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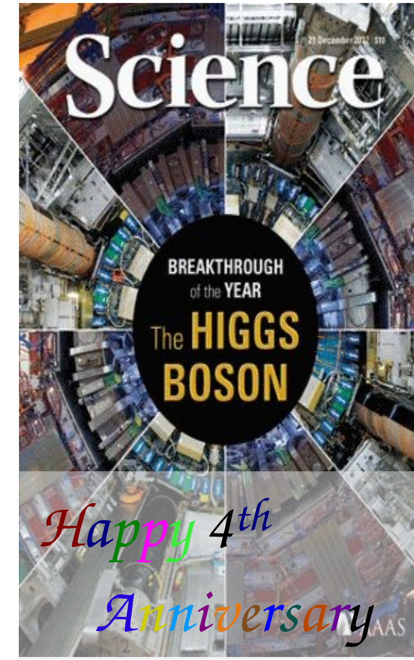

Experimental Aspects of the BEH-Mechanism and Discovery of the Higgs Boson

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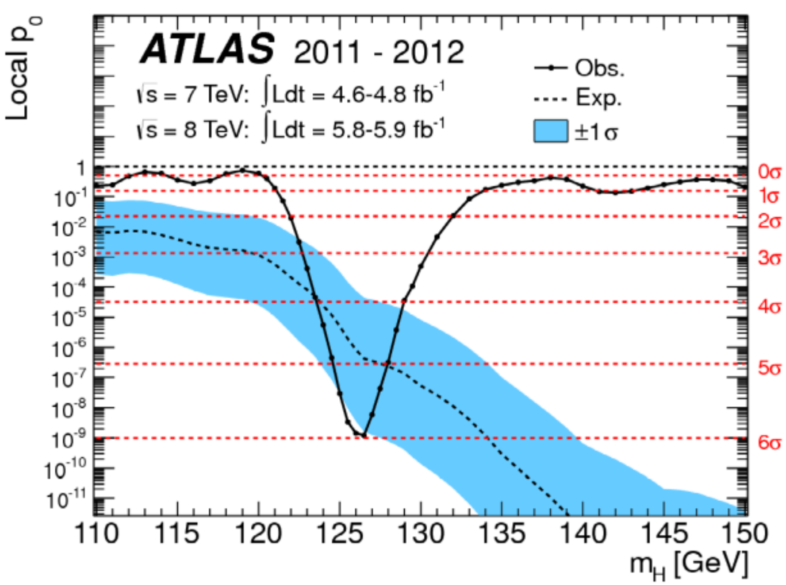
Fakultät für Physik
Institut für Experimentelle Kernphysik

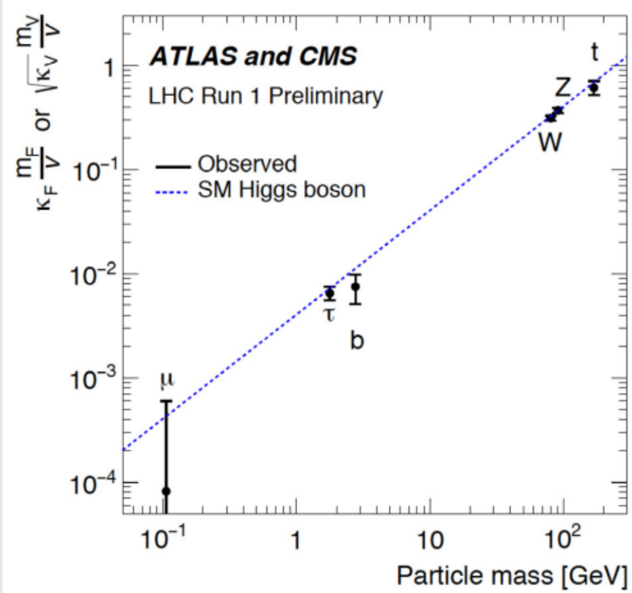
International Summer School, Dresden, Sept. 2, '16



2012
discovery

→

measurement
2016



The “Anderson-Higgs” Mechanism

Semiconductor

Anderson Theory Phys. Rev. 112, 1900 (1958)

virtual mass of photons
→ shielding of magnetic field in superconductor

Nature, Jan. 2015

The Higgs mode in disordered superconductors close to a quantum phase transition

Daniel Sherman[1,2†], Uwe S. Pracht[2], Boris Gorshunov[2,3,4], Shachaf Poran[1], John Jesudasan[5], Madhavi Chand[5], Pratap Raychaudhuri[5], Mason Swanson[6], Nandini Trivedi[6], Assa Auerbach[7], Marc Scheffler[2], Aviad Frydman[1*] and Martin Dressel[2]

→ first experimental evidence for

"Higgs" state in superconductors

Particle Physics

Brout-Englert-Higgs (BEH) Mechanism

mass of W and Z bosons
→ “shielding” - i. e. short range - of weak interaction

Higgs Boson is an excitation of the field

Announcement of discovery of “A new particle” on July 4th, 2012, by LHC experiments **ATLAS** and **CMS**

more data and refined analyses later confirmed Higgs-like properties.

Is it the only one of its kind, is it **the** Standard Model Higgs Boson ?

Part 1

Introduction

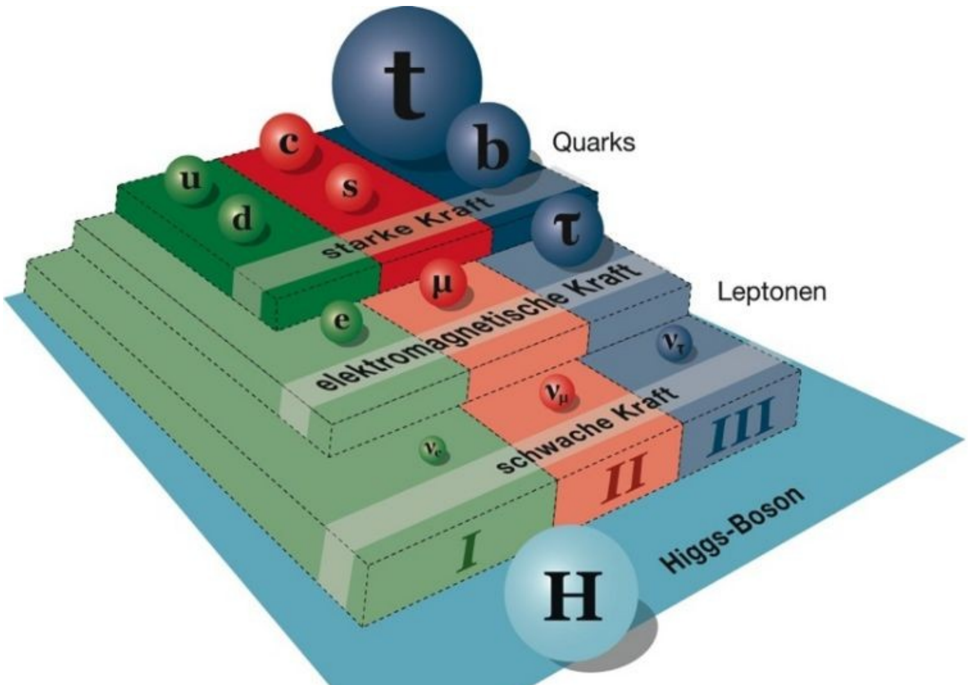
The (minimal) Standard Model of Particle Physics

3 fundamental forces

(electromagnetic and weak force unified)

12 fundamental particles (fermions)

3 families with 2 leptons and quarks each



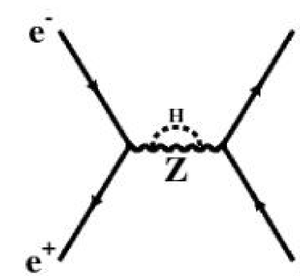
- $U_1 \times SU_{2(L)} \times SU_3$ **Gauge field theory**
- **weak boson masses** via spontaneous breaking of electroweak symmetry
  → **need ≥1 Higgs boson**
- **fermion masses** through Yukawa coupling of fermions to Higgs boson

- **masses of W and Z boson**
  are non-zero and precisely measured
  responsible for the short interaction range of the weak force

- **fermion masses cover a wide range:**
  <~0.5 eV (e-neutrino) **– 173.3 GeV** (top quark)
  explanation in SM needs BEH-Mechanism & postulated Higgs-Fermion Yukawa-Couplings

- **within the SM, everything is fixed if the Higgs boson mass is known**

- **precision measurements are sensitive to Higgs Boson mass via loops:**

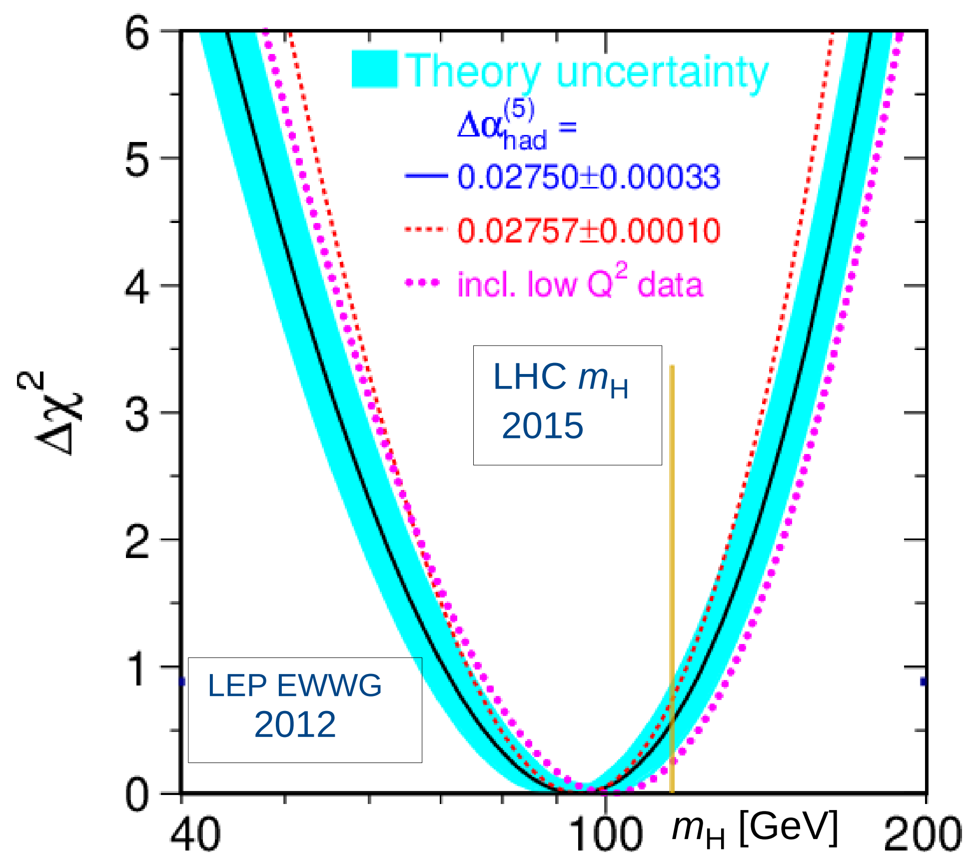


Precision Tests of the Theory

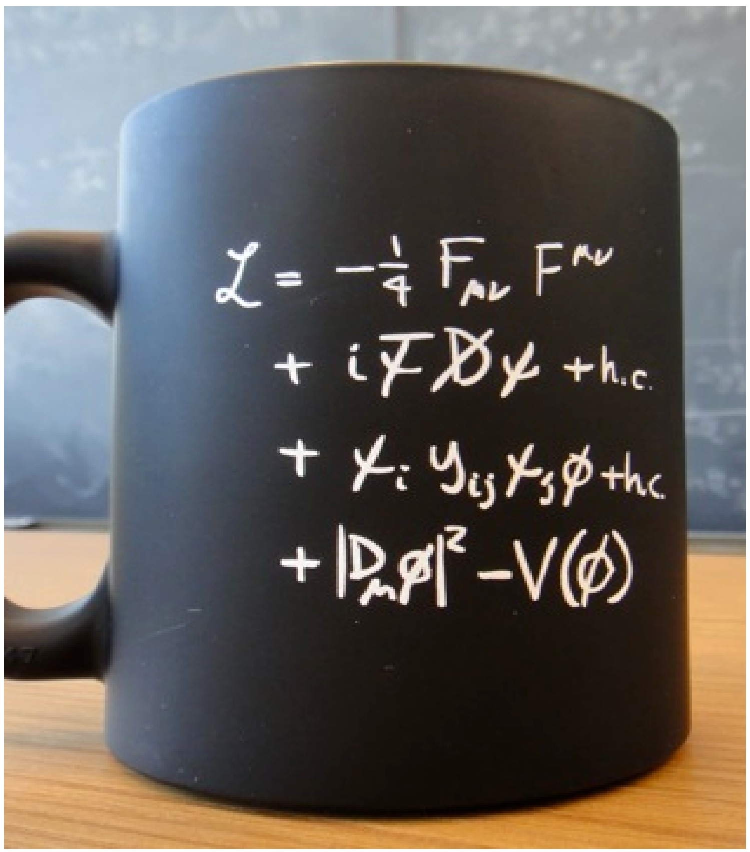
extremely successfully passed many ***precision tests*** *over the past decades at e^+e^- and hadron colliders*

last piece: the **Higgs Boson**

are **all consistent** with the Standard Model for a Higgs Boson Mass ~100 GeV



Establishing the **Higgs particle** and the BEH-Mechanism
is a crucial corner stone for the Standard Model of the ew interaction



If a new particle is found,

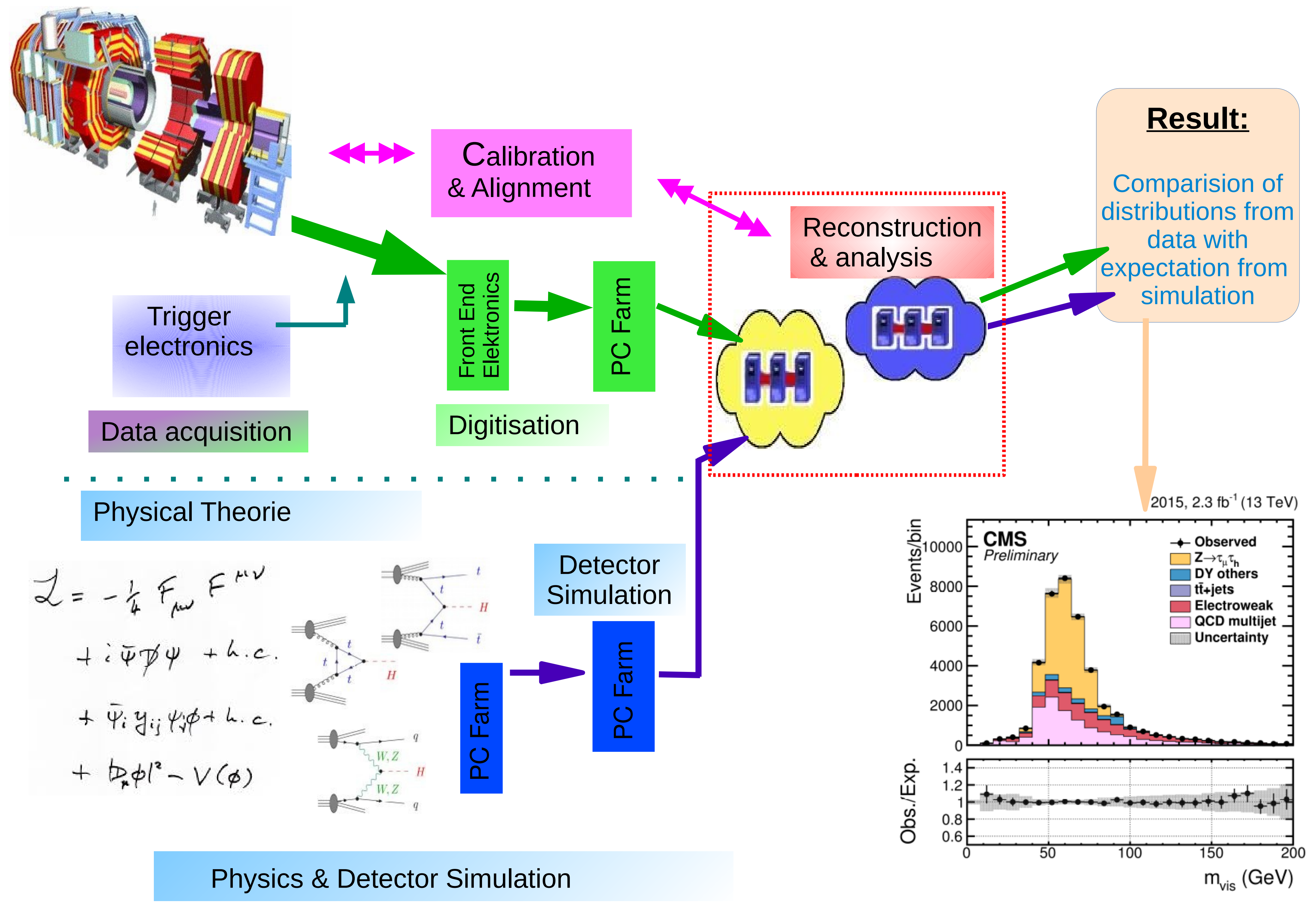
check consistency with expectations
from theory and other measurements **:**

- mass (a-priory unknown, but constrained by precision measurements)
- couplings to W and Z bosons
  defined by gauge symmetry
- couplings to Fermions (prop. to mass)
- spin and CP state (0+, like vacuum)
- does it couple to yet unknown particles ?
  (“invisible” contribution to total width).
- are there more than one of its kind ?
- Higgs self-coupling ?
- Higgs contribution to WW scattering ?

Part 2

Experimental Methods

Simulation and Analysis Chain



cross section:

transition rate initial → final state

in theory	experimentally

Fermi's golden rule

$$\lambda_{i\rightarrow f} = 2\pi |M_{fi}|^2 \rho$$

amplitude or "matrix element" of underlying process

phase space

Cross Section

$$\sigma = \frac{|\mathcal{M}|^2 \cdot [\text{Phase space}]}{[\text{Colliding particle flux}]}$$

$$\sigma = \frac{N_{cand} - N_{bkg}}{\alpha\,\epsilon \cdot f} \frac{1}{T}$$

N_{cand} : number of observed events
N_{bkd} : number of expected background events
α : acceptance
ϵ : efficiency
f : flux
T : measurement time

Cross section measurement

the experimentalists' master formula:

signal candidates

background events

$$\sigma = \frac{N_{cand} - N_{bkg}}{\alpha\epsilon \cdot \int L}$$

acceptance and efficiency

integrated Luminosity

product of many factors:
– detector acceptance
– trigger efficiency
– reconstruction efficiency
– selection efficiency
– background rejection efficiency

usually determined using well-known reference reaction:

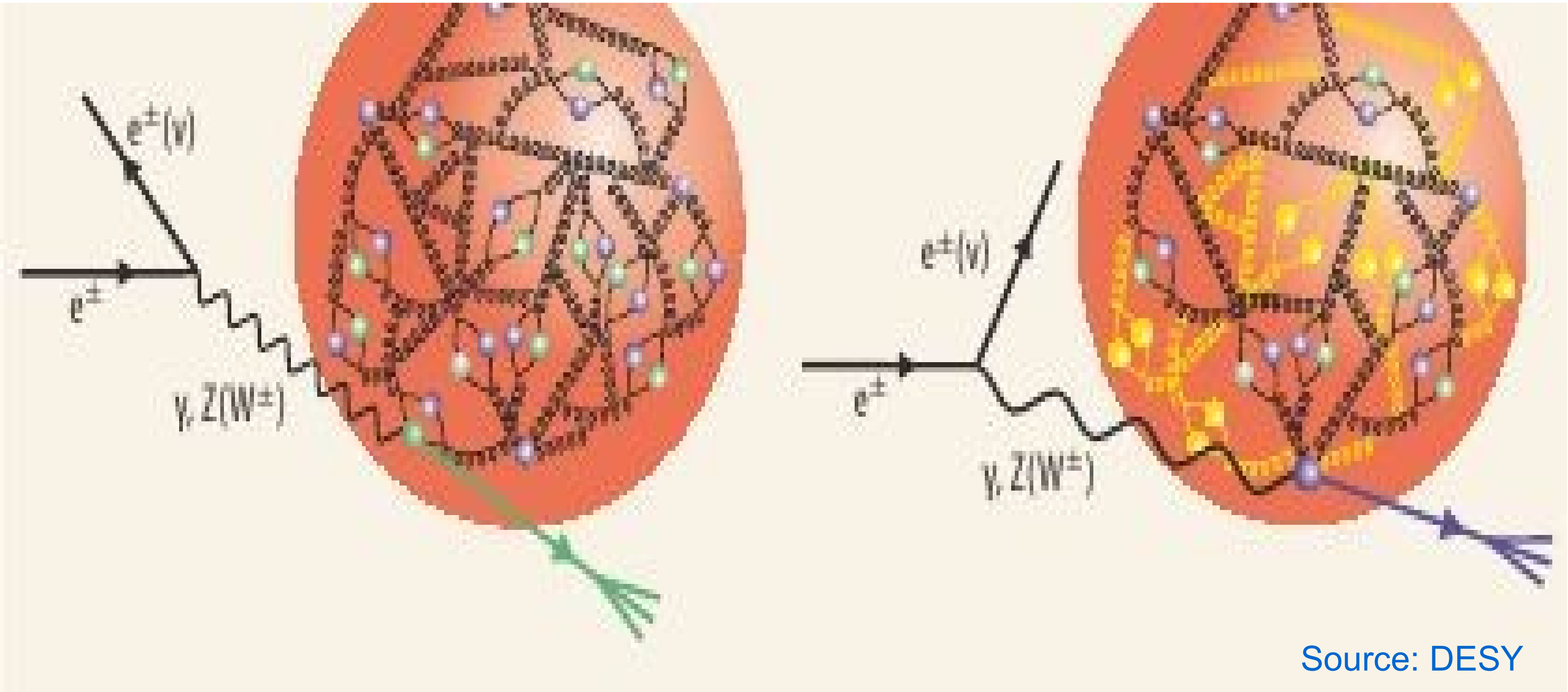
$$\int L = N_{ref} \,/\, \sigma_{ref}$$

The determination of $\boldsymbol{N_{cand}}$ and optinal **separation from backgrounds** is a classification problem and typically requires multivariate analysis techniques

in fact, the proton is complicated:

composed of
- **valence quarks**
- **sea quarks**
- **gluons** (carry 50% of momentum)

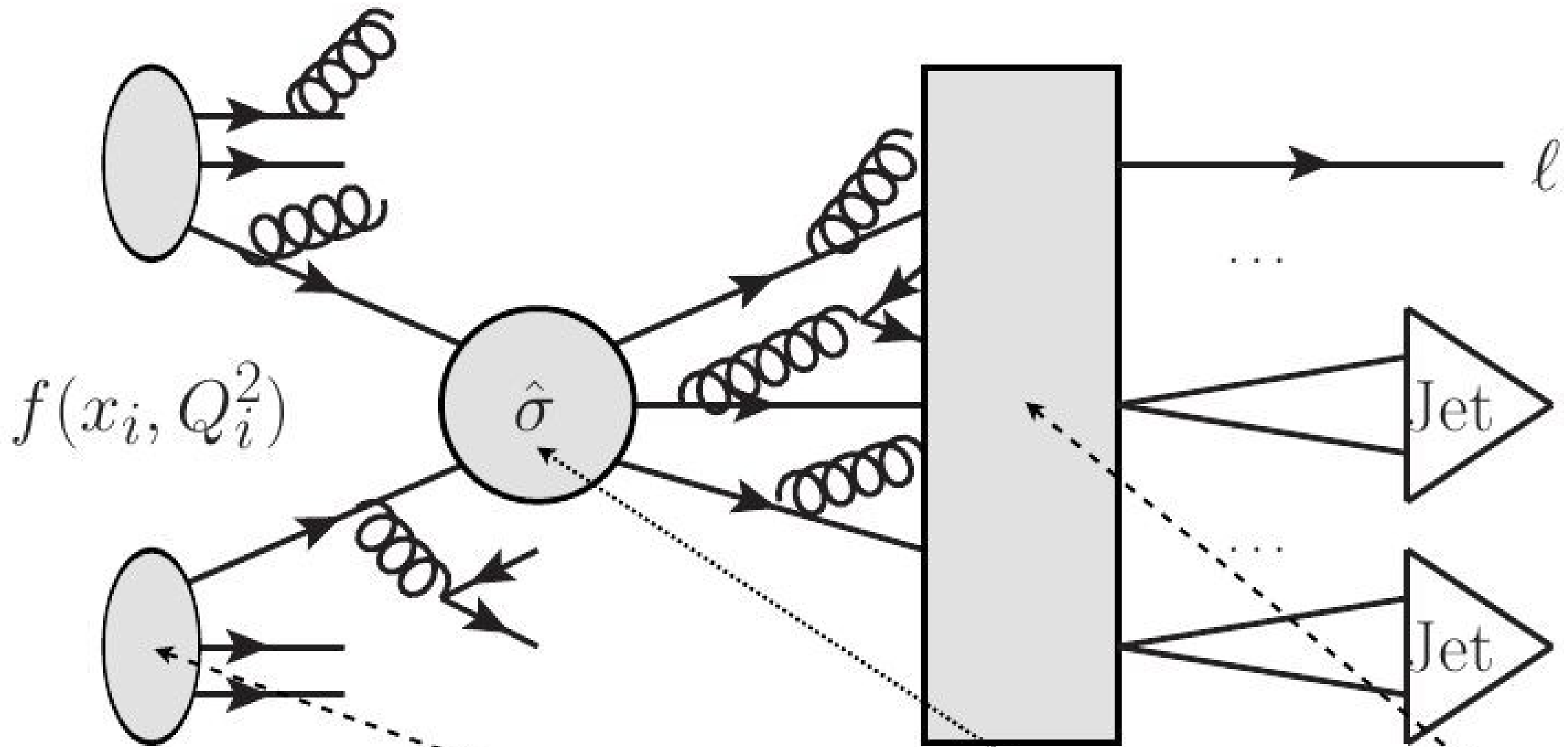
Precision study of proton composition in electron-proton scattering
HERA at DESY in Hamburg



