



DE ZOEKTOCHT NAAR HET HIGGS BOSON

Ivo van Vulpen

Als de Higgs ontdekt wordt
gaat het de geschiedenisboeken in



Als de Higgs **niet** ontdekt wordt
gaat het **ook** de geschiedenisboeken in



Real Madrid - Barcelona

theguardian

News | Sport | Comment | Culture | Business | Money | Life & style | Travel | Environment | TV

Sport | Football | La Liga

Real Madrid v Barcelona – as it happened

Real scored after only 21 seconds, but Barcelona came back at them to close the gap at the top

Min-by-min | Observer report | Guardian report | Match facts | Ratings

La Liga

Real Madrid 1
Barcelona 3

Benzema 1
Sánchez 30, Xavi 53, Fàbregas 66

Scott Murray
guardian.co.uk, Saturday 10 December 2011 22.54 GMT
Article history

Football
La Liga · Real Madrid · Barcelona

Sport

More minute by minutes

More match reports

More on this story

Illness rules out Fletcher indefinitely
Man Utd midfielder Darren Fletcher is not expected to play again this season because of a health problem



27 min: Two bookings in a minute. First Xabi Alonso for a needless rake across Messi's shins, then Alexis for a pointless hack on Di Maria. It's been played in a good spirit so far, but there we are with the first signs of it kicking off. Again, I suppose I'm duty bound to say we don't like to see this sort of thing, but we sort of do, don't we.

29 min: Dani Alves cries murder after Marcelo clatters into him. The referee sighs wearily. There's an edge now.

30 min: GOAL!!! Real Madrid 1-1 Barcelona. This was so simple, and so brilliant. Messi, from the centre circle, drives down the middle, drawing three white shirts. He eventually slides a pass down the inside-right channel to spring Alexis free. From the edge of the box, just to the right of goal, Alexis whips a low shot straight into the bottom-left corner. Casillas had no chance. That came from nothing. Barca, who have been poor so far, are right back in this! Ronaldo will rue that useless shot of a few minutes ago.

33 min: All of a sudden, Barcelona's pretty triangles are sticking to feet. Their confidence is back, after being knocked to buggery in the opening 21 seconds. "As a result of GB being cut off from all things eurozone by the mighty bluster of our PM, I fear this is the last el classico the Guardian will be allowed to cover. Soon a euro-sceptic curtain will descend behind which the UK and a trapped Tevez will sit in isolation." Ladies and gentlemen, that was the week that was, with Ian Copestake, the David Frost *de nos jours*.

35 min: Dani Alves leaves his foot in a 50-50 challenge with Xabi Alonso. He should be booked for his sauce, but isn't. Just for a

CERN Higgs seminar

theguardian

News | Sport | Comment | Culture | Business | Money | Life & style | Travel | Environment | TV

News | Science | Higgs boson

NOTES&THEORIES

DISPATCHES FROM THE SCIENCE DESK

Higgs boson seminar: have physicists found the 'God particle'? – live

Physicists announce the latest results from the proton-colliding experiments at the Large Hadron Collider (LHC) including tentative evidence for the existence of the Higgs boson

Alok Jha, science correspondent
guardian.co.uk, Tuesday 13 December 2011 17.24 GMT
Article history

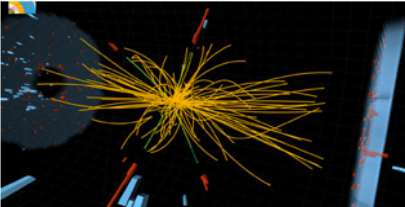
Tweet | 230
Recommend | 1k
reddit this
Comments (281)

larger | smaller

Science
Higgs boson · Cern · Particle physics · Physics

More minute by minutes

More on the Higgs



else that takes the role of the "standard" Higgs particle, perhaps a family of several Higgs particles or something even more exotic. The unexpected is always the most exciting.

1.33pm: Watching Fabiola's presentation, particle physicist @TaraShears has tweeted: "So this channel excludes 114-115, and 135-136 GeV. #higgsupdate"

It's worth following Tara (and our own @jonmbutterworth) if you want real-time updates on Twitter. Jon's latest: "126 GeV... (probably) #higgsupdate"

Also from Jon: "That 126 GeV was where the ATLAS excess Fabiola just showed is. Not conclusive, but suggestive. ZZ and CMS to come..."

1.43pm: From Cern: "#ATLAS sees a small excess at a Higgs mass of 126 GeV coming from 3 channels. Local significance: 3.6 sigma but only 2.4 sigma globally"

That's not enough for a "discovery" (which technically needs 5 sigma) but it is very interesting evidence for the Higgs.

Also: "#ATLAS excludes a #Higgs mass between 131 and 453 GeV at 95% confidence level at #CERN Higgs seminar"

1.49pm: Fabiola Gianotti has finished her presentation. So far, we know that Atlas seems to have found evidence for a bump around 126GeV for something that looks like the Higgs.

Live blog comments
the Guardian

Het Higgs mechanisme

Massieve kracht(deeltjes) in een lokale ijk-invariante theorie

$$SU(2)_L \otimes U(1)_Y \otimes SU(3)_C$$

dan moet er een Higgs boson zijn

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS

Math Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 17 July 1964

Recently a number of people have discussed the Goldstone theorem^{1,2,3}; this says that in a Lorentz-invariant theory which contains an internal symmetry operation of that theory must contain a massless scalar particle. Klein and Lee⁴ showed that this theorem does not necessarily apply in non-relativistic theories and implied that their considerations would apply equally well to Lorentz-invariant field theories. Gilbert^{5,6}, however,

gave a proof that the failure of the Goldstone theorem in the non-relativistic case is of a type which cannot exist when Lorentz invariance is imposed on a theory. The purpose of this note is to show that Gilbert's argument fails for an important class of field theories, that in which the conserved currents are coupled to gauge fields.

Following the procedure used by Gilbert⁵, let us consider a theory of two Hermitian scalar fields

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$\phi_1(x)$, $\phi_2(x)$ which is invariant under the phase transformation

$$\phi_1 \rightarrow \phi_1 \cos \theta + \phi_2 \sin \theta, \quad (1)$$

$$\phi_2 \rightarrow -\phi_1 \sin \theta + \phi_2 \cos \theta.$$

Then there is a conserved current j_μ such that

$$i[\int d^3x j_0(x), \phi_1(x)] = \phi_2(x), \quad (2)$$

We assume that the Lagrangian is such that symmetry is broken by the nonvanishing of the vacuum expectation value of ϕ_2 . Goldstone's theorem is proved by showing that the Fourier transform of $\langle \phi_1(x), \phi_1(0) \rangle$ contains a term $2\pi \delta(k) \langle \phi_2 | \phi_2 | 0 \rangle$, where $\delta(k)$ is the momentum, as a consequence of Lorentz invariance, the conservation law and eq. (2).

Klein and Lee⁴ avoided this result in the non-relativistic case by showing that the most general form of this Fourier transform is now, in Gilbert's notation,

$$F(k) = \langle \phi_2 | \phi_2 | 0 \rangle + \langle \phi_2 | \phi_2 | 0 \rangle + C \langle \phi_2 | \phi_2 | 0 \rangle, \quad (3)$$

where $\langle \phi_2 | \phi_2 | 0 \rangle$ which may be taken as 1, 0, 0, 0, (3) gives not a special Lorentz frame. The conservation law then reduces eq. (3) to the less general form

$$F(k) = \langle \phi_2 | \phi_2 | 0 \rangle + [\langle \phi_2 | \phi_2 | 0 \rangle + \langle \phi_2 | \phi_2 | 0 \rangle] \delta(k) + C \langle \phi_2 | \phi_2 | 0 \rangle. \quad (4)$$

It turns out, on applying eq. (4), that all three terms in eq. (4) can contribute to $\langle \phi_2 | \phi_2 | 0 \rangle$. Thus the Goldstone theorem fails if $\delta(k) \neq 0$, which is possible only if the other terms exist. Gilbert's remark that no special timelike vector n_μ is available in a Lorentz-invariant theory appears to rule out this possibility in such a theory.

There is however a class of relativistic field theories in which a vector n_μ does indeed play a part. This is the class of gauge theories, where an auxiliary well defined vector n_μ must be introduced in order to define a radiation gauge in which the vector gauge fields are well defined operators. Such theories are nevertheless Lorentz-invariant, as has been shown by Schwinger^{7,8}. (This has, of course, long been known of the simplest such theory, quantum electrodynamics.) There seems to be no reason why the vector n_μ should not appear in the Fourier transform under consideration.

It is characteristic of gauge theories that the conservation laws hold in the strong sense, as a consequence of field equations of the form

$$\partial_\mu F^{\mu\nu} = j_\nu, \quad (5)$$

Except in the case of Abelian gauge theories, the fields A_μ , $F_{\mu\nu}$ are not simply the gauge field variables A_μ , $F_{\mu\nu}$, but contain additional terms with contributions of the structure constants of the group as coefficients. Now the structure of the Fourier transform of $\langle \phi_2 | \phi_2 | 0 \rangle$ must be given by eq. (4). Applying eq. (5) to this commutator gives us as the Fourier transform of $\langle \phi_2 | \phi_2 | 0 \rangle$ the single term $[A_\mu n_\mu - k_\mu n_\mu] \langle \phi_2 | \phi_2 | 0 \rangle$. We have thus excluded both Goldstone's zero-mass bosons and the "ignorable" state ($k_\mu = 0$) proposed by Klein and Lee.

In a subsequent note it will be shown, by considering some classical field theories which display broken symmetries, that the introduction of gauge fields may be expected to produce qualitative changes in the nature of the particles described by such theories after quantization.

