Physics at the Large Hadron Collider

Part I: The Experimental Challenge

Part II: Precision Physics and Searches

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LLWI 2005
Physics at the Large Hadron Collider

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
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 $y$. 

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MW and M_{\text{top}}

\[ M_W \] dependence through radiative corrections

Precision measurements of \( M_W \) and \( M_{\text{top}} \) provide important tests of the SM

P.D.G. 2004 values:

\[
M_{\text{top}} = 174.3 \pm 5.1 \text{ GeV} \\
M_W = 80.425 \pm 0.038 \text{ GeV}
\]

In 2007, expect

\[ \Delta M_W \approx 25 \text{ MeV (0.3\%)} \text{ from LEP/Tevatron} \]
\[ \Delta M_{\text{top}} \approx 3.0 \text{ GeV (1.7\%)} \text{ from Tevatron} \]

\{ LHC can do better thanks to large statistics \}

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W production

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

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

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

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

LHC is a W,Z factory

\[ \sim 180 \text{ Hz at } 10^{33} \text{ cm}^{-2}\text{s}^{-1} \]
**W Mass Measurement**

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

- Drell-Yan $W \rightarrow \text{jet jet}$ 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 $E_T^{\text{miss}}$ 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$^{-1}$
  - $\sim 300 \times 10^6$ events produced in one year
  - $\sim 60 \times 10^6$ events selected after analysis cuts in one year
  - about $50 \times$ Tevatron statistics
  - about $6000 \times$ the statistics of WW at LEP
W Mass Measurement

Consider \( W \rightarrow \ell \nu + X \), then

\[
M_W^2 = \left( p_\ell + p_\nu \right)^2 = \left( E_\ell + E_\nu \right)^2 - \left( \vec{p}_\ell + \vec{p}_\nu \right)^2
\]

We define the \( W \) transverse mass

\[
\left( M_T^W \right)^2 \equiv \left( E_T^\ell + E_T^\nu \right)^2 - \left( \vec{p}_T^\ell + \vec{p}_T^\nu \right)^2
\]

\[
\approx 2 E_T^\ell E_T^\nu \left( 1 - \cos \Delta \phi_{\ell \nu} \right)
\]

The transverse mass

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

\[
\frac{M_T^W}{\hat{M}_T^W} = 1 + O(\beta_W^2)
\]

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 $\Delta M_W \sim 25$ MeV per experiment, per channel

Combining both channels and both experiment could yield $\Delta M_W \sim 15$ MeV

Very difficult measurement

$m_W = 79.8$ GeV

$m_W = 80.3$ GeV

$M_W$ (GeV)
Top Quark

The top quark is a most intriguing fermion

- Discovery in 1994 at the Tevatron
- $m_{\text{top}} \approx 174$ GeV $\approx M_{(76\text{Os})}$
  - studying top may reveal clues about the origin of mass?
- $\Gamma_{\text{top}} \approx 1.8$ GeV so $\Gamma^{-1}_{\text{top}} \approx 3.7 \times 10^{-25}$ 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

\( \bar{t}t \) production = 833 pb
\( \approx 8 \times 10^6 \bar{t}t \) pairs produced for 10 fb\(^{-1} \)

- Wg fusion \( \approx 245 \) pb
- Wt production \( \approx 60 \) pb
- W* channel \( \approx 10 \) pb

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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**
  \[ t\bar{t} \rightarrow WbWb \rightarrow jjbjjb \]
  \[ \text{BR} \approx 44\% \text{ but large QCD multijet background} \]

- **dilepton channel**
  \[ t\bar{t} \rightarrow WbWb \rightarrow \ell\nu b \ell\nu b \]
  \[ \text{BR} \approx 5\% \text{ for } \ell = e, \mu \]

- **lepton plus jet channel**
  \[ t\bar{t} \rightarrow WbWb \rightarrow \ell\nu bjjb \]
  \[ \text{BR} \approx 30\% \text{ for } \ell = e, \mu \]
  preferred channel

In all cases, two jets are b-jets

- tagged using **displaced vertices** in the inner detector
- lifetime of b-hadrons \( \sim 1.5 \text{ ps} \), 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: $\Delta M_{\text{top}} << 100 \text{ MeV}$

