针对两个无穷的物理研究：硕士法国暑期学校

Physics for both infinities: École d'été France excellence

Physics @ CMS

Anne-Catherine Le Bihan

july 2017

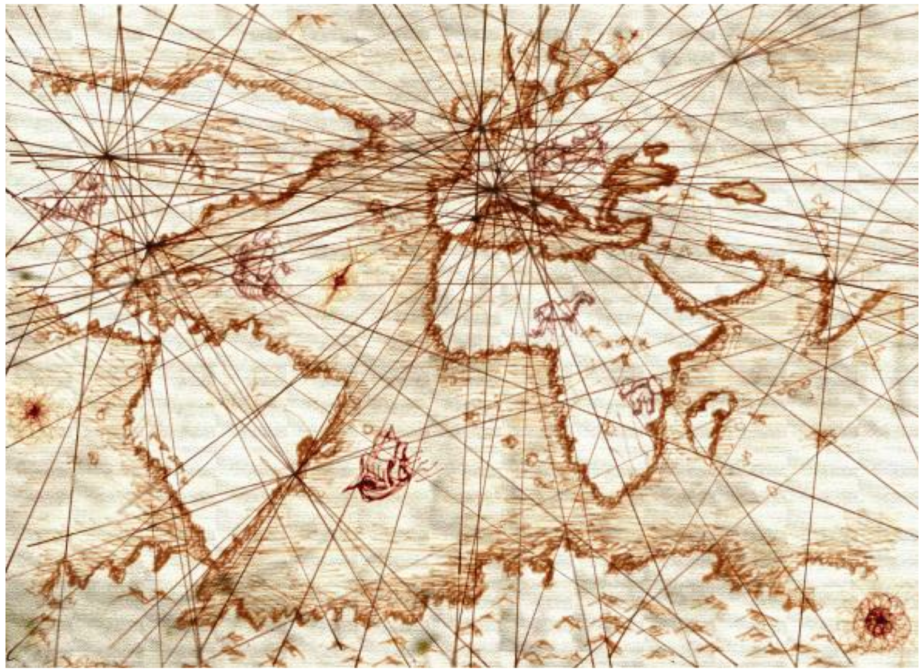
IPHC Institut Pluridisciplinaire Hubert CURIEN STRASBOURG

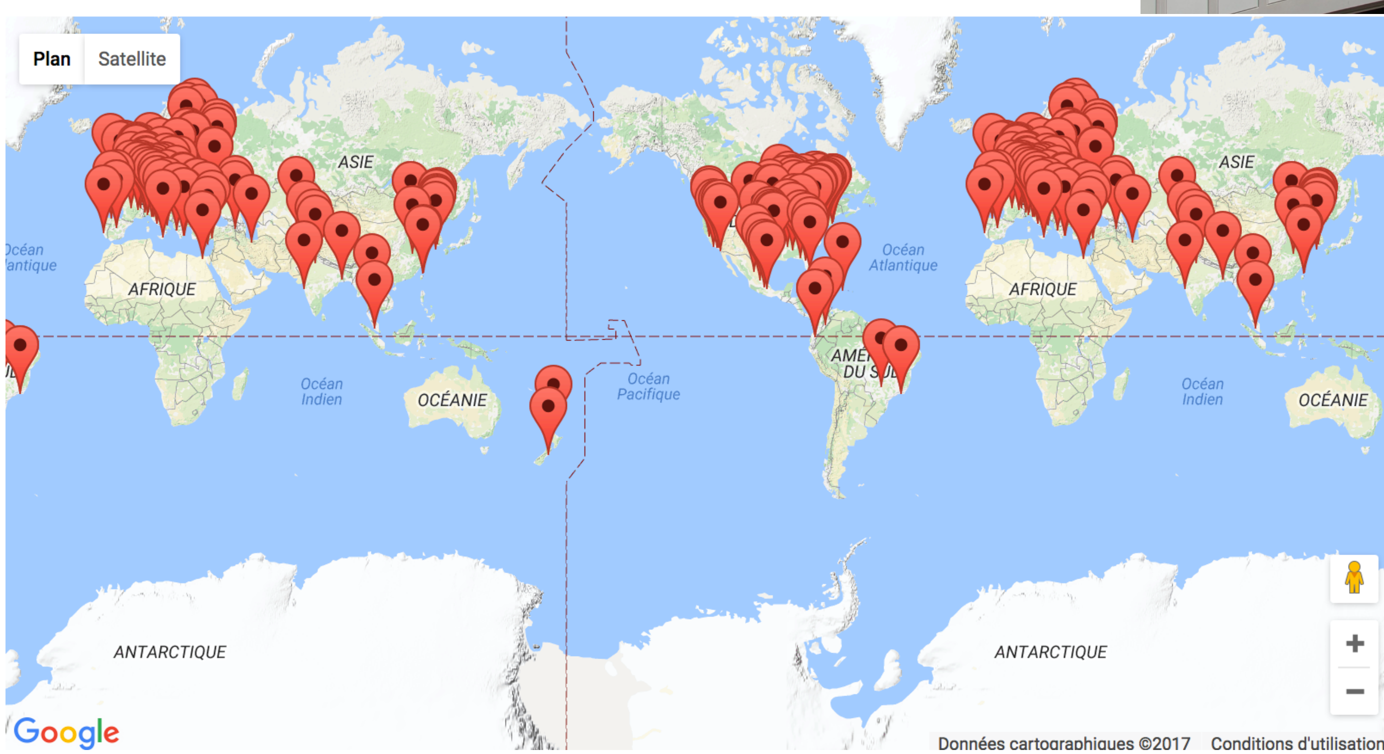
Université de Strasbourg

CNRS IN2P3 Les deux infinis

CMS ?

The CMS collaboration





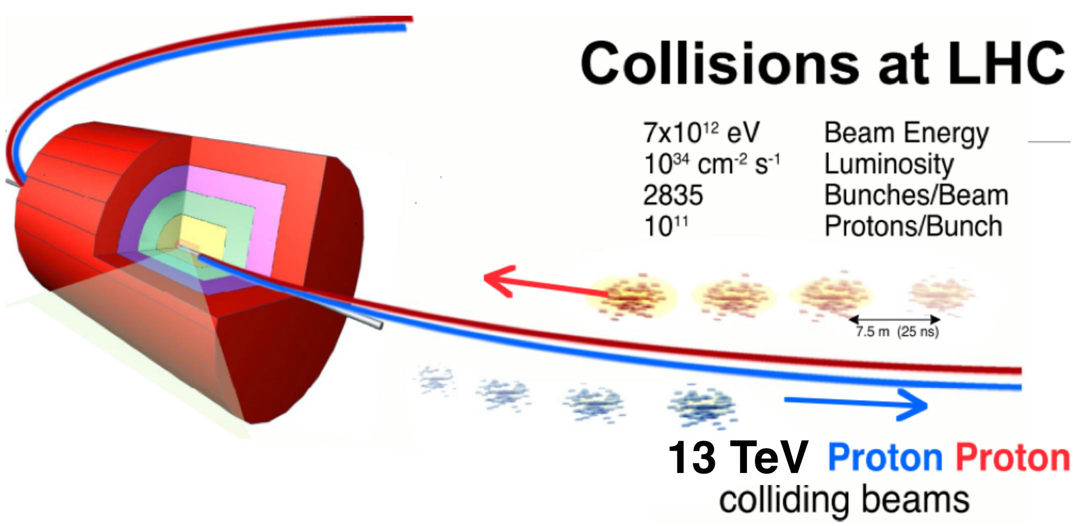
~3500 scientists
from 200 institutes
in 46 countries

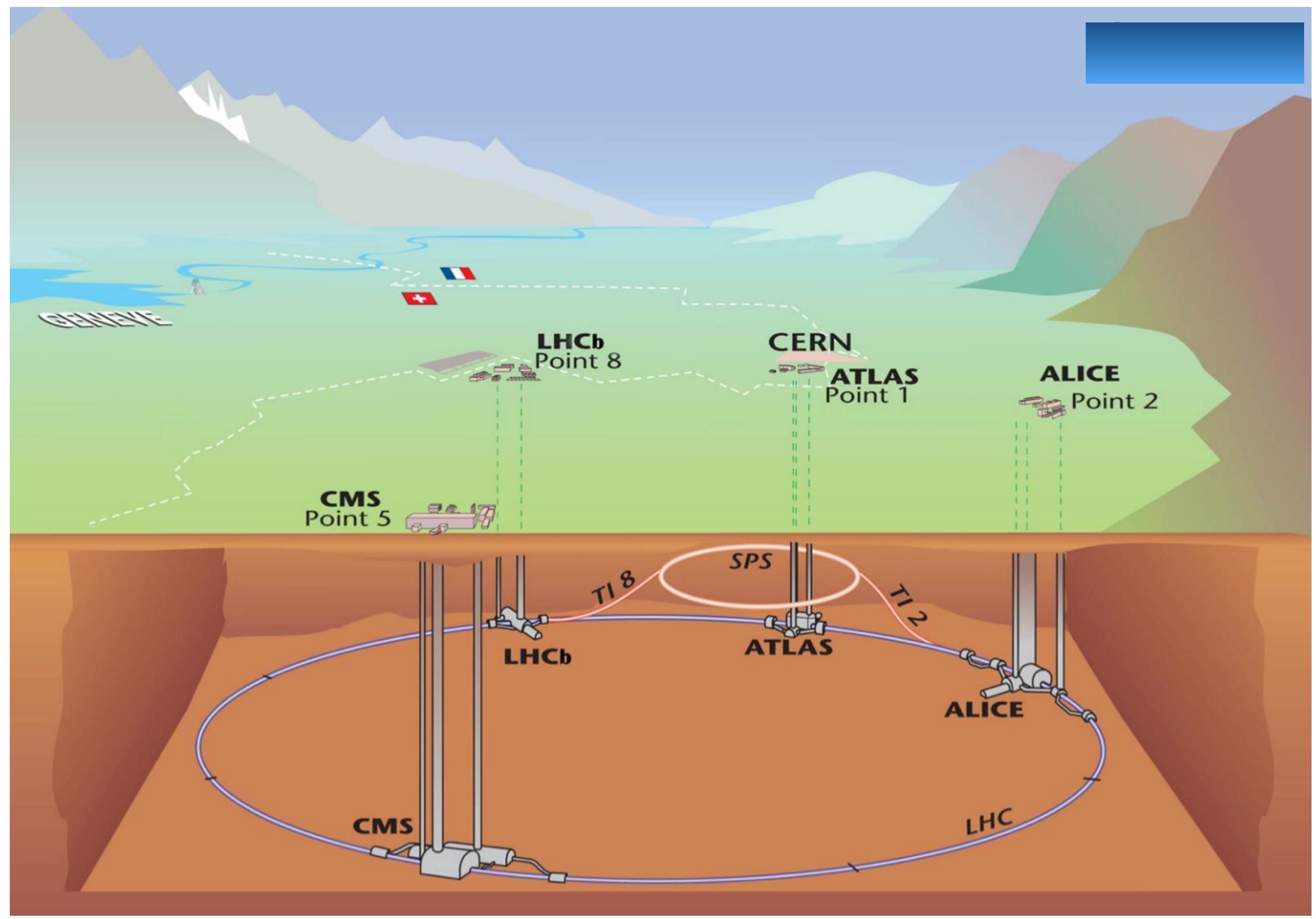
The Large Hadron Collider (LHC)

Large diameter: 27 km !

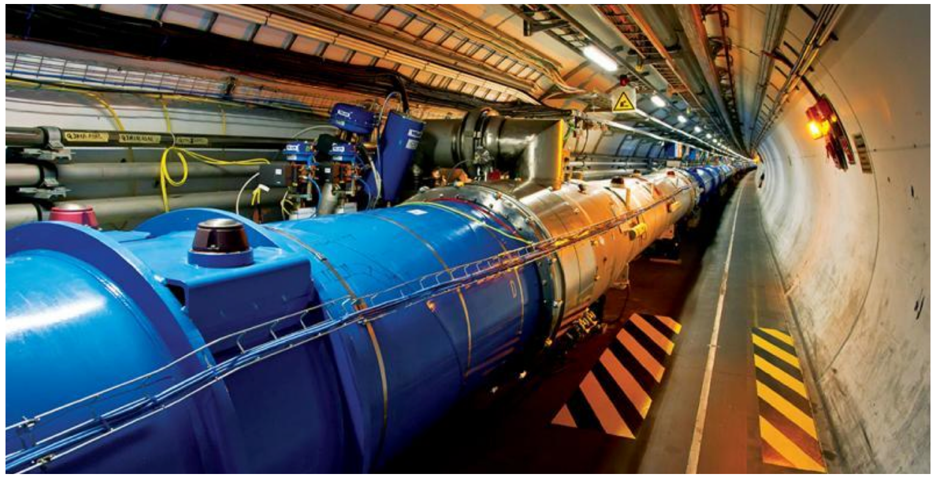
Collides two counter-circulating beams of protons.

40 millions of collisions per second.





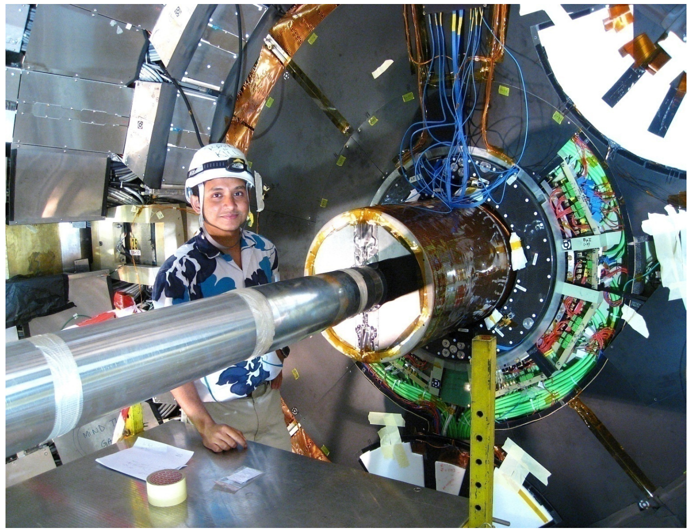
Neat numbers to remember about LHC…



Over 2000 superconducting dipoles at 8.3 T.

Pressure in long vacuum pipes is 10^{-13} atm

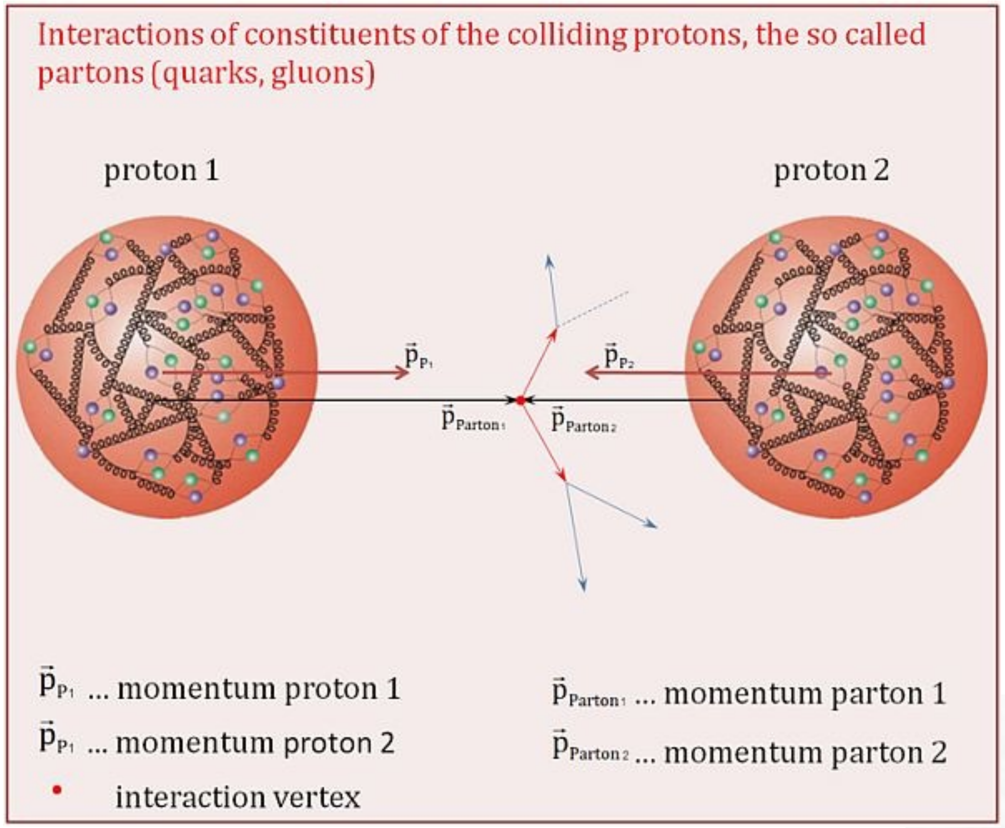
→ lower than on the moon



Magnets kept at 1.9 K, using over 100 tons of liquid helium

→ colder than deep space

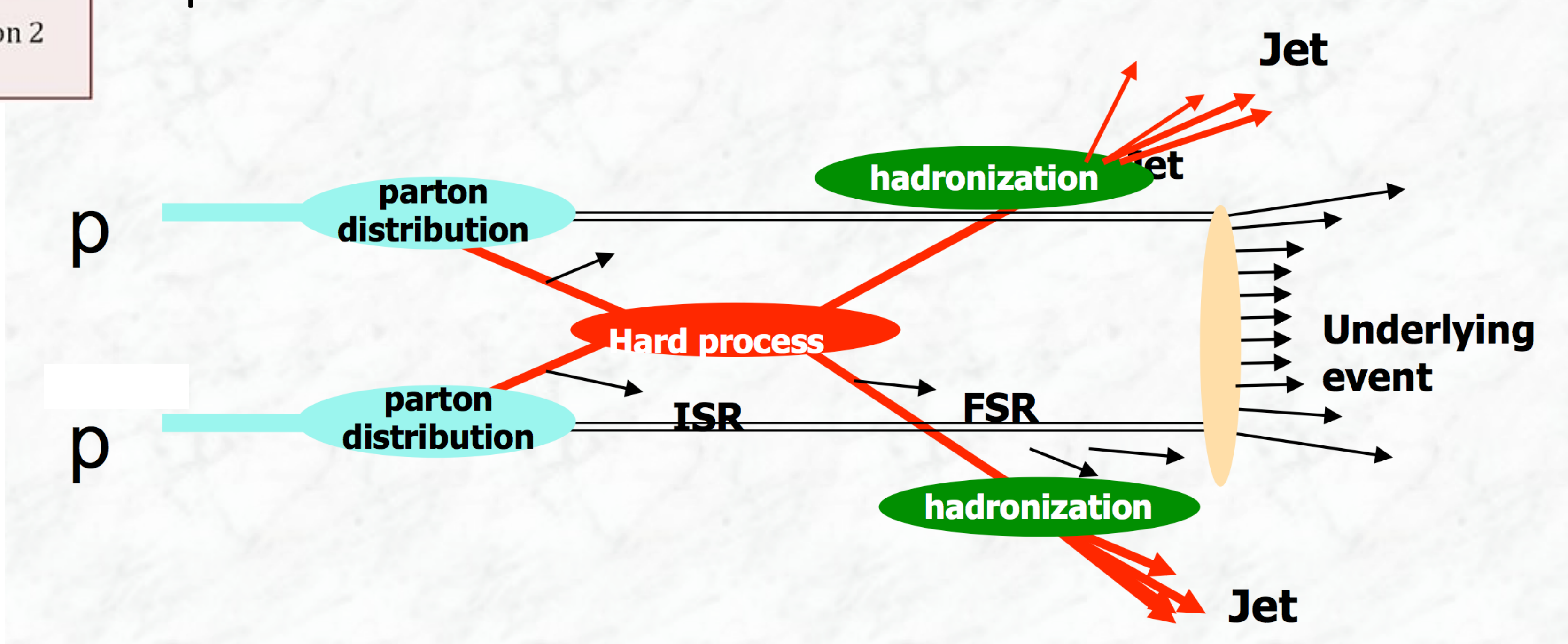
What is produced ?



Cross section:

$$\sigma(pp \rightarrow f) = \int \sigma(q_1 q_2 \rightarrow f, \hat{s}, q^2) f_{q1}(x_1, q^2) f_{q2}(x_2, q^2) dx_1 dx_2$$

Partons follow PDFs: f(x,q), probability to find a parton with momentum x, x+dx.
q momentum transfer.



What is detected ?

Can see particles because they interact with matter.

What can we detect?

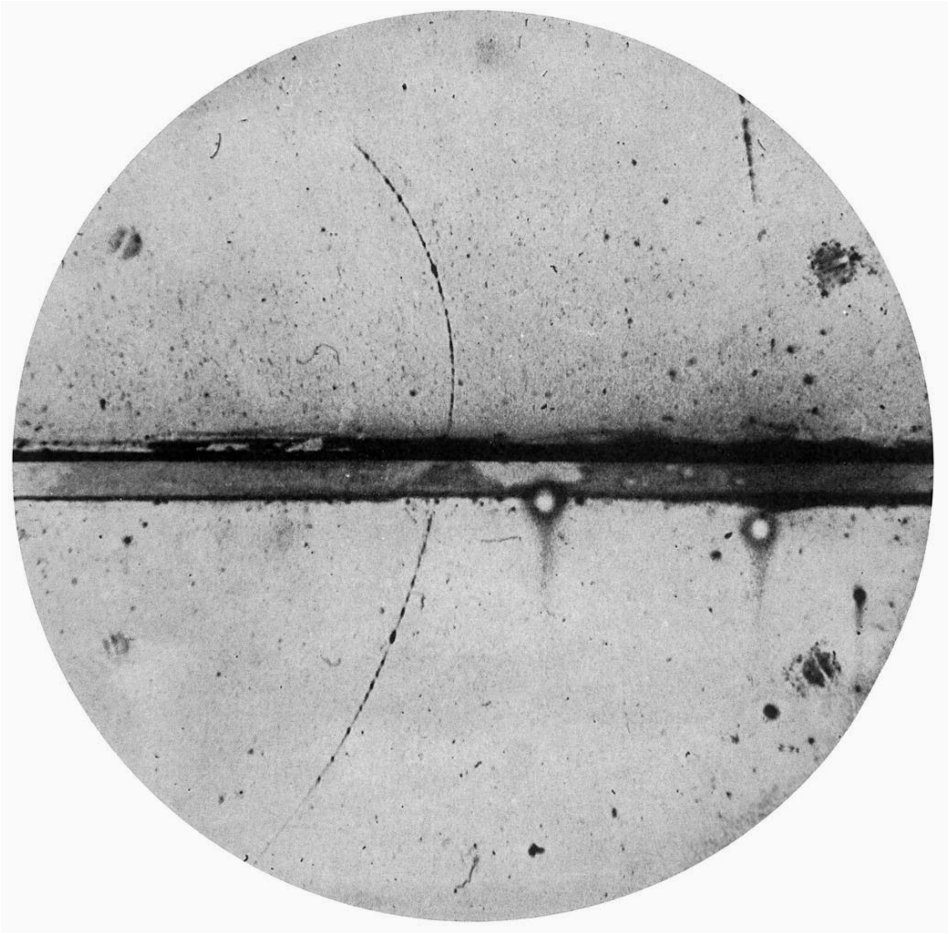
- Has to have strong or EM interactions
- Sufficiently long-lived to make it through the detector

Can directly observe:

- Electrons, muons, photons
- Neutral and charged hadrons

Can indirectly observe:

- Weakly interacting particles (via missing energy)
- Short-lived particles (from kinematics of decay products)

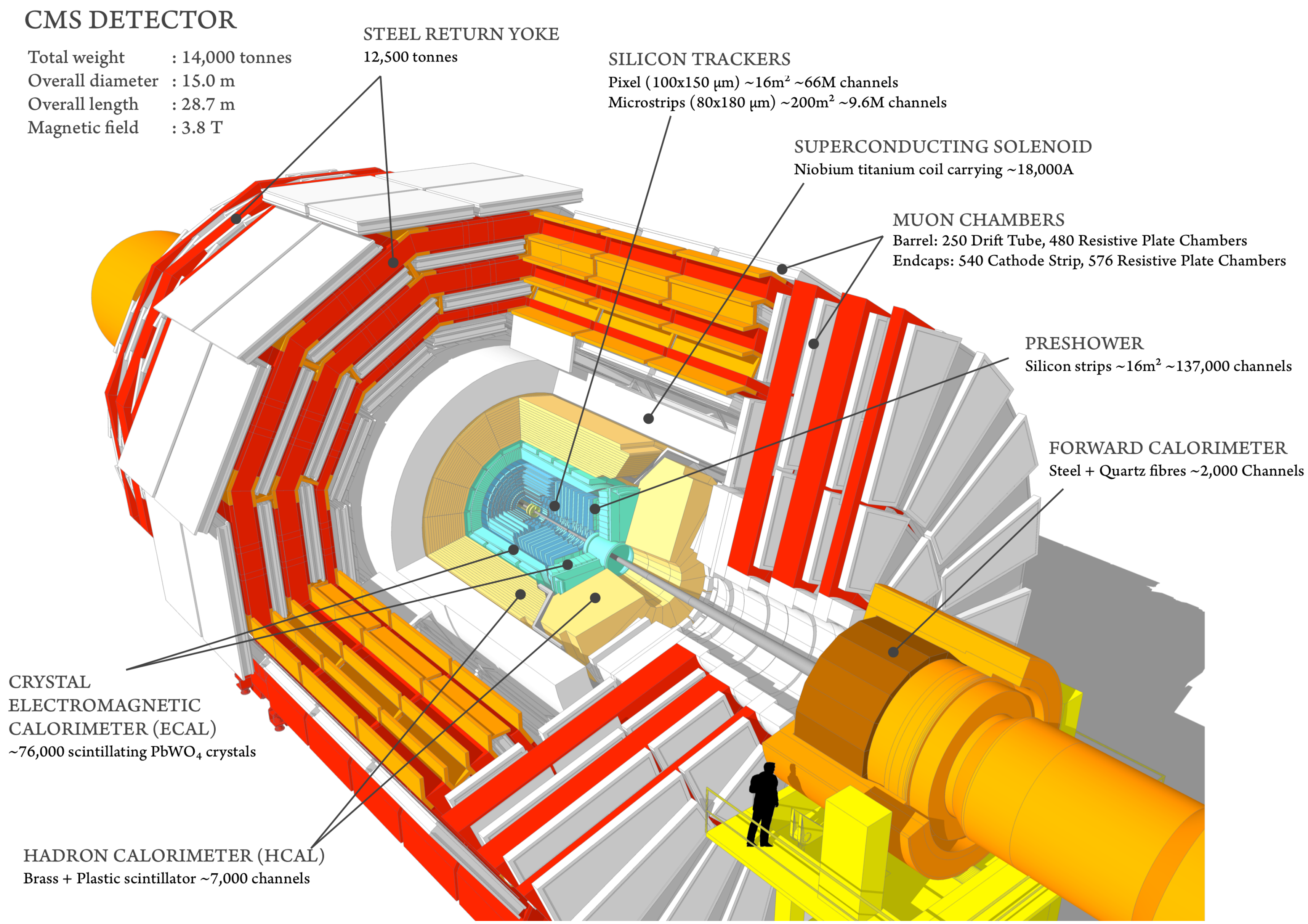


(*) positron discovery 1932

The CMS experiment

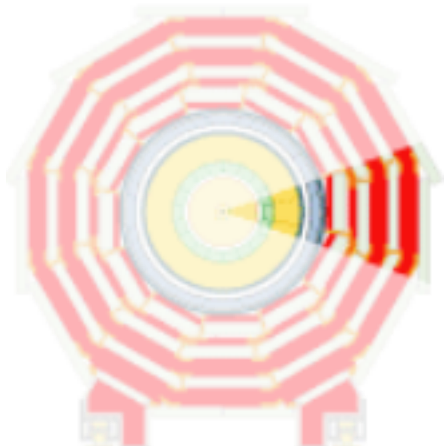
Multipurpose detector:

- Find Higgs and measure its properties
- Find supersymmetry
- Find whatever other high-energy physics that comes along…



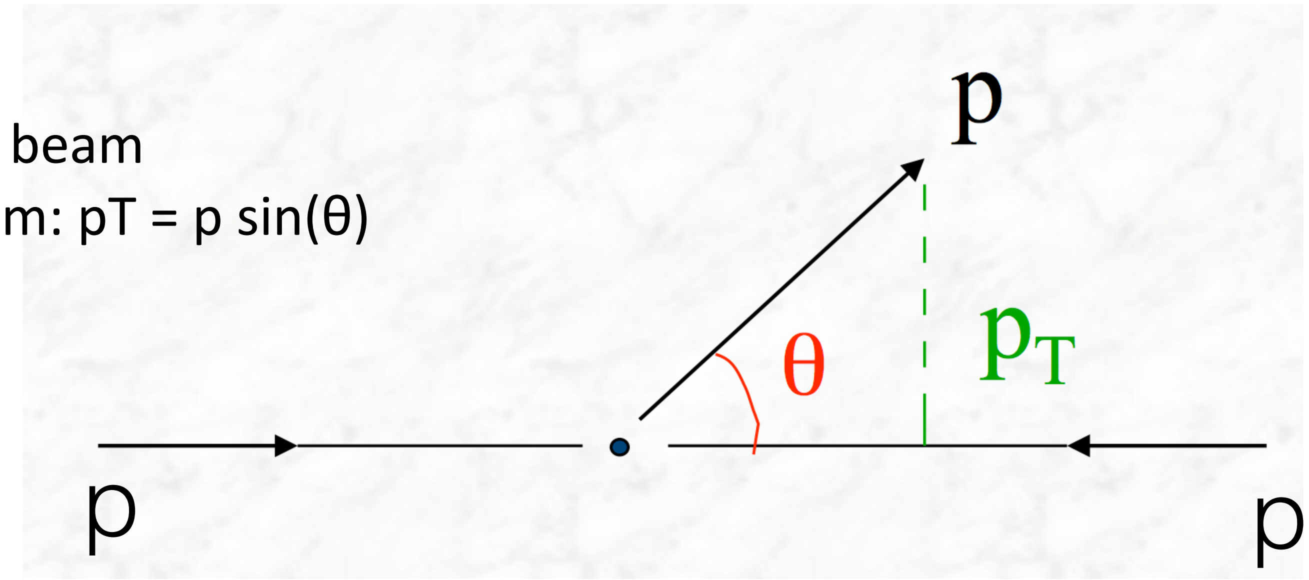
14000 tons.
15 m diameter, 28.7 m length.
3.8 T magnetic field.

Coordinate system



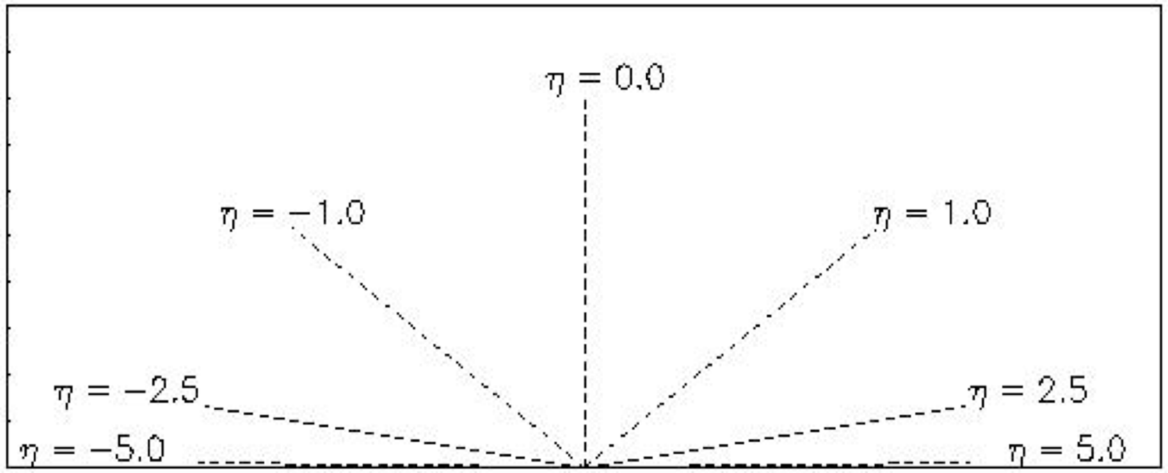
Transverse slice through CMS

Transverse plane:
perpendicular to the beam
transverse momentum: pT = p sin(θ)

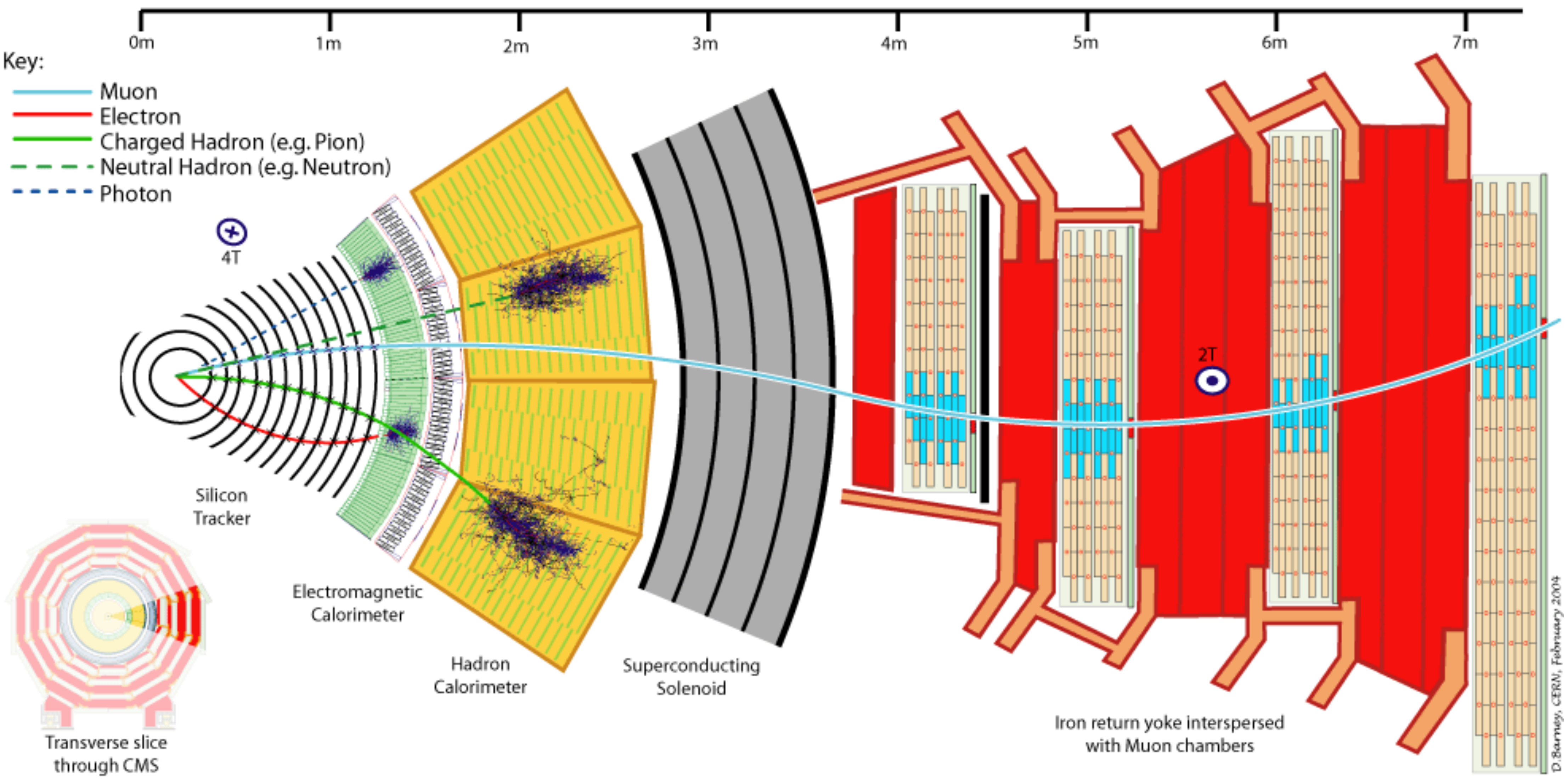


Pseudo-rapidity:
η= - ln(tanθ/2)

dσ/ dp_T dη is Lorentz-invariant



How do we identify particles in CMS ?

