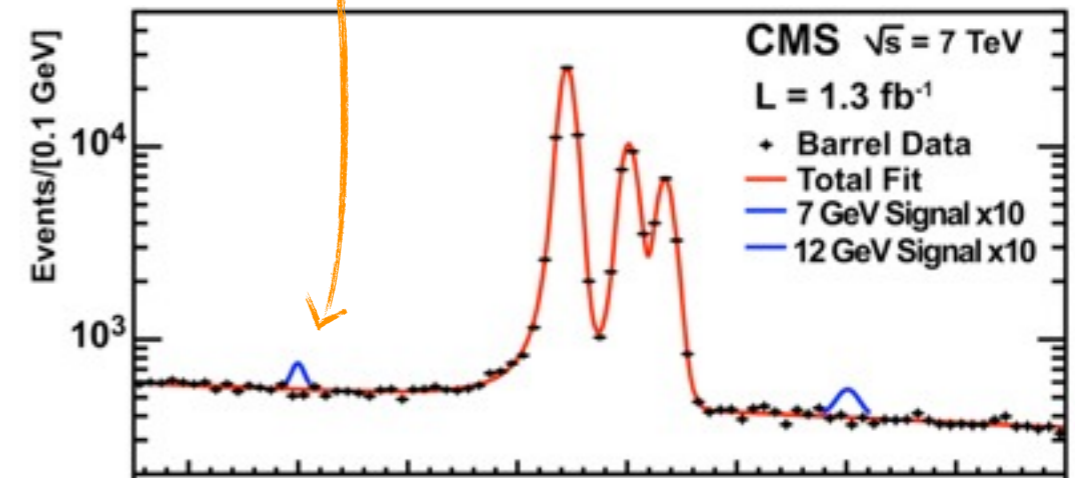
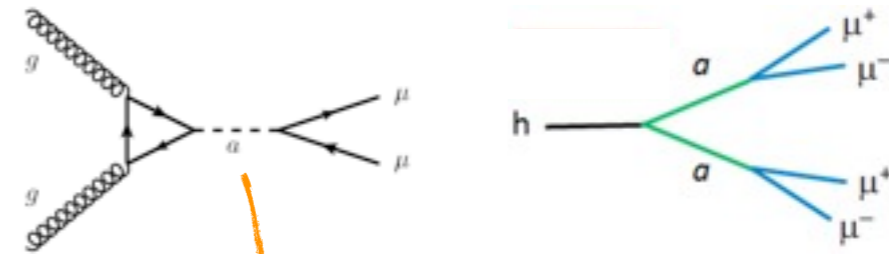
- exotic spectroscopy: since the discovery of  $X(3872)$  by Belle in 2003, the field has remained active, with new intriguing additions...



found @LHC

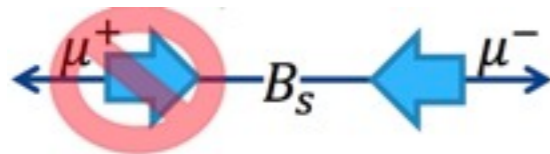
# search for new light resonances $a \rightarrow \mu\mu$

- search the low-mass dimuon spectrum for NP resonances
- physics case: light pseudo-scalar Higgs boson predicted by NP models, eg NMSSM,  $h \rightarrow aa$ ,  $a \rightarrow \mu\mu$
- challenges: trigger; residual vector mesons tails (FSR)



# rare decay search: $B \rightarrow \mu\mu$ (i)

- the ‘golden’ rare decays:  $B_{d/s} \rightarrow \mu\mu$ 
  - actively searched for since 3 decades
- highly suppressed in SM:
  - effective FCNC, forbidden at tree level, can only proceed through higher-order loops diagrams
  - helicity suppressed, by factor of  $(m_\mu/m_B)^2$

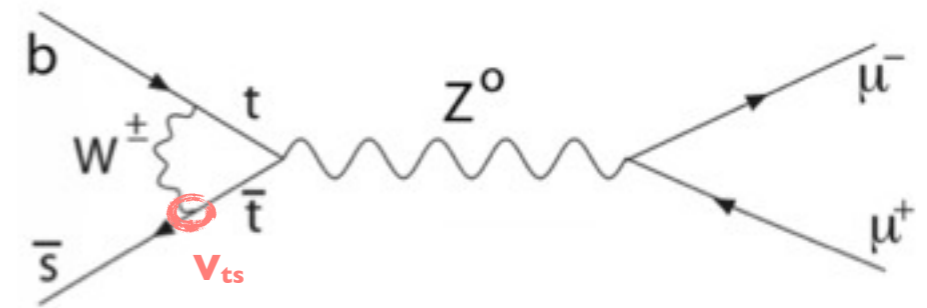


- Cabibbo suppressed  $|V_{ts(td)}|^2$

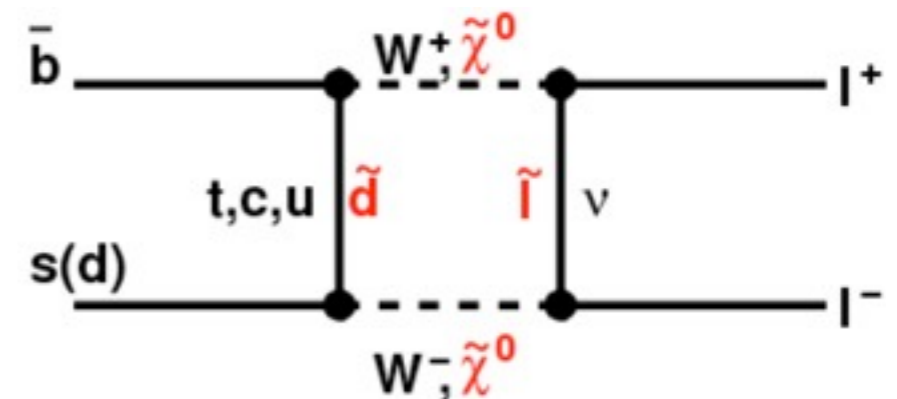
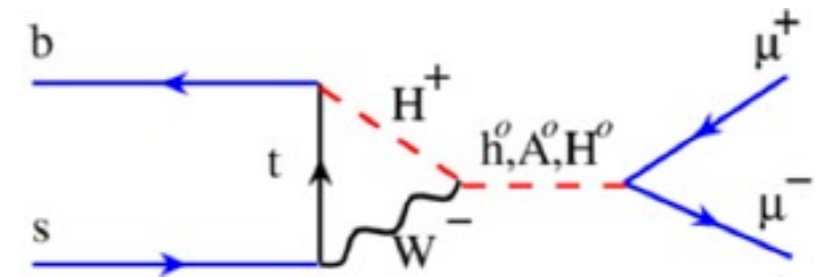
- high sensitivity to new physics contributions in the loops

- NP scenarios with extended scalar sectors
- may enhance or suppress the decay rates

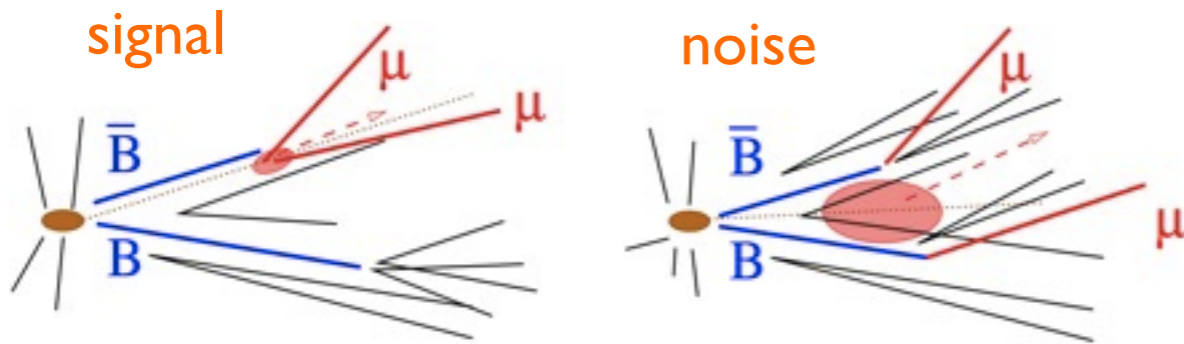
eg standard-model contribution:



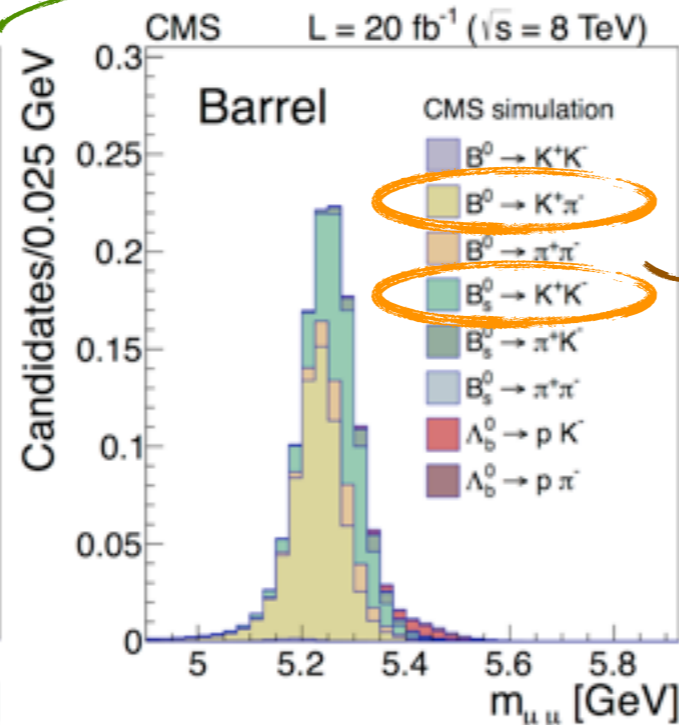
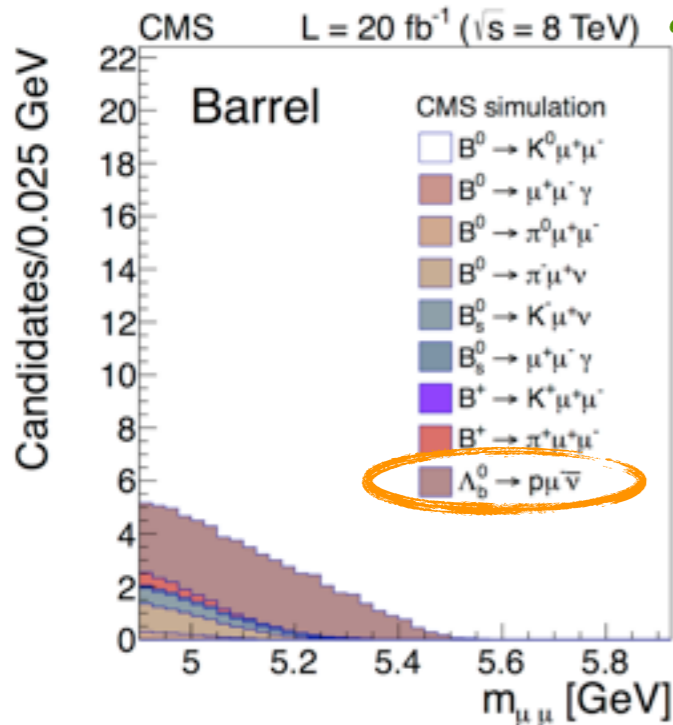
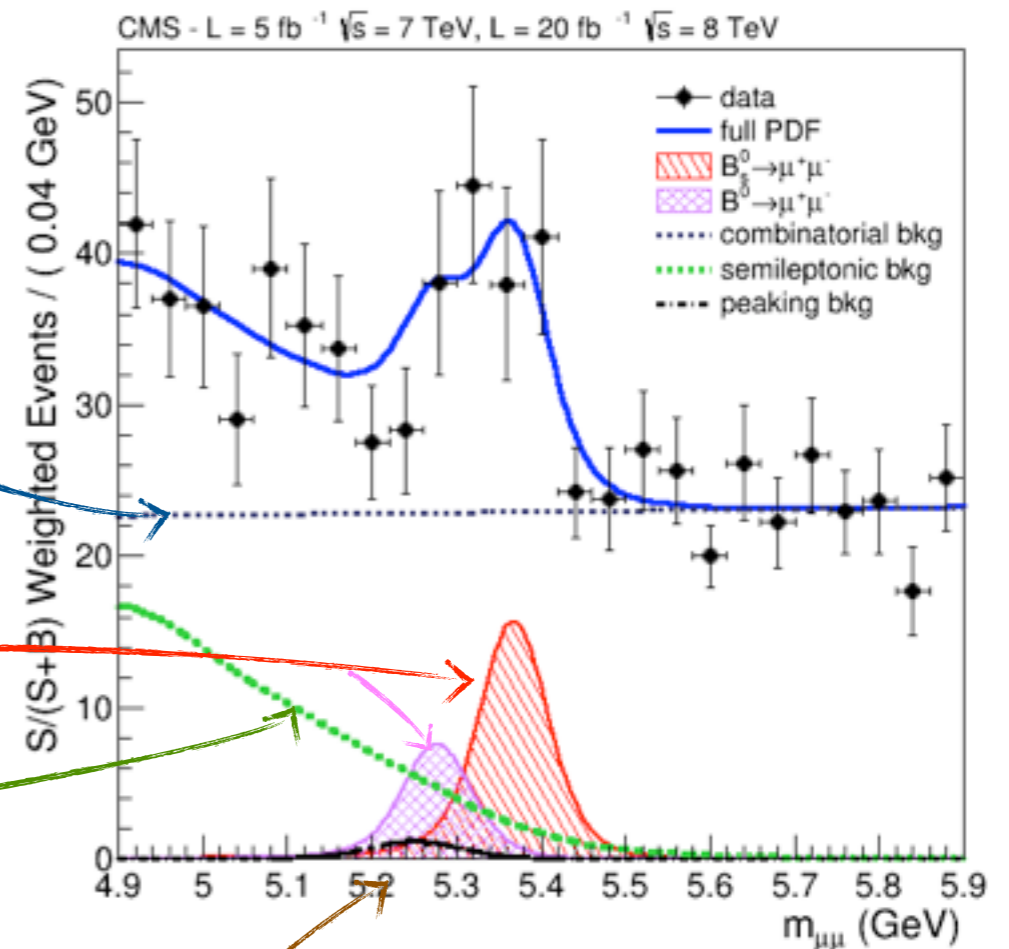
eg new-physics contributions:



# rare decay search: $B \rightarrow \mu\mu$ (ii)



- prompt background
  - removed via vertex displacement cut
- combinatorial background
  - uncorrelated muon pairs
- $B_d$  and  $B_s$  signals
  - shapes from simulation



[physics backgrounds]

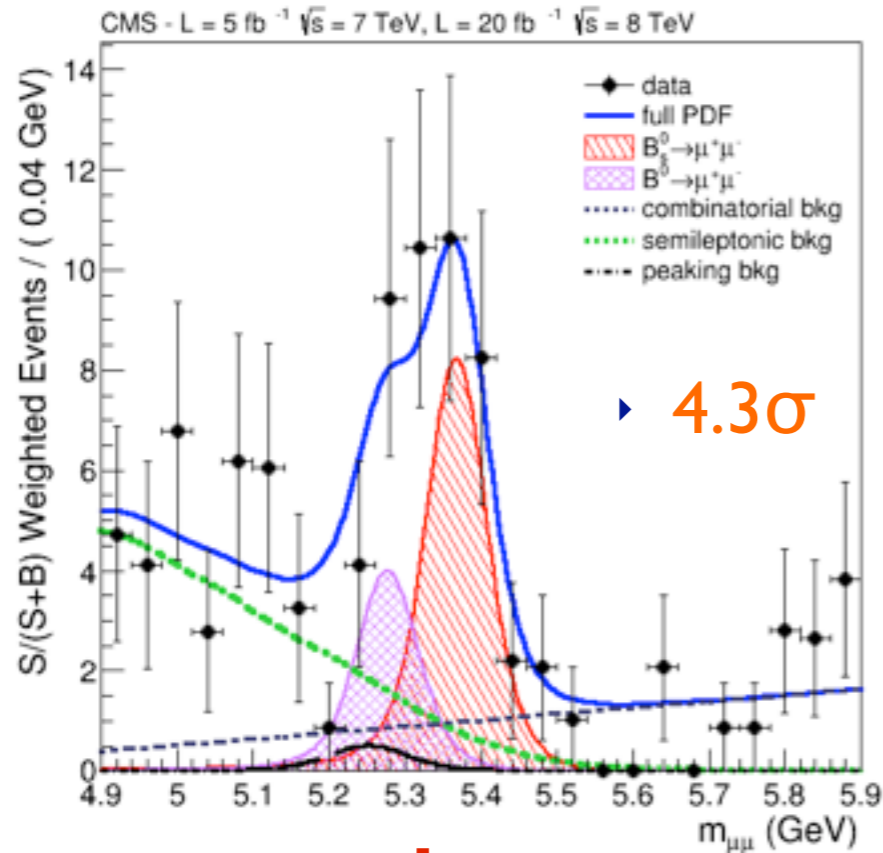
- muon mis-identification
  - $b \rightarrow q\mu\nu \rightarrow \mu\mu$
  - $b \rightarrow hh \rightarrow \mu\mu$
- use MVA algorithm
  - $\%o$ -level fake rates ( $h \rightarrow \mu$ )

# rare decay search: $B \rightarrow \mu\mu$ (iii)

[opening the box]

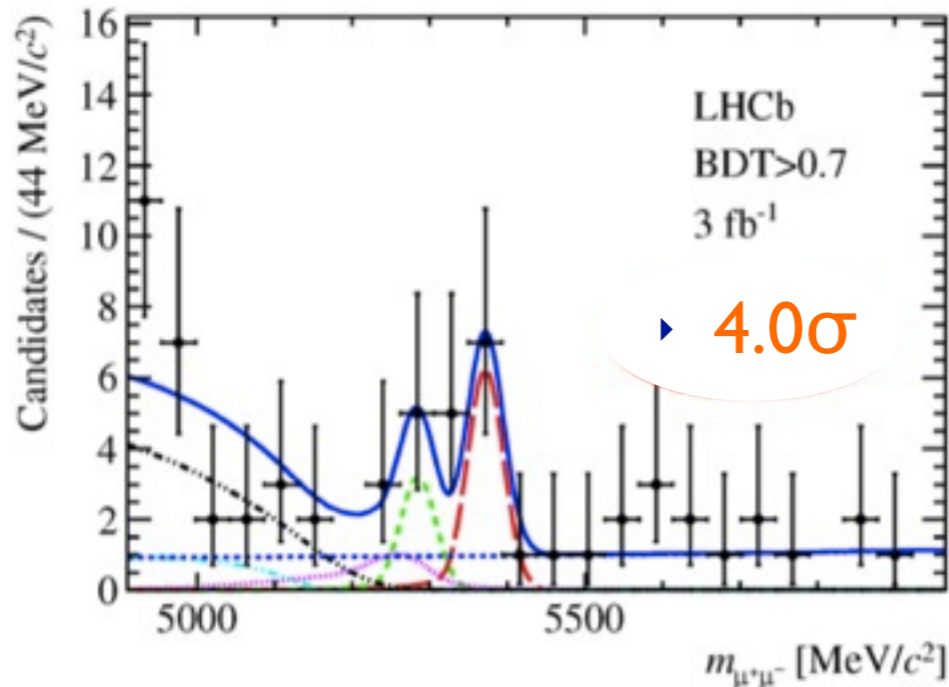
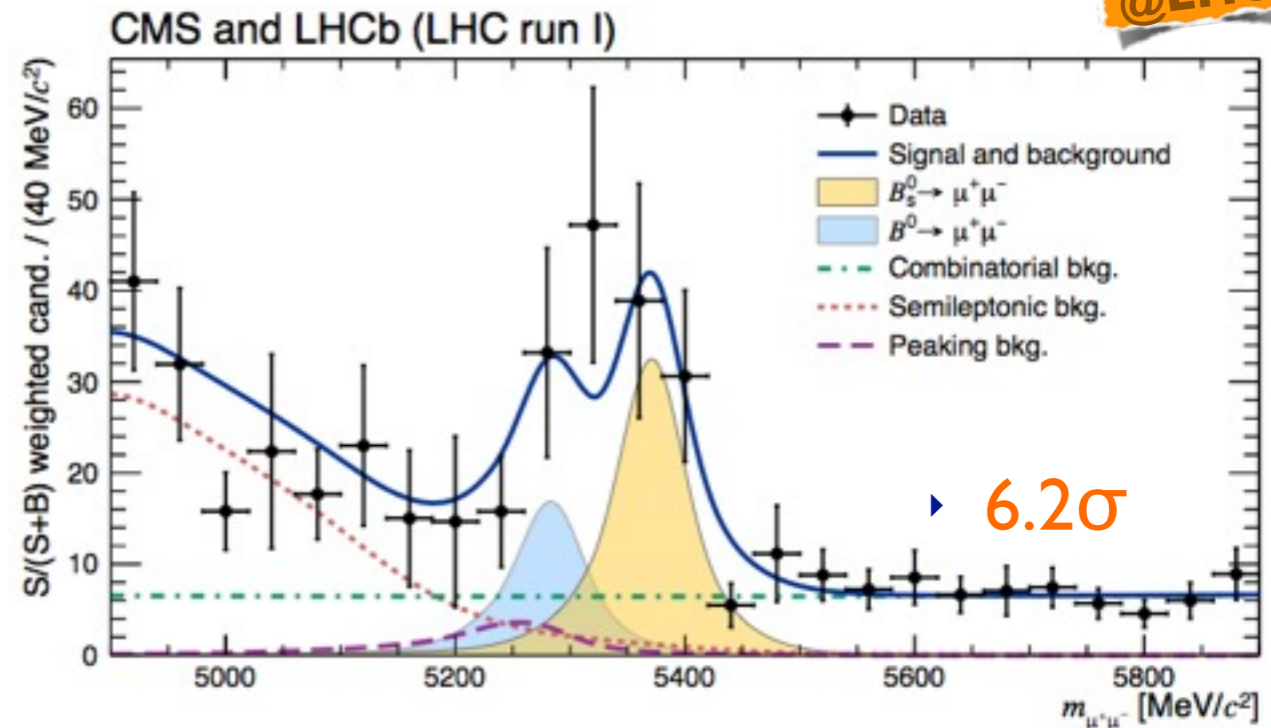
- CMS and LHCb have performed a combined analysis of their full Run I datasets, and delivered a first definitive observation of  $B_s \rightarrow \mu\mu$

found @LHC



+

=



$$B(B_s^0 \rightarrow \mu^+\mu^-) = (2.8_{-0.6}^{+0.7}) \times 10^{-9} \quad (6.2\sigma)$$

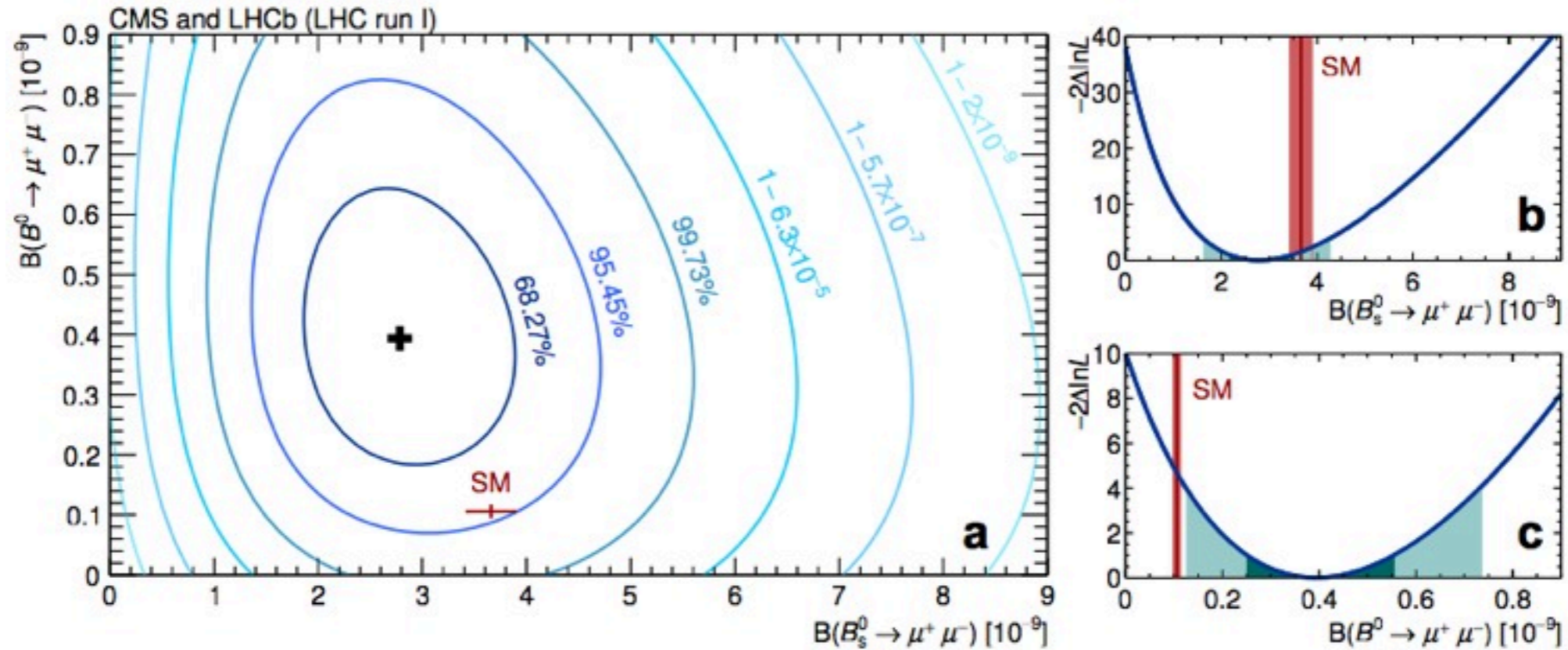
$$B(B^0 \rightarrow \mu^+\mu^-) = (3.9_{-1.4}^{+1.6}) \times 10^{-10} \quad (3.0\sigma)$$