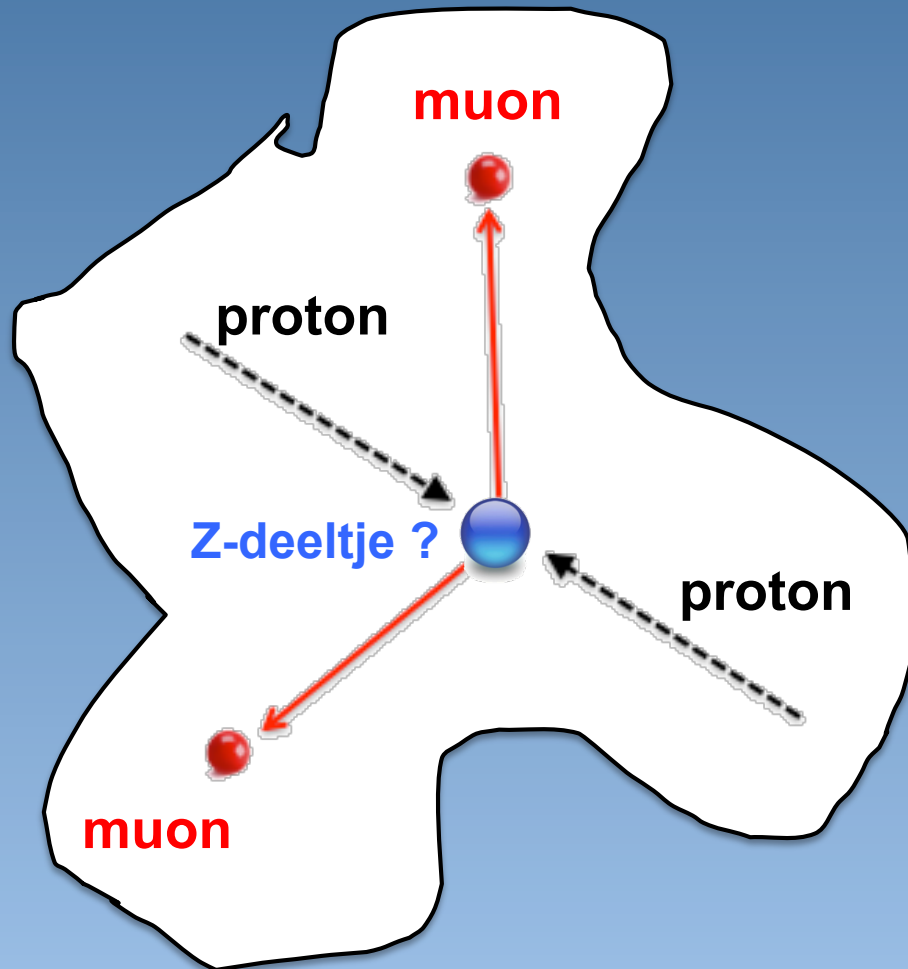
References

1. J. Goldstone, Nuovo Cim. 18 (1962) 184.
2. J. Goldstone, A. Salam and S. Weinberg, Phys. Rev. 127 (1962) 965.
3. A. Klein and B. W. Lee, Phys. Rev. Letters 12 (1964) 180.
4. B. Gilbert, Phys. Rev. Letters 13 (1964) 115.
5. J. Schwinger, Phys. Rev. 127 (1962) 235.

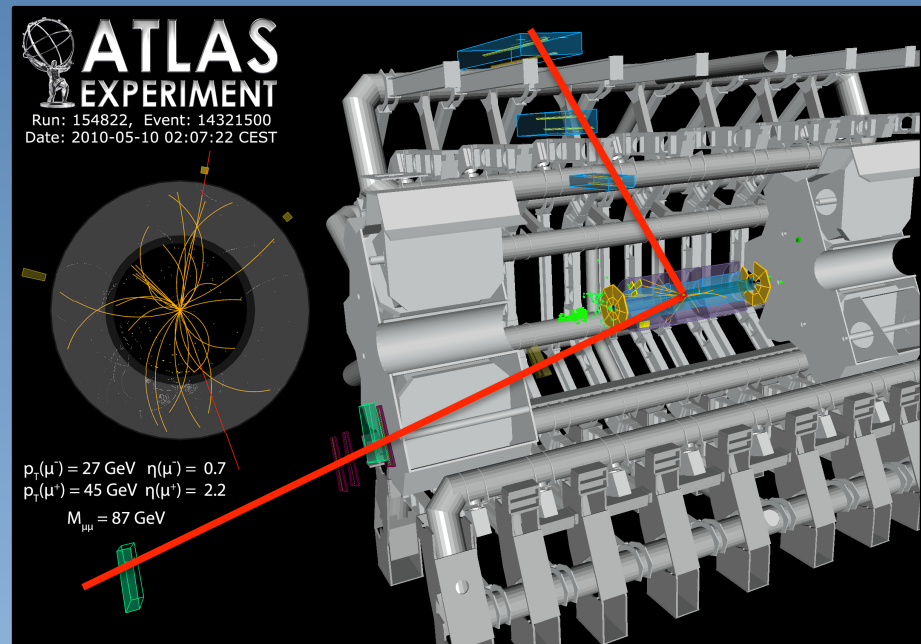
- September 1964 -

Hoe ontdek je het Z-deeltje ?

Afwijkingen van voorspelling zonder Z-boson



2-muonen gezien in ATLAS



Wat is de 'vingerafdruk' van het Z-deeltje:
→ de massa van het 2-muon systeem

2-muon massa

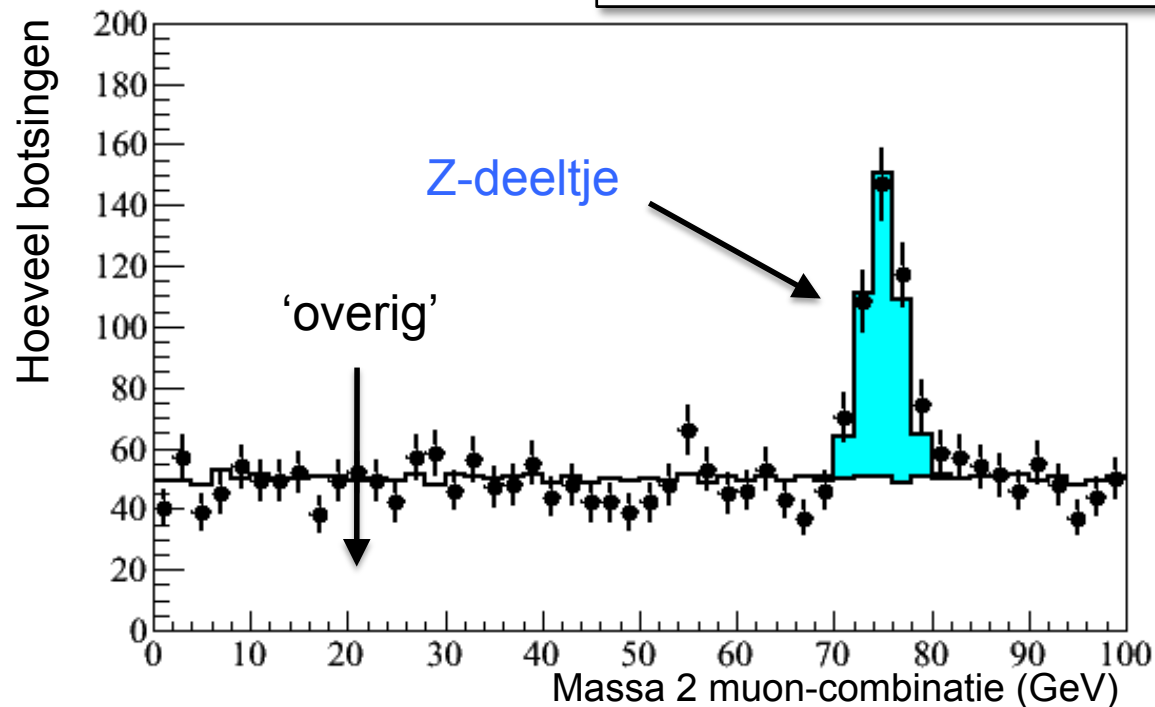


'overig': geen voorkeur, vlak

Z-deeltje: $E = mc^2$ bijna altijd dezelfde waarde
(massa van het Z-deeltje)

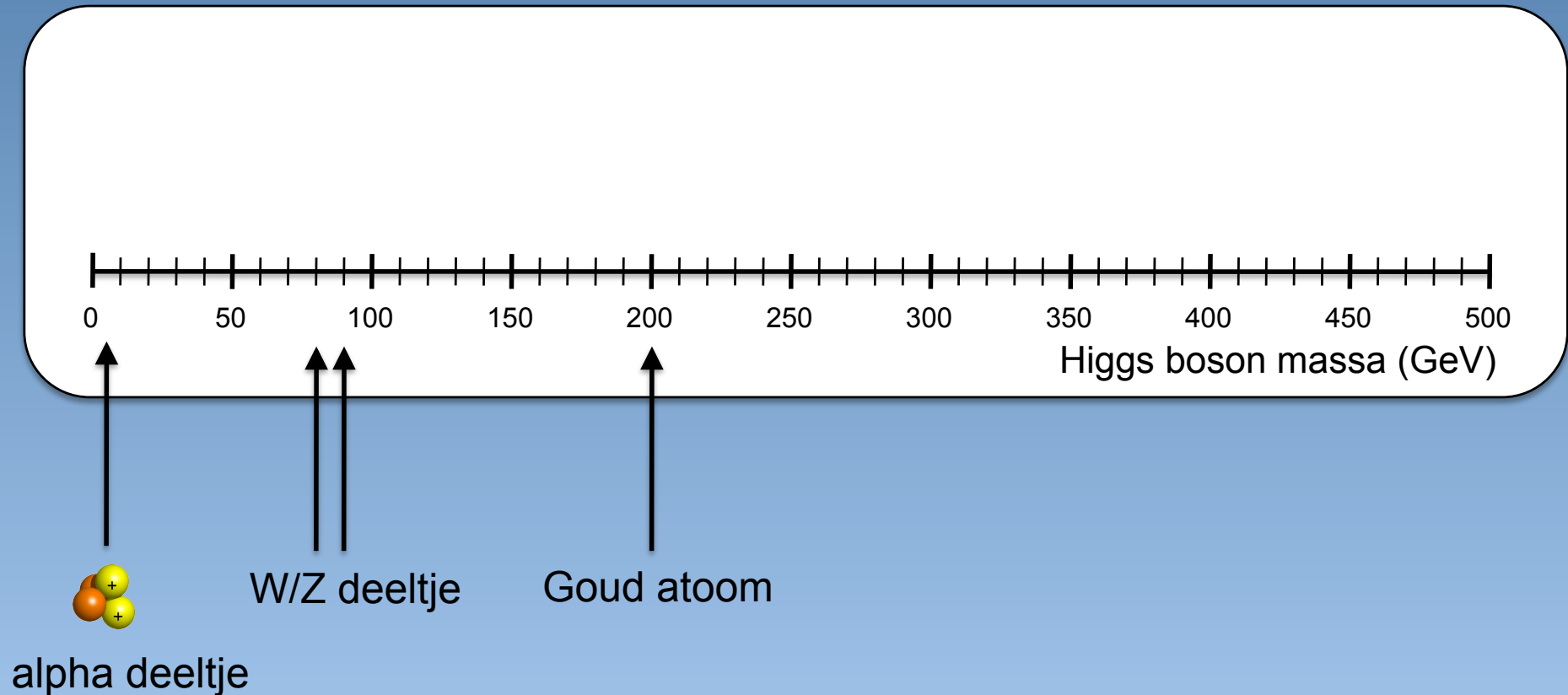


Massa 2 muon-combinatie



De massa van het Higgs boson

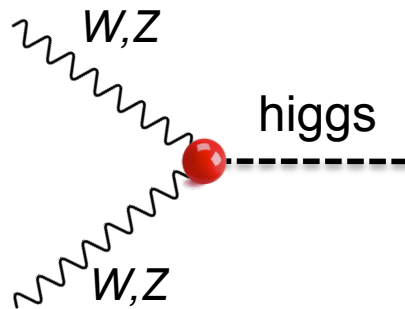
1 GeV $\rightarrow$ massa proton = massa Waterstof atoom



Hoe maak je een Higgs deeltje ?