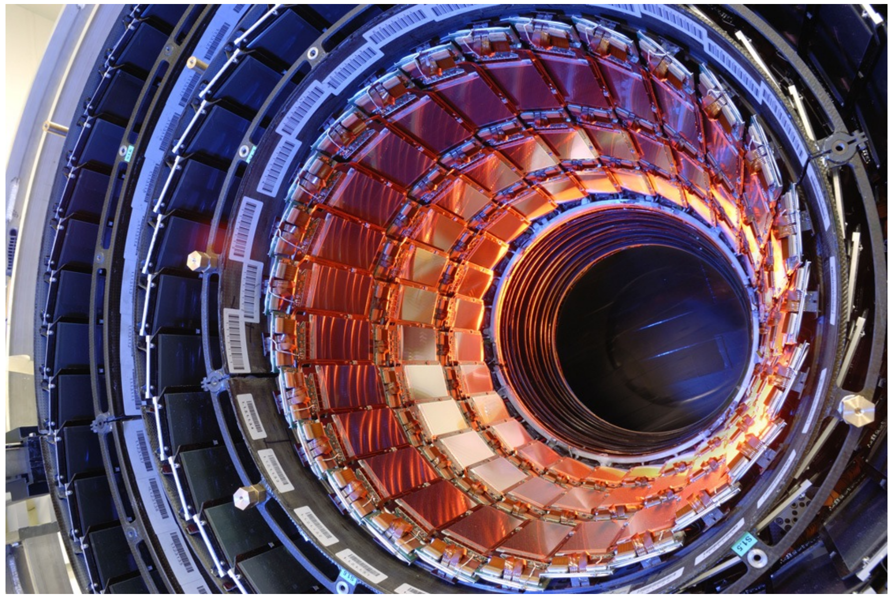


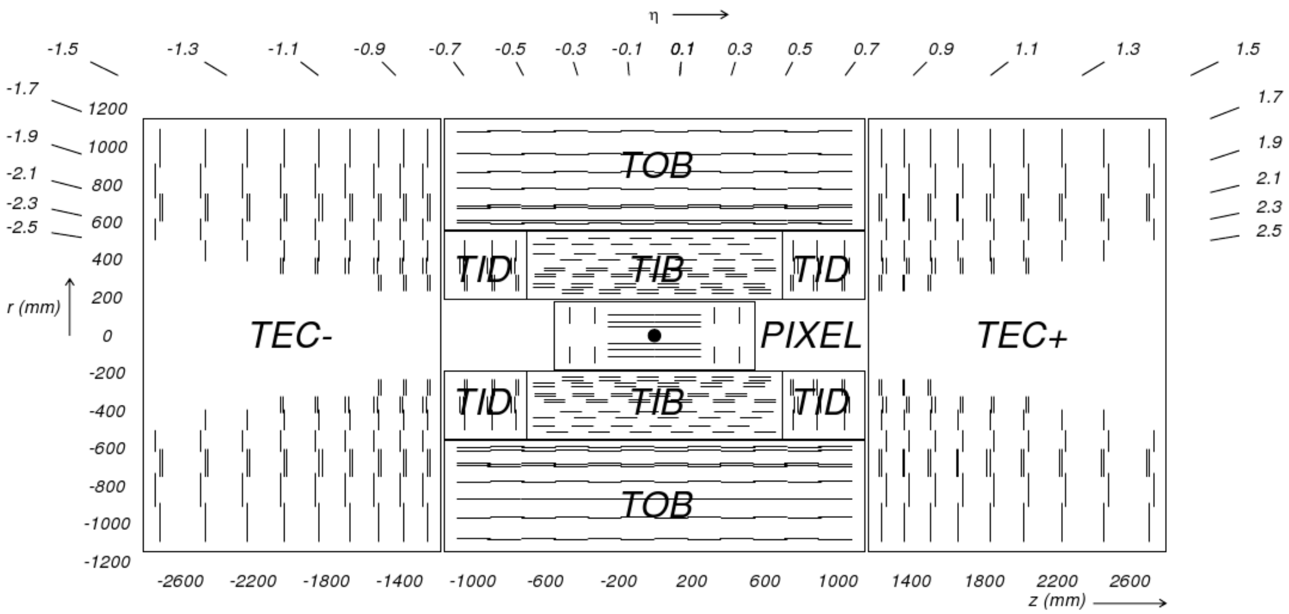
Like an onion.
Each layer/detector measures E or p.

The CMS tracker

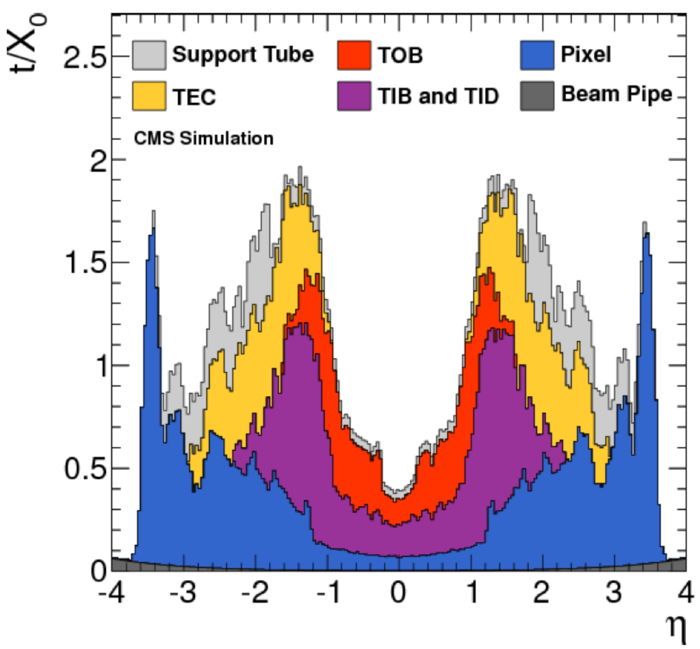
Reconstruct trajectories of all the charged particles from collisions.

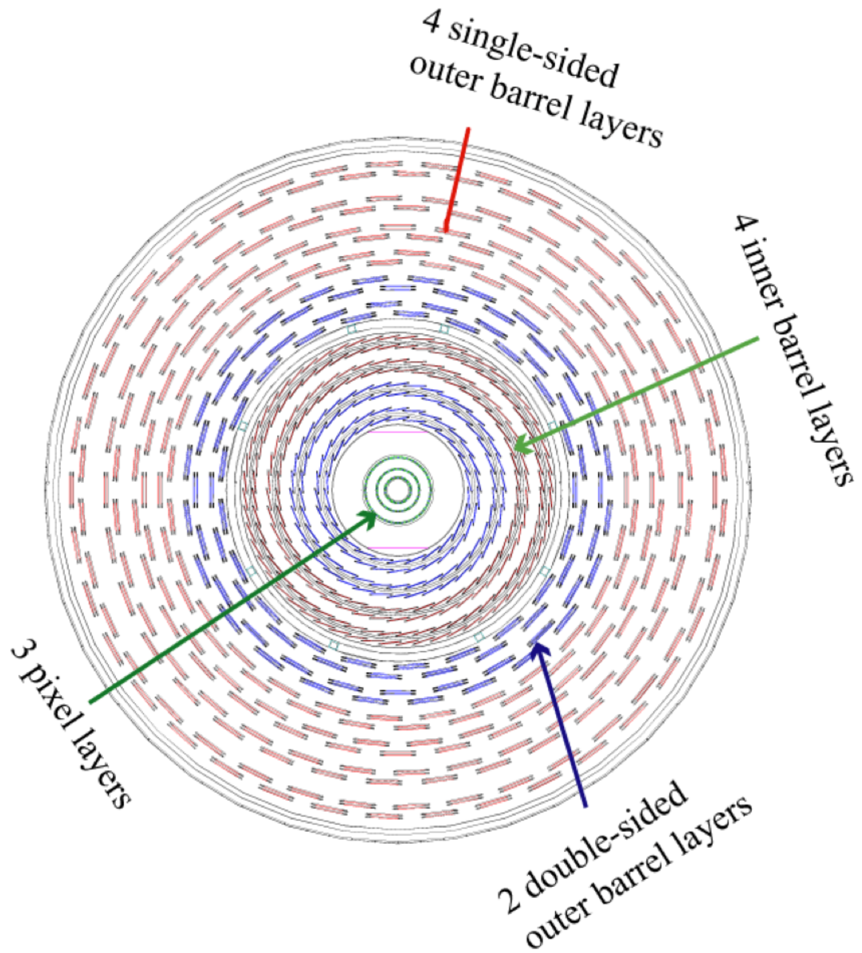
214 m^2 silicon, 65.9 M silicon pixels, 11.4 M silicon strips.





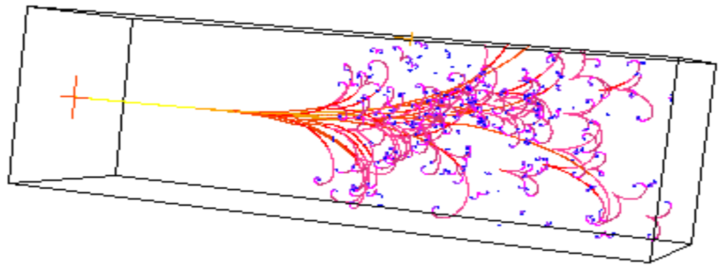
Heavy material budget !





The CMS calorimeters

ECAL



76k scintillating PbWO4 crystals:

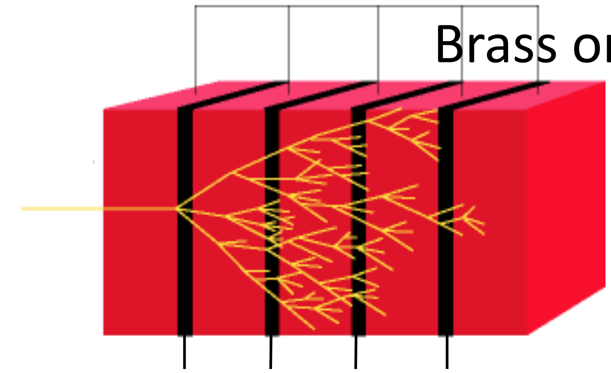
→ Heavy (so particles interact with it a lot)

→ Transparent (so you can collect the light at the end)

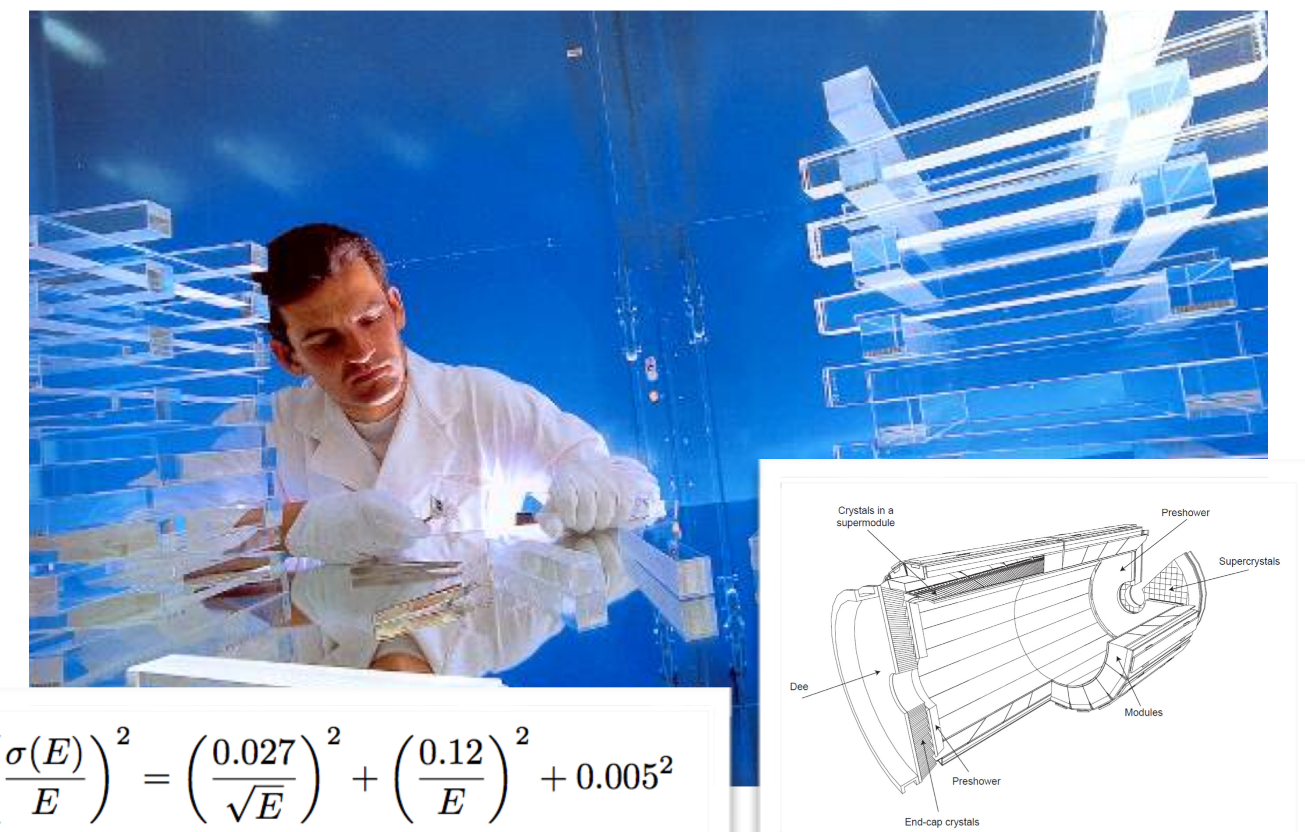
Detection principle :

stop a particle
measure its signal

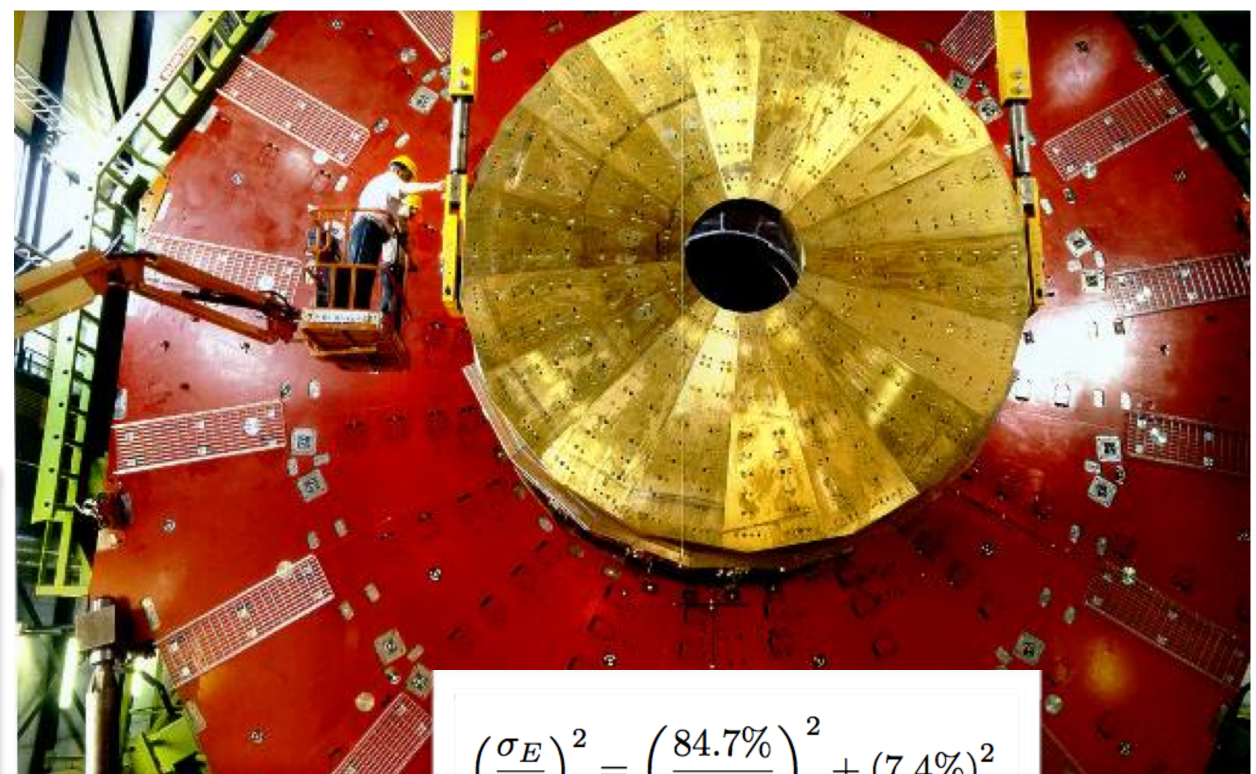
HCAL



Transparent scintillating plastic



$$\left(\frac{\sigma(E)}{E}\right)^2 = \left(\frac{0.027}{\sqrt{E}}\right)^2 + \left(\frac{0.12}{E}\right)^2 + 0.005^2$$



$$\left(\frac{\sigma_E}{E}\right)^2 = \left(\frac{84.7\%}{\sqrt{E}}\right)^2 + (7.4\%)^2$$

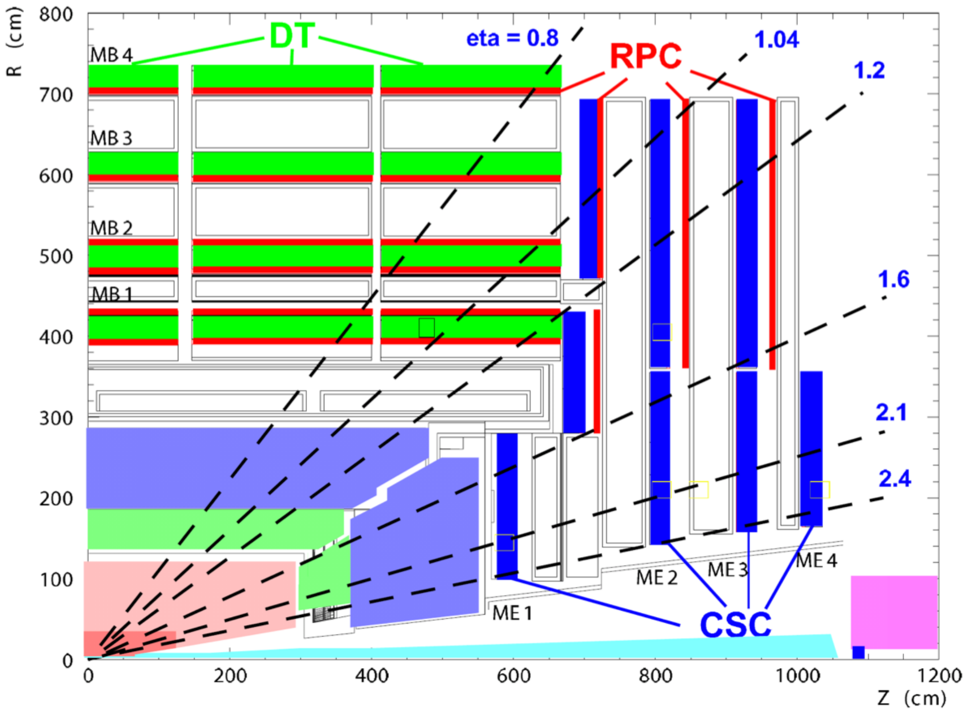
Muon chambers

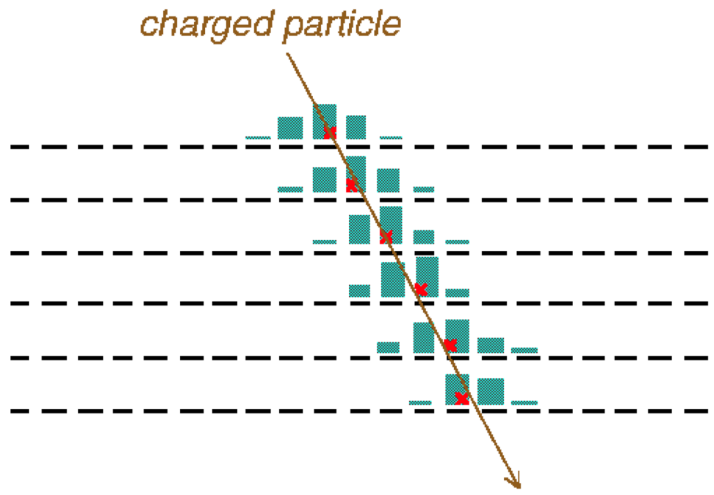
Muons are typically very penetrating.

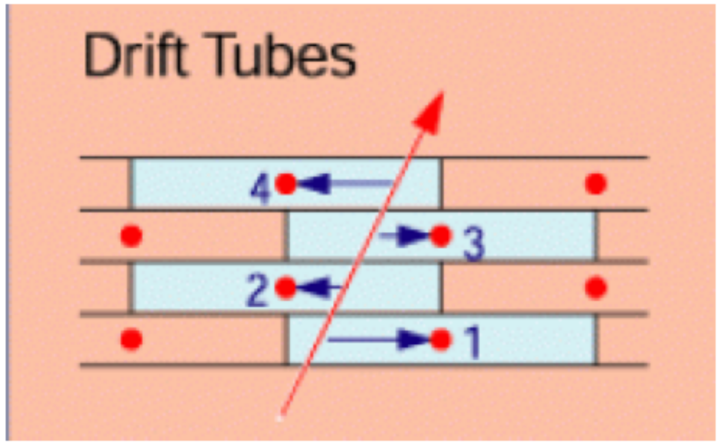
Stick the detectors in giant hunks of iron so nothing else gets through.

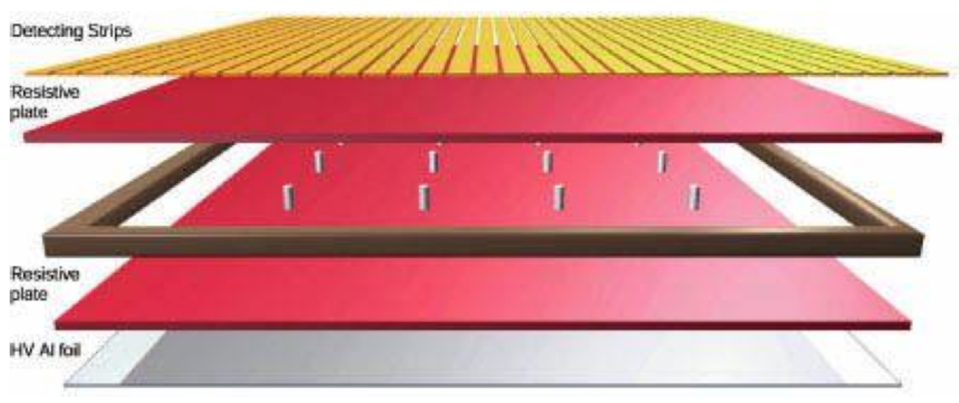
Three types of detectors → redundancy

- drift tubes (DT) → fast !
- resistive plate chambers (RPC) → fast, radiation tolerant
- cathode strip chambers (CSC) → radiation tolerant









How to combine all these measurements ?

What properties can we measure?

- Energy (calorimeter)
- Momentum (tracking) $F = qvB = mv^2/R \rightarrow p = mv = qBR$
- Charge (also tracking, using the bend direction)
- Lifetime (also tracking)
- Mass $E^2 = p^2 + m^2 \rightarrow m = \text{sqrt}(E^2 - p^2)$

Particle flow algorithm

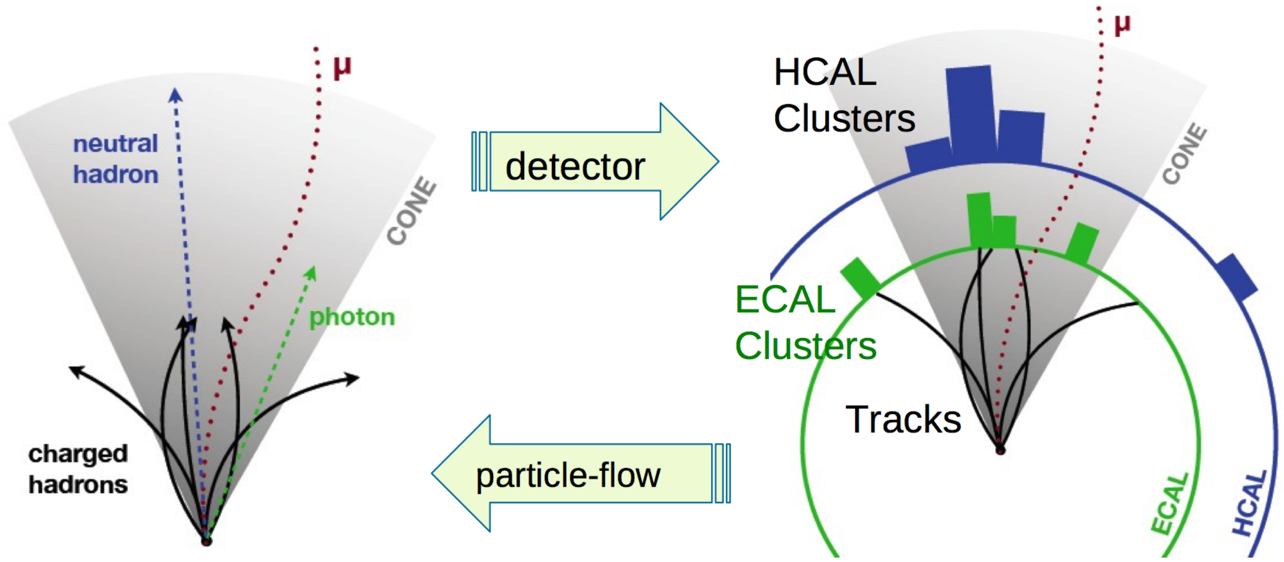
✦ Particles well separated in the **3.8 T magnetic field**

✦ **Silicon tracker of 1m radius**: excellent track resolution, able to go down to very low momenta (a few hundred of MeV)

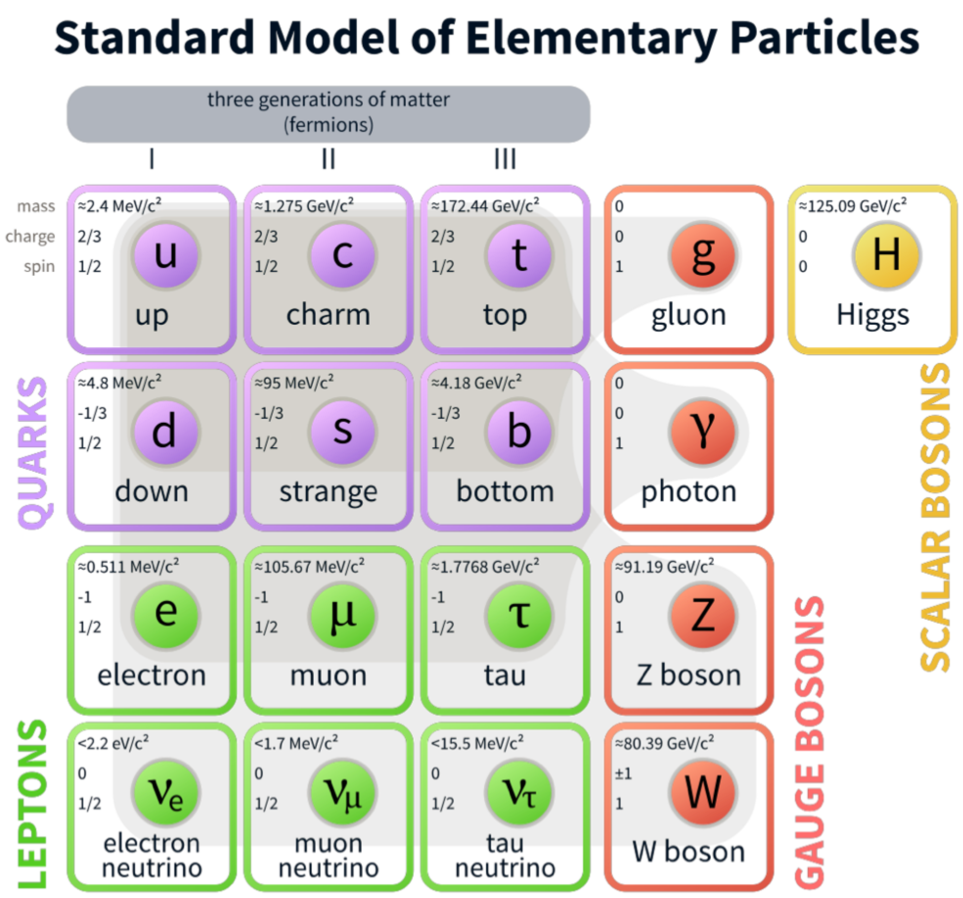
✦ **Highly granular calorimeters:**

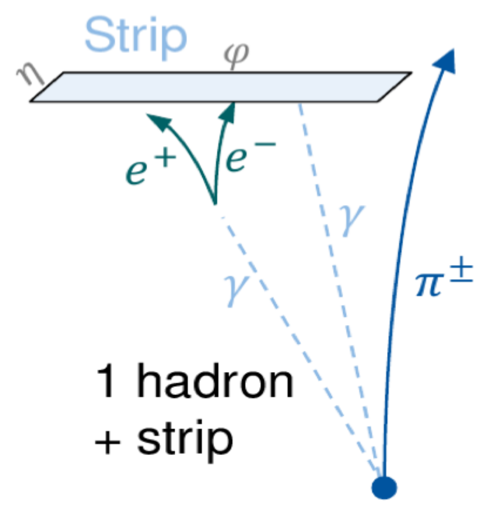
- ✦ **excellent resolution of the EM calorimeter**
- ✦ Only 10% of the energy stems from neutral hadrons, that can only be measured by the HCAL

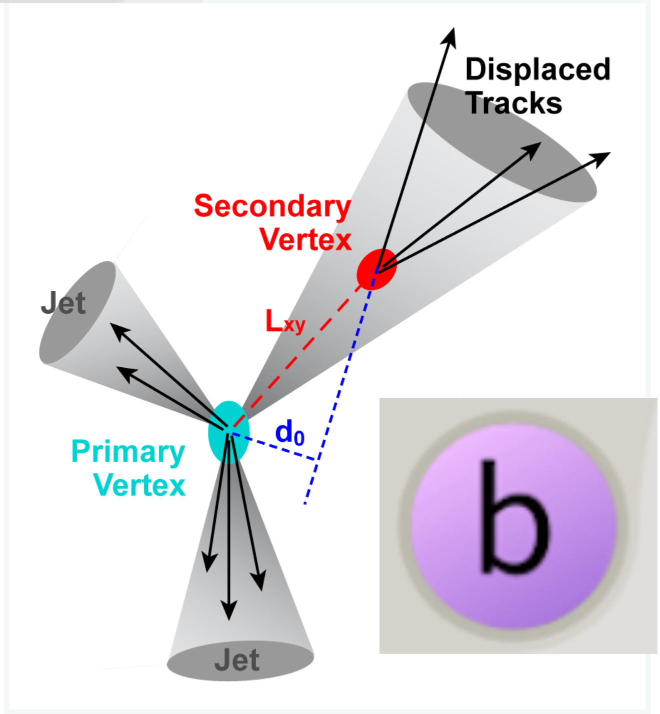
→ Information from all detectors combined optimally to reconstruct each particle
→ Tracking is used together with calorimetry to reconstruct showers, jets, etc

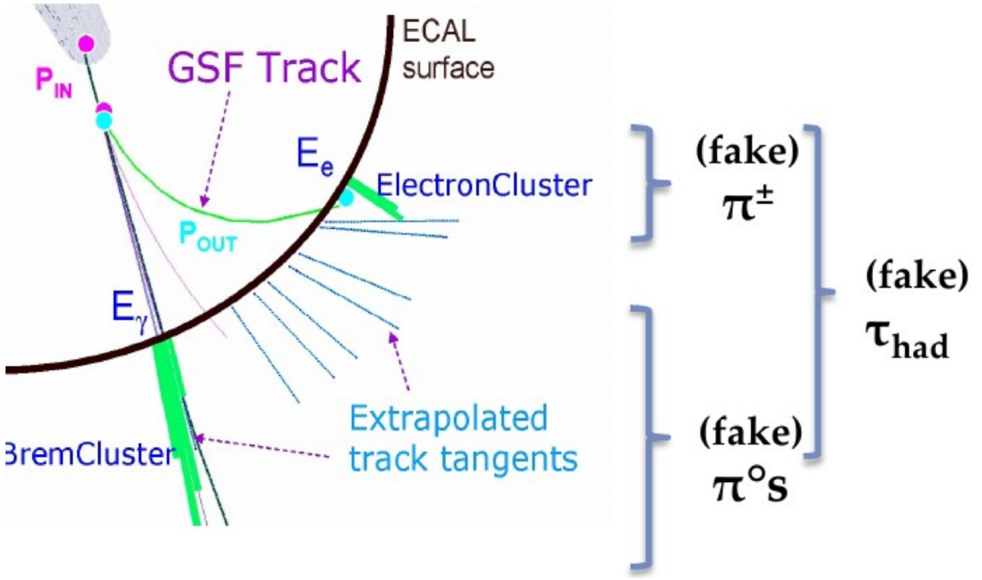


Particle identification





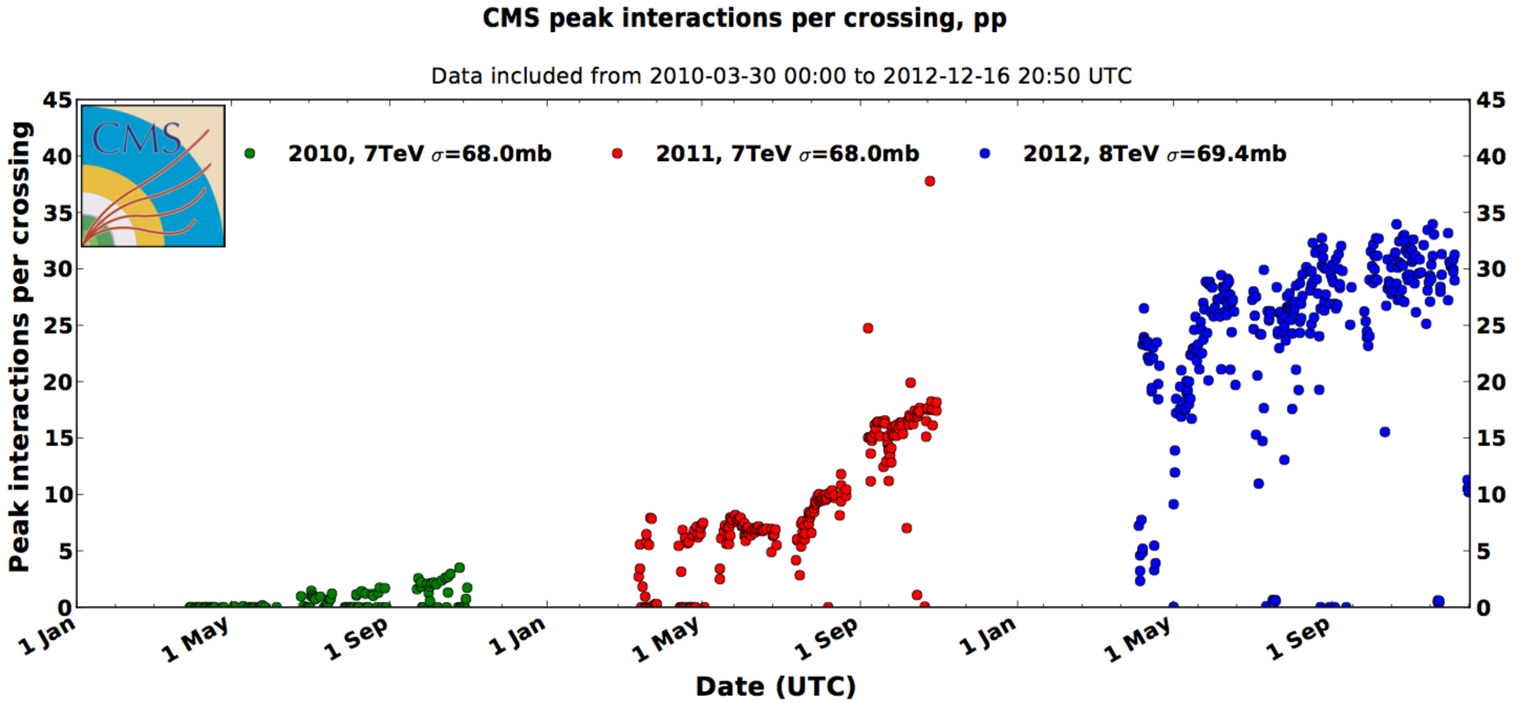




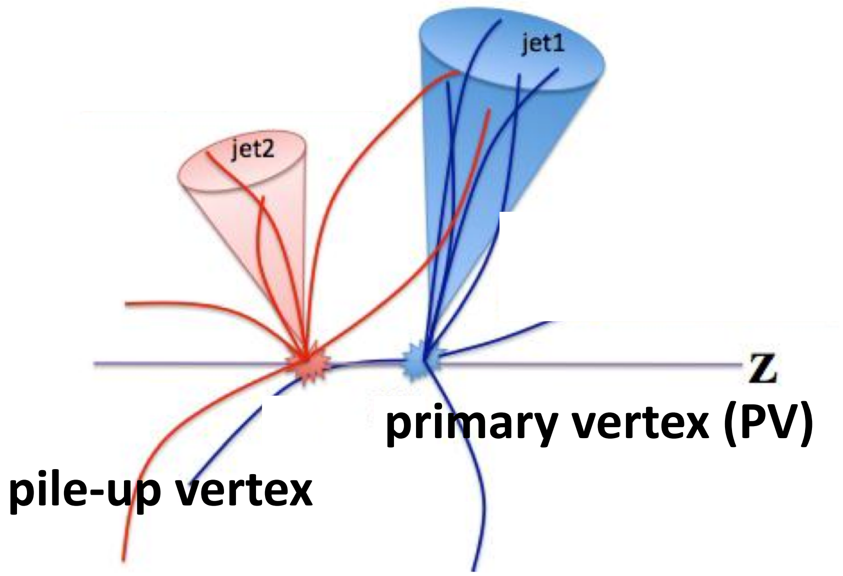
Dedicated algorithms to identify key particles…

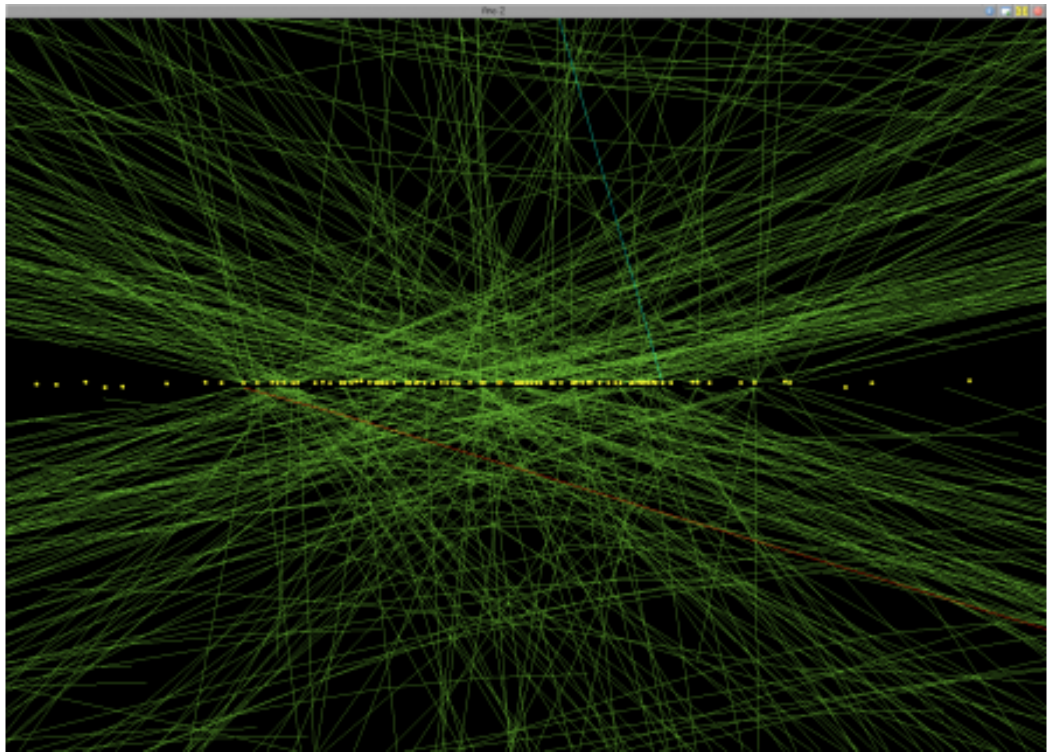
+ μ in muon chambers and γ in ECAL

Pile up ?