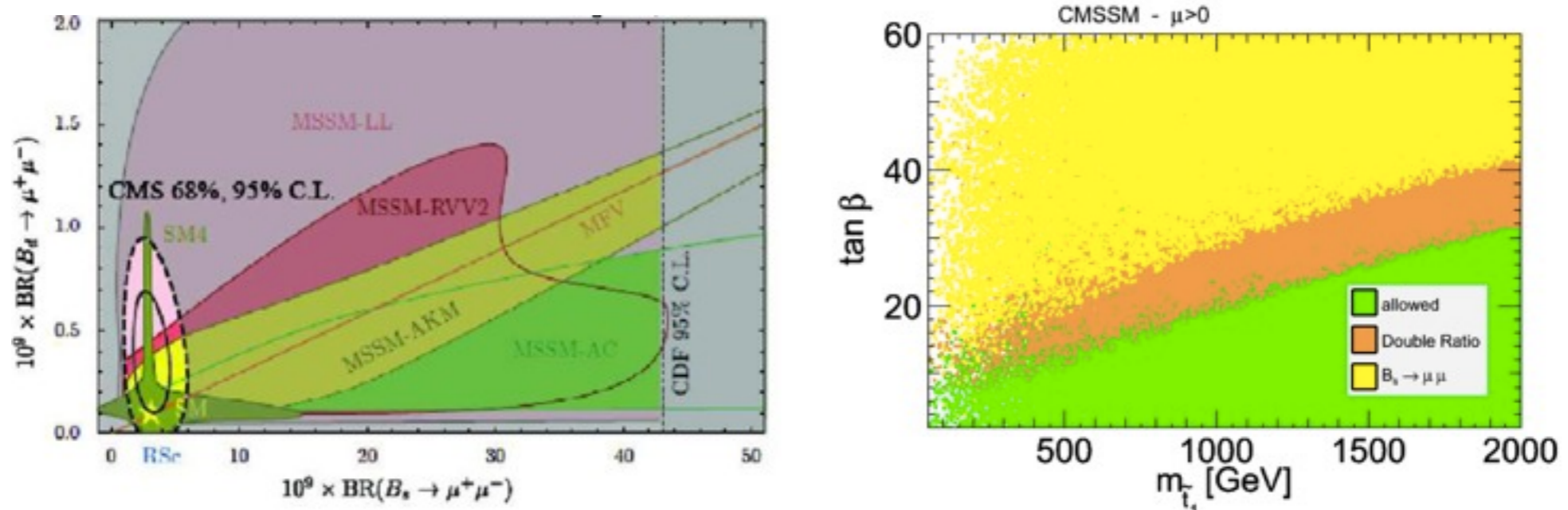
# rare decay search: $B \rightarrow \mu\mu$ (iv)

[comparison to theory expectation]

SM  $\Rightarrow$

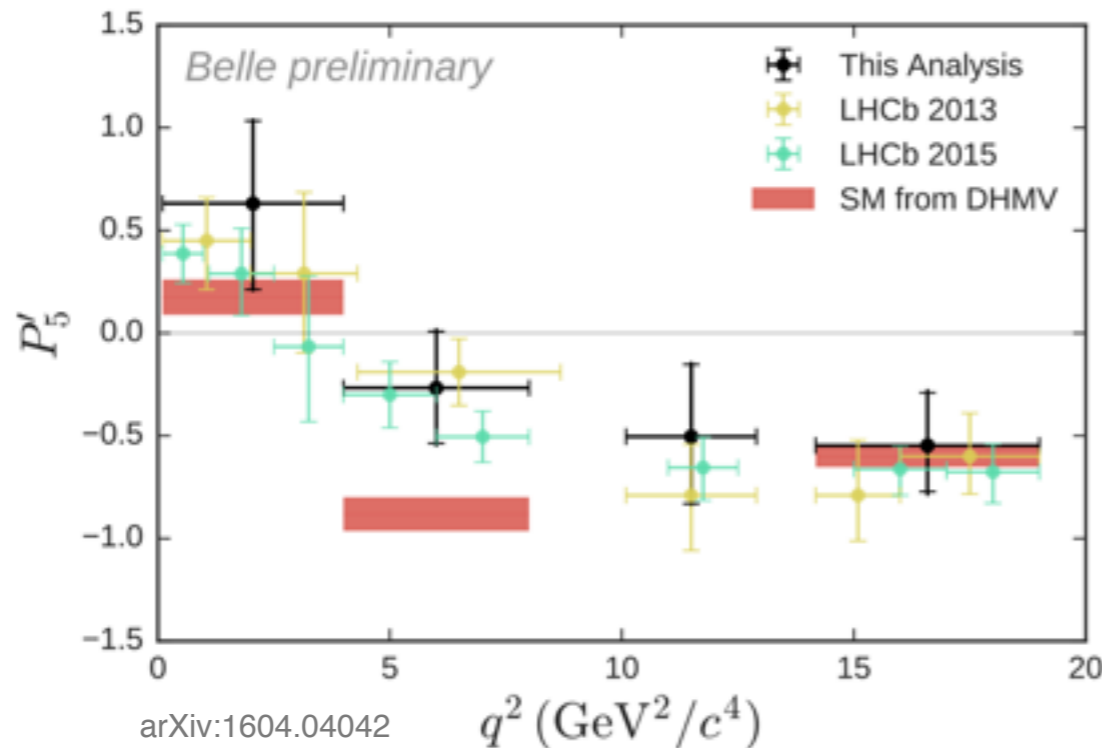
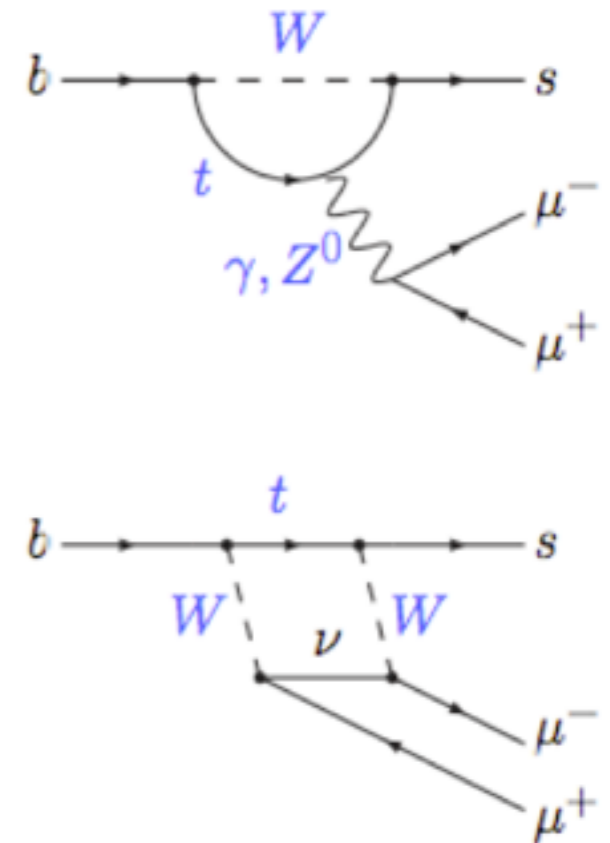
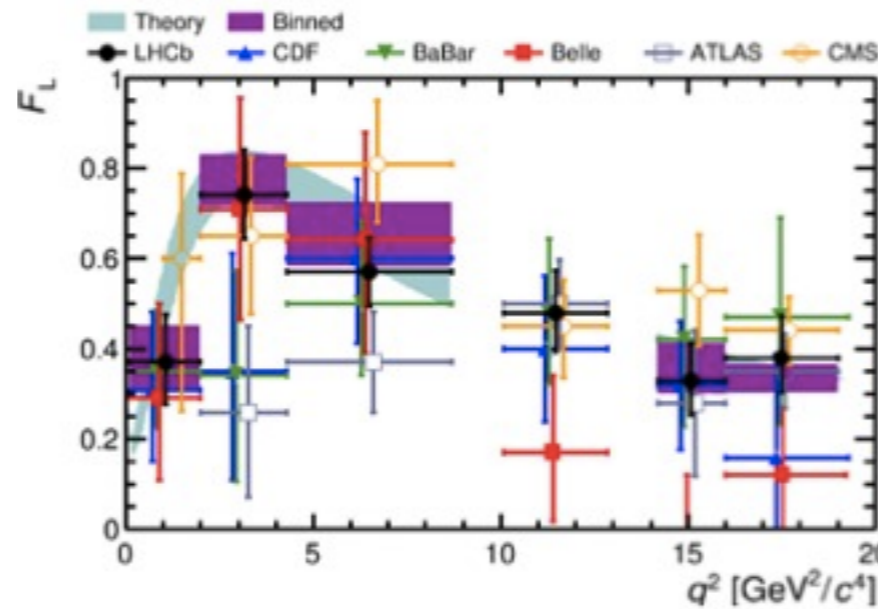
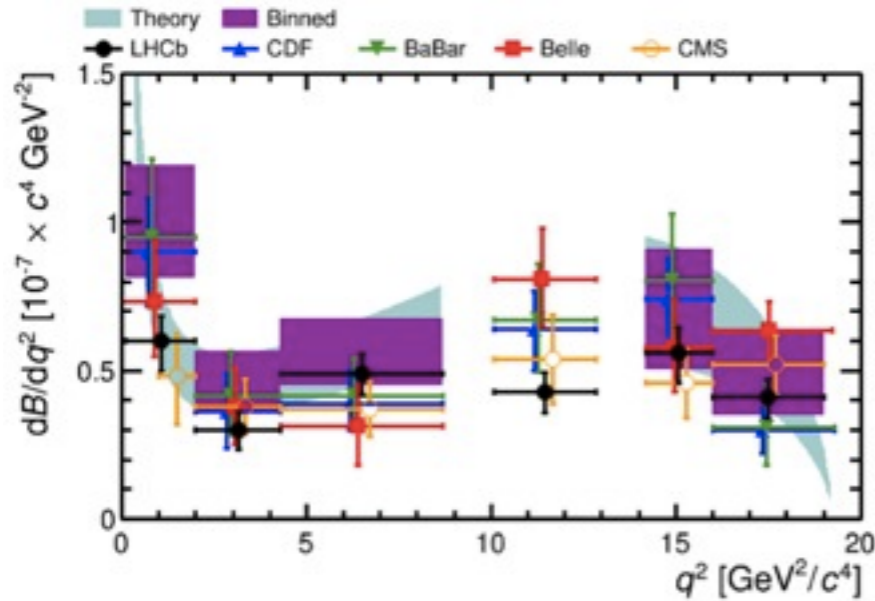


NP  $\Rightarrow$



# [extra: a non-resonant (!) view of $b \rightarrow sll$ ]

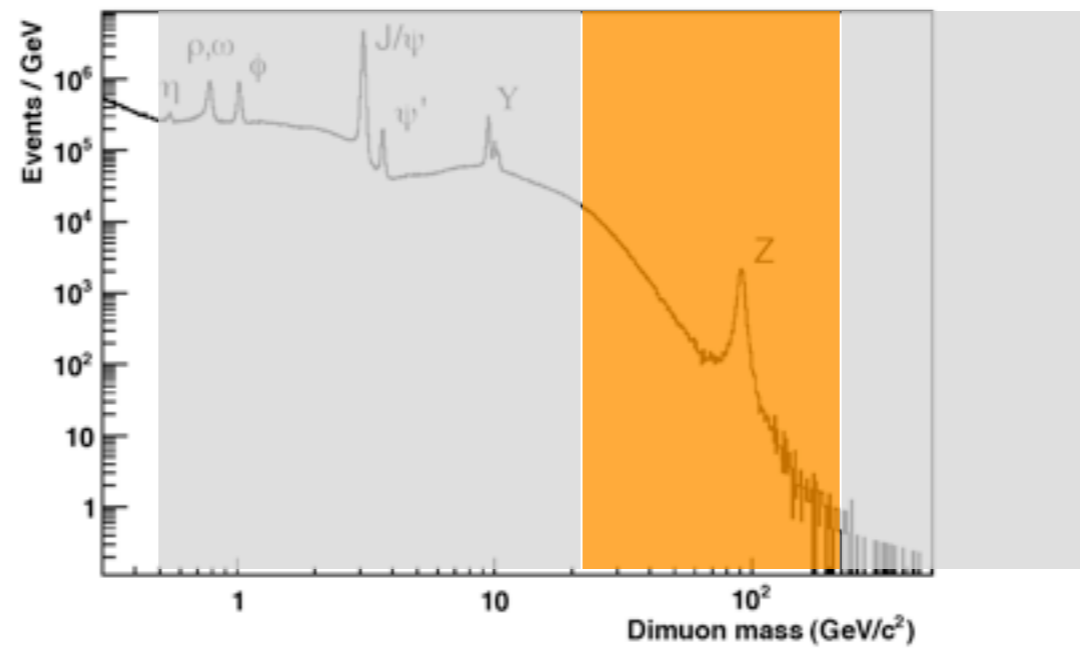
- $B \rightarrow K^{(*)}ll$  is a FCNC process, sensitive to NP by exploring multiple observables



arXiv:1604.04042

- the  $P_5'$  anomaly

- ▶ LHCb reported discrepancy wrt SM at level of  $3.4\sigma$
- ▶ confirmed by Belle at  $2.1\sigma$  level
- ▶ results from ATLAS, CMS expected soon

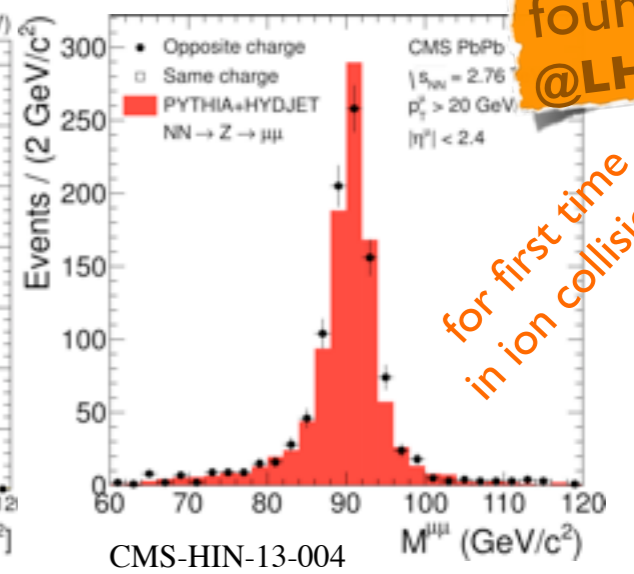
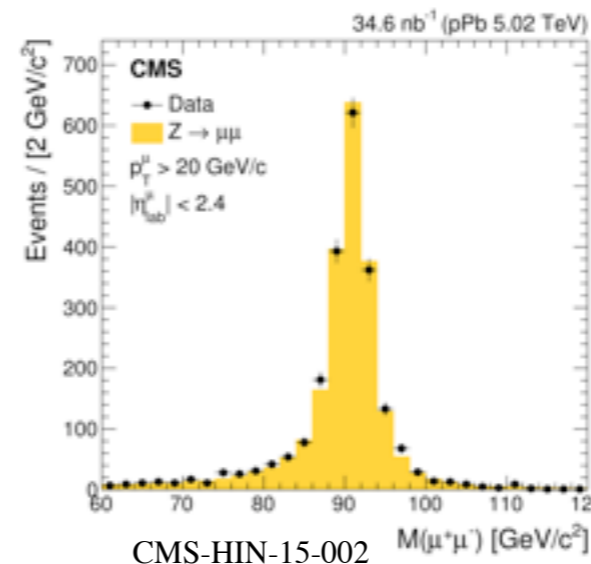
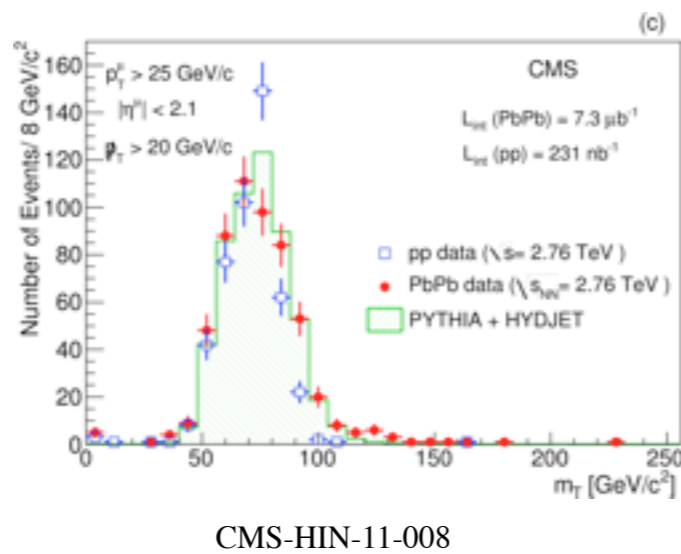
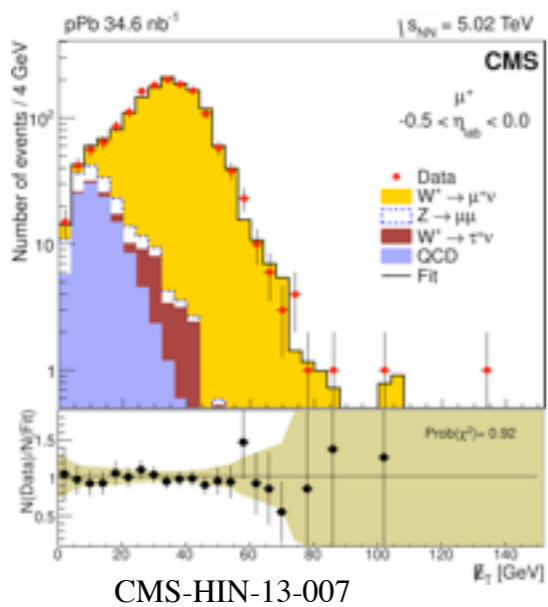
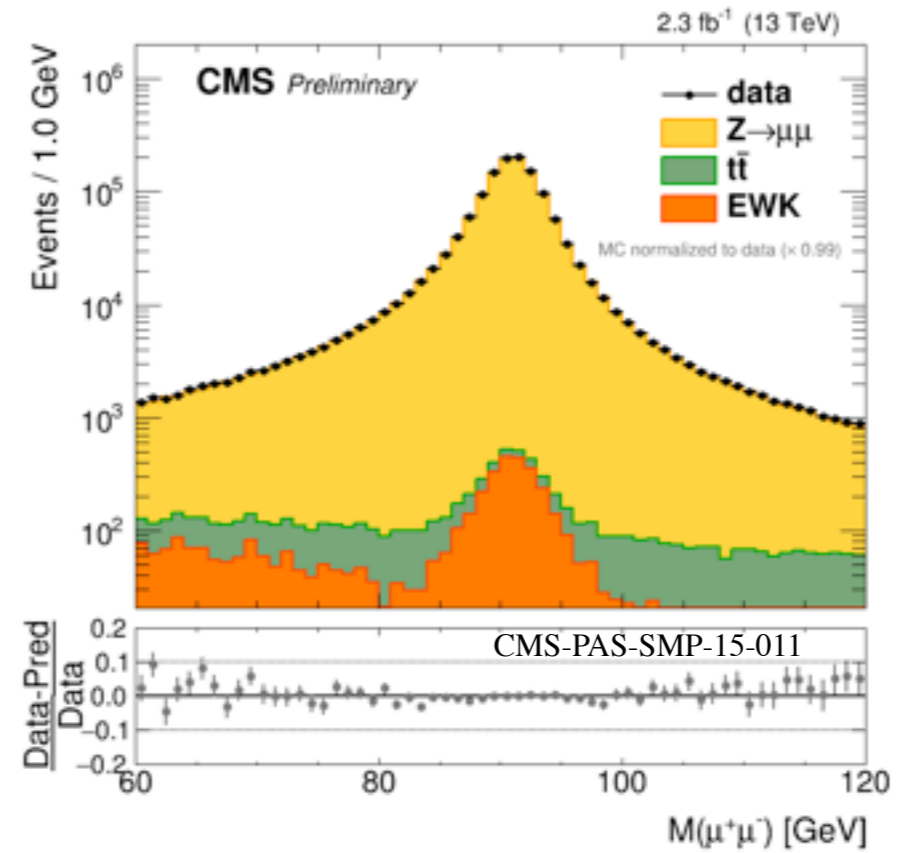
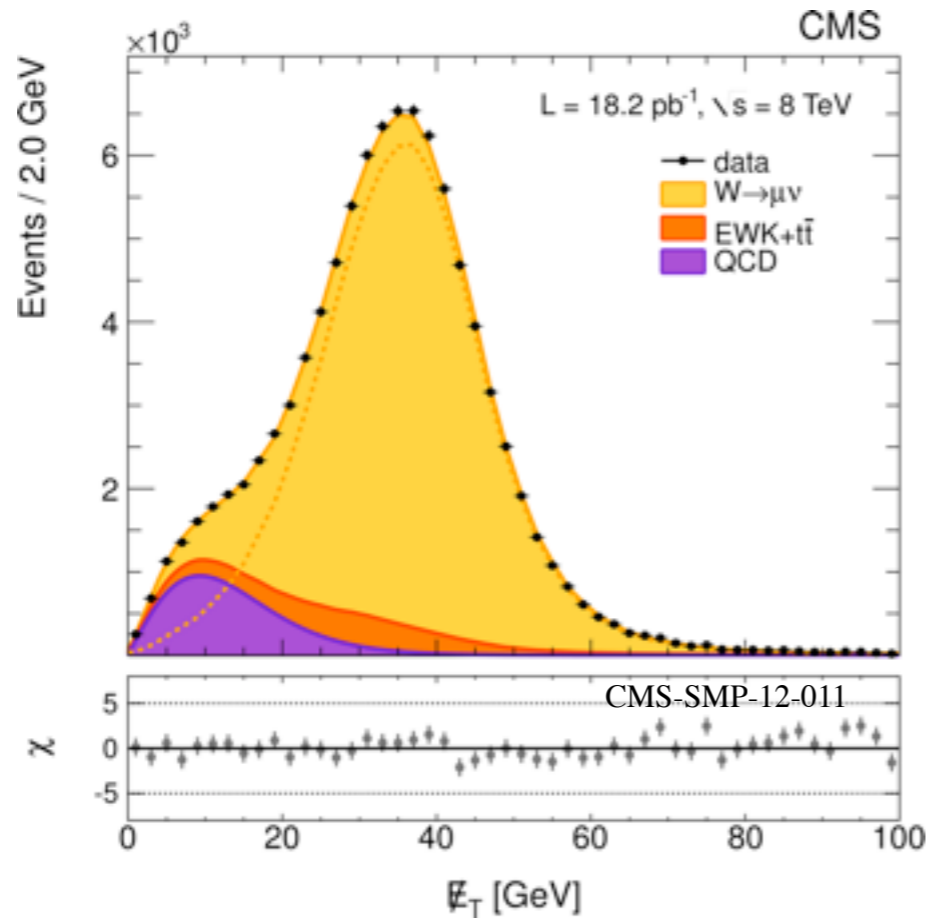


resonances: medium mass

# medium-mass resonances

- EWK's realm
  - vector bosons
  - the 125GeV Higgs-like resonance
- new physics via
  - precision measurements
  - rare processes, FCNC, lepton flavor violation (Z,H,t)
  - NP resonances
- Disclaimer
  - not covered: EWK, Higgs, top properties and precision measurements