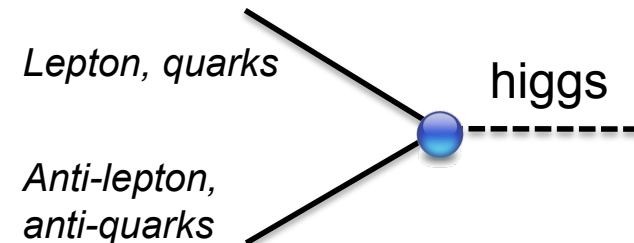
Krachtdeeltjes

*Massief krachtdeeltje ?
...dan koppelt het aan de Higgs!*



Bouwstenen

*Massief deeltje ?
... dan koppelt het aan de Higgs!*



Higgs boson productie

Hoeveel Higgs bosons zijn
er geproduceerd in 2011 ?



Als hij niet bestaat:

0

‘gewoon’ even uitrekenen

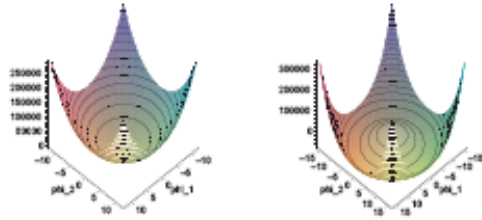


FIG. 1: The potential $V(\phi)$ ($\phi = \phi_1 + i\phi_2$) plotted for an arbitrary positive value of λ and for an arbitrary positive (right) or negative (left) value of μ^2 .

broken, and new interesting features emerge. To be more specific, let's pick the following ϕ_0 minimum (along the direction of the real part of ϕ , as traditional) and shift the ϕ field accordingly:

$$\phi_0 = \left(-\frac{\mu^2}{2\lambda}\right)^{1/2} = \frac{v}{\sqrt{2}} \rightarrow \phi(x) = \phi_0 + \frac{1}{\sqrt{2}}(\phi_1(x) + i\phi_2(x)) . \quad (5)$$

The Lagrangian in Eq. (3) can then be rearranged as follows:

$$\mathcal{L} = \underbrace{-\frac{1}{4}F^{\mu\nu}F_{\mu\nu}}_{\text{massive vector field}} + \underbrace{\frac{1}{2}g^2v^2A^\mu A_\mu + \frac{1}{2}(\partial^\mu\phi_1)^2 + \mu^2\phi_1^2 + \frac{1}{2}(\partial^\mu\phi_2)^2}_{\text{massive scalar field}} + \underbrace{gvA_\mu\partial^\mu\phi_2}_{\text{Goldstone boson}} + \dots \quad (6)$$

and now contains the correct terms to describe a massive vector field A^μ with mass $m_A^2 = g^2v^2$ (originating from the kinetic term of $\mathcal{L}_\phi$), a massive real scalar field ϕ_1 with mass $m_{\phi_1} = -2\mu^2$, that will become a *Higgs boson*, and a massless scalar field ϕ_2 , a so called *Goldstone boson* which couples to the gauge vector boson A^μ . The terms omitted contain couplings between the ϕ_1 and ϕ_2 fields irrelevant to this discussion. The gauge symmetry of the theory allows us to make the particle content more transparent. Indeed, if we parameterize the complex scalar field ϕ as:

$$\phi(x) = \frac{e^{i\chi(x)}}{\sqrt{2}}(v + H(x)) \xrightarrow{U(1)} \frac{1}{\sqrt{2}}(v + H(x)) , \quad (7)$$

the χ degree of freedom can be *rotated away*, as indicated in Eq. (7), by enforcing the $U(1)$ gauge invariance of the original Lagrangian. With this gauge choice, known as *unitary gauge* or *unitarity gauge*, the Lagrangian becomes:

$$\mathcal{L} = \mathcal{L}_A + \frac{g^2v^2}{2}A^\mu A_\mu + \frac{1}{2}\left(\partial^\mu H\partial_\mu H + 2\mu^2 H^2\right) + \dots \quad (8)$$

a factor of two, making therefore almost a factor of four at the rate level. All other mass corrections, in the matrix element and phase space entering the calculation of the $H \rightarrow Q\bar{Q}$ decay rate, can in first approximation be safely neglected.

4. Loop induced Higgs boson decays: $H \rightarrow \gamma\gamma, \gamma Z, gg$

At the lowest order the decay rate for $H \rightarrow \gamma\gamma$ can be written

$$\Gamma(H \rightarrow \gamma\gamma) = \frac{G_F \alpha^2 M_H^4}{128\sqrt{2}\pi^3} \left| \sum_f N_f^2 Q_f^2 A_f^H(\tau_f) + A_W^H(\tau_W) \right|^2 , \quad (102)$$

where $f = l, q$ respectively), Q_f is the charge of the f fermion species, and A_f^H is defined as:

$$f(\tau) = \begin{cases} \arcsin^2 \frac{1}{\sqrt{\tau}} & \tau \geq 1 \\ -\frac{1}{4} \left[\ln \frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi \right]^2 & \tau < 1 \end{cases} , \quad (103)$$

and A_W^H are given by:

$$A_f^H = 2\tau[1 + (1-\tau)f(\tau)] , \quad (104)$$

$$A_W^H(\tau) = -[2 + 3\tau + 3\tau(2-\tau)f(\tau)] .$$

The decay rate for $H \rightarrow \gamma Z$ is given by:

$$\Gamma(H \rightarrow \gamma Z) = \frac{M_H^2 \alpha M_Z^2}{64\pi^4} \left(1 - \frac{M_Z^2}{M_H^2}\right)^2 \left| \sum_f A_f^H(\tau_f, \lambda_f) + A_W^H(\tau_W, \lambda_W) \right|^2 , \quad (105)$$

and $\lambda_i = 4M_i^2/M_Z^2$ ($i = f, W$), and the form factors $A_f^H(\tau, \lambda)$ and

$$= 2N_f^2 \frac{Q_f(I_1 I_2 - 2Q_f \sin^2 \theta_W)}{\cos \theta_W} [I_1(\tau, \lambda) - I_2(\tau, \lambda)] , \quad (106)$$

$$= \cos \theta_W \left\{ \left[\left(1 + \frac{2}{\tau}\right) \tan^2 \theta_W - \left(5 + \frac{2}{\tau}\right) \right] I_1(\tau, \lambda) + 4(3 - \tan^2 \theta_W) I_2(\tau, \lambda) \right\} , \quad (107)$$

defined after Eq. (102), and I_2^f is the weak isospin of the f fermion

$$\frac{\tau\lambda}{(\tau-\lambda)} + \frac{\tau^2\lambda^2}{2(\tau-\lambda)^2}[f(\tau) - f(\lambda)] + \frac{\tau^2\lambda}{(\tau-\lambda)^2}[g(\tau) - g(\lambda)] ,$$

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$$\frac{\tau\lambda}{(\tau-\lambda)} + \frac{\tau^2\lambda^2}{2(\tau-\lambda)^2}[f(\tau) - f(\lambda)] + \frac{\tau^2\lambda}{(\tau-\lambda)^2}[g(\tau) - g(\lambda)] ,$$

Hoeveel Higgs bosons zijn
er geproduceerd in 2011 ?



Als hij wel bestaat:

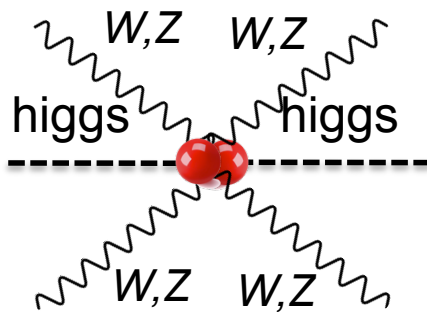
$m_h = 120 \text{ GeV: } 60.000$

$m_h = 200 \text{ GeV: } 30.000$

Hoe kom je weer van een Higgs boson af ?

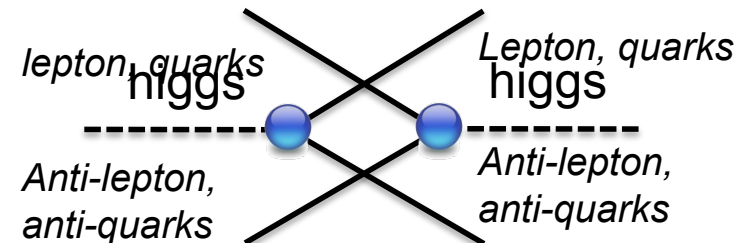
Krachtdeeltjes

*Massief krachtdeeltje ?
...dan koppelt het aan de Higgs!*



Bouwstenen

*Massief deeltje ?
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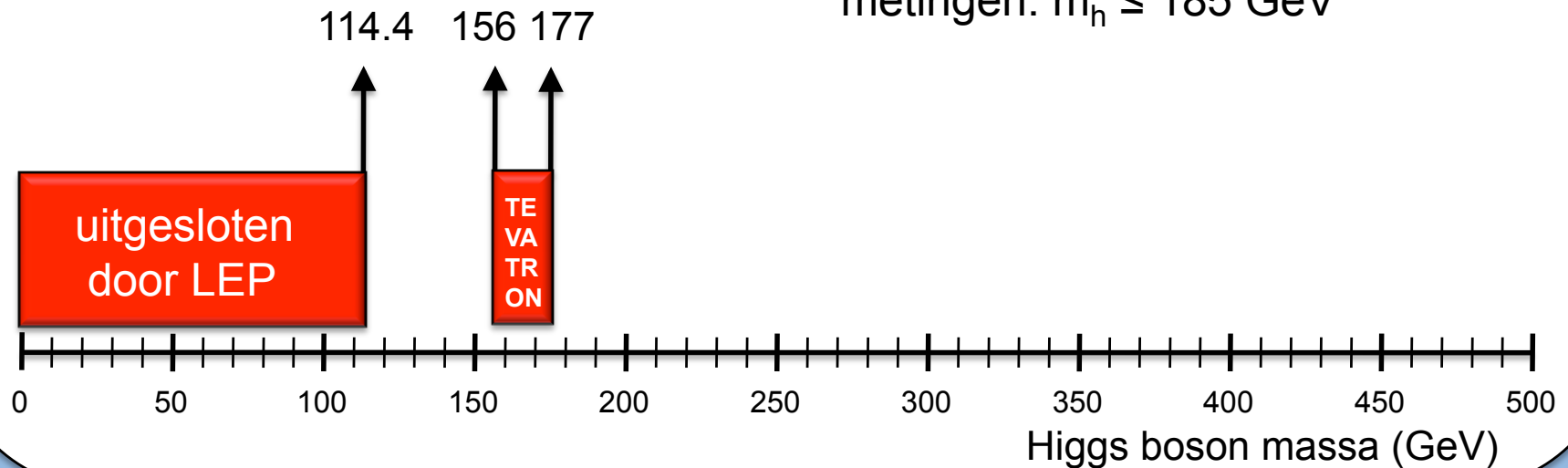
Higgs boson productie

