The Higgs Boson and other new Physics

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The Standard Model
The Higgs Boson
Supersymmetry
other new Physics

PHYSICS AT THE TERA SCALE
Helmholtz Alliance

Elementary Particles

Leptons

knowledge in 1974

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \left(\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}\right)$$

discovery 2000

discovery 1975

Quarks

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

discovery 1995

discovery 1977

In addition an anti particle exists for each particle

Particles and Forces

fermions			interaction	gauge bosons
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}$	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$	$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$	weak	Z, W^+, W^-
			electromagnetic	γ
$\begin{pmatrix} u \\ d \end{pmatrix}$	$\begin{pmatrix} c \\ s \end{pmatrix}$	$\begin{pmatrix} t \\ b \end{pmatrix}$	strong	$g_1, g_2, g_3, g_4, g_5, g_6, g_7, g_8$

Gauge group: $SU(3)_C \times SU(2)_L \times U(1)_Y$

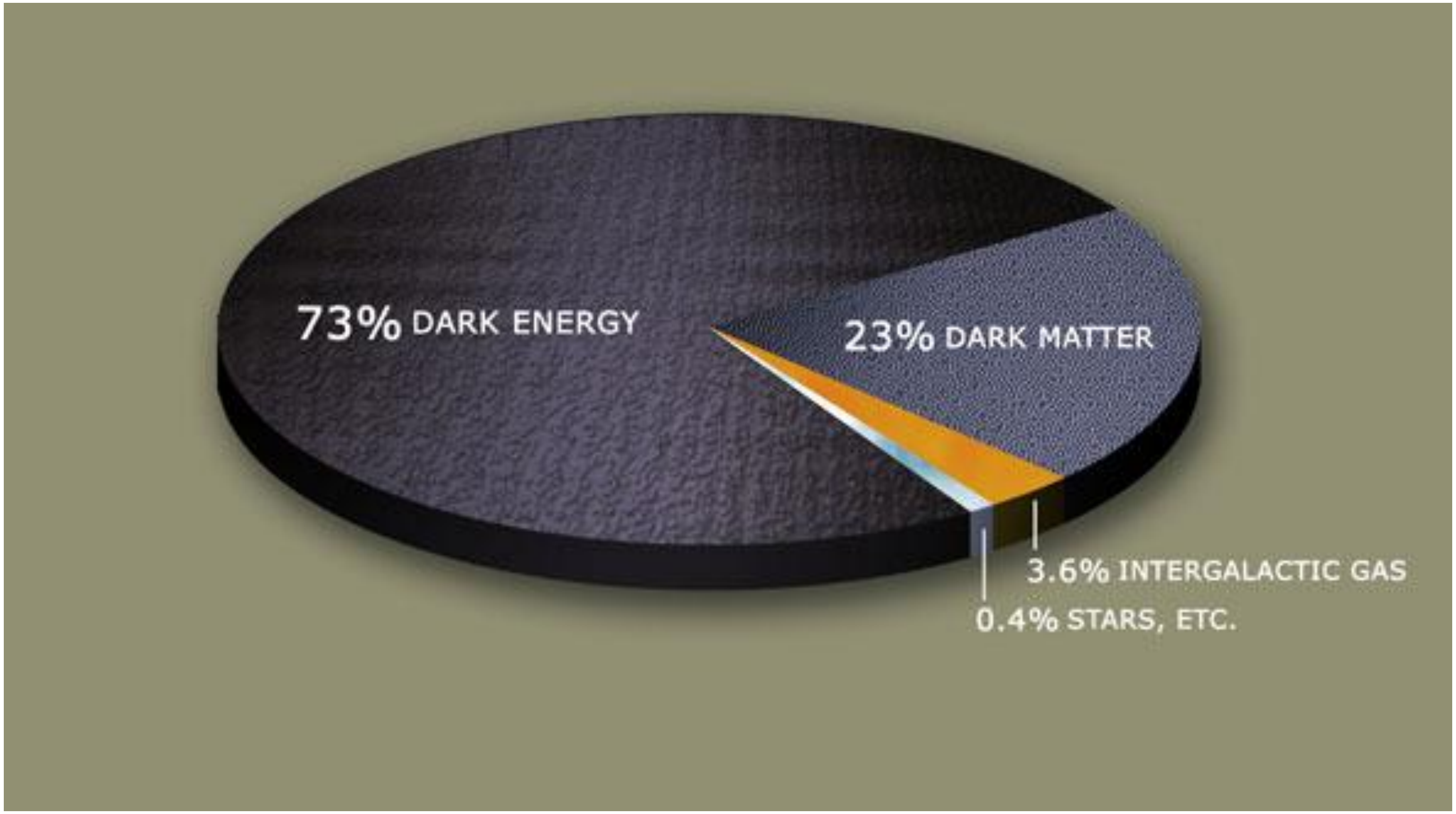
Problem: all particles are massless

Solution: Higgs-field ➔ Higgs particle (not yet discovered)

Free parameters:

- fermion masses	12
- boson masses	M_W, M_H
- coupling constants	α, α_s, $\cos\theta_W$
- Kobayashi-Maskawa matrix elements	4+4

Components of the Universe



accelerated expandierending universe needs dark energy

Gravitational movement in galaxies needs dark matter

only 4% of the universe consists of known matter

Lagrange Densities

Dirac Equation $$\left(i\gamma^{\mu}\partial_{\mu}-m\right)\Psi=0$$

corresponding Lagrange density $$L=i\overline{\Psi}\gamma^{\mu}\partial_{\mu}\Psi-\mathrm{m}\overline{\Psi}\Psi$$

$\Psi,\overline{\Psi}$ are bispinors with 4 components

describe spin ½ particles,e.g. electrons or positrons, with mass m, without interaction

Klein Gordon Lagrange density $$L=\left(\partial_{\mu}\phi^{*}\right)\partial^{\mu}\phi-\mathrm{m}^{2}\phi^{*}\phi$$

ϕ: wave function for particle with spin 0 and mass m

Local Gauge Invariance

requirement of local gauge invariance introduces interactions into Lagrange densities
i.e. fields can adapt local phase transformation

global phase transformation: $\phi \rightarrow \phi' = \phi \cdot e^{i\alpha} \rightarrow \phi'^{*} = \phi^{*} \cdot e^{-i\alpha}$

local phase transformation: $\phi \rightarrow \phi' = \phi \cdot e^{i\alpha(x)}$

e.g.: Klein Gordon Lagrange density $L = \left(\partial_{\mu}\phi^{*}\right)\partial^{\mu}\phi - \mathrm{m}^{2}\phi^{*}\phi$

invariant under global phase transformation
not invariant under local phase transformation, as derivatives also act on α(x)

solution: introduce terms that cancel derivatives
→ these terms describe the gauge bosons

Electroweak Unification

for standard model $SU(2)_L$ x $U(1)$ (left handed doubletts and right handed singuletts)

3 + 1 gauge fields result from local gauge invariance

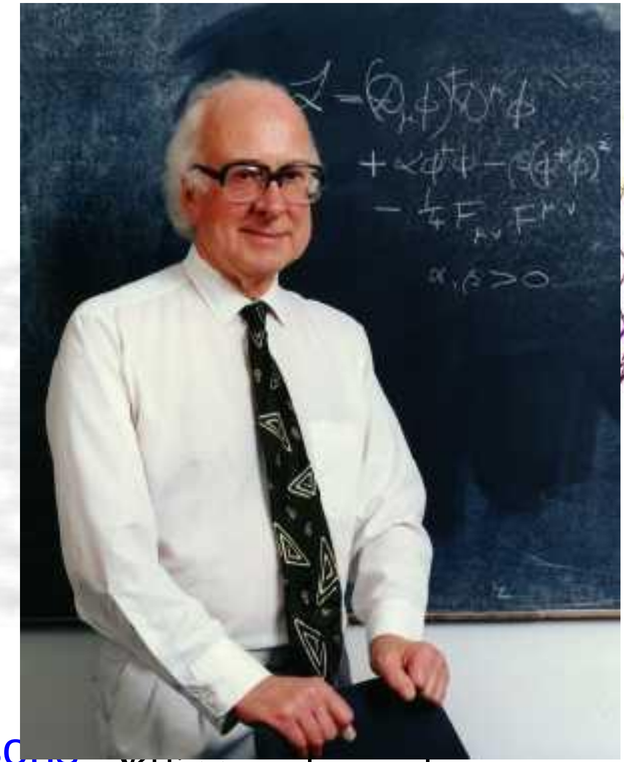
these are W^+, W^-, Z^0 and photon

problem: to fulfill local gauge invariance these gauge bosons have to be massless

contradiction to experiment

$$m(Z) = 91{,}1875 \pm 0{,}0021 \text{ GeV}/c^2$$
$$m(W) = 80{,}399 \pm 0{,}025 \text{ GeV}/c^2$$

Higgs Mechanism



introduce new field $\boldsymbol{\phi}$
new feature: ground state not equal to zero

need two complex fields to give mass to W and Z boso ϕ_{Higgs} … ϕ^{0}

Higgs Lagrange density $$L = \frac{1}{2}\left(\partial^{\mu}\phi\right)^{+}\left(\partial_{\mu}\phi\right) + \frac{1}{2}\mu^{2}\phi^{+}\phi - \frac{1}{4}\lambda^{2}\left(\phi^{+}\phi\right)^{2}$$

with $\mathrm{v} \equiv \dfrac{\mu}{\lambda}$

Gauge Boson Masses

develop around ground state and requirement of local gauge invariance:

$$\mathcal{L} = \left[\tfrac{1}{2}\left(\partial^\mu \eta\right)\left(\partial_\mu \eta\right) - \boxed{\mu^2}\eta^2\right] + \tfrac{1}{2}\boxed{\frac{g^2 v^2}{4}}\left[\left|W^+\right|^2 + \left|W^-\right|^2\right] + \tfrac{1}{2}\boxed{\frac{v^2}{4}\,\frac{g^2}{\cos\Theta_W^2}}\left|Z^0\right|^2$$

plus interaction terms

mass like terms

Higgs (η field), W and Z bosons aquire mass terms
photon does not aquire mass term

masses of W and Z bosons correlated, m(Z) = m(W) / cos θ_W
mass of Higgs boson (m(H) = μ) still unknown, as only v = μ/λ can be measured

$$\mathrm{v} = \frac{\mu}{\lambda} = 2\frac{M_W}{g} = \sqrt{\frac{1}{\sqrt{2}G_F}} = 246\,\mathrm{GeV}$$

G_F: Fermi constant

well measured from muon lifetime

$$\tau_\mu = \frac{192\pi^3}{G_F^2 m_\mu^5}$$

Fermion Masses

fermion masses do not come naturally

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}$$

left handed fermion doubletts have only one mass value in electroweak gauge unification
experiment: $m(e^-) \neq m(\nu_e)$

mass term in Lagrangian has to be set to zero

additional Yukawa Lagrangian needed for each fermion

result of development around minimum of Higgs potential:

interaction term of Higgs boson with fermion (coupling strength g_f)
and mass term for fermion $m_f = g_f \ v$
→coupling of Higgs Boson to fermions proportional to fermion mass

coupling strength $g_f = m_f / v$ depends on Higgs boson mass $m(H) = \mu = v \cdot \lambda$

Interactions

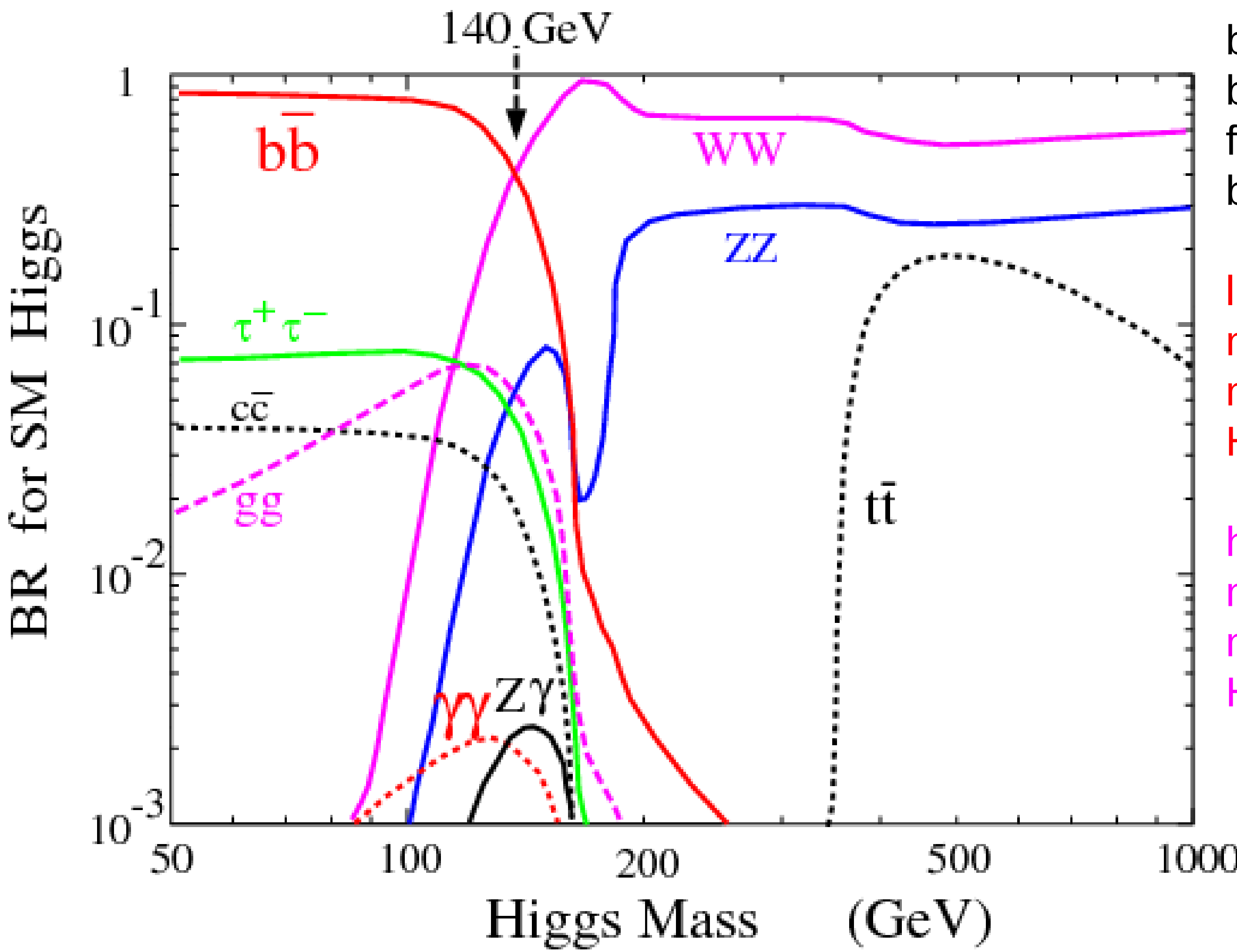
concept of gauge invariance introduces also interaction terms

$$\mathcal{L}_{WW} = -\frac{m_H^2}{2v}H^3 - \frac{m_H^2}{8v^2}H^4 - \frac{m_f}{v}\overline{f}Hf - m_f\overline{f}f$$
$$+ M_W^2 W_\mu^+ W^{\mu-}\left(1 + \frac{2}{v}H + \frac{1}{v^2}H^2\right) + \frac{1}{2}M_Z^2 Z_\mu Z^\mu \left(1 + \frac{2}{v}H + \frac{1}{v^2}H^2\right)$$

strength of coupling to gauge bosons ~ mass$^{\mathbf{2}}$ of gauge bosons

couplings of gauge bosons and fermions to Higgs boson (and Higgs self couplings) can be calculated in the Standard Model
but they depend on the Higgs boson mass

Branching Ratios

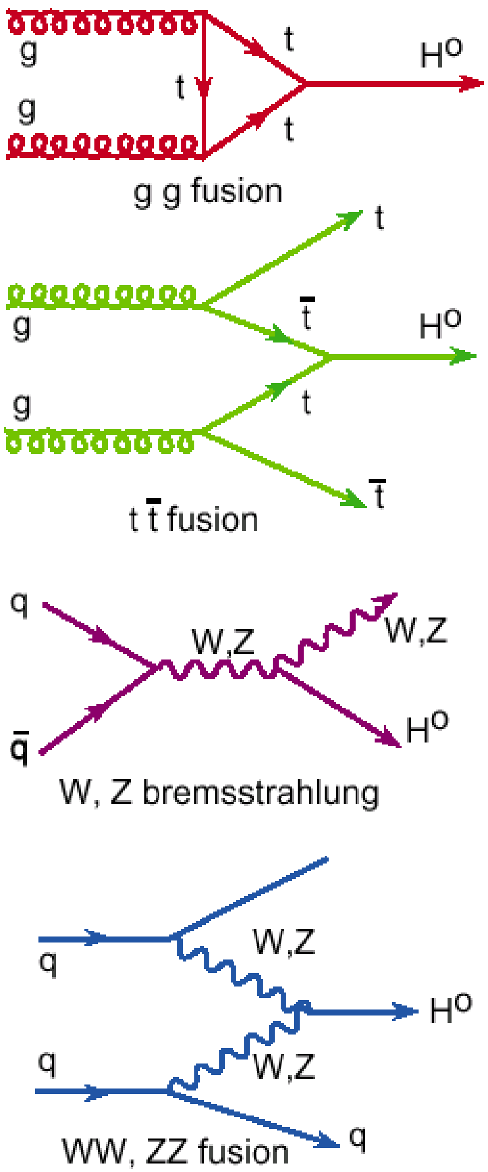


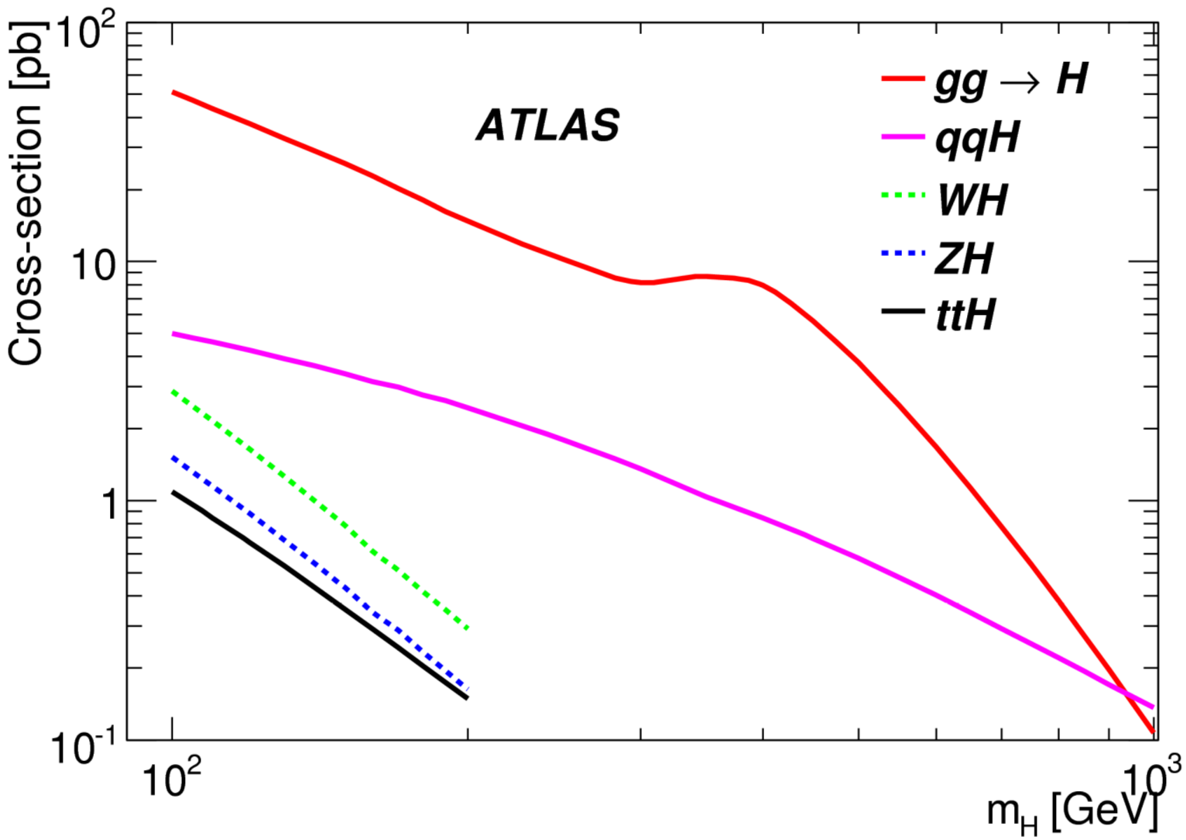
branching ratios can be calculated as function of Higgs boson mass