Pile-up :
additional p-p interactions inside a bunch crossing





Pile up removal !

Pile Up Per Particle Identification (PUPPI) method:

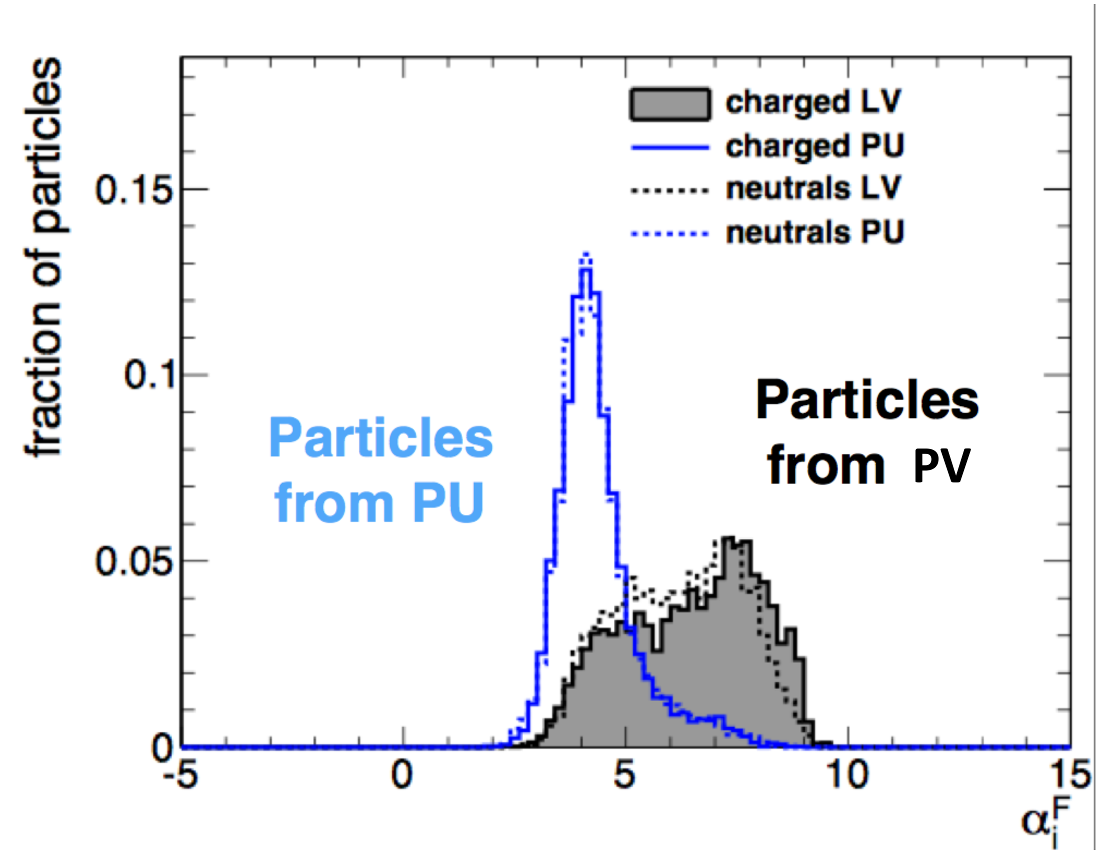
Weight each p-flow particle according to the presence of neighbours...

Weight α allows to separate PU particles from others.

$$\alpha_i = \log \sum_{j \in \text{event}} \frac{P_T^j}{\Delta R_{ij}} \Theta(R_{\min} < \Delta R_{ij} < R_0)$$

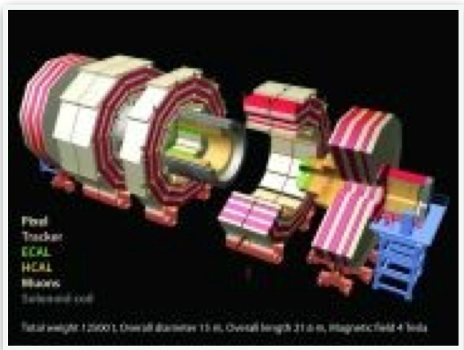
PT sum weighted with distance

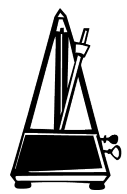
Step function to take into account only particles around it.



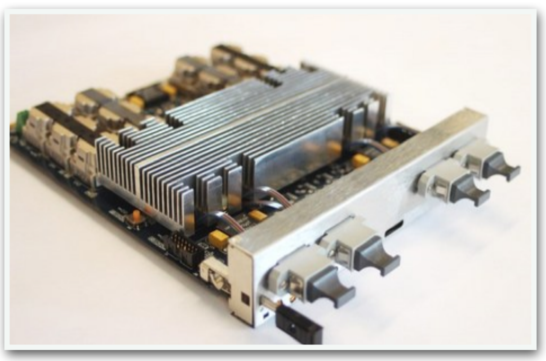
Trigger system

Trigger strategy



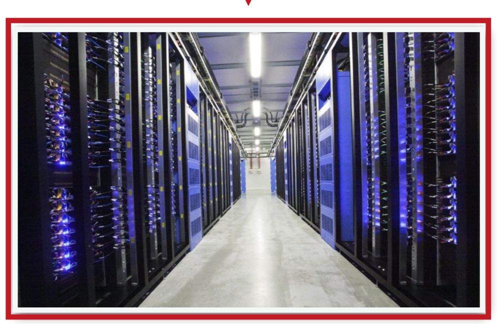


L1 40 MHz



hardware

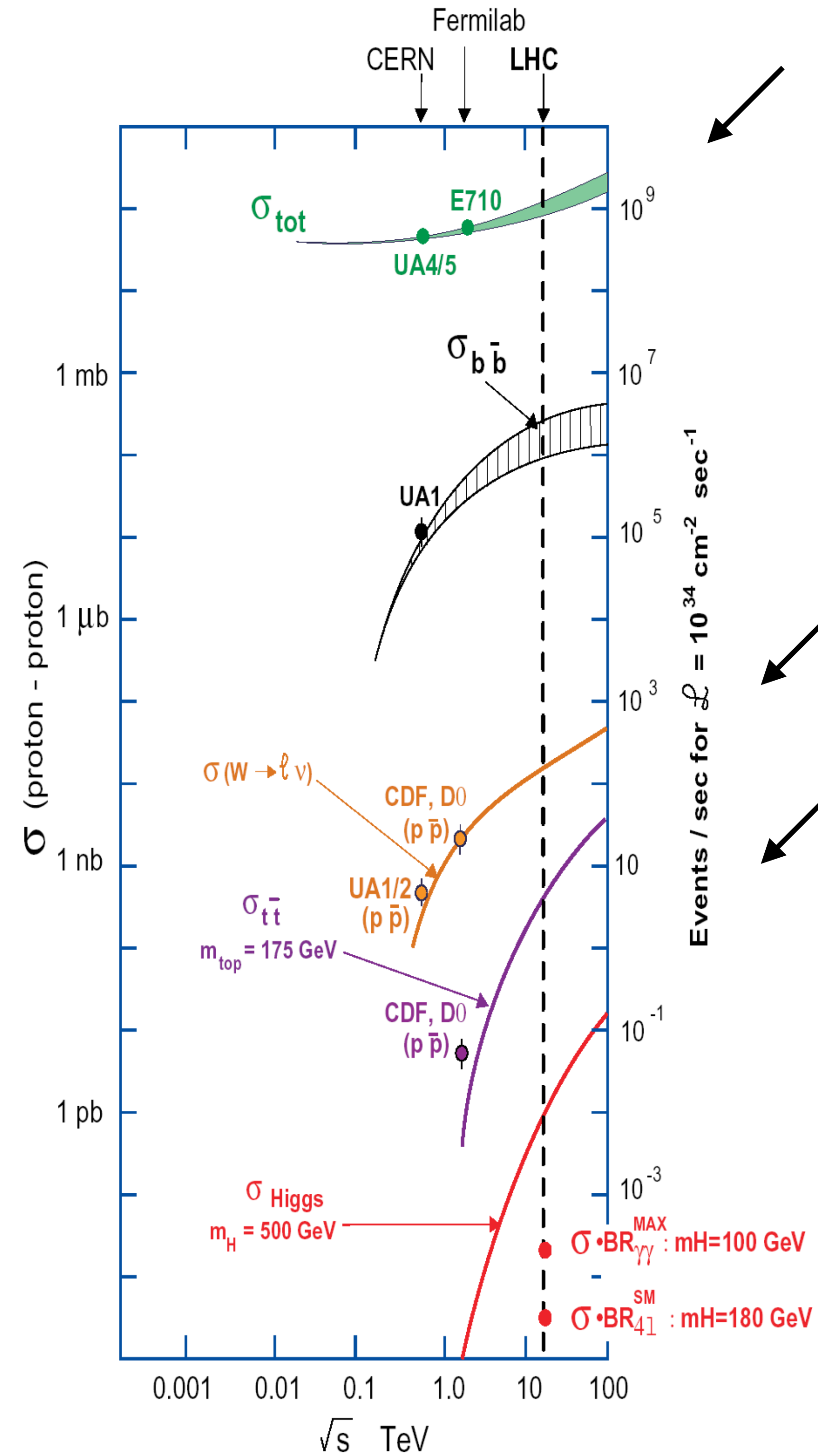
HLT 100 kHz



software

1 kHz

STORAGE

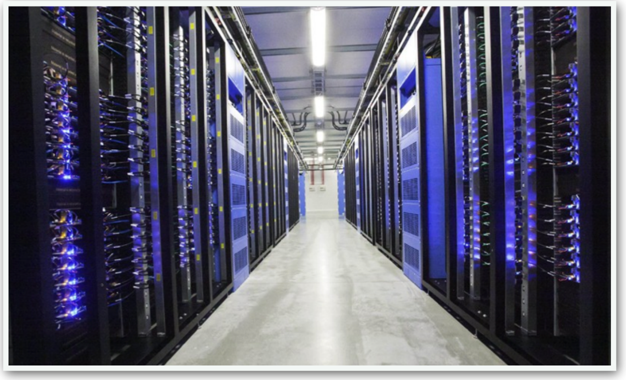


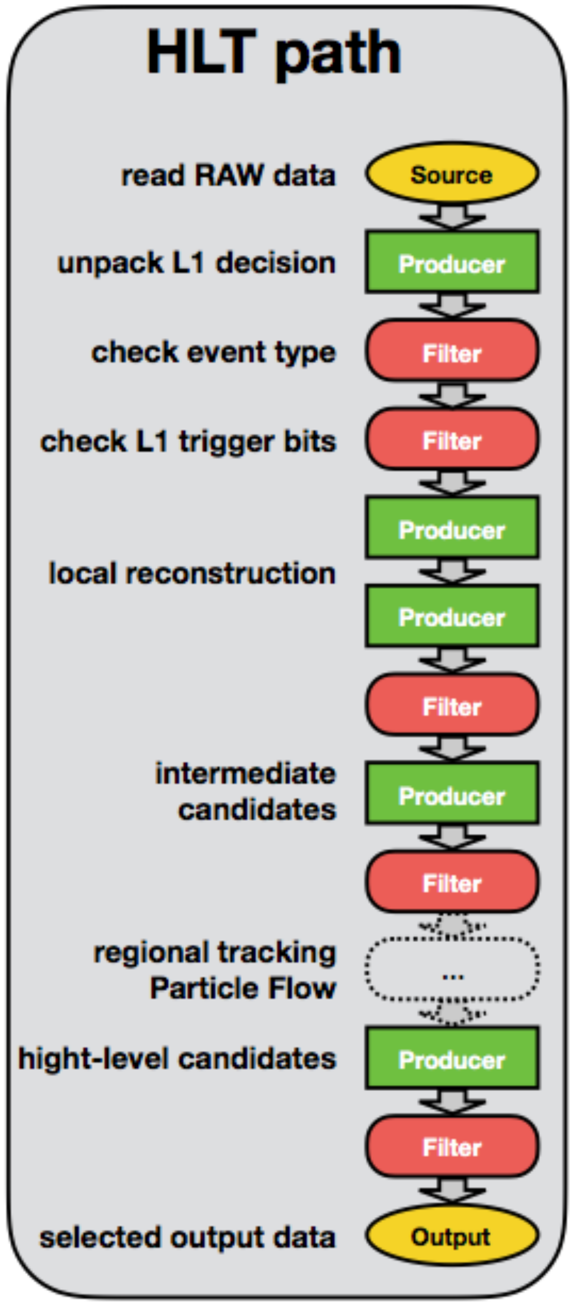
LHC rate = 40 MHz

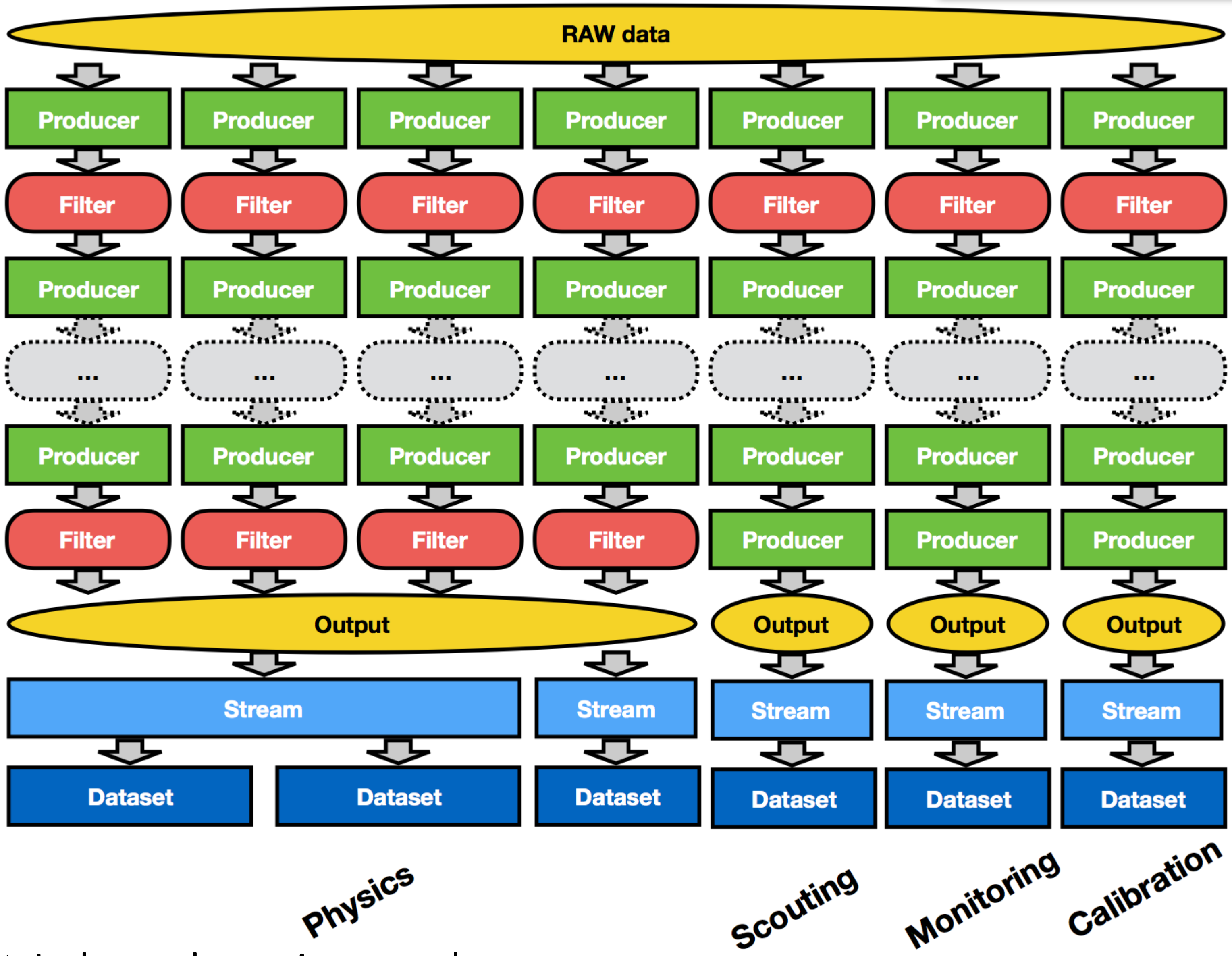
Rate to be written on disk
1 kHz

Physics rate
10 Hz

How does the trigger work ?



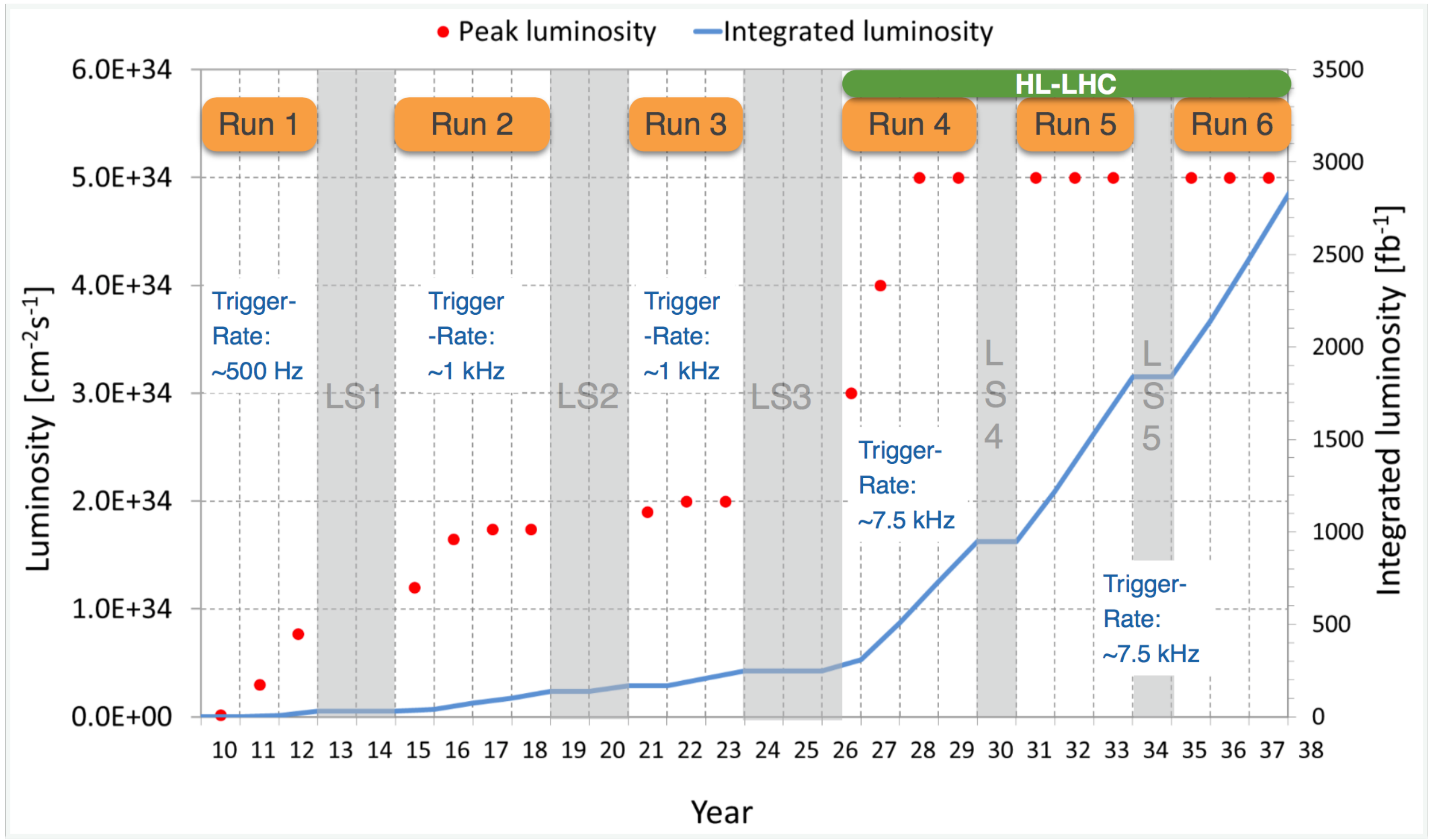




- ✦ Independent trigger paths ;
- ✦ **Common sequences** ;
- ✦ Different **streams and datasets** ;
- ✦ **Specific trigger memus for** commissioning, cosmics, low PU and heavy ions.

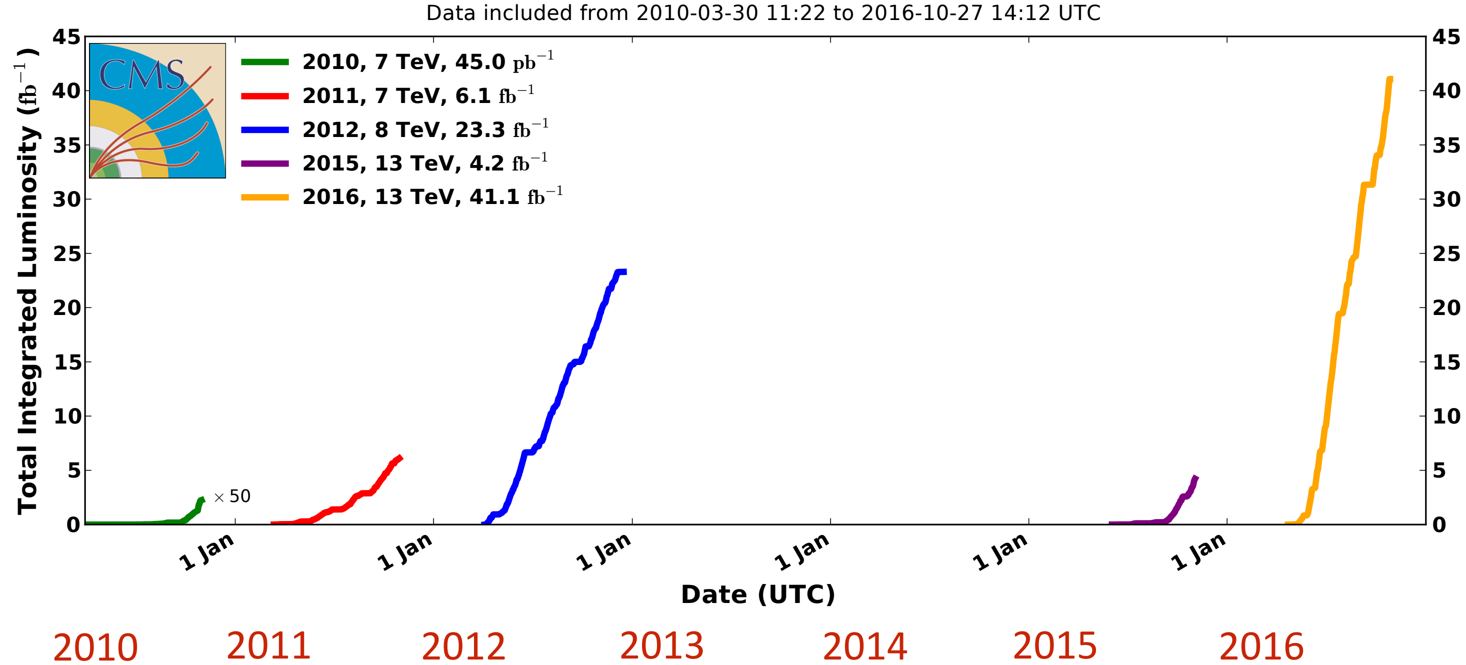
LHC schedule

Run 1	2009-2012	**7, 8 TeV**
LS 1	2012-2015	
Run 2	2015-2018	**13 TeV**



CMS Integrated Luminosity, pp

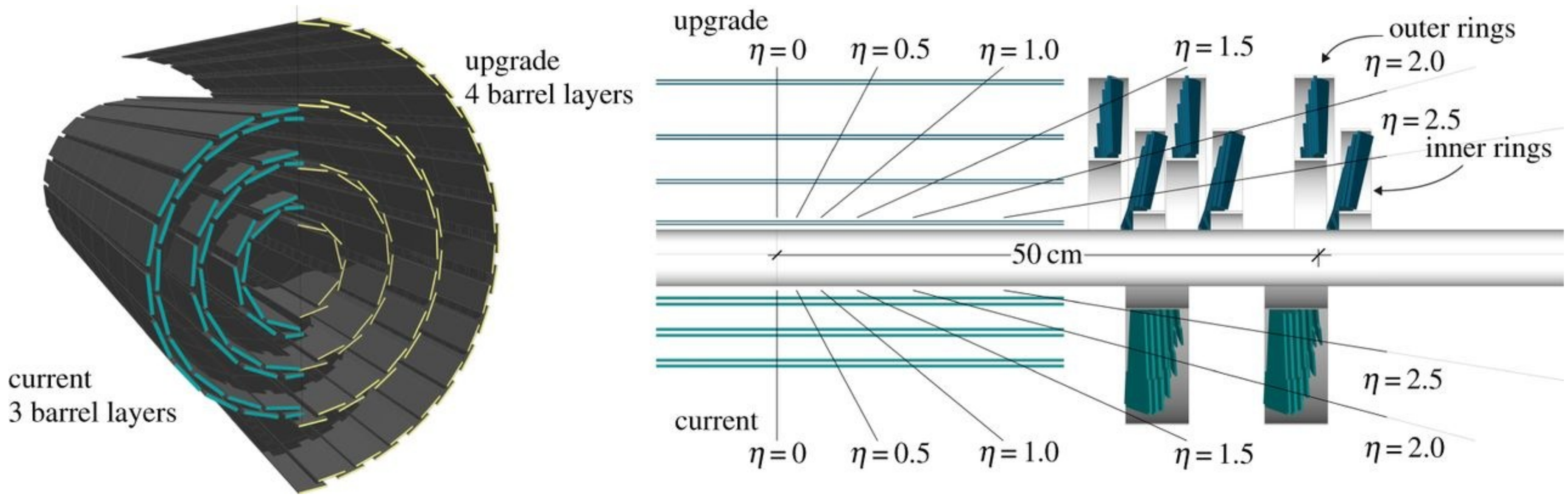
Data included from 2010-03-30 11:22 to 2016-10-27 14:12 UTC

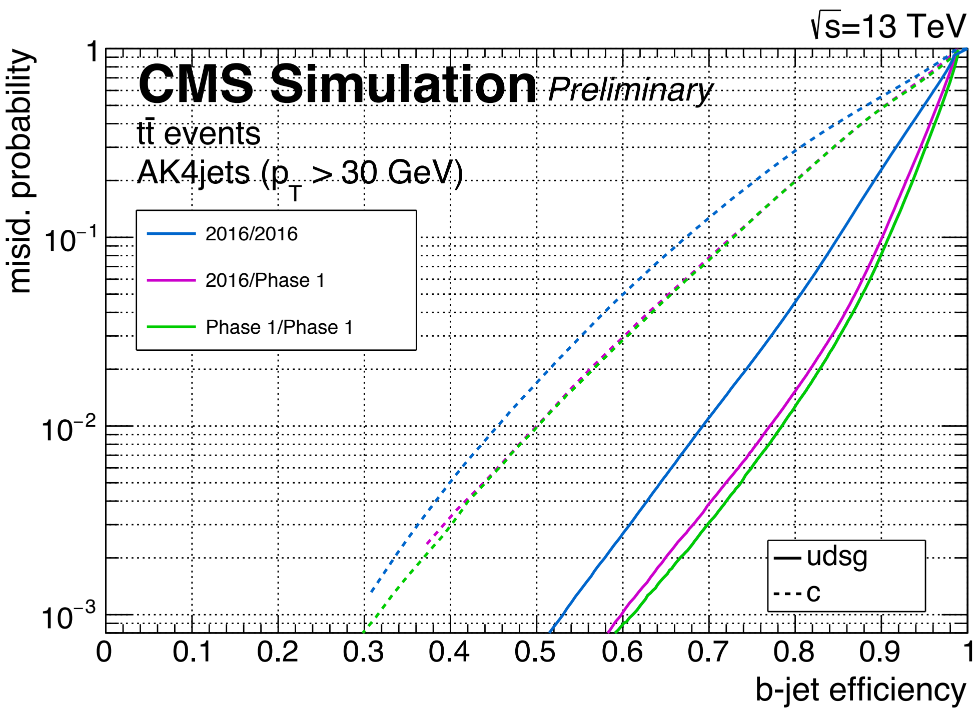


N(events) = cross section * integrated luminosity

Instantaneous luminosity depends on LHC parameters.

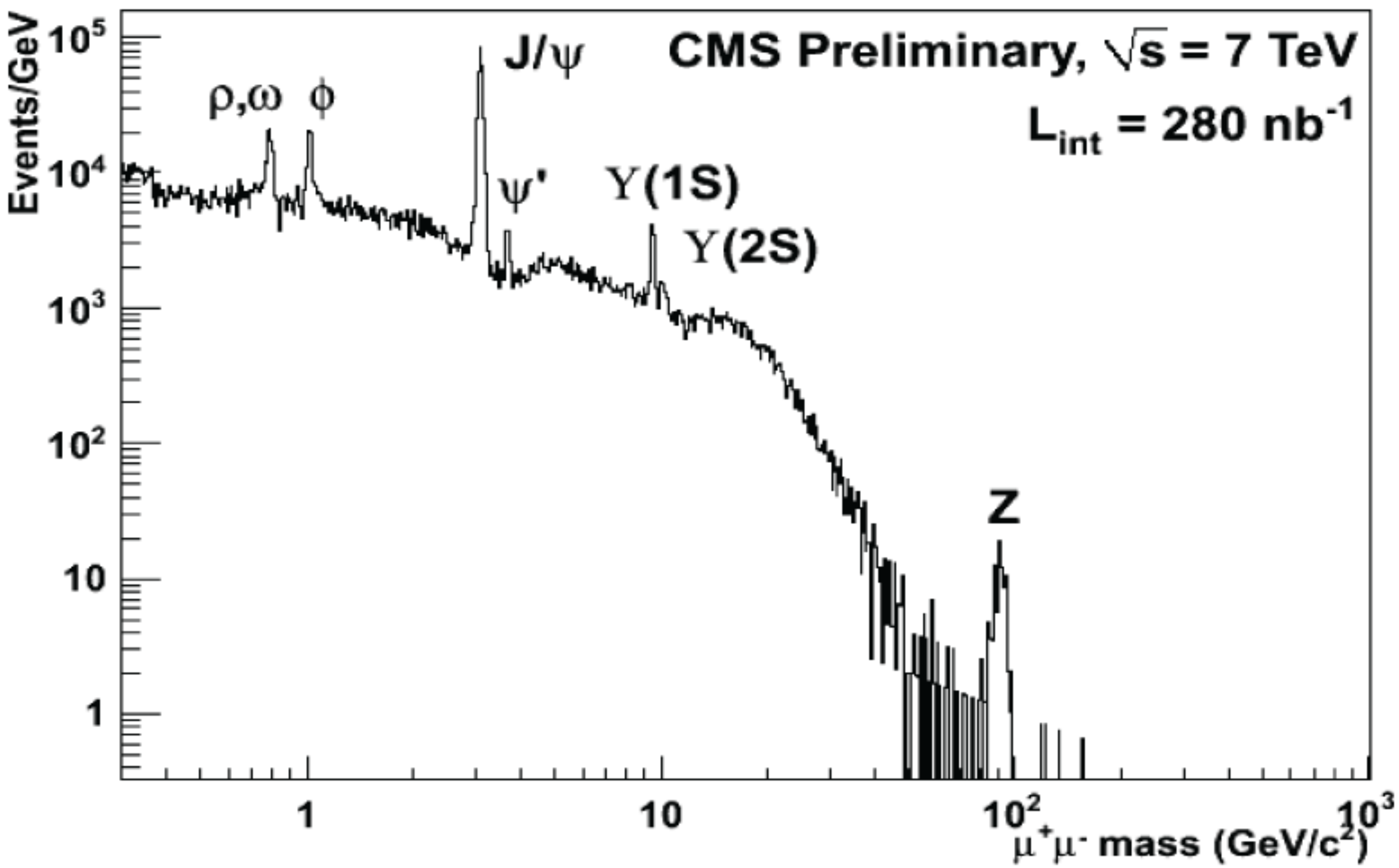
Where do we stand ? 2017, a new pixel detector !





