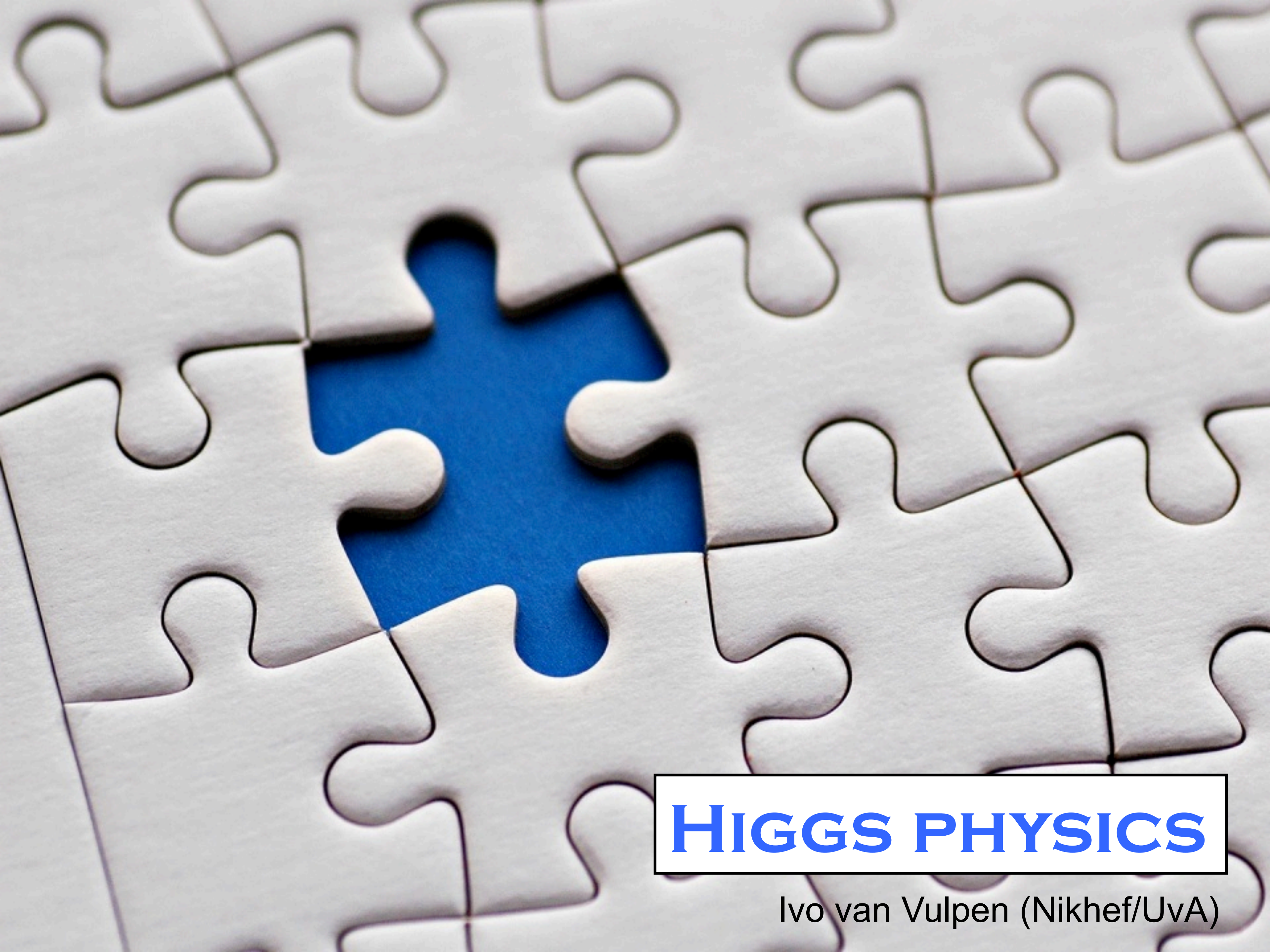
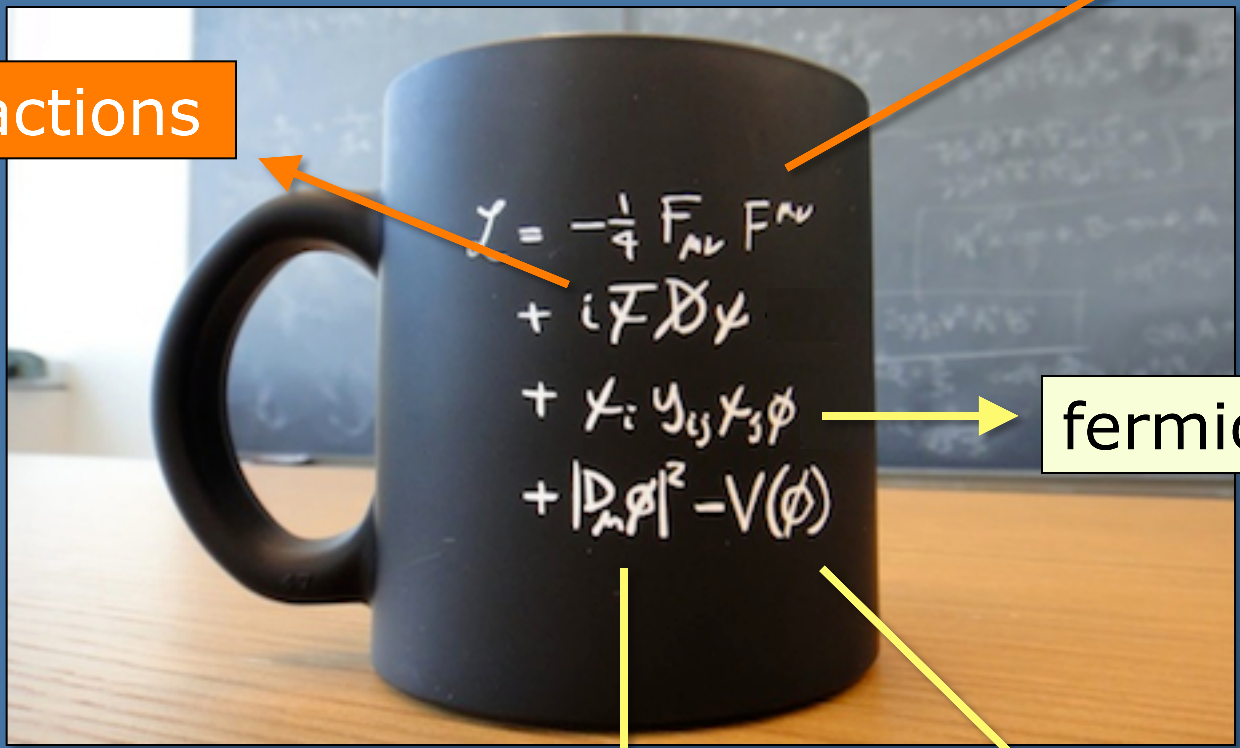


Higgs physics

Ivo van Vulpen (Nikhef/UvA)

Structure of the Standard Model



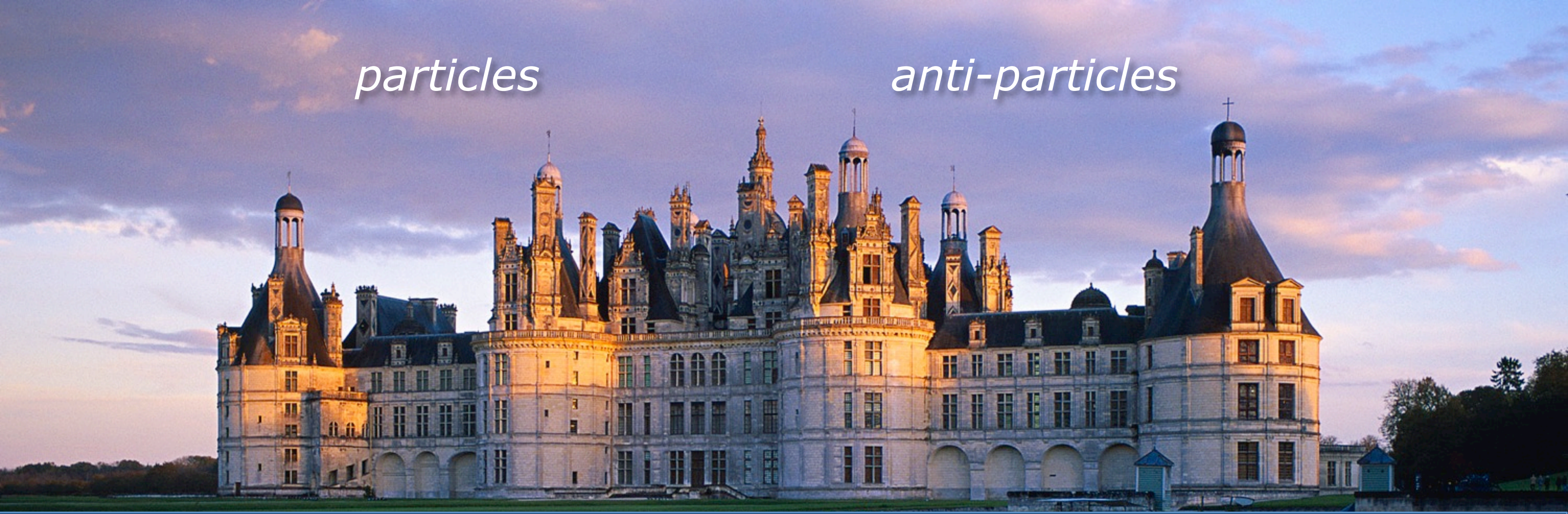
force carriers

interactions

fermion masses

gauge boson masses

Higgs boson



$$-m\bar{\psi}\psi$$

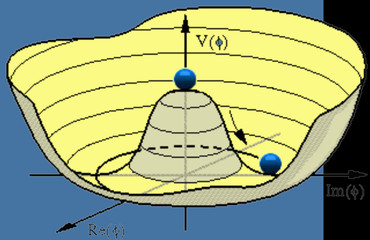
Mass term fermion

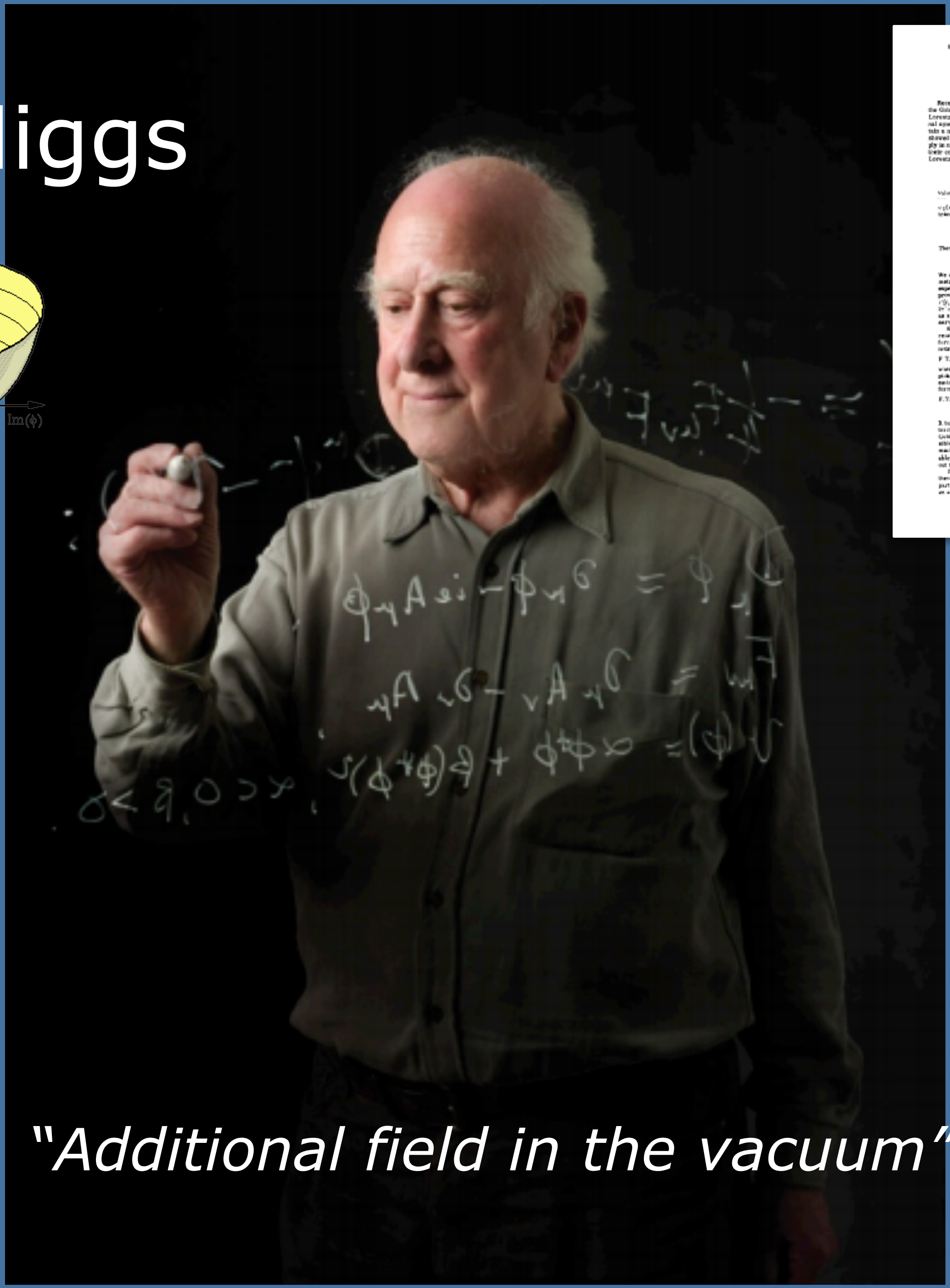
$$-\frac{1}{2}m_V^2 V^2$$

Mass term gauge boson

Standard Model does ***not*** allow for massive gauge bosons or fermions

Peter Higgs






BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS

1964, 1 page

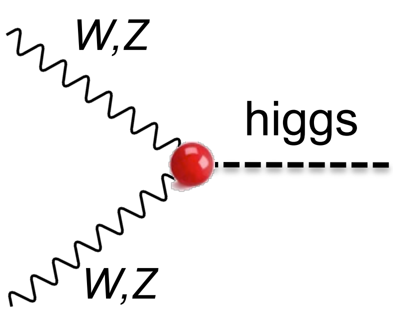
"Additional field in the vacuum"

Higgs production & decay at the LHC

Production of the Higgs boson

Gauge bosons

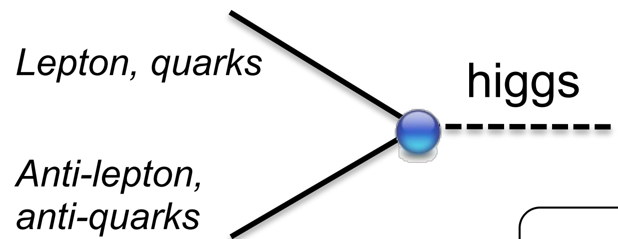
Massive gauge boson ?
… then the Higgs couples to it



$$\propto m_V^2$$

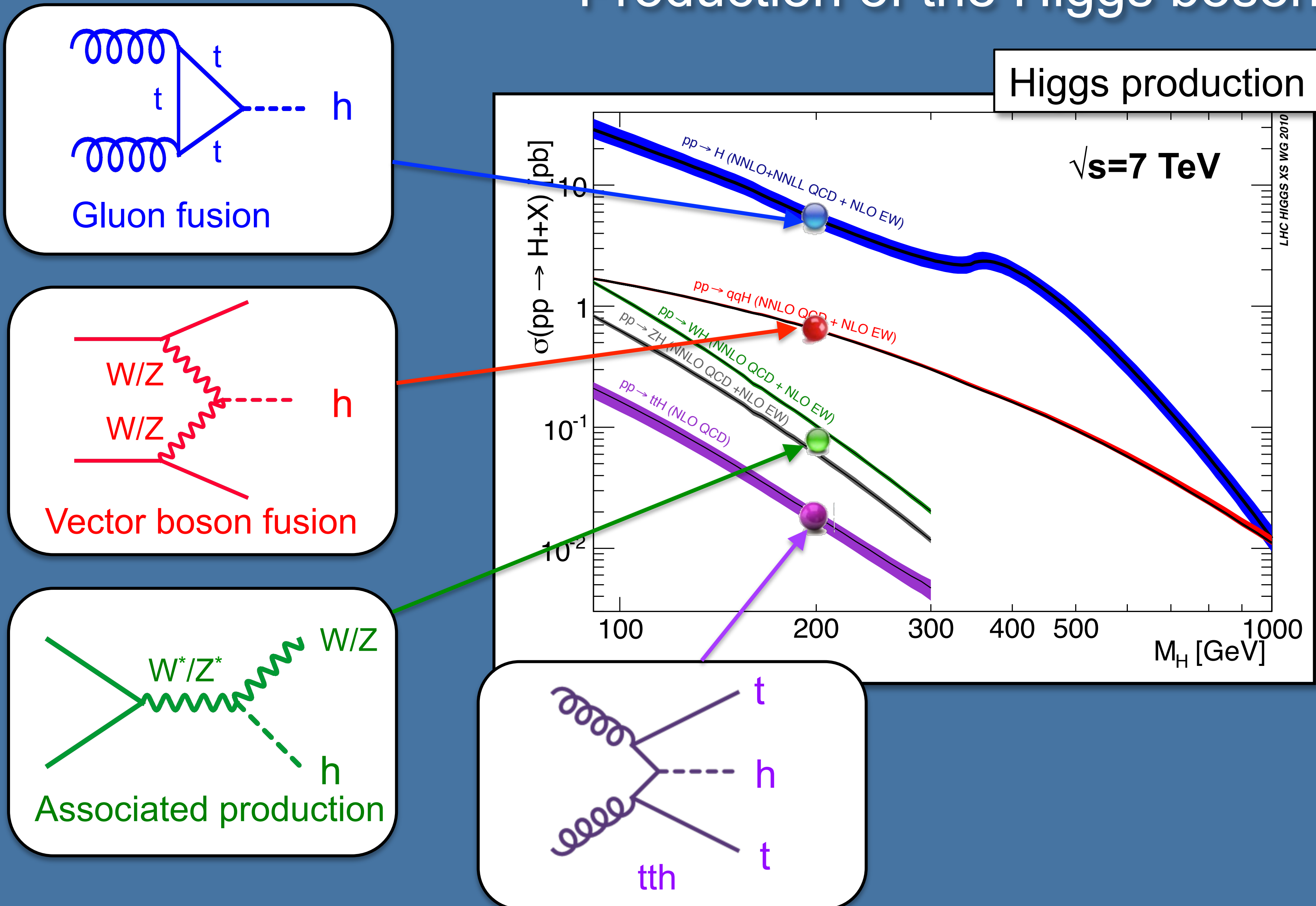
Fermions

Massive fermion ?
… then the Higgs couples to it



$$\propto m_f^2$$

Production of the Higgs boson

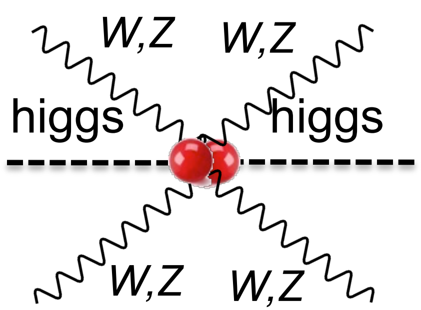


https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageBR3

Decay of the Higgs boson

Gauge boson

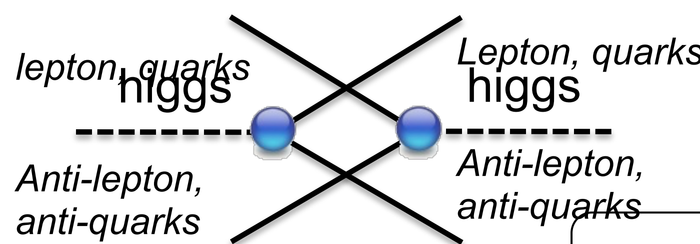
Massive gauge boson ?
… then the Higgs couples to it