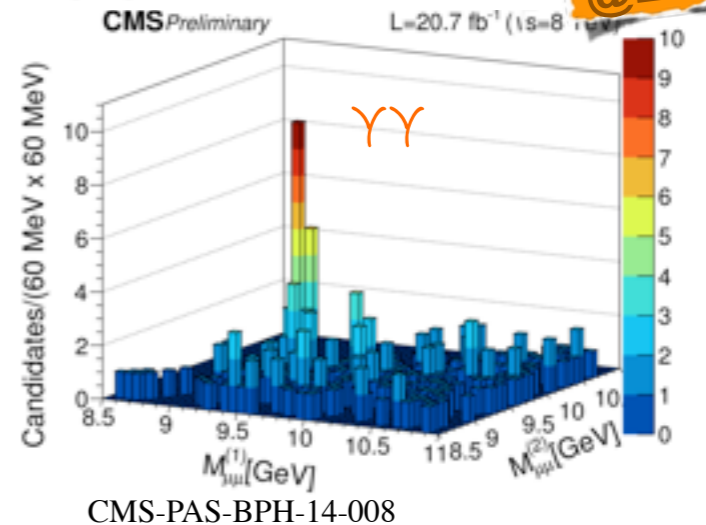
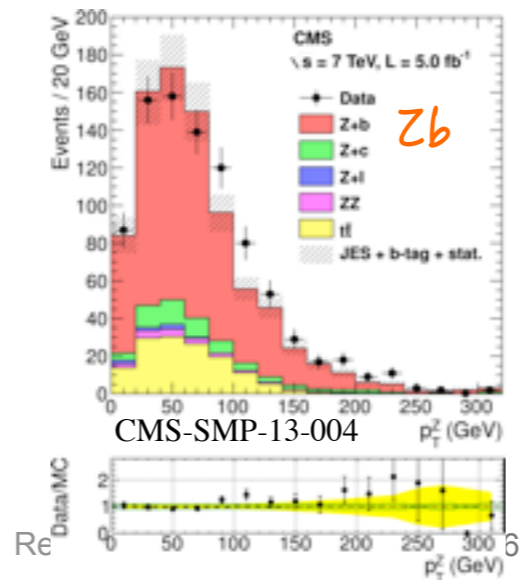
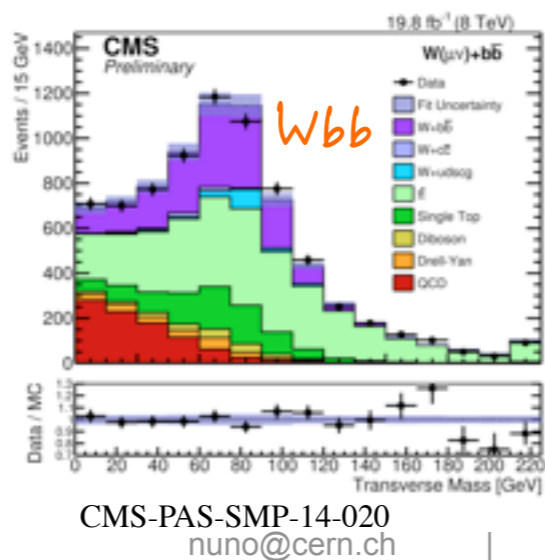
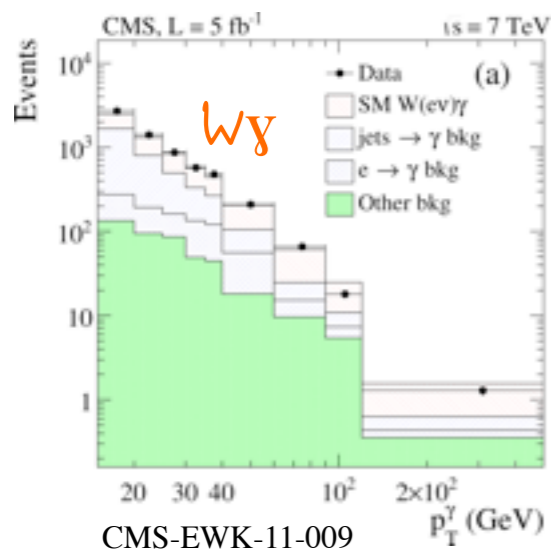
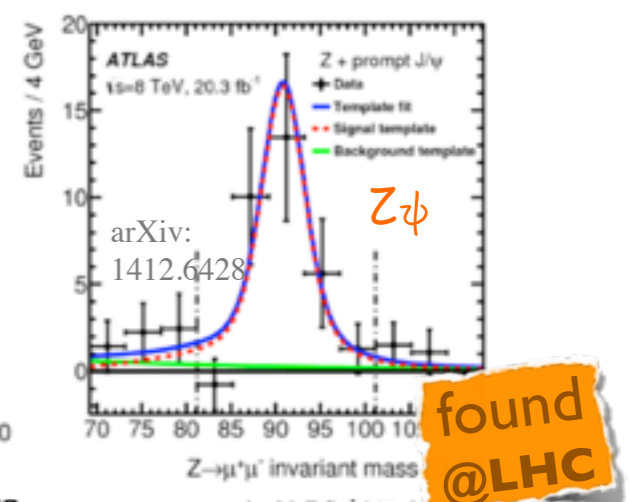
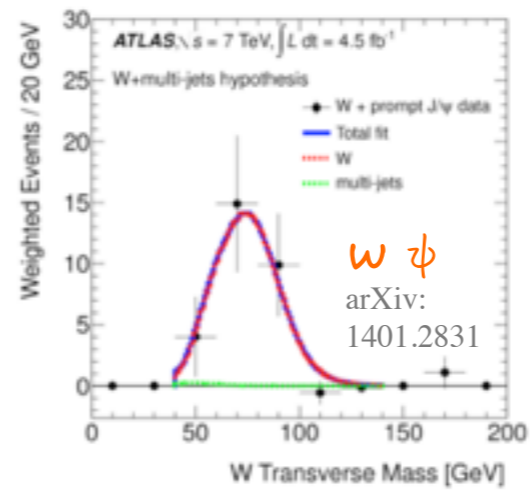
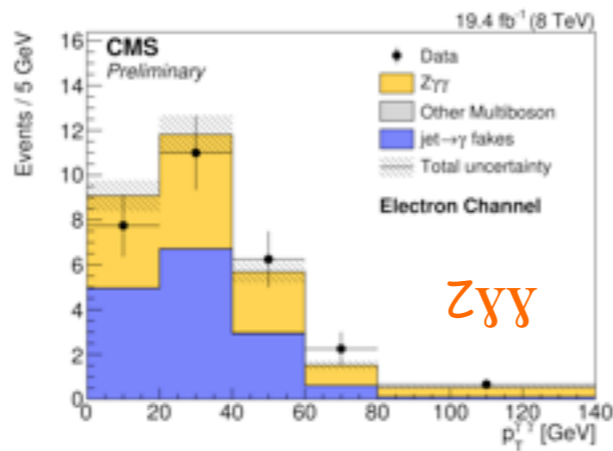
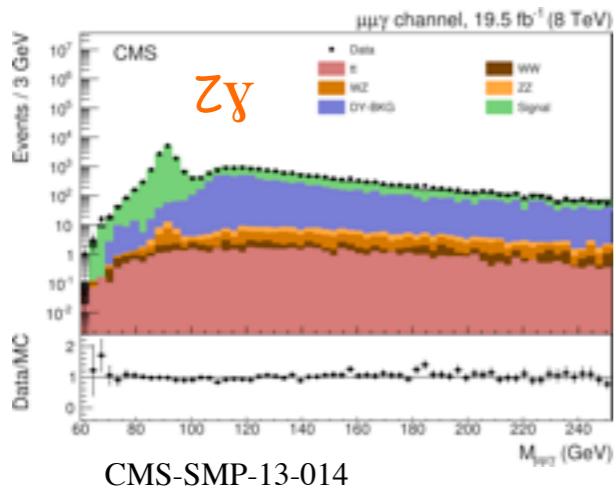
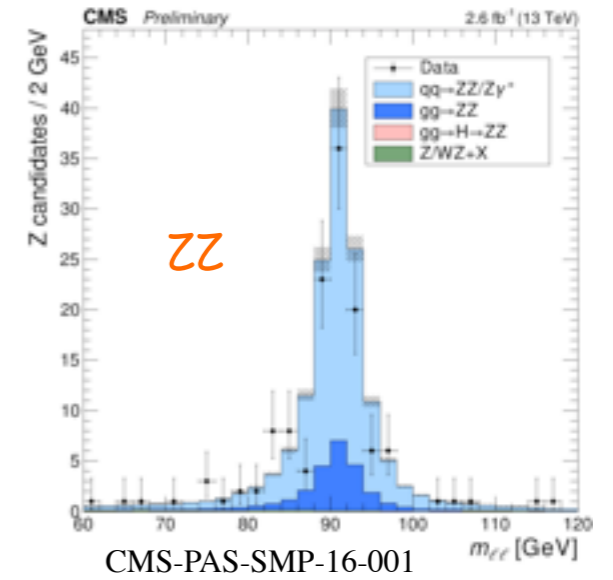
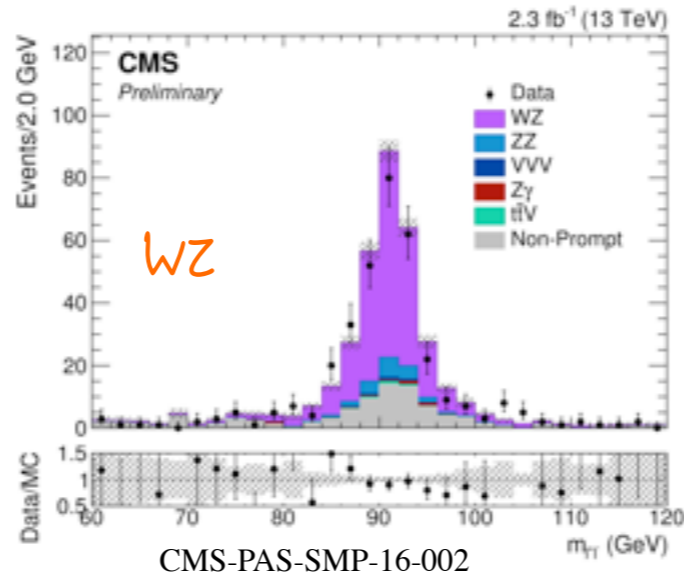
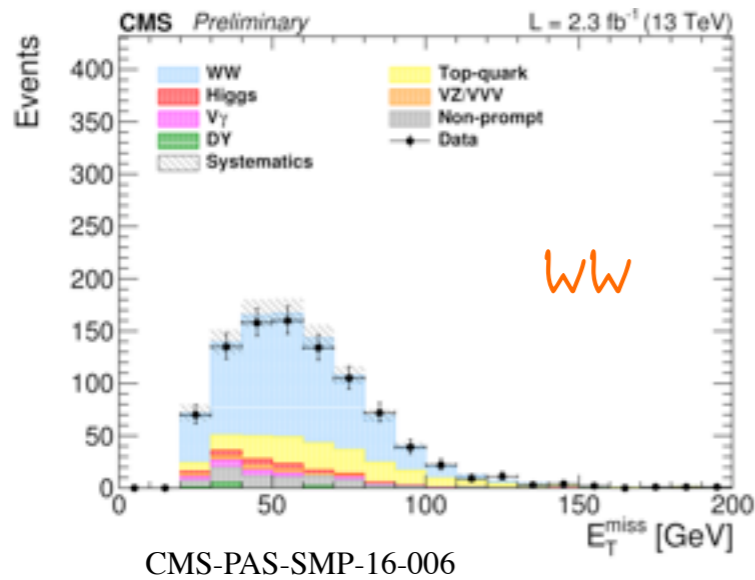
# W & Z



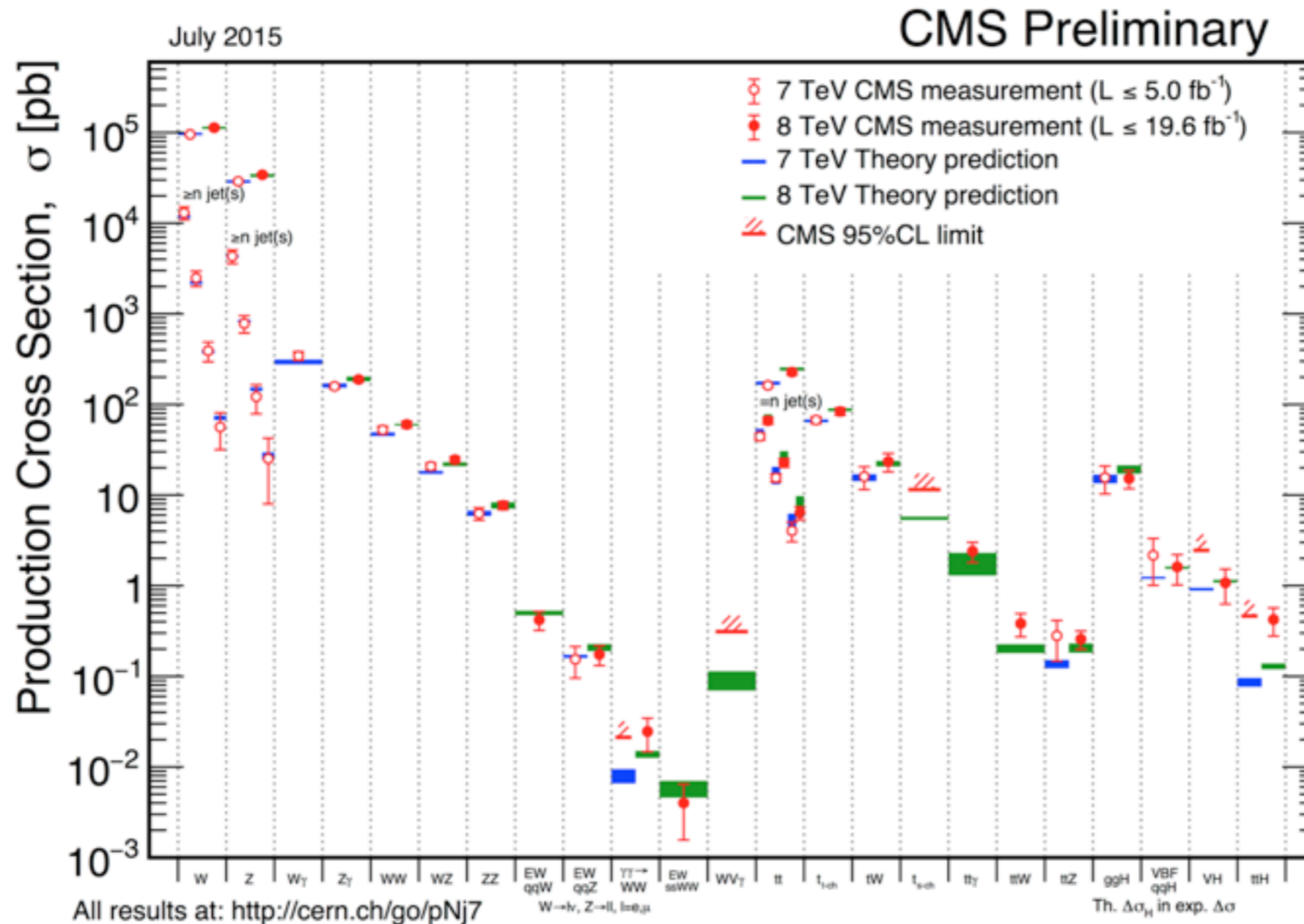
found @LHC

for first time in ion collisions

# associated production



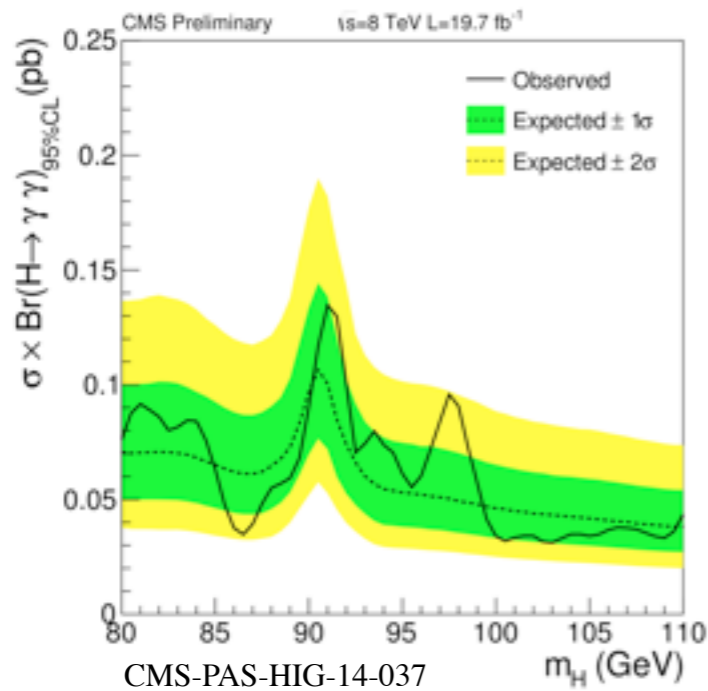
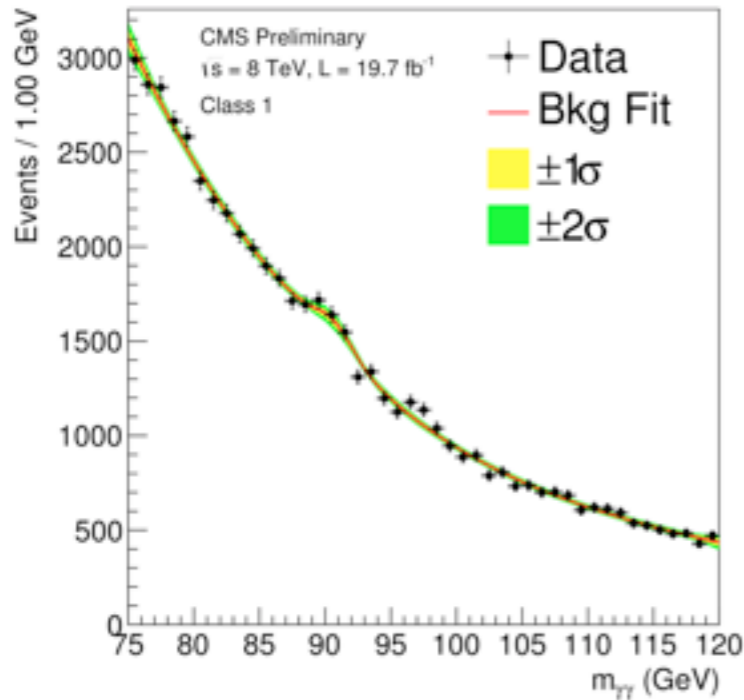
# EWK grand summary



- precision production measurements for an extensive list of SM processes
- these processes constitute main backgrounds for direct NP searches
- each of these **final states can be explored to search for NP resonances !**

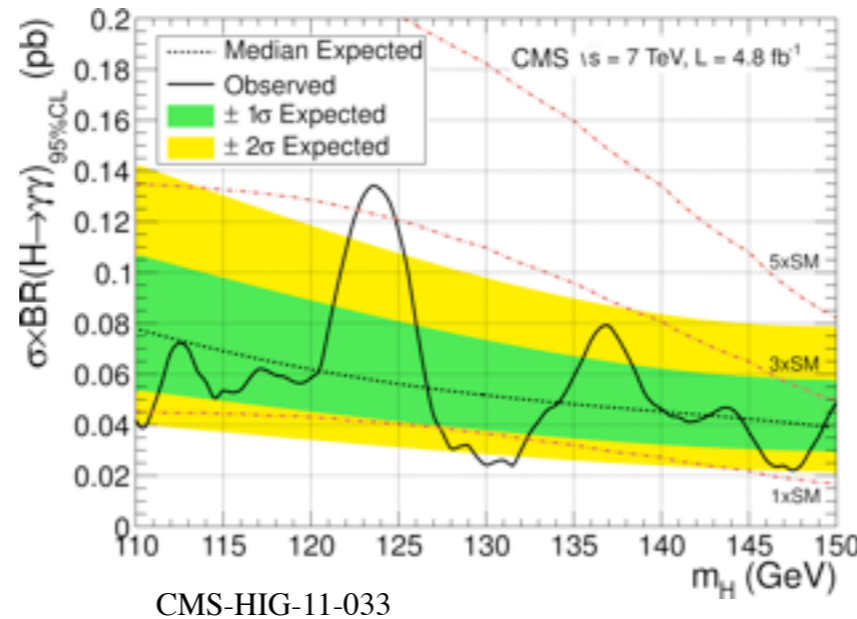
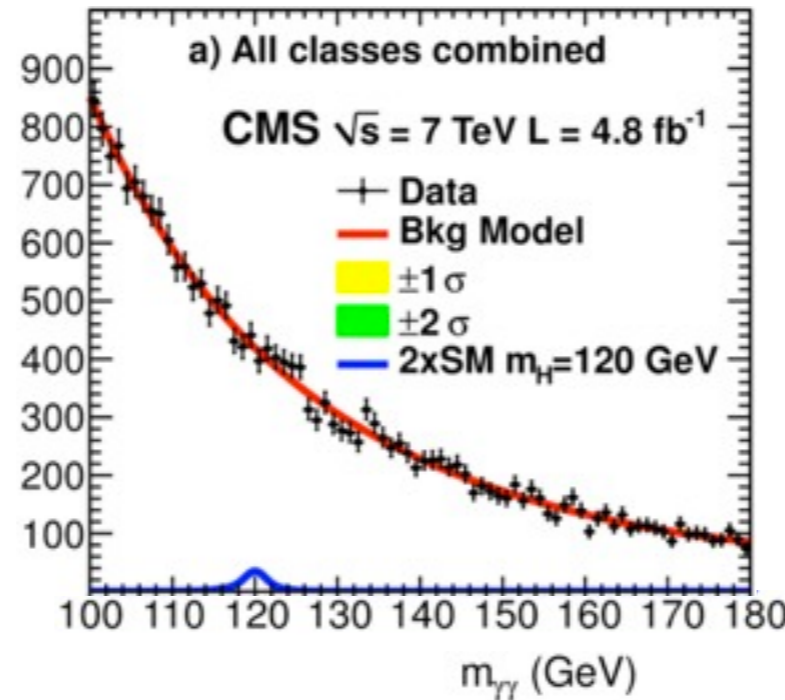
# search for resonances in the di-photon spectrum

80 < m < 110 GeV



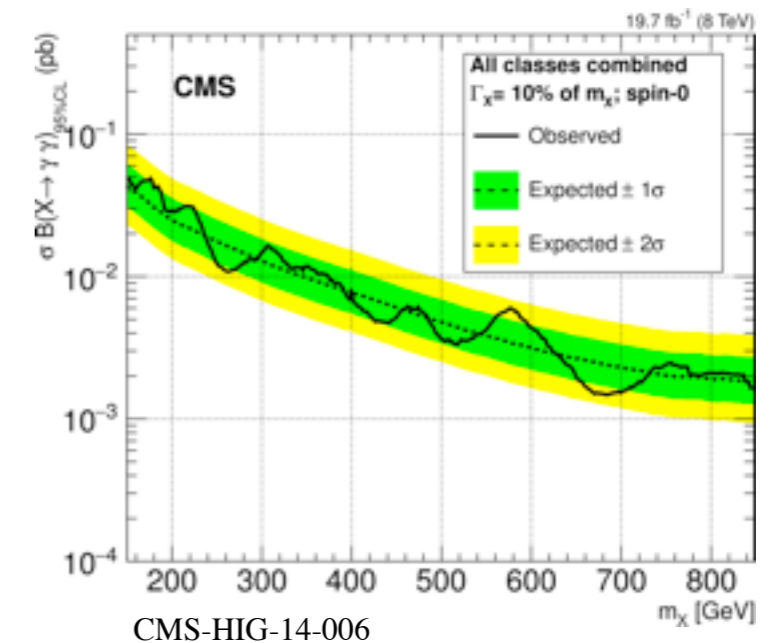
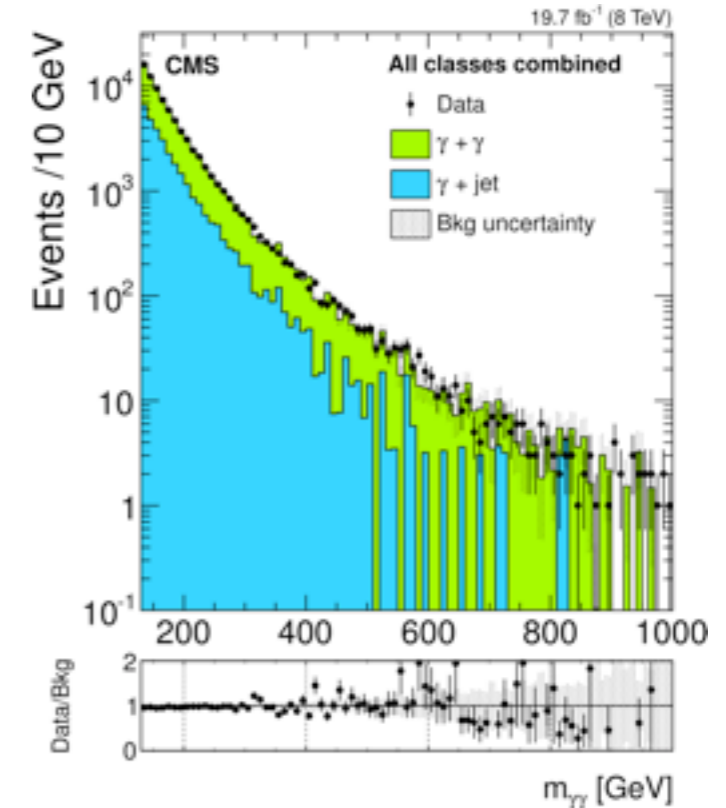
note 'double-fake' from  $Z \rightarrow ee$

110 < m < 150 GeV



hint of an excess detected at  $m \sim 124 \text{ GeV}$   
 with significance  $3.1\sigma$  (local)  
 $1.8\sigma$  (global, in 110-150 GeV range)

150 < m < 850 GeV

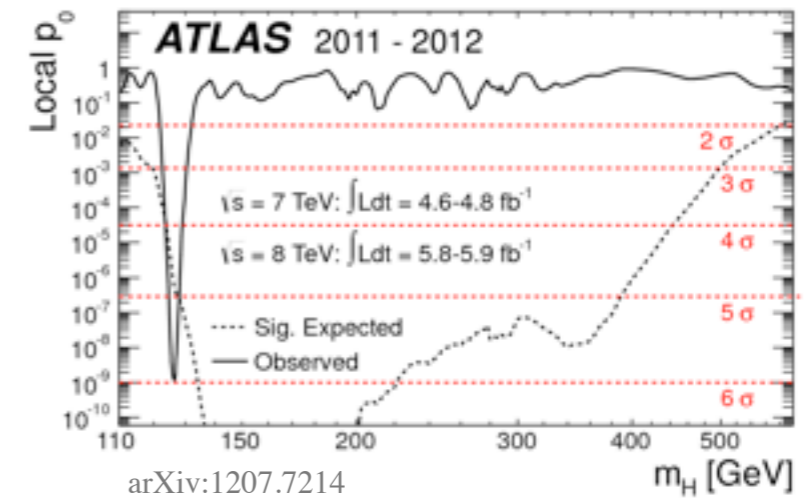
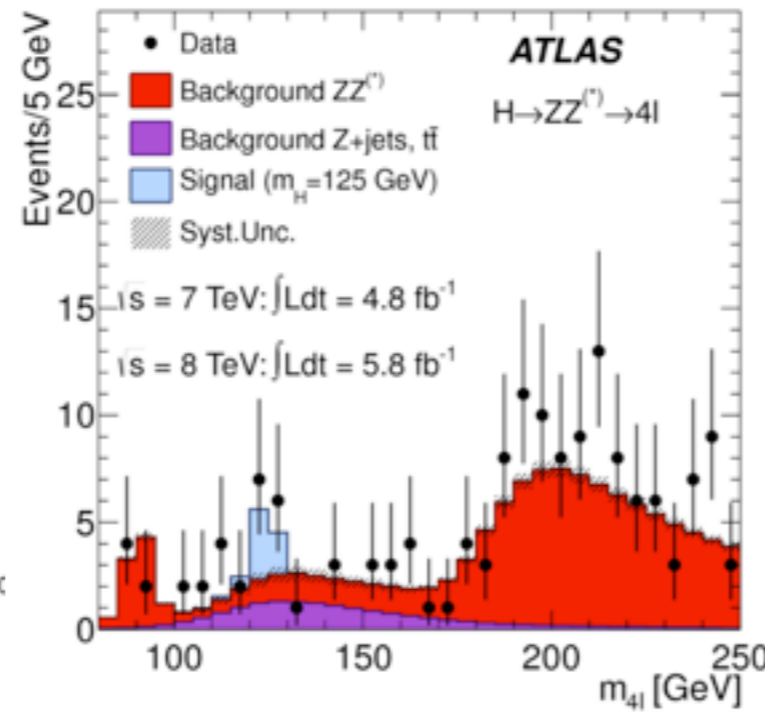
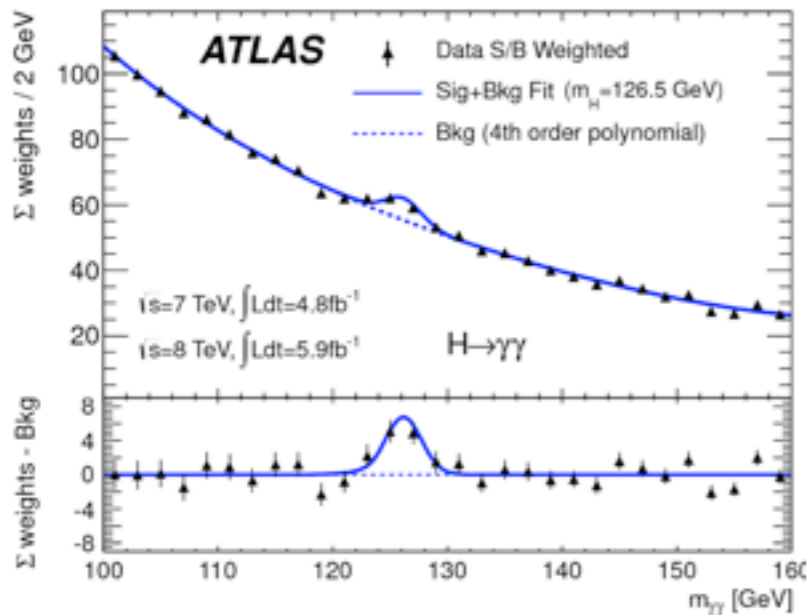
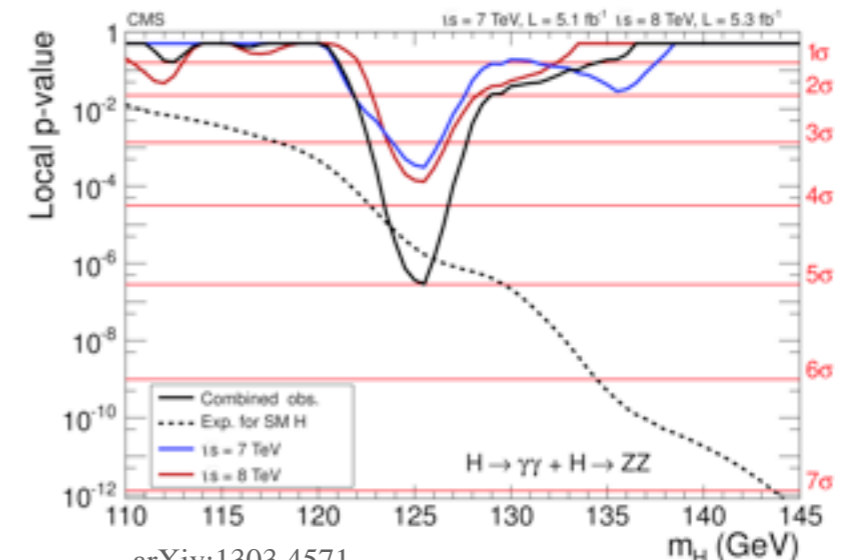
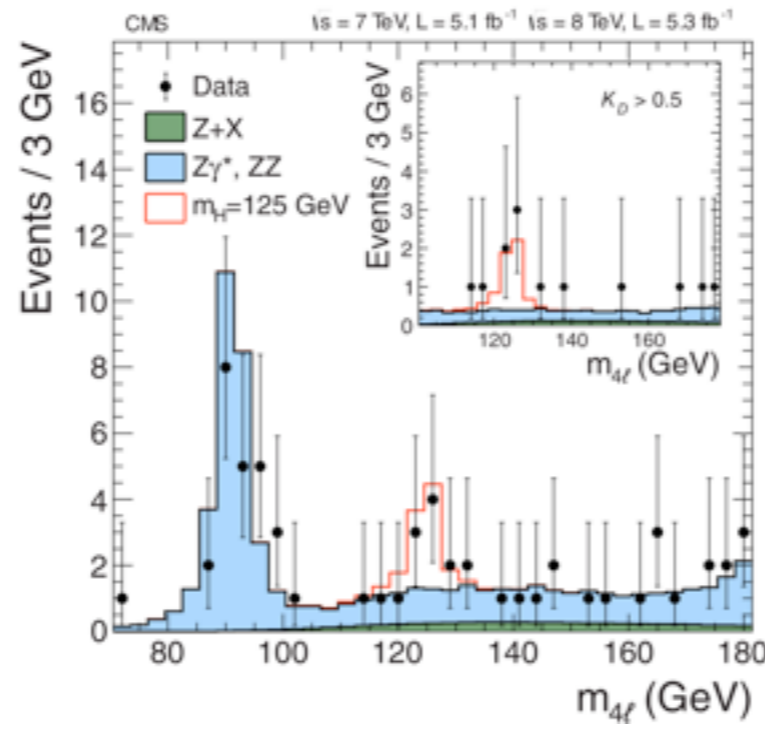
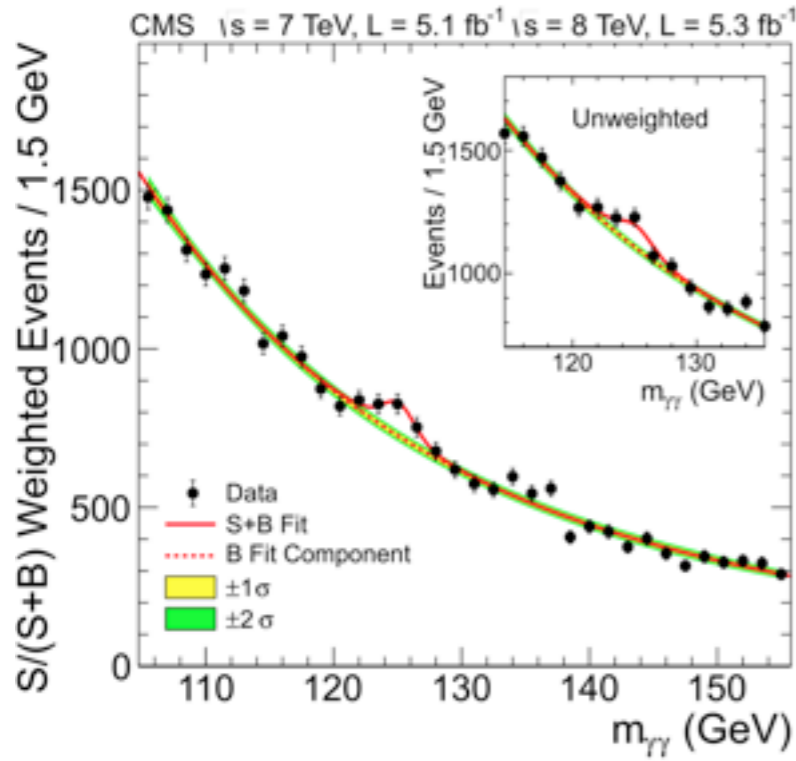