light Higgs boson
m(H) < 140 GeV
main decay mode
$H \rightarrow bb$

heavy Higgs boson
m(H) > 140 GeV
main decay mode
$H \rightarrow W^+W^-$

Higgs Production at the LHC

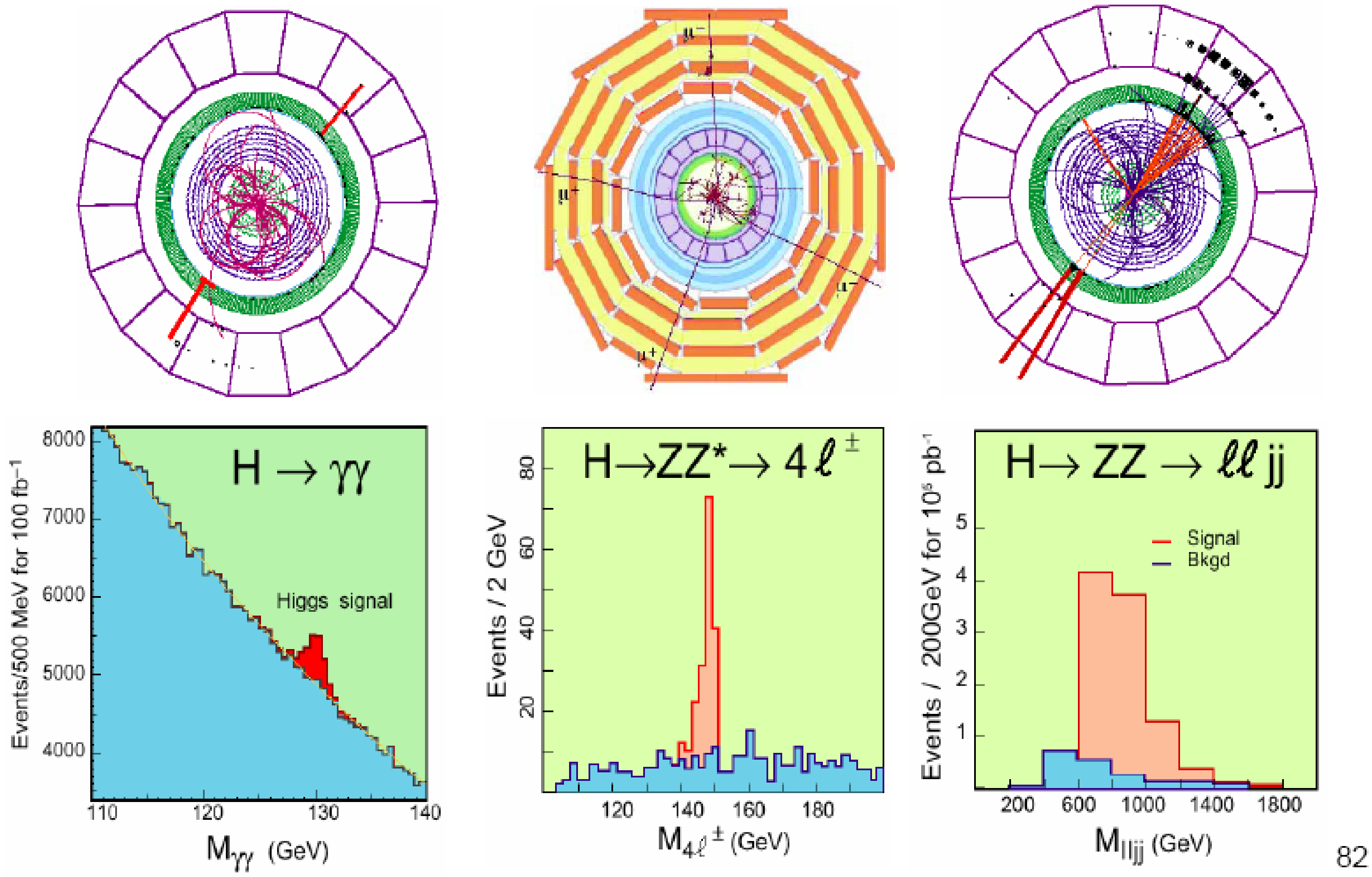




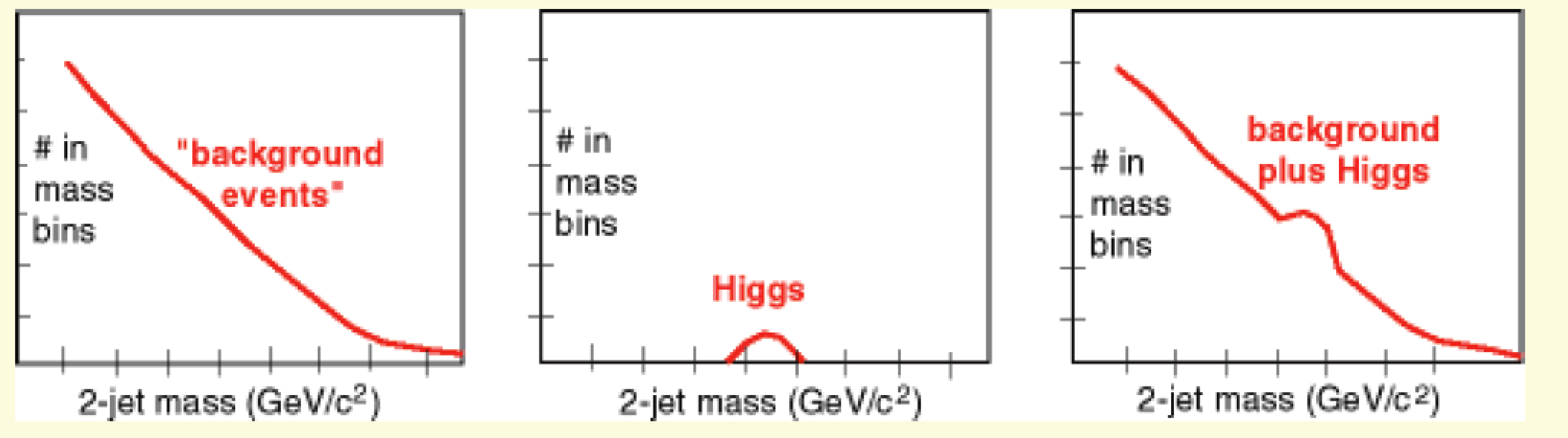
Main production mode: gluon fusion, but for decay into bottom quarks too much background

Expected Signatures

Standard Model Higgs signal examples in CMS



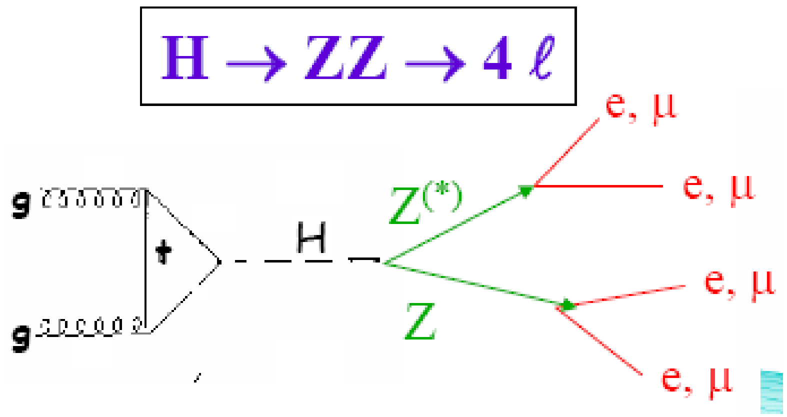
Signal and Background



Higgs signal will be small bump on top of SM events

try to fit background from data, as predictions from simulation less accurate

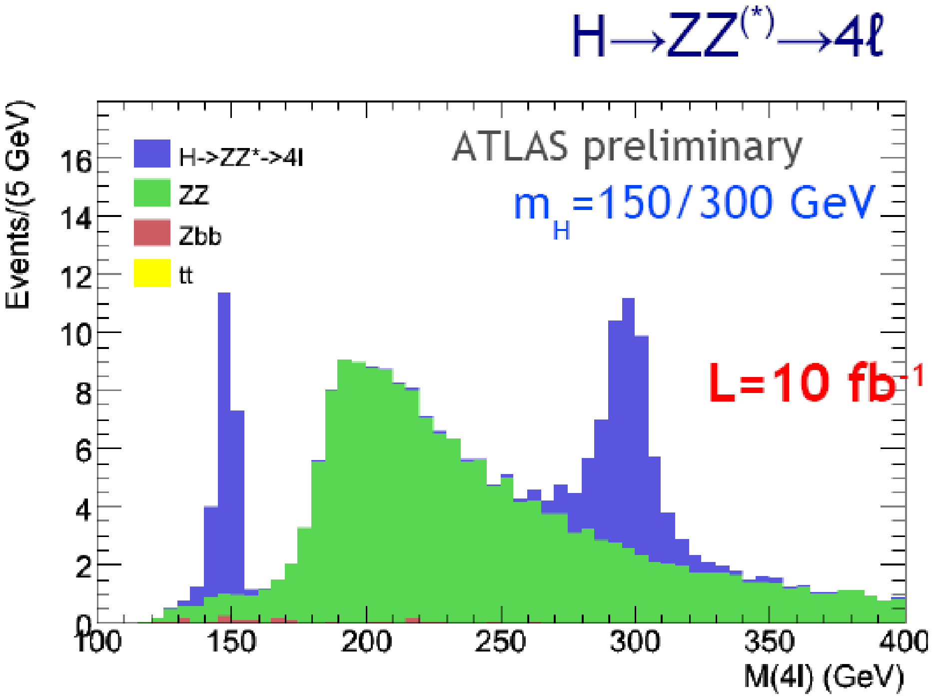
Higgs → ZZ



- gold plates channel
- properties of Z boson very well known
- decay into leptons
  → very good mass resolution
- low branching ratio

background mainly irreducible ZZ production

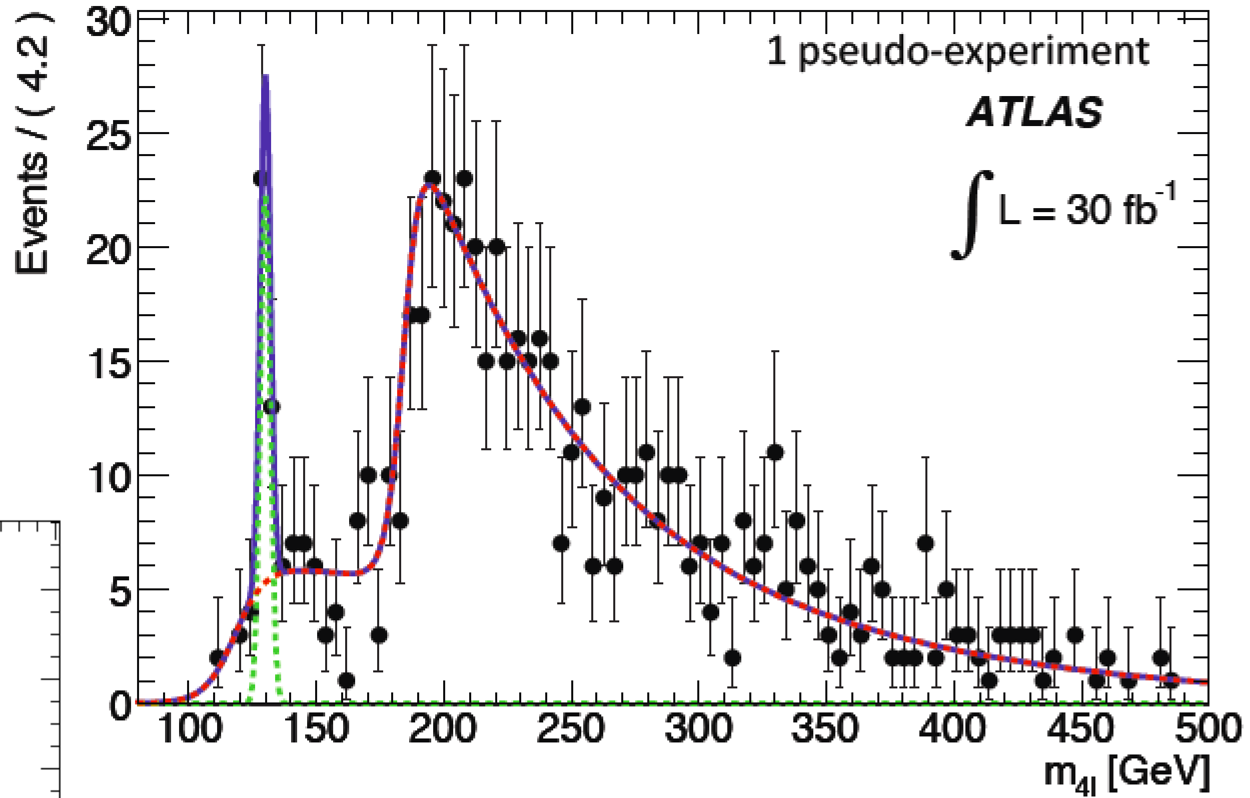
BR of Higgs boson into ZZ small for m(H)<140 GeV