$\propto m_V^2$

Fermion

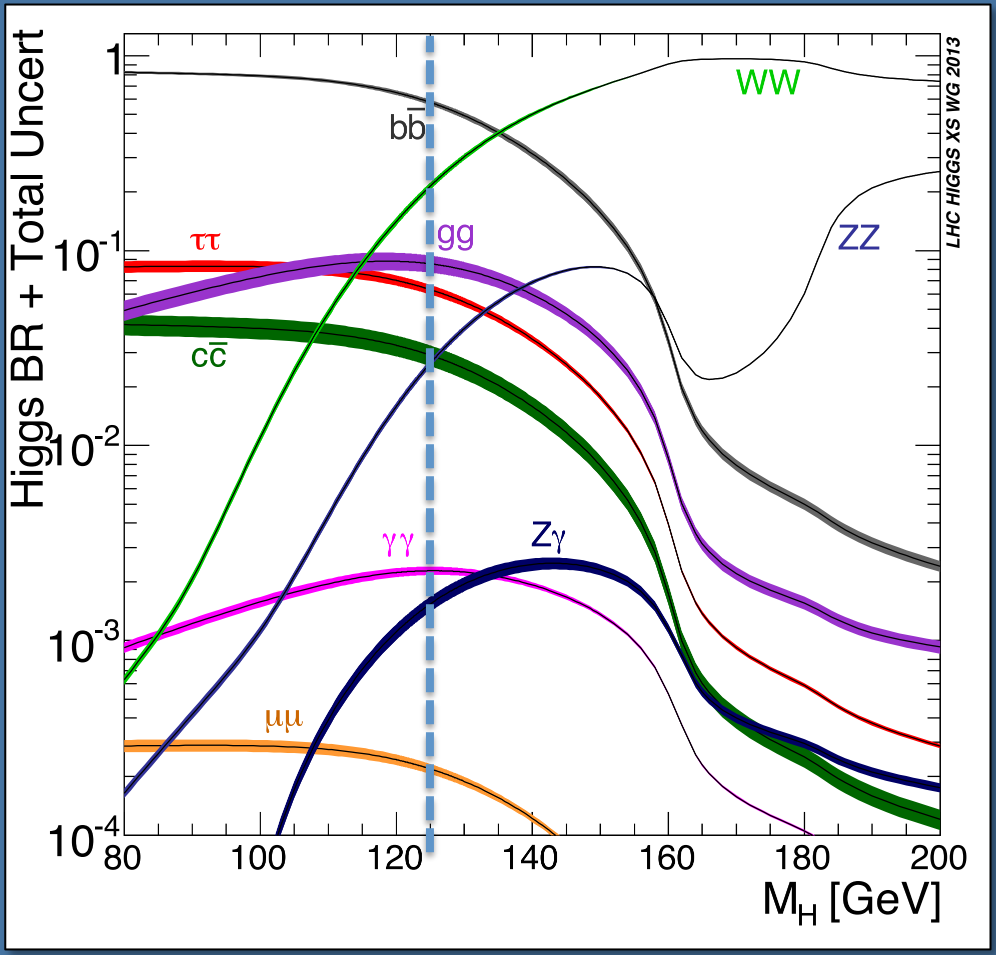
Massive fermion ?
… then the Higgs couples to it



$\propto m_f^2$

Higgs boson production
Higgs boson decay

Higgs branching fractions



m_h = 125 GeV

$Br(h \rightarrow bb)$ = 57.7 %

$Br(h \rightarrow WW)$ = 21.5 %

$Br(h \rightarrow \tau\tau)$ = 6.32 %

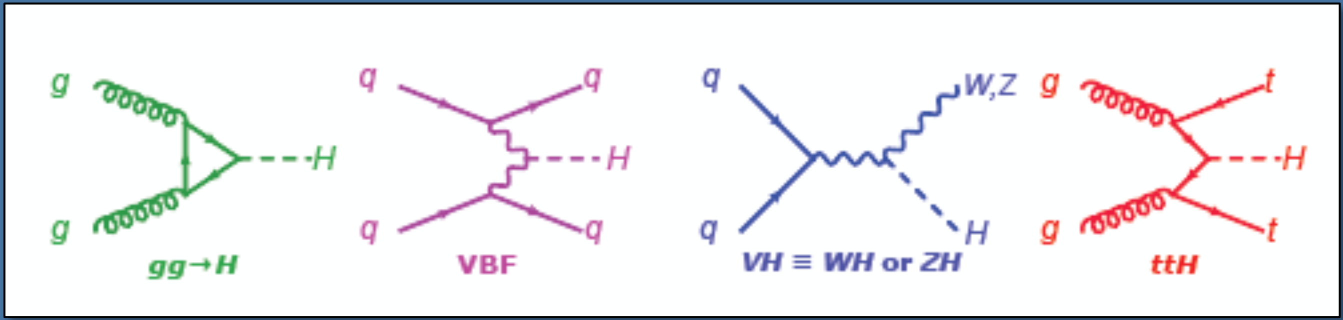
$Br(h \rightarrow ZZ)$ = 2.64 %

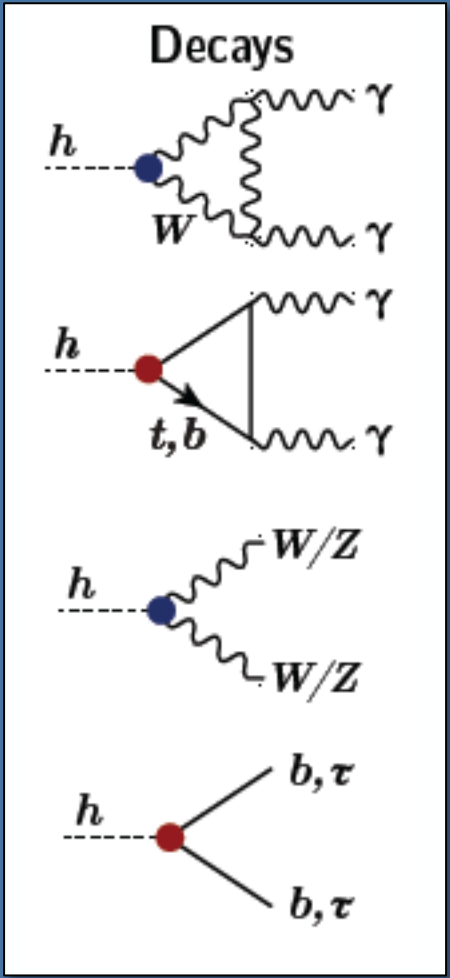
$Br(h \rightarrow \gamma\gamma)$ = 0.23 %

$Br(h \rightarrow Z\gamma)$ = 0.15 %

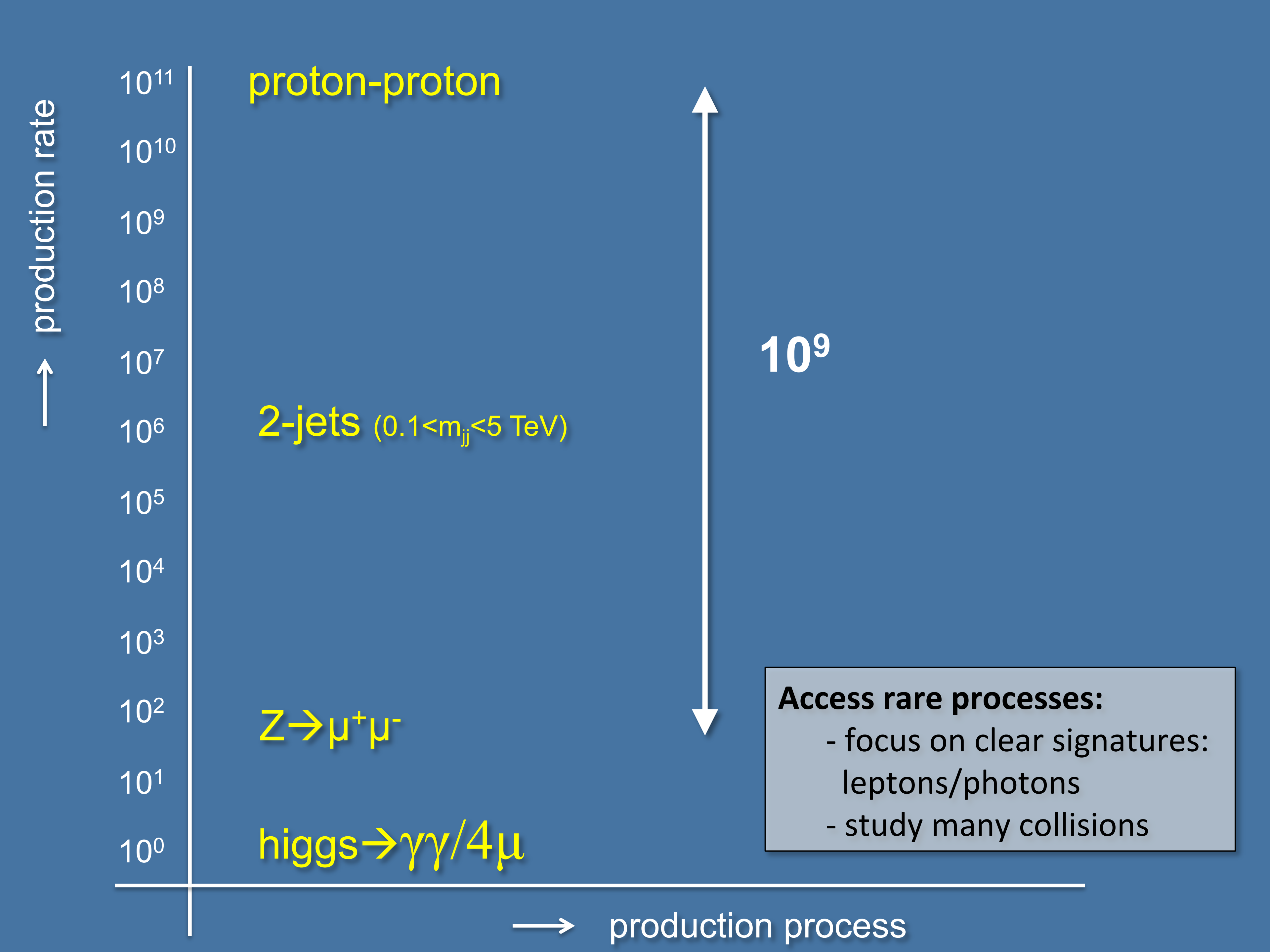
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageBR3

