ATLAS EXPERIMENT

Run 166466 Event 26227945

Time 2010-10-07 22:16:39 UTC

μ^-

e

Recent Results from the LHC

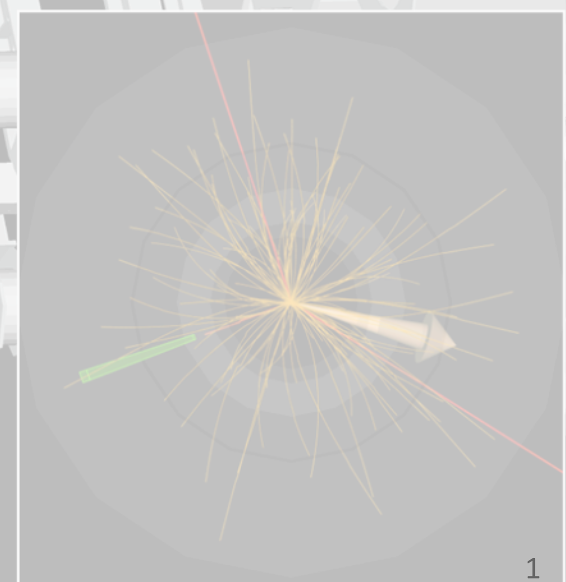
Norbert Wermes

Universität Bonn

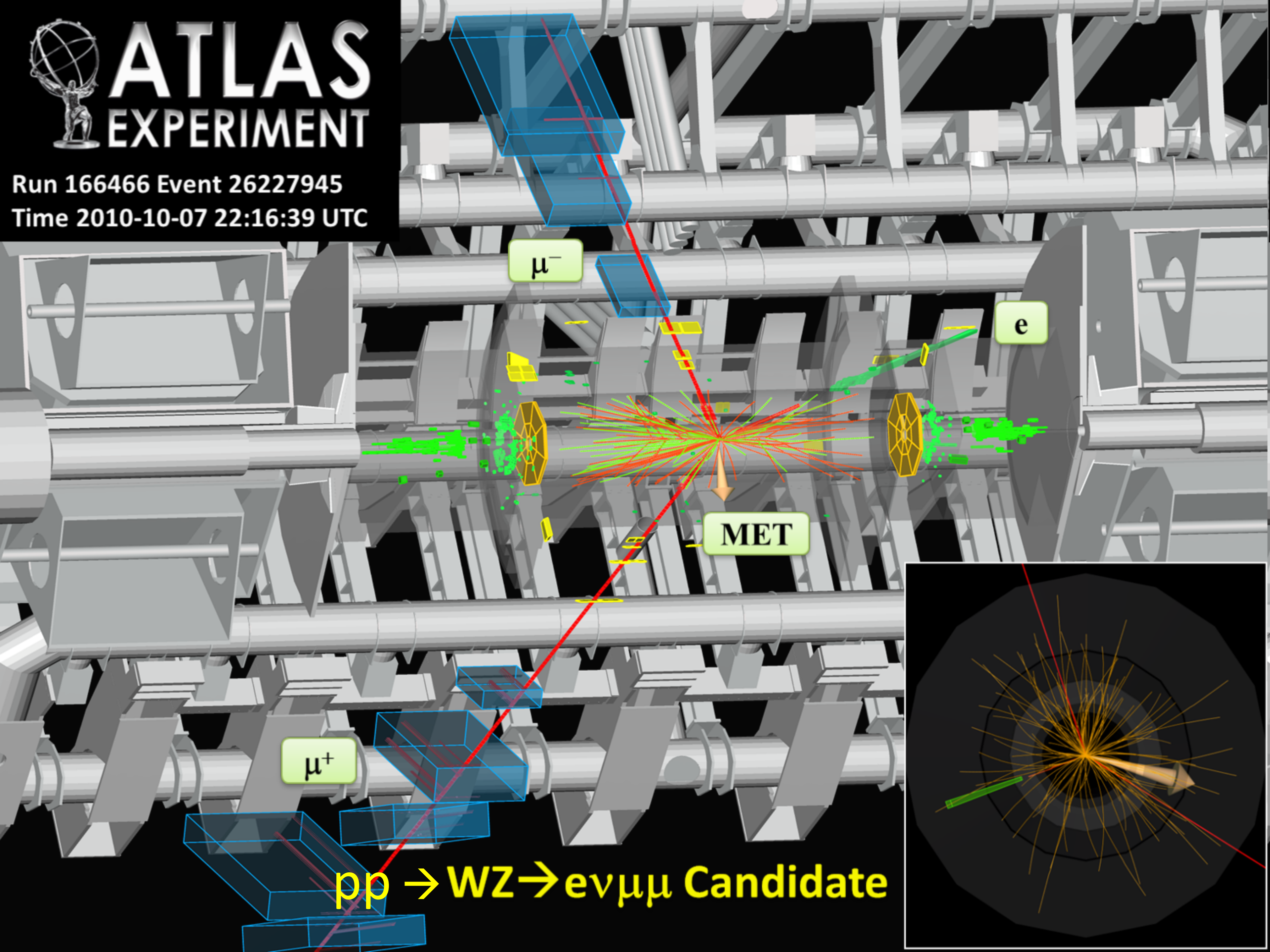
MET

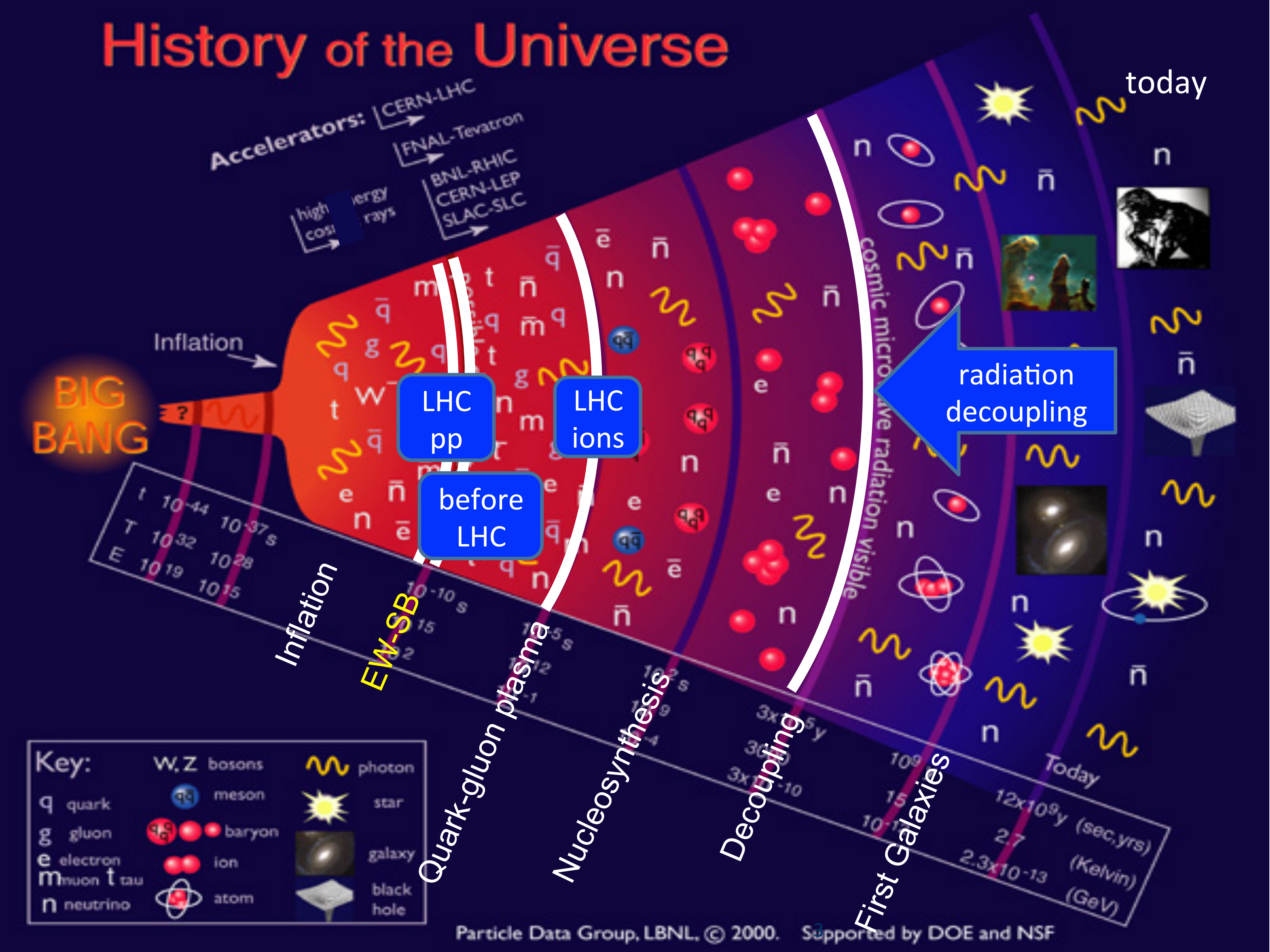
μ^+

WZ→$e\nu\mu\mu$ Candidate



TR33 Korfu Meeting, 18. Sep. 2012


ATLAS EXPERIMENT
Run 166466 Event 26227945
Time 2010-10-07 22:16:39 UTC
μ⁻
e
MET
μ⁺
pp → WZ→ eνμμ Candidate



History of the Universe
today
Accelerators: CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high energy cosmic rays
Inflation
BIG BANG
LHC pp
LHC ions
before LHC
radiation decoupling
cosmic microwave radiation visible
Inflation
EW-SB
Quark-gluon plasma
Nucleosynthesis
Decoupling
First Galaxies
Today
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W,Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

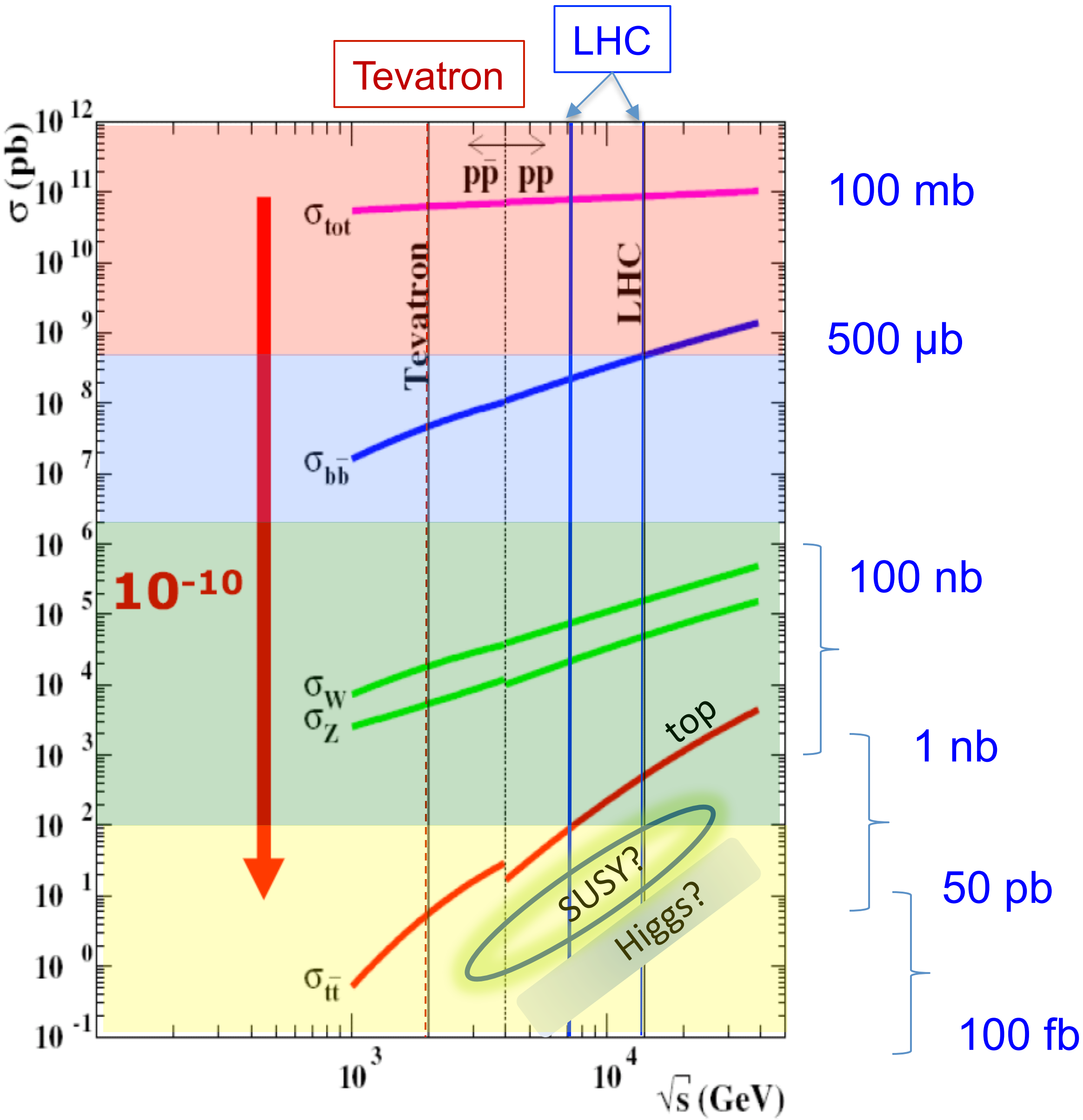
Outline ... a selection of ...

- LHC experiments - a "how to"
- Standard Model and Top-Quark
- Higgs
- SUSY & BSM
- else ... e.g. $B^0 \rightarrow \mu\mu$

apologies ... my slight bias towards ATLAS

Cross sections

$$\dot{N} = \sigma \cdot \mathcal{L}$$



Not even interesting

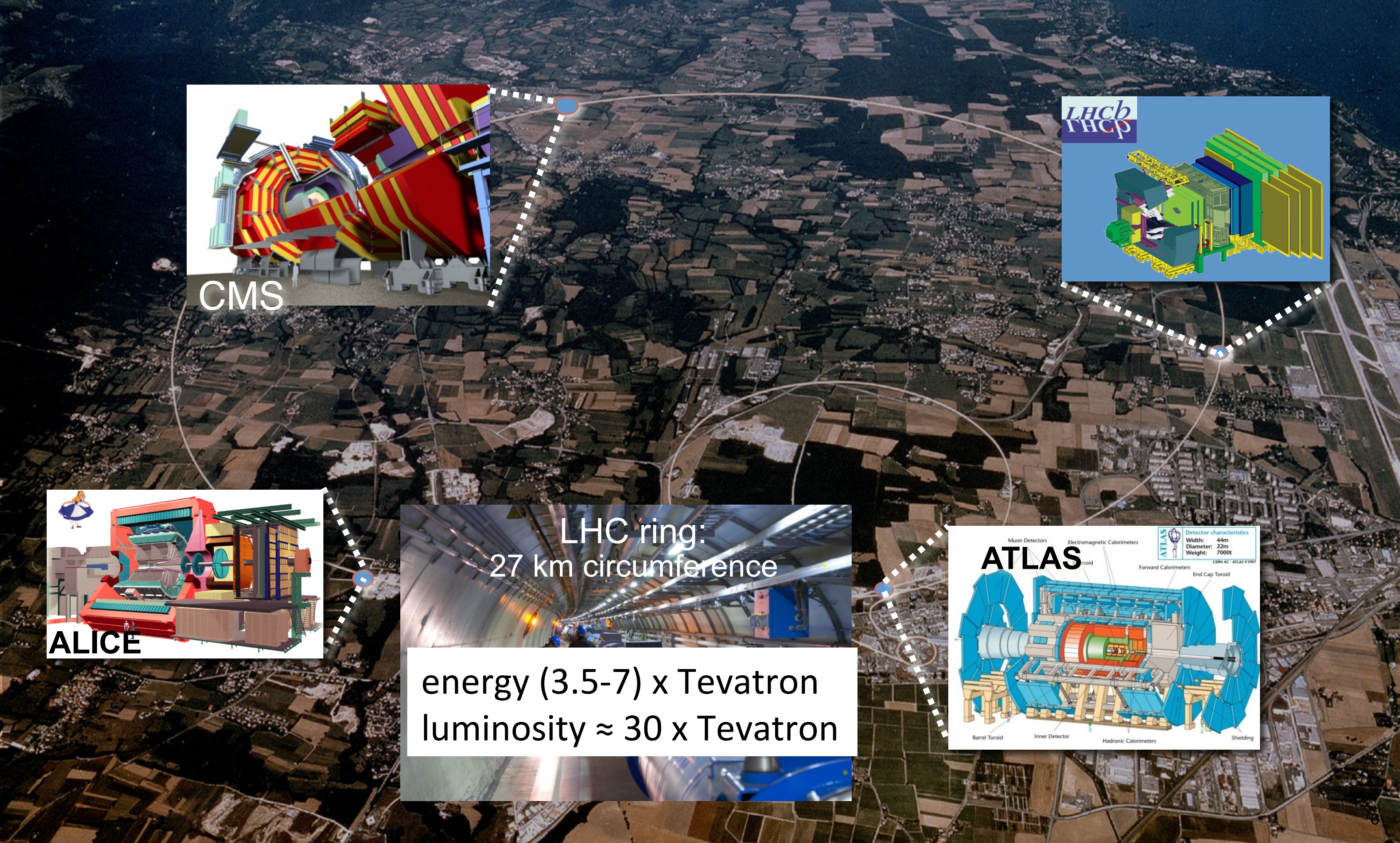
Useful

"Nice" experiments

New physics

LHC startup for physics: March 2010

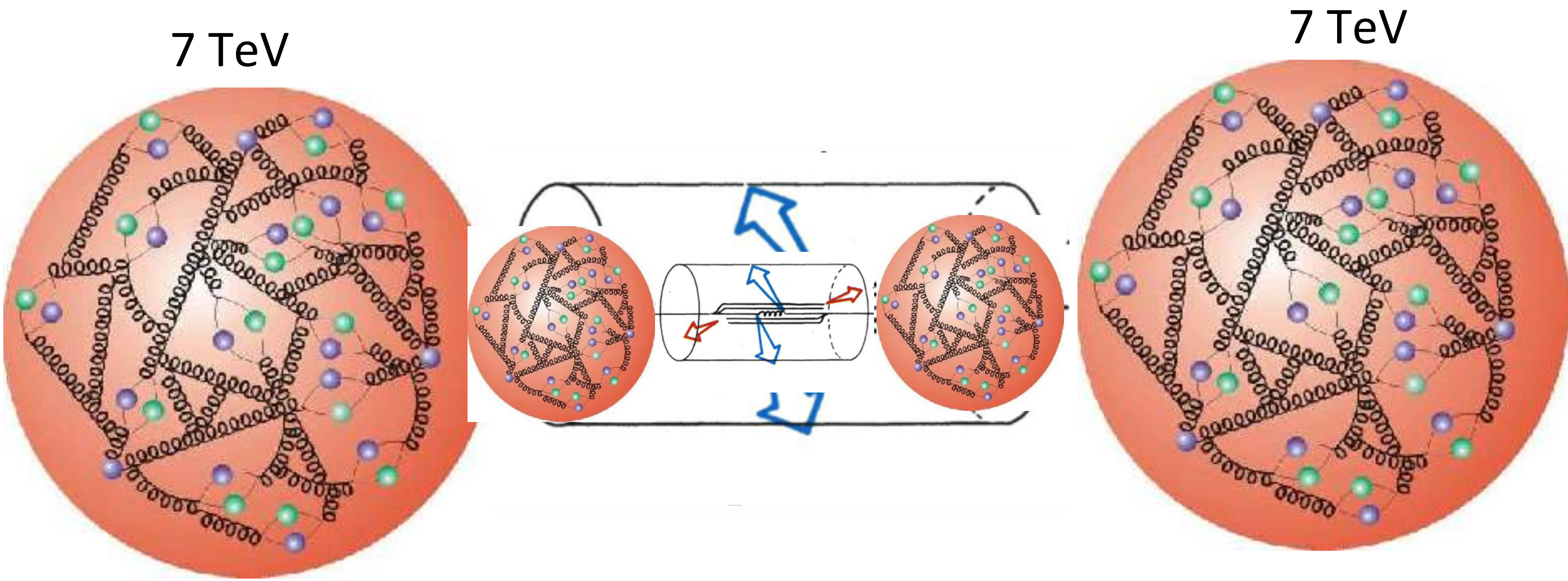
The new energy frontier
Proton-proton collisions at E_{CM} = 7-14 TeV



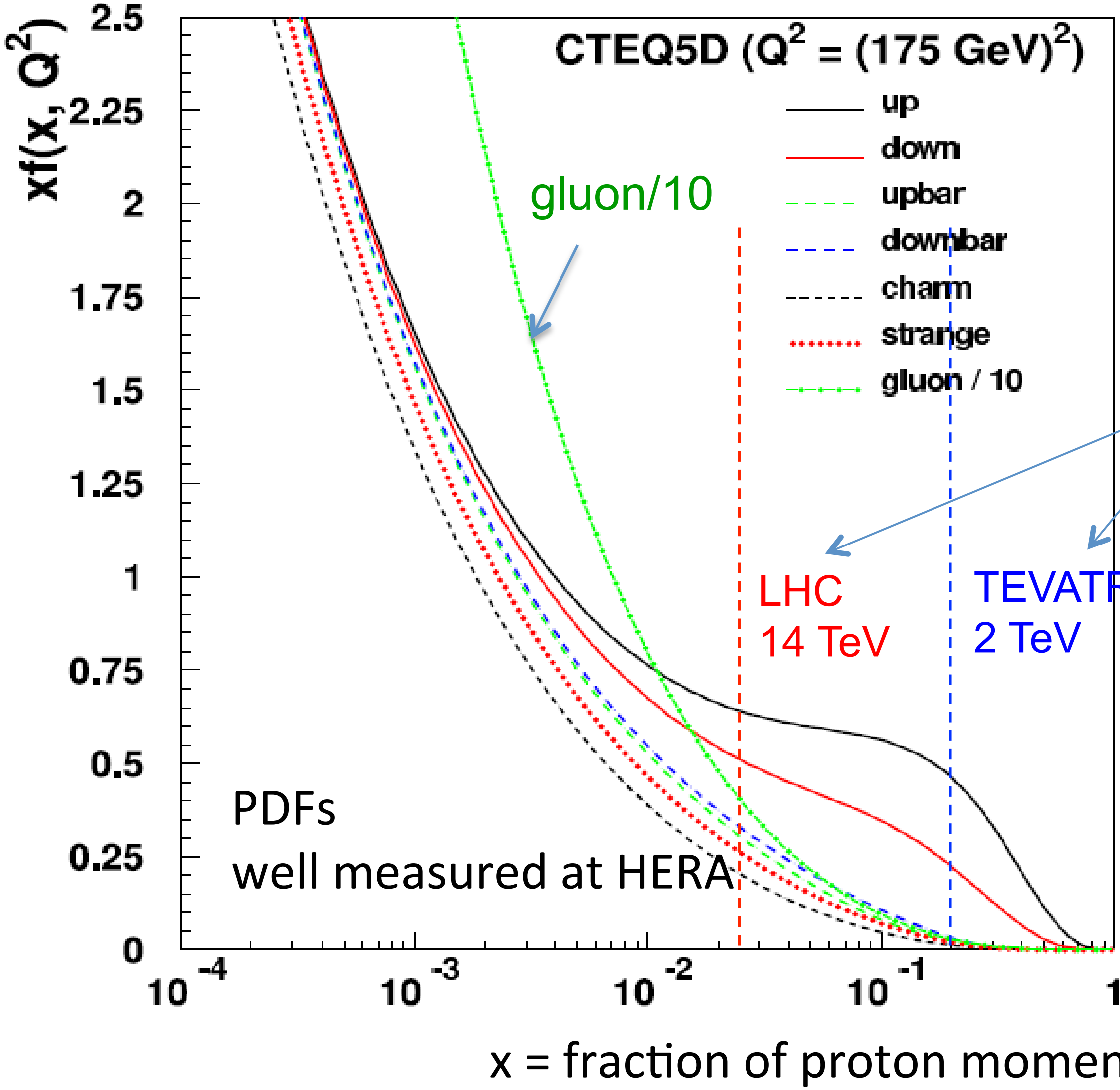
energy (3.5-7) x Tevatron
luminosity ≈ 30 x Tevatron

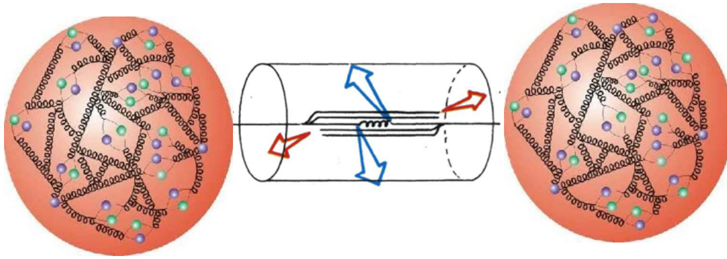
pp collisions

- with protons the highest cm-energies are attainable, but …

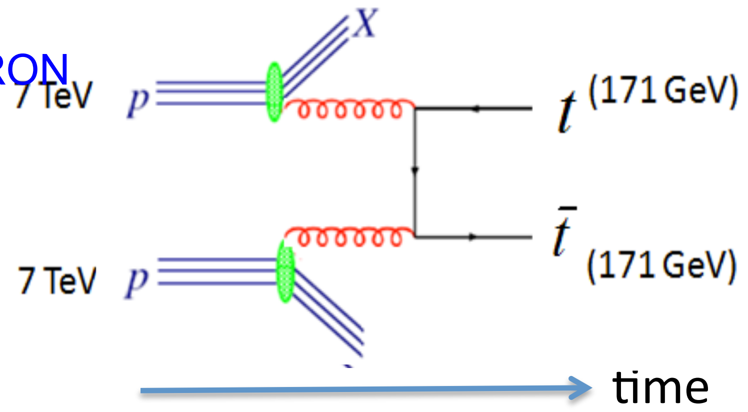


pp collisions





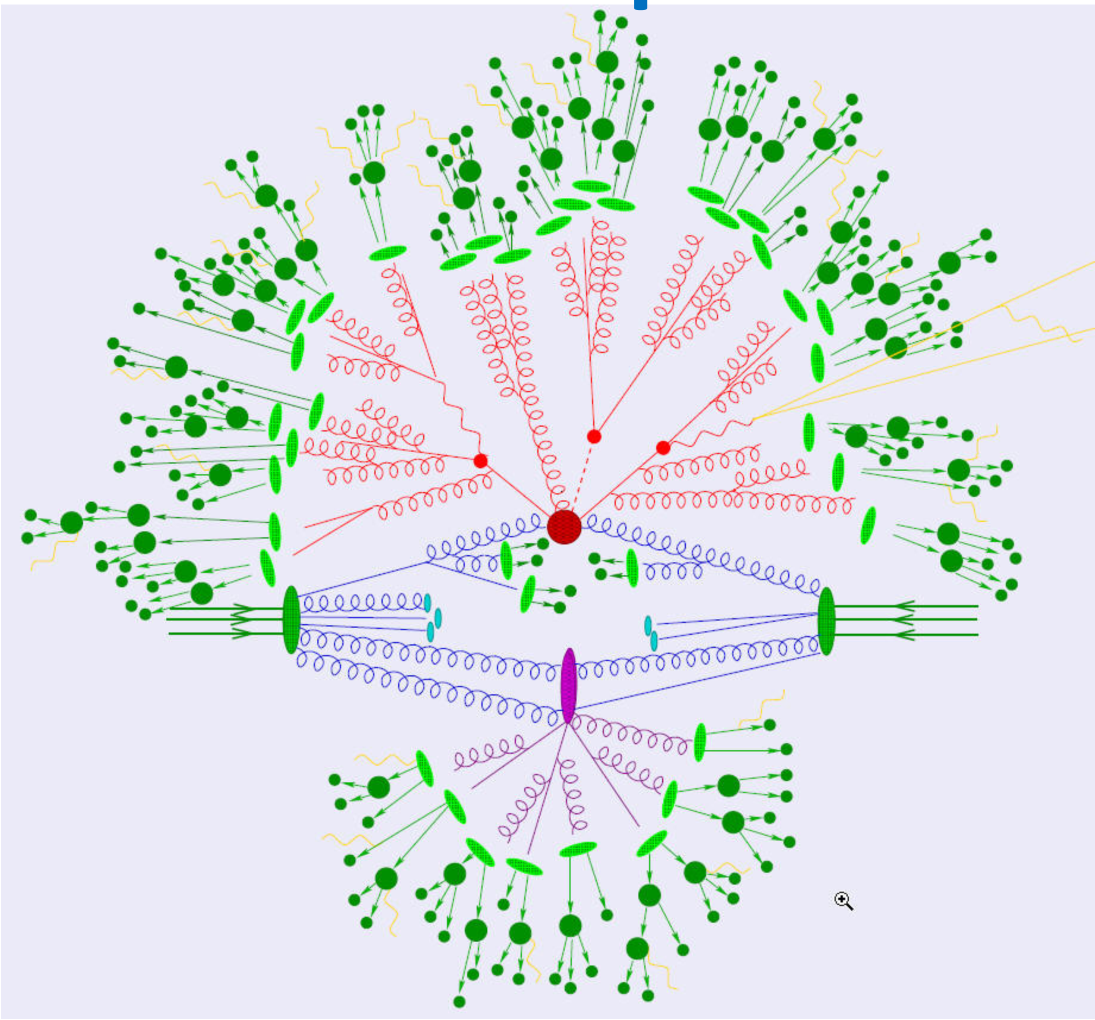
to produce $2m_{top} \approx 340$ GeV



advantage: scan a range of cm energies for the subprocesses

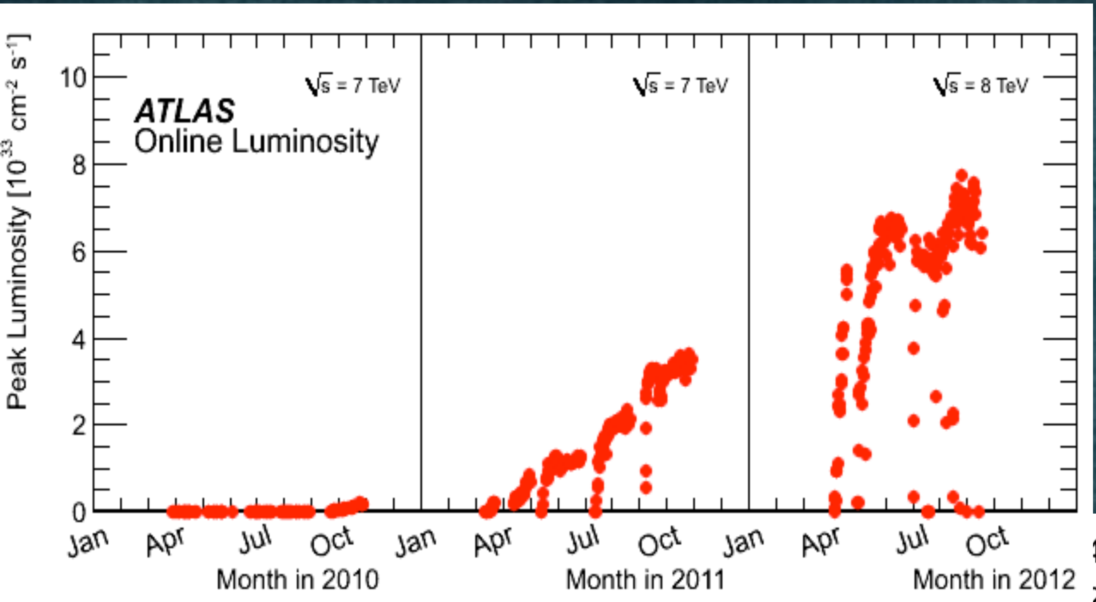
disadvantage: very “dirty”

from quark/gluon processes to measurable particles



"hadronisation" into detectable particles

Peak and Integrated Luminosity



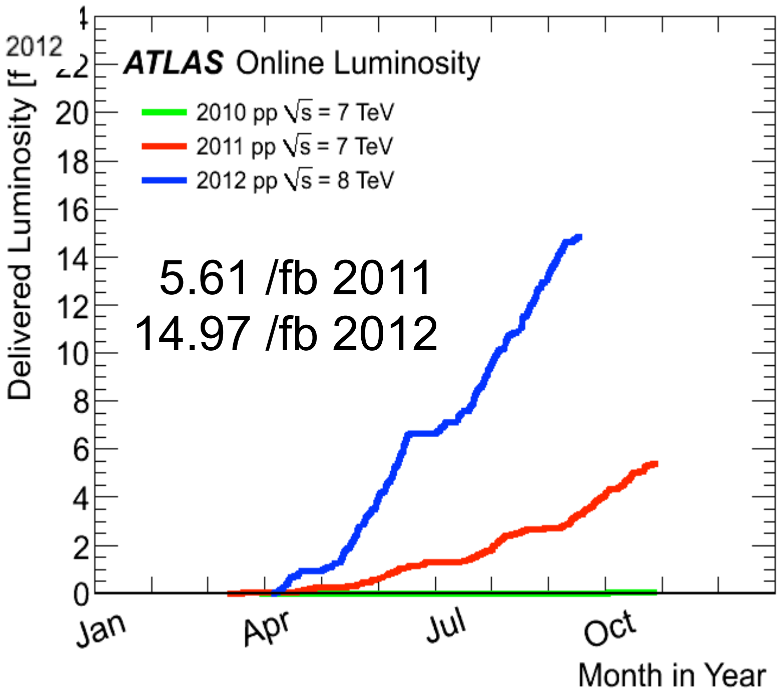
Peak Luminosity 0.8 10^{34} cm^{-2}s^{-1}

~ 600 million pp collisions/s

$$N_{reactions} = \sigma \int L\, dt$$

differential/specific

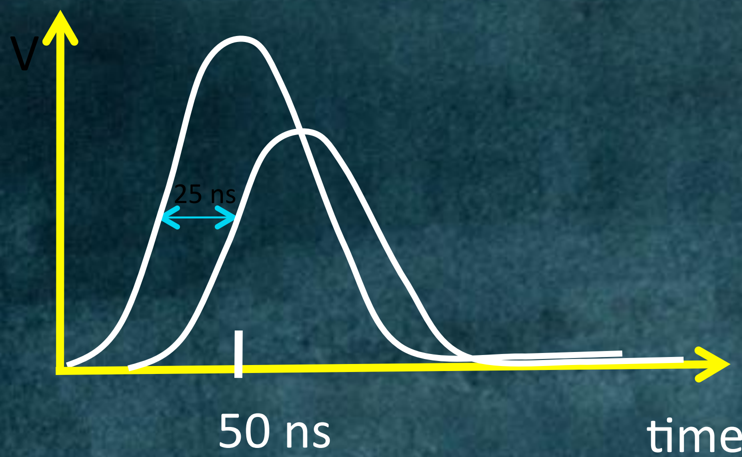
integrated

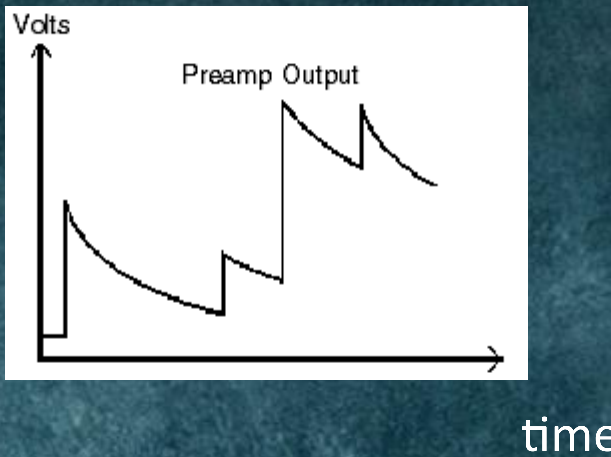


5.61 /fb 2011
14.97 /fb 2012

Challenges for the experiments / detectors

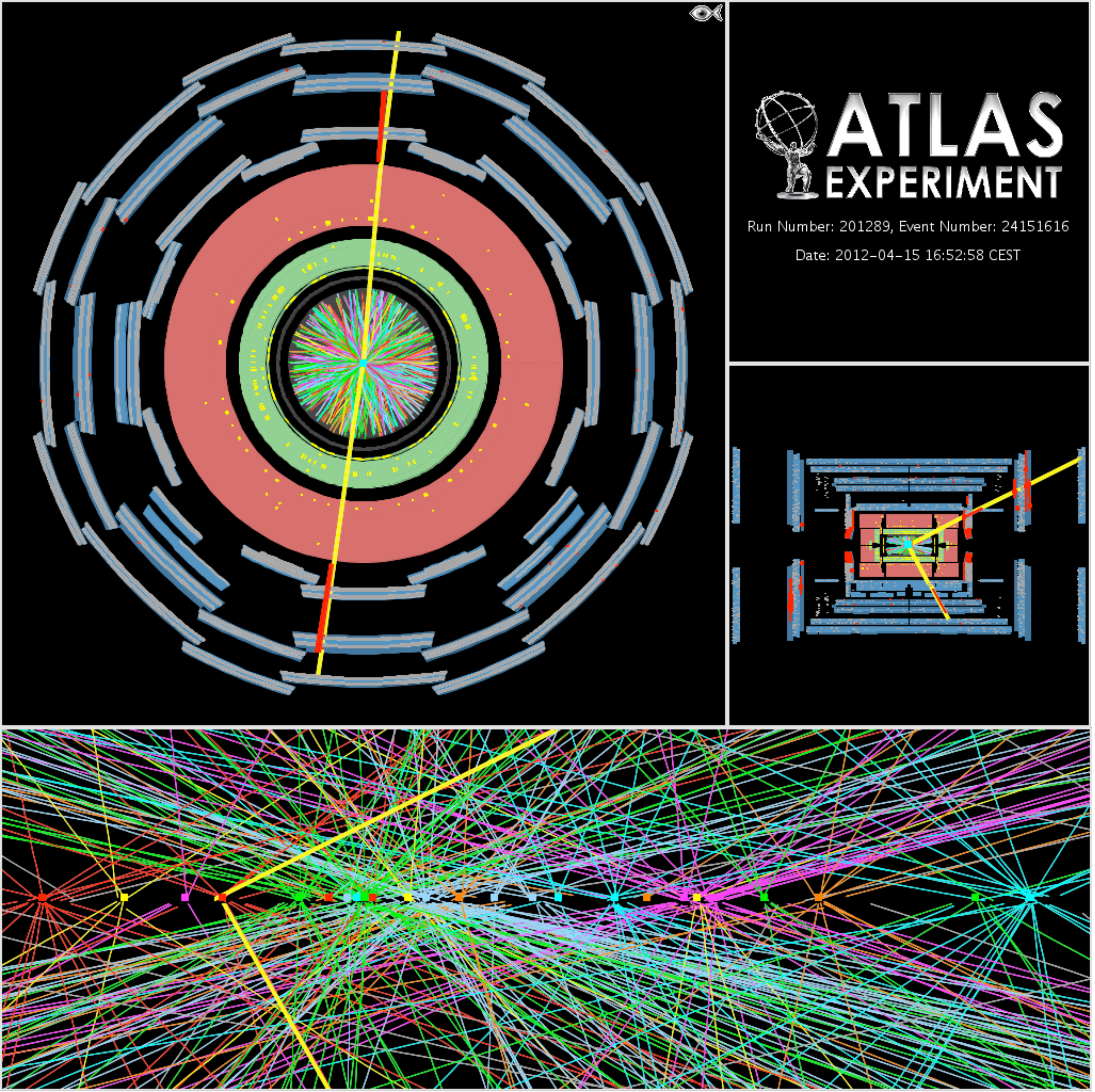
- beam (10^{11} protons/bunch, 2808 bunches) collisions every 25 (50) ns
- bunch size 16 µm x 77 mm (pencil shape)
- on average ~25+ simultaneous pp - reactions per bunch crossing
- on average 120 stable particles per reaction
- ⇒ ~2500 particles/collision (25 ns) ⇒ 10^{11} per second
- ⇒ filter x 10^{-5} and then store 2 CD/s





- measure tracks with high granularity detectors (pixels close to IP)
- energy and position of "jets" measured with "calorimeters"
- muons filtered out and measured precisely "outside"

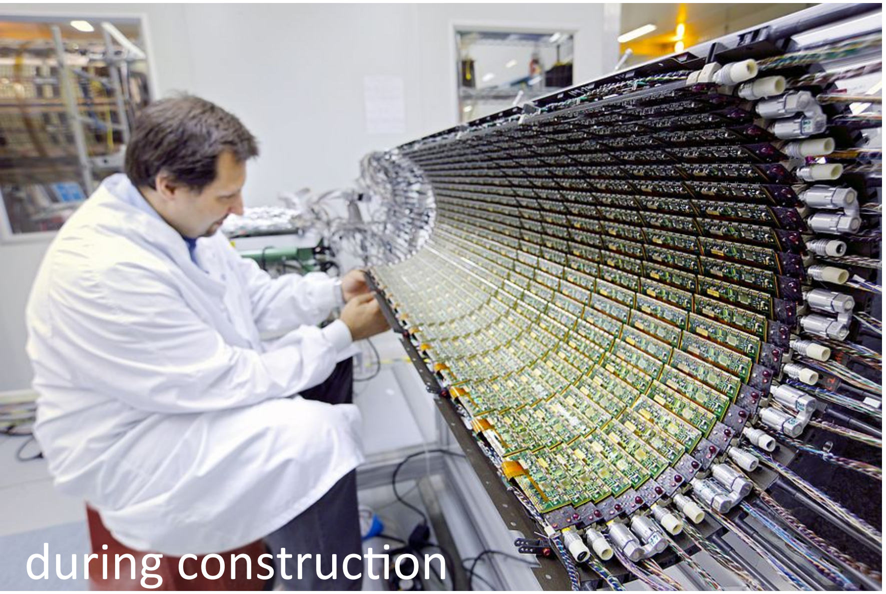
Pile up

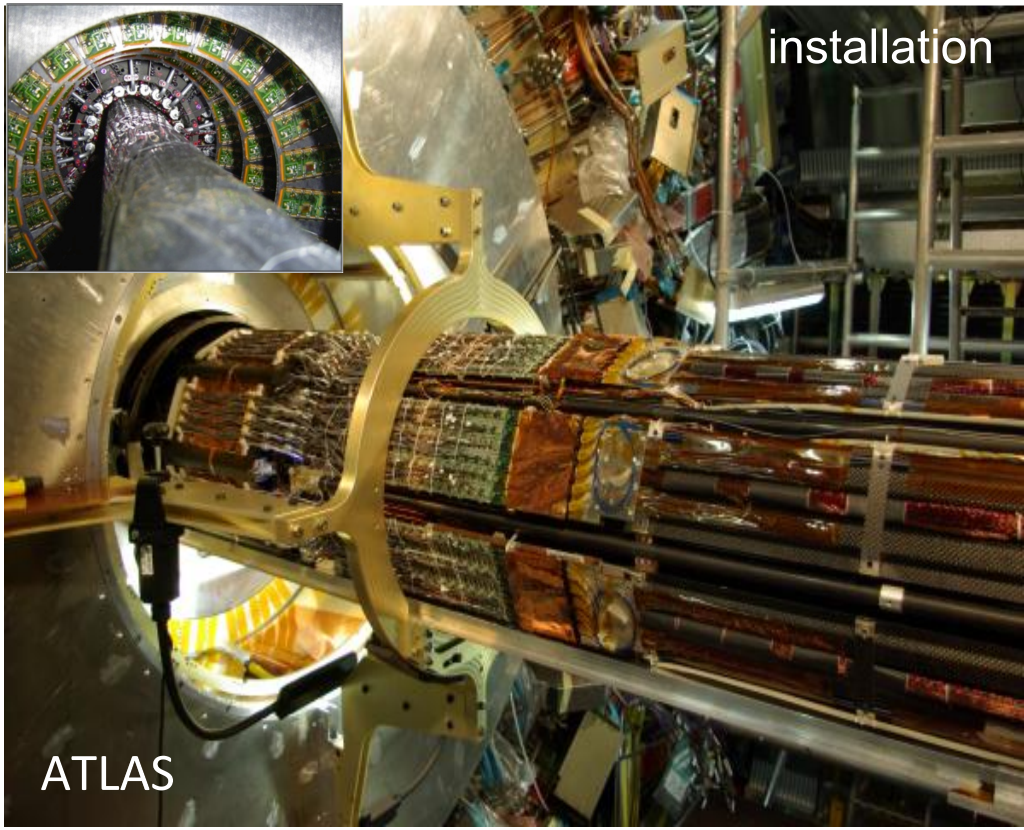


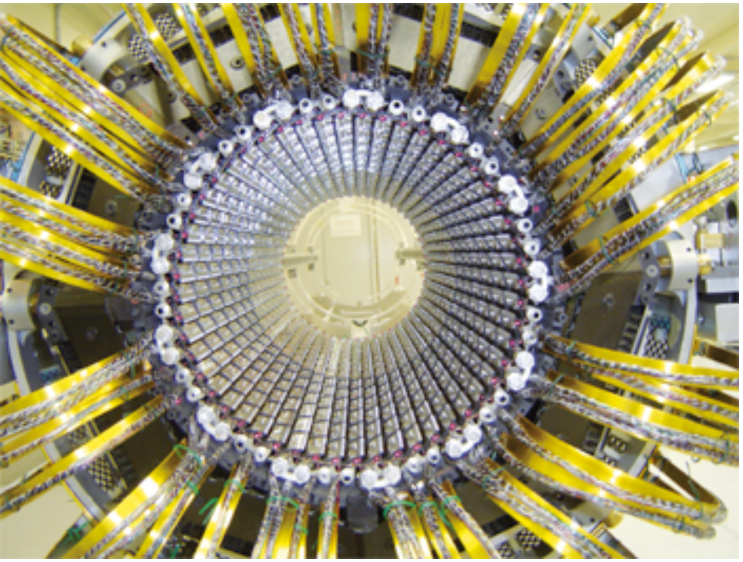
Z → μμ event
with 25 simultaneous interactions

highest average pile-up = 37

Pixel Detector (closest to IP)