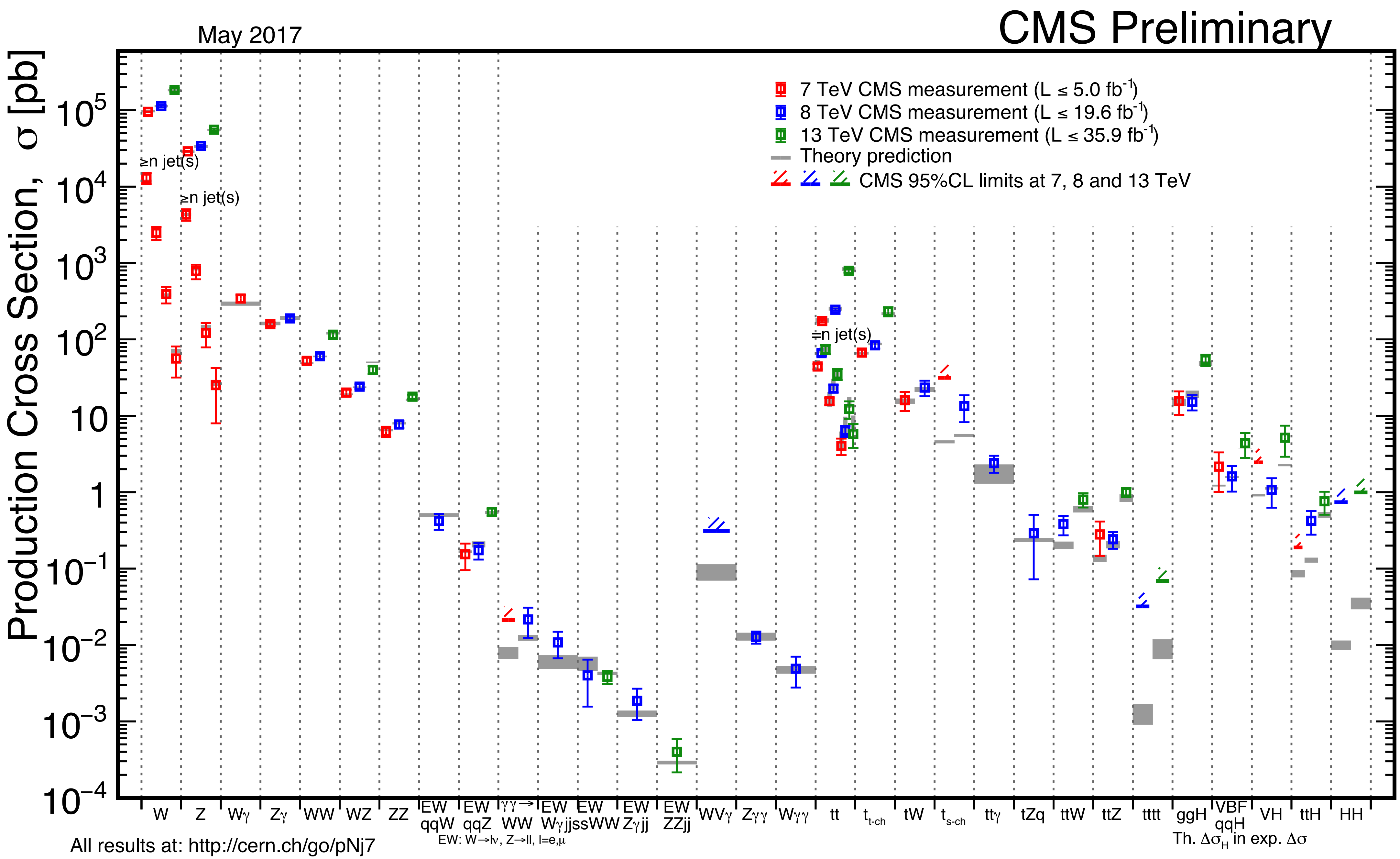
Physics ?

Spectacular confirmation of the Standard Model of particle physics



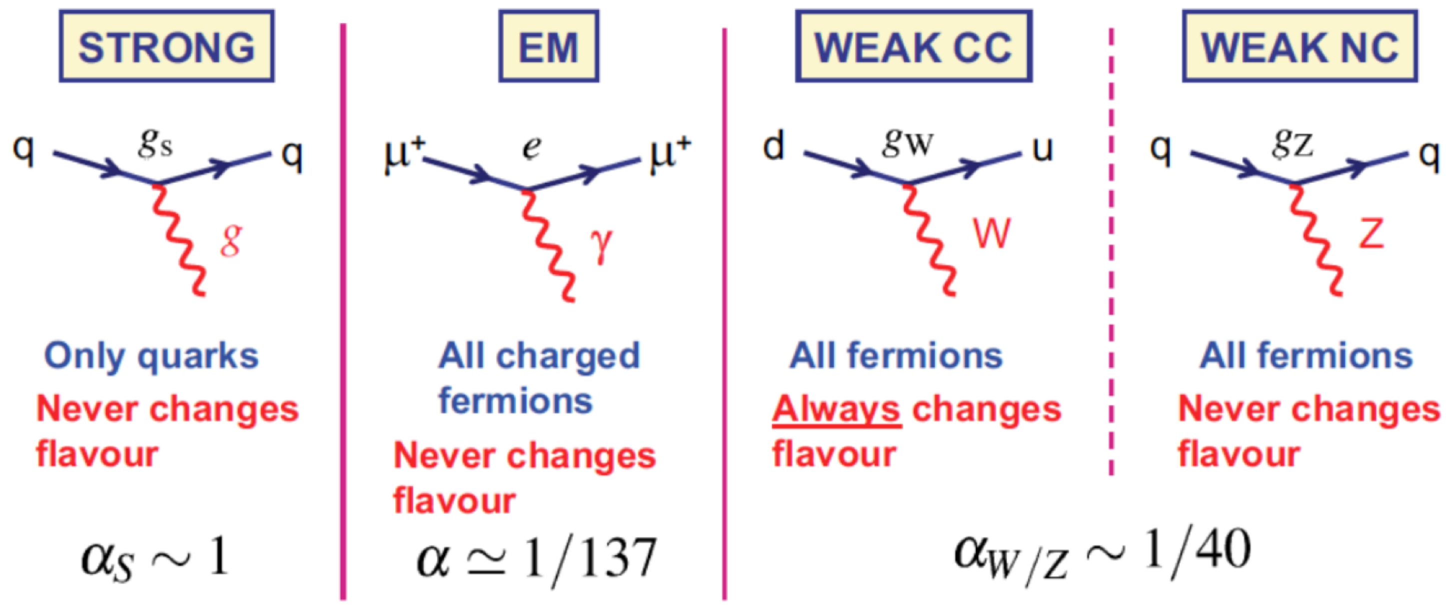
Observation of well known resonances in first data !

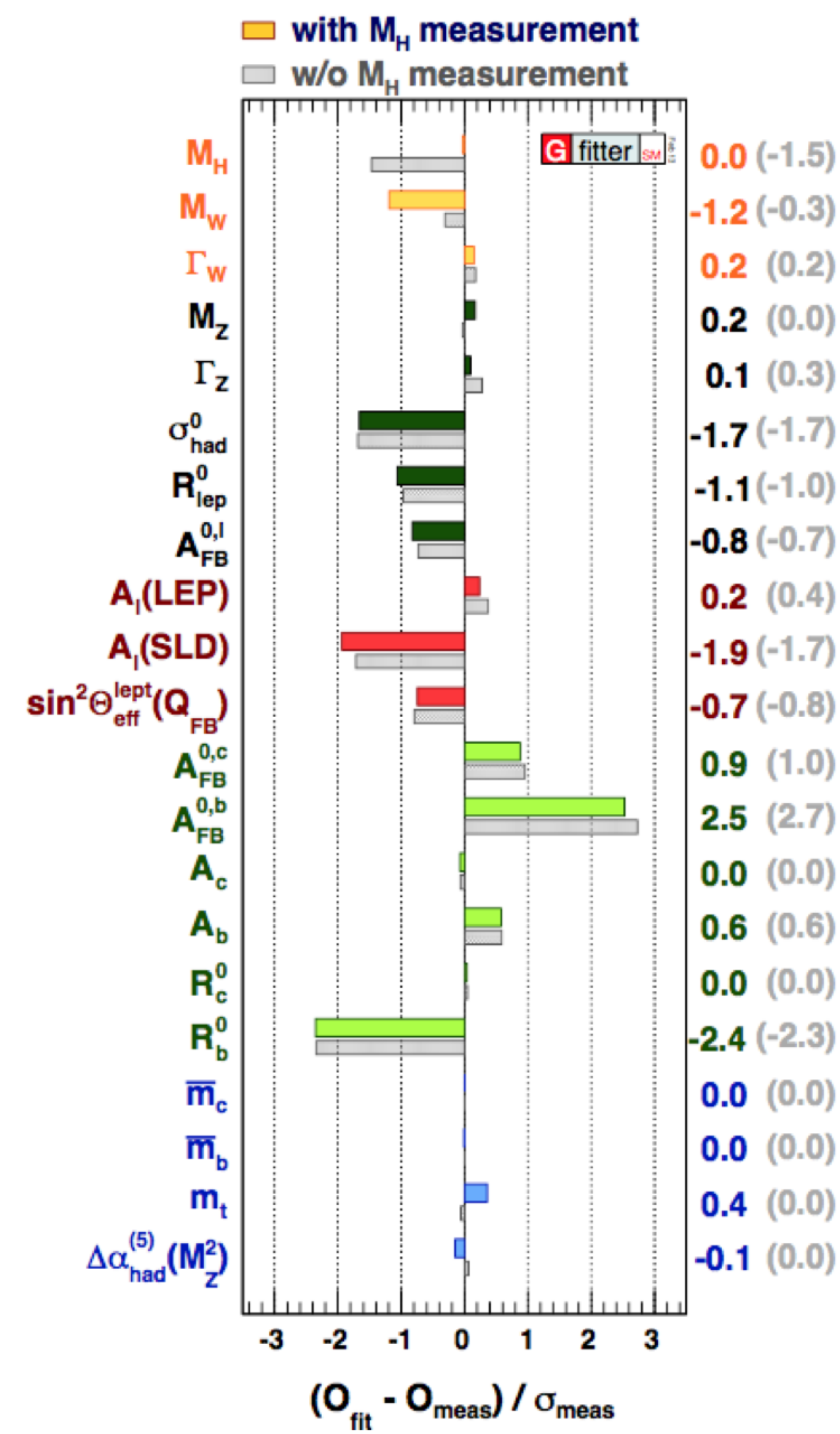
Spectacular confirmation of the Standard Model of particle physics



Measurements of the production cross sections of various processes !

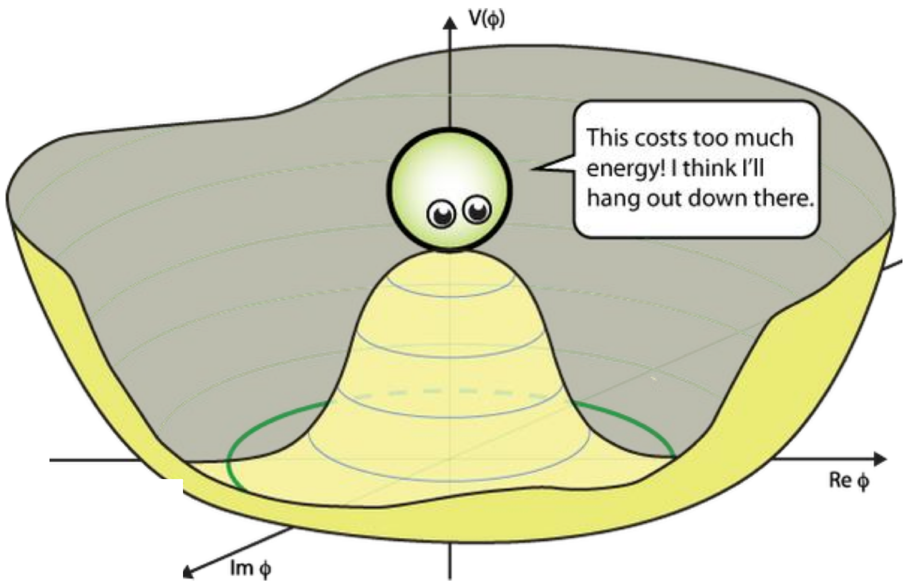
Spectacular confirmation of the Standard Model of particle physics





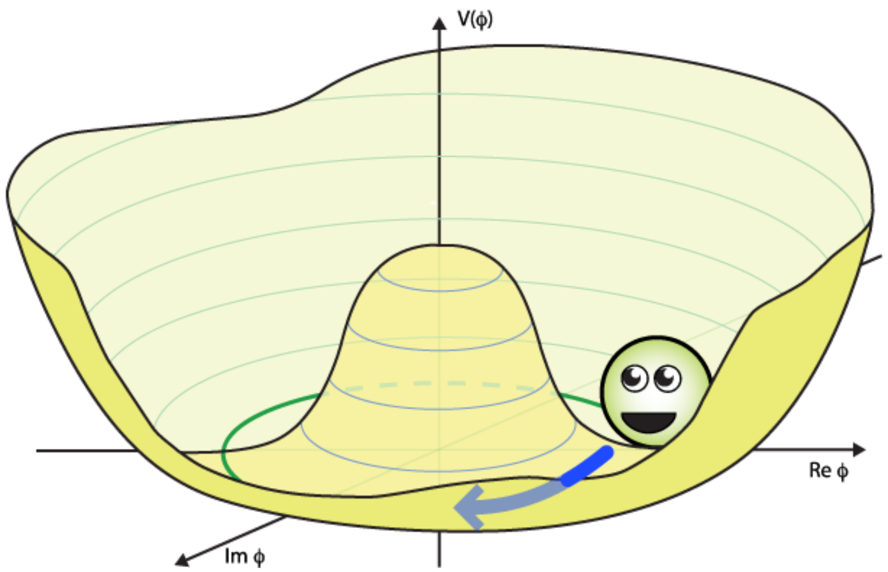
Last missing piece

In the SM: gauge invariance if all particles are massless.



Introduction of field with "mexican hat" potential:

- At origin particles are massless
- When particles see this potential, the minimum energy state is to hang out in fundamental state
- This is called electroweak symmetry breaking
- W and Z bosons get mass from this mechanism
- Any particle that interacts with the field will get mass.



Last missing piece

$$\mathcal{L}_{SM} = \mathcal{L}_{gauge}(A_a, \psi_i) + \mathcal{L}_{Higgs}(\phi, A_a, \psi_i)$$

Natural
Experimentally tested with high accuracy
Stable w.r.t. quantum corrections
Symmetric

Ad hoc
Necessary to describe data
Not stable w.r.t. quantum corrections
Introduces a flavour structure in the model

$$\mathcal{L}_{higgs}(\phi, A_a, \psi_i) = D\phi^+ D\phi - V(\phi)$$

$$V(\phi) = -\mu^2 \phi^+\phi + \lambda(\phi^+\phi)^2 + Y^{ij}\, \psi_L^{\,i}\, \psi_R^{\,j}\, \phi$$

Can be measured in LHC data !

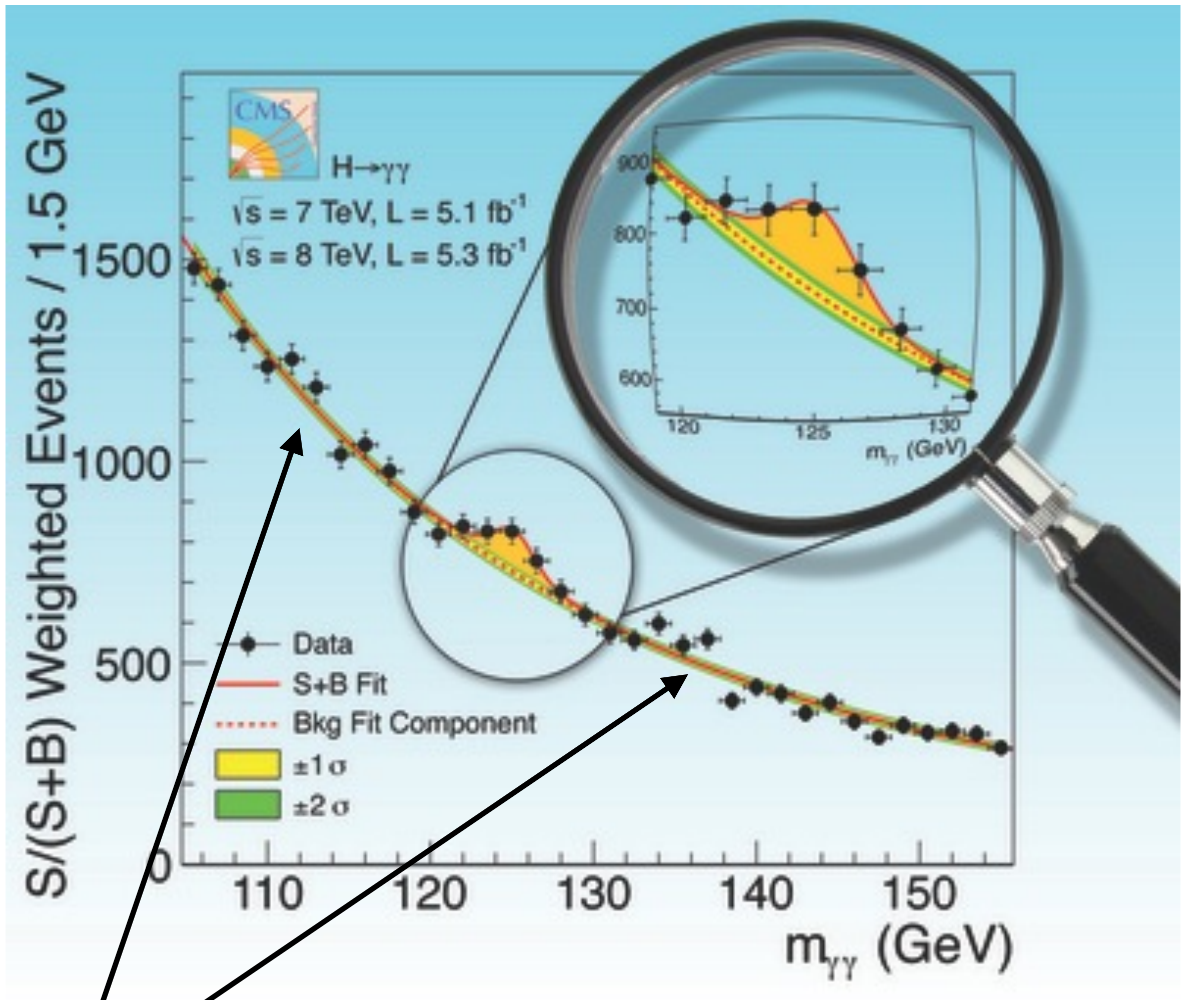
$\lambda = 1/2\ m_H^2/v^2$ $\mu^2 = 1/2\ m_H^2$ $m_W = 1/2 gv$ Y^{ij} = Yukawa couplings

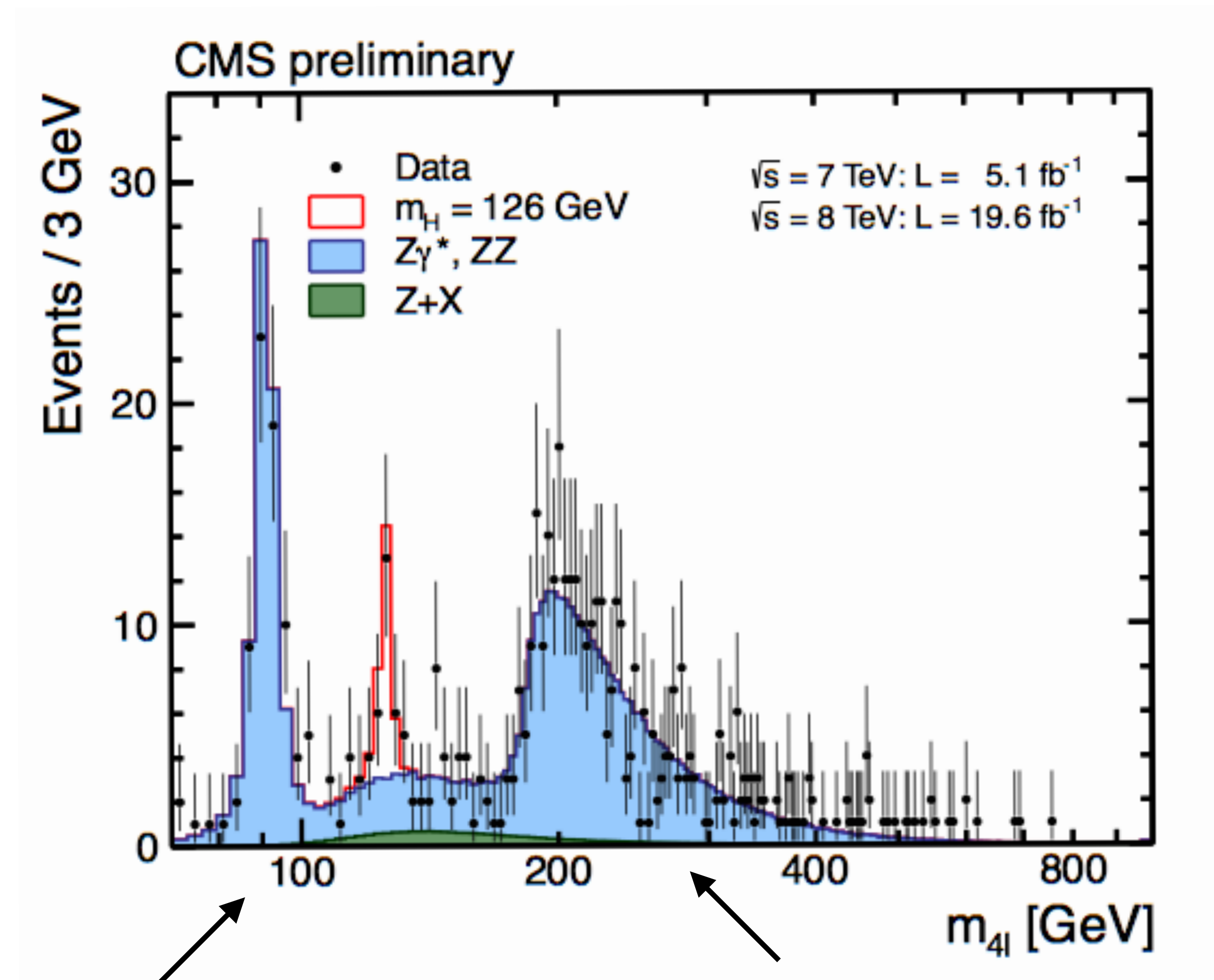
(v= 246 GeV, Higgs vacuum expectation value)

Higgs boson discovery

Announced by ATLAS and CMS
on july 4th 2012 !

Higgs boson discovery - historical plots

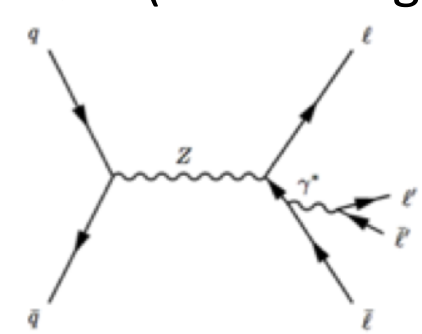




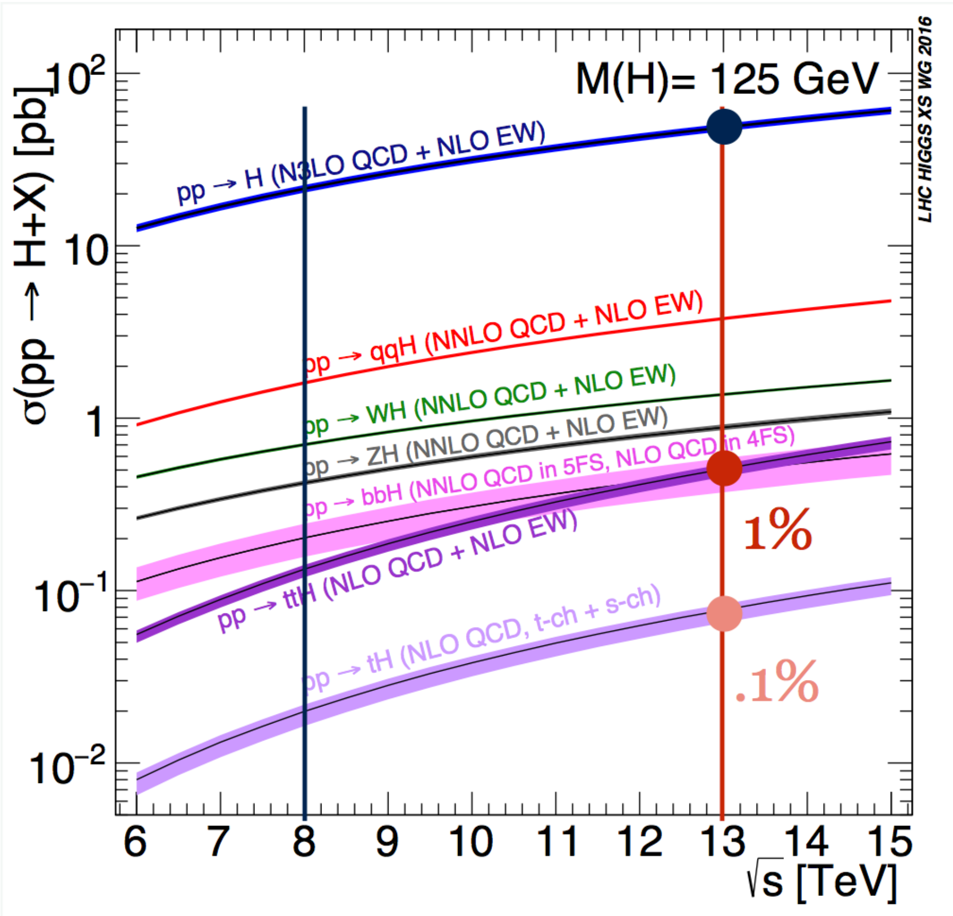
Z→4l (control region)

ZZ→4l

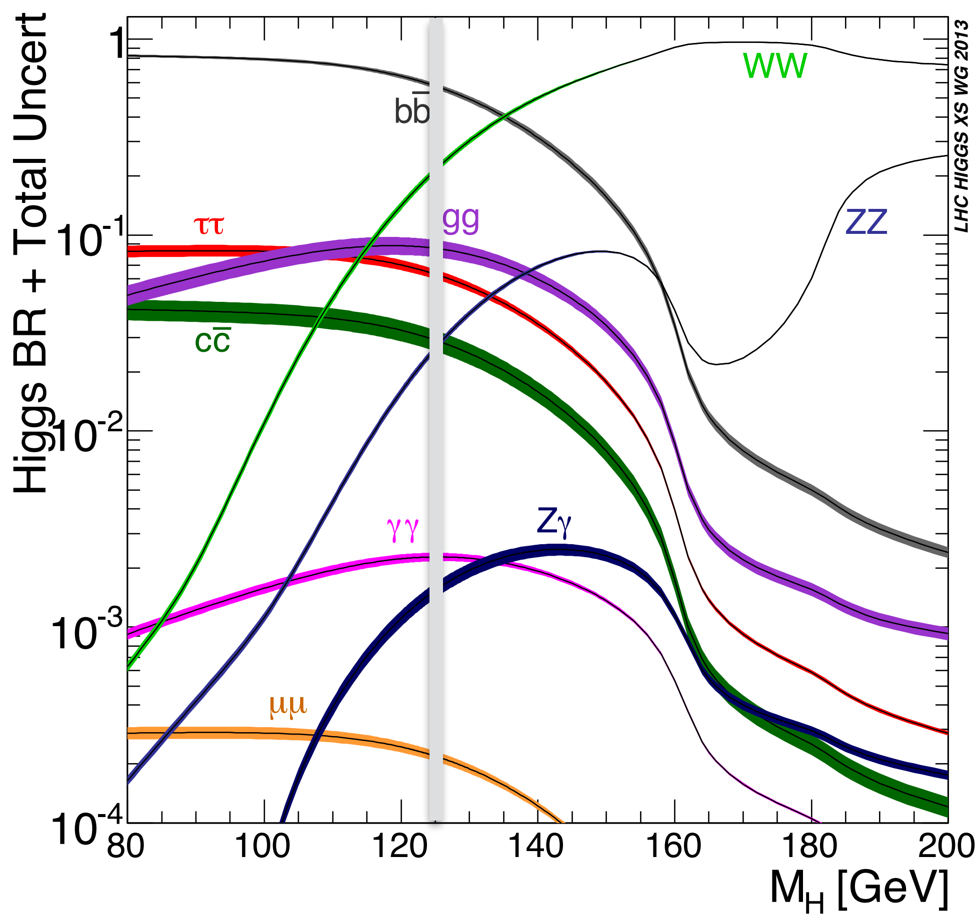
ɣ+jet, jet+jet backgroud
jet faking ɣ



What have we learned about the Higgs boson ?



ttH and tH not yet observed !



Decay modes observed :

ZZ, $\gamma\gamma$

$\tau\tau$, new !

WW ongoing…

bb, cc, huge background !

μμ, very small cross section !

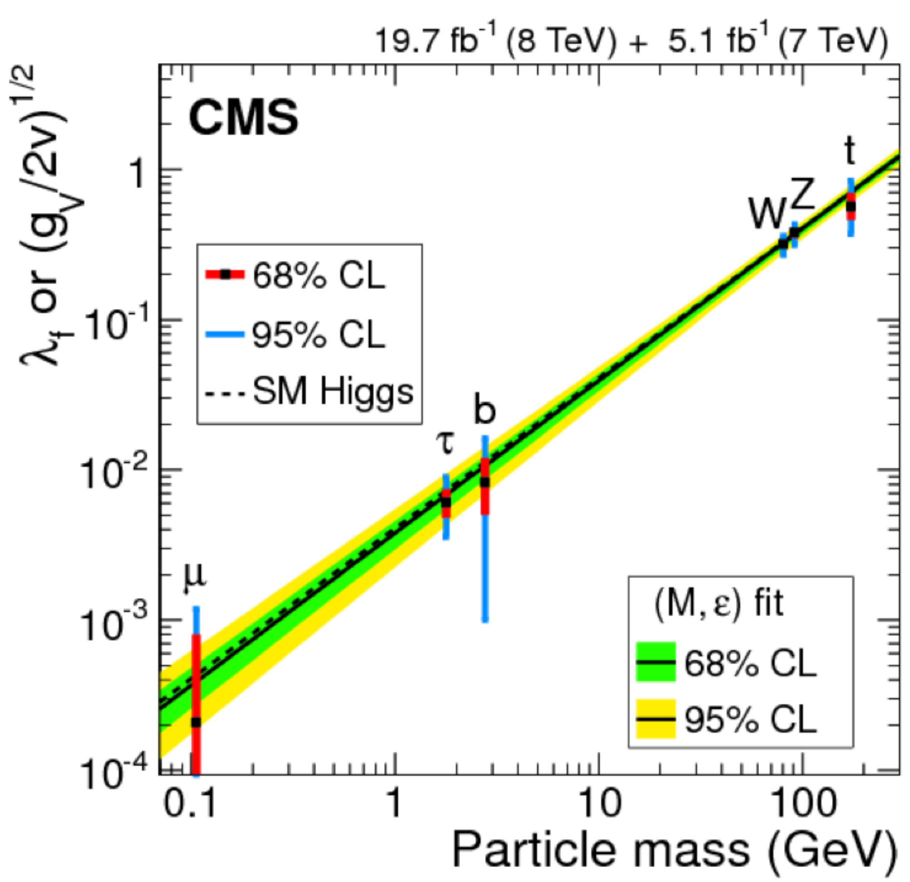
Higgs boson to heavy to decay to top-quarks !