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

More details see talk from Steven Lowette
The Standard Model Particles

fermions

{ leptons

\begin{pmatrix}
  \nu_e \\
  e \\
  \nu_\mu \\
  \mu \\
  \nu_\tau \\
  \tau \\
  u \\
  c \\
  t \\
  d \\
  s \\
  b
\end{pmatrix}

\begin{pmatrix}
  0 \\
  -1 \\
  +2/3 \\
  -1/3
\end{pmatrix}

quarks

U(1)_Y

SU(2)_L

SU(3)_C

bosons

\{ \text{Higgs doublet} \}

\begin{pmatrix}
  \varphi_1 \\
  i \varphi_2 \\
  \varphi_3 \\
  i \varphi_4
\end{pmatrix}

\begin{pmatrix}
  0 \\
  \gamma \\
  W^+ \\
  W^- \\
  Z^0 \\
  g_{1-8}
\end{pmatrix}

\begin{pmatrix}
  B \\
  W_1 \\
  W_2 \\
  W_3 \\
  g_{1-8}
\end{pmatrix}

\text{electro-weak}

\text{radiation}

\text{strong}

wanted!
Goldstone Model

We want: gauge invariance to generate interactions
We need: gauge invariant mechanism to generate mass

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 $\phi(x) \neq 0$
Lorentz invariance $\phi(x)$ is a scalar

Goldstone model: consider

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

$$\mathcal{V}(\phi) = -\mu^2 \phi^* \phi + \lambda \left( \phi^* \phi \right)^2 \quad \lambda > 0$$

$\mu^2 < 0$ Self-interacting Klein-Gordon field where $m^2 = -\mu^2$
$\mu^2 > 0$ $\mathcal{V}(\phi)|_{\min} = -\frac{\mu^2 v^2}{4} \Rightarrow |\phi|^2 = |\phi_0|^2 = \frac{\mu^2}{2\lambda} \equiv \frac{v^2}{2} > 0$

The equilibrium is characterized by $\phi_0 = \frac{v}{\sqrt{2}} e^{i\theta}$
Nature spontaneously chooses, say, $\theta = 0 \rightarrow \phi_0 = \frac{v}{\sqrt{2}} > 0$

always possible because of global U(1) phase invariance

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Goldstone Model

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

\[
\mathcal{L} = \frac{1}{2} \left( \partial_{\mu} \sigma \right) \left( \partial^\mu \sigma \right) - \mu^2 \sigma^2 + \frac{1}{2} \left( \partial_{\mu} \eta \right) \left( \partial^\mu \eta \right) + \mathcal{L}_{\text{int}}
\]

\[
\mathcal{L}_{\text{int}} = -\lambda \nu \sigma \left( \sigma^2 + \eta^2 \right) - \frac{1}{4} \lambda \left( \sigma^2 + \eta^2 \right)^2
\]

We can interpret: \( \sigma \rightarrow \) real Klein-Gordon field \( \frac{1}{2} m^2 = \mu^2 \)

\( \eta \rightarrow \) real Klein-Gordon field \( m_\eta = 0 \)

and n.d.f do add up

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

\( \pi^0, \pi^+, \pi^- \) come pretty close...
Higgs Model

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

Obtain
\[
\mathcal{L} = \left( D_\mu \varphi \right)^* \left( D^\mu \varphi \right) - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} - \mathcal{V}(\varphi)
\]
\[
\mathcal{V}(\varphi) = -\mu^2 \varphi^* \varphi + \lambda \left( \varphi^* \varphi \right)^2 \quad \lambda > 0
\]

Invariant under
\[
\varphi \xrightarrow{\epsilon(x)} \varphi' = e^{-i\epsilon(x)} \varphi
\]
\[
A_\mu \xrightarrow{\epsilon(x)} A'_\mu = A_\mu + \frac{1}{q} \partial^\mu \epsilon
\]

\( \mu^2 < 0 \quad \rightarrow \quad \text{Scalar electrodynamics with self-interacting Klein-Gordon field where } m^2 = -\mu^2 \)

\( \mu^2 > 0 \quad \rightarrow \quad V(\varphi)_{\text{min}} = -\frac{\mu^2 v^2}{4} \Rightarrow |\varphi|^2 = |\varphi_0|^2 = \frac{\mu^2}{2\lambda} = \frac{v^2}{2} > 0 \)