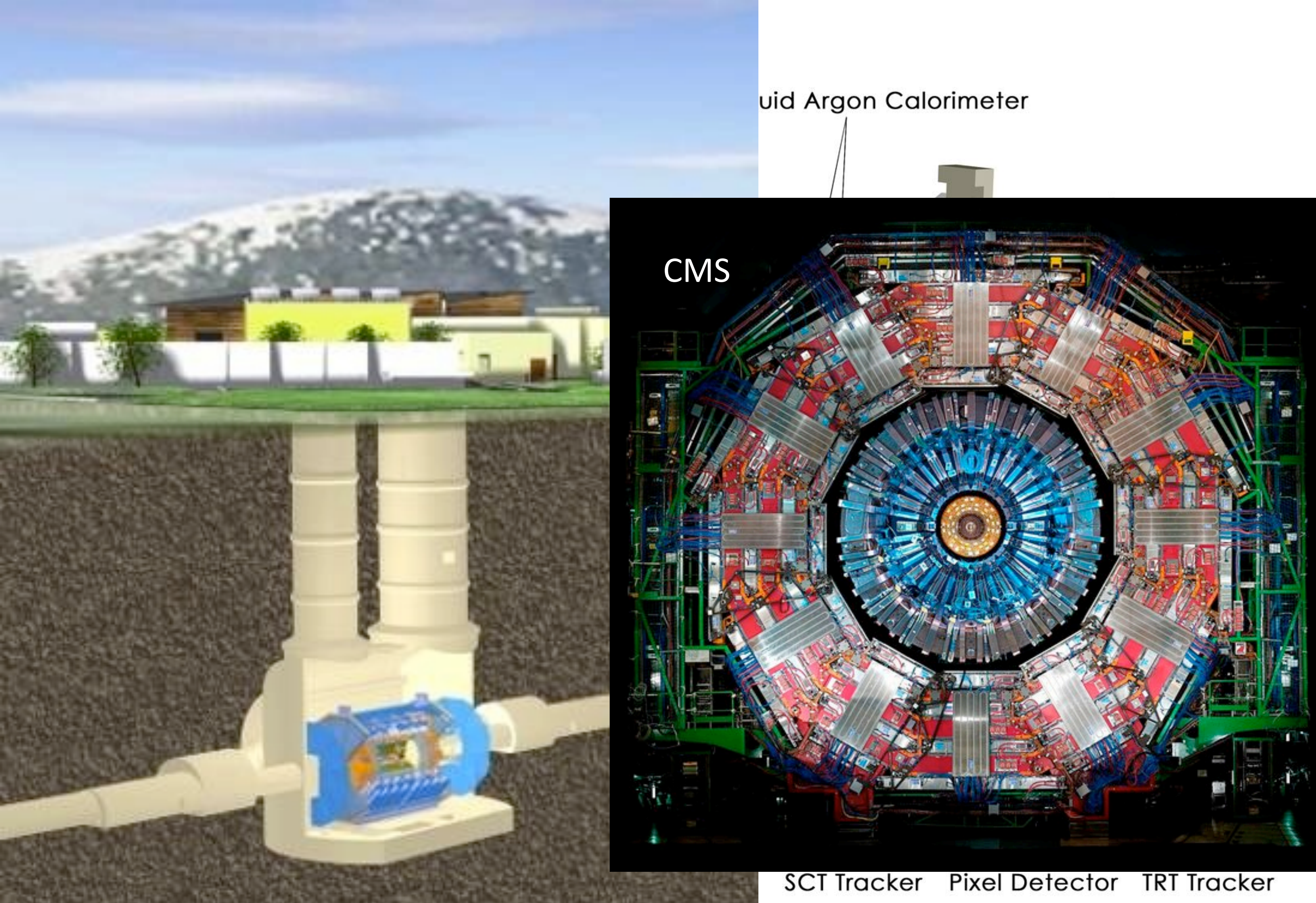






outermost cylinder (of 3)

- a new invention/development for LHC
- pixel camera with 40 MHz exposure rate
- ~15 years from idea to realization

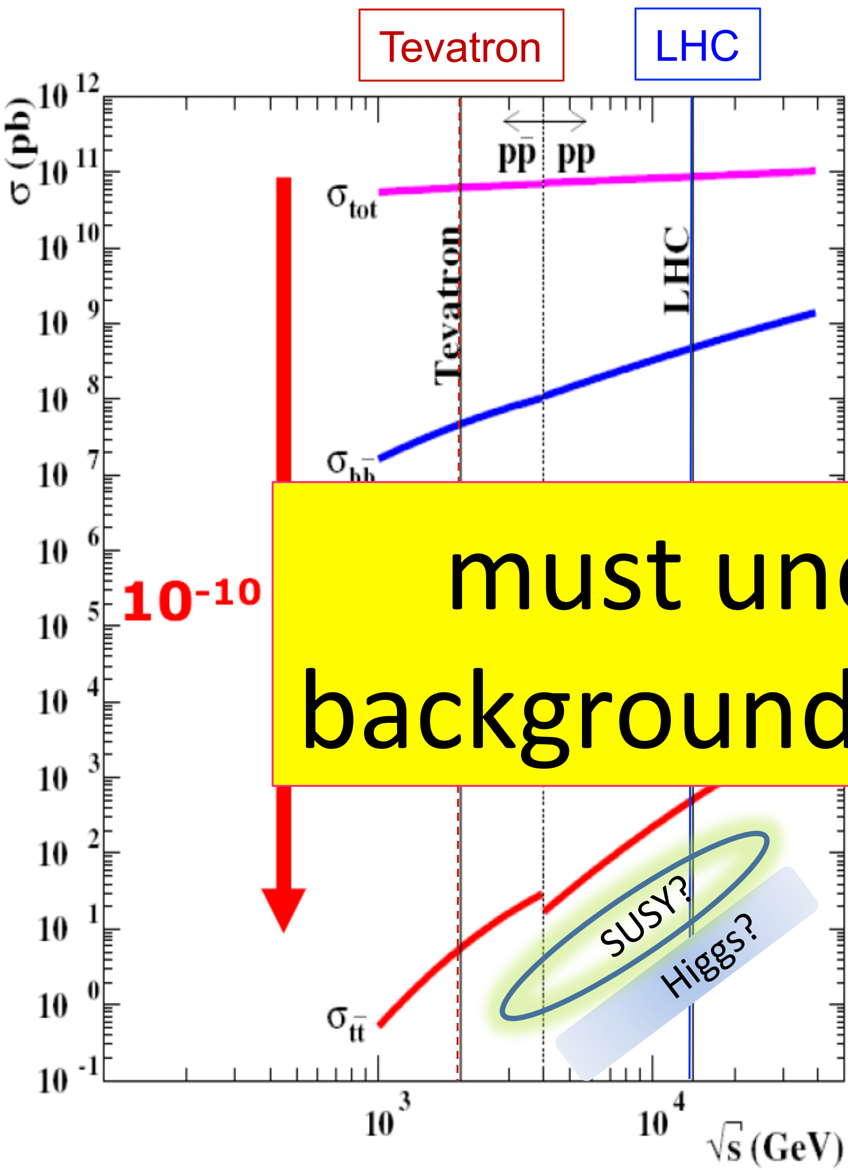

uid Argon Calorimeter
CMS
SCT Tracker
Pixel Detector
TRT Tracker

… to watch further

- irradiation by particles (protons, neutron, pions)
  - ~ 10^{15} particles/cm^2/LHC life time (near IP)
  - ≙ 500 kGy (50 Mrad) dose
  - → need radhard materials and electronics

- no access for several years

Cross sections



100 mb — **all collisions → not interesting**

trigger (2.5 μs)

500 μb

store → possibly interesting (0.0005%)

poss. discoveries → only 0.000000001%

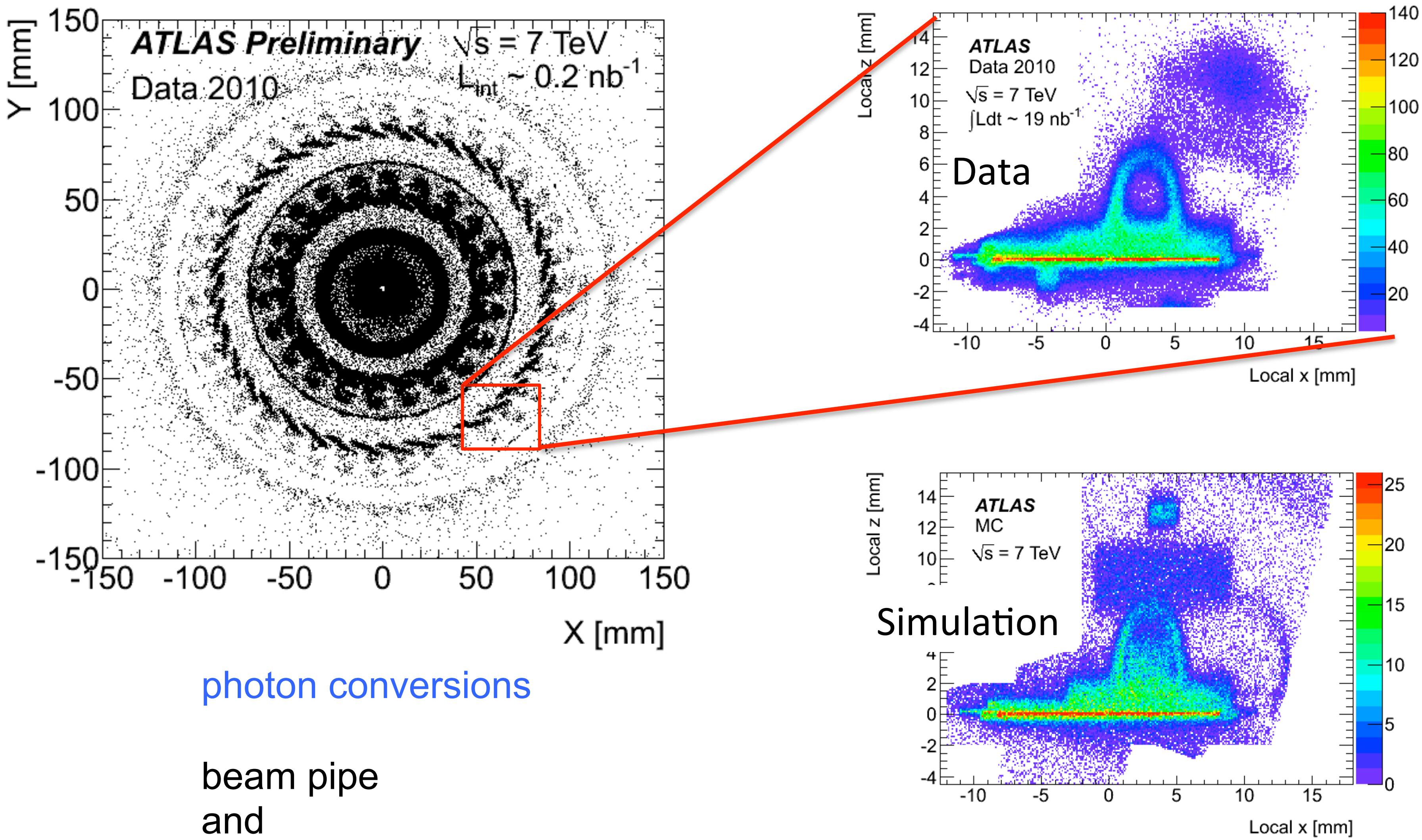
50 pb

a few years

100 fb

must understand the background extremely well

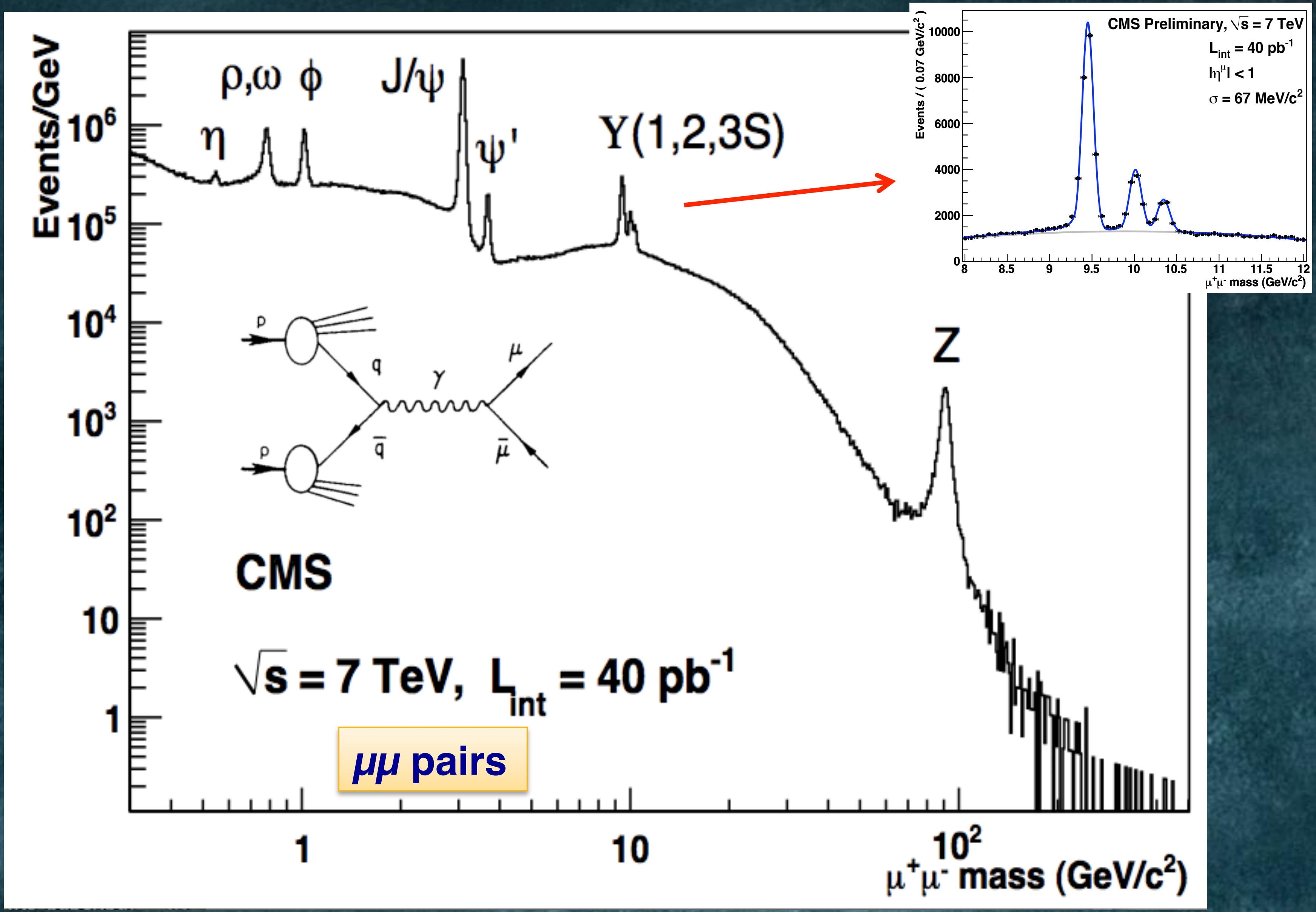
… the particles “X-ray” the material

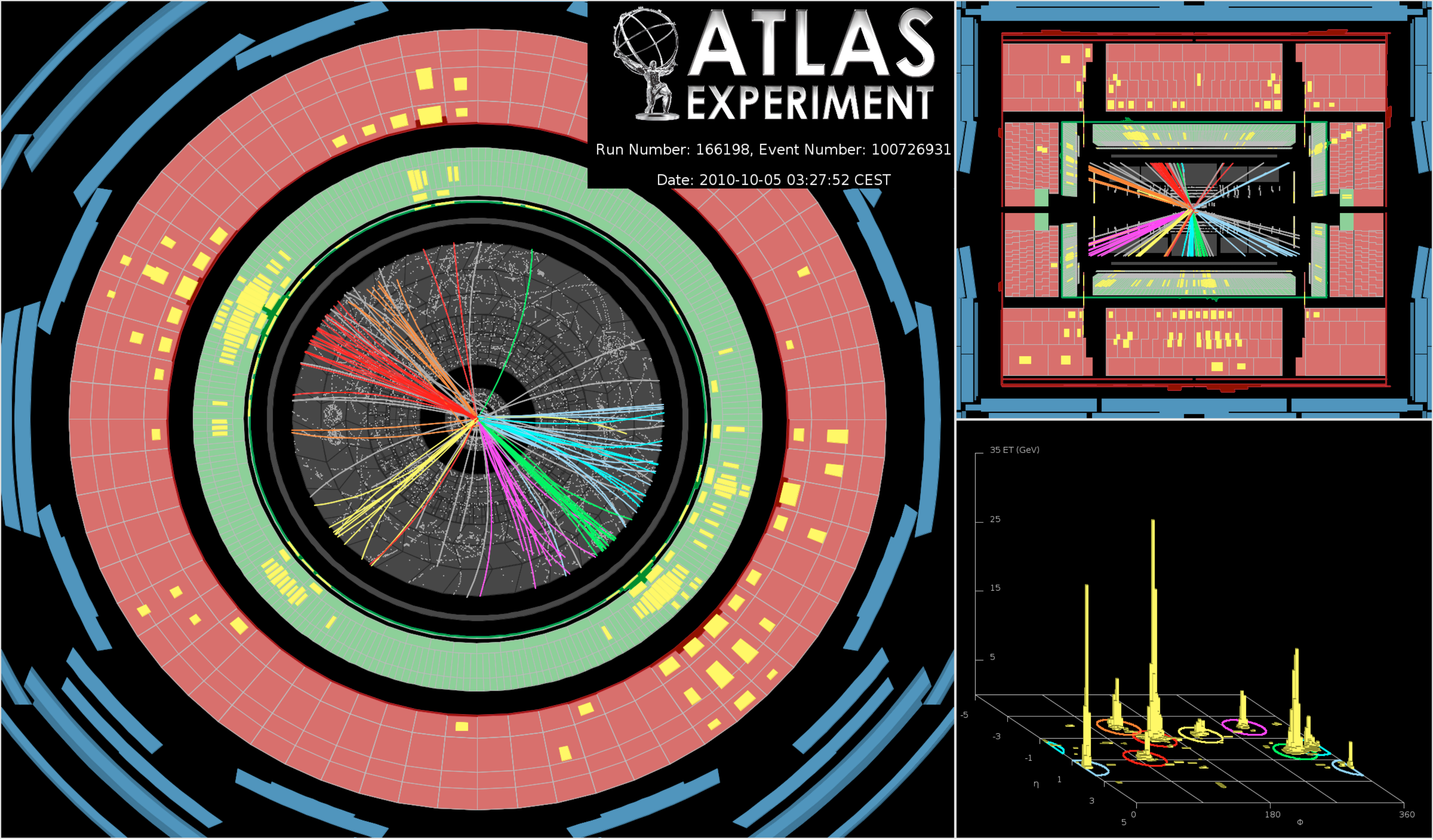


photon conversions

beam pipe
and
pixel detector layers

An Example of Performance





Jets

8 Jets with transverse momenta > 60 GeV

Important: Jets ≙ Quarks/Gluons

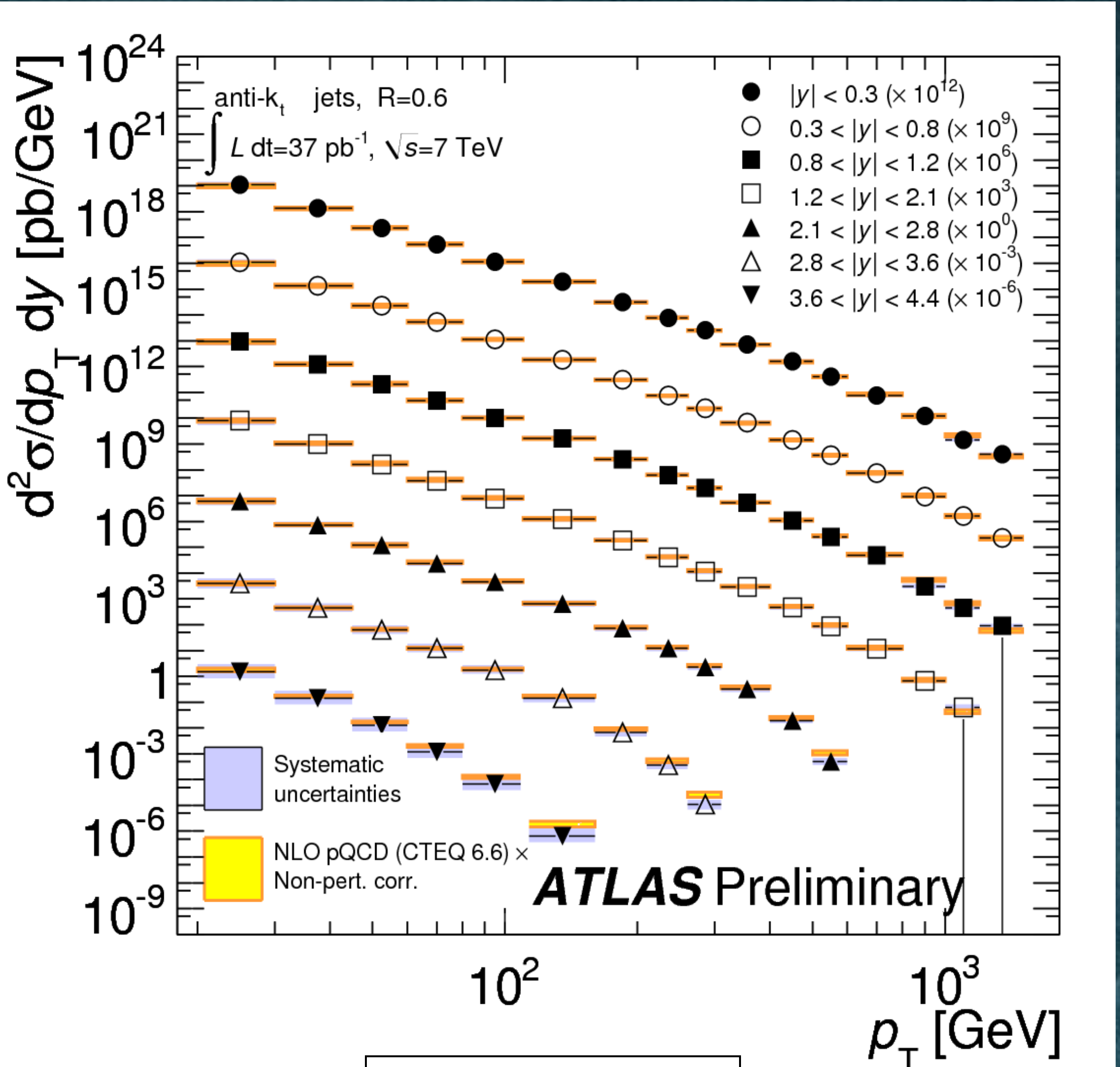
Very detailed jet measurements are done LHC that are compared with QCD calculations …

Inclusive jet cross sections
in various angular intervals

The data are spanning:

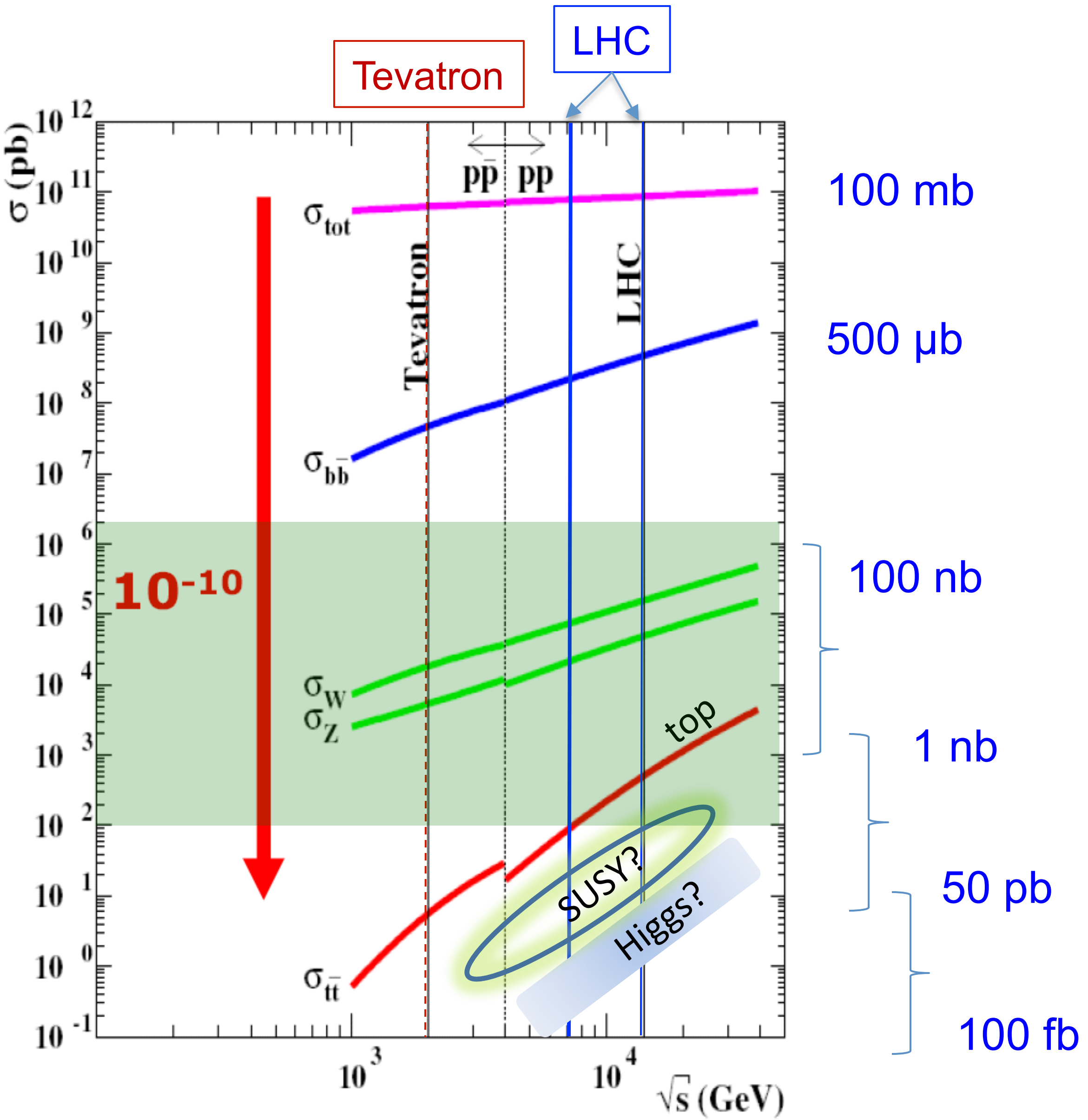
- 20 GeV < p_T < 1500 GeV

- 9 resp 25 orders of magnitude in cross-section



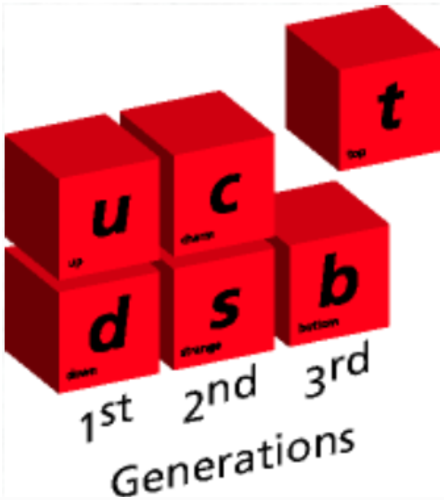
ATLAS-CONF-2011-047

Cross sections



"Nice" experiments

Top Quark



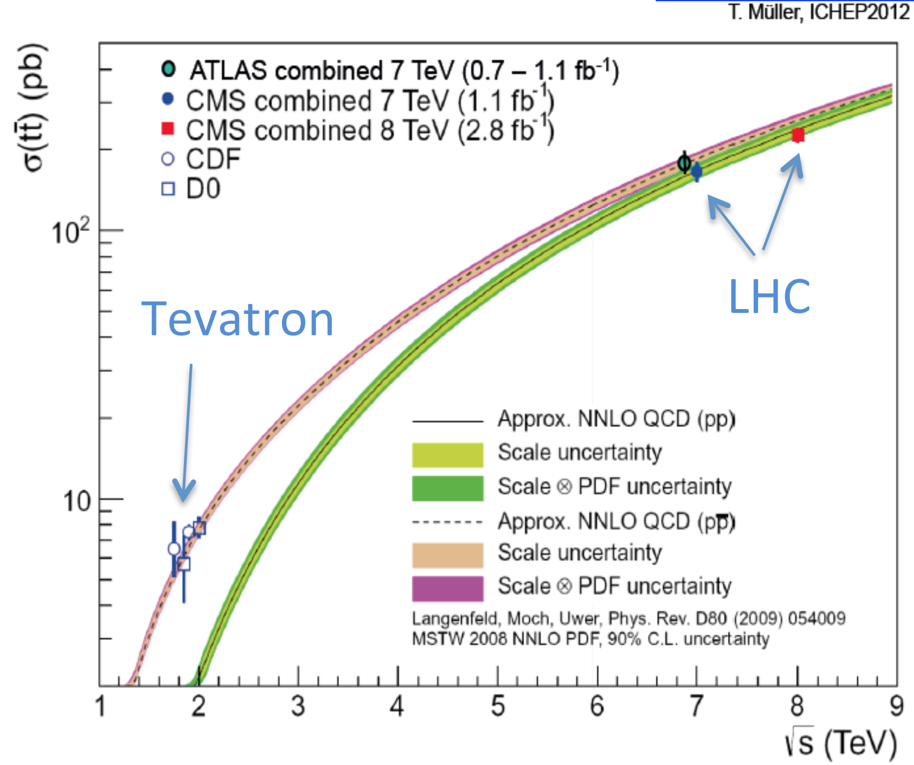
- very heavy (~170 GeV)
- short life time (~5×10^{-25} s)
- decays as a "bare" quark
- Yukawa coupling ≈ 1

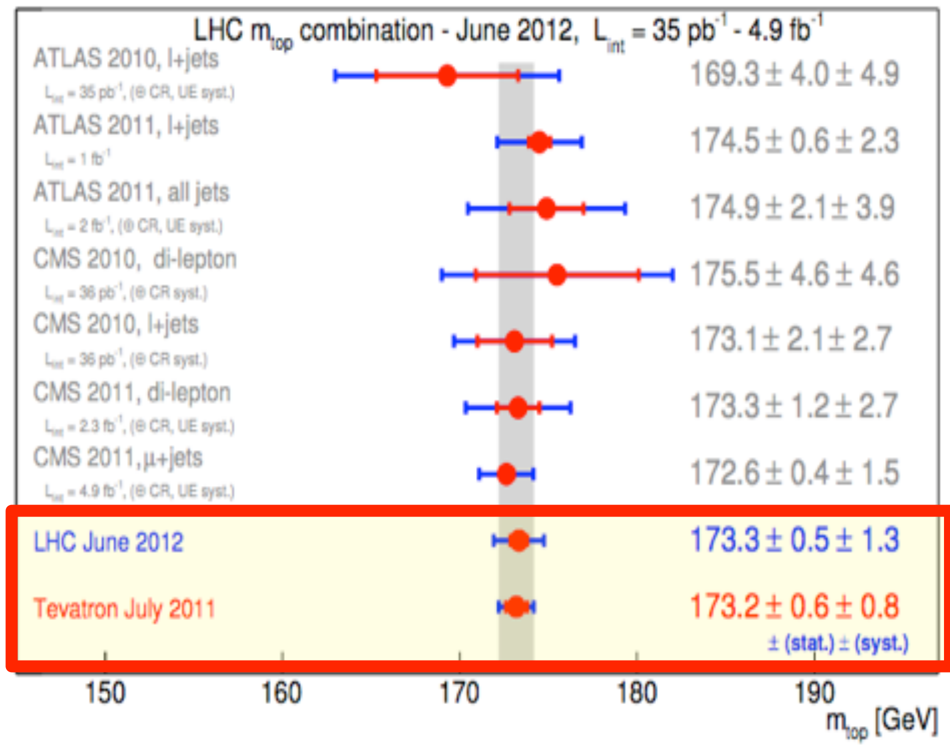
$$m_t = \frac{1}{\sqrt{2}} g_t v$$

$$\Rightarrow g_t = \frac{m_t}{246\,\mathrm{GeV}/\sqrt{2}} = \frac{m_t}{173.9\,\mathrm{GeV}}$$

~2 Million tt-pairs produced

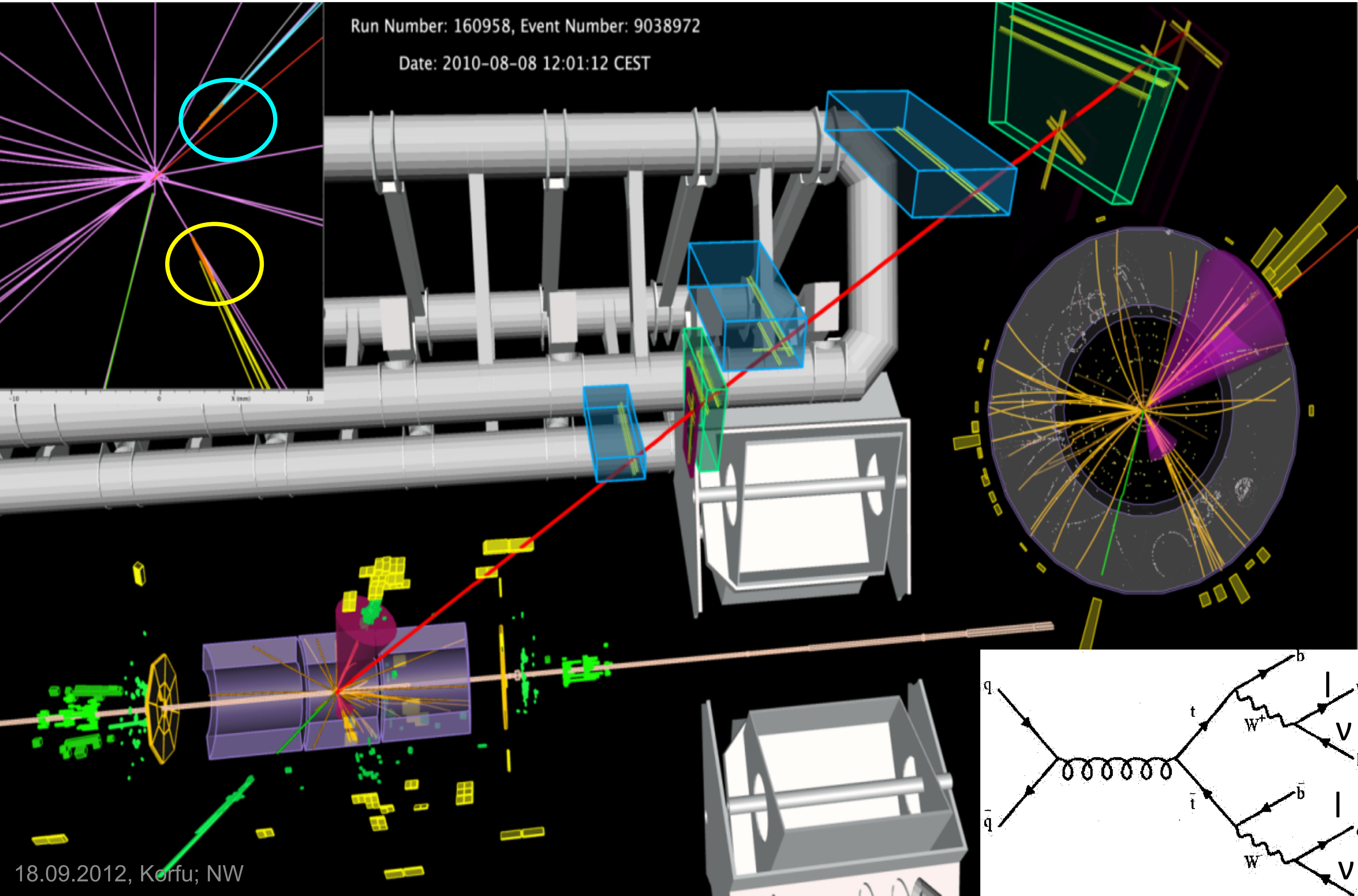
T. Müller, ICHEP2012



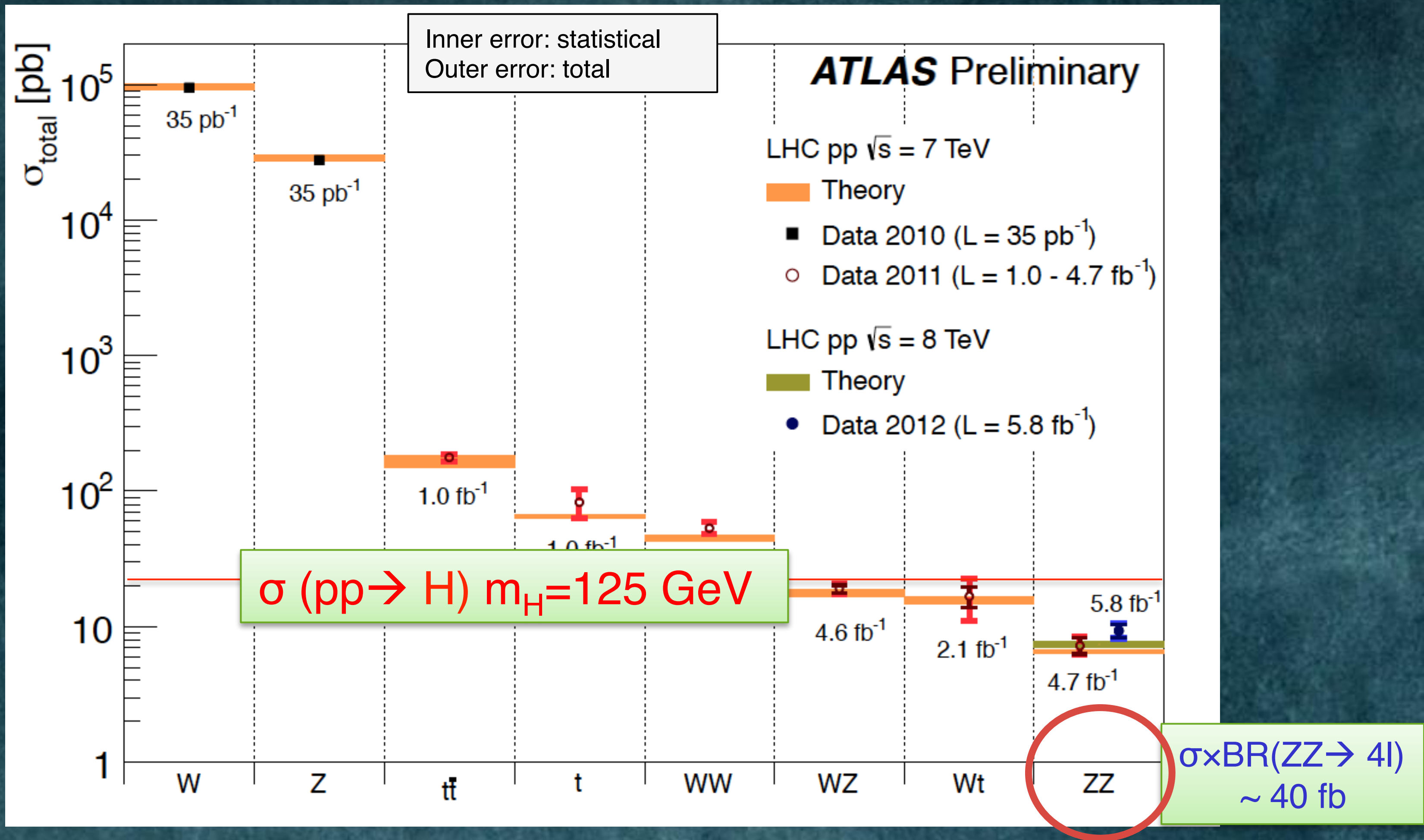


$t\bar{t}$ candidate event

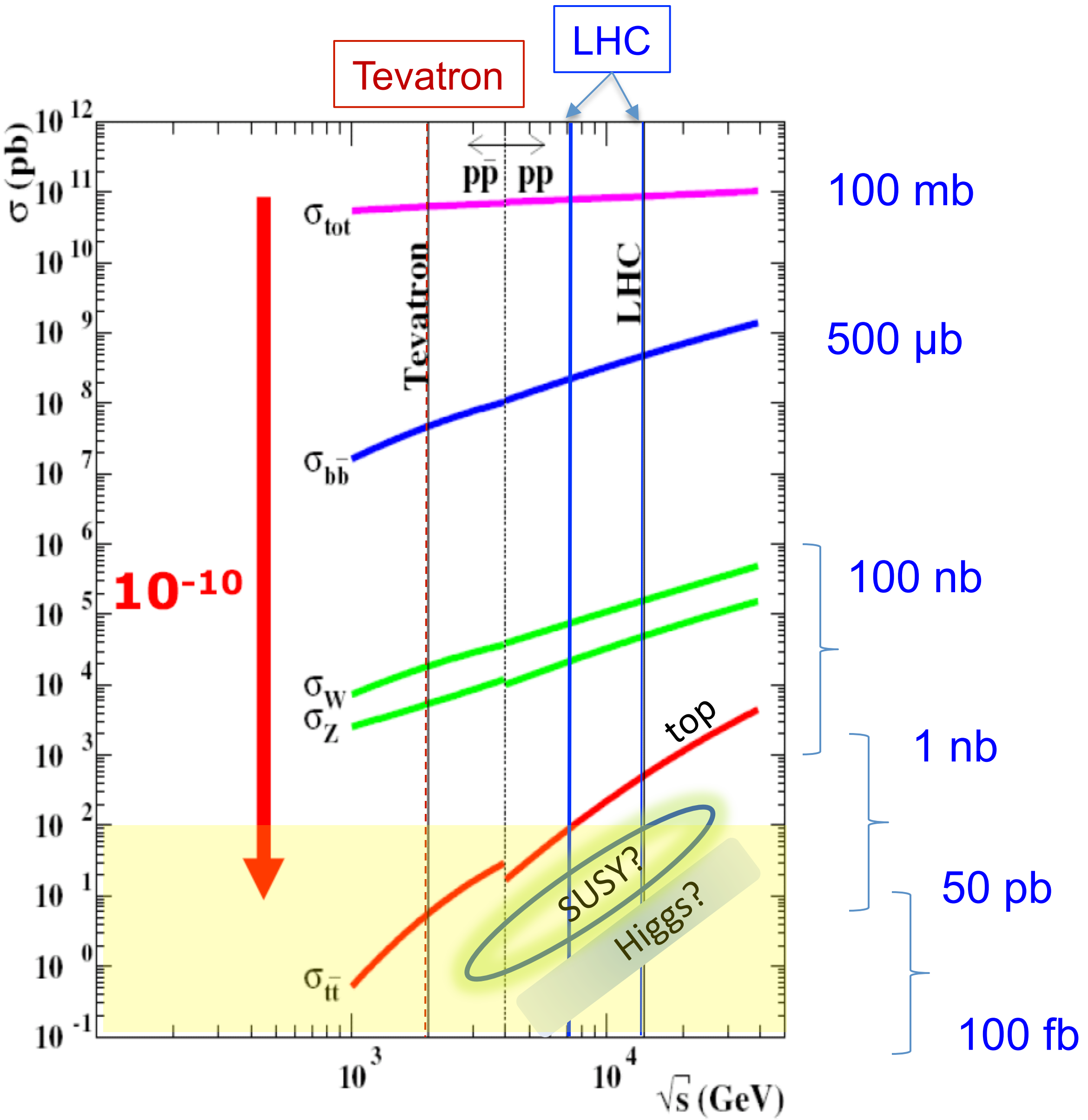
e + μ + 2 jets (b-tagged) +ETmiss



The big picture:
A summary of the main electroweak and top measurements



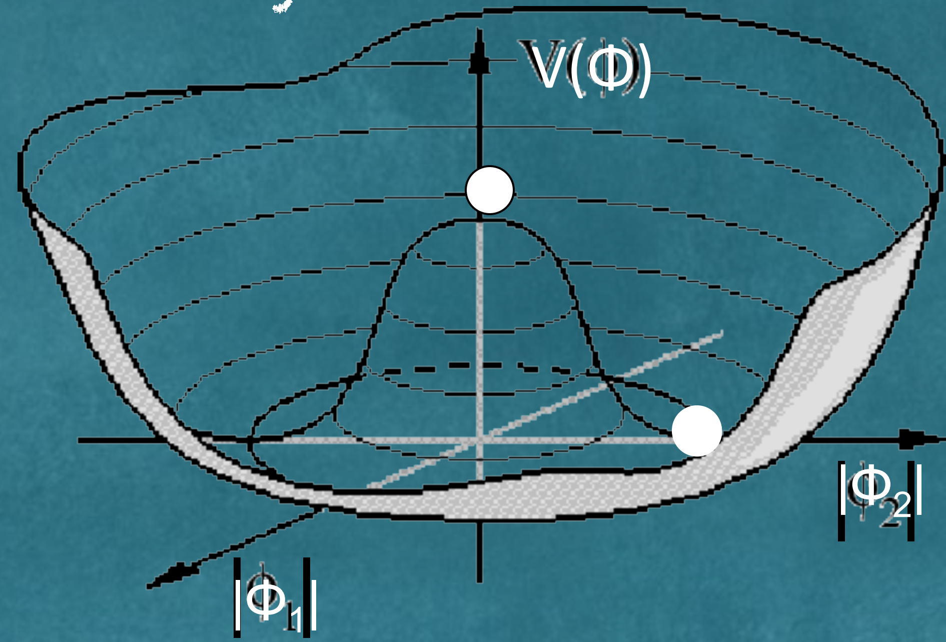
Cross sections



New physics

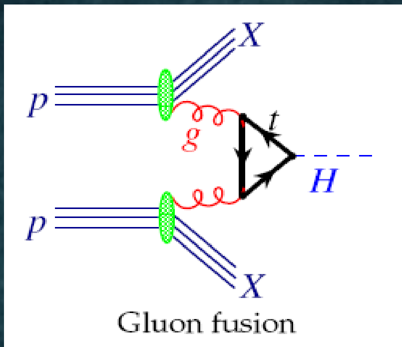
Search for the Higgs

The SM says ...