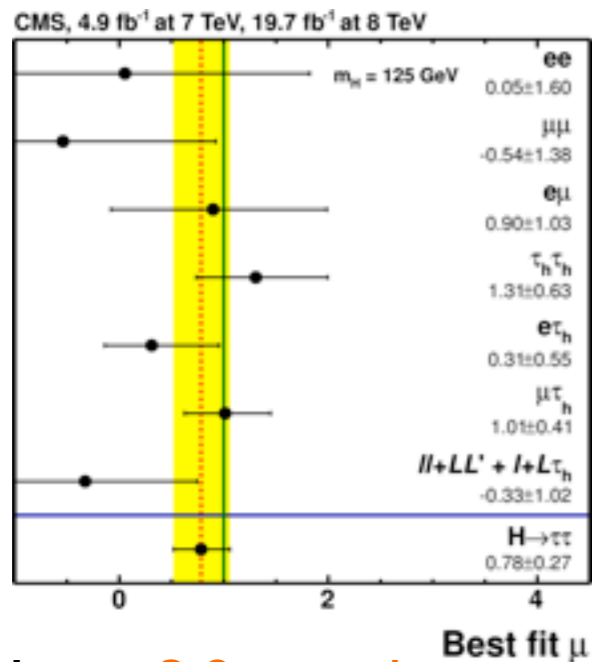
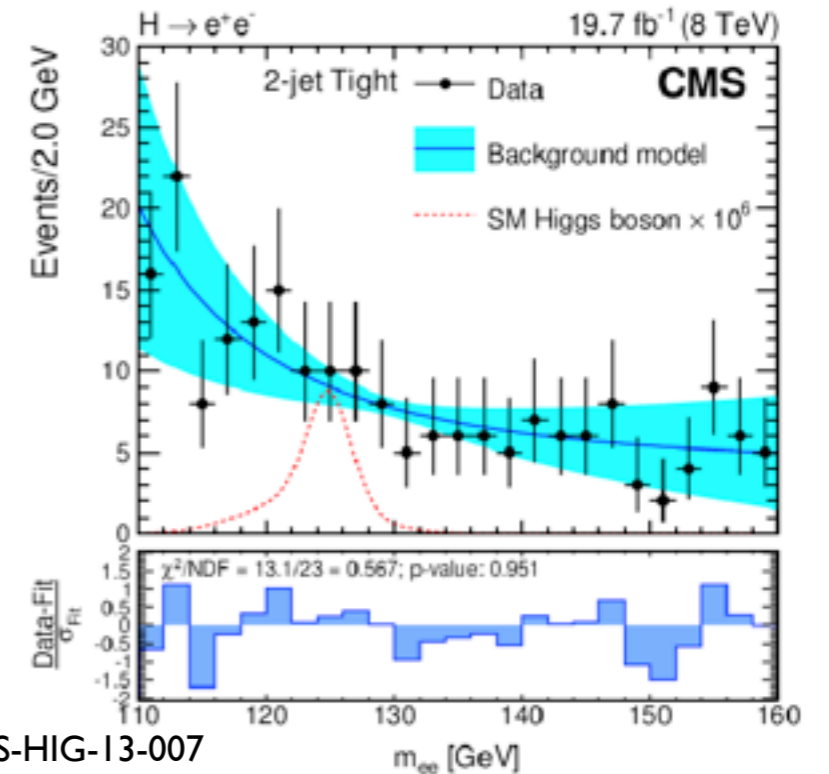
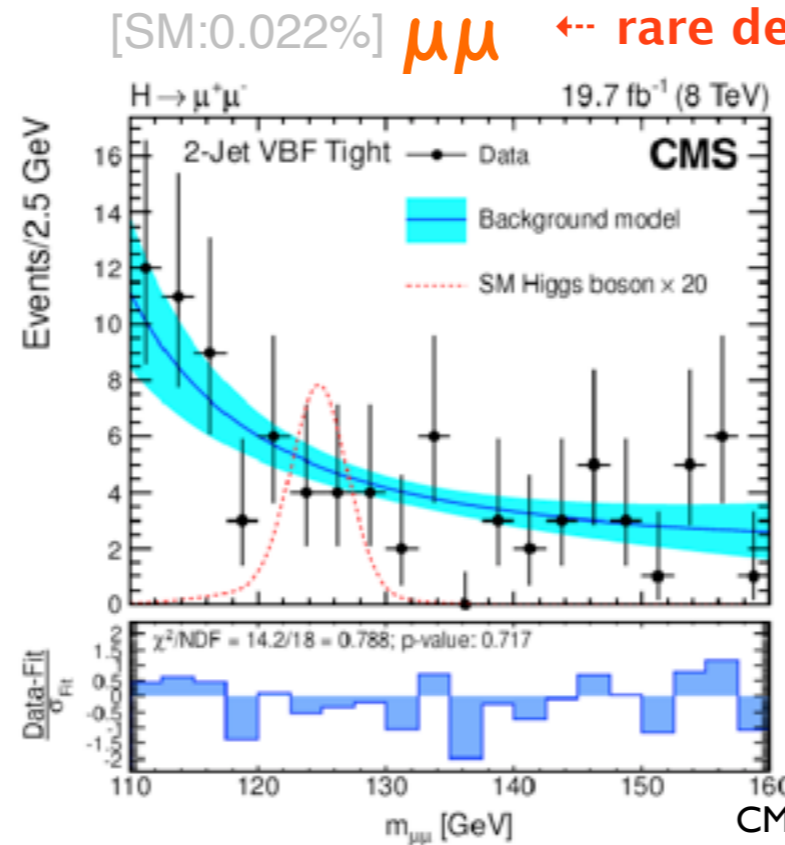
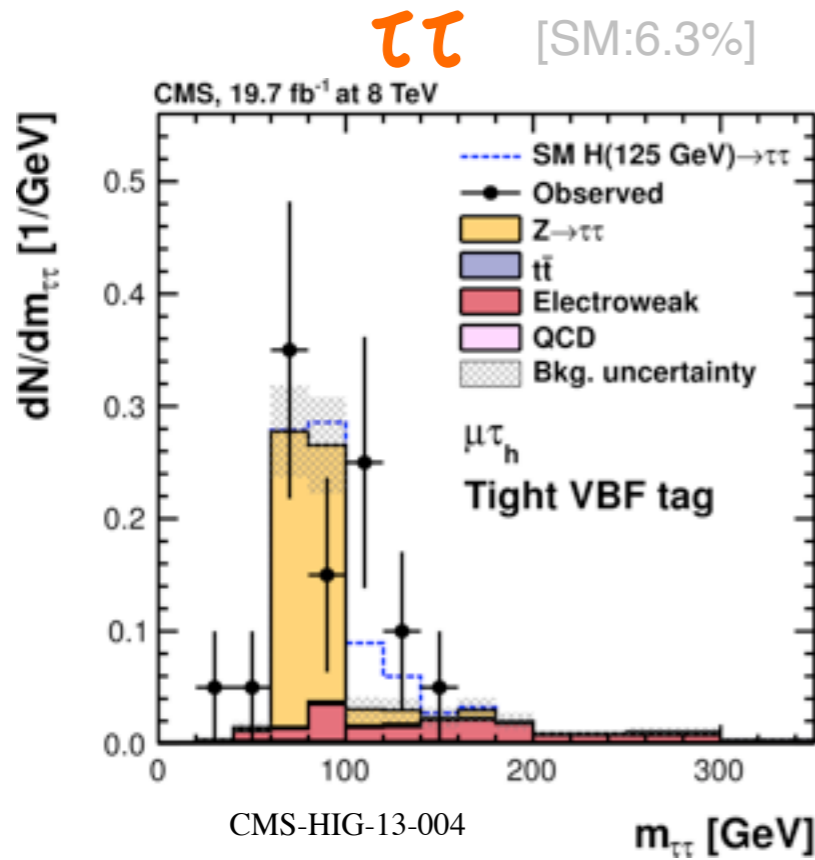
# the Higgs-like resonance at 125 GeV

found @LHC

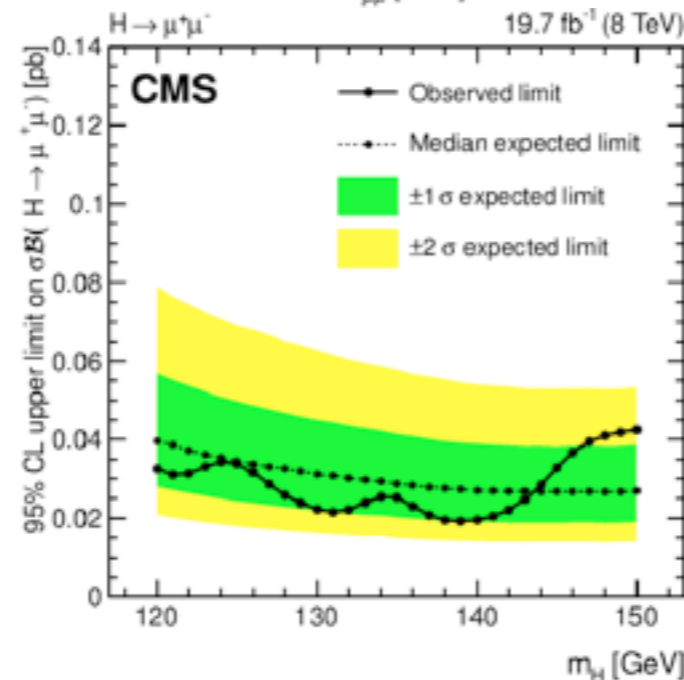
"I think we have it."  
CERN DG, 4.7.2012



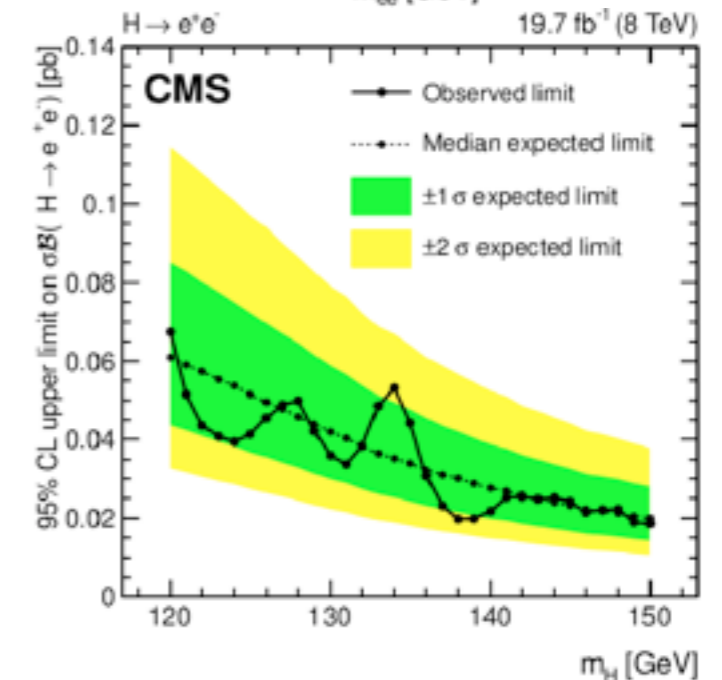
# search for $H \rightarrow \mu\mu$



$H \rightarrow \tau\tau$  3.2 $\sigma$  evidence



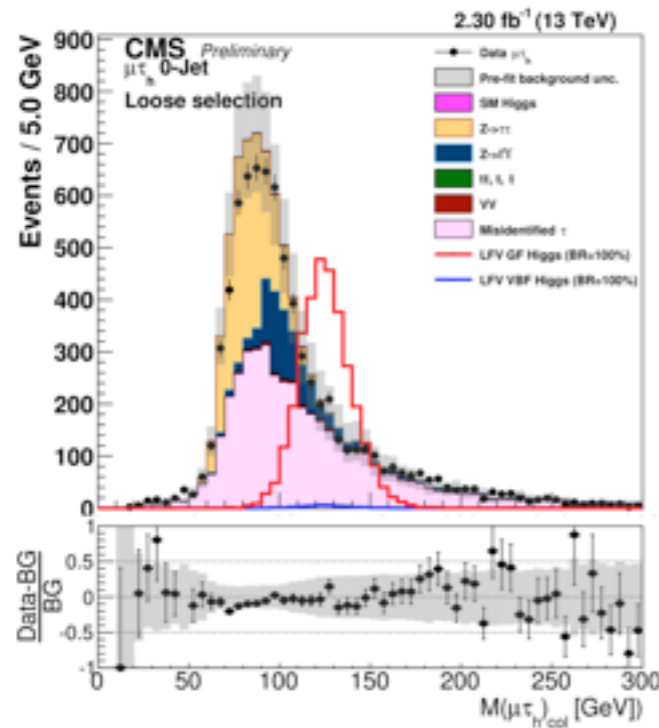
$B(H \rightarrow \mu\mu) < 1.6 \times 10^{-3}$  [=7.3xSM]



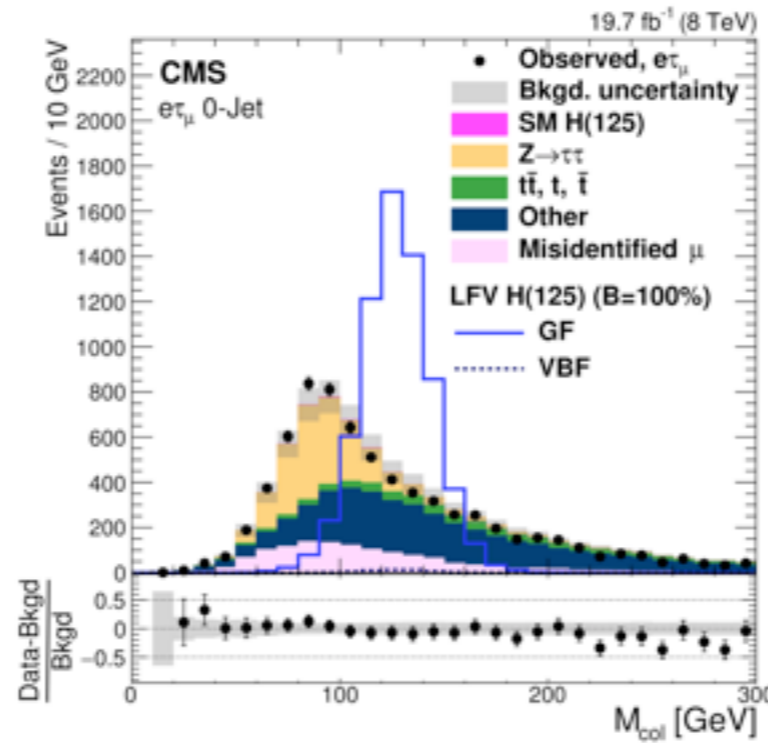
$B(H \rightarrow ee) < 0.0019$  [=3.7x10<sup>5</sup>xSM]

# search for LFV decays $H \rightarrow \ell\ell'$

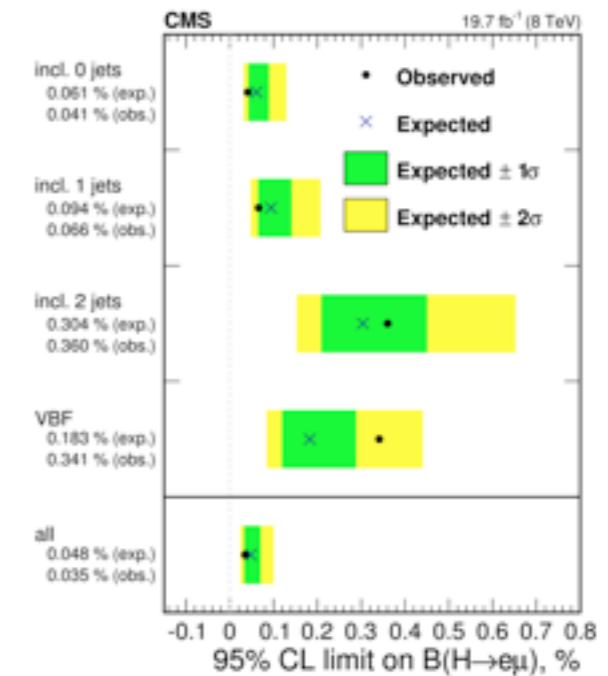
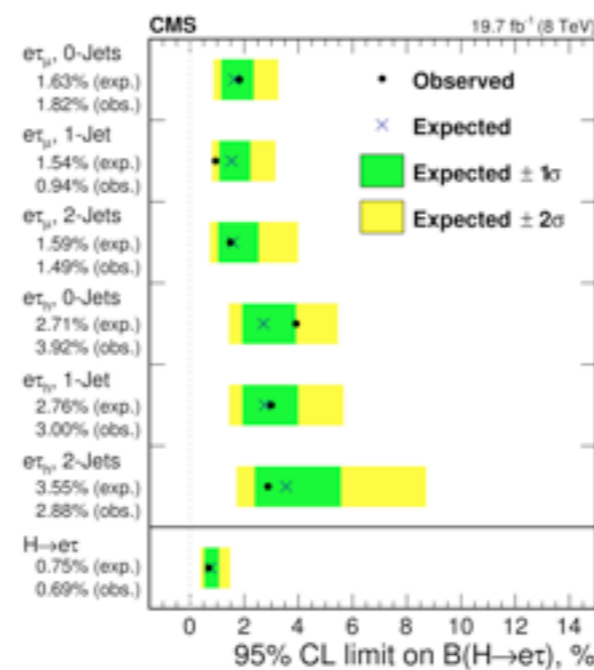
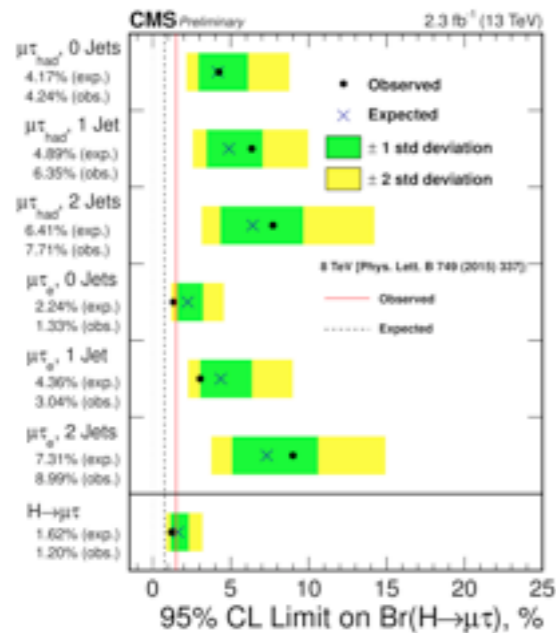
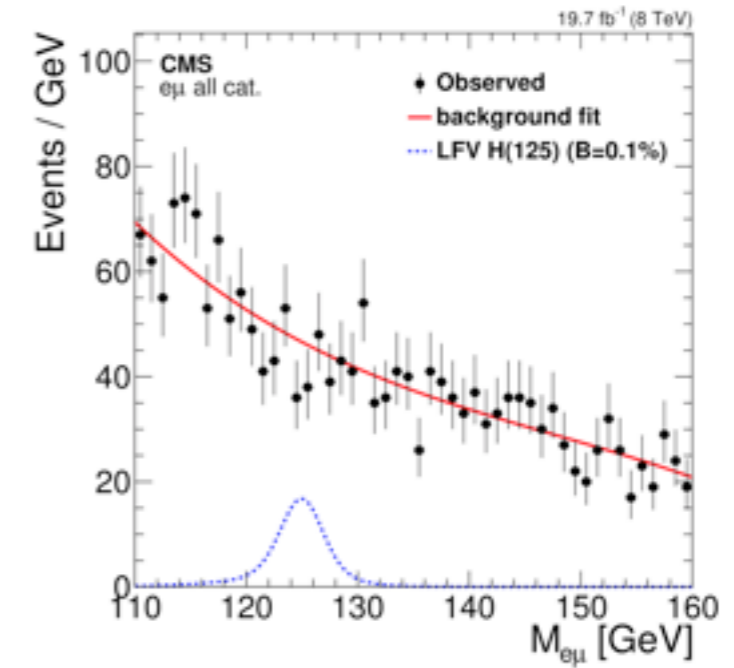
$\tau\mu$