Source: DESY

Calculation of Cross sections

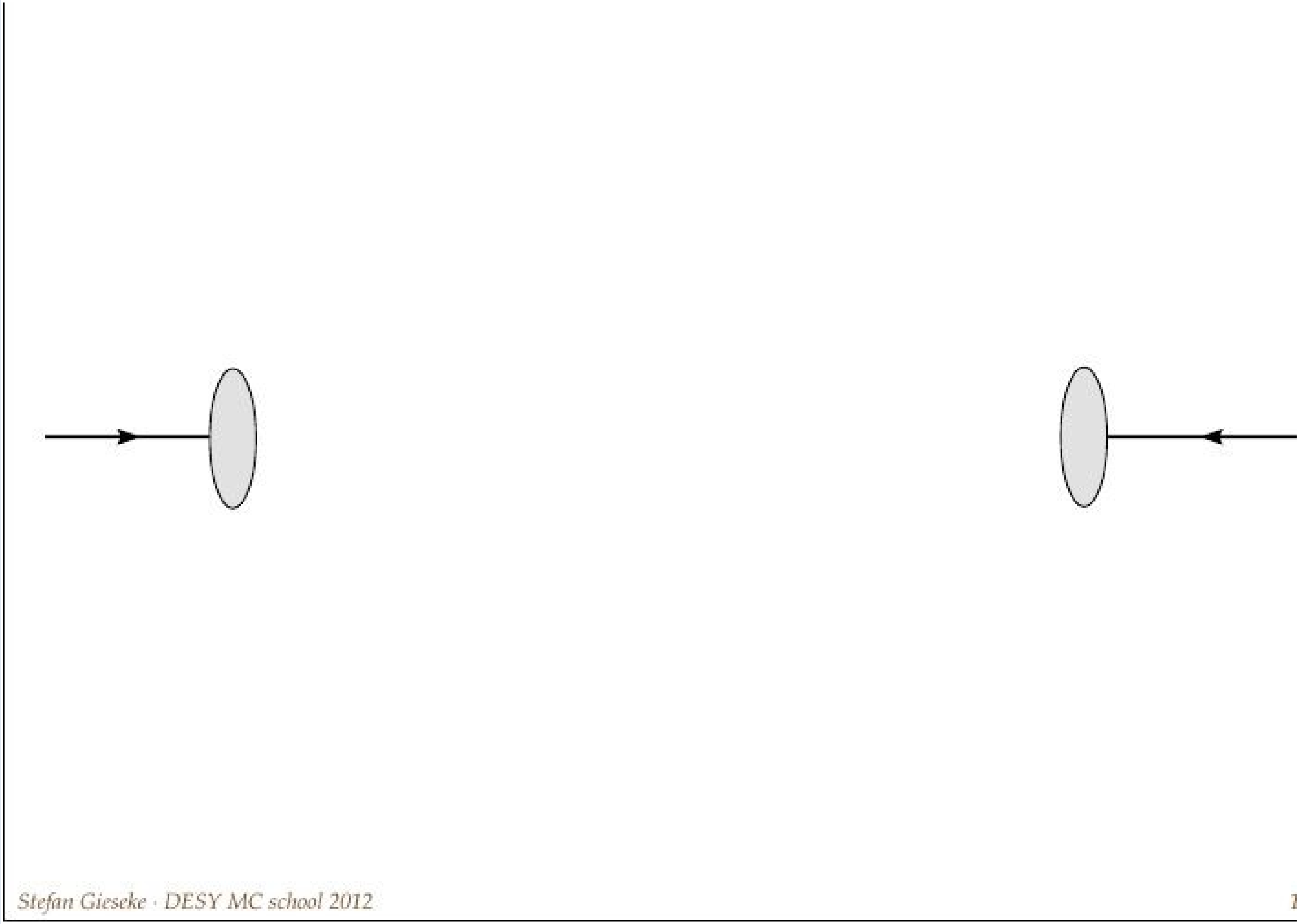
σ = PDFs ⊗ 2→n process ⊗ hadroniszation



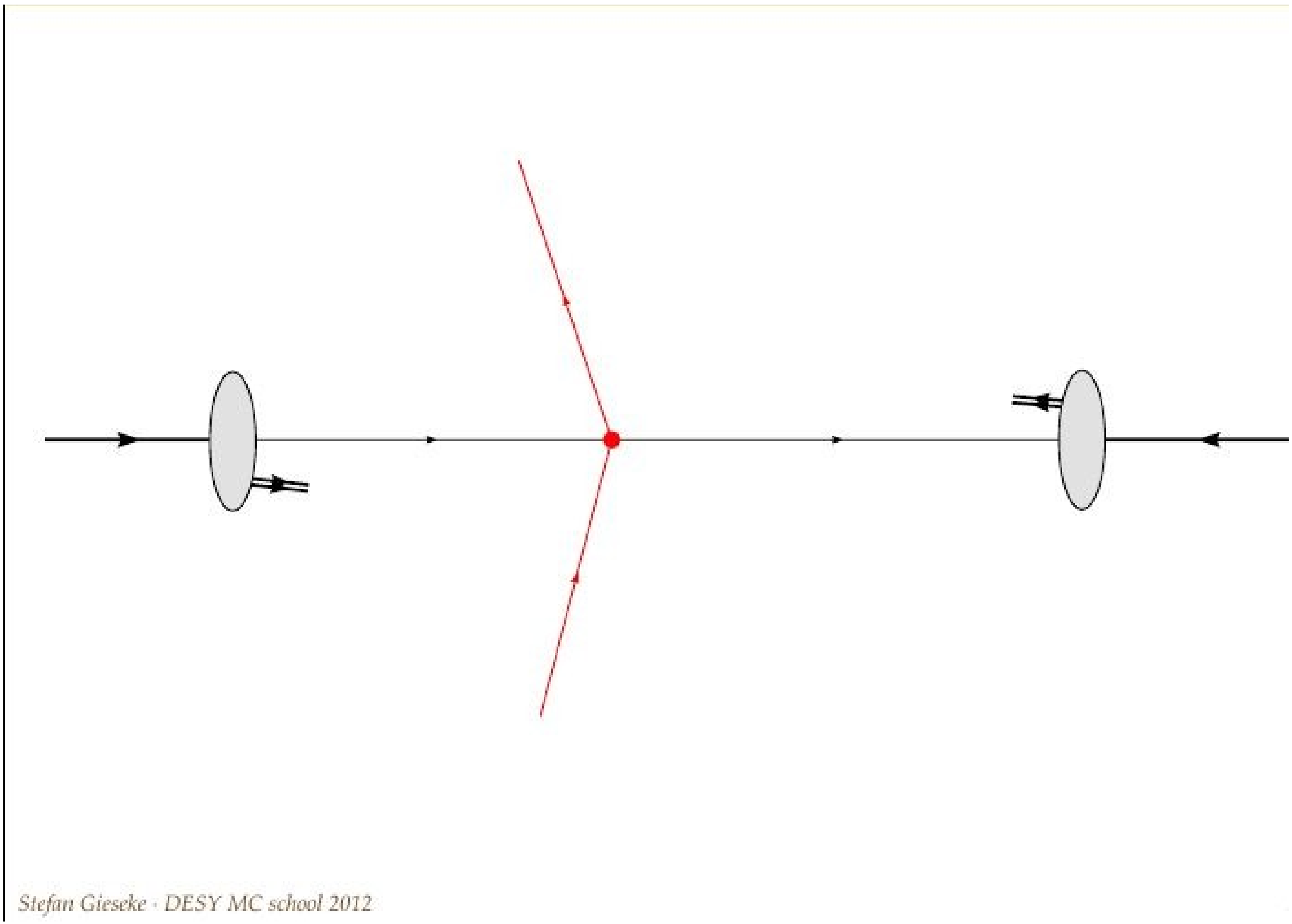
$$\sigma_{\text{QCD}} = \sum_{jk} \int dx_j \, dx_k \; f_j(x_j, \mu_F^2) \, f_k(x_k, \mu_F^2) \cdot \hat{\sigma}(x_j x_k s, \mu_F^2, \mu_R^2) \otimes \text{hadronization}$$

Complicated process – use MC techniques to calculate cross sections, phenomenological modes to describe hadronization process (quarks → jets)

Example: pp collision

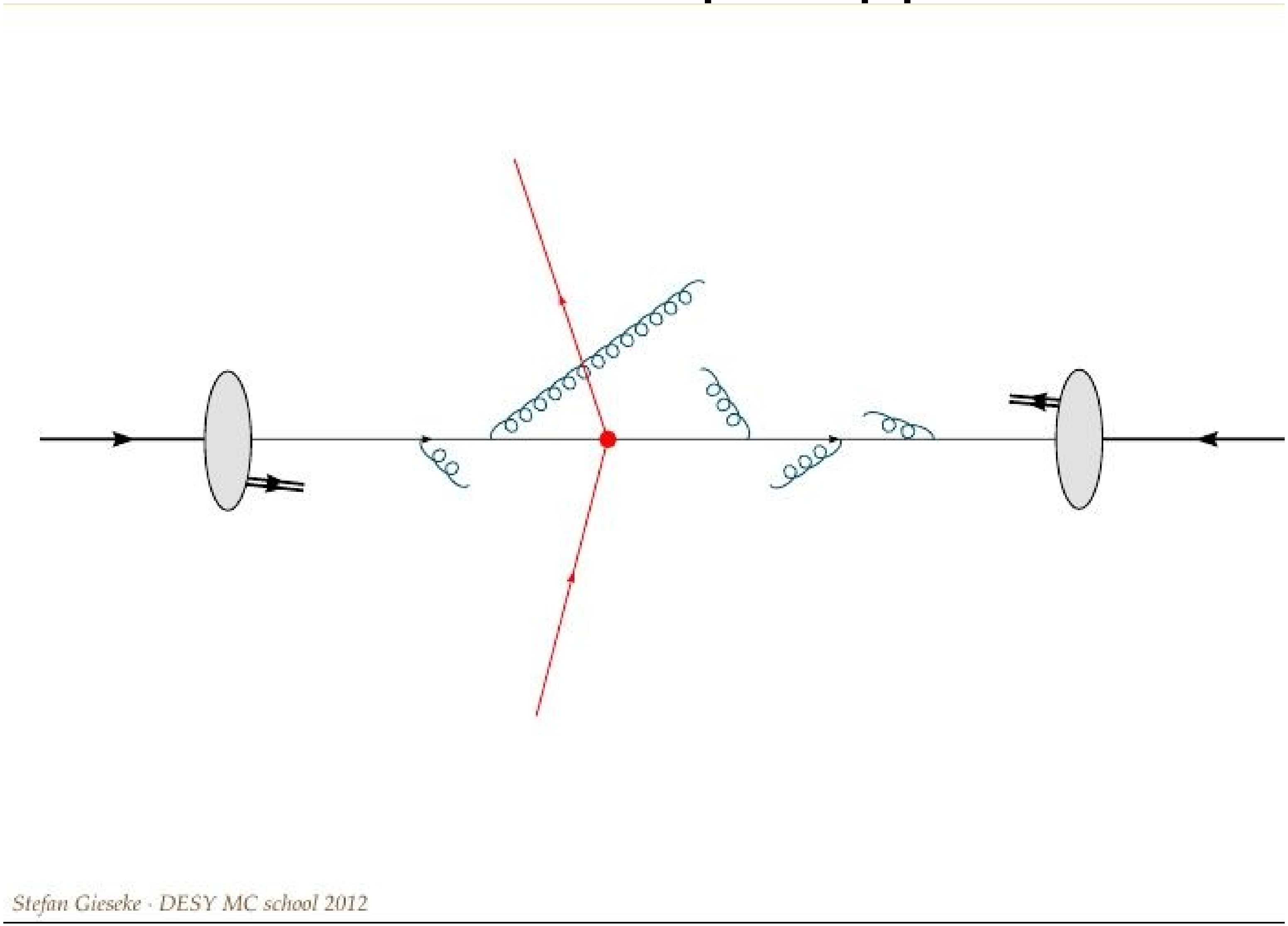


Example: pp collision



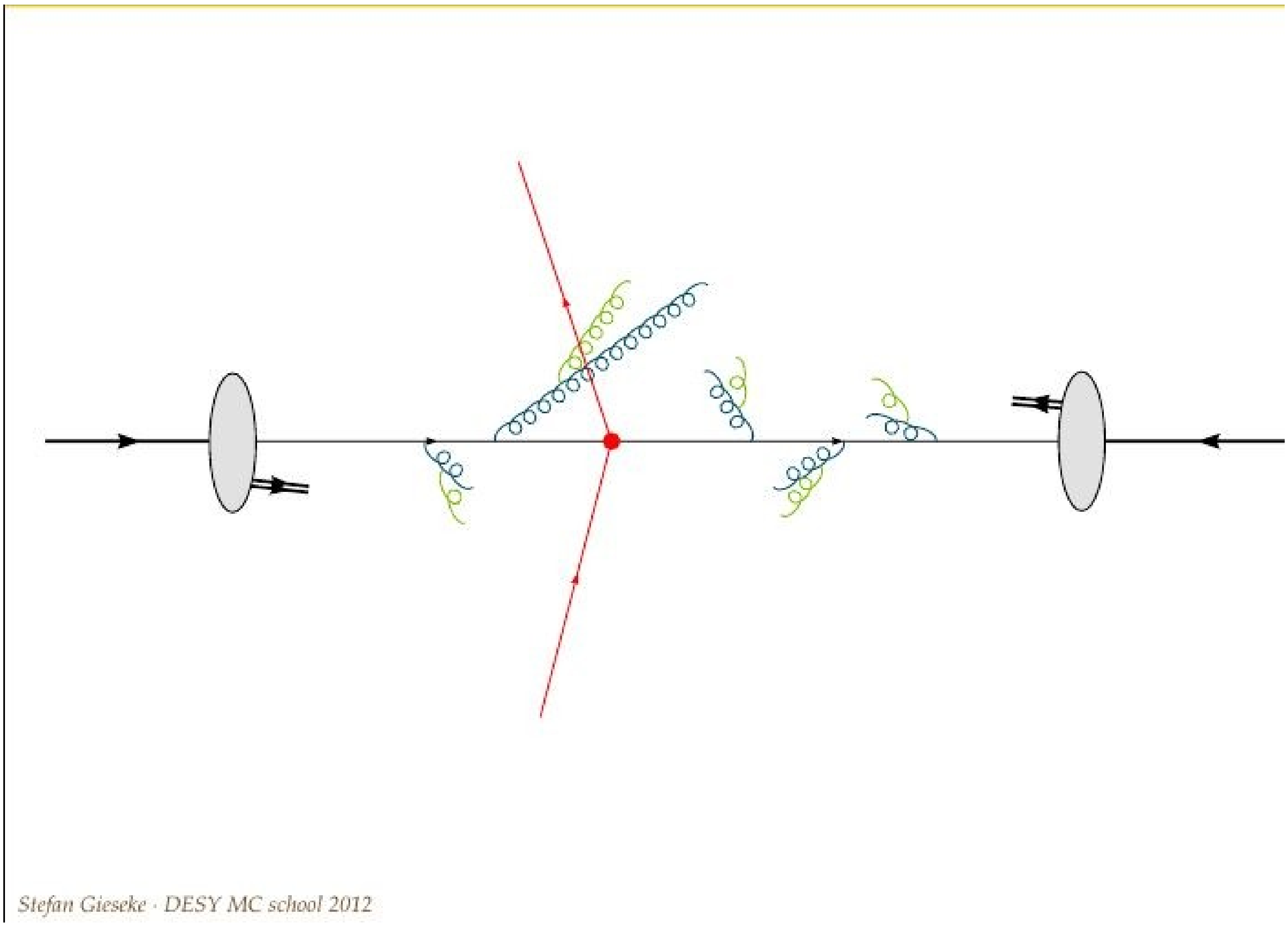
matrix element of hard process

Example: pp collision



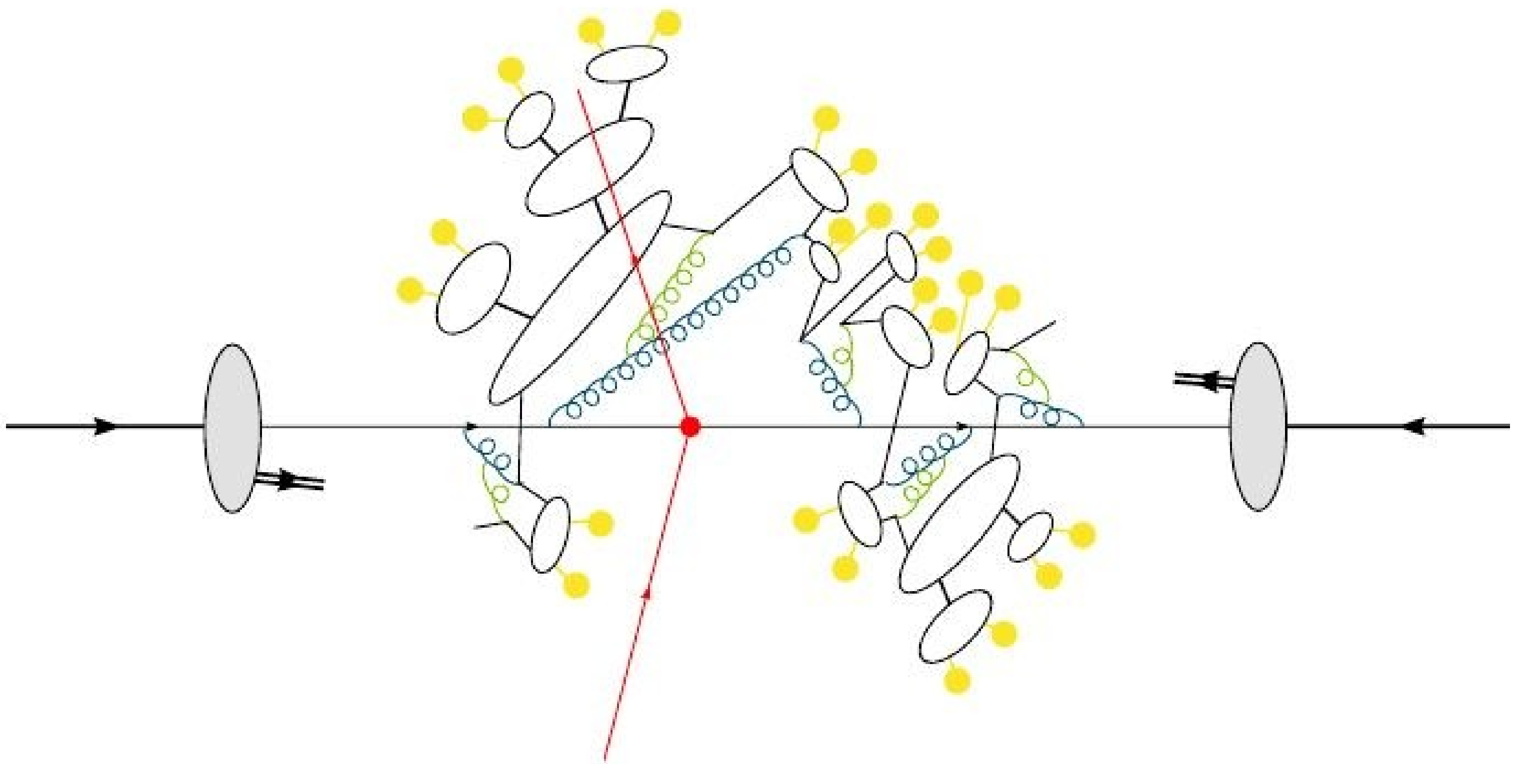
parton shower

Example: pp collision



parton shower

Example: pp collision

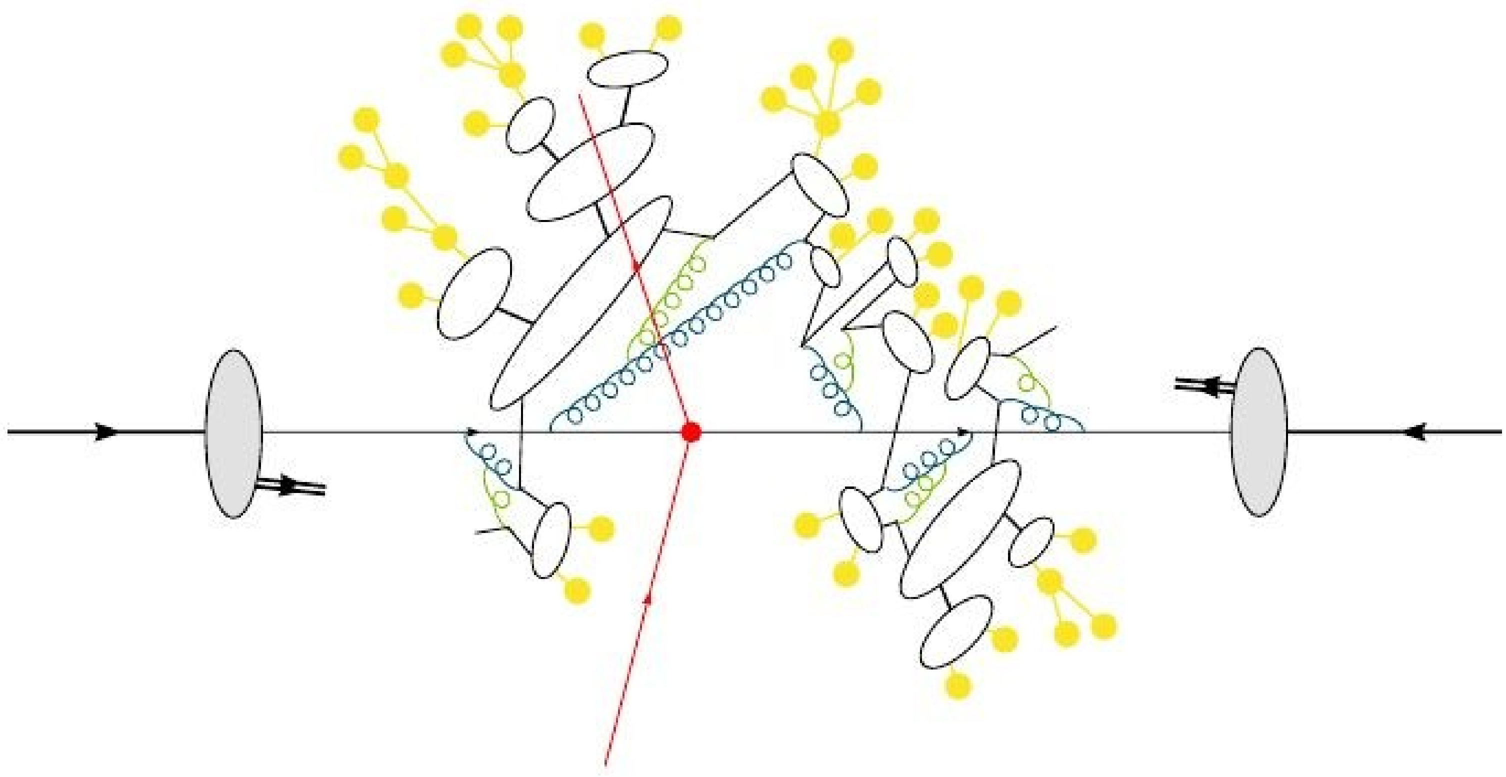


Stefan Gieseke · DESY MC school 2012

hadronization

phenomenological:
Lund string model
(Pythia)
or
cluster hadronisation
(Herwid(++))