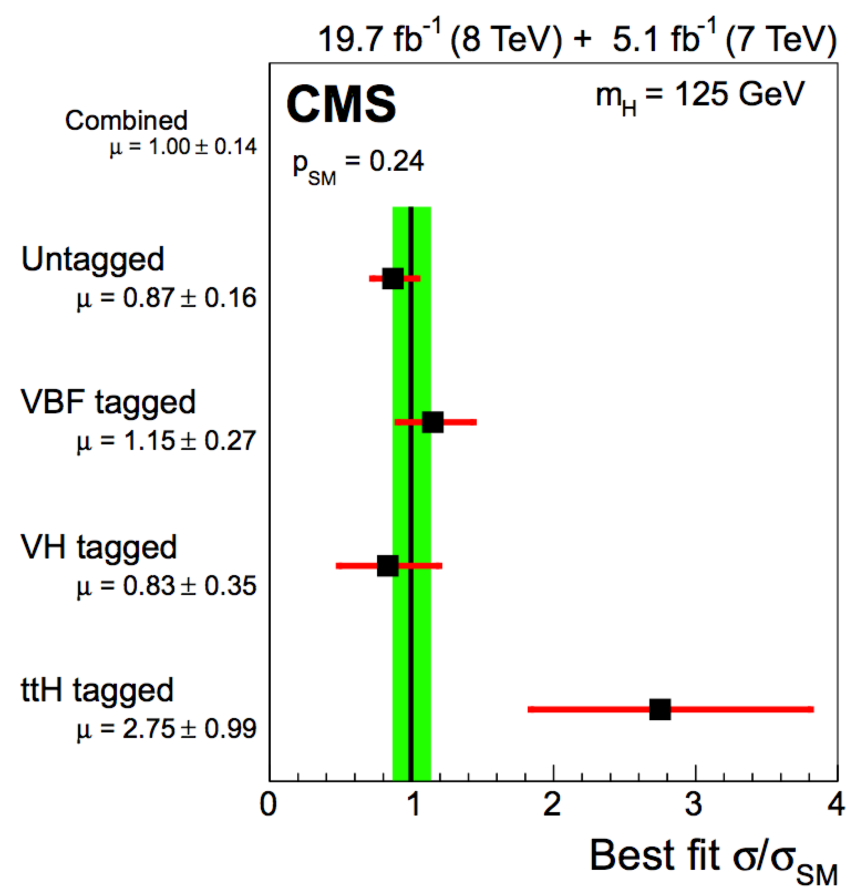
What have we learned about the Higgs boson ?

m_H = 125.09 ± 0.21 (stat) ± 0.11 (syst) GeV
Γ_H < 26 MeV

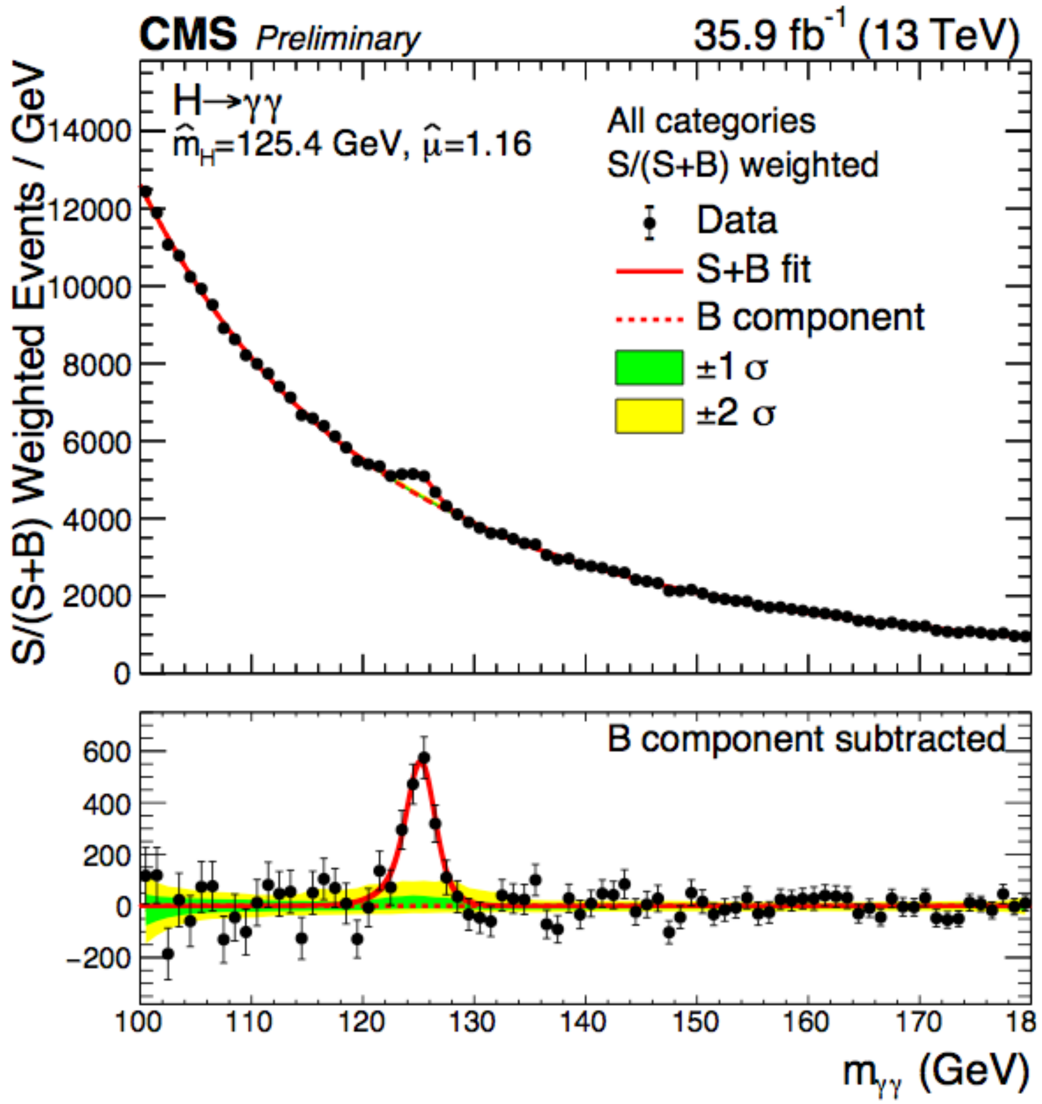
Higgs boson seems to behave in a standard model like way:

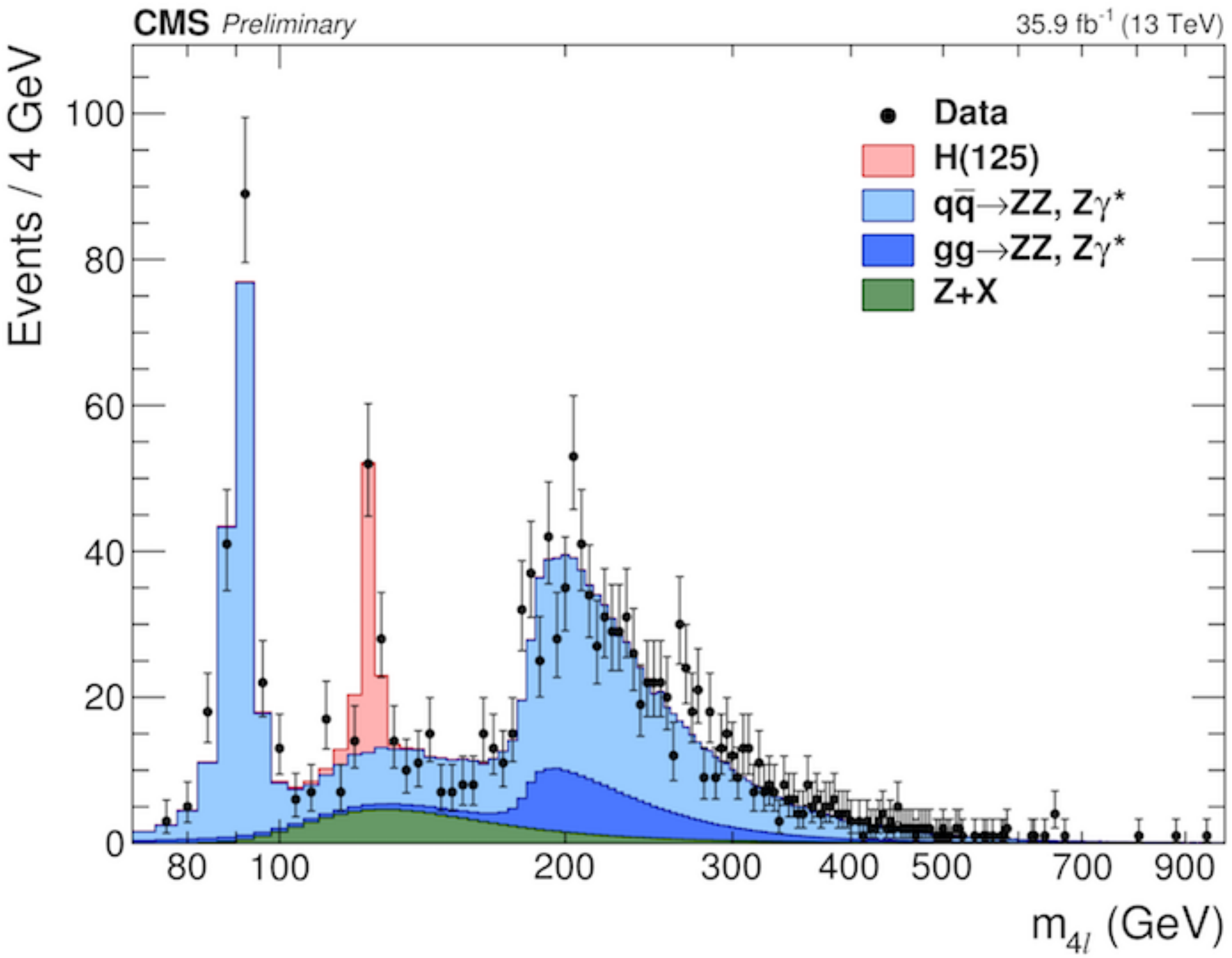
- $J^{CP} = 0^+$
- Yukawa couplings follow the SM within measured precision
- BR (H→BSM) < 34% at 95% CL





Historical plots - an update…

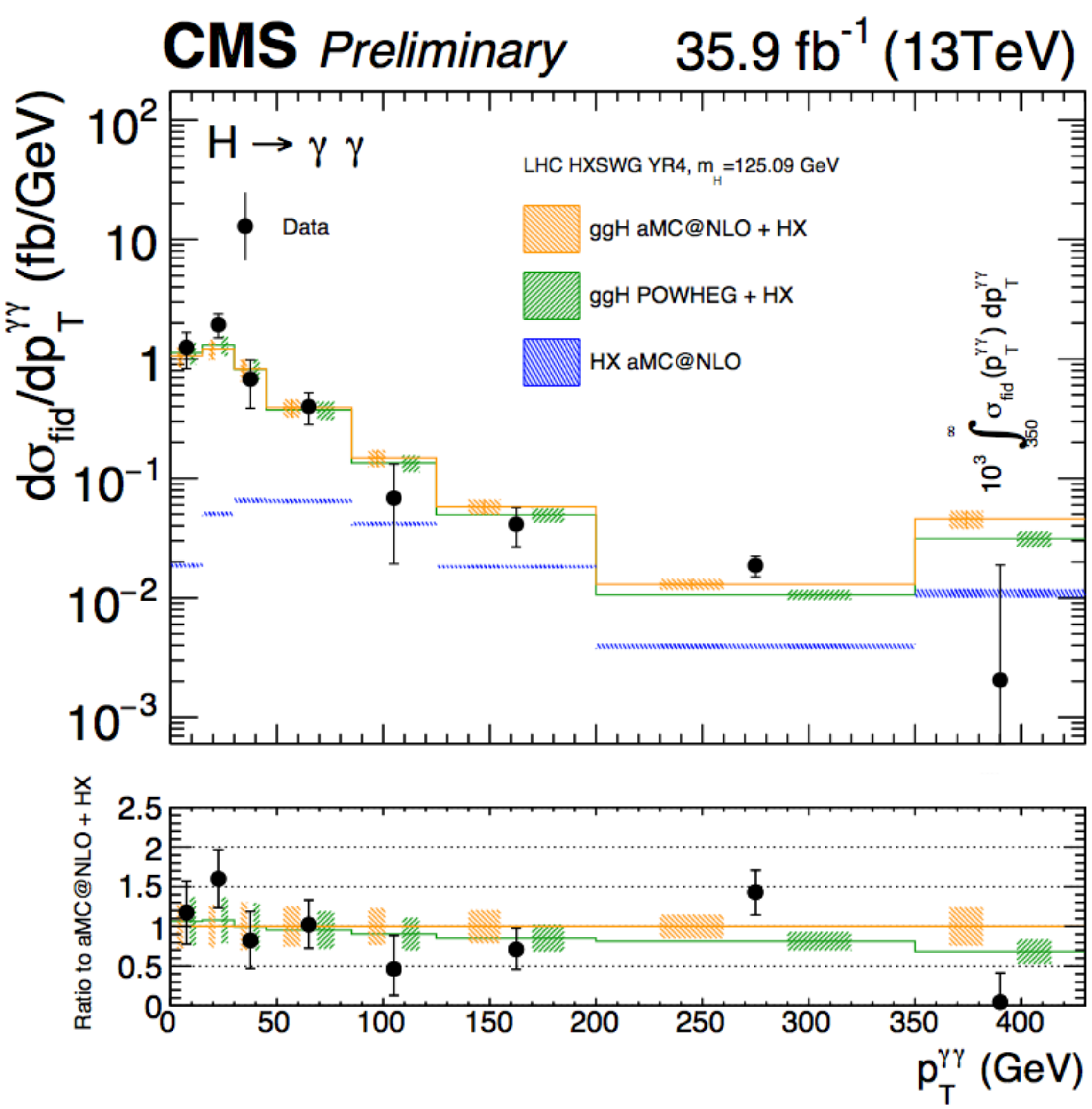


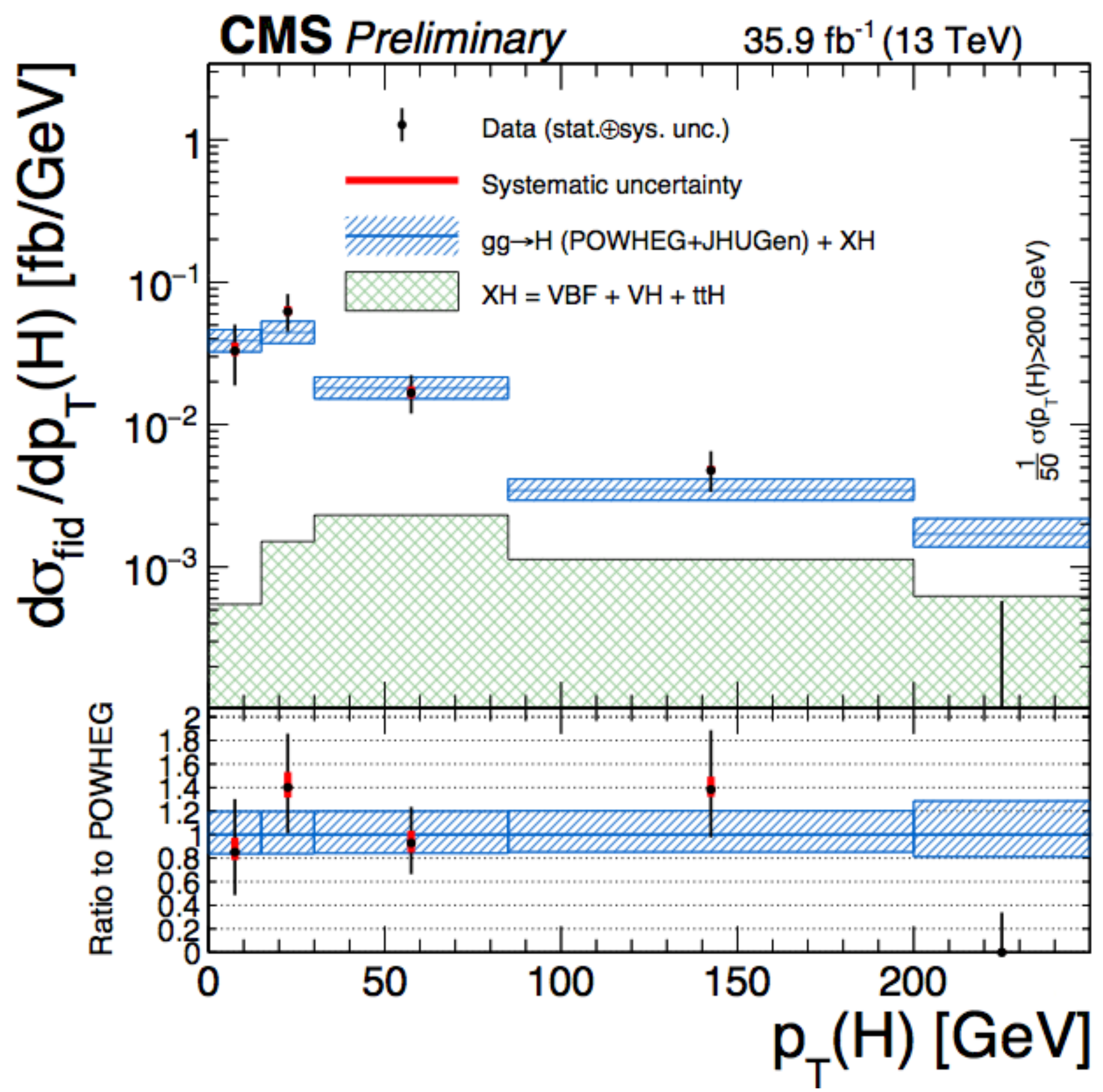


New measurement of m_H in H→4l:

m_H = 125.26 ± 0.20 (stat) ± 0.08 (syst) GeV

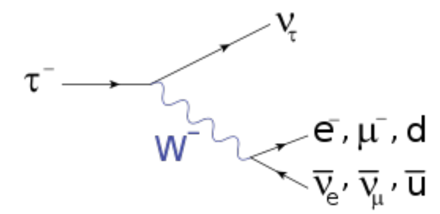
First differential measurements !



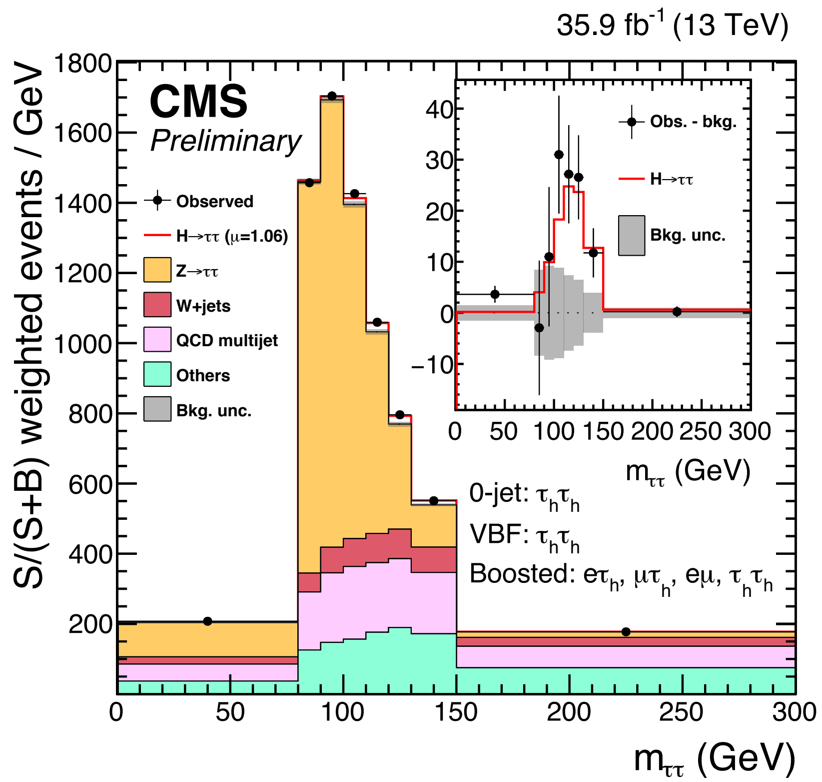


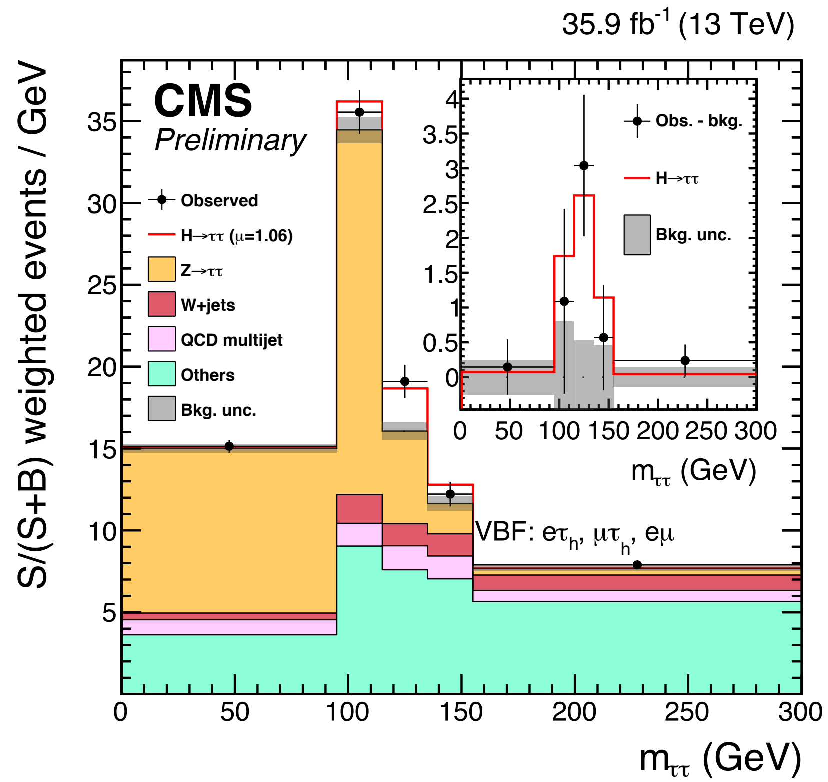
Cross check observables with theoretical calculations and simulation !

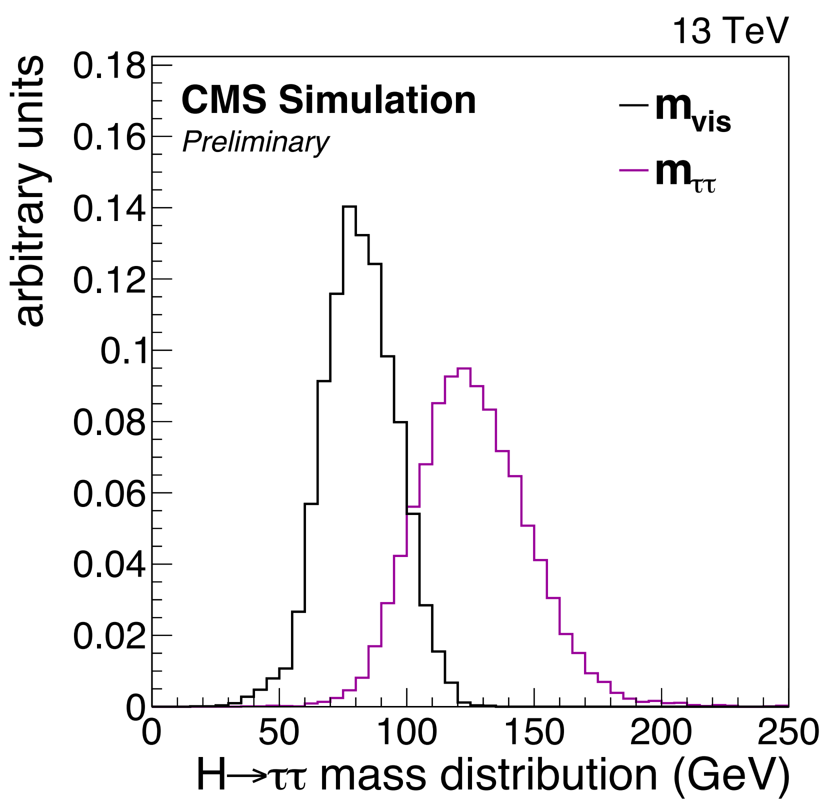
Observation of H→ττ



H→ττ observation !
Difficult channel, neutrinos from taus escape detection.





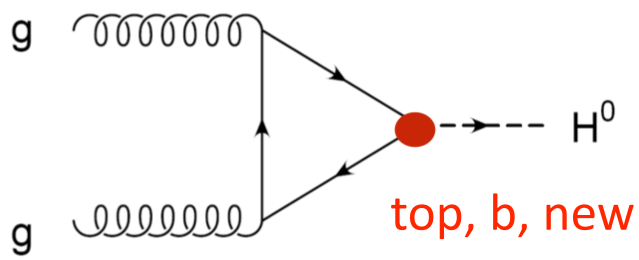


Higgs boson mass reconstructed with a dynamical likelihood algorithm, called SVFit.

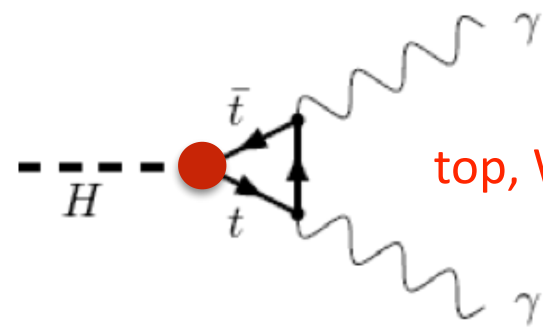
Search for top-antitop-Higgs

Higgs bosons can't decay in top quarks, how can one measure the top Yukawa coupling ?

Indirect access to top-Higgs coupling

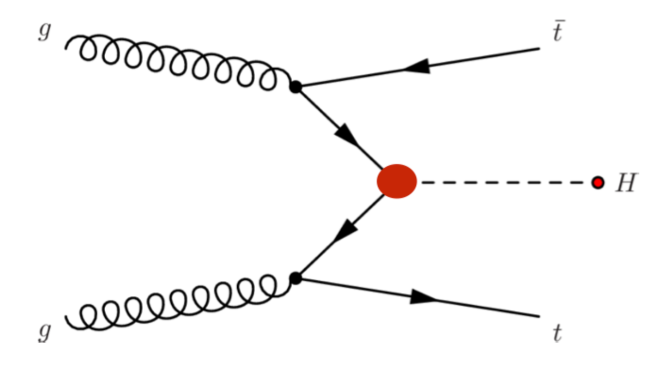


top, b, new particule ?

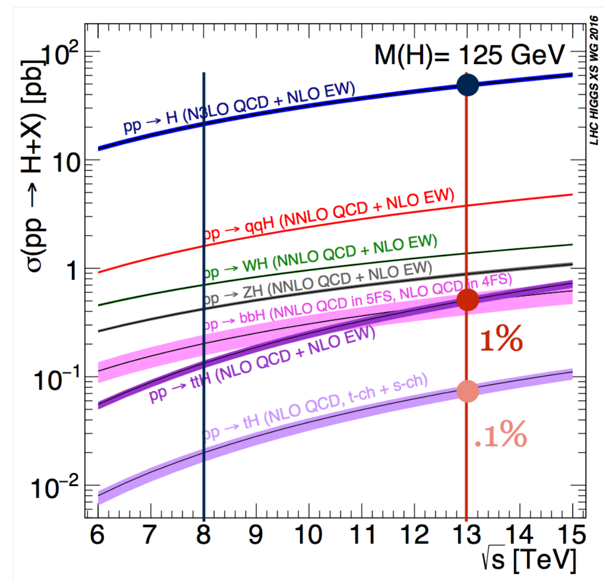


top, W, new particule ?

Direct measurement



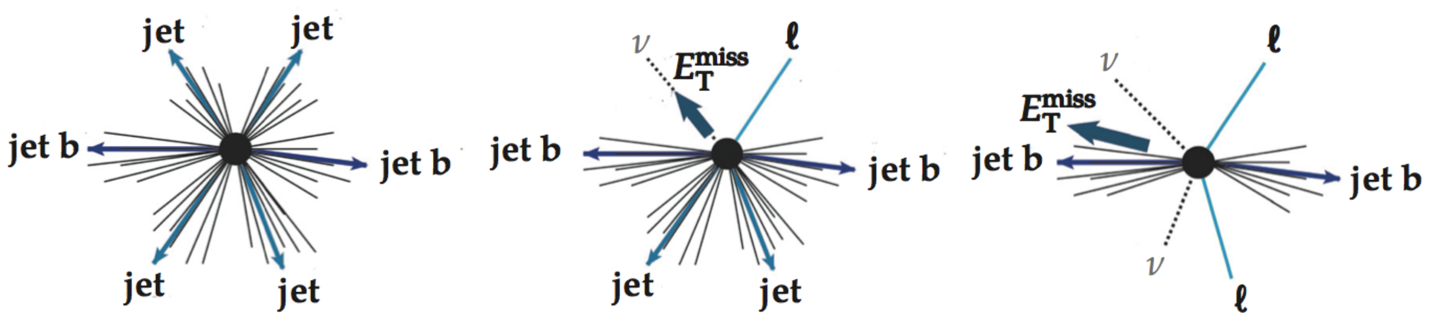
top-Higgs coupling: √σ(ttH)

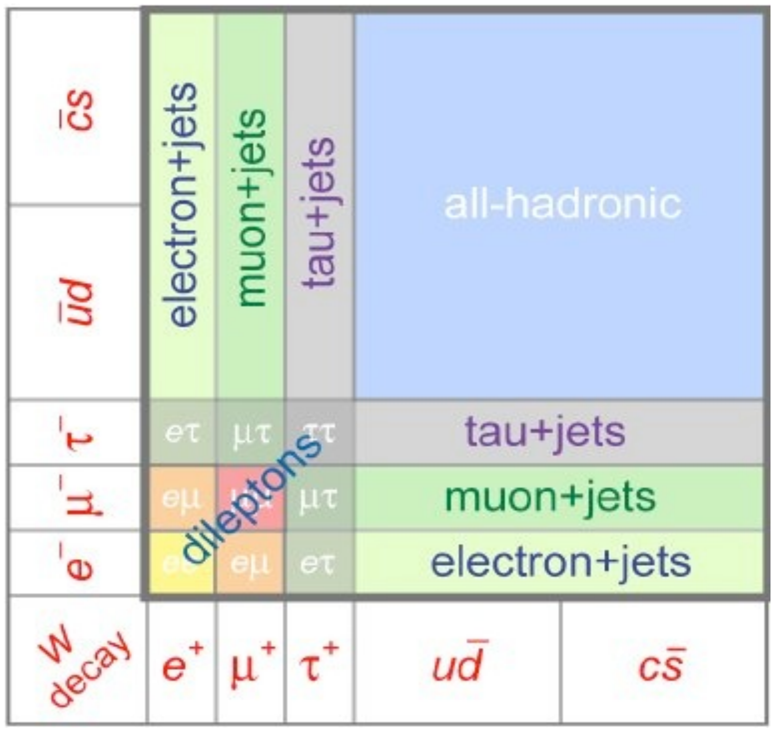


1% of the Higgs boson production cross section

Top-antitop-Higgs: several final states

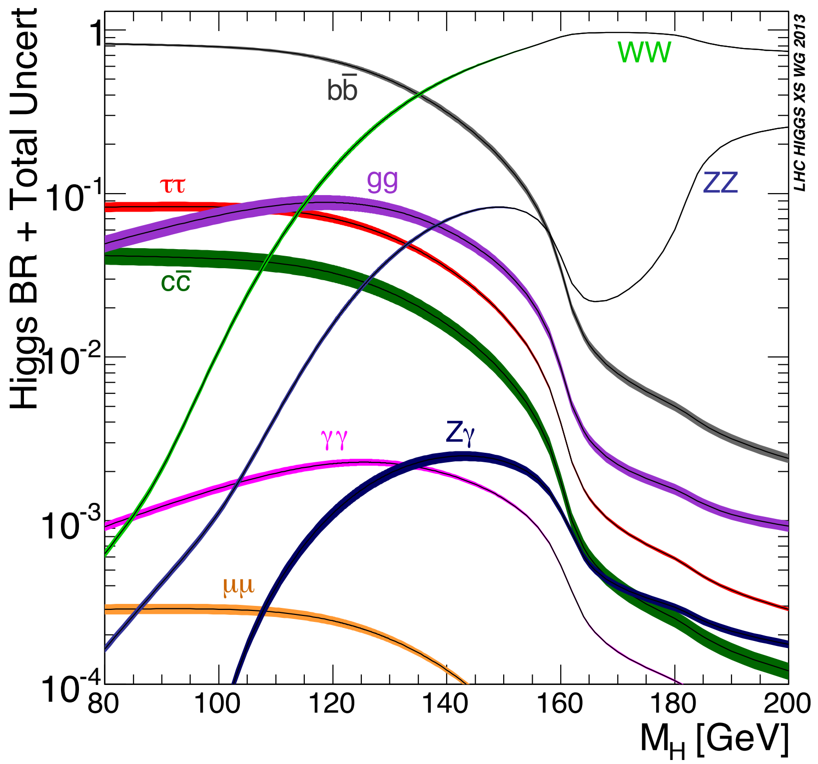
Need to identify top quark pairs:
top → W^+ b (~100%)



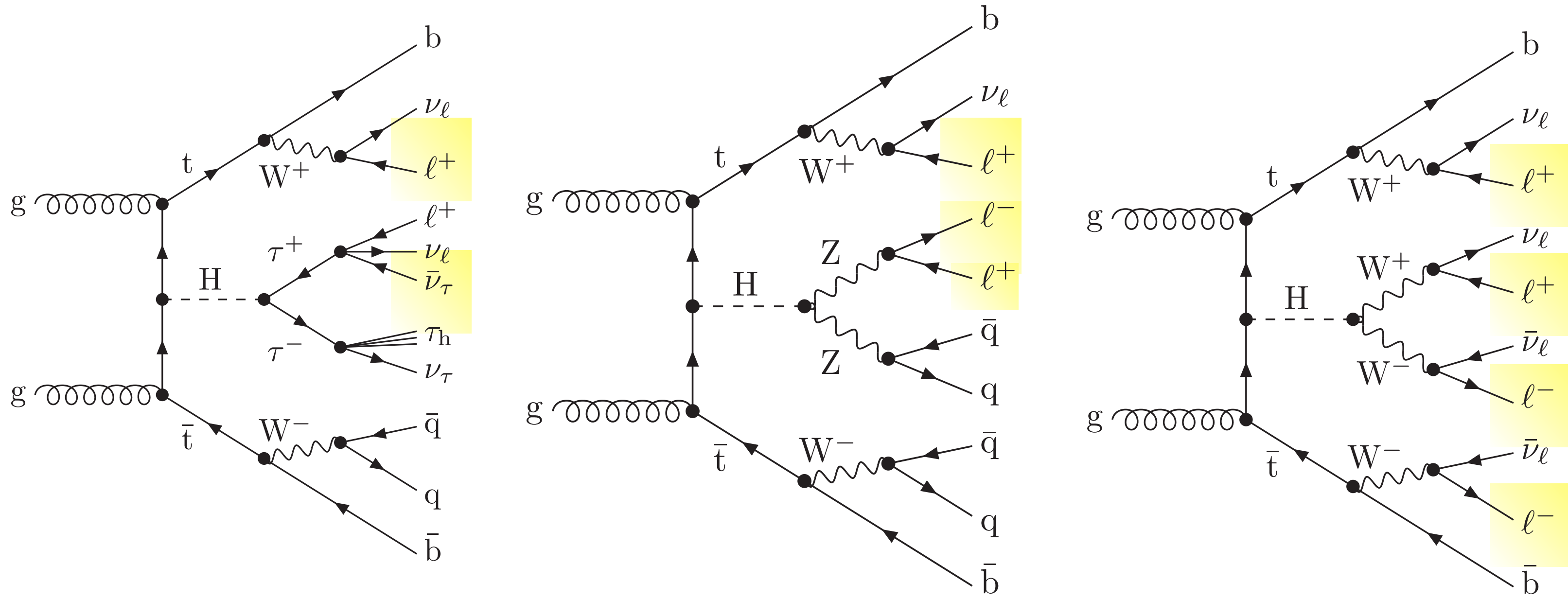


+

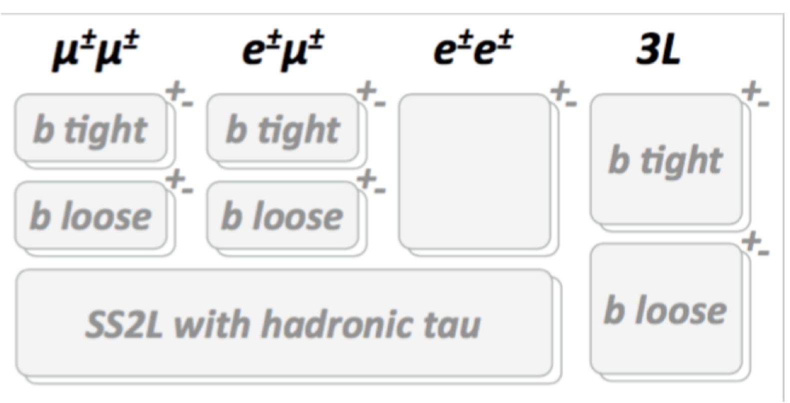
Higgs boson final states:
several possible final states…



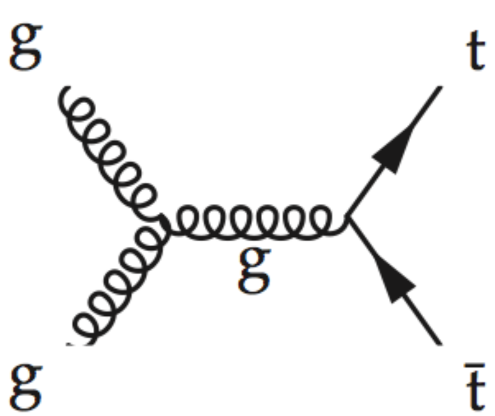
Top-antitop-Higgs: multileptons final state

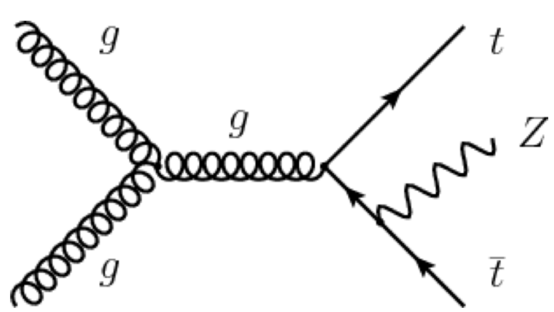


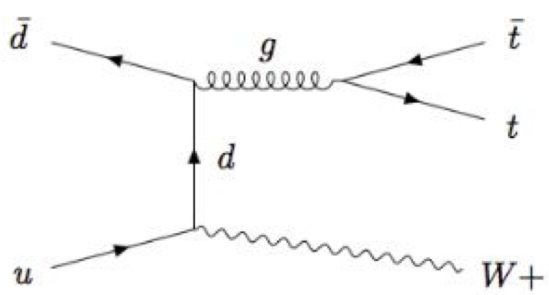
Categories



Main backgrounds : fake leptons, tt, ttZ, ttW, WZ, ZZ

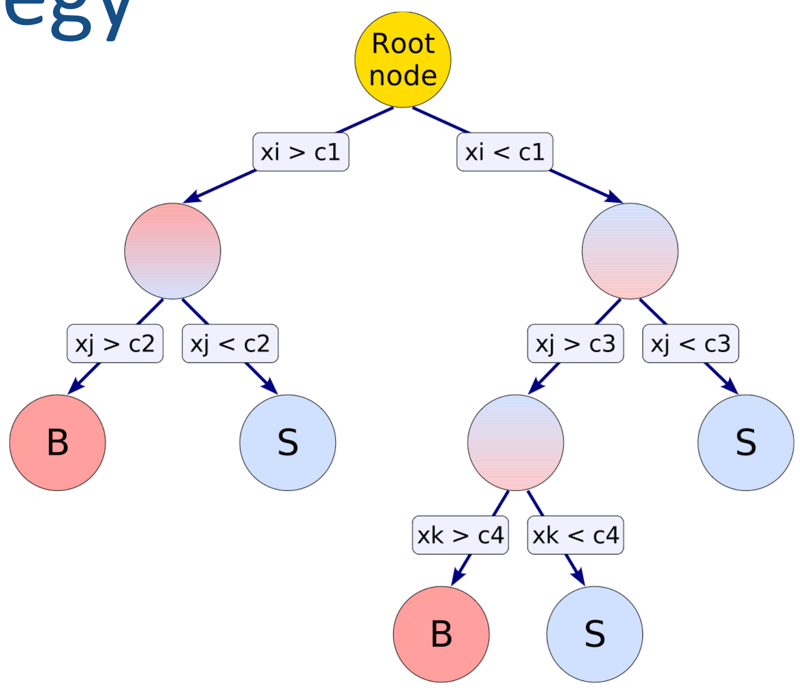






...