$\tau e$



$\mu e$



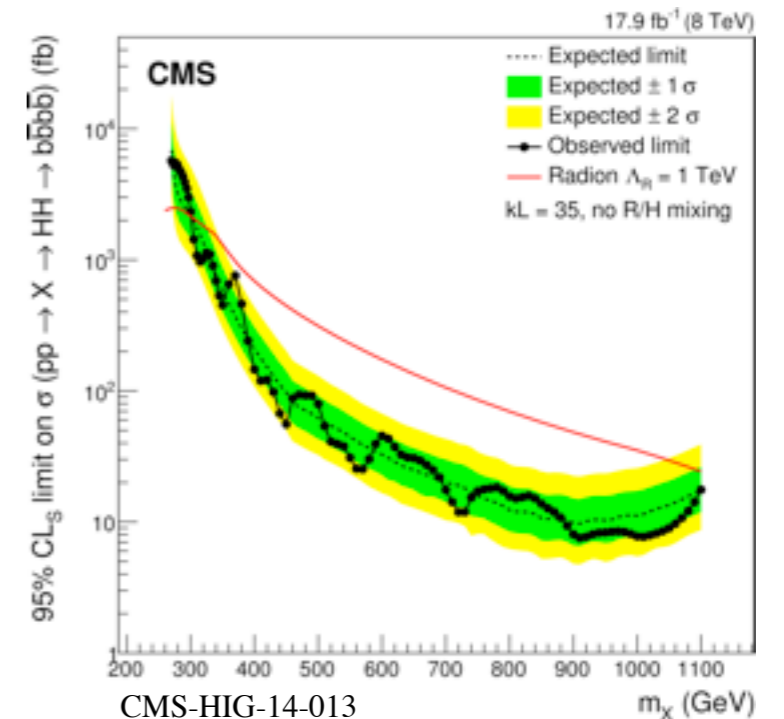
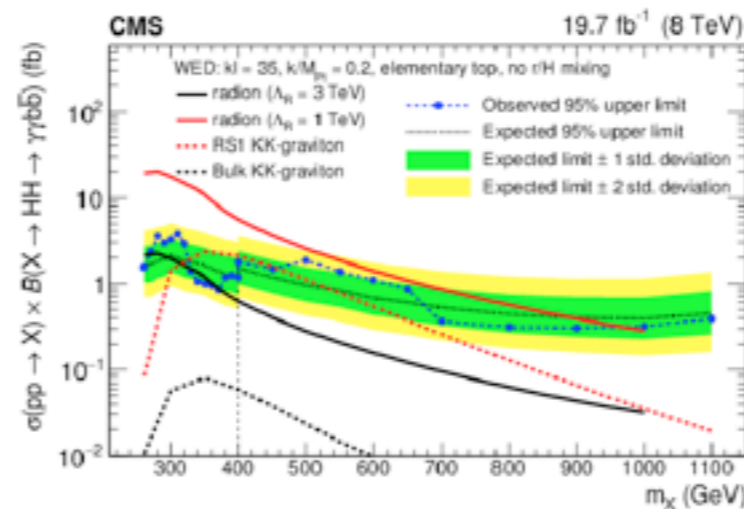
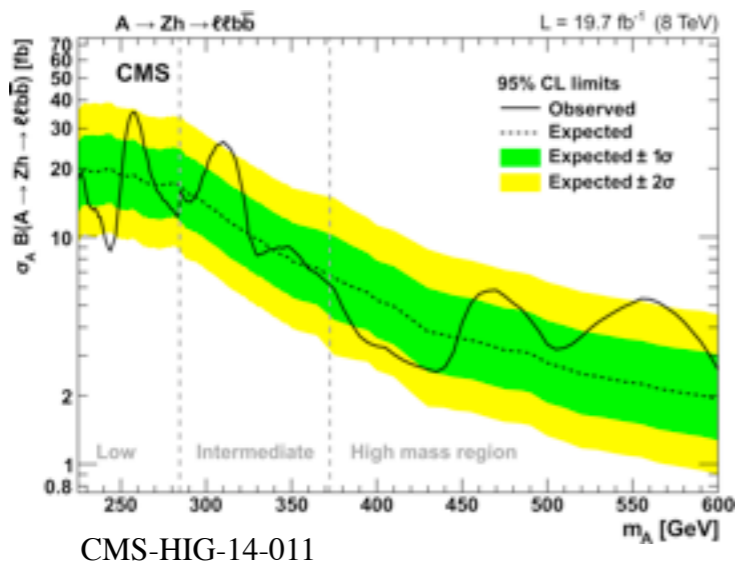
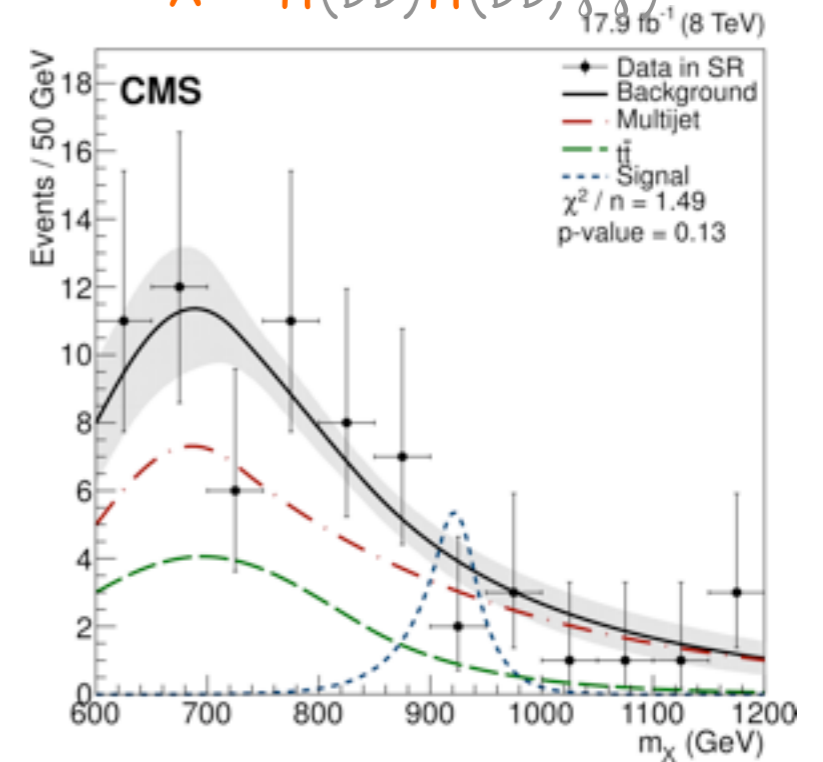
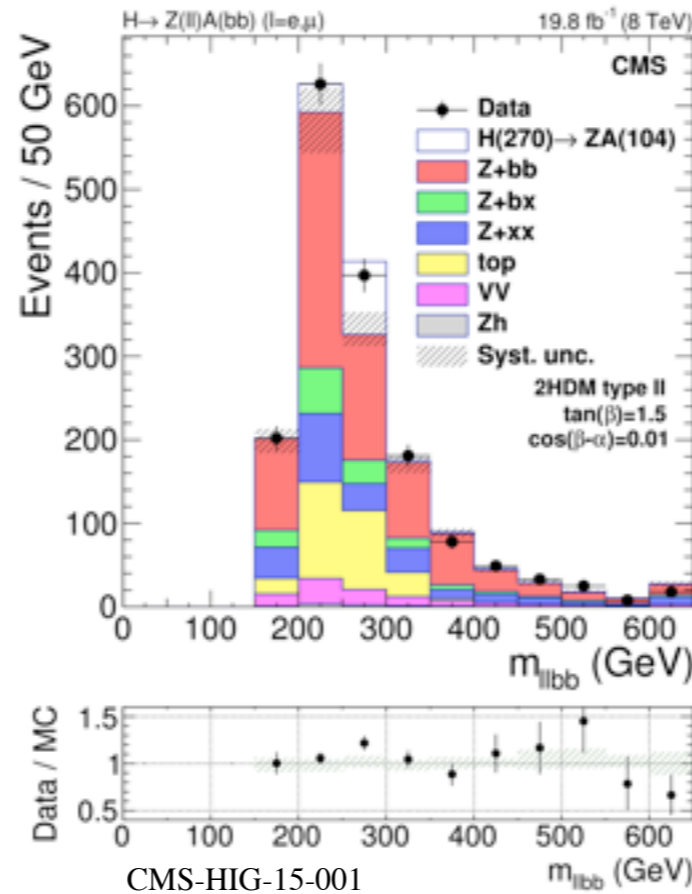
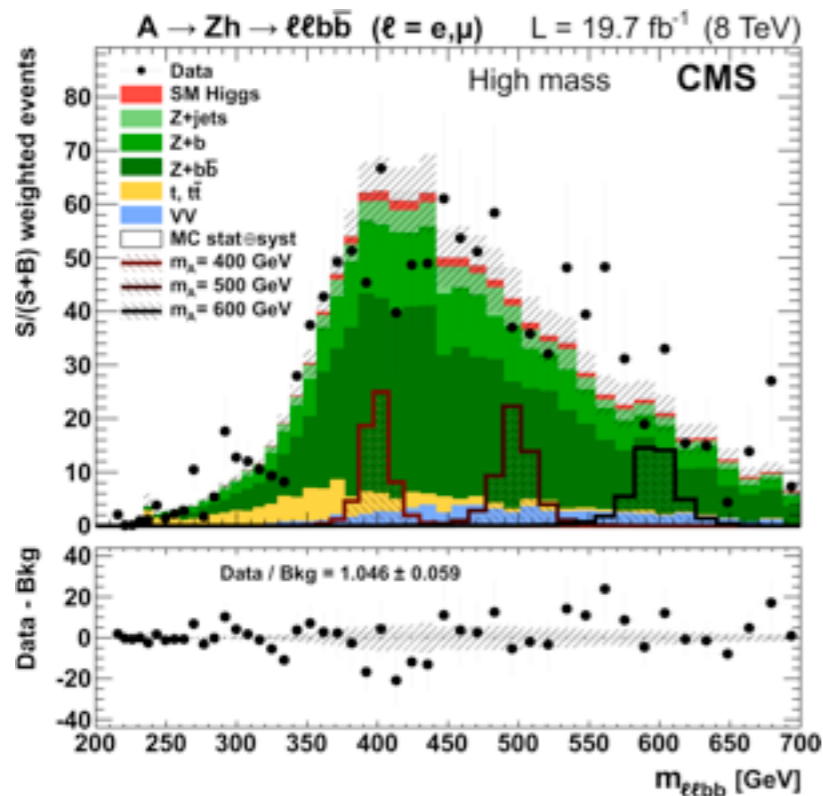
# search for resonances decaying to H

« or yesterday's discoveries are today's background tools »

$$X \rightarrow Z(\ell\ell)H(bb)$$

$$X \rightarrow Z(\ell\ell)h(bb, \tau\tau)$$

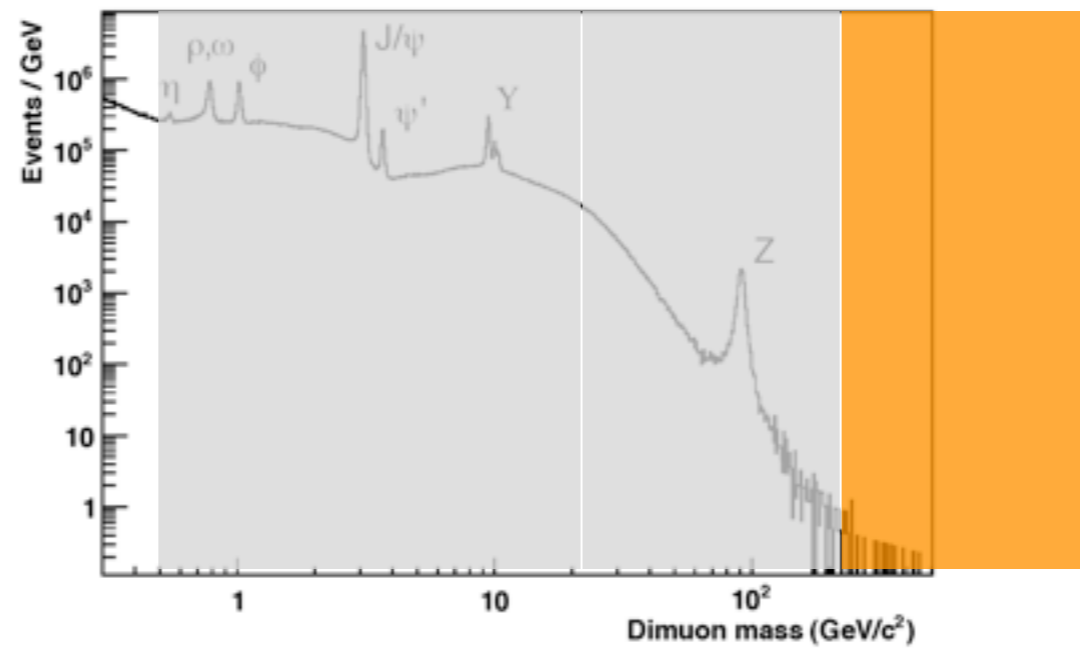
$$X \rightarrow H(bb)H(bb, \gamma\gamma)$$



CMS-HIG-14-011

CMS-HIG-15-001

CMS-HIG-14-013

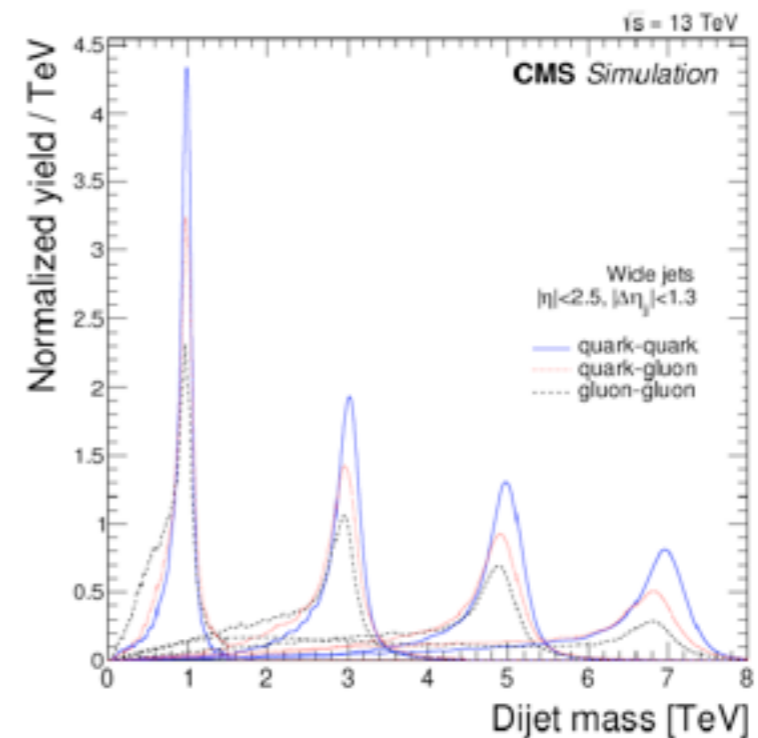
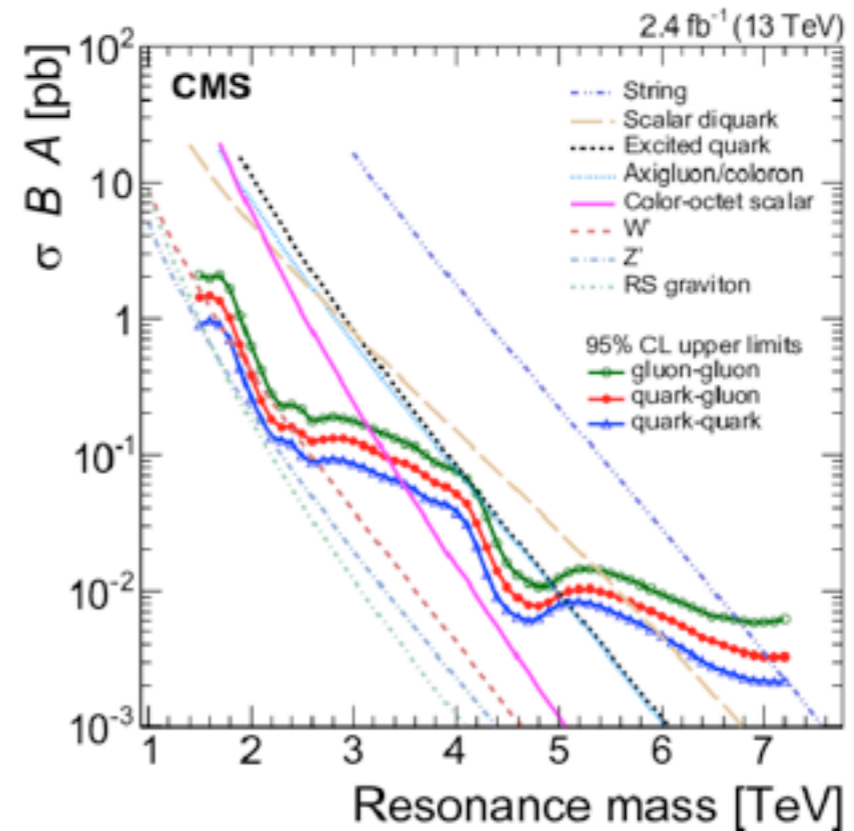
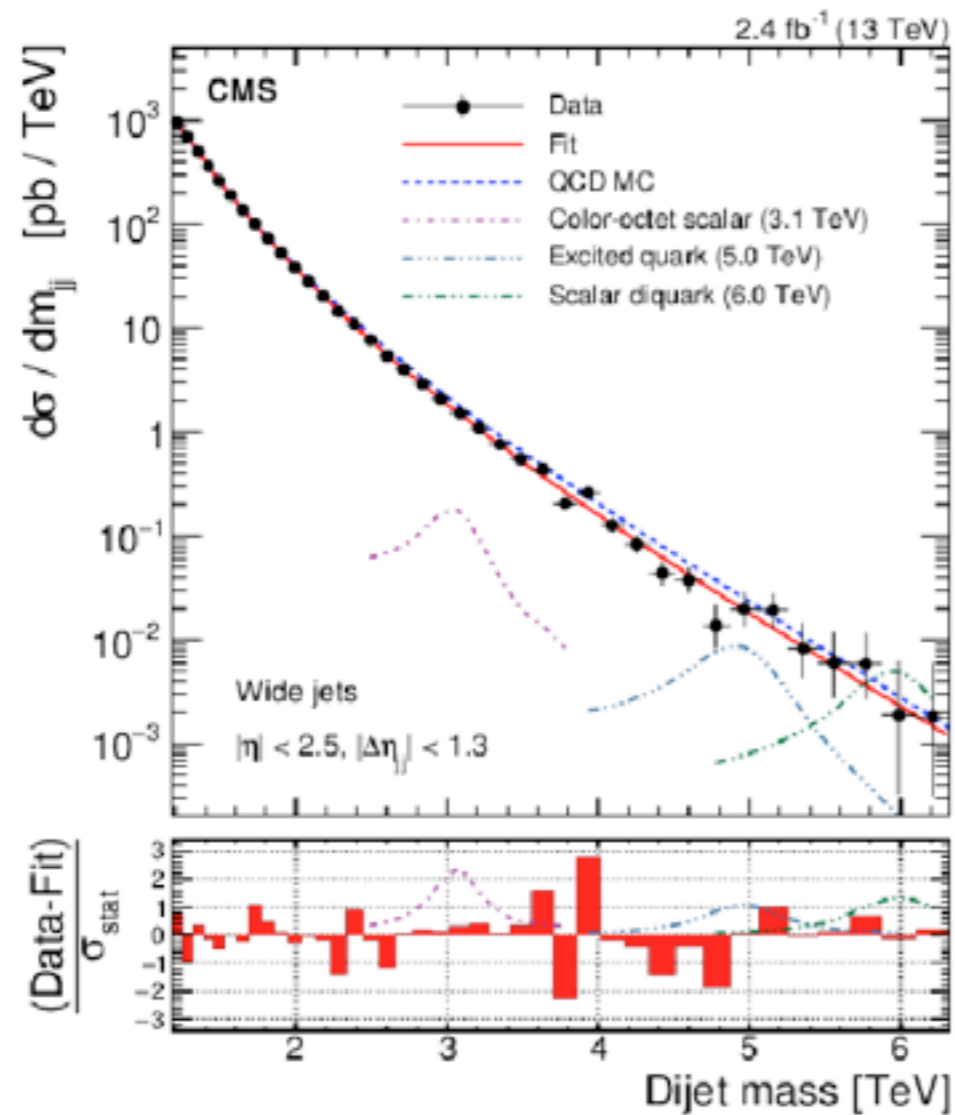


**resonances: high mass**

# high-mass resonances

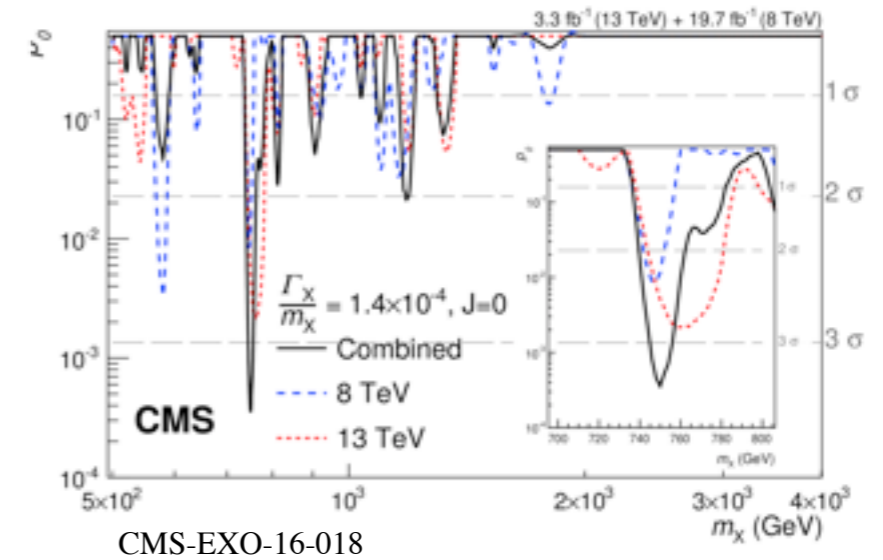
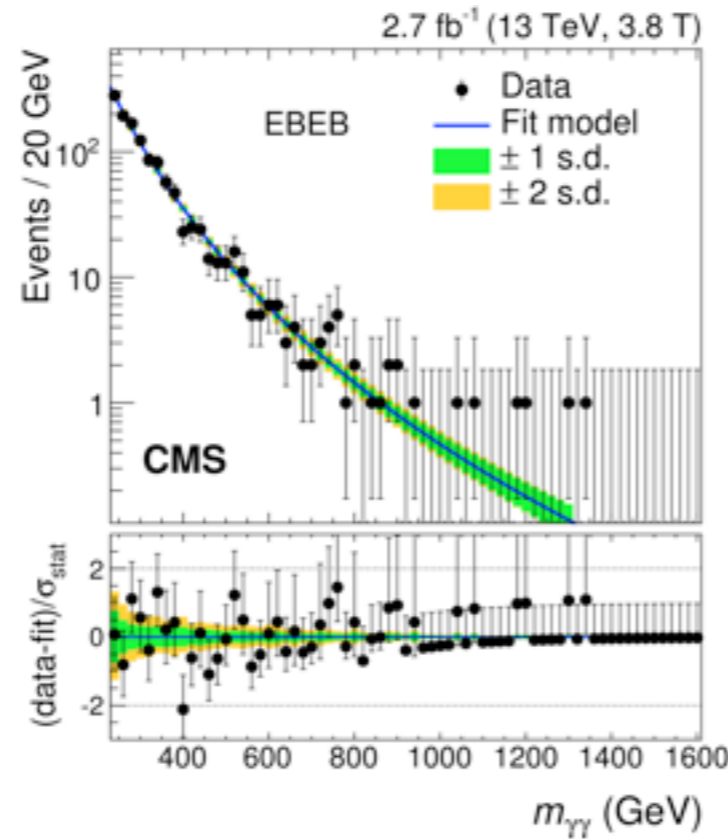
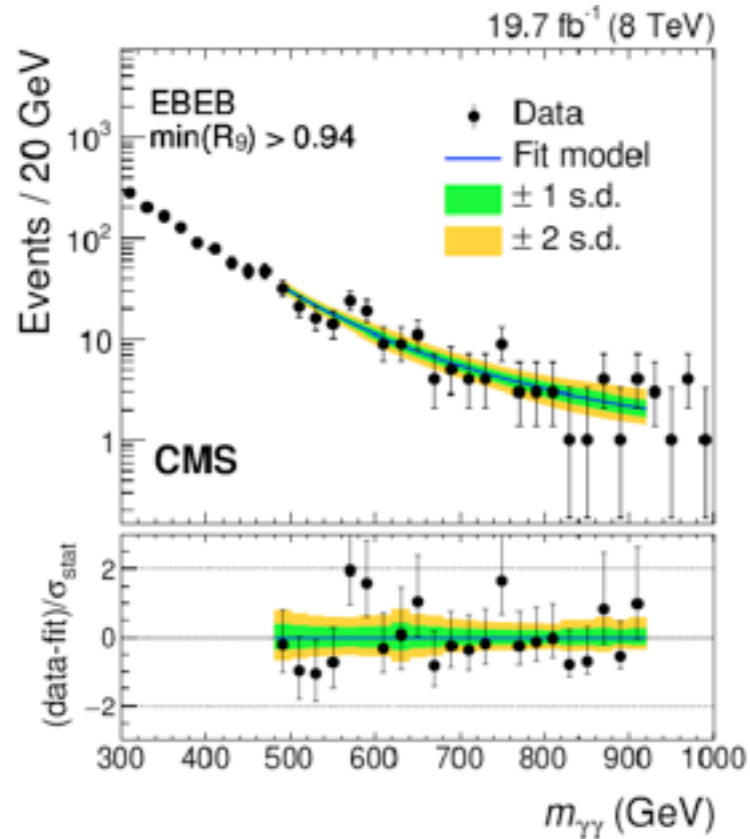
- New Physics realm
  - directly search for new massive states
- small selection of 13 TeV results only
  - based on 2015 data taking
  - much more data collected already in 2016, being processed
- Disclaimer
  - very reduced selection of resonance searches is shown

# search resonance decays $X \rightarrow jj$



Model	Final State	Obs. Mass Limit [TeV]	Exp. Mass Limit [TeV]
String	qg	7.0	6.9
Scalar diquark	qq	6.0	6.1
Axigluon/coloron	q $\bar{q}$	5.1	5.1
Excited quark (q*)	qg	5.0	4.8
Color-octet scalar	gg	3.1	3.3
Heavy W (W')	q $\bar{q}$	2.6	2.3

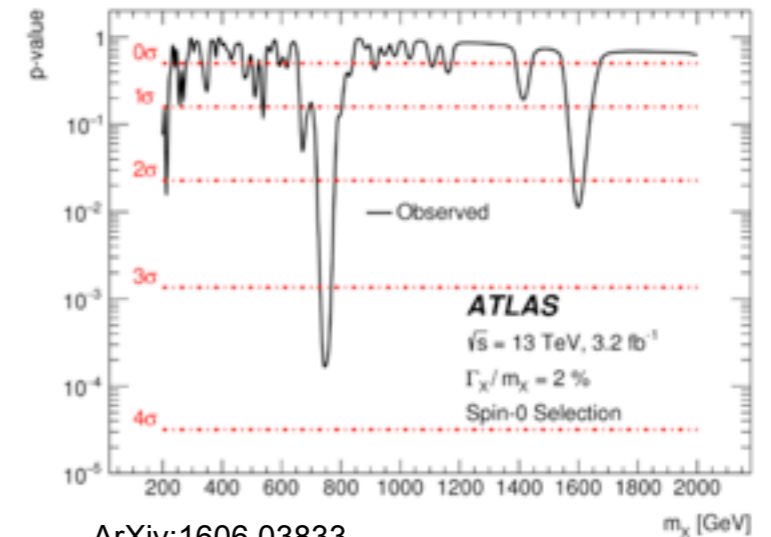
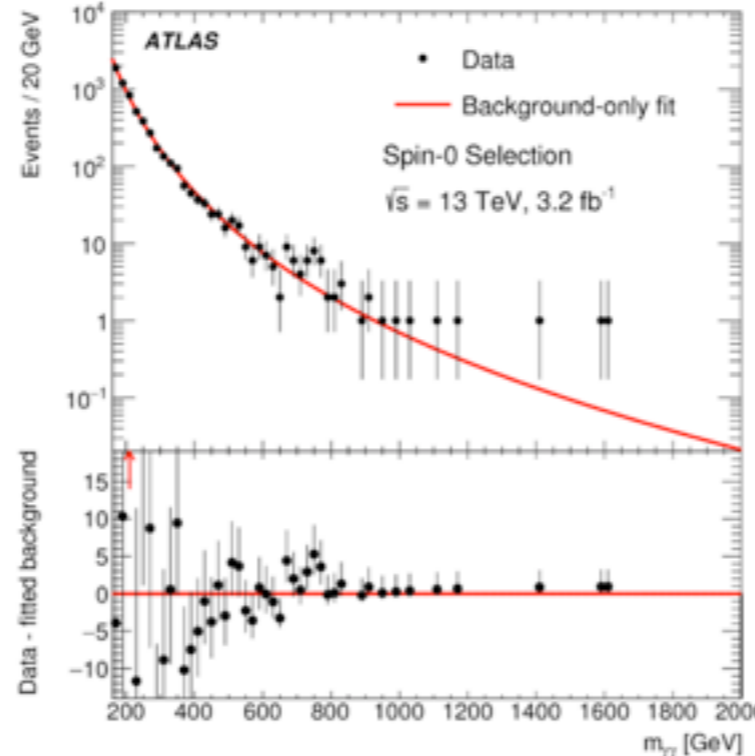
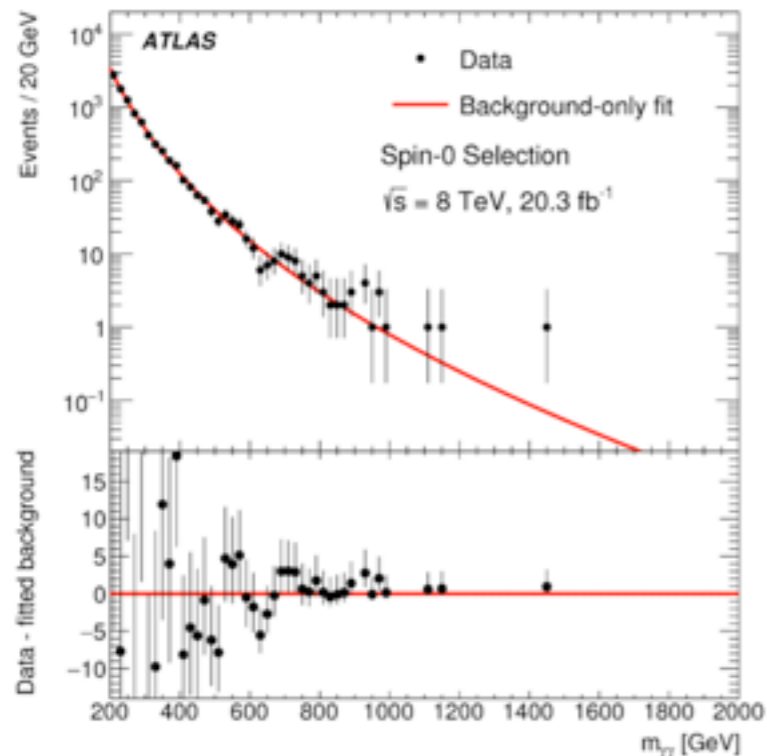
# search resonance decays $X \rightarrow \gamma\gamma$