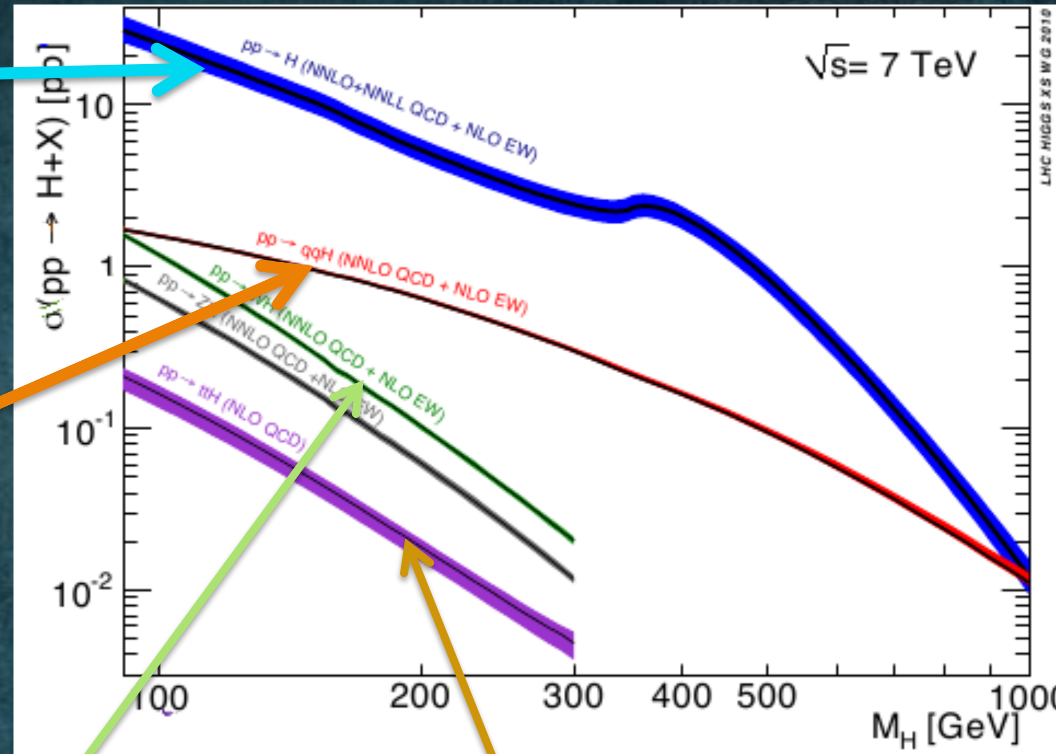


-> in SM: origin of particle masses

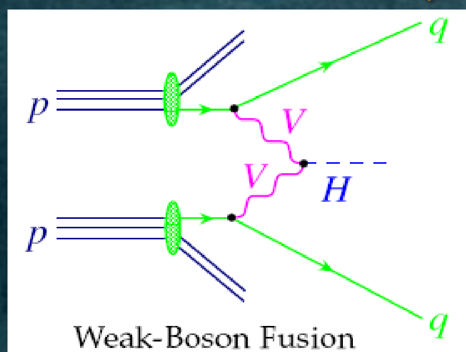
How the Higgs is produced in pp collisions ...



Gluon fusion

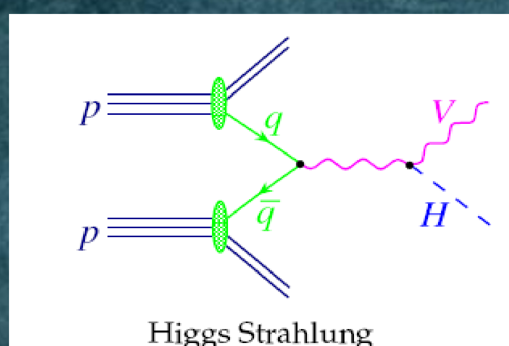


is 10 x larger than



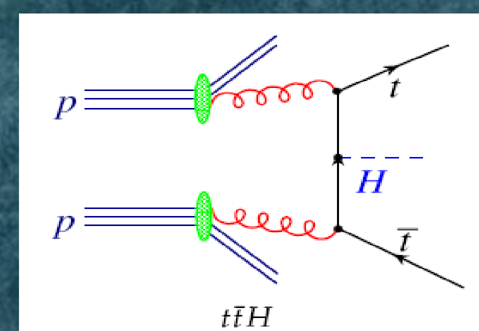
Weak-Boson Fusion

but extra jets as handle



Higgs Strahlung

smaller still but distinct signature



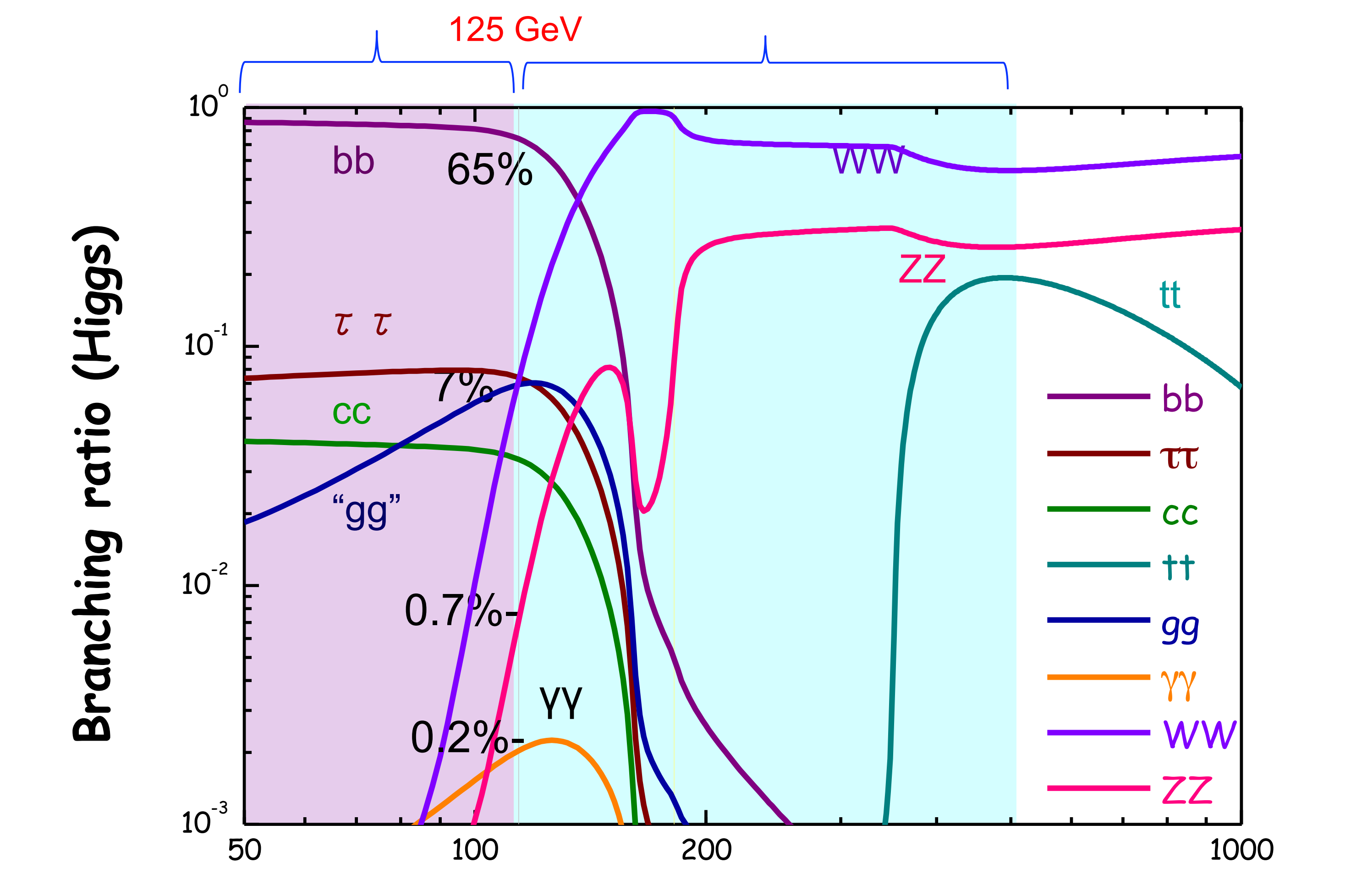
$t\bar{t}H$

small and exp. difficult

Higgs Decay

given the mass the decay properties are fixed

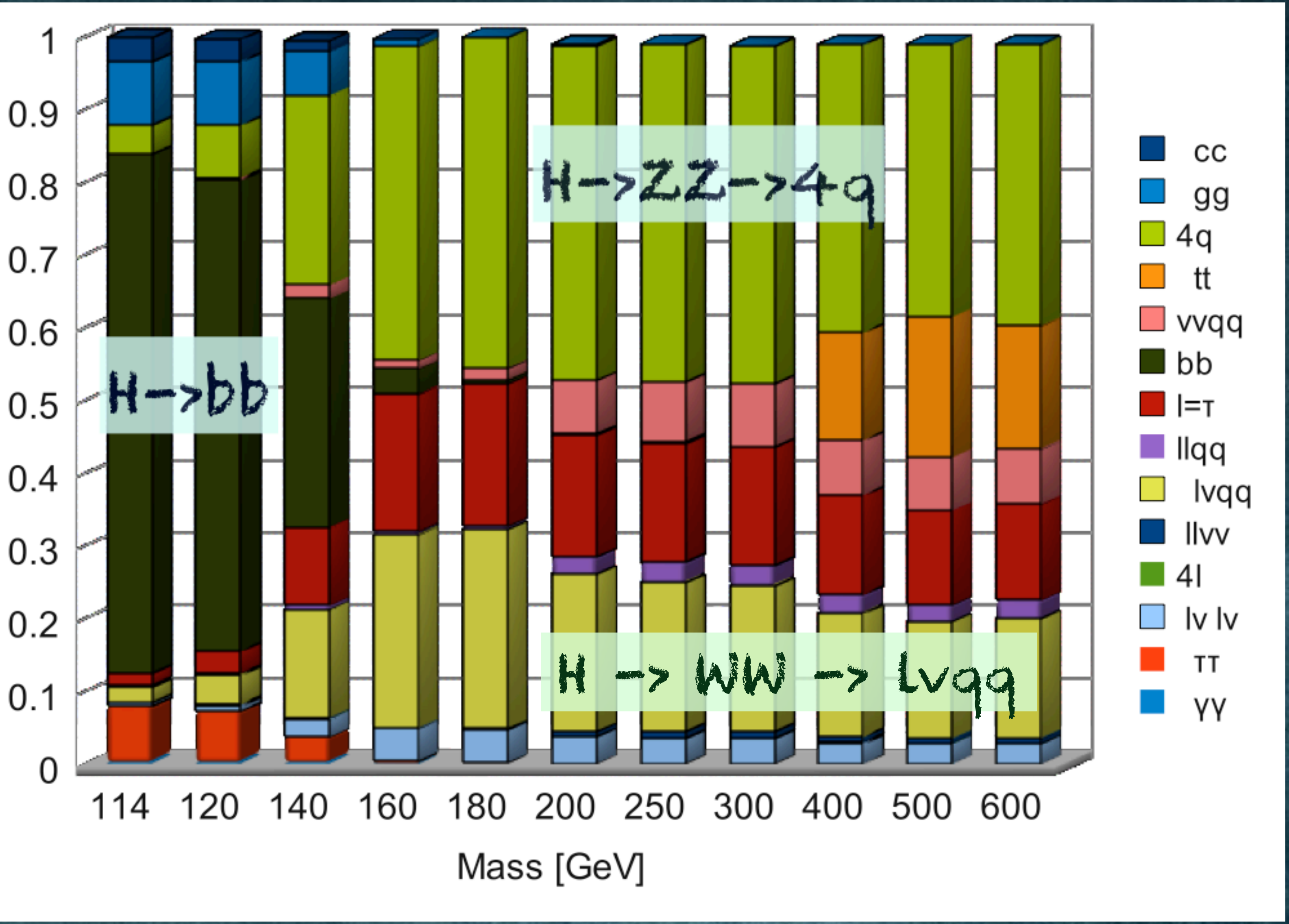
light heavy



$BR = \Gamma_i / \Gamma_{tot}$

note logarithmic scale

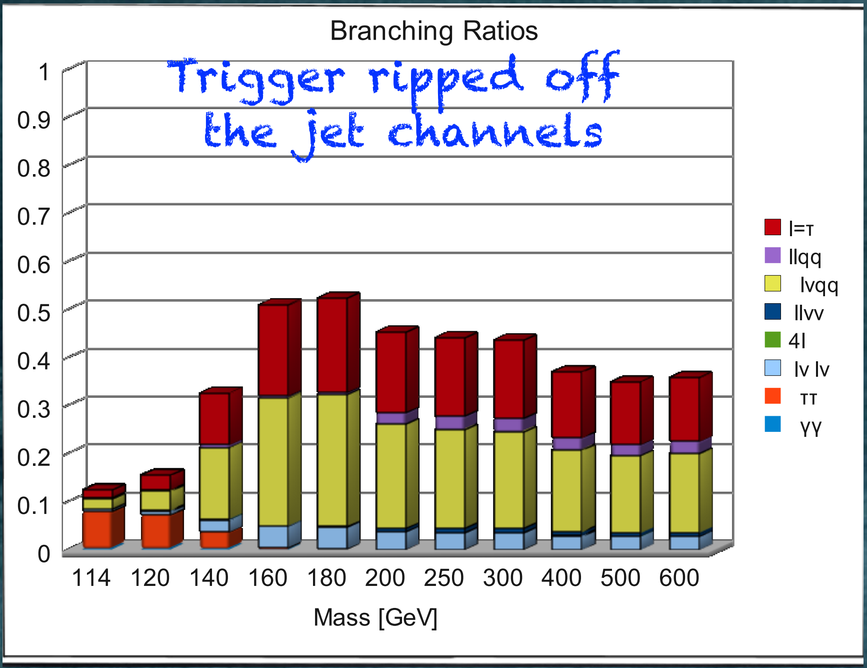
Fractions of Higgs final states

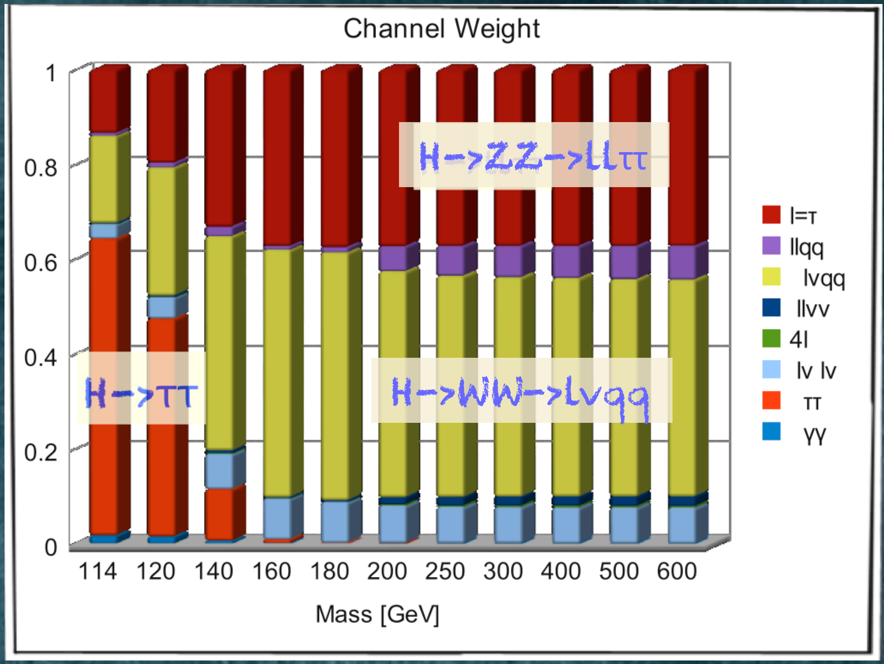


courtesy: E. Gross

After triggering ...

most effective triggers contain leptons





courtesy: E. Gross

The detection efficiency changes the picture again...
For different mass regions different final states contribute with different "weight" to the Higgs sensitivity ...

at low mass

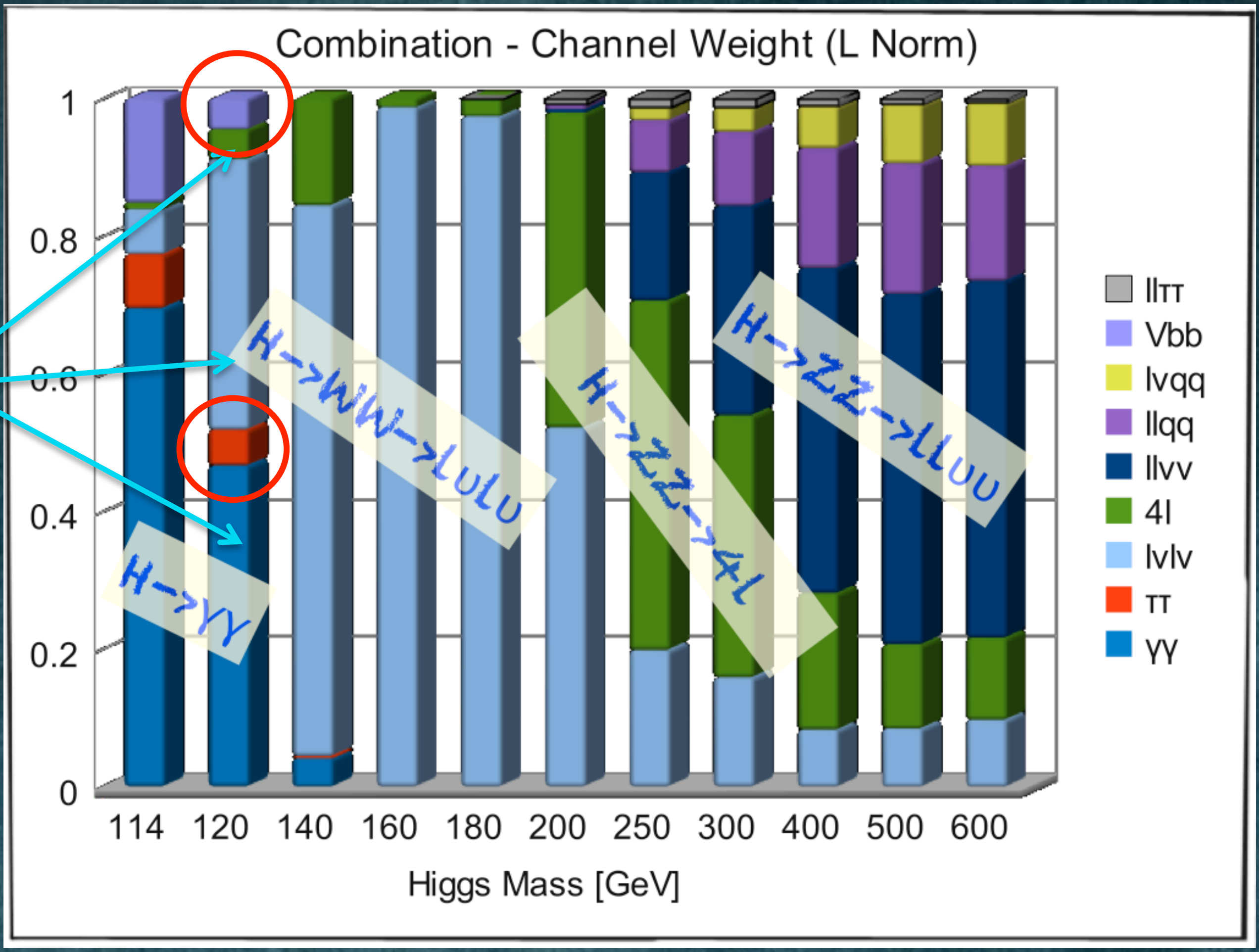
H -> γγ

H -> WW

H -> ZZ

are the most sensitive search channels

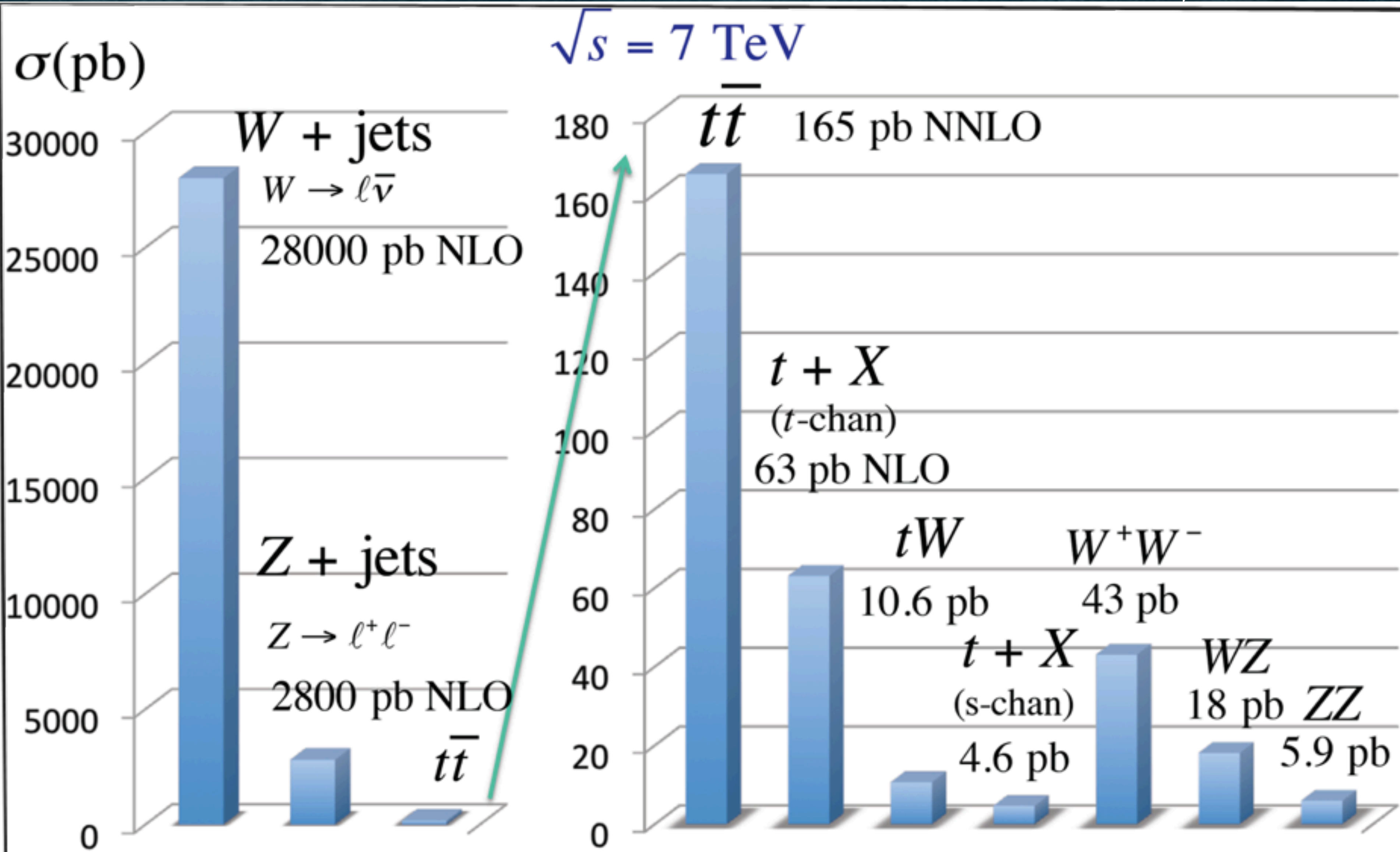
next: ττ and Wbb



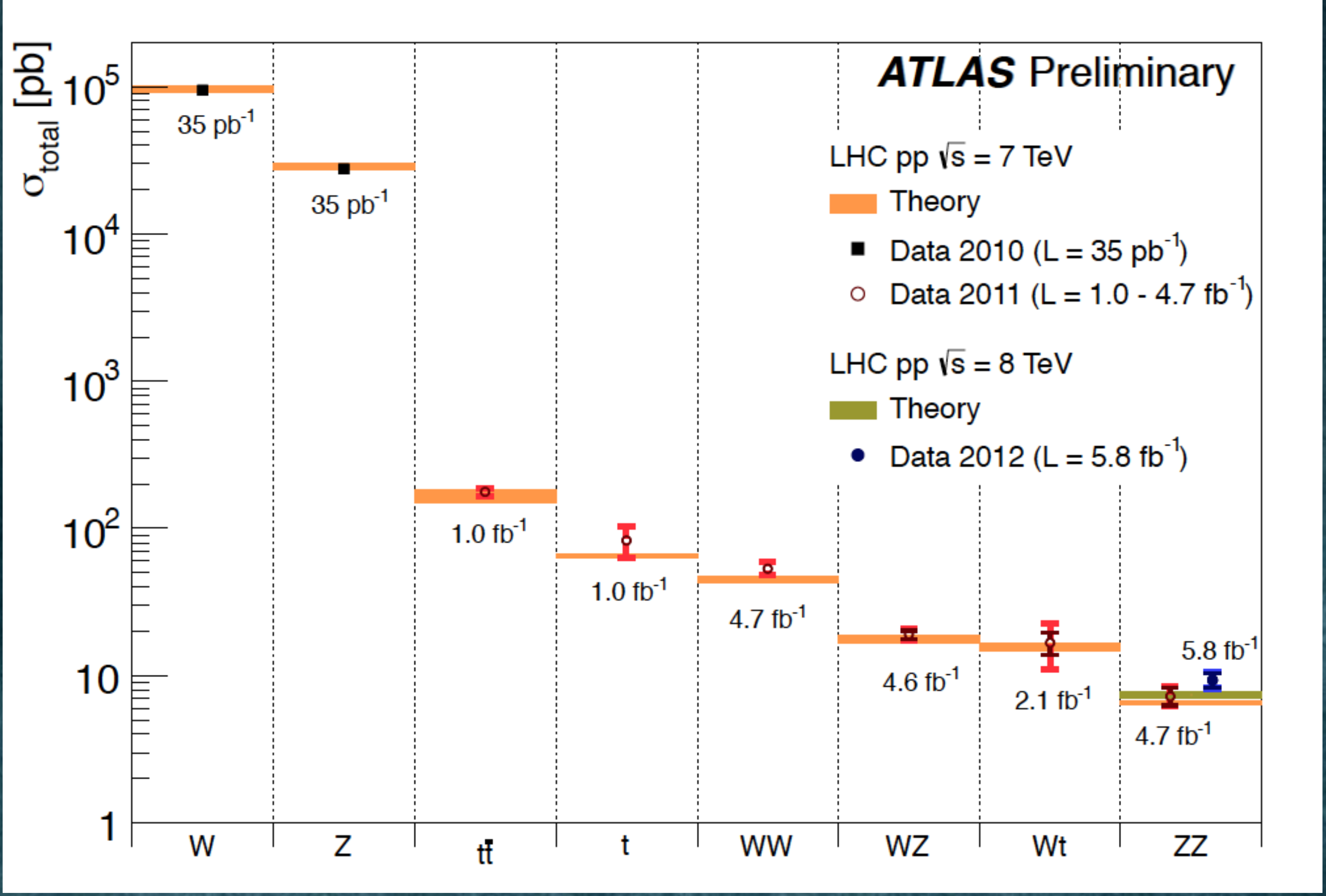
courtesy: E. Gross

The backgrounds (σ_{Higgs} ~ 10 fb - 10 pb)

... are fierce ...



… but are (largely) measured



Hypothesis testing and Limits (*)

1) Try to reject the H_0 hypothesis (opposite to what you look for)

i.e. "b": data consistent with background only, NO Higgs (observation test)

or "s+b": data consistent with Higgs+SM-background (exclusion test, limit)

2) Construct a likelihood for the data to be as they appear:

$$\mathcal{L}(\text{data} \,|\, \mu, \theta) = \text{Poisson}\,(\,\text{data} \,|\, \mu \cdot s(\theta) + b(\theta)\,) \cdot p(\tilde{\theta}|\theta)\,.$$

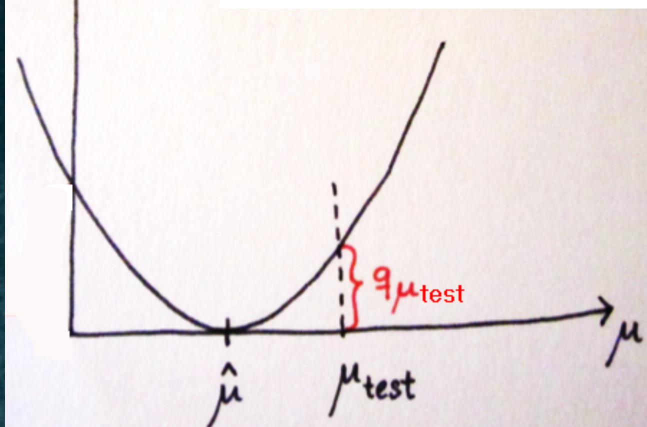
where $\mu = \boldsymbol{\sigma}/\boldsymbol{\sigma}_{SM}$ is the "signal strength factor",
θ is a set of "nuisance" quantities → treatment of systematics (e.g. bkg levels)

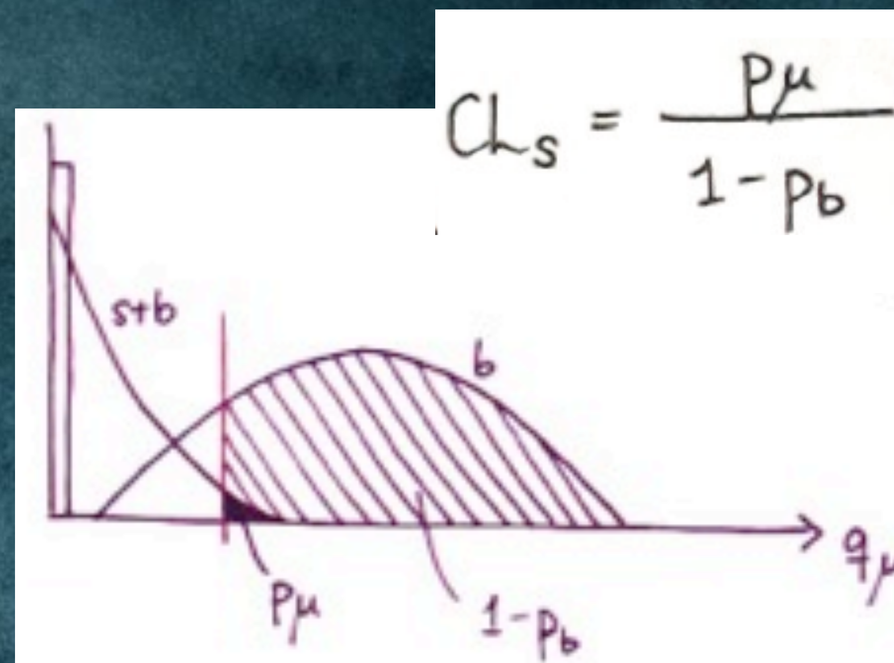
(*) see (1) A. Read; (2) Glowan, Cranmer, Gross, Vitellis; (3) T. Junk

Hypothesis testing and Limits

3) to assess whether the measured data are compatible with e.g. s+b
a “test statistic” is constructed (“hat” values are fitted):

$$q_\mu = -2\ln\frac{\mathcal{L}(\text{data}|\mu,\hat{\theta}_\mu)}{\mathcal{L}(\text{data}|\hat{\mu},\hat{\theta})}$$

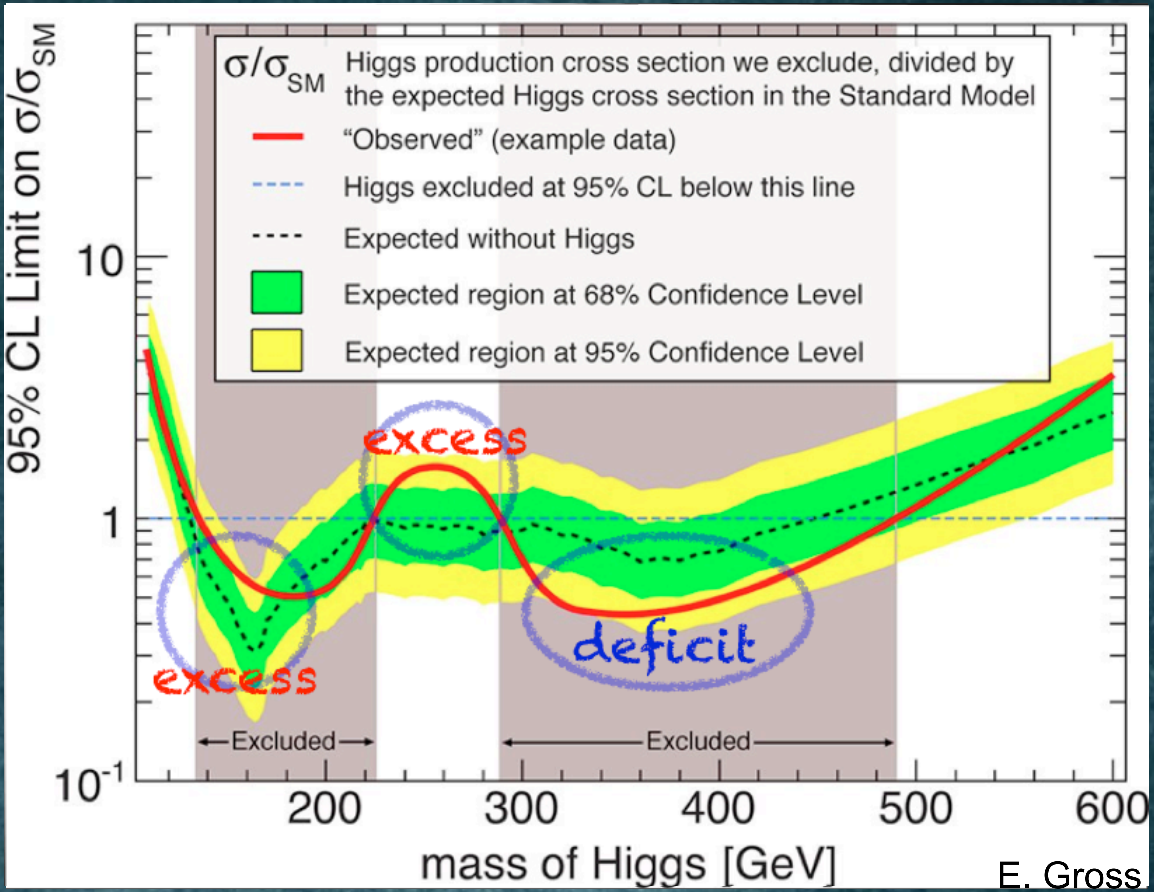




The green/yellow limit bands

4) If for **μ**=1 (=SM) CL_s < **5%**, we would state that the SM Higgs boson is excluded with 95% confidence level.

To find the 95% CL sensitivity bands we change μ (toy) until CL_s = 5% is reached.