Top-antitop-Higgs: multileptons analysis strategy

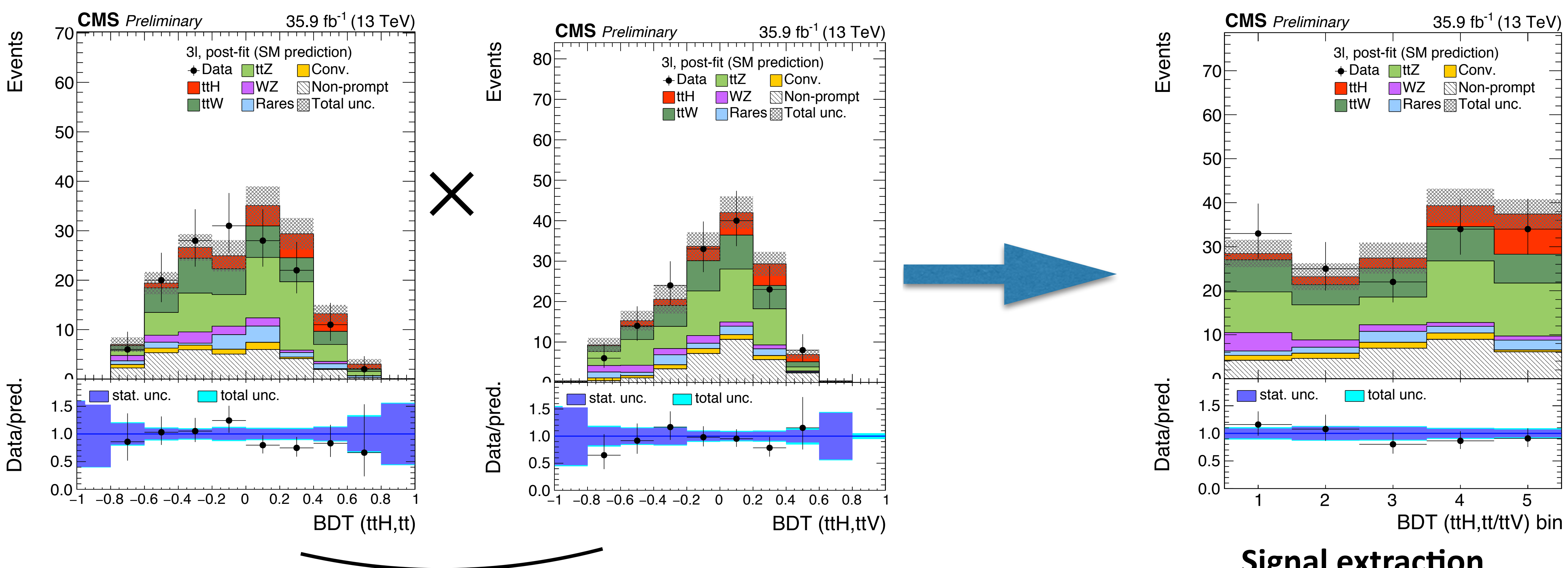


Multivariate techniques, e.g. boosted decision tree (BDT)

Figure 15: Schematic view of a decision tree. Starting from the root node, a sequence of binary splits using the discriminating variables x_i is performed. Each split uses the variable that at this node gives the best separation between signal and background when being cut on. The same variable may thus be used at several nodes, while others might not be used at all. The leaf nodes at the bottom end of the tree are labeled "S" for signal and "B" for background depending on the majority of events that end up in the respective nodes.

BDT against tt

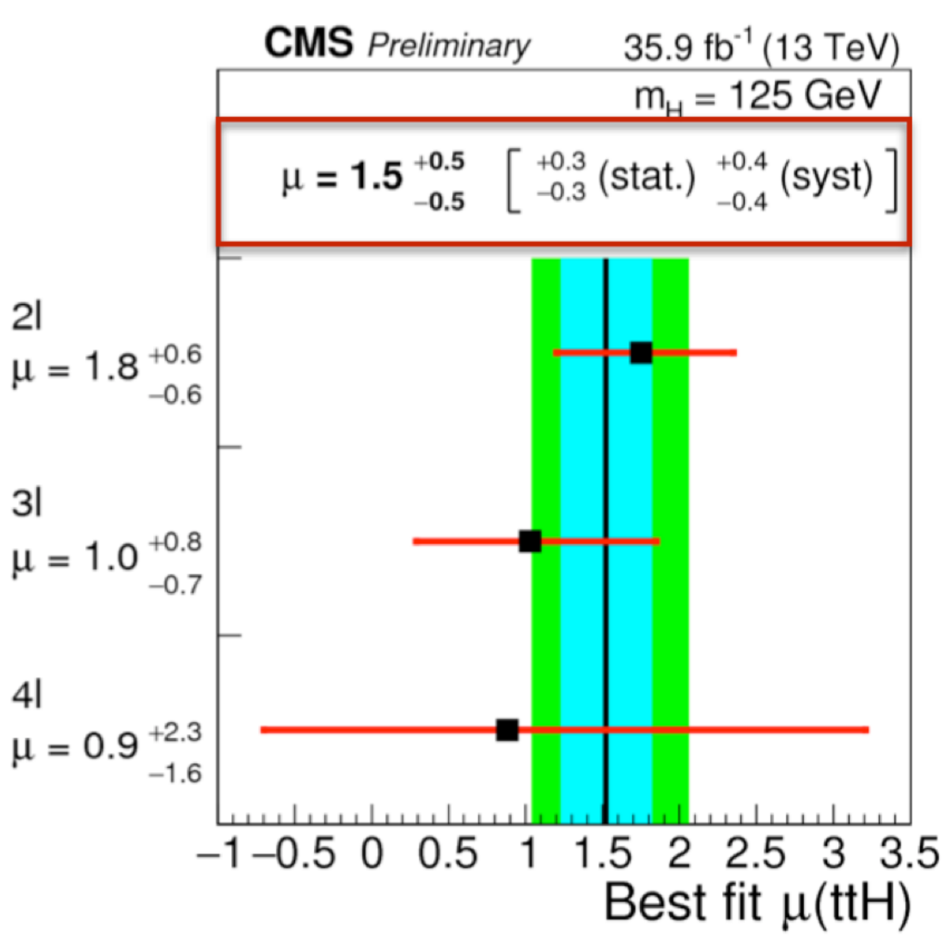
BDT against ttZ and ttW

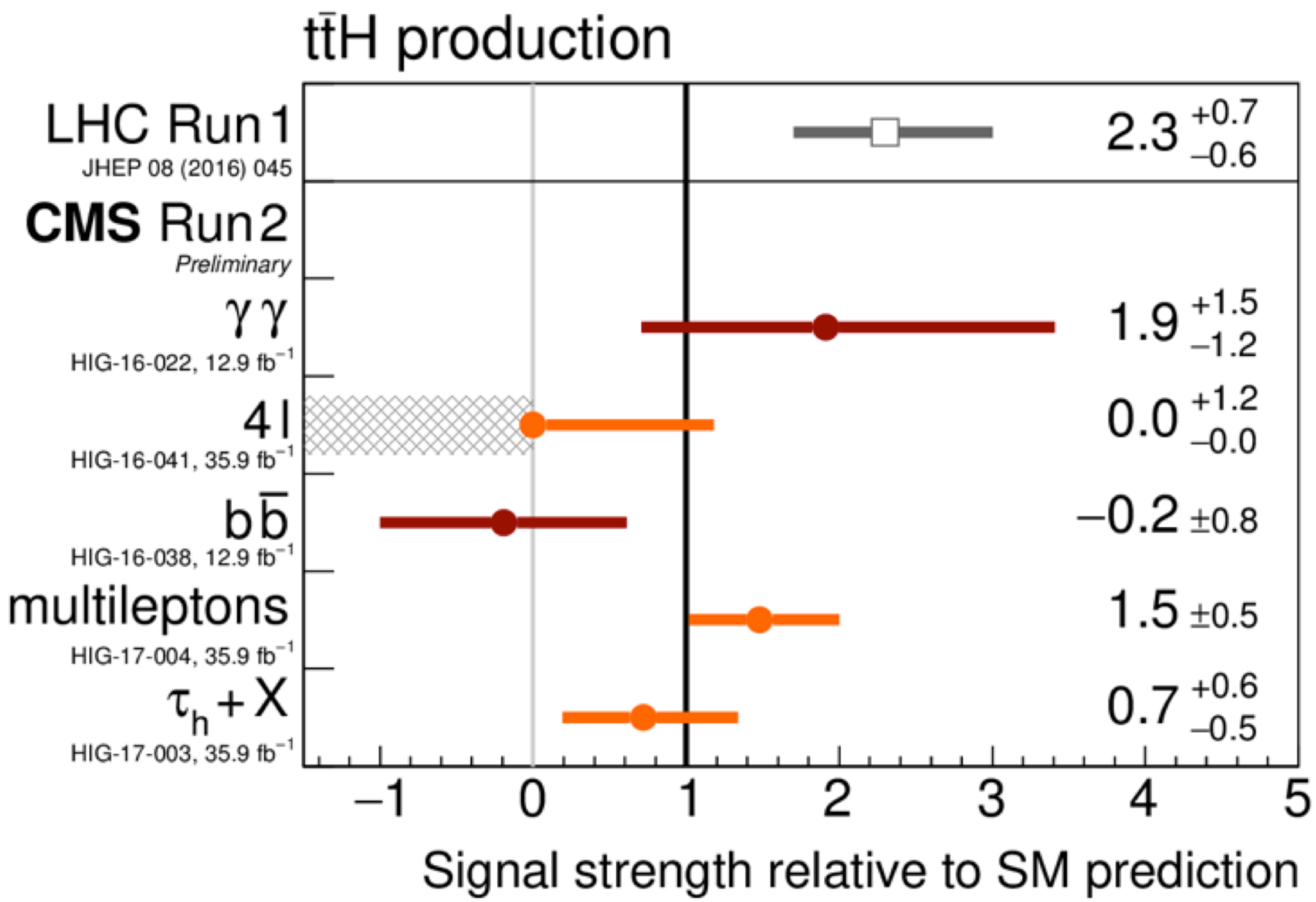


2D plot →1D binning

Signal extraction
Bins with constant S/B

Top-antitop-Higgs - latest results



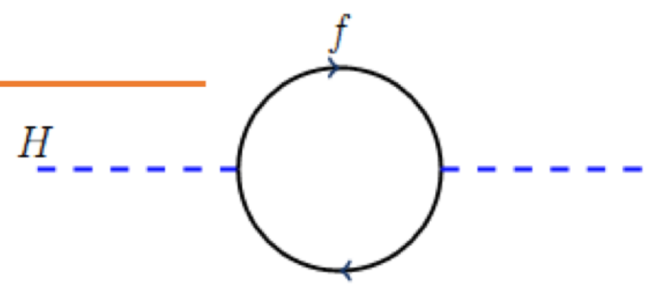


Expected signal strength **μ = 1.0 $^{+0.45\ -0.41}$**, **2.4σ** significance w.r.t. the absence of signal hypothesis

Observed signal strength **μ = 1.5 $^{+0.5 -0.5}$**, **3.3σ** significance, first evidence !

Higgs boson mass is problematic…

$$m_H^2 = (m_H^2)_0 - \frac{|\lambda_f|^2}{8\pi^2}\Lambda_{UV}^2 + \cdots$$



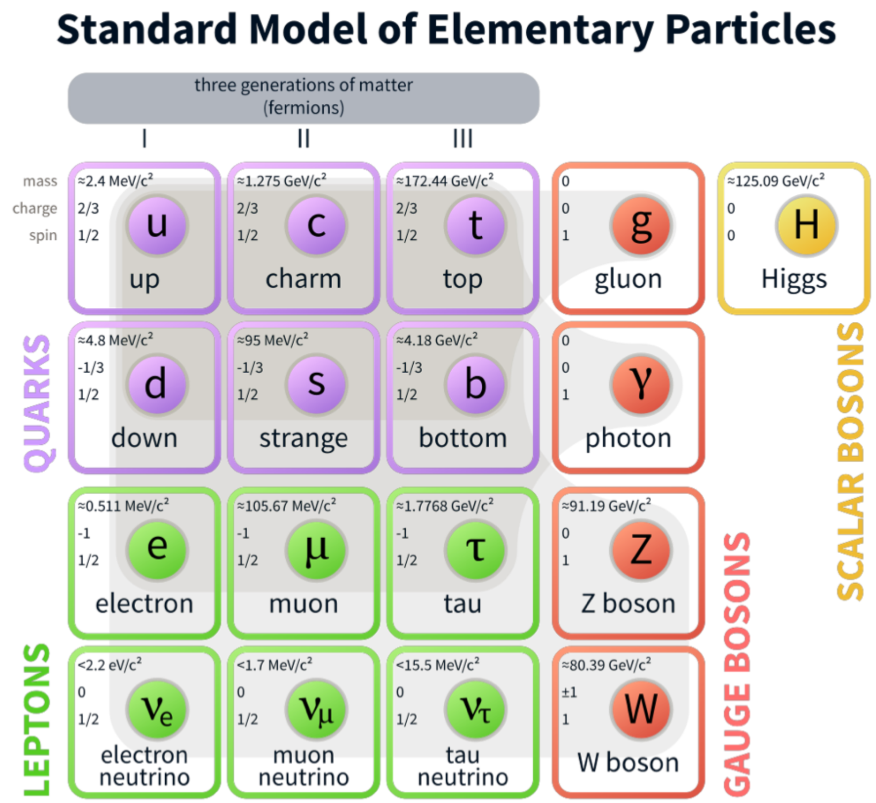
Higgs mass should also get corrections from loops of "virtual" particles.

Λ_{UV} : energy where new physics comes along (Planck scale 10^{19} GeV ?)

$\Lambda^2{}_{UV}$, quadratic term, corrections are important !

How do these corrections cancel out, so that m_H = 125 GeV ?

Supersymmetry



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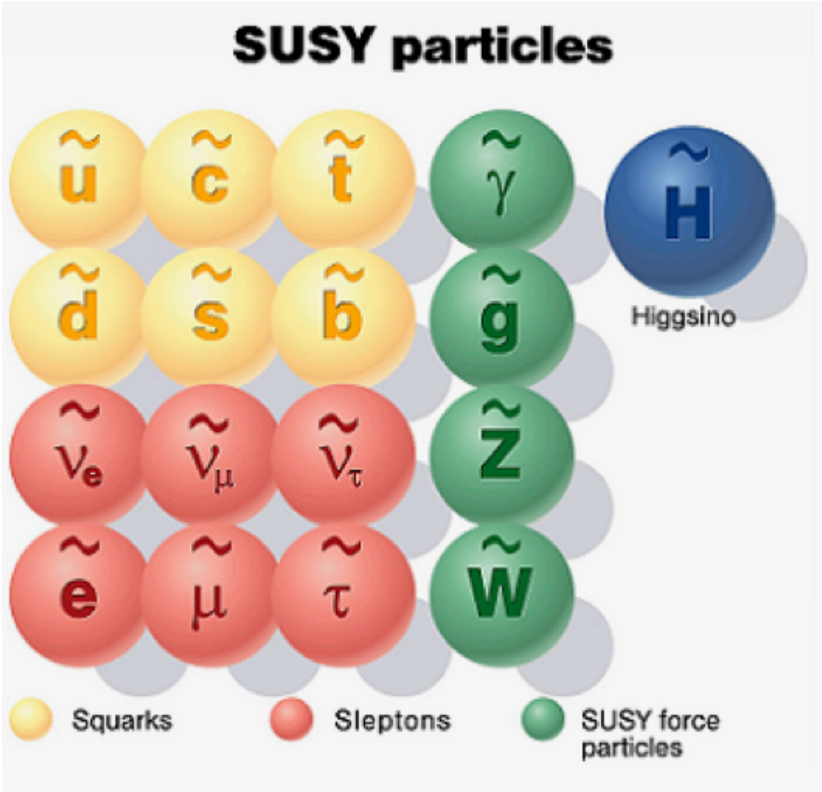


SM bosons:	
gluon ↔ gluino	$\tilde{g}$
W ↔ wino	$\widetilde{W}$
B ↔ bino	$\widetilde{B}$
Higgs ↔ Higgsino	$\tilde{h}$

SM fermions:	
quark ↔ squark	$\tilde{q}/\tilde{q}^*$
top ↔ stop	$\tilde{t}$
bottom ↔ sbottom	$\tilde{b}$
lepton ↔ slepton	$\tilde{l}$

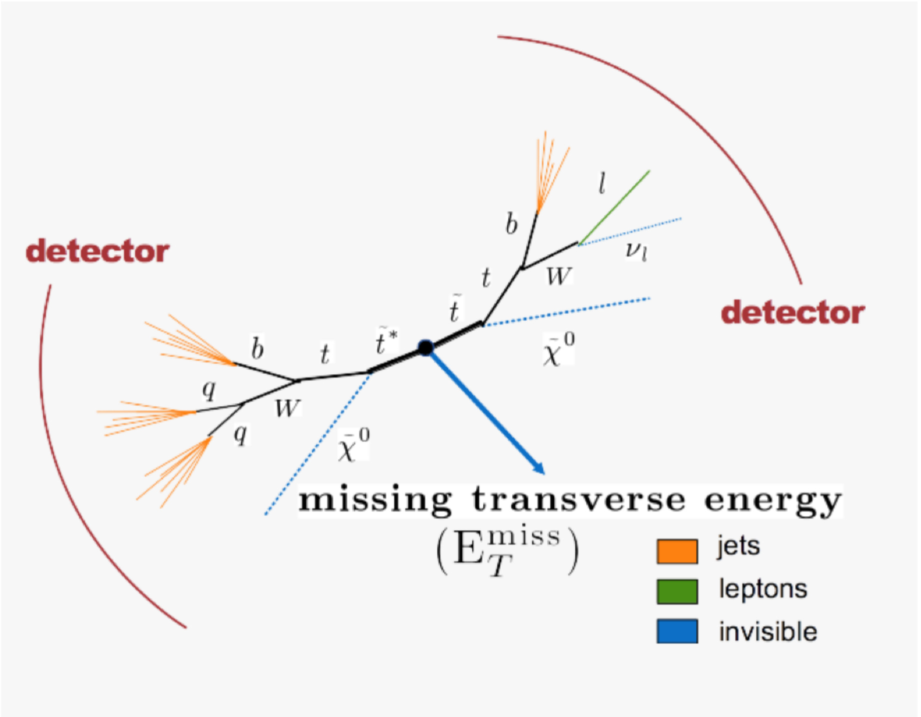
SUSY particles have not been observed.
→ Supersymmetry must be a broken symmetry
→ SUSY particles must have a higher mass

Supersymmertry

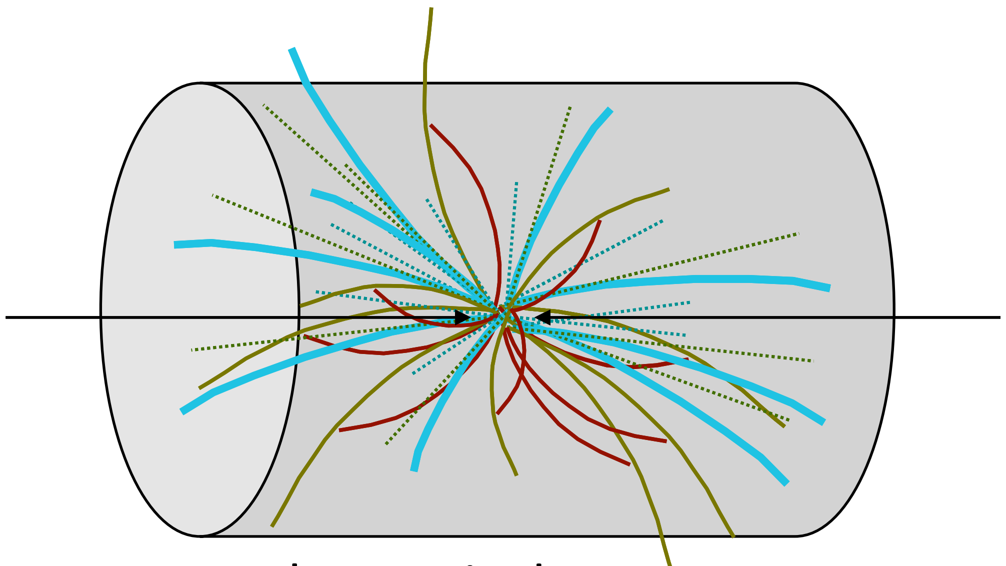
New quantum number introduced: R-parity = $(-1)^{3B+2L+S}$
Else protons would decay…
All SM particles have R = +1, all SUSY particles have R = -1

Consequences:

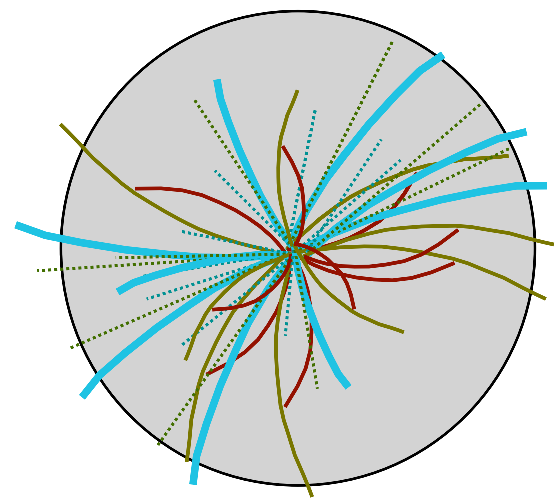
- SUSY particles go in pairs
- If a SUSY particle decays, it has to go to another SUSY particle
- The lightest SUSY particle (LSP) is completely stable



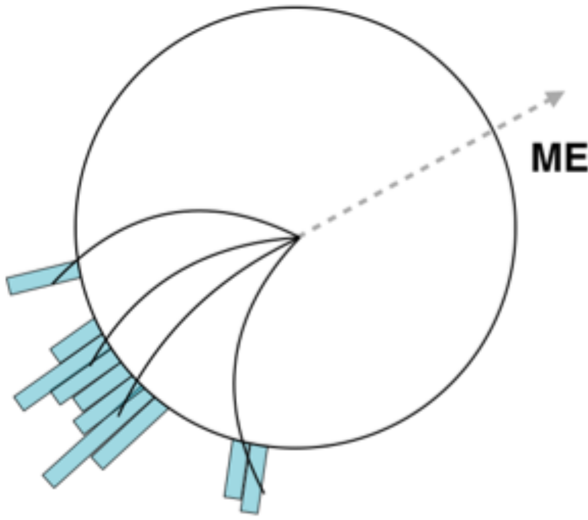
Key ingredient: missing transverse energy (MET)



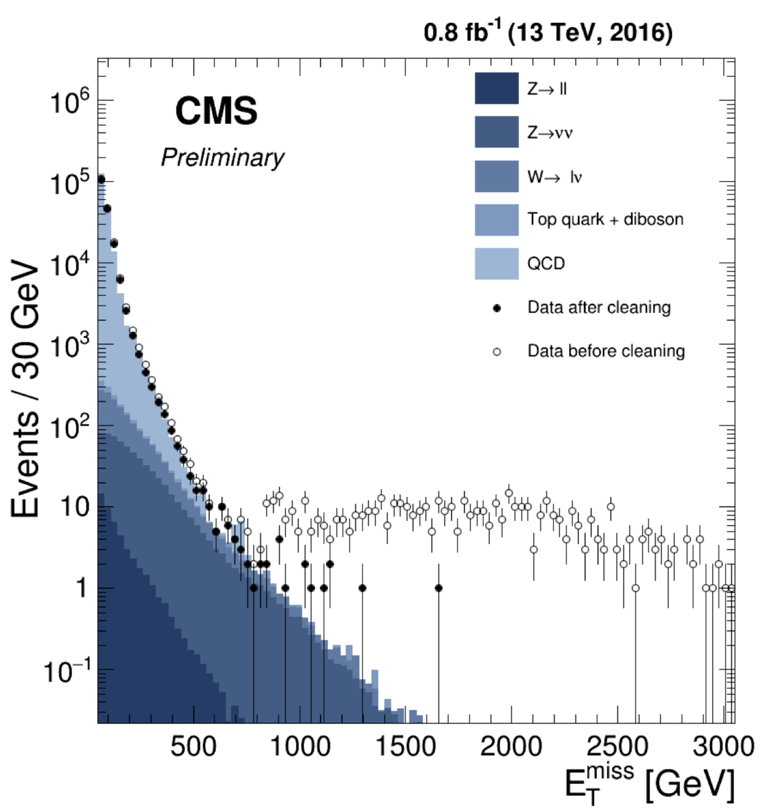
hermetic detector



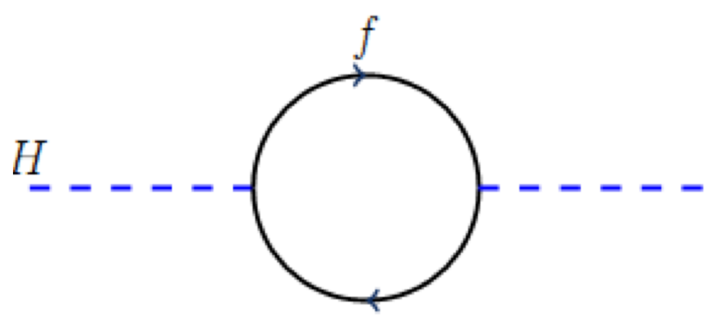
energy balance in transverse plane



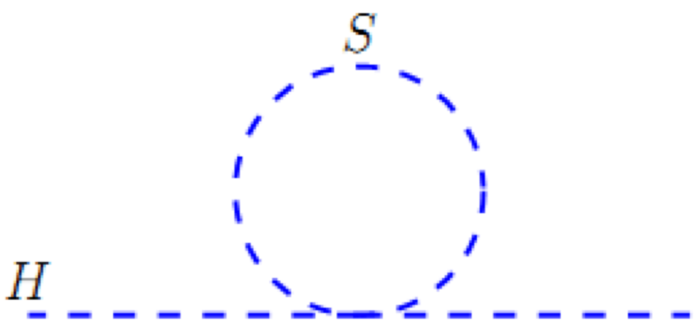
$\vec{MET} = -\Sigma\vec{E}_T$(measured)



Higgs boson mass is problematic…



$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{UV}^2 + \cdots$$



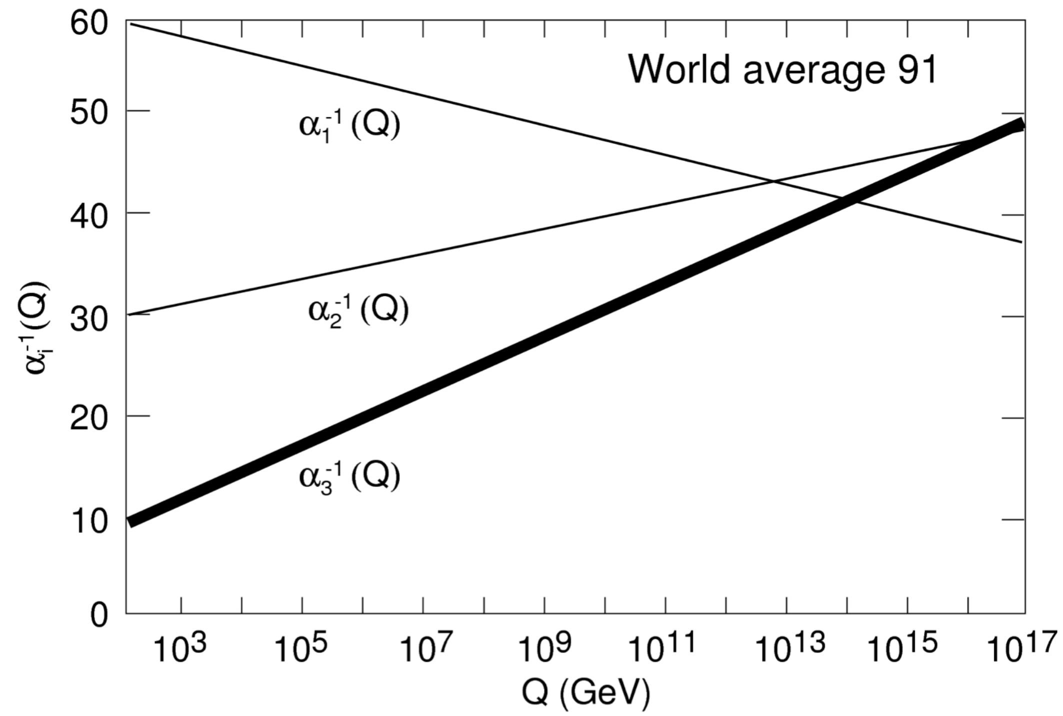
$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}\Lambda_{UV}^2 + \cdots$$

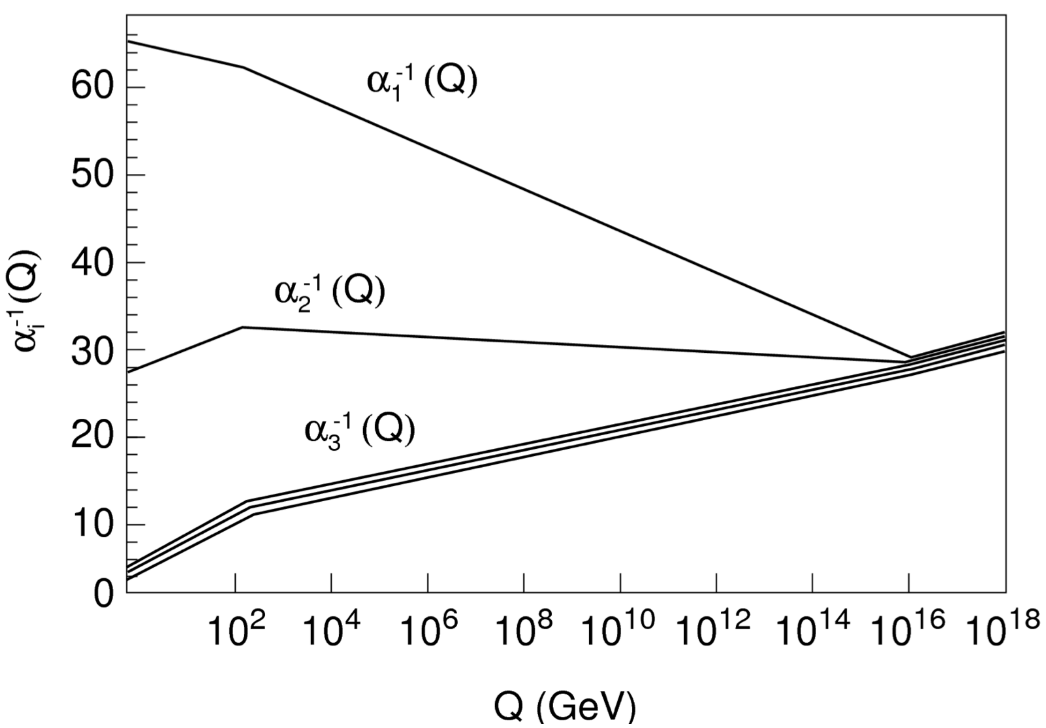
Higgs bosons mass: additional correction with opposite sign from SUSY particle.

Λ_{UV}: mass scale of the new SUSY particles ?

Mass scale of SUSY particles needs to be ~ 1—2 TeV, so that SUSY remains “natural”.

Other reasons to search for supersymmetry ?

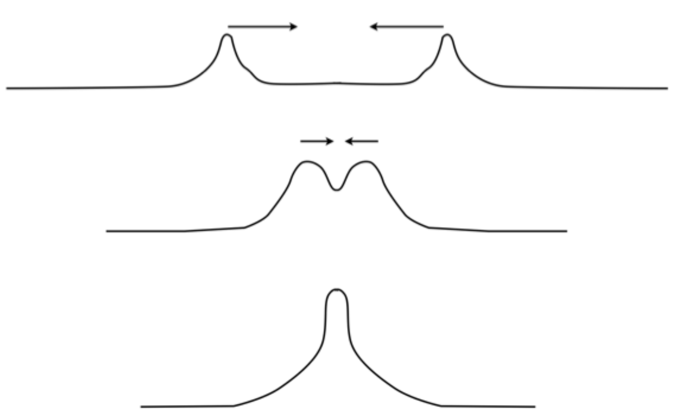




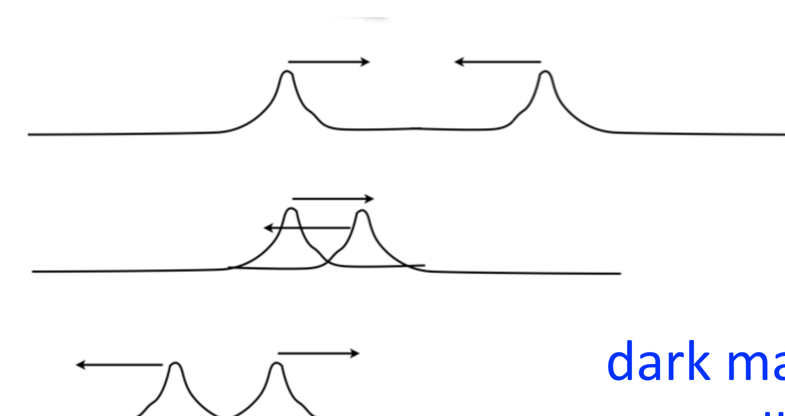
Other reasons to search for supersymmetry ?

LSP could be an excellent dark matter candidate :

- neutral
- weakly-interacting
- completely stable



Gas interacts



dark matter is non collisional

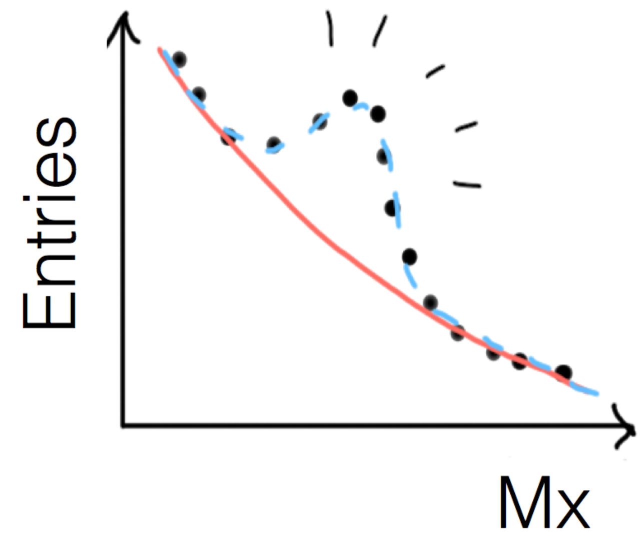
Heavy resonances - bump searches…

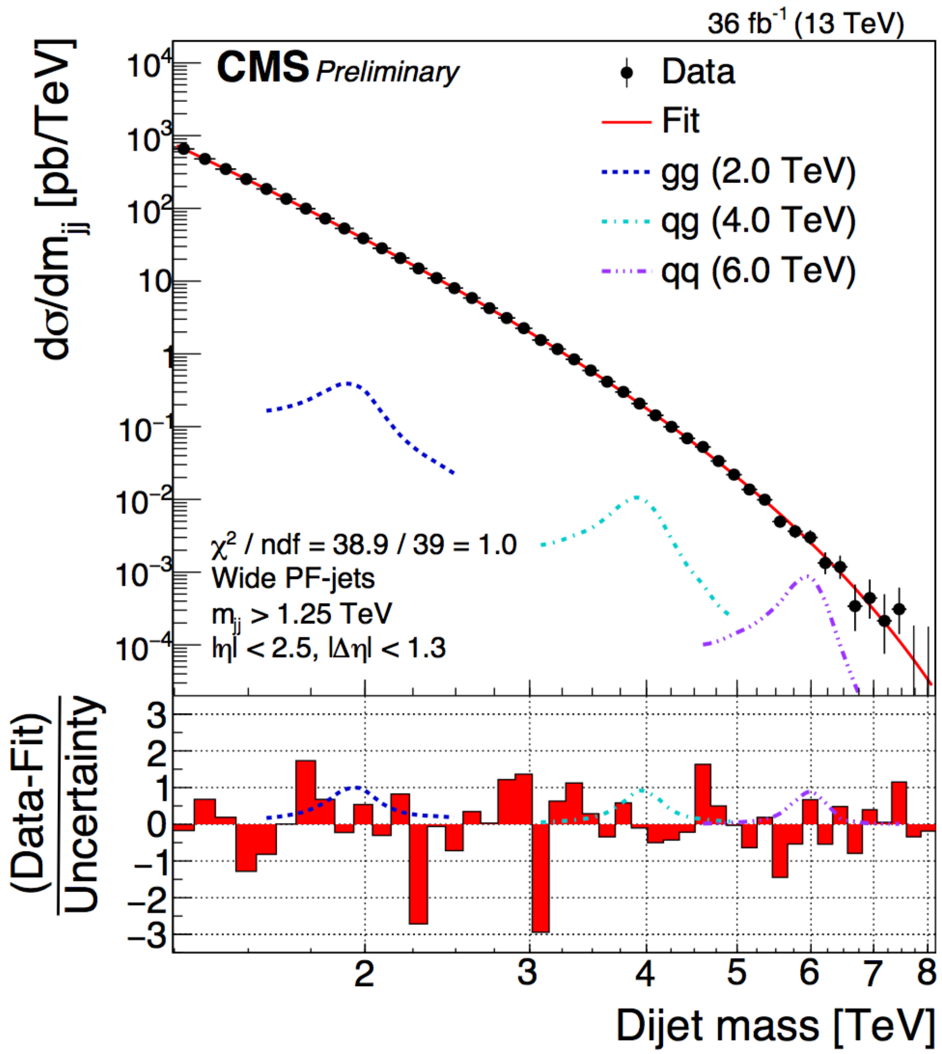
Select final state objects: electrons, muons, taus, photons, jets…

Form invariant mass of the objects (or transverse mass…)

Model independent: for a given mass put limit on cross section.