Example: pp collision



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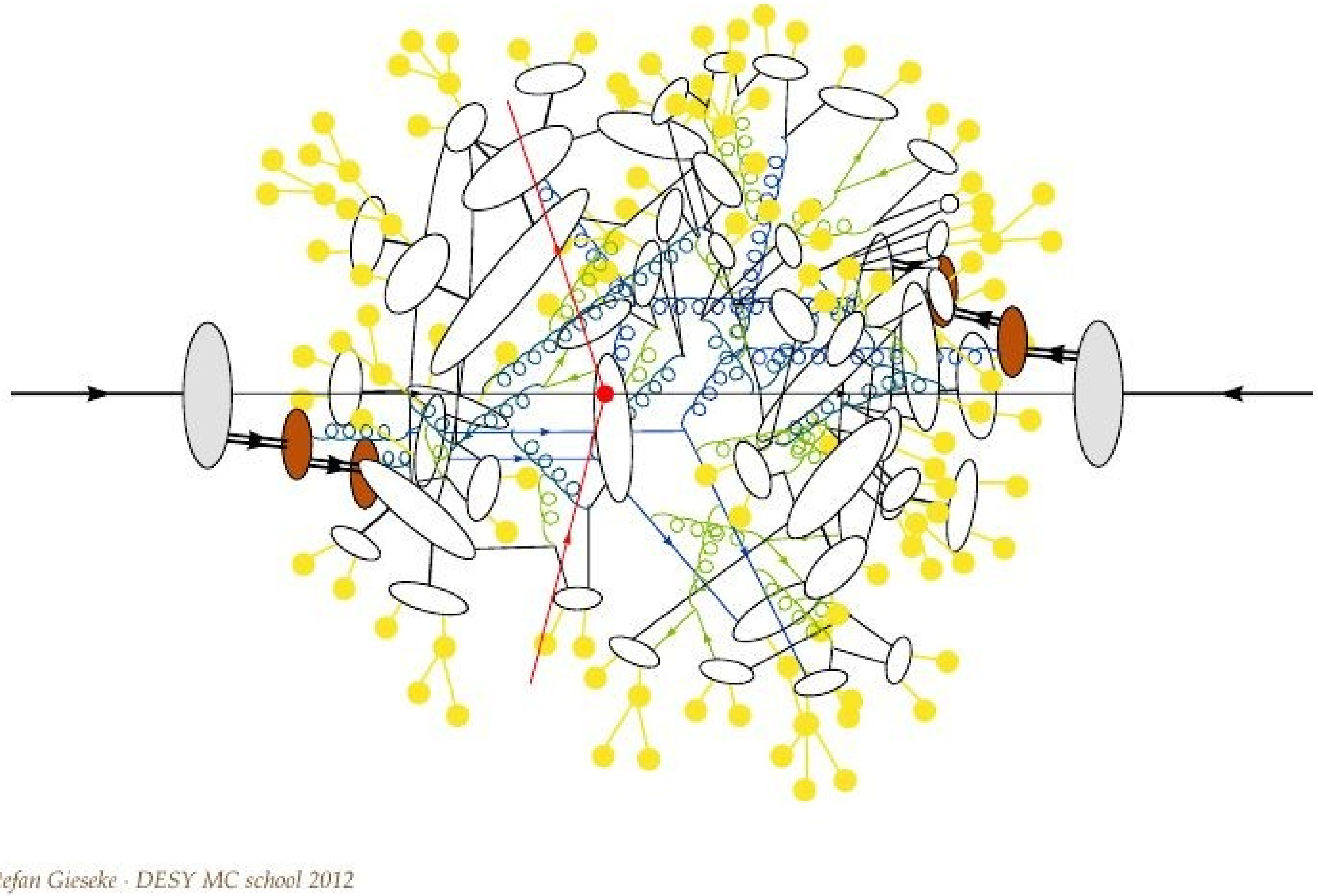
hadron decays

tedious -
relies on
measurements

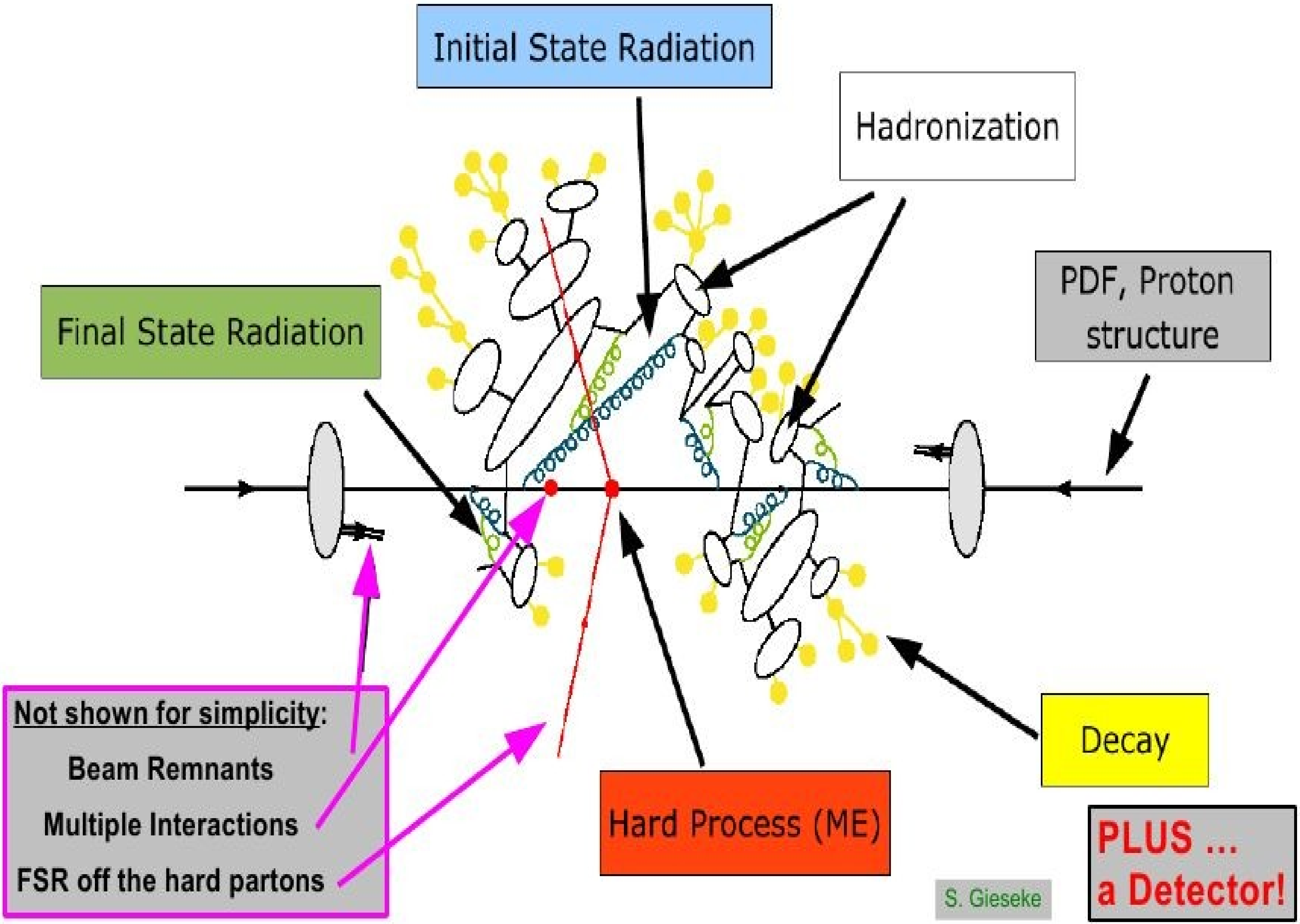
Example: pp collision



relies on models
& measurements
→ needs „tunig“

Multi-parton interactions and
underlying event

Summary: pp collision



Last step: Detector Simulation and Event reconstruction

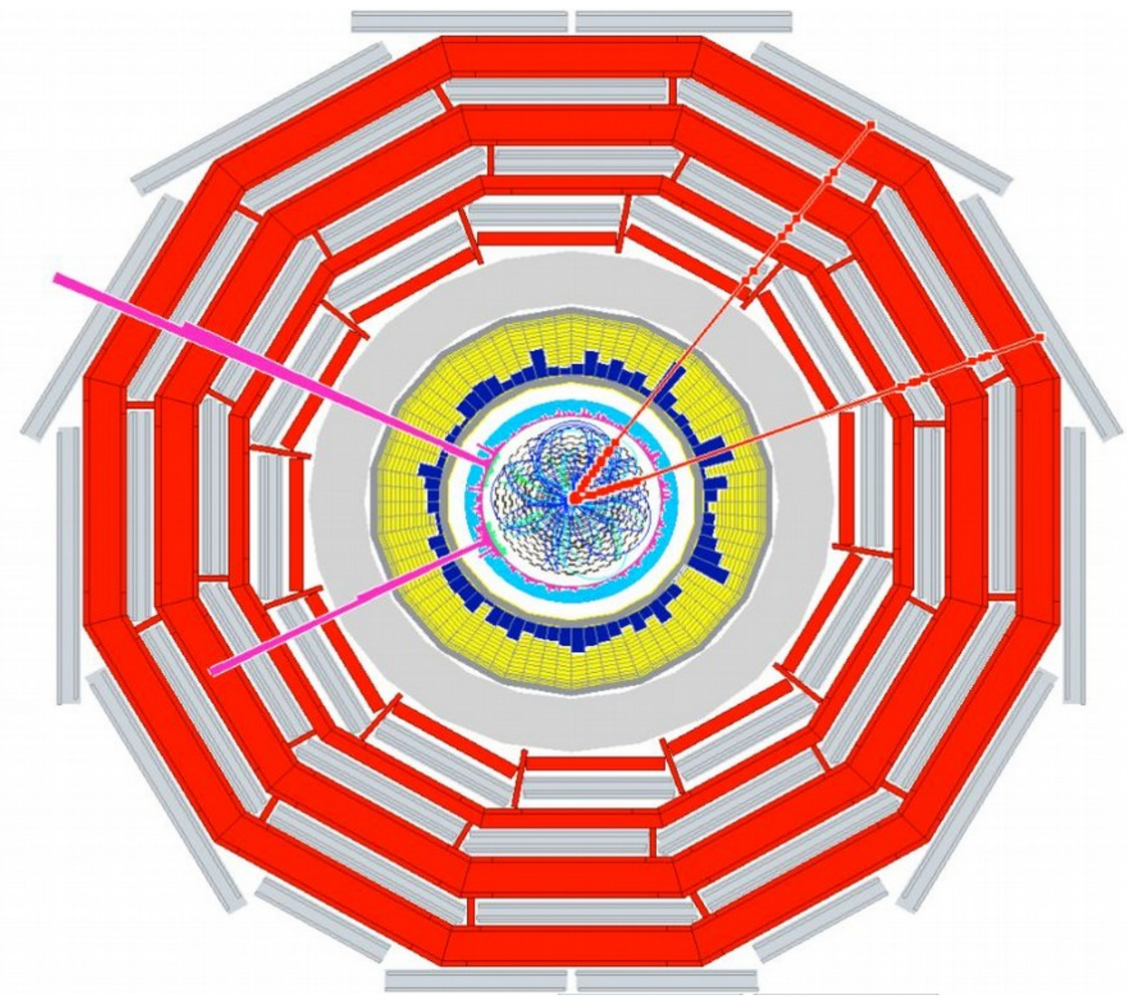
- follow each (sufficiently stable) particle through the detector and simulate energy deposits
- convert energy deposits into electronic signals, add noise

⇒ **simulated event**

- convert electronic signals to "hits", reconstruct energy deposits
- apply pattern recognition to find particle tracks
- combine reconstructed objects to particle candidates

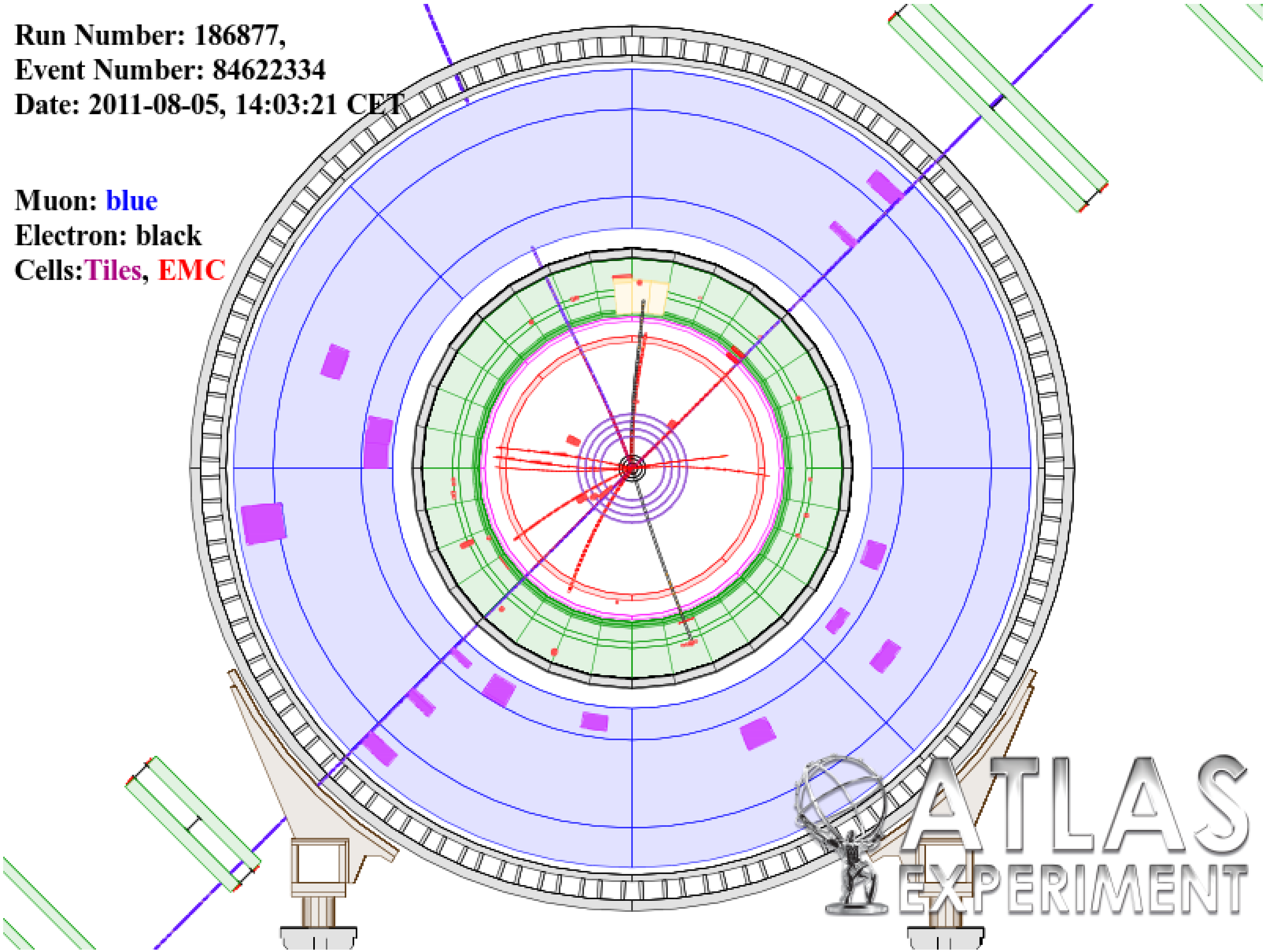
⇒ **reconstructed event**

reconstructed objects only approximately correspond to "true" properties



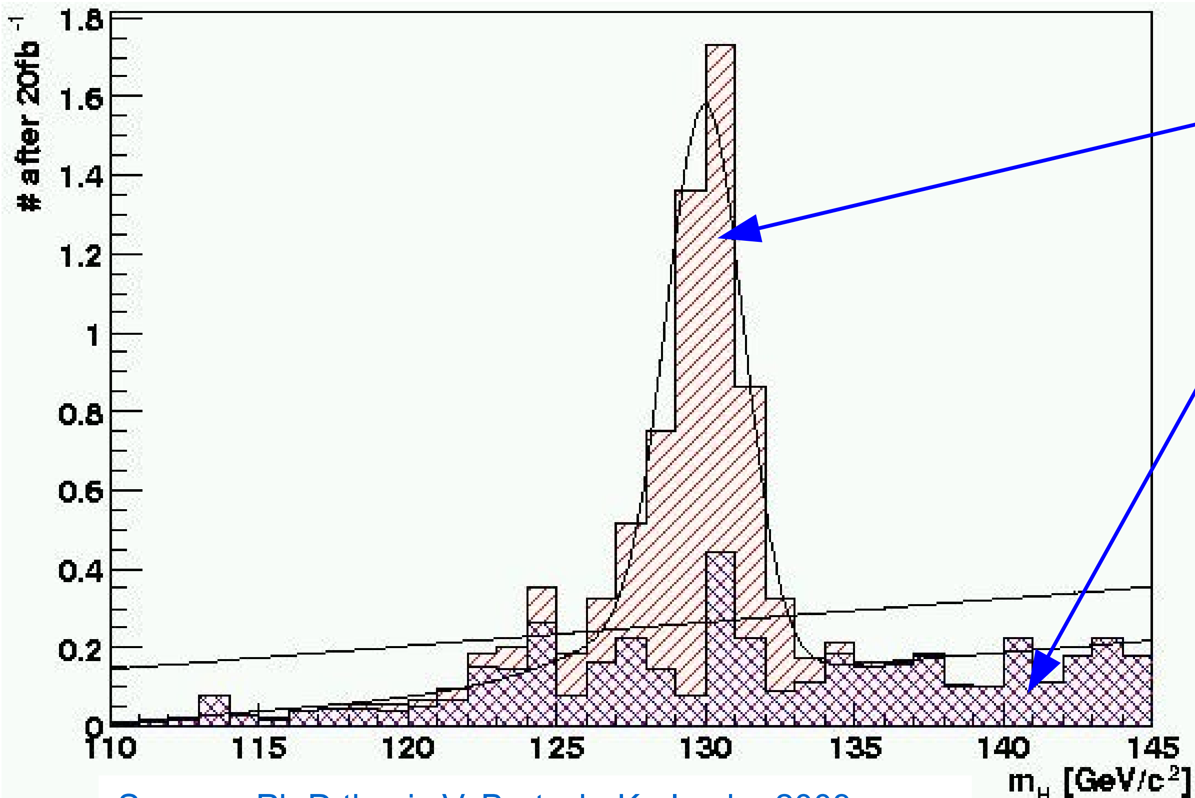
CMS: simulated Higgs → 2e4μ decay with hits and reconstructed objects

An observed H → 2e 2 μ event in the ATLAS Detector



Example: Expected Distributions of Signal and Background

Early Study of H → ZZ



Source: Ph.D thesis V. Bartsch, Karlsruhe 2003

Distribution(s) of

- signal events
- background events

from scaled MC

Used to formulate „signal+background“ (S+B) and „background-only“ (B) hypotheses for

- comparison with data and
- statistical inference

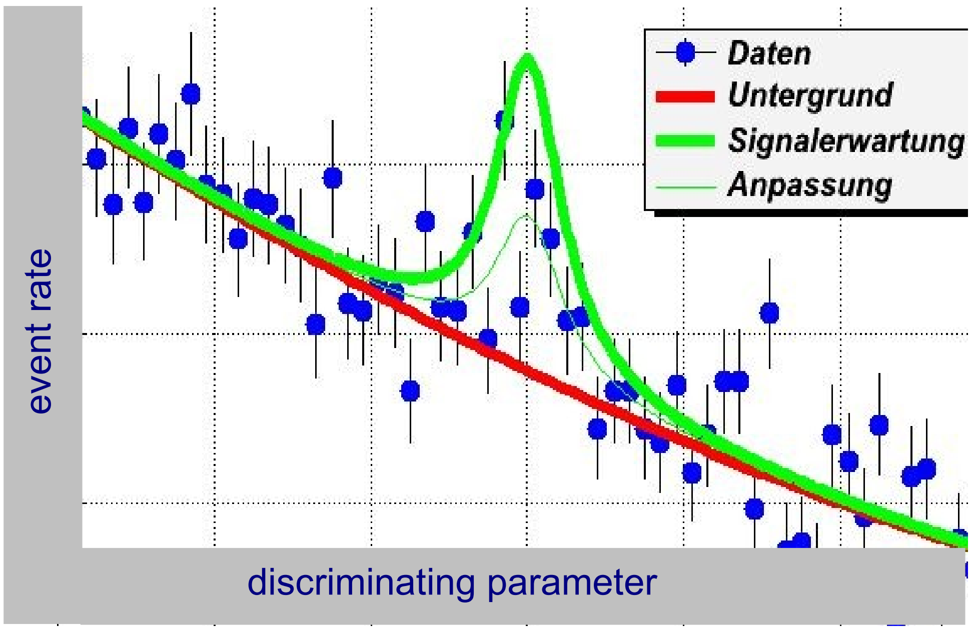
Hint: in the real experiment, only very small numbers are expected to be observed (see y-axis), and therefore statistical fluctuations will be large

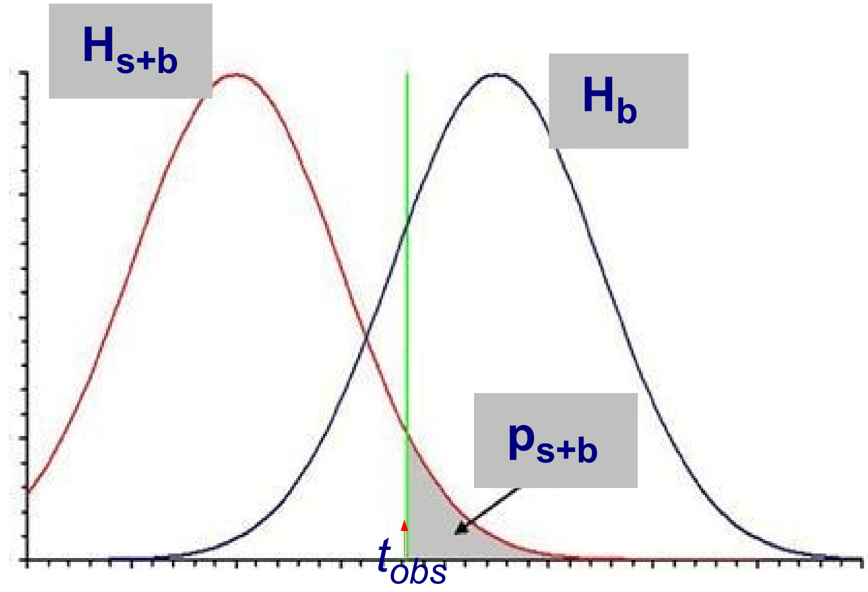
– the question will be:
are they best described by the S+B or the B-only shape?

→ need for mulivariate methods in the selection process and sophisticated statistical treatment

The problem: an excess over expectation of observed events can have two causes:

1. **true signal** on top of background
2. **upward fluctuation of background** due to statistics or insufficient understanding of background (systematic error)





From a statistical view point, this is a **hypothesis test**: H_{s+b} vs. H_b

Definition of a suitable test statistic t as a funciton of the data: t_{obs}

calculation of probability p_{s+b}= Prob (t>t_{obs} | H_{s+b})

resp. p_b = Prob (t < t_{obs} | H_b)

(„p-value“ w.r.t. s+b- or b-only hypothesis)

To claim a signal, must exclude a background fluctuation with high probability !

Statistics (2): LHC teststatistic

for (Higgs) searches: use negative logarithm of **Likelihood Ratio** as teststatistic

Profile-Likelihood w.r.t. signal strength μ (μ=0: no signal, μ=1: nominal signal)

normalised to global maximum of likelihood

teststatistic for limits

Signal strength

Set of nuisance parameters (= systematic uncertainties)

$$q_\mu = -2\ln\frac{\mathcal{L}(data|\mu,\hat{\Theta}_\mu)}{\mathcal{L}(data|\hat{\mu},\hat{\Theta})}\ ,\ 0 \le \hat{\mu} \le \mu$$

condition ensures μ ≥ 0 and one-sided limit

Best-fit values of all parameters

^ = maximize likelihood w.r.t. parameter

$$\mathcal{L}(\mathrm{data}|\mu,\Theta) = \prod \mathrm{Poisson}(\mathrm{N_i}|\mu\cdot s_i(\{\Theta\}) + b_i(\{\Theta\}))\cdot p(\{\tilde{\Theta}\}|\{\Theta\}))$$

Determine ***distribution of*** q_μ *,* $f(q_\mu\,|\,\mu)$ *,*

for ***background hypothesis*** *(μ=0) and for* ***signal hypothesis*** *(μ≠0),*

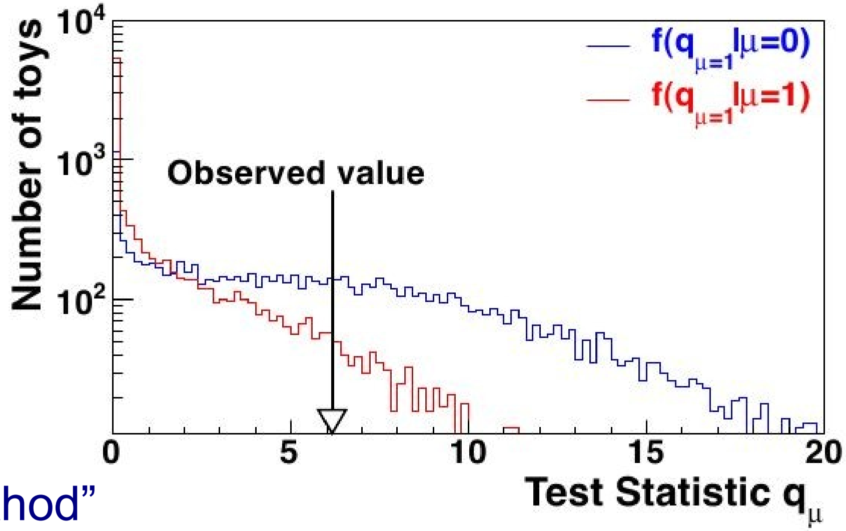
via pseudo experiments or asymptotic formulae for large data sets.

then:

- determination of p-values:

$$p_\mu = \text{Prob}(q_\mu > q_\mu^{\text{obs}} | \mu \cdot s + b)$$

$$p_0 = \text{Prob}(q_\mu > q_\mu^{\text{obs}} | b)$$



- calculation of a confidence level using "CL_s method"

$$CL_s = \frac{p_\mu}{p_0}$$

robust against downward fluctuations of background

CL_s quantifies agreement with signal hypothesis

- For μ=1, CL_s = α a Higgs boson is excluded with confidence level (1- α)

  convention: α=0.05, exclusion at 95% CL

- usually: specify value of μ which is excluded at 95% CL

Then: run **pseudo experiments** to determine **expected limit**, i. e. the median of the limit distribution (**dashed line**), and the regions for 68% („**1 σ**", **green band**) and 95% („**2σ**", **yellow band**)