Higgs production and decay

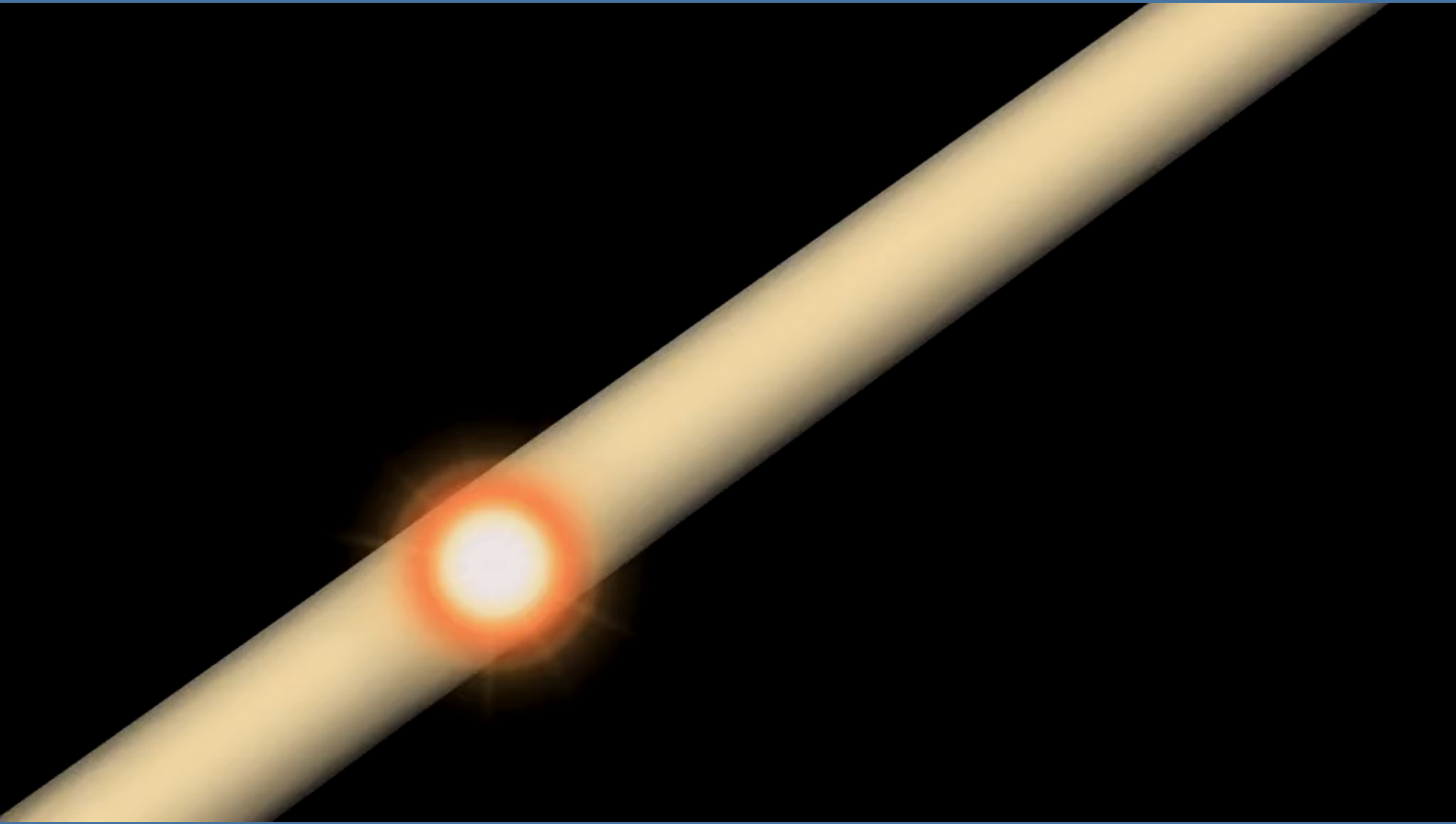




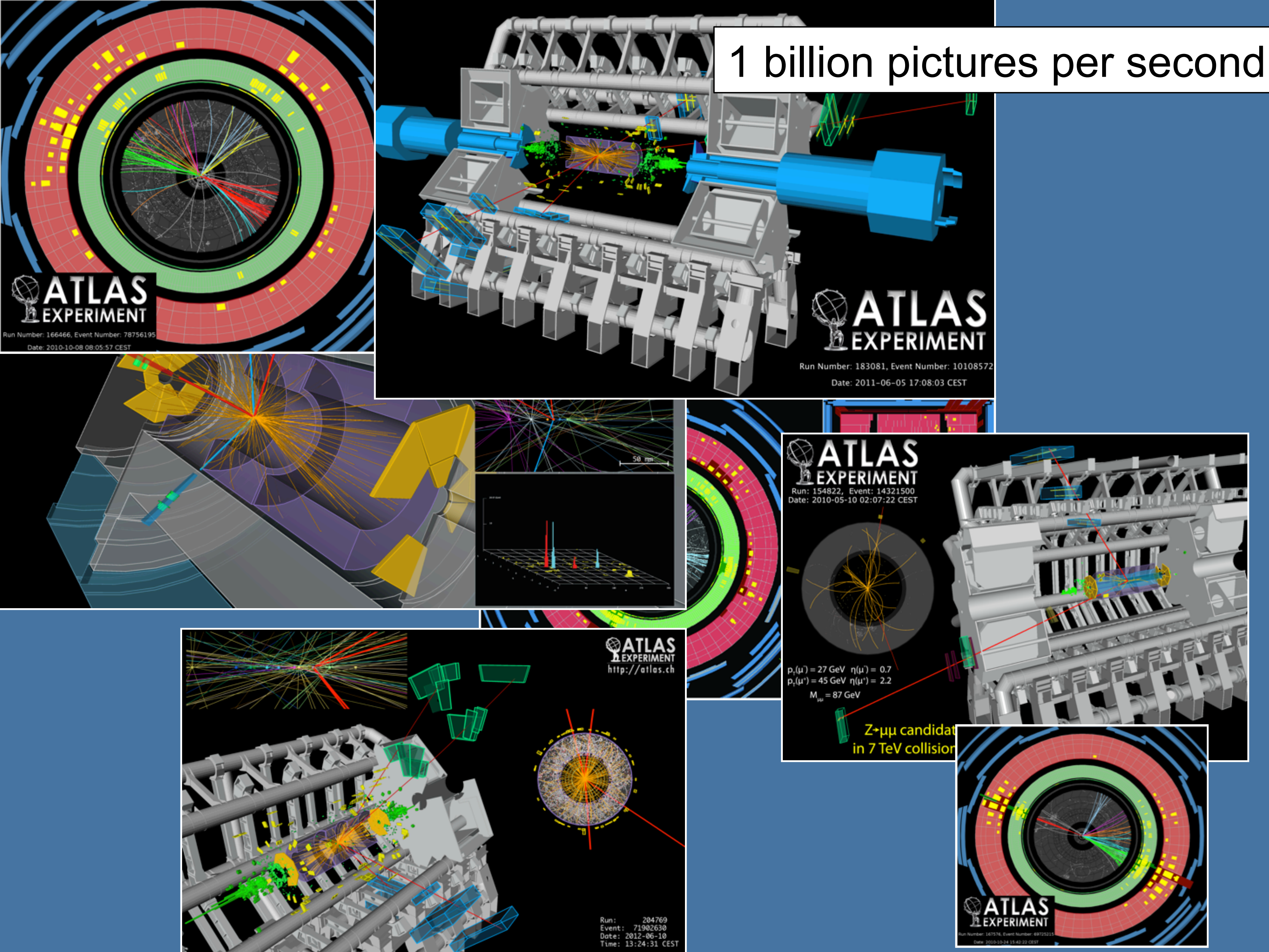
Test all combinations

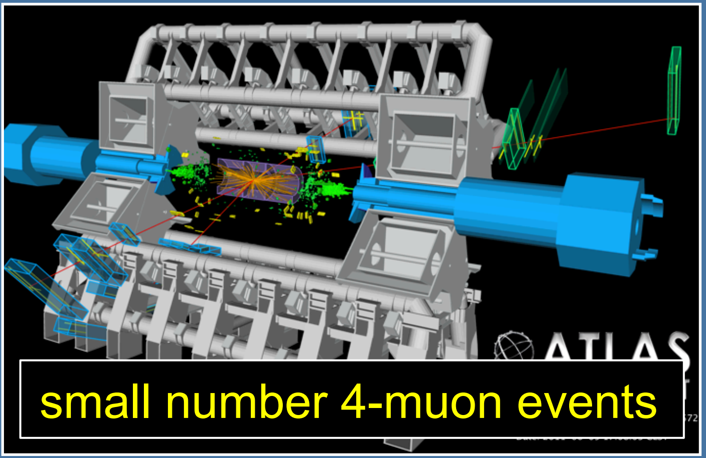

production rate
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
proton-proton
2-jets ($0.1<m_{jj}<5$ TeV)
$Z \rightarrow \mu^+\mu^-$
higgs$\rightarrow\gamma\gamma/4\mu$
10^9
production process
Access rare processes:
- focus on clear signatures: leptons/photons
- study many collisions

The Large Hadron Collider at CERN



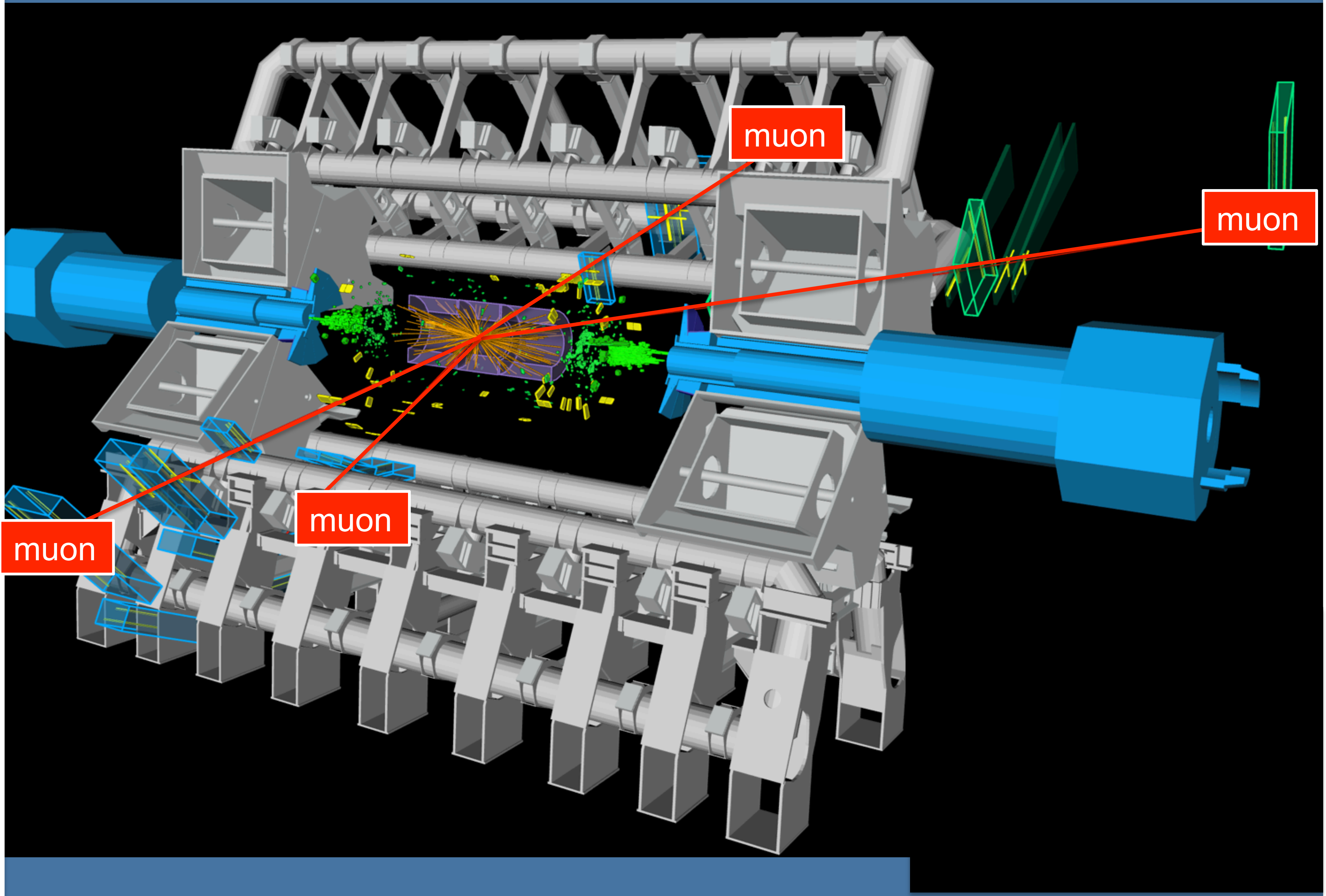
1 billion pictures per second





Tricky:

- 1 billion per second
  …. can only store 200

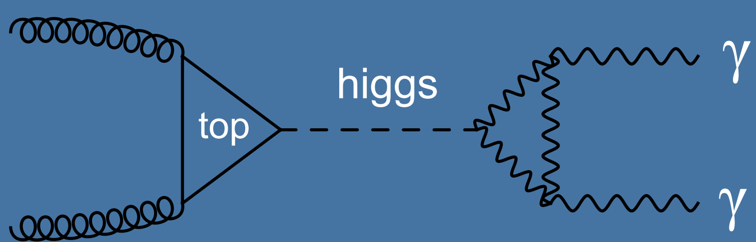

muon
muon
muon
muon

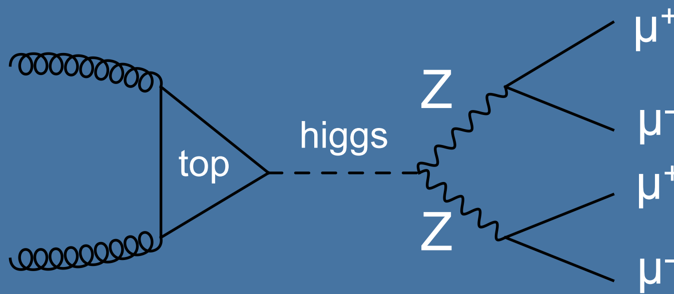
Liu Bolin

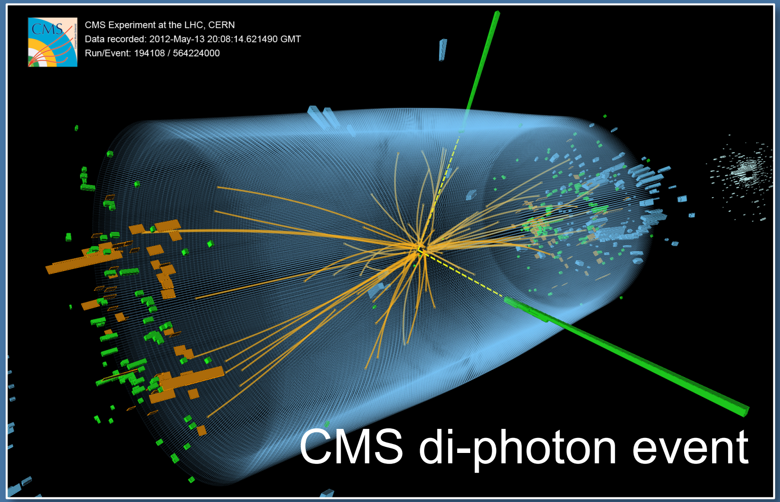

discovery

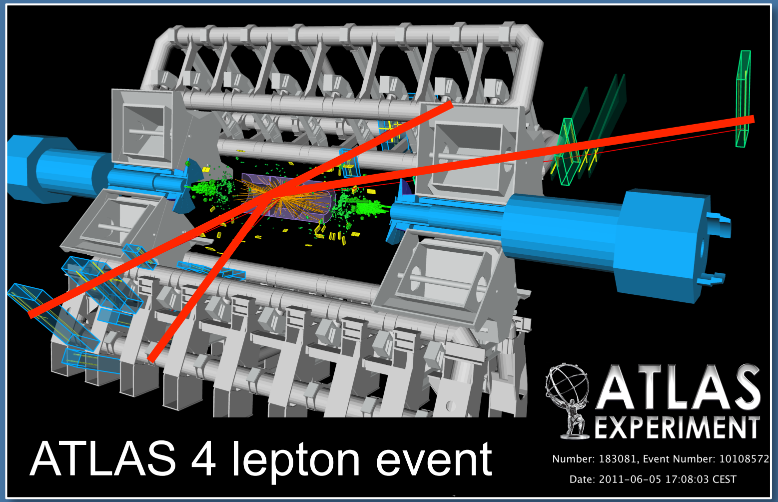
Higgs boson decay to 2 photons

Higgs boson decay to 4 leptons

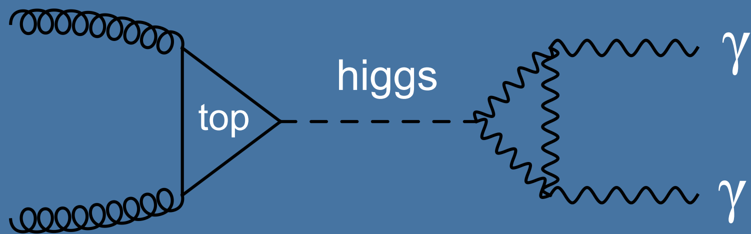


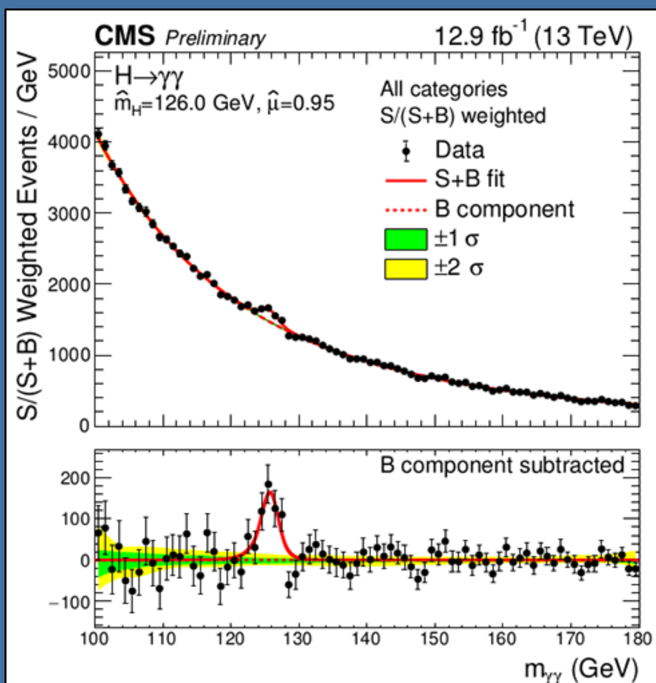




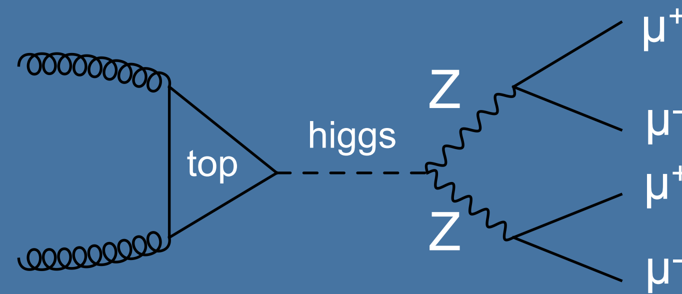


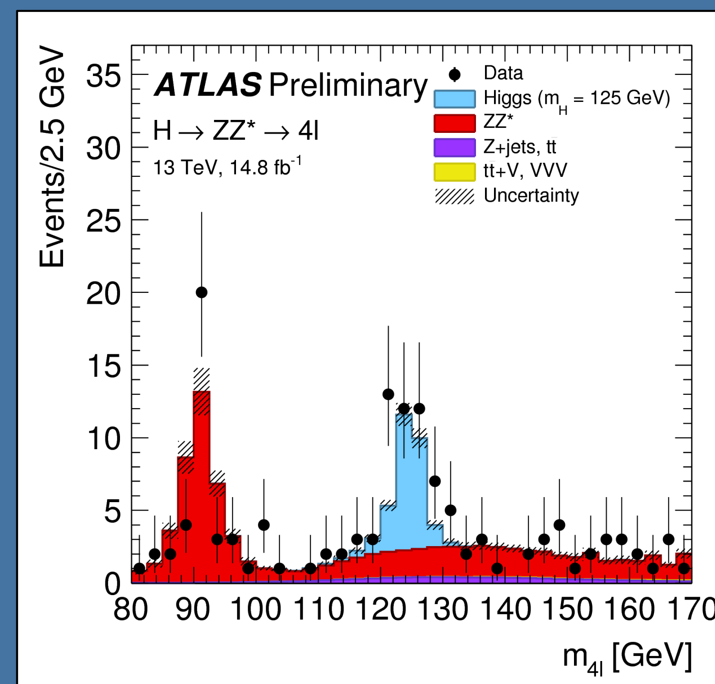
Higgs boson decay to 2 photons





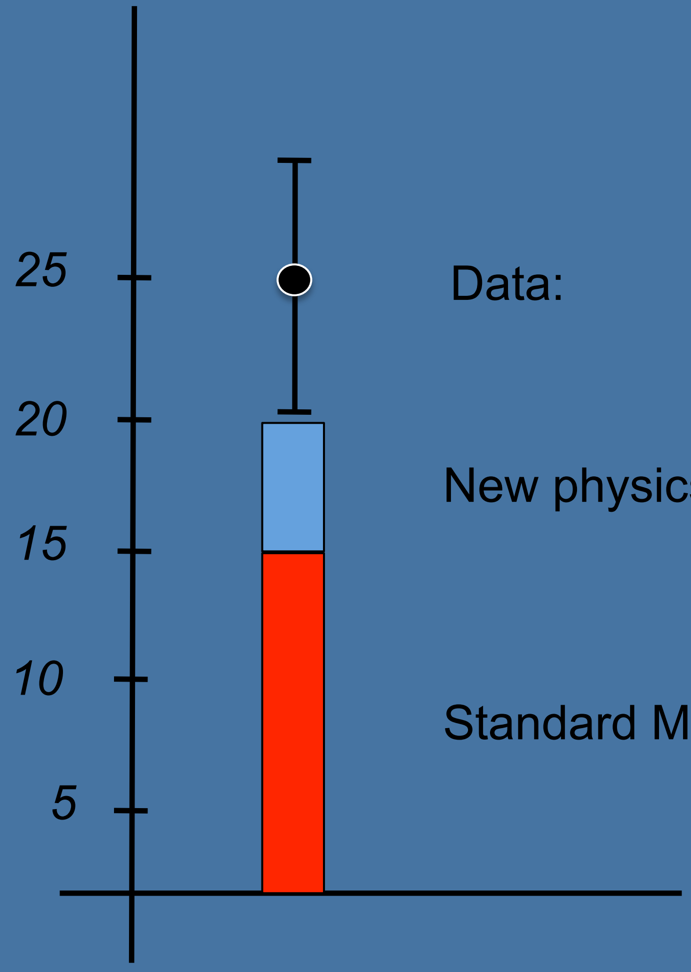
Higgs boson decay to 4 leptons





ATLAS+CMS: m_h = 125.09 ± 0.21(stat) ± 0.11(syst) GeV

What is significance ?