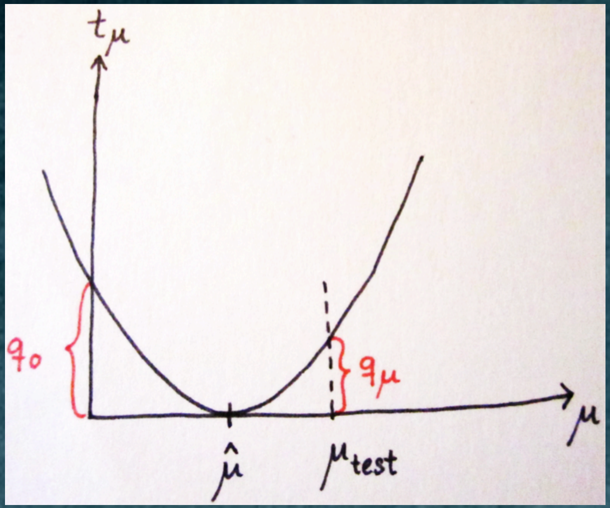


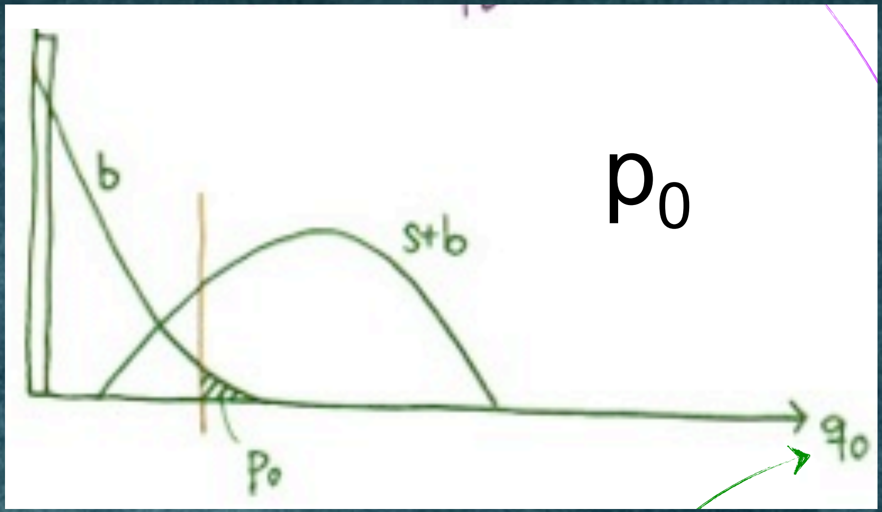
Hypothesis testing and Limits

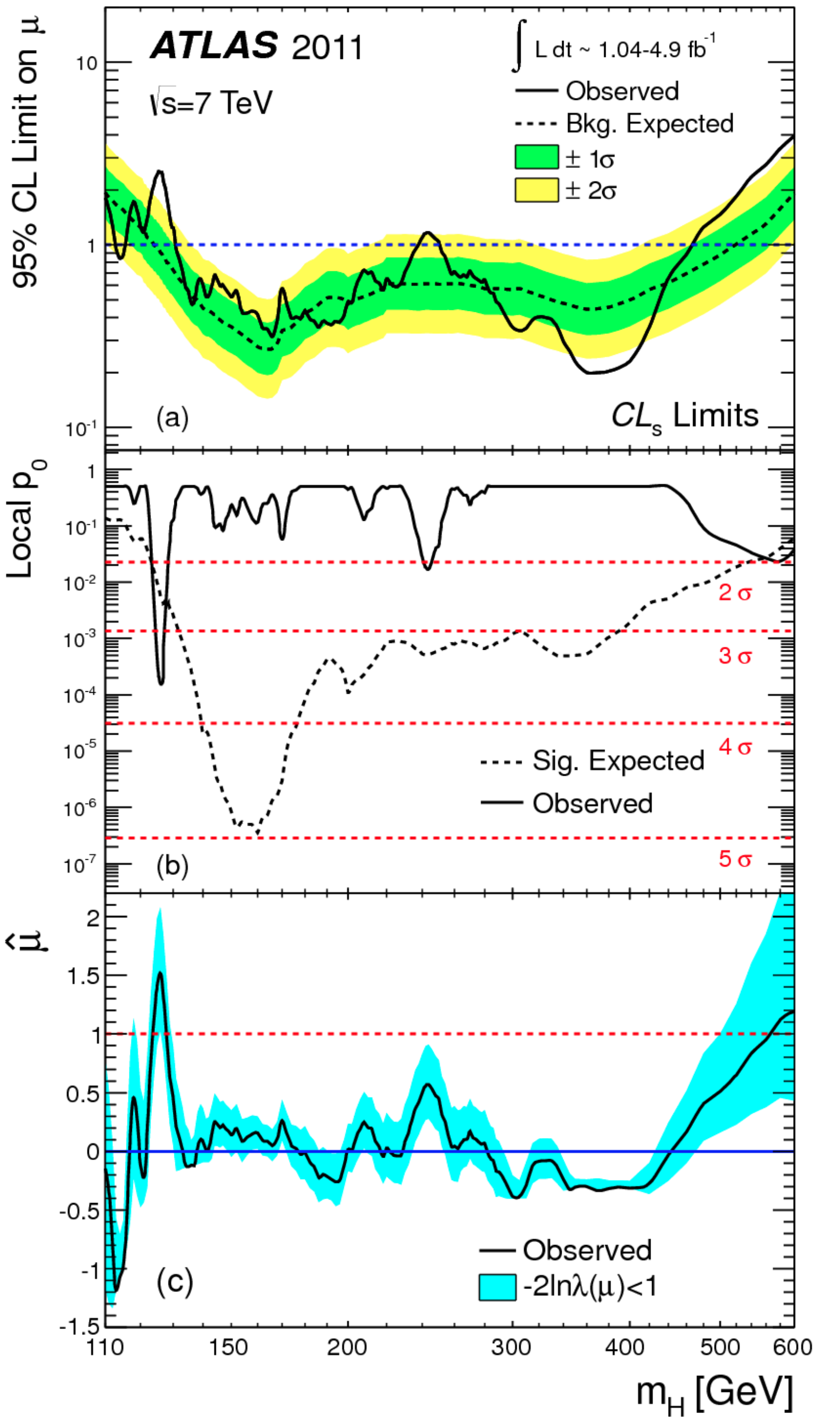
5) likewise we can test the background-only hypothesis (observation test)

$$q_0 = -2\ln\frac{\mathcal{L}(\mathrm{data}|\mu=0,\hat{\theta}_\mu)}{\mathcal{L}(\mathrm{data}|\hat{\mu},\hat{\theta})}$$

and ask for the probability p_0 that the data are consistent with it.







Do this for all possible Higgs test masses

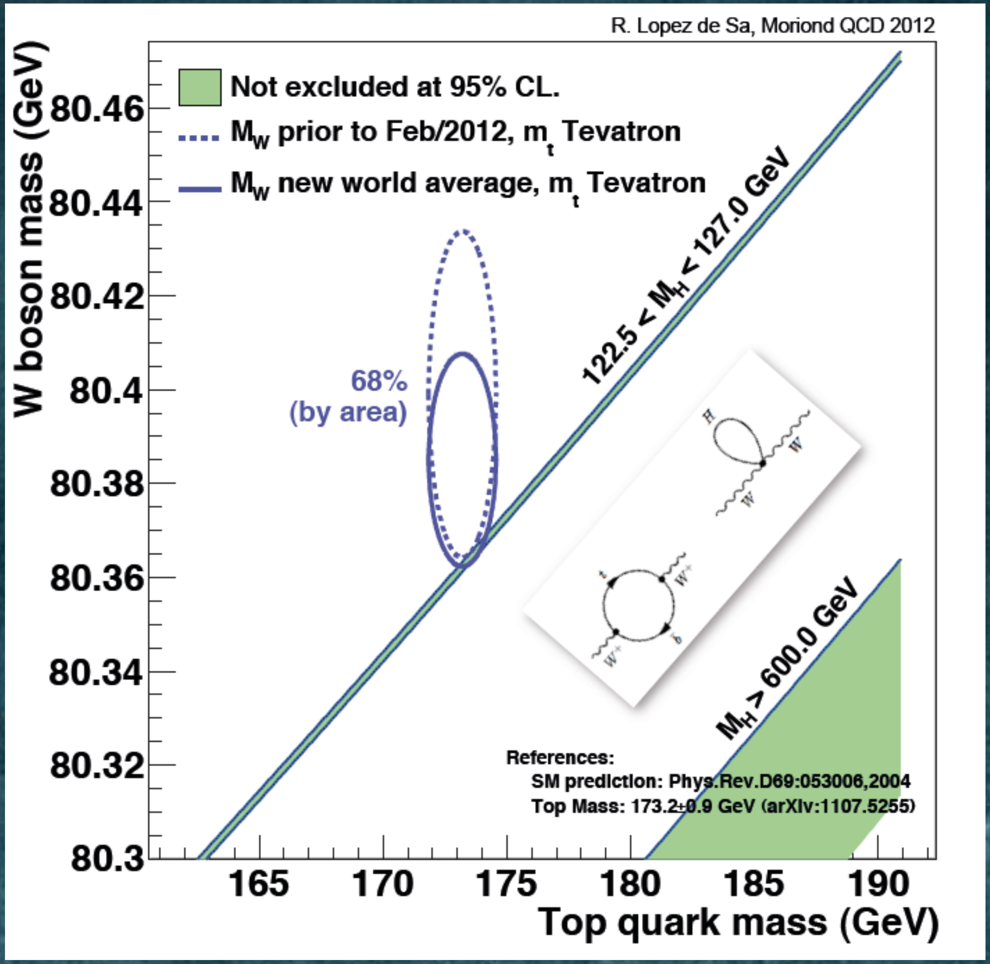
Situation before July 4th

s + b exclusion limits

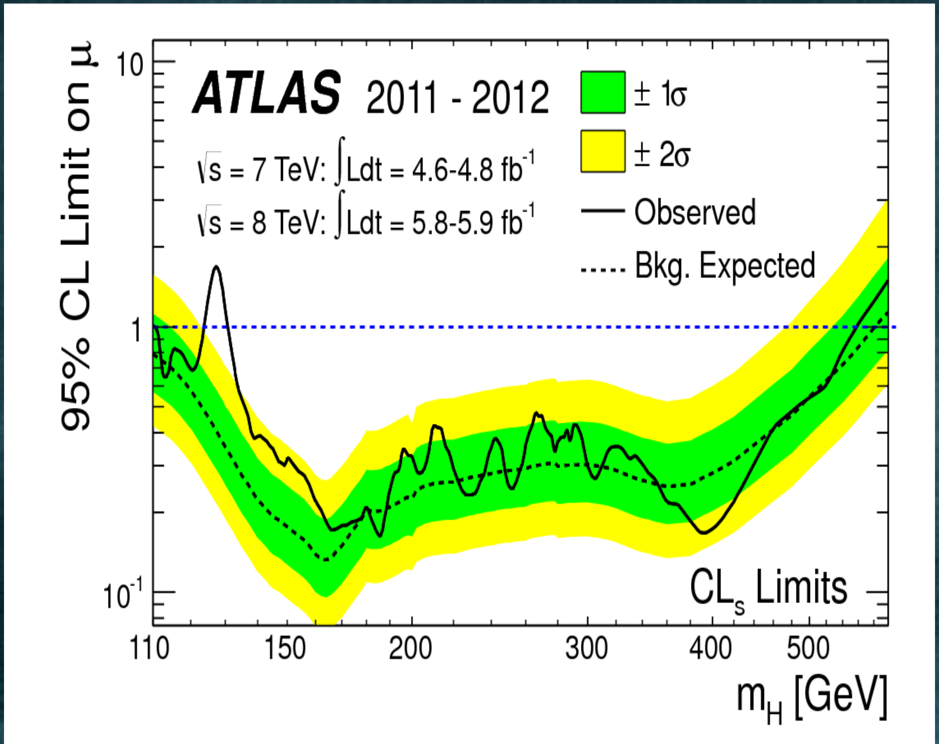
bkg only compatibility

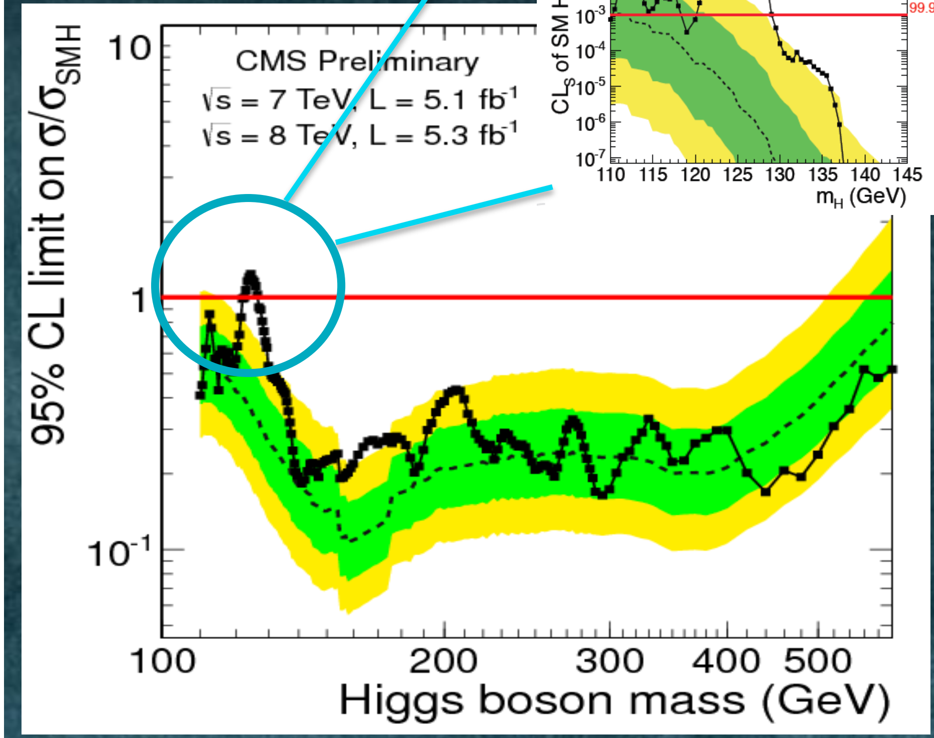
compatibility with SM Higgs hypothesis

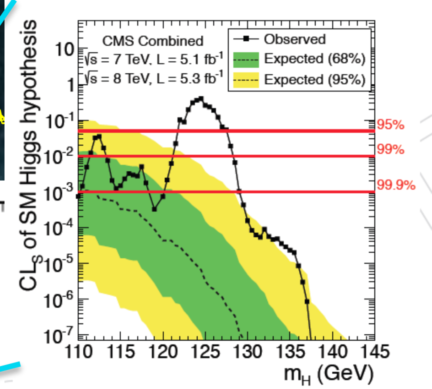
Together with knowledge of m_{top} and M_W The situation before 4th of July



July 4th ICHEP2012, exclusion







Expected: 110 < M_H < 582 GeV

Observed: 111 < M_H < 122 GeV and 131 < M_H < 559 GeV

110 < m_H < 600 GeV

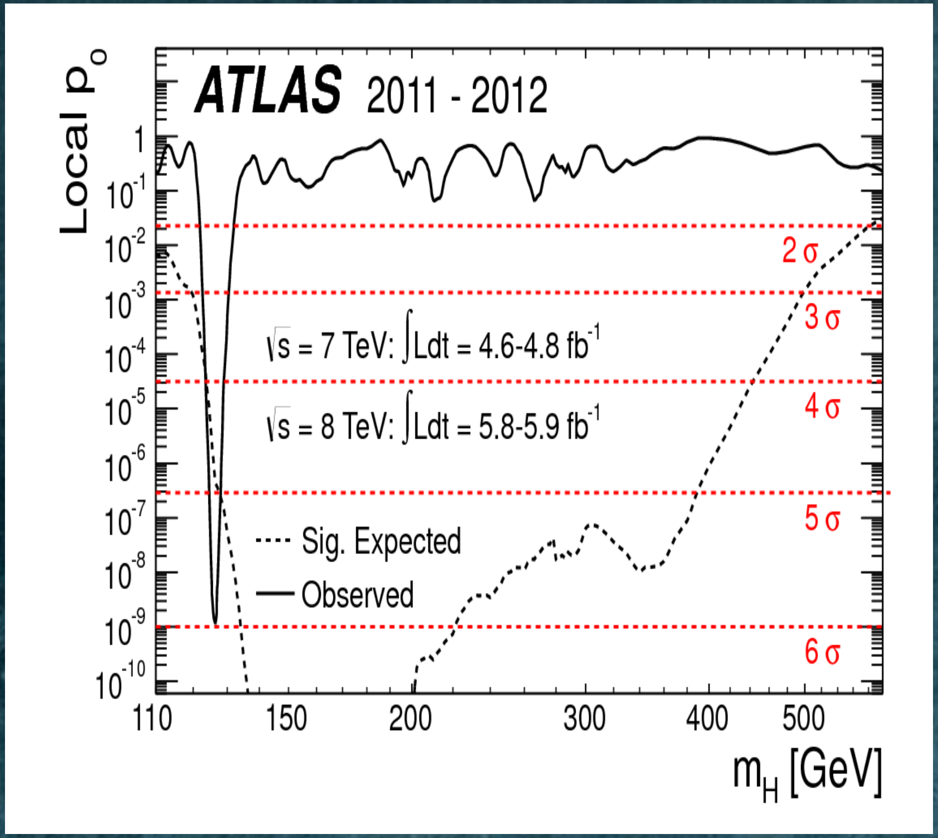
110 < M_H < 121.5 GeV and 128 < M_H < 600 GeV

in a signficant mass range a SM Higgs is excluded

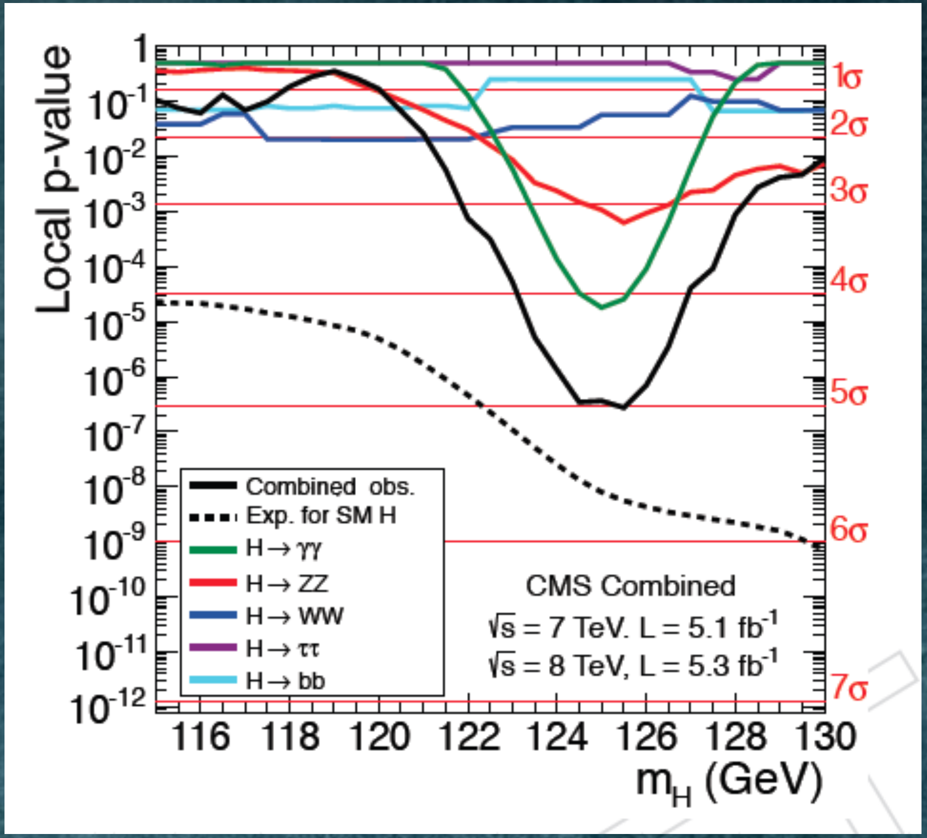
in both experiments exclusion is much weaker than expected at low masses

Higgs discovery test: (p_0) consistency with background only hypothesis

development with time: 3 channels



contribution of 5 decay channels



5.9 σ for m_H~126.5 GeV

5.0 σ for m_H~125.5 GeV

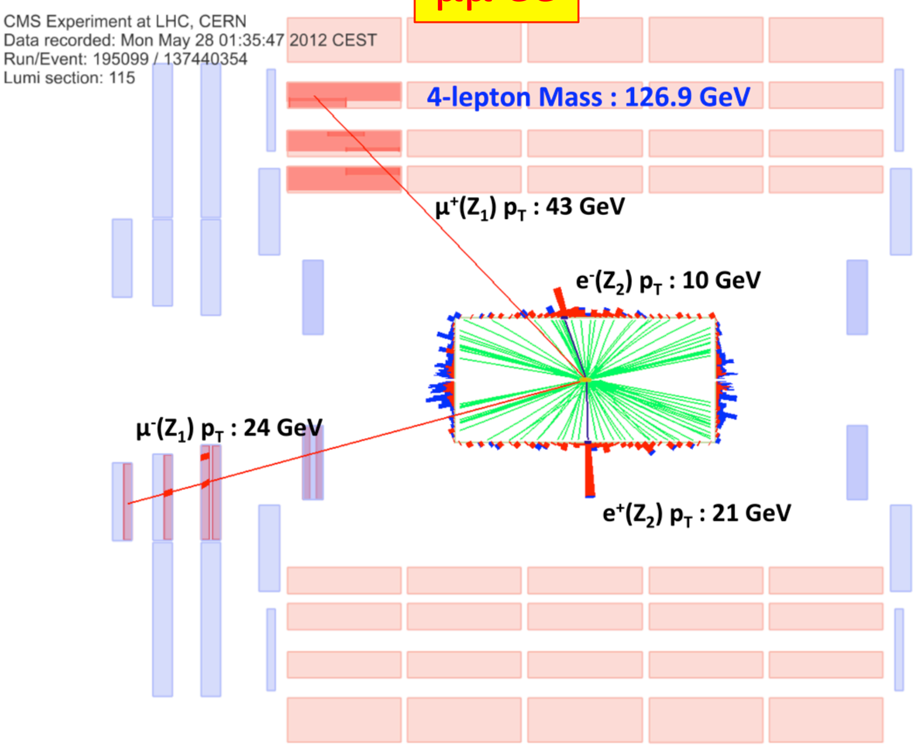
w/ LEE: 5.1(5.3) σ in 110<M_H<600(150) GeV

4.6(4.5) σ in 110 < M_H <130 (145) GeV

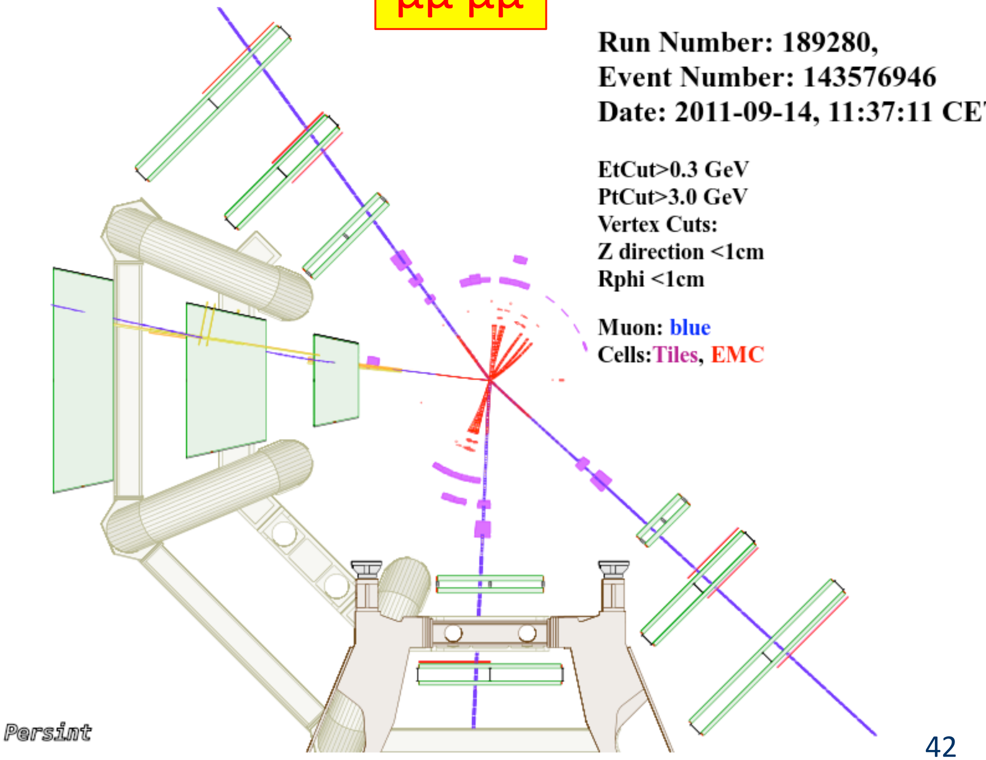
The Golden Channel H → $ZZ^{(*)}$ → 4l

- small signal rate at low Higgs mass
- 4 isolated leptons, consistent with decay Z→2 l
- reconstruction of M_{4l}
- good mass resolution: ~2 GeV

μμ ee

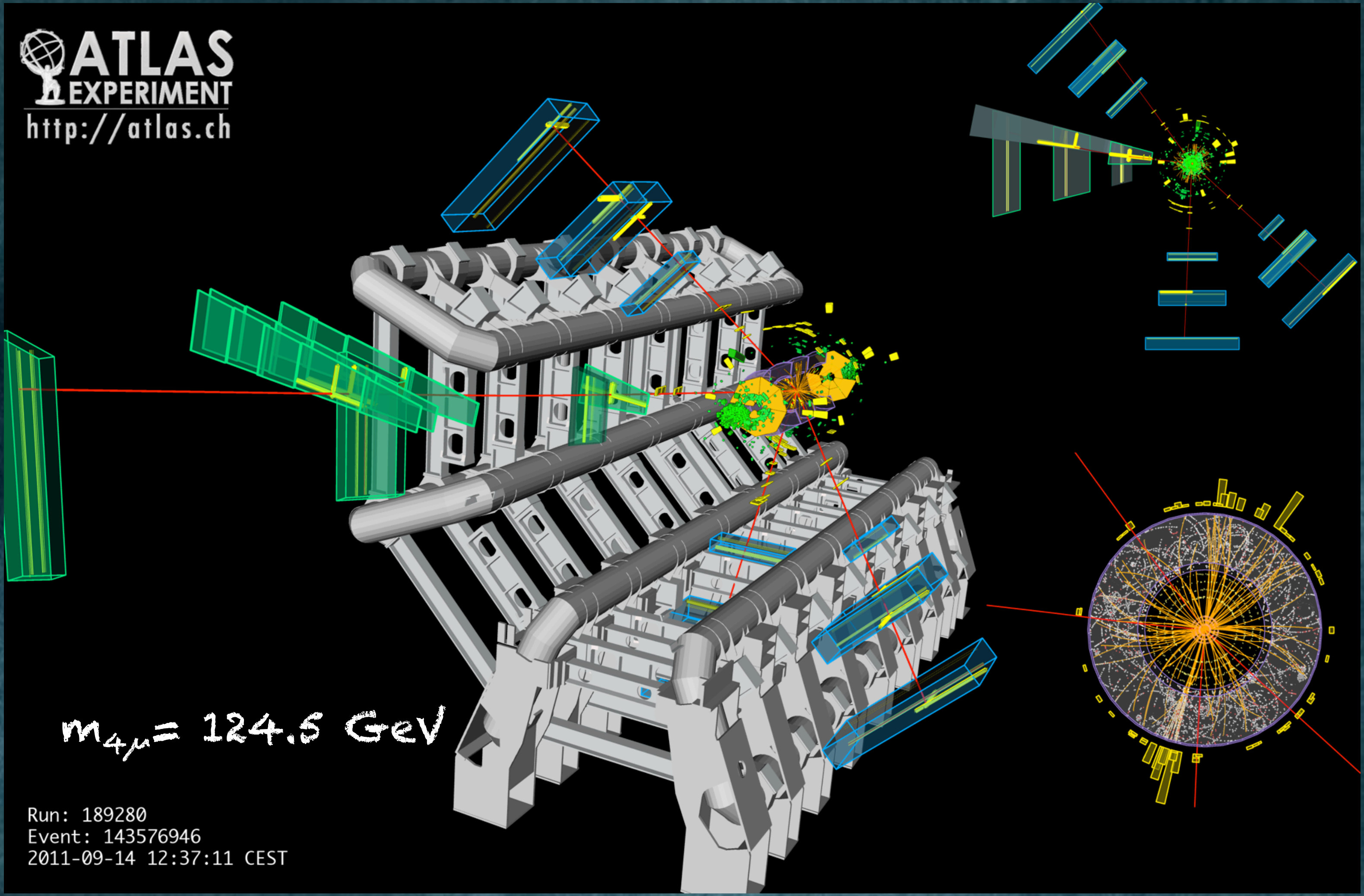


μμ μμ

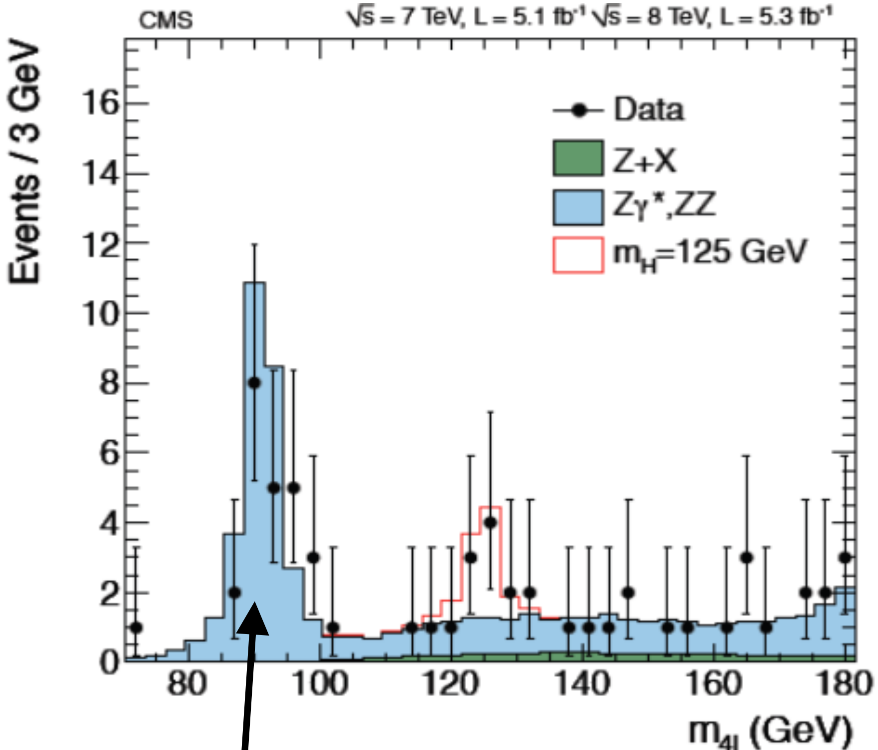


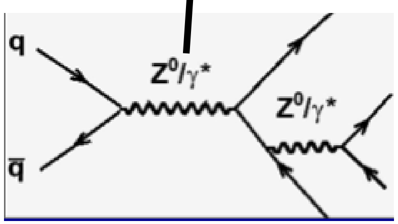
H -> ZZ -> μμ μμ

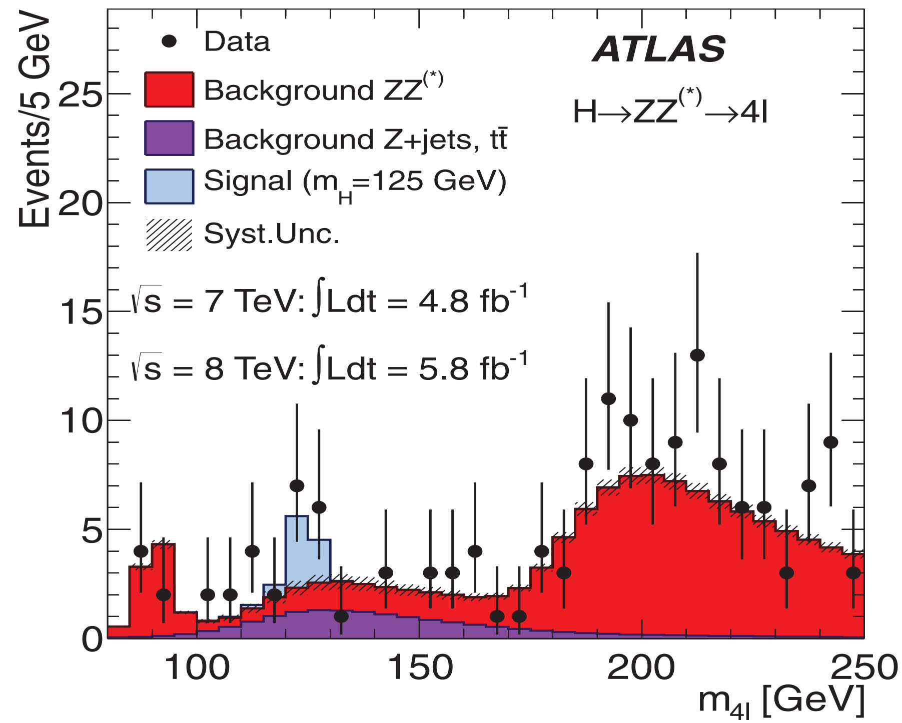
- very clean but low rate
- kinematics can be fully reconstructed: $m_{2\mu}$, $m_{4\mu}$



H→ZZ→4l





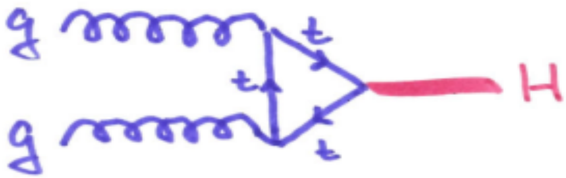


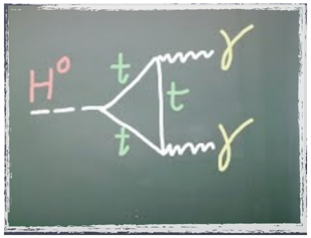
excess at M_{4l} = ~125 GeV

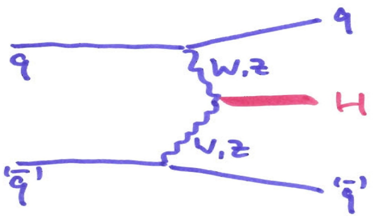
excess at M_{4l} = 125.6 GeV

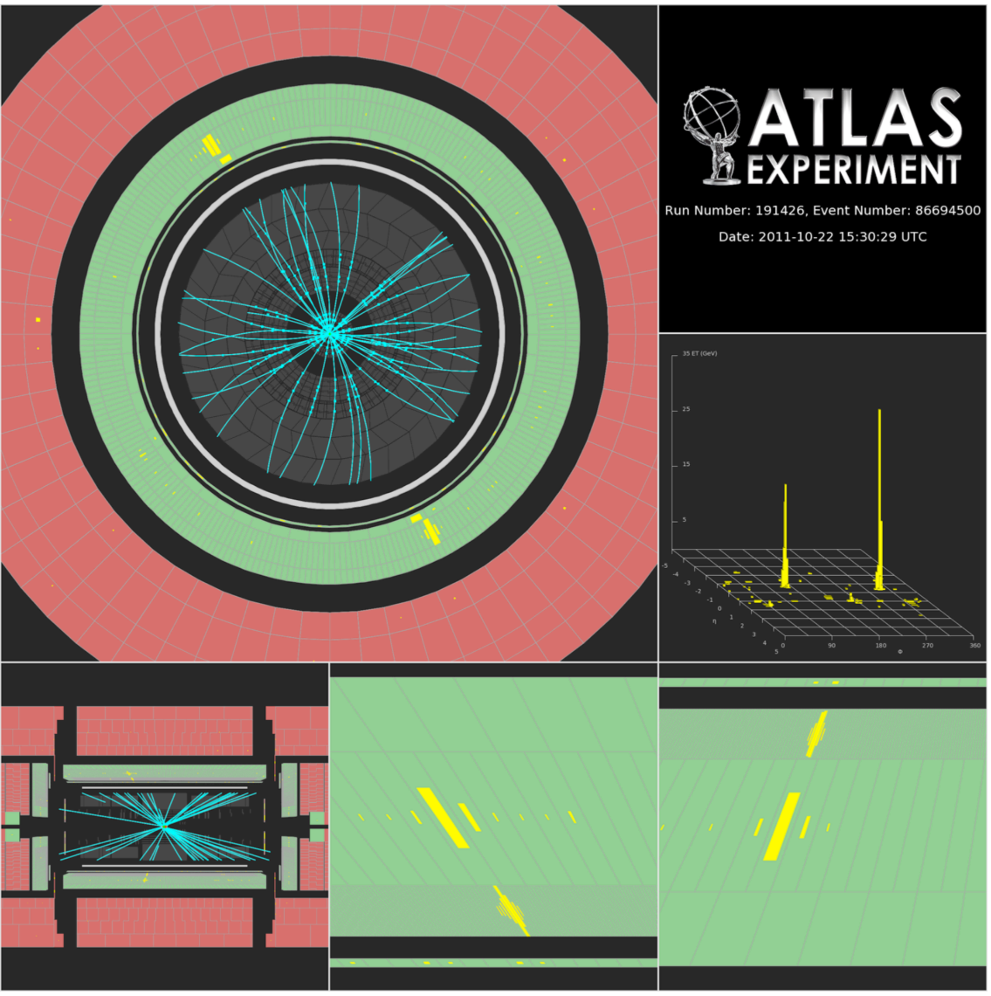
	ATLAS	CMS(*)
4l		
Background	5.1	4.17
Data	13	7
mH=125 GeV	5.3	~8.
S/B	1.04	1.9

H → 2 Photons









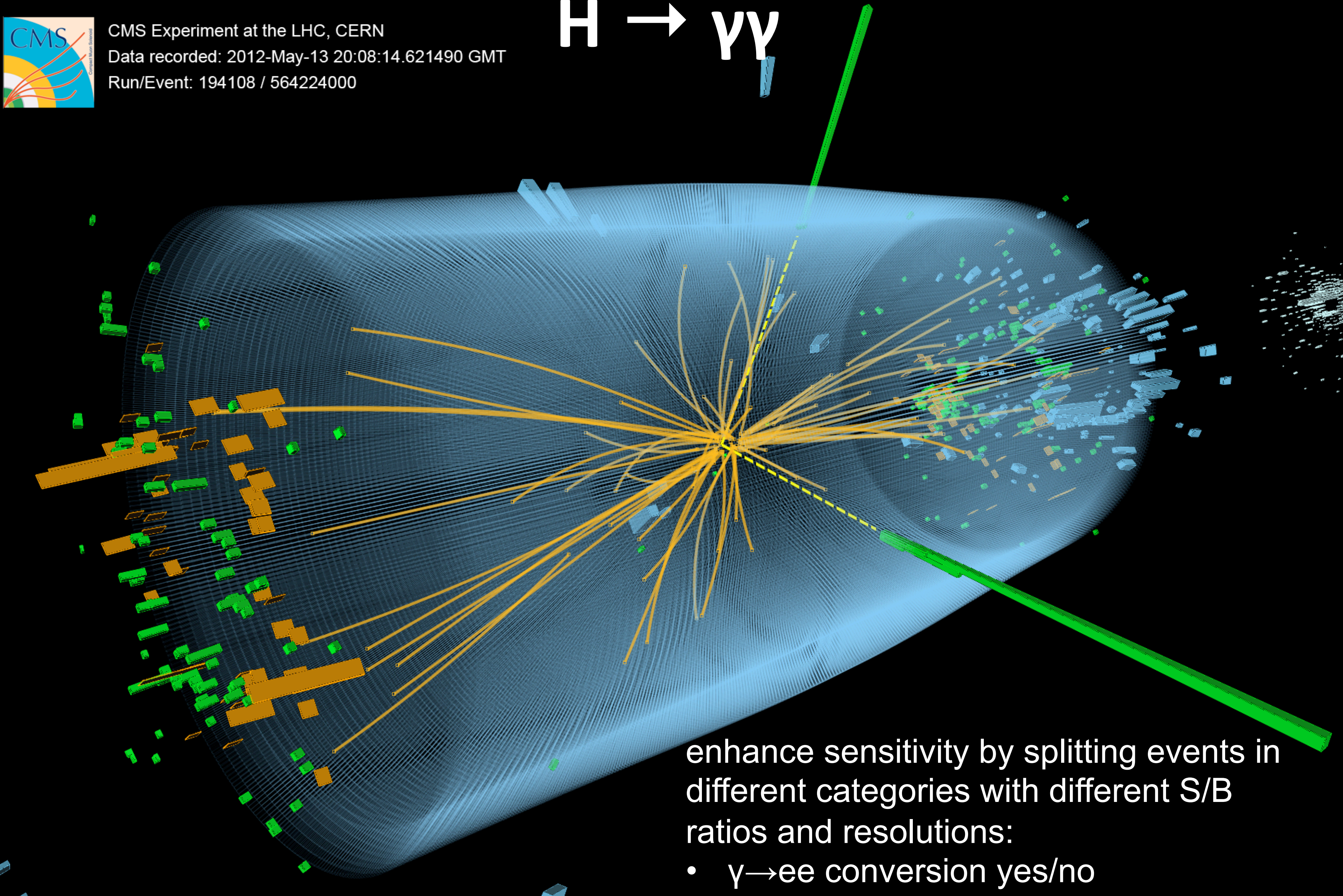
- clean identification of high p_T photons
- reconstruction invariant di-photon mass

- ATLAS: longitudinally segmented LAr calorimeter

- CMS: $PbWO_4$ crystal calorimeter

- mass resolutions 1.5 - 2 GeV

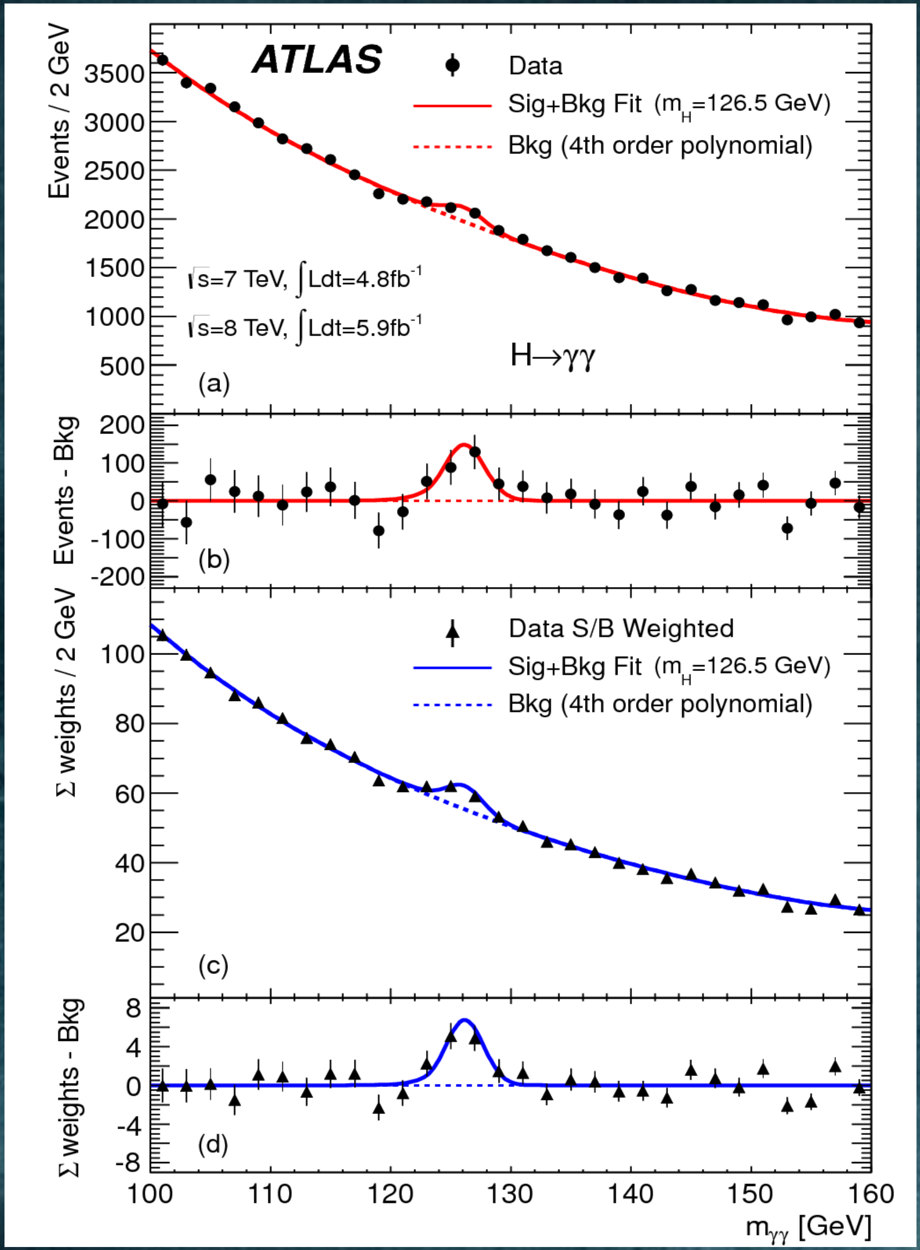
$H \to \gamma\gamma$

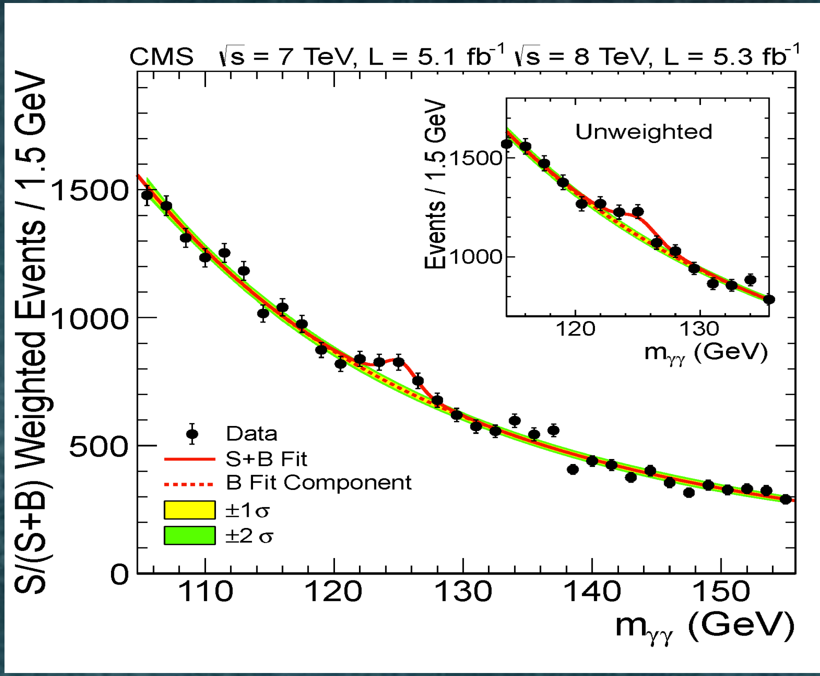


enhance sensitivity by splitting events in different categories with different S/B ratios and resolutions:

- γ→ee conversion yes/no
- central/forward region of detector
- etc.