Stand van zaken voorjaar 2011

Indirect:

Theorie: $m_h \leq 600$ GeV

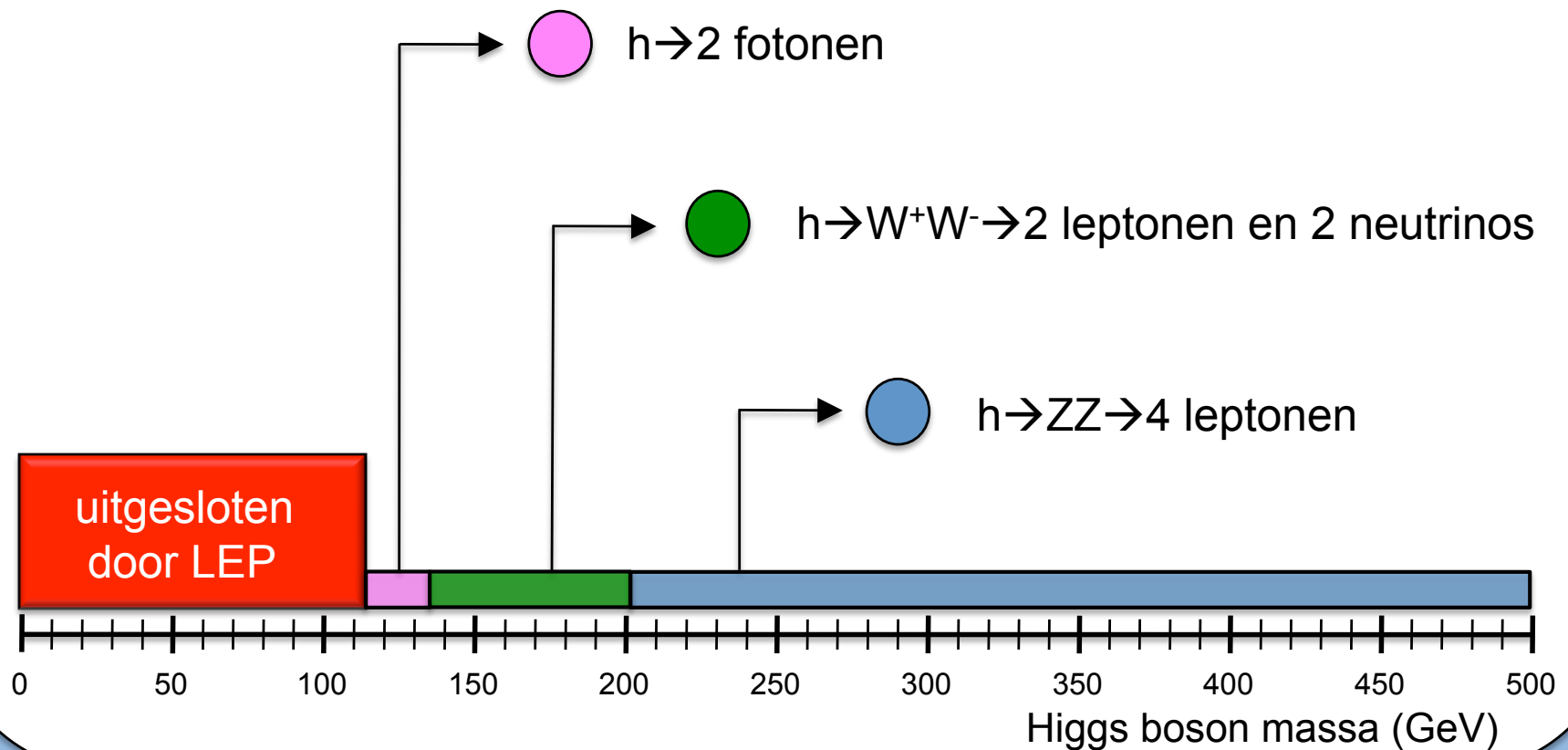
Electrozwakke precisie-
metingen: $m_h \leq 185$ GeV



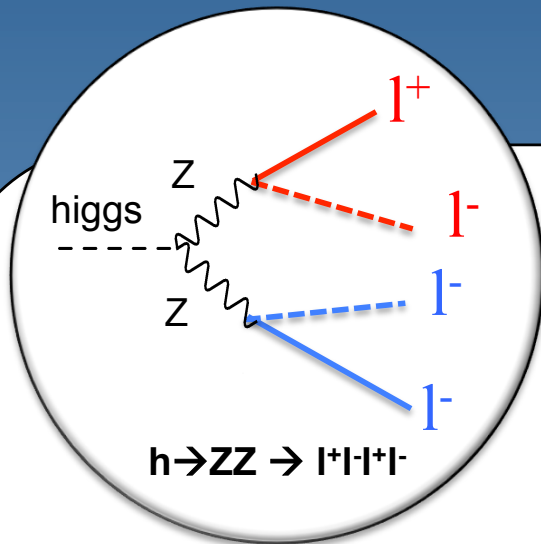
Experimenten bij de LHC gevoelig in het gebied 114-1000 GeV