Data: $N_{data} = 25$

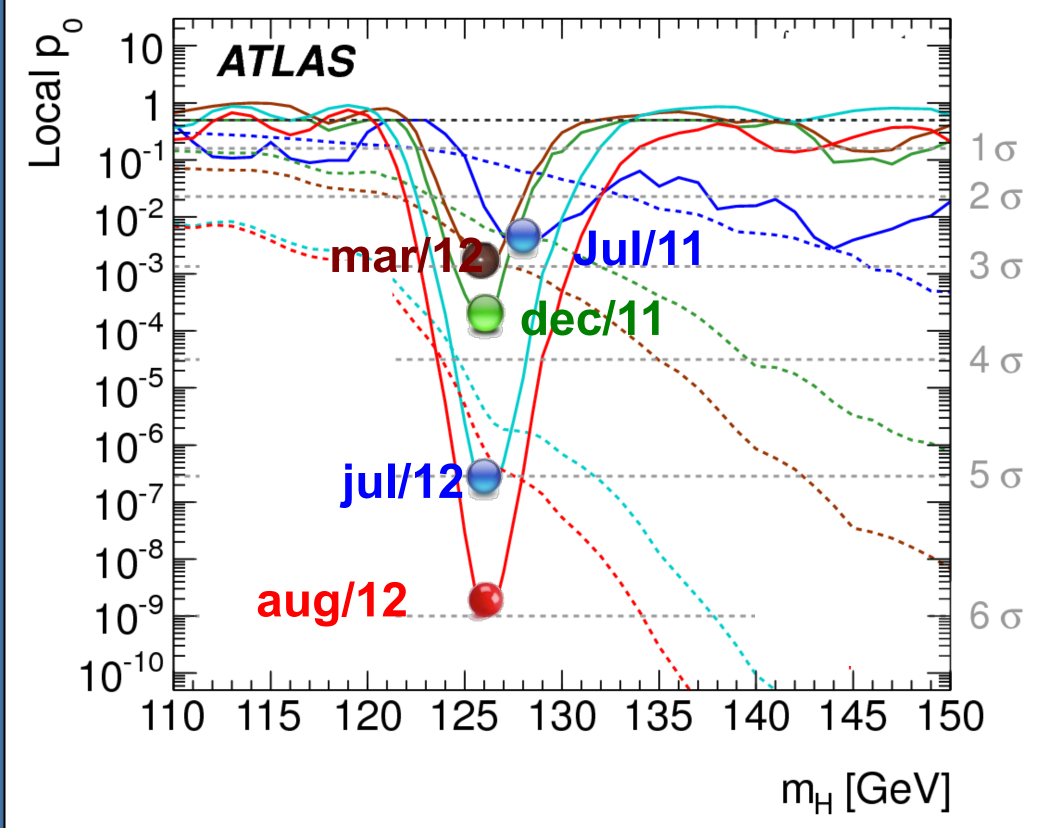
New physics: $N_{sig} = 5$

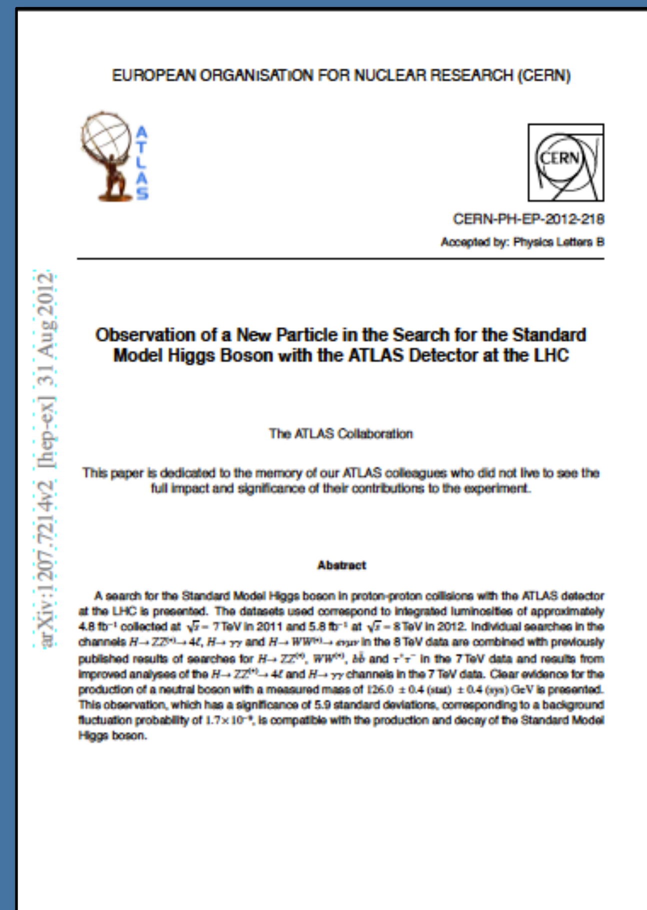
Standard Model: $N_{bgr} = 15$

Significance: probability to measure N events (or more) under the background-only hypothesis

A textbook discovery in slow-motion

Local p-value versus mass





EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

CERN-PH-EP-2012-218

Accepted by: Physics Letters B

arXiv:1207.7214v2 [hep-ex] 31 Aug 2012

Observation of a New Particle in the Search for the Standard Model Higgs Boson with the ATLAS Detector at the LHC

The ATLAS Collaboration

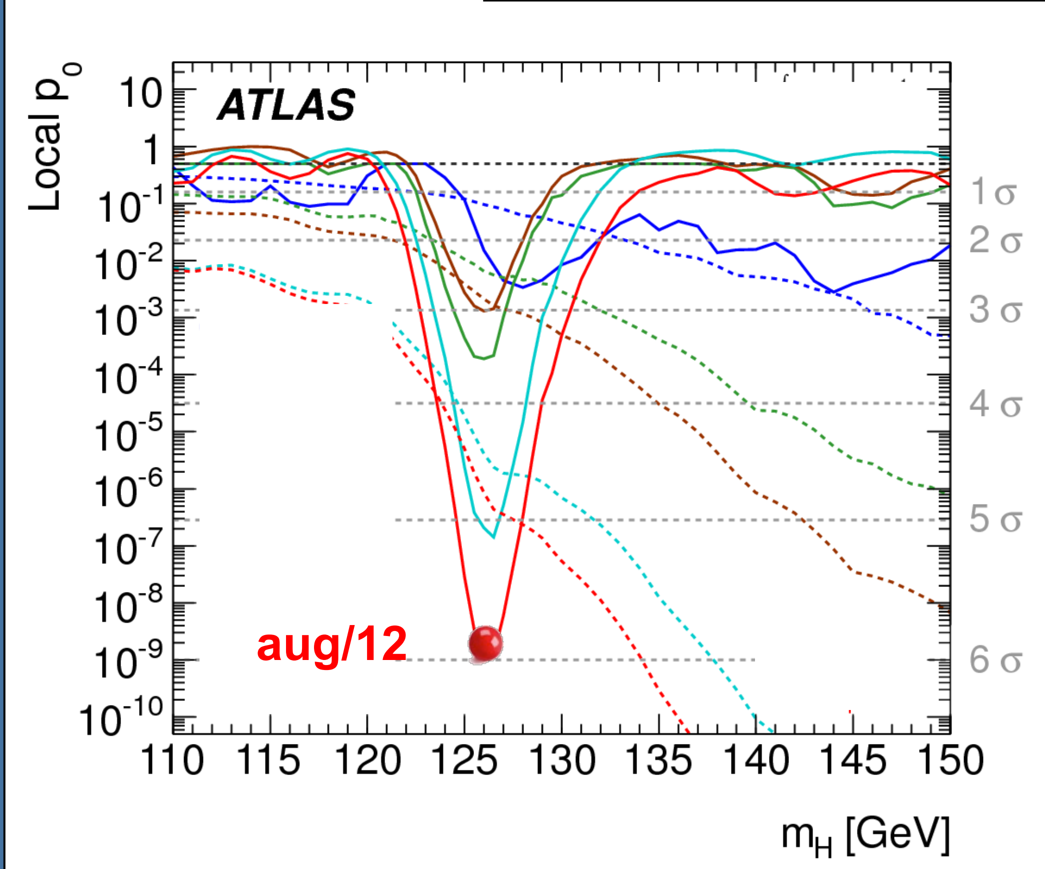
This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

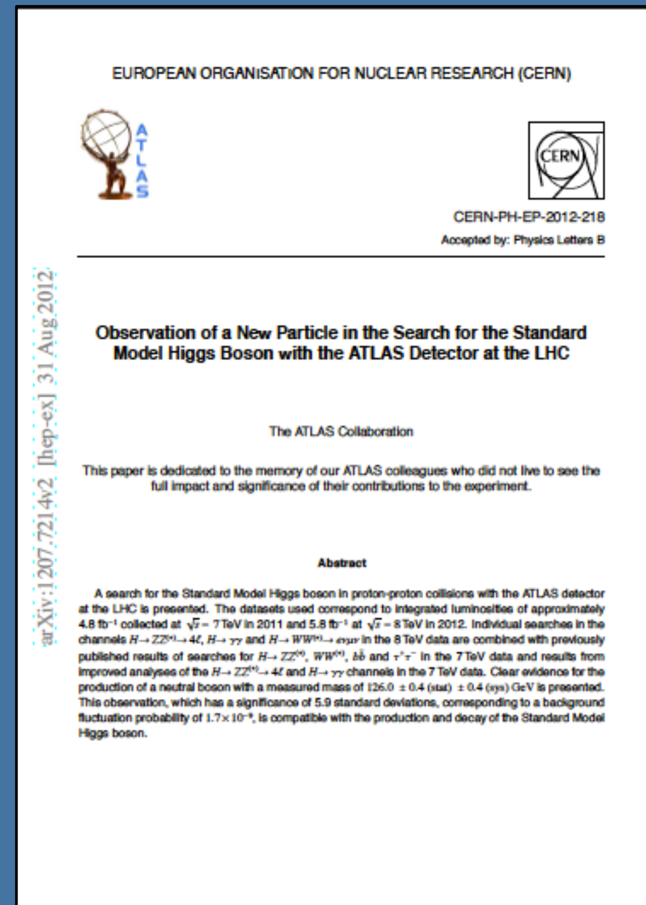
Abstract

A search for the Standard Model Higgs boson in proton-proton collisions with the ATLAS detector at the LHC is presented. The datasets used correspond to integrated luminosities of approximately 4.8 fb^{-1} collected at $\sqrt{s}$ = 7 TeV in 2011 and 5.8 fb^{-1} at $\sqrt{s}$ = 8 TeV in 2012. Individual searches in the channels $H \to ZZ^{(*)} \to 4\ell$, $H \to \gamma\gamma$ and $H \to WW^{(*)} \to e\nu\mu\nu$ in the 8 TeV data are combined with previously published results of searches for $H \to ZZ^{(*)}$, $WW^{(*)}$, $b\bar{b}$ and $\tau^+\tau^-$ in the 7 TeV data and results from improved analyses of the $H \to ZZ^{(*)} \to 4\ell$ and $H \to \gamma\gamma$ channels in the 7 TeV data. Clear evidence for the production of a neutral boson with a measured mass of $126.0 \pm 0.4\,(\text{stat}) \pm 0.4\,(\text{sys})$ GeV is presented. This observation, which has a significance of 5.9 standard deviations, corresponding to a background fluctuation probability of 1.7×10^{-9}, is compatible with the production and decay of the Standard Model Higgs boson.

A textbook discovery in slow-motion

Local p-value versus mass





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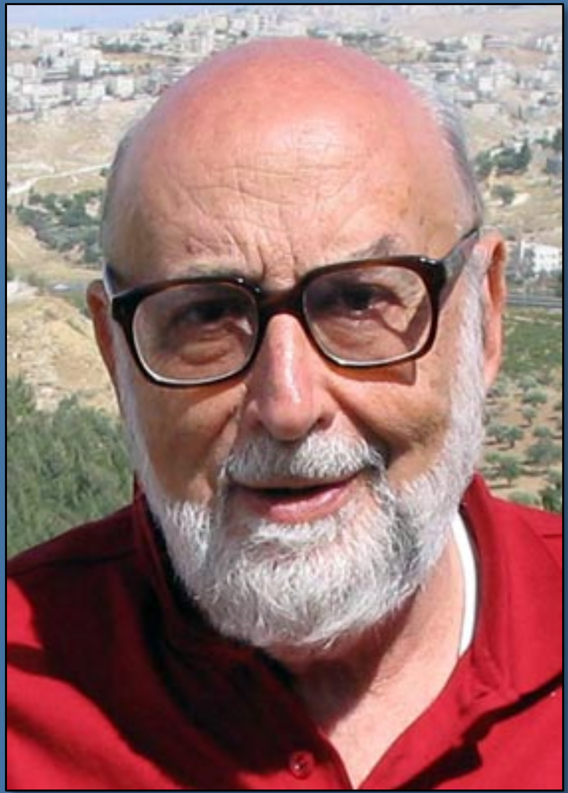
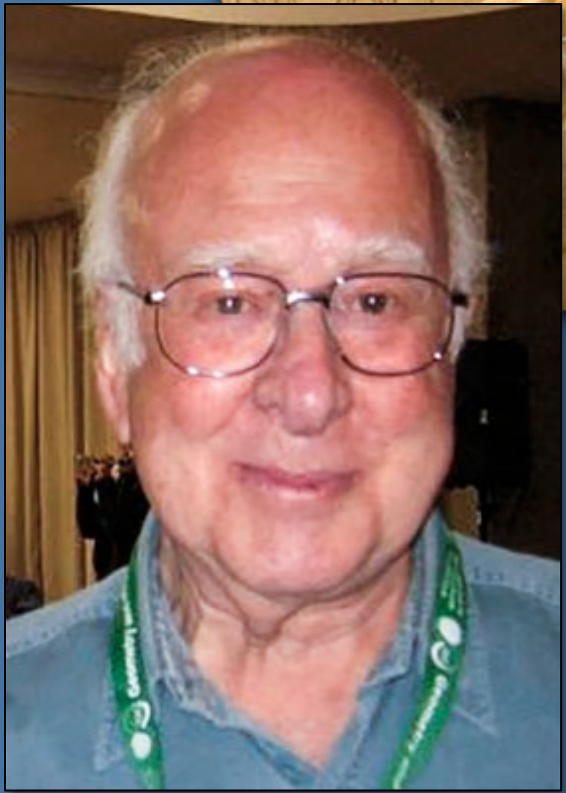
Nobelprize Physics 2013

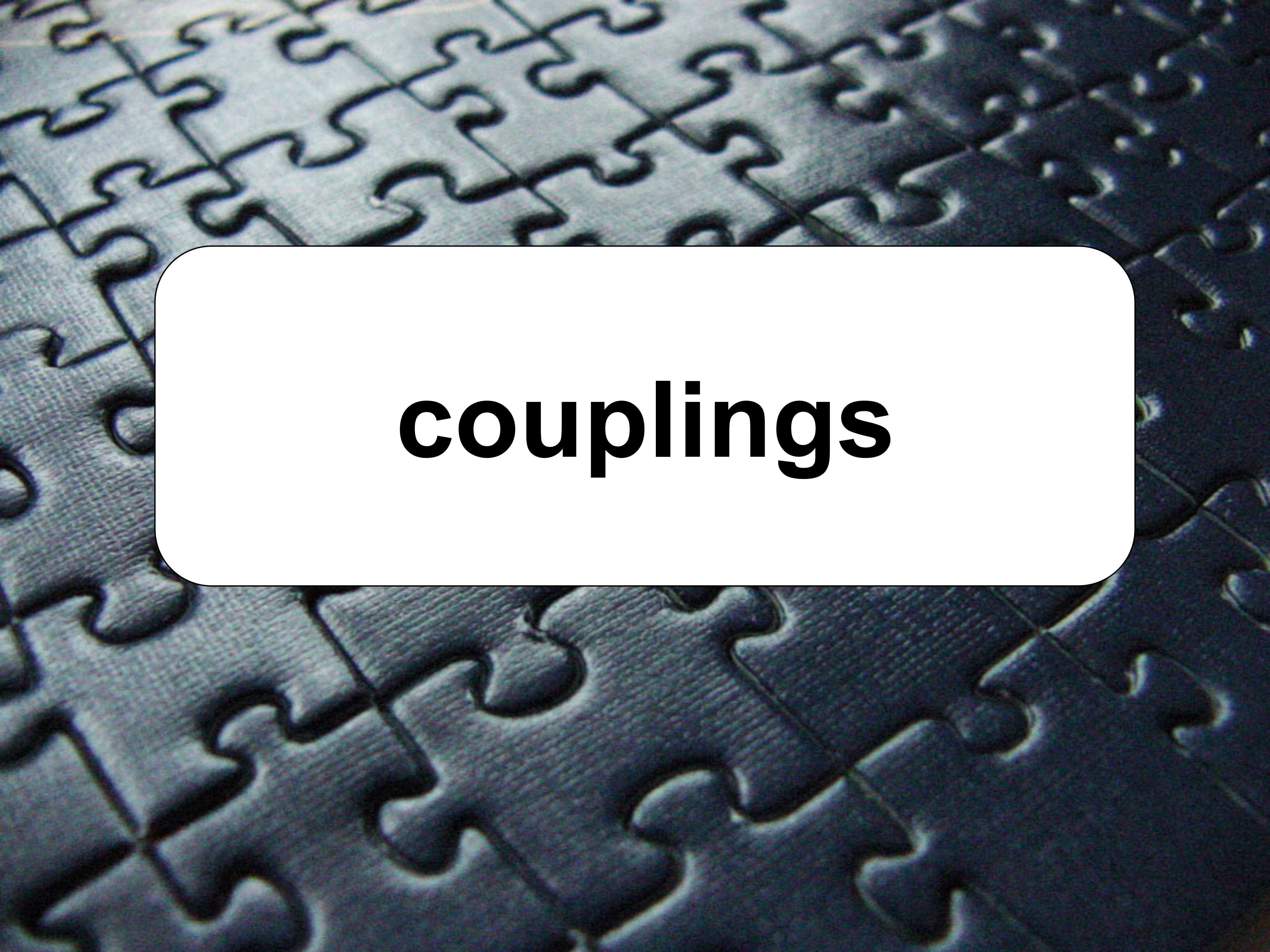
“There is a Higgs field in the vacuum”



