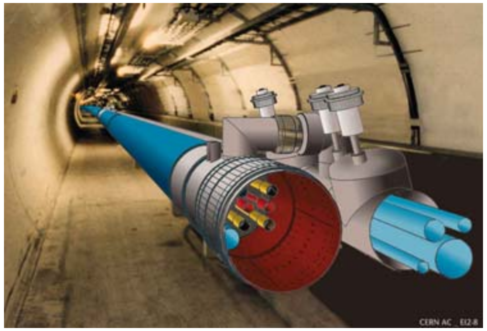
Physics at the Large Hadron Collider

Part I: The Experimental Challenge

Part II: Precision Physics and Searches

Lake Louise Winter Institute
Chateau Lake Louise
Alberta, Canada
20-26 February 2005



Michel Lefebvre
Physics and Astronomy
University of Victoria
British Columbia, Canada

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Part I: The Experimental Challenge

- Motivations
- The LHC and related experiments
- Overview of the physics programme
- Basics of proton-proton collisions at the LHC
- The ATLAS and CMS experiments

Part II: Precision Physics and Searches

- **Precision measurements**
- **Higgs searches**
- **Physics beyond the Standard Model**
  - **SUSY**
  - **extra-dimensions**
  - **other exciting searches**

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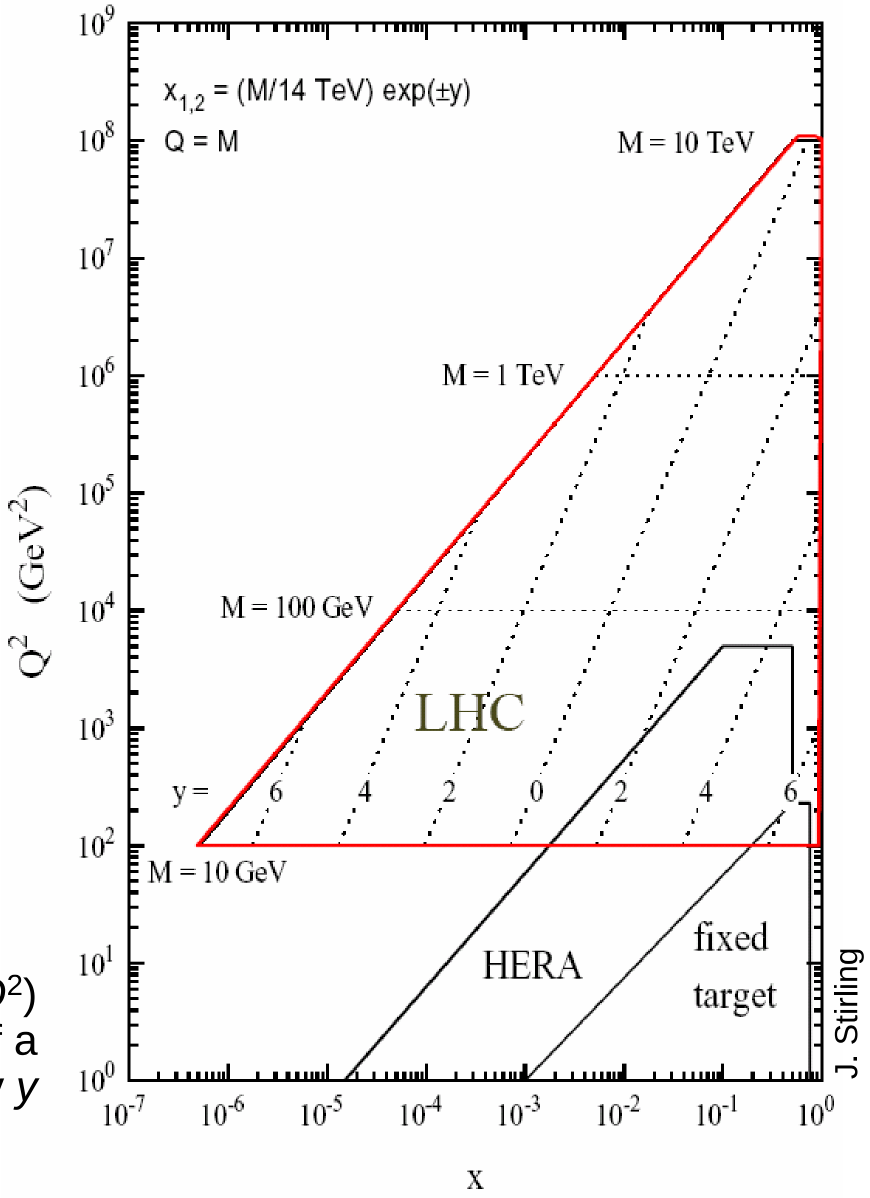
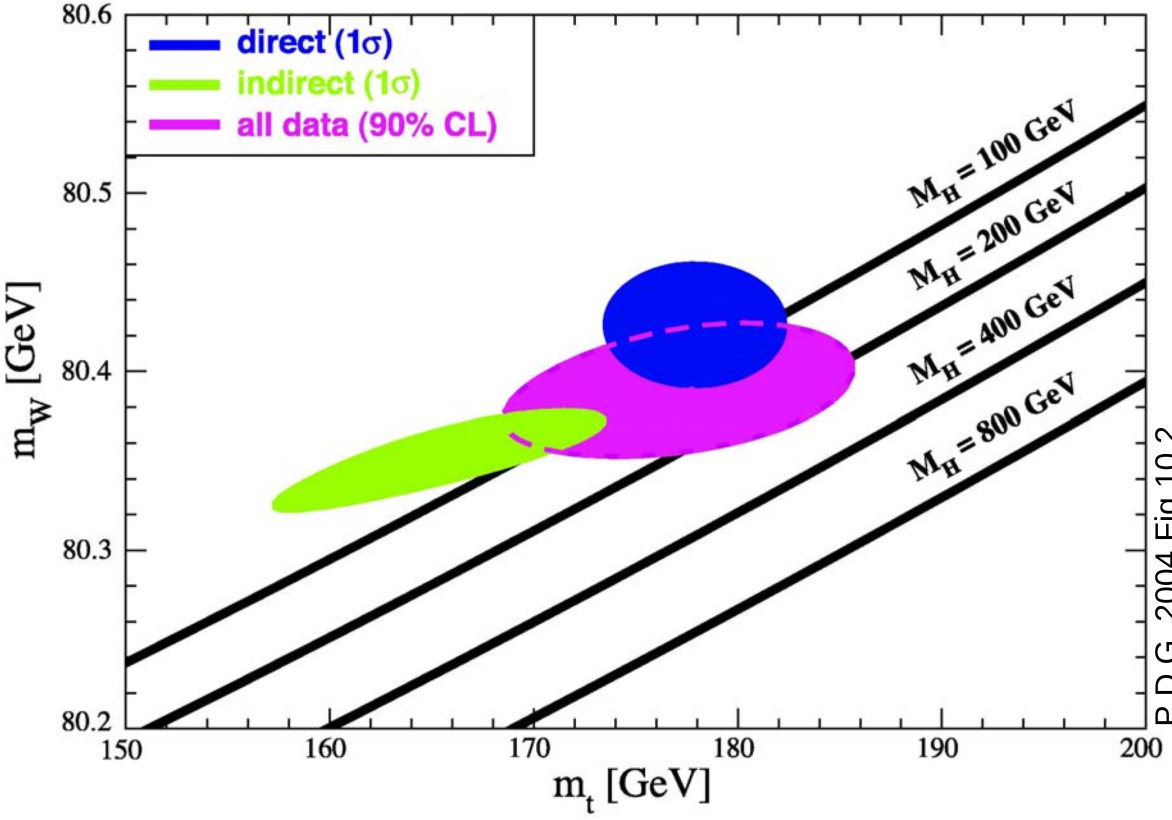
QCD Physics

- A variety of QCD processes can be studied at the LHC
- accessing new kinematics regime
- further tests of QCD
- precise measurement of inclusive jet cross section → $\Delta\alpha_s \approx 10\%$
- look for quark compositeness!



Parton kinematics at the LHC in the (x, Q^2) kinematics plane for the production of a particle of mass M at rapidity y

M_W and M_{top}



P.D.G. 2004 Fig 10.2

M_H dependence through radiative corrections

Precision measurements of M_W and M_{top} provide important tests of the SM

P.D.G. 2004 values:

$M_{top} = 174.3 \pm 5.1$ GeV

$M_W = 80.425 \pm 0.038$ GeV

In 2007, expect

$\Delta M_W \approx$ 25 MeV (0.3‰) from LEP/Tevatron

$\Delta M_{top} \approx$ 3.0 GeV (1.7%) from Tevatron

$\Bigg\}$ LHC can do better thanks to large statistics

W production

At hadron colliders, the dominant W production mechanism is the Drell-Yan process

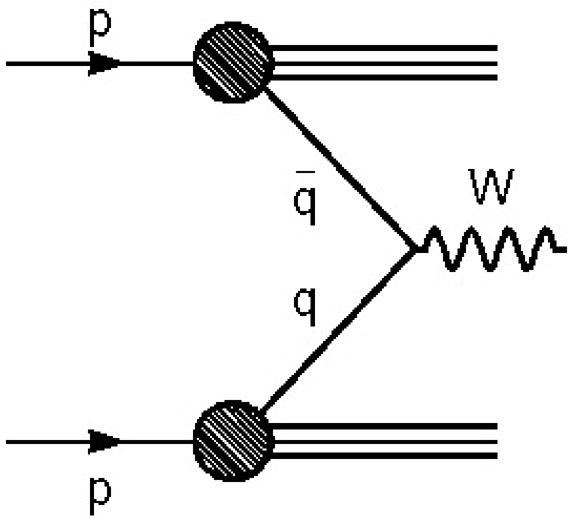
LHC is a W,Z factory

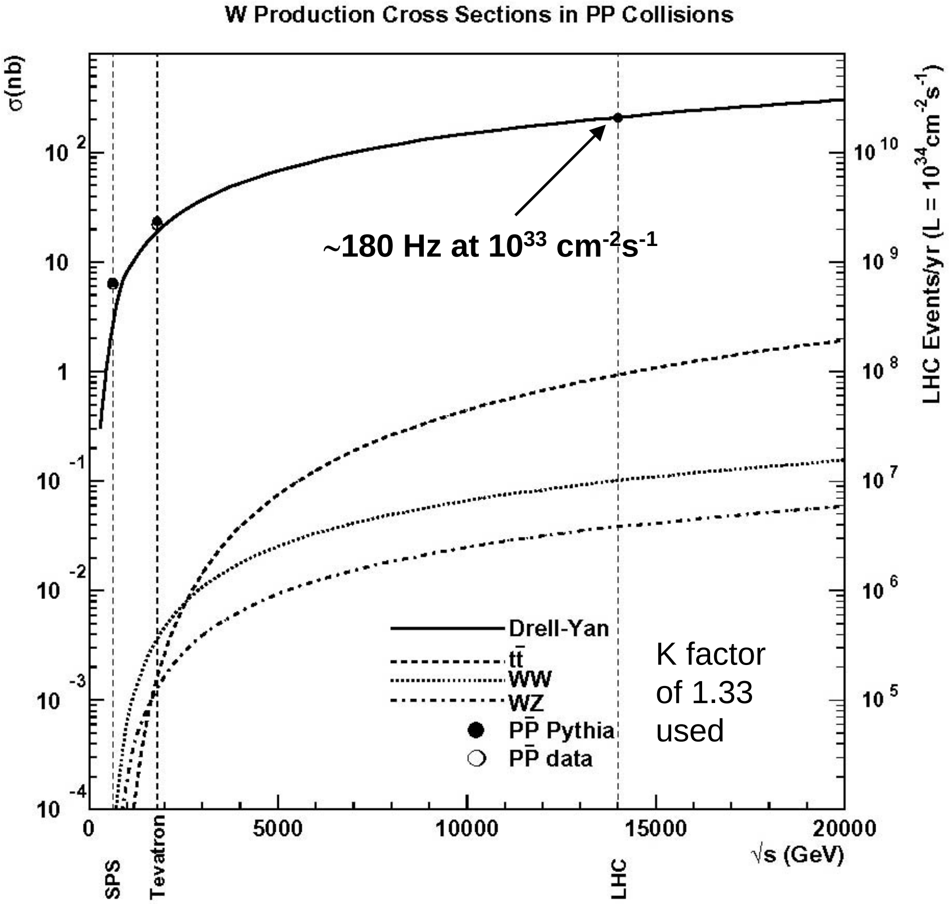
$$\frac{d\sigma}{dy}\left(W^{+}\right)=\frac{2\pi G_F}{3\sqrt{2}}\sum_{q,\bar{q}'}\left|V_{q,\bar{q}'}\right|^2 x_1 x_2\left[q\left(x_1,M_W^2\right)\bar{q}'\left(x_2,M_W^2\right)+q\left(x_2,M_W^2\right)\bar{q}'\left(x_1,M_W^2\right)\right]$$

where y is the W rapidity and $x_{1,2}=\frac{M_W}{\sqrt{s}}e^{\pm y}$

The total cross section is obtained by integrating over the kinematically allowed rapidity range

$$x_{1,2}\leq 1 \quad\Rightarrow\quad -\ln\frac{\sqrt{s}}{M_W}\leq y\leq \ln\frac{\sqrt{s}}{M_W}$$





~180 Hz at 10^{33} cm^{-2}s^{-1}

K factor of 1.33 used

Dugan O'Neil, Candidacy Paper, Victoria, Dec 1997.