CMS-EXO-16-018

excess seen at  $m \sim 750$  GeV  
3.4σ (local), 1.6σ (global)

more data is needed  
to clarify possible excess



ArXiv:1606.03833

excess seen at  $m \sim 750$  GeV  
3.6σ (local), 2.0σ (global)

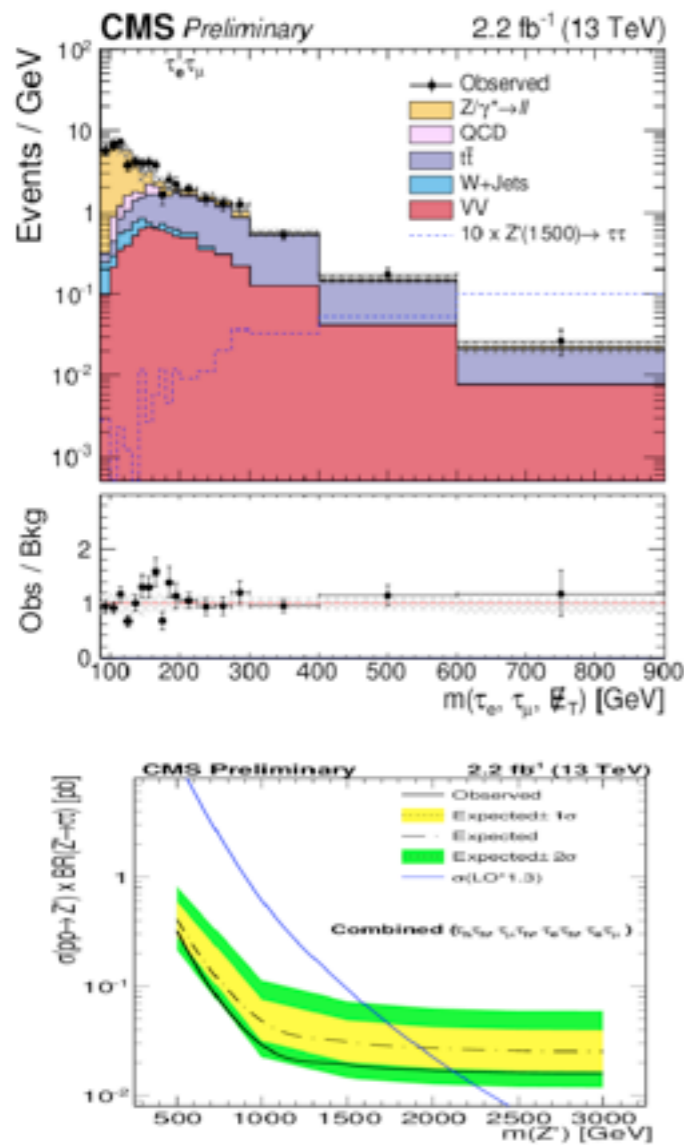


# search for resonance decays $X \rightarrow ll$

$\tau\tau$

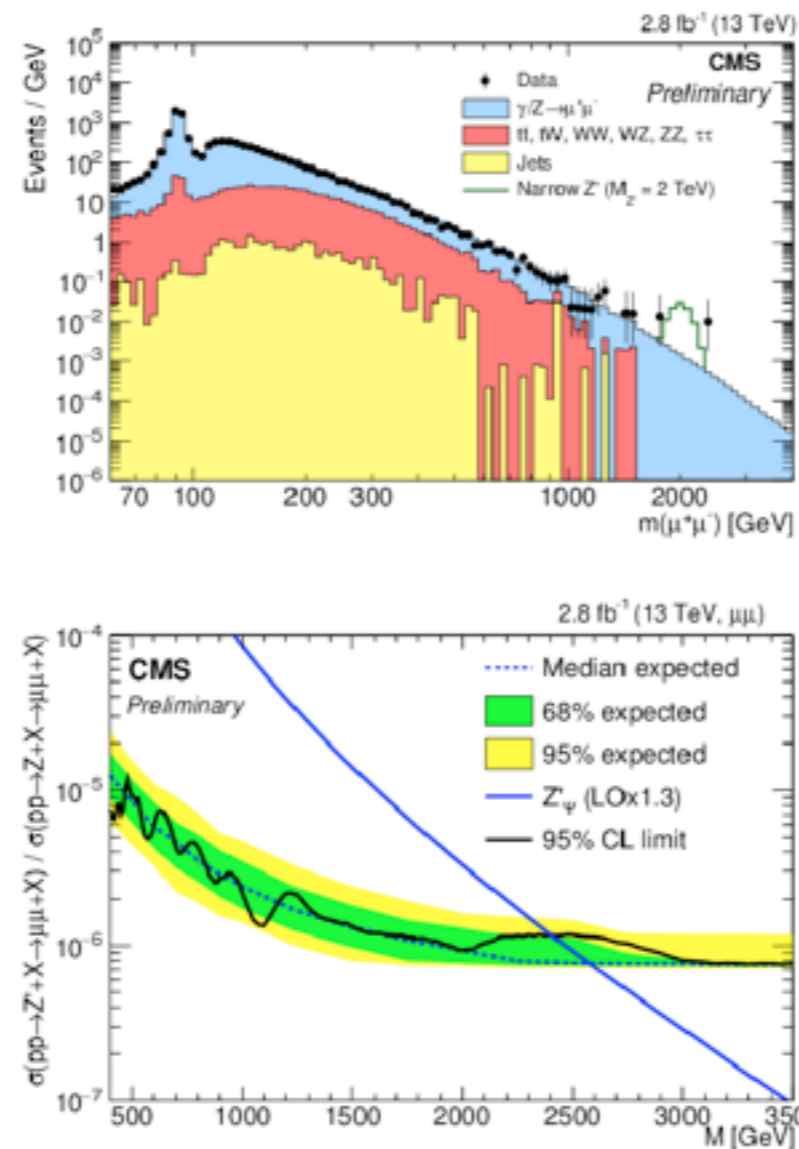
$\mu\mu$

$ee$



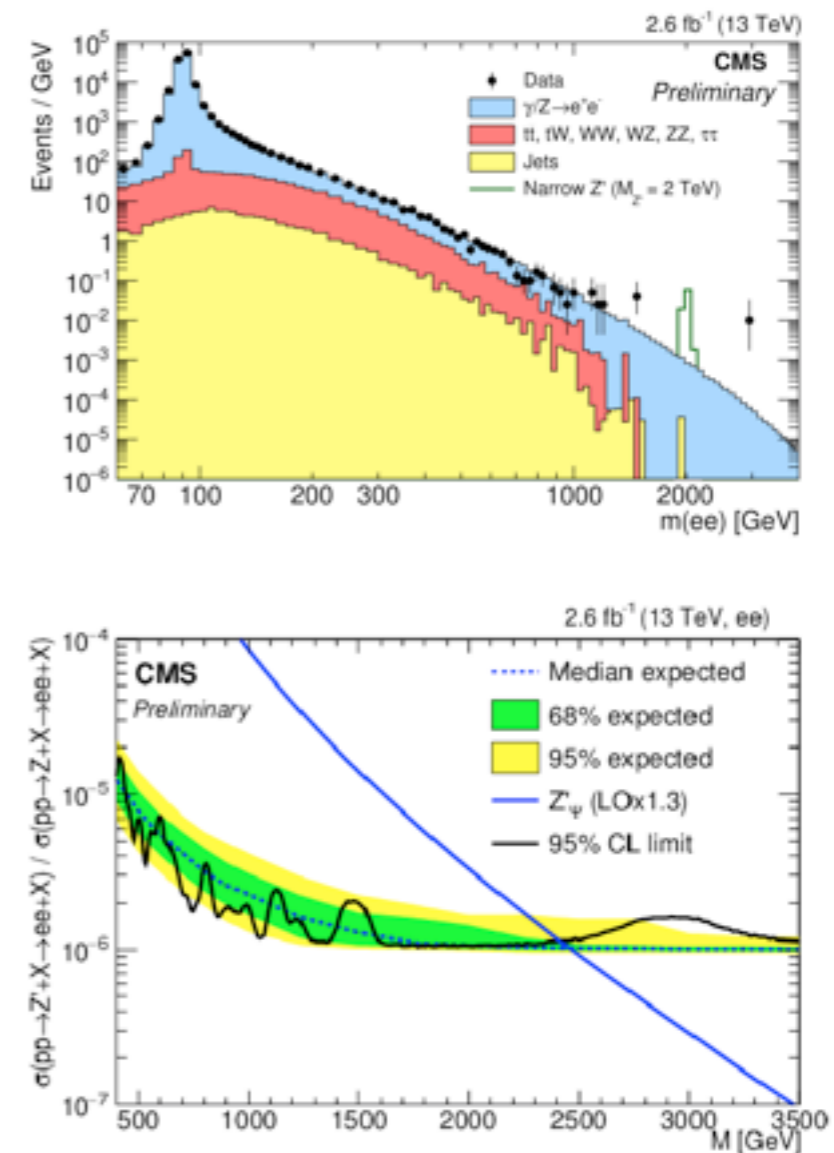
CMS-PAS-EXO-16-008

$m(Z') > 2.1 \text{ TeV}$



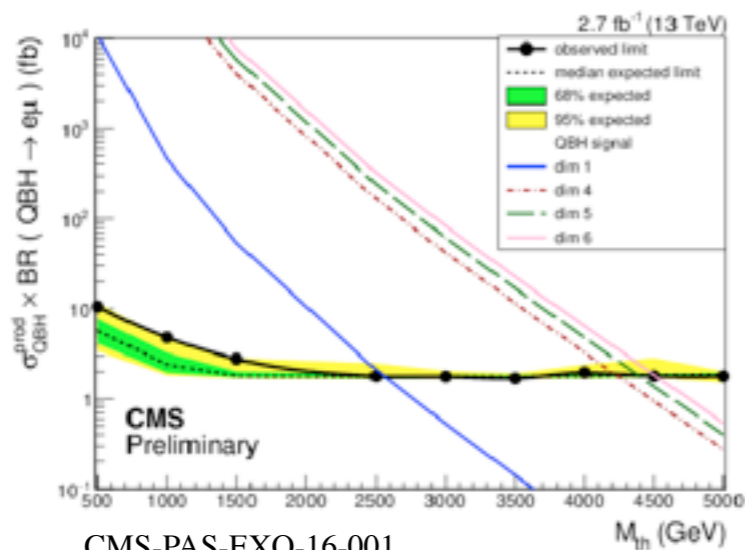
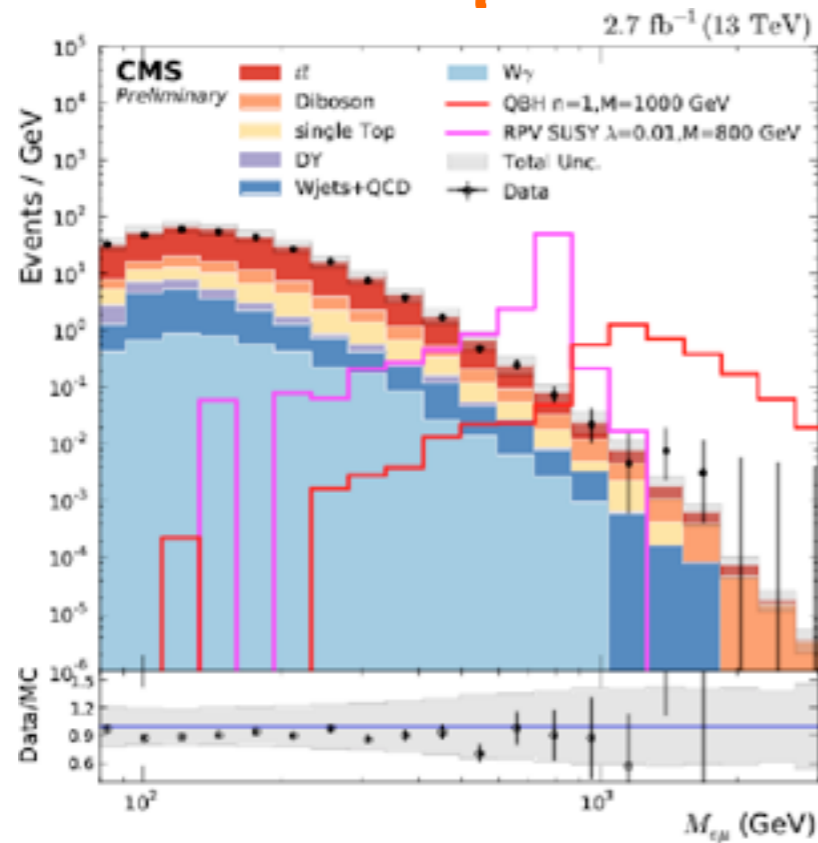
CMS-PAS-EXO-15-005

$m(Z') > 2.60\text{-}3.15 \text{ TeV}$



# search for resonance decays $X \rightarrow l l'$

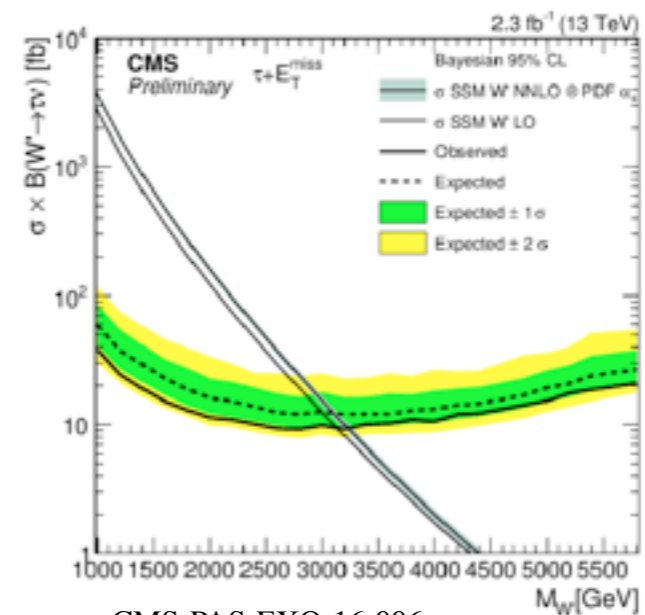
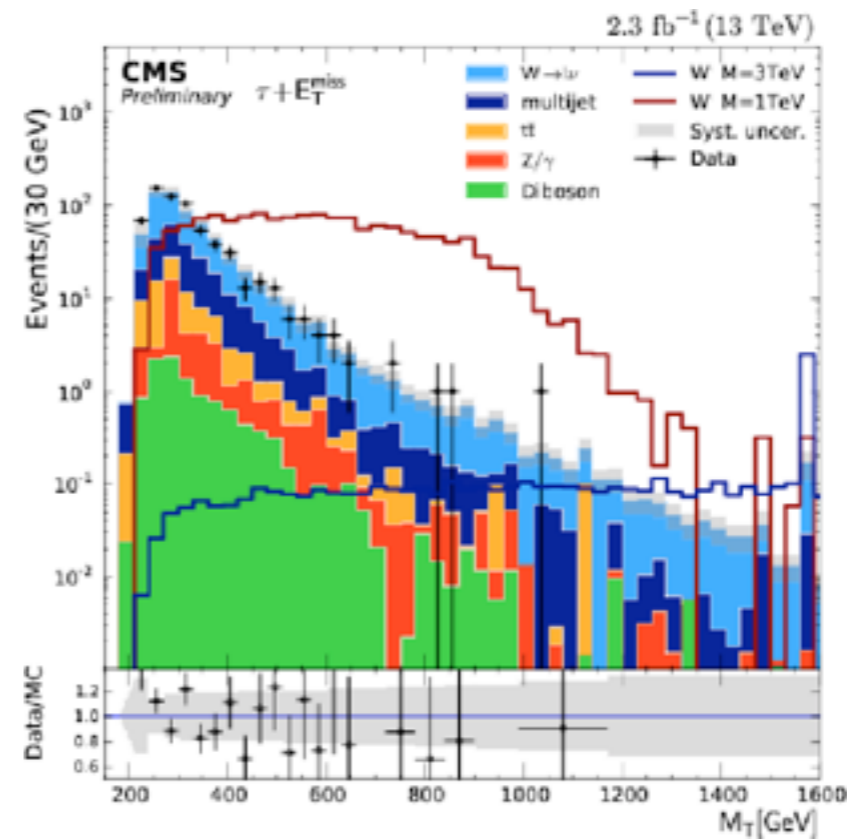
$X \rightarrow \mu e$



CMS-PAS-EXO-16-001

$m(\text{QBH}) > 2.5\text{-}4.5 \text{ TeV}$

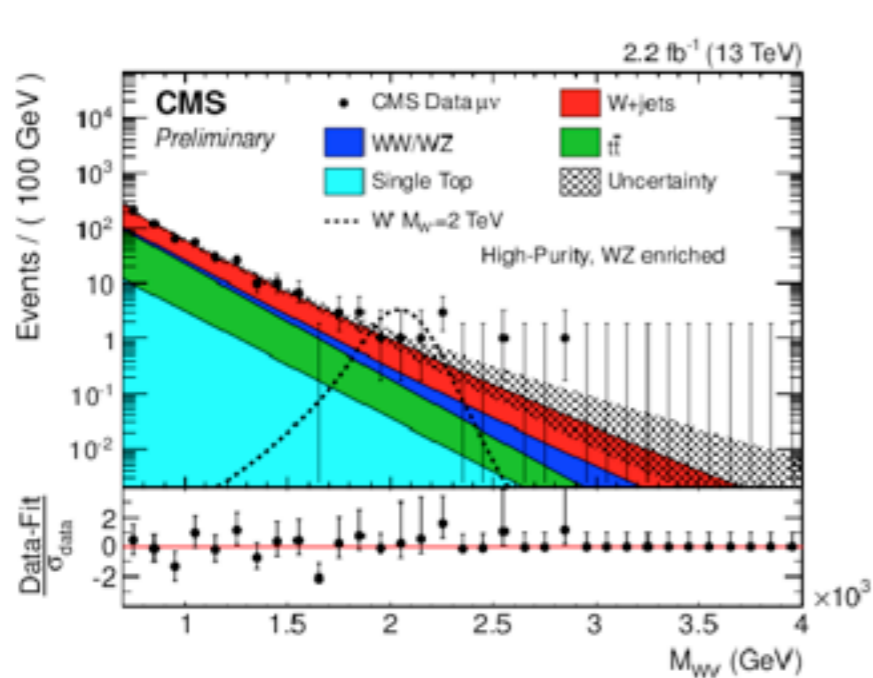
$X \rightarrow \tau \nu$



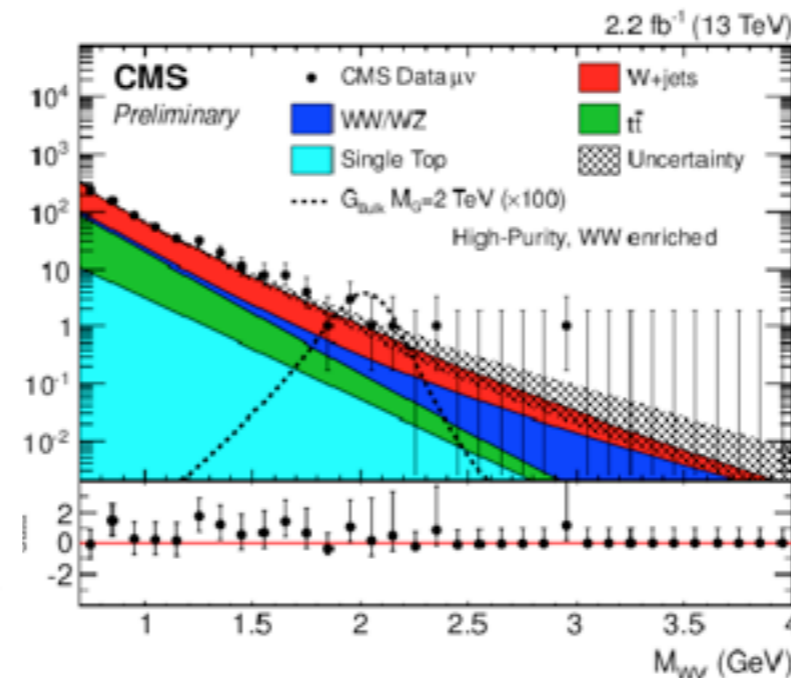
CMS-PAS-EXO-16-006

# search for resonance decays $X \rightarrow VV$

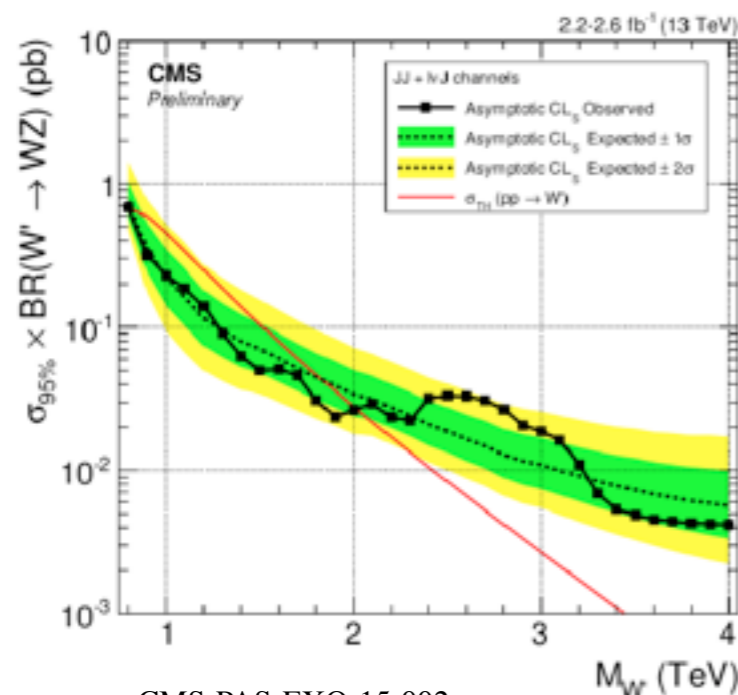
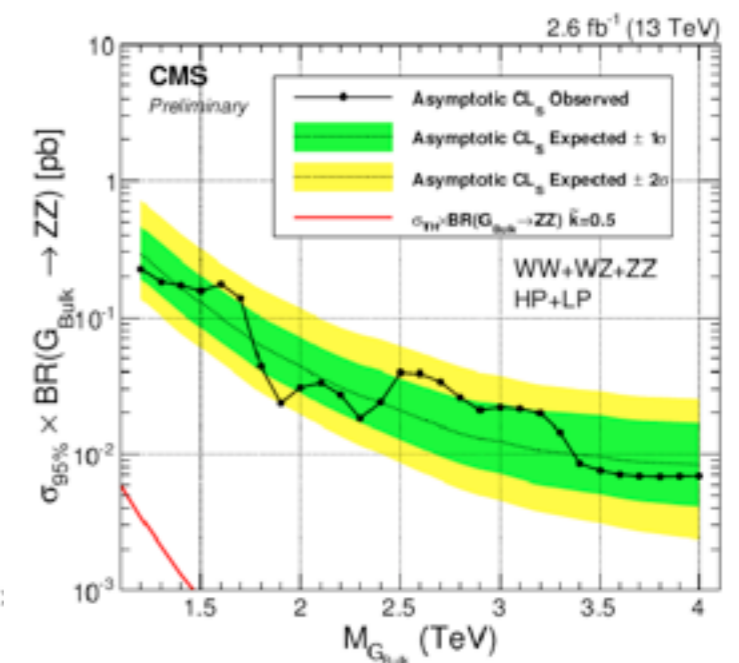
$X \rightarrow WZ$