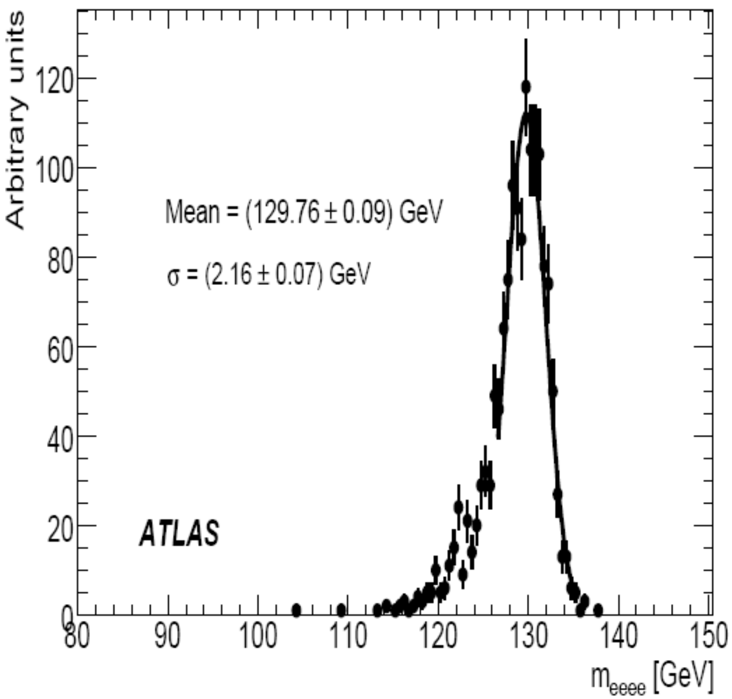


Example

expected result for
m(H) = 130 GeV

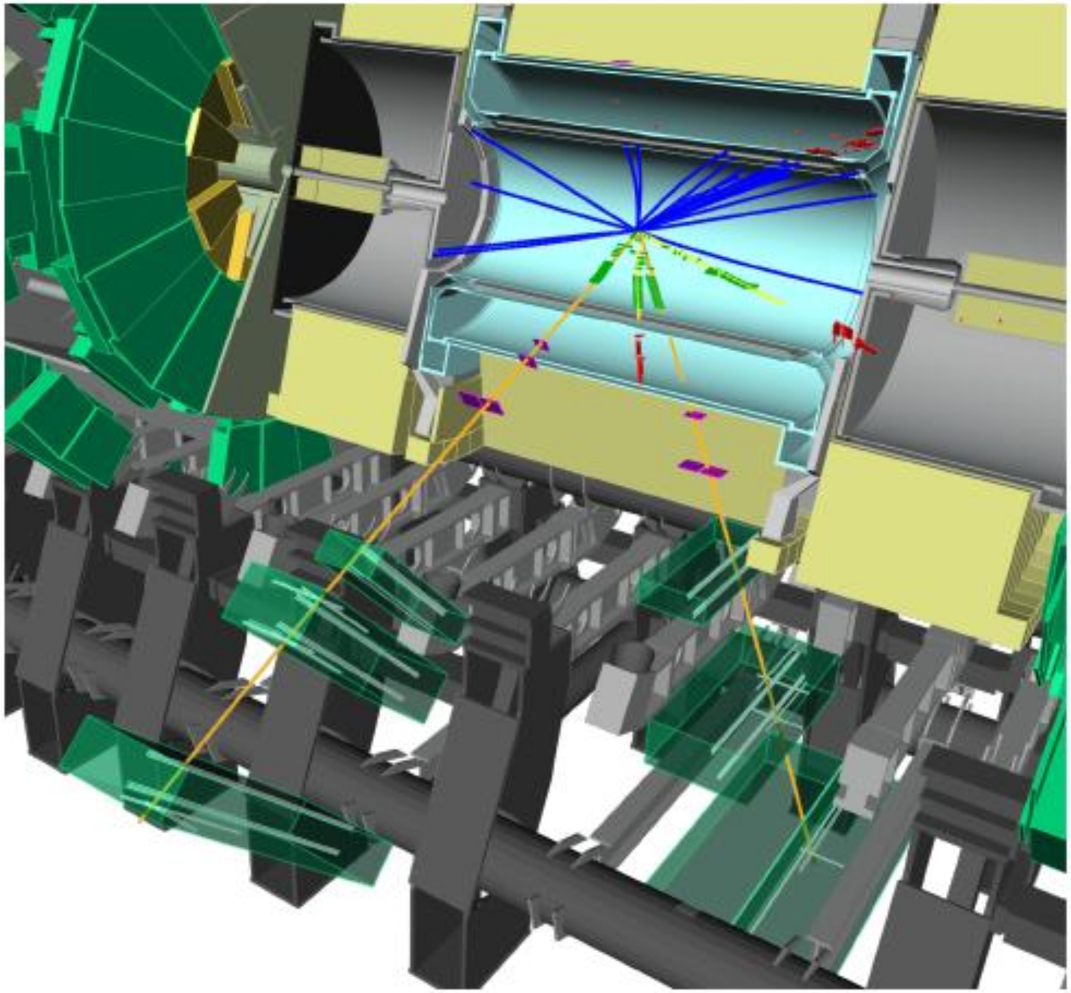
background described by smooth function





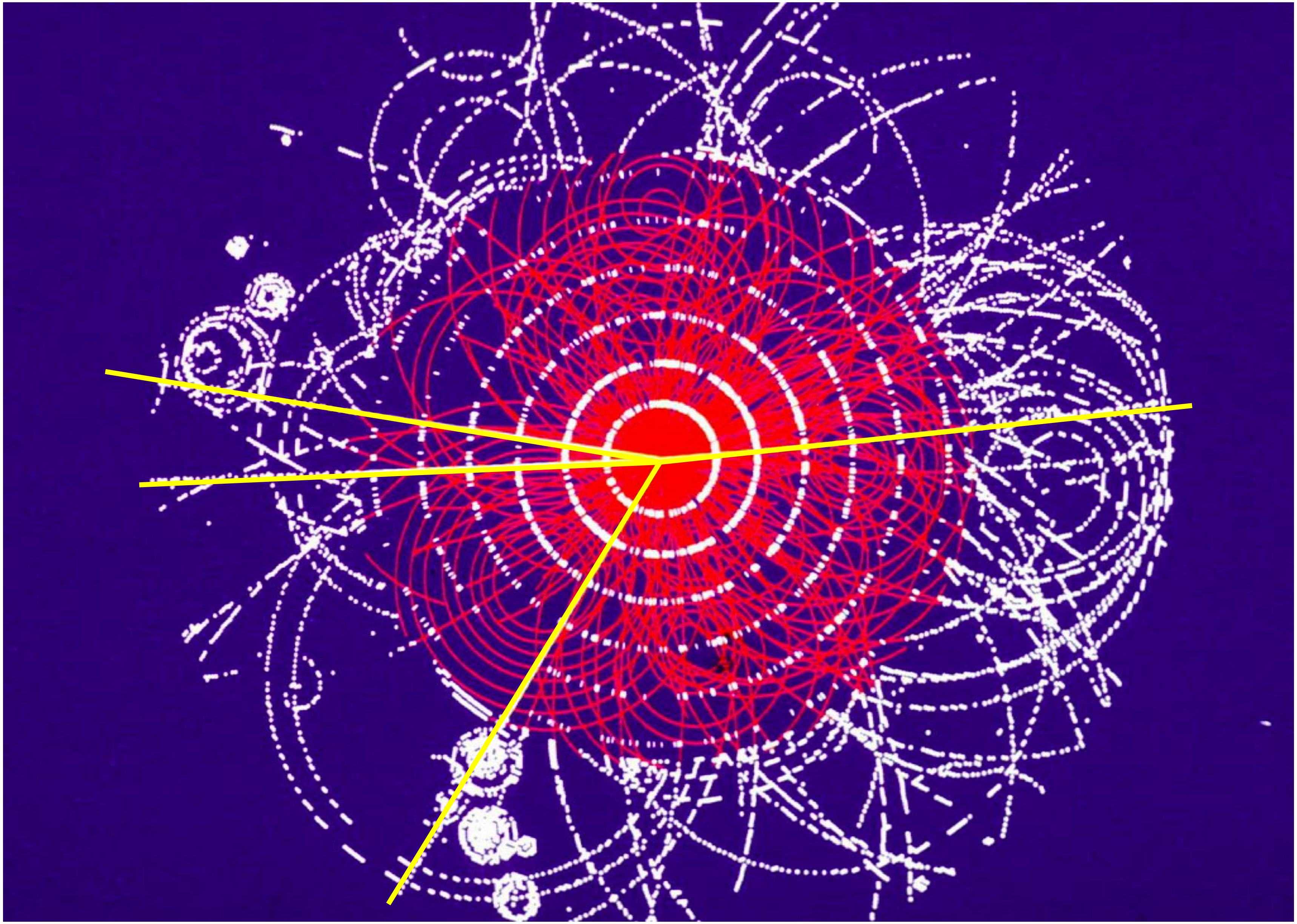
width of signal only 2 GeV

Event Display

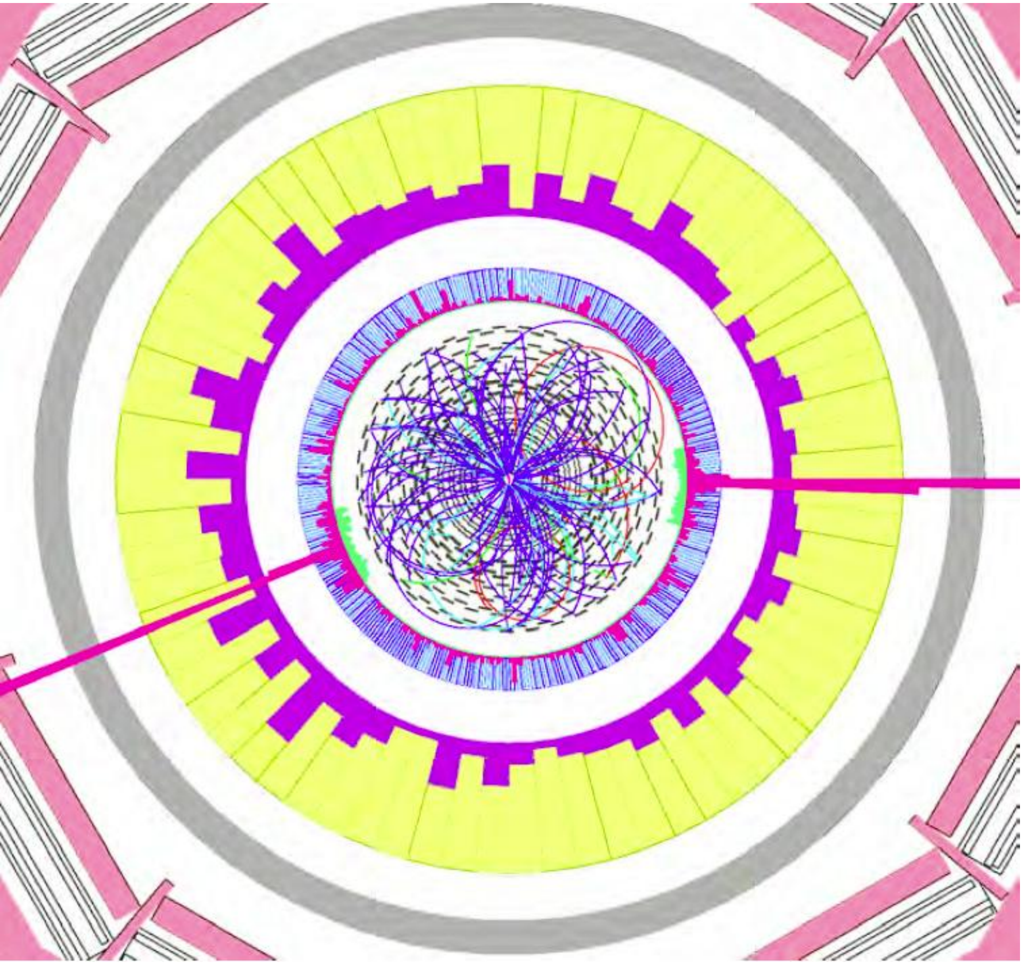


Display of a high-p_T $H \rightarrow ZZ \rightarrow ee\mu\mu$ decay (m_H = 130 GeV), after full simulation and reconstruction in the ATLAS detector. The four leptons and the recoiling jet with E_T = 135 GeV are clearly visible.

Higgs Event



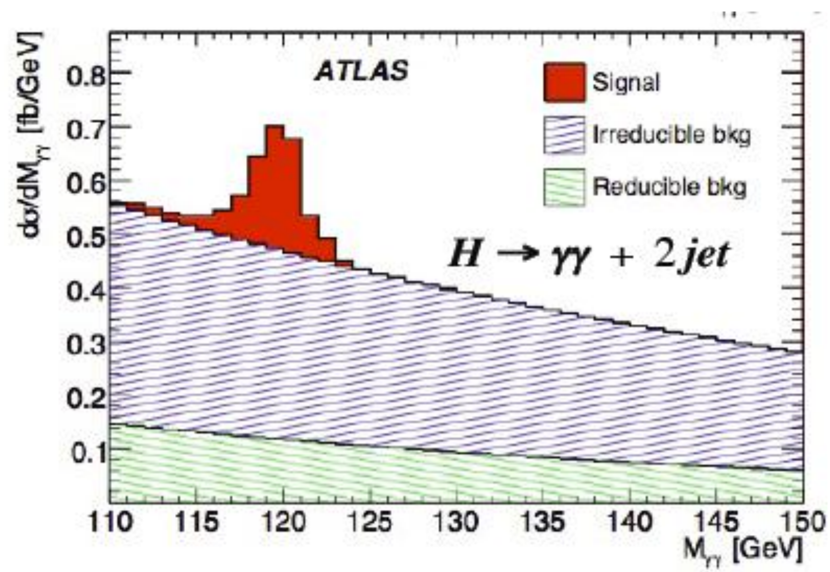
H→$\gamma\gamma$



very low branching ratio as loop process

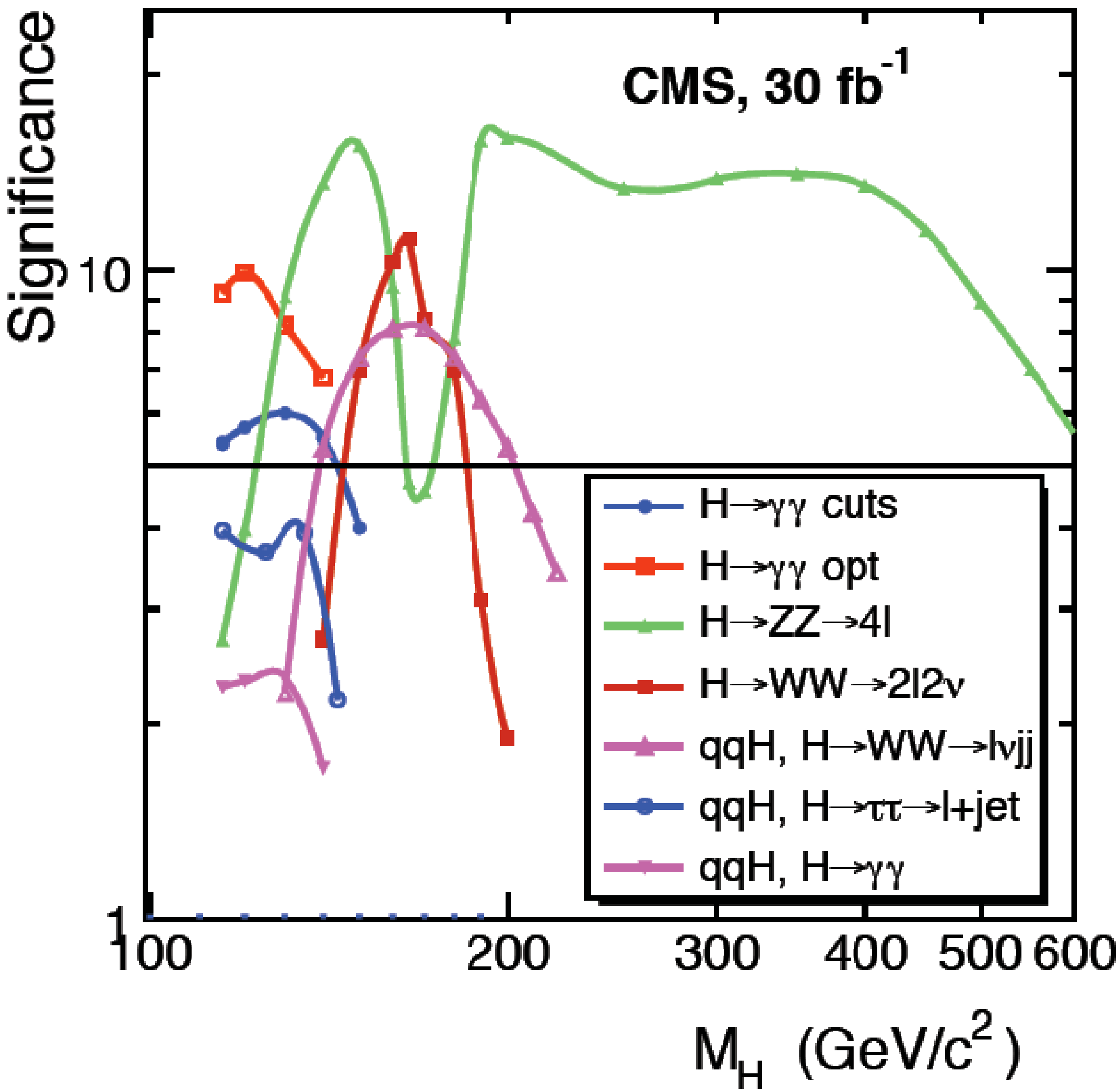
no direct coupling of Higgs boson to photon

clean signature and good mass resolution



for m(H)<125 GeV best channel

Total Significance



different optimisations of experiments for different analyses

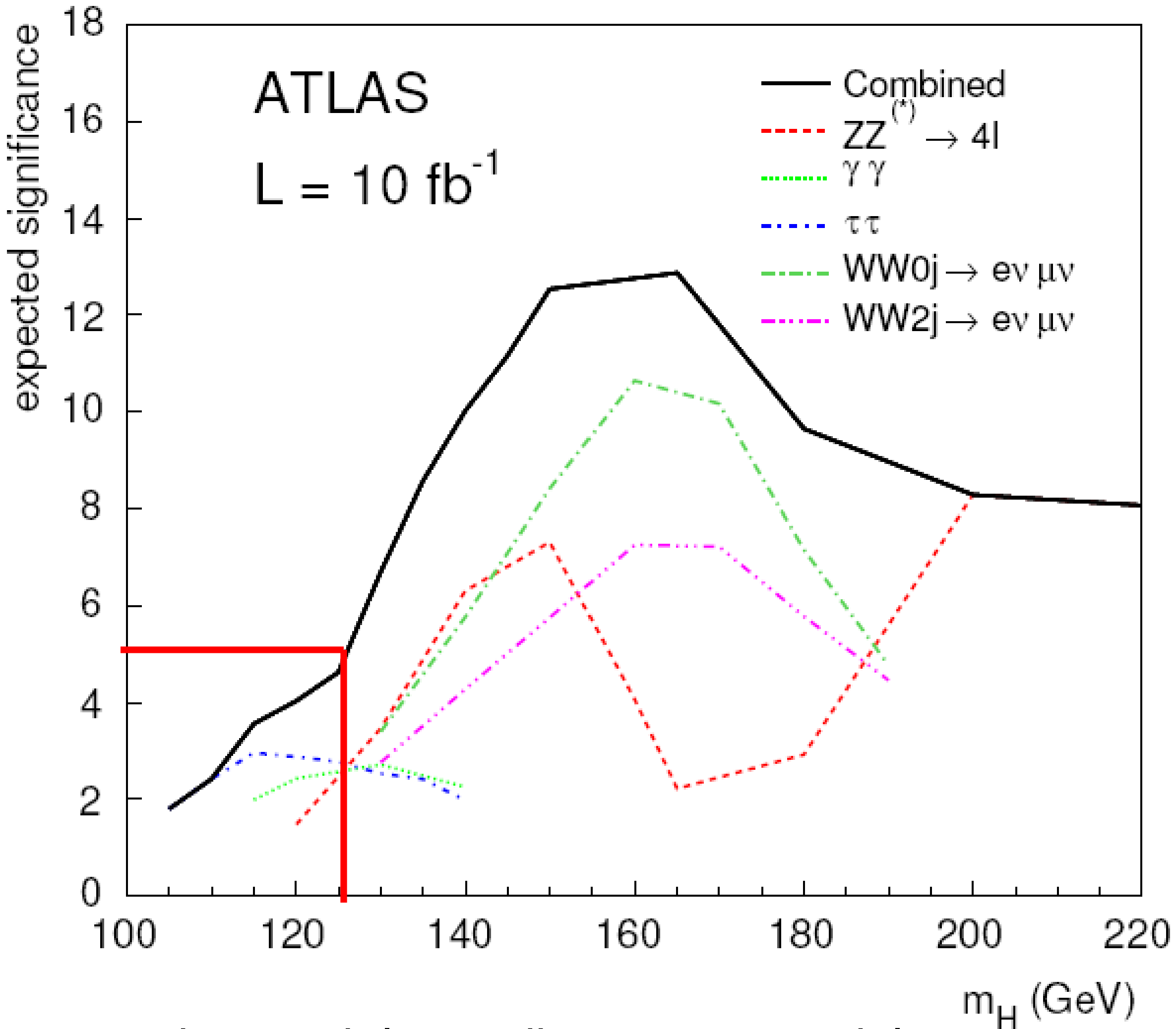
very good electromagnetic calorimeter of CMS allows very good photon ID