De duidelijkste vingerafdruk van het Higgs boson

Voor elke massa zijn er meerdere kanalen: dit zijn de belangrijkste



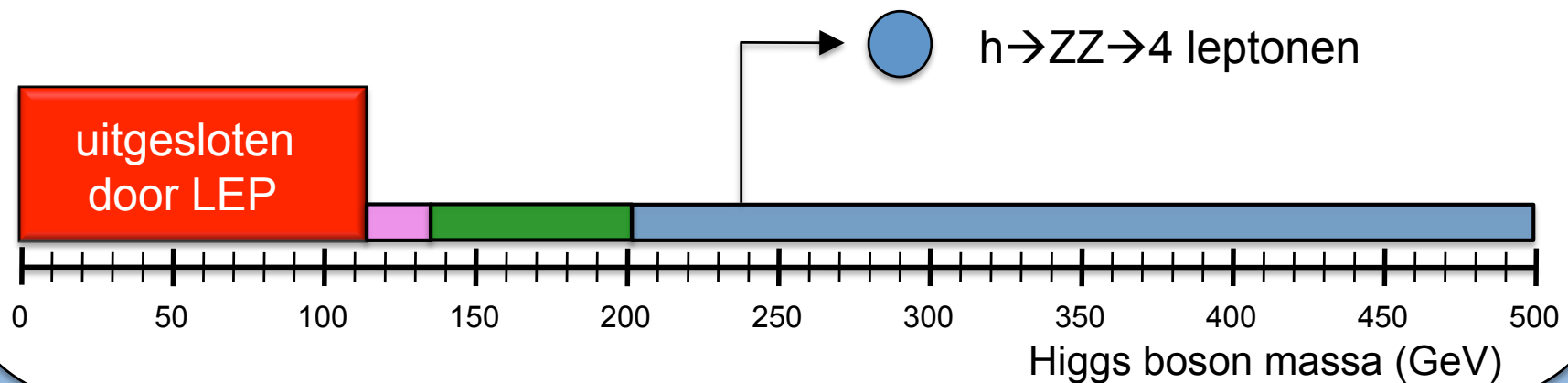
Hoge massa's: $m_H > 200$ GeV

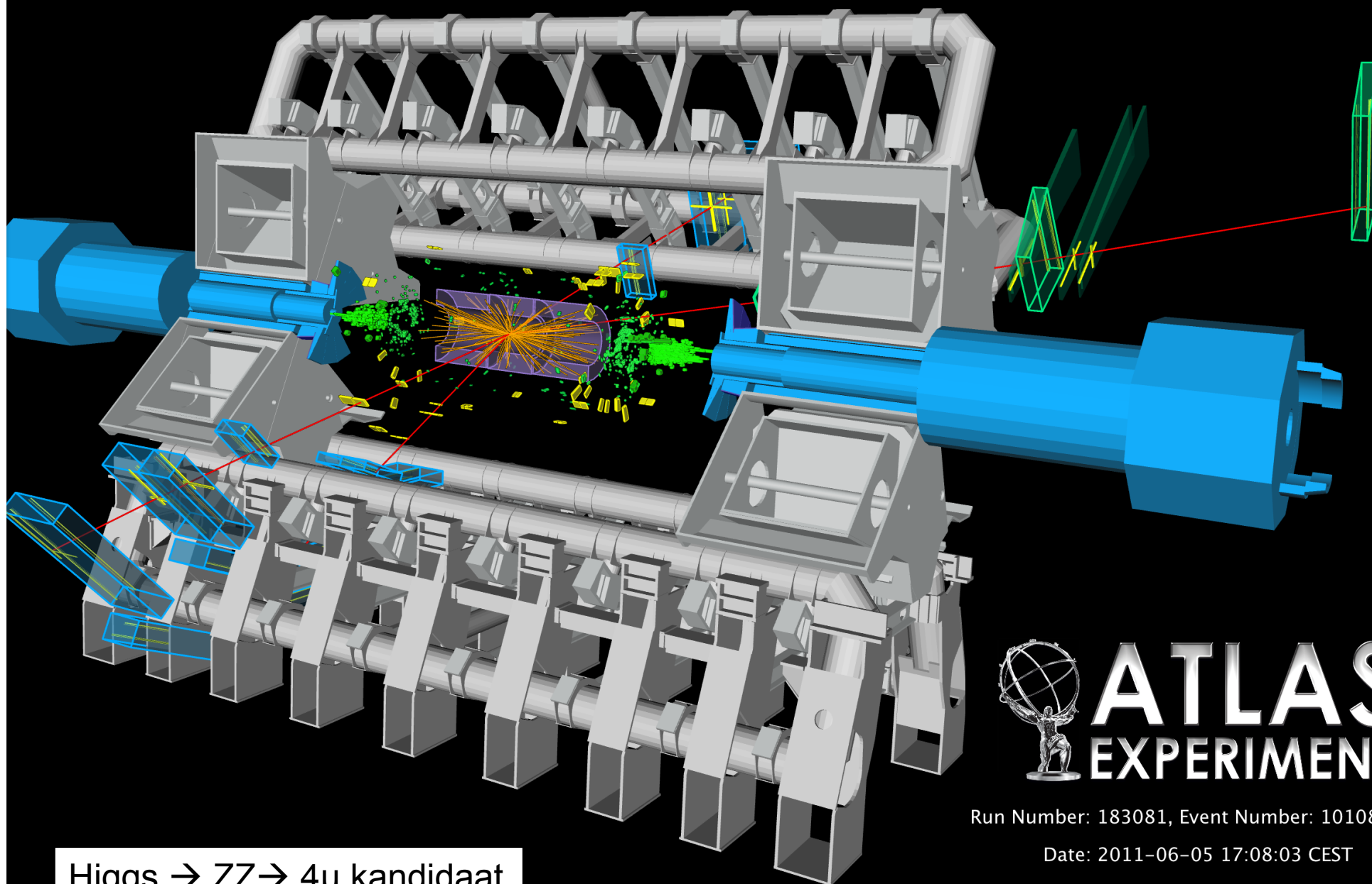


The golden channel

- 4 leptonen (e/ μ)
- Erg zeldzaam: Higgs of ZZ

Vingerafdruk: 4-lepton massa





Higgs $\rightarrow$ ZZ $\rightarrow$ 4 μ kandidaat



ATLAS
EXPERIMENT

Run Number: 183081, Event Number: 10108572

Date: 2011-06-05 17:08:03 CEST

Higgs $\rightarrow$ ZZ $\rightarrow$ 4 leptonen

klein aantal schitterende botsingen

30.000 Higgs bosonen

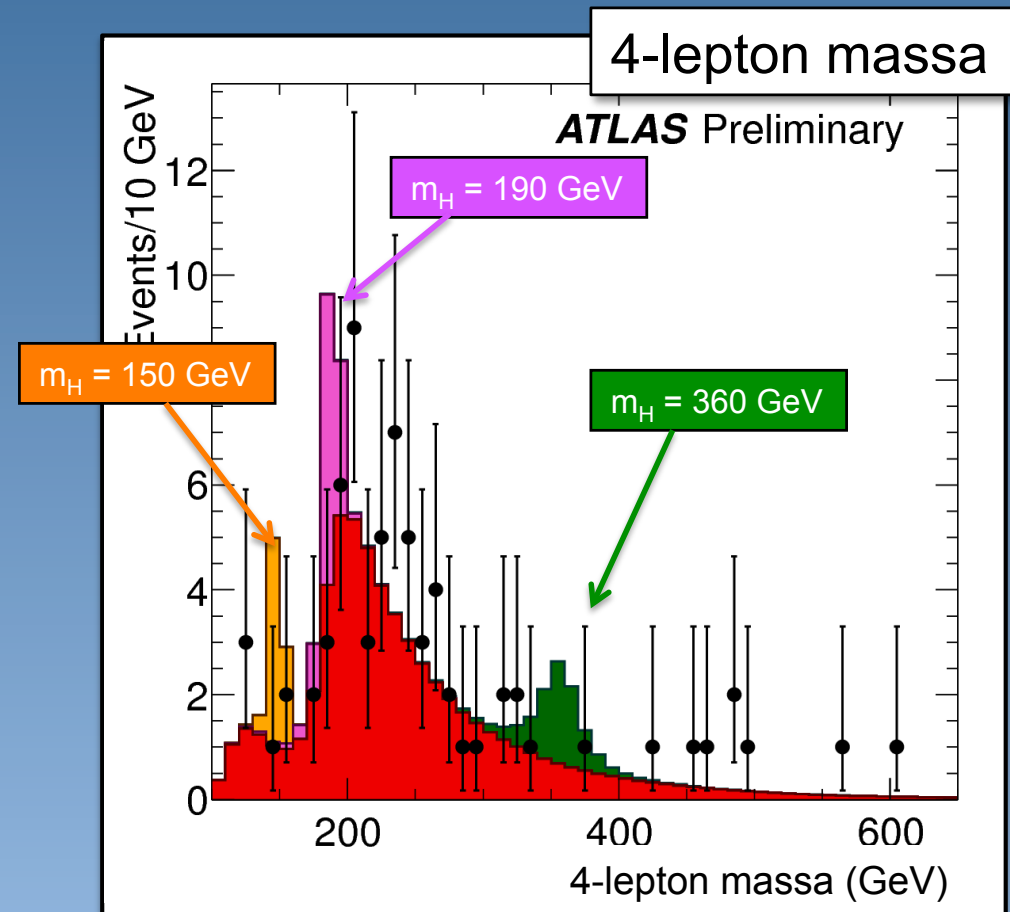


- Maar 1 op de 1000 Higgs bosonen vervalt naar 4 leptonen
- 50% kans dat ATLAS detector ze allemaal goed terugvindt



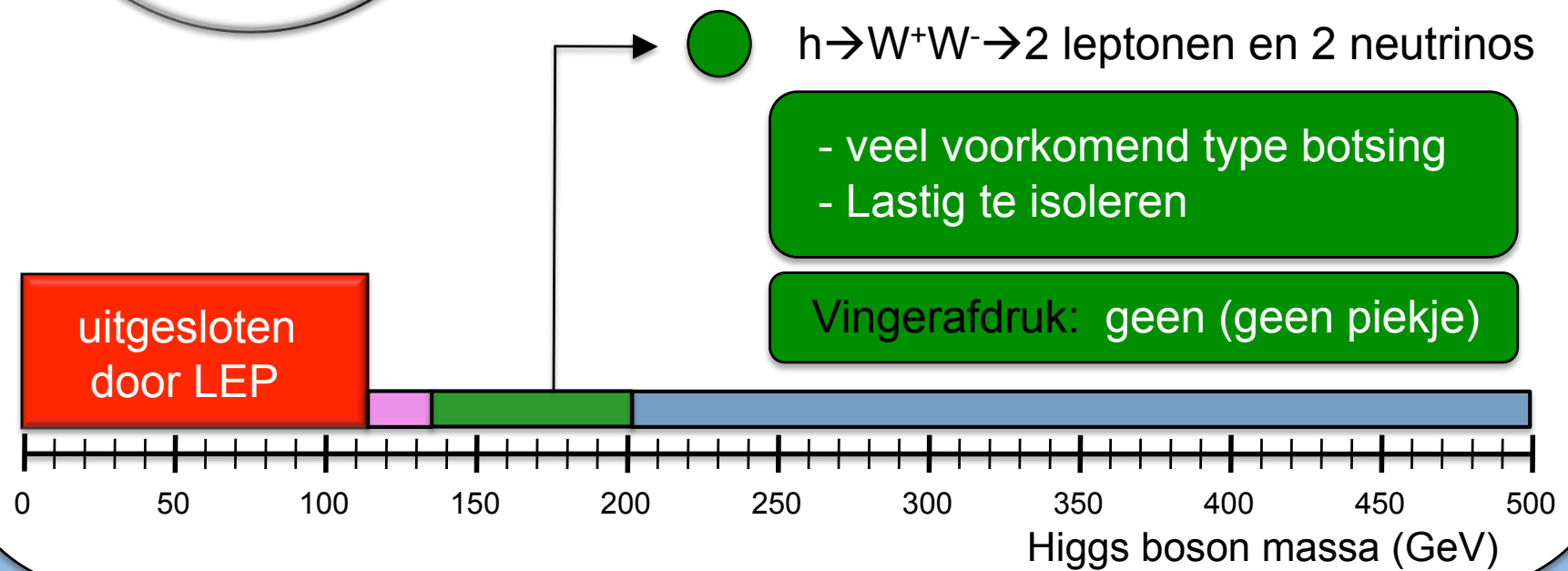
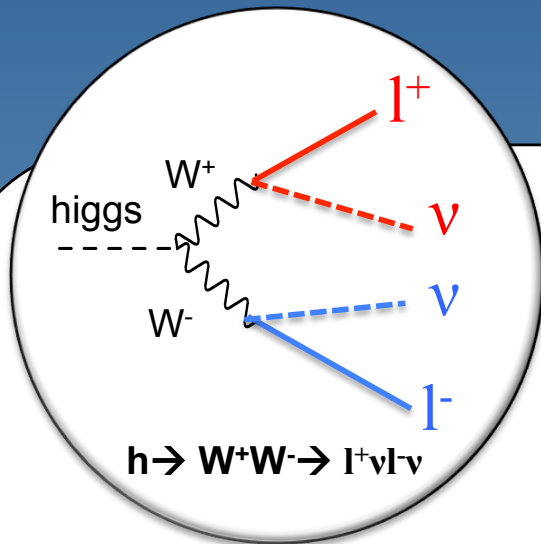
16 Higgs $\rightarrow$ 4 lepton events