H → γγ mass Spectrum



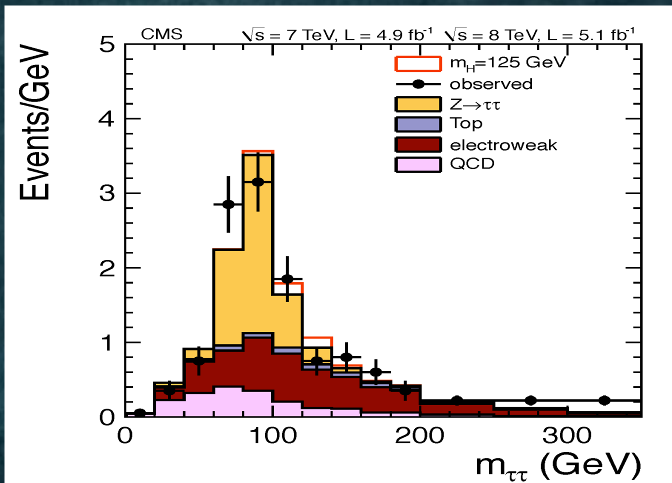


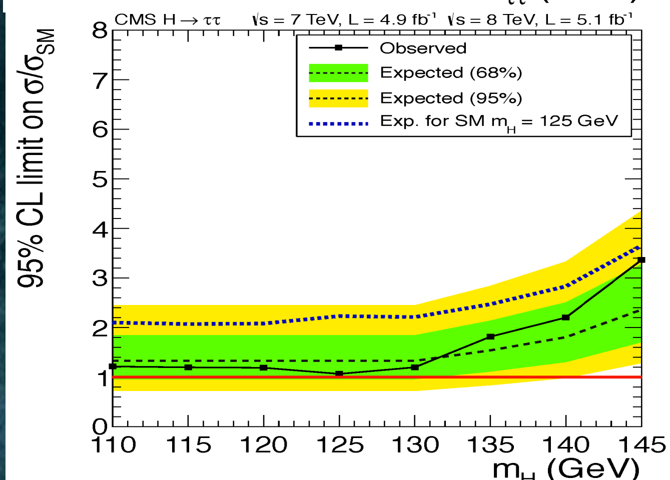
CMS: excess at 125 GeV
signal strength: 1.6±0.4 x SM

ATLAS: excess at $M_{\gamma\gamma}$= 126.5 GeV
signal strength 1.8±0.5 x SM

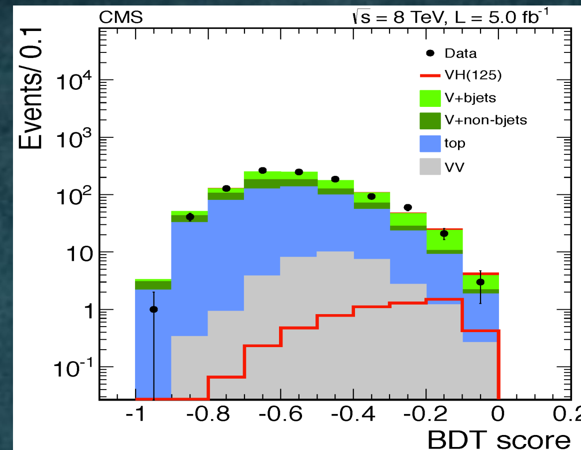
H→ ττ, H→bb, and H→WW

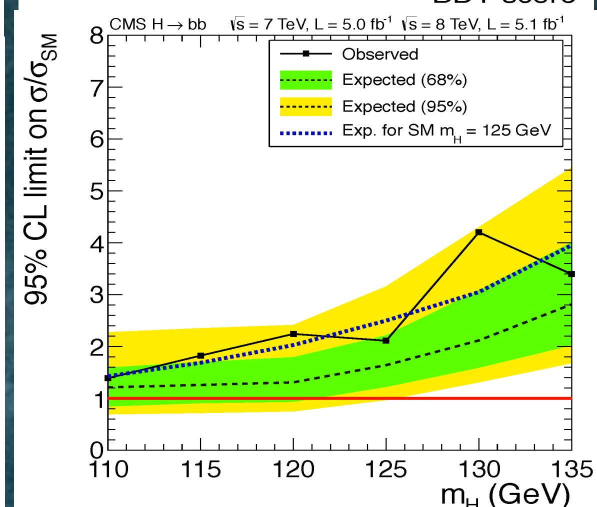
H→ττ



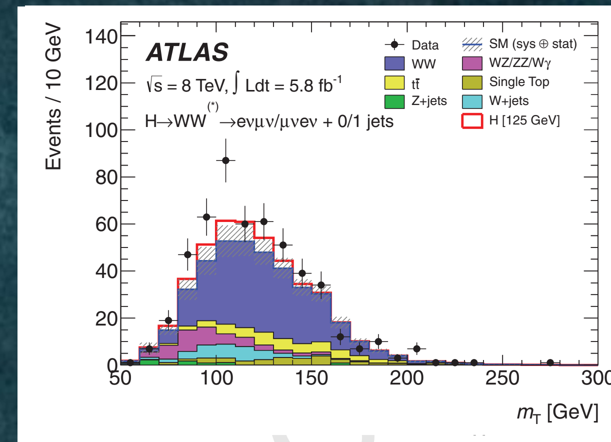


VH, H→bb

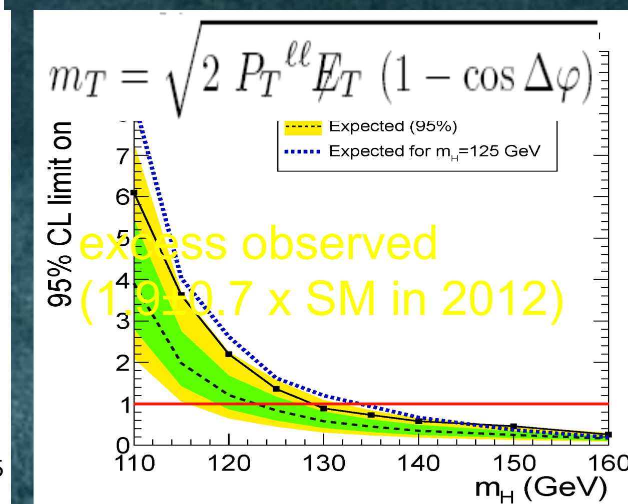




H→WW→lνlν



$$m_T = \sqrt{2\, P_T^{\ell\ell} \not{E}_T \left(1 - \cos\Delta\varphi\right)}$$



excess observed
(1.9±0.7 x SM in 2012)

observed (expected) sensitivities at M_H=125 GeV

limit: 1.1 (1.3 exp)

limit: 2.1 (1.6 exp)

limit: 1.4 (1.6 exp)

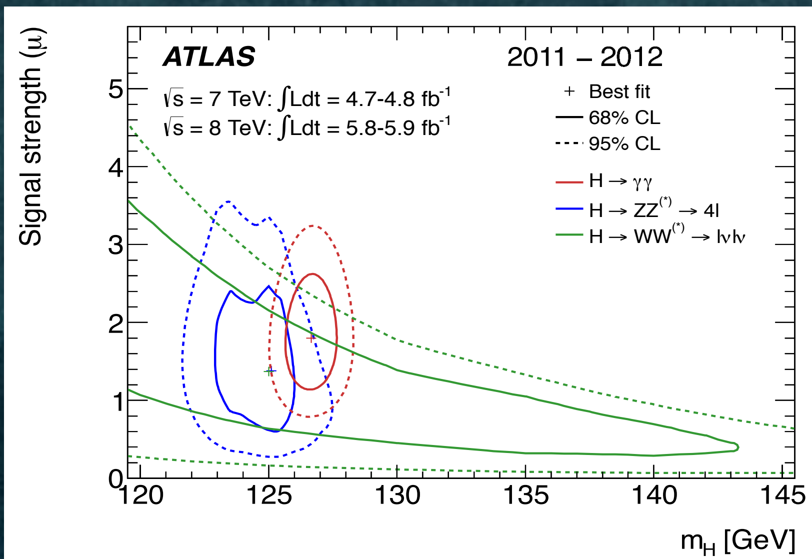
Is the Higgs THE Higgs?

- mass
- spin and parity (J^P)
- CP (even, odd or a mixture)
- couplings to vector bosons
  - is this particle related to EWSB ?
  - is custodial symmetry at work ?
- couplings to fermions
  - is Yukawa - interaction at work ?
- only one Higgs ? elementary or composite ?
- does it show self interaction … HHH ?
- is it condensed in the universe ?

Mass versus Signal Strength

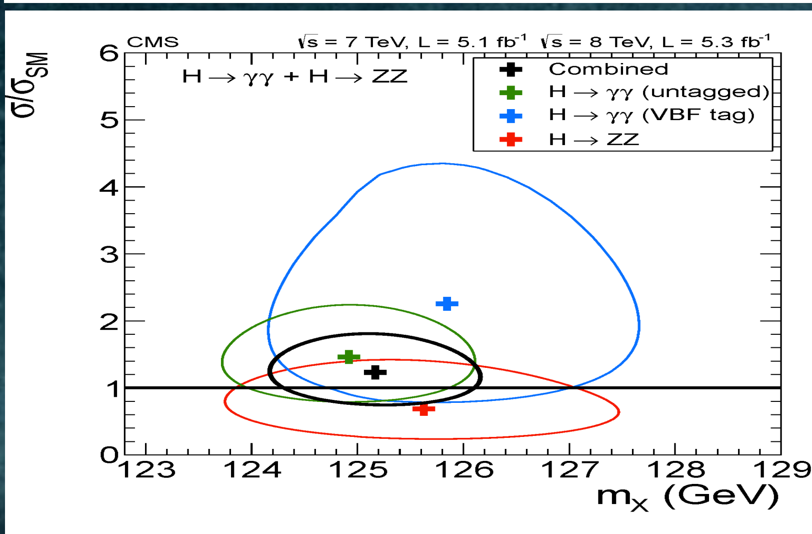
in each final state: determine best μ and M_H

$$\lambda(\mu, m_H) = \frac{L(\mu, m_H, \hat{\hat{\theta}}_\mu)}{L(\hat{\mu}, \hat{m}_H, \hat{\theta}_\mu)}$$



ATLAS:

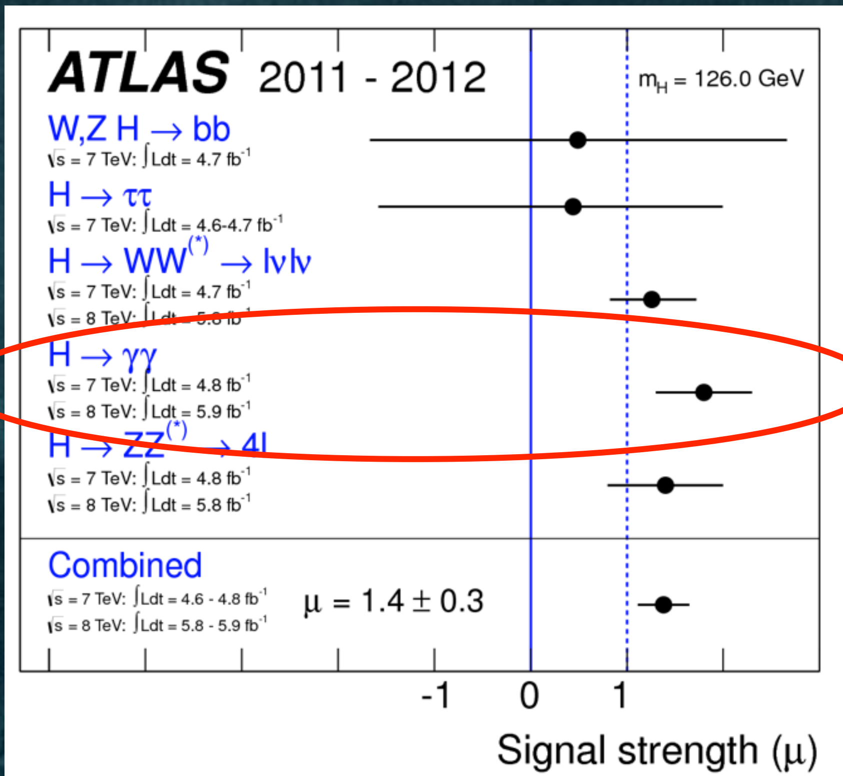
M_{new}= 126.0 ± 0.4(stat) ±0.4 (sys) GeV

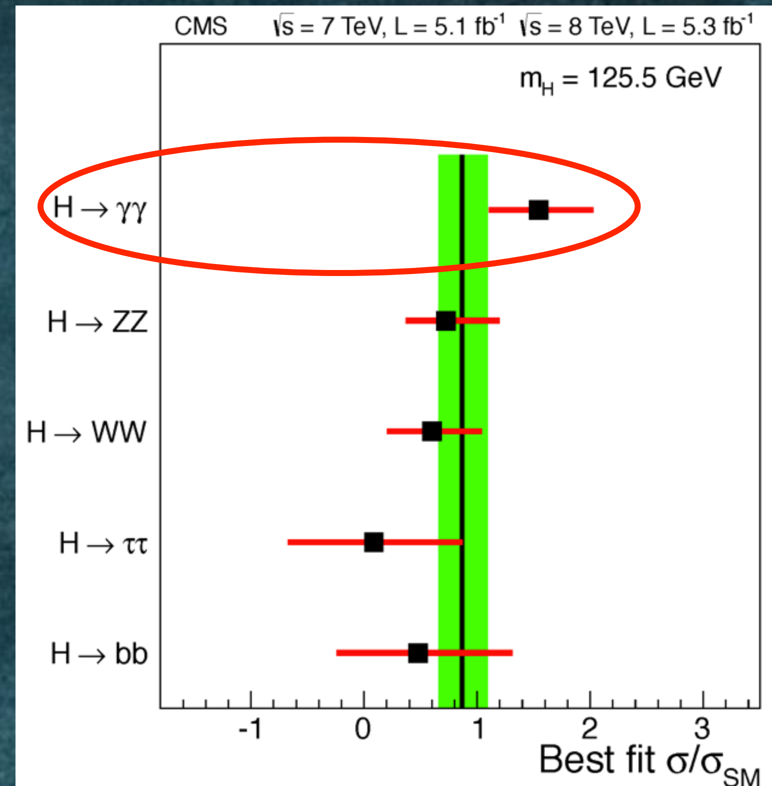


CMS:

M_{new}= 125.3 ± 0.4(stat) ± 0.5(sys) GeV

Signal strength per decay mods





overall consistent with SM

ATLAS: 1.4 ± 0.3 @126 GeV CMS: 0.87 ± 0.23 @ 125 GeV

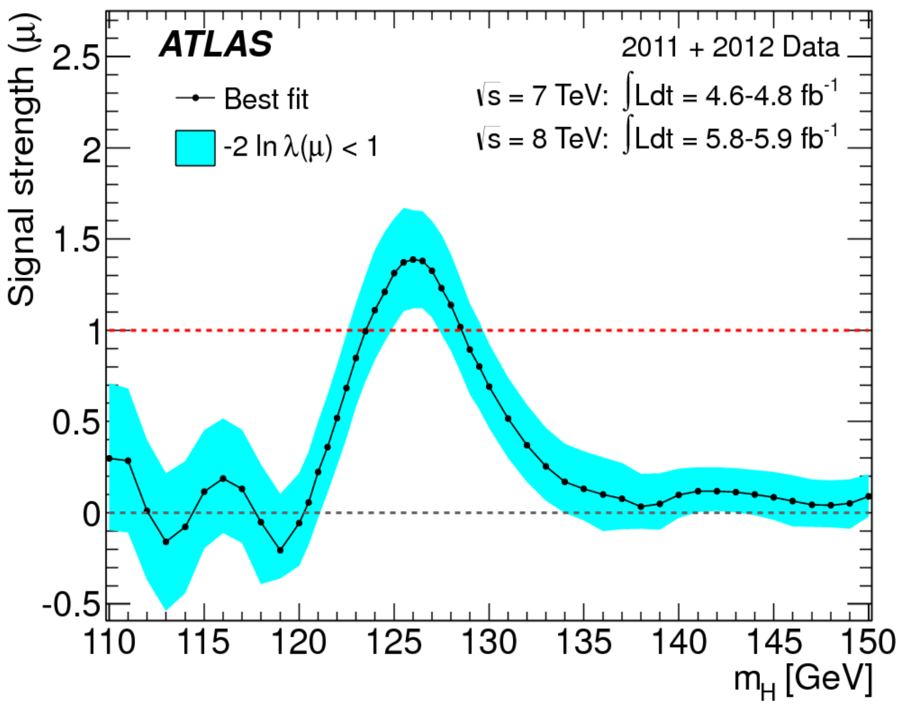
currently most striking observation: high γγ – rate

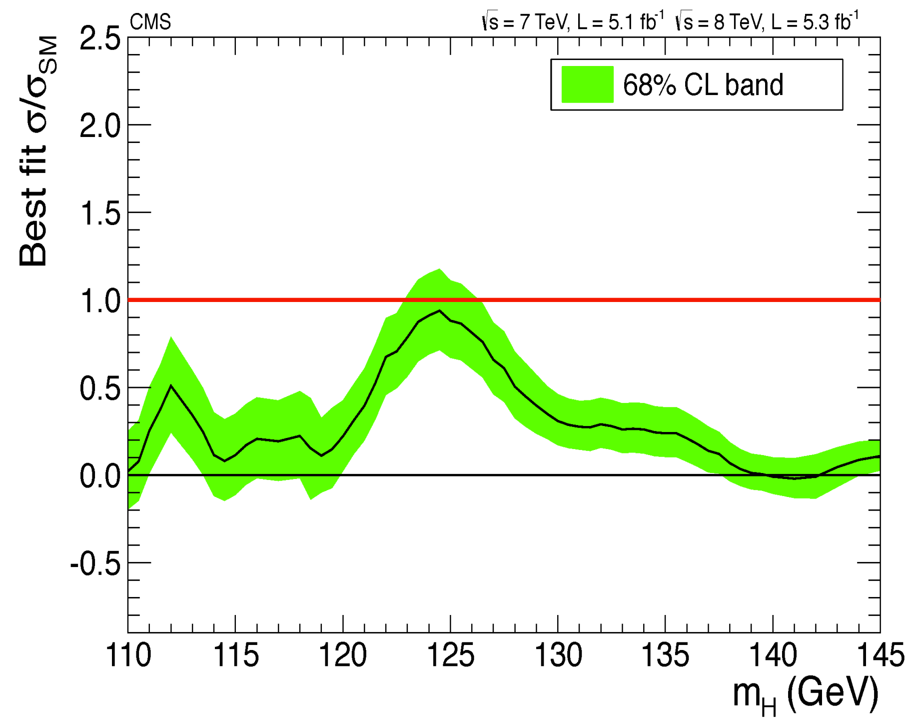
ATLAS: 1.8 ± 0.5 CMS: 1.6 ± 0.4

Overall signal strength

Determination of the “best” signal strength $\mu = \sigma_{beob}/\sigma_{SM}$ for each hypothetical M_H

assumption: ratio of σ_{Prod}’s and BR’s are as predicted in Standard Model





largest signal strength at m_H= 126.0 GeV

μ = 1.4 ± 0.3

largest signal strength at m_H= 125.5 GeV

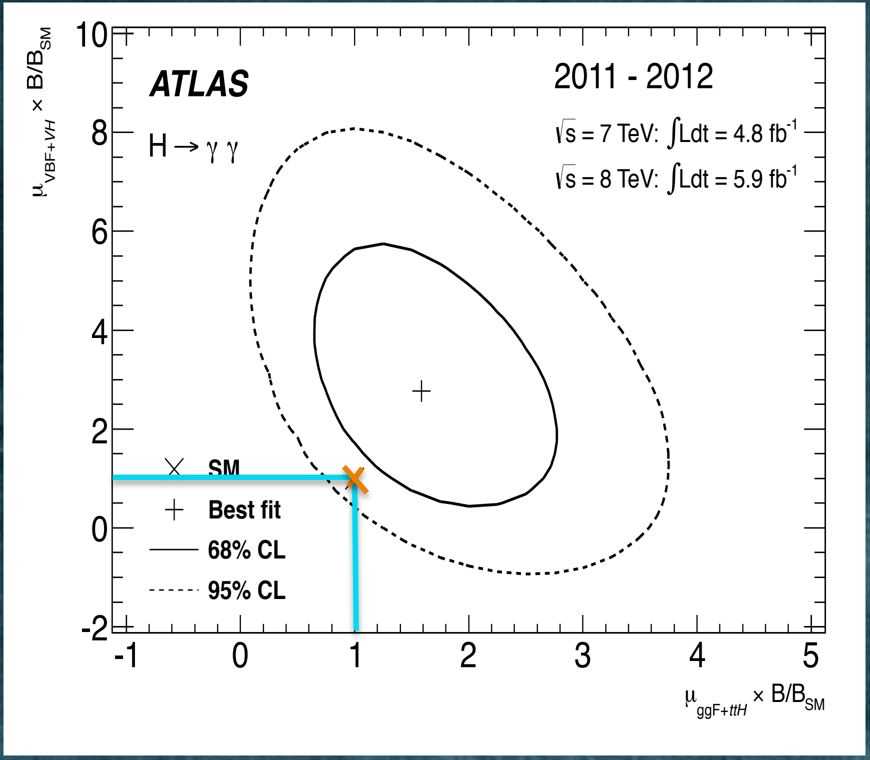
μ = 0.87 ± 0.23

consistent with expectation in Standard Model

A first look at the couplings

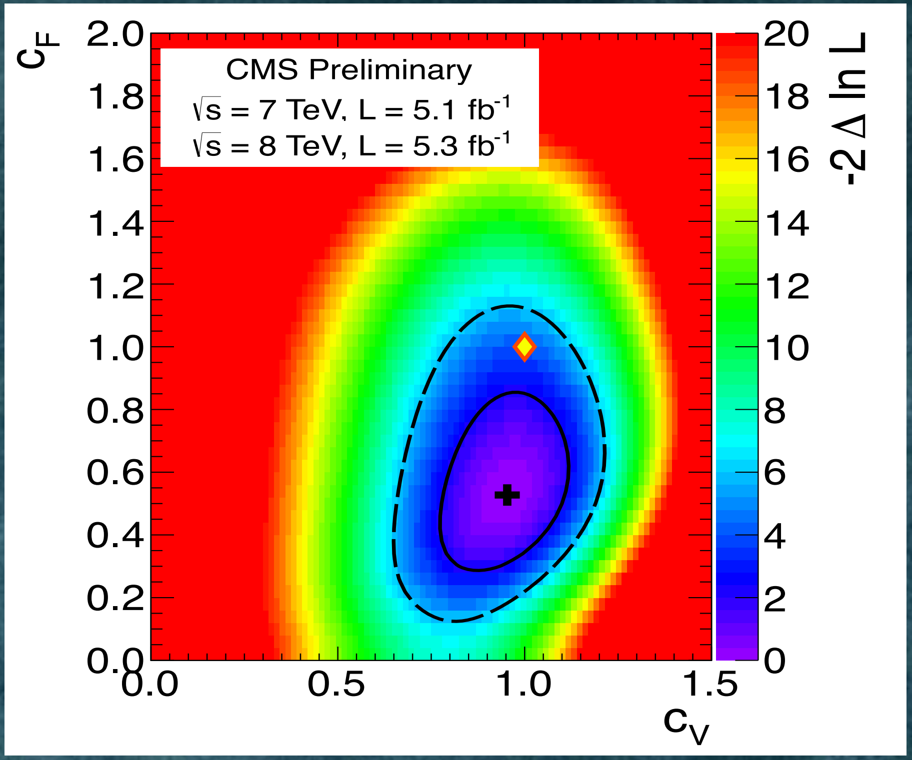
assumed: only SM decays and only SM particles in loops

ATLAS: test $H \rightarrow \gamma\gamma$ decay
assume: $gg \rightarrow H$ and ttH scale with $\mu_{ggF+ttH}$
VBF and VH scale with μ_{VBF+VH}



consistent with SM at 1.5 σ level

CMS: test fermion against boson coupling
assume: common scaling of
- H to fermion by C_F
- H to W/Z by C_V

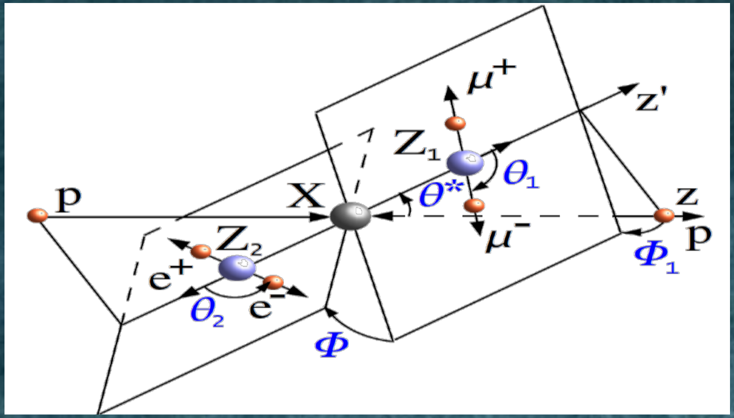


consistent with SM at < 2σ level

Spin and Parity ?

- Cannot be spin 1 due to Yang's theorem

- J^P tests ongoing
  - use angular correlations in ZZ^*, WW^* and $\gamma\gamma$
  - can separate 0^+ vs 0^- or 2^+ at 4σ level in 2012



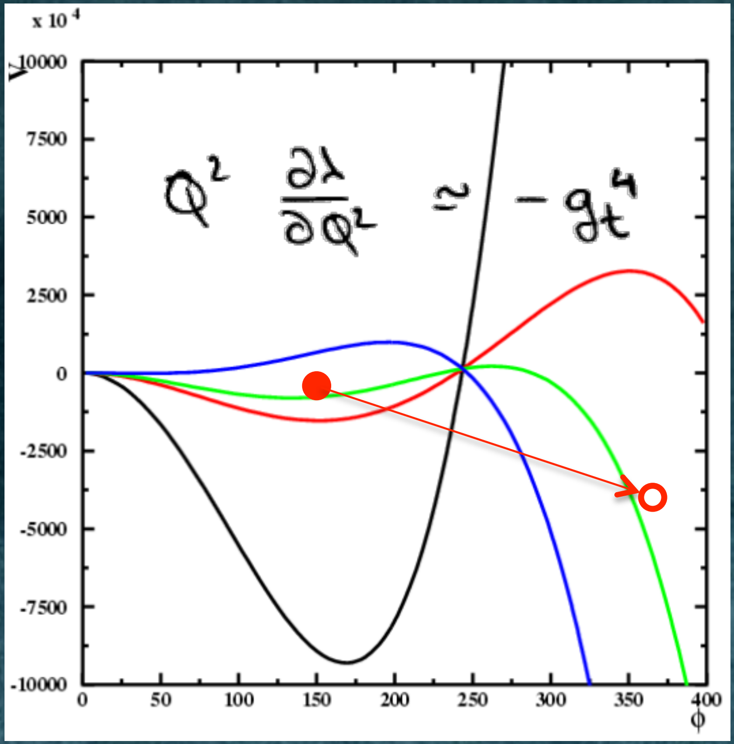
- CP more tricky as mixture of CP-odd/even possible -> distinguish pure odd from pure even at 3.5σ soon.

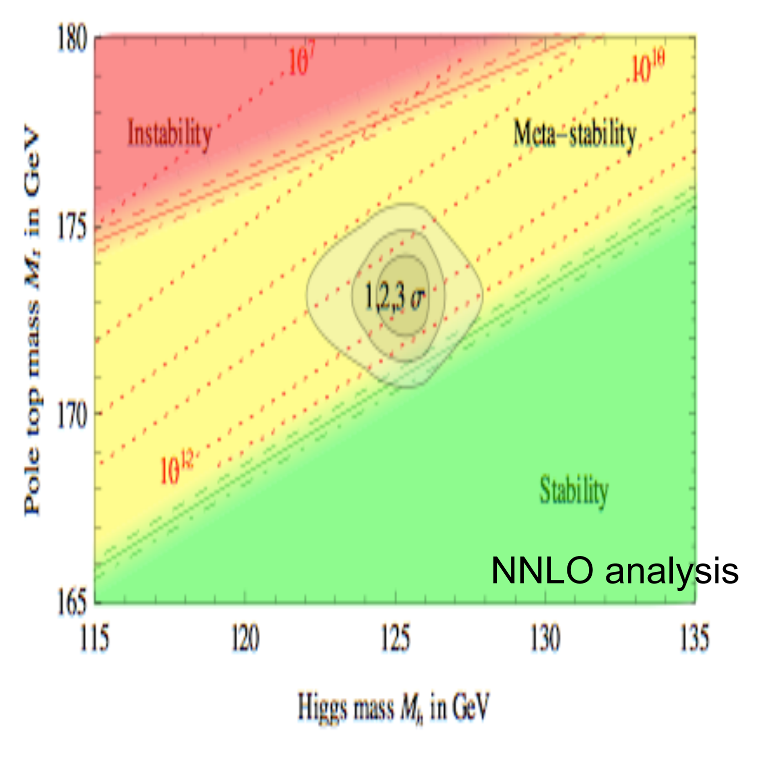
Standard Model (meta)-stable up to M_{pl} ?

See e.g.: Cabibbo, et al.; Hung (79); Elias-Miro, et al. (11); Degrassi et al.; Alekhin et al.; Bezrukov et al. (12)

$$V(\phi) \simeq -\mu^2 \phi^* \phi + \lambda(\phi^* \phi)^2$$

m_{top} and m_H well known



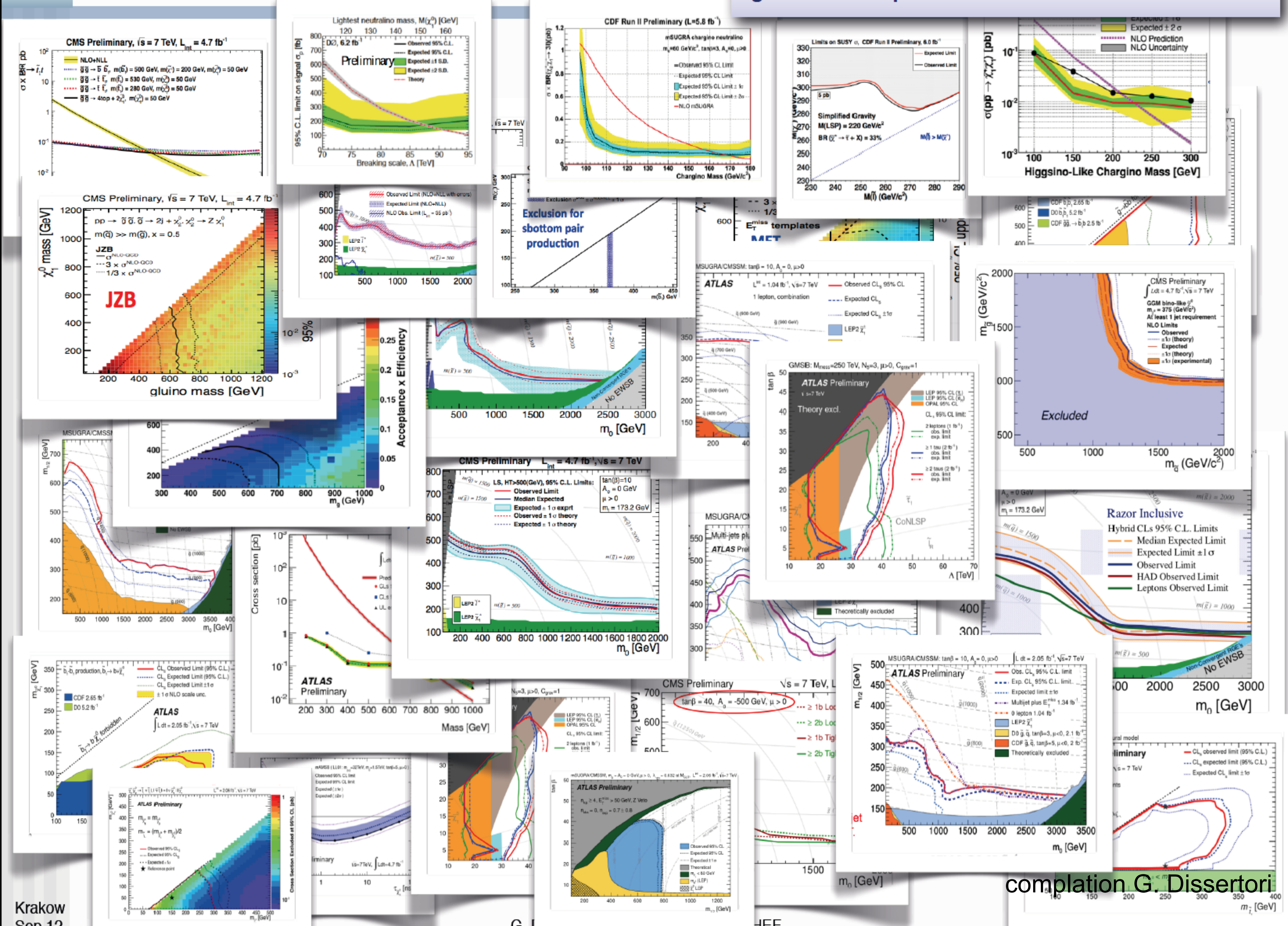


Degrassi, Vita, Elias-Miro, Espinosa, Giudice, Isidori & Strumia

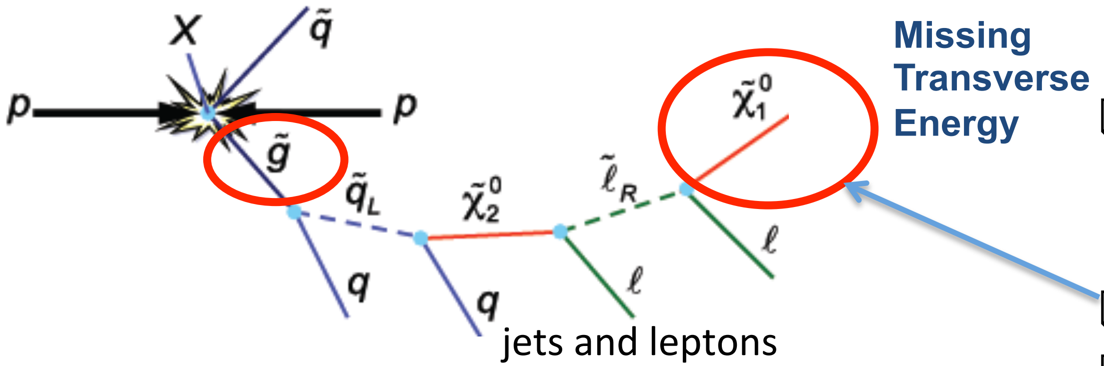
if top were heavier by only 3% => instability
but also: SM may be (meta-)stable up to M_{PL}

SUSY

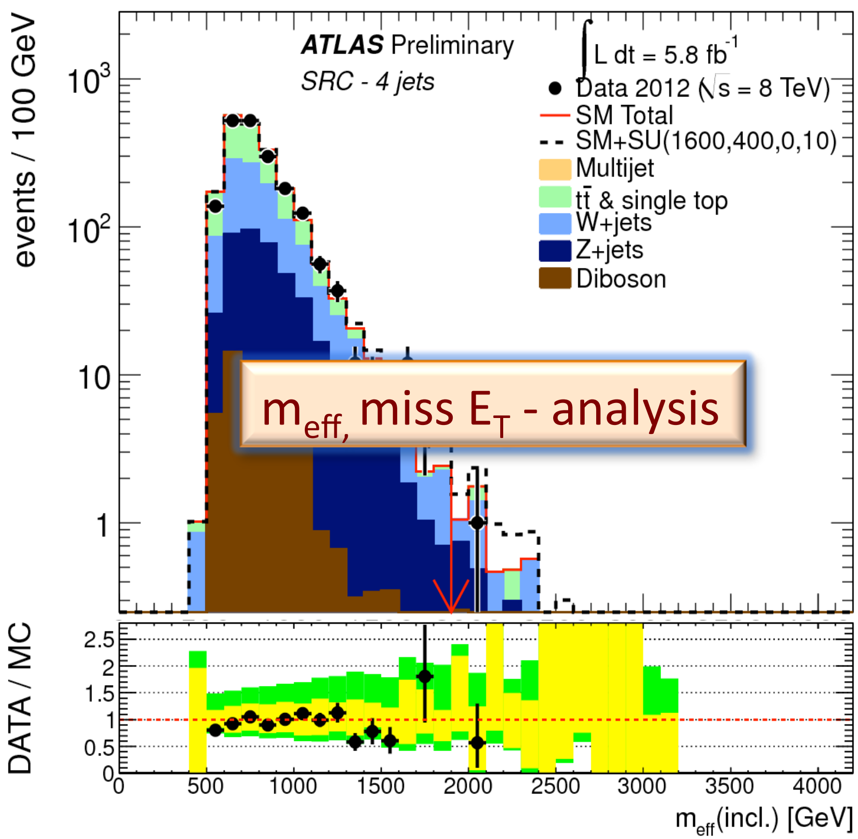
eg. exclusions plots shown at Moriond QCD 2012....