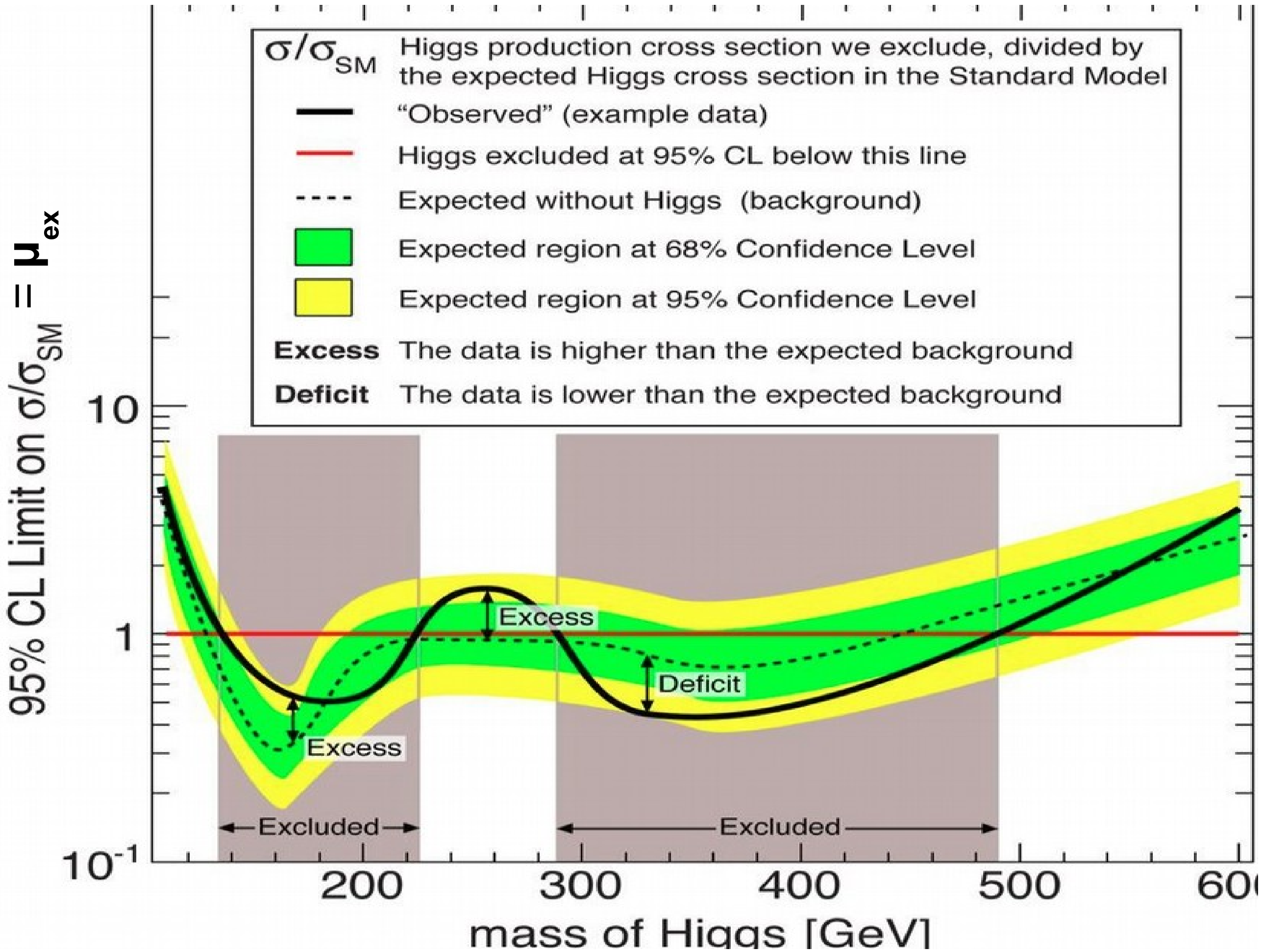
(see figure below)

Repeat all of the above for different values of Higgs mass

⇒ graph of **signal strength μ_{ex} excluded @ 95% CL**

for
– data (**black line**)
– median and 68% / 95% regions of the expectation from pseudo experiments (dashed line and green resp. yellow band)

Higgs boson excluded
for **μ_{ex}< 1**
(below red line, vertical grey bands)



Statistics (5): „significance" of a discovery

If a signal cannot be excluded, what then is
the "significance" of the new discovery ?

concept of "local significance":
assuming an observation of N events on top of expected background N_b
→ number of signal events $N_s = N - N_b$
compare N_s with statistical fluctuations of background, N_b:

significance is expressed in terms of the
p-value w.r.t. the background-only hypothesis

Usual in HEP: significance of a signal excess in "number of sigmas" ("z-value"),
corresponding to the p-value of a Gaussian distribution

in the Gaussian limit (N_b > ~50) $$S = \frac{N_s}{\sqrt{N_b}}$$

"'The observed signal is S times larger than the standard deviation of the expected background fluctuations"

Part 3

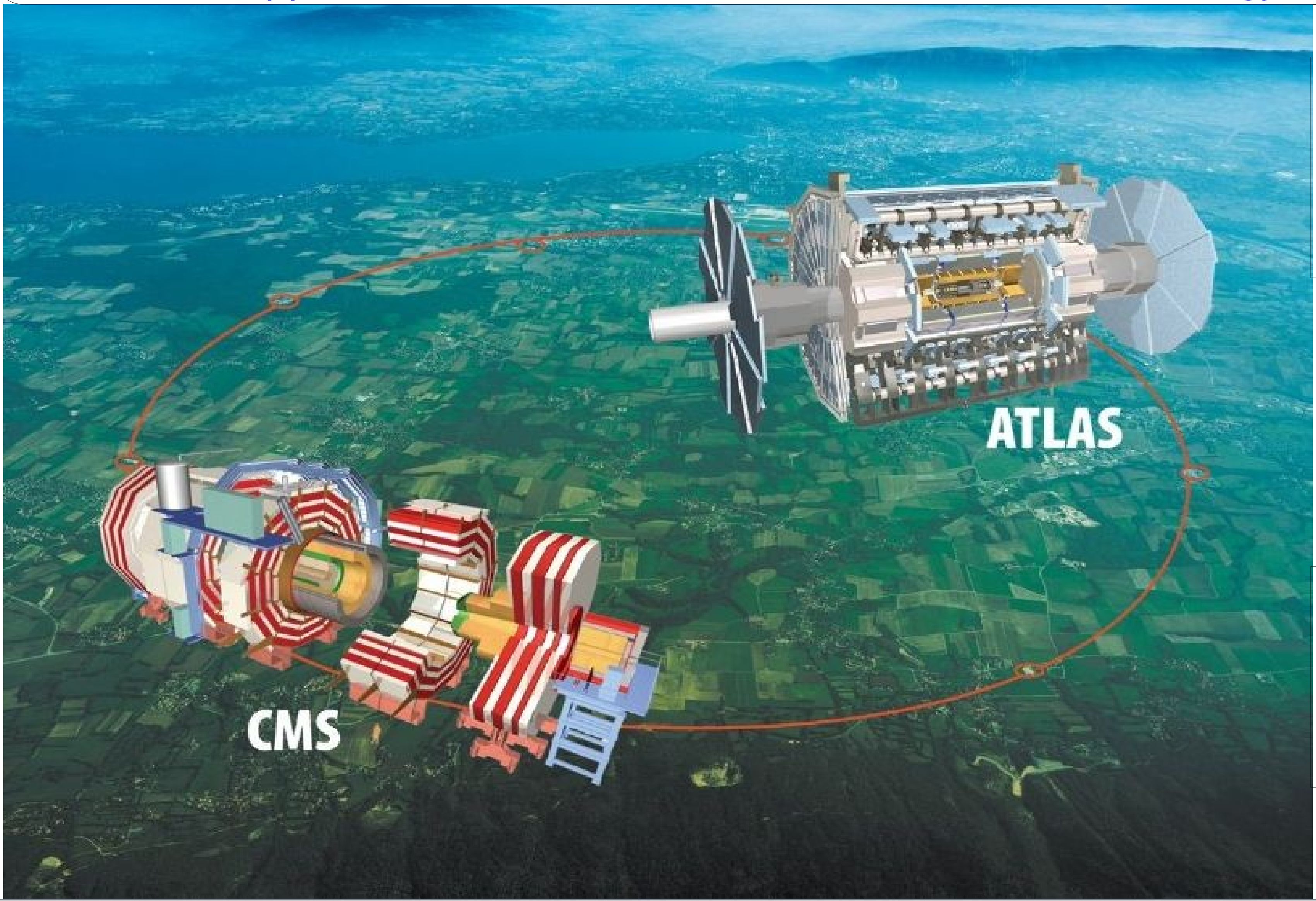
Higgs Hunt @ LHC

The Large Hadron Collider (LHC) and the Experiments

LHC: two rings with 26.7 km circumference
1232 superconducting dipoles
858 quadrupoles

max. 2808 proton bunches,
40 MHZ collision rate,
~10^{11} Protons / bunch

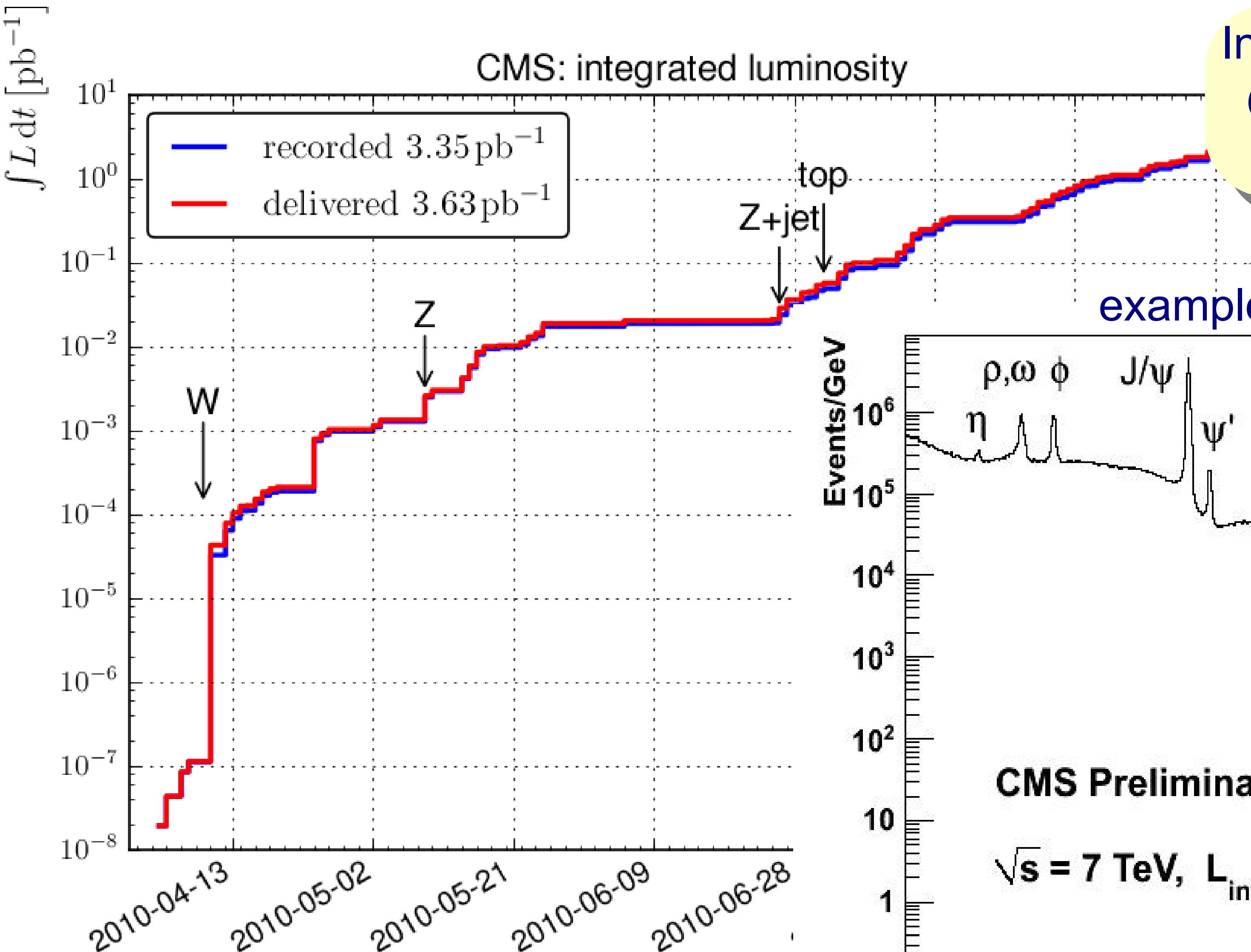
~500 million pp collisions / s at 7, 8 & 13 TeV centre of mass energy



ATLAS:
Hight: 25 m
Length: 40 m
Weight: 7000 t

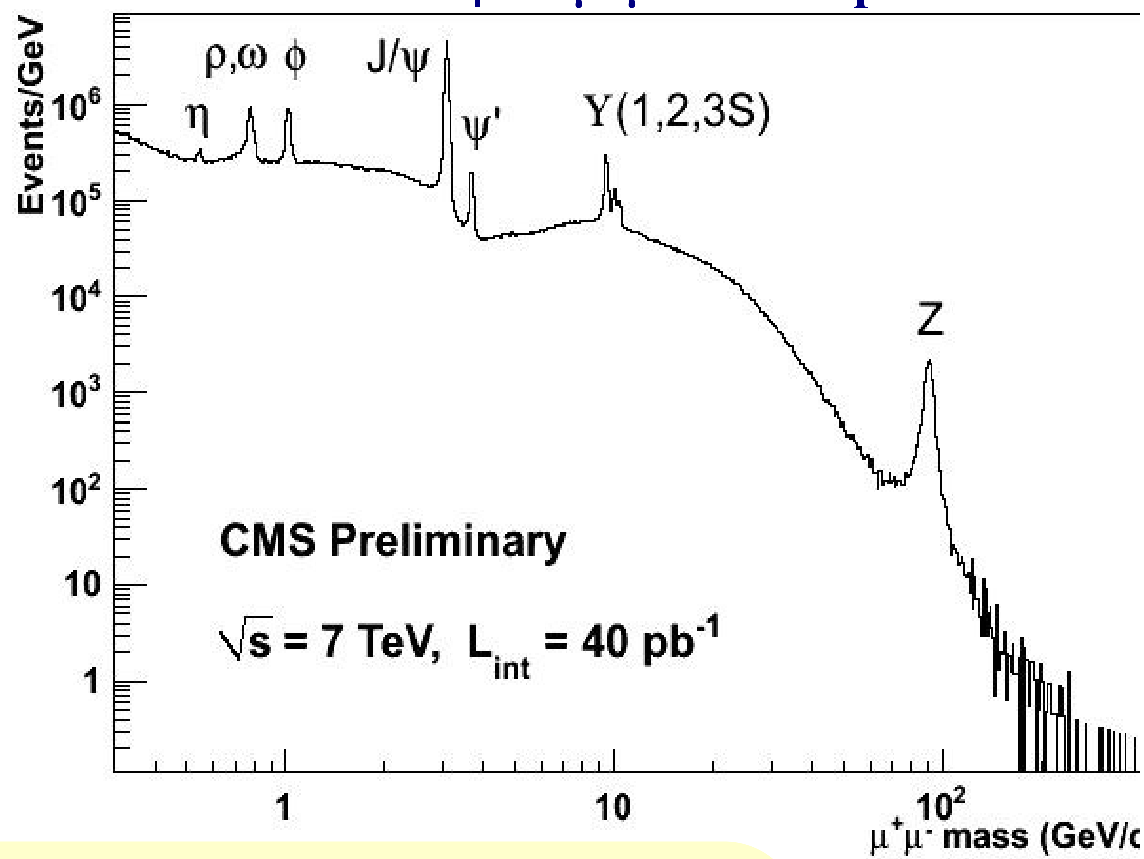
CMS:
Hight: 15 m
Length: 22 m
Weight: 12500 t

2010: first year of LHC operation @ 7 TeV



Integrated Luminosity @ 7 TeV in 2010: **40 pb^{-1}**

example: **$\mu^+\mu^-$ mass spectrum**



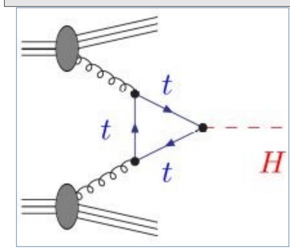
All known particles observed during first year

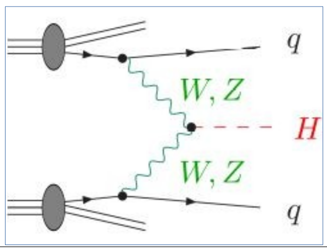
"50 years of particle physics in "fast motion"

(SM) Higgs Boson Phenomenology @ LHC fixed if $\boldsymbol{m_H}$ is known

(main) production channels @ LHC:

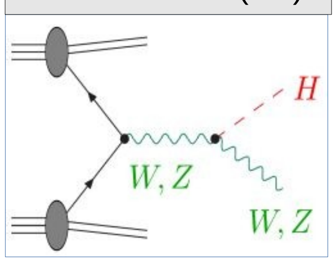
gluon Fusion (ggF)

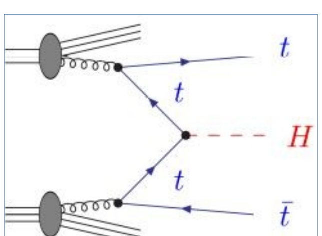




Vector-Boson Fusion (VBF)

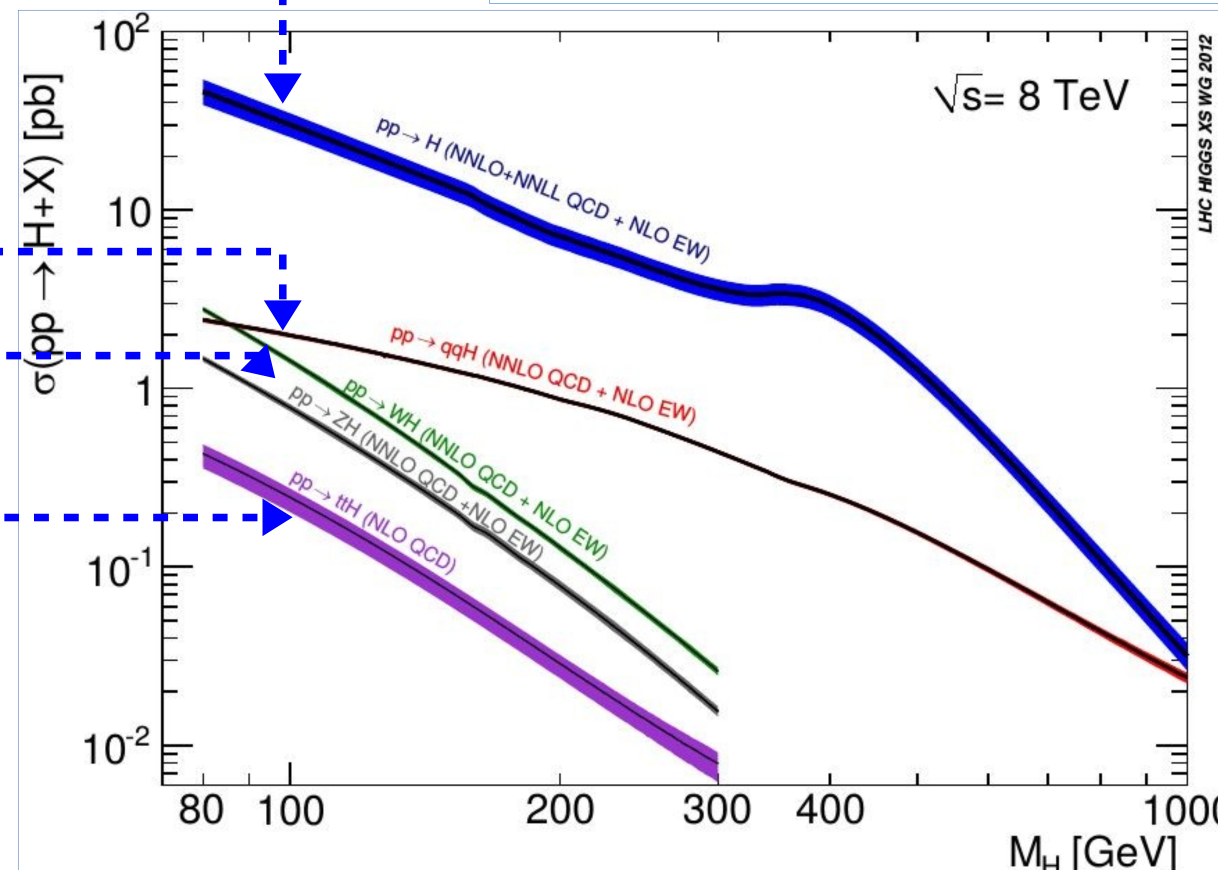
Associated V (VH)





associated top (ttH)

SM Cross Section pp →H+X vs. m_H

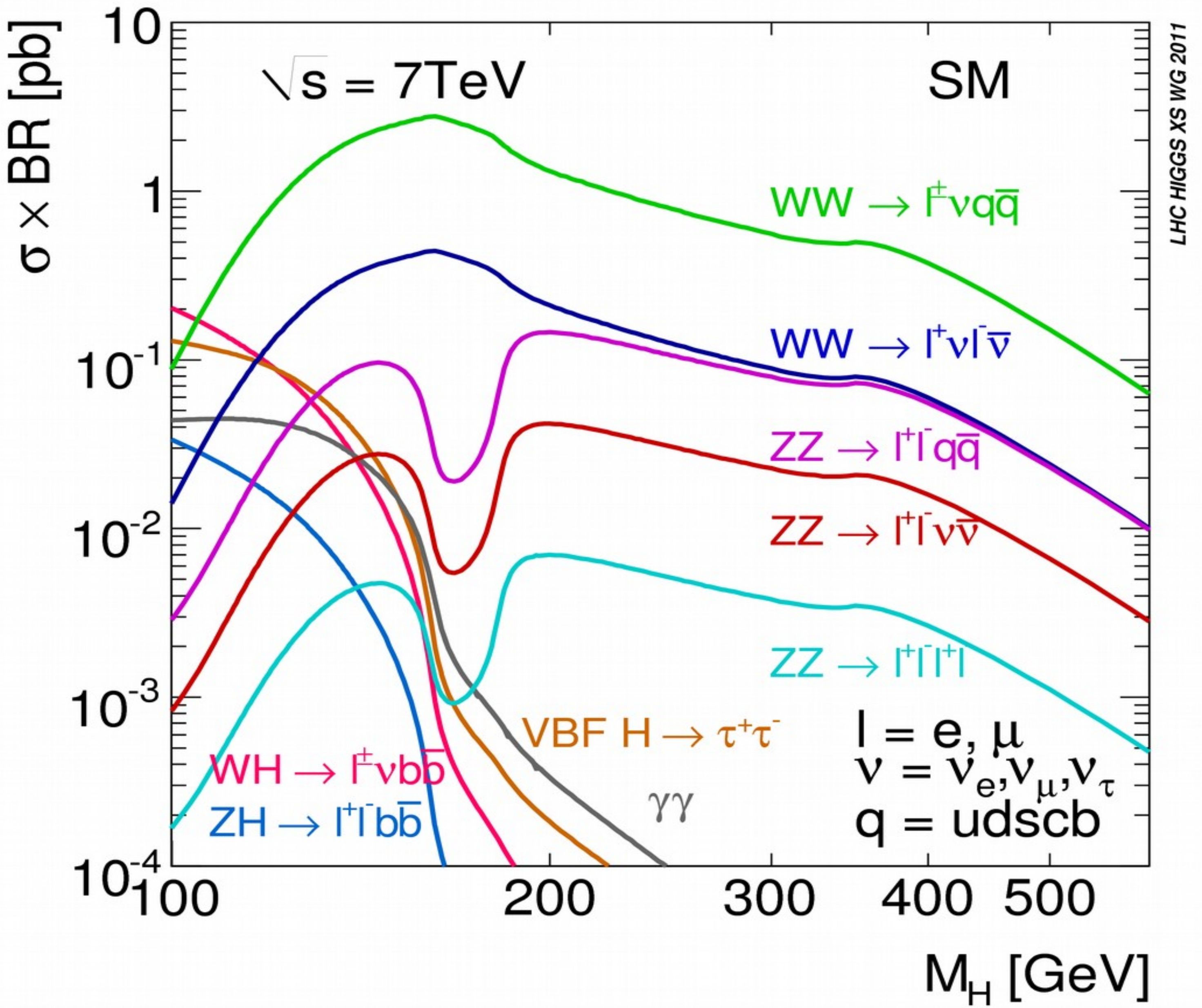


Source: LHC Higgs Cross Section WG

cross section × branching ratio
determines number of events in detector

at high H masses:
- WW
- ZZ

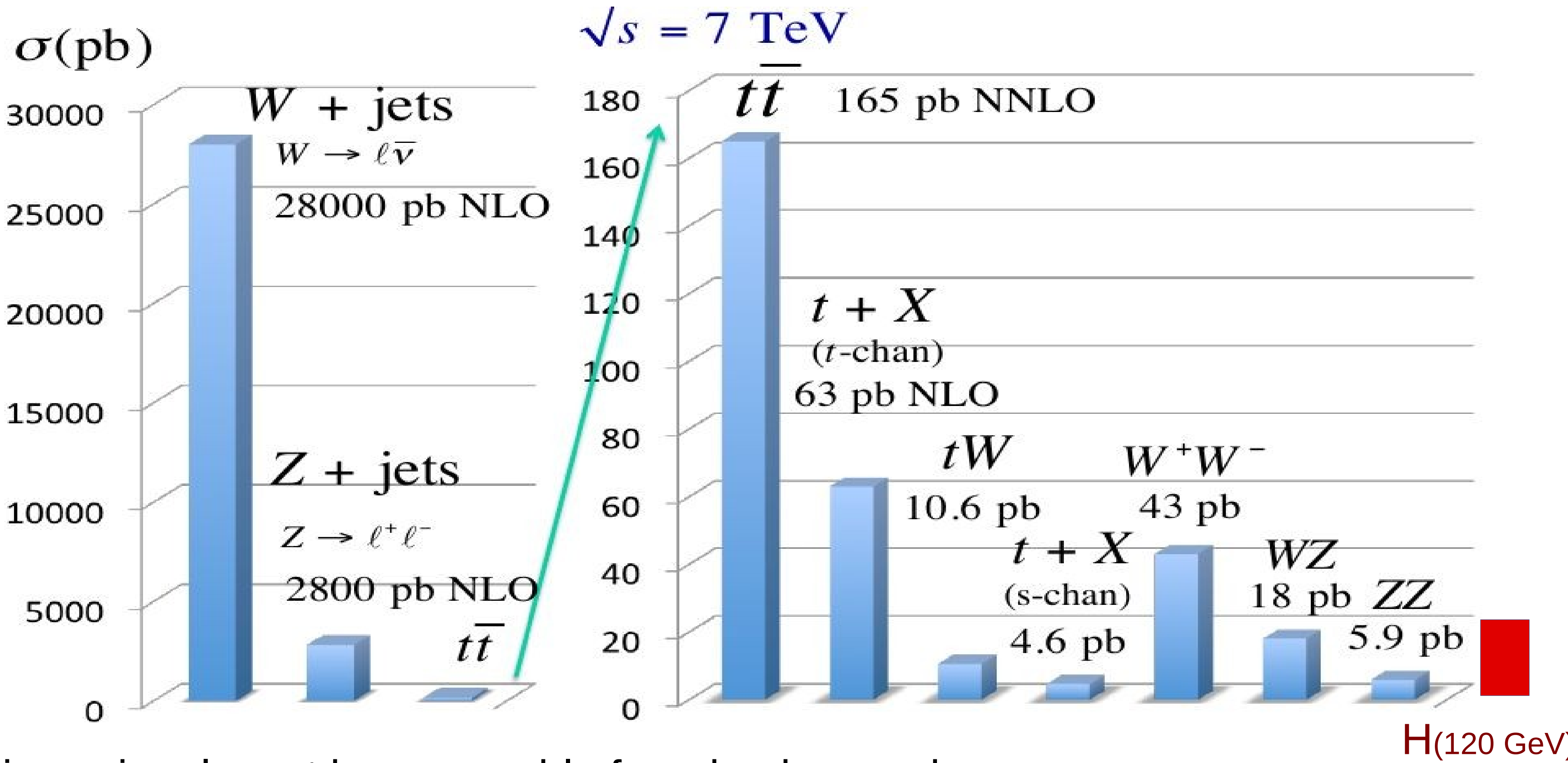
at low H masses:
- bb (not shown)
- $\tau^+ \tau^-$
- $\gamma\gamma$



this is not all . . .