François Englert

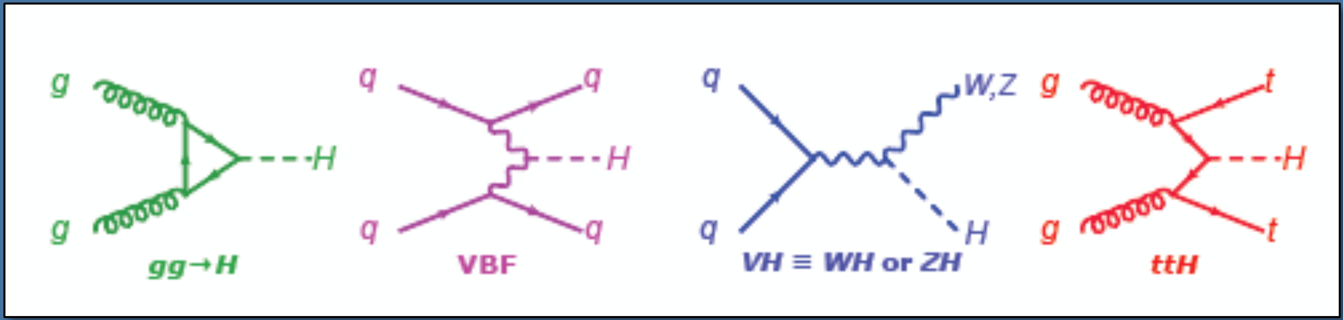


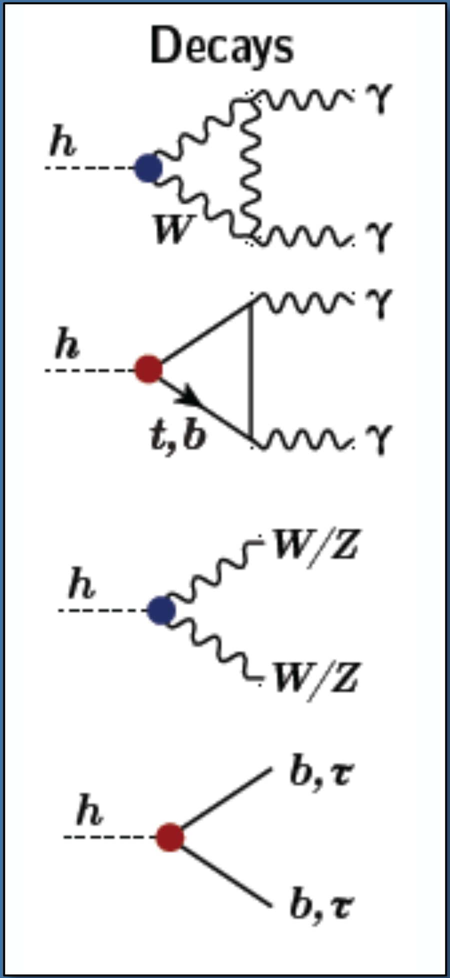
Peter Higgs



couplings

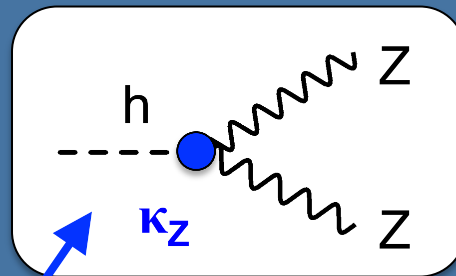
Higgs production and decay

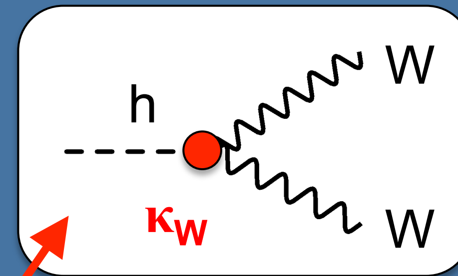




Test all combinations

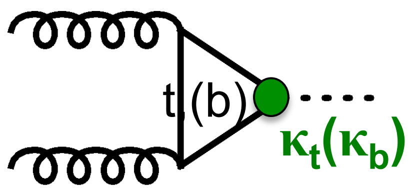
Effective Lagrangian



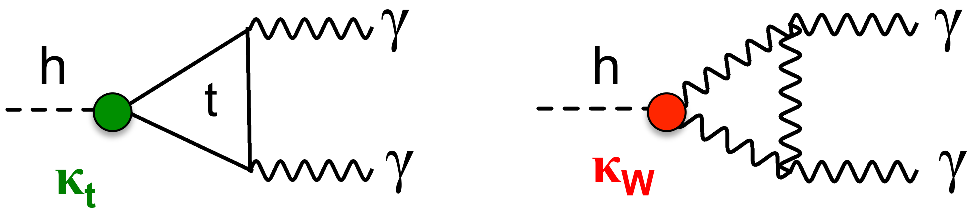


Use scale factors κ to parametrise deviations from SM (κ=1):

$$
\begin{aligned}
\mathcal{L} = &\ \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H \\
&+ \kappa_g \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v} A_{\mu\nu} Z^{\mu\nu} H \\
&- \left(\kappa_t \sum_{f=u,c,t} \frac{m_f}{v} f\bar{f} + \kappa_b \sum_{f=d,s,b} \frac{m_f}{v} f\bar{f} + \kappa_\tau \sum_{f=e,\mu,\tau} \frac{m_f}{v} f\bar{f} \right) H
\end{aligned}
$$



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



$$\kappa_\gamma^2 \propto 1.59\kappa_W^2 - 0.66\kappa_W\kappa_t + 0.07\kappa_t^2$$

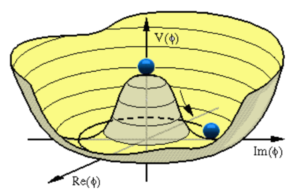
$$\mathcal{L} = \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H$$
$$+ \kappa_g \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v} A_{\mu\nu} Z^{\mu\nu} H$$
$$- \left(\kappa_t \sum_{f=u,c,t} \frac{m_f}{v} f\bar{f} + \kappa_b \sum_{f=d,s,b} \frac{m_f}{v} f\bar{f} + \kappa_\tau \sum_{f=e,\mu,\tau} \frac{m_f}{v} f\bar{f} \right) H$$

Rates and relations are modified if non-SM particles enter in the loops

Extending the Higgs sector

(1) compositeness

(2) extra EW singlet



SM-doublet &
$V(\phi) = \mu^2\phi^2 + \lambda\phi^4$

(3) Two Higgs doublet models

Standard Model:
1 doublet CP-even neutral scalar

h *A* *H* H^+ H^-

specific couplings h to fermions/bosons

(4) Dark Matter portal

Invisible Higgs decays

Two Higgs doublet models

5 Higgs bosons, lightest one looks very much like the SM one

Coupling lightest Higgs boson w.r.t Standard Model prediction:

Coupling scale factor	Type I	Type II	Type III	Type IV
vector bosons	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
up-type quarks	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
down-type quarks	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
leptons	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$

TYPE I:
- 1 doublet for vector bosons
- 1 doublet for fermions

TYPE II: MSSM-like:
- 1 doublet for up-type
- 1 doublet for down-type

Why measure the mass to high precision ?

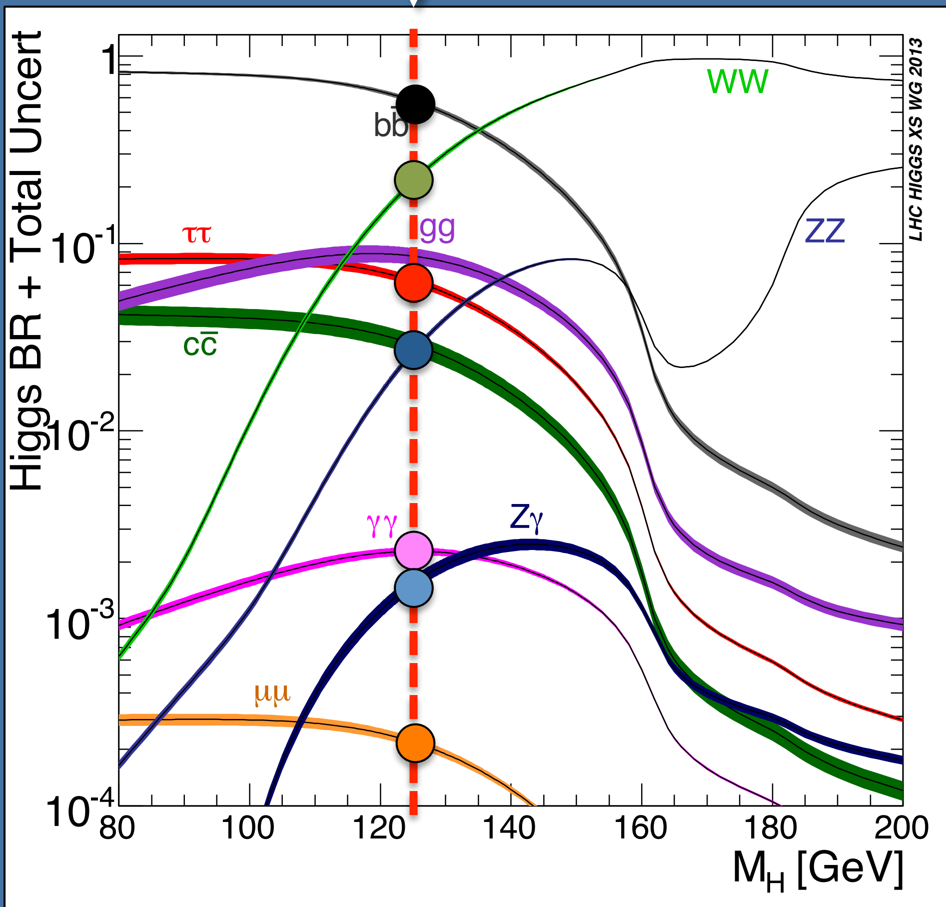
Branching ratio's depend on the mass of the Higgs boson

		Δm	$\Delta \Gamma/\Gamma_{125}$
m_h = 123.7 GeV	$\Gamma(h \rightarrow ZZ)$ = 2.34%	-1%	-11%
m_h = 124.0 GeV	$\Gamma(h \rightarrow ZZ)$ = 2.41%		
m_h = 124.5 GeV	$\Gamma(h \rightarrow ZZ)$ = 2.52%	0.4%	-4.5%
m_h = 125.0 GeV	$\Gamma(h \rightarrow ZZ)$ = 2.64%	0.0%	0.0%
m_h = 125.5 GeV	$\Gamma(h \rightarrow ZZ)$ = 2.76%	0.4%	+4.5%
m_h = 126.0 GeV	$\Gamma(h \rightarrow ZZ)$ = 2.89%		
m_h = 126.3 GeV	$\Gamma(h \rightarrow ZZ)$ = 2.97%	+1%	+12%

Higgs boson couplings

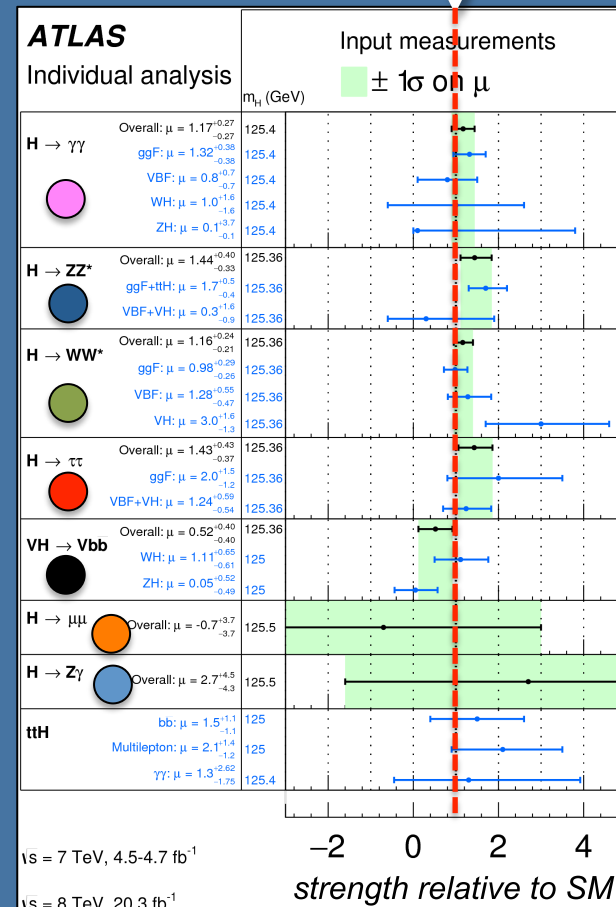
Theory

125 GeV



Experiment

SM



Change in m_h of 500 MeV (0.4%) changes $\Gamma(h \rightarrow ZZ)$ by ± 4.5%

Observed particle looks very much like SM Higgs boson

Higgs potential

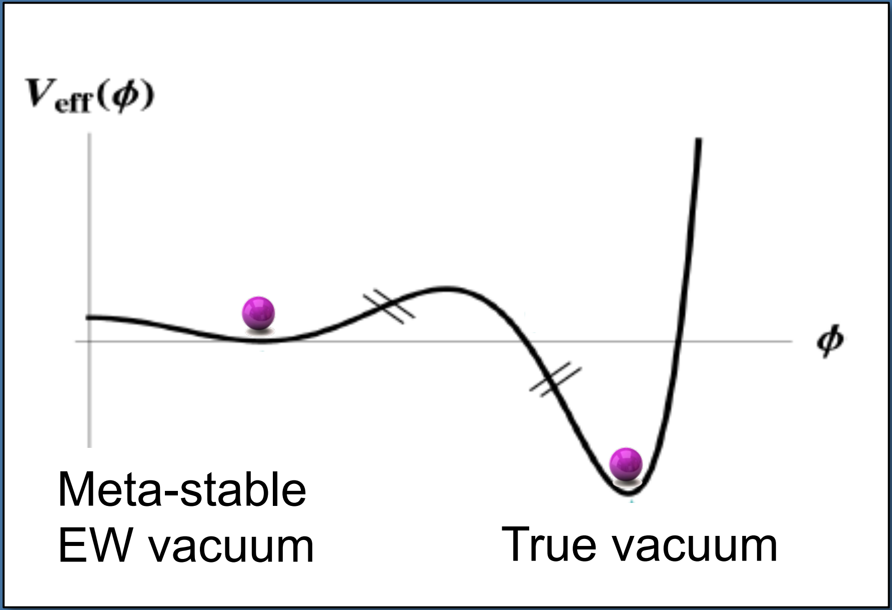
Stability of the vacuum: meta-stability

New physics at the Planck scale:
2 higher dimensional operators

$$V(\phi) = \frac{\lambda}{4}\phi^4 + \frac{\lambda_6}{6}\frac{\phi^6}{M_P^2} + \frac{\lambda_8}{8}\frac{\phi^8}{M_P^4}$$

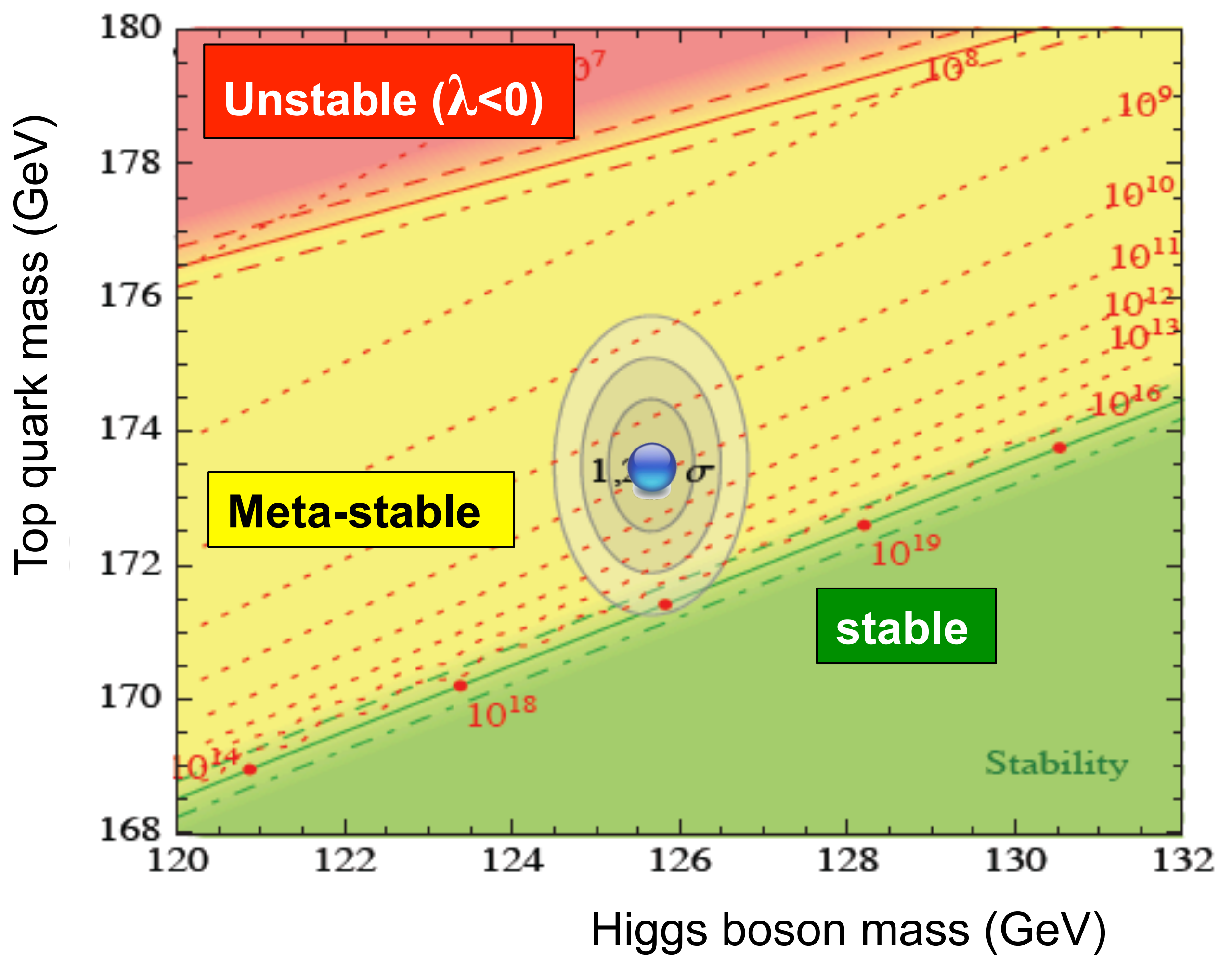
Tunneling time to true vacuum

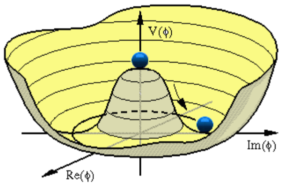
$$\Gamma = \frac{1}{\tau} = T_U^3 \frac{S[\phi_b]^2}{4\pi^2}\left|\frac{\det'\left[-\partial^2 + V''(\phi_b)\right]}{\det\left[-\partial^2 + V''(v)\right]}\right|^{-1/2} e^{-S[\phi_b]}$$