For L_{int} = 30 fb^{-1} full Higgs boson mass range above 5σ

Total Significance

5 σ discovery potential at 10 fb^{-1}:

m(H) > 127 GeV



For lower centre-of-mass energies much lower discovery potential

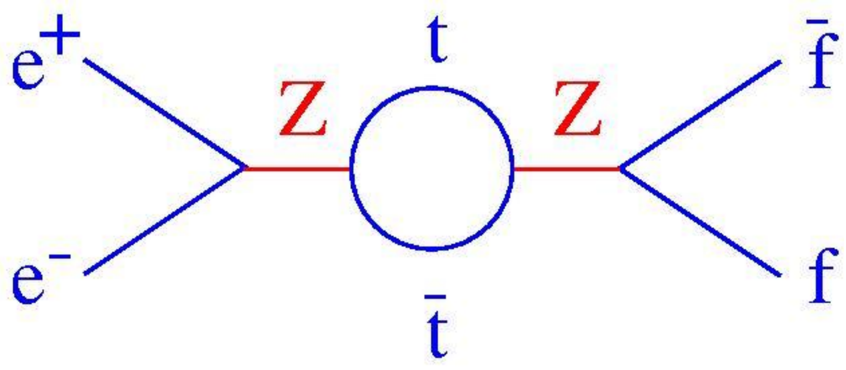
Radiative Corrections

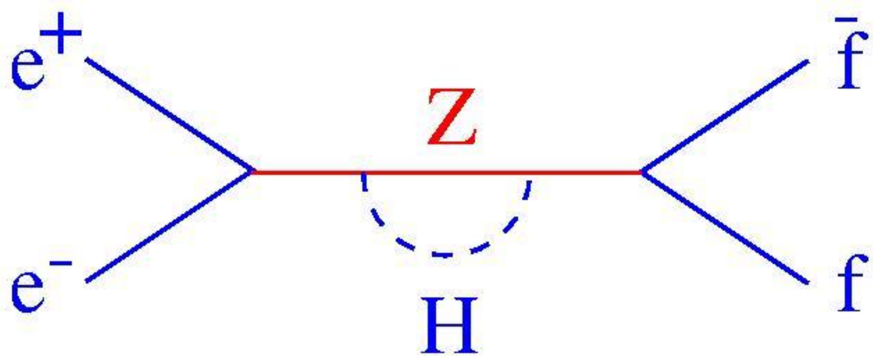
Feynman rules:

• Matrix elements valid for given order in pertubation theory

• Pertubation theory, coupling constant <<1: $\alpha \approx 1/137$
• Problems for α_s at small momentum transfer

Higher order processes contain virtual particles
→ sensitivity for particles with mass larger than centre-of-mass energy





$\sim \log(m_{Higgs} / \mathrm{GeV}/c^2)$

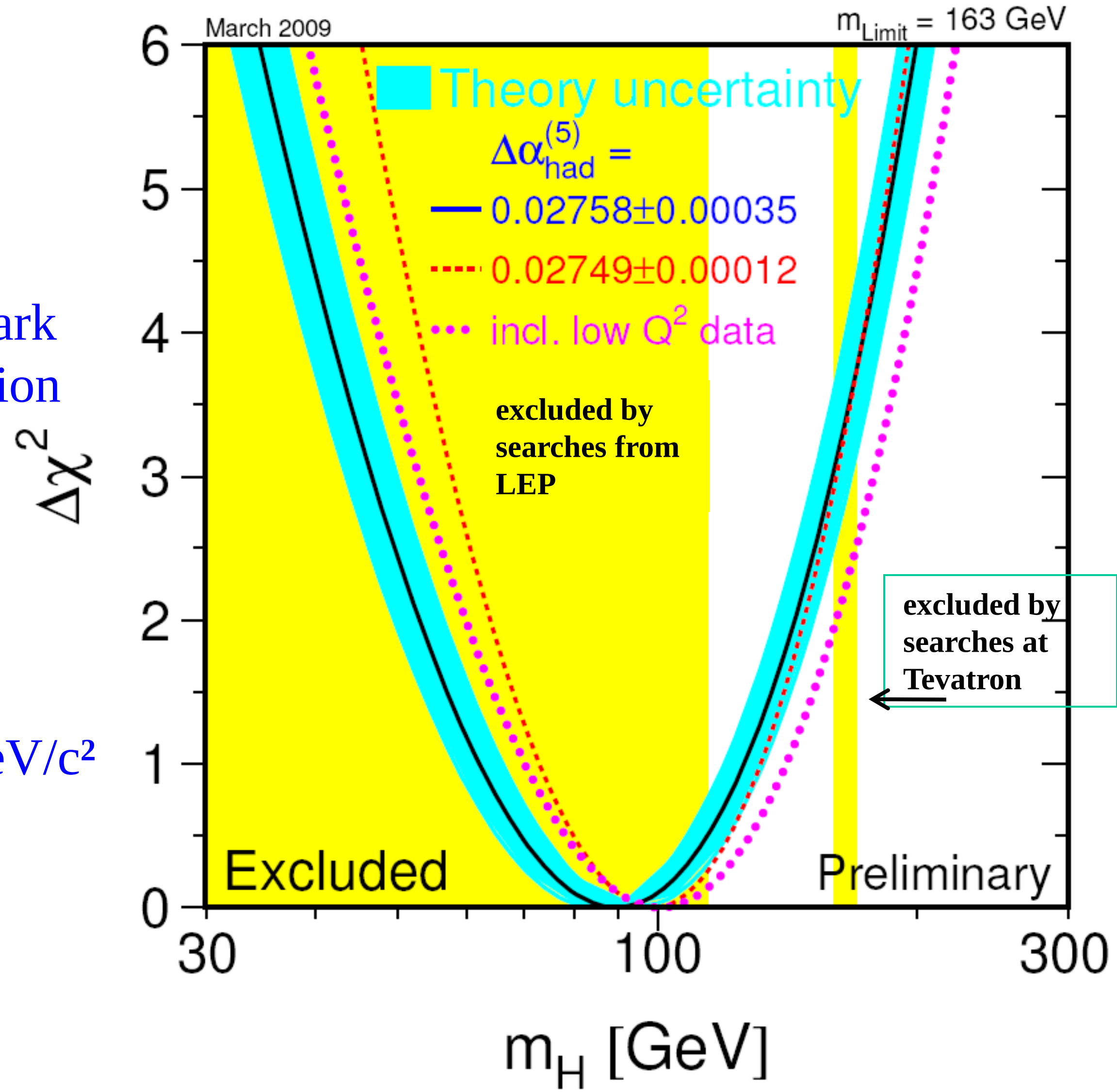
Higgs Mass

last free parameter:
Higgs boson mass

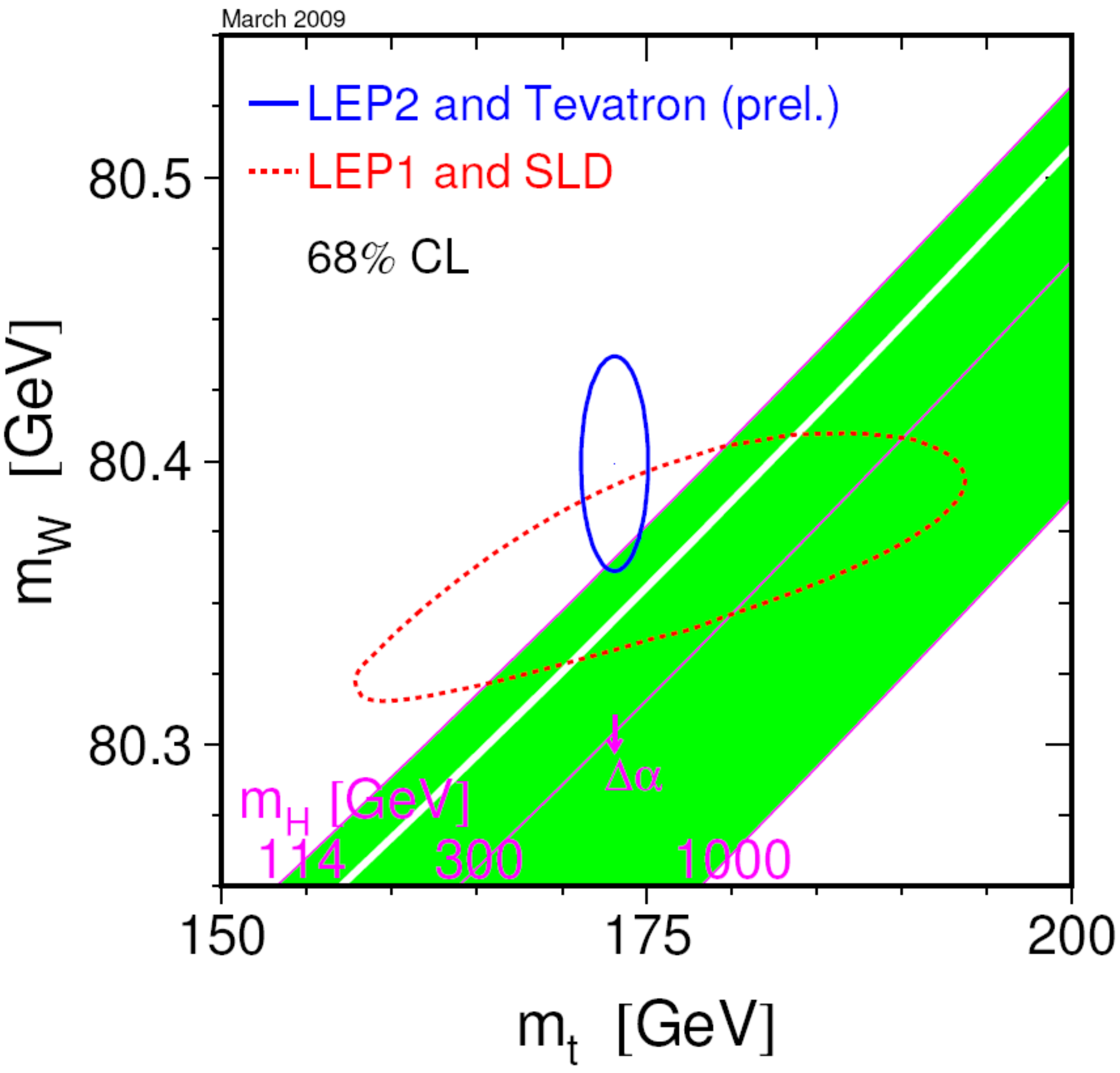
Tevatron measurement of top quark mass has large impact on prediction of Higgs mass

most probable value for higgs mass 90^{+36}_{-27} GeV/c^2

upper limit (95% CL) is 163 GeV/c²



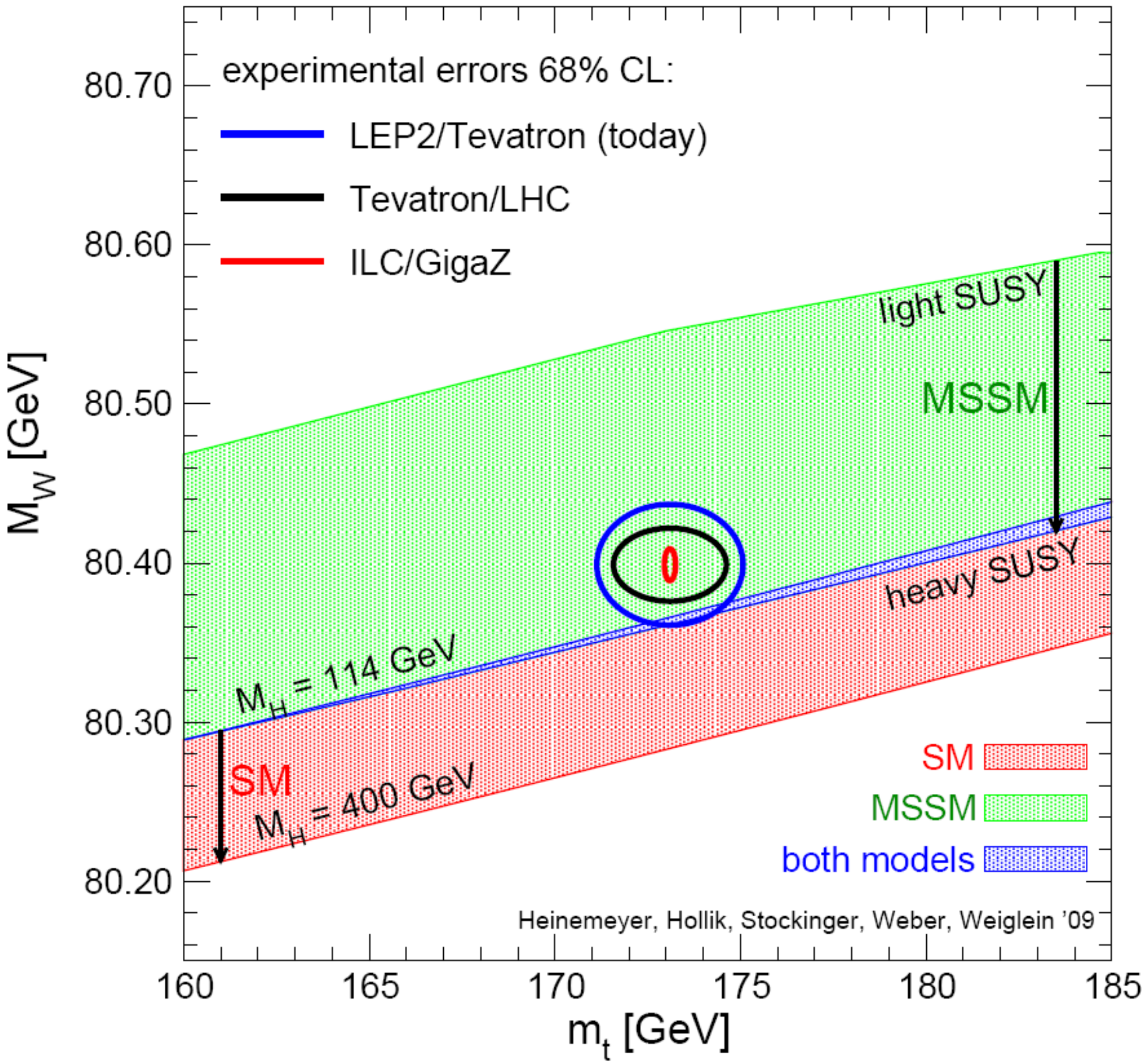
Limits on Higgs Boson Mass



direct measurements of top quark mass and W boson mass give strong limits on higgs boson mass

current direct measurements at lower limit of excluded Higgs mass range

Super Symmetry



Direct measurement of
W boson and top quark mass

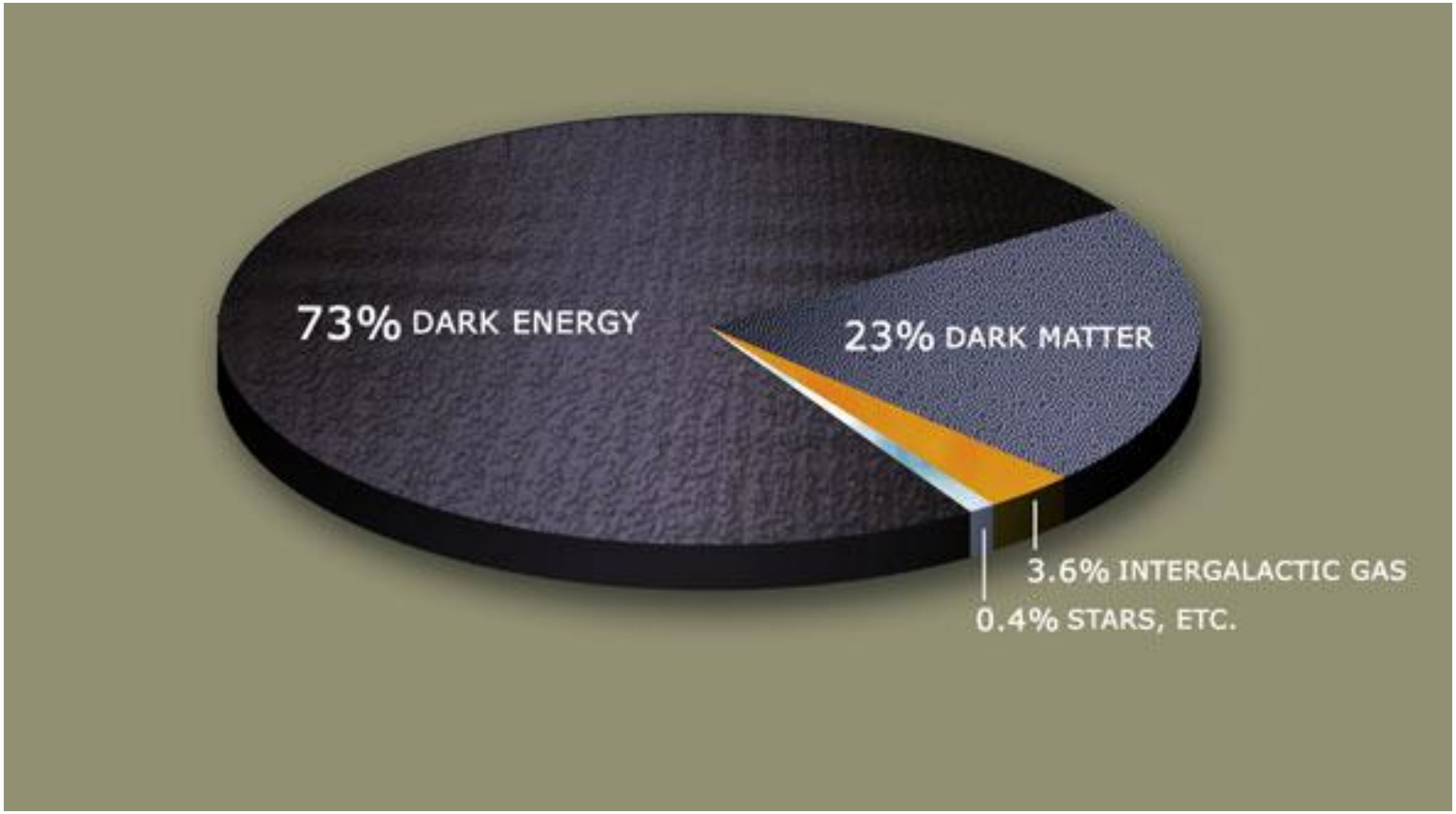
comparison with prediction from other electroweak measurements as function of Higgs boson mass
(last free parameter)

recent measurements prefer SUSY

uncertainty still large

LHC and ILC should answer this question

Components of the Universe



mass of stable matter, e.g. stars:

1% from Higgs mechanism

99% from binding energy

Cross Sections

total cross section: 10^{8} nb

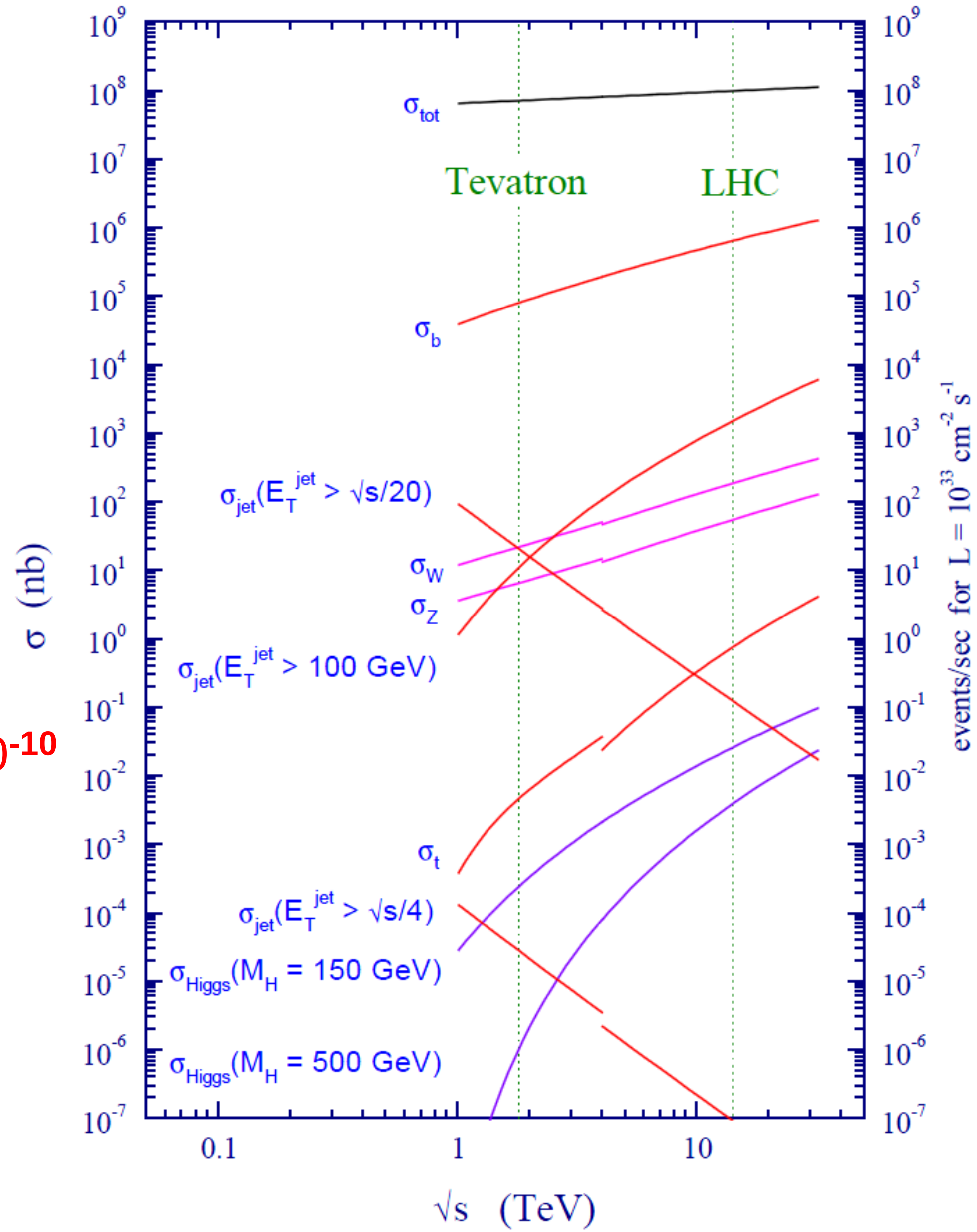
production of heavy gauge bosons:
$\sigma \approx 100$ nb

production of top quark pair:
$\sigma \approx 1$ nb

production of Higgs boson:
$\sigma \approx 0.01$ nb

interesting events order of 10^{-6} to 10^{-10}

cross section for heavy particles increases strongly with centre-of-mass energy as pdf's are very steep

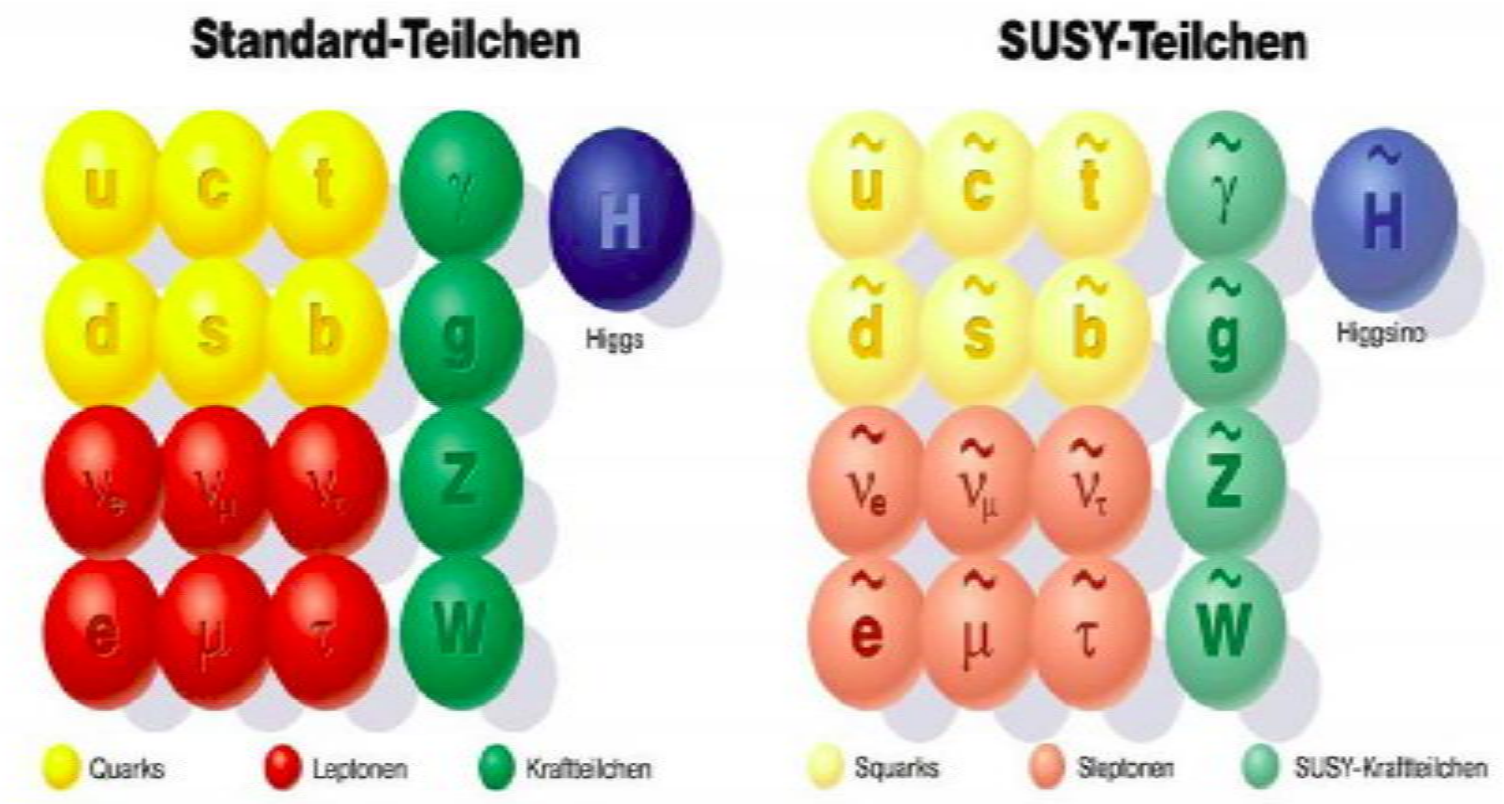


SUSY

Standard modell of particle physics has many open questions:
- values of masses
- electric charge of leptons and quarks
- number of families

In SUSY every fermion gets bosonic partner and each boson gets fermionic partner
→ symmetry between bosons and fermions

But many new free parameters



SUSY Motivation

Mass of Higgs boson requires very accurate cancellantions (O (-16))

1. order pertubation theory: $M_h^2 \propto M_{h0}^2 + \frac{\lambda}{4\pi}\Lambda^2 + \delta M_h^2$

in SM no new physics up to Planck scale
→ $\Lambda \approx$ Planck scale = 10^{19} GeV
→ fine tuning of δM_h^2 of O (-16), to be repeated in each order pertubation theory

→ equal number of fermions and bosons solve hirarchy problem
(loop contribution with opposite sign → cancel each other)

SUSY particles not yet observed (e.g. SUSY partner of electron not discovered yet)
→ SUSY broken
→corrections to Higgs boson mass ~ SUSY mass scale rather than M_{planck}

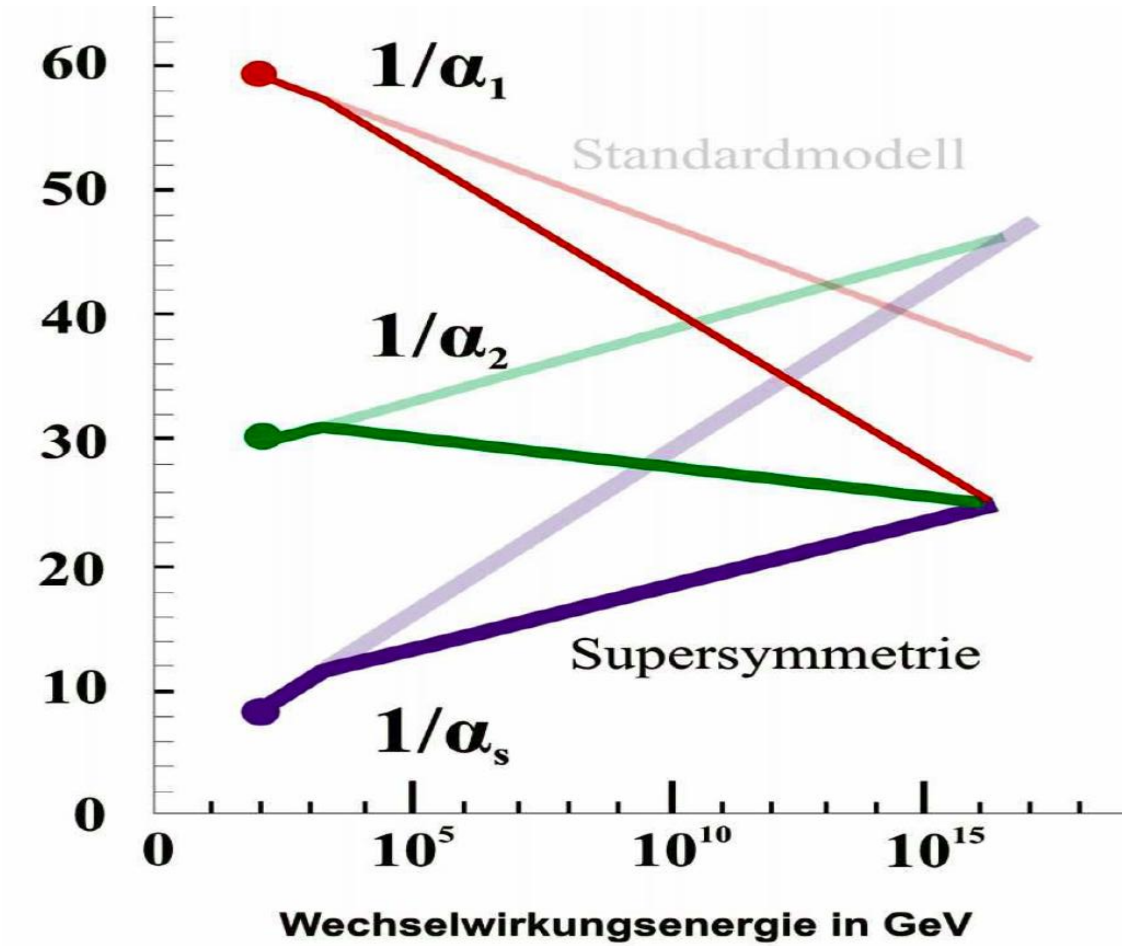
- each Standard Model particle gets SUSY partner
- spins differ by ½
- 2 Higgs doubletts needed to give mass to up- and down-type quarks

Particle Spectrum

SM	Supersymmetry			
	weak eigenstates	name	mass eigenstates	
q	$\tilde{q}_L$, $\tilde{q}_R$	s–Quark	$\tilde{q}_1$, $\tilde{q}_2$	
ℓ	$\tilde{\ell}_L$, $\tilde{\ell}_R$	s–Lepton	$\tilde{\ell}_1$, $\tilde{\ell}_2$	
ν	$\tilde{\nu}$	s–Neutrino	$\tilde{\nu}$	
g	$\tilde{g}$	gluino	$\tilde{g}$	
$W^\pm$	$\tilde{W}^\pm$	wino		
H_1^+	$\tilde{H}_1^+$	higgsino	$\tilde{\chi}_{1,2}^\pm$	Chargino
H_2^-	$\tilde{H}_2^-$	higgsino		
W^0	$\tilde{W}^0$	wino		
B^0	$\tilde{B}^0$	bino		
H_1^0	$\tilde{H}_1^0$	higgsino	$\tilde{\chi}_{1,2,3,4}^0$	Neutralino
H_2^0	$\tilde{H}_2^0$	higgsino		

Higgs sector: five Higgs particles: h, H, A, H^+, H^-

Coupling Constants



additional feature of SUSY:

all 3 coupling constants meet at ~10^{16} GeV

→ can be embedded in Grand unified theories

 m_0 (GeV)

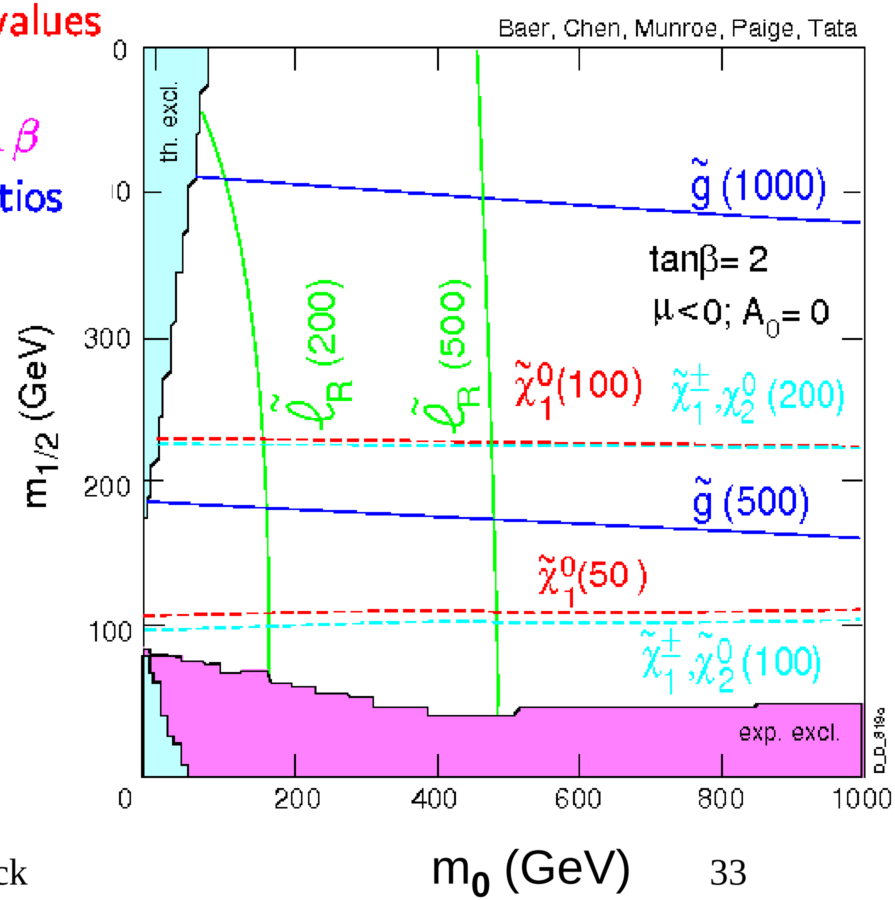
mSUGRA

common masses for sfermions and gauginos at GUT scale

- m_0 : common mass for sfermions at GUT scale
- $m_{1/2}$: common masses for gauginos at GUT scale
- A_0 : common trilinear Higgs-sfermion-sfermion coupling at GUT scale
- μ : mixing of Higgs doublets
- $\tan\beta = \frac{\langle \nu_2 \rangle}{\langle \nu_1 \rangle}$: ratio of Higgs vacuum expectation values

$\rightarrow$ 5 free parameters: m_0, $m_{1/2}$, A_0, sign(μ), $\tan\beta$

determine all masses, cross-sections, branching ratios



Sparticle Masses and Decay Chains

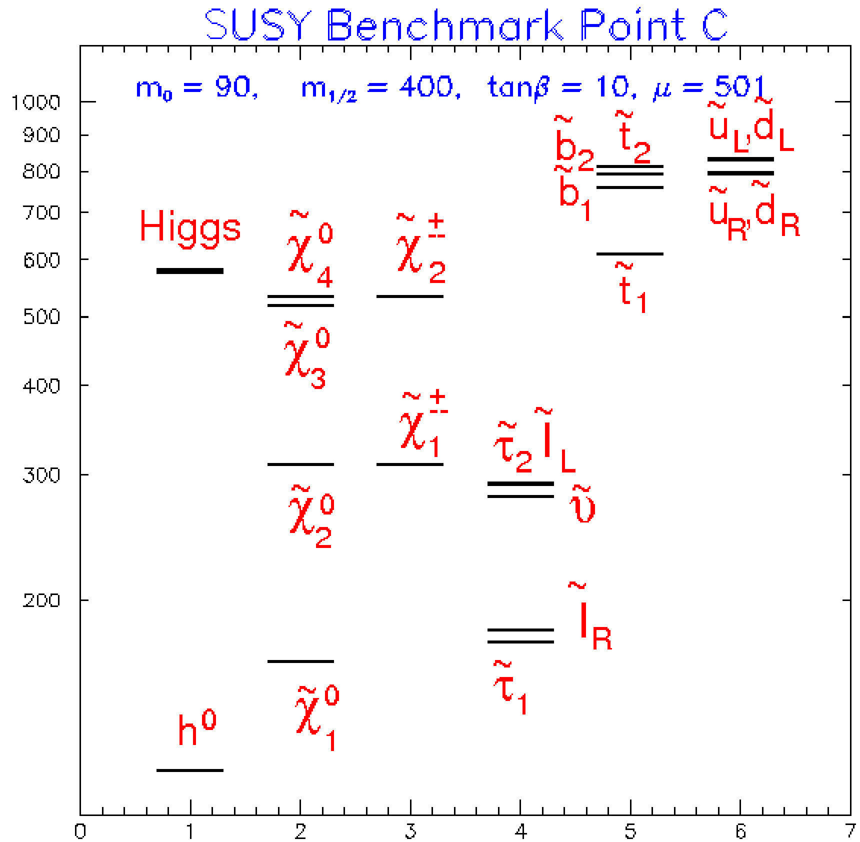
$m^2(\tilde{\ell}_R) \approx m_0^2 + 0.15\ m_{1/2}^2$ $\quad m^2(\tilde{\ell}_L) \approx m_0^2 + 0.52\ m_{1/2}^2$

$m(\tilde{\chi}_1^0) \approx 0.45\ m_{1/2}$ $\quad m(\tilde{\chi}_2^0) \approx m(\tilde{\chi}_1^\pm) \approx 0.9\ m_{1/2}$