there is huge Background

Production rate of other processes is larger by many orders of magnitude



Higgs signal must be separable from background

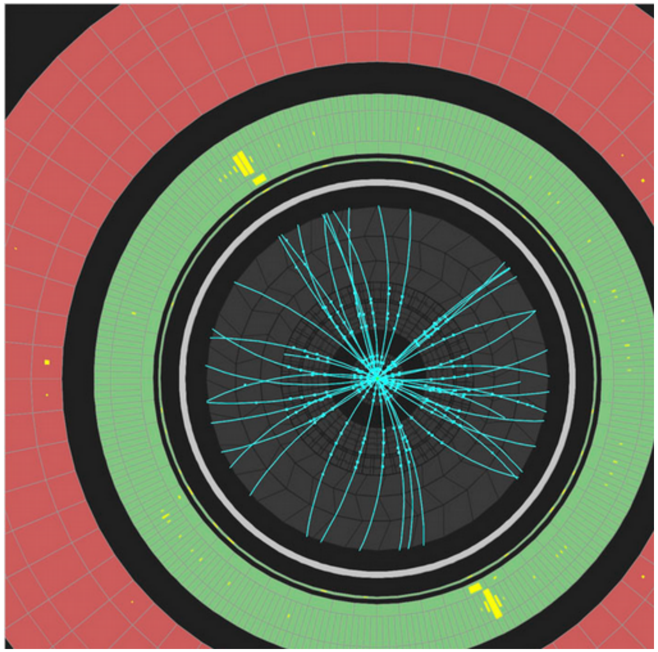
→ **background changes importance of individual decay channels**

statistical significance also plays a role:

higher experimental resolution of a Higgs signal lead to higher significance

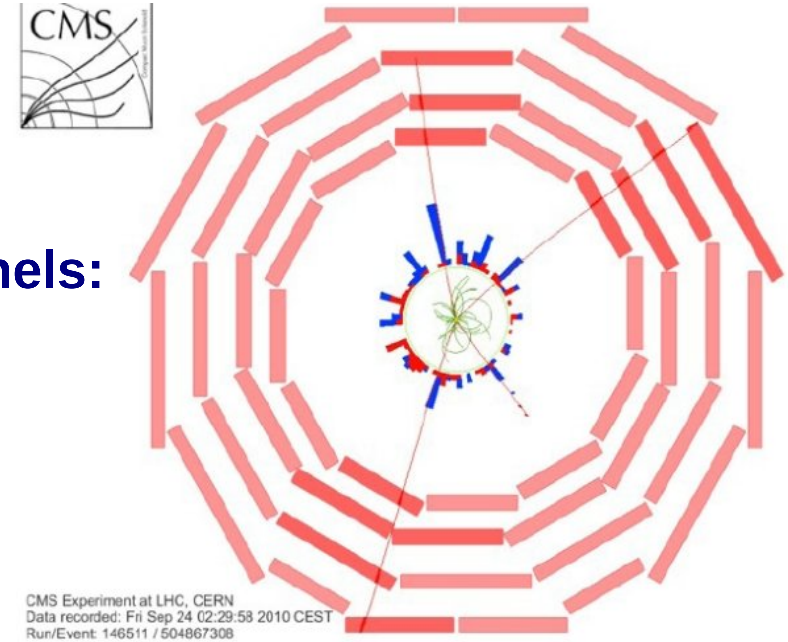
→ **disfavours signatures with jets and / or missing energy**

Higgs candidate events 2010/11



most sensitive channels:

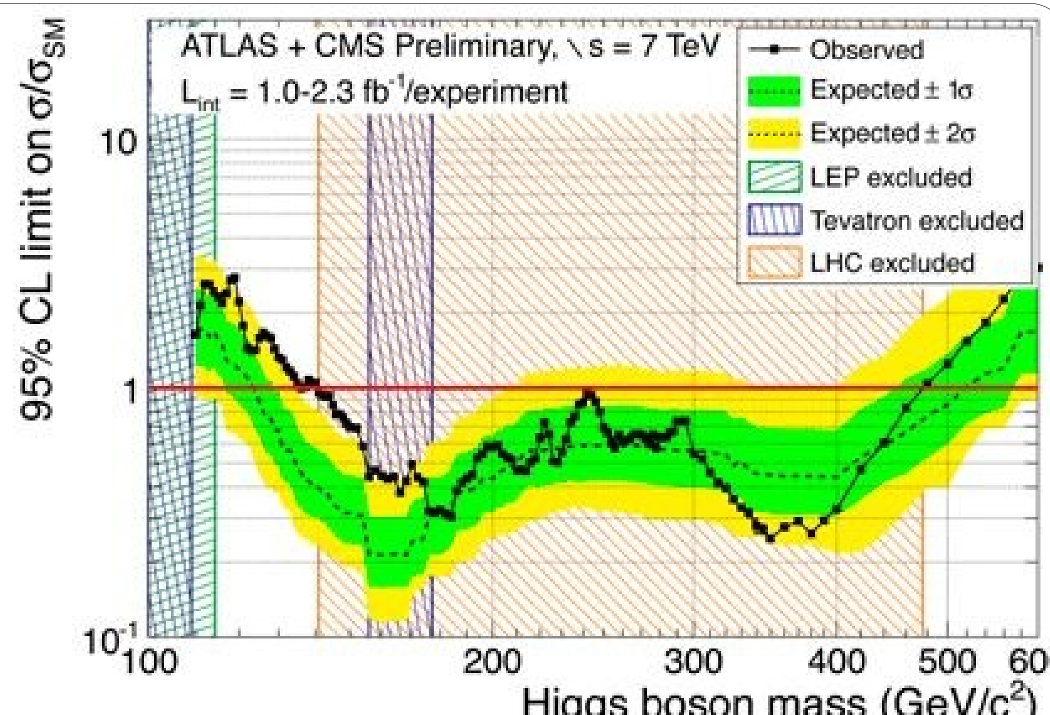
$H \rightarrow ZZ$
$H \rightarrow \gamma\gamma$
$H \rightarrow WW$



Exclusion Autumn 2011 (95% CL):

ATLAS:
expected: 125 – 520 GeV/c²
observed: 113–115.5, 131–453 GeV/c²

CMS:
expected: 117 – 543 GeV/c²
observed: 127 – 600 GeV/c²

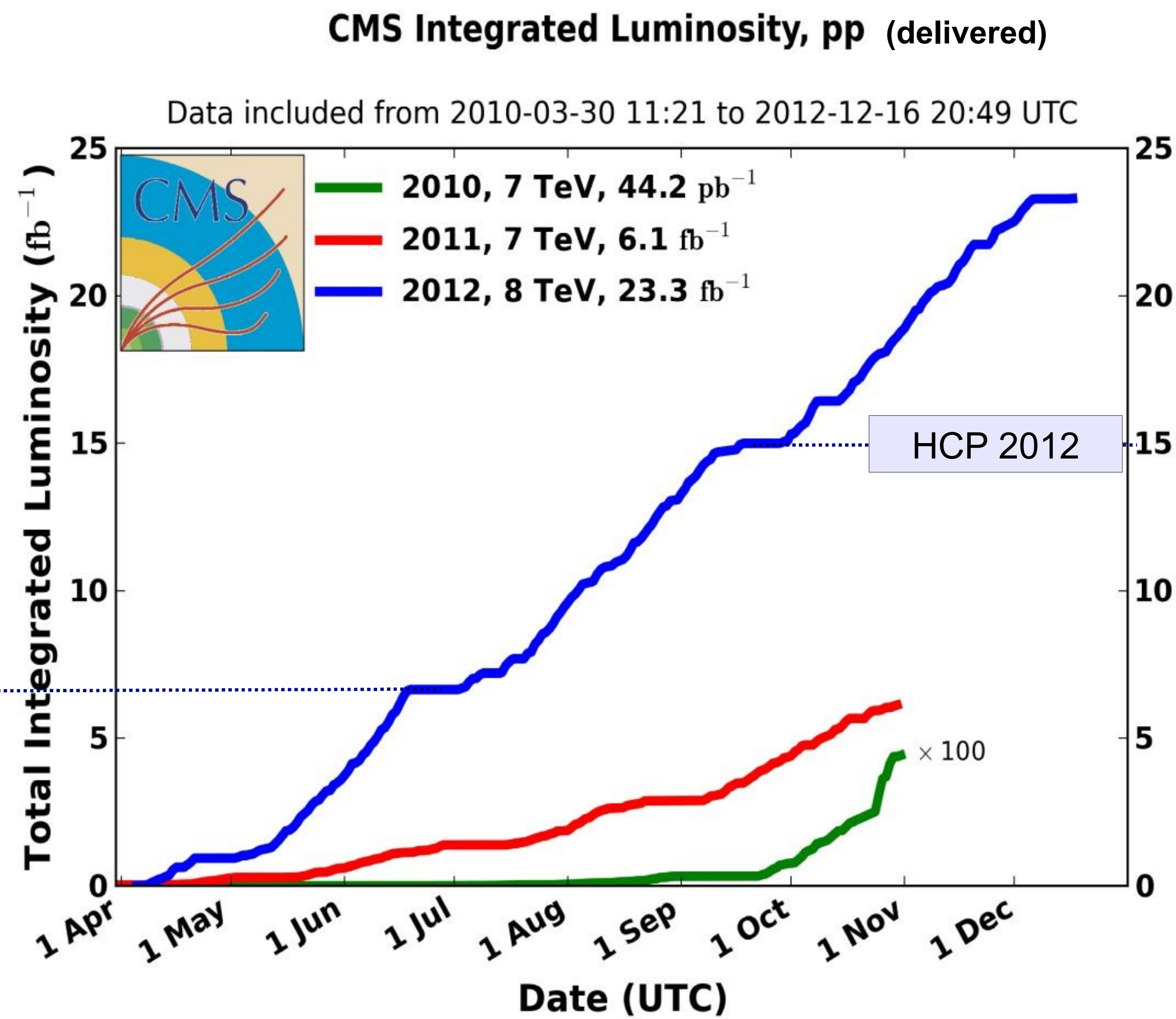


LHC Data taking 2012

New records:

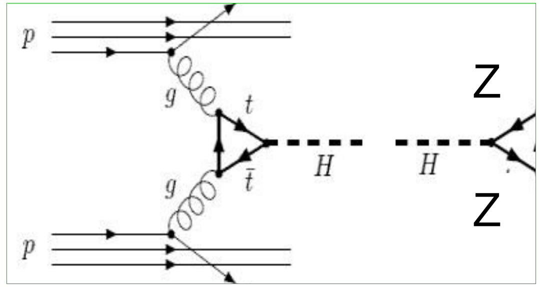
- **centre-of-mass energy 8 TeV**
- **peak luminosity 0.77· 10^{34} / cm² /sec**
- **best week ∫L=1.35 fb^{-1}**

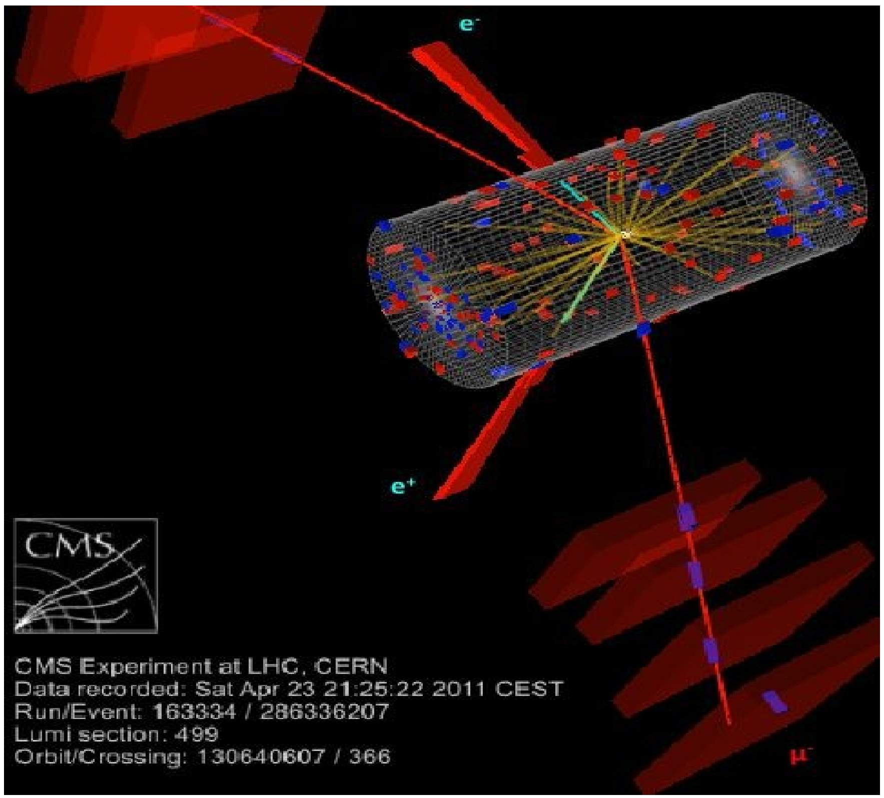
(75% design luminosity
@ half energy
& half # of bunches)

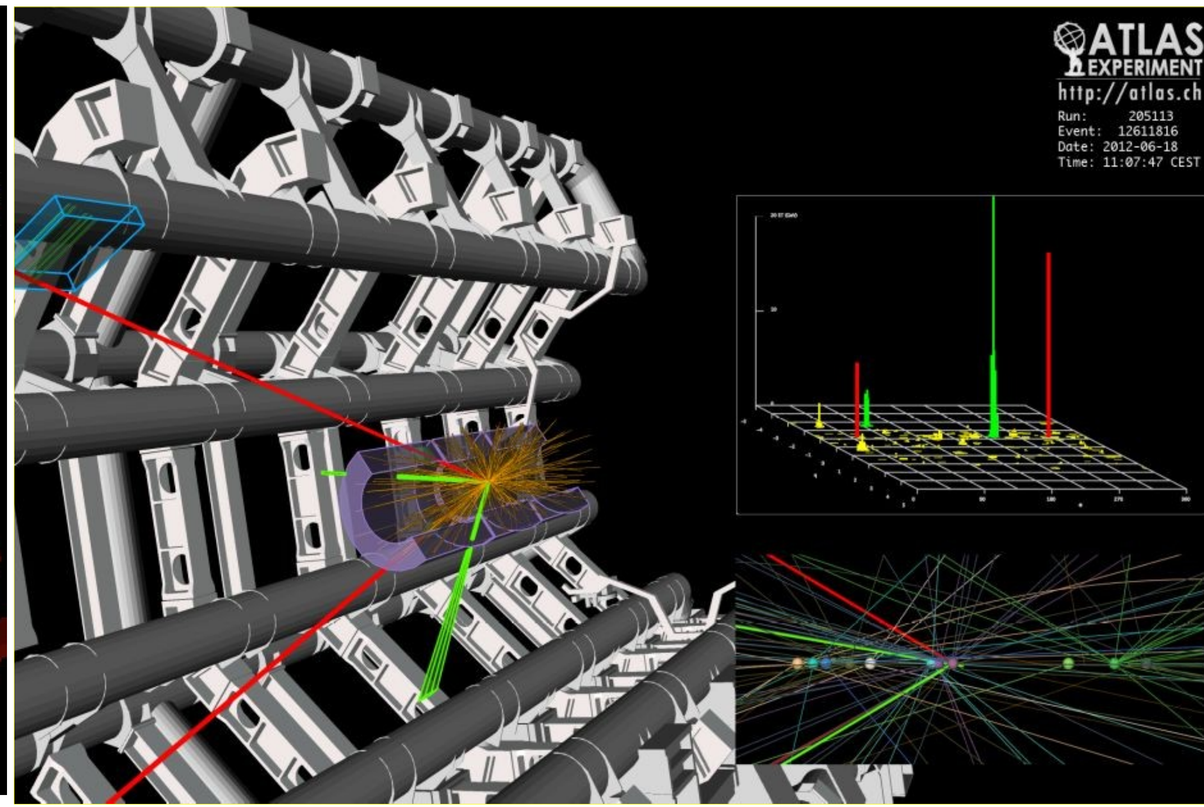


summer conferences 2012

more events $H \rightarrow ZZ \rightarrow 4e,\ 4\mu,\ 2e2\mu$

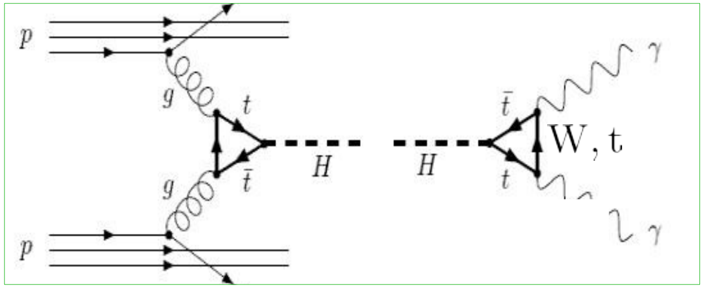


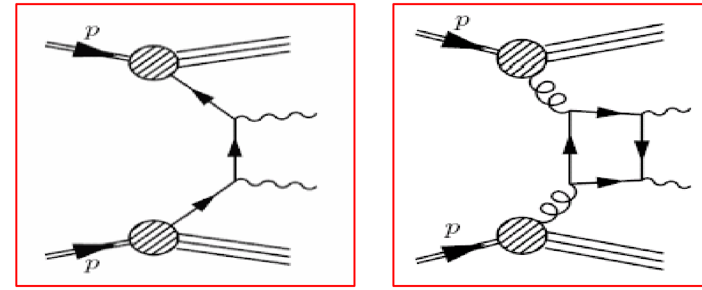




- Background $t\bar{t}$, $Zb\bar{b}$, irreducible: ZZ
- **favourable** ratio (~1) of signal to background
- **signal very small a low H mass**

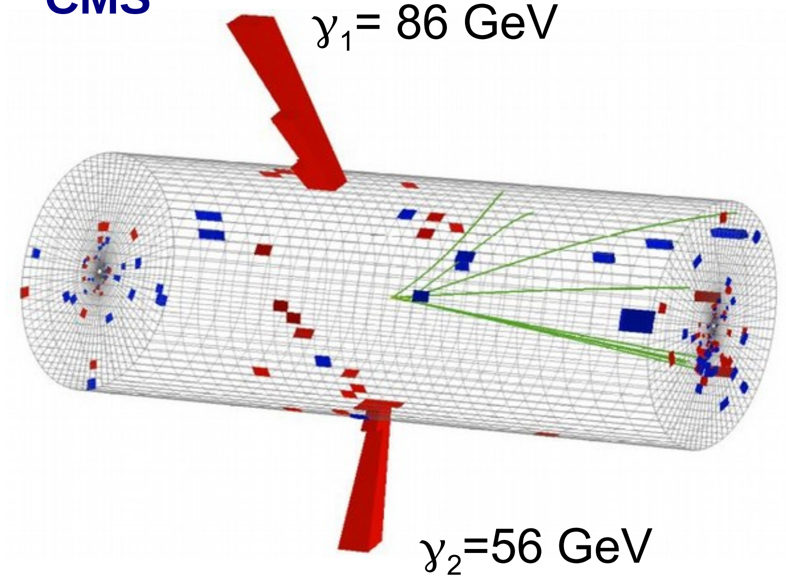
Higgs search in $\gamma\gamma$ channel – small H masses