W Mass Measurement

Method different from the one used at e^+e^- colliders

- Drell-Yan W → jet jet cannot be extracted from QCD jet-jet production (UA2 was first and probably last able to do this!)
- $W \rightarrow \tau\nu$ is problematic because of $\tau \rightarrow \nu + X$, which further confuses the E_T^{miss} signature

Only $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ decays are used to measure M_W

- $\sigma(pp \rightarrow W+X \rightarrow (e \text{ or } \mu)\nu + X) \approx 30$ nb
- at 10^{33} $cm^{-2}s^{-1}$
  - ~ 300×10^6 events produced in one year
  - ~ 60×10^6 events selected after analysis cuts in one year
  - about 50 × Tevatron statistics
  - about 6000 × the statistics of WW at LEP

W Mass Measurement

Consider W → $\ell\nu$ + X, then

$$M_{\mathrm{W}}^{2} = \left(p_{\ell} + p_{\nu}\right)^{2} = \left(E_{\ell} + E_{\nu}\right)^{2} - \left(\vec{p}_{\ell} + \vec{p}_{\nu}\right)^{2}$$

We define the W transverse mass

$$\left(M_{\mathrm{T}}^{\mathrm{W}}\right)^{2} \equiv \left(E_{\mathrm{T}}^{\ell} + E_{\mathrm{T}}^{\nu}\right)^{2} - \left(\vec{p}_{\mathrm{T}}^{\,\ell} + \vec{p}_{\mathrm{T}}^{\,\nu}\right)^{2}$$

$$\approx 2E_{\mathrm{T}}^{\ell}E_{\mathrm{T}}^{\nu}\left(1 - \cos\Delta\varphi_{\ell\nu}\right)$$

The transverse mass

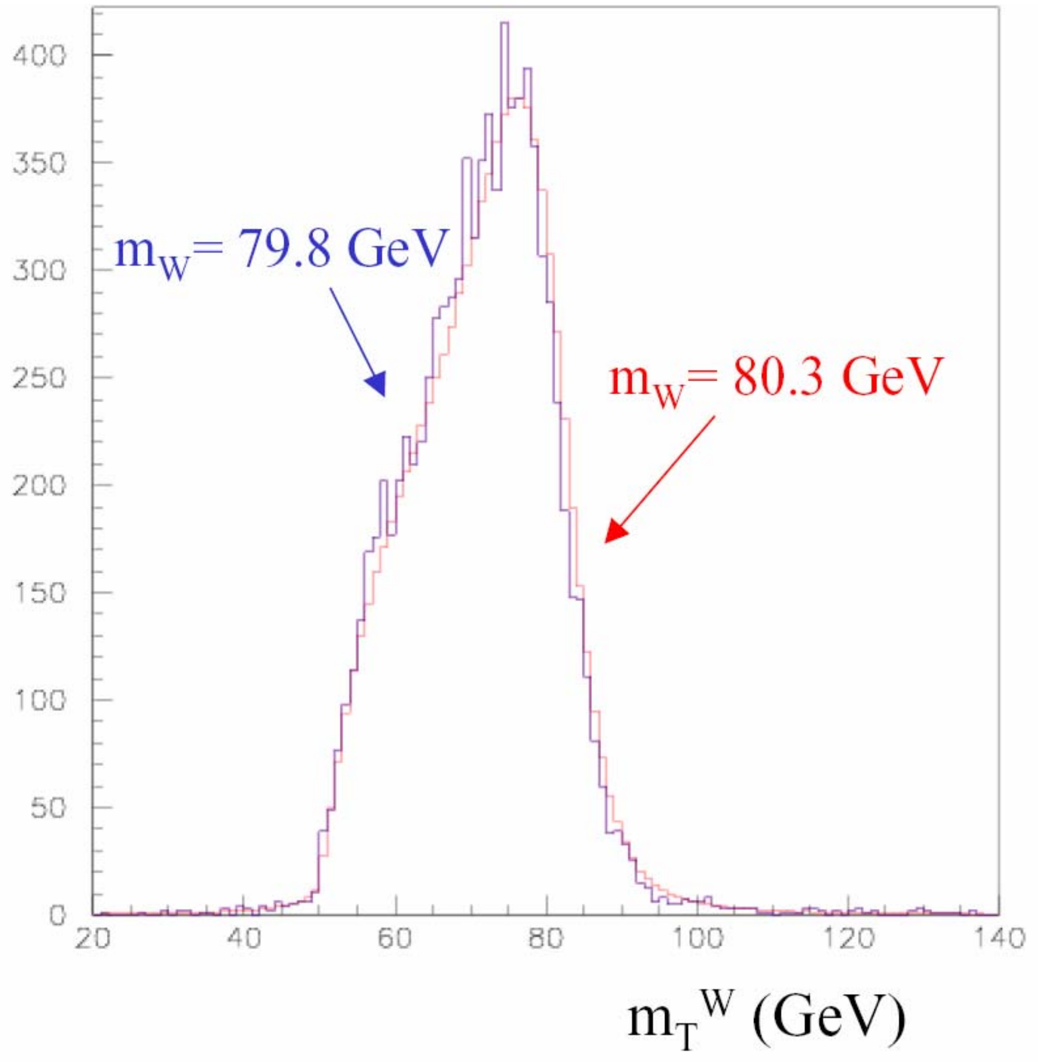
- is independent of the W longitudinal momentum
- is weakly dependent on the W transverse momentum

in W rest frame

$$\frac{M_{\mathrm{T}}^{\mathrm{W}}}{\hat{M}_{\mathrm{T}}^{\mathrm{W}}} = 1 + O\left(\beta_{\mathrm{W}}^{2}\right)$$

It is this last property that makes the W transverse mass so useful

W Mass Measurement



The transverse mass distribution is sensitive to M_W. Comparison of data with simulation yields an estimate of M_W

Statistical error negligible

Dominant error: knowledge of the lepton energy scale of the detector

ATLAS and CMS hope to reach ΔM_W ~ 25 MeV per experiment, per channel

Combining both channels and both experiment could yield ΔM_W ~ 15 MeV

Very difficult measurement

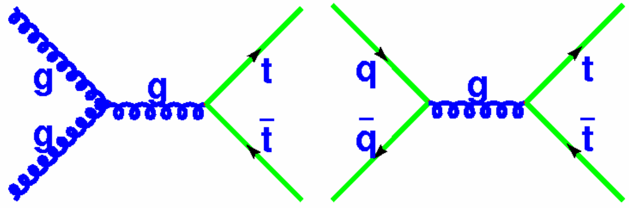
Top Quark

The top quark is a most intriguing fermion

- Discovery in 1994 at the Tevatron
- $m_{\text{top}} \approx 174$ GeV $\approx$ M($_{76}$Os)!
  - studying top may reveal clues about the origin of mass?
- $\Gamma_{\text{top}} \approx 1.8$ GeV so $\Gamma^{-1}_{\text{top}} \approx 3.7\times10^{-25}$ s $< \Lambda^{-1}_{\text{QCD}}$
  - the top decays before hadronizing!
- top is expected to decay to Wb nearly 100% of the time (SM!)
- rare top decays are promising ways to search for physics beyond the SM

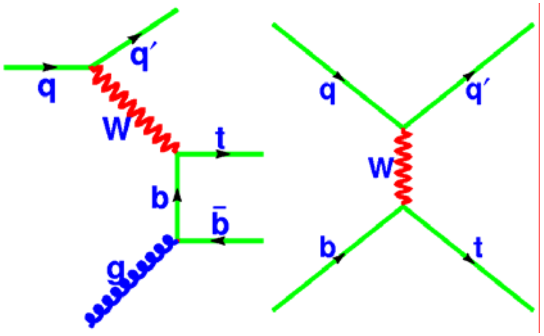
Top Quark Production

LHC is a top factory

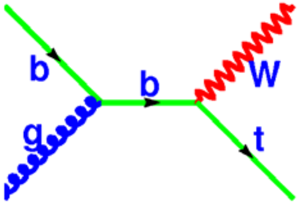


$t\bar{t}$ production = 833 pb Nucl. Phys B 529 (1998) 524

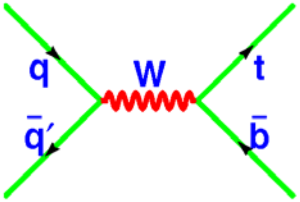
≈ 8×10^6 $t\bar{t}$ pairs produced for 10 fb^{-1}



Wg fusion ≈ 245 pb



Wt production ≈ 60 pb



W* channel ≈ 10 pb

} Electroweak single top production

Top Quark Production

$t\bar{t}$ production

- top mass measurement
- major source of SM background to searches
- allows in-situ calorimeter energy scale calibration

Electroweak single top production

- cross section proportional to $|V_{tb}|^2$
  - only way to measure this coupling at a hadron collider
- source of highly polarized quarks
  - precise prediction from the SM
  - top decays before hadronizing, so polarization effects are transmitted to its decay product

Large top sample!

- Allows many studies
  - mass, cross section, branching ratios, V_{tb}, single top, rare decays, resonances, etc.

Top Mass Measurement

In the SM, top decays almost exclusively to Wb

For top mass reconstruction, the following channels are considered

- all jet channel

  $t\bar{t} \rightarrow WbWb \rightarrow jjbjjb$

  BR ≈ 44% but large QCD multijet background

- dilepton channel

  $t\bar{t} \rightarrow WbWb \rightarrow \ell\nu b\ell\nu b$

  BR ≈ 5% for ℓ = e, μ

- lepton plus jet channel

  $t\bar{t} \rightarrow WbWb \rightarrow \ell\nu bjjb$

  BR ≈ 30% for ℓ = e, μ

  preferred channel

In all cases, two jets are b-jets

- tagged using displaced vertices in the inner detector
- lifetime of b-hadrons ~ 1.5 ps, decay vertex a few mm from primary vertex, detected using high-granularity tracker

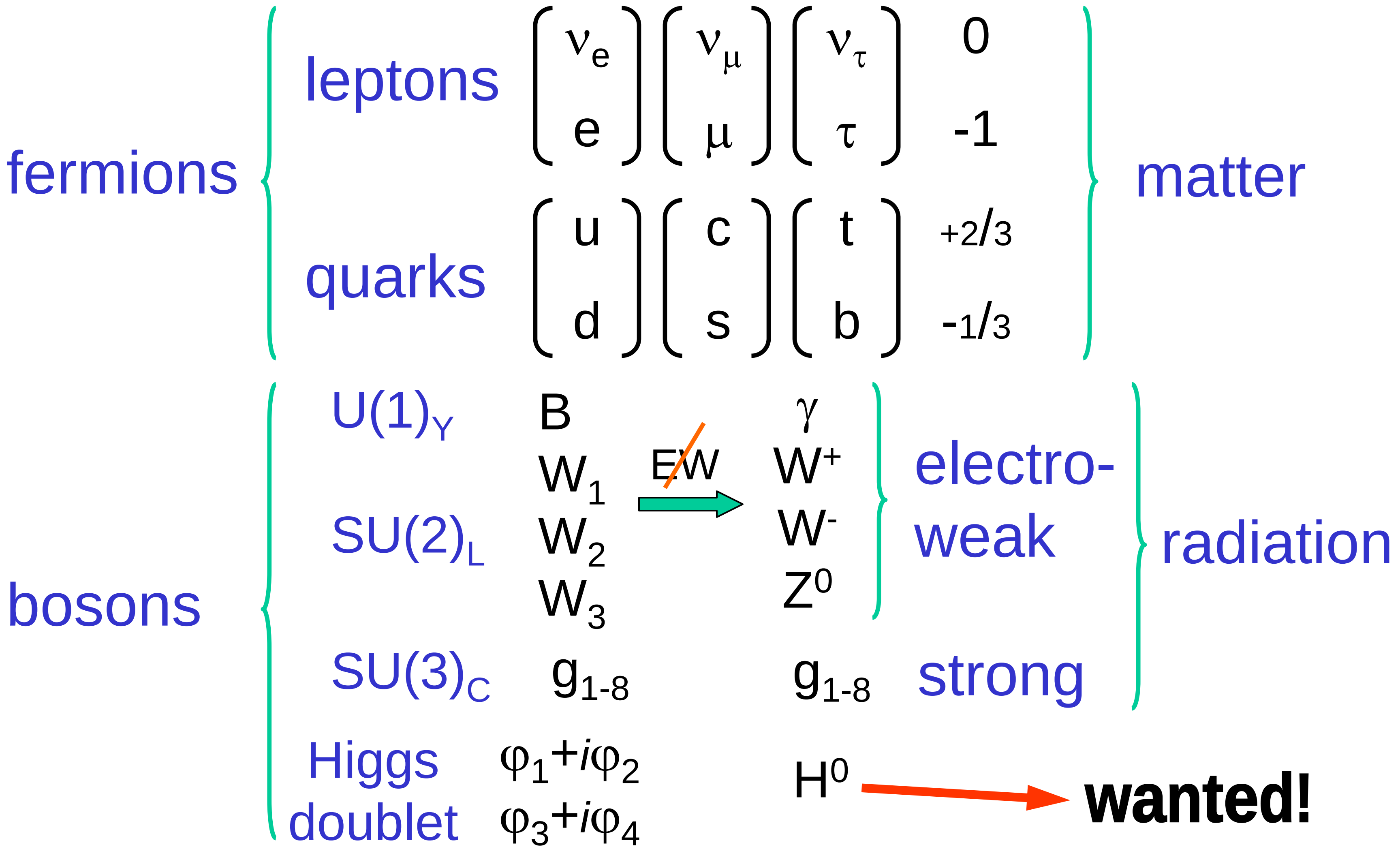
Top Mass Measurement

- Many different and complementary analyses considered
- In general, one performs an analytic fit to an event by event reconstructed invariant top mass
- In most cases, precision is limited by systematics
  - physics uncertainties (background, final state radiation, initial state radiation, b-fragmentation, etc.)
  - jet energy scale (b-jet, light-quark jet)
  - statistical error: $\Delta M_{\text{top}} << 100$ MeV

- Prospect per experiment: $\Delta M_{\text{top}} \sim 1$ GeV for 10 fb^{-1}

More details see talk from Steven Lowette

The Standard Model Particles



fermions

leptons
$$\begin{pmatrix}\nu_e\\ e\end{pmatrix}\begin{pmatrix}\nu_\mu\\ \mu\end{pmatrix}\begin{pmatrix}\nu_\tau\\ \tau\end{pmatrix}\quad\begin{matrix}0\\ -1\end{matrix}$$

quarks
$$\begin{pmatrix}u\\ d\end{pmatrix}\begin{pmatrix}c\\ s\end{pmatrix}\begin{pmatrix}t\\ b\end{pmatrix}\quad\begin{matrix}+2/3\\ -1/3\end{matrix}$$

matter

bosons

$U(1)_Y$	B		γ	electro-weak	radiation
$SU(2)_L$	W_1 W_2 W_3	$\xrightarrow{\cancel{EW}}$	W^+ W^- Z^0		
$SU(3)_C$	$g_{1\text{-}8}$		$g_{1\text{-}8}$	strong	
Higgs doublet	$\varphi_1+i\varphi_2$ $\varphi_3+i\varphi_4$		H^0 $\rightarrow$ **wanted!**		

Goldstone Model

We want: gauge invariance to generate interactions

We need: gauge invariant mechanism to generate mass

$\Longrightarrow$ hidden symmetry (spontaneous symmetry “breaking”)

Consider a model where the equilibrium state is not unique

nature makes a choice, hiding the invariance of the theory

equilibrium state: all fields null, except one $\varphi(x)\neq 0$

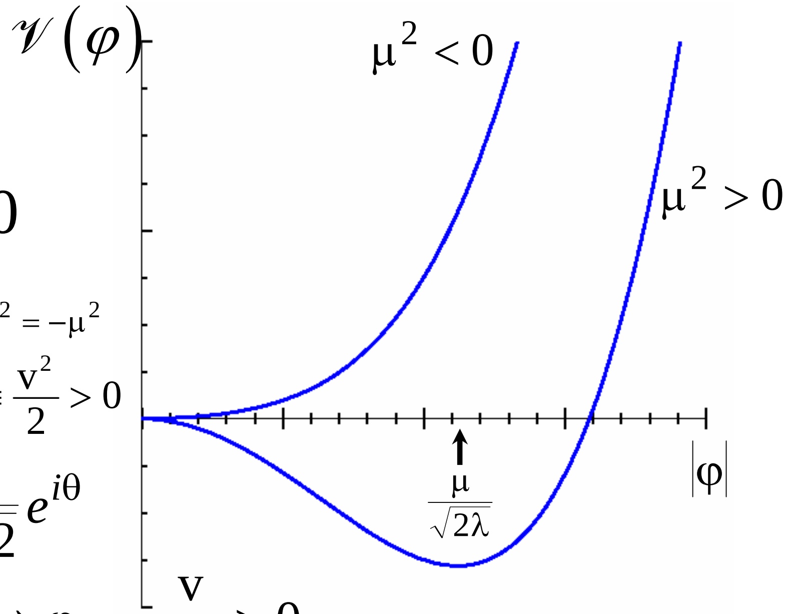
Lorentz invariance $\Longrightarrow$ $\varphi(x)$ is a scalar