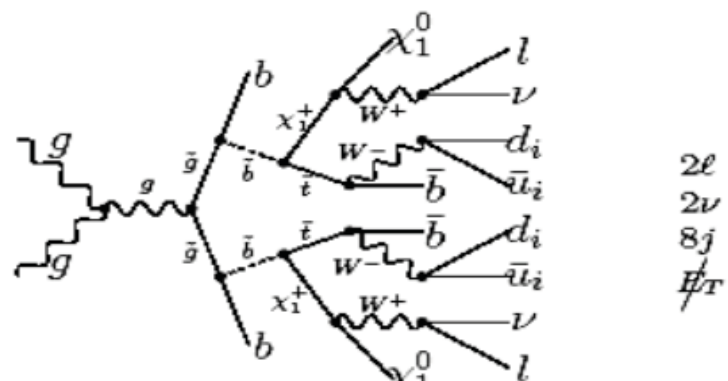


Generic approach (SUSY cascades)

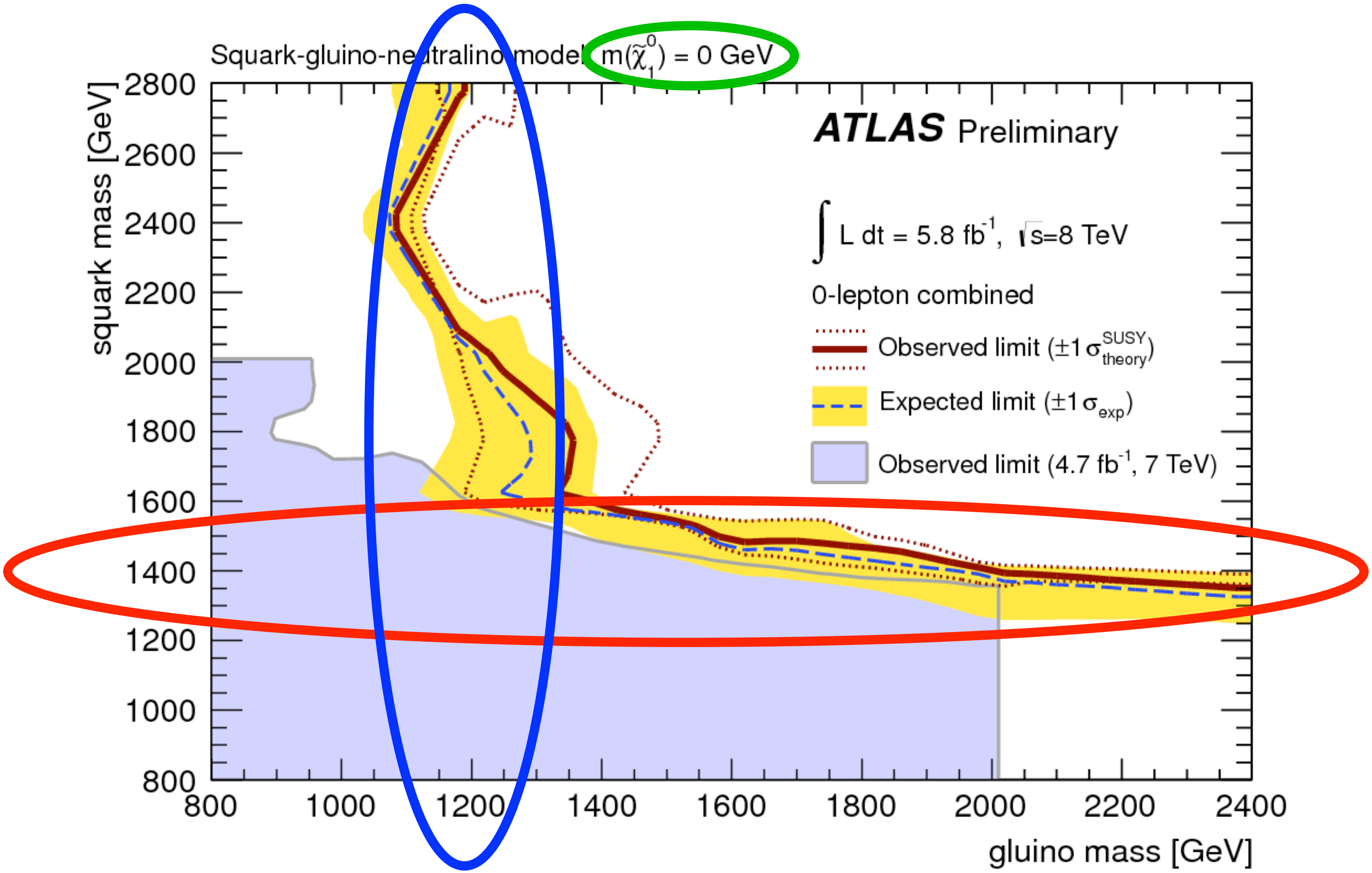


- search for strongly produced (heavy) sparticles, that decay via cascades
- assume a stable LSP -> missing E_T
- → (many) jets&leptons, large overall E_T plus missing E_T
- do "robust" searches, background largely controlled from data
- define "signal regions" count events and estimate backgrounds
- → interpretation within models

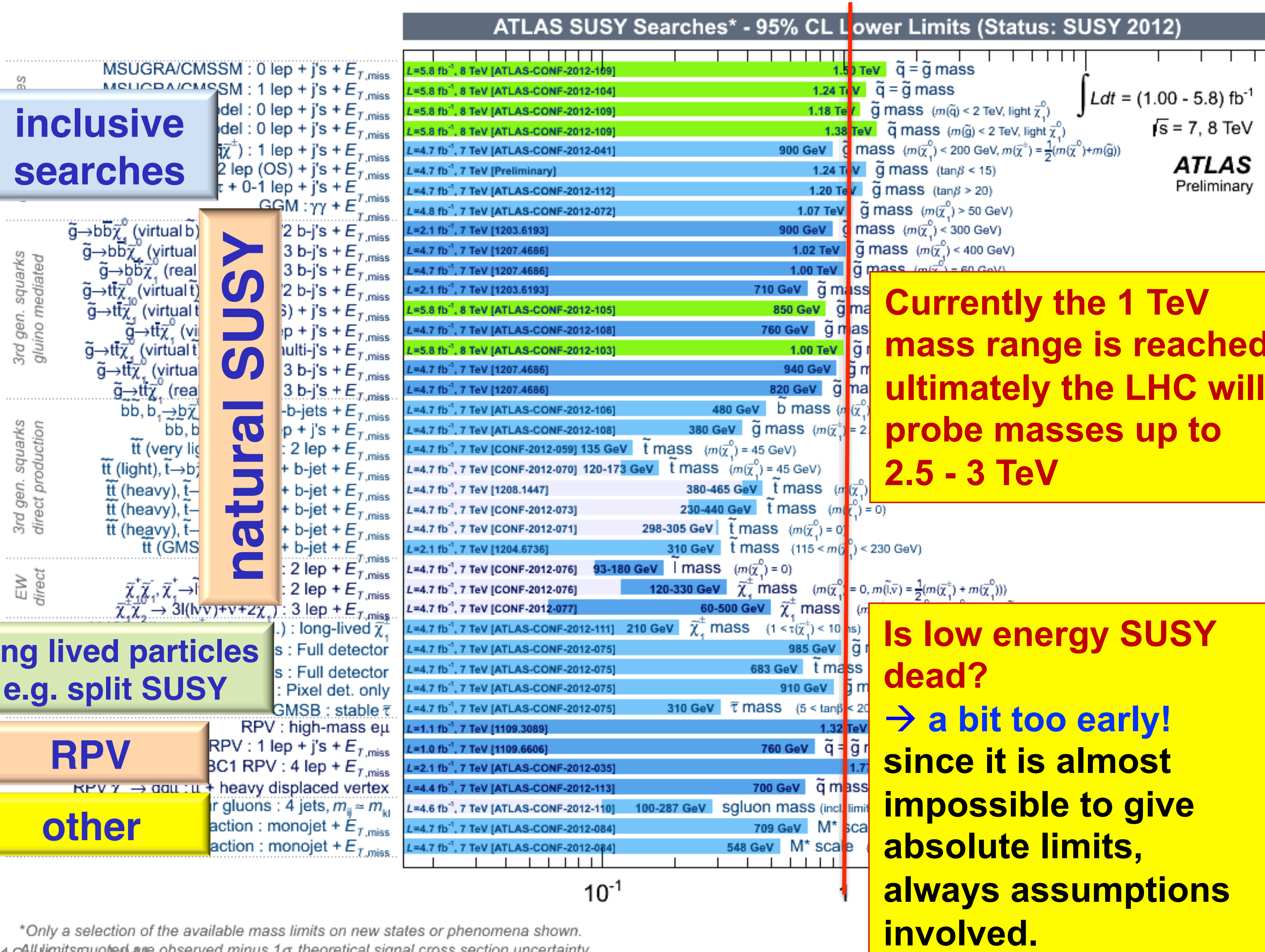




Result of a generic search



A non-exhaustive summary of current SUSY limits (CMS has similar limits)



inclusive searches

natural SUSY

long lived particles e.g. split SUSY

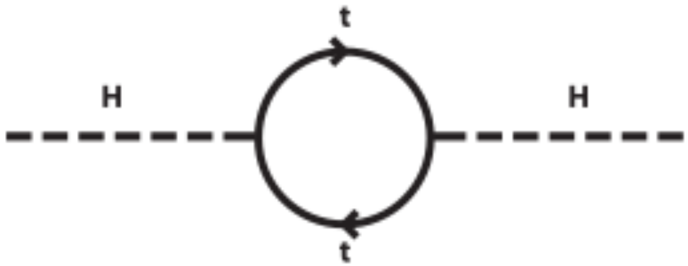
RPV

other

Currently the 1 TeV mass range is reached, ultimately the LHC will probe masses up to 2.5 - 3 TeV

Is low energy SUSY dead?
→ a bit too early!
since it is almost impossible to give absolute limits, always assumptions involved.

A hot topic: the stop and the light/heavy Higgs

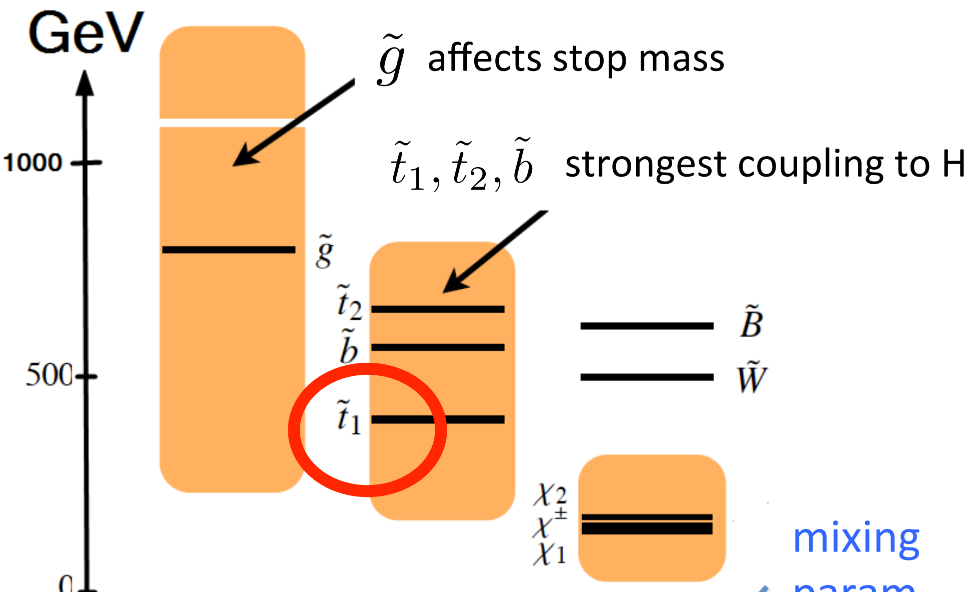


$$\Delta m_H^2 = \frac{|\lambda_t|^2}{16\pi^2}\left[-2\Lambda_{UV}^2 + 6m_{\mathrm{t}}^2 \ln(\Lambda_{\mathrm{UV}}/\mathrm{m_t}) + \ldots\right]$$

$$\Delta m_H^2 = \frac{\lambda_{\tilde{t}}}{16\pi^2}\left[\Lambda_{UV}^2 - 2m_{\tilde{\mathrm{t}}}^2 \ln(\Lambda_{\mathrm{UV}}/\mathrm{m}_{\tilde{\mathrm{t}}}) + \ldots\right]$$

$$m_{\tilde{\mathrm{t}}}^2$$

SUSY stabilizes the Higgs mass against quantum loop corrections



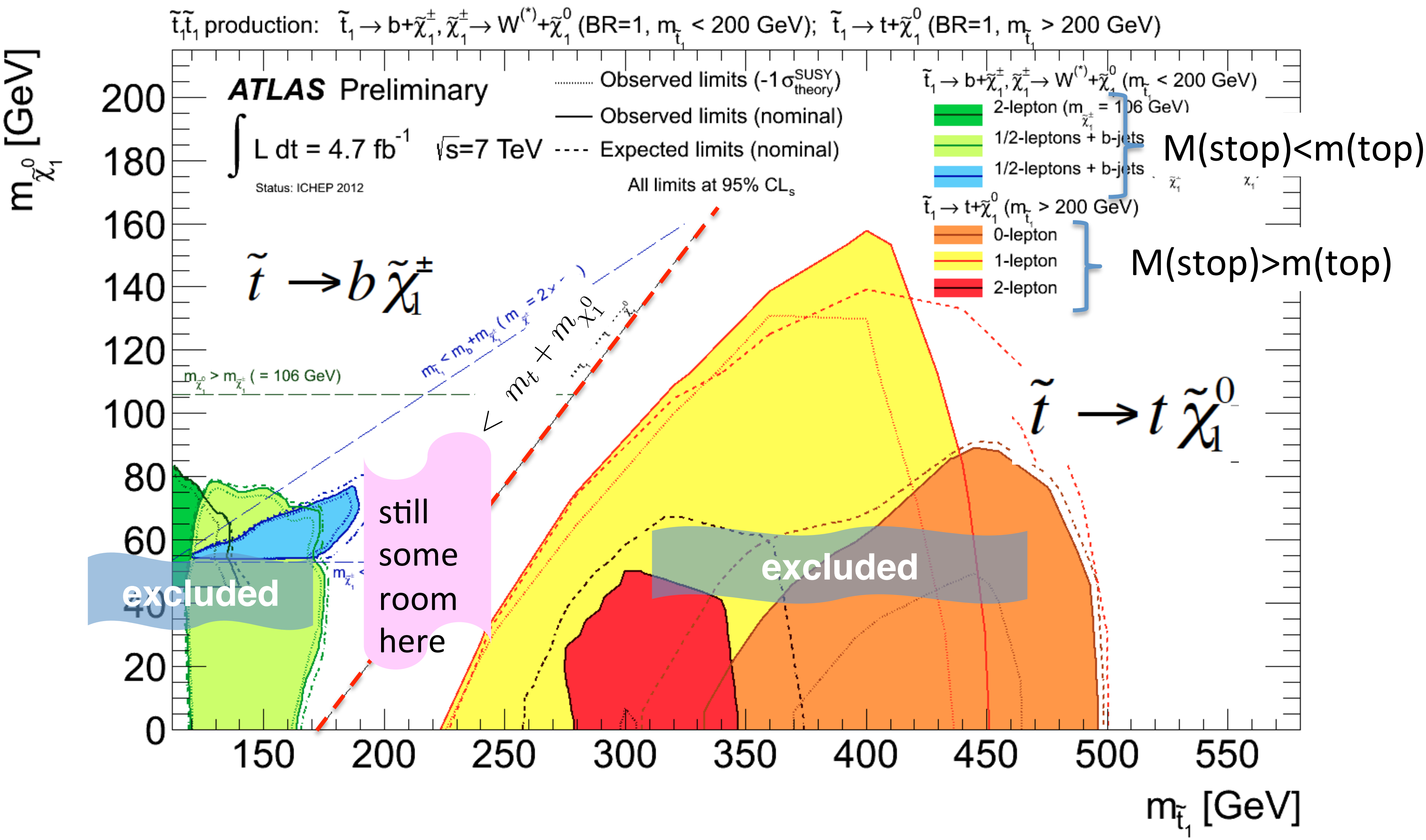
mixing param

$$m_H^2 = M_Z^2 \cos^2 2\beta + \frac{3\mathrm{m_t^4}}{2\pi^2 \mathrm{v}^2}\left[\ln\frac{\mathrm{M_S^2}}{\mathrm{m_t^2}} + \frac{\mathrm{X_t^2}}{\mathrm{M_S^2}}\left(1 - \frac{\mathrm{X_t^2}}{12\mathrm{M_S^2}}\right)\right]$$

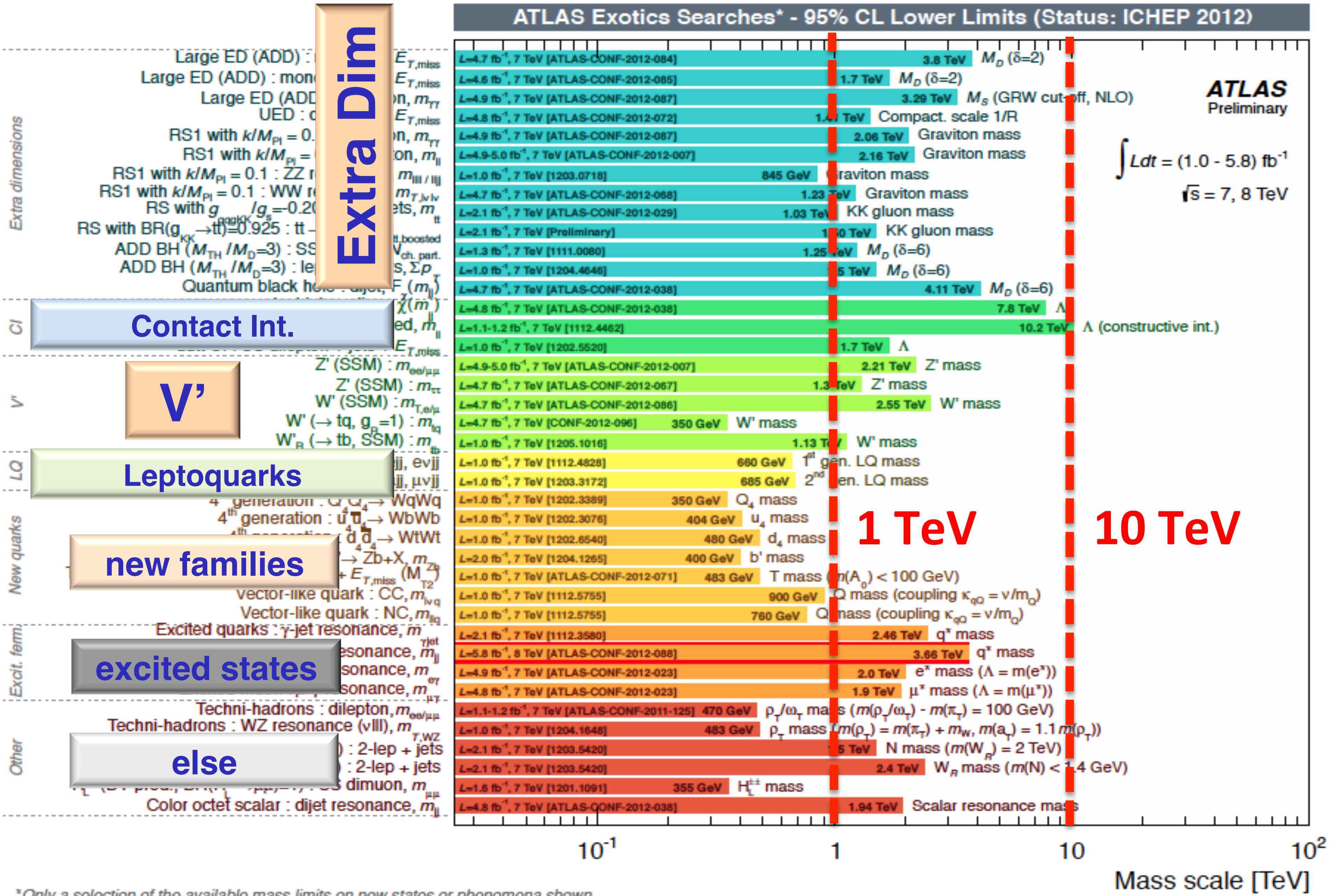
(125 GeV)^2 $\quad M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$ $\quad$ > (87 GeV)^2

In the MSSM maximal stop mixing is required to avoid multi-TeV stops

LSP mass versus stop mass

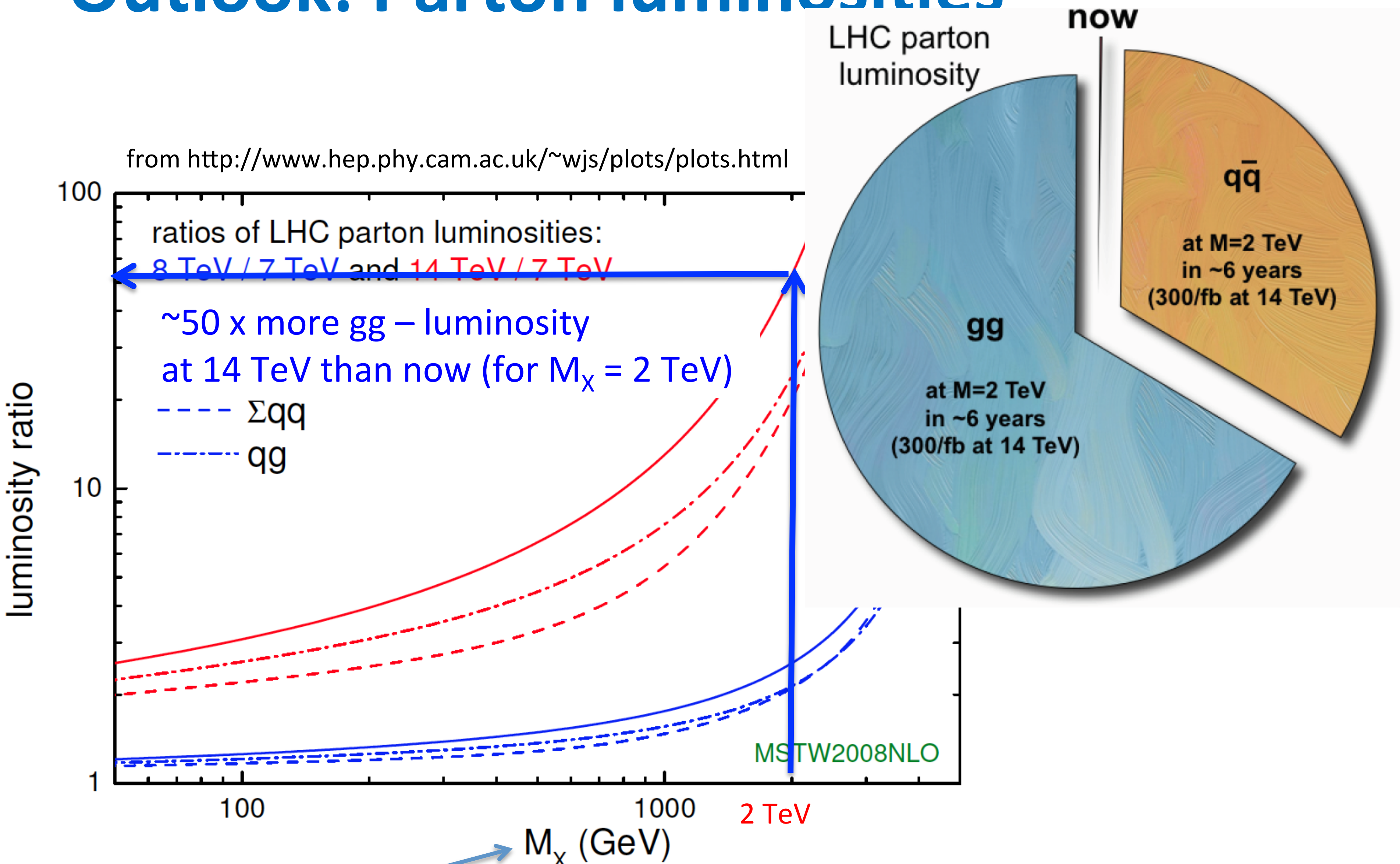


other BSM searches



Outlook: Parton luminosities

from http://www.hep.phy.cam.ac.uk/~wjs/plots/plots.html



assumed mass to be produced

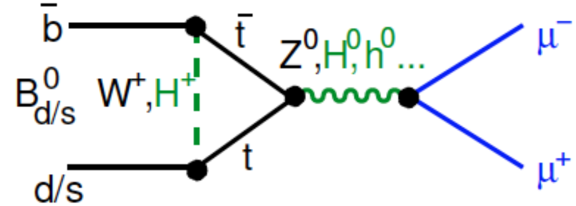
$B^0 \to \mu\mu$

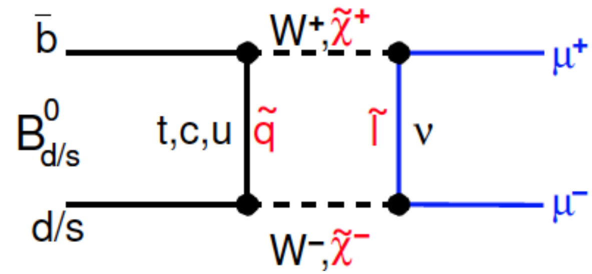
$B^0 \rightarrow \mu\mu$

- Highly SM-suppressed decays are sensitive to new physics
  - is effective FCNC
  - SM prediction is

$$\mathcal{B}(B^0_s \rightarrow \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$$
$$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = (1.0 \pm 0.1) \times 10^{-10}$$

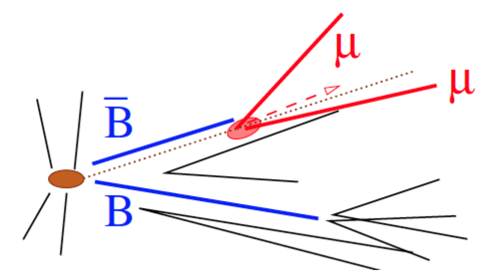
  - Cabibbo enhancement ($|V_{ts}| > |V_{td}|$) favoring $B^0_s \rightarrow \mu\mu$ over $B^0_d \rightarrow \mu\mu$



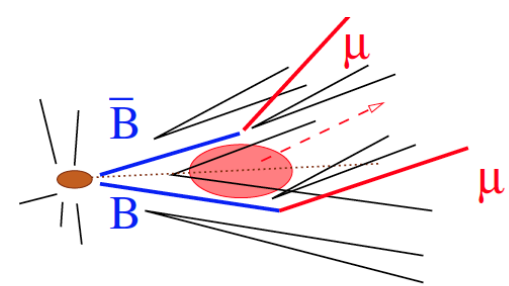


- Nice channel
  - good detection efficiency
  - small theoretical error
  - new physics sensitivity
    - 2HDM: BR ~ $(\tan\beta)^4$
    - MSSM: BR ~ $(\tan\beta)^6$

signal

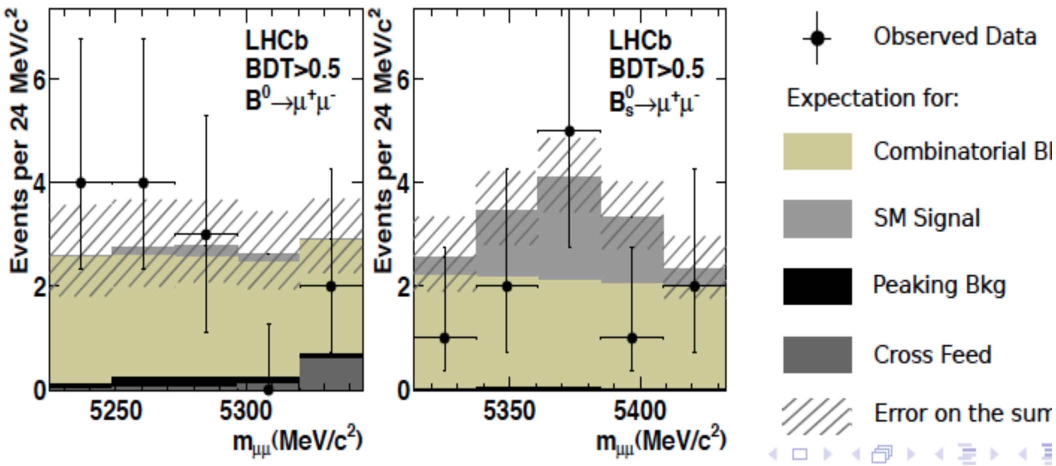


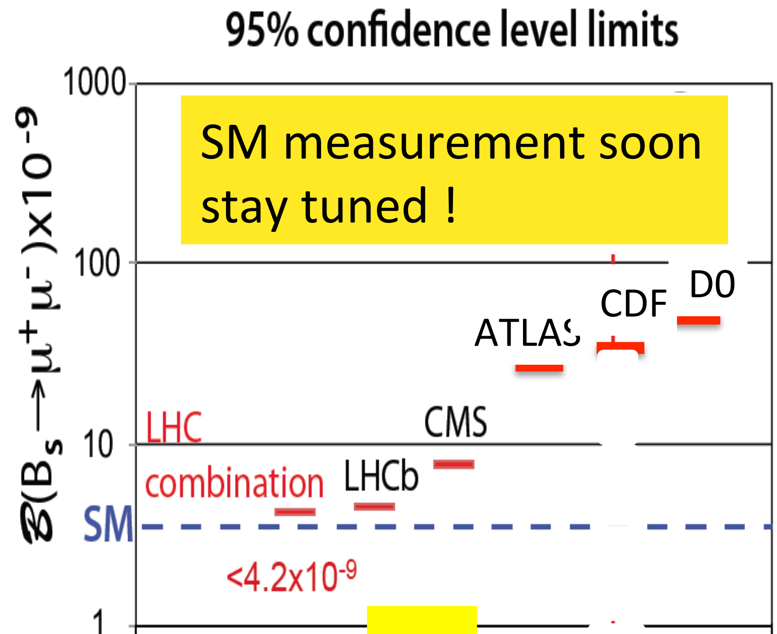
bkg



The measurements

- normalize to a well known decay: $B^{\pm} \to (J/\psi \to \mu\mu) K^{\pm}$





$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.0 \pm 0.1) \times 10^{-10}$$

Limits for B^0 at 95% C.L.

- CDF
  - $BR(B^0 \to \mu^+\mu^-) < 4.6\times10^{-9}$
- CMS
  - $BR(B^0 \to \mu^+\mu^-) < 1.8\times10^{-9}$
- LHCb
  - $BR(B^0 \to \mu^+\mu^-) < 1.0\times10^{-9}$

Limits for B^0_s at 95% C.L.

- D0
  - $BR(B^0_s \to \mu^+\mu^-) < 51\times10^{-}$
- CDF
  - $BR(B^0_s \to \mu^+\mu^-) < 31\times10^{-9}$
- ATLAS
  - $BR(B^0_s \to \mu^+\mu^-) < 22\times10^{-9}$
- CMS
  - $BR(B^0_s \to \mu^+\mu^-) < 7.7\times10^{-9}$
- LHCb
  - $BR(B^0_s \to \mu^+\mu^-) < 4.5\times10^{-9}$

combined

$$BR(B^0_d \to \mu\mu) < 8.1 \times 10^{-10}$$
$$BR(B^0_s \to \mu\mu) < 4.2 \times 10^{-9}$$

My personal conclusions

- LHC and its experiments ... are running extremely well ...

- The Higgs ... is not just a SM confirmation

  ... but rather (if it is <u>the</u> Higgs)
  - it is the first time that a fundamental scalar particle is found
  - it is likely to play a key role in our understanding of the fundamental laws of Nature
  - symmetries which are spontaneously broken exist in nature

- ... and perhaps one finds BSM physics by scrutinizing the Higgs

Backup Slides

Higgs

Higgs mechanism in the nut shell

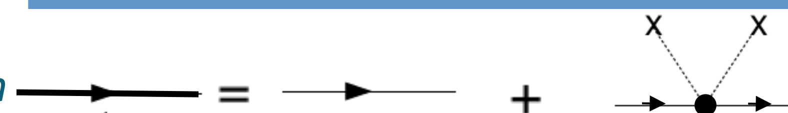
Empty vacuum (unbroken phase)
Massless particles traverse with the speed of light.
All particles are massless and move with same speed.

Vacuum filled with Higgs field (broken phase)
Massless particles interact with a background `Higgs' field, present everywhere, and slow down.
Effectively they acquire a mass.
Speed (=mass) of particle depends on *interaction strength* with the Higgs field.

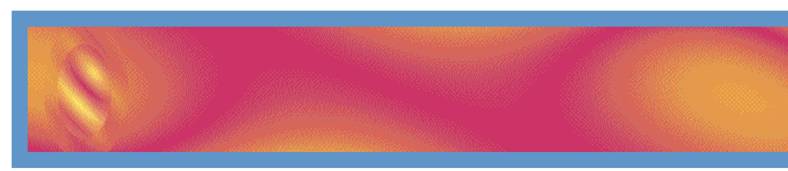
Higgs particle
Quantum mechanical fluctuations of the background itself: the Higgs particle.
A necessary consequence of the Higgs background field.

The syrup analogy

$$\frac{1}{q^2}$$



$$\frac{1}{q^2-M_W^2} = \frac{1}{q^2} + \frac{1}{q^2}\left(\frac{gv}{2}\right)^2\frac{1}{q^2}$$



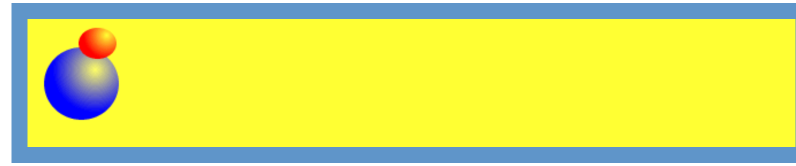
$$v = \left(\sqrt{2}\,G_F\right)^{-\frac{1}{2}} = 246 \text{ GeV}$$

to match β - decay

Higgs in the vacuum (2)

The syrup analogy

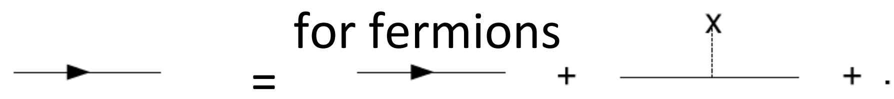
Empty vacuum (unbroken phase)
Massless particles traverse with the speed of light.
All particles are massless and move with same speed.



$$\frac{1}{q^2}$$

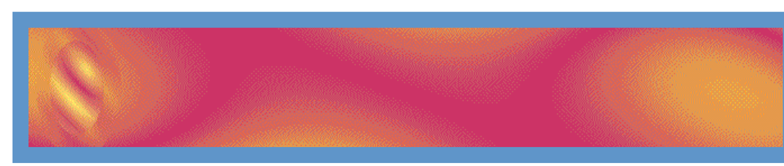
Vacuum filled with Higgs field (broken phase)
Massless particles interact with a background `Higgs' field, present everywhere, and slow down.
Effectively they acquire a mass.
Speed (=mass) of particle depends on interact strength with Higgs field.

for fermions



$$g_f \frac{v}{\sqrt{2}}$$

Higgs particle
Quantum mechanical fluctuations of the background itself: the Higgs particle.
A necessary consequence of the Higgs background field.



$$v = \left(\sqrt{2}\, G_F\right)^2 = 246\ \mathrm{GeV}$$

to match β - decay

Noble history

- Early 'Electroweak model' of quarks and leptons
  - Weinberg, Glashow & Salam (late sixties) – Nobel prize 1979
- Problem: Electroweak SU(2)⊗U(1) model not renormalizable!
  - Serious calculations (loop level) produced infinities.
  - *Useless?*
- Renormalisation of *massless* Yang-Mills gauge theories
  - Veltman & 't Hooft (~1972)

One believer left: Veltman

- How to give the vector bosons (W^+,W^-,Z^0) mass without destroying renormalization?
  - 't Hooft: Symmetry breaking with Higgs-mechanism, and apply it to the Standard Model
  - Mechanism preserves renormalization: it works!

Veltman: 'verrek, dat is het!'

No experimental clue that this is the correct description for EW symmetry breaking

For elucidating the quantum structure of electroweak interactions in physics

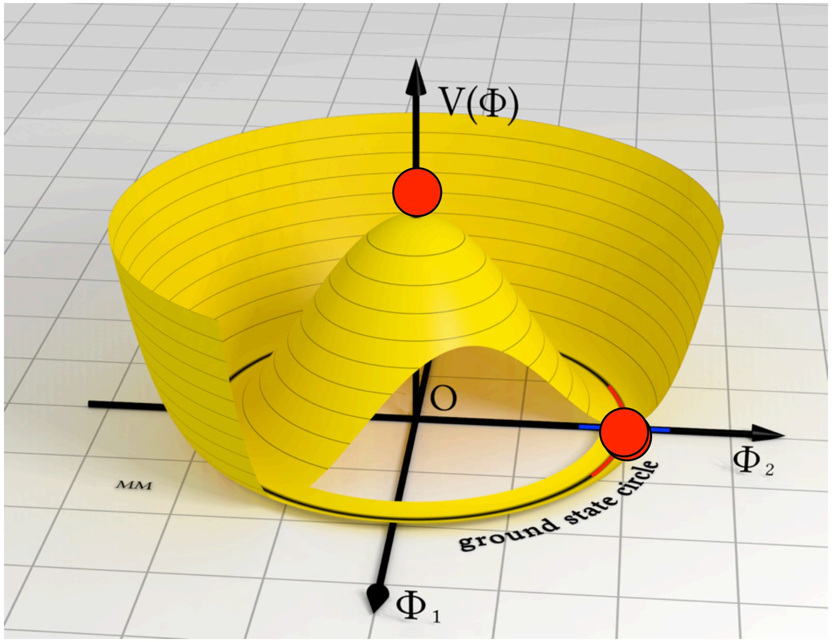
Nobel prize 1999
t'Hooft + Veltman

Higgs mechanism

- Potential $V(\varphi)$ minimal for $\varphi \neq 0$.
- Symmetry breaks spontaneously → non-zero vacuum expectation value (vev) for φ:

$$\Phi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} \rightarrow \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$$

  We consider fluctuation around this minimum.
- Breaking of rotational symmetry leads to goldstone bosons that are absorbed by W^+, W^-, Z^0 (3rd polarization degree)→ gauge bosons become massive
- Excitations of the Higgs field around minimum lead to Higgs particle d.o.f.



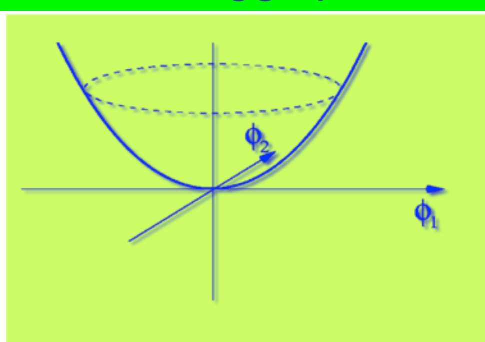
- Counting of degrees of freedom:
  ϕ has two complex = 4 real d.o.f. ,
  W^+, W^-, Z^0 absorb three, one real d.o.f. remains → Higgs boson
  (the absorbed d.o.f. correspond to the new long. pol. d.o.f. needed)

… in mathematical language

Broken vacuum at scale v=246 GeV

$SU_W(2) \otimes U_Y(1)$ symmetry	$U_Q(1)$ symmetry
3 massless $SU_W(2)$ vector bosons 1 massless $U_Y(1)$ vector boson	3 massive vector bosons: W^+, W^-, Z^0 1 massless $U_Q(1)$ boson: γ
1 complex doublet self-interacting Higgs fields (=4 real scalar fields)	1 real scalar Higgs field *+3 Goldstone Bosons 'eaten' by the massive vector bosons*
Interaction between Higgs doublet and massless quarks & leptons	Mass terms for quarks & leptons

Unbroken Higgs potential



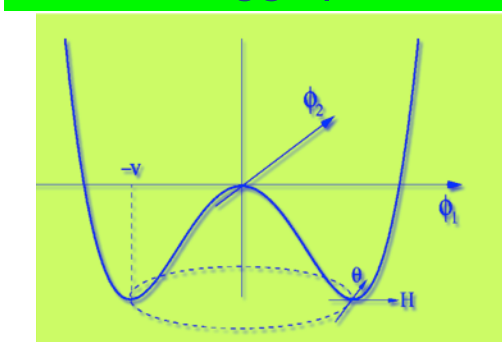
$\mu^2 > 0$

$$\mathcal{L}_{\text{Higgs}} = (D_\mu \Psi)^\dagger (D^\mu \Psi) - V(\Psi)$$

$$V(\Psi) = \mu^2 |\Psi|^2 + \lambda |\Psi|^4$$

$$\frac{\partial V}{\partial \Psi} = 0 \rightarrow |\Psi_0|^2 = -\frac{\mu^2}{2\lambda} \equiv \frac{1}{2} v^2$$

Broken Higgs potential

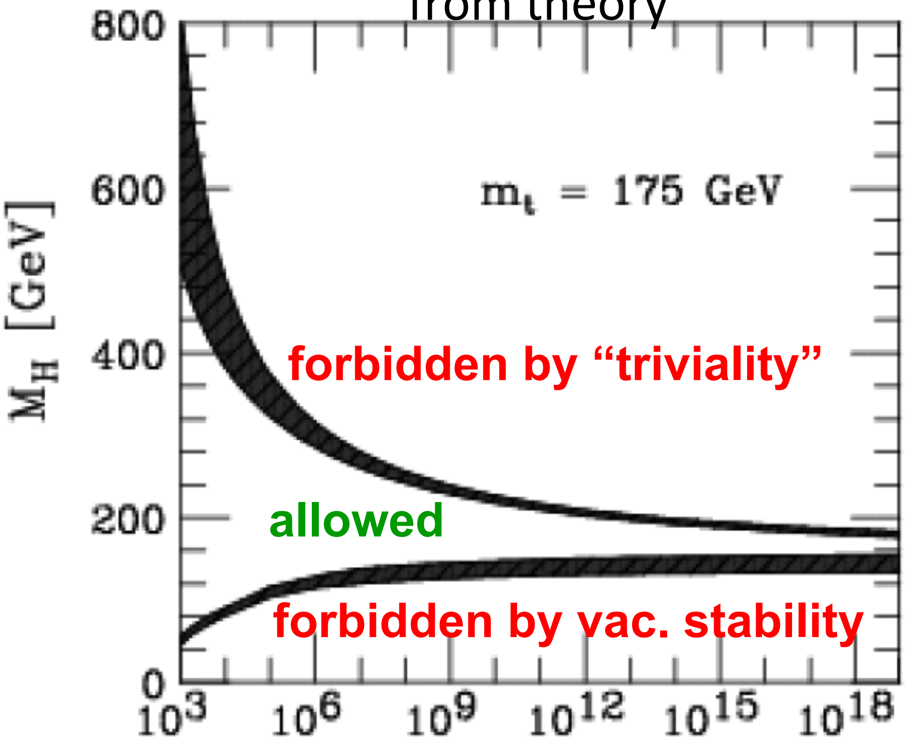


$\mu^2 < 0$

What do we know already ?

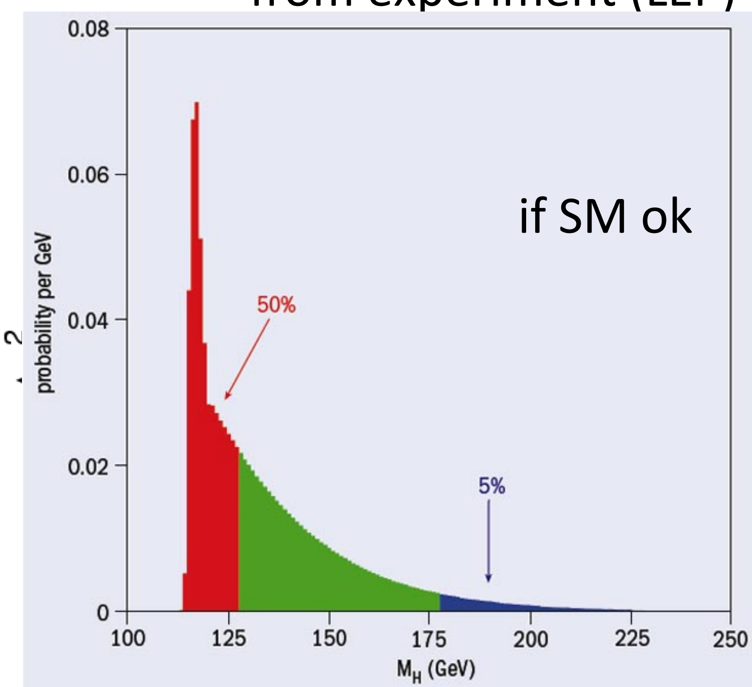
- $m^2_H = 2\lambda v^2$ → 1 parameter in SM
- A Higgs (or similar) is needed to save unitarity of weak i.a. → m_H < 870 GeV
- Triviality … all coupling "constants" run … also λ → must be small at $Q^2 = v^2$
- Vacuum Stability … EWSB must "happen" → must have a W-shaped potential

from theory



Λ = scale of "new" physics

from experiment (LEP)

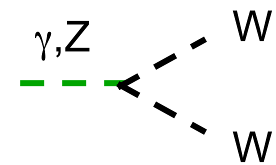


m_H [GeV]

… list of interaction terms:

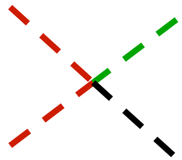
fermion — gauge - - higgs ⋯

Gauge interactions WWγ WWZ ~~ZZZ~~



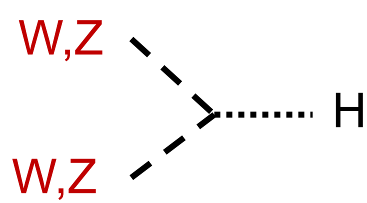
3 gauge

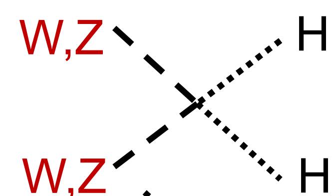
4 gauge



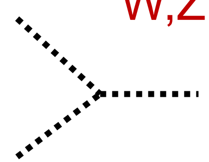
WWγγ WWZZ WWγZ WWWW

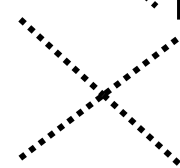
Gauge-Higgs interactions WWH ZZH WWHH ZZHH



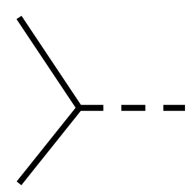


Higgs self interactions HHH HHHH

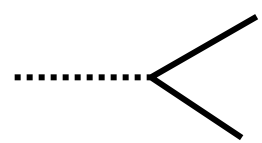




Fermion (l,q)-Gauge i.a. llγ qqγ llZ qqZ ννZ νlW qq'W



Fermion-Higgs (Yukawa) llH qqH

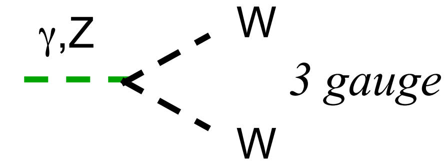


… list of interaction terms:

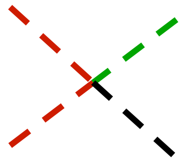
fermion — gauge - - higgs ⋯⋯

Gauge interactions

WWγ | WWZ | ~~ZZZ~~



4 gauge



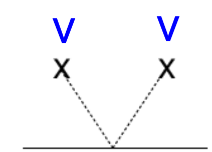
WWγγ | WWZZ | WWγZ | WWWW

Gauge-Higgs interactions

WWH | ZZH | WWHH | ZZvv

$$\mathcal{L} \sim \frac{g^2}{8cos^2\theta_W}\ (v+H)^2\ Z_\mu Z^\mu$$

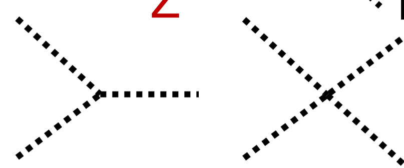
=



W – mass term

Higgs self interactions

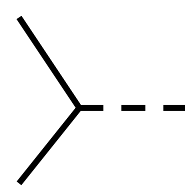
HHH | HHHH



Fermion (l,q)-Gauge i.a.