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

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

Again, use \( \varphi(x) = \frac{1}{\sqrt{2}} [v + \sigma(x) + i\eta(x)] \)
Higgs Model

Obtain
\[ \mathcal{L} = \frac{1}{2} (\partial_\mu \sigma)(\partial^\mu \sigma) - \mu^2 \sigma^2 + \frac{1}{2} (\partial_\mu \eta)(\partial^\mu \eta) - \frac{1}{4} F_{\mu \nu} F^{\mu \nu} + \frac{1}{2} (q v)^2 A_\mu A^\mu + q v (\partial_\mu \eta) A^\mu + \mathcal{L}' \]

can interpret \( \sigma \rightarrow \text{real Klein-Gordon field} \) \( \frac{1}{2} m^2 = \mu^2 \)

but cannot interpret \( \eta \rightarrow \text{real Klein-Gordon field} \) \( m_\eta = 0 \)
\( A_\mu \rightarrow \text{real Proca field} \quad M_A = q v \)

and n.d.f would NOT add up

Initially:
\[
\begin{aligned}
\{ &\{\text{complex } \varphi \rightarrow 2 \} \\
&\{\text{real massless } A_\mu \rightarrow 2 \} \}
\end{aligned}
\]

\[ \rightarrow 4 \]

\[ \downarrow \]

\[ \begin{aligned}
\{ &\{\text{real massive } \sigma \rightarrow 1 \} \\
&\{\text{real massless } \eta \rightarrow 1 \} \\
&\{\text{real massive } A_\mu \rightarrow 3 \} \}
\end{aligned} \]

\[ \rightarrow 5 \]

\( \mathcal{L} \) contains an unphysical field which can be eliminated through a gauge transformation yielding the form

\[ \varphi(x) = \frac{1}{\sqrt{2}} [v + \sigma(x)] \quad \text{unitary gauge} \]

\( \eta(x) \rightarrow \text{would-be Goldstone boson field} \)
Higgs Mechanism

In this gauge, we obtain
\[ \mathcal{L} = \frac{1}{2} \left( \partial_{\mu} \sigma \right) \left( \partial^{\mu} \sigma \right) - \mu^{2} \sigma^{2} - \frac{1}{4} F_{\mu \nu} F^{\mu \nu} + \frac{1}{2} \left( q v \right)^{2} A_{\mu} A^{\mu} + \mathcal{L}_{\text{int}} \]

\[ \mathcal{L}_{\text{int}} = -\lambda v \sigma^{3} - \frac{1}{4} \lambda \sigma^{4} + \frac{1}{2} q^{2} A_{\mu} A^{\mu} \left( 2 v \sigma + \sigma^{2} \right) \]

can interpret \( \sigma \rightarrow \) real Klein-Gordon field \( \frac{1}{2} m^{2} = \mu^{2} \)

\[ A^{\mu} \rightarrow \) real Proca field \]

\[ M_{A} = q v \]

and n.d.f do add up

Initially:
\[ \begin{cases} 
\text{complex} \ \varphi & \rightarrow 2 \\
\text{real massless} \ A^{\mu} & \rightarrow 2 \\
\text{real massive} \ \sigma & \rightarrow 1 \\
\text{real massive} \ A^{\mu} & \rightarrow 3 
\end{cases} \rightarrow 4 \]

After:
\[ \begin{cases} 
\text{complex} \ \varphi & \rightarrow 2 \\
\text{real massless} \ A^{\mu} & \rightarrow 2 \\
\text{real massive} \ \sigma & \rightarrow 1 \\
\text{real massive} \ A^{\mu} & \rightarrow 3 
\end{cases} \rightarrow 4 \]

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 \( \sigma \) and \( A^{\mu} \)!
The Standard Model
of Electroweak and Strong Interactions

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

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
  - $\nu_e$
  - $\nu_\mu$
  - $\nu_\tau$
- quarks
  - $u$
  - $d$
  - $c$
  - $s$
  - $t$
  - $b$

matter

bosons

- $U(1)_Y$
- $SU(2)_L$
- $SU(3)_C$
- Higgs doublet

electro-weak

radiation

strong

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

$M_H$ is too large: the higgs self-coupling blows up at some scale $\Lambda$

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

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

130 GeV $\approx < M_H < 180$ GeV

then, in principle consistent with $\Lambda=M_{PL}$
SM Higgs Production at the LHC