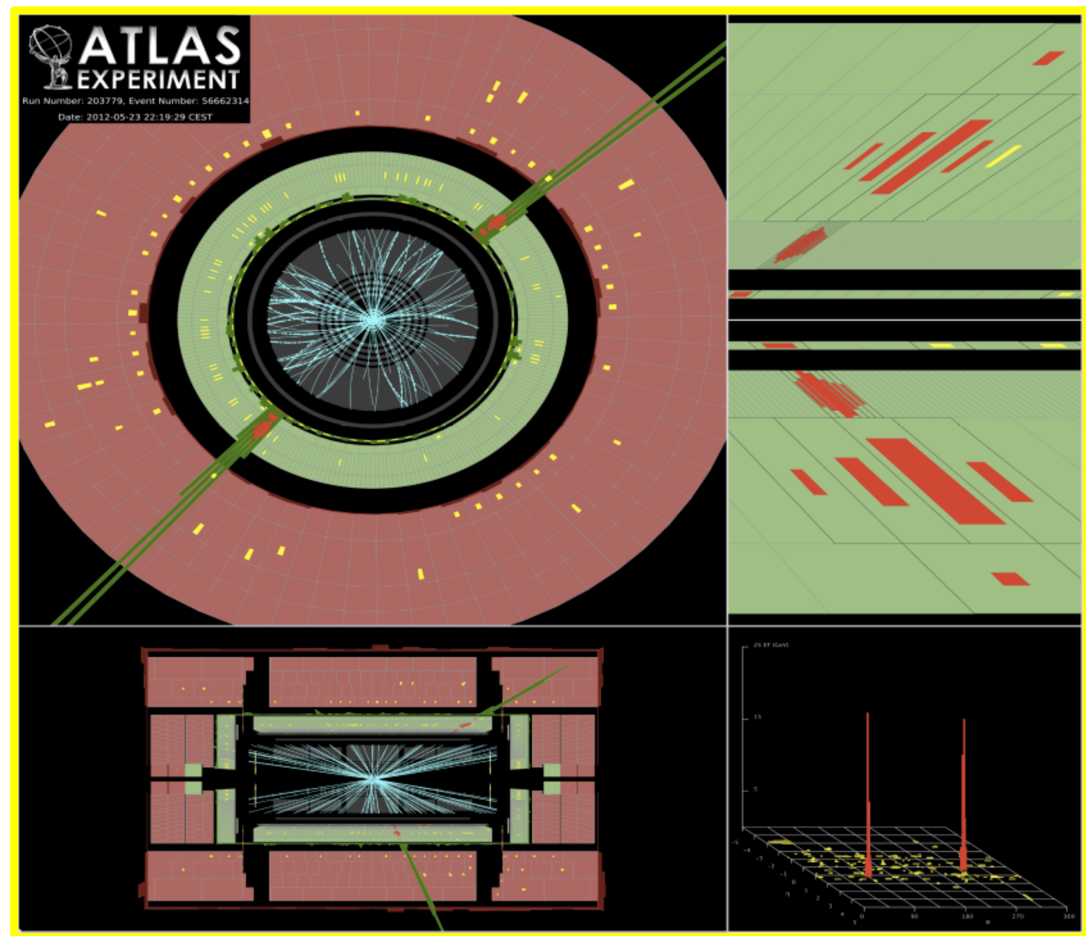




QCD background

CMS

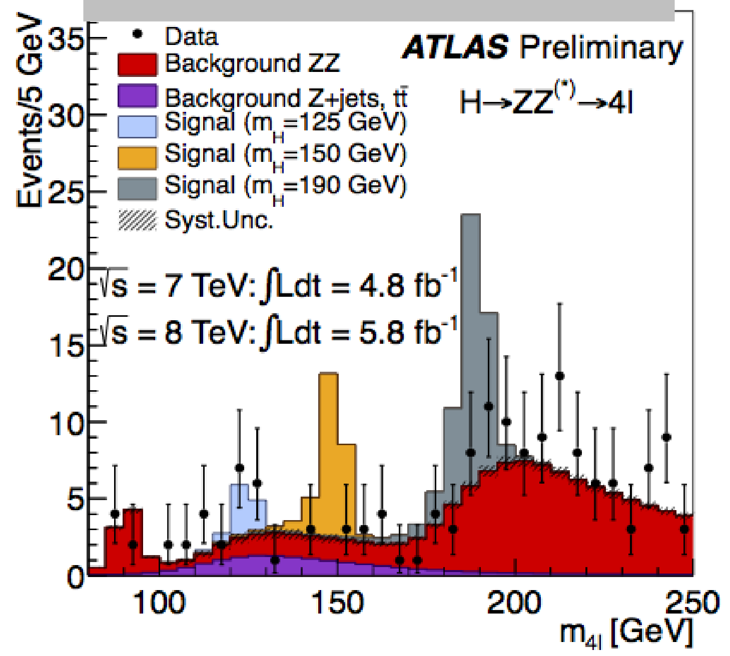




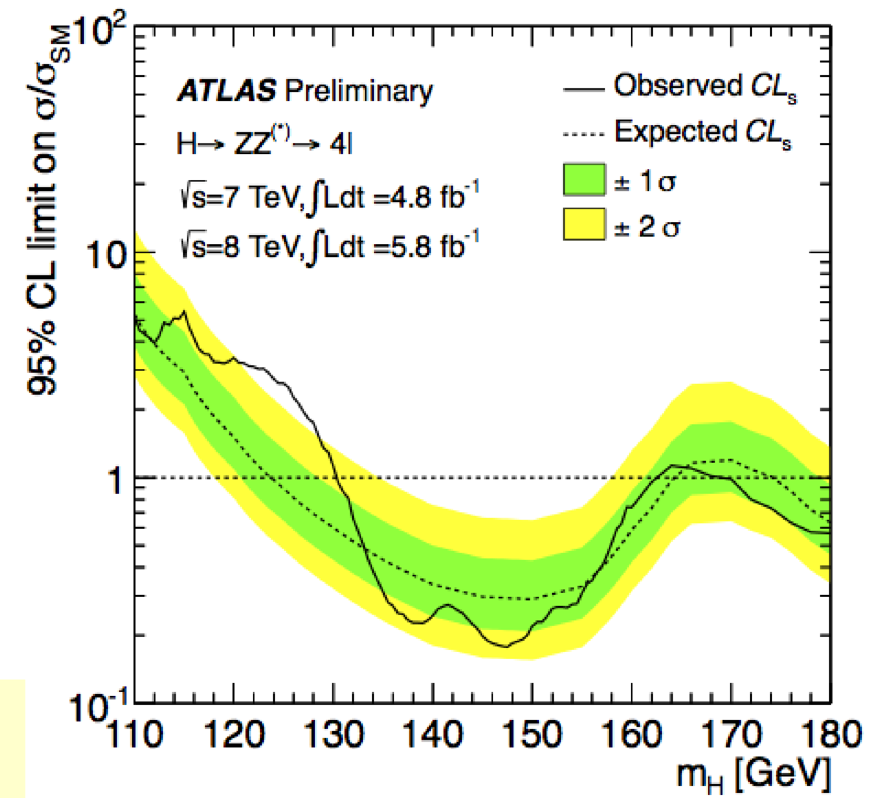
Seminar @ CERN on July 4th

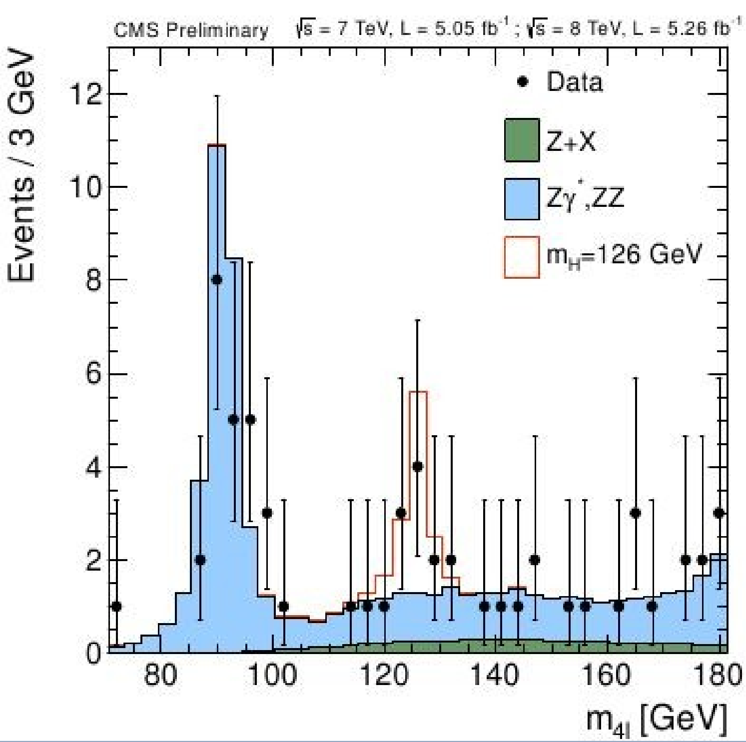
H → ZZ →4e, 4μ, 2e2μ

Distribution of 4l mass

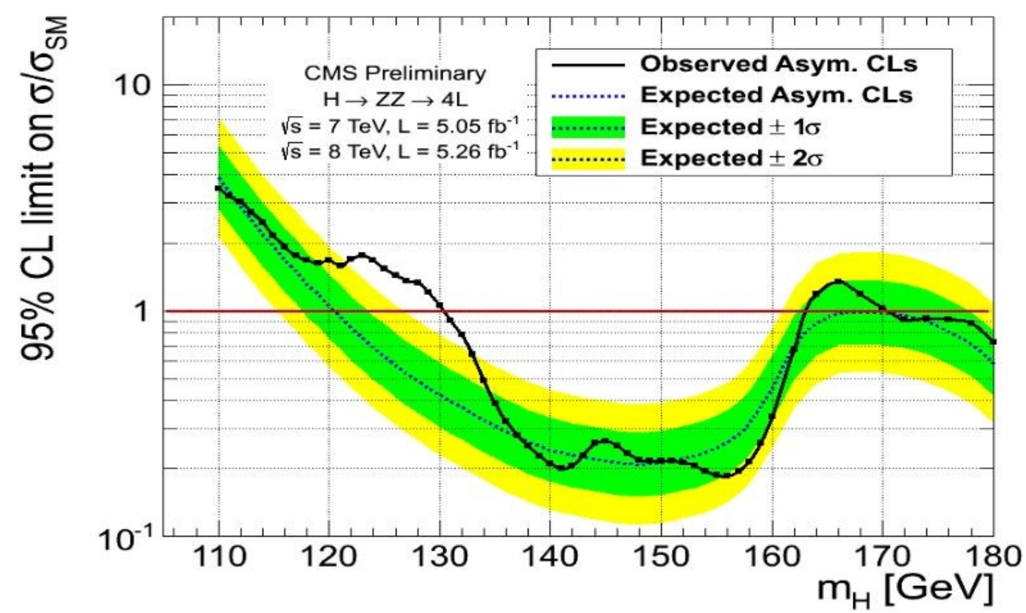


events 125+/-5 GeV
observed: 13
expected: b=5,1,
s(125 GeV)=5,3

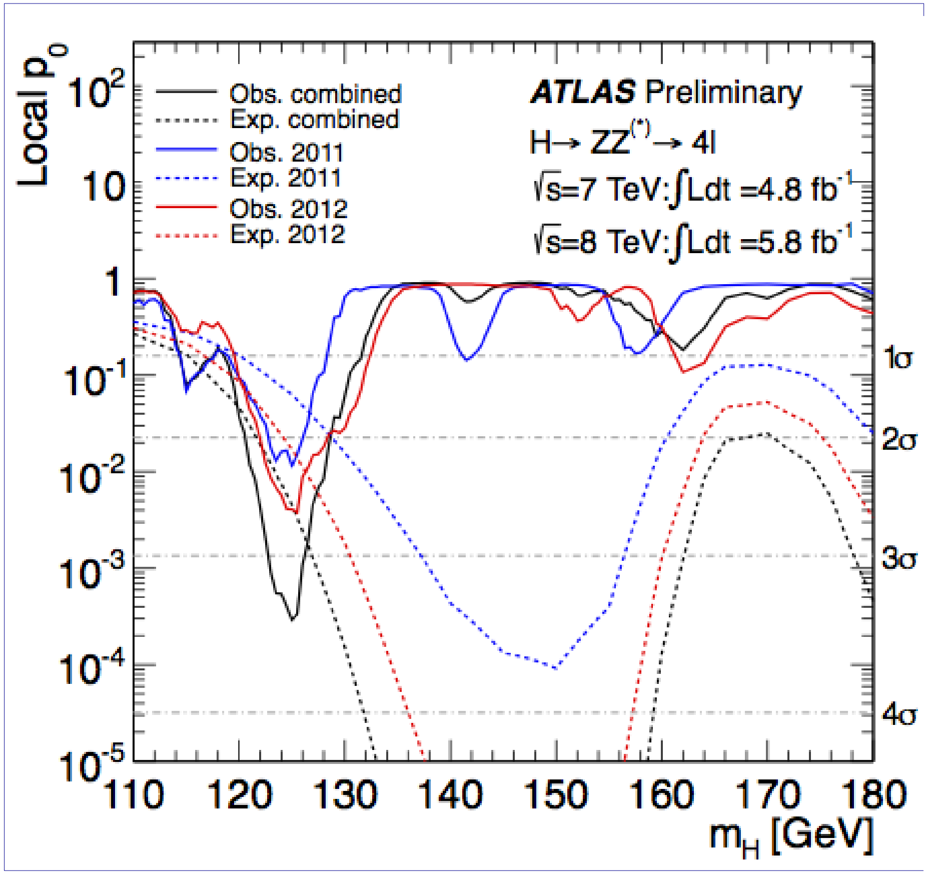


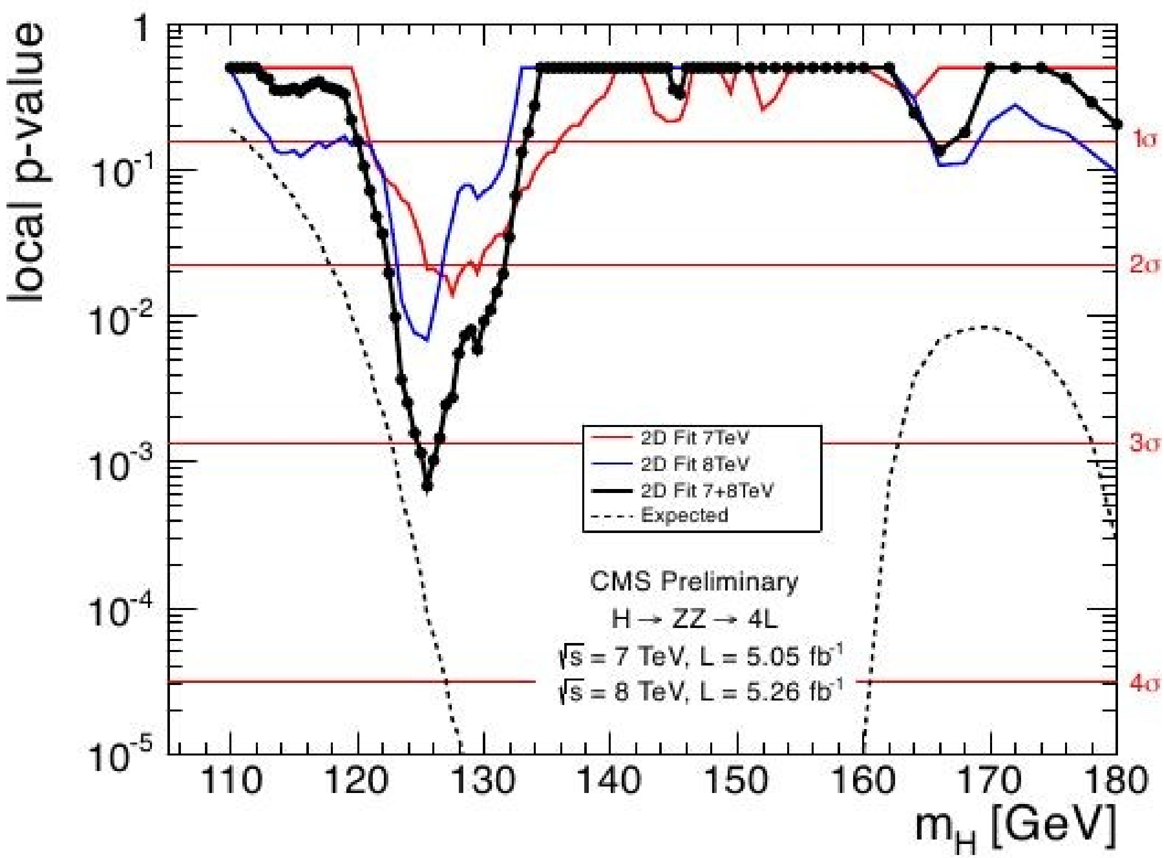


Signal-like excess
around125 GeV



H → ZZ → 4e, 4μ, 2e2μ   p-value w.r.t. background

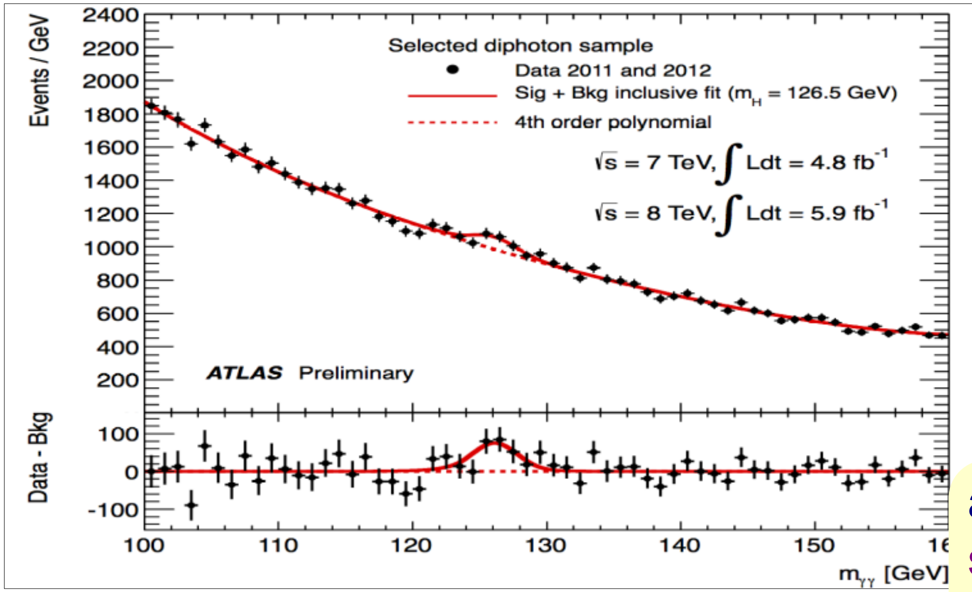


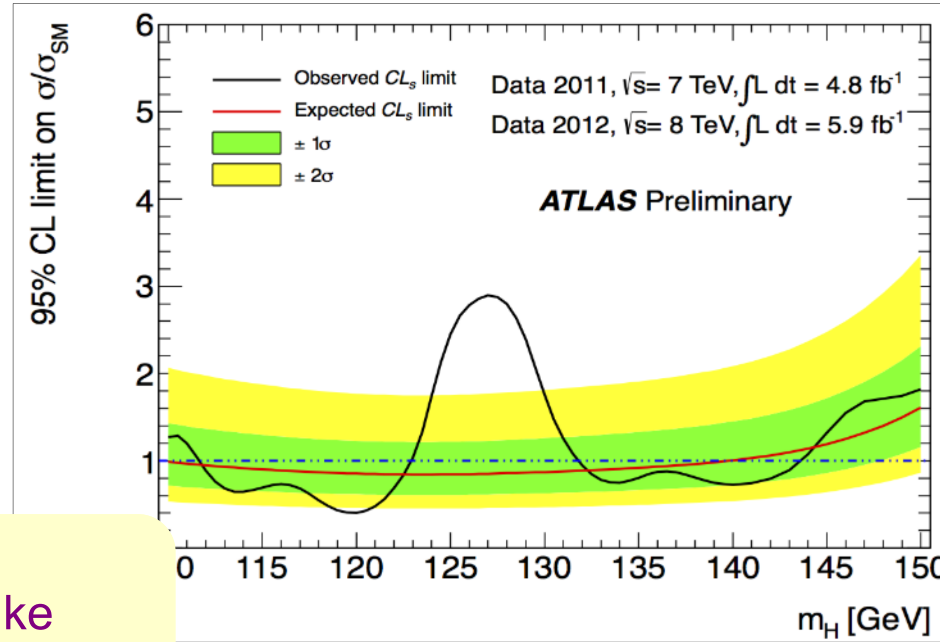


consistent signal excess in Atlas and CMS,
compatible with background at a probability of only ~0.1%

Higgs Search in $\gamma\gamma$ channel

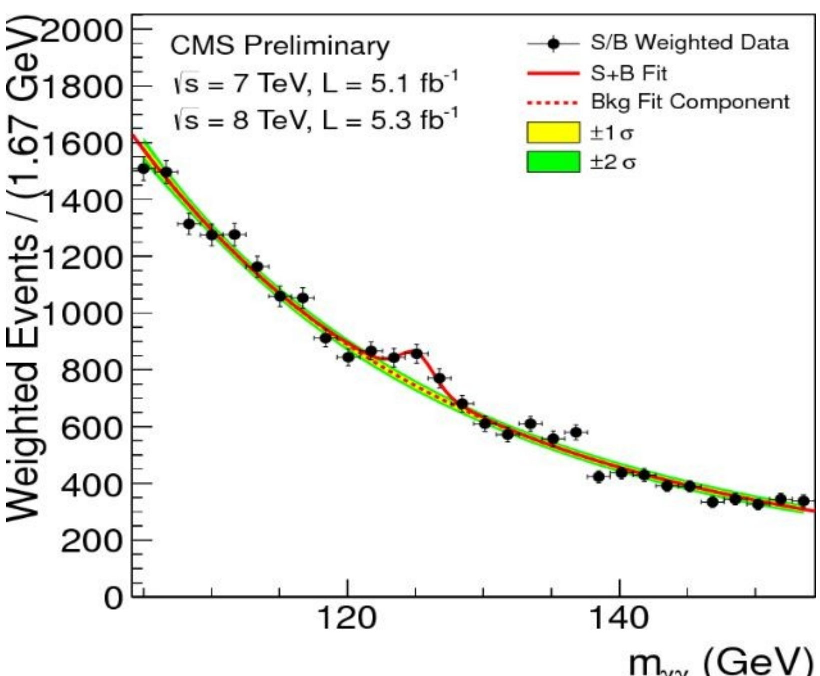
$\gamma\gamma$ spectrum ATLAS

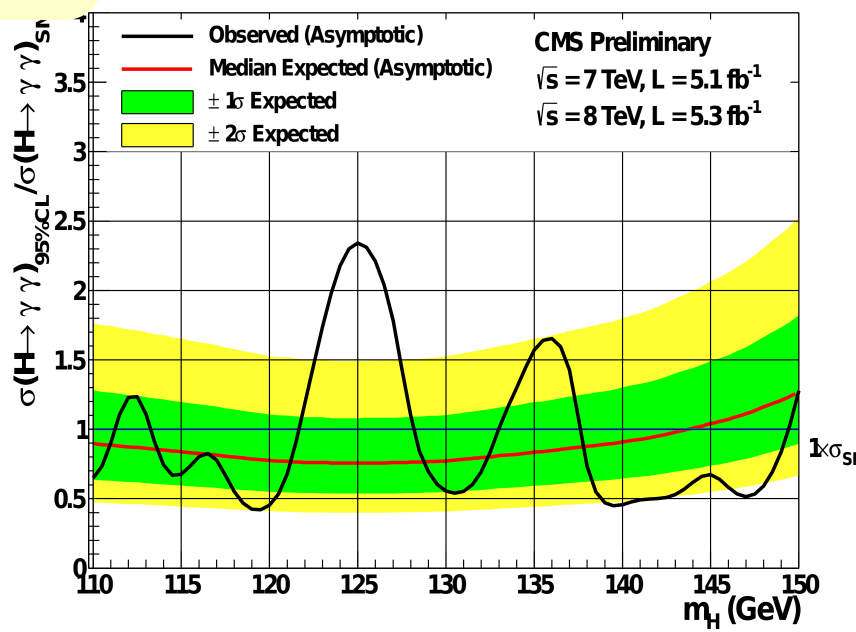




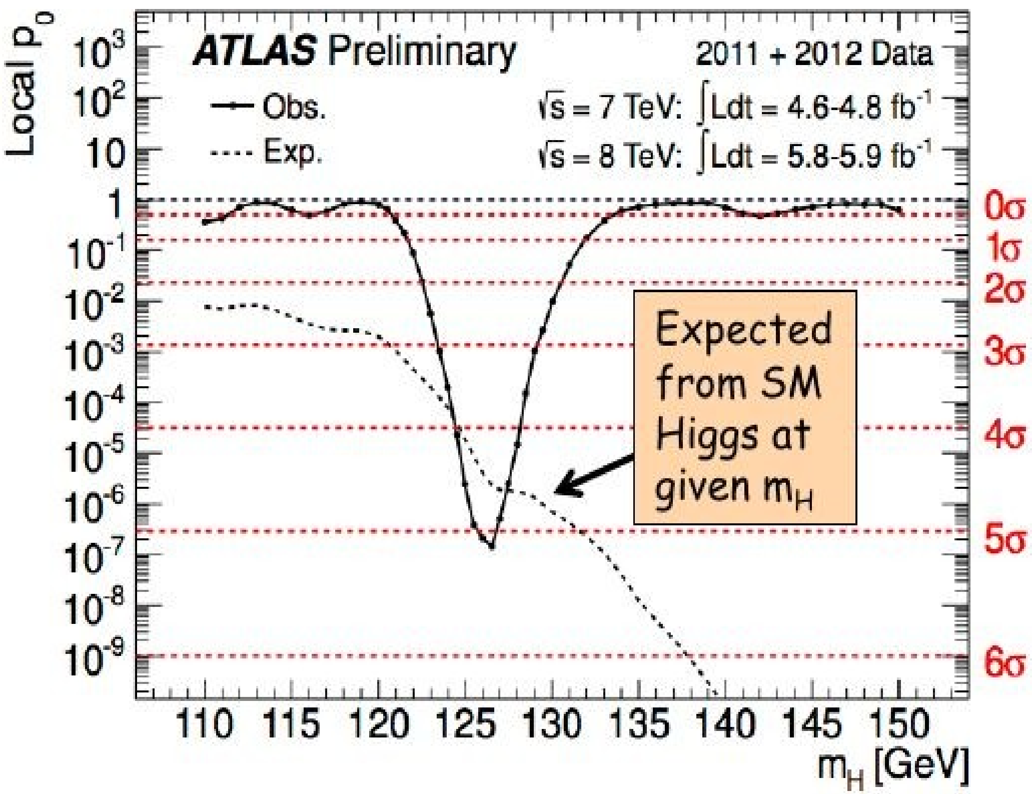
again:
signal-like
excess
at 125 GeV !

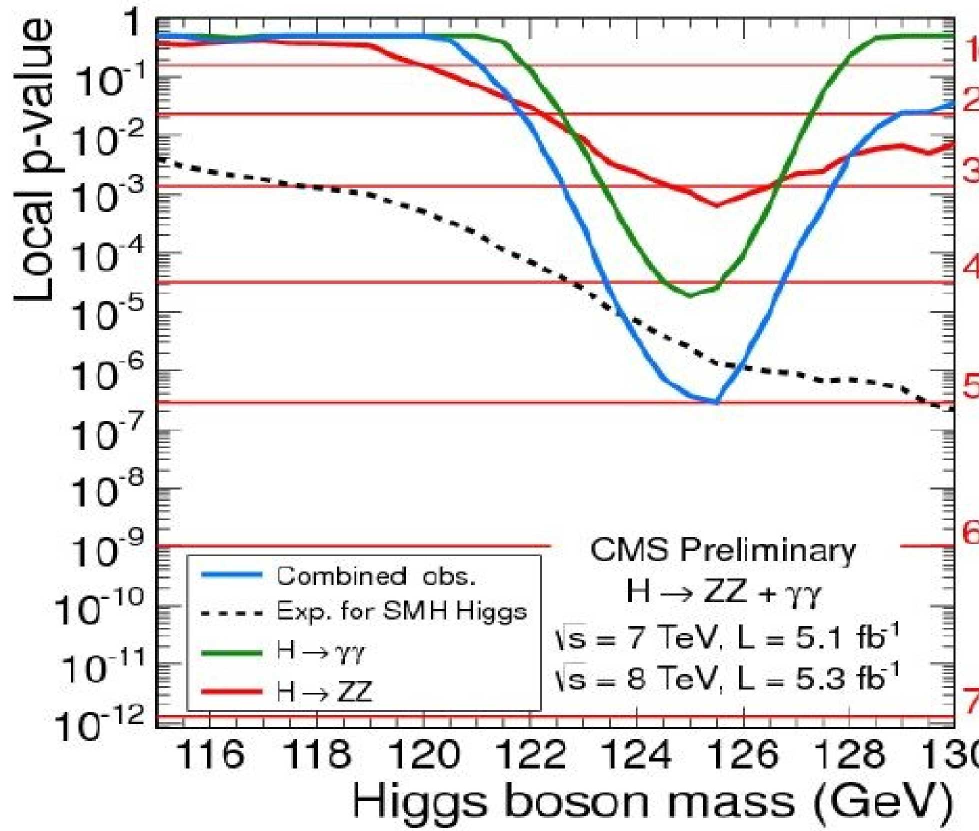
γ spektrum CMS





$\gamma\gamma$ and ZZ channel combined – Background Compatibility





Both ATLAS and CMS observe consistent excess
in $\gamma\gamma$ and ZZ ~5.0 σ larger than background fluctuations !