$\varphi(x)$ is a complex scalar

Goldstone model: consider

$$\mathscr{L}=\left(\partial_\mu\varphi\right)^*\left(\partial^\mu\varphi\right)-\mathscr{V}\left(\varphi\right)$$

$$\mathscr{V}\left(\varphi\right)=-\mu^2\varphi^*\varphi+\lambda\left(\varphi^*\varphi\right)^2 \qquad \lambda>0$$



$\mu^2<0 \Longrightarrow$ **Self-interacting Klein-Gordon field where** $m^2=-\mu^2$

$\mu^2>0 \Longrightarrow$ $V(\varphi)\big|_{\min}=-\frac{\mu^2v^2}{4}\Rightarrow|\varphi|^2=|\varphi_0|^2=\frac{\mu^2}{2\lambda}\equiv\frac{v^2}{2}>0$

The equilibrium is characterized by $\varphi_0=\frac{v}{\sqrt{2}}e^{i\theta}$

Nature spontaneously chooses, say, $\theta=0\rightarrow\varphi_0=\frac{v}{\sqrt{2}}>0$

always possible because of **global U(1) phase** invariance

Goldstone Model

We write $\varphi(x)=\frac{1}{\sqrt{2}}\left[\mathrm{v}+\sigma(x)+i\eta(x)\right]$ where $\sigma(x)$ and $\eta(x)$ measure the deviation of $\varphi(x)$ from equilibrium. We get

$$\mathscr{L}=\tfrac{1}{2}\left(\partial_\mu\sigma\right)\left(\partial^\mu\sigma\right)-\mu^2\sigma^2+\tfrac{1}{2}\left(\partial_\mu\eta\right)\left(\partial^\mu\eta\right)+\mathscr{L}_{\text{int}}$$

$$\mathscr{L}_{\text{int}}=-\lambda\mathrm{v}\sigma\left(\sigma^2+\eta^2\right)-\tfrac{1}{4}\lambda\left(\sigma^2+\eta^2\right)^2$$

We can interpret: $\sigma\rightarrow$ real Klein-Gordon field $\quad \tfrac{1}{2}m^2=\mu^2$

$\eta\rightarrow$ real Klein-Gordon field $\quad m_\eta=0$ → Goldstone boson field

and n.d.f do add up →

n.d.f

Initially: complex $\varphi \rightarrow 2$

After : real massive $\sigma \rightarrow 1$

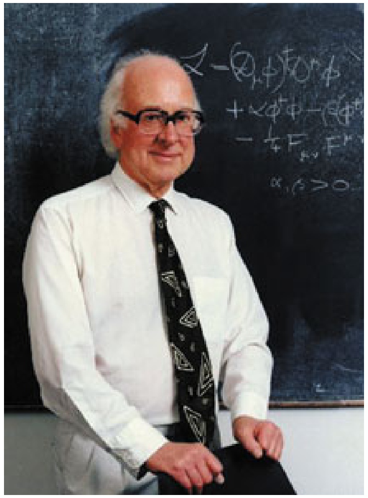
real massless $\eta \rightarrow 1$

No **truly** massless Goldstone bosons are observed in nature

π^0, π^+, π^- come pretty close...

Higgs Model

Generalize the Goldstone model to be invariant under U(1) gauge transformation $\partial_\mu \to D_\mu = \partial_\mu + iqA_\mu$



Higgs
1929-

Obtain
$$\mathscr{L} = \left(D_\mu\varphi\right)^*\left(D^\mu\varphi\right) - \tfrac{1}{4}F^{\mu\nu}F_{\mu\nu} - \mathscr{V}(\varphi)$$
$$\mathscr{V}(\varphi) = -\mu^2\varphi^*\varphi + \lambda\left(\varphi^*\varphi\right)^2 \qquad \lambda > 0$$

Invariant under
$$\varphi \xrightarrow{\varepsilon(x)} \varphi' = e^{-i\varepsilon(x)}\varphi$$
$$A^\mu \xrightarrow{\varepsilon(x)} A'^\mu = A^\mu + \tfrac{1}{q}\partial^\mu\varepsilon$$

$\mu^2 < 0 \Longrightarrow$ **Scalar electrodynamics with self-interacting Klein-Gordon field where** $m^2 = -\mu^2$

$\mu^2 > 0 \Longrightarrow \mathrm{V}(\varphi)\big|_{\min} = -\dfrac{\mu^2 v^2}{4} \Rightarrow |\varphi|^2 = |\varphi_0|^2 = \dfrac{\mu^2}{2\lambda} \equiv \dfrac{v^2}{2} > 0$

The equilibrium is characterized by $\varphi_0 = \dfrac{v}{\sqrt{2}}e^{i\theta}$

Nature spontaneously chooses, say, $\theta = 0 \to \varphi_0 = \dfrac{v}{\sqrt{2}} > 0$
always possible because of global U(1) phase invariance

again, use $\varphi(x) = \tfrac{1}{\sqrt{2}}\left[v + \sigma(x) + i\eta(x)\right]$

Higgs Model

Obtain

$$\mathscr{L} = \tfrac{1}{2}\left(\partial_\mu\sigma\right)\left(\partial^\mu\sigma\right) - \mu^2\sigma^2 + \tfrac{1}{2}\left(\partial_\mu\eta\right)\left(\partial^\mu\eta\right) - \tfrac{1}{4}F^{\mu\nu}F_{\mu\nu} + \tfrac{1}{2}\left(q\mathrm{v}\right)^2 A^\mu A_\mu + q\mathrm{v}\left(\partial_\mu\eta\right)A^\mu + \mathscr{L}'_{\text{int}}$$

can interpret $\sigma \rightarrow \text{real Klein - Gordon field}$ $\quad \tfrac{1}{2}m^2 = \mu^2$

but cannot interpret $\eta \rightarrow \text{real Klein-Gordon field } m_\eta = 0$

Aaarg!

$A^\mu \rightarrow \text{real Proca field} \qquad M_A = q\mathrm{v}$

n.d.f

and n.d.f would NOT add up ⟶

$$\text{Initially: } \left\{\begin{array}{ll} \text{complex } \varphi & \rightarrow\ 2 \\ \text{real massless } A^\mu & \rightarrow\ 2 \end{array}\right\} \rightarrow\ 4$$

!

$$\text{After}\ :\ \left\{\begin{array}{ll} \text{real massive } \sigma & \rightarrow\ 1 \\ \text{real massless } \eta & \rightarrow\ 1 \\ \text{real massive } A^\mu & \rightarrow\ 3 \end{array}\right\} \rightarrow\ 5$$

$\mathscr{L}$ contains an unphysical field which can be eliminated through a gauge transformation yielding the form

$$\varphi(x) = \frac{1}{\sqrt{2}}\left[\mathrm{v} + \sigma(x)\right] \qquad \text{unitary gauge}$$

$\eta(x)$ ⟶ would-be Goldstone boson field

Higgs Mechanism

In this gauge, we obtain

$$\mathscr{L} = \tfrac{1}{2}\left(\partial_\mu \sigma\right)\left(\partial^\mu \sigma\right) - \mu^2\sigma^2 - \tfrac{1}{4}F^{\mu\nu}F_{\mu\nu} + \tfrac{1}{2}\left(qv\right)^2 A^\mu A_\mu + \mathscr{L}_{\text{int}}$$

$$\mathscr{L}_{\text{int}} = -\lambda v \sigma^3 - \tfrac{1}{4}\lambda\sigma^4 + \tfrac{1}{2}q^2 A^\mu A_\mu \left(2v\sigma + \sigma^2\right)$$

can interpret $\sigma \rightarrow$ real Klein-Gordon field $\tfrac{1}{2}m^2 = \mu^2$

$A^\mu \rightarrow$ real Proca field $M_A = qv$

and n.d.f do add up →

$$\begin{array}{lllll} & & & \text{n.d.f} & \\ \text{Initially:} & \left\{\begin{array}{l}\text{complex } \varphi \\ \text{real massless } A^\mu\end{array}\right. & \begin{array}{l}\rightarrow \\ \rightarrow\end{array} & \left.\begin{array}{l}2 \\ 2\end{array}\right\} & \rightarrow 4 \\ \text{After :} & \left\{\begin{array}{l}\text{real massive } \sigma \\ \text{real massive } A^\mu\end{array}\right. & \begin{array}{l}\rightarrow \\ \rightarrow\end{array} & \left.\begin{array}{l}1 \\ 3\end{array}\right\} & \rightarrow 4 \end{array}$$

The massless Goldstone boson field $\eta(x)$ has disappeared from the theory and has allowed the $A^\mu(x)$ field to acquire mass!! →

$\sigma(x)$ is a Higgs boson field

vector boson acquires mass without spoiling gauge invariance

→ Higgs mechanism

...and we get a prescription for the interactions between σ and A^μ!

The Standard Model
of Electroweak and Strong Interactions

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


Glashow
1932


Salam
1926 1996


Weinberg
1933

Spontaneous symmetry hiding in the electroweak sector

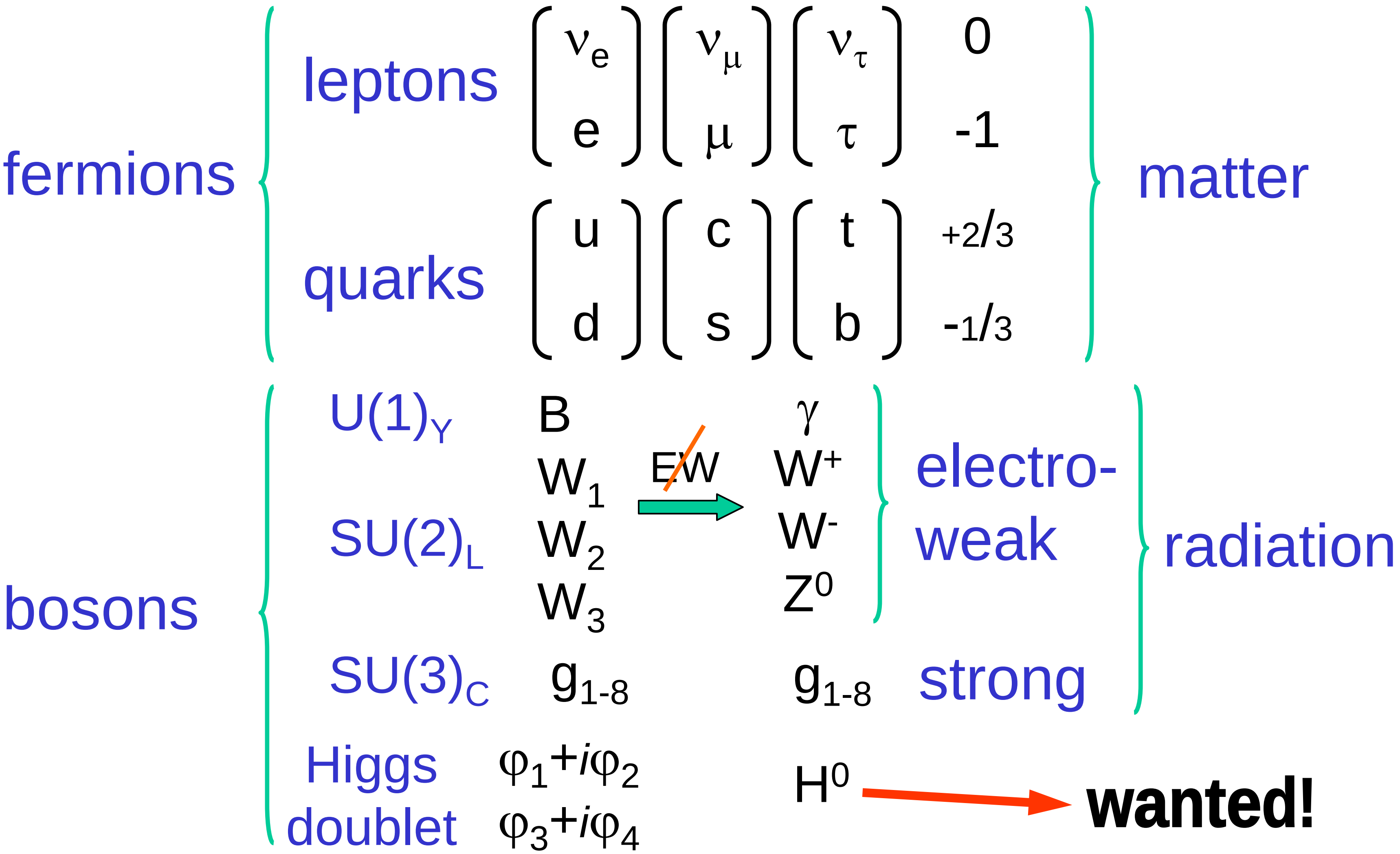
Higgs mechanism: **$U(1)_Y \times SU(2)_L \rightarrow U(1)_Q$**

Residual (non-hidden) symmetry: **$U(1)_Q \times SU(3)_C$**

massless photons

massless gluons

The Standard Model Particles



fermions

leptons $\begin{pmatrix}\nu_e\\ e\end{pmatrix}\begin{pmatrix}\nu_\mu\\ \mu\end{pmatrix}\begin{pmatrix}\nu_\tau\\ \tau\end{pmatrix}$ $\begin{matrix}0\\ -1\end{matrix}$

quarks $\begin{pmatrix}u\\ d\end{pmatrix}\begin{pmatrix}c\\ s\end{pmatrix}\begin{pmatrix}t\\ b\end{pmatrix}$ $\begin{matrix}+2/3\\ -1/3\end{matrix}$

matter

bosons

$U(1)_Y$ B γ

$SU(2)_L$ W_1 W_2 W_3 $\xrightarrow{\cancel{EW}}$ W^+ W^- Z^0 electro-weak

$SU(3)_C$ $g_{1\text{-}8}$ $g_{1\text{-}8}$ strong

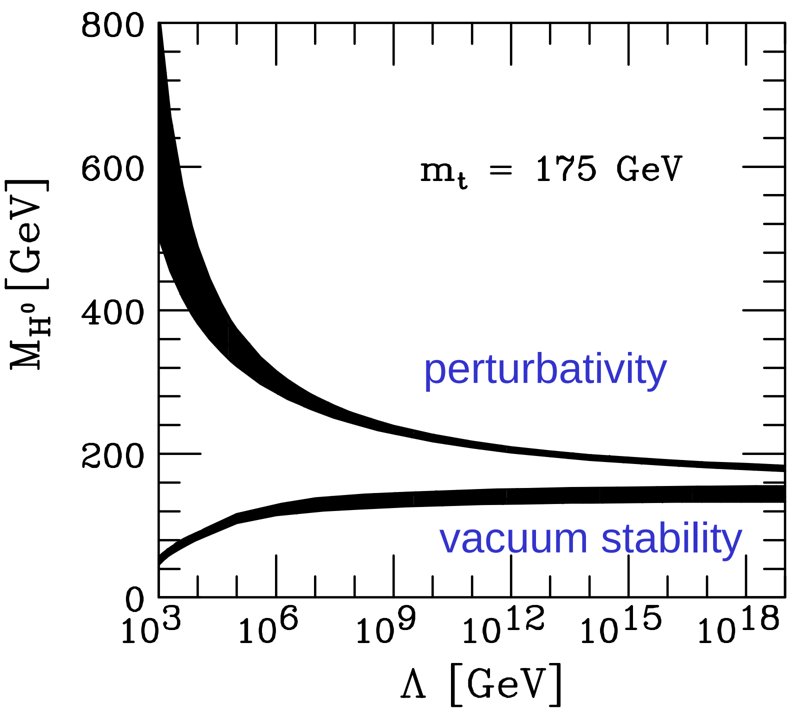
radiation

Higgs doublet $\varphi_1+i\varphi_2$ $\varphi_3+i\varphi_4$ H^0 → **wanted!**

Theoretical Constraints on M_H

M_H is a free parameter of SM

but it must lie in a limited region for electroweak symmetry hiding to work

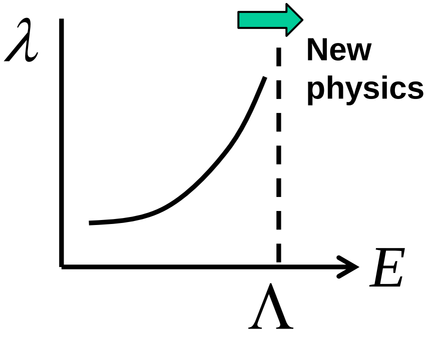


$130\,\text{GeV} \approx< M_H \approx< 180\,\text{GeV}$

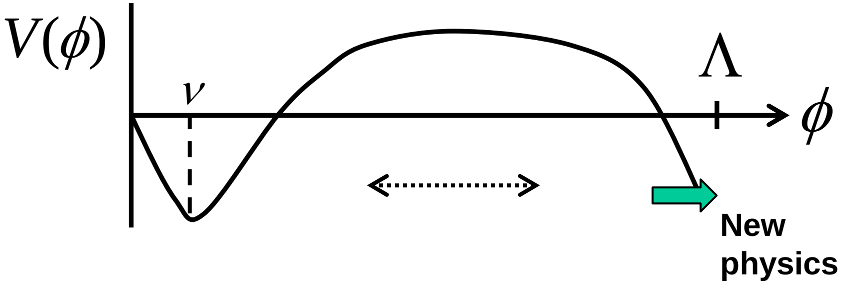
then, in principle consistent with $\Lambda = M_{PL}$