Not before these guys become World Champion

Stability of the vacuum: Higgs potential at high energy

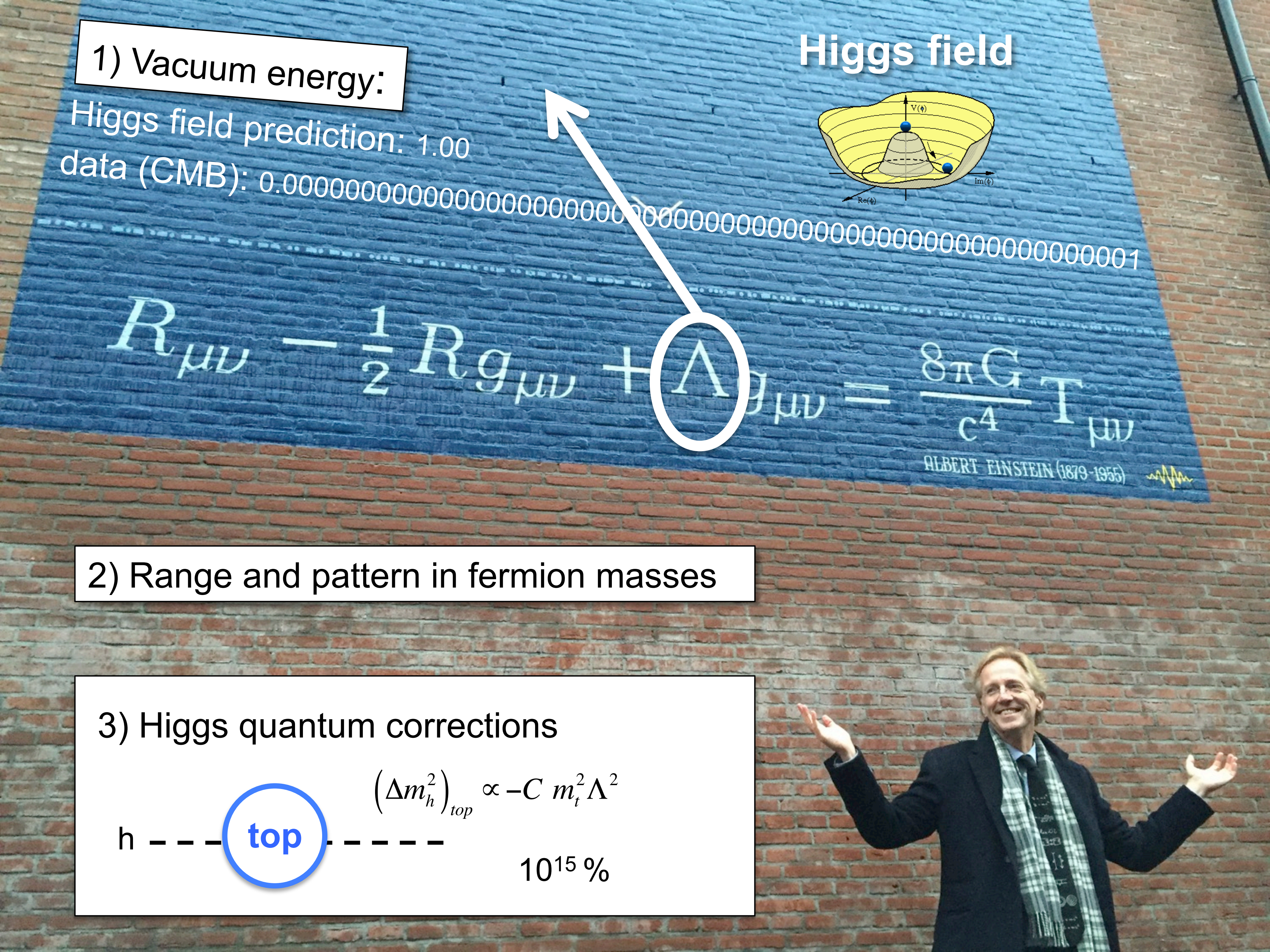




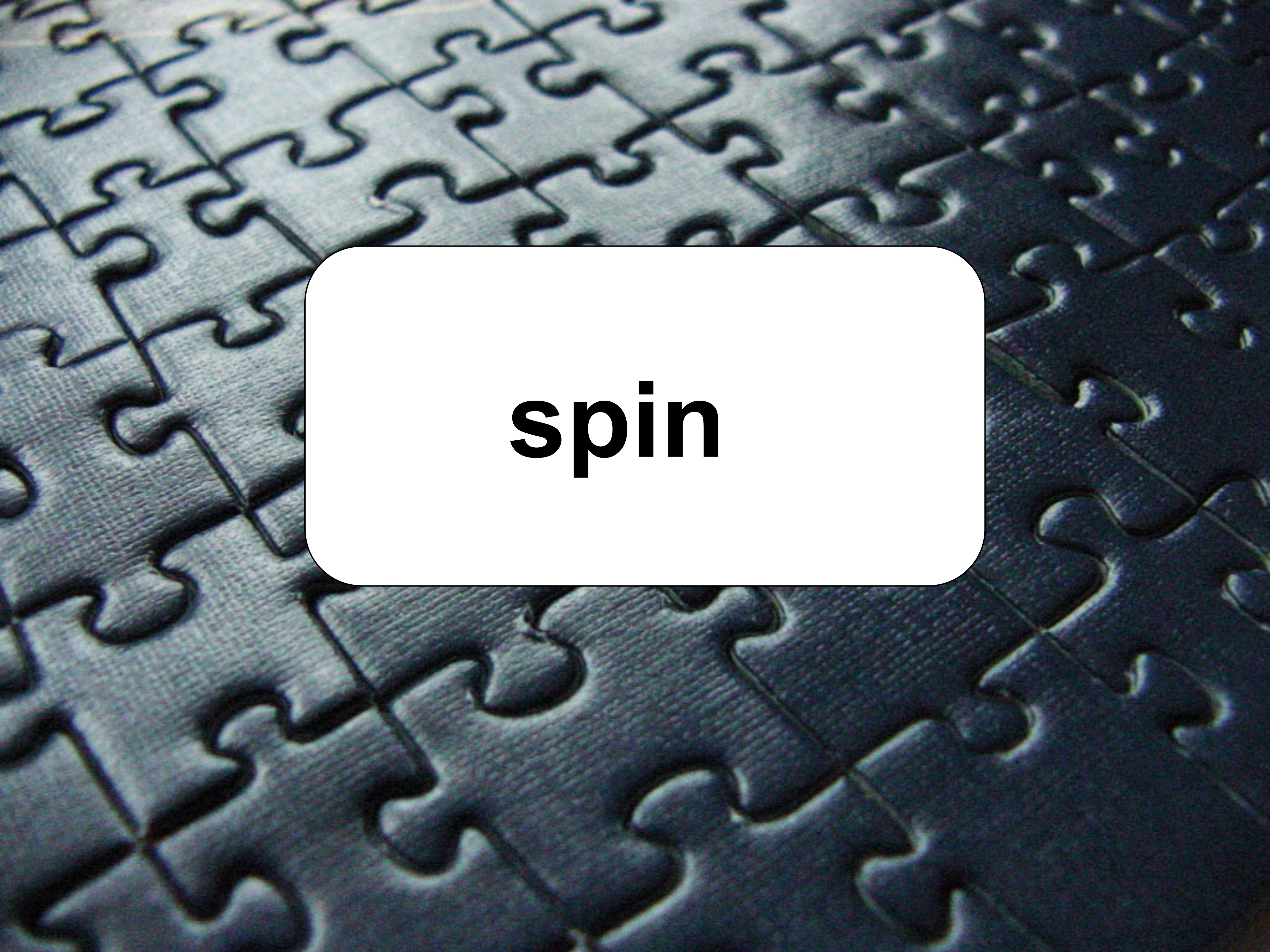
SM-doublet &

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

Branchia ICHEP



1) Vacuum energy:
Higgs field prediction: 1.00
data (CMB): 0.0000000000000000000000000000000000000000000000000000001
Higgs field
V(ϕ)
Im(ϕ)
Re(ϕ)
$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$
ALBERT EINSTEIN (1879-1955)
2) Range and pattern in fermion masses
3) Higgs quantum corrections
$\left(\Delta m_h^2\right)_{top} \propto -C\ m_t^2 \Lambda^2$
h
top
10^{15} %


spin

Higgs quantum numbers: spin and parity

Parity = +

Charge conjugation = +

Scalar spin=0

$$J^{PC}$$

Differences in each of these parameters lead to different event topologies

- Production angle for different production mechanisms
- Decay angles and event topologies for decay channels

Different scenario's for new particle X

scenario	production	parameters	Model
0_m^+	$gg \to X$	$g_1^{(0)} \neq 0$	SM Higgs scalar boson
0_h^+	$gg \to X$	$g_2^{(0)} \neq 0$	scalar higher-dim. op.
0^-	$gg \to X$	$g_4^{(0)} \neq 0$	pseudo-scalar
1^+	$q\bar{q} \to X$	$b_2 \neq 0$	exotic pseudo-vector
1^-	$q\bar{q} \to X$	$b_1 \neq 0$	exotic vector
2_m^+	$g_1^{(2)} \neq 0$	$g_1^{(2)} = g_5^{(2)} \neq 0$	RS graviton min. coupl.
2_h^+	$g_4^{(2)} \neq 0$	$g_4^{(2)} \neq 0$	tensor higher-dim. op.
2_h^-	$g_8^{(2)} \neq 0$	$g_8^{(2)} \neq 0$	"pseudo-tensor"

Structure of the matrix element

Spin 0 (qq production)

$A(X \to$ $$A(X \to V_1 V_2) = v^{-1} \epsilon_1^{*\mu} \epsilon_2^{*\nu} \left(a_1 g_{\mu\nu} m_X^2 + a_2\, q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta}\, q_1^\alpha q_2^\beta \right) \tilde{f}^{*(2),\mu\nu} \Big)$$

Spin 1 (qq production)

$$A(X \to V_1 V_2) = b_1 \left[(\epsilon_1^* q)(\epsilon_2^* \epsilon_X) + (\epsilon_2^* q)(\epsilon_1^* \epsilon_X) \right] + b_2 \epsilon_{\alpha\mu\nu\beta} \epsilon_X^\alpha \epsilon_1^{*,\mu} \epsilon_2^{*,\nu} \tilde{q}^\beta$$

Spin 2 (gg and qq production)

$$\begin{aligned}
A(X \to V_1 V_2) = \Lambda^{-1} \Bigg[& 2 g_1^{(2)} t_{\mu\nu} f^{*(1)\mu\alpha} f^{*(2)\nu\alpha} + 2 g_2^{(2)} t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*(1)\mu\alpha} f^{*(2)\nu\beta} + g_3^{(2)} \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu} \left(f^{*(1)\mu\nu} f^{*(2)}_{\mu\alpha} + f^{*(2)\mu\nu} f^{*(1)}_{\mu\alpha} \right) \\
& + g_4^{(2)} \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*(1)\alpha\beta} f^{*(2)}_{\alpha\beta} + m_V^2 \left(2 g_5^{(2)} t_{\mu\nu} \epsilon_1^{*\mu} \epsilon_2^{*\nu} + 2 g_6^{(2)} \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu} \left(\epsilon_1^{*\nu} \epsilon_2^{*\alpha} - \epsilon_1^{*\alpha} \epsilon_2^{*\nu} \right) + g_7^{(2)} \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon_1^* \epsilon_2^* \right) \\
& + g_8^{(2)} \frac{\tilde{q}_\mu \tilde{q}_\nu}{\Lambda^2} t_{\mu\nu} f^{*(1)\alpha\beta} \tilde{f}^{*(2)}_{\alpha\beta} + m_V^2 \left(g_9^{(2)} \frac{t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} \epsilon_1^{*\nu} \epsilon_2^{*\rho} q^\sigma + \frac{g_{10}^{(2)} t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^4} \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma \left(\epsilon_1^{*\nu} (q\epsilon_2^*) + \epsilon_2^{*\nu} (q\epsilon_1^*) \right) \right) \Bigg]
\end{aligned}$$

Conclusions:

Vacuum is indeed filled with the Higgs field

Feels, smells, tastes like SM Higgs

Big questions still open

LHC run 2 already started

bigger problems

Standard Model is not the final theory:

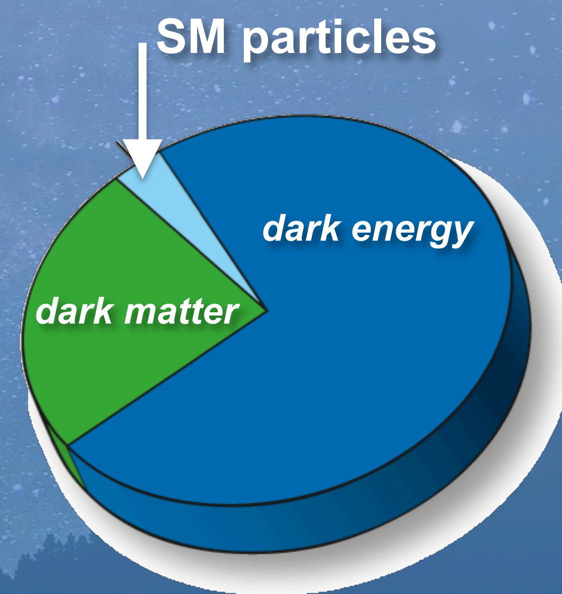
- Higgs boson - contribution to vacuum energy 10^{50} wrong
- Higgs boson - quantum corrections diverge

- Fermions: range of fermion masses (10^{12})
- Fermions: neutrino mass & fermion/majorana

- Structure: why 3 particle families, why 3 forces
- Structure: why is gravity not included

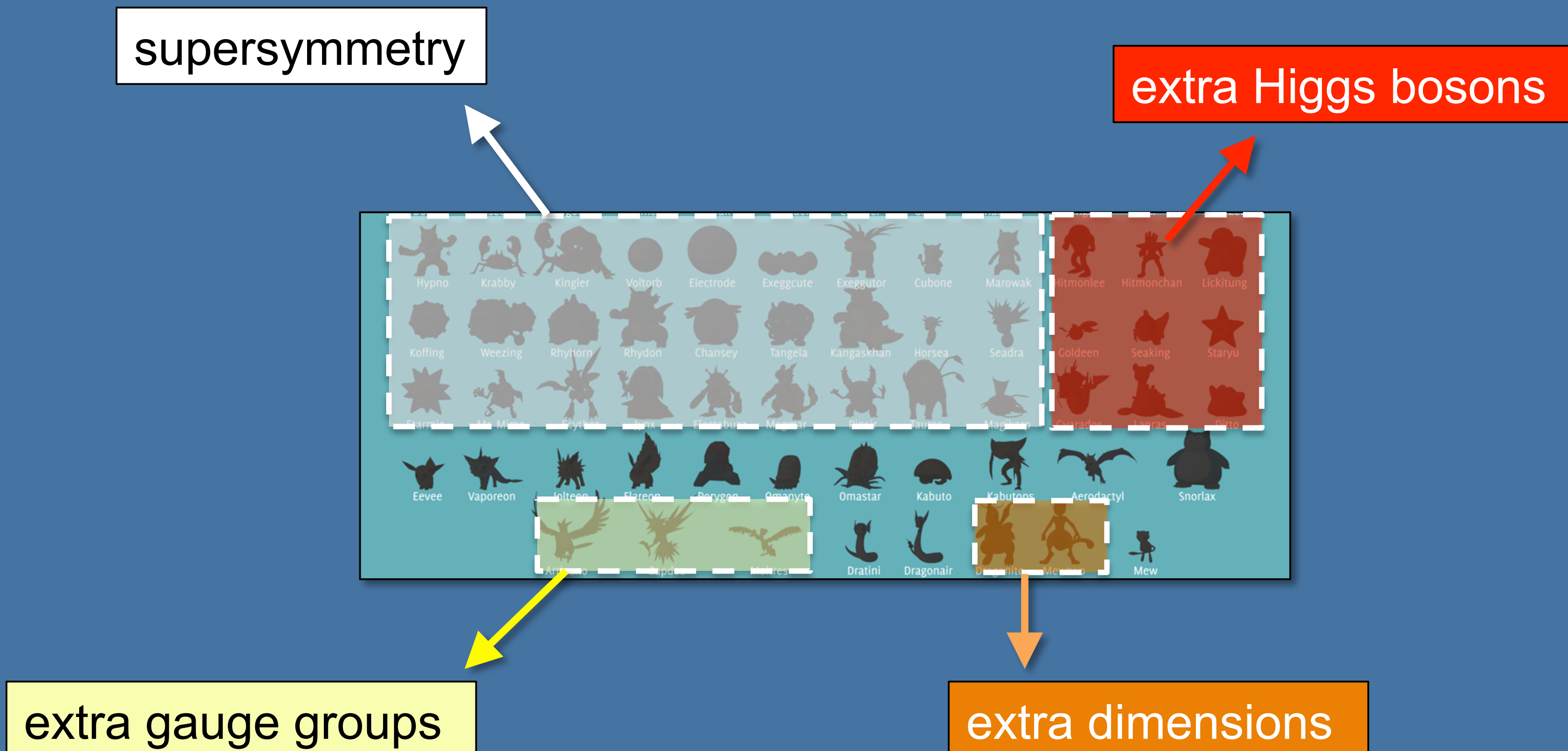
- Universe: where is the anti-matter
- Universe: what composes dark matter