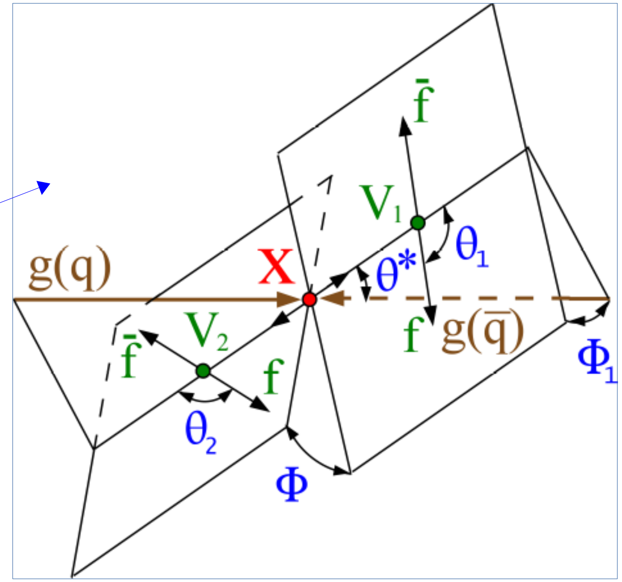
Discovery of a new “Higgs-like” particle at the LHC

Spin – CP (methods)

sufficiently high statistical precision and cleanliness of di-boson channels allows exploitation of kinematic variables for discriminating spin-parity hypotheses

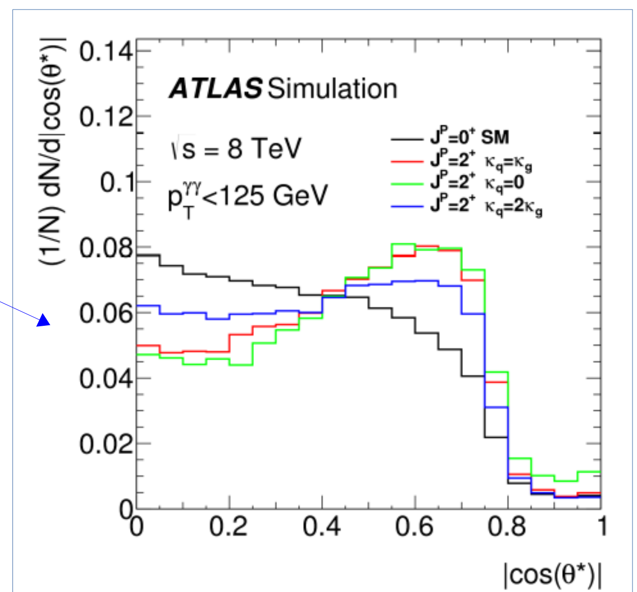
$H \to Z^{(*)}Z \to 4\ell$

matrix element depends on
- 5 angles
- 3 masses



$H \to \gamma\gamma$

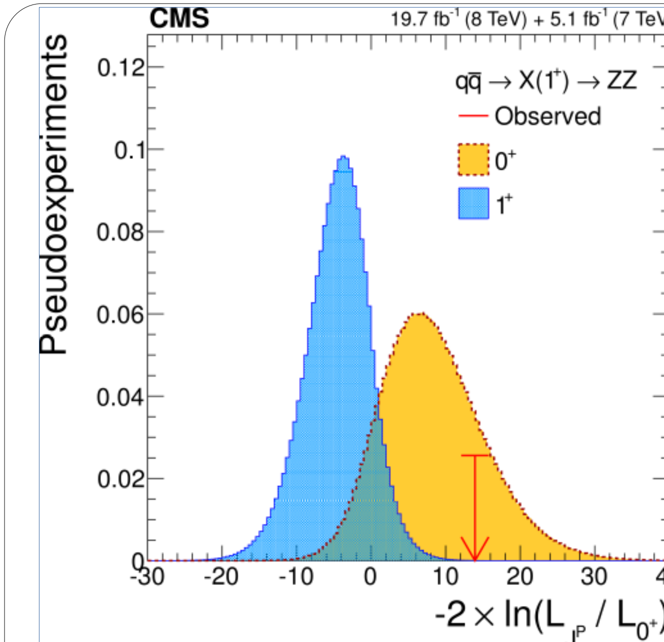
variables used:
– $p_T(\gamma\gamma)$
– $\cos\theta^*$ in Collins-Soper frame



$H \to W^{(*)}W \to \ell\nu\ell\nu$

ATLAS:
BTD with $\Delta\Phi(ll)$, $p_T(ll)$, $m(ll)$

CMS:
2D-distribution of $m(ll)$ & m_T



example of hypothesis test in ZZ^* 1^+ vs. 0^+

classical hypothesis test using log-Likelihood ratio of the SM vs. the alternative scenario as the test-statistic

Part 4

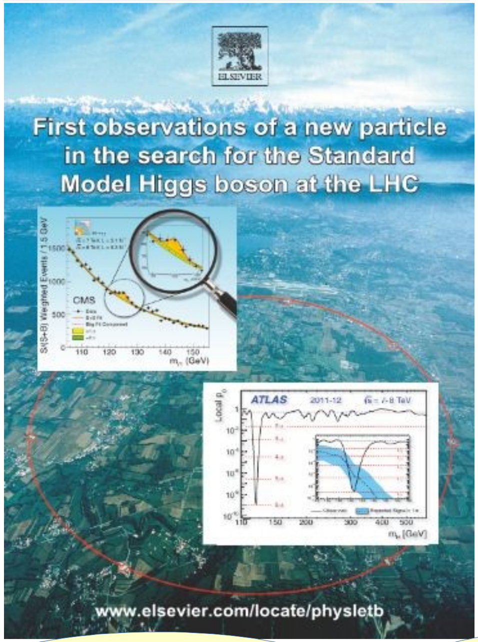
Present Status

ATLAS and CMS combined results on SM Higgs measurements

summary: Higgs Hunt @ the LHC

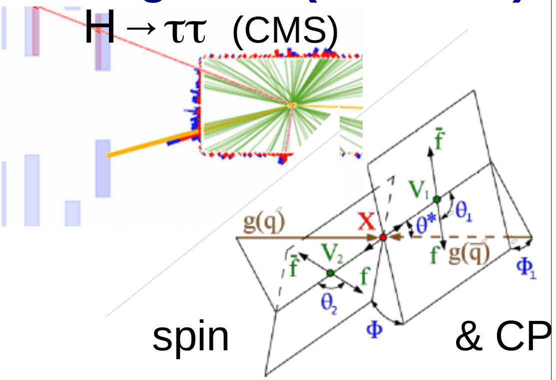
Summer '12 (~10 fb $^{-1}$)

Announcement of
“a new particle”



New particle !

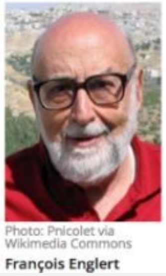
during 2013 (~20 fb $^{-1}$)



Higgs-like ?

Dec. 2013

Nobel Prize

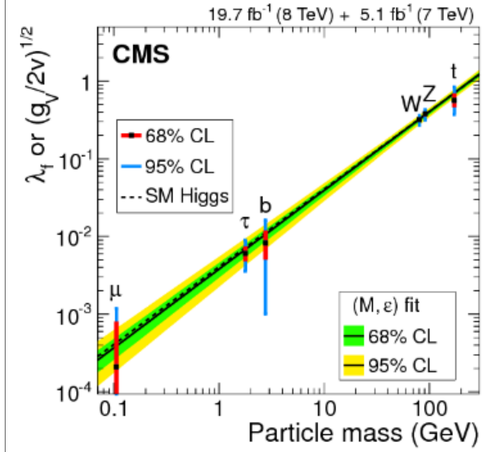


(& EPS Prize
+ many others)

A Higgs !

2014/15

refined analyses
&
(many) final publications



THE SM-Higgs ???

LHC Run 1: pp-collisions at E_{CM} of 7 and 8 TeV

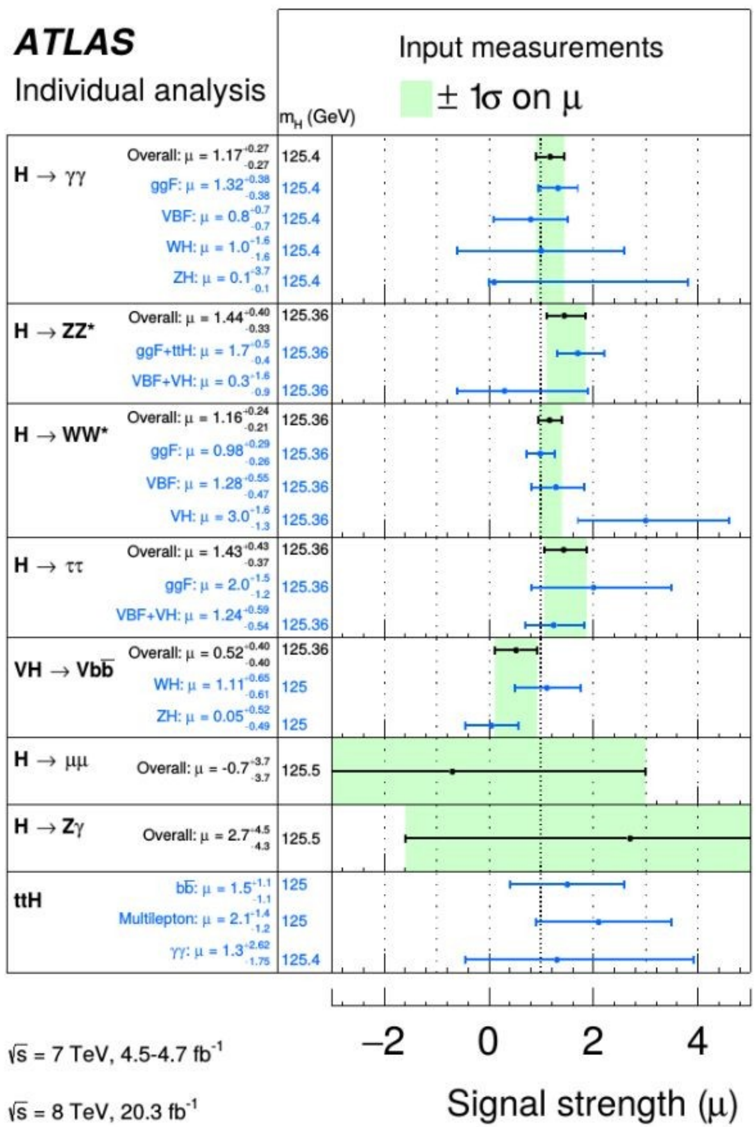
- Peak Luminosity: 7×10^{33} cm^{-2} s^{-1}
- Integrated Luminosity: ~5 fb $^{-1}$ (2011@7 TeV) ~(5+15) fb $^{-1}$ (2012@8 TeV)
- time between bunches: 50 ns ⇒ 9–21 overlayed pp-interactions on average

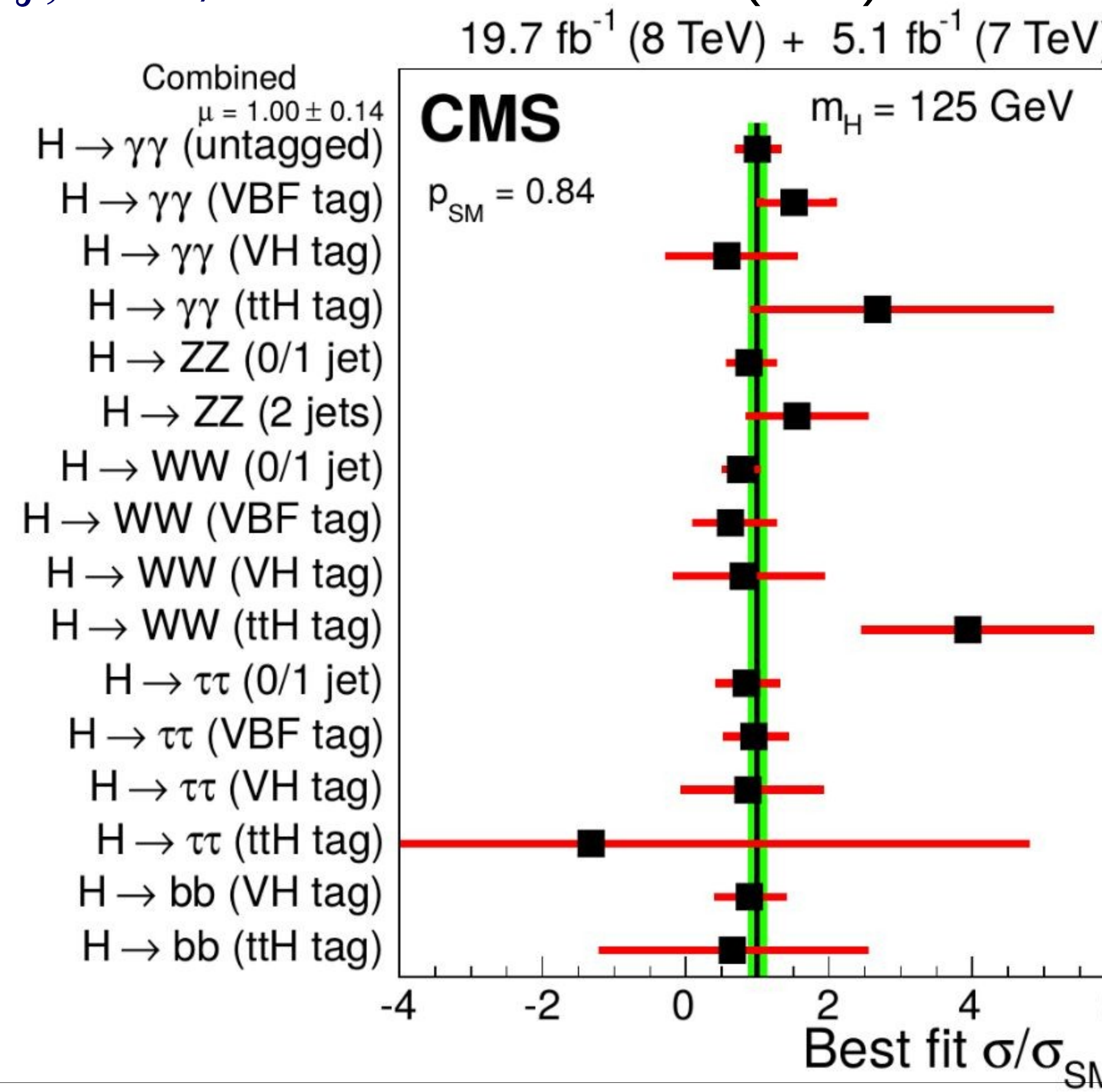
LHC Run 2 started at E_{CM} 13 TeV

- first results from Higgs analyses shown this summer

Where are we now – 2016 ?

Results based on integrated luminosities of
~5/fb @ 7 TeV (2011) and ~20/fb @ 8 TeV (2012) per experiment
for the "big five" H→ ZZ, γγ, WW, ττ and bb + some (rare) others





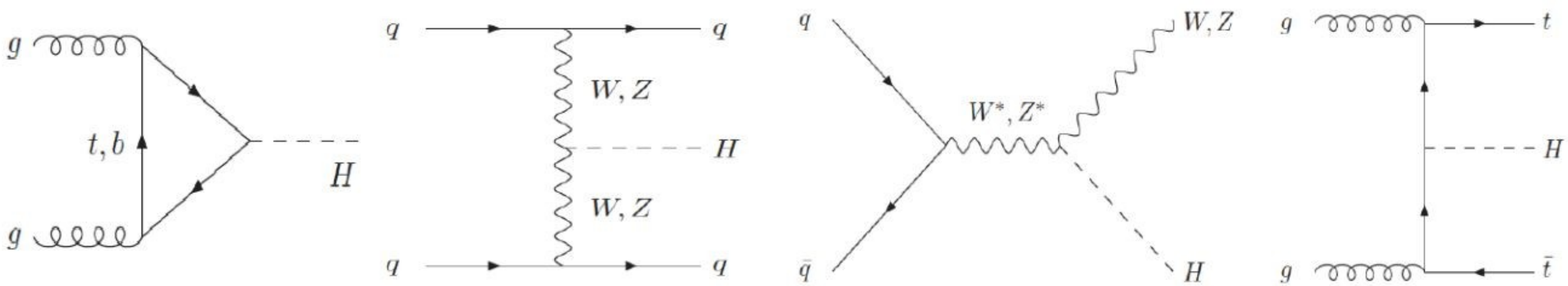
ATLAS Mass: PRL 114, 191803
ATLAS Couplings: arXiv:1507.04548

CMS Mass & Couplings
EPJ 75 (2015) 212

Couplings from Combination of ATALS & CMS data

- **Combination of Measurements** of Higgs-Boson Production by ATLAS and CMS in

ggF **VBF** **W/Z H** **ttH**



production modes

in the **decay channels**

H➔ ZZ **γγ** **WW** **ττ** and **bb** (and **μμ**)

note: γγ proceeds though W, t & b loops

- individual results corrected to common Higgs-boson mass of 125.09 GeV
  (and latest theory predictions, common treatment of background models etc. in some cases)

- **gain factor ~√2 in precision *w.r.t.* the individual results**,
  as measurements are dominated by independent errors

`published in JHEP 08 (2016) 045`

Signal parameterisations

In the narrow width approximation, which decouples production and decay, a measurement of **σ·Br** in the process $i \to H \to f$ is characterised by

signal strength modifiers μ:

$$\mu_i^f = \frac{\sigma_i}{(\sigma_i)_{\mathrm{SM}}} \cdot \frac{\mathrm{Br}^f}{(\mathrm{Br}^f)_{\mathrm{SM}}} = \mu_i \cdot \mu^f$$

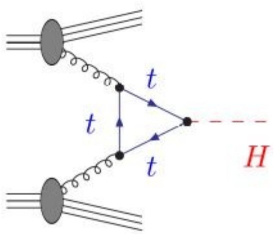
i = ggF, VBF, VH, ttH, … , *f = bb, WW, gg, ττ, cc, ZZ, γγ, Zγ, μμ*

Or, at (LO) coupling level, introduce

coupling modifiers κ:

$$\sigma_i \cdot \mathrm{Br}^f = \frac{\sigma_i(\{\kappa\}) \cdot \Gamma^f(\{\kappa\})}{\Gamma_H(\{\kappa\})}$$

alternatively:
loops resolved to contributing particles, *e.g.* ggF:



$$\kappa_g^2 \simeq 1.06\kappa_t^2 + 0.01\kappa_b^2 - 0.07\kappa_t\kappa_b$$

$$\kappa_i^2 = \frac{\sigma_j}{\sigma_i^{\mathrm{SM}}} \text{ or } \kappa_f^2 = \frac{\Gamma^f}{\Gamma^f_{\mathrm{SM}}}$$

$$\kappa_H^2 = \frac{\Gamma_H}{\Gamma_H^{\mathrm{SM}}}$$

SM particles only:

$$\kappa_H^2 = \sum_f \mathrm{Br}^f_{\mathrm{SM}} \kappa_f^2$$

with BSM-contributions:

$$\kappa_H^2 = \frac{(1-\mathrm{Br}_{\mathrm{BSM}})\Gamma_H}{\Gamma_H^{\mathrm{SM}}}$$

Overall Signal Strength μ

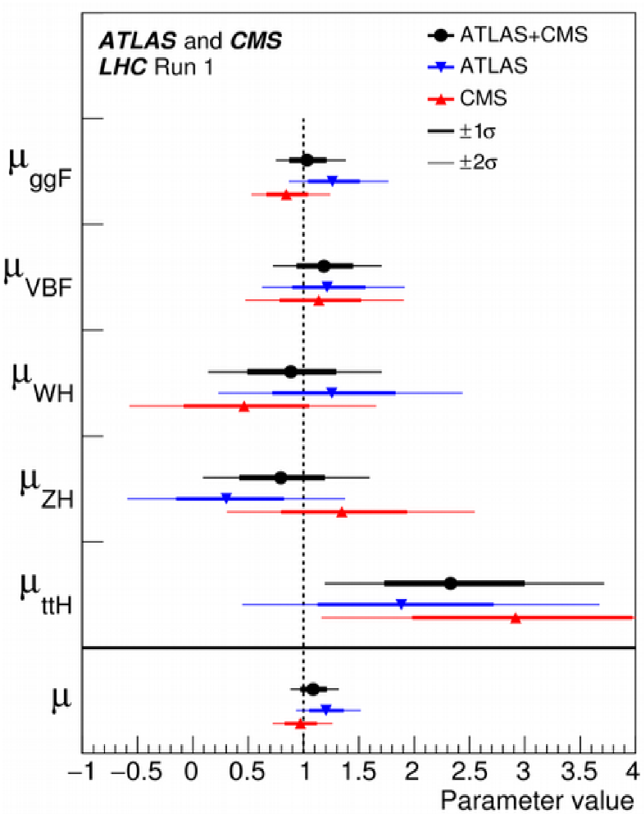
only one fit parameter

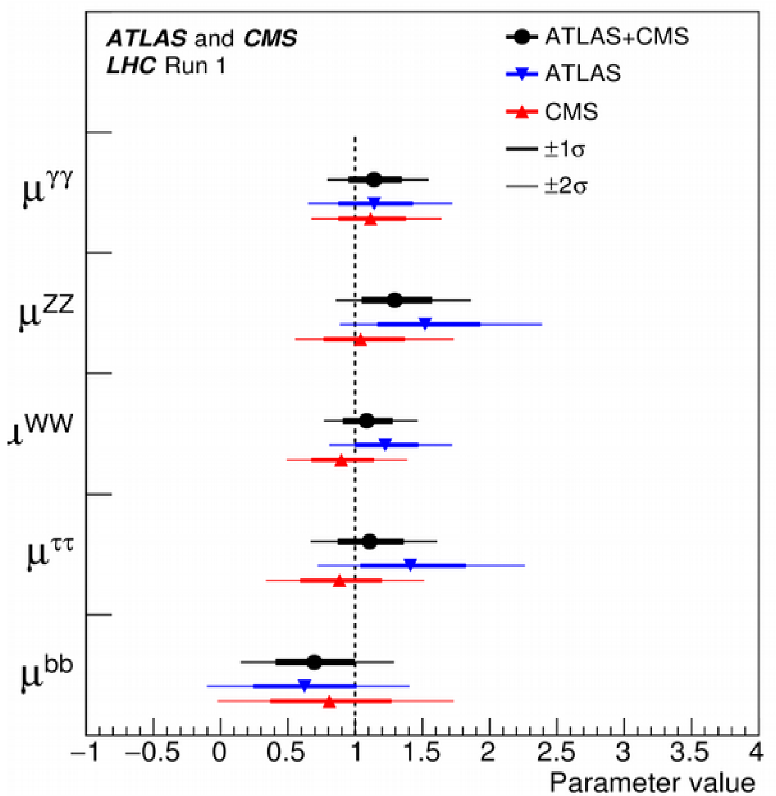
assumption: $\mu_i = \mu_f := \mu$

$$\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}\,(\text{stat})\,^{+0.04}_{-0.04}\,(\text{expt})\,^{+0.03}_{-0.03}\,(\text{thbgd})^{+0.07}_{-0.06}\,(\text{thsig})$$

most precise measurement, theoretical error as large as the statistical one !

μ_i & μ^f





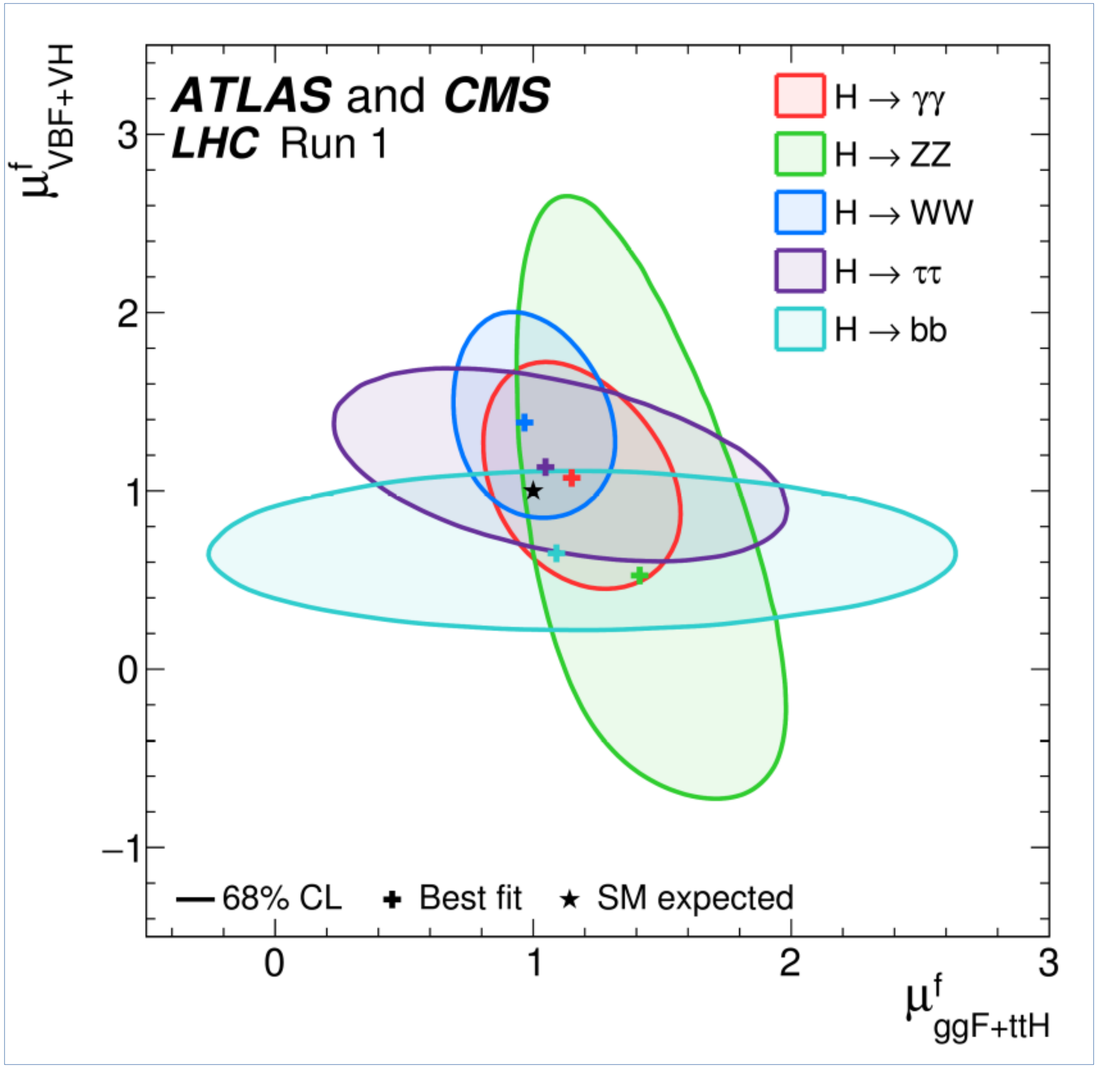
Fremion- and Boson-mediated production modes

two fit parameters for each decay channel f

assumption: $\mu^f_{\mathrm{VBF}} = \mu^f_{\mathrm{VH}}$ and $\mu^f_{\mathrm{ttH}} = \mu^f_{\mathrm{ggF}}$

boson fermion

mediated



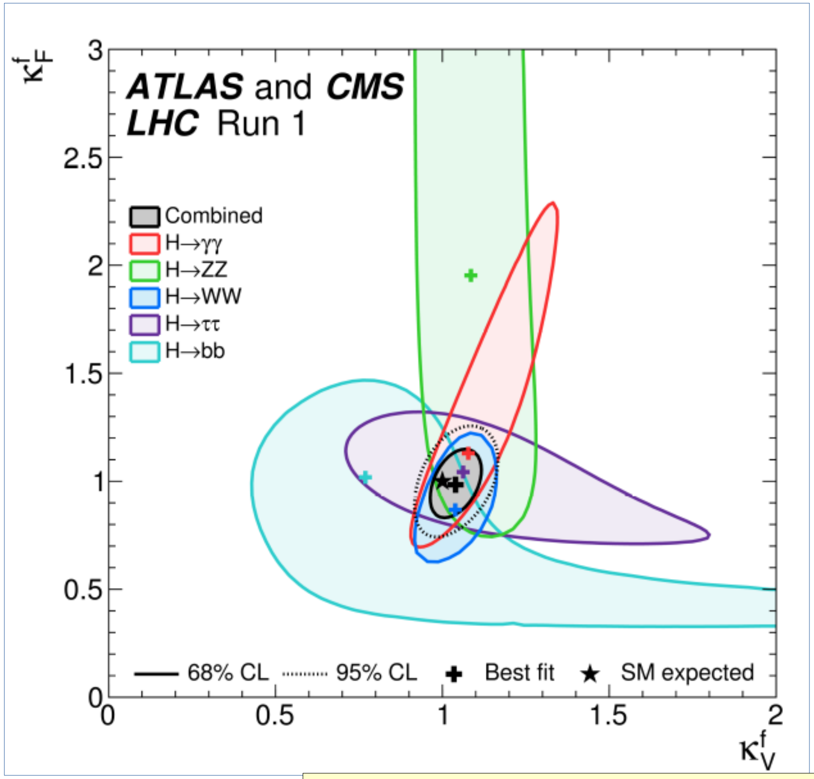
fitting for the ratio yields:

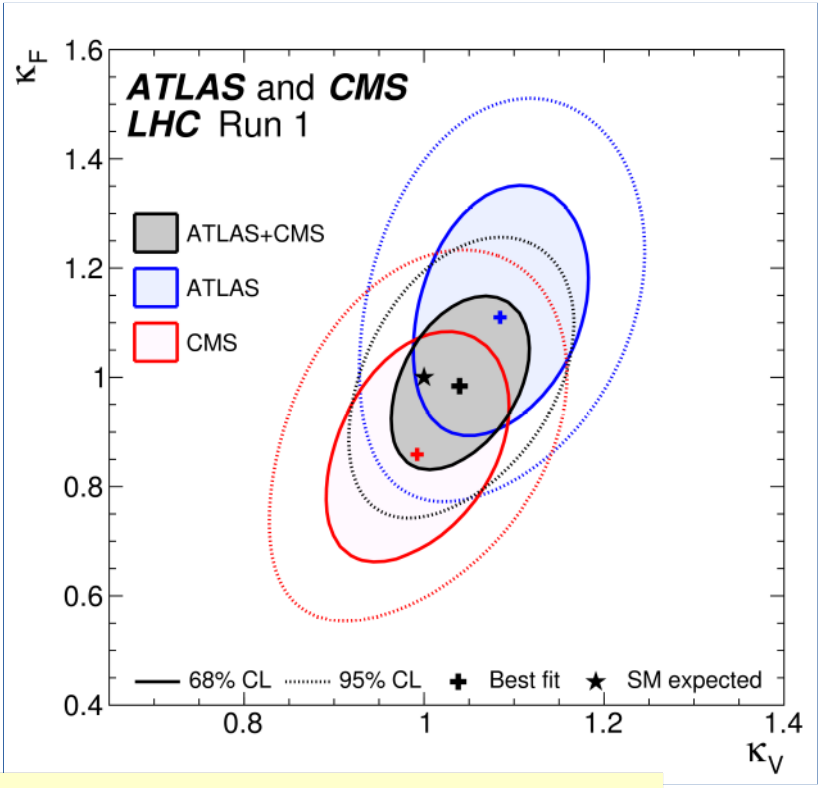
$$\frac{\mu_V}{\mu_F} = 1.09^{+0.36}_{-0.28}$$

method independent of
assumptions on Br's

H Couplings to Fermions and Bosons

1. assume universal scaling factors for couplings to fermions and bosons: κ_F and κ_V
2. only SM physics in loops





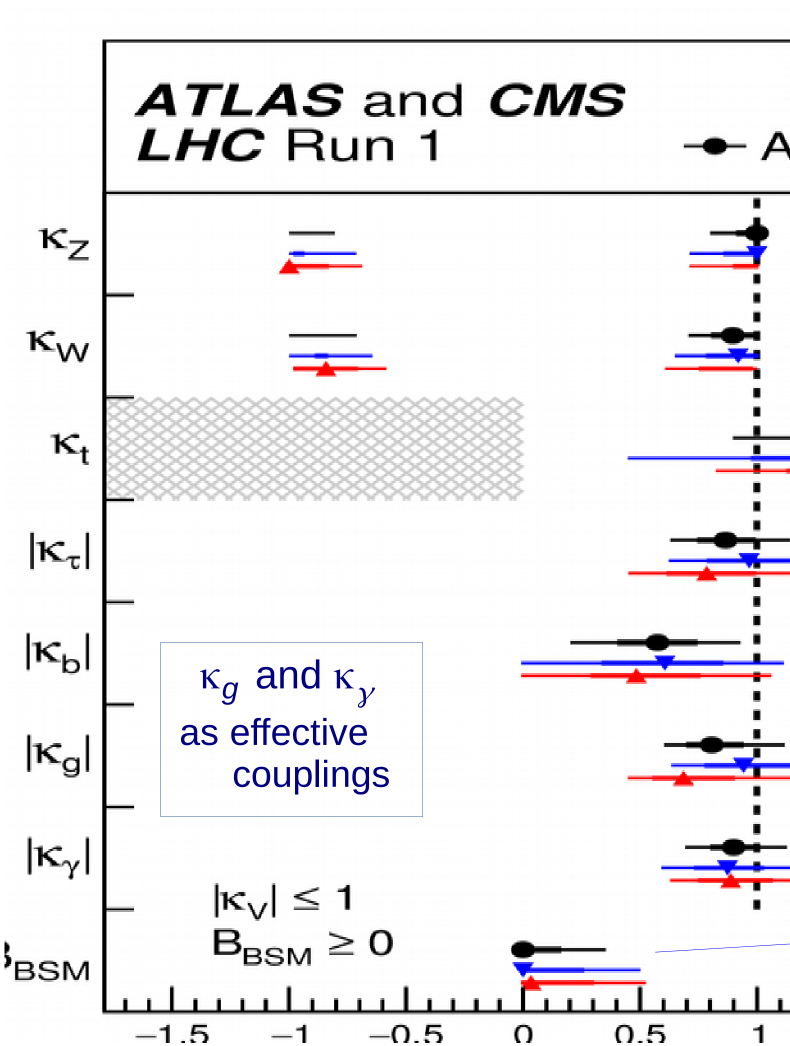
Cannels & Experiments consistent among each other and with SM expectation

Beyond SM ?

Total Higgs boson width sensitive to invisible (or undetected) H decays, but not known precisely enough experimentally.

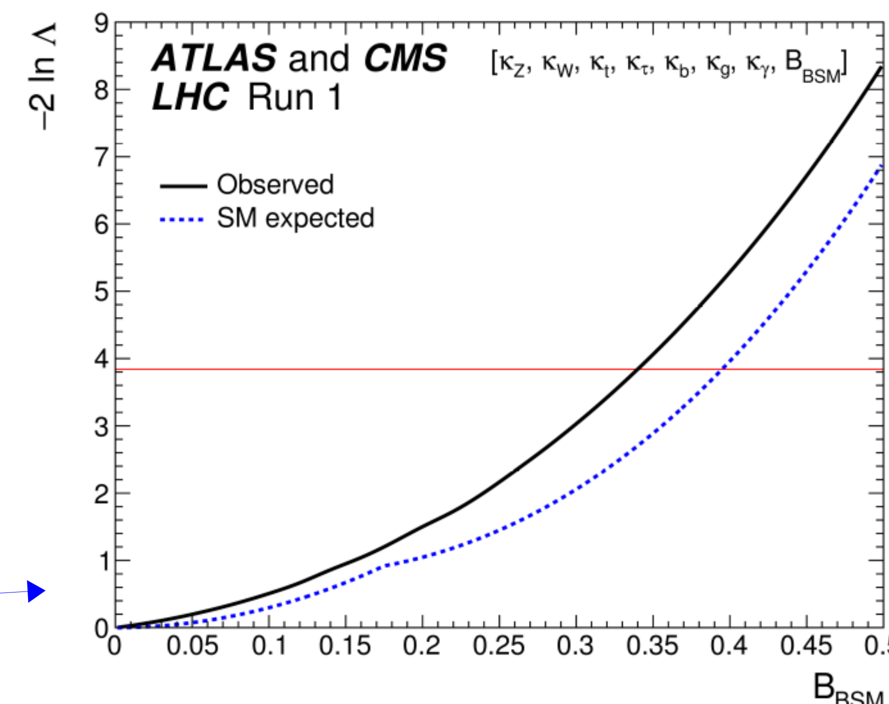
assume $\kappa_W < 1$ and $\kappa_Z < 1$

⇒ (some) sensitivity to Br_{BSM}



κ_g and κ_γ as effective couplings

profile likelihood scan of Br_{BSM}

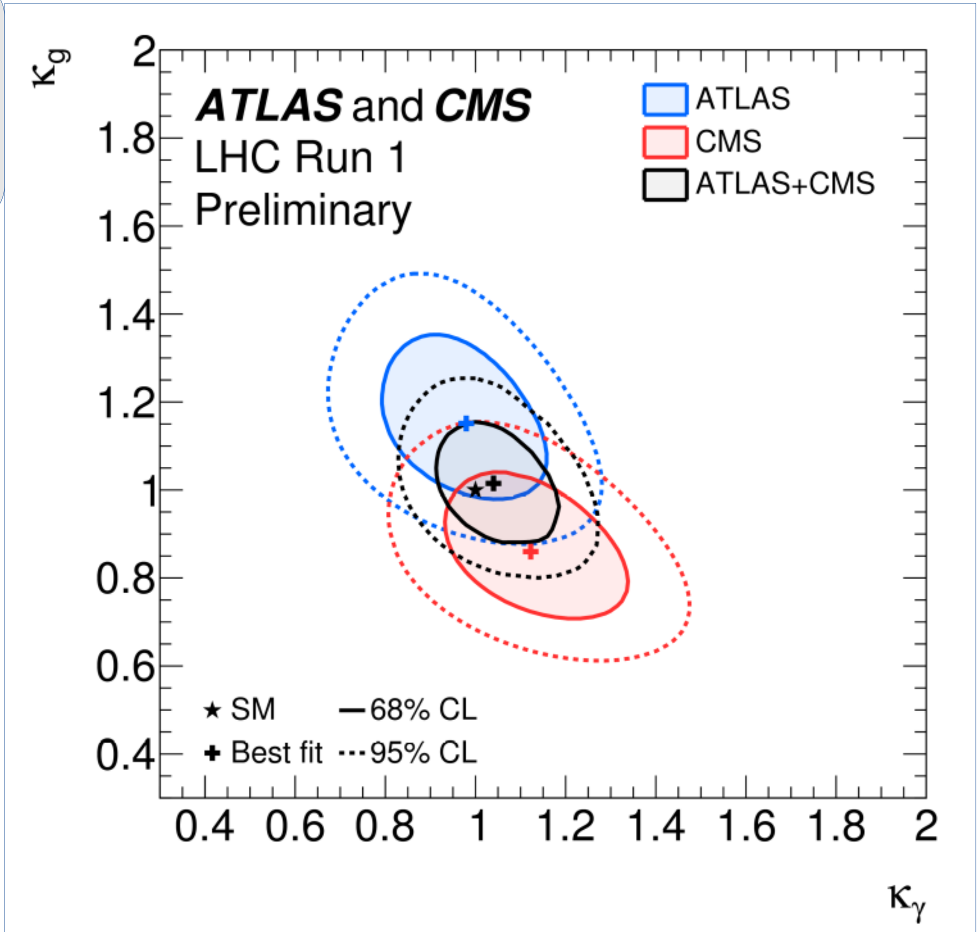


Br_{BSM} < 0.34 @ 95% C.L.

Physics beyond SM in loops ?

assume $_{BSM} = 0 \text{ and } \kappa_i = 1$

new physics my enter through effective couplings $\kappa_\gamma \text{ and } \kappa_{\mathrm{g}}$

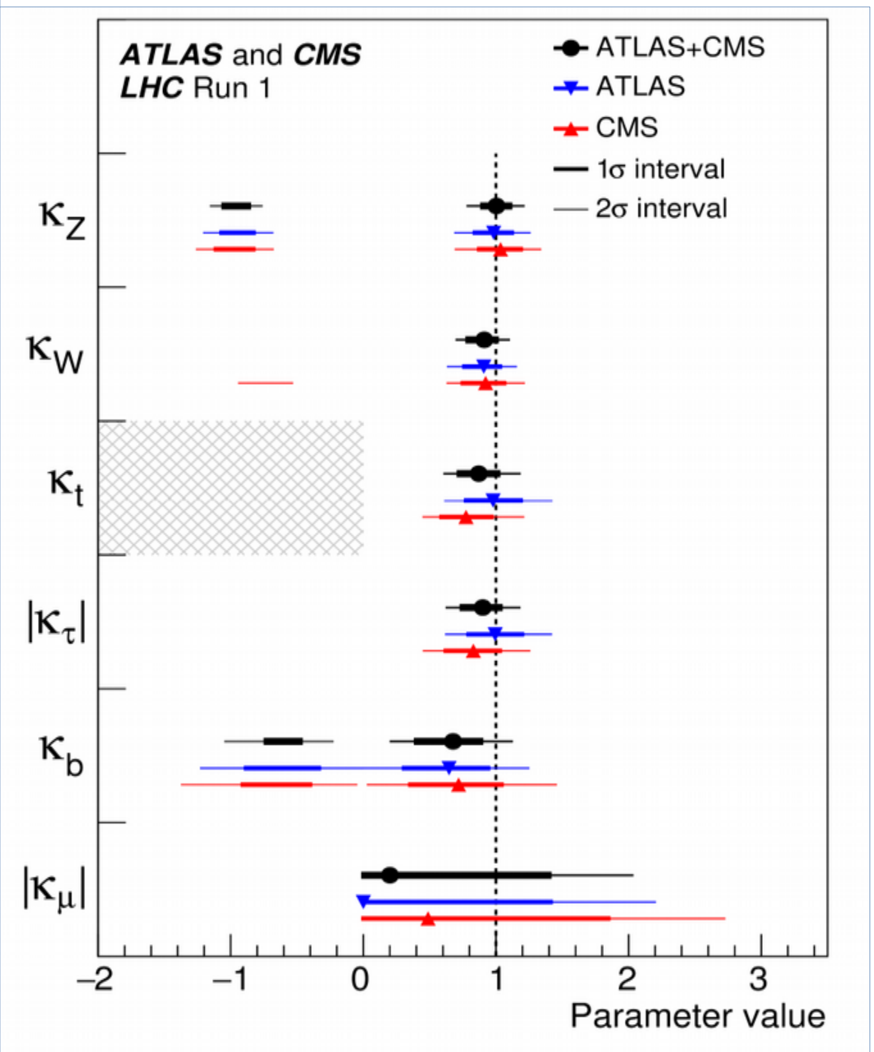


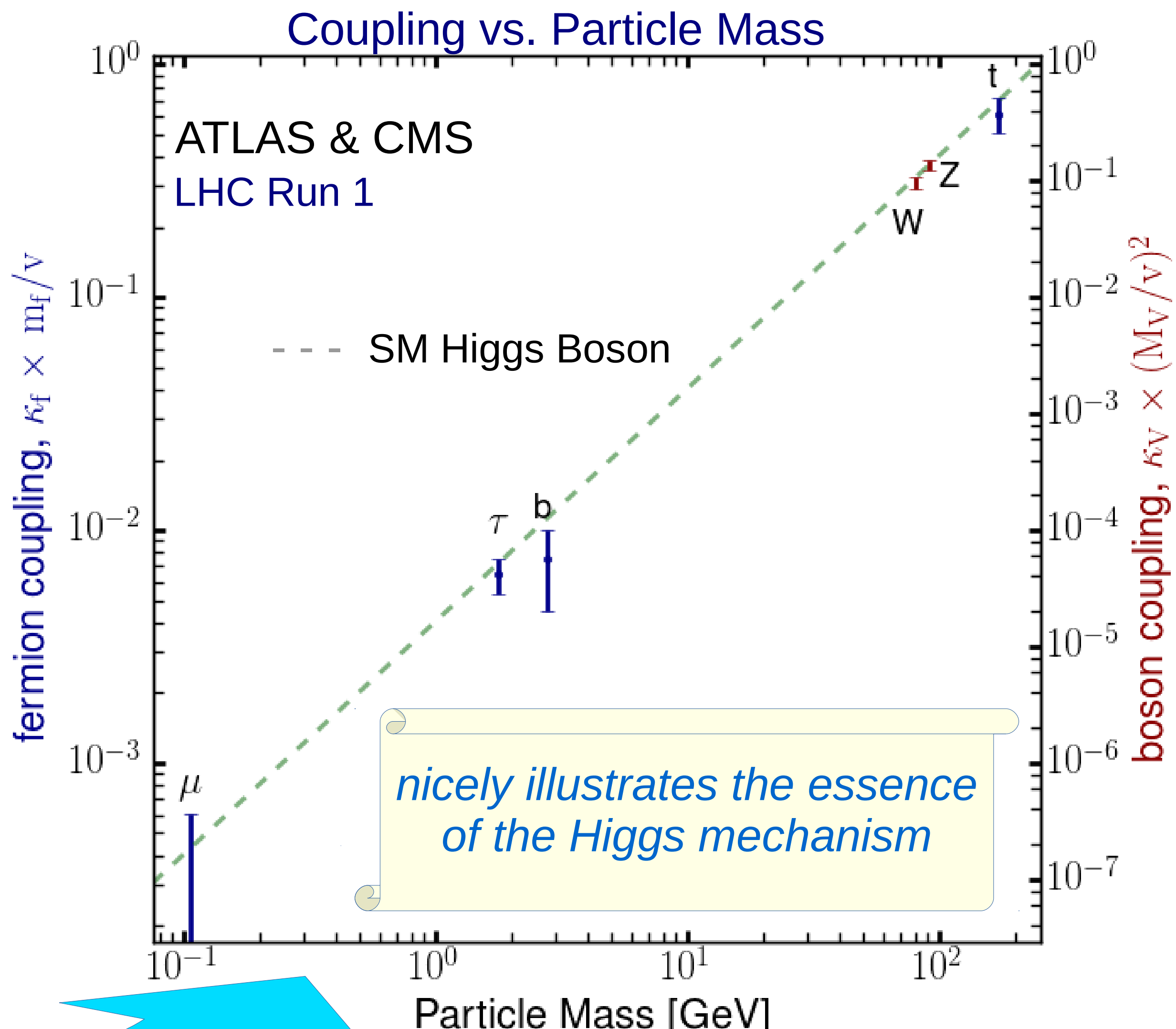
p-value for compatibility of data and SM is 82%

Higgs Couplings (in SM)

Assumption: No other than SM particles couple to Higgs boson, $Br_{BSM} = 0$

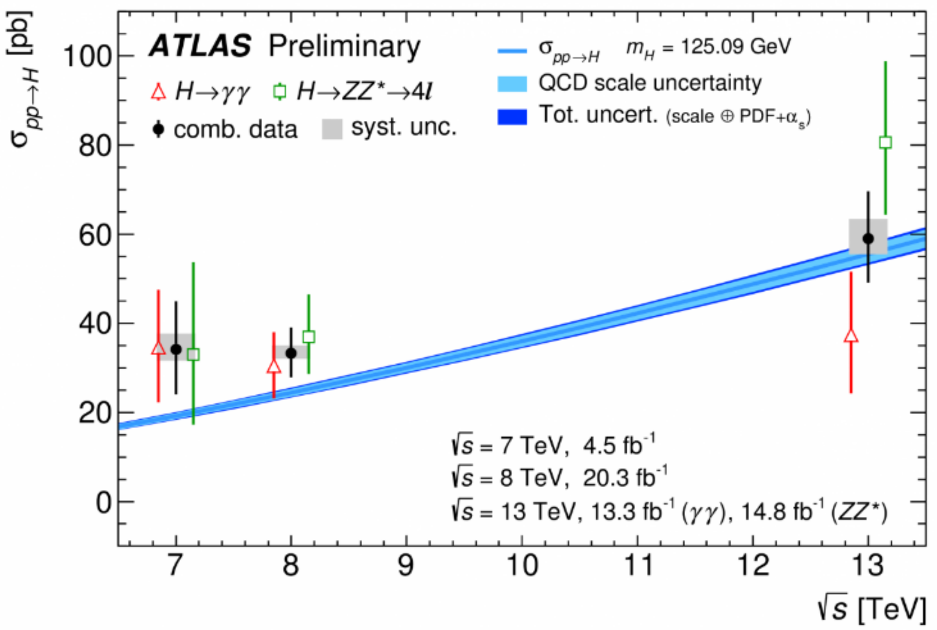
remark: low value of κ_b reduces total width Γ_H ⇒ **all κ_i come out a bit low**





nicely illustrates the essence of the Higgs mechanism

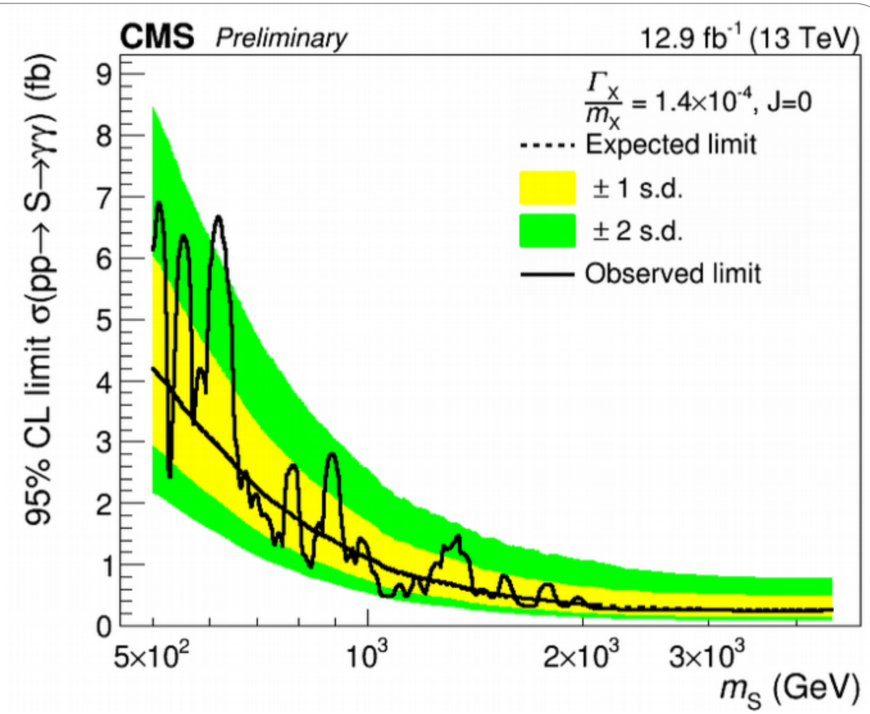
LHC Run 2: first results



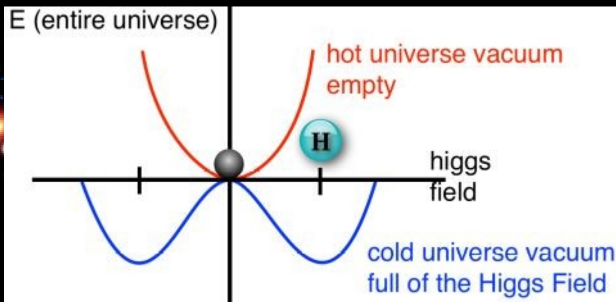
Higgs signal clearly visible in new run2 data in ZZ and γγ channels with >5σ significance in each channel and in both ALTAS and CMS

Searches for Higgs-like states
or a new γγ resonance
at high invariant masses
did not show any signifcant signal

(~750 GeV excess in 2015 data
gone as well ...)



Conclusion



Discovery of a Higgs -like Boson @ LHC …

– is the result of an incredible amount of work by theorists, engineers and experimentalists

– is a remarkable triumph of a theoretical idea

– helps coming closer to an understanding of “mass” in general

– marks the beginning of an **new era** in particle physics

- **H(125)** is (so far) the only one of its kind
- tests of relations between Higgs couplings to SM particles show no significant deviations
- precision measurements still needed

  LHC Run 2 offers good perspectives !
- searches for other Higgs-like particles continues

What is beyond the Standard Model ?

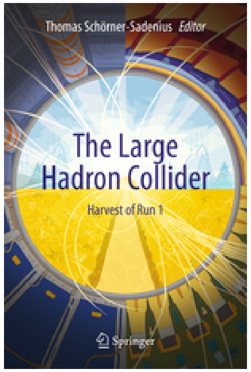
Literature

Topics of this lecture meanwhile well covered

in various lectures
- Master course on Higgs Physics, KIT
- CERN Summer Student lectures
- and many, many others

and (didactical) literature:

- The large Hadron Collider – Harvest of Run 1, Springer 2015



- The Higgs Boson discovery at the large Hadron Collider R. Wolf, Springer, 2015