**gluon fusion**
don dominant process

**vector boson fusion**
20% of gg at 120 Gev

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

**associated prod.**
t t or b b, 1-5% of gg

4 production mechanisms is the key to measuring H parameters

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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
  \[
  v = \left(\frac{\sqrt{2} G_F}{\sqrt{2} G_F} \right)^{1/2} = 246 \text{ GeV}
  \]

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

Higgs couplings proportional to mass →

\[
G^2 = 4\sqrt{2} G_F M_W^2
\]

- $\varphi(x)$ interacts with fermion fields, $H$ and $\bar{f}$
- $H$ interacts with $W^+$, $W^-$, $Z$
- $\gamma$ and $g$ interactions with $H$

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Main SM Higgs Discovery Channels

Low $M_H$ region, $M_H < 2M_Z$

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

Dominant BR:

$\sigma(H \rightarrow b\bar{b}) \approx 20$ pb
$\sigma(b\bar{b}) \approx 500$ $\mu$b

Cannot trigger or extract fully hadronic final states

Must look for final states with $\ell(e,\mu), \gamma$

$M_H = 120$ GeV, direct production

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Main SM Higgs Discovery Channels

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

- $H \rightarrow ZZ \rightarrow 4\ell$  Gold plated 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

\[ M_H < 150 \text{ GeV} \]
\[ \sigma(pp \to H_{(100\text{GeV})}) \times \text{BR}(H \to \gamma\gamma) \approx 50 \text{ fb} \]
\[ \text{one every } \sim 30 \text{ min at } 10^{34} \text{ cm}^{-2}\text{s}^{-1} \]

- Select events with two photons in the detector with \( p_T \sim 50 \text{ GeV} \)
- 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: $H \rightarrow \gamma\gamma$

Main backgrounds

- $\gamma\gamma$ production
  - irreducible (same final state as signal!), e.g.
    \[
    \frac{\sigma(\gamma\gamma)}{\sigma(H \rightarrow \gamma\gamma)} \approx 60 \quad \text{for} \quad m_{\gamma\gamma} \approx 100 \text{ GeV}
    \]

- $\gamma$ jet + $\gamma$ jet production where one or both jets fake a photon
  - reducible, e.g.
    \[
    \frac{\sigma(jj)}{\sigma(H \rightarrow \gamma\gamma)} \approx 10^8 \quad \text{for} \quad m_{\gamma\gamma/jj} \approx 100 \text{ GeV}
    \]
Light Higgs Discovery: $H \rightarrow \gamma\gamma$

Dealing with backgrounds: $\gamma$ jet + jet jet production

- reducible
- requires excellent $\gamma$/jet separation, in particular $\gamma/\pi^0$ separation, to reject jets faking photons; $R_{\text{jet}} \approx 10^3$ needed for $\varepsilon_{\gamma} \approx 80\%$
- ATLAS and CMS have calorimeters with good granularity to separate single $\gamma$ from jets or from $\pi^0 \rightarrow \gamma\gamma$

ATLAS simulation

with this performance

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

$\rightarrow$ 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 $\sim \sigma(m)^{-1/2}$

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

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

energy resolution of EM calorimeters

resolution of the measurement of $\theta_{12}$

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
  - longitudinal segmentation allows the measurement of $\gamma$ direction
  
  \[
  \frac{\sigma(E)}{E} \approx \frac{10\%}{\sqrt{E \text{ (GeV)}}} \\
  \sigma(\theta) \approx \frac{50 \text{ mrad}}{\sqrt{E \text{ (GeV)}}}
  \]

  \[
  \sigma(m) \approx 1.3 \text{ GeV for } M_H \approx 100 \text{ GeV and } \varepsilon \approx 30\%
  \]

- **CMS**
  - homogeneous PbWO$_4$ crystal EM calorimeter
  - no longitudinal segmentation, so harder to pick up the right vertex at high luminosity using secondary tracks from spectator partons

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

  \[
  \sigma(m) \approx 0.7 \text{ GeV for } M_H \approx 100 \text{ GeV and } \varepsilon \approx 20\%
  \]
Light Higgs Discovery: $H \rightarrow \gamma \gamma$

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 10³⁴ 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

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

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Maximal extension of the Poincaré group

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 $M_{\text{SUSY}} \lesssim 1$ TeV. SUSY can be viable up to $M_{\text{PL}}$ AND be natural!