M_H is too large: the higgs self-coupling blows up at some scale Λ

$$m_H^2 = 2\lambda(m_H)v^2$$

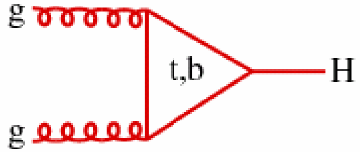


M_H is too small: the higgs potential develops a second (global!) minimum values of the scalar field of the order of Λ

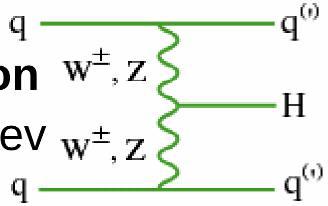


SM Higgs Production at the LHC

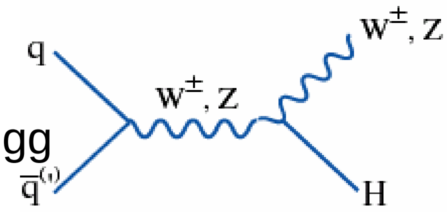
gluon fusion
dominant process



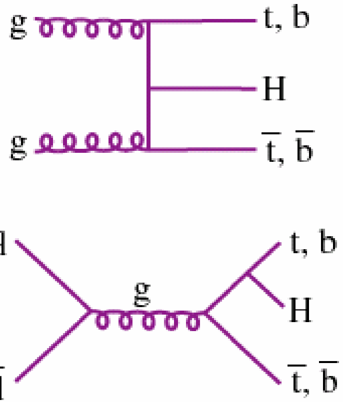
vector boson fusion
20% of gg at 120 Gev

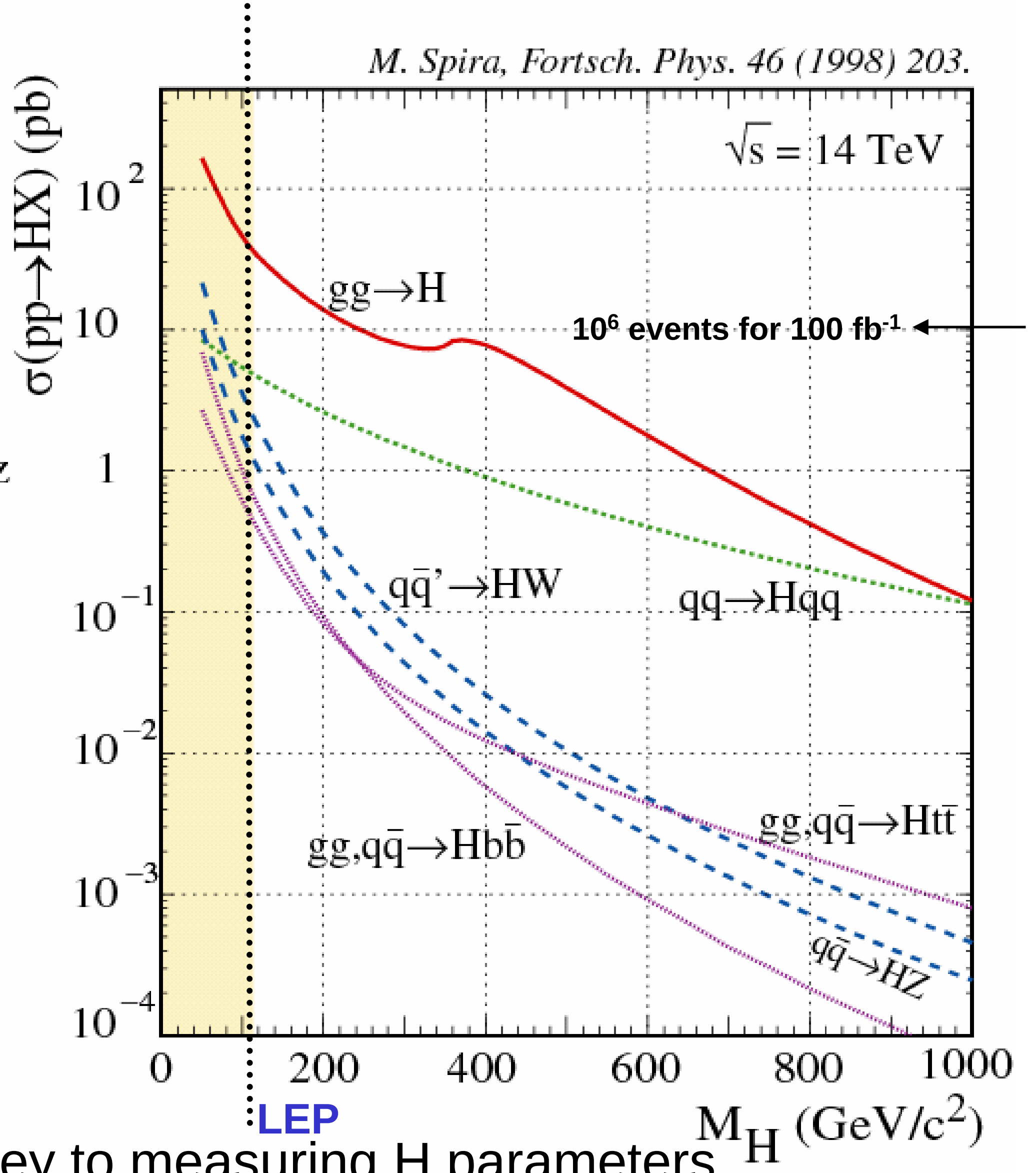


associated prod.
W or Z, 1-10% of gg



associated prod.
t t̄ or bb̄, 1-5% of gg





4 production mechanisms is the key to measuring H parameters

SM Higgs Interactions

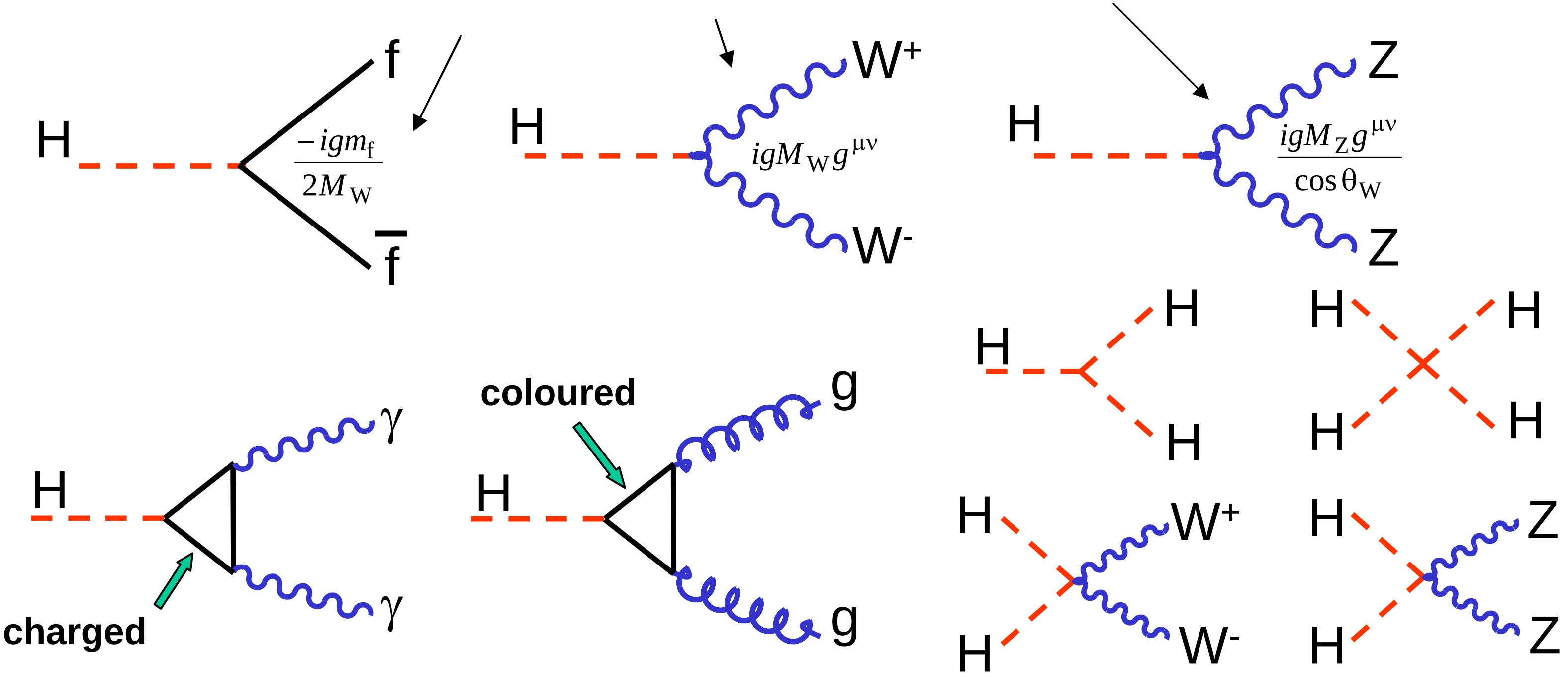
SM ⟶ Higgs mechanism with $U(1)_Y \times SU(2)_L$ gauge

$\varphi(x)$ is a complex doublet ⟶ W^+, W^-, Z acquire mass
left with one massive Higgs boson

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

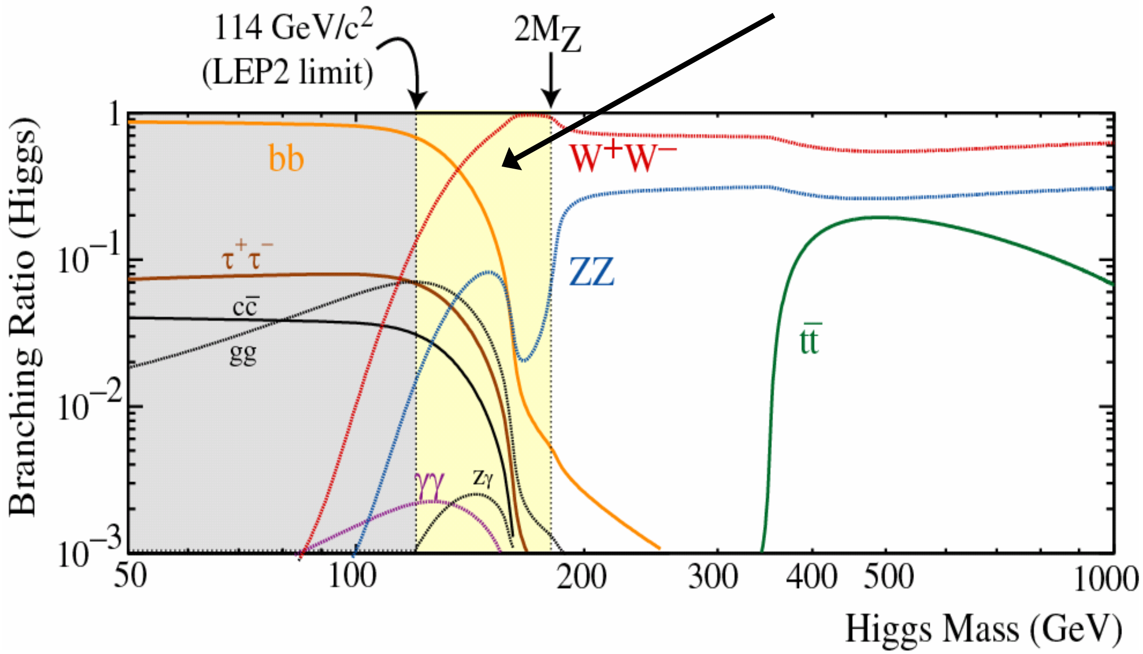
$\varphi(x)$ coupling with massless fermion fields ⟶ fermion masses

Higgs couplings proportional to mass $g^2 = 4\sqrt{2} G_F M_W^2$



Main SM Higgs Discovery Channels

Low M_H region, $M_H < 2M_Z$



Dominant BR:

$\sigma(H \to b\bar{b}) \approx 20$ pb
$\sigma(b\bar{b}) \approx 500$ μb

M_H=120 GeV, direct production

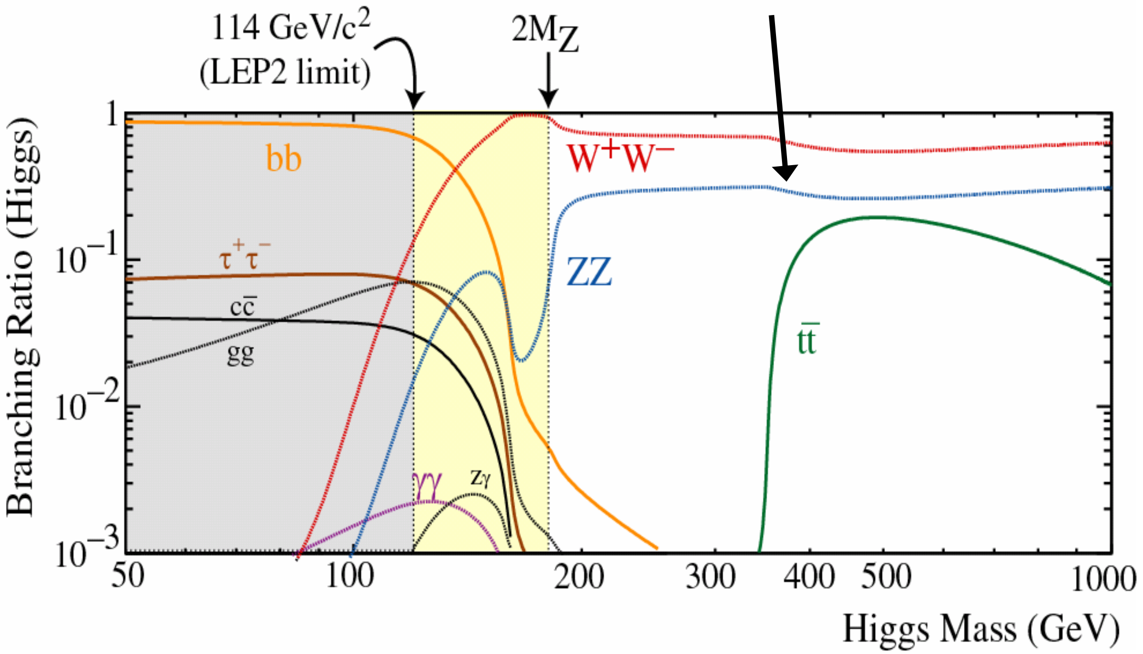
Cannot trigger or extract fully hadronic final states

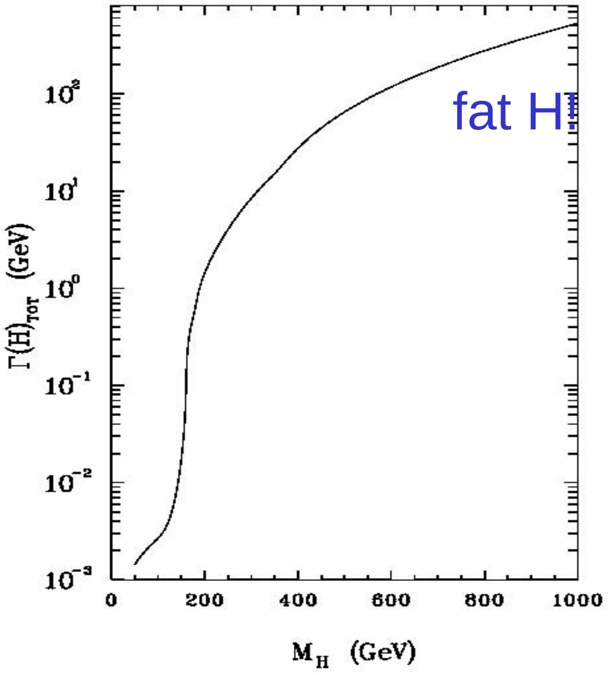
Must look for final states with ℓ(e,μ), γ

- $H \to \gamma\gamma$ small BR, best resolution
- $H \to b\bar{b}$ good BR, poor resolution: use $t\bar{t}H$, WH associated prod
- $H \to \tau\tau$ uses vector boson fusion (VBF) production
- $H \to ZZ^* \to 4\ell$
- $H \to WW^* \to \ell\nu\ell\nu$ or $\ell\nu jj$ uses VBF production

Main SM Higgs Discovery Channels

High M_H region, $2M_Z < M_H < 1$ TeV



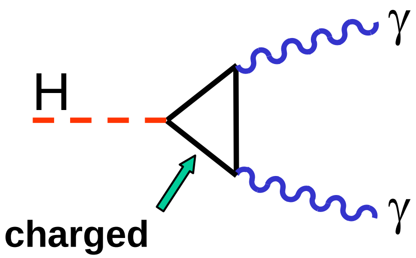


fat H!

- $H \rightarrow ZZ \rightarrow 4\ell$ Gold platted channel!!
- $qqH \rightarrow ZZ \rightarrow \ell\ell\nu\nu$
- $qqH \rightarrow ZZ \rightarrow \ell\ell jj$
- $qqH \rightarrow WW \rightarrow \ell\nu jj$

For M_H > 300 GeV use forward jet tag

Light Higgs Discovery: H → γγ



$M_H < 150$ GeV

$\sigma(pp\rightarrow H_{(100\text{GeV})})\times BR(H\rightarrow\gamma\gamma) \approx 50$ fb

one every ~ 30 min at 10^{34} cm ^{2}s ^{1}

rare decay!

- Select events with two photons in the detector with p_T ~ 50 GeV
- Measure energy and direction of each photon
- Measure the invariant mass of the photon pair

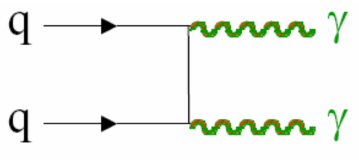
$$m_{\gamma\gamma}^2 = \left(E_1 + E_2\right)^2 - \left(\vec{p}_1 - \vec{p}_2\right)^2$$

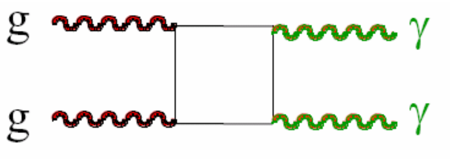
- Higgs should appear as a peak in $m_{\gamma\gamma}$ distribution
- Most challenging channel for LHC electromagnetic calorimeters

Light Higgs Discovery: H → $\gamma\gamma$

Main backgrounds

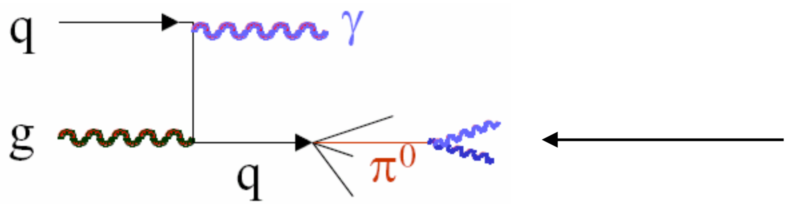
- $\gamma\gamma$ production
  - irreducible (same final state as signal!), e.g.





$$\frac{\sigma(\gamma\gamma)}{\sigma(H \to \gamma\gamma)} \approx 60 \quad \text{for} \quad m_{\gamma\gamma} \approx 100 \text{ GeV}$$

- γ jet + γ jet production where one or both jets fake a photon
  - reducible, e.g.



fake photon

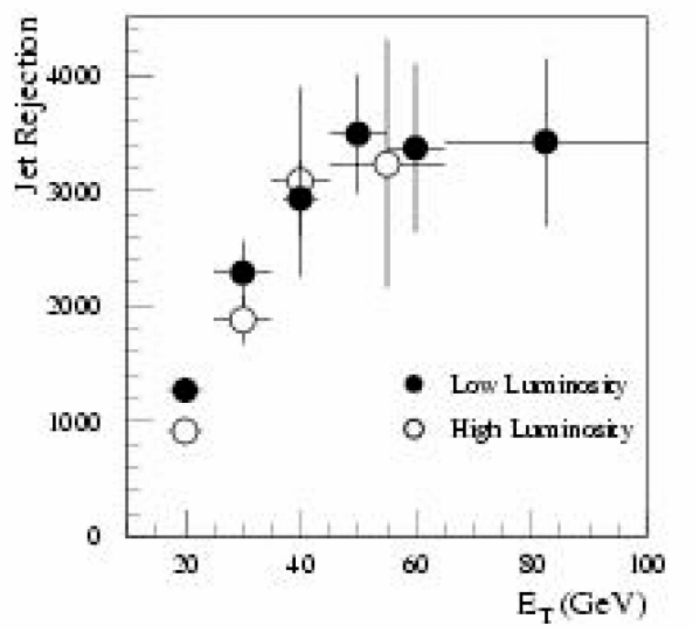
$$\frac{\sigma(\text{jj})}{\sigma(H \to \gamma\gamma)} \approx 10^8 \quad \text{for} \quad m_{\gamma\gamma/\text{jj}} \approx 100 \text{ GeV}$$

Light Higgs Discovery: H → $\gamma\gamma$

Dealing with backgrounds: γ jet + jet jet production

- reducible
- requires excellent γ/jet separation, in particular γ/π^o separation, to reject jets faking photons; $R_{jet} \approx 10^3$ needed for $\varepsilon_\gamma \approx 80\%$
- ATLAS and CMS have calorimeters with good granularity to separate single γ from jets or from $\pi^o \to \gamma\gamma$

ATLAS simulation



with this performance

$\sigma(\gamma \text{ jet + jet jet}) \leq 30\% \ \sigma(\gamma\gamma)$

→ small

Light Higgs Discovery: $H \rightarrow \gamma\gamma$

Dealing with backgrounds: $\gamma\gamma$ production

- cannot be reduced
- signal can be extracted from background if the $m_{\gamma\gamma}$ resolution is good enough
- recall that the Higgs width is 0.1‰ M_H at $M_H \approx 100$ GeV
- significance ~ $\sigma(m)^{-1/2}$

$$m_{\gamma\gamma}^2 = \left(E_1 + E_2\right)^2 - \left(\vec{p}_1 - \vec{p}_2\right)^2 = 2E_1E_2\left(1 - \cos\theta_{12}\right)$$

$$\sqrt{2}\,\frac{\sigma(m)}{m} = \frac{\sigma(E_1)}{E_1} \oplus \frac{\sigma(E_2)}{E_2} \oplus \frac{\sigma(\theta_{12})}{\tan\frac{1}{2}\theta_{12}}$$

energy resolution of
EM calorimeters

resolution of the
measurement of θ_{12}

If $\varphi_{12} = \pi$ then $\theta_{12} = \theta_1 + \theta_2$ and $\sigma(\theta_{12}) = \sigma(\theta_1) \oplus \sigma(\theta_2)$

Light Higgs Discovery: H $\rightarrow \gamma\gamma$

Dealing with backgrounds: $\gamma\gamma$ production

- ATLAS
  - LAr-Pb sampling EM calorimeter

    $$\frac{\sigma(E)}{E} \approx \frac{10\%}{\sqrt{E(\text{GeV})}}$$

  - longitudinal segmentation allows the measurement of γ direction

    $$\sigma(\theta) \approx \frac{50\ \text{mrad}}{\sqrt{E(\text{GeV})}}$$

  - $\sigma(m) \approx 1.3\ \text{GeV}$ for $M_\text{H} \approx 100\ \text{GeV}$ and $\varepsilon \approx 30\%$
- CMS
  - homogeneous PbWO_4 crystal EM calorimeter

    $$\frac{\sigma(E)}{E} \approx \frac{(2\ \text{to}\ 5)\%}{\sqrt{E(\text{GeV})}}$$

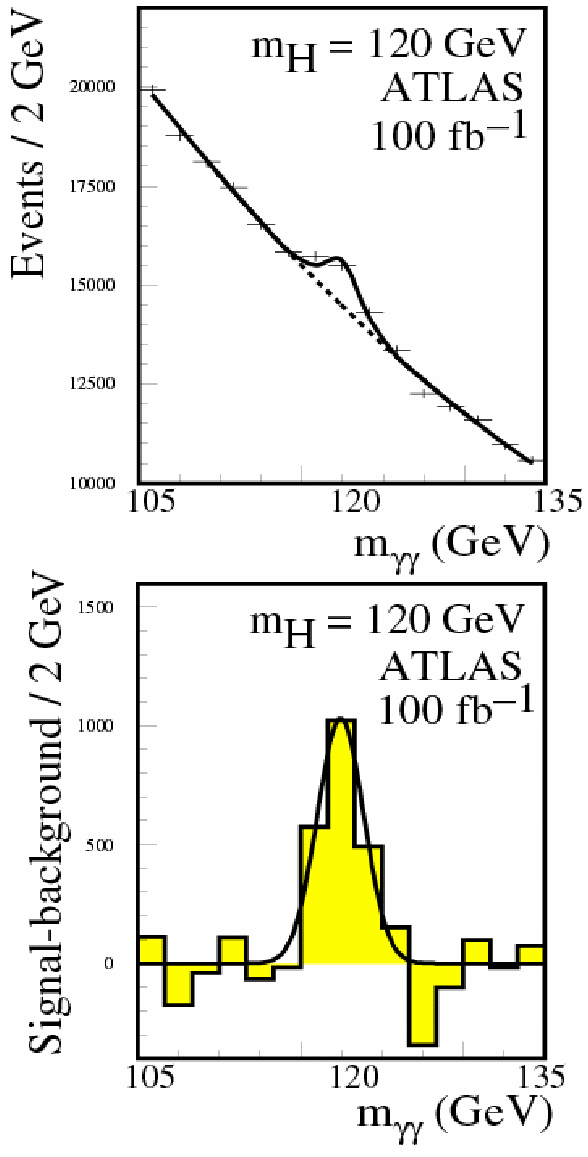
  - no longitudinal segmentation, so harder to pick up the right vertex at high luminosity using secondary tracks from spectator partons
  - $\sigma(m) \approx 0.7\ \text{GeV}$ for $M_\text{H} \approx 100\ \text{GeV}$ and $\varepsilon \approx 20\%$

Light Higgs Discovery: $H \to \gamma\gamma$

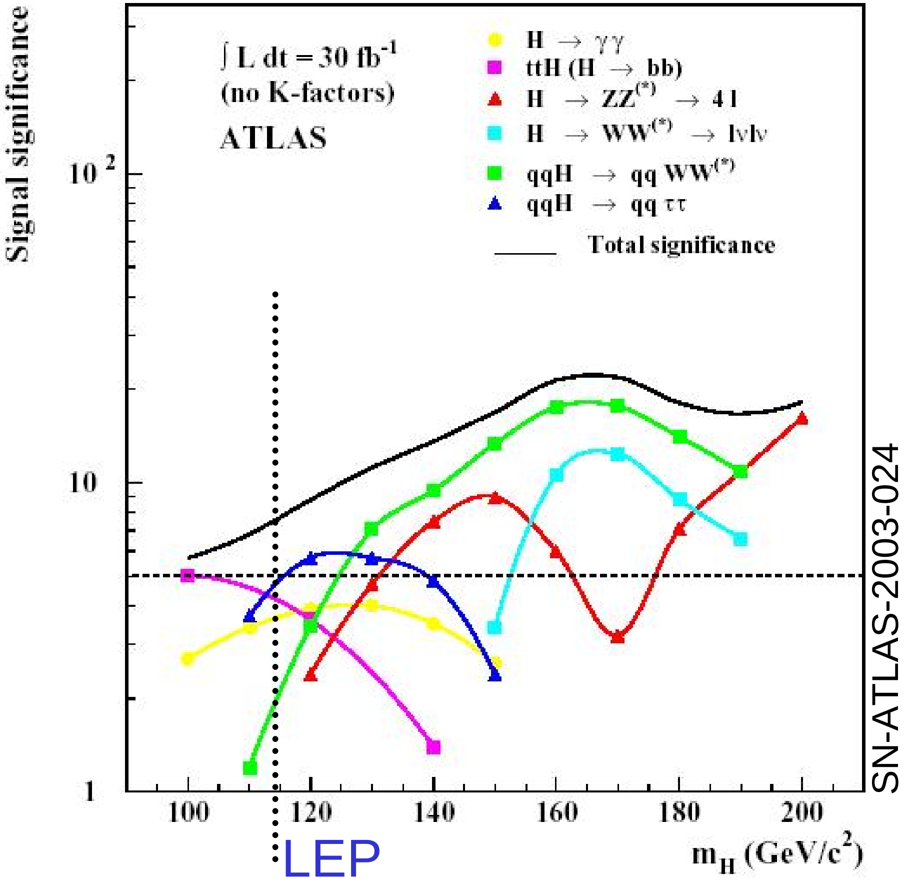
Expected performance for 100 fb^{-1}

Signal significance

- **ATLAS**
  - M_H = 100 GeV: 4.4
  - M_H = 120 GeV: 6.5
  - M_H = 150 GeV: 4.3
- **CMS**
  - about 10% better, due to better EM calorimeter resolution