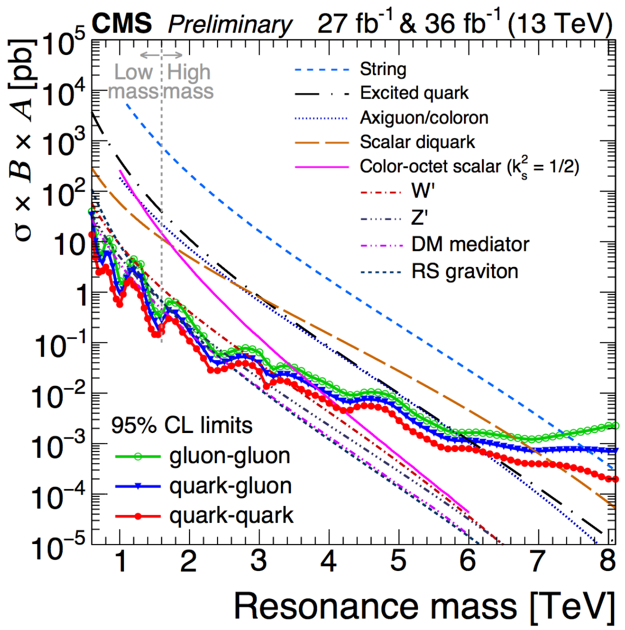
Or model dependent: cross section limit is turned into mass limit.





Electrons, muons, photons provide the cleanest channels.

But many BSM physics include resonances that decay to di-jets.

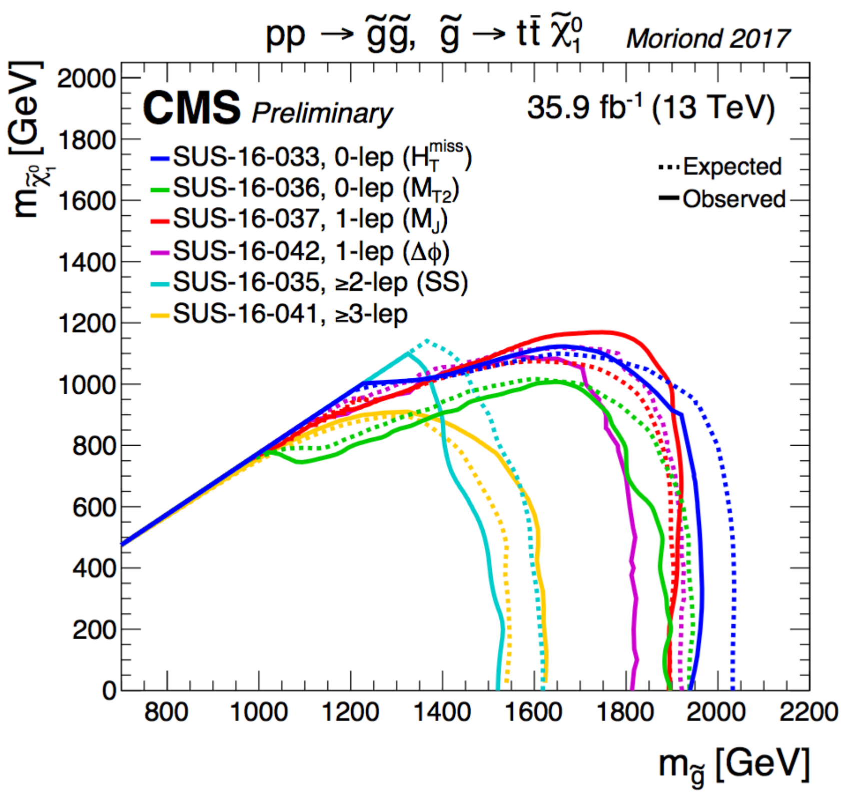


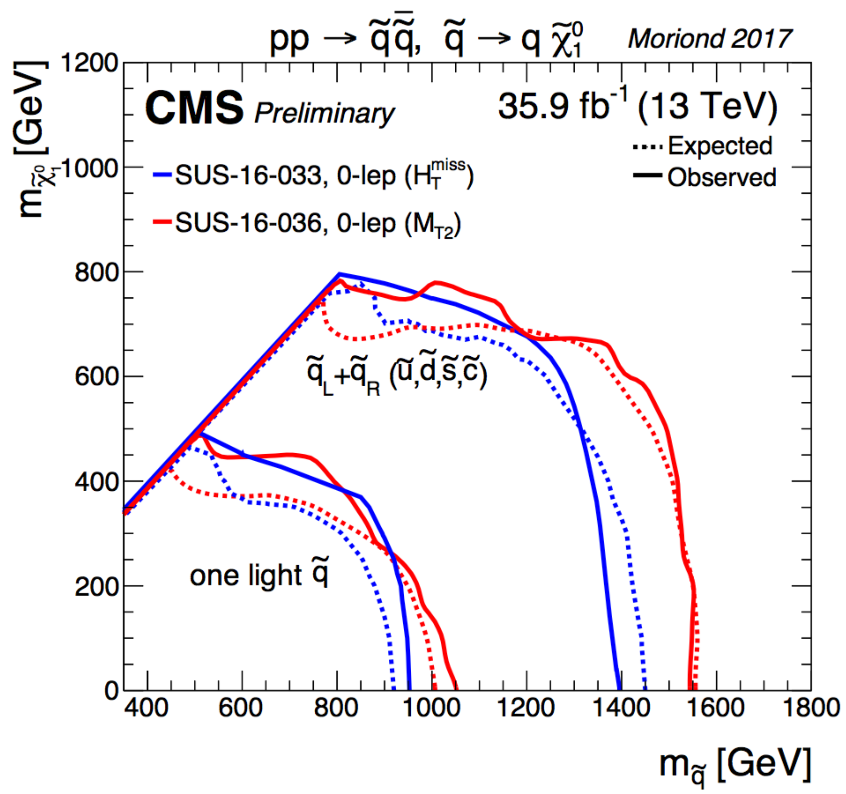
Supersymmetry - strong production

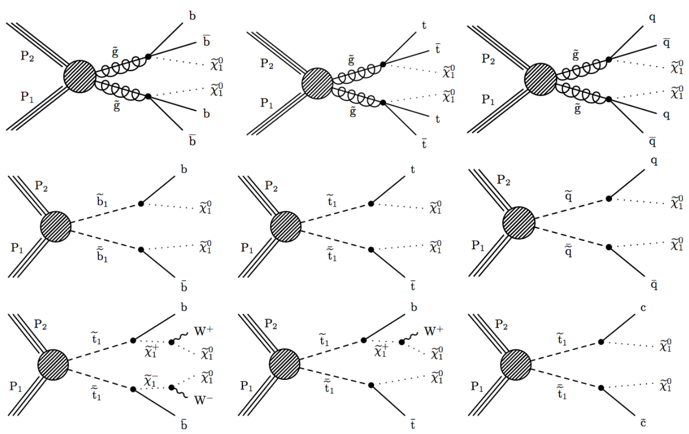
Simplified models of SUSY assumed, specific final state assumed, branching fractions…

High jet multiplicity is expected from strong production.

Flagship analyses : 0, 1, 2, and three or more leptons, high jet multiplicity and significant ME_T.







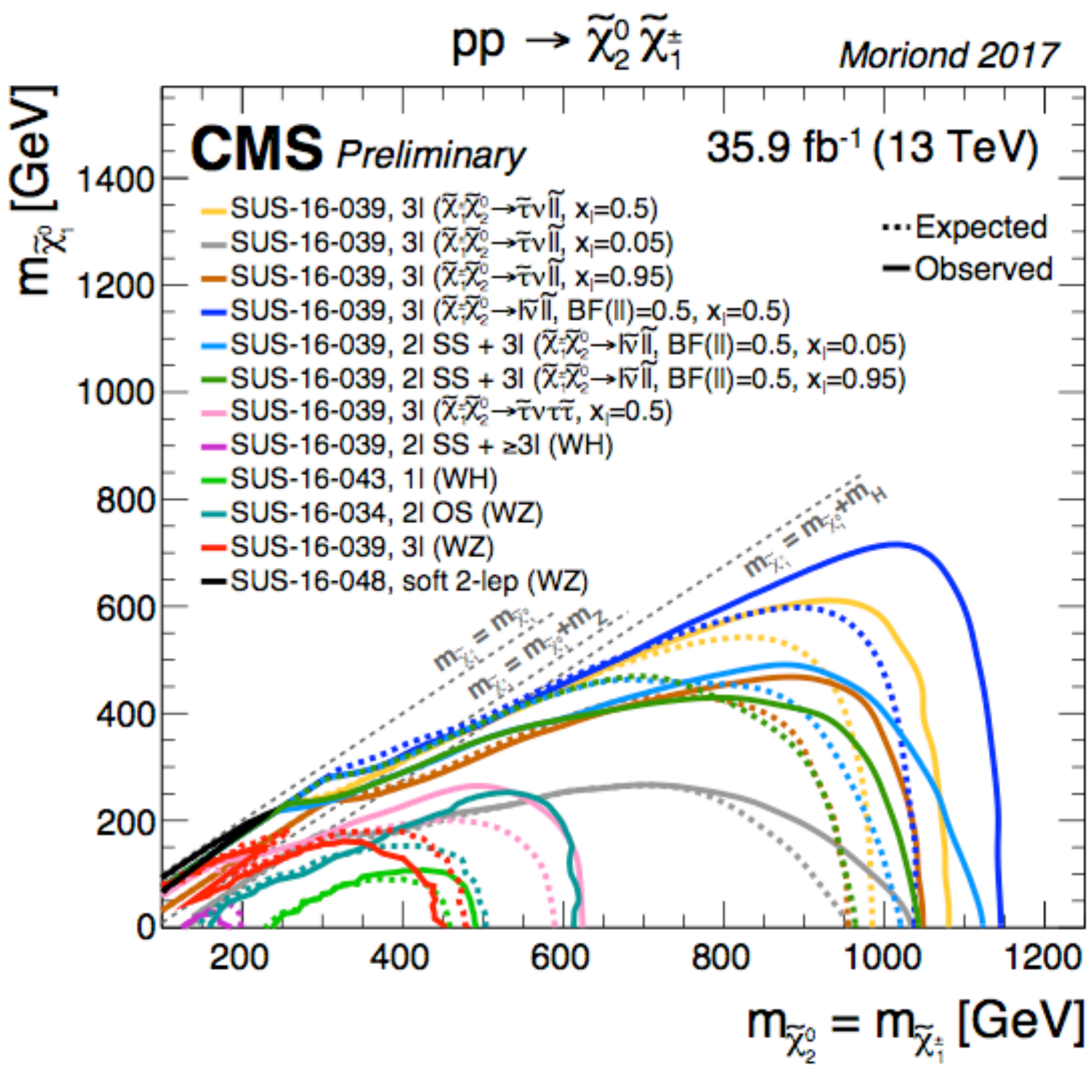
Gluino pair production decaying to tops: gluino masses up to **about 2 TeV excluded**.

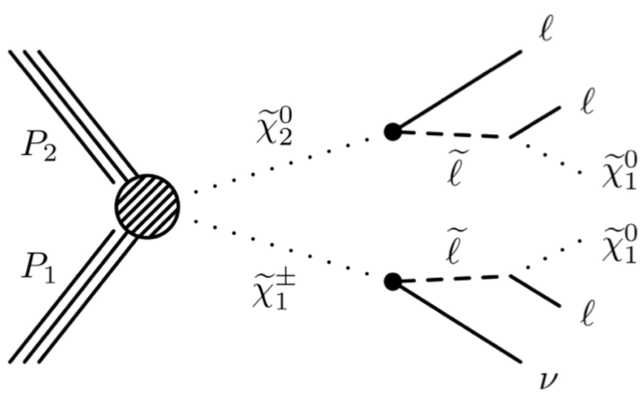
Squark pair production: **masses up to 1.5 TeV** excluded.

Supersymmetry - electroweak production

If **squarks and gluinos too heavy,** EWK production may be the only accessible production mechanism.

Searches **target chargino-neutralino production** decaying via sleptons (and then leptons) or via W, Z or H bosons (R-parity conserving models).





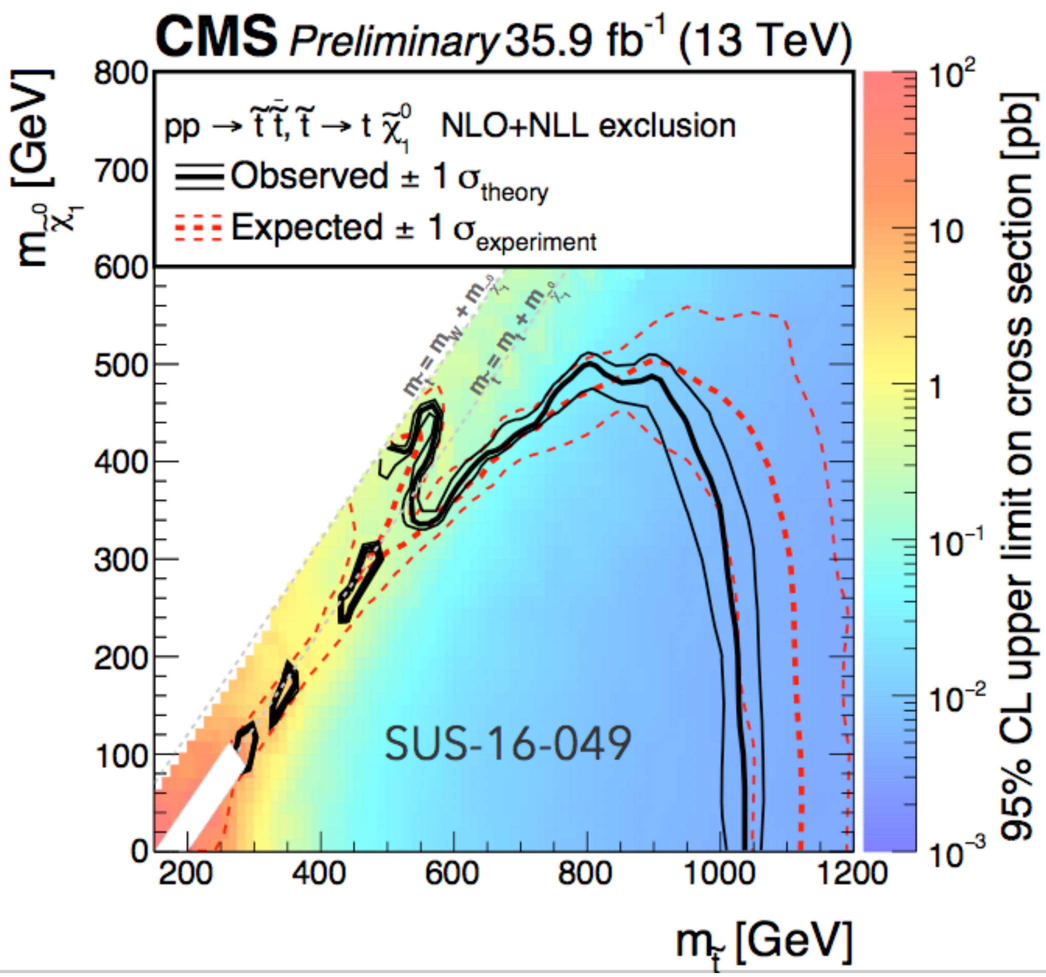
Neutralino 2, chargino 1 masses excluded up to **1.2 TeV**.

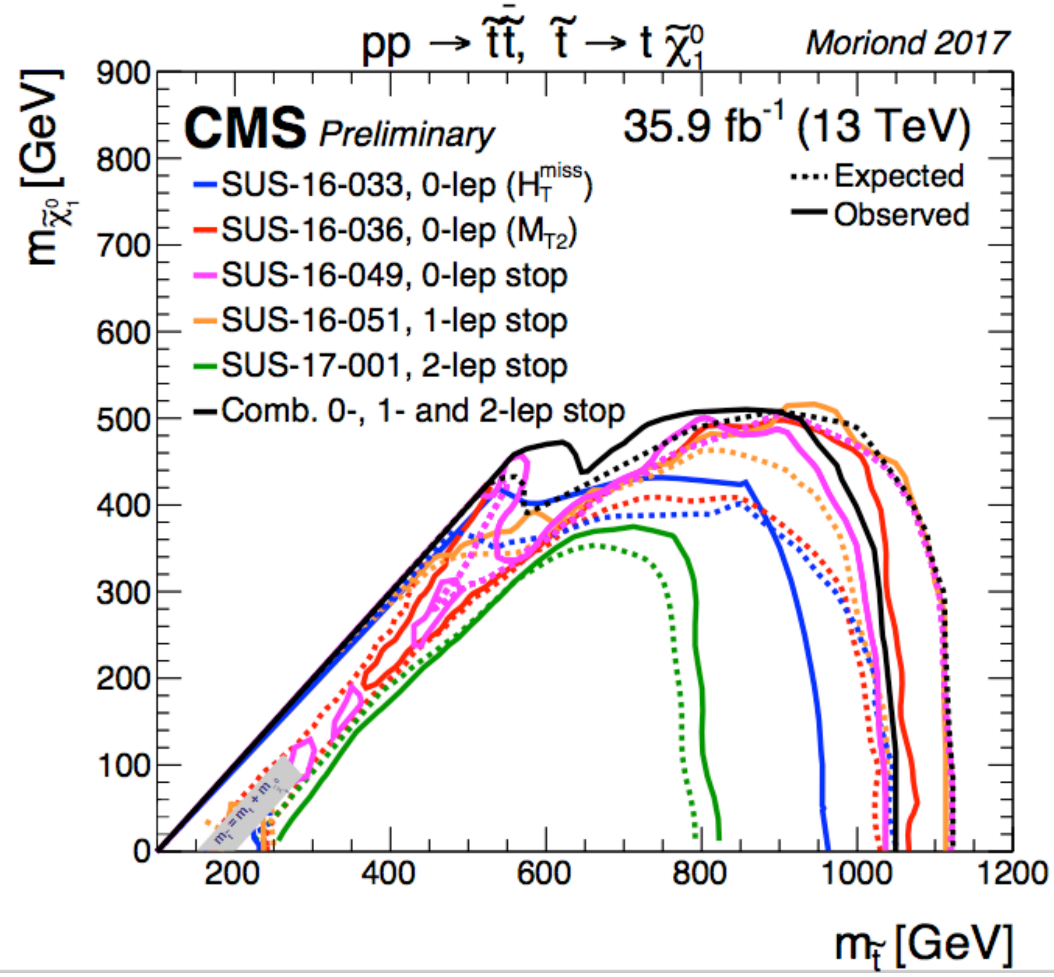
Supersymmetry - stop searches

Top quarks are very important in SUSY searches.

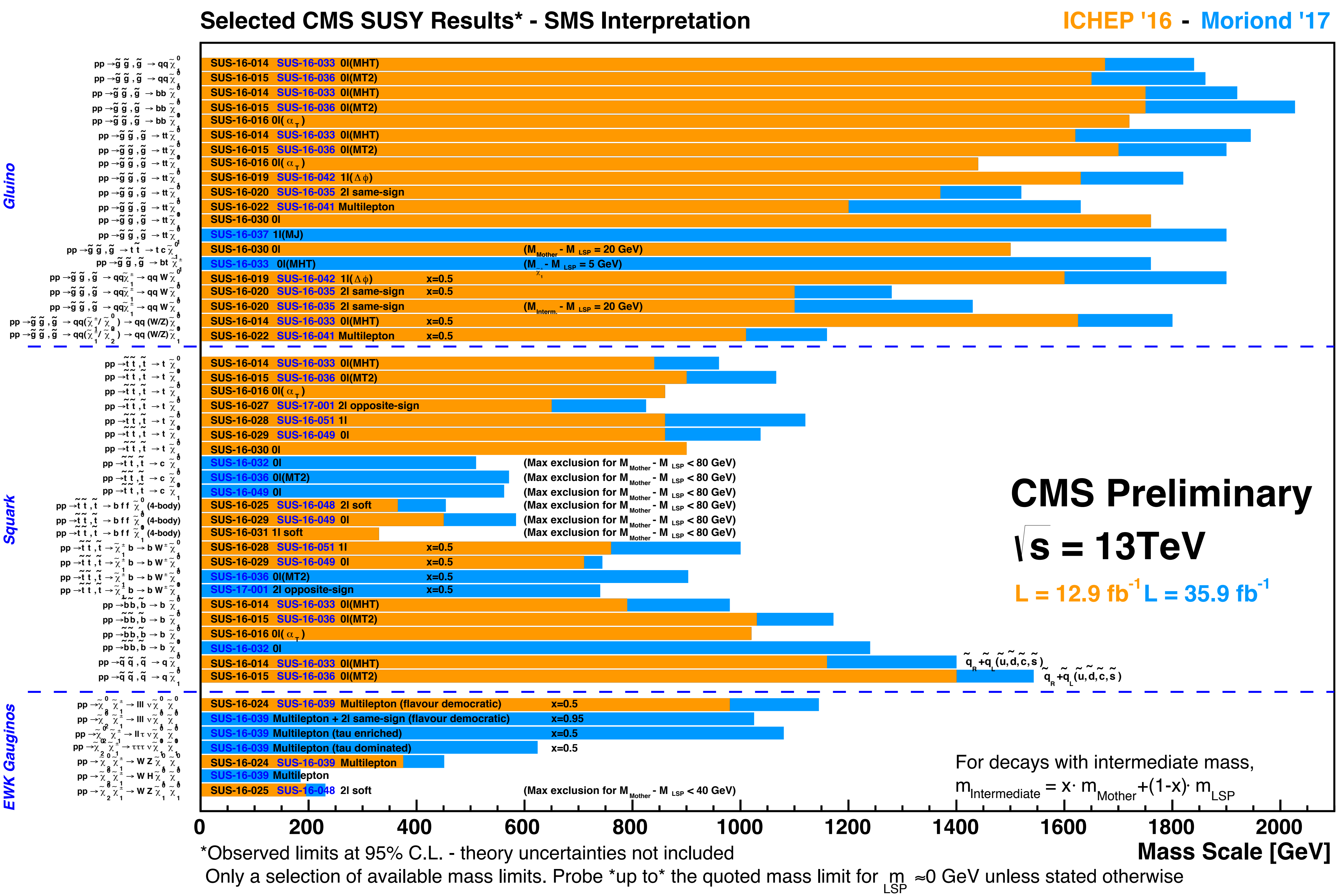
Stop expected to be light, cf “natural” SUSY.

Direct stop searches: stop excluded up to **1.1 TeV**.

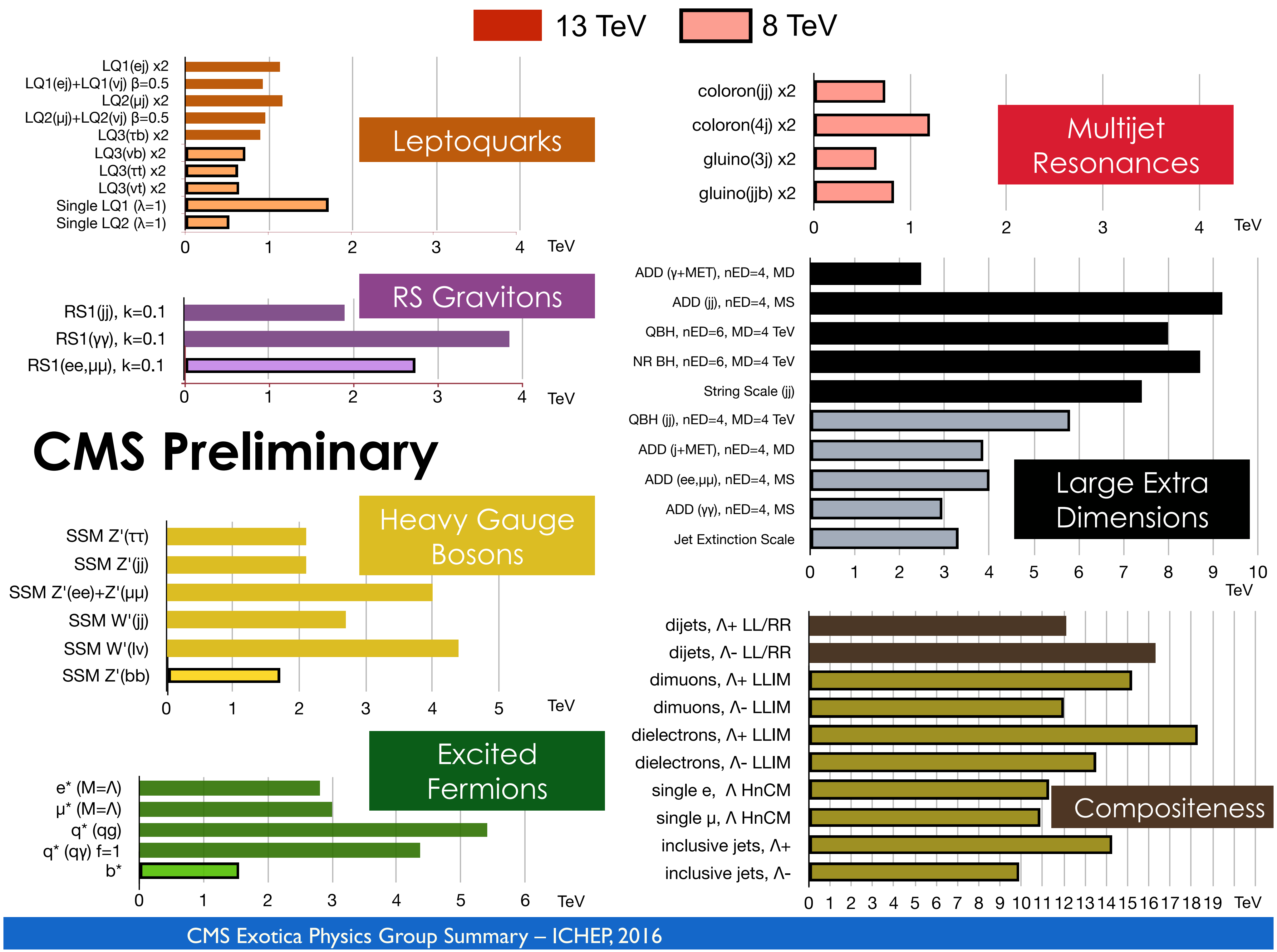




Supersymmetry

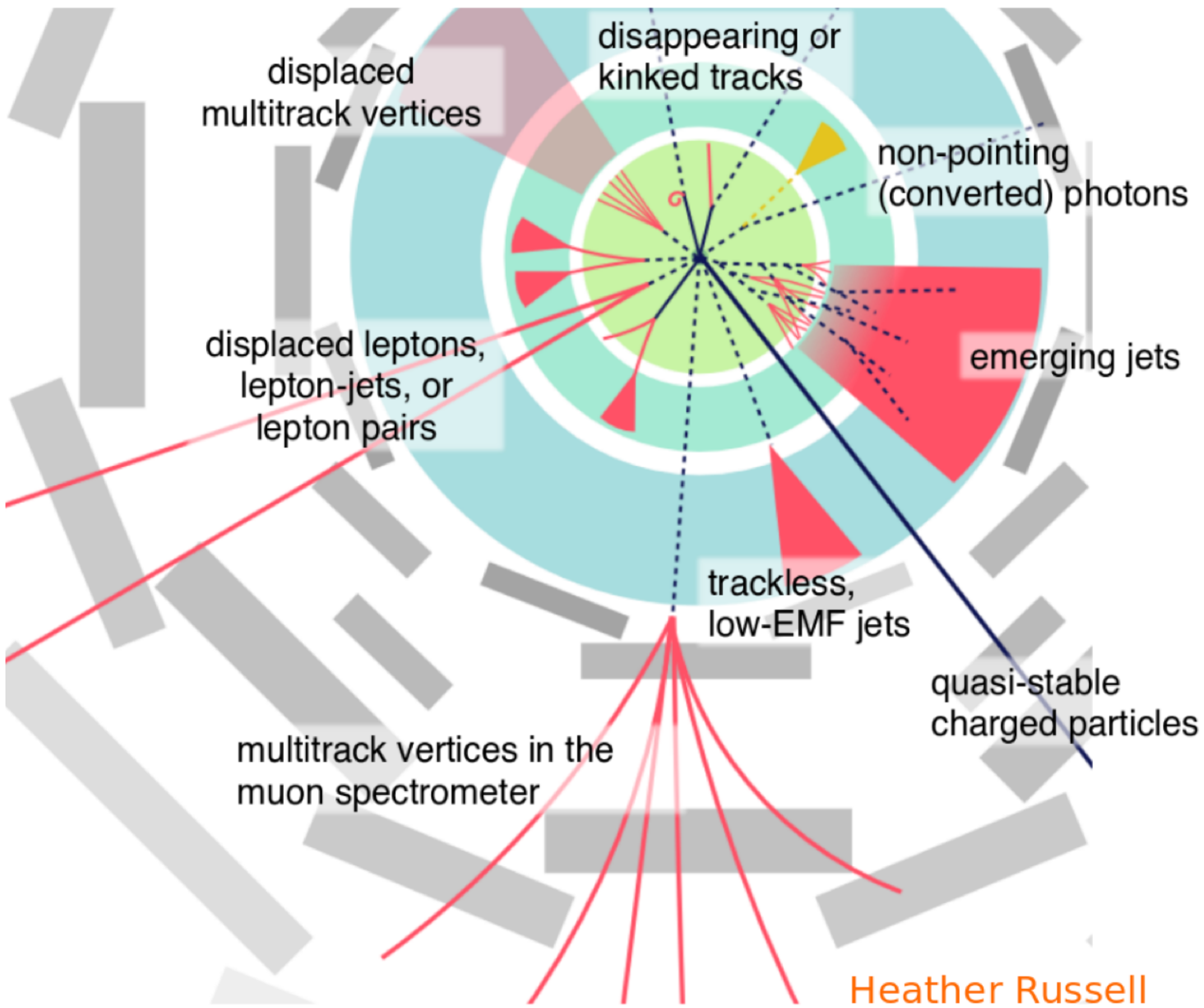


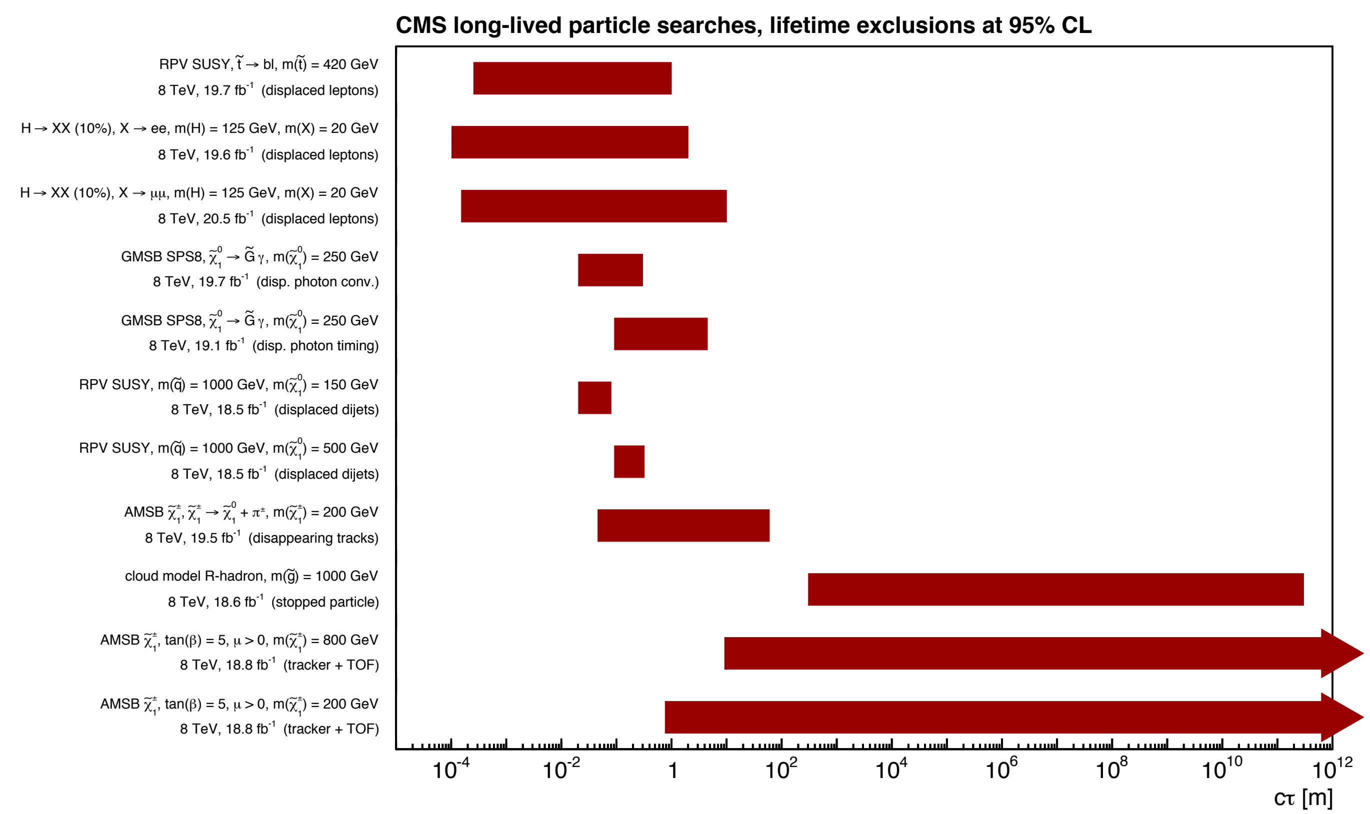
“Exotic searches”…



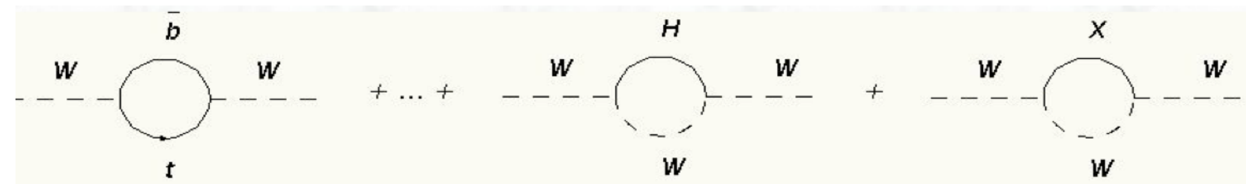
Long lived particles

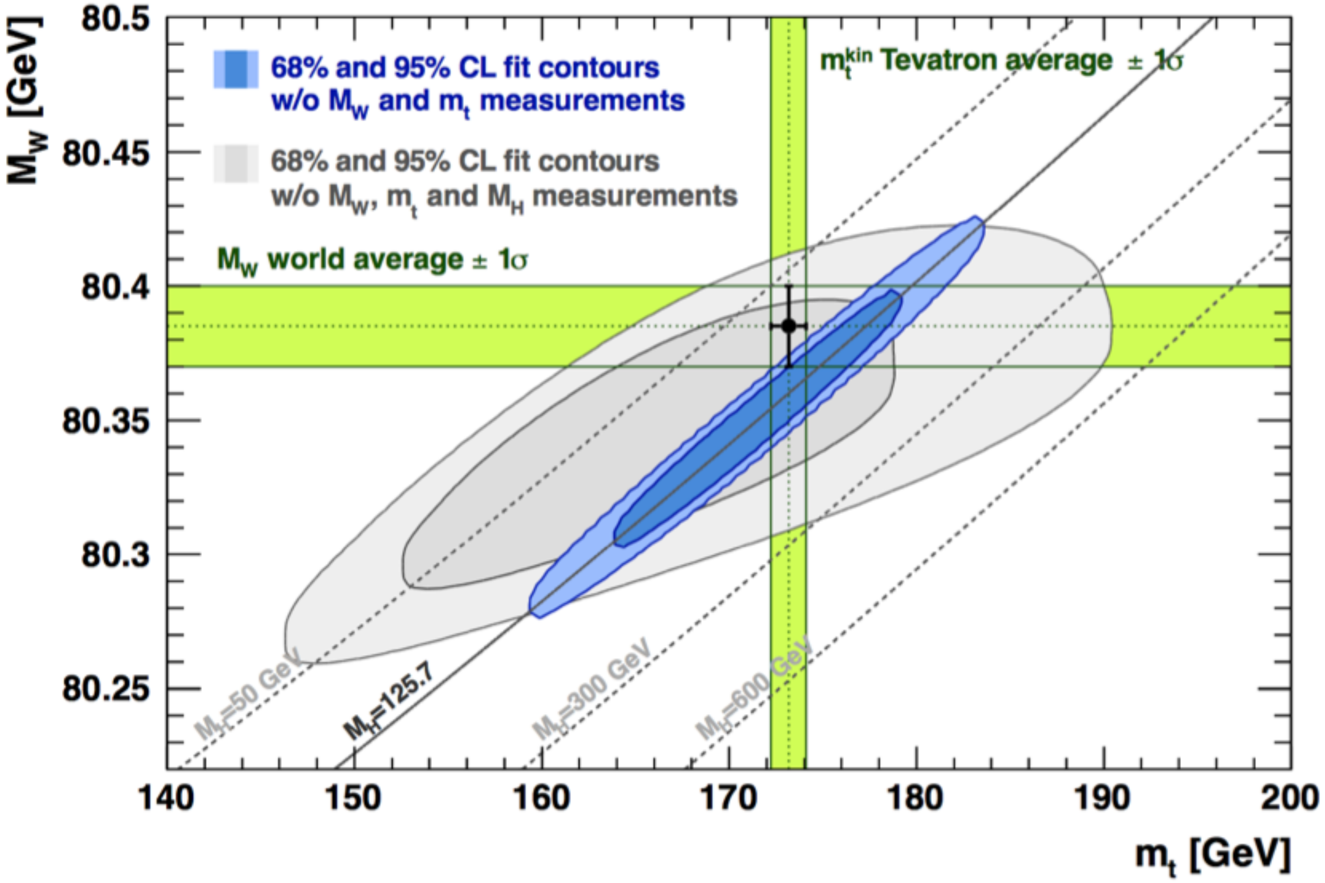
Many different signatures possible, many dedicated searches needed, with specialised triggers…