About half the particles already discovered!

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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 $M_{\text{SUSY}} \approx 1 \text{ TeV}$

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

Local SUSY is SUperGRAVity

SUSY is an ingredient of string theories $\rightarrow$ superstrings

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

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

MSSM: SM + an extra Higgs doublet + SUSY partners

SUSY breaking

| 0  | $H_d^-$ $H_d^0$ $H_u^0$ $H_u^+$ | $	ilde{H}_d^-$ $\tilde{H}_d^0$ $\tilde{H}_u^0$ $\tilde{H}_u^+$ | $\tilde{q}_R^d$ $\tilde{q}_L^d$ $\tilde{q}_R^u$ $\tilde{q}_L^u$ $\tilde{v}_L$ $\tilde{v}_R$ $\tilde{I}_R$ $\tilde{I}_L$ |
|----|----------------|----------------|----------------|----------------|
| $\frac{1}{2}$ | $B^0$ $W^0$ $\tilde{W}^-$ $\tilde{W}^+$ $g$ | $B^0$ $W^0$ $\tilde{W}^-$ $\tilde{W}^+$ $g$ |
| 1  | $u_L$ $d_L$ $u_R$ $d_R$ |

EW symmetry breaking

| 0  | $A$ $H$ $h$ $H^-$ $H^+$ | $\tilde{q}_2^d$ $\tilde{q}_1^d$ $\tilde{q}_2^u$ $\tilde{q}_1^u$ $\tilde{v}_1$ $\tilde{l}_2$ $\tilde{l}_1$ |
|----|----------------|----------------|----------------|----------------|
| $\frac{1}{2}$ | $\chi_4^0$ $\chi_3^0$ $\chi_2^0$ $\chi_1^0$ $\chi_2^- \chi_1^- \chi_2^+ \chi_1^+$ $\tilde{g}$ | $\chi_4^0$ $\chi_3^0$ $\chi_2^0$ $\chi_1^0$ $\chi_2^- \chi_1^- \chi_2^+ \chi_1^+$ $\tilde{g}$ |
| 1  | $Z^0$ $\gamma$ $W^-$ $W^+$ $g$ |

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”)

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

Note that we also have the following mixings

$$B^0, W^0 \rightarrow \gamma, Z^0$$
$$\tilde{W}^\pm, \tilde{H}^\pm \rightarrow \chi_{1,2}^\pm$$
$$\tilde{B}^0, \tilde{W}^0, H_u^0, H_d^0 \rightarrow \chi_{1,2,3,4}^0$$
$$\tilde{l}_L, \tilde{l}_R \rightarrow \tilde{l}_1, \tilde{l}_2$$

with off-diagonal elements proportional to fermion masses

$q_L, q_R \rightarrow q_1, q_2$
SUSY Particle Production

Squarks and gluinos produced via strong processes:

large cross sections

example:

\[ m_{\tilde{q}, \tilde{g}} \sim 1 \text{ TeV} \quad \Rightarrow \quad \sigma \sim 1 \text{ pb} \]

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

example:

\[ m_{\chi} \sim 150 \text{ GeV} \quad \Rightarrow \quad \sigma \sim O(\text{pb}) \]

\( \tilde{q}q, \tilde{q}g, \tilde{g}g \) 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 + $E_T^{\text{miss}}$

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Discovering SUSY

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

\[ \tilde{q}, \tilde{g} \text{ are heavy } (m > 250 \text{ GeV}) \]

\[ \text{decays through cascades favoured:} \]
many high $P_T$ jets, leptons, $W$, $Z$ in the final state, and $E_T^{\text{miss}}$

\[ \text{should be easy to extract SUSY from SM background at the LHC} \]
"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


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

\[
V_{3+1+n}(r) = \frac{-m_1 m_2}{8\pi (2\pi)^n M_D^{n+2} r^{n+1}} \quad \text{for} \quad r < R
\]

while

\[
V(r) = \frac{-m_1 m_2}{8\pi M_{Pl}^2 r} \quad \text{for} \quad r > R
\]

where

\[
\bar{M}_{Pl}^2 = \frac{1}{8\pi} M_{Pl}^2 = (8\pi G_N)^{-1}
\]

hence

\[
\bar{M}_D^{2+n} = \frac{\bar{M}_{Pl}^2}{(2\pi R)^n}
\]