SM Higgs Discovery Potential



30 fb^{-1} is equivalent to three years at $10^{33}\ cm^{-2}s^{-1}$

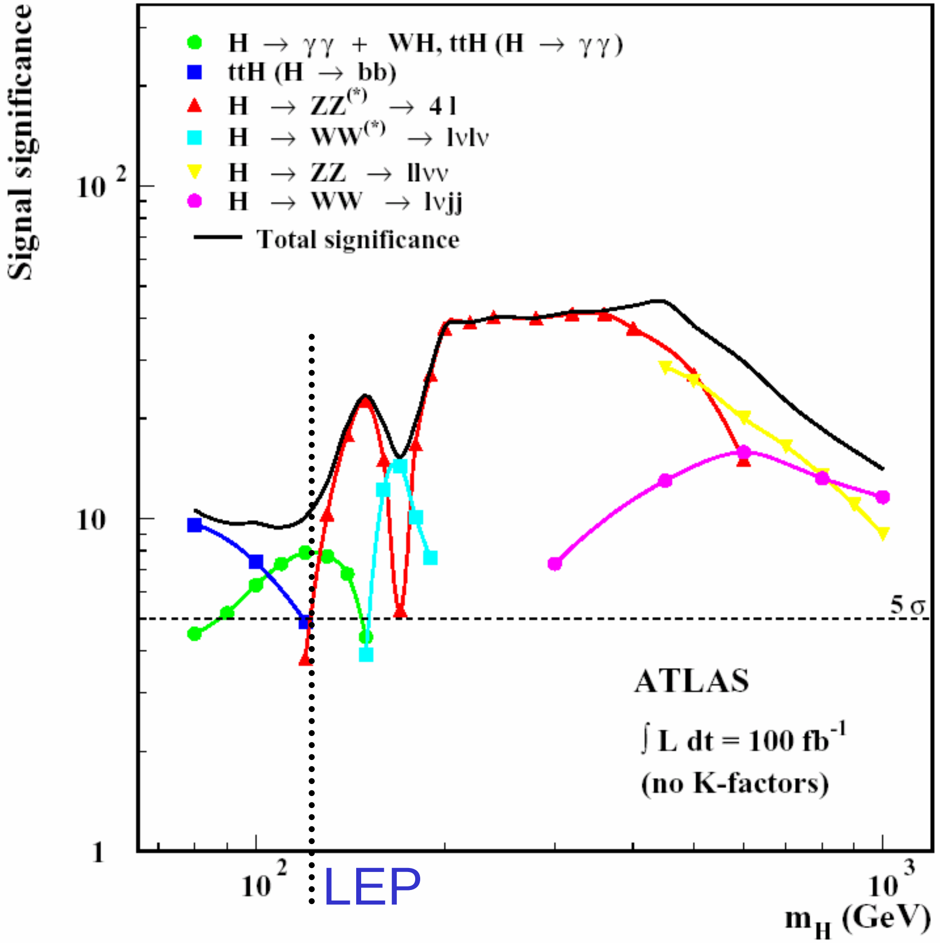
combining ATLAS and CMS increases significance by $\sim \sqrt{2}$

SM light Higgs can be discovered with 30 fb^{-1}

In most cases, more than one channel is available.

Signal significance is $S/B^{1/2}$ or using Poisson statistics

SM Higgs Discovery Potential



100 fb^{-1} is equivalent to one year at 10^{34} cm^{-2}s^{-1}.

combining ATLAS and CMS increases significance by $\sim\sqrt{2}$

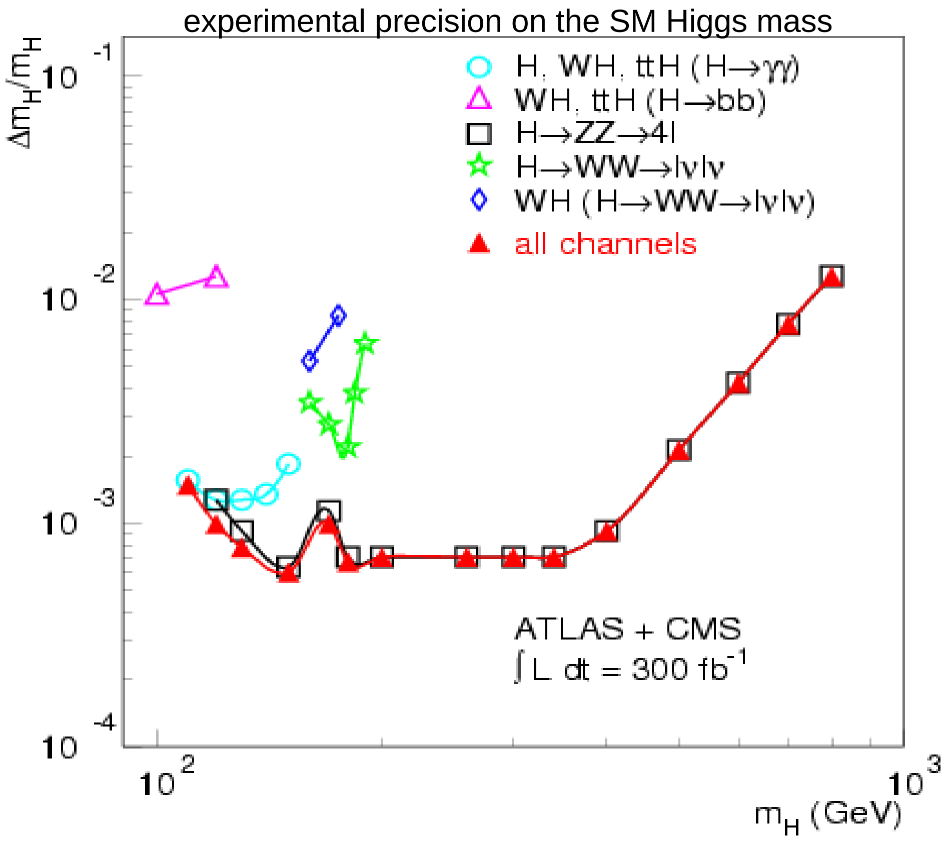
see also talk from Jim Brooke (CMS)

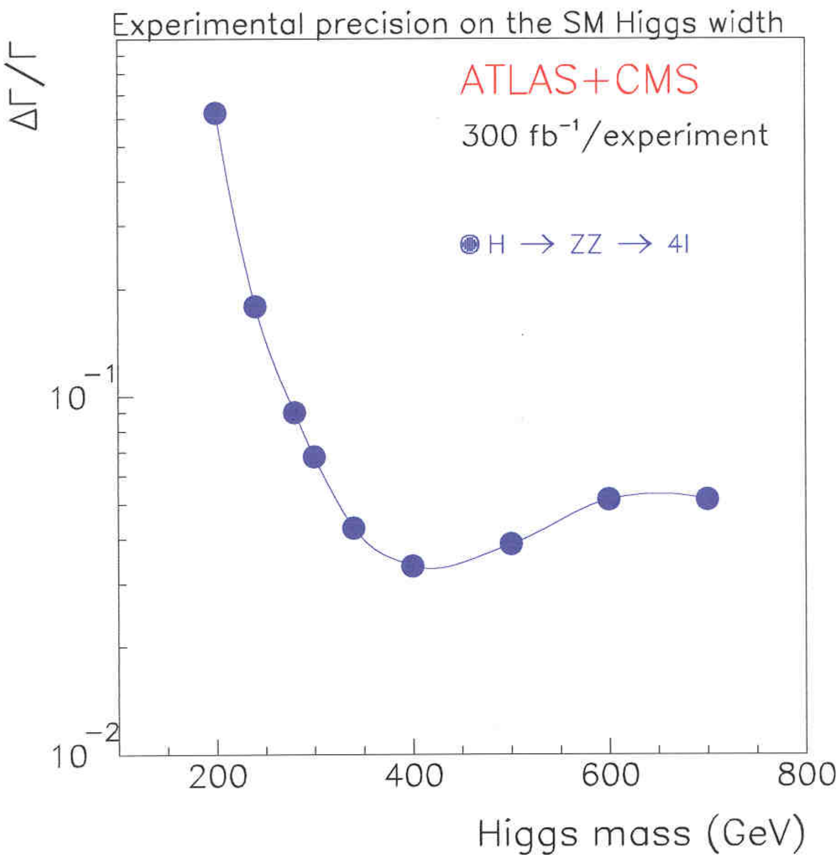
More than significance = 10 over the full mass range with 100 fb^{-1}

Signal significance is S/B$^{1/2}$ or using Poisson statistics

If SM Higgs exists, it will be discovered at the LHC

SM Higgs Mass and Width


experimental precision on the SM Higgs mass


Experimental precision on the SM Higgs width

Other Higgs sector parameters can be measured by comparing rates from various Higgs channels

Supersymmetry

Maximal extension of the Poincaré group

$$\left.\begin{array}{l}\left.\begin{array}{l}\left.\begin{array}{l}\textbf{3D rotations}\\ \textbf{pure boosts}\end{array}\right\}\textbf{Lorentz}\\ \textbf{4D translations}\end{array}\right\}\textbf{Poincare}'\\ \textbf{SUSY translations}\end{array}\right\}\textbf{superPoincare}'$$

SUSY actions are invariant under superPoincaré

they are composed of an equal number of bosonic and fermionic degrees of freedom

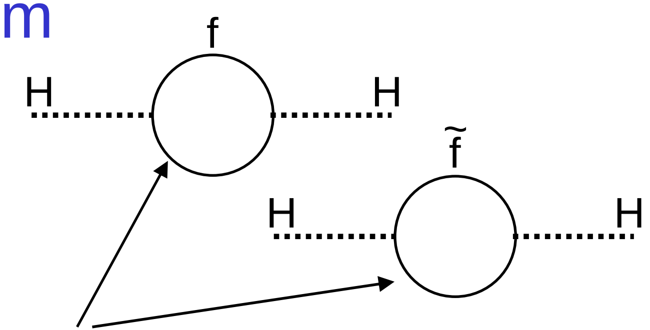
SUSY mixes fermions and bosons

exact SUSY → there should exist fermions and bosons of the same mass
clearly NOT the case → SUSY IS BROKEN → WHY BOTHER WITH SUSY??

Many SUSY breaking scenarios have been proposed...

A solution to the hierarchy problem

If the Higgs is to be light without unnatural fine tuning, then (softly broken) SUSY particles should have M_{SUSY}<~ 1 TeV. SUSY can be viable up to M_{PL} AND be natural!



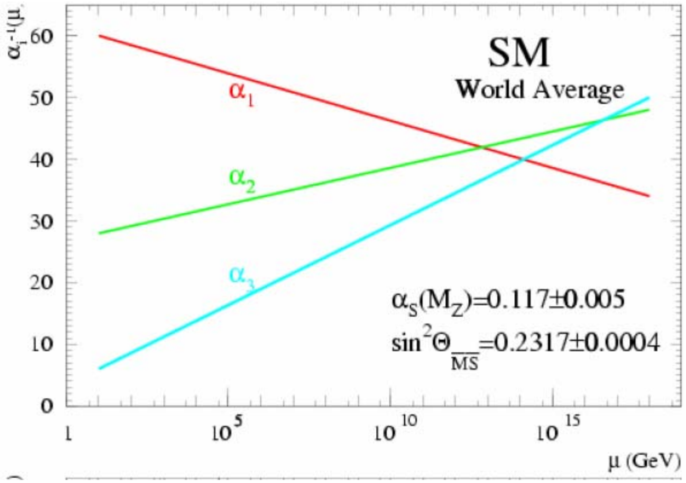
opposite sign contributions

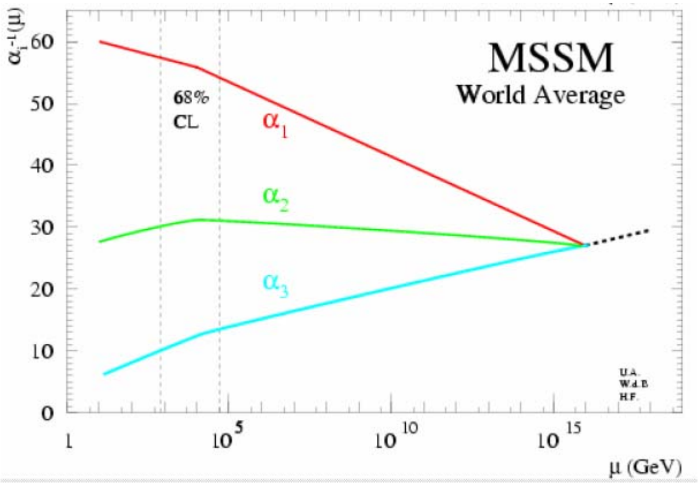
About half the particles already discovered!