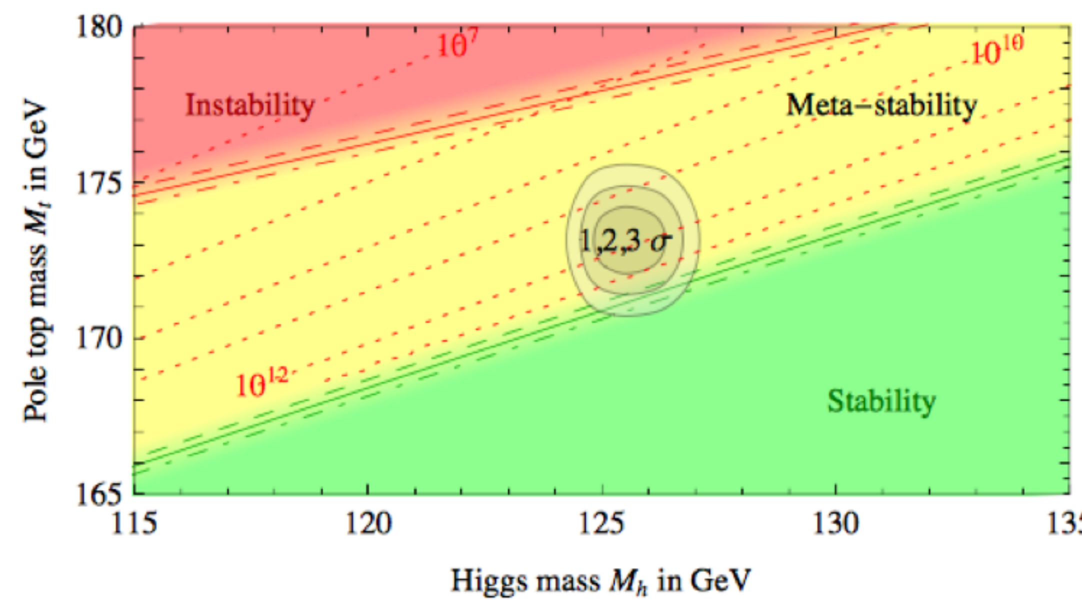




Other ways to search for physics beyond the Standard Model ?
“Precision physics”…



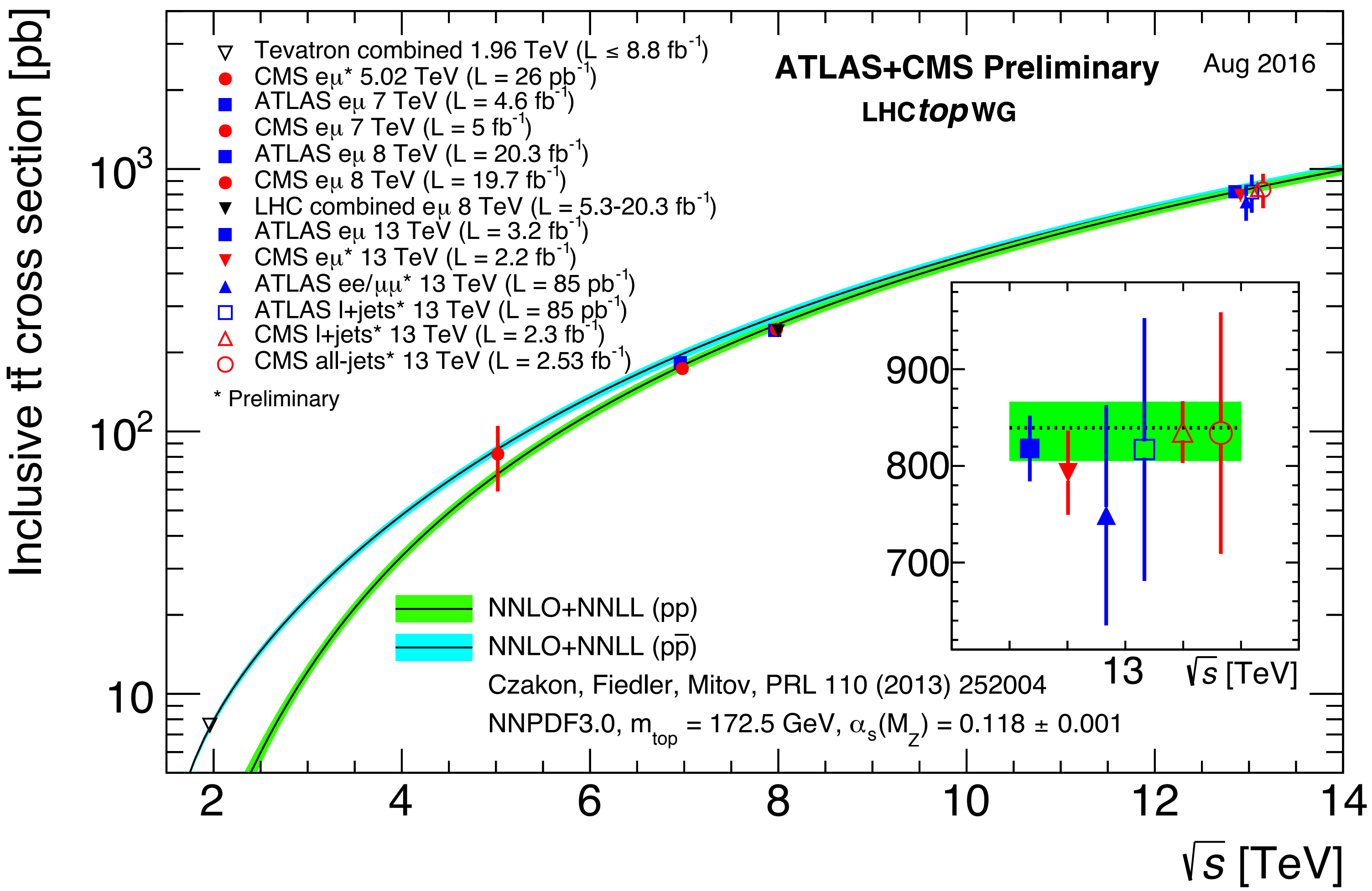


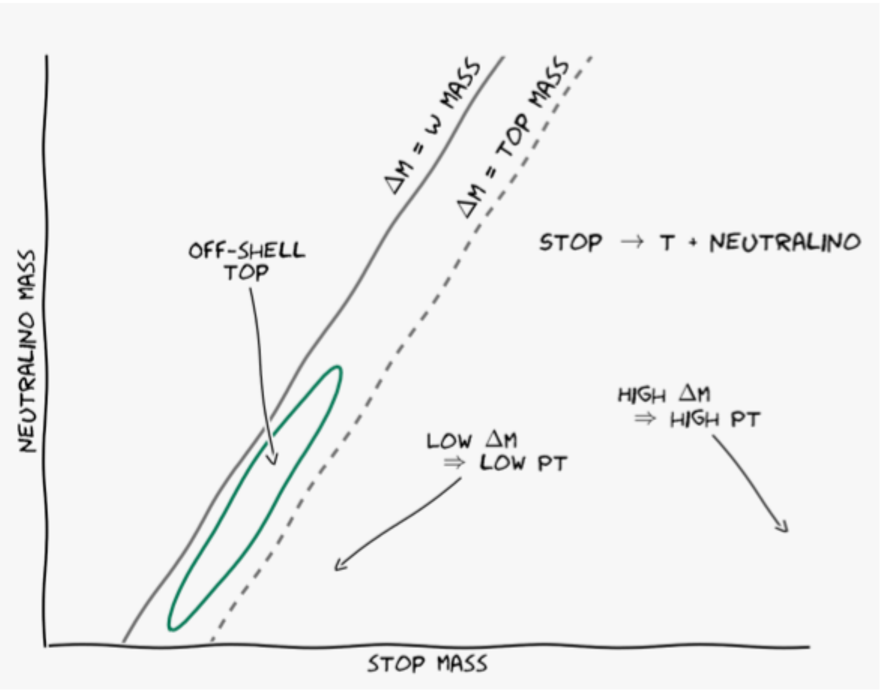


New measurement of M_W by ATLAS: 80369.5 ± 18.5 MeV !

M_{top} measured with 0.5% accuracy, but still third systematic in $B_S \rightarrow \mu\mu$ searches,
plays a role to understand if the Higgs potential is stable or metastable, indirect W mass measurement…

Other ways to search for physics beyond the Standard Model ?
"Precision physics"…





Use the top-antitop cross section to search for stop pair production where the stop mass is close to the neutralino 1 + top mass.

Other ways to search for physics beyond the Standard Model ?
One example in the Higgs sector…

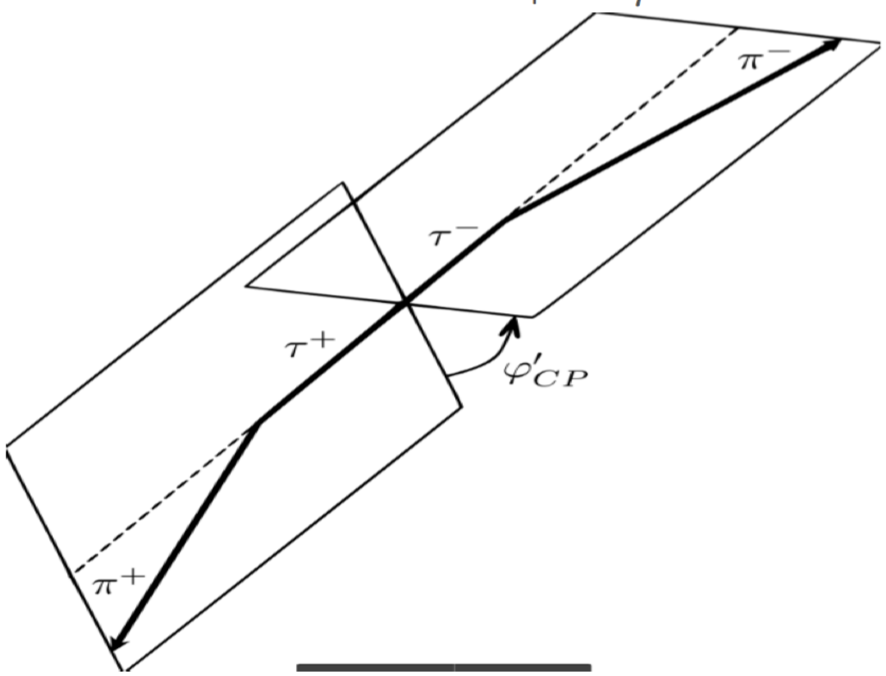
CP violation in Higgs coupling to fermions ?

$$\mathcal{L}_Y = g_\tau(\cos\alpha_\tau \bar{\tau}\tau + \sin\alpha_\tau \bar{\tau}\gamma_5\tau)$$

$\alpha_\tau \neq 0$?

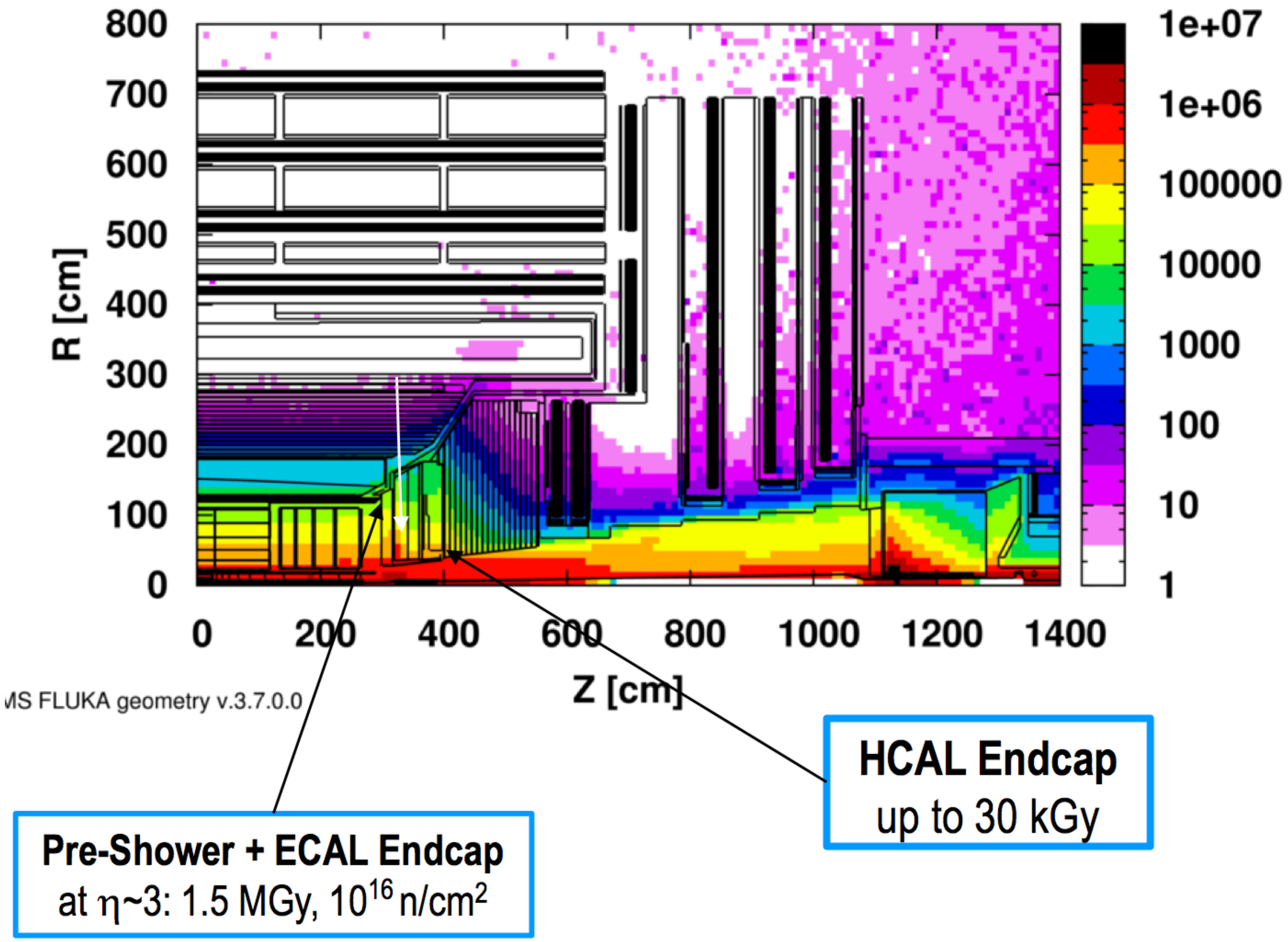
Study tau spin observables in Higgs decays.

$h \to \tau^-\tau^+ \to \pi^-\pi^+ + 2\nu_\tau$



S. Berge, arXiv:1308.2674

HL-LHC phase 2 (2026 - 2035)

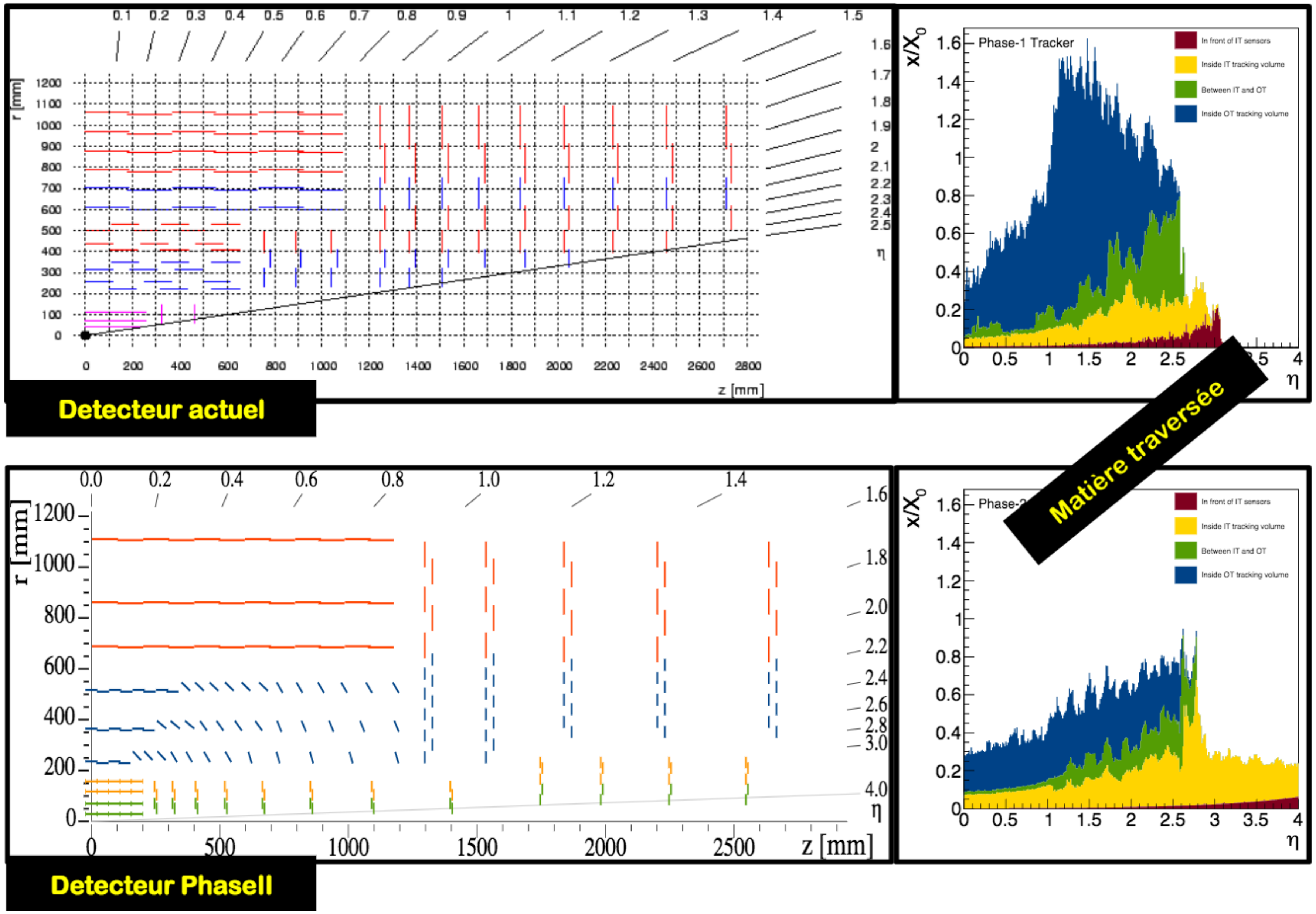


Tracker and forward calorimeter need to be replaced !

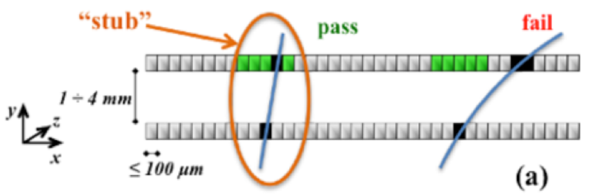
HL-LHC: 140-200 pile-up events per bunch crossing (x 5 LHC)
Instantaneous luminosity : $5e^{34}$ $cm^{-2}.s^{-1}$ (x 2-3 LHC)

HL-LHC phase 2

New tracker !

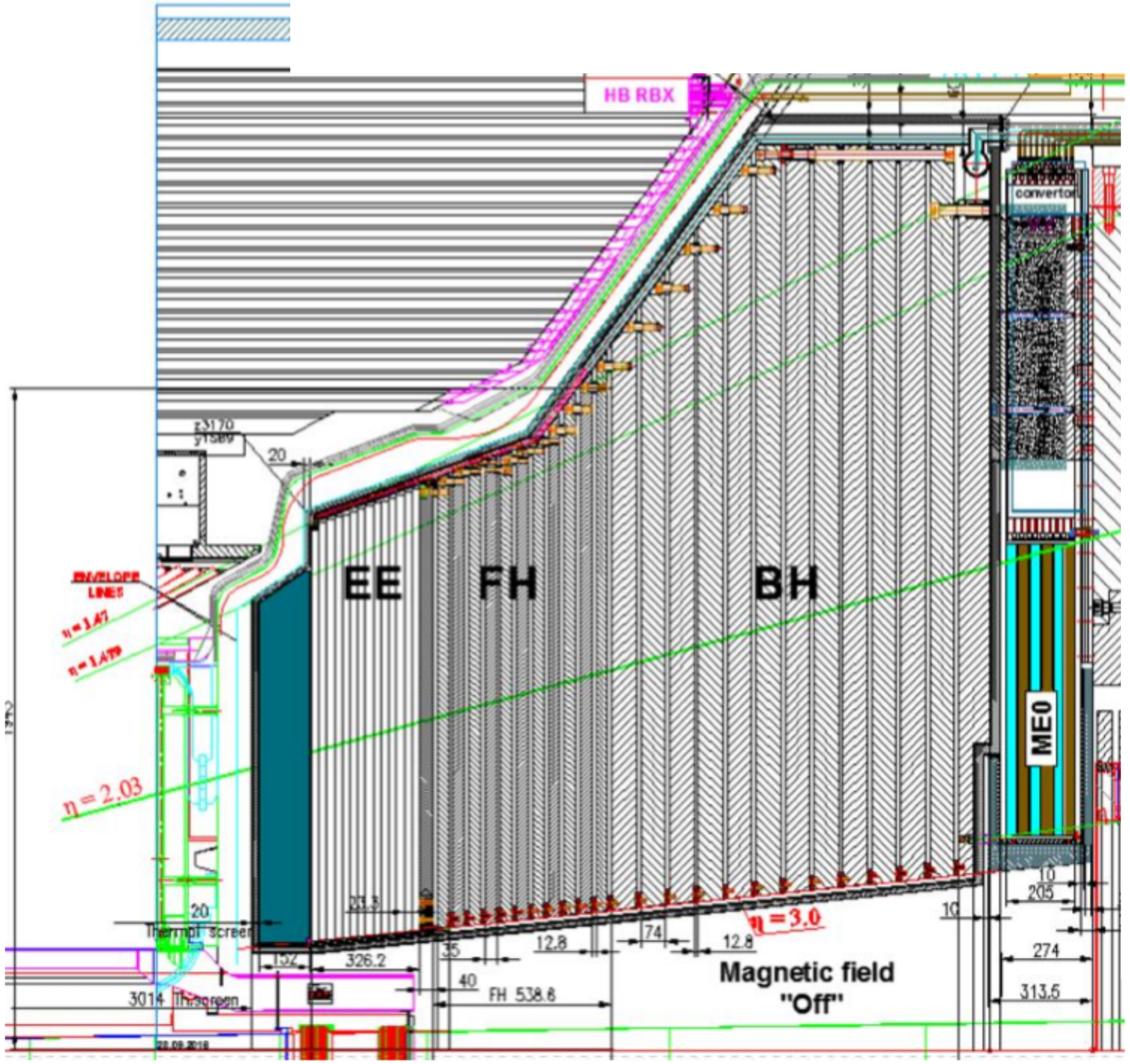


New strategy !
Include tracker information in first trigger level !



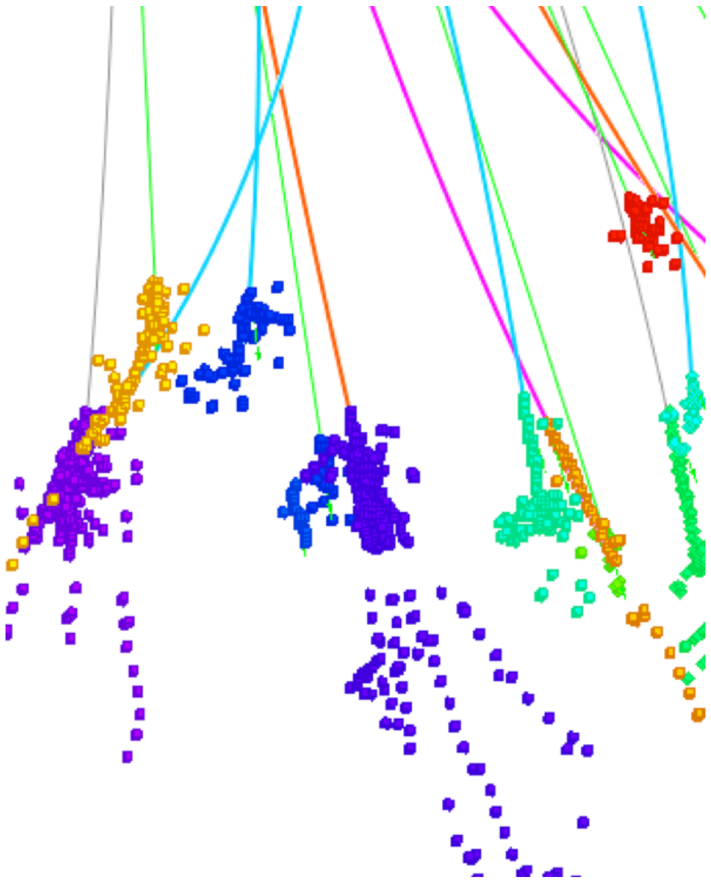
HL-LHC phase 2

HGCAL: high granularity forward calorimeter $1.5<|\eta|<3$
6M Si channels (x 100 CMS calorimeter)



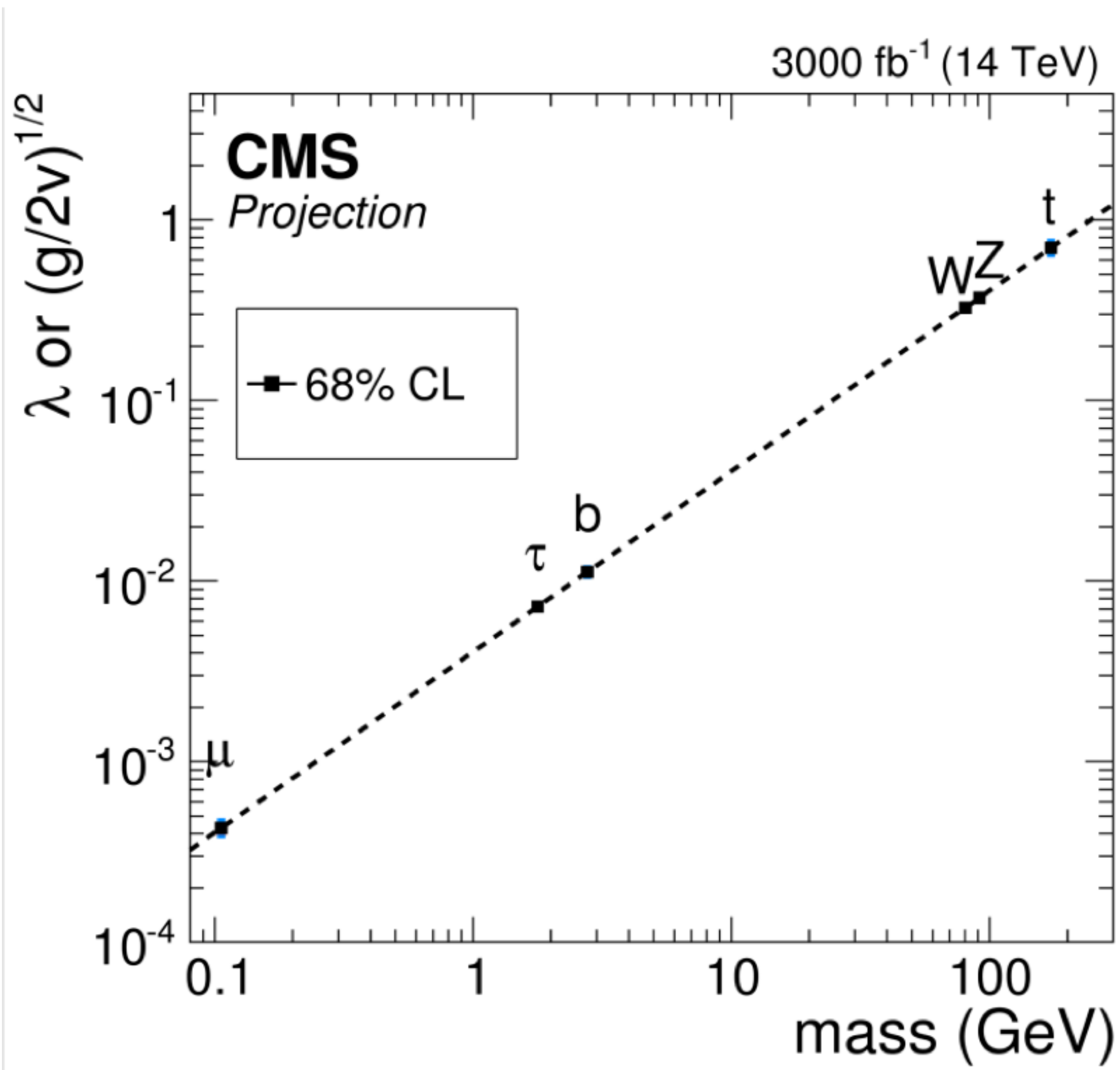
Energy
3D position
50 ps time resolution

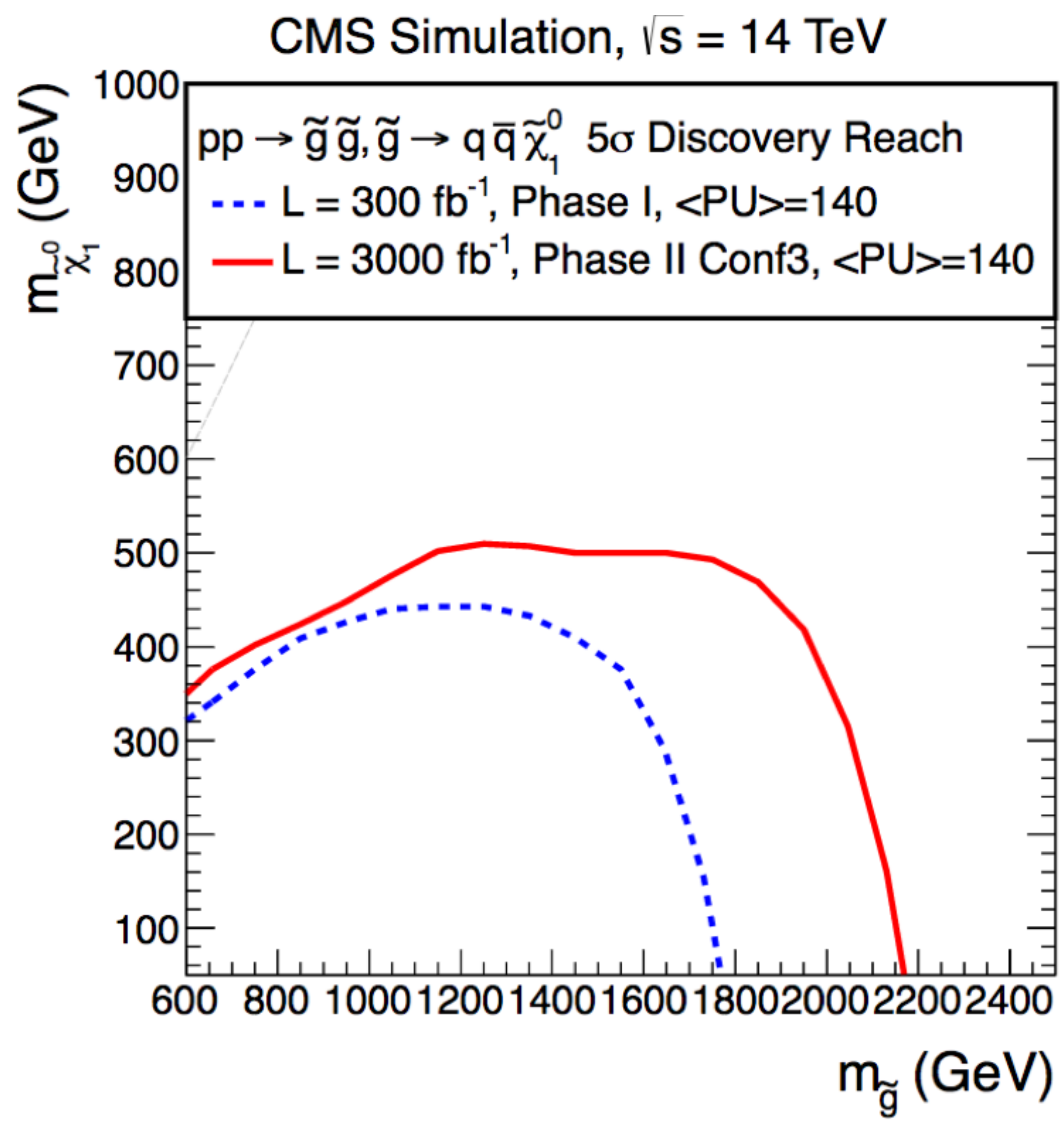
Operated at -30 deg



High granularity + timing will allow to deal with pile-up and background rejection : p-flow !

What physics at HL-LHC ?





Observe Higgs self-coupling: HH observation
Observe rare decays: $\mu\mu$, $Z\gamma$
Search for forbidden decays: $\mu\tau$…

Search for SUSY, dark matter,
other Higgs bosons…