$m^2(\tilde{g}) \approx 6.25\ m_{1/2}^2$ $\quad m^2(\tilde{q}) \approx m_0^2 + 6\ m_{1/2}^2$

for $m_0 > 0.45\ m_{1/2}$ sleptons heavier than $\tilde{\chi}_2^0, \tilde{\chi}_1^\pm$

3rd generation sparticles lighter due to mixing and large Yukawa couplings



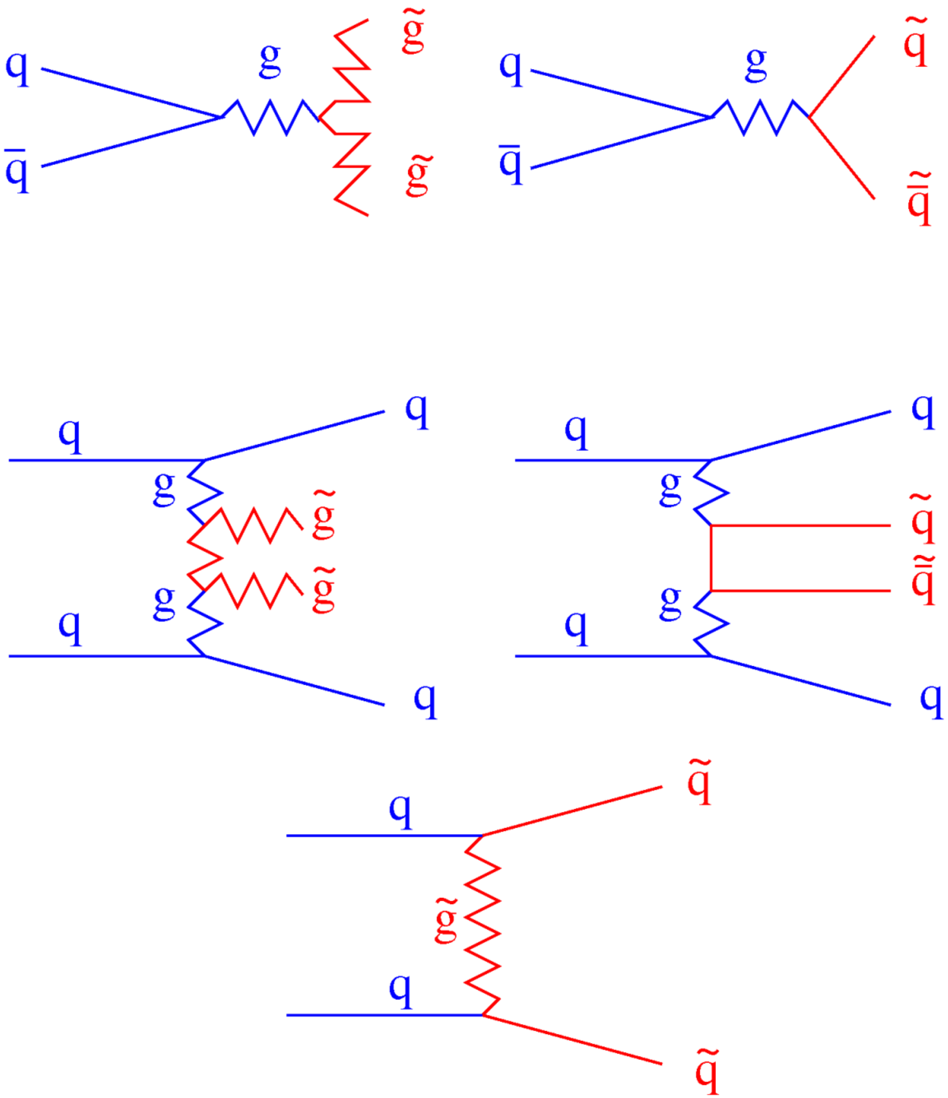
Production of SUSY Particles

LHC is hadron collider, so largest cross section for coloured particles

same diagramms as for SM quarks and glouns

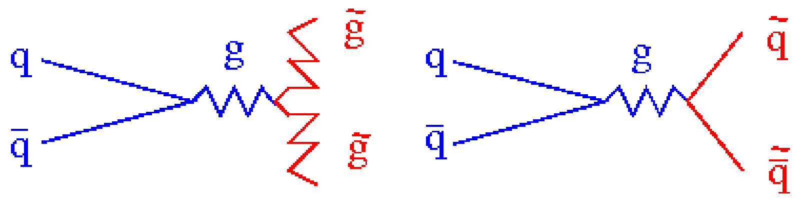
dominant production:
pair production of squarks or gluinos

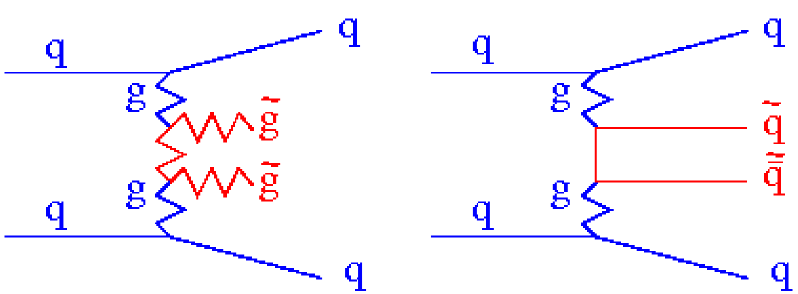
cross section depends only on mass of SUSY particles

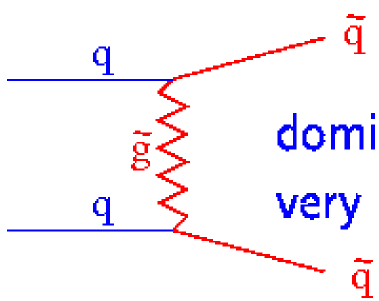


First Discoveries

- largest cross-section for squark and gluino production
- for $m(\tilde{g}) \leq m(\tilde{q})$ gluino pair-production dominant

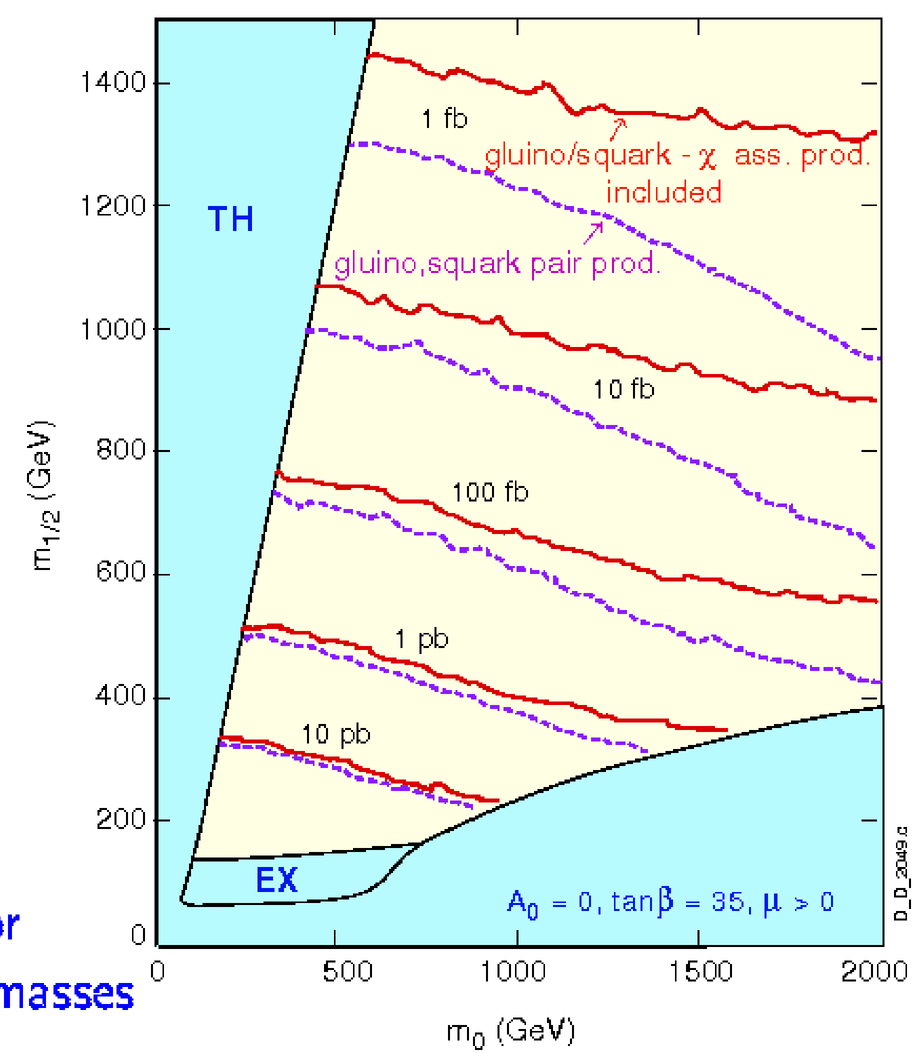






dominant graph for very large squark masses

SUSY total cross sections (mSUGRA)



SUSY Decays

In SUSY new conserved quantity: R-parity

R(Susy particle) = -1
R(SM particle) = 1

➔ SUSY particles can only be produced in pairs
➔ SUSY particles have to decay into uneven number (mostly one) of SUSY particles and any number of SM particles

➔ lightest SUSY particle is stable
➔ lightest SUSY particle is candidate for dark matter
➔ lightest SUSY particle has no electric charge
➔ lightest SUSY particle is lightest neutralino $\tilde{\chi}_1^0$

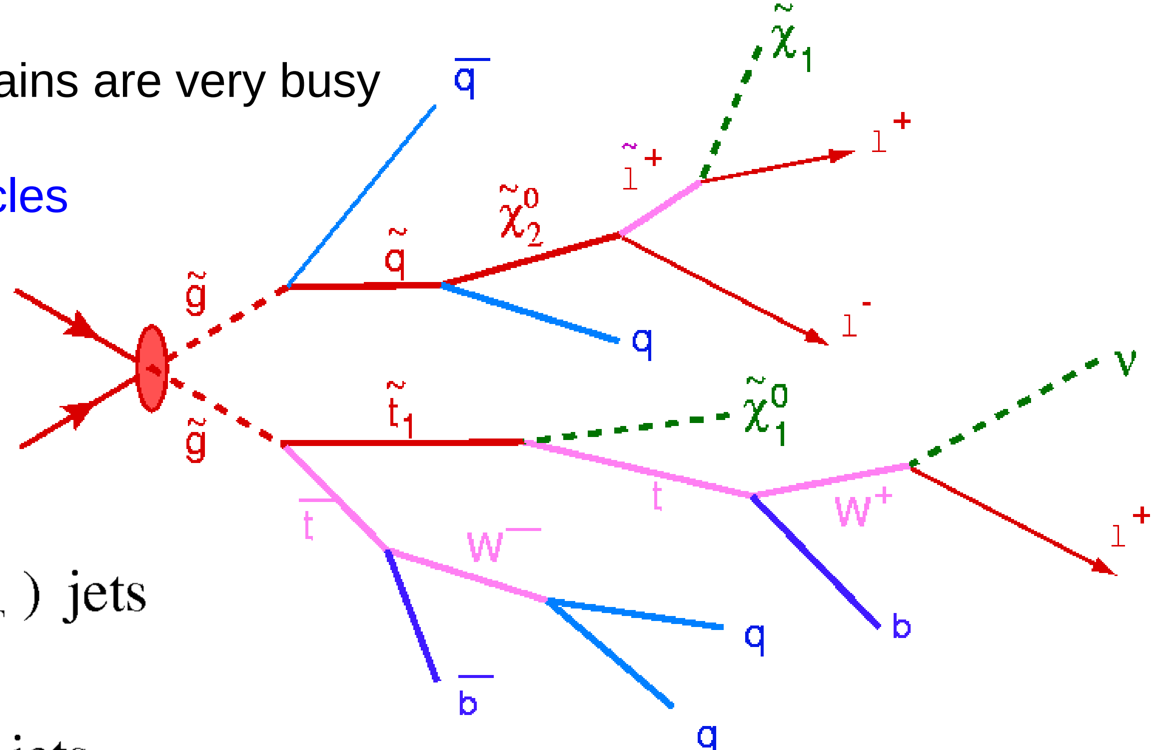
there exit also models with broken R-parity

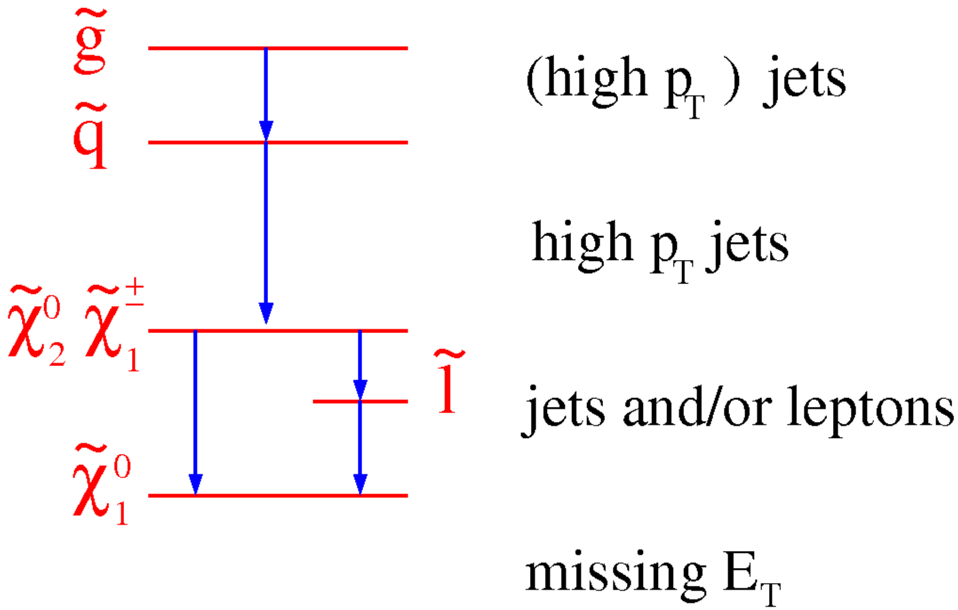
these lead to proton decay and are in contradiction to experiments for large part of parameter space

Decay

signatures from SUSY decay chains are very busy

production of lighter SUSY particles
mainly in decay chain of
squarks or gluinos



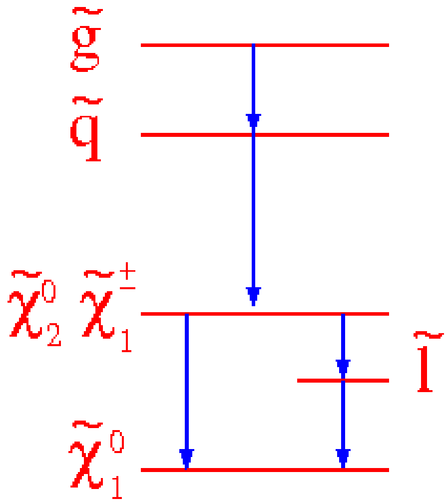


Signature:

- high p_T jets
- sometimes leptons
- large missing E_T due to neutralinos

First Discovery

Decay chain:

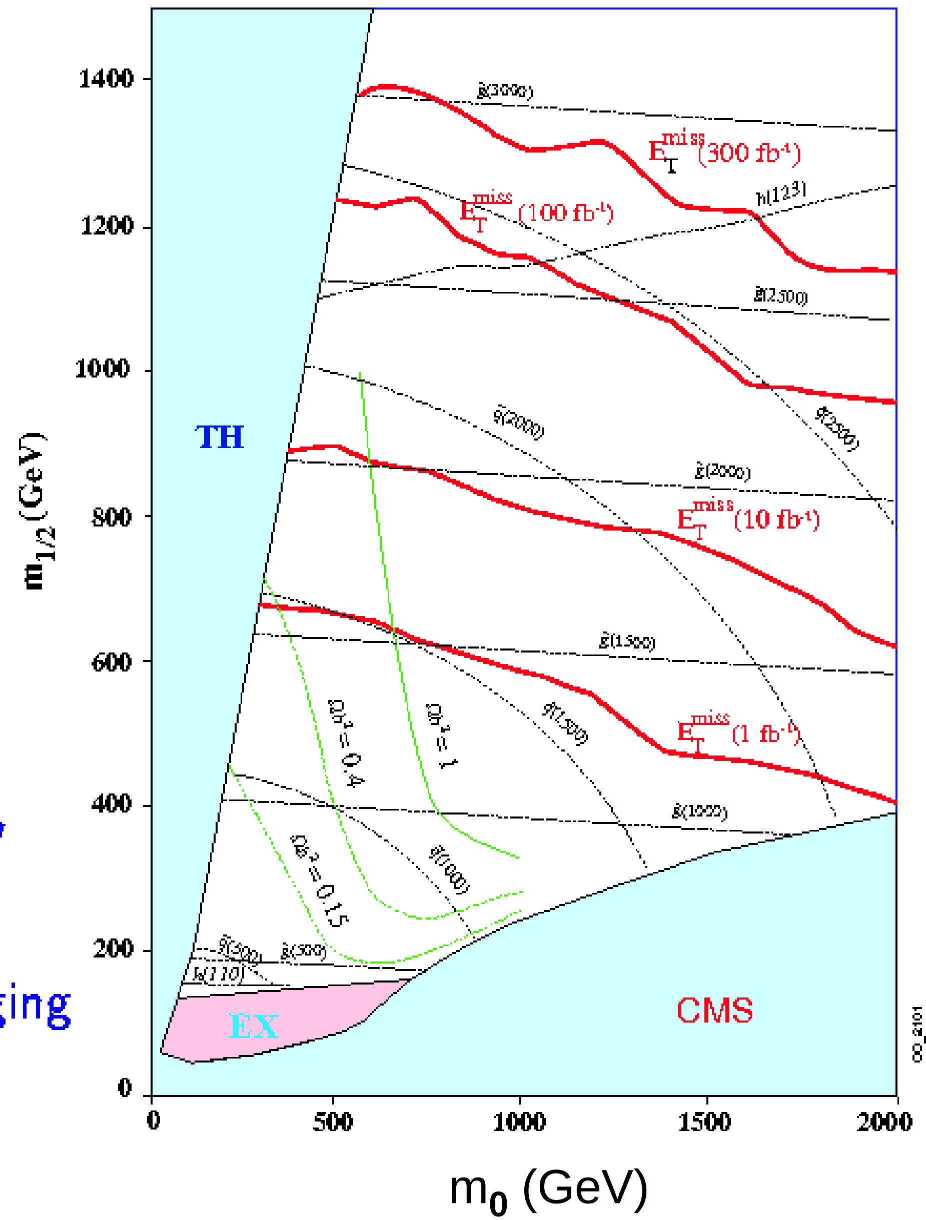


(high p_T) jets

high p_T jets

jets and/or leptons

missing E_T



→ discovery of SUSY using missing energy and large p_t jets is easy

determination of model parameters challenging

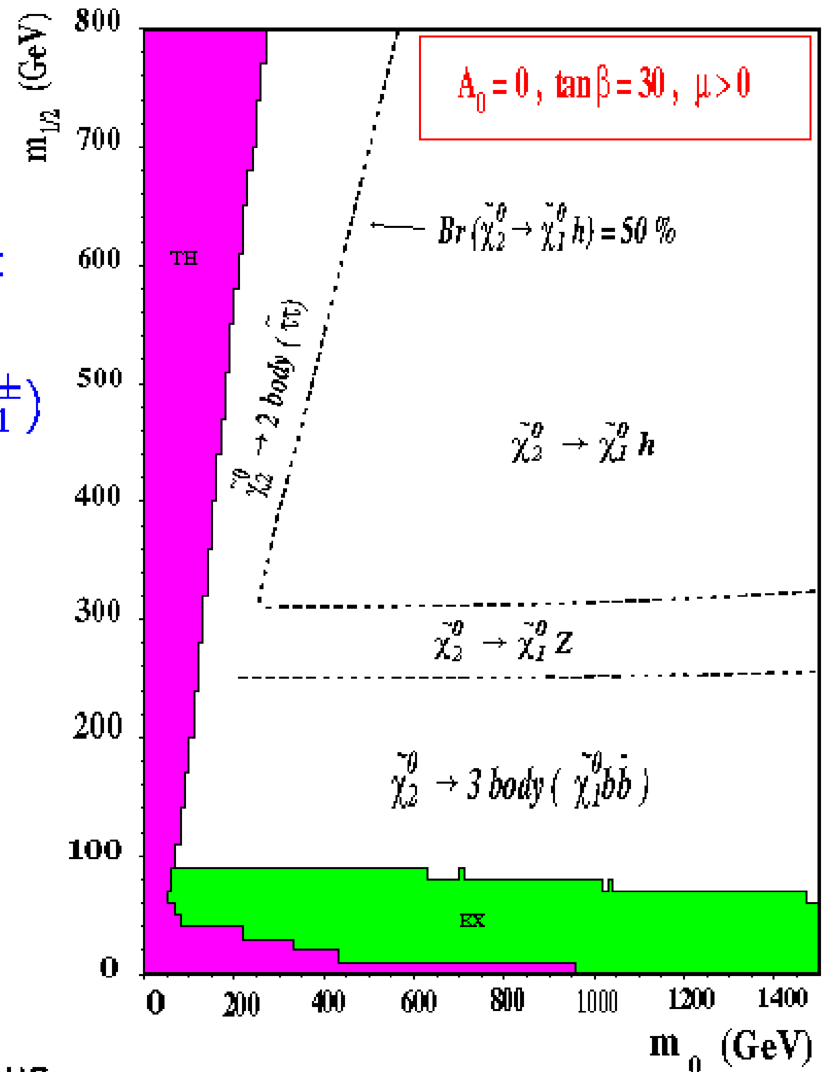
SUSY is background for SUSY

Gaugino decays

$\tilde{\chi}_2^0$ and $\tilde{\chi}_1^{\pm}$ produced in decay chain of squarks and gluinos

decay of gauginos depends on SUSY parameters:

I	2 body decay chain		$m(\tilde{\ell}) < m(\tilde{\chi}_2^0),\ m(\tilde{\chi}_1^{\pm})$
	$\tilde{\chi}_2^0 \to \tilde{\ell}\ell \to \ell\ell\tilde{\chi}_1^0$		$\tilde{\chi}_1^{\pm} \to \tilde{\ell}\nu \to \ell\nu\tilde{\chi}_1^0$
II	2 body decay		
	$\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0$		$\tilde{\chi}_1^{\pm} \to W^{\pm}\tilde{\chi}_1^0$
III	2 body decay		
	$\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0$		$\tilde{\chi}_1^{\pm} \to W^{\pm}\tilde{\chi}_1^0$
IV	3 body decay via		virtual Z, W or $\tilde{\ell}$
	$\tilde{\chi}_2^0 \to f\bar{f}\tilde{\chi}_1^0$		$\tilde{\chi}_1^{\pm} \to f\bar{f}'\tilde{\chi}_1^0$



N.B. for large $\tan\beta$ lepton will be dominantly taus

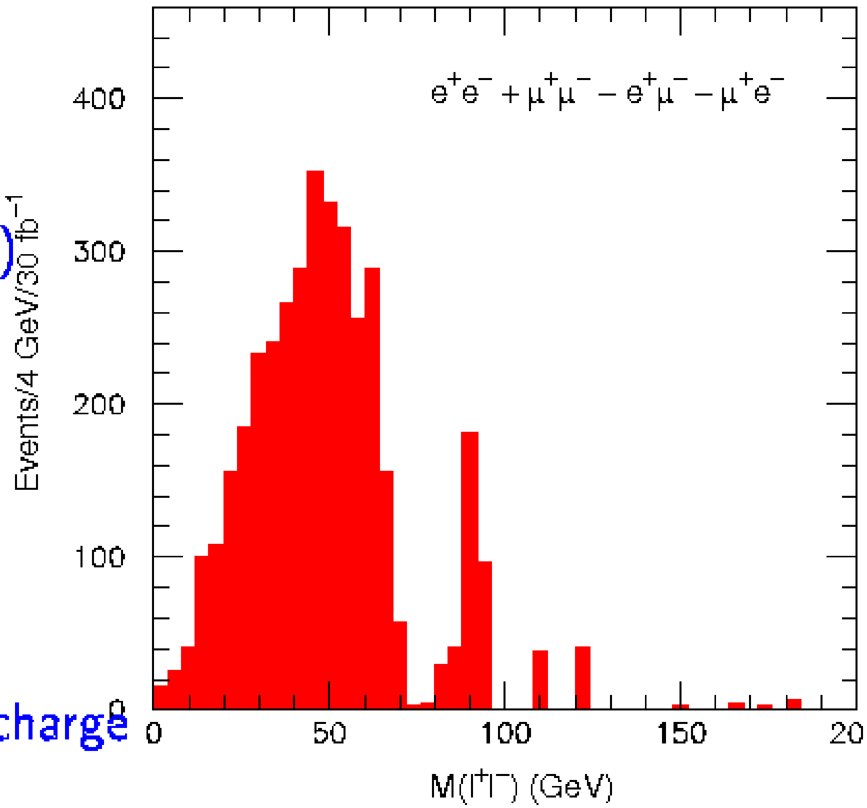
Gaugino 3 body decay

decays with leptons easiest to detect
but branching ratio small

for 3 body decay $\tilde{\chi}_2^0 \to f\bar{f}\tilde{\chi}_1^0$
BR at least 3% for each lepton flavour (like Z)
BR larger, if sleptons are light

$\max(m(\ell^+\ell^-)) = m(\tilde{\chi}_2^0) - m(\tilde{\chi}_1^0)$
edge in mass distribution = mass difference

measurement error ~ 0.1 % (for given model)



signal: 2 leptons with same flavour, opposite charge
background: combinatorial

combinatorical background supression by subtracting wrong flavour combinations

peak at Z from SUSY signals

Gauginos

Gauginos

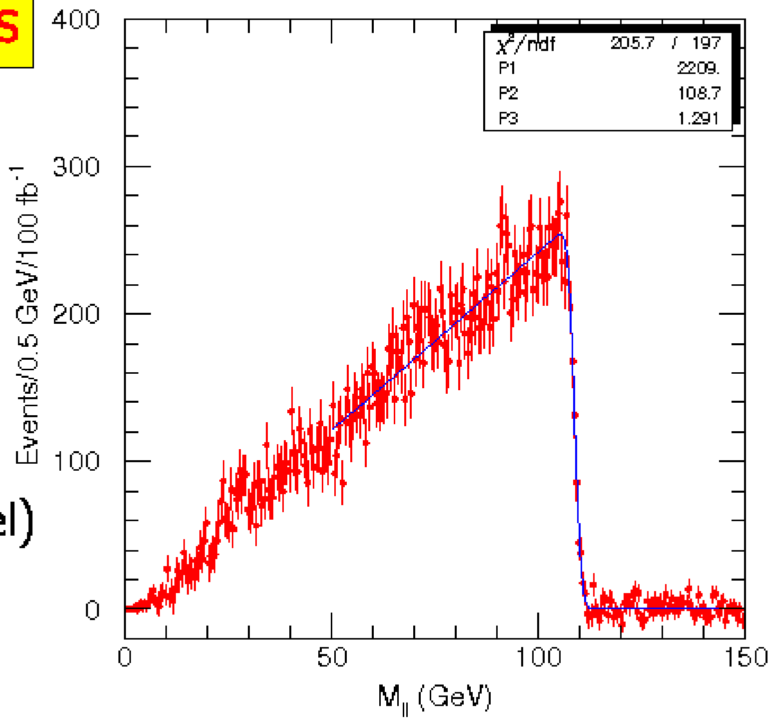
for 2 body decay chain

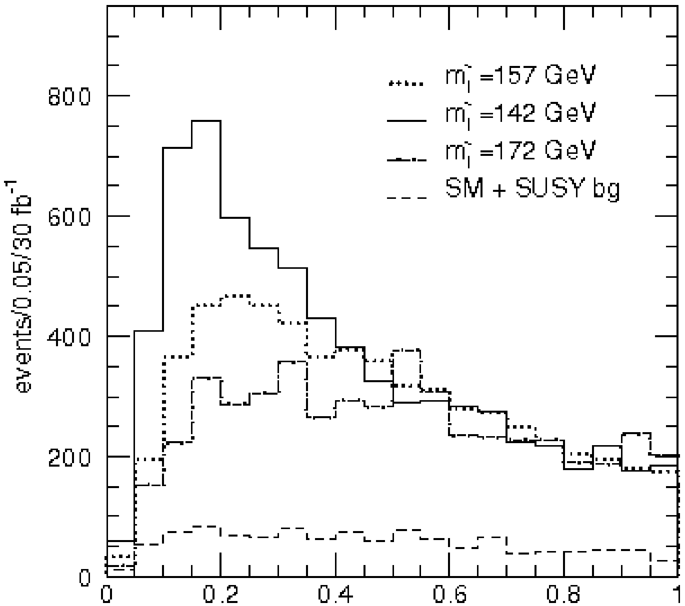
$\tilde{\chi}_2^0 \rightarrow \tilde{\ell}^{\pm}\ell^{\mp} \rightarrow \ell^+\ell^-\tilde{\chi}_1^0$

edge depends on $m(\tilde{\chi}_2^0)$, $m(\tilde{\ell})$, and $m(\tilde{\chi}_1^0)$

$$\max(m(\ell^+\ell^-)) = m(\tilde{\chi}_2^0)\sqrt{1-\frac{m^2(\tilde{\ell})}{m^2(\tilde{\chi}_2^0)}}\sqrt{1-\frac{m^2(\tilde{\chi}_1^0)}{m^2(\tilde{\ell})}}$$

measurement precision: 0.5 GeV (for given model)





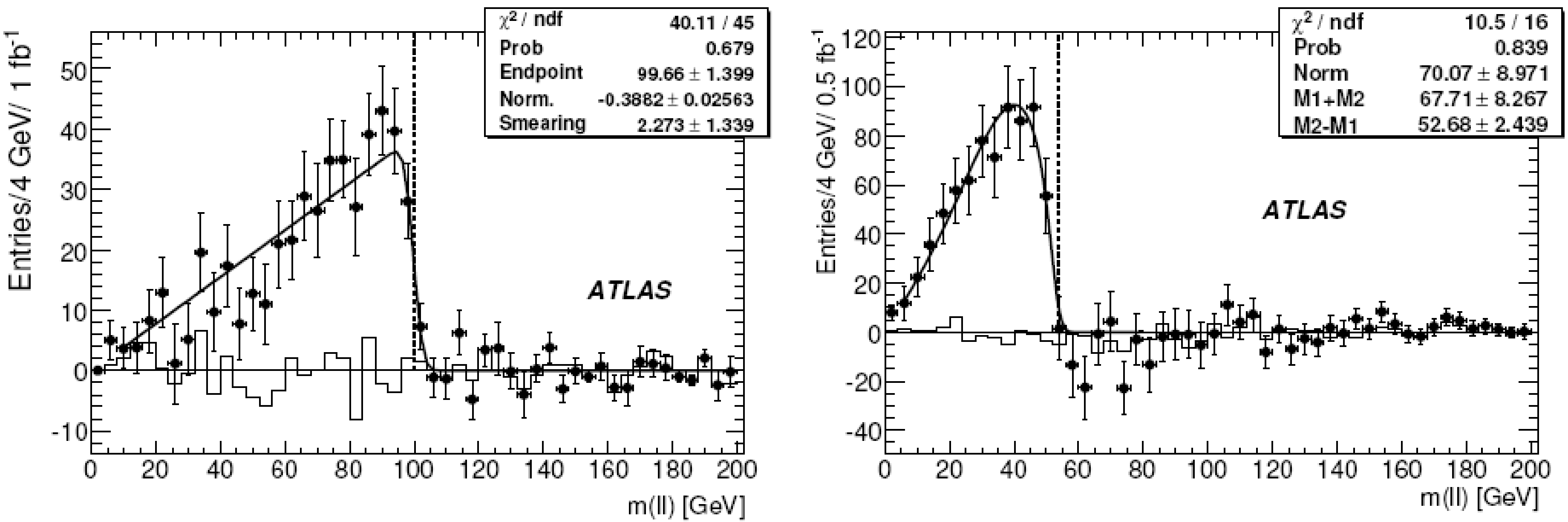
more information available:

p_t of leptons depends on mass difference

measure $\frac{p_T(l_1)}{p_T(l_2)}$

Low Luminosity

$$M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0} \quad \text{or} \quad \sqrt{(M^2_{\tilde{\chi}_2^0} - M^2_{\tilde{\ell}})(M^2_{\tilde{\ell}} - M^2_{\tilde{\chi}_1^0})/M^2_{\tilde{\ell}}}$$



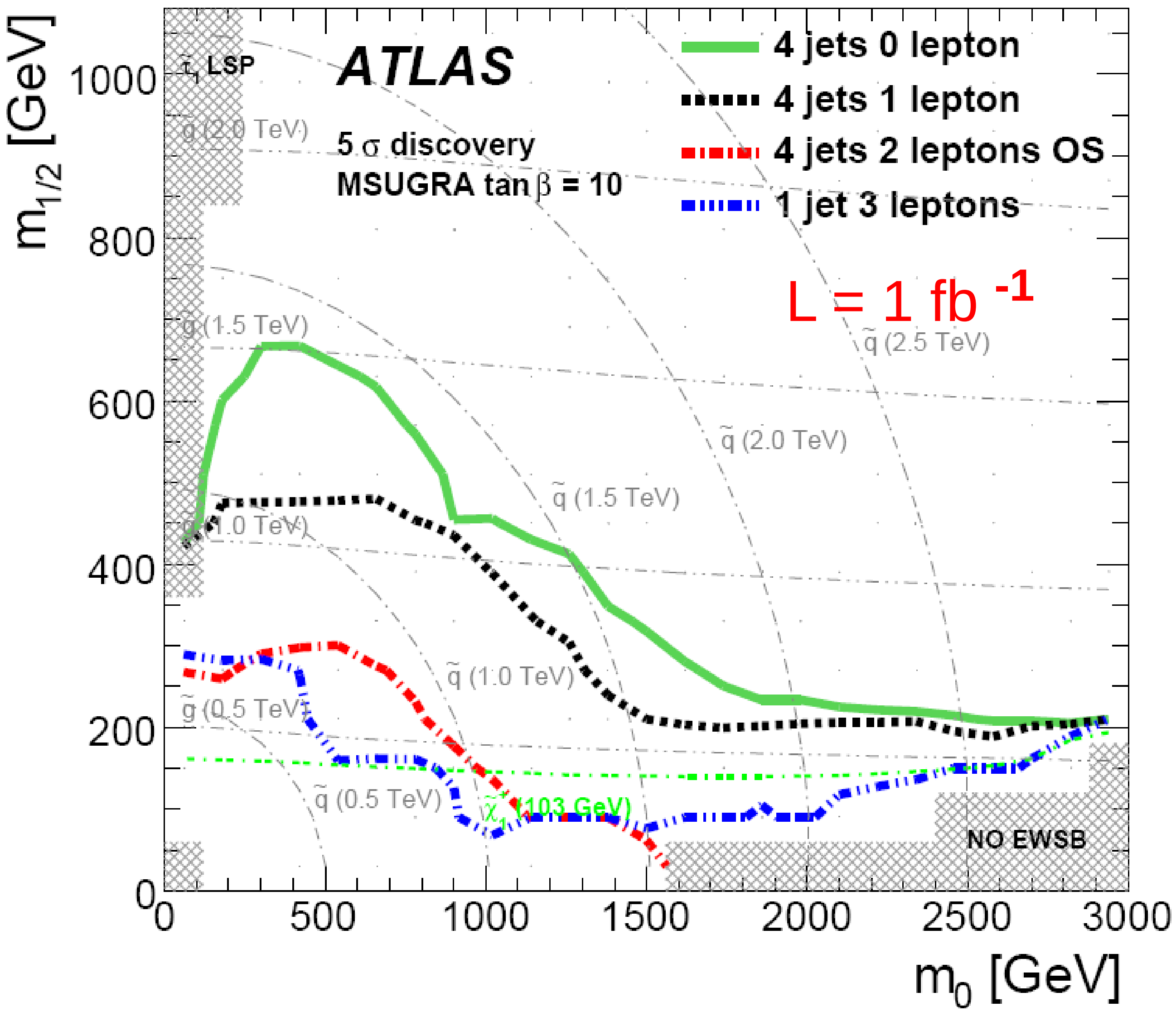
even for L = 1 fb $^{-1}$ good measurement of end points for many model parameters possible