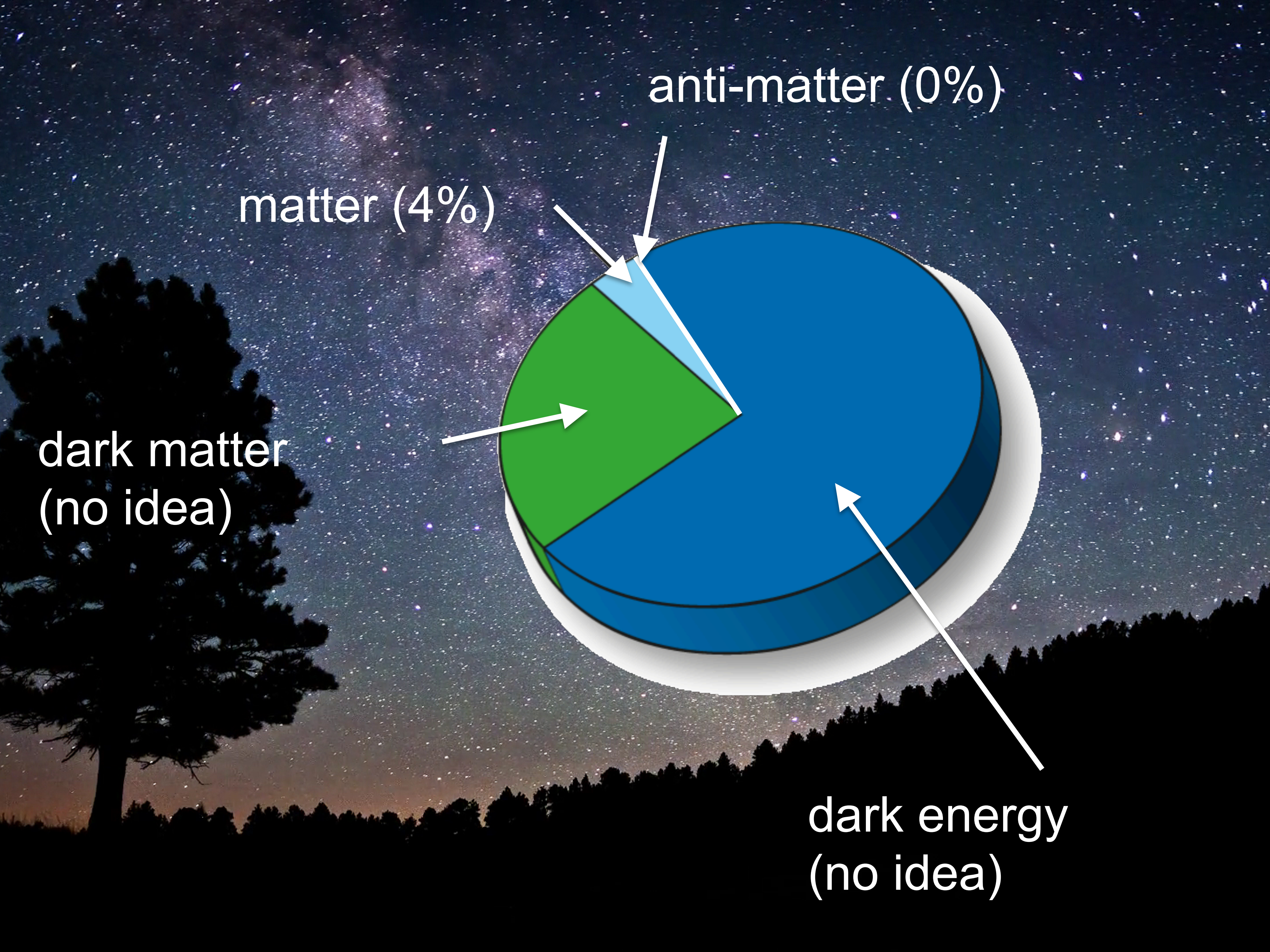
- …

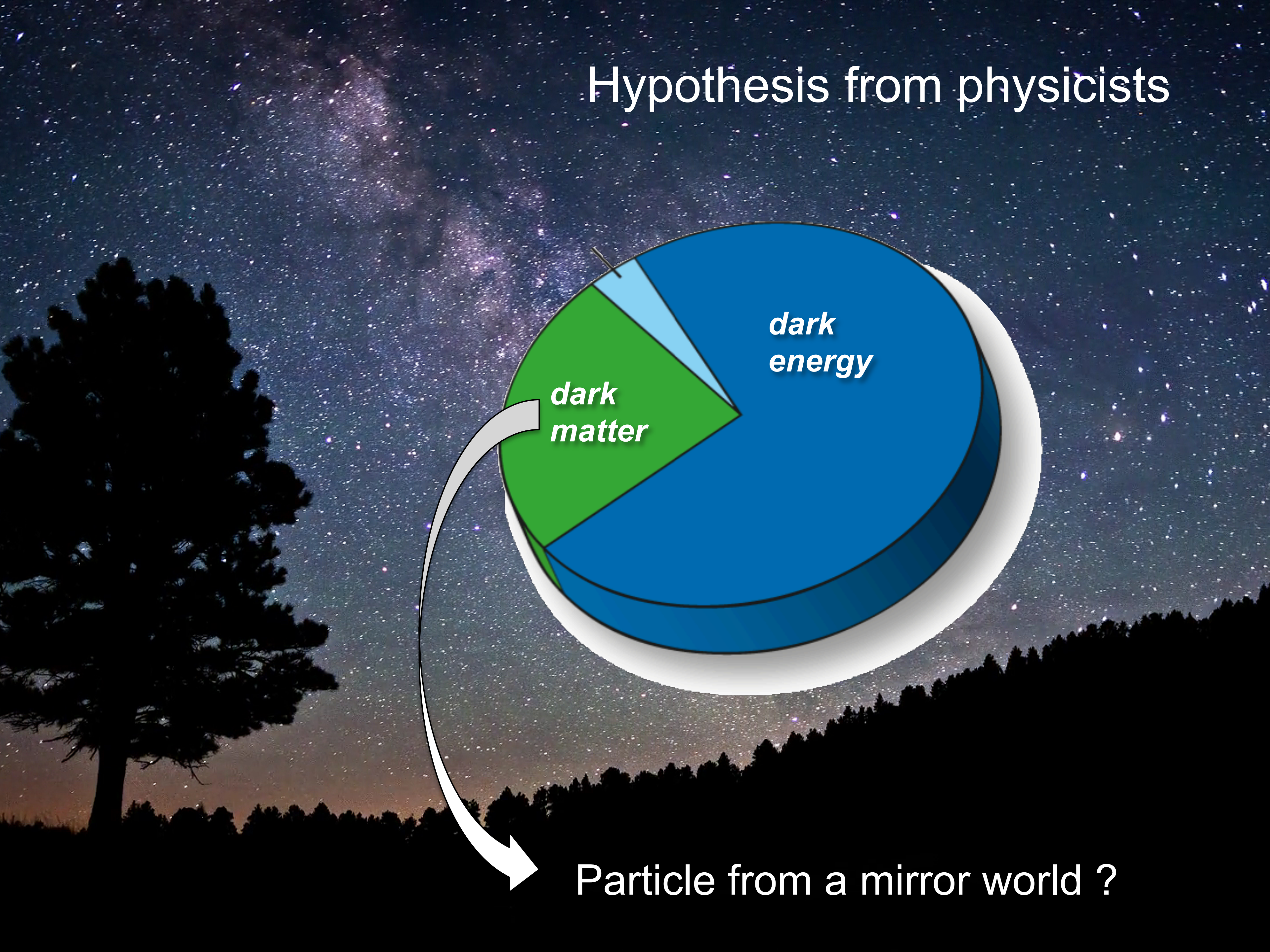


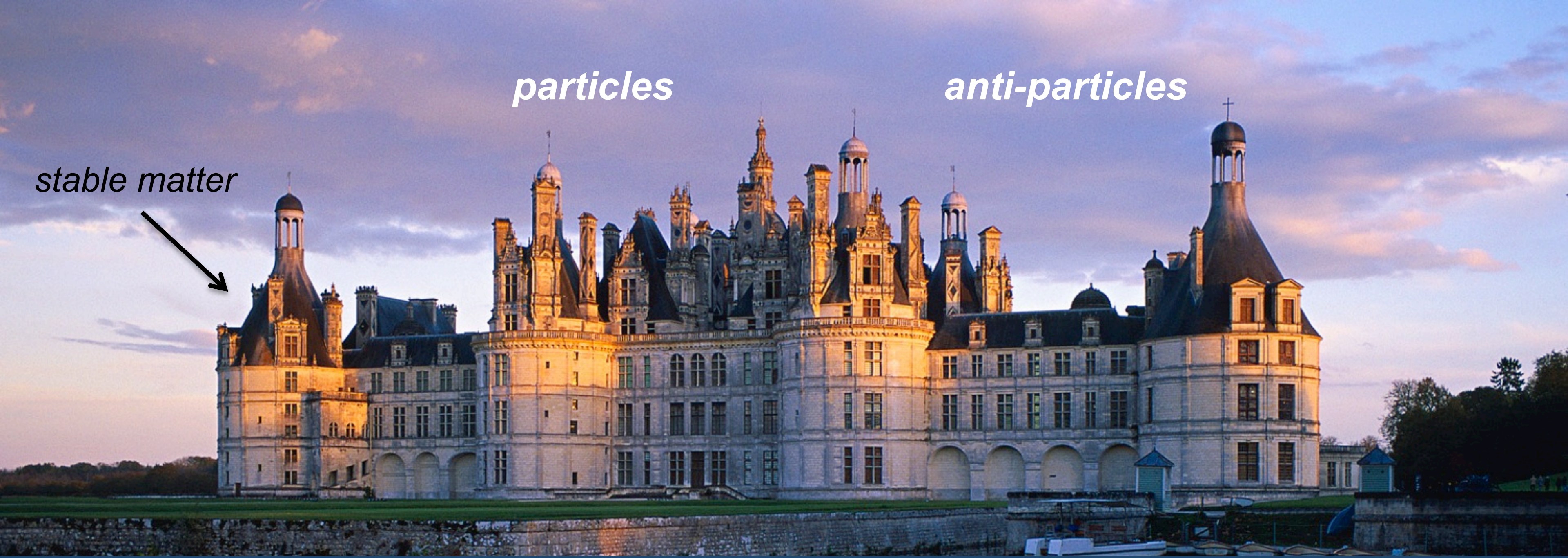
Solutions predict deviations from SM & new phenomena … at 10^{-20} m (10 TeV)

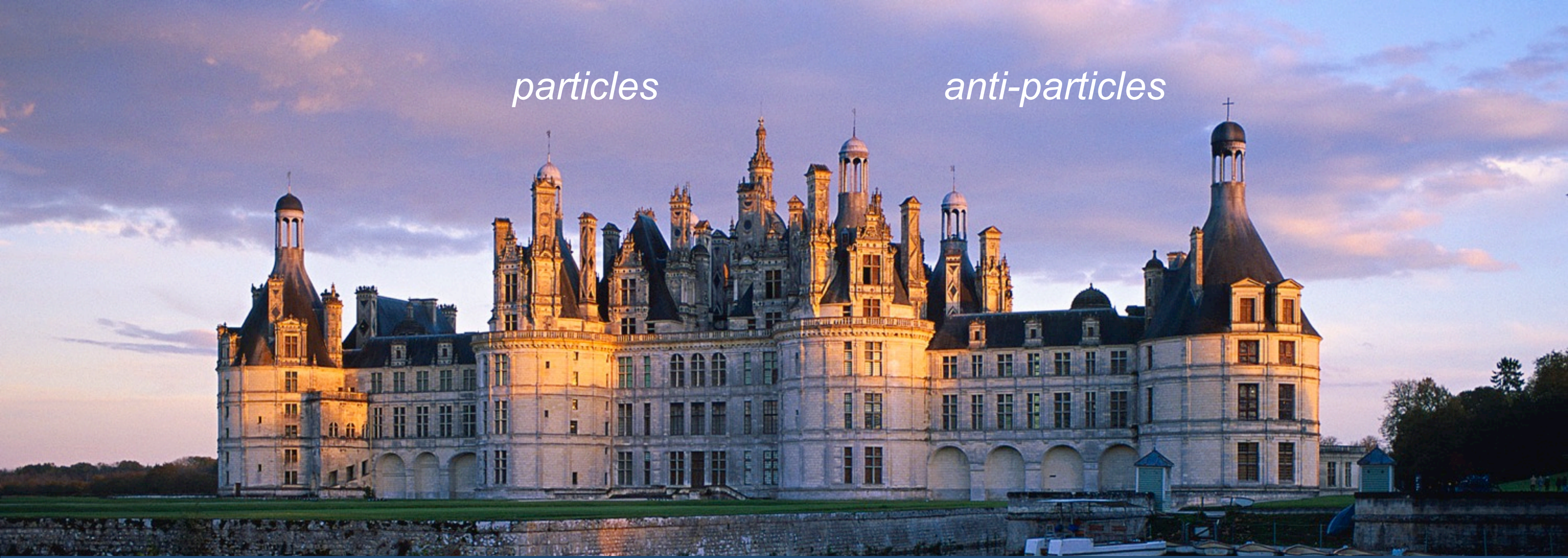
Dreams at the Large Hadron Collider

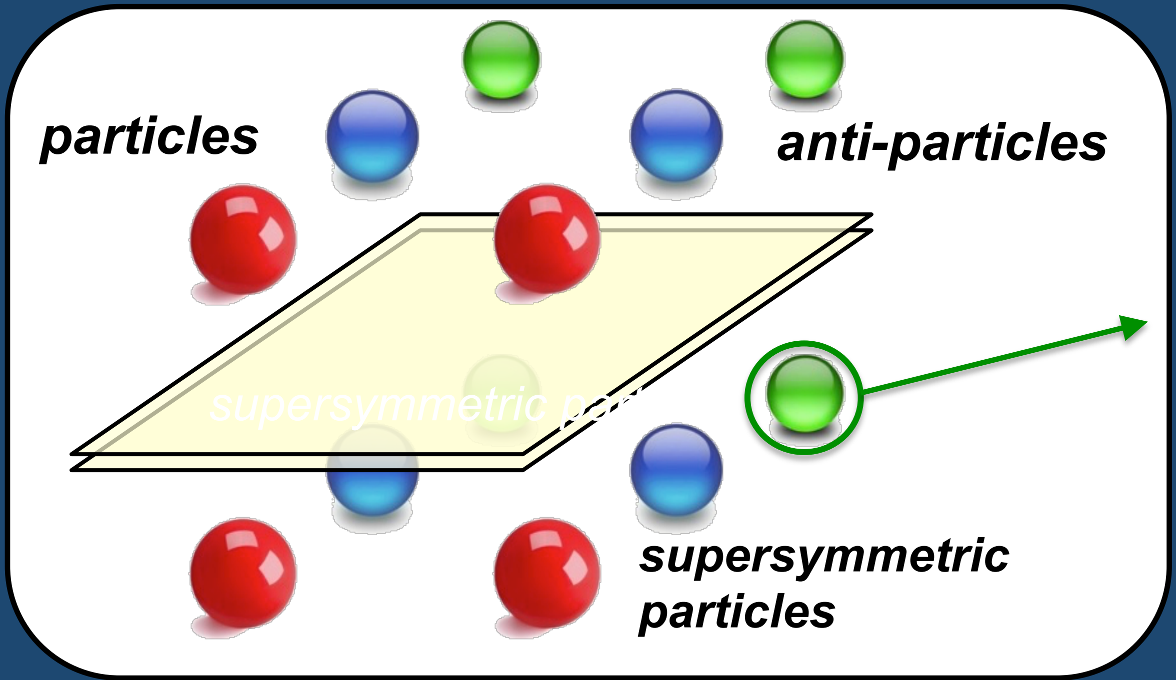



anti-matter (0%)
matter (4%)
dark matter
(no idea)
dark energy
(no idea)


Hypothesis from physicists
dark energy
dark matter
Particle from a mirror world ?

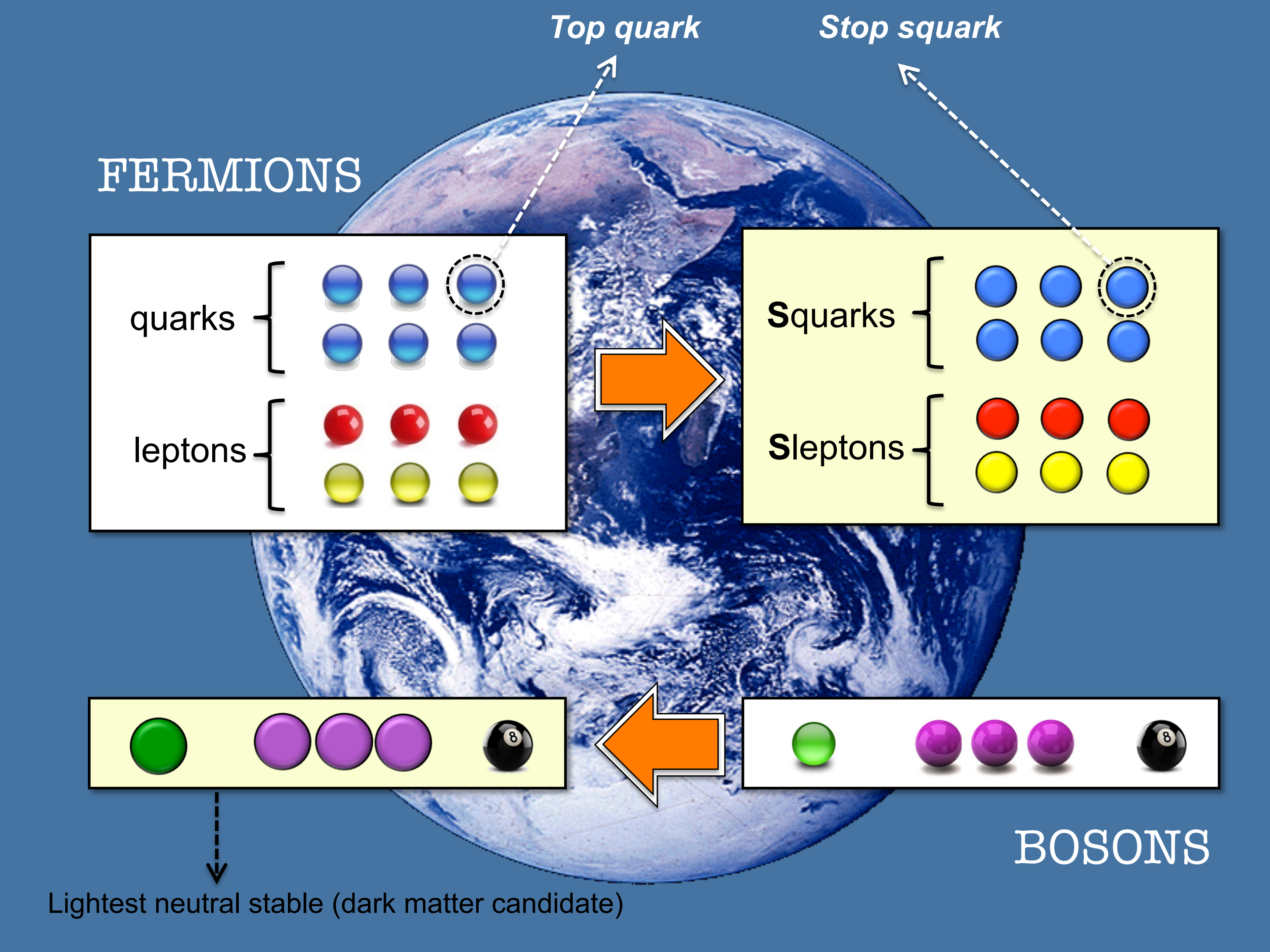

particles
anti-particles
stable matter





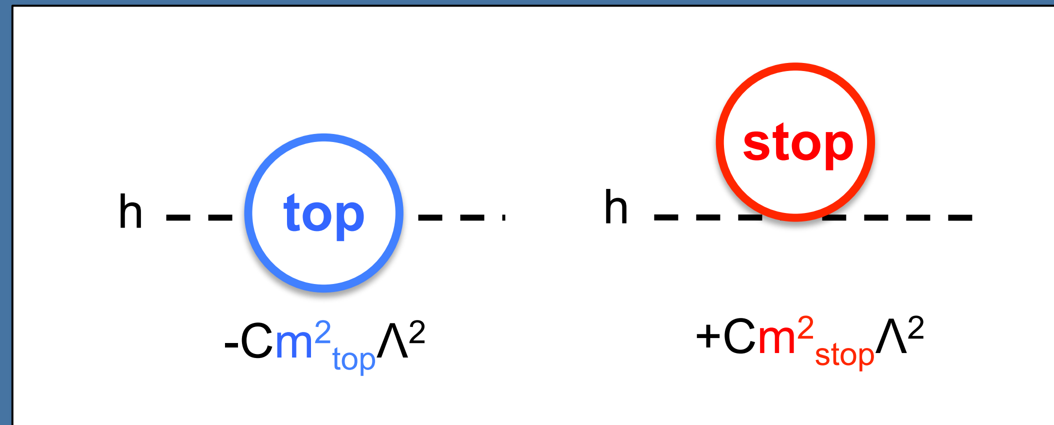
Lightest particle is stable

→ dark matter ?