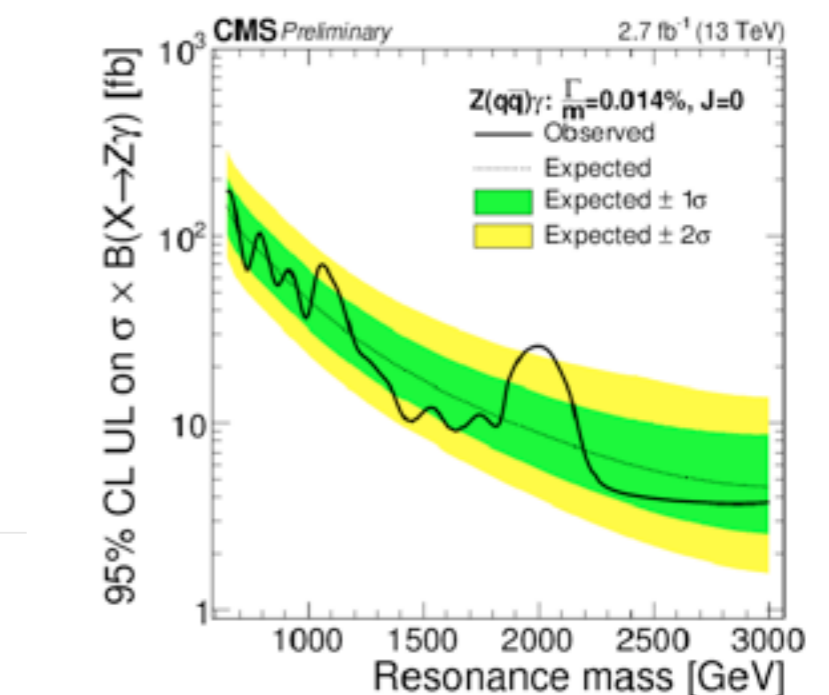
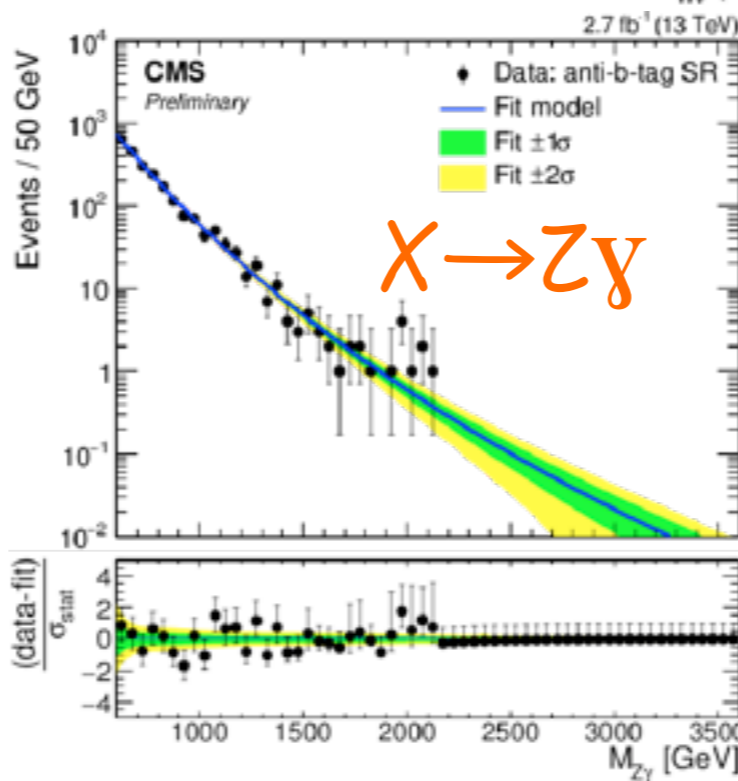
$X \rightarrow WW$



$X \rightarrow ZZ$



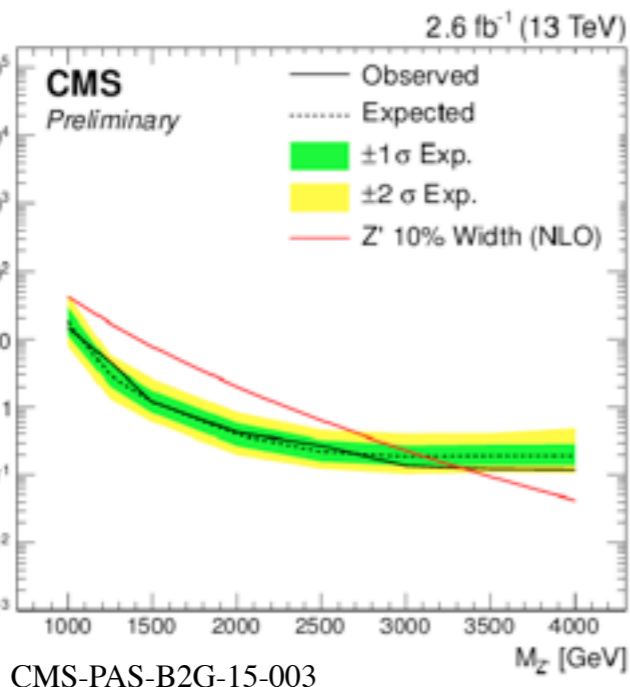
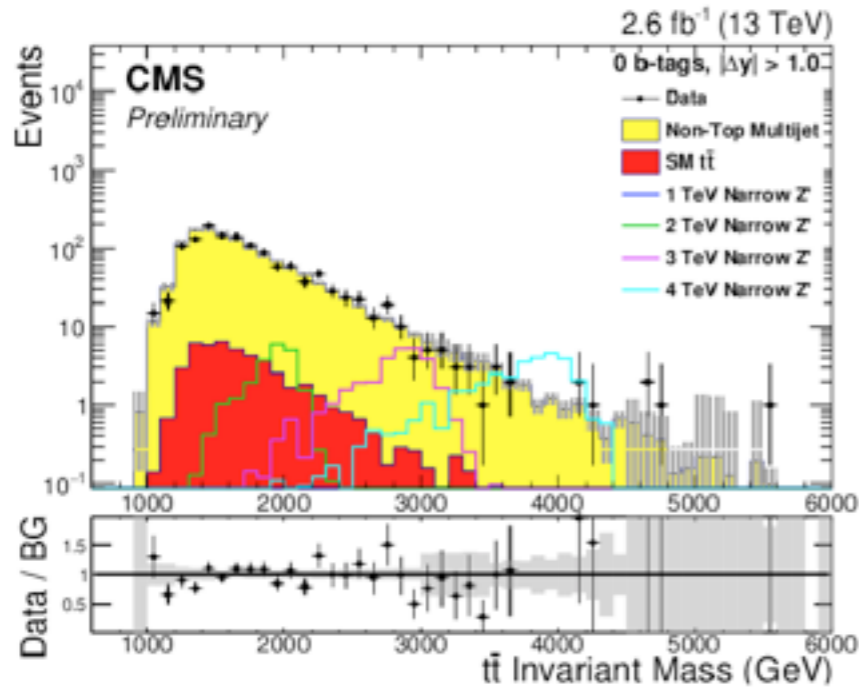
CMS-PAS-EXO-15-002



CMS-PAS-EXO-16-020

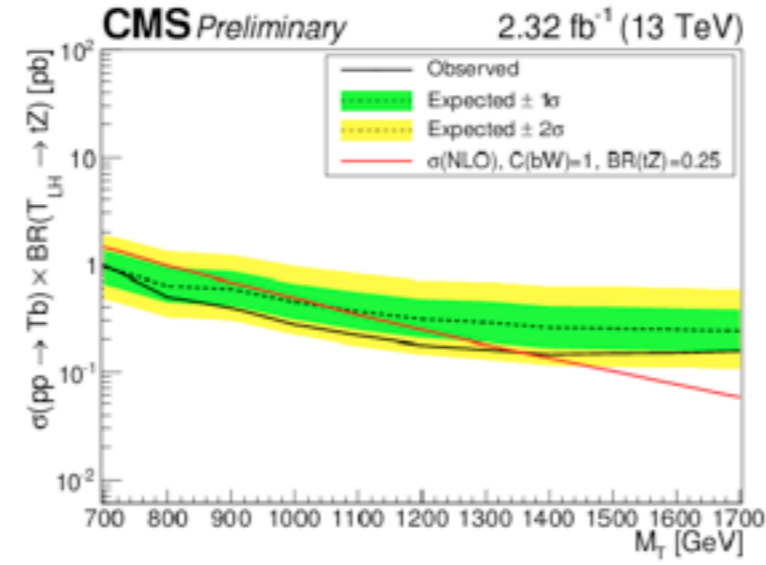
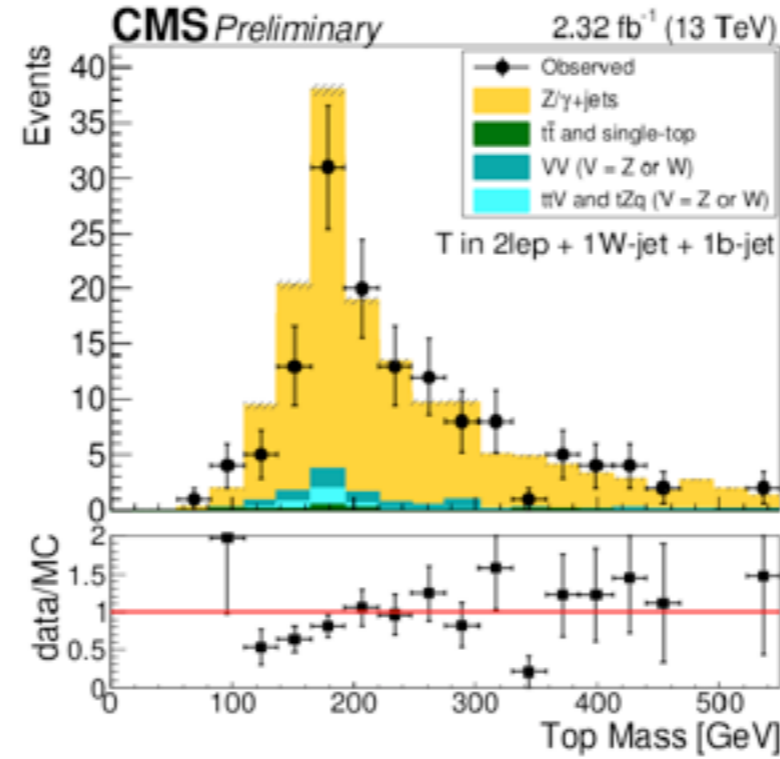
# search for resonances decaying to top

$X \rightarrow tt$



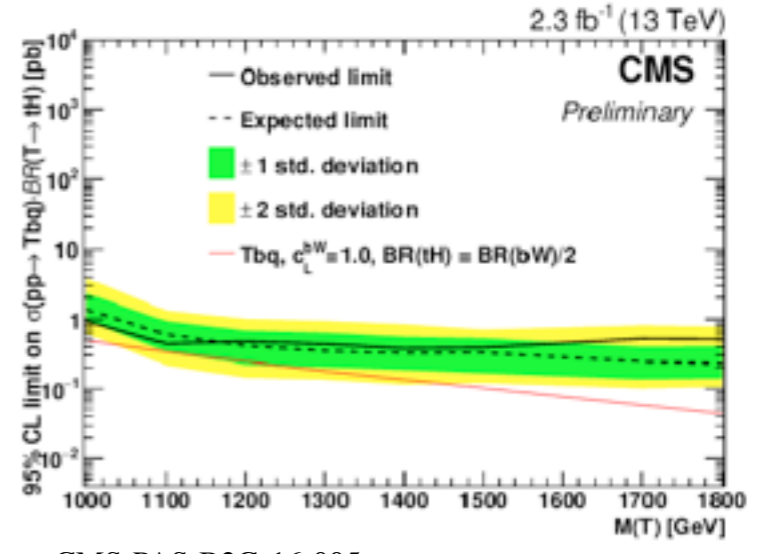
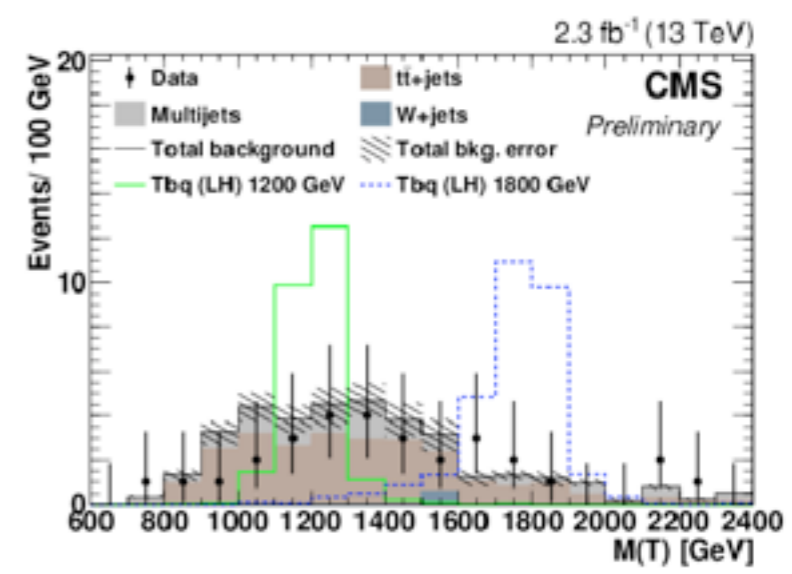
CMS-PAS-B2G-15-003

$X \rightarrow Zt$



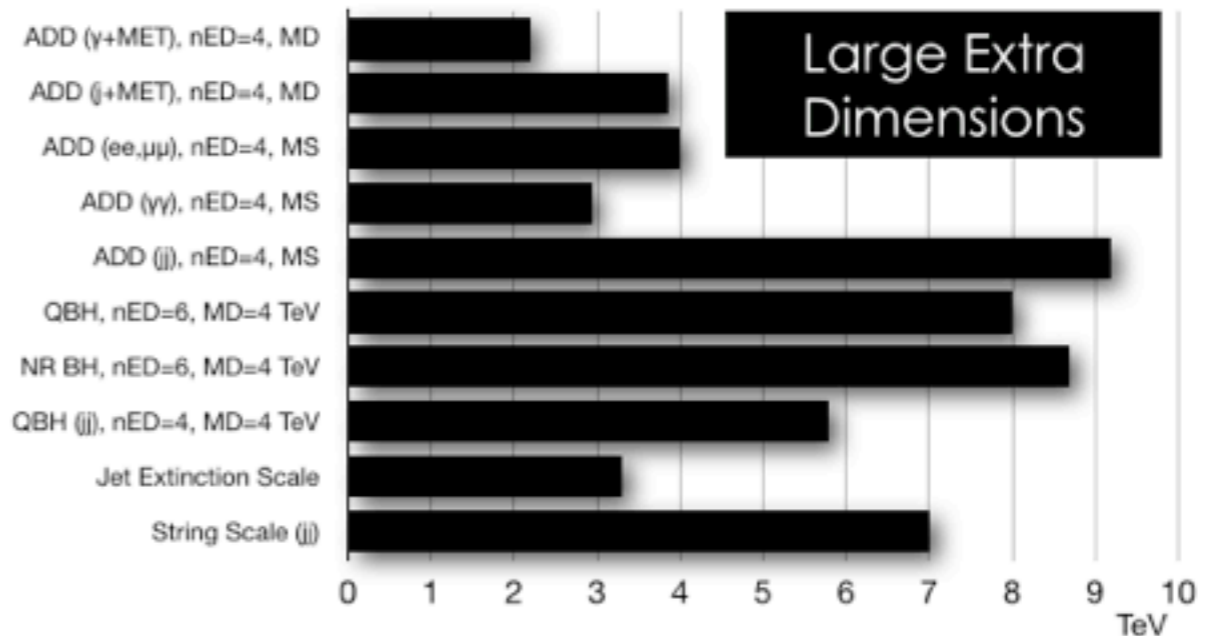
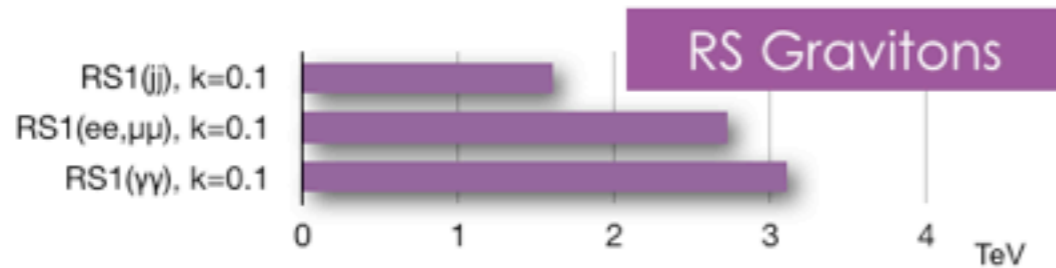
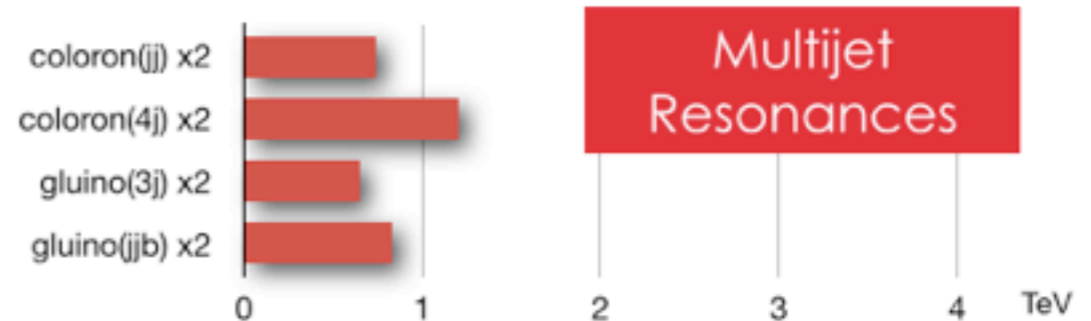
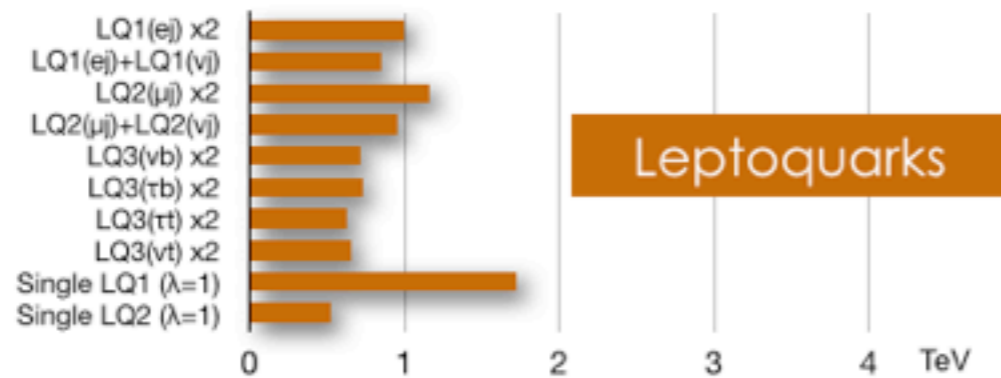
CMS-PAS-B2G-16-001

$X \rightarrow Ht$

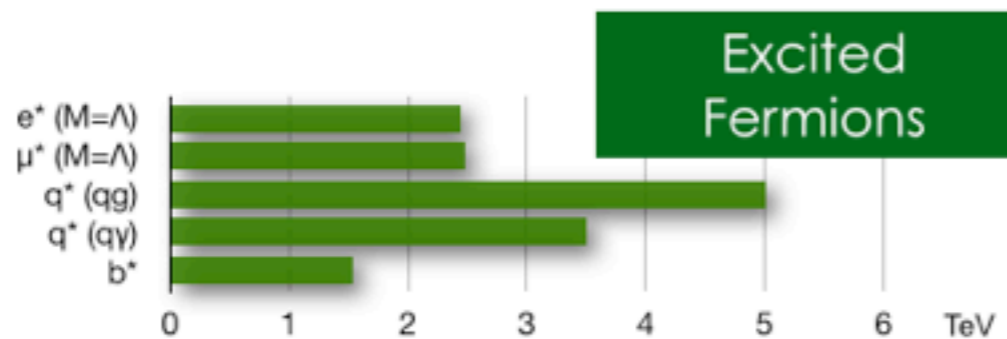
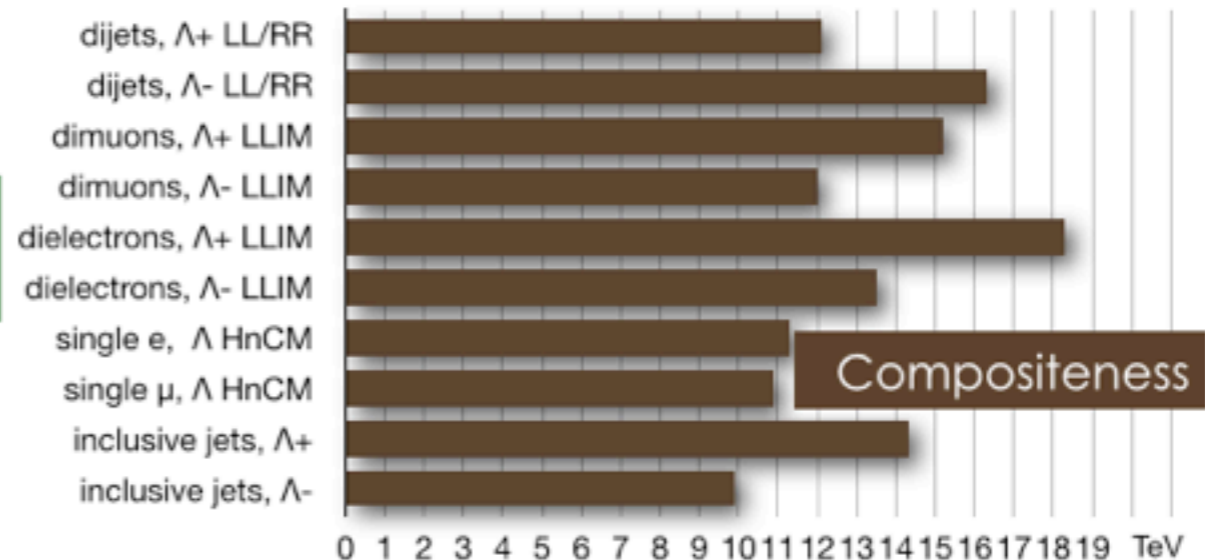
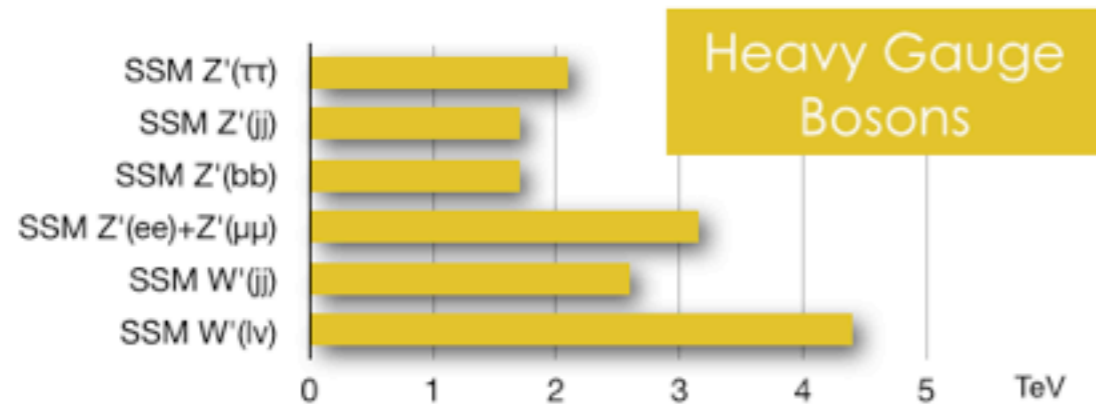