Weakness of gravity is only apparent in 3+1
Large Compact Extra Dimensions

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

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

Kaluza-Klein states of graviton with mass $k/R$

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

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

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

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

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

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

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Large Compact Extra Dimensions

\[ V(r) = -G_N \frac{m_1 m_2}{r} \left( 1 + \alpha e^{-r/\lambda} \right) \]

for \( n = 2 \), then
\( \alpha = 4 \) for 2-torus
\( \alpha = 3 \) for 2-sphere

E. G. Adelburger for the Eöt-Wash Group, hep-ex/0202008
\( R_{n=2} < 150 \, \mu m \) @ 95% CL

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

\( R_{n=2} < 200 \, \mu m \) \( \Rightarrow \) \( \bar{M}_D > 0.62 \, \text{TeV} \)
# Constraints on Large Extra Dimensions

<table>
<thead>
<tr>
<th>Constraint</th>
<th>δ=2</th>
<th>δ=3</th>
</tr>
</thead>
<tbody>
<tr>
<td>max R (mm)</td>
<td>min $M_D$ (TeV)</td>
<td>max R (mm)</td>
</tr>
<tr>
<td>Gravitational force law</td>
<td>0.2</td>
<td>0.6</td>
</tr>
<tr>
<td>SN1987A cooling by graviton emission</td>
<td>$7 \times 10^{-4}$</td>
<td>10</td>
</tr>
<tr>
<td>Diffuse cosmic ray background ($G^{(k)} \rightarrow \gamma\gamma$)</td>
<td>$9 \times 10^{-5}$</td>
<td>25</td>
</tr>
<tr>
<td>other reheating scenarios</td>
<td></td>
<td></td>
</tr>
<tr>
<td>decays after SN explosion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heating of neutron stars (trapped $G^{(k)}$ decaying)</td>
<td>$8 \times 10^{-6}$</td>
<td>90</td>
</tr>
<tr>
<td>$\gamma G, ZG, virtual$</td>
<td></td>
<td>~ 1 TeV</td>
</tr>
<tr>
<td>Tevatron</td>
<td></td>
<td>~ 1 TeV</td>
</tr>
</tbody>
</table>

G. F. Giudice and J. March-Russel, *PDG review 2002*
Large Compact Extra Dimensions

Possible signature in ATLAS and CMS:

- \( pp \rightarrow G^{(k)} + j \) → Jet + missing energy
- \( pp \rightarrow G^{(k)} + \gamma \) → single photon
- \( pp \rightarrow G^{(k)} + Z \)

Jet + missing energy

<table>
<thead>
<tr>
<th>( n )</th>
<th>( M_D^{\text{min}}(\text{TeV}) )</th>
<th>( M_D^{\text{max}}(\text{TeV}) )</th>
<th>( R )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>( \sim 4 )</td>
<td>7.5</td>
<td>10 µm</td>
</tr>
<tr>
<td>3</td>
<td>( \sim 4.5 )</td>
<td>5.9</td>
<td>300 pm</td>
</tr>
<tr>
<td>4</td>
<td>( \sim 5 )</td>
<td>5.3</td>
<td>1 pm</td>
</tr>
</tbody>
</table>

Single photon

<table>
<thead>
<tr>
<th>( n )</th>
<th>( M_D^{\text{min}}(\text{TeV}) )</th>
<th>( M_D^{\text{max}}(\text{TeV}) )</th>
<th>( R )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>( \sim 3.5 )</td>
<td>3.7</td>
<td>30 µm</td>
</tr>
</tbody>
</table>

Graviton escape into the bulk!!

ATL-PHYS-2000-016
Black holes

Object confined to a volume of radius $R < R_S$

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

$M_D \sim 1 \text{ TeV} \quad \Rightarrow \quad \pi R_S \approx O(100 \text{ pb})$


Production at the LHC through collisions with impact parameter $< R_S$

Formation of black holes!

“The end of short scale physics”!!!

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
- ...

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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!