'overig'	52 events
Met Higgs	68 events



Geen duidelijk piekje helaas
 $\rightarrow m_h < 200$ GeV

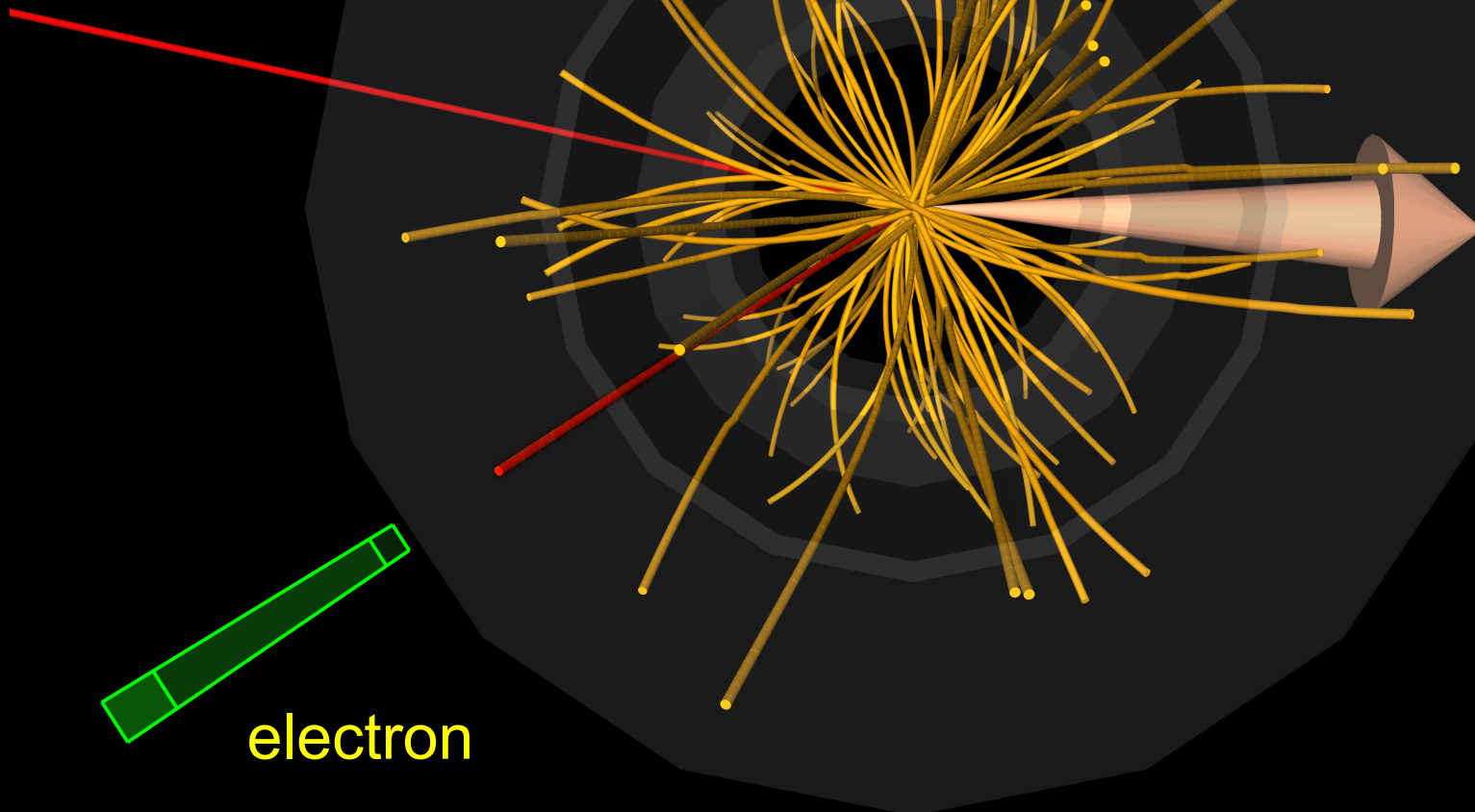
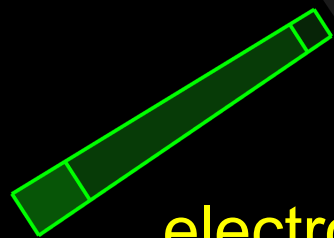
Midden-regio: $130 < m_H < 200$ GeV



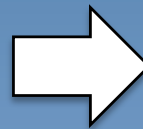
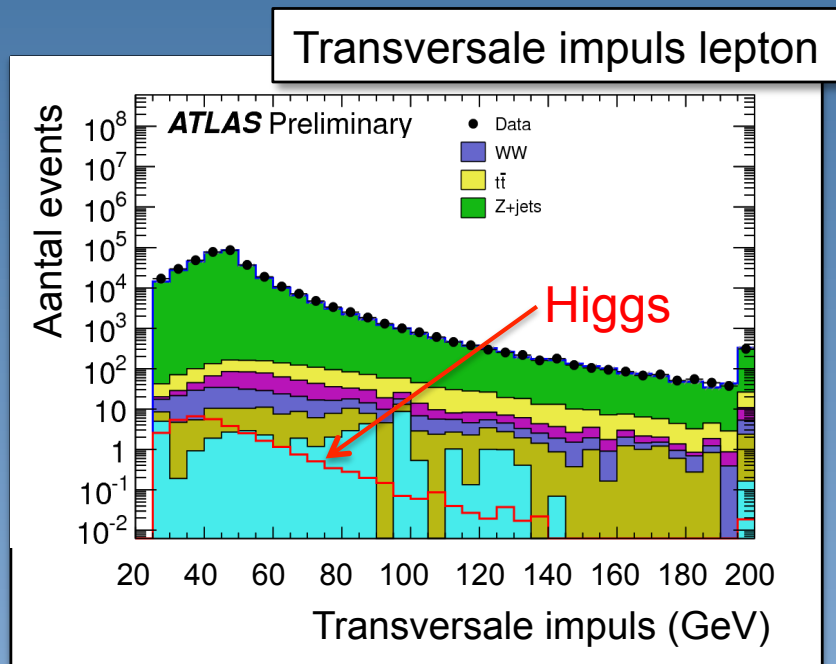
muon

Missende
energie

electron



Het mogelijke Higgs signaal is goed verborgen



Delicate multi-dimensionale selectie:
wegsnijden andere processen met
behoud van (meeste) signaal

signaal < 1/10.000 van het totaal

Diamanten zoeken



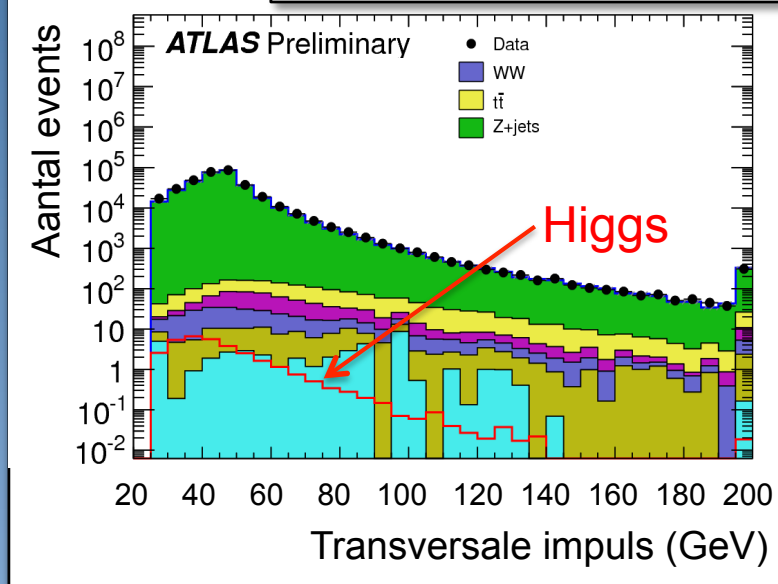
Hard werken ... en slimme nieuwe ideeën zoeken



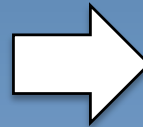
Veel slimme studenten nodig ... hebben we gelukkig ook