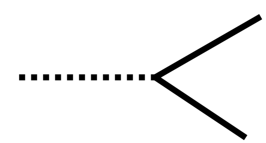
llγ | qqγ | llZ | qqZ | ννZ

νlW | qq'W



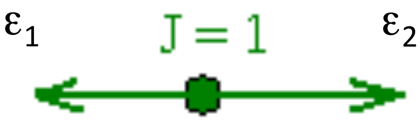
Fermion-Higgs (Yukawa)

llH | qqH



Yang's Theorem

- **Theorem:** a Spin-1-particle cannot decay into two massless photons
- **Proof:** in cms of the decaying particles



$\mathcal{M}_{fi}$ can only depend on observables of the decay particles and must be rotationally invariant → $\mathcal{M}_{fi} \sim \mathbf{J} \cdot \mathbf{M}$

with vector **M** constructed (linearly) from the photon polarization vectors $\boldsymbol{\varepsilon}_1$, $\boldsymbol{\varepsilon}_2$ and the momentum vector **k** of the photons ($\mathbf{k} = \mathbf{k}_1 = -\mathbf{k}_2 = -\mathbf{k}$)

2γ wave function Ψ(2γ) must be symmetric ⇒ $\mathcal{M}_{fi}$ must be invariant unter $\gamma_1 \leftrightarrow \gamma_2$

possibilities to construct **M** are:

i. $\mathbf{M} = \boldsymbol{\varepsilon}_1 \times \boldsymbol{\varepsilon}_2$ … then under 1⇔2: $\mathbf{M}_{21} = \boldsymbol{\varepsilon}_2 \times \boldsymbol{\varepsilon}_1 = -\boldsymbol{\varepsilon}_1 \times \boldsymbol{\varepsilon}_2 = -\mathbf{M}_{12}$ ⇒ **NO**

ii. $\mathbf{M} = (\boldsymbol{\varepsilon}_1 \cdot \boldsymbol{\varepsilon}_2)\,\mathbf{k}$ … then under 1⇔2: $\mathbf{M}_{21} = (\boldsymbol{\varepsilon}_2 \cdot \boldsymbol{\varepsilon}_1)(-\mathbf{k}) = -\mathbf{M}_{12}$ ⇒ **NO**

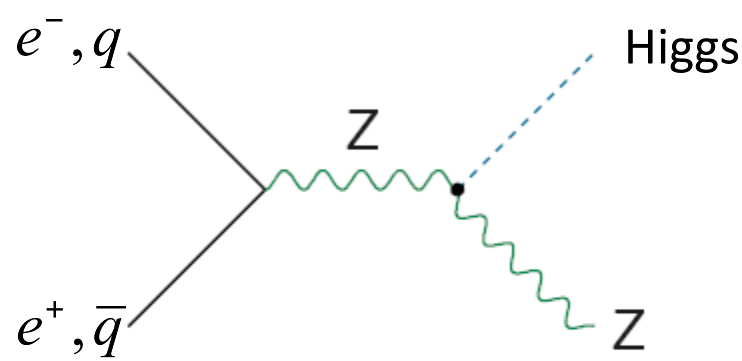
iii. $\mathbf{M} = \mathbf{k} \times (\boldsymbol{\varepsilon}_1 \times \boldsymbol{\varepsilon}_2)$ … then under 1⇔2: $\mathbf{M}_{21} = \boldsymbol{\varepsilon}_1 \underbrace{(\mathbf{k} \cdot \boldsymbol{\varepsilon}_2)} - \boldsymbol{\varepsilon}_2 \underbrace{(\mathbf{k} \cdot \boldsymbol{\varepsilon}_1)} = 0$

= 0, for m=0 (transverse) photons

thus M_{fi} (J = 1) ~ J·M not possible

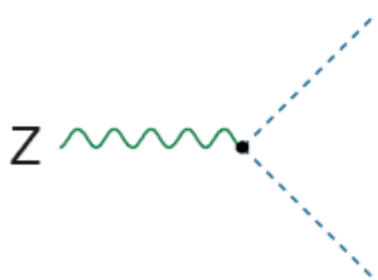
… prove that it is "condensed"

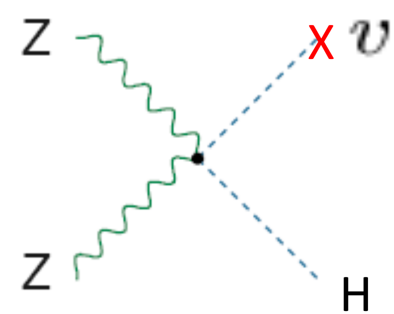
- first find the ZH final state
  i.e. a ZZH vertex



- generally we know: if
  Z = gauge boson
  Φ = a arbitrary scalar particle
  $\Rightarrow$ only two vertices

$$\mathcal{L} \sim \Phi^* \Phi \; Z_\mu Z^\mu$$





- to make a ZZH vertex ..
  we need a condensate v

$$\mathcal{L} \sim \frac{g^2}{4 cos^2 \theta_W} \; vH \; Z_\mu Z^\mu$$

$\Rightarrow$ this proves that it is "condensed" in the universe

Hitoshi Murayama, hep-ex/9606001

Local p-values

- The local p-value is the probability that the backround only will fluctuate up to the observed local significance (Z_{max}) or more.

- An approximate way to calculate the LEE, i.e. the probability to see an excess anywhere in the search mass range above some Z_{max} is calculated via the most famous formula in the world ☺

$$p_{global} = p_{min} + N_0 e^{-Z_{max}^2/2}$$

N_0 is the average number of upcrossings at Z=0 which is estimated from data, and Z_{max} is the local significance. Formula is asymptotically accurate for increasing Z_{max}

A. Read

Background (scan m_H)	$\lambda(\mu = 0, m_H) = \frac{L(\mu=0, m_H, \hat{\theta})}{L(\hat{\mu}, m_H, \hat{\hat{\theta}})}$
Signal (scan m_H)	$\lambda(\mu, m_H) = \frac{L(\mu, m_H, \hat{\theta})}{L(\hat{\mu}, m_H, \hat{\hat{\theta}})}$
Mass consistency	$\lambda(m_H) = \frac{L(m_H, \hat{\hat{\mu}}_1, \hat{\hat{\mu}}_2, \hat{\hat{\theta}})}{L(\hat{m}_{1H}, \hat{m}_{2H}, \hat{\mu}_1, \hat{\mu}_2, \hat{\theta})}$
Mass	$\lambda(m_H) = \frac{L(m_H, \hat{\hat{\mu}}_1, \hat{\hat{\mu}}_2, \hat{\hat{\theta}})}{L(\hat{m}_H, \hat{\mu}_1, \hat{\mu}_2, \hat{\theta})}$
Signal and mass	$\lambda(\mu, m_H) = \frac{L(\mu, m_H, \hat{\hat{\theta}}_\mu)}{L(\hat{\mu}, \hat{m}_H, \hat{\theta}_\mu)}$

test statistic = ratio of profiled likelihoods (PDF for it known in asymptotic limit)

L = likelihood to observe data depending on parameters M_H and μ and …

signal strength $\boldsymbol{\mu} = \sigma_{signal}/\sigma_{SM\text{-}H}$, θ = nuisance parameters for sys. uncertainties

Higgs' J^{PC}

Have we observed a scalar?

Spin $\leftrightarrows$ angular distribution of final decay products

- ☑ spin-1: forbidden by Landau-Yang's theorem (ie Bose symmetry)
- ☑ $gg \to X \to \gamma\gamma$ and $q\bar{q} \to X \to \gamma\gamma$ e.g., Gao et al '10
  - ❖ spin-0: flat in cos θ*
  - ❖ spin-2: quartic in cos θ*: $\frac{d\sigma}{d\Omega} \propto \frac{1}{4} + \frac{3}{2}\cos^2\theta + \frac{1}{4}\cos^4\theta$
- ☑ $gg \to X \to ZZ^\star \to 4l$ Choi et al '02 De Rujula et al. '10
- ☑ $gg \to X \to WW^\star \to 2l2\nu$ Ellis, Hwang '12

Parity $\leftrightarrows$ angular distribution of final decay products

- ☑ CP-odd: couplings to W and W are loop-induced only! Hard to explain data.
- ☑ angular distribution of leptons in $gg \to X \to ZZ^\star \to 4l$
- ☑ angular distribution of jets produced in VBF Plehn et al '01
- ☑ spin correlations in $X \to \tau\tau$ Berge et al '08

Can be solved at LHC_8 (may be), LHC_{14} (for sure)

too academic questions? Sensitivity to degree admixture of admixture even/odd?

References

Combined Standard Model Higgs boson searches with up to 2.3 fb^{-1} of pp collision data at $\sqrt{s} = 7$ TeV at the LHC

The ATLAS and CMS Collaborations

References

[1] F. Englert and R. Brout. Broken symmetry and the mass of gauge vector mesons. *Phys. Rev. Lett.*, 13:321–323, 1964.

[2] P.W. Higgs. Broken symmetries, massless particles and gauge fields. *Phys. Lett.*, 12:132–133, 1964.

[3] P.W. Higgs. Broken symmetries and the masses of gauge bosons. *Phys. Rev. Lett.*, 13:508–509, 1964.

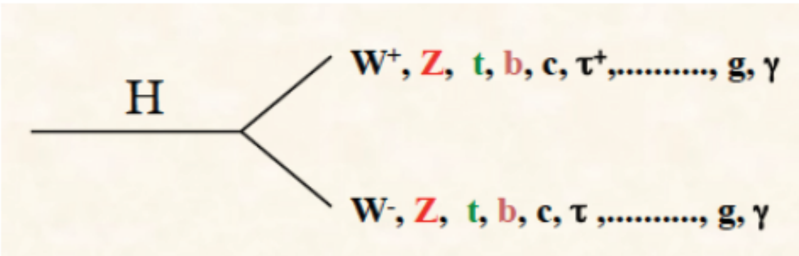
[4] G.S. Guralnik, C.R. Hagen, and T.W.B. Kibble. Global conservation laws and massless particles. *Phys. Rev. Lett.*, 13:585–587, 1964.

[5] P.W. Higgs. Spontaneous symmetry breakdown without massless bosons. *Phys. Rev.*, 145:1156–1163, 1966.

[6] T.W.B. Kibble. Symmetry breaking in non-Abelian gauge theories. *Phys. Rev.*, 155:1554–1561, 1967.

[7] LEP Working Group for Higgs boson searches. Search for the Standard Model Higgs boson at LEP. *Phys. Lett.*, B565:61–75, 2003.

Given a H mass, decay properties are fixed



$$\Gamma(H \to f\bar{f}) = N_C \frac{G_F}{4\sqrt{2}\pi} m_f^2(M_H^2) M_H$$

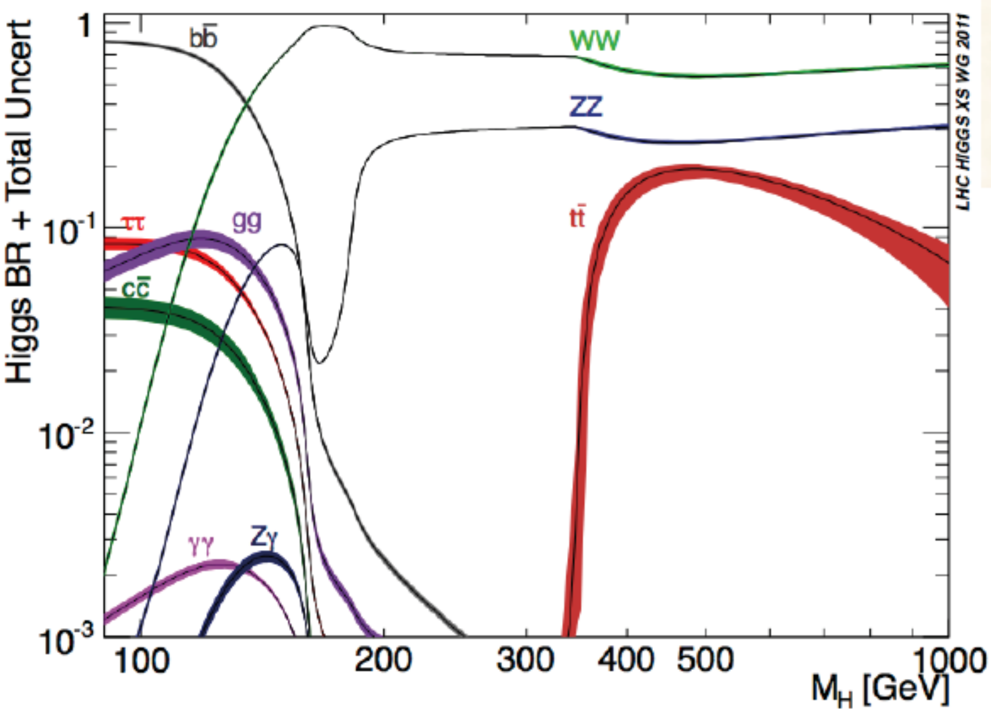
$$\Gamma(H \to VV) = \delta_V \frac{G_F}{16\sqrt{2}\pi} M_H^3 (1 - 4x + 12x^2)\beta_V$$

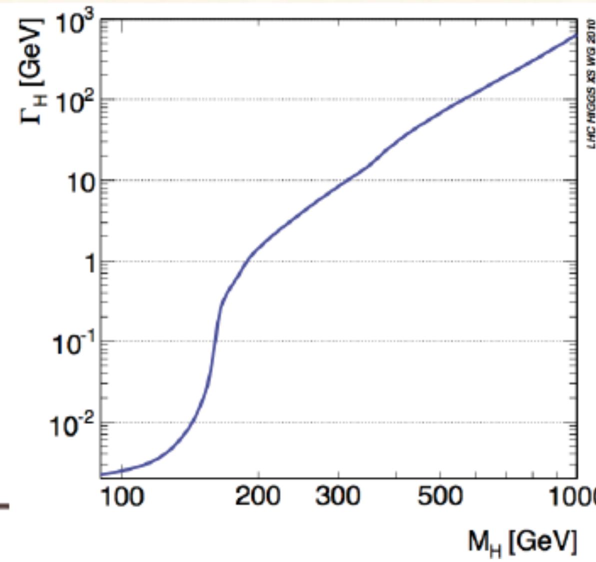
where: $\delta_Z = 1,\ \delta_W = 2,\ x = M_V^2 / M_H^2,\quad \beta = \text{velocity}$

(+ W-loop contributions)

$$\Gamma(\mathrm{H} \to \mathrm{gg}) = \frac{G_F \alpha_a^2(M_H^2)}{36\sqrt{2}\pi^3} M_H^3 \left[1 + \left(\frac{95}{4} - \frac{7N_f}{6}\right)\frac{\alpha_a}{\pi}\right]$$

$$\Gamma(H \to \gamma\gamma) = \frac{G_F \alpha_a^2}{128\sqrt{2}\pi^3} M_H^3 \left[\frac{4}{3} N_C e_t^2 - 7\right]^2$$





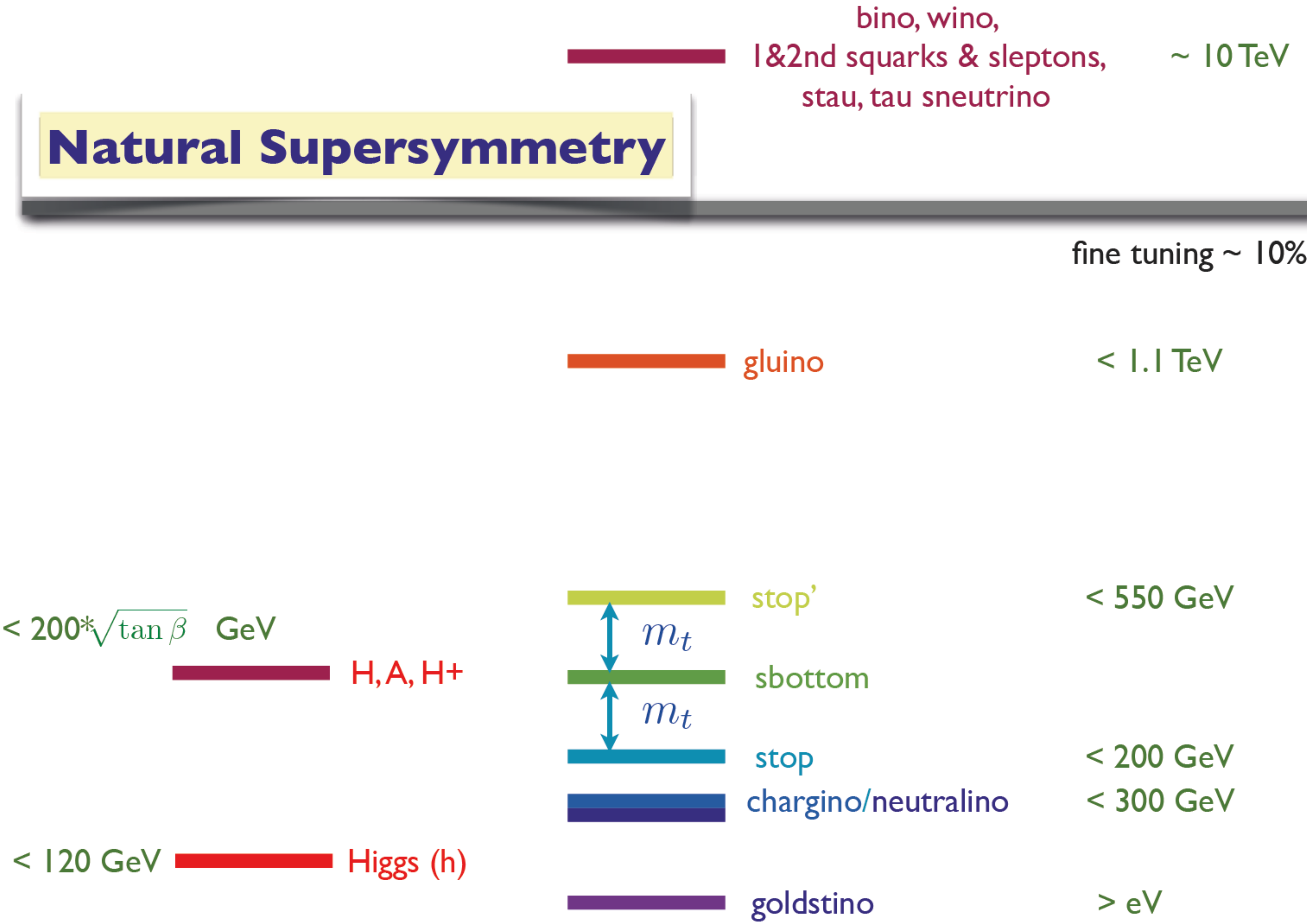
Cargese 2012

13

rino & CERN

SUSY

Natural Supersymmetry



"Naturalness" in TeV scale SUSY

"Natural" SUSY spectrum is something like:

- light stop$_L$, stop$_R$ and light sbottom$_L$

$$m_{\tilde{t}_{L,R},\tilde{b}_L} \lesssim 500 \text{ GeV} \sin\beta \left(\frac{3}{\log M/(1 \text{ TeV})}\right)^{\frac{1}{2}} \left(\frac{m_h^{tree}}{100 \text{ GeV}}\right) \left(\frac{\Delta}{10}\right)^{\frac{1}{2}}$$

- (relatively) light gluino

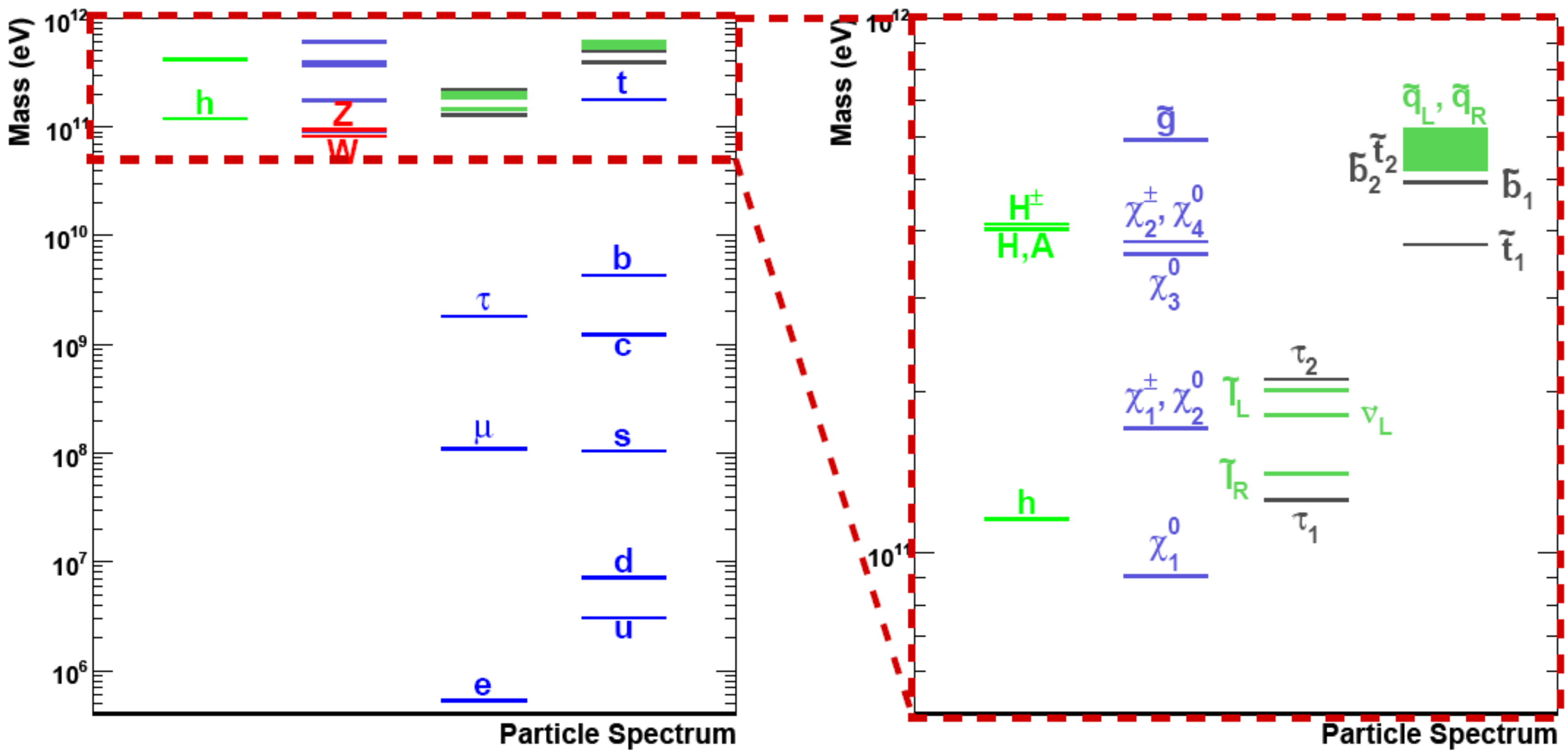
$$m_{\tilde{g}} \lesssim 1100 \text{ GeV} \sin\beta \left(\frac{3}{\log M/(1 \text{ TeV})}\right)^{\frac{1}{2}} \left(\frac{m_h^{tree}}{100 \text{ GeV}}\right) \left(\frac{\Delta}{10}\right)^{\frac{1}{2}}$$

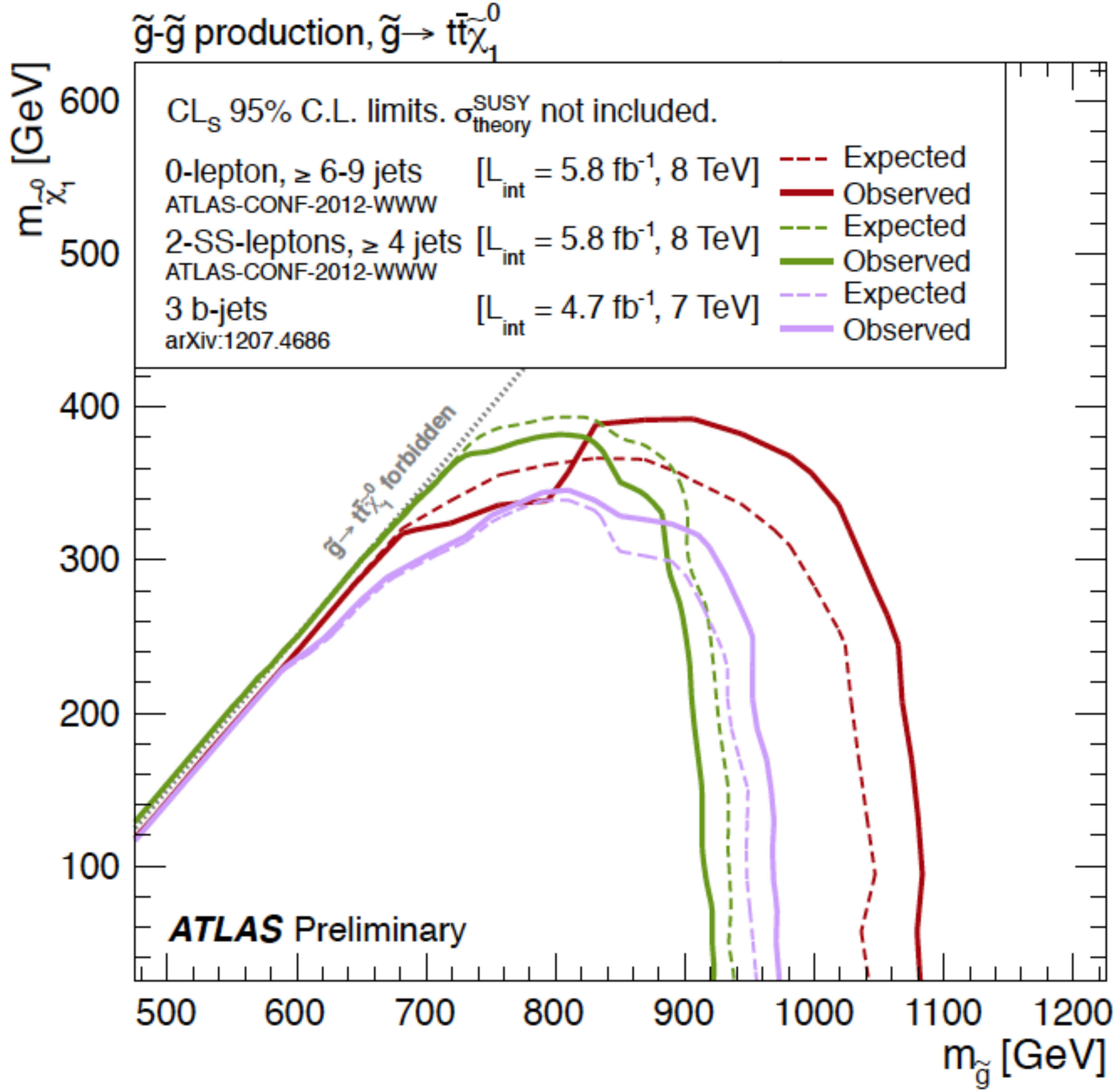
- small μ parameter

$$\mu \lesssim 250 \text{ GeV} \left(\frac{m_h^{tree}}{100 \text{ GeV}}\right) \left(\frac{\Delta}{10}\right)^{\frac{1}{2}}$$

SUSY particle spectrum

- BUT … SUSY particles must be heavy ! … otherwise already found
  → SUSY symmetry must be broken
  → how ? … in a “hidden” sector coupling to the “visible” sector
  via gravity (mSUGRA) or gauge interactions (GSMB) or anomalies
  → ugly





$\tilde{g}$-$\tilde{g}$ production, $\tilde{g}\rightarrow t\bar{t}\tilde{\chi}_1^0$
CL$_S$ 95% C.L. limits. σ^{SUSY}_{theory} not included.
0-lepton, ≥ 6-9 jets [L_{int} = 5.8 fb^{-1}, 8 TeV]
ATLAS-CONF-2012-WWW
2-SS-leptons, ≥ 4 jets [L_{int} = 5.8 fb^{-1}, 8 TeV]
ATLAS-CONF-2012-WWW
3 b-jets [L_{int} = 4.7 fb^{-1}, 7 TeV]
arXiv:1207.4686
Expected
Observed
Expected
Observed
Expected
Observed
$\tilde{g}\rightarrow t\bar{t}\tilde{\chi}_1^0$ forbidden
ATLAS Preliminary
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{g}}$ [GeV]
100
200
300
400
500
600
500
600
700
800
900
1000
1100
1200

Extra Dim

&

BHs

Example

If LHC reaches the fundamental mass = Planck mass m_{pl}^{2+n}

$$10^{38}\text{GeV} = \left(10^{3}\text{GeV}\right)^{2+n} \cdot R^{n}$$

then it probes …

n	R [m]
1	10^{13}
2	10^{-3}
3	$4.5 \cdot 10^{-9}$
4	10^{-12}
5	$2.5 \cdot 10^{-13}$

Note: Hierarchy problem solved, but a *new parameter* R

Randall-Sundrum Graviton production

Analyses:

Diphoton resonance search (2010 data only)

- Fully data driven background – fit of smooth parameterisation
- **RS Graviton mass m_G > 920 (545) GeV** at 95% CL, for coupling k/M_D = 0.1 (0.02)

Dilepton resonances

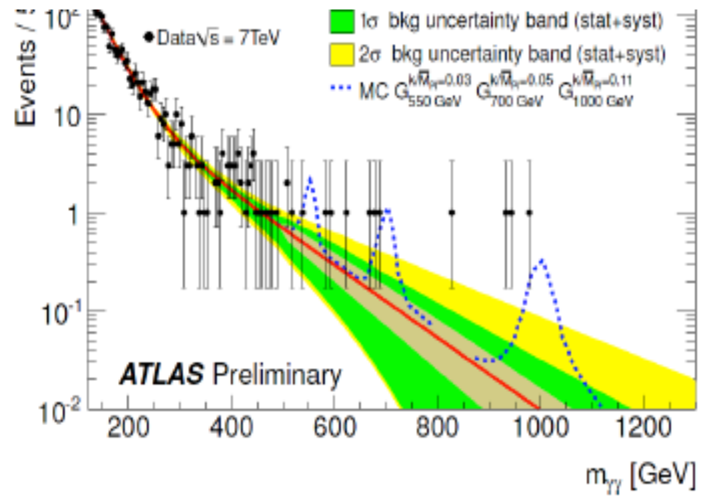
(2011 data, combined with search for Z')*

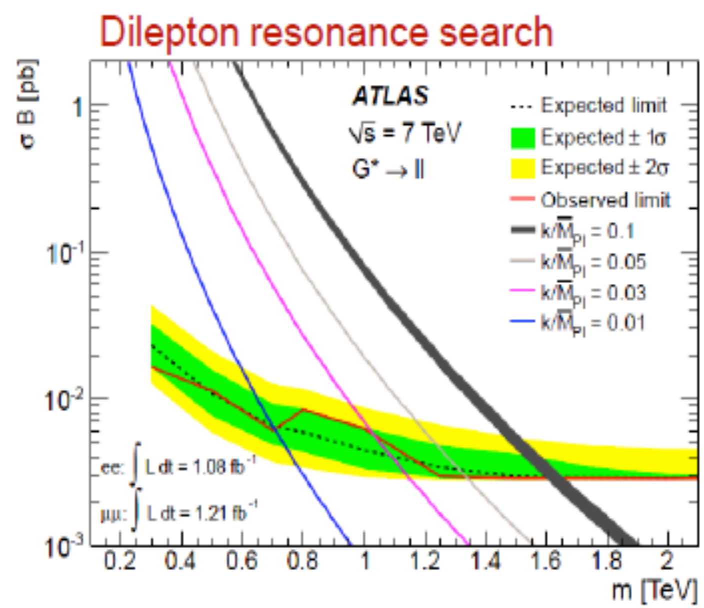
- μ and e channel combined
- Data consistent with Drell-Yan production
- **RS m_G > 1.63 TeV** at 95% CL (k/M_D = 0.1)

	RS Graviton			
Model/Coupling	0.01	0.03	0.05	0.1
Mass limit [TeV]	0.71	1.03	1.33	1.63

Tevatron:

RS m_G > 1.08 TeV at 95% CL (k/M_D = 0.1)





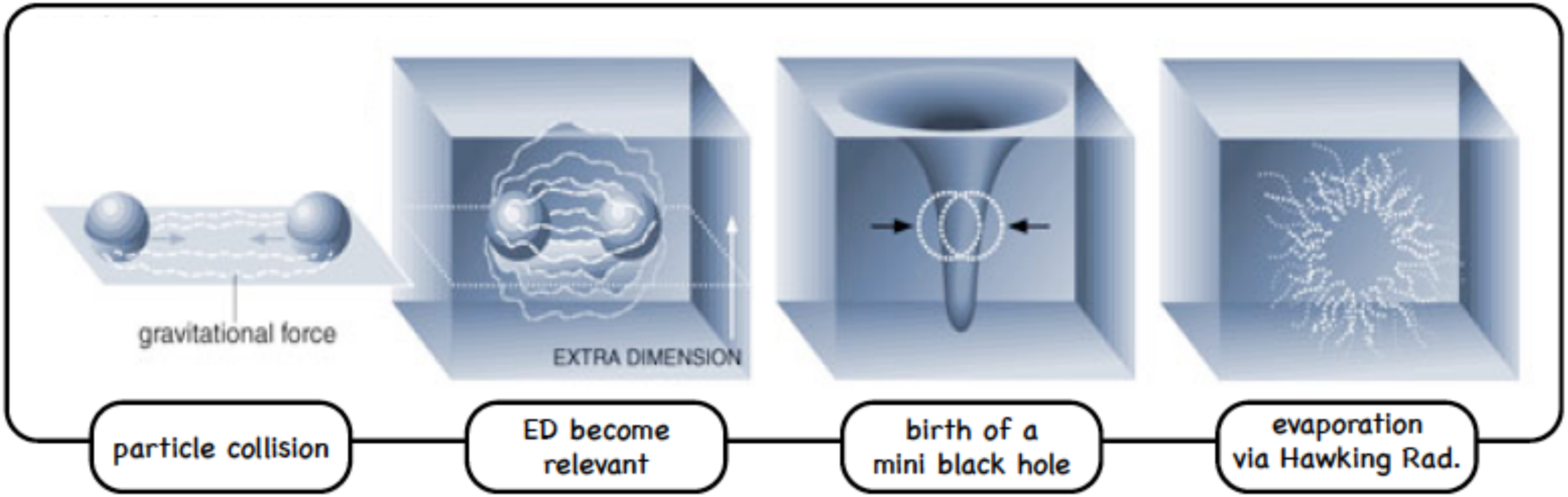
Mini Blck Holes

Schwarzschild radius scales with “new real planck mass” M_S like

$$r_{\rm BH} \approx \frac{1}{M_S}\left(\frac{M_{\rm BH}}{M_S}\right)^{\frac{1}{n+1}}$$

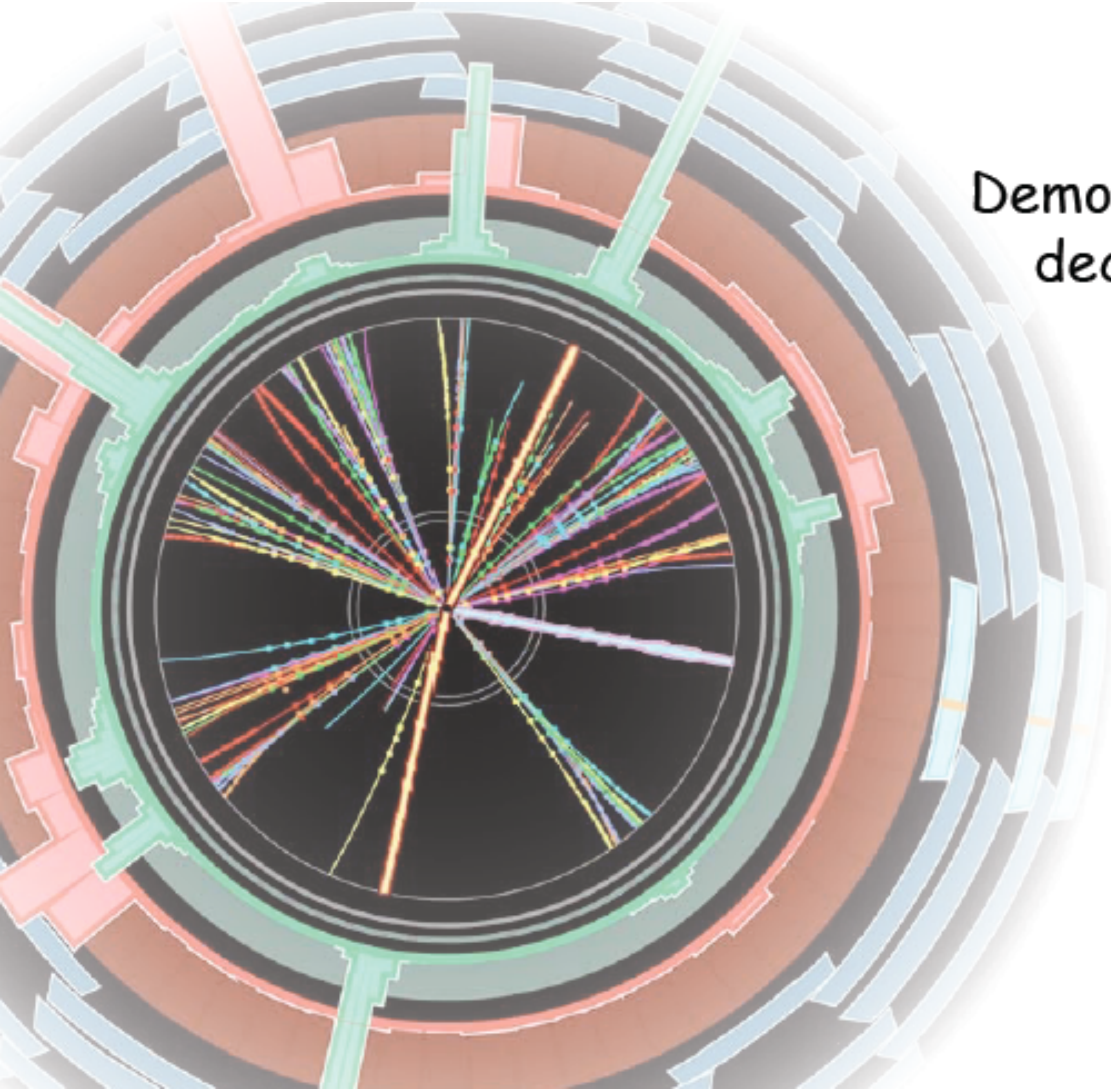
M_S small → r_{BH} large

$E_{cms} > M_S$, $b < r_{BH}$ → black hole



Mini Black Holes at the LHC

(if theories with Extra Dimensions are true)

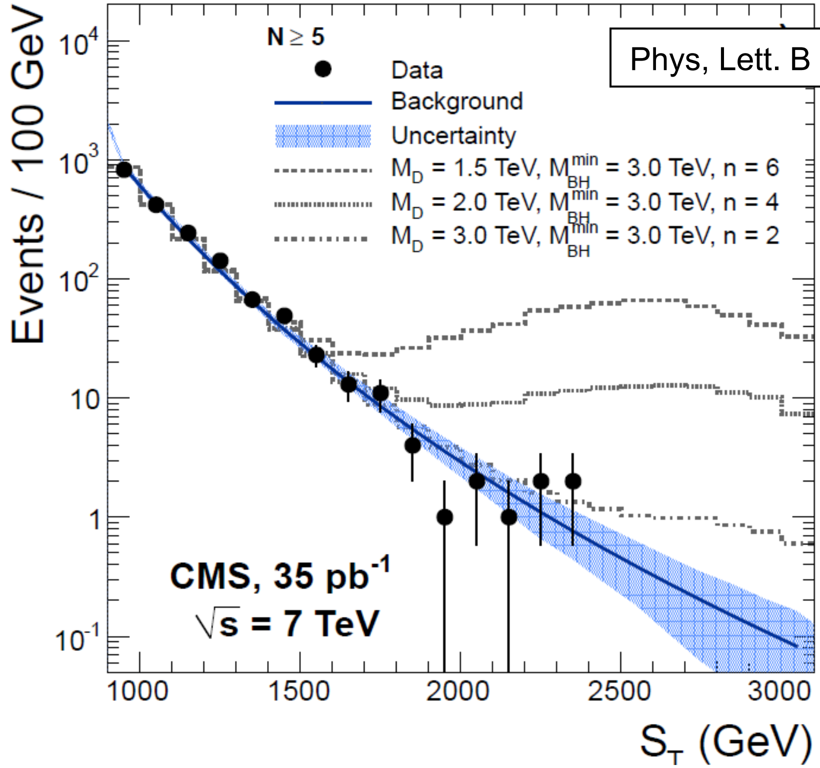


q/g : ℓ : W/Z : ν/g : H : γ
72% : 11% : 8% : 6% : 2% : 1%

Democratic
decay into SM particles
[Emparan et al., hep-th/0003118]

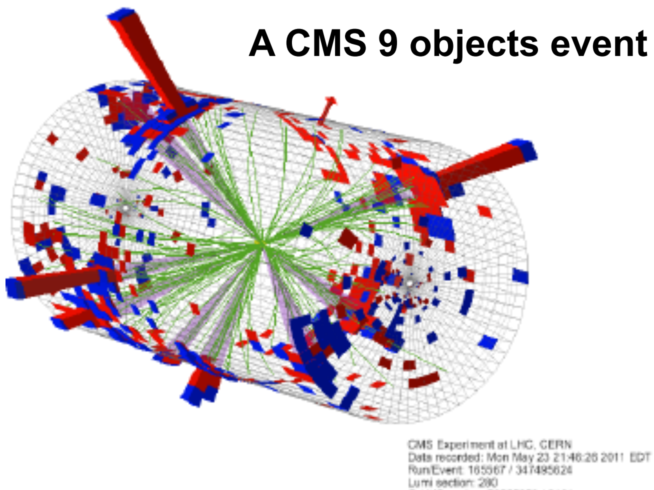
- High multiplicity
  [e.g. M_{BH} = 10 TeV: 50 part. with E ~ 200 GeV]
- Spheric Events
  [production at high x without Boost]
- Electrons and muons with high energy