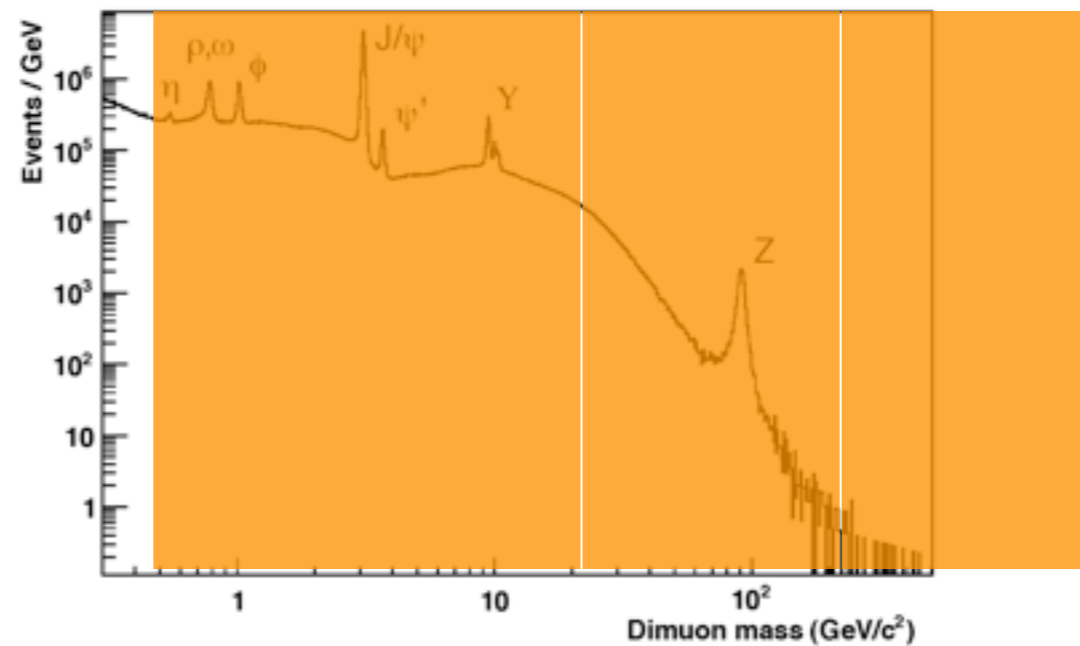
CMS-PAS-B2G-16-005

# high-mass grand summary




## CMS Preliminary



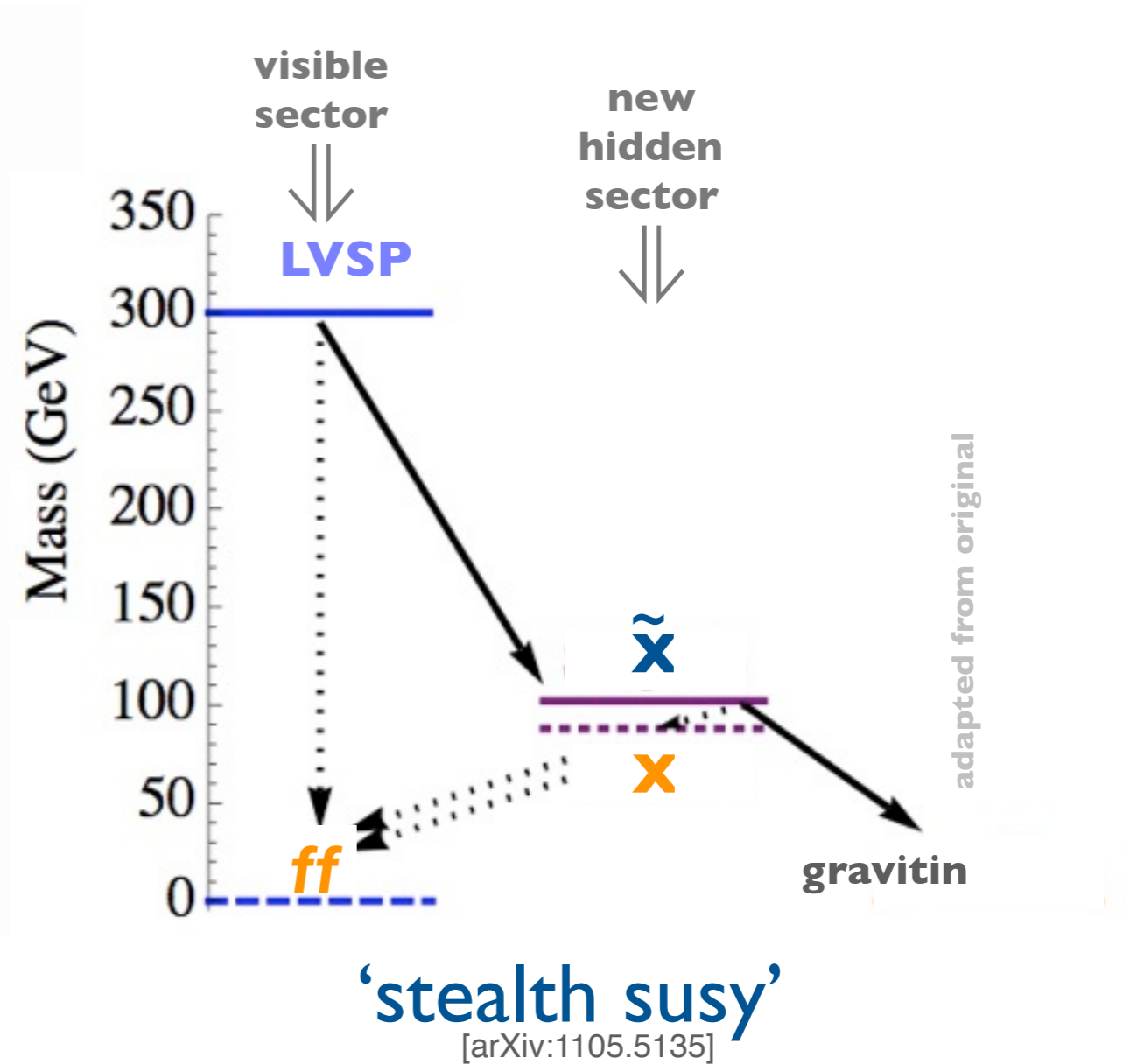
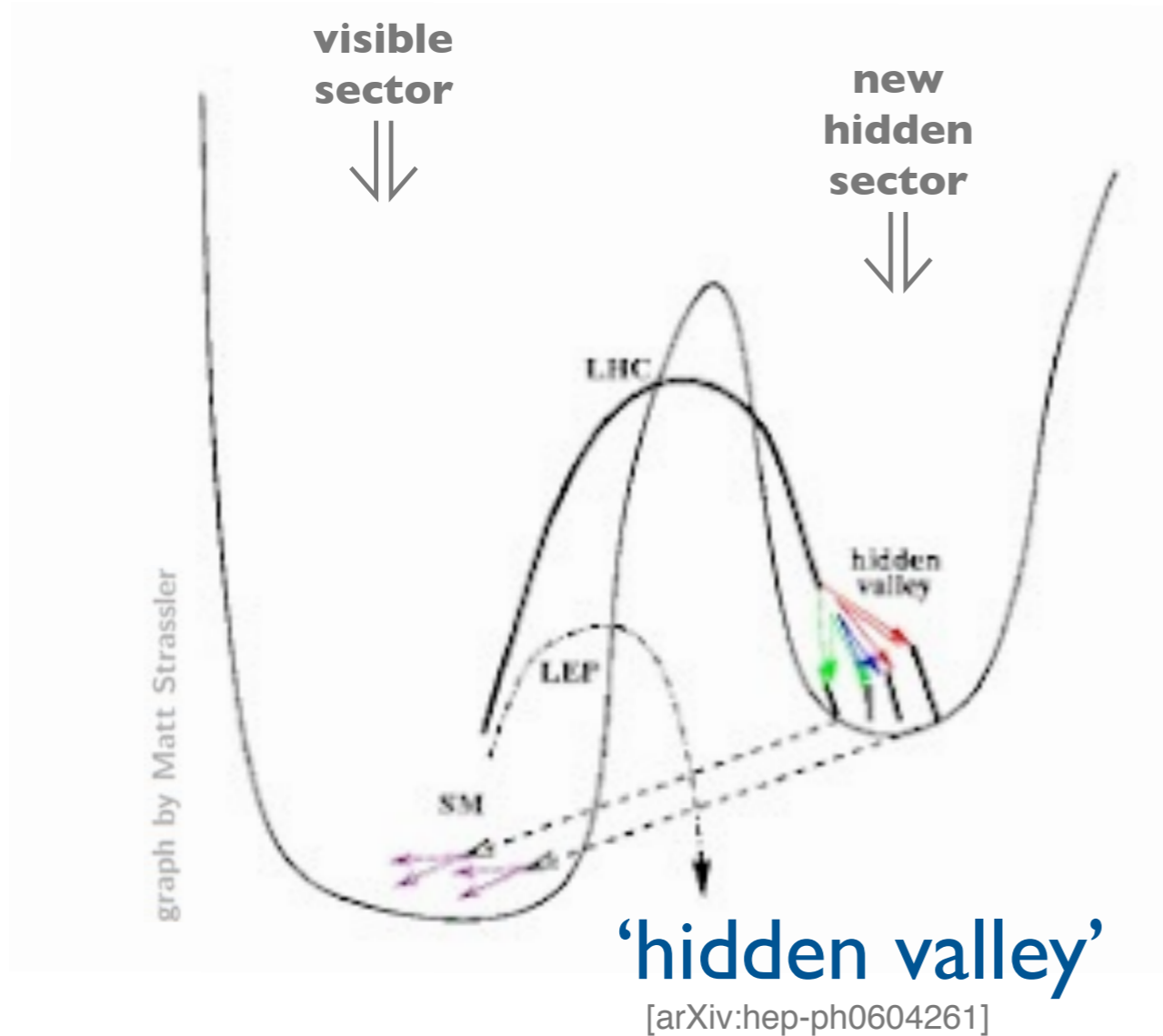


**resonances: long lived**  
(*& other exotica*)

# non-standard searches

- what if ?
  - New Physics is being produced abundantly at the LHC collisions
  - and it is being missed by the bulk of our searches
-  explore non-standard signatures
  - displaced vertices, leptons, photons, jets (\*)
  - stable massive charged particles (slow, highly ionizing [dE/dx, tof])
  - stopped particles (look for their decays during empty bunch crossings)
  - disappearing tracks (with missing its in outer layers and no calo. energy)
  - ...
  - (\*) recall standard reconstruction algorithms assume particles originate from the primary interaction point; standard searches would not be sensitive to these displaced signatures

# phenomenology (example scenarios)



various other scenarios:

Split Susy; arXiv:hep-ph/0408248

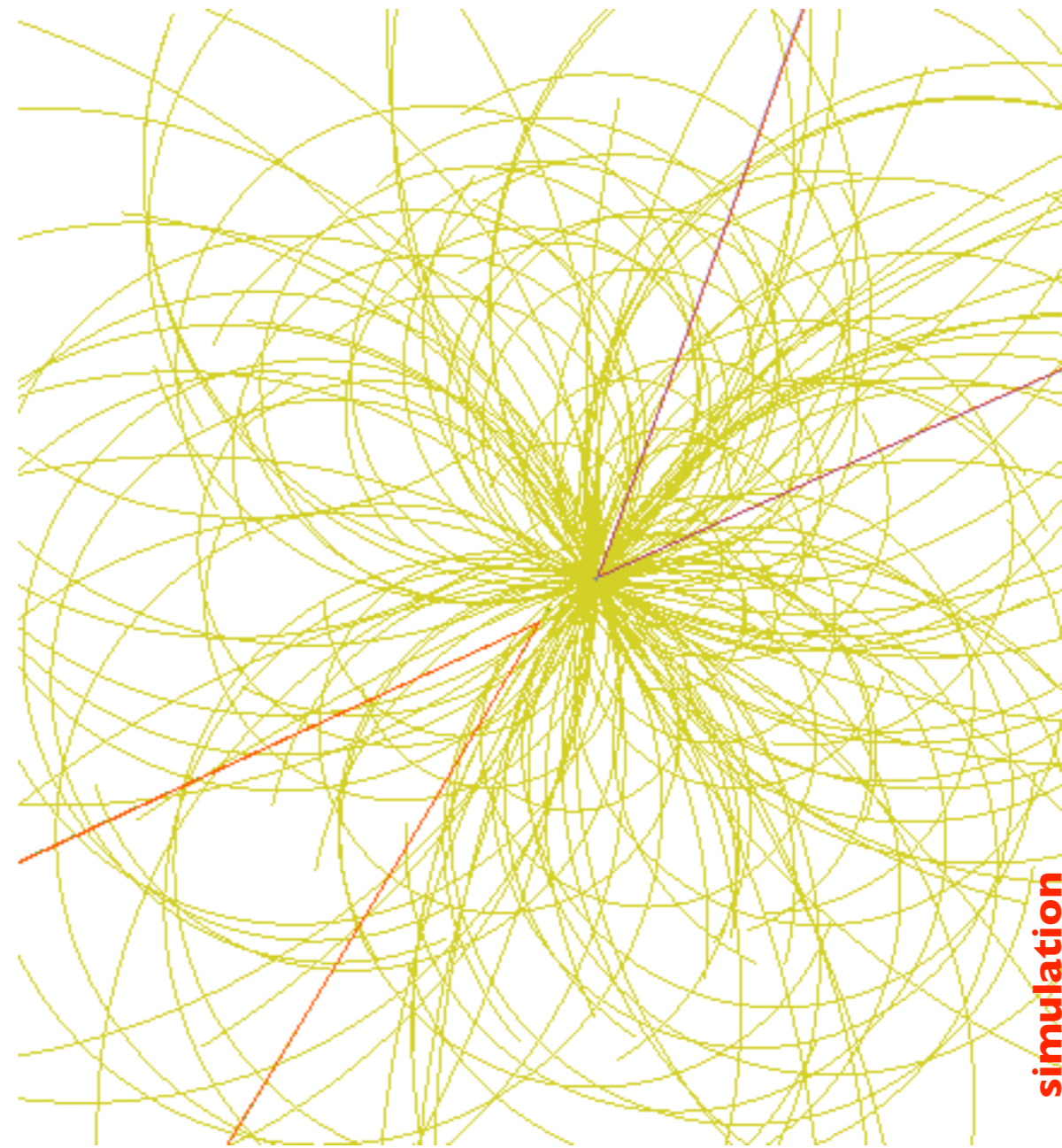
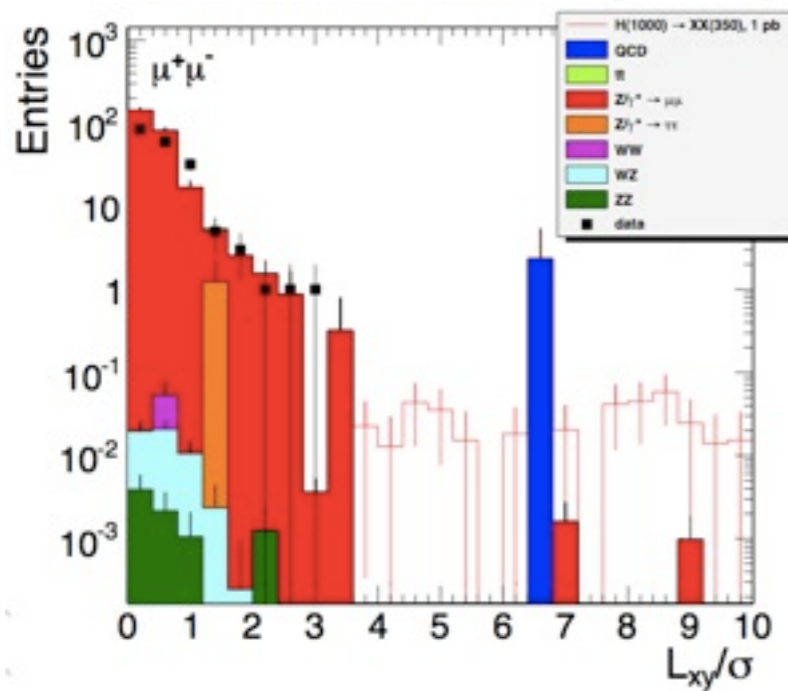
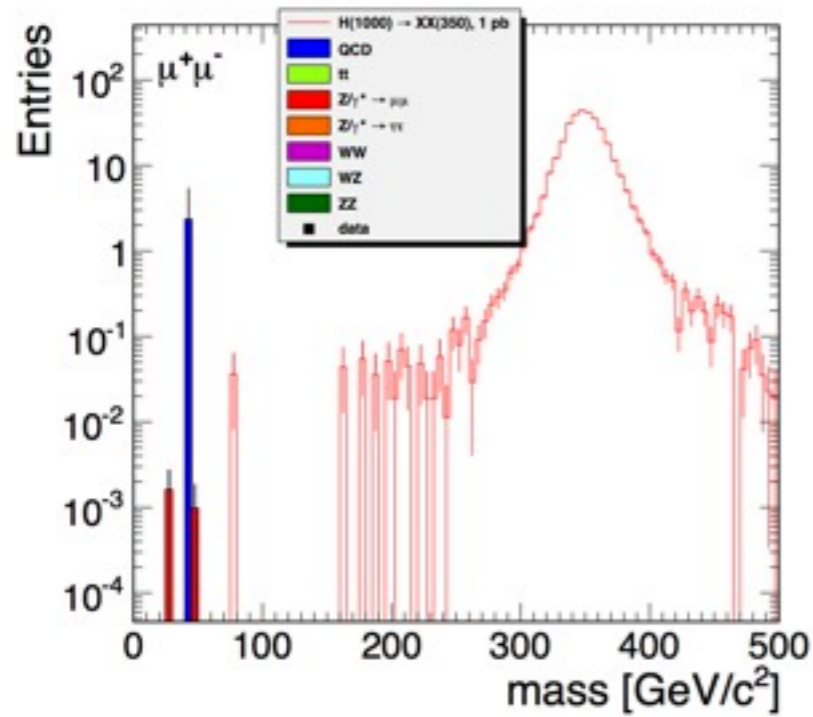
Displaced Susy, arXiv:1204.6038

VS ~ NHS suppressed coupling  $\Rightarrow$  long lived hidden particles



# displaced vertices

- signature-based search for neutral, long lived, narrow resonances decaying to leptons pairs inside the CMS tracker volume

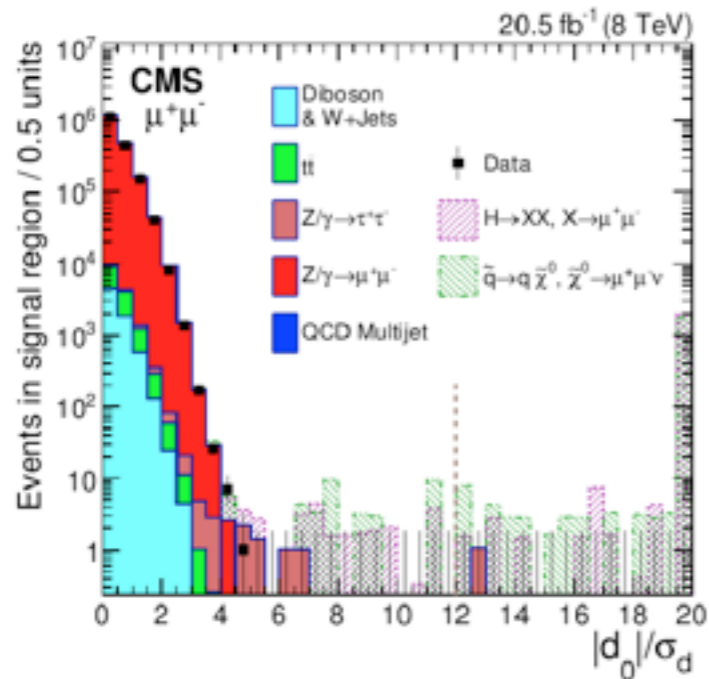


simulation

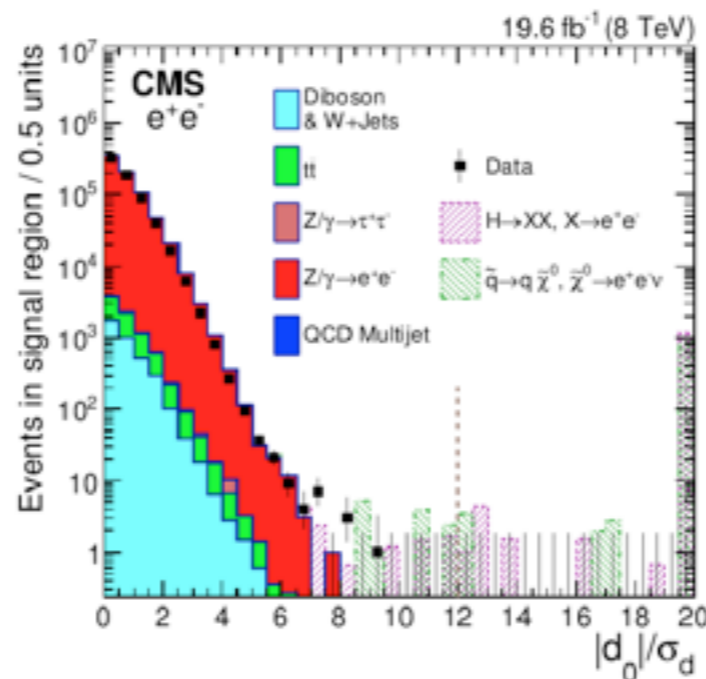
possible additional background source: cosmic muons

# displaced lepton search

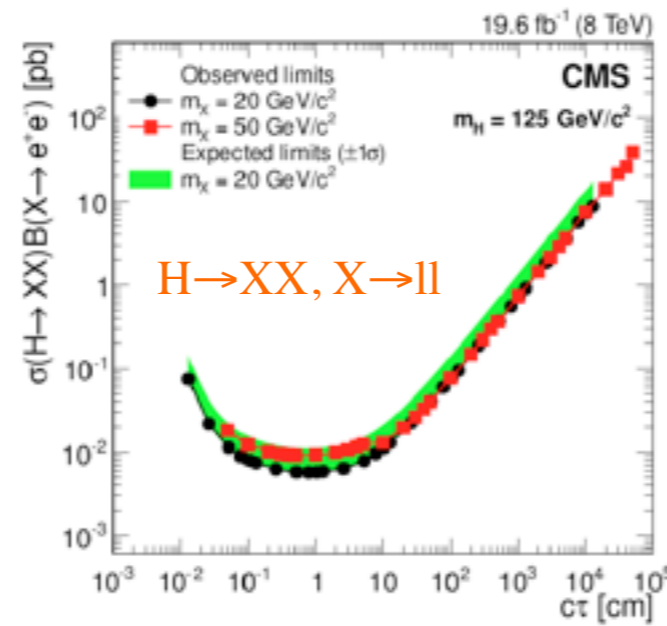
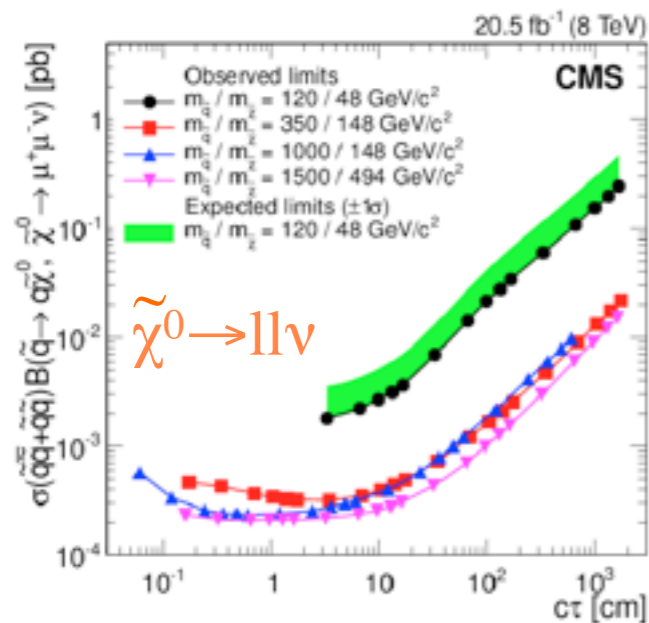
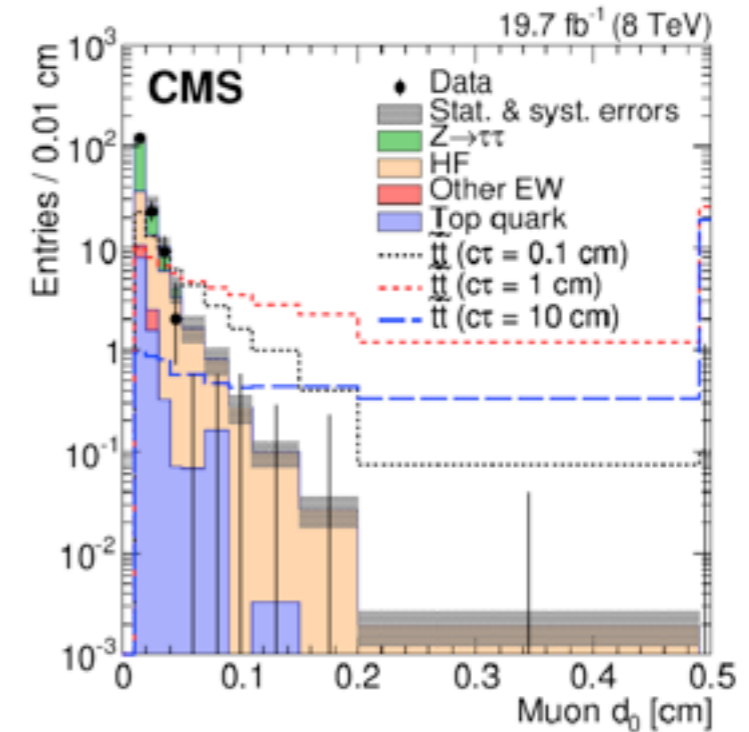
$\mu\mu$



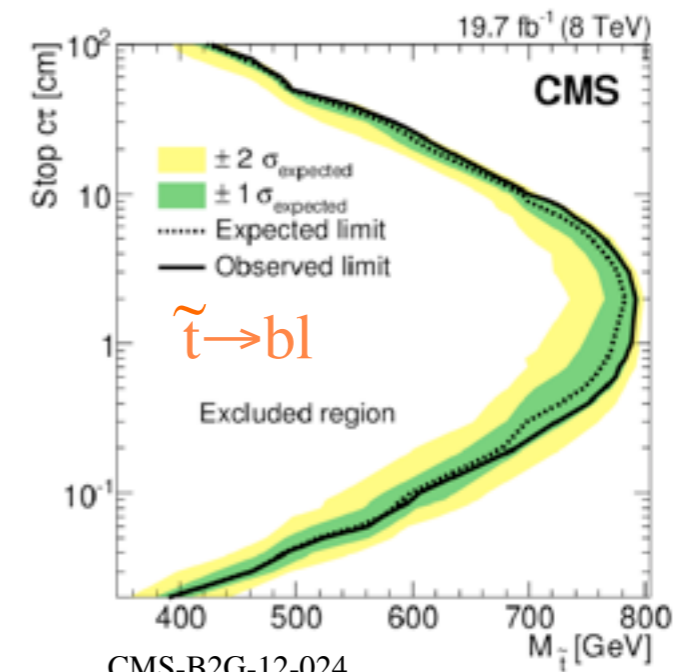
$ee$



$\mu e$



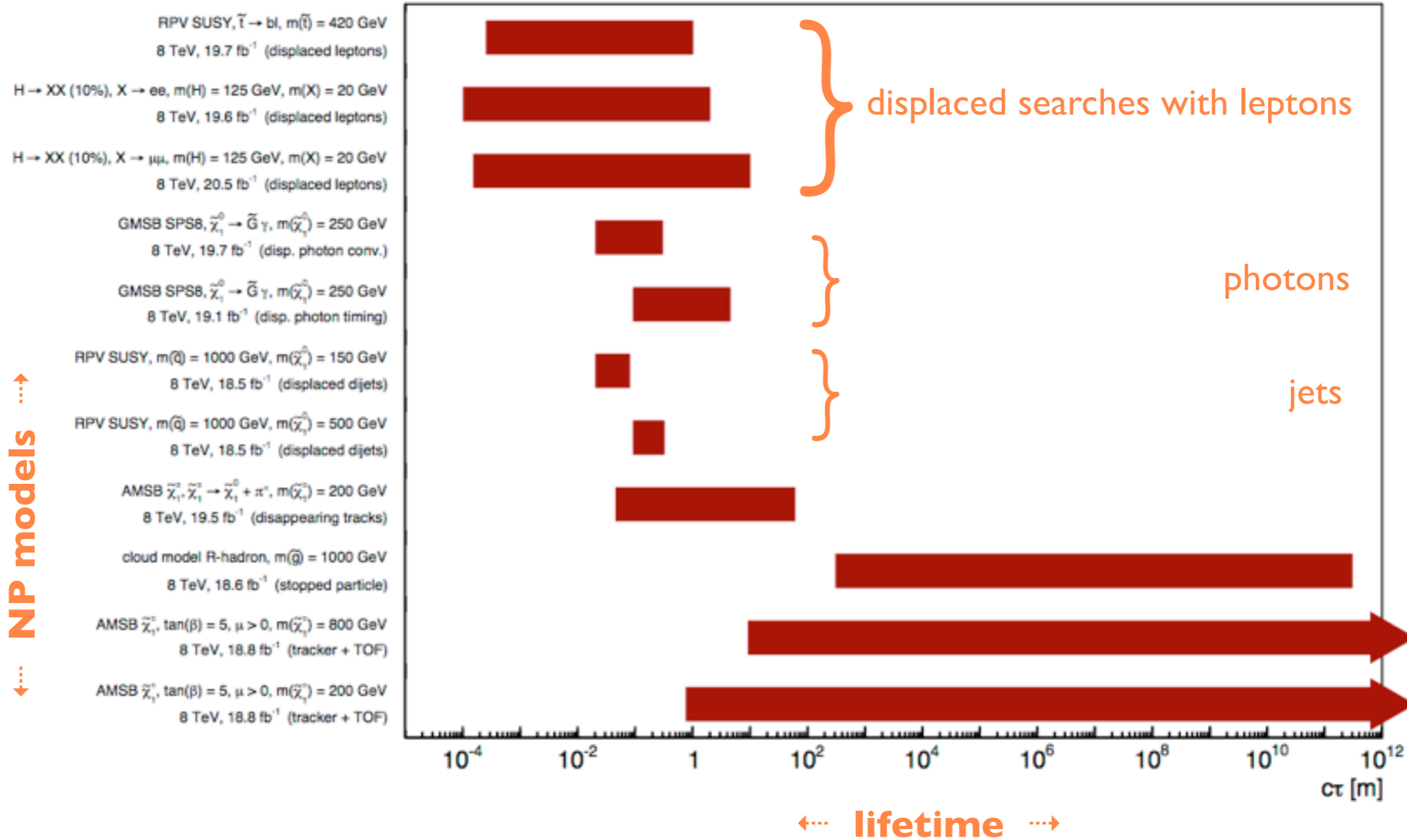
CMS-EXO-12-037



CMS-B2G-12-024

# long-lived grand summary

CMS long-lived particle searches, lifetime exclusions at 95% CL



# summary

- the LHC is providing unique datasets at unprecedented energies and luminosities
- the search for new resonances and new physics is carried out in a multitude of ways, final states, topologies
- explore wide energy spectrum, from GeV to TeV scales
  - low scale: several new (expected and unexpected) bumps in 5-10 GeV
  - medium scale: measure properties of the 125 GeV H-like resonance
  - high scale: intriguing evidence for excess in diphoton spectrum at 750 GeV
  - long lived: leaving no stone unturned !
- LHC will have accumulated a record luminosity by year's end
  - more than  $15\text{fb}^{-1}$  (and counting) already on tape from this year's running
- stay tuned and fasten your seat belts for a (hopefully) **bumpy** ride!