Het mogelijke Higgs signaal is goed verborgen

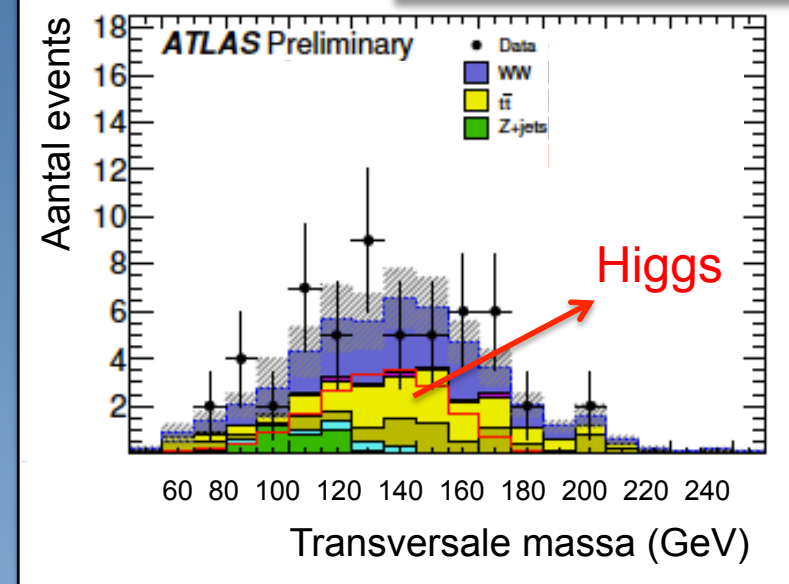
Transversale impuls lepton



signaal = 1/10.000 van het totaal



Transversale massa

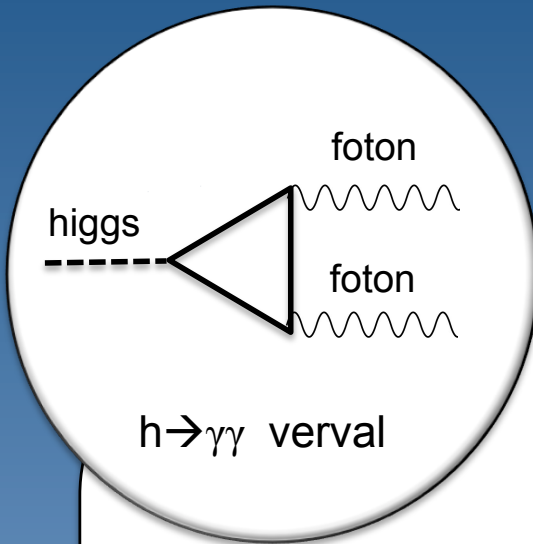


signaal = 1/3 van het totaal

Overig	23
Met Higgs	35

LHC data: **23 (helaas)**

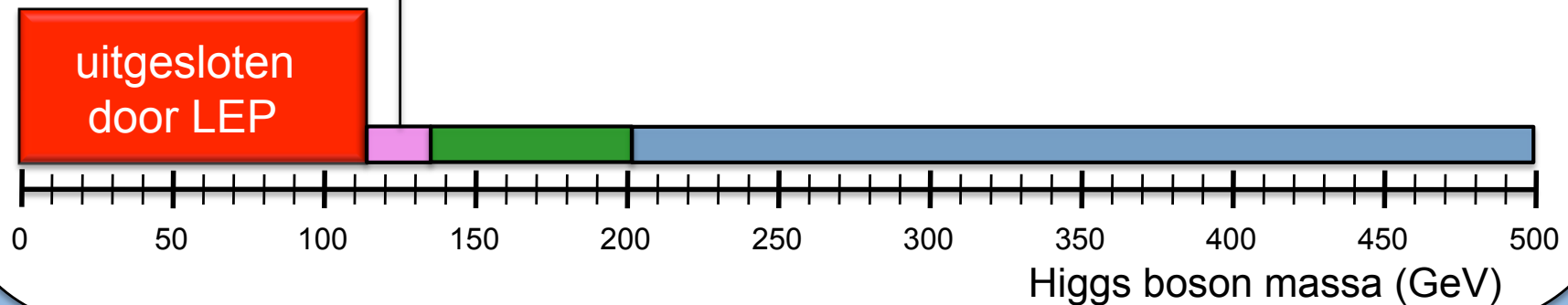
De laagste massa's



 $h \rightarrow 2$ fotonen

- 2 energetische geïsoleerde fotonen
- detector gevoelig voor 'valse' signalen

Vingerafdruk: 2-foton massa



Event-type	Aantal events
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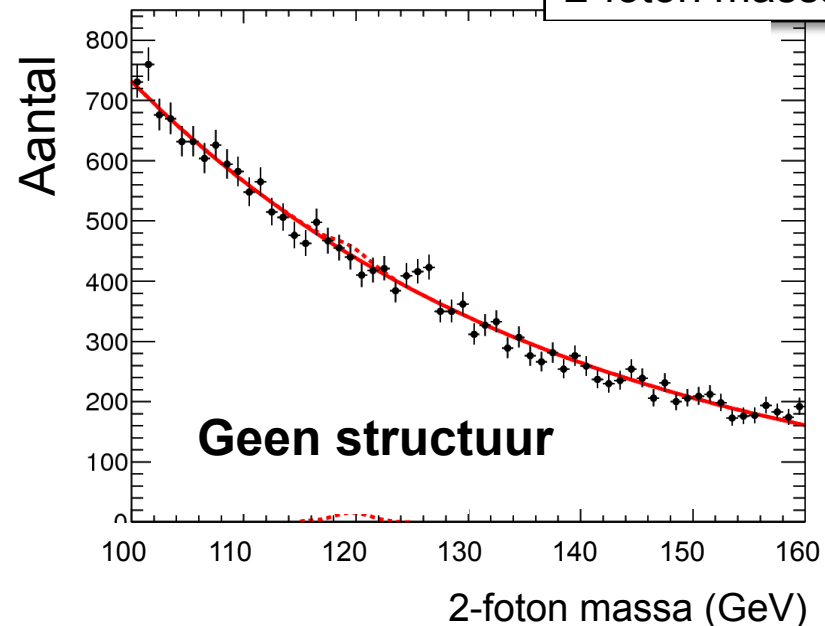
Overig

$\gamma\gamma$	3650	± 100	± 290
γ + jet	1110	± 60	± 270
Di-jet	220	± 20	± 130
Drell-Yan	86	± 1	± 14
'normaal'	5066		

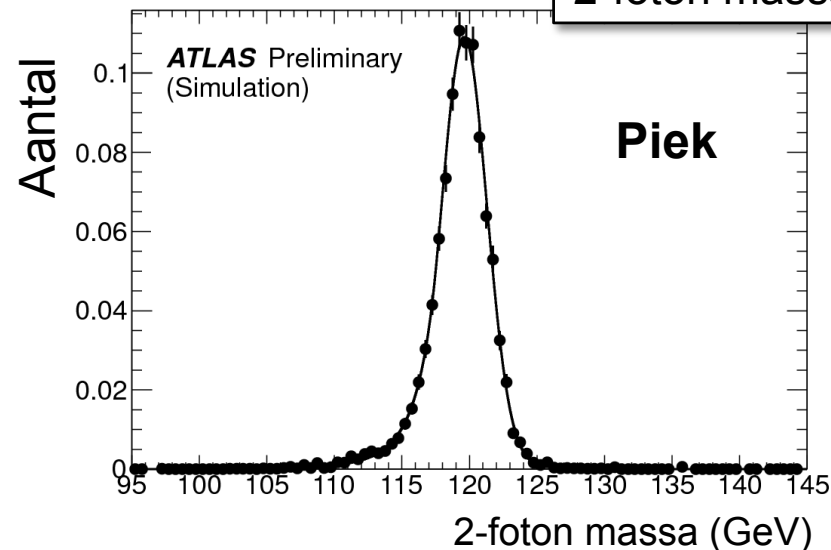
Higgs

Higgs signal	17.6
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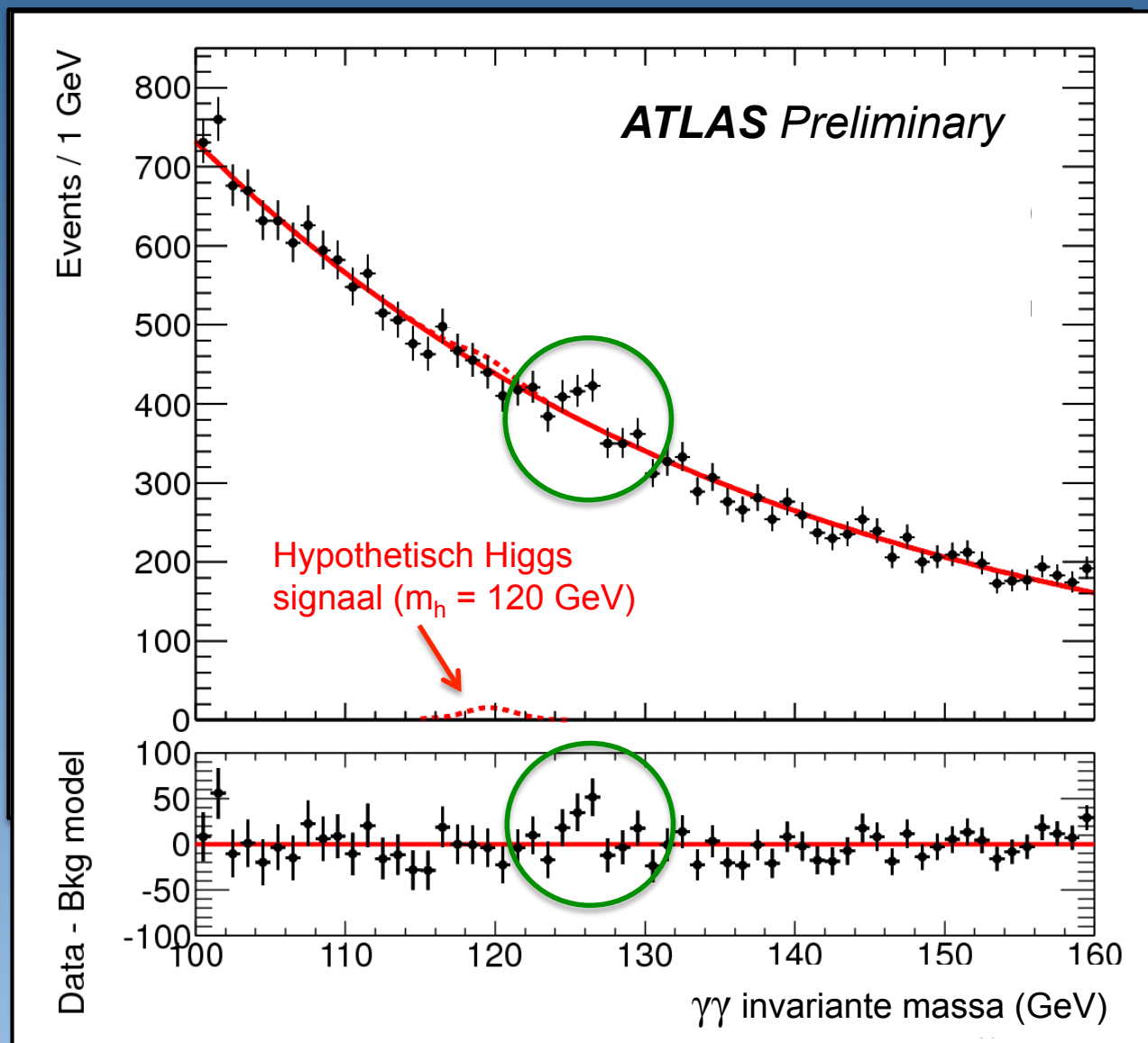
2-foton massa



2-foton massa

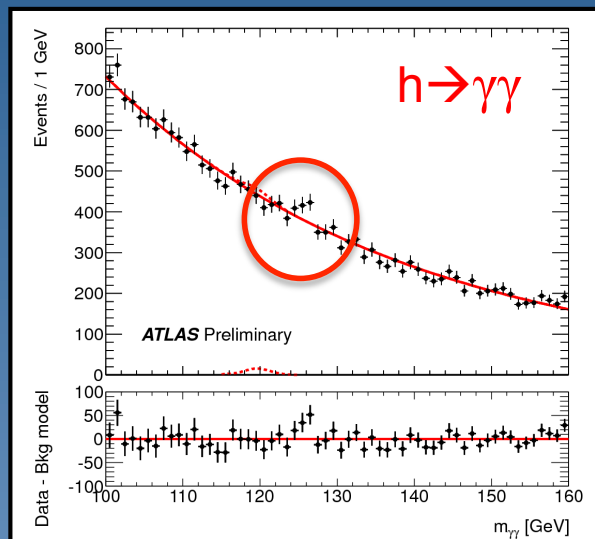


De 'echte' LHC data



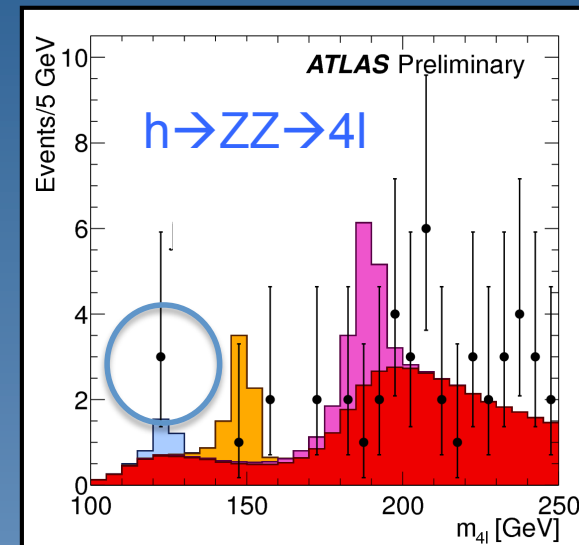
piekje ?