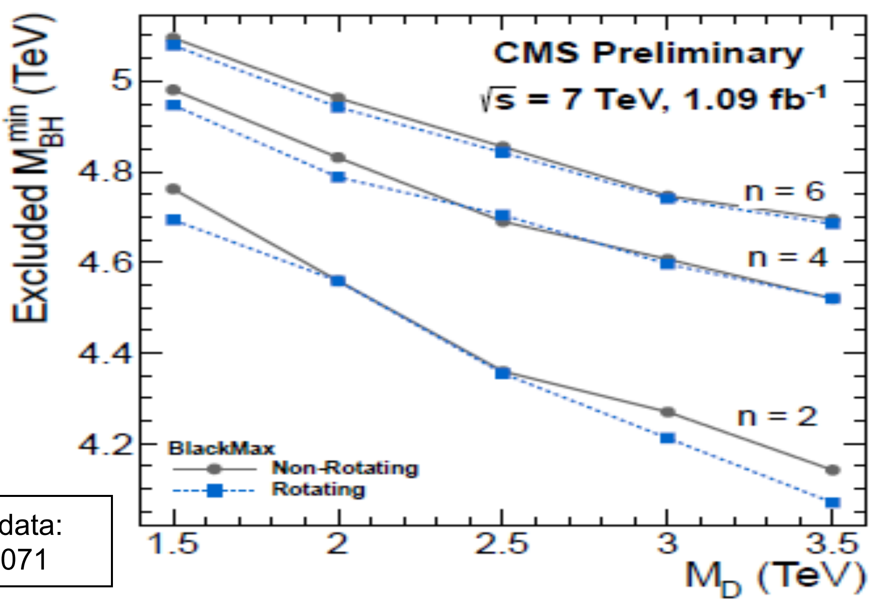
Example for a search for Microscopic Black Hole production in models with large extra dimensions
(Arkani-Hamed, Dimopoulos, Dvali)



Decay into many objects (jets, leptons, photons)

S_T : scalar sum of the E_T of the N objects in the event

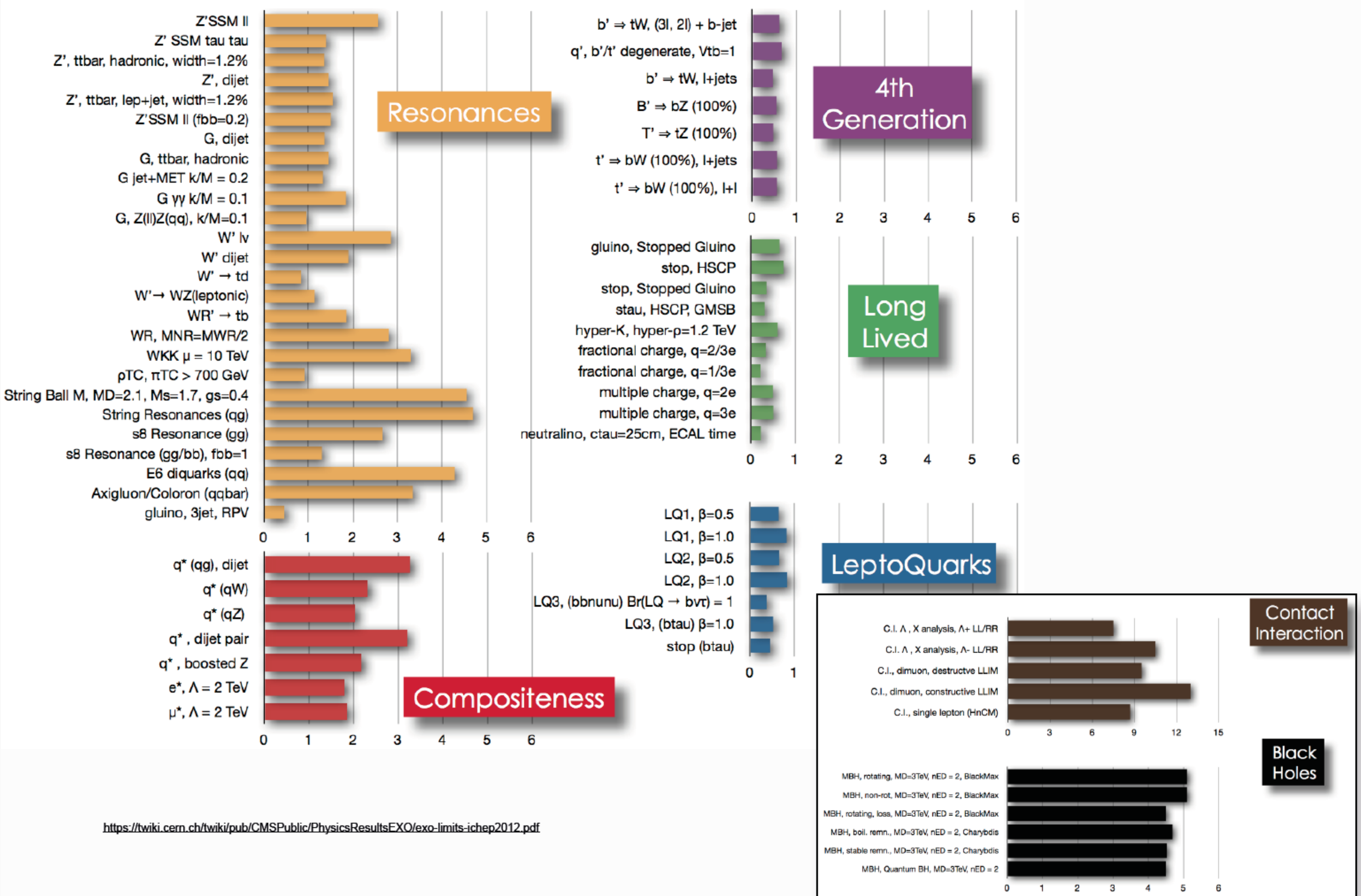




Updated with 2011 data:
CMS-PAS-EXO-11-071

Exotica: executive summary (CMS)

- CMS searches at ICHEP2012 (lower limits in TeV), similar picture for ATLAS



https://twiki.cern.ch/twiki/pub/CMSPublic/PhysicsResultsEXO/exo-limits-ichep2012.pdf

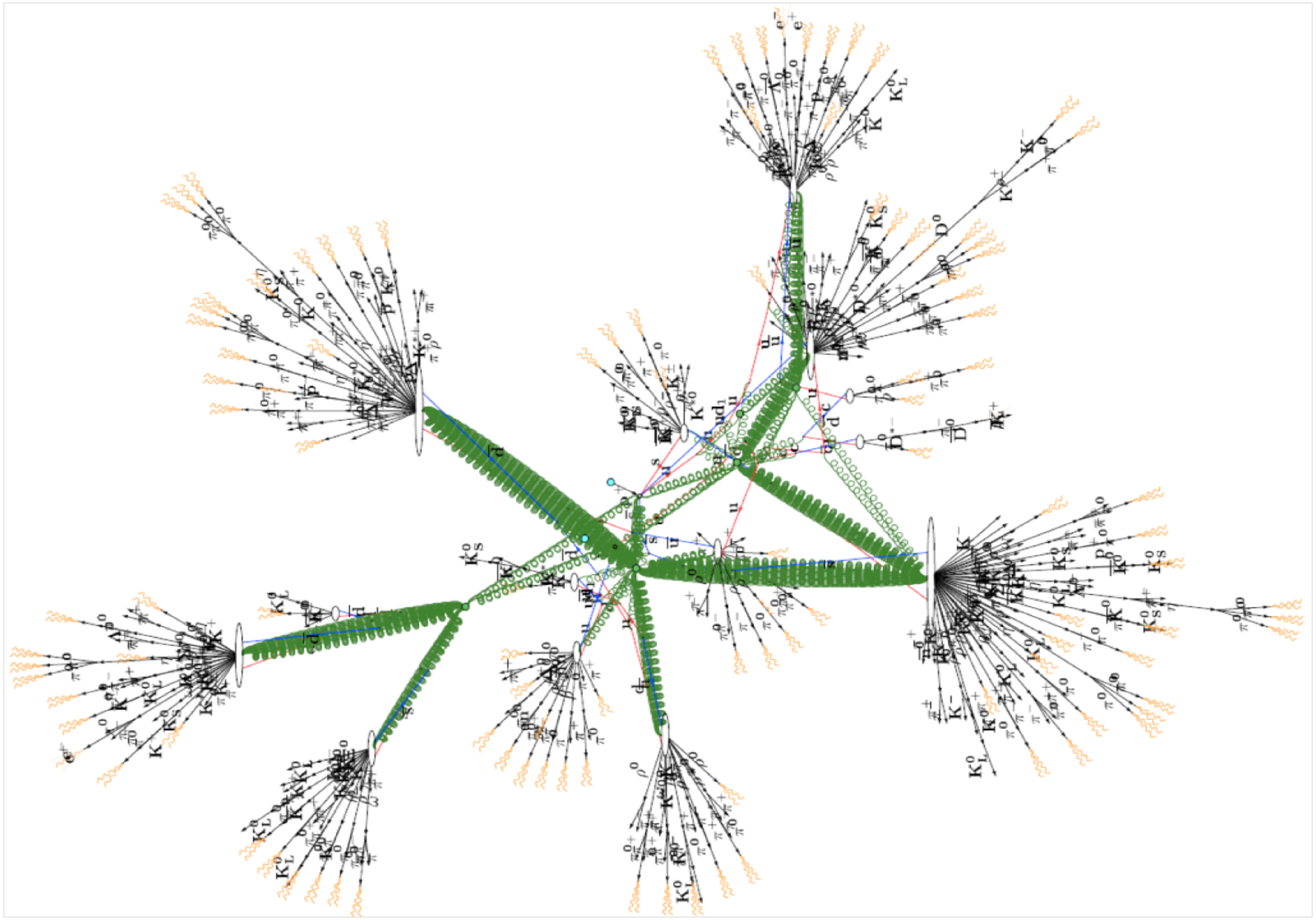
Resolutions

Resolutions

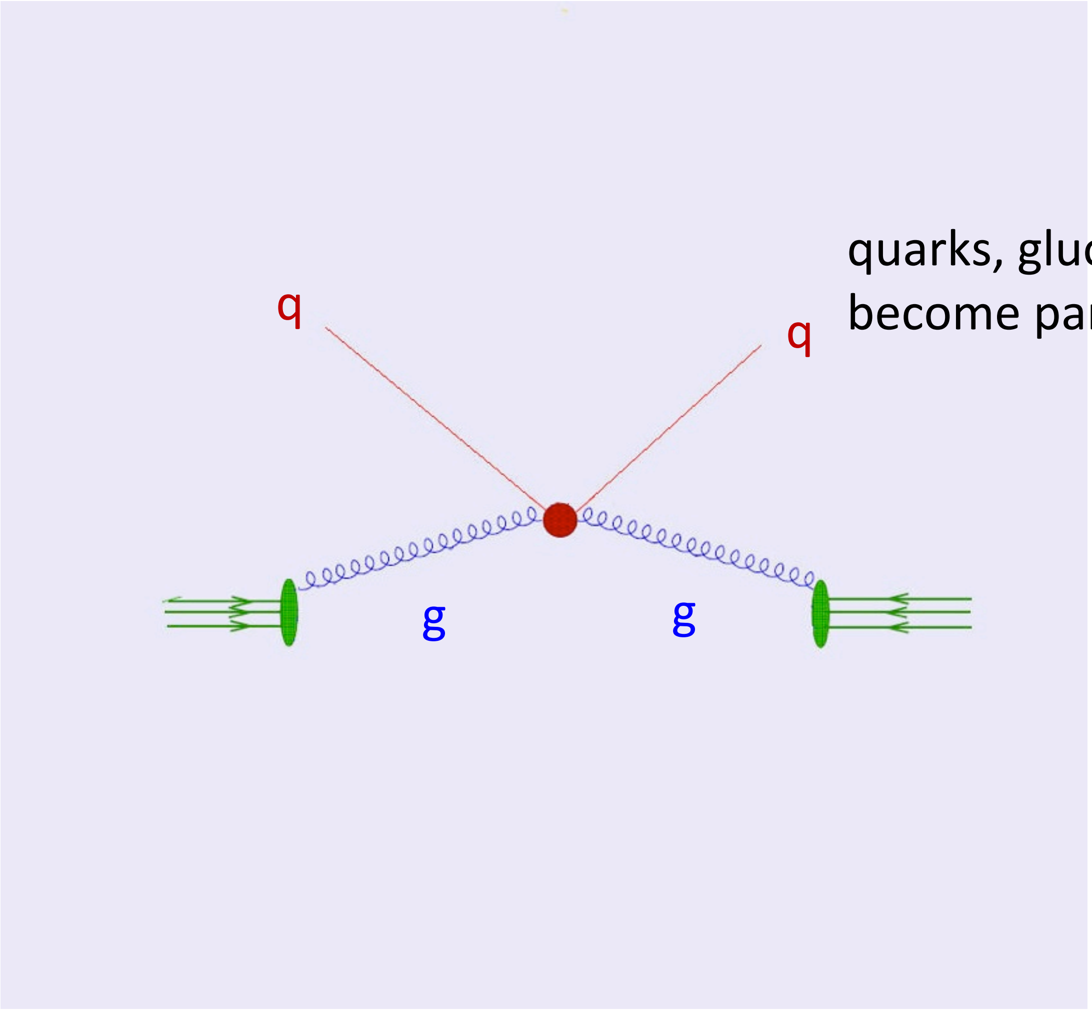
- Resolutions of various detectors

Detector component	Required resolution	η coverage	
		Measurement	Trigger
Tracking	$\sigma_{p_T}/p_T = 0.05\%\ p_T \oplus 1\%$	± 2.5	
EM calorimetry	$\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$	± 3.2	± 2.5
Hadronic calorimetry (jets)			
barrel and end-cap	$\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$	± 3.2	± 3.2
forward	$\sigma_E/E = 100\%/\sqrt{E} \oplus 10\%$	$3.1 < \lvert\eta\rvert < 4.9$	$3.1 < \lvert\eta\rvert < 4.9$
Muon spectrometer	σ_{p_T}/p_T=10% at $p_T = 1$ TeV	± 2.7	± 2.4

Else



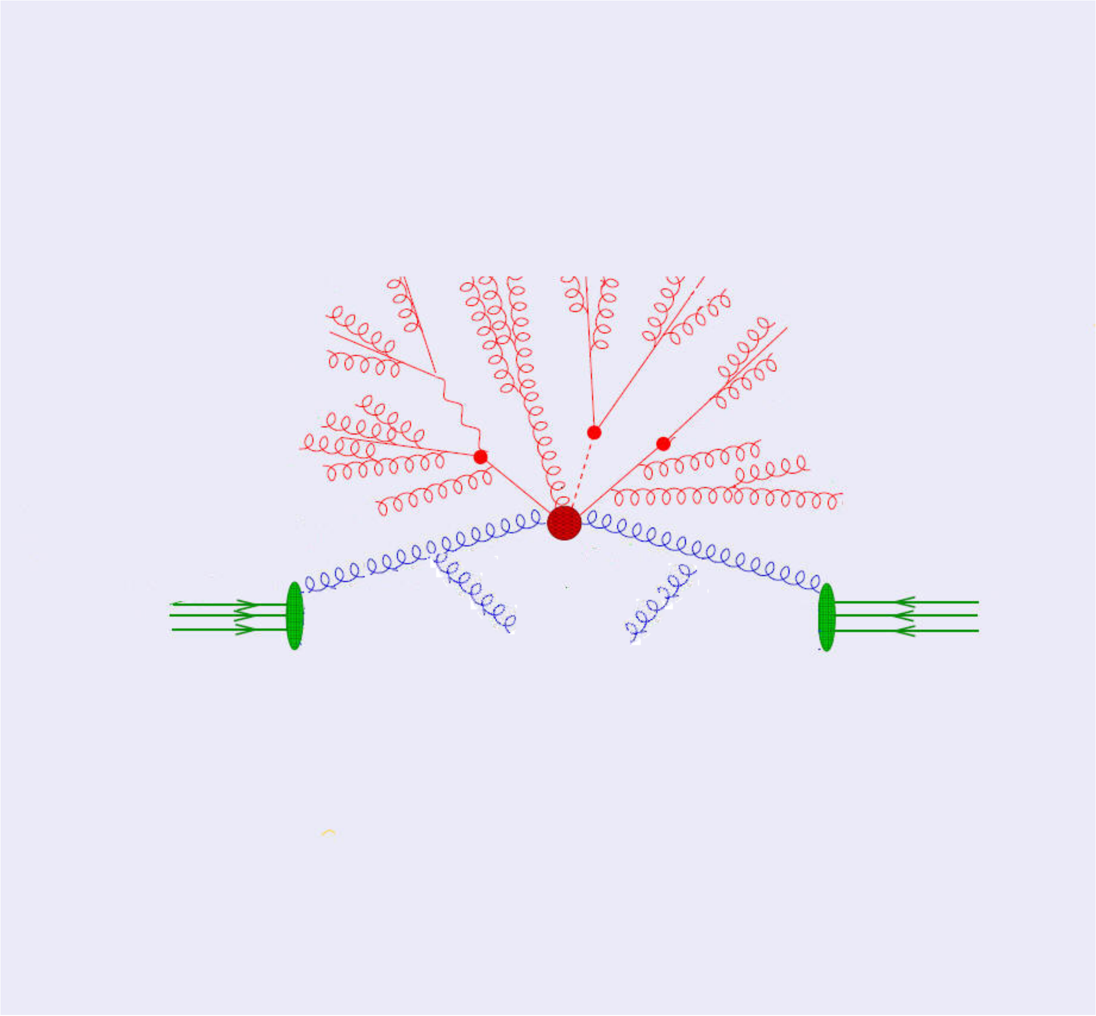
Point-like Parton-Parton Process



quarks, gluons not free
become particle "jets"

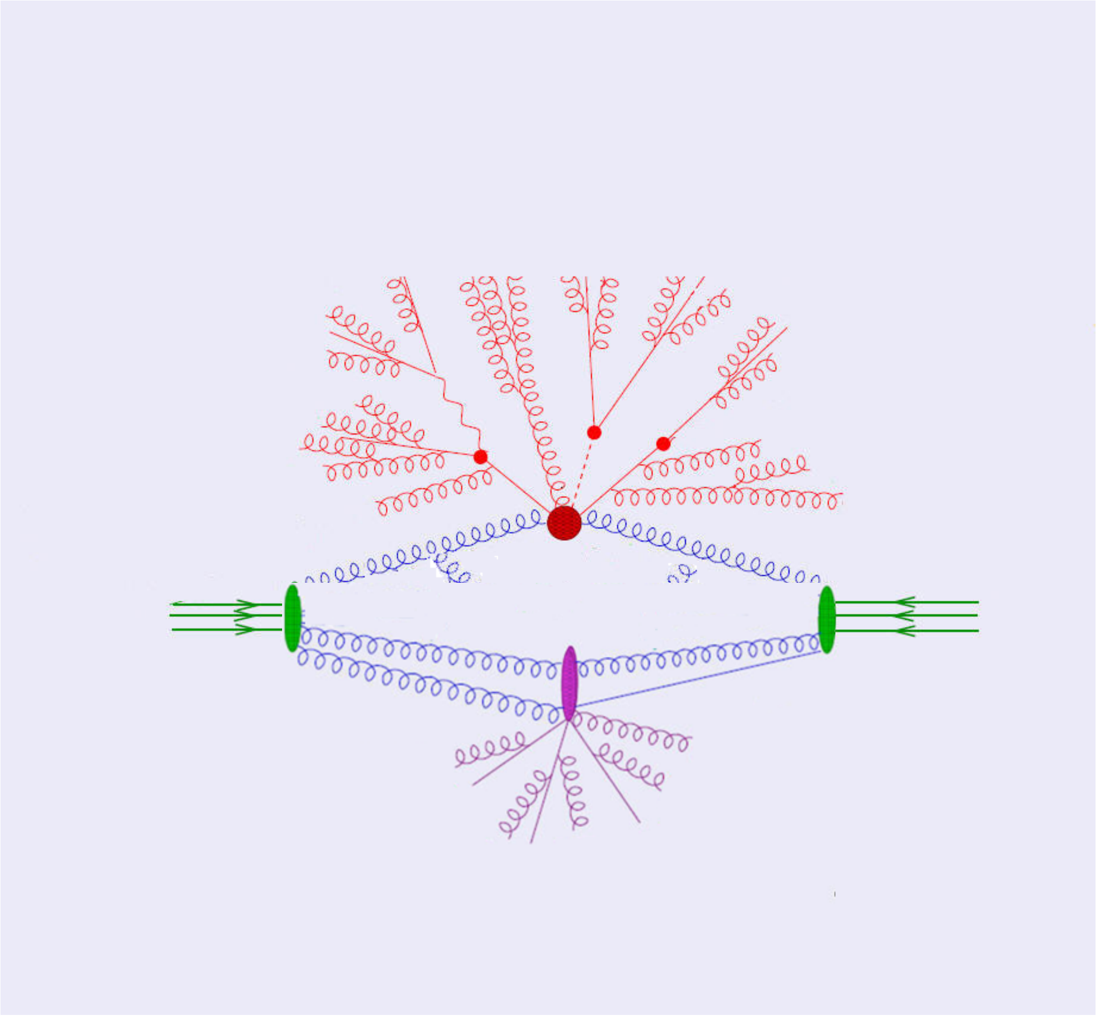
elementary process, lowest order

Point-like Parton-Parton Process



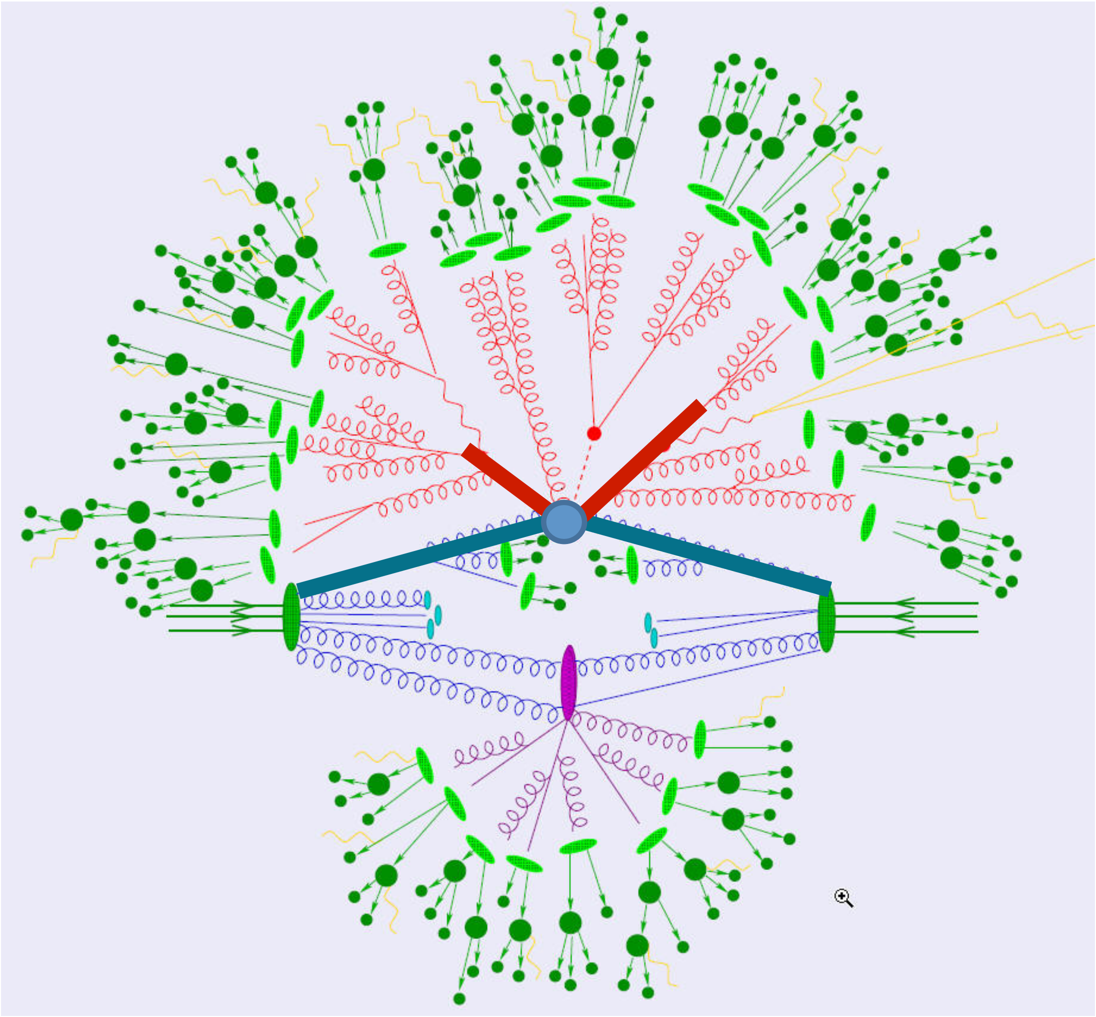
higher order “effects”

Point-like Parton-Parton Process



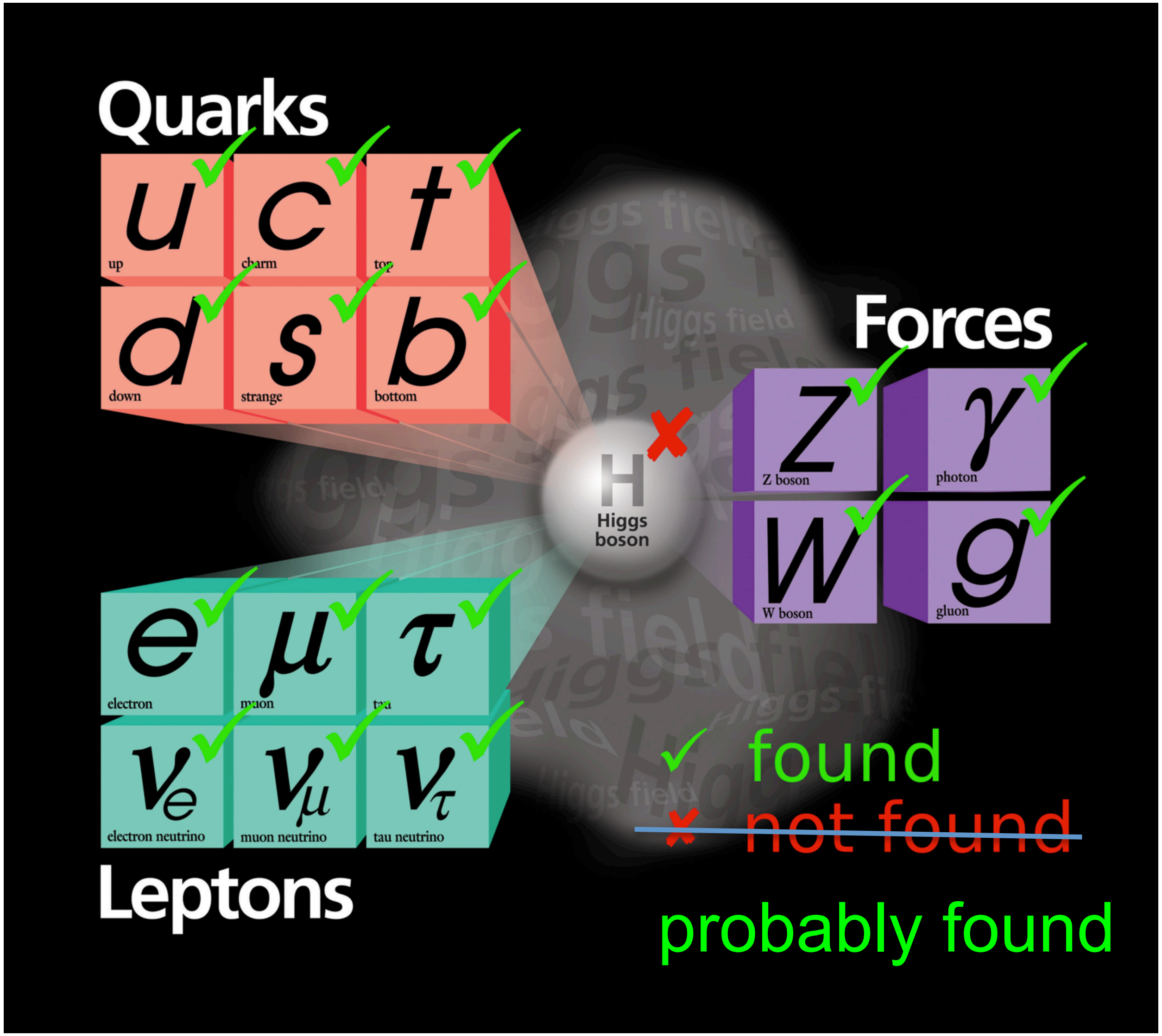
interactions of the “rest” → underlying event

Point-like Parton-Parton Process



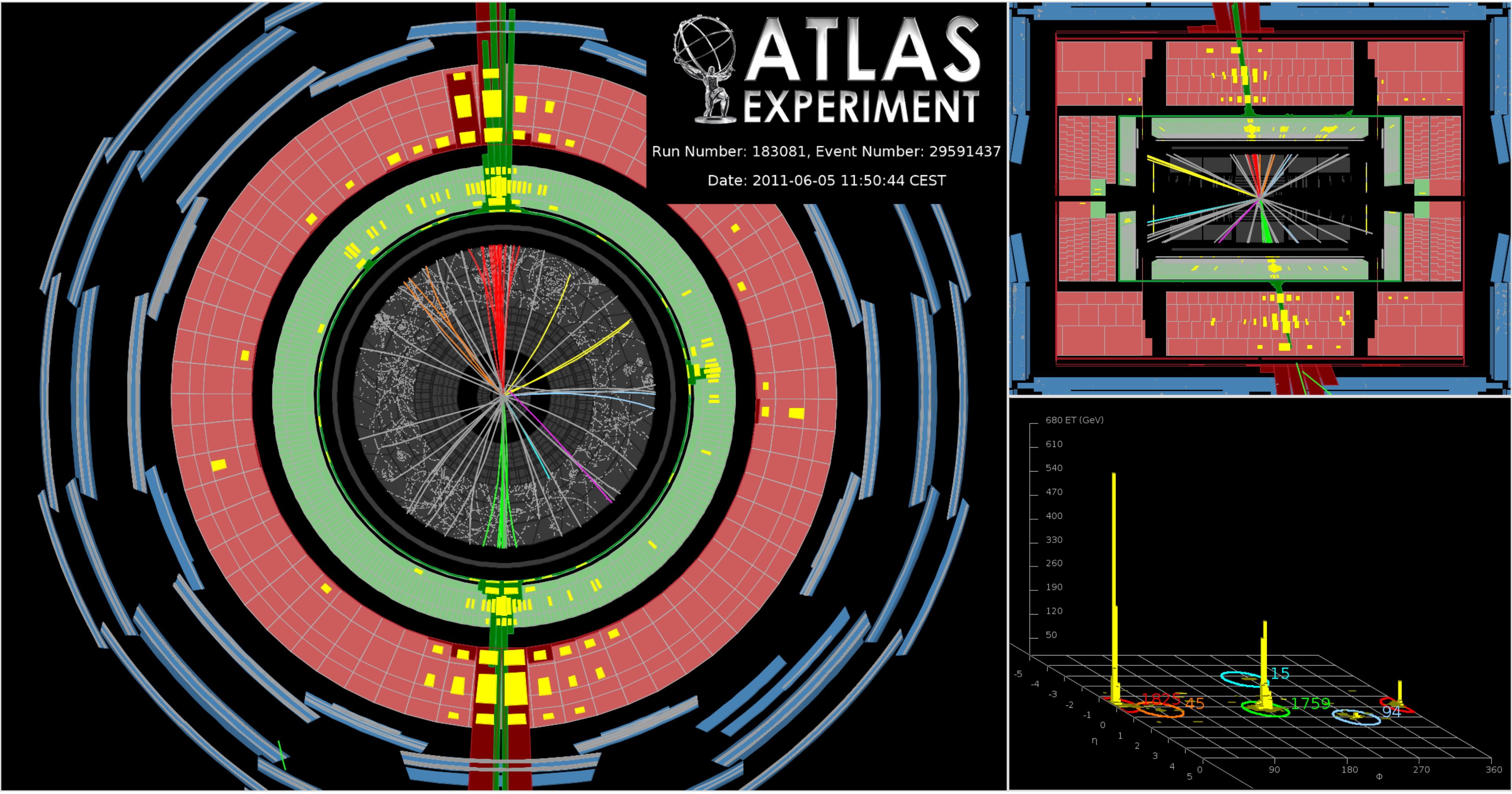
"hadronisation" into detectable particles

Standard Model Particles



- except Higgs

SM Higgs
should be light

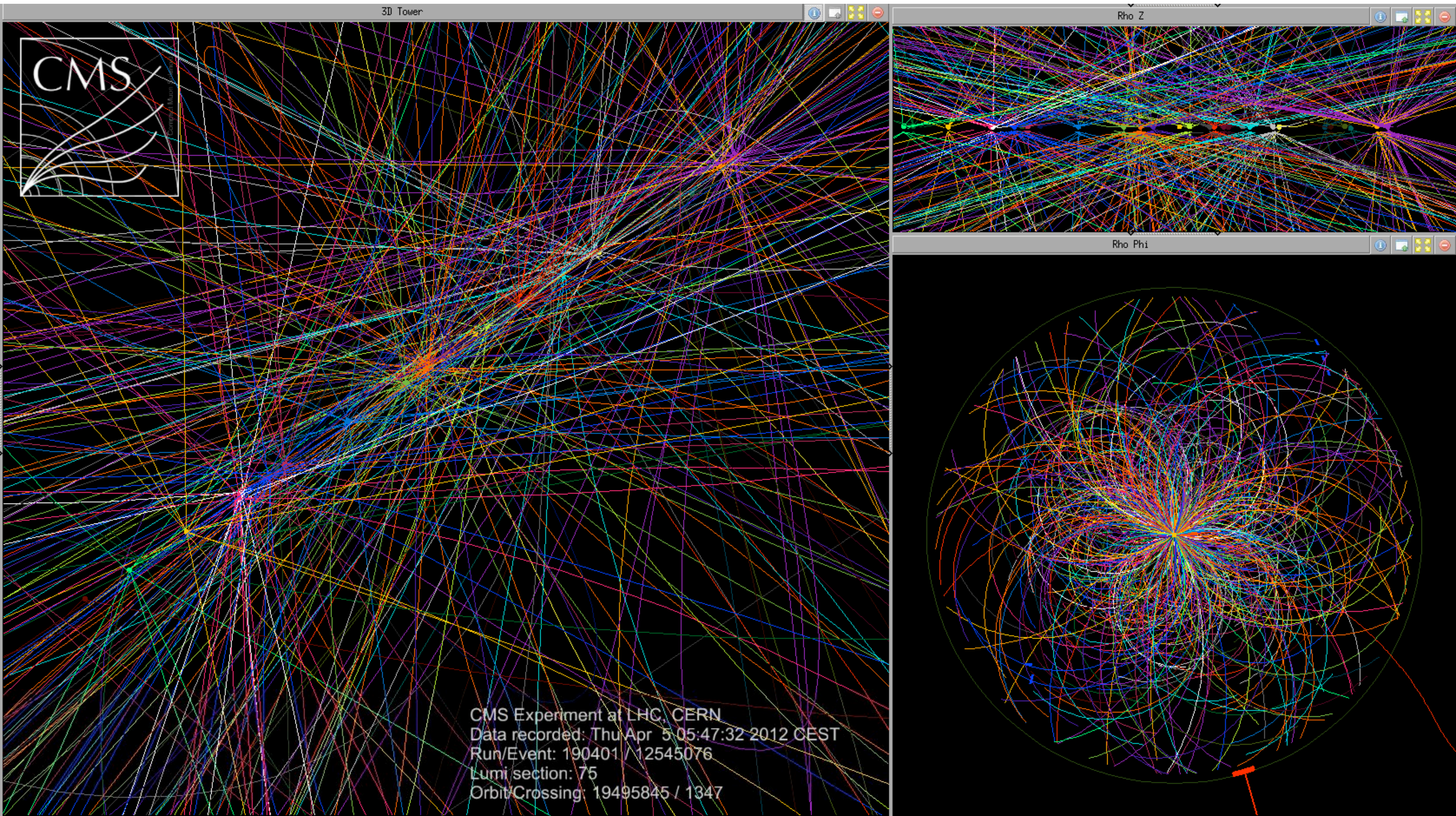


Jets

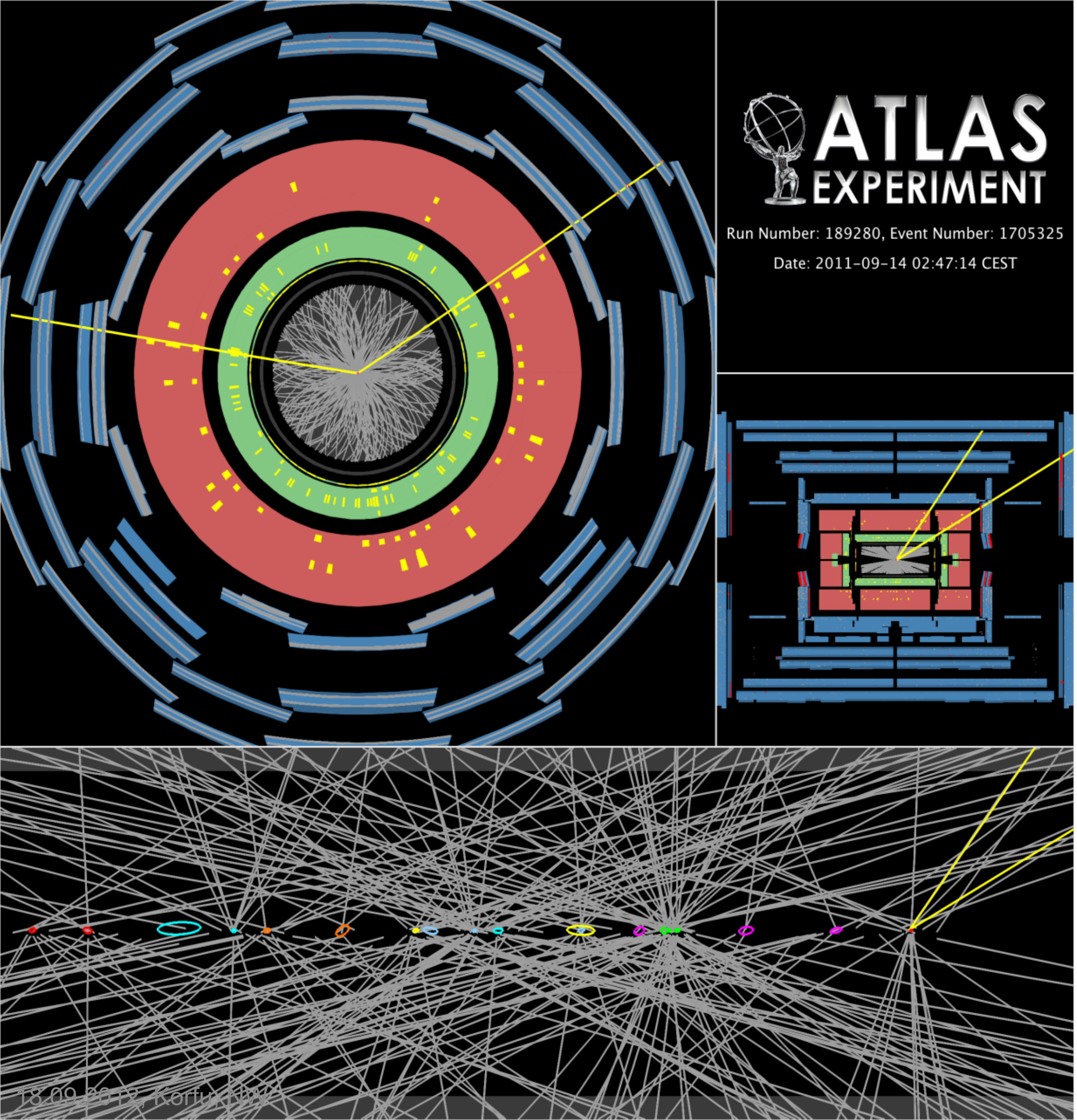
Jets with 1.9 and 1.7 TeV transverse momenta (p_T)

Pile up

Collision event
with 29 simultaneous
interactions

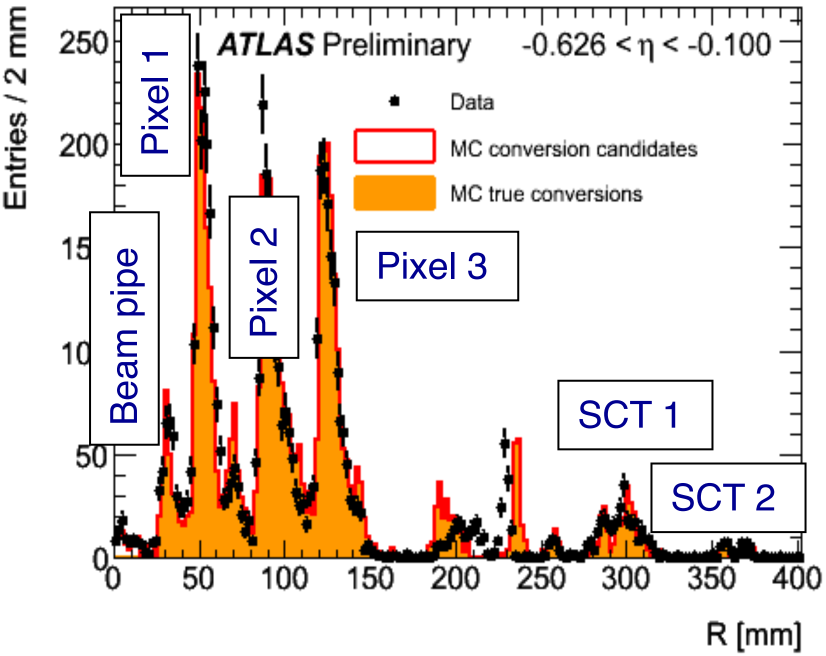


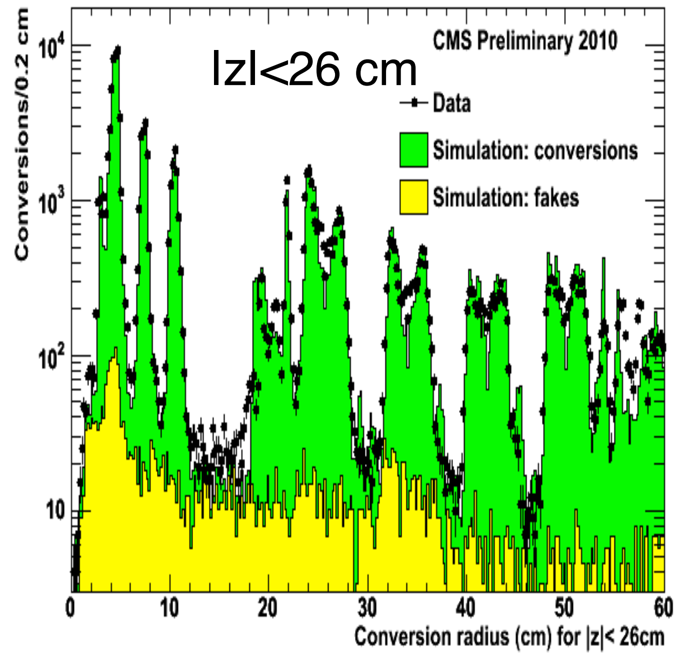
Pile up



Z → μμ event
with 20 simultaneous
interactions

Need to understand the detector response very precisely





e.g. Monte Carlo samples are generated for background and a "signal". After generation the events are passed through the full detector simulation and analyzed with the same analysis code as measured data are.

Software is in good shape ! (simulation, reconstruction and analysis)