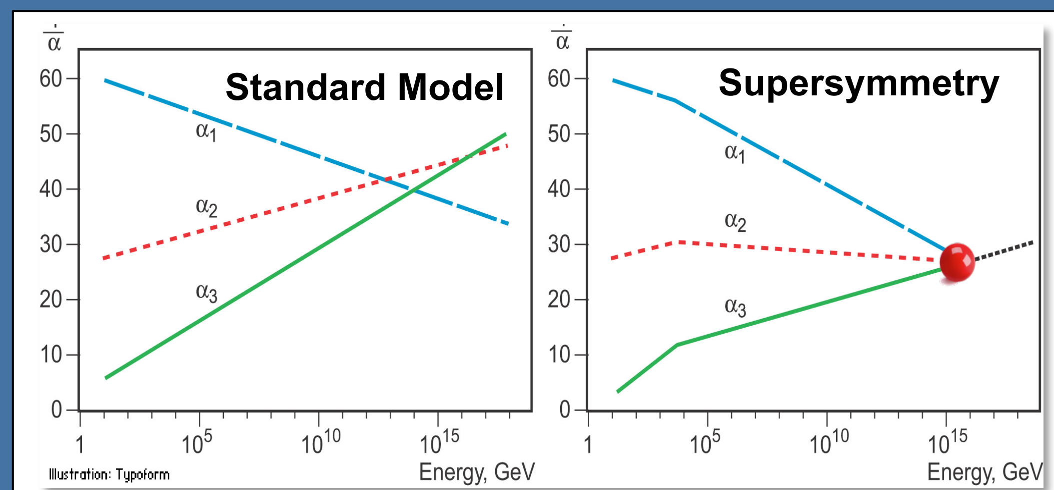

Top quark
Stop squark
FERMIONS
quarks
leptons
Squarks
Sleptons
BOSONS
Lightest neutral stable (dark matter candidate)

the super in supersymmetry

1) Higgs propagator



2) Unification forces



3) Dark Matter

Lightest supersymmetric particle is stable

Resonances

Extra gauge bosons and Kaluza-Klein graviton towers (extra dimensions)

New gauge bosons:

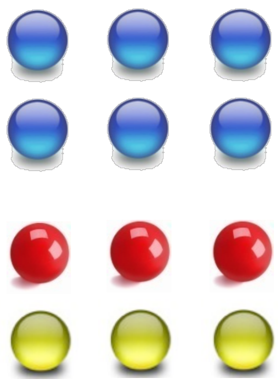
Elementary particles

up-quark

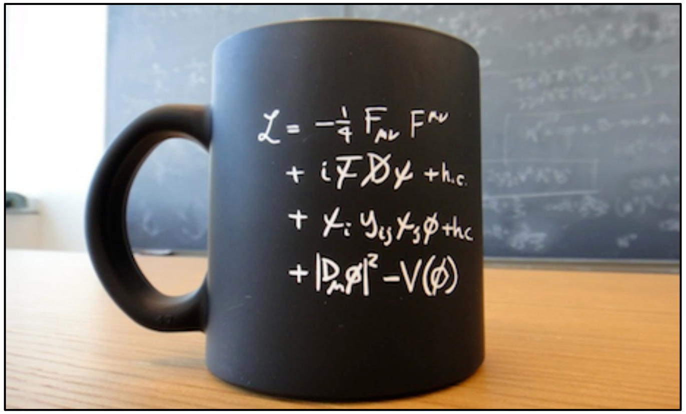
down-quark

elektron

neutrino



Interactions



$U(1)_B$ x $U(1)_Y \times SU(2)_L \times SU(3)_C$

β g', g, α_s

Z' γ, W^+, W^-, Z,   8 gluons

single spinor (1 big family)

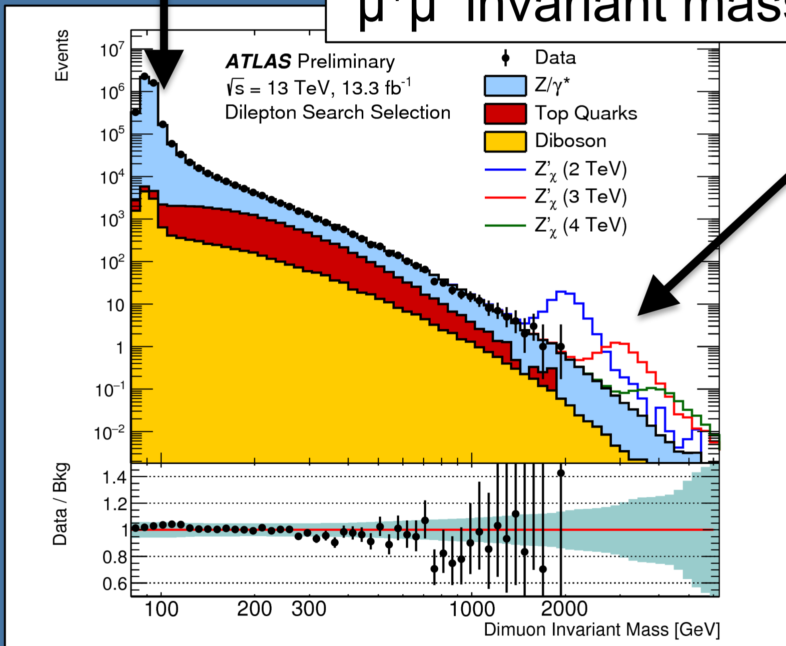
gauge unification: SO(10)

Looking for di-lepton Z'-resonances

old resonance Z-boson (91 GeV)

new resonances (simulation)

$\mu^+\mu^-$ invariant mass



Constraints on Z' masses [TeV]

Model	Width [%]	θ_{E_6} [Rad]	Lower limits on $m_{Z'}$ [TeV]					
			ee		$\mu\mu$		$\ell\ell$	
			Obs	Exp	Obs	Exp	Obs	Exp
Z'_{SSM}	3.0	-	3.85	3.86	3.49	3.53	4.05	4.06
Z'_χ	1.2	0.50	3.48	3.49	3.18	3.19	3.66	3.67
Z'_{S}	1.2	0.63 π	3.43	3.44	3.14	3.14	3.62	3.61
Z'_I	1.1	0.71 π	3.37	3.37	3.08	3.08	3.55	3.55
Z'_η	0.6	0.21 π	3.25	3.25	2.96	2.94	3.43	3.42
Z'_{N}	0.6	-0.08 π	3.23	3.23	2.95	2.94	3.41	3.41
Z'_ψ	0.5	0 π	3.18	3.18	2.90	2.88	3.36	3.35

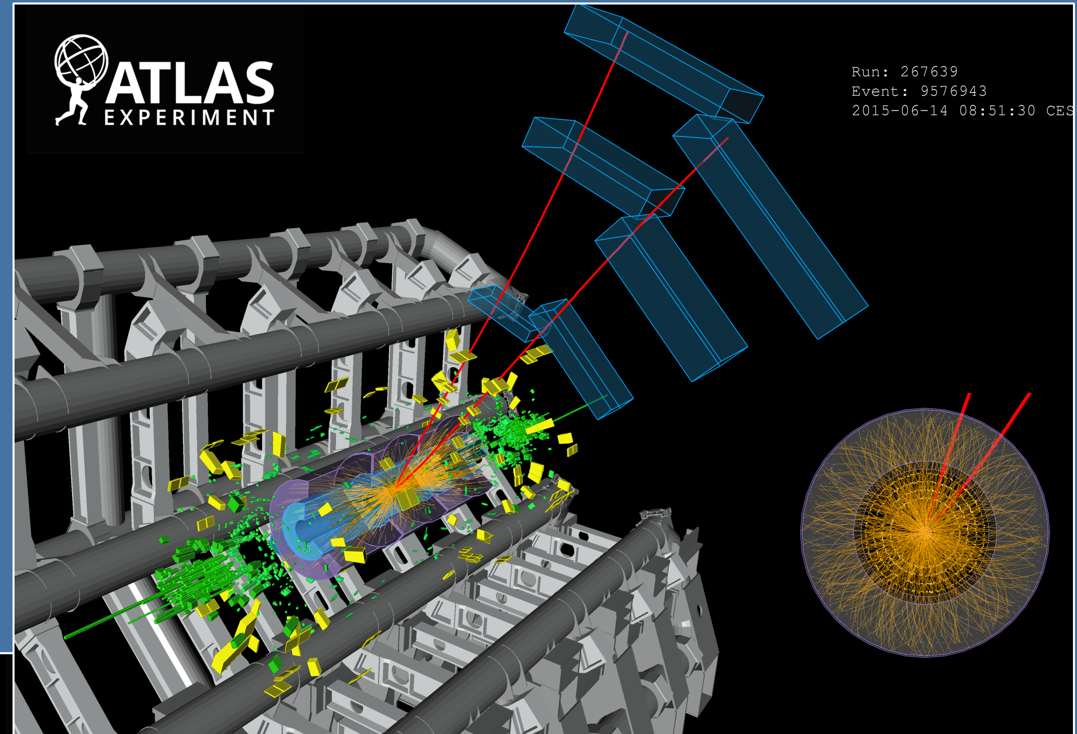
Models with extra (space) also predict di-lepton resonances (Kaluza-Klein)

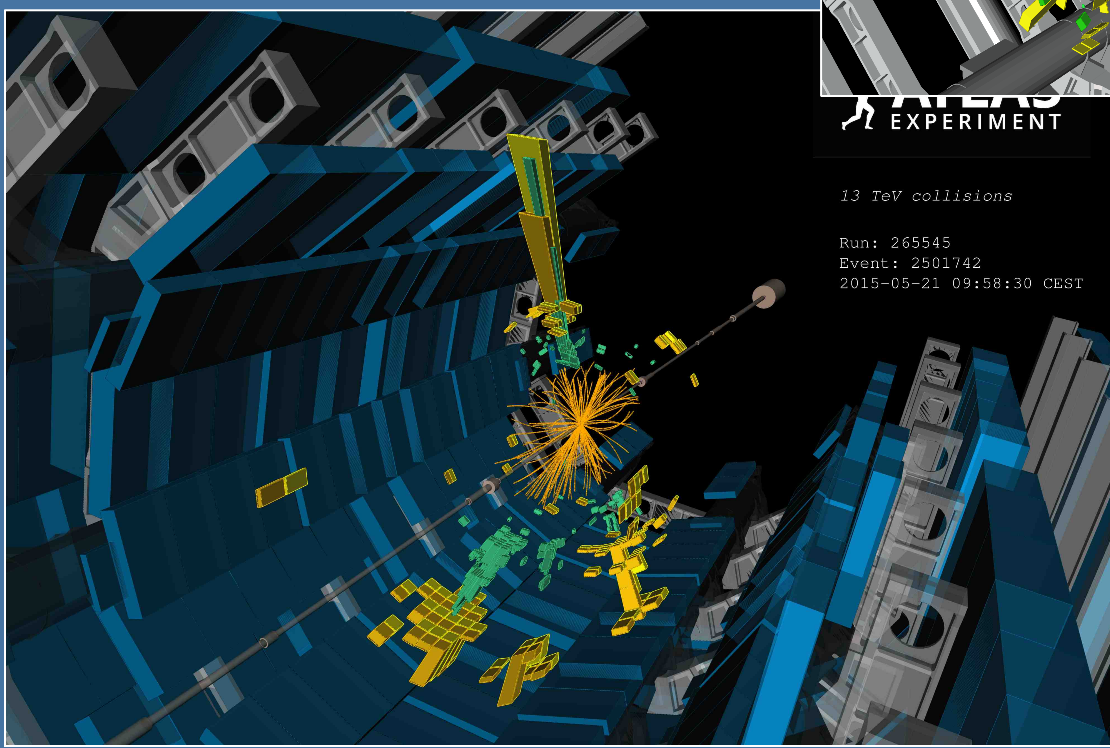
backup


ATLAS
control room

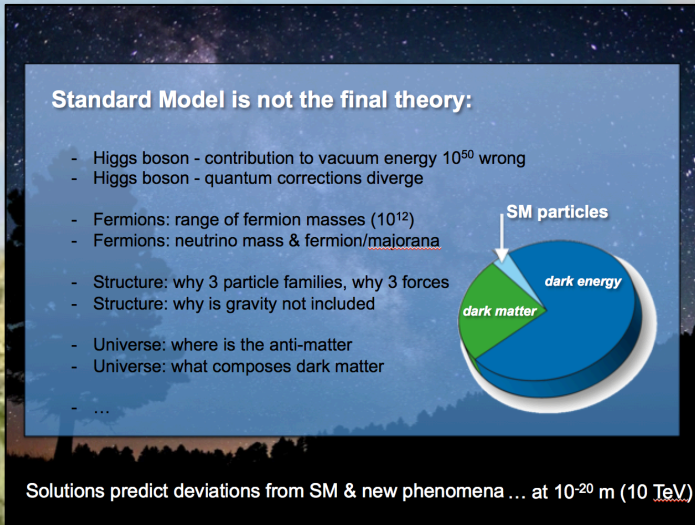
Looking for breakdown of the Standard Model

All results are public:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic





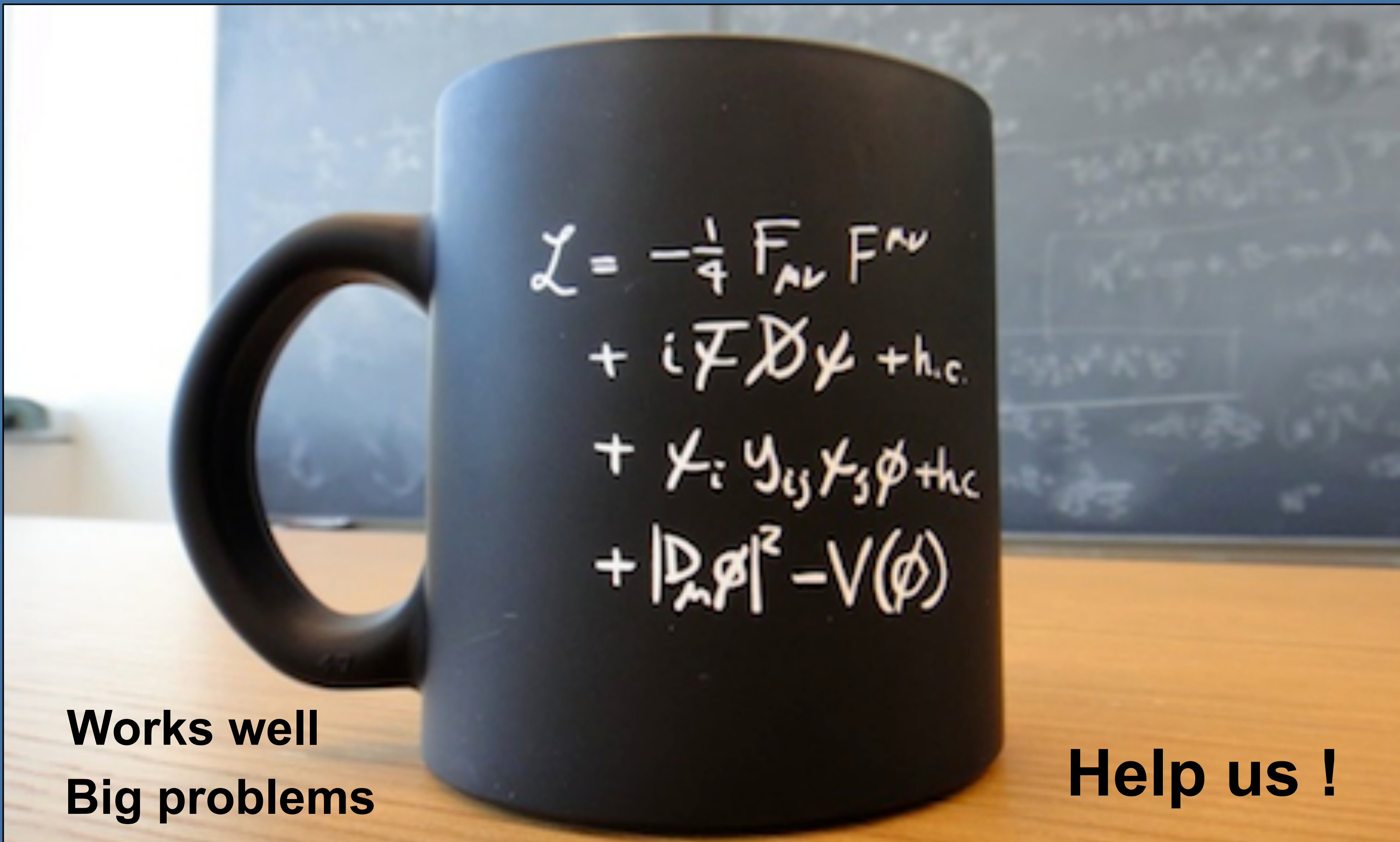
problems



dreams

Much more data coming up …

The Standard Model



Works well

Big problems

Help us !