Higgs $\rightarrow$ 2 fotonen

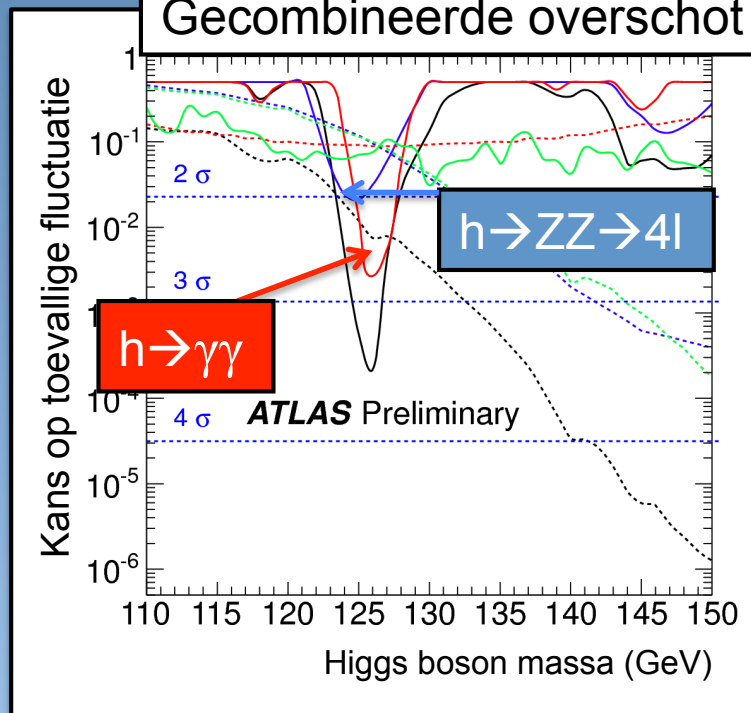


Overschot in twee kanalen zichtbaar

Higgs $\rightarrow$ 4 leptonen



Gecombineerde overschot



Kans $\sim 1/100$ (2.3 σ)

Interpretatie overschot in ATLAS

Kans op toevallige fluctuatie zoals geobserveerd of nog groter: ~ 1 op 100

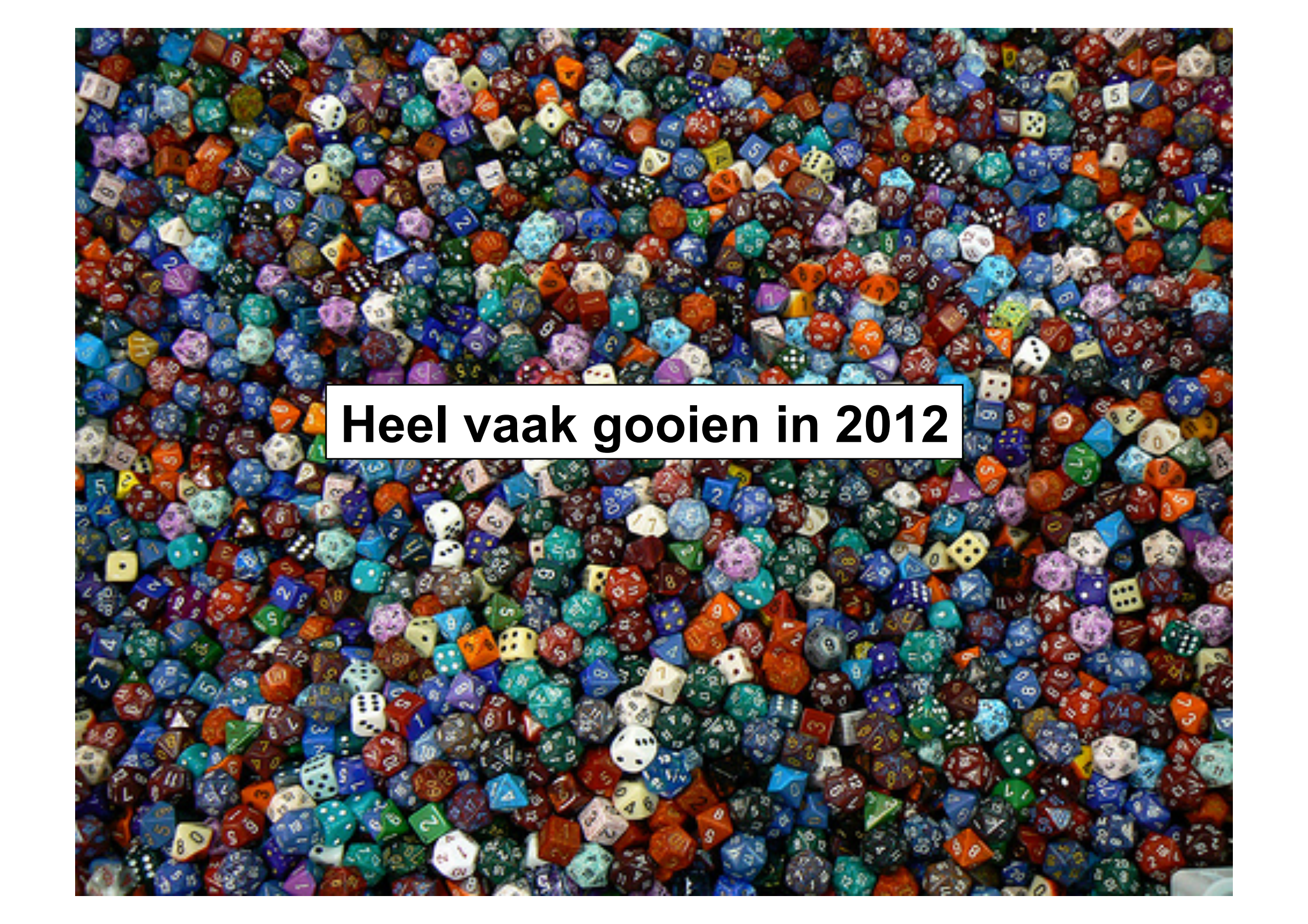
Toeval of valse dobbelsteen ?



Claim pas ontdekking als:

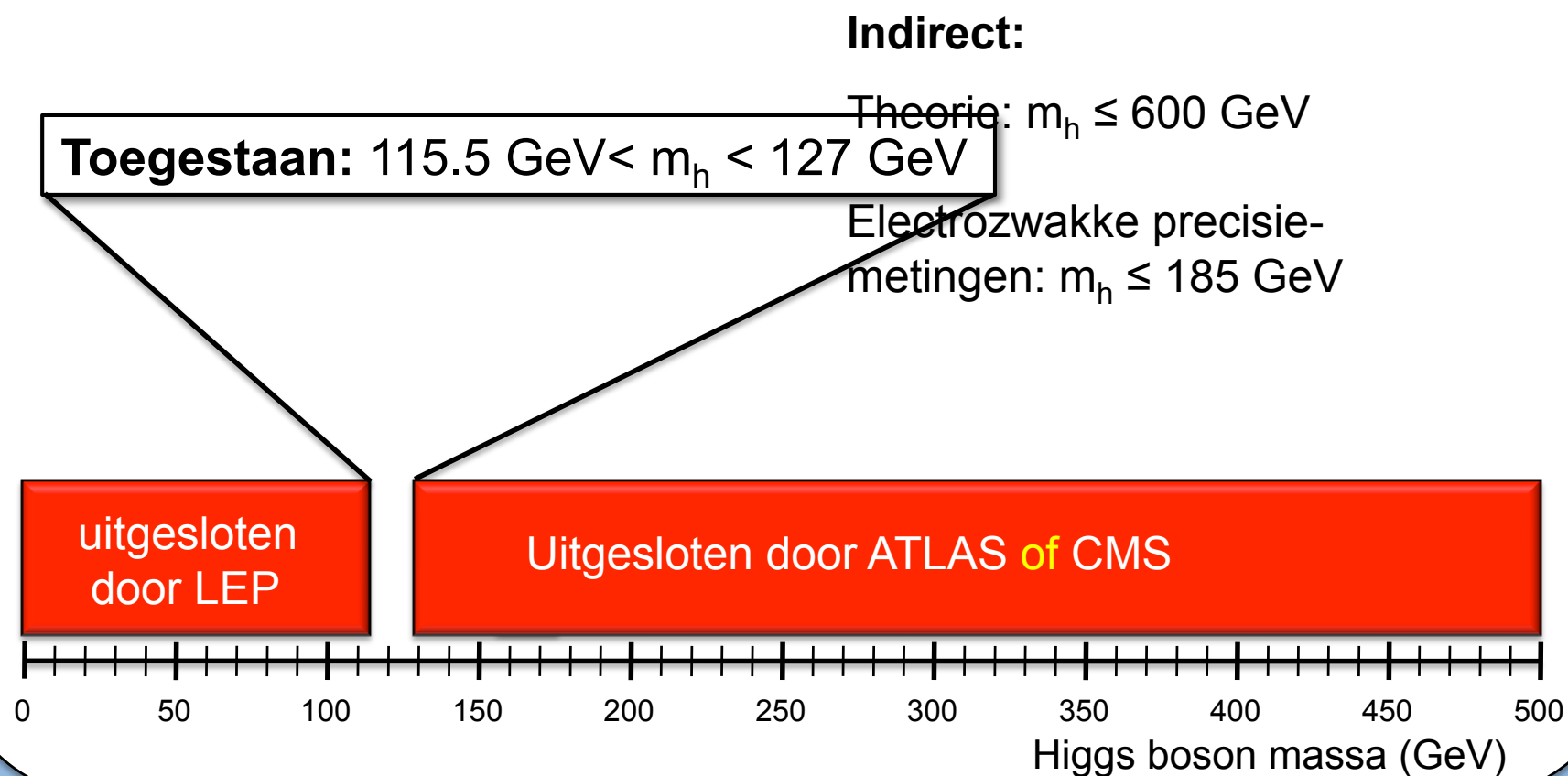
Kans op toevallige fluctuatie zoals geobserveerd kleiner dan 1 op 1,000,000

8 keer 6 gooien achter elkaar



Heel vaak gooien in 2012

Stand van zaken 11 januari 2012



... misschien hebben we hem al gezien

Samenvatting

0) Large Hadron Collider en experimenten werken fan-tas-tisch!

1) Zoektocht de Higgs in 2011

Groot massa-gebied uitgesloten

Overschot bij lage massa (~ 125 GeV) $\rightarrow$ nog geen ontdekking

2) Zoektocht de Higgs in 2012

Als het Higgs boson bestaat zullen het CMS en ATLAS experiment hem (samen) ontdekken

backup

IN HET KADER VAN OPENHEID

ATLAS experiment

ATLAS Higgs resultaten:

<http://www.atlas.ch/news/2011/status-report-dec-2011.html>

Alle ATLAS resultaten: publicaties en plaatjes

<https://twiki.cern.ch/twiki/bin/view/AtlasPublic>

CMS experiment

Higgs resultaten:

<http://cms.web.cern.ch/news/cms-search-standard-model-higgs-boson-lhc-data-2010-and-2011>