Discovery Potential

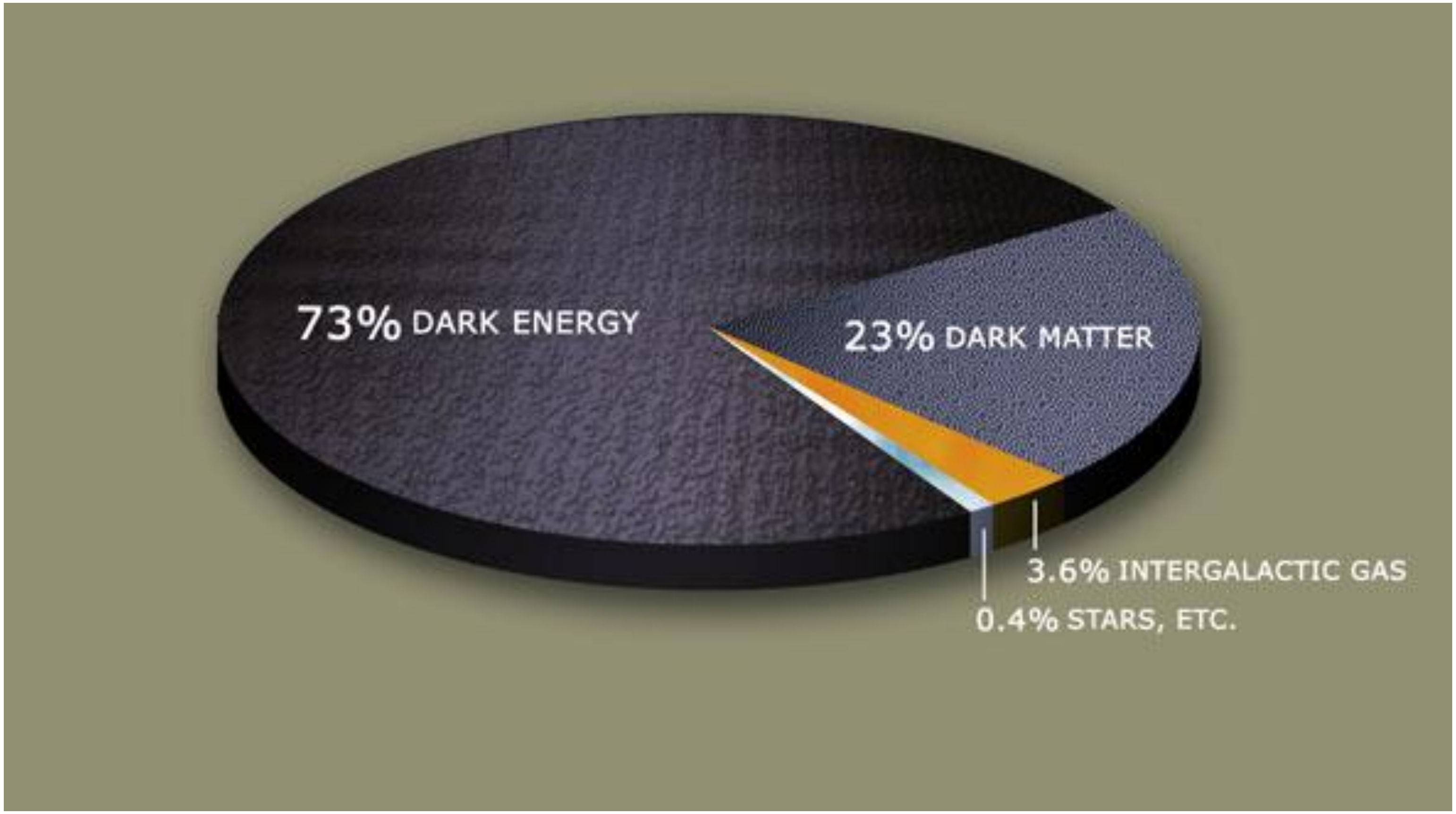
large discovery potential already for low luminosities

squark and gluino masses above 1TeV accesible already for L = 1 fb^{-1}

BUT: SUSY has large parameter space, some part will never be excluded



Components of the Universe



lightest SUSY particle, neutralino, could explain dark matter, i.e. 23% of the energy of the universe

Z prime

What is a Z prime:

any additional neutral and massive boson outside of the Standard Model

several extentions of the Standard Model predict these bosons

- SO(10), SU(5), E(6)
- extra dimensions

SM Z boson and new neutral boson mix
→ mass eigenstates: $Z^{\mathbf{0}}$ and Z‘

Signatures:

decays like SM Z boson
decay into leptons best visible channel

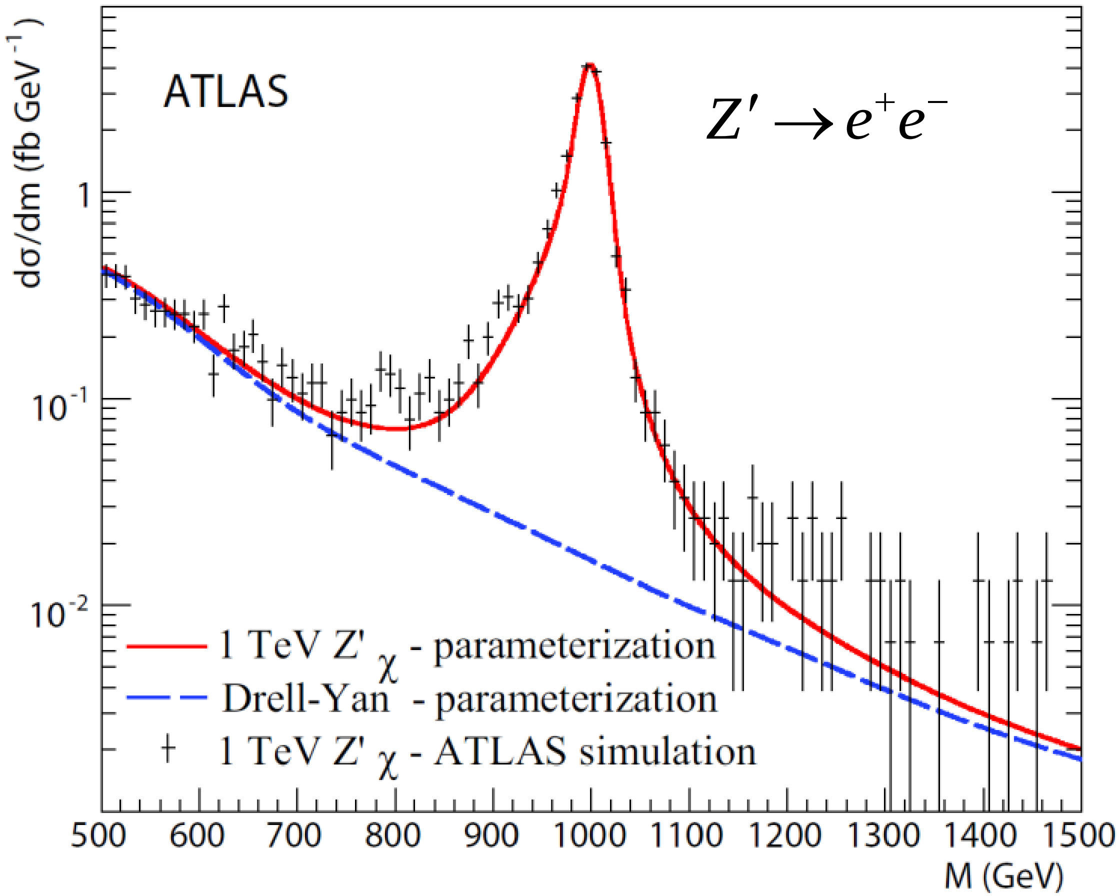
New Physics

some new physics easy to detect,e.g. new particle decay into leptons

final states with jets more difficult, especially as QCD background not well known

but decay into top quarks has good discovery potential

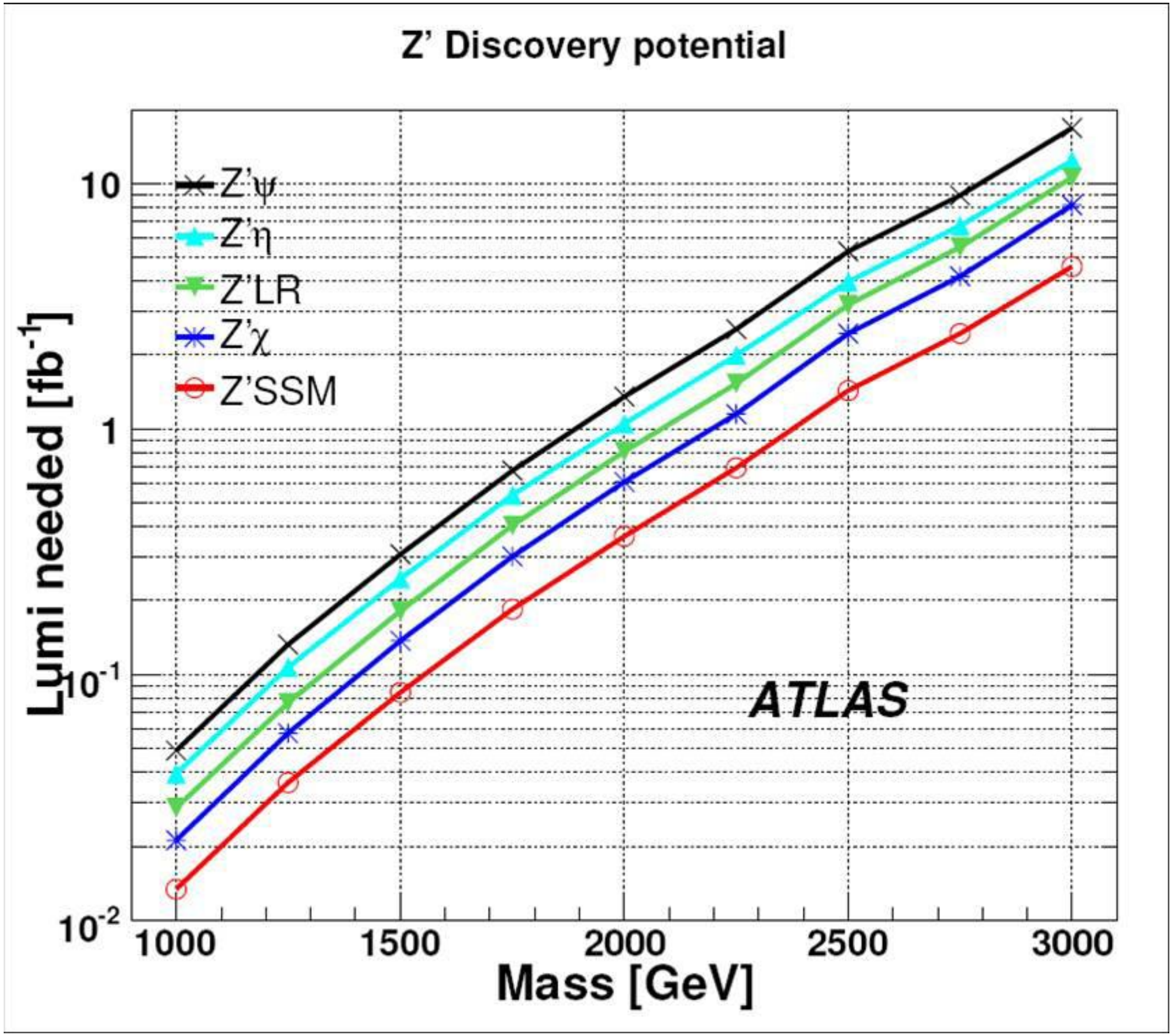
background shape well understood



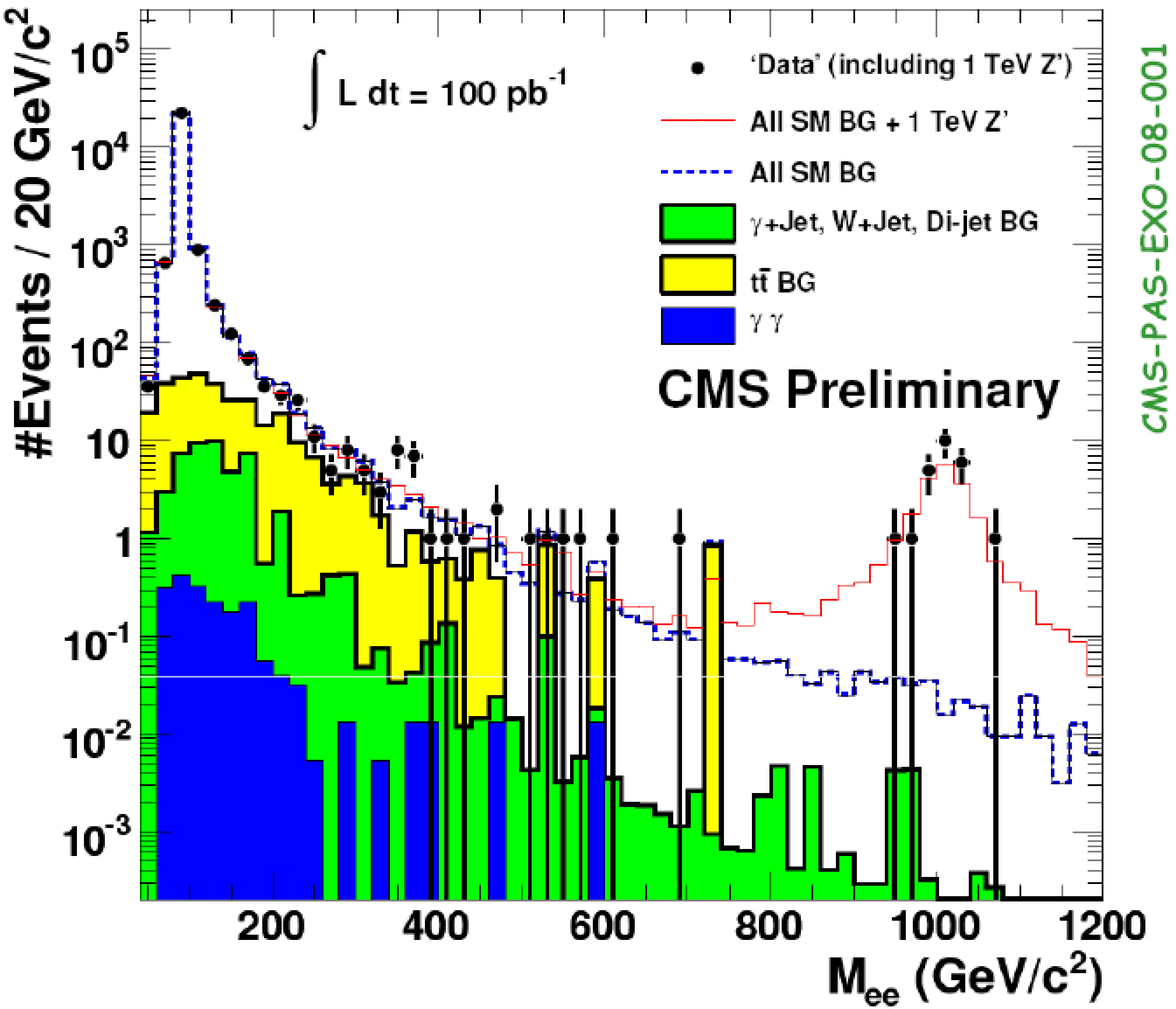
Discovery Potential

discovery potential depends on model

as cross section depends on model



Z' in first Data



Conclusions

Standard model of particle physics well understood and experimentally verified

Higgs boson gives mass to fermions and gauge bosons

- **mass due to Higgs mechanism contributes only 0.05% to the energy of the universe**

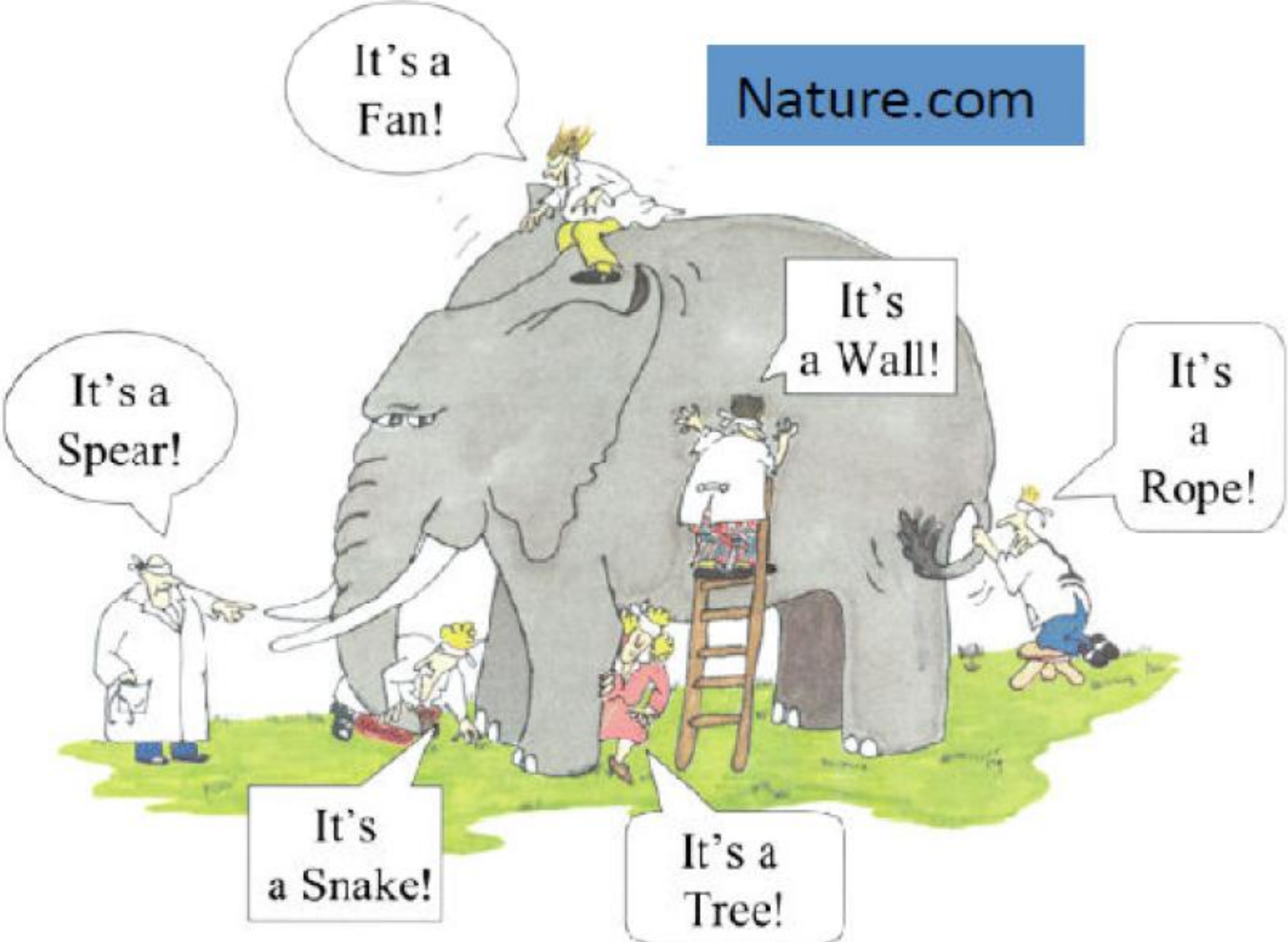
Supersymmetrie makes fermions and bosons equal and unifies gauge couplings

- **lightest SUSY particle is dark matter candidate and could explain 23% of the energy of the universe**

many other new theories predicted

The LHC is a discovery machine, largest centre-of-mass energy

looking forward to results from experiments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