Supersymmetry

GUT acceptable coupling constant evolution

The precision data at the Z mass (LEP and SLC) are inconsistent with GUT's using SM evolution, but are consistent with GUT's using SUSY evolution, if $M_{SUSY} \approx$ 1 TeV





A natural way to break EW symmetry

The large top Yukawa coupling can naturally drive the Higgs quadratic coupling negative in SUSY

Lightest SUSY particle is stable and a cold dark matter candidate

For R-parity conserving models, SUSY particles are produced in pairs and the LSP is stable and weakly interacting

$$R = (-1)^{3(B-L)+2S} = \begin{cases} +1 & \text{SM particles} \\ -1 & \text{SUSY particles} \end{cases}$$

Local SUSY is SUperGRAvity

SUSY is an ingredient of string theories → superstrings

Supersymmetry

SUSY does not contradict low energy predictions of the SM

BUT no experimental evidence for SUSY so far... which means

SUSY does not exist **OR** **M_{SUSY} too large for present machines**

LHC will find out if SUSY exist for $M_{SUSY} \leq$ a few TeV

Minimal SUSY

MSSM: SM + an extra Higgs doublet + SUSY partners

SUSY breaking

0	H_d^-	H_d^0	H_u^0	H_u^+						$\tilde{q}_R^d$	$\tilde{q}_L^d$	$\tilde{q}_R^u$	$\tilde{q}_L^u$	$\tilde{\nu}_L$	$\tilde{l}_R$	$\tilde{l}_L$
$\frac{1}{2}$	$\tilde{H}_d^-$	$\tilde{H}_d^0$	$\tilde{H}_u^0$	$\tilde{H}_u^+$	$\tilde{B}^0$	$\tilde{W}^0$	$\tilde{W}^-$	$\tilde{W}^+$	$\tilde{g}$	q_R^d	q_L^d	q_R^u	q_L^u	ν_L	l_R	l_L
1					B^0	W^0	W^-	W^+	g							

EW symmetry breaking

	CP odd	CP even														
0	A	H	h	H^-	H^+					$\tilde{q}_2^d$	$\tilde{q}_1^d$	$\tilde{q}_2^u$	$\tilde{q}_1^u$	$\tilde{\nu}_l$	$\tilde{l}_2$	$\tilde{l}_1$
$\frac{1}{2}$	χ_4^0	χ_3^0	χ_2^0	χ_1^0	χ_2^-	χ_1^-	χ_2^+	χ_1^+	$\tilde{g}$	q_R^d	q_L^d	q_R^u	q_L^u	ν_l	l_R	l_L
1					Z^0	γ	W^-	W^+	g							

→ **5 massive Higgs particles, with $M_h < 130$ GeV**

At tree level, all Higgs boson masses and couplings can be expressed in terms of two parameters only
(in “constrained MSSM”)

$$m_A \quad \text{and} \quad \tan\beta = \frac{\langle 0|H_u|0\rangle}{\langle 0|H_d|0\rangle}$$

Note that we also have the following mixings

$$B^0, W^0 \to \gamma, Z^0$$
$$\tilde{W}^\pm, \tilde{H}^\pm \to \chi_{1,2}^\pm$$
$$\tilde{B}^0, \tilde{W}^0, \tilde{H}_u^0, \tilde{H}_d^0 \to \chi_{1,2,3,4}^0$$
$$\tilde{l}_L, \tilde{l}_R \to \tilde{l}_1, \tilde{l}_2$$
$$\tilde{q}_L, \tilde{q}_R \to \tilde{q}_1, \tilde{q}_2$$

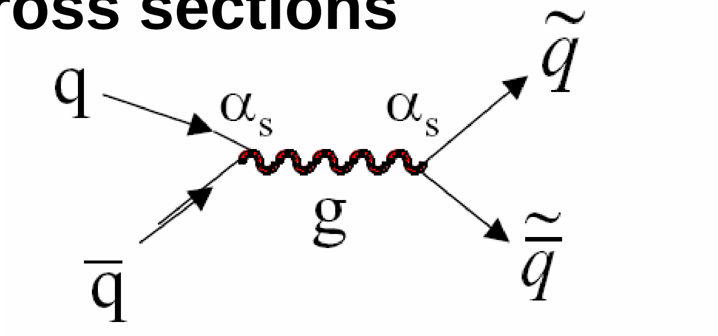
with off-diagonal elements proportional to fermion masses

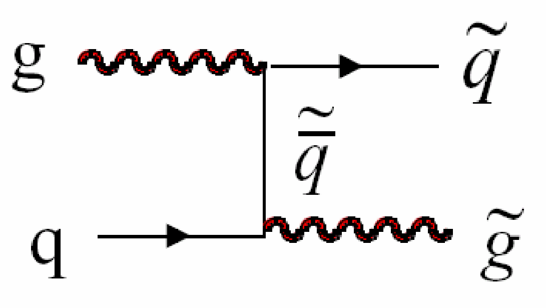
SUSY Particle Production

Squarks and gluinos produced via strong processes:

large cross sections

example:



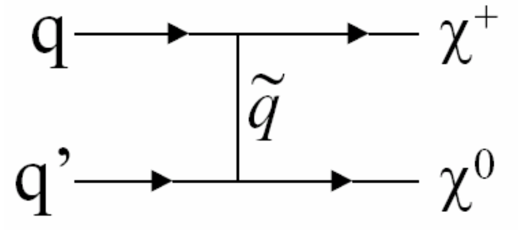


$$m_{\tilde{q},\tilde{g}} \sim 1\ \mathrm{TeV} \quad \Rightarrow \quad \sigma \sim 1\ \mathrm{pb}$$

10^4 events per year at $10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

Charginos, neutralinos, sleptons produced via electroweak processes: **much smaller rates**

example:



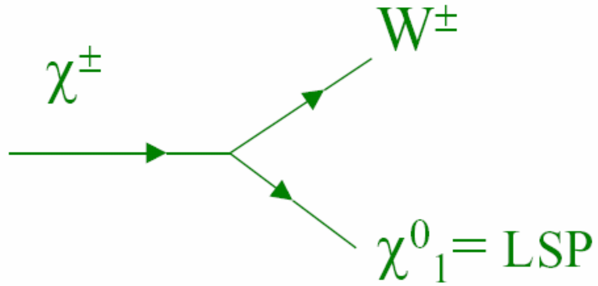
$$m_\chi \sim 150\ \mathrm{GeV}$$

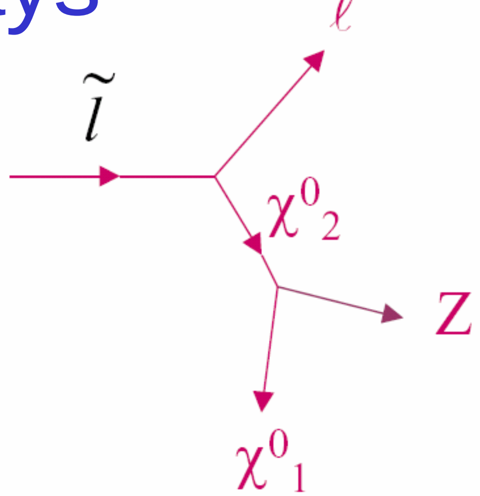
$$\Rightarrow \quad \sigma \sim O(\mathrm{pb})$$

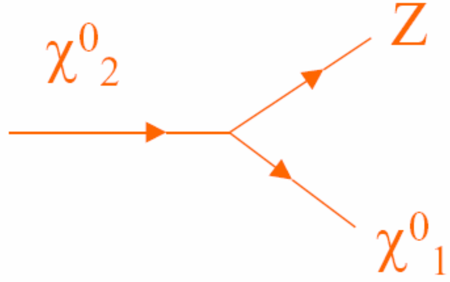
$\tilde{q}\tilde{q},\ \tilde{q}\tilde{g},\ \tilde{g}\tilde{g}$ **are dominant SUSY production processes at LHC if kinematically accessible**

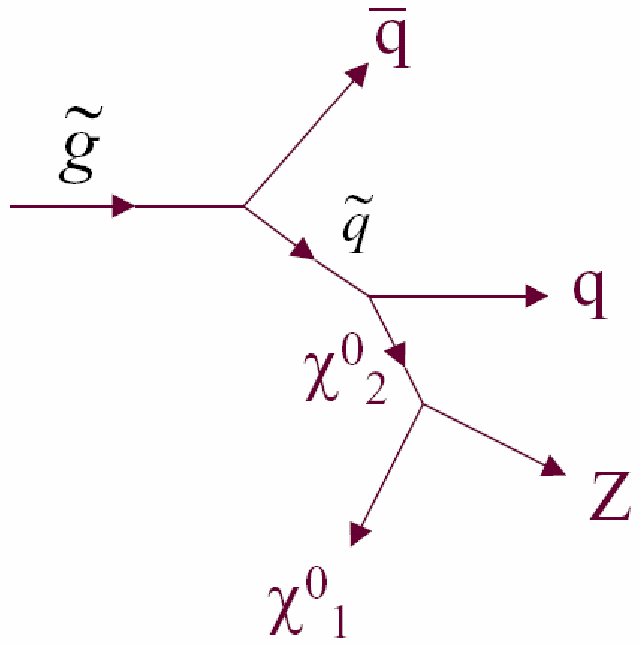
SUSY Particle Decays

a few examples









squarks and gluinos are heavier, producing more complicated decay chains

Cascade decays involve many leptons and/or jet + E_T^{miss}

Discovering SUSY

The exact decay chains depend on model parameters (masses, couplings). BUT independent of the model we know that

$$\tilde{q}, \tilde{g} \text{ are heavy } \left(m > 250\ \text{GeV}\right)$$

⬇

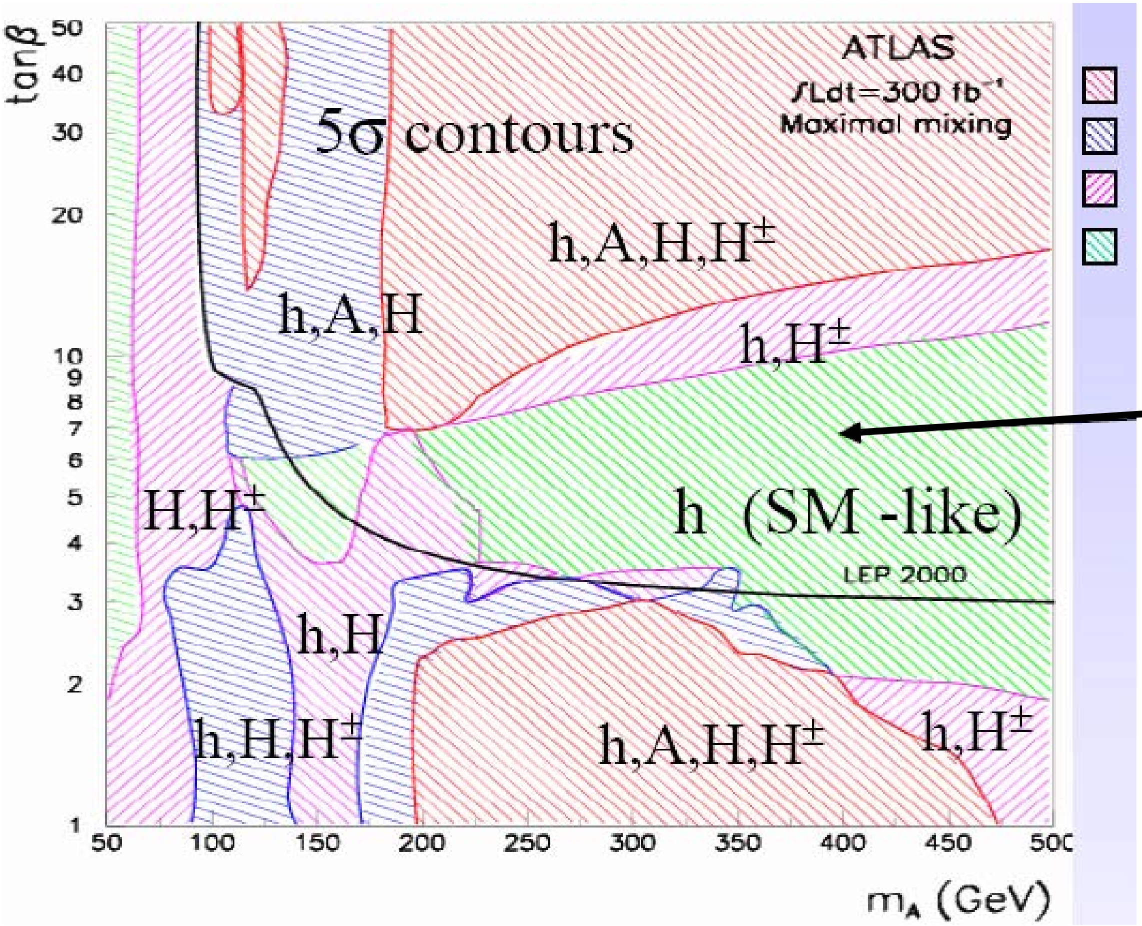
decays through cascades favoured:

many high P_T jets, leptons, W, Z in the final state, and E_T^{miss}

⬇

should be easy to extract SUSY from SM background at the LHC

Minimal SUSY Higgs Searches



4
3
2
1

number of observable Higgs

only SM-like h observable (and also SUSY particles...)

"All" parameter space covered!

If MSSM Higgs exists, they will be discovered at the LHC

Extra Dimensions

Why extra dimensions?

- string theory requires 10 dimensions!
  - different models represent different limiting cases of M-theory in 11 dimensions, including supergravity
  - the new (space) dimensions are compactified
- Many models attempt to solve the hierarchy problem by postulating the existence of extra dimensions

Large Compact Extra Dimensions

e.g. Arkani-Hamed, Dimopoulos, Dvali model **(Phys.Lett. B429 (1998) 263 (hep-ph/9803315, also see Scientific American Aug 2000)**

SM in 3+1 dimensions (the wall), gravitons free to propagate in 3+1+*n* dimensions (the bulk), where the *n* dimensions are compactified, with a common size *R*. Gravity with fundamental scale M_D would then follow Gauss' Law in 3+*n* spatial dimensions

Weakness of gravity is only apparent in 3+1

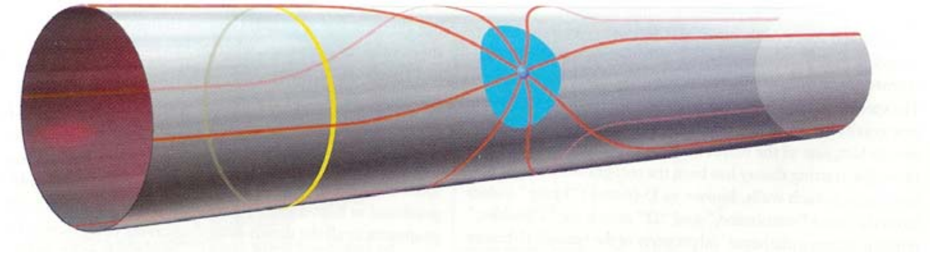
$$V_{3+1+n}(r) = \frac{-m_1 m_2}{8\pi (2\pi)^n \bar{M}_{\mathrm{D}}^{n+2} r^{n+1}} \qquad \text{for} \quad r < R$$

while

$$V(r) = \frac{-m_1 m_2}{8\pi \bar{M}_{\mathrm{Pl}}^2 r} \qquad \text{for} \quad r > R \qquad \text{where} \quad \bar{M}_{\mathrm{Pl}}^2 \equiv \tfrac{1}{8\pi} M_{\mathrm{Pl}}^2 = (8\pi G_{\mathrm{N}})^{-1}$$

hence

$$\bar{M}_{\mathrm{D}}^{2+n} = \frac{\bar{M}_{\mathrm{Pl}}^2}{(2\pi R)^n}$$



Large Compact Extra Dimensions

For compactification in circles graviton field is periodic in extra dimensions (y_i)

$$\varphi(\vec{x},\vec{y}) = \sum_{k_1=-\infty}^{\infty} \sum_{k_2=-\infty}^{\infty} \cdots \sum_{k_n=-\infty}^{\infty} \varphi^{(k)}(\vec{x}) \exp\left(i \frac{\vec{k}\cdot\vec{y}}{R}\right)$$

Kaluza-Klein states of graviton with mass k/R

Reformulate the hierarchy problem through large extra dimensions by demanding that $M_D \approx 1$ TeV. If $M_D = 1$ TeV then

$n = 1 \rightarrow R = 9.4 \times 10^{26}\ \text{GeV}^{-1} = 1.9 \times 10^{13}\ \text{cm} = O(\text{solar system})$

Excluded!

$n = 2 \rightarrow R = 3.9 \times 10^{11}\ \text{GeV}^{-1} = 0.078\ \text{mm}$

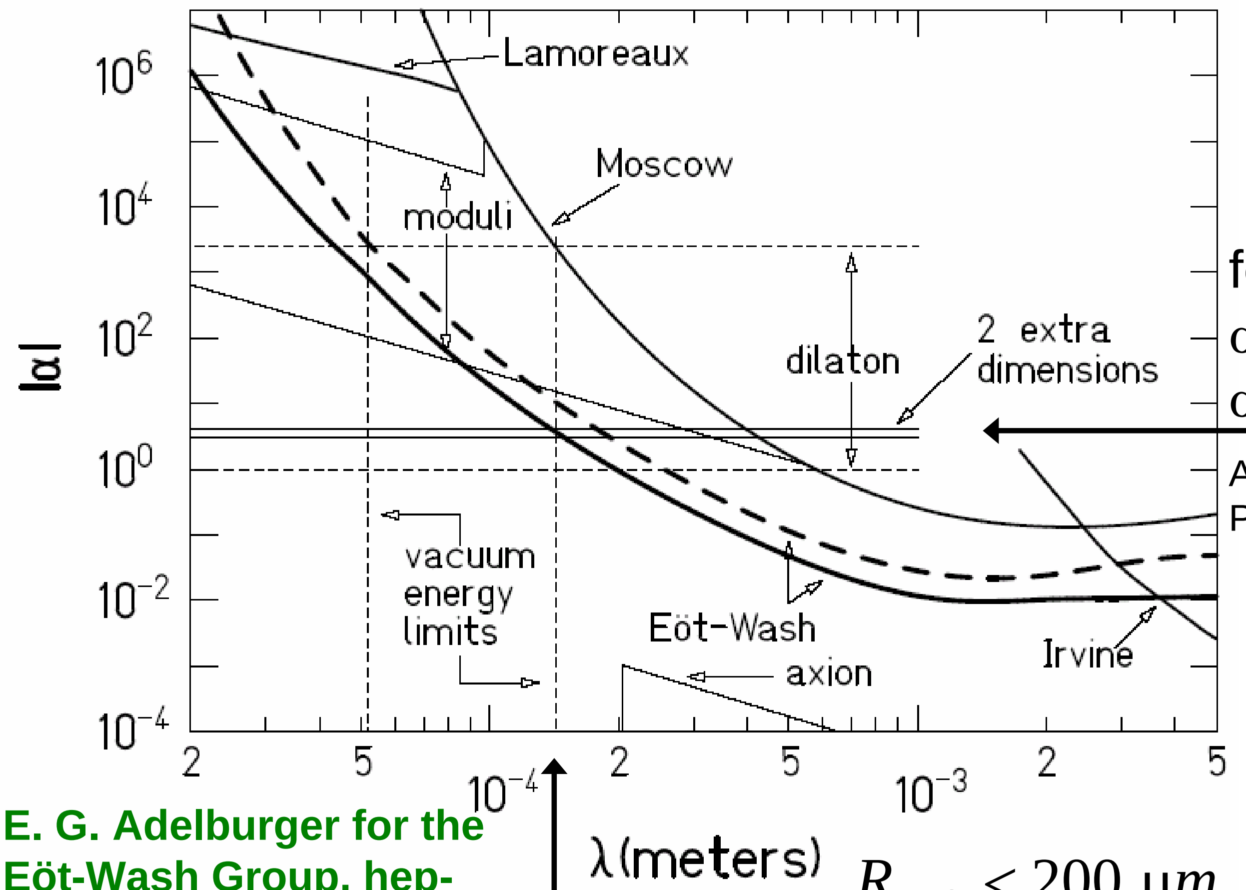
$n = 3 \rightarrow R = 2.9 \times 10^{6}\ \text{GeV}^{-1} = 57\ \text{nm}$

$n = 4 \rightarrow R = 7.9 \times 10^{3}\ \text{GeV}^{-1} = 1.6\ \text{pm}$

KK states separation very small: for n = 2, $R^{-1} = 2.5$ meV. High density of states compensates for low $\sim 1/M_{Pl}$ coupling, yielding chances to observe graviton effects at the LHC

Large Compact Extra Dimensions

$$V(r) = -G_{\mathrm{N}} \frac{m_1 m_2}{r}\left(1 + \alpha e^{-r/\lambda}\right)$$



for n = 2, then

α = 4 for 2-torus

α = 3 for 2-sphere

A. Kehagias, K. Sfetsos
PL B472 (2000) 39

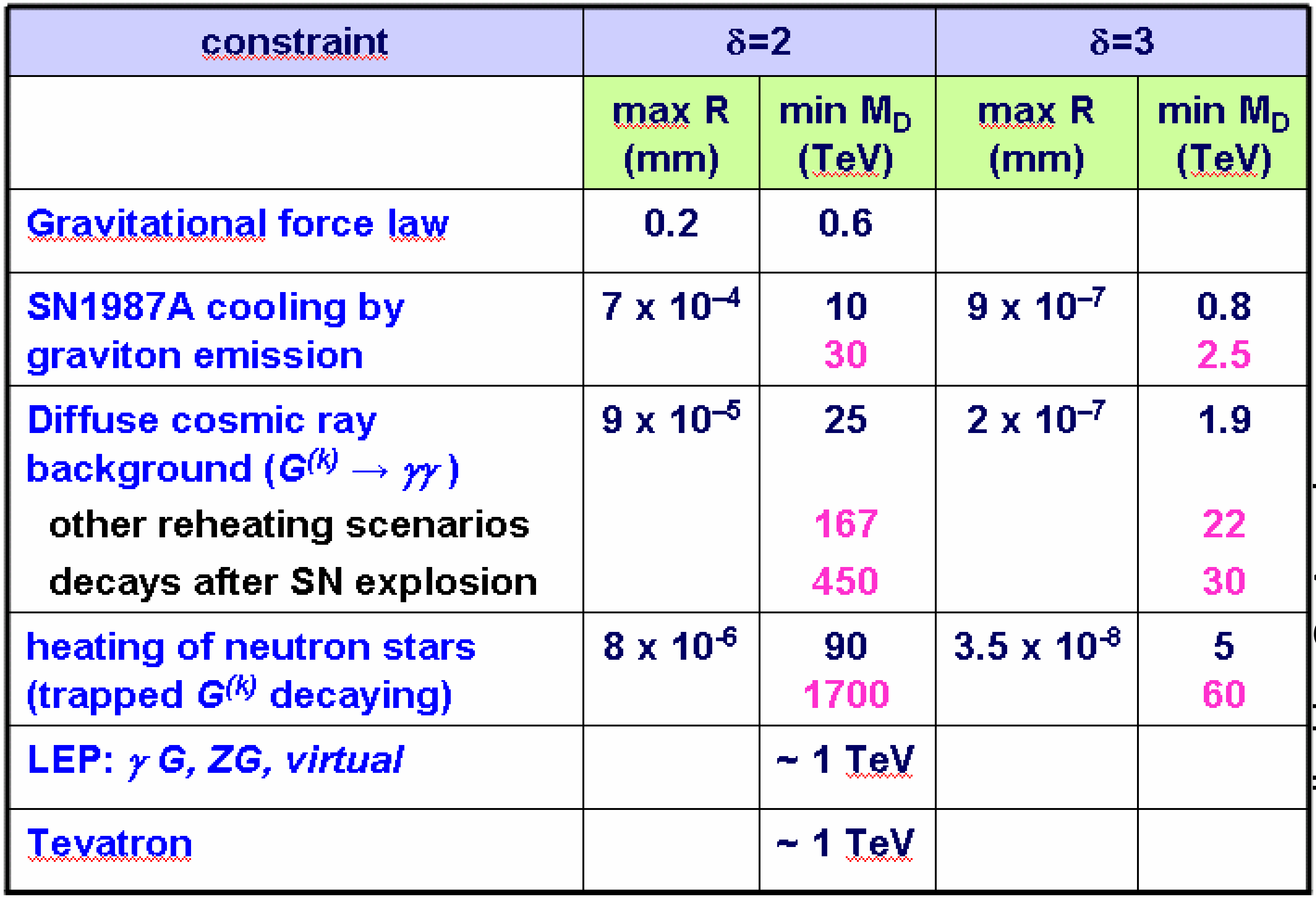
E. G. Adelburger for the Eöt-Wash Group, hep-ex/0202008

$R_{n=2}$ < 150 μm @ 95% CL

< 0.2 mm

$$R_{n=2} < 200\ \mu m \quad \Rightarrow \quad \bar{M}_{\mathrm{D}} > 0.62\ \mathrm{TeV}$$

Constraints on Large Extra Dimensions



constraint	δ=2		δ=3	
	max R (mm)	min M_D (TeV)	max R (mm)	min M_D (TeV)
Gravitational force law	0.2	0.6		
SN1987A cooling by graviton emission	7×10^{-4}	10 30	9×10^{-7}	0.8 2.5
Diffuse cosmic ray background ($G^{(k)} \to \gamma\gamma$)	9×10^{-5}	25	2×10^{-7}	1.9
other reheating scenarios		167		22
decays after SN explosion		450		30
heating of neutron stars (trapped $G^{(k)}$ decaying)	8×10^{-6}	90 1700	3.5×10^{-8}	5 60
LEP: γ *G, ZG, virtual*		~ 1 TeV		
Tevatron		~ 1 TeV		

compiled by G. Azuelos

G. F. Giudice and J. March-Russel, *PDG review 2002*

J. Hewett, M. Spiropulu, *Ann.Rev.Nucl.Part.Sci. 52 (2002) 397, hep-ph/0205106*

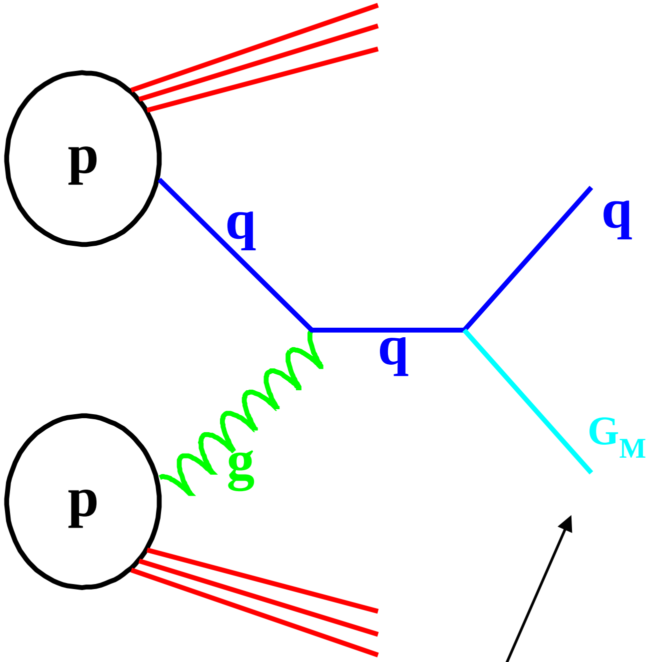
Large Compact Extra Dimensions

Possible signature in ATLAS and CMS:

$$\mathbf{pp} \to \mathbf{G}^{(k)} + \mathbf{j} \longrightarrow$$ Jet + missing energy

$$\mathbf{pp} \to \mathbf{G}^{(k)} + \gamma \longrightarrow$$ single photon

$$\mathbf{pp} \to \mathbf{G}^{(k)} + \mathbf{Z}$$



Graviton escape into the bulk!!

Jet + missing energy

n	$M_D^{\min}(\mathrm{TeV})$	$M_D^{\max}(\mathrm{TeV})$	R
2	~ 4	7.5	10 μm
3	~ 4.5	5.9	300 pm
4	~ 5	5.3	1 pm

single photon

n	$M_D^{\min}(\mathrm{TeV})$	$M_D^{\max}(\mathrm{TeV})$	R
2	~ 3.5	3.7	30 μm

ATL-PHYS-2000-016

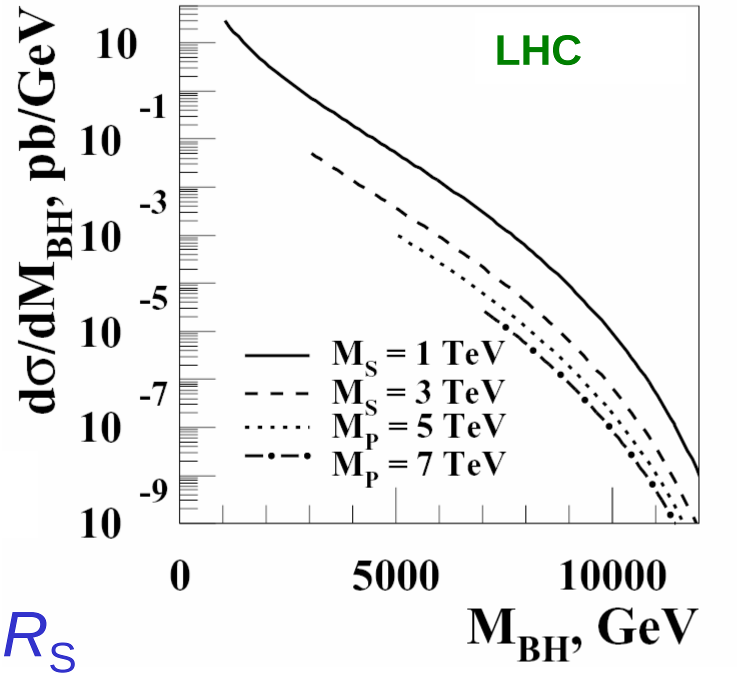
Black holes

Object confined to a volume of radius $R < R_\mathrm{S}$

$$R_\mathrm{S} = \frac{1}{\sqrt{\pi} M_\mathrm{D}} \left[\frac{M_\mathrm{BH}}{M_\mathrm{D}} \left(\frac{8\Gamma\left(\frac{n+3}{2}\right)}{n+2} \right) \right]^{\frac{1}{n+1}}$$

$$M_\mathrm{D} \sim 1\ \mathrm{TeV} \quad \Rightarrow \quad \pi R_\mathrm{S} \approx O(100\ \mathrm{pb})$$

contested approximation: Voloshin PL B518 (2001) 137, PL B524 (2002) 376, Rychkov hep-ph/0401116



Dimopoulos et Landsberg, hep-ph/0106295

Production at the LHC through collisions with impact parameter $< R_\mathrm{S}$

Formation of black holes!

“The end of short scale physics”!!!

Giddings and Thomas, hep-ph/0106219

Many theoretical uncertainties...

Characteristics: blackbody radiation, emission of particles: high multiplicity, “democratic emission”, spherical distribution

Many search ideas at the LHC

- technicolour
- leptoquarks
- extra gauge bosons
- heavy leptons
- excited quarks, leptons
- quark substructure
- more complicated SM higgs sector
- Higgsless models
- Little Higgs
- many models with extra dimensions
- monopoles
- ...

Acknowledgements

Many thanks to F. Gianotti, K. Jakobs, G. Pollesello for very useful material and to G. Azuelos for material and enlightening discussions!

Many thanks also to the Institute organizers for giving me the opportunity to give these lectures in such a fantastic setting...

Conclusions

LHC and its experiments are the most ambitious high energy physics project ever attempted

- technical challenge, complexity, human and financial resources

The LHC will make a thorough exploration of the 1 TeV scale

- understand the origin of electroweak symmetry breaking and the origin of mass
- search for physics beyond the Standard Model
  - TeV SUSY and many interesting extensions
- test new concepts of spacetime

The LHC will study quark-gluon plasma

A truly fantastic adventure that will most likely improve